

The LHeC Detector Design

and its possible marriage with a novel heavy-ion detector at IP2



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, Components]

Installation Study

Interaction Region

Integration of AA and eh Detectors

Inner Tracker

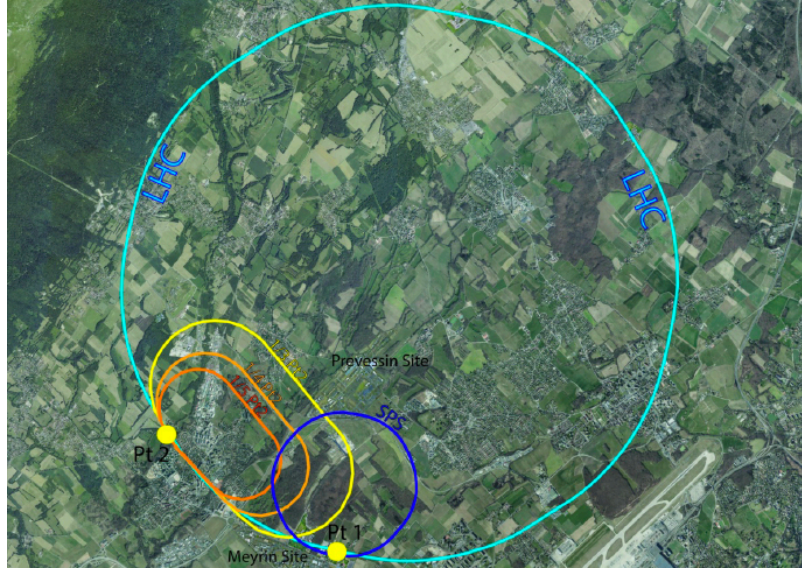
Dual Collisions at IP2

Remarks on Physics

Summary

LHeC – Project, Physics, Parameters

LHeC, PERLE and FCC-eh



50 x 7000 GeV²: 1.2 TeV ep collider

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

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

Upgrade to 10³⁴ cm⁻²s⁻¹, for Higgs, BSM

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

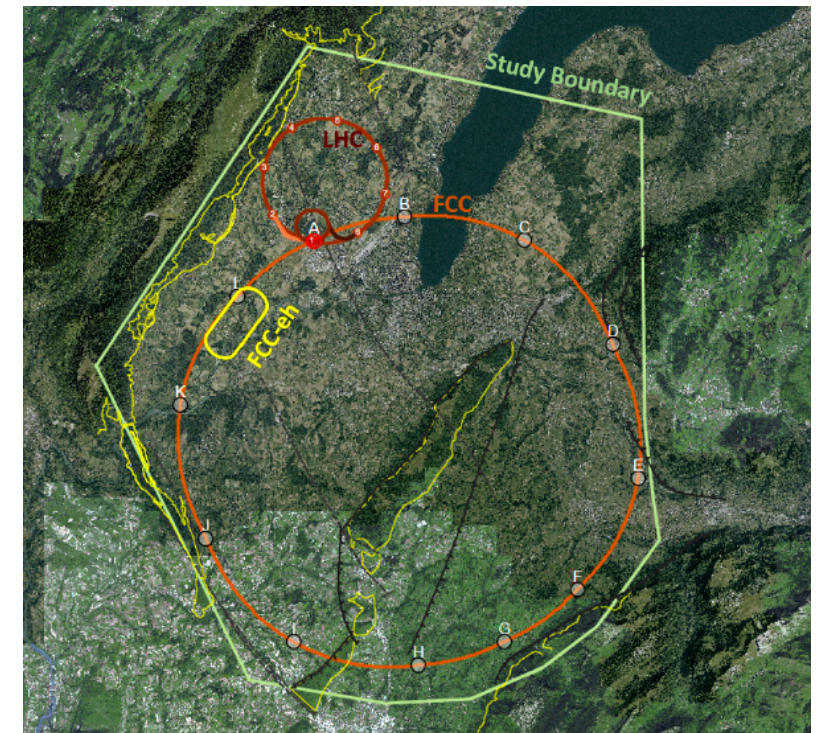
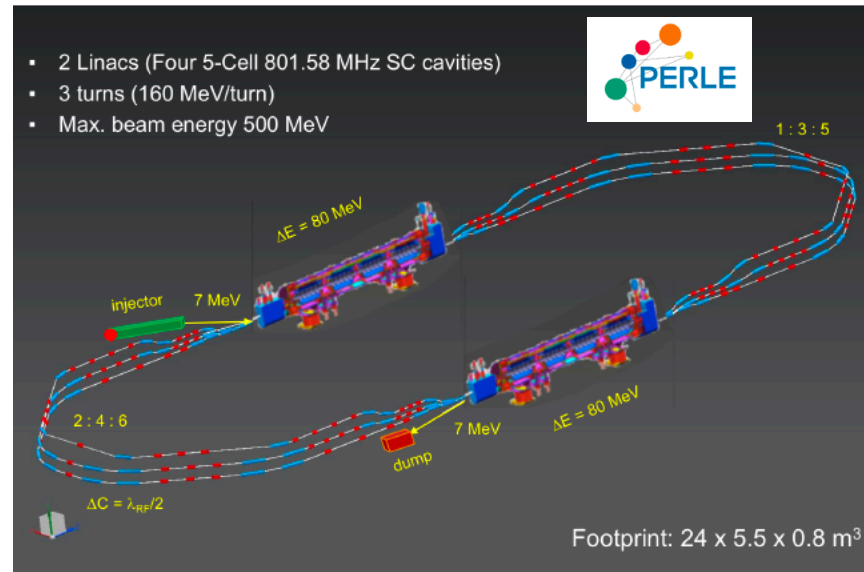
arXiv:2007.14491, subm J.Phys.G

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, Daresbury, Jlab, Liverpool, Orsay (IJC), +



60 x 50000 GeV²: 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+

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
-

Published in 2020

CERN-ACC-Note-2020-0002
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The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group



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

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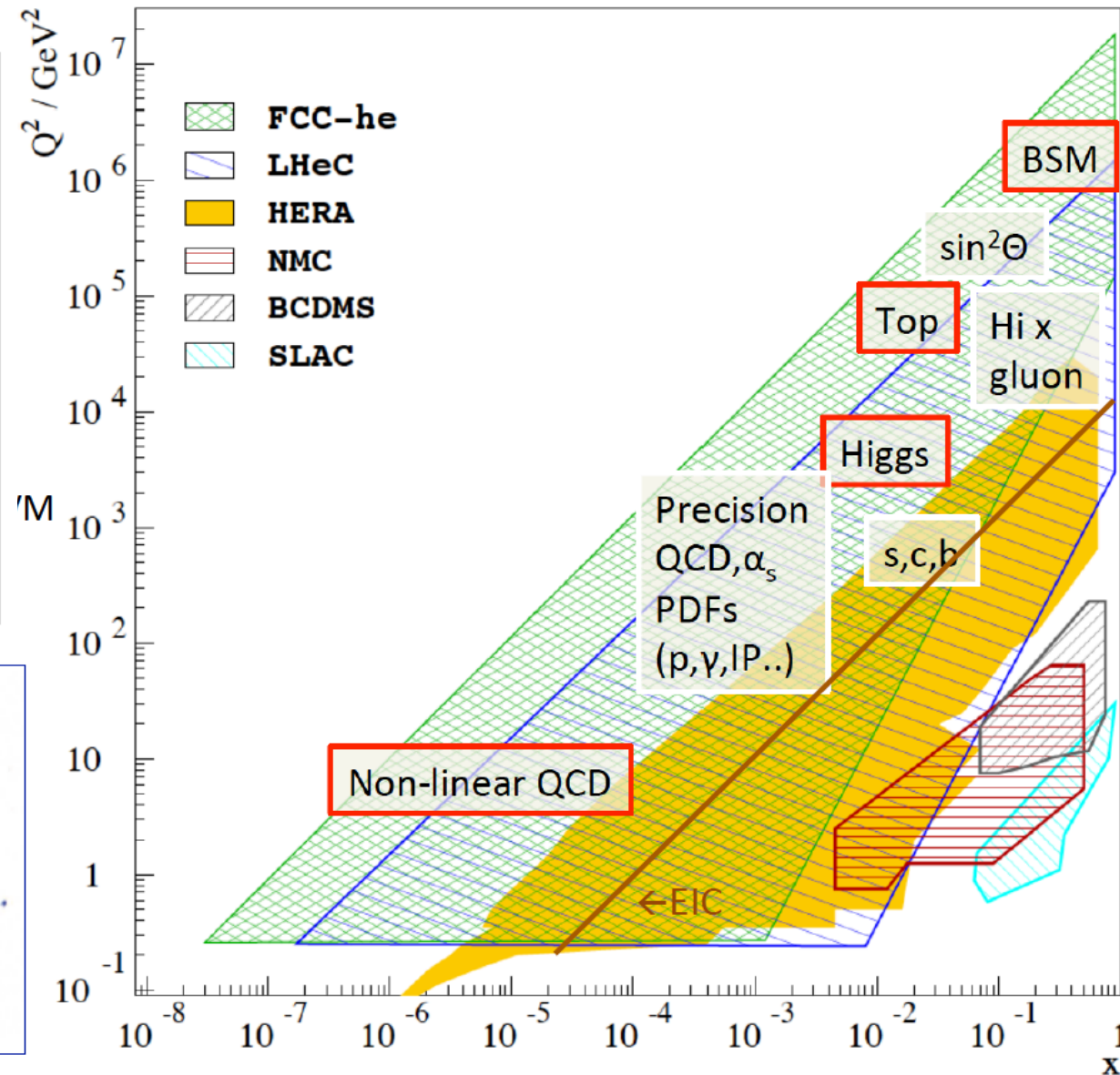
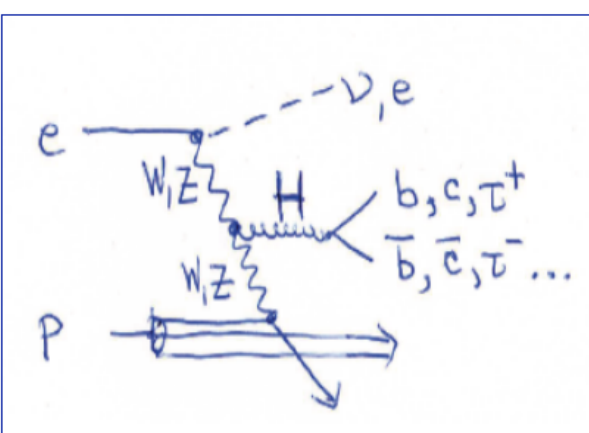
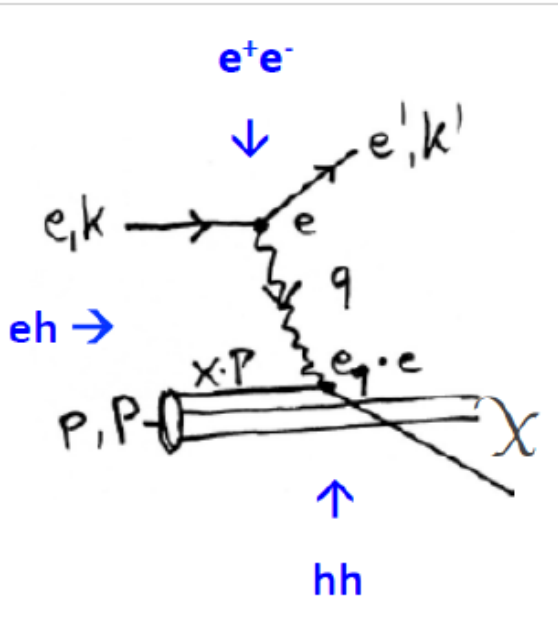
5 page summary: ECFA Newsletter Nr 5., August 20

<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 ν 's..) Beyond the Standard Model

A Unique Nuclear Physics Facility

Higgs in ep and pp [LHC and FCC]

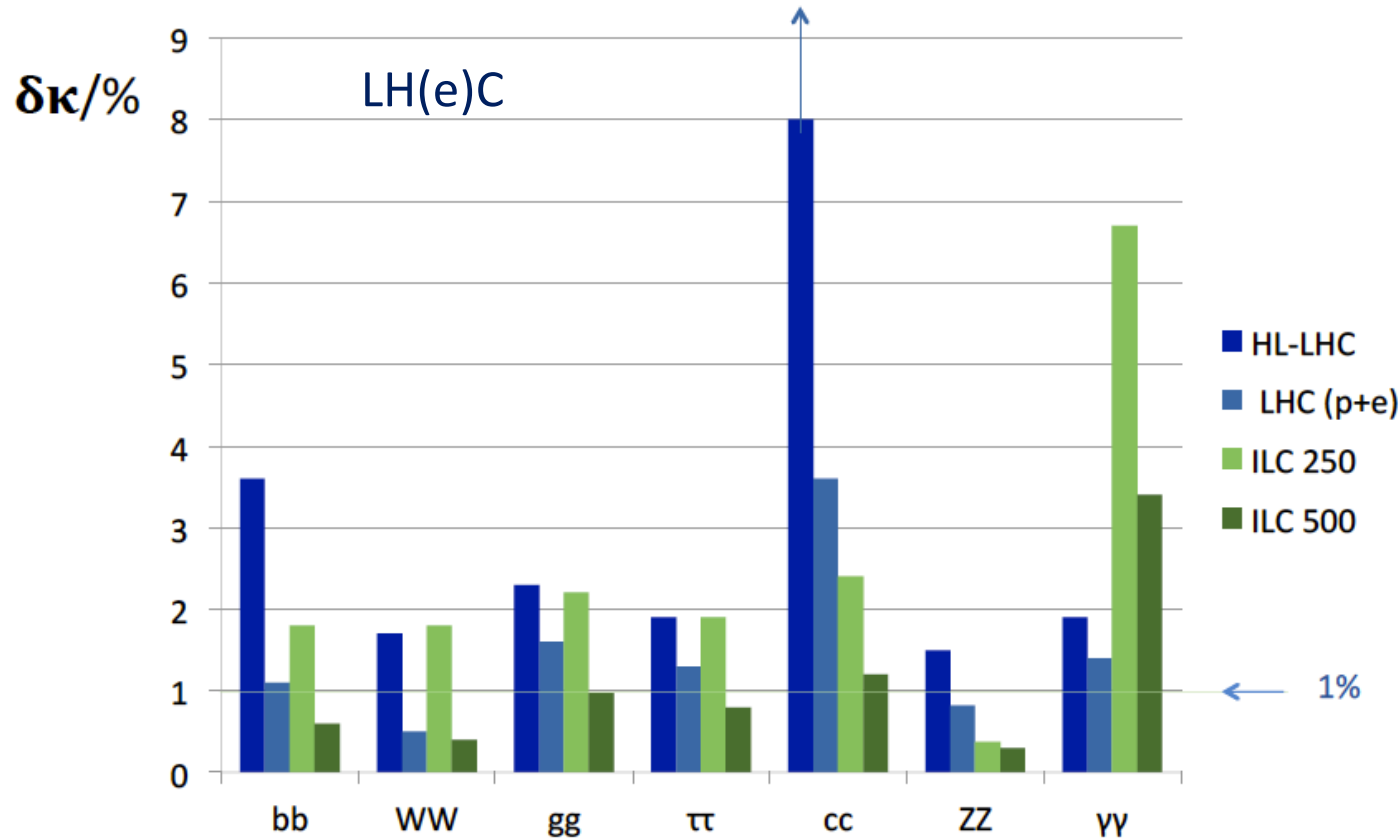


Fig.1: Results of prospect evaluations of the determination of Higgs couplings in the SM kappa framework for HL-LHC (dark blue), LHC with LHeC combined (p+e, light blue), ILC 250 (light green) and ILC-500 (dark green).

