

# The LHeC – an Experiment for the LHC



Max Klein, University of Liverpool, for the LHeC/FCC-eh Study Group



Circles in a circle  
W Kandinsky

## The LHeC Project

Physics of DIS

Detector [Overview, IR, Components]

Joint eA - AA Detector Option

Summary

At this workshop

Oliver Bruening: Monday HL-LHC and LHeC Option

Bruce Mellado: Higgs Physics with ep

CDR: 1206.2913 J.Phys.G

Update:2007.14491, J.Phys.G  
to appear

Energy frontier deep inelastic scattering - following HERA: 1992-2007: 27 x 920 GeV<sup>2</sup>: 0.3 TeV ep collider

Presented to the HK Conference, 19.1.2021.

Kevin Andre, Nestor Armesto, Oliver Bruening, Andrea Gaddi, Bernhard Holzer, John Jowett, Uta Klein, Peter Kostka, Bruce Mellado, Paul Newman, Ercan Pilicer, Alessandro Polini, Eva Villela, Yuji Yamazaki

special thanks to

# LHeC, PERLE and FCC-eh



50 x 7000 GeV<sup>2</sup>: 1.2 TeV ep collider

Operation: 2035+, Cost: O(1) BCHF

CDR: 1206.2913 J.Phys.G (550 citations)

Upgrade to 10<sup>34</sup> cm<sup>-2</sup>s<sup>-1</sup>, for Higgs, BSM

CERN-ACC-Note-2018-0084 (ESSP)

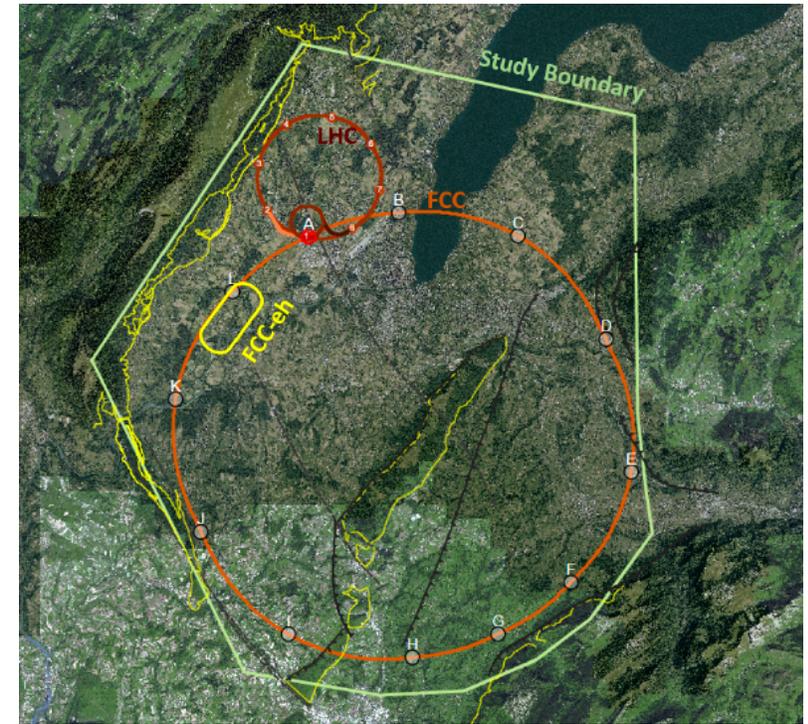
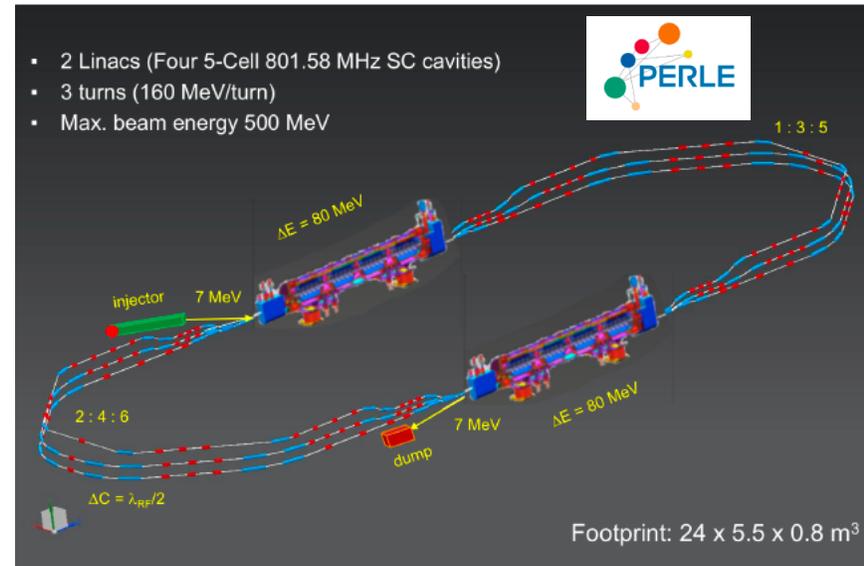
arXiv:2007.14491, subm J.Phys.G

Powerful ERL for Experiments @ Orsay  
 CDR: 1705.08783 J.Phys.G  
 CERN-ACC-Note-2018-0086 (ESSP)

Operation: 2025+, Cost: O(20) MEuro

LHeC ERL Parameters and Configuration  
 $I_e=20\text{mA}$ , 802 MHz SRF, 3 turns  $\rightarrow$   
 $E_e=500\text{ MeV}$   $\rightarrow$  first 10 MW ERL facility

BINP, CERN, Cornell, Daresbury, Jlab, Liverpool, Orsay, +



60 x 50000 GeV<sup>2</sup>: 3.5 TeV ep collider

Operation: 2050+, Cost (of ep) O(1-2) BCHF

Concurrent Operation with FCC-hh

FCC CDR:

*Eur.Phys.J.ST* 228 (2019) 6, 474 Physics

*Eur.Phys.J.ST* 228 (2019) 4, 755 FCC-hh/eh

Future CERN Colliders: 1810.13022 Bordry+

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Geneva, July 28, 2020



## The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group



arXiv:2007:14491 (400 pages, 300 authors)

To be submitted to J. Phys. G

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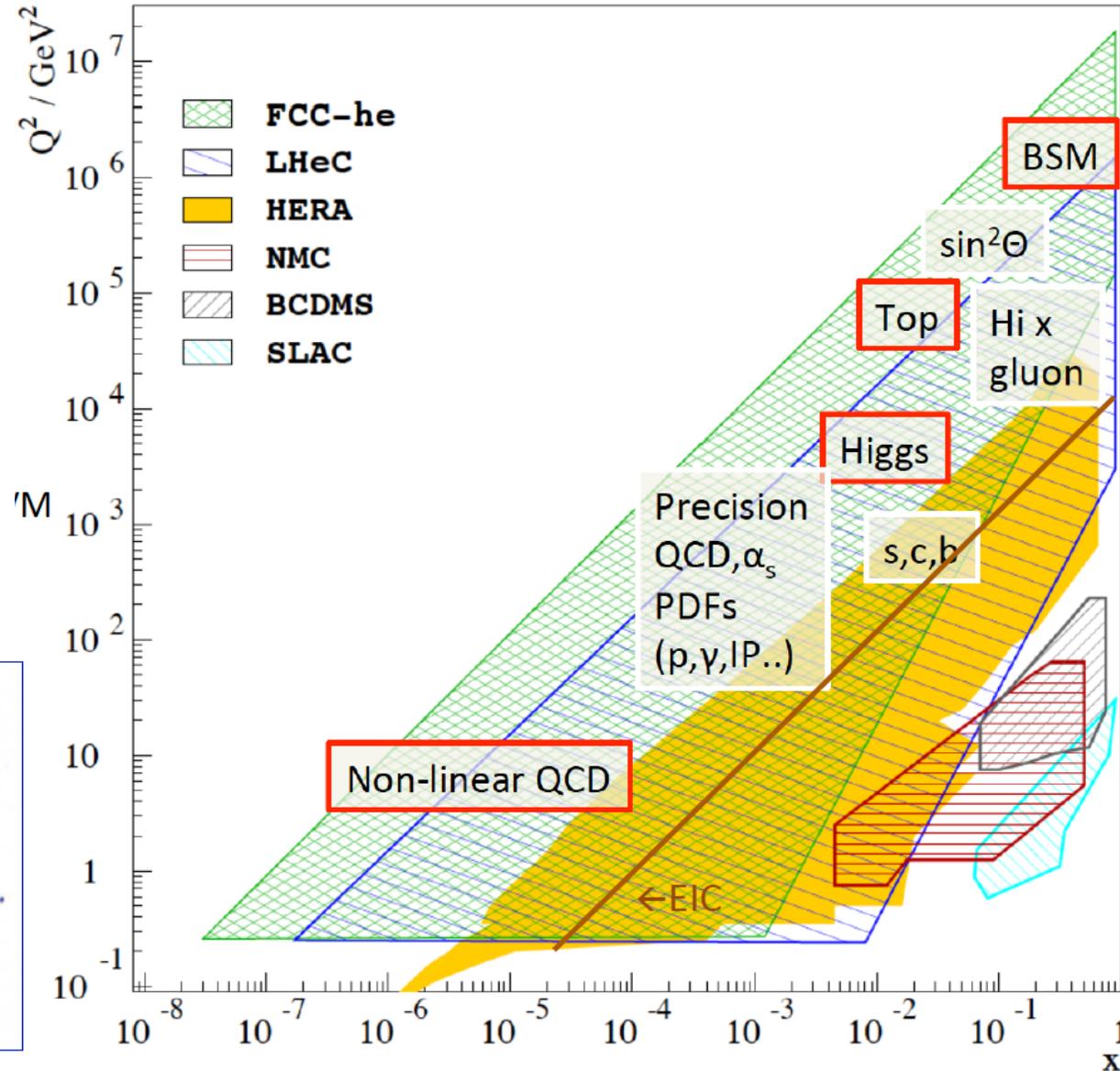
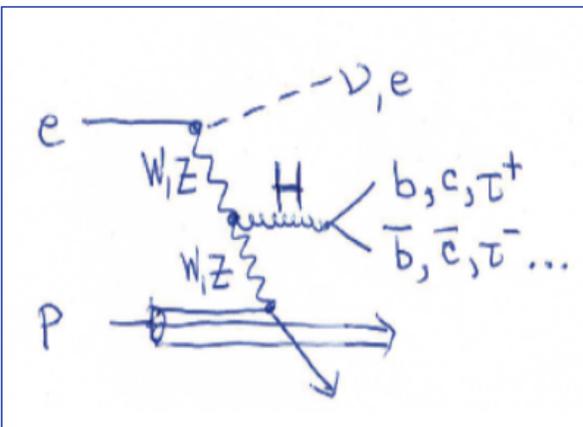
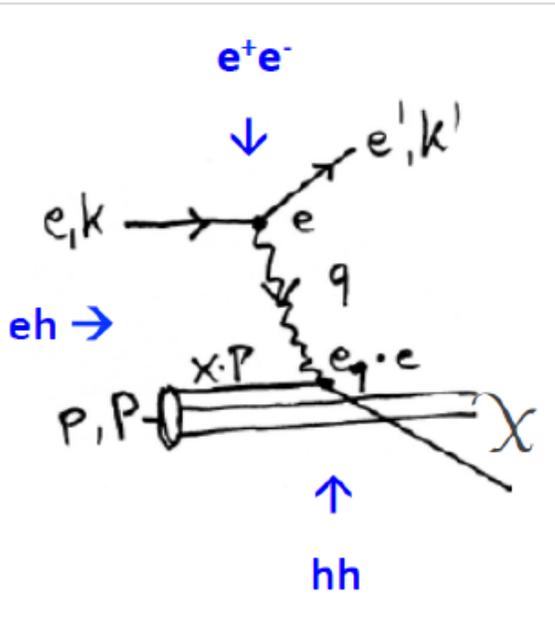
5 page summary: ECFA Newsletter Nr 5., August 20

