A detector for top-energy DIS

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on behalf of the LHeC/FCCeh Study Group

(remote presentation)

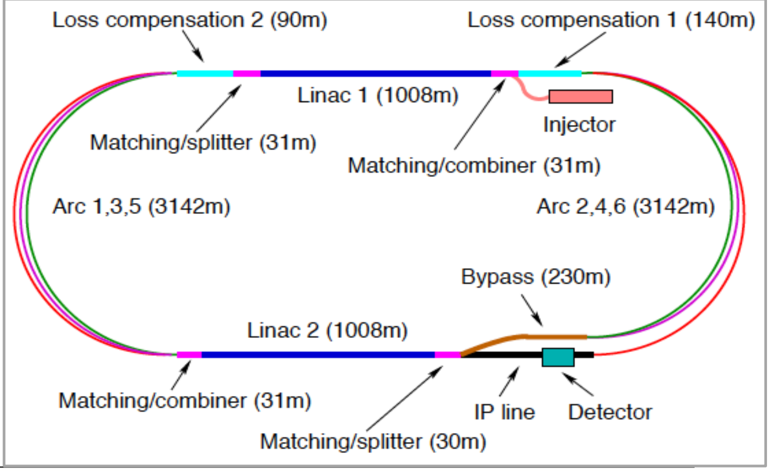
Outline of this talk

- Introduction: LHeC / FCC-eh parameters and detector studies
- ep/eA physics, collision kinematics and detector requirements
  - for DIS and for Higgs / EW / Top / BSM physics
- LHeC baseline detector and extensions for FCC-eh
  - Central tracker and beam pipe
  - Calorimetry
  - Interaction point and magnet
- Design of the interaction region for concurrent ep/eA and $pp/pA/AA$ operation
- Adapting LHeC/FCC-eh detector for hh

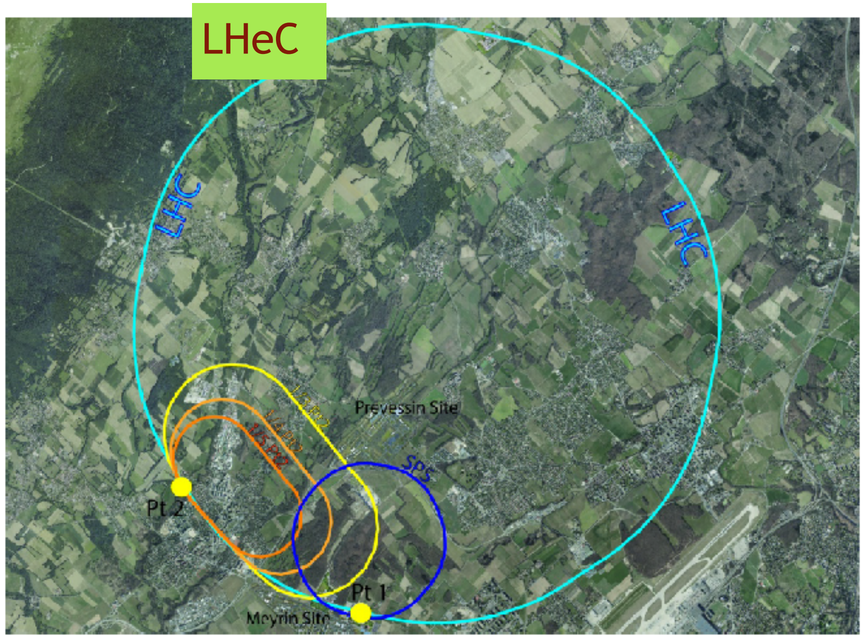
The LHeC and FCC-eh accelerators

ERL Roadmap see talk J. D'Hondt

- Electrons from dedicated Energy Recovery Linac (ERL)
- Hadrons from LHC/FCC rings



LHeC



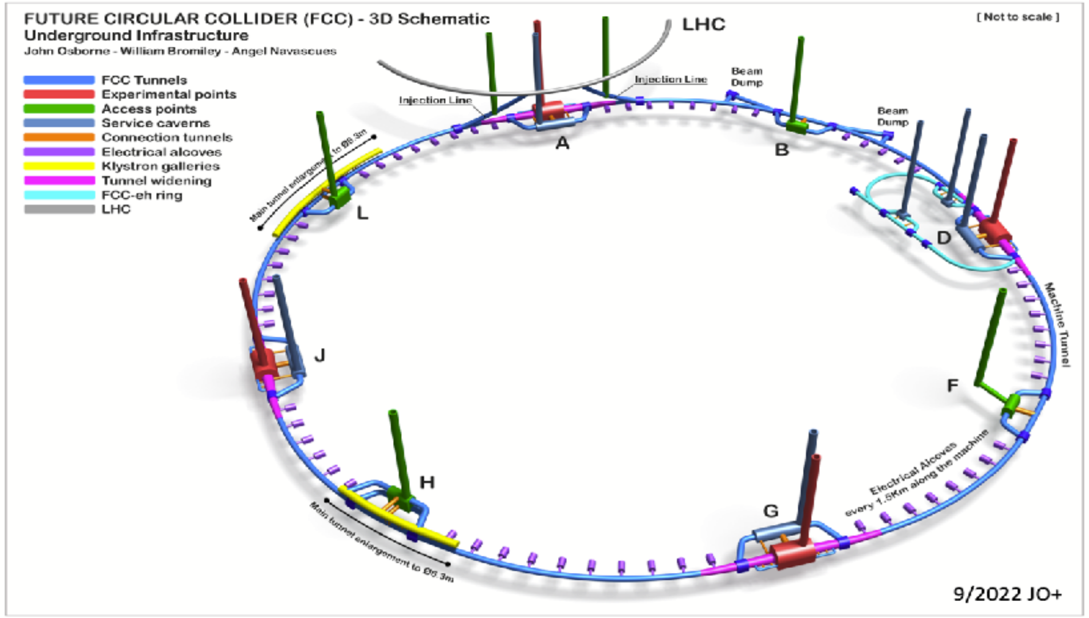
LHeC baseline:

50 GeV(e) × 7 TeV (p) 2.76 TeV/nucl. (A)

- $\sqrt{s} = 1.18\ (p)$ or $= 0.74\ (\mathrm{A})$ TeV
- $10^{33} - 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Electrons via 3-track ERL
  ~1/4 of LHC circumference

FCC-eh

CDR: 8 point FCC: point D

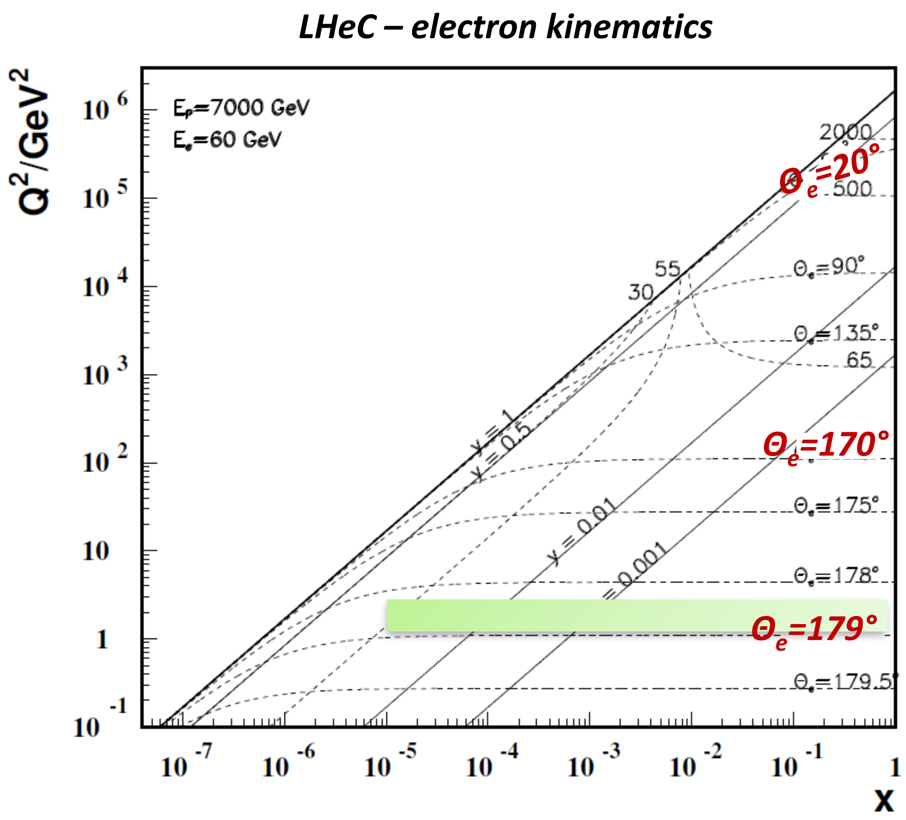


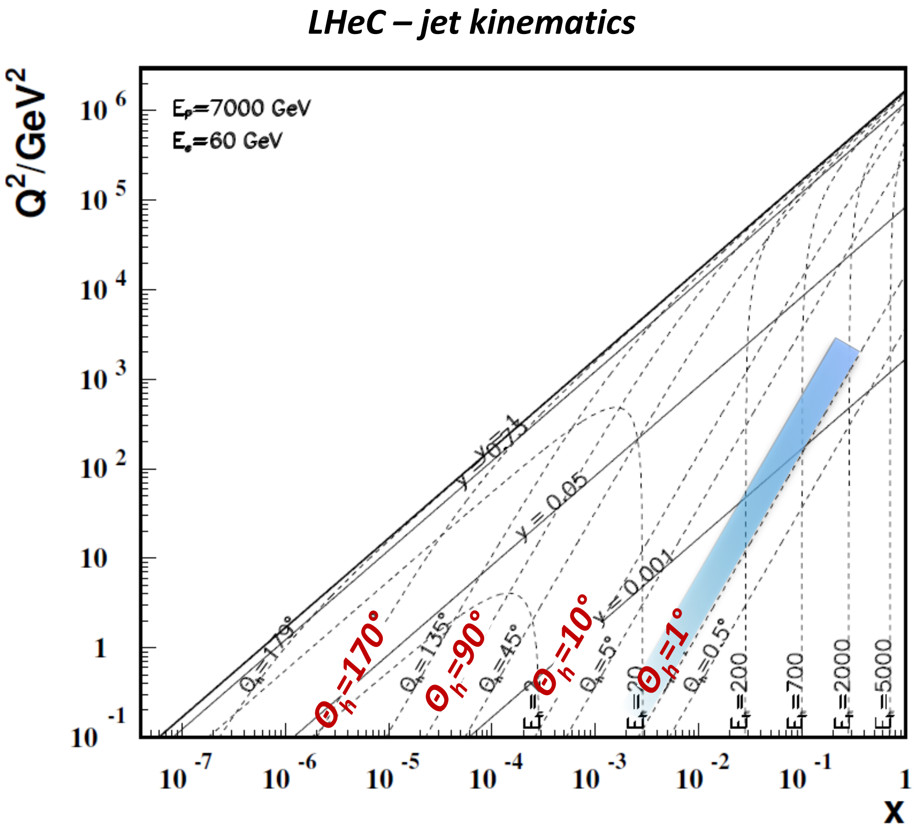
60 GeV(e) × 20–50 TeV (p) 7.9–19.7 TeV/nucl. (A)

Ref [1]

- $\sqrt{s} = 2.2 - 3.5\ (p)$ or $= 1.4 - 2.2\ (\mathrm{A})$ TeV
- $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Electrons via 3-track ERL

DIS Kinematics


LHeC – electron kinematics

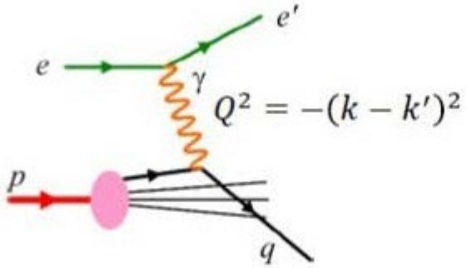

LHeC – jet kinematics

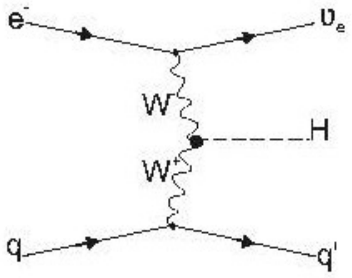
- High x and high Q^2: few TeV HFS scattered forward:
- → Need forward calorimeter of few TeV energy range down to 1^0
- Mandatory for charged currents where the outgoing electron is missing
- Scattered electron:
  Need very bwd. angle acceptance for accessing
  the low Q^2 and high y region

Asymmetric energy flow
particles go mostly to incoming proton direction (forward), e to backward
But they go to everywhere in practice, especially towards small angles

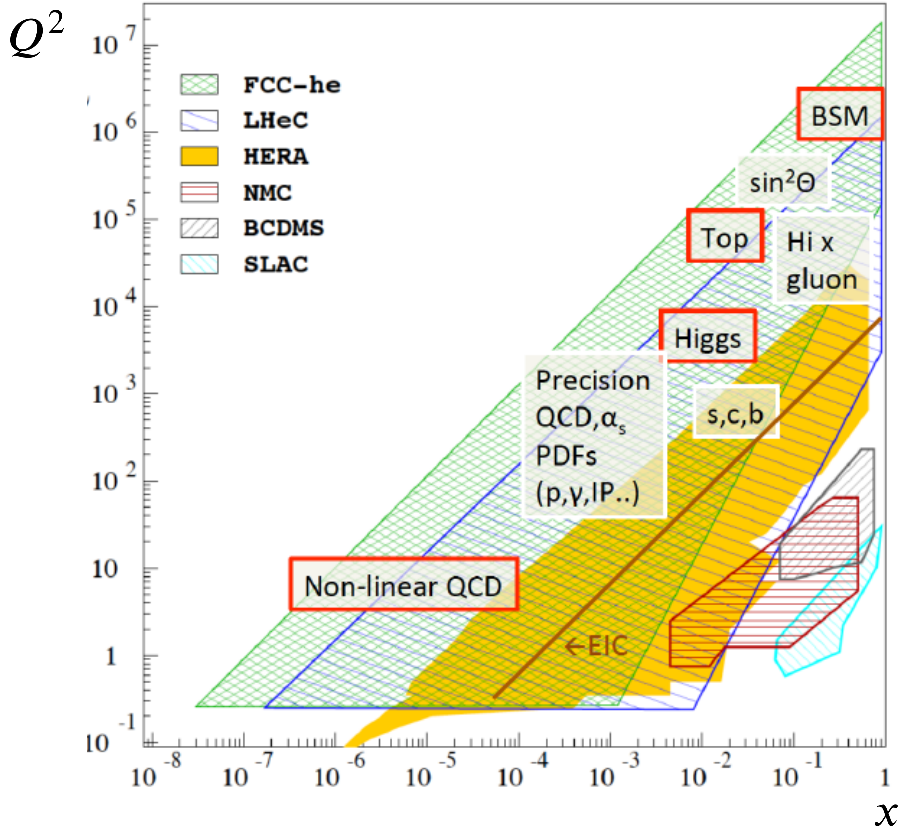
DIS kinematic plane and event topology

Ref [1], [2]





$$x = \frac{Q^2}{p \cdot q} \quad y = \frac{p \cdot q}{p \cdot k}$$
$$sxy = Q^2$$



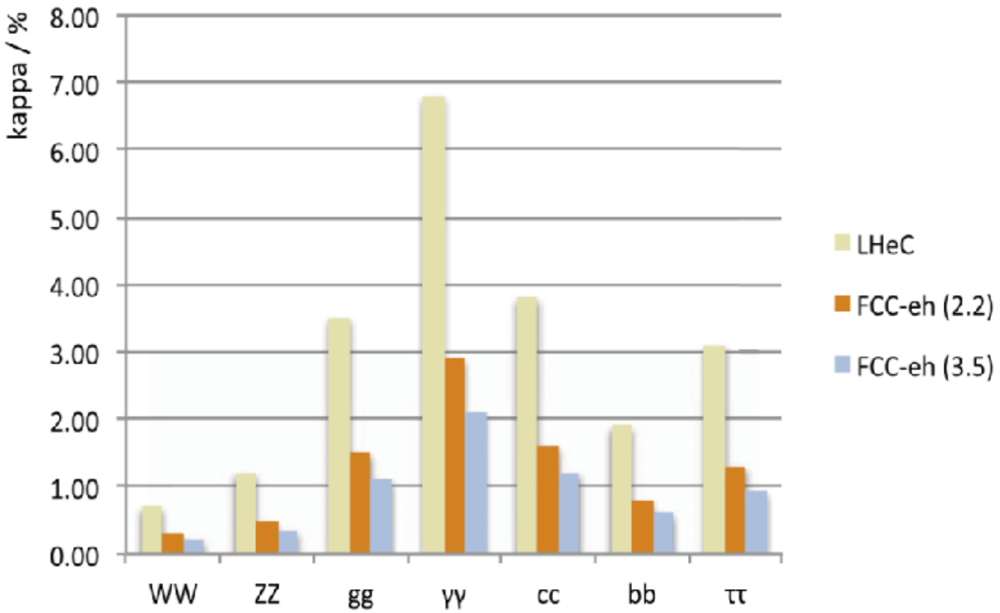


Figure 106. Summary of uncertainties of Higgs couplings from *ep* for the seven most abundant decay channels, for the LHeC (gold), the FCC-eh at 20 TeV of proton energy (brown) and for $E_p = 50$ TeV (blue).