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

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
ϵ_p	μm	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
β^*	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 1fb^{-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 ϵ_n	μm	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 β_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.

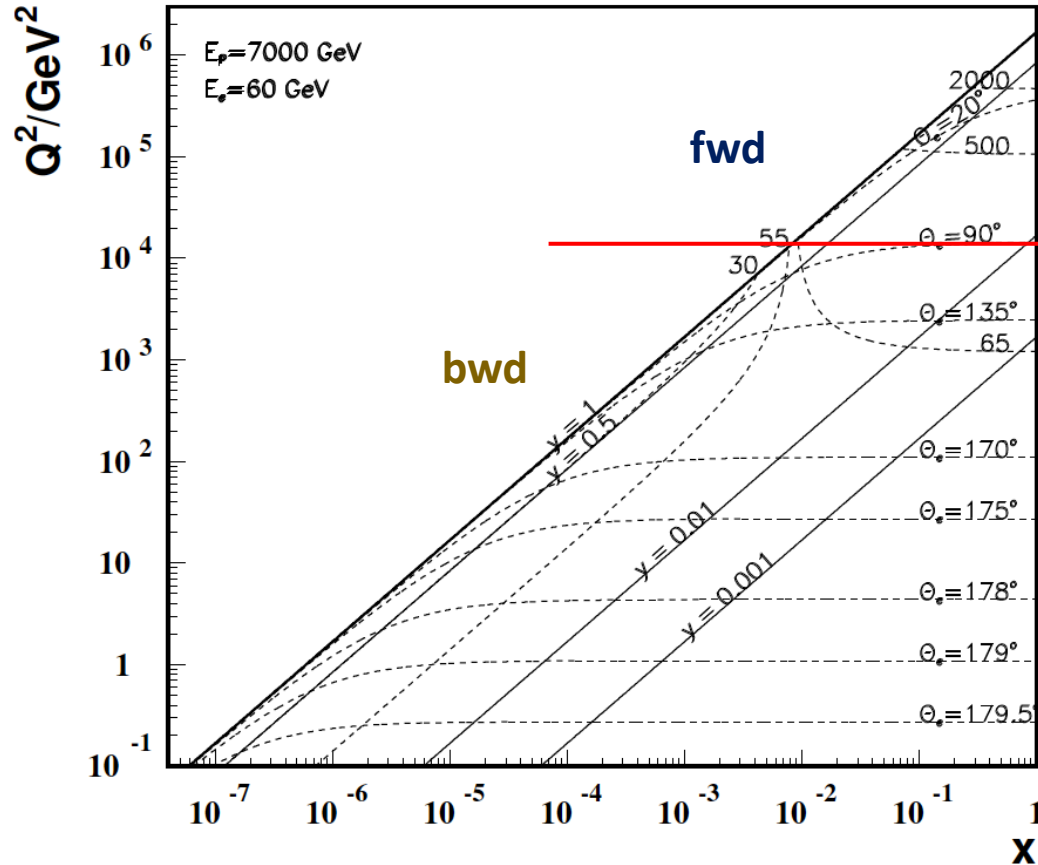
arXiv:2007.14401

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, ..

LHeC Detector Design and Installation Study

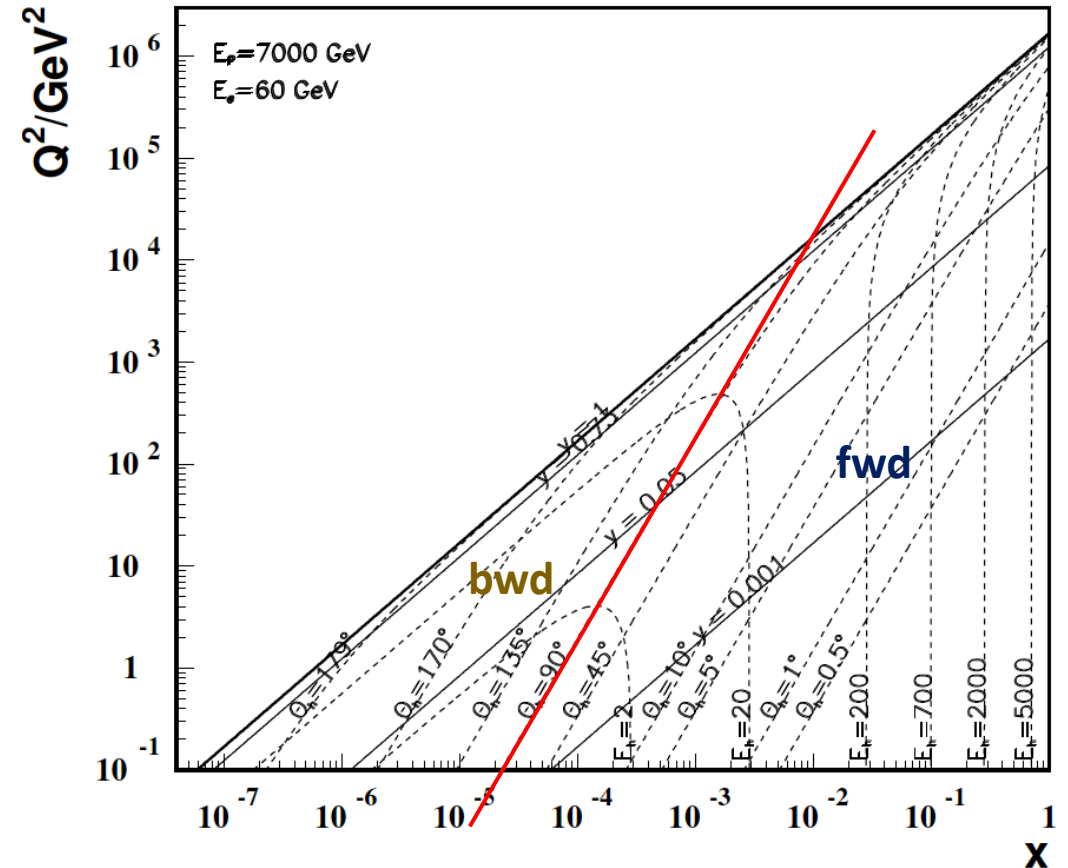
Kinematics: fwd: in p beam direction, bwd: e direction

LHeC - electron kinematics



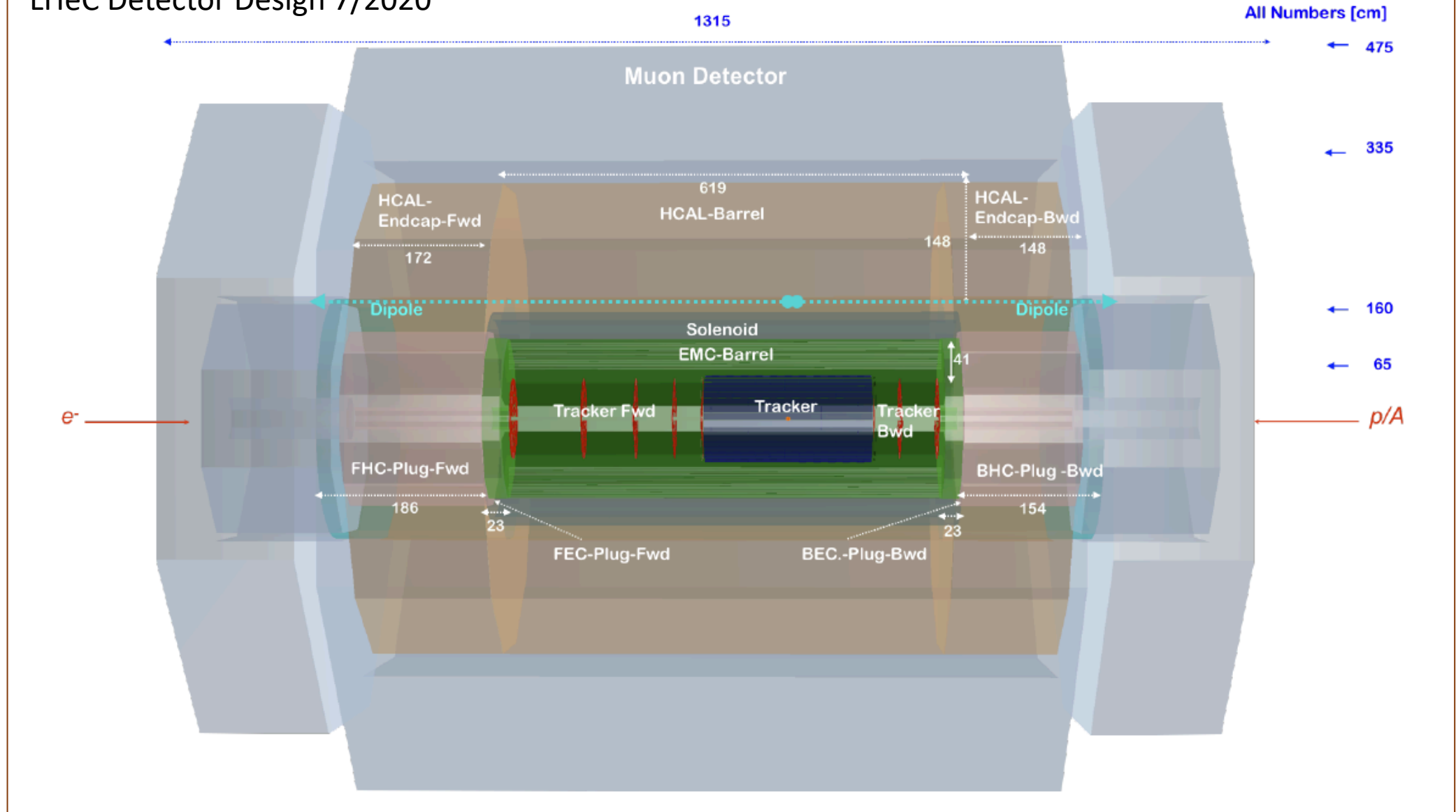
Electrons in bwd direction have low energy ($E'_e < E_e$ beam)
 in fwd direction high energy up to E_p , Rutherford backscattering
 $Q^2=1 \text{ GeV}^2$ is 179° , or $\eta = 4.74 = \ln \tan \theta/2$, $\sim E_e^2$!

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 9m² [CMS 21 x 15m², ATLAS 45 x 25 m²].

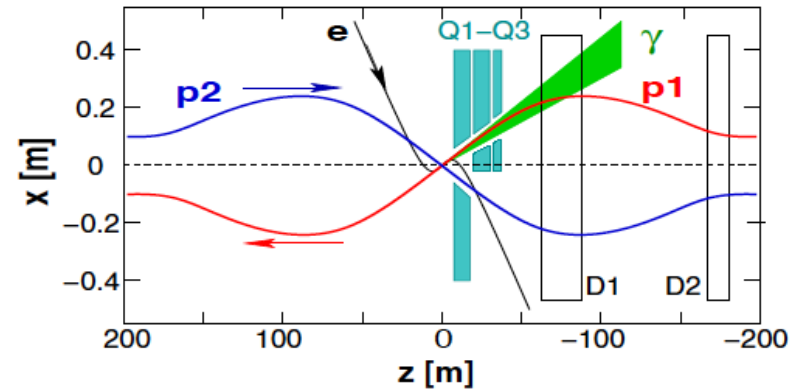
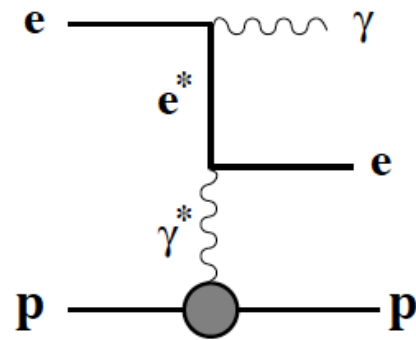
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LHeC Detector in the CDR (1206.2913)

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 (γ)	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