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

156 Institutions involved

# Physics with Energy Frontier DIS

Deep Inelastic Scattering



**Raison(s) d'être of ep/eA at the energy frontier**

Cleanest High Resolution Microscope: QCD Discovery

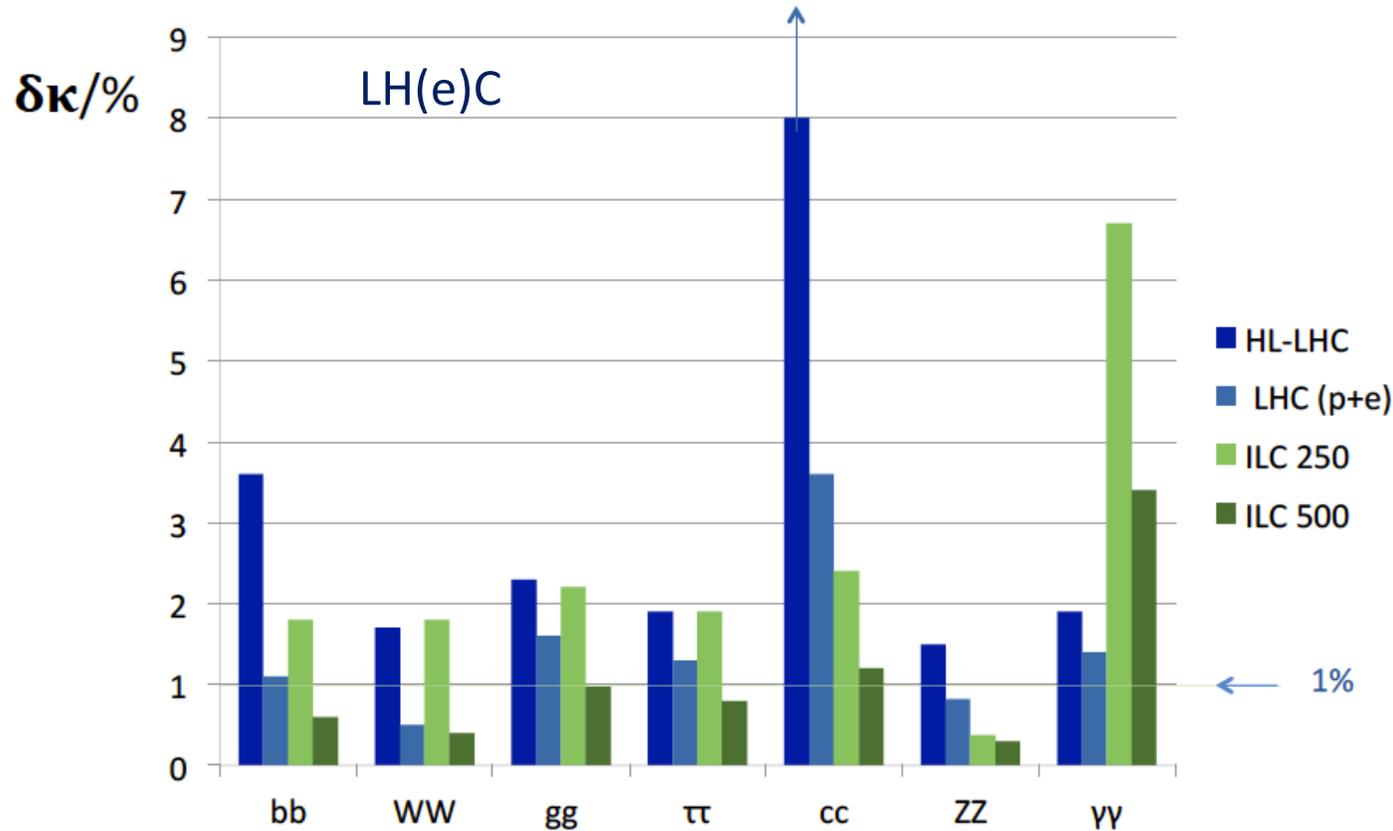
Empowering the LHC/FCC Search Programme

Transformation of LHC/FCChh into high precision Higgs facility

Discovery (top, H, heavy  $\nu$ 's..) Beyond the Standard Model

A Unique Nuclear Physics Facility

# Higgs in ep and pp [LHC and FCC]

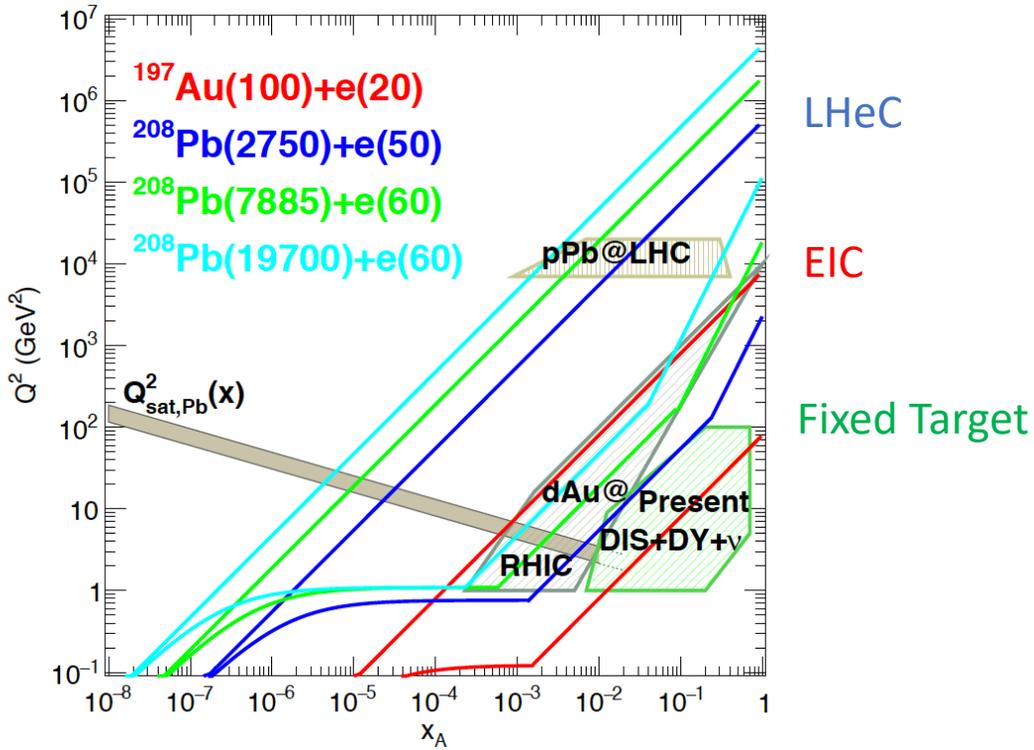


**Fig.1:** Results of prospect evaluations of the determination of Higgs couplings in the SM kappa framework for HL-LHC (dark blue), LHC with LHeC combined (p+e, light blue), ILC 250 (light green) and ILC-500 (dark green).

Collider	FCC-ee	FCC-eh
Luminosity ( $\text{ab}^{-1}$ )	+1.5 @ 365 GeV	2
Years	3+4	20
$\delta\Gamma_{\text{H}}/\Gamma_{\text{H}}$ (%)	<b>1.3</b>	SM
$\delta g_{\text{HZZ}}/g_{\text{HZZ}}$ (%)	<b>0.17</b>	0.43
$\delta g_{\text{HWW}}/g_{\text{HWW}}$ (%)	<b>0.43</b>	0.26
$\delta g_{\text{Hbb}}/g_{\text{Hbb}}$ (%)	<b>0.61</b>	0.74
$\delta g_{\text{Hcc}}/g_{\text{Hcc}}$ (%)	<b>1.21</b>	1.35
$\delta g_{\text{Hgg}}/g_{\text{Hgg}}$ (%)	<b>1.01</b>	1.17
$\delta g_{\text{H}\tau\tau}/g_{\text{H}\tau\tau}$ (%)	<b>0.74</b>	1.10
$\delta g_{\text{H}\mu\mu}/g_{\text{H}\mu\mu}$ (%)	<b>9.0</b>	n.a.
$\delta g_{\text{H}\gamma\gamma}/g_{\text{H}\gamma\gamma}$ (%)	<b>3.9</b>	2.3
$\delta g_{\text{H}tt}/g_{\text{H}tt}$ (%)	–	1.7
$\text{BR}_{\text{EXO}}$ (%)	<b>&lt; 1.0</b>	n.a.

Prospects for high precision measurements of **Higgs couplings at FCC ee and ep**. Note ee gets the width with Z recoil. ee is mainly ZHZ, while ep is mainly WWH: complementary also to pp

# Partons in Nuclei

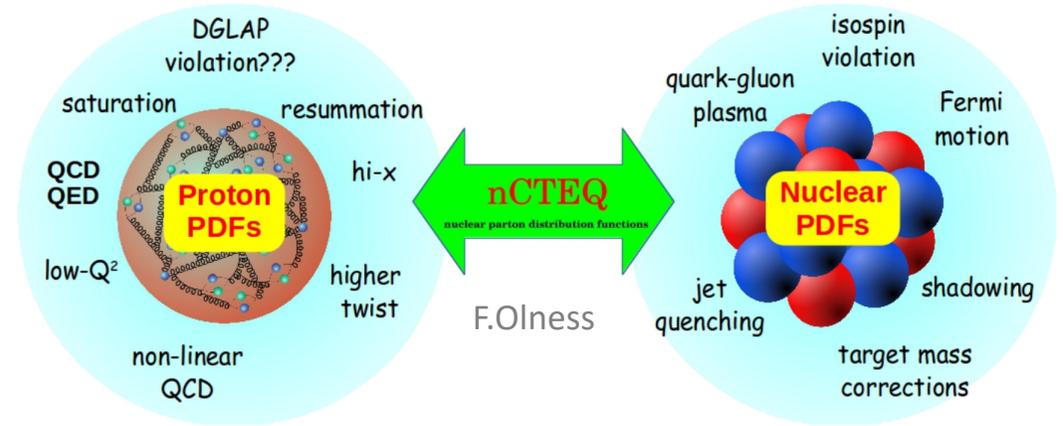


Direct measurements of R:

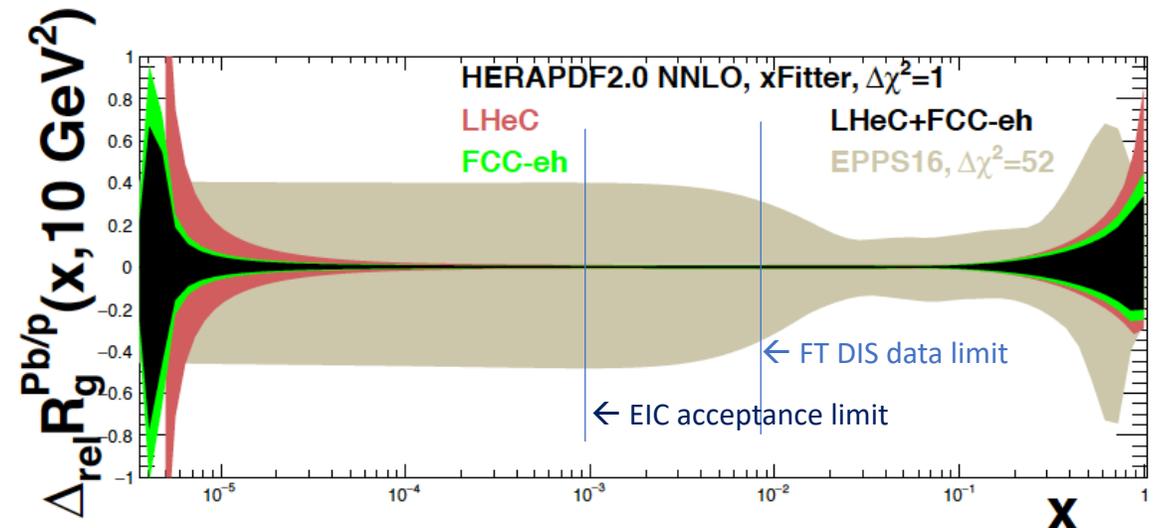
$$R_i(x, Q^2) = \frac{f_i^A(x, Q^2)}{A f_i^p(x, Q^2)}, \quad i = u, d, s, c, b, g, \dots$$

Resolution of complete quark and gluon structure (NC+CC)  
 Disentanglement of nuclear + parton dynamic effects  
 Deep into saturation region with small strong coupling (pQCD)

## Complexity of (de) confinement in proton and nuclei



## Direct determination of $R_g$ with proton and lead data, full error



# Detector Requirements and Characteristics

NC Cross Section Correlated Uncertainties ( $Q^2=20000 \text{ GeV}^2$ )

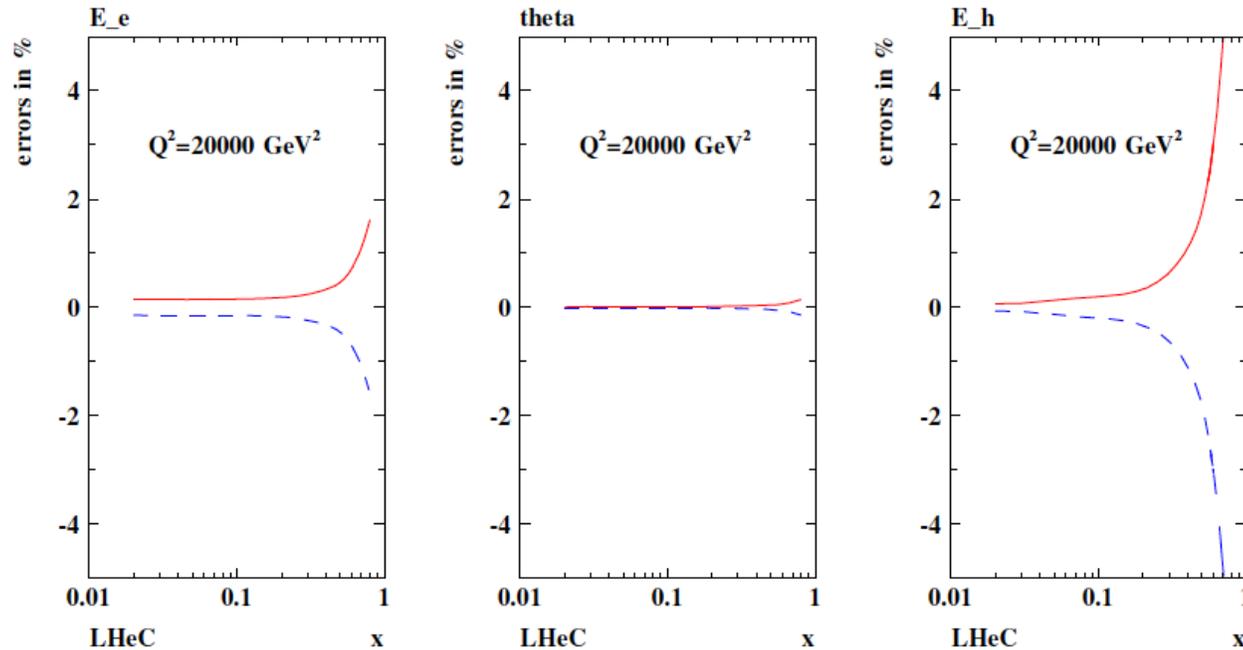


Figure 3.3: Neutral current cross section errors, calculated for  $60 \times 7000 \text{ GeV}^2$  unpolarised  $e^-p$  scattering, resulting from scale uncertainties of the scattered electron energy  $\delta E'_e/E'_e = 0.1\%$ , of its polar angle  $\delta\theta_e = 0.1 \text{ mrad}$  and the hadronic final state energy  $\delta E_h/E_h = 0.5\%$ , at large  $Q^2 = 20000 \text{ GeV}^2$  and correspondingly large  $x$ . Note that the characteristic behaviour of the relative uncertainty at large  $x$ , i.e. to diverge  $\propto 1/(1-x)$ , is independent of  $Q^2$ , i.e. persistently observed at  $Q^2 = 200000 \text{ GeV}^2$  for example too.

- No pile-up, low radiation level, clean events

- Clear distinction of NC and CC

- e-h redundant kinematic reconstruction  $\rightarrow$  potential for very high precision (e.g. cf left)

- High resolution of hadronic final state

$\rightarrow$  Base of BSM discovery (long lived, r.h neutrinos, Higgsinos..) 2007.14491  
Find rare signatures that are in the hh 'noise' [similar to ee, but t channel]

$\rightarrow$  Very high precision: PDF, top, H, eweak, ...

Characteristics:

5-10  $\mu\text{m}$  impact parameter resolution [c,b]

5-10%/sqrt(E) electromagnetic

30-50%/sqrt(E) hadronic, small constant terms

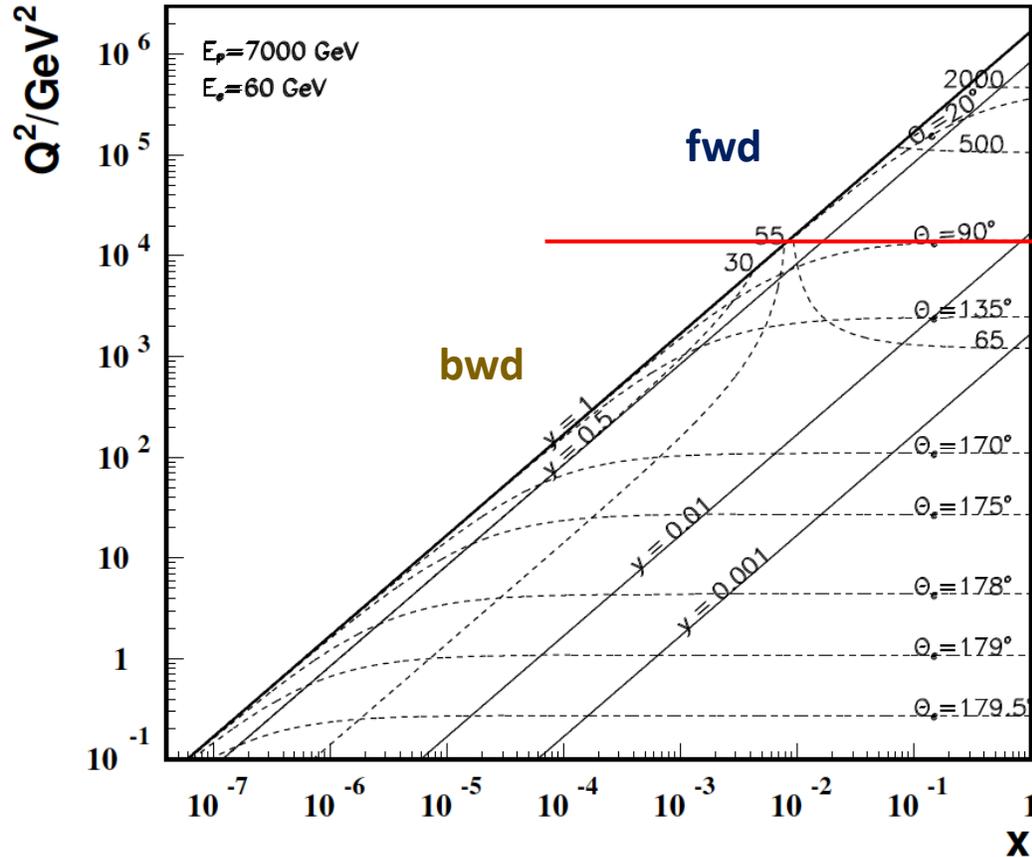
Rapidity range of up to 5 (low  $Q^2$ , high  $x$ , Higgs)