Structure of nucleon and nuclei through DIS

- Higgs couplings; physics in CC and NC DIS
- Precision EW and QCD physics (e.g.: α_s, top production, …)
- BSM physics

– Leptoquarks, heavy neutrinos, …

All measured with small event pile-up and well-controlled detector
– redundant kinematics from e and jet: also for calibration

see physics talks @ EPS2023: D. Britzger, F. Giuli, M. D'Onofrio

The baseline LHeC detector

Covering from 1 to 179 degrees

All-silicon tracker extended forward wheels

EM calorimeter

Solenoid and dipole

HCAL

Good resolution for HCAL

Muon system embedded in return yoke

+ Forward/backward detectors (p/n/e/γ-tagger) along beamline

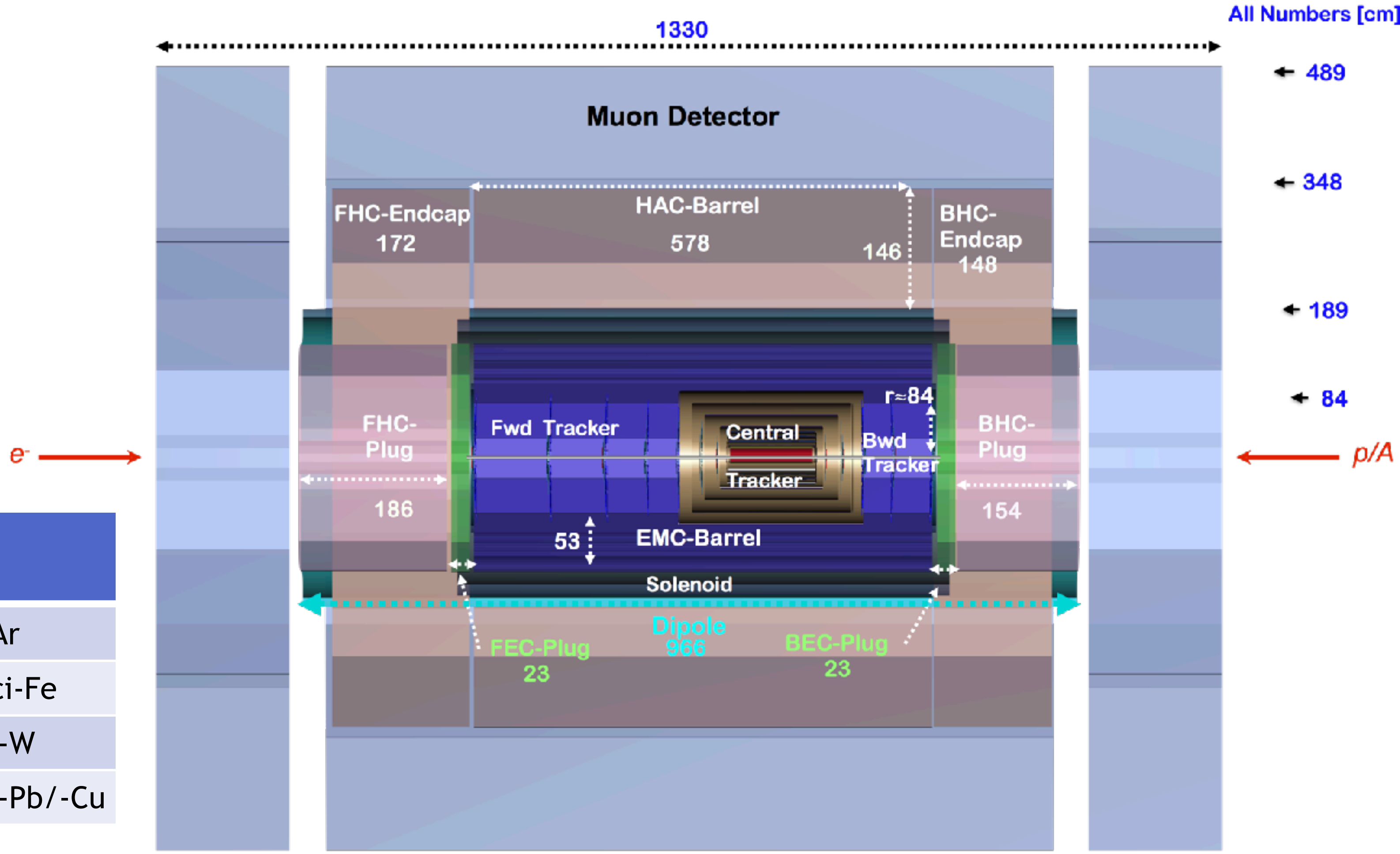
Covering wide η with small X_0

Calorimeter Baseline configurations

EM barrel	LAr
Had barrel + Endcap	Sci-Fe
EM+Had forward Plug	Si-W
EM+Had backward Plug	Si-Pb/-Cu

rad-hard very forward Plug Calo

fine segmented EM calo
high granularity: support of energy flow measurement, tracking calorimetry

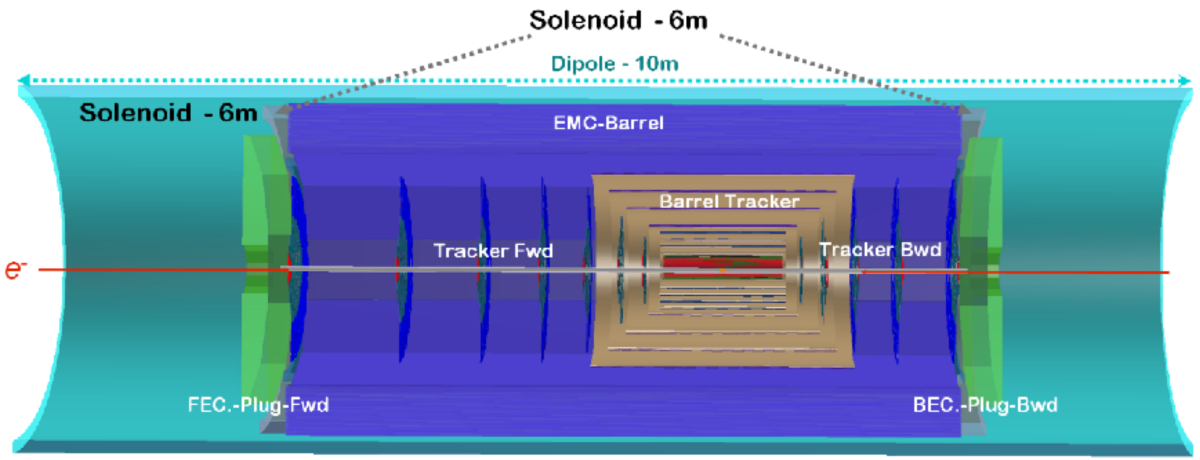


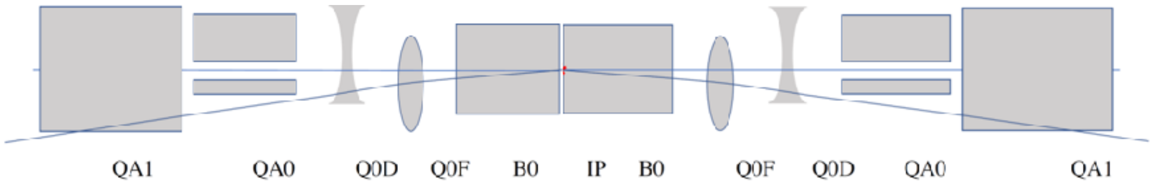
Aiming for compact, modular and very hermetic detector

Ref [2]

Interaction Point and Magnets

- Dipole magnet integrated in the detector to bend electron beam
  - Beam-1 p and e brought in head-on collisions
  - Beam-2 in a different plane
- Detector needs to be away and shielded from the synchrotron radiation fan

