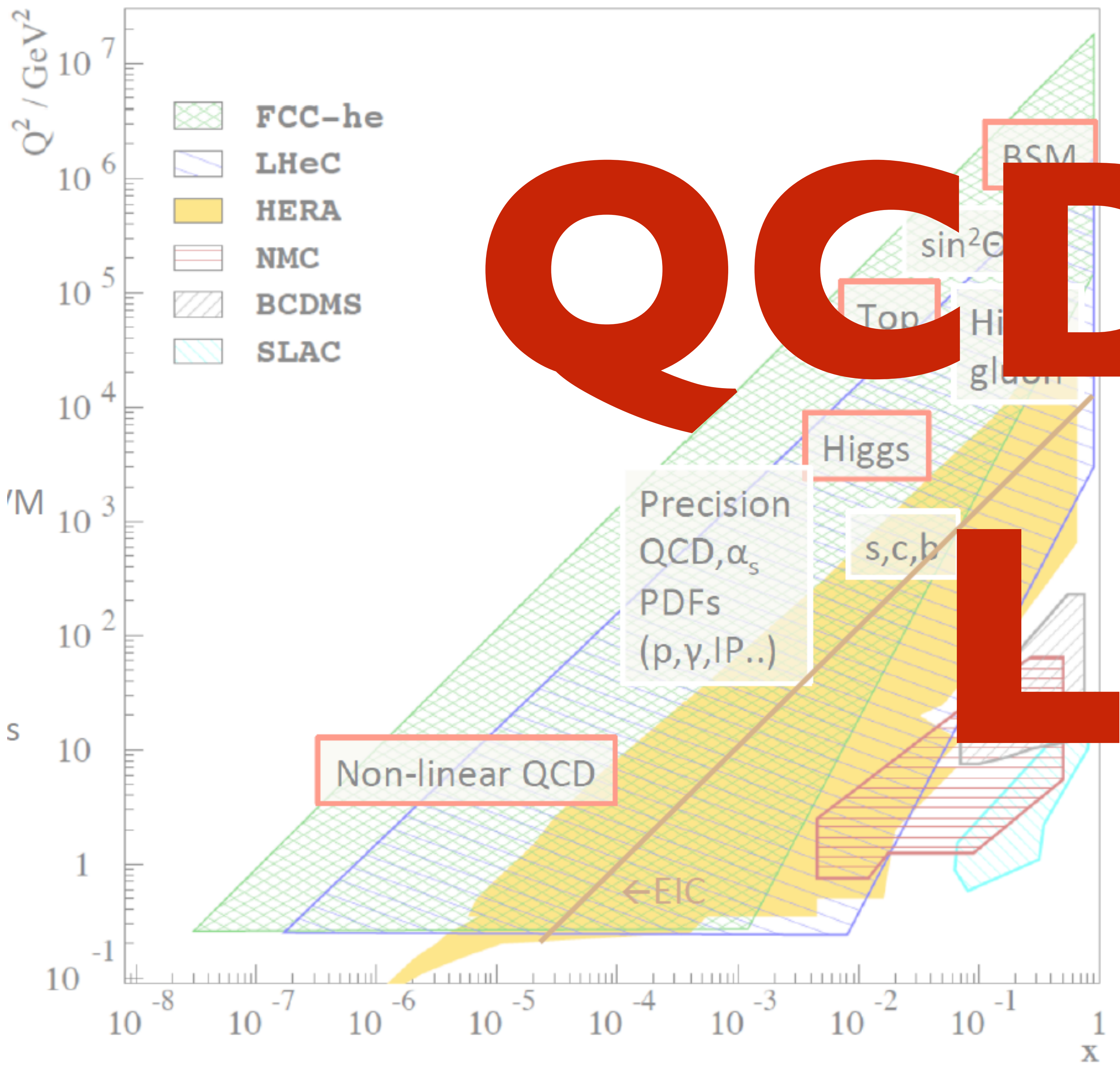
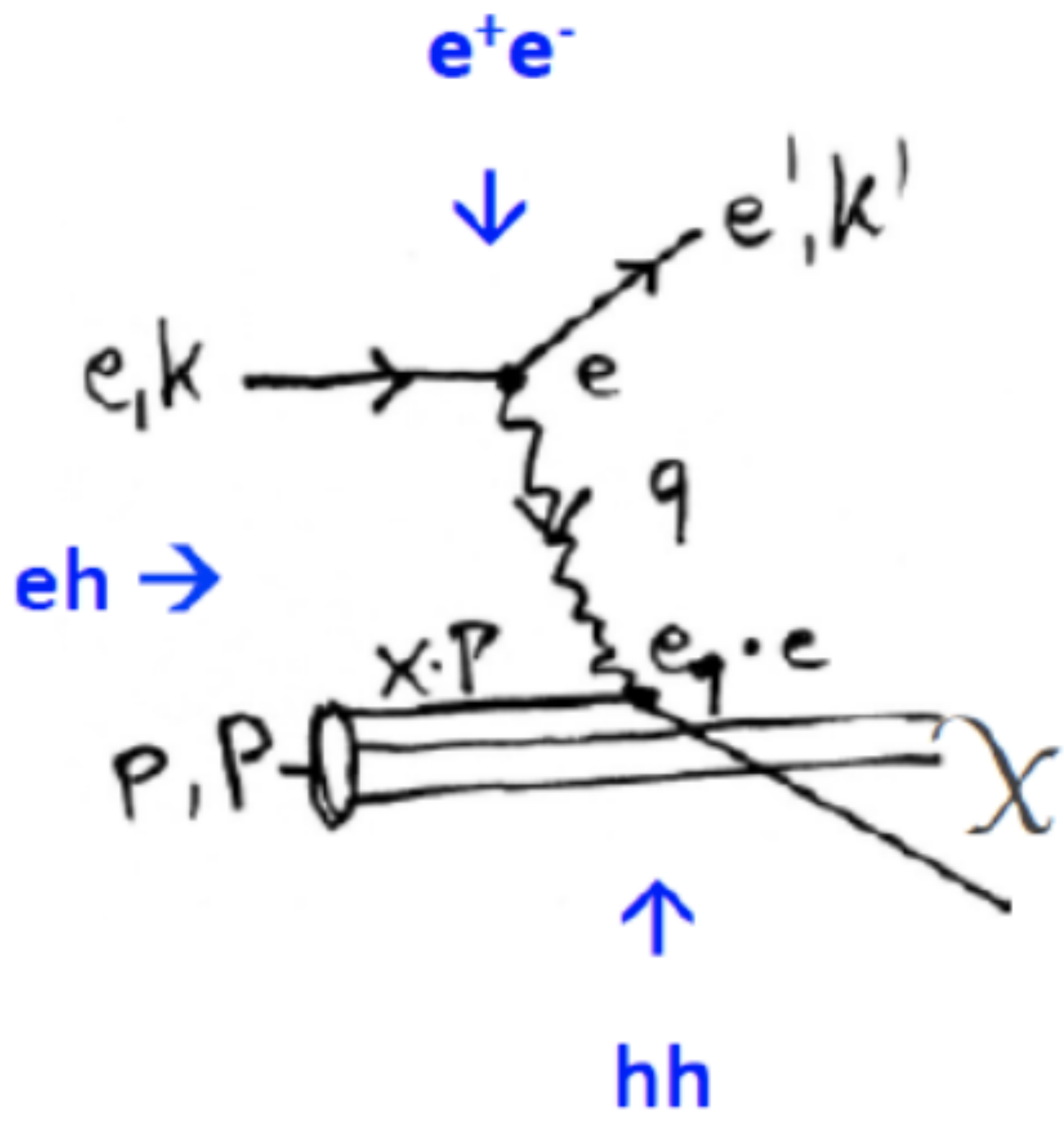
INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS IGFAE

2025 European Physical Society Conference on High Energy Physics
Marseille, July 11th 2025



QCD at the LHeC



Néstor Armesto
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for the LHeC/FCC-eh Study Group, https://indico.cern.ch/event/lhecfcceh.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA · MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES · AGENCIA ESTATAL DE INVESTIGACIÓN · EXCELENCIA MARÍA DE MAEZTU 2024-2030 · XUNTA DE GALICIA · CENTROS CIGUS · Cofinanciado pola Unión Europea · Fondos Europeos

Contents:

1. Introduction.

2. QCD:
   - ➜ Collinear PDFs.
   - ➜ α_s.
   - ➜ Small x.
   - ➜ Diffraction and 3D structure.

3. Summary.

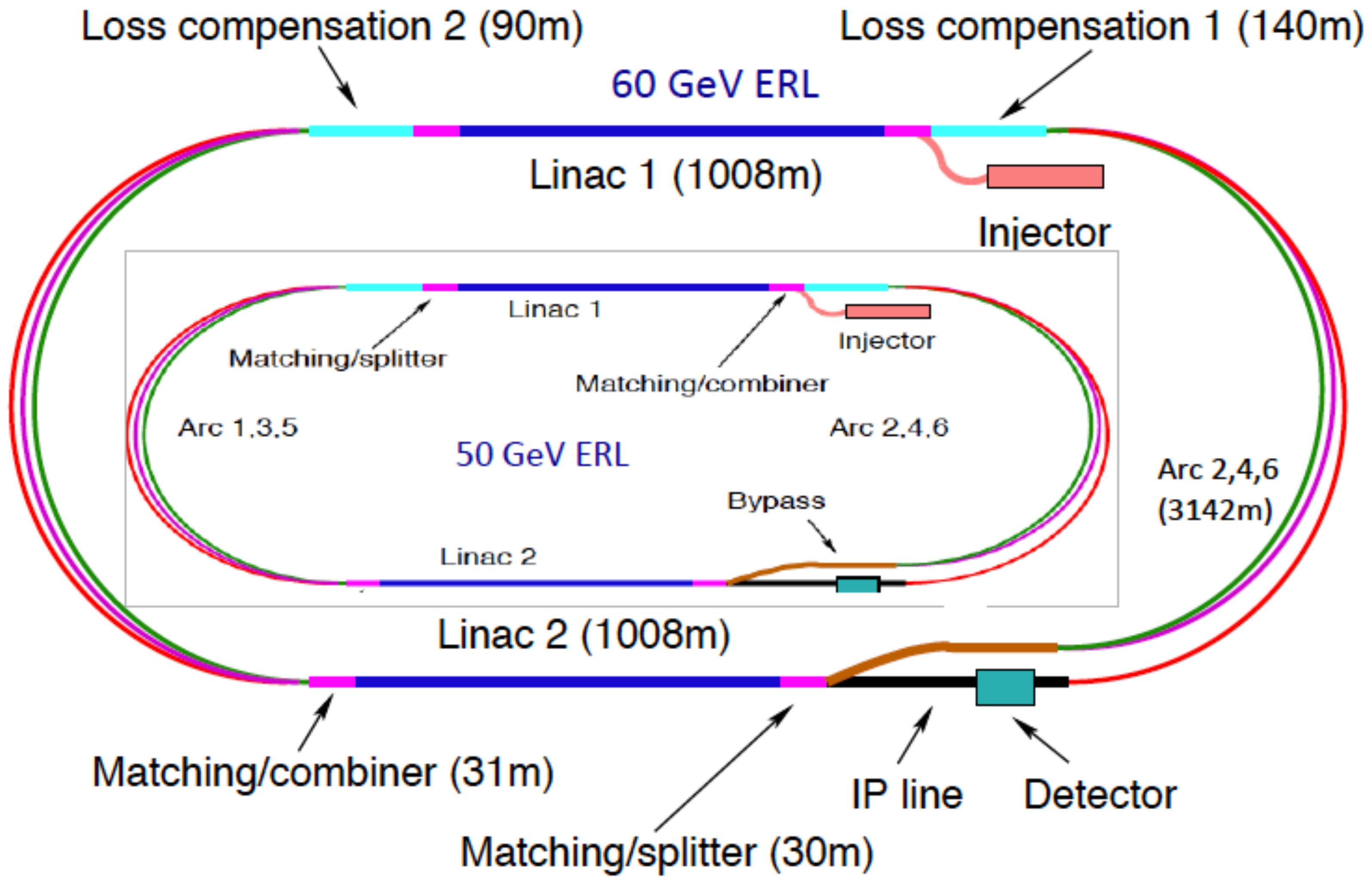
Further talks at EPS-HEP 2025:
- BSM physics at the LHeC and the FCC-eh, 8 Jul 2025, 17:30, Christian Schwanengerger, T09.
- The LHeC collider as a bridge between major colliders at CERN, 9 Jul 2025, 08:30, Jorgen D'Hondt, T13.
- A detector for top energy DIS (poster), Laurent Forthomme, T11.
- Higgs physics at the LHeC, 11 Jul 2025, 09:00, Néstor Armesto, T08.
- Top and EW physics at the LHeC, 11 Jul 2025, 09:10, Christian Schwanengerger, T06.
- Two-photon processes in future electron-hadron facilities, 11/07/2025, 09:30, Laurent Forthomme, T06.

References:
- *Future Circular Collider CDR: Vol. 1 Physics opportunities (Eur. Phys. J. C79 (2019) no.6, 474) and Vol. 3 FCC-hh: The Hadron Collider (Eur. Phys. J. ST 228 (2019) no.4, 755-1107);*
- *LHeC CDR, 1206.2913;*
- *European Strategy Update: Briefing Book, 1910.11775;*
- *Update of the 2012 LHeC CDR, 2007.14491;*
- *2201.02436;*
- *LHeC/FCC-eh talks at ICHEP2024, https://indico.cern.ch/event/1291157/, and DIS2025, https://indico.cern.ch/event/1436959/.*
- *Talks at the Synergy workshop between ep/eA and pp/pA/AA physics experiments, February 29th-March 1st 2024, https://indico.cern.ch/event/1367865/.*
- ***White paper: 2503.17727**, annex to the EPPS submission.*

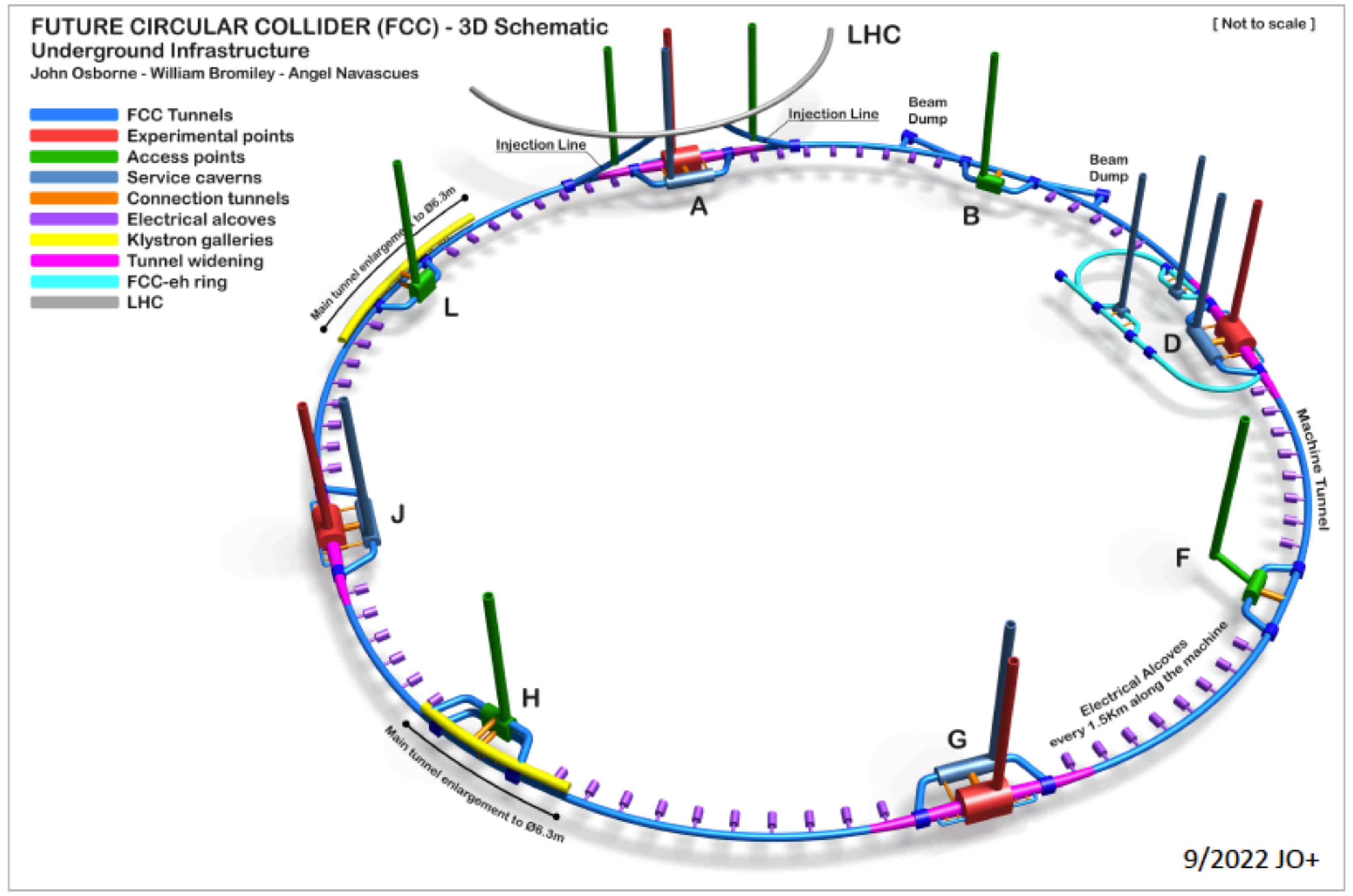
https://indico.cern.ch/event/lhecfcceh

Accelerators:

LHeC



FCC-eh



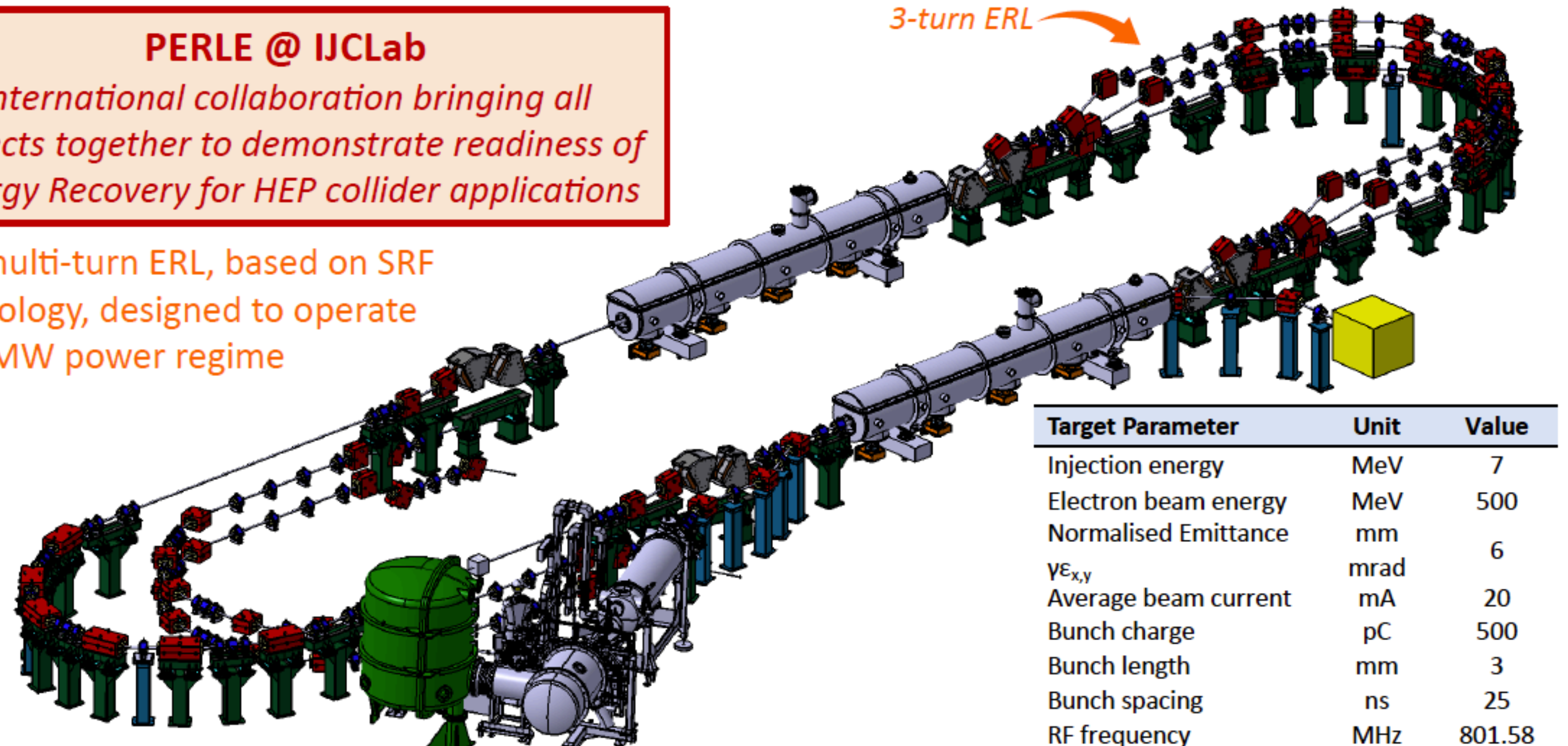
FCC-eh

$$\text{DIS at } \sqrt{s} \simeq 1.2/2.2/3.5 \ \ \text{TeV}, \quad \int \mathscr{L} dt \sim 1-2 \ \ \text{ab}^{-1} \sim 1000 \times \text{HERA}$$

PERLE

PERLE @ IJCLab
international collaboration bringing all aspects together to demonstrate readiness of Energy Recovery for HEP collider applications

first multi-turn ERL, based on SRF technology, designed to operate at 10MW power regime



Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

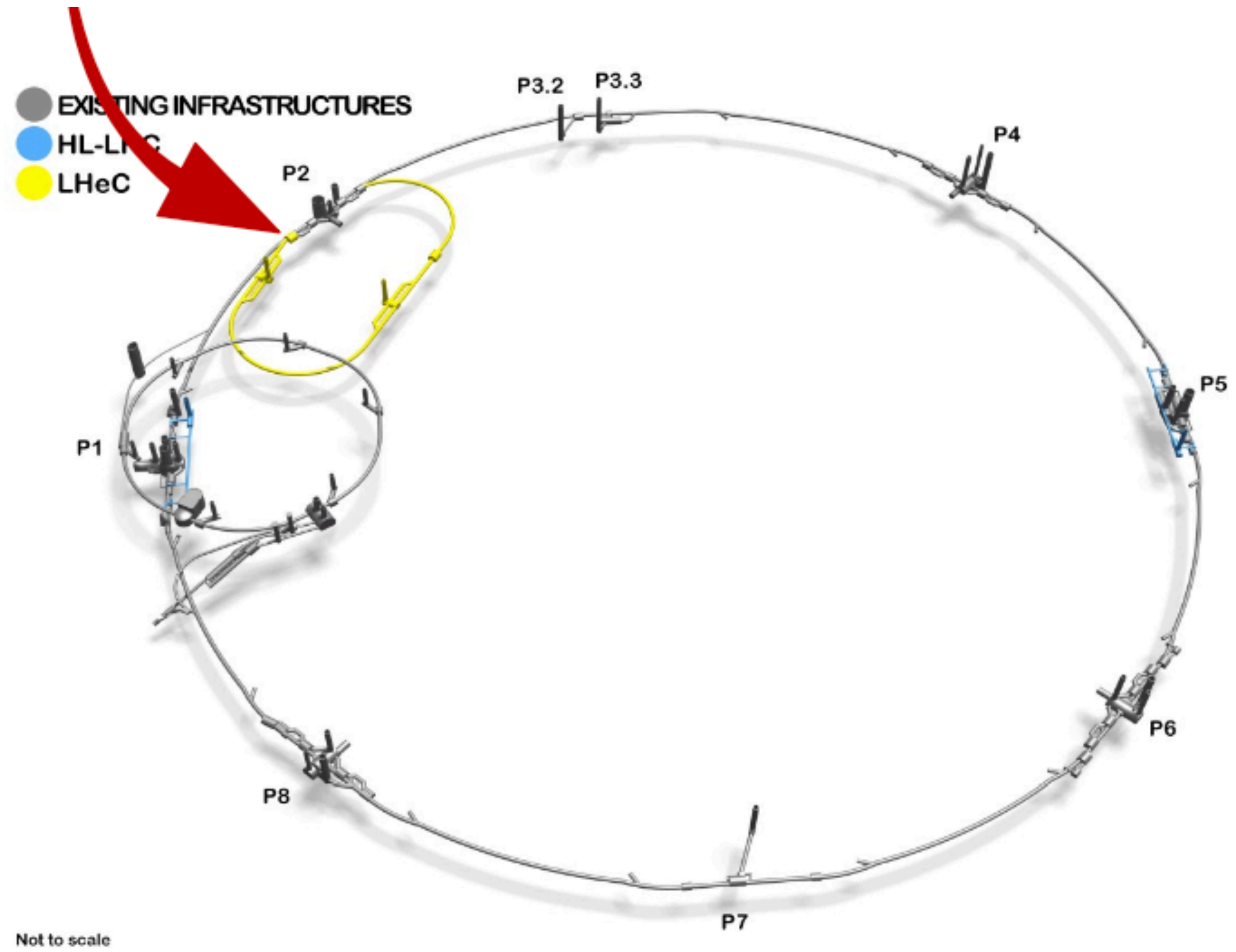
PERLE – Powerful Energy Recovery Linac for Experiments

Parameter	Unit	LHeC				FCC-eh	
ep	P=±0.8 (e^-)	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

1810.13022

Accelerators:

LHeC



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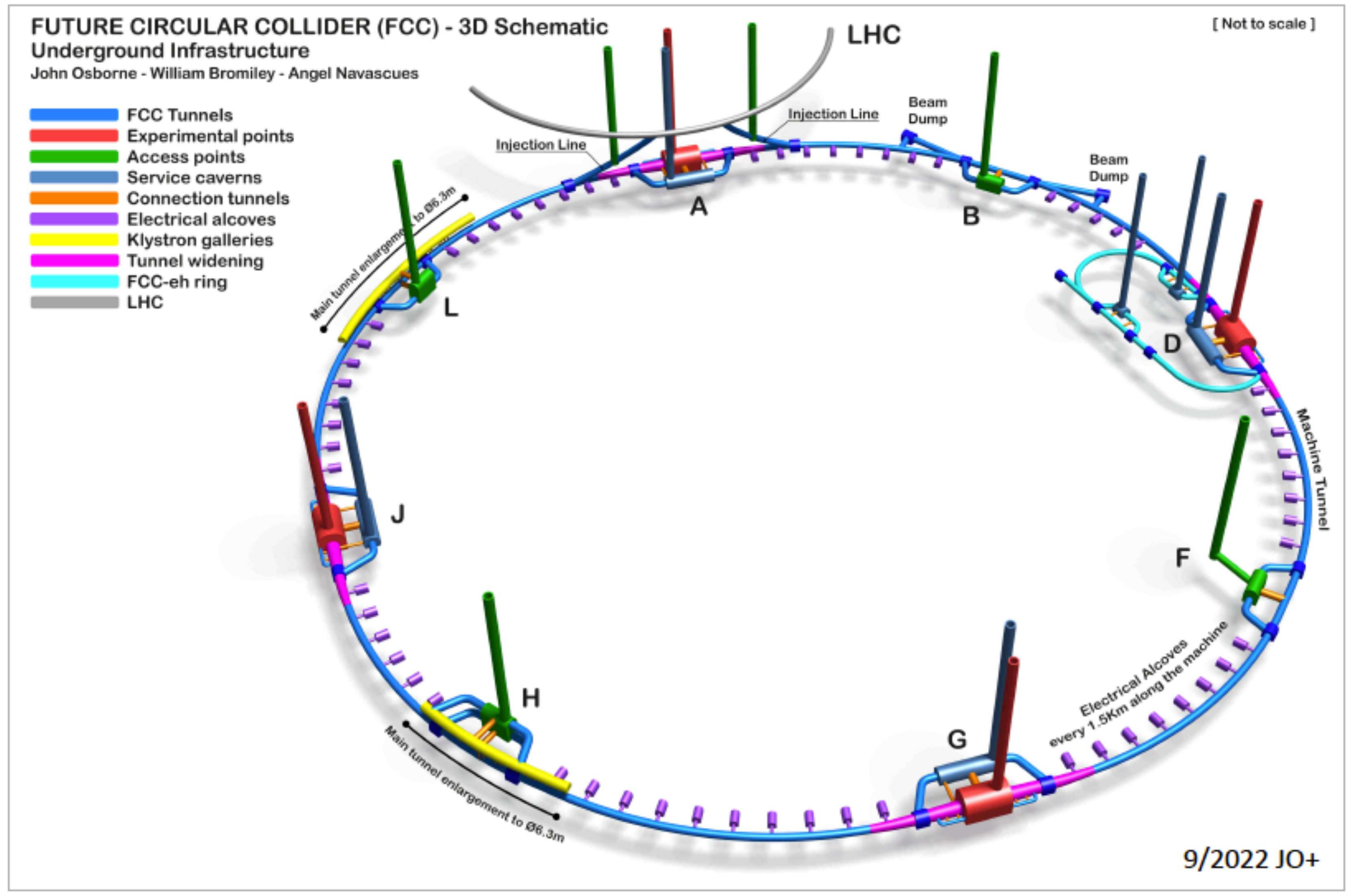

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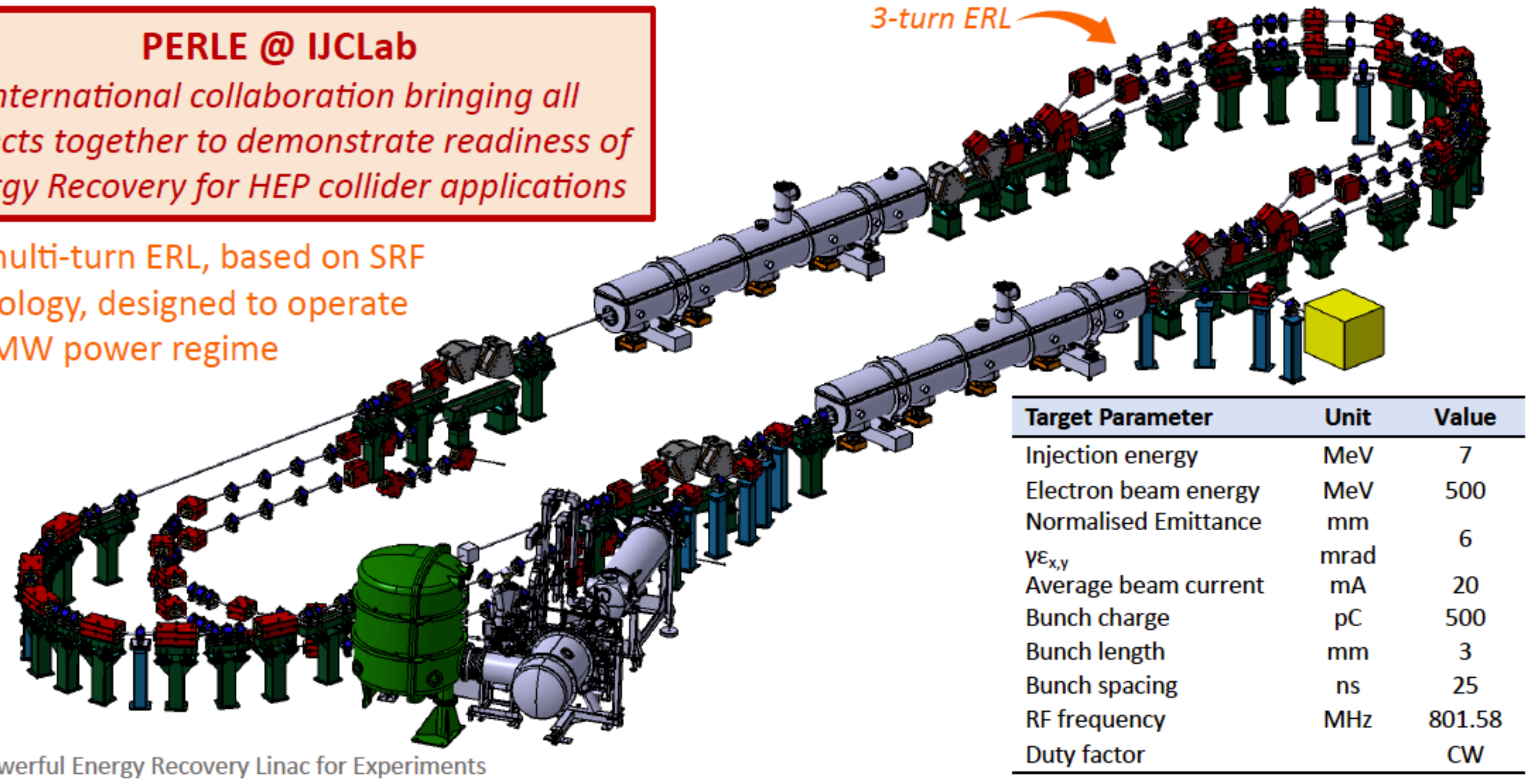

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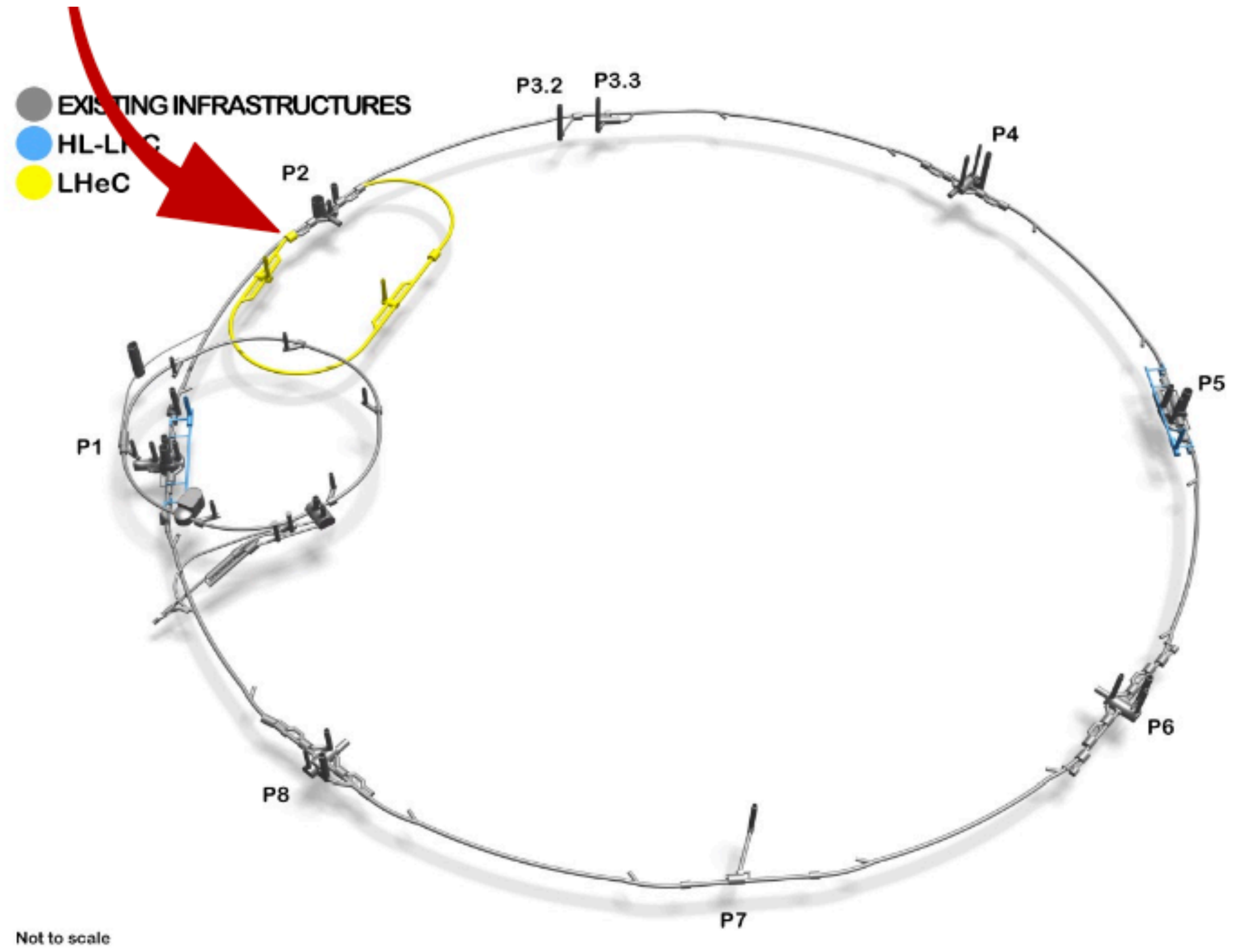
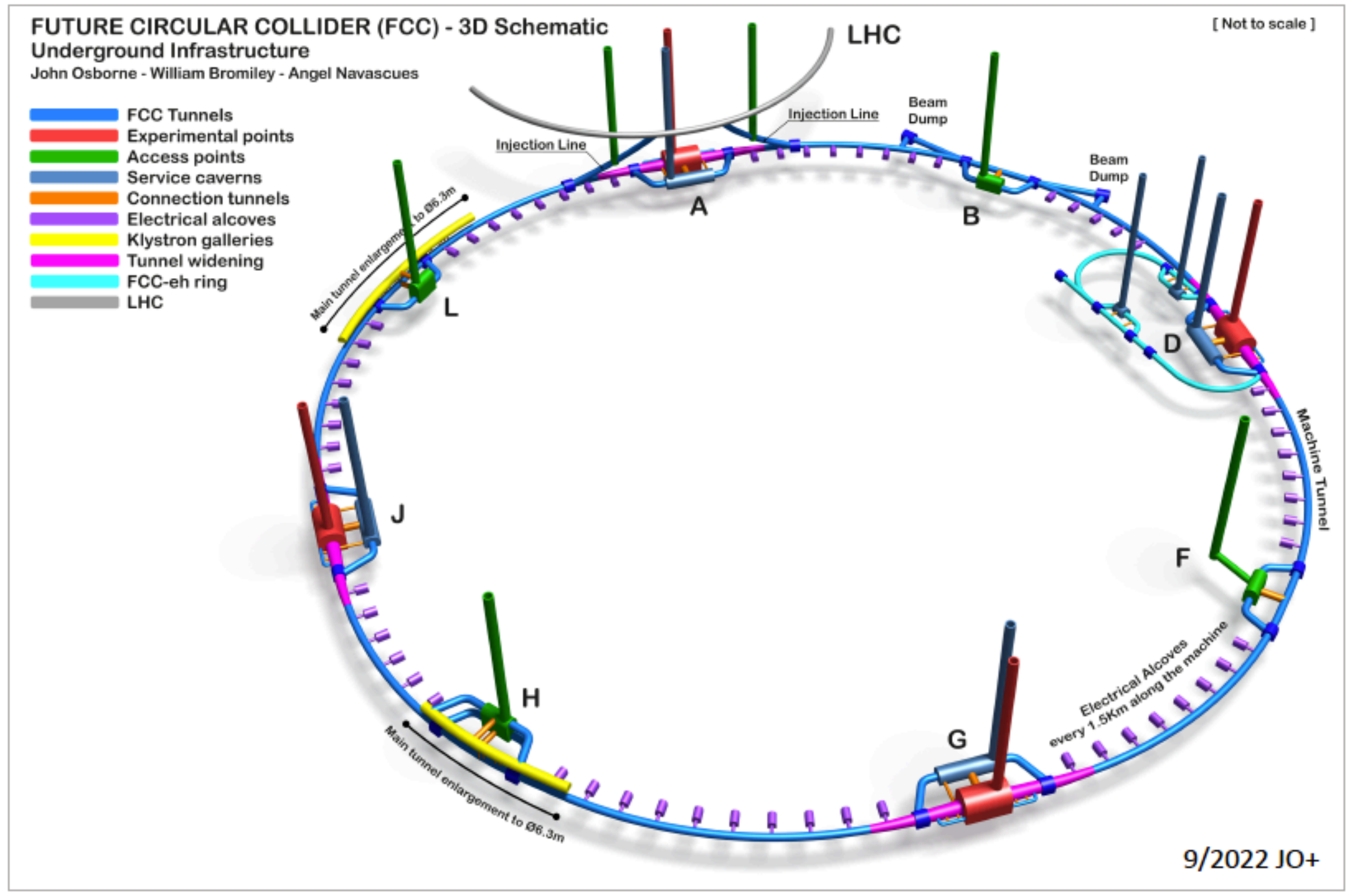


FCC-eh



ePb

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}cm^{-2}s^{-1}	7	14	35

1810.13022

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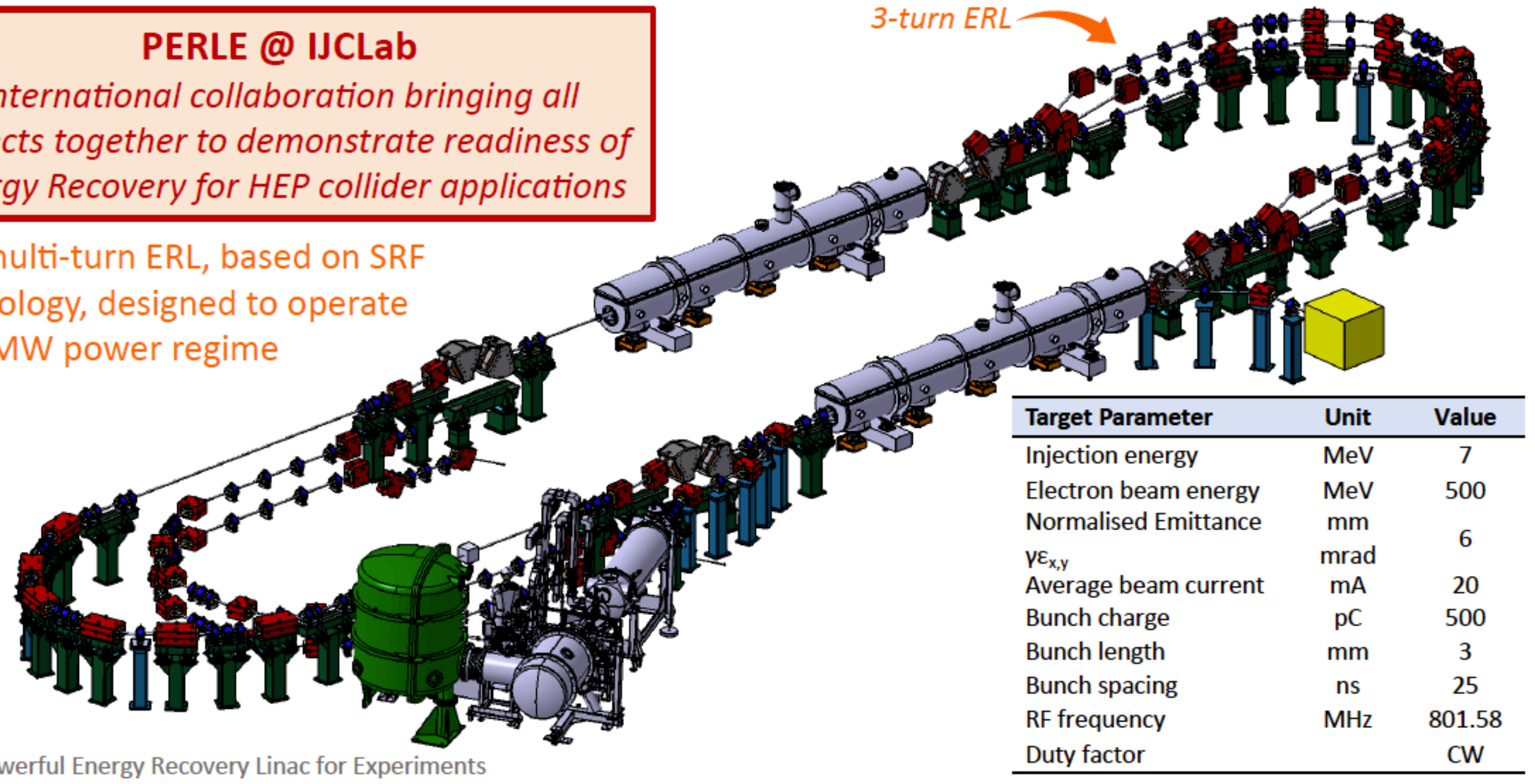

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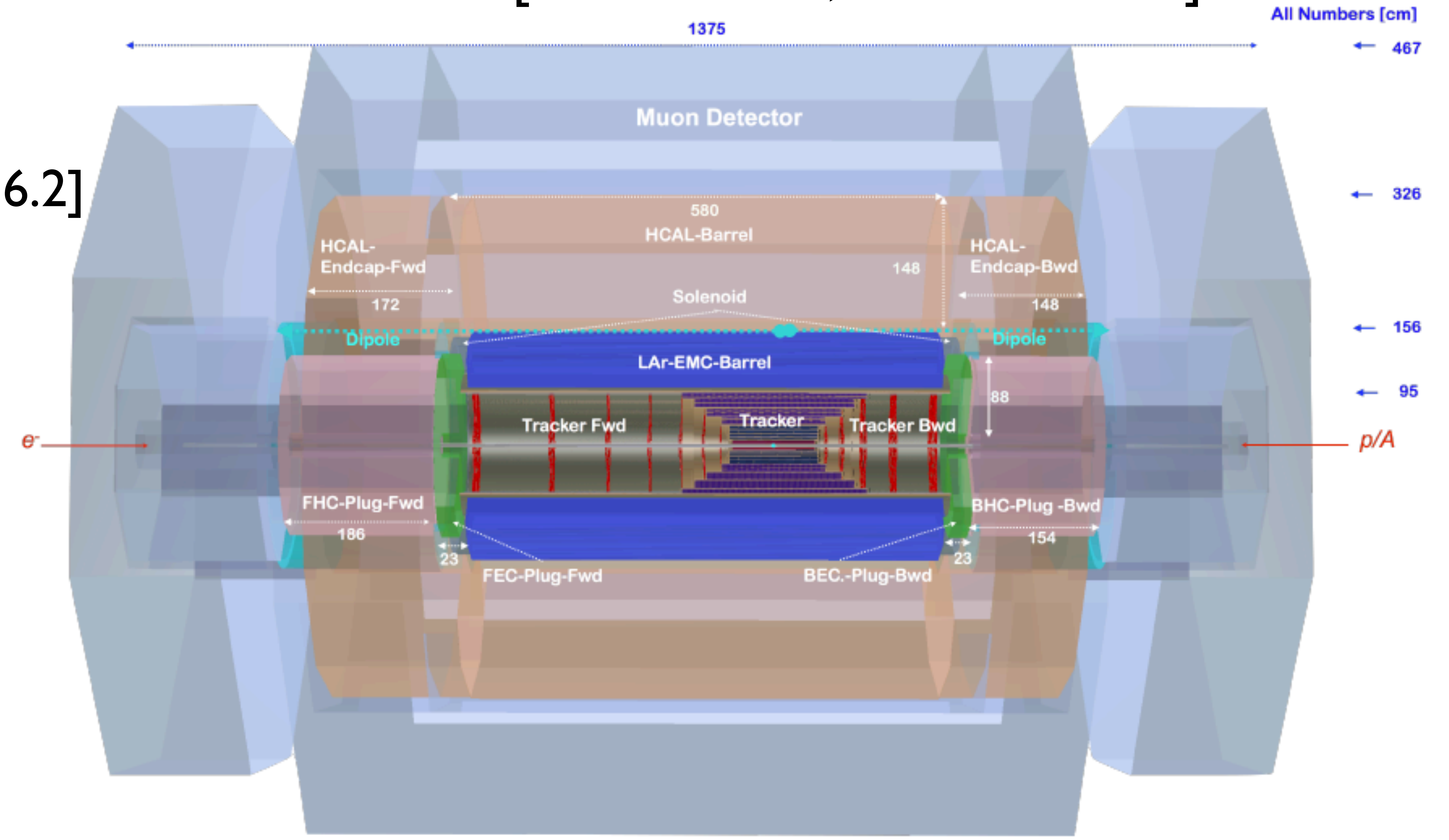
Detectors:

L=13.2 m [FCC-eh: 19.3, about CMS size]

R=4.8 m
[FCC-eh: 6.2]



➜ Large acceptance, precision device: design determined by kinematics ($H \rightarrow b\bar{b}$ in CC).

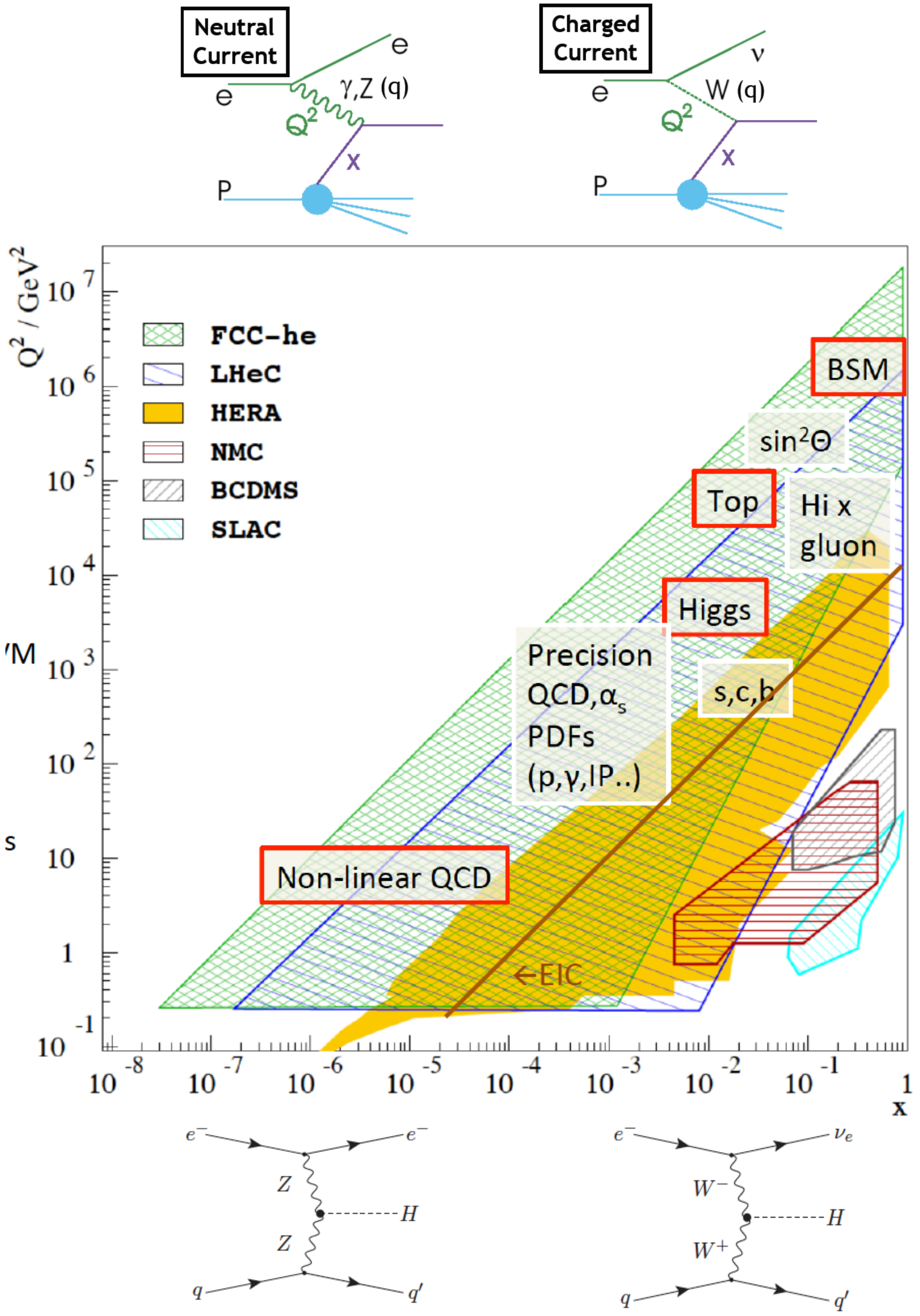
➜ Low radiation (1/100 that of pp) enables sensitive technology such as HV CMOS to be used.

➜ Low field dipole inserted before the HCAL to ensure head-on ep collision; conventional solenoid.

➜ Forward (p,n) and backward (e, γ) tagging detectors.

➜ Modular structure for fast installation, fitting inside the L3 magnet in IP2.
➜ Forward-backward symmetrised version would allow eh and hh collisions in the same IP (2201.02436).

Summary of physics:



- ep/eA colliders are the cleanest High Resolution Microscope:
  - ➜ Precision and discovery in QCD;
  - ➜ Study of EW / VBF production, LQ, multi-jet final states, forward objects,…

- Empower the LHC Search Programme (e.g., PDFs, EW measurements).
- Transform the LHC into a precision Higgs facility.
- Unique and complementary discovery potential of BSM particles (prompt and long-lived).

- It is also a $\gamma\gamma$ facility.

