Electrons for the LHC

Uta Klein

Speaker's affiliations:

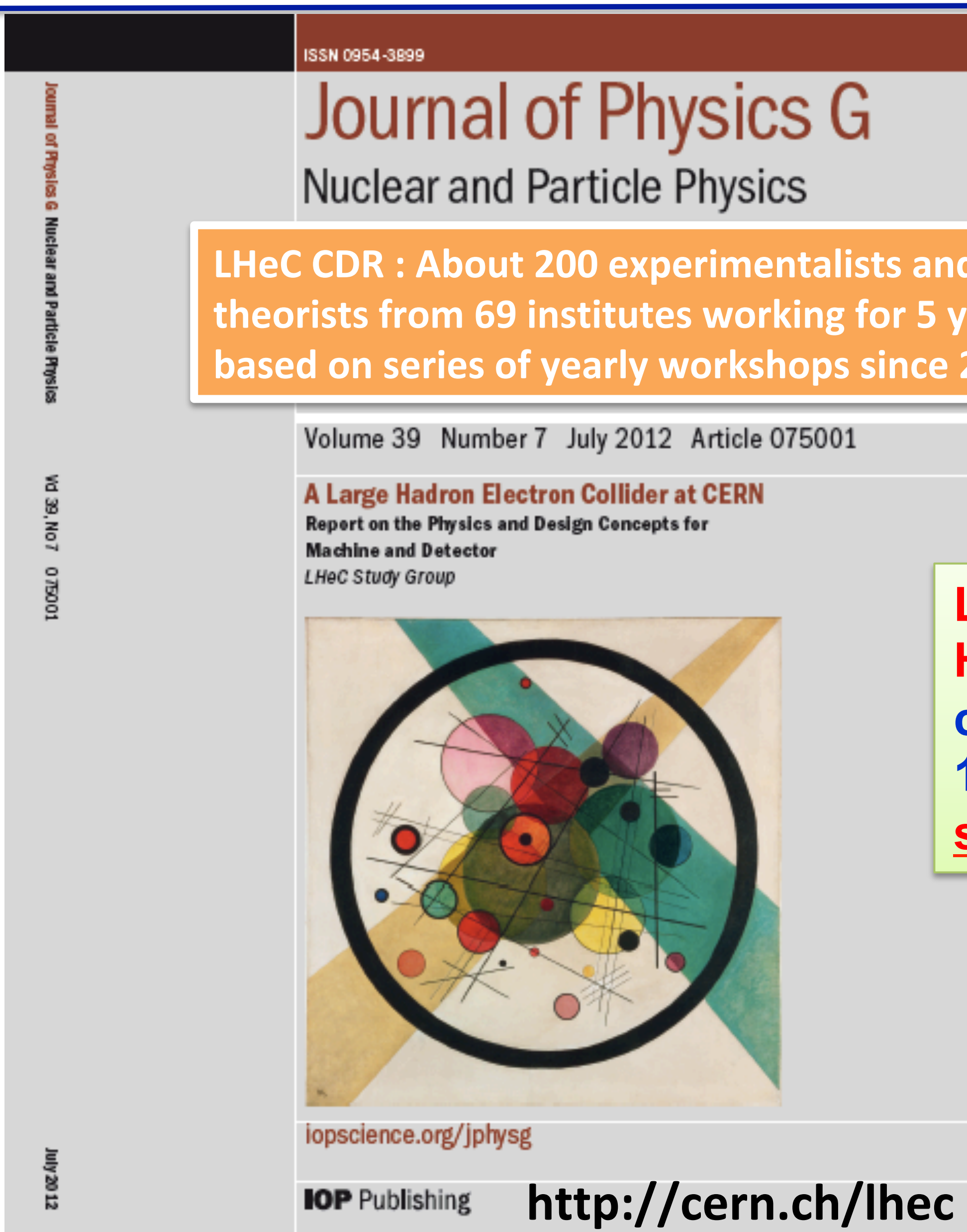
UNIVERSITY OF LIVERPOOL

DESY, Zeuthen, February 28th 2018

CDR "A Large Hadron Electron Collider at CERN"

J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001 [arXiv:1206.2913]

"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]



LHeC CDR : About 200 experimentalists and theorists from 69 institutes working for 5 years based on series of yearly workshops since 2008

http://cern.ch/lhec

International referees invited by CERN

Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)

Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)

Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)

Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)

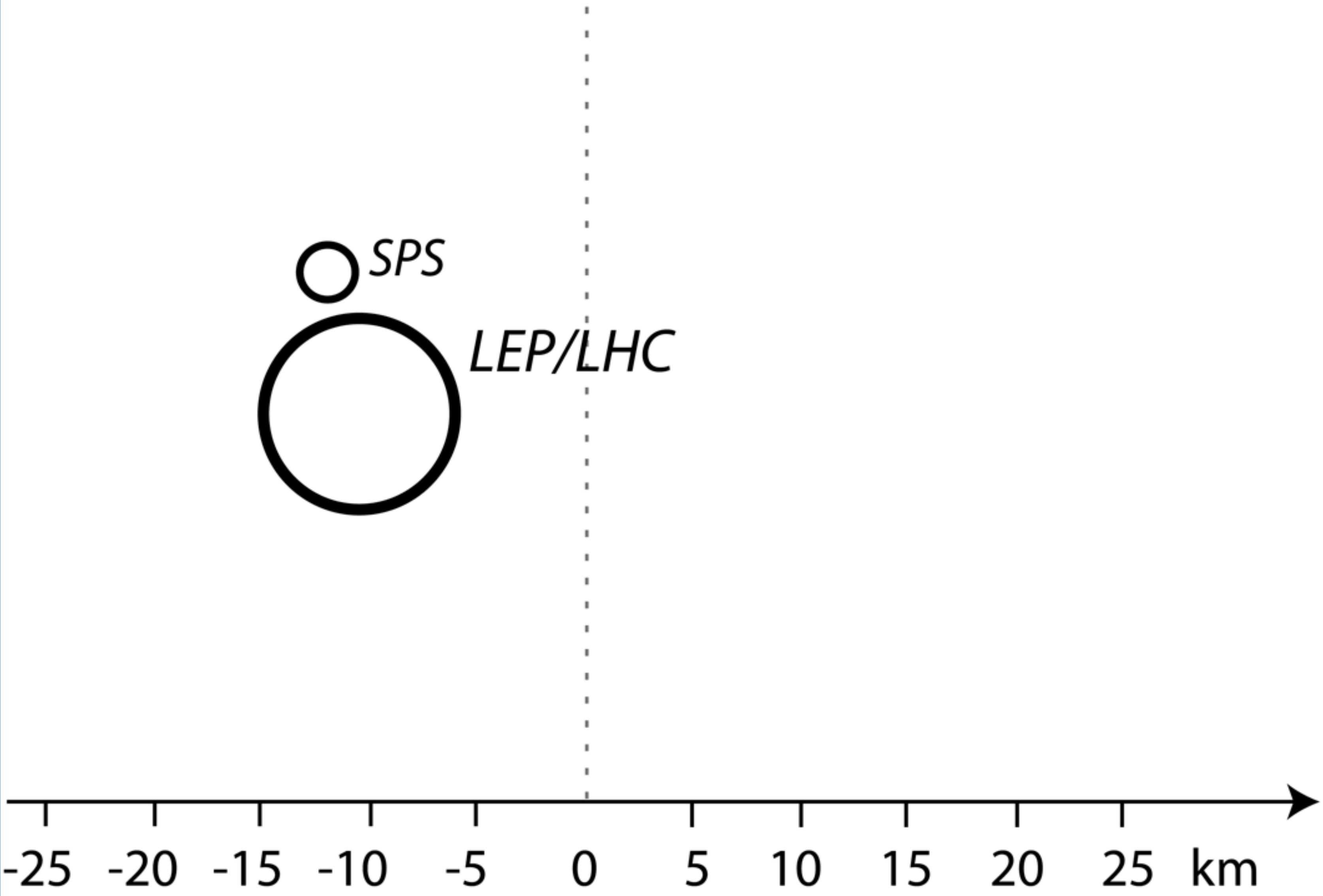
Gian Giudice (CERN)
Michelangelo Mangano (CERN)

Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)

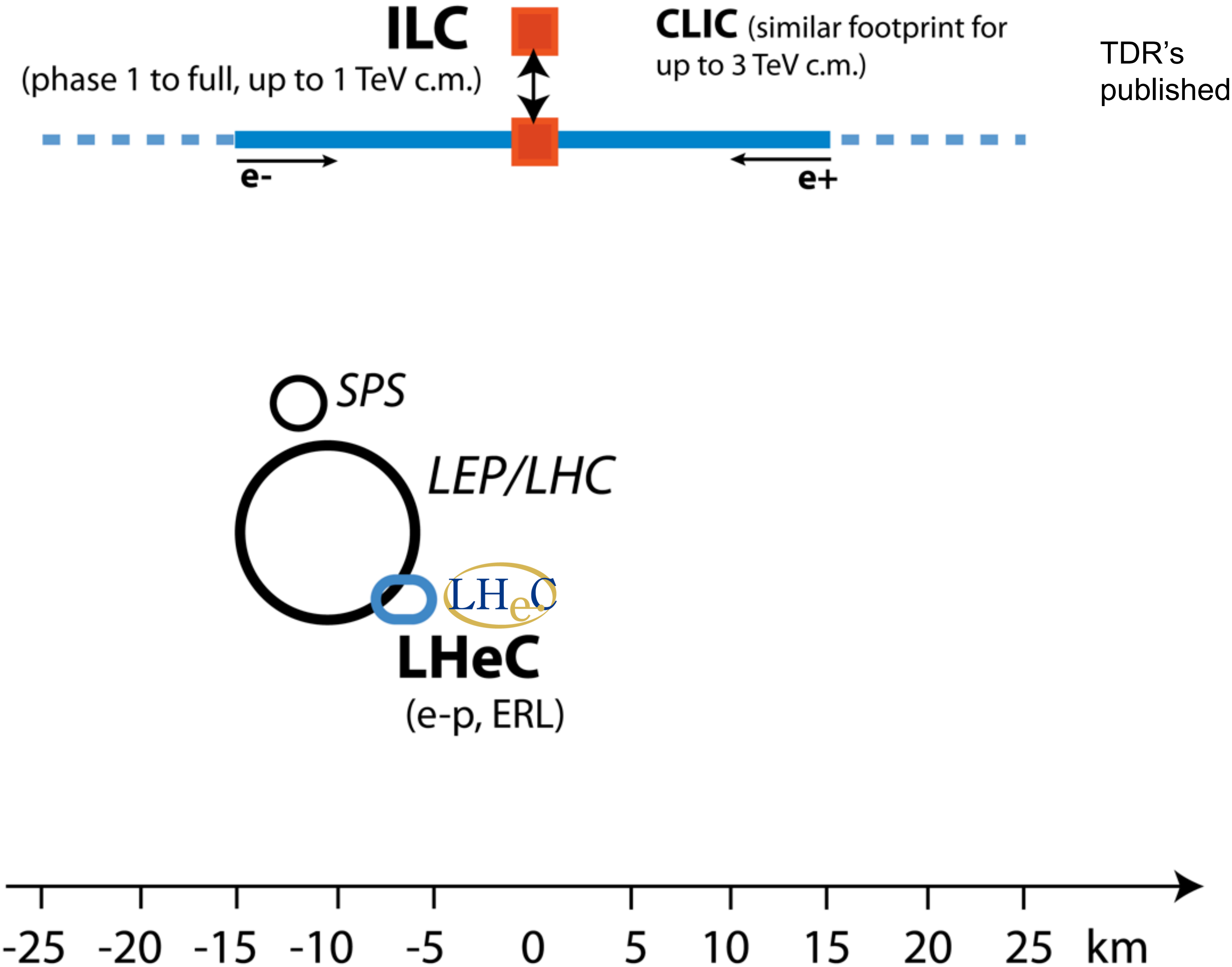
Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

LHeC and FCC-he
High-energy frontier e-p and e-A colliders to follow HERA with factor 1000 higher luminosity running simultaneously with HL-LHC / FCC-hh.

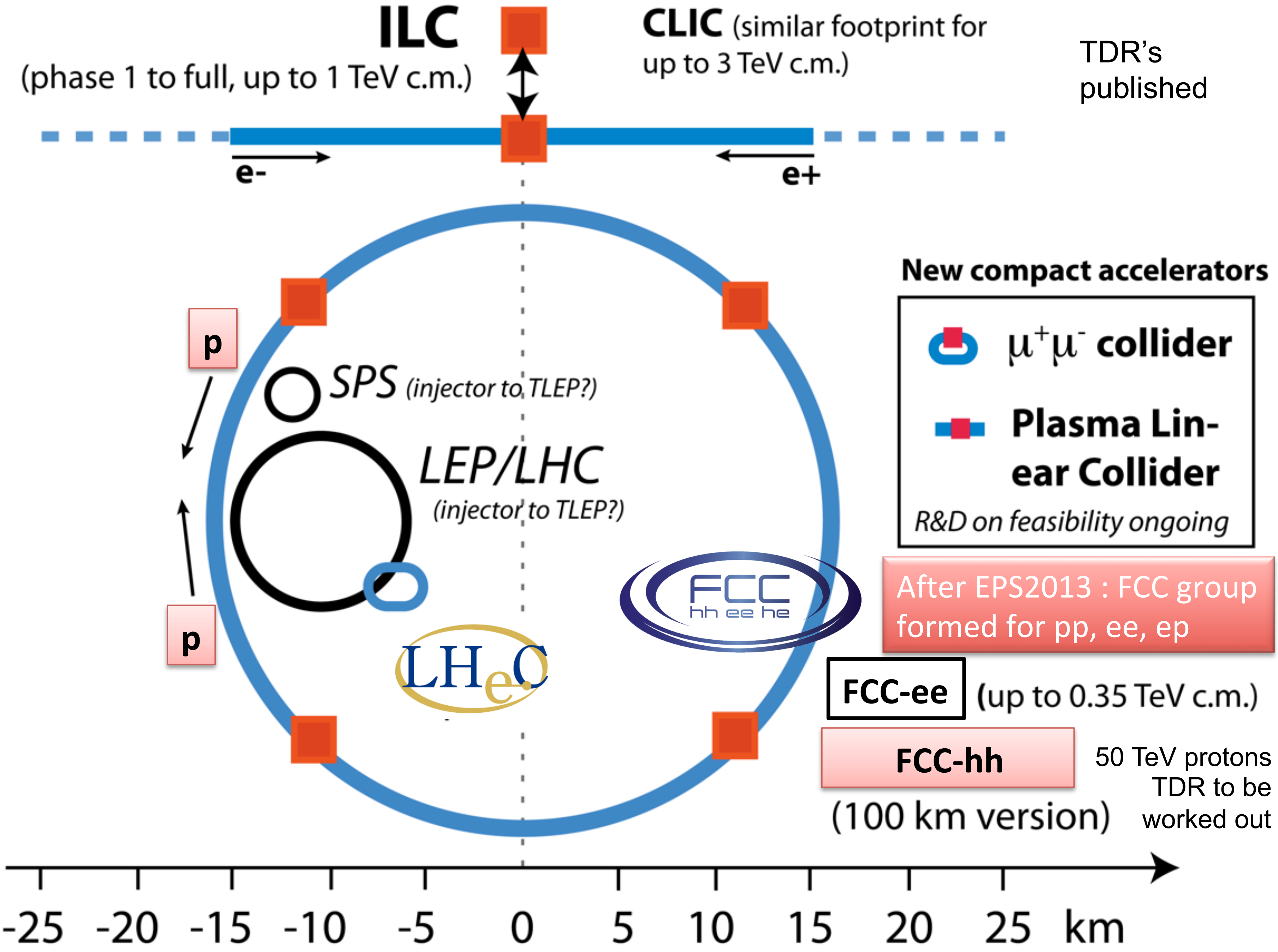
Slide by Ralf Assmann@EPS2013



Collider options beyond LHC-Run II



Collider options beyond LHC-Run III



Slide partially from R. Assmann EPS2013

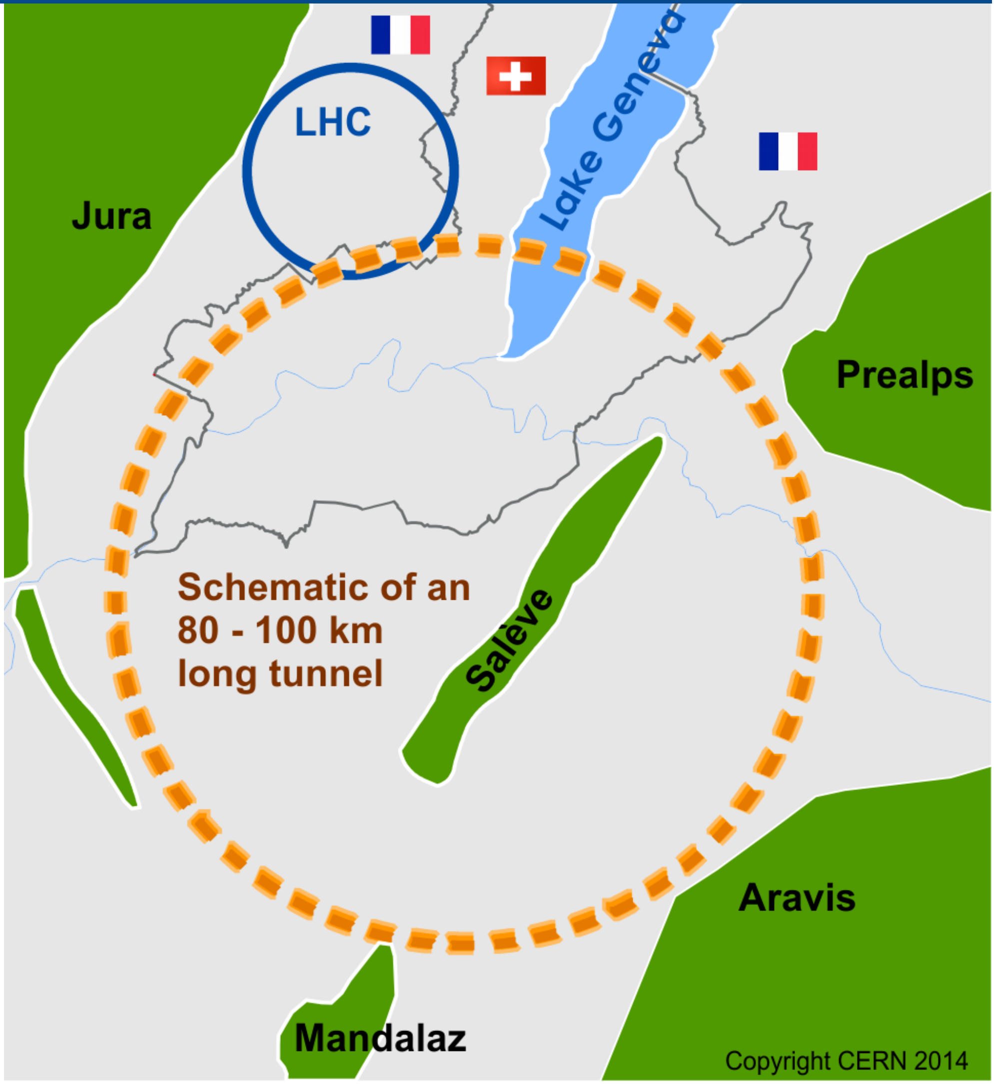
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018/19

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology

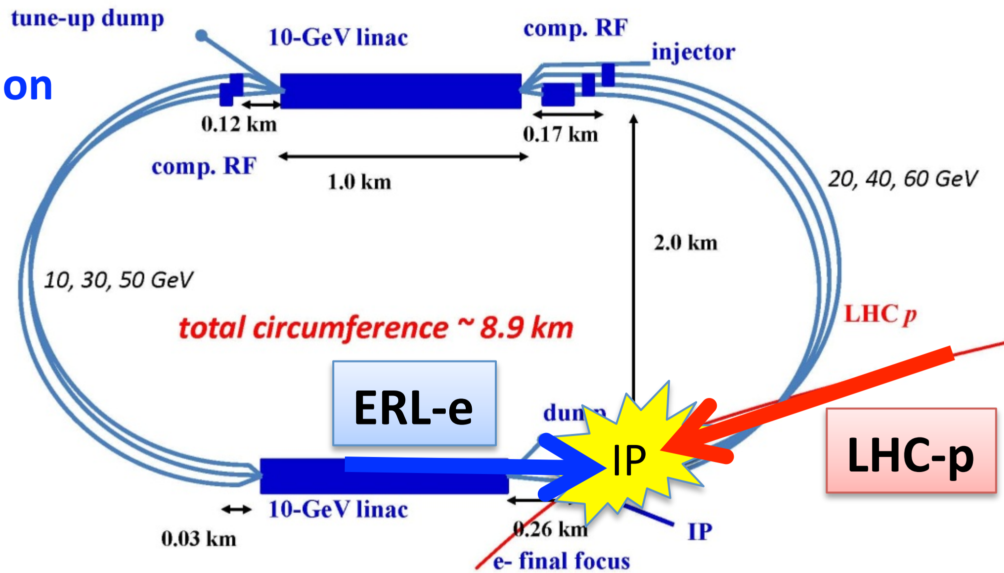


Accelerator Configuration and PERLE

electrons for LHC : ERL + LHC

- Two Electron LINACs + 3 return arcs: using energy recovery in same structure: 'green' technology with power consumption < 100 MW : E_e = 60 GeV
- Beam dump: no radioactive waste!
- high electron polarisation of 80-90%
- Installation decoupled from LHC operation

Concurrent ep and HL-LHC operation!
Same idea holds for HE-LHC and FCC-hh



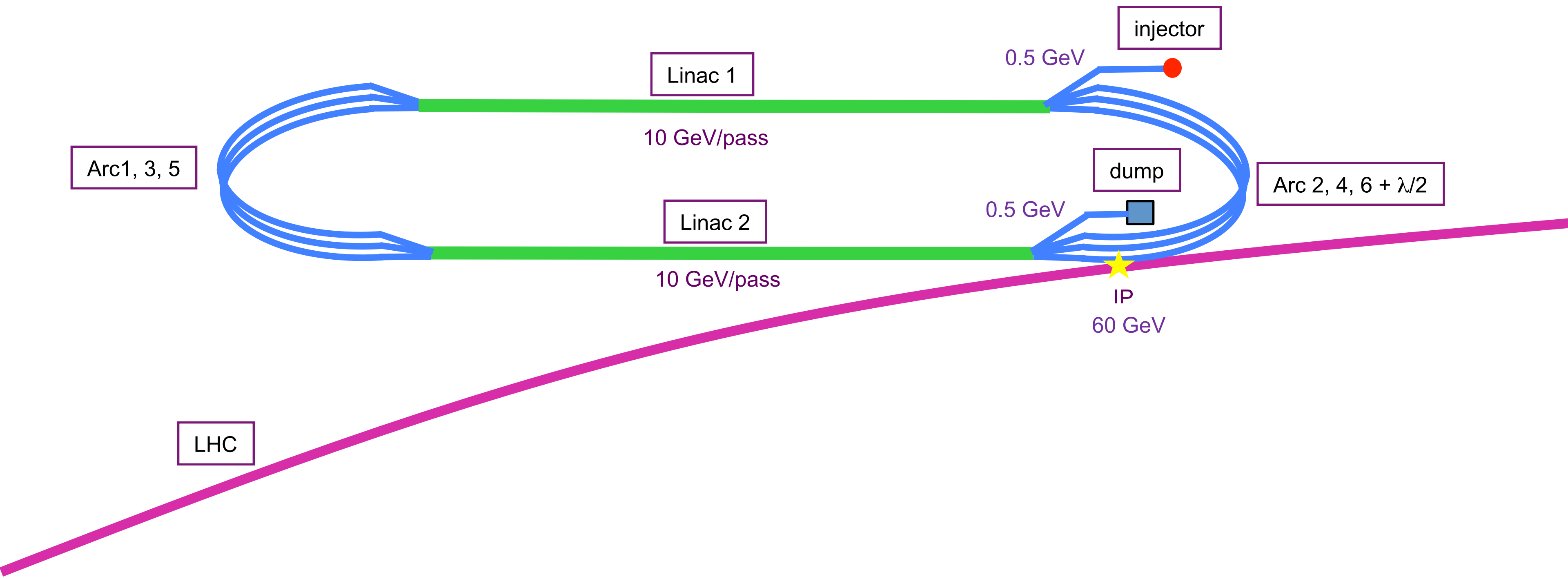
- ep Lumi 10^{34} cm s^{-2} s^{-1} **
- 100 fb^{-1} per year, e.g. ~2030-2040 (HL-LHC)
- L= 1000 fb^{-1} total collected in 10 years
- eA luminosity estimates ~ 10^{33} cm s^{-2} s^{-1} eA

** based on existing HL-LHC proposal

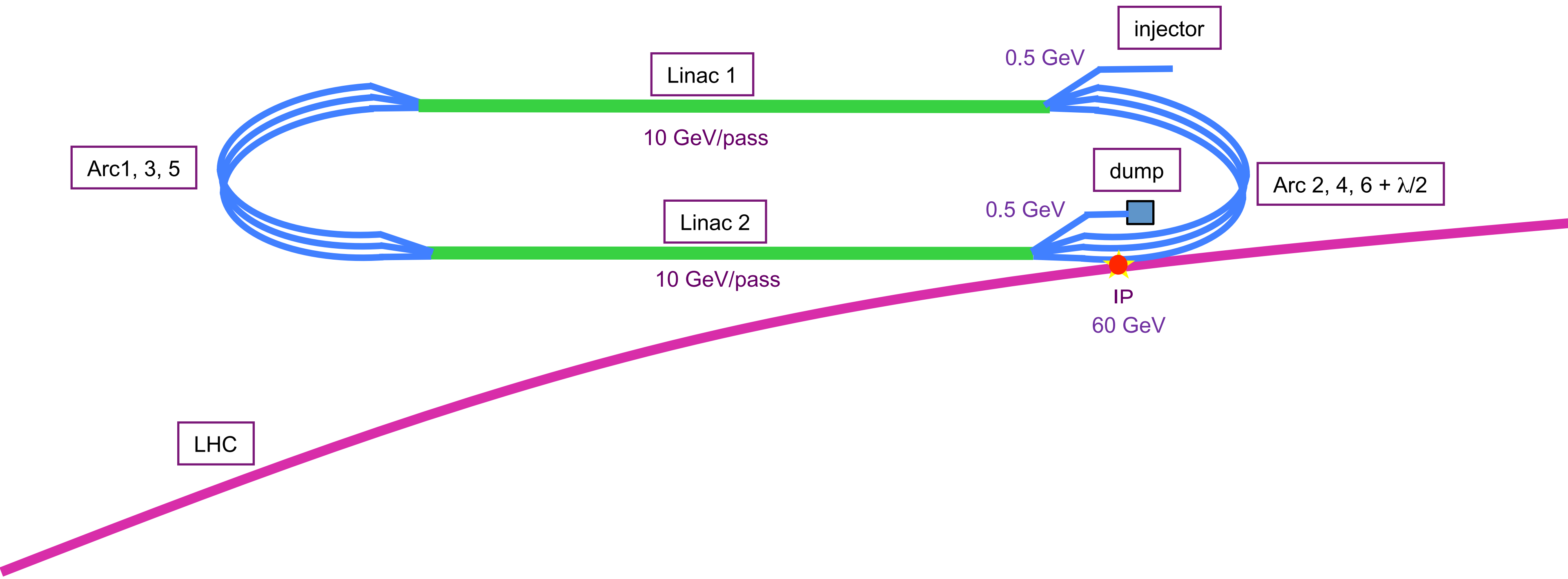
Detector Design
for HL+HE+FCC ep
Peter Kostka et al.

LHeC CDR: arXiv:1206.2913 and updates at LheC/FCC-eh WS@CERN, 9/17

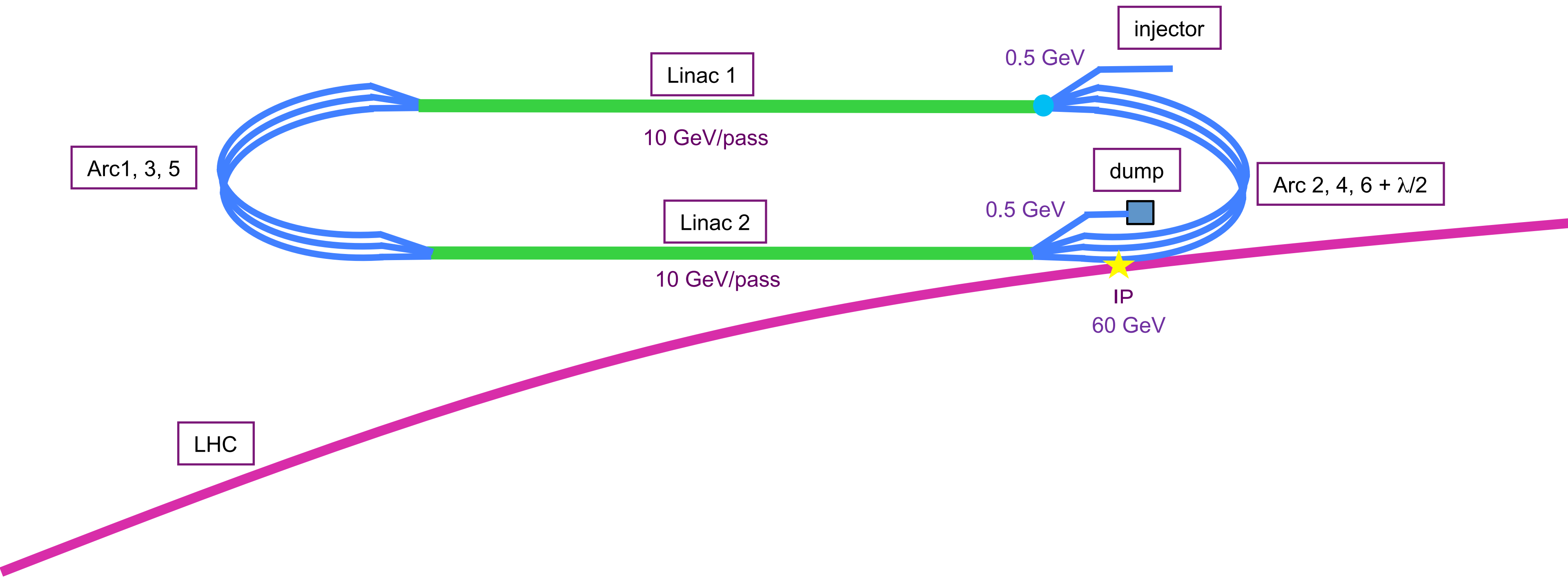
LHeC Recirculator with Energy Recovery



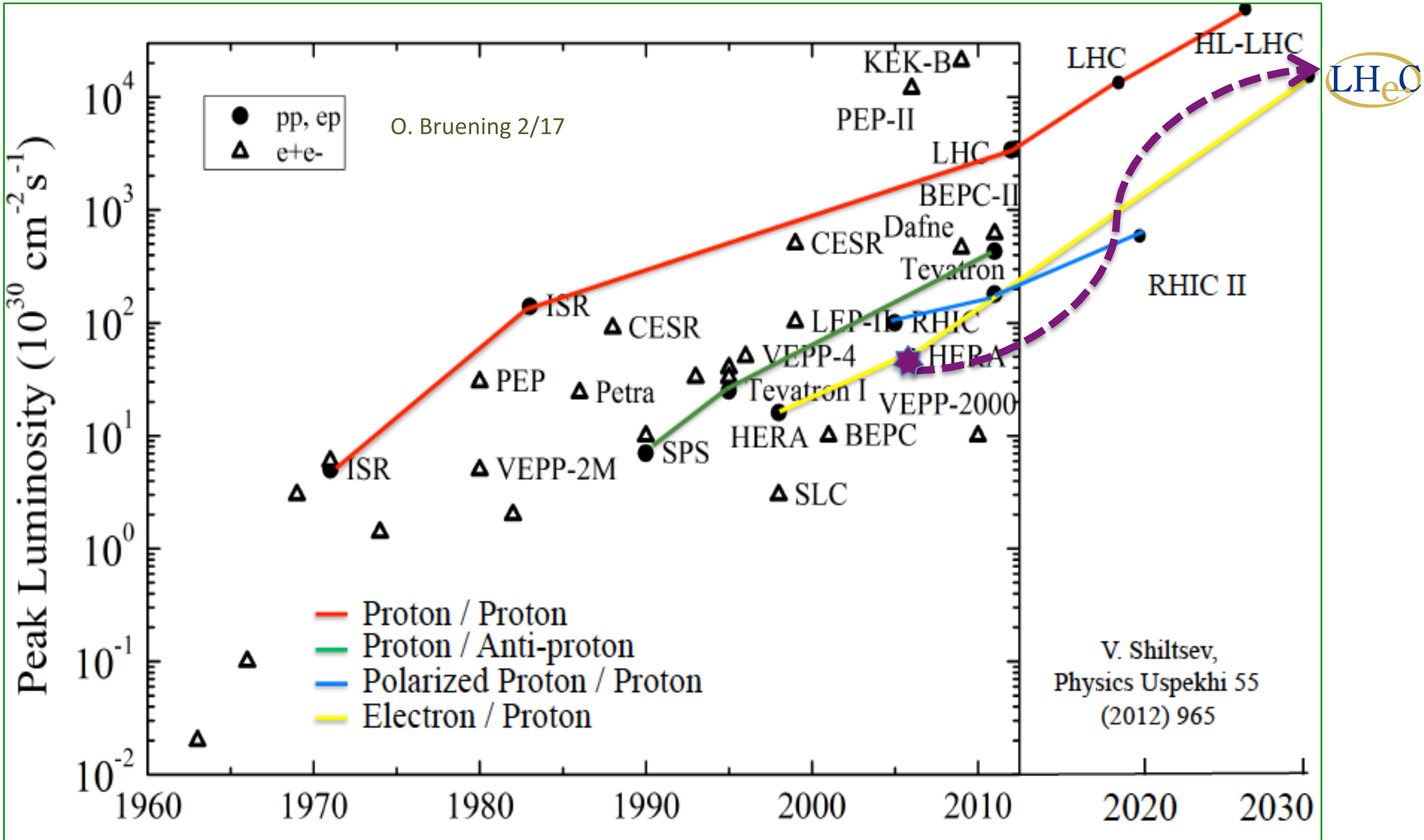
LHeC Recirculator with Energy Recovery



LHeC Recirculator with Energy Recovery



Collider Luminosities vs Year (pp and ep)



HL LHC programme: 3ab^{-1} (in pp scattering) in 10 years of operation: LHC until almost 2040

FCC-pp and HE-LHC: not before ~2040 due to required 16 T magnet developments [MB, 1/18]

Luminosity for LHeC, HE-LHeC and FCC-he

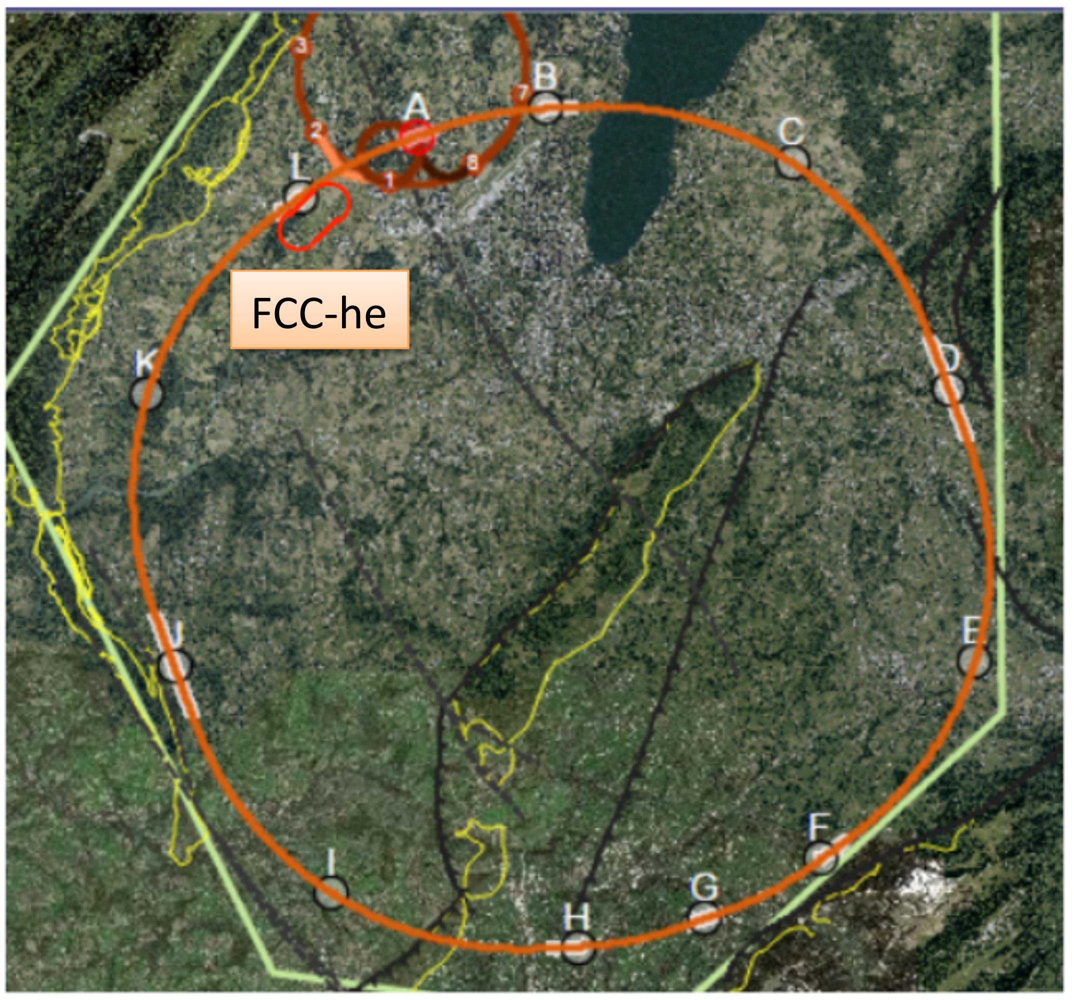
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV] c.m.s.	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

Oliver Brüning[1], John Jowett[1], Max Klein[2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]

EDMS 17979910 | FCC-ACC-RPT-0012

Contains update on eA:
6 10^{32} cm^{-2}s^{-1} in e-Pb for LHeC.

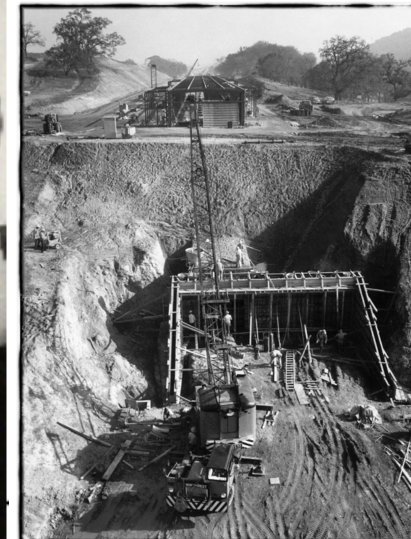
FCC-he Site and Integration to FCC-hh

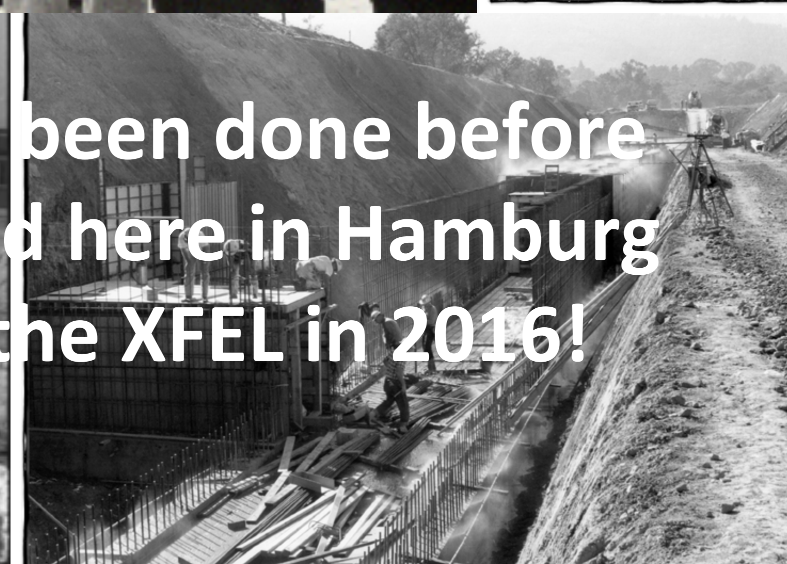


60 GeV ERL tangential to FCC-hh. IP: L for geological reasons. L= 1.5 10^{34} Higher s, Q^2, 1/x

Can one build a 2 km long Linac?