LR: photon detector
← acceptance 95%

→ Luminosity from
BH photons to 1%

BH to another order

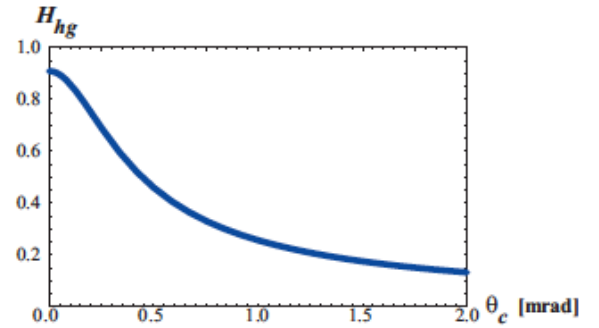
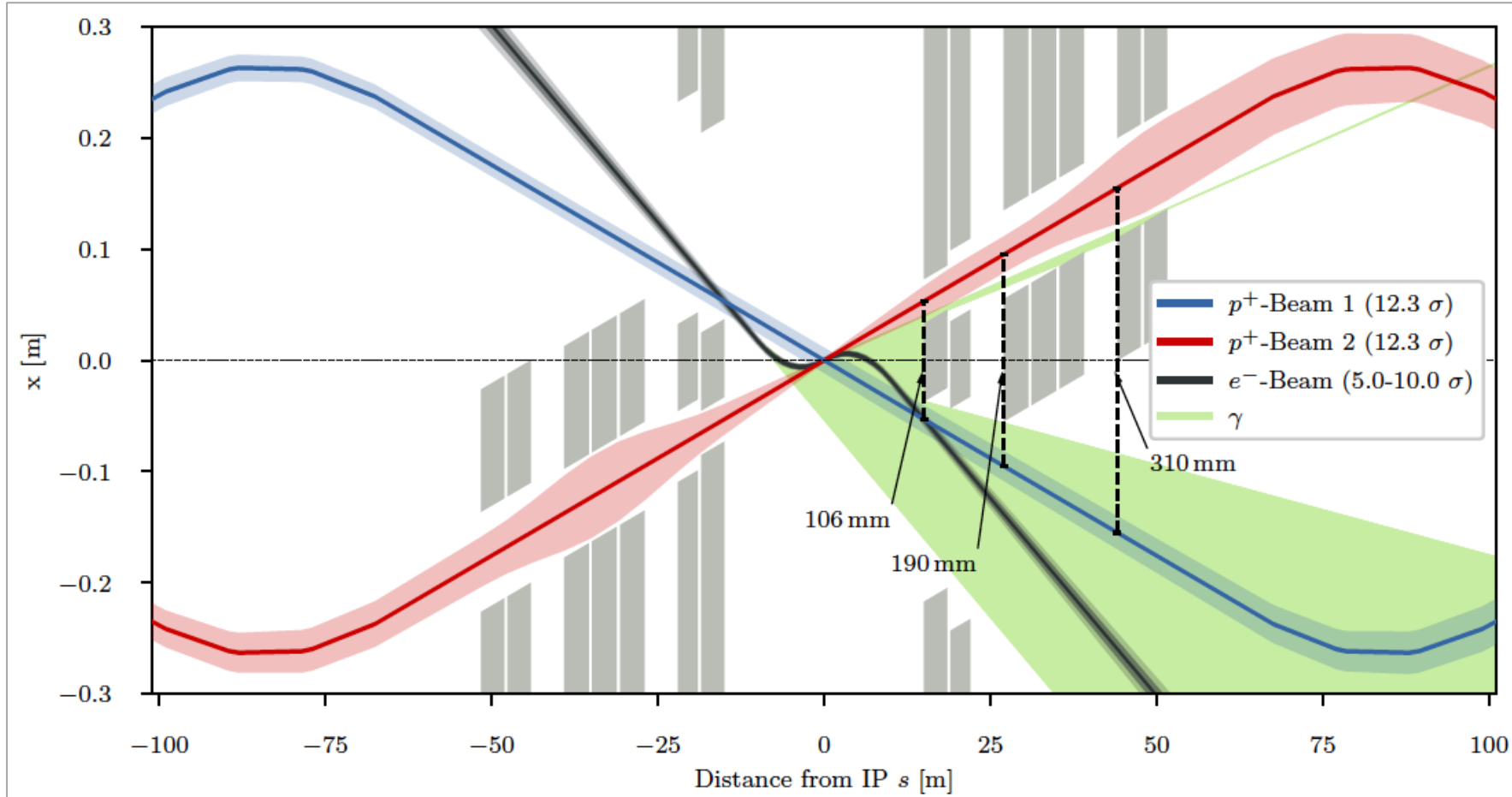
... BH(e), QEDC, F_2
as cross checks

Forward
Taggers:

See Yuji
Yamazaki
at ICHEP
and in
2007.14491

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

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

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

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

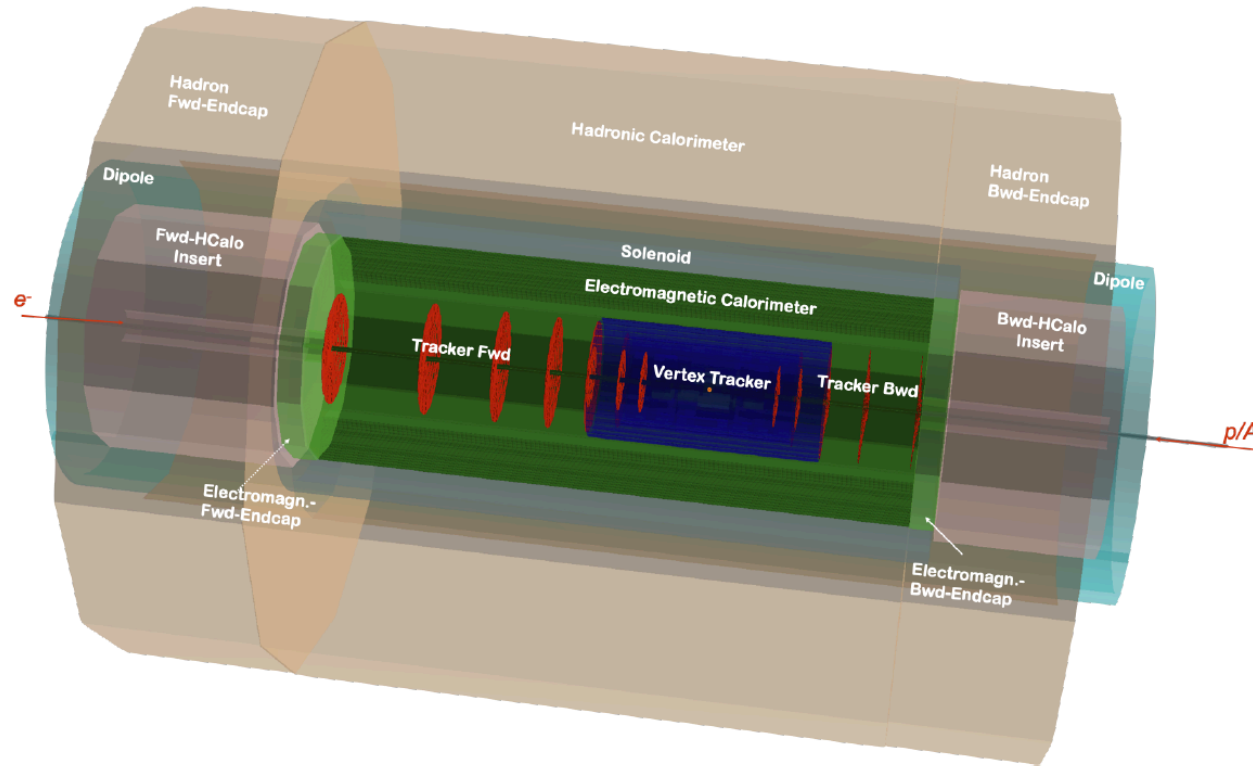
H ten Kate (EP-RD, 16.3.18)

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.

New ideas on thin magnets
 cf. E Perez at FCC workshop

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 \rightarrow bb and other reactions demand resolution of HFS

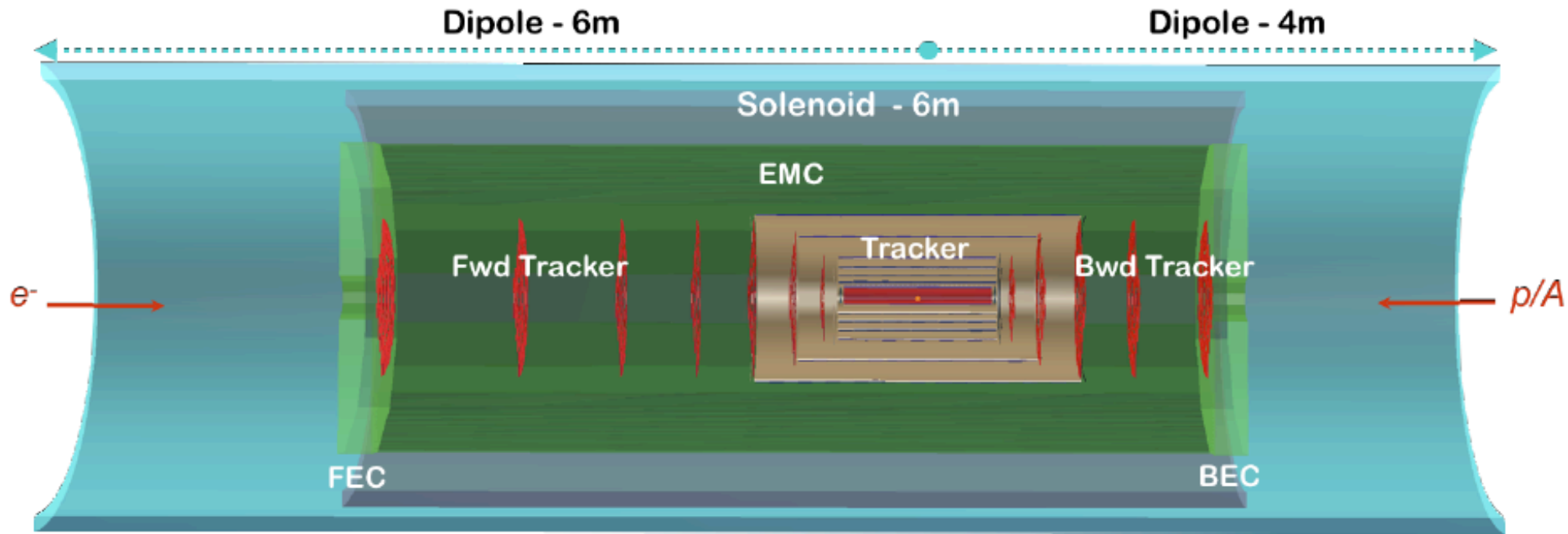
Backward Region: in DIS only deposits of $E < E_e$

Barrel Calorimeters

Forward/Backward Calorimeters

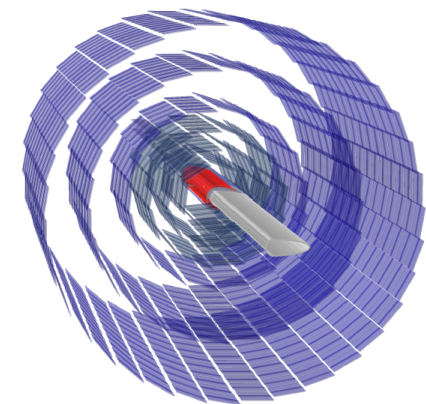
Calo (LHeC)	EMC		HCAL	
	Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber Layers	Sci,Pb 38	Sci,Fe 58	Sci,Fe 45	Sci,Fe 50
Integral Absorber Thickness [cm]	16.7	134.0	119.0	115.5
η_{\max}, η_{\min}	2.4, -1.9	1.9, 1.0	1.6, -1.1	-1.5, -0.6
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	12.4/1.9	46.5/3.8	48.23/5.6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

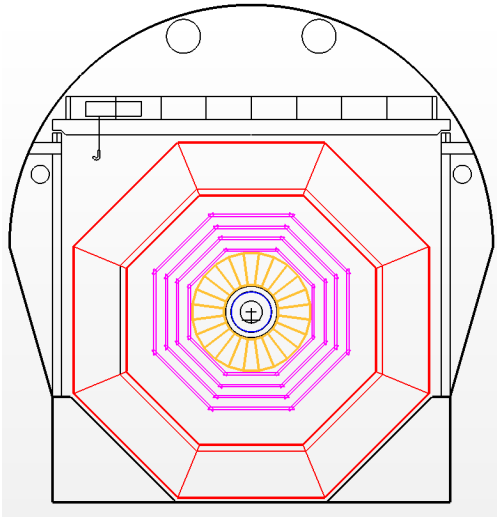
Calo (LHeC)	FHC	FEC	BEC	BHC
	Plug Fwd	Plug Fwd	Plug Bwd	Plug Bwd
Readout, Absorber Layers	Si,W 300	Si,W 49	Si,Pb 49	Si,Cu 165
Integral Absorber Thickness [cm]	156.0	17.0	17.1	137.5
η_{\max}, η_{\min}	5.5, 1.9	5.1, 2.0	-1.4, -4.5	-1.4, -5.0
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	51.8/5.4	17.8/1.4	14.4/2.8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



Inner Tracker
 Rapidity to ~ 5
 $r_0 = 60$ cm
 impact resolution
 5-10 μm
 40.7 m^2 Si

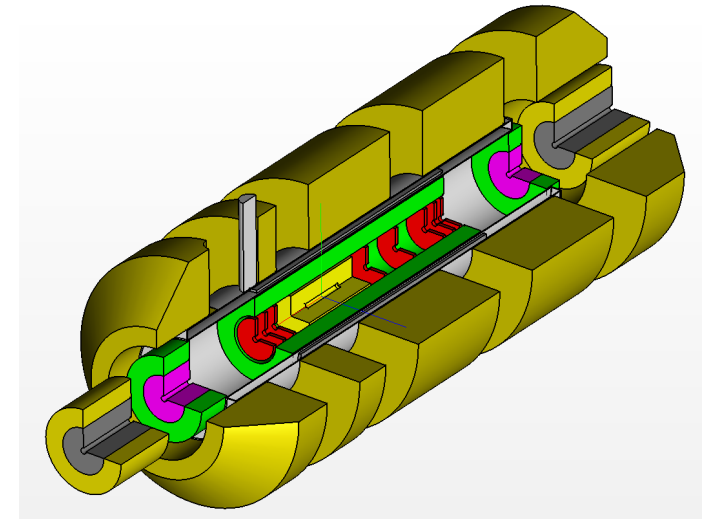
Tracker (LHeC)	Fwd Tracker			Bwd Tracker		Total (incl. Tab. 12.1)
	pix	pix _{macro}	strip	pix _{macro}	strip	
$\eta_{\text{max}}, \eta_{\text{min}}$	5.3, 2.6	3.5, 2.2	3.1, 1.6	-4.6, -2.5	-2.9, -1.6	5.3, -4.6
Wheels	2	1	3	2	4	
Modules/Sensors	180	180	860	72	416	10736
Total Si area [m^2]	0.8	0.9	4.6	0.4	1.8	40.7
Read-out-Channels [10^6]	404.9	68.9	26.4	27.6	10.6	2934.2
pitch ^{r-ϕ} [μm]	25	100	100	100	100	
pitch ^z [μm]	50	400	50k ²⁾	400	10k ¹⁾	
Average X_0/Λ_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>								█