- **Overall: a unique Particle and Nuclear Physics Facility.**

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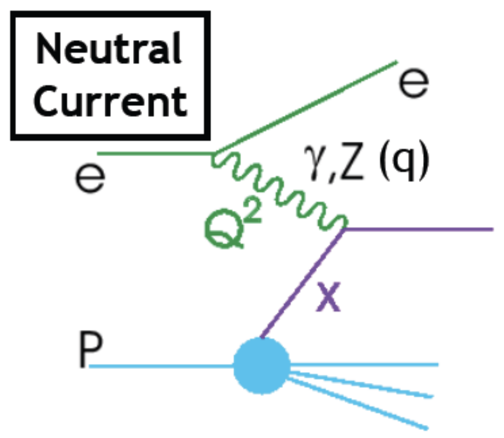
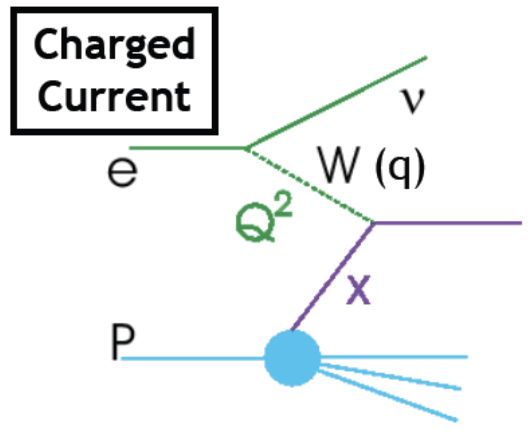
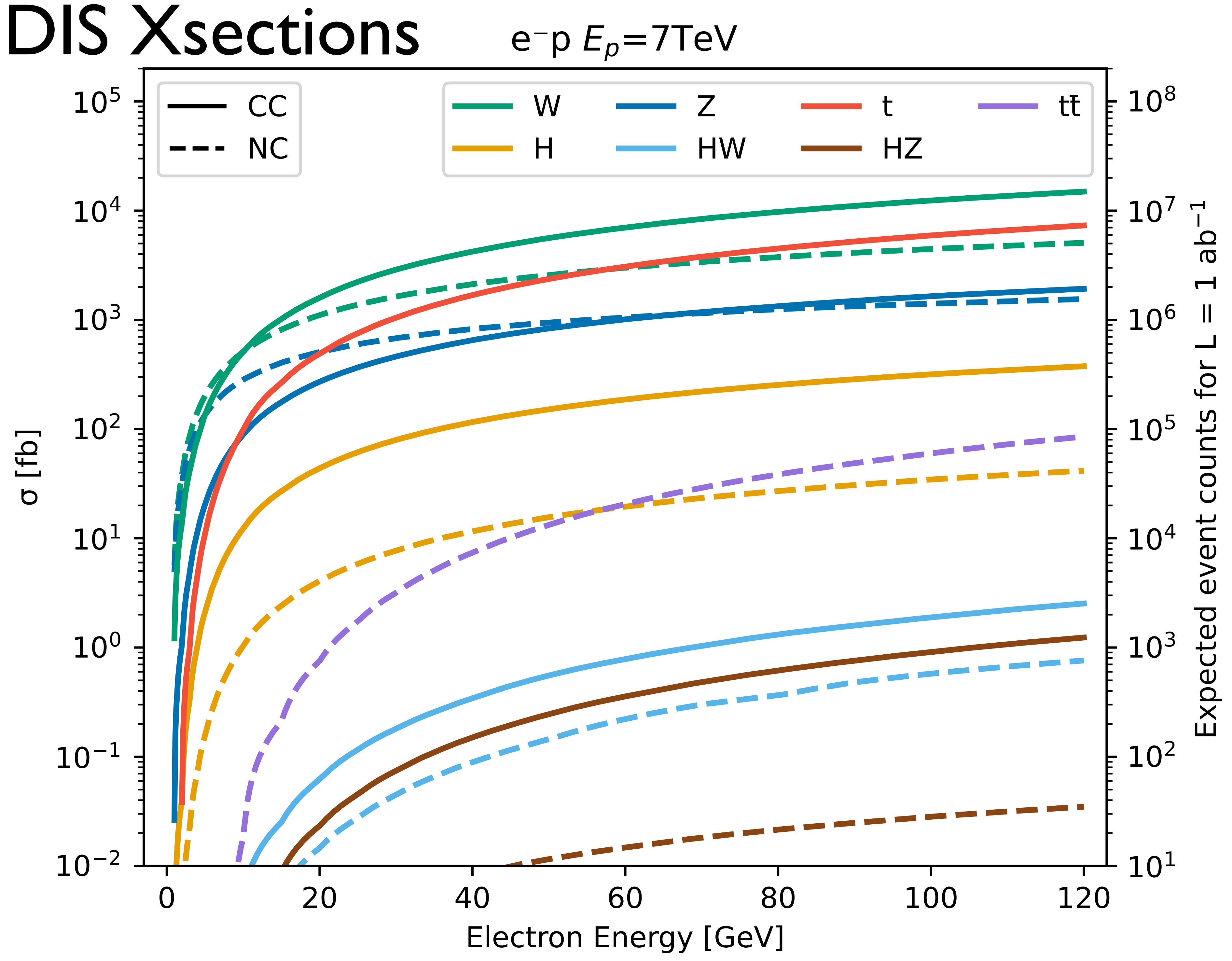
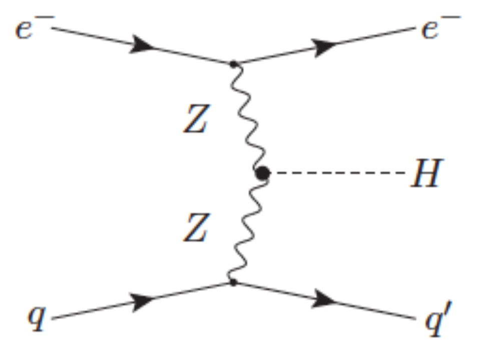
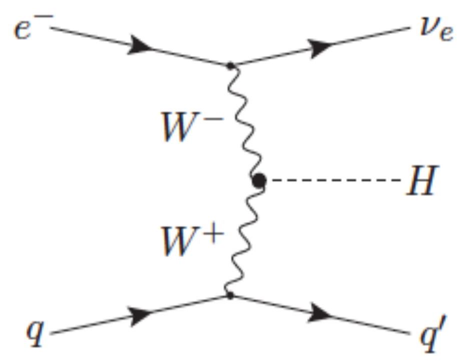




DIS Xsections







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QCD: parton densities

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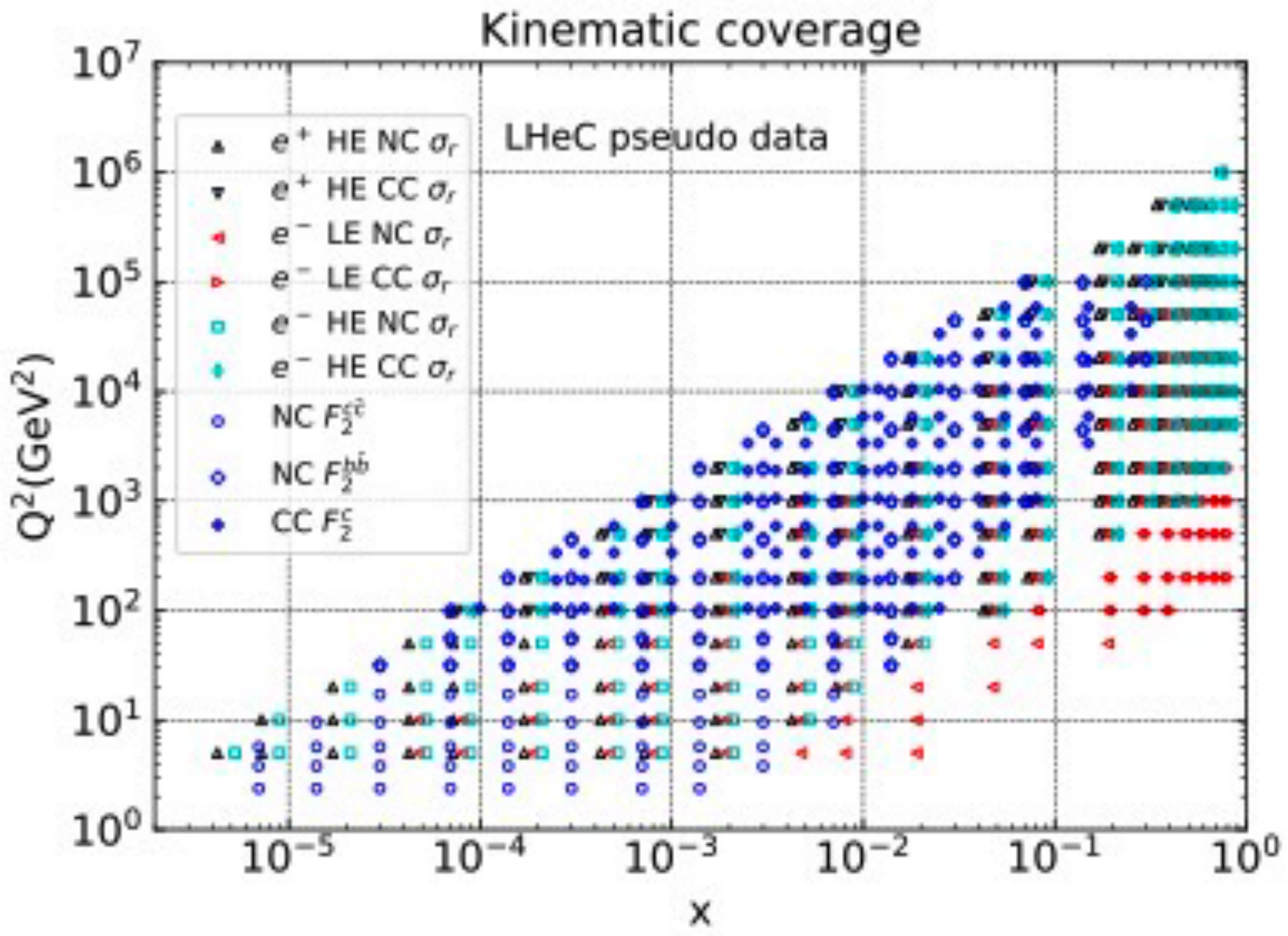

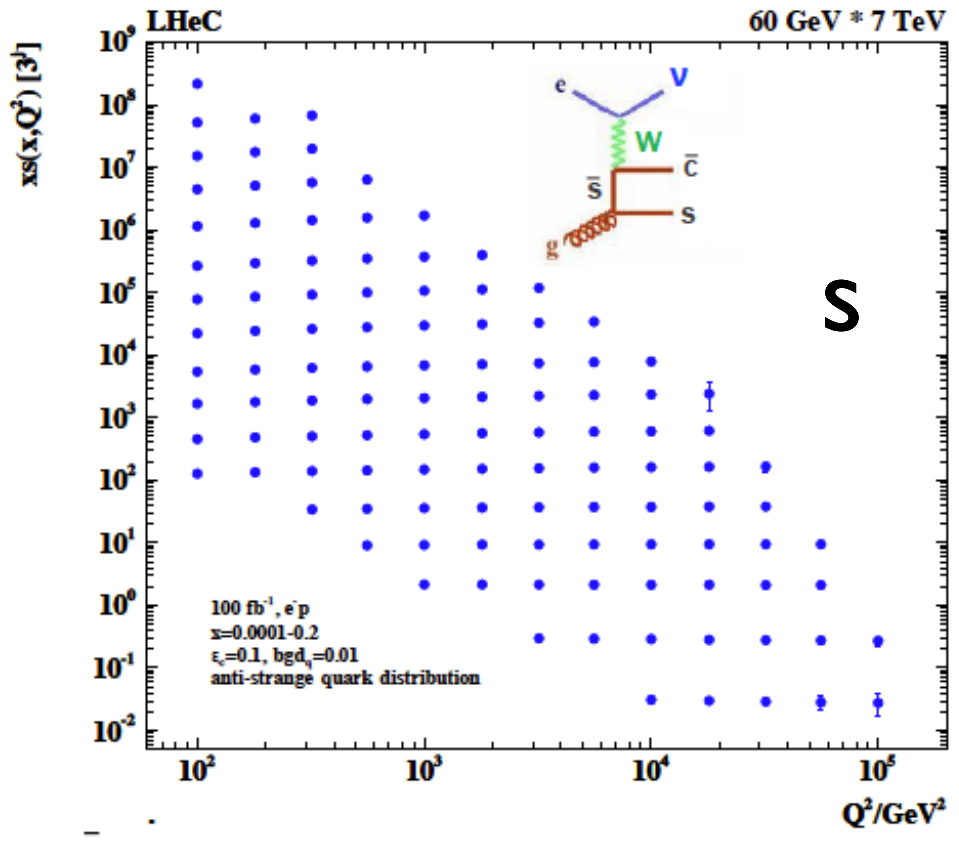

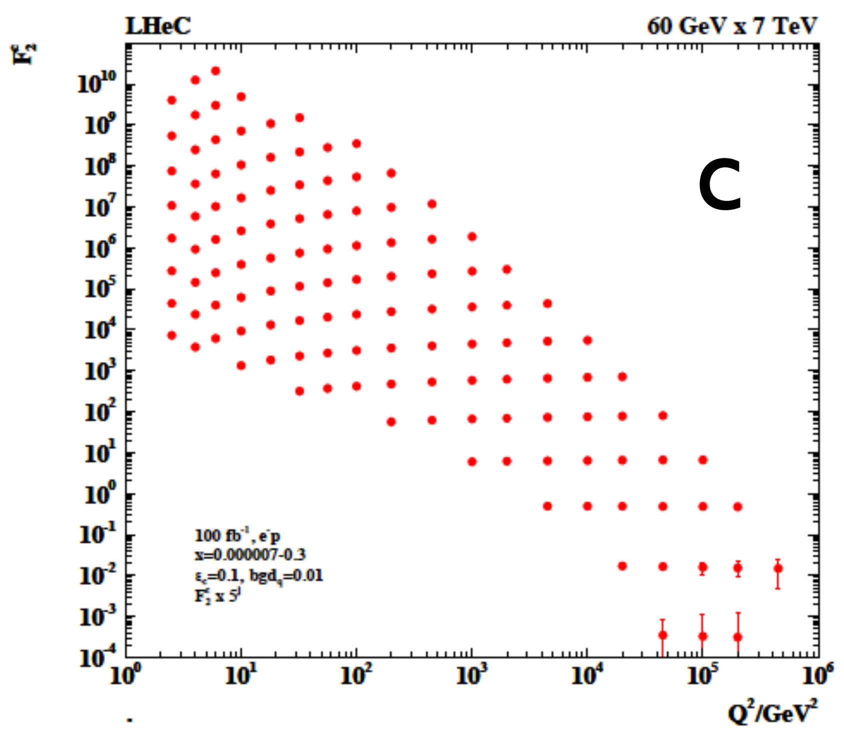

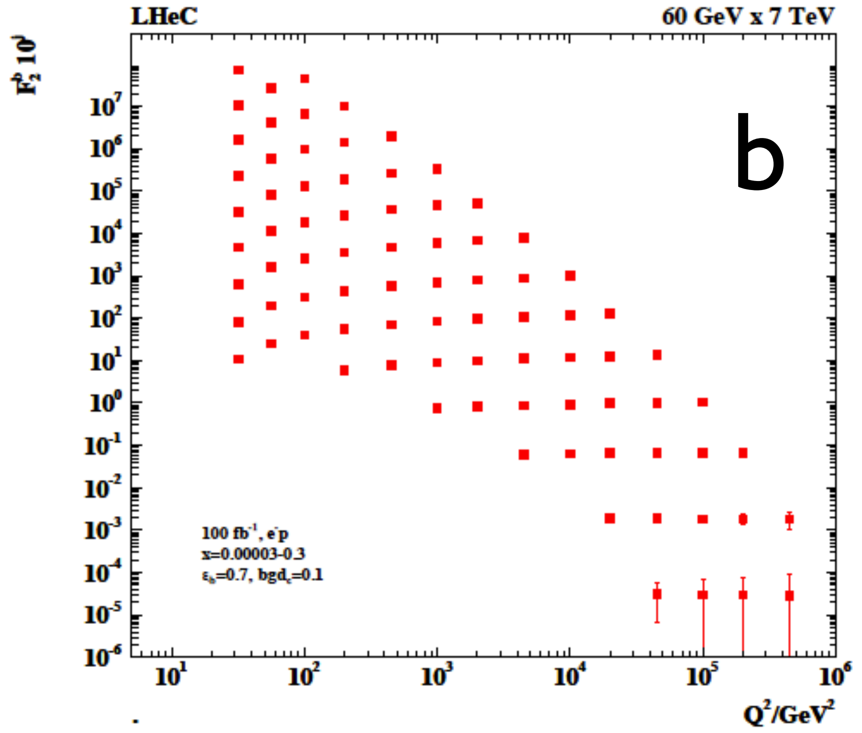

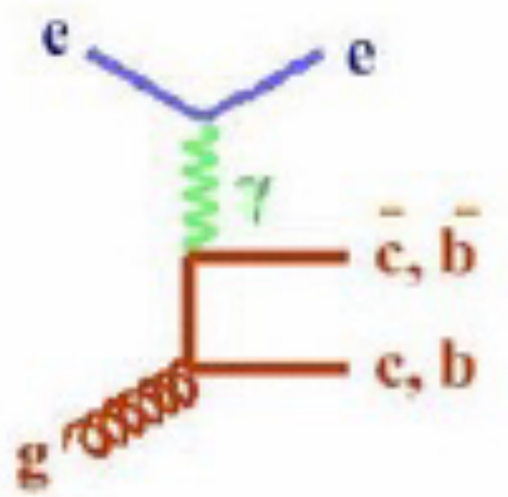

- PDFs and α_s crucial for HL-LHC: high precision electro-weak, Higgs measurements (e.g. remove essential part of QCD uncertainties of gg→H), extension of high mass search range, non-linear low x parton evolution: saturation.

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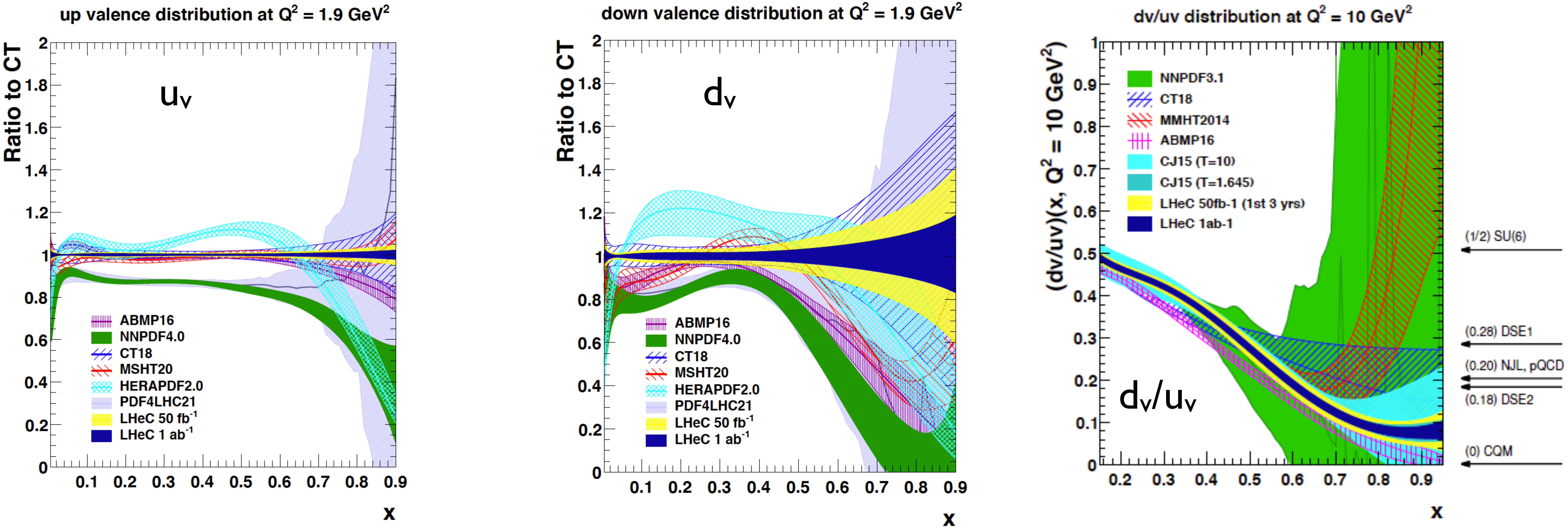

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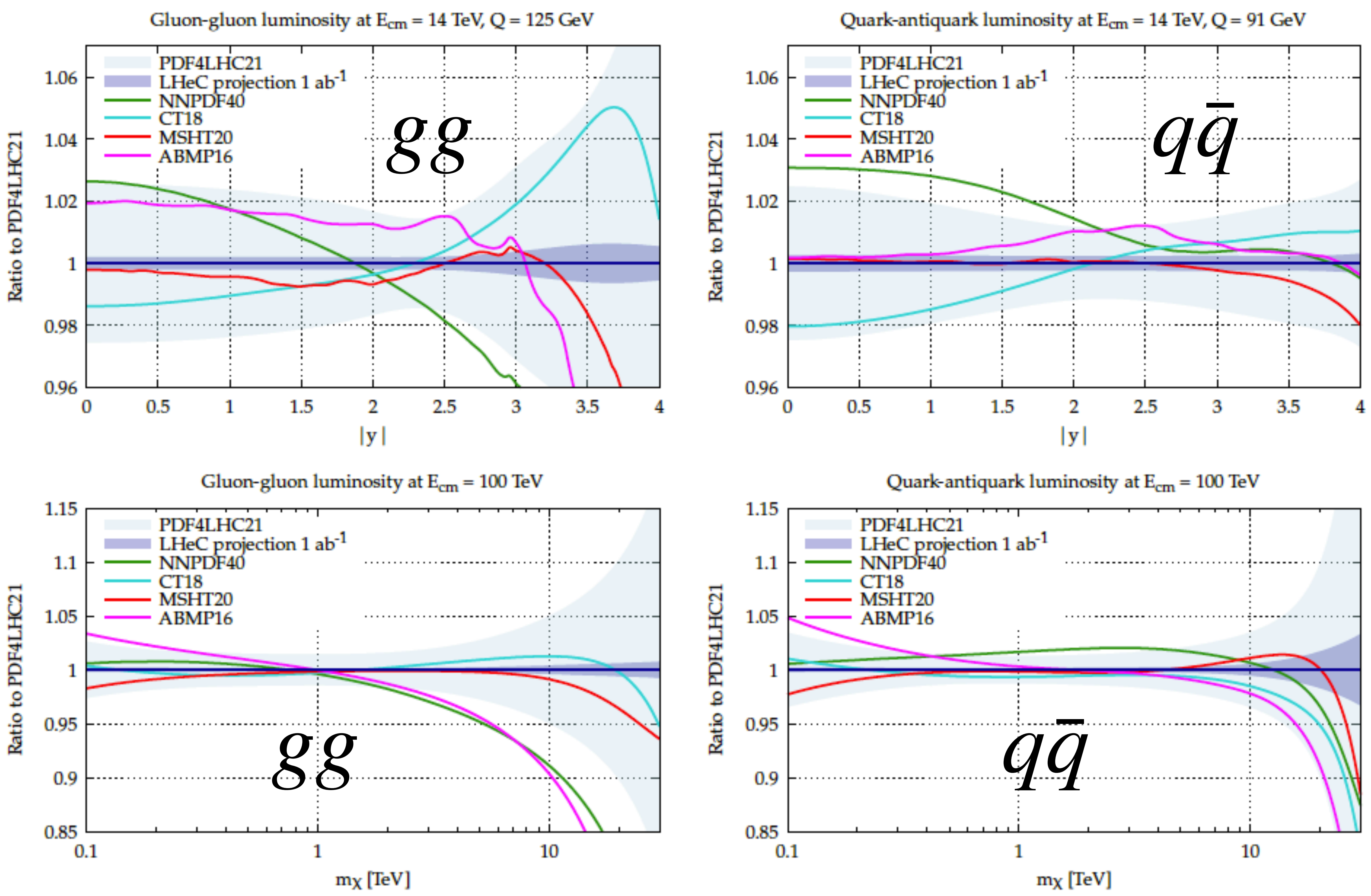
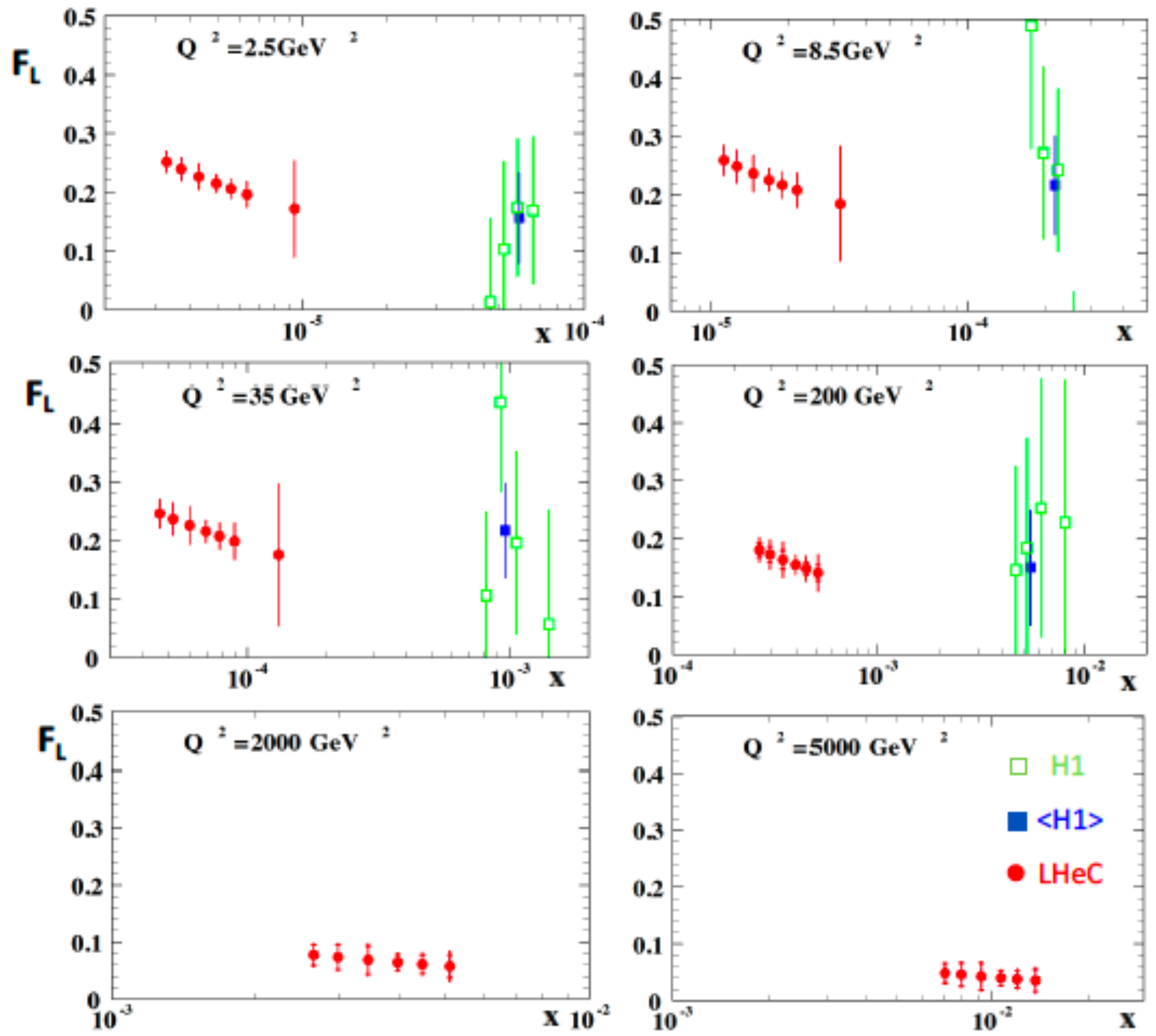