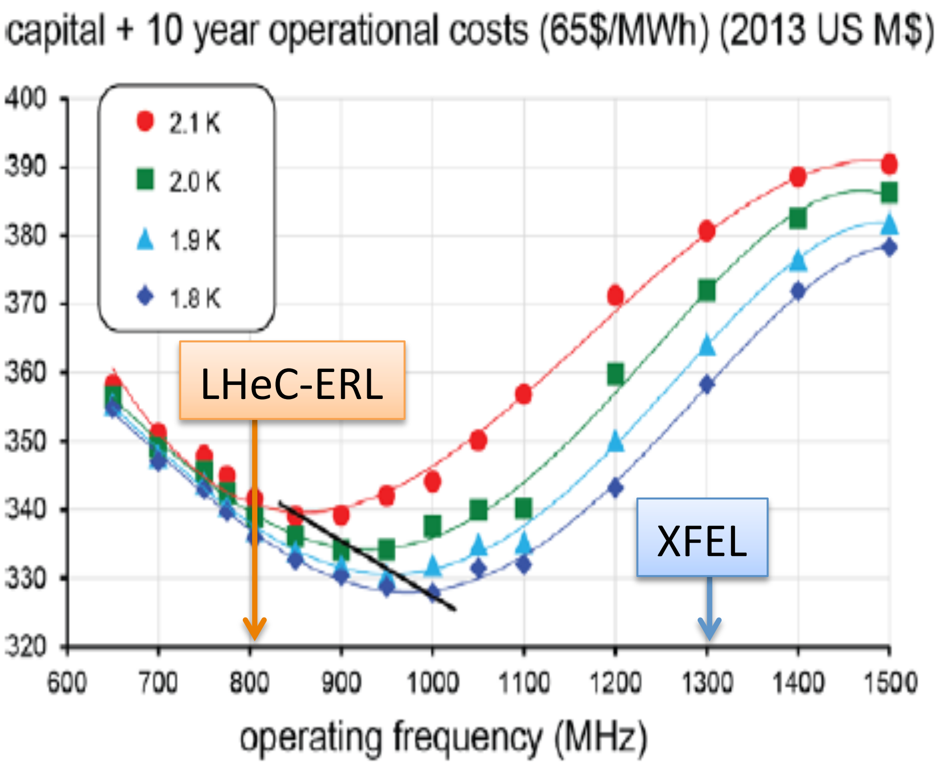
It has been done before

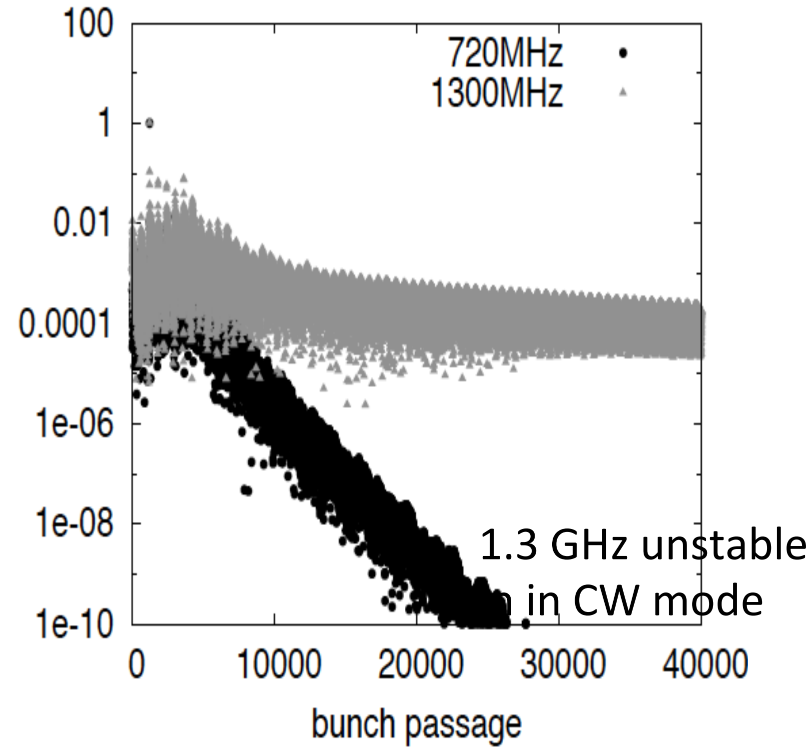
… and here in Hamburg

with the XFEL in 2016!

Courtesy F.Zimmermann

Frequency Choice for SC Cavities in CW: 801.58 MHz





- **Cost, dynamic heat losses, resistance, Q_0… point to f < 1 GHz (F Marhauser, Orsay 2/17)**
- **Beam beam interactions unstable for f > 1 GHz (D Schulte, D Pellegrini March 2013)**
- **Compatibility with LHC: Decision for 802 MHz (E Jensen CI Workshop 1/2015, FM input)**

PERLE: Powerful ERL for Experiments

Collaboration of BINP, CERN, Daresbury/Liverpool, Jlab, Orsay INP+LAL + : CDR 2016/17, **TDR 2018/19** ..

PERLE

PERLE

Powerful Energy Recovery Linac for Experiments

Conceptual Design Report

Version for Publication in J.Phys.G

CELIA Bordeaux, MIT Boston, CERN, Cockcroft and ASTeC Daresbury, TU Darmstadt, U Liverpool, Jefferson Lab Newport News, BINP Novosibirsk, IPN and LAL Orsay

October 23rd, 2017

arXiv:1705.08783

J Phys G in print

WHY PERLE?

An Accelerator Test Facility Supporting the LHeC

University of Liverpool, November 2017

https://indico.cern.ch/event/680603/

Steve Benson, Alex Bogacz, David Douglas, and Chris Tennant

for the Jlab PERLE Study Group

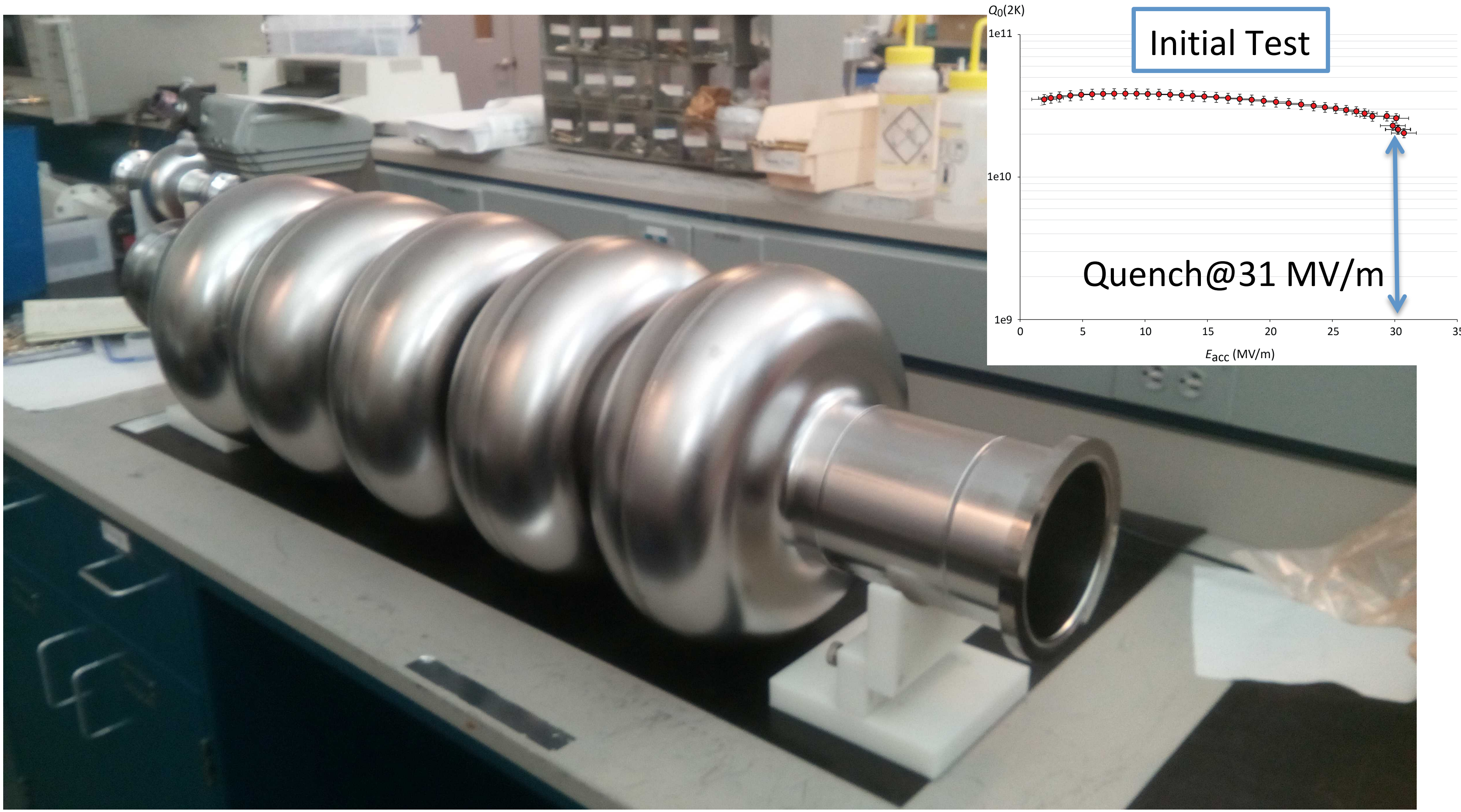
Saturday, November 11, 2017

Jefferson Lab

- ✓ **Demonstrator of ERL for ep at LHC/FCC**
- ✓ **SC RF Beam based development facility**
- ✓ **Low E electron and photon beam physics**
- ✓ **High intensity: O(100) x ELI**

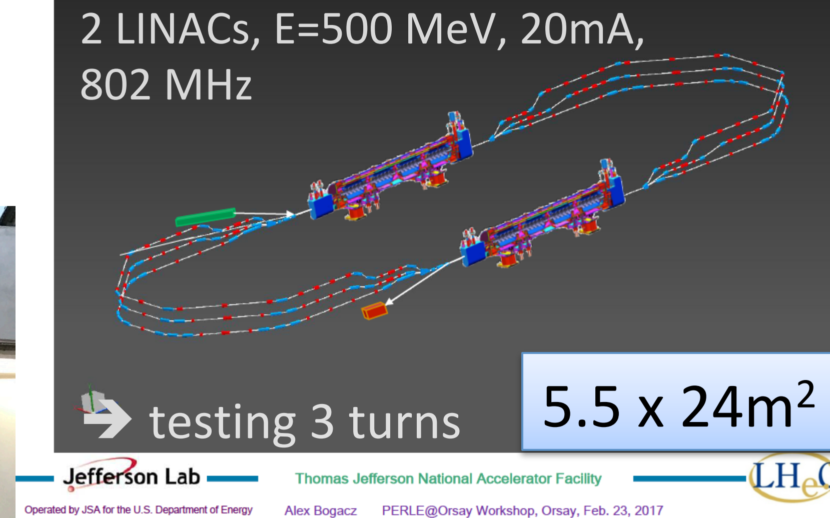
First 802 MHz Cavity

CERN-JLAB design
produced at JLAB **Nov 2017**



- **Initial test: High quality and operation point in CW@18 MV/m**
- **Goal: $Q_0 > 10^{10}$ operated in CW in the PERLE+LHeC ERLs**
- **Prototype also for FCC-ee**

PERLE at Orsay



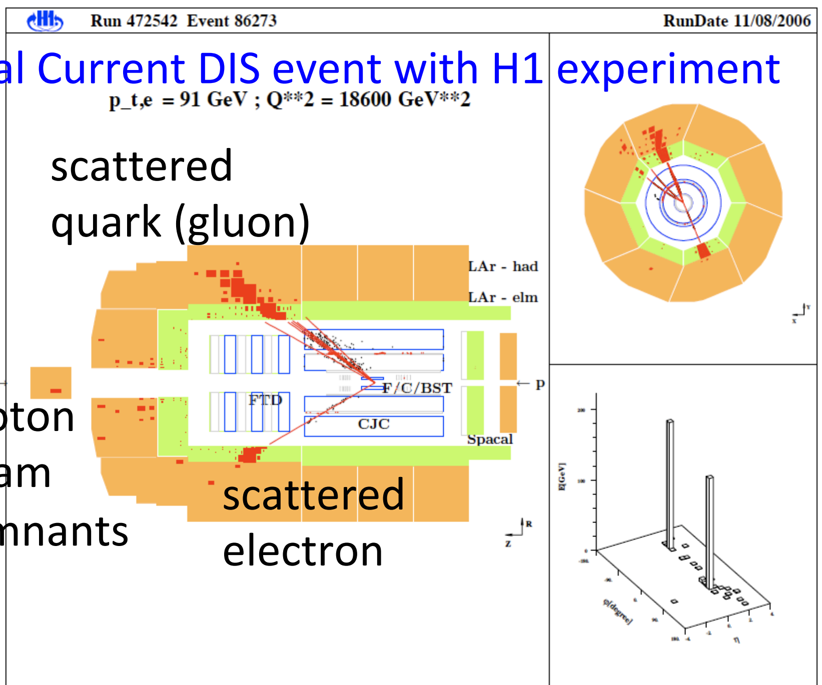
W Kaabi, O Bruening, F Bodry, M Klein, P Kostka, P Thonet, D Douglas
A Stocchi B Rimmer

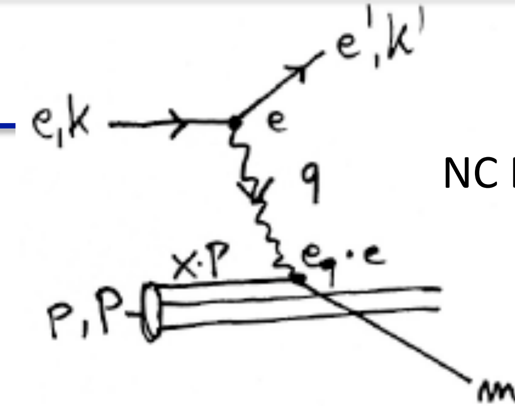
Electron-Proton Physics at the Energy Frontier

ep : Some Basics

The only ep collider so far : HERA @ DESY
with a **c.m.s. energy of 0.32 TeV** using
electrons/positrons with E_e= 27.6 GeV
protons with E_p= 0.92 TeV [like Tevatron protons]
Precise probe of proton structure using Deep Inelastic Scattering (DIS) in a new kinematic range
with a resolution up to 10^{-18} m : ep = Supermicroscope

Neutral Current DIS event with H1 experiment





NC DIS

$$q = (k - k'), q^2 = -Q^2$$

$$s = (k + P)^2$$

$$(xP + q)^2 = m^2, P^2 = M_p^2$$

$$if\ (Q^2 >> x^2 M_p^2, m^2):$$

$$q^2 + 2xPq = 0$$

$$x = \frac{Q^2}{2Pq}$$

$$Q^2 = sxy$$

relation to pp

$x_{1,2}$= (M/√s) exp(±y)

$Q^2 = M^2$

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{e^4 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)} \left[W_2(q^2, W) + 2W_1(q^2, W) \tan^2(\theta/2)\right]$$

SLAC-PUB-642
August 1969

@SLAC: birth of DIS, 50 years ago.

HERA Run 2

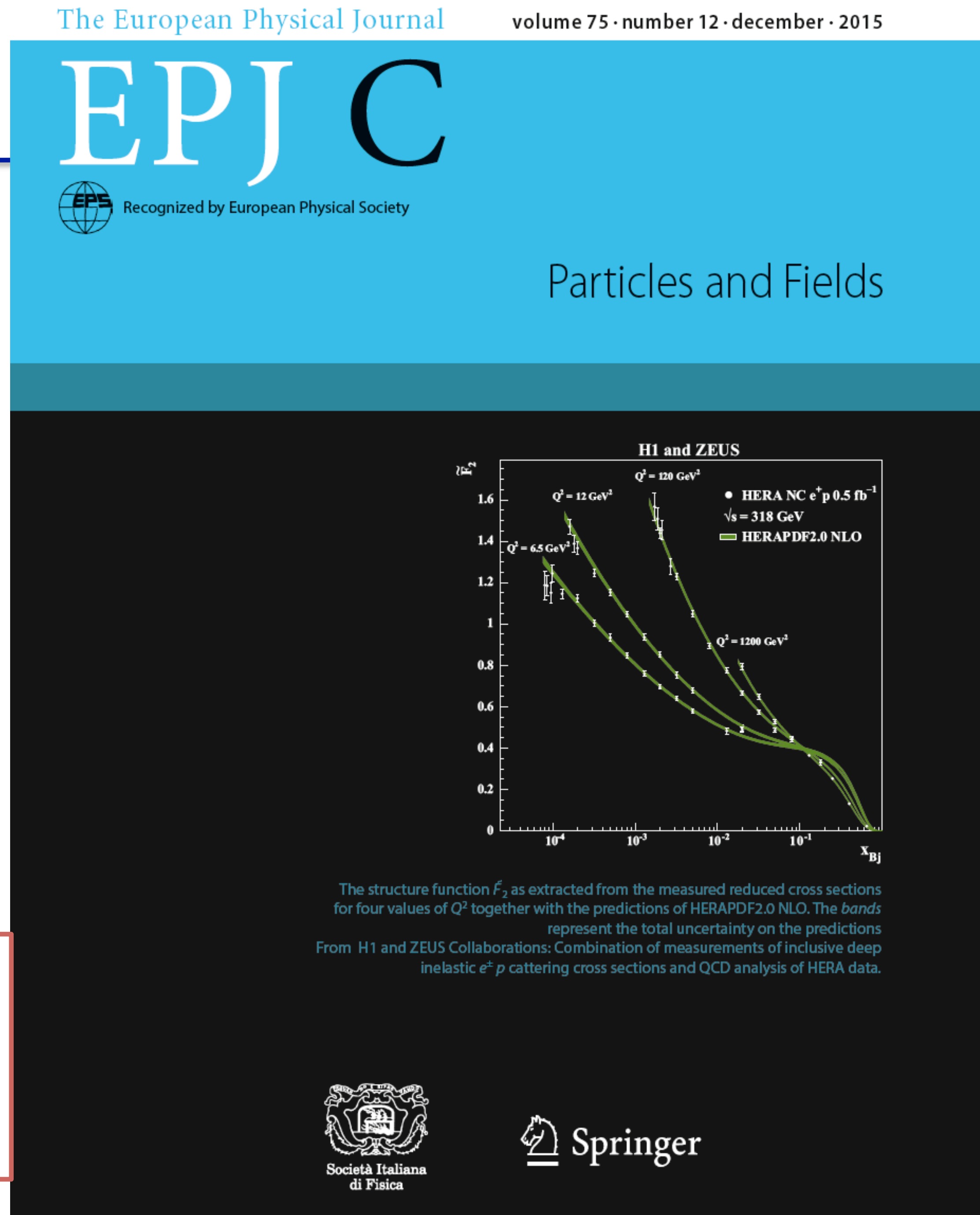
→ **Mandatory input for our currently best knowledge about the quark-gluon dynamics of the proton,** e.g. LHC Higgs cross section predictions.

"Limitations" of HERA

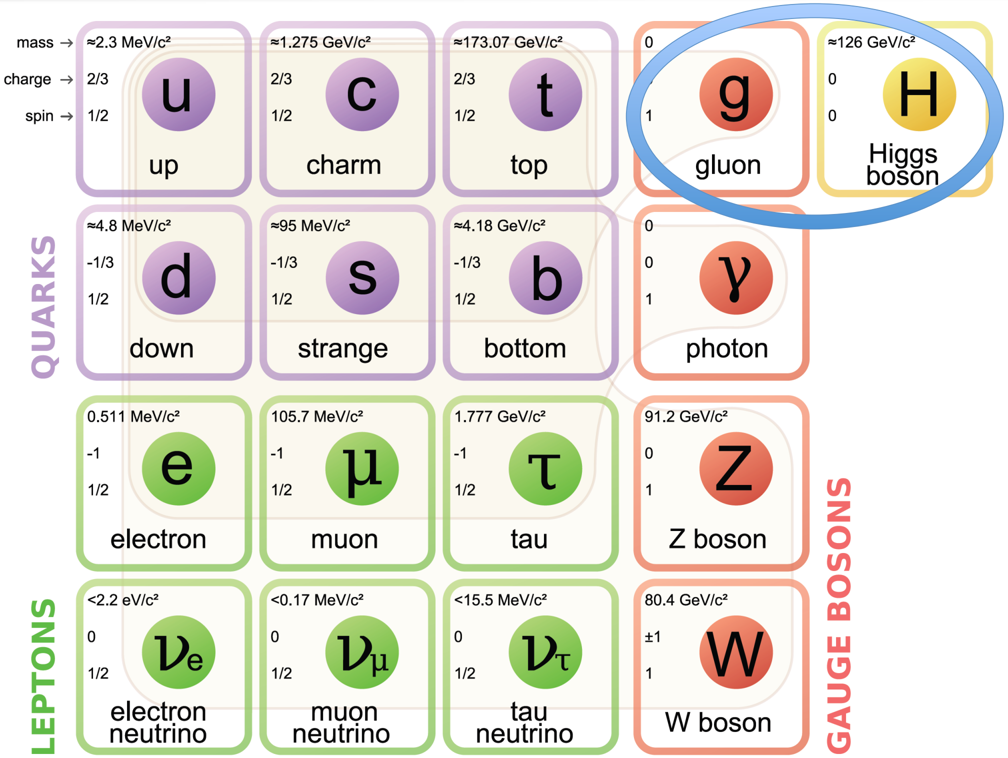
→ **Luminosity 1-4•10^{31} cm^{-2} s^{-1}**

→ **No eA collisions**

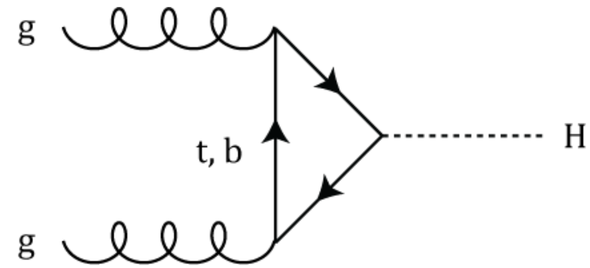
→ **No polarised protons**



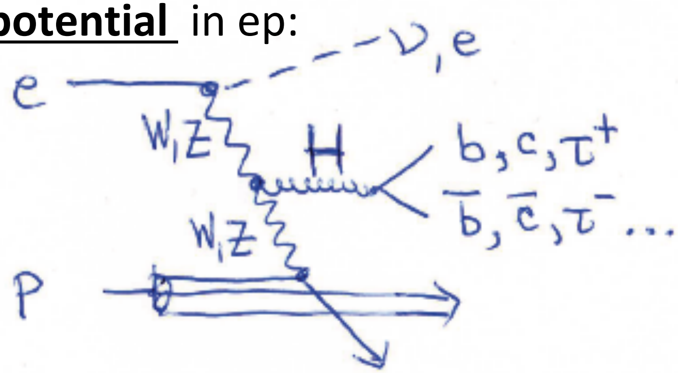
Standard Model Particles & QCD



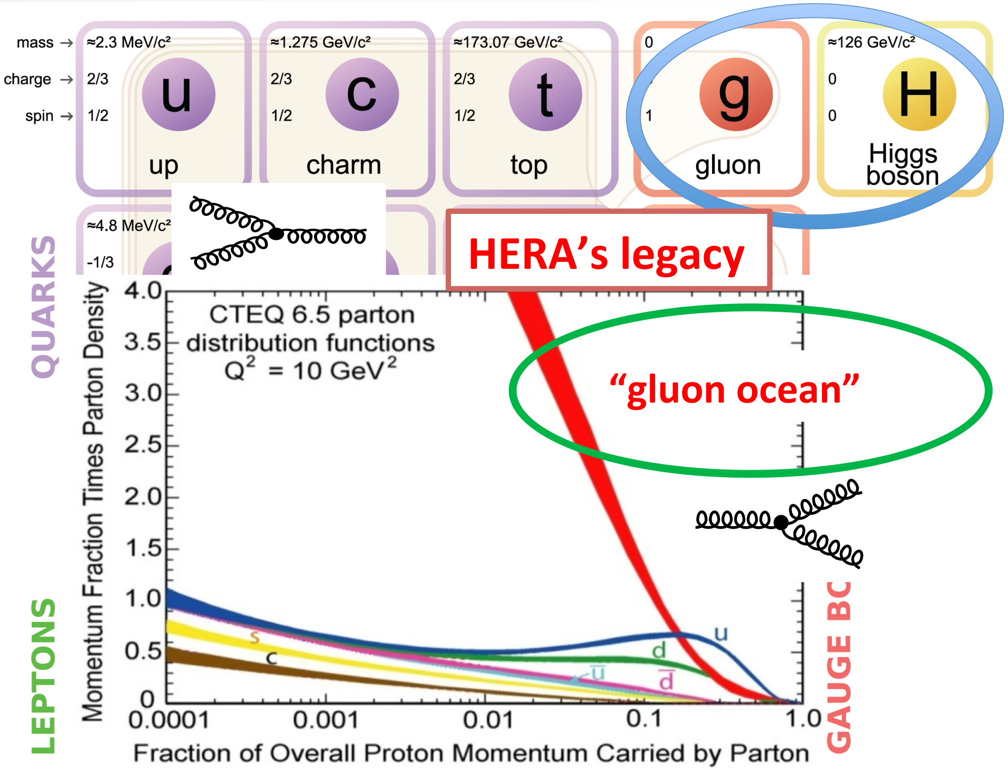
Higgs discovery at LHC via gluon-gluon fusion



Higgs potential in ep:



Standard Model Particles & QCD



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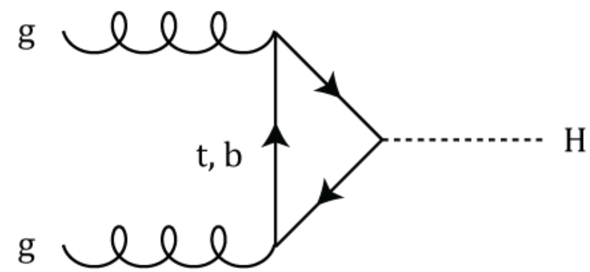

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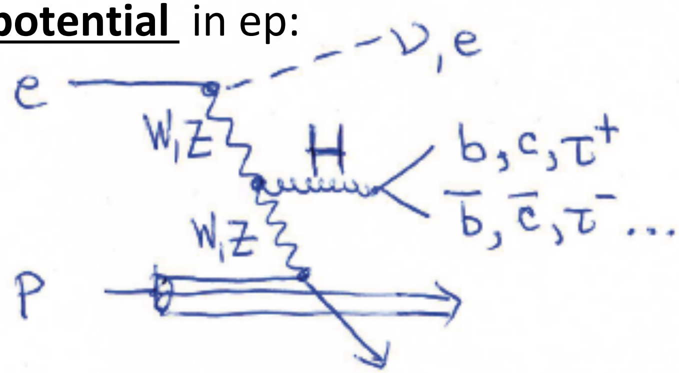
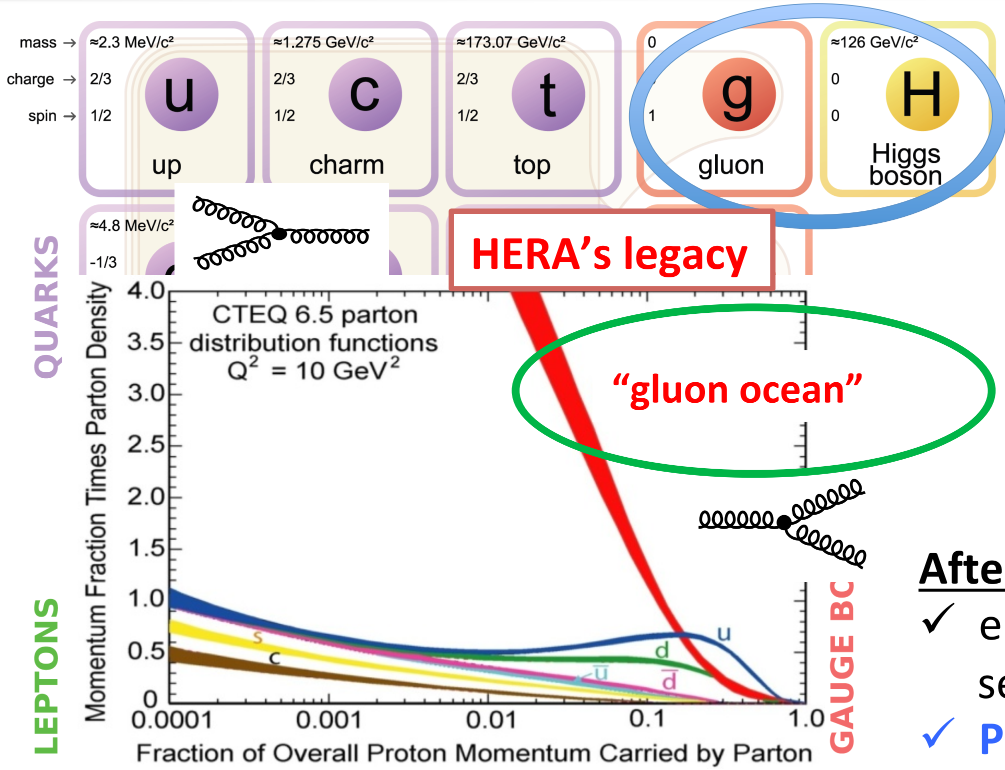


SM, Higgs and QCD



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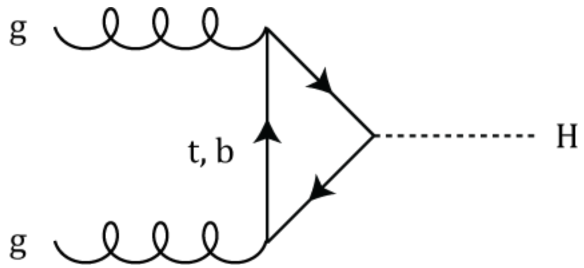
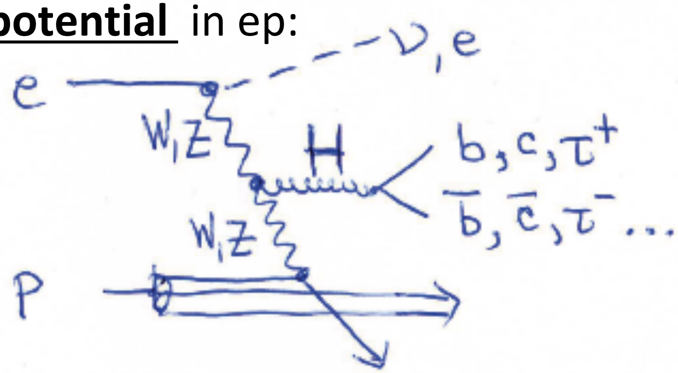


Higgs potential in ep:



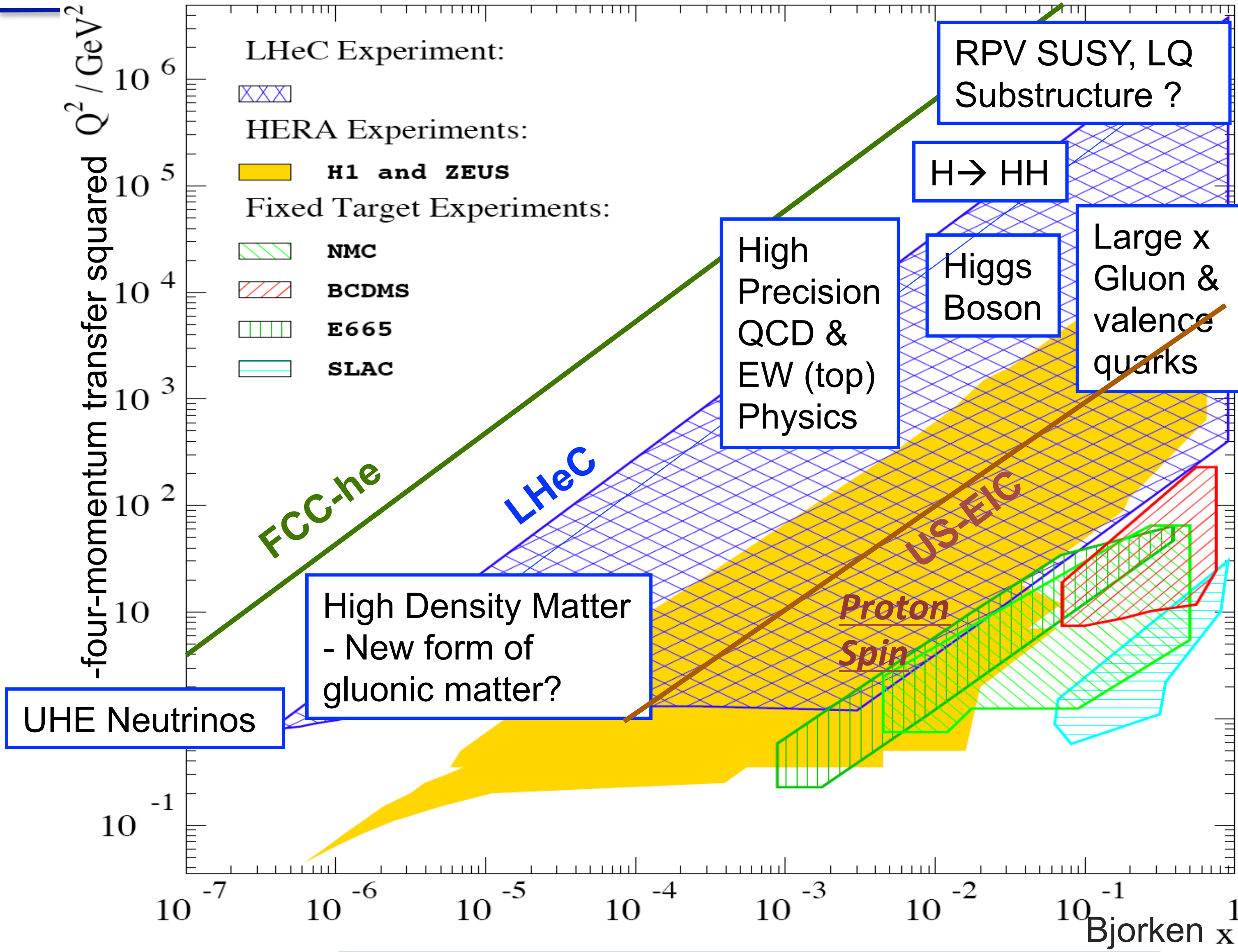
After the Higgs discovery:

- ✓ ep : High precision quark-gluon dynamics for sensitive searches; top & Higgs physics
- ✓ **Parallel running of pp and ep : Compelling synergy for exploring the EW and QCD sector to unprecedented precision.**

Higgs physics & EW symmetry breaking:

① **High precision coupling measurements**
② **Higgs as the portal for new physics, DM etc.**
③ **Non-resonant BSM searches**

The ep Physics at the Energy Frontier



HERA established the validity of pQCD down to $x>10^{-4}$ (DGLAP) due to a very high lever arm in Q^2.

Extensions of both x and Q^2 ranges are crucial for new experiments and HEP theory developments!

Relation to pp : $x_{1,2}$= (M/√s) exp(±y) & $Q^2 = M^2$

Neutrino-Nucleon Cross Section at UHE

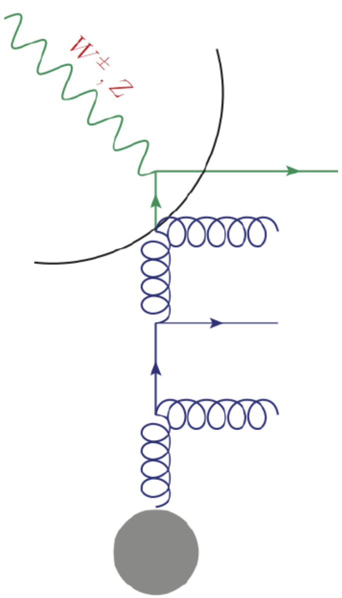
& its *astrophysical* Implications

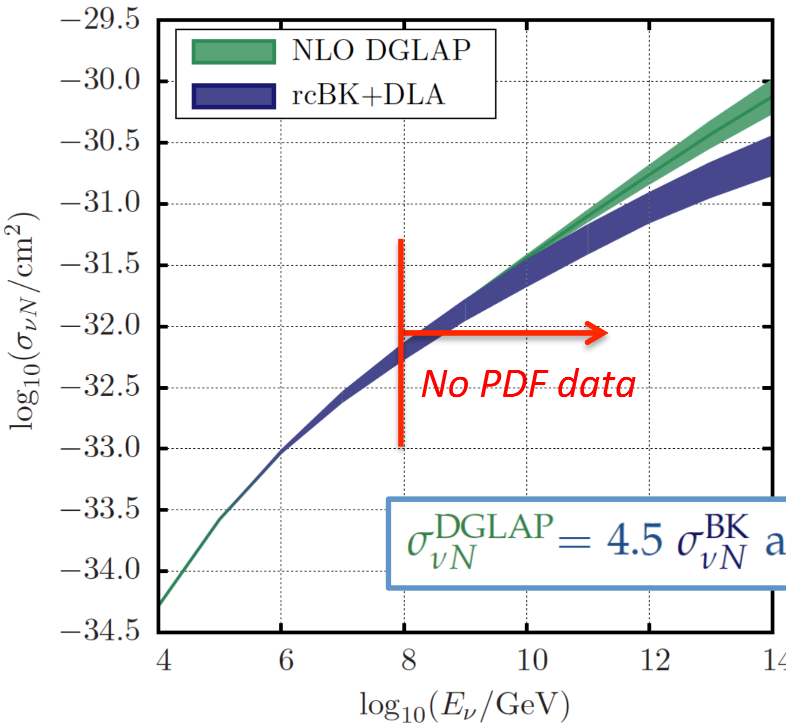
Alba SOTO ONTOSO,
@POETIC VI
PRD 92, 014027 (2015)

$$\sigma_{\nu N} \sim \underbrace{\begin{pmatrix} \text{Probability of} \\ \text{finding a quark/gluon} \\ \text{in nucleon} \end{pmatrix}}_{\text{Low energy QCD}} \otimes \underbrace{\sigma^{q/g-\nu}}_{\text{Perturbative}}$$

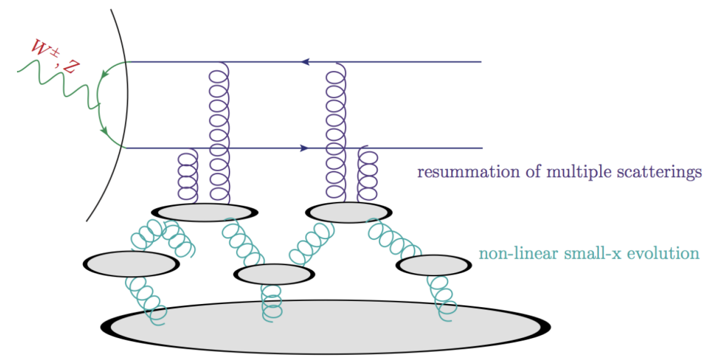
DGLAP approach $(\alpha_s \ln(Q^2/Q_0^2) \sim 1)$

À la BK $(\alpha_s \ln(x_0/x) \sim 1)$





$$\sigma_{\nu N}^{\mathrm{DGLAP}} = 4.5\ \sigma_{\nu N}^{\mathrm{BK}} \text{ at } E_\nu = 10^{14}\ \mathrm{GeV}.$$



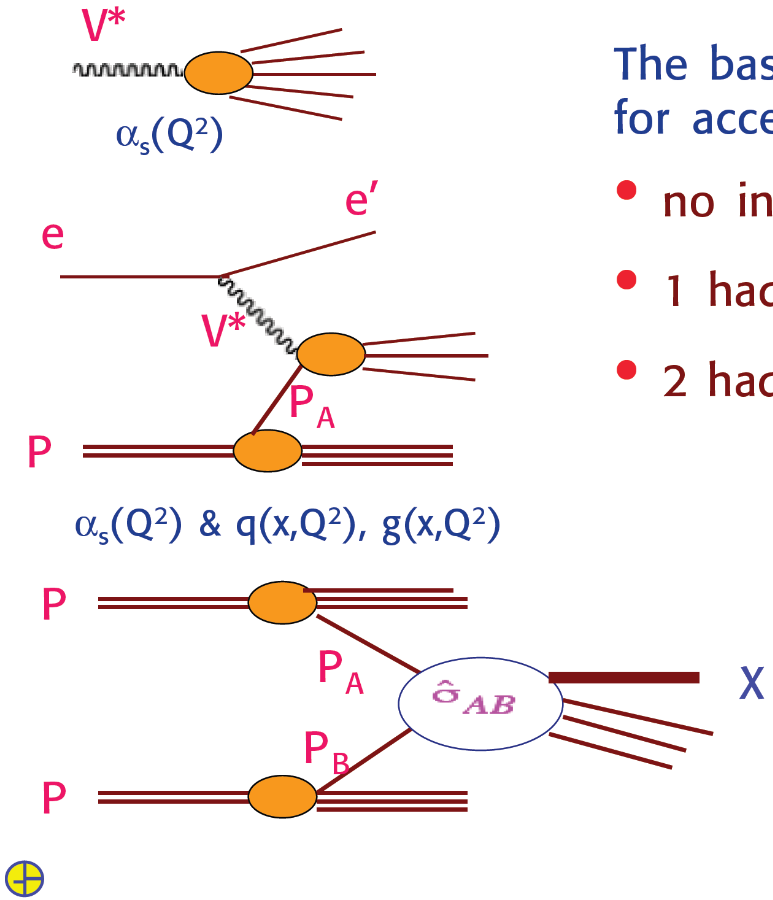
Limits on astrophysical ν fluxes

… have a **much larger uncertainties** than currently assumed :

factors 1.4 to 4.5 for $10^9 < E_\nu < 10^{14}$ GeV.

