The DIS Landscape: High-energy & high-luminosity electron-proton/nucleon scattering

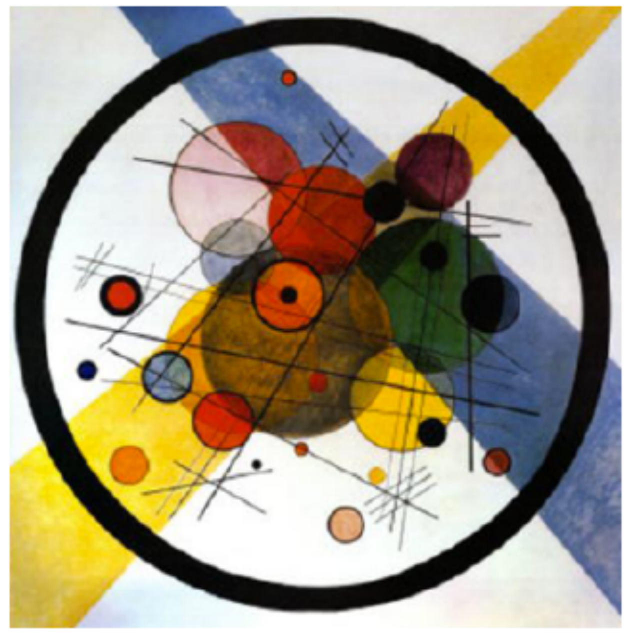
Christian Schwanenberger
DESY
University of Hamburg

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

German strategy workshop "The future of Collider Physics"

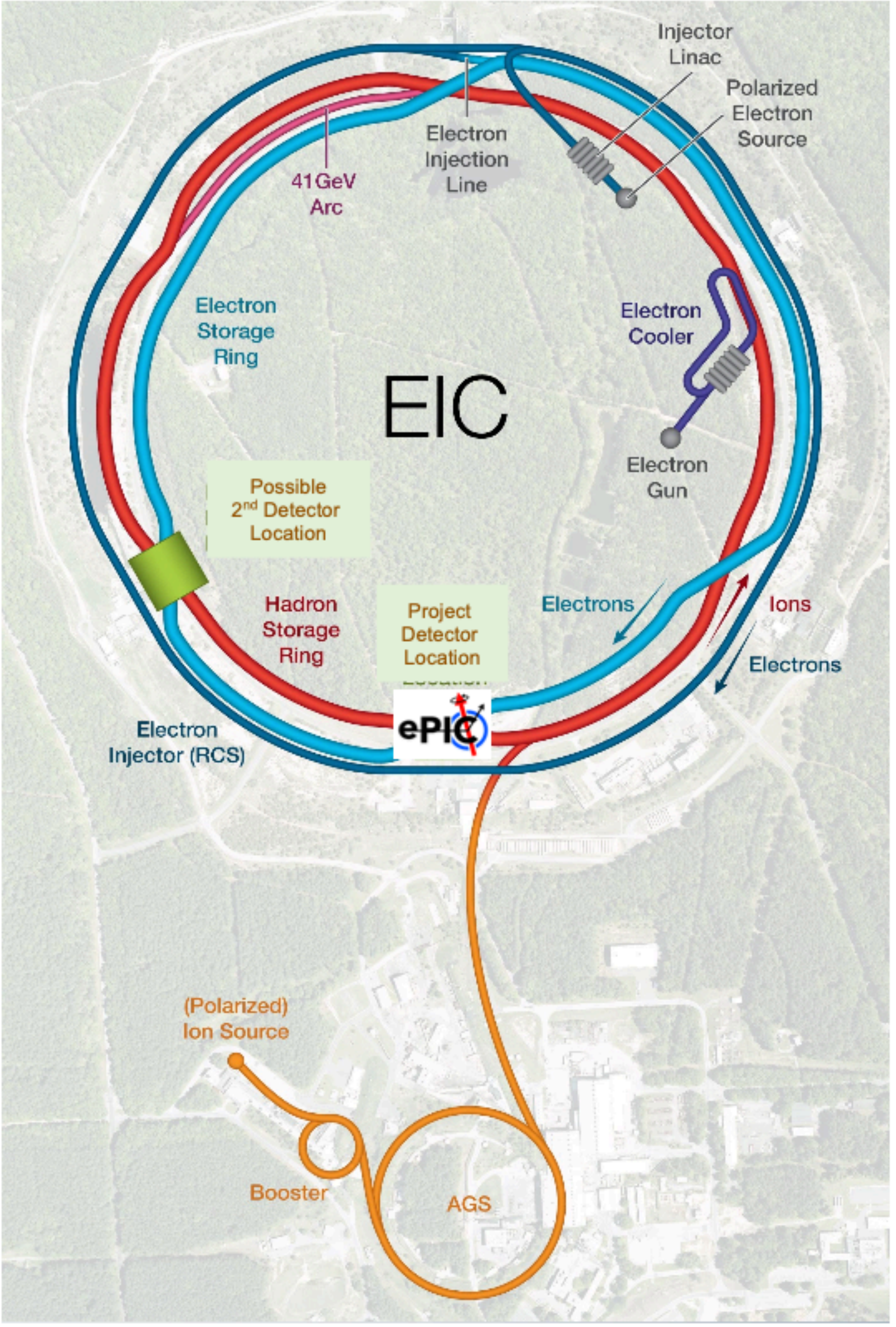
in preparation of the ESPP update



Circles in a circle
W Kandinsky

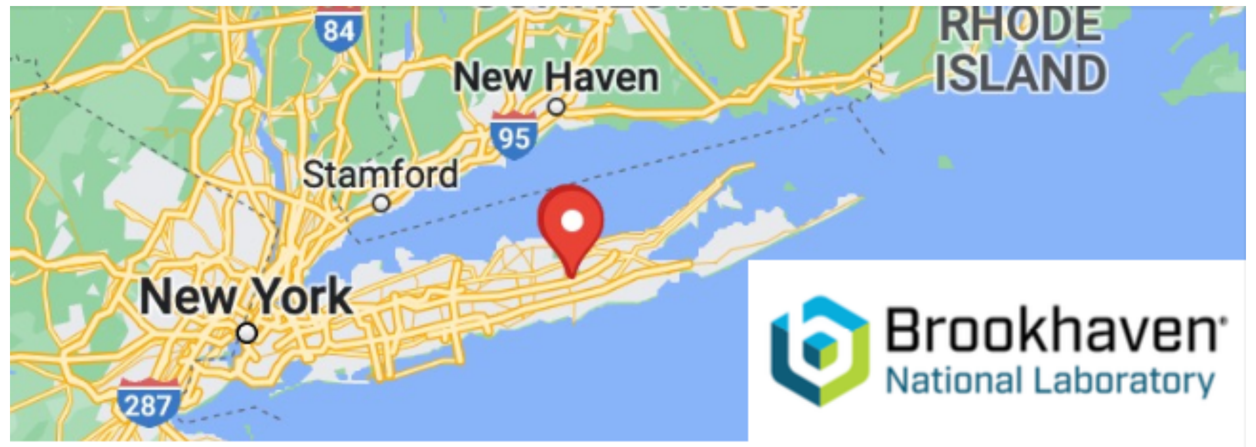
DESY
28 November 2024

The Electron-Ion Collider (EIC)



New electron ring, to collide with RHIC p, A

- Energy range **28 < $\sqrt{s}$ < 140 GeV**, accessing moderate / large x values compared with HERA



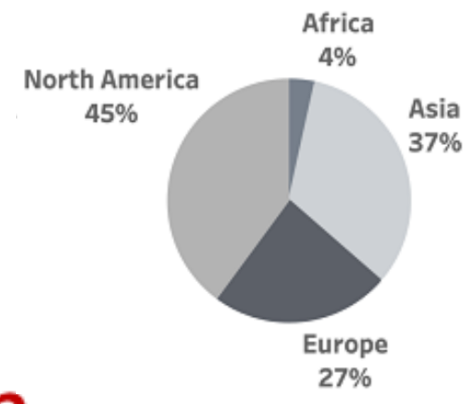
World's first …

- High lumi ep Collider
  (~ 10^{34} cm^{-2} s^{-1} → ~100 fb^{-1} per year)
- Double-polarised DIS collider
  (~70% for leptons & light hadrons)
- eA collider
  (Ions H to U)

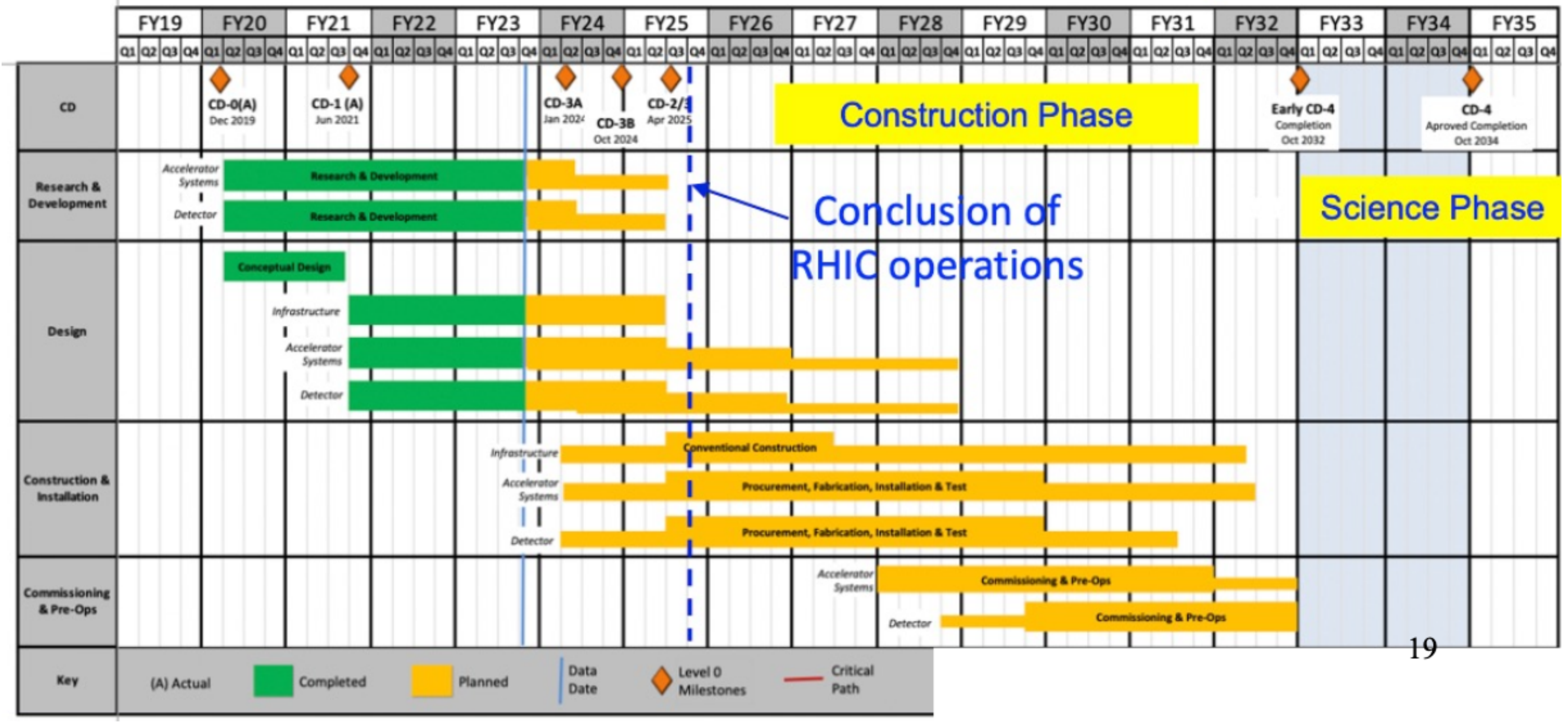
CD-0 (Mission need)	Dec 2019
CD-1 (Cost range)	June 2021
CD-3A (Start construction)	April 2024
CD-3B	March 2025
CD-2 (Performance baseline)	2025?
CD-4 (Operations / completion)	2032-34

Technical Design Report: end 2025 (prelim 2024)

- Total cost ~$2.5Bn (US project funds accelerator + most of one detector)



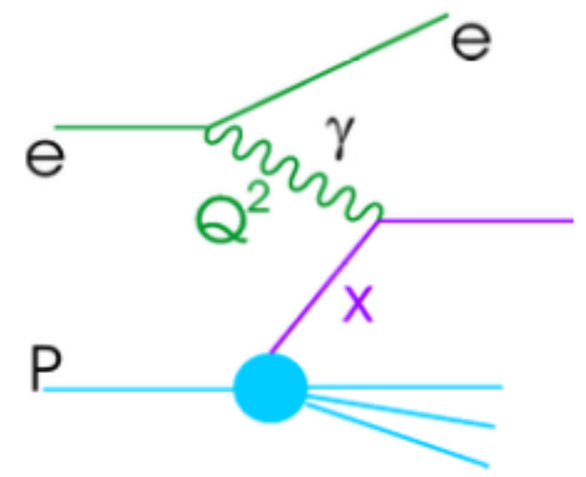
- Still several steps to go, but on target for operation early/mid 30s



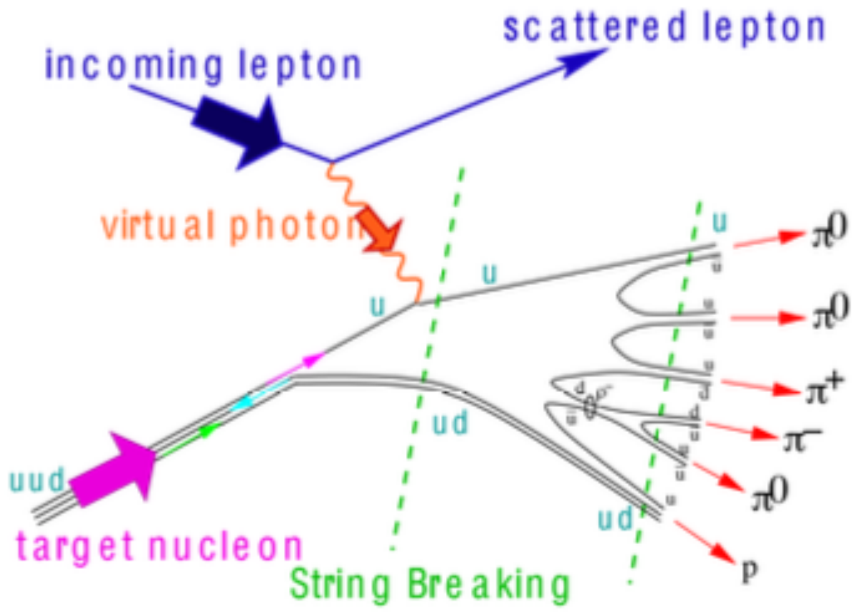
ePIC: currently >850 collaborators, 171 institutions, 24 countries
Germany: GSI, KIT, Wuppertal
32 German users (theory, experiment, accelerator)

Physics questions to be addressed at EIC

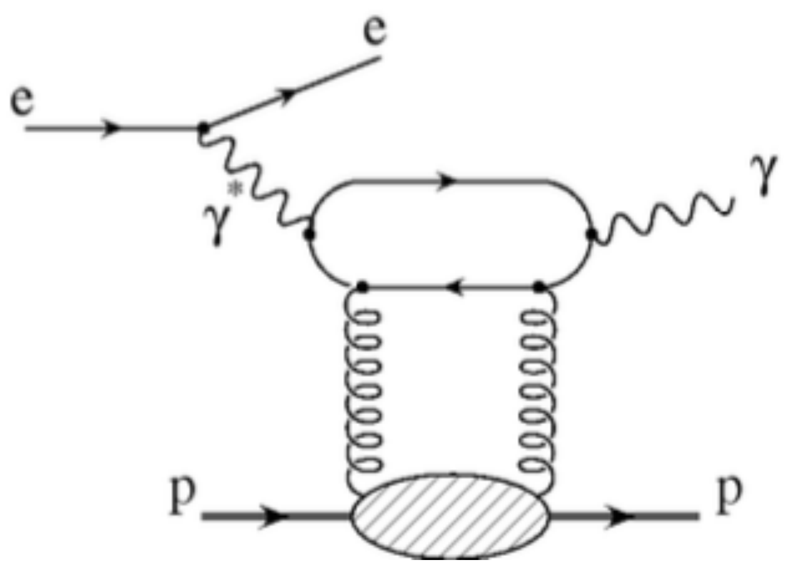
Inclusive



Semi-Inclusive



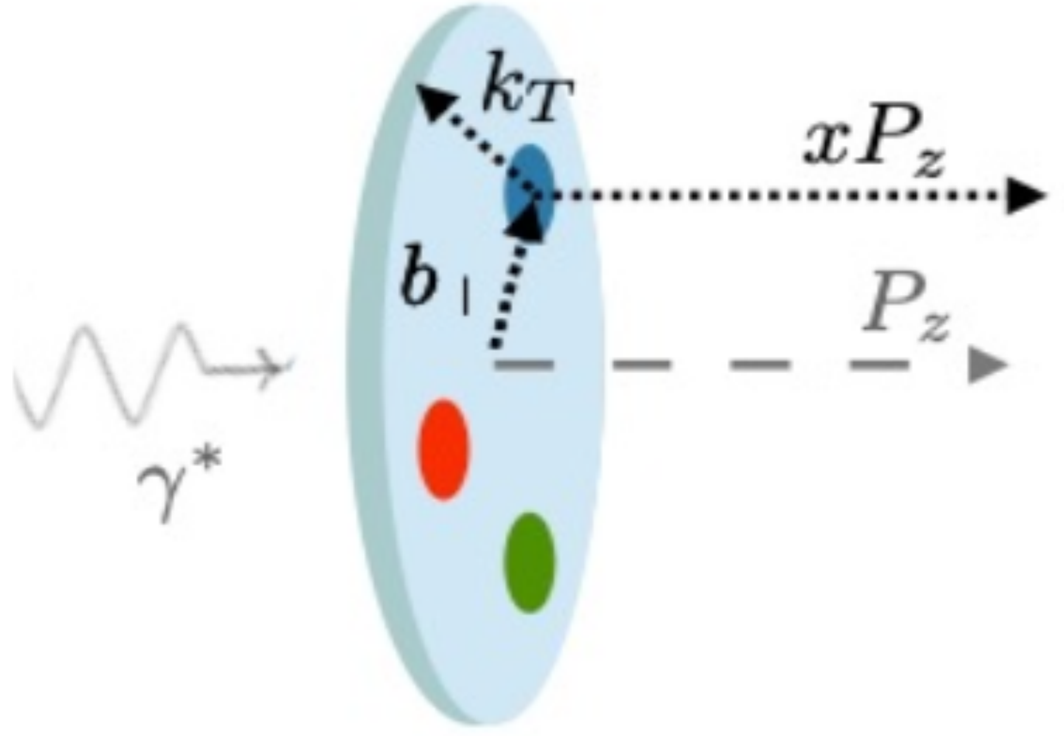
Exclusive / Diffractive



- How is proton mass generated from quark and gluon interactions?

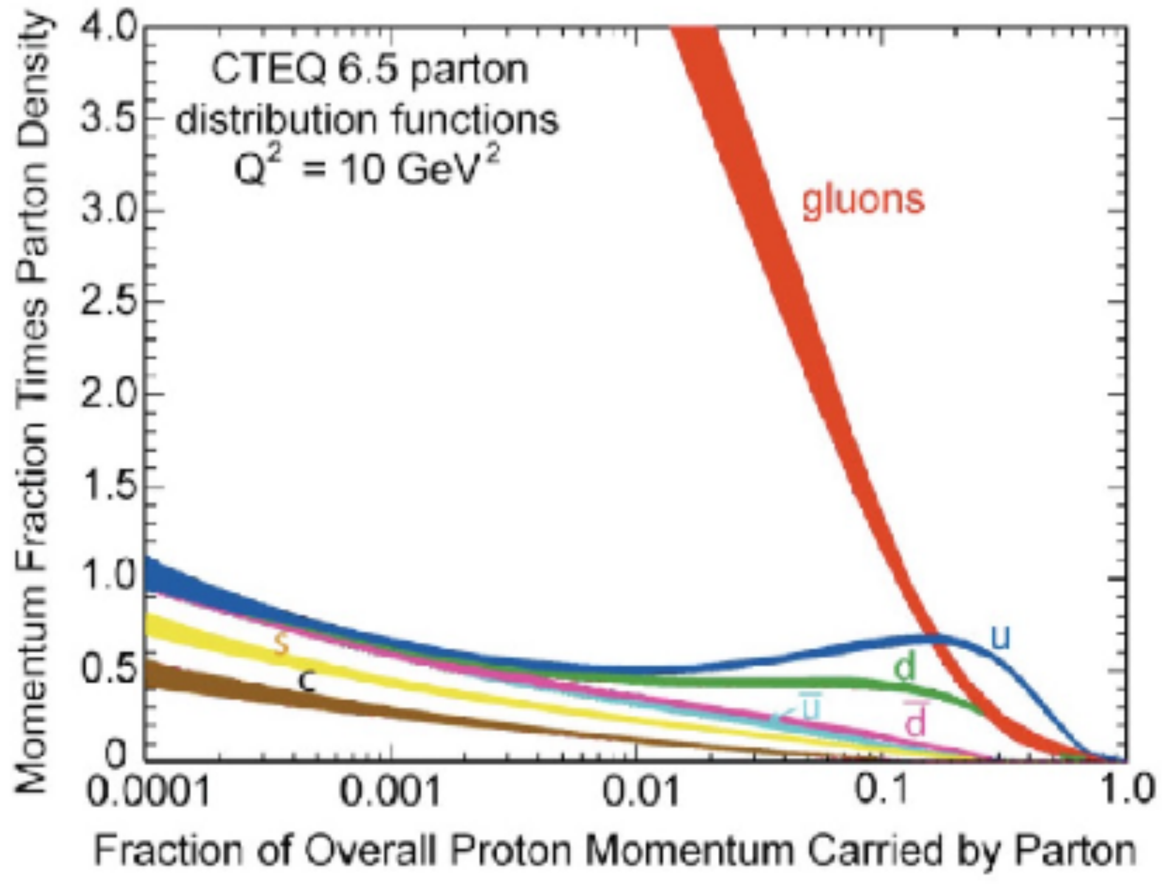
Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

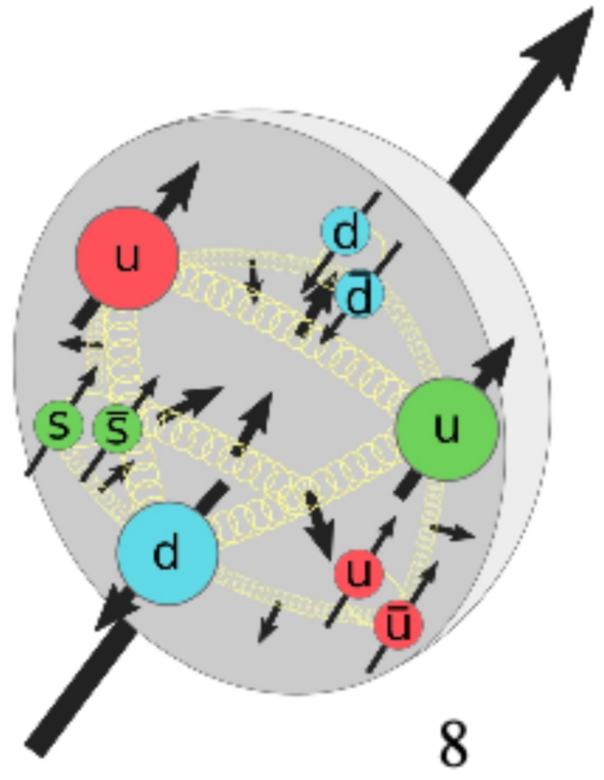
- What does the proton look like in 3D?



- How is proton spin generated?

- How do the dynamics of high density systems of gluons tame the low x growth?

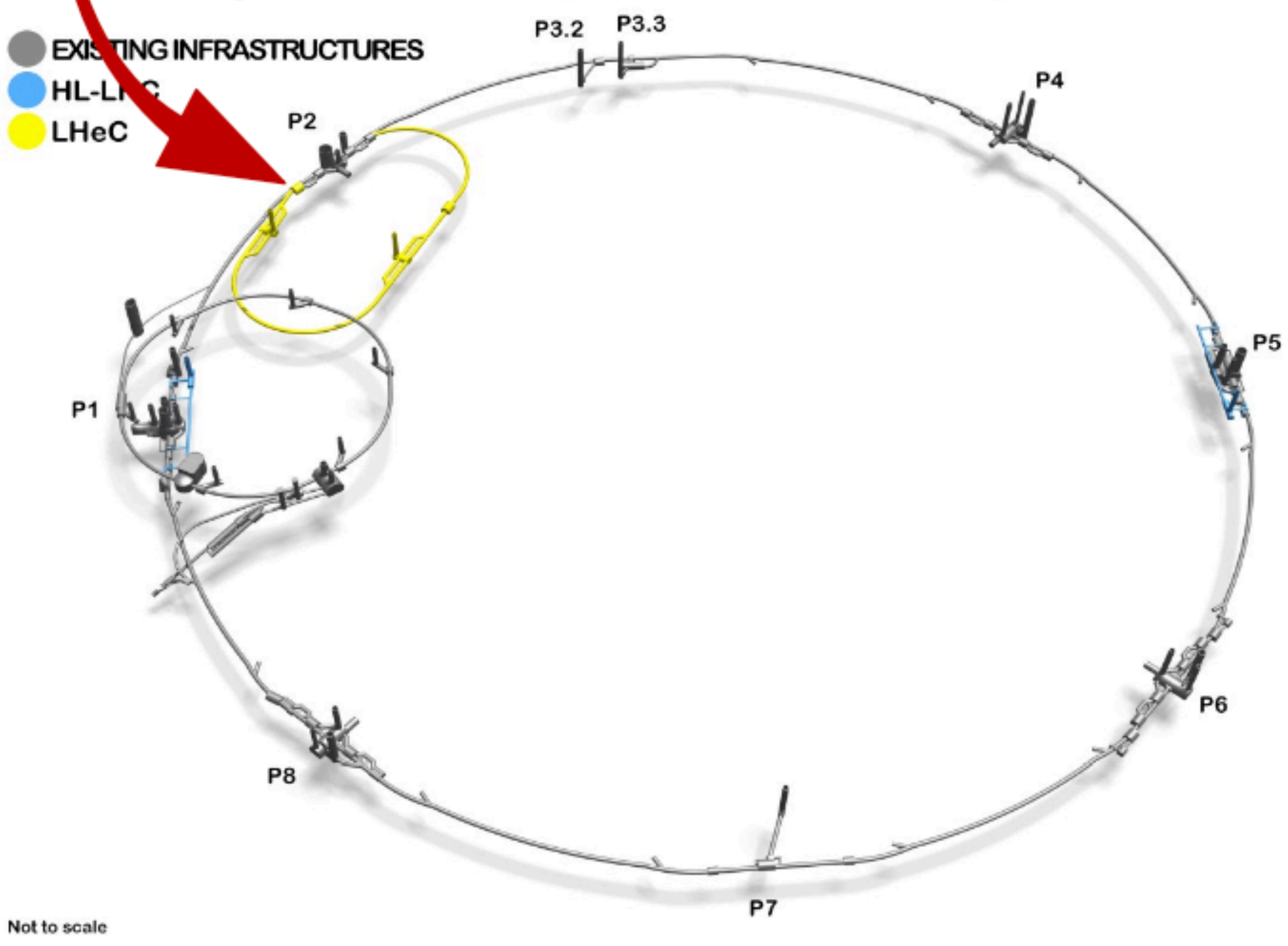




Linac-Ring Collider, LHeC and FCC-eh

LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳Run5)

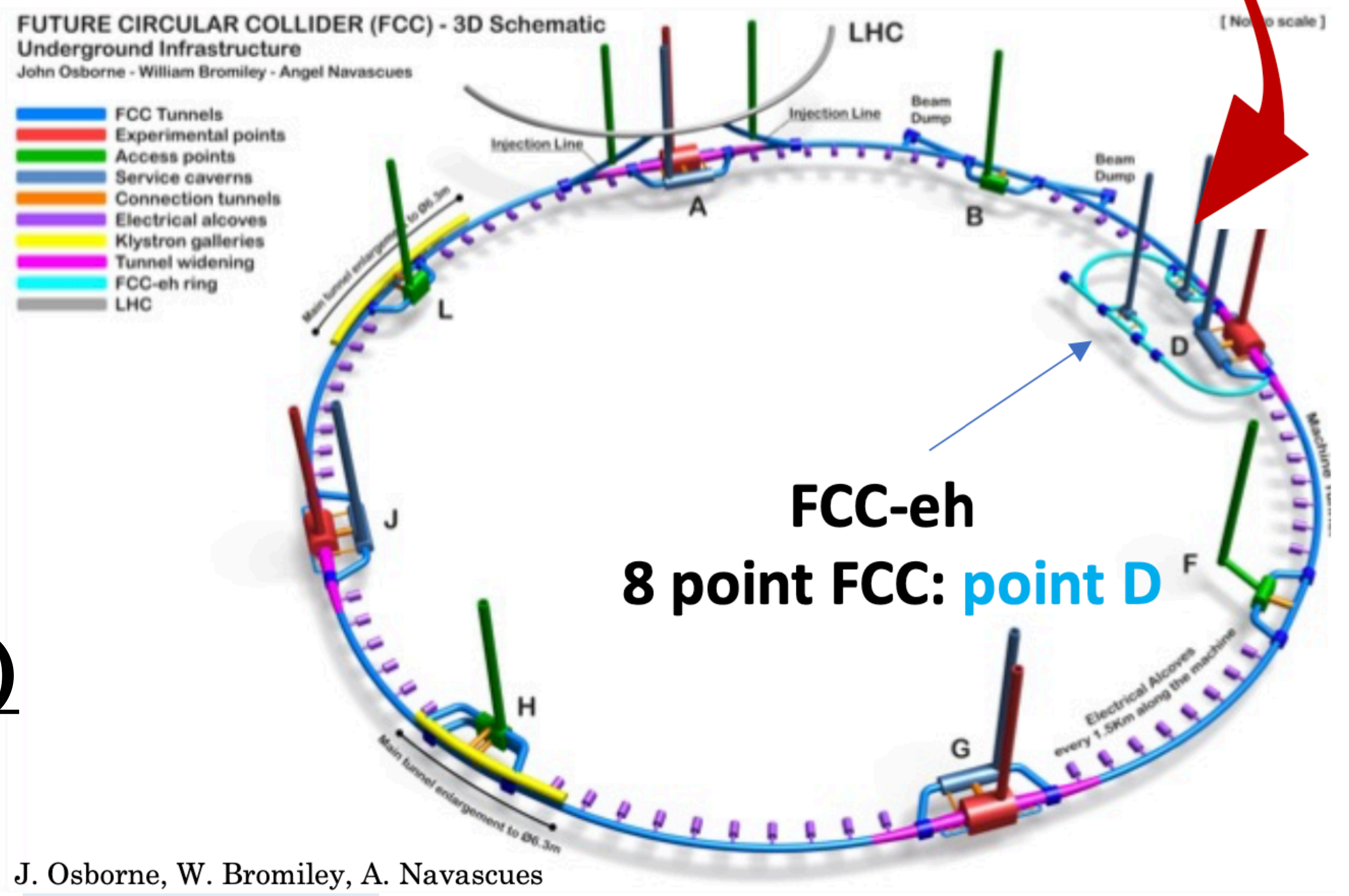
- operated synchronously with HL-LHC



- operated synchronously with FCC-hh

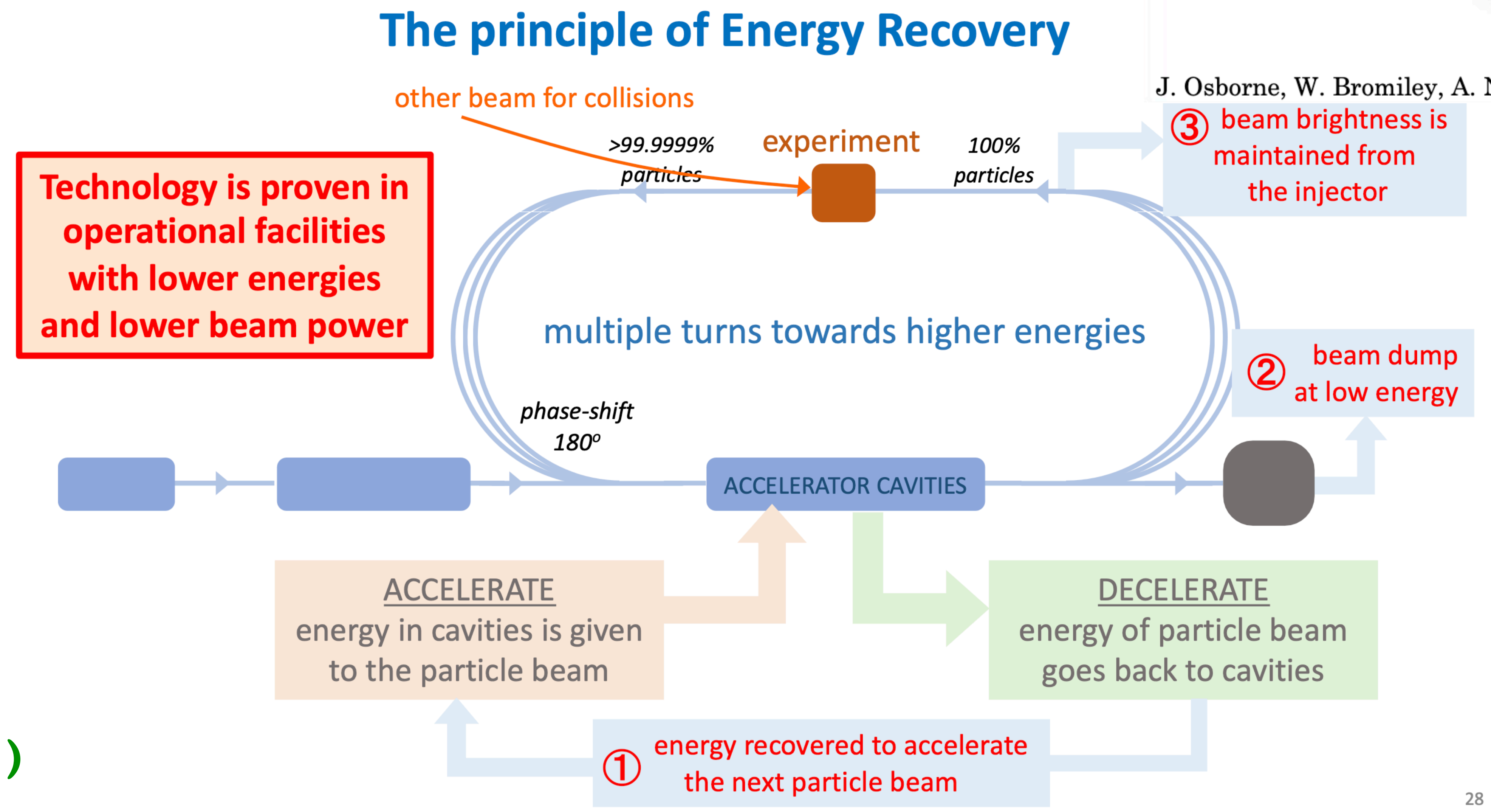
L_{int} = 1-2 ab^{-1} (1000×HERA!)

FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh



J. Osborne, W. Bromiley, A. Navascues

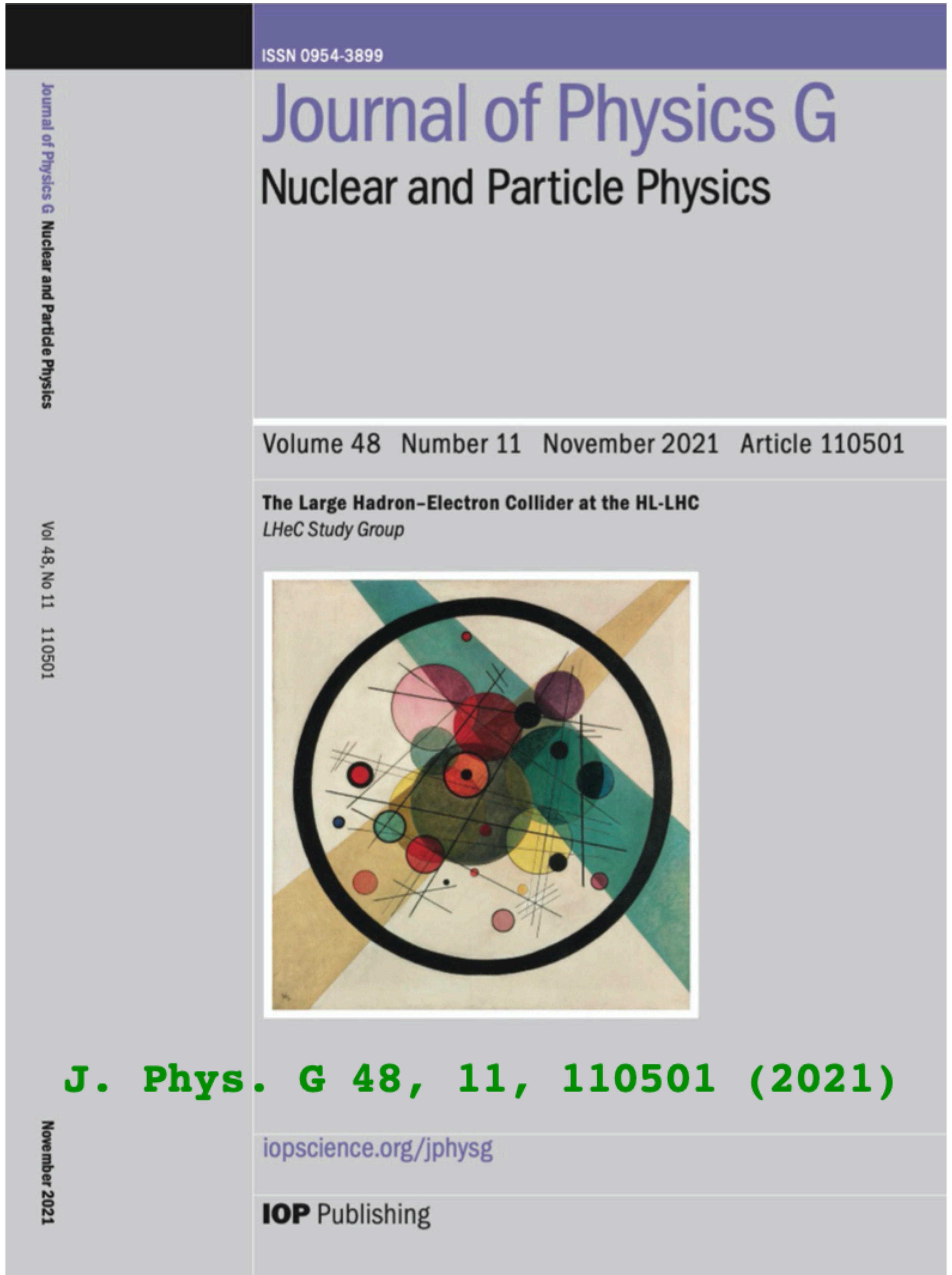
Energy Recovering Linac (ERL)



LHeC CDRs:
arXiv:1206.2913, J. Phys. G 39 075001 (2012)
arXiv:2007.14491, J. Phys. G 48, 11, 110501 (2021)

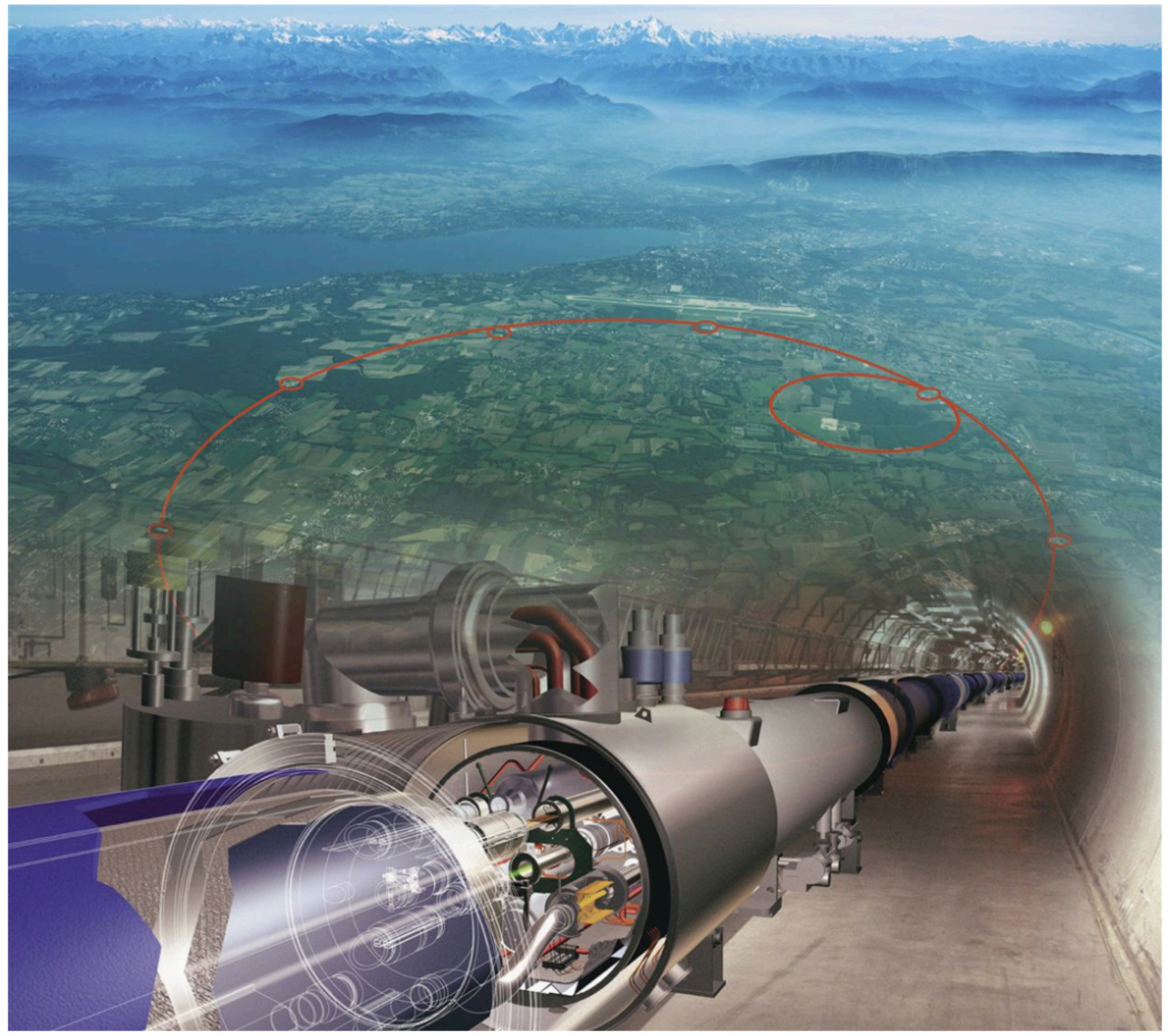
FCC CDR:
Eur. Phys. J. C 79, no. 6, 474 (2019) – Physics
Eur. Phys. J. ST 228, no. 4, 755 (2019) – FCC-hh/eh

The Large Hadron-Electron Collider at the HL-LHC



5 pages summary:

ECFA Newsletter #5



O. Brüning, M. Klein

Following the Plenary ECFA meeting, 13 July 2020
https://indico.cern.ch/event/933318/
Summer 2020

https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf

An Experiment for Electron-Hadron Scattering at the LHC

K. D. J. André[1,2], L. Aperio Bella[3], N. Armesto[a,4], S. A. Bogacz[5],
D. Britzger[6], O. S. Brüning[1], M. D'Onofrio[2], E. G. Ferreiro[4], O. Fischer[2],
C. Gwenlan[7], B. J. Holzer[1], M. Klein[2], U. Klein[2], F. Kocak[8], P. Kostka[2],
M. Kumar[9], B. Mellado[9,10], J. G. Milhano[11,12], P. R. Newman[13],
K. Piotrzkowski[14], A. Polini[15], X. Ruan[9], S. Russenschuk[1],
C. Schwanenberger[3], E. Vilella-Figueras[2], Y. Yamazaki[16]

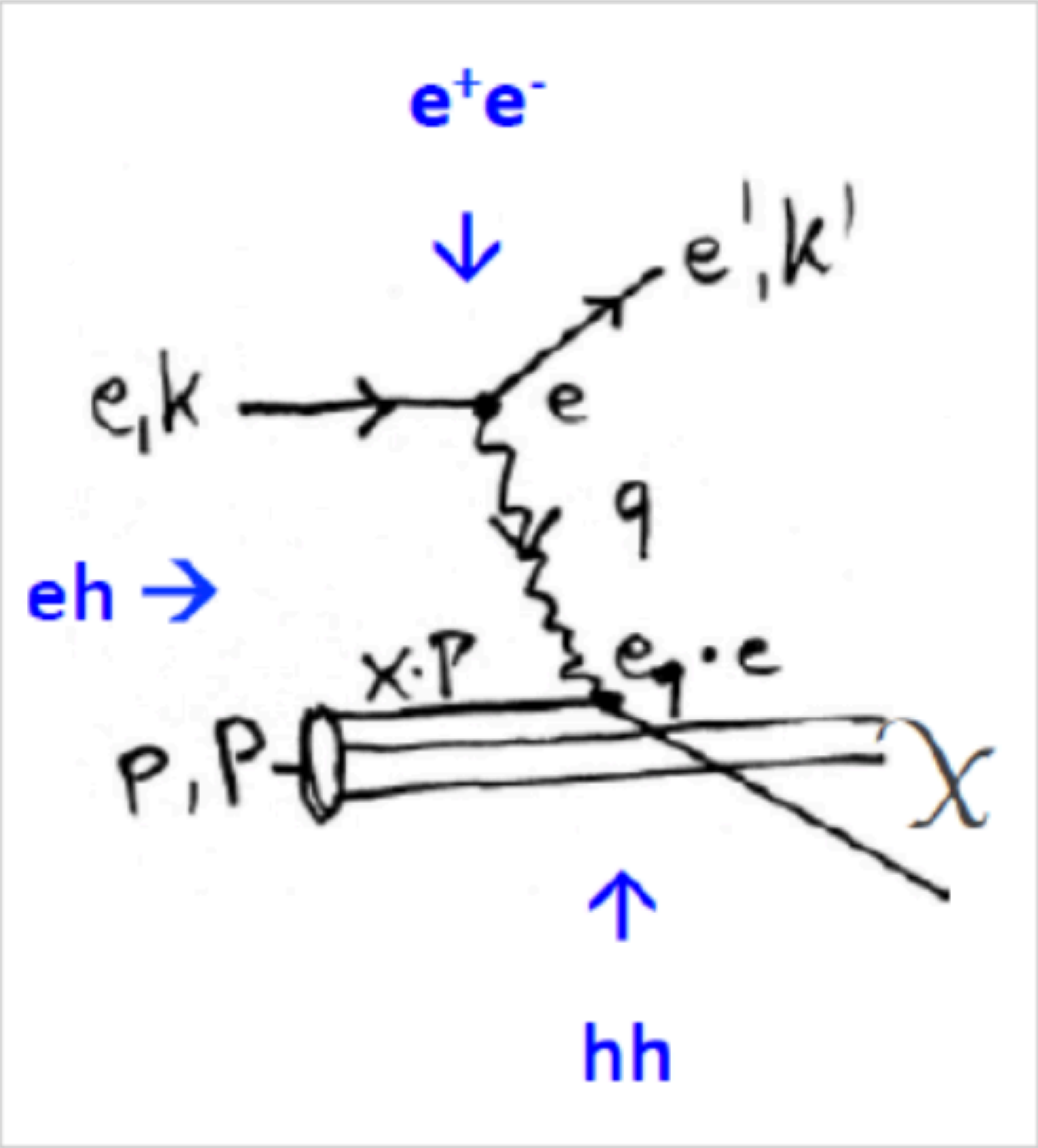
Eur. Phys. J. C 82 (2022) 1, 40

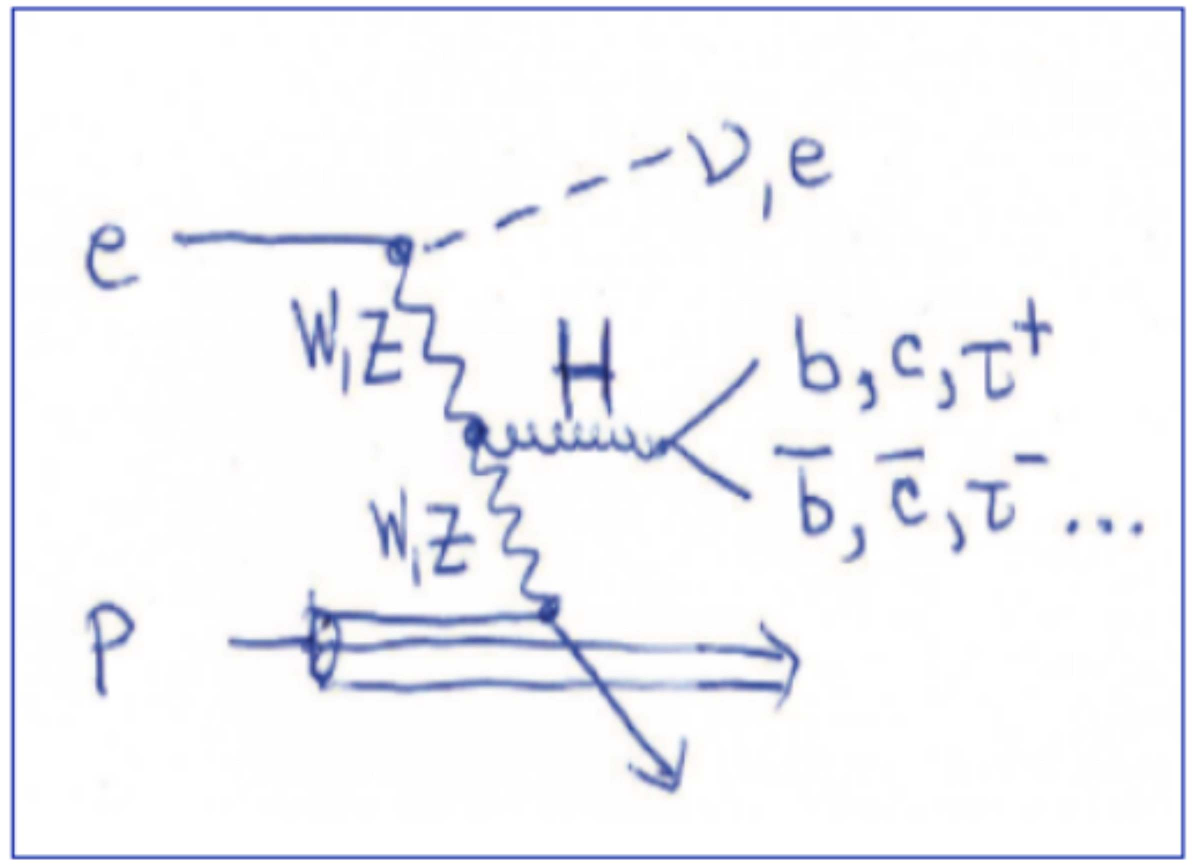
The Large Hadron electron Collider
as a bridge project for CERN

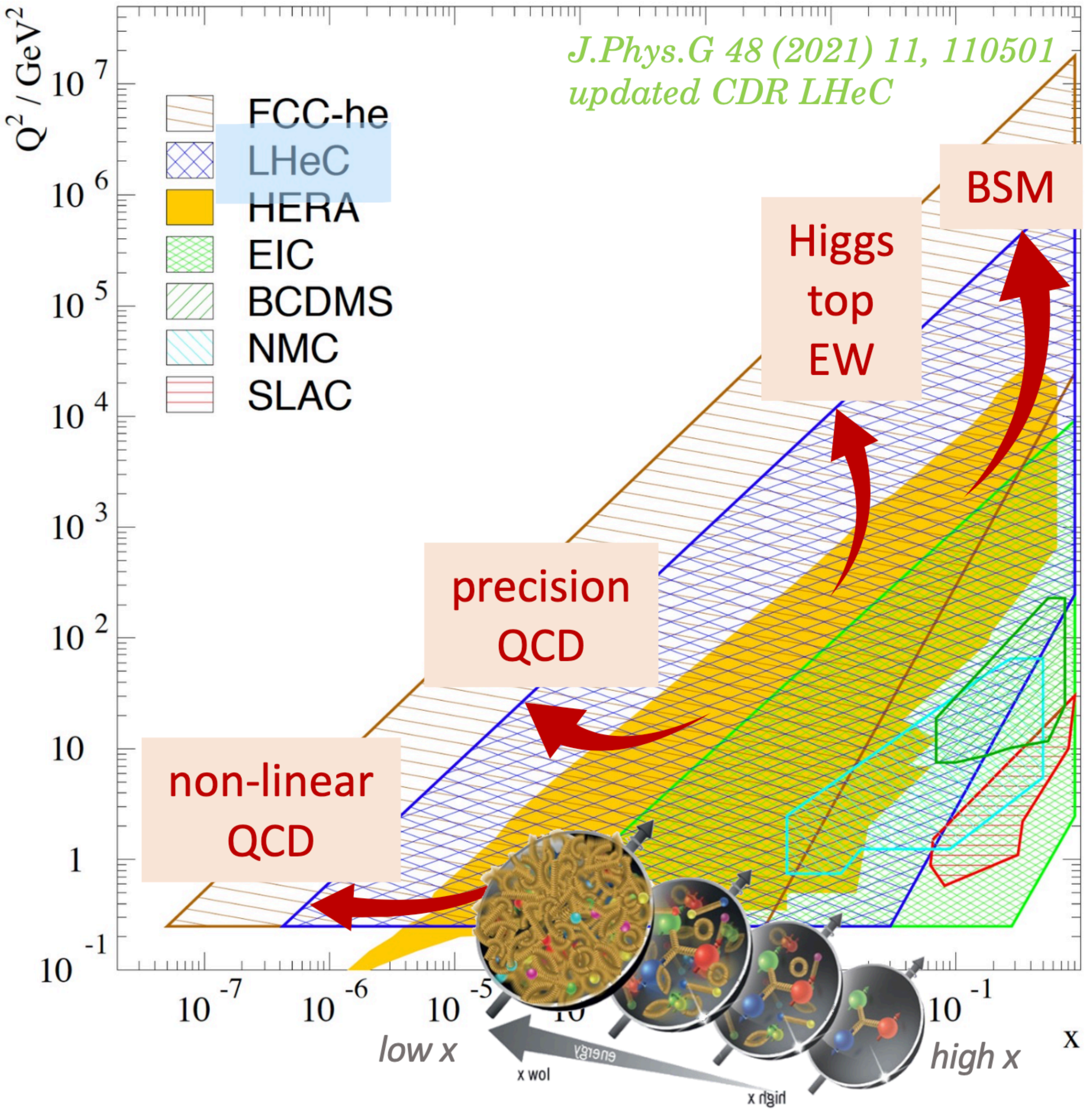
White Paper coming soon…

Max Klein
1951-2024

Deep Inelastic Scattering at the Energy Frontier



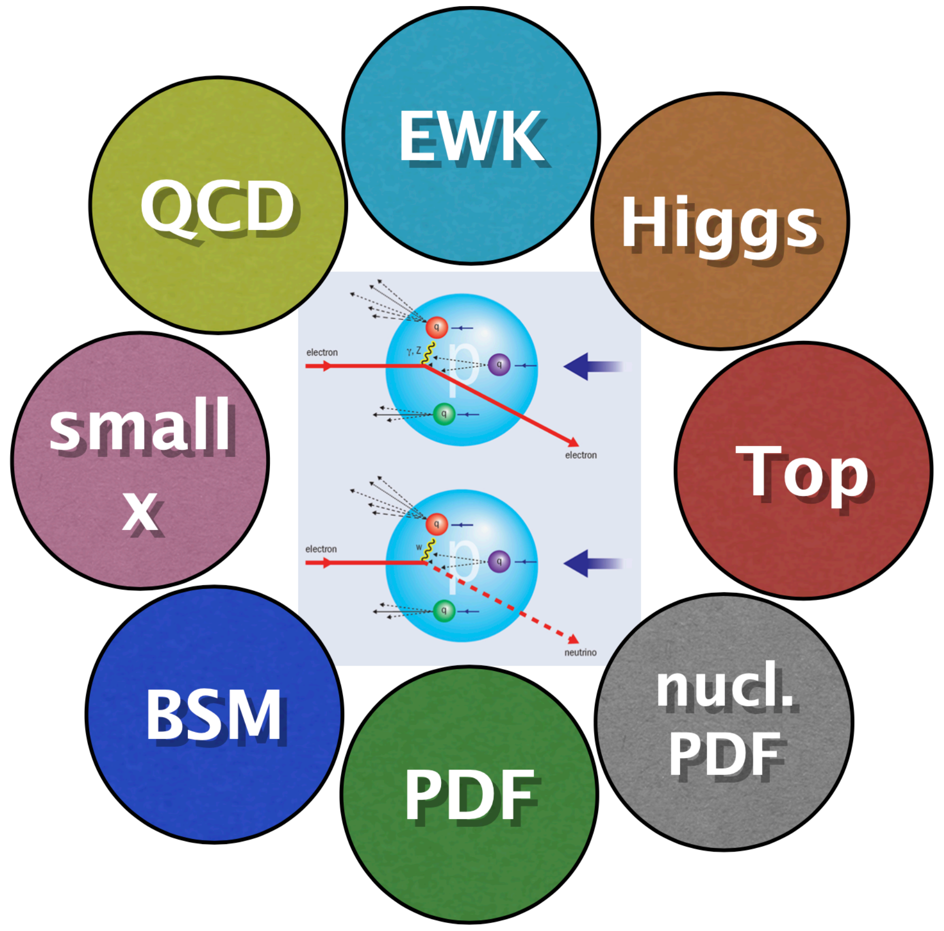




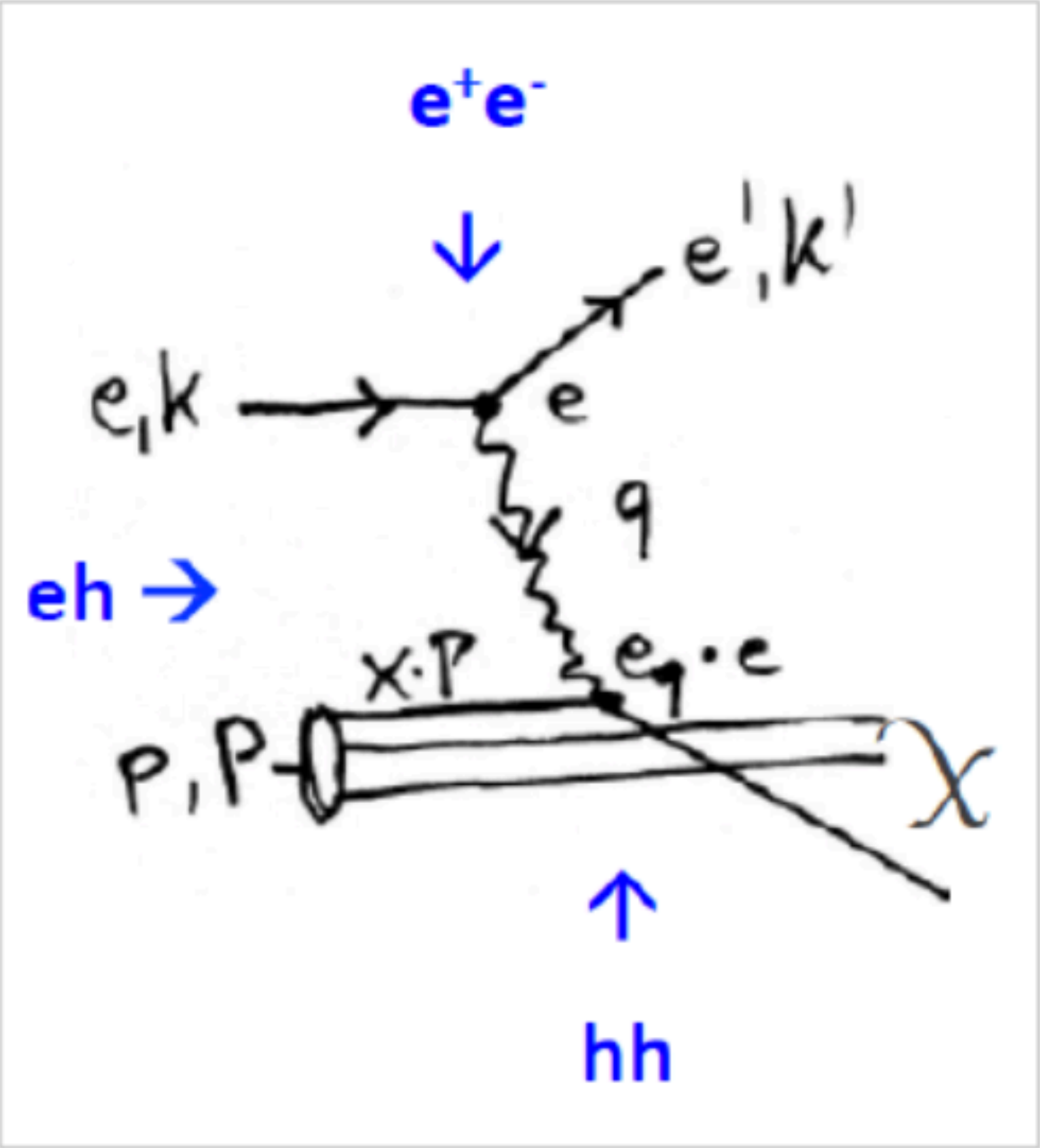
deliveries of ep/eA

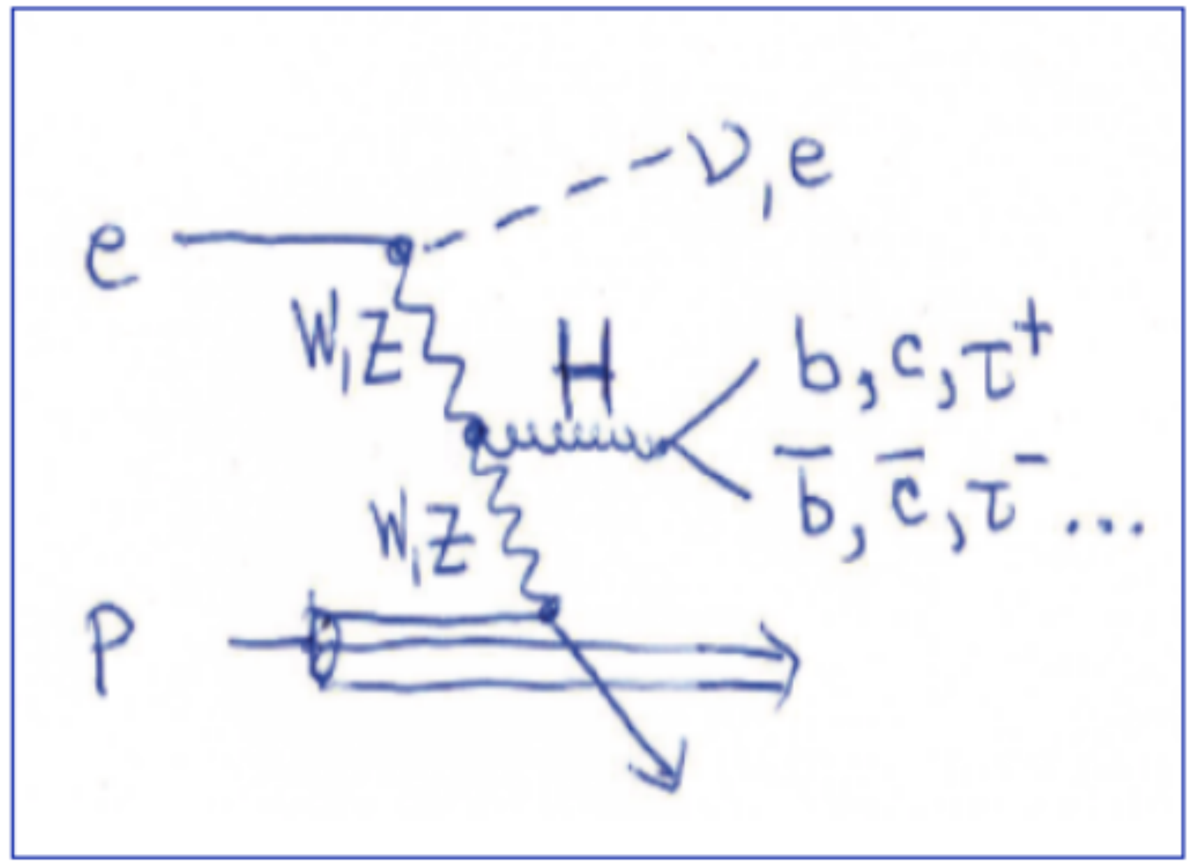
- cleanest high resolution microscope: QCD discovery
- empowering the LHC/FCC search program
- precision Higgs facility together with LHC/FCC-hh
- precision and discovery facility (top, EWK, BSM)
- unique nuclear physics facility
- precision proton PDFs including low x parton dynamics in ep, eA

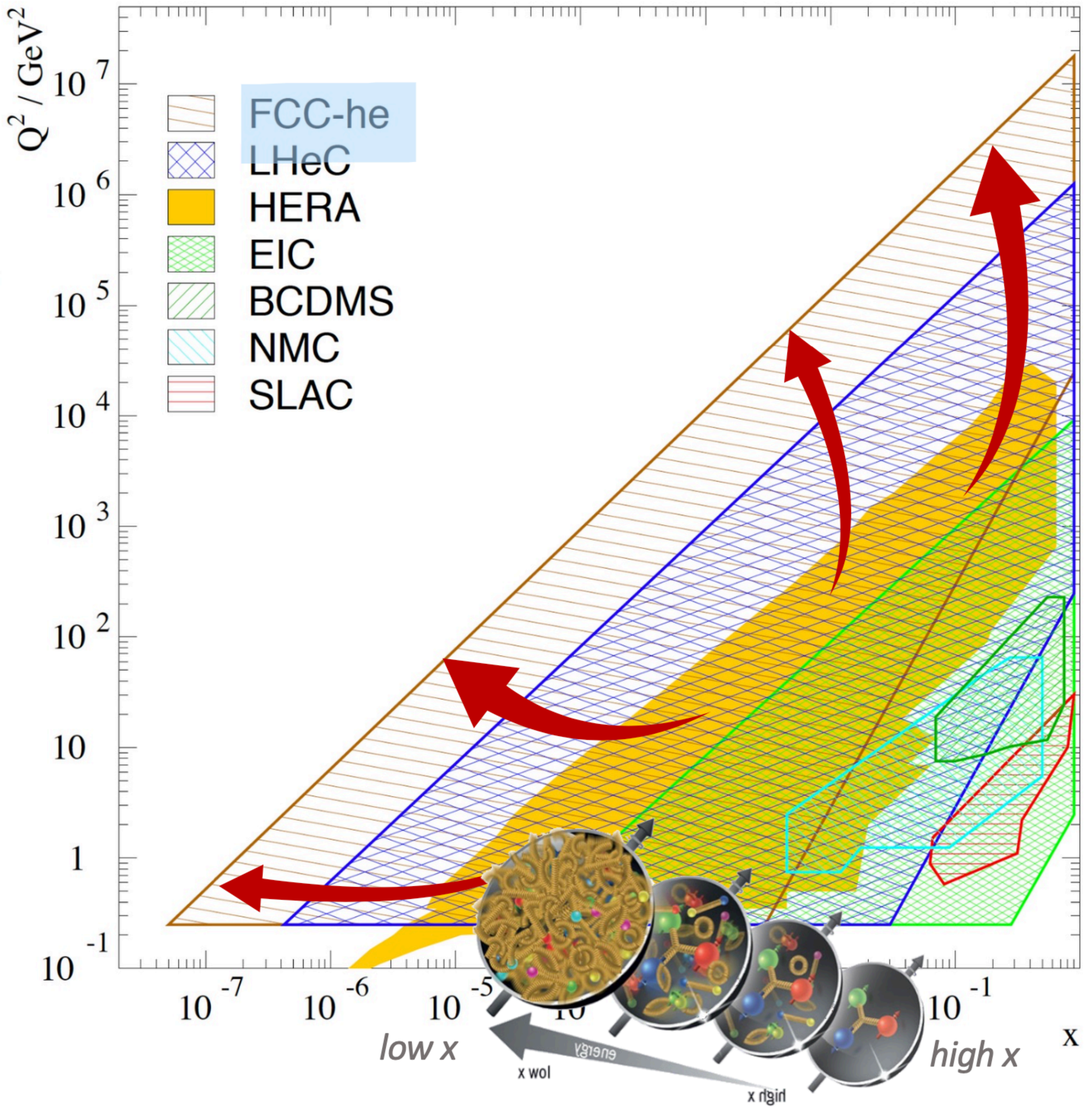
Wide-ranging deep physics programme



Deep Inelastic Scattering at the Energy Frontier







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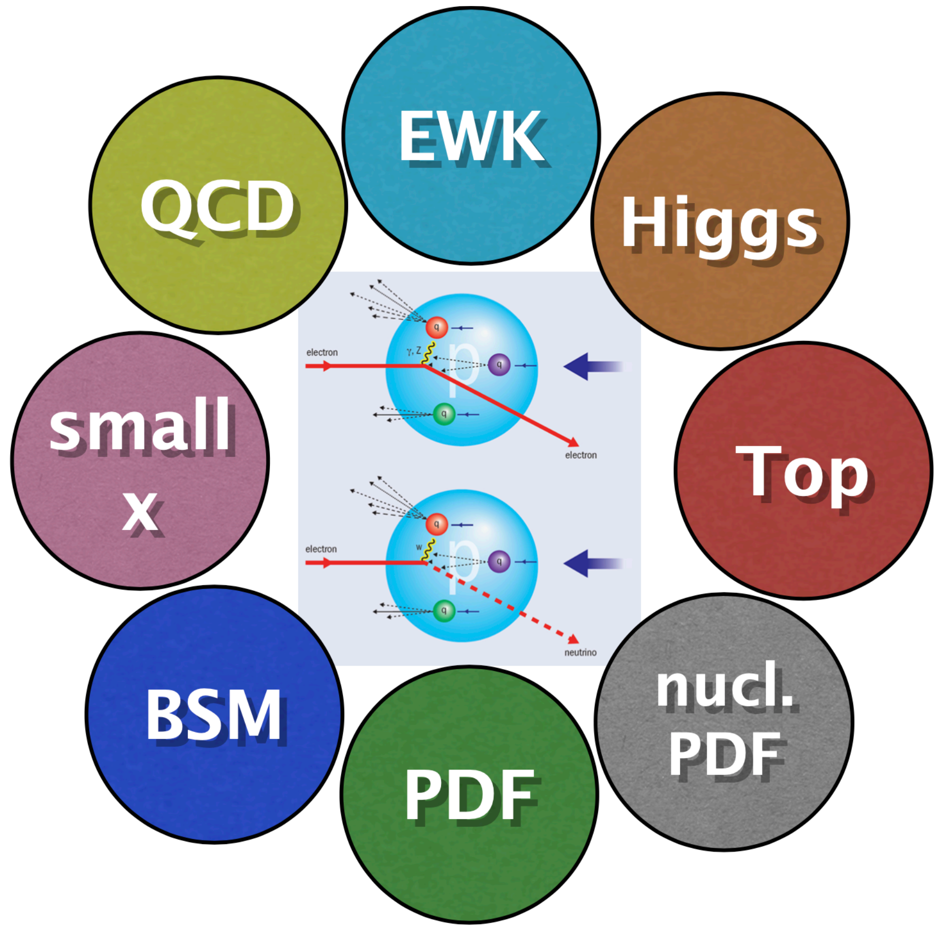
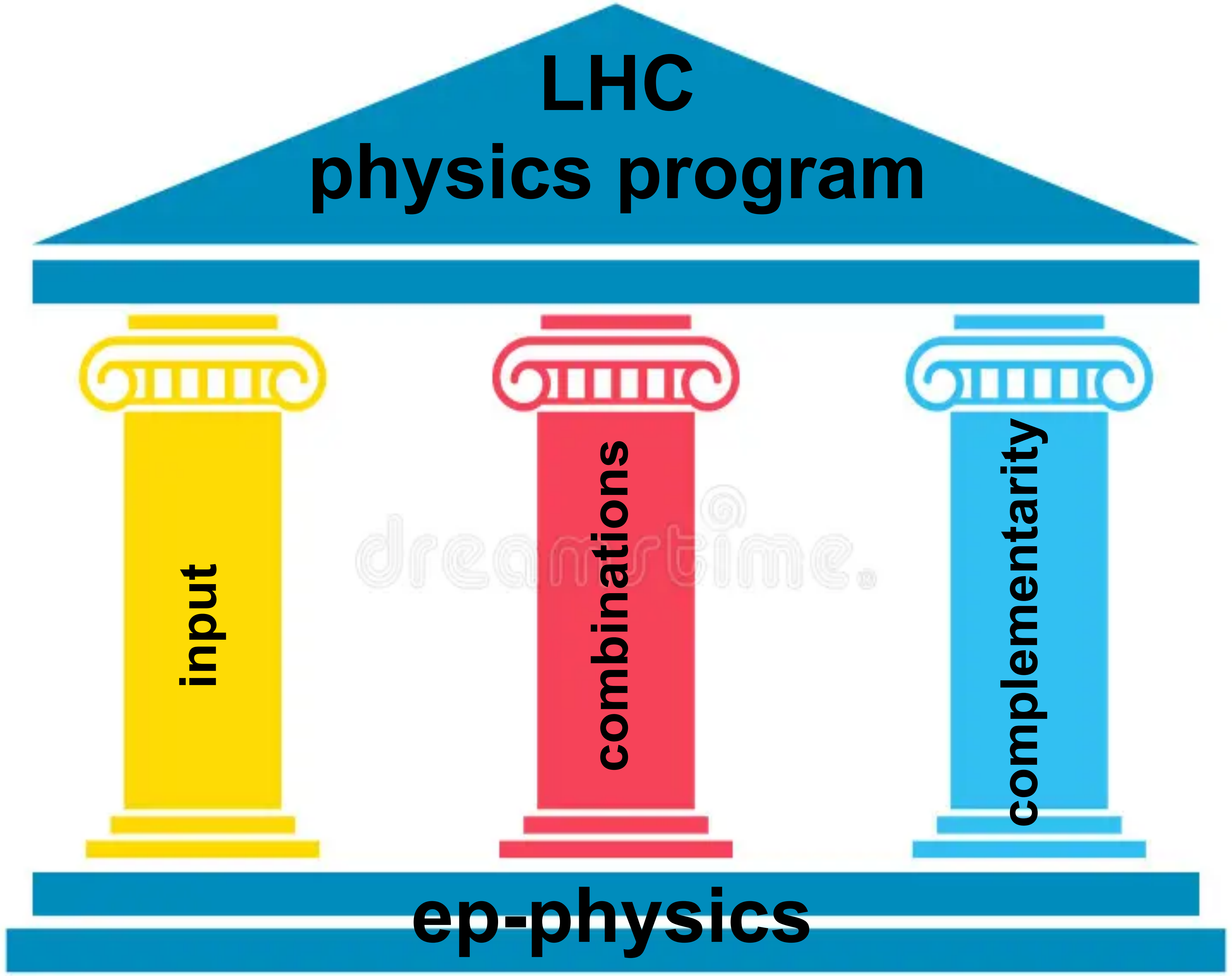
Wide-ranging deep physics programme



Short recap of physics programme



High precision *ep* measurements used as input in LHC analyses for their improvements

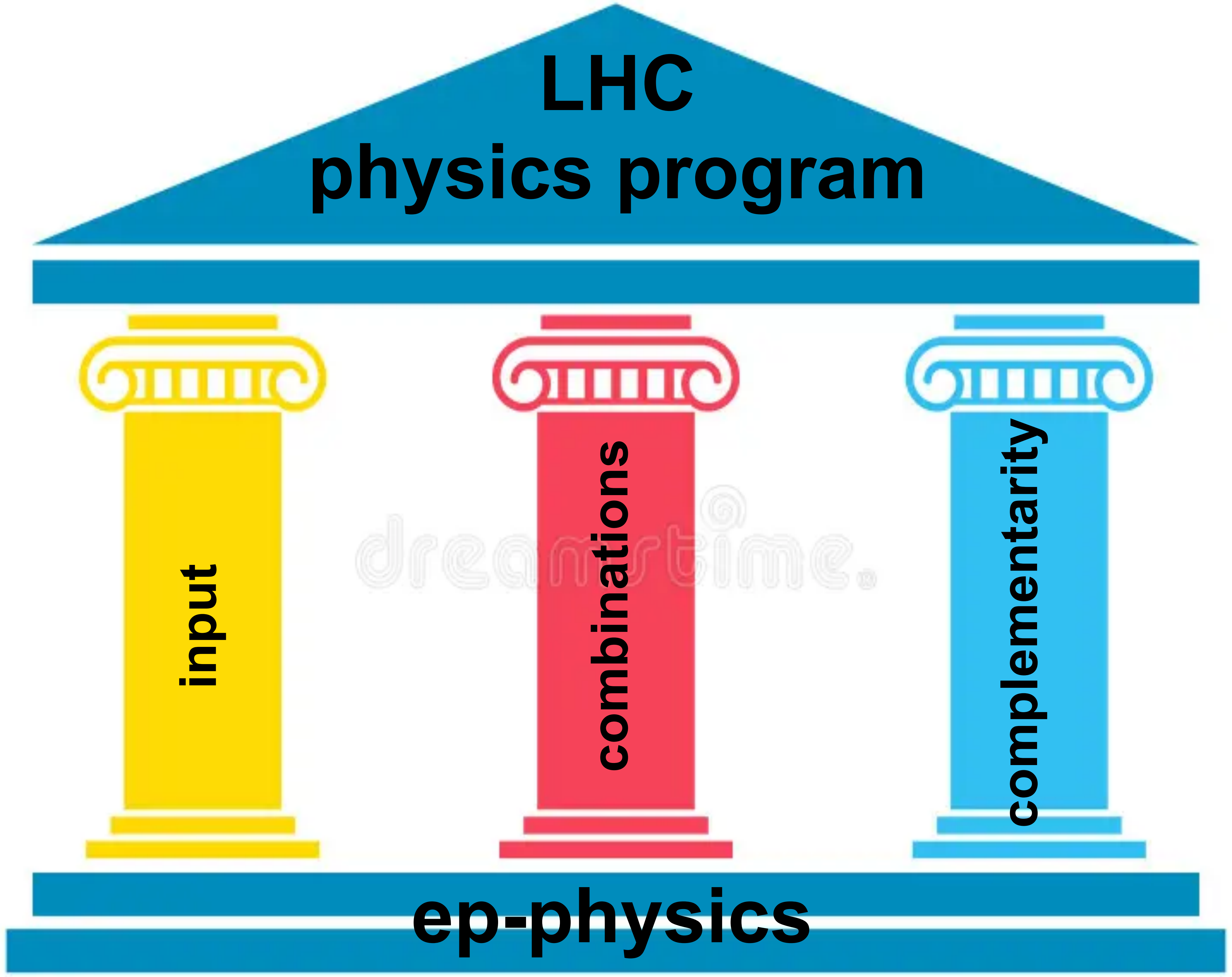
ep analyses with sensitivity complementary to LHC analyses to complete the overall LHC physics program

ep measurements to considerably improve LHC physics output, e.g. in final combinations

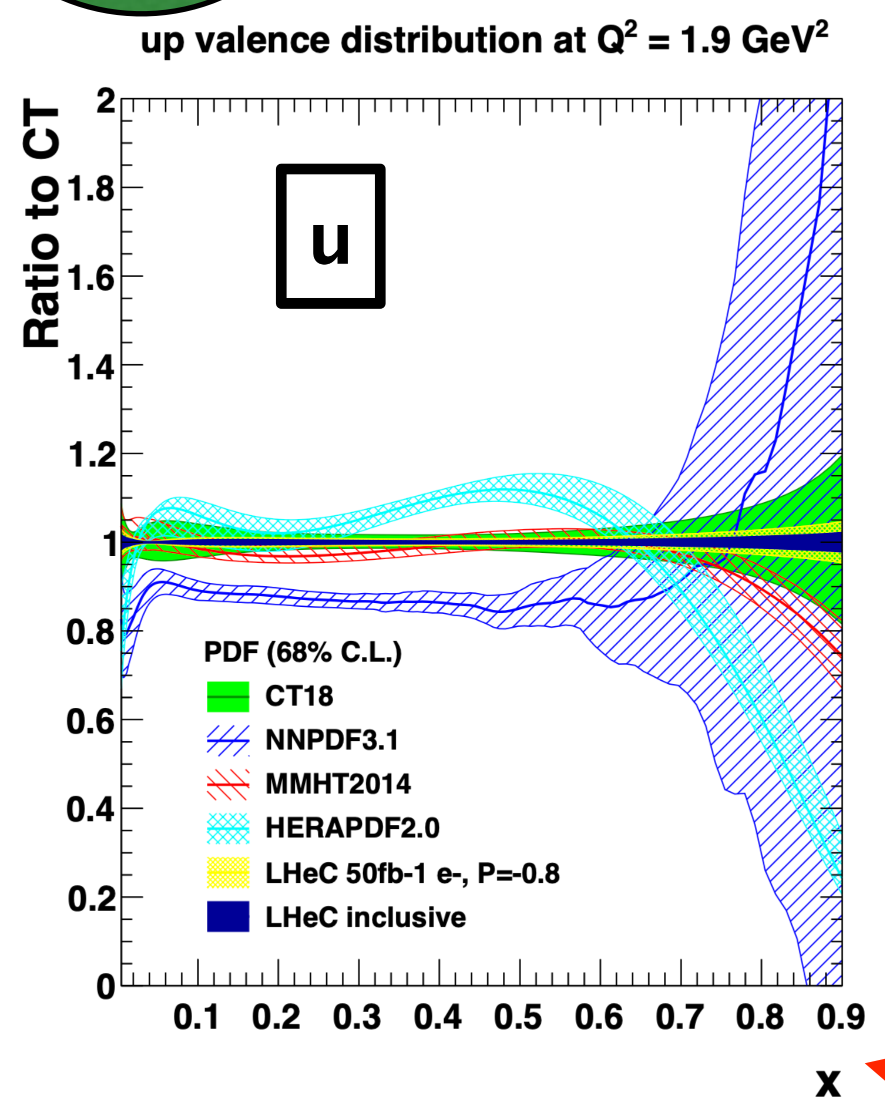
Synergies between LHeC and HL-LHC physics

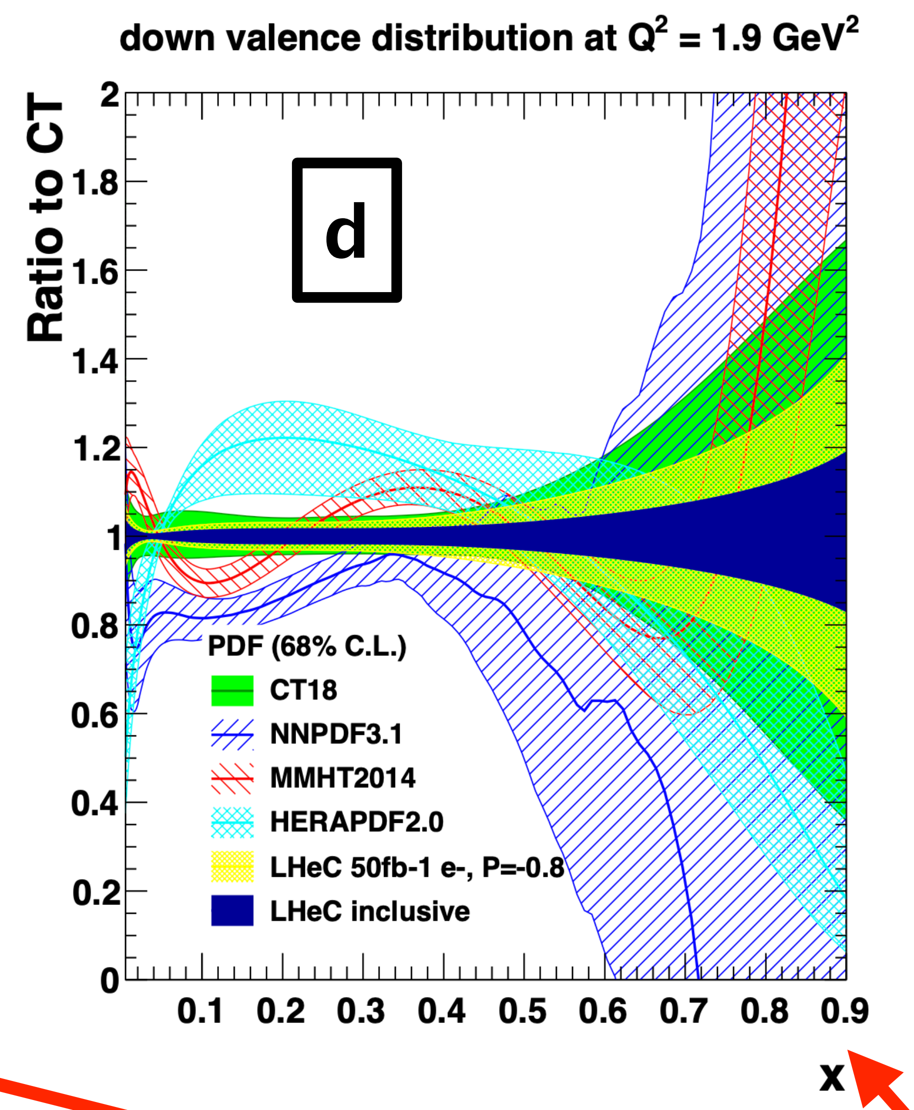
→ Empowerment of LHC program
→ Input to pp physics analyses improving sizable uncertainties and limitations

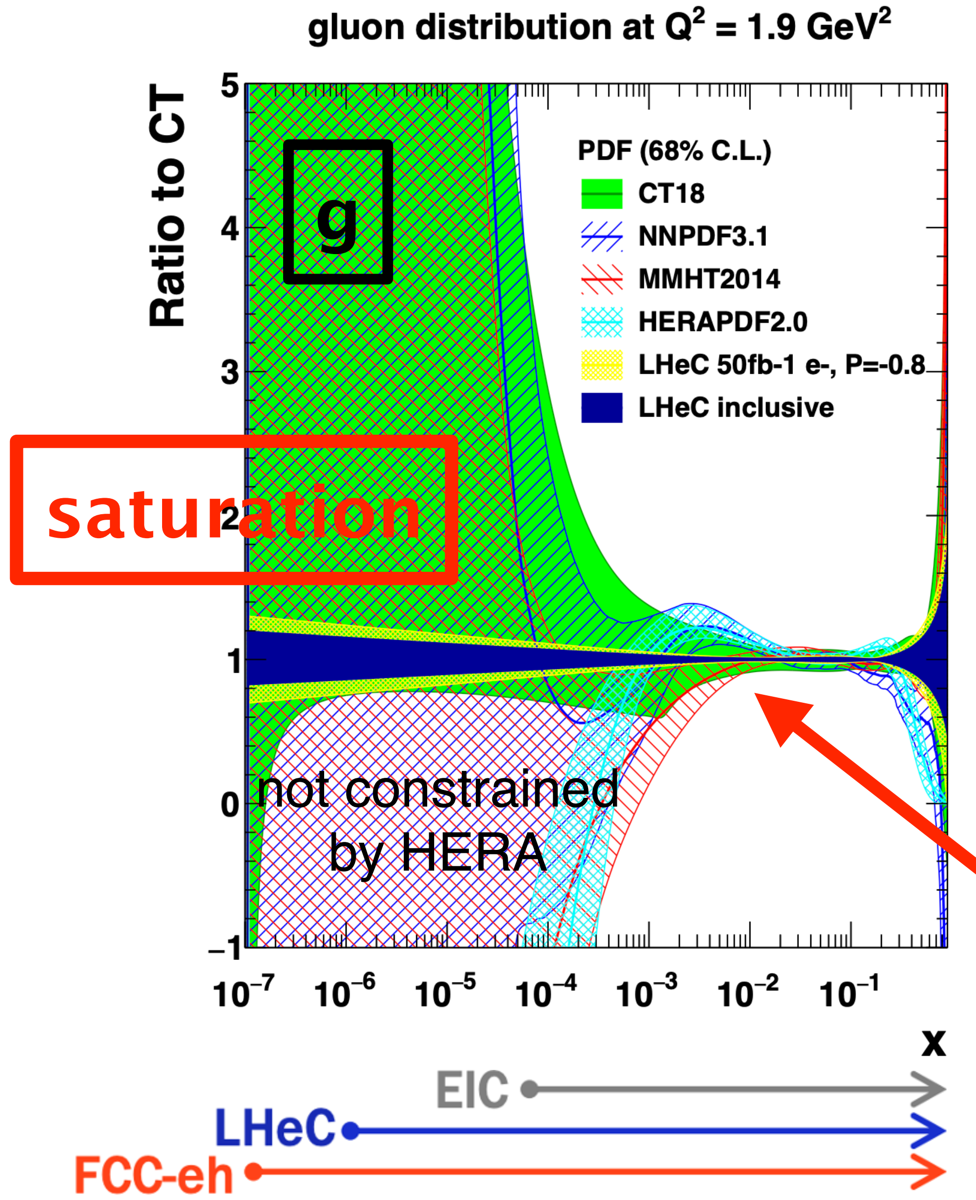
High precision *ep* measurements used as input in LHC analyses for their improvements

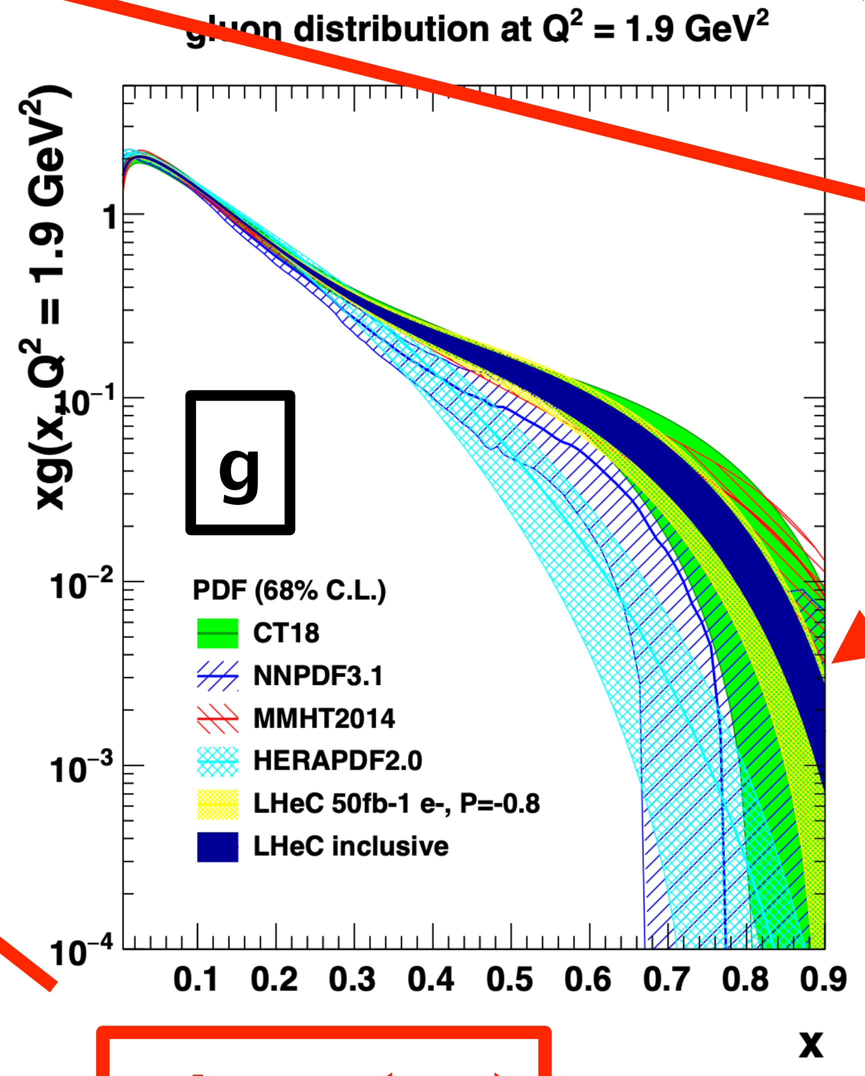


PDF — Parton Density Functions — EWK BSM







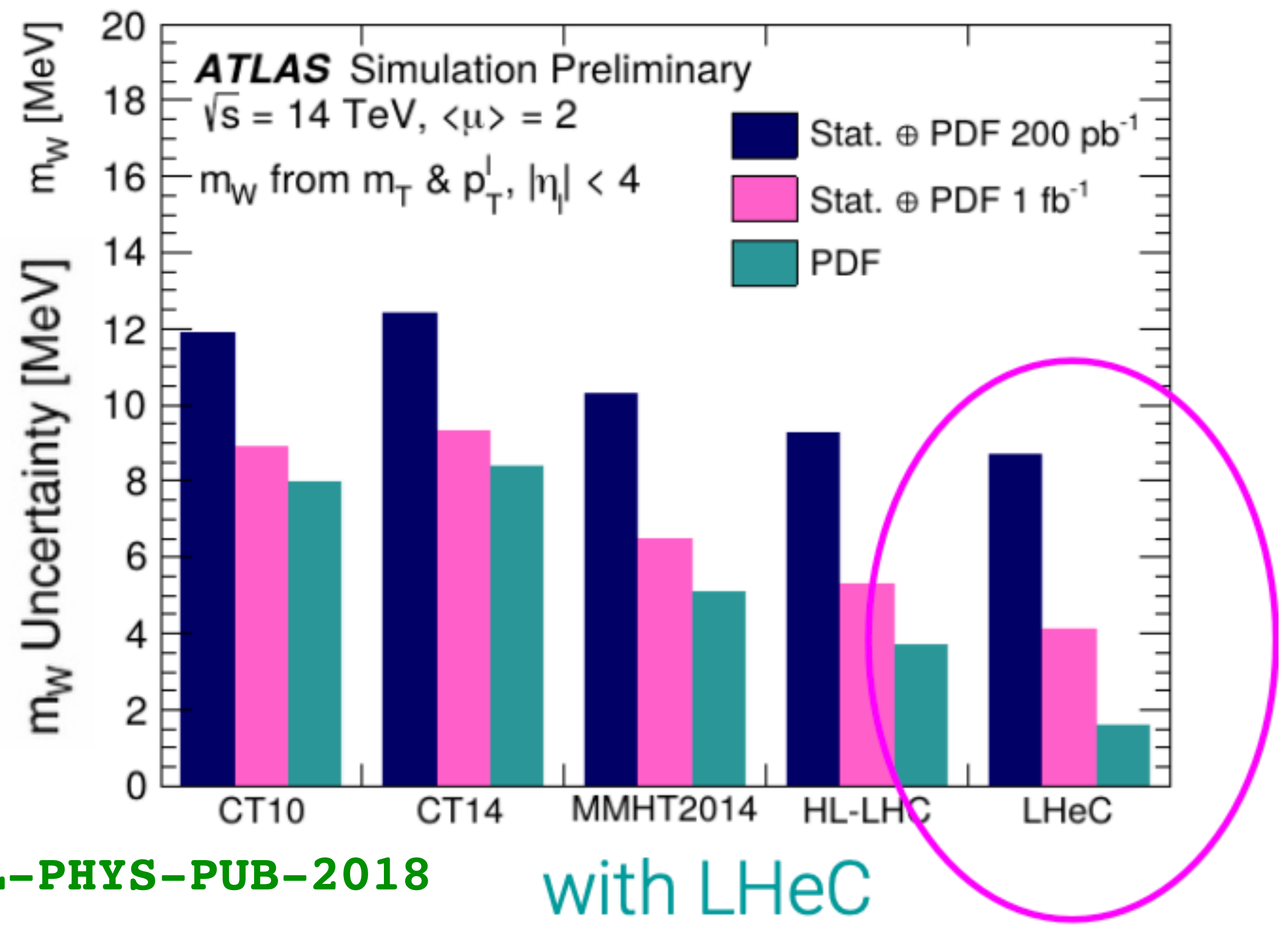


BSM (pp)

Higgs (pp)

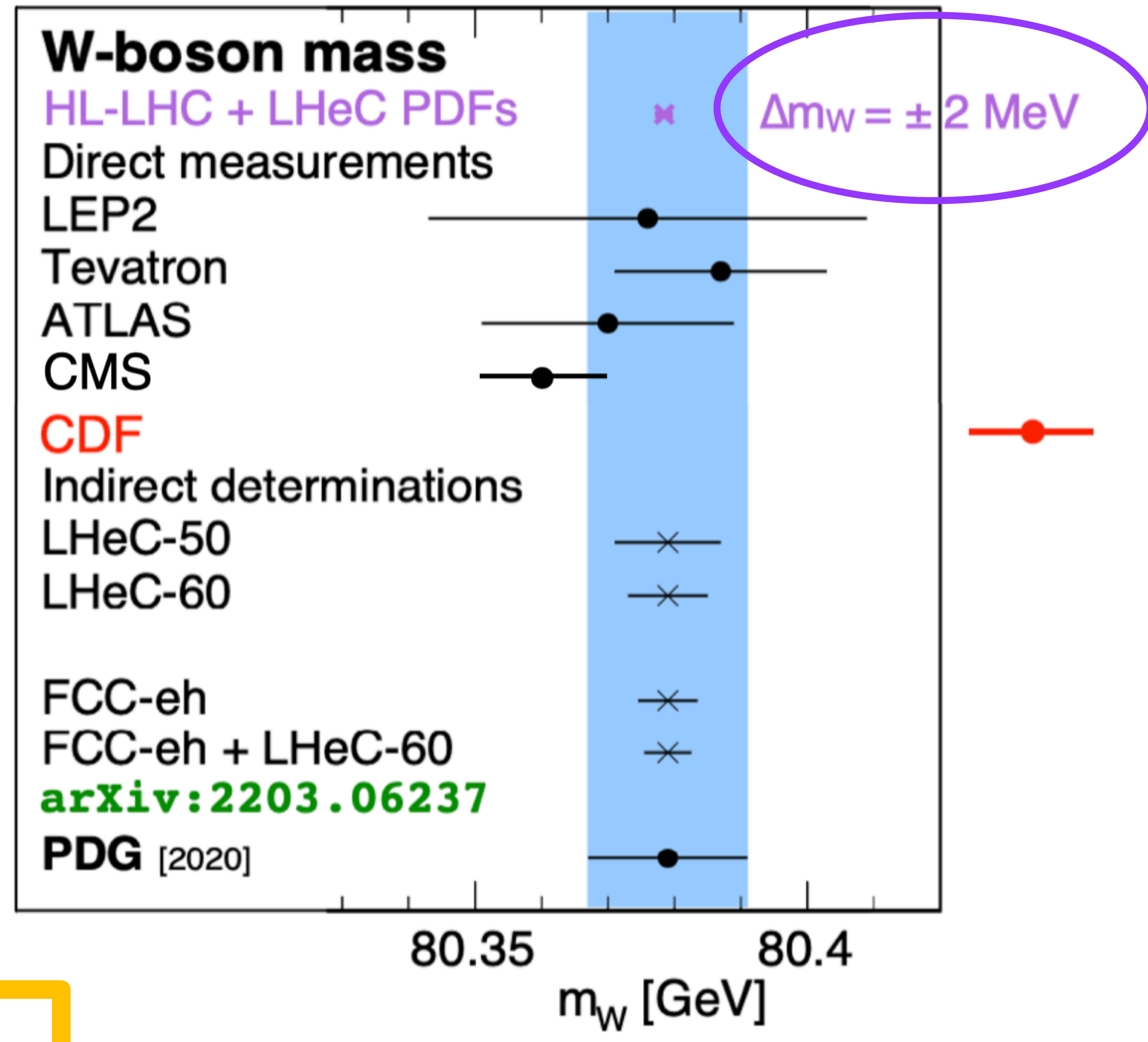
W mass uncertainty prospects @ HL-LHC

ATLAS low-<μ> HL-LHC prospects



ATL-PHYS-PUB-2018

with LHeC



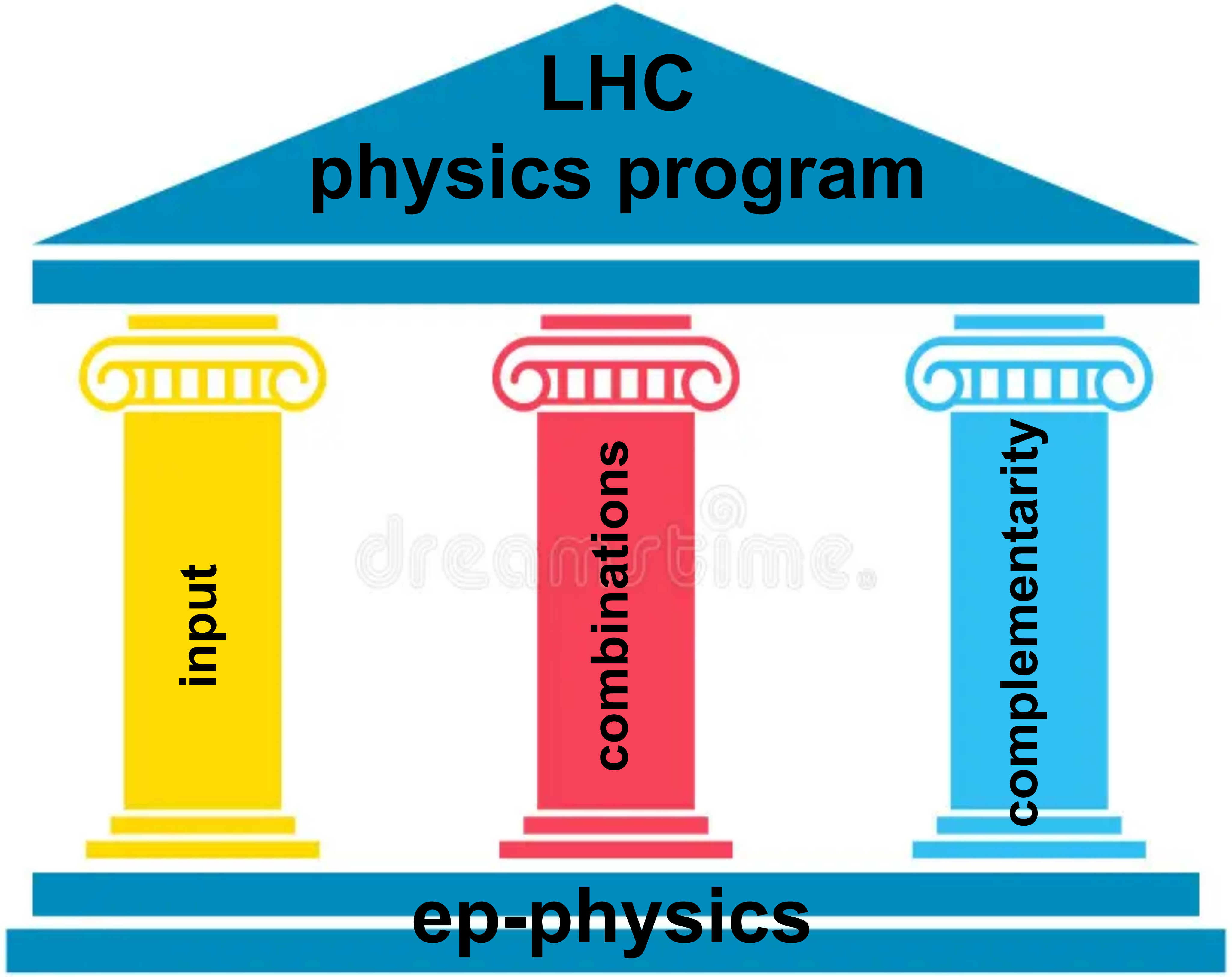
Contact Interactions @ HL-LHC

Model	ATLAS (Ref. [702])	HL-LHC	
	$\mathcal{L} = 36\,\mathrm{fb}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (LHeC)
LL (constr.)	28 TeV	58 TeV	96 TeV
LL (destr.)	21 TeV	49 TeV	77 TeV
RR (constr.)	26 TeV	58 TeV	84 TeV
RR (destr.)	22 TeV	61 TeV	75 TeV
LR (constr.)	26 TeV	49 TeV	81 TeV
LR (destr.)	22 TeV	45 TeV	62 TeV

up to factor 1.7

$$\mathcal{L}_{CI} = \frac{g^2}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma_\mu q_i)(\bar{\ell}_i\gamma^\mu\ell_i)$$

Synergies between LHeC and HL-LHC physics

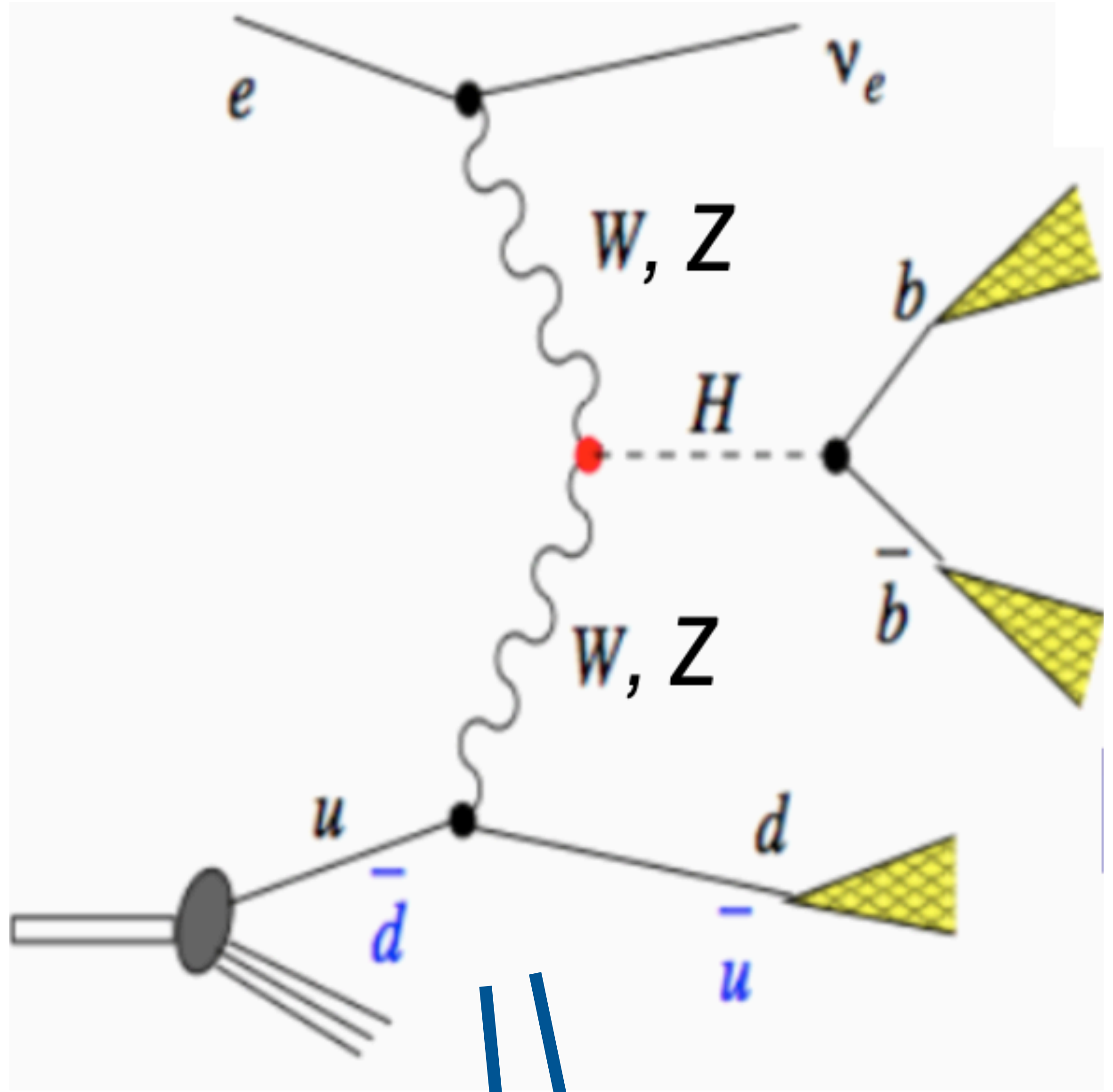


→ Competitive precision of measurements and combination of results
→ uncorrelated uncertainties
→ resolve correlations in parameters of interest
→ resolve common/ correlated uncertainties between ATLAS&CMS
→ empowers global fits