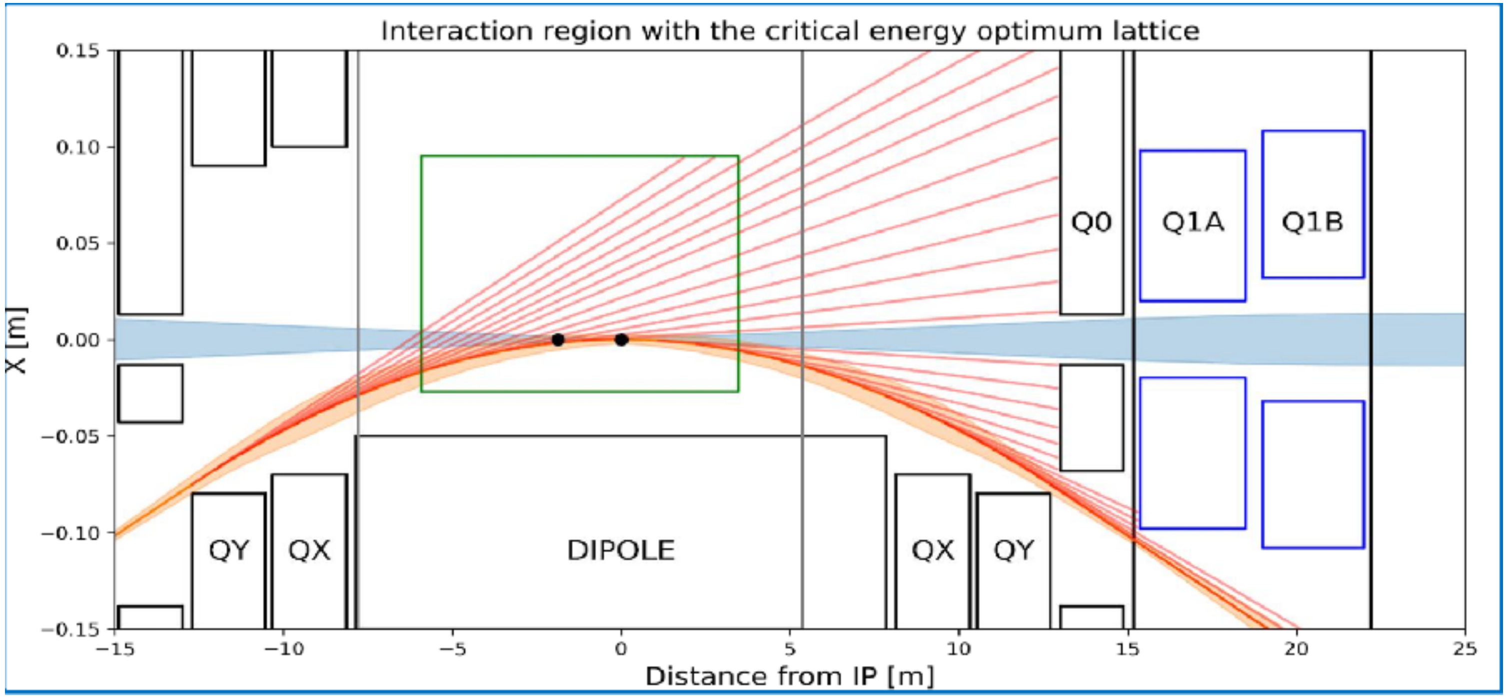




Synchrotron radiation fan (orange)
- optimised optics

p beam 1

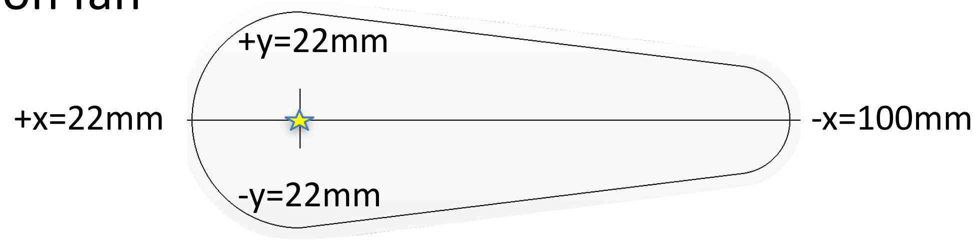
e beam

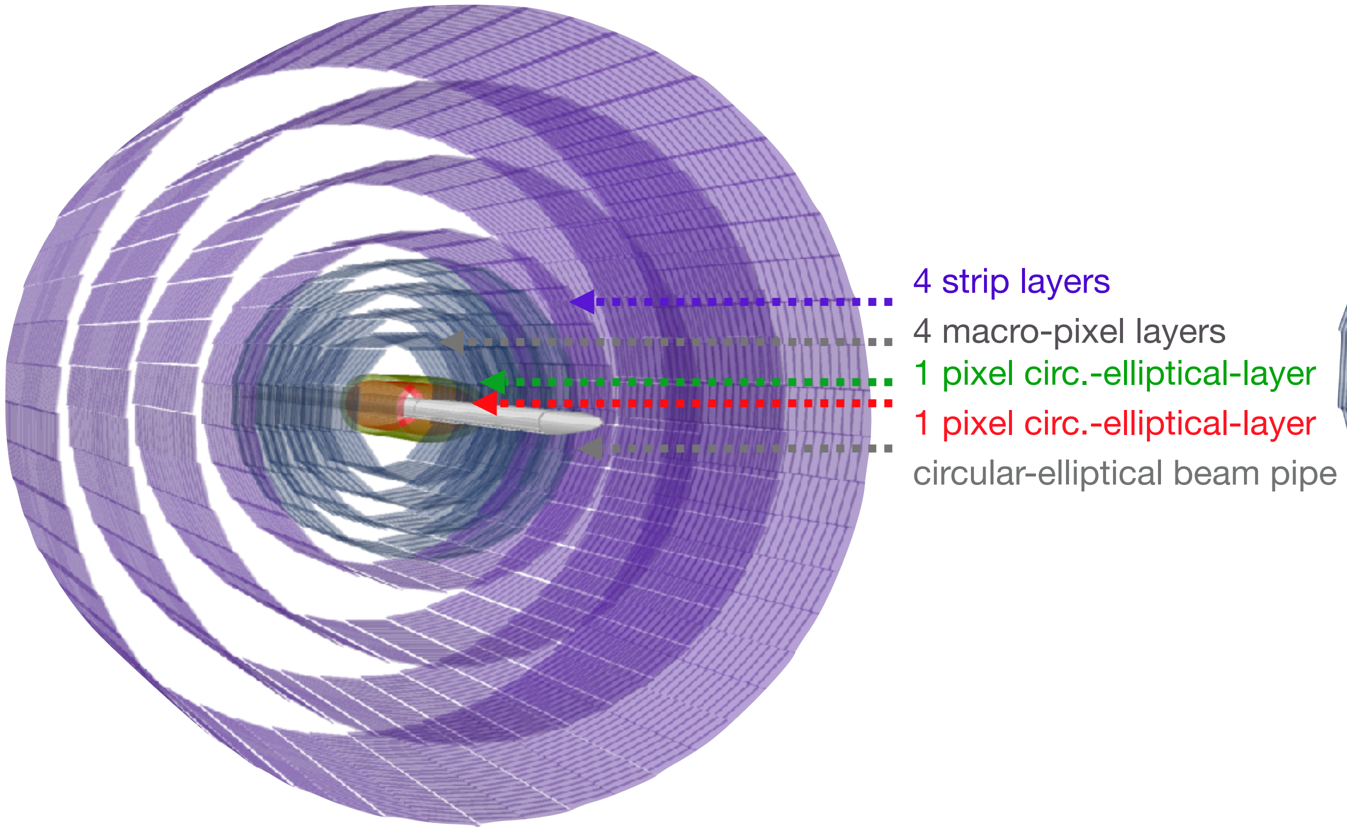


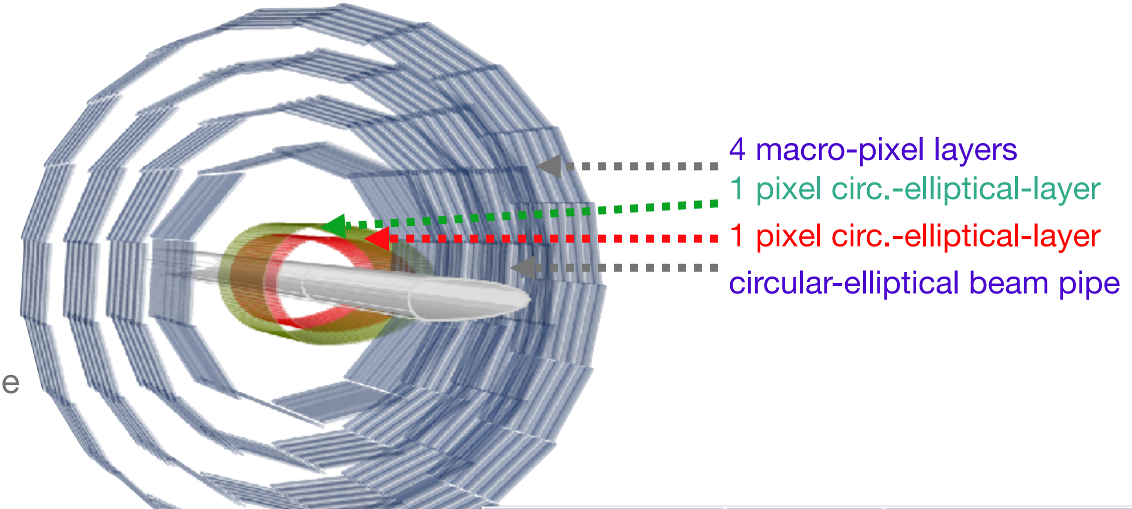
FCC Conference London Ref. [4]

Barrel sensors and beampipe (version LHeC)

- Circular-elliptical beam-pipe to accommodate synchrotron radiation fan
- Innermost sensor layers are bent (like developed for ALICE3)





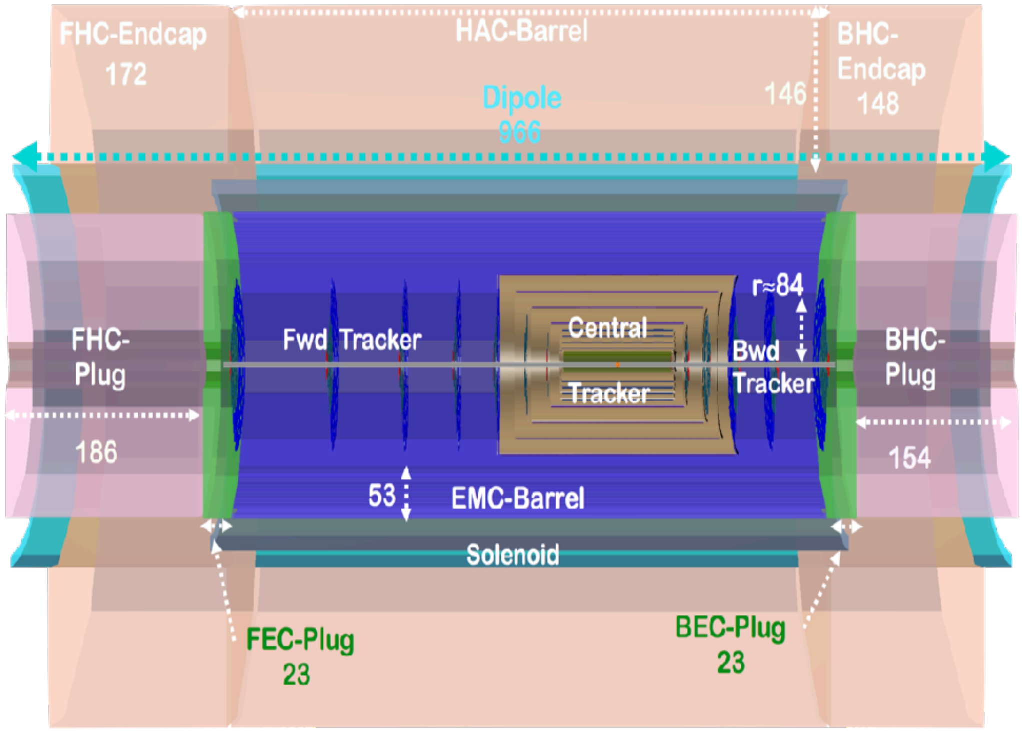


Pitch (μm)	$r\phi$	z
pixel	25	50
macro pixel	100	400
strip	100	10-50mm

[Efforts from DRDT 8.3 (ultra-light stable high precision mechanics, Machine-detector interfaces) should be pursued (from ECFA Detector Roadmap)]

LHeC Calorimetry

- High-performance barrel ($|\eta| < 2.8$) "cold" option
    - Baseline: LAr EMC inside solenoid with shared cryostat
    - R&D ongoing to make the barrel layer thinner, also cryostat (goal: a few % of X_0)
    - HadCal uses scintillator for good e/h identification (scintillating plastic tiles and iron plates)
- Fine-segmented plugs with compact shower with Si sensor
    - technology developed for ILC / FCC-ee; energy flow meas. support & tracking capability
- "warm" option
    - Sci-Pb → modular (installation inside the L3 magnet)
    - Comparable performance: LAr still advantageous for resolution, segmentation, long term & radiation stability



Complete coverage to +- 5 in (pseudo)rapidity

EMC Central Region: 2012: LAr, 2020: Sci/Pb option

Forward Region: dense, high energy jets of few TeV

H = bb_{bar} and other reactions demand resolution of HFS

Backward Region: significant lower energy deposited

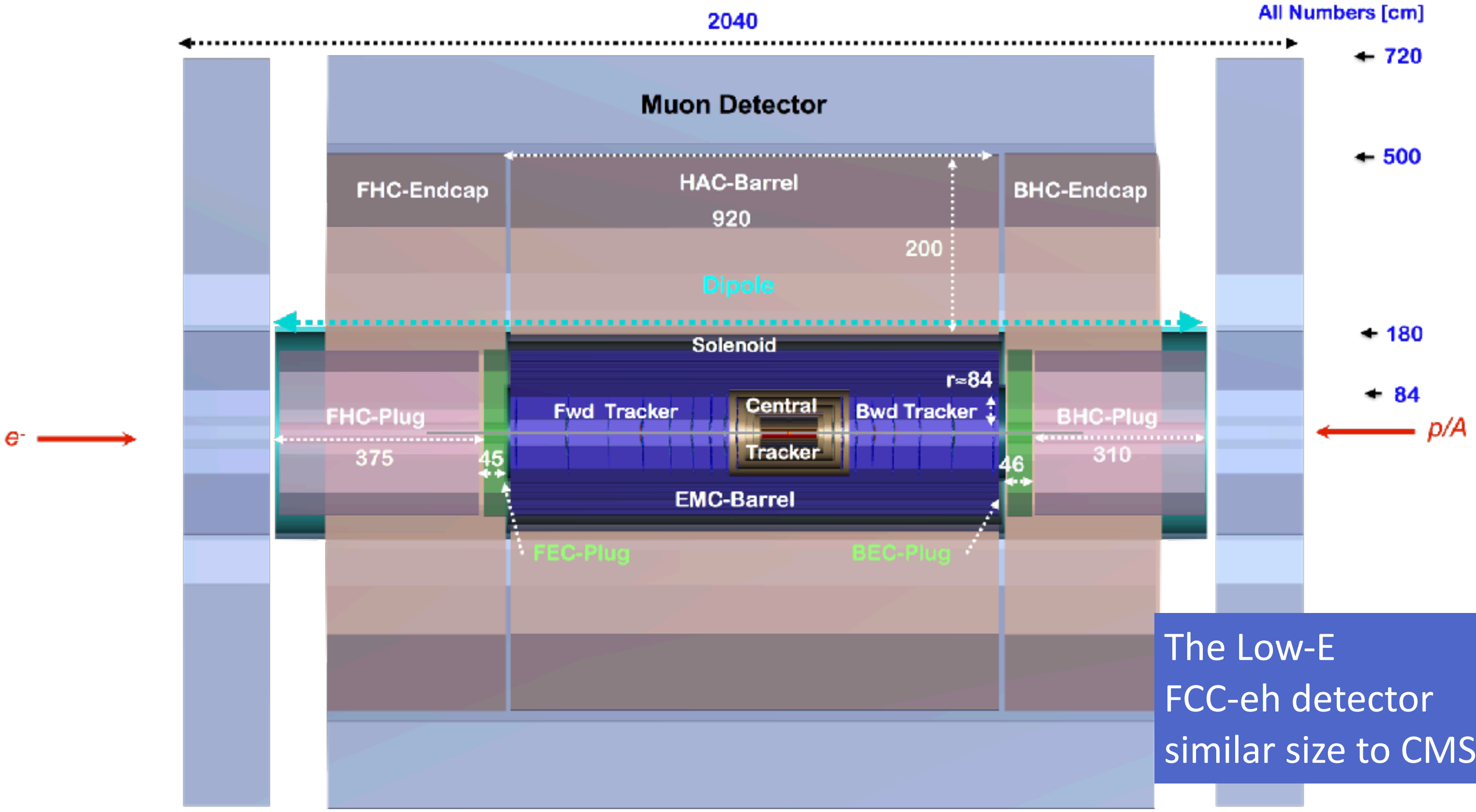
Baseline configuration		coverage	angular coverage
EM barrel	LAr	$-2.3 < \eta < 2.8$	6.6° — 168.9°
Had barrel + Endcap	Sci-Fe	(~ behind EM barrel)	
EM+Had forward Plug	Si-W	$2.8 < \eta < 5.5$	0.48° —
EM+Had backward Plug	Si-Pb/Si-Cu	$-2.3 < \eta < -4.8$	-179.1°

Detector design for FCC-eh – extension of the LHeC detector

- Proton 20 and 50 TeV, electron 60 GeV
  - As for LHeC 50 or 60 GeV electrons to be measured in backward direction
- Design for LHeC with extended volume / layers will serve also for FCC-eh
  - **Forward/Central: scales in $\sim\log E_{had}$ for calo**

— Experiment Magnets: Solenoid + Dipole

— Even longer track region
to retain 1° performance



The Low-E
FCC-eh detector
similar size to CMS

Total length 13.3 → 20.4m
Radius 4.9 → 7.2m

Central tracker also with (possibly tilted) wheels

Fwd tracker 4 → 8 disks
Bwd tracker 2 → 6 disks

HadCal:
12-15 interaction lengths

Most demanding: forward detectors

Ref [2]

Central Tracker Extension for FCC-eh

— All Silicon

— HV-CMOS MAPS (High-Voltage CMOS Monolithic Active Pixel Sensors)

low material, low power consumption, good resolution and tracking capabilities, compact design, fewer external connections required, good radiation hardness, custom design possibility and cost-effective

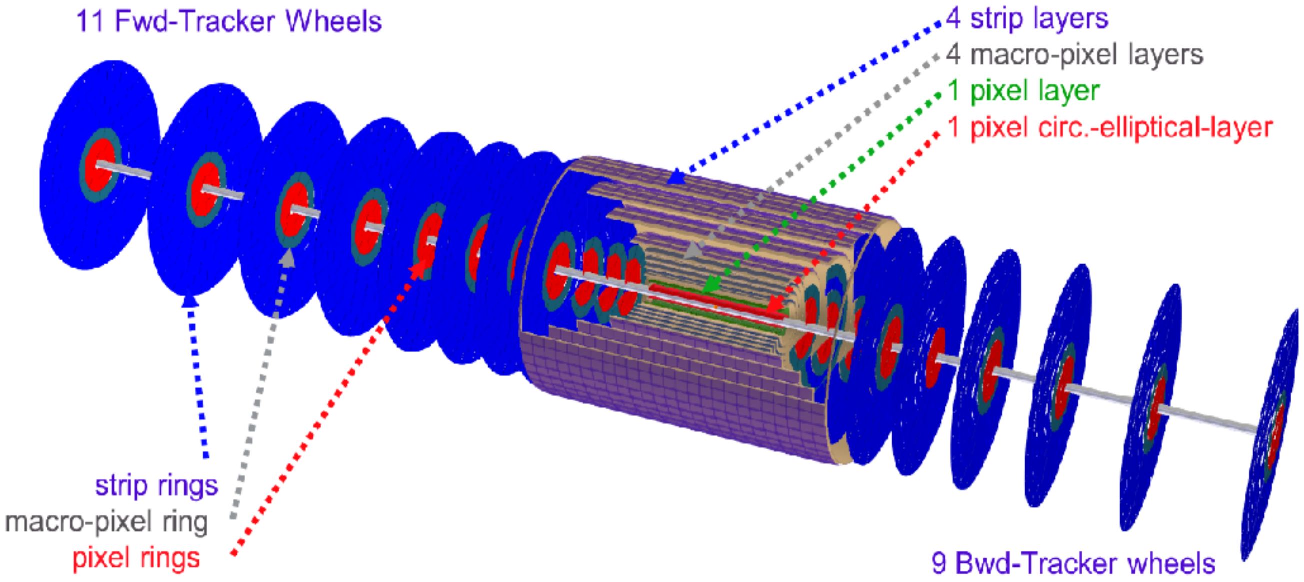
— Bent / stitched wafers for inner layers (as ALICE and ePIC)

