ICHEP 2022 BOLOGNA

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XLI International Conference on High Energy Physics
Bologna (Italy)

XLI International Conference on High Energy Physics ICHEP2022
Bologna, July 7th 2022

# eA and high parton densities at the LHeC and FCC-he


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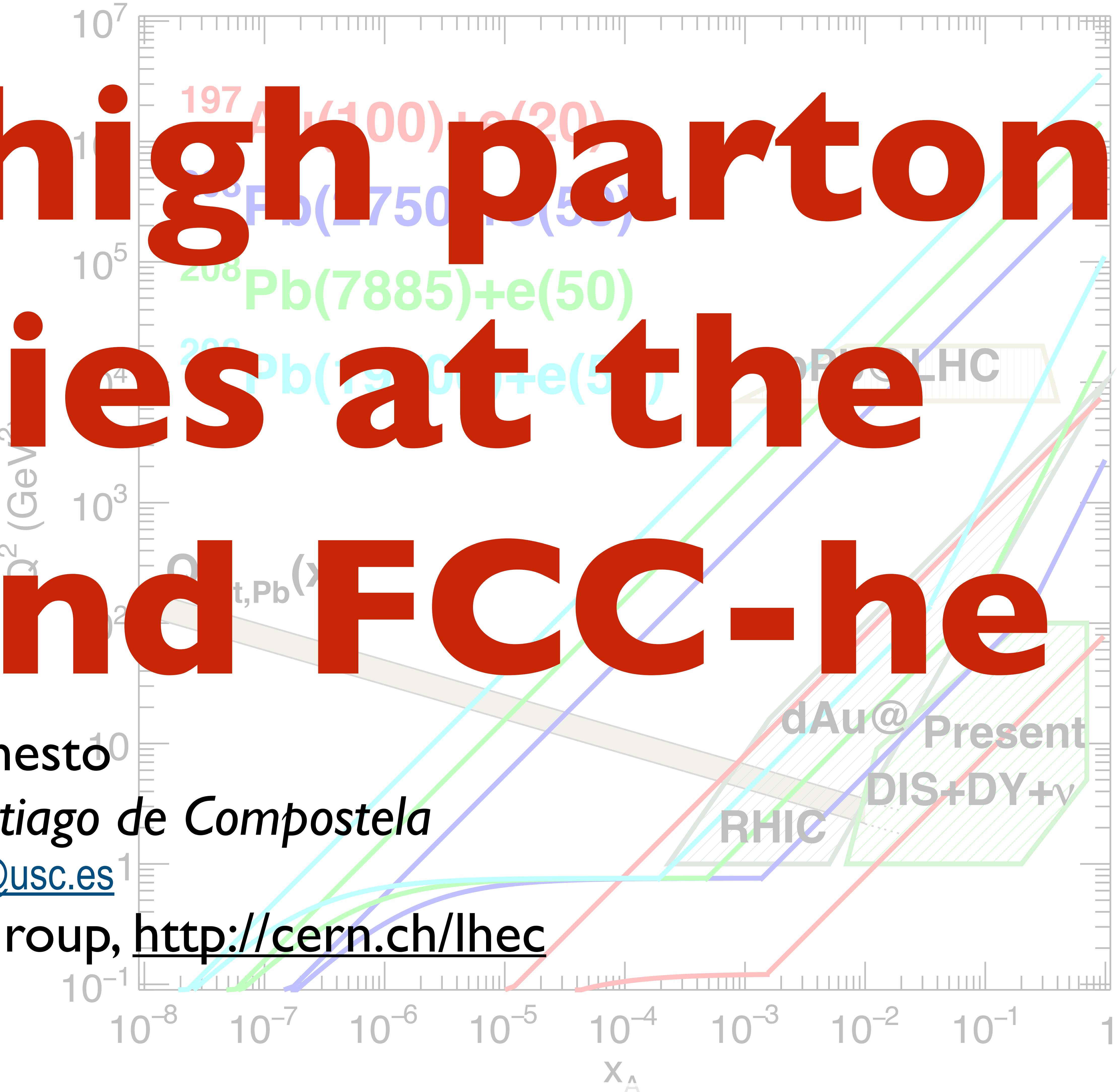
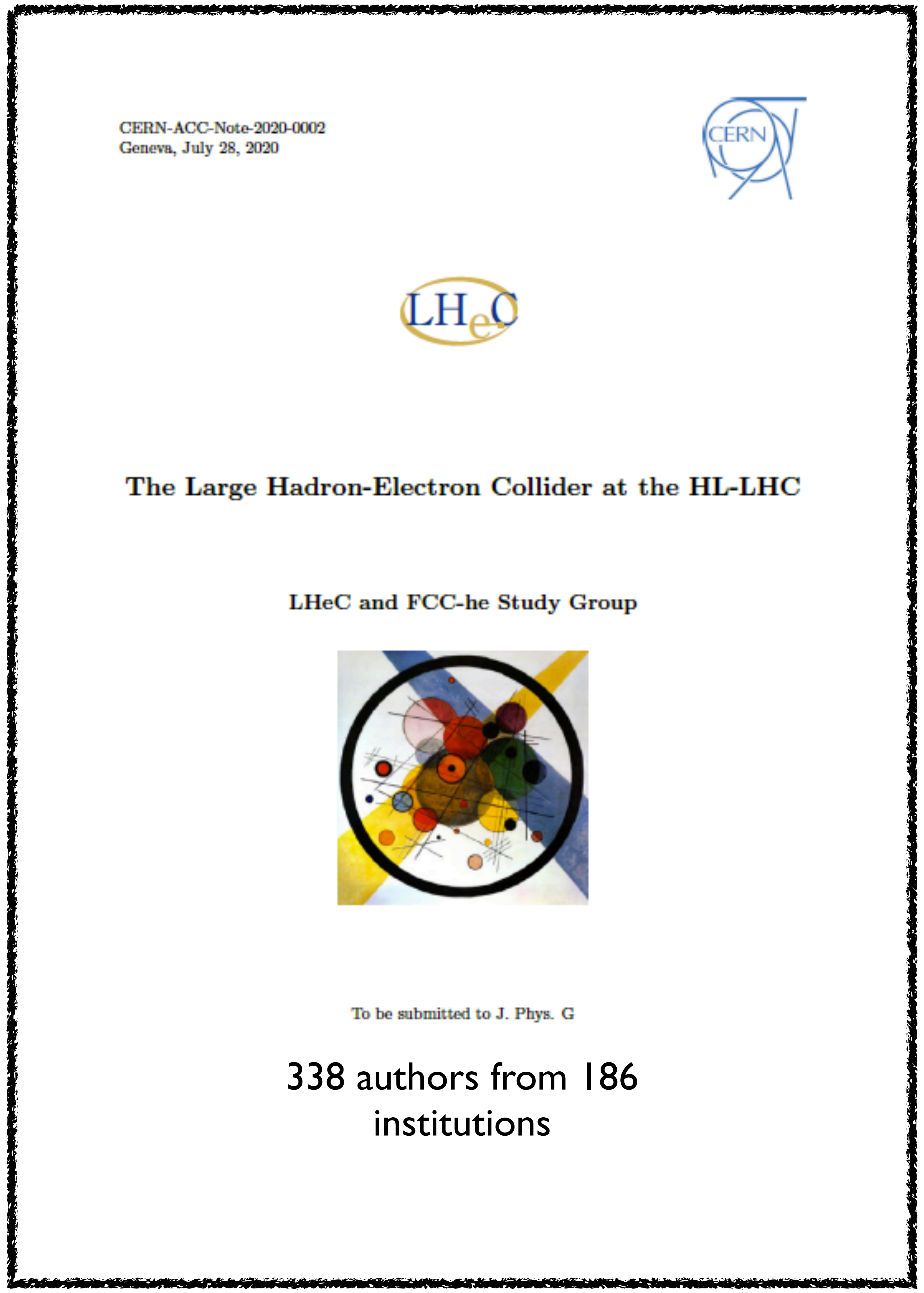