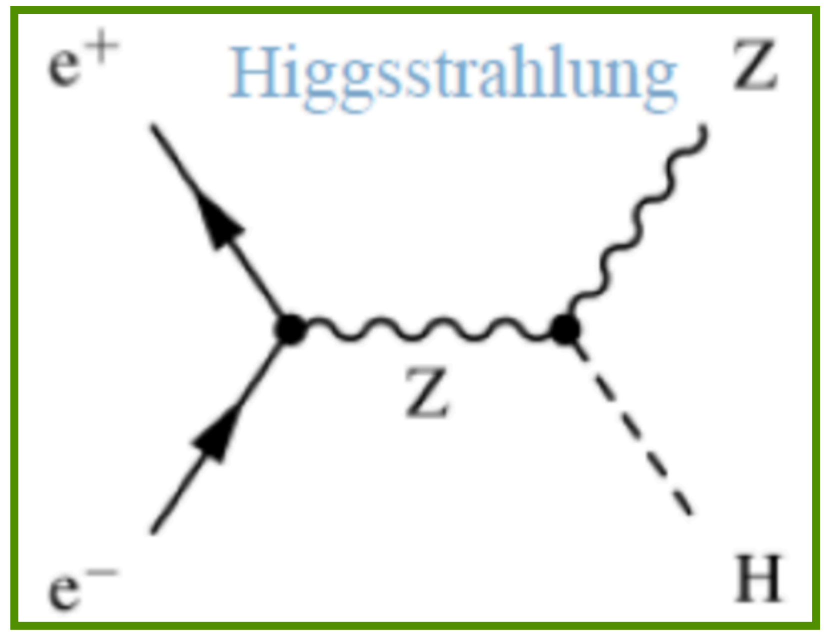
ep **measurements to considerably improve LHC physics output, e.g. in final combinations**

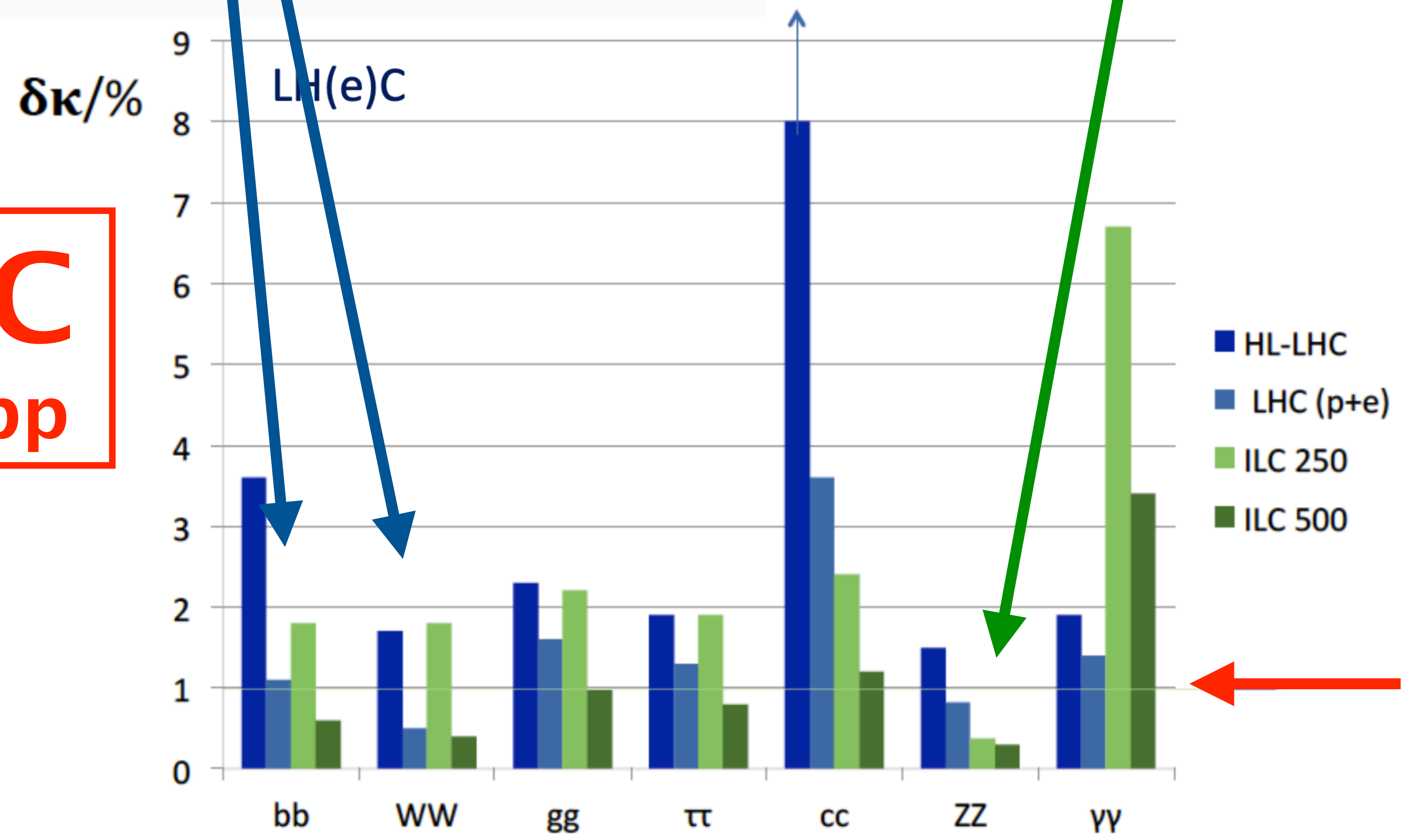
Higgs coupling combinations in κ−framework

CC(e⁻p)



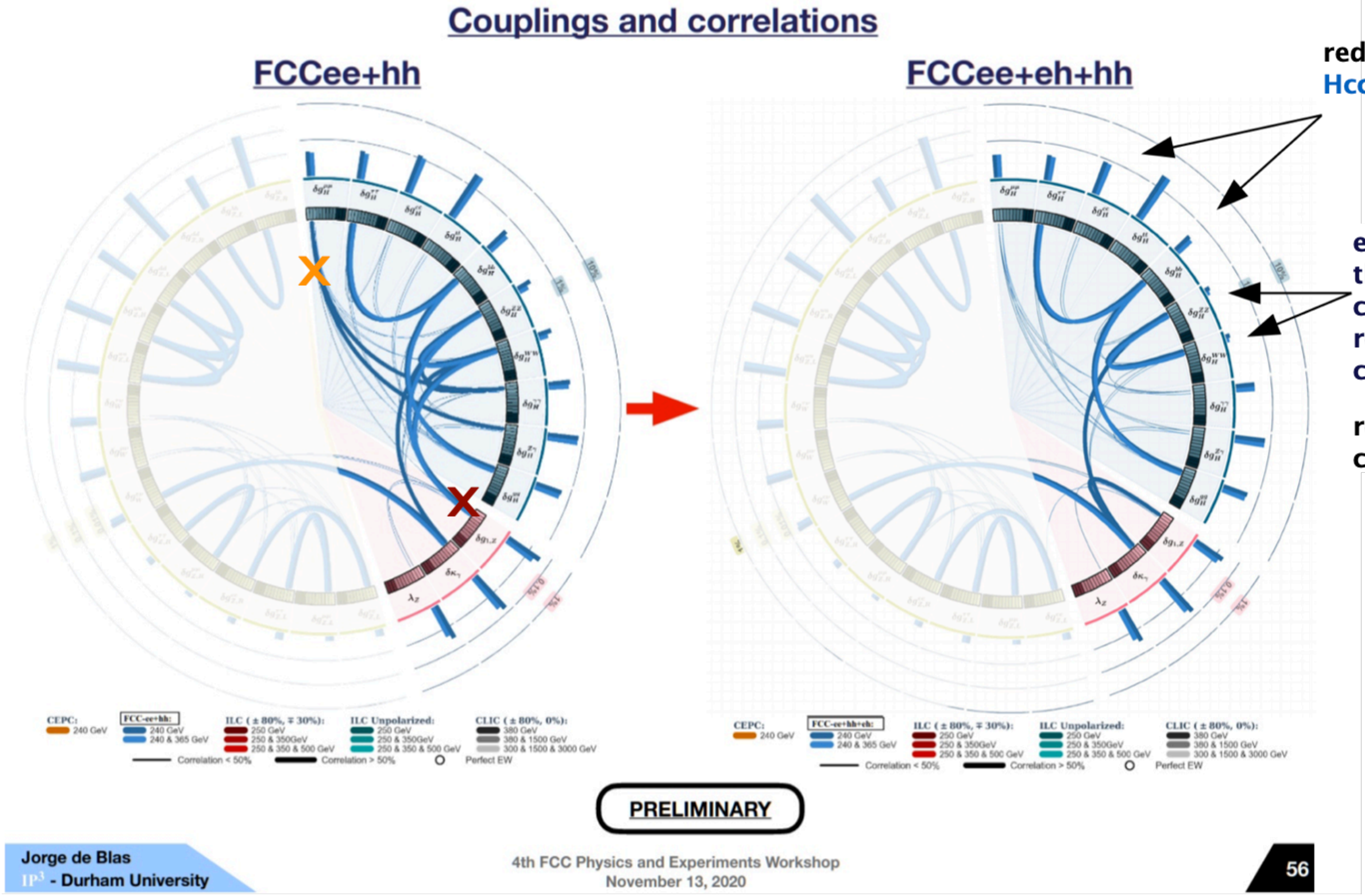
we profit from diversity through complementarity





LHC
ep+pp

← 1%



reduction for Hcc and Hbb

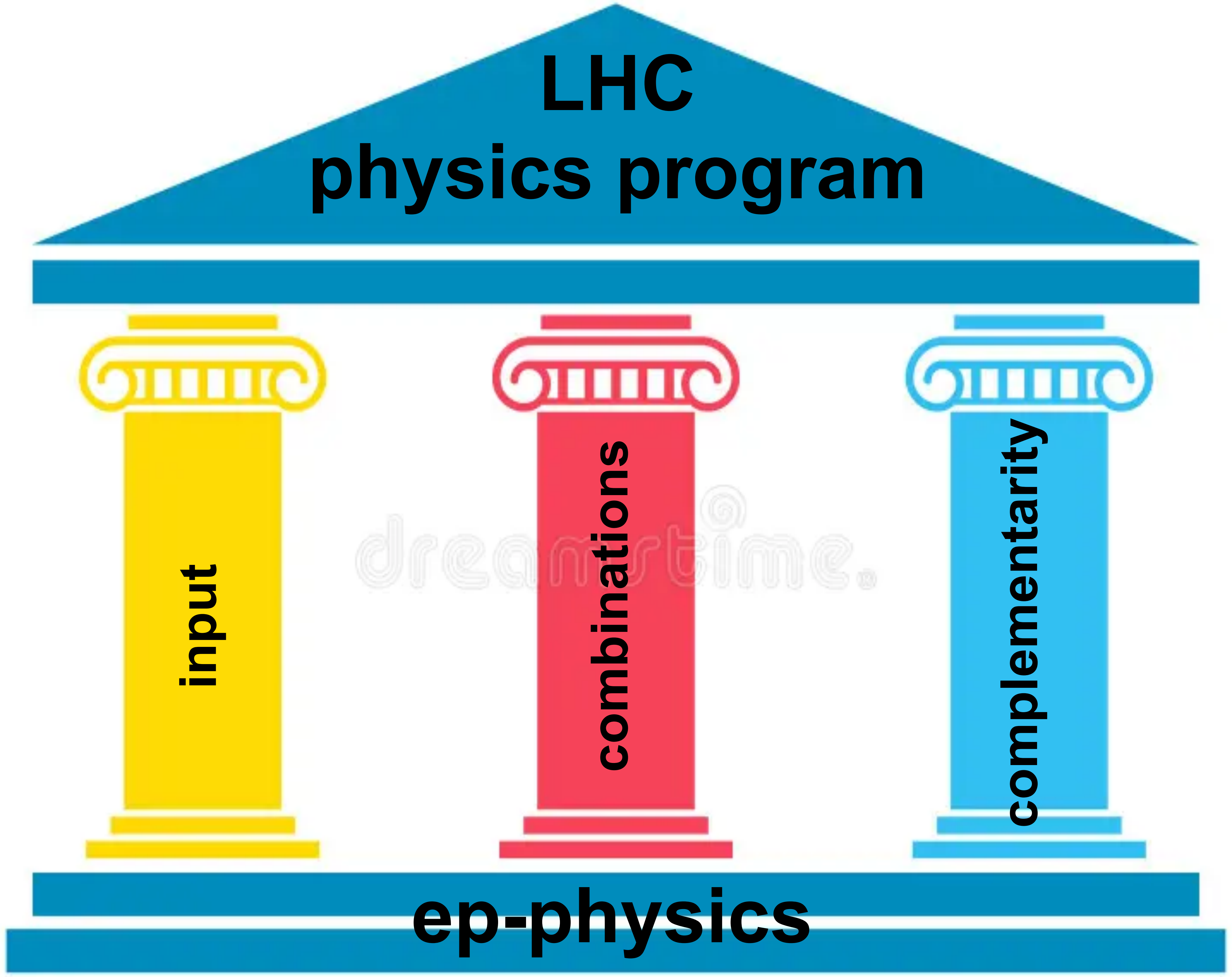
eh contributes to the HWW and HZZ couplings and resolves their correlation X

reduces further correlations X

→ adding electrons makes the LHC a Higgs precision facility

Higgs SMEFT coupling combinations profit from diversity: ee, ep, and pp

Synergies between LHeC and HL-LHC physics

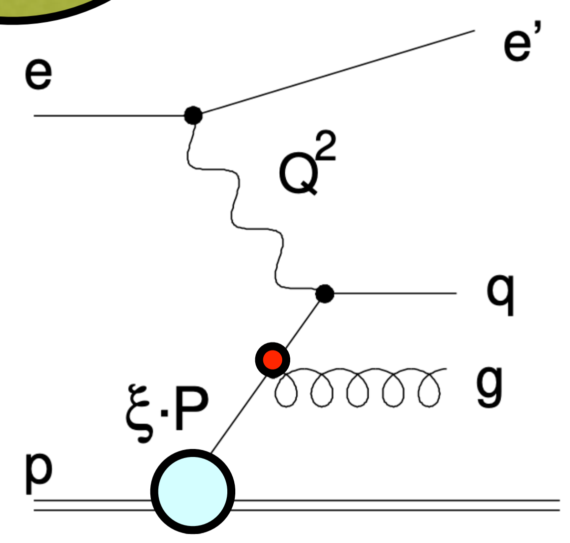


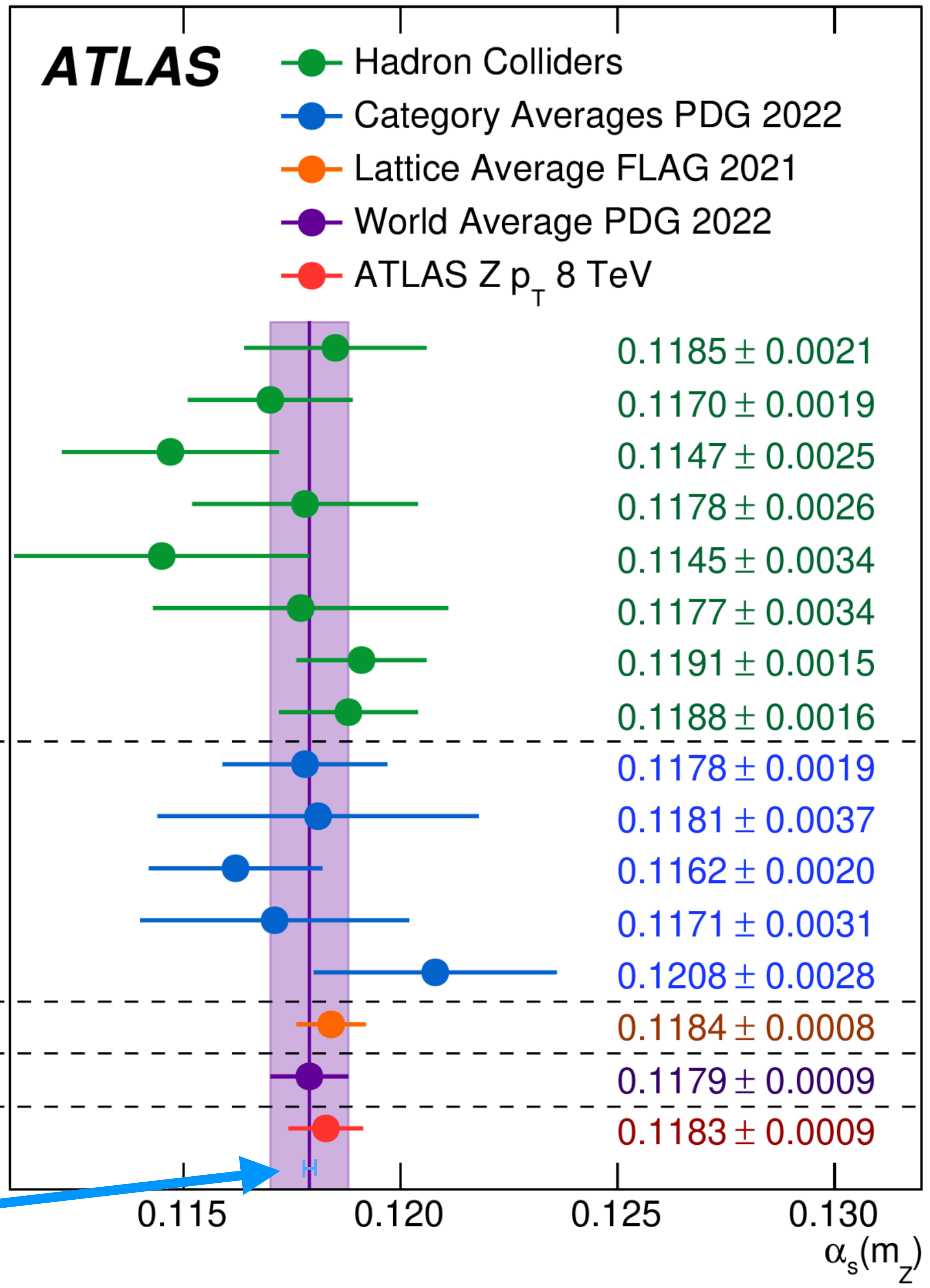
ep **analyses with sensitivity** **complementary** **to LHC analyses to** **complete** **the overall LHC physics program**

→ high precision QCD analyses
→ high precision measurements of specific parameters
→ searches in complementary phase space regions

SM parameters: strong coupling and V_{tb}

QCD | Top





LHeC

Achievable precision: $\mathcal{O}(0.1\%)$ - **x5-10** better than today

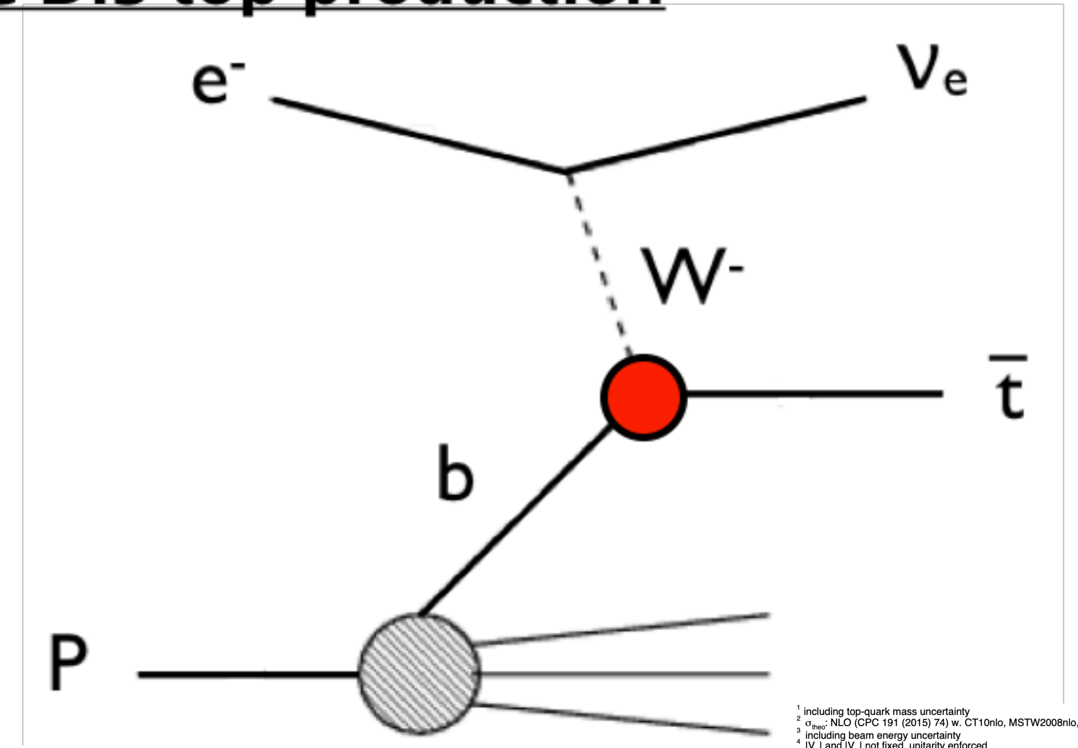
→ **unprecedented precision**

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}\left(f_V^L P_L - f_V^R P_R\right)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\left(f_T^L P_L - f_T^R P_R\right)tW_\mu^- + h.c.$$

= 1 in SM

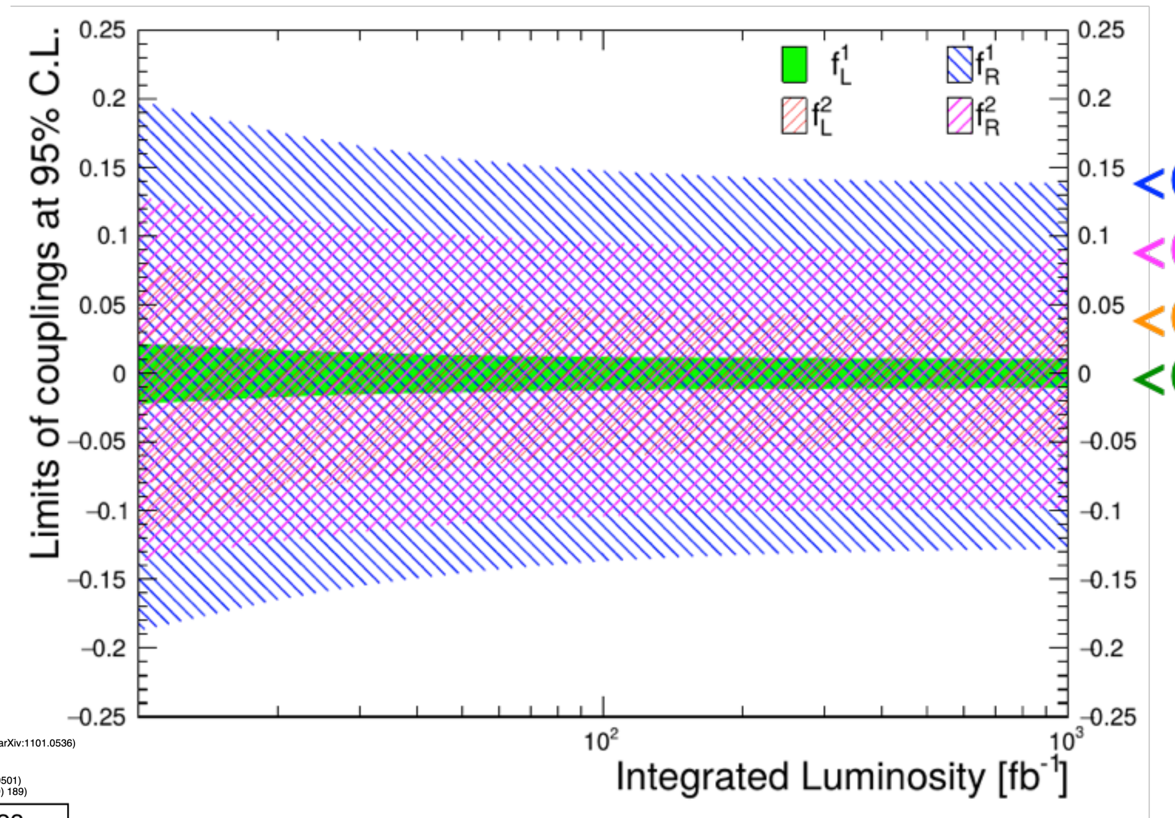
Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688
Kumar, Ruan, to be publ.

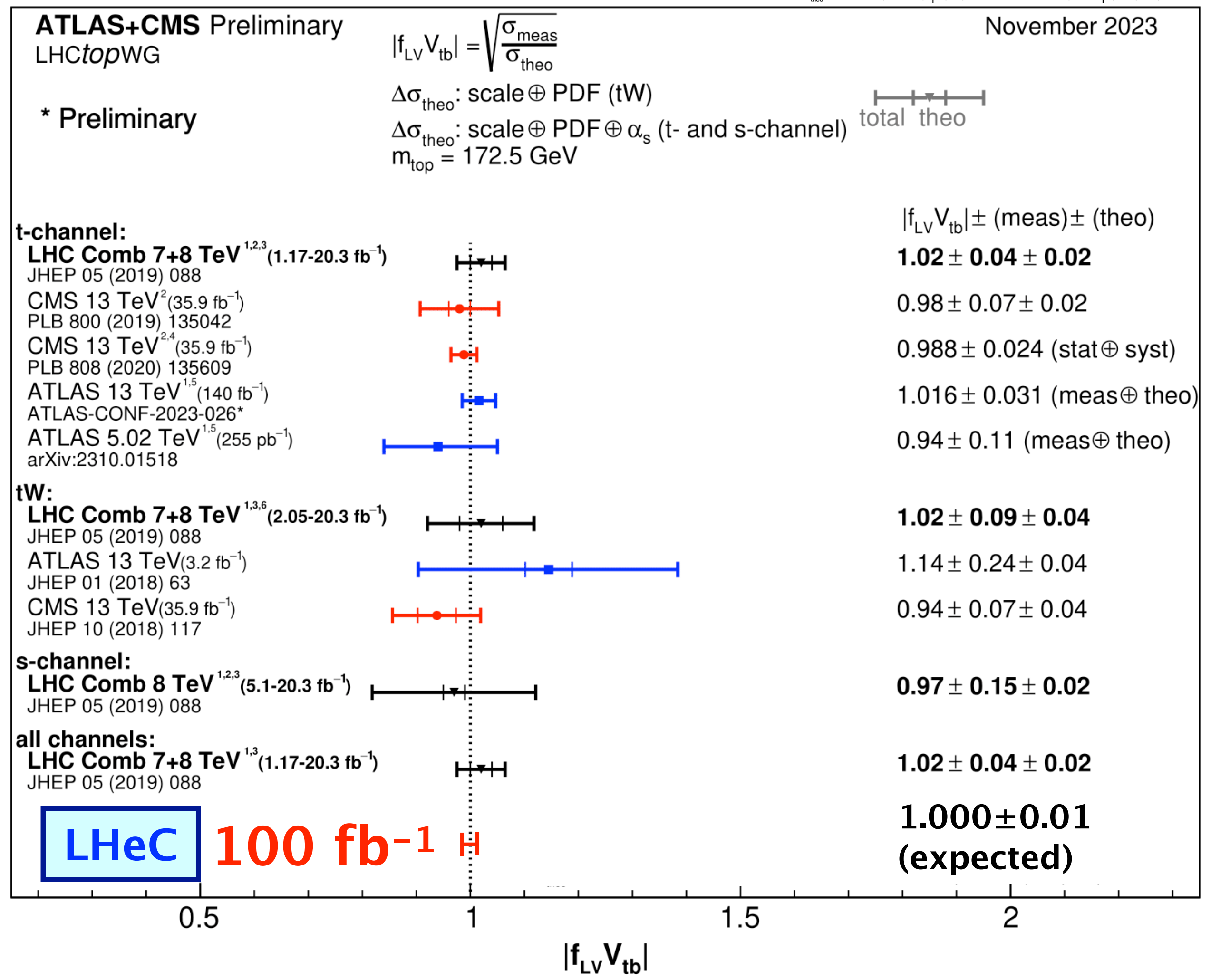
CC DIS top production



LHeC

hadronic channel:

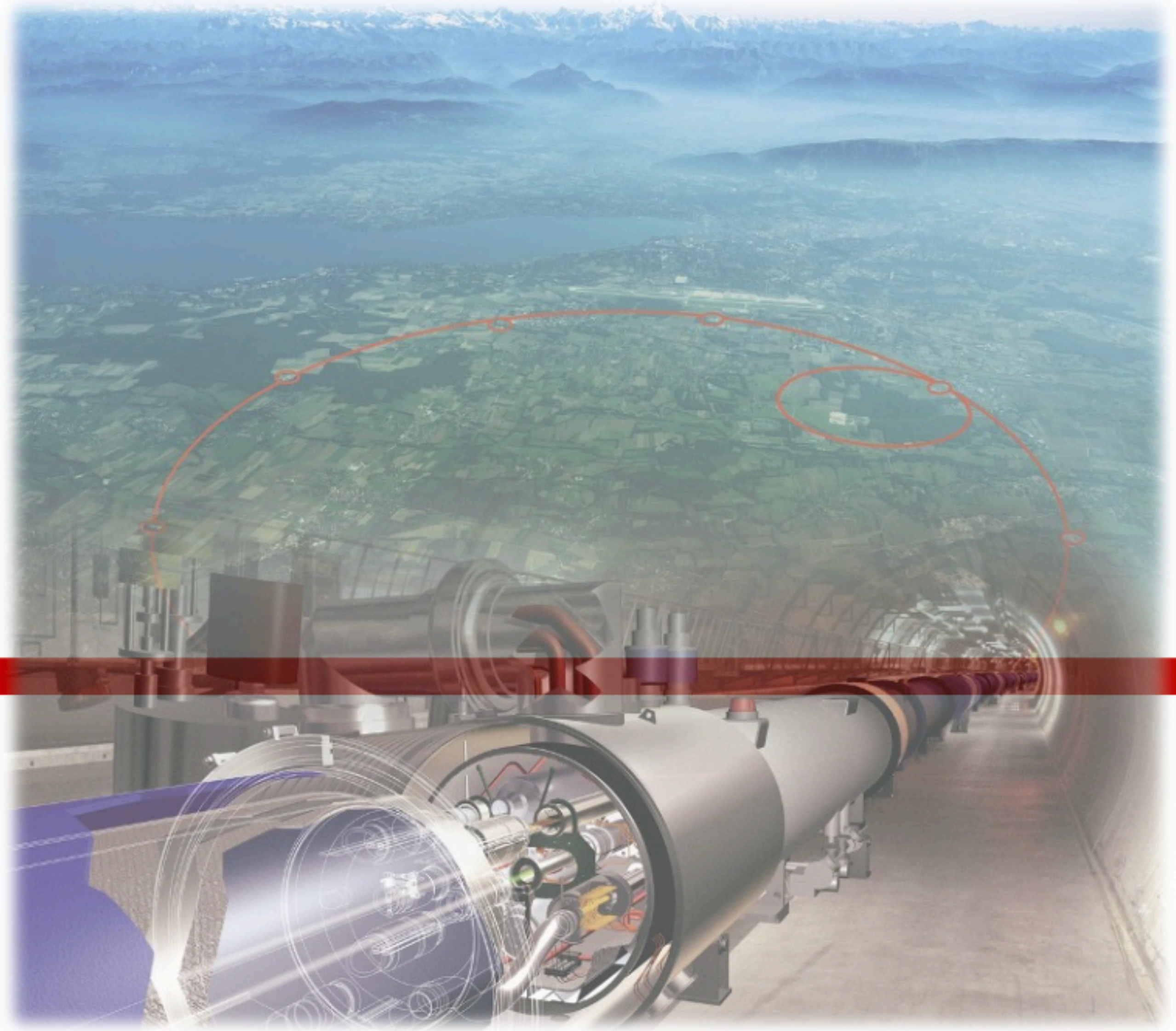




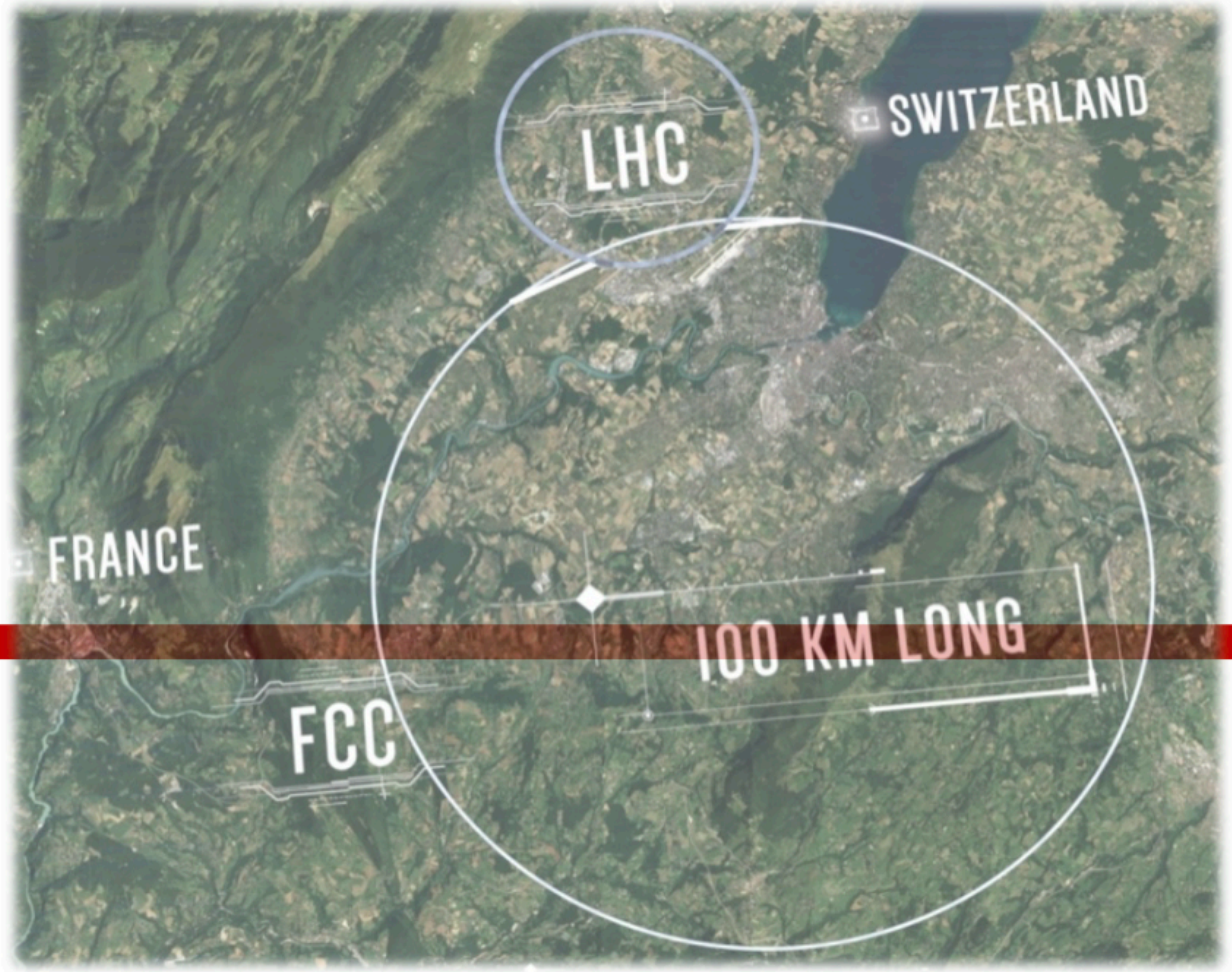
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unprecedented precision < 1%

Possible site: “Bridge” between major colliders @ CERN



LHC



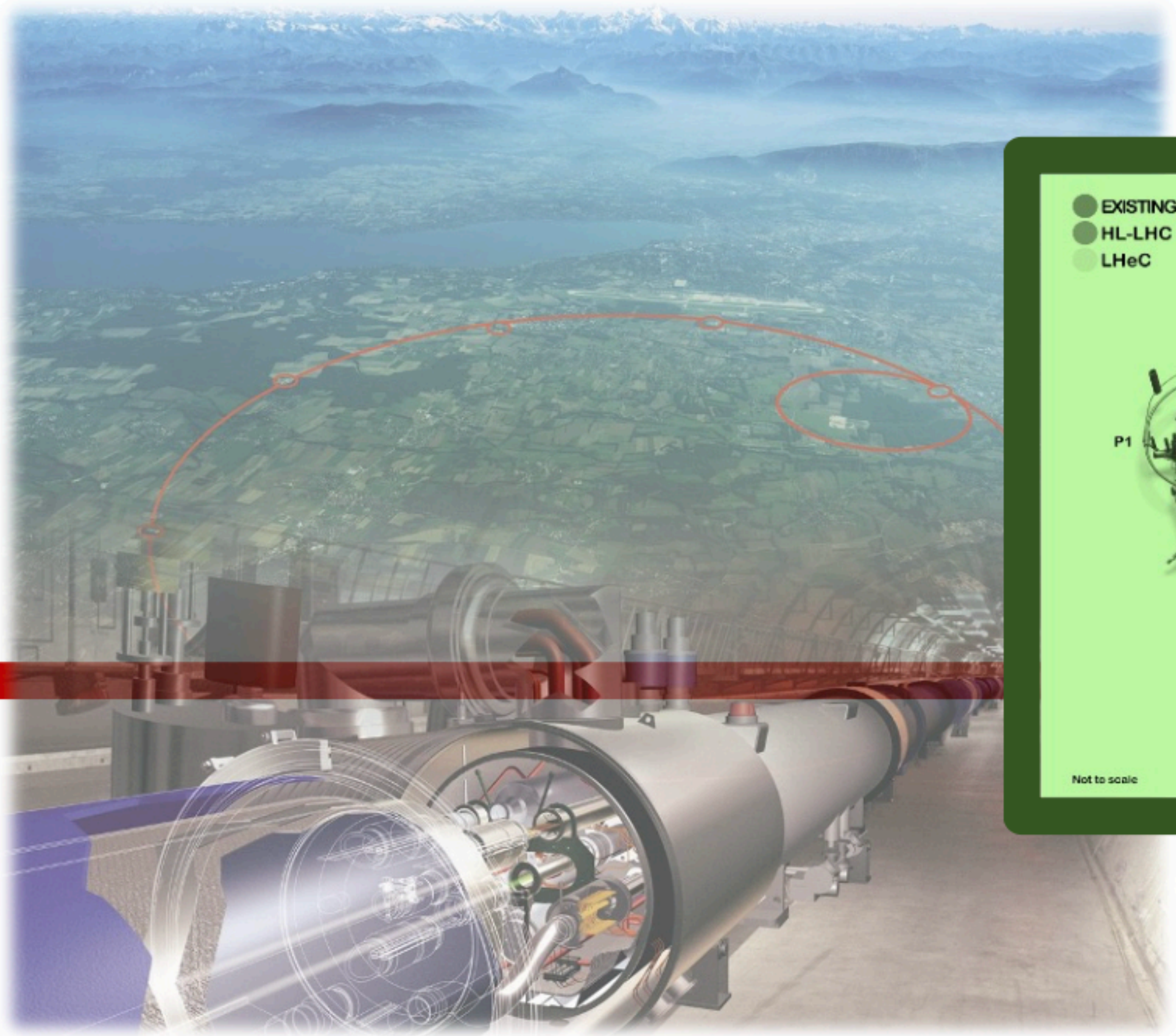
e.g. FCC (ee or hh)

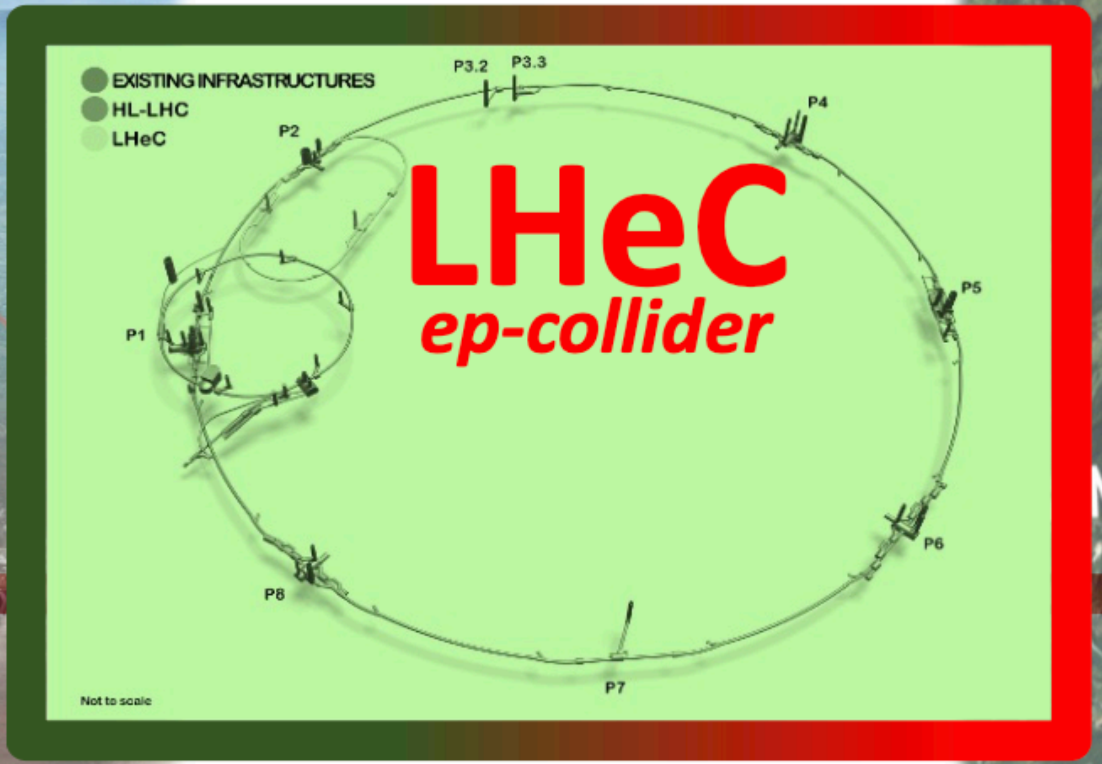
J. d’Hondt

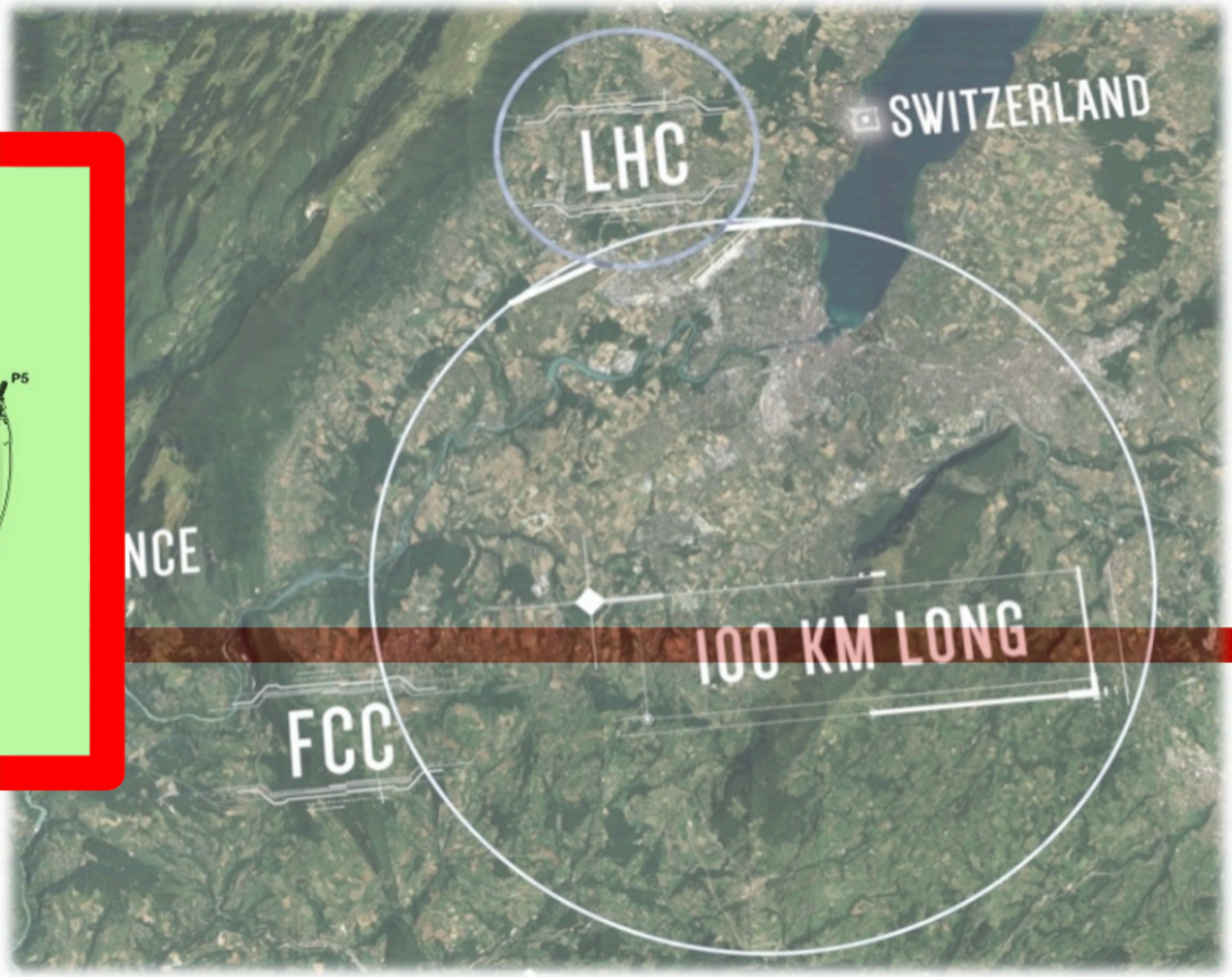
Possible site: “Bridge” between major colliders @ CERN

ep-option with HL-LHC: LHeC

e.g. 6 years ep-only@LHC > 1 ab^{-1}







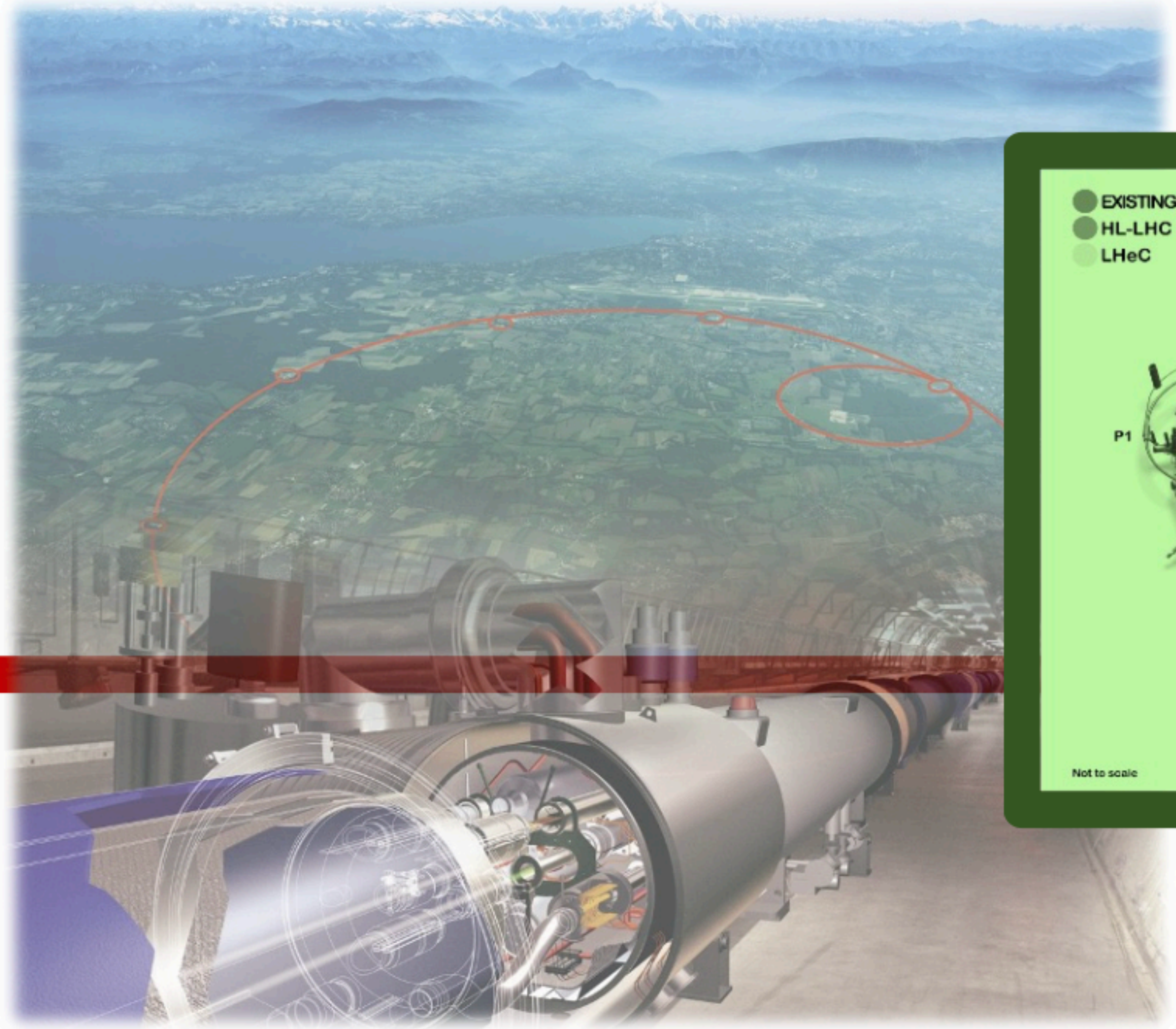
LHC

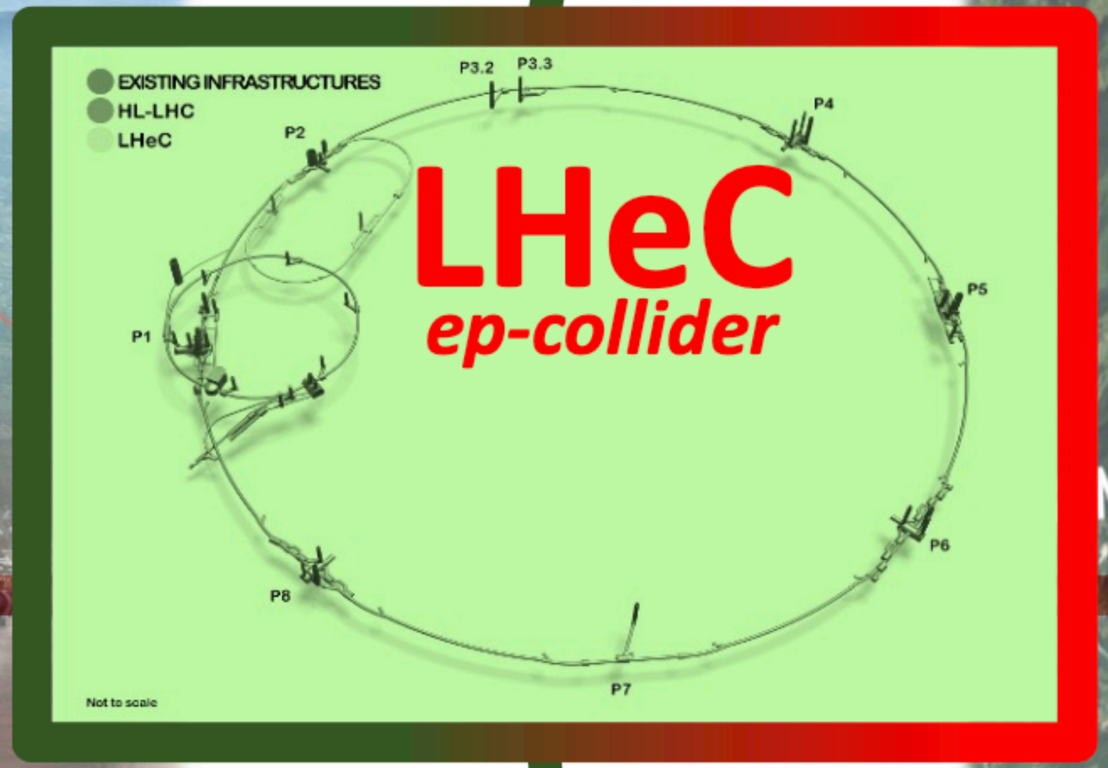
e.g. FCC (ee or hh)

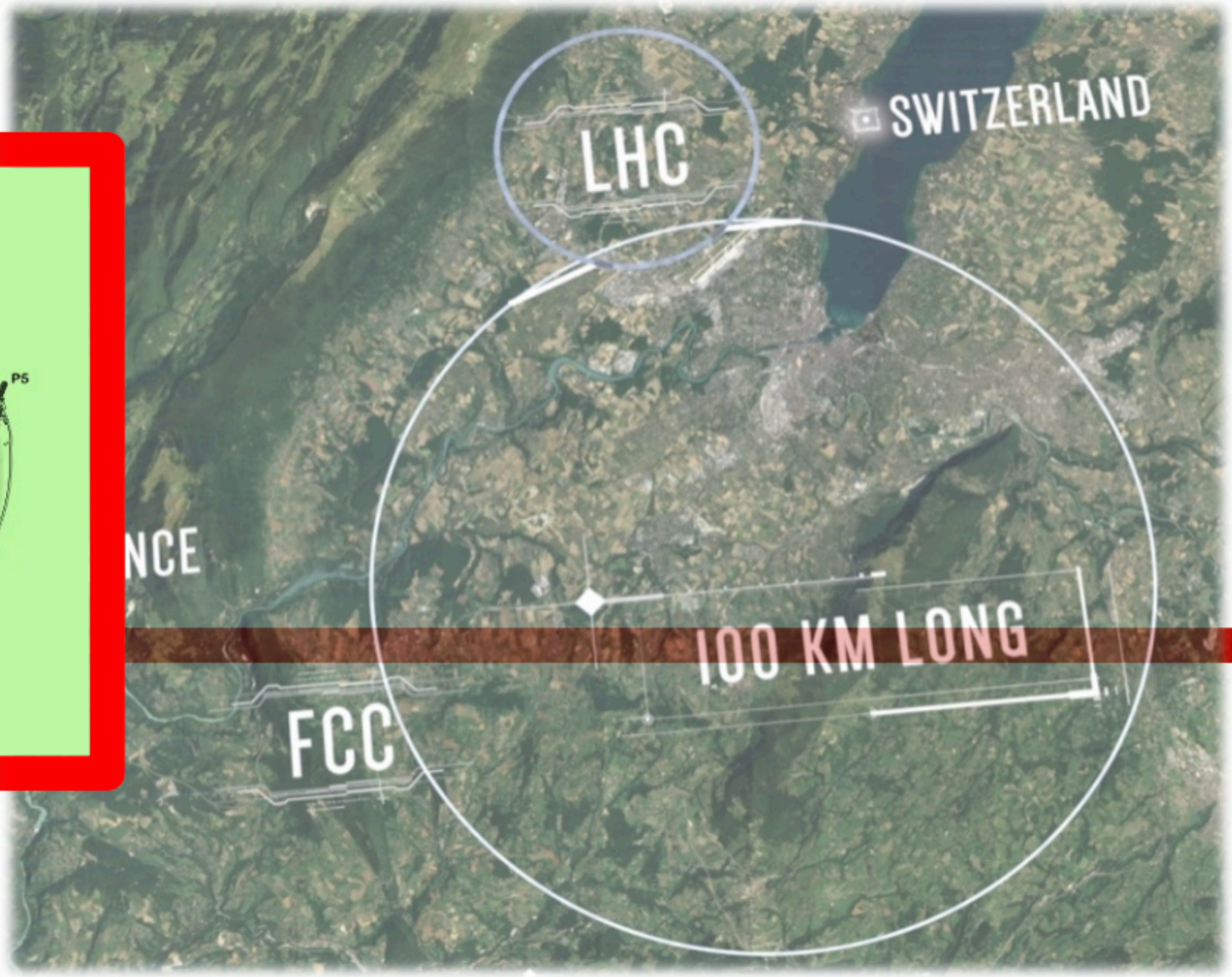
J. d’Hondt

Possible site: “Bridge” between major colliders @ CERN

ultimate upgrade of the LHC physics reach







fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

J. d’Hondt

Possible site: "Bridge" between major colliders @ CERN

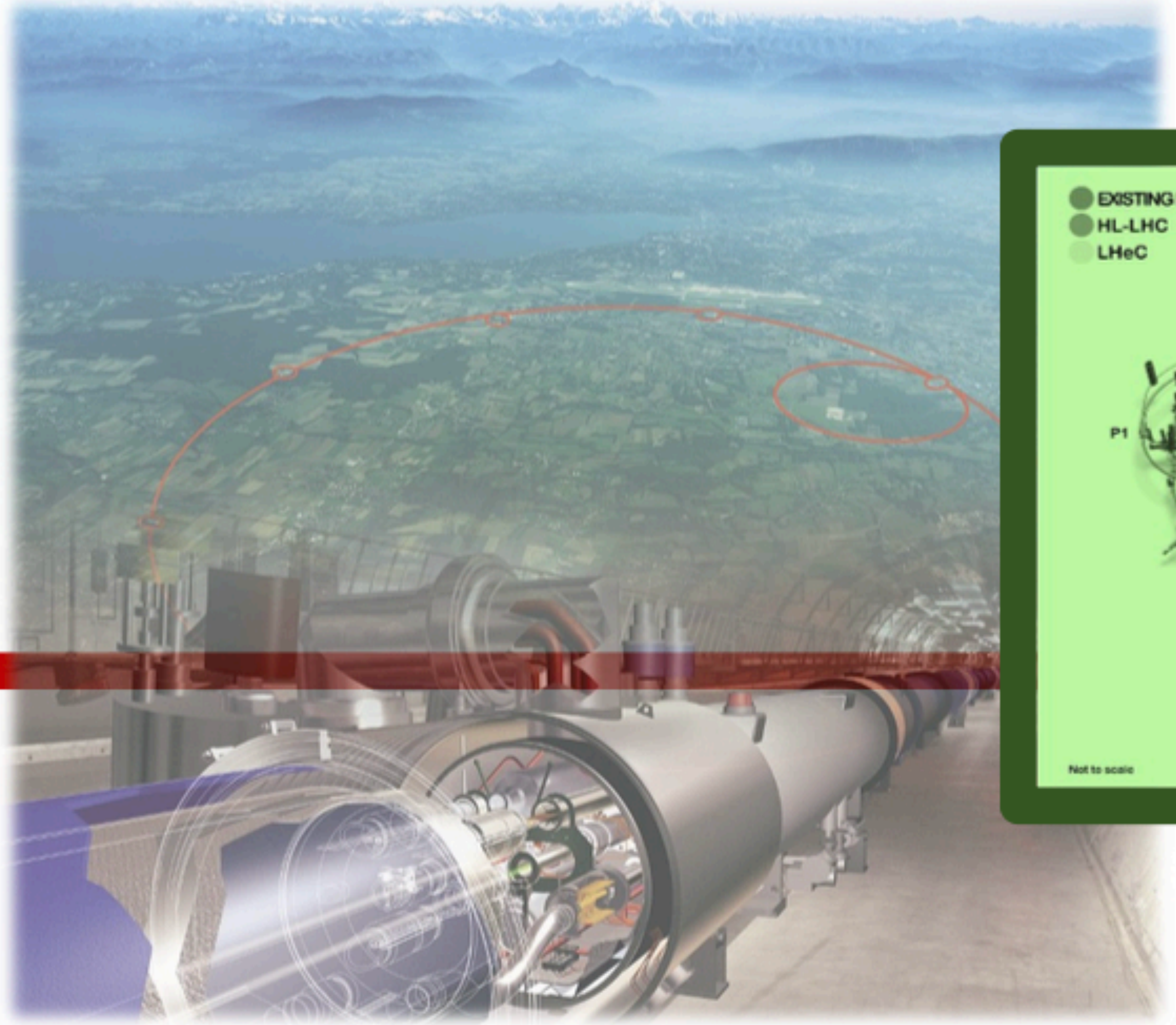
cost-effective investment

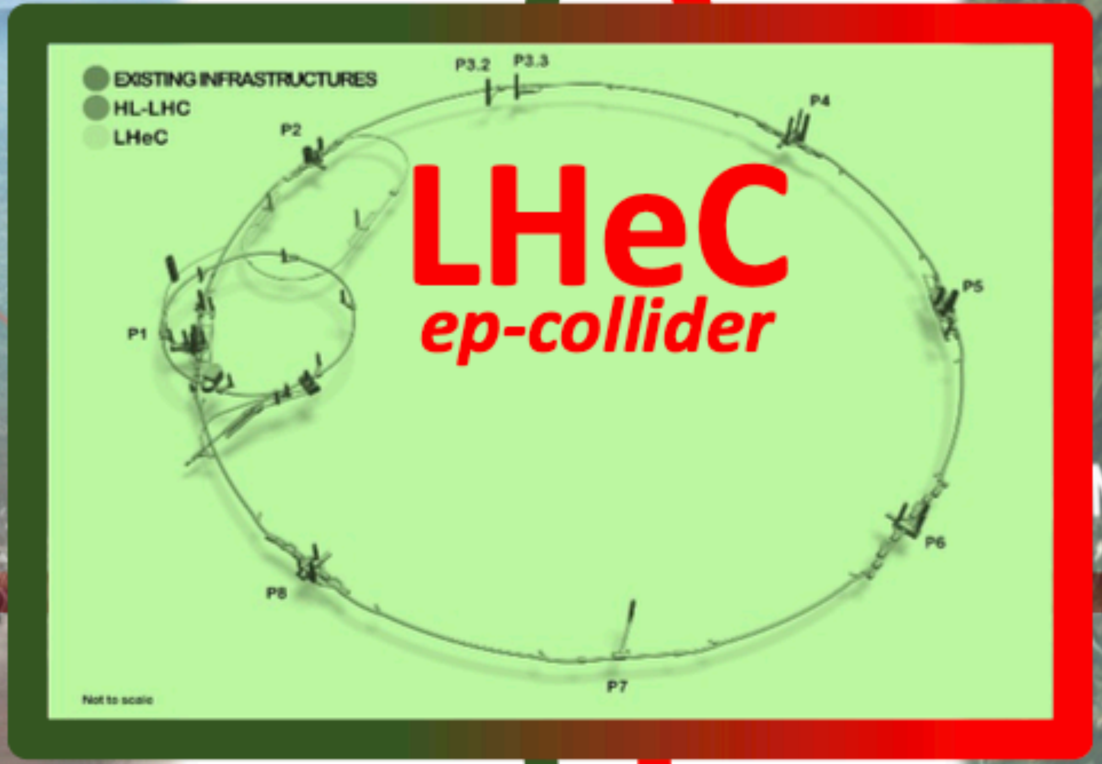
re-use
FCC-hh/eh

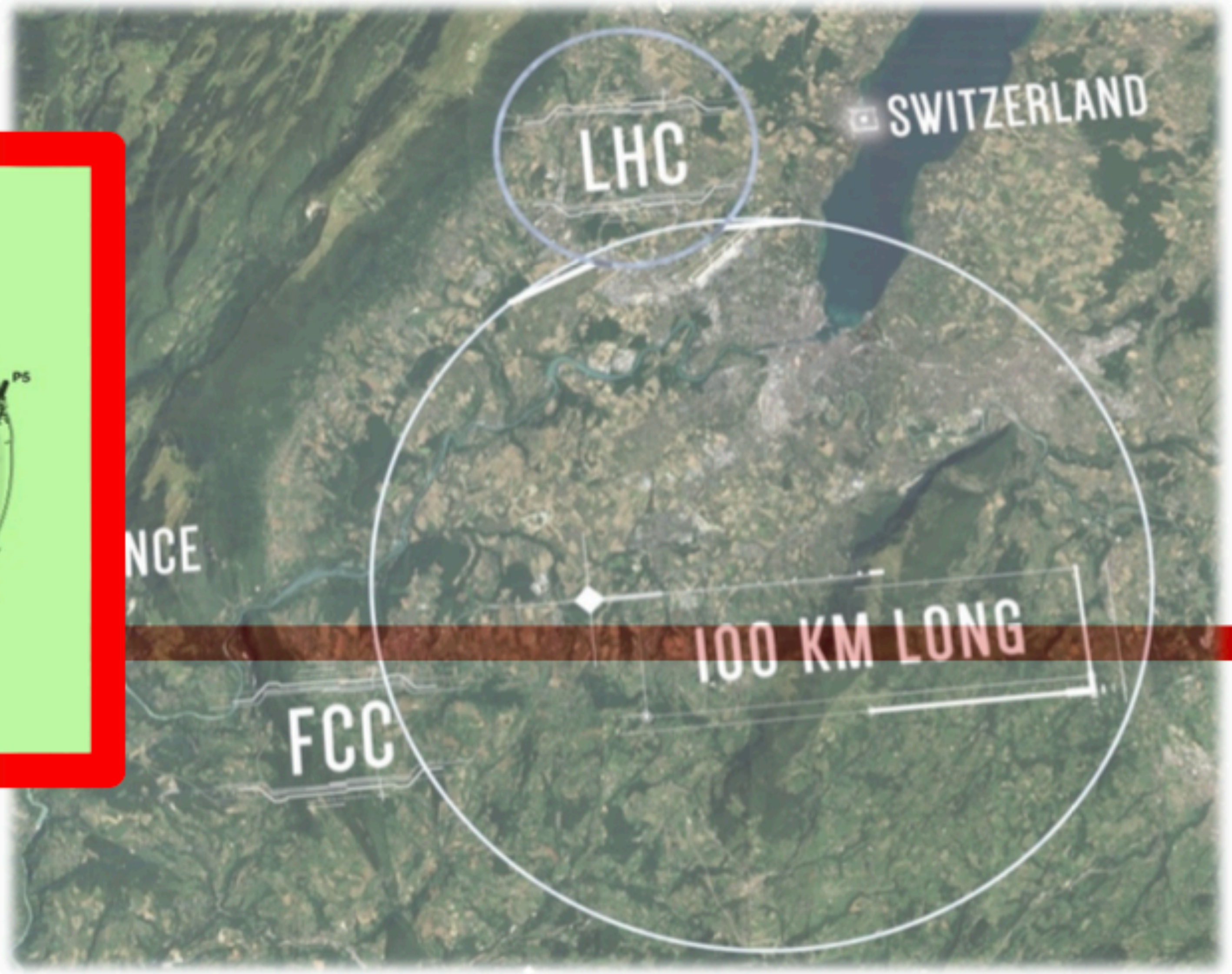
injector
FCC-ee

essential enabler for the physics at any new high-energy hadron collider

ultimate upgrade of the LHC physics reach
see previous slide







i.e. SRF@LHeC as prototype series and training for SRF@FCC-ee

fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

fast-track to the optimal SRF performance of a H-factory & cost/risk reduction for SRF at FCC-ee

J. d'Hondt

Possible site: “Bridge” between major colliders @ CERN

ultimate upgrade of the LHC physics reach

cost-effective investment

re-use

injector

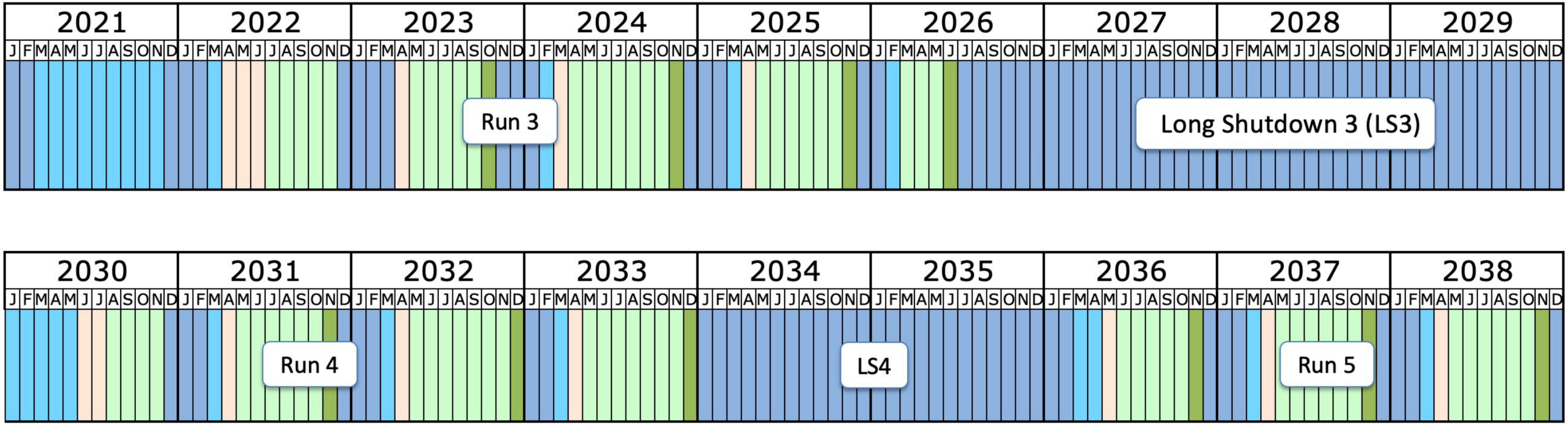
essential enabler for the physics at any new high-energy hadron collider

fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

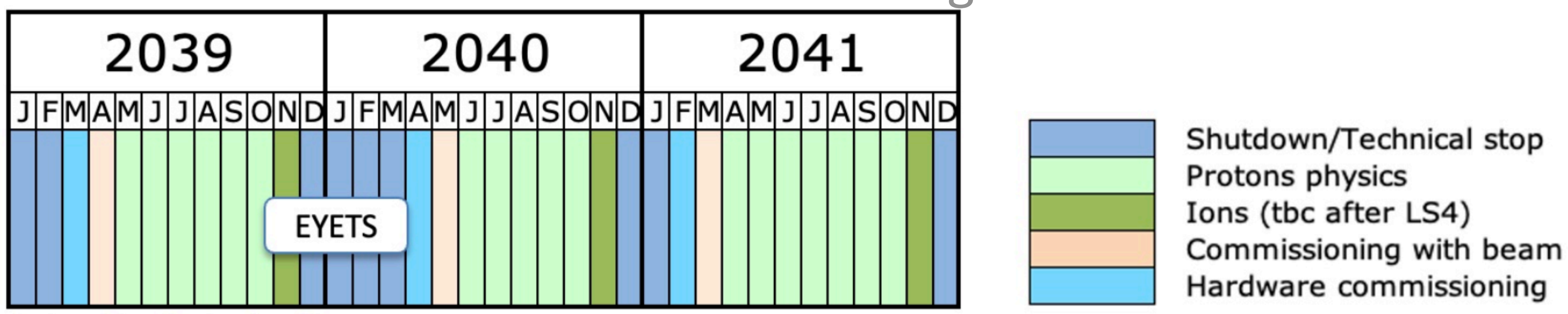
fast-track to the optimal SRF performance of a H-factory & cost/risk reduction for SRF at FCC-ee

J. d'Hondt

Time schedule



Staged Scenario: Installation Running at 15 mA (e beam)



- $e^{\pm}p$ 50 GeV x 7 TeV with lepton polarization +0.8 / 0 / -0.8
- eA 50 GeV x 2.76 TeV at 10 fb^{-1} per year

Running at 25 mA (e beam) Running at 50 mA (e beam)

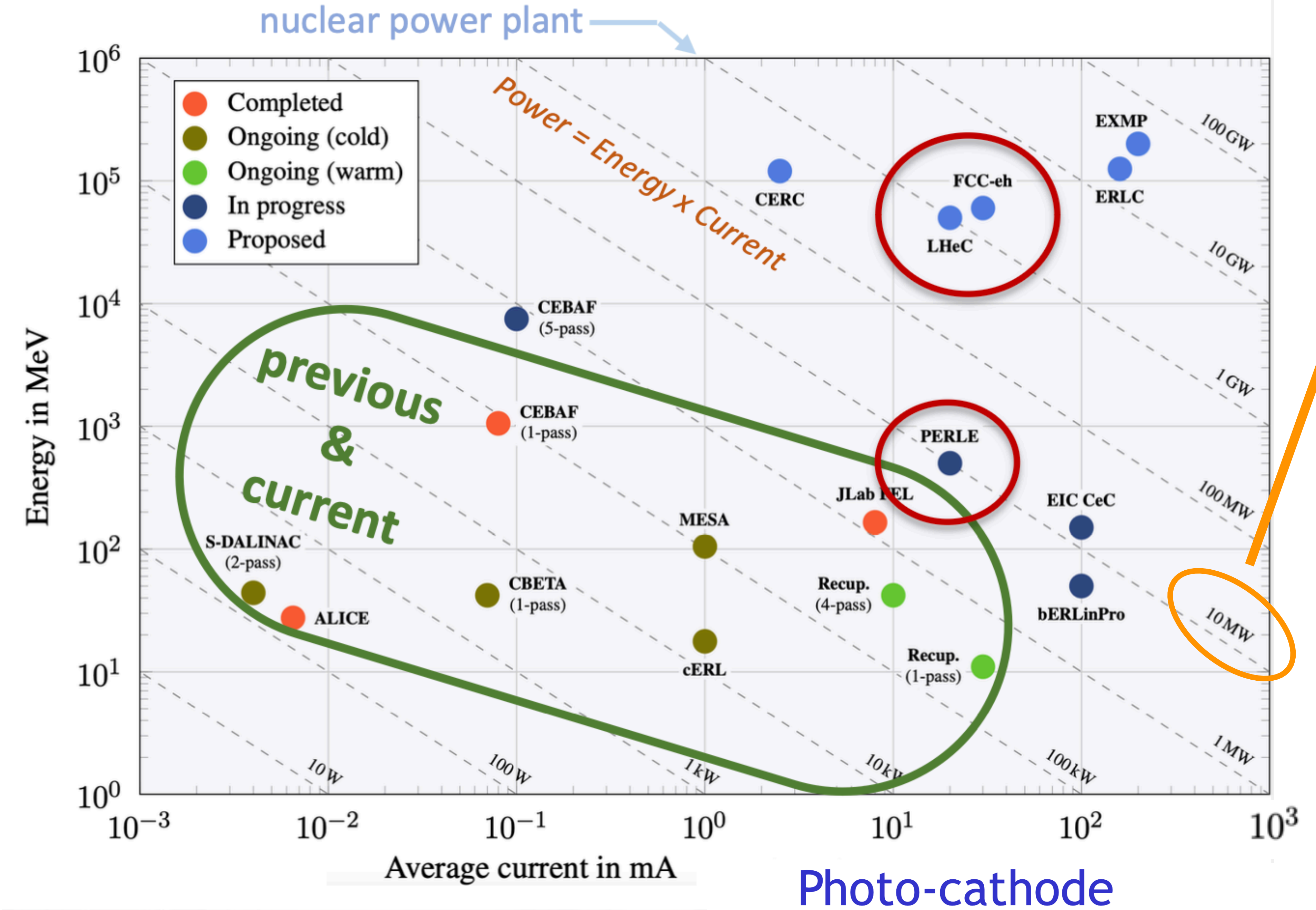
Scenario: Running in standalone ep mode

… integrated lumi of 180 fb^{-1} per year
→ 1 ab^{-1} total target in a few years

Status of the facility: Energy Recovery Linacs (ERL)

- Demonstrating ERL: scalability is critical path
- Prototype (PERLE @ IJCLab / Orsay) implementation started
- First stage (one turn) by 2028, 3 turns in 2029

multi-turn ERL based on SRF technology
(3-turns, 500 MeV, 20 mA)

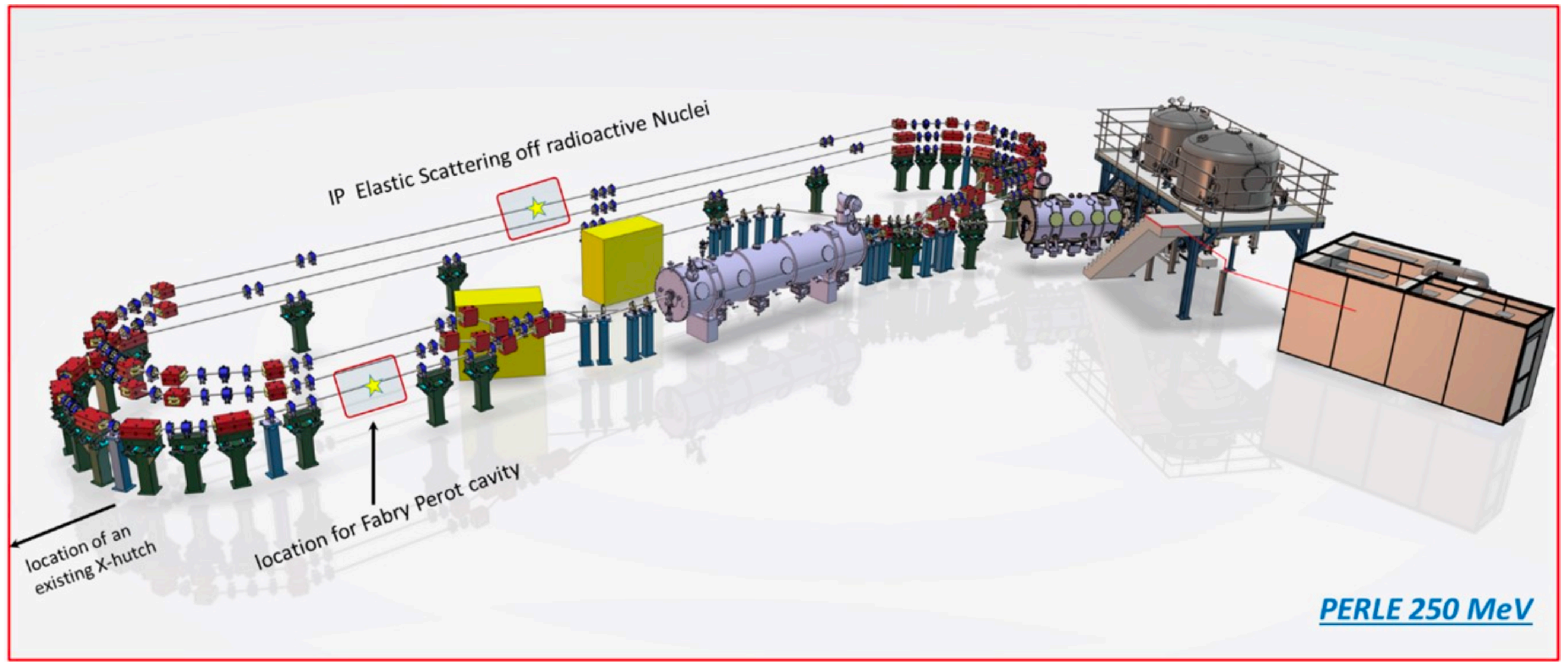


→ first 10 MW ERL facility

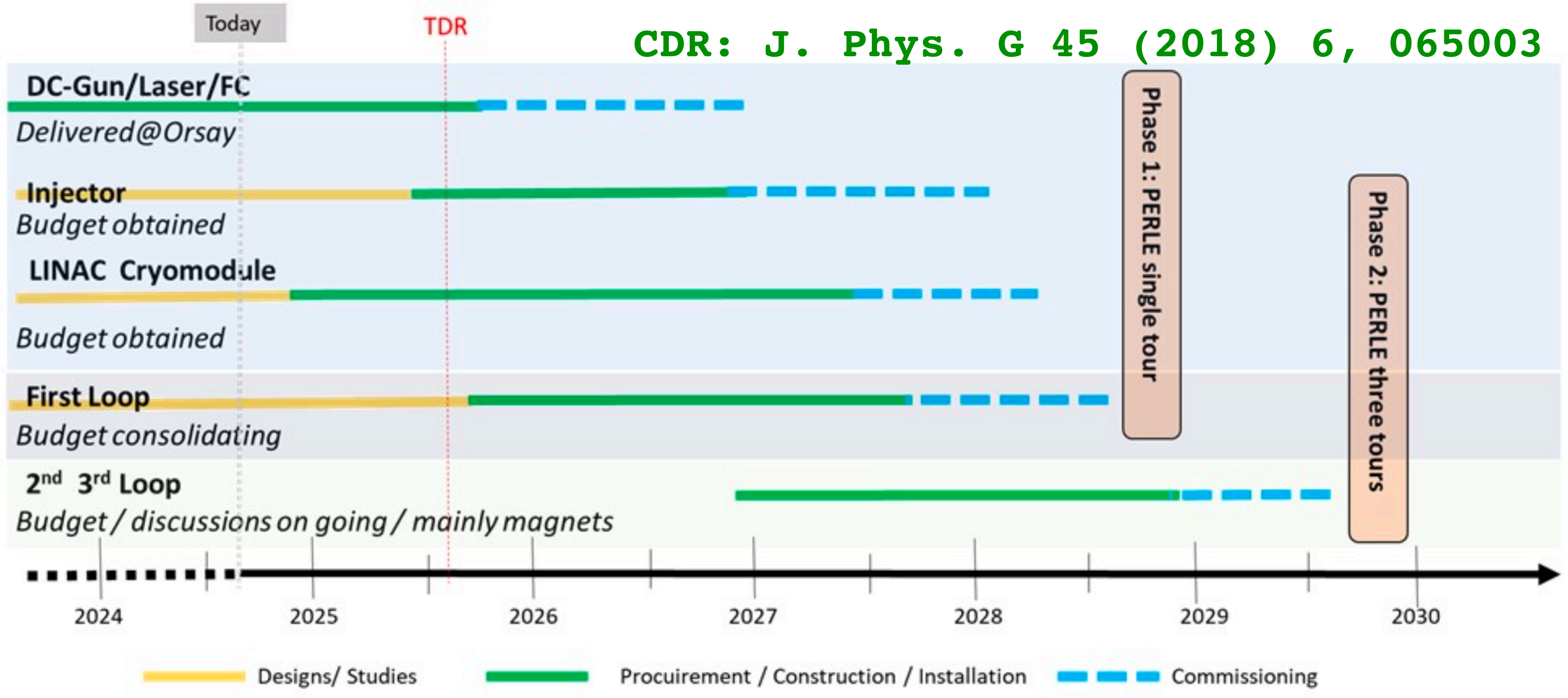
HV tanks

Photo-cathode

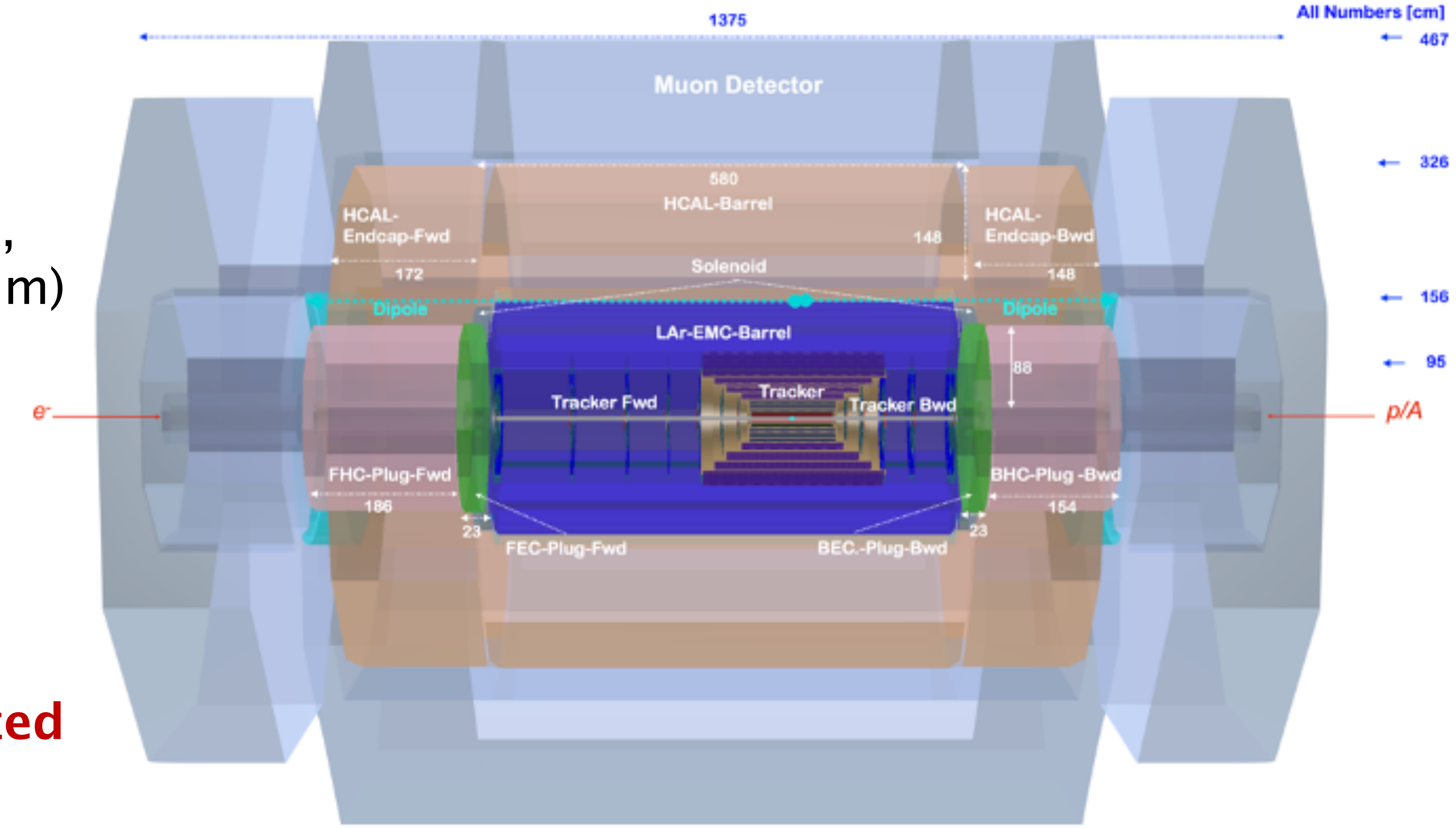
Electron DC-gun



CDR: J. Phys. G 45 (2018) 6, 065003



R&D Need: Detector Design



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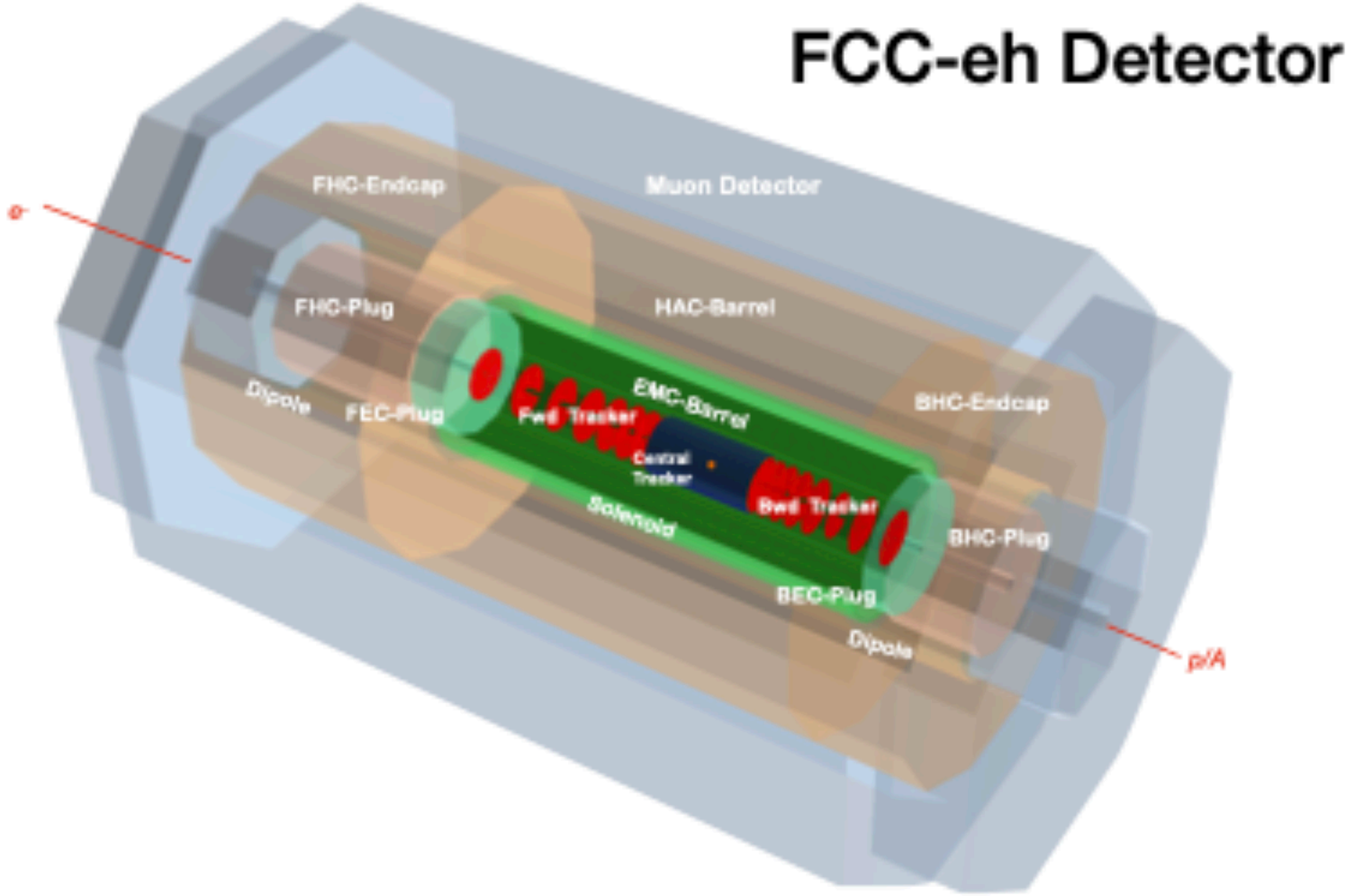
Compact
13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)

Hermetic
– 1° tracking acceptance forward & backward

Beamline also well instrumented

FCC-eh: 19m x 12m



Could be built now, but many open questions:

- a snapshot in time, borrowing heavily from (HL)-LHC (particularly ATLAS)
- possibly lacking components for some ep/eA physics (e.g. Particle ID)
- not particularly well integrated or optimized

… synergies with EIC, LHCb, ALICE3, future lepton colliders still to be explored

Organisational structure / Political organisation

LHeC / FCC-eh study group: 337 collaborators (CDR), 156 institutes (9 German) from 6 continents

https://indico.cern.ch/e/LHeCFCCeh

2023 | WS | 2024 | WS | 2025 | TWS | *input to ESPP*

proton and nuclear structure from EIC and HERA to LHeC and FCC-eh
novel QCD with high-energy DIS physics: what do we discover when breaking protons and nuclear matter in smaller pieces

general-purpose high-energy physics programme: precision physics and searches
enabling direct discoveries and measurements in EW, Higgs and top physics with high-energy DIS collisions

ep/eA-physics empowering pp/pA/AA-physics (LHC and FCC)
improving the ATLAS, CMS, LHCb and ALICE discovery potential with results from a high-energy DIS physics programme

developing a general-purpose ep/eA detector for LHeC and FCC-eh
critical detector R&D (DRD collaborations), integrate in the FCC framework, one detector for joint ep/pp/eA/pA/AA physics

developing a sustainable LHeC and FCC-eh collider programme
design the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …

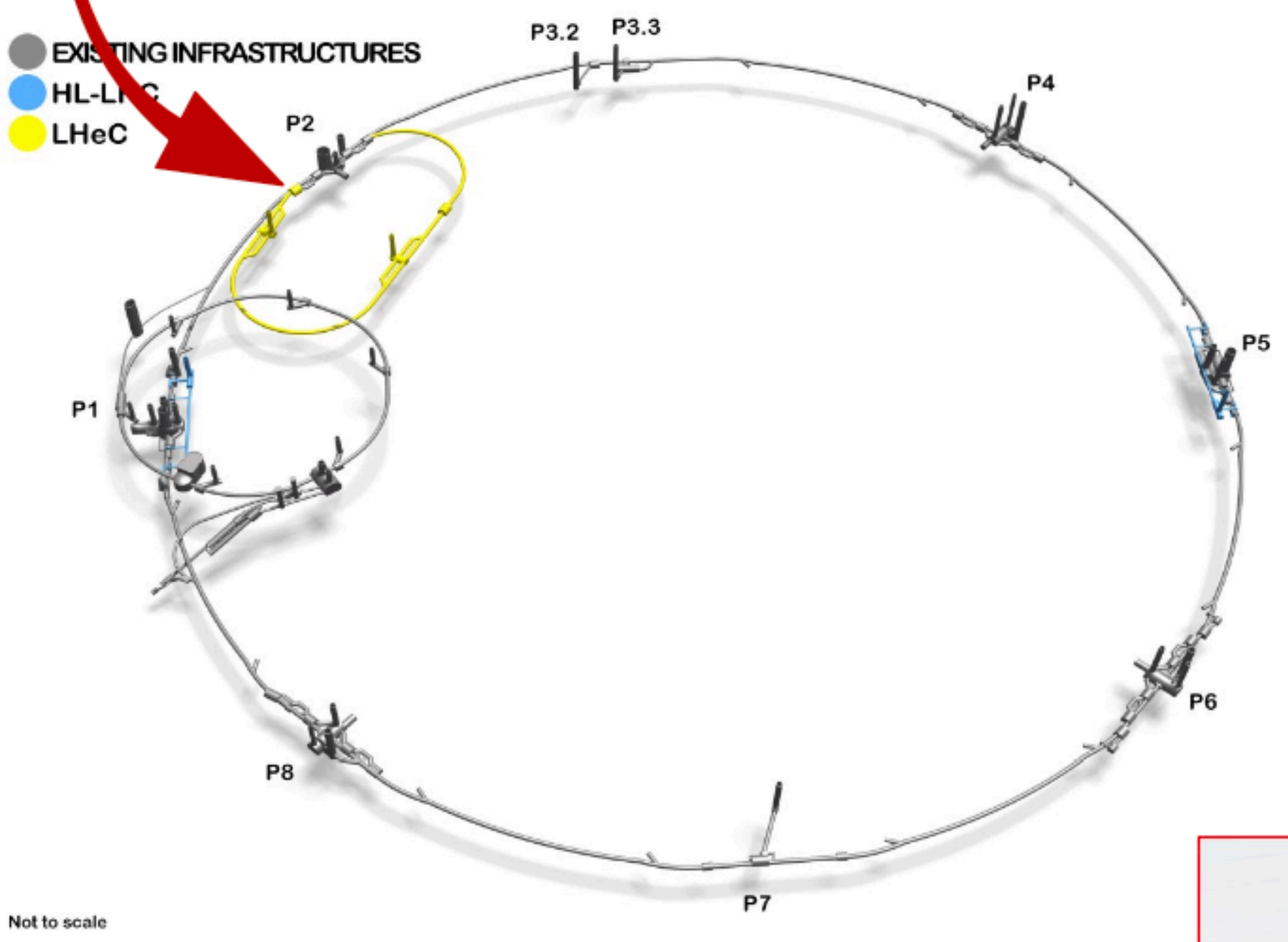
- typically 2-3 conveners per theme
- annual ep/eA workshops (**WS**)
- final thematic workshop with closing reports to inform the upcoming Strategy process with impactful information (**TWS**)
- inform the community with regular ep/eA Newsletters
- everybody is welcome to join

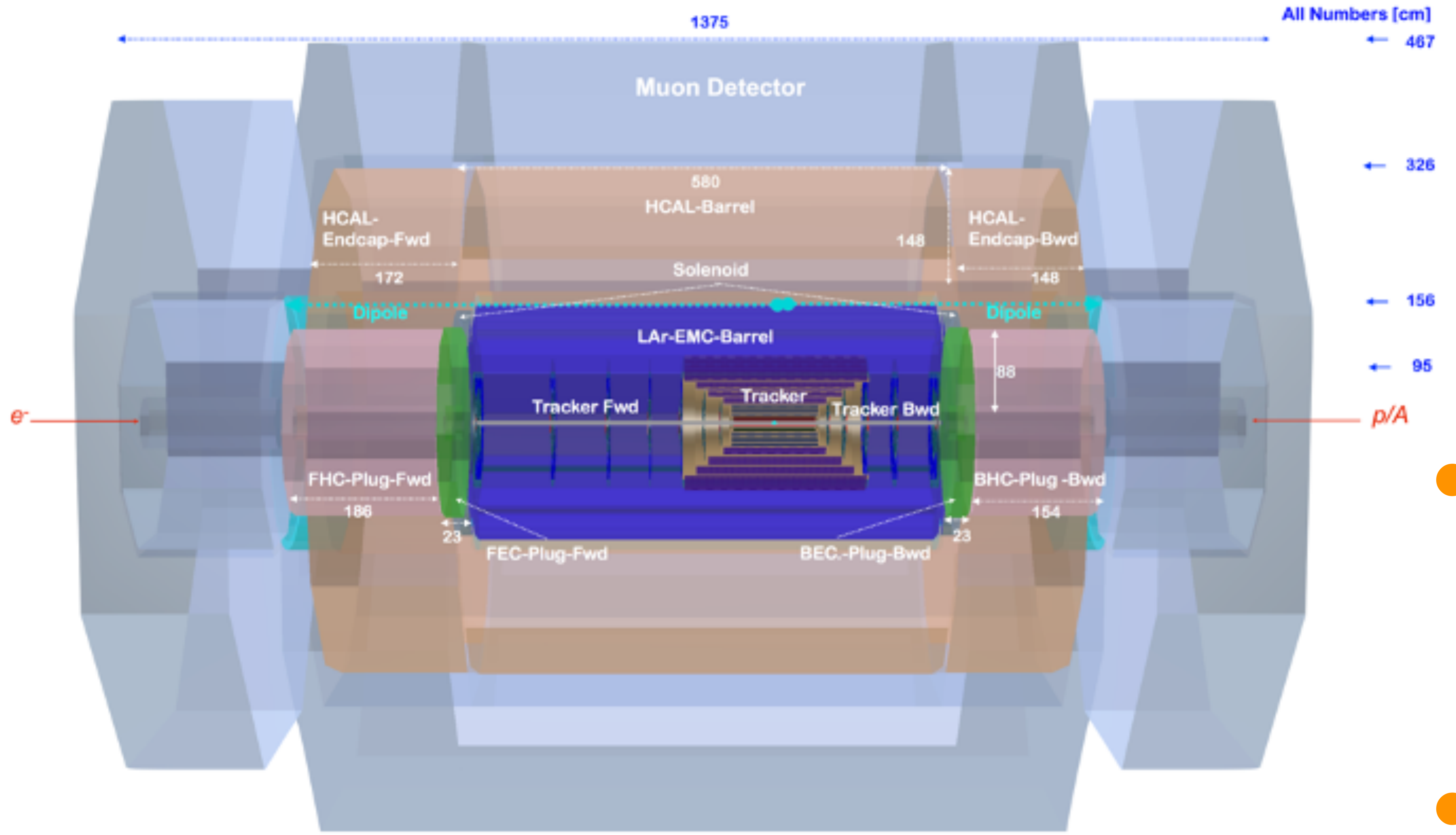
Coordination Panel: N. Armesto, M. Boonekamp, O. Brüning, D. Britzger, J. D'Hondt (spokesperson), M. D'Onofrio, C. Gwenlan, U. Klein, P. Newman, Y. Papaphilippou, C. Schwanenberger, Y. Yamazaki

- CERN support with the mandate for the ep/eA@CERN study group
- It can be expected that the large EIC community can engage in a natural way in the LHeC, but also ATLAS/CMS communities or Heavy Ion community with eA collisions in mind
- German leadership with HERA and ERL research in bERLinPro (HZB), S-DALINAC (Darmstadt), MESA (Mainz)

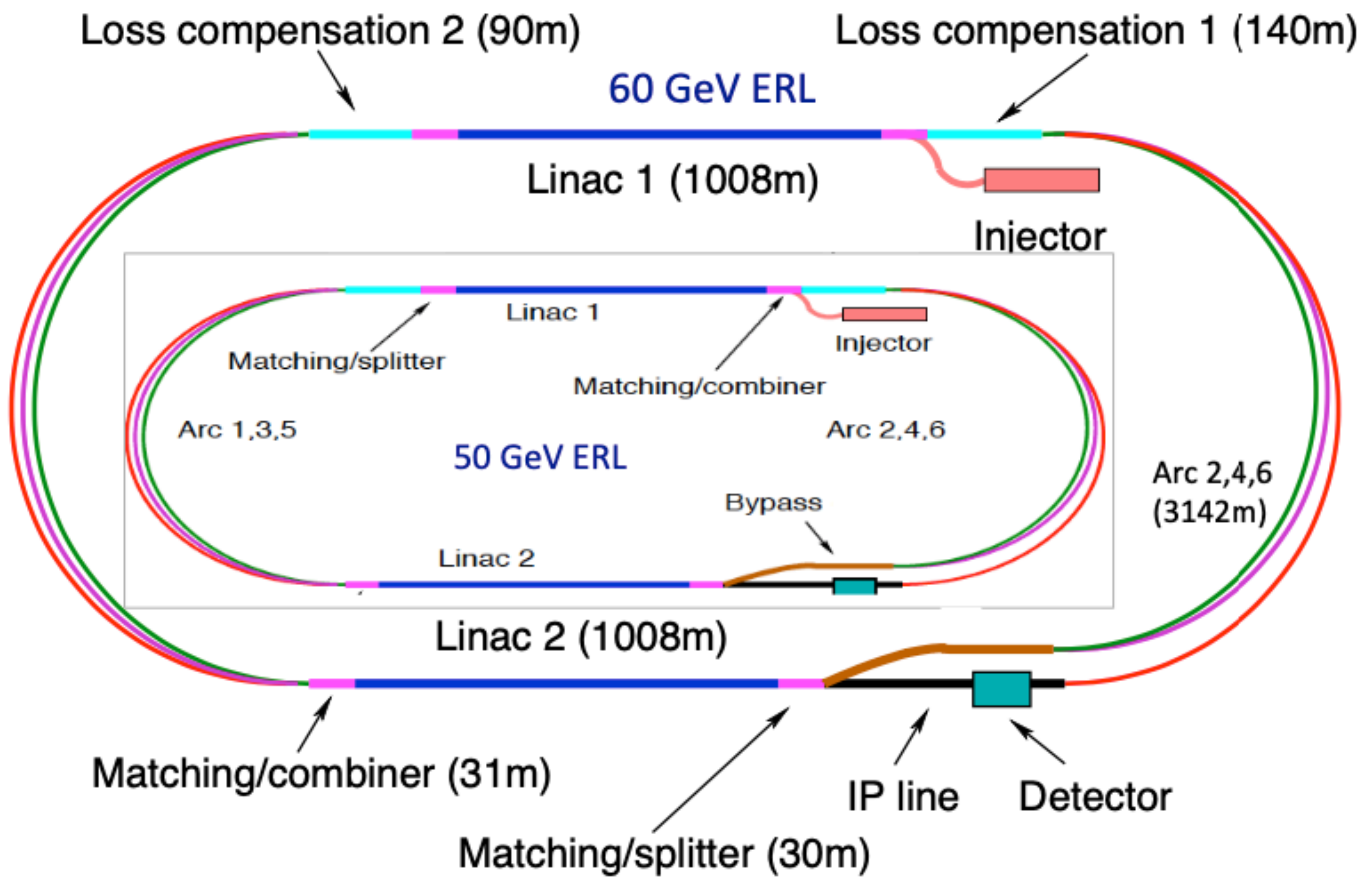
Estimates of sustainability

LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳Run5)

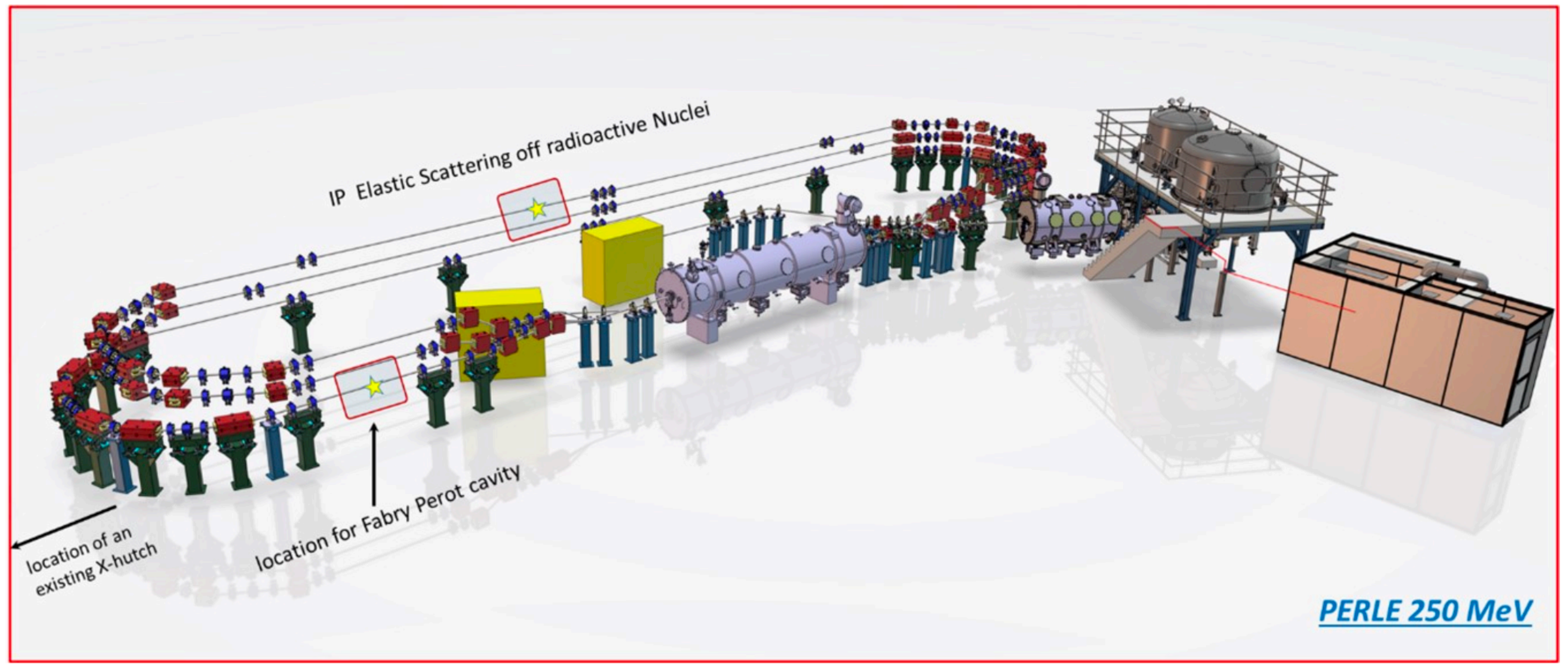




- ‘sustainable’ acceleration:
  ~100 MW (similar to LHC today)
- green technology



→ aspects of sustainability are being collected and reviewed by a dedicated working group of the LDG (Lab Directors Group), in due time this report will become public



Costs and personpower

CERN-ACC-2018-0061, ATS report approved by director of accelerators, Frederick Bordry

Budget Item	Cost 30GeV	➔ 50GeV
SRF System	402MCHF	+268MCHF
SRF R&D and Proto Typing	31MCHF	
Injector	40MCHF	
Magnet and Vacuum System	103MCHF	
SC IR magnets	105MCHF	
Dump System and Source	5MCHF	
Cryogenic Infrastructure	41.5MCHF	+28MCHF
General Infrastructure and installation	58MCHF	
Civil Engineering	289MCHF	
Total	1075MCHF	➔ 1371MCHF

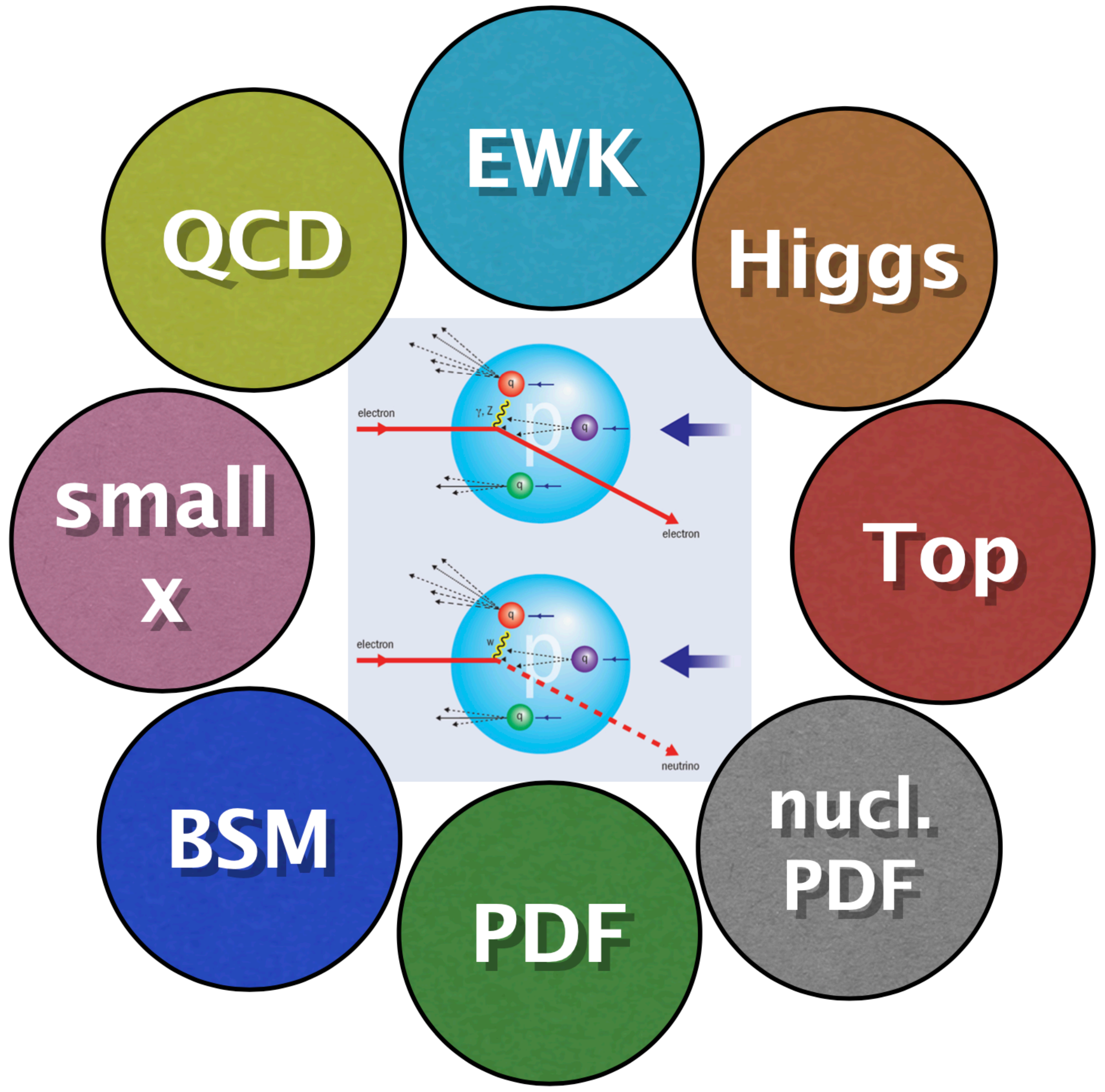
costs: 2018

- 1-1.8 BCHF: in 10 years means ~8-14% of the CERN annual budget
- detector: ~few x 100 MCHF, presumably mostly coming from contributions via an experimental collaboration, so not core CERN funds
- Considering electricity price of 0.1CHF/kWh: additional operation cost for the LHeC at around 15MCHF to 30MCHF per year (similar to LHC)
- accelerator implementation: total personpower need of ca. 2500 Person Years (2300 of CERN staff plus personpower from international collaborations)
- operating the LHeC: with only one experimental insertion of one proton beam and ERL facility is comparable to the needs of to HL-LHC with two proton beams and 4 experimental insertions

Conclusions

- **EIC** is happening: from mid 2030s it will transform our understanding of nucleon and nuclear structure, scientifically complementing past / future energy frontier DIS facilities
- **LHeC** as a bridge between HL-LHC and FCC-ee that supports technological development and offers a wide-ranging deep physics programme
- **LHeC** would also be a natural bridge between HL-LHC and FCC-hh/HE-LHC, with impactful physics to empower the high-energy pp physics
- **LHeC** is not the next major collider for CERN
- **LHeC** could be an impactful final upgrade to LHC…
  - potentially 'affordable' on required timescale
  - technically realisable for late 2030s (ERL technology = critical path)
  - extending energy frontier sensitivity within a few years of running
  - complementing and enabling HL-LHC programme, keep communities alive
  - ensuring continuity of collisions and scalar sector exploration in the 2040s
  - exploring SRF (802 MHz as FCC-ee), ERL options & detector technologies

… as a testing ground (injector?) for a future major facility



The **LHeC** offers an achievable bridging project for CERN, with an impactful physics programme, including further empowerment of the LHC and exploration of the scalar sector.