Longitudinal structure function



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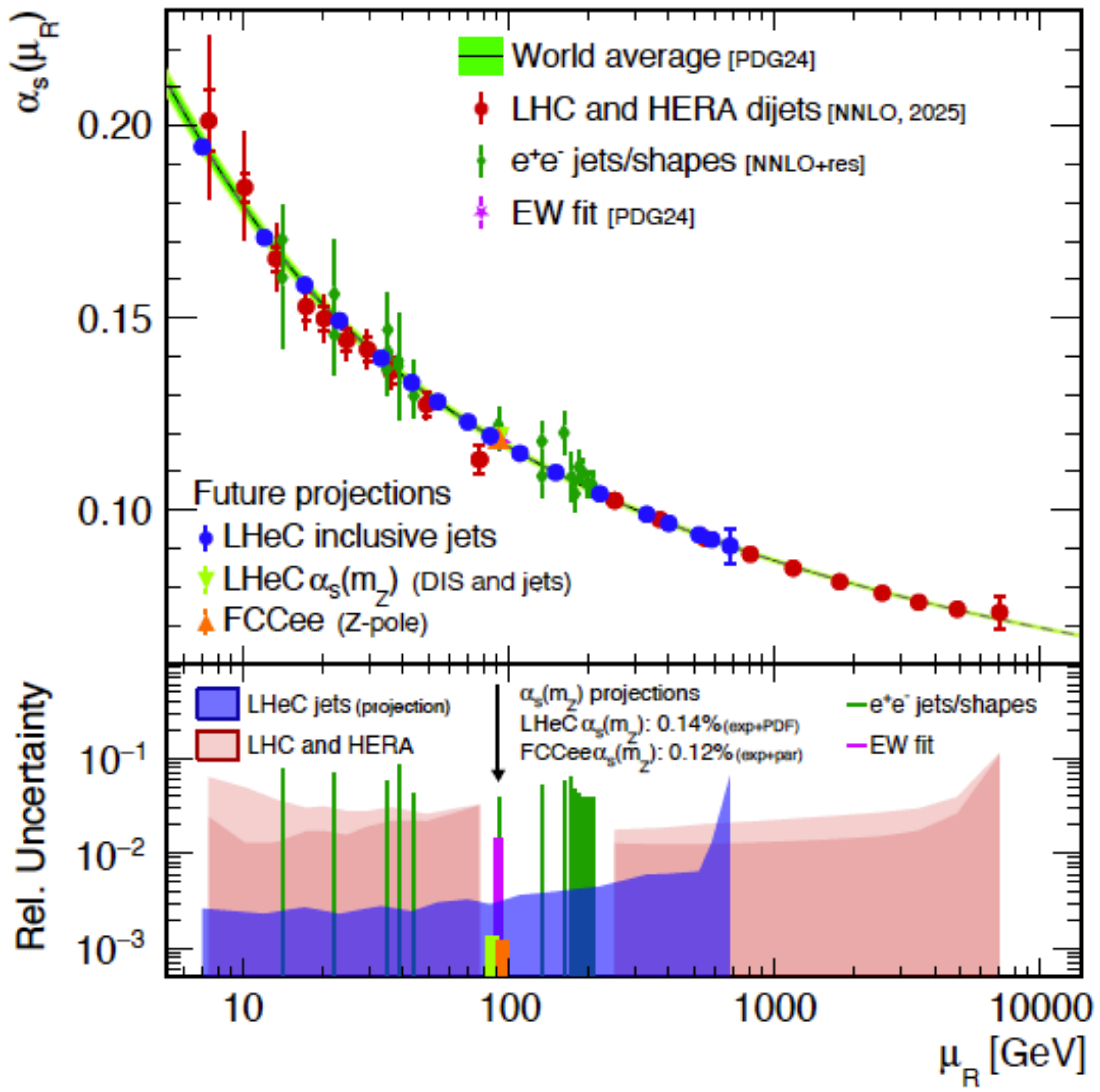
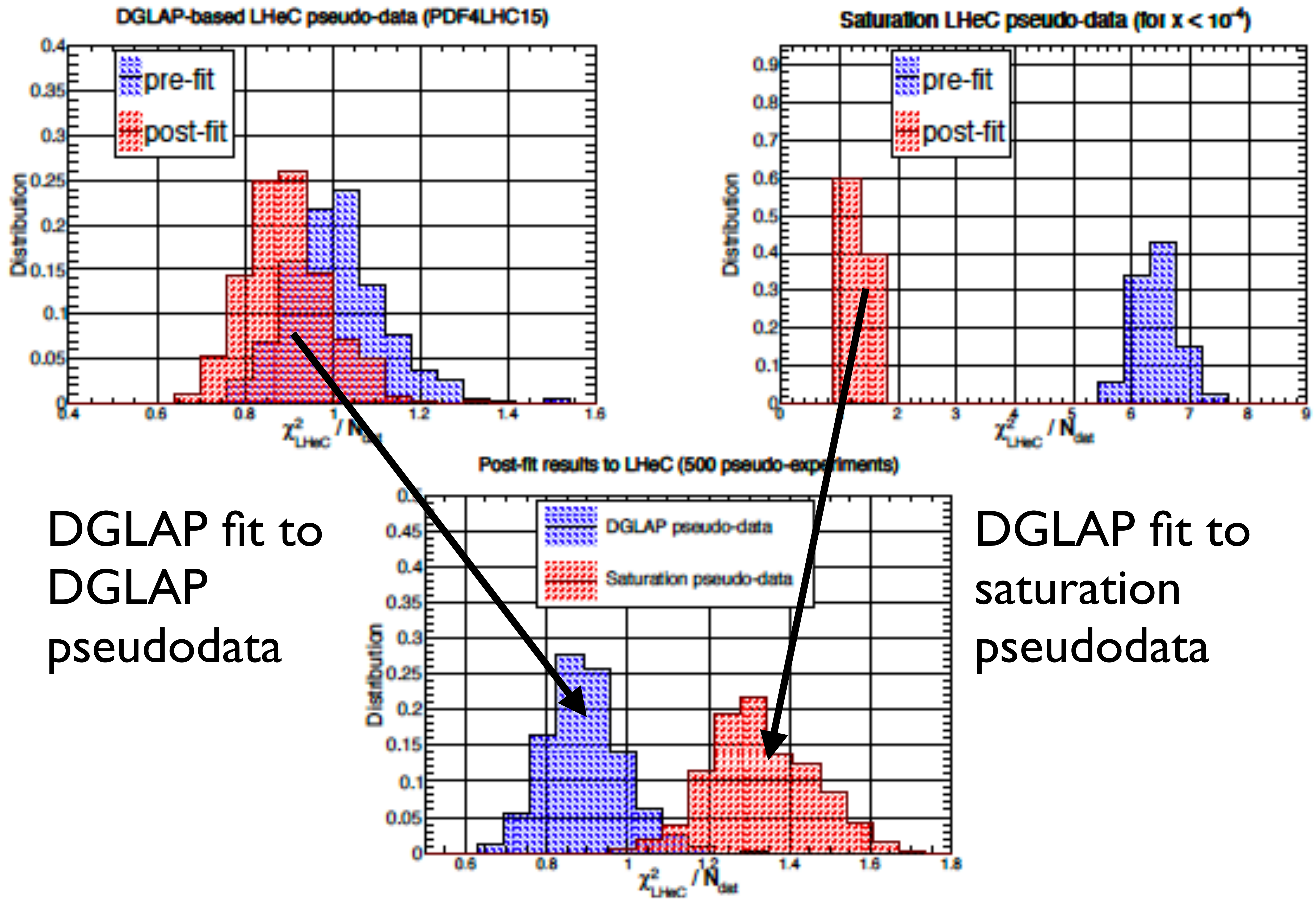
QCD: α_s and small x

- α_s to per mille accuracy (incl.+jets):

$$\Delta\alpha_s(M_Z)\ (\text{incl. DIS}) = \pm\, 0.00022_{(\text{exp+PDF})}$$
$$\Delta\alpha_s(M_Z)\ (\text{incl. DIS \& jets}) = \pm\, 0.00016_{(\text{exp+PDF})}$$



- Breaking of *standard* factorisation: resummation and new non-linear regime of QCD, implications for FCC (e.g., gg→H).



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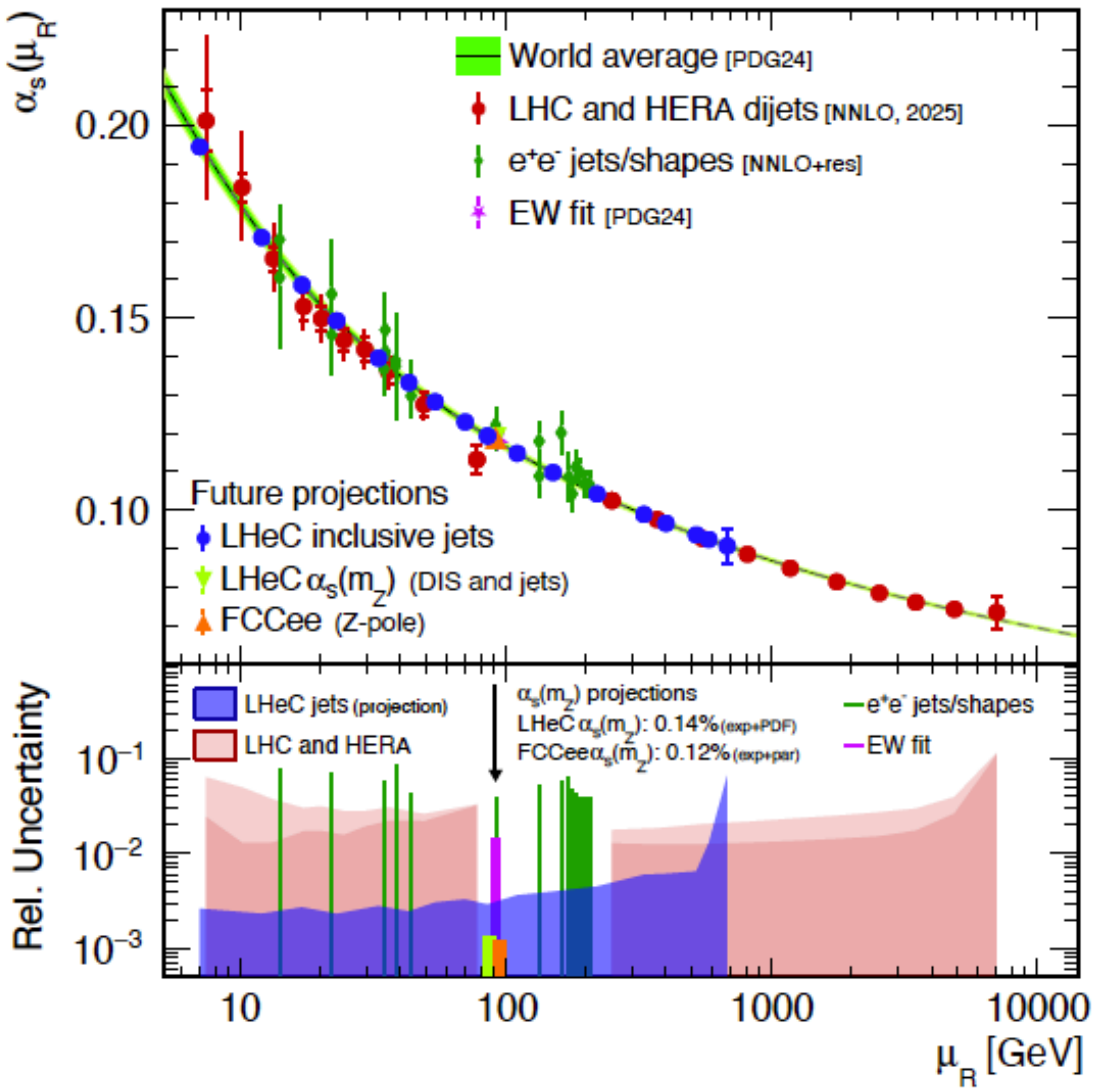

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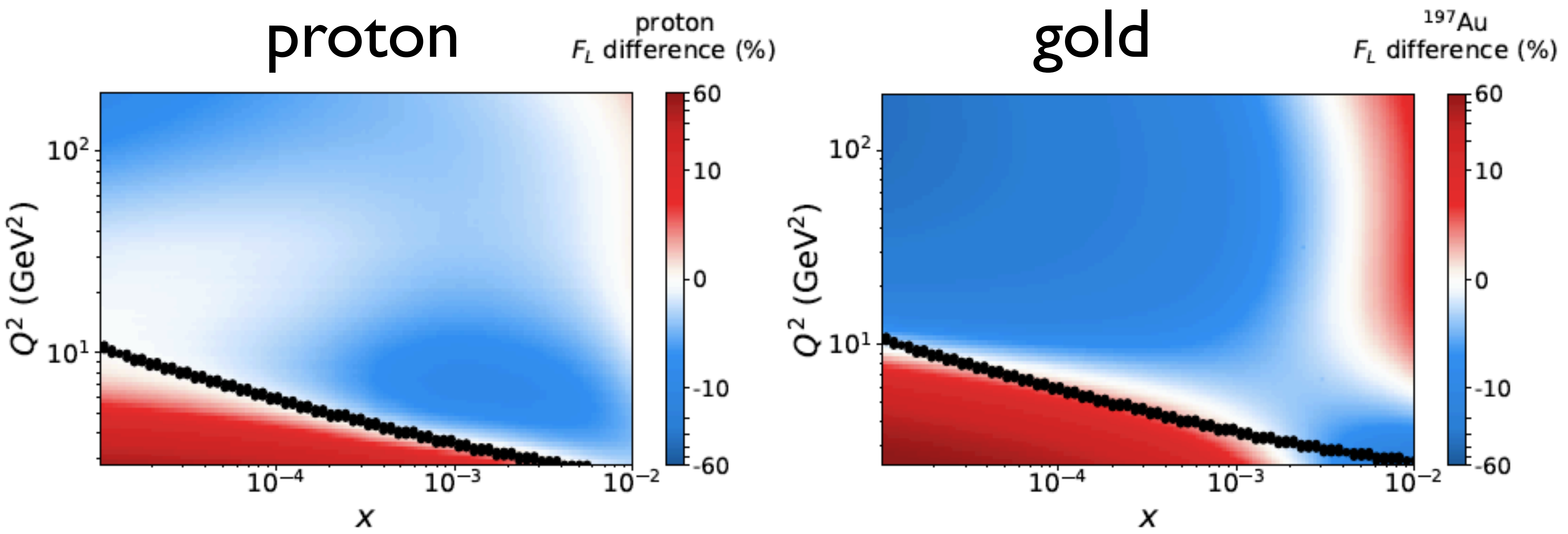
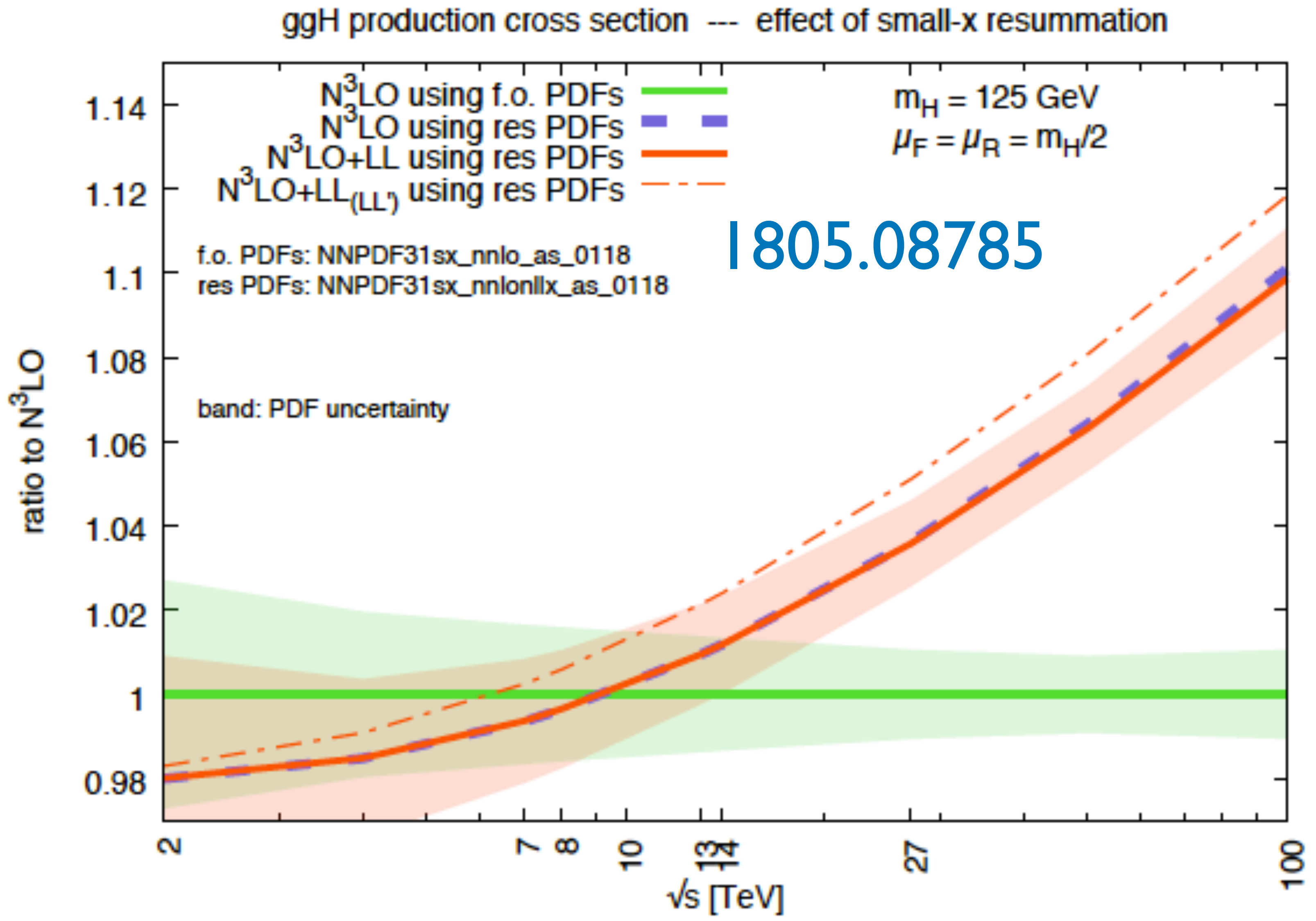


$$\frac{F_L^{DGLAP} - F_L^{saturation}}{F_L^{saturation}}$$

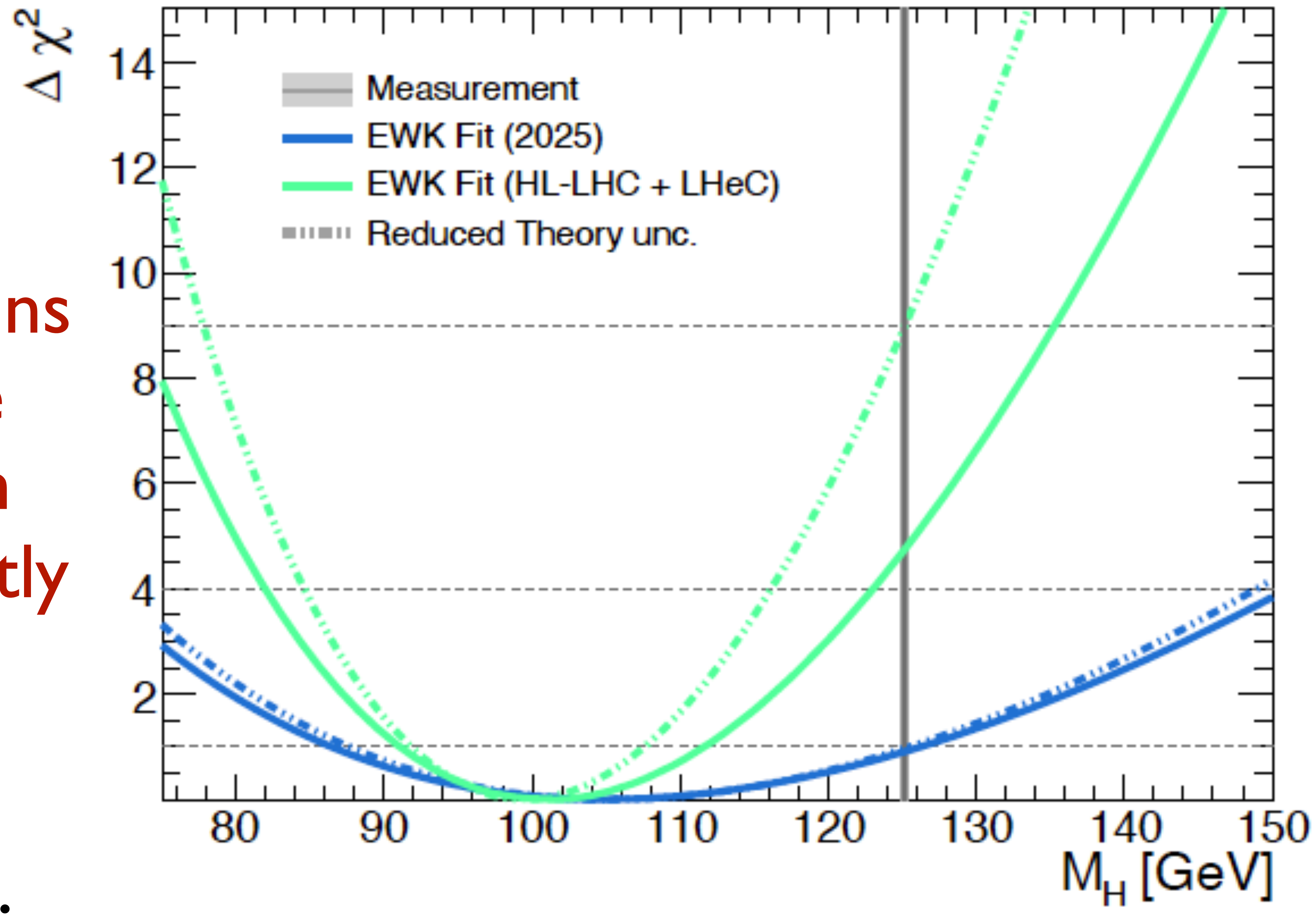
Implications: Higgs

- PDFs+α_s measurements at the LHeC reduce very strongly the corresponding uncertainties in the Higgs cross section.

$\sqrt{s}$ [TeV]	$\sigma_{gg\to H}$ [pb]	TH uncertainty		PDF+α_S uncertainty			Total		
		Ref.	S2	Ref.	S2	S2+LHeC	Ref.	S2	S2+LHeC
14	54.7	3.9%	2.0%	3.2%	1.6%	0.5%	5.1%	2.6%	2.0%
27	146.6	4.0%	2.0%	3.3%	1.7%	0.6%	5.2%	2.6%	2.1%
100	804.4	4.2%	2.1%	3.7%	1.9%	0.7%	5.6%	2.8%	2.2%

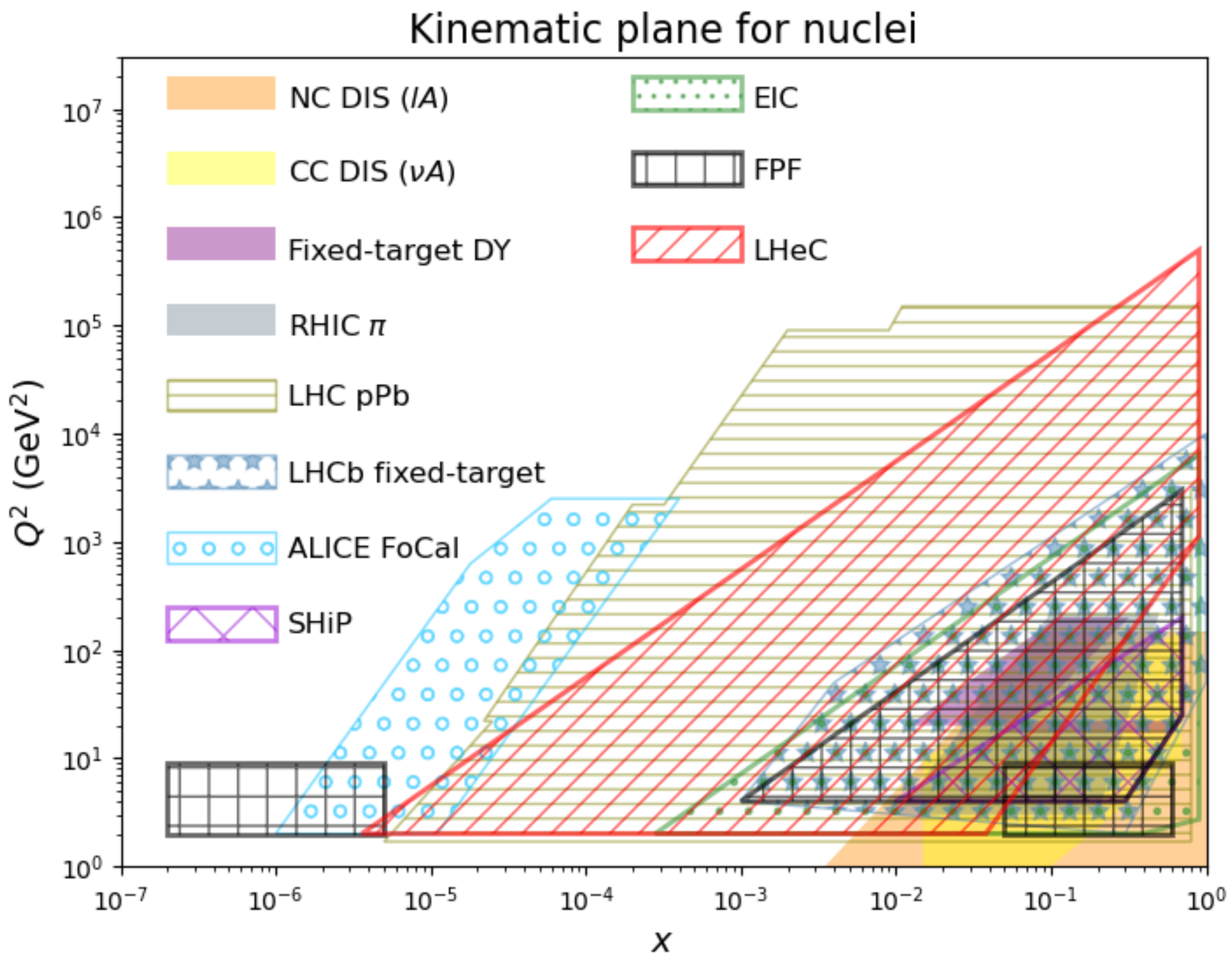


- Also constrains the mass in the SM indirectly in EWK fits (mostly effect of m_W).