— Circular-elliptical inner layers

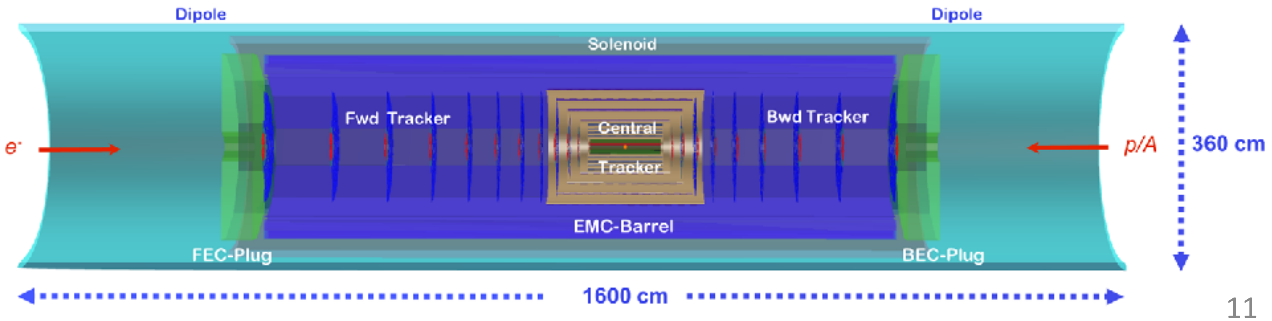
- More layers in Forward / Backward
  - 6m (LHeC) to 9.2m in length, rapidity coverage 5.3 → 5.6
  - # of forward disk: 4 → 7 or 8
- Planar (cost) and inclined (performance) options being considered
  - Inclined option: < 10% of X_0 achieved all over
- Area of rapid development: the final design would be further optimised

Ref [2]

FCCeh Tracker

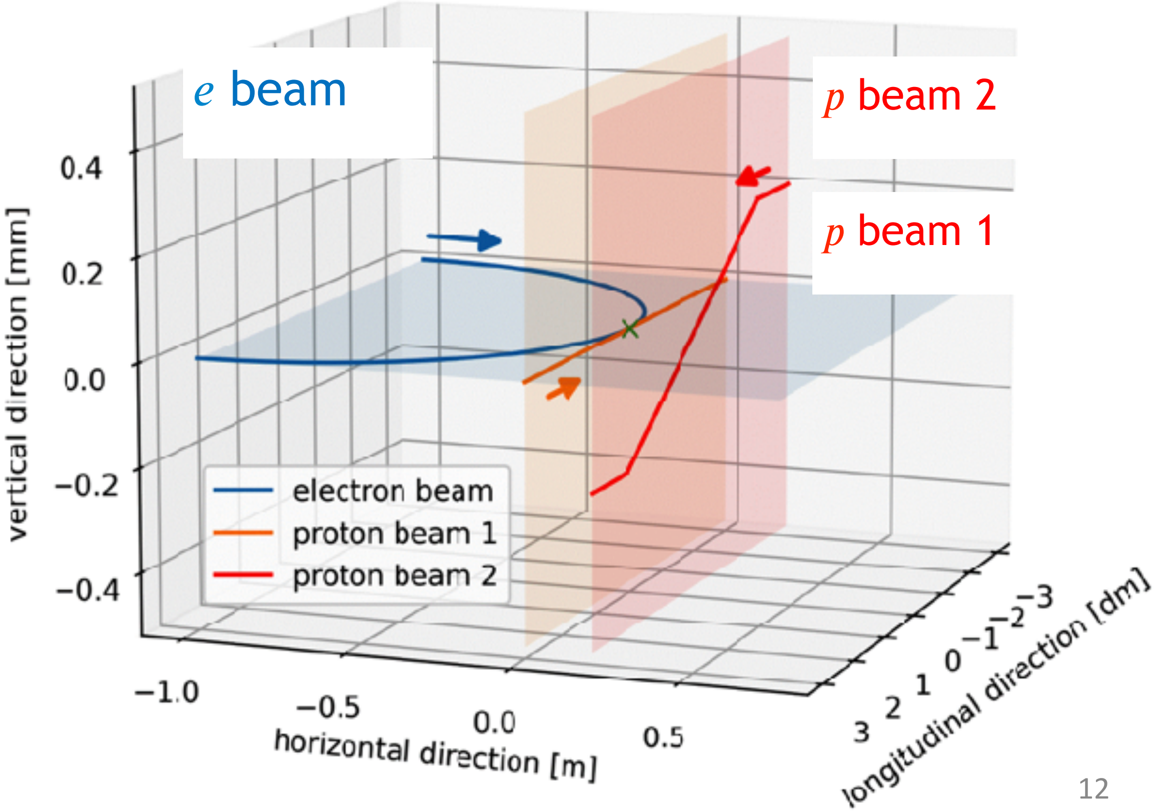


Overall length 9.2m, Radius 84cm



Design of the Interaction Region/Detector - Main Aspects

- LHeC/FCCeh - asymmetric detector: dense & high energy particle production in forward (proton)
  Forward Instrumentation: high granularity, resolving dense jet-structures, identify secondary vertices & supporting energy flow measurement - tagging neutral particles
- Calorimeter tracking capabilities (extending/supporting Tracker measurements)
- New achievements in 3 beam machine steering
  Novel Concept of beam usage at
  an electron extended hadron collider! [4]
- e-h and h-h interaction alternate in one IP
  of HL-LHC/FCC - NO disturbance of other IP's
- Ensure tolerable synch-rad load!
  (masks, absorbers,
  rad-hard det. components) see [3],[4]

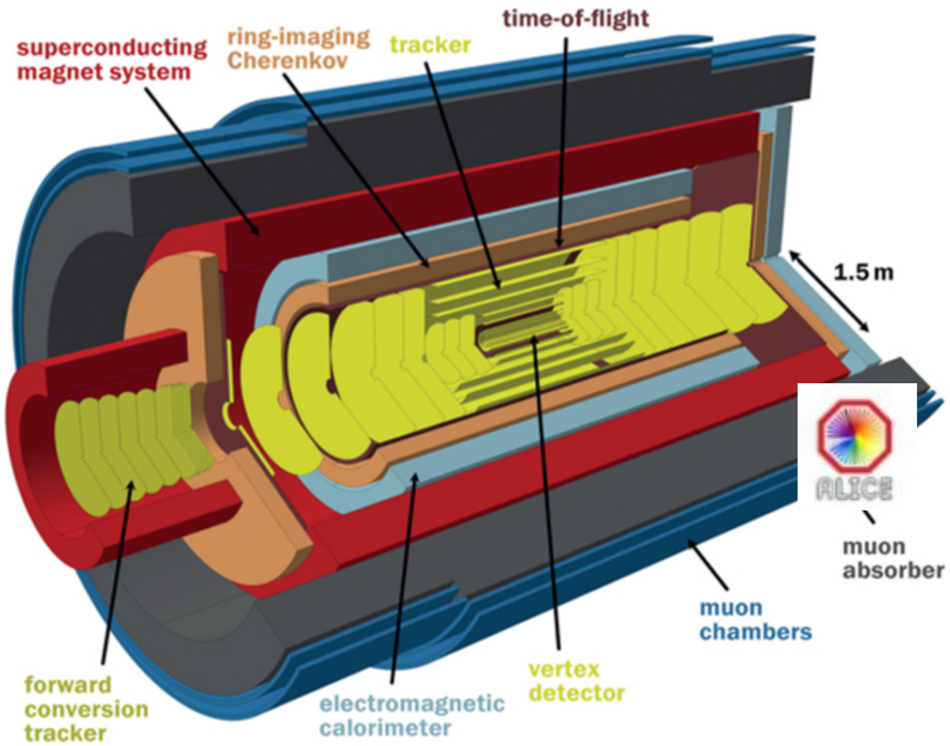


New IR design for both eh and hh collisions at HL-LHC IP2

Adapting LHeC / FCC-eh Detector for hh ⟶ LHeC-hh / FCC-eh-hh at same IP

- Use the more “powerful” equipped LHeC/FCC-eh forw. detector in the backw. region as well
  - symmetric sensitivity for hh- & eh-interactions in one detector
  - combining the physics programs of hh & eh fields - covering beyond $|\eta|<5$

from https://indico.cern.ch/event/1063724/, talk “ALICE 3 overview” by M. van Leeuwen



FCC-(eh)-hh detector produces a vast amount of data for each collision in hh mode → FCC-(eh)-hh possess advanced triggering and data acquisition systems to quickly gather, filter, and store the data like the ALICE3 detector proposed for HL-LHC:

Which foresees (compared to LHeC)

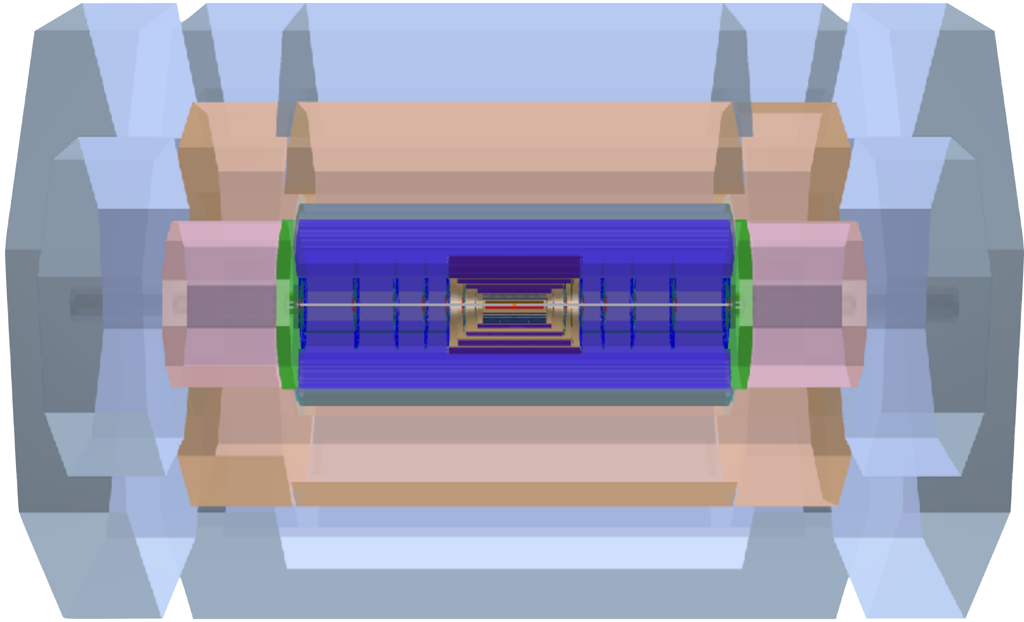
- a tracker with similar concept/size
- additional TOF, Čerenkov & dedicated fwd conversion tracker
- Calorimetry requirements met by LHeC detector already (tbc by simulations)

All components of the proposed eh/hh detector re-evaluated
- best performance for LHeC-hh / FCC-eh-hh, for $pp/pA/AA$ and ep/eA physics programs
- would be a novelty in HEP
The LHeC beamline detectors need to be reconsidered as well

FCC Conference London Ref. [1], [5]

ep/eA and $pp/pA/AA$ Collisions at the FCC-eh IP

- The eh detector is optimised for precision measurement
- low-pileup pp collisions for precision SM physics at the FCC-eh IP may perform better
  - with higher acceptance to lower p_T (moderate B field)
  - with high-η detectors chosen for precision rather than radiation
  - **… and detectors will be better calibrated through DIS events**



A symmetrised LHeC detector

Summary

- ERL based e-machine added to LHC; LHeC detector collision kinematic
  - Asymmetric - 50 GeV(e) ON 7 TeV (p) 2.76 TeV/nucl. (A) - detector asymmetric
  - **Low dose, low pile-up:** can try aggressive options
- Baseline LHeC detector design
  - Low-material Si tracker covering very forward/backward esp. for heavy flavour tagging
  - Hermetic calorimetry with very good jet resolution and granularity
  - Equipped with muon system and forward detectors (e, p, neutrals)
- Extended version of the LHeC detector design achieves the performance goals for FCC-eh
- Extrapolation from LHeC:
  the FCC-he detector is feasible, the design will benefit from coming technology progress
  (sensors, magnets, low power consumption, cooling, mechanical systems, electronics …)

- It also meets basic requirements for state-of-art measurement of hh collisions
- New 3 beam optics for LHeC & FCC-eh allow measurements of eh and hh collisions at same IP

- Experimental demands are lighter for ep than for pp reduced radiation level, no pileup concern and a cleaner final state
- Redundant DIS kinematics allows cross calibration & very high precision, such as 0.1% electron energy scale calibration
- The ep configuration uniquely selects the WW-H and ZZ-H vertices for production
  - ep → νH(bb)X: O(1)% precision on H-bb couplings - matching theoretical uncertainties
- FCC-eh reaches the H→μμ decay, with O(1000) events
  - μ measurement essential
- Demanding:
  - ep → νHHX ep produces the Higgs from WW → double Higgs
- FCC-eh will be a Higgs factory
  - desire to measure also rare decays,
  - maximum coverage for all kinds of decays

Sources

[1] P. Kostka, A. Polini, Y. Yamazaki,
’Physics and design of the eh detector’, The FCC Conference 2023 in London, 8 June 2023

[2] Detector designs for future highest-energy colliders
- very detailed studies in LHeC CDR 2012 LHeC Study Group,
2012 J. Phys. G: Nucl. Part. Phys. 39 075001
- for FCC-eh detector in FCC CDR vol. 3 EPJ Special Topics 228, 755–1107(2019)
- LHeC Collaboration and FCC-eh Study Group: P. Agostini et al., J. Phys. G 48 (2021) 11, 110501,
e-Print: 2007.14491 [hep-ex]
- OFFSHELL-2021 — The virtual HEP conference on Run4@LHC, EPJC Eur.Phys.J.C 82 (2022) 1, 40

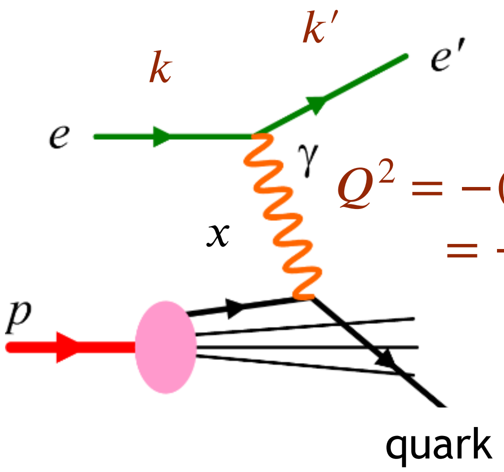
[3] T .von Witzleben, K. D. J. André, R. De Maria, B. Holzer, M. Klein, J. Pretz, M. Smith,
‘Beam Dynamics for Concurrent Operation LHeC and the HL-LHC’, IPAC 2023

[4] T. von Witzleben, K.D.J. André, M. Giovannozzi, B. Holzer, M. Klein, G. P. Segurana, J. Pretz,
’Design of the Interaction Region for Concurrent e-p and p-p Operation’,
The FCC Conference 2023 in London, 8 June 2023

[5] P. Newman for the LHeC / FCC-eh study group, ‘An Interaction Region and Detector for High Energy DIS at CERN’, DIS 2023 Michigan State University 28 March 2023