Backup

Running scenarios considered in CDR

- $e^{\pm}p$ 50 GeV x 7 TeV with lepton polarization +0.8 / 0 / -0.8

Parameter	Unit	Run 5 Period	Run 6 Period	Dedicated
Brightness $N_p/(\gamma\epsilon_p)$	10^{17}m^{-1}	2.2/2.5	2.2/2.5	2.2/2.5
Electron beam current	mA	15	25	50?
Proton β^*	m	0.1	0.7	0.7
Peak luminosity	$10^{34}\,\text{cm}^{-2}\text{s}^{-1}$	0.5	1.2	2.4
Proton beam lifetime	h	16.7	16.7	100
Fill duration	h	11.7	11.7	21
Turnaround time	h	4	4	3
Overall efficiency	%	54	54	60
Physics time / year	days	160	180	185
Annual integrated lumi.	fb^{-1}	20	50	180

[Pile-up ~0.1]

Running concurrently with pp at HL-LHC:
... integrated lumi of 20 fb-1 per year at Run 5 → 50 fb^{-1} initial dataset
... integrated lumi of 50 fb-1 per year at Run 6 → few 100 fb^{-1} total @ HL-LHC

Running in standalone ep mode:
... integrated lumi of 180 fb-1 per year → 1 ab^{-1} total target in a few years

- eA 50 GeV x 2.76 TeV at 10 fb-1 per year

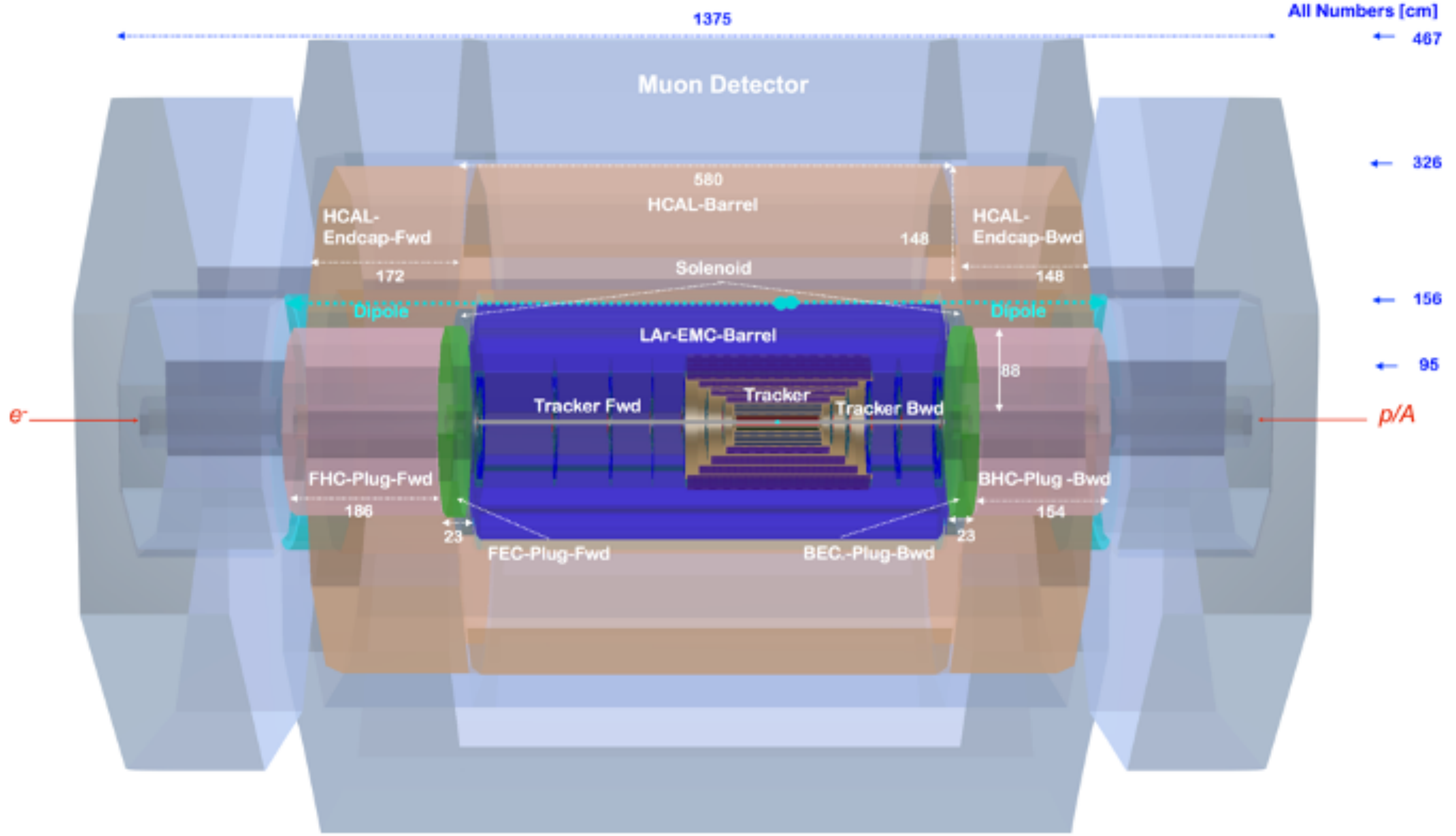
P. Newman

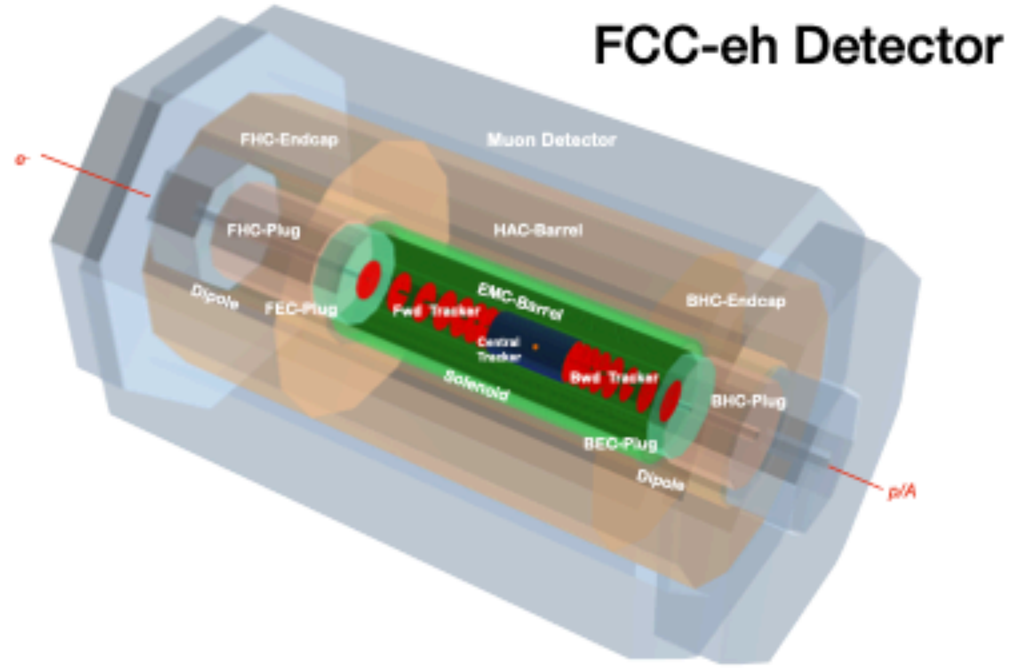
LHeC Detector Design

Eur. Phys. J. C 82 (2022) 1, 40

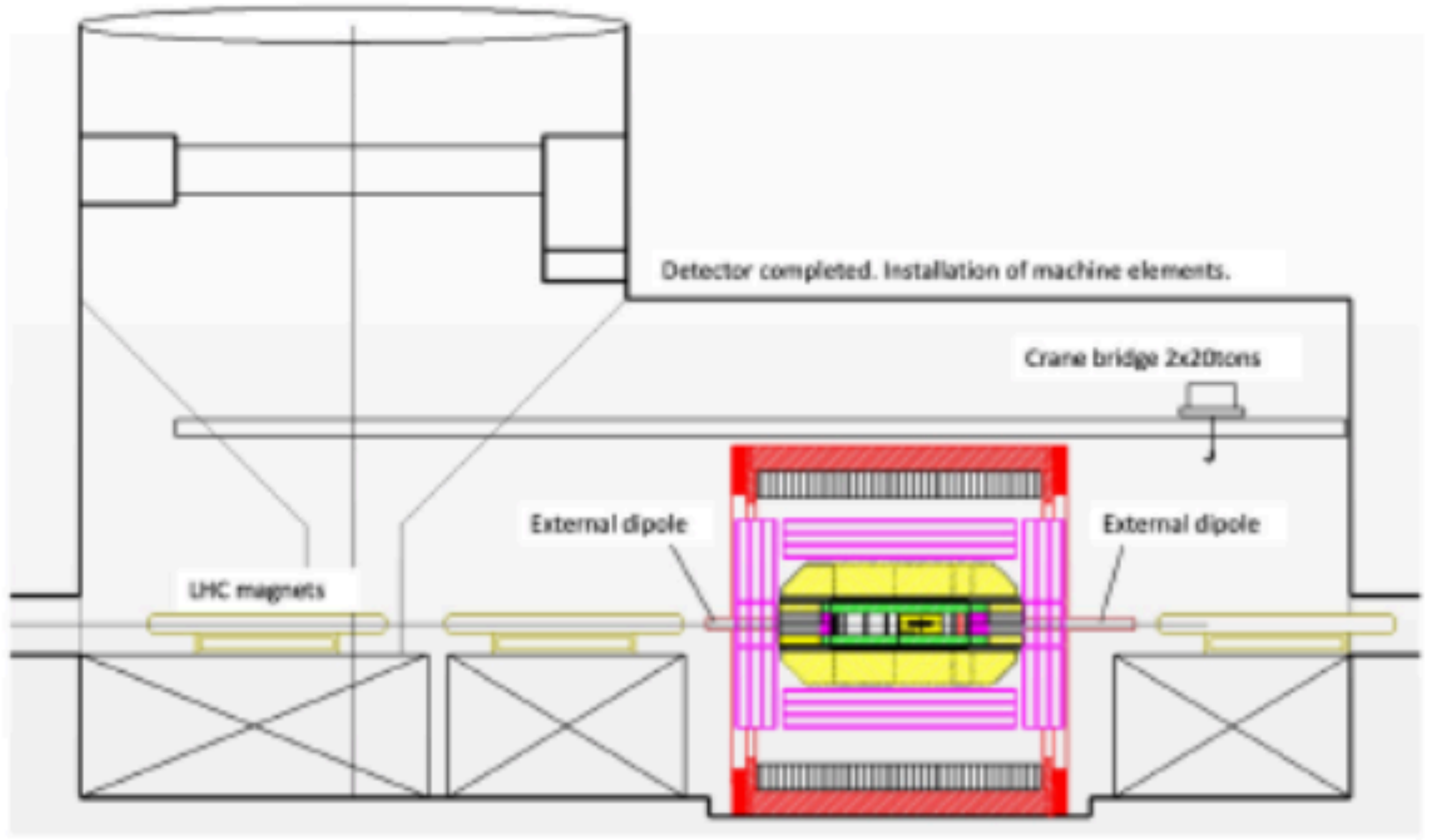
L=13.2 m [FCCeh:19.3 about CMS size]

R=4.8 m
[6.2 FCCeh]





Study of installation (sequence)
of LHeC detector in IP2 cavern
using L3 magnet support structure
[commensurate with 2 year shutdown
due to modular structure]



- large acceptance, precision device: design is determined by kinematics and high precision demands as from the H→bb reaction in CC
- low radiation (1/100 that of pp) enables sensitive technology such as HV CMOS to be used
- the need to ensure head-on ep collisions introduces a long, low field dipole to be inserted before the HCAL, the solenoid is a rather conventional magnet
- complemented by forward (p,n) and backward (e, γ) tagging detectors

LHeC Detector Design

forward-backward symmetrised detector permits alternately eh and hh physics

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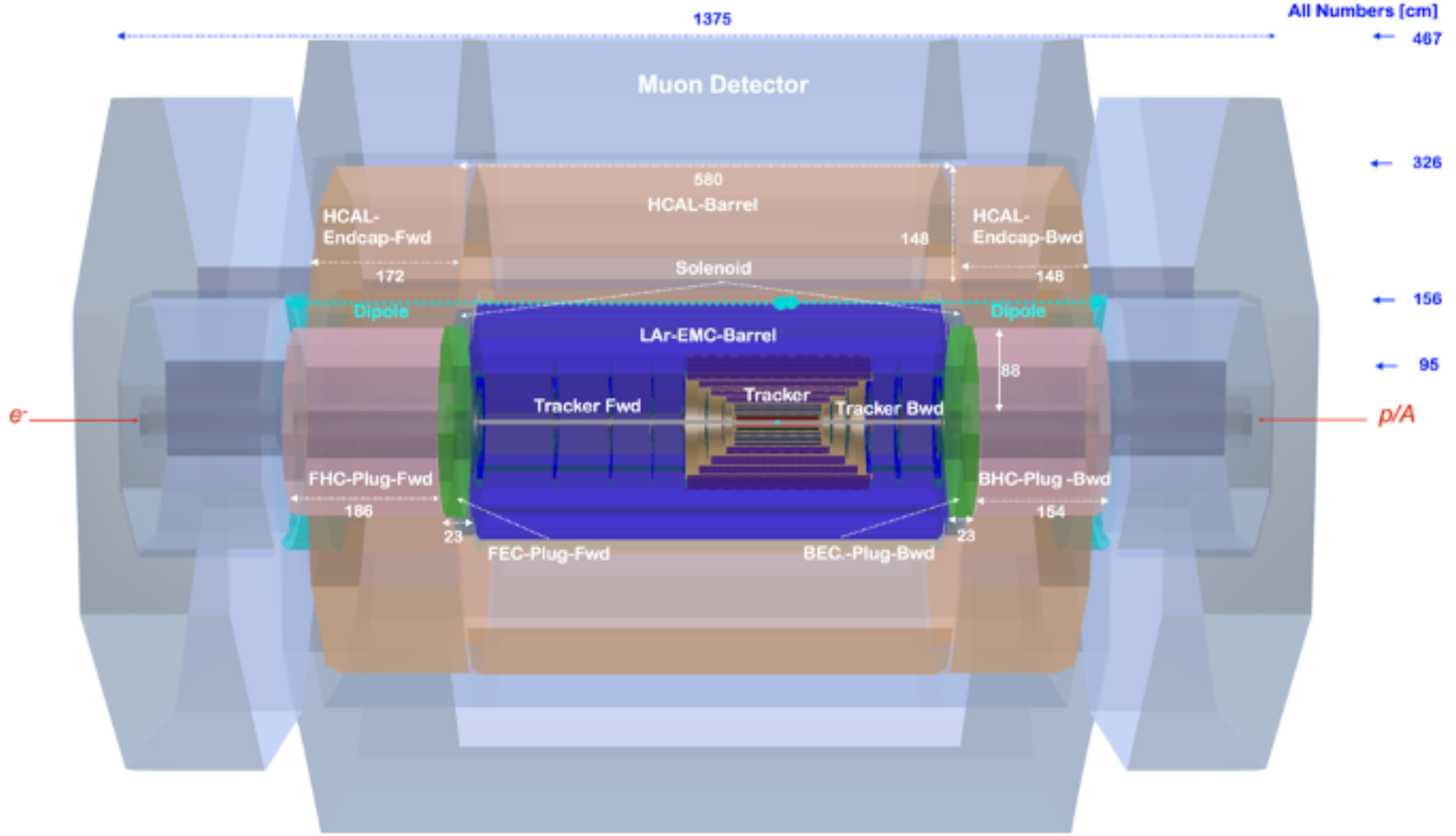

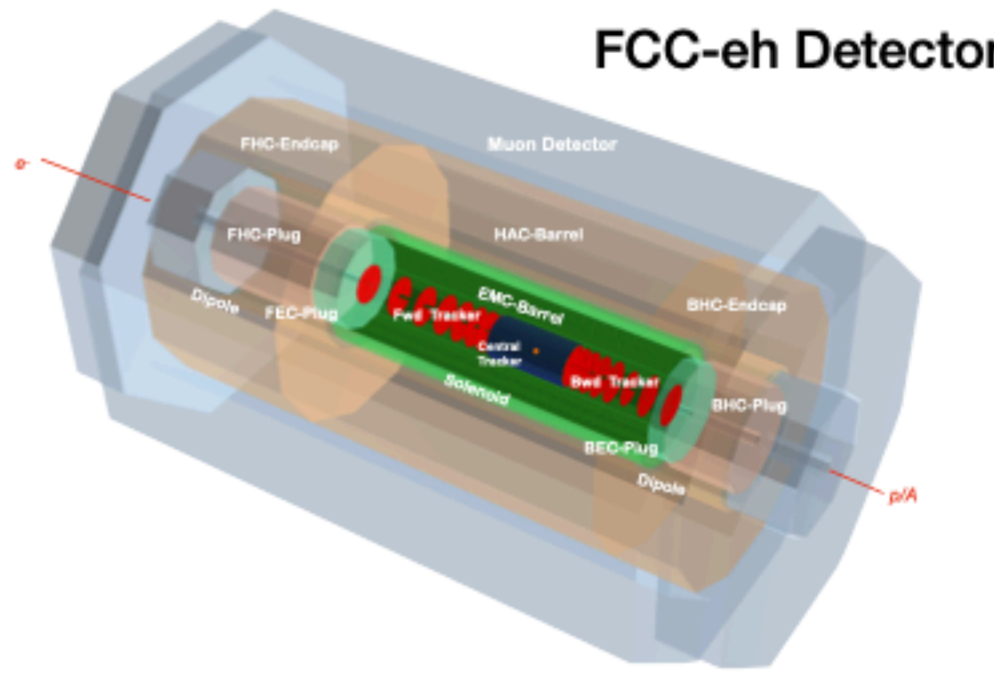

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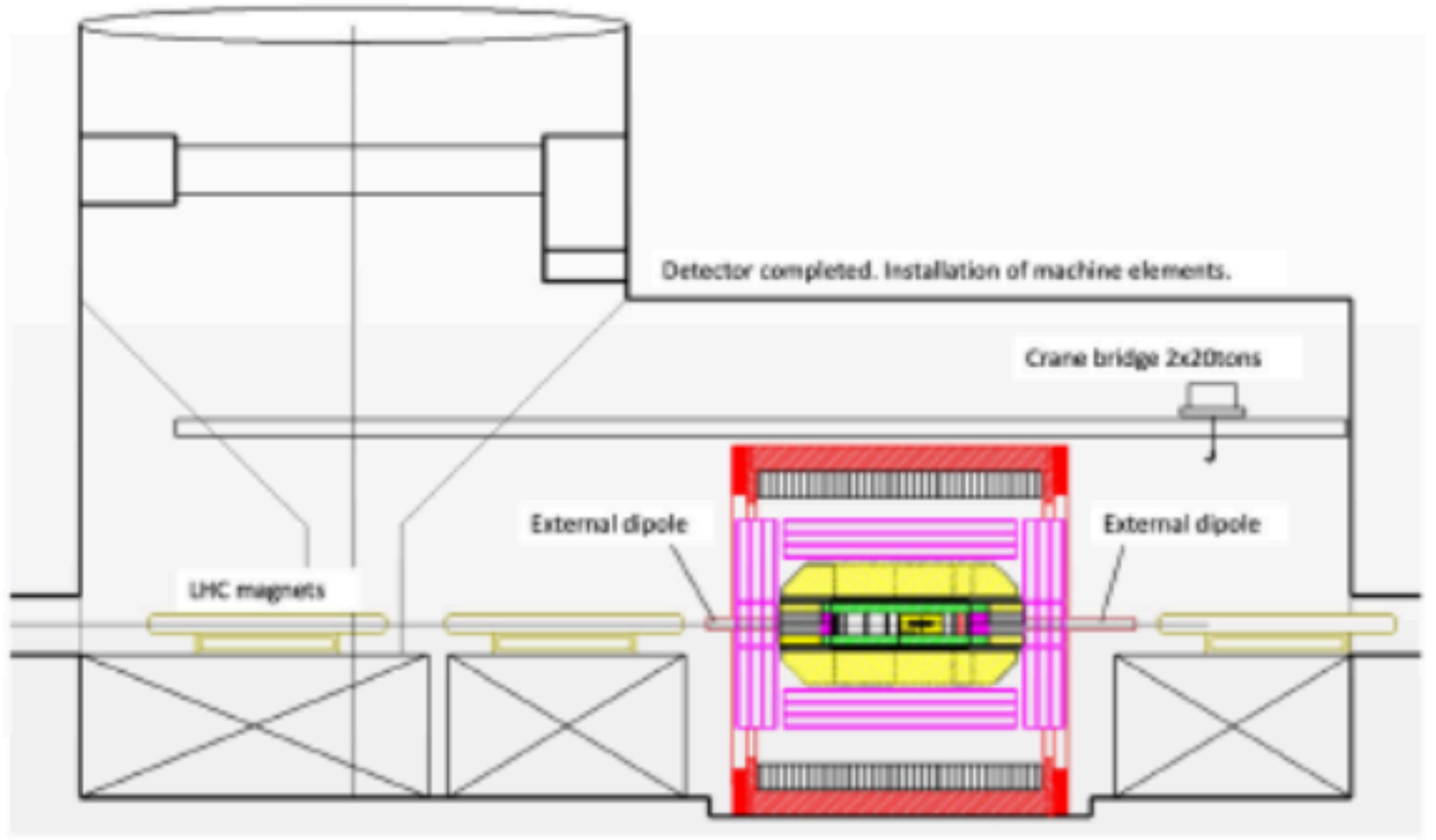

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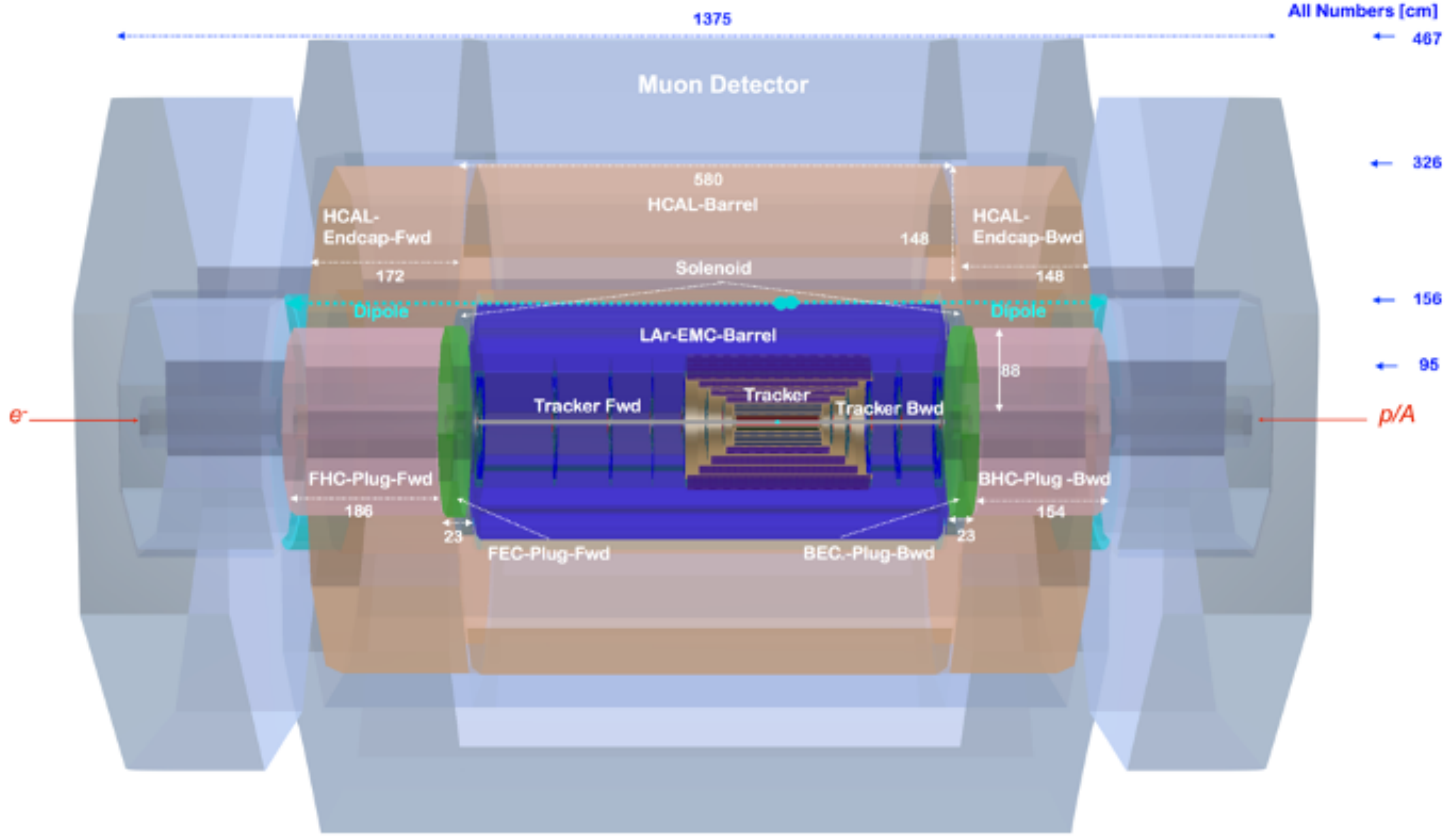

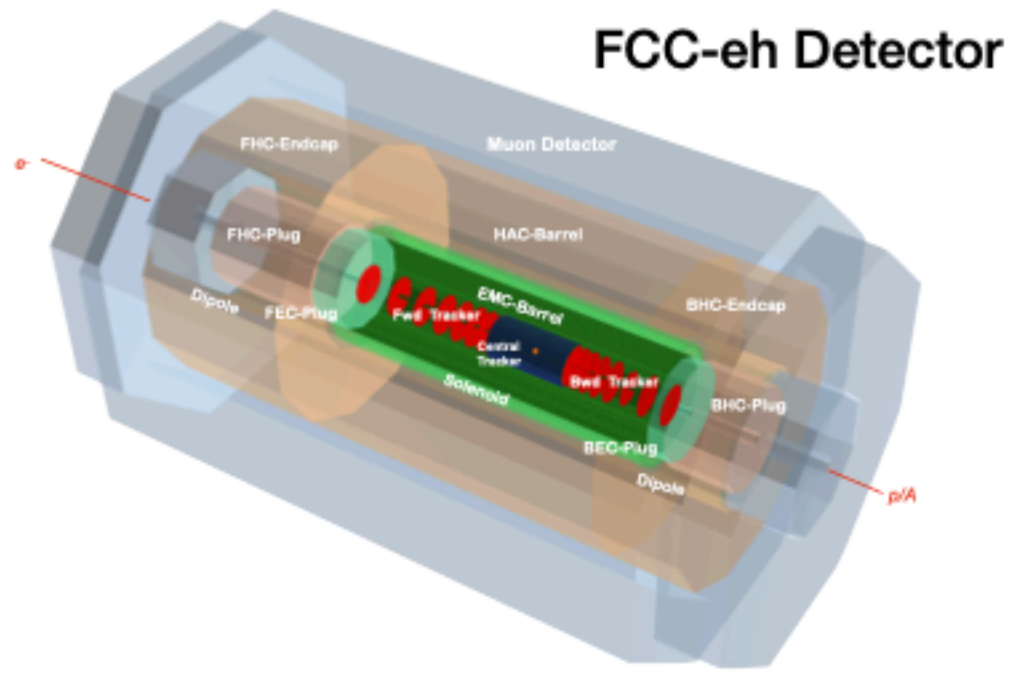

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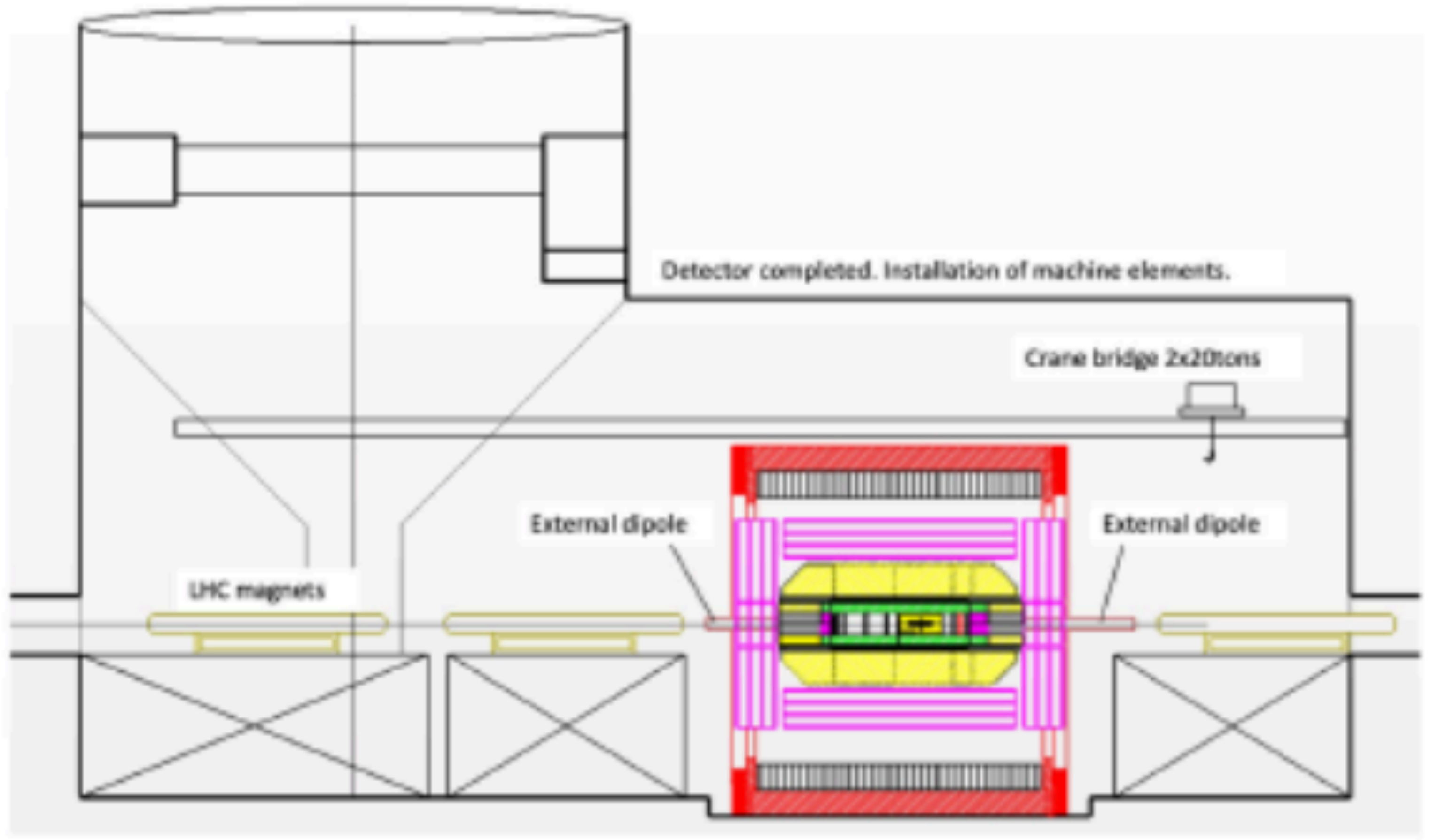

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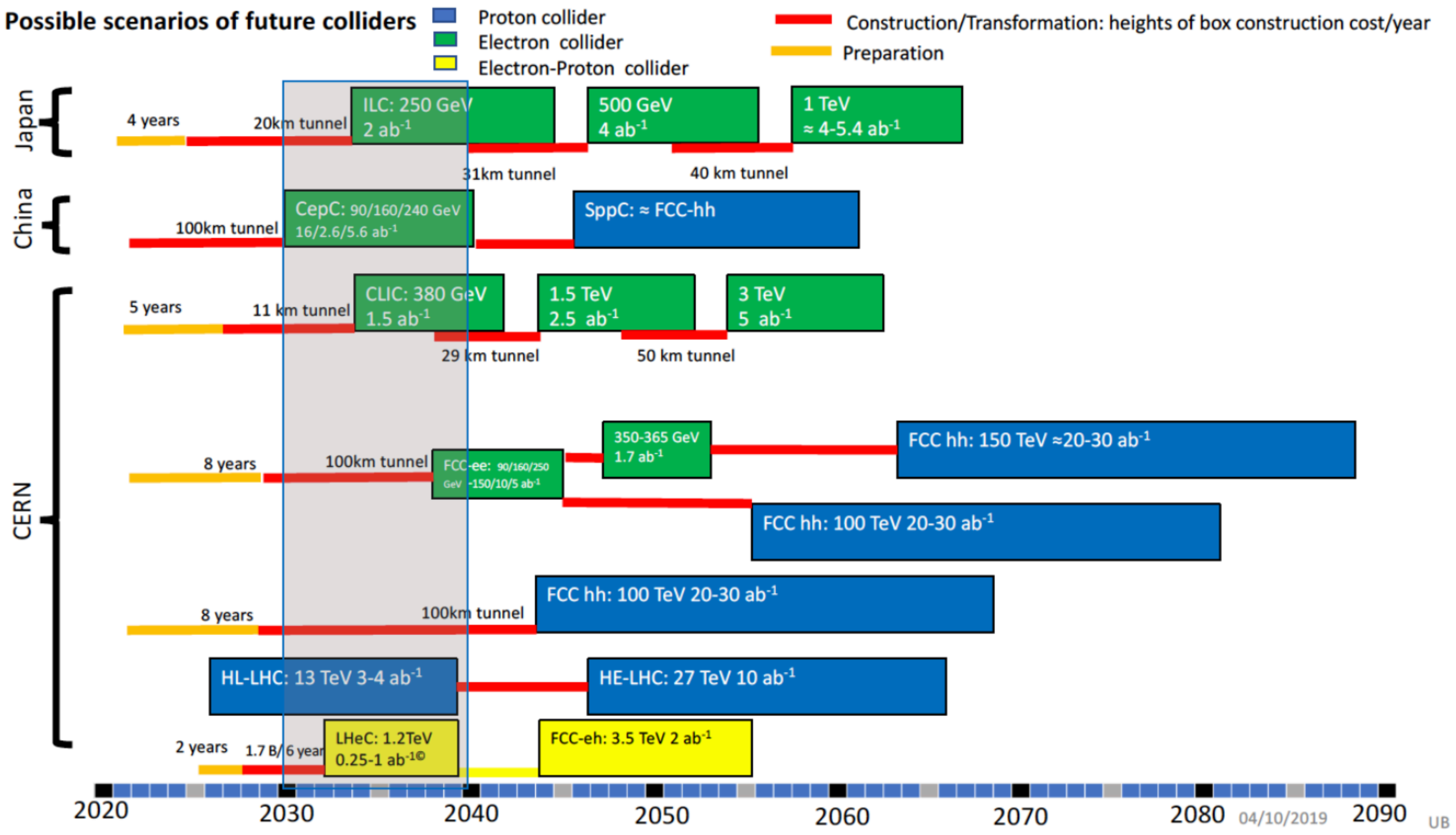
Timeline of Future Colliders in European Strategy



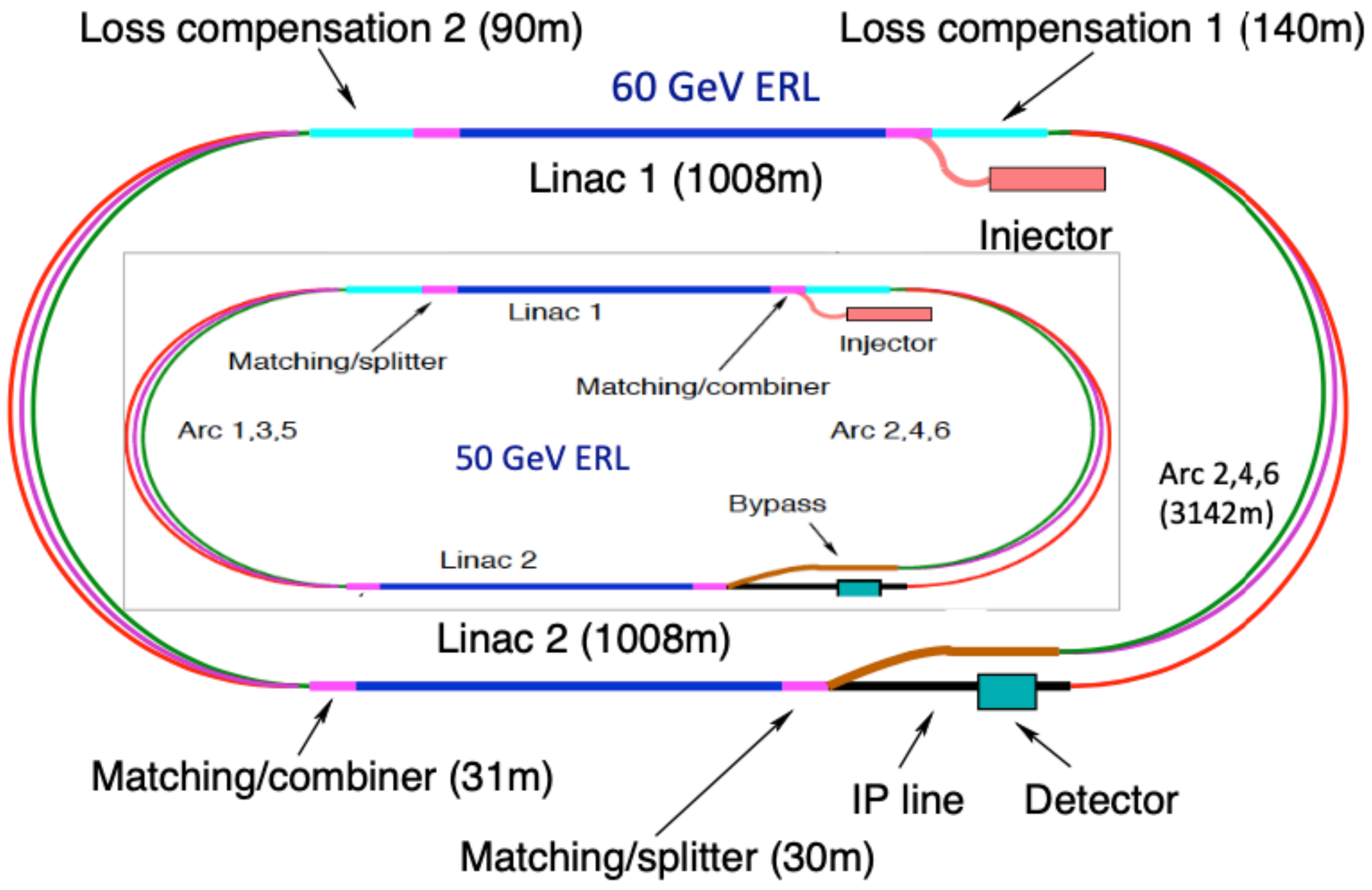
CERN/ESG/05b

extracted from submitted inputs by U. Bassler

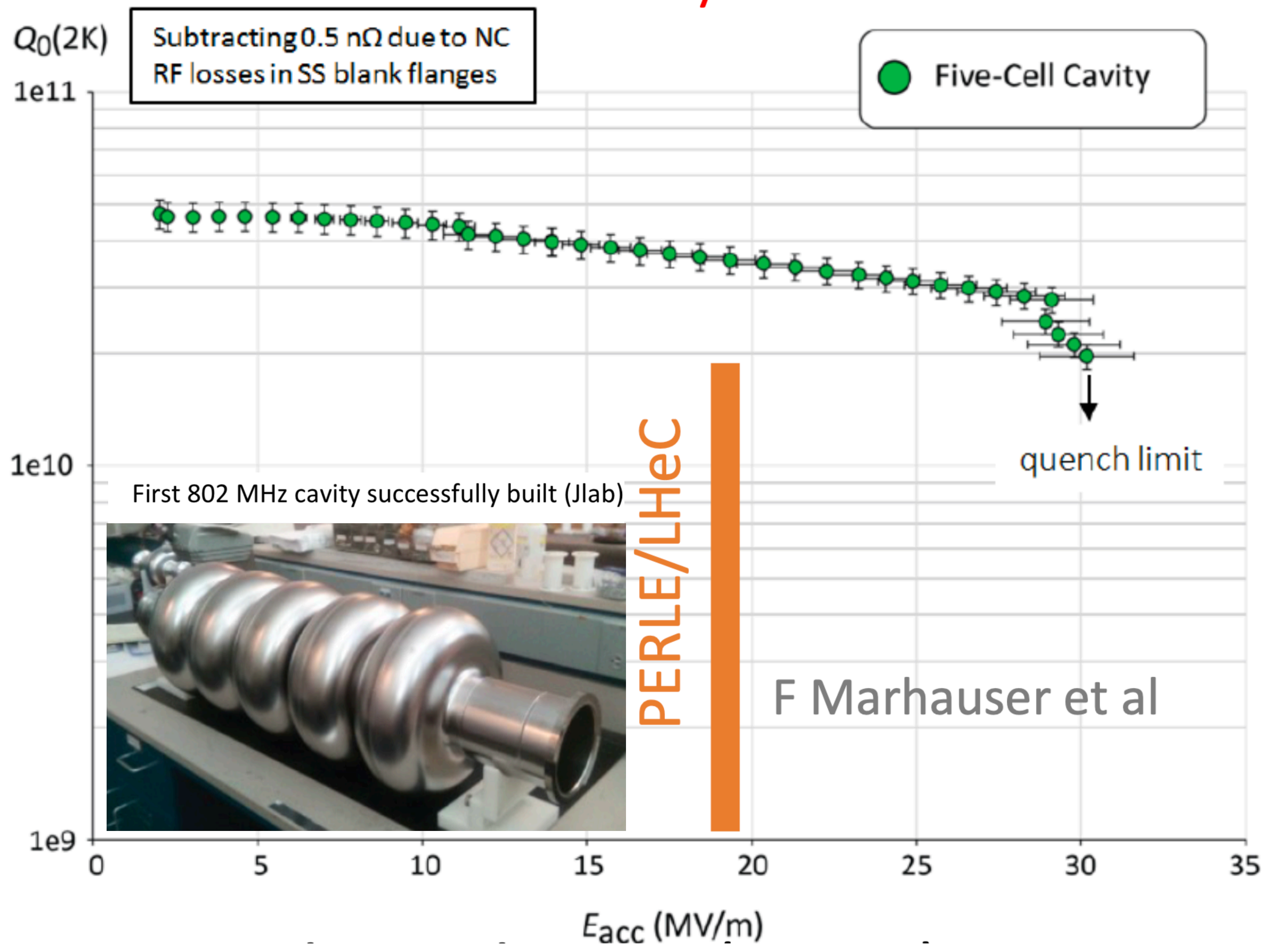
Energy Recovering Linac (ERL)

LHeC/FCC-eh: needs high luminosity, high energy:

High ERL power facility $P=I_e E_e$



Jointly with FCC-ee



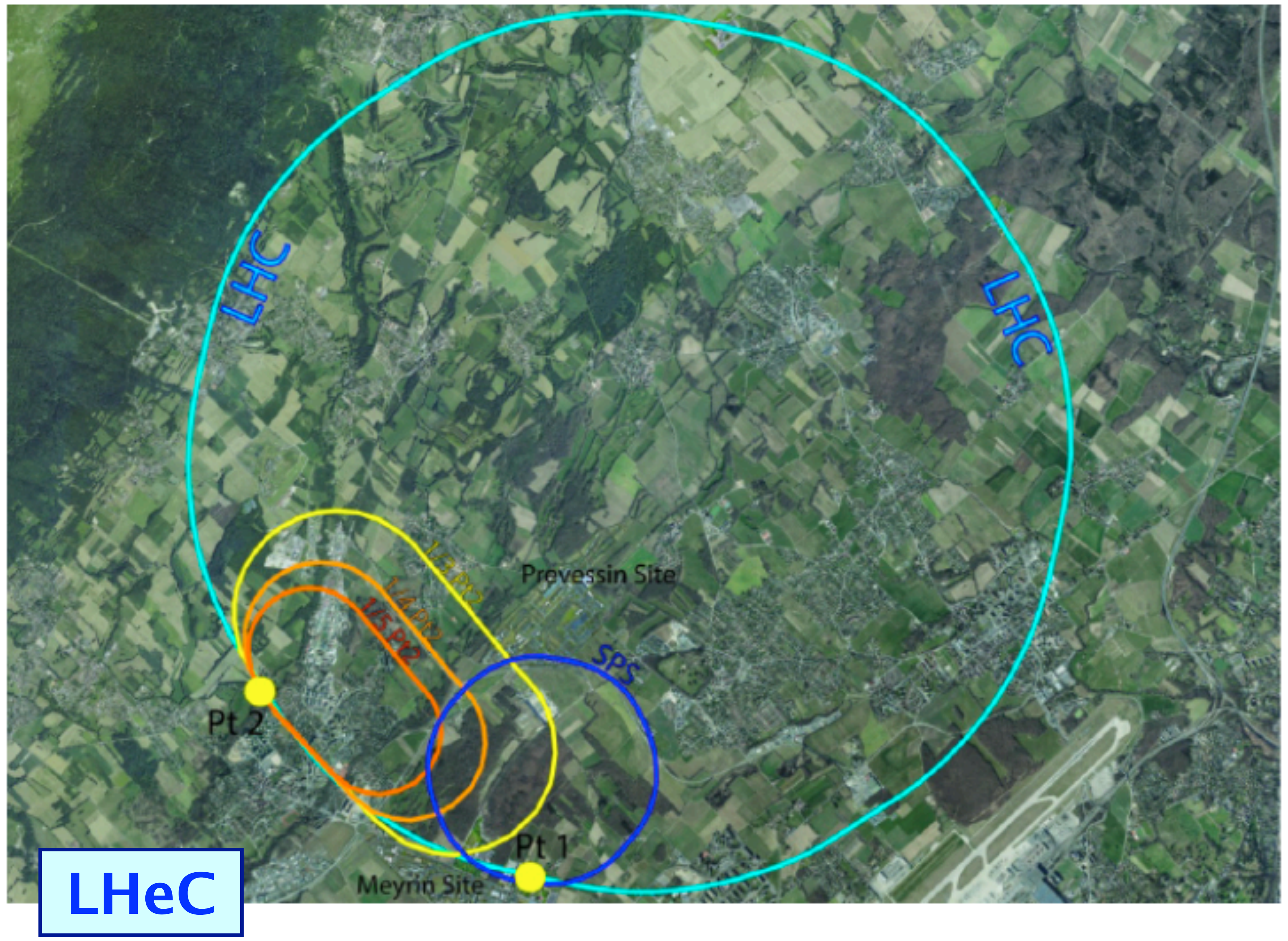
- **high quality Superconducting Radio Frequency: 802 MHz**
- **first 5-cell Niobium cavity built at JLAB: $Q_0 \simeq 3 \cdot 10^{10}$**

- LHeC Configuration reduced from 60 to 50 GeV
- LINAC: 112 cryomodules with 4 cavities each
  → total number of cavities: 896 [ILC: $O(10^4)$]
- configuration may be staged with less RF
- tunnel is small part of cost and better not reduced further, synchrotron loss, upgrades…
- ERL reduces power to ≪ GW and dumps at < GeV

- **high current sources**
- **multiturn (3 passes) to reach high E_e**

→ **novel, "green" revolutionary accelerator technology and save energy**

Linac-Ring Collider, LHeC and FCC-eh



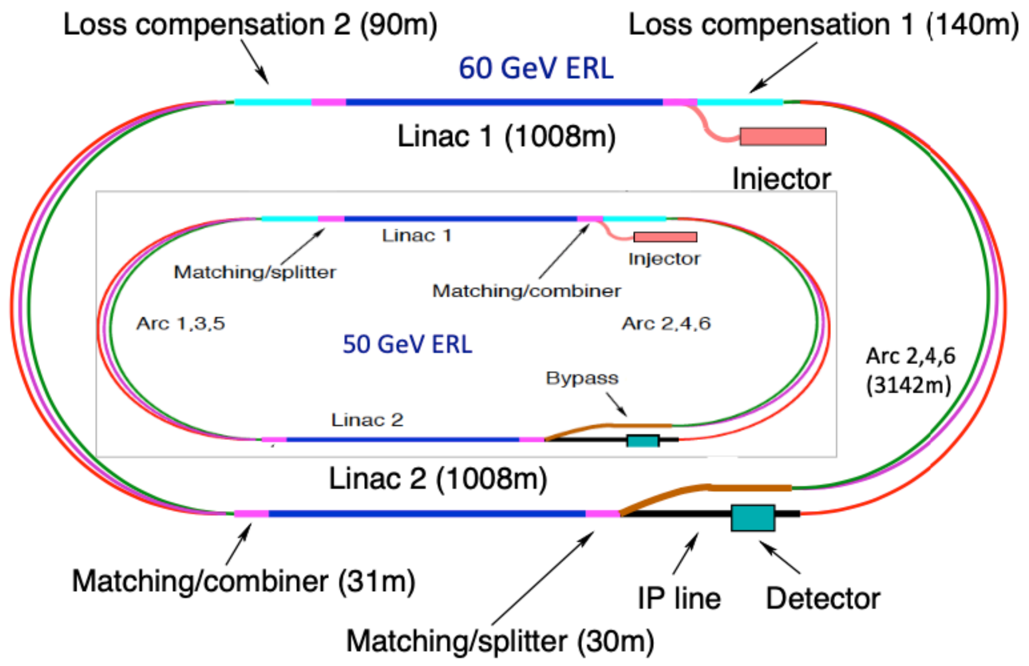
- operated synchronously with HL-LHC:
  e beam: 50 GeV × p beam: 7 TeV:
  $\sqrt{s}$=1.2 TeV J. Phys. G 48, 11, 110501 (2021)
- operation: 2035+
- cost: O(1) BCHF
- luminosity of 10^{34} cm^{-2}s^{-1}

- operated synchronously with FCC-hh:
  e beam: 60 GeV × p beam: 50 TeV:
  $\sqrt{s}$=3.5 TeV
- operation: 2045+
- cost: O(1-2) BCHF

FCC CDR:
Eur. Phys. J. C 79, no. 6, 474 (2019) - Physics
Eur. Phys. J. ST 228, no. 4, 755 (2019) - FCC-hh/eh

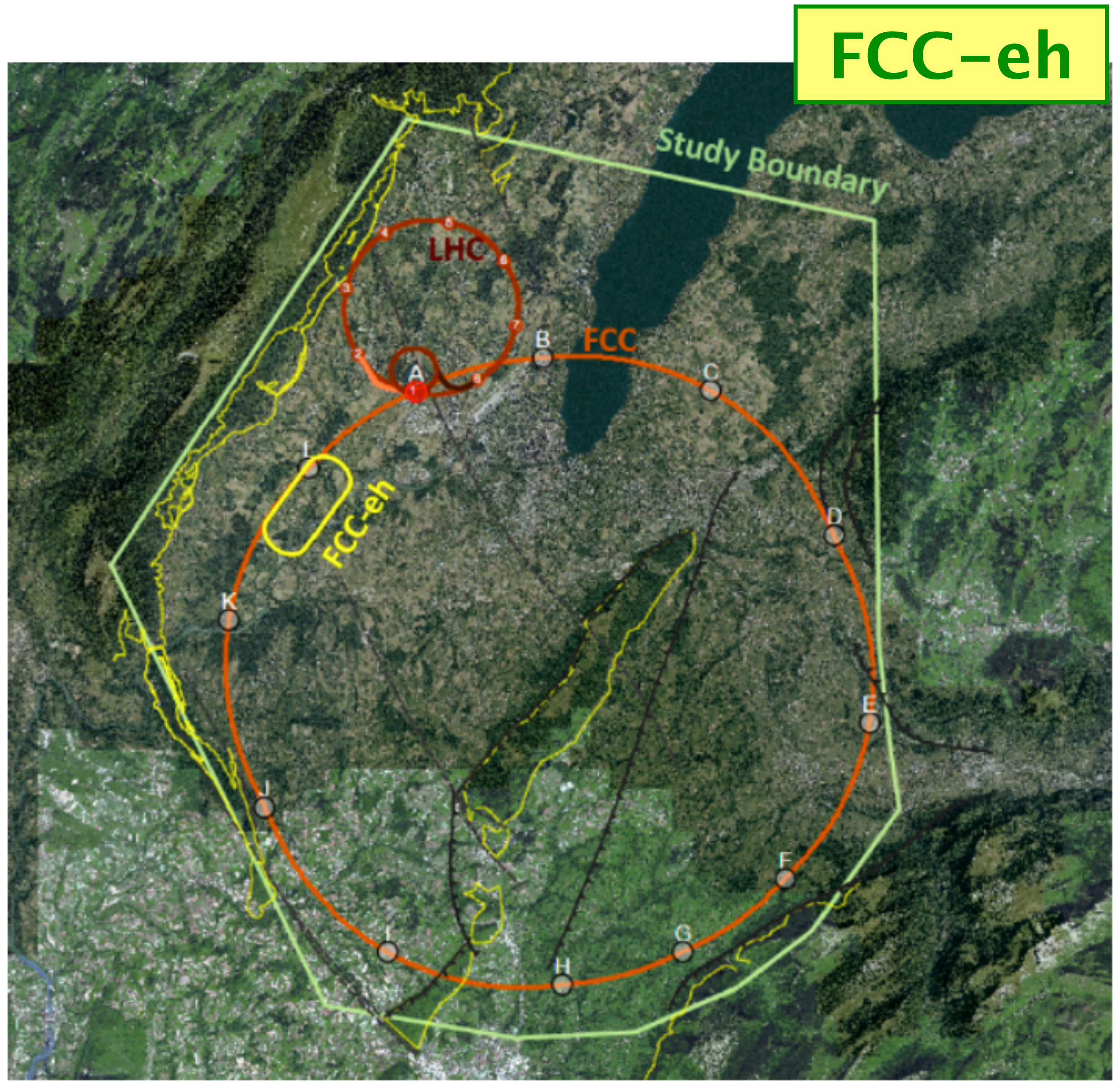
Energy Recovering Linac

e beam: 50, 60 GeV



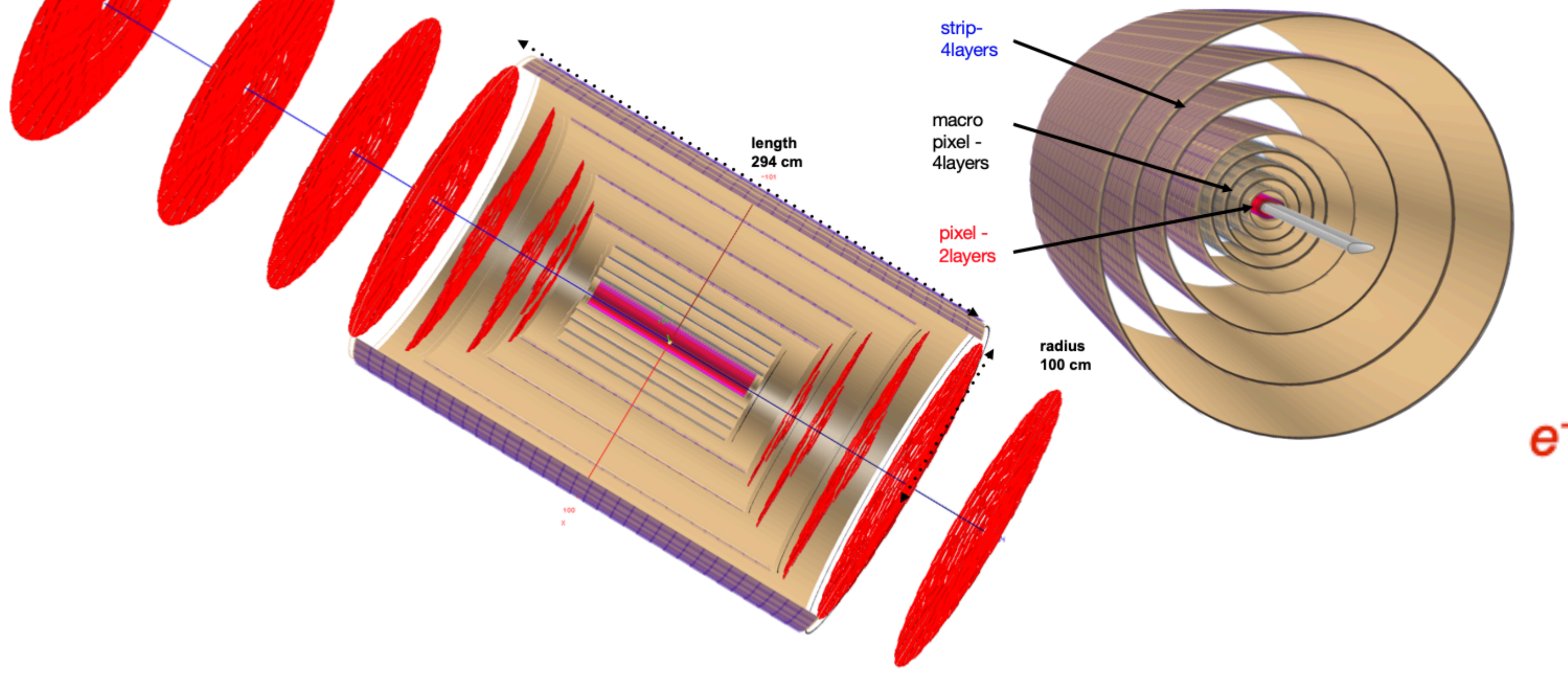
L_{int} = 1-2 ab^{-1} (1000×HERA!)

LHeC CDRs:
arXiv:1206.2913, J. Phys. G 39 075001 (2012)
arXiv:2007.14491, J. Phys. G 48, 11, 110501 (2011)



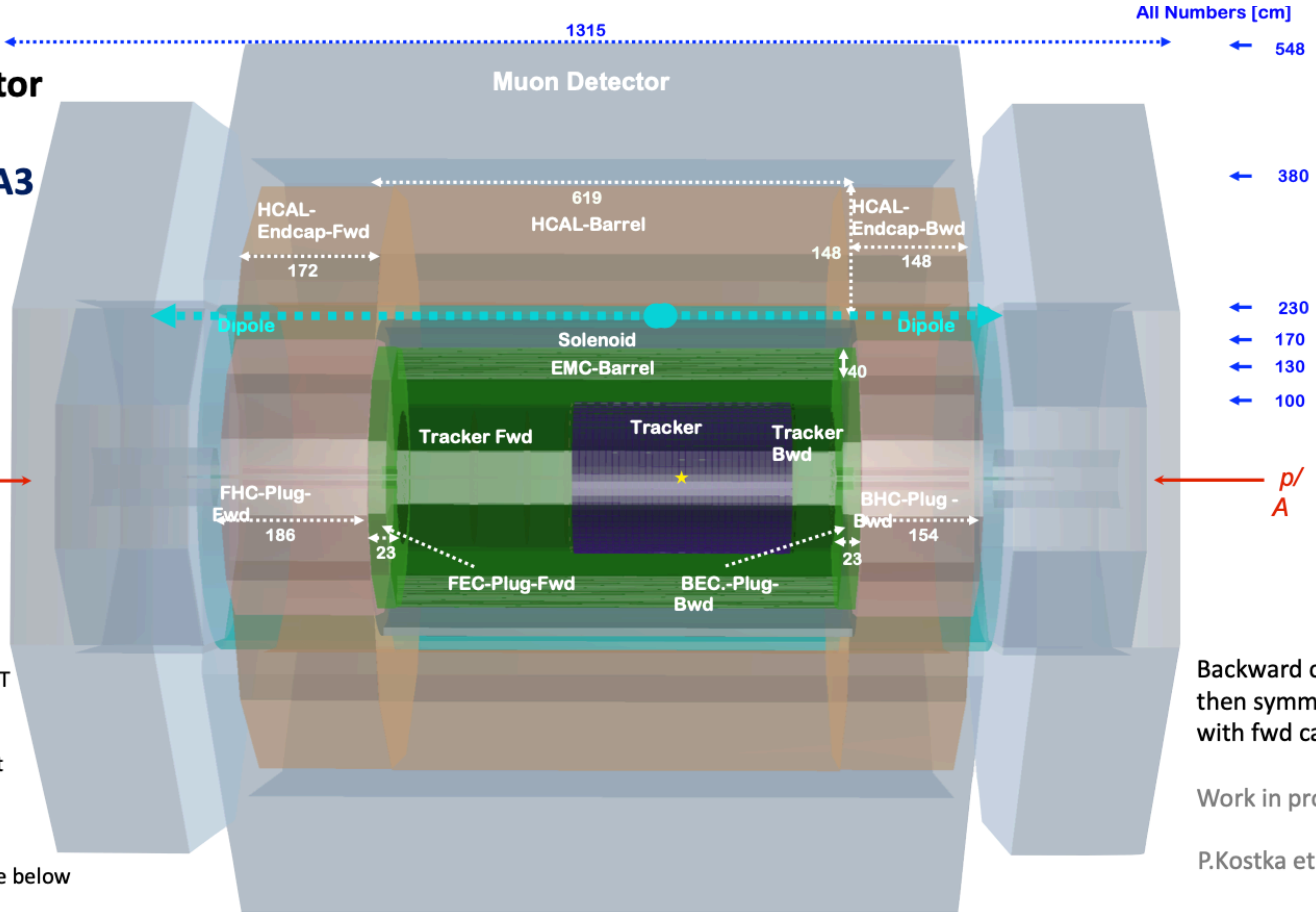
New idea to combine LHeC and A3

Possible Arrangement for a combined A3 - LHeC Tracker
NOT OPTIMISED



arXiv:1902.01211

LHeC detector
with
integrated A3



Increase of radii, tracker to 1m, may reduce B to 1.3T for same resolution

Overall detector just fits in L3 support R_{free}(L3)=560 cm

Vertex positions: see below

Backward calos then symmetric with fwd calos

Work in progress

P.Kostka et al.

New idea to combine LHeC and A3

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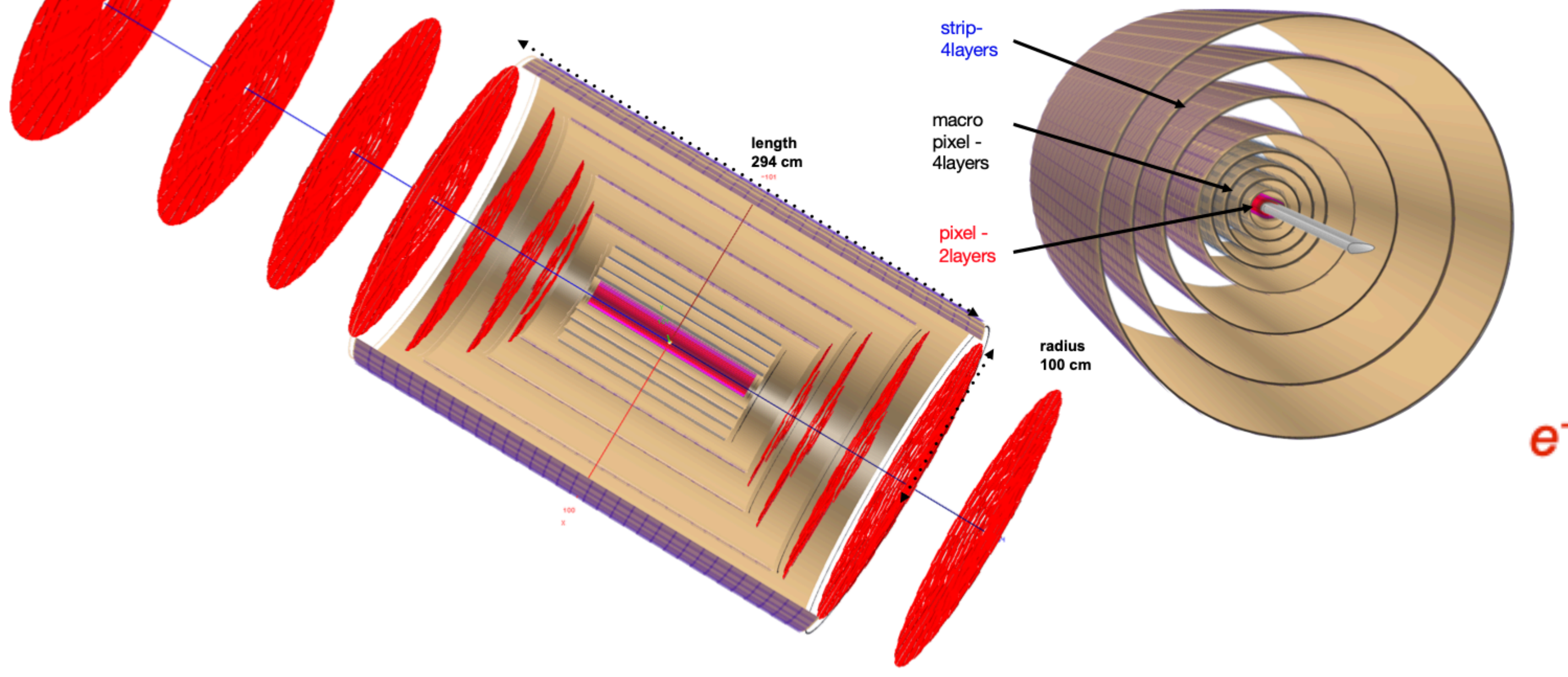

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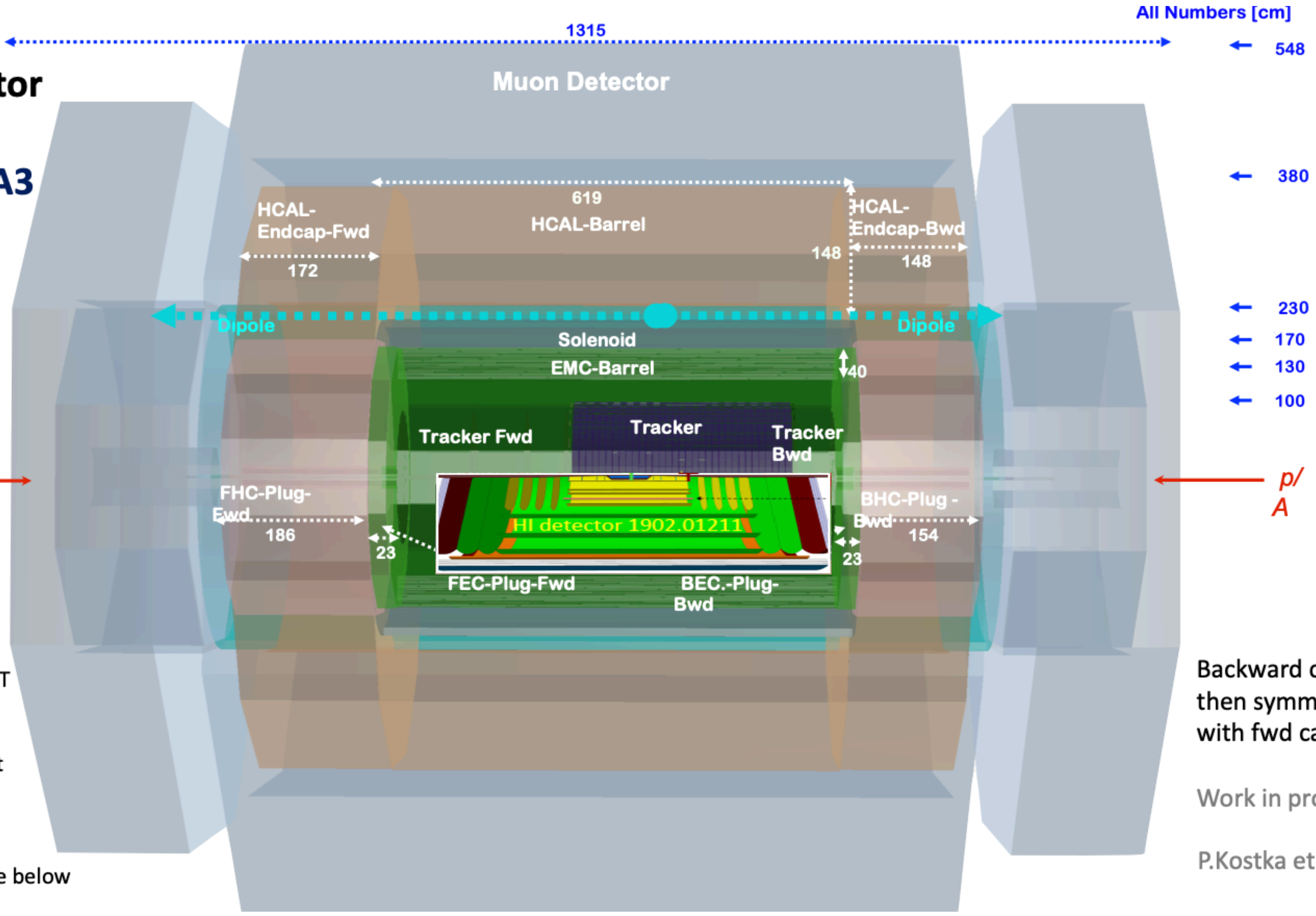

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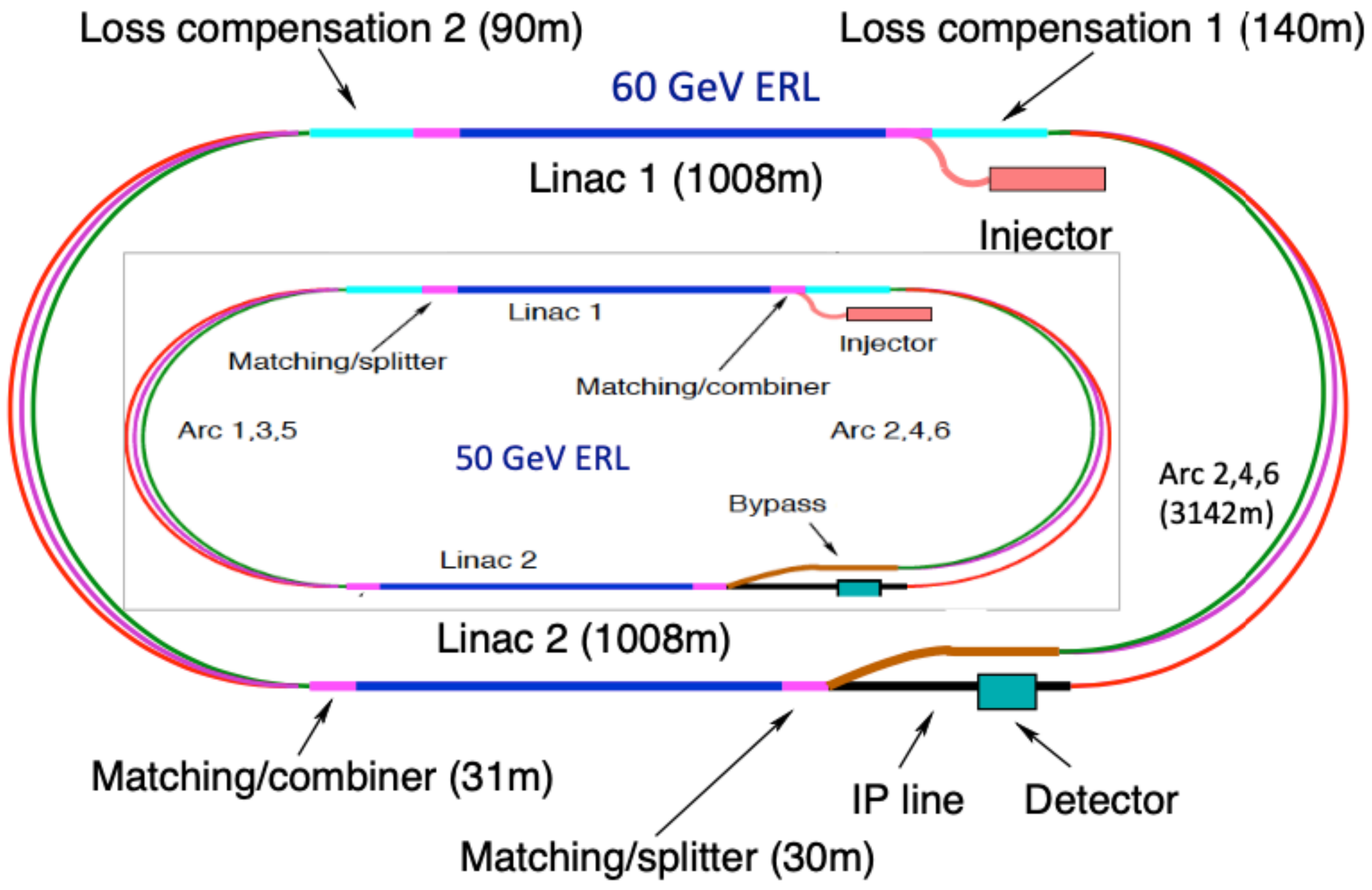

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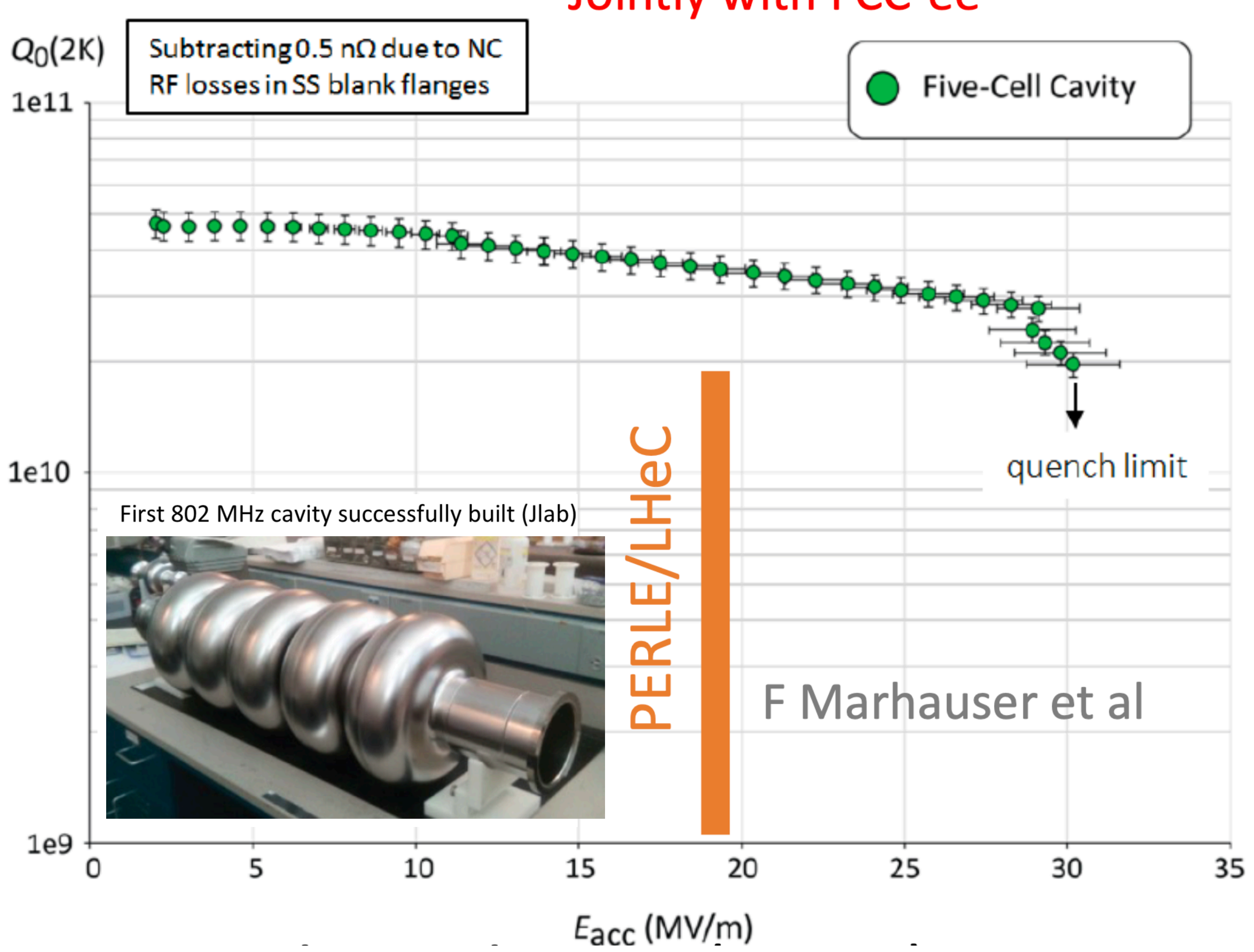
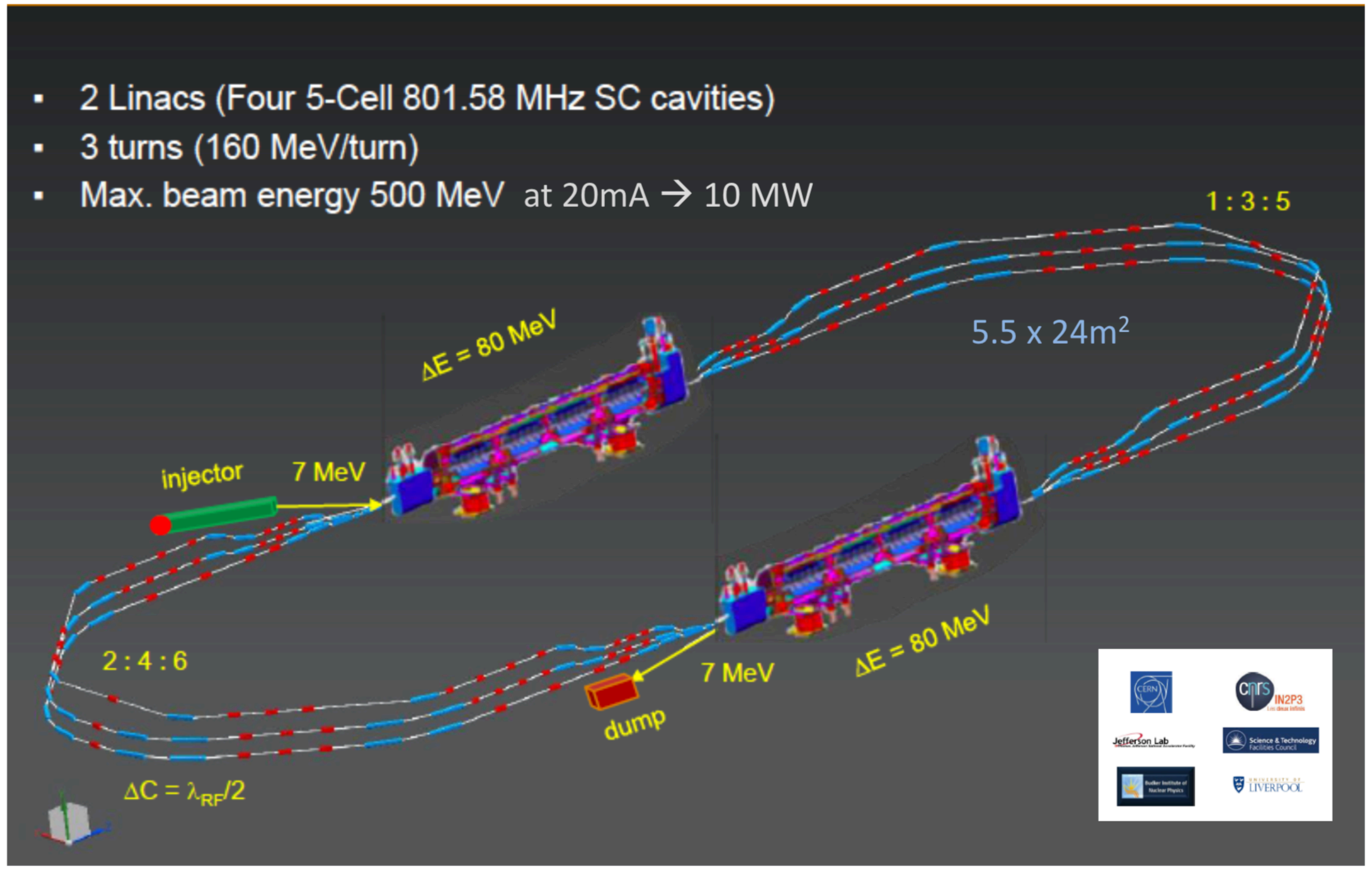


- high current sources
- multiturn to reach high E_e

Technical Synergies of LHeC with other applications

- **operate the ILC as an ERL**: boost luminosity to 10^{36} $cm^{-2}s^{-1}$
  Vladimir Telnov at the March 21 LCWS
- SAPPHIRE: a γγ collider : Higgs, EWK and QCD machine
  F. Zimmermann et al., arXiv:1208.2827
- Racetrack as an injector into FCC-ee [direct into Z]
  O. Bruening, Y. Papaphilippou
- HeC-FEL
  F. Zimmermann et al., work in progress
- Injector into FCC-hh
  R. Calaga
- Proposal of ERL Version of FCC-ee for high Lumi at high E_e
  V Litvinenko, T Roser, M Chamizo-Llatas arXiv: 1909.04437
- 802 MHz technology: PERLE, FCC-ee, eSPS
  F Marhauser, B Rimmer et al.
- 704 MHz SPL Cryomodule (CERN) modified for PERLE
  F Gerigk, E Jensen et al.
- ALICE (Daresbury) Gun delivered to Orsay for PERLE
  D Angal-Kalinin, B Militsyn et al.
- JLEIC Booster (Jlab) likely to be used in PERLE
  F Hannon, B Rimmer et al.
- Forward Calorimetry: FCC-hh and ee colliders / CALICE…
- Inner Tracker/CMOS: ee colliders, new HI detector at IP2
- …

Powerful ERL for Experiments (PERLE) @ Orsay



CDR: 1705.08783, J. Phys. G
CERN-ACC-Note-2018-0086 (ESSP)

PERLE Collaboration (2021): CERN, Cornell, Daresbury, JLab, Liverpool, Novosibirsk (BINP), Orsay (IJC)

- **Technology Development Facility at 500 MeV at Orsay for development of ERL with LHeC conditions**
- **high luminosity particle and nuclear physics experiments**
- **part of global ERL Developments (Roadmap end of 2021)**
- **synergies: ERL Concepts for FCC-ee and ILC**

→ **high precision elastic ep scattering, photo-nuclear reactions, …**

Summary, Outlook

PERLE

- PERLE – Baseline Design (500 MeV)
  - Multi-pass linacs configured with the SPL style cryomodules
  - Switchyard configuration with two B-com magnets
  - A pair of Experimental Areas – Low-β inserts at 500 MeV
  - 'Six bend' Arc architecture based on Flexible Momentum Compaction Optics
- Next Steps (2021/22…)
  - Complete injector design (re-use JLEIC Booster, tbc)
  - End-to-end tracking to validate the design
  - Magnet specs and prototyping of B-com magnets
  - HOM design and test of dressed cavity
  - Preparation of ALICE gun installation at Orsay
  - PERLE TDR by end of 2022, with the goal of first beam by the mid-twenties
  - Integration of PERLE into the European Roadmap for Accelerators
    - Both FCC-ee and recently ILC are proposed as ERL Colliders with significantly increased luminosity and substantially reduced power consumption
- PERLE becomes a key part of future: HEP, PP and NP facilities

Jefferson Lab — Thomas Jefferson National Accelerator Facility

Operated by JSA for the U.S. Department of Energy — Alex Bogacz — DIS Workshop, Stony Brook, NY, April 12-16, 2021 — 19

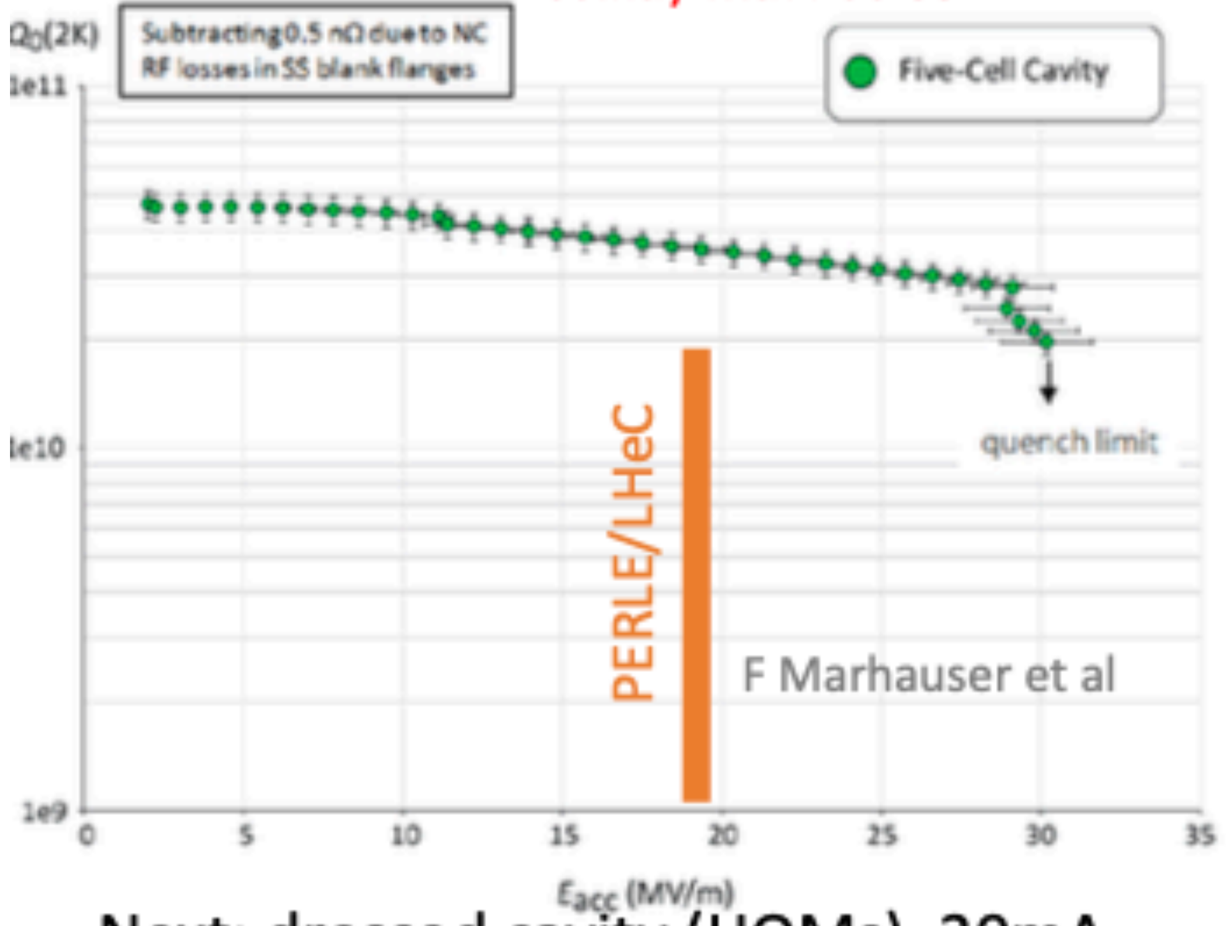
Further developments

Developments +Partners

Cf recent meeting: https://indico.cern.ch/event/923021/

SCRF: High Q_0, complete Cryomodule

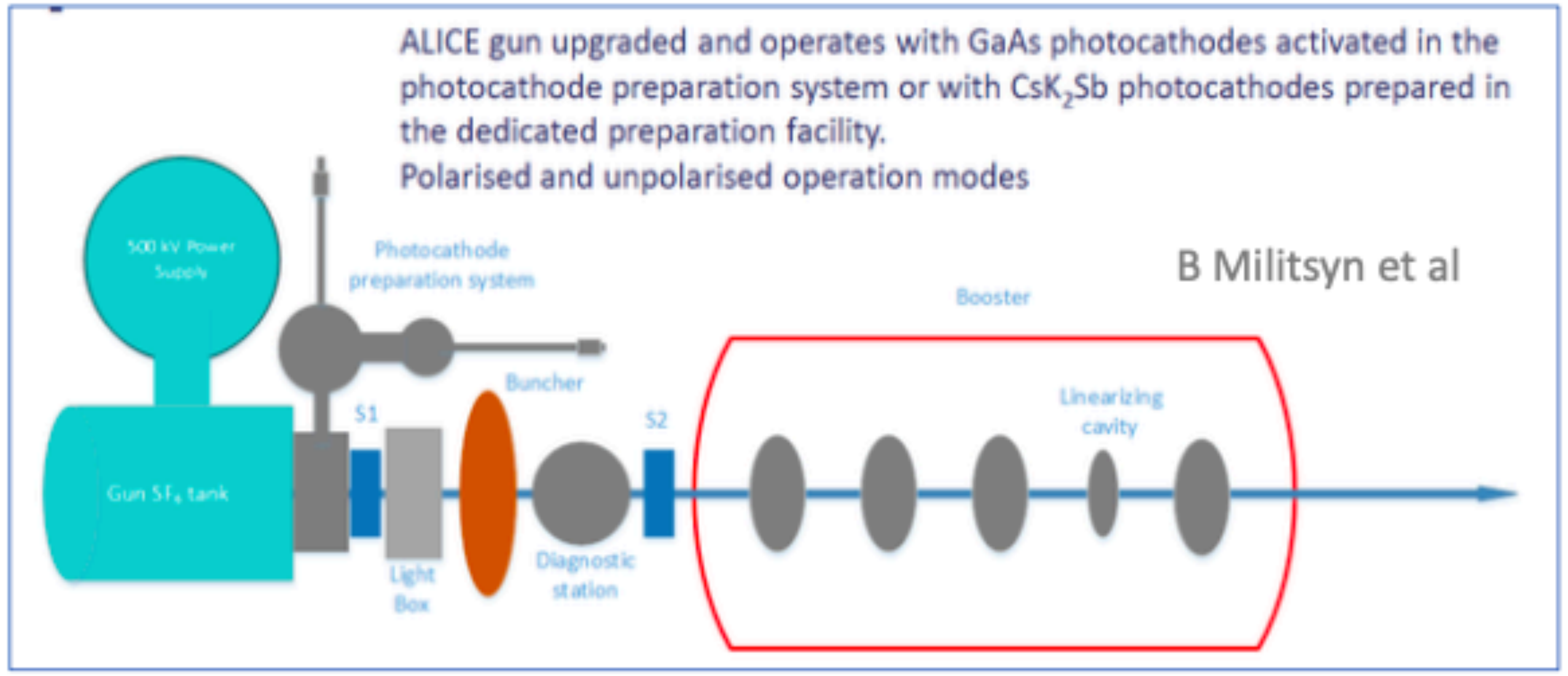
Jointly with FCC-ee



Next: dressed cavity (HOMs), 20mA
Adapt SPL Cryomodule for PERLE

CERN, Jlab, Orsay +

High Current Source (e^-, P, e^+)

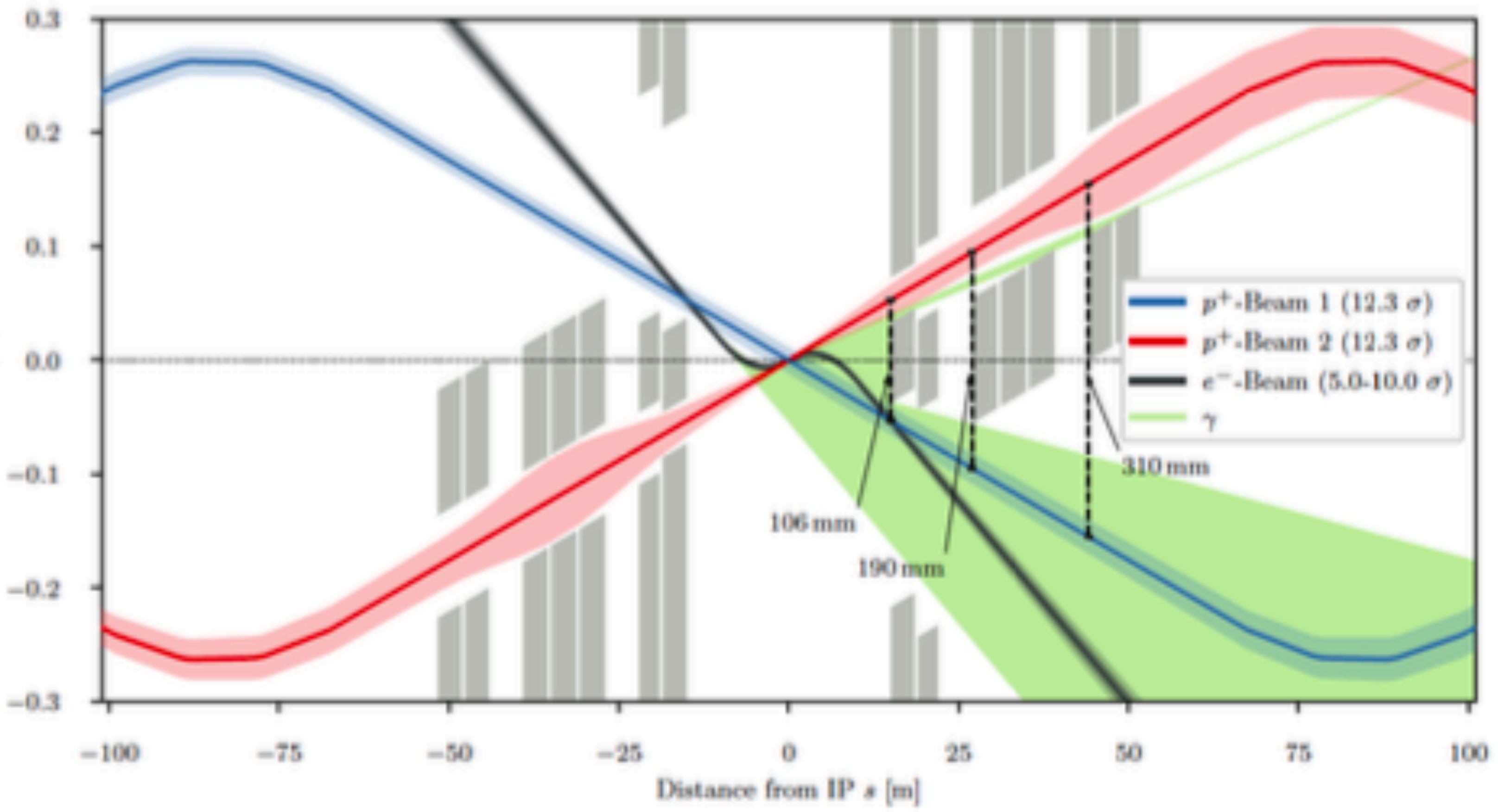


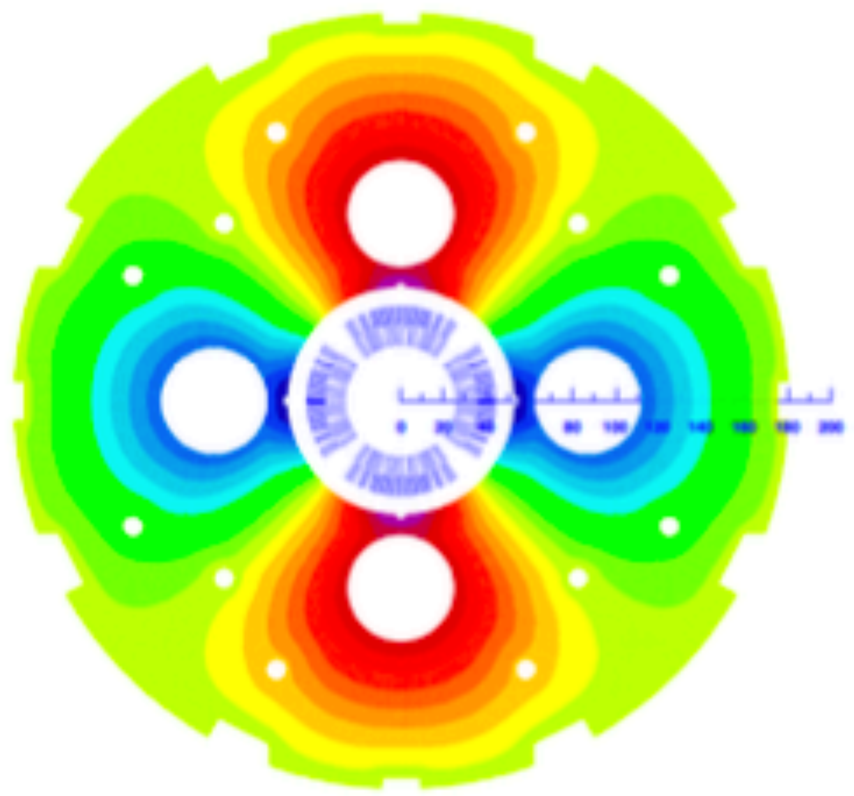
PERLE will begin with 5mA ALICE source, which has been transferred from Daresbury to Orsay while UK was in EU..

BINP, BNL/Cornell (cBETA), Daresbury, IJC, Jlab, +

Interaction Region Design and Q_1 Prototype:

B Holzer, B Parker, S Russenschuck et al

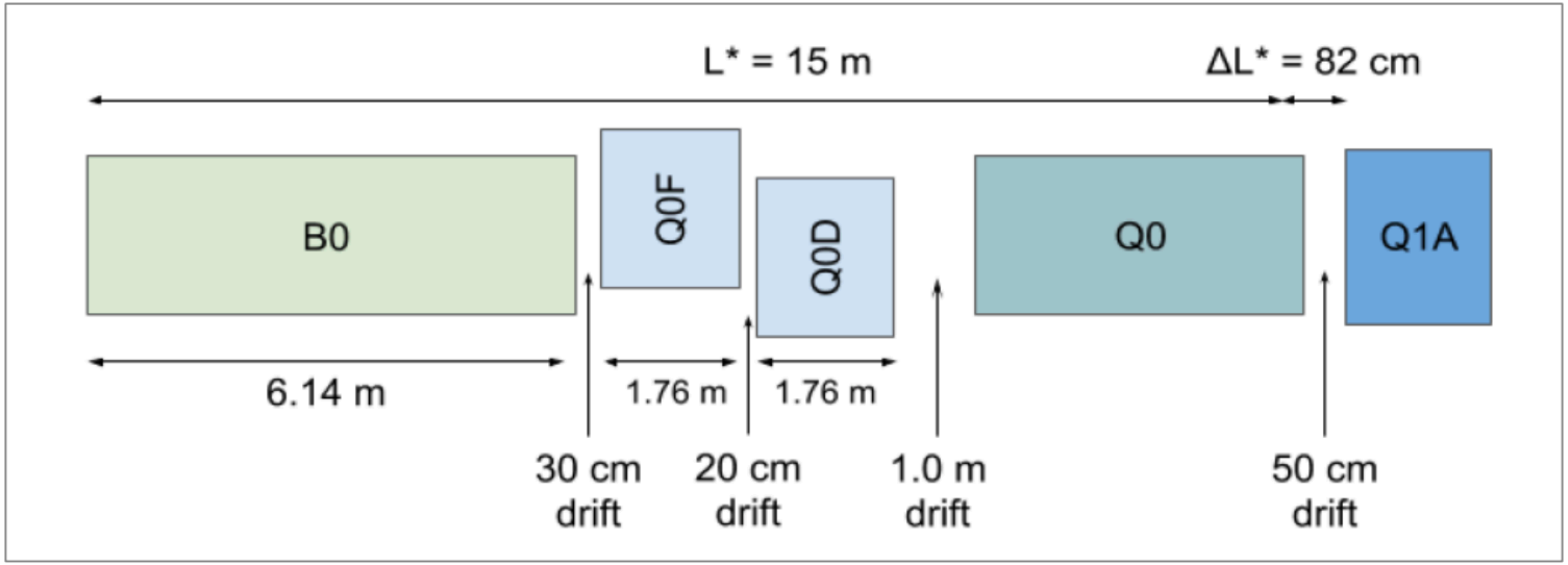




BNL, CERN, +

Max Klein

LHeC IR modified for dual purpose



Optimisation of synchrotron radiation (power and E_{crit})

		LHeC	HERA
E_{crit}	keV	270	150
Synrad Power	kW	30	28

Detector dipole — Staggered quads — Half-quad (NC) — First of triplet qaudrupoles

For ep/A: synchronous with pp/AA in GPDs and LHCb – keep non-colliding beam apart
with option of pp/AA the non-colliding beam needs to be kept inside pipe:
then: shift transversely (as in regular injection mode) and possibly in time

For pp/AA in IP2: no electron beam in. Collisions at nominal IP (or shifted by 25/4ns)

Max Klein

Technical synergy

LHeC-FEL

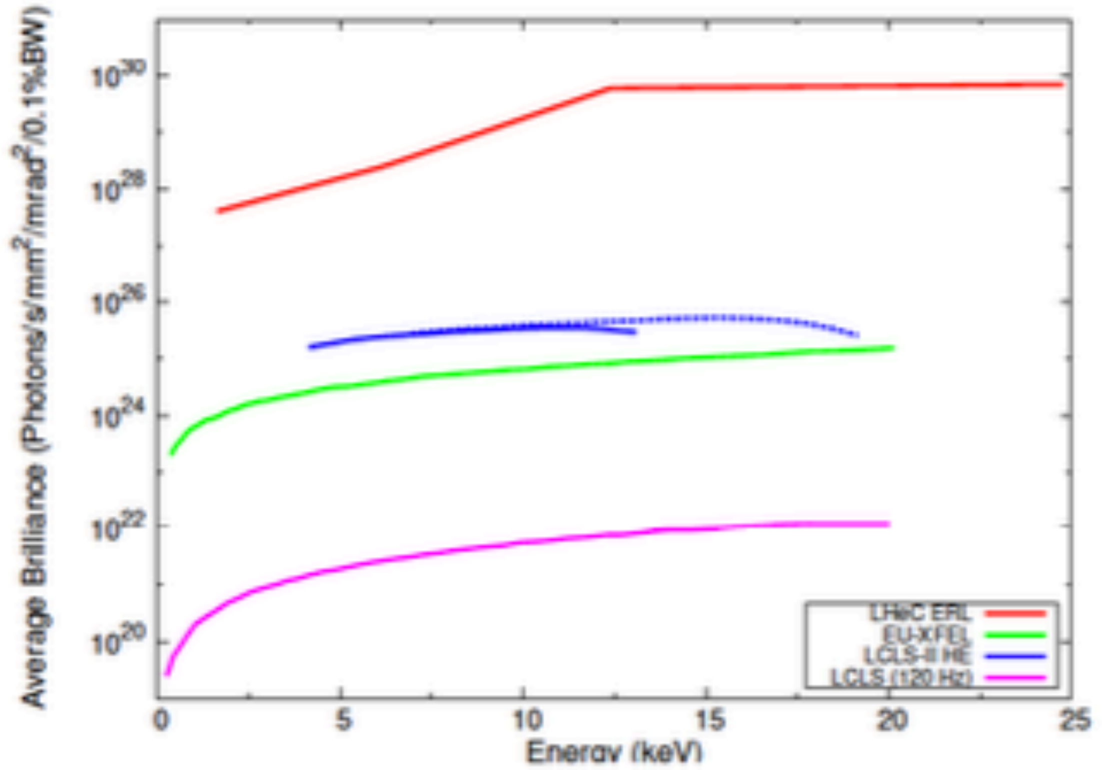


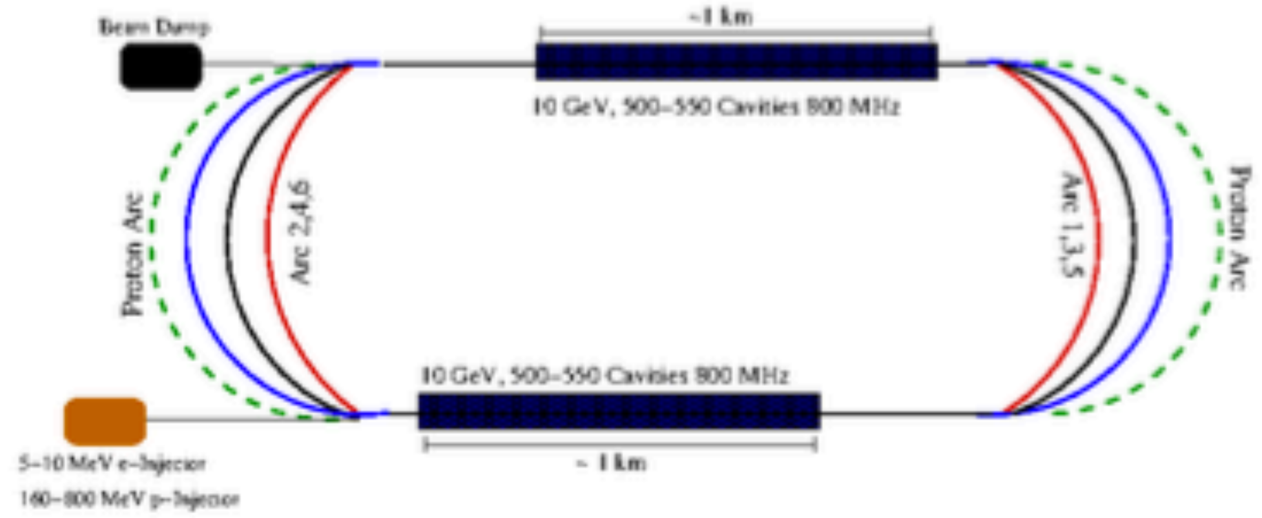
Figure 9: Comparison of FEL average brilliance for the LHeC-FEL with existing and planned world-leading hard X-ray FEL sources.