focus: feasibility design(s): initially 2012: DIS

$\rightarrow$  updated 2020: Higgs, technology, FCC-eh

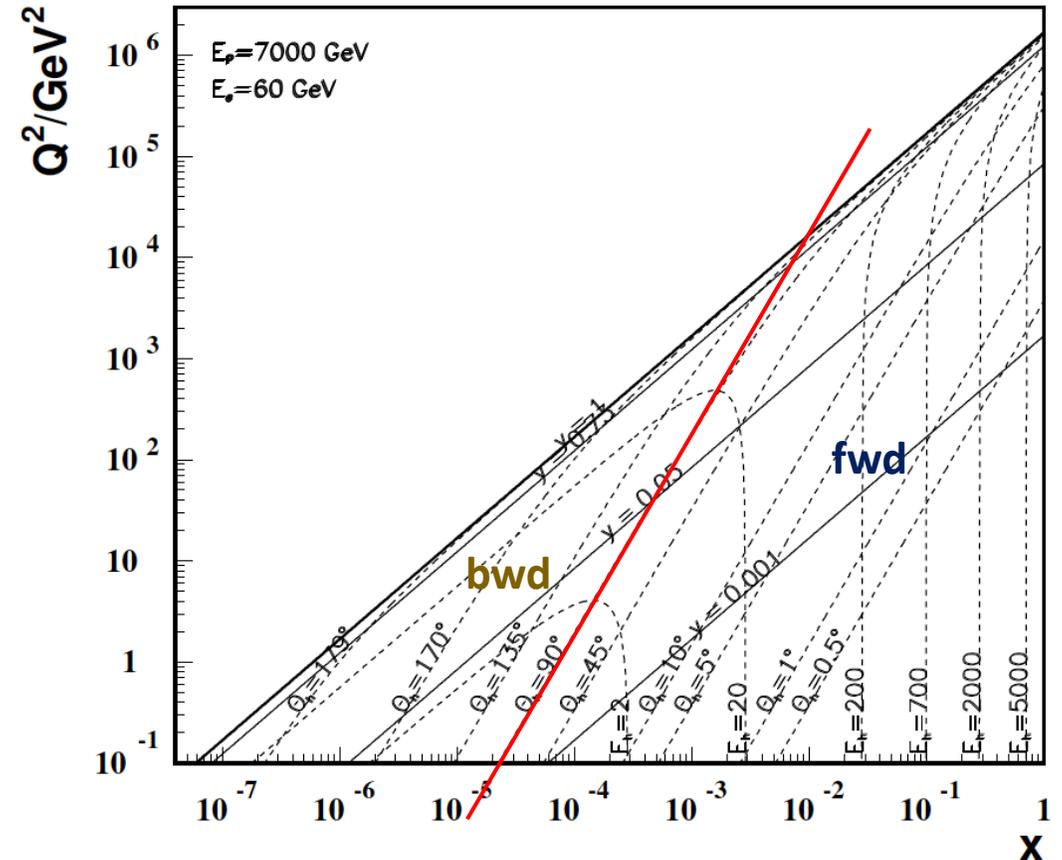
# Kinematics: fwd: in p beam direction, bwd: e direction

LHeC - electron kinematics



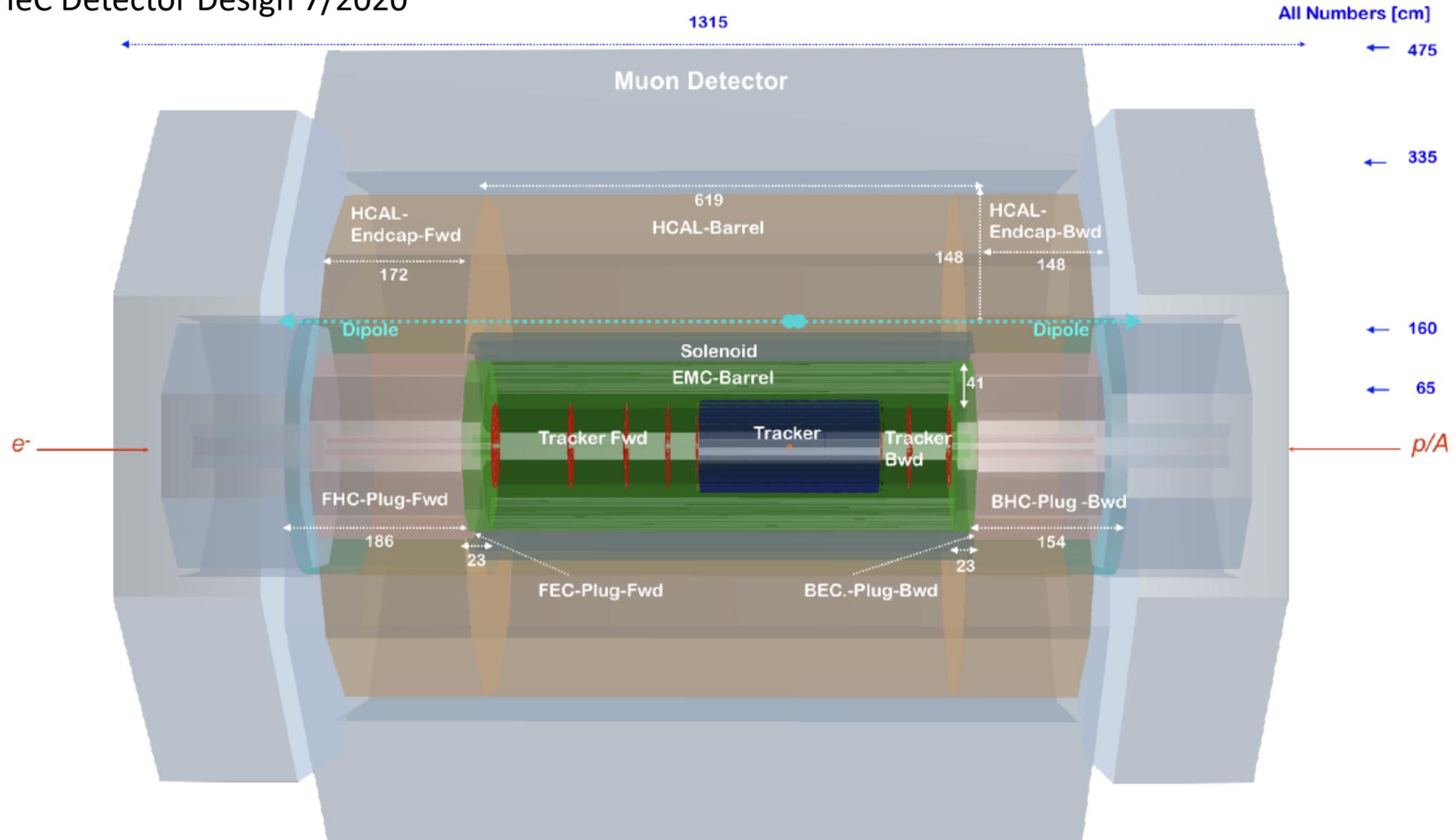
**Electrons** in bwd direction have low energy ( $E'_e < E_e$  beam)  
 in fwd direction high energy up to  $E_p$ , Rutherford backscattering  
 $Q^2=1$  GeV<sup>2</sup> is  $179^\circ$ , or  $\eta = 4.74 = \ln \tan \theta/2$ ,  $\sim E_e^2$  !

LHeC - hadronic final state kinematics



Hadrons in bwd direction have low energy  $E_h < E_e$  beam  
 in fwd direction hadrons carry energy up to  $E_p$  beam

→ Asymmetric energy coverage of LHeC detector. Fwd region: resembles hh conditions



No pile up, low radiation wrt pp; high precision through overconstrained kinematics: e-h; modular for rapid installation  
 Tracker radius 40 → 60cm, B 3.5T; LxD = 13 x 9m<sup>2</sup> [CMS 21 x 15m<sup>2</sup>, ATLAS 45 x 25 m<sup>2</sup>]. Software: DD4HEP (P.Kostka et al)

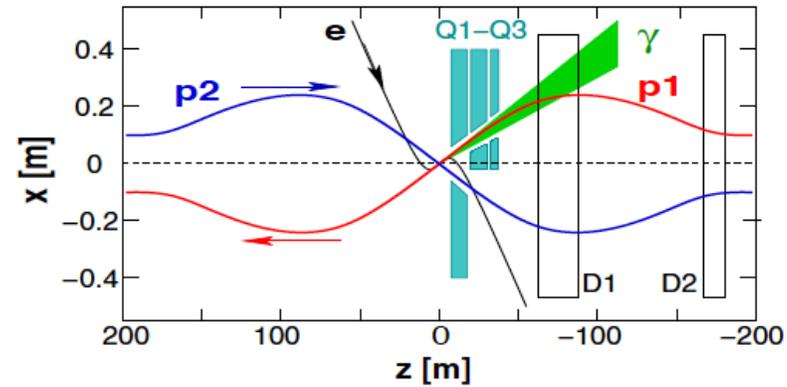
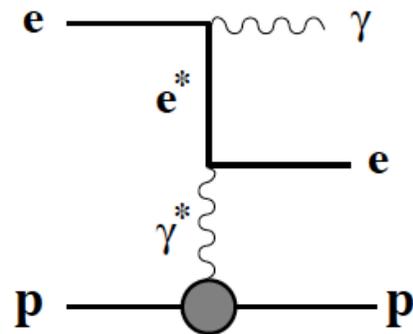
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**LHeC Detector (Initial Design)  
Detailed Descripton in the CDR (1206.2913)**

**Update in 2007.14491**

# Bethe Heitler - Luminosity measurement at the LHeC

CDR  
1206.2913  
JPhysG39  
075001(12)  
p561-566



Method	Stat. error	Syst.error	Systematic error components	Application	
BH ( $\gamma$ )	0.05%/sec	1–5%	$\sigma(E \gtrsim 10\text{GeV})$ acceptance, $A$ $E$ -scale, pileup	0.5% $10\%(1-A)$ 0.5 – 4%	Monitoring, tuning, short term variations
BH ( $e$ )	0.2%/sec	3–6%	$\sigma(E \gtrsim 10\text{GeV})$ acceptance background $E$ -scale	0.5% 2.5 – 5% 1% 1%	Monitoring, tuning, short term variations
QEDC	0.5%/week	1.5%	$\sigma(\text{el/inel})$ acceptance vertex eff. $E$ -scale	1% 1% 0.5% 0.3%	Absolute $\mathcal{L}$ , global normalisation
NC DIS	0.5%/h	2.5%	$\sigma(y < 0.6)$ acceptance vertex eff. $E$ -scale	2% 1% 1% 0.3%	Relative $\mathcal{L}$ , mid-term variations

Table 13.1: Dominant systematics for various methods of luminosity measurement.

LR: photon detector  
← acceptance 95%

→ Luminosity from  
BH photons to 1%

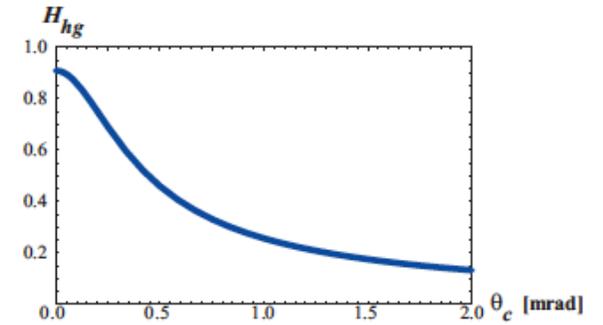
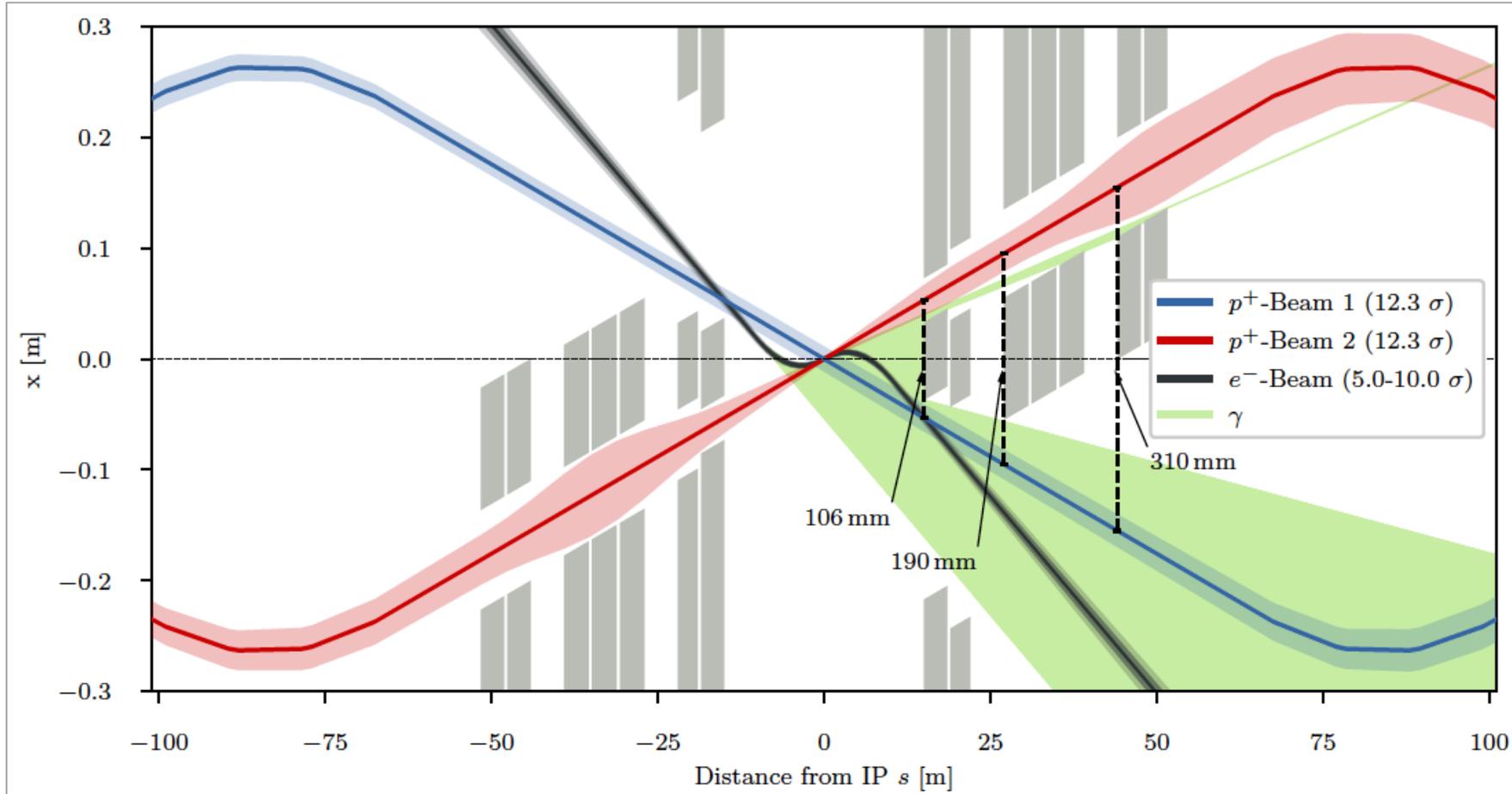
Needs BH Thy to another  
Order to reach below %

... BH( $e$ ), QEDCompton,  
and DIS/ $F_2$  as cross checks

Forward  
Taggers:

See Yuji  
Yamazaki  
at ICHEP  
and in  
2007.14491

# 3-beam ep/eA Interaction Region



$$H_{hg} = \frac{\sqrt{\pi} z e^{z^2} \operatorname{erfc}(z)}{S},$$

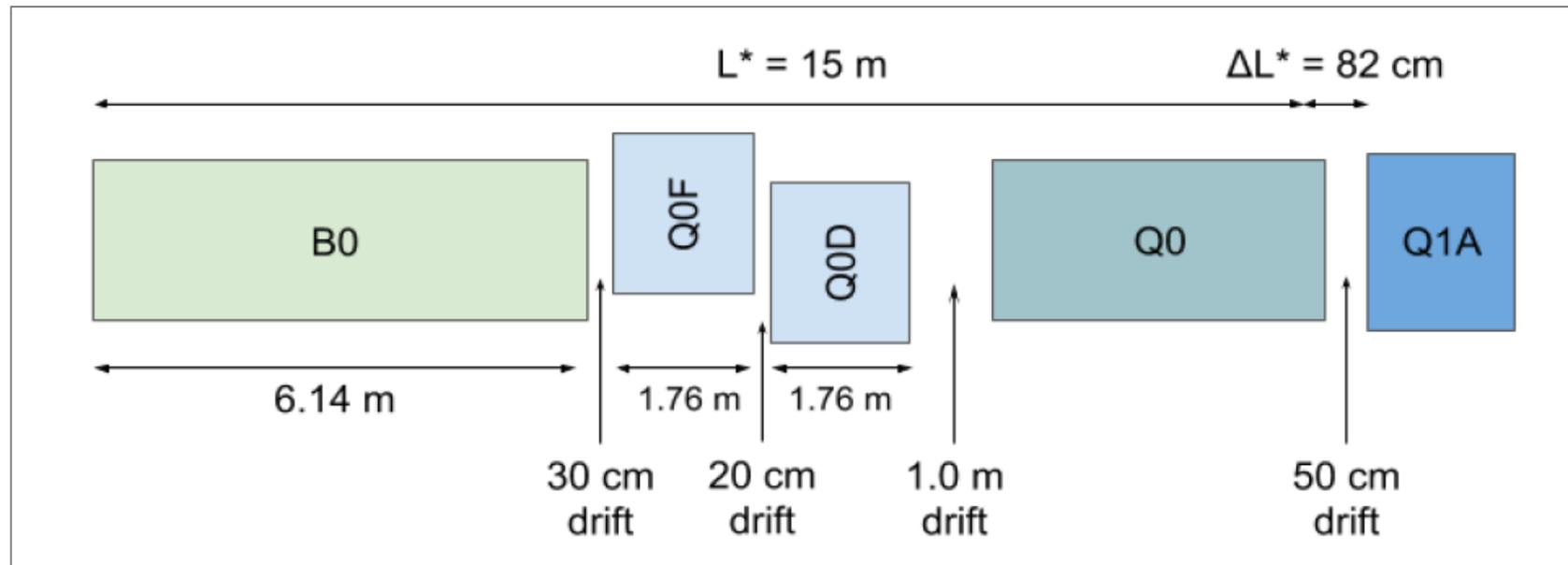
$$z \equiv 2 \frac{(\beta_e^* / \sigma_{z,p})(\epsilon_e / \epsilon_p)}{\sqrt{1 + (\epsilon_e / \epsilon_p)^2}} S$$

$$S \equiv \sqrt{1 + \frac{\sigma_{x,p}^2 \theta_c^2}{8 \sigma_p^{*2}}}$$

Synchronous ep/pp operation! Non-interacting p beam to freely pass: aperture  
Matching e and p beam sizes (experience from HERA, also for magnet placement)

Head-on collisions →  
Dipole magnet before  
Hadron Calorimeter

# Optimised Interaction Region Design 2007.14491



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

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

Detector dipole

Staggered quads

Half-quad (NC)

First of triplet quadrupoles

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

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

# Q1 and further Quadrupoles

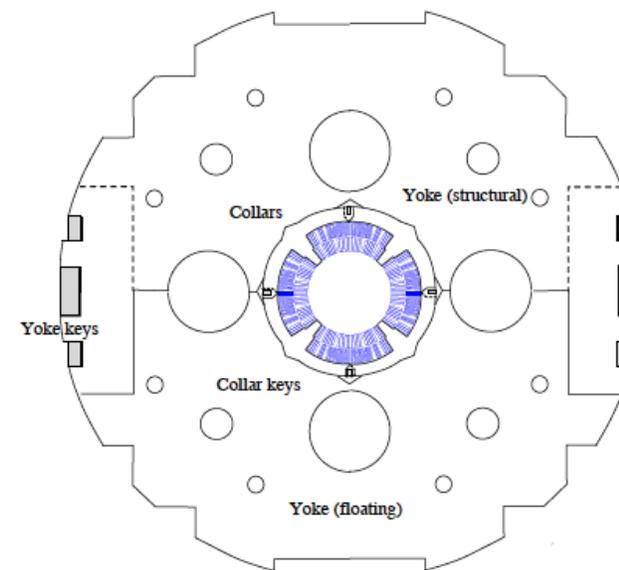
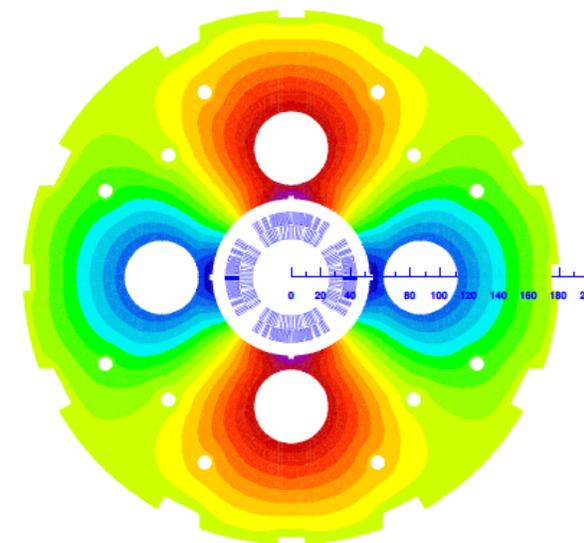
Magnet parameter	Unit	Magnet type			
		Q1A	Q1B	Q2 type	Q3 type
Superconductor type		Nb-Ti	Nb-Ti	Nb <sub>3</sub> Sn	Nb <sub>3</sub> Sn
Coil aperture radius $R$	mm	20	32	40	45
Nominal current $I_{\text{nom}}$	A	7080	6260	7890	9260
Nominal gradient $g$	T/m	252	164	186	175
Percentage on the load line	%	78	64	71	75
Beam separation distance $S_{\text{beam}}$	mm	106-143	148-180	233-272	414-452

**Table 10.28:** Main triplet magnet parameters

Q2, Q3 desirably NOT Nb<sub>3</sub>Sn but Nb-Ti as suggested by current experience

B Holzer, S Russenschuck

Aperture of Q1A needs study, when non-colliding p beam is kept in vacuum



It will look like.....a stretched and squeezed ATLAS solenoid,  
 2 T scaled up to 3.5T (2 layer coil, slightly less free bore but a bit longer)



Relatively small bore but long, and efficient coil with 1.8 m free bore, 7.1 m long

- $\approx 11$  km Al stabilized NbTi/Cu superconductor for 10 kA
- $\approx 80$  MJ stored energy and  $\approx 24$  t mass including cryostat.

H ten Kate (EP-RD, 16.3.18)

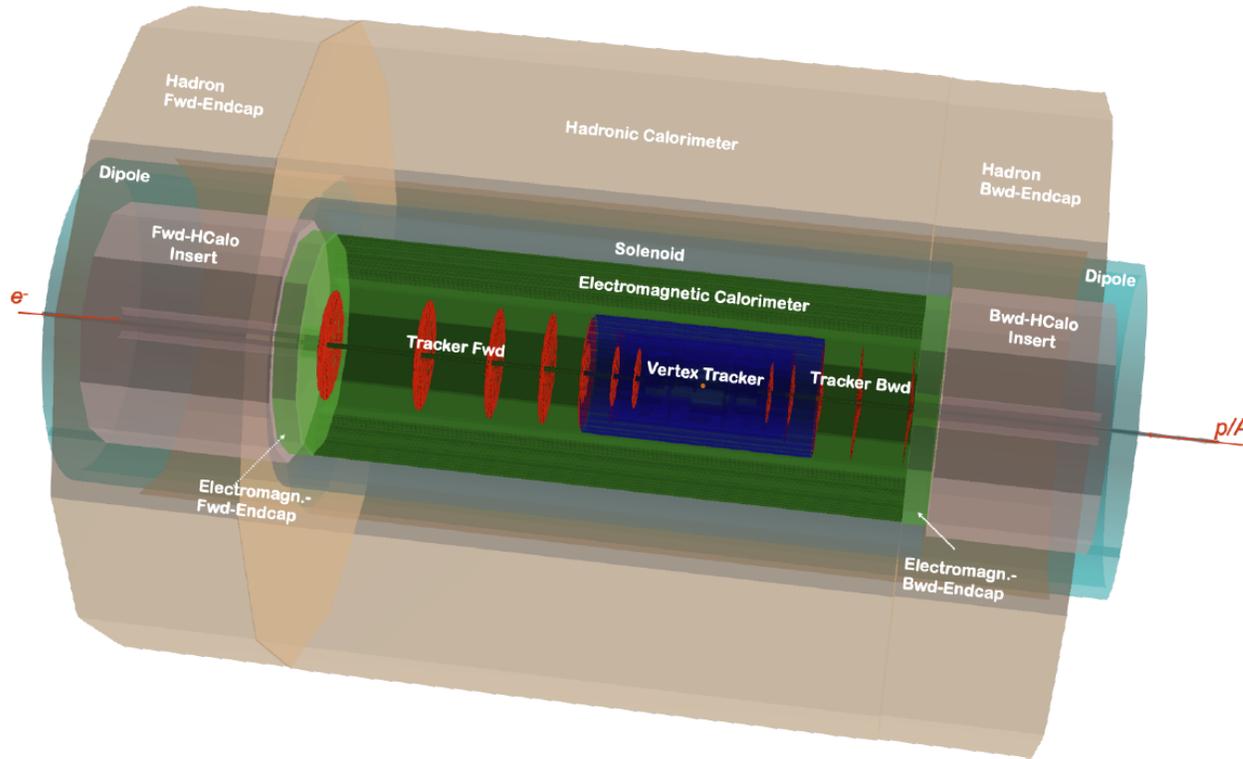
**No specific R&D needed, except detailed analysis of the dipole load case**

- Design concept: minimum cost, R&D and risk, relies on present technology for detectors magnets
- **3.5 T Solenoid & 2 Dipoles** in same cryostat around EMC, Muon tagging chambers in outer layer
- **Solenoid and dipoles have a common support cylinder in a single cryostat**; free bore of 1.8 m; extending along the detector with a length of 10 m.

For magnet specs, see  
 CDR: arXiv:1206.2913

New ideas on  
 thin solenoids

# LHeC Calorimeters



Complete coverage to  $\pm 5$  in (pseudo)rapidity

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

Forward Region: dense, high energy jets of few TeV

H  $\rightarrow$  bb and other reactions demand resolution of HFS

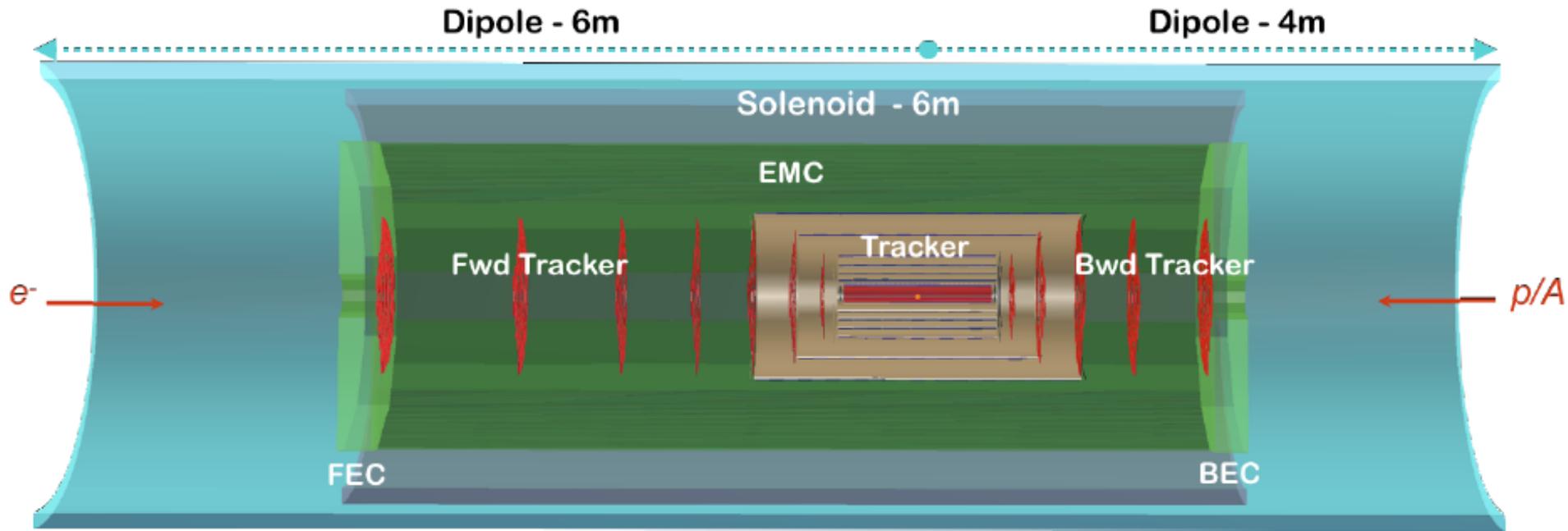
Backward Region: in DIS energy deposits of  $< E_e$

## Barrel Calorimeters

## Forward/Backward Calorimeters

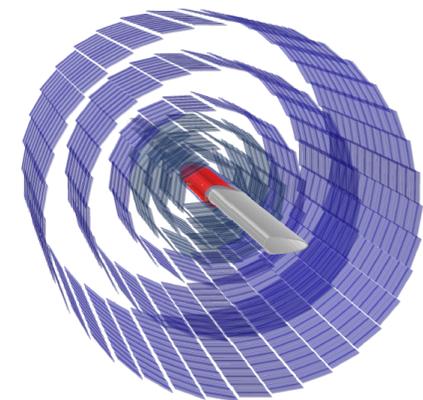
Calo (LHeC)	EMC		HCAL	
	Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber Layers	Sci,Pb 38	Sci,Fe 58	Sci,Fe 45	Sci,Fe 50
Integral Absorber Thickness [cm]	16.7	134.0	119.0	115.5
$\eta_{\max}, \eta_{\min}$	2.4, -1.9	1.9, 1.0	1.6, -1.1	-1.5, -0.6
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	12.4/1.9	46.5/3.8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

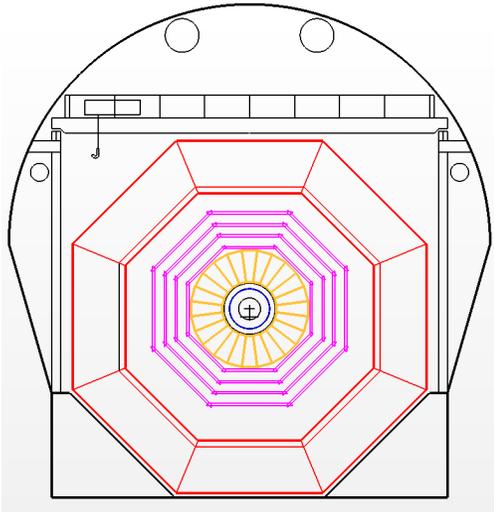
Calo (LHeC)	FHC	FEC	BEC	BHC
	Plug Fwd	Plug Fwd	Plug Bwd	Plug Bwd
Readout, Absorber Layers	Si,W 300	Si,W 49	Si,Pb 49	Si,Cu 165
Integral Absorber Thickness [cm]	156.0	17.0	17.1	137.5
$\eta_{\max}, \eta_{\min}$	5.5, 1.9	5.1, 2.0	-1.4, -4.5	-1.4, -5.0
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	51.8/5.4	17.8/1.4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



Inner Tracker  
 Rapidity to  $\sim 5$   
 $r_0 = 60$  cm  
 impact resolution  
 5-10  $\mu\text{m}$   
 40.7  $\text{m}^2$  Si