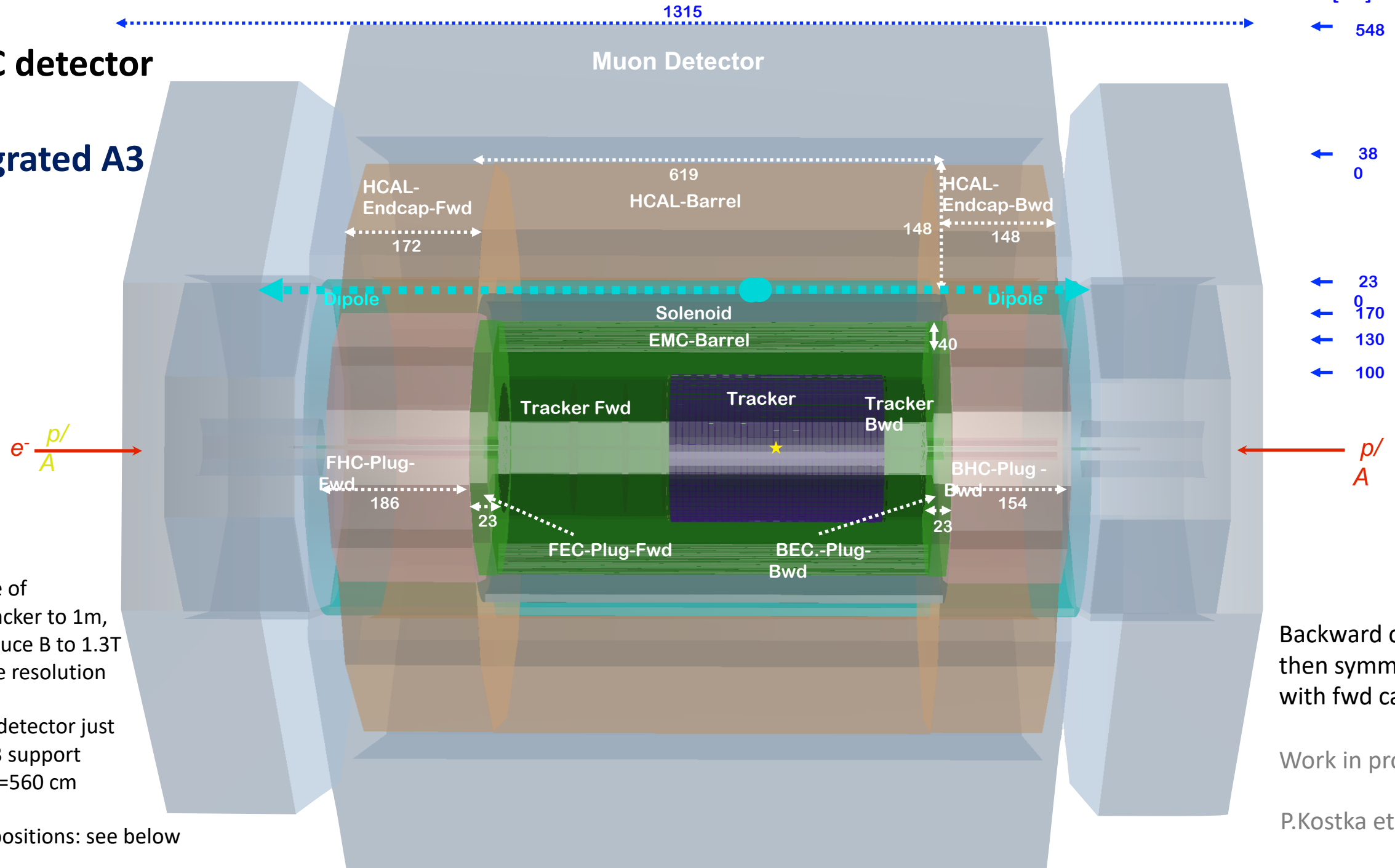
Detector Installation possible within about two-years shutdown: pre-mounting on surface

Personal note on **TAKRAF cranes**
Tagebau-Ausrüstungen, **KRA**ne und **Förderanlagen**

~1983 for L3,
In-kind contribution from IfH Zeuthen, AdW DDR

Integration of eA and AA Detector Concepts

LHeC detector with integrated A3



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

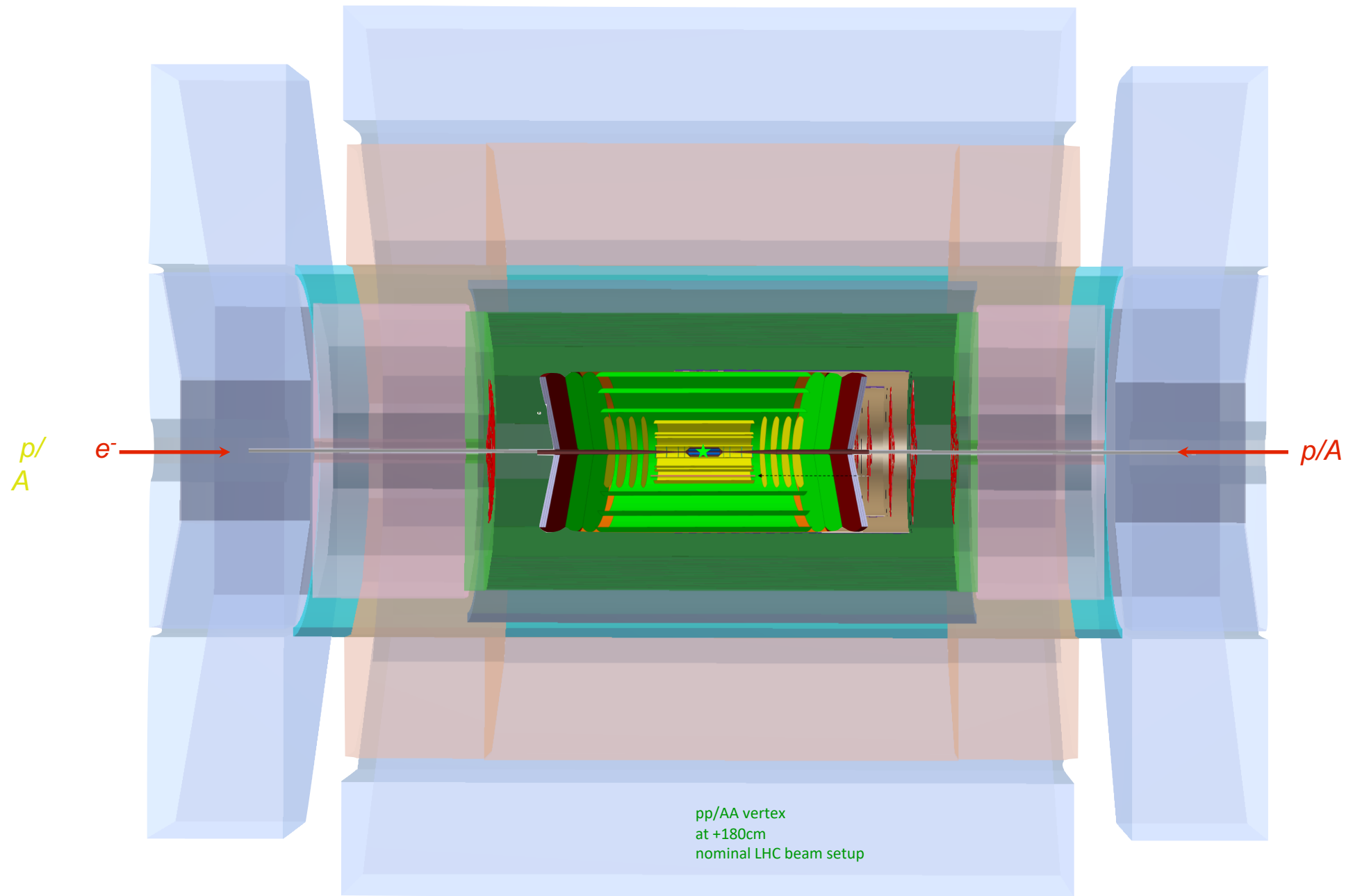
Overall detector just fits in L3 support $R_{free}(L3)=560$ cm

Vertex positions: see below

Backward calos then symmetric with fwd calos

Work in progress

P.Kostka et al.



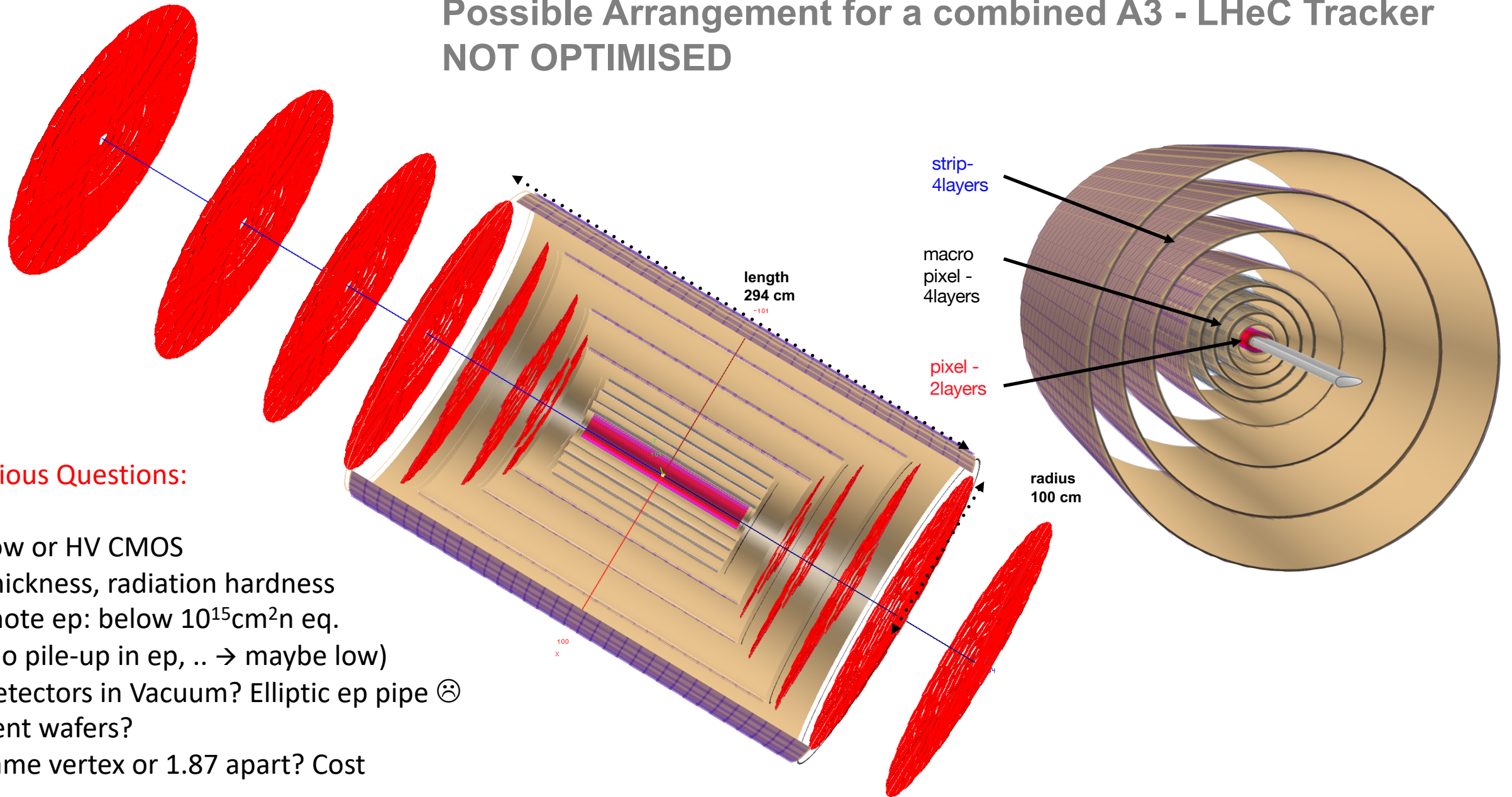
p/A

e^-

p/A

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

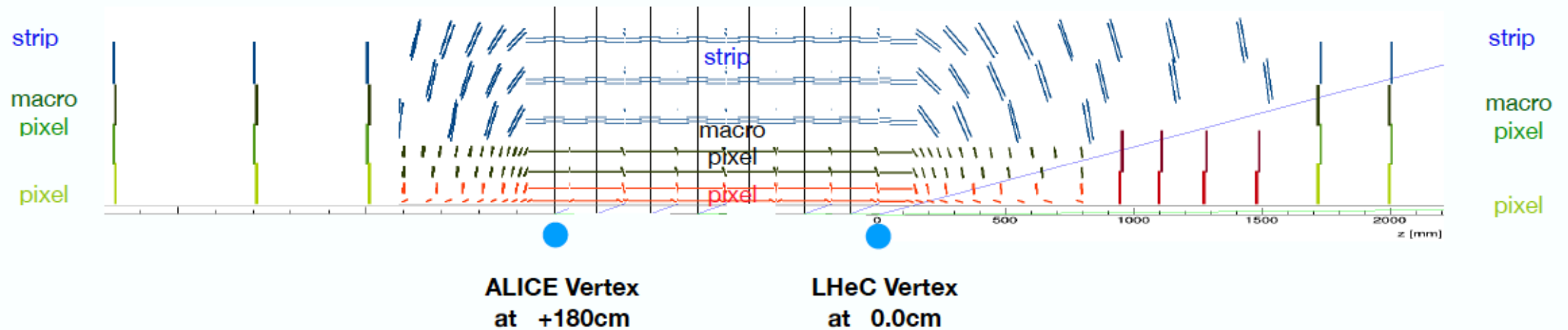
Possible Arrangement for a combined A3 - LHeC Tracker NOT OPTIMISED



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
- ...