On the Synergies of ee, ep and pp

Guido Altaralli
Cern June 2015



The basic experimental set ups
for accelerator particle physics:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (Tevatron, LHC, FCC)

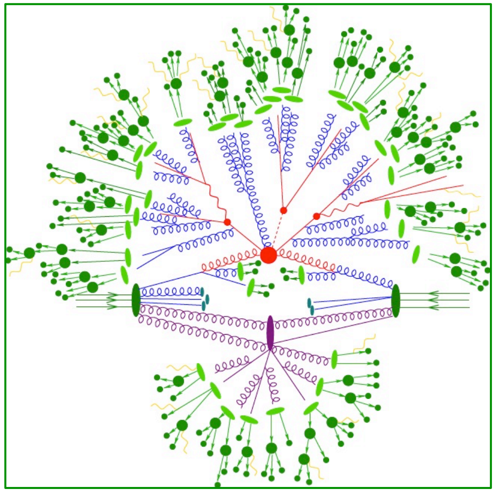
The pdf are defined
in DIS

The theory of inclusive DIS
is crystal clear

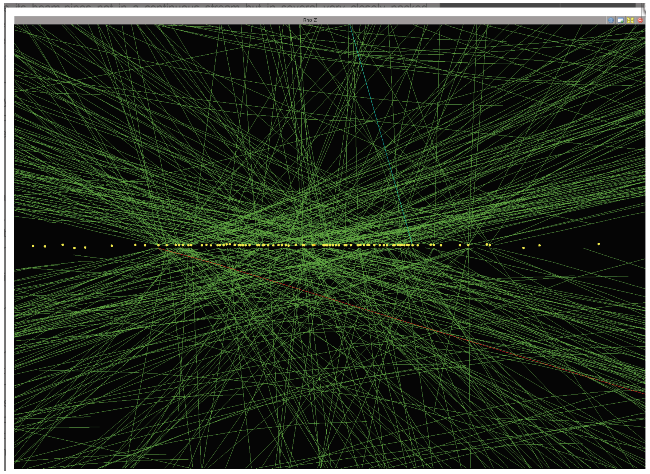
Thru the factorization
"theorem" the pdf's and α_s
determine the hadron
collider rates

… a closer look to pp …

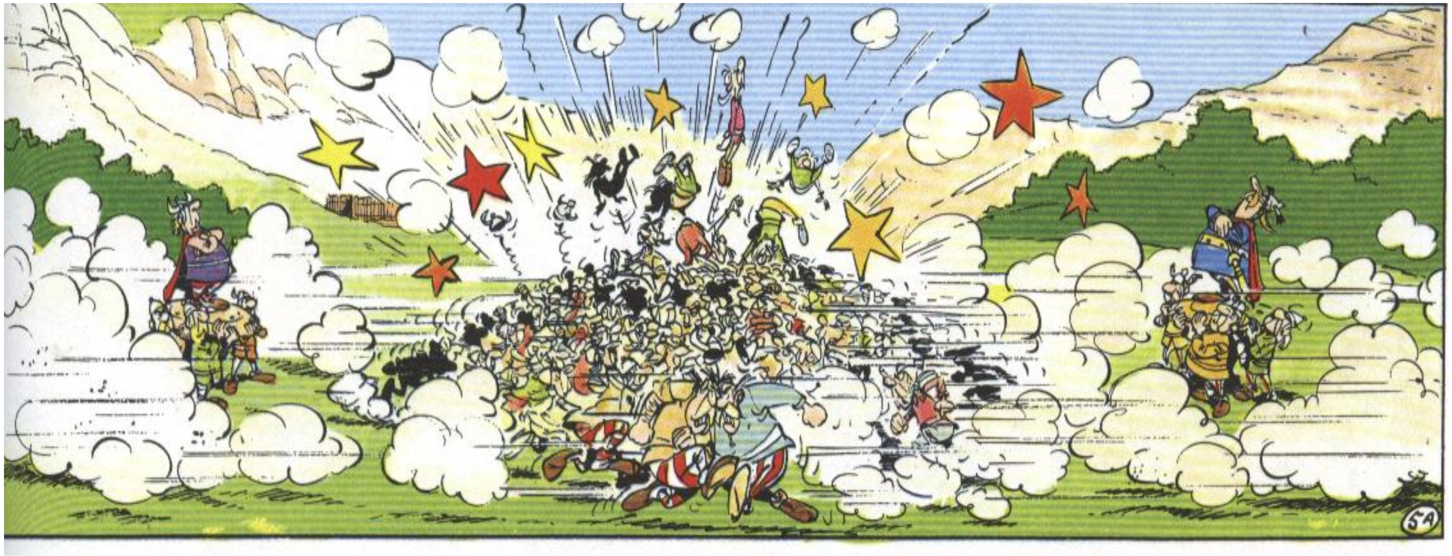
A Monte Carlo view



78 PU events at CMS [image:Andre Holzner]

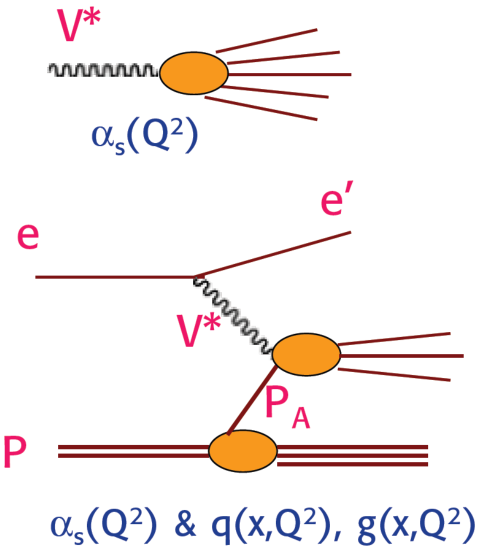


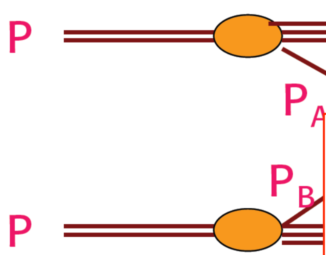
and a French artist's view on LHC physics: 140-200 pileup events at HL LHC



On the Synergies of ee, ep and pp

Guido Altaralli
Cern 6/2015





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for accelerator particle physics:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
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The pdf are defined
in DIS

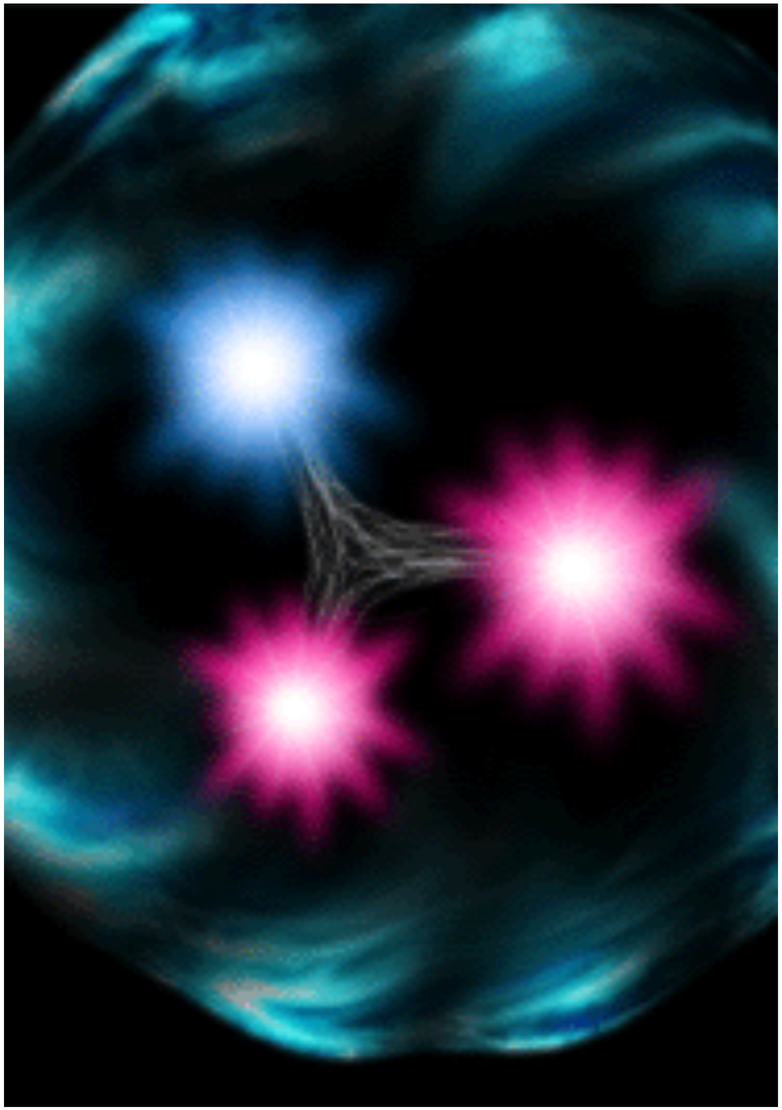
The theory of inclusive DIS
is crystal clear

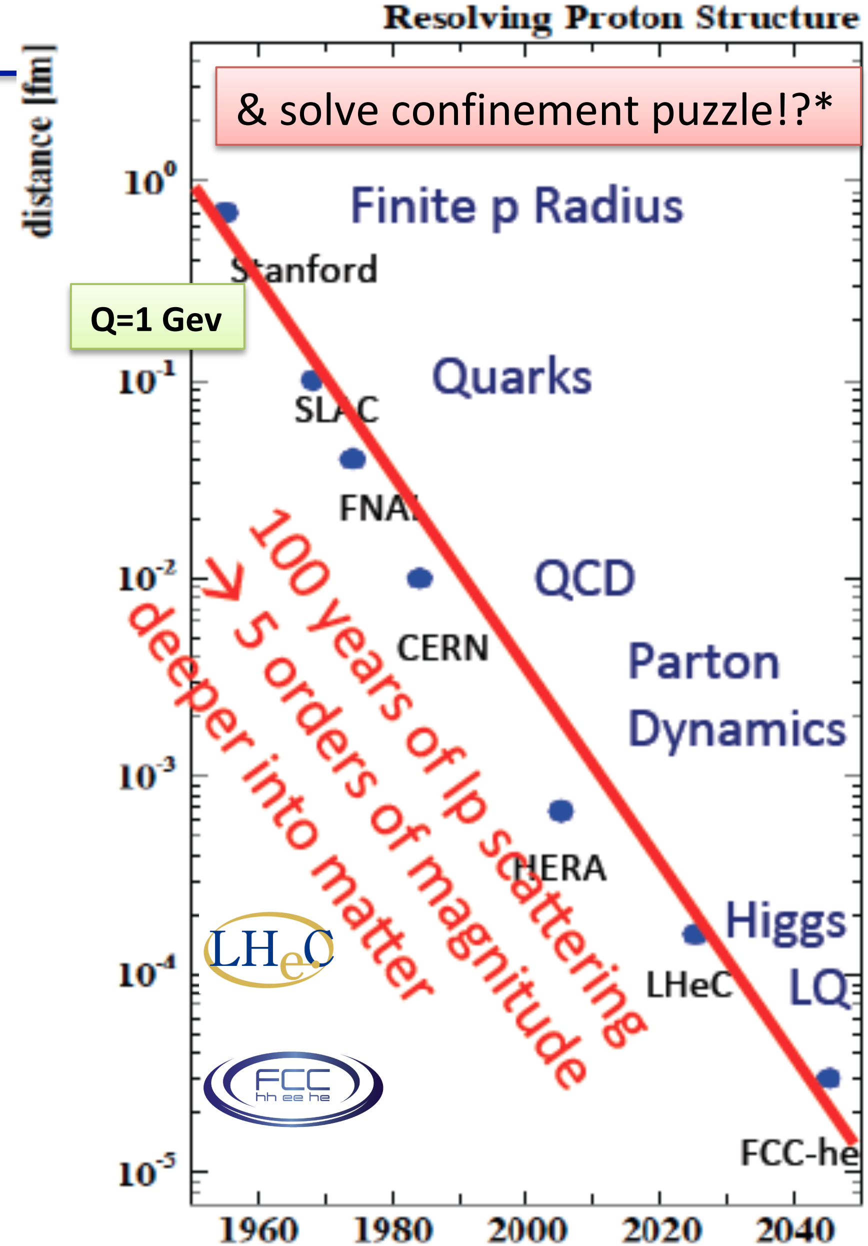
We often hear the statement that all the relevant info on pdf's can directly be obtained from the LHC without need of the LHeC

Not really true. Certainly not at the same level of precision
One example:

The factorization "theorem" is essential.
Not fully proved theoretically (beware of non pert. effects)
[nearly complete arguments only for Drell-Yan & similar]
Should finally be experimentally tested with precision

ep: Resolving a non-trivial Structure…

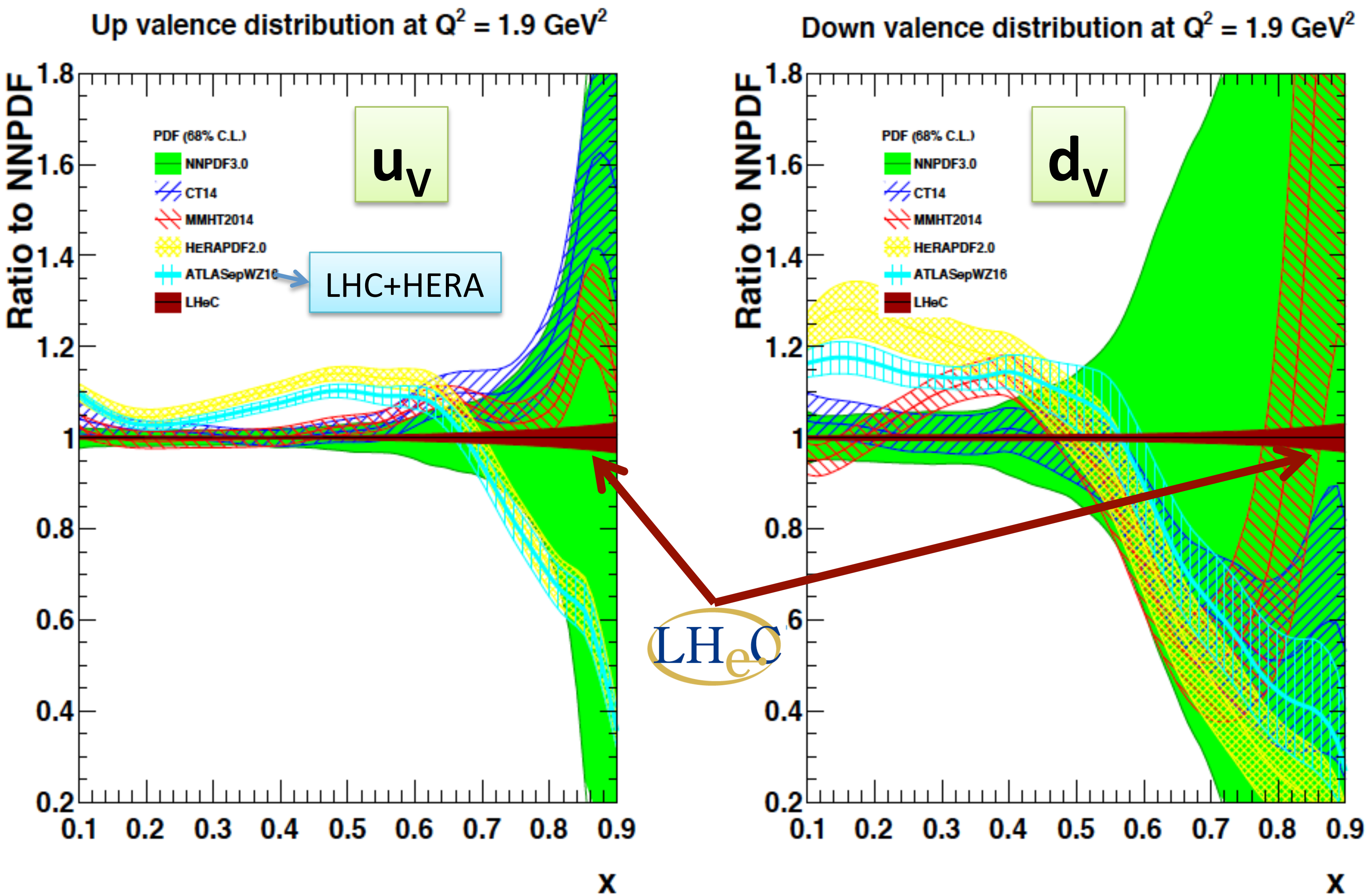




*Jaffe&Witten 2000: 1 out of 7 millenium prize questions

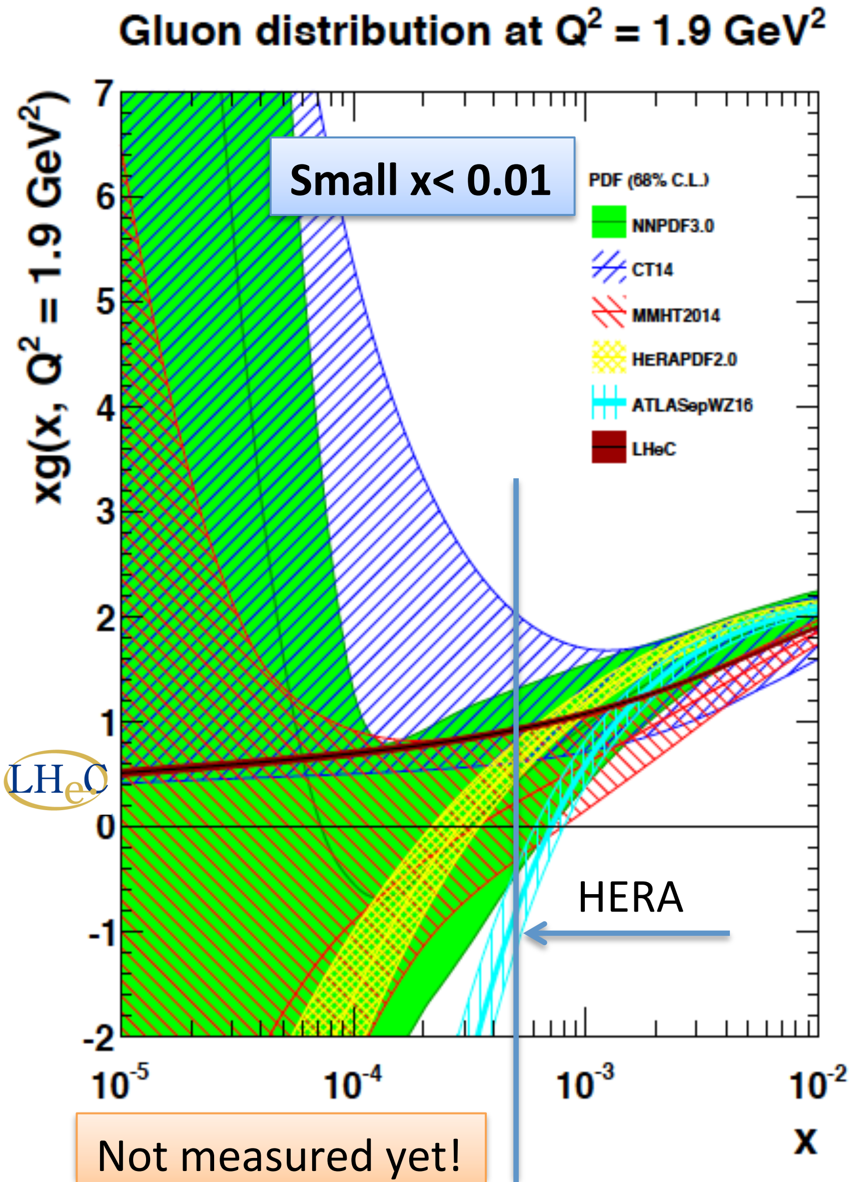
Valence Quark Distributions

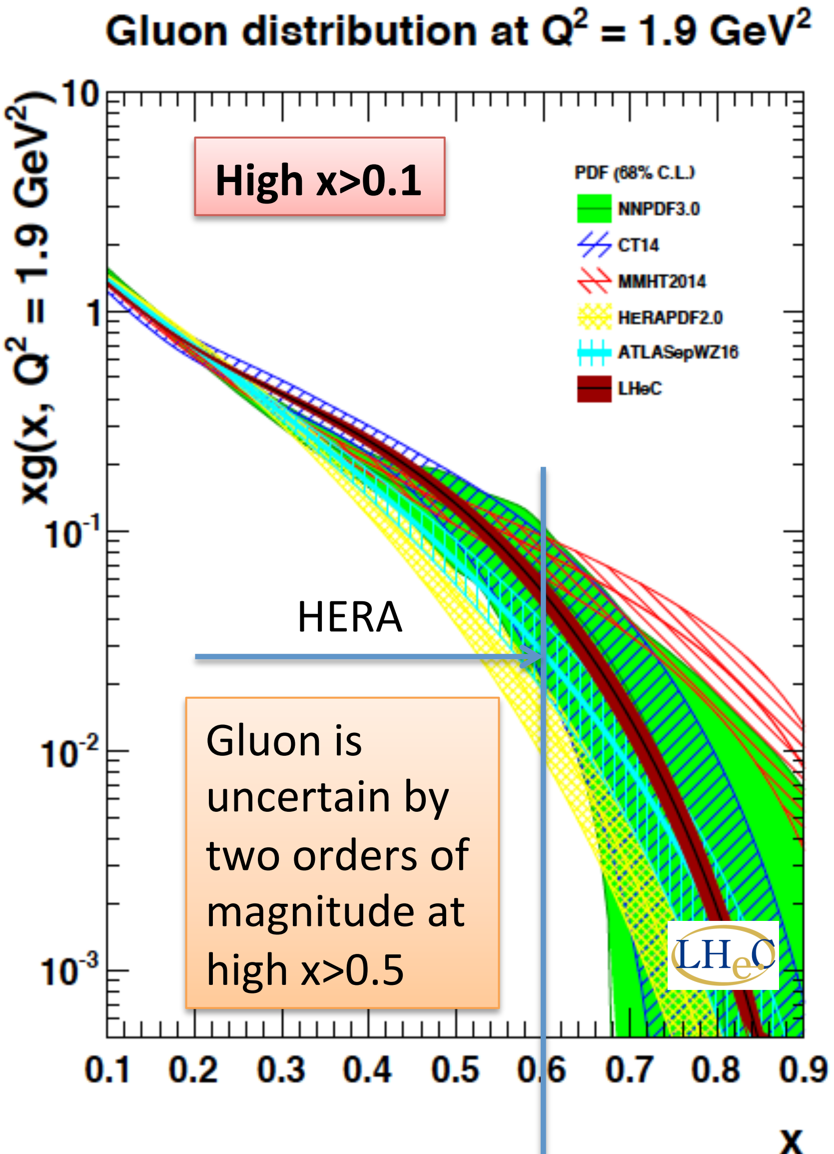
normalised to NNPDF 3.0



...and the Gluon

Low and high x are intertwined by momentum sum rules!





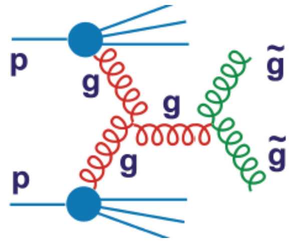
Empowering Discoveries at LHC (pp)

External, accurate input is crucial for search extension + non-resonant interpretations

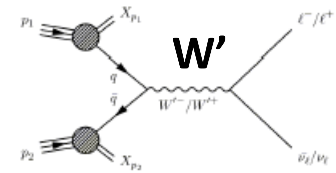
Two unknowns, PDFs and new physics, require two independent sources of input.

GLUON

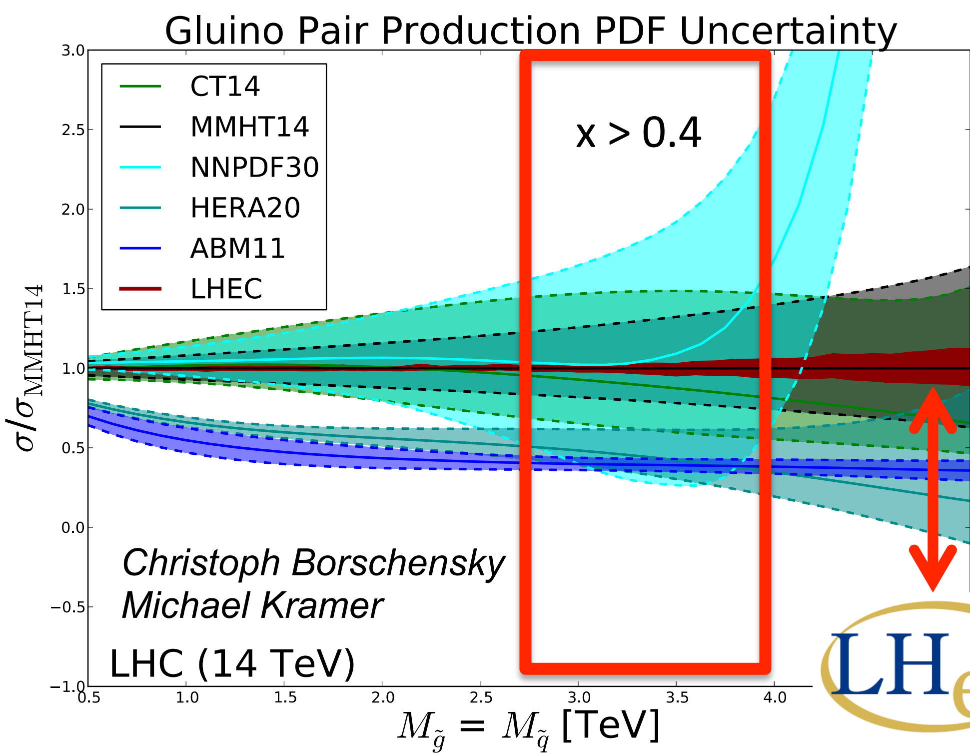
SUSY, RPC, RPV, LQS..



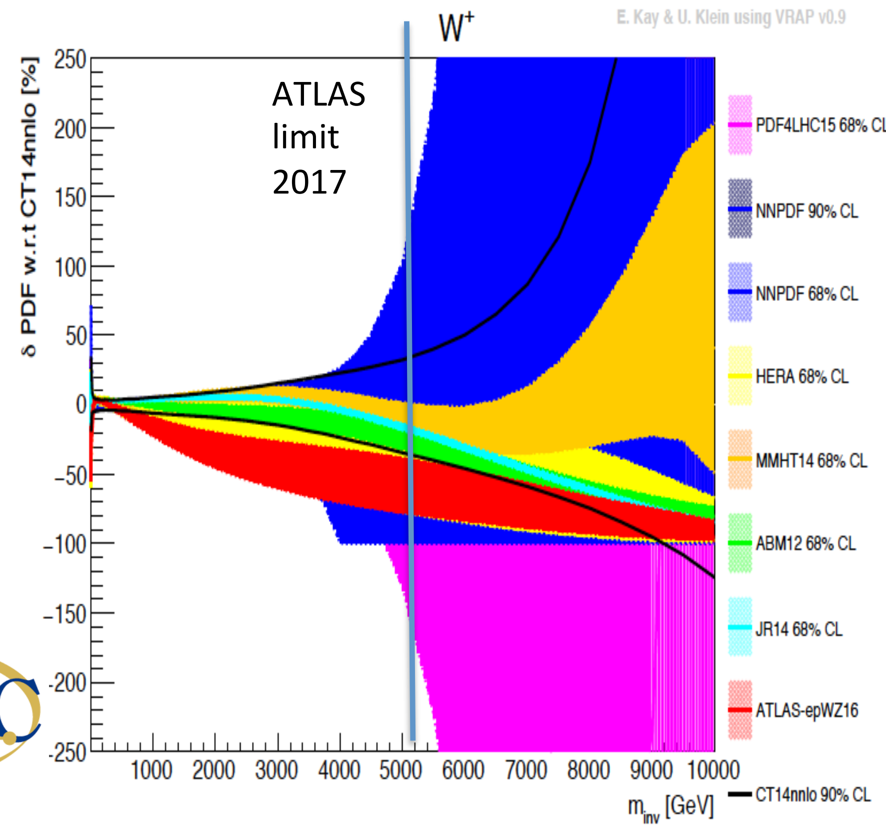
QUARKS



Exotic+ Extra boson searches at high mass



update of arXiv:1211.5102



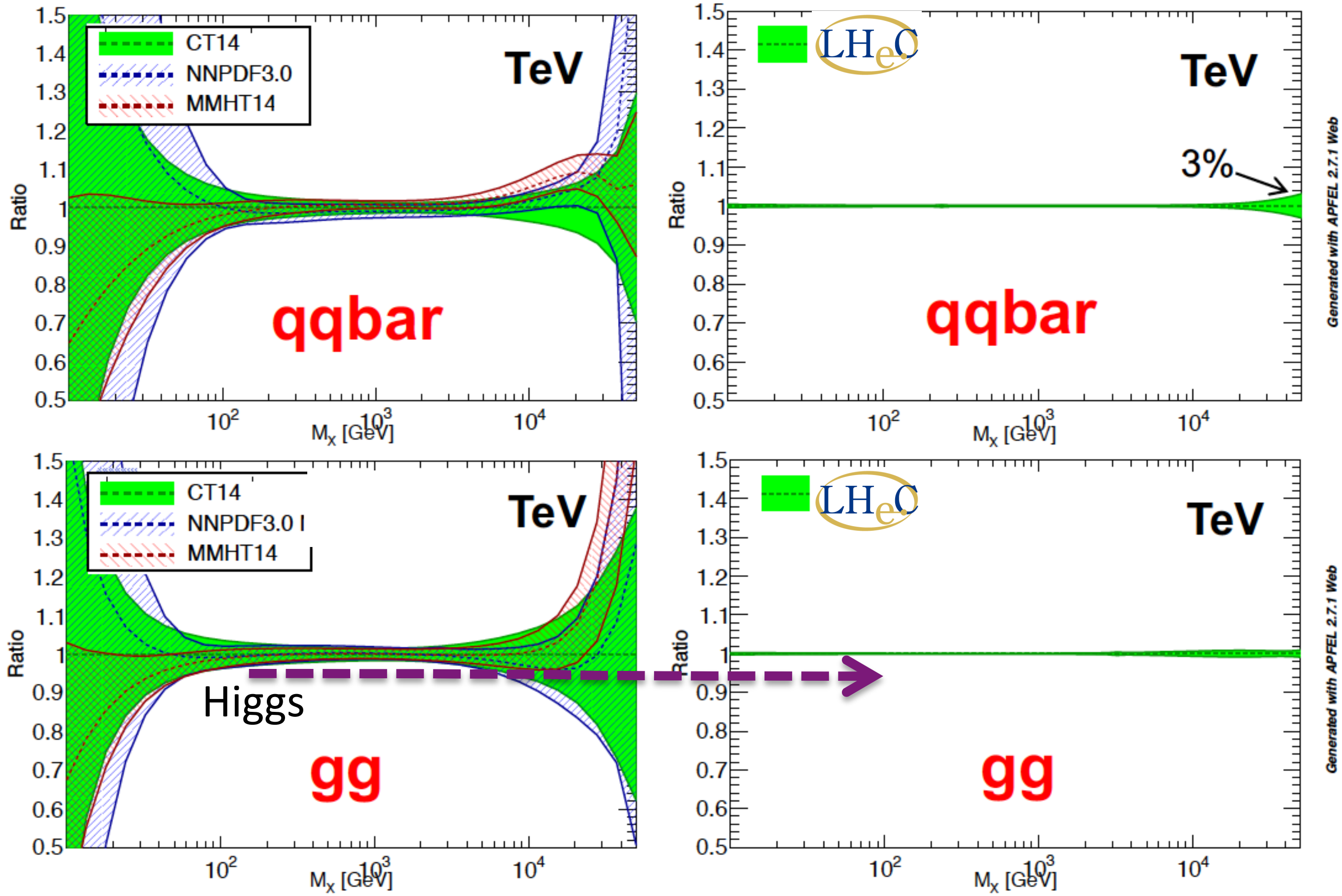
NNPDF3.0: 'Issues' with negative replica

The LHeC PDF Programme

Resolve parton structure of the proton completely: u_v,d_v,s_v?,u,d,s,c,b,t and xg
Unprecedented range, sub% precision, free of parameterisation assumptions,
Resolve p structure, solve non linear and saturation issues, test QCD, N^3LO…

Strong Coupling in inclusive DIS at LHeC to 0.1%

Lattice??
Jets??
BCDMS??
GUTs?
Higgs in pp



Solve the PDF issues for pp and test QCD with permille measurement of strong coupling

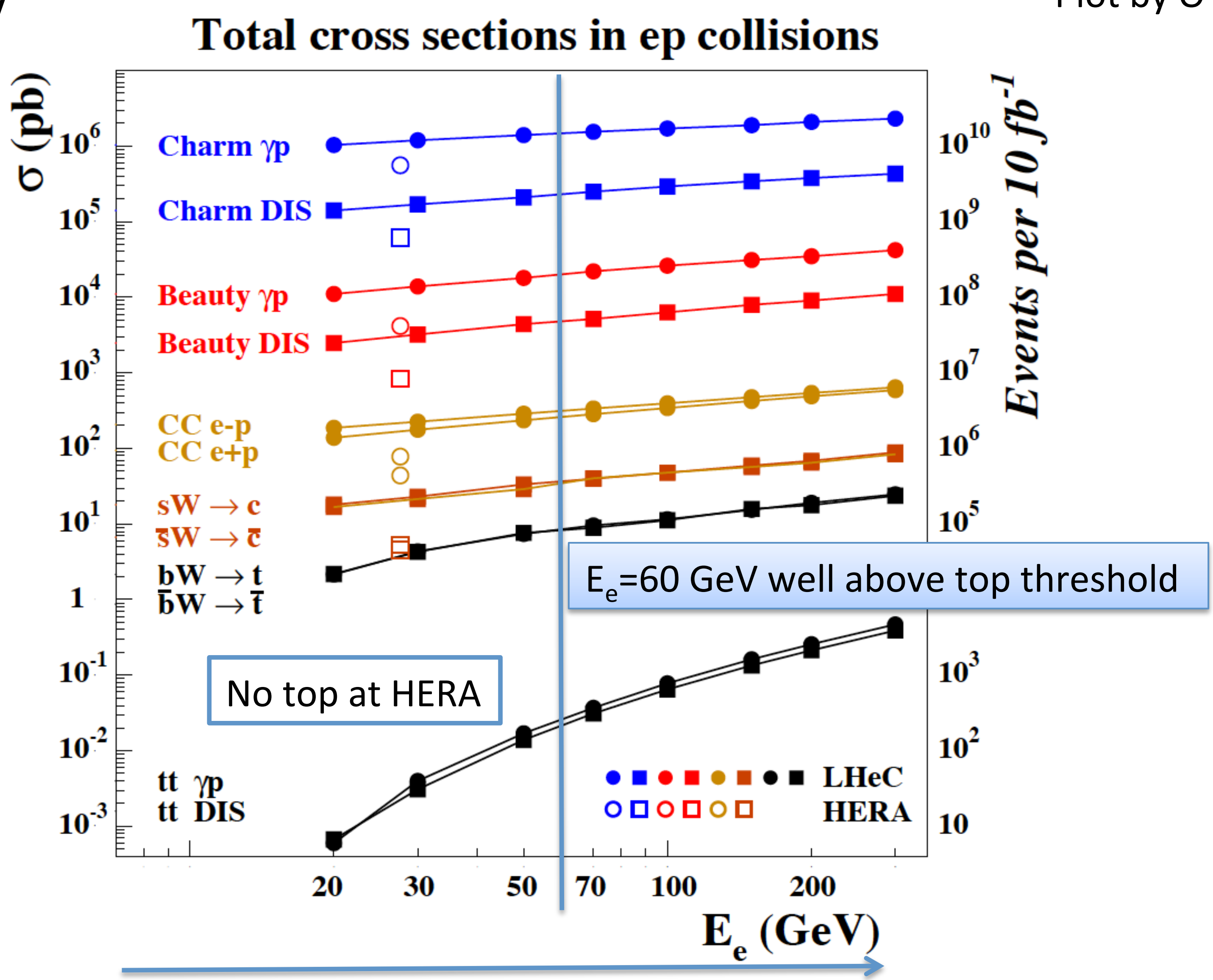
Plenty of charm, beauty and top

…to explore in detail and with high precision heavy flavour schemes

E_p=7 TeV

Plot by O Behnke

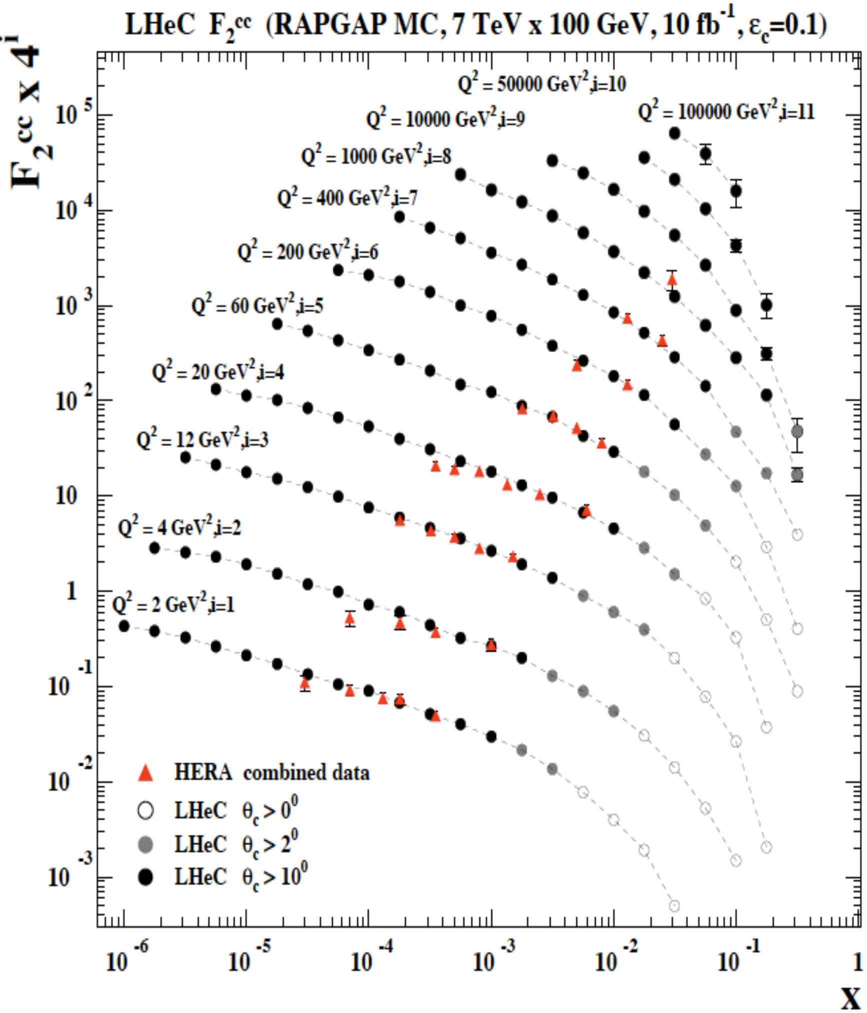
titl



LHeC CDR arXiv:1206.2913

Charm F_2^{cc} and Mass

LHeC CDR arXiv:1206.2913



HERA 0.0005 - 0.05 for 2.5-2000 GeV²
LHeC 0.00001- 0.2 for 1-200000 GeV²

ε(c) assumed 10%, 1% light background, ~3% δ(syst)

Heavy Flavour with LHeC
Beam spot (in xy): 7µm
Impact parameter: better than 10µm
Modern Silicon detectors, no pile-up
Higher E, L, Acceptance, ε, than at HERA
→ Huge improvements predicted

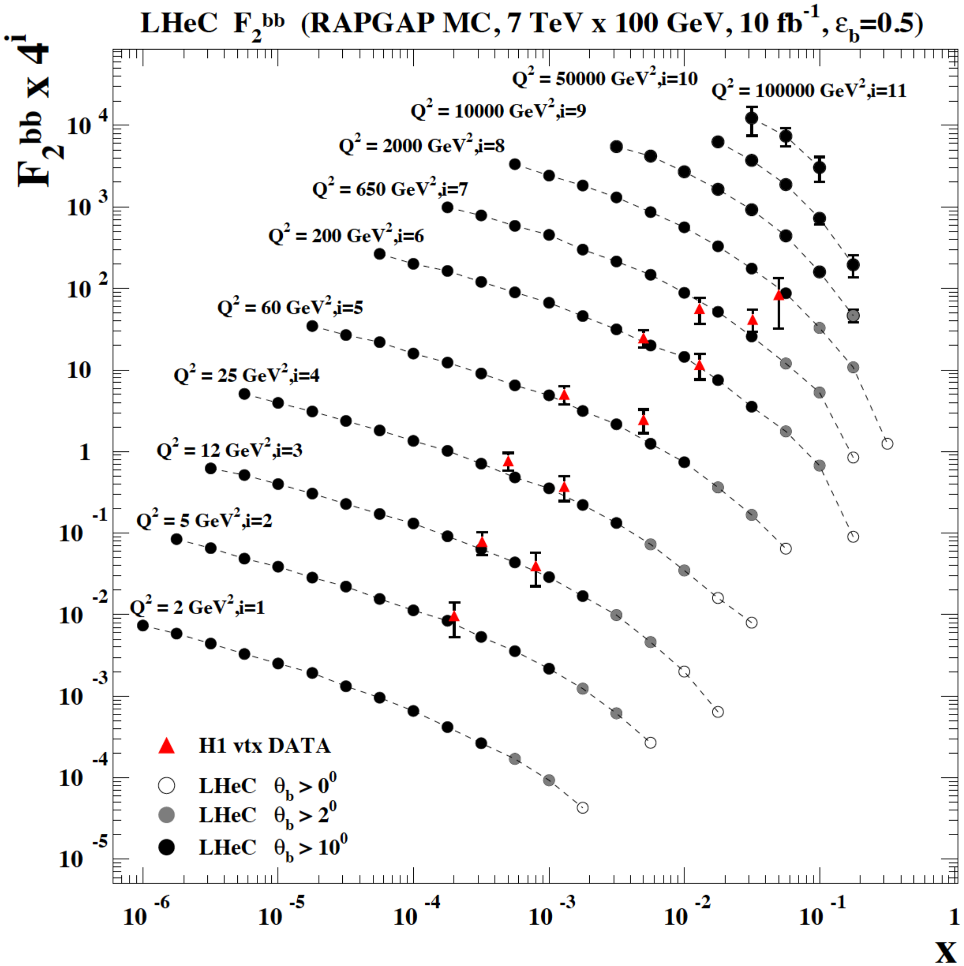
	HERA	LHeC
$m_c(m_c)$/GeV	1.26	?
δ(exp)	0.05	0.003
δ(mod)	0.03	~0.002
δ(par)	0.02	~0.002
$\delta(\alpha_s)$	0.02	0.001

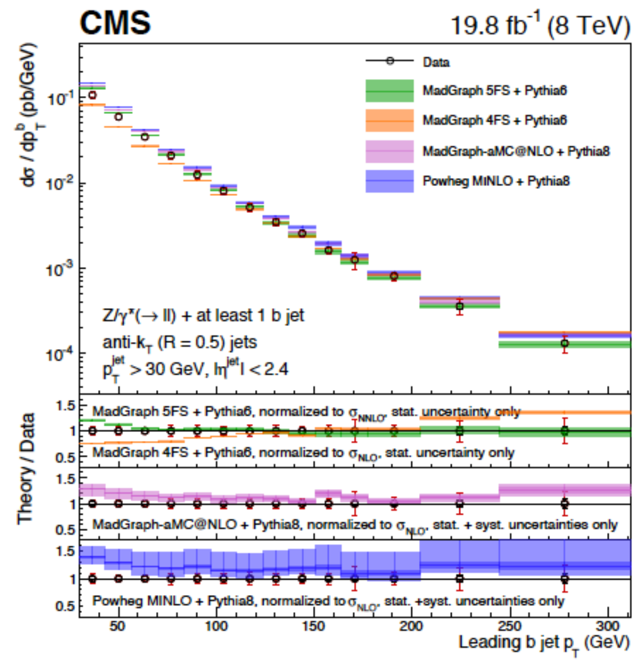
LHeC determines strong coupling to 0.1%
High precision PDF data will reduce the model and parameterization uncertainties.