- Sizeable effect of the type of factorisation at small x.

eA:



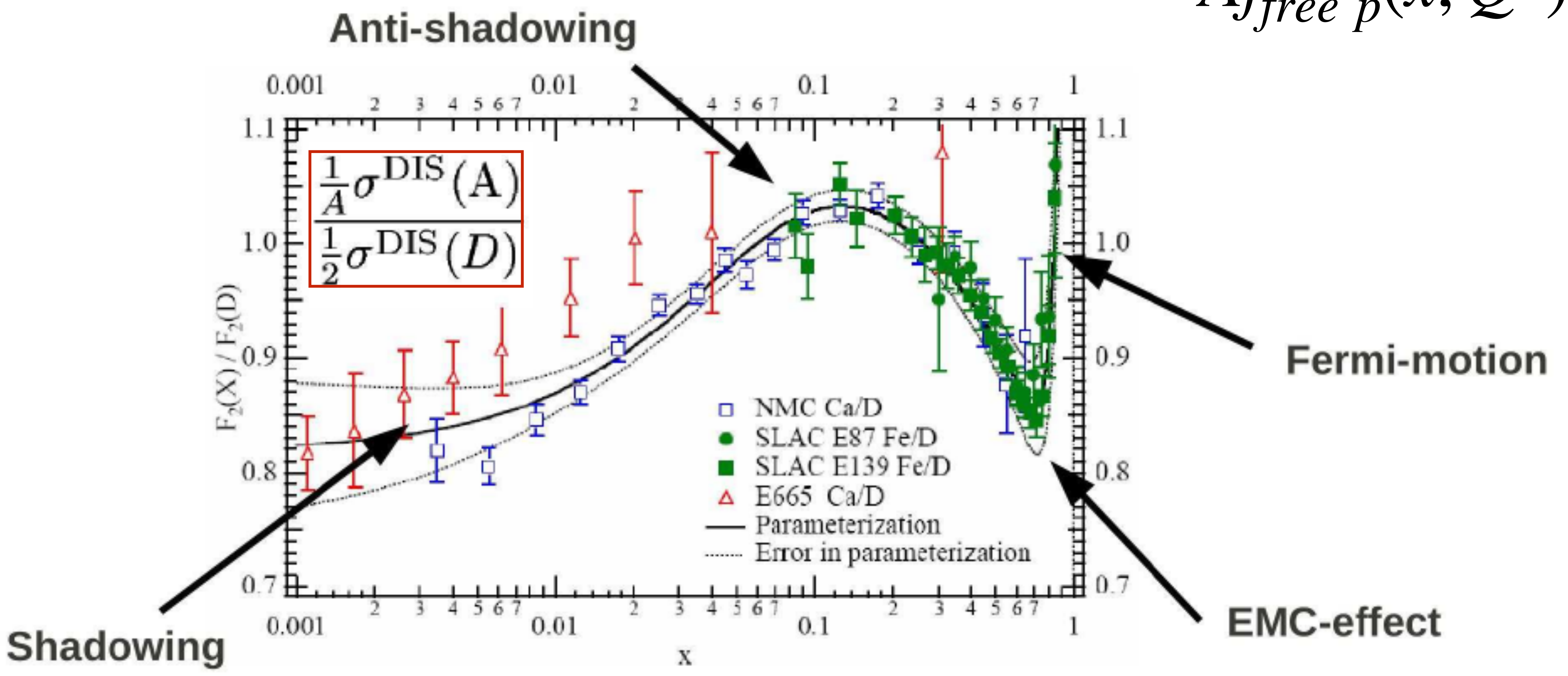
- eA collisions at LHeC/FCC-eh: region presently explored in DIS extended by ~4 decades down in x and up in Q^2.
- Determination of inclusive and diffractive nuclear parton densities for a single nucleus, with flavour unfolding.
- Studies of 3D structure.
- Saturation (ep & eA, nuclear enhancement).
- Flavour dependent anti shadowing, Gribov relation with diffraction,…

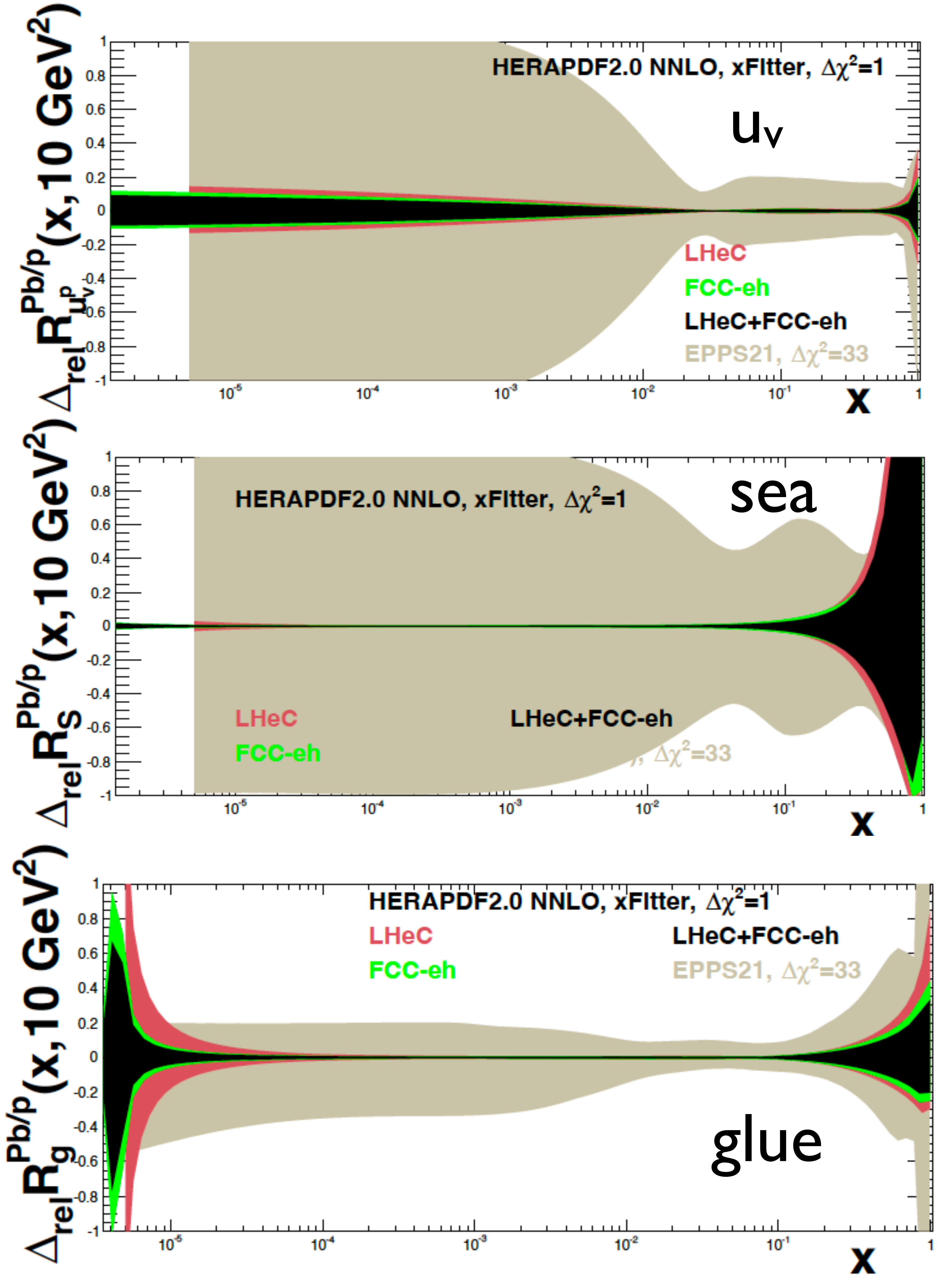
with strong implications on the pA/AA programmes at the HL-LHC and FCC-hh.

eA:

- eA collisions at LHeC/FCC-eh: region presently explored in DIS extended by ~4 decades down in x and up in Q^2.

$$R_f = \frac{f_{p\ in\ A}(x, Q^2)}{A f_{free\ p}(x, Q^2)}$$

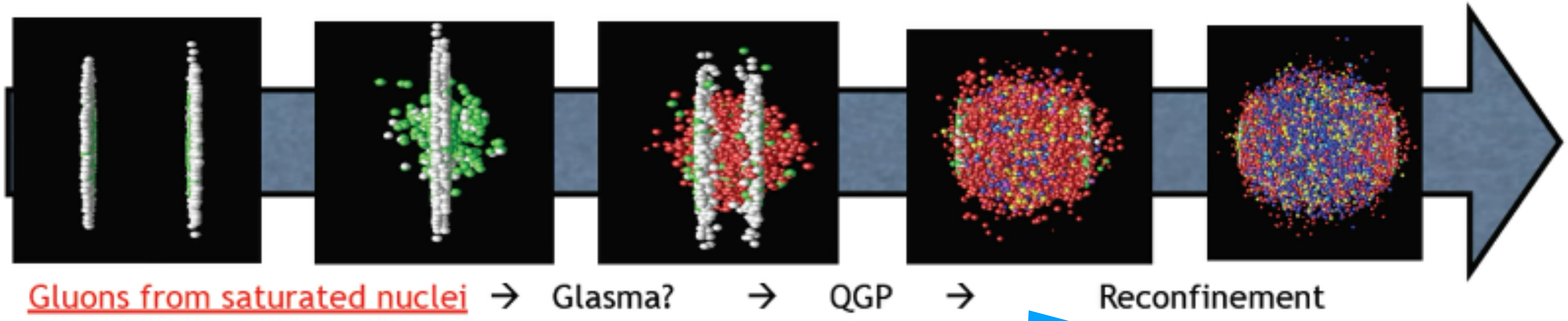


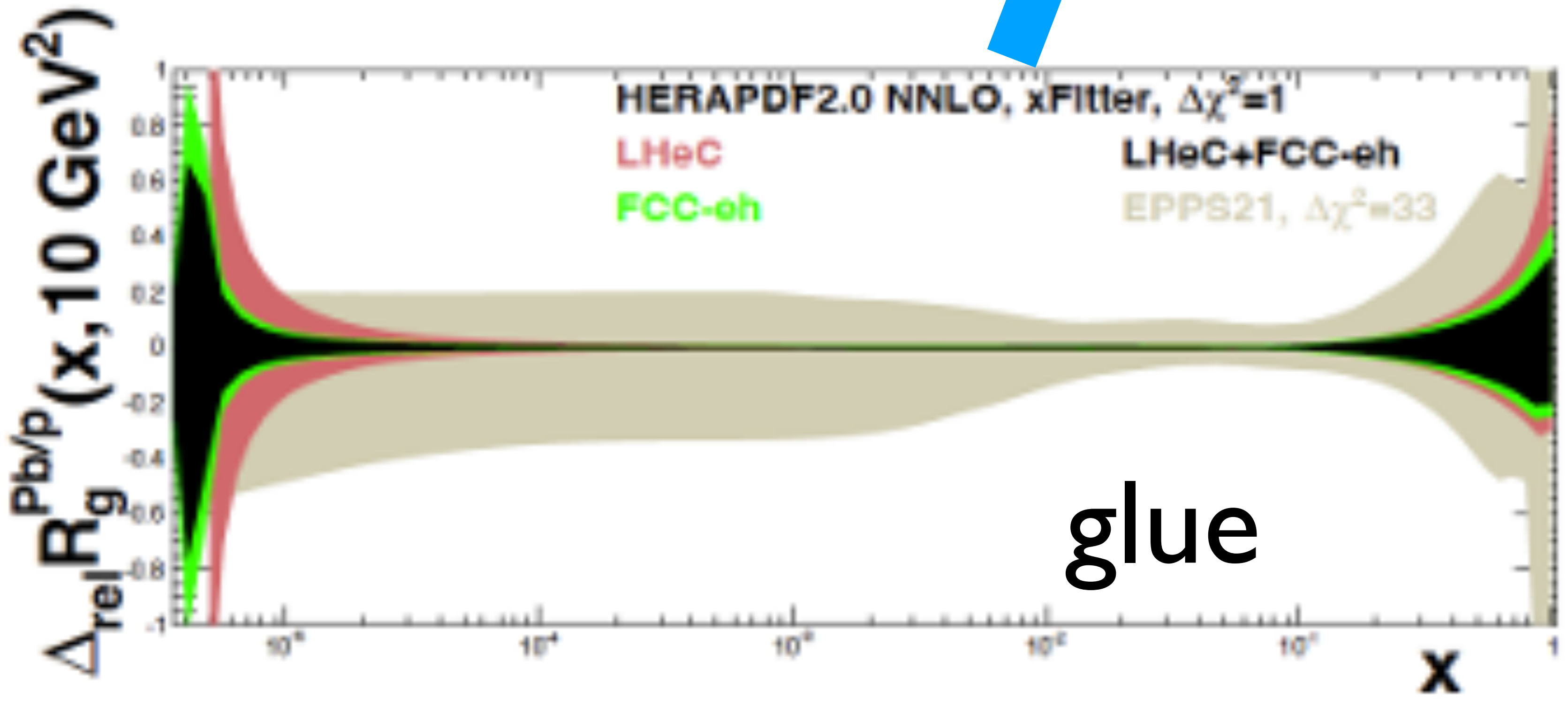


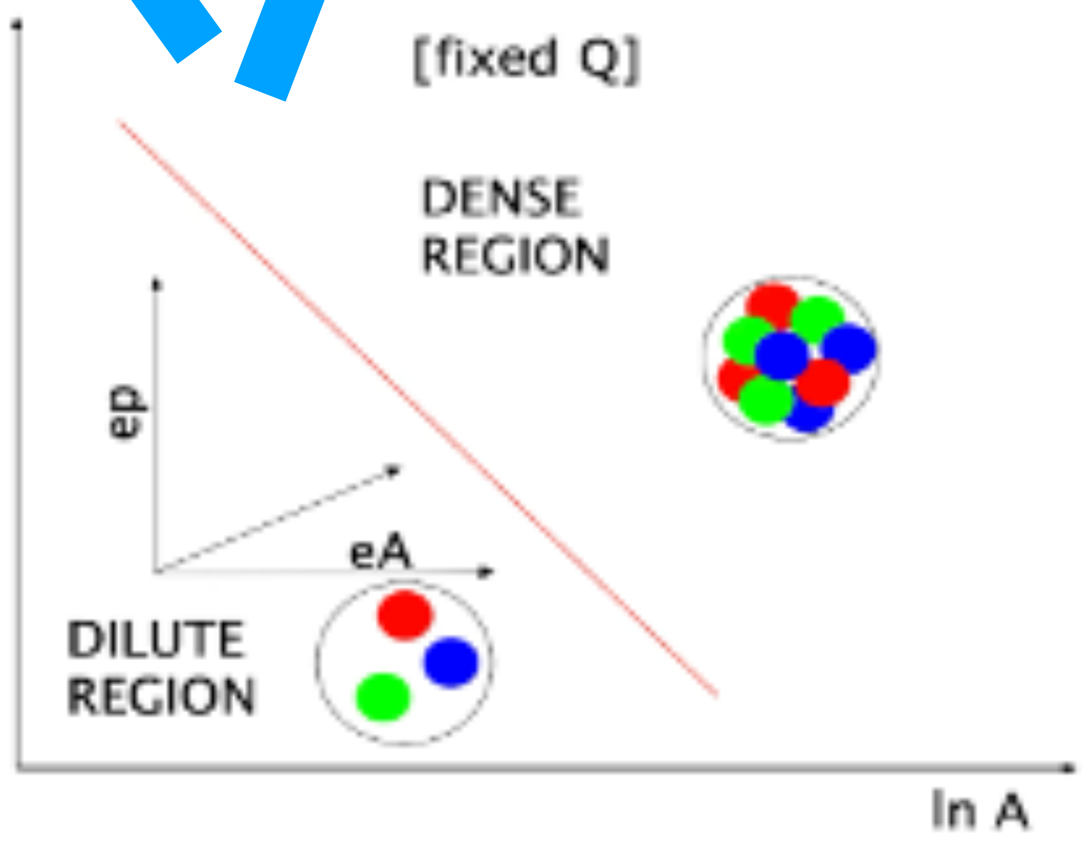
Implications of eA on pA/AA:

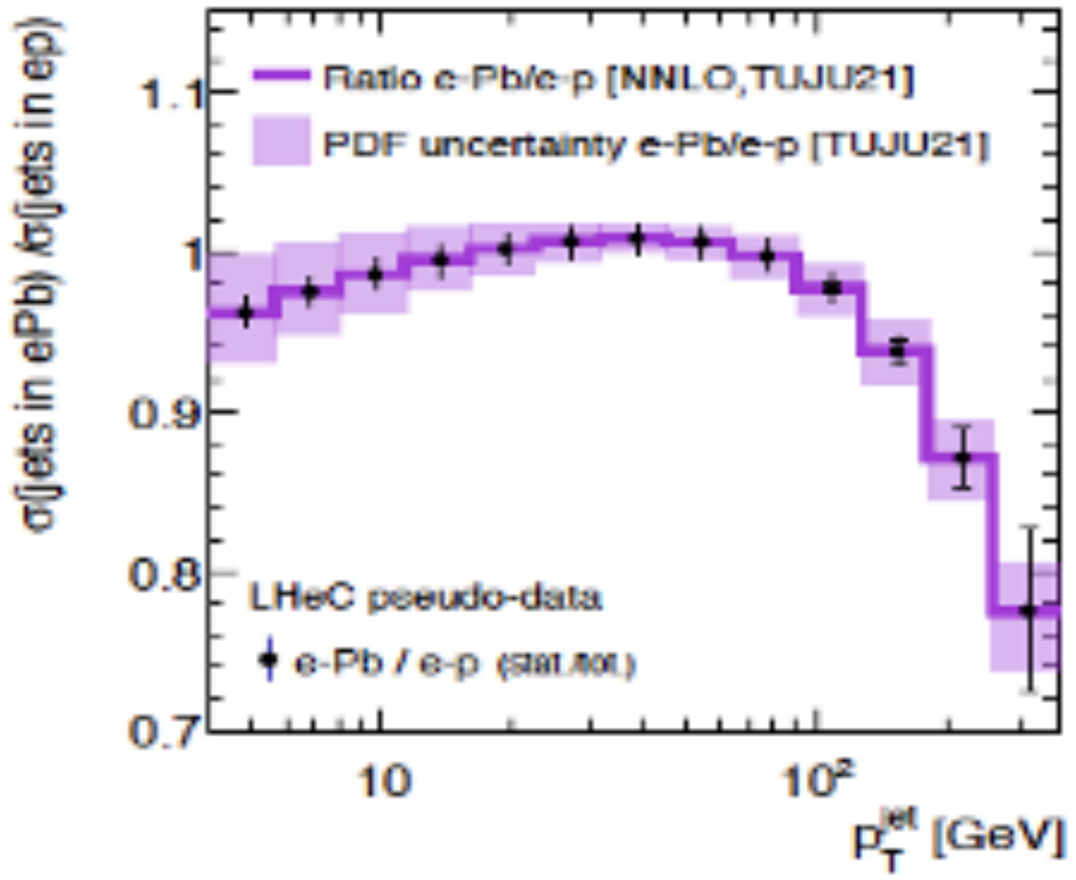
- eA collisions at the LHeC will provide precise information on the partonic structure of nuclei and the dynamics of dense partonic systems (a new non-linear regime of QCD which requires ep and eA), relevant for all stages of HICs.

[B. Cole]







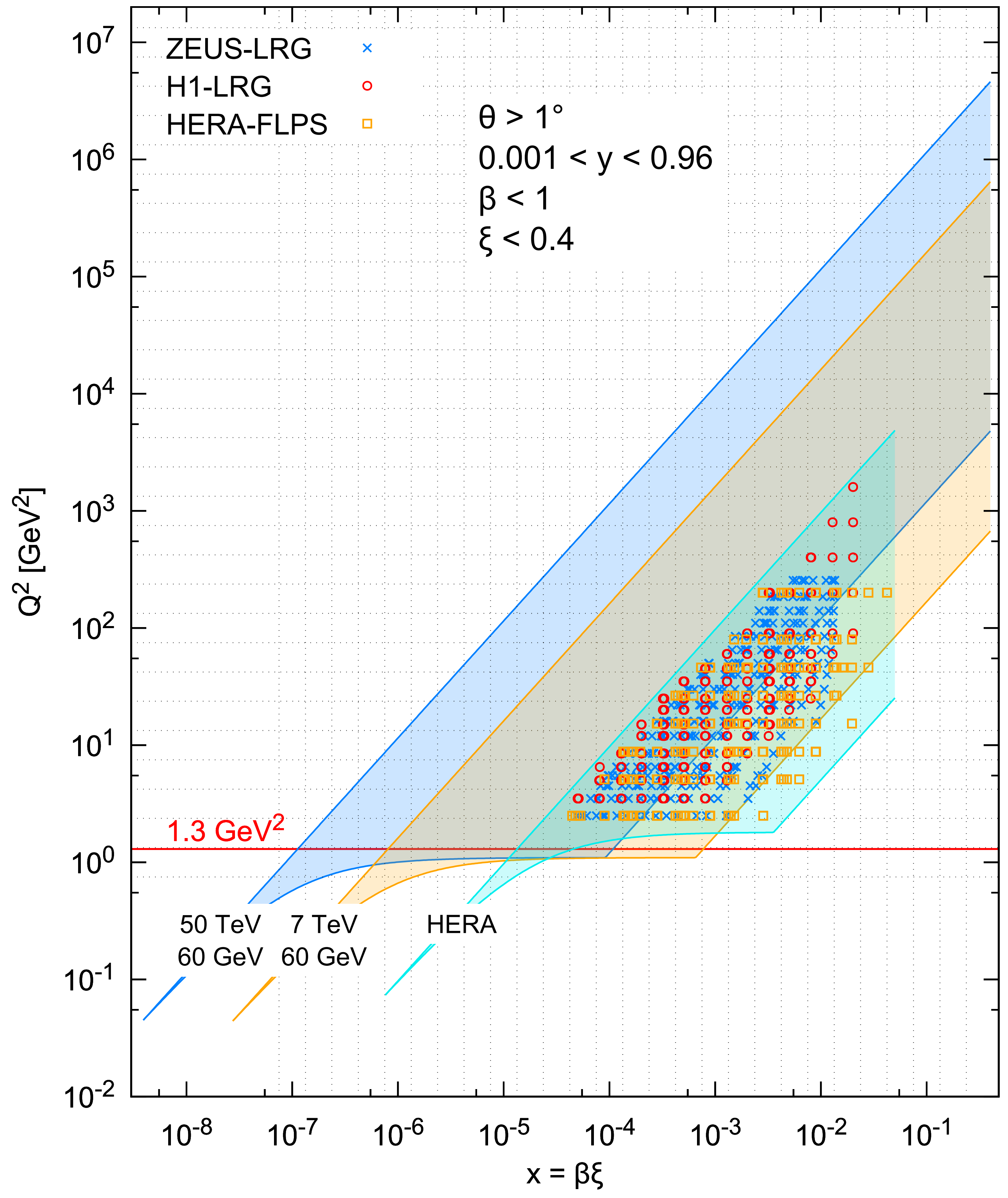


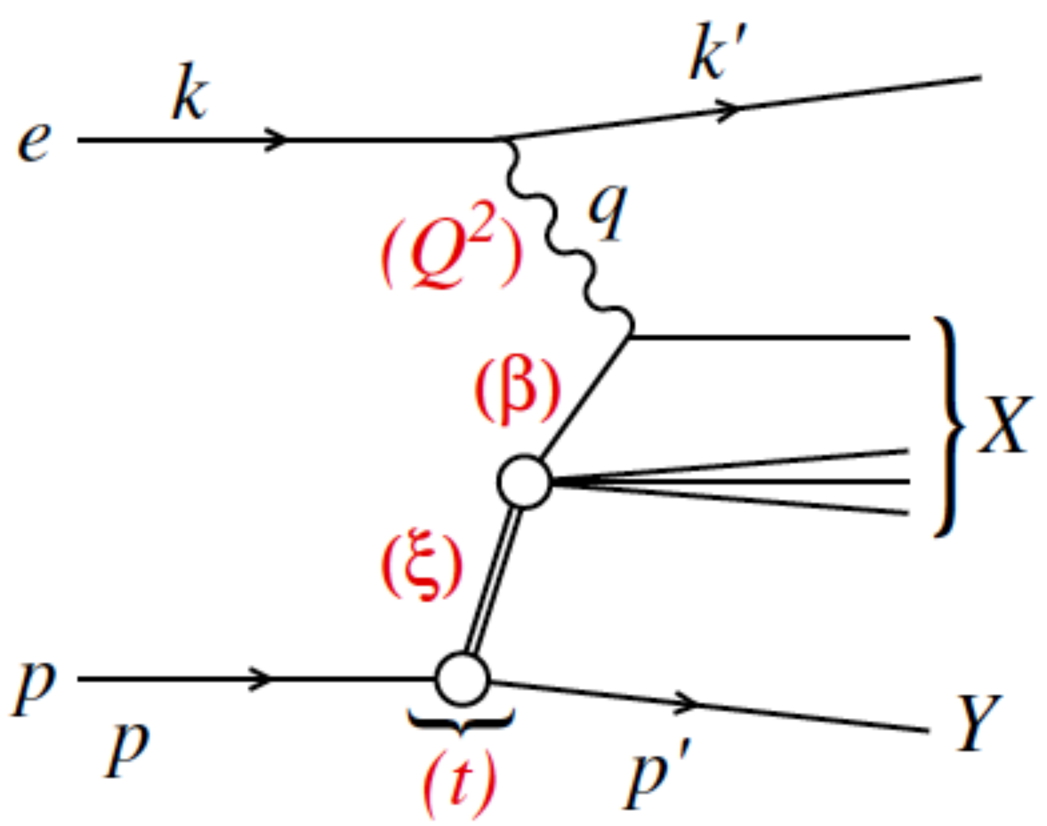
R_{eA}^{jets}

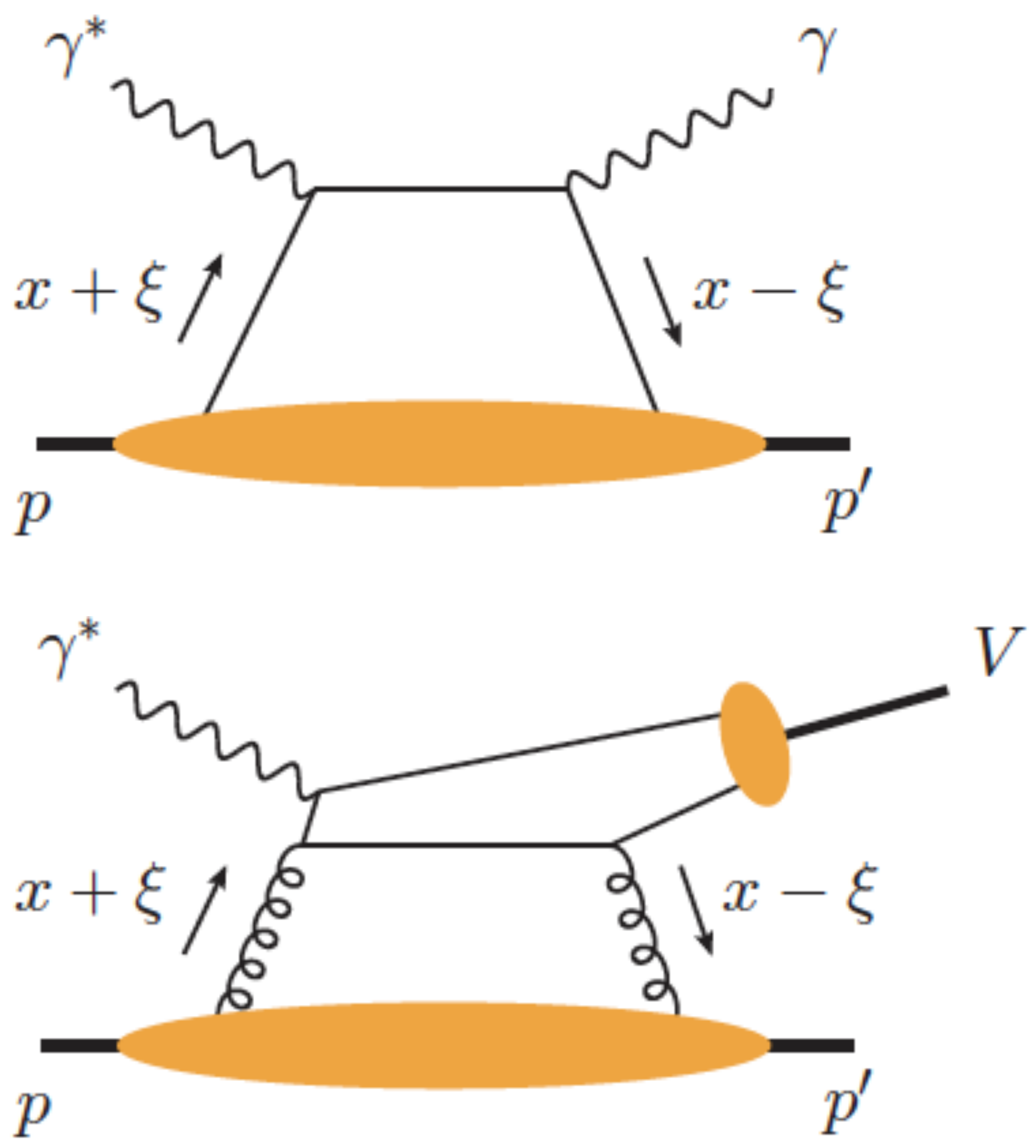
Diffraction and 3D structure:

- Diffraction: probability of ep inelastic interaction keeping the proton intact (10-15 % at HERA).