Backup

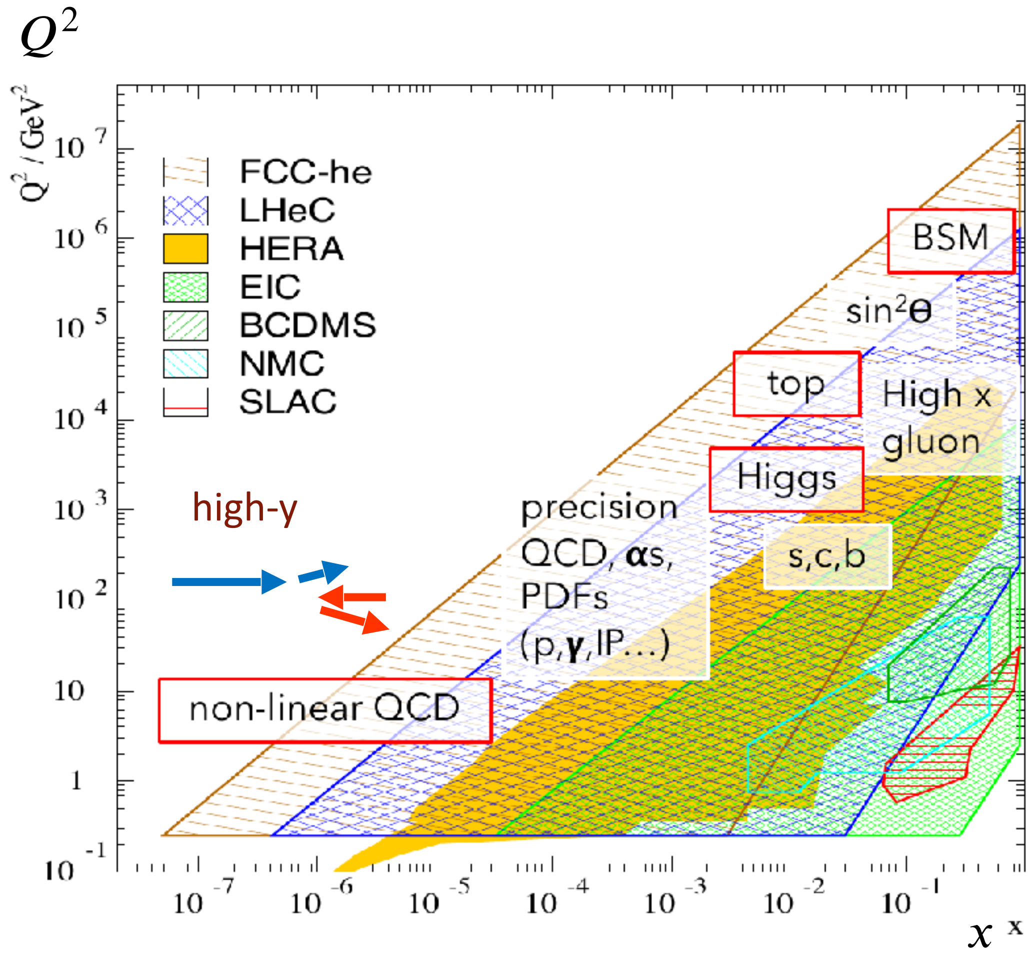
DIS kinematic plane and event topology

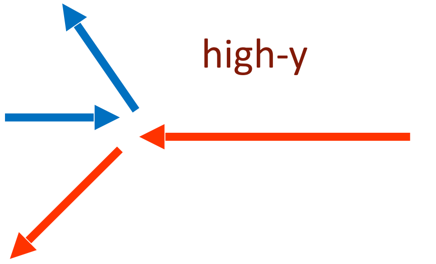


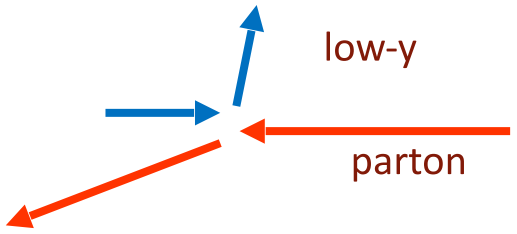
$$Q^2 = -(k-k')^2$$
$$= -q^2$$

$$x = \frac{Q^2}{p \cdot q} \qquad y = \frac{p \cdot q}{p \cdot k}$$

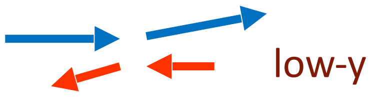
$$sxy = Q^2$$





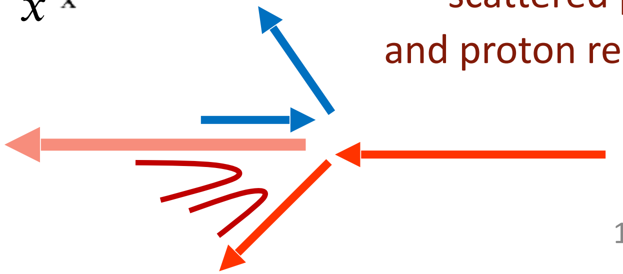


high-x, high Q2



low-x, low Q2

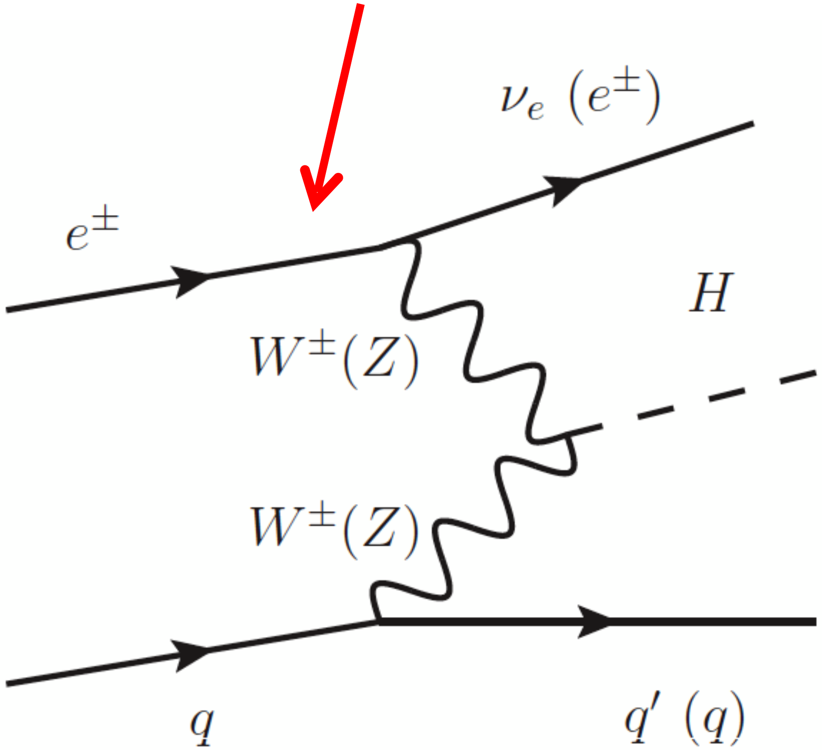
QCD radiation between
scattered parton
and proton remnant



Higgs at LHeC

At LHC replace
lepton lines by quark lines
but dominantly gg → H

- It is remarkable that VBF diagrams were calculated for lepton nucleon collisions before for pp!
- Consider feasibility for the following LHeC point:



$$E_p = 7\,TeV, \quad E_e = 60\,GeV, \quad m_H = 125\,GeV$$

FCC-eh Physics Benchmarks e.g.

Uta & Max Klein, Contribution to FCC Workshop, 16.1.2018, preliminary

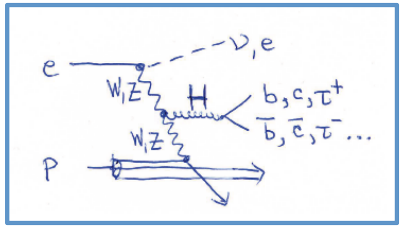
CC DIS WWH → H

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

bb/cc

both vertex tagging demanding somewhere between 5-10μm resolution required; accompanied by excellent calorimeter measurement



→ 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:

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

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

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

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

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

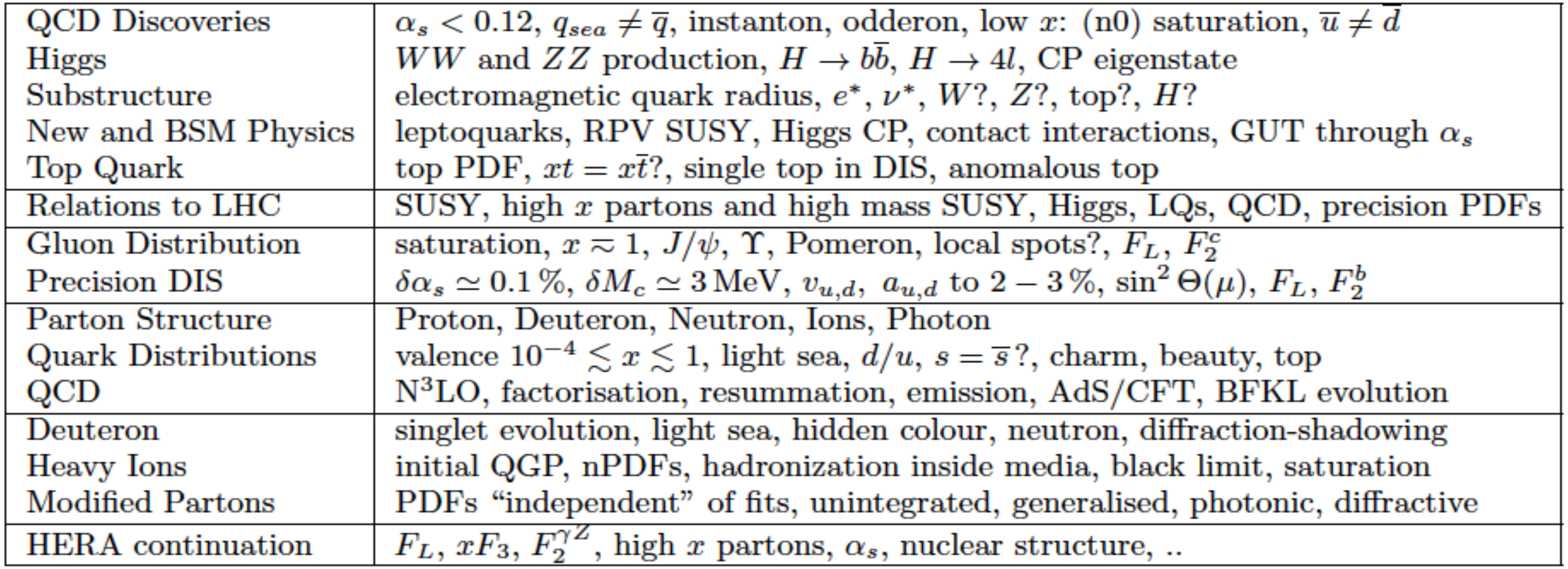
$$\sigma(WW \to H \to ZZ) \propto \kappa^2(HWW) \bullet \kappa^2(HZZ)$$

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

18

LHeC Physics Programme

CDR, arXiv:1211.4831 and 5102
http://cern.ch/lhec

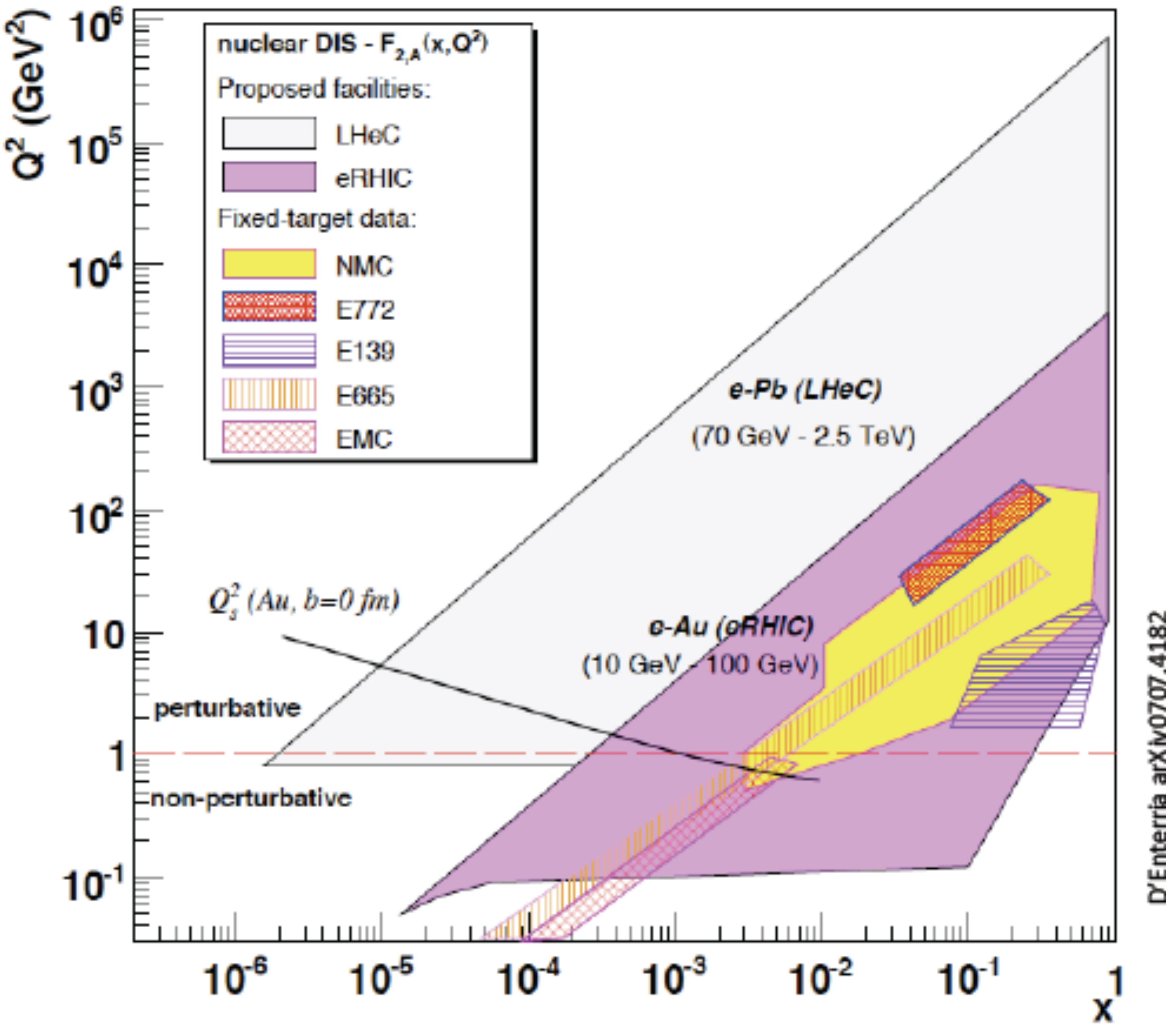


QCD Discoveries	$\alpha_s < 0.12$, $q_{sea} \neq \bar{q}$, instanton, odderon, low x: (n0) saturation, $\bar{u} \neq \bar{d}$
Higgs	WW and ZZ production, $H \to b\bar{b}$, $H \to 4l$, CP eigenstate
Substructure	electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H?
New and BSM Physics	leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s
Top Quark	top PDF, $xt = x\bar{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c
Precision DIS	$\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure	Proton, Deuteron, Neutron, Ions, Photon
Quark Distributions	valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \bar{s}$?, charm, beauty, top
QCD	N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing
Heavy Ions	initial QGP, nPDFs, hadronization inside media, black limit, saturation
Modified Partons	PDFs “independent” of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

Ultra high precision (detector, e-h redundancy) - new insight
Maximum luminosity and much extended range - rare, new effects
Deep relation to (HL-) LHC (precision+range) - complementarity

Strong coupling 0.1%; Full unfolding of PDFs; Gluon: low x: saturation?, high x: HL LHC searches…