Determination of charm mass to 3 MeV: crucial for M_W in pp or H→ cc in ep
cf also NNPDF3.1 (arXiv:1706.00428) and refs

Bottom F_2^{bb} and Mass

LHeC CDR arXiv:1206.2913





Bottom density not well known

Scheme dependence affects LHC interpretations

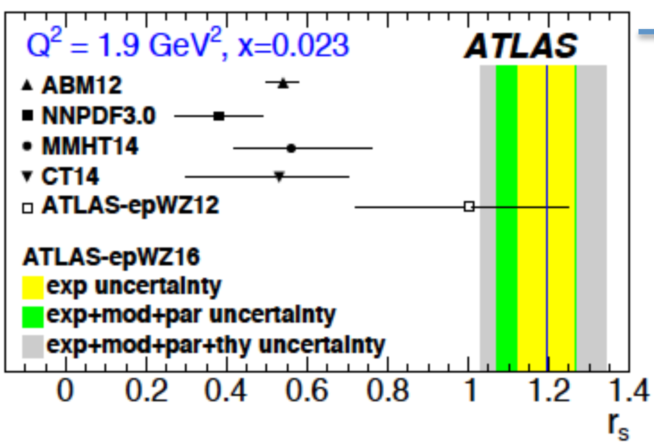
In MSSM: Higgs from bb→ H not gg (we only miss the MSSM..)

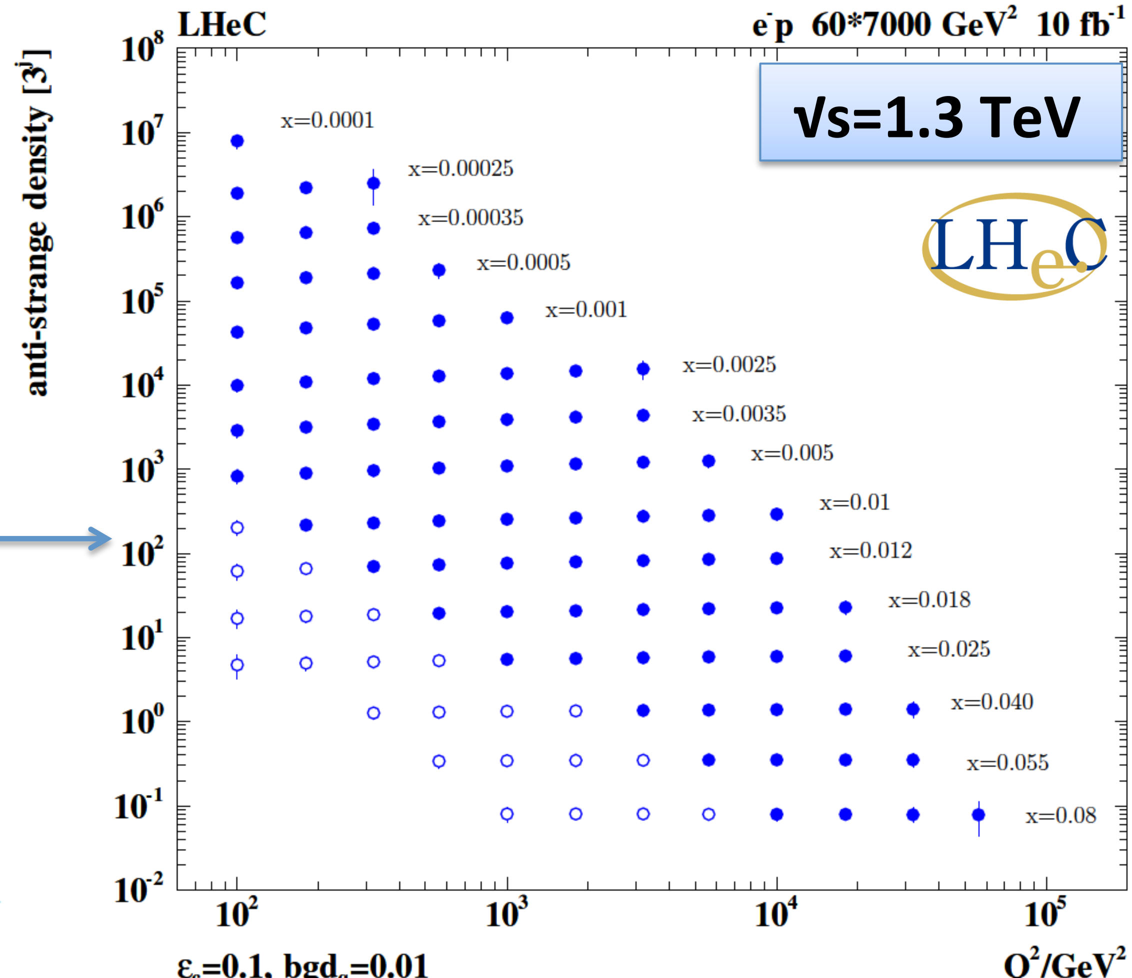
Huge improvement vs HERA for the same reasons as for charm

$m_b(m_b)$ with LHeC to 10 MeV

Strange Strange Quark Distributions

Evidence of enhanced strange-to-light sea density at x~0.01
ATLAS 2016: 1612.0301, PRD
→ based on high precision W and Z data and ~ 5 years of analysis and joint HERA+ATLAS QCD fit



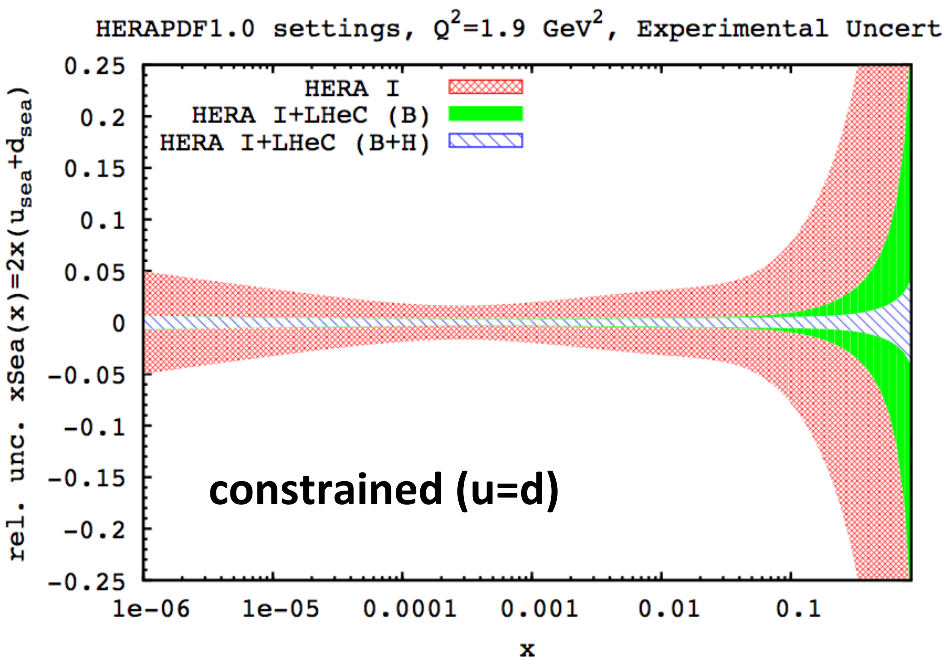


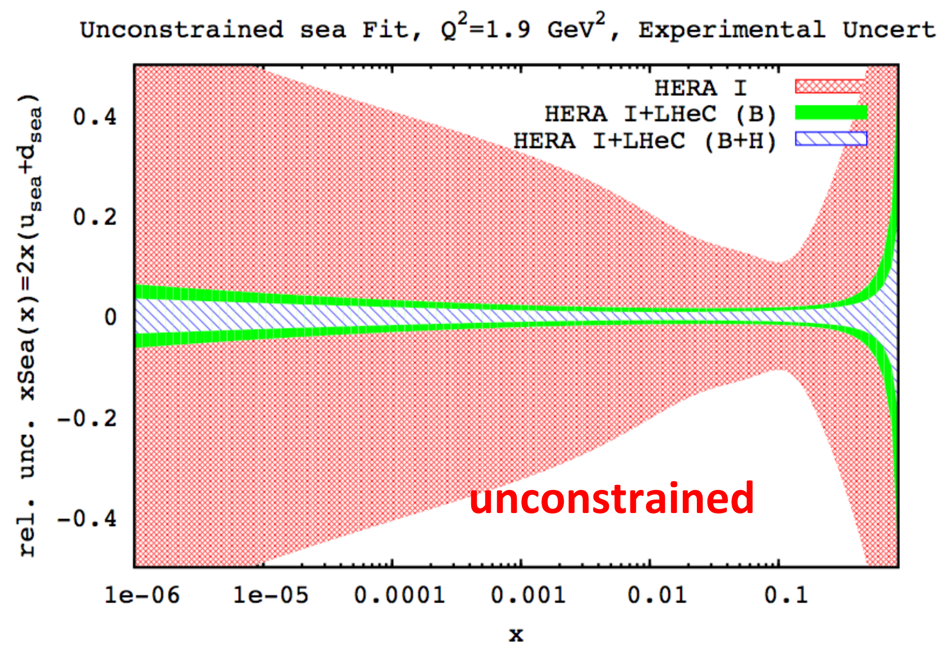
LHeC : Precision measurement of (anti) strange
→ Complete unfolding of the flavour structure of the proton for the first time.

Resolving Partonic Structure

accurate and free of symmetry assumptions

Voica Radescu &
Max Klein , 2014





- One can see that for HERA data, if we relax the low x constraint on u and d, the "PDF errors" are increased tremendously!

➔ when adding the LHeC simulated data, we observe that uncertainties are visibly improved even without this assumption.

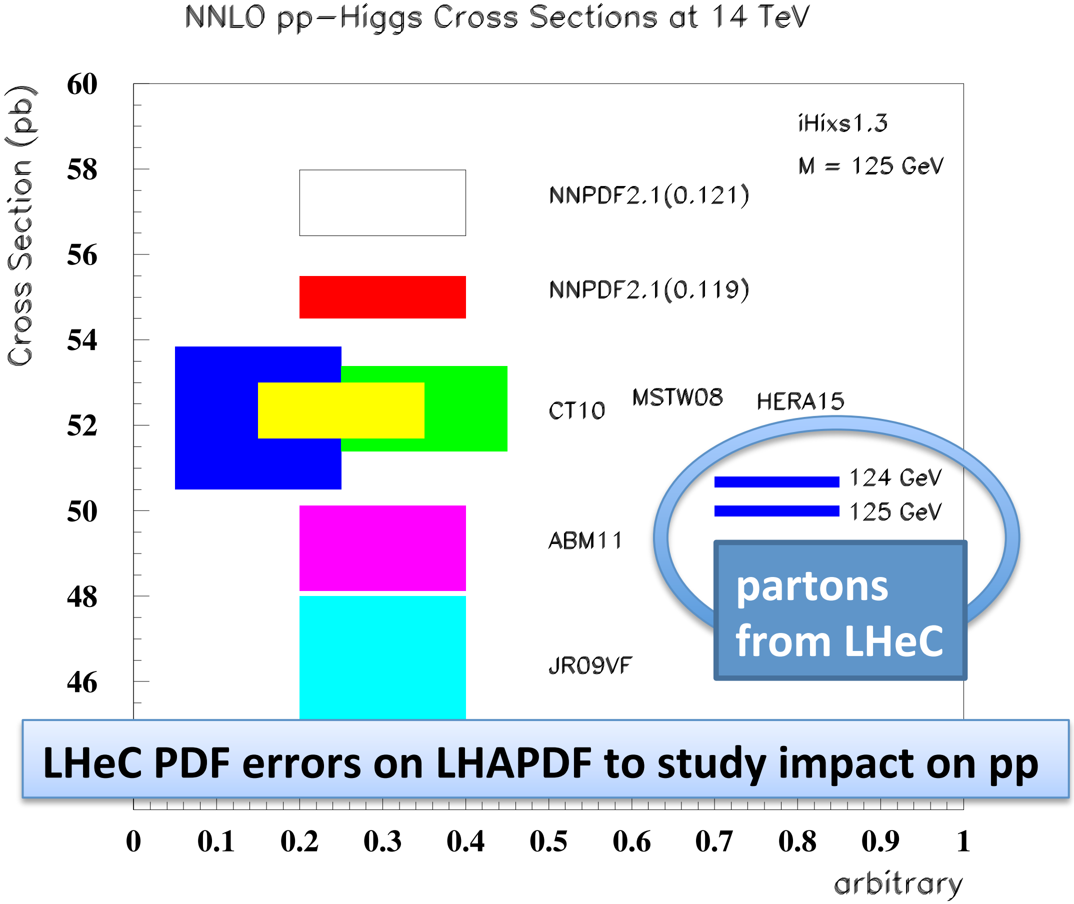
- Further important cross check comes from the deuteron measurements, with tagged spectator and controlling shadowing (small x partons) with diffraction…
- **All parton distribution functions of the proton at N^{3}LO !**

LHeC Precision Partons for Higgs@pp

→ **<u>Using LHeC input</u>**: experimental uncertainty of predicted **LHC Higgs cross section due to PDFs and α_s** is strongly **reduced to <~0.5%**

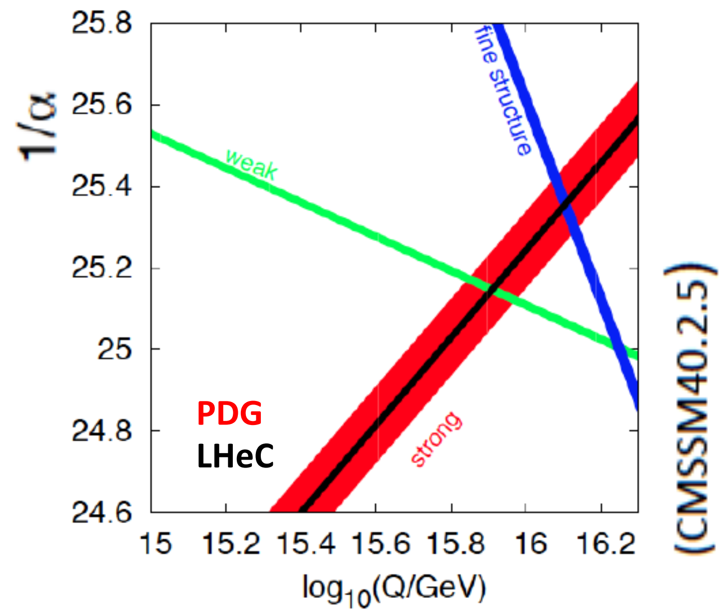
→ ***theoretically clean path to determine N³LO PDFs*** using ep DIS

→ ***ALL those 'benefits' for pp within the first few years, using ~100 fb^{-1} ep data***

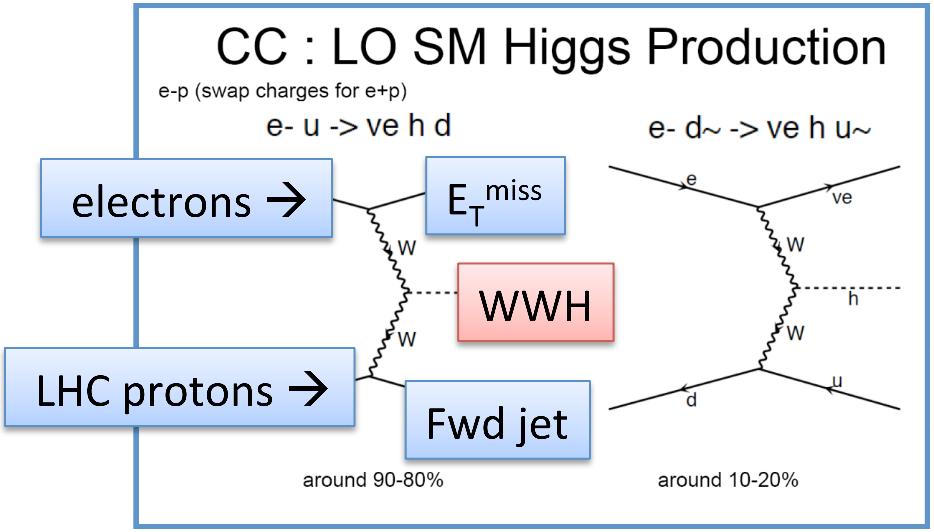


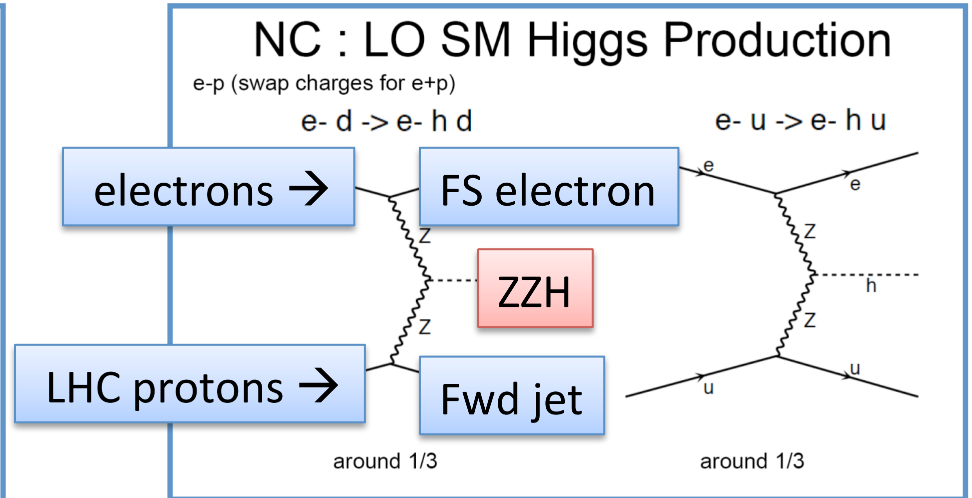
LHeC PDF errors on LHAPDF to study impact on pp

→ **precision from LHeC can add a very significant constraint on the Higgs mass** *and challenge Lattice QCD calculations for α_S:*



SM Higgs Production in ep





→ In ep, direction of quark (FS) is well defined.

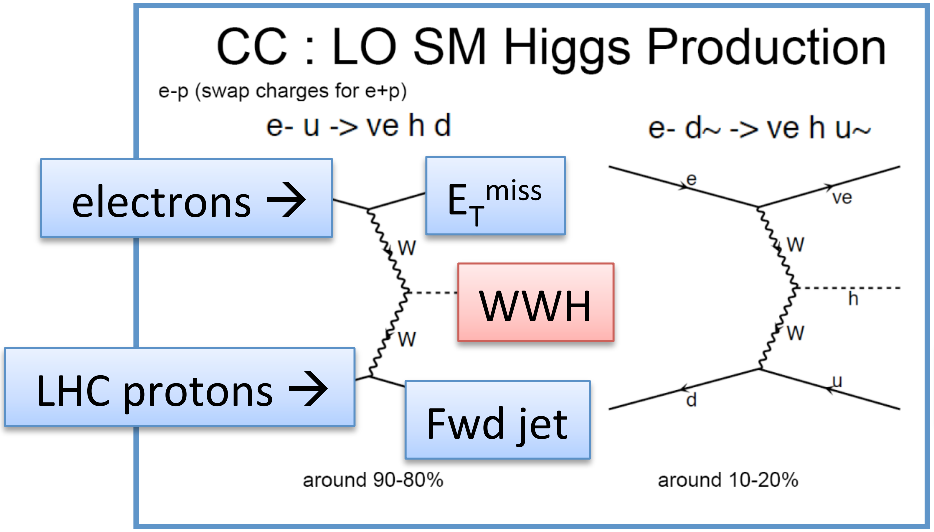
Total cross section [fb]
(LO QCD CTEQ6L1 M_H=125 GeV)

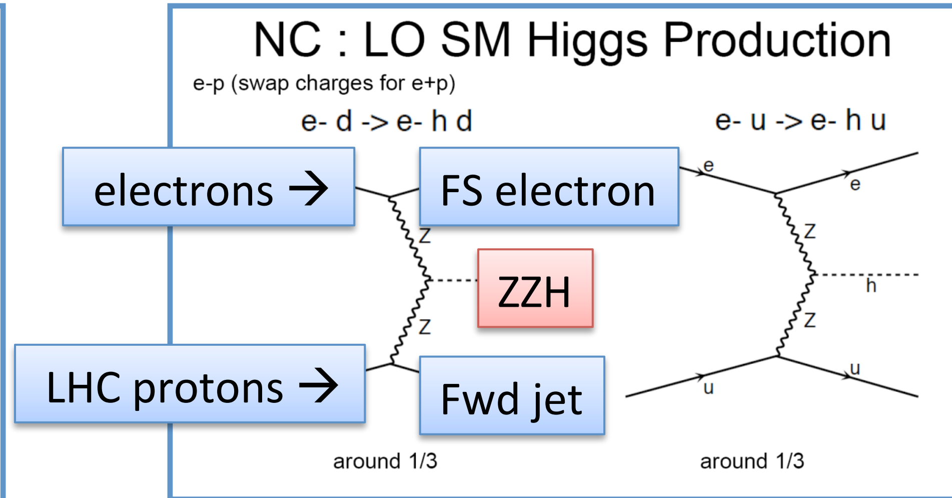
c.m.s. energy	1.3 TeV LHeC	3.5 TeV FCC-he
CC DIS	109	560
NC DIS	21	127
P=-80%		
CC DIS	**196**	**1008**
NC DIS	**25**	**148**

- **Scale dependencies of the LO calculations are in the range of 5-10%.**
- **NLO QCD corrections are small, but shape distortions of kinematic distributions up to 20%. QED corrections up to -5%.**

[J. Blumlein, G.J. van Oldenborgh , R. Ruckl, Nucl.Phys.B395:35-59,1993]
[B.Jager, arXiv:1001.3789]

SM Higgs Production in ep





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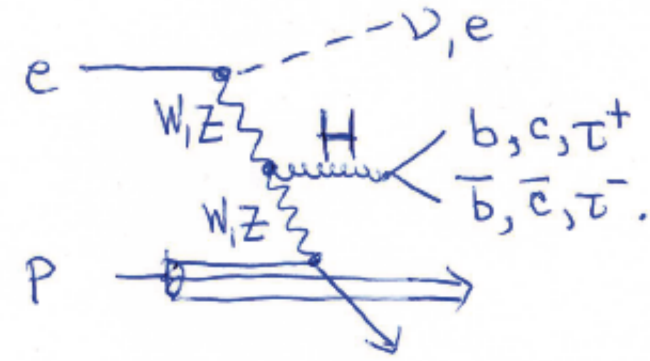
•Scale dependencies of the LO calc ns are in the range of 5-10%.
• NLO QCD correctio , but shape distortions of distributions up to 20%. ions up to -5%.

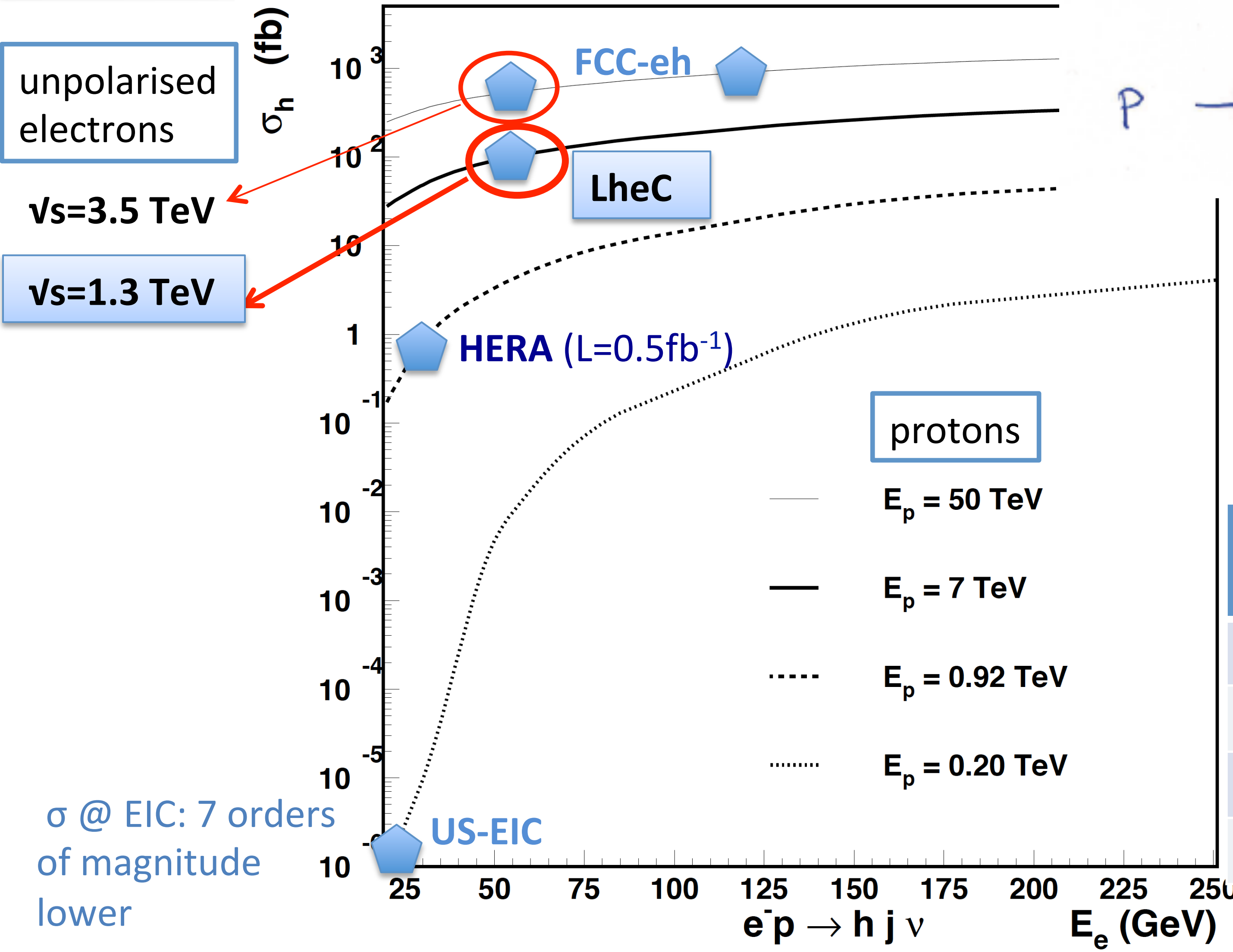
Theory well under control in ep!

ein, G.J. van Oldenborgh , R. Ruckl, Nucl.Phys.B395:35-59,1993]
[B.Jager, arXiv:1001.3789]

SM Higgs in ep

U. Klein, @DIS2015





Higgs in eA @FCC-ePb

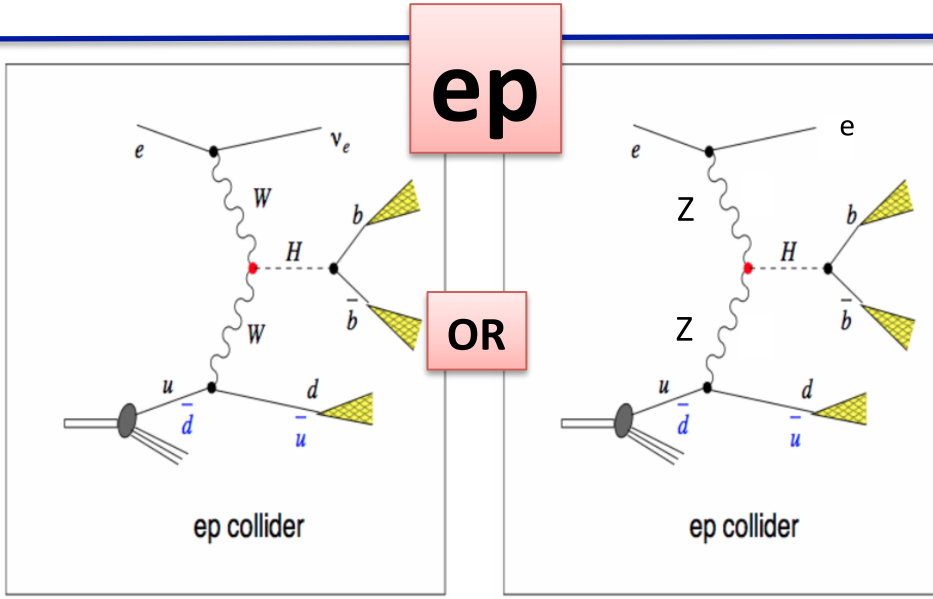
σ_{Higgs} [fb]

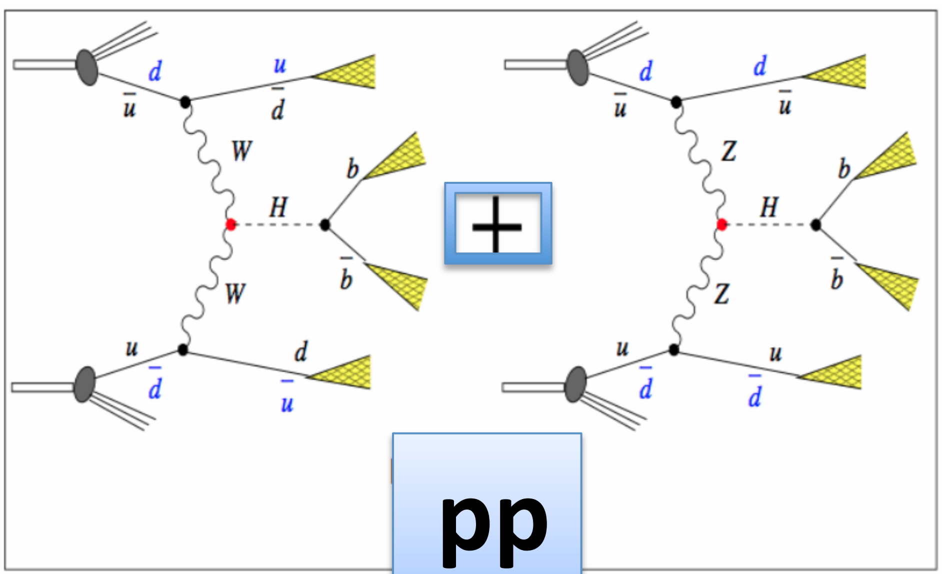
eff. 'Ep'=19.7 TeV

E_e [GeV]	$P_e = 0$	-0.8
20	105	190
30	153	276
50	242	436
60	282	507

LHeC / FCC-eh: Sizeable Higgs rates in charged current (CC) DIS for L=100-1000 fb^{-1}

VBF Higgs Production in ep (top) and pp (bottom)





ep: Higgs production in ep comes uniquely from either CC or NC DIS via VBF

Clean bb final state, S/B >1
e-h Cross Calibration for Precision ep
Clean, precise reconstruction and easy distinction of ZZH and WWH <u>without pile-up</u>:
<0.1@LHeC up to 1@FCCeh events

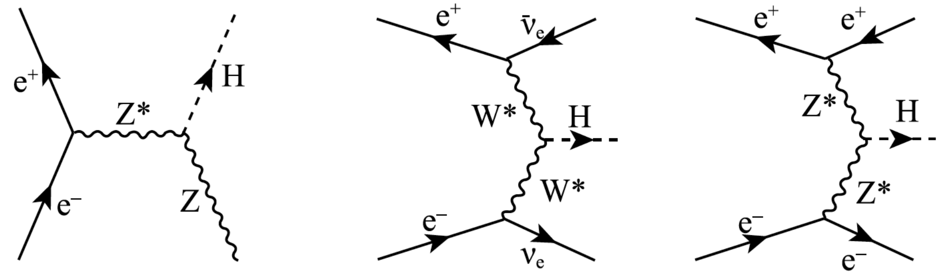
<u>VBF: Small theoretical uncertainties!</u>

pp: Higgs production in pp comes predominantly from gg→ H :
high rates crucial for rare decays
LHC VBF cross section about 200 fb (about as large as at the LHeC).