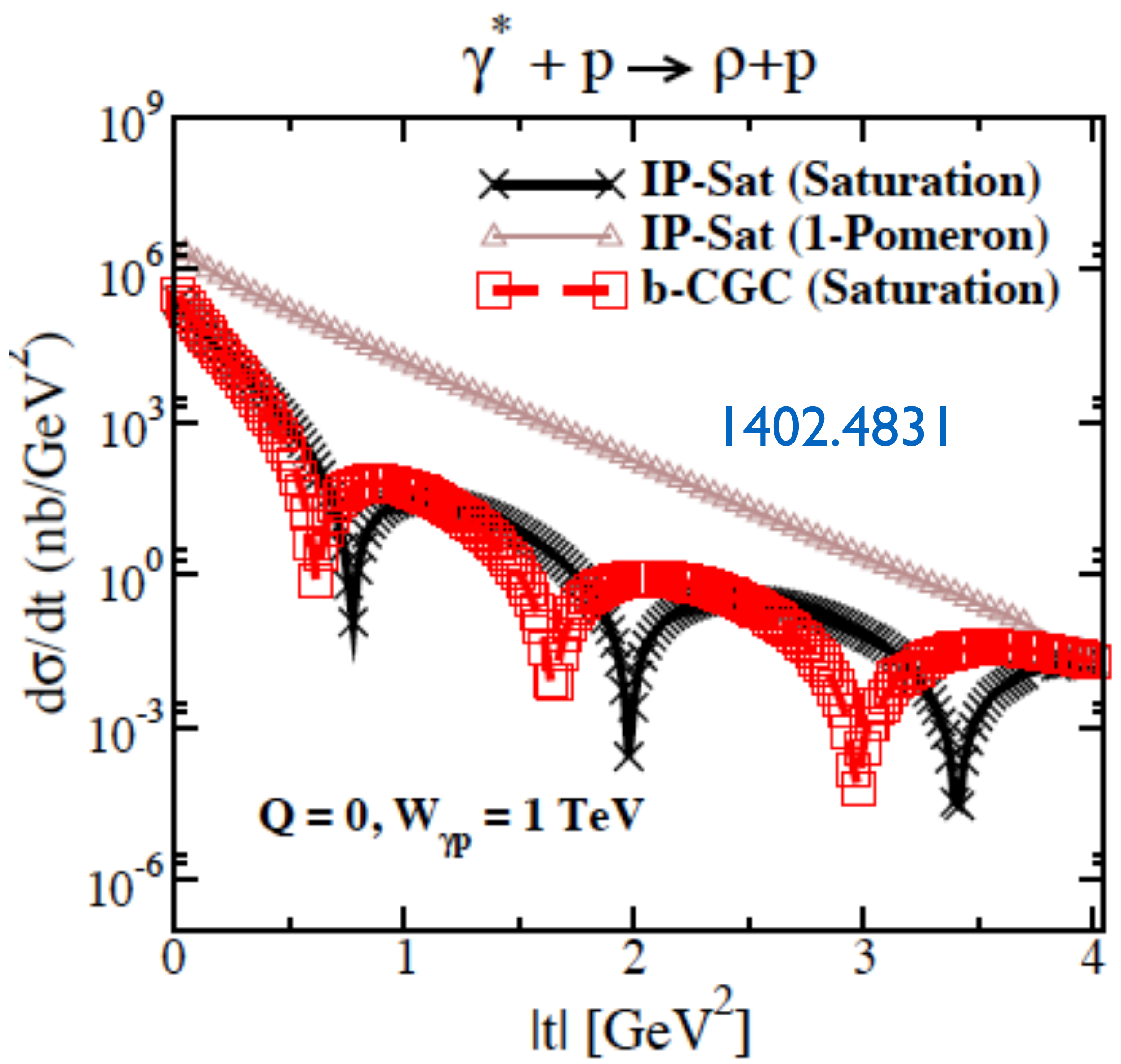
- Inclusive diffraction: precise determination of diffractive PDFs.



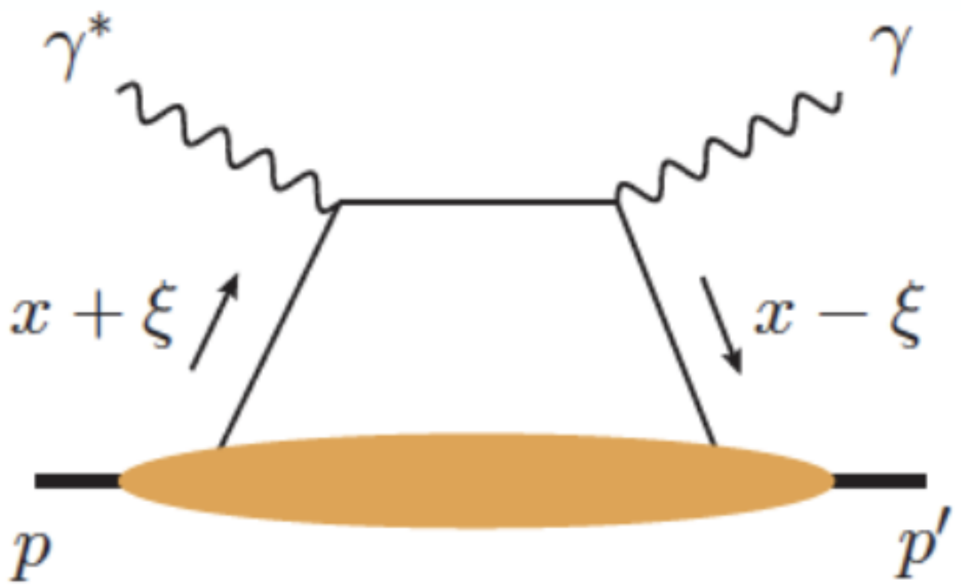




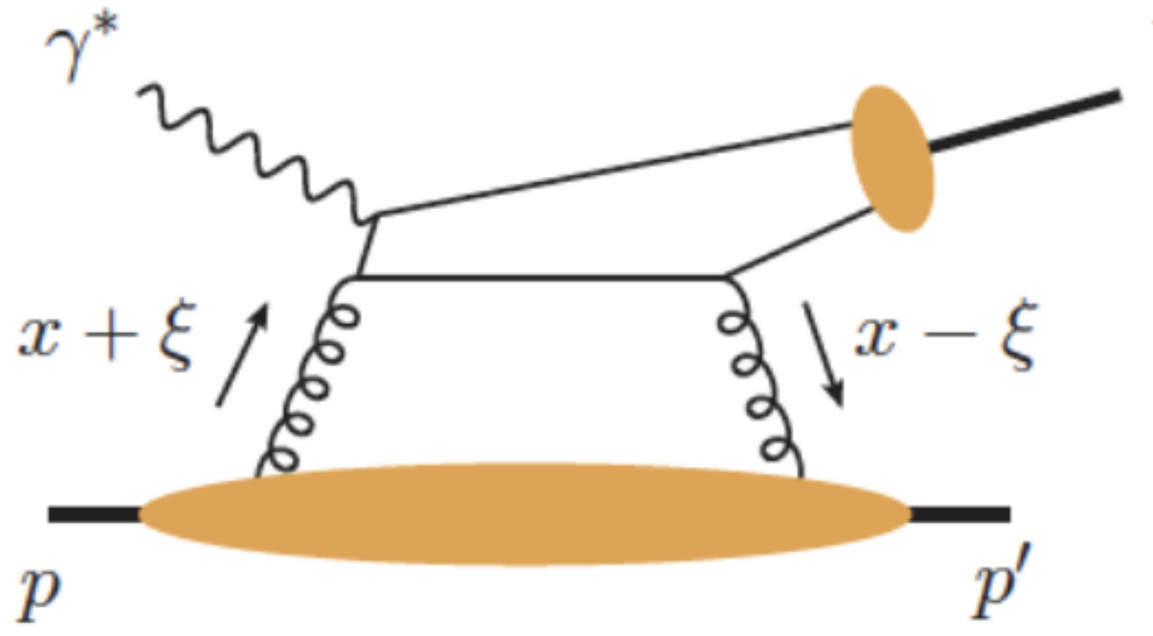
- Exclusive diffraction: transverse partonic structure, hot spots (fluctuations of density in coherent ep→eXp versus incoherent ep→eXp*), small x.

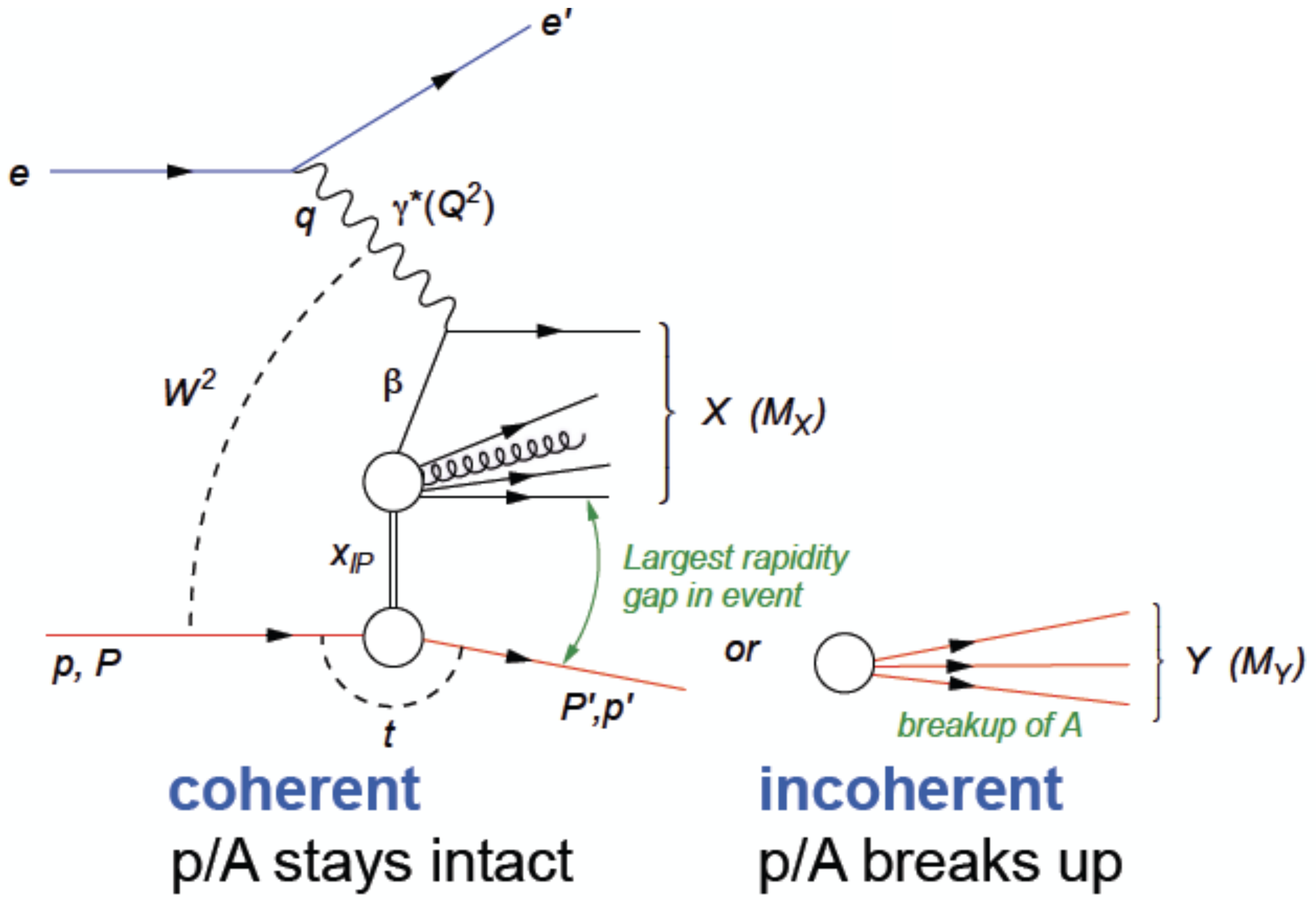


Quark and gluon GPDs:

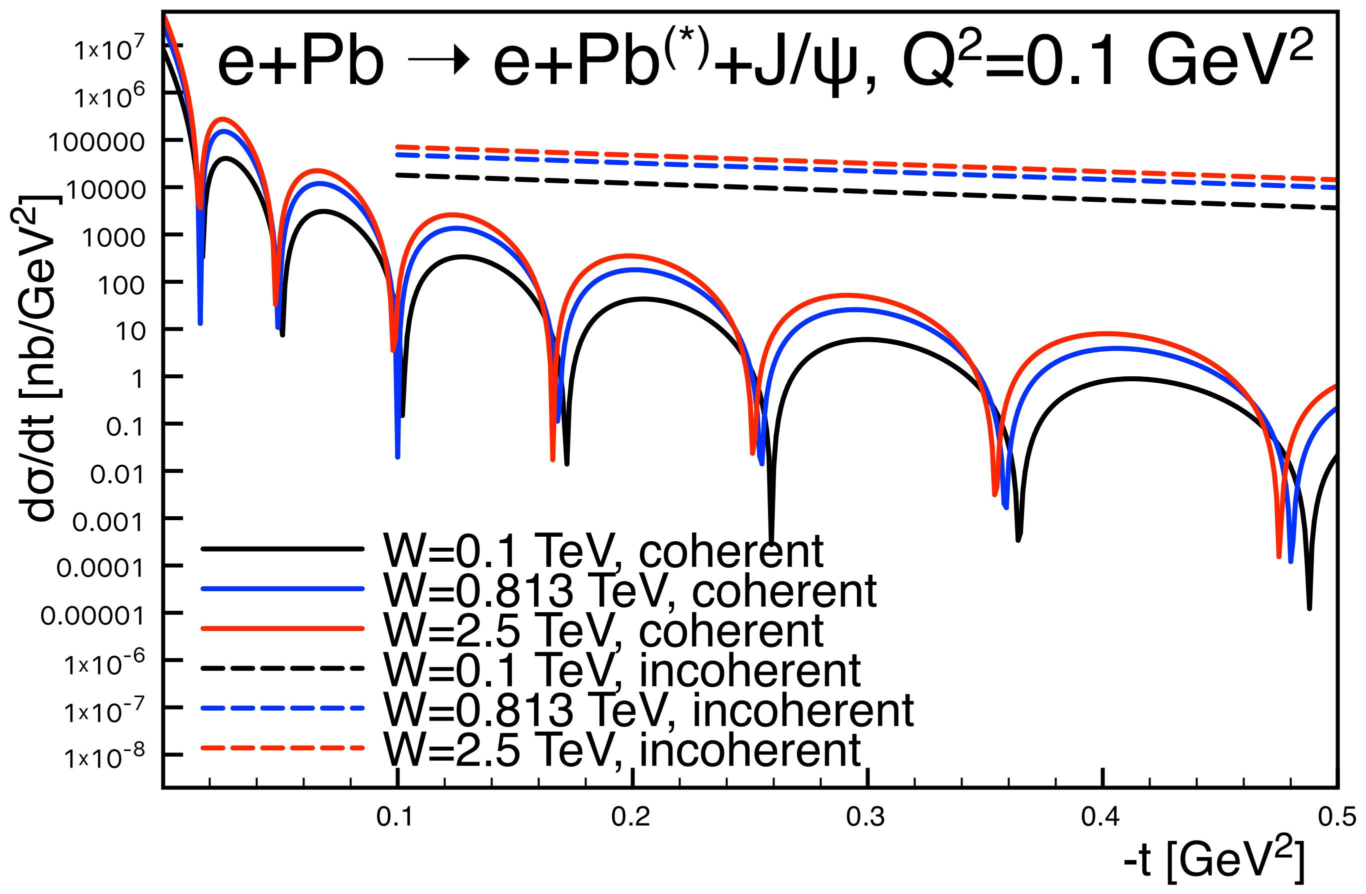


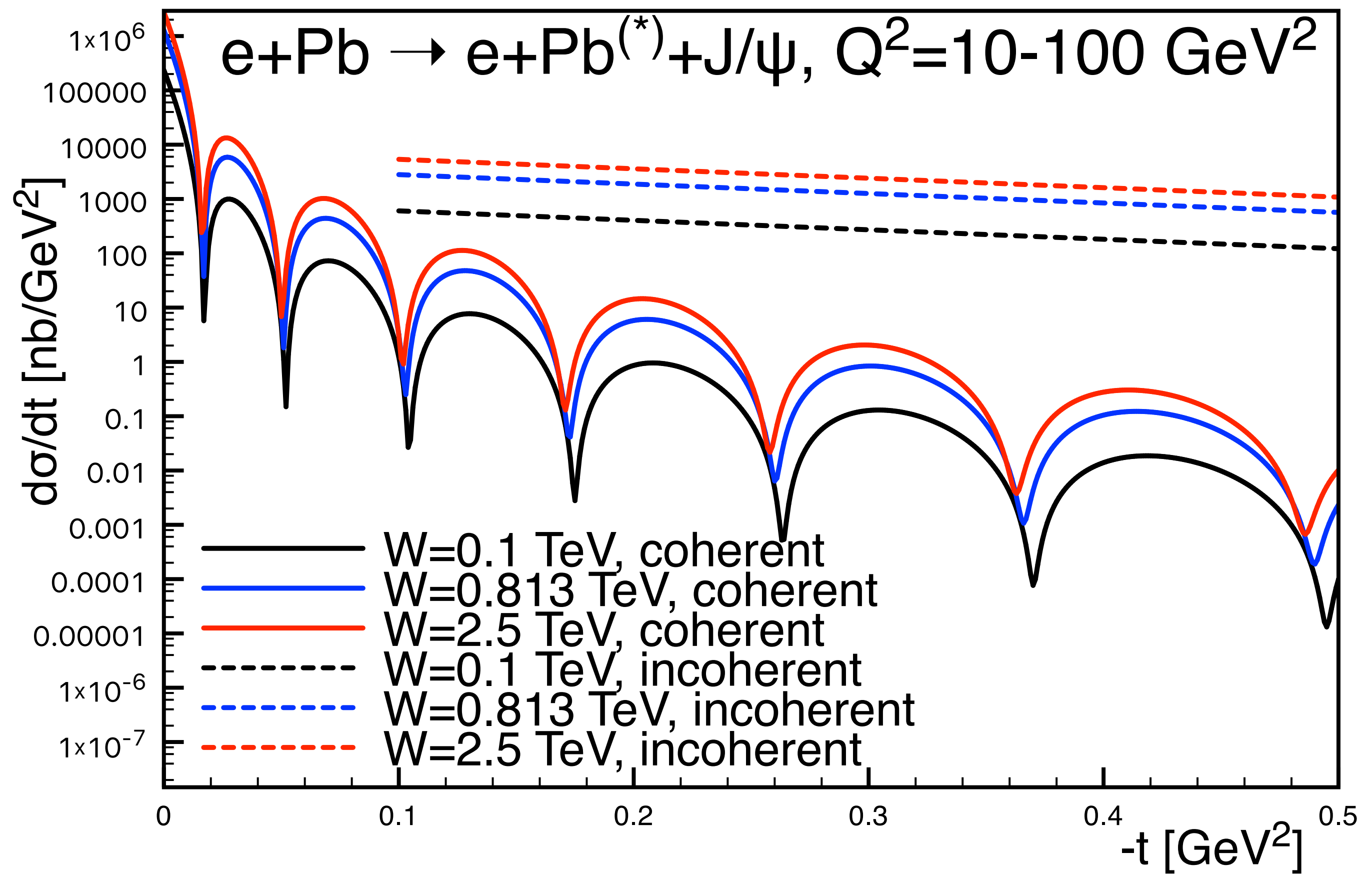
$$\int \frac{dw^-}{2\pi} e^{-i\xi P^+ w^-} \left\langle P' \middle| T \overline{\psi}_j \left(0, \frac{1}{2}w^-, \mathbf{0}_T\right) \frac{\gamma^+}{2} \psi_j \left(0, -\frac{1}{2}w^-, \mathbf{0}_T\right) \middle| P \right\rangle_c$$



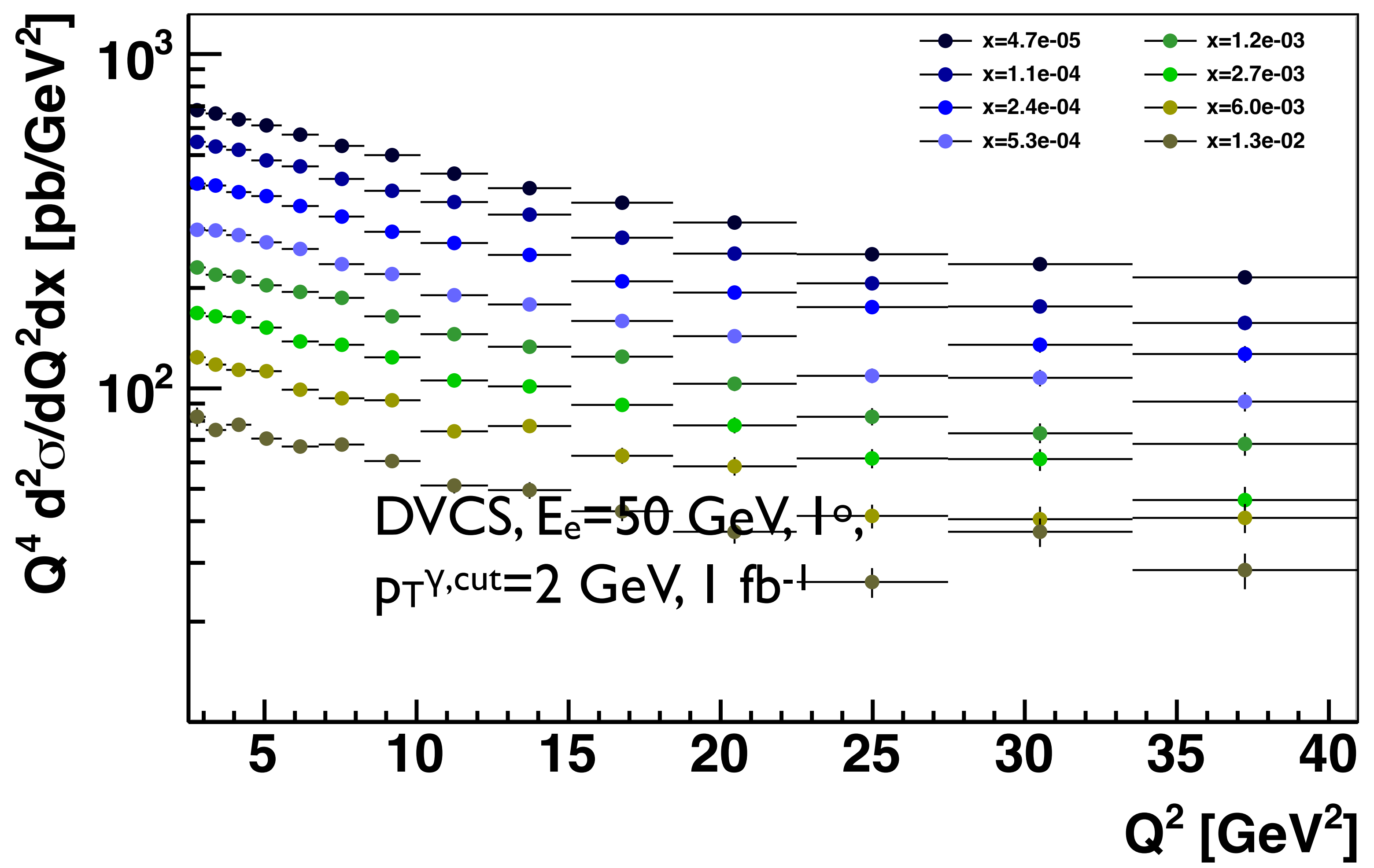


- Coherent exclusive production of γ and VM yields information about q and g GPDs.