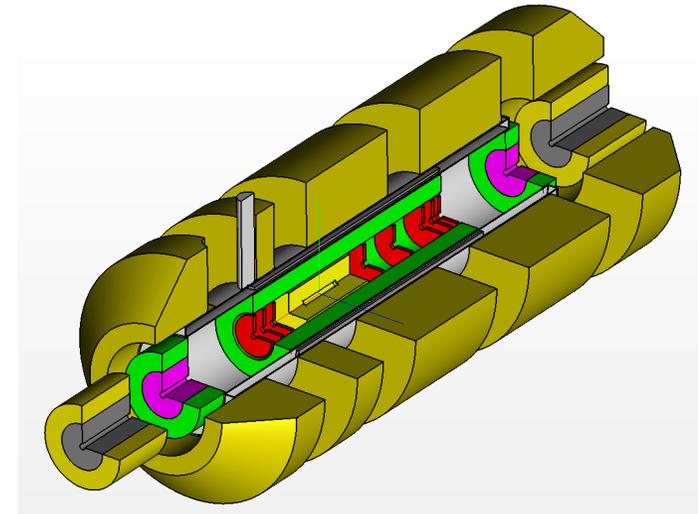
Tracker (LHeC)	Fwd Tracker			Bwd Tracker		Total (incl. Tab. 12.1)
	pix	pix <sub>macro</sub>	strip	pix <sub>macro</sub>	strip	
$\eta_{\text{max}}, \eta_{\text{min}}$	5.3, 2.6	3.5, 2.2	3.1, 1.6	-4.6, -2.5	-2.9, -1.6	5.3, -4.6
Wheels	2	1	3	2	4	
Modules/Sensors	180	180	860	72	416	10736
Total Si area [ $\text{m}^2$ ]	0.8	0.9	4.6	0.4	1.8	40.7
Read-out-Channels [ $10^6$ ]	404.9	68.9	26.4	27.6	10.6	2934.2
pitch <sup><math>r-\phi</math></sup> [ $\mu\text{m}$ ]	25	100	100	100	100	
pitch <sup><math>z</math></sup> [ $\mu\text{m}$ ]	50	400	50k <sup>2)</sup>	400	10k <sup>1)</sup>	
Average $X_0/\Lambda_I$ [%]	6.7 / 2.1			6.1 / 1.9		
incl. beam pipe [%]						40 / 25





Detector fits in L3 magnet support

# Installation Study



Modular structure

## LHeC INSTALLATION SCHEDULE

ACTIVITY	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
DETECTOR CONSTRUCTION ON SITE TO START BEFORE LHC LONG SHUT-DOWN								
<i>LHC LONG SHUTDOWN START (T0)</i>								
COIL COMMISSIONING ON SURFACE	█							
ACTUAL DETECTOR DISMANTLING	█	█						
PREPARATION FOR LOWERING		█						
LOWERING TO CAVERN			█	█	█	█	█	
HCAL MODULES & CRYOSTAT			█	█	█			
CABLES & SERVICES				█	█	█	█	
BARREL MUON CHAMBERS				█	█			
ENDCAPS MUON CHAMBERS					█	█		
TRACKER & CALORIMETER PLUGS						█	█	
BEAMPIPE & MACHINE								█
DETECTOR CHECK-OUT								█
<i>LHC LONG SHUTDOWN END (T0+24m)</i>								█

Detector Installation possible within about two-years shutdown: pre-mounting on surface

LHeC should not delay main LHC programme in any significant way.

# Integration of eA and AA Detector Concepts

Novel thought/study first mentioned in: <https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf>

Could one merge the LHeC (2007.14491) and a novel Heavy Ion detector (“A3”, 1902.01211) concepts? in order to commonly use the Interaction Region 2 (near St Genis). If yes have two kinds of operations:

- a) hh: pp or AA data taking in all 4 IPs of LHC
- b) eh and hh: eh data taking in IP2 synchronous to hh data taking by ATLAS, CMS and LHCb

This enriches the physics potential, and requires study of the joint detector and to the IR design. First thoughts:

# What we can learn in an ep/eA collider

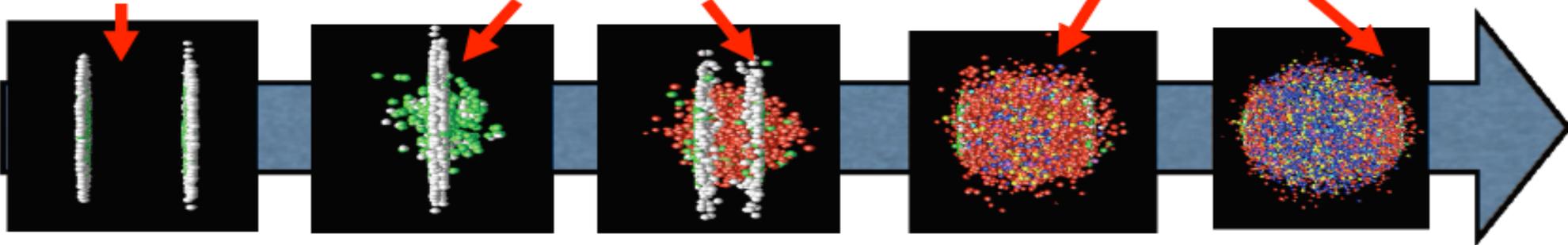
We do not have a **QUANTITATIVE** understanding of the nuclear behaviour

required for A-A and QGP studies

The colliding objects

Early stages

Analyzing the medium



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

Dense regime: lack of information about

- small-x partons
- correlations
- transverse structure

Particle production at the very beginning:

- Which factorization?
- How can a system behave as isotropised so fast?

Probing the medium through energetic particles:

- Dynamical mechanisms for opacity
- How to extract accurately medium parameters?

ep and eA:

- nuclear WF & PDFs
- mechanism of particle production
- tomography

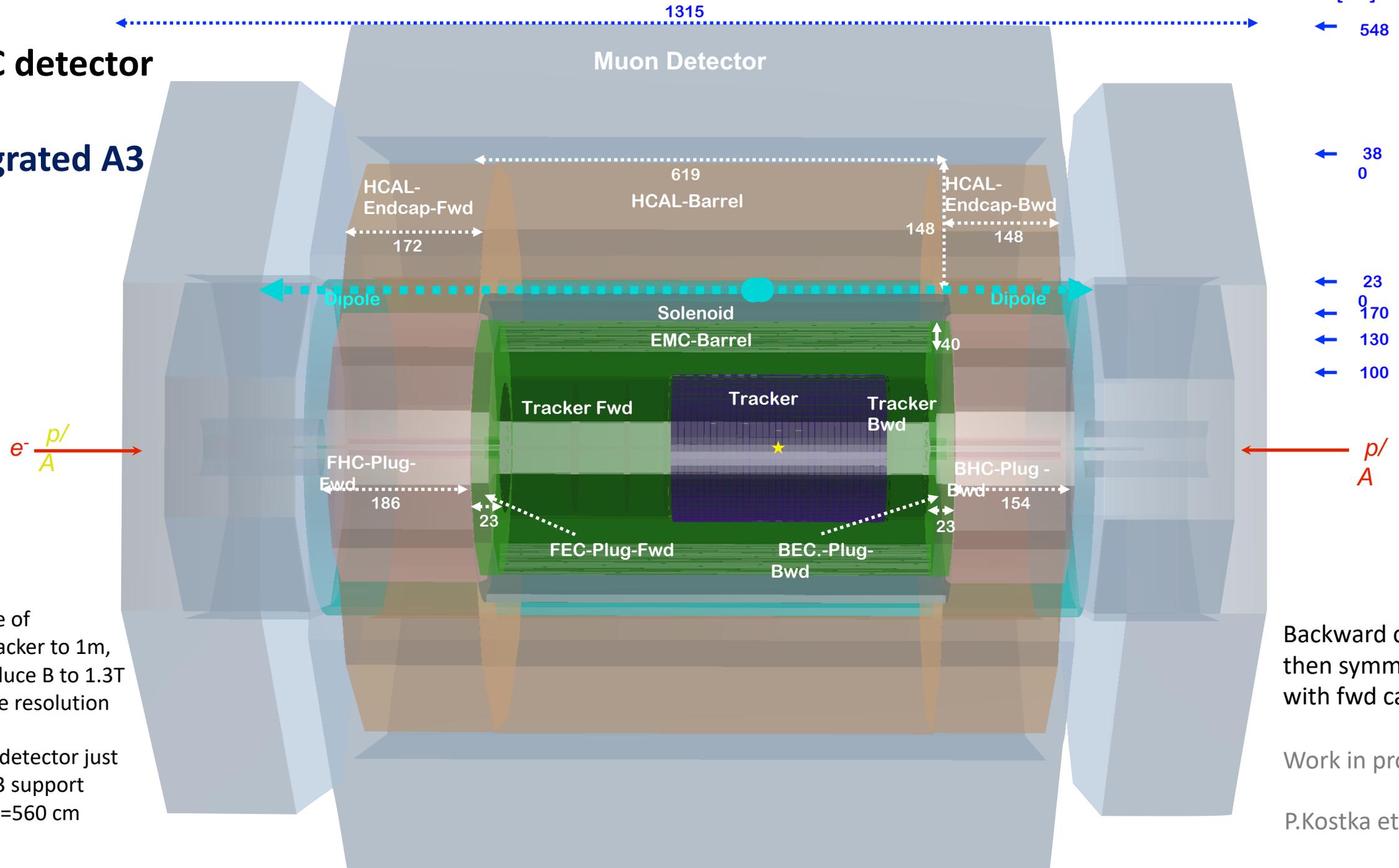
ep and eA:

- initial conditions for plasma formation
- how small can a system be and still show collectivity?

ep and eA:

- modification of radiation and hadronization in the nuclear medium
- initial effects on hard probes

# LHeC detector with integrated A3



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

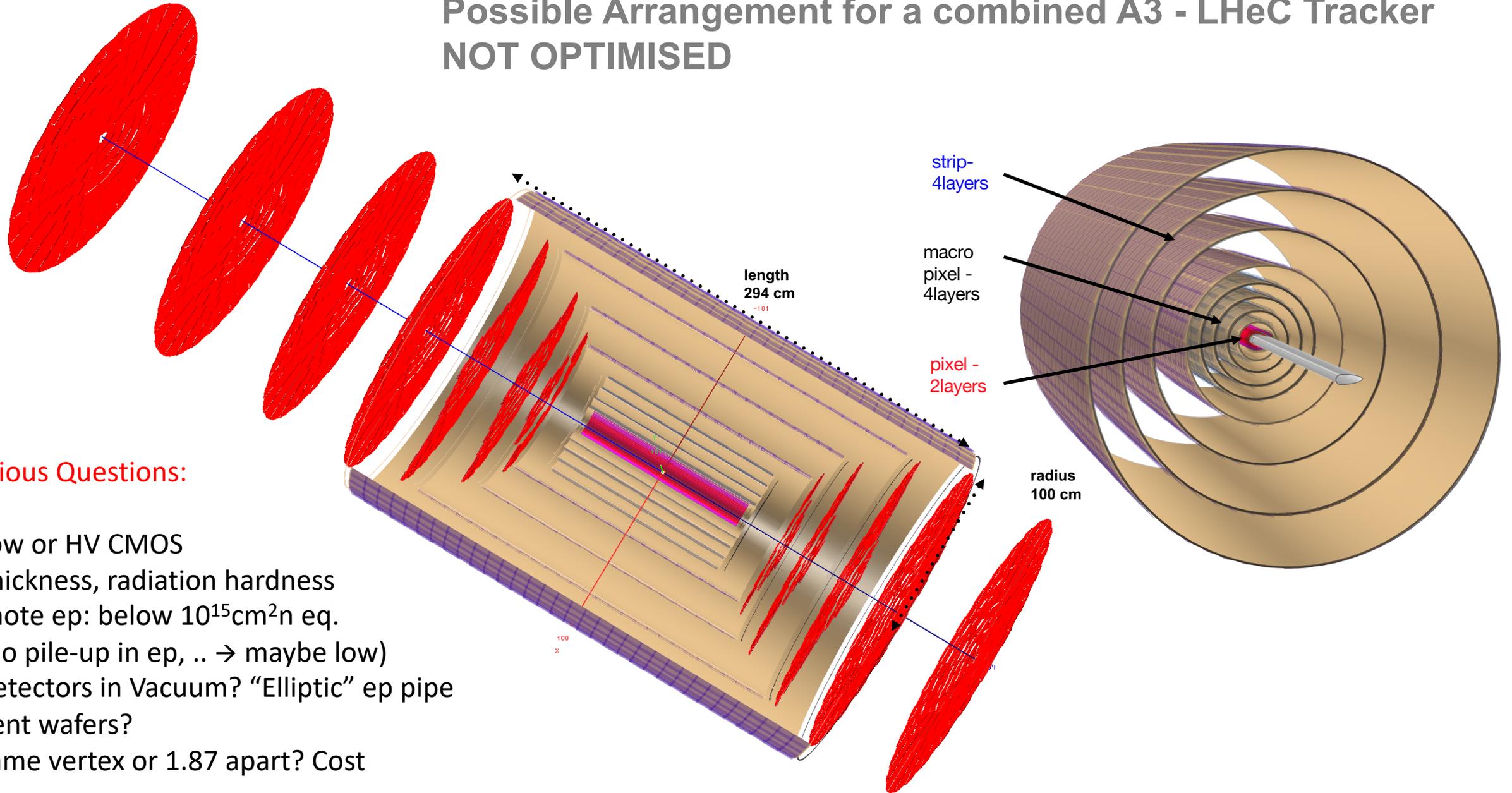
Overall detector just fits in L3 support  
 $R_{free}(L3)=560\text{ cm}$

Backward calos then symmetric with fwd calos

Work in progress

P.Kostka et al.

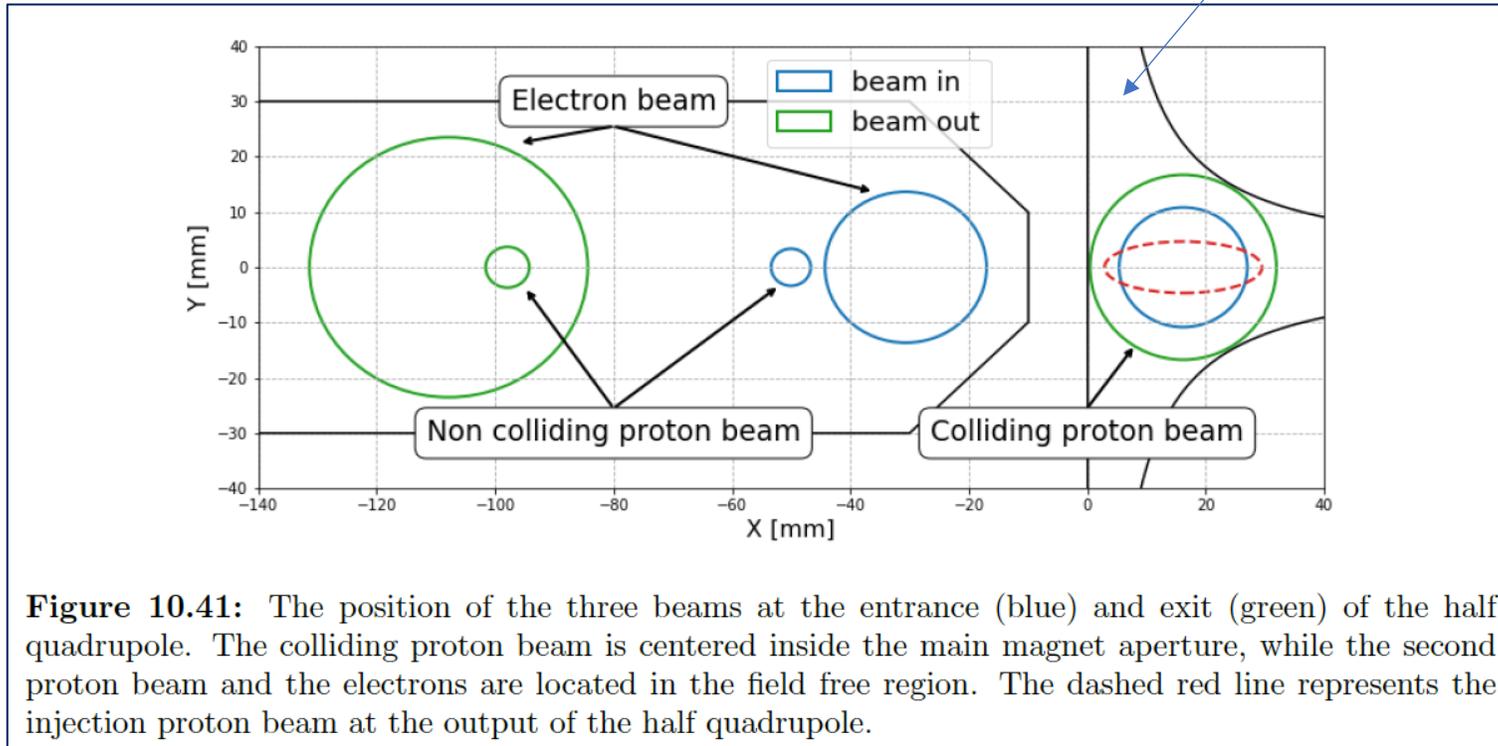
# Possible Arrangement for a combined A3 - LHeC Tracker NOT OPTIMISED