Work in progress, F Zimmermann et al. [in between LHeC and FCC-hh potentially]

e-ERL for Proton Injection

Recall: "SPL+PS2" as a new high brightness injector was already considered and abandoned for LHC

Proposal to use a single recirculating linac to directly inject to SPS (26 GeV) or SPS+ (~50 GeV), especially for 5ns bunch spacing.



Presented by R Calaga, 2017 [worth reconsidering]

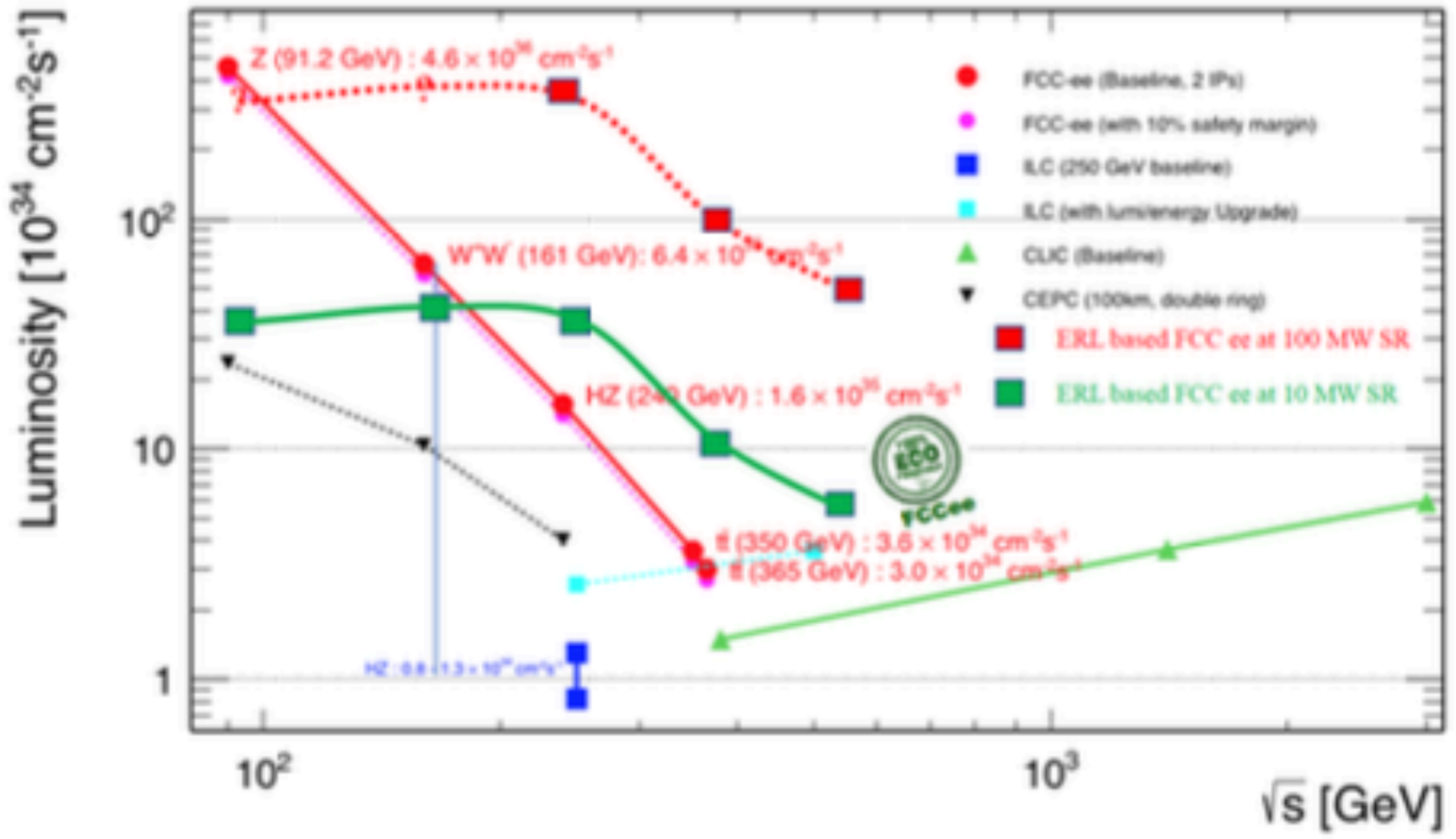
FCC-ee Injector Complex

Applications/ Synergy - examples

- FCC-ee Baseline Injector Plan: e^+/e^-
  - Linac with 6 GeV followed by 20GeV pre-booster ring [SPS] or 20GeV linac
  - 2.0 10^{10} N_b with 2 bunches per pulse and 200Hz rep-rate ➔ < 2μA average current
  - Requires transfer lines from SPS or linac to FCC ➔ ca. 10km tunnel structures?
- Using LHeC type Recirculating Linac as injector: e^+/e^-
  - Common hardware and infrastructure: one could use the FCC-ee pre-series SRF
    - -Either using a 5km long racetrack suitable for 50GeV upgrade for FCC-eh and / or direct injection into the FCC-ee for Z production mode
    - -Dedicated smaller tunnel optimized for FCC-ee injector at 6 GeV or 20 GeV
  - In both cases I assume installation near point 'L' to minimize transfer line length
  - In all cases the machine would be used as re-circulating linac and not in ERL mode

Presented by O Bruening, March 2019 [being rediscussed. Note PSI FEL concept]

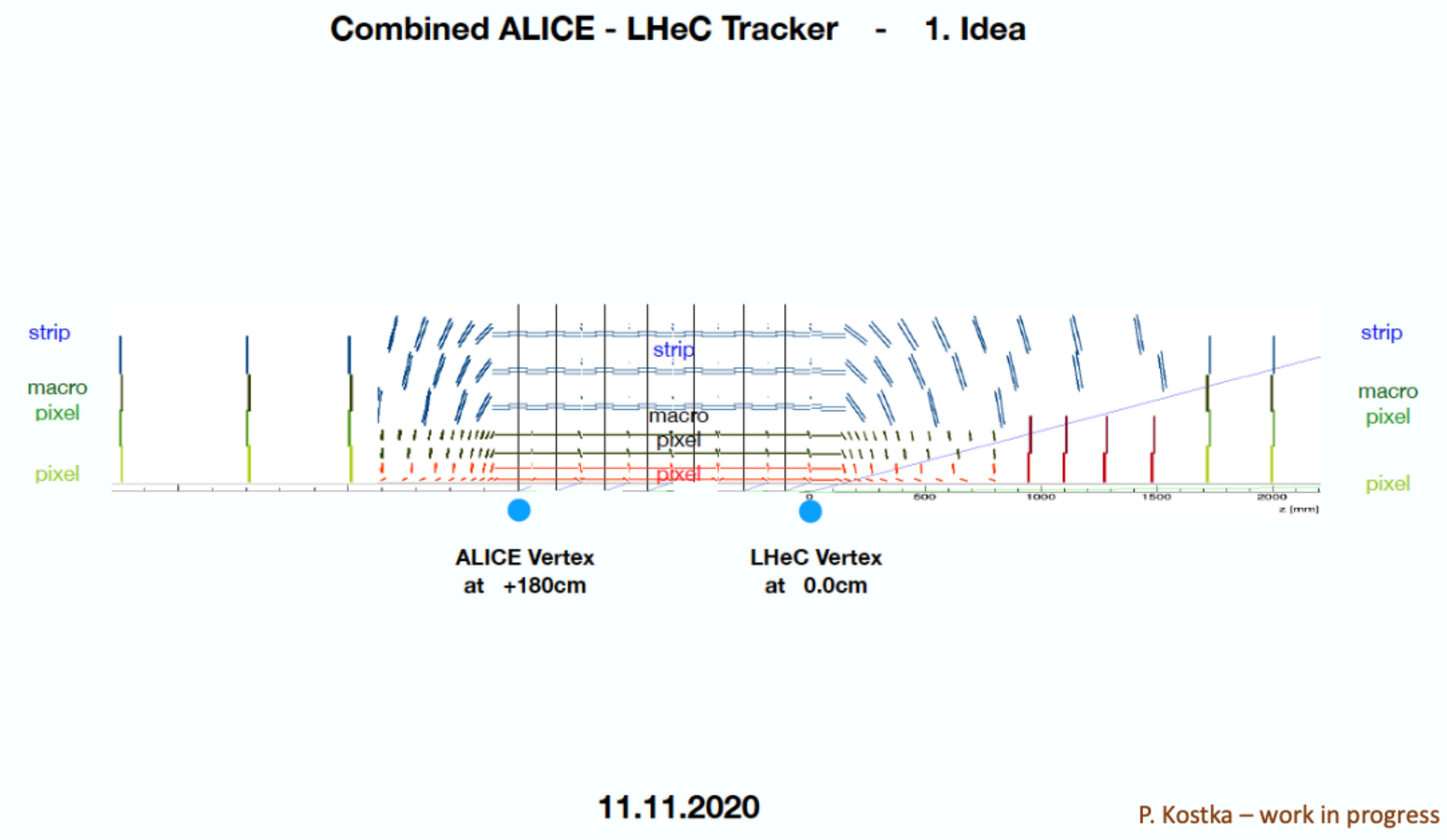
Energy recovery configuration of FCC-ee



V Litvinenko, T Roser, M Chamizo-Llatas arXiv: 1909.04437, [ongoing study]

Max Klein

Combined A3 – LHeC Tracker

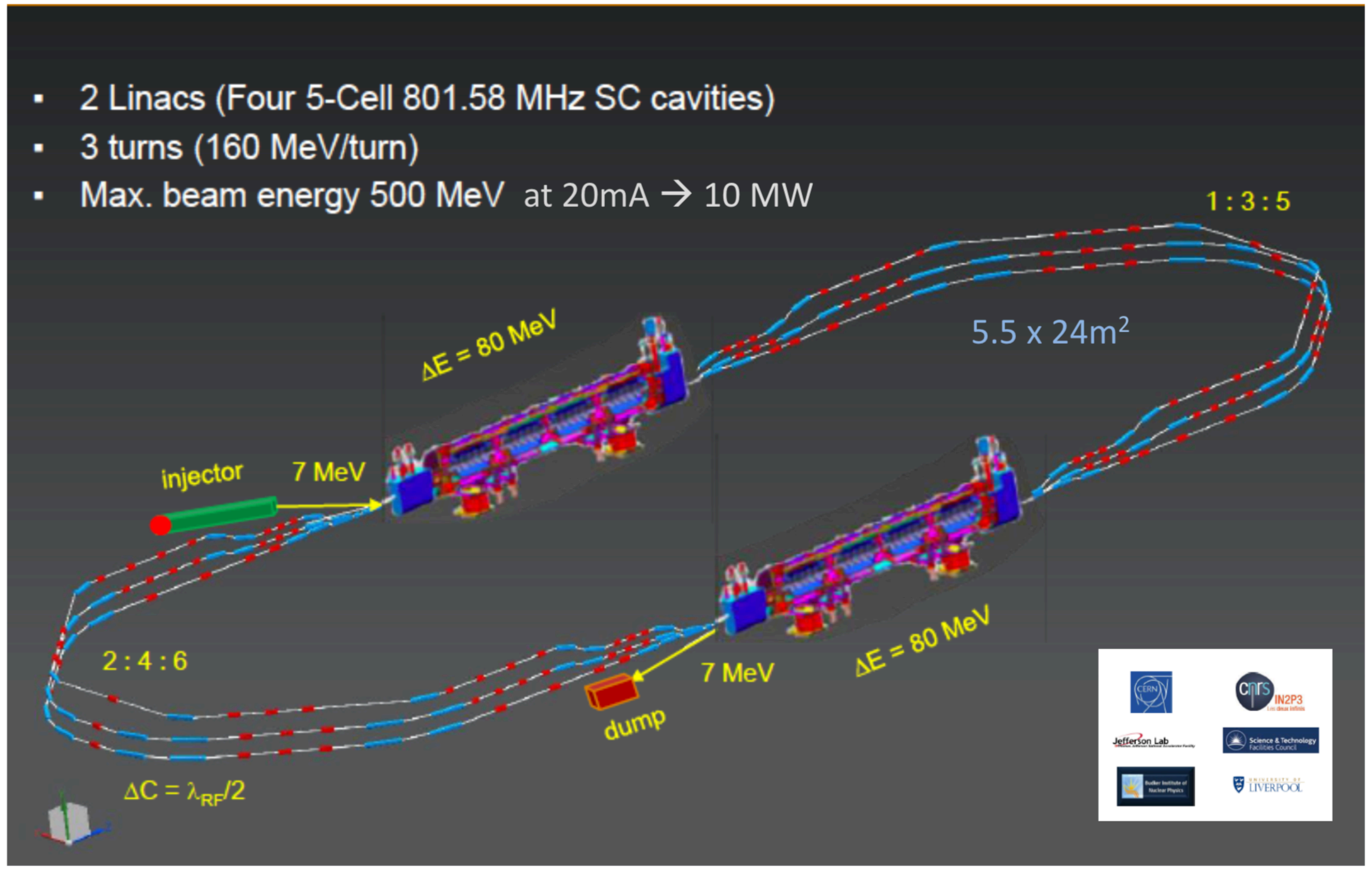


Various Questions:

- Low or HV CMOS
- Thickness, radiation hardness
  (note ep: below $10^{15}cm^2$n eq.
  no pile-up in ep, .. → maybe low)
- Detectors in Vacuum? Elliptic ep pipe ☹
- Bent wafers?
- Same vertex or 1.87 apart? Cost
- …

P. Kostka

Powerful ERL for Experiments (PERLE) @ Orsay



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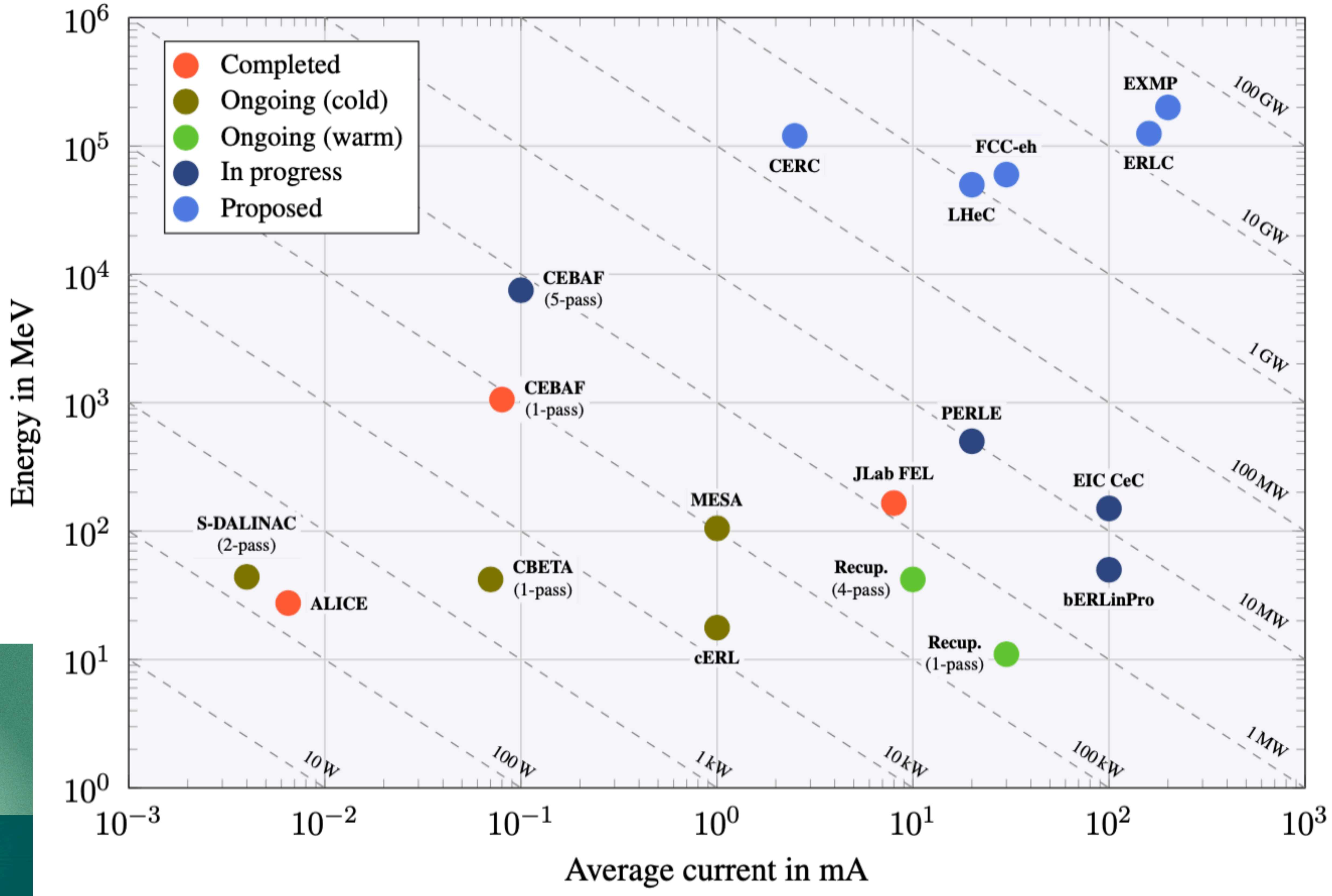
First PERLE Physics Workshop: 09.05.2022 (by invitation)

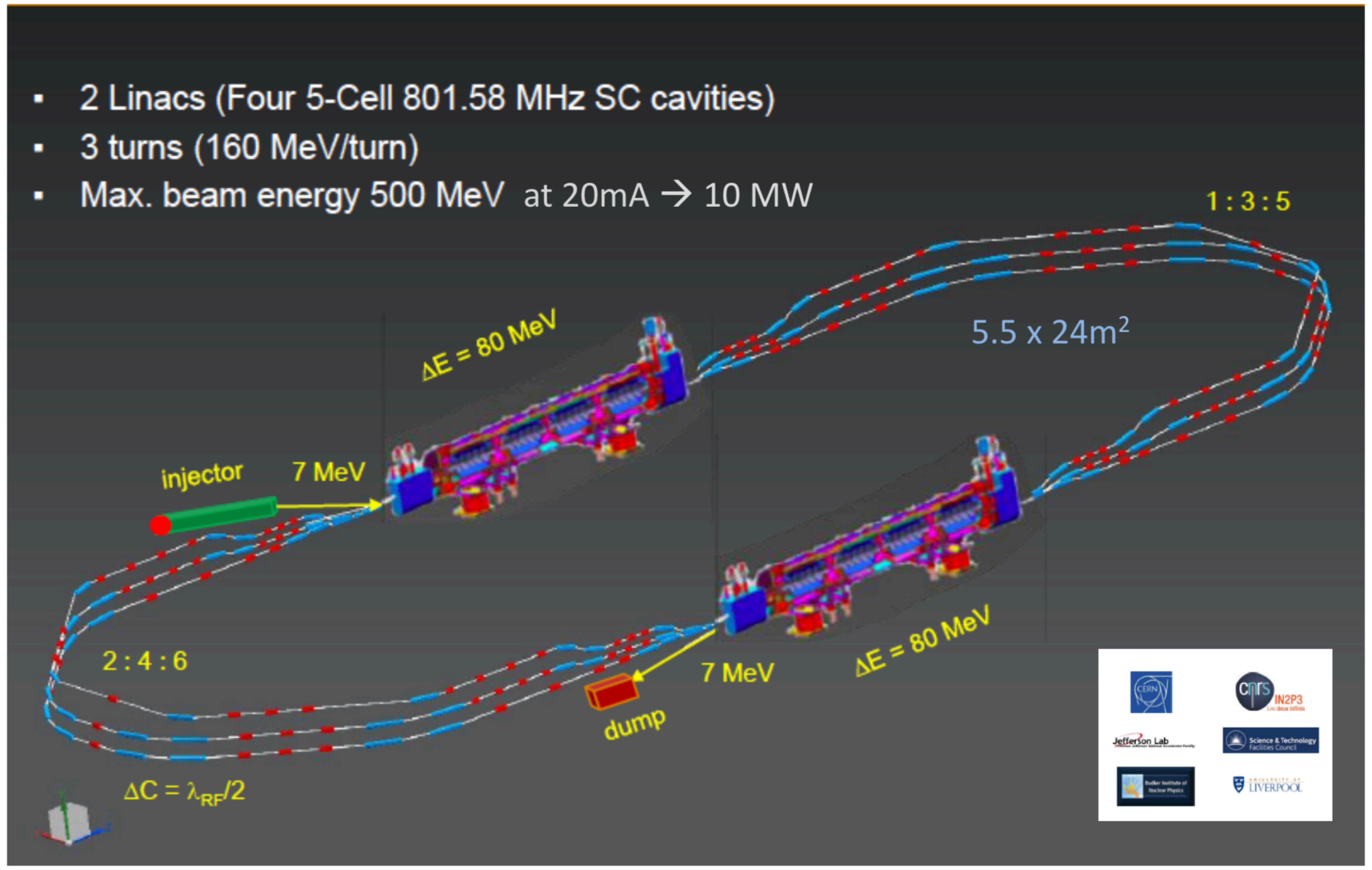
arXiv: 2201.07895

Status: see talk by Achille Stocchi, 05/05

CDR: 1705.08783, J. Phys. G
CERN-ACC-Note-2018-0086 (ESSP)



Powerful ERL for Experiments (PERLE) @ Orsay

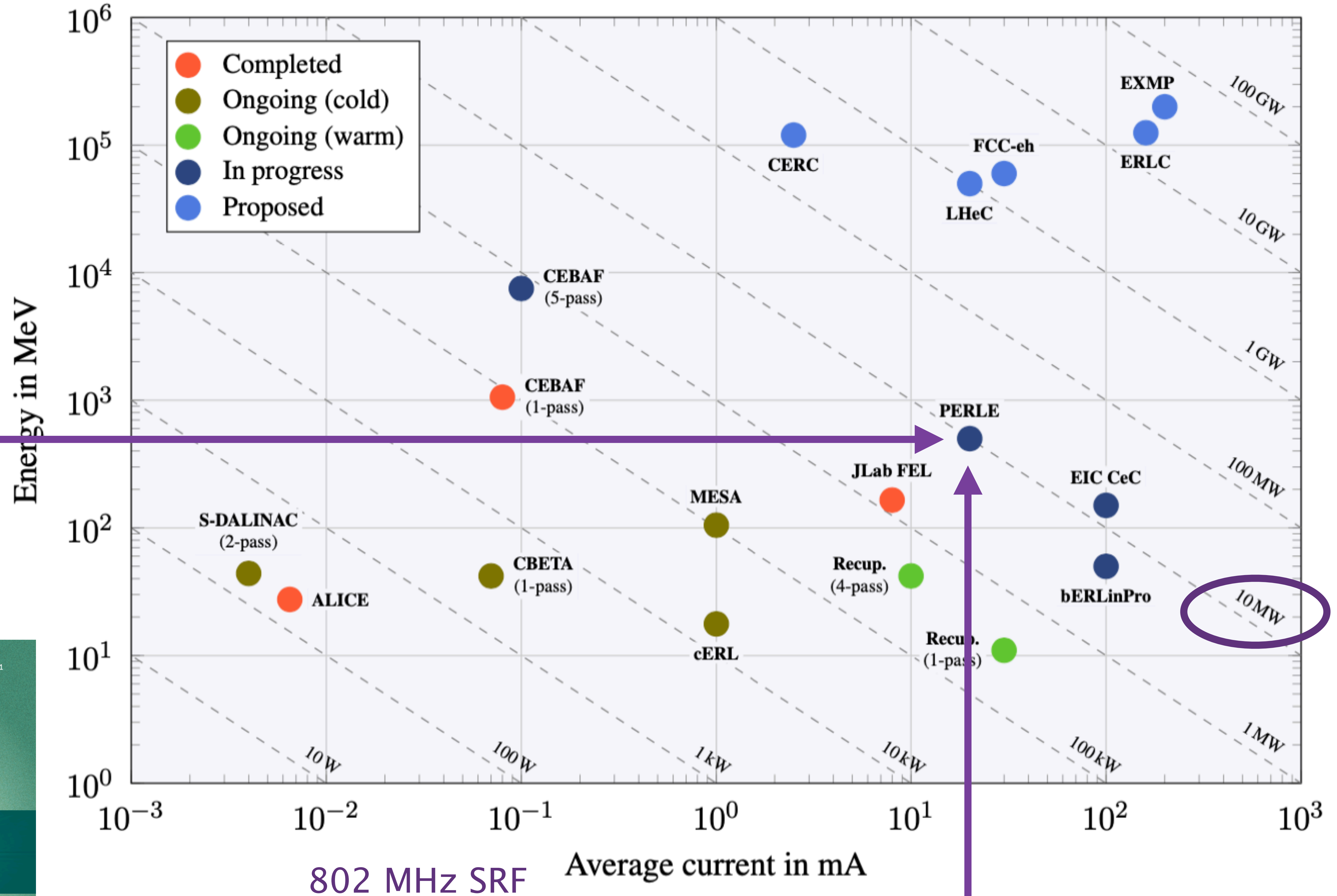


PERLE

Status: see talk by Achille Stocchi, 05/05

CDR: 1705.08783, J. Phys. G
CERN-ACC-Note-2018-0086 (ESSP)

E_e=500 MeV



802 MHz SRF

3 turns

I_e=20mA

→ first 10 MW ERL facility

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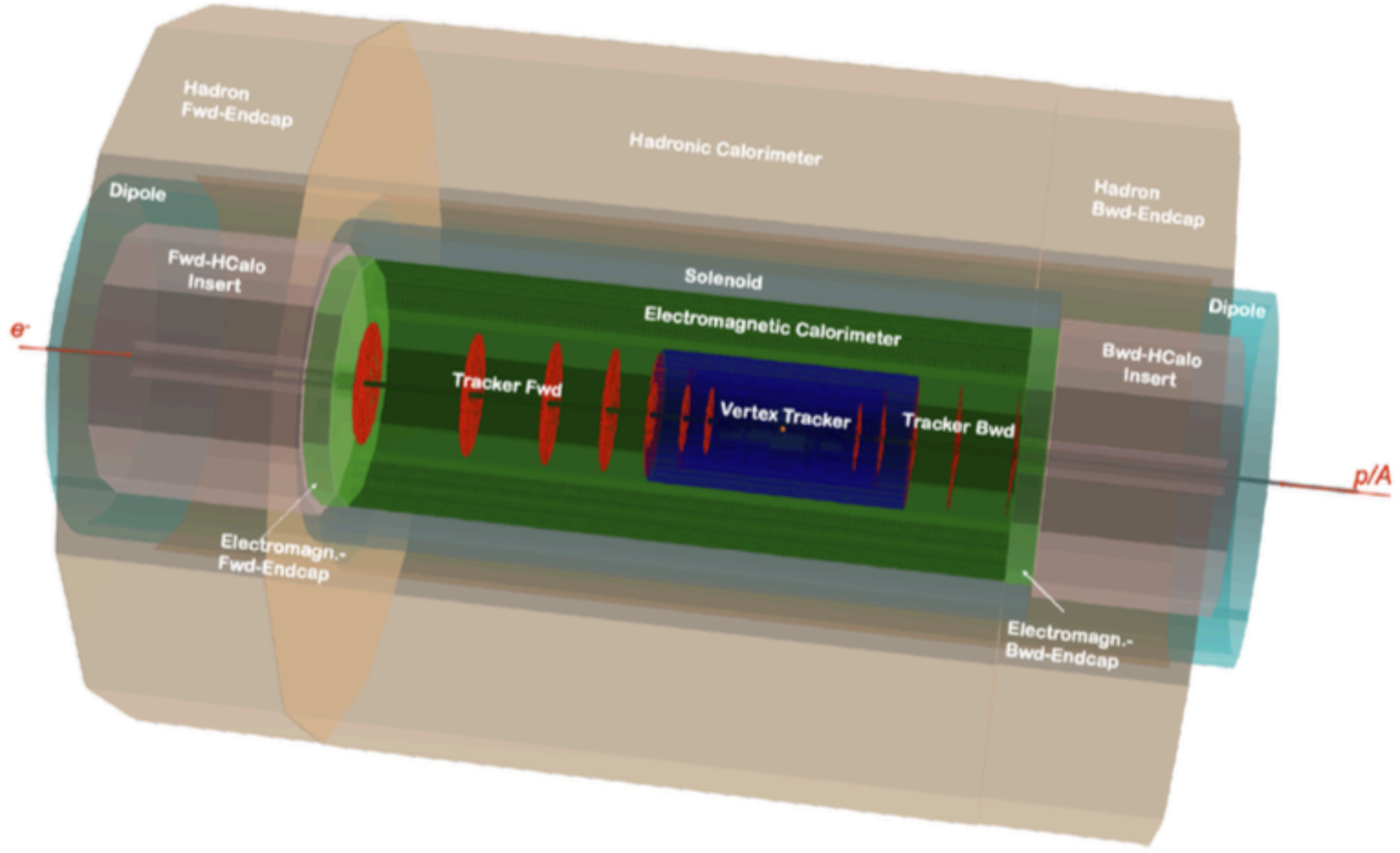
LHeC Calorimeter Design



LHeC Calorimeters

Complete coverage to +- 5 in (pseudo)rapidity

Central Region: 2012: LAr, 2020 Sci/Fe option.

Forward Region: dense, high energy jets of few TeV

H → bb and other reactions demand resolution of HFS

Backward Region: in DIS only deposits of $E < E_e$

Barrel Calorimeters

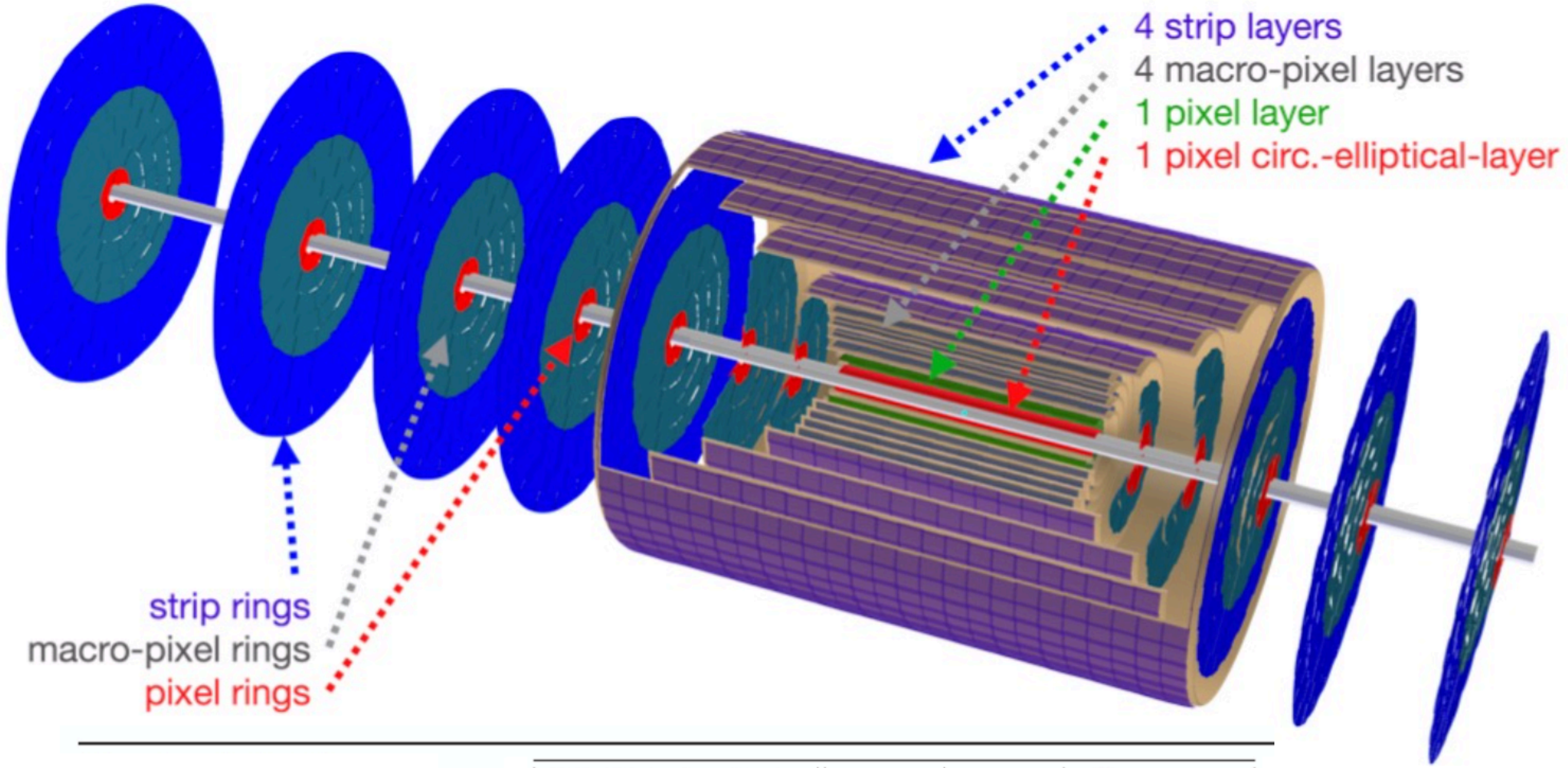
Calo (LHeC)	EMC	HCAL		
	Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber	Sci,Pb	Sci,Fe	Sci,Fe	Sci,Fe
Layers	38	58	45	50
Integral Absorber Thickness [cm]	16.7	134.0	119.0	115.5
η_{max}, η_{min}	2.4, −1.9	1.9, 1.0	1.6, −1.1	−1.5, −0.6
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	12.4/1.9	46.5/3.8	48.23/5.6	51.7/4.3
Λ_I / X_0	$X_0 = 30.2$	$\Lambda_I = 8.2$	$\Lambda_I = 8.3$	$\Lambda_I = 7.1$
Total area Sci [m^2]	1174	1403	3853	1209

Forward/Backward Calorimeters

Calo (LHeC)	FHC Plug Fwd	FEC Plug Fwd	BEC Plug Bwd	BHC Plug Bwd
Readout, Absorber	Si,W	Si,W	Si,Pb	Si,Cu
Layers	300	49	49	165
Integral Absorber Thickness [cm]	156.0	17.0	17.1	137.5
η_{max}, η_{min}	5.5, 1.9	5.1, 2.0	−1.4, −4.5	−1.4, −5.0
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	51.8/5.4	17.8/1.4	14.4/2.8	49.5/7.9
Λ_I / X_0	$\Lambda_I = 9.6$	$X_0 = 48.8$	$X_0 = 30.9$	$\Lambda_I = 9.2$
Total area Si [m^2]	1354	187	187	745

arXiv:2007.14491

LHeC Tracker Design



Inner Tracker

Rapidity to ~5

r_O = 60 cm

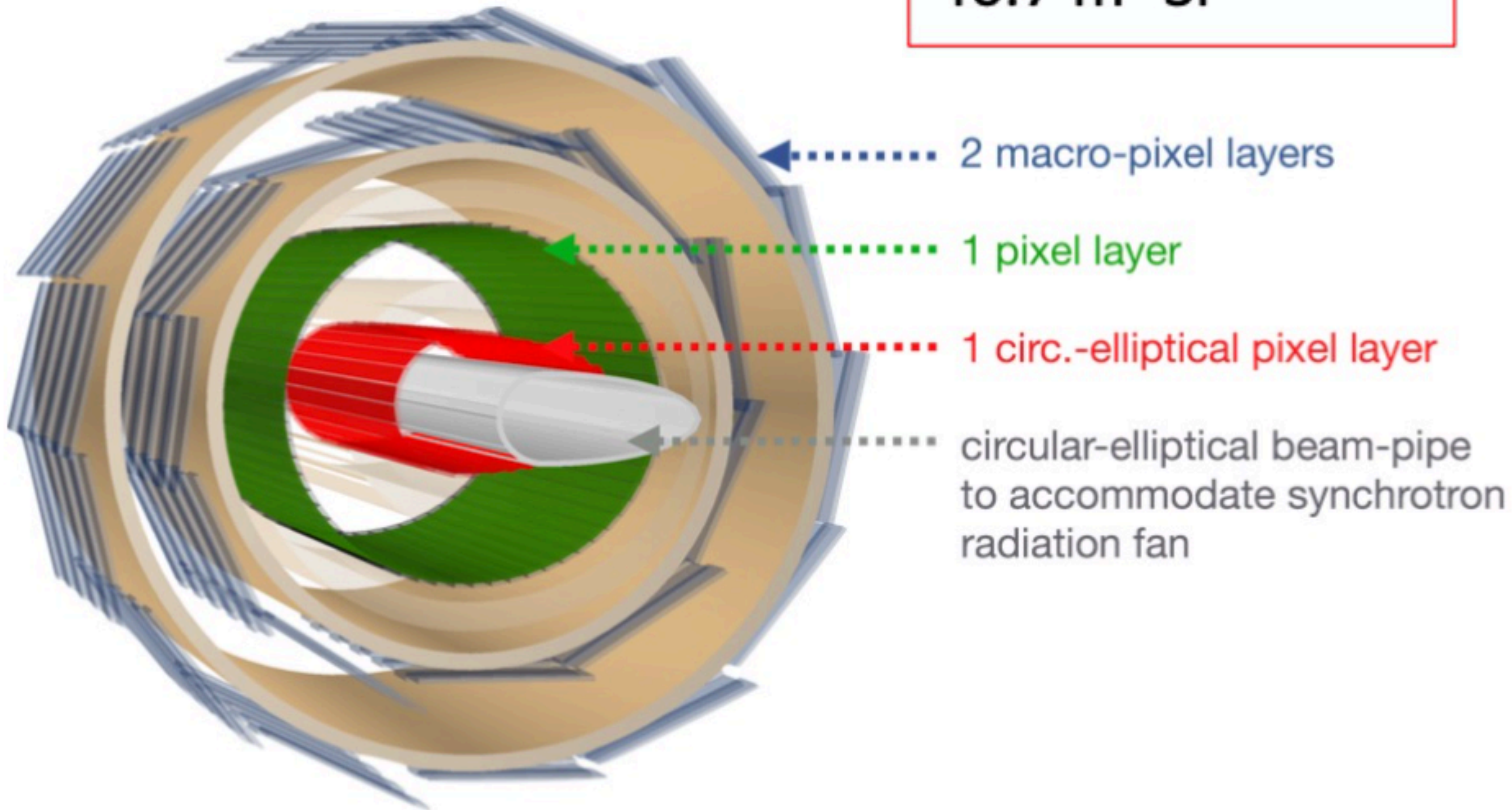
impact resolution 5-10 µm

40.7 m² Si

LHeC Trackers

η_{max}, η_{min}	
Wheels	
Modules/Sensors	
Total Si area	[m^2]
Read-out-Channels	[10^6]
pitch$^{r-\phi}$	[μm]
pitch^z	[μm]
Average X_0/Λ_I	[%]
incl. beam pipe	[%]

LHeC Tracker Part		η_{max}	η_{min}	#Layers$_{Barrel}$
Inner Barrel	pix	3.3	-3.3	2
	pix$_{macro}$	2.	-2.	4
	strip	1.3	-1.3	4
				#Rings$_{Wheels}$
End Caps	pix	4.1/-1.1	1.1/-4.1	2
	pix$_{macro}$	2.3/-1.4	1.4/-2.3	1
	strip	2./-0.7	0.7/-2.	1-4
Fwd Tracker	pix	5.2	2.6	2
	pix$_{macro}$	3.4	2.2	1
	strip	3.1	1.4	4
Bwd Tracker	pix	-2.6	-4.6	2
	pix$_{macro}$	-2.2	-2.9	1
	strip	-1.4	-2.5	4
Total $\eta_{max/min}$		5.2	-4.6	

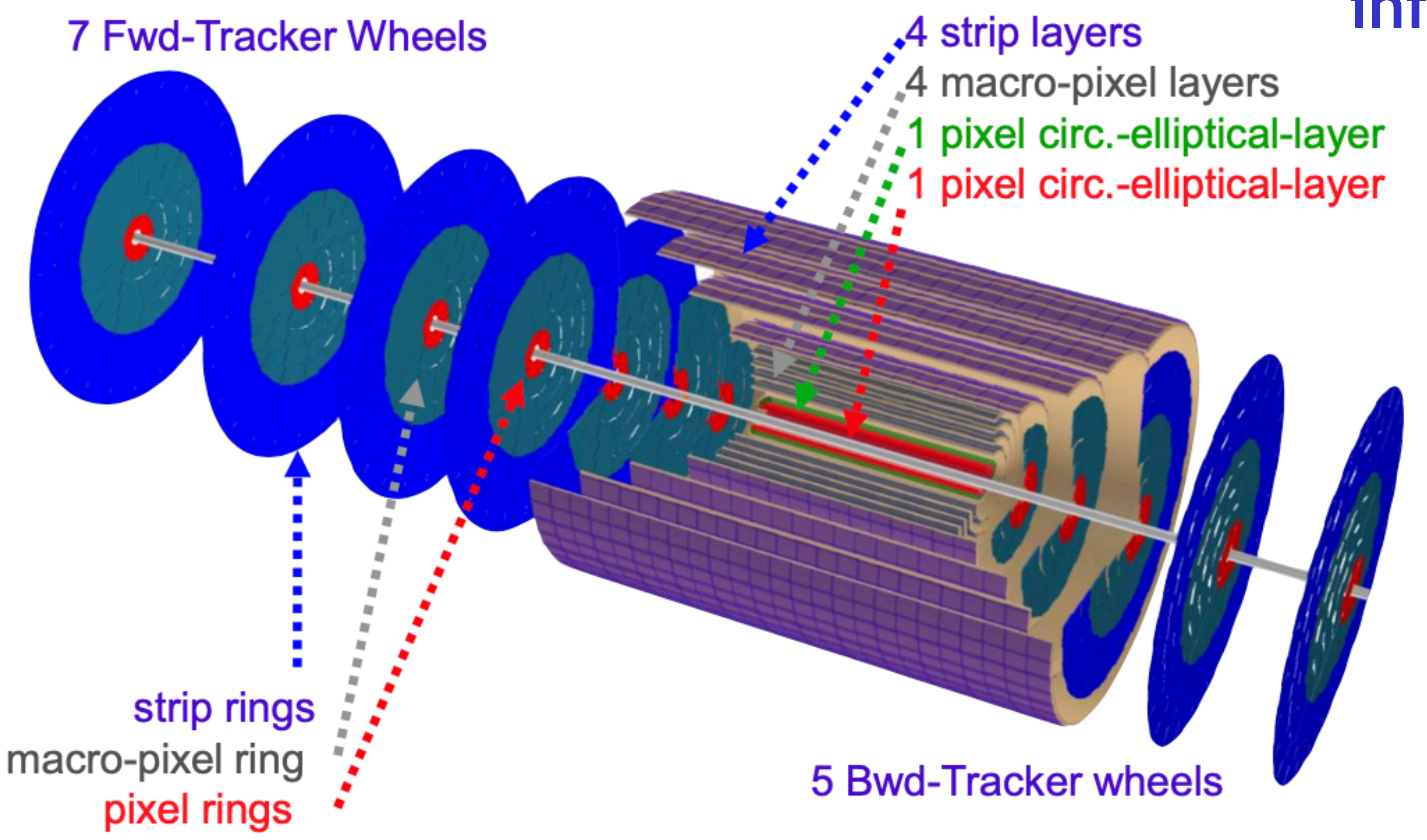


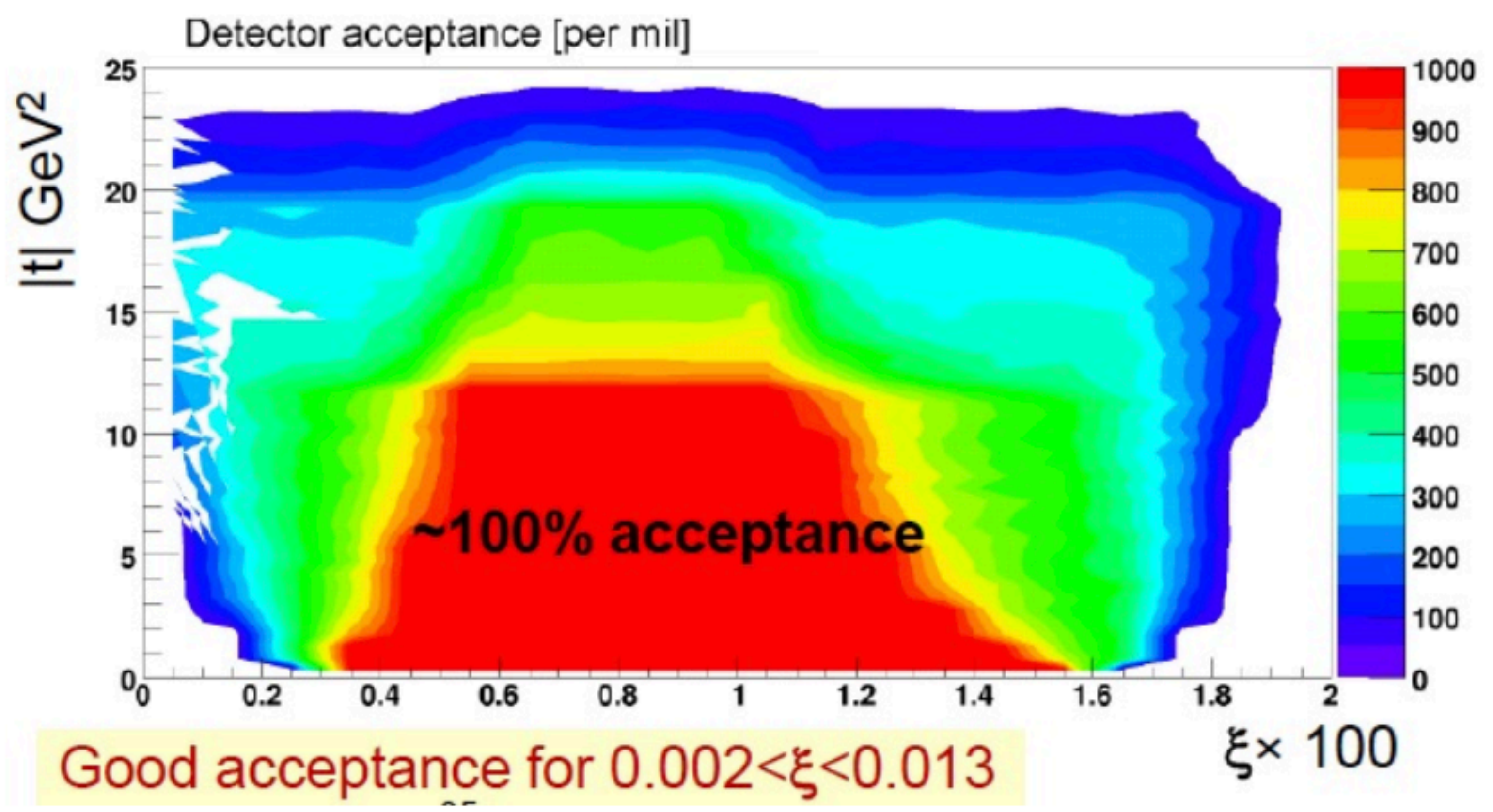
Detector technologies build on LHC and EIC

inform future lepton colliders

e.g. Silicon tracker design in CDR

- HV-CMOS MAPS with bent / stitched wafers (as ALICE and ePIC) and semi-elliptical inner layers to cope with synchrotron fan → ~20% X_0 / layer up to η~4.5





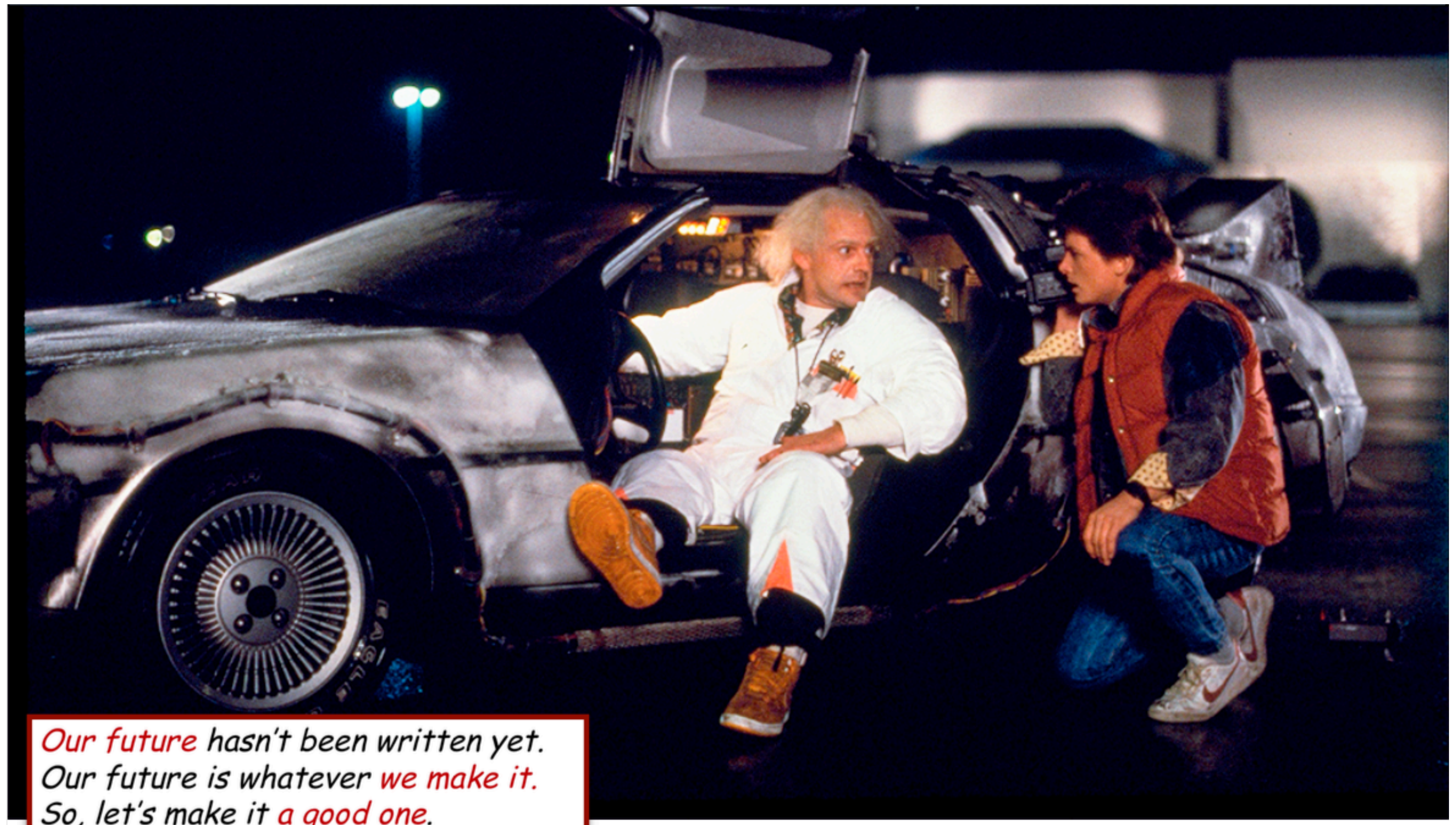
e.g. Forward proton spectrometer in cold region (~420m)?

- Reuse of technology proposed for LHC, accessing protons scattered at very low momentum loss

FP420

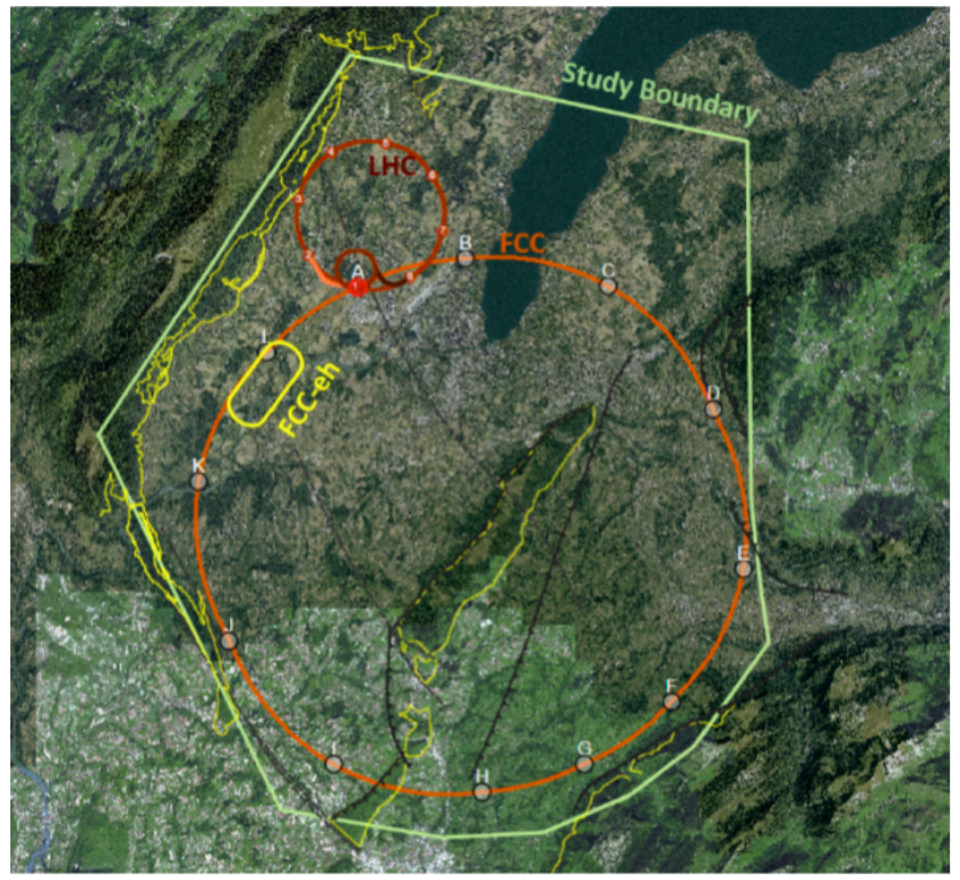
The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC 27

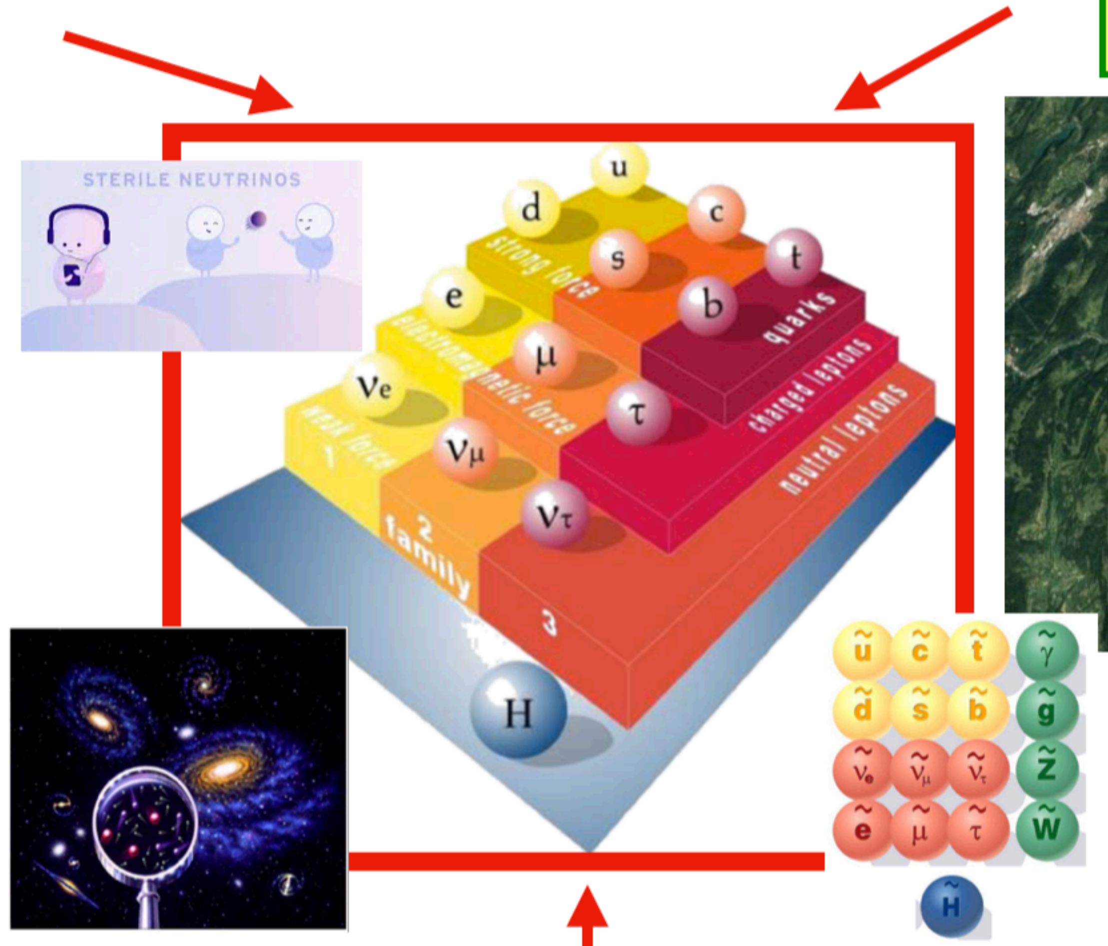
Conclusions



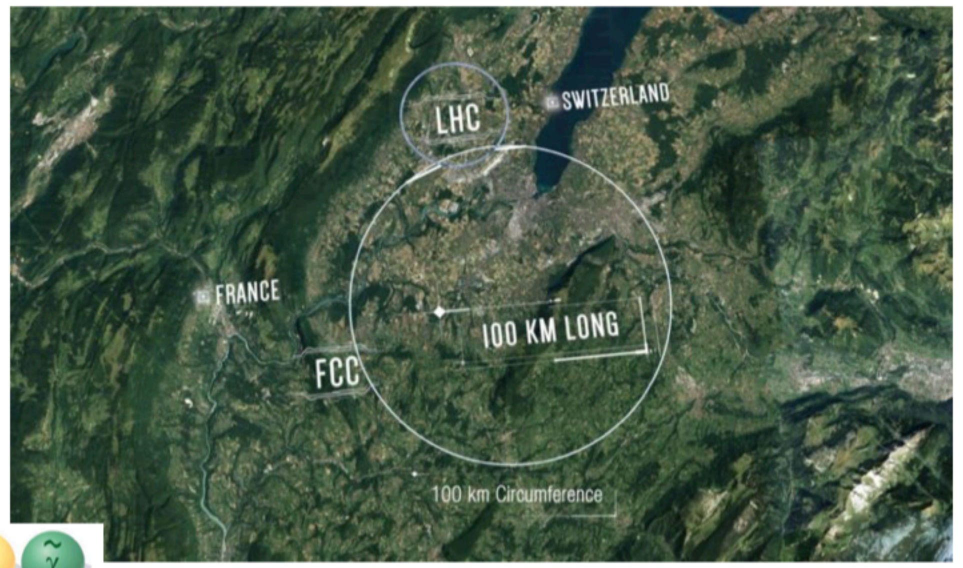
Our future hasn't been written yet.
Our future is whatever we make it.
So, let's make it a good one.
(Doc Brown)

FCC-eh **ep**

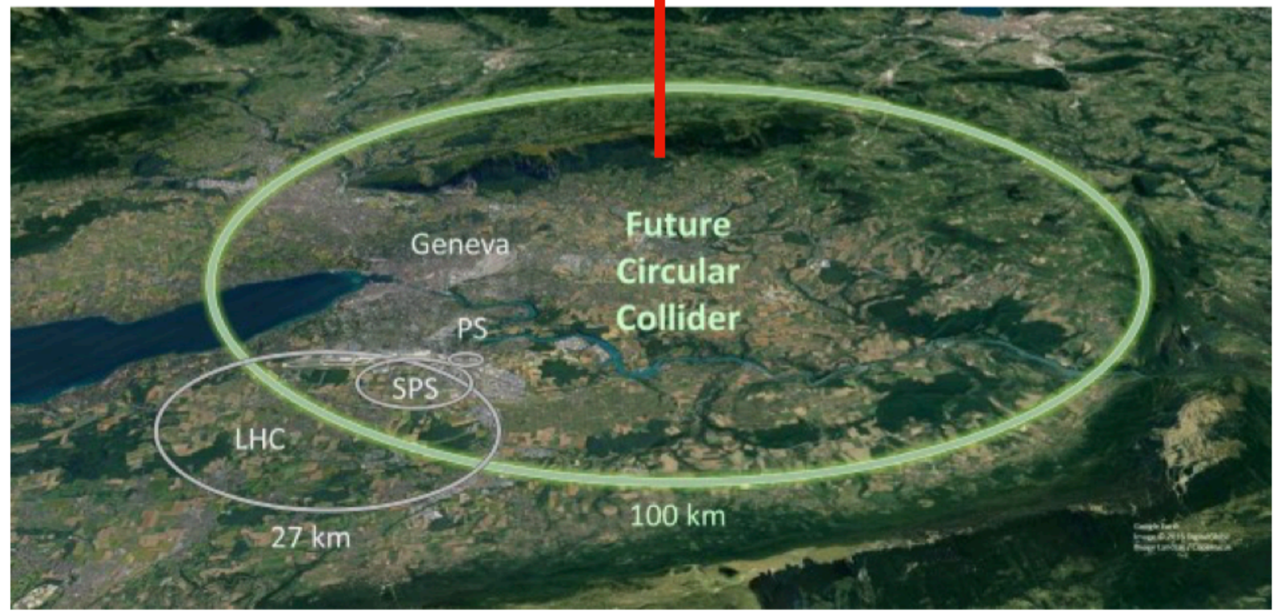




pp FCC-hh



ee



FCC-ee

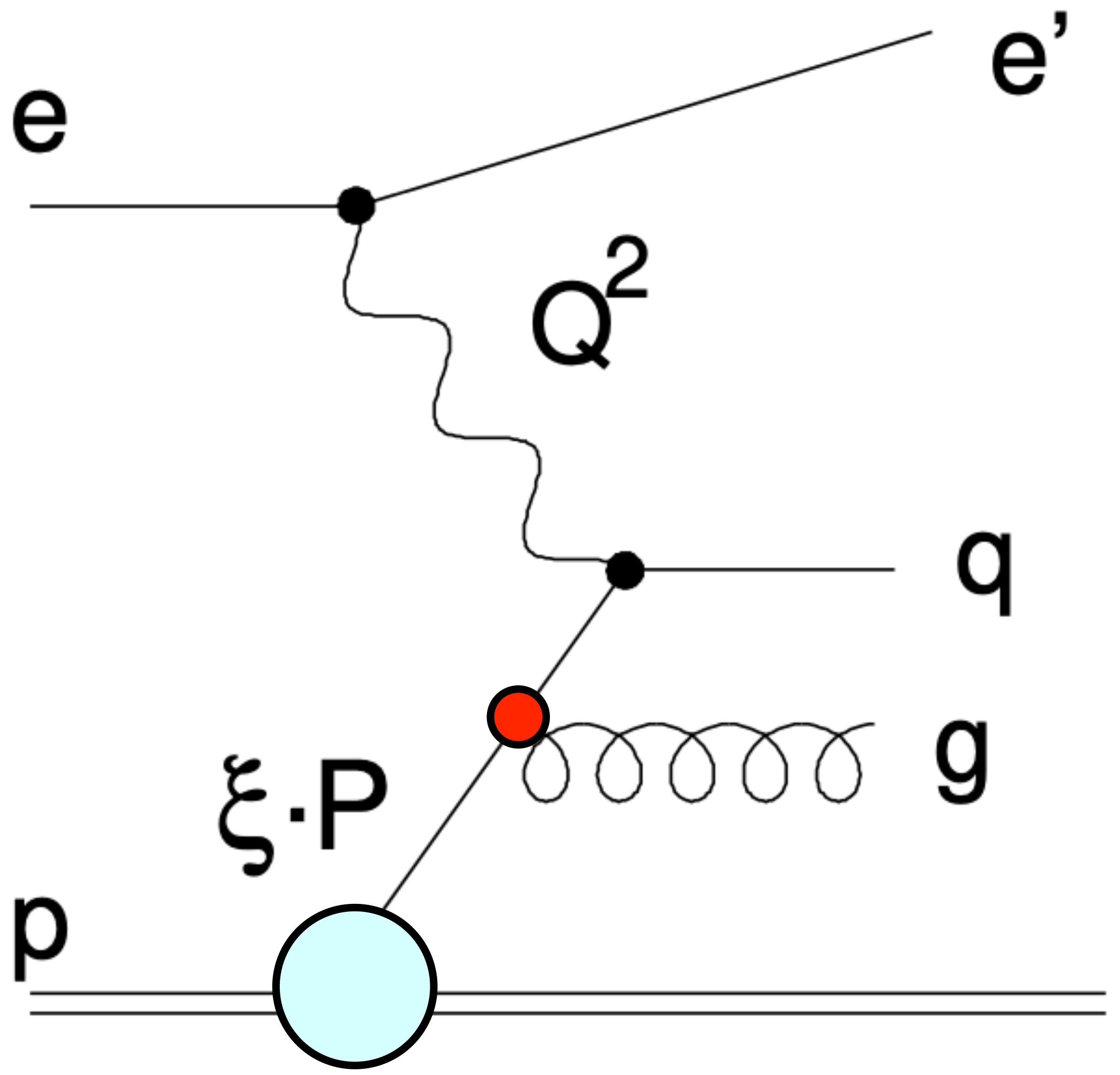
→ let's make it a diverse one

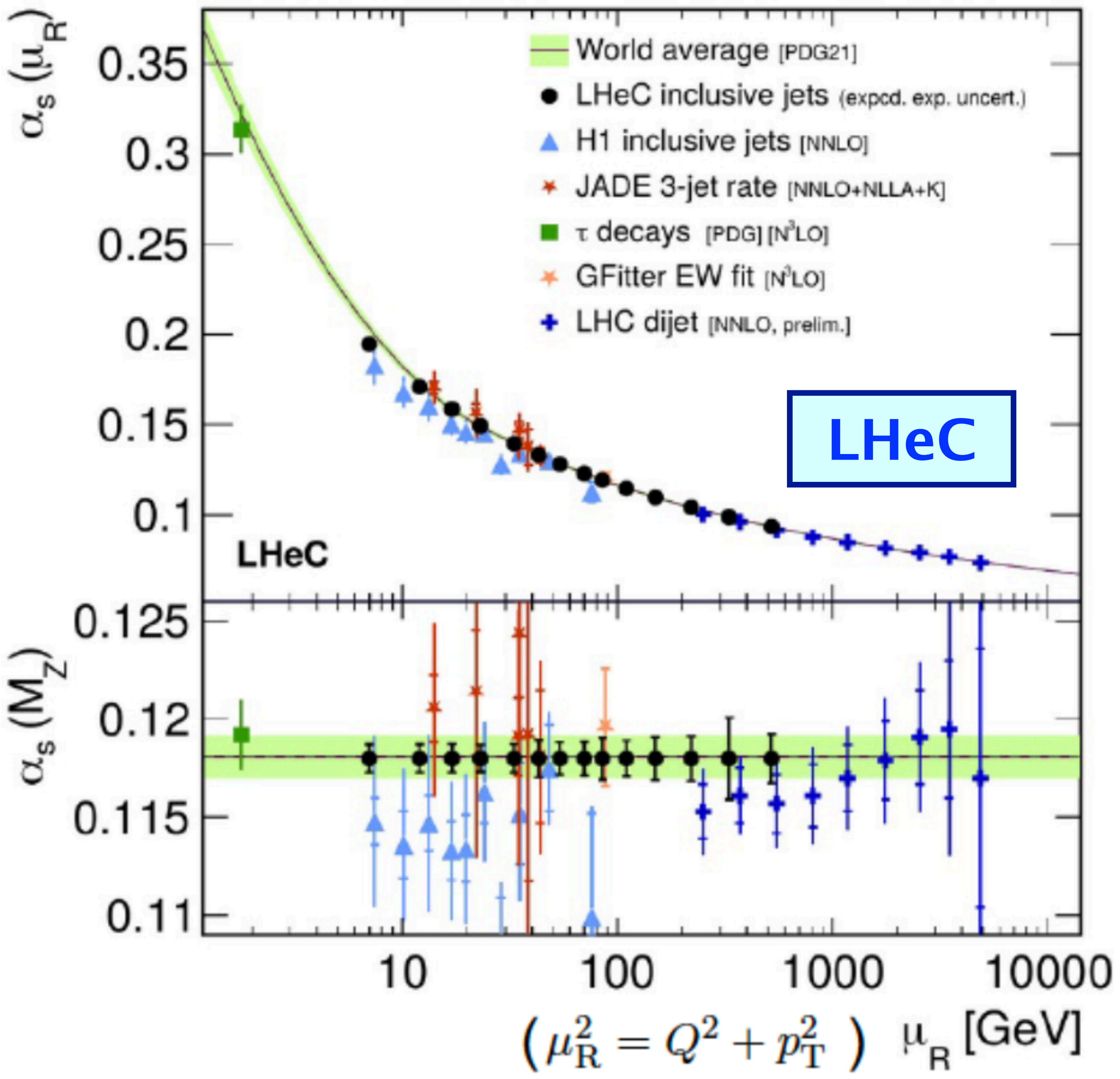
Physics Results Backup

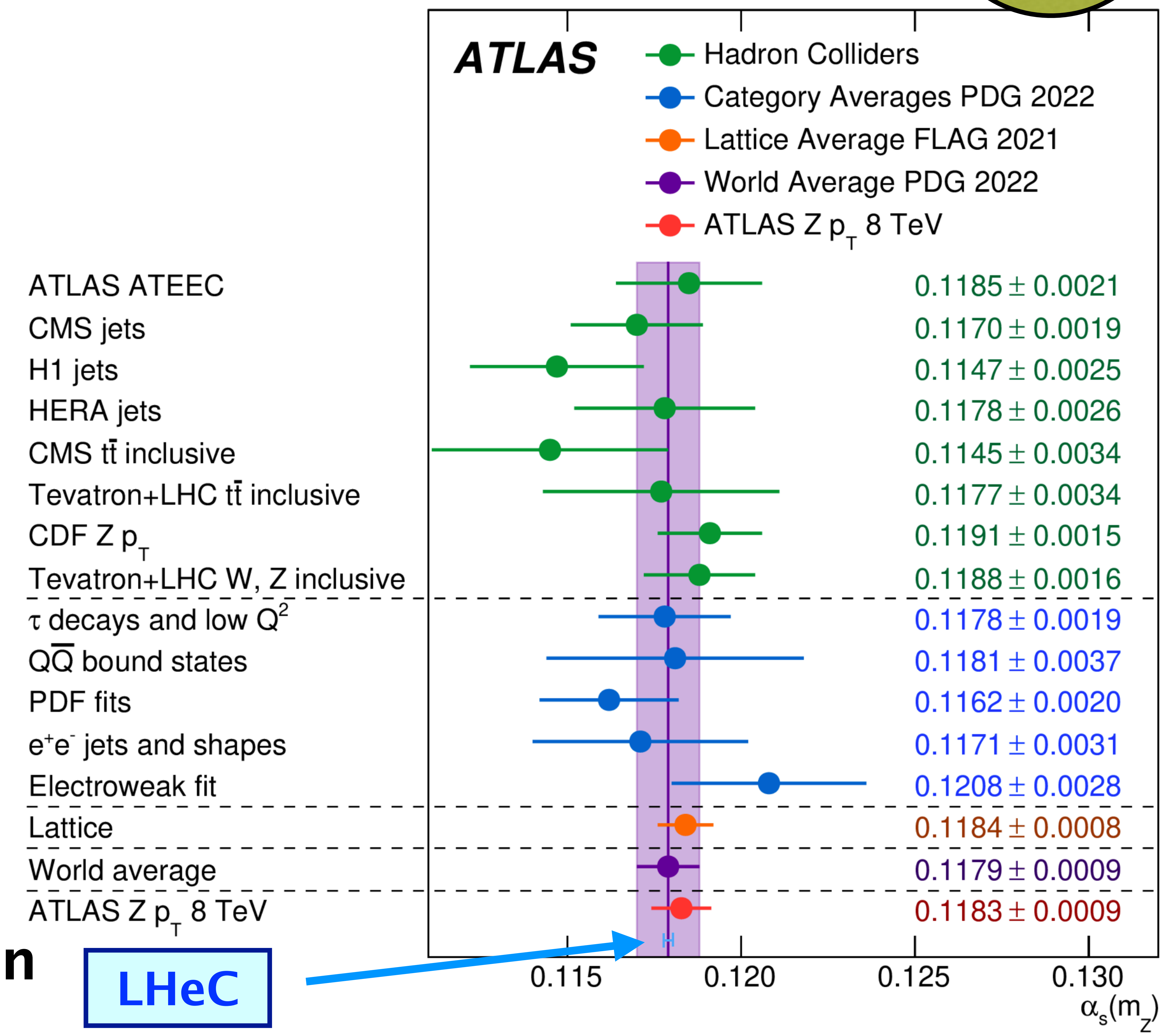
Determination of the strong coupling

QCD

- α_s is least known coupling constant







- α_s from fits to ep jet production

LHeC CDRs and arXiv:2203.08271

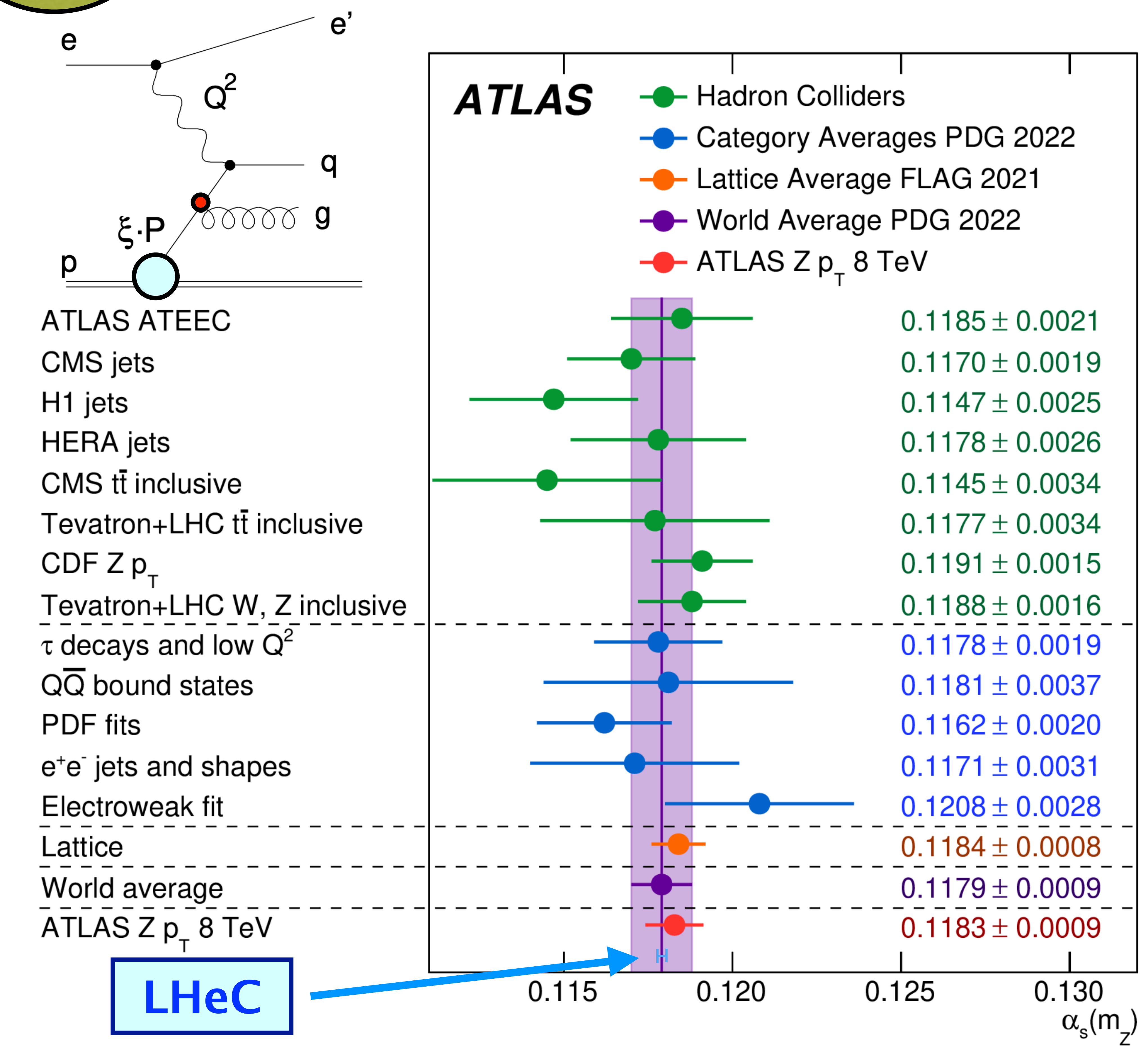
LHeC simultaneous PDF+α_s fit:

- $\Delta\alpha_s(m_Z) = \pm 0.00022_{(\text{exp.+PDF})}$
- $\Delta\alpha_s(m_Z) = \pm 0.00018$ (with ep jets)

Achievable precision: $\mathcal{O}(0.1\%)$ - **x5-10** better than today

→ **considerable improvement of world average**

QCD SM parameters: strong coupling and $\sin^2\theta_W$ EWK



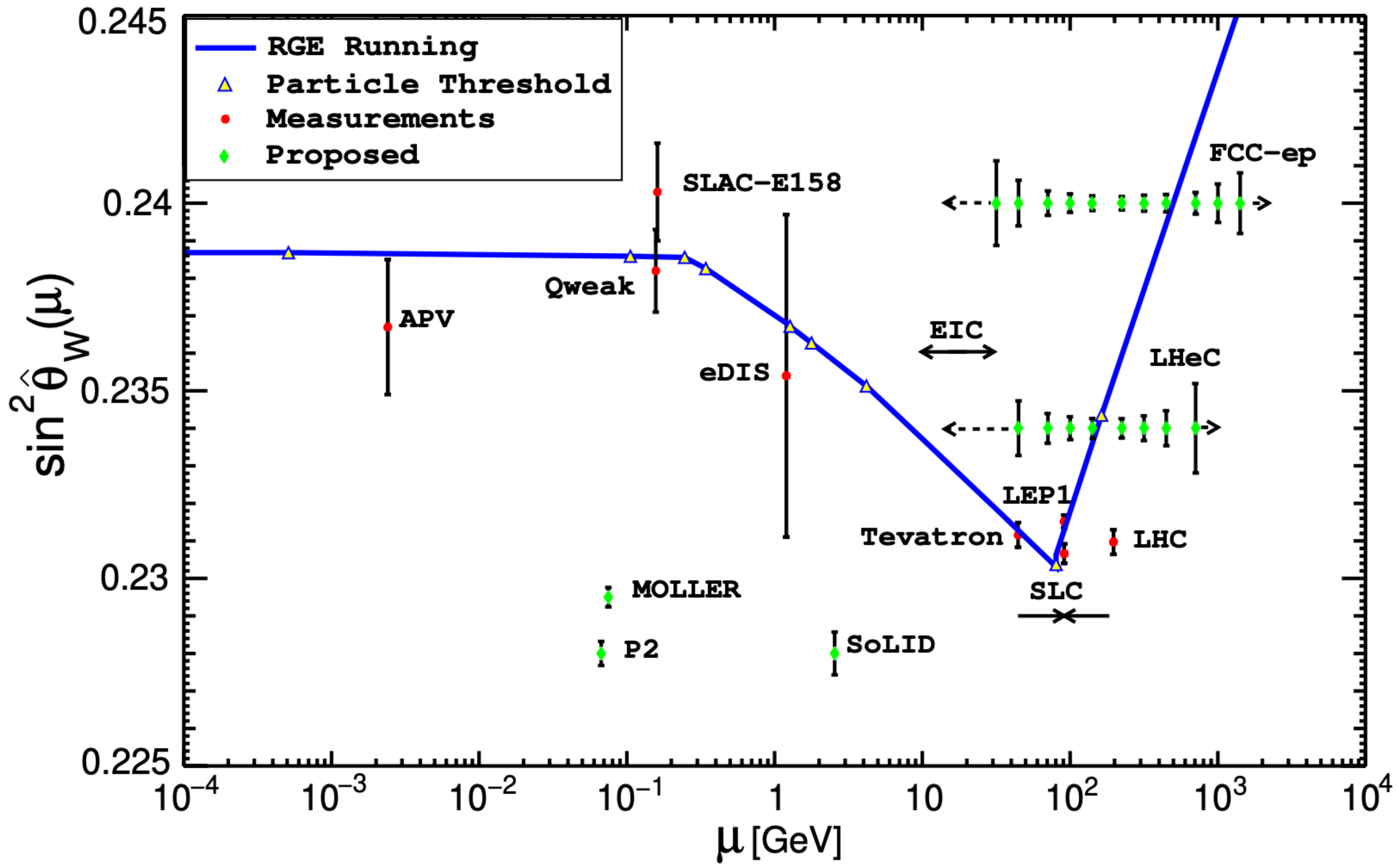
Achievable precision: $\mathcal{O}$(0.1%) - **x5-10** better than today

→ **unprecedented precision**

PERLE CDR, CERN-ACC-NOTE-2018-0086

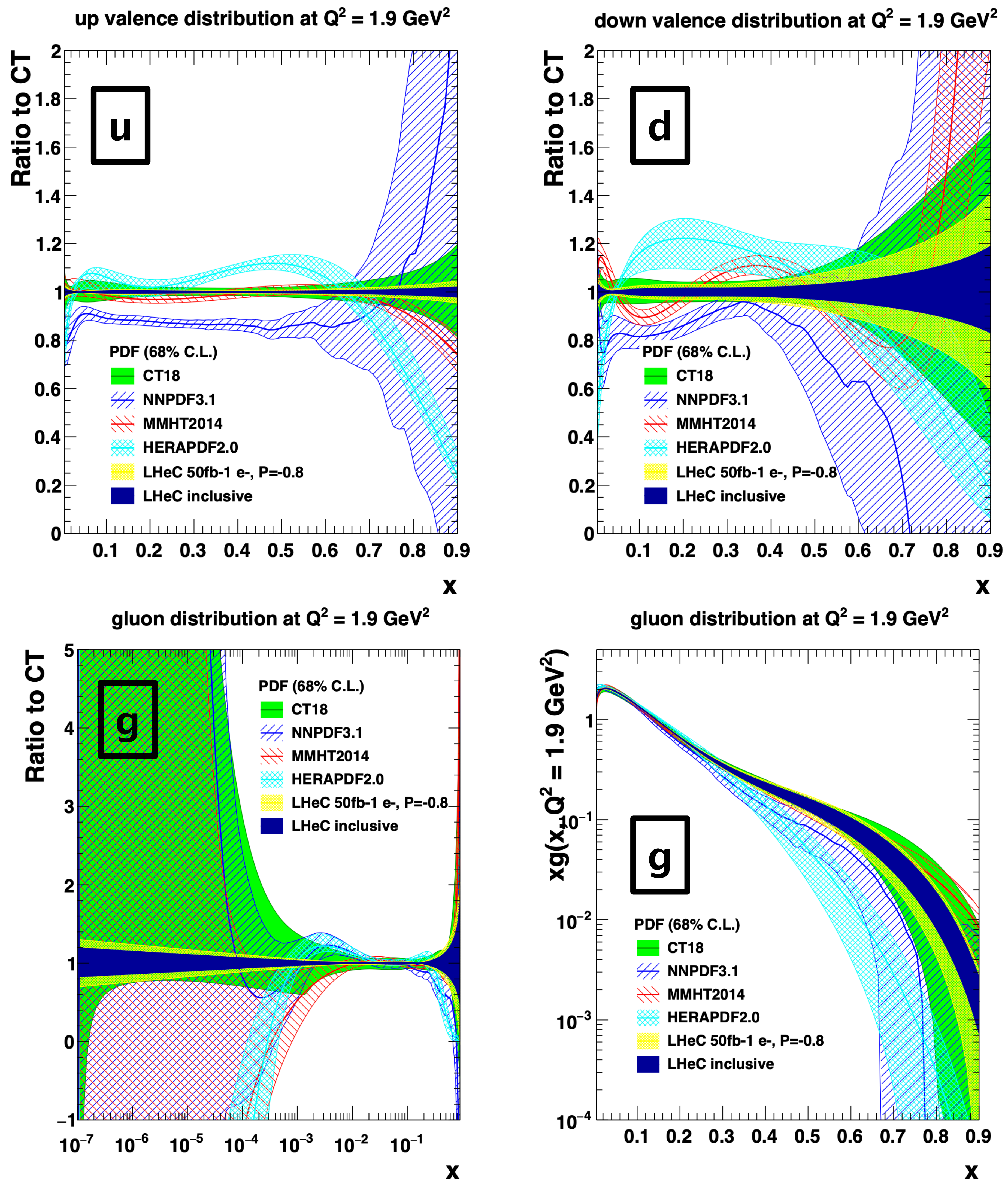
arXiv:2203.06237

LHeC CDR, J.Phys. G39, 075001 (2012)



→ **probe large range of scale dependence**

Parton Density Functions



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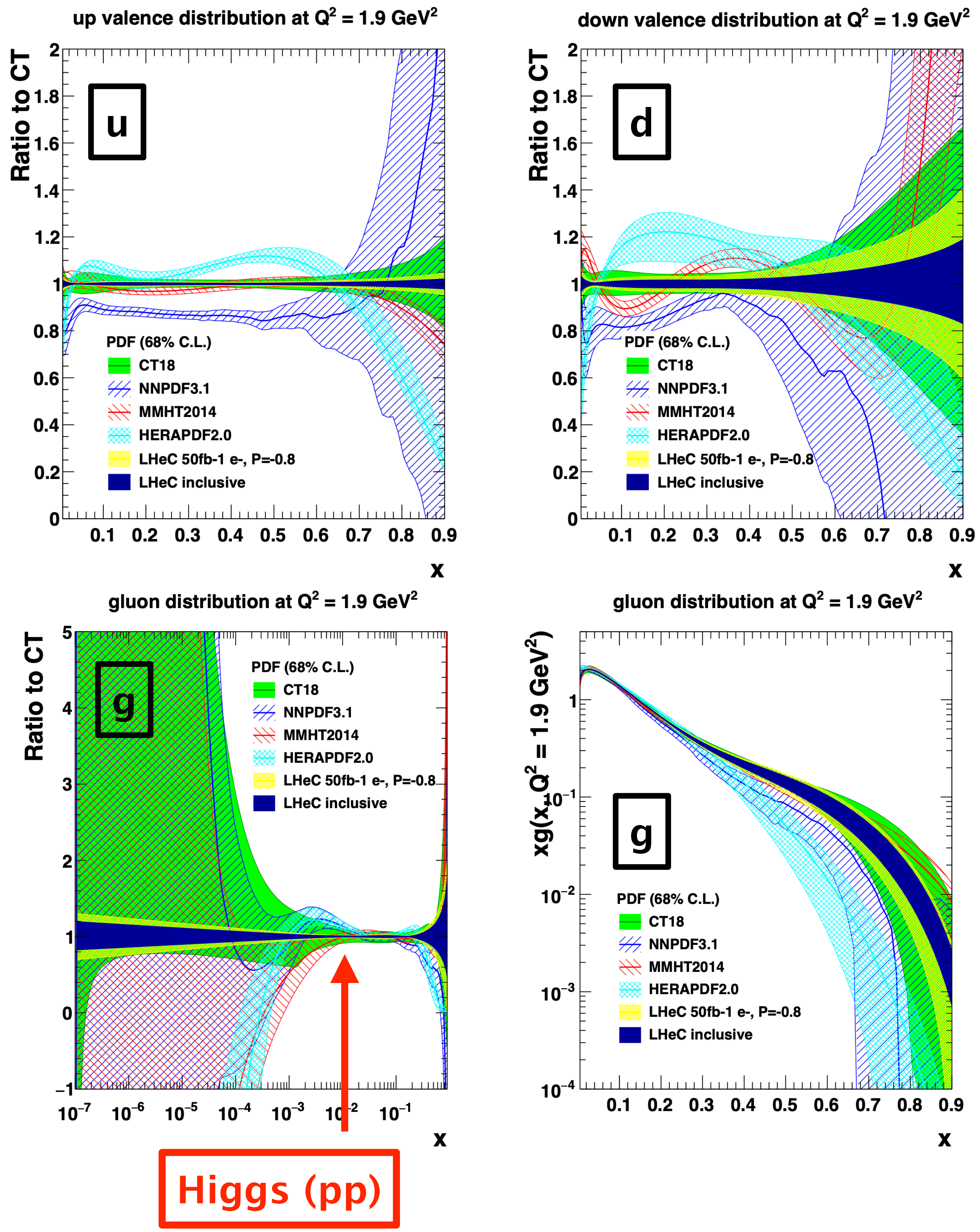

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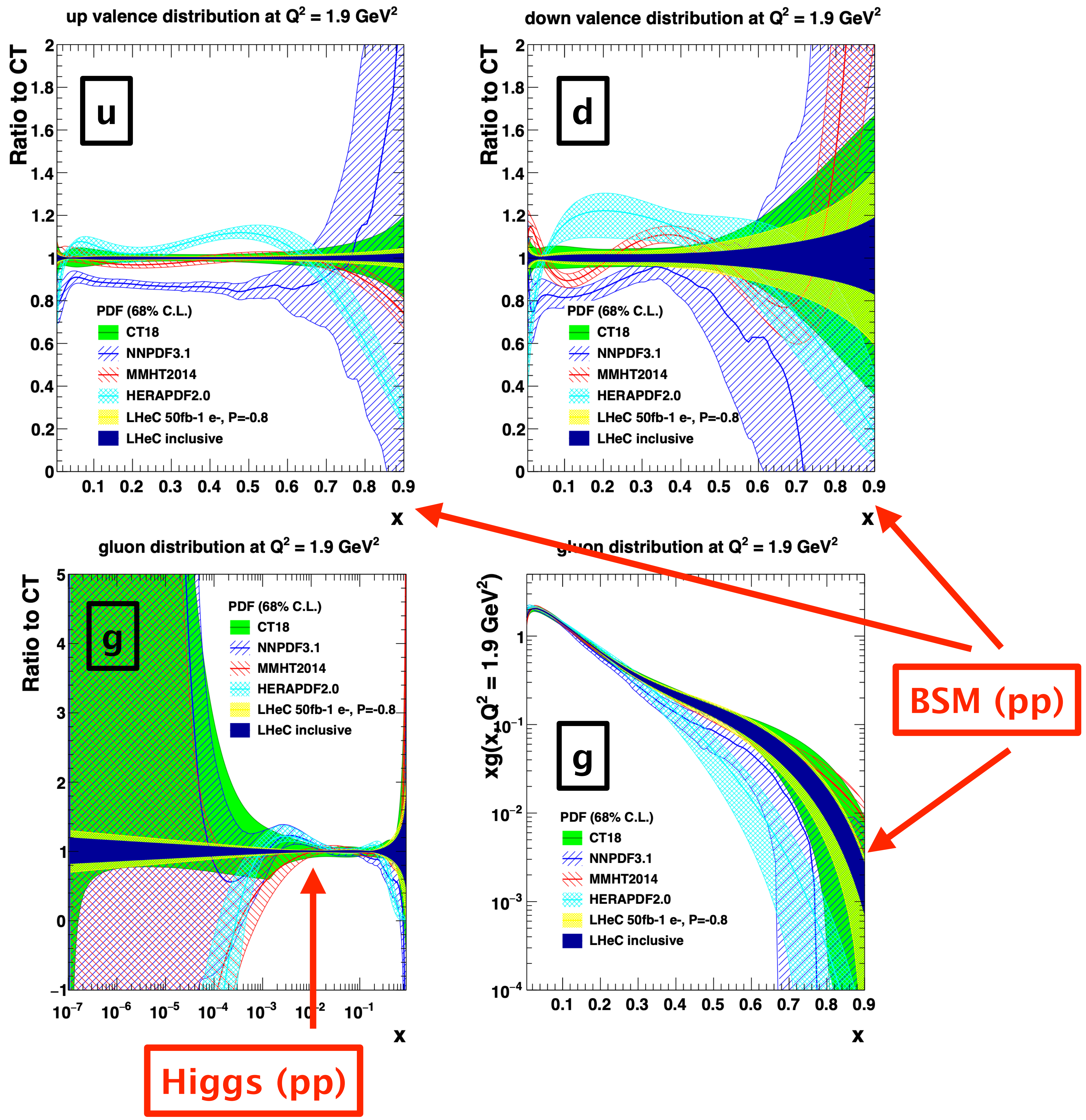

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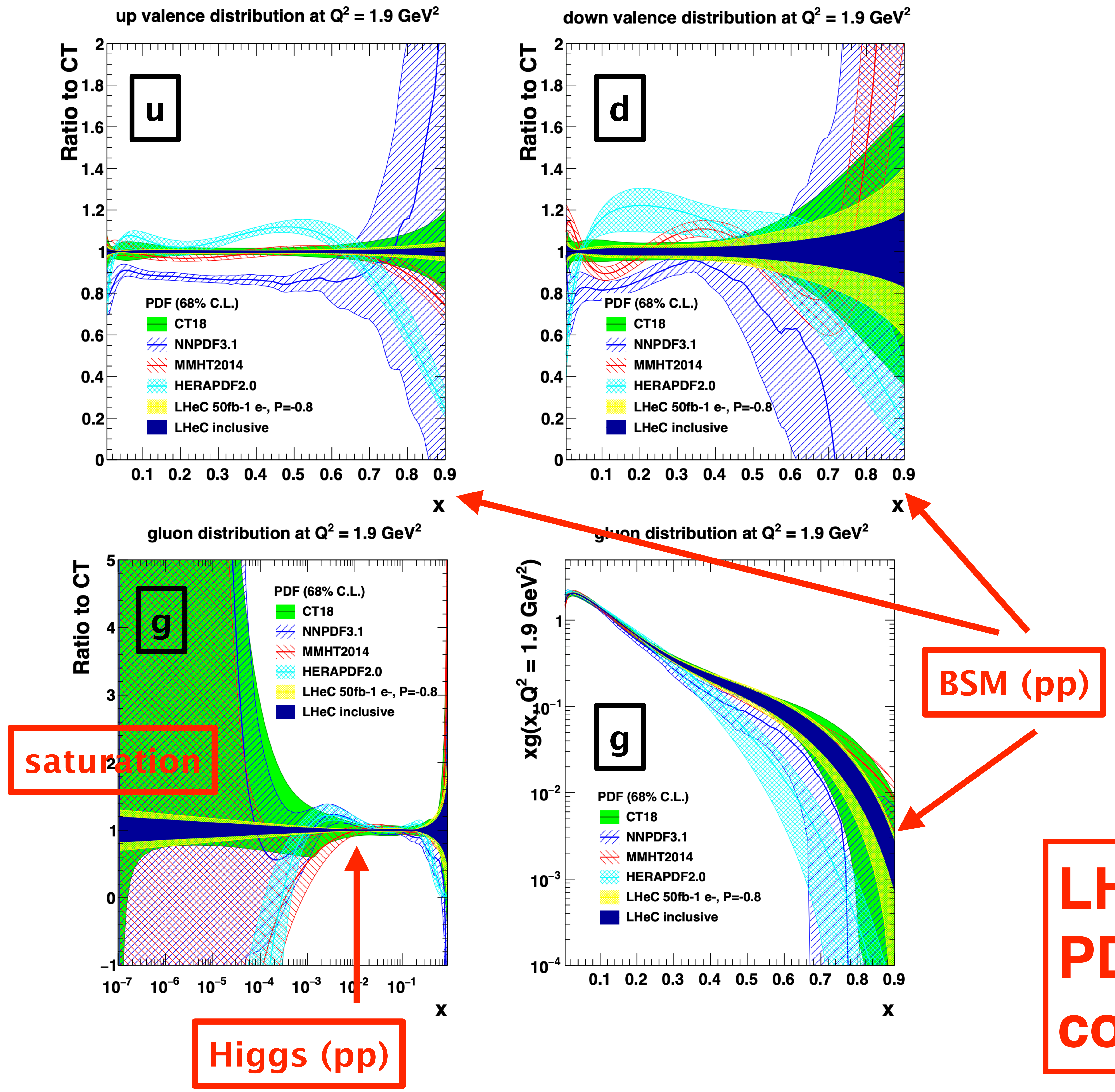
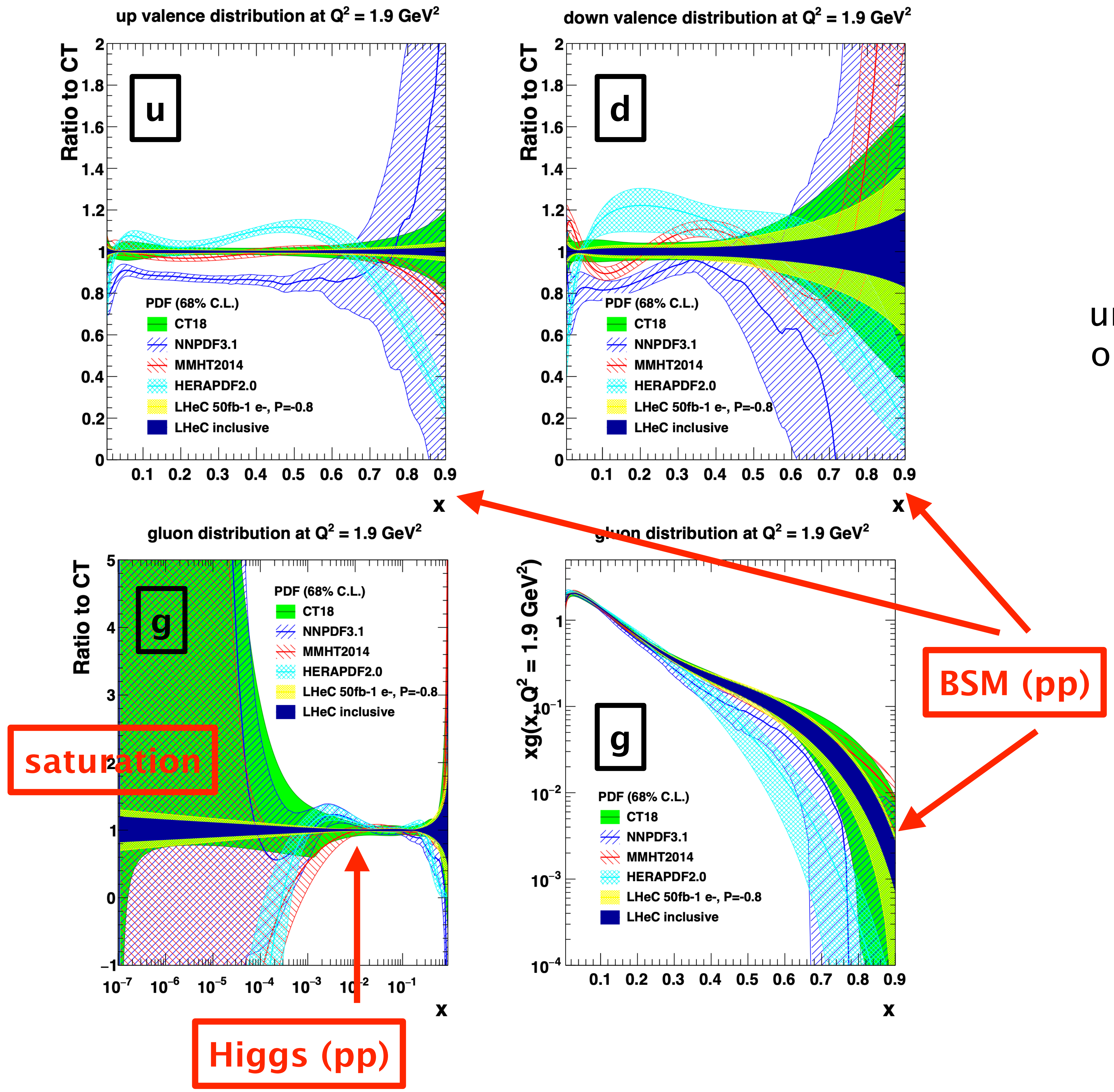


LHeC provides a single, coherent base for PDF determination to N^3LO, as pure and complete as only DIS can deliver

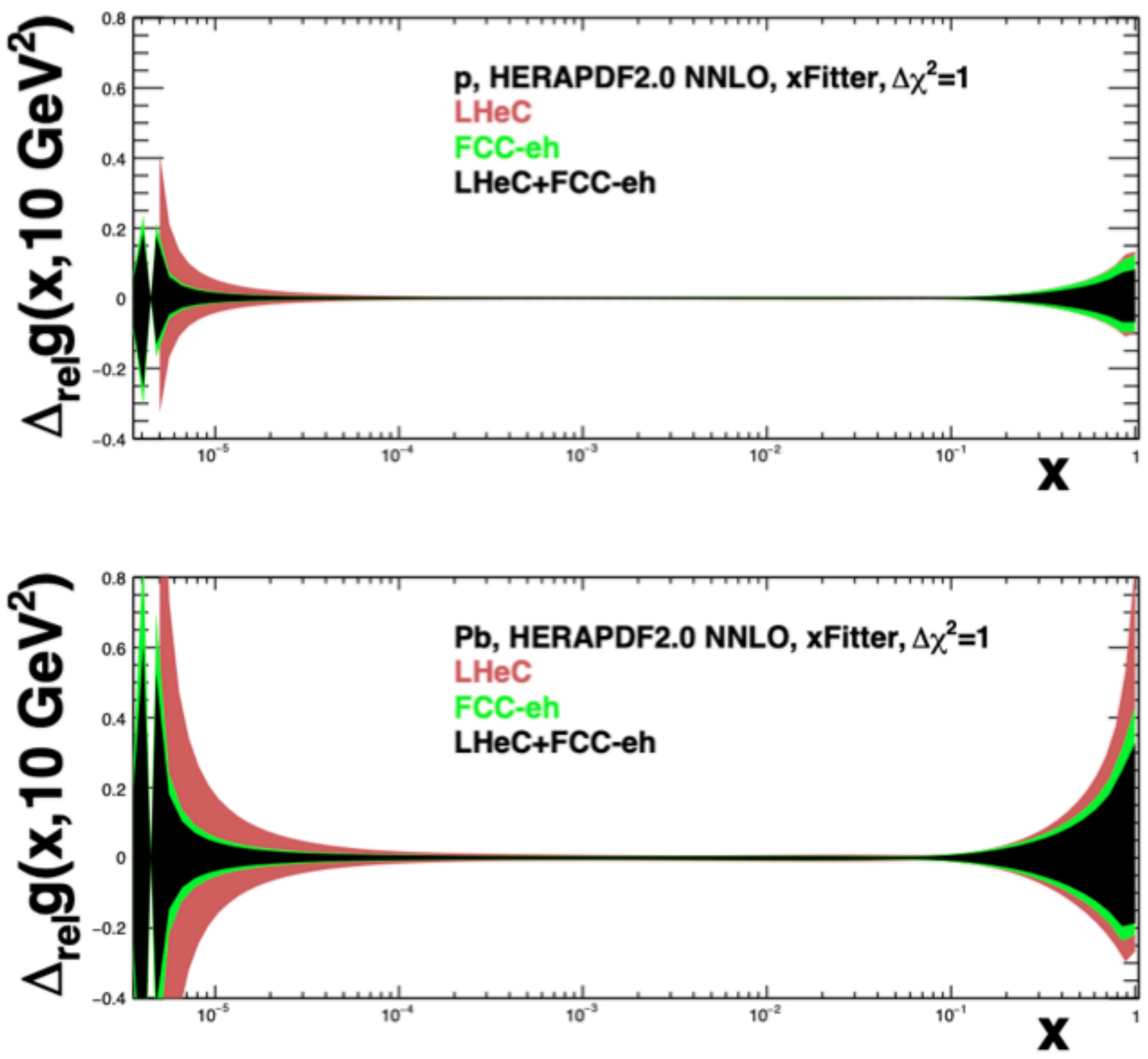
Parton Density Functions



uncertainties on the gluon

p

Pb



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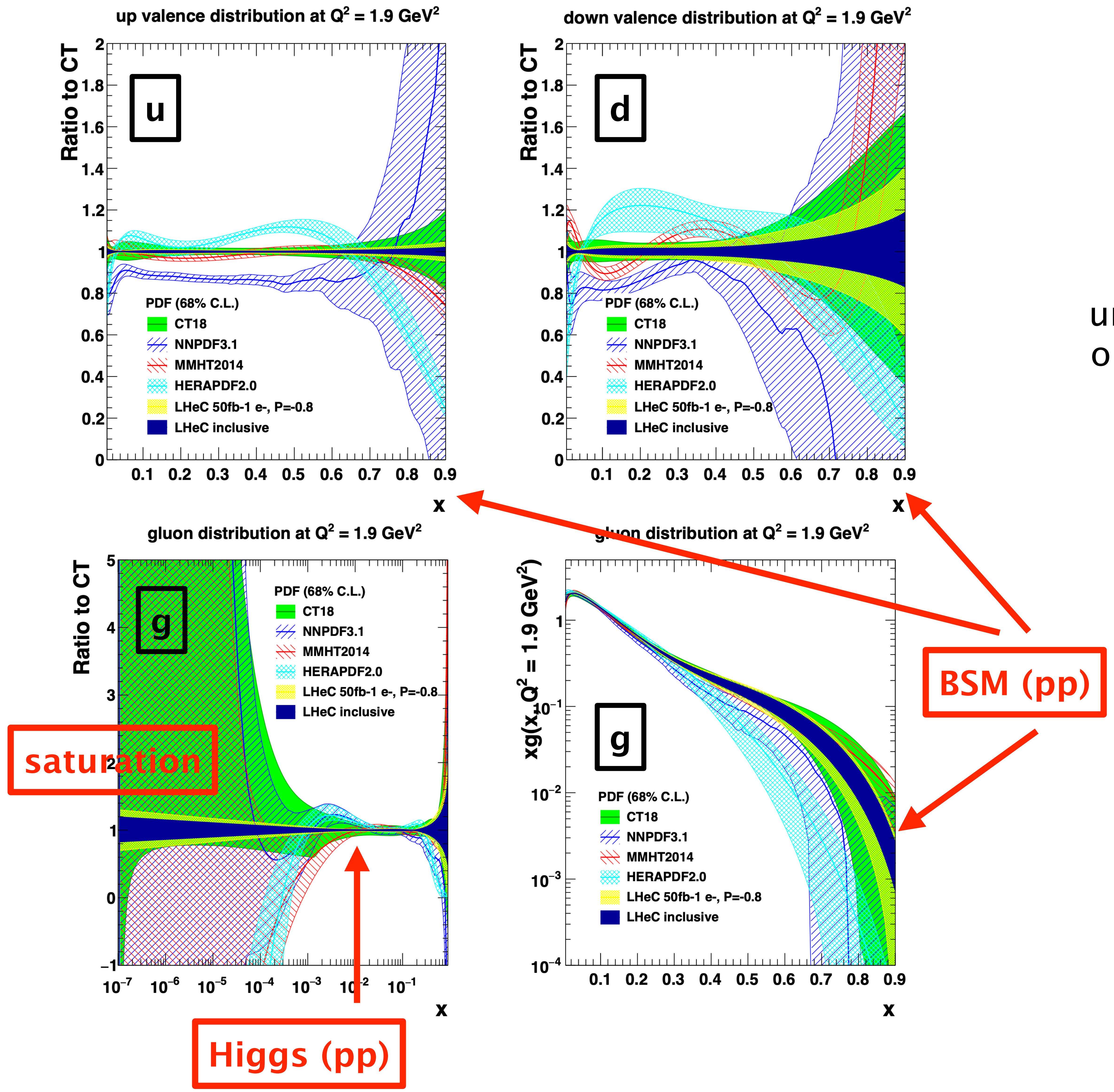