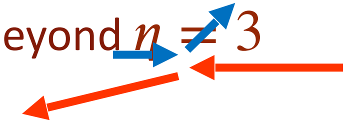
eA Collisions



Processes & Challenges (1): Neutral Current (NC) $ep \to eX$

low-x / low-Q^2 events

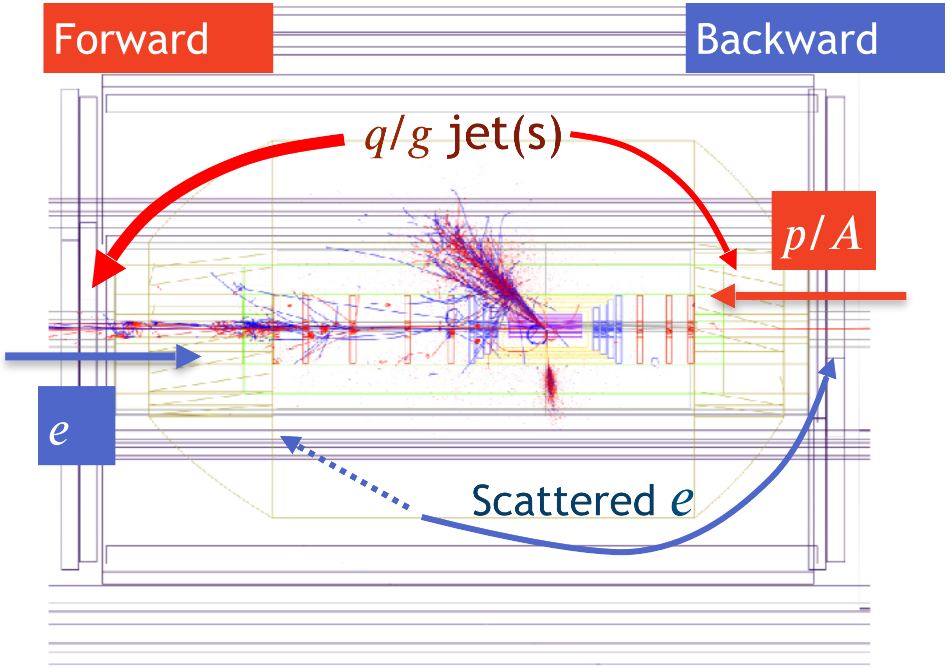
- Scattered electron (e) towards small angle (< 179°)
- Hadrons (X) go to forward (low-y) OR backward (high-y)
- High-y = small energy e to be distinguished with $\pi^{\pm}/\pi^0$ **from photoproduction events $\gamma p \to X$**
- b/c tagging for decomposing pdf beyond $\eta = 3$



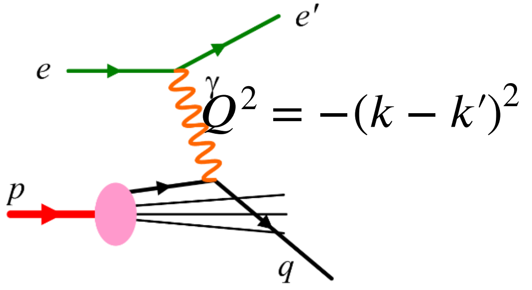
high-x / high-Q^2 events

- electrons almost everywhere
- very high-energy jets ($O(\mathrm{TeV})$) also everywhere, especially in forward

- Hermetic and thick EM and Hadron calorimetry
  - Fine granularity for e/π separation (esp. backward)
- Fine-pitch tracking for vertexing
  - for heavy-flavour tagging (esp. forward)



An NC (leptoquark) event at LHeC



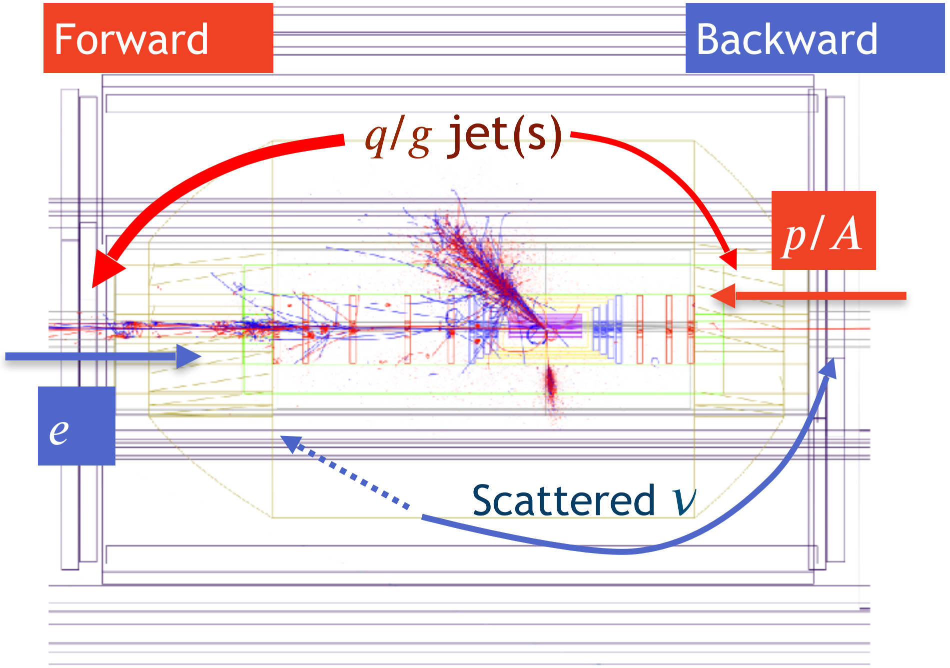
$Q^2 = -(k - k')^2$

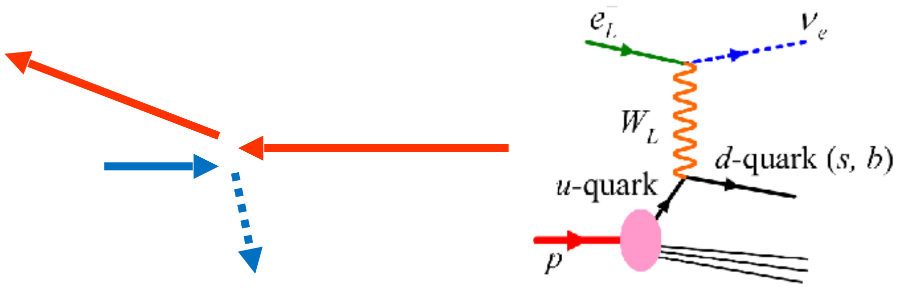
NC

Processes & Challenges (2): Charged Current (CC) $ep \rightarrow \nu X$

- A jet like high-x / high-Q^2 NC, but w/o scattered e
  - Kinematics should be reconstructed only from the hadronic system angle and missing p_T
- This also helps for:
  - QCD studies with jets
    - including photoproduction ($e \rightarrow e'\gamma, \quad \gamma p \rightarrow X$)
  - detector cross-calibration using NC DIS:
    - two energies and angles (e and hadronic system): over-constrained

- Hermeticity (esp. forward)
- good HadCal resolution (e/h etc.)
  - tracking should help (particle flow algorithm)



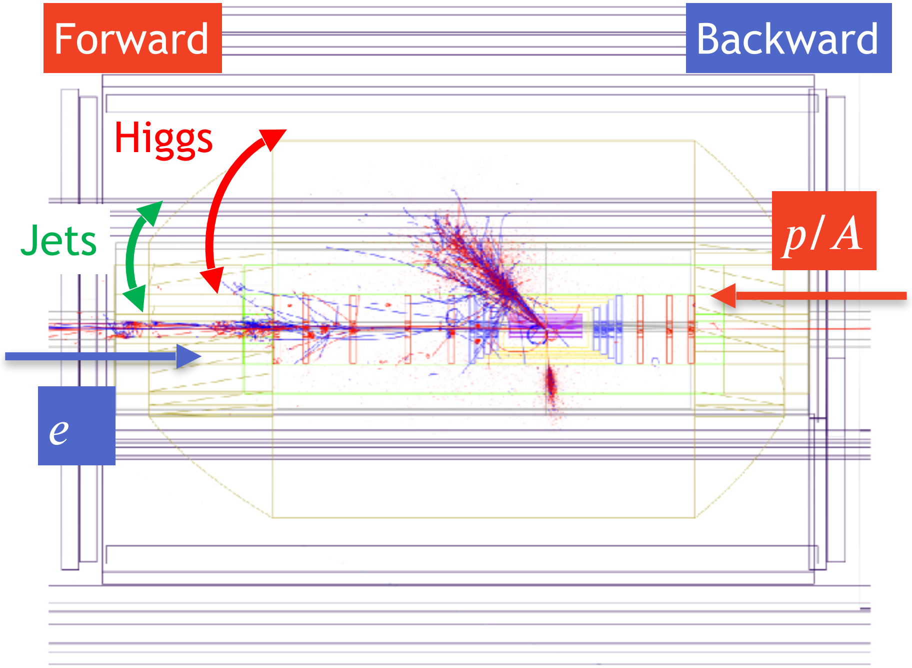


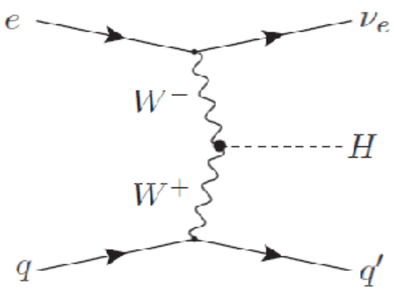
CC

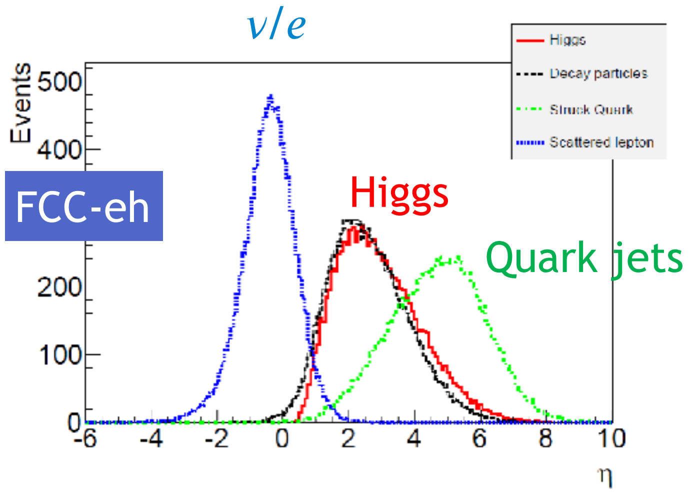
Processes & Challenges (3) Higgs / EW / top / BSM

- Higgs
  - Thru WW fusion in CC or ZZ in NC:
    - need to detect forward "VBF jet"
  - Precise coupling to $b\bar{b}$, $c\bar{c}$, and $\tau\tau$:
    - Need very good flavour tagging in forward direction
    - Jet resolution for mass reconstruction
- EW and top physics
  - similar mass range:
    similar requirement for flavour and jets
- BSM physics
  - high-mass → large-x events

- generic detector for high-Q^2 NC/CC should also serve for these processes







Detector Requirements from Physics

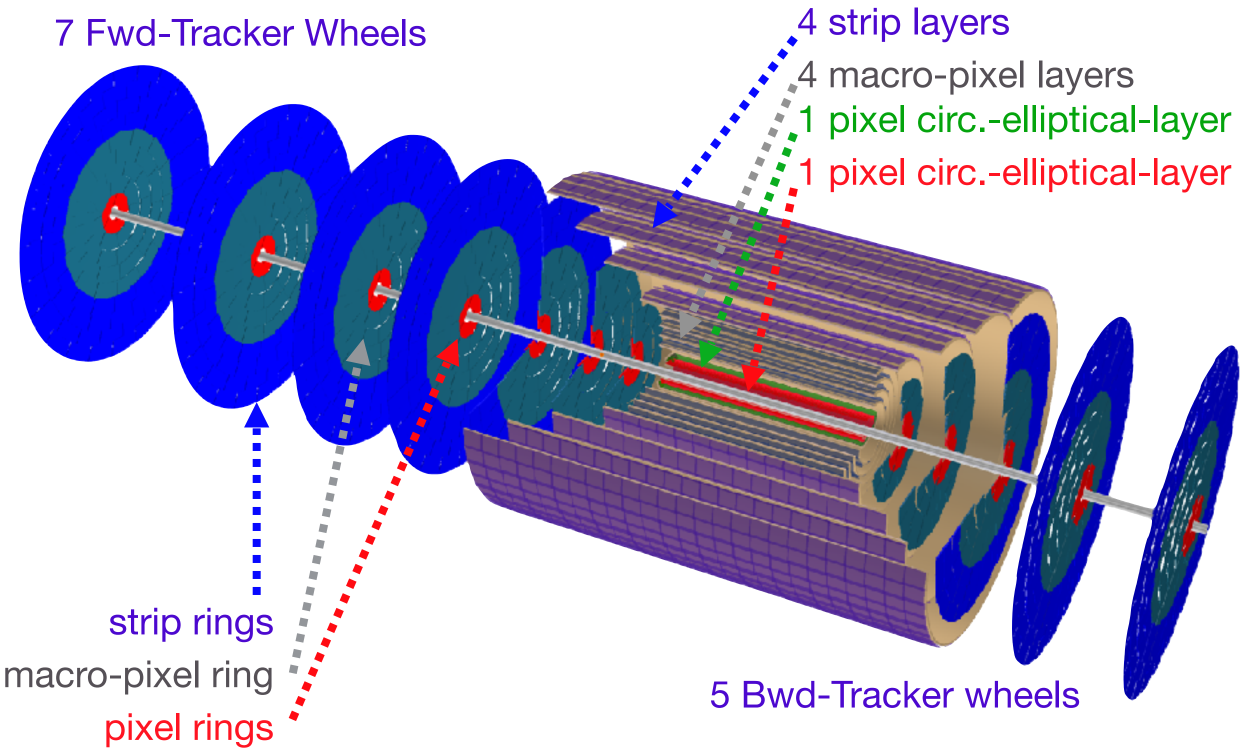
- High resolution tracking system
  - excellent primary vertex resolution
  - resolution of secondary vertices down to small angles in forward direction for high x heavy flavor physics and searches
  - precise p_t measurement matching to calorimeter signals (high granularity), calibrated and aligned to 1 mrad accuracy
- The calorimeters
  - electron energy to about 10%/ √ E calibrated using the kinematic peak and double angle method, to permille level