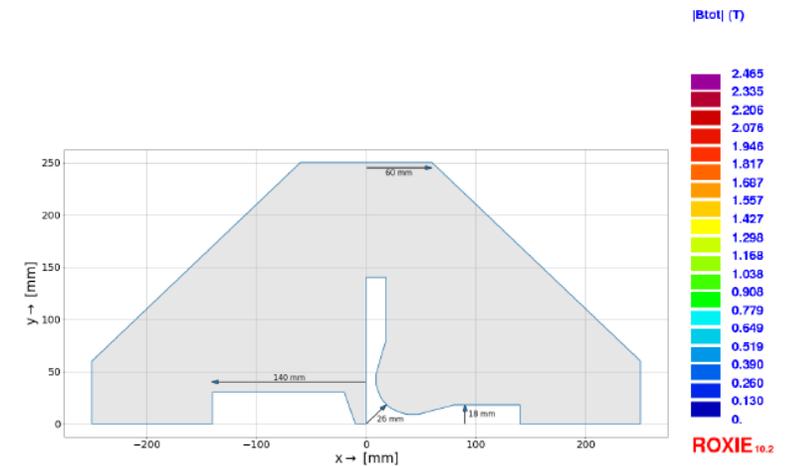
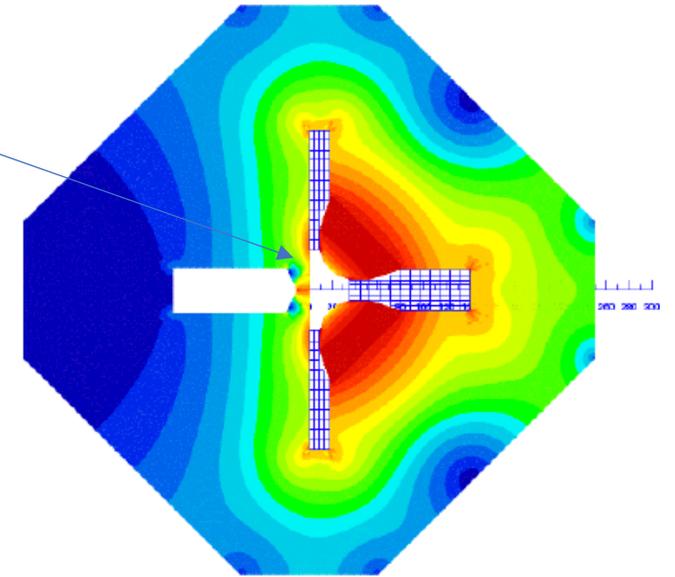
## Various Questions:

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

# Aperture Half-Quadrupole



**Figure 10.41:** The position of the three beams at the entrance (blue) and exit (green) of the half quadrupole. The colliding proton beam is centered inside the main magnet aperture, while the second proton beam and the electrons are located in the field free region. The dashed red line represents the injection proton beam at the output of the half quadrupole.



# Questions and Tentative Comments on Merger

Initial thoughts and questions

and tentative answers

First derived questions:

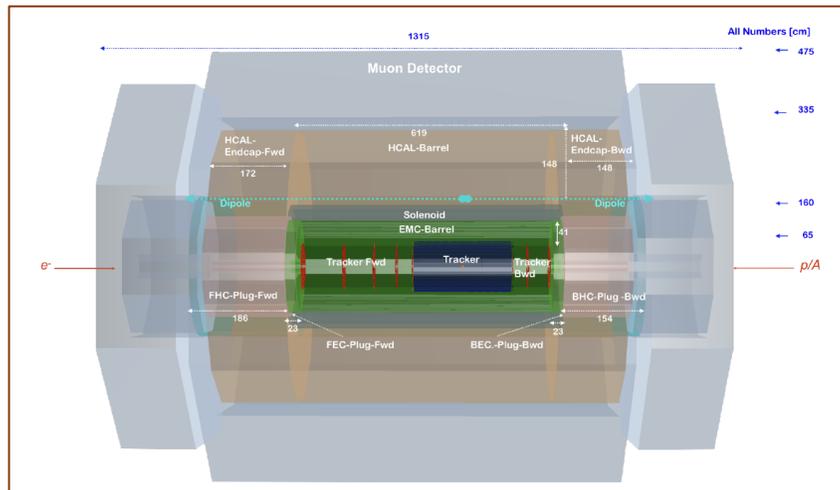
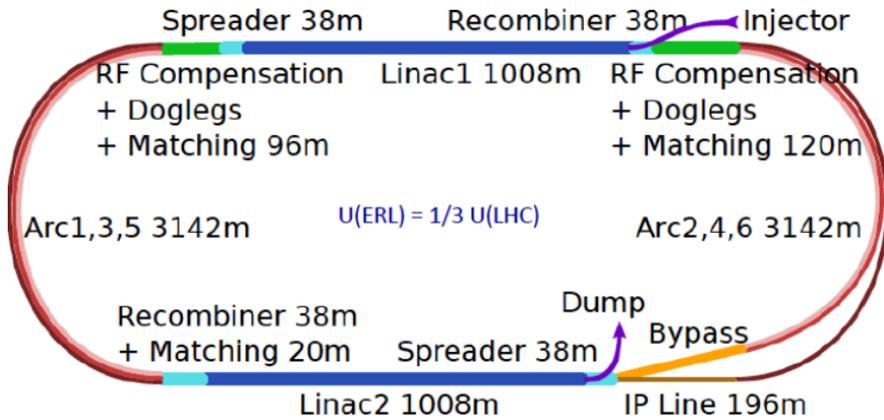
- Can we generate luminosity at 0 and +1.8m for pp/AA and ep/eA, respectively? **yes, time needed sharing**
- How does LHeC detector change if we integrate A3 into LHeC **extension in radius, B reduced, low V CMOS, ..**
- How would A3 detector change? Would it profit from the ep detector environment?  
Muons, calorimetry? **Better answered with A3 insight, one would expect this leads to a hard scale program**
- How does the physics potential change? **eA programme at TeV scales. LHeC is most powerful EIC one can build**

Detailed Questions

- Magnetic fields: solenoid: if we go to half our value, and enlarge the radius by 2, we gain factor 2 resolution **ok**  
Dipole: the dipole (and solenoid) would move further out, any problem? **Rather not. Note low material magnets**
- Choice of Silicon technology for IT, are we compatible with them? Probably yes. **low V CMOS probably ok for LHeC**
- Readout and Trigger: speed, data volume, 2 trigger and r/o branches or 1 etc. **To be studied**
- For c,b tagging the extended ep beam pipe is a nuisance (as it is for ours) --> place Si inside pipe?? **challenging**
- There are many more..

**→ It indeed seems feasible to combine the two detectors and IR concepts (further machine studies ongoing)**

# Concluding Remarks



LHeC is indeed **affordable** - O(1) billion CHF for another TeV collider

It **sustains the HL-LHC** and exploits this massive O(5) BCHF investment

**Physics: Unique:** Microscope of substructure (not resolved!), empowers LHC searches and Higgs measurements challenging  $e^+e^-$ , Discovery in electroweak and strong i.a. sector, Revolution of HI physics

**Technology:** Accelerator: highest energy ERL application - green. Detector: exciting place for new technology (CMOS, timing, thin calo.. etc) in classic DIS, low radiation environment, no pileup. Exciting place also for known technology to reappear and work.

**Merging LHeC with A3** resolves conceptual conflict on IP2 and promises to lead to new chapter of HI and accelerator physics (tentative)

**Next steps:** PERLE facility at Orsay, considerations for a detector proposal to LHCC, embedded and subject to CERN's future, which is also related to that of the CEPC, physics eh-hh, Interaction Region

The LHeC group believes that **diversity** (at the energy frontier too) **is key** to help particle physics theory to restore its predictive power..

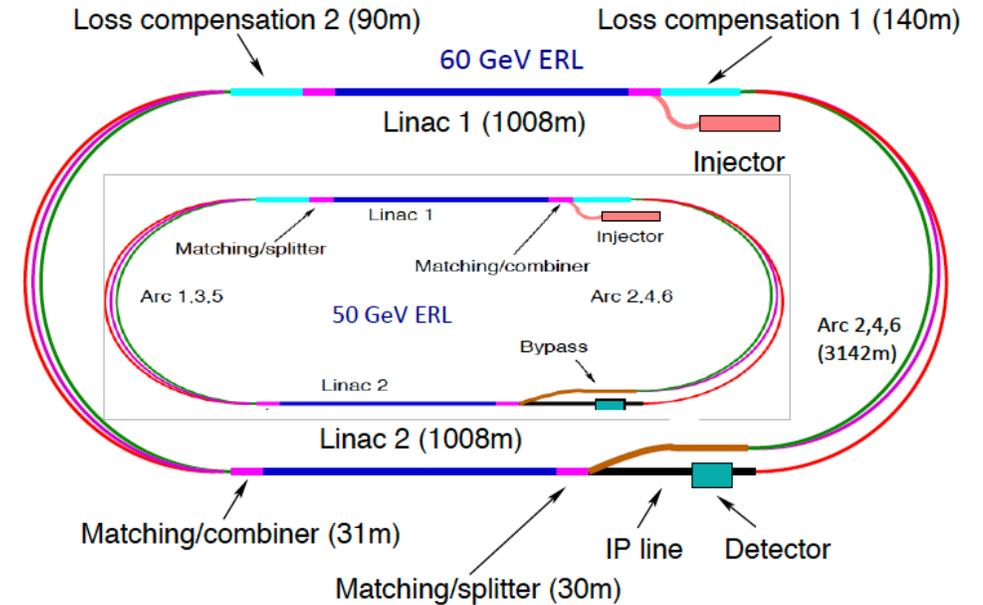
backup

# The ERL in more Detail

Parameter	Unit	Value
Injector energy	GeV	0.5
Total number of linacs		2
Number of acceleration passes		3
Maximum electron energy	GeV	49.19
Bunch charge	pC	499
Bunch spacing	ns	24.95
Electron current	mA	20
Transverse normalized emittance	$\mu\text{m}$	30
Total energy gain per linac	GeV	8.114
Frequency	MHz	801.58
Acceleration gradient	MV/m	19.73
Cavity iris diameter	mm	130
Number of cells per cavity		5
Cavity length (active/real estate)	m	0.918/1.5
Cavities per cryomodule		4
Cryomodule length	m	7
Length of 4-CM unit	m	29.6
Acceleration per cryomodule (4-CM unit)	MeV	289.8
Total number of cryomodules (4-CM units) per linac		112 (28)
Total linac length (with with spr/rec matching)	m	828.8 (980.8)
Return arc radius (length)	m	536.4 (1685.1)
Total ERL length	km	5.332

Table 10.1: Parameters of LHeC Energy Recovery Linac (ERL).

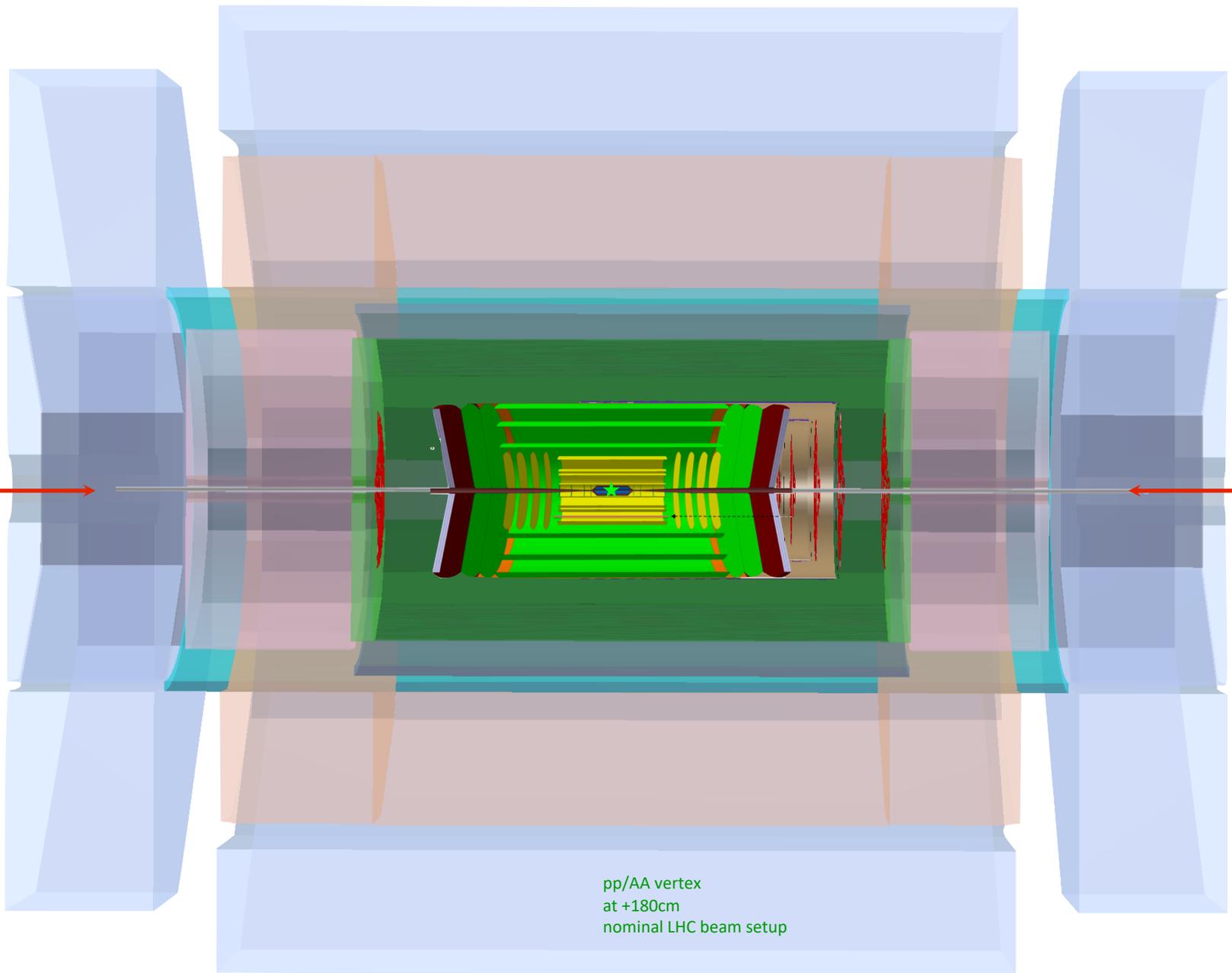
**Positrons:** 500pC is  $3 \cdot 10^9 e^-/\text{bunch} \rightarrow 20\text{mA}$  and  $1.2 \cdot 10^{17} e^-/\text{s}$   
 LHeC programme needs  $e^-p$  predominantly (Higgs) and only smaller  $e^+p$  sample,  $\sim \text{fb}^{-1} \rightarrow O(10^{15}) e^+/\text{s}$ , still demanding!