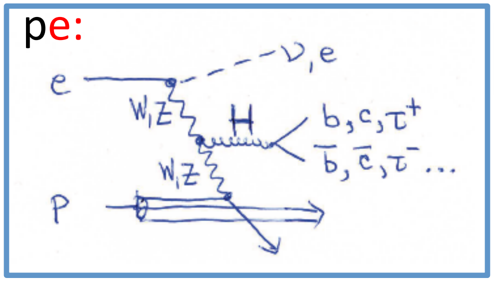
Pile-up in pp at 5 10^{34} cm^{-2} s^{-1} is 150@25ns
FCC-hh: pile-up 500-1000
S/B very small for bb
Final Precision in pp needs accurate N^3LO PDFs & α_s

Higgs in ee vs pe

ee: Dominant Higgs productions



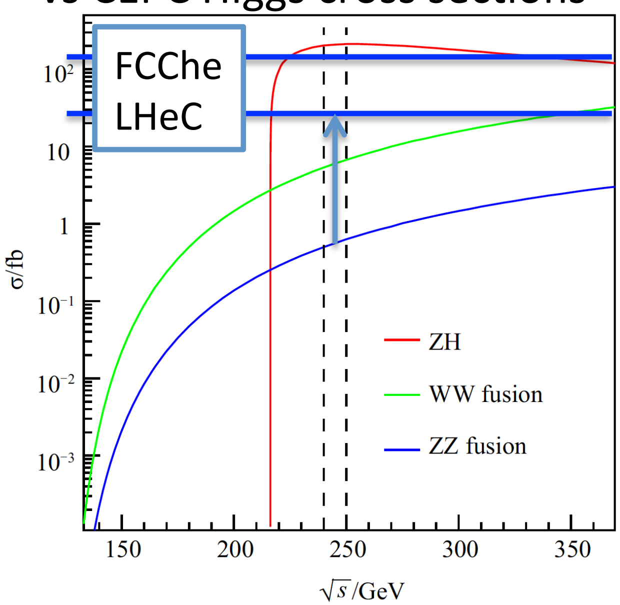
pe:

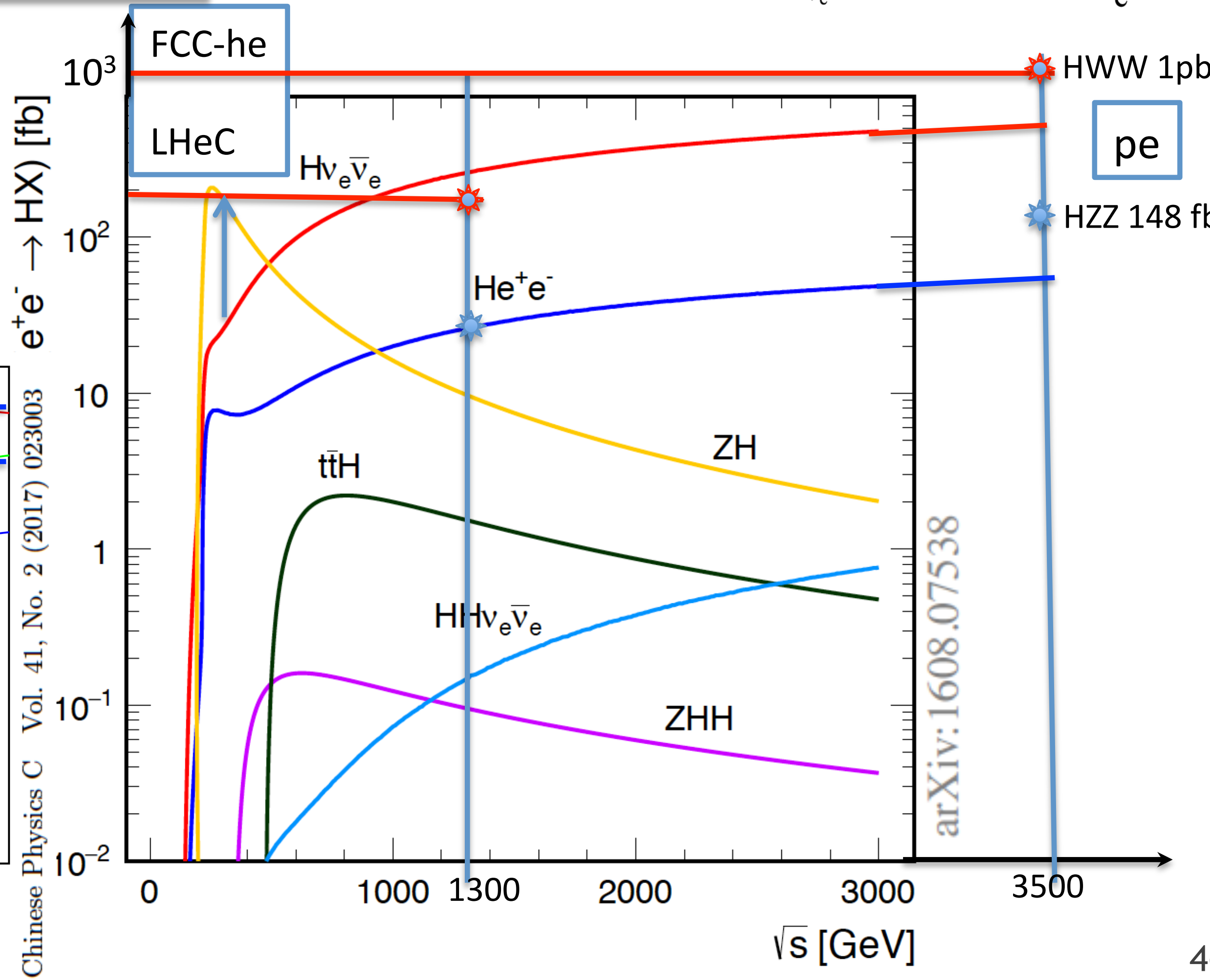


pe:WW Fusion

pe: ZZ Fusion

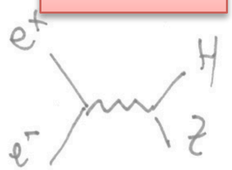
vs CEPC Higgs cross sections





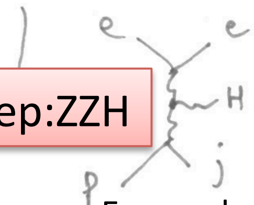
Kinematics and M_H : ee vs pe

ee: ZZH



e^+e^-

ep:ZZH



ep

$J_e := (e+j)$

xE_p: quark in DIS carries fraction x of initial proton energy

$$(p_{e^-}+p_{e^+})^2 = s = (p_H+p_Z)^2 = M_H^2+M_Z^2+2(E_H E_Z-\vec{p}_H\vec{p}_Z)$$

$$p_e^+ = (E_e, -E_e, \vec{0}_\perp),\quad p_e^- = (E_e, E_e, \vec{0}_\perp)$$

$$\curvearrowright\ 2E_e = E_H+E_Z$$
$$\vec{p}_H = -\vec{p}_Z$$

$$s = M_H^2+M_Z^2+2(E_Z\cdot(2E_e-E_Z))+2p_Z^2$$

$$s = M_H^2+M_Z^2-2M_Z^2+4E_Z\cdot E_e$$

$$s = M_H^2-M_Z^2+2\sqrt{s}\cdot E_Z$$

$$\to M_H^2 = s+M_Z^2-2\sqrt{s}\cdot E_Z$$

ee: x=1 no PDF or form factor involved

$$(p_e+p_p)^2 = s = 4E_eE_p x = M_H^2+M_{J_e}^2+2(E_H\cdot E_{J_e}-\vec{p}_H\cdot\vec{p}_{J_e})$$

$$p_e = (E_e, -E_e, \vec{0}),\quad p_p = (xE_p, xE_p, \vec{0})$$

$$E_e+xE_p = E_H+E_{J_e}\ ;\ (\vec{p}_H+\vec{p}_{J_e})_z = xE_p-E_e$$

$$s = M_H^2+M_{J_e}^2+2E_{J_e}\cdot(E_e+xE_p-E_{J_e})-2\vec{p}_{J_e,z}[(xE_p-E_e)-\vec{p}_{J_e,z}]$$

$$= M_H^2+M_{J_e}^2-2M_{J_e}^2+2E_{J_e}(E_e+E_p)-2\vec{p}_{J_e,z}(E_p-E_e)$$

$$\to M_H^2 = s+M_{J_e}^2-2(E_e+xE_p)\cdot E_{J_e}+2(xE_p-E_e)\cdot\vec{p}_{J_e,z}$$

for $xE_p = E_e$, $J_e = Z$ this is equivalent to M_H in e^+e^-

12.8.17.

→ x in DIS can be determined via electron angle and energy or inclusive hadron kinematics or combinations of it

LHeC@HL-LHC: SM Higgs @ 1 ab^{-1}

Baseline: Full MG5 + Pythia + Delphes feasibility studies

➔ also used for extrapolations to FCC-he

Total rates √s= **1.3 TeV**

LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity $[ab^{-1}]$		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	$N^H_{CC}\ e^-p$	$N^H_{NC}\ e^-p$	$N^H_{CC}\ e^+p$
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

Ultimate polarised e-beam of 60 GeV and LHC 7 TeV p-beams, 10 years of operation

➔ Decay to bb is dominating decay mode : 58%

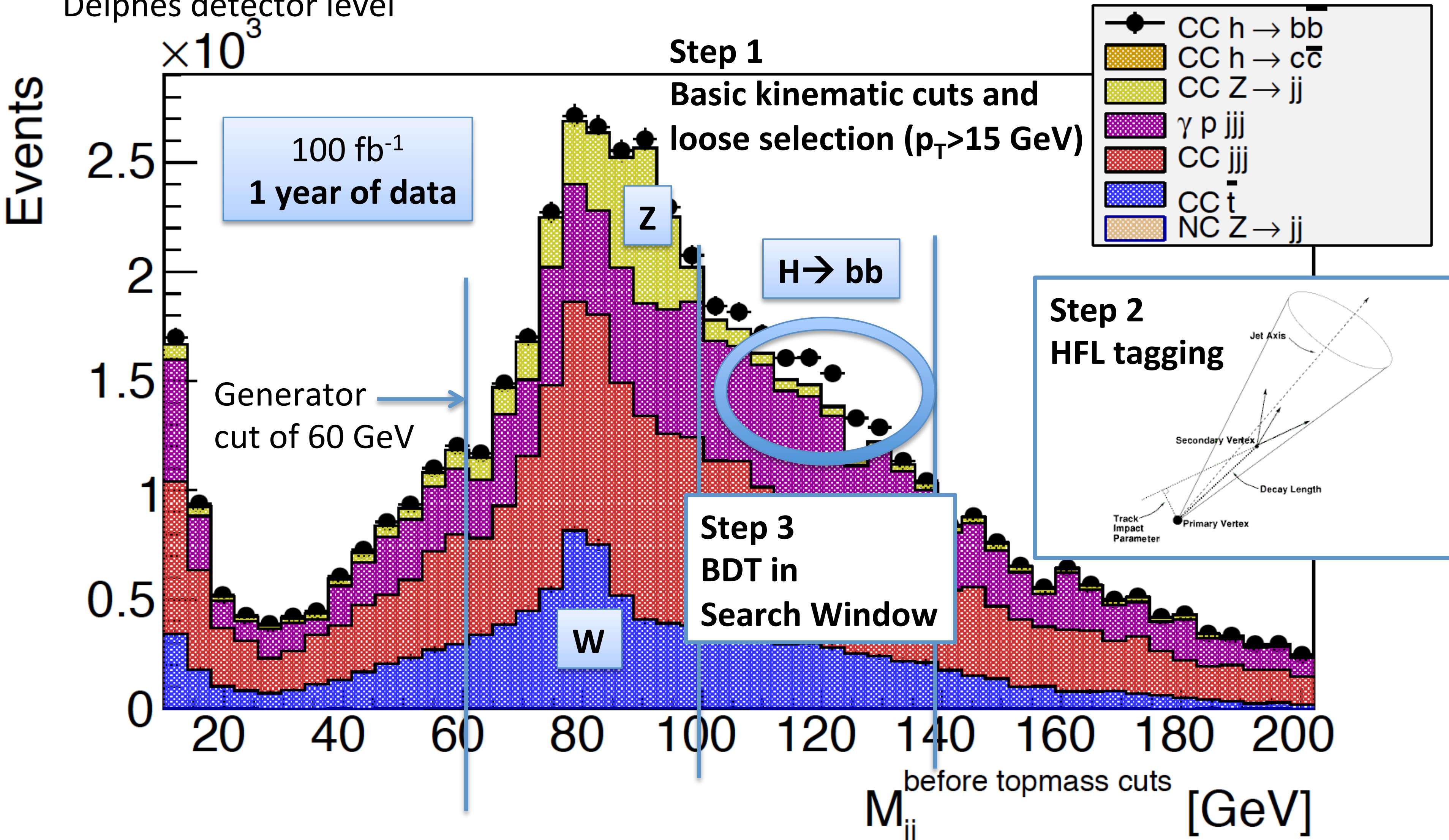
Higgs decay to charm is factor 20 less likely than Hbb

pp: perfect Higgs factory for gluon-induced rare decays

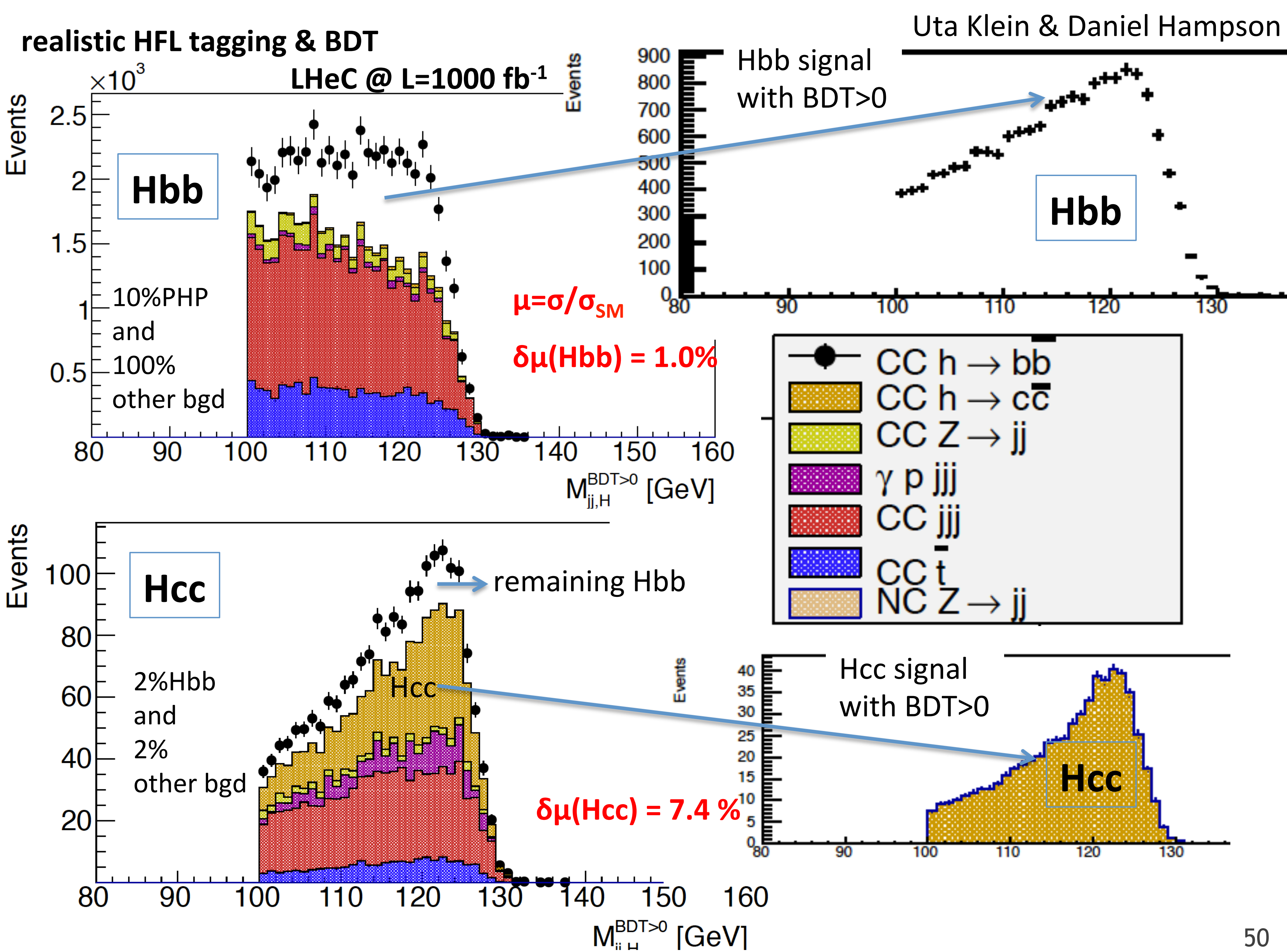
BDT:U Klein; Cut-based: M Kuze, M Tanaka

Dijet Mass Candidates *HFL untagged*

Delphes detector level



'Worst' case scenario plot : Photoproduction background (PHP) is assumed to be 100%!
→ However, addition of small angle electron taggers will reduce PHP to ~1-2%

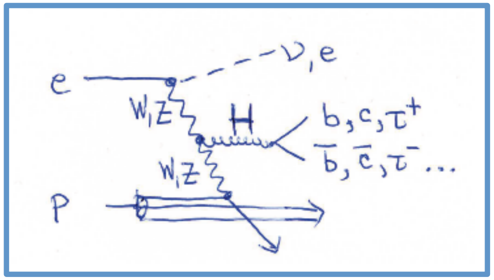


Uta Klein & Daniel Hampson
realistic HFL tagging & BDT
LHeC @ L=1000 fb^{-1}
Hbb
10%PHP
and
100%
other bgd
$\mu=\sigma/\sigma_{SM}$
$\delta\mu$(Hbb) = 1.0%
Hbb signal
with BDT>0
Hbb
CC h → b$\bar{b}$
CC h → c$\bar{c}$
CC Z → jj
γ p jjj
CC jjj
CC $\bar{t}$
NC Z → jj
Hcc
remaining Hbb
2%Hbb
and
2%
other bgd
Hcc
$\delta\mu$(Hcc) = 7.4 %
Hcc signal
with BDT>0
Hcc
Events
$M_{jj,H}^{BDT>0}$ [GeV]

CC DIS WW→ H

FCC-he L=2 ab^{-1}

	bb	WW	gg	ττ	cc	ZZ	γγ
BR	**0.577**	**0.215**	**0.086**	**0.0632**	**0.0291**	**0.0264**	**0.00228**
δBR_{theory}	3.2%	4.2%	10.1%	5.7%	12.2%	4.2%	5.0%
N	**$1.15\ 10^6$**	**$4.3\ 10^5$**	**$1.72\ 10^5$**	**$1.26\ 10^5$**	**$5.8\ 10^4$**	**$5.2\ 10^4$**	**4600**
f	2.86 $_{BDT}$	16	7.4	5.9	5.6 $_{BDT}$	8.9	3.23
δμ/μ [%]	**0.27**	**2.45**	**1.78**	**1.65**	**2.36**	**3.94**	**3.23**
$\delta\kappa = \frac{1}{2}\frac{\delta\mu}{\mu}$	0.14	0.61*	0.89	0.83	1.18	1.97	2.37



→ Sum of first 6 branching fractions that could be measured

LHeC : 0.9964 +- 0.02

FCChe: 0.9964 +- 0.01

pp: < 0.99 → cc? gg?

Further coupling constraints to be explored:

$$\sigma(WW \to H \to WW) \propto \kappa^4(HWW)$$

$$\sigma(WW \to H \to bb) \propto \kappa^2(HWW)\bullet\kappa^2(Hbb)$$

$$\sigma(WW \to H \to \tau\tau) \propto \kappa^2(HWW)\bullet\kappa^2(H\tau\tau)$$

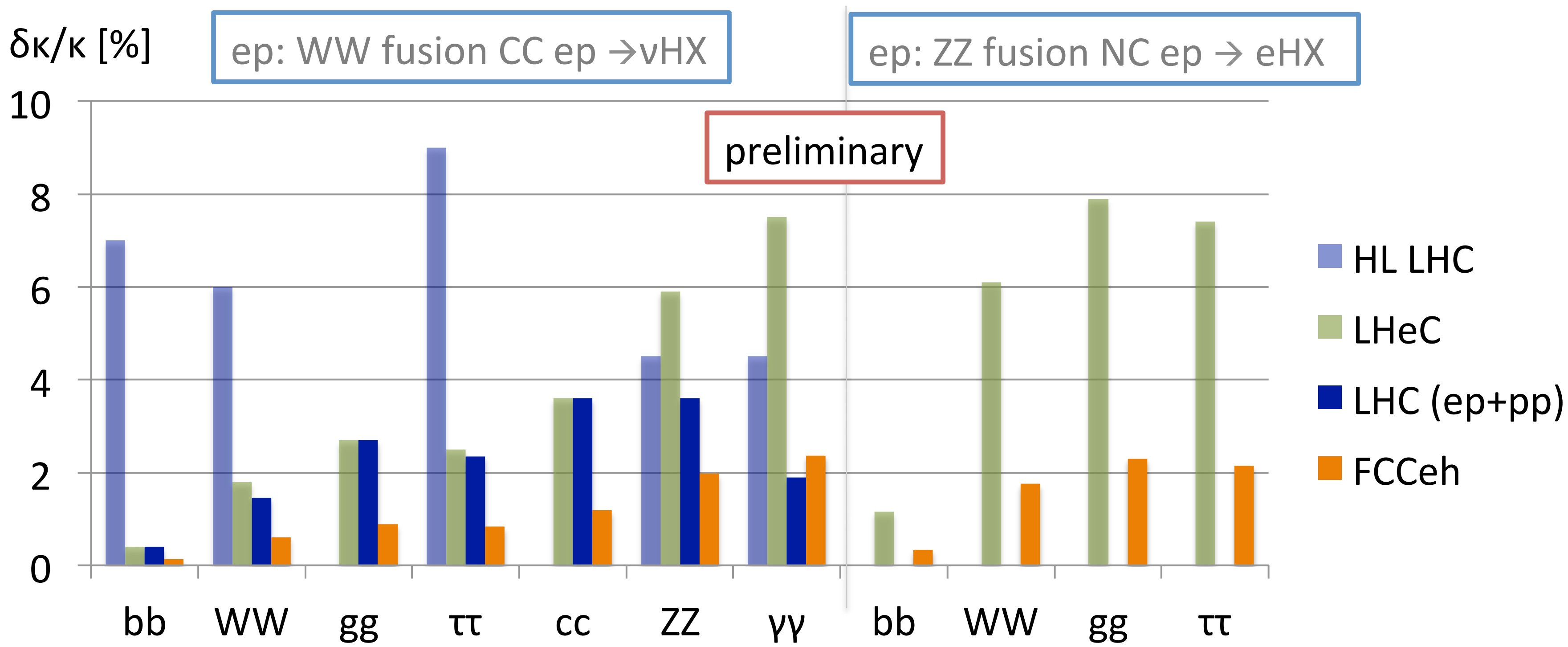
$$\sigma(WW \to H \to gg) \propto \kappa^2(HWW)\bullet\kappa^2(Hgg)$$

$$\sigma(WW \to H \to cc) \propto \kappa^2(HWW)\bullet\kappa^2(Hcc)$$

$$\sigma(WW \to H \to ZZ) \propto \kappa^2(HWW)\bullet\kappa^2(HZZ)$$

$$Note: \sigma(ZZ \to H \to WW) \propto \kappa^2(HZZ)\bullet\kappa^2(HWW)$$

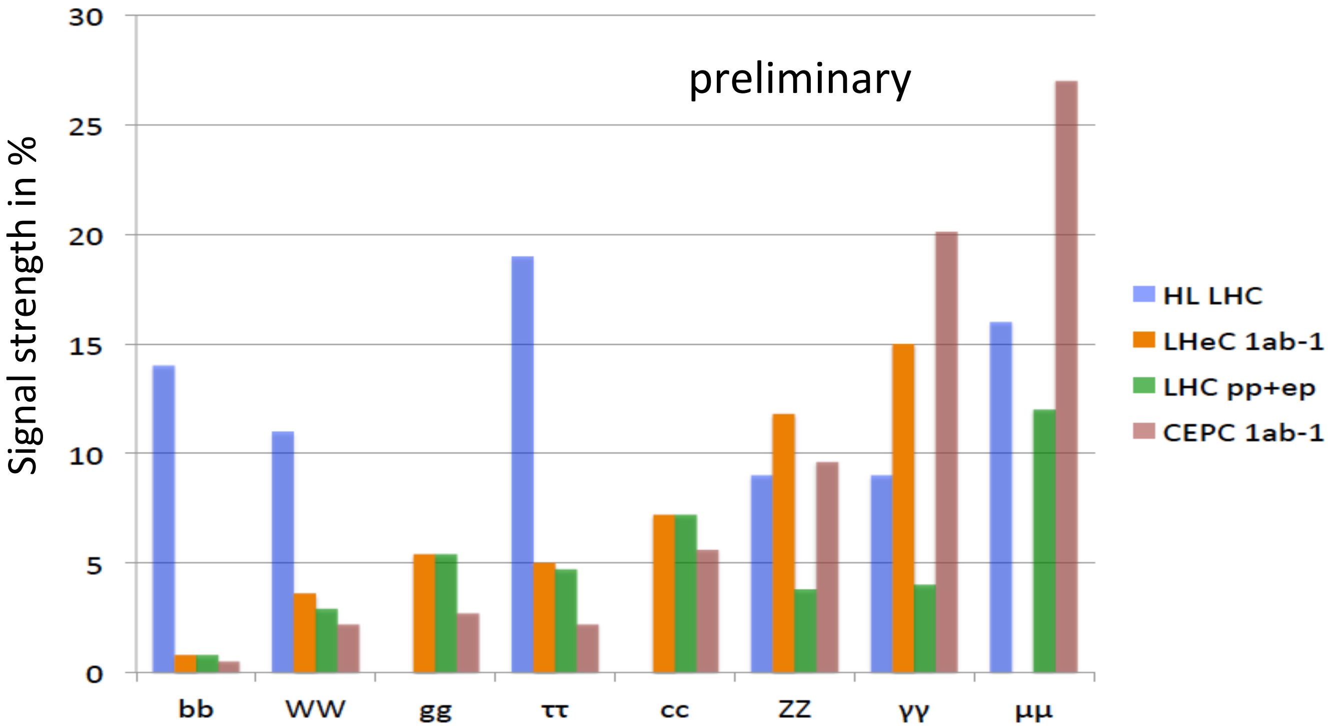
Higgs SM Coupling Prospects: ep+pp



HL LHC: ATLAS-PUB-2014-016 14 TeV 3ab^{-1} – LHC has no gg, no cc, and poor bb, but rare channels as γγ
LHeC: 1ab^{-1}, 60 GeV x 7 TeV - Work in progress. ep also provides precise: xg, α_s and PDFs to N^{3}LO..
LHC (ep+pp): HL LHC with reduced theory uncertainty combined with LHeC –**running in parallel**
FCCeh: 2ab^{-1}, 60 GeV x 50 TeV - Work in progress. ep also provides precise: xg, α_s and PDFs to N^{3}LO..

Improvements: ATLAS 2014 conservative, no CMS. ep (LHeC/FCCeh) are overconstrained:
CC+NC, ratios, sum(br)=1.. → joint coupling determination: especially WW and ZZ should improve

Signal Strength: LHeC+LHC and CEPC



LHC: ATLAS 2014
(will be better)

LHeC: M+U Klein
FCC WS1/18

LHC: pp (no thy) + ep

CEPC: M Ruan, 14.1.17
scaled to $1ab^{-1}$

The **ep** and the **e^+e^-** prospects of measuring Higgs decays are (about) the same for same L.
Note that $1ab^{-1}$ is 10 years of operation at 10^{34} , at high reliability.
J Gao: CEPC wants 3 10^{34} and hopes for 5 ab^{-1}. Theorists write about a 350 GeV operation.

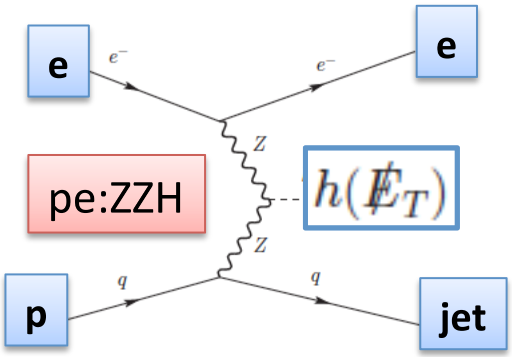
Sum of all major decay channels: LHC 0.89+-0.12, LHeC 0.99 +- 0.02, LHCep+pp: 1.00+-0.01
The addition of the LHeC to the HL LHC transforms that into a high precision Higgs facility
➔ LHeC could improve LHC Higgs precision by factor 10

Branching for invisible Higgs

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

Values given in case of 2σ and L=1 ab^{-1}

Delphes detectors	LHeC 1.3 TeV	FCC-he 3.5 TeV
LHC-style	4.7%	1.9%
First 'ep-style'	5.7%	2.6%
+BDT Optimisation	5.5% (4.5%*)	1.7% (2.1%*)



- ✓ **Uses ZZH fusion process to estimate prospects of Higgs to invisible decay using *standard cut/BDT analysis techniques***
- ✓ **Results for full MG5+Delphes analyses look very encouraging for a measurement of the branching of Higgs to invisible in ep down to 1.7% to 1.2% for 1 to 2 ab^{-1}**

- ✓ We also checked LHeC ←→ FCC-he scaling with the corresponding cross sections (* results in table) : Downscaling FCC-he simulation results to LHeC would give 4.5%, while up-scaling of LHeC simulation to FCC-he would result in 2.1% ➔ all well within uncertainties of projections of ~25%
- employ further synergies within LHC community and HL-LHC&FCC study group
  ➔ **further detector and analysis details have certainly an impact on results**

Top Physics

Top electric charge

EDM and MDM

Anomalous t-q-γ and t-g-Z

V_{tb} to 1.00+-0.01 and W-t-b

Top spin

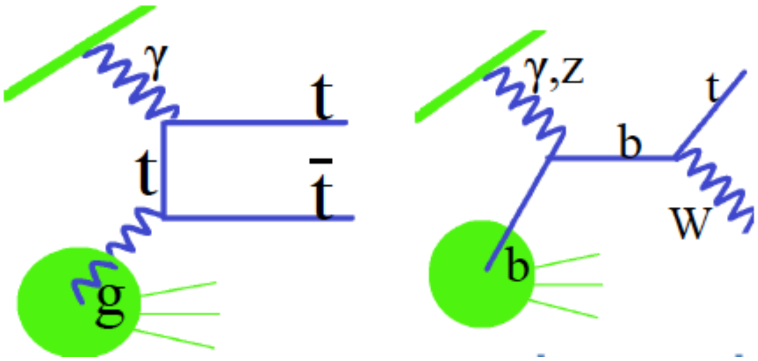
Top PDF

Top mass

Top-Higgs (1602.04670)

CP nature of ttH (1702.03426)

Pair production   Single production



σ=0.05pb @ LHeC   **σ=1.73pb @ LHeC**
σ=1.14pb @ FCC-ep   **σ=15.3pb @ FCC-ep**

LHeC and even more FCC-eh are top factories with huge BSM potential

For top itself: maximise Ee. For t as background for Higgs: not too much

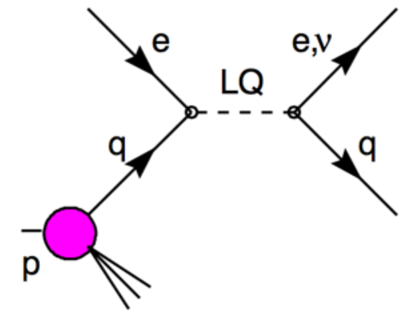
cf Christian Schwanenberger, Top in ep, Talk at FCC Physics Week 17.1.18

Exploring SM EFT & New Physics

M. Trott @ LHeC Workshop 2014
http://lhec.web.cern.ch

In the absence of any explicit new states, or overwhelming theory prejudice, the goal is to systematically study the SM EFT for hints of NP, using all possible future facilities to maximize physics conclusions.

What is the SM EFT? A linear realization of gauge symmetry and the new state is a 0+ scalar:



Four fermion operators with leptons and quark fields:

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

- ➔ 59 operators or 2499 parameters experimentally to constraint!
- ➔ where nearly 50% of the parameters (1053) are sensitive to lepton-quark interactions – not just about lepto-quarks
- ➔ **ep potential for general BSM searches 'that look like hadronic noise' in pp**

M d'Onofrio, G Azuelos

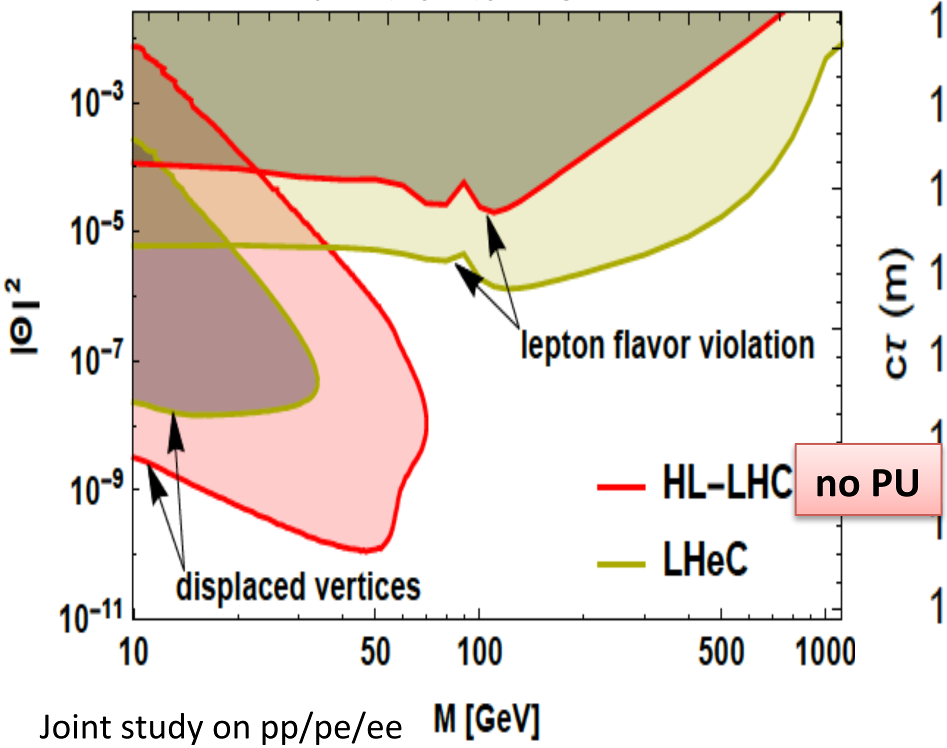
BSM: LHeC-LHC complementarity

Compositeness	• *4-fermion EFT: Lepton-quark compositeness scale* • ***Quark radius***
Leptoquarks and RPV squark decay	• *Accessible range largely excluded, but not completely* • ***Better measure of LQ characteristics, if they exist***
Anomalous Triple Gauge Couplings	• *Comparable to LHC*
Top FCNC couplings	• ***couplings – great potential wrt HL-LHC***
Vector-like leptons, heavy/excited leptons, bileptons, higher isospin lepton multiplets	• *No constraints on VLL, so far, at LHC* • *Extend sensitivity to for lower masses*
Heavy neutrinos, Majorana neutrinos, sterile neutrinos	• *Symmetry-protected see-saw model* • ***LHeC reach similar or better than HL-LHC***
SUSY EW: compressed scenario, **Higgsino**, (dark sector)	• *Long-lived neutral particles* • ***Disappearing tracks – low background, compensate the low signal production rate***
Anomalous Quartic Gauge Couplings	• *Better control on background: no gluon exchange diagrams (mostly FCC?)*
extended Higgs sector: higher isospin multiplet	• *Singly- and doubly- charged higgs by VBF (mostly FCC)*

Lots of important new papers on BSM in ep

Sterile (heavy) Neutrinos in ep → NX

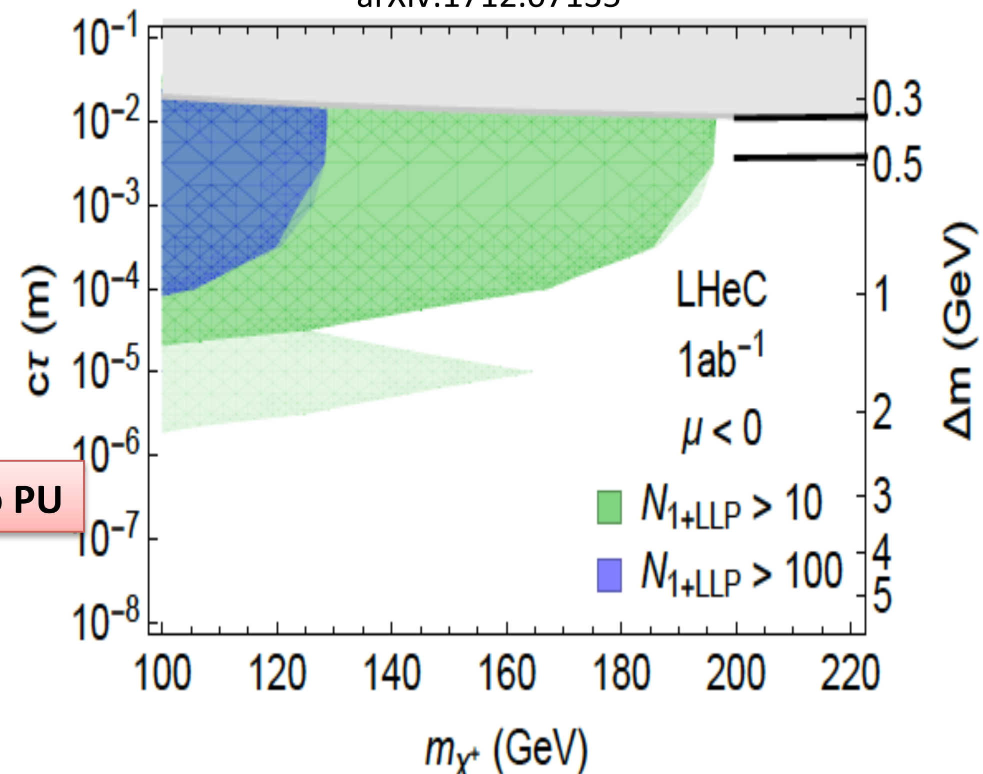
arXiv:1612.02728

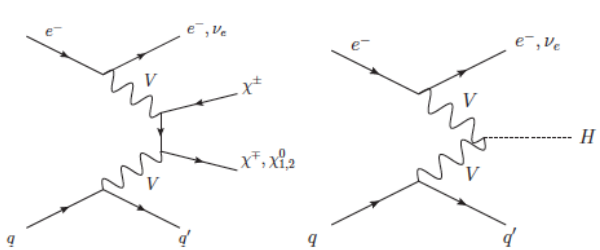


Joint study on pp/pe/ee

Search for Higgsino at LHeC

arXiv:1712.07135



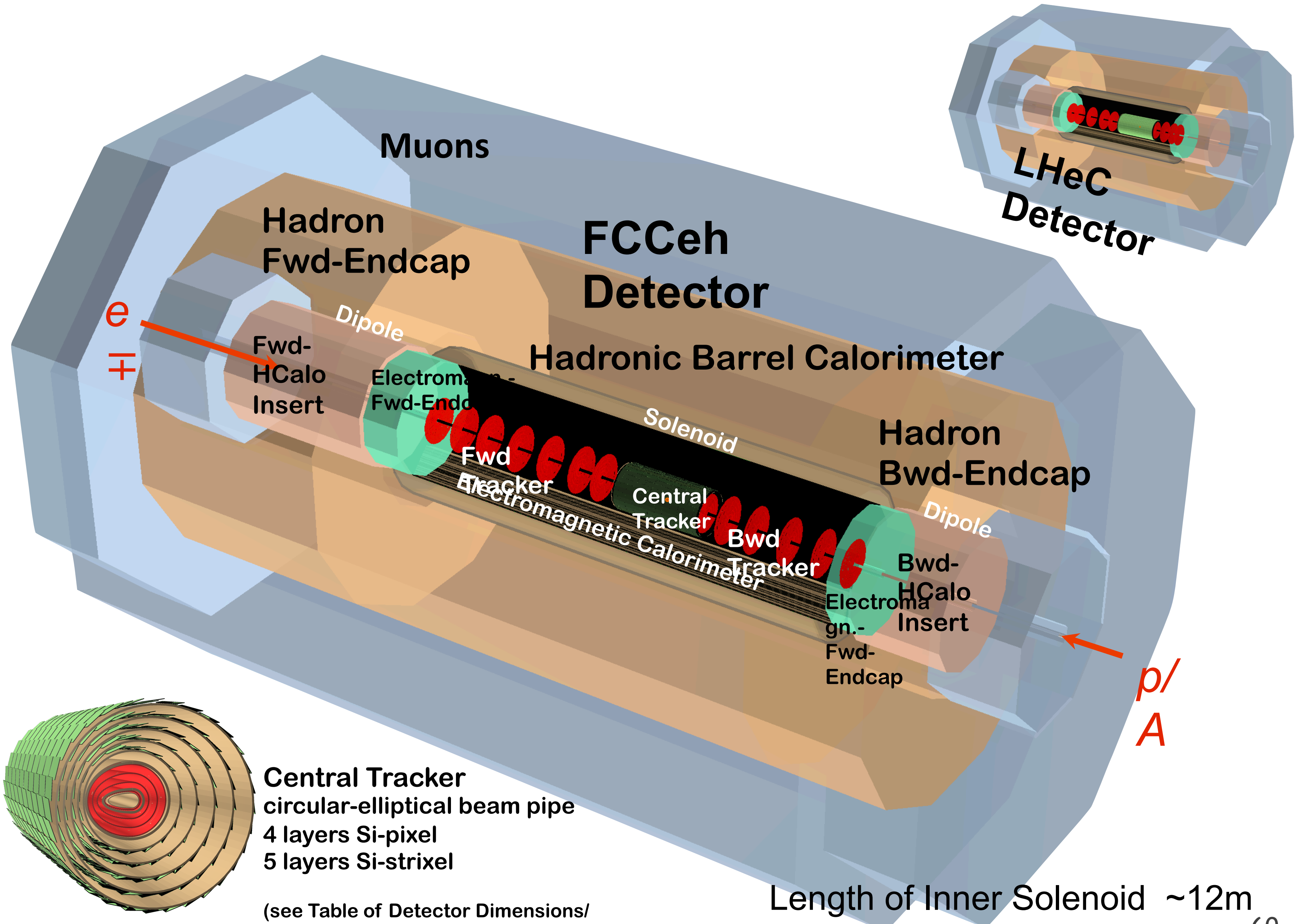


This adds significant motivation for the construction of future e^-p colliders. Together with the invaluable proton PDF data, as well as precision measurements of EW parameters, top quark couplings and Higgs couplings, our results make clear that adding a DIS program to a pp collider is necessary to fully exploit its discovery potential for new physics.

Detector Development for LHeC and Installation Issues

LHeC/FCC ep/eA detector

P Kostka et al.