Combined ALICE - LHeC Tracker - 1. Idea

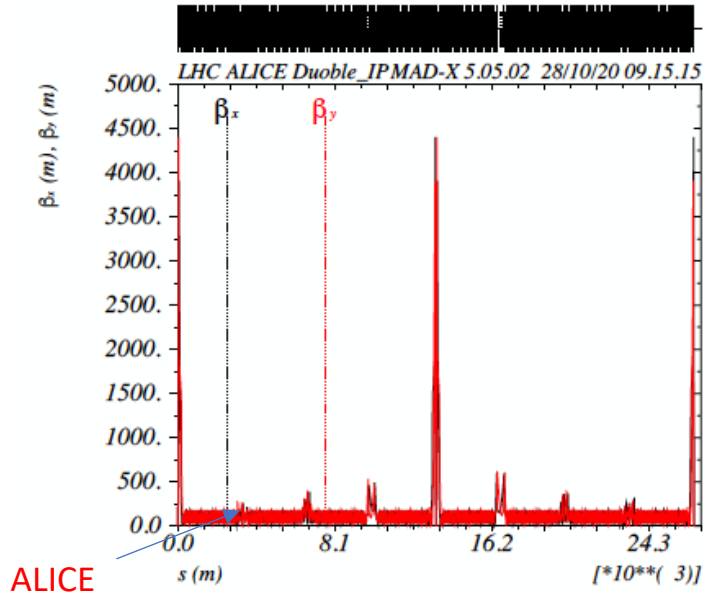


11.11.2020

P. Kostka – work in progress

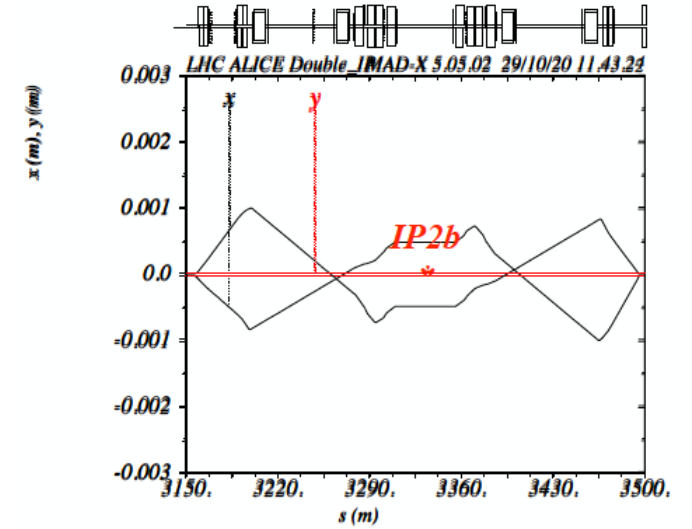
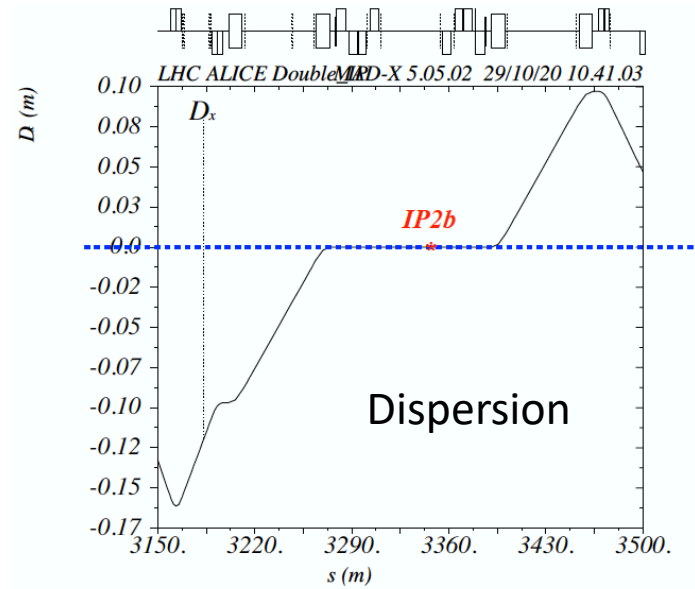
Dual Collisions: AA and eA at IP2

Optics for IP2

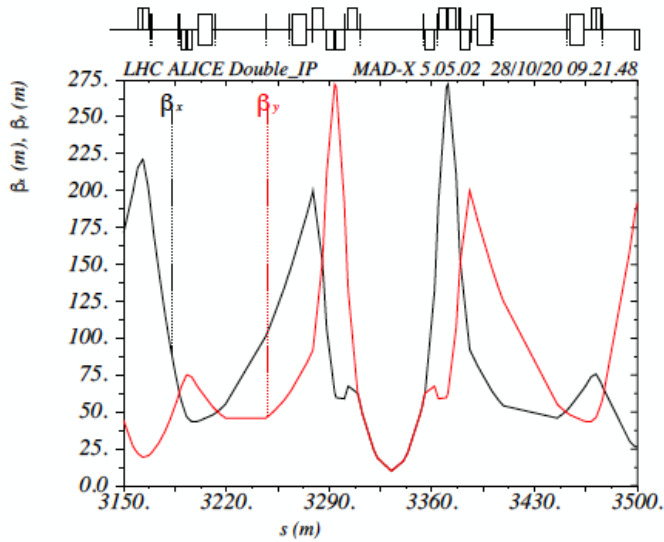


LHC Optics – beta vs path

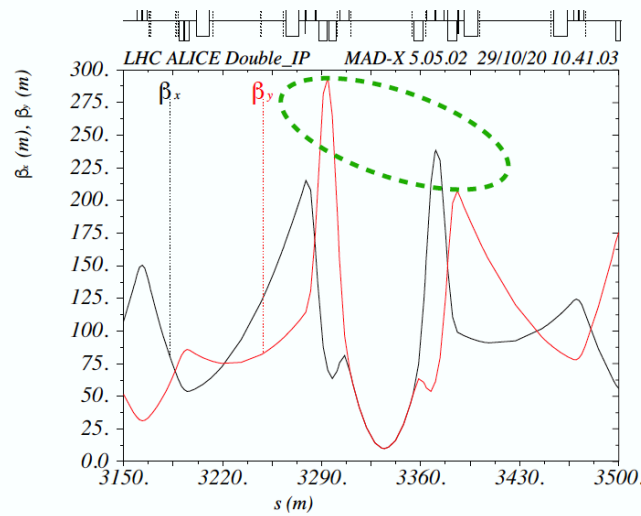
ALICE



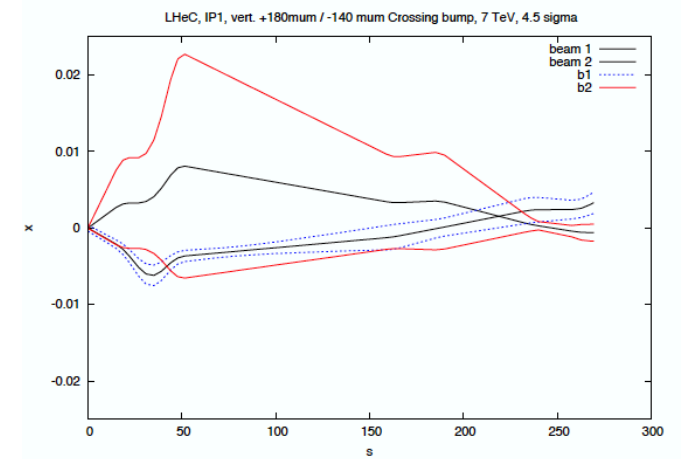
Separation bump (std LHC procedure)



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



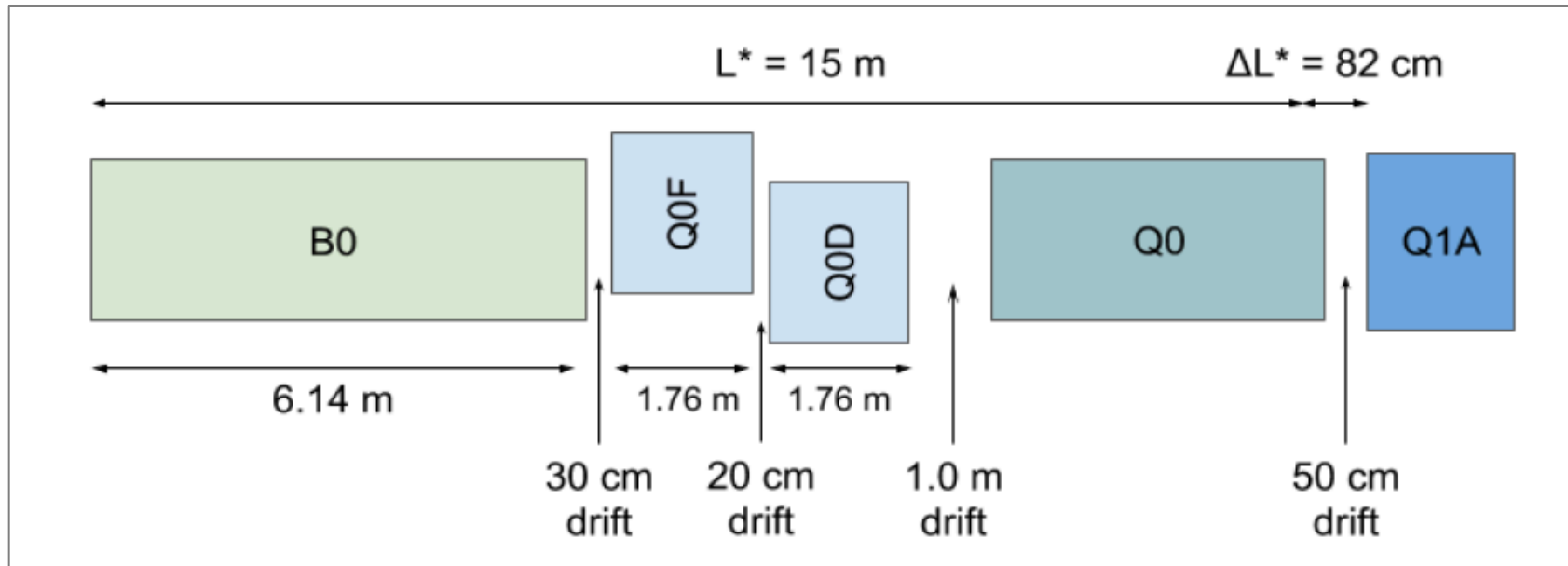
ALICE Luminosity Optics: IP2b=1.87m



Shift in time and vertical xing 140mrad

→ No showstopper for ep and AA

LHeC IR modified for dual purpose



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

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

Detector dipole

Staggered quads

Half-quad (NC)

First of triplet 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)

Aperture Staggered Quadrupoles

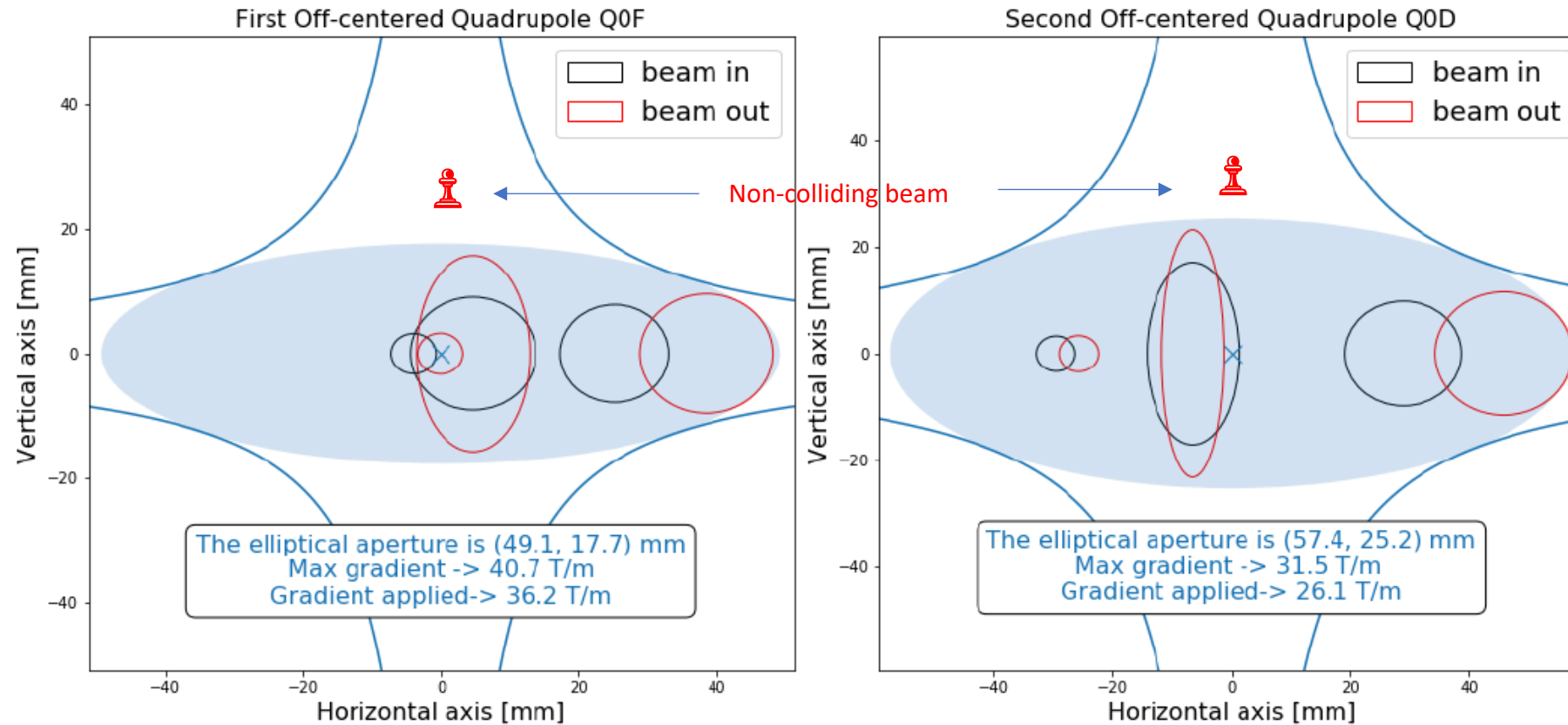


Figure 10.42: The position of the three beams at the entrance (black) and exit (red) of the electron doublet magnets. Following the internal convention, 15σ plus 20% beta beating plus 2mm orbit tolerances beam envelopes are chosen for the proton beams. The beam size of the electrons refer to 20σ . From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