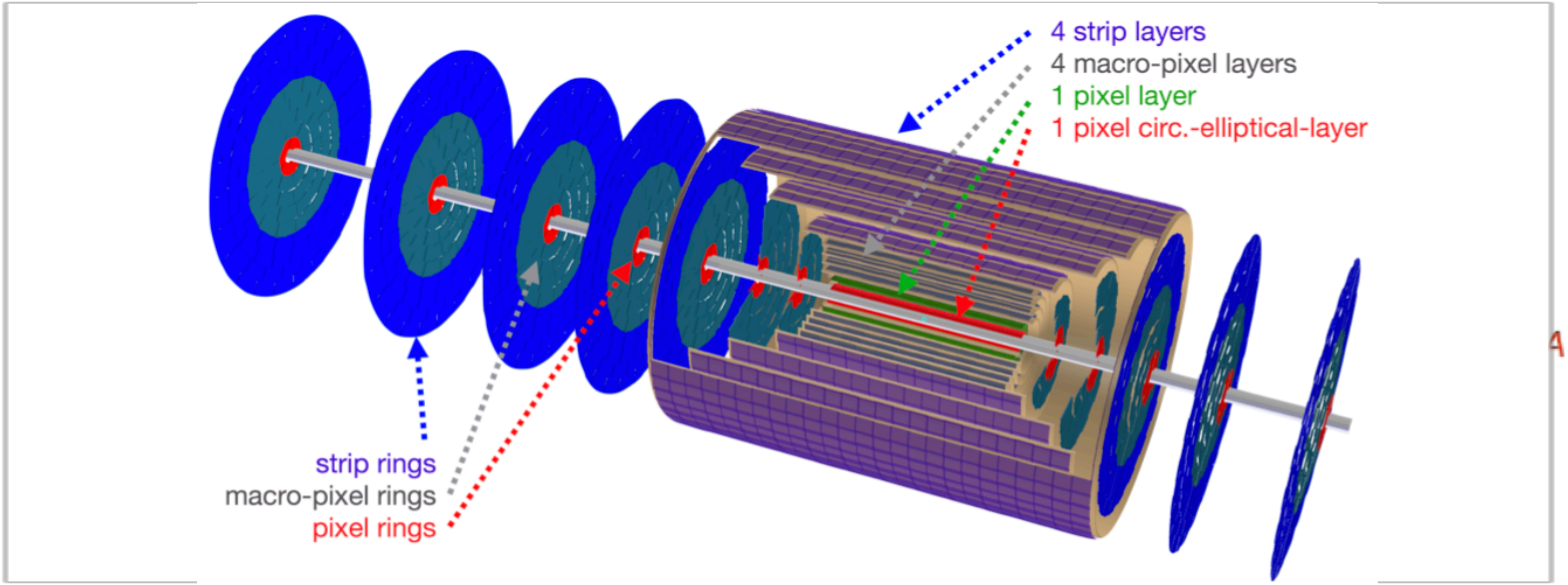
    Tagging of γ's and backward scattered electrons -
    precise measurement of luminosity and photo-production physics
  - hadronic part 40%/√ E calibrated with p_{t_e} / p_{t_h} to 1% accuracy
  - Tagging of forward scattered proton, neutron and deuteron - diffractive and deuteron physics
- Muon system, very forward detectors, luminosity measurements

LHeC Central tracker with Modern Silicon

- Technology advanced from CDR 2012 period
- Low-material tracker by DMAPS
  - CMOS sensors (HV-CMOS for this update)
    Readout electronics integrated
- Very thin: 0.1mm for all sensors
  - Small material budget
    for forward/backward
- Rad hard up to $2 \times 10^{15}\ 1\mathrm{MeV}\ n_{eq}/\mathrm{cm}^2$
  (cf. HL-LHC fluence $\gtrsim 10^{16}$)
- 5-8 layers for $-3.5 < \eta < 4$
  2 hits for $-4.2 < \eta < 5$

Pitch ()		
pixel	25	50
macro pixel	100	400
strip	100	10-50mm





Inner Tracker

Rapidity to ~5

r_O = 60 cm

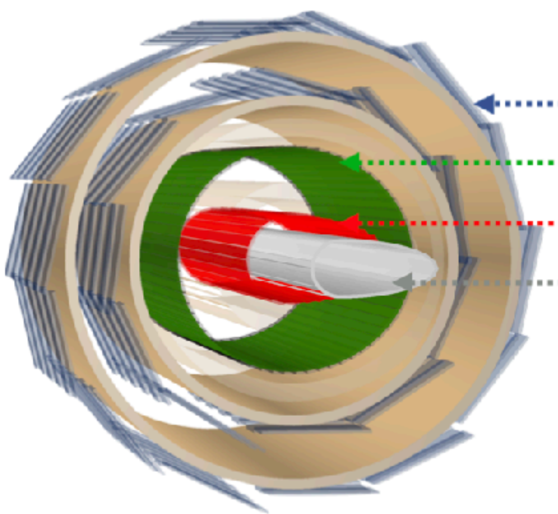
impact resolution 5-10 µm

40.7 m^2 Si

LHeC Trackers

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

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



LHeC Calorimeters

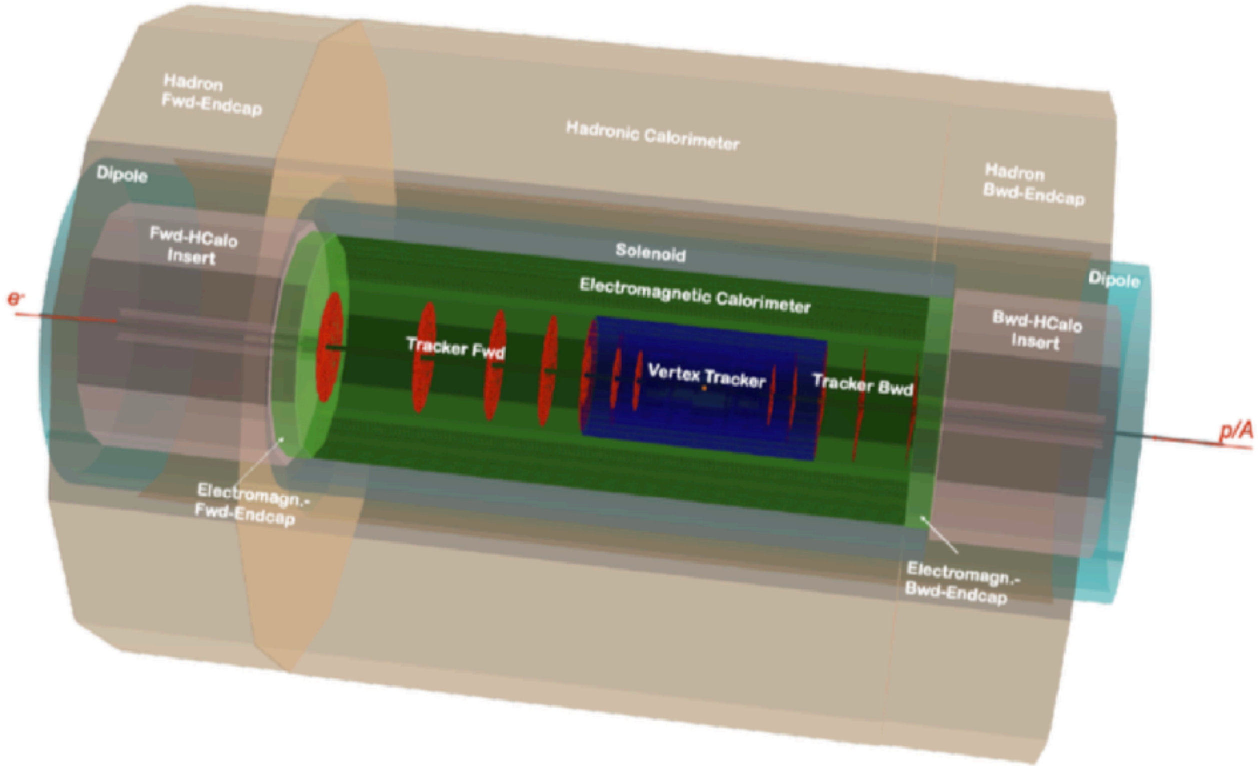
Complete coverage to +- 5 in (pseudo)rapidity

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
$\eta_{\max}, \eta_{\min}$	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
$\eta_{\max}, \eta_{\min}$	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

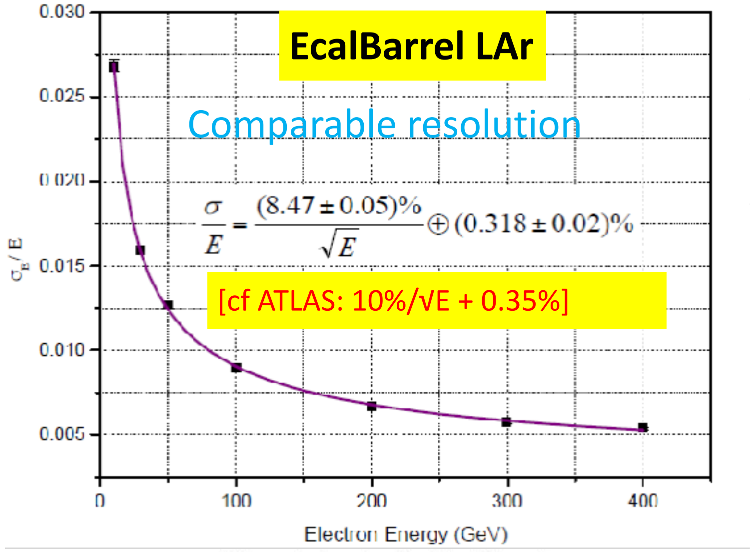
arXiv:2007.14491

EMC - 2012 CDR Accordion Geometry Baseline Design

Cold Option

2.2mm lead + 3.8mm LAr layers

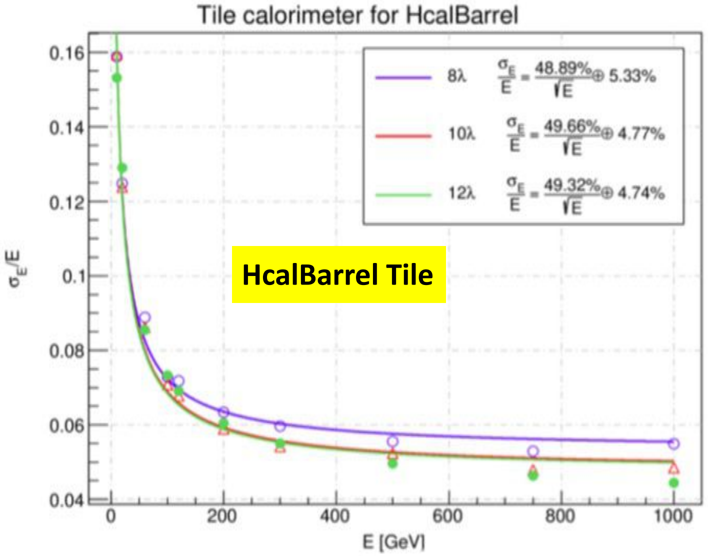
LAr (~25X_0) 8.47 /$\sqrt{E}$ ⊕ 0.32%



EcalBarrel LAr

Comparable resolution

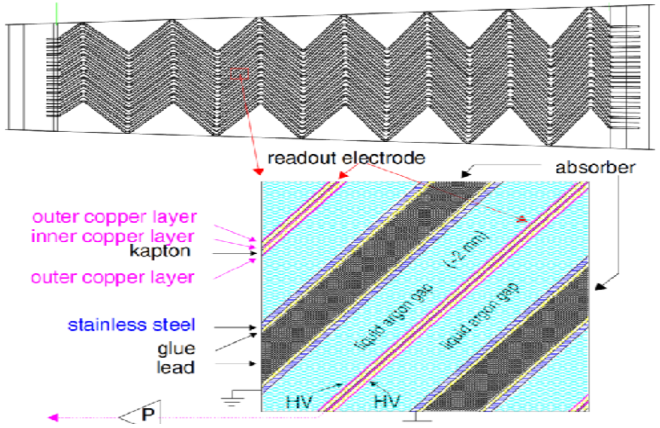
[cf ATLAS: 10%/√E + 0.35%]



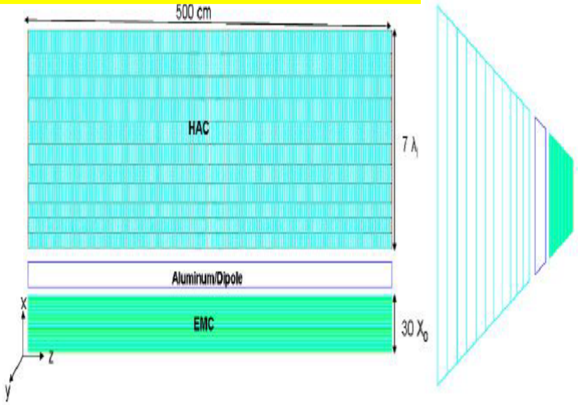
Tile calorimeter for HcalBarrel

HcalBarrel Tile

GEANT4 simulation of response to electrons at normal incidence



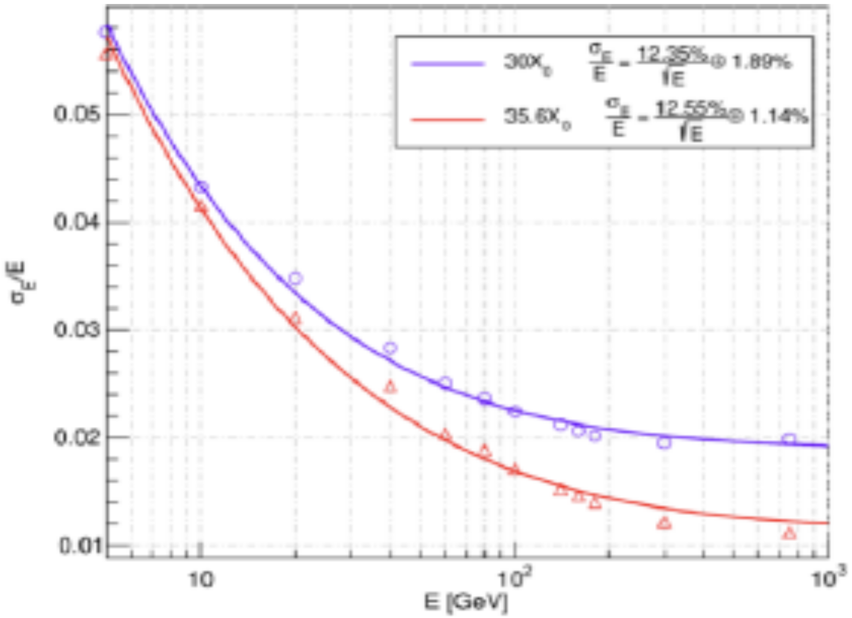
Ecal Barrel LAr + HcalBarrel Tile



Warm Option

20 x 0.85 cm Pb layers interspaced by 4 mm Scint.