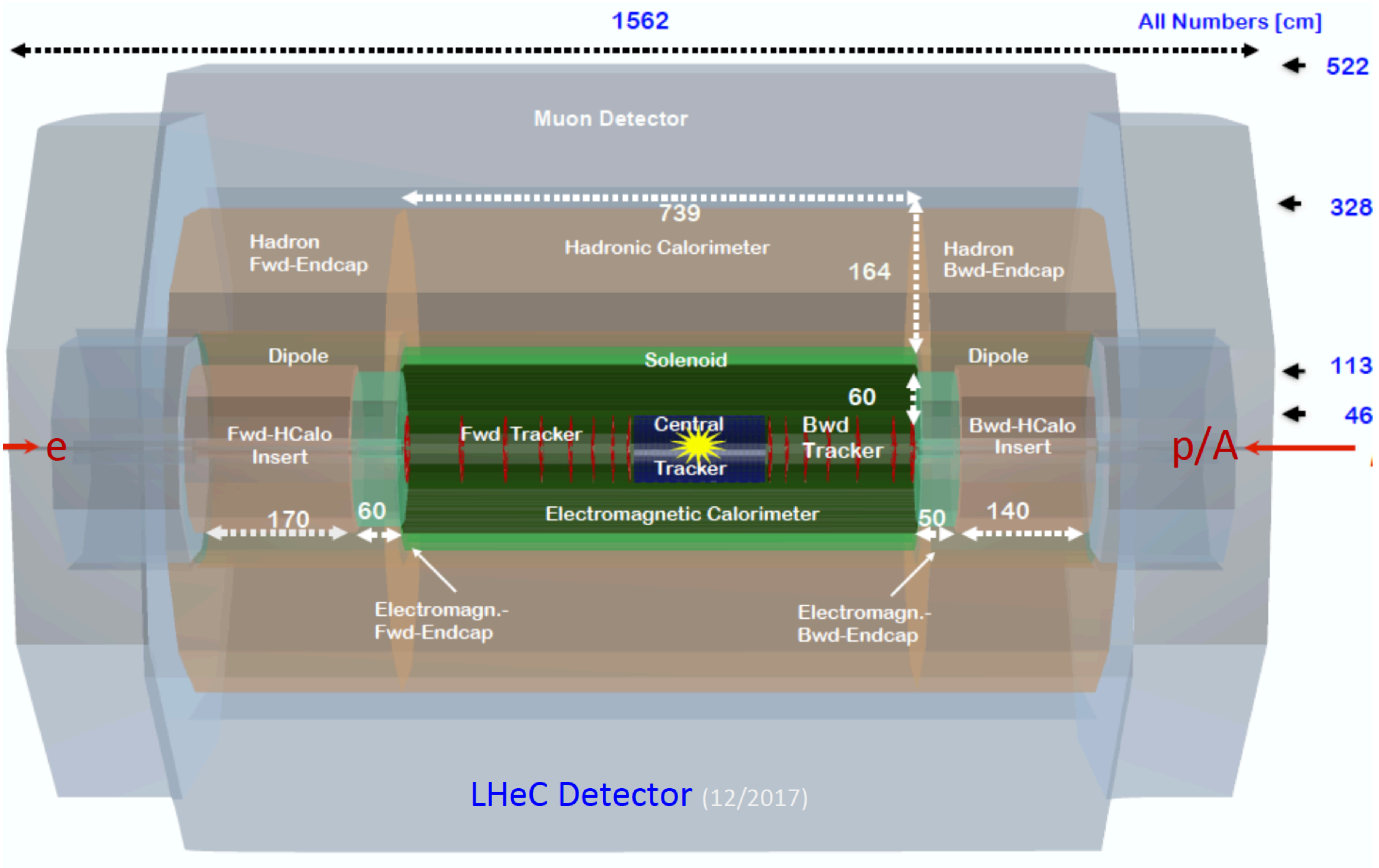
Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel
5 layers Si-strixel

(see Table of Detector Dimensions/ Parameters in backup)

Length of Inner Solenoid ~12m

LHeC Detector for the HL/HE-LHC

[arXiv:1802.04317]



Length x Diameter: LHeC (13.3 x 9 m^2)   HE-LHC (15.6 x 10.4) FCCeh (19 x 12)

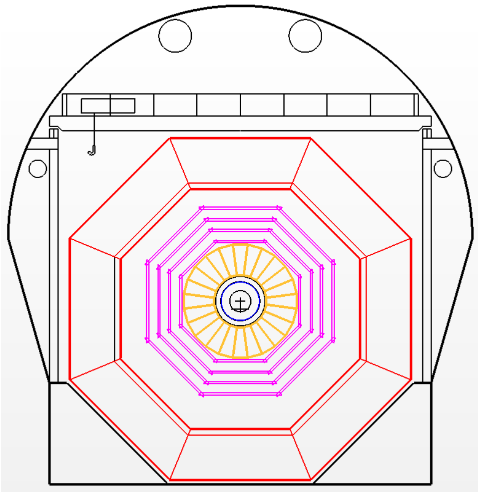
ATLAS (45 x 25) CMS (21 x 15): [LHeC < CMS, FCC-eh ~ CMS size]

If CERN decides that the HE LHC comes, the LHeC detector should anticipate that

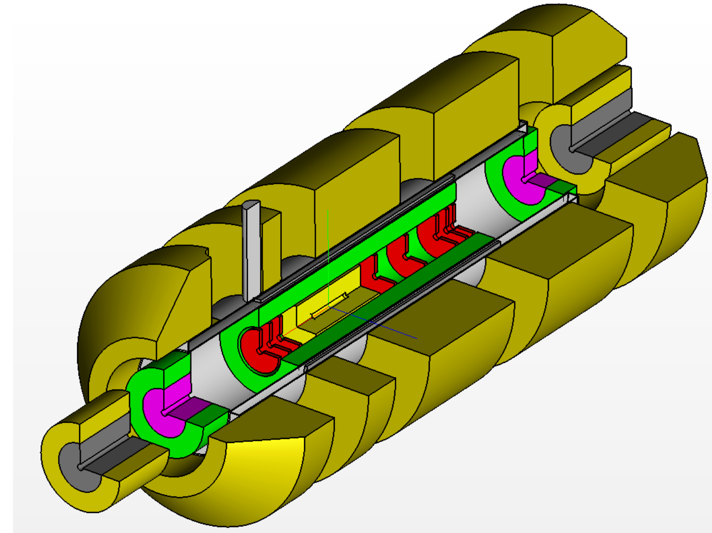
Installation Study

to fit into LHC shutdown needs directed to IP2

Andrea Gaddi et al

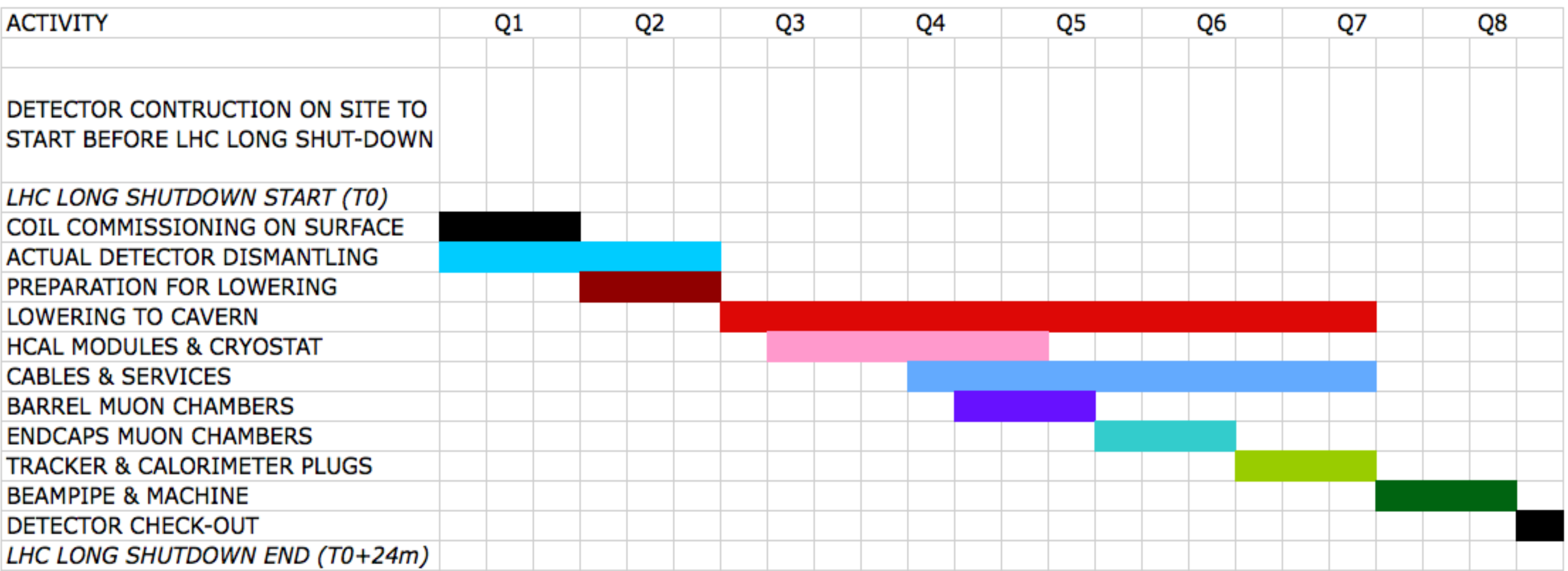


Detector fits in L3 magnet support



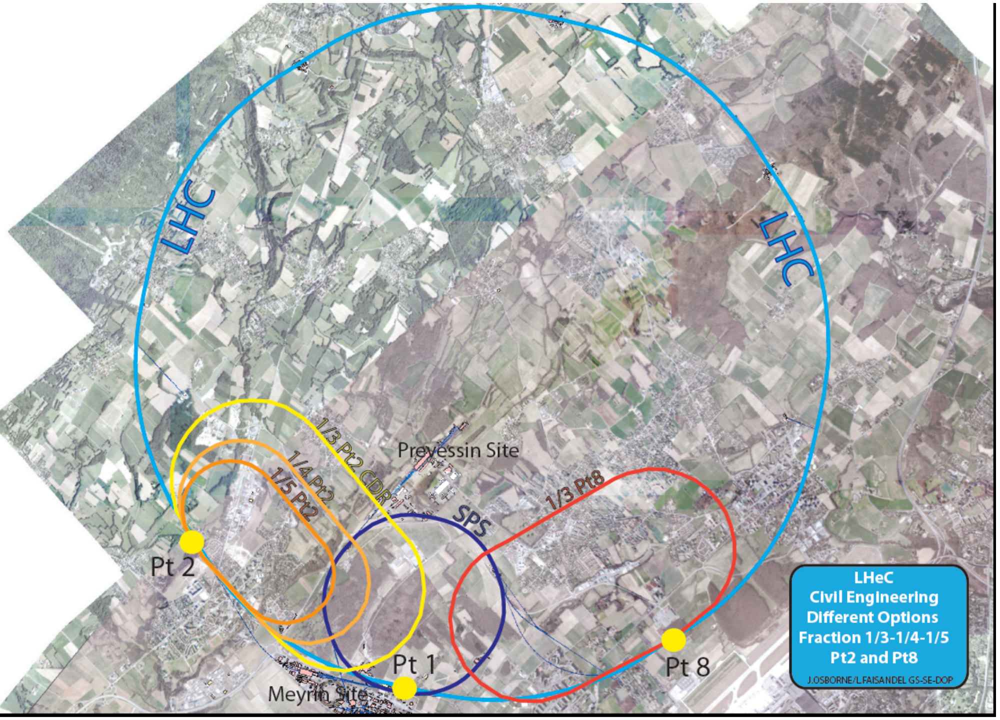
Modular structure

LHeC INSTALLATION SCHEDULE



… to take home

- The LHC is fantastic – let's use it as best as we can!
- An ep@LHC collider – dubbed LHeC - could be build as an upgrade to HL-LHC: ep running in parallel with HL-LHC pp (until ~2040) and for HE-LHC.
- LHeC would complement the pp program by providing invaluable DIS data and high precision PDFs, α_s and N^3LO → turn HL-LHC into a powerful Higgs facility joining ep+pp measurements: Sum of branching ratios to 1.00+-0.01



- LHeC is surprisingly good at probing Higgs couplings precisely - comparable to lepton colliders
- BSM sensitivity of ep 'that looks like hadronic noise in pp', e.g. sterile neutrinos and Higgsino
- Next: LHeC/FCC-eh Reports (Physics, Detector, Accelerator) by end of 2018

Workshops

Recent: September 2017
https://indico.cern.ch/event/639067/

Next: 26-29 June 2018 Orsay
https://indico.cern.ch/event/698368/
Preparation for strategy:
Physics, Accelerator, Detector, PERLE

Many eh related workshops
FCC: Physics week (CERN Jan 2018)
and in April 2018 (Amsterdam)
POETIC in March (Regensburg)
DIS 2018 in April (Kobe)
HL-HE LHC Physics June 2018 (CERN)
which includes ep/eA

https://lhec.web.cern.ch

LHeC + FCC-he Organisation*)

International Advisory Committee

"..Direction for ep/A both at LHC+FCC"

Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – Chair
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (ESS)

We miss Guido Altarelli.

Coordination Group

Accelerator+Detector+Physics

Nestor Armesto
Oliver Brüning – Co-Chair
Andrea Gaddi
Erk Jensen
Walid Kaabi
Max Klein – Co-Chair
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann

5(11) are members of the FCC coordination team

OB+MK: FCC-eh responsibles
MDO: physics co-convenor

Working Groups

PDFs, QCD
Fred Olness,
Claire Gwenlan
Higgs
Uta Klein,
Masahiro Kuze
BSM
Georges Azuelos,
Monica D'Onofrio
Top
Olaf Behnke,
Christian Schwanenberger
eA Physics
Nestor Armesto
Small x
Paul Newman,
Anna Stasto
Detector
Alessandro Polini
Peter Kostka

*)September 2017

Additional Sources & Thanks to

The LHeC/FCC-eh study group, http://cern.ch/lhec.

"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]

- Much more material can be found here: LHeC and FCC-eh Workshop, September 2017, CERN https://indico.cern.ch/event/639067/
- 1st and 2nd FCC Physics Workshop, Jan 2017 and 2018, CERN https://indico.cern.ch/event/550509/ https://indico.cern.ch/event/618254/
- M. Klein, "Future of Deep Inelastic Scattering with the LHeC" [arXiv:1802.04317]

Special thanks to my 'old' and 'new' colleagues in the LHeC/FCC-study group, the project leader Max Klein, our detector expert Peter Kostka, and our bi-weekly Higgs-top working group discussions.

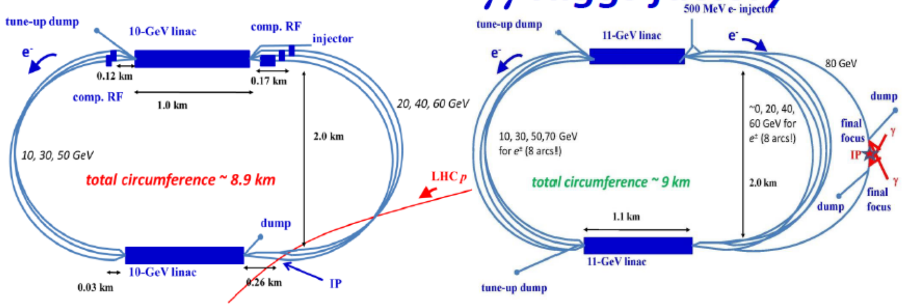
Further use of ERL in between HL and HE-LHC

Reconfiguring *LHeC → SAPPHiRE*

LHeC-ERL

*SAPPHiRE**

γγ Higgs factory

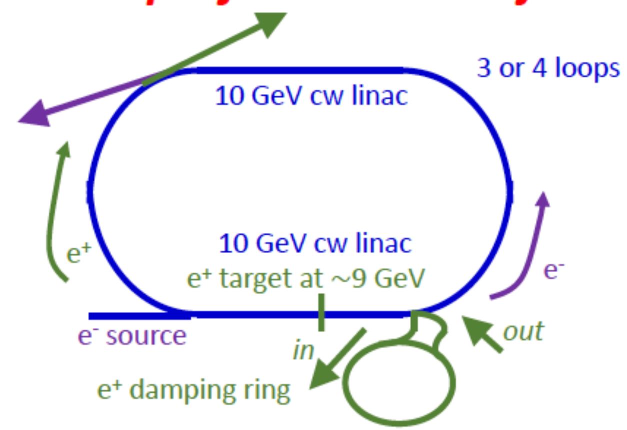


*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

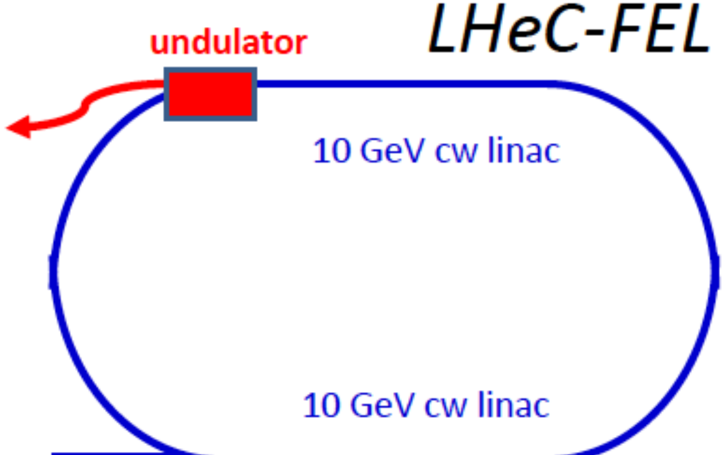
S. A. Bogacz, J. Ellis, L. Lusito, D. Schulte, T. Takahashi, M. Velasco, M. Zanetti, F. Zimmermann, 'SAPPHiRE: a Small Gamma-Gamma Higgs Factory,' arXiv:1208.2827

F.Zimmermann at LHeC WS 9/17

LHeC: perfect FCC-ee injector!



LHeC-FEL



up to 60 GeV,
~25 mA,
1 MeV photons?

3-15x higher beam energy
(10-200x higher γ energies),
300-600x higher current

XFEL: 20GeV e, 0.03mA, 24keV photons. LCLSII: 4 GeV e, 0.06mA, 5 keV photons

New: Estimates of Higgs Prospects

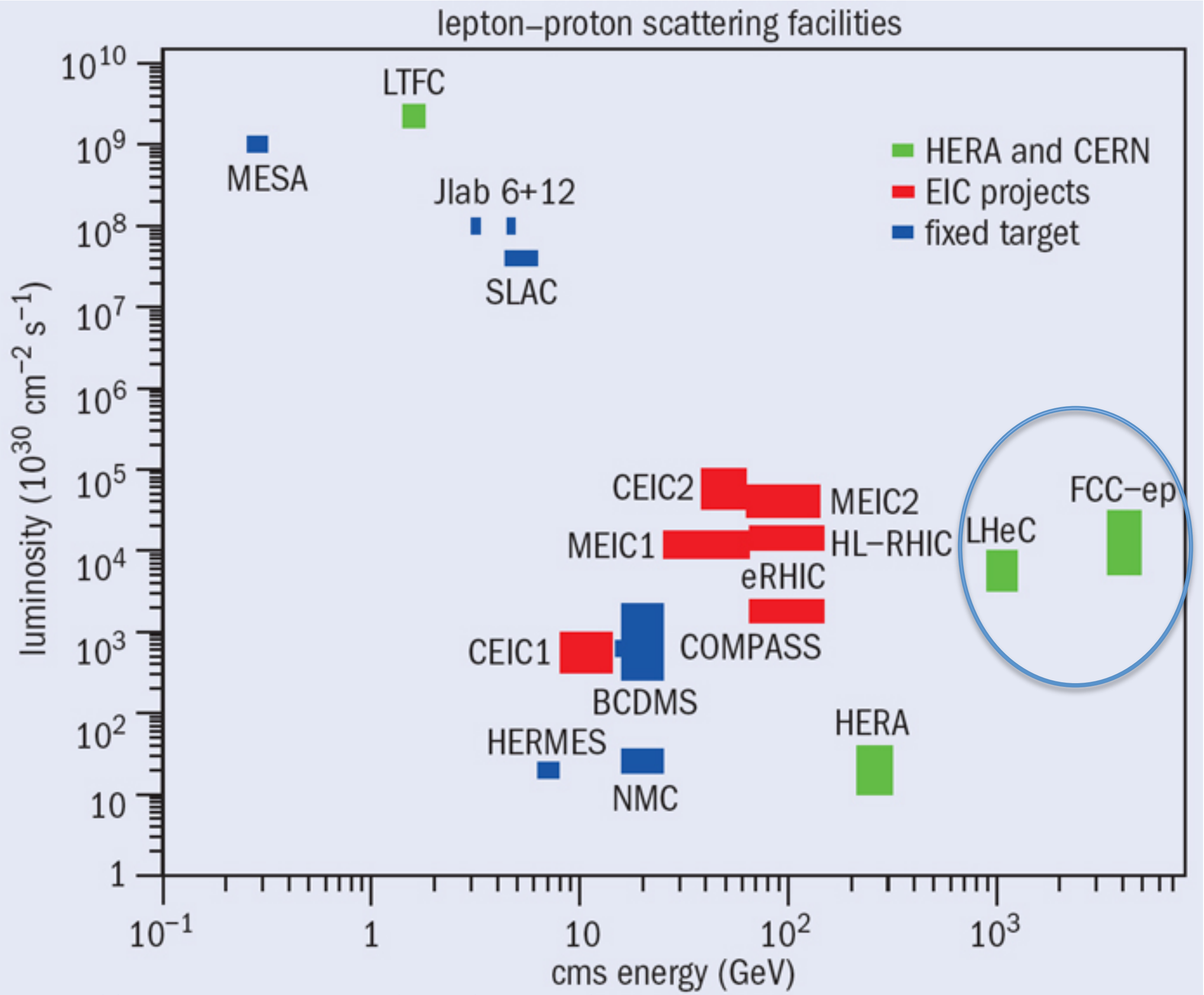
- Use LO Higgs cross sections **σ_H for M_H=125 GeV, in [fb],** and branching fractions BR(H→XX from Higgs Cross Section Handbook (c.f. appendix)
- Apply further branching, BR(X→FS) in case e.g. of W→ 2 jets and use acceptance, Acc, estimates based on MG5, for further decay
- Use reconstruction efficiencies, ε, achieved at LHC Run-1, see e.g. prospect calculations explored in arXiV:1511.05170
- Use fully simulated LHeC Hbb and Hcc results as baseline for S/B ranges
- Use fully simulated Higgs to invisible for 3 ep c.m.s. scenarios as guidance for extrapolation uncertainty (~25%)
- Estimate HIggs events per decay channel for certain Luminosity in [fb^{-1}]

$$N = \sigma_H \bullet BR(H \to XX) \bullet BR(X \to FS) \bullet L$$

- Calculate uncertainties of signal strengths w.r.t. SM expectation $\mu = \frac{\sigma}{\sigma_{SM}}$

$$\frac{\delta\mu}{\mu} = \frac{1}{\sqrt{N}} \bullet f \quad \text{with} \quad f = \sqrt{\frac{1 + 1/(S/B)}{Acc \bullet \varepsilon}}$$

The ep Landscape : Luminosity vs √s



http://cerncourier.com/cws/article/cern/57304

China
CEIC1 = Chinese version of Electron-Ion Collider
("A dilution-free mini-COMPASS")

U.S.
MEIC1 = **EIC**@Jlab

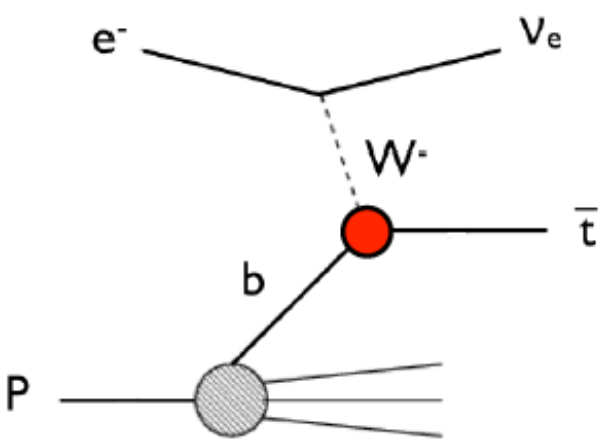
eRHIC = **EIC**@BNL

Europe
LHeC = ep/eA collider @ CERN

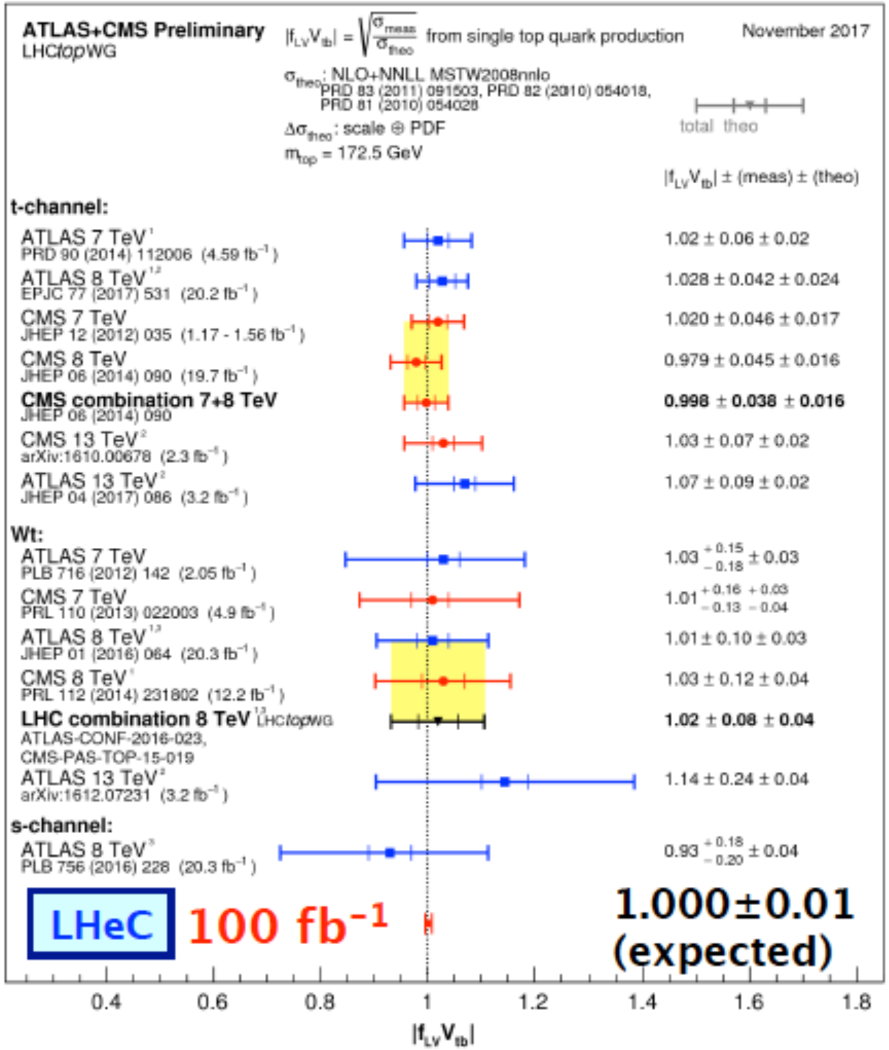
CEIC2
MEIC2
HL-eRHIC
FCC-he
} future extensions

Direct Measurement of $|V_{tb}|$

[1] including top-quark mass uncertainty
[2] σ_{theo}: NLO PDF4LHC11 NPPS205 (2010) 10, CPC191 (2015) 74
[3] including beam energy uncertainty



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

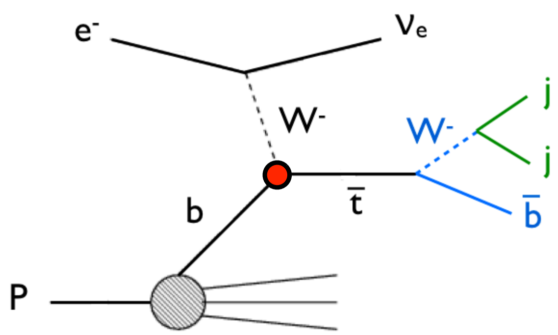


Top Quark & EW in ep

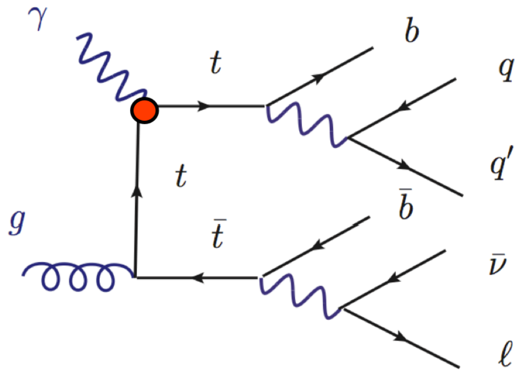
…. a few examples only

C. Schwanenberger, @DIS2015

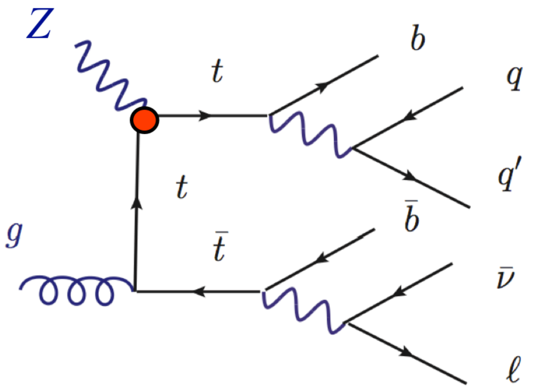
precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations) : **top quark expected to be most sensitive to BSM physics, due to large mass**



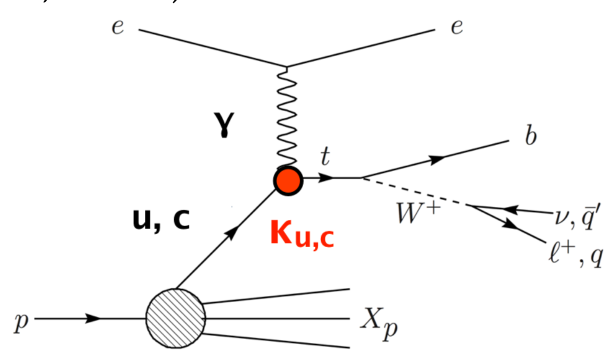
- high precision measurements of Vtb and search for **anomalous Wtb** couplings



- direct measurement of top quark charge and search for **anomalous ttbarγ** couplings (eg. EDM, MDM)

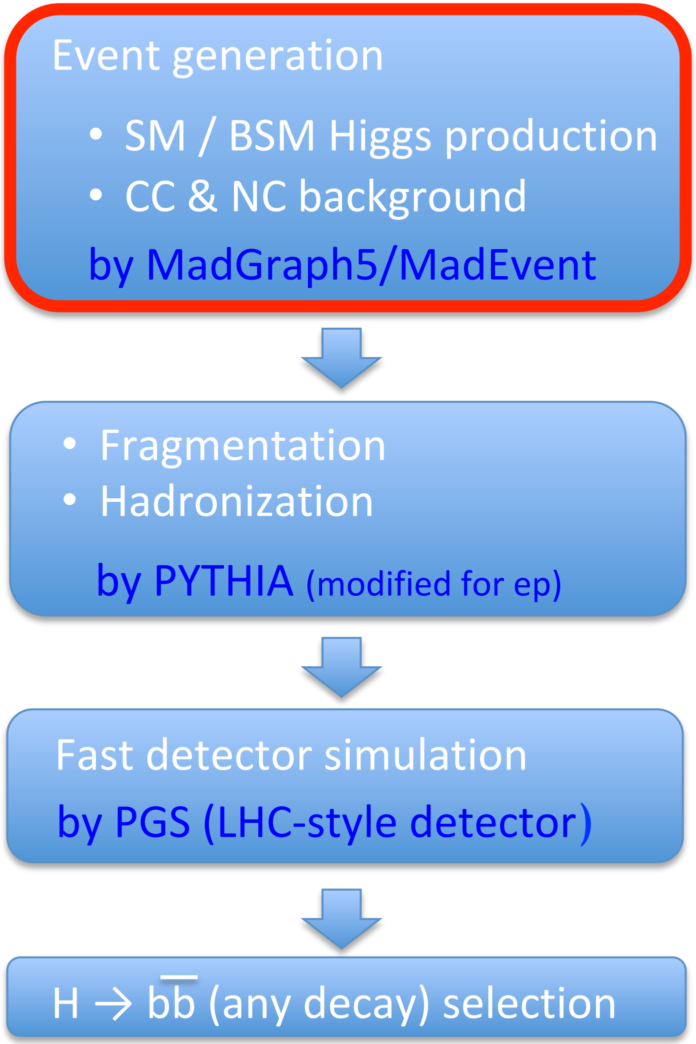


- measurement of top isospin and search for **anomalous ttbarZ** couplings (eg. EDM, MDM)



- sensitive search **for FCNC couplings** will constrain BSM models that predict FCNC (eg. SUSY, little Higgs, technicolour)

Analysis Framework & New Developments



- Calculate cross section with tree-level Feynman diagrams using pT of scattered quark as scale (CDR ŝ) for ep processes like single t, Z, W, H

→ Standard HERA tools can NOT to be used !

- **NEW:** full update for Madgraph5 (CDR MG4)
- **Higgs mass 125 GeV as default for sm and sm-full** (for Hcc)→ BR corrected to ‘best’ HDECAY
- Fragmentation & hadronisation uses ep-**customised** Pythia.
- **Interface to Delphes ‘detector’ →displaced vertices and signed impact parameter distribution analysis for Hcc!**

→ powerful method to optimise detector tuning and S/N for various Higgs decays

Valid for ep only. Any other model can be easily tested → non-SM higgs, SUSY etc.

[eA needs modelling of nuclear fragmentation]

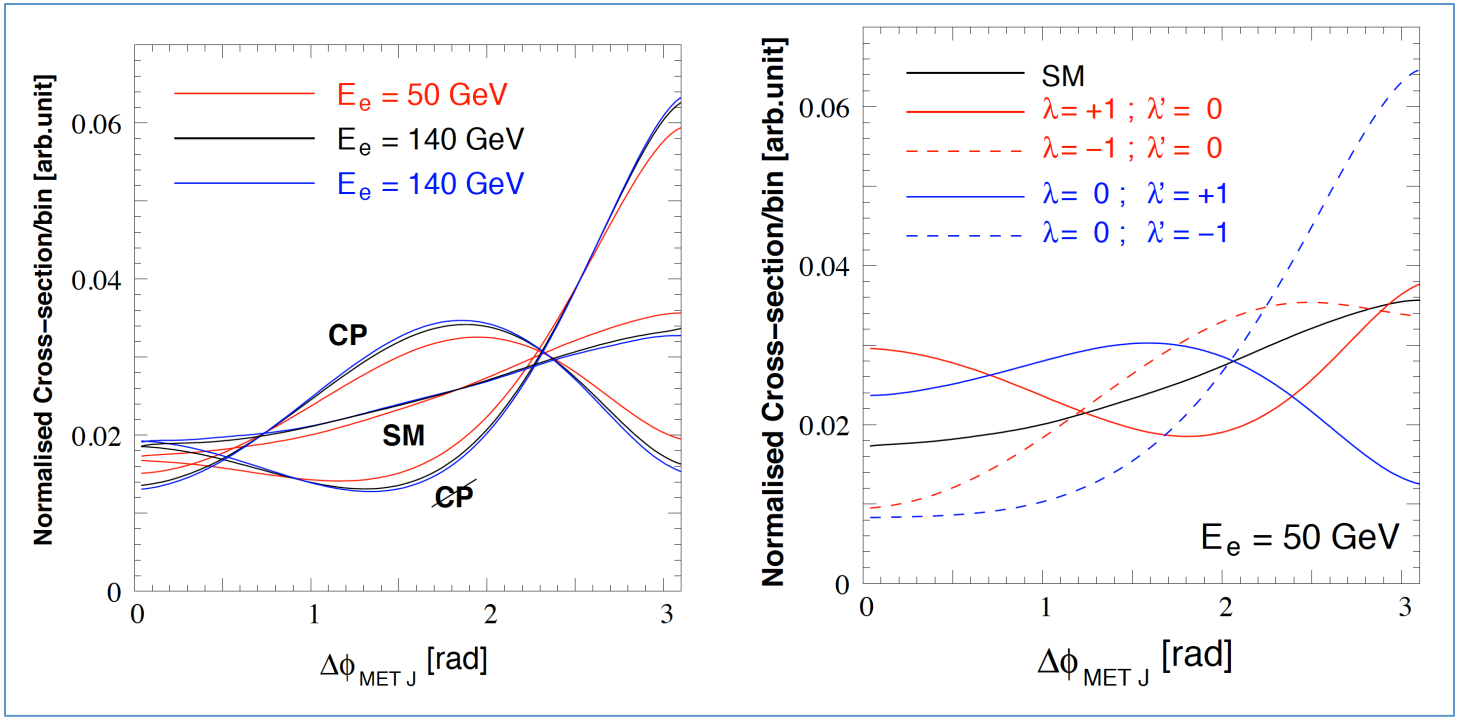
Measure CP Properties of Higgs

[LHeC CDR before Higgs discovery M_H=120 GeV, E_p=7 TeV]

- Higgs couplings with a pair of gauge bosons (WW/ZZ) and a pair of heavy fermions (t/b/τ) are largest.
- Higgs@LHeC allows uniquely to **access HWW vertex ➔** explore the CP properties of HVV couplings: BSM will modify CP-even (λ) and CP-odd (λ') states differently

$$\Gamma^{\mu\nu}_{(SM)}(p,q) = g M_W \, g^{\mu\nu} \quad \rightarrow \quad \Gamma^{(BSM)}_{\mu\nu}(p,q) = \frac{-g}{M_W}\left[\lambda\,(p.q\,g_{\mu\nu} - p_\nu q_\mu) + i\,\lambda'\,\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

- Study ***shape changes*** in DIS normalised CC Higgs→ bb cross section versus the azimuthal angle, $\Delta\phi_{MET,J}$, between $E_{T,miss}$ and forward jet.



CDR initial study of HWW vertex:

CP couplings probed to

λ~0.05

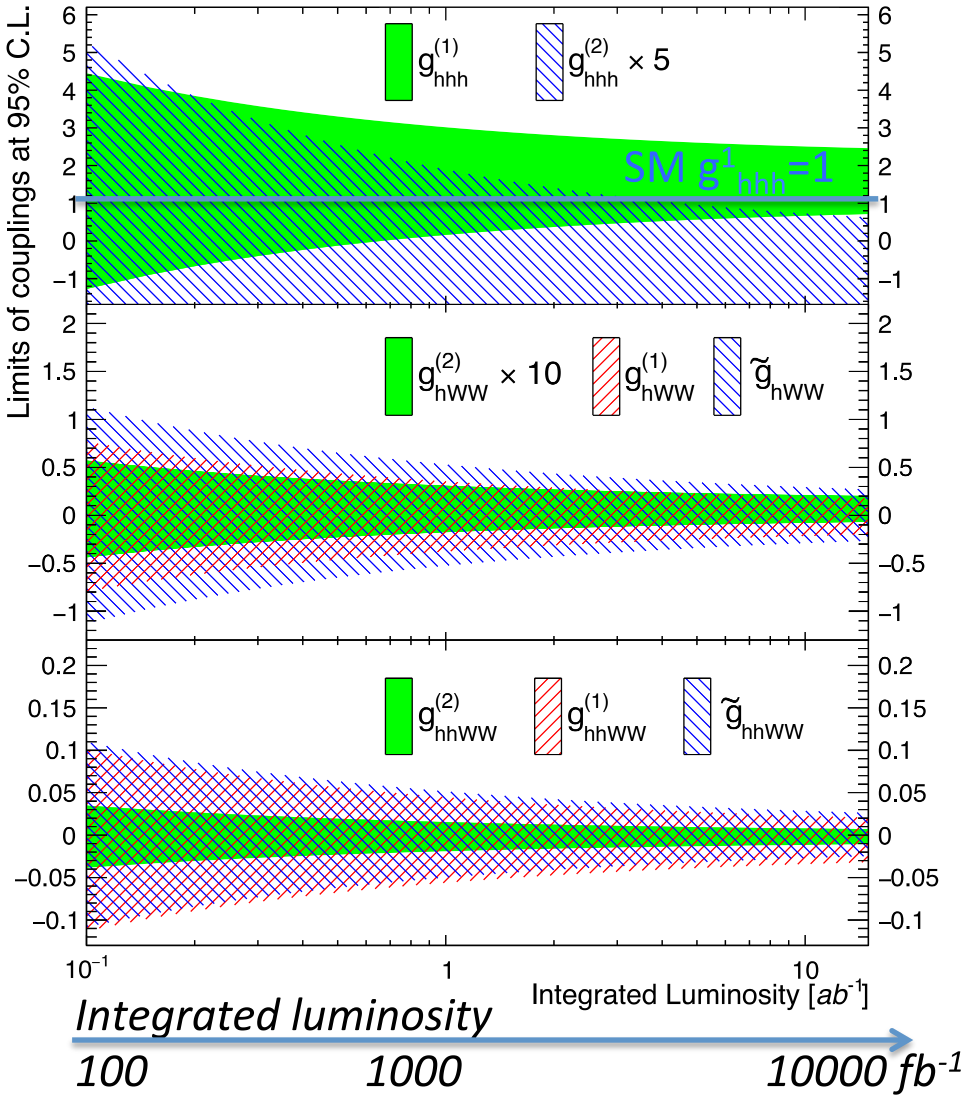
λ'~0.2

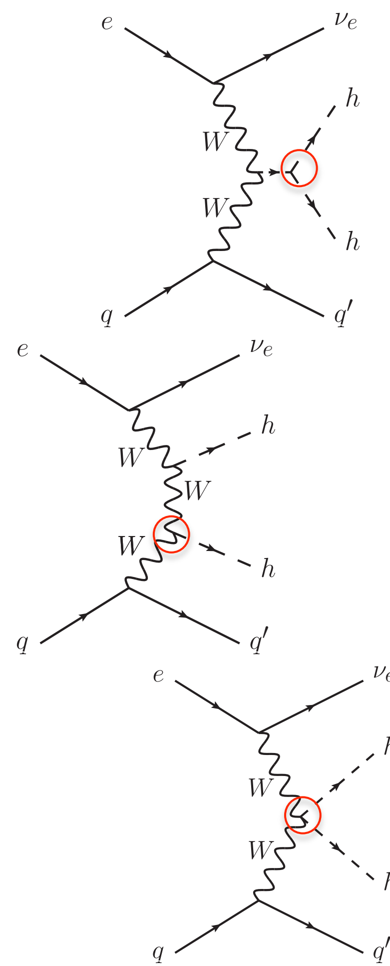
based on 50 fb^{-1}

Double Higgs Production in ep

[1509.04016]

FCC-eh 5% systemtatic uncertainty included





1σ for SM hhh for E_e 60 (120)GeV and 10ab^{-1}

$$g^{(1)}_{hhh} = 1.00^{+0.24(0.14)}_{-0.17(0.12)}$$

Probing anomalous couplings: limits are obtained by scanning one of the non-BSM coupling while keeping other couplings to their SM values.