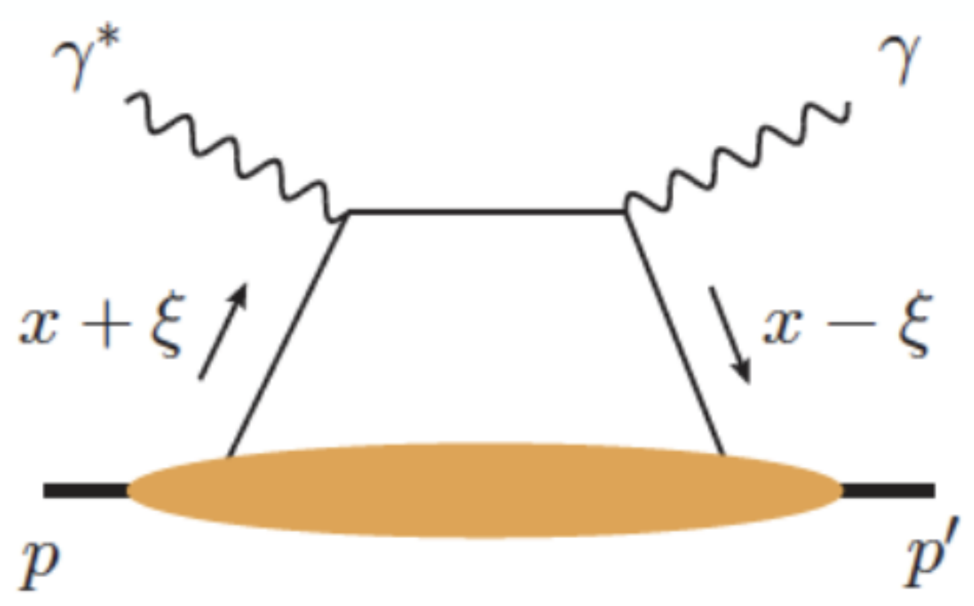


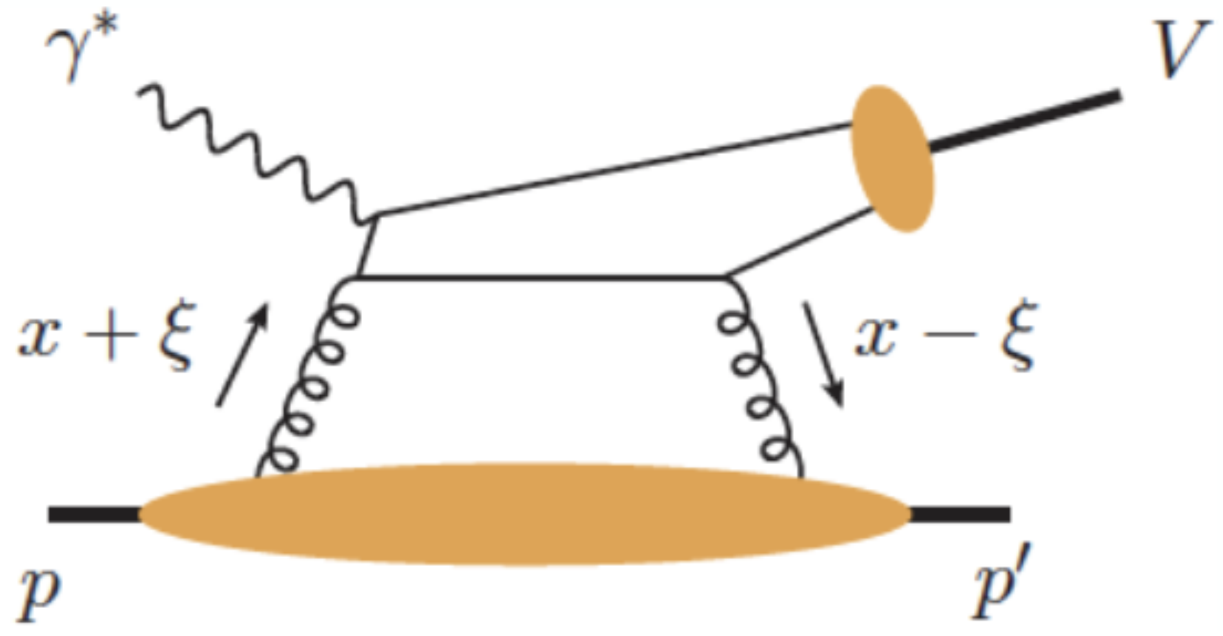


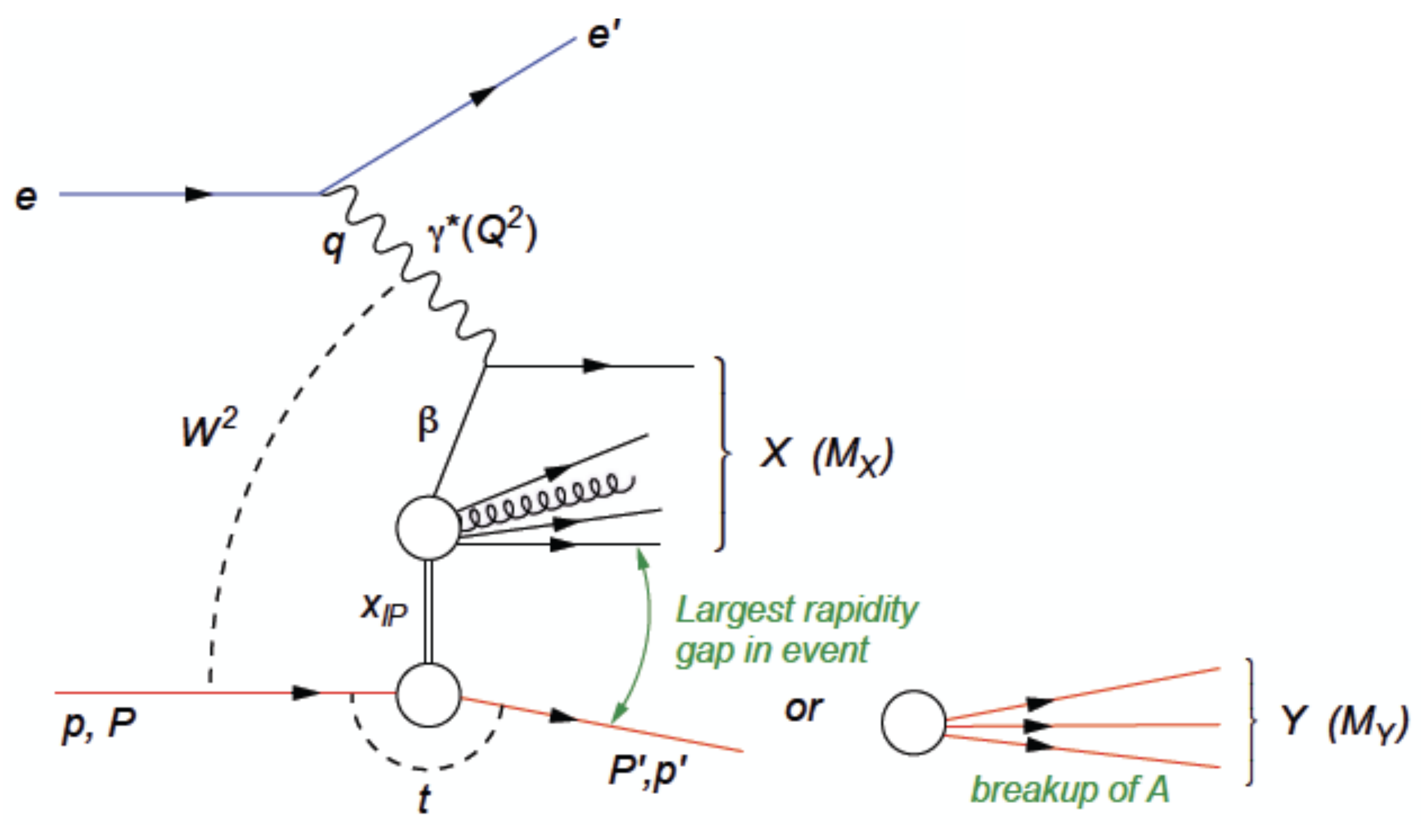
LHeC 1206.2913



Quark and gluon GPDs:





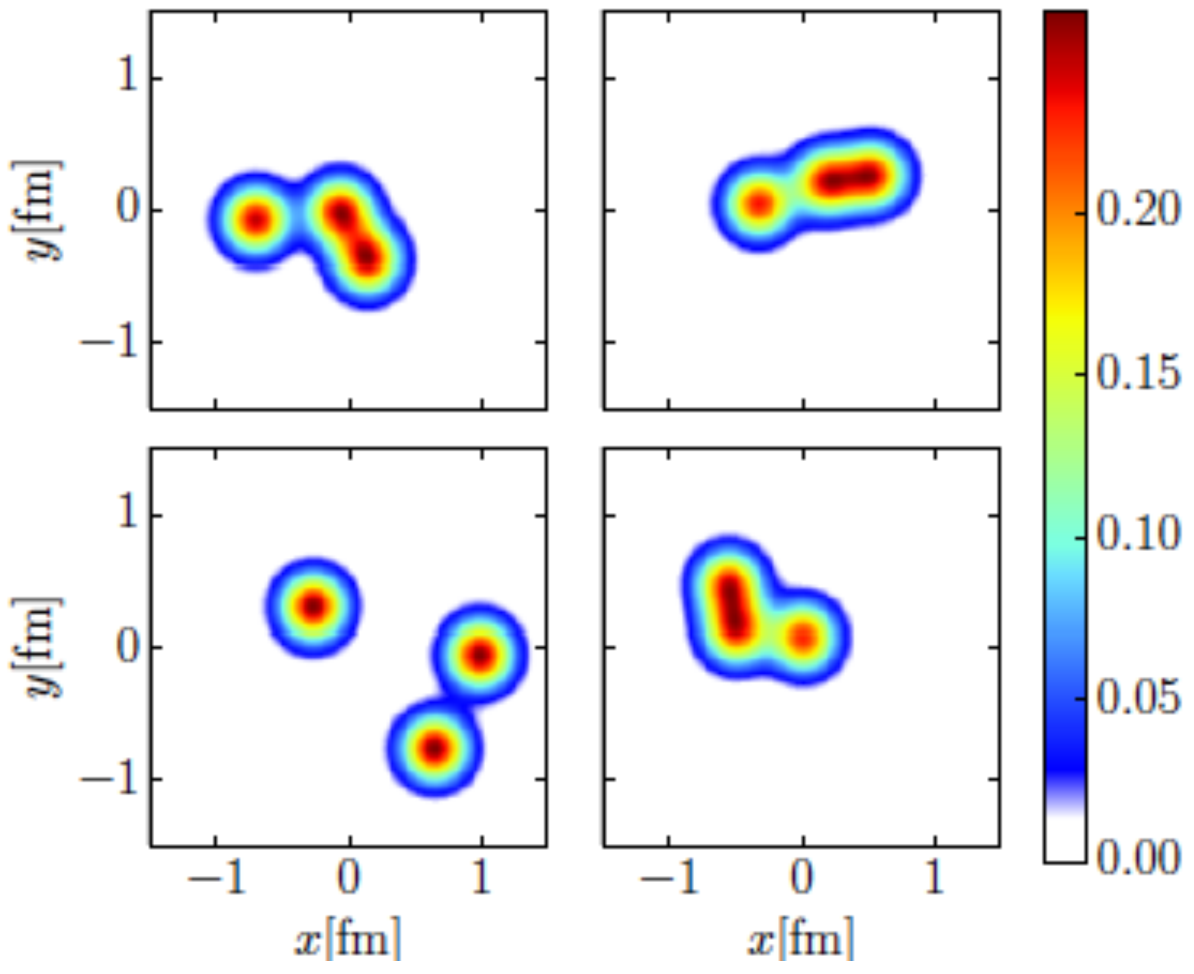


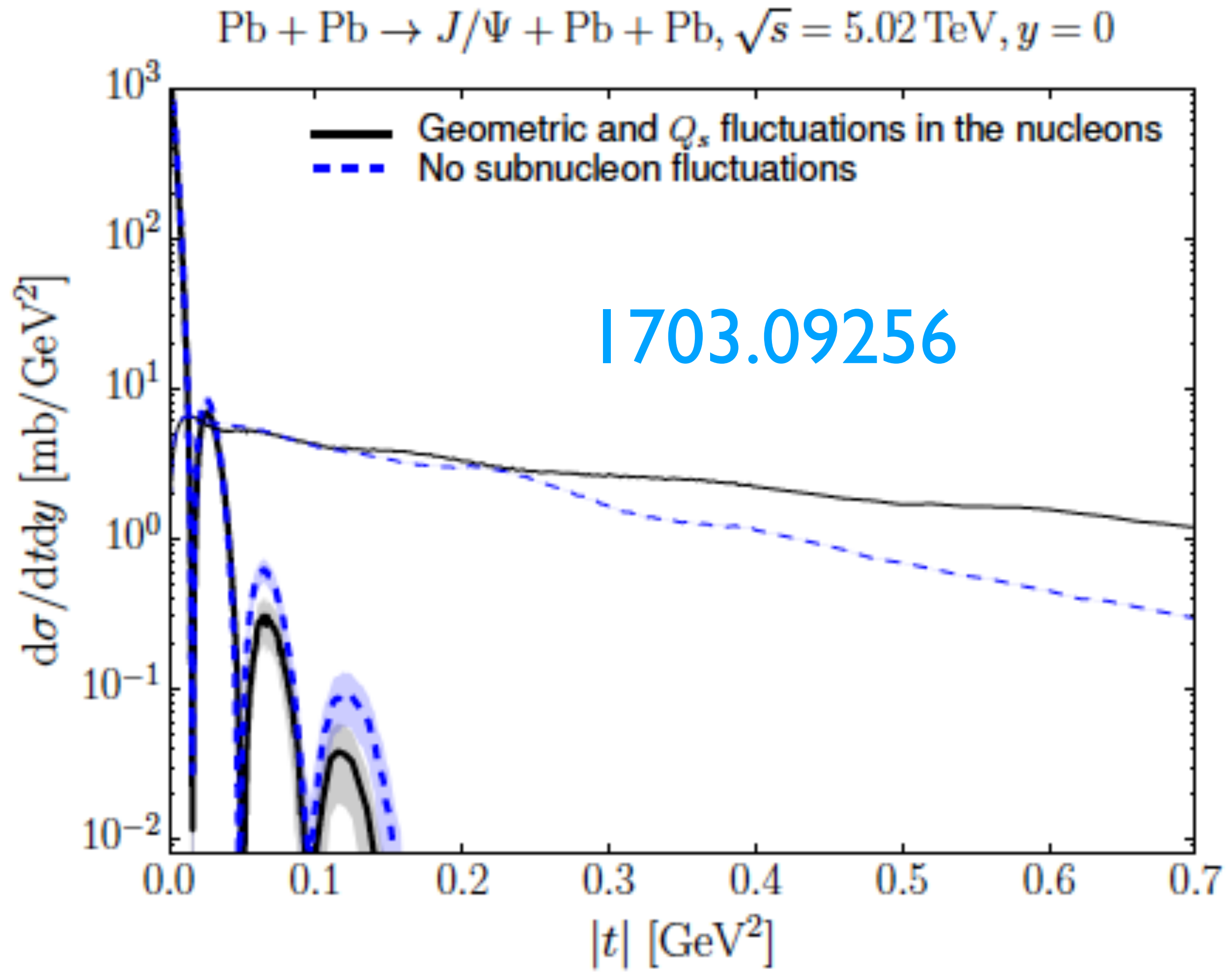
$$\int \frac{\mathrm{d}w^-}{2\pi} e^{-i\xi P^+ w^-} \left\langle P' \middle| T\bar{\psi}_j\left(0, \frac{1}{2}w^-, \mathbf{0}_\mathrm{T}\right) \frac{\gamma^+}{2} \psi_j\left(0, -\frac{1}{2}w^-, \mathbf{0}_\mathrm{T}\right) \middle| P \right\rangle_c$$

coherent
p/A stays intact

incoherent
p/A breaks up

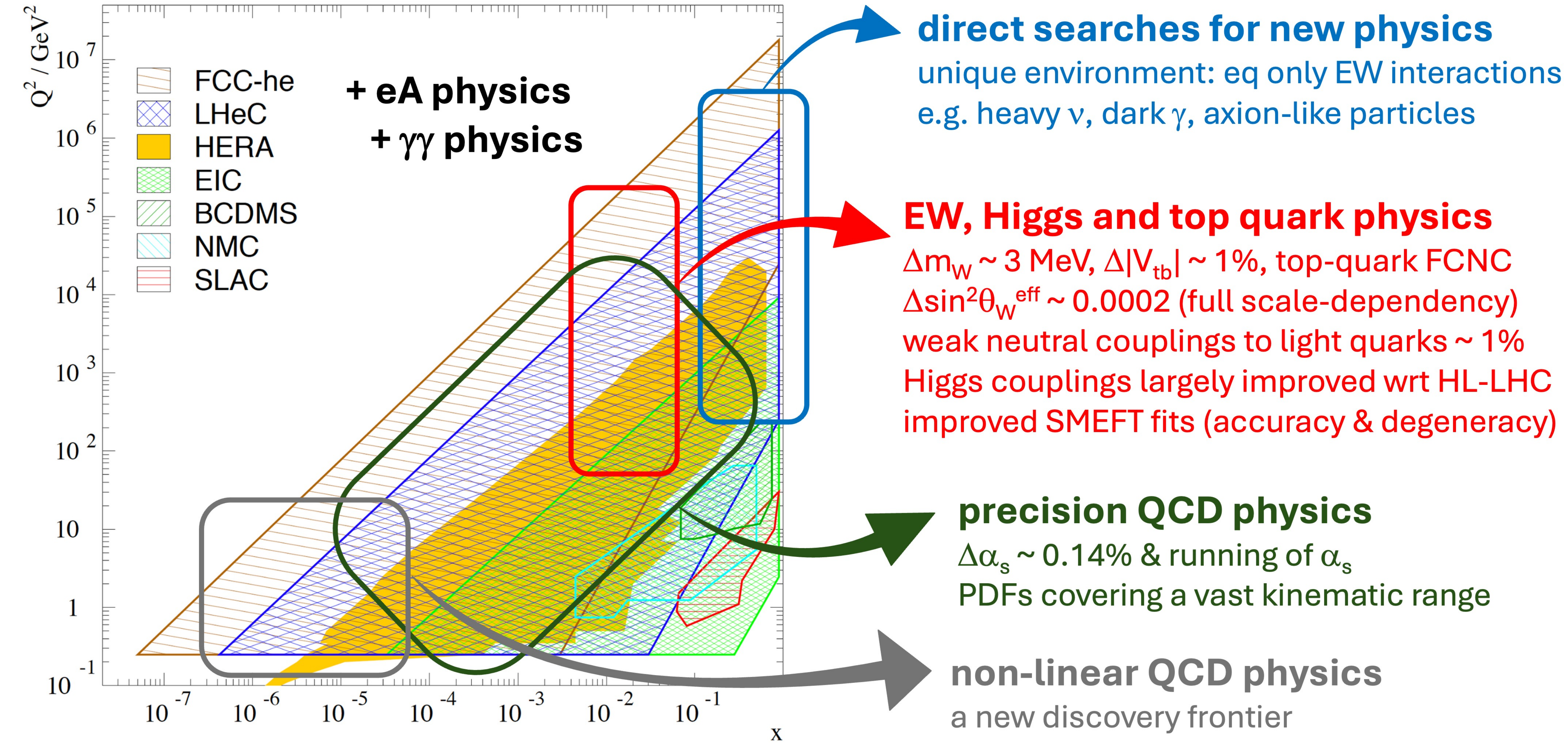
- Coherent exclusive production of γ and VM yields information about q and g GPDs.
- Incoherent exclusive production yields information about fluctuations: hot spots.





Summary:

1.2 TeV ep collisions cover the (Q^2,x) plane → ***General Purpose Experiment***

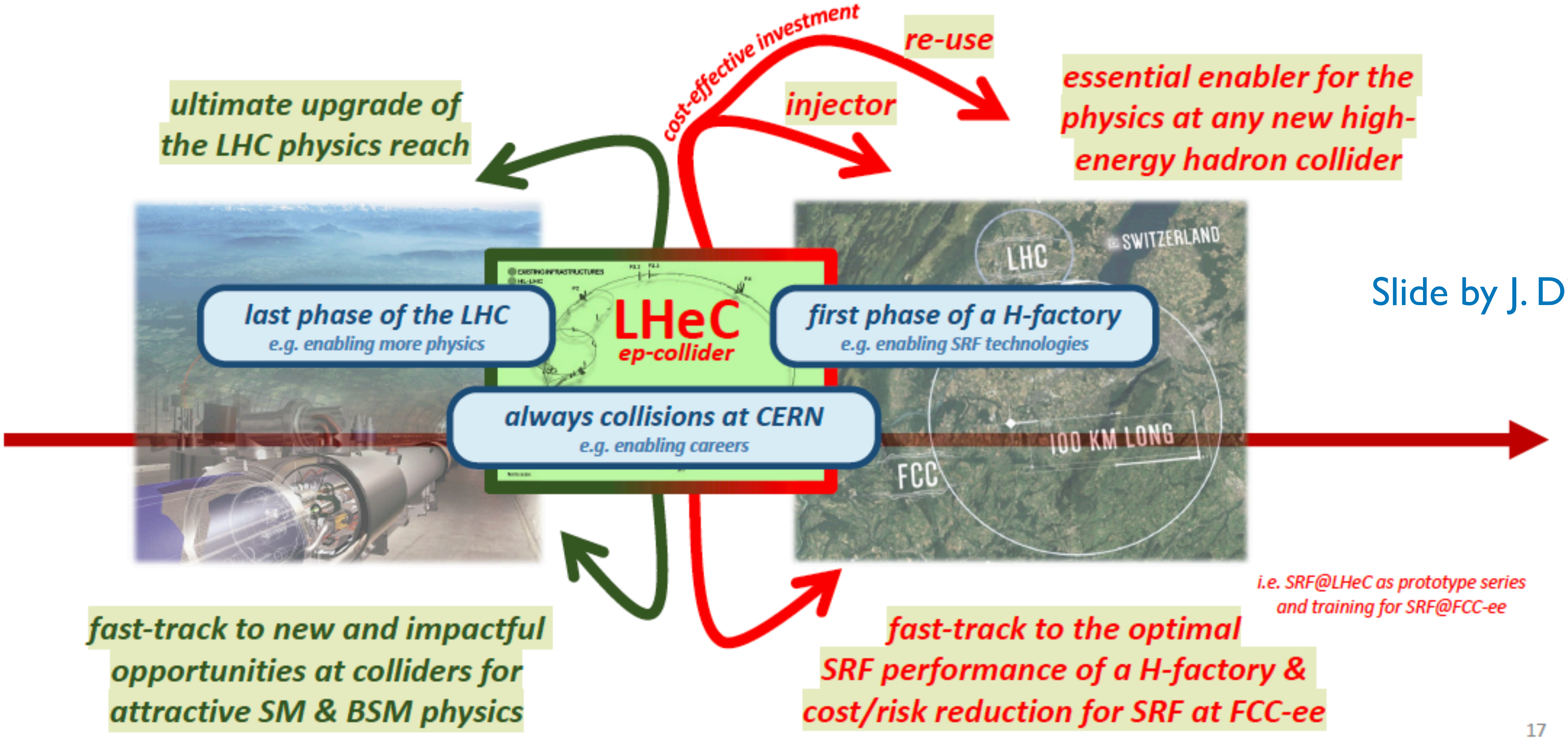


- **LHeC in the landscape of particle physics colliders:**
  - ➜ Physics case on their own: QCD (precision and discovery in ep & eA), EW, top, Higgs, BSM.
  - ➜ Enlarge the reach of hadronic colliders into (higher) precision, both for pp and for AA.
  - ➜ Complementarities/synergies with hh & e^+e^-.

- **LHeC is not the next flagship project at CERN but it may serve as bridge between HL-LHC and a new major project at CERN (2503.17727):**
  - ➜ Ultimate exploitation of the results of the LHC (e.g., m_W, Higgs couplings).
  - ➜ Physics program on its own: proton/nuclear structure and dynamics, EW, top , Higgs, BSM.
  - ➜ It facilitates technology (SRF, ERL, detector) and physics (e.g., PDFs for pp and AA, combinations of Higgs couplings, complementary regions on searches) for future projects.

LHeC as a bridge:

- In standalone mode (ep/eA only), LHeC may be a bridge between major colliders at CERN, between the end of the HL-LHC (2041) and the next flagship CERN collider.



Slide by J. D'Hondt

LHeC as a bridge:

- In standalone mode (ep/eA only), LHeC may be a bridge between major colliders at CERN, between the end of the HL-LHC (2041) and the next flagship CERN collider.

Slide by J. D'Hondt

→ Thank you very much to the organisers for the invitation to deliver this talk!

→ Thank you very much for your attention!