Aperture Half-Quadrupole

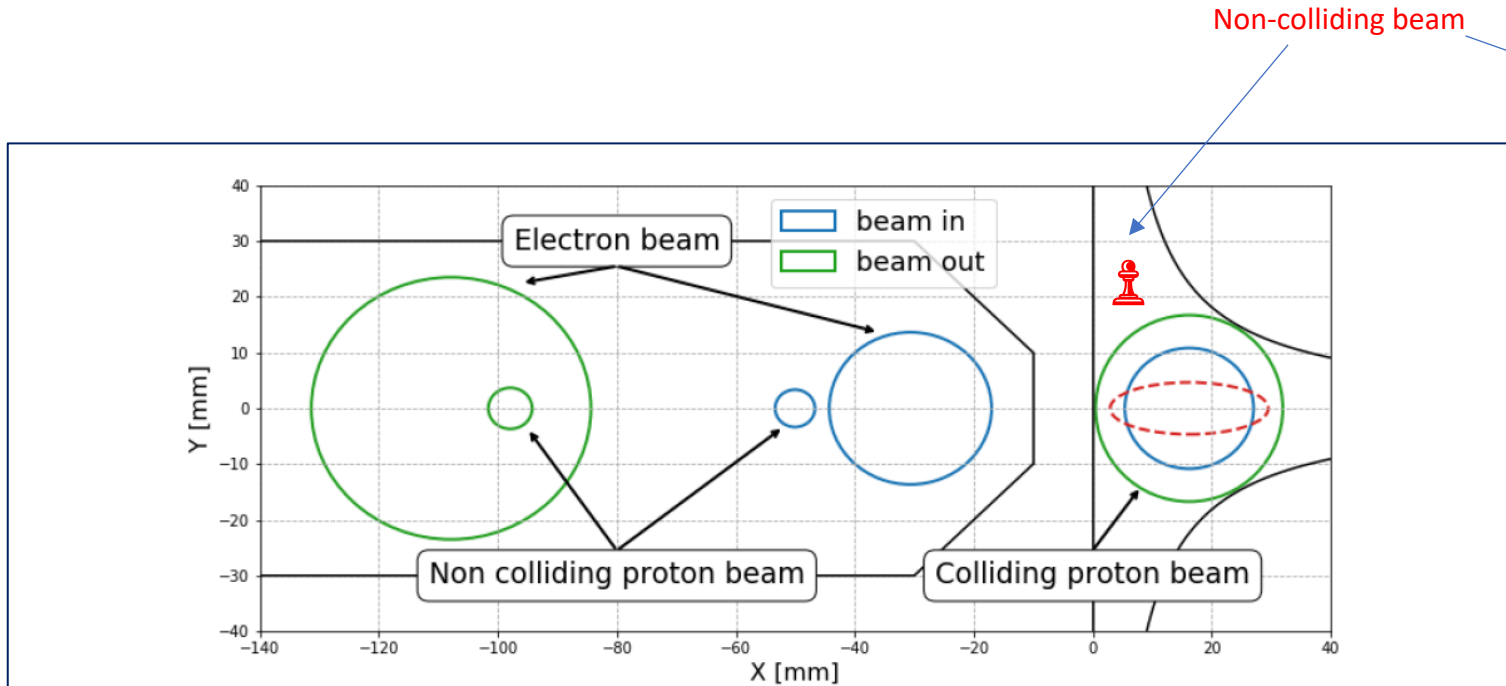
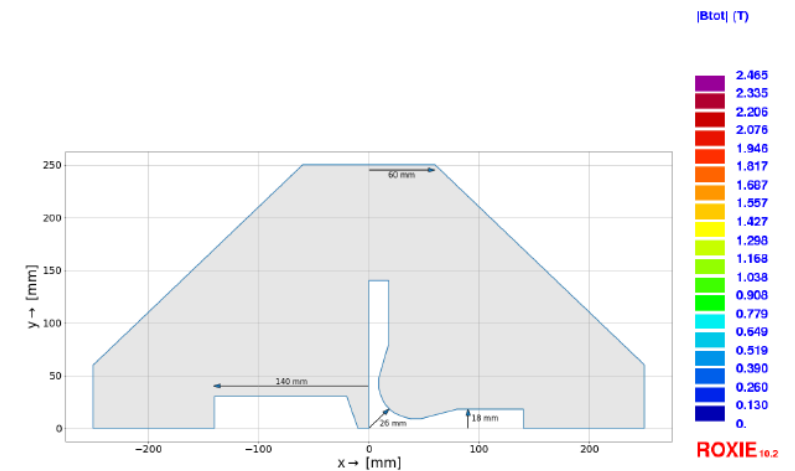
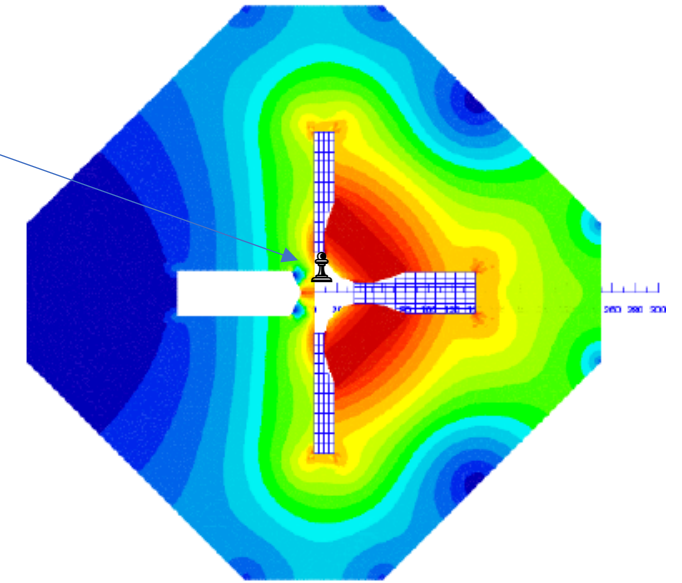


Figure 10.41: The position of the three beams at the entrance (blue) and exit (green) of the half quadrupole. The colliding proton beam is centered inside the main magnet aperture, while the second proton beam and the electrons are located in the field free region. The dashed red line represents the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



Q1 and further Quadrupoles

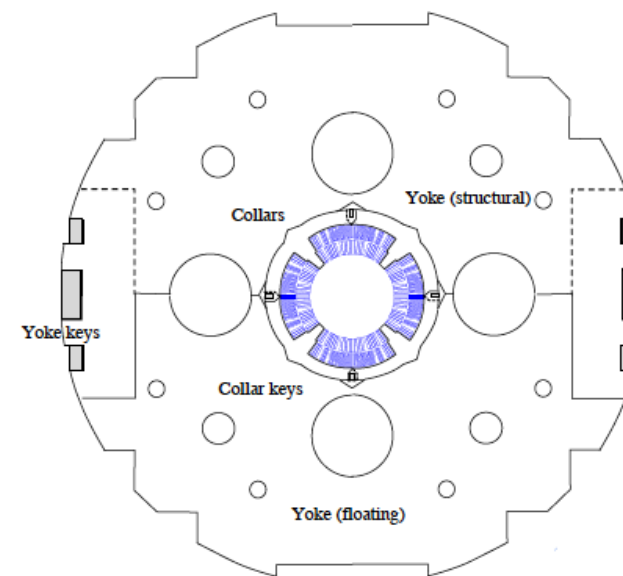
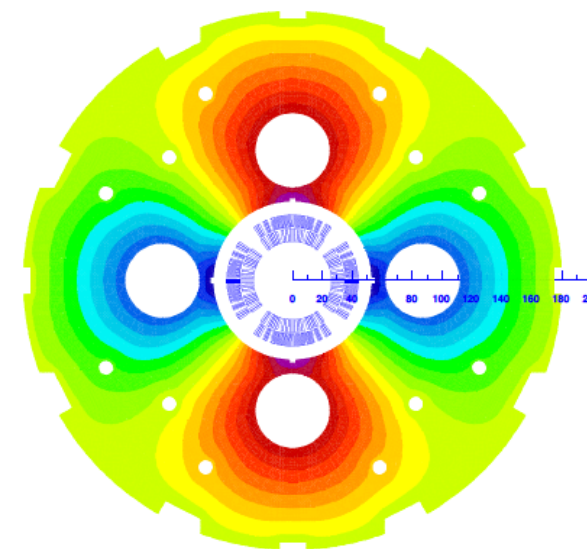
Magnet parameter	Unit	Magnet type			
		Q1A	Q1B	Q2 type	Q3 type
Superconductor type		Nb-Ti	Nb-Ti	Nb ₃ Sn	Nb ₃ Sn
Coil aperture radius R	mm	20	32	40	45
Nominal current I_{nom}	A	7080	6260	7890	9260
Nominal gradient g	T/m	252	164	186	175
Percentage on the load line	%	78	64	71	75
Beam separation distance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

Table 10.28: Main triplet magnet parameters

Q2, Q3 desirably NOT Nb₃Sn 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



Remarks on Heavy Ion Physics

What we can learn in an ep/eA collider

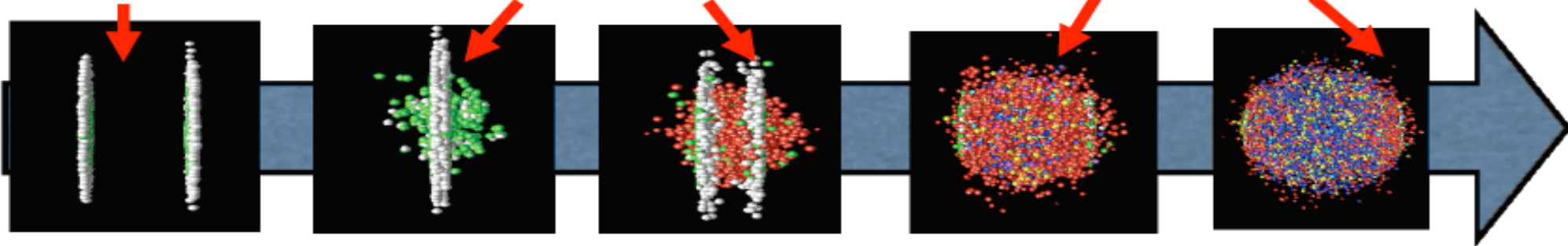
We do not have a **QUANTITATIVE** understanding of the nuclear behaviour

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

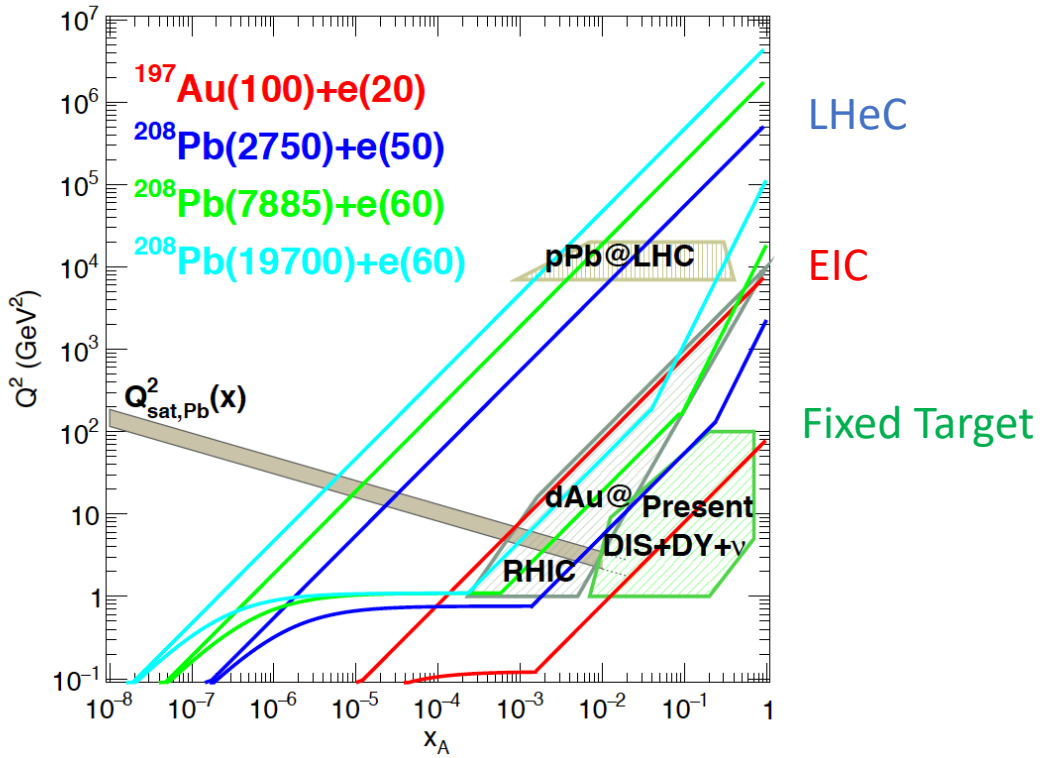
ep and eA:

- 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

Partons in Nuclei

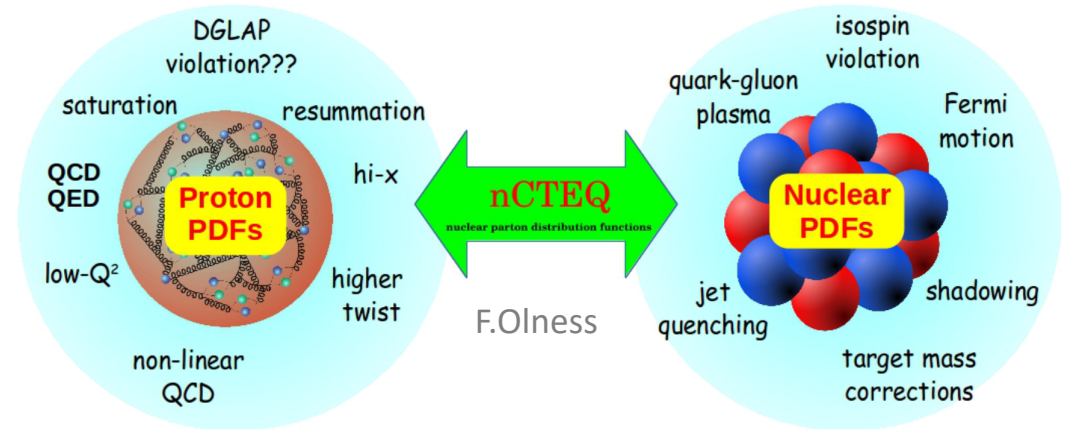


Direct measurements of R:

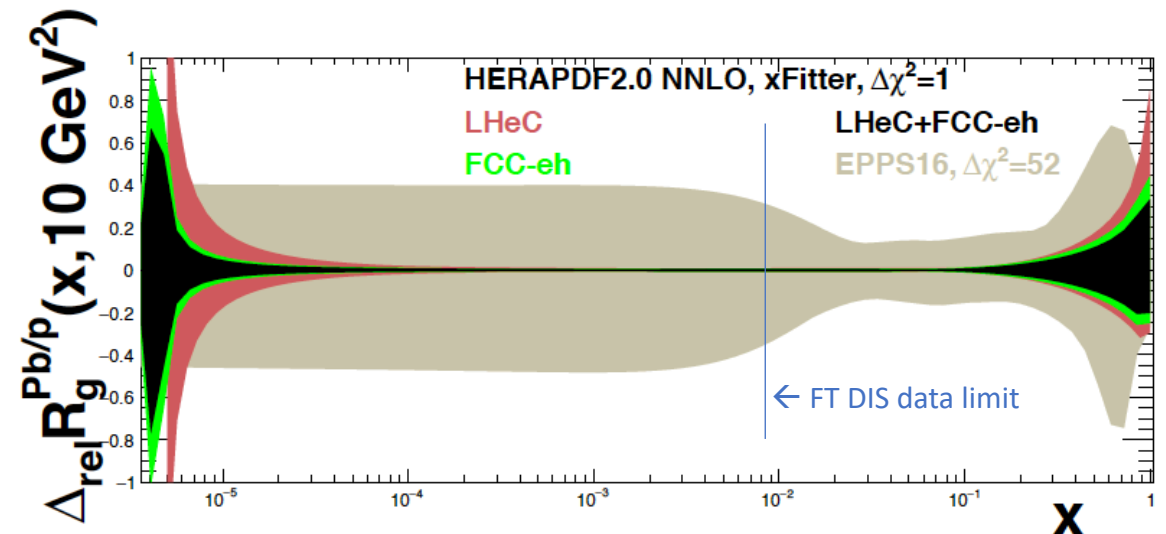
$$R_i(x, Q^2) = \frac{f_i^A(x, Q^2)}{A f_i^p(x, Q^2)}, \quad i = u, d, s, c, b, g, \dots$$

- 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



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

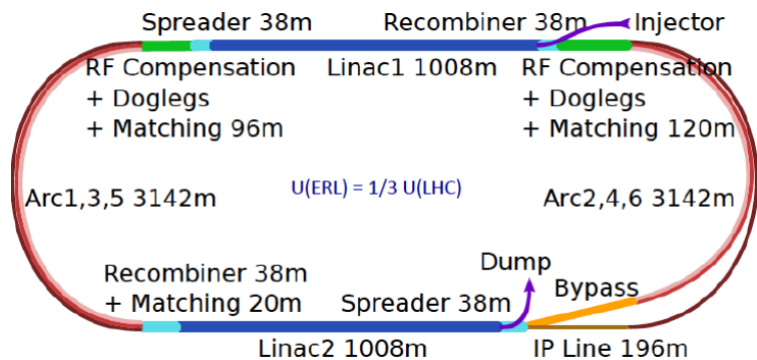
from low p_T , to quarkonia + hard scales

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.