Explore LHeC and HE-LHeC potential!

Here $g^{(i)}_{(\dots)}, i = 1, 2$, and $\tilde{g}_{(\dots)}$ are real coefficients corresponding to the CP-even and CP-odd couplings respectively, of the hhh, hWW and $hhWW$ anomalous vertices.

Invisible Higgs@LHeC
relating the Higgs and the 'dark' sectors

Y.-L. Tang et al.,
arXiv: 1508.01095

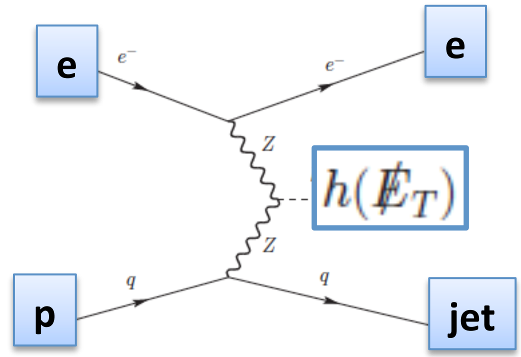
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

$\mathrm{Br}(h \to \not{E}_T)$ < 3.5% @95% C.L., MVA based

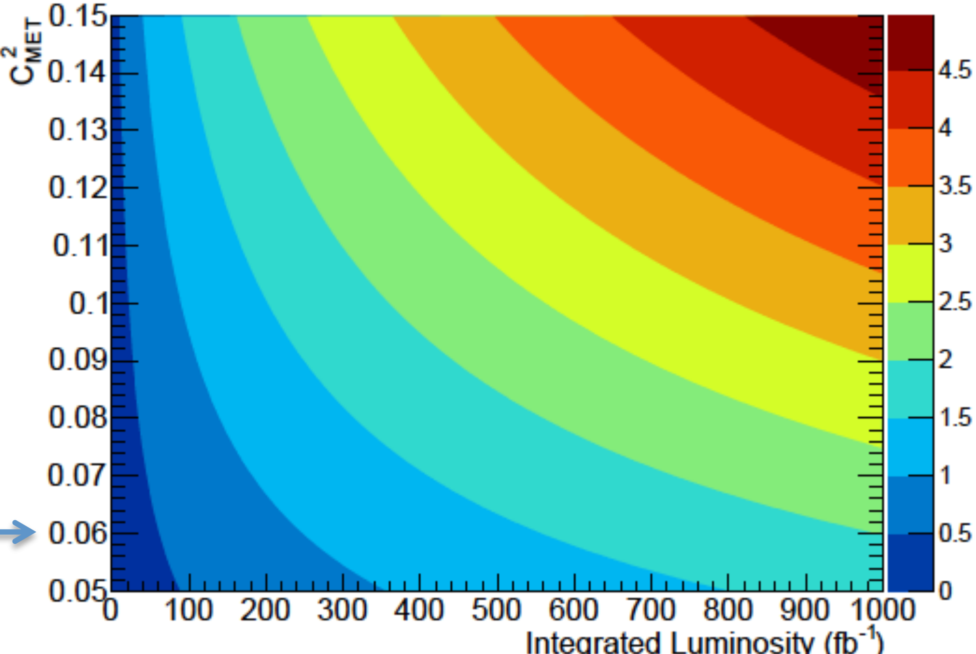
For **LHeC**, assume : 1ab^{-1}, P_e=-0.9, <u>cut based</u>

$\mathrm{Br}(h \to \not{E}_T)$ < 6% @ 95 % C.L.

$$C^2_{\mathrm{MET}} = \kappa_Z^2 \times \mathrm{Br}(h \to \not{E}_T)$$



κ_Z : BSM w.r.t. SM HZZ coupling



Colours:
expected statistical significance

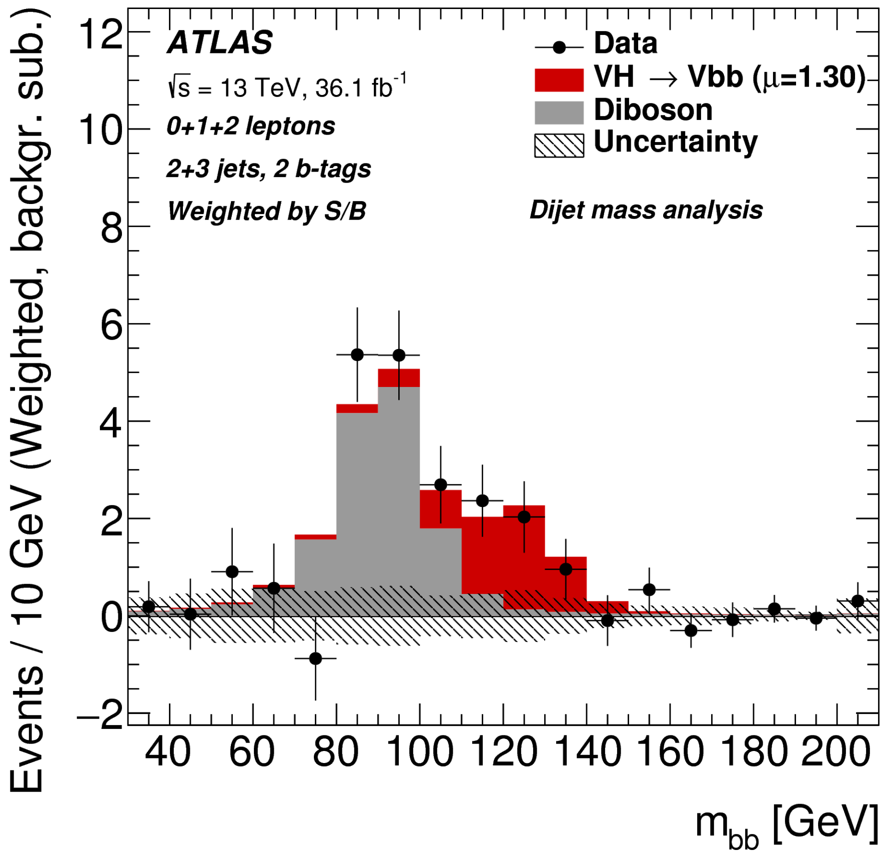
- ➔ **NEW studies performed on Delphes detector-level using our Madevent framework**
- ➔ **potential much enhanced for FCC-eh @ 3.5 TeV and HE-LHC-eh @ 1.8 TeV**

LHC: First 3σ Hbb Evidence!

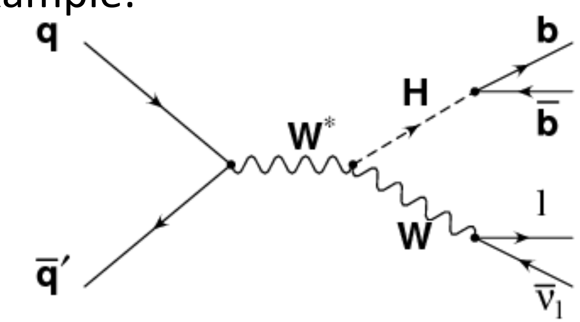
ATLAS, Aug 2017, sub. to JHEP

https://arxiv.org/abs/1708.03299

- use Higgs→bb in associated production with a W or Z boson
- explore various final states (e.g. Z→νν, W→lν, Z→ll categories)
- Run-I and II combined, S/B-weighted categories : μ=0.9±0.28(stat+syst)



Example:



- ✓ Encouraging result for HL-LHC prospects
- ✓ **Very encouraging for prospects in ep that we can handle S/B ~10^{-3} processes with sophisticated analysis techniques**

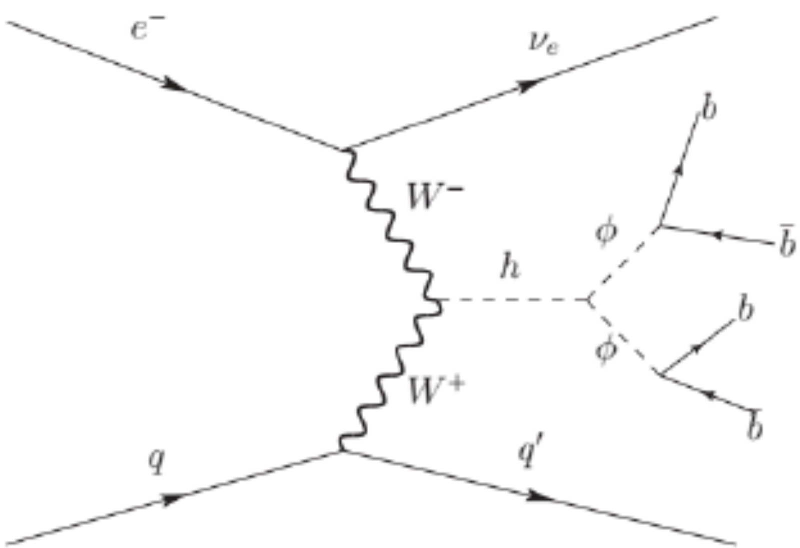
Hbb expectation @ LHeC for 36 fb^{-1} (½ year data)**: δμ~7-8% with significance of ~14**

Exotic Higgs Decays

$$h \to \phi\phi \to 4b$$

ϕ: a spin-0 particle from new physics.

$$eq \to \nu_e h q' \to \nu_e \phi\phi q' \to \nu_e b\bar{b}b\bar{b}q'$$



$$C_{4b}^2 = \kappa_V^2 \times \mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}^2(\phi \to b\bar{b})$$

ϕ mass range targeted in this study: [20,60]GeV, scanned in 1 GeV step.

$$\mathcal{L}_{eff} = \lambda_h v h \phi^2 + \lambda_b \phi \bar{b} b + \mathcal{L}_{\phi\,\mathrm{decay,other}}$$

S. Liu, Y. L. Tang, C. Zhang, S. Zhu, 1608.08458

- Well motivated signature in extended Higgs sector.
- Difficult to probe at hadron colliders.
- LHeC signal: here using CC channel.
- Backgrounds: CC multijet, CC t/h/W/Z+jets, PHP multijet.
- PHP backgrounds assumed to be negligible after MET requirements and electron tagging.
- Current analysis is done at parton level.

Exotic Higgs at LHeC@1ab^{-1}

[arXiv:1608.08458]

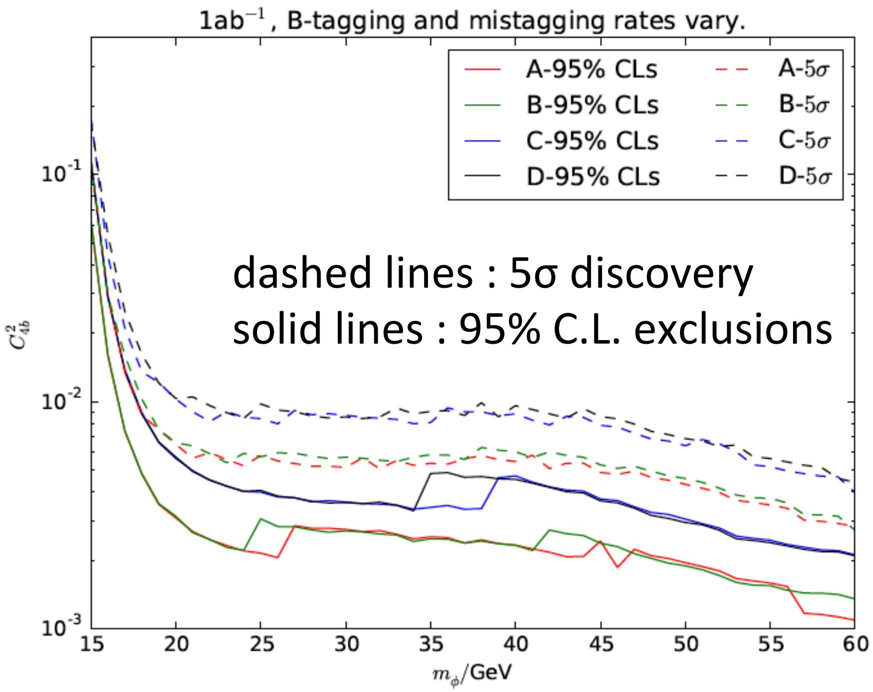
Btag scenarios

(A) $\epsilon_b = 70\%, \epsilon_c = 10\%, \epsilon_{g,u,d,s} = 1\%$

(B) $\epsilon_b = 70\%, \epsilon_c = 20\%, \epsilon_{g,u,d,s} = 1\%$

(C) $\epsilon_b = 60\%, \epsilon_c = 10\%, \epsilon_{g,u,d,s} = 1\%$

(D) $\epsilon_b = 60\%, \epsilon_c = 20\%, \epsilon_{g,u,d,s} = 1\%$

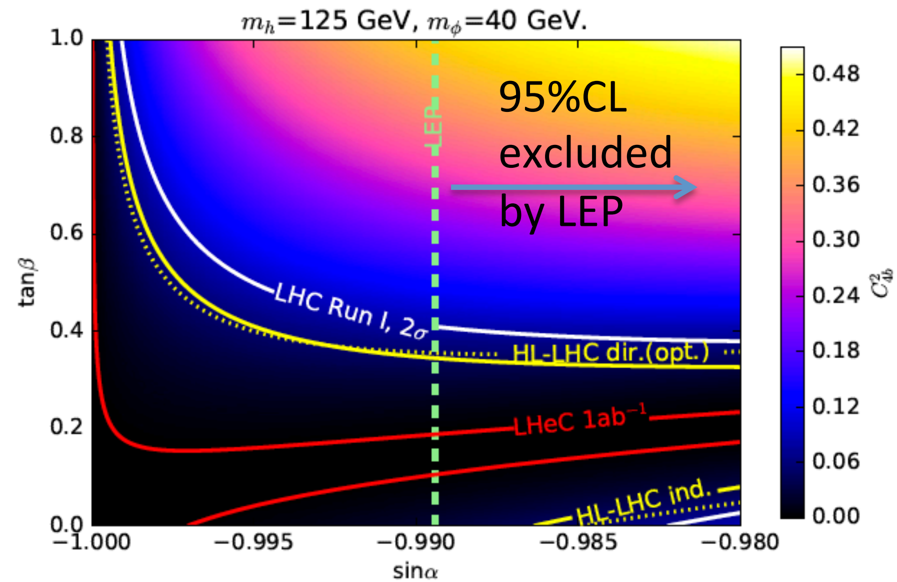


95% C.L. for m_ϕ of 20, 40, 60 GeV for

$$C^2_{4b} = \kappa_V^2 \times \mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}^2(\phi \to b\bar{b})$$

is 0.3%, 0.2% and 0.1%

Sensitivity comparison in Higgs Singlet Model



$$\Phi \equiv \begin{pmatrix} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix}, S \equiv \frac{h' + x}{\sqrt{2}} \qquad (12)$$

Here $v = 246$ GeV ensures the correct mass generation for W, Z bosons and SM fermions. The gauge eigenstates $\tilde{h}, h'$ can be related to mass eigenstates ϕ, h via an orthogonal rotation

$$\begin{pmatrix} \phi \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix} \qquad (13)$$

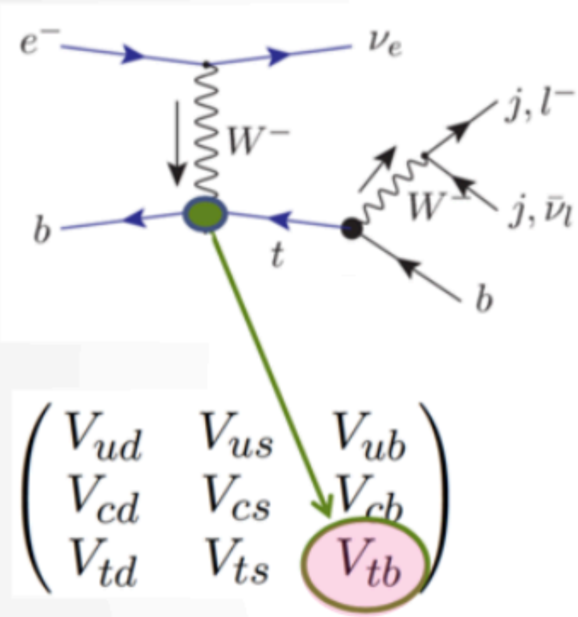
Now it is convenient to parameterize the model in terms of five more physical quantities: (m_ϕ, m_h are masses of ϕ and h respectively)

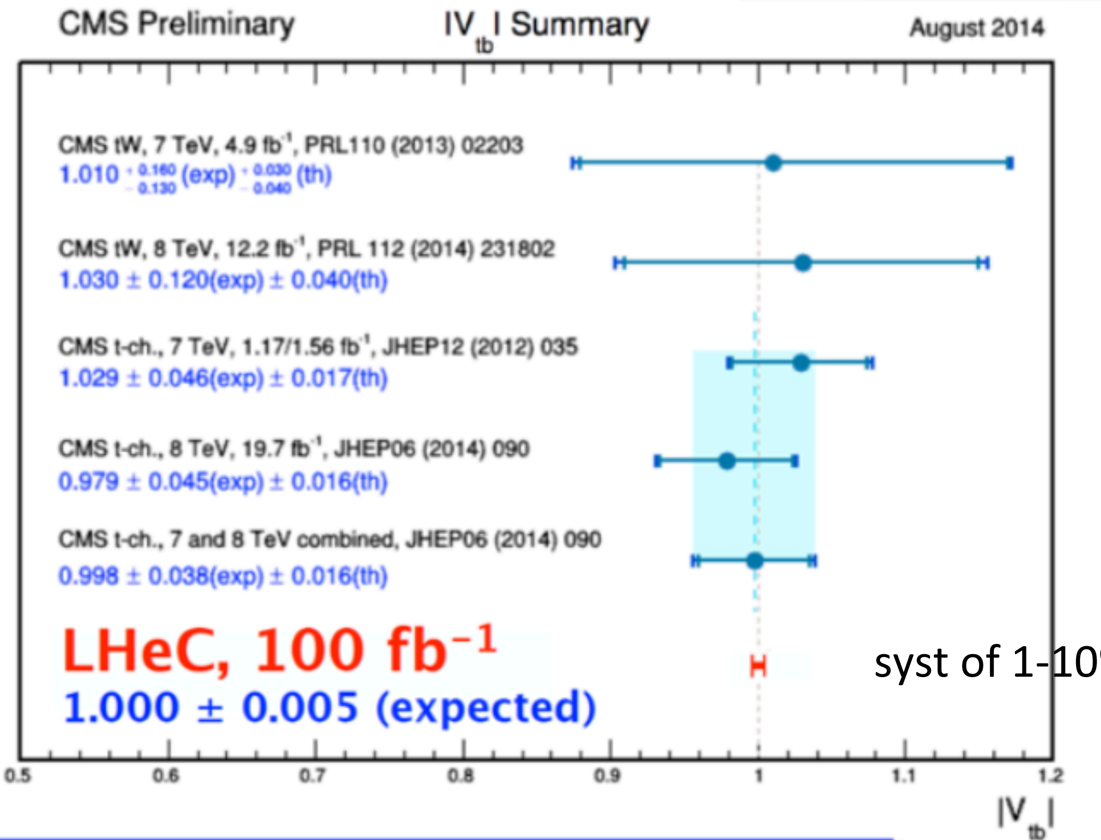
$$m_\phi, m_h, \alpha, v, \tan\beta \equiv \frac{v}{x} \qquad (14)$$

MEASUREMENT OF Vtb

➤ the results can also be applied conservatively to the FCC-ep.

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688 [hep-ph]





e beam: 60 GeV

L_{int} = 100 fb^{-1} and simple cuts:

HAD: N_t = 22000, S/B=1.2

LEP: N_t = 11000, S/B=11

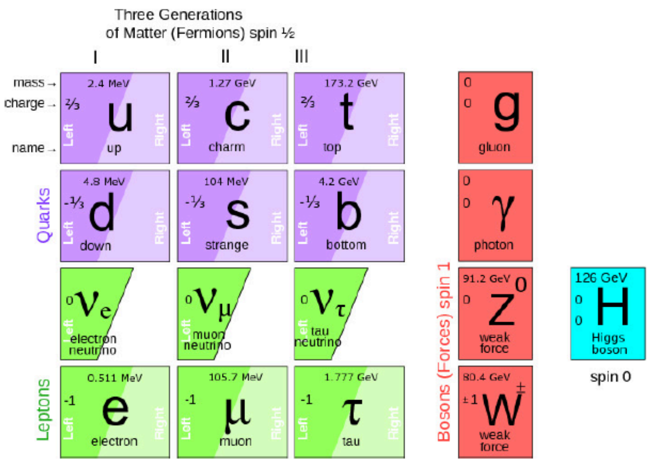
LHeC: very high precision measurement

current LHC+Tevatron average: $|V_{tb}|$=1.009 ±0.031

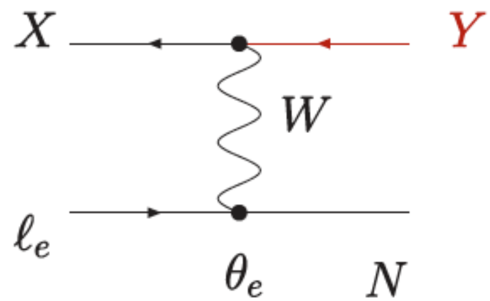
Sterile Neutrino Searches

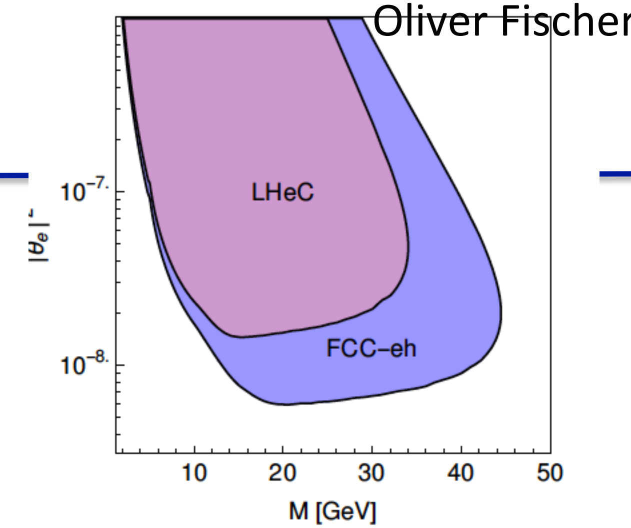
Oliver Fischer

$$\mathscr{L}_N = -\underbrace{(Y_\nu)_{i\alpha}}_{\nu\text{ Yukawa matrix}}\overline{\nu_R^i}\,\widetilde{\phi}^\dagger L^\alpha - \frac{1}{2}\overline{\nu_R^i}\underbrace{M_{ij}}_{\text{sterile }\nu\text{ mass matrix}}(\nu_R^j)^c + \text{H.c.}$$

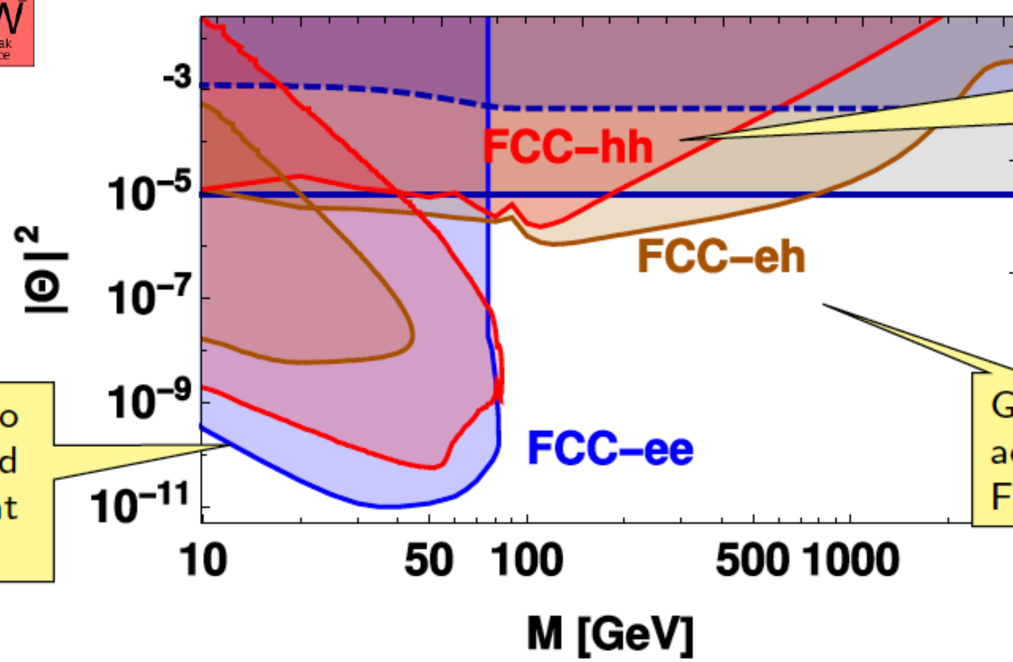


Shaposhnikov et al.





Non-unitarity parameters: $\varepsilon_{\alpha\alpha} = -\theta^*_\alpha\theta_\alpha$



FCC-hh able to test all flavour combinations.

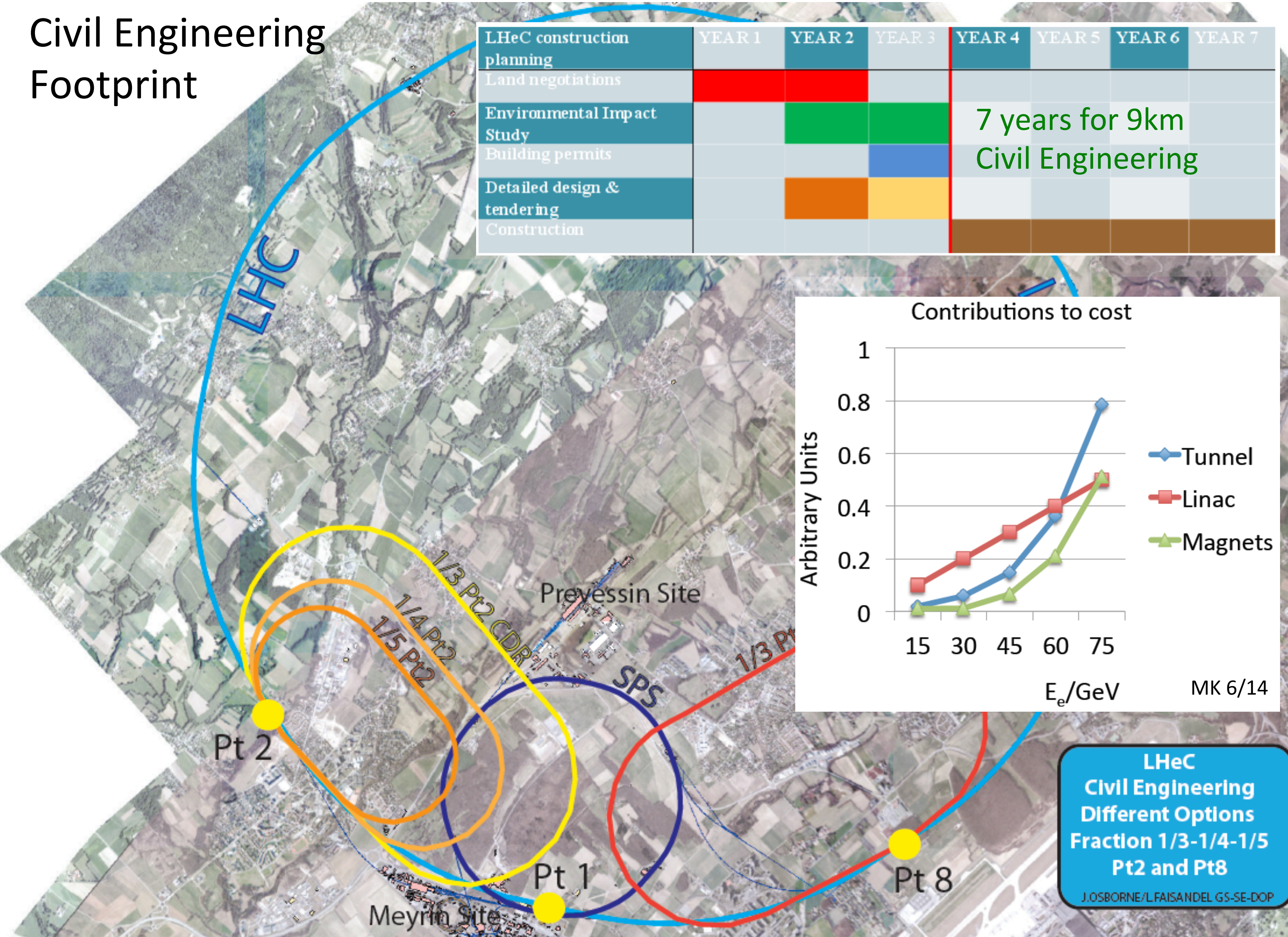
Good sensitivity reach from FCC-hh & FCC-eh.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Civil Engineering Footprint

LHeC construction planning	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7
Land negotiations							
Environmental Impact Study							
Building permits							
Detailed design & tendering							
Construction							

7 years for 9km Civil Engineering



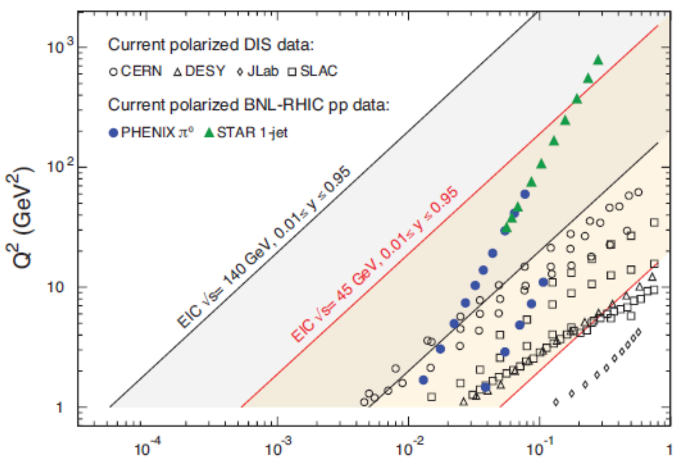
EIC vs LHeC with L ~ $10^{33\text{-}34}$ $cm^{-2}s^{-1}$

EIC: $E_{c.m.s.}$ ~ 20-100 GeV

- *Polarised electrons with E_e>3 GeV*
- ***Polarised proton*** *(70%) beams and unpolarised heavy ion beams (A≤200)*
- *High luminosity for **spin physics.***

World's first polarised e-p collider and lower energy e-A collider.

x_{min} ~ 1 x 10^{-4}

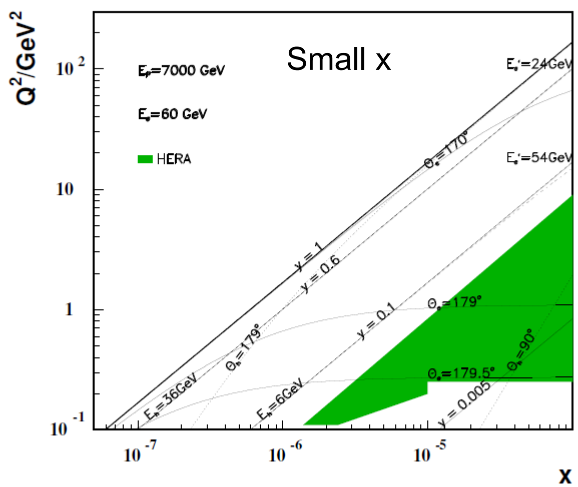


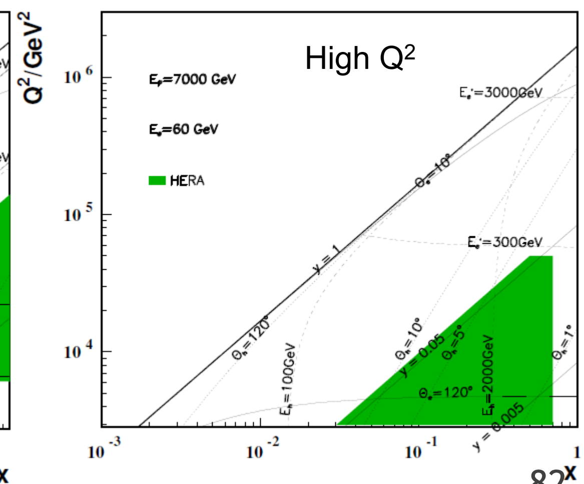
LHeC: $E_{c.m.s.}$ ~ 1.3 TeV

- *Add ~60 GeV **polarised** electrons to probe unpolarised LHC proton and ions*

High-energy frontier e-p and e-A collider to follow HERA with factor 1000 higher luminosity <u>running simultaneously</u> with HL-LHC.

x_{min} ~ 6 x 10^{-7}

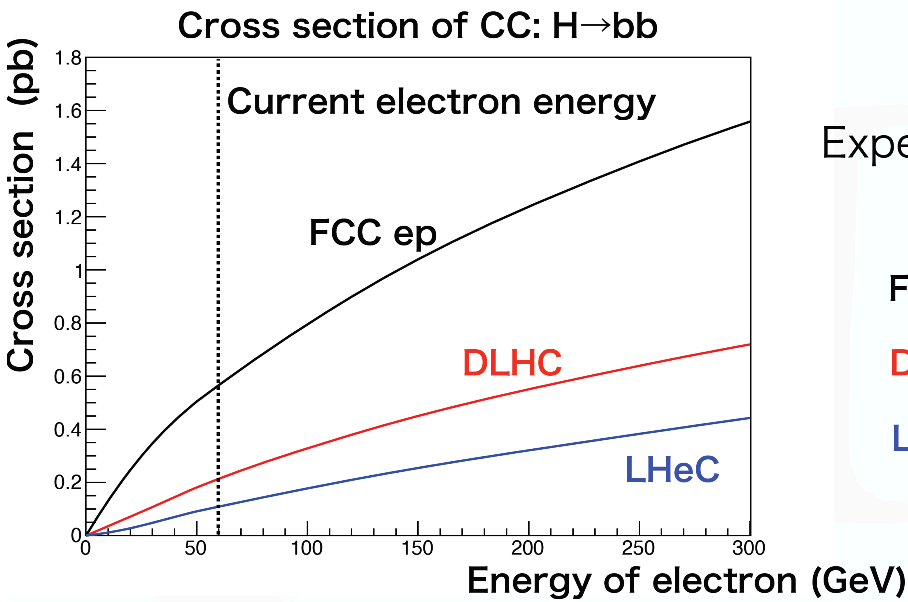




Uta Klein et al.