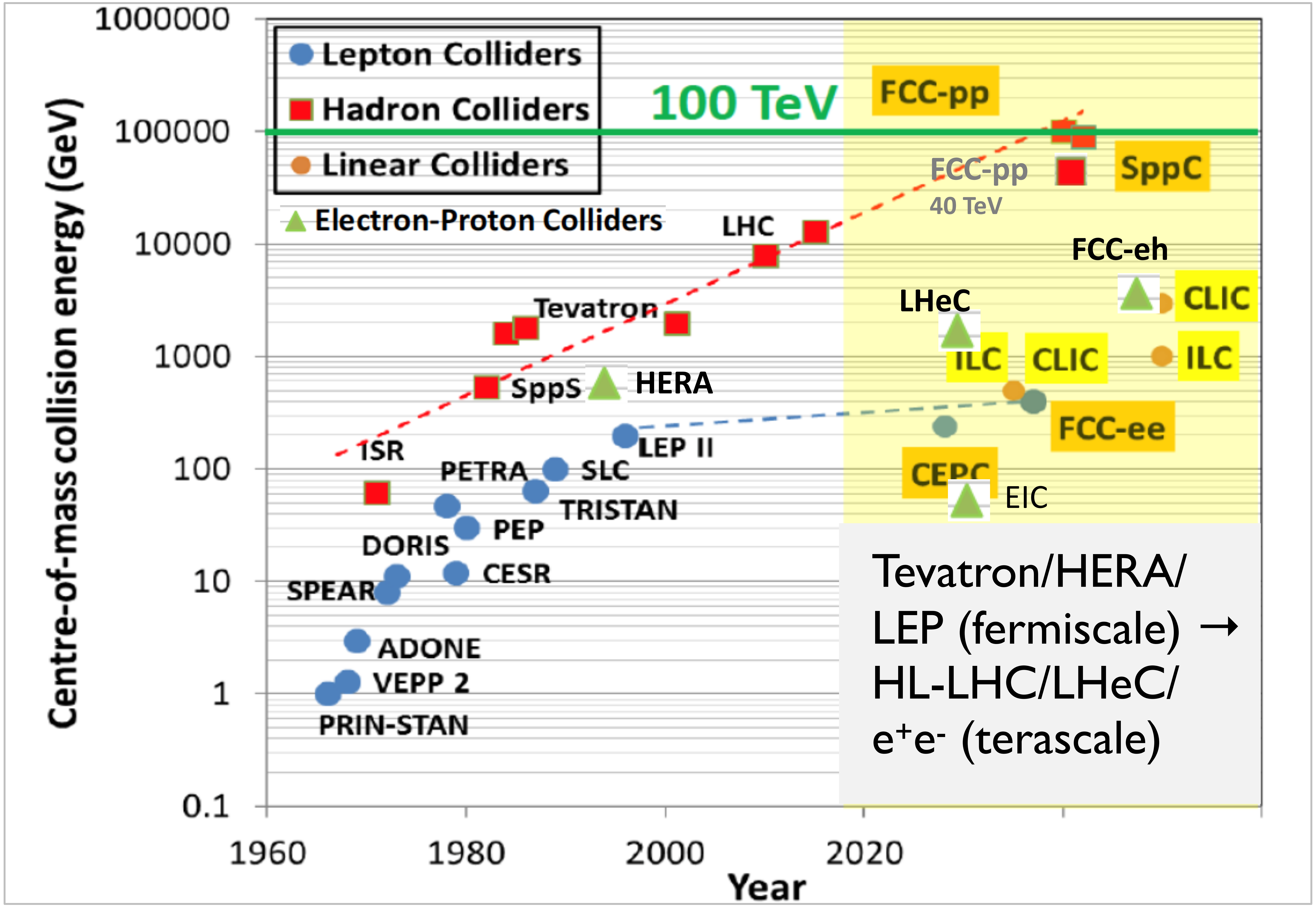
Backup:

Accelerators:

- Thoughts of combining LEP with LHC came from the start (1990's).

- LHeC idea born in 2005: upgrade of the HL-LHC to study DIS at the terascale.

- **It should be able to run concurrently with pp** (also FCC-eh), plus limitations on power consumption, high luminosity for Higgs studies,… ⇒ energy recovery linac as baseline.



Tevatron/HERA/LEP (fermiscale) → HL-LHC/LHeC/ e^+e^- (terascale)

Parton densities: synergies with HL-LHC

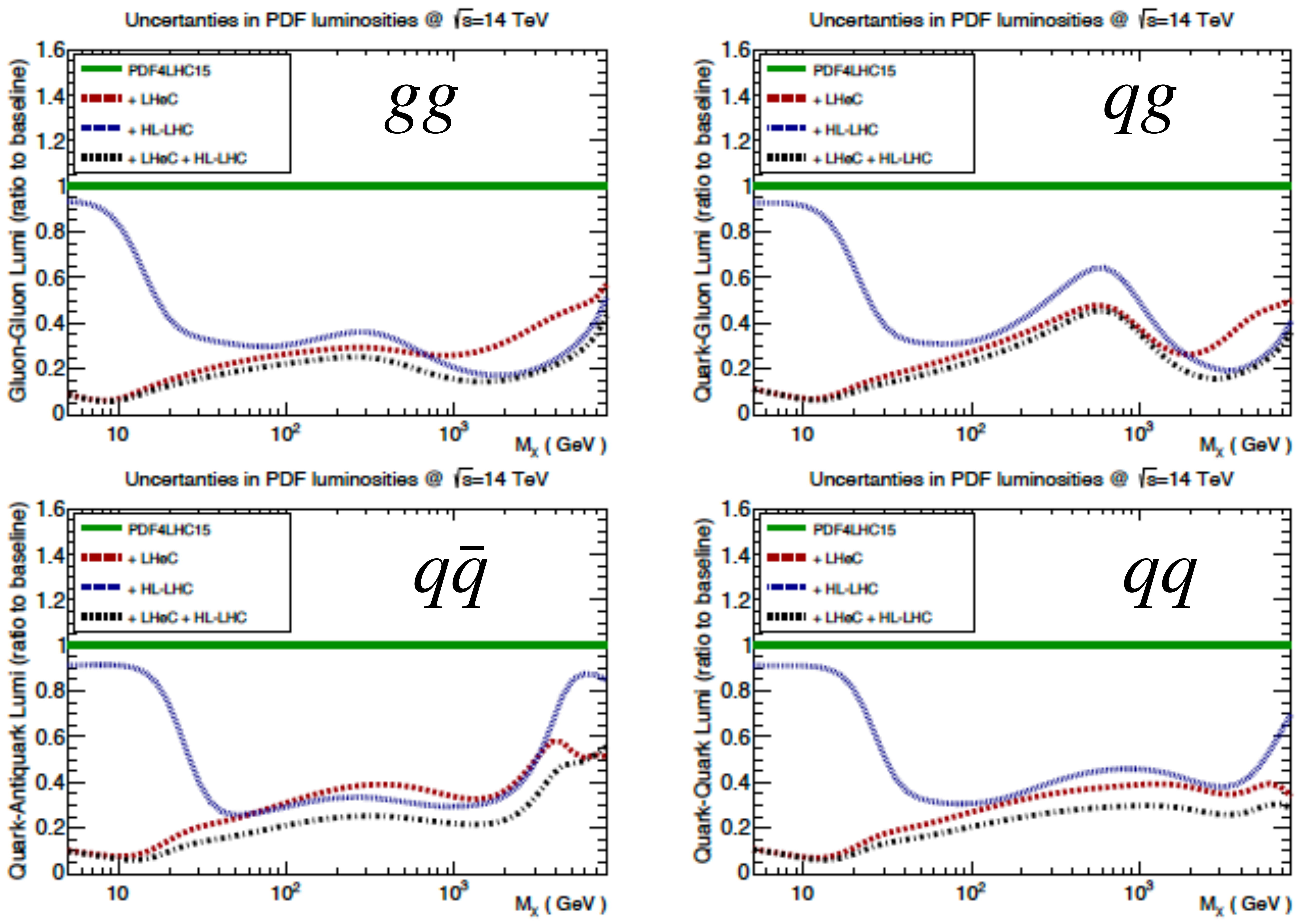
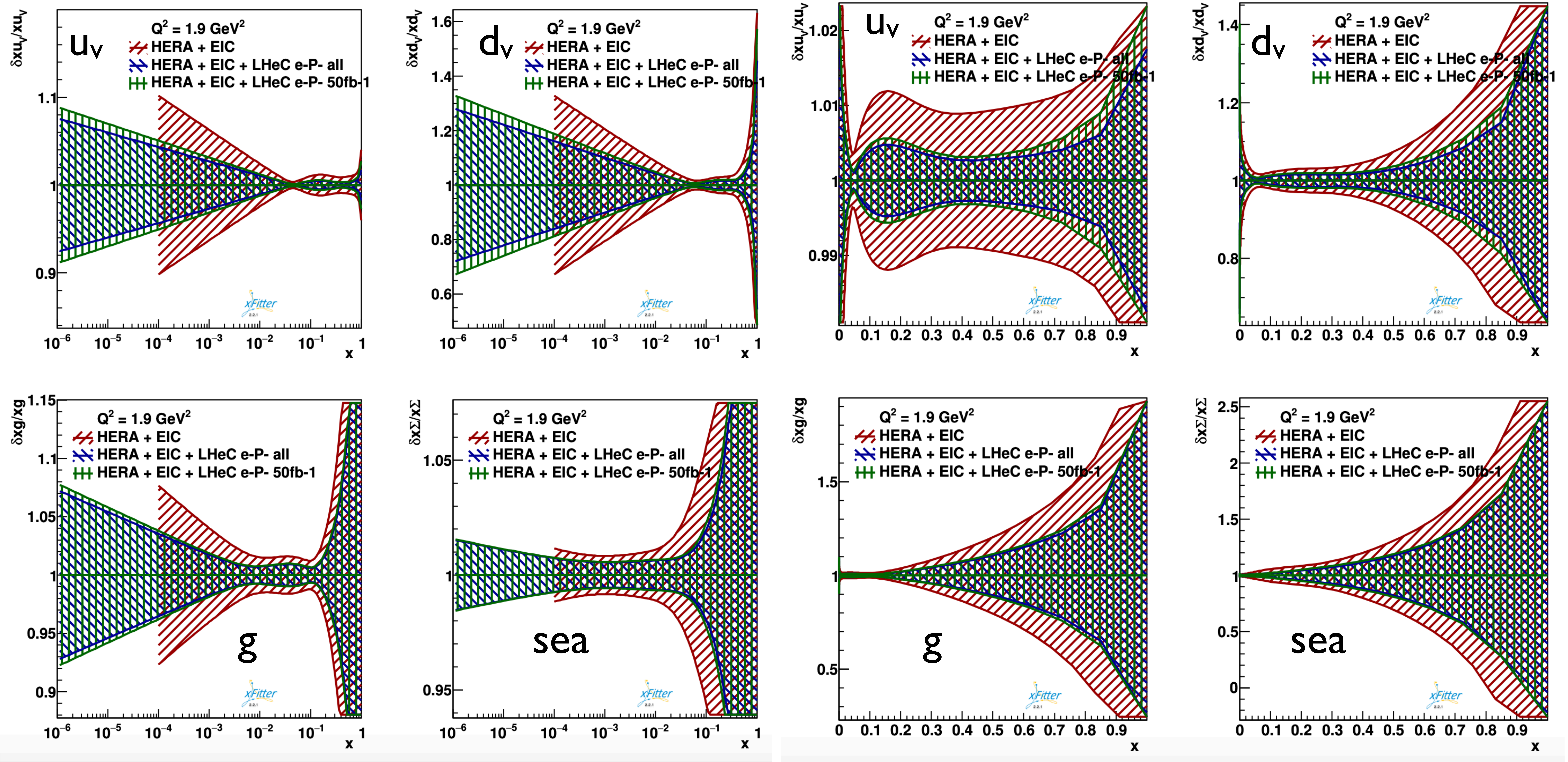


Figure 9.10: Impact of LHeC, HL-LHC and combined LHeC + HL-LHC pseudodata on the uncertainties of the gluon-gluon, quark-gluon, quark-antiquark and quark-quark luminosities, with respect to the PDF4LHC15 baseline set. In this comparison we display the relative reduction of the PDF uncertainty in the luminosities compared to the baseline.

Parton densities: synergies with EIC

K.Wichmann at the Synergy workshop between ep/eA and pp/pA/AA physics experiments, February 29th-March 1st 2024, https://indico.cern.ch/event/1367865/.



Components, cost, sustainability:

Section	Horizontal Dipoles			Vertical Dipoles			Quadrupoles			RF Cavities		
	Number	*Field*	*Mag. Length*	*Number*	*Field*	*Mag. Length*	*Number*	*Gradient*	*Mag. Length*	*Number*	*Frequency/Cell*	*RF Gradient*
LINAC 1							29	1.9	1.0	448	802/5	20.0
LINAC 2							29	1.9	1.0	448	802/5	20.0
Arc 1	344	0.039	4.0	8	0.51	4.0	158	9.3	1.0			
Arc 2	294	0.077	4.0	6	0.74	4.0	138	17.7	1.0			
Arc 3	344	0.123	4.0	6	0.92	4.0	158	24.3	1.0	6	1604/9	30.0
Arc 4	294	0.181	4.0	6	1.23	4.0	138	27.2	1.0	6	1604/9	30.0
Arc 5	344	0.189	4.0	4	0.77	4.0	156	33.9	1.0	18	1604/9	30.0
Arc 6	344	0.226	4.0	4	1.49	4.0	156	40.8	1.0	30	1604/9	30.0
Total	**1964**			**34**			**962**			**956**		

Units: meter (m), Tesla (T), T/m, MHz, MV/m

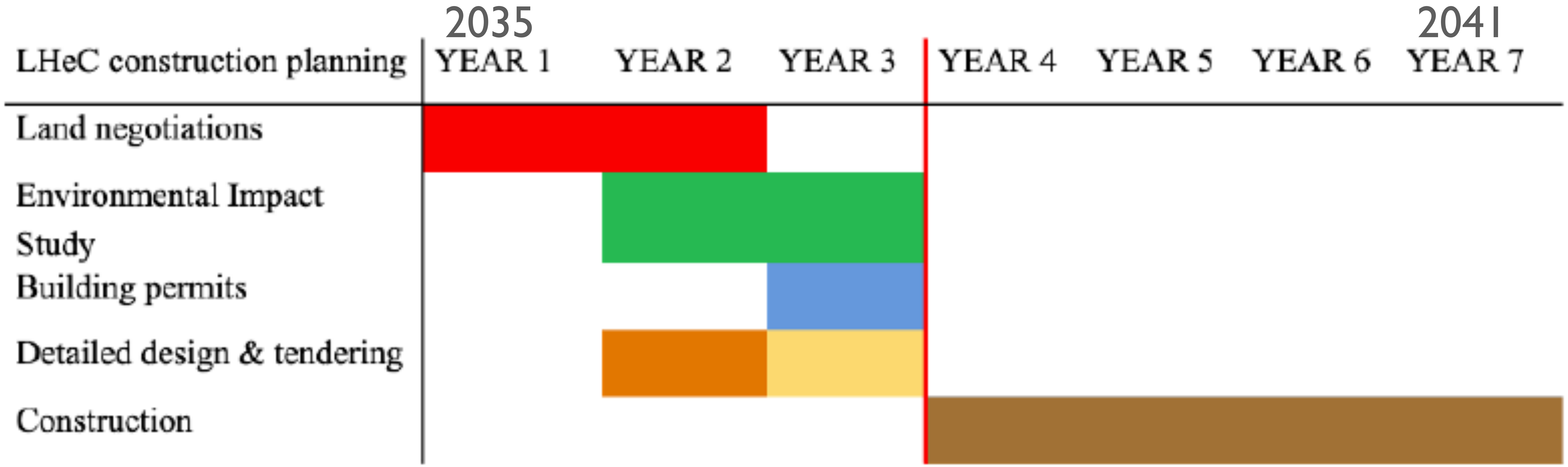
A. Bogacz, full lattice simulation for ERL at 50 GeV

Budget Item	**Cost**
SRF System	671 MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	386MCHF
Total	1622 MCHF

- Cost estimate for 1/3rd of the LHC, 50 GeV racetrack: 1.6 BCHF (2018 cost, CERN-ACC-2018-0061), 46% corresponding to the SRF ERL accelerator and 24% to civil engineering; detector: 360 MCHF (75% calorimetry).

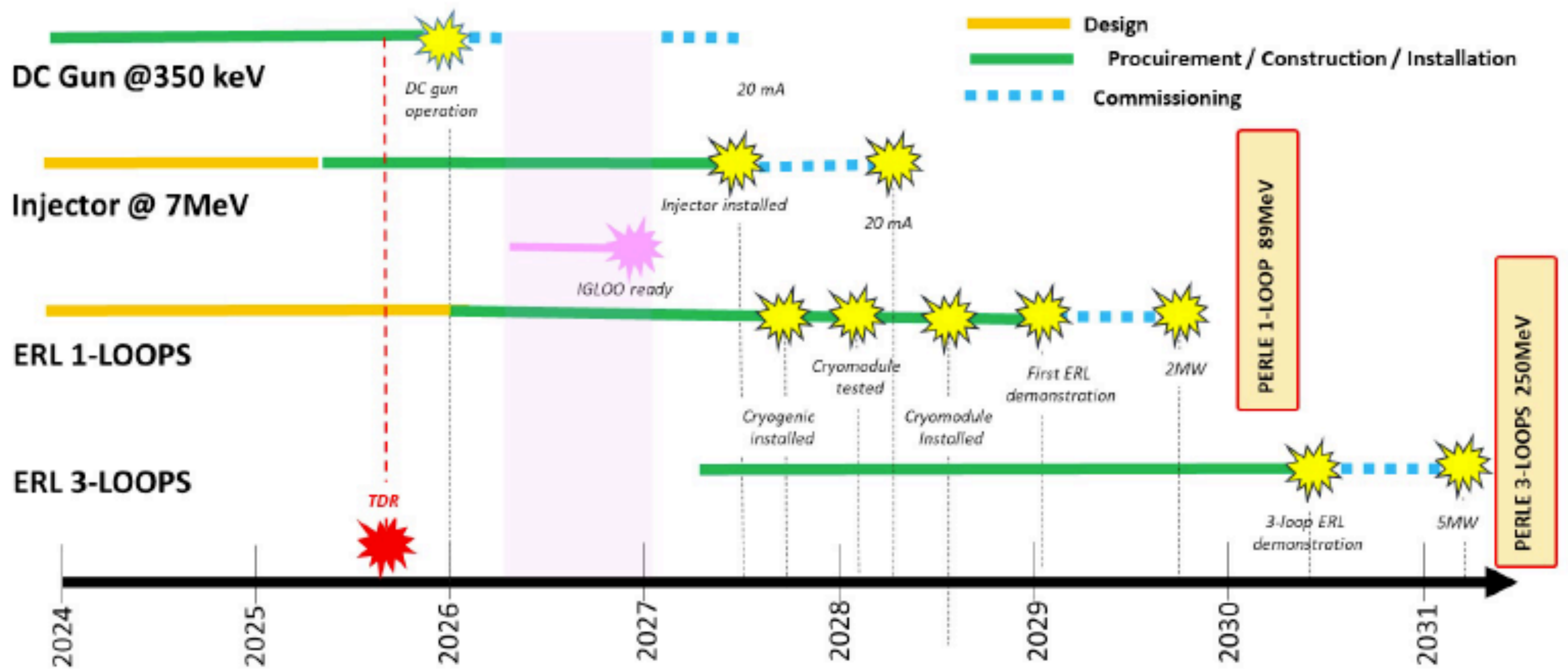
- Power consumption for this option: 220 MW including the ERL, the single-beam HL-LHC and the detector ⟶ +60 MW w.r.t. HL-LHC and +75 MW w.r.t. nominal LHC operation.

Feasibility:



- Target ep luminosity of $1\ \mathrm{ab}^{-1}$ can be achieved in 6 years: two years for installation and commissioning plus one year LS leads to completion in 2050.

- Demonstration of multi-turn high-current ERL in PERLE in 2029/2030:



Challenges:

- Accelerator (ERL in the ECFA Accelerator Roadmap and in the 2020 strategy):
  - ➜ High quality SRF cavities integrated in the cryomodule: PERLE (iSAS).
  - ➜ High-current, multi-pass ERL → PERLE as demonstrator (2029 1-turn, 2030 3-turn).
- Detector (in the ECFA Detector Roadmap):
  - ➜ Keep material budget in the forward direction low (MAPS) → synergies with ALICE(3) and ePIC.
  - ➜ Choose between more conservative or more aggressive proposal: particle ID, EMCAL? → synergies with EIC.
  - ➜ Further develop an ep/pp option and the possibility of reusing existing detectors.
- Machine-detector interface:
  - ➜ Synchrotron radiation protection: beam pipe and inner tracking.
  - ➜ 3-beam IR: high aperture, field-free region Q1 (HL-LHC complexity). 2-beam configuration simpler.

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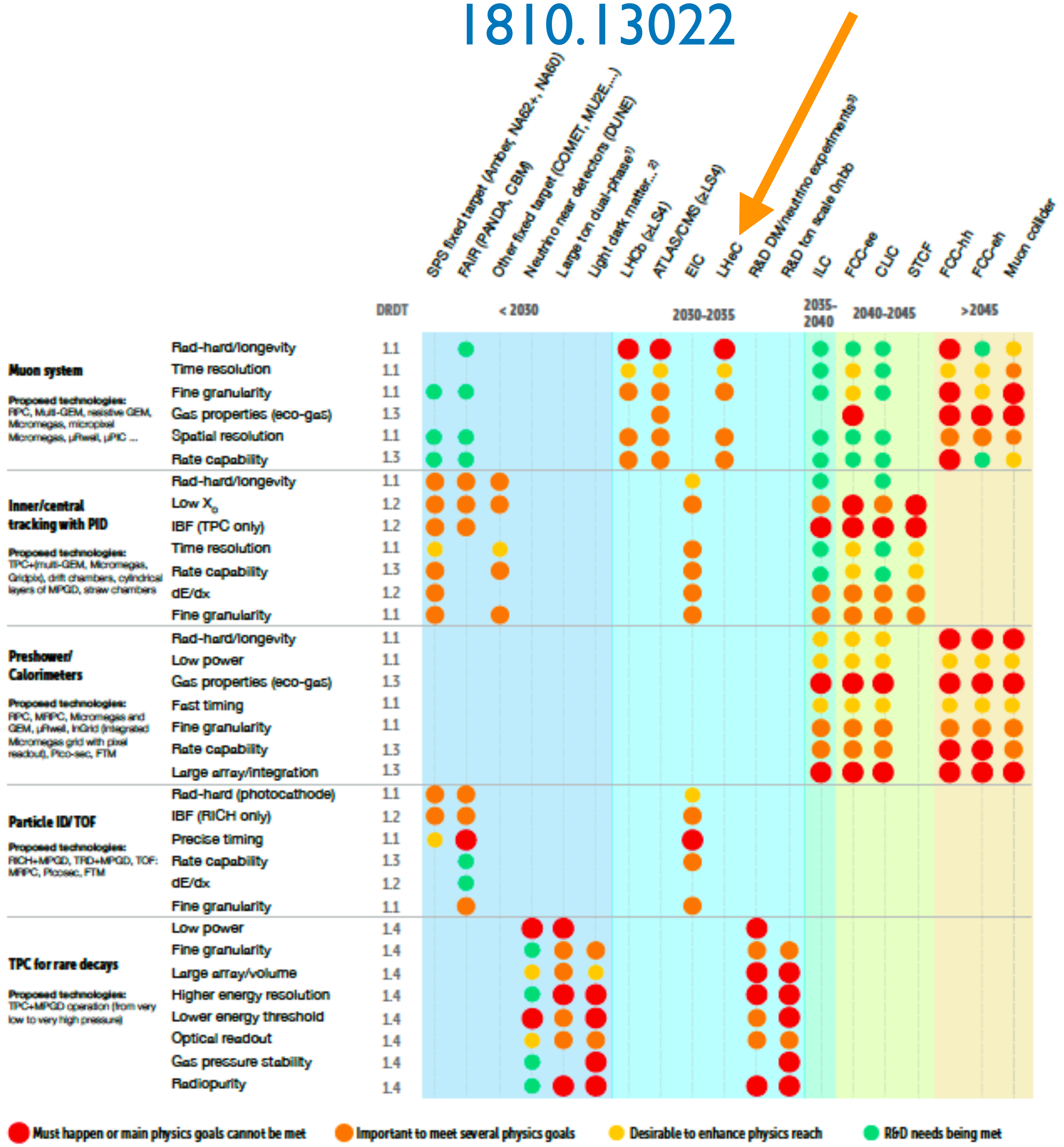
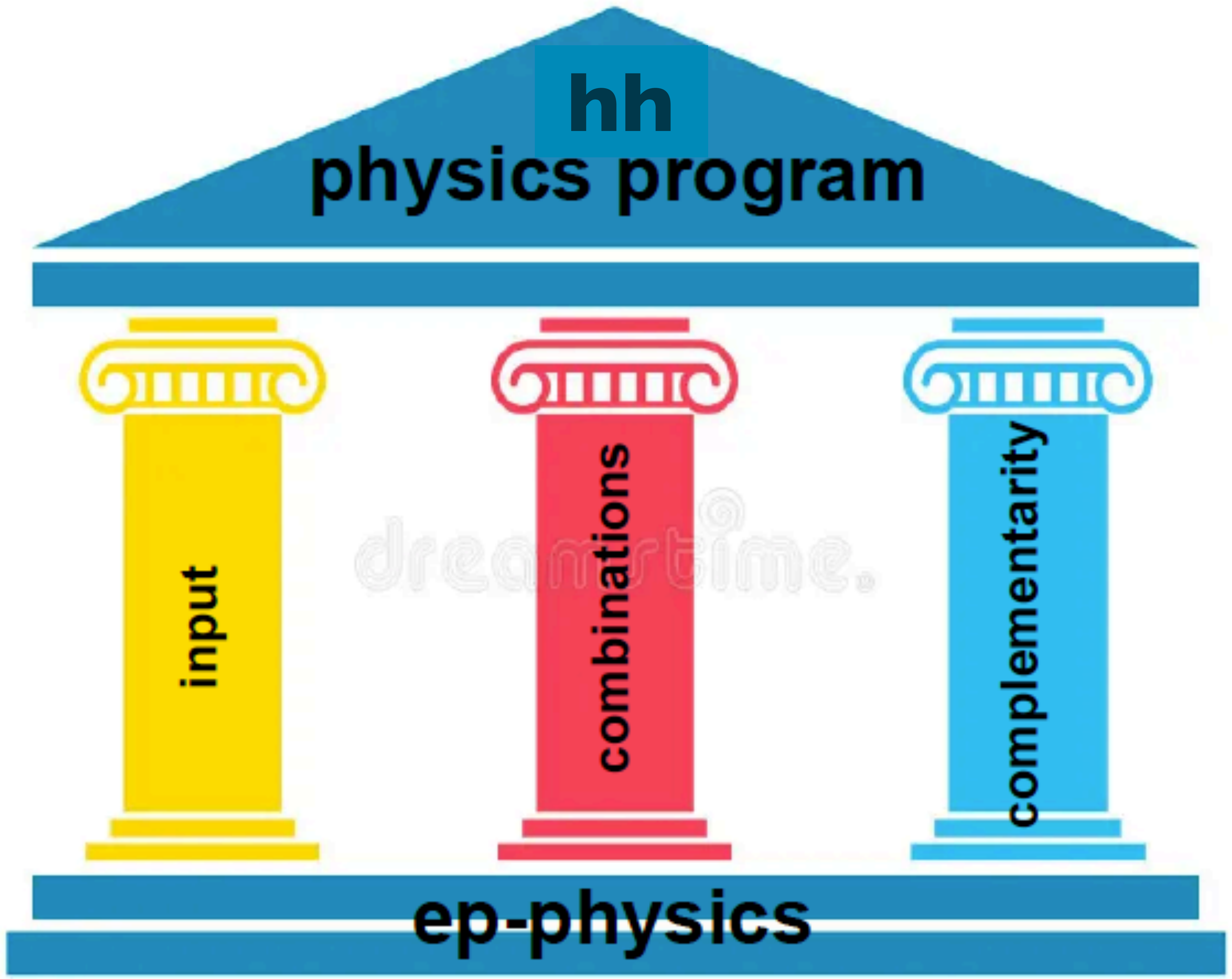


Synergies between eh and hh programes:

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

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



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

→ High precision QCD analyses.
→ High precision measurements of specific parameters.
→ Searches in complementary phase space regions.

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

→ Competitive measurements and combination of results.
→ Uncorrelated uncertainties.
→ Resolve common/correlated expt. uncertainties.
→ Resolve correlations in parameters of interest.
→ Empowers global fits.