- LHeC Configuration reduced from 60 to 50 GeV.
- LINAC: 112 cryomodules with 4 cavities each  
 $\rightarrow$  Total number of cavities: 896 [ILC:  $O(10^4)$ ]
- Configuration may be staged with less RF
- Tunnel is small part of cost and better not reduced further, synchrotron loss, upgrades..
- ERL reduces power to  $\ll \text{GW}$  and dumps at  $< \text{GeV}$   
 $\rightarrow$  novel, "green" accelerator technology

$p/A$

$e^-$



$p/A$

pp/AA vertex  
at +180cm  
nominal LHC beam setup

# Machine Parameters and Operation - ep

arXiv:2007.14401

Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	$E_p=20$ TeV	$E_p=50$ TeV
$E_e$	GeV	60	30	50	50	60	60
$N_p$	$10^{11}$	1.7	2.2	2.2	2.2	1	1
$\epsilon_p$	$\mu\text{m}$	3.7	2.5	2.5	2.5	2.2	2.2
$I_e$	mA	6.4	15	20	50	20	20
$N_e$	$10^9$	1	2.3	3.1	7.8	3.1	3.1
$\beta^*$	cm	10	10	7	7	12	15
Luminosity	$10^{33} \text{cm}^{-2}\text{s}^{-1}$	1	5	9	23	8	15

**Table 2.3:** Summary of luminosity parameter values for the LHeC and FCC-eh. Left: CDR from 2012; Middle: LHeC in three stages, an initial run, possibly during Run 5 of the LHC, the 50 GeV operation during Run 6, both concurrently with the LHC, and a final, dedicated, stand-alone  $ep$  phase; Right: FCC-eh with a 20 and a 50 TeV proton beam, in synchronous operation.

No pileup

For comparison, HERA I operated at  $10^{31}\text{cm}^{-2}\text{s}^{-1}$ , and was upgraded by a factor of up to 4 for HERA II. The total luminosity delivered was  $1 \text{fb}^{-1}$  over a running period of 15 years, including shutdowns. LHeC may operate at  $20 \times 1000 \text{GeV}^2$  and "repeat" all of HERA in a short running period.

The initial CDR considers a Ring-Ring  $ep$  collider as a back-up solution. May be revived for HE-LHC.

# Machine Parameters - eA

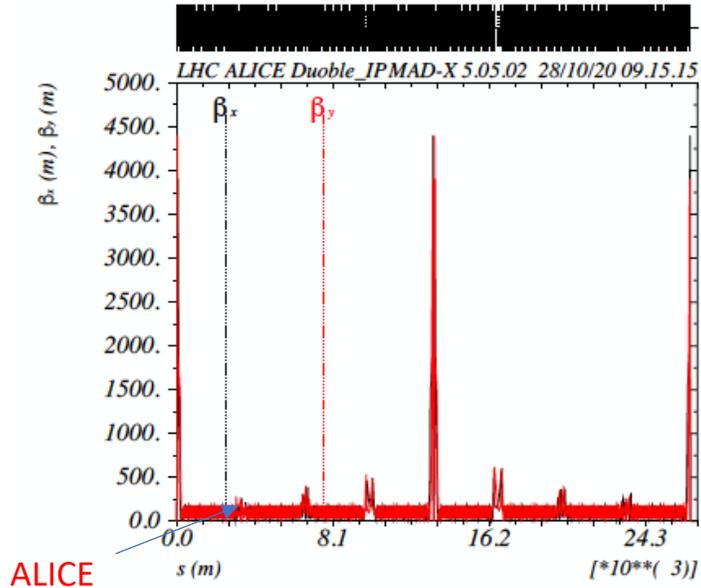
Parameter	Unit	LHeC	FCC-eh ( $E_p=20$ TeV)	FCC-eh ( $E_p=50$ TeV)
Ion energy $E_{Pb}$	PeV	0.574	1.64	4.1
Ion energy/nucleon $E_{Pb}/A$	TeV	2.76	7.88	19.7
Electron beam energy $E_e$	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	$10^8$	1.8	1.8	1.8
Normalised emittance $\epsilon_n$	$\mu\text{m}$	1.5	1.5	1.5
Electrons per bunch	$10^9$	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function $\beta_A^*$	cm	10	10	15
e-N Luminosity	$10^{32}\text{cm}^{-2}\text{s}^{-1}$	7	14	35

**Table 2.4:** Baseline parameters of future electron-ion collider configurations based on the electron ERL, in concurrent  $eA$  and  $AA$  operation mode with the LHC and the two versions of a future hadron collider at CERN. Following established convention in this field, the luminosity quoted, at the start of a fill, is the *electron-nucleon* luminosity which is a factor  $A$  larger than the usual (i.e. electron-nucleus) luminosity.

arXiv:2007.14401

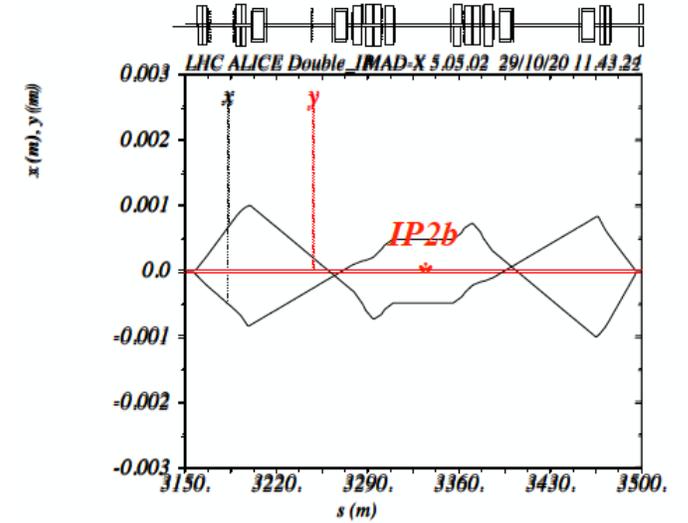
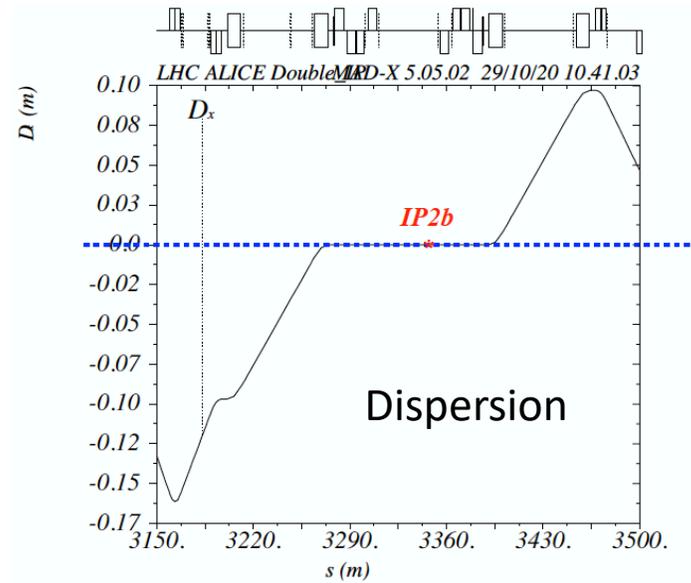
The LHeC and FCC-eh are the highest energy, most powerful electron-ion colliders the world may build. Saturation, Parton Dynamics and Structure in Nuclei, Quarkonia, Jets, Tomography of p and Nuclei, ..

# Optics for IP2

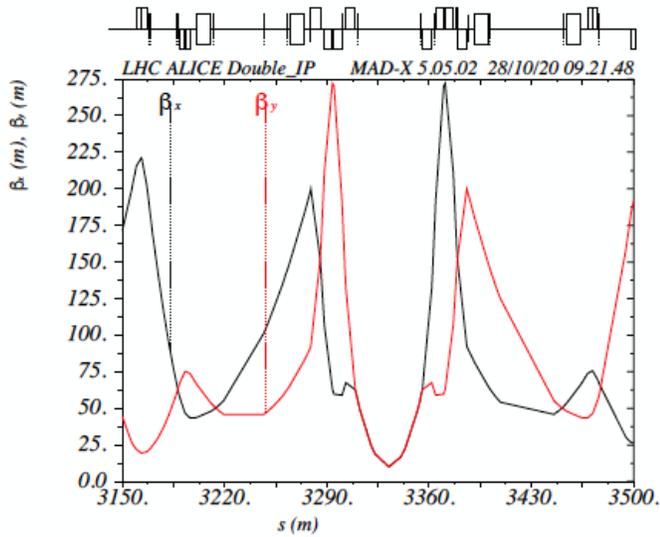


LHC Optics – beta vs path

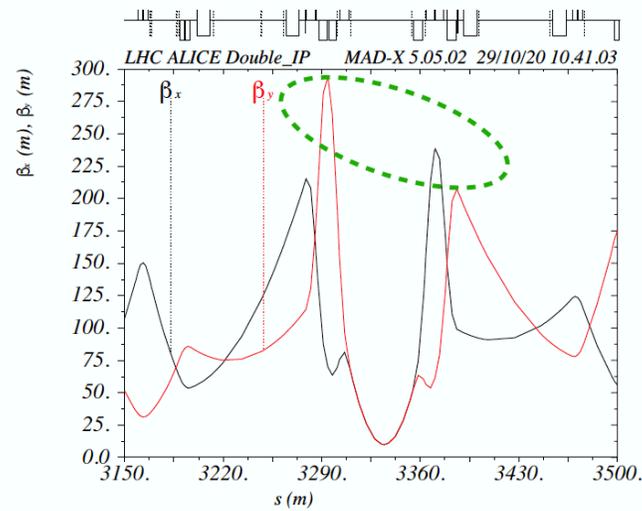
ALICE



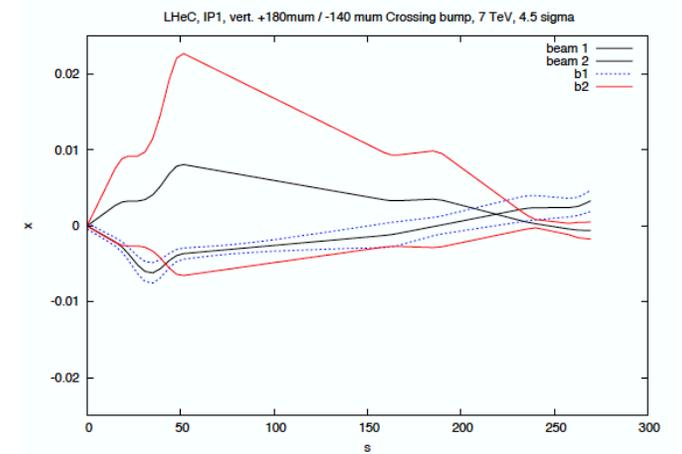
Separation bump (std LHC procedure)



ALICE Luminosity Optics  $\beta_x^* = 10\text{m}$



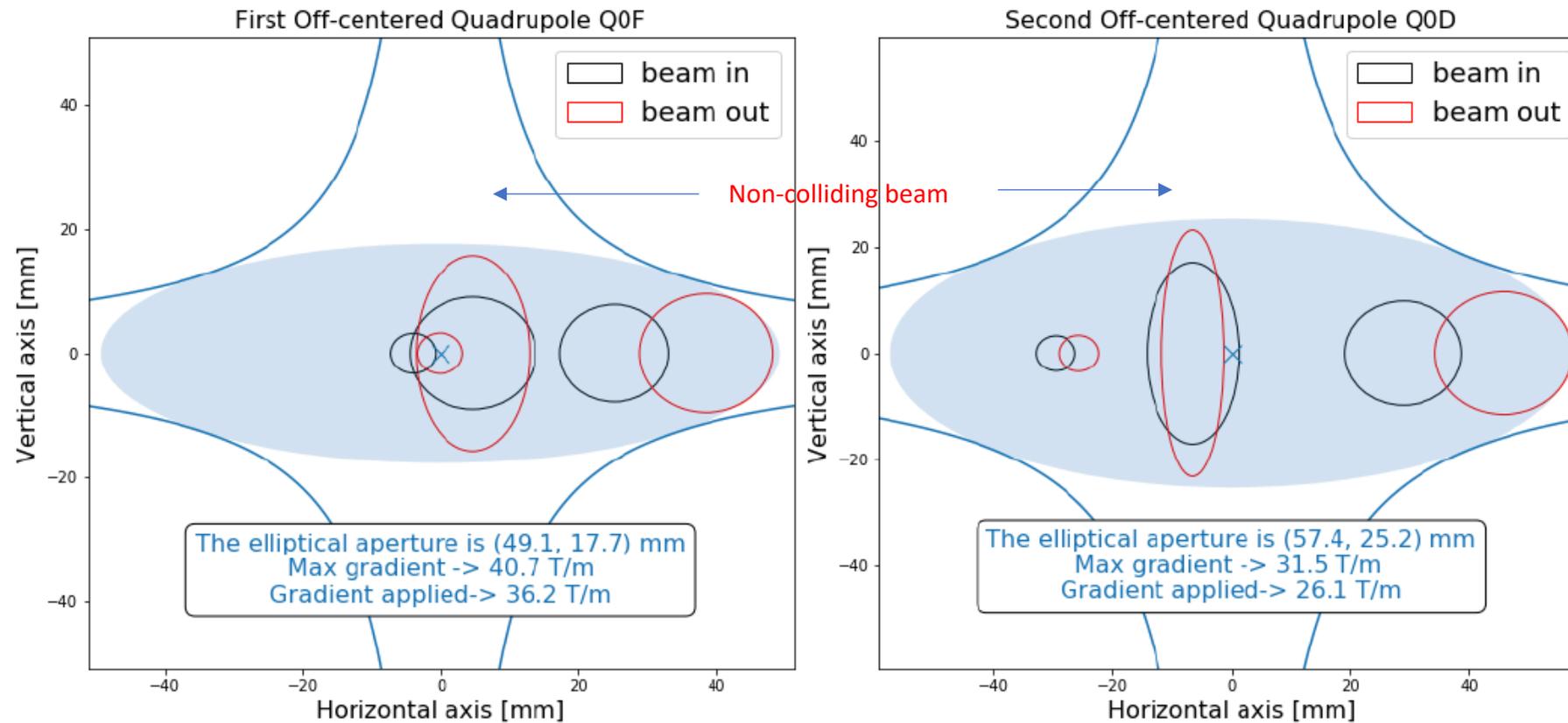
ALICE Luminosity Optics: IP2b=1.87m



Shift in time and vertical xing 140mrad

→ No showstopper for ep and AA

# Aperture Staggered Quadrupoles



**Figure 10.42:** The position of the three beams at the entrance (black) and exit (red) of the electron doublet magnets. Following the internal convention,  $15\sigma$  plus 20% beta beating plus 2mm orbit tolerances beam envelopes are chosen for the proton beams. The beam size of the electrons refer to  $20\sigma$ . From left to right the three beams are respectively the non colliding proton beam (tiny circles), electron beam (squeezed ellipses) and the colliding proton beam.

# Energy Recovery and Synergies

LHeC/FCC-eh: high luminosity, high energy  
→ High ERL power facility  $P = I_e E_e$

**This is a programme for high quality SRF ( $Q_0 > 10^{10}$ ), high current sources, and multiturn to reach high  $E_e$**

## **Future/current ERL developments: distribution of emphasis**

- CBETA: high current, single turn - for e cooler (EIC)
- MESA: polarised beam - for new PV asymmetry exp.
- CEBAF: few GeV energy - for study of syn. radiation
- PERLE: high current, multiturn - for exp's and future

Plans: Daresbury, Darmstadt, Berlin. Revival of KEK ERL normal conducting ERL machine at BINP

Coordination: Lab Director Group (A Stocchi JLab for ERL)  
European Accelerator R+D Roadmap: CERN council 9/21  
ERL Network. ERL workshop series

## **Technical Synergies of LHeC with other applications**

- SAPPHIRE: a  $\gamma\gamma$  collider : Higgs, eweak and QCD machine  
F. Zimmermann et al, arXiv:1208.2827
- Racetrack as an injector into FCC-ee [direct into Z]  
O. Bruening, Y. Papaphilippou
- LHeC-FEL  
F. Zimmermann et al, work in progress
- Injector into FCC-hh  
R. Calaga
- Proposal of ERL Version of FCC-ee for high Lumi at high  $E_e$   
V Litvinenko, T Roser, M Chamizo-Llatas arXiv: 1909.04437
- 802 MHz technology: PERLE, FCC-ee, eSPS  
F Marhauser, B Rimmer et al
- 704 MHz SPL Cryomodule (CERN) modified for PERLE  
F Gerigk, E Jensen et al.
- ALICE (Daresbury) Gun delivered to Orsay for PERLE  
D Angal-Kalinin, B Militsyn et al
- JLEIC Booster (Jlab) likely to be used in PERLE  
F Hannon, B Rimmer et al
- Forward Calorimetry: FCC-hh and ee colliders / CALICE..
- Inner Tracker/CMOS: ee colliders, new HI detector at IP2
- ....