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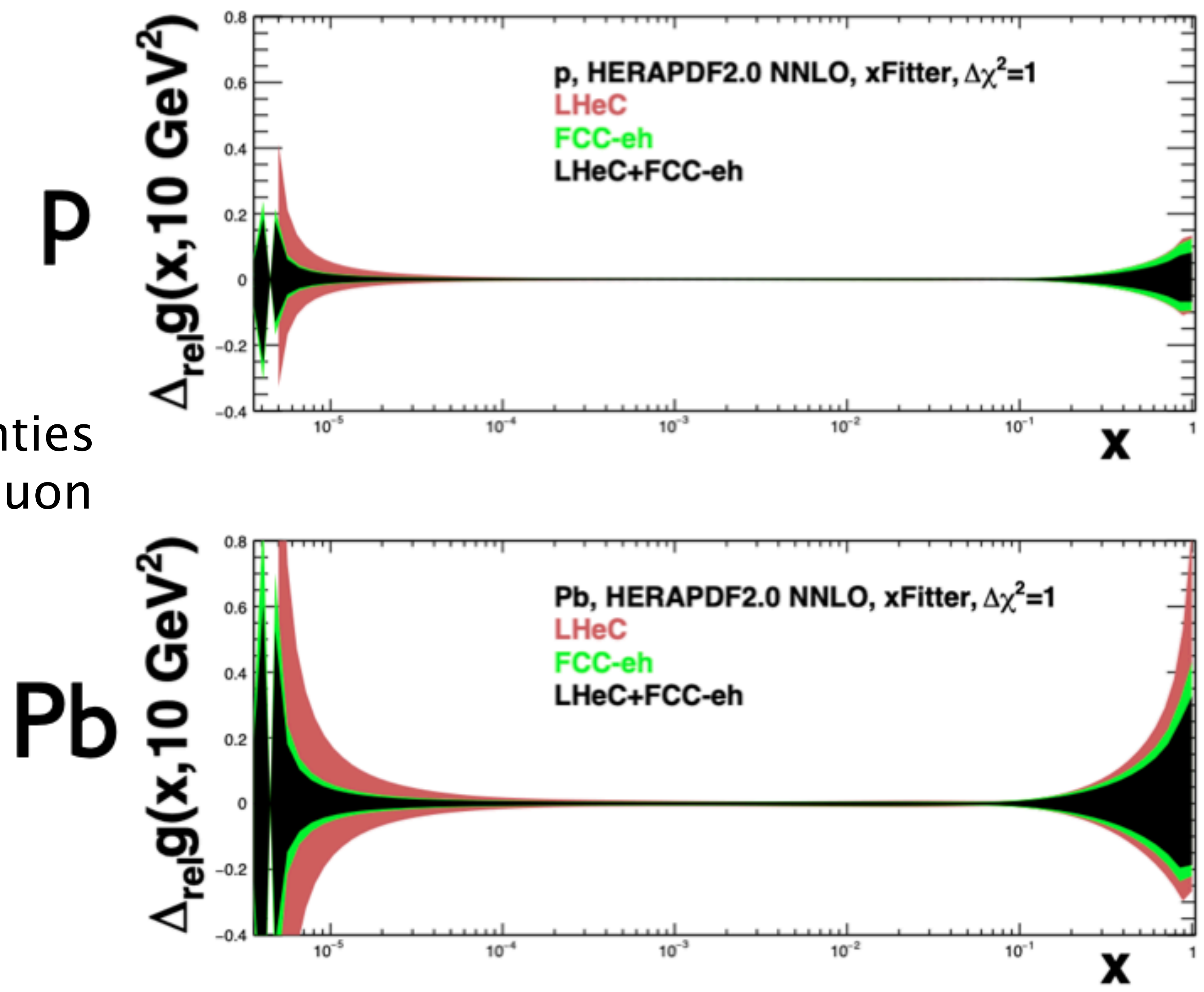

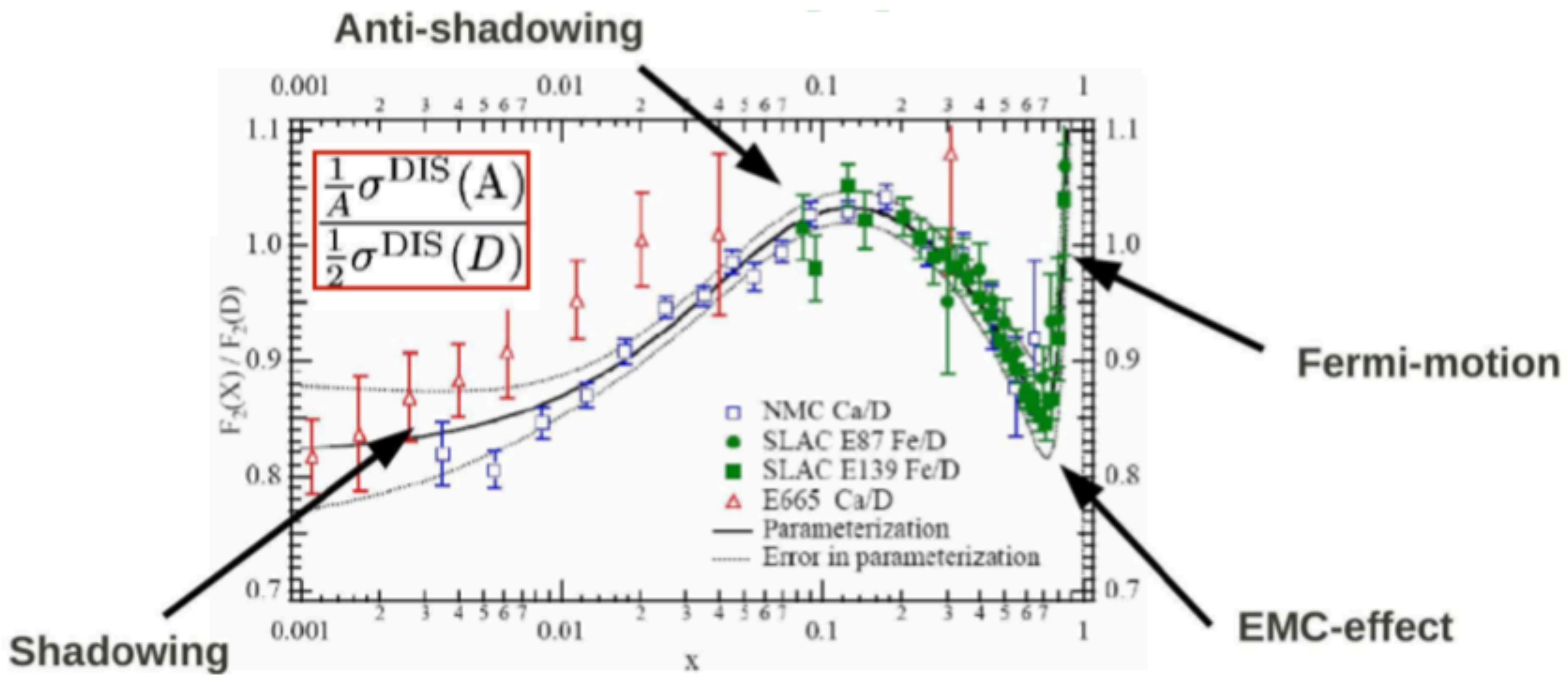

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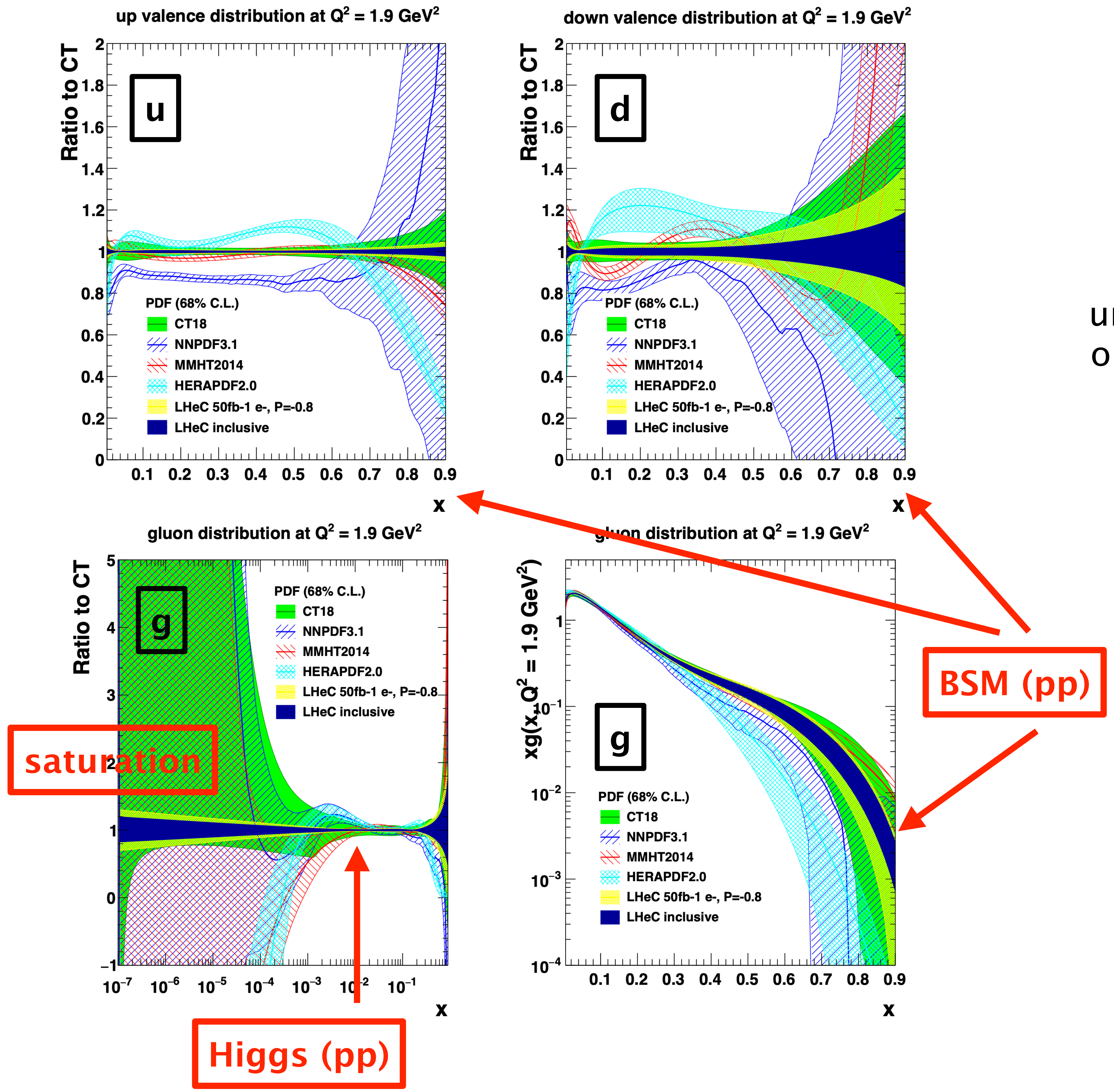

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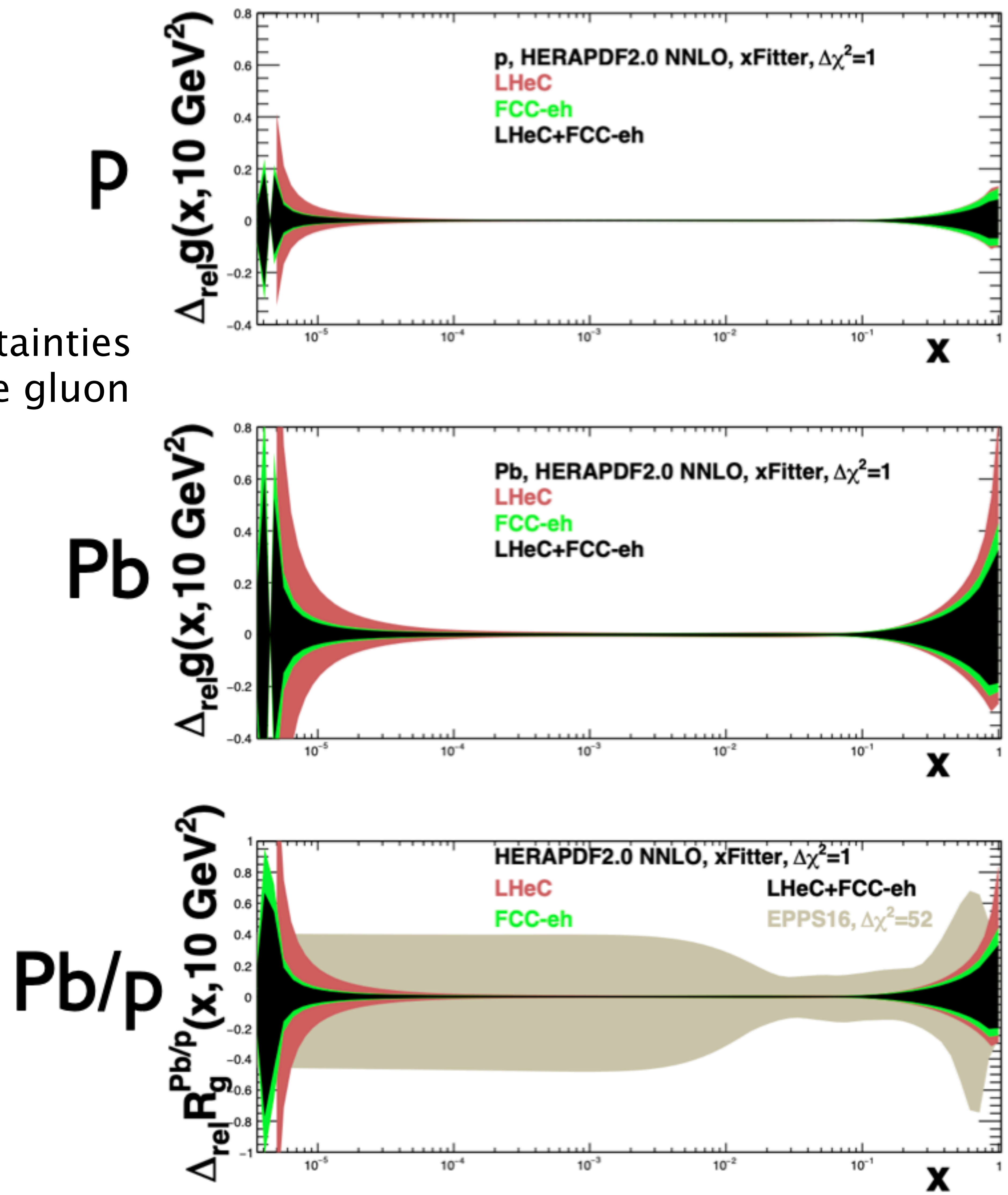
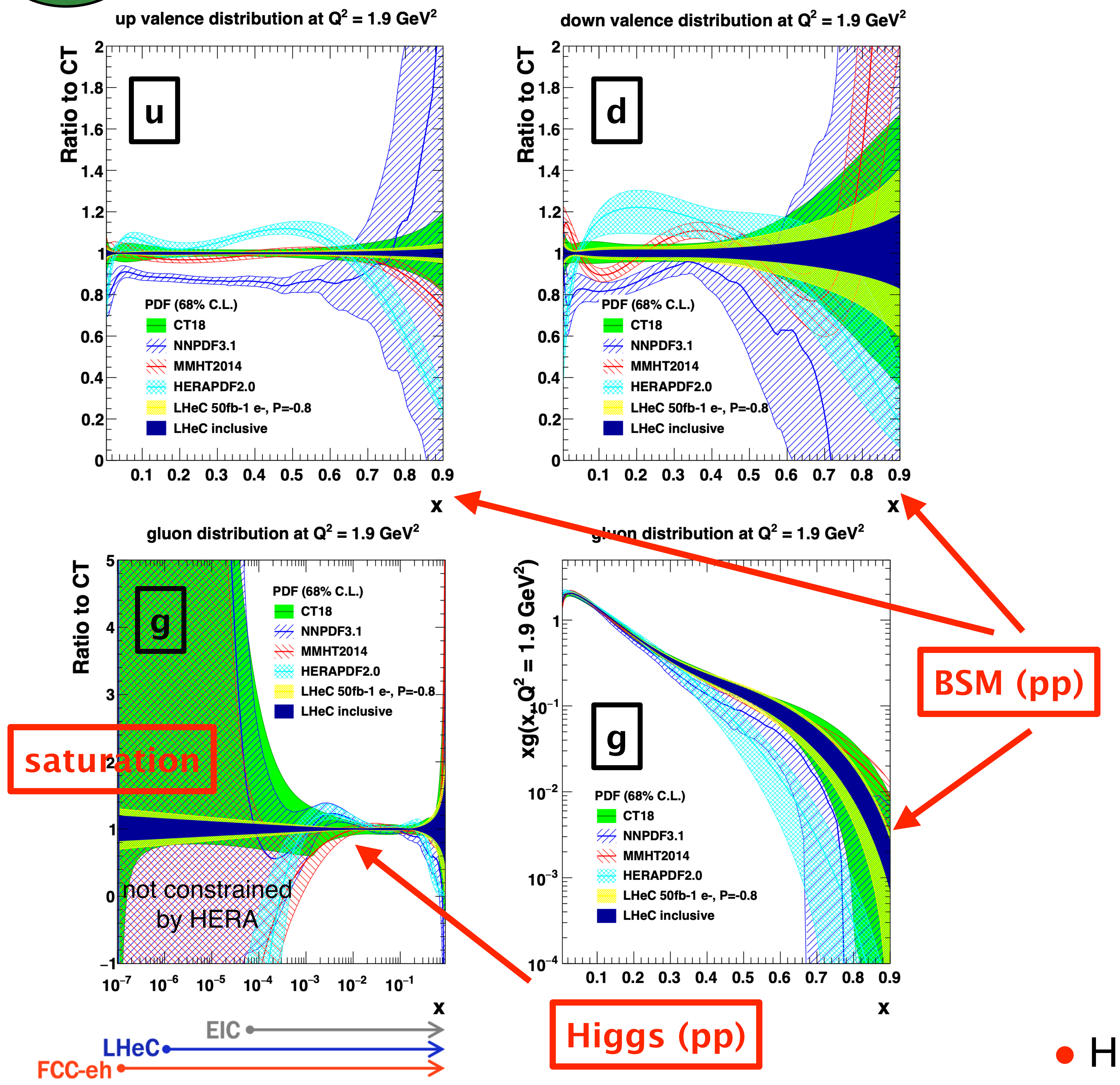
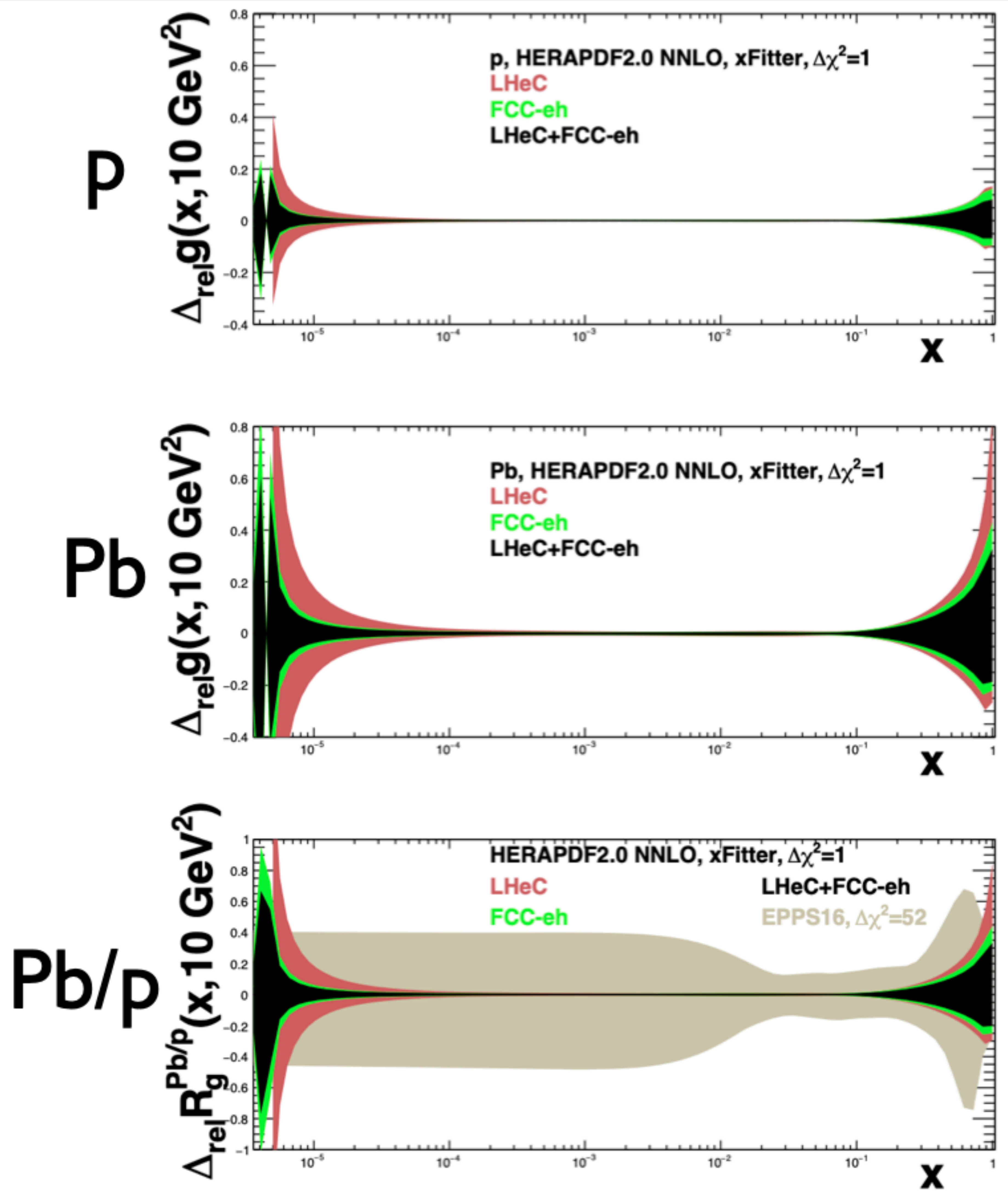


Parton Density Functions

PDF

QGP



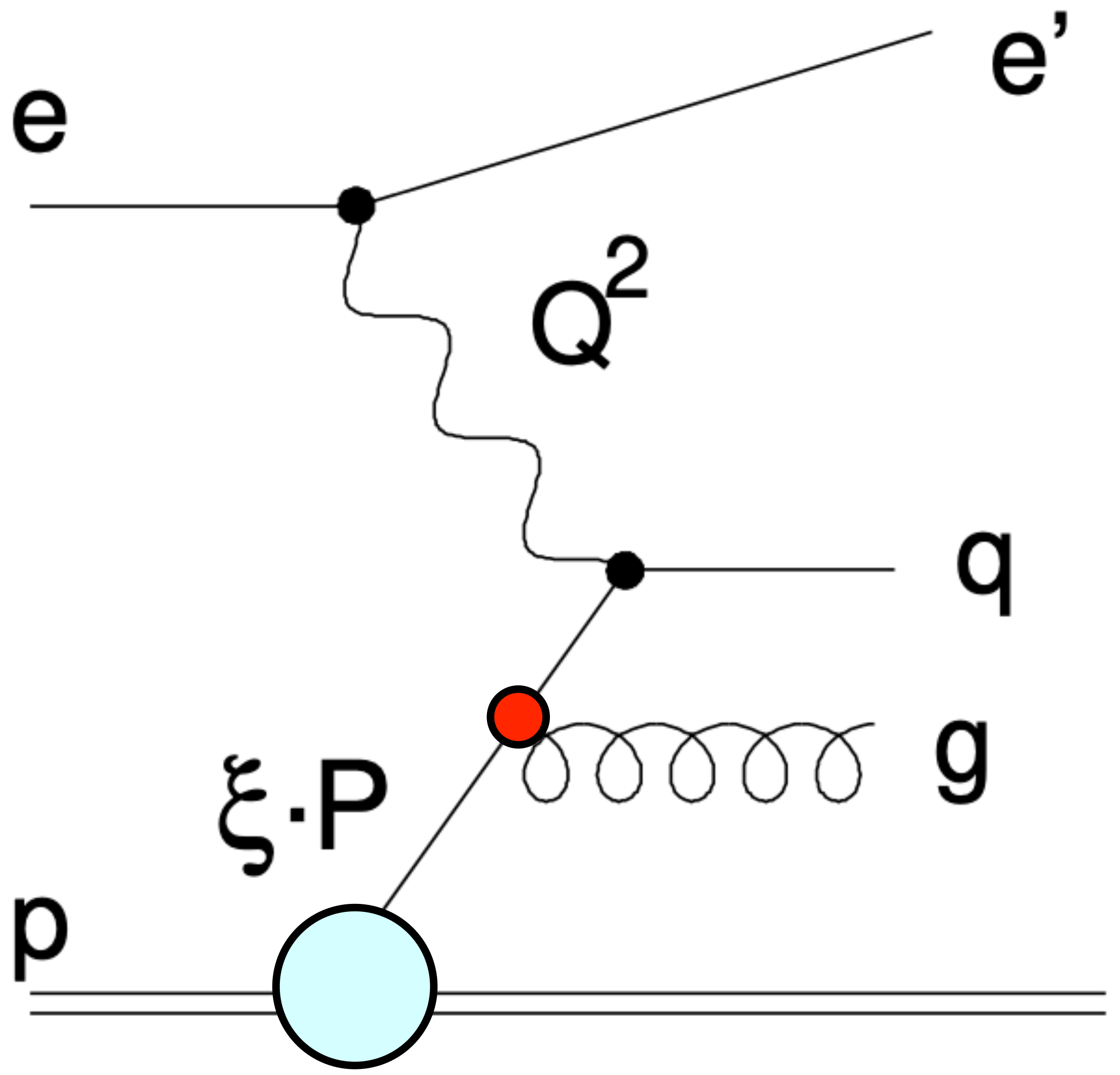


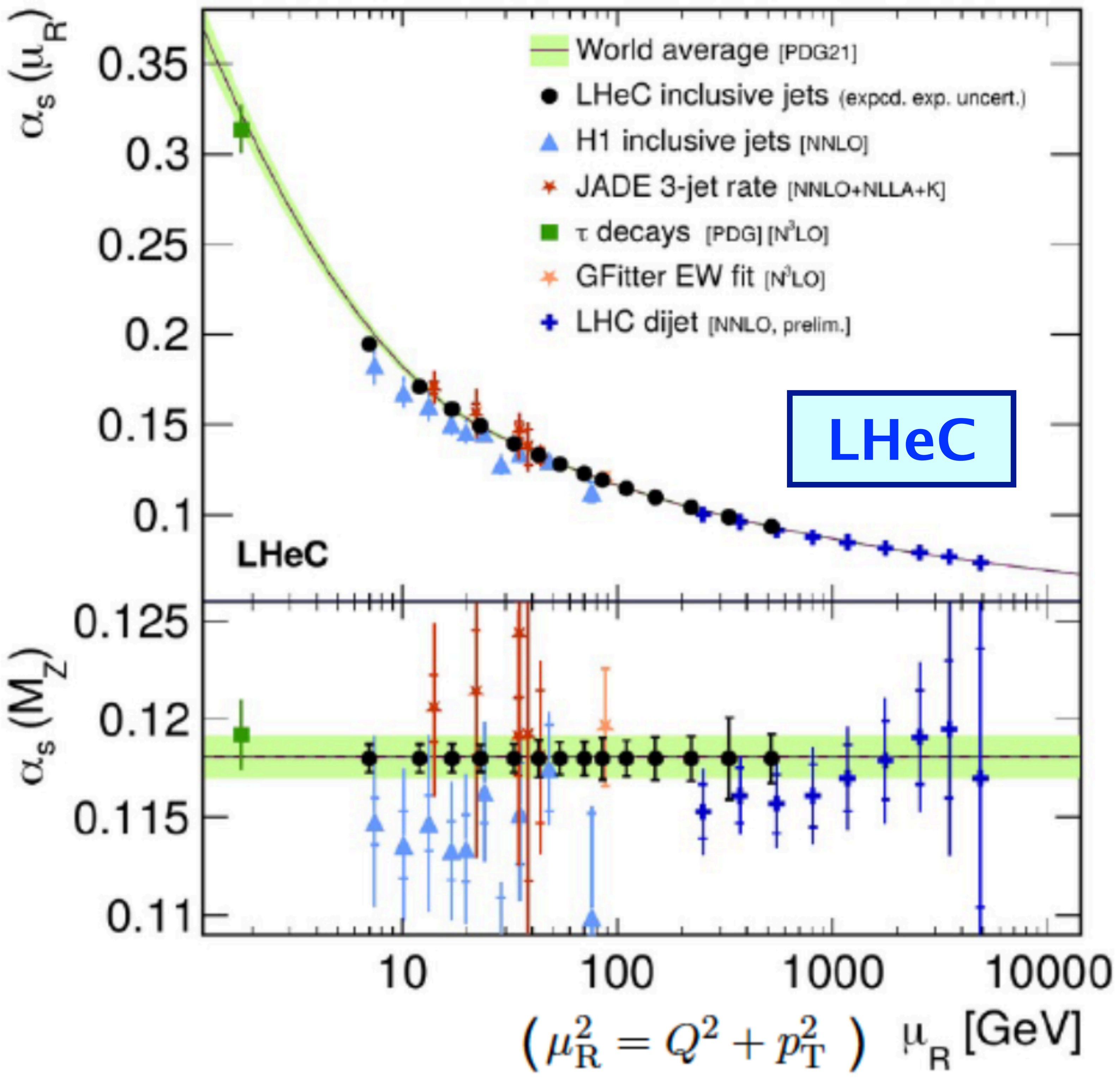
- High-energy and high-density measurements of heavy ion collisions

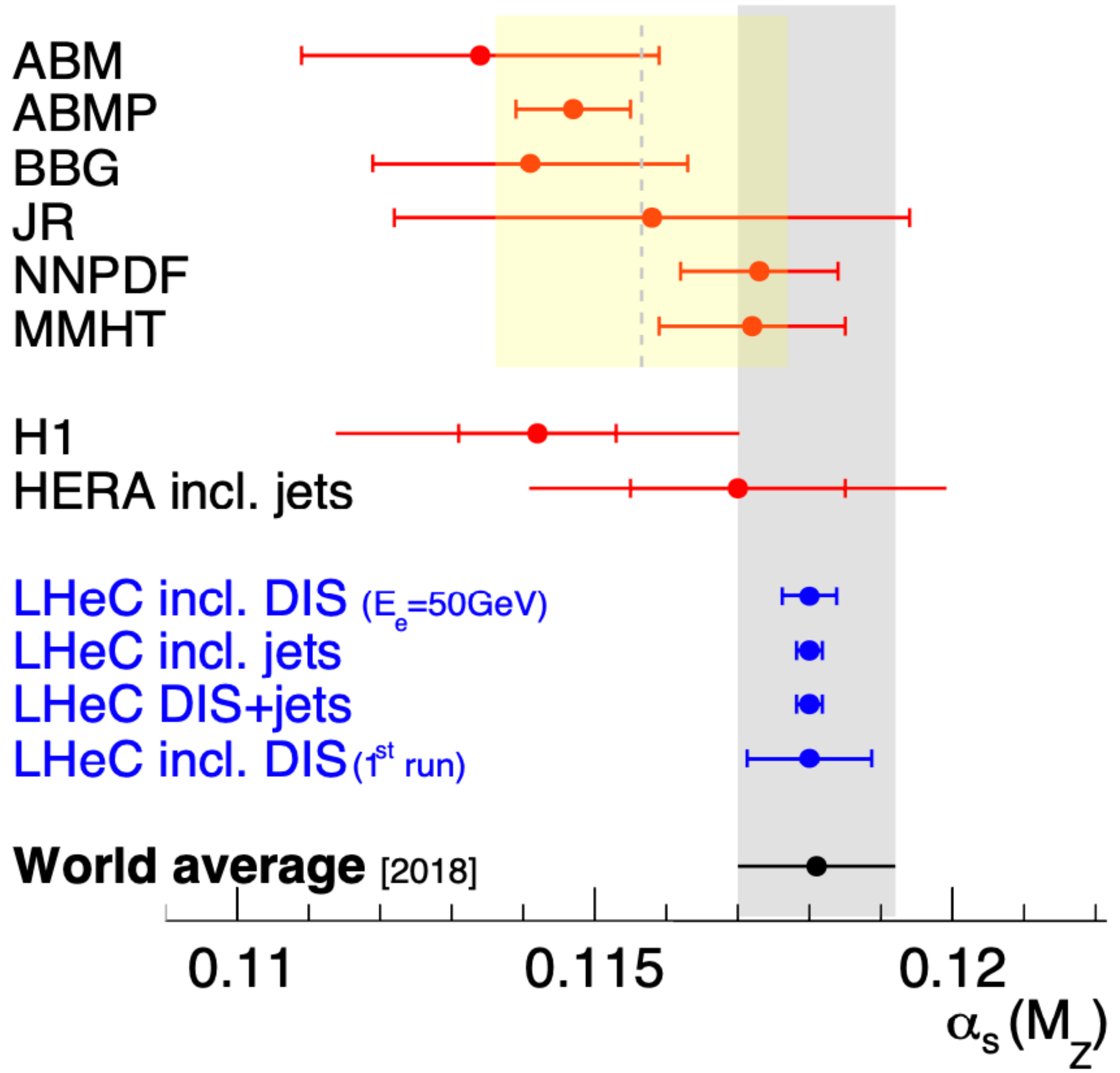
Determination of the strong coupling

QCD

- α_s is least known coupling constant







- α_s from fits to ep jet production

LHeC simultaneous PDF+α_s fit:

- $\Delta\alpha_s(m_Z) = \pm 0.00022_{(\text{exp.+PDF})}$
- $\Delta\alpha_s(m_Z) = \pm 0.00018$ (with ep jets)

LHeC CDRs and arXiv:2203.08271

Achievable precision: $\mathcal{O}(0.1\%)$ - **x5-10** better than today

→ **unprecedented precision**

Determination of the strong coupling

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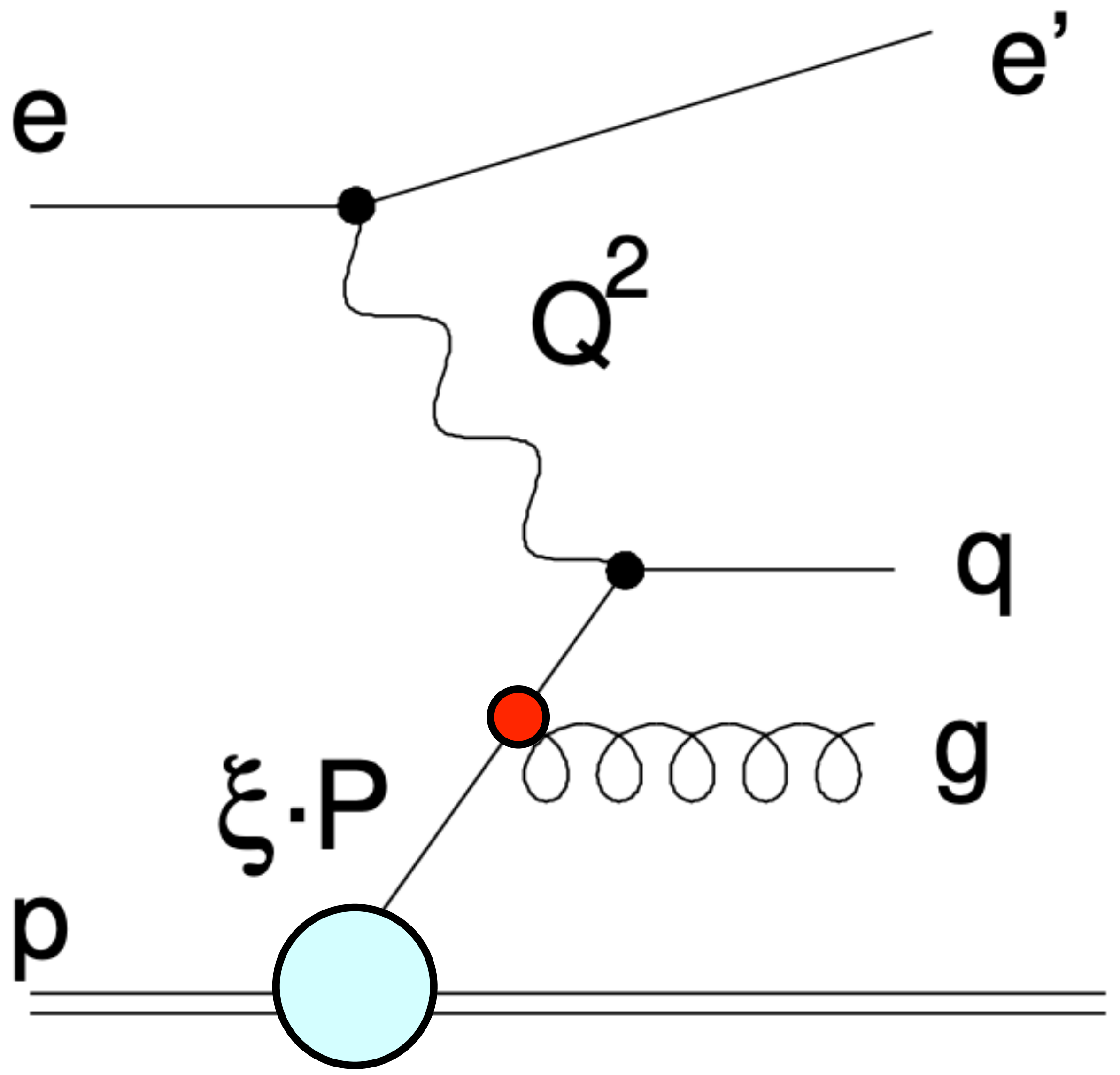

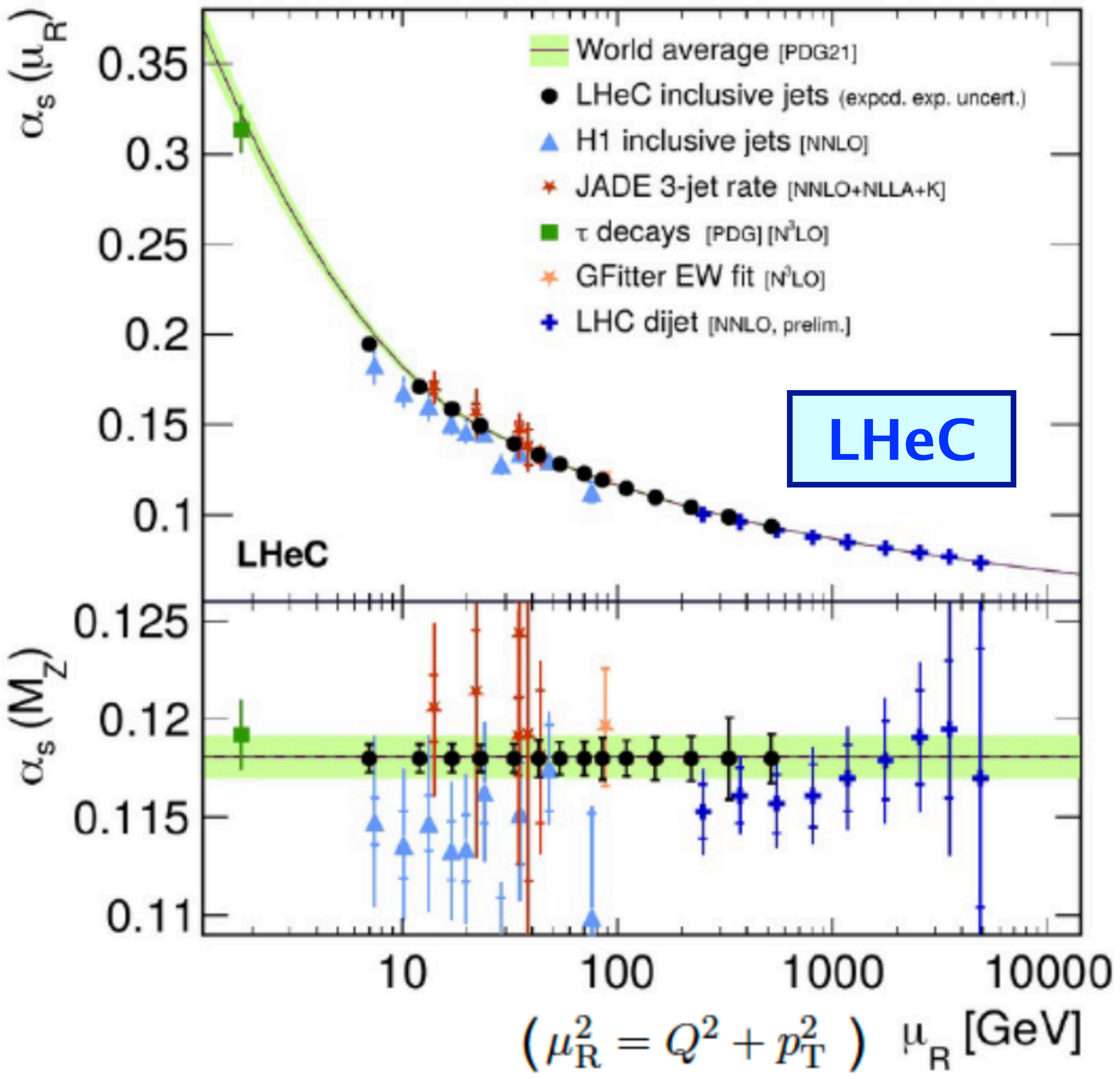

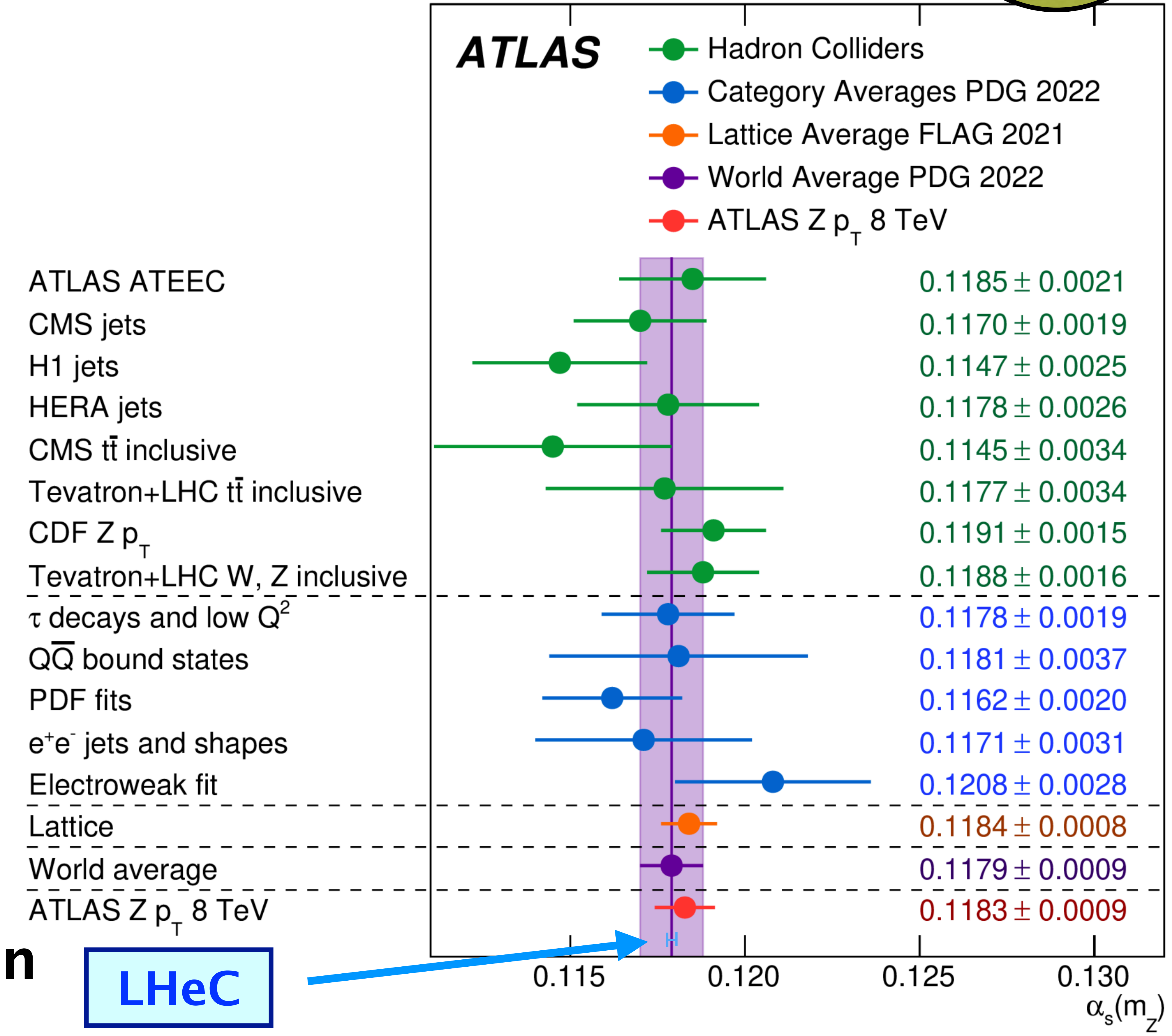

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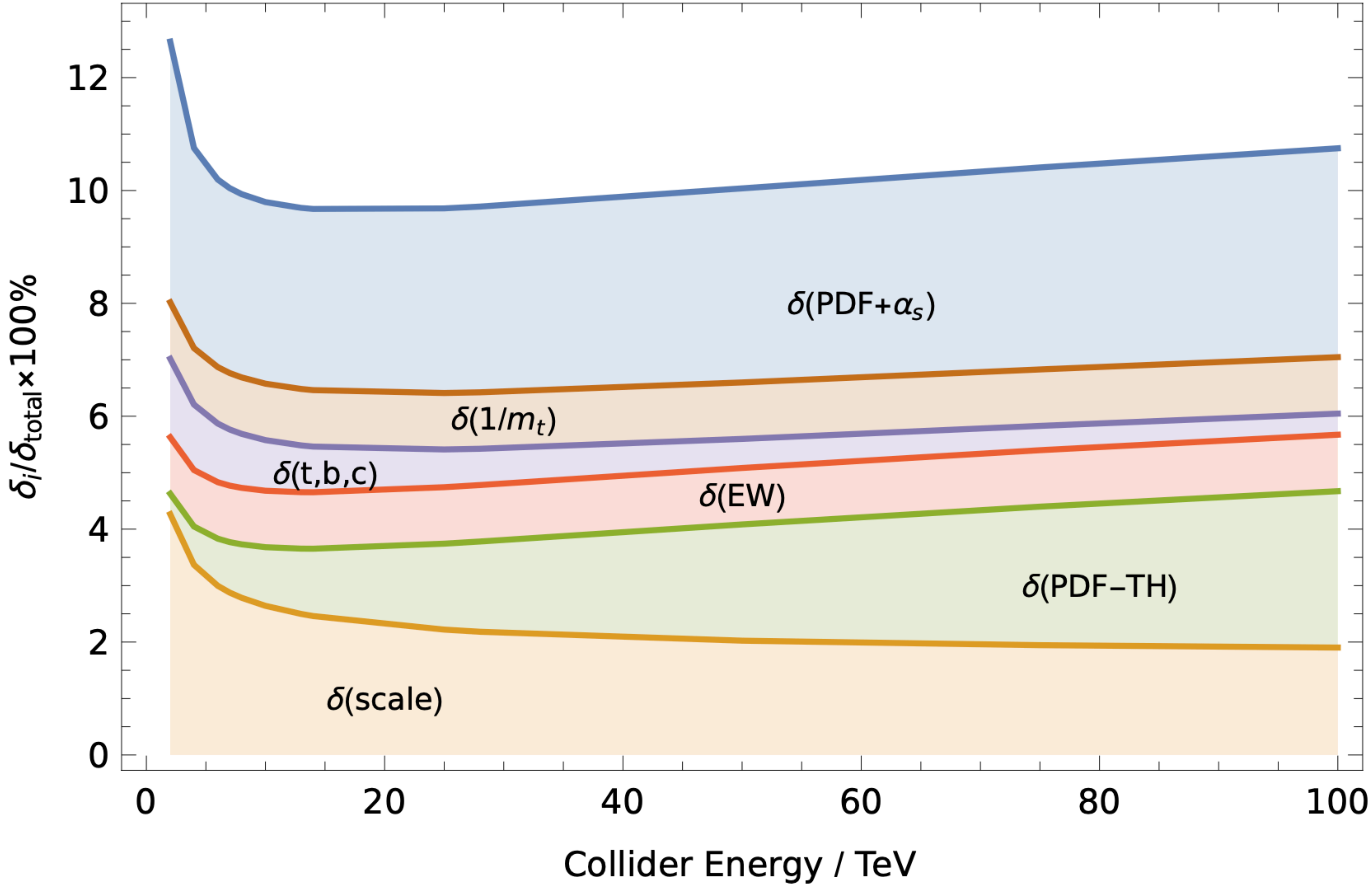
LHeC CDRs and arXiv:2203.08271

Achievable precision: $\mathcal{O}(0.1\%)$ - **x5-10** better than today

→ considerable improvement of world average

Uncertainties for inclusive Higgs boson production cross section

arXiv:1902.00134 [hep-ph]



imprecise knowledge of the strong coupling constant and of parton distribution functions combined in quadrature

Effects due to finite quark masses neglected in QCD corrections beyond NLO

Missing higher-order effects of electroweak and mixed QCD-electroweak corrections at and beyond $O(\alpha_S \alpha)$

Mismatch in the perturbative order of the parton distribution functions (PDF) evaluated at NNLO and the perturbative QCD cross sections evaluated at N^3LO

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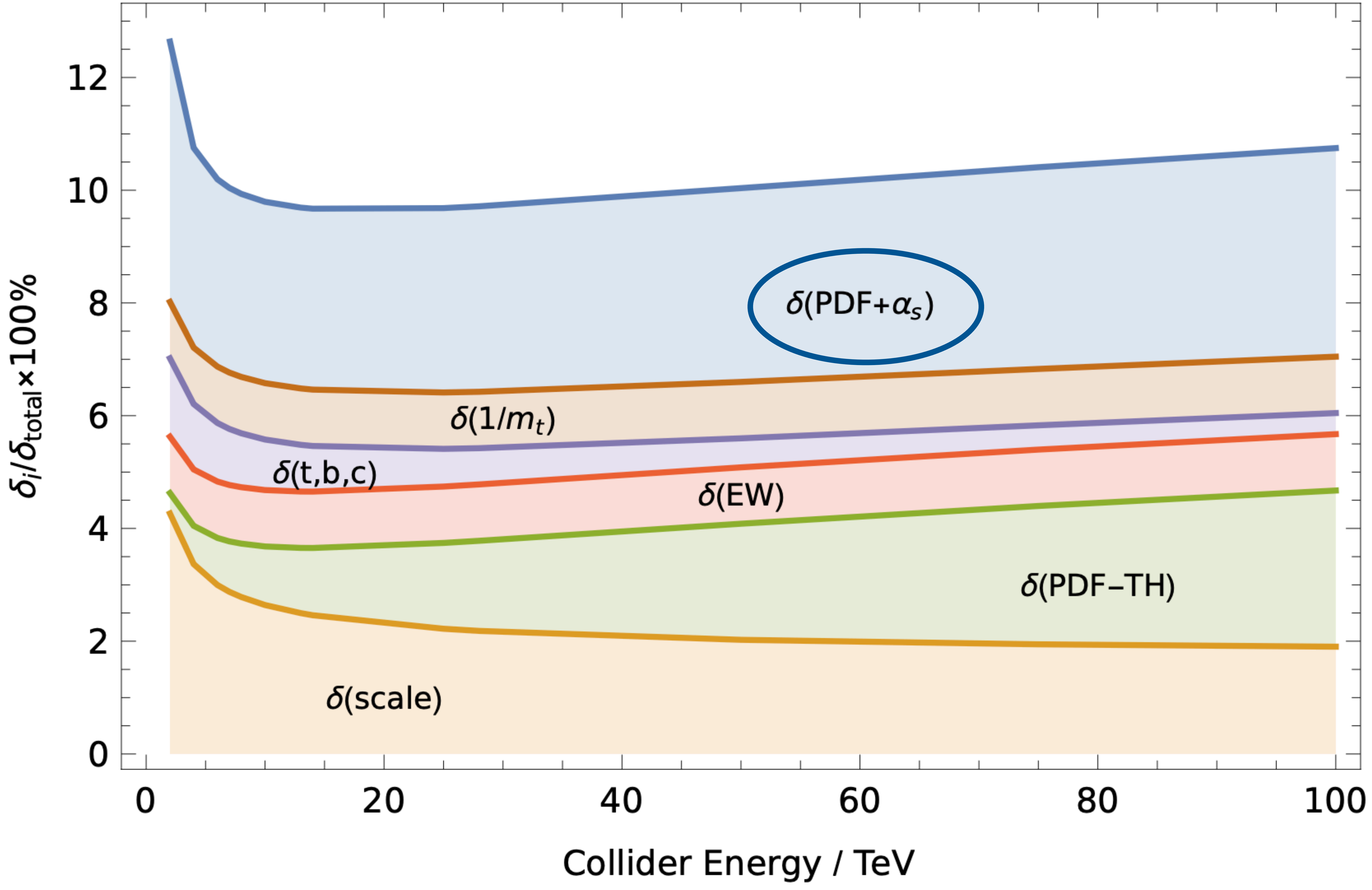

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Missing higher-order effects of QCD corrections beyond N^3LO

High Mass Searches at the LHC via EFT

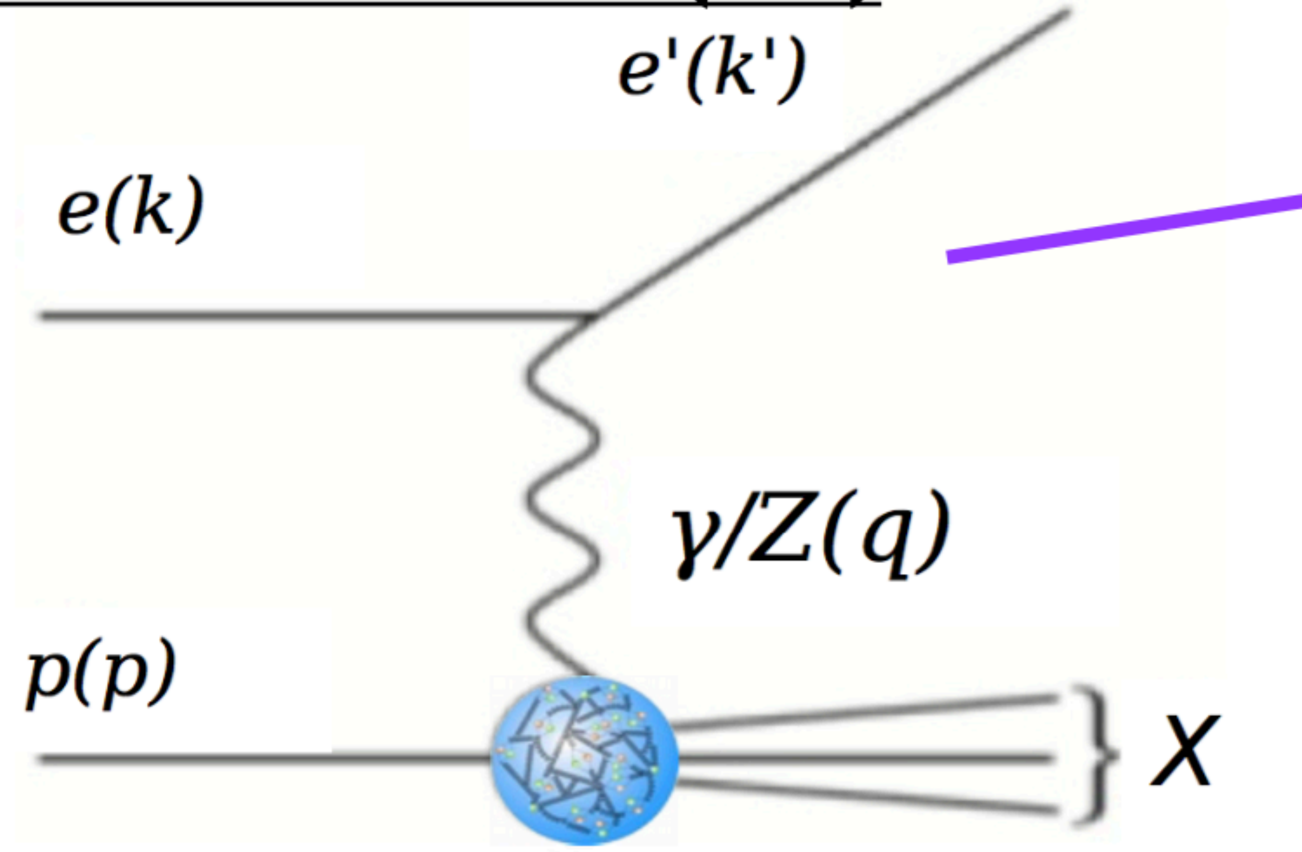
$$\mathcal{L}_{\rm CI} = \frac{g^2}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma_\mu q_i)(\bar{\ell}_i\gamma^\mu\ell_i),$$

Model	ATLAS (Ref. [702])	HL-LHC	
	$\mathcal{L} = 36\,\mathrm{fb}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (LHeC)
LL (constr.)	28 TeV	58 TeV	96 TeV
LL (destr.)	21 TeV	49 TeV	77 TeV
RR (constr.)	26 TeV	58 TeV	84 TeV
RR (destr.)	22 TeV	61 TeV	75 TeV
LR (constr.)	26 TeV	49 TeV	81 TeV
LR (destr.)	22 TeV	45 TeV	62 TeV

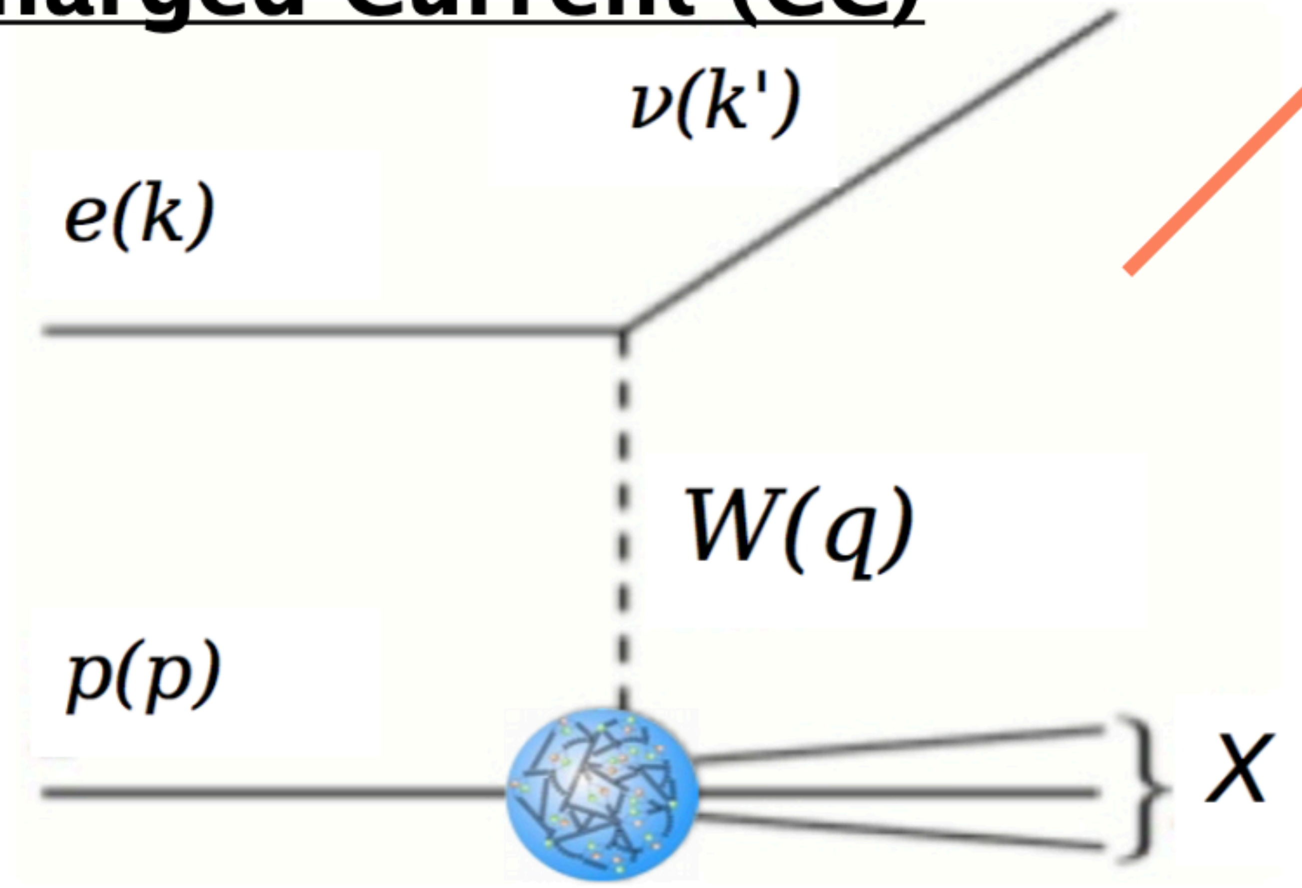
→ **considerable improvement (up to factor 1.7) in reach of new physics mass scale using LHeC PDFs and α_s**

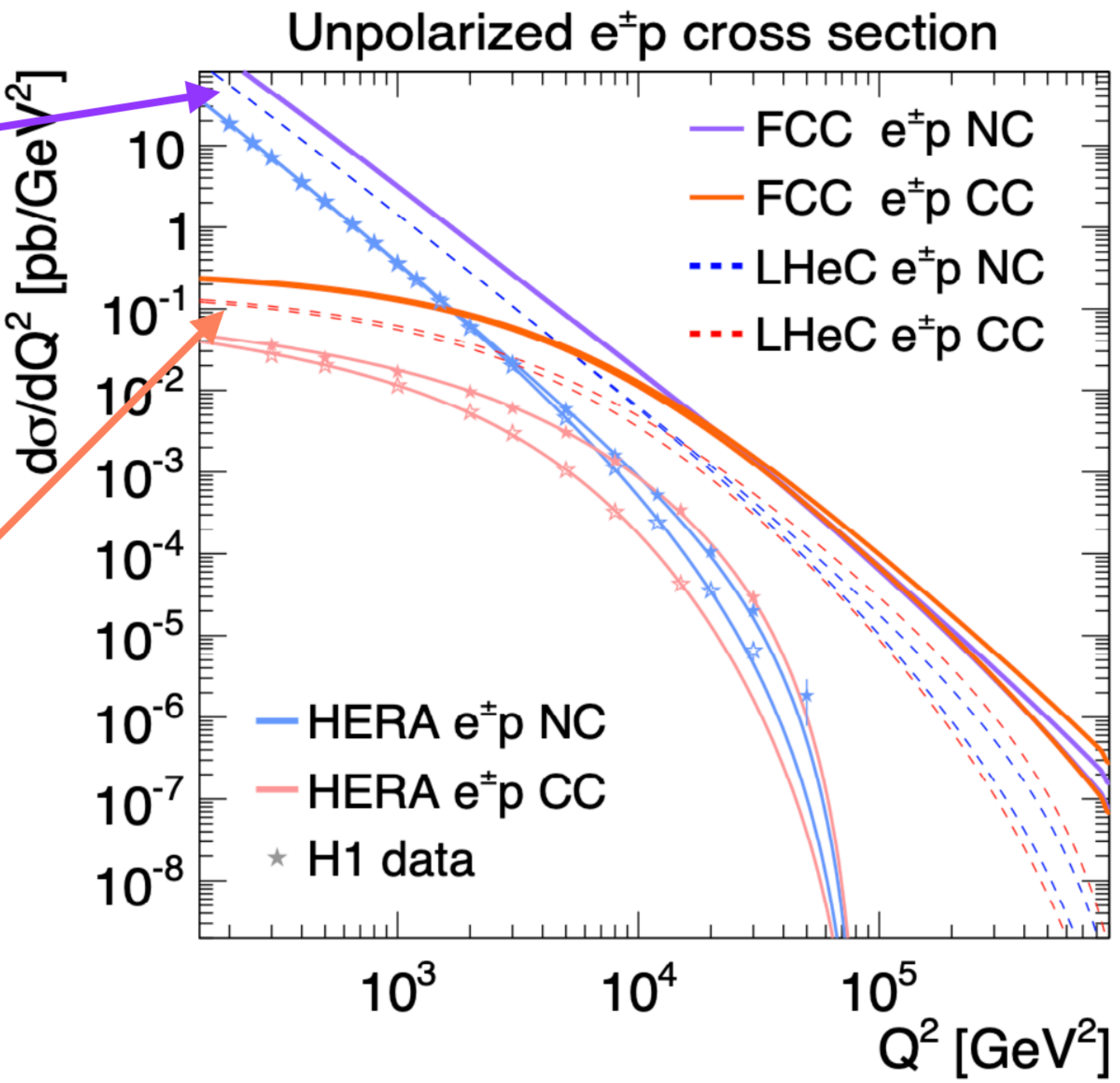
Deep Inelastic Scattering and EKW observables

Neutral Current (NC)



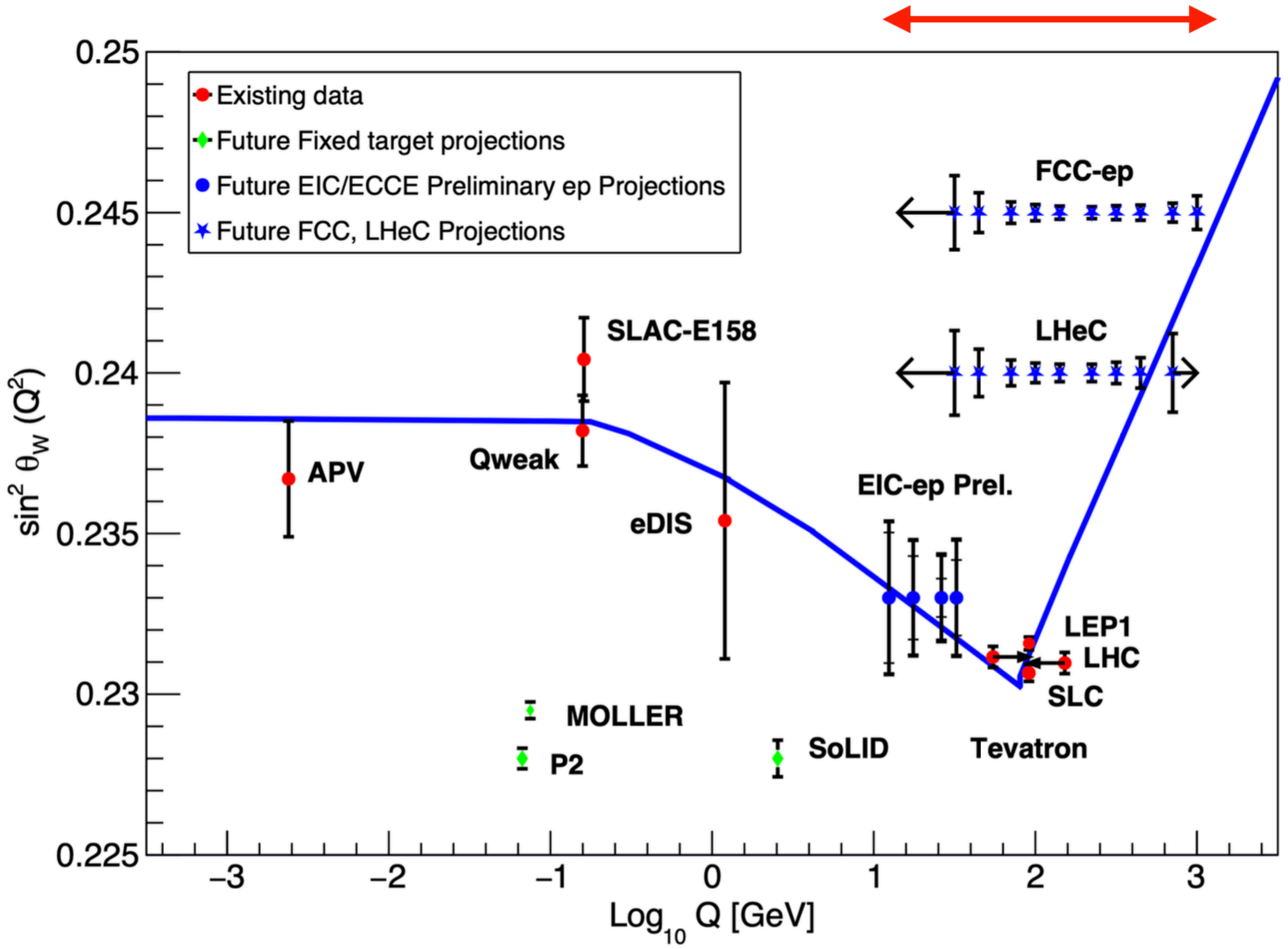
Charged Current (CC)





→ **LHeC/FCC-eh are unique facilities for testing EW theory:**
NC+CC, two e-beam charge and polarisation states, p or isoscalar targets

Effective electroweak mixing angle



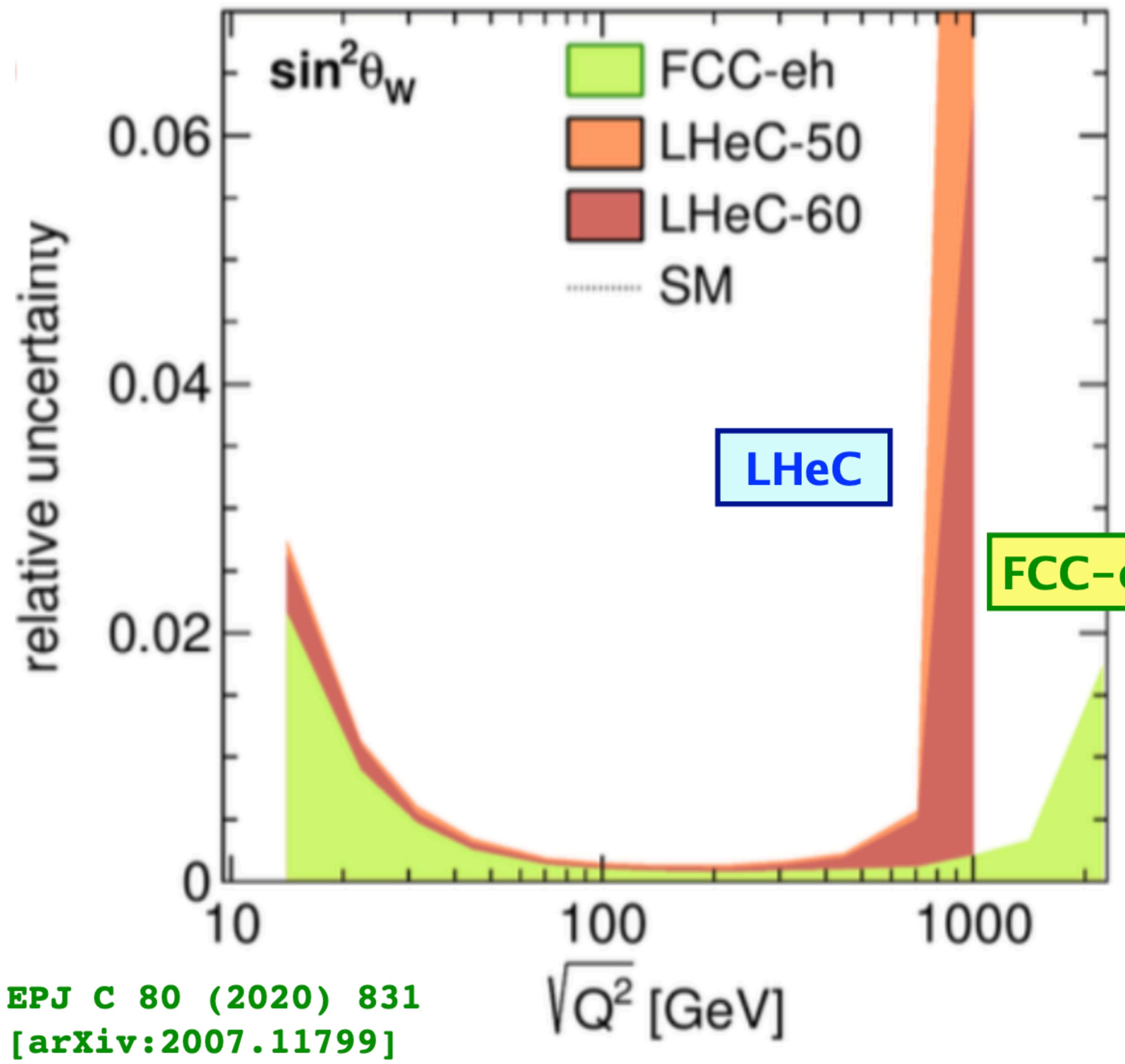
FCC-eh

LHeC

→ **probe large range of scale dependence**

arXiv:2203.06237

NC+CC DIS

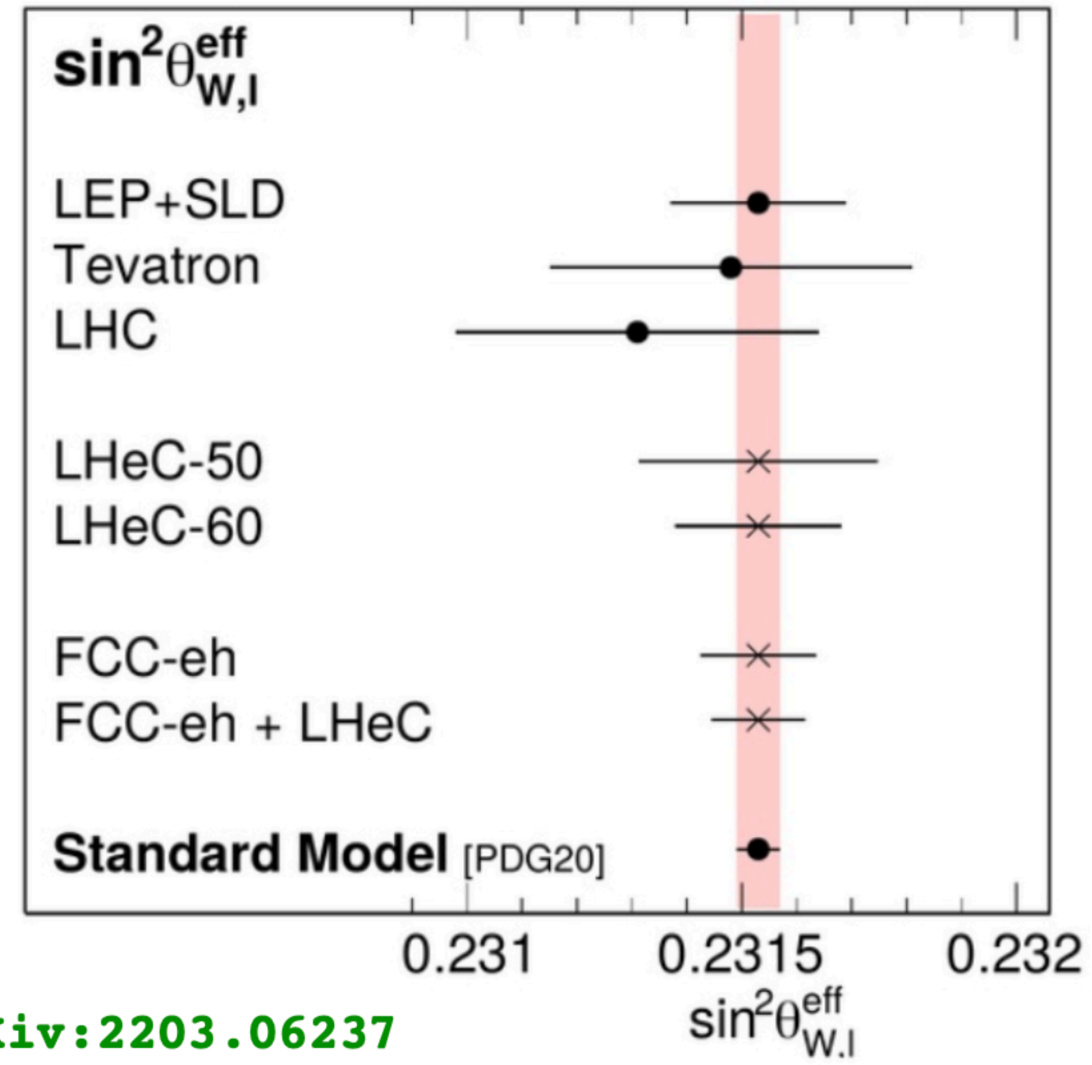


EPJ C 80 (2020) 831
[arXiv:2007.11799]

→ **probe large range of scale dependence**

$\Delta\sin^2\theta_w$ (FCC-eh) = ±0.00011
= ±0.00010$_{(exp)}$ ±0.00004$_{(PDF)}$

→ **precision per mille level**



arXiv:2203.06237

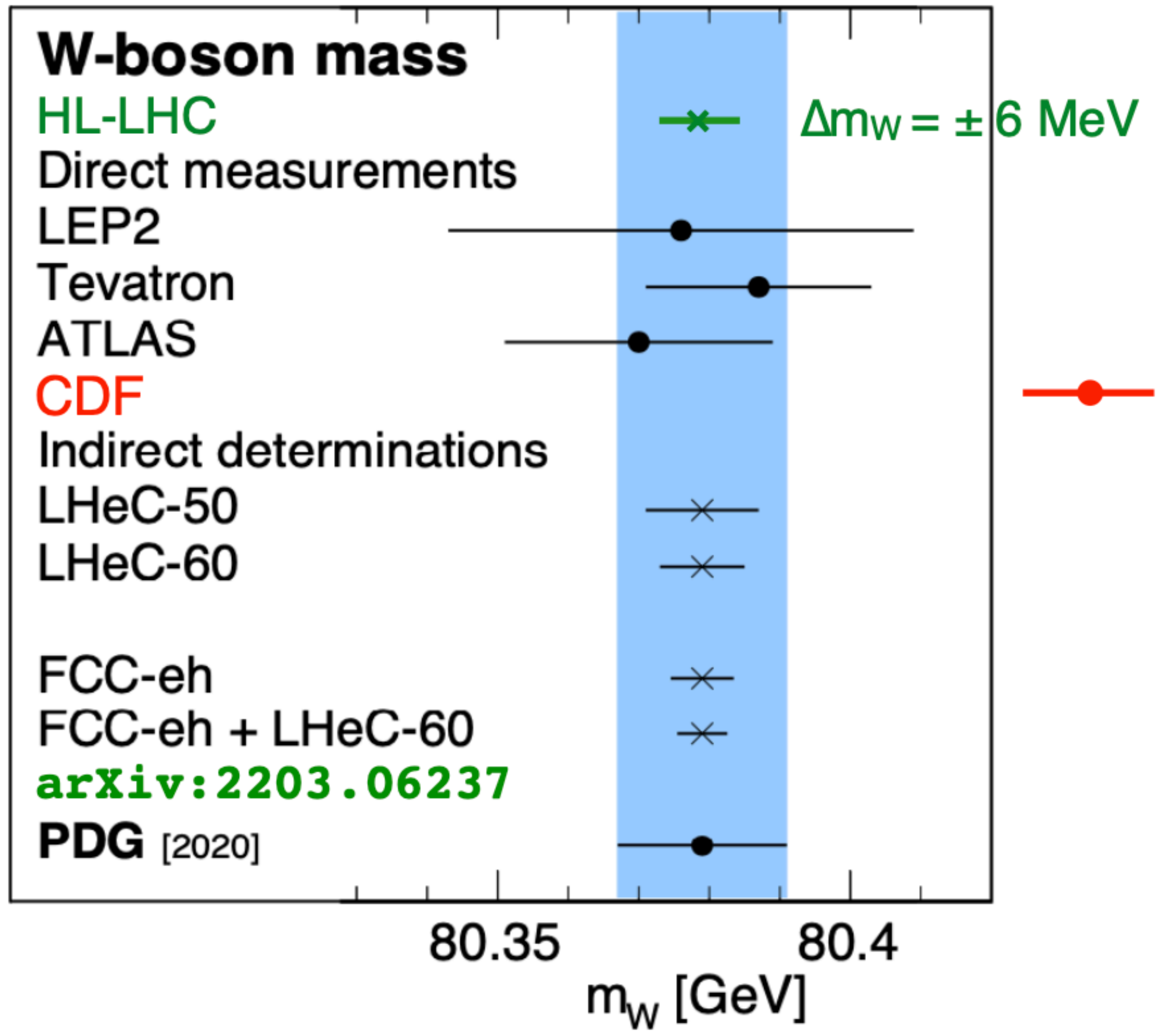
on-shell definition $\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$

$\Delta m_W = \pm 4.5$ MeV

(includes PDF uncertainty of about ±3.6 MeV)

Precision of W mass and effective electroweak mixing angle

W mass uncertainty prospects @ HL-LHC



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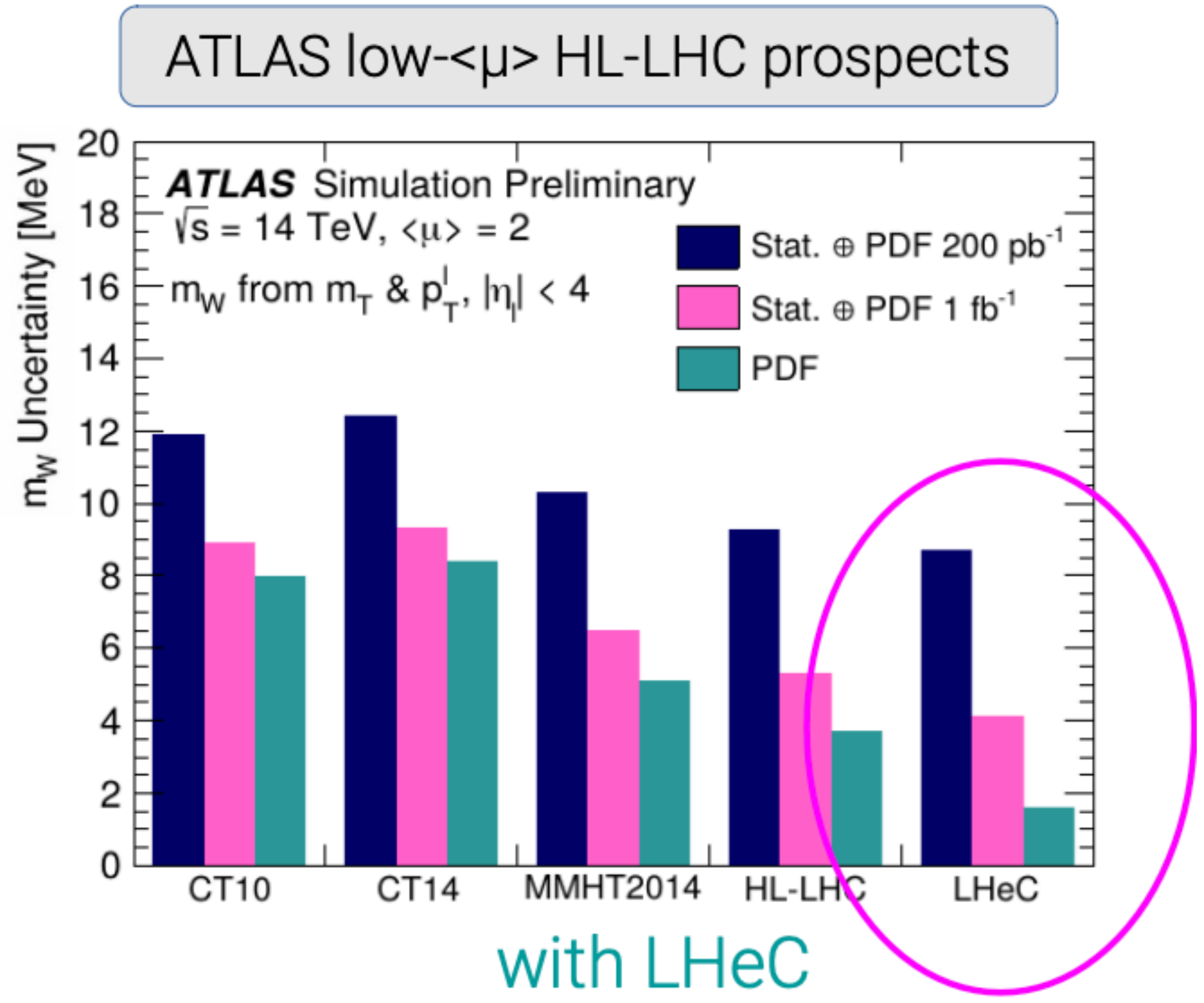

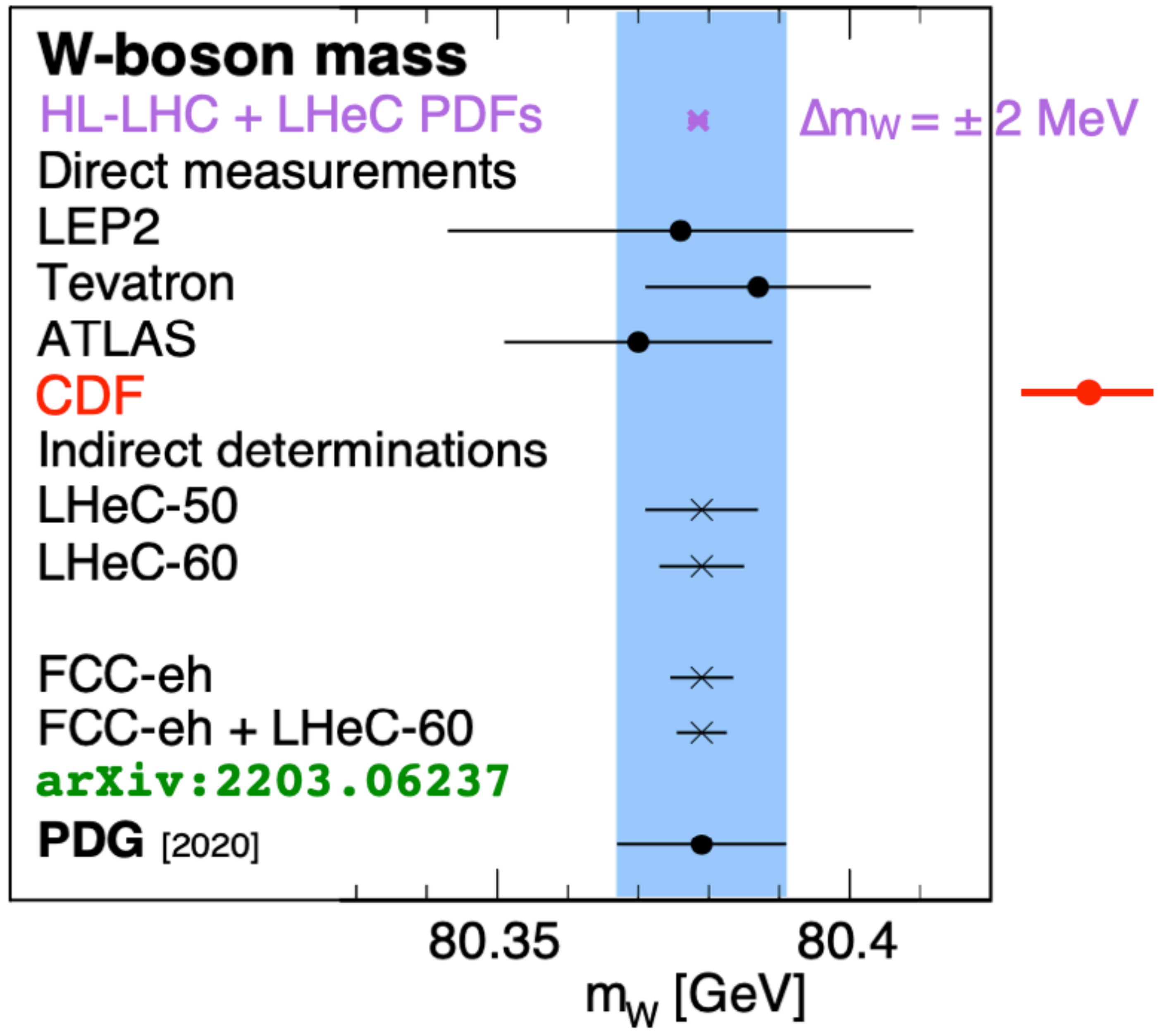

Precision of W mass and effective electroweak mixing angle

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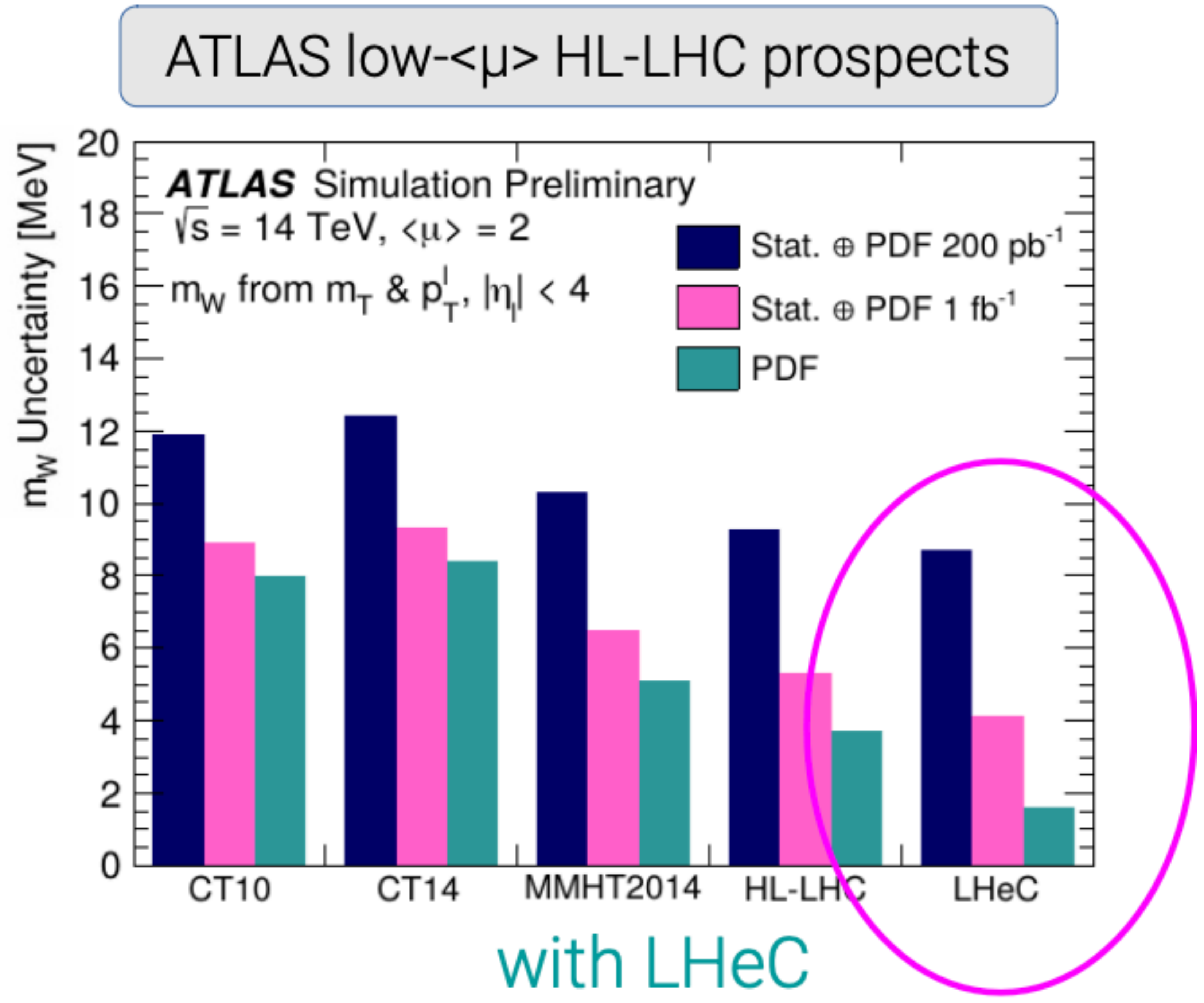
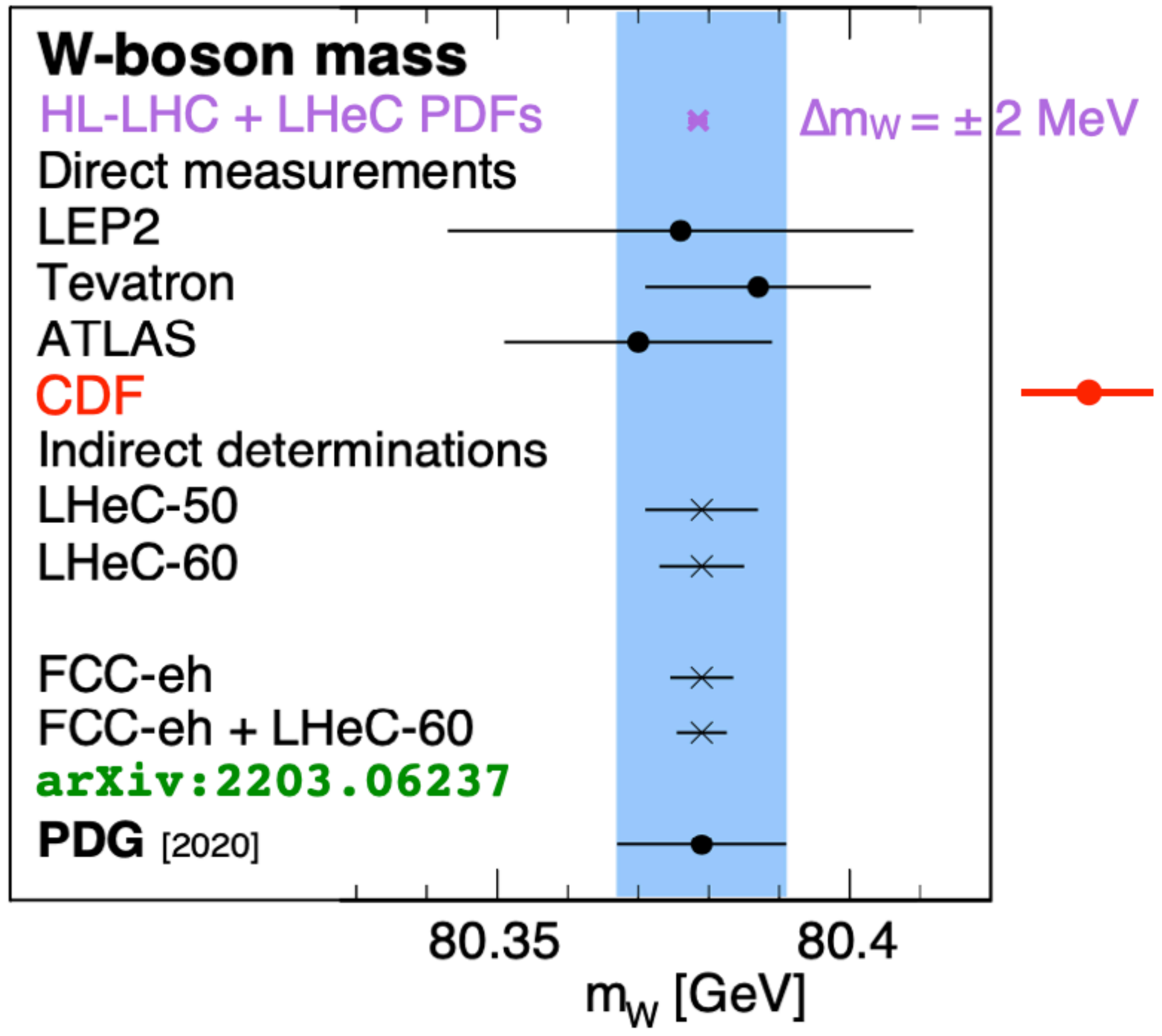
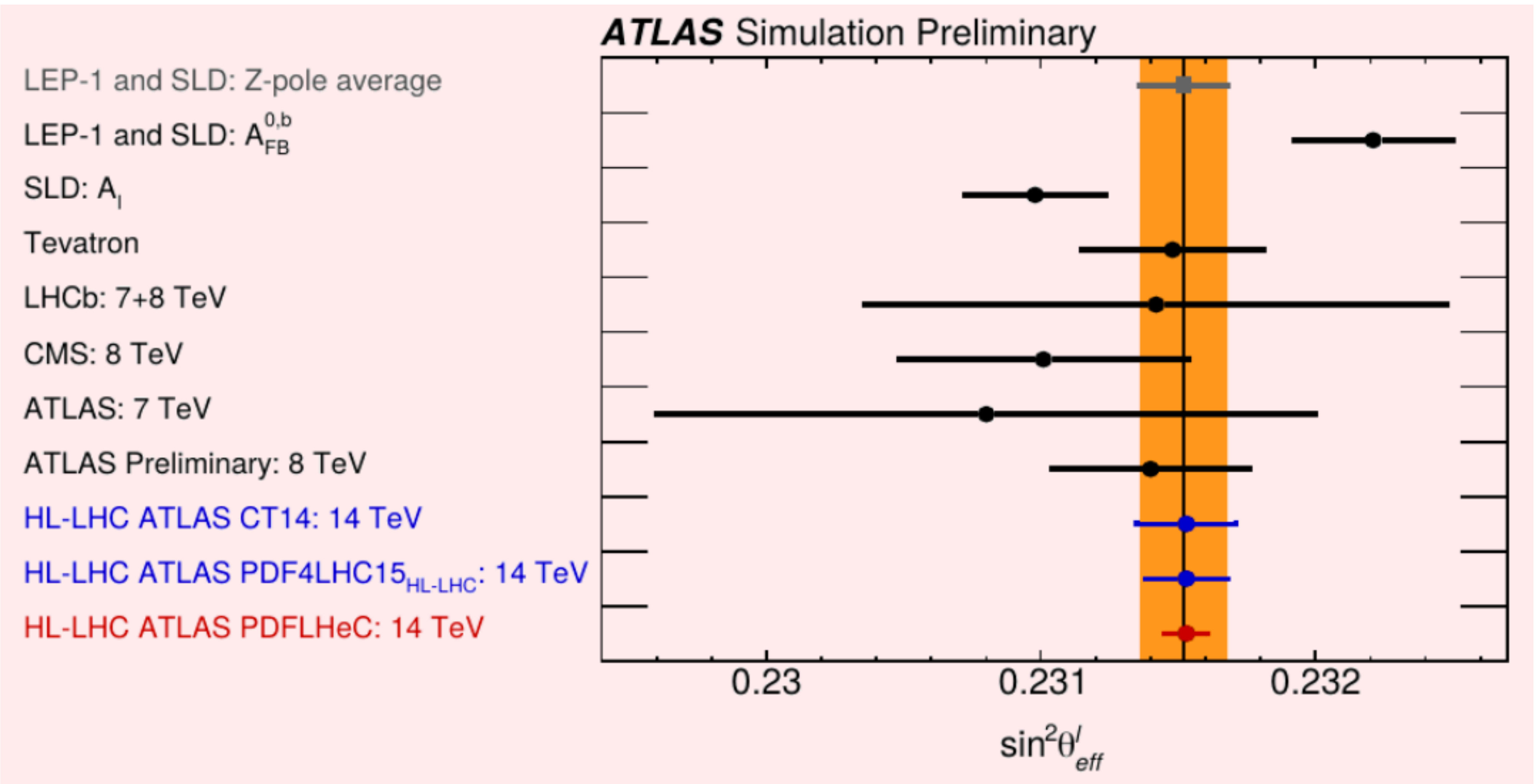
$\sin^2\Theta_W$ prospects @ HL-LHC







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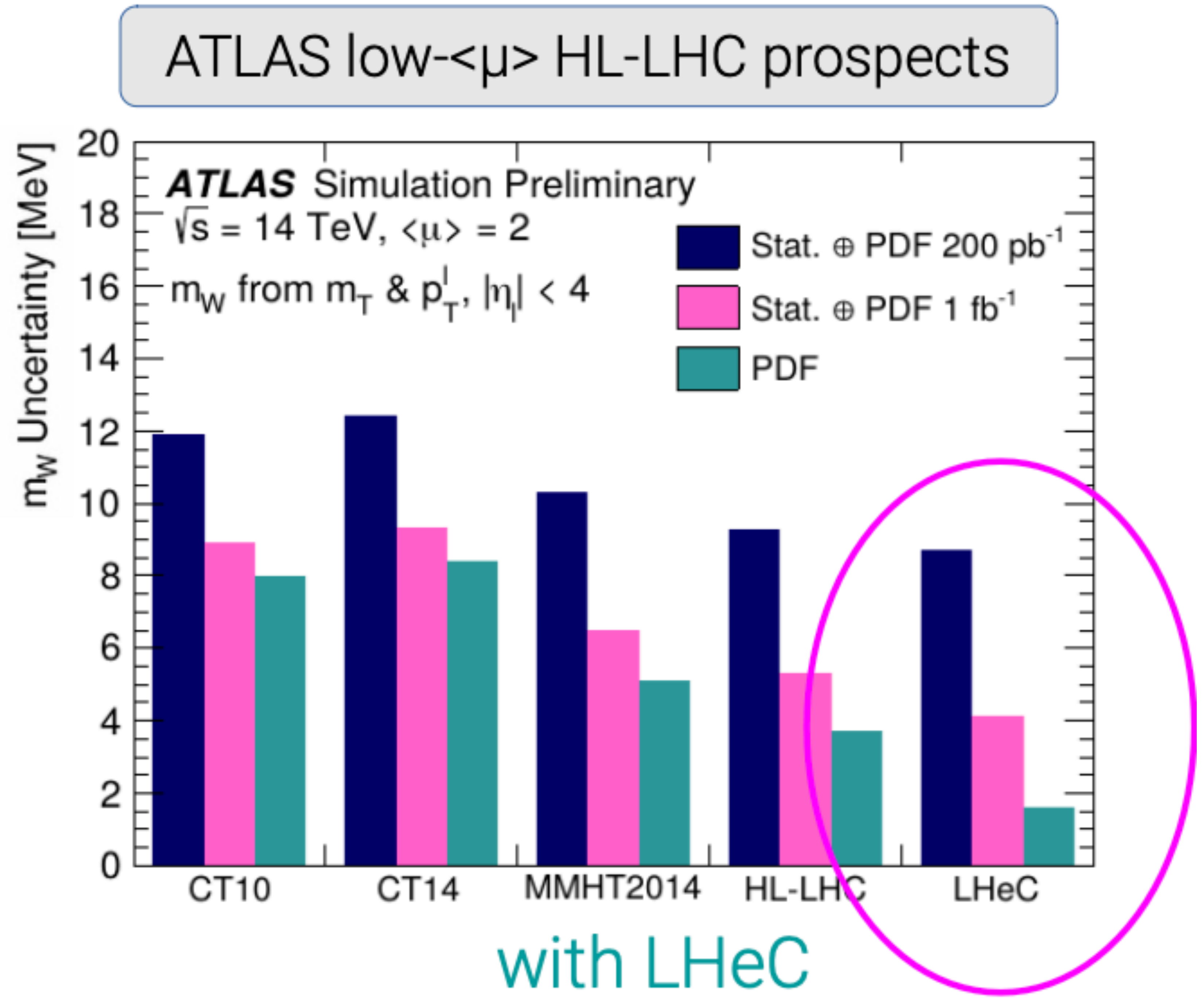
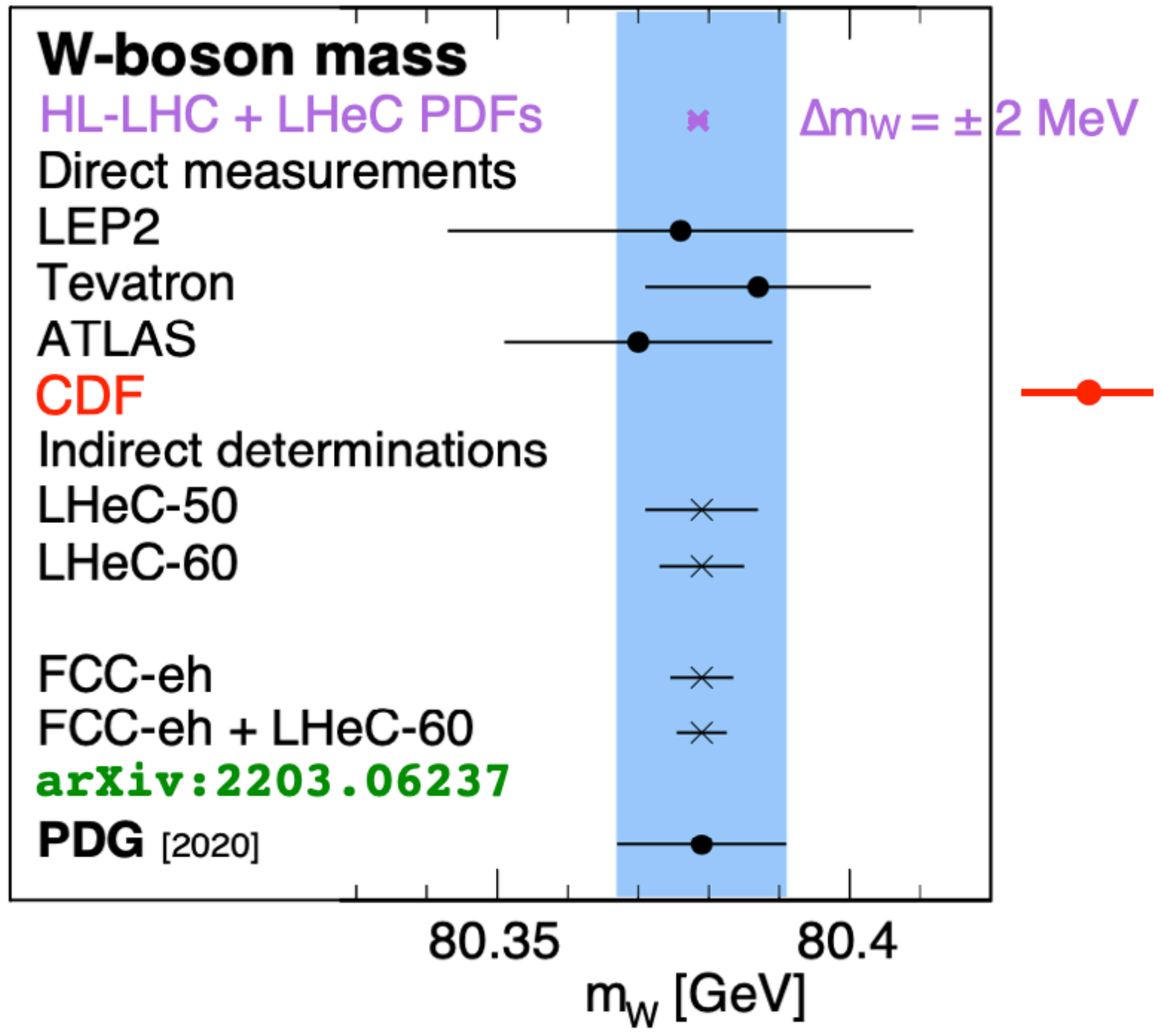
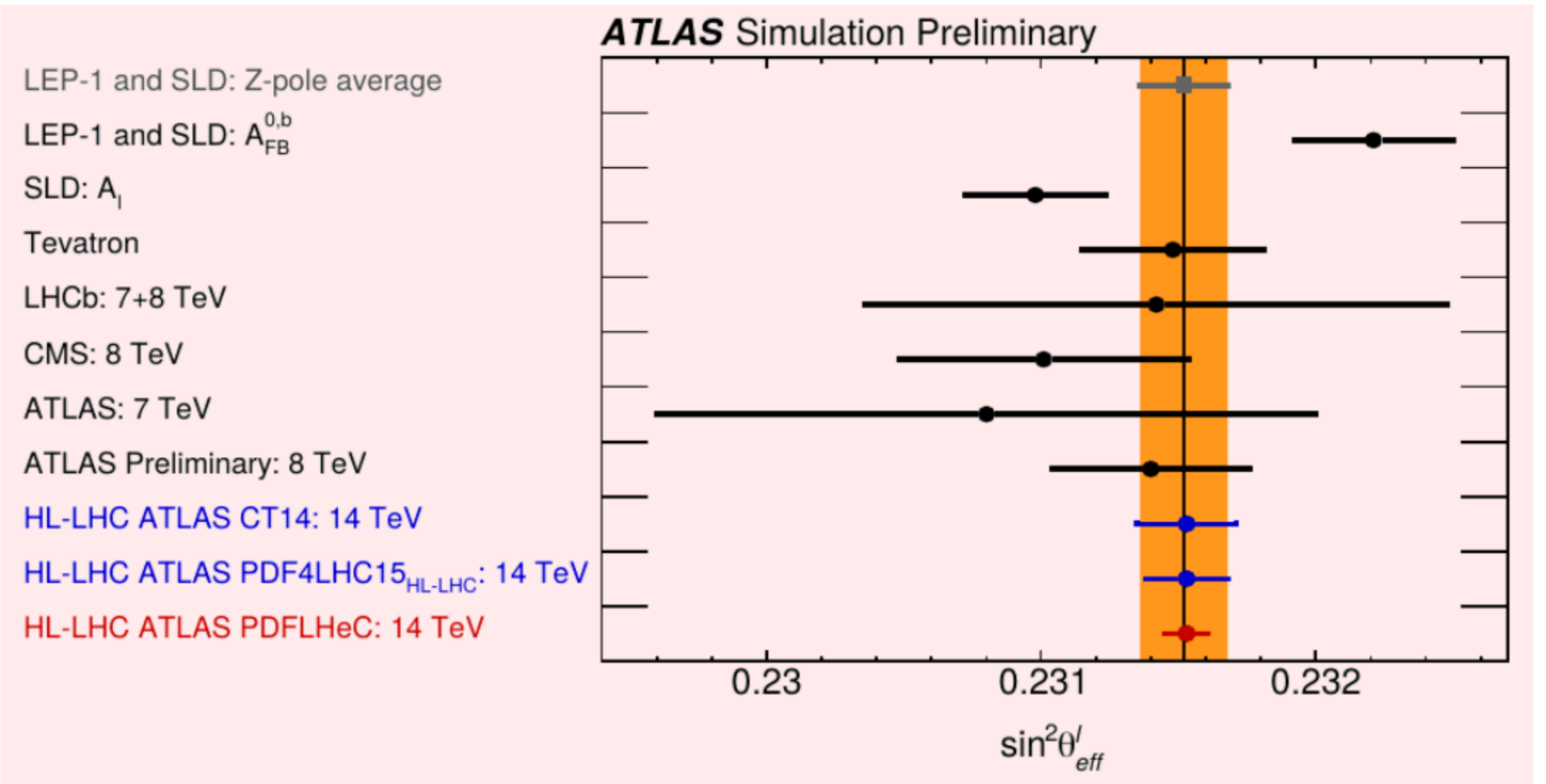
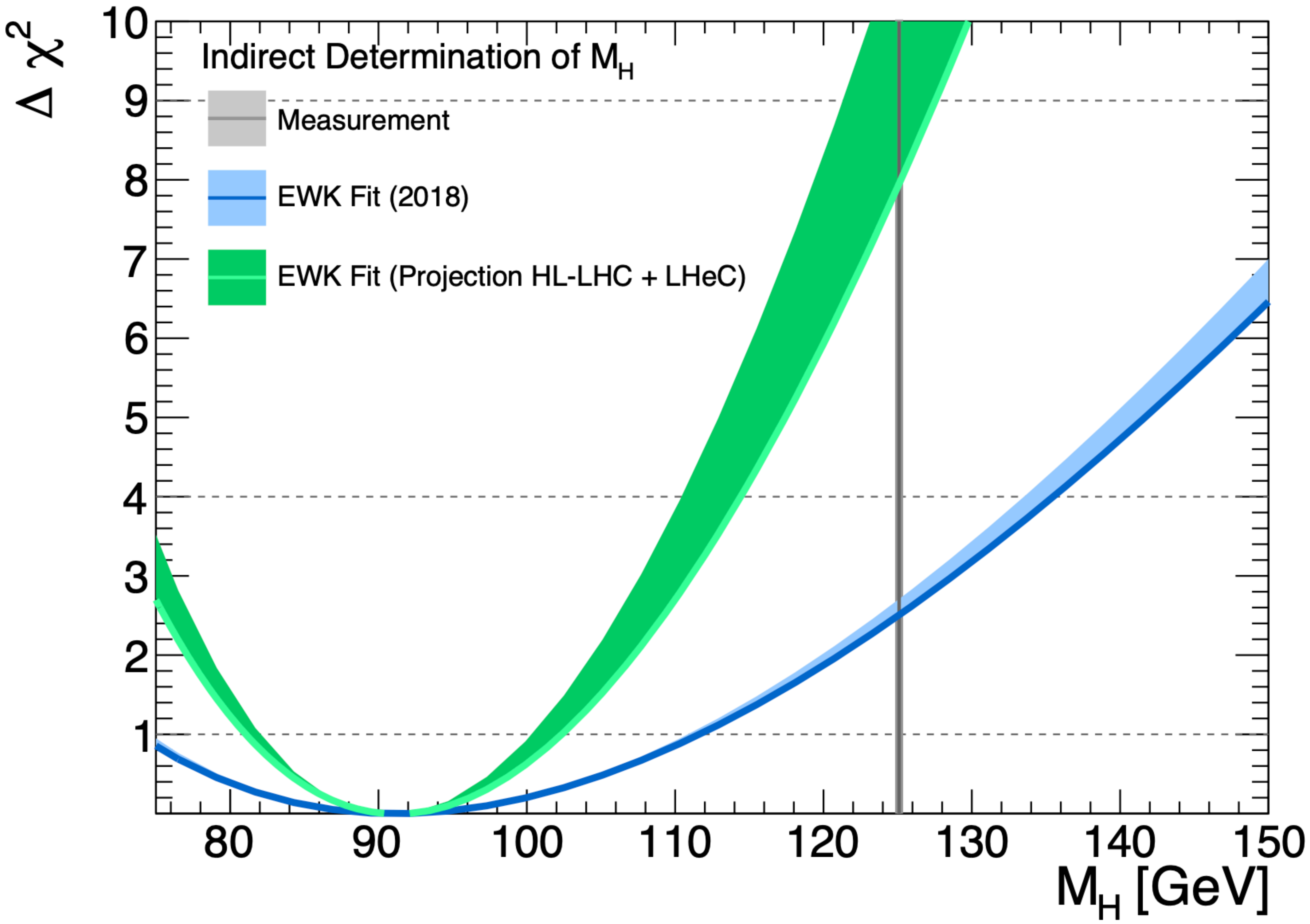