Sci-Pb (30X_0) 12.55/ $\sqrt{E}$ ⊕ 1.89%



The ongoing evaluations aim to determine if the entire calorimeter's resolution meets the specifications required for specific physical events, such as the decay of the Higgs boson into two W bosons (H->WW), bottom quark pairs (bb), and the top quark

A Geant4 Simulation Study for the Warm Option

v1

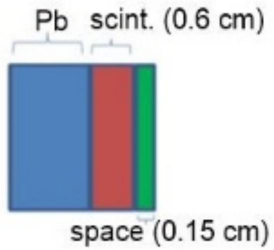
$30X_o$

Number of Layers	6	8	11
Thickness of Pb (cm)	0.5	0.6	0.8

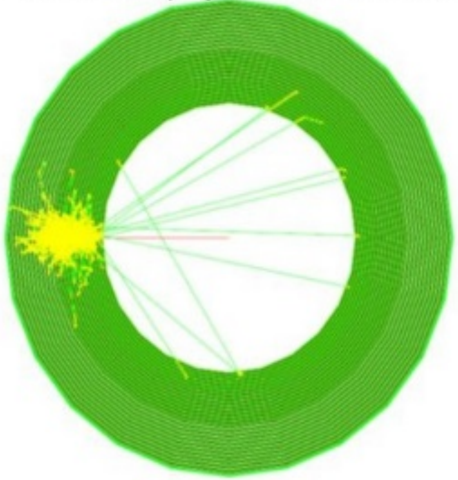
v2

$30X_o$

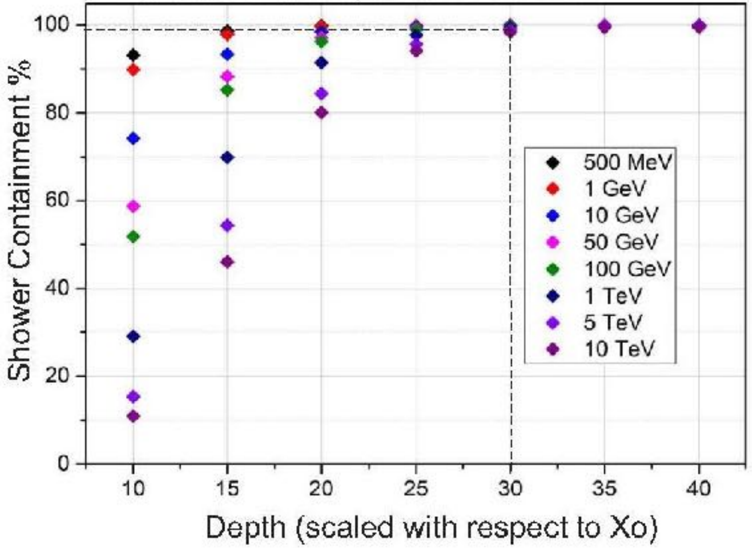
Number of Layers	8	13	18
Thickness of Pb (cm)	0.3	0.4	0.5

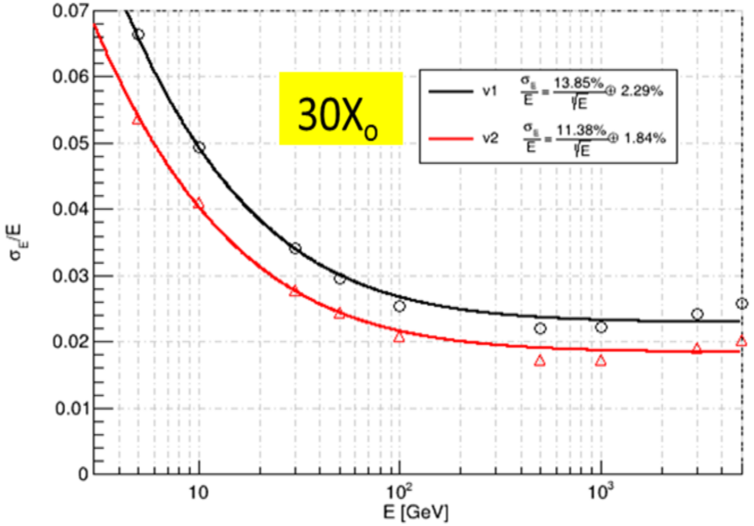


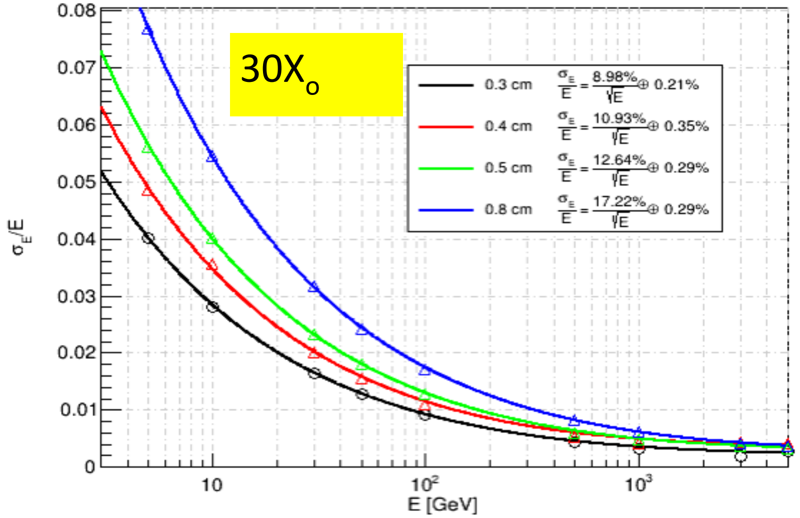
an event display for a 5 GeV electron

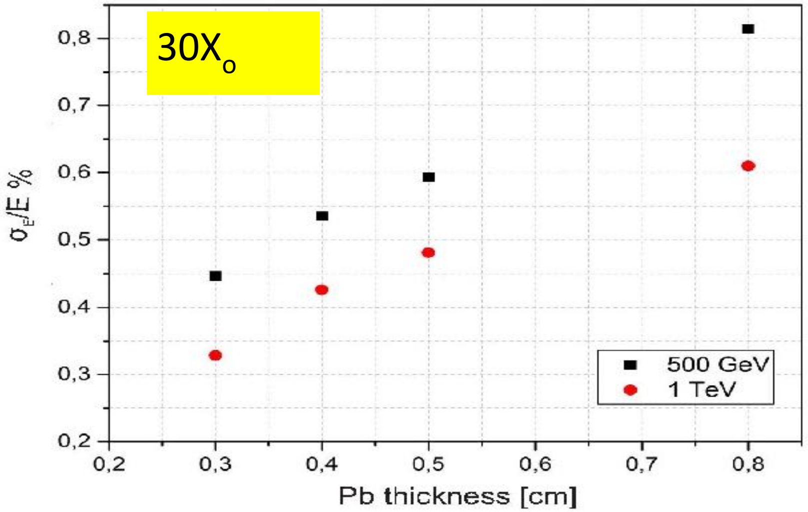


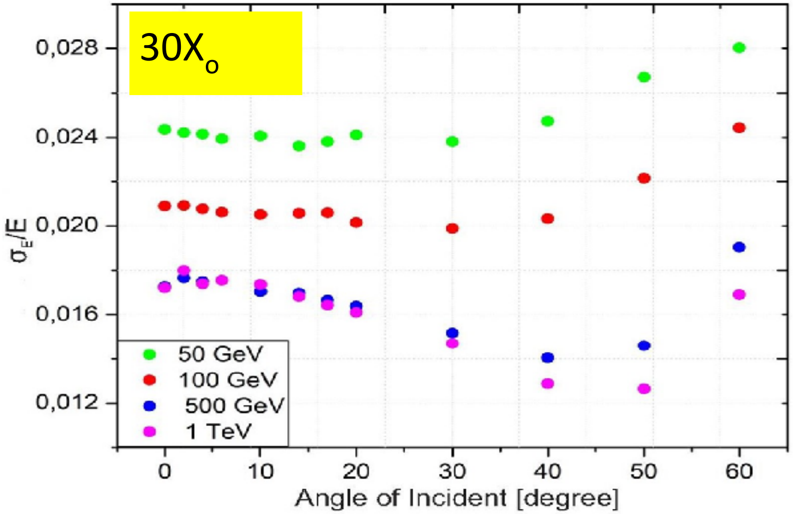
~98% containment up to 10 TeV at 30 Xo





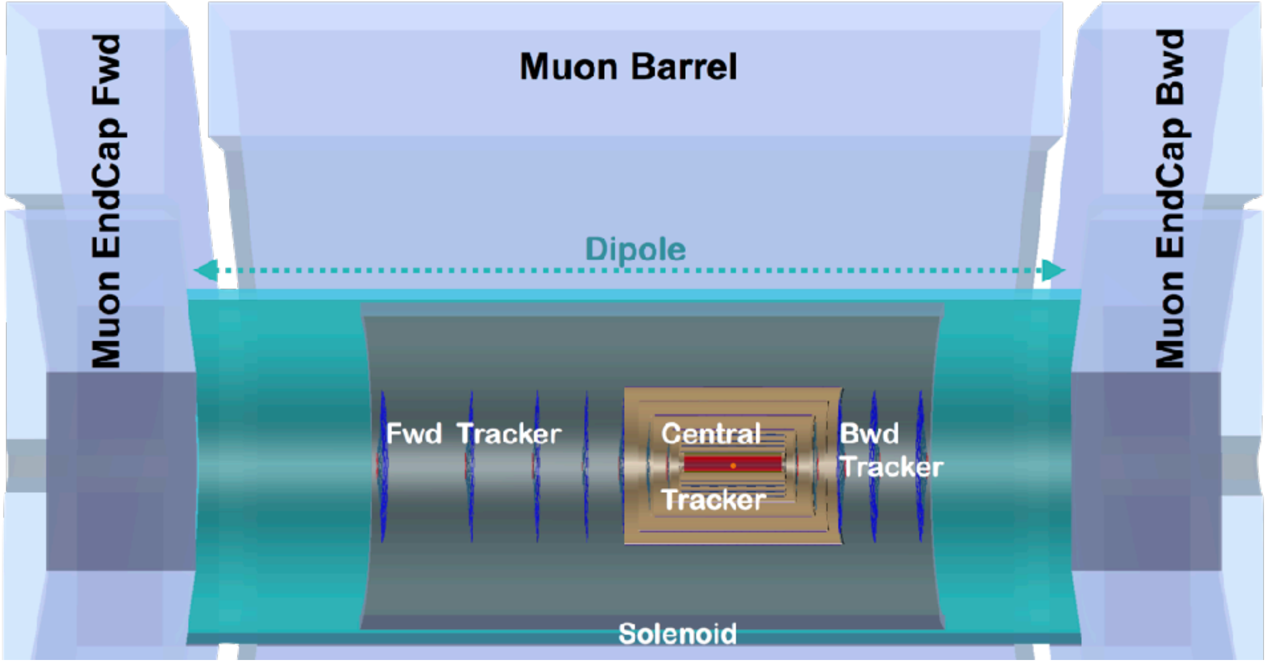




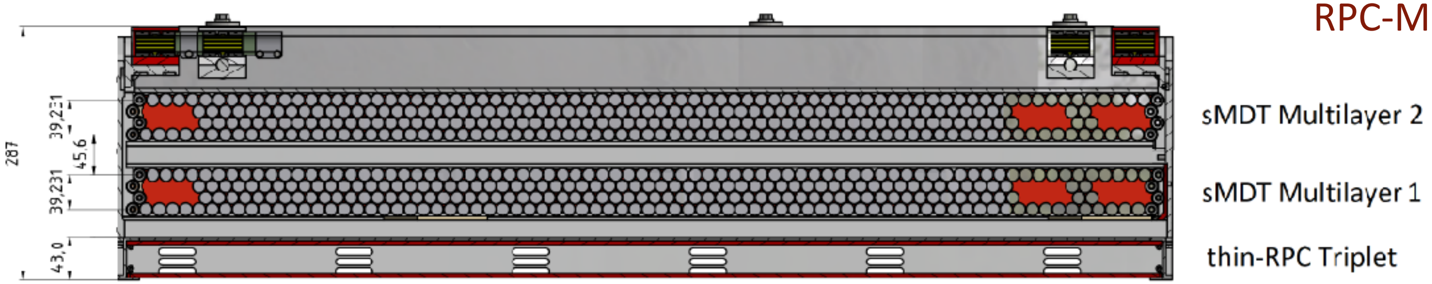


Z. Hashimi , F. Kocak

Muon system



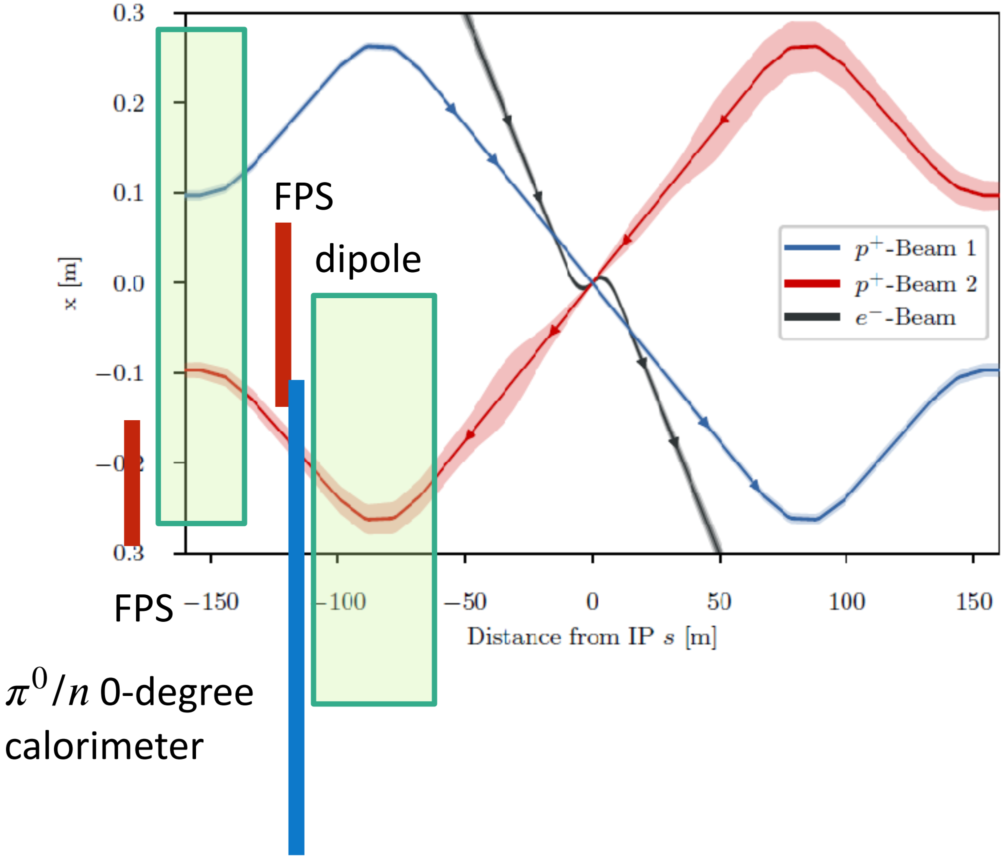
- Baseline: no dedicated magnetic field (solenoid return thru iron only)
  - Momentum by central tracker
  - Good tagging + fast trigger
  - 3-stations, each with $\geq$ double layer
- HL-LHC technology serves for that
  - Very thin RPC (1mm gas gap) for higher rate capability and timing (<1ns)
  - sMDT: $\phi = 1.5$cm drift tubes for precise position measurement
- Possible extensions
  - Dedicated forward toroid or outer solenoid



ATLAS Phase-I
RPC-MDT assembly

Around zero-degrees

- Backward e tagger + photon tagger
  - for photoproduction and luminosity ($ep \to ep\gamma$)
- Forward Proton spectrometer following the LHC design apart from stations close to IP
- IP design (eh-only scheme 2020) allows to place a ZDC
  - Transvers size ± 30 cm: shower leak moderate
  - Aperture very big: 0.35 mrad or 2.4 GeV in p_T
- ZDC Technology candidate: Si-W
  - Need < 1mm resolution for p_T resolution $\ll$ 100 MeV for 7 TeV neutron i.e. very fine segmentation (e.g. ALICE FoCal)
  - Radiation dose: O(10MGy) or more
    - Much less than LHC, possibility to use silicon



IP design 2020 and the candidate places for forward detectors

Consideration for full luminosity pp runs with LHeC detector

- If we like to run at the full HL-LHC luminosity:
  - Thin and readout-integrated Si sensors for high dose is available: it is just a more expensive option
  - Calorimeter can stand: may need minor adjustment (boundary Fe-Sci. and W/Pb-Si)
  - Forward detectors (FPS, ZDC) should be "retractable": they should be in place only for ep/eA runs
- The LHeC detector is optimised for precision measurement
  - It may be more interesting to focus on low-pileup runs for SM physics in pp with high acceptance to lower p_T
    - with high-η detectors chosen for precision rather than radiation (especially HadCal, currently extended to $|\eta| < 2.8$)
    - **using well-calibrated detector through DIS events**

Design of the Interaction Region for Concurrent e-p and p-p Operation @ FCC

Summary Statements at FCC Conference London [4]:

- An electron interaction region has been optimised to minimise the synchrotron radiation power
- The local impact of the electron magnets on the proton beam orbit and optics can be corrected in the new FCC-hh lattice
- 2 schemes to separate the proton beams have been designed for the LHeC → they can be adapted for the FCC-eh
- **Outlook:** implement both separation schemes into the new hh lattice (for HL-LHC)
- Tracking simulations to investigate the impact of the proton beams on each other