## New paradigm: small systems

Totally unexpected:

- the discovery of correlations –ridge, flow- in small systems **pA & pp**
- Smooth continuation of heavy ion phenomena to small systems and low density
- **Small systems as pA and pp show QGP-like features**

Two serious contenders remain today:

- **initial state:** quantum correlations as calculated by CGC
- **final state:** interactions leading to collective flow described with hydrodynamics => **equilibration?**

The **old paradigm** that

- we study hot & dense matter properties in heavy ion **AA** collisions
- cold nuclear matter modifications in **pA**
- and we use **pp** primarily as comparison data **appears no longer sensible**

We should examine a **new paradigm**, where the physics underlying soft collective signals can be the same in all high energy reactions, **from  $e^+e^-$  to central AA**

Joint eA/ep and pp/pA/AA physics in a common apparatus is probably an ideal for new heavy ion physics to very high precision.

A common/dual/joint - you name it- experiment would have unprecedented reach into physics

AA

from low  $p_T$ , to quarkonia + hard scales

eA

DIS extended by 3-4 orders of magnitude.

Invites new and further thinking, and to carefully evaluate gains and drawbacks of such an enterprise.

# Partonic evolution and hadronization

Relevant for particle production and QGP analysis in HIC:

jets plentiful in eA

benchmark for jet quenching studies in AA

Low energy:

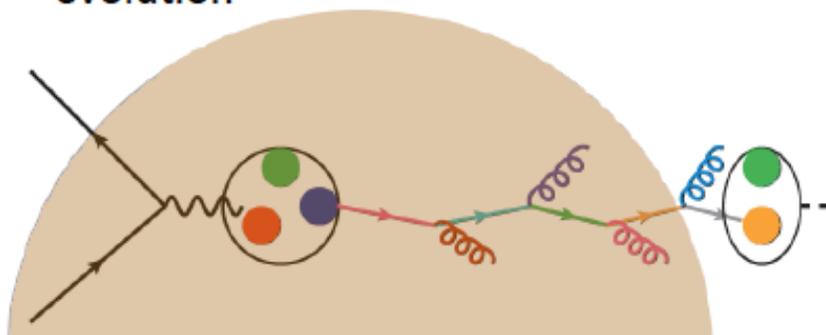
hadronization in matter

- (pre)hadronic absorption
- formation time

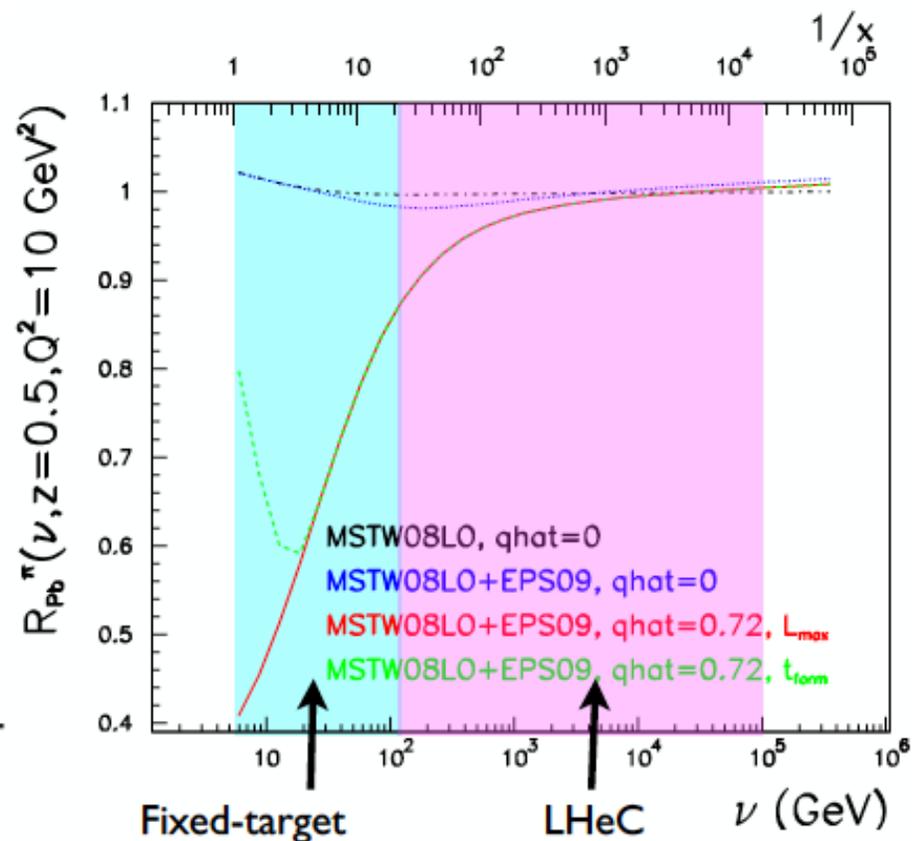


High energy:

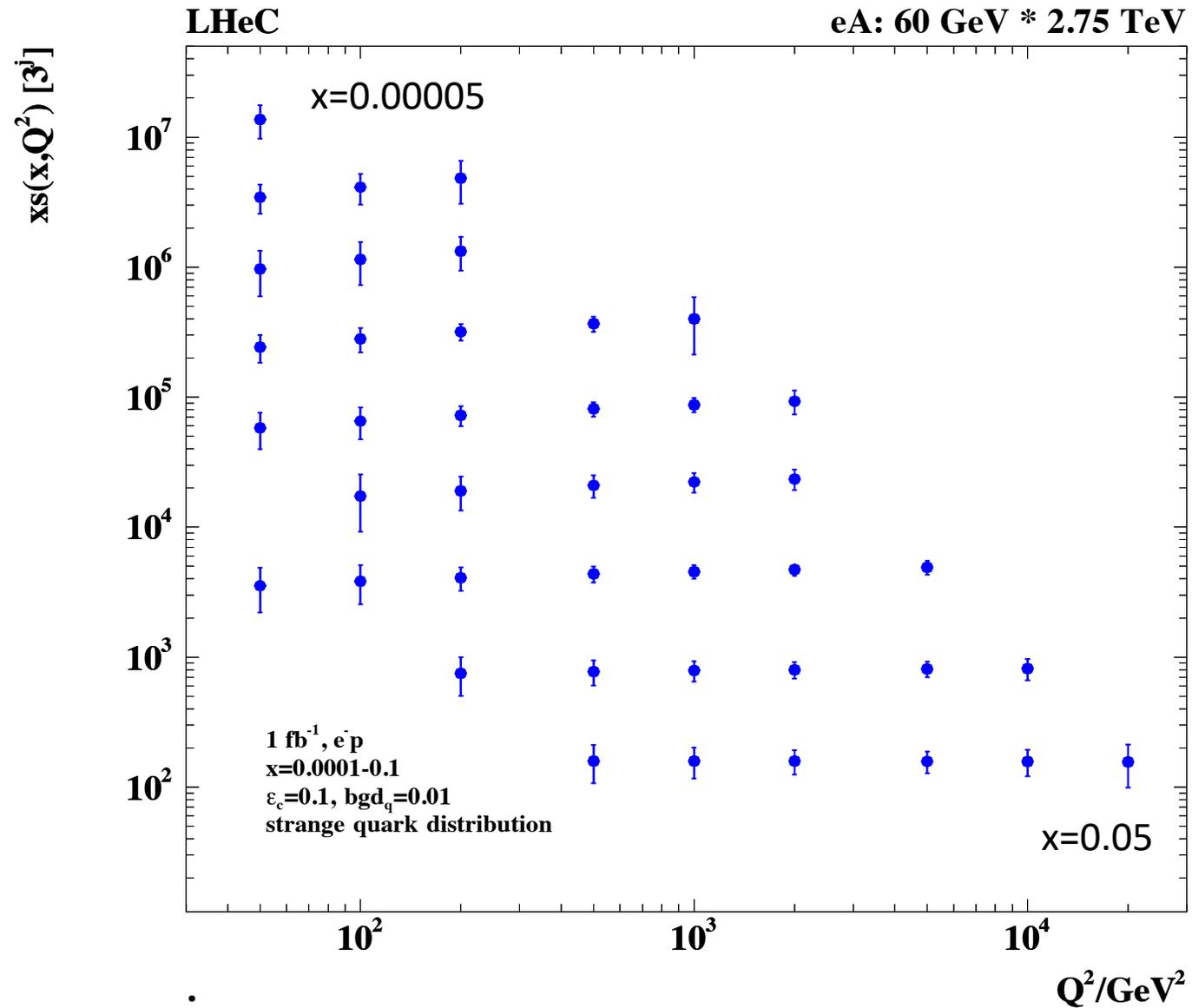
- modification of partonic evolution



Ratio of fragmentation functions Pb/p



# Heavy Flavour – Strange in ePb - from CC



# Other possible studies: quarkonium production

## Production mechanism and polarization:

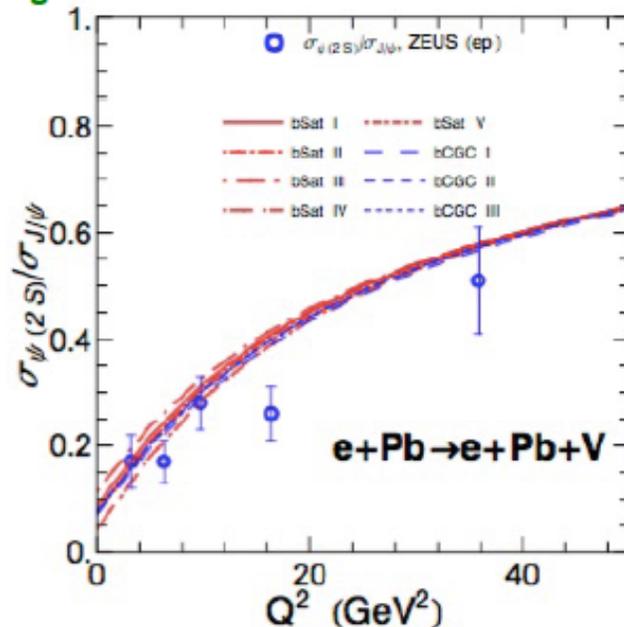
polarized  $J/\psi$  photoproduction can be studied more precisely and up to much larger values of  $p_T$  in **ep @ LHeC**

⇒ test NRQCD factorization in charmonium physics

**Butenschoen Kniehl**

**Charmonium WF** in diffractive DIS within the dipole formalism

**Cheng et al.**



## Spatial and Momentum Tomography of Hadrons and Nuclei

**Gluon TMDs** could be directly probed by looking at  $p_T$  distributions and azimuthal asymmetries in  $e p \rightarrow e Q \bar{Q} X$

**Boer, Lansberg, Pisano**

## Gluon GPDs

**Y** production at an EIC to determine the gluon density transverse spatial profiles in a wide range of  $x$  and consequently provide a path to determine the gluonic radius of the nucleon and the contribution of the total angular momentum of gluons to the nucleon spin

**Joosten and Meiziani**

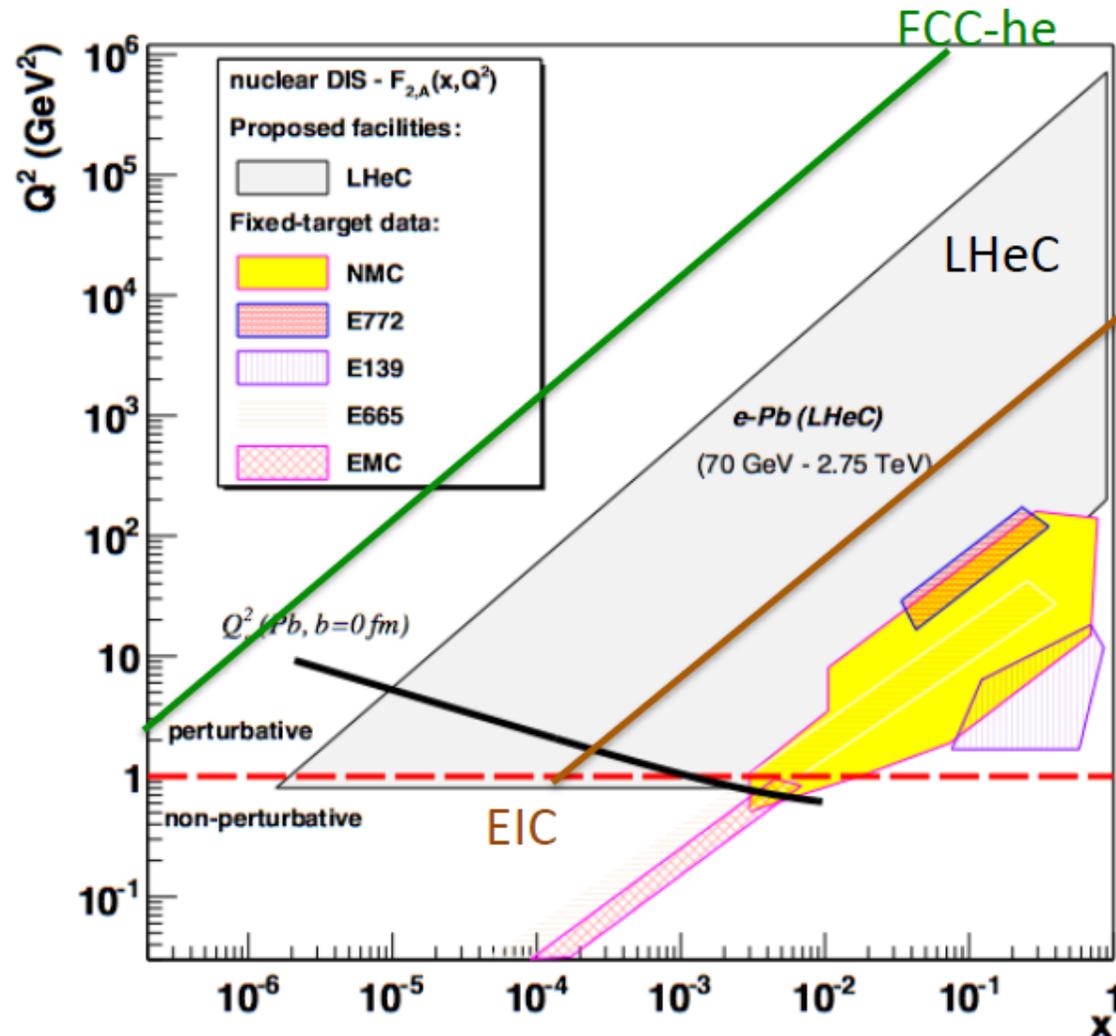
# Kinematic Ranges of IA DIS – Past and Future

HERA missed the electron-ion phase.  
No deuterons either.  
cf HERA3 in 2001..

Note that **LHeC may be tuned to low energies**  
 $\sqrt{s} \approx 100$  GeV instead of 1 TeV – direct overlap  
EICs and HERA.

**FCC-eh: highest  $Q^2$ ,  $1/x$**

Expect saturation of rise at  
 $Q_s^2 \approx xg \alpha_s \approx c x^{-\lambda} A^{1/3}$   
Note that the gluon is valence like at low  $Q^2$



**Luminosity:** crucial for efficient operation, to access rare channels and high  $x$ , and  $Q^2$   
15 years of HERA luminosity collection may shrink to a few days (ATLAS now up to  $1\text{fb}^{-1}/\text{day}$ )