LHeC PDFs will shrink uncertainties in HL-LHC measurements of many (not only electroweak) parameters dramatically

Indirect Determination of Higgs Mass



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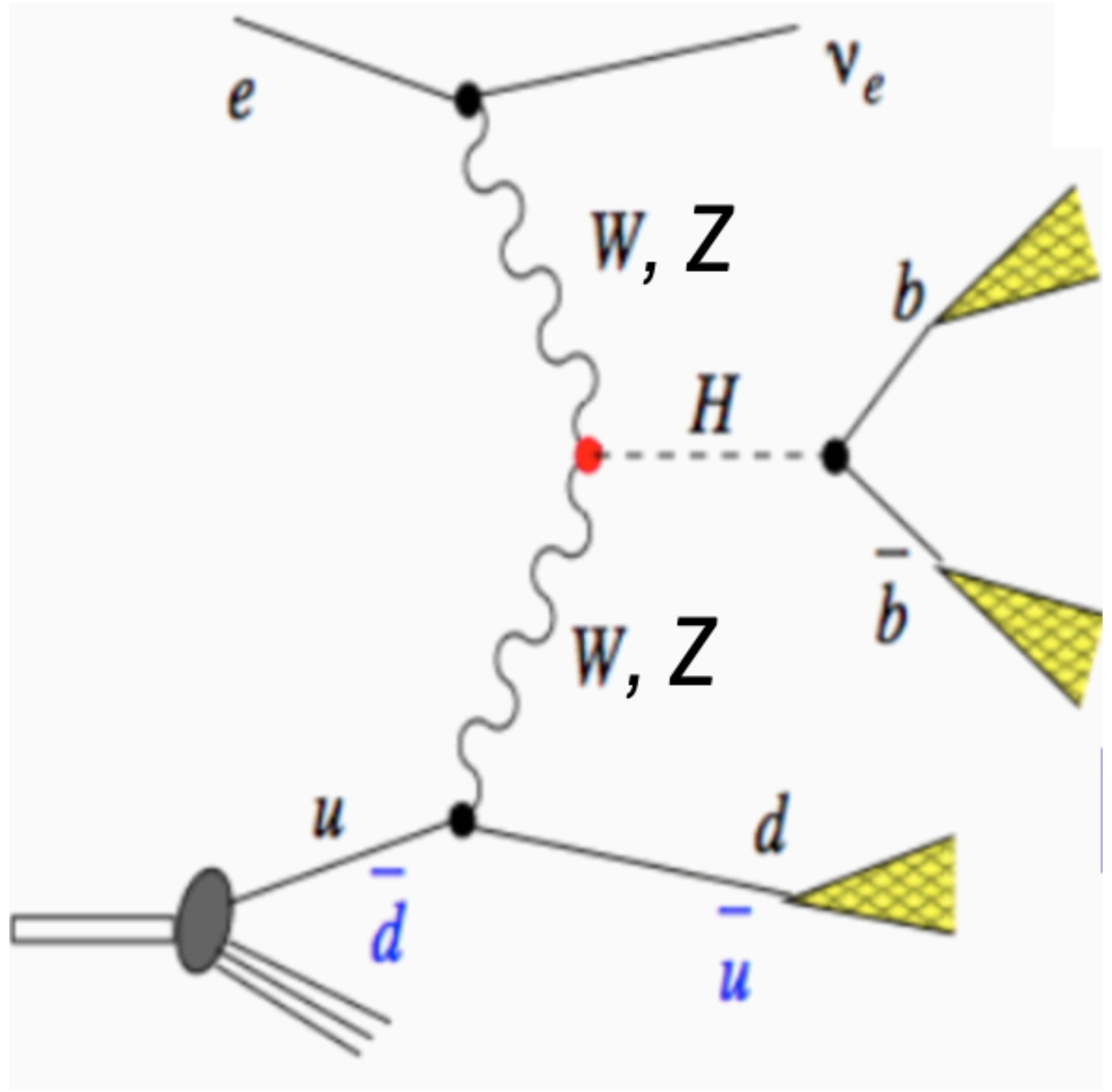
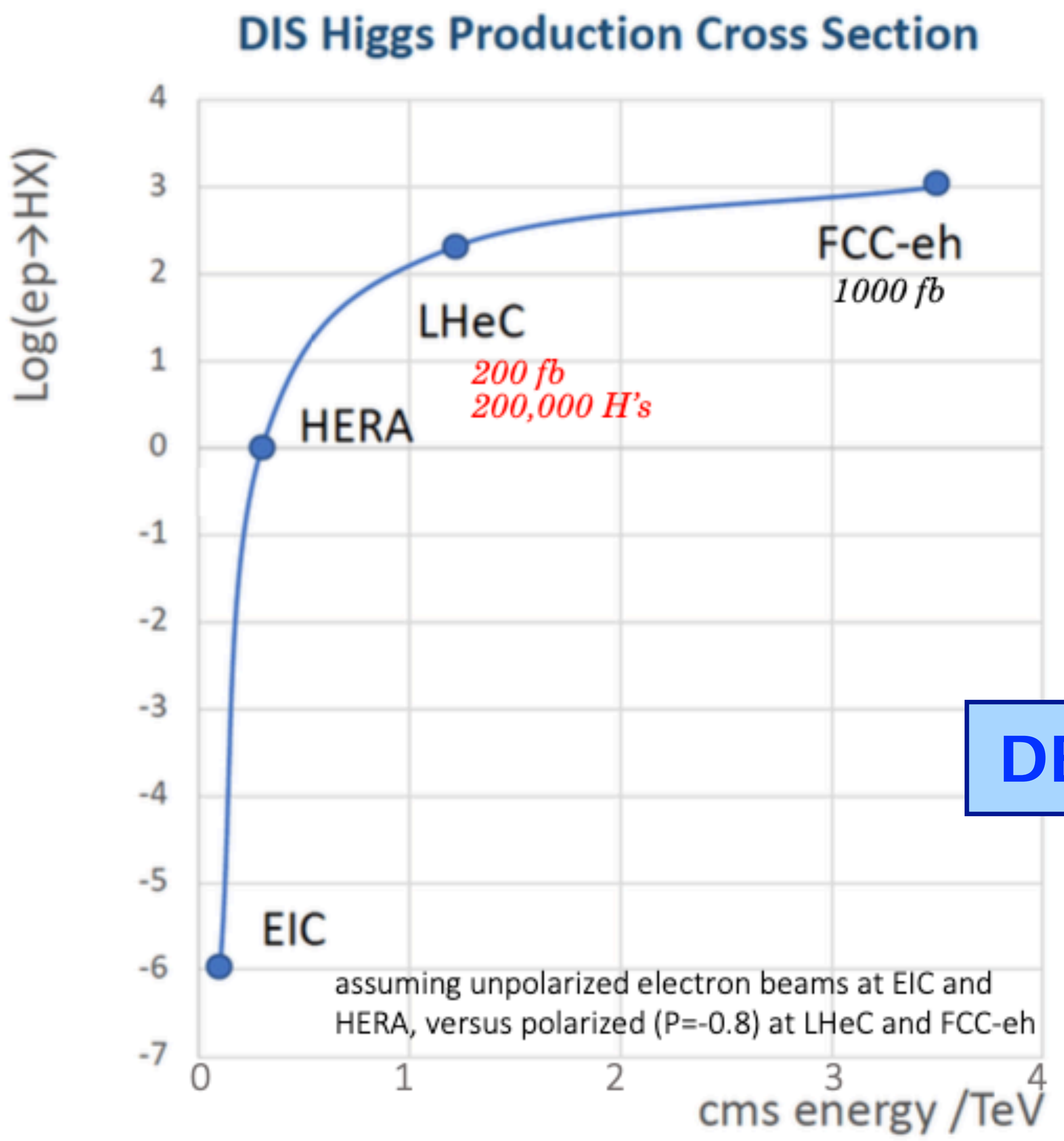
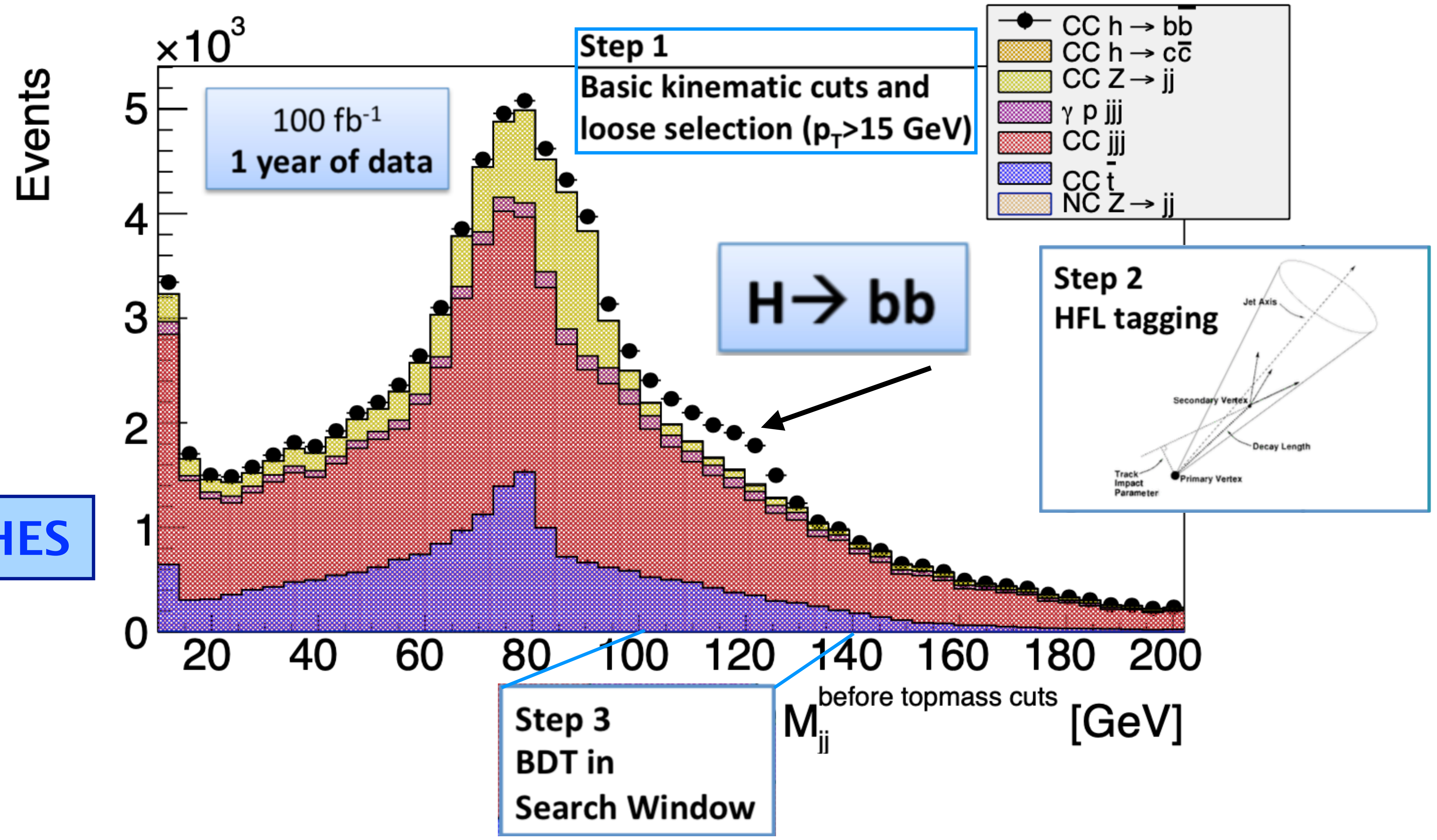
Higgs physics at the LHeC

CC(e⁻p)





DELPHES



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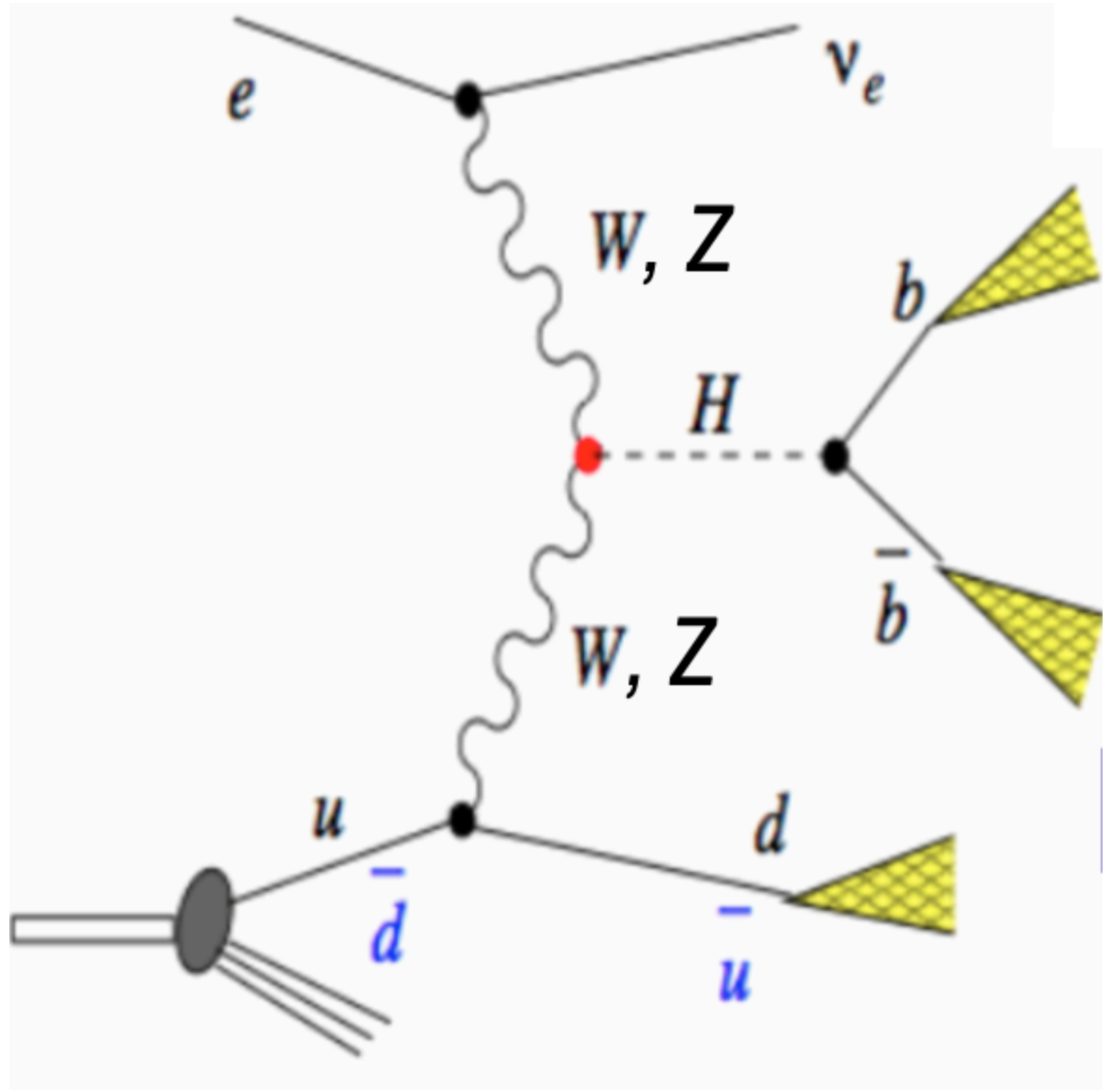

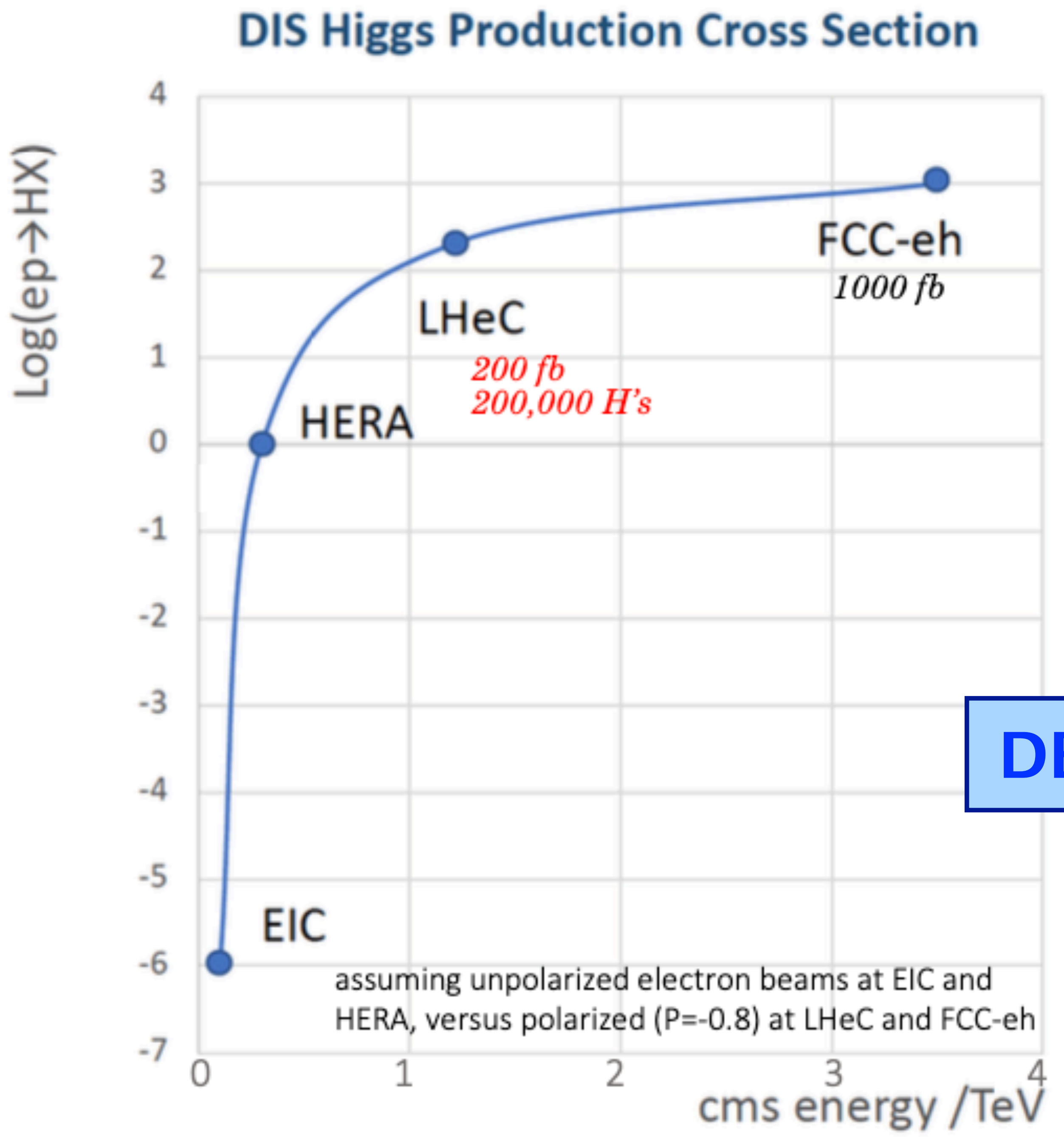

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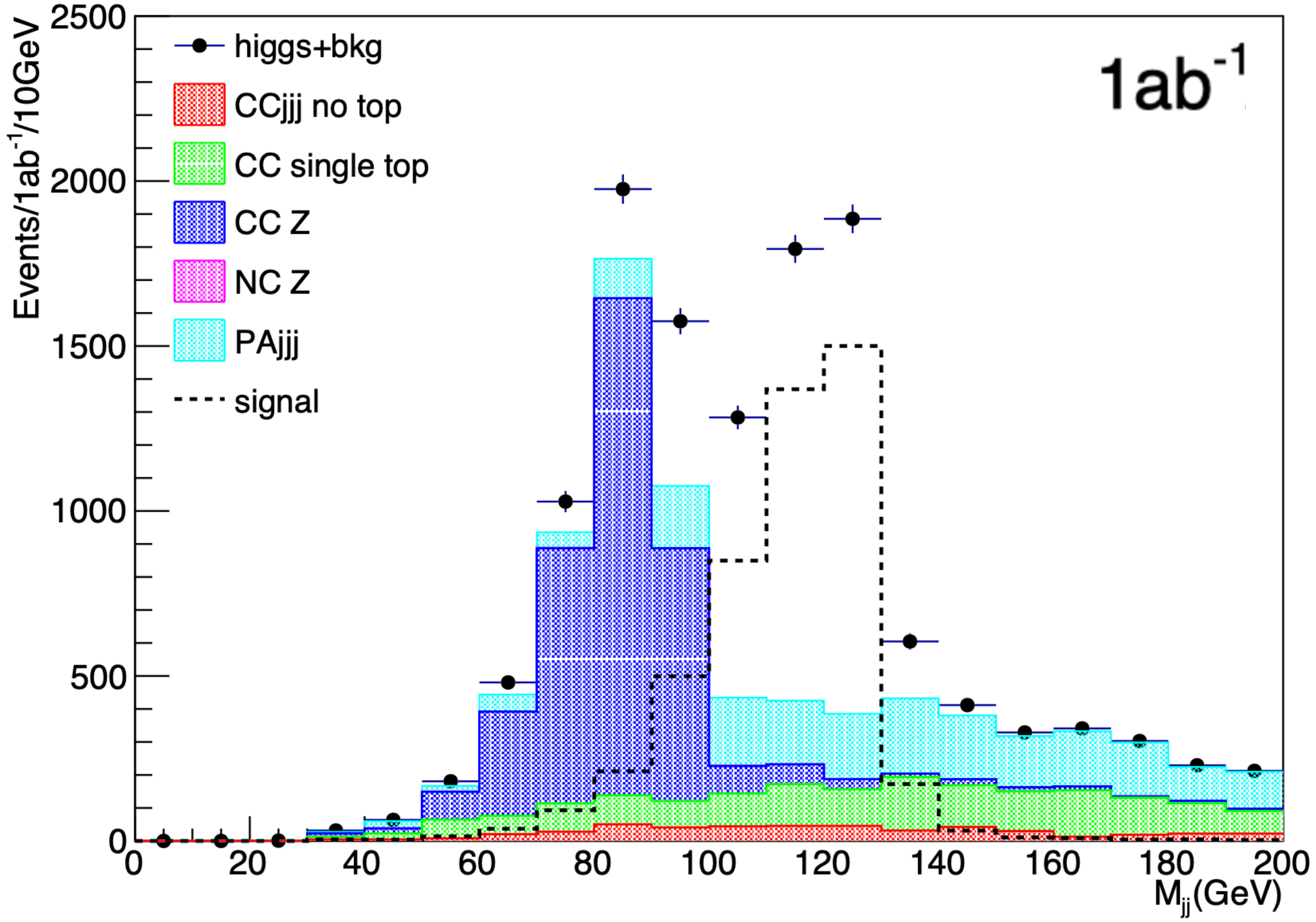
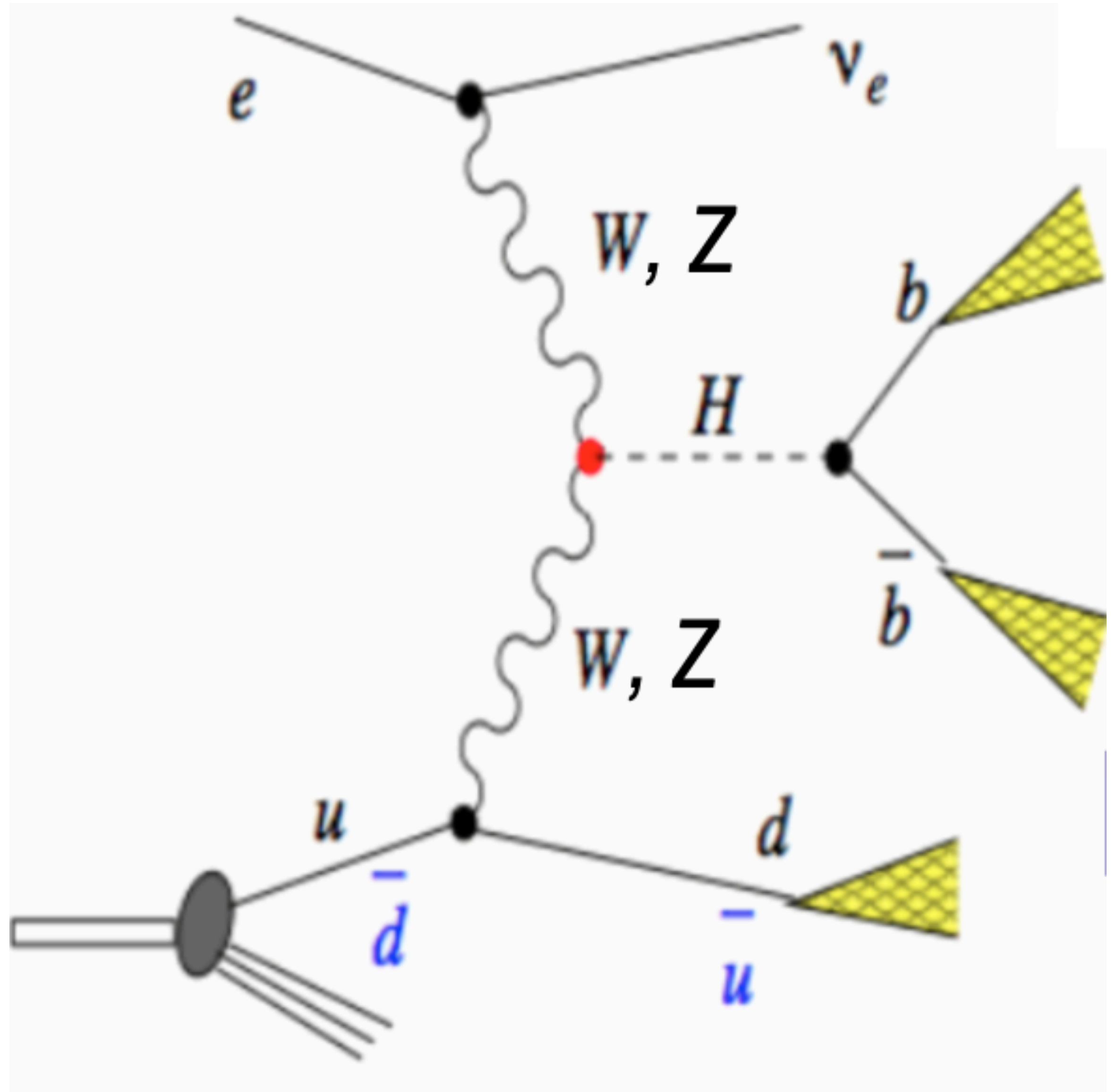
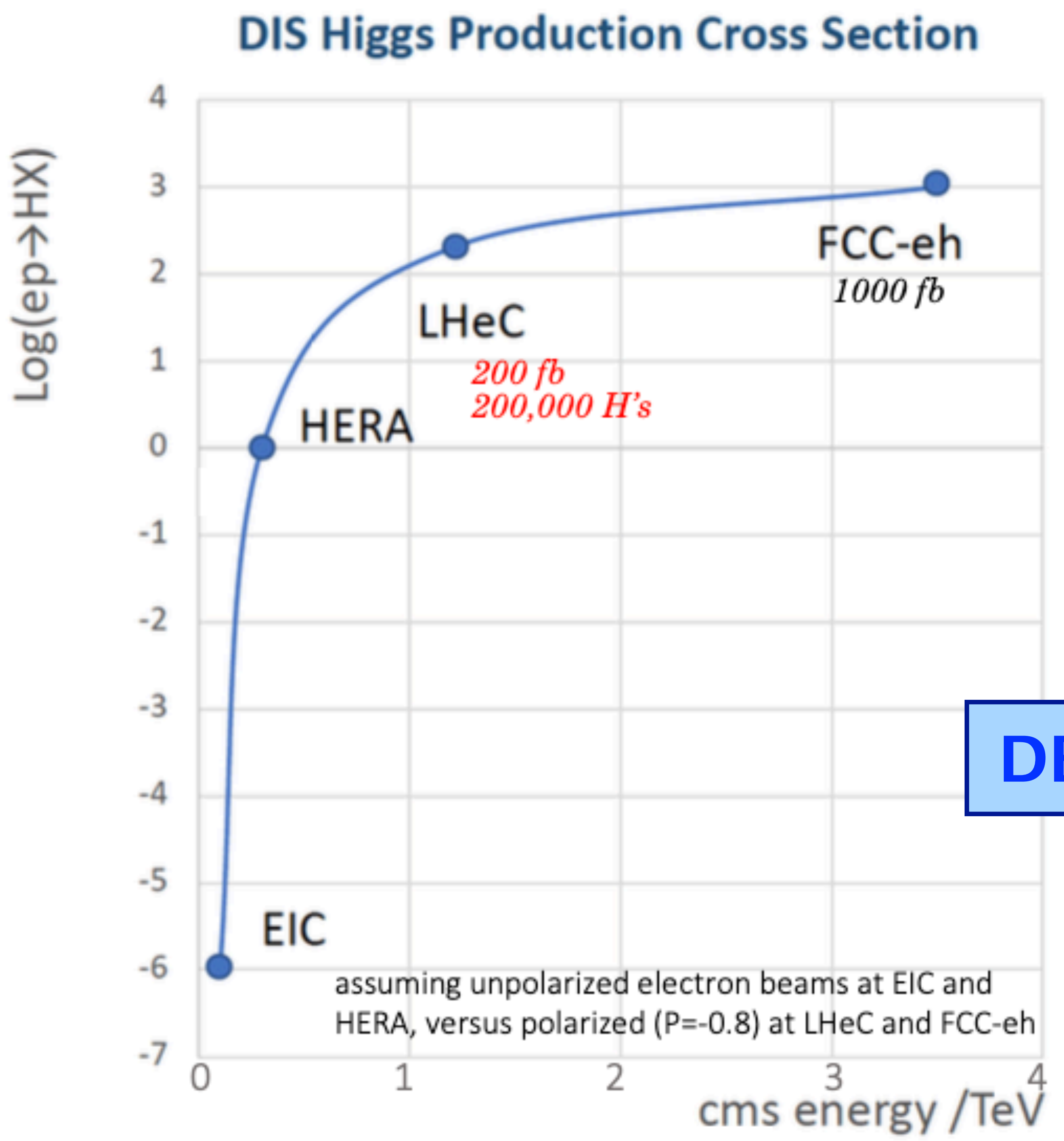


Higgs coupling combinations in κ−framework

CC(e⁻p)





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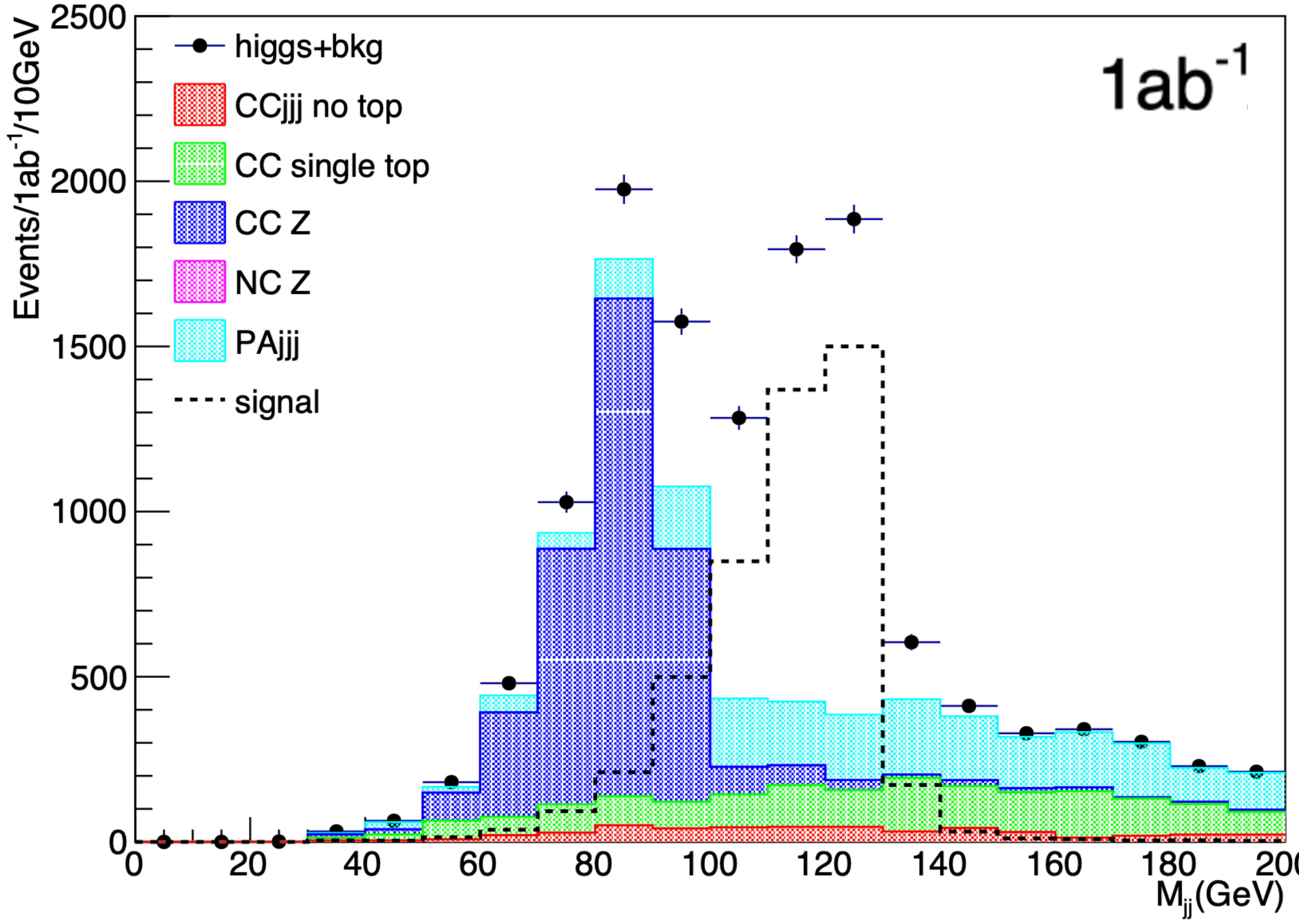
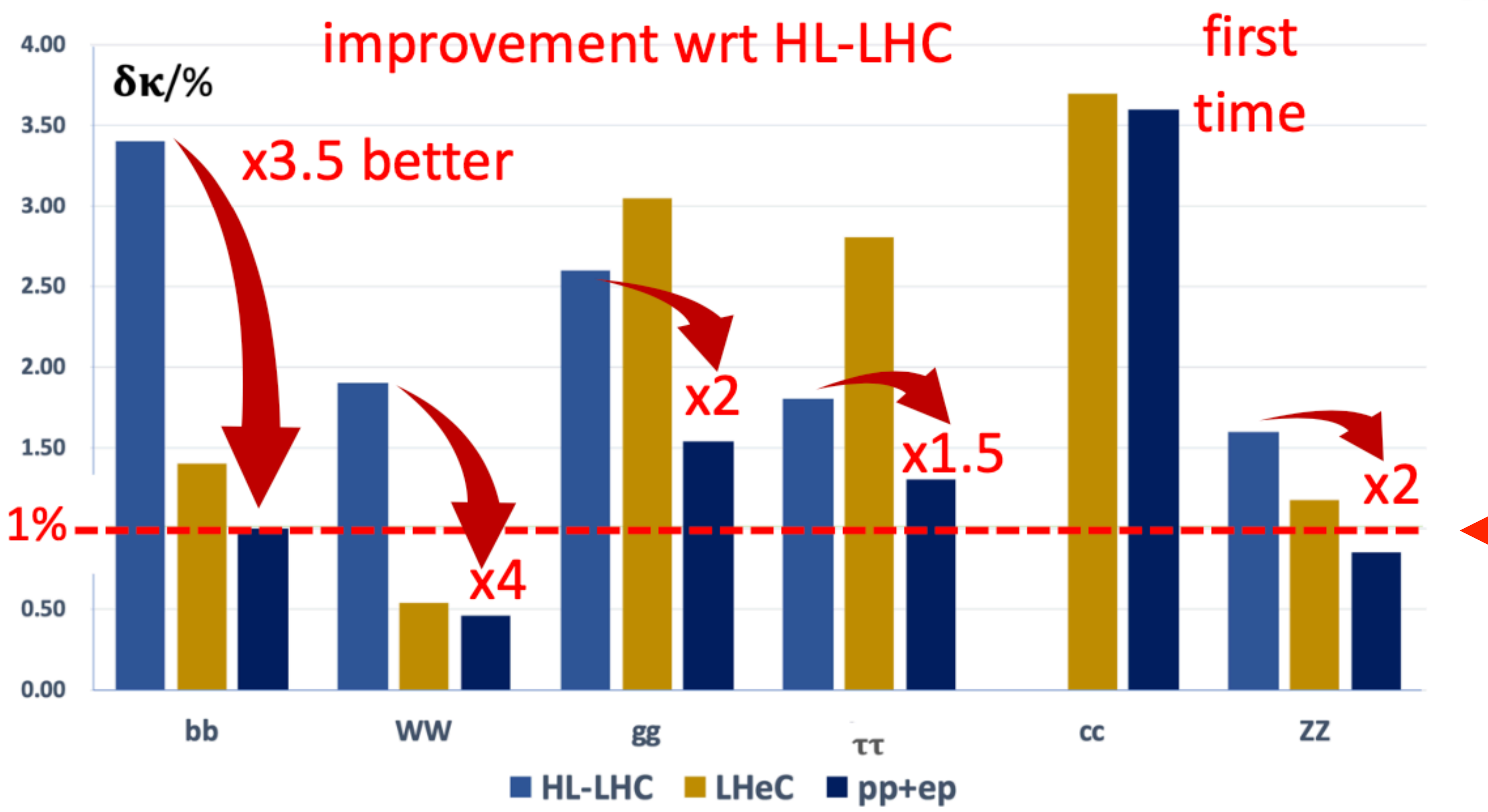


LHC
ep+pp

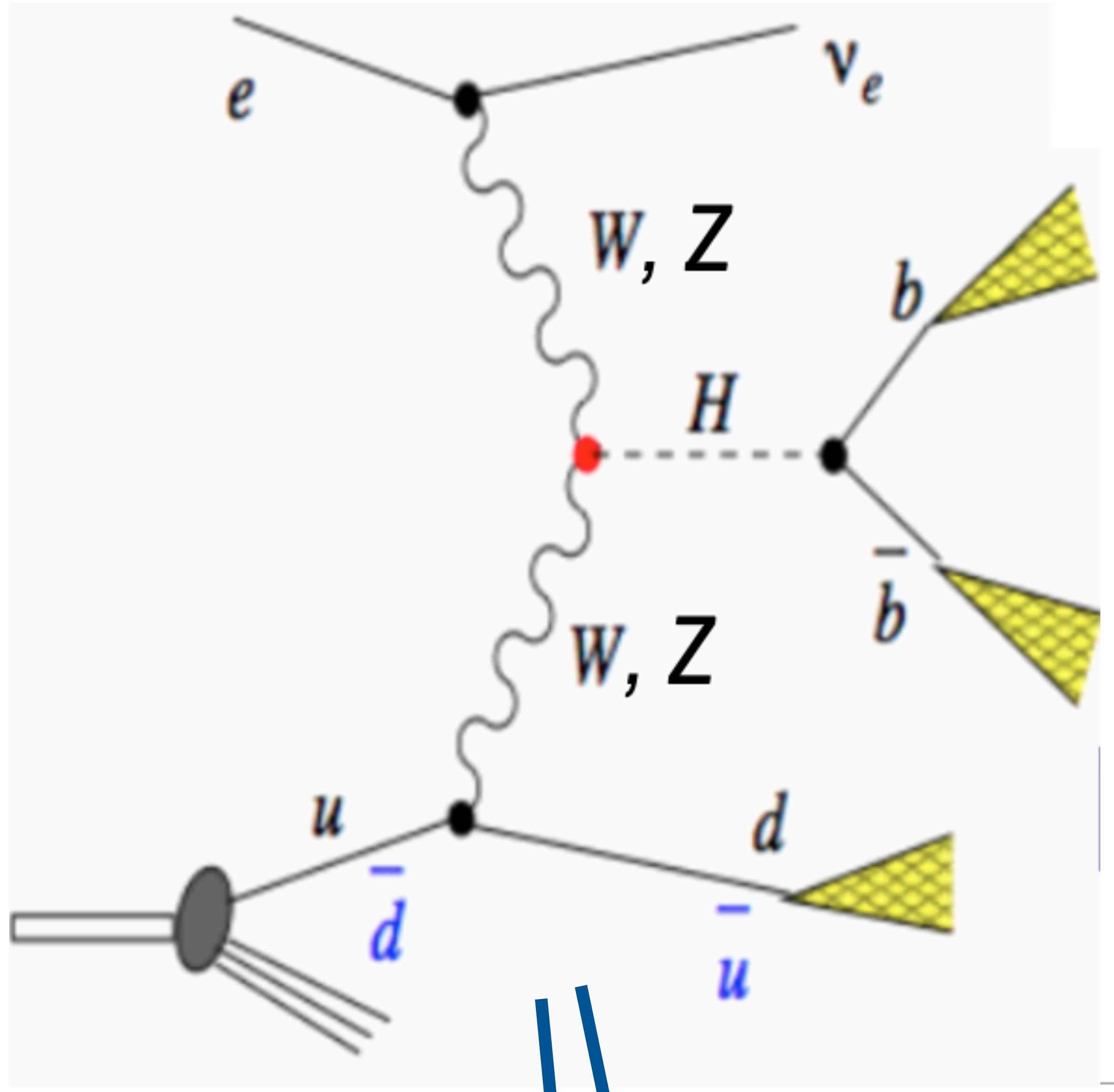


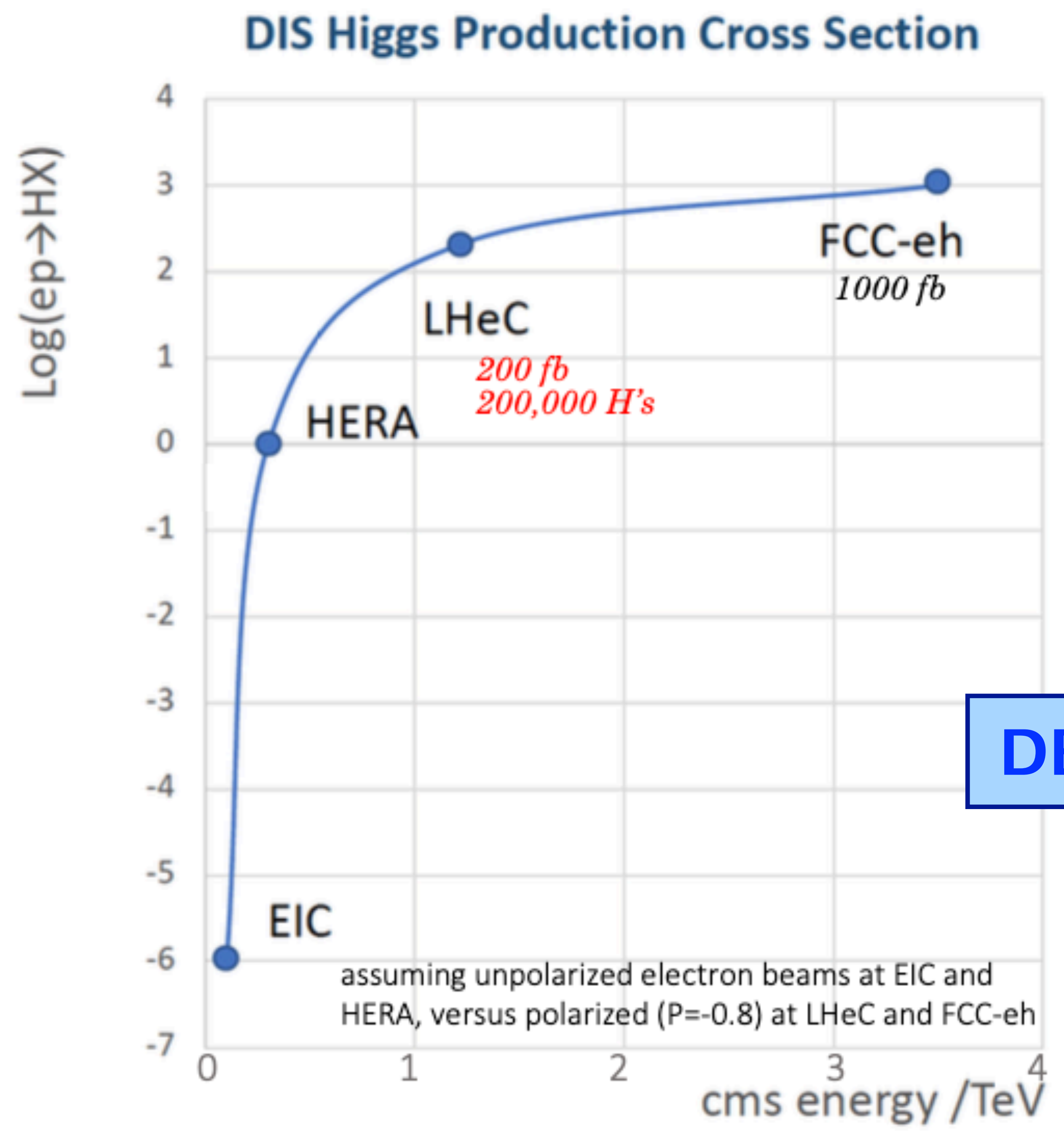
1%

→ adding electrons makes the LHC a Higgs precision facility

Higgs coupling combinations in κ−framework

CC(e⁻p)





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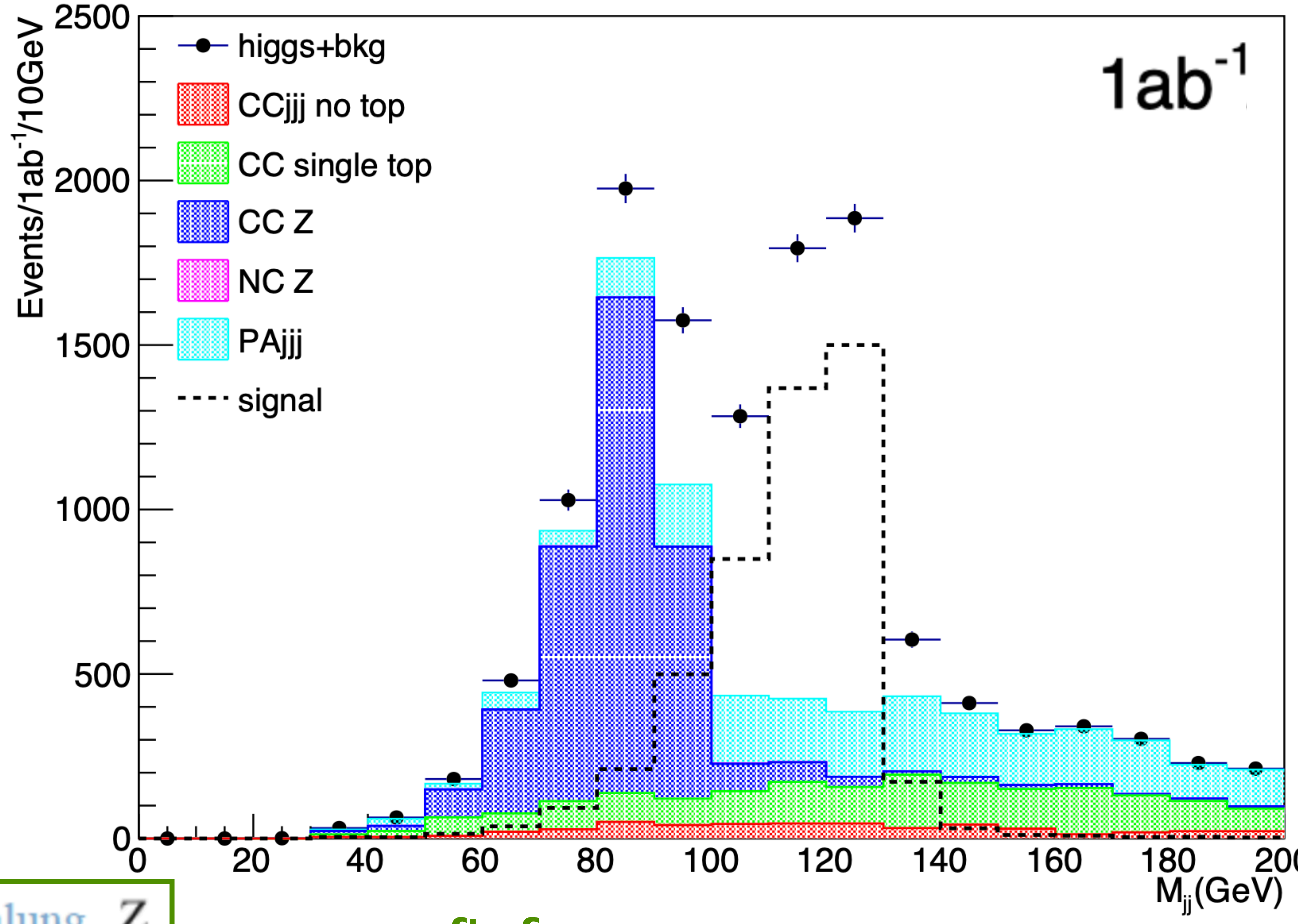

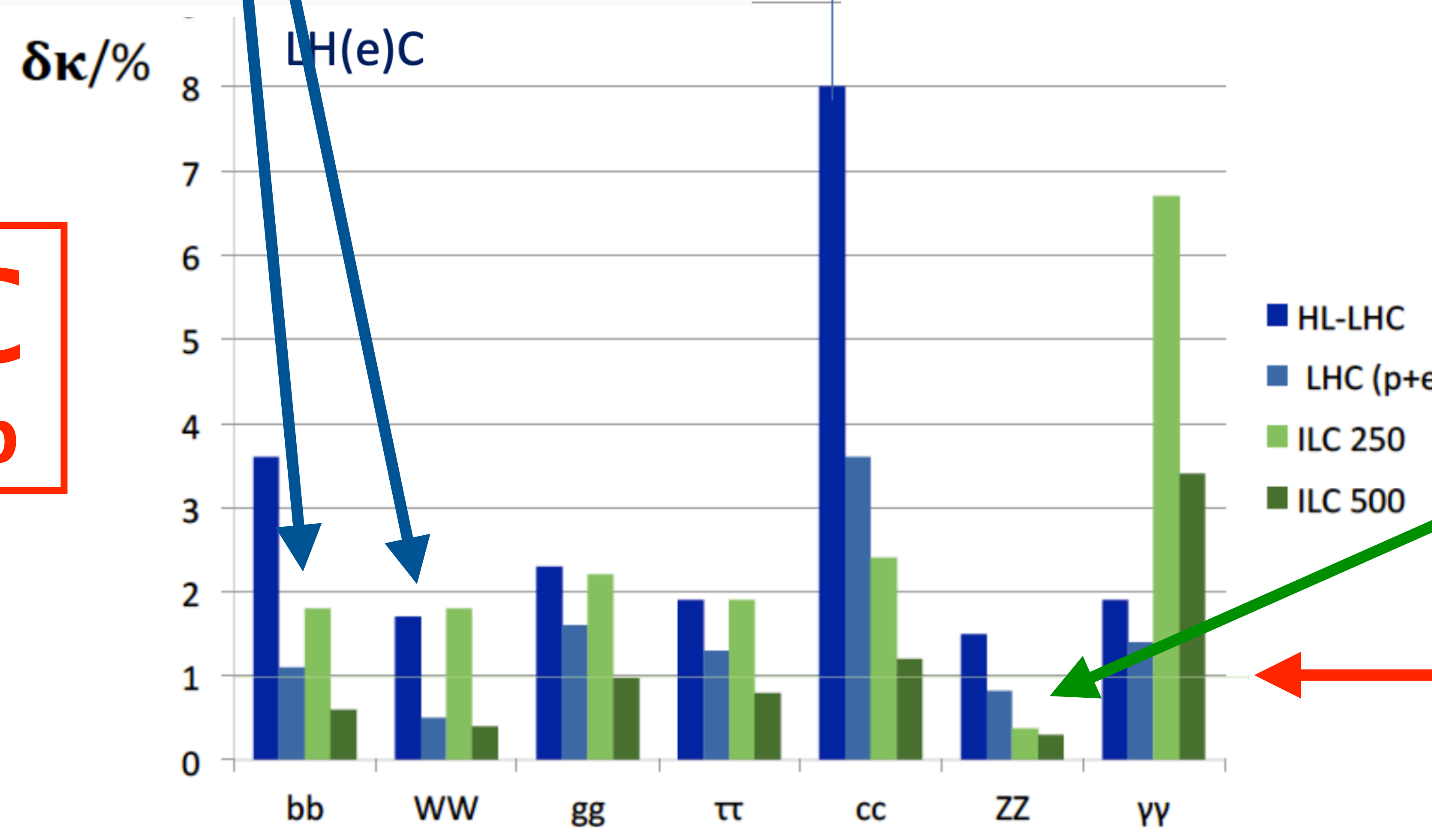

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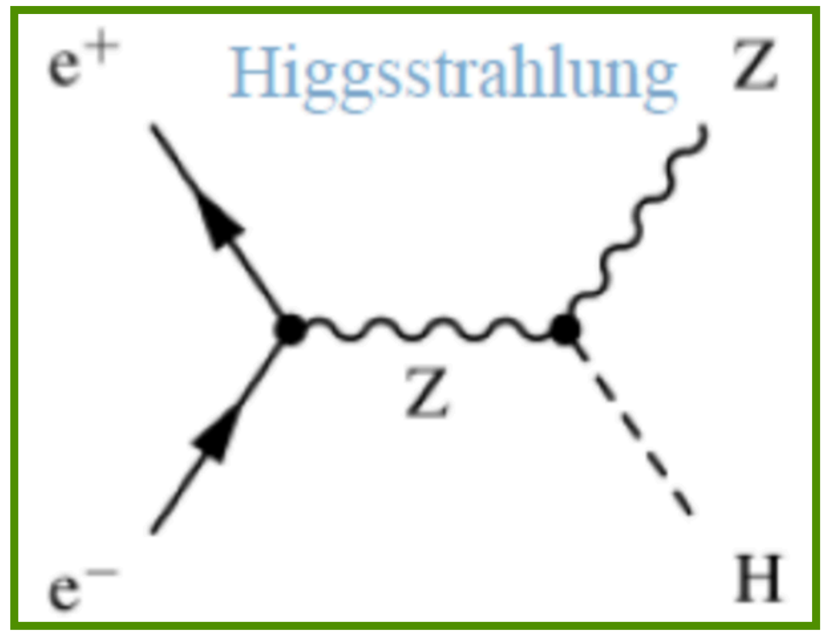
1%

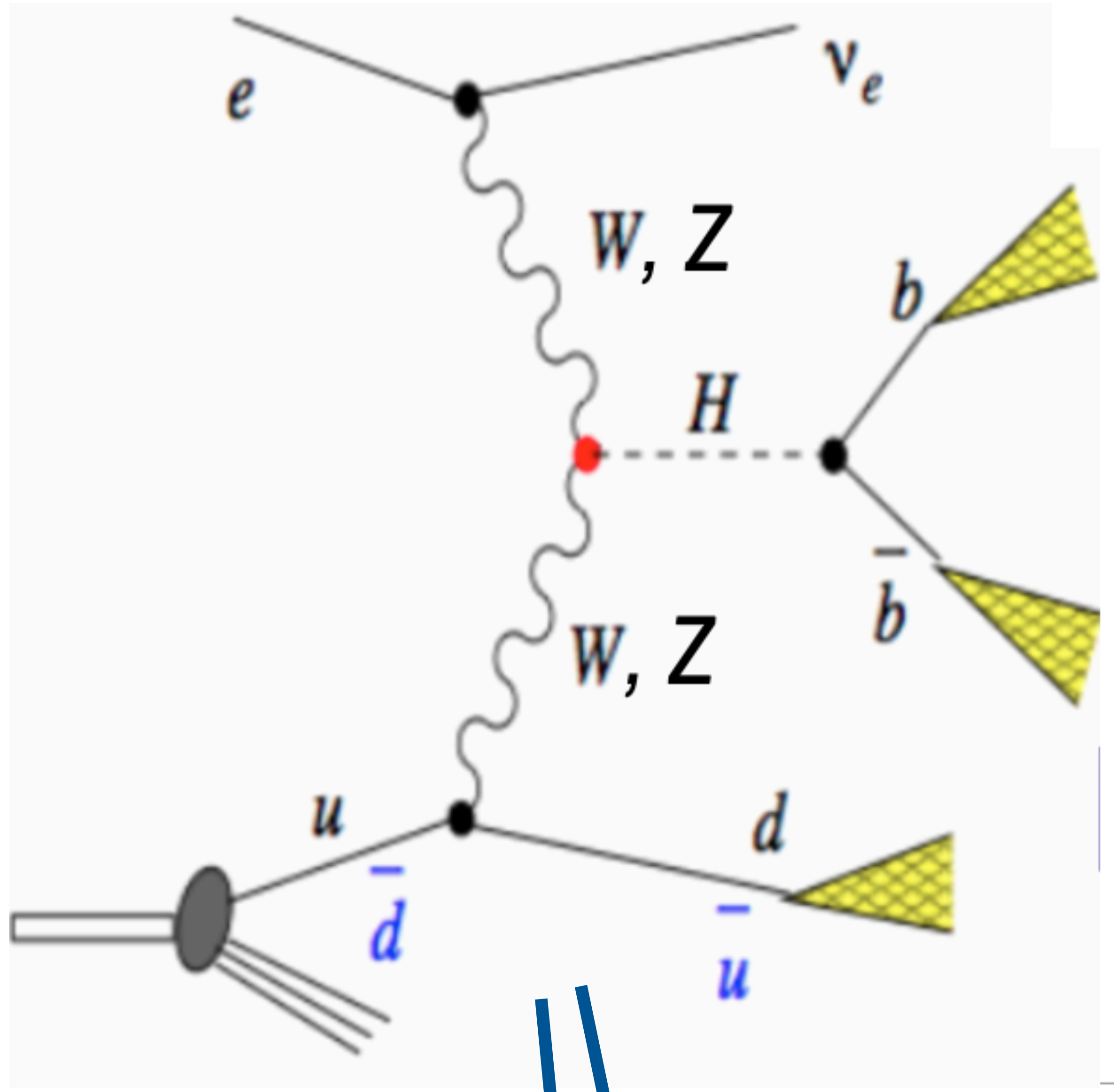


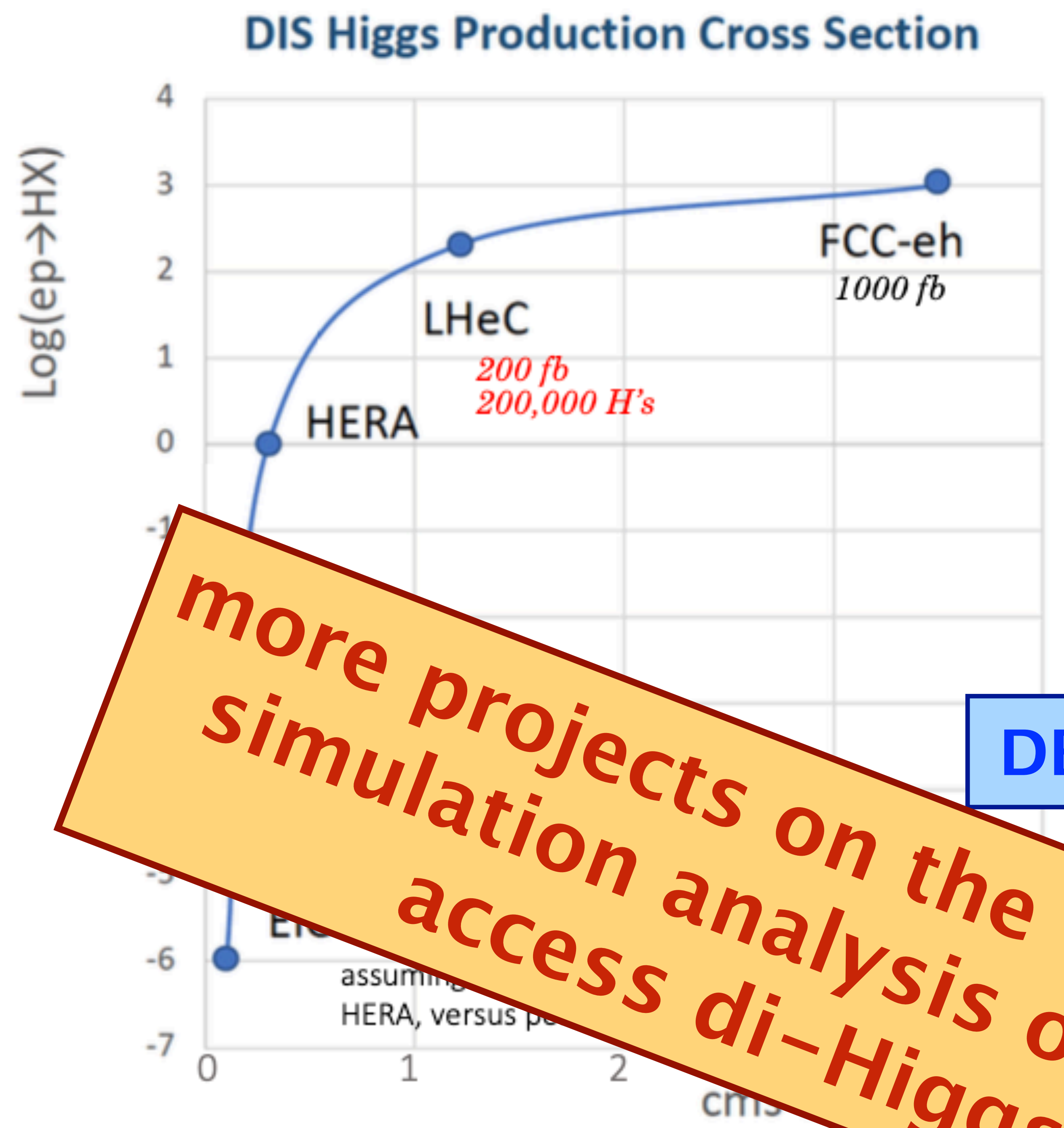
we profit from diversity through complementarity

→ adding electrons makes the LHC a Higgs precision facility

Higgs coupling combinations in κ-framework

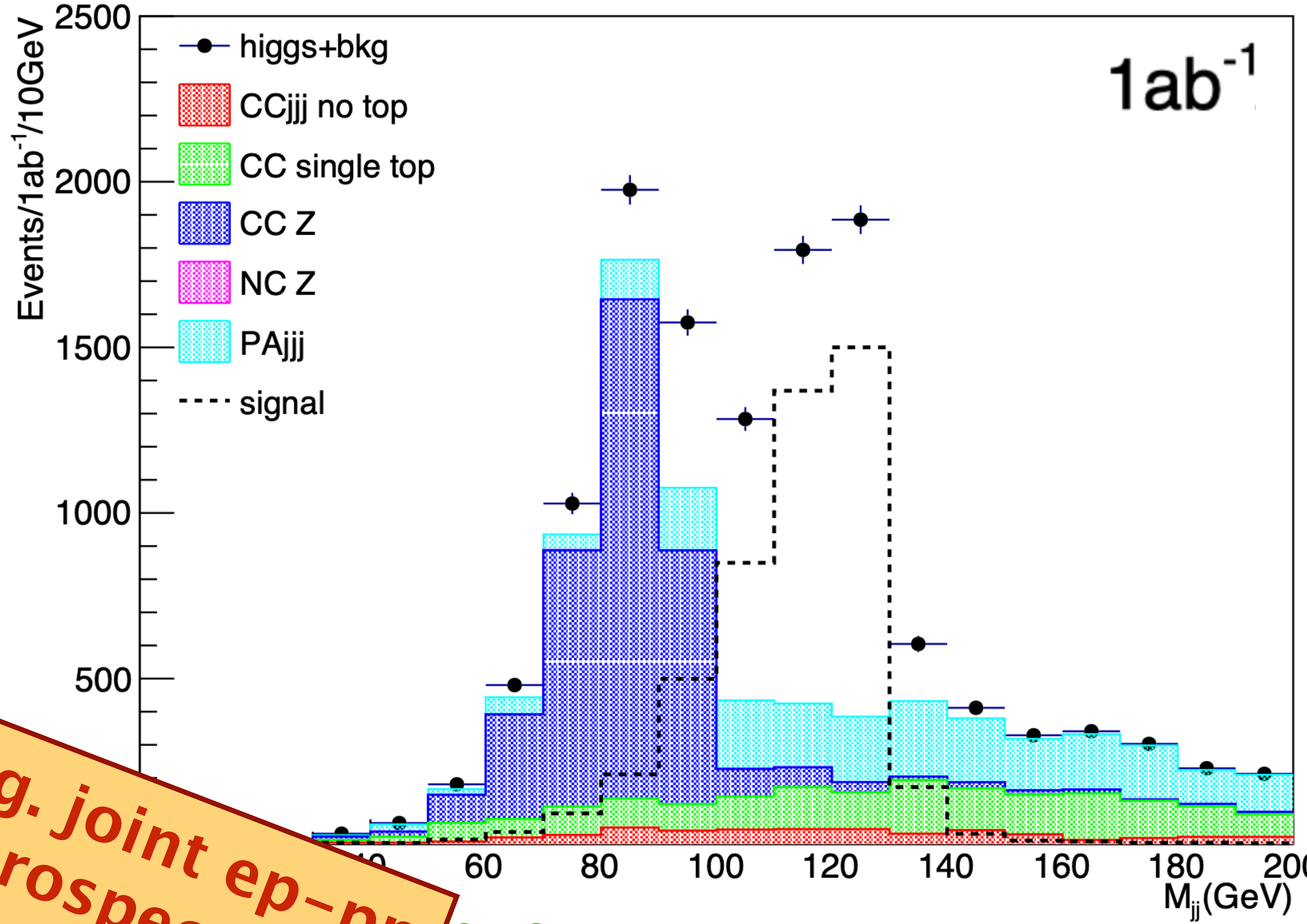
CC(e⁻p)





more projects on the way: e.g. joint ep-pp simulation analysis of the prospects to access di-Higgs production

DELPHES



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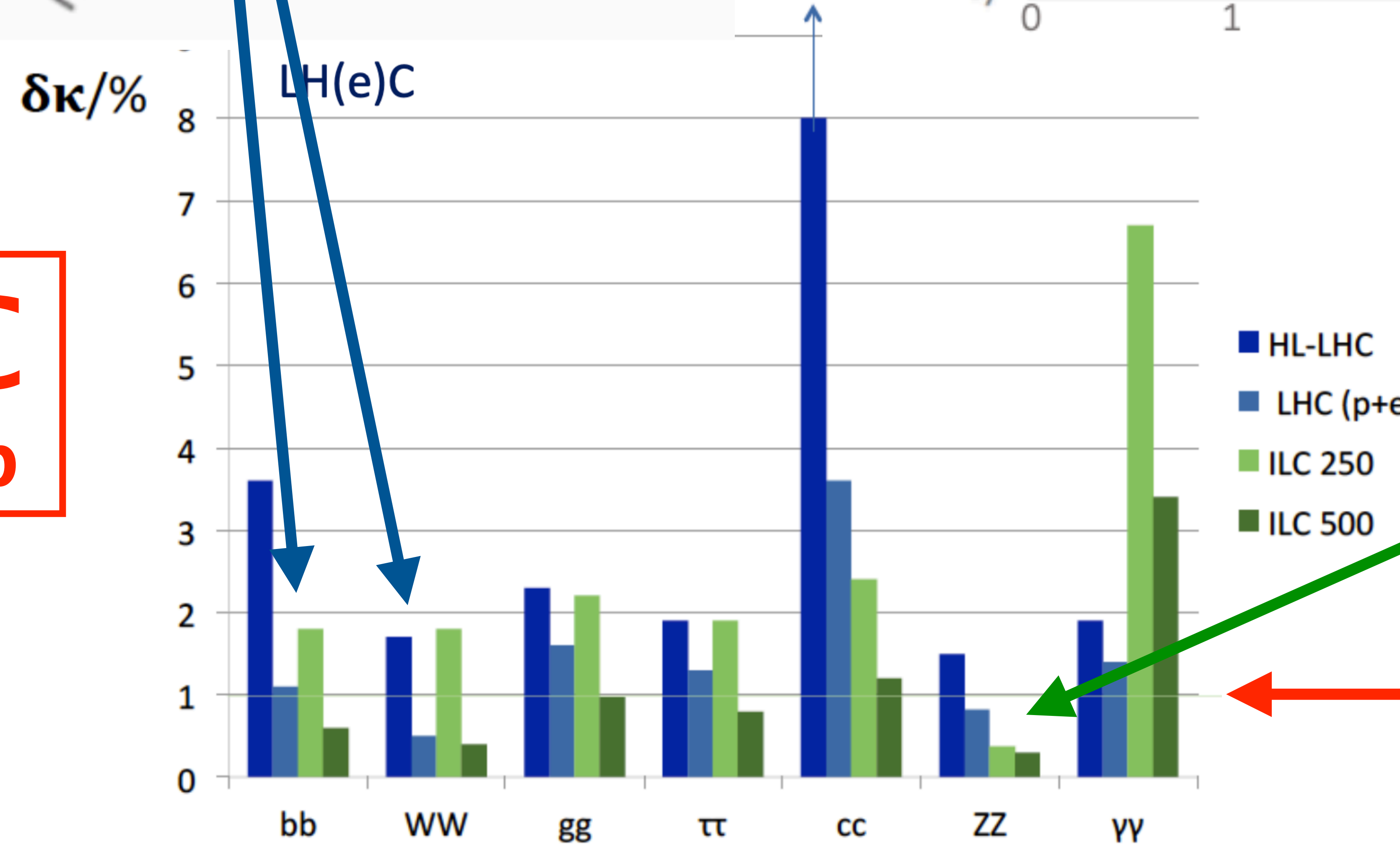
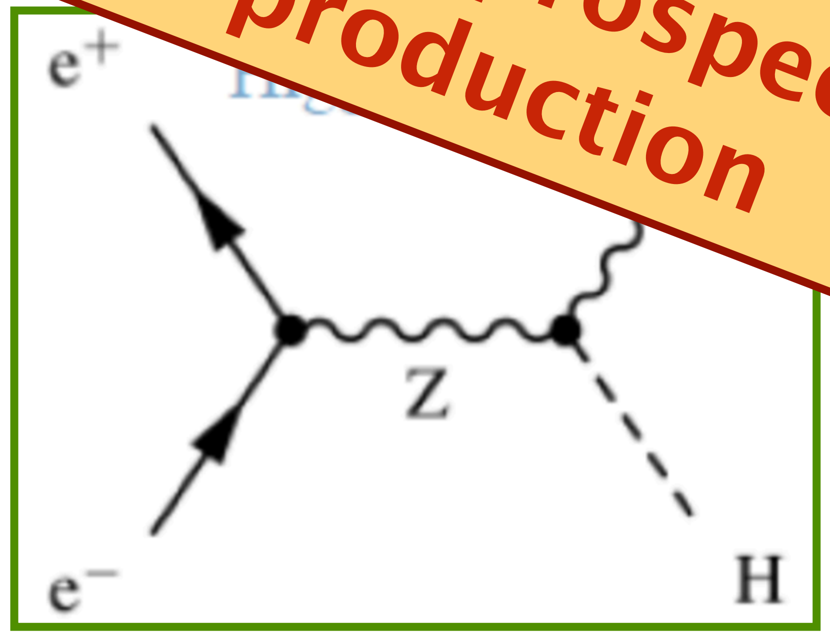


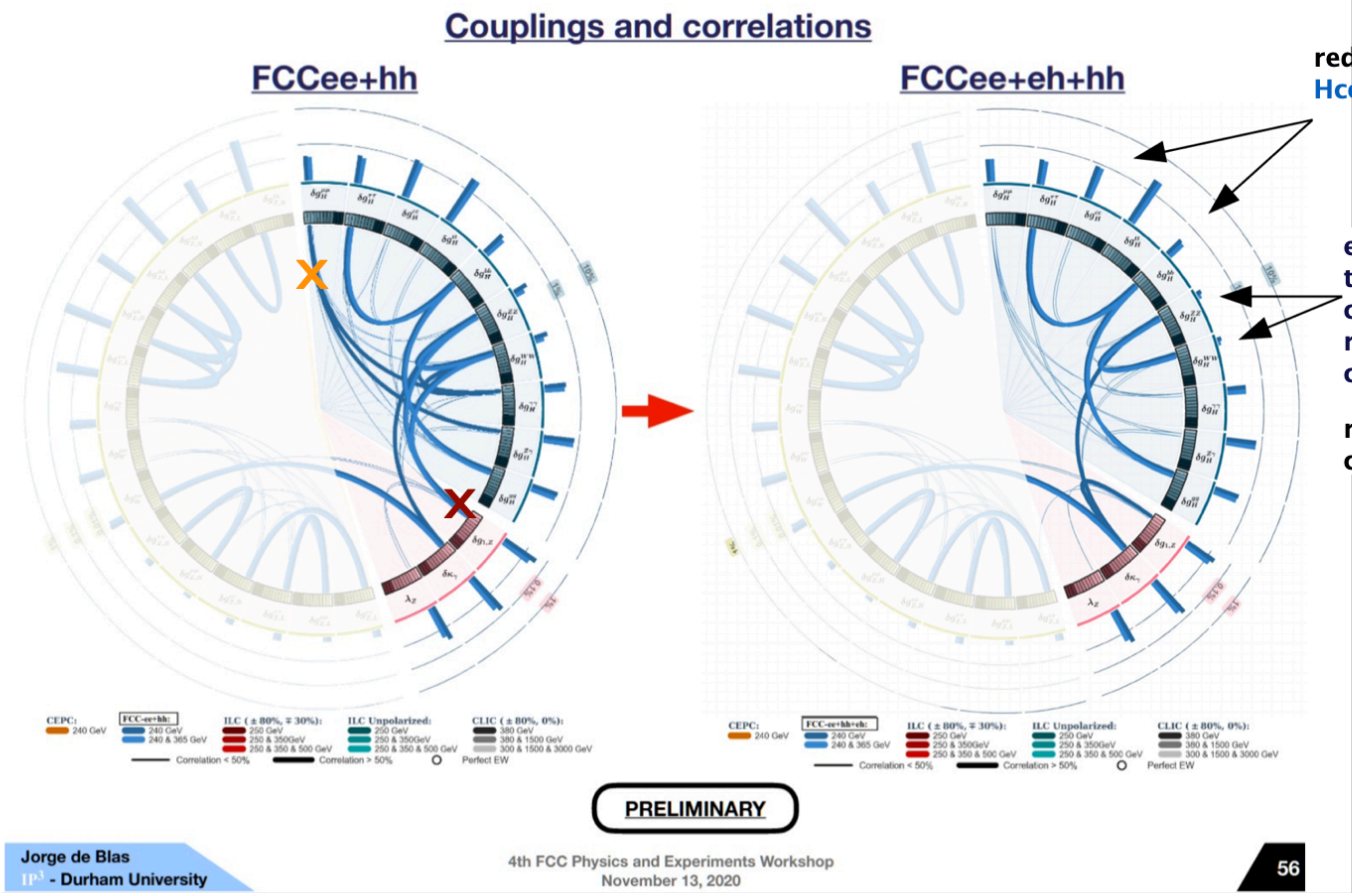


← 1%

...fit from
...ty through
...ementarity

→ adding electrons makes the LHC a Higgs precision facility

SMEFT fit results after FCC era



reduction for **Hcc** and **Hbb**

eh contributes to the **HWW** and **HZZ** couplings and resolves their correlation X

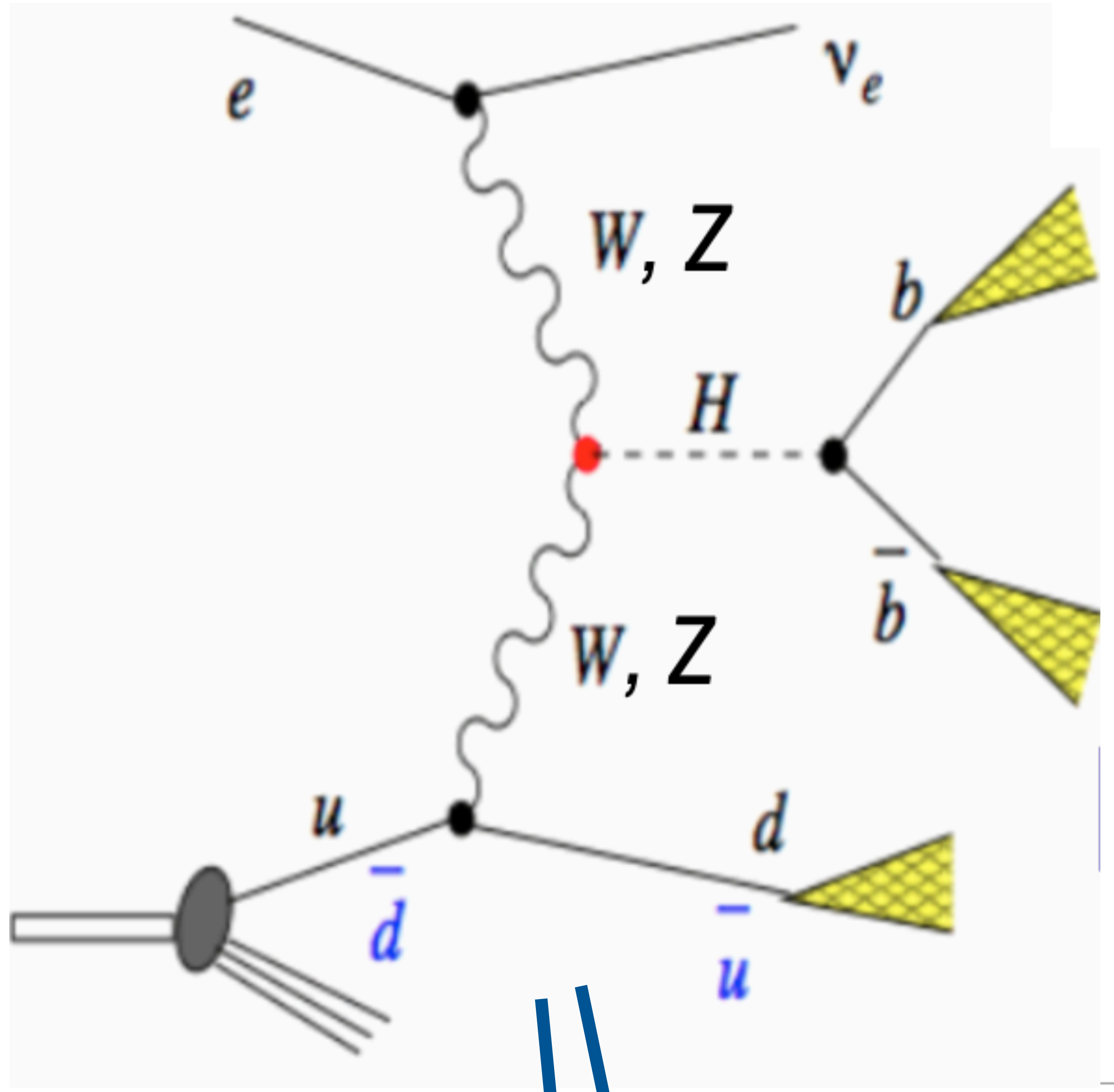
reduces further correlations X

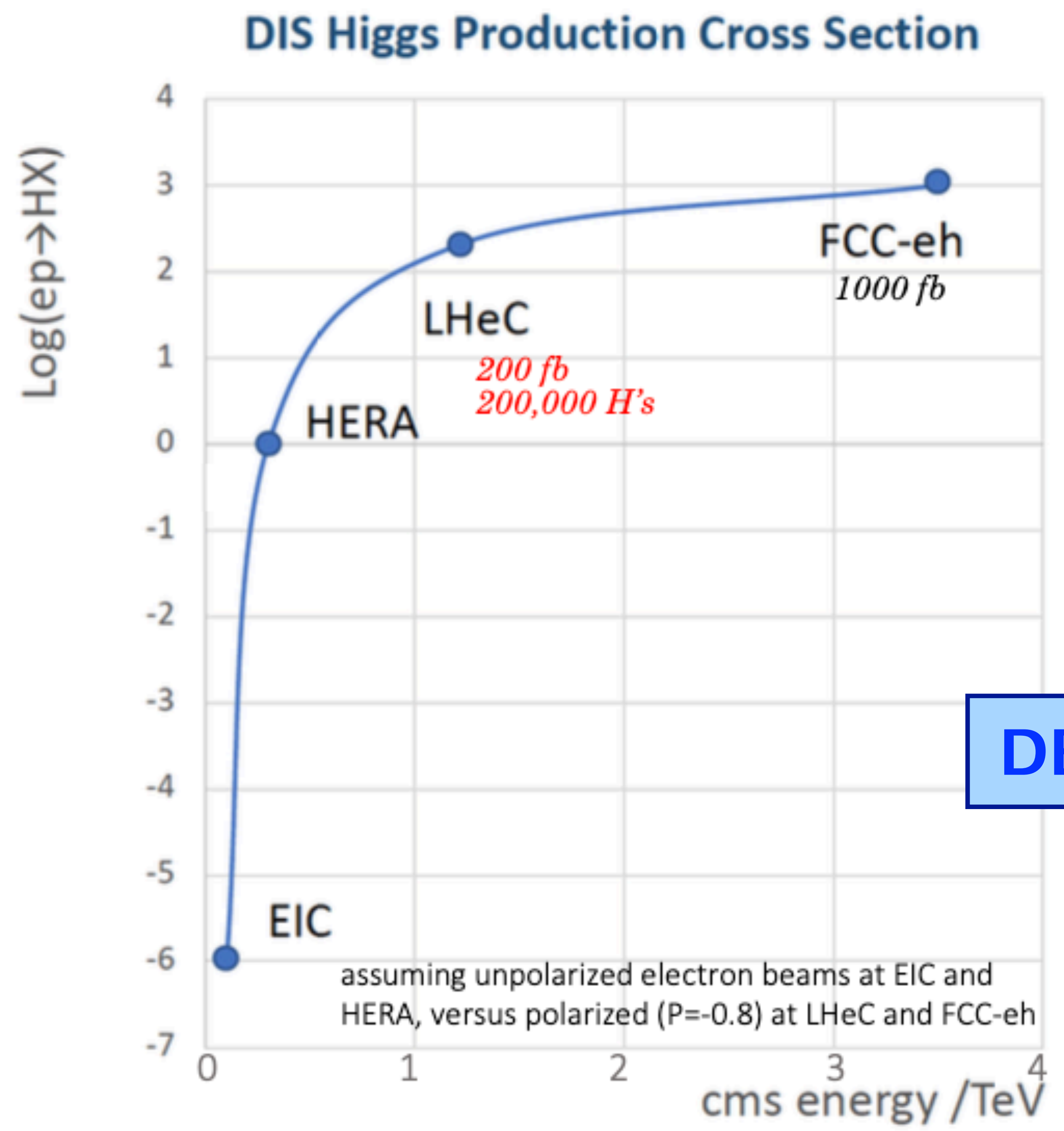
Higgs SMEFT coupling combinations profit from diversity: ee, ep, and pp

Higgs coupling combinations in κ–framework

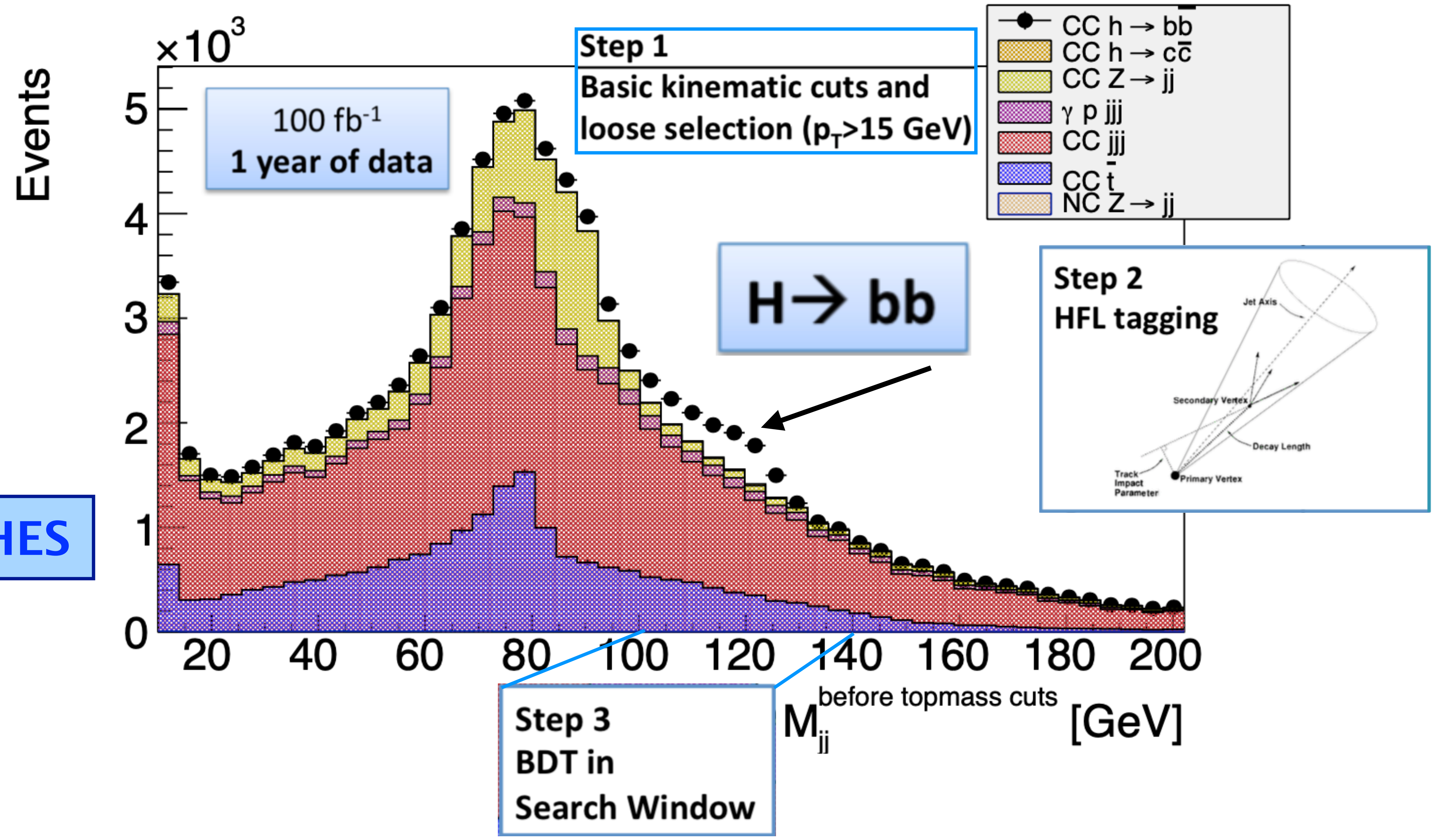
Higgs

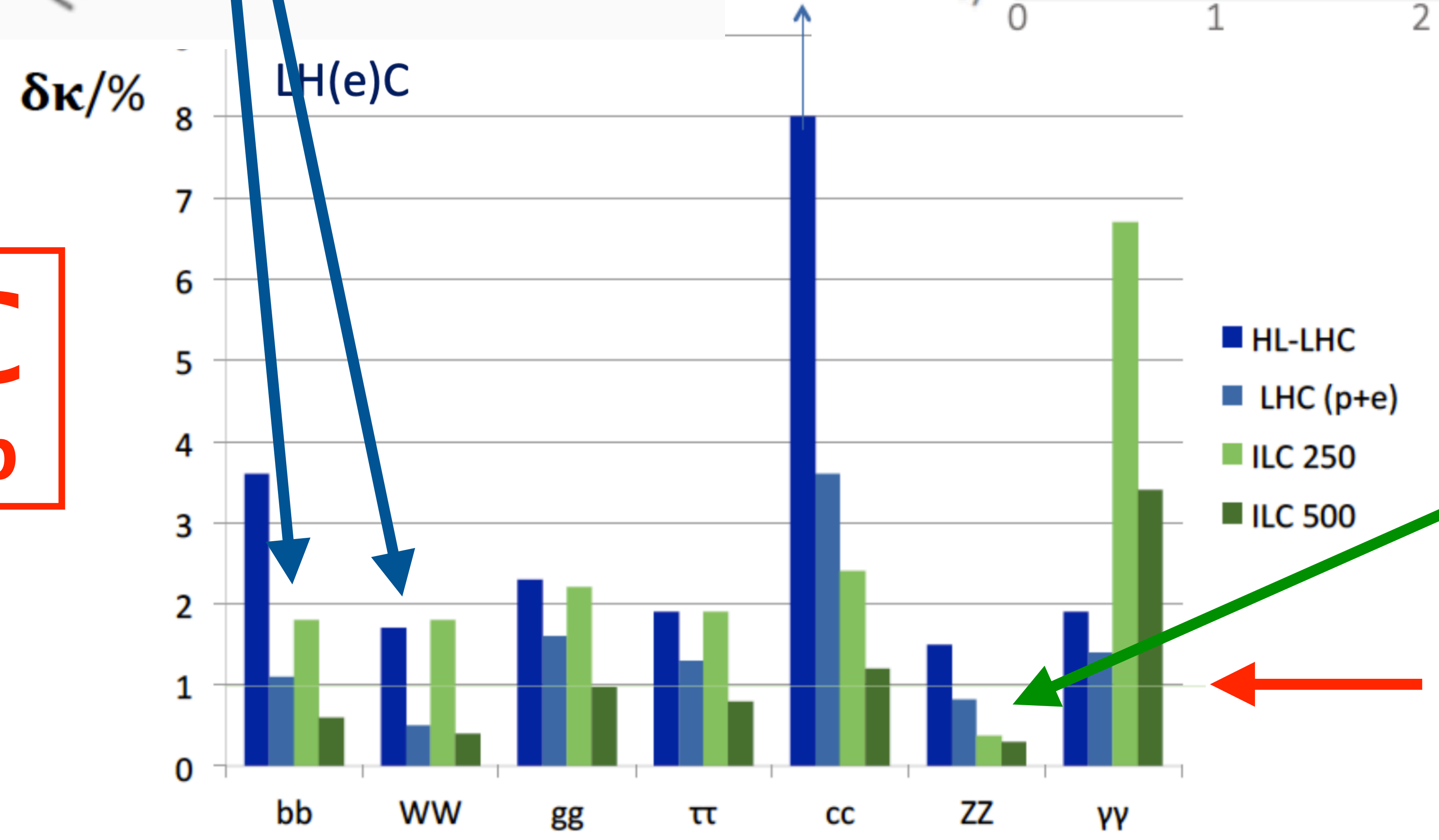
CC(e⁻p)





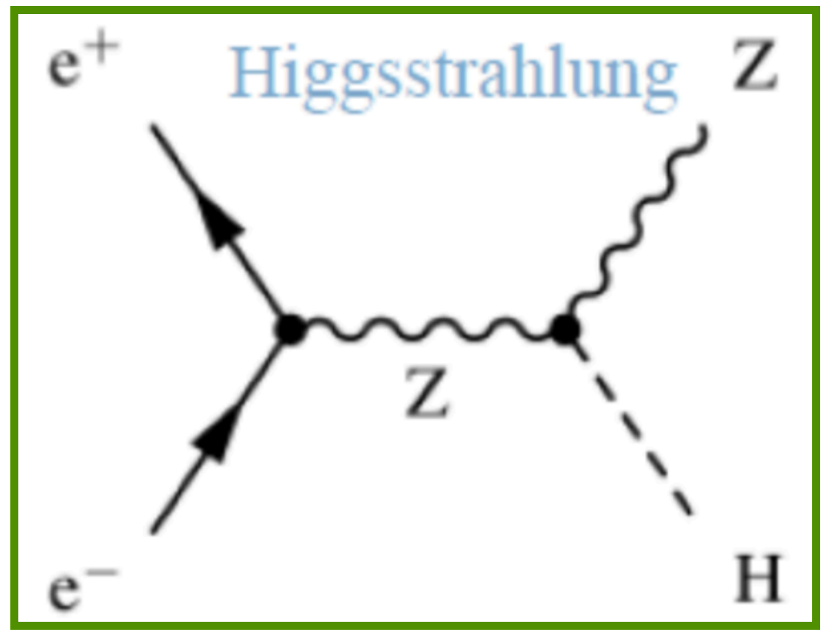
DELPHES





LHC
ep+pp

← **1%**



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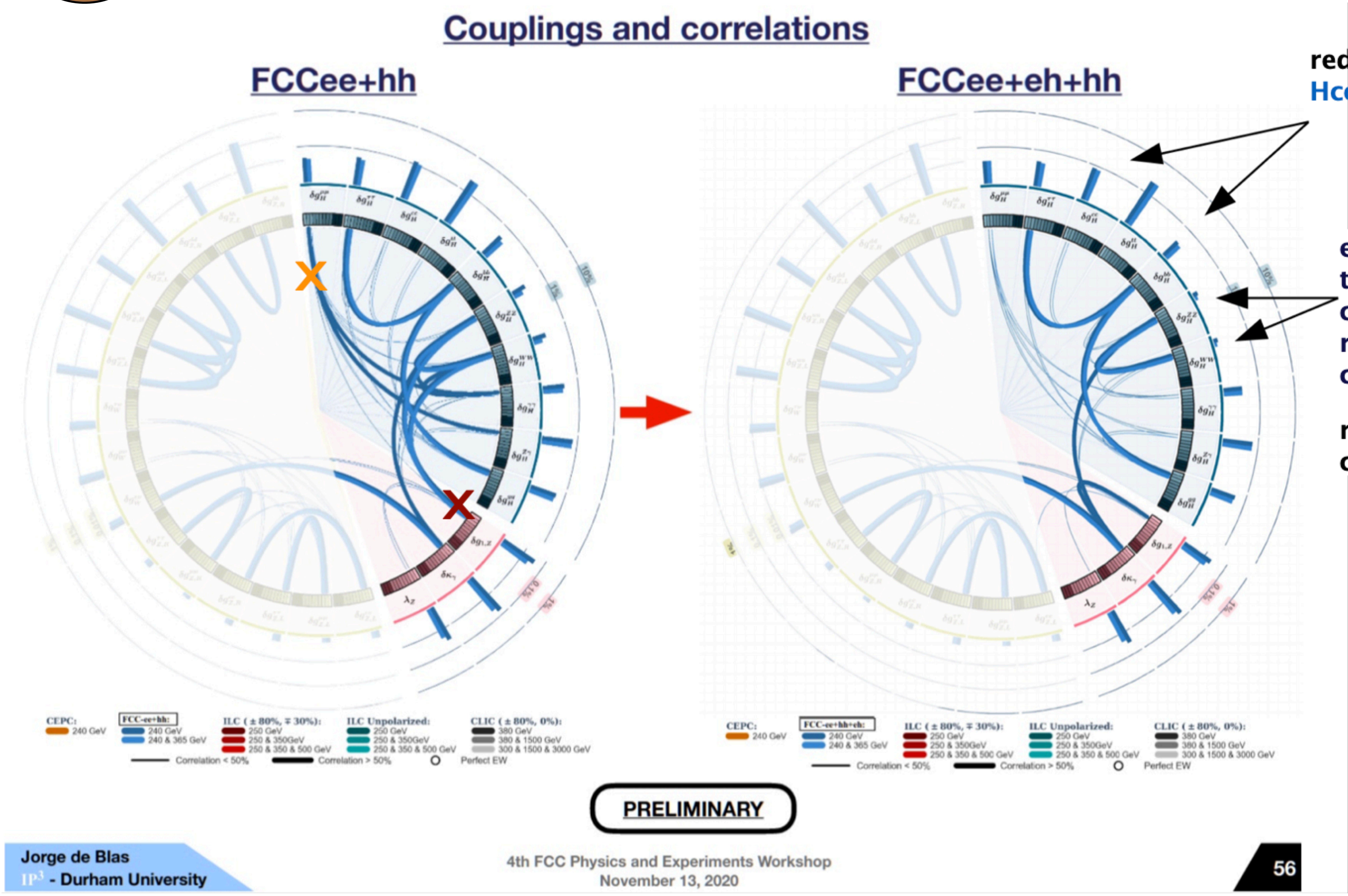

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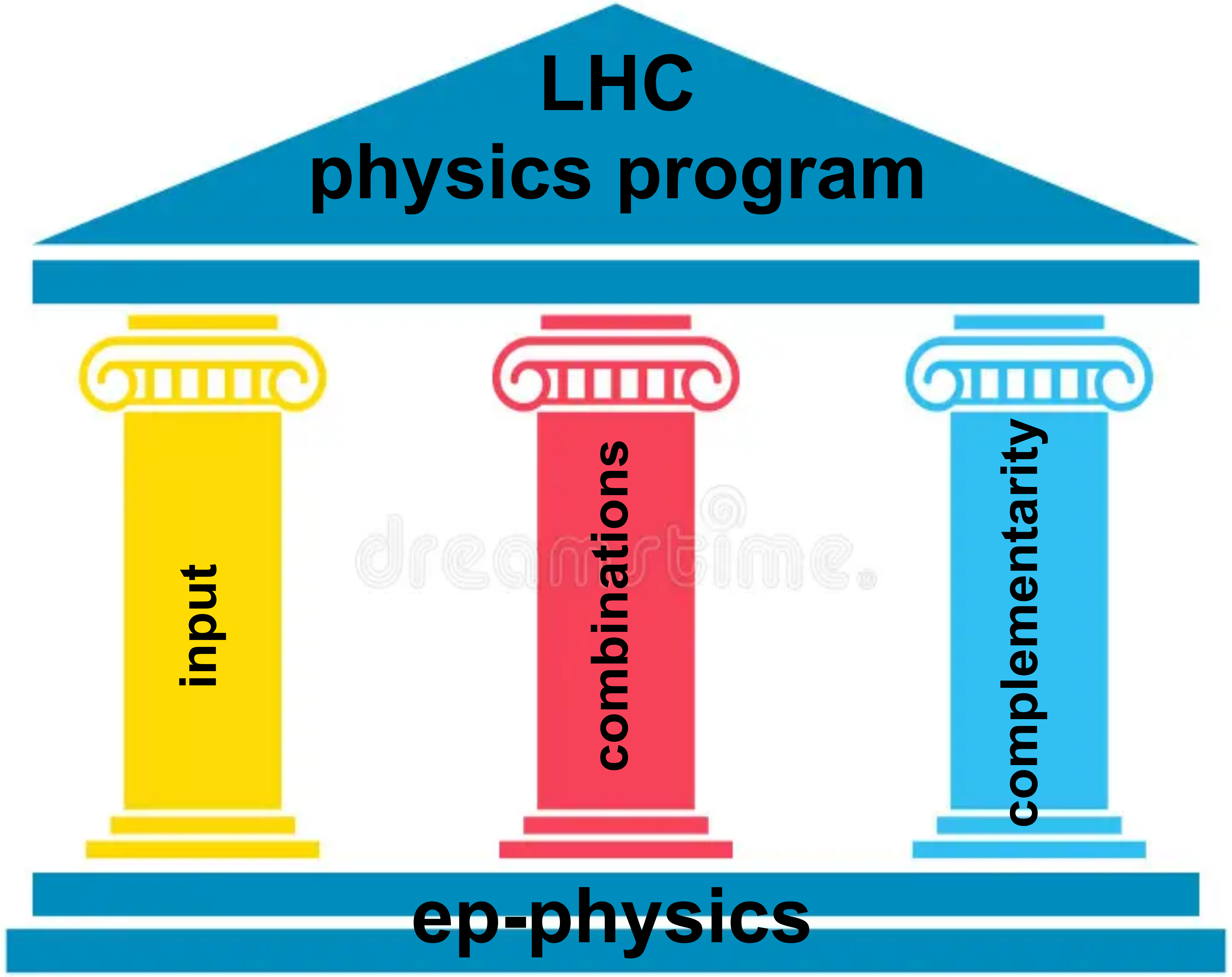
Higgs SMEFT coupling combinations profit from diversity: ee, ep, and pp