Concluding Remarks



Three Raisons d'être of the LHeC

Physics

- **Microscope:** World's Cleanest High Resolution
- **Empowerment** of the LHC Physics Programme
- **Creation** of a high precision, novel Higgs facility
- **Discovery** Beyond the Standard Model
- **Revolution** of Nuclear Particle Physics

Sustainability and Cost

LHC:

- see: SM, Higgs and no BSM
- use: Investment of O(5) BSF
- run: HL LHC until ~2040

LHeC [1206.2913, 2007.14491]

- 1.2 TeV ep/A for O(1)BSF

→ Establish novel ep+pp

Twin Collider Facility at CERN:

sustains HL LHC and bridges to CERN's long term future

For installation during LS4 (2030+) and long term use (HE LHC, FCCeh)

Technology

Accelerator: Novel SRF ERL, green power facility

Detector: Novel high tech (CMOS..) apparatus

→ Keep accelerator and detector base uptodate while preparing for colliders that cost O(10)BSF

Questions and Tentative Comments

Initial thoughts and questions: LHeC Meeting 29.10.

and tentative answers 23.11.20

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 our detector change if we integrate A3 into LHeC **extension in radius, B reduced, low V CMOS, ..**
- How would their detector change? Would they 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 their design the extended ep beam pipe is a nuisance (as it is for ours) --> place Si inside pipe?? **challenging**
- There are many more..

Programme until about 2025

The following focus points are evident for the coming years:

- * The closer inspection of the relation of ep and pp , as well as eA with AA (pA), physics;
- * The development of the BSM and Higgs physics of eh and its relation to ee and hh ;
- * Theory developments as outlined;
- * The realisation of the first phase of PERLE (injector) towards 250 MeV beam at IJClab Orsay;
- * The formation of an international proto-detector Collaboration able to present the LHeC to the LHCC at CERN and to collaborate on detector technology R&D,
- * Conclusion on the machine-detector interface, including a mock-up of the first quadrupole, a plan for absorbers+masks and a prototype solution of the elliptic beam pipe.

Following a statement of the LHeC/FCC-eH Advisory Committee, chaired by Herwig Schopper, published in 2007.14491

A first analysis of the merits and opportunities of integrating the LHeC and “A3” detectors could be interesting to be pursued further.

backup

Statement of the IAC to DG, published in 2007.14491

In conclusion it may be stated

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

Recommendations

- i) It is recommended to further develop the ERL based ep/A scattering plans, both at LHC and FCC, as attractive options for the mid and long term programme of CERN, resp. Before a decision on such a project can be taken, further development work is necessary, and should be supported, possibly within existing CERN frameworks (e.g. development of SC cavities and high field IR magnets).
- ii) The development of the promising high-power beam-recovery technology ERL should be intensified in Europe. This could be done mainly in national laboratories, in particular with the PERLE project at Orsay. To facilitate such a collaboration, CERN should express its interest and continue to take part.
- iii) It is recommended to keep the LHeC option open until further decisions have been taken. An investigation should be started on the compatibility between the LHeC and a new heavy ion experiment in Interaction Point 2, which is currently under discussion.

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

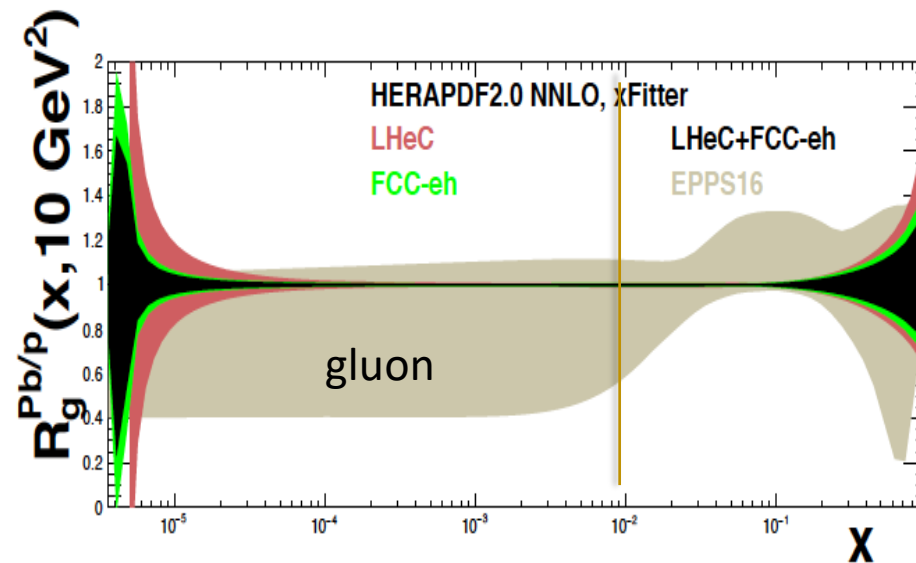
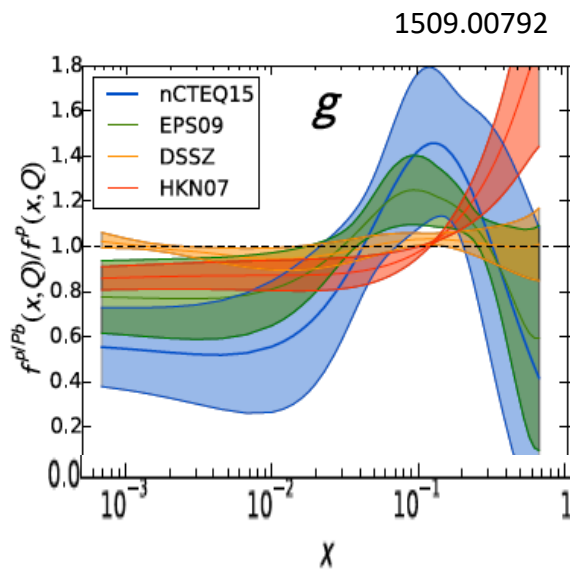
Herwig Schopper, Chair of the Committee,

Geneva, November 4, 2019

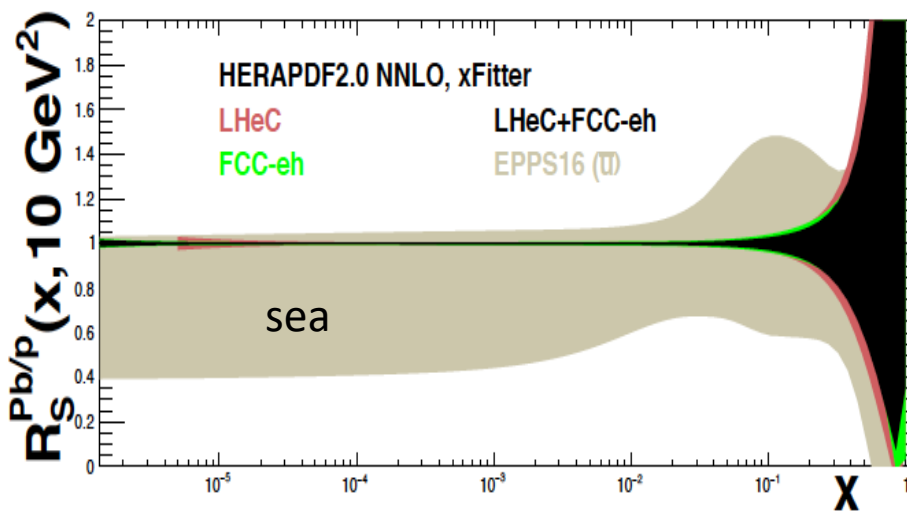
There follows a programme for the coming years which is being established and for us to shape.

Determination of p and A PDFs at LHeC/FCCeh

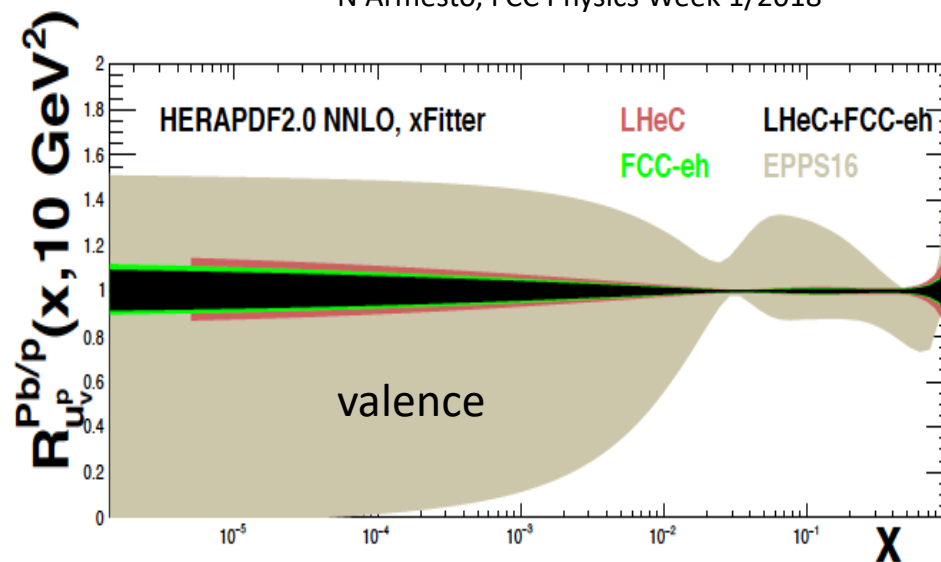
present status →
on xg
Pb/p



N Armesto, FCC Physics Week 1/2018



LHeC: Full error, $\Delta\chi^2=1$. EPPS $\Delta\chi^2=52$



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:

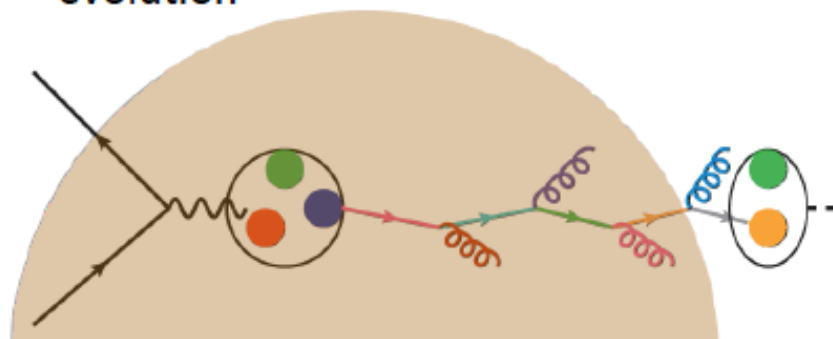
hadronization in matter

- (pre)hadronic absorption
- formation time

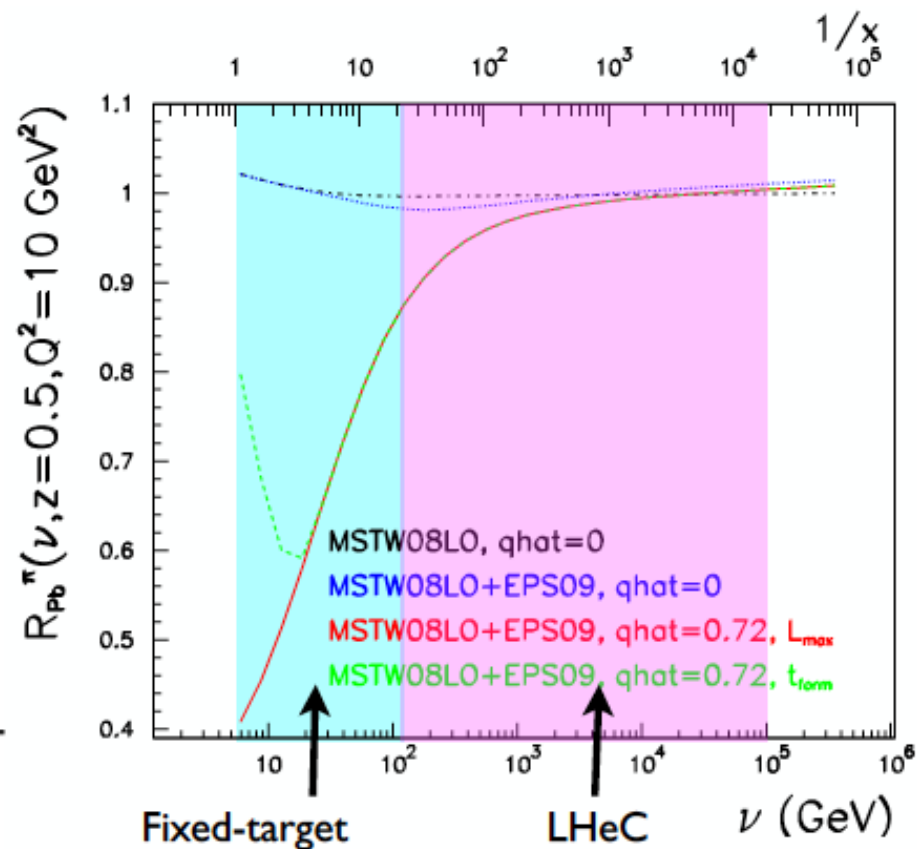


High energy:

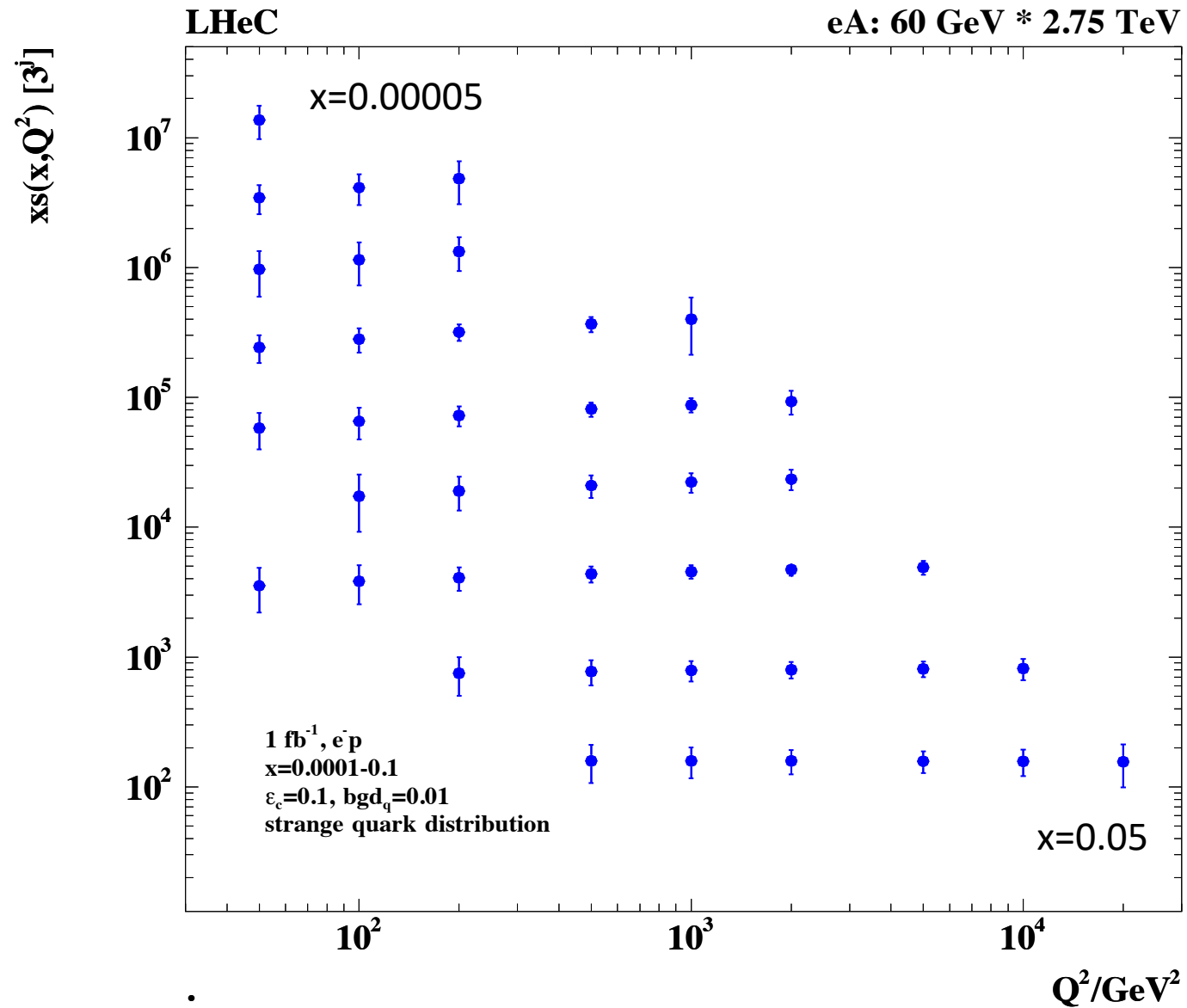
- modification of partonic evolution



Ratio of fragmentation functions Pb/p



Heavy Flavour – Strange in ePb - from CC

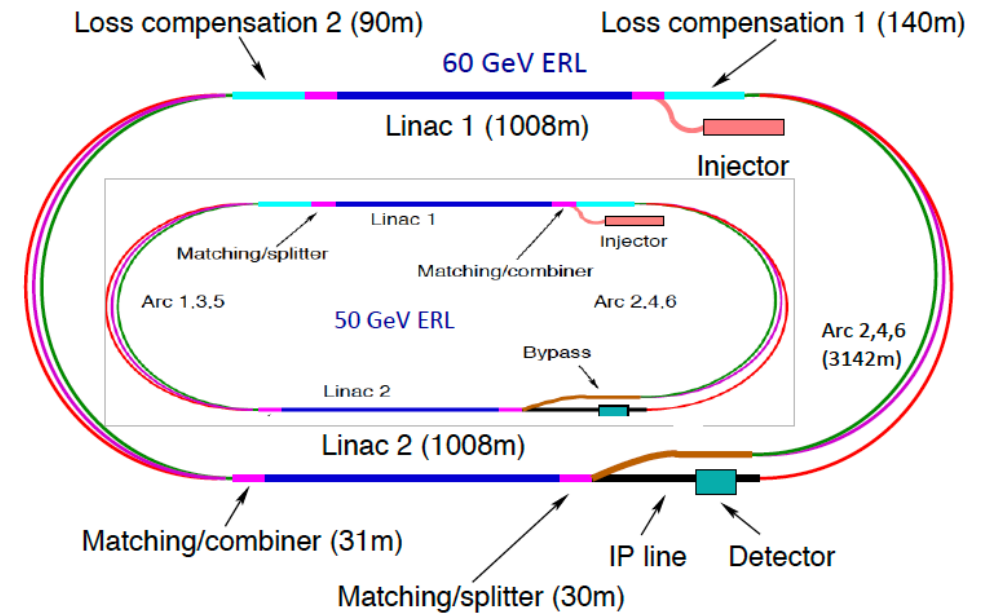


The ERL in more Detail

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	μm	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 20mA 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 GW and dumps at $<$ GeV
 \rightarrow novel, "green" accelerator technology

Other possible studies: quarkonium production

Production mechanism and polarization:

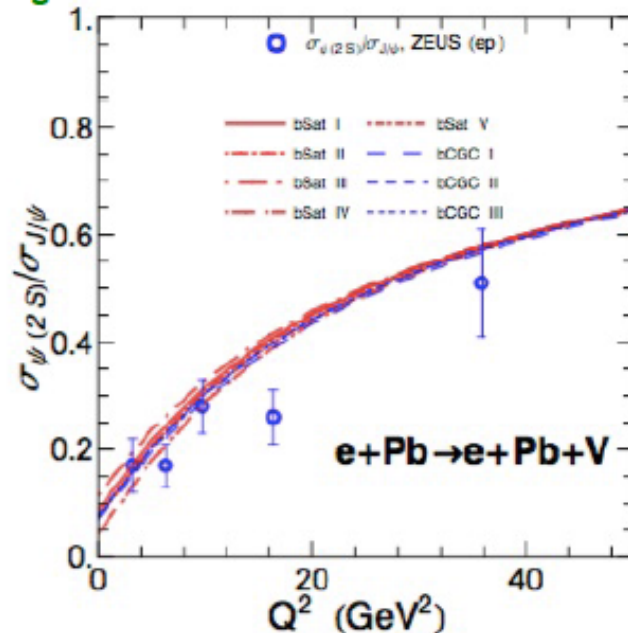
polarized J/ψ photoproduction can be studied more precisely and up to much larger values of p_T in **ep @ LHeC**

⇒ 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

γ 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

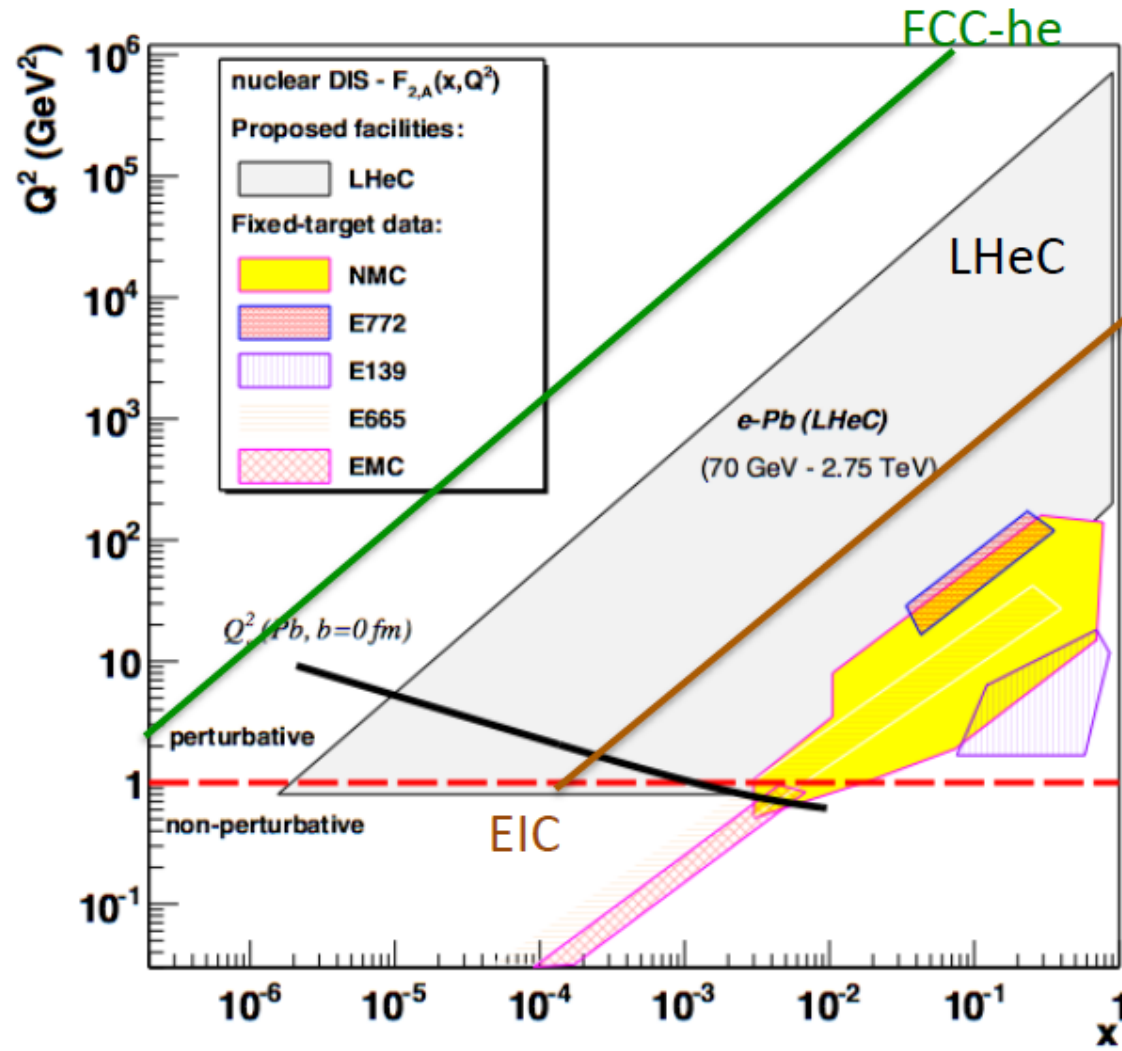
Kinematic Ranges of IA DIS – Past and Future

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

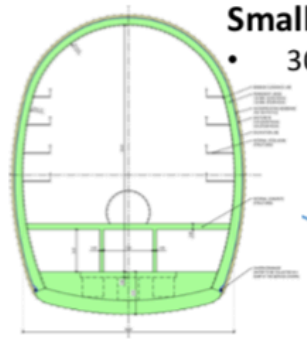
Note that **LHeC may be tuned to low energies**
 $v_s \approx 100$ GeV instead of 1 TeV – direct overlap
EICs and HERA.

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 $1\text{fb}^{-1}/\text{day}$)

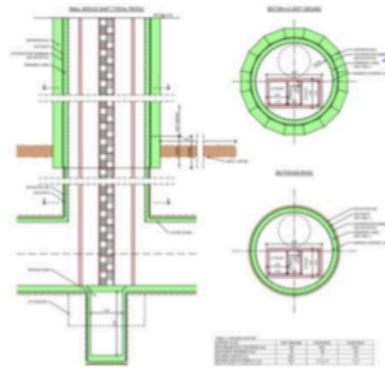


Small Experimental Caverns

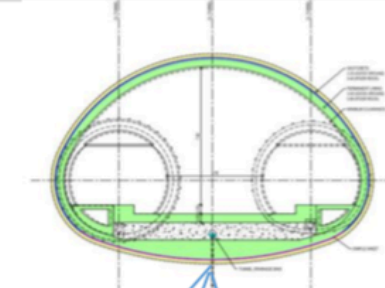
- 30 m x 35 m x 66m

Shafts:

2 x Service shafts:
9 m dia. x 175 m depth

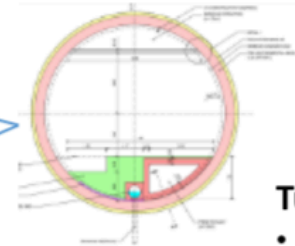
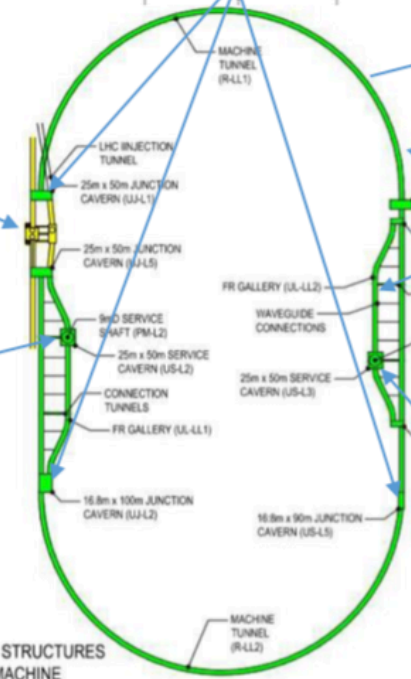


■ FCC STRUCTURES
■ EH MACHINE



Junction Caverns

- 16.8 m x 15 m x 100 m
- 25 m x 15 m x 50 m
- 16.8 m x 15 m x 90 m



Service Caverns

- 25 m x 15 m x 50 m

Tunnels:

- 9.091 km of 5.5m dia. machine tunnel.
- 2 x 1.04 km of 5.5m dia RF tunnel.