SM Higgs into HFL Summary

- Assume a 60 GeV polarized electron beam and 1000 fb^{-1} (~10 years running)
- Expected number of signal events and error of coupling constant from BDT results.
- Background assumed to be known to ~2%



Expected number of signal events
(E_e = 60 GeV)

FCC ep (~85,000 H→bb events)

DLHC (~35,000 H→bb events)

LHeC (~15,000 H→bb events)

$$\delta\kappa = \frac{1}{2}\frac{\delta\mu}{\mu}$$

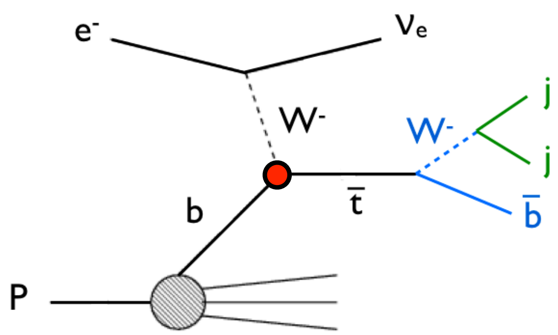
	LHeC (E_p = 7 TeV √s ~1.3 TeV)	DLHC (E_p = 14 TeV √s ~1.8 TeV)	FCC ep (E_p = 50 TeV √s ~ 3.5 TeV)
κ (Hbb)	0.5%	0.3%	0.2%
κ (Hcc)	4%	2.8%	1.8%

Top Quark & EW in ep

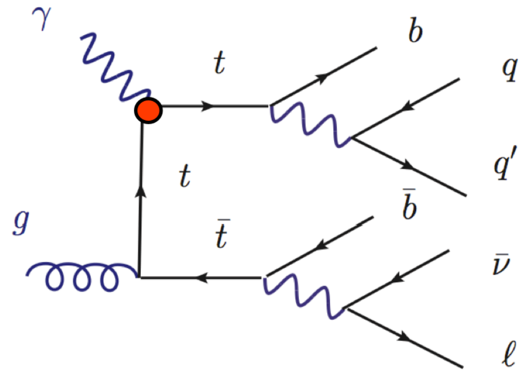
…. a few examples only

C. Schwanenberger,
@DIS2015

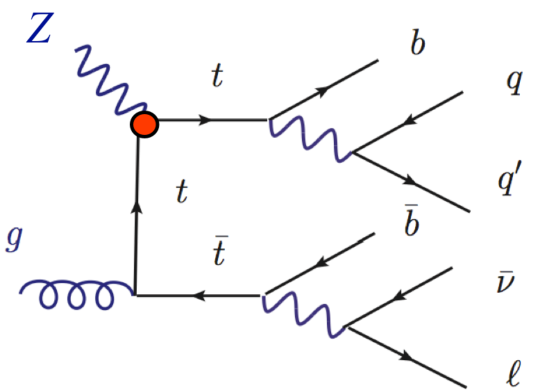
precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations) : **top quark expected to be most sensitive to BSM physics, due to large mass**



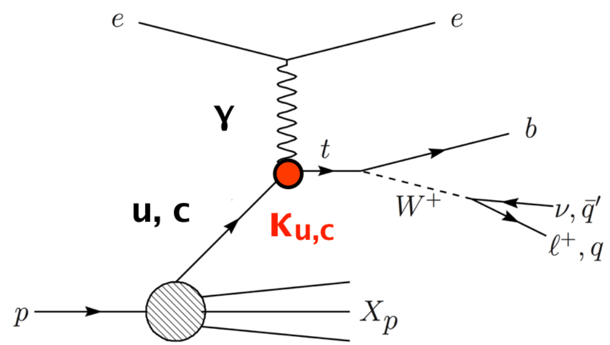
- high precision measurements of Vtb and search for **anomalous Wtb** couplings



- direct measurement of top quark charge and search for **anomalous ttbarγ** couplings (eg. EDM, MDM)



- measurement of top isospin and search for **anomalous ttbarZ** couplings (eg. EDM, MDM)



- sensitive search **for FCNC couplings** will constrain BSM models that predict FCNC (eg. SUSY, little Higgs, technicolour)

Pile-up estimate for LHeC

- high luminosity option using $L=10^{34}\ cm^{-2}s^{-1}$ (LHeC) and $L=5x10^{34}\ cm^{-2}s^{-1}$ (HL-LHC) with 150 pile-up events (25 ns)
  [calculations by M. Klein]

➔ Pile-up events expected for LHeC <~0.1

Using pp LHC pile-up estimates

$$N(ep)=N(pp) \times s(yp)/s(pp) \times L(ep)/L(pp)$$
$$= 150 * 0.003 * 0.2$$
$$= 0.1$$

Direct calculation using total gamma-proton cross section of 300 μb

$$N(ep) = 300\ 10^{-6}\ 10^{-24}\ cm^2 \times 10^{34}\ cm^{-2}s^{-1} \times 25\ 10^{-9}s$$
$$= 0.075$$

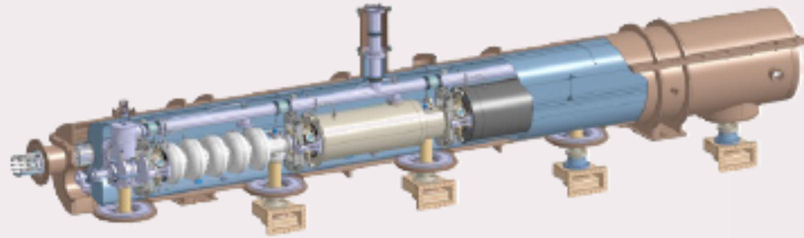
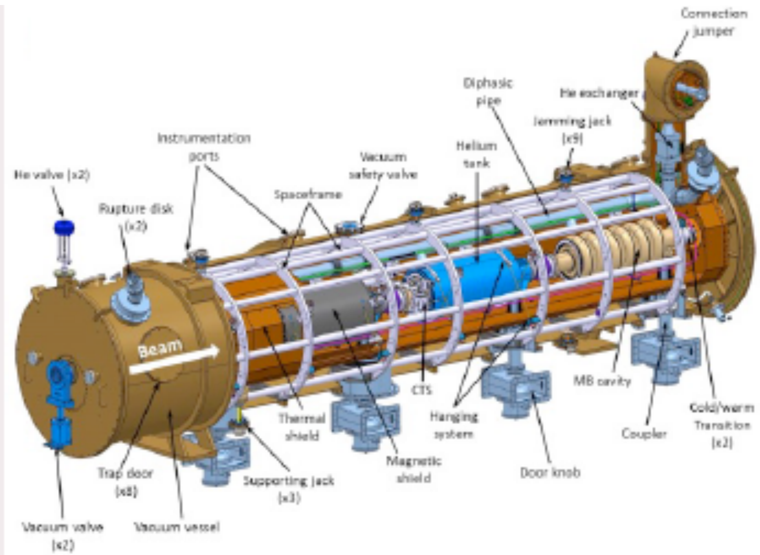
Post-CDR: LHeC Baseline Parameter

→ **for first time a realistic option of an 1 ab^{-1} electron-proton collider** also due to **excellent performance of LHC;** ERL : 960 superconducting cavities (20 MV/m) and 9 km tunnel [arXiv:1211.5102, arXiv:1305.2090; EPS2013 talk by D. Schulte]

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS (NEW)	ELECTRONS (NEW)	PROTONS (CDR)	ELECTRONS (CDR)
Beam Energy [GeV]	7000	60	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20	3.75	50
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10	0.1	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4	7	7
rms Beam divergence $\sigma'^*_{x,y}$ [μrad]	80	40	70	58
Beam Current [mA]	1112	25	430 (860)	6.6
Bunch Spacing [ns]	25	25	25 (50)	25 (50)
Bunch Population	$2.2*10^{11}$	$4*10^{9}$	$1.7*10^{11}$	$(1*10^{9})\ 2*10^{9}$
Bunch charge [nC]	35	0.64	27	(0.16) 0.32

Operation in parallel with HL-LHC *pp* data taking

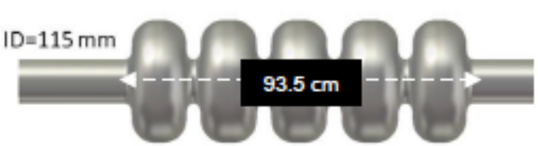
Next Step: Cryomodule

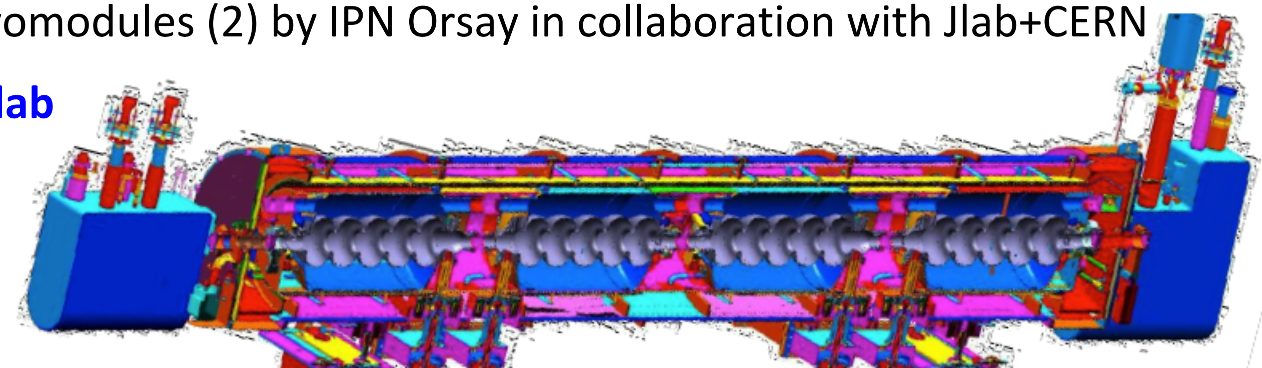
SPL « Short cryomodule »	5-cells Elliptical 700 MHz, β = 1.0 X 4	Full length top lid closure Cold mass supported by power couplers	
ESS Elliptical cryomodule(s)	5&6-cells Elliptical 700 MHz β = 0.67 & 0.86 X 4	Side loading Space frame	

Plan for production of PERLE cryomodules (2) by IPN Orsay in collaboration with Jlab+CERN

Jlab

SNS 805 MHz cryomodule





Source: DC Photocathode

Material	Typical oper.λ	Work function	Observed Q.E.	Laser power for 20 mA	Observed max current	Obs. lifetime
Sb-based unpolarised	532 nm	1.5-1.9 eV	4-5%	4.7 W at Q.E.=1%	65 mA [Cornell]	Days rep.
GaAs-based polarised	780 nm	1.2 eV at NEA state	0.1-1.0%	31.8 W at Q.E.=0.1%	5-6 mA [JLAB]	Hours

Table 4.1: Characteristics of photocathode materials available for PERLE

← Boris Militsyn's kukhnja at Daresbury

GaAs photocathode preparation facility designed for 4GLS and ALICE gun upgrade.

Why PERLE [as seen from LHeC]?

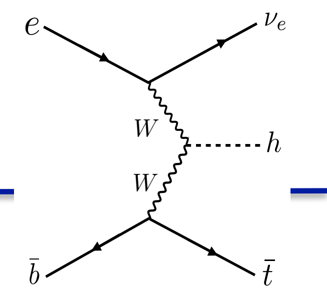
PERLE

FUNDAMENTAL MOTIVATION:

- **Validation of key LHeC Design Choices**
- **Build up expertise in the design and operation for a facility with a fundamentally new operation mode:**
  ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no 'automatic' longitudinal phase stability, etc.)
- **Proof validity of fundamental design choices:**
  Multi-turn recirculation (other existing ERLs have only 1-2 passages)
  Implications of high current operation (2 * 3 * [6mA – 25mA] → 30-150mA!!)
- **Verify and test machine and operation tolerances before designing a large scale facility**
  Tolerances in terms of field quality of the arc magnets and cavity alignment
  Required RF phase stability (RF power) and LLRF requirements
  Halo and beam loss tolerances

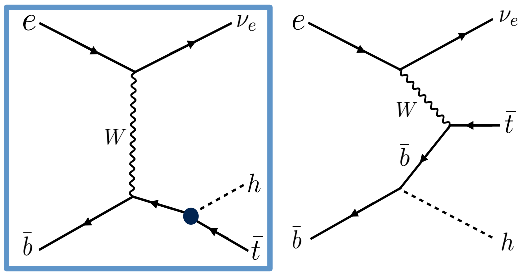
Top Yukawa Coupling @ LHeC

B.Coleppa, M.Kumar, S.Kumar, B.Mellado, Phys. Lett. B770 (2017) 335

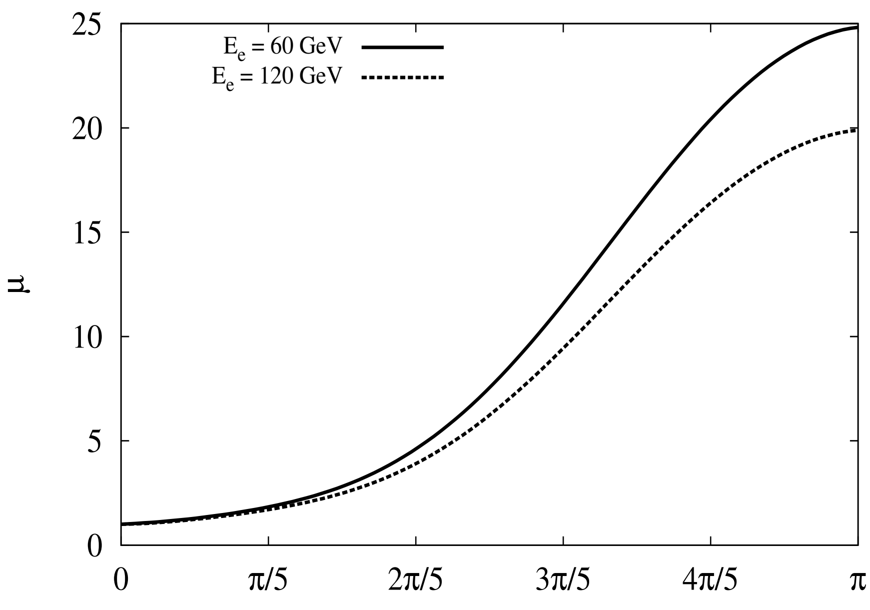


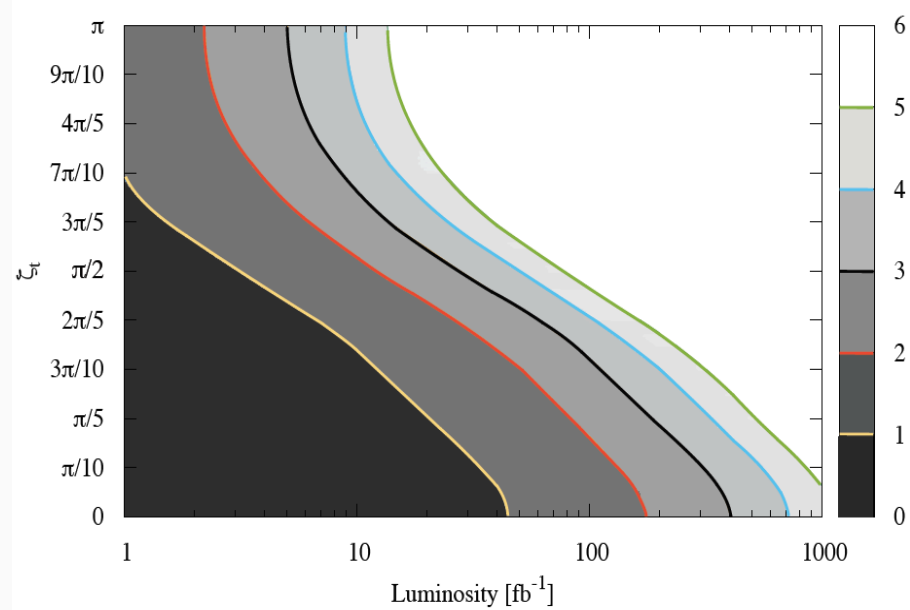
Introduce phase dependent top Yukawa coupling

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



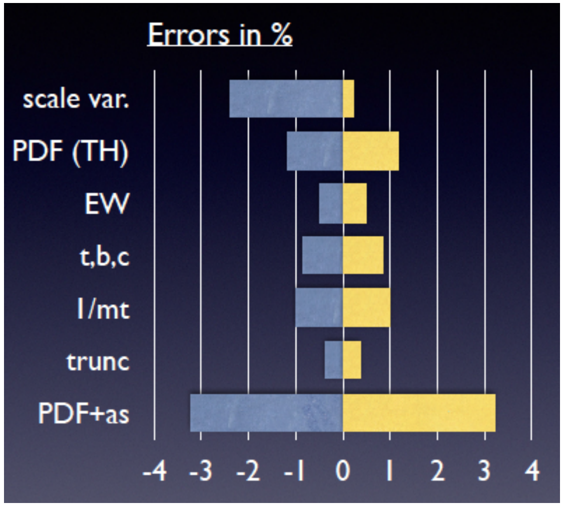
Enhancement of the cross-section as a function of phase



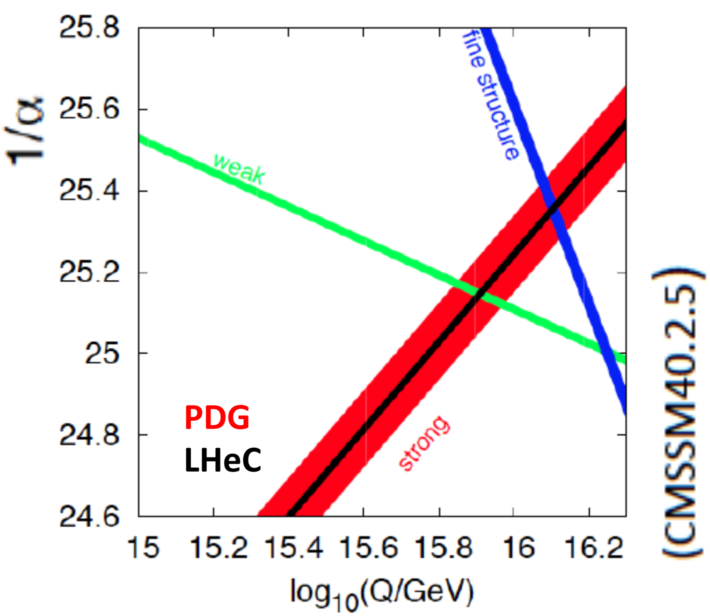


Observe/exclude non-zero phase to better than 4σ ➔ With Zero Phase: Measure ttH coupling with 17% accuracy ➔ work ongoing on HE-LHeC & FCC-eh prospects

Strong Coupling Constant



Uncertainty on Higgs cross section
Giulia Zanderighi, Vietnam 9/16,
from C.Anastasiou et al, 1602.00695
who also discuss the ABM alpha_s..



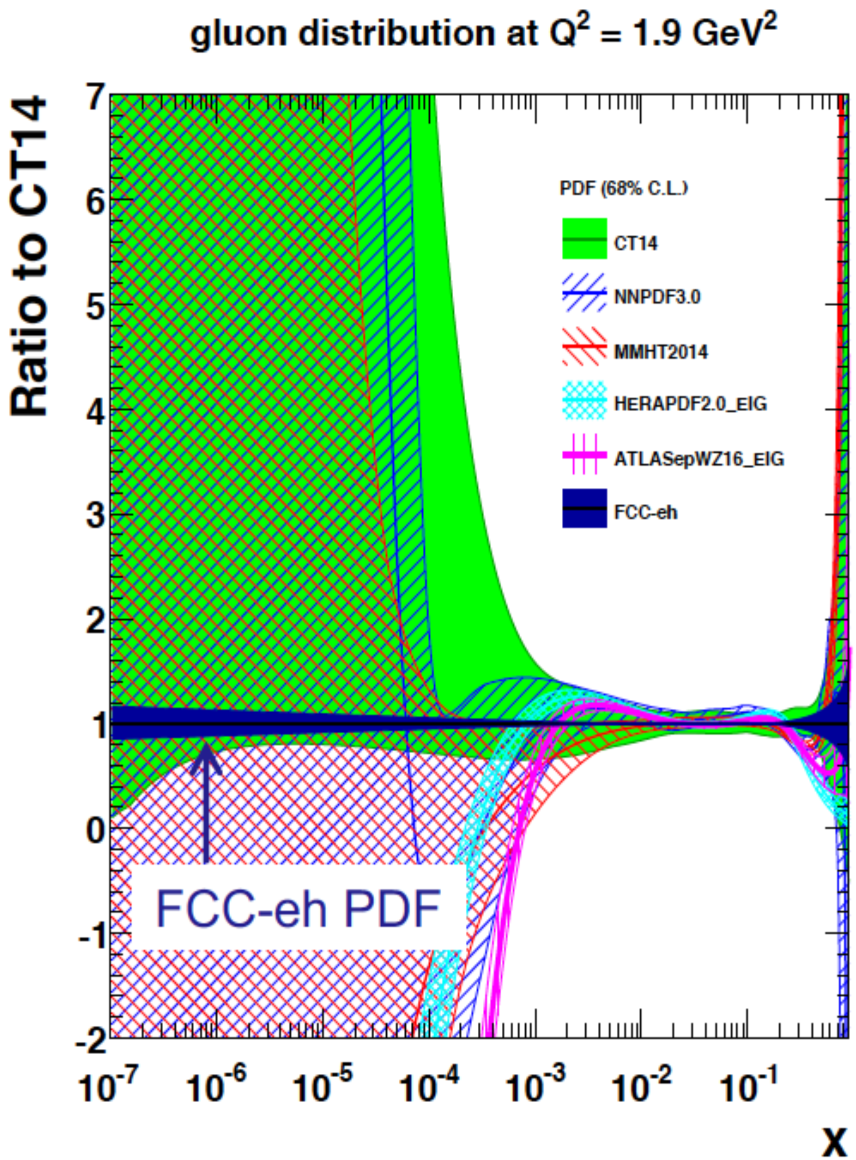
- α_s least known of coupling constants
  Grand Unification predictions need smaller $\delta\alpha_s$
- Is α_s(DIS) lower than world average (?)
- LHeC: per mille - independent of BCDMS!
- High precision from inclusive data – α_s(jets)
  → for HERA : now NNLO calculations available
- Challenge lattice QCD

LHeC simulation, NC+CC inclusive, total exp error

case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

Two independent QCD analyses using LHeC+HERA/BCDMS

Exploring even smaller x



gluon at low x:

recall – no current data much below $x=5\times10^{-5}$ to directly constrain; so even this is an extrapolation for current PDFs at low x

FCC-eh would provide single, precise and unambiguous dataset

(explore low x QCD, DGLAP vs BFKL, non-linear evolution, gluon saturation; implications also for ultra high energy neutrino cross sections)

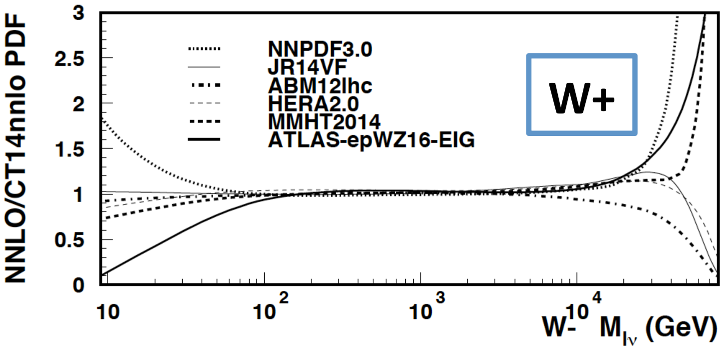
W and Z @ FCC-hh

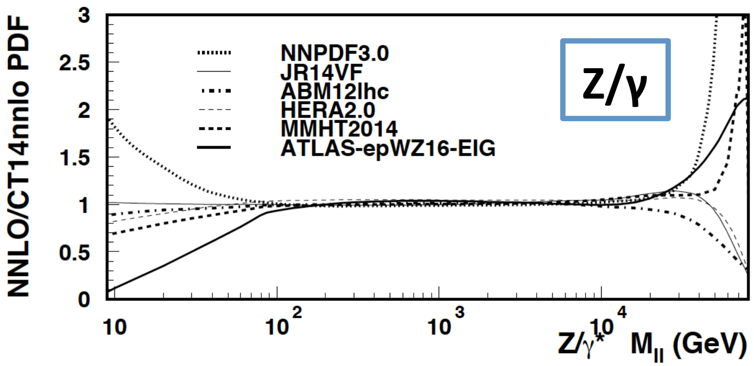
Assuming collinear factorization & momentum sum rule…

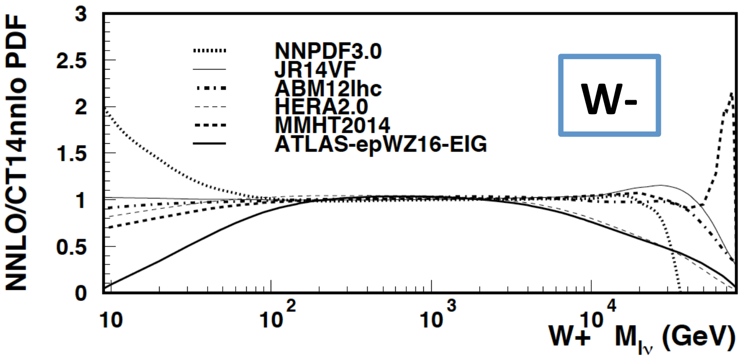
Impact of PDF: High mass Drell-Yan

- Non resonant searches for ED (interference) sensitive to tails of DY distributions thus to PDF. Predominantly q-qbar

Uta Klein
VRAP 0.9 for NNLO QCD





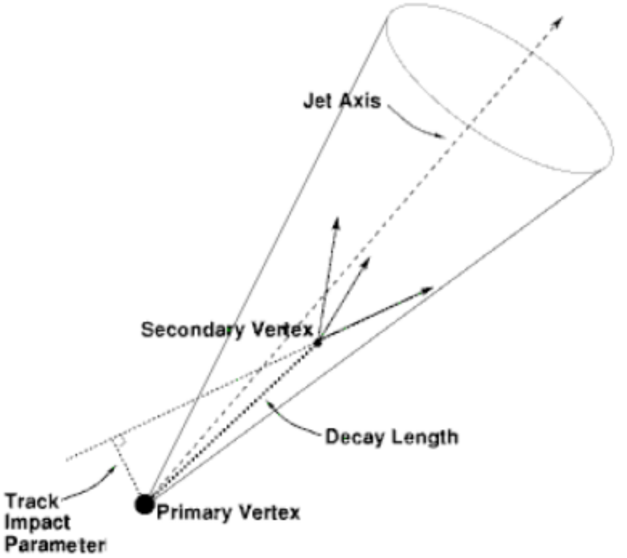


"Troubles" at low and high x

FCCeh (and before, LHeC) can improve low and high M(ll) and M(lν) precision for standard candle measurements and searches for new physics

HFL Tagging

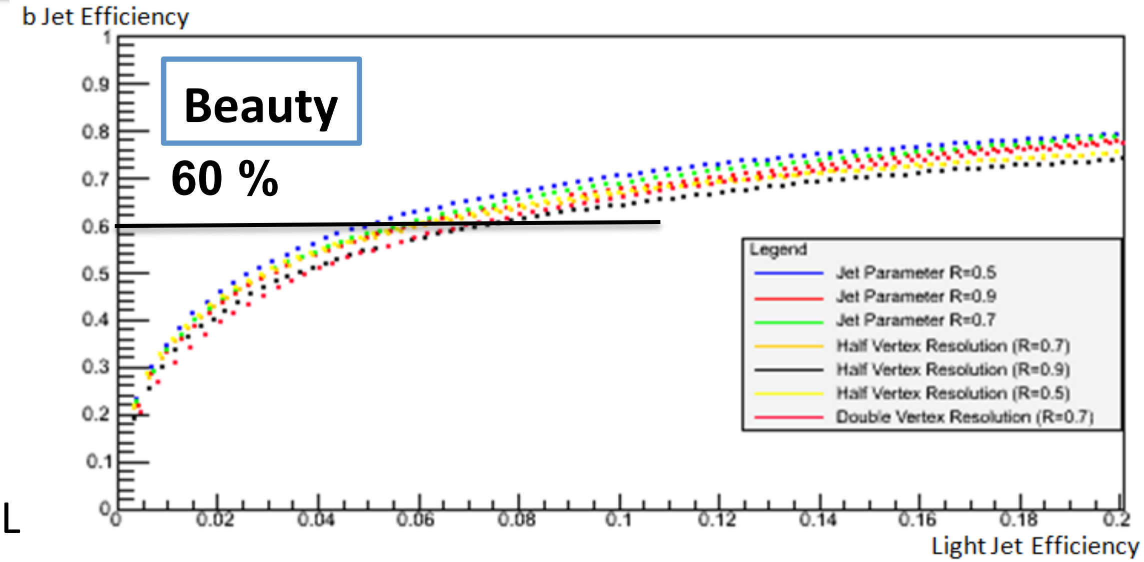
Uta Klein &
Daniel Hampson

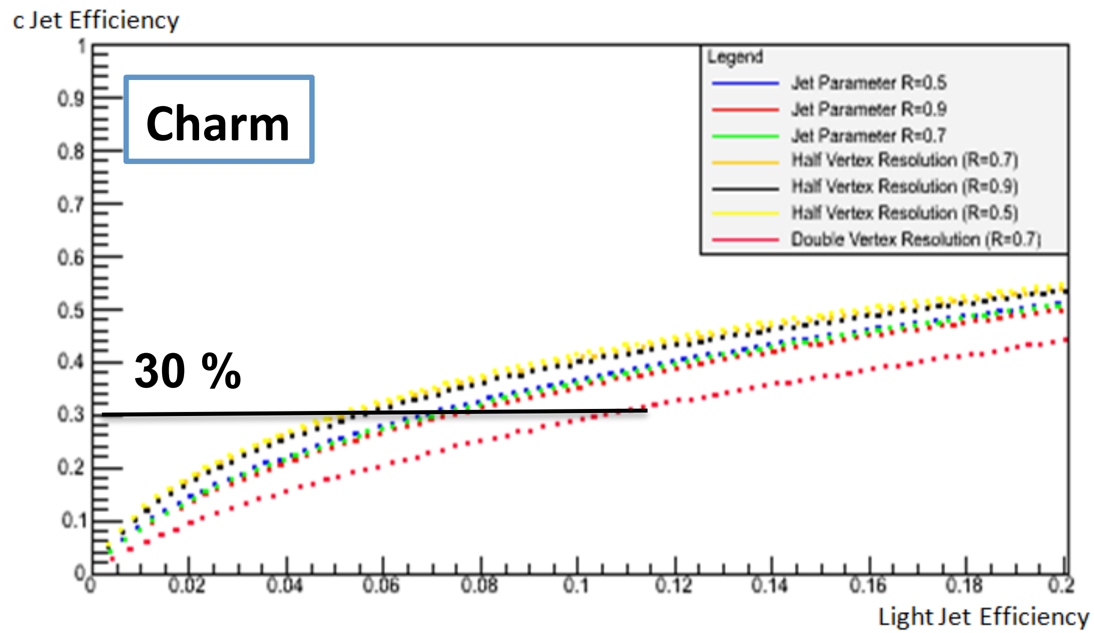


→ Realistic and conservative HFL tagging within Delphes realised, and dependence on vertex resolution (nominal 10 µm) and anti-kt jet radius studied

→ Light jet rejection very conservative, i.e. factor 10 worse than ATLAS

→ **used in full LHeC analysis and for FCC-eh extrapolations**

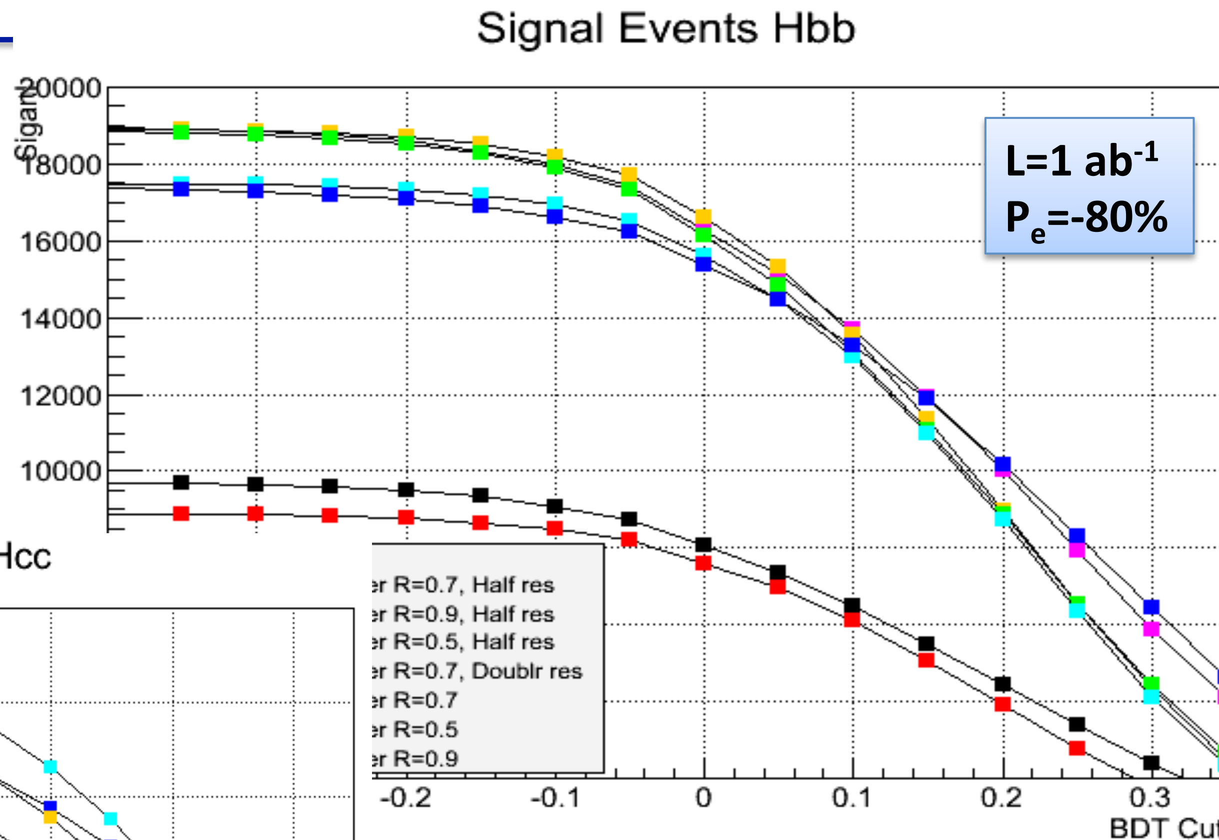


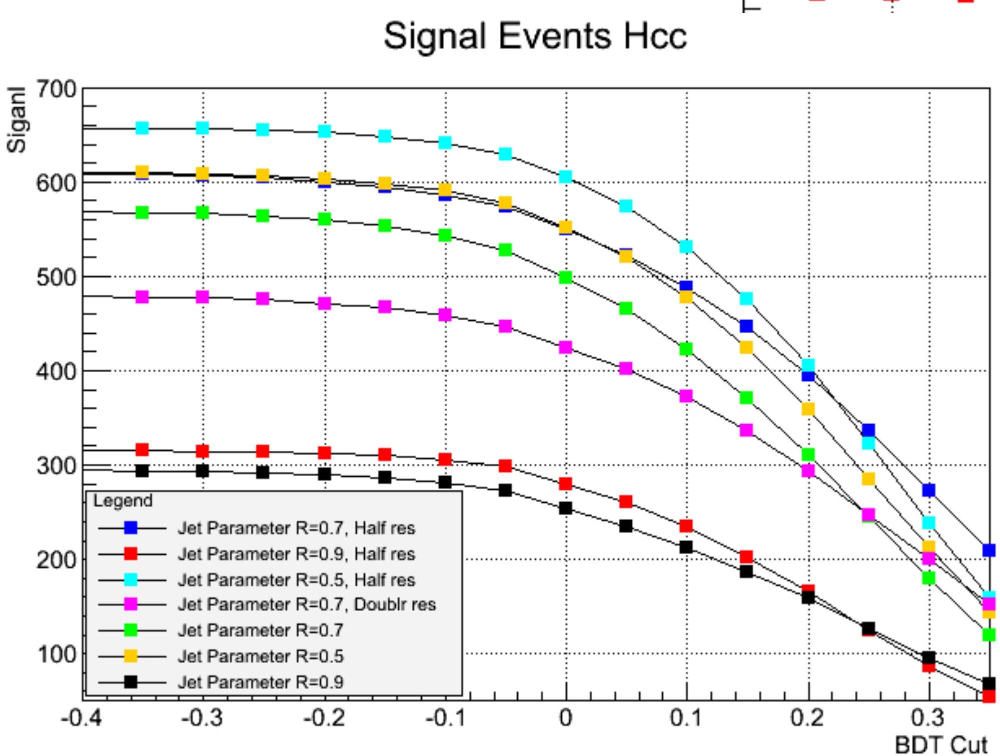


BDT Results for Higgs @ LHeC

Uta Klein &
Daniel Hampson

Hbb : Clear sensitivity to chosen jet radius; rather robust w.r.t. vertex resolution in range of 5 to 20 μm

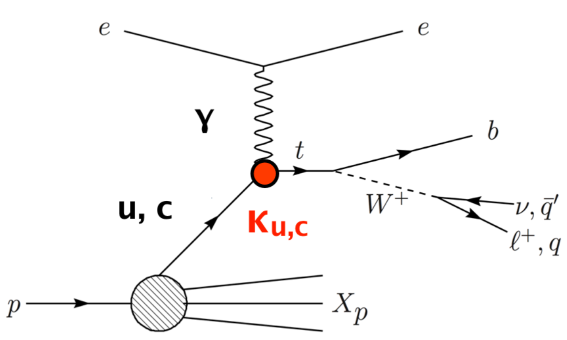


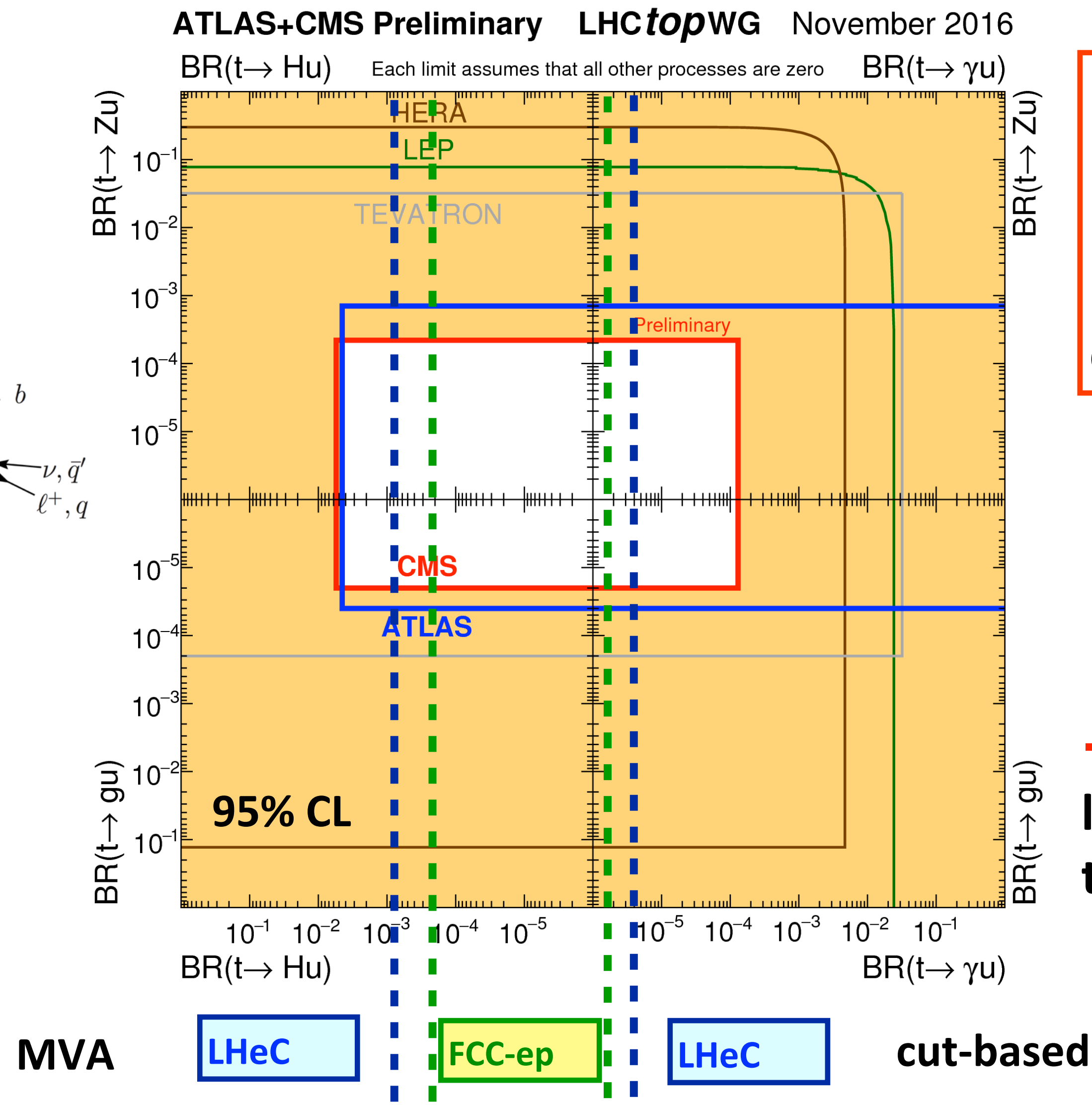


Hcc : High sensitivity to vertex resolution (nominal 10 μm) and jet radius

→ expect about 400-600 Hcc candidates

FCNC Branching Ratios at Colliders





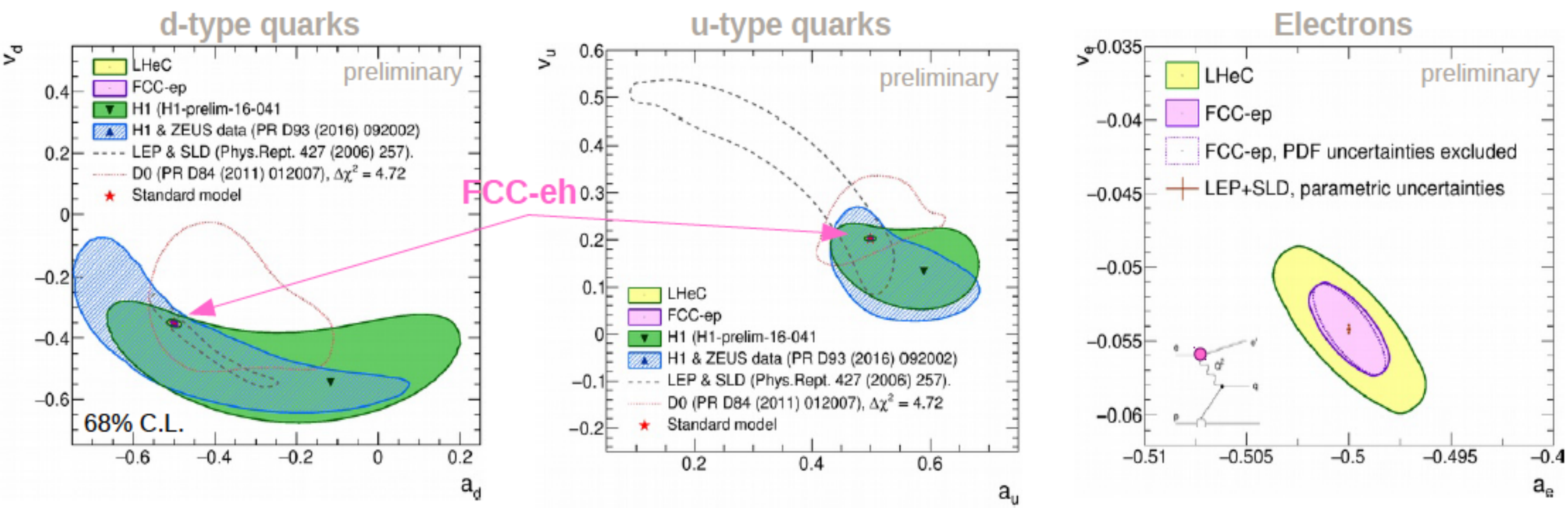
- improve limits on BR(t→γu), BR(t→Hu) considerably

→ test SUSY, little Higgs, technicolor...

E_e=60 GeV
1000 fb^{-1}

Electroweak Physics: LHeC and FCCeh

Weak neutral couplings: quarks, electrons



Weak neutral quark couplings

- u- and d-quark couplings determined simultaneously
- Very precise measurements feasible

```
a_u =  0.5  +/- 0.003
a_d = -0.5  +/- 0.005
v_u =  0.20 +/- 0.002
v_d = -0.35 +/- 0.005
```

Electron couplings

- High precision
- Though:
  LEP with 'ulitmate' precision

High precision test of electroweak sector of Standard Model

Complementary test