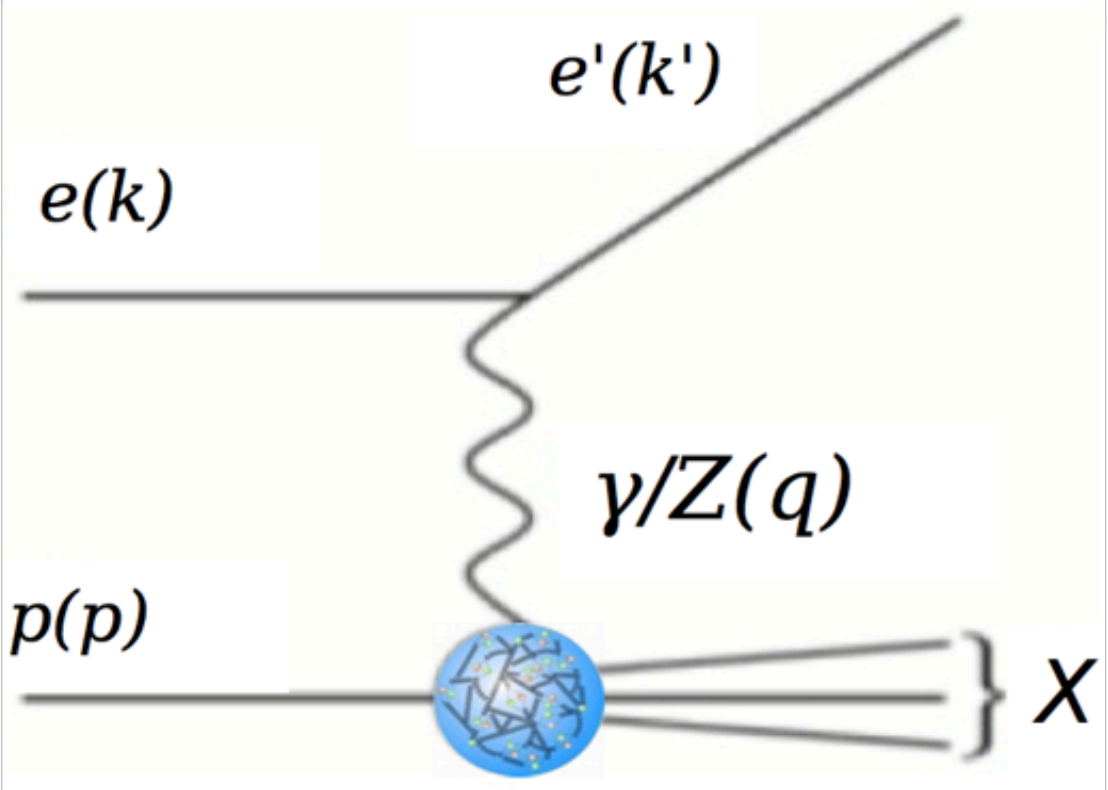
Synergies between LHeC and HL-LHC physics



ep **analyses with sensitivity complementary to LHC analyses to complete the overall LHC physics program**

→ high precision QCD analyses
→ high precision measurements of specific parameters
→ searches in complementary phase space regions

Electroweak Fermion Couplings and SMEFT couplings



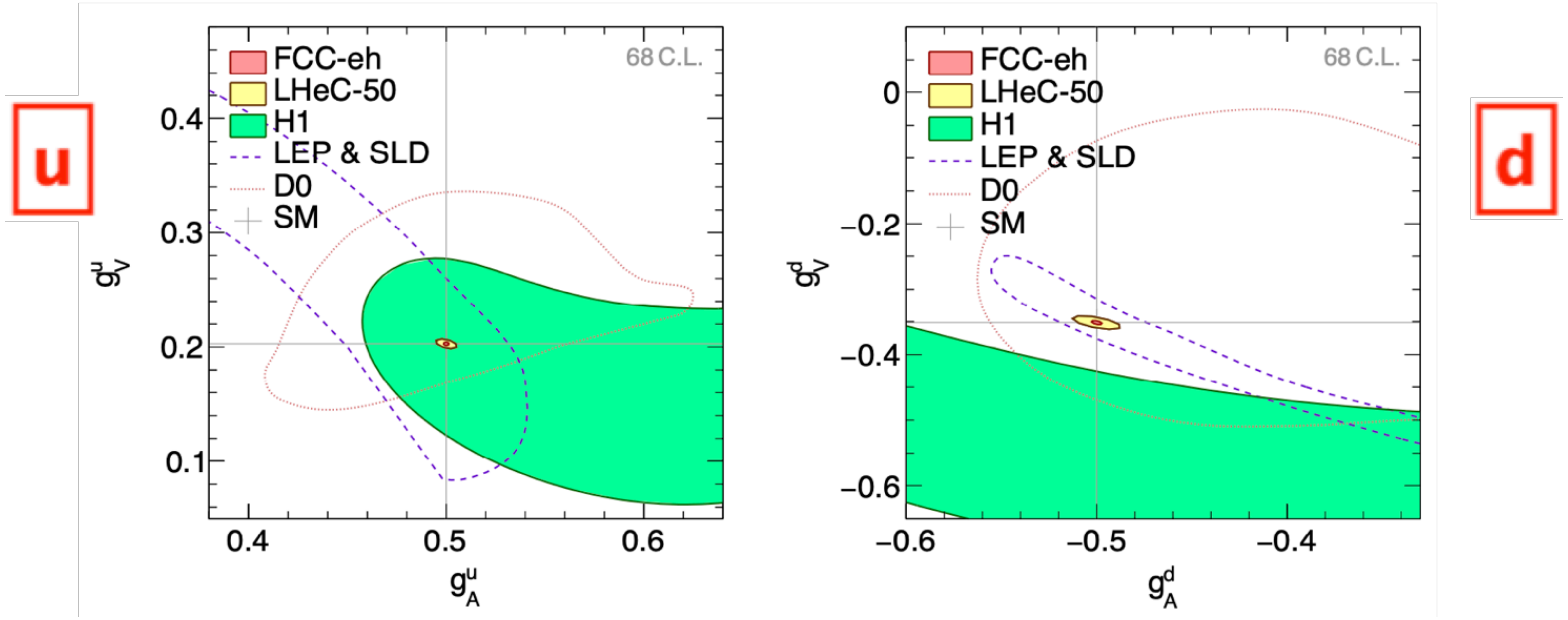
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}} I^3_{\mathrm{L},f} ,$$

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}} \left(I^3_{\mathrm{L},f} - 2Q_f \kappa_{\mathrm{NC},f}\kappa'_{\mathrm{NC},f} \sin^2\theta_W \right)$$

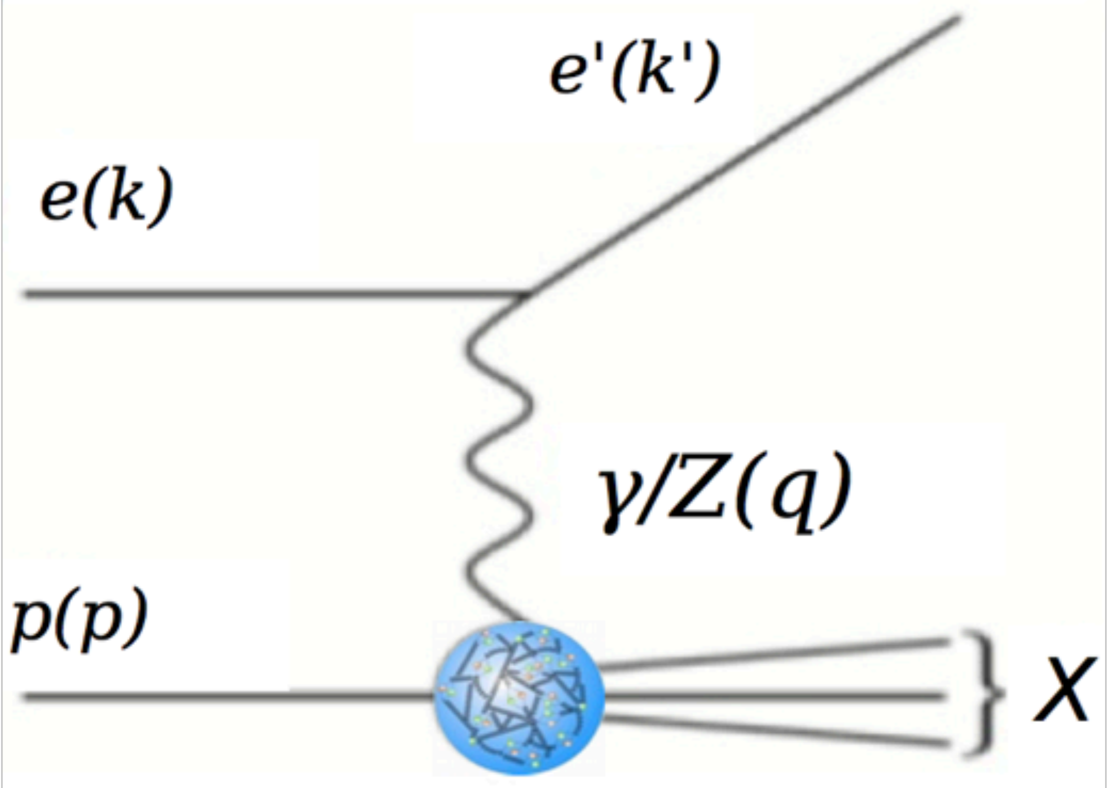
Britzger, Klein, Spiesberger, Eur.Phys.J.C 80 (2020) 831

→ **precision on per mille level**

(largely unaccessible in e^+e^-)



Electroweak Fermion Couplings and SMEFT couplings



$$g_A^f = \sqrt{\rho_{NC,f}\rho'_{NC,f}}I^3_{L,f} ,$$

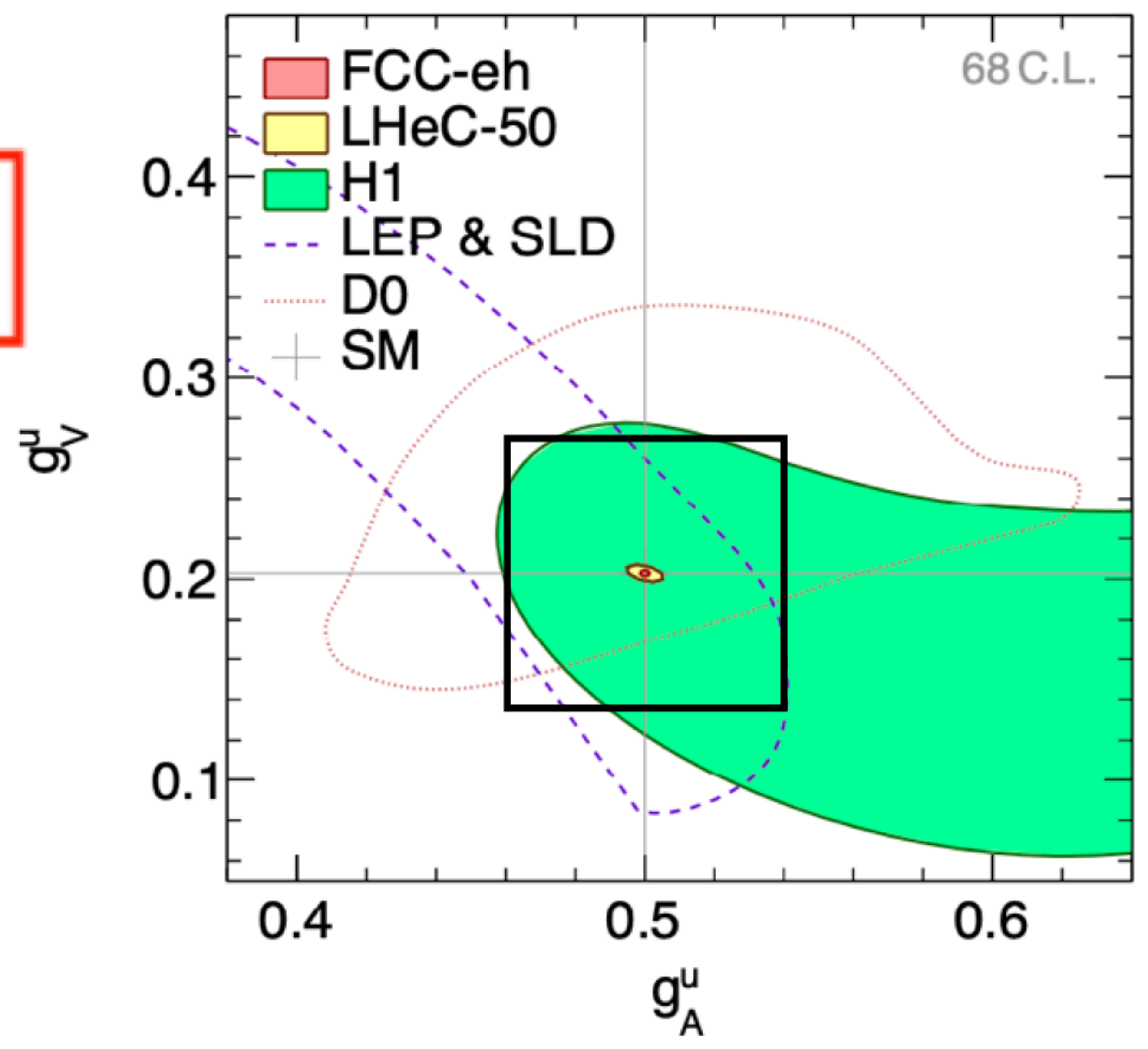
$$g_V^f = \sqrt{\rho_{NC,f}\rho'_{NC,f}}\left(I^3_{L,f} - 2Q_f\kappa_{NC,f}\kappa'_{NC,f}\sin^2\theta_W\right)$$

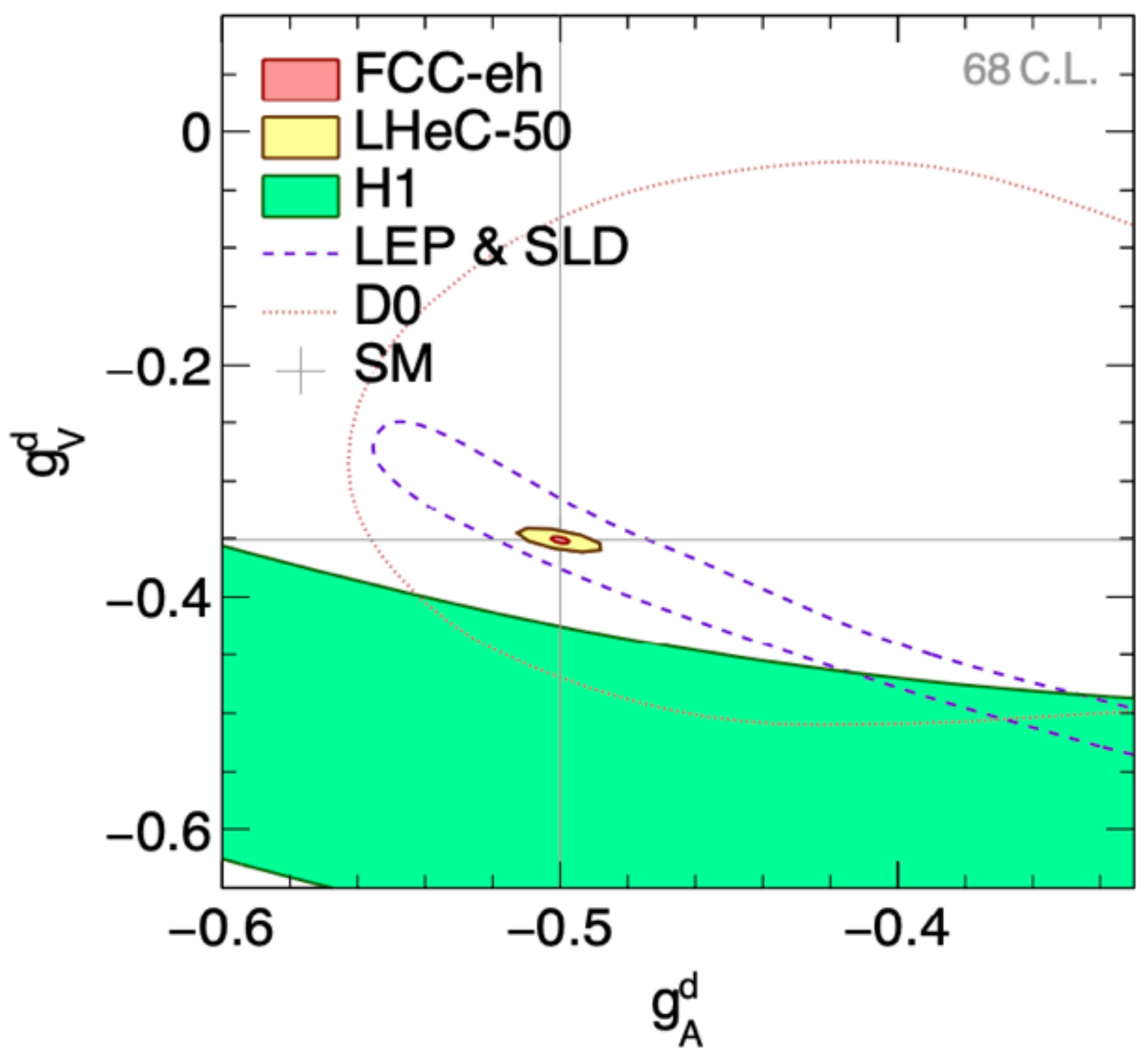
Britzger, Klein, Spiesberger, Eur.Phys.J.C 80 (2020) 831

→ **precision on per mille level**

(largely unaccessible in e^+e^-)

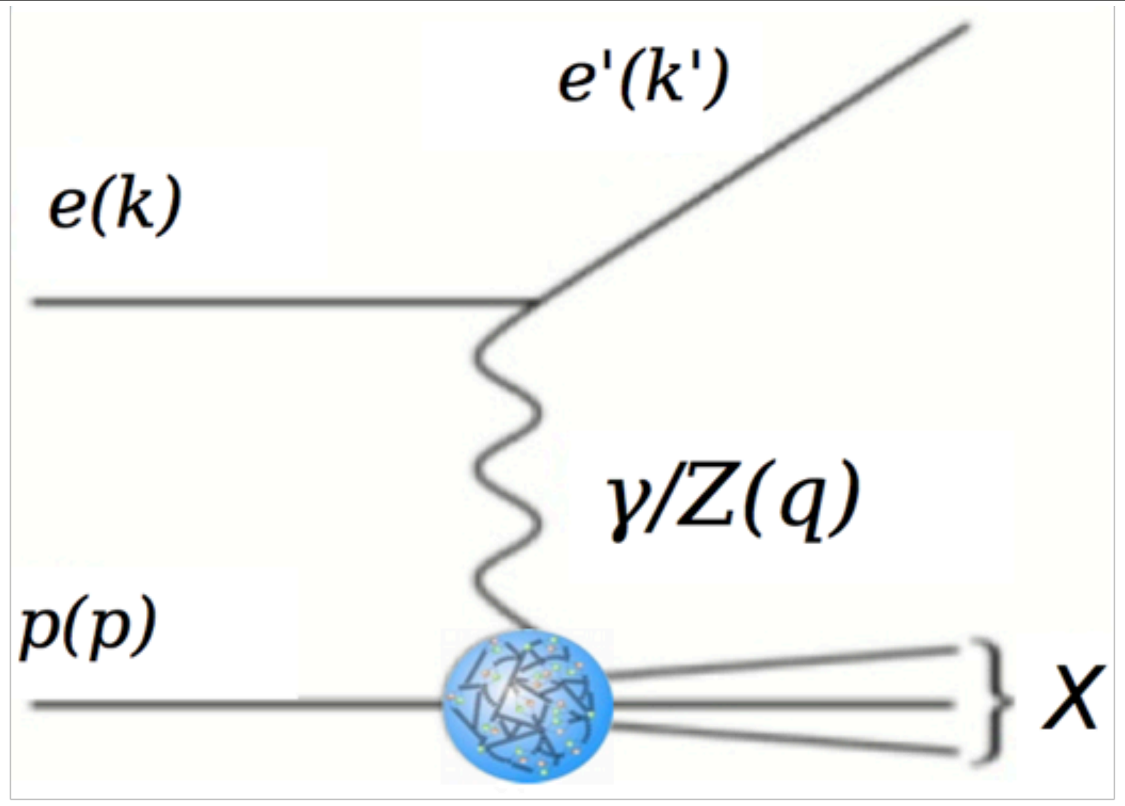
u





d

Electroweak Fermion Couplings and SMEFT couplings



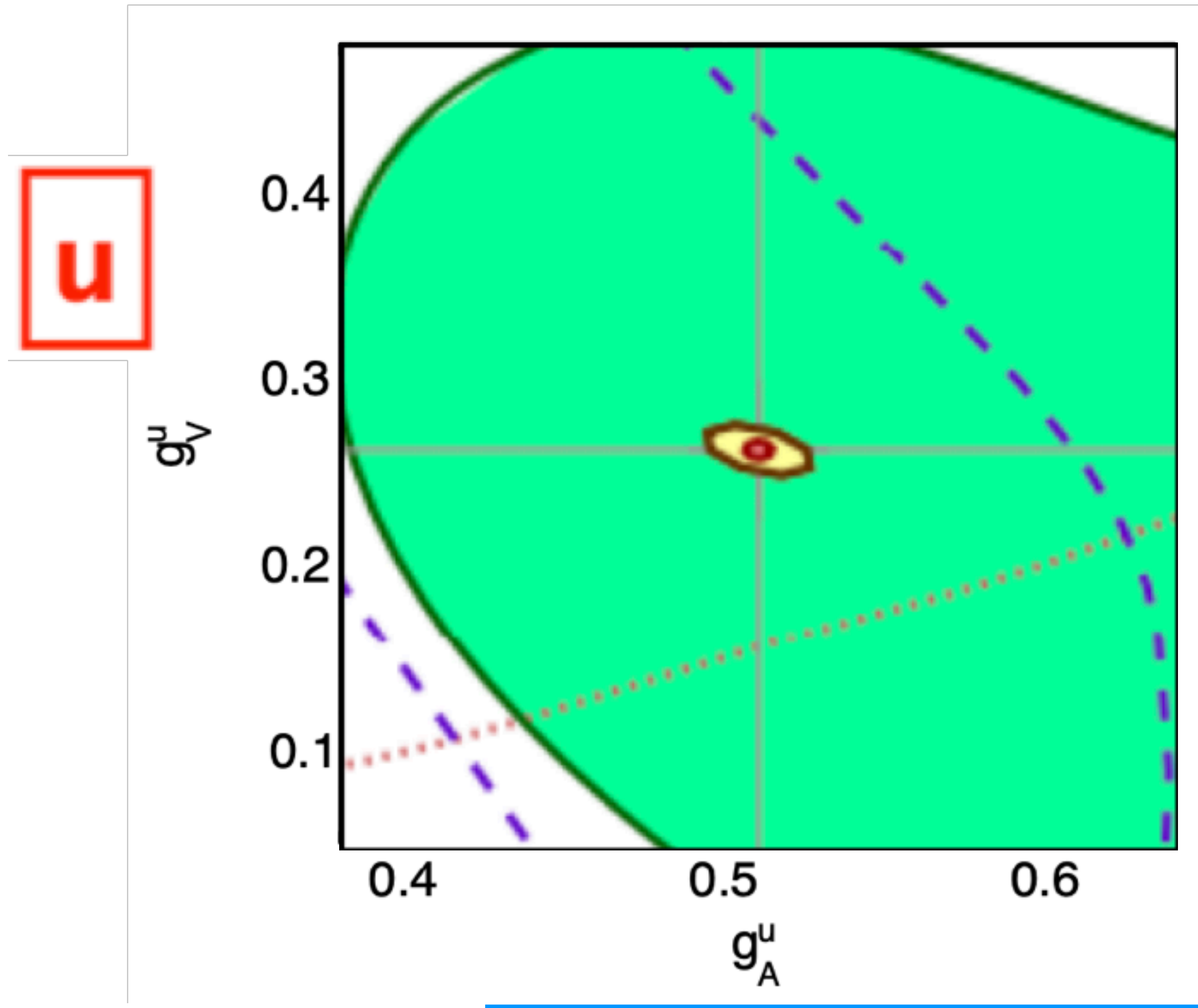
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}} I^3_{\mathrm{L},f} ,$$

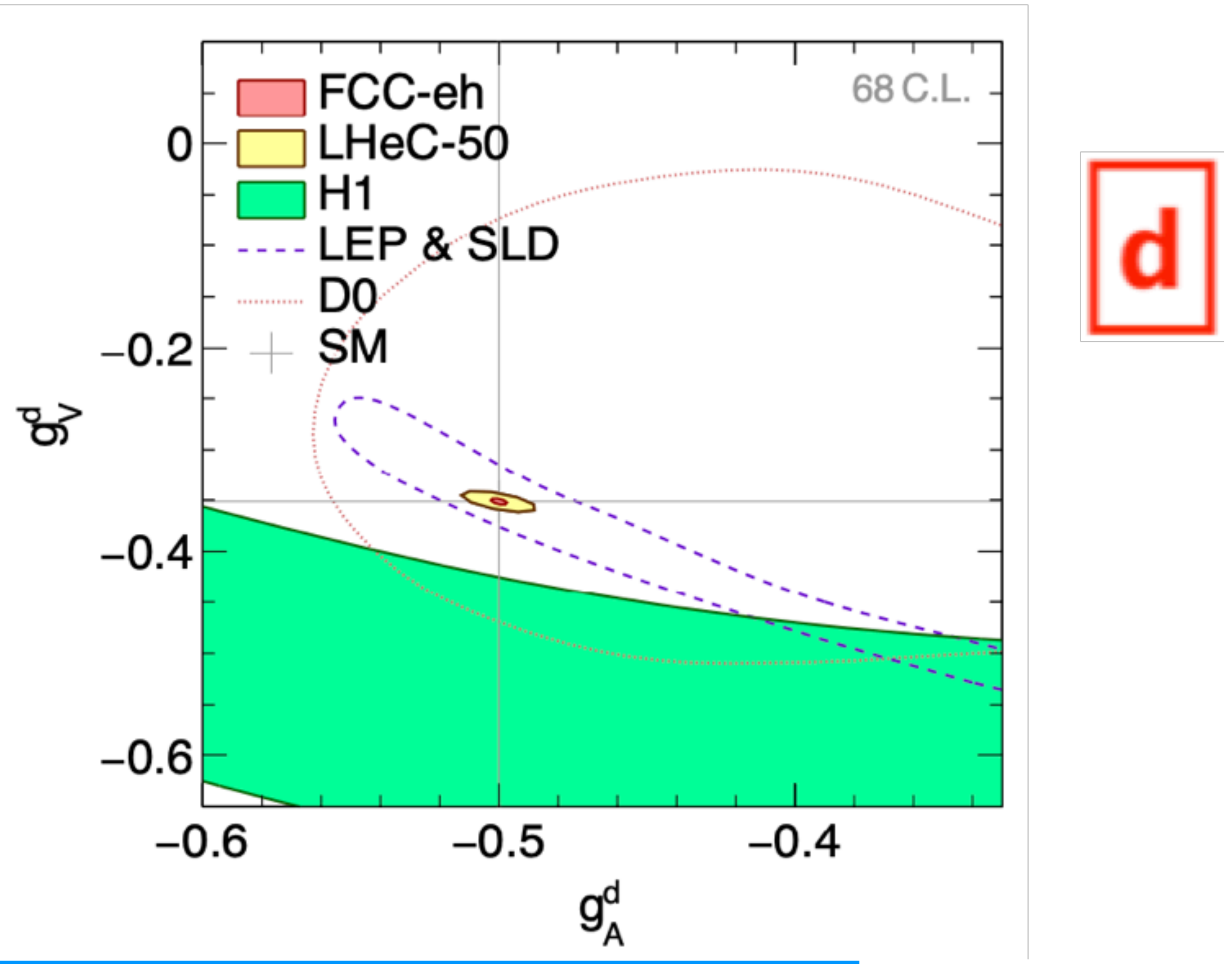
$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}} \left(I^3_{\mathrm{L},f} - 2Q_f \kappa_{\mathrm{NC},f}\kappa'_{\mathrm{NC},f} \sin^2\theta_W\right)$$

Britzger, Klein, Spiesberger, Eur.Phys.J.C 80 (2020) 831

→ **precision on per mille level**

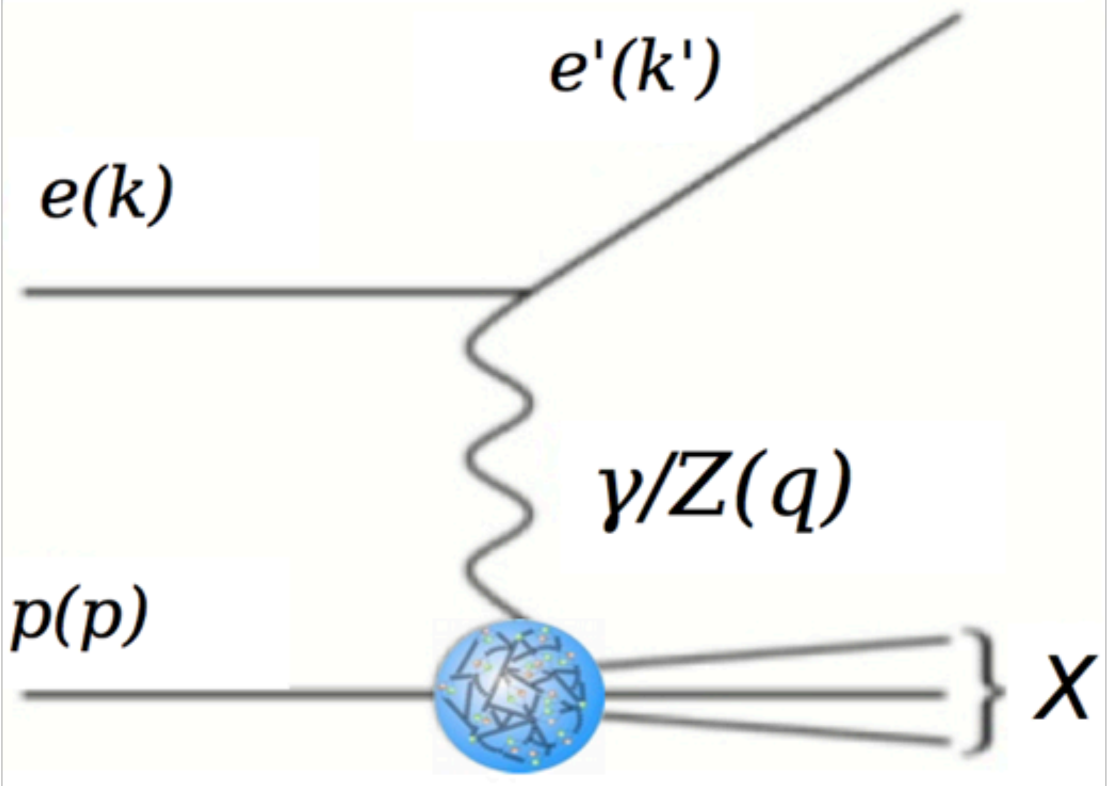
(largely unaccessible in e+e-)





Electroweak physics of 1st generation quarks are largely inaccessible in other colliders

Electroweak Fermion Couplings and SMEFT couplings



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Britzger, Klein, Spiesberger, Eur.Phys.J.C 80 (2020) 831

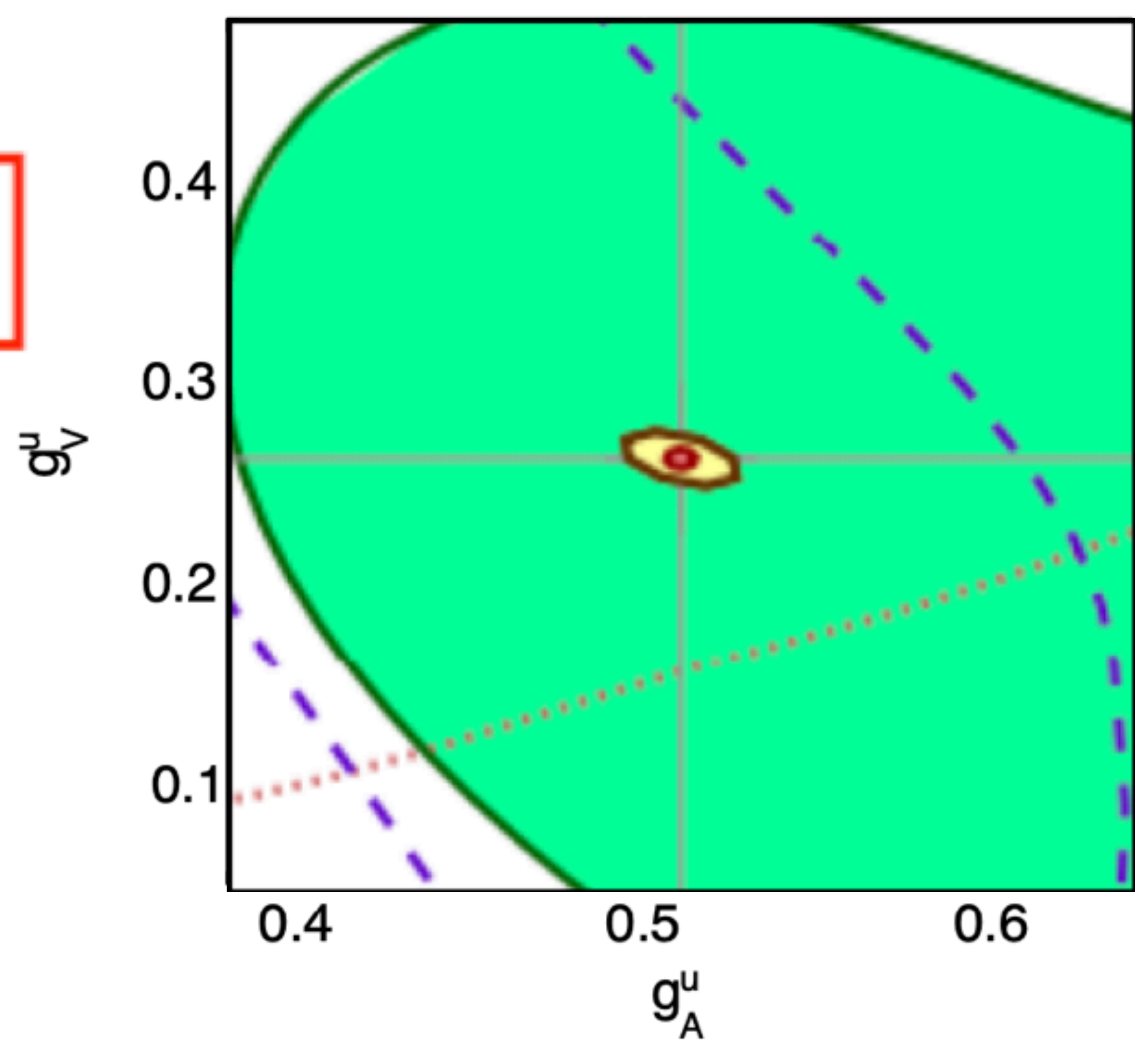
→ **precision on per mille level**

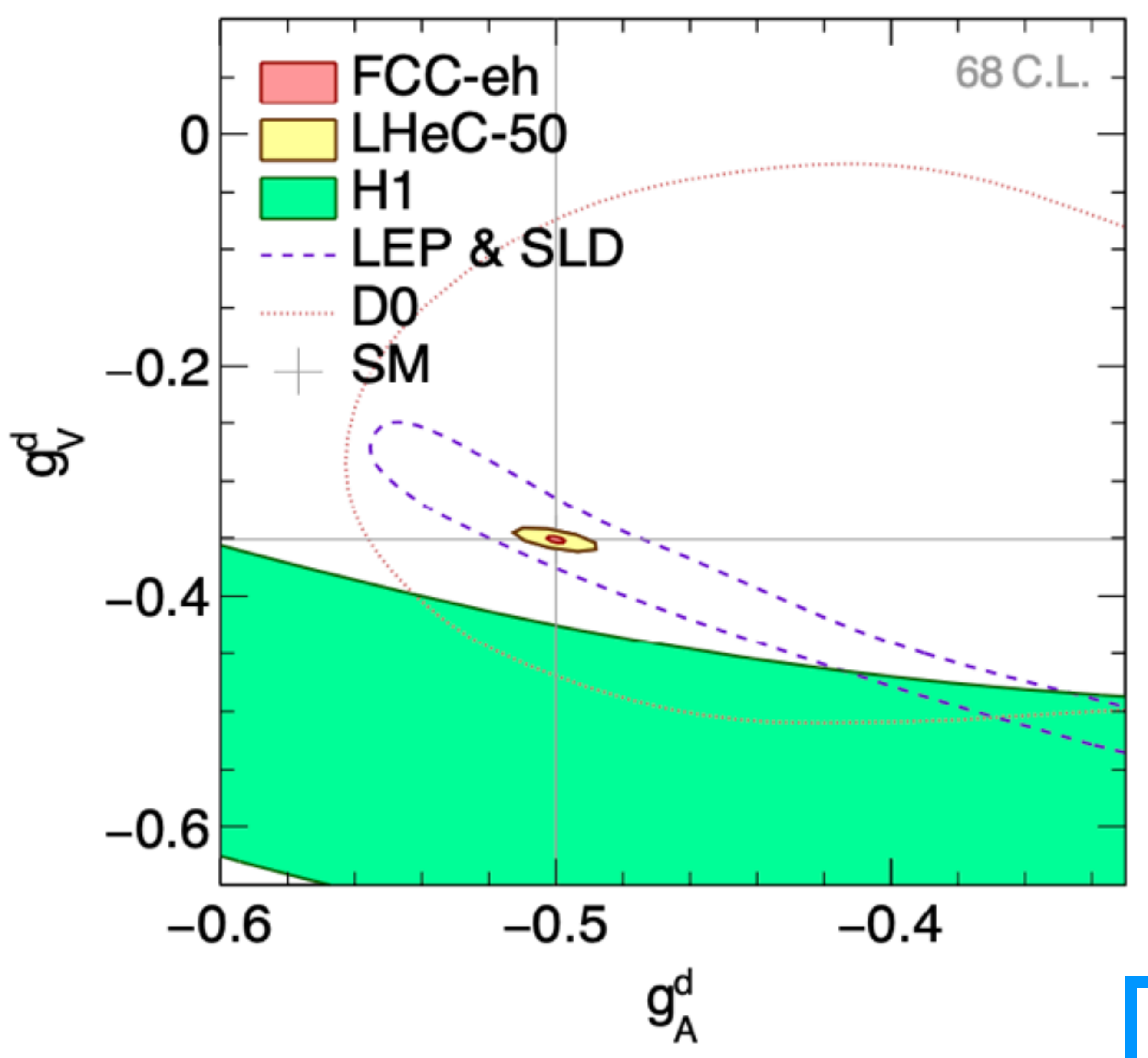
(largely unaccessible in e^+e^-)

$$O_{\varphi q}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{q}\gamma^\mu \tau^I q)$$

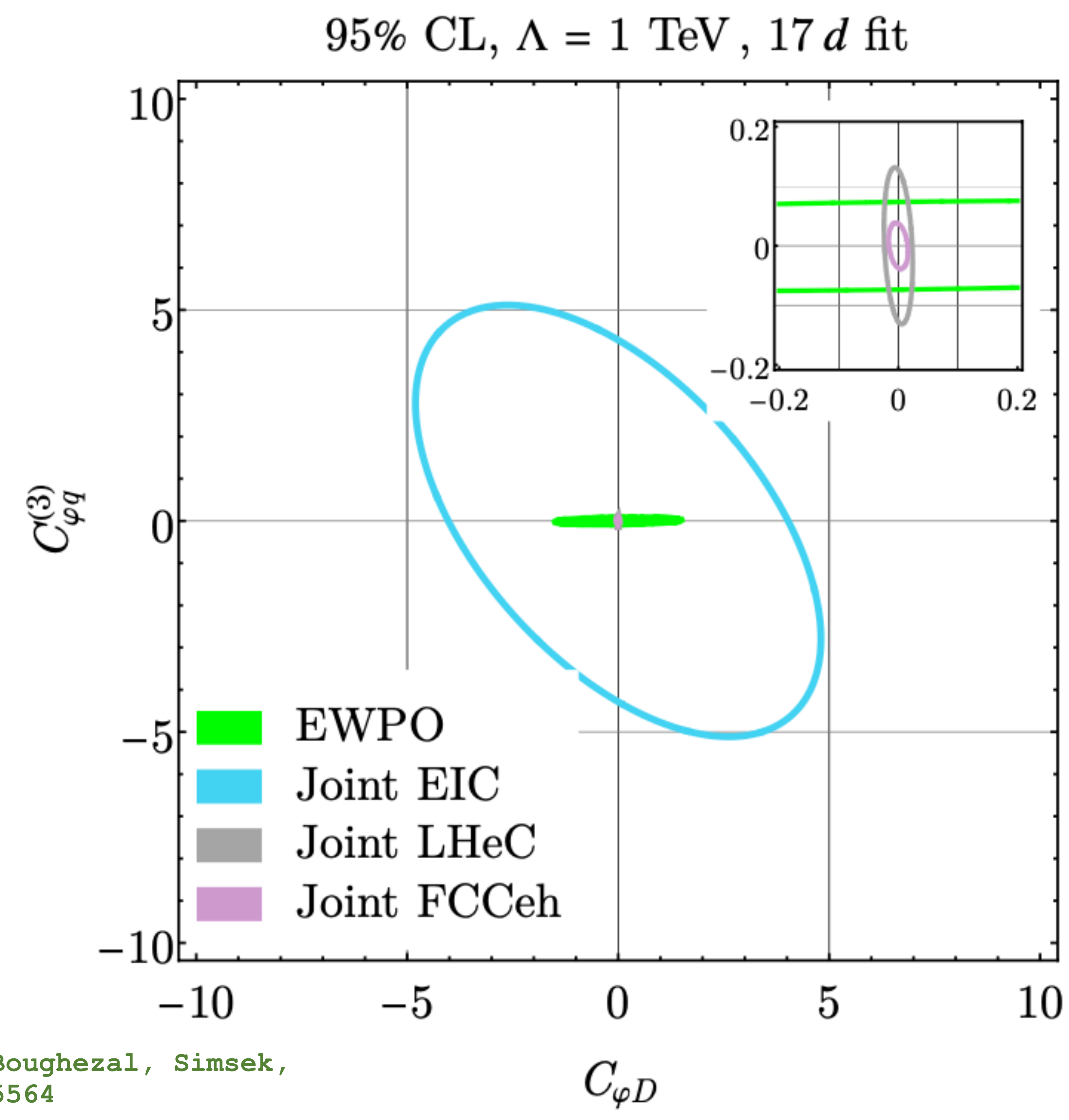
$$O_{\varphi D} = (\varphi^\dagger D_\mu \varphi)^* (\varphi^\dagger D^\mu \varphi)$$

u





d



Bissolotti, Boughezal, Simsek, arXiv:2306.05564

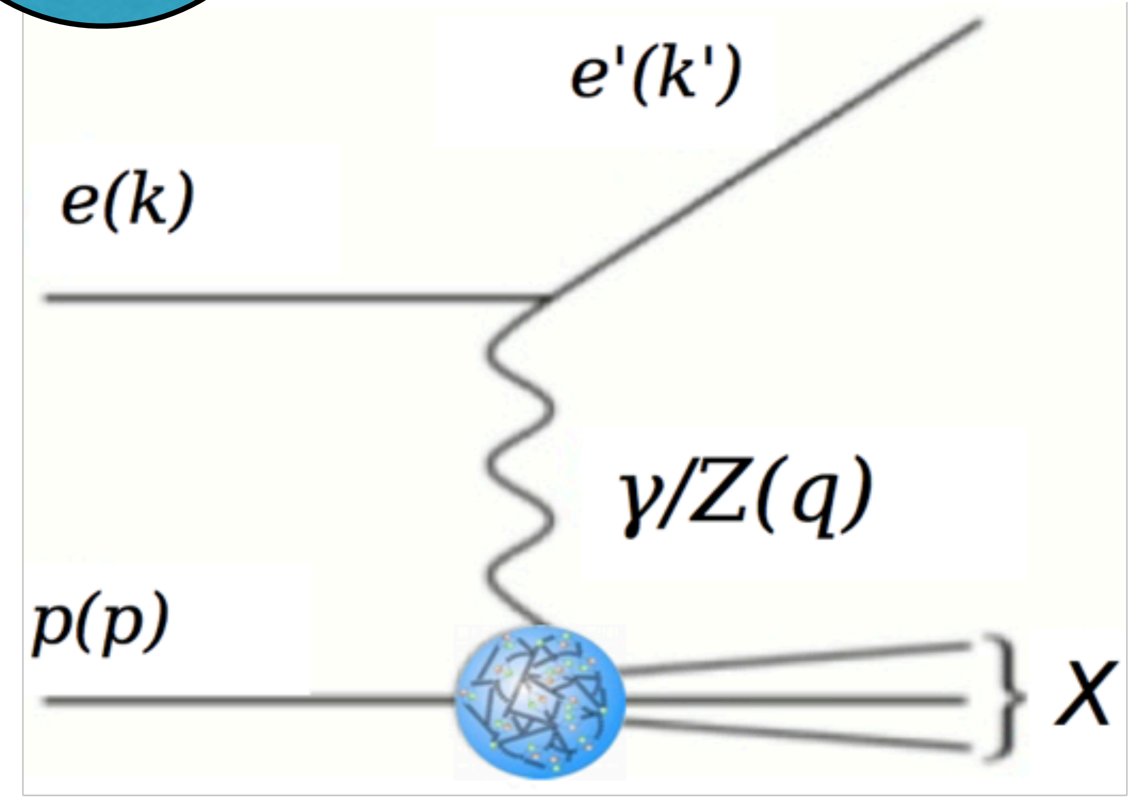
Electroweak physics of 1st generation quarks are largely inaccessible in other colliders

FCC-eh and LHeC will improve upon existing precision electroweak bounds in SMEFT parameter space in many cases, also for correlations

EWK Fermion Couplings and SMEFT couplings

EWK

BSM



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Britzger, Klein, Spiesberger, Eur.Phys.J.C 80 (2020) 831

→ **precision on per mille level**

(largely unaccessible in e^+e^-)

$$O^{(3)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{q}\gamma^\mu \tau^I q)$$

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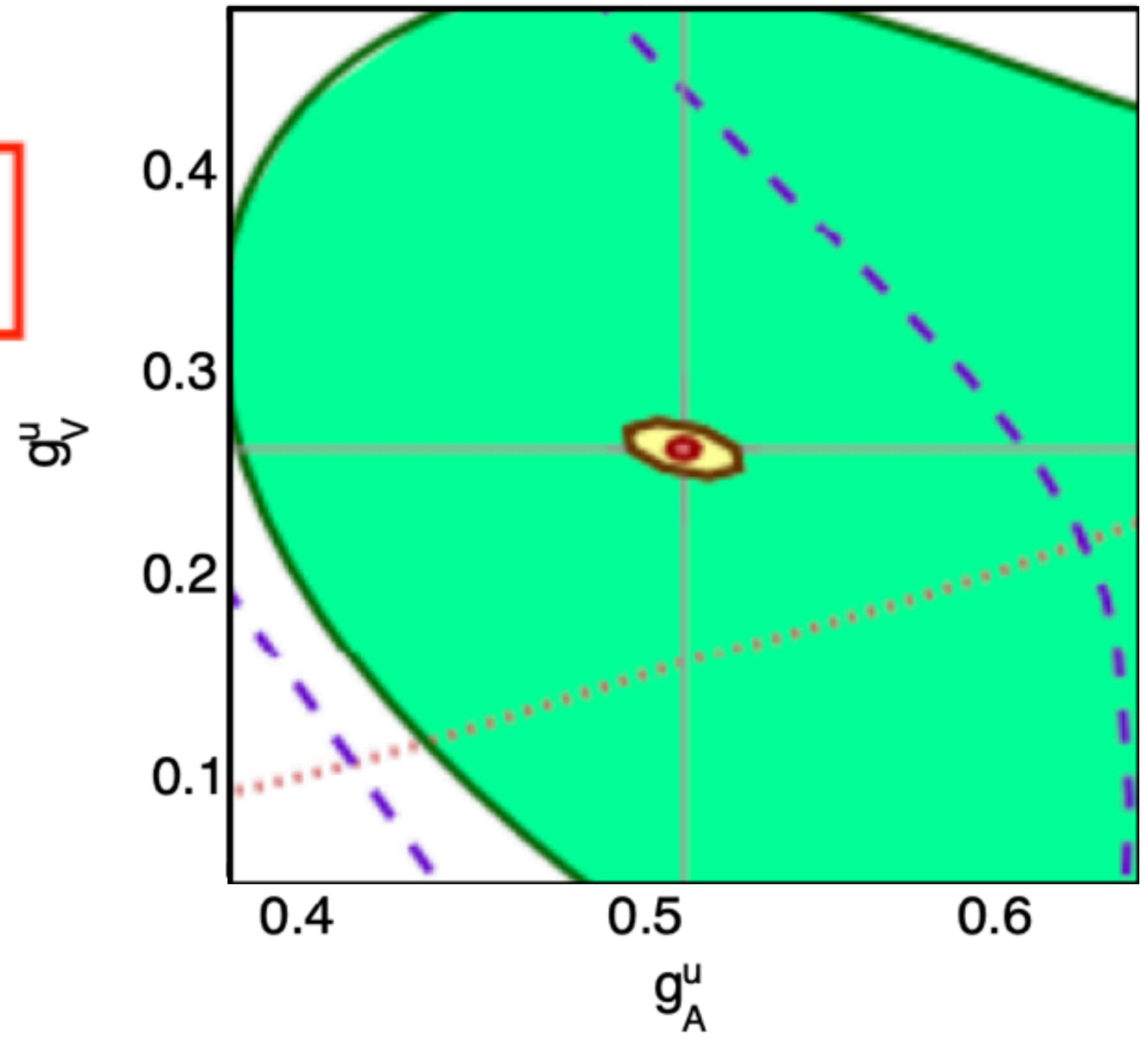
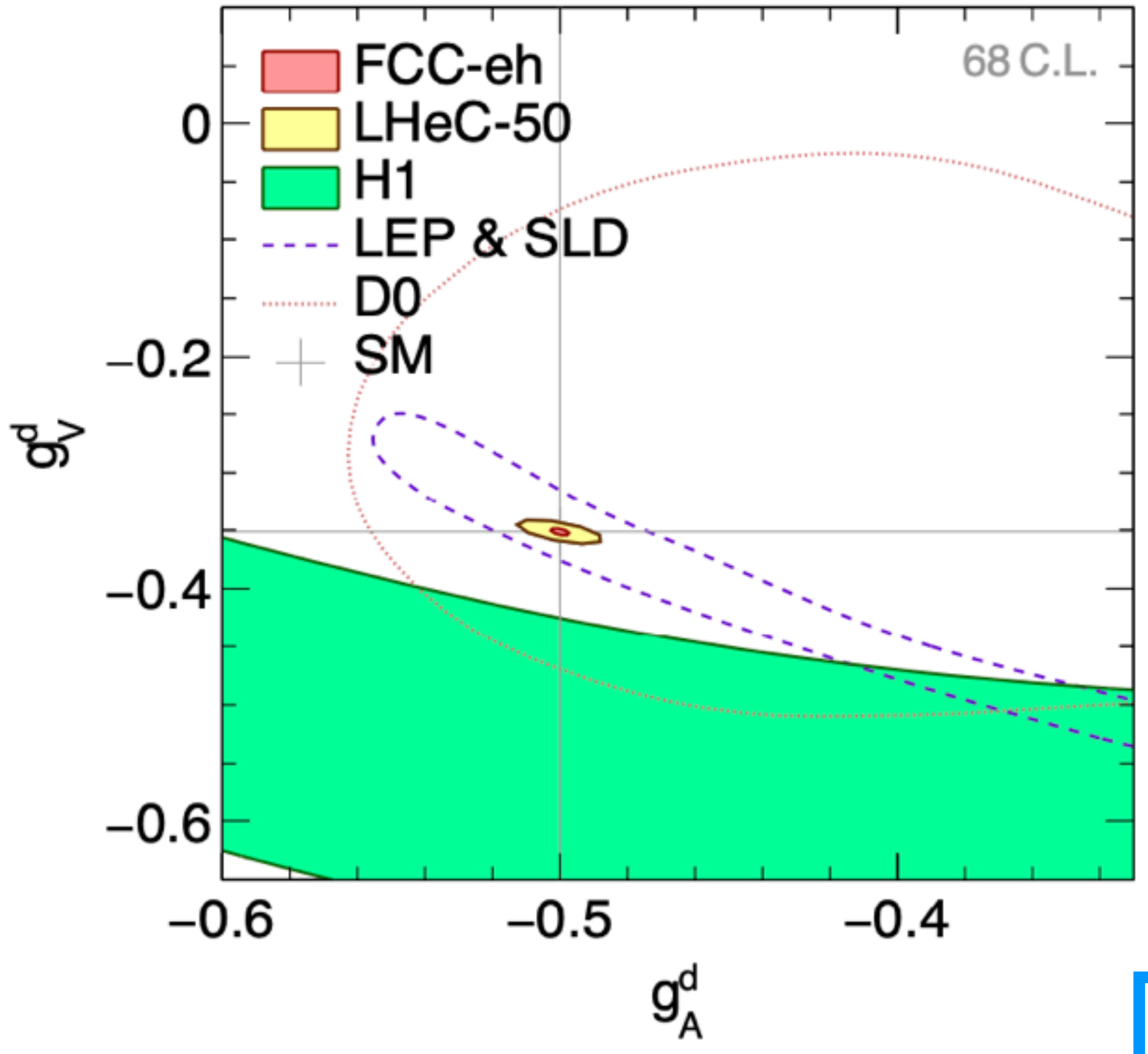
u





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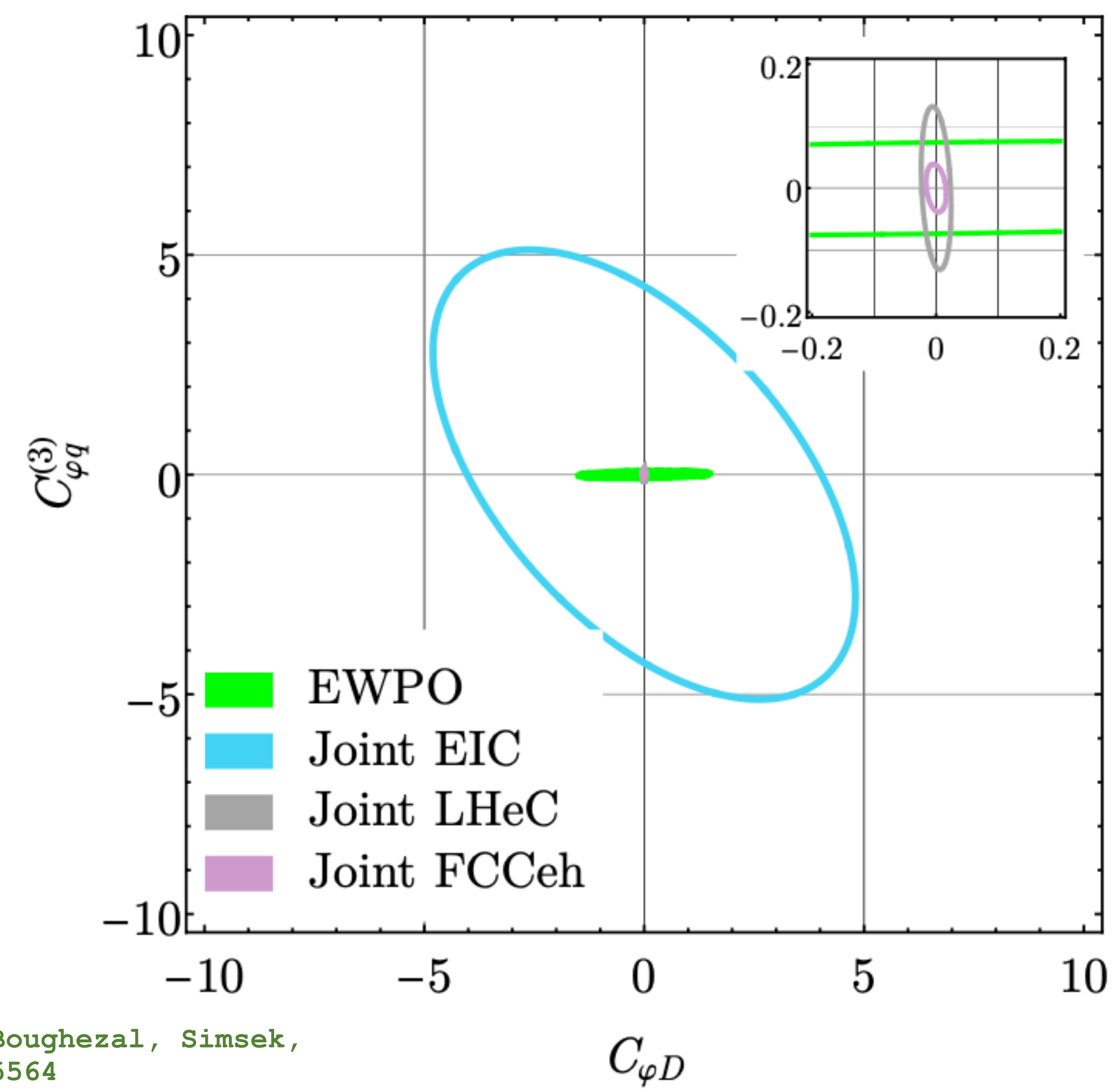


Bissolotti, Boughezal, Simsek, arXiv:2306.05564

Electroweak physics of 1st generation quarks are largely inaccessible in other colliders

FCC-eh and LHeC will improve upon existing precision electroweak bounds in SMEFT parameter space in many cases, also for correlations

EWK

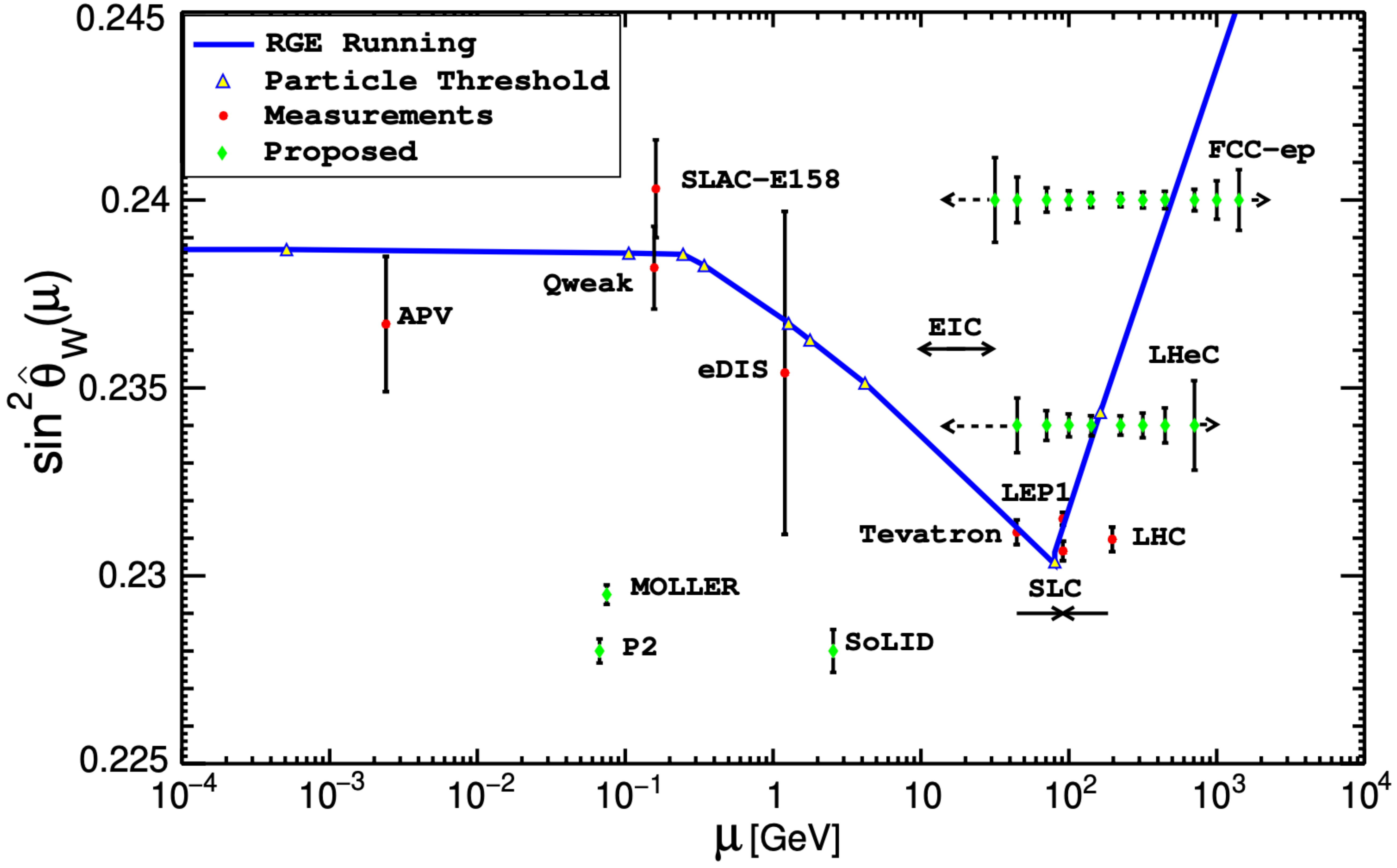
Scale Dependence of $\sin^2\theta_W$

BSM

PERLE CDR,
CERN-ACC-NOTE-2018-0086

arXiv:2203.06237

LHeC CDR,
J.Phys. G39,
075001 (2012)



→ probe large range of scale dependence

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\left(I^3_{\mathrm{L},f} - 2Q_f\kappa_{\mathrm{NC},f}\sin^2\theta_W\right)$$

$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}}\, I^3_{\mathrm{L},f}$$

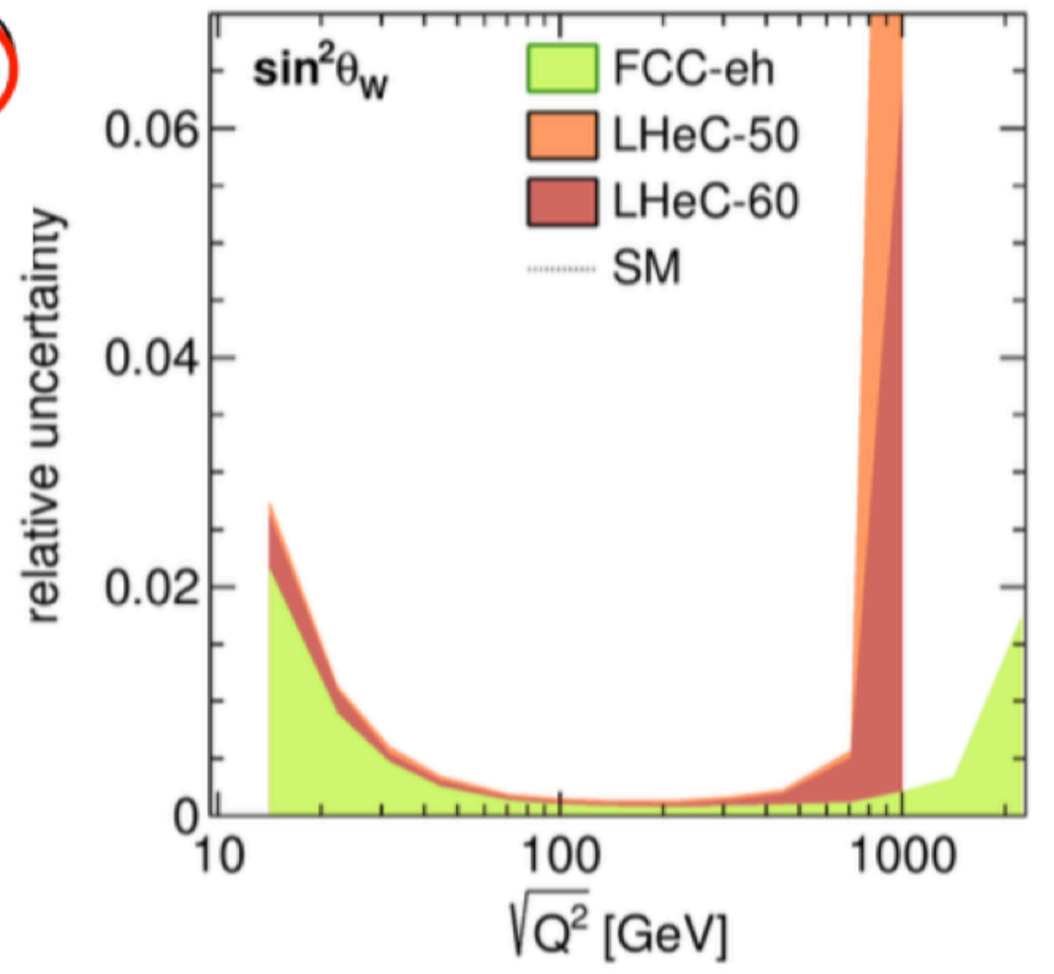
→ precision per mille level

→ scale dependence

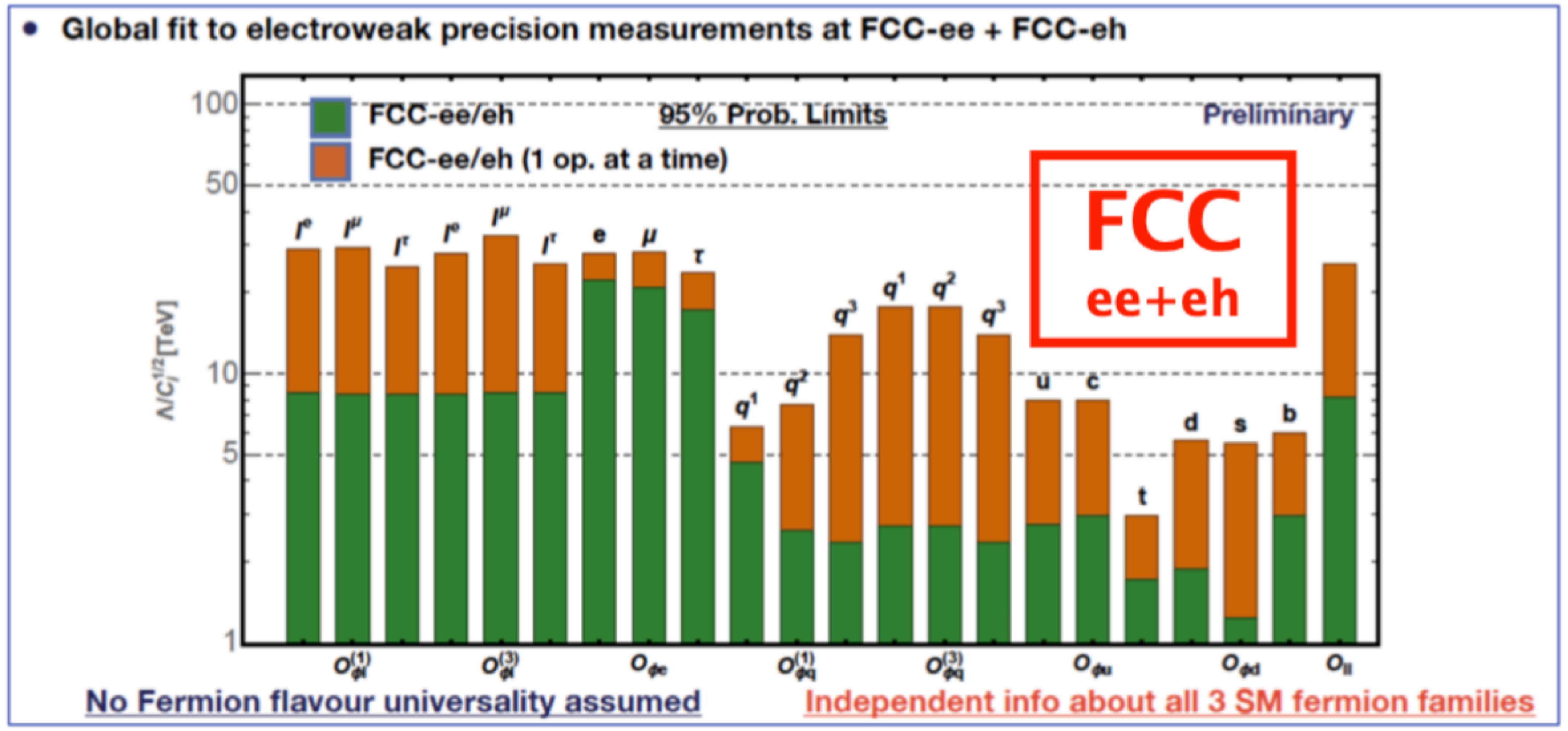
$\Delta\sin^2\theta_w$ (FCC-eh) = ±0.00011
= ±0.00010$_{(exp)}$ ±0.00004$_{(PDF)}$

Δm_W = ± 4.5 MeV

(includes PDF uncertainty of about ±3.6 MeV)

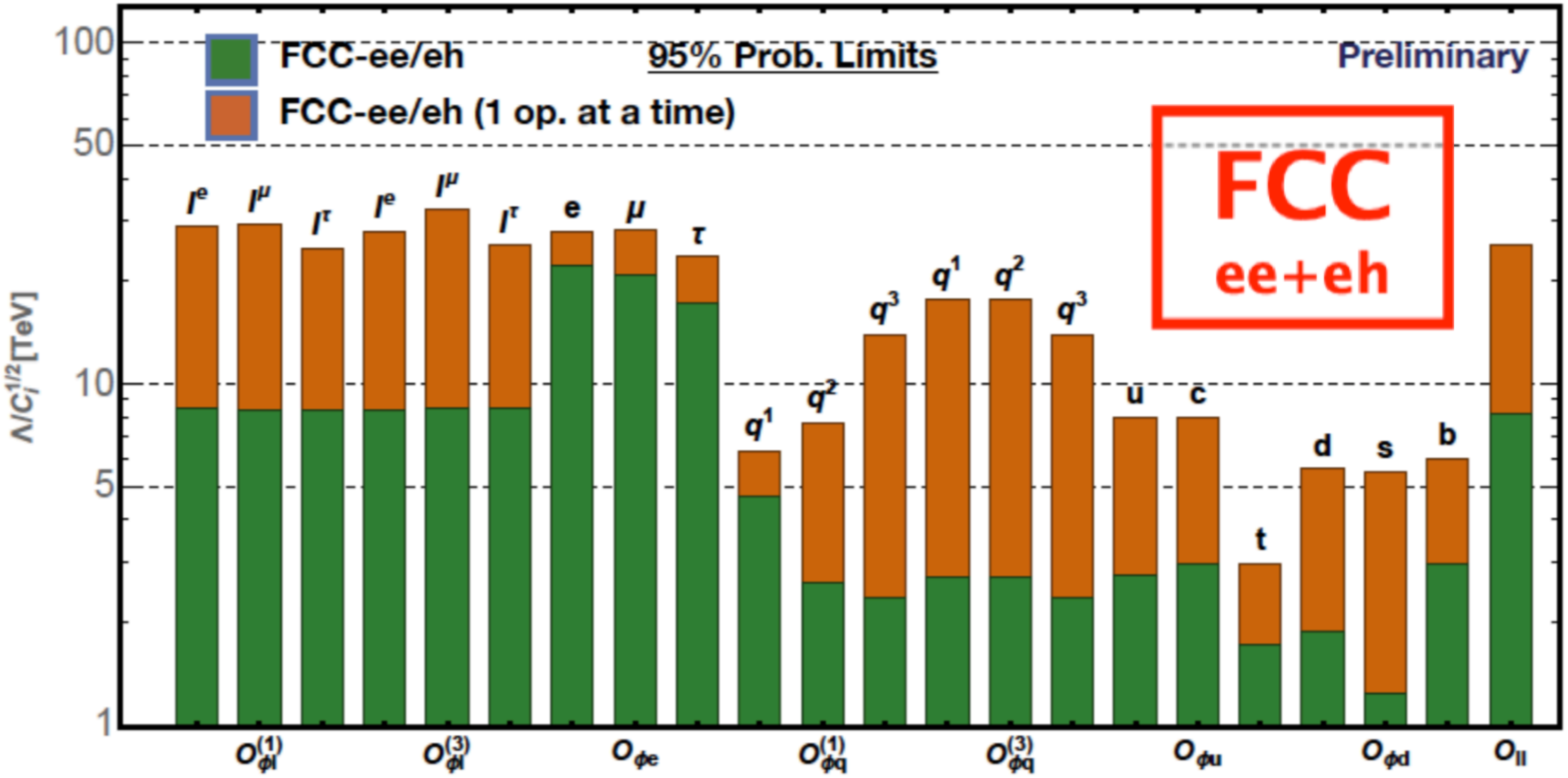


→ high sensitivity to NP



Constraints on New Physics

- Global fit to electroweak precision measurements at FCC-ee + FCC-eh



No Fermion flavour universality assumed

Independent info about all 3 SM fermion families

→ **high sensitivity to NP**

Expected measurements of Wtb couplings

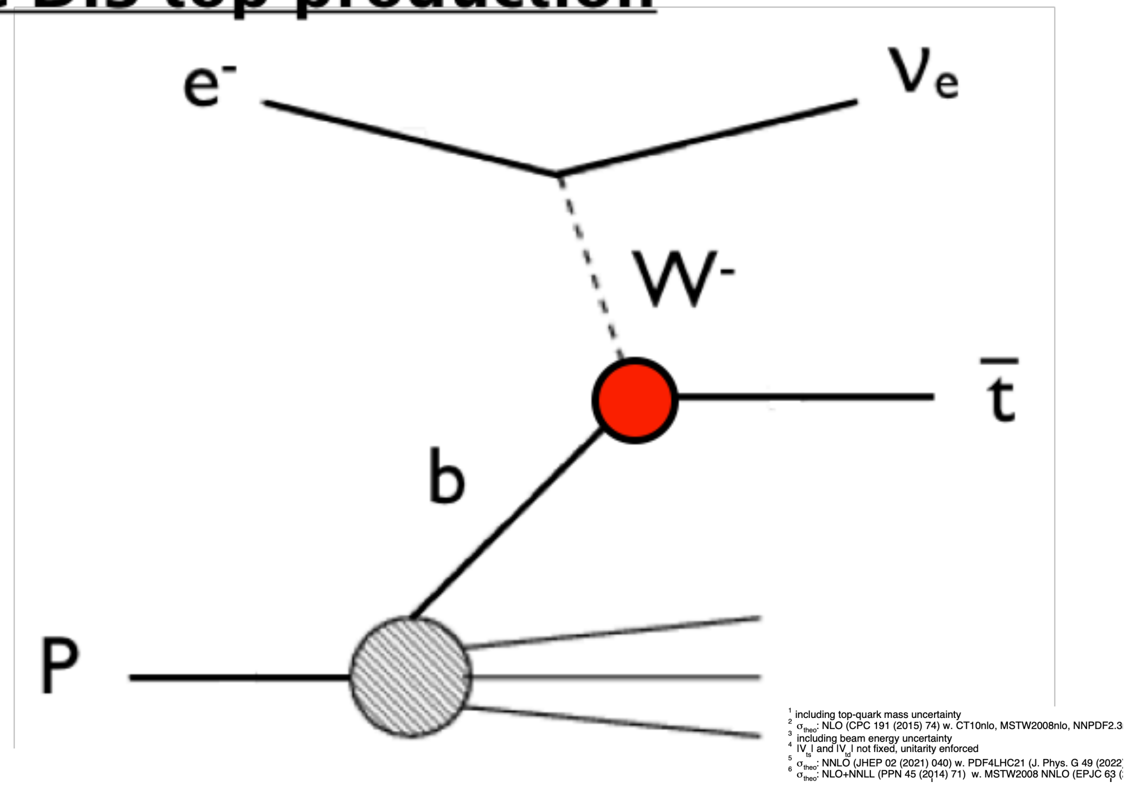
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

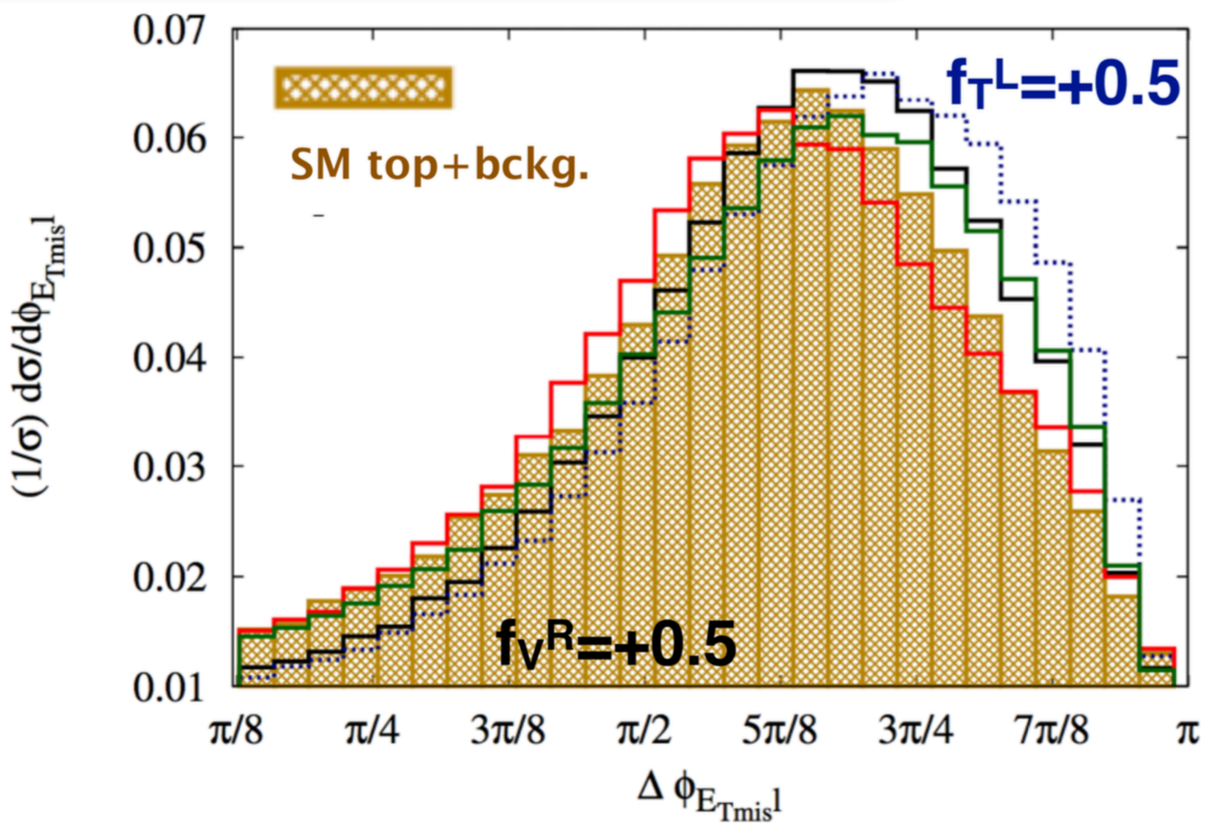
= 1 in SM

Dutta, Goyal, Kumar, Mellado,
arXiv:1307.1688
Kumar, Ruan, to be publ.

LHeC

CC DIS top production





+ other variables sensitive on W helicity

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Expected measurements of Wtb couplings

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Dutta, Goyal, Kumar, Mellado,
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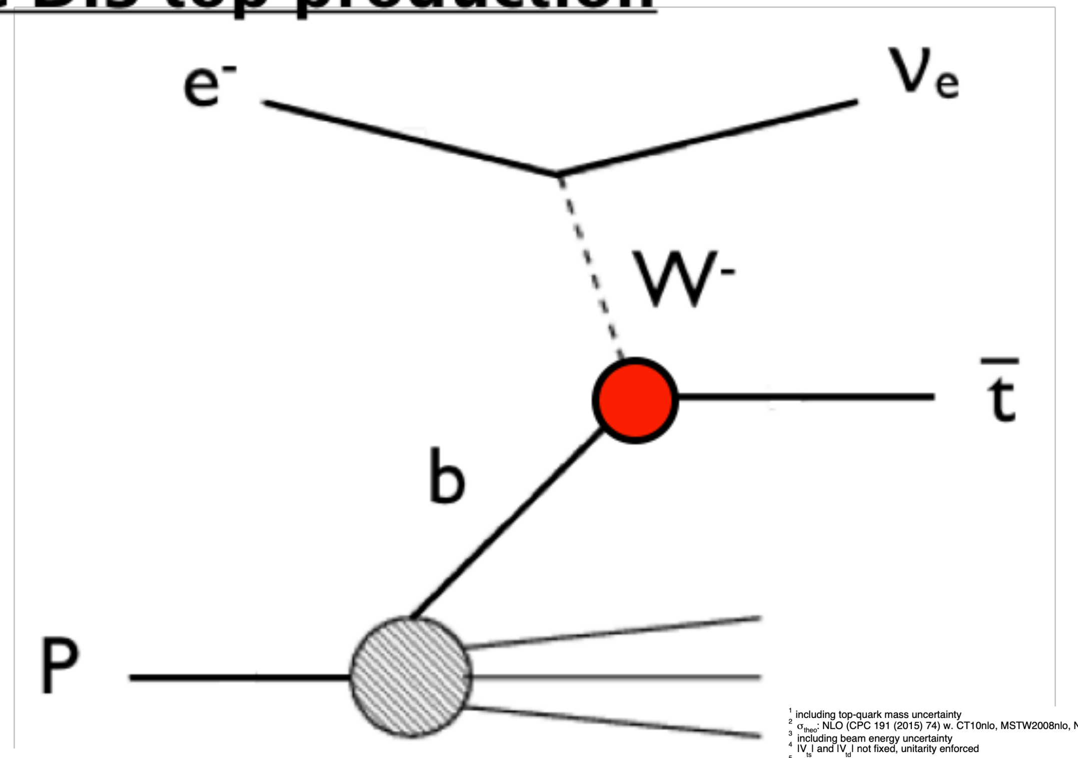
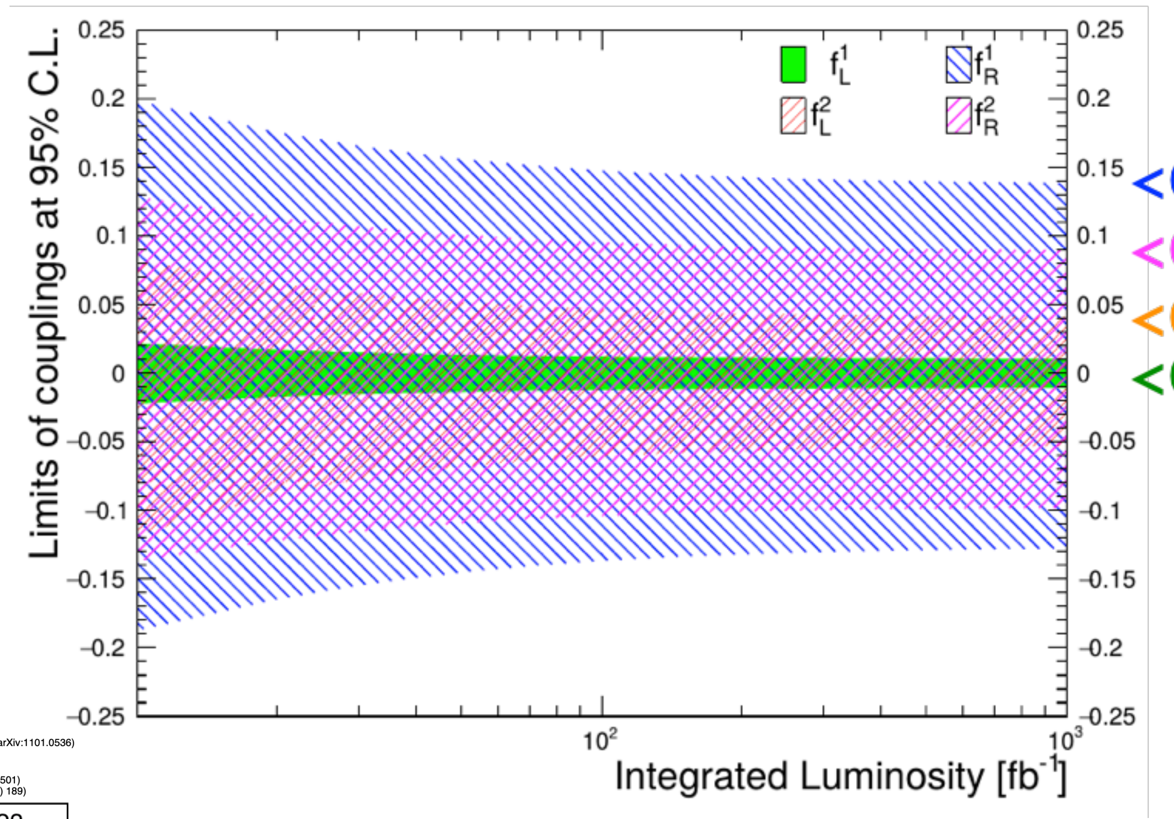
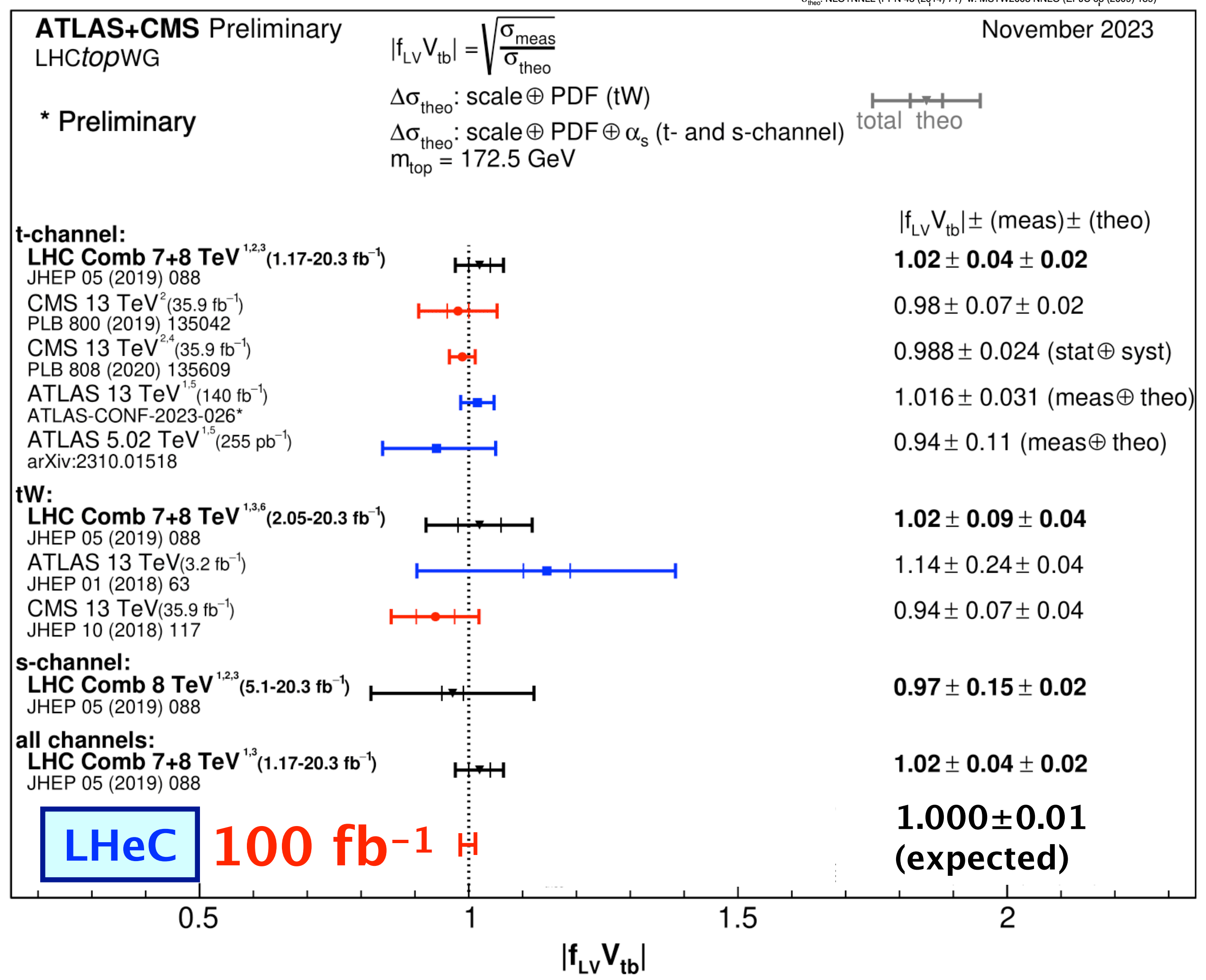


LHeC

hadronic channel:





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Unprecedented precision < 1%

Expected measurements of Wtb couplings

= 1 in SM

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Dutta, Goyal, Kumar, Mellado,
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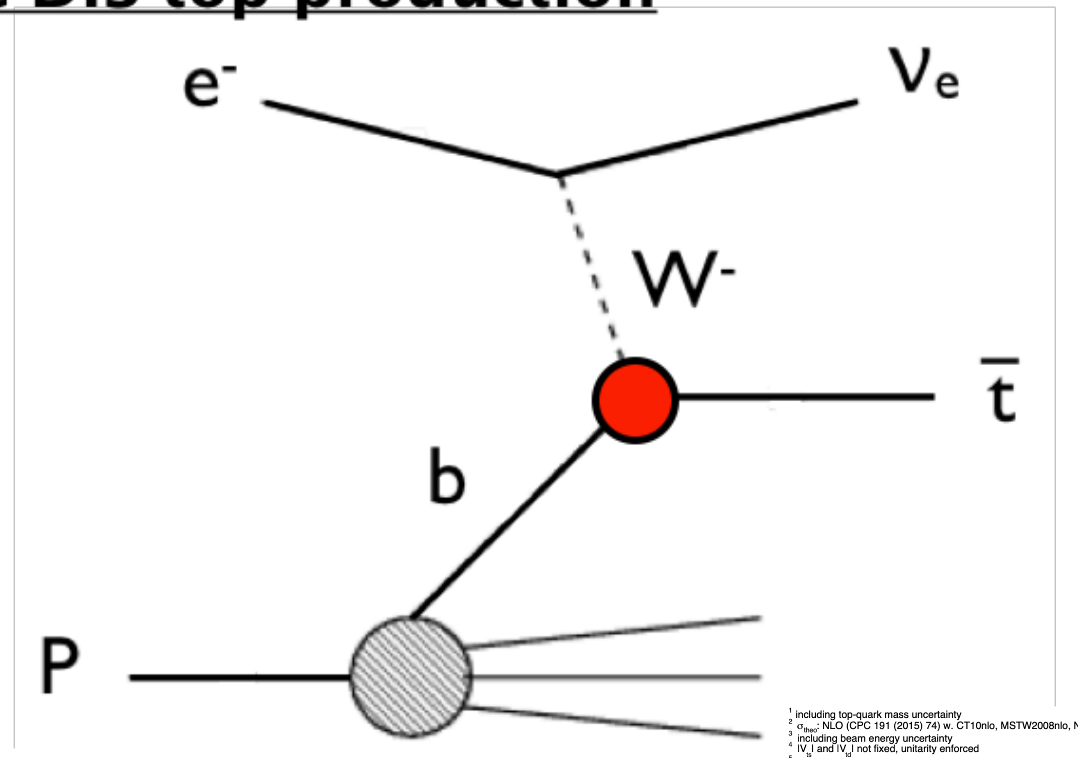

LHeC

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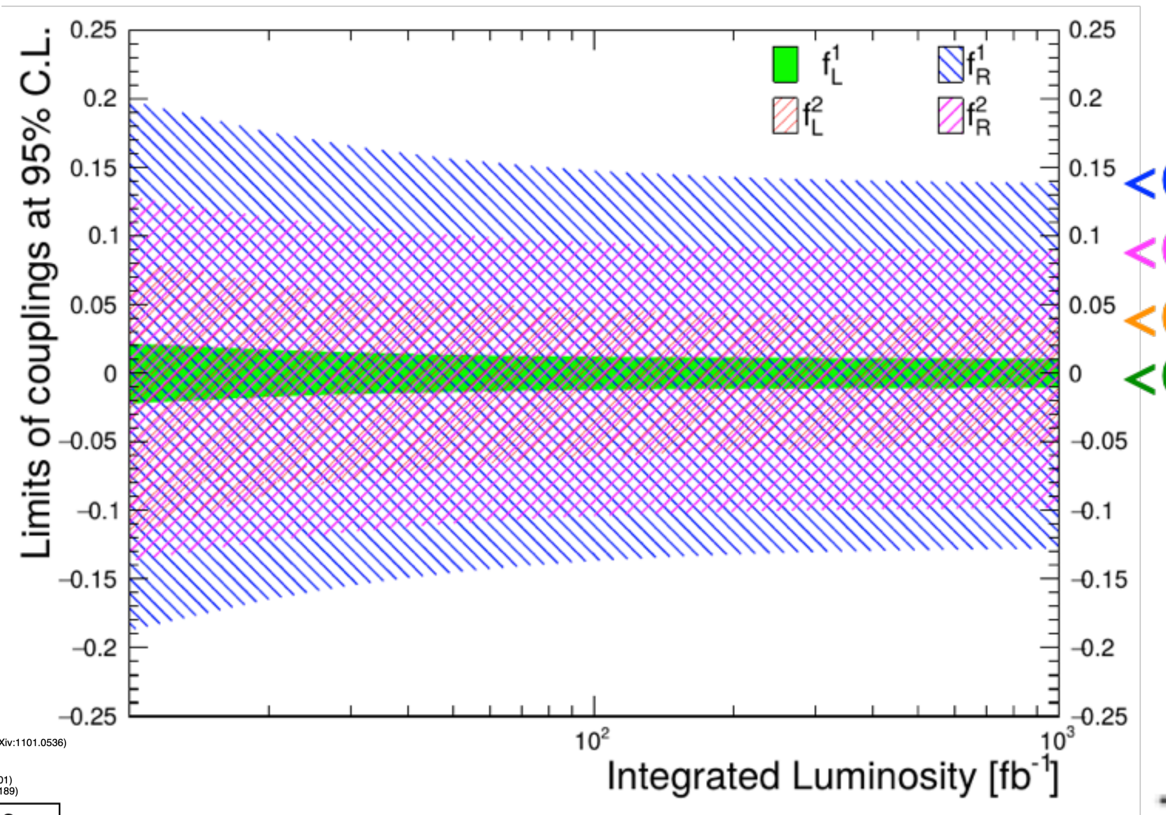
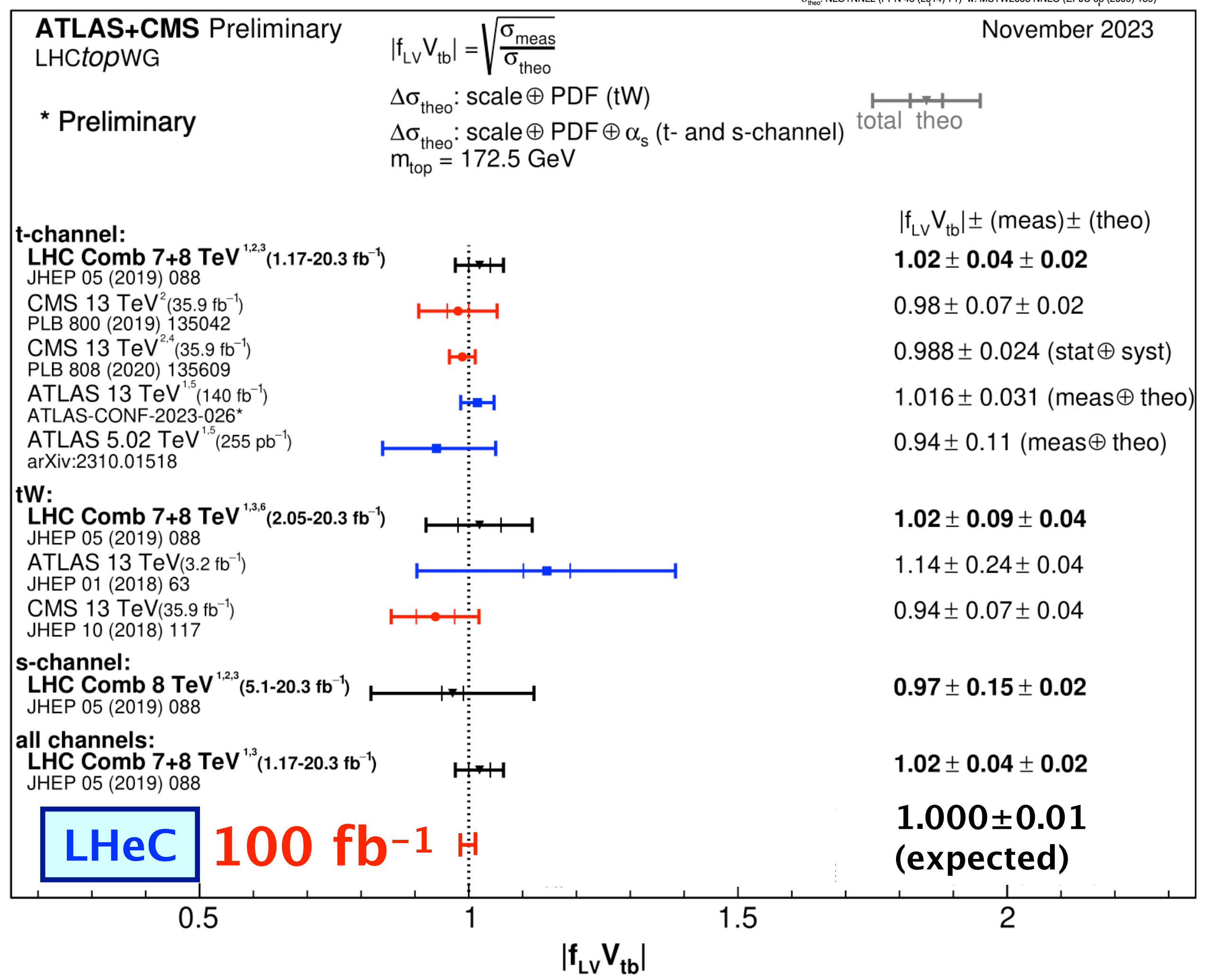


<0.14
<0.09
<0.04
<0.01



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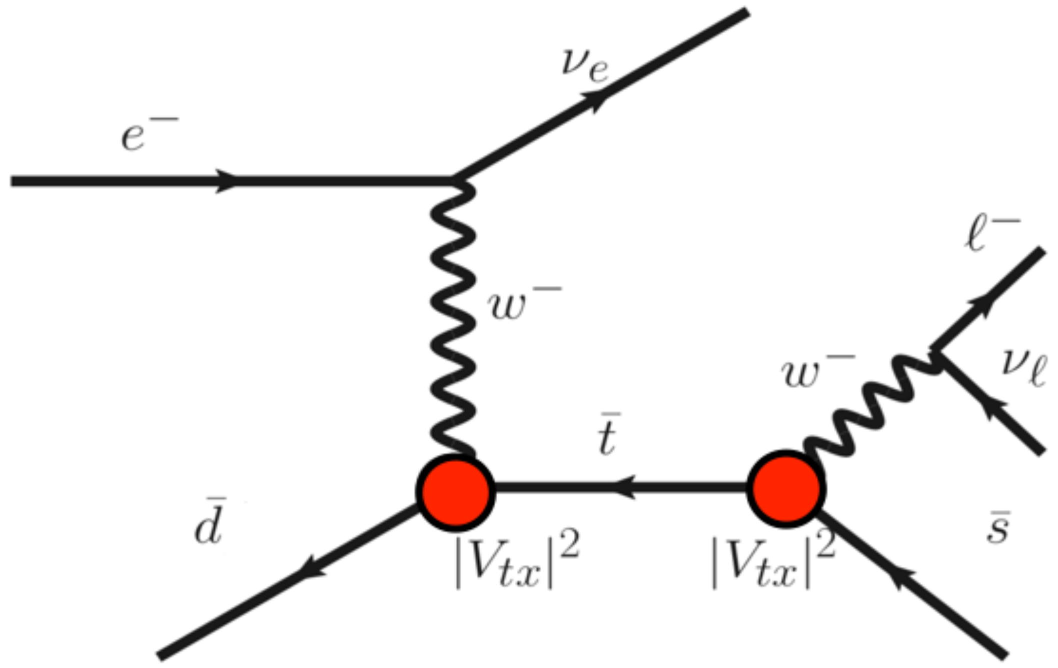
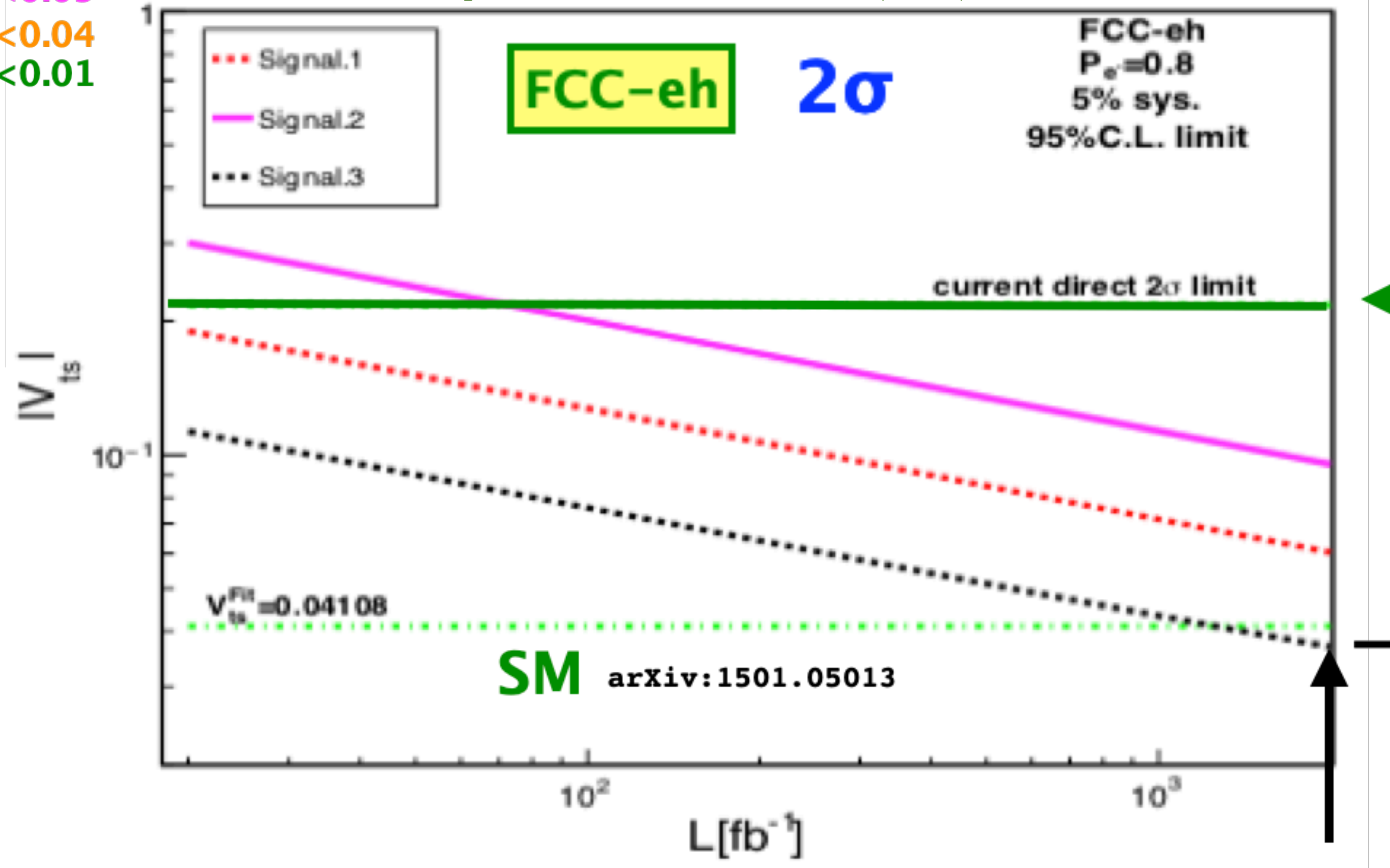


FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)

H. Sun PoS DIS 2018, 167 (2018)



arXiv:1709.07887

LHC

→ $|V_{ts}|<0.037$

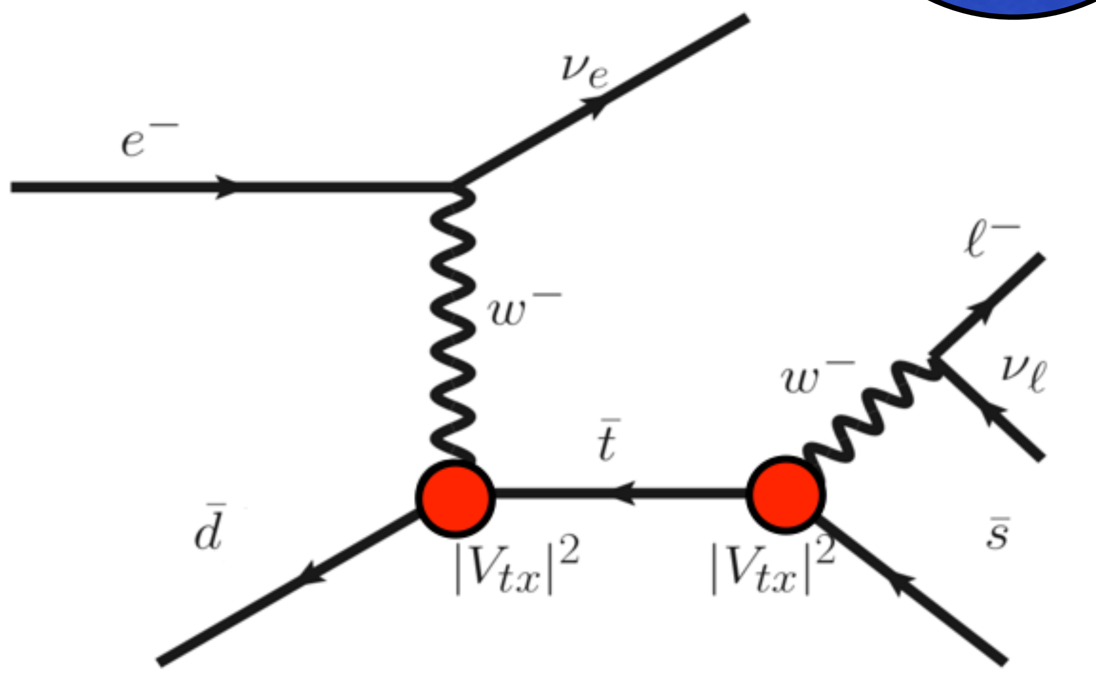
Probing SM prediction directly for the first time

Top — Expected measurements of Wtb couplings — BSM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_\mu^- + h.c.$$

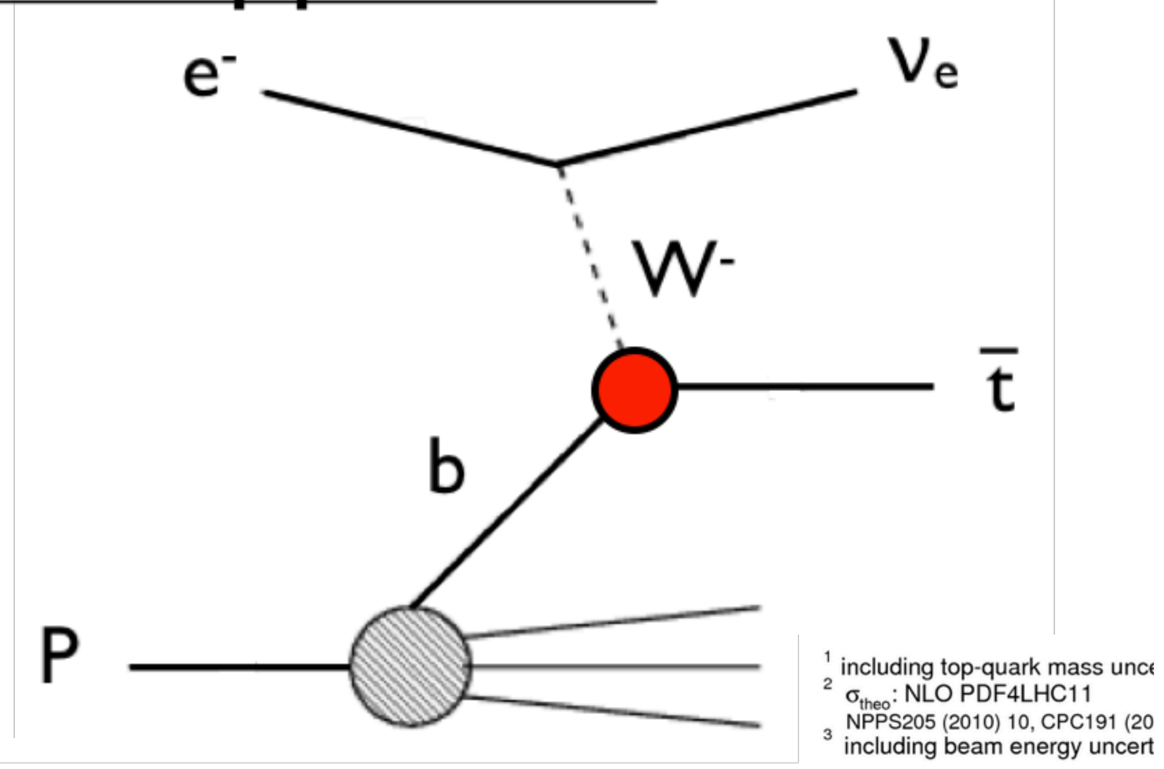
= 1 in SM

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688
Kumar, Ruan, to be publ.



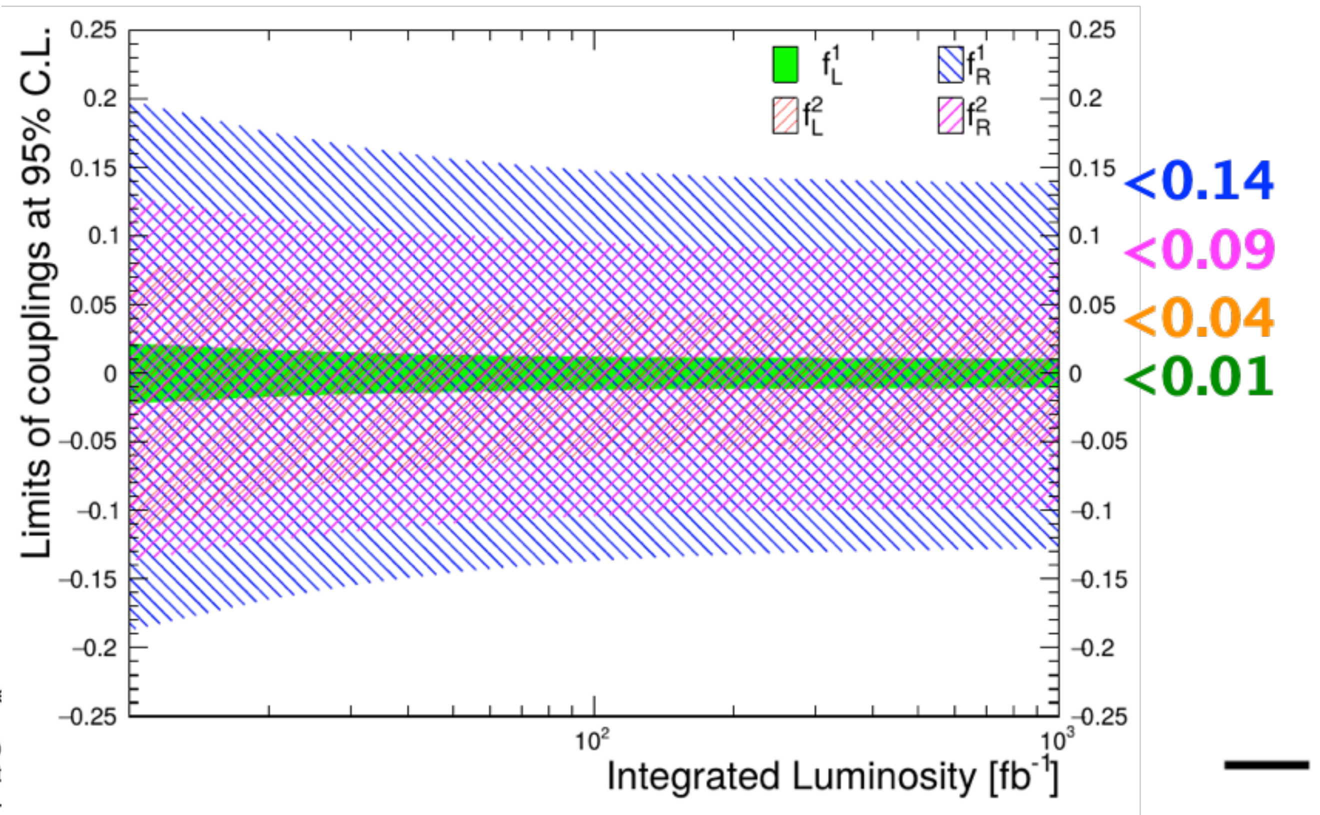
FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)   H. Sun PoS DIS 2018, 167 (2018)

CC DIS top production

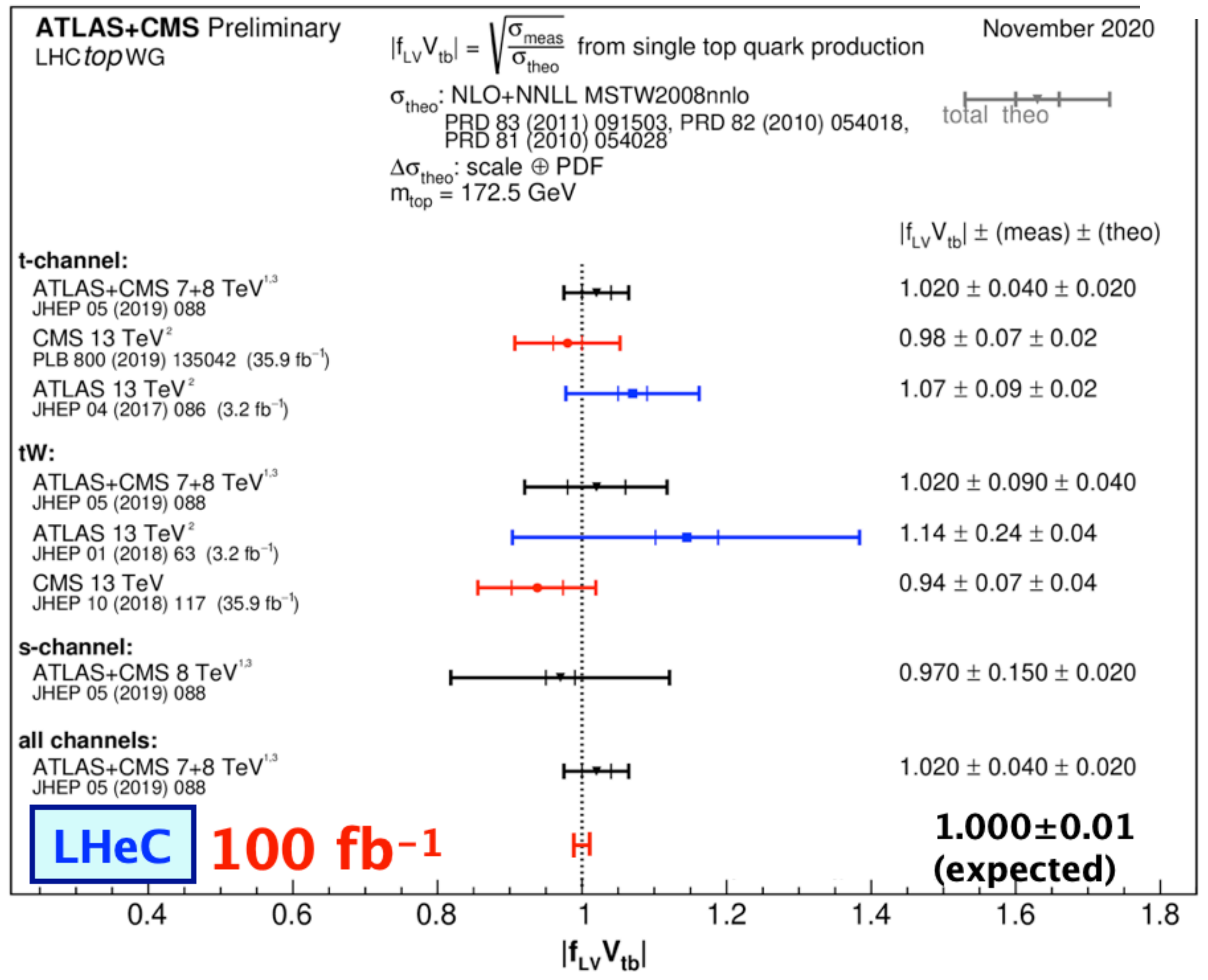


hadronic channel:

LHeC



1 including top-quark mass unce
2 σtheo: NLO PDF4LHC11 NPPS205 (2010) 10, CPC191 (20
3 including beam energy uncert



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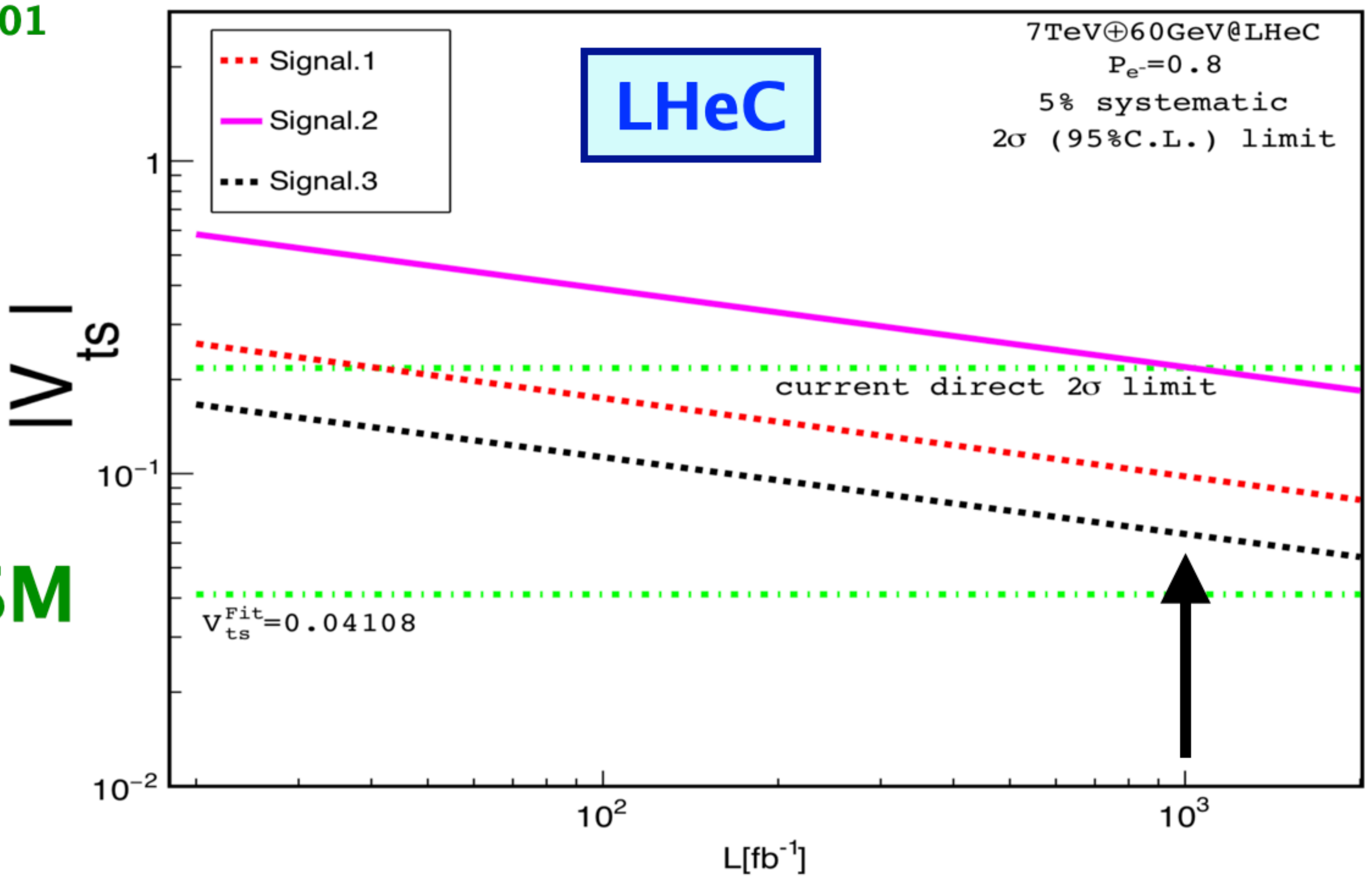
SM

Unprecedented precision < 1%

2σ

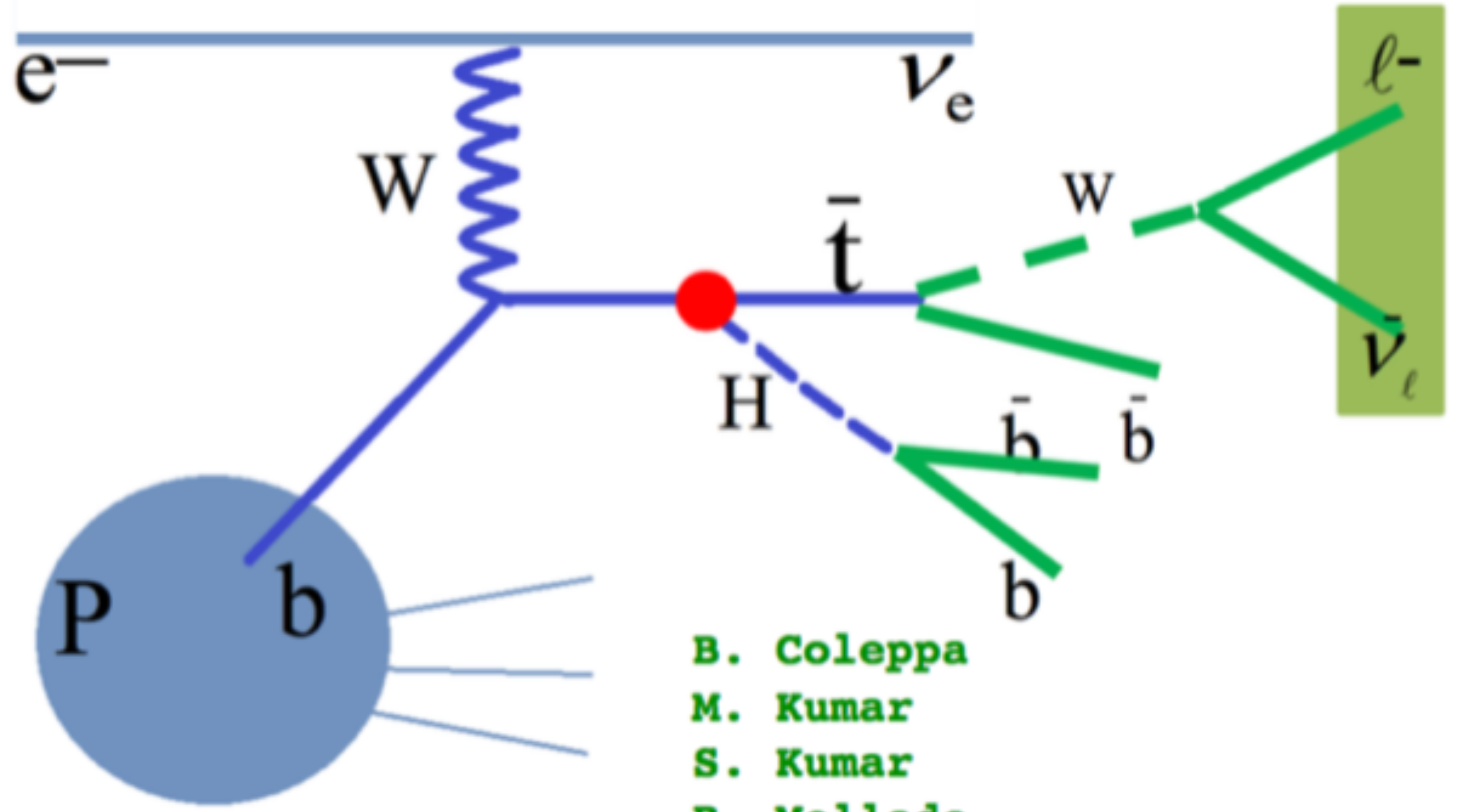


LHC

→ $|V_{ts}|<0.06$

Probing SM prediction directly for the first time

Top Quark Yukawa Coupling and CP Nature

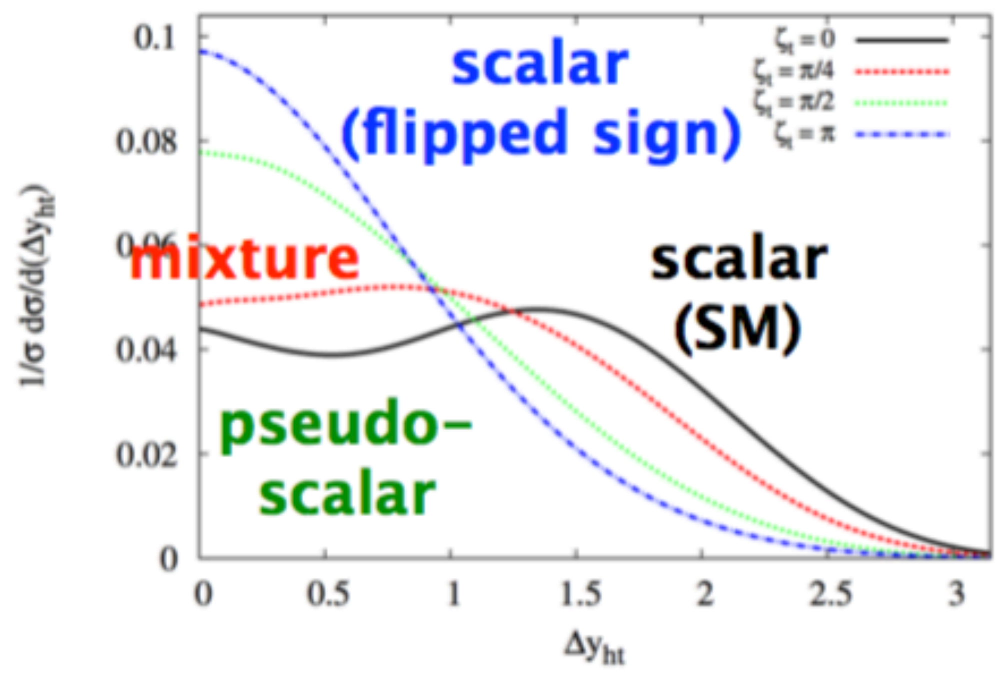


B. Coleppa
M. Kumar
S. Kumar
B. Mellado

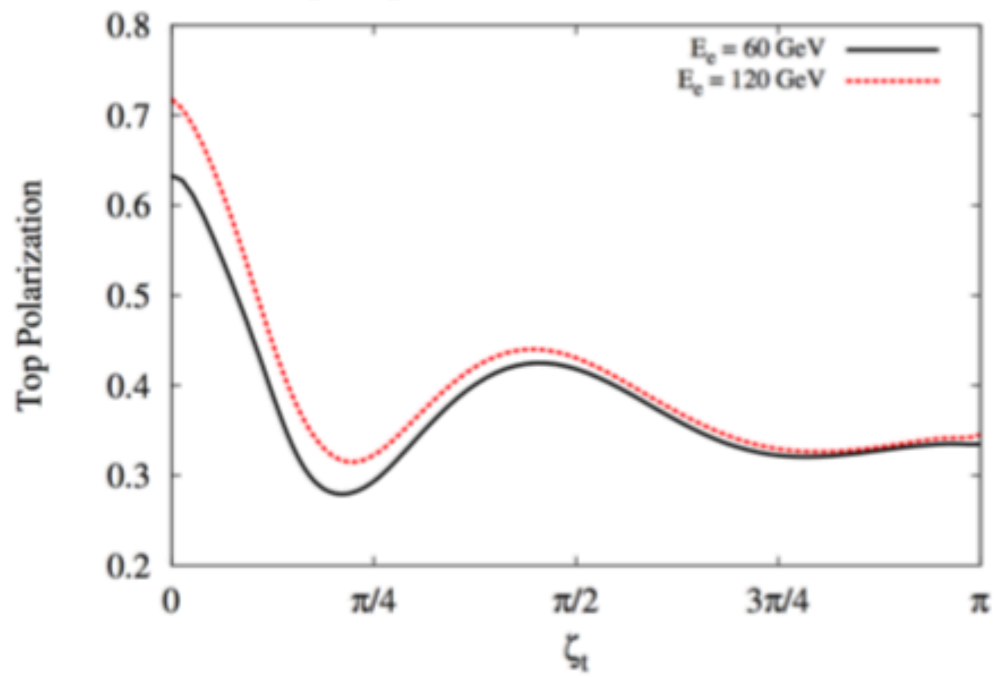
parton level

Phys. Lett. B770 (2017) 335

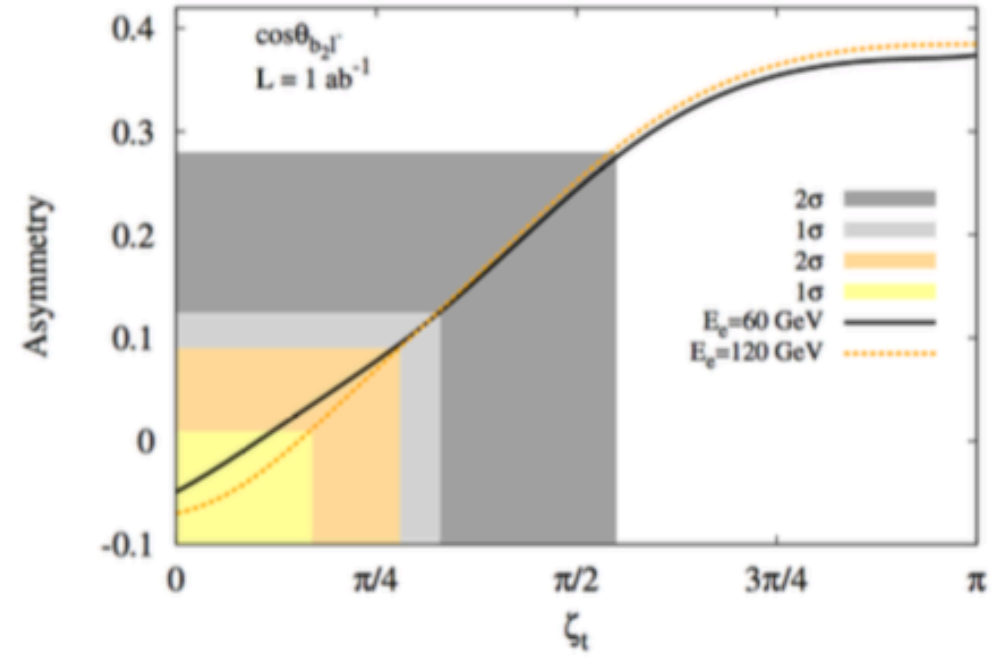
rapidity difference (H,$\bar{t}$)



top polarisation



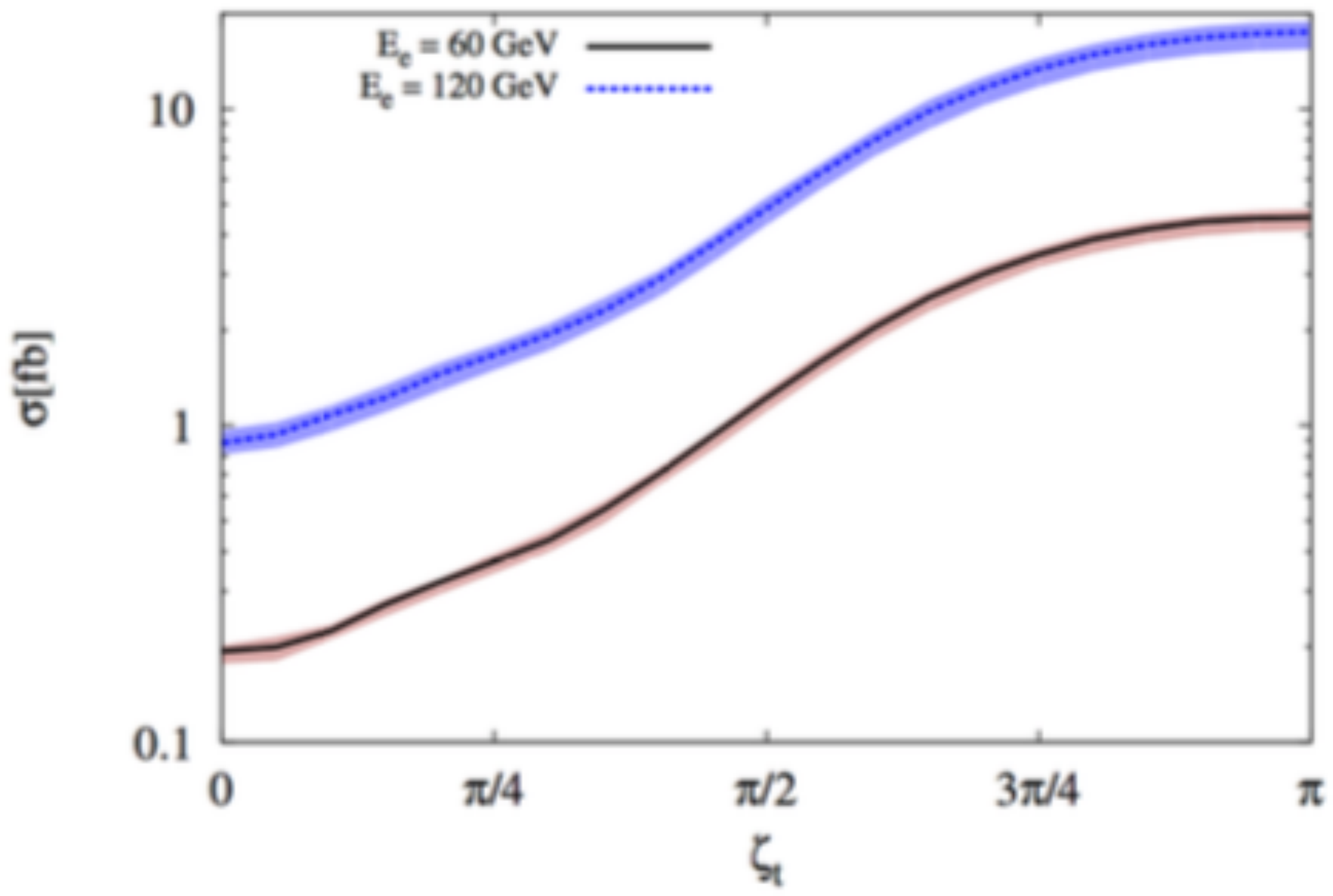
angular asymmetries (b_2,l^-)



$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]\,t\,h$$

LHeC

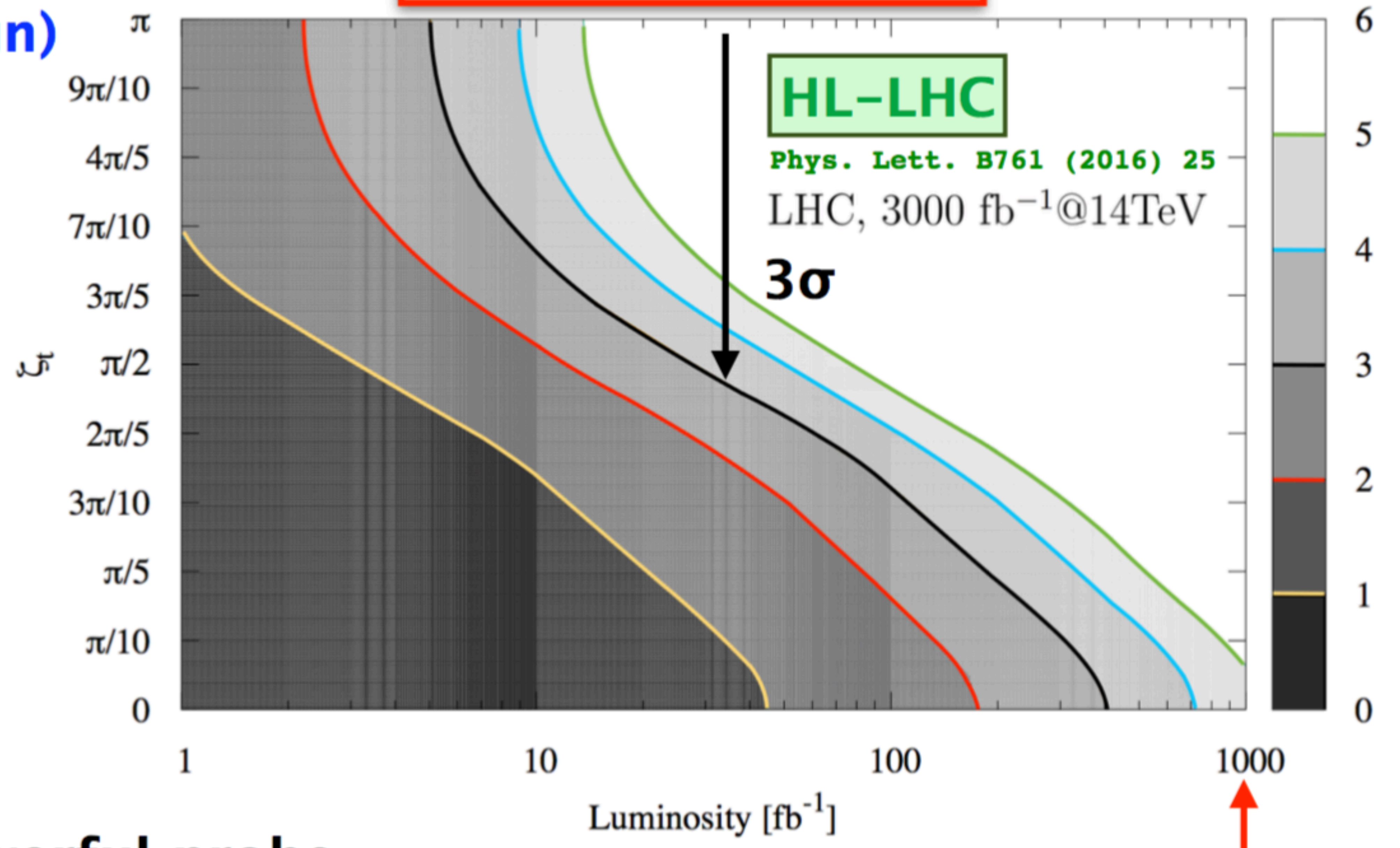
fiducial incl. cross-section



CP-even
(flipped sign)

CP-odd

CP-even
(SM)



→ powerful probe
of ttH coupling

10% uncertainty on
background yields

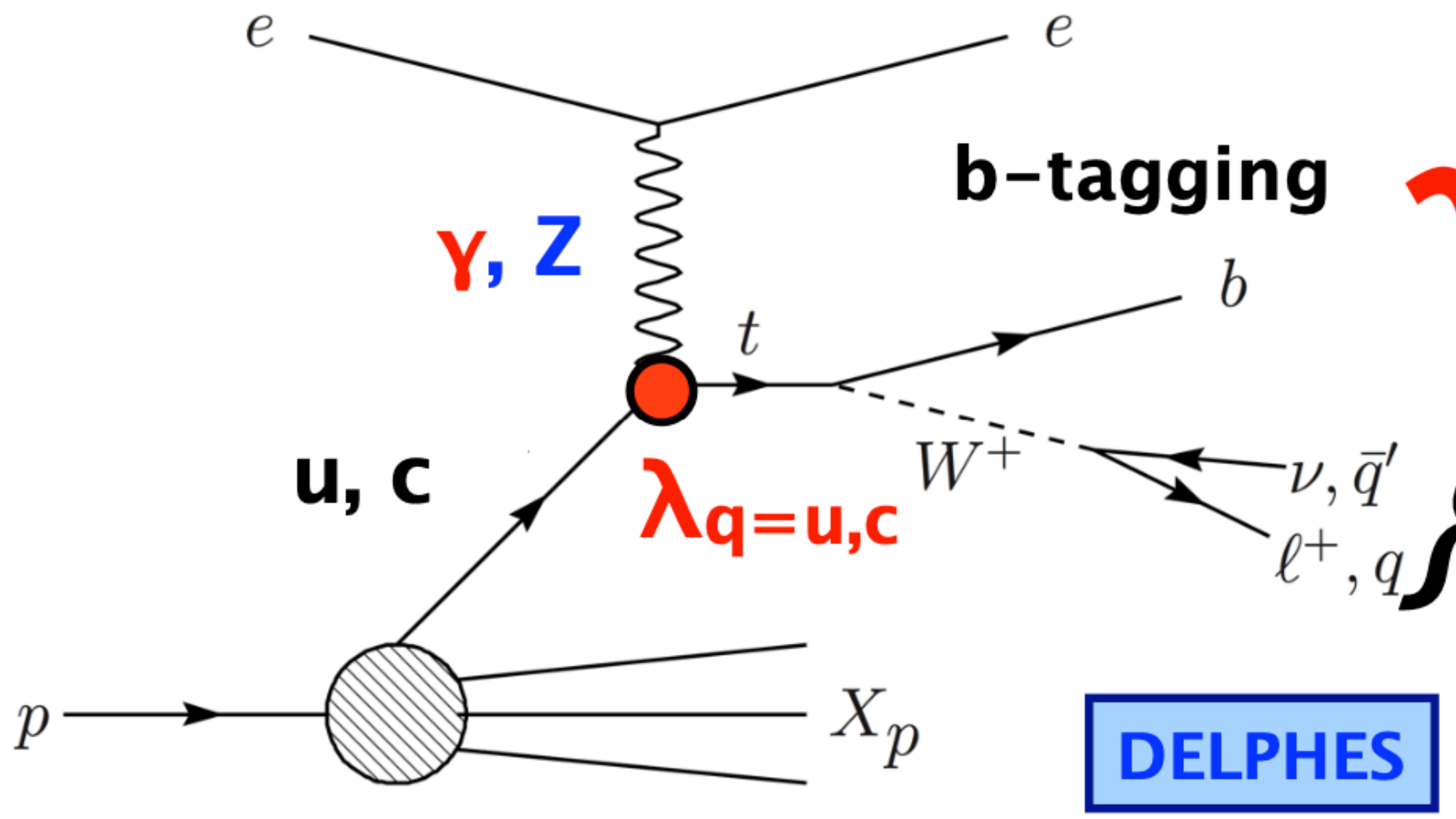
$\kappa = 1.00 \pm 0.17$

- LC: analysis of CP nature profits from direct production at high energies

Anomalous FCNC tuγ, tuZ Couplings

signal

I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)



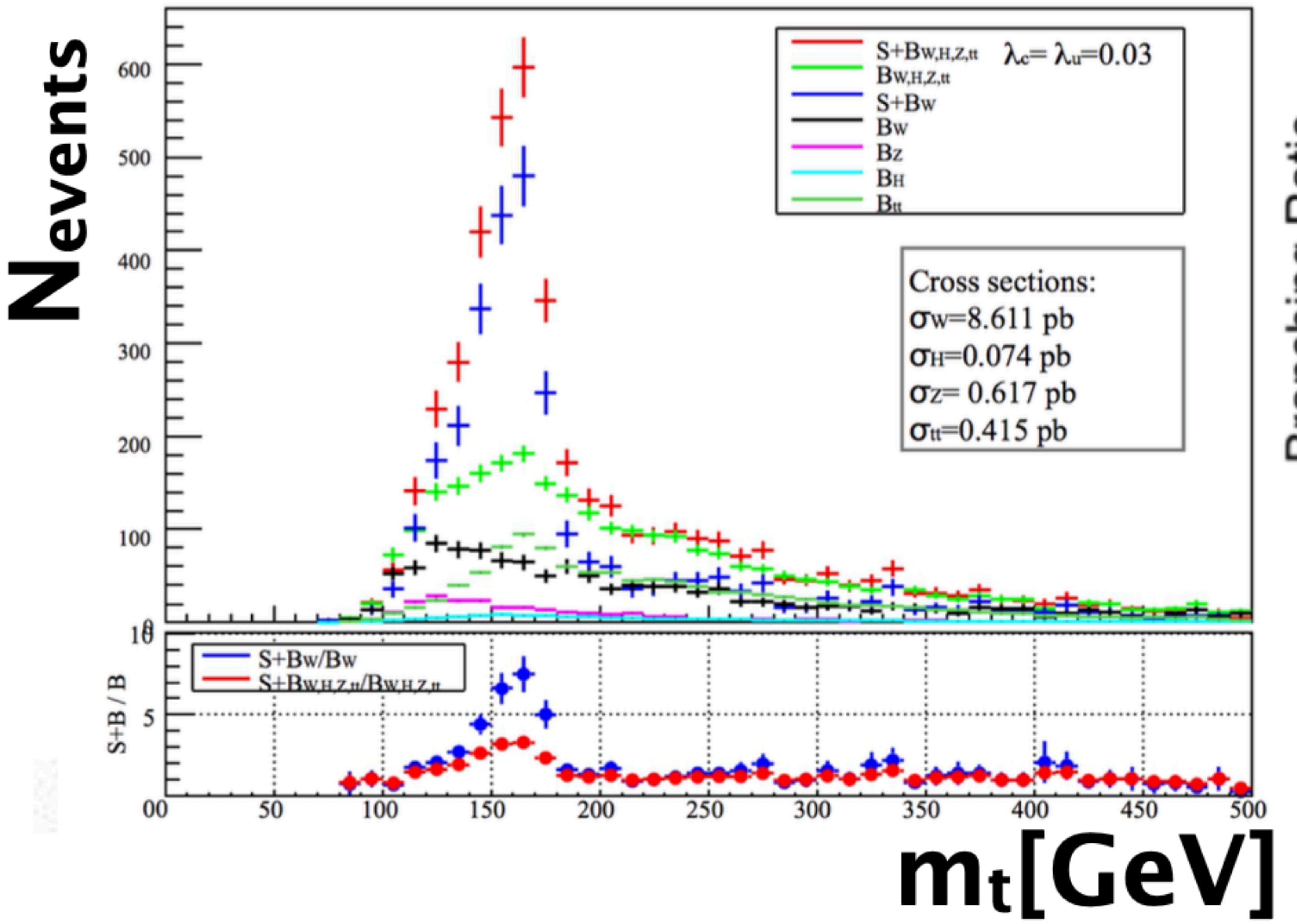
b-tagging

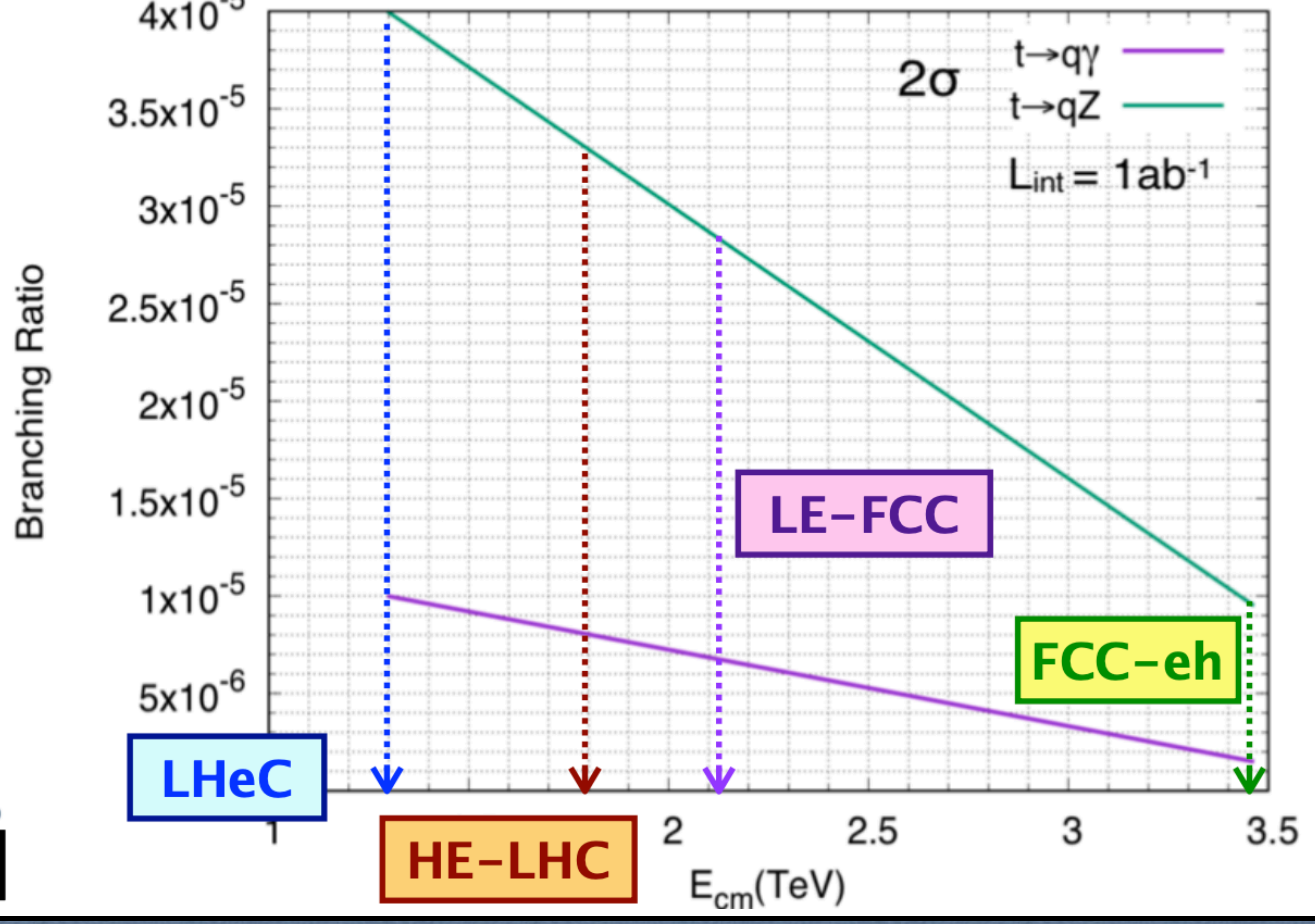
$130 < M_{Wb} < 190$ GeV

$50 < M_{jj} < 100$ GeV

DELPHES

$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$

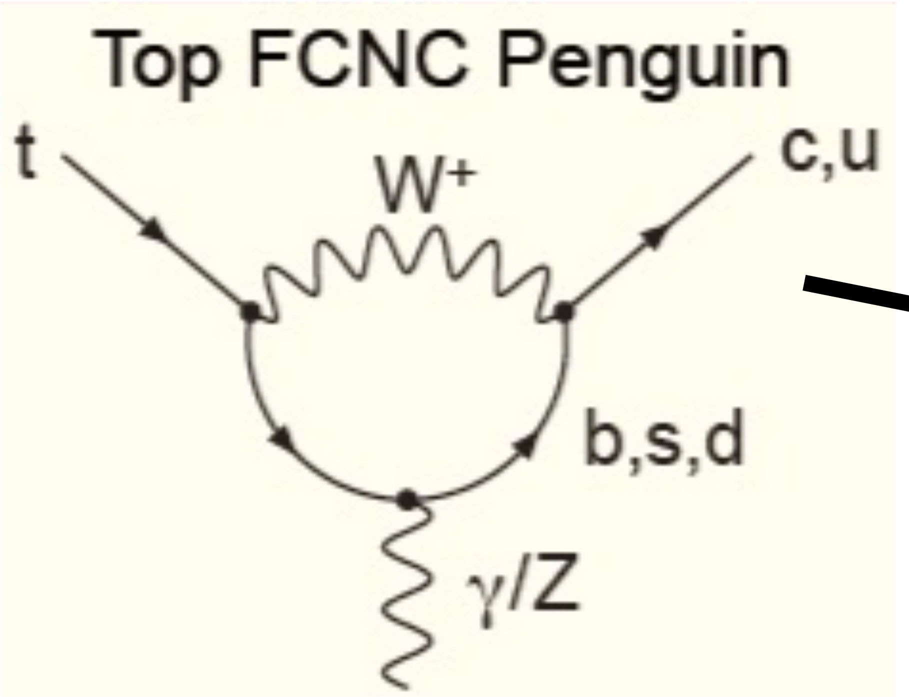


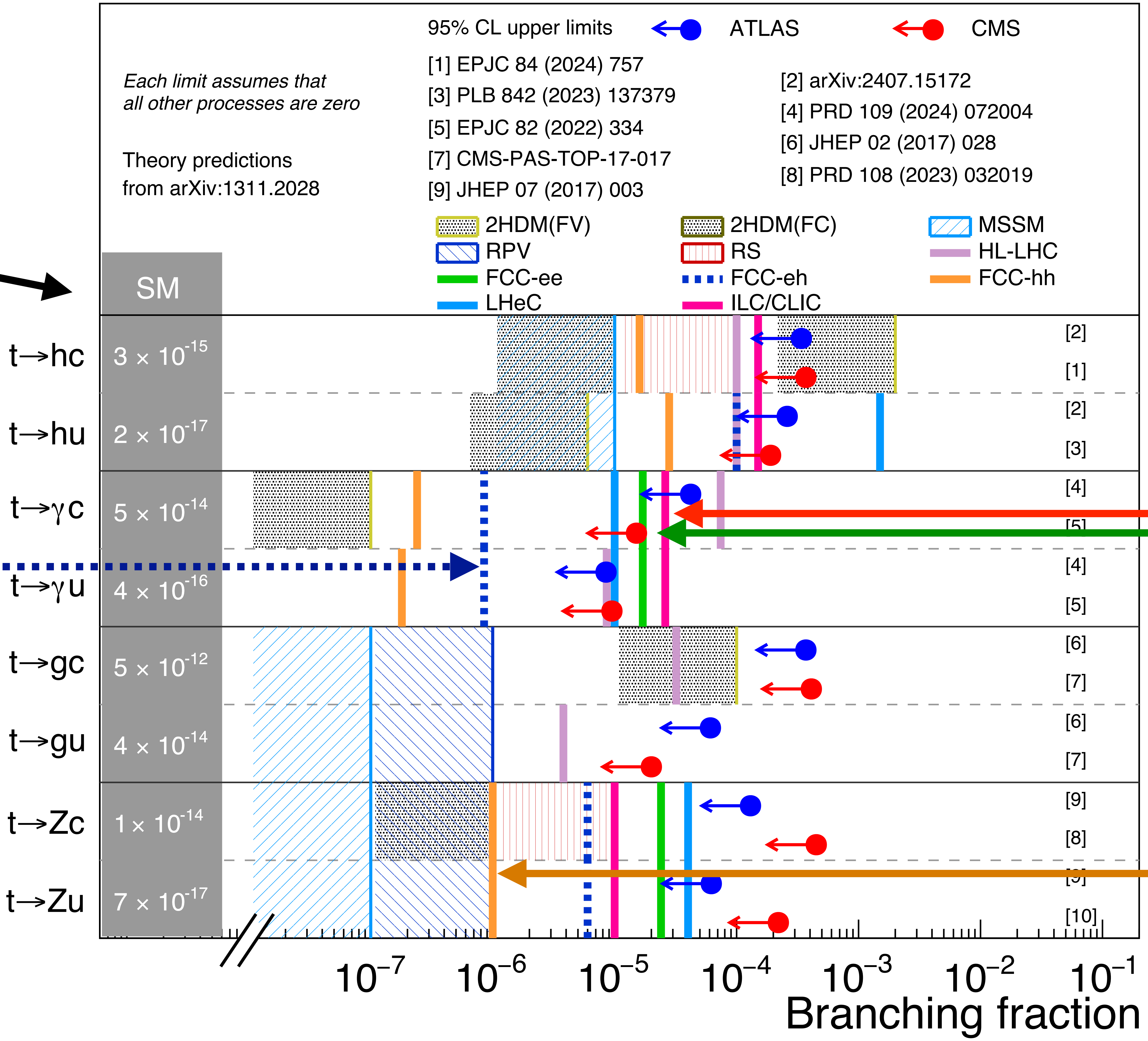


test exotic models leading to FCNC

FCNC Branching Ratios at Colliders

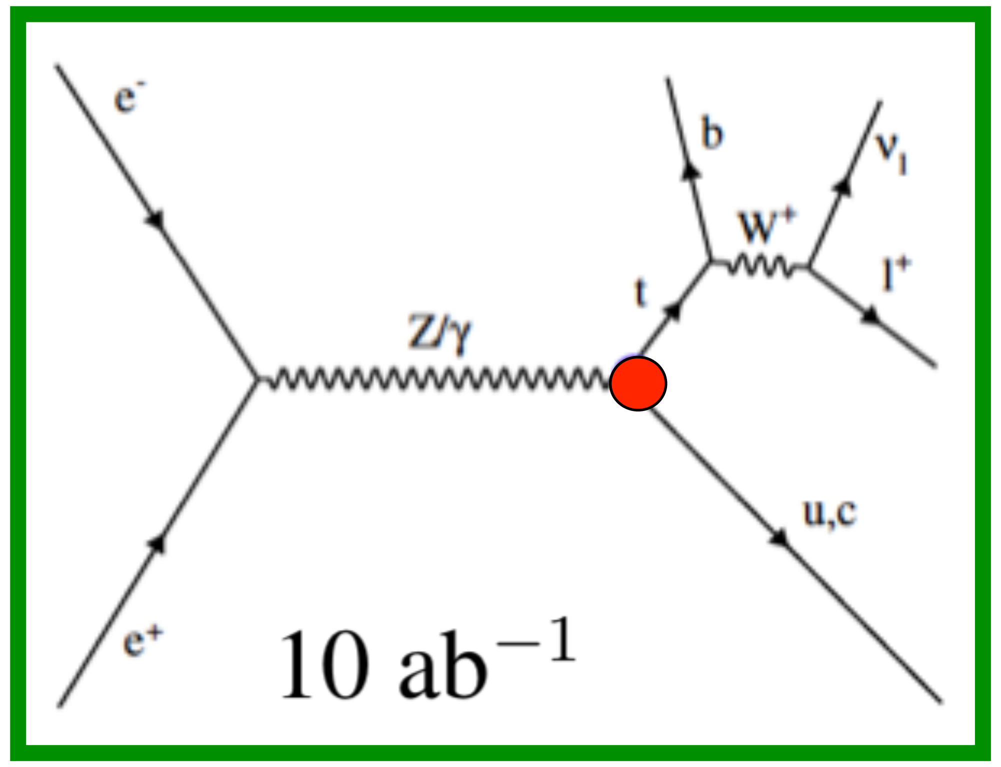
FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019), updated by K. Skovpen, 10/2024

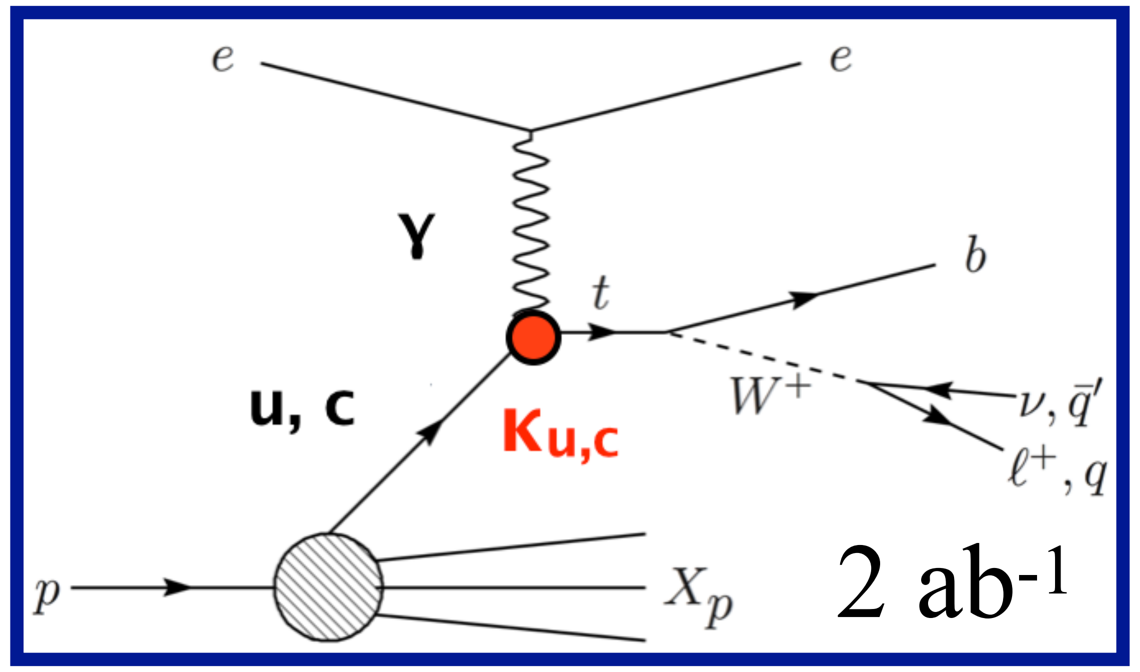




ILC/CLIC

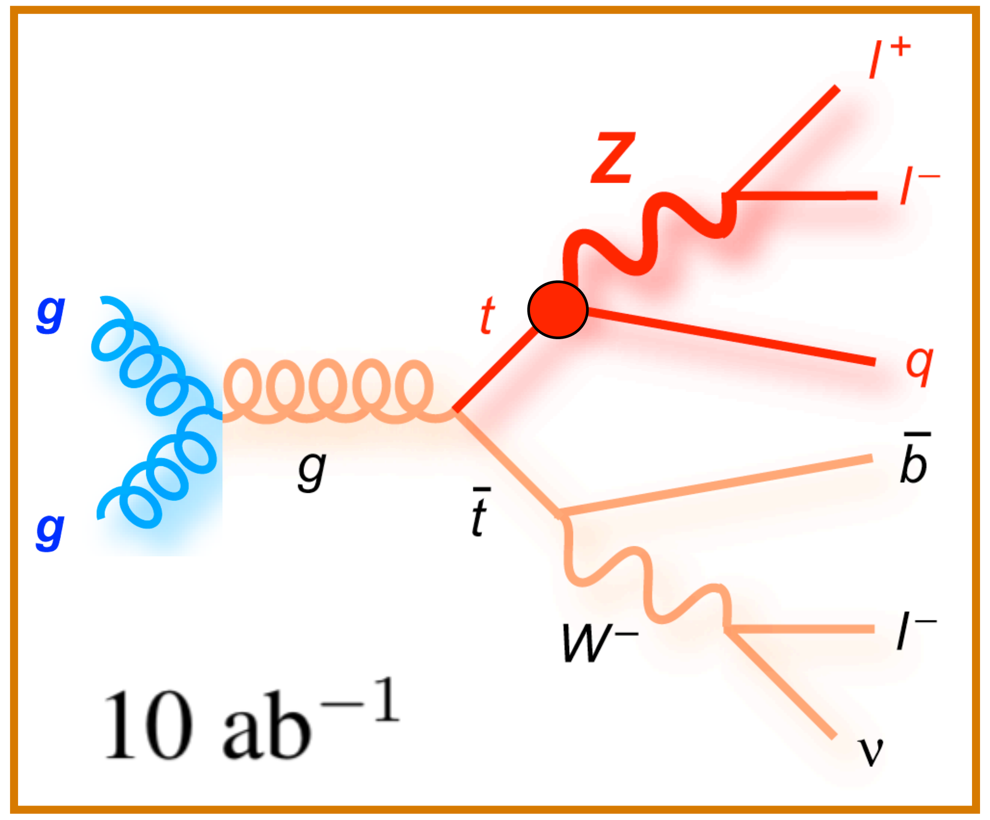
FCC-ee





FCC-eh

FCC-pp



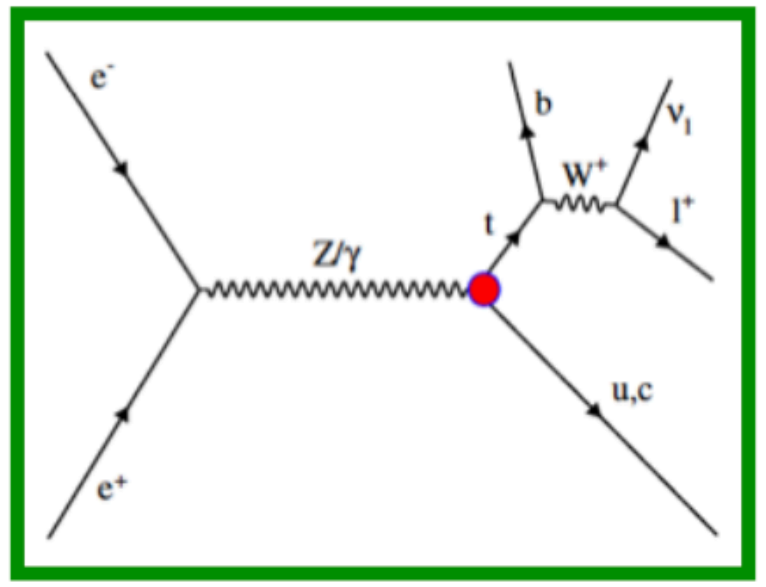
→ test SUSY, little Higgs, technicolor…

FCNC Top Quark Couplings

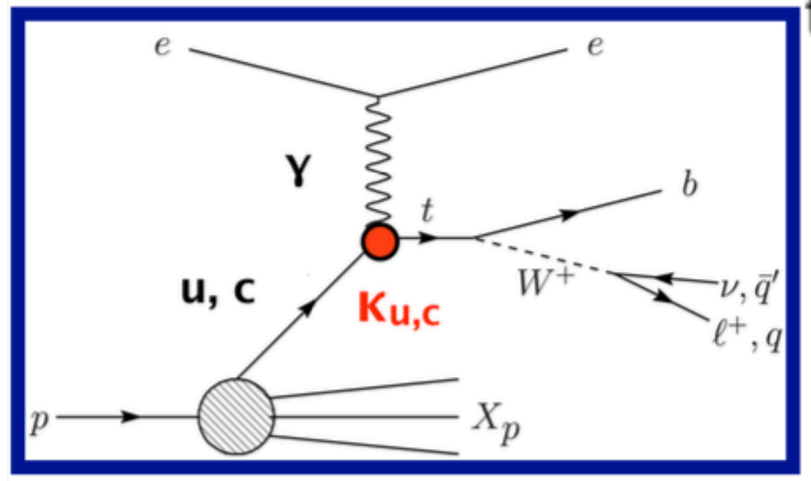
FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)

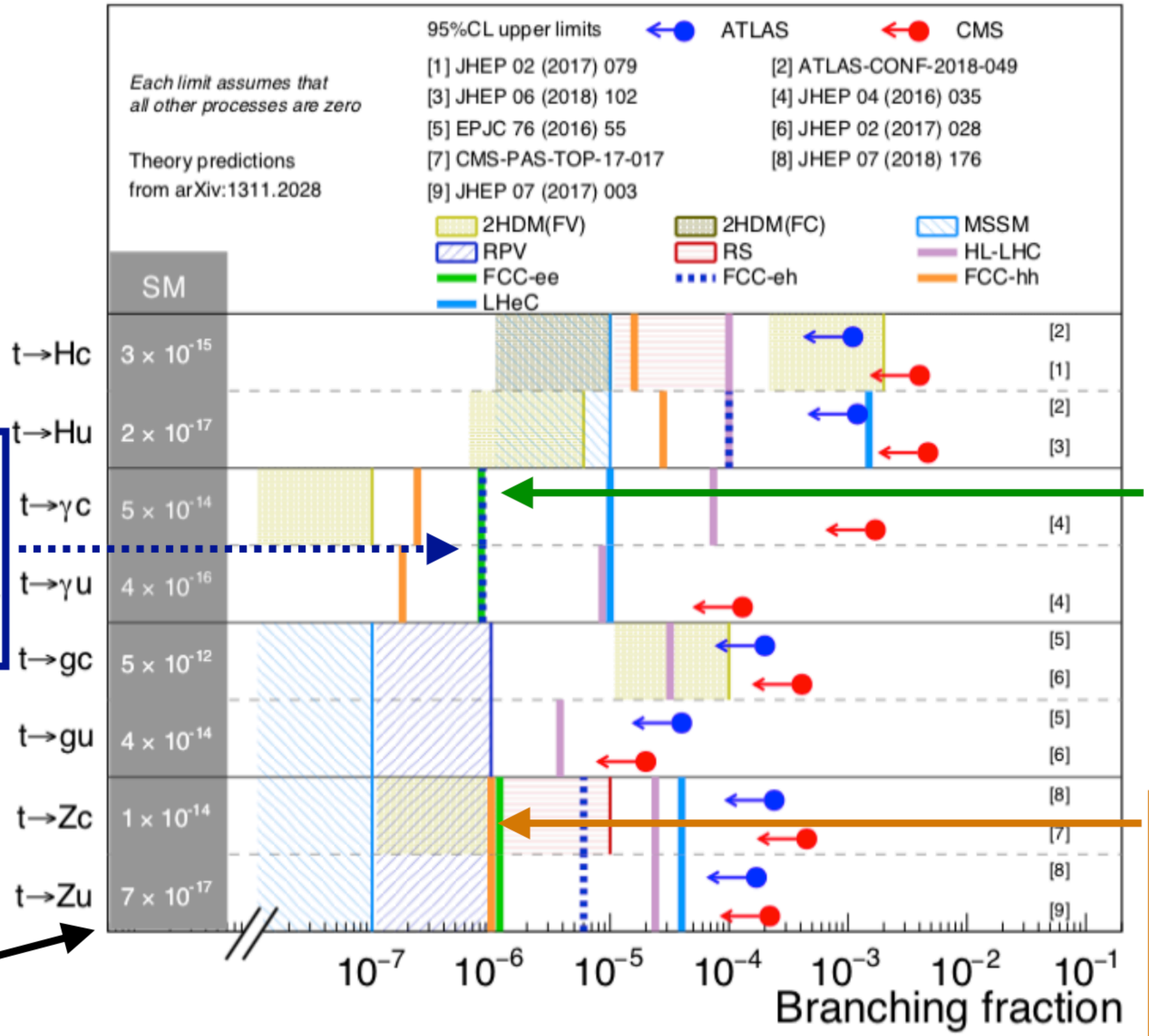
complementarity of colliders

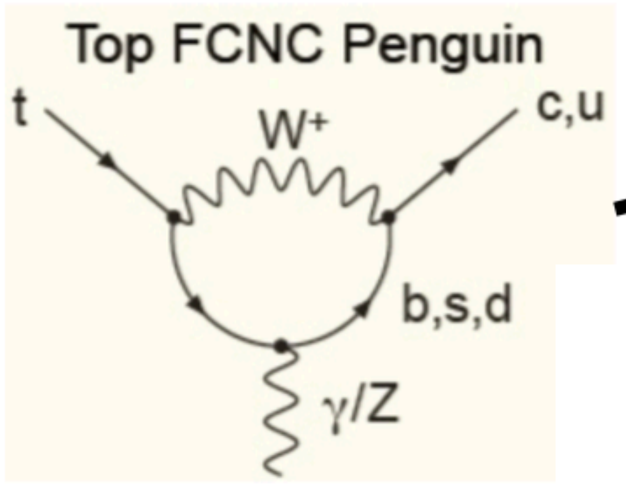
FCC-ee



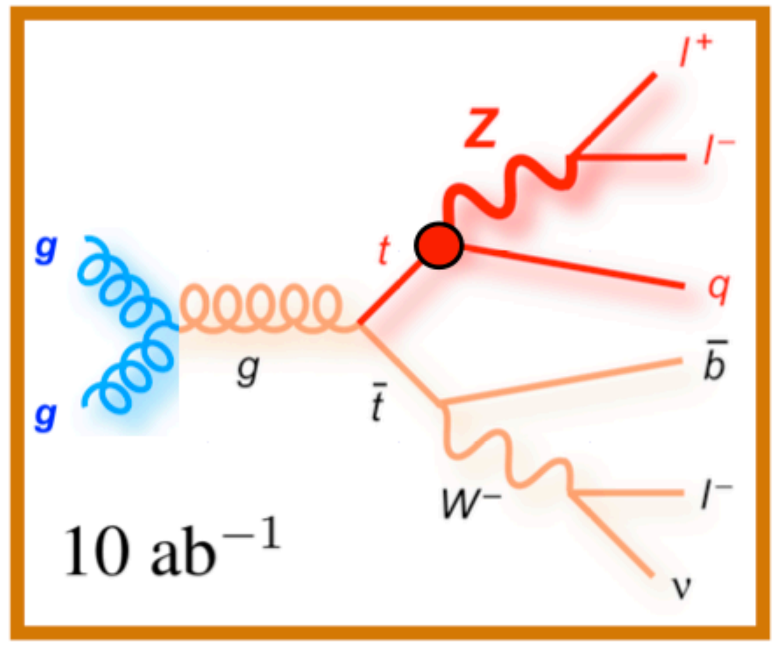
FCC-eh







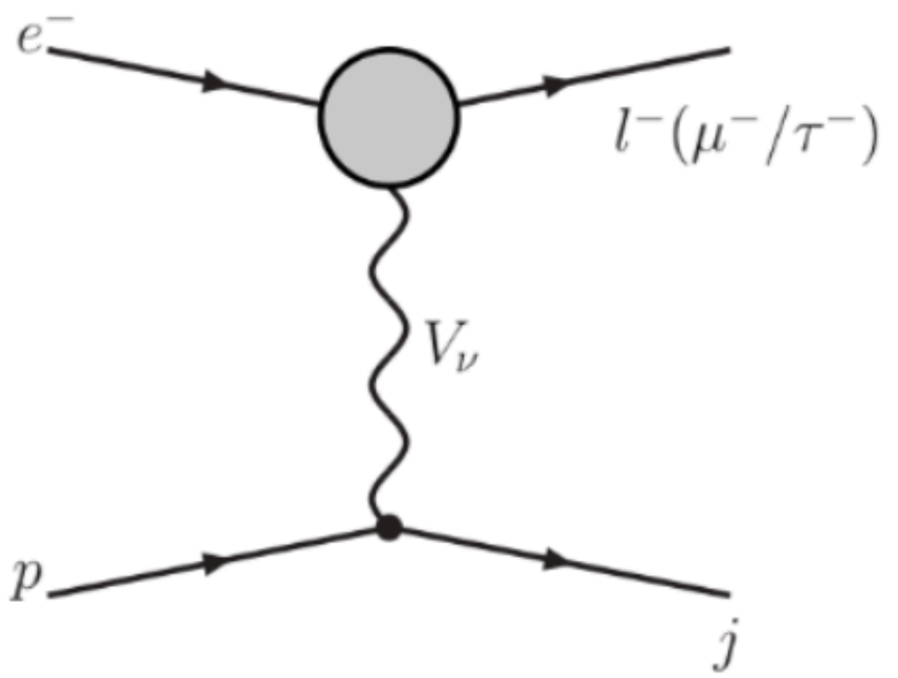
FCC-pp

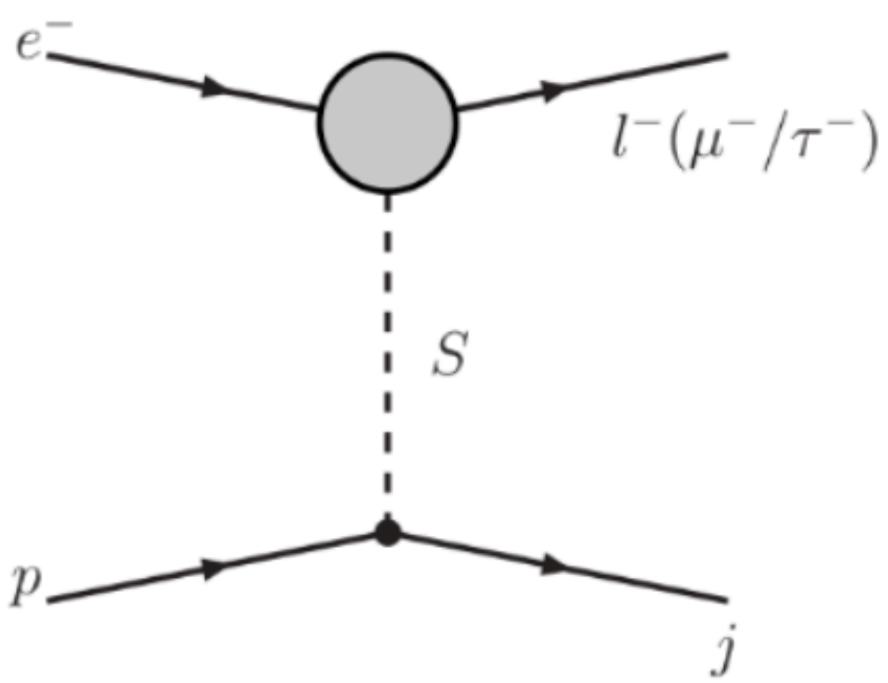


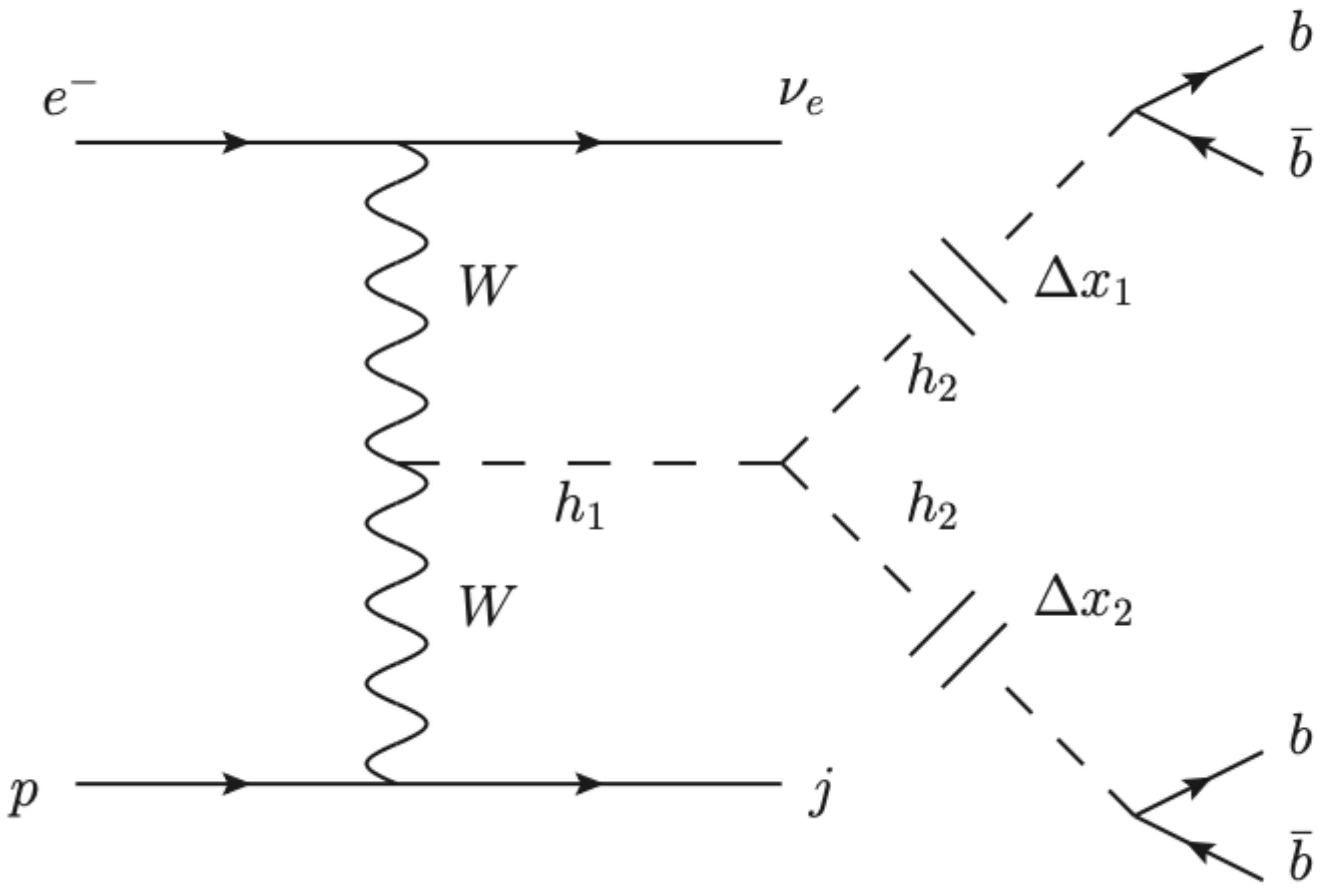
test little Higgs, SUSY, technicolor, …

Complementary searches for new phenomena

LHeC and FCC CDRs: and several dedicated publications

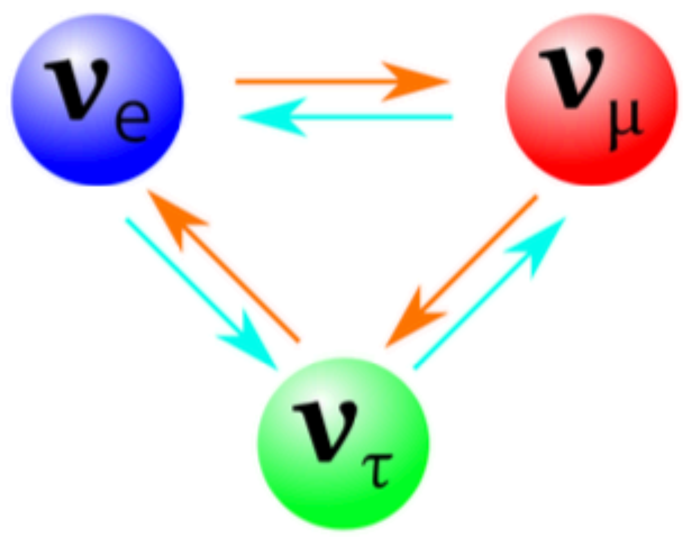


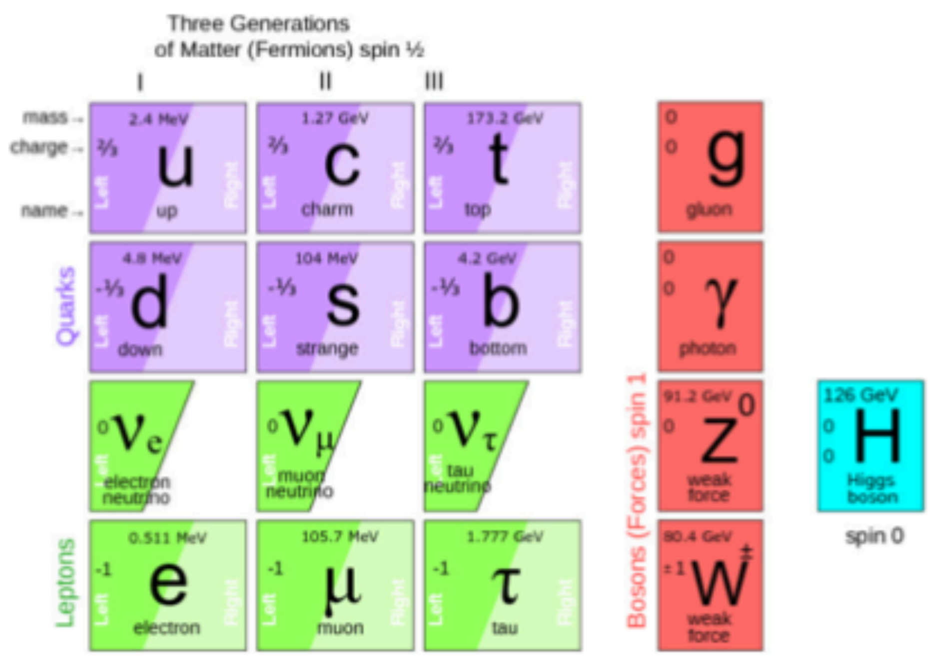




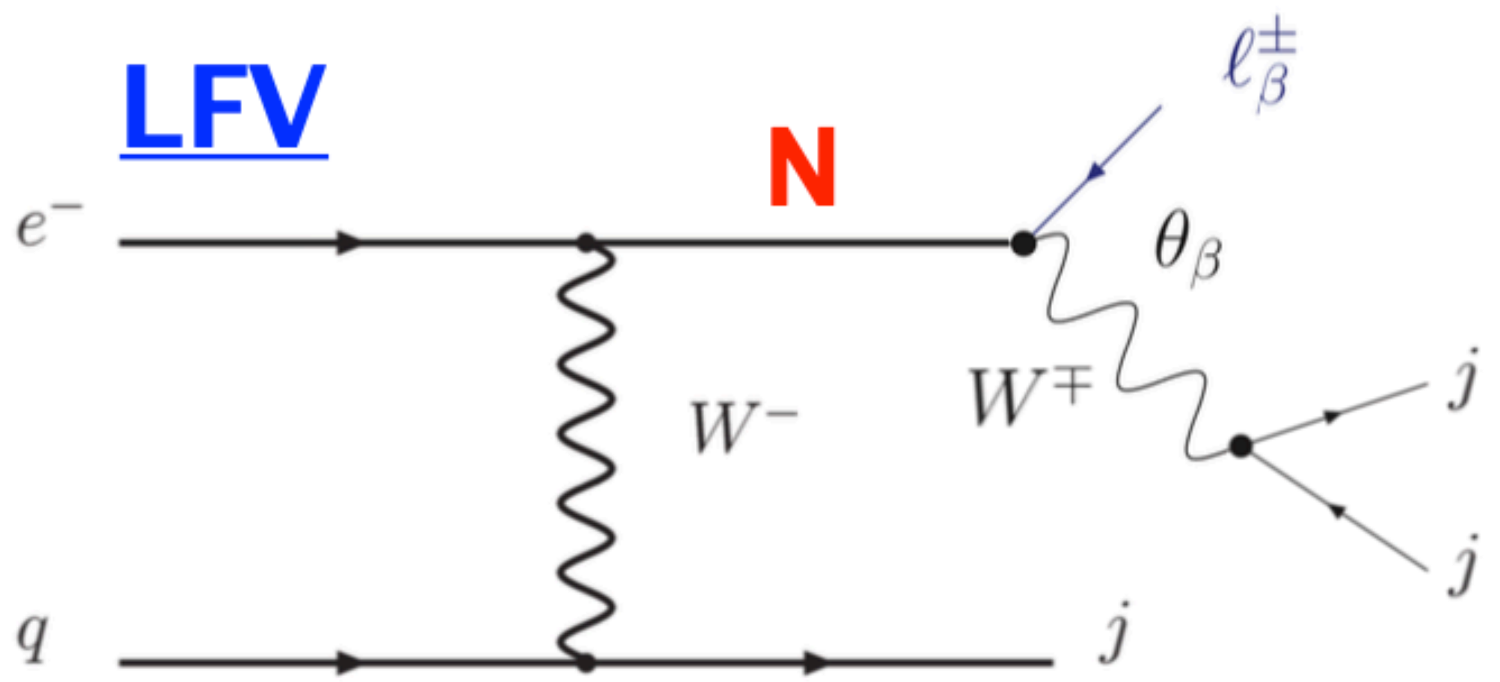
… and much more

Complementary searches for BSM: heavy sterile neutrinos

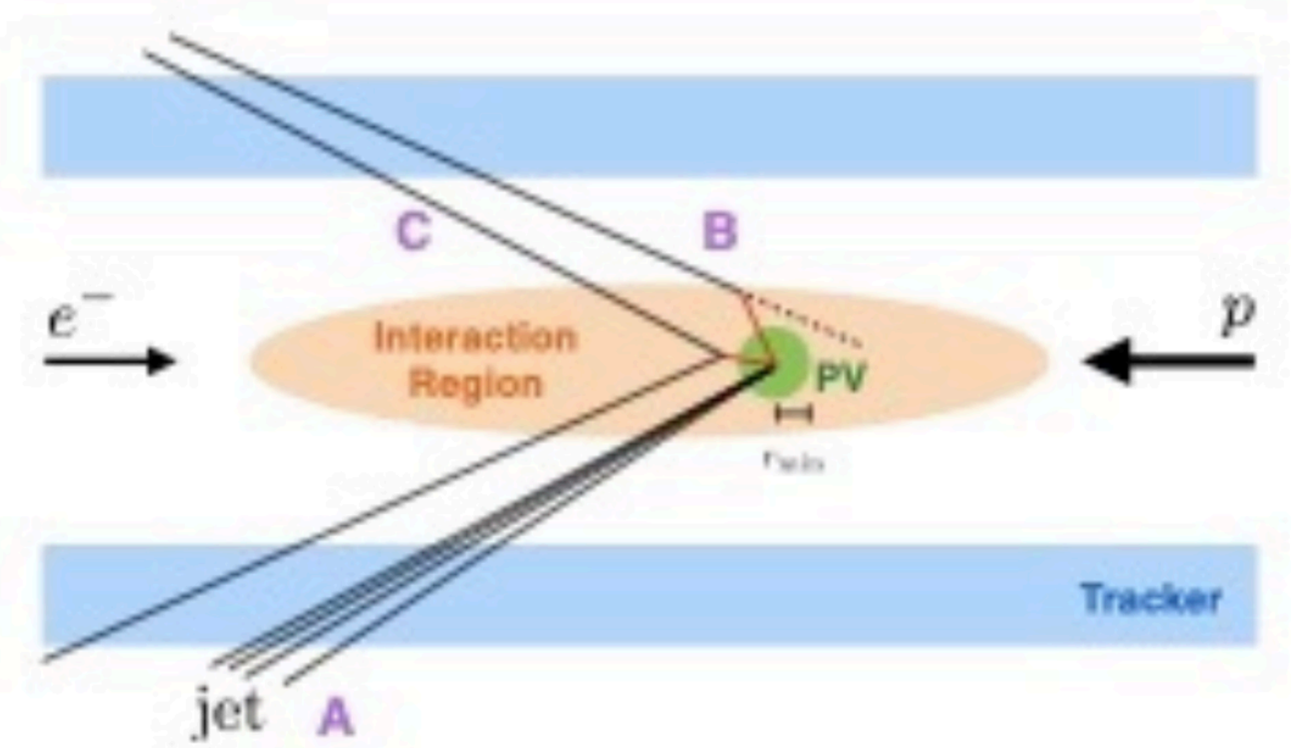


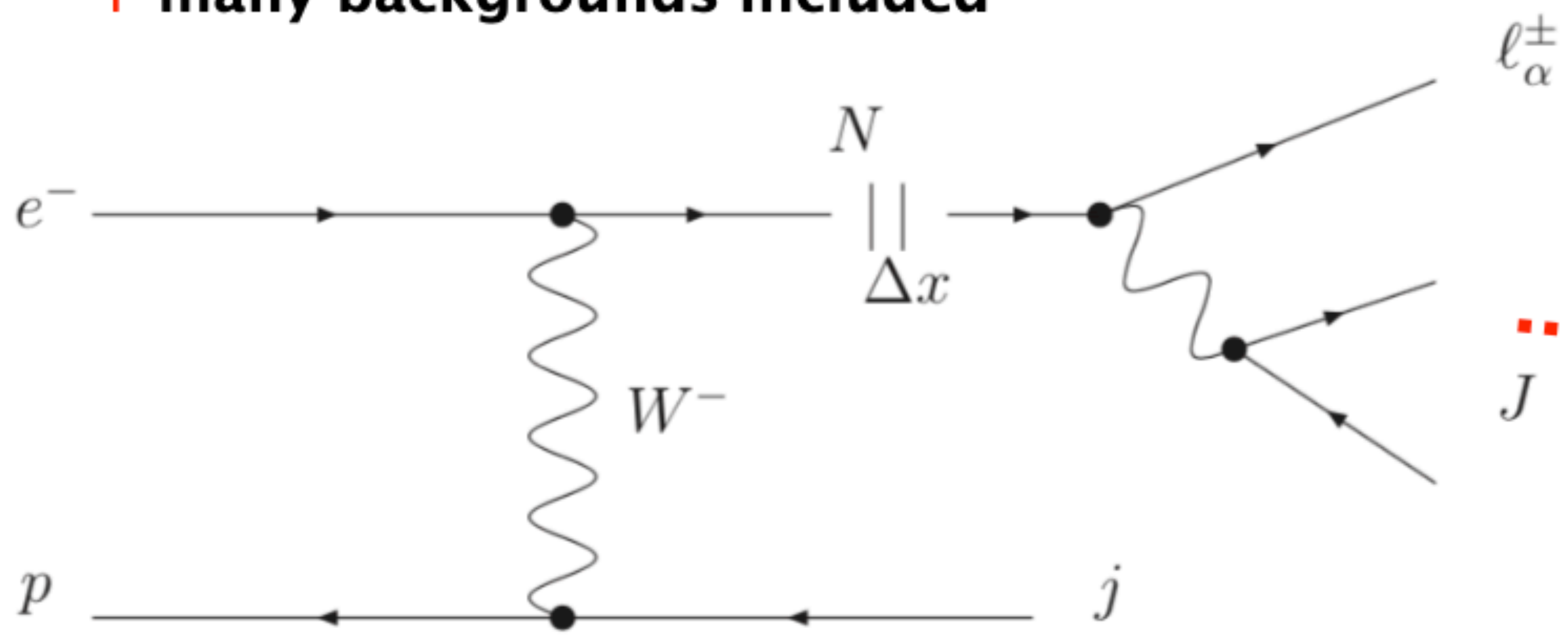


LFV

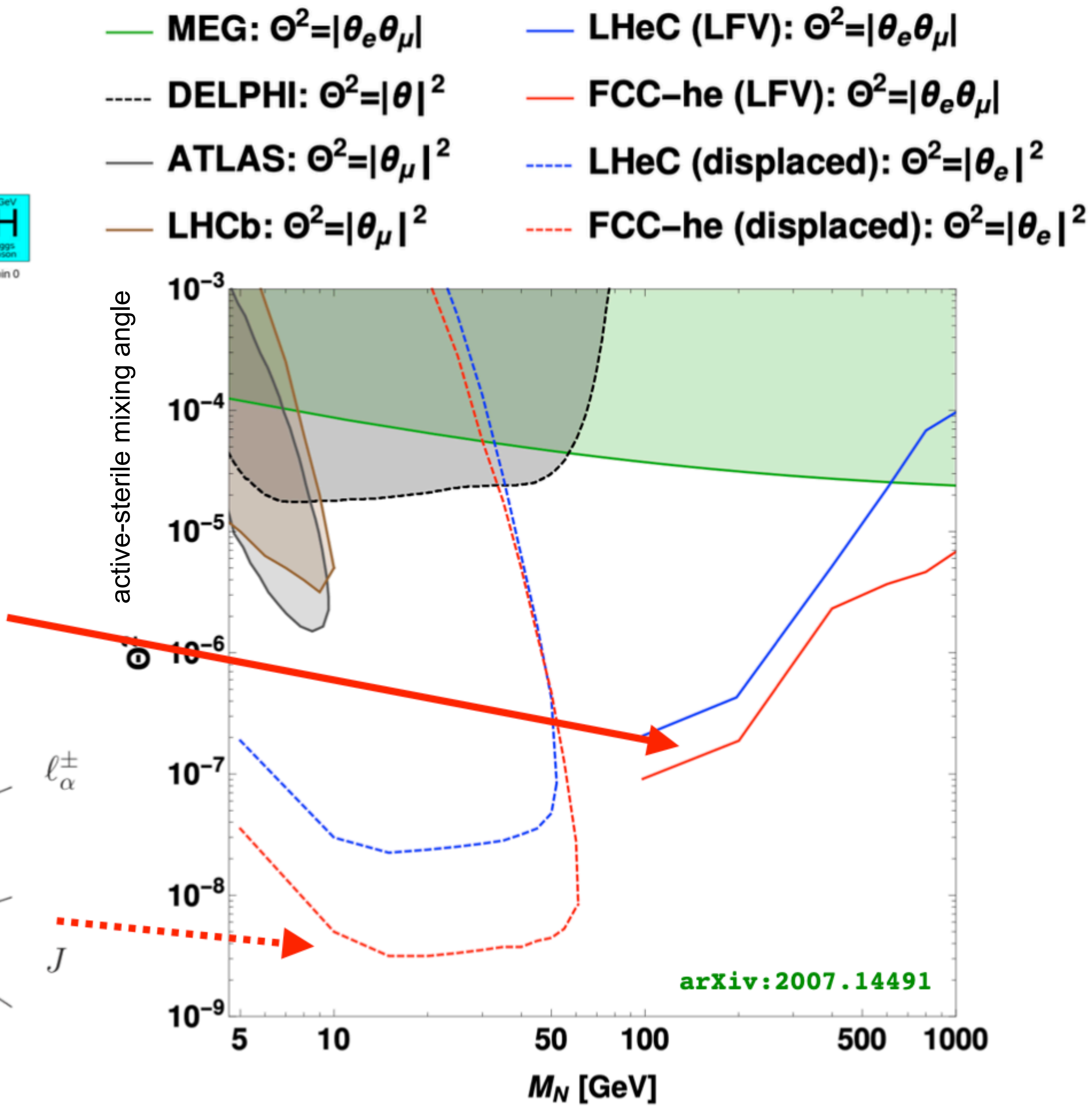


+ many backgrounds included



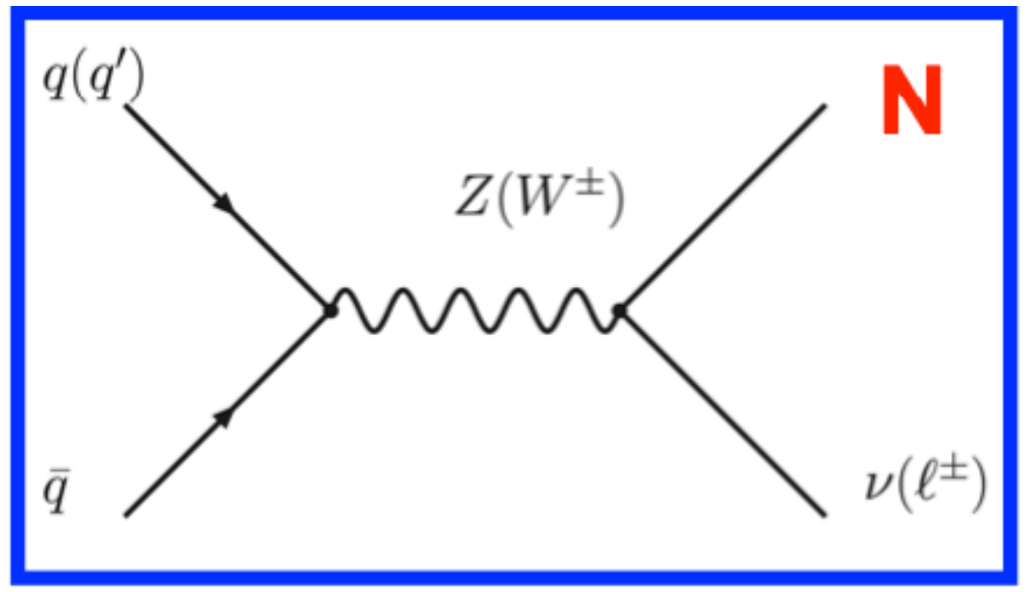


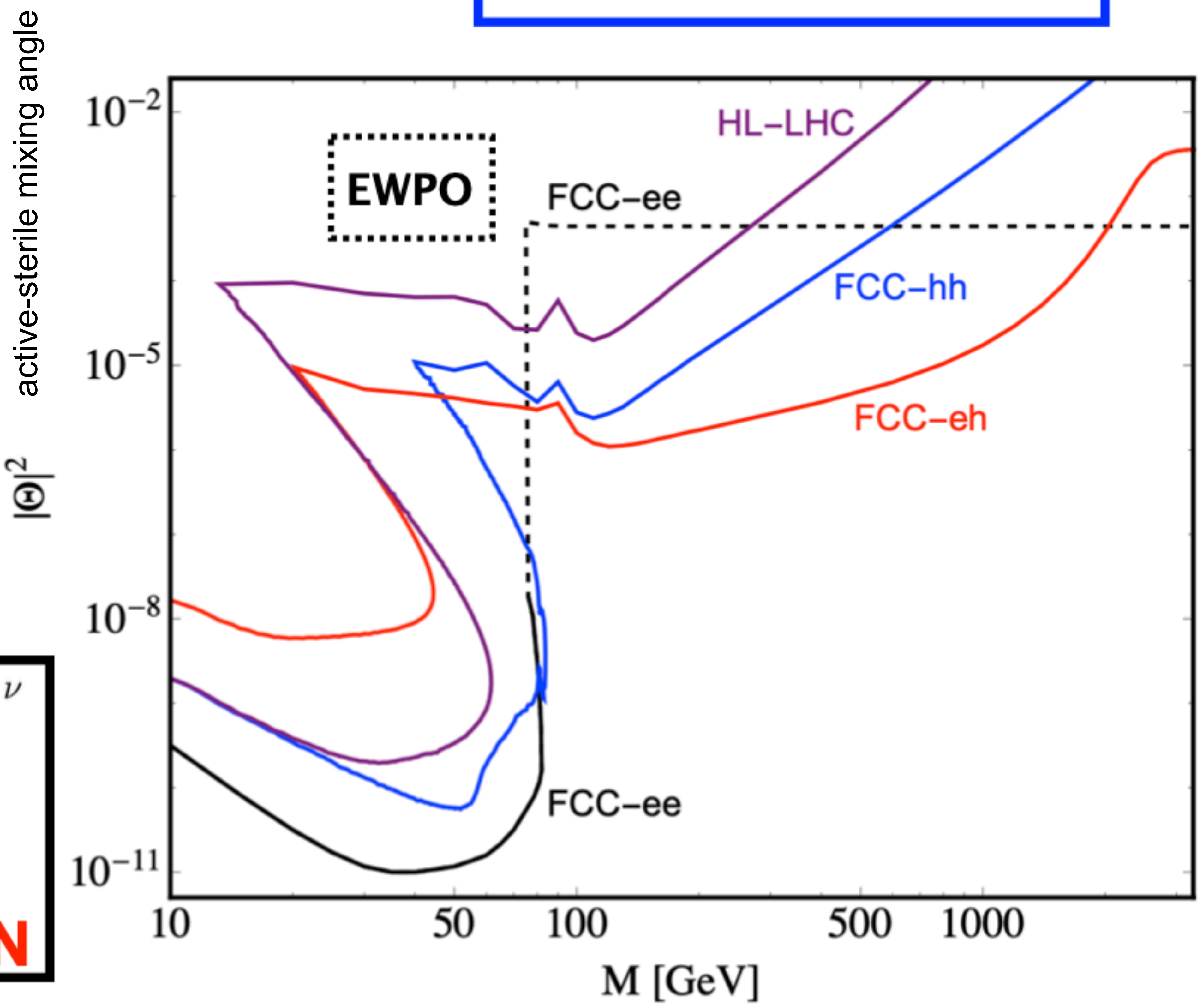
arXiv:1908.02852

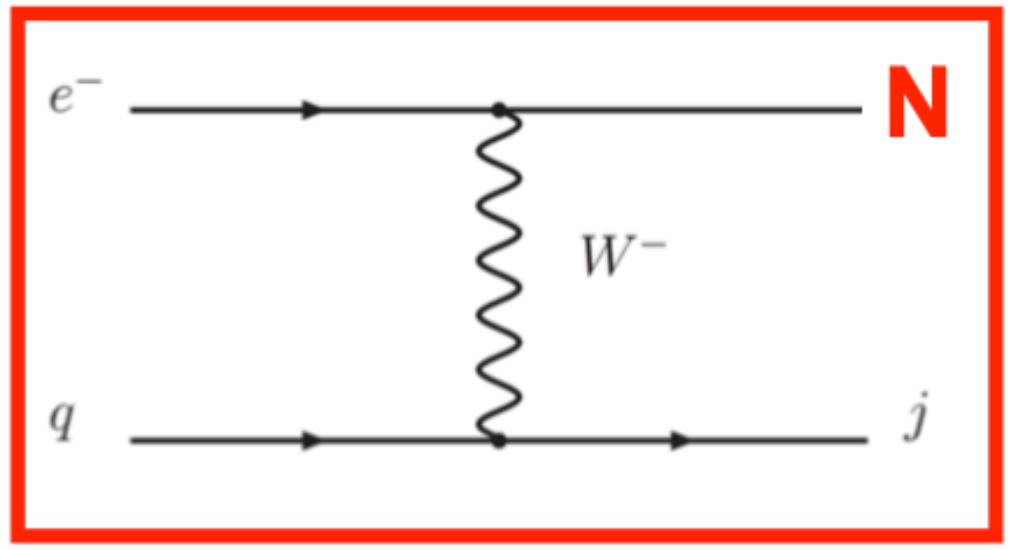


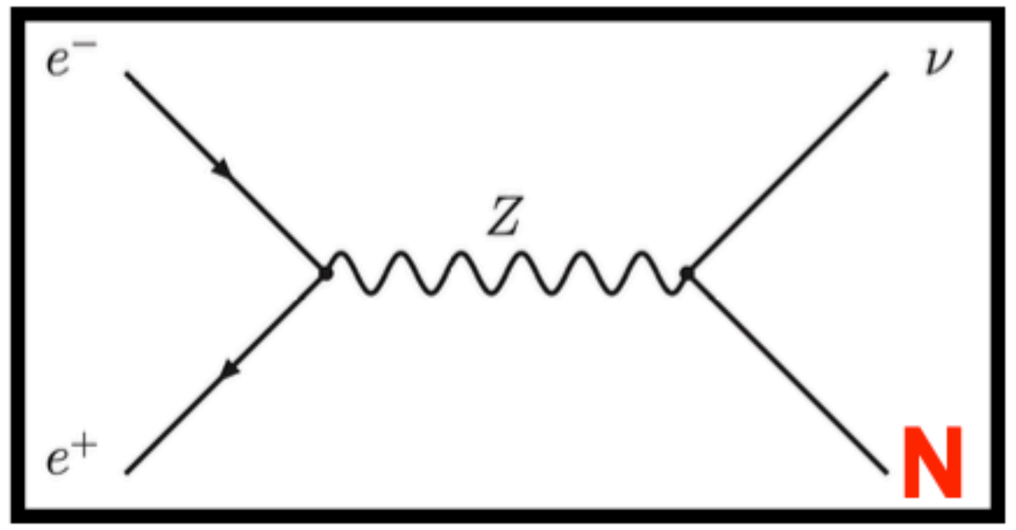
Search for heavy sterile neutrinos

FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)
arXiv:1612.02728 [hep-ph]





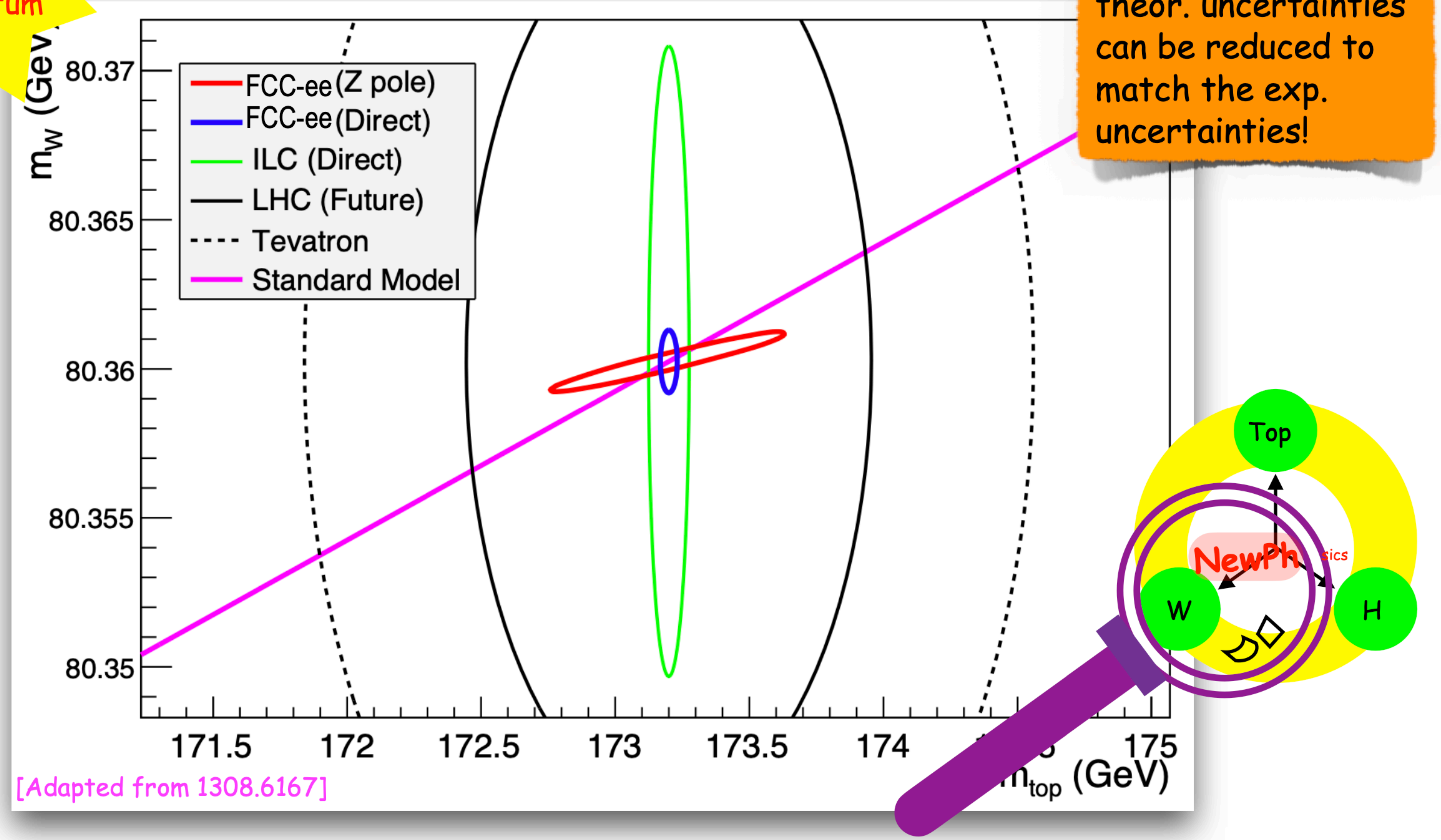




→ **complementary prospects for discovery in ee, ep and pp**

History m_{top} vs. M_W

Consistency test of SM at quantum level



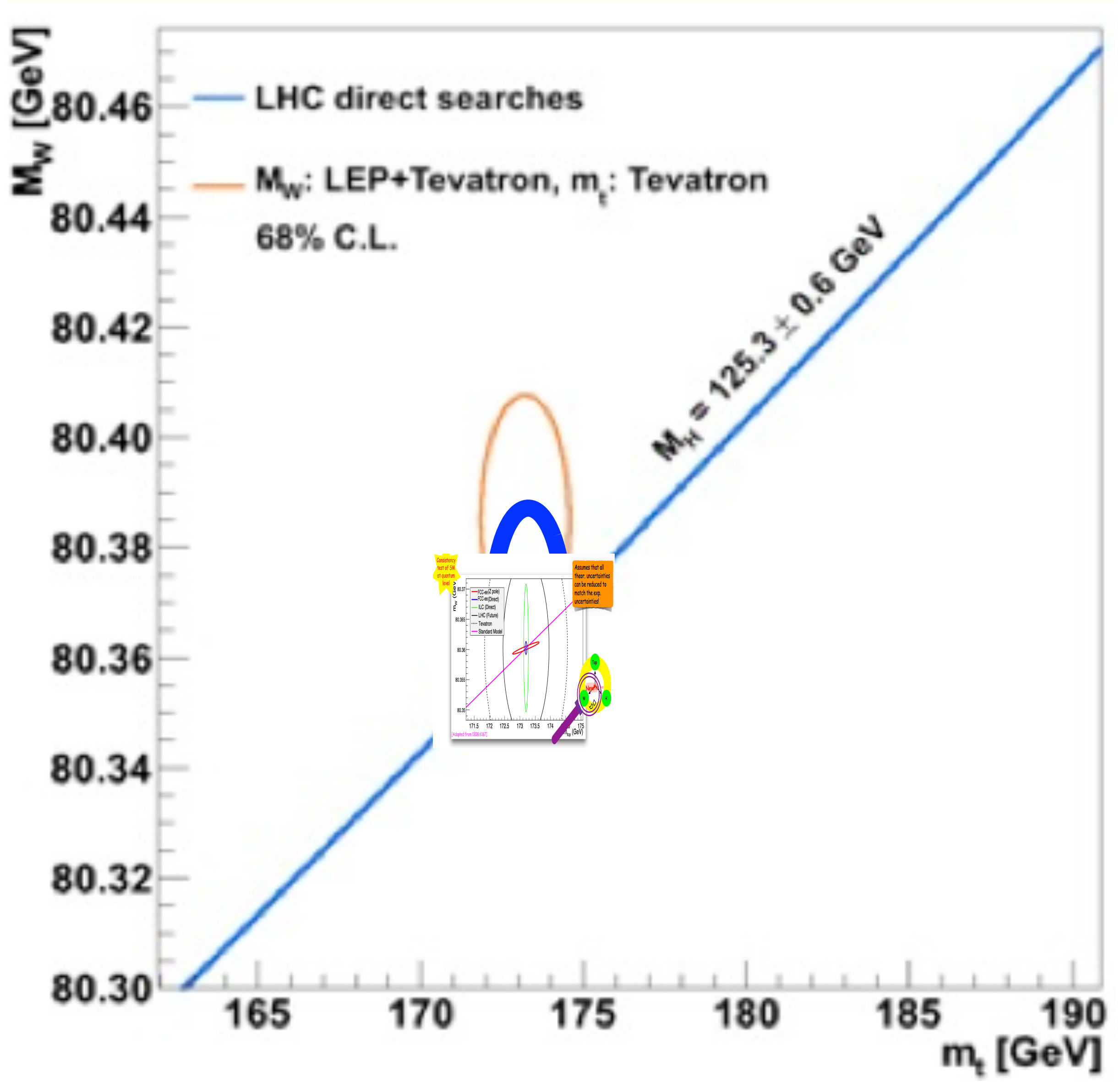
[Adapted from 1308.6167]

Assumes that all theor. uncertainties can be reduced to match the exp. uncertainties!

History m_{top} vs. M_W

M_W=80370±19 MeV

today using world average for m_t



→ agreement with the SM

LINAC at Stanford

Three Messages from the 2m LINAC at Stanford

-- **you do NOT need to promise to discover dark matter or know what new to expect when you increase the energy range** (we yet may have to readjust our perception about nature, its richness and as well our ability to predict and understand it. 'we like to see the field to be driven by experiment' – Burt Richter 2009)

-- **you can build a 2 mile electron linac in 3 years time, if you really want it**
we surely could build LHeC and FCC-eh in short time when decided to do so

-- **electron-proton scattering is the best means to explore the substructure of matter**
a crucial complement to the LHC/FCC and moreover, now a unique Higgs facility

50 years since the discovery of quarks by the SLAC-MIT ep scattering experiment

---

W.K.H. PANOFSKY   Vienna 8/1968   SLAC-PUB-502

Therefore theoretical speculations are focused on the possibility that these data might give evidence on the behaviour of point-like, charged structures within the nucleon.

Max Klein

Conclusions: Statement of the IAC to DG

J. Phys. G 48, 11, 110501 (2011)

In conclusion it may be stated

- The installation and operation of the LHeC has been demonstrated to be commensurate with the currently projected HL-LHC program, while the FCC-eh has been integrated into the FCC vision;
- The feasibility of the project as far as accelerator issues and detectors are concerned has been shown. It can only be realised at CERN and would fully exploit the massive LHC and HL-LHC investments;
- The sensitivity for discoveries of new physics is comparable, and in some cases superior, to the other projects envisaged;
- The addition of an ep/A experiment to the LHC substantially reinforces the physics programme of the facility, especially in the areas of QCD, precision Higgs and electroweak as well as heavy ion physics;
- The operation of LHeC and FCC-eh is compatible with simultaneous pp operation; for LHeC the interaction point 2 would be the appropriate choice, which is currently used by ALICE;
- The development of the ERL technology needs to be intensified in Europe, in national laboratories but with the collaboration of CERN;
- A preparatory phase is still necessary to work out some time-sensitive key elements, especially the high power ERL technology (PERLE) and the prototyping of Intersection Region magnets.

Recommendations

i) It is recommended to further develop the ERL based ep/A scattering plans, both at LHC and FCC, as attractive options for the mid and long term programme of CERN, resp. Before a decision on such a project can be taken, further development work is necessary, and should be supported, possibly within existing CERN frameworks (e.g. development of SC cavities and high field IR magnets).

ii) The development of the promising high-power beam-recovery technology ERL should be intensified in Europe. This could be done mainly in national laboratories, in particular with the PERLE project at Orsay. To facilitate such a collaboration, CERN should express its interest and continue to take part.

iii) It is recommended to keep the LHeC option open until further decisions have been taken. An investigation should be started on the compatibility between the LHeC and a new heavy ion experiment in Interaction Point 2, which is currently under discussion.

After the final results of the European Strategy Process will be made known, the IAC considers its task to be completed. A new decision will then have to be taken for how to continue these activities.

Herwig Schopper, Chair of the Committee, Geneva, November 4, 2019

→ LHeC/FCCeh developments are part of detector and accelerator roadmaps
→ PERLE a key part of the ERL development
→ exciting rich programme for the coming years that substantially strengthens HL-LHC
→ is established and for us to shape

https://lhec.web.cern.ch/