European Commission
European Research Council
galicia Xacobeo 2021
UNIÓN EUROPEA
XUNTA DE GALICIA
FONDO EUROPEO DE DESENVOLVEMENTO REXIONAL “Unha maneira de facer Europa”
EXCELENCIA MARÍA DE MAEZTU
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

# Contents:

1. Introduction.
2. Nuclear PDFs.
3. Further topics:
   ➜ Small x.
   ➜ Diffraction.
4. Summary.


CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

To be submitted to J. Phys. G

338 authors from 186 institutions

References:

- *Future Circular Collider: Vol. 1 Physics opportunities, CERN-ACC-2018-0056, and 1605.01389;*
- *LHeC CDR, 1206.2913; update 2007.14491;*
- *LHeC talks at DIS 2022, https://indico.cern.ch/event/1072533/;*
- *O. Brüning and M. Klein, ECFA Newsletter #5;*
- *Recent IR and detector developments (ep/eA and eh/hh), 2201.02436.*

Other PERLE/LHeC/FCC-he talks at ICHEP:
Parton structure - Claire Gwenlan, Thu 07/07 10.30am
Overview - Bernhard Holzer, Thu 07/07 2.45pm
PERLE - Walid Kaabi, Thu 07/07 3.05pm
Higgs - Uta Klein, Fri 08/07 3.00pm
Top and EW - Daniel Britzger, Fri 08/07 6.30pm
eh/hh IR and detector - poster, Fri 08/07 7.05pm
BSM - Oliver Fischer, Sat 09/07 5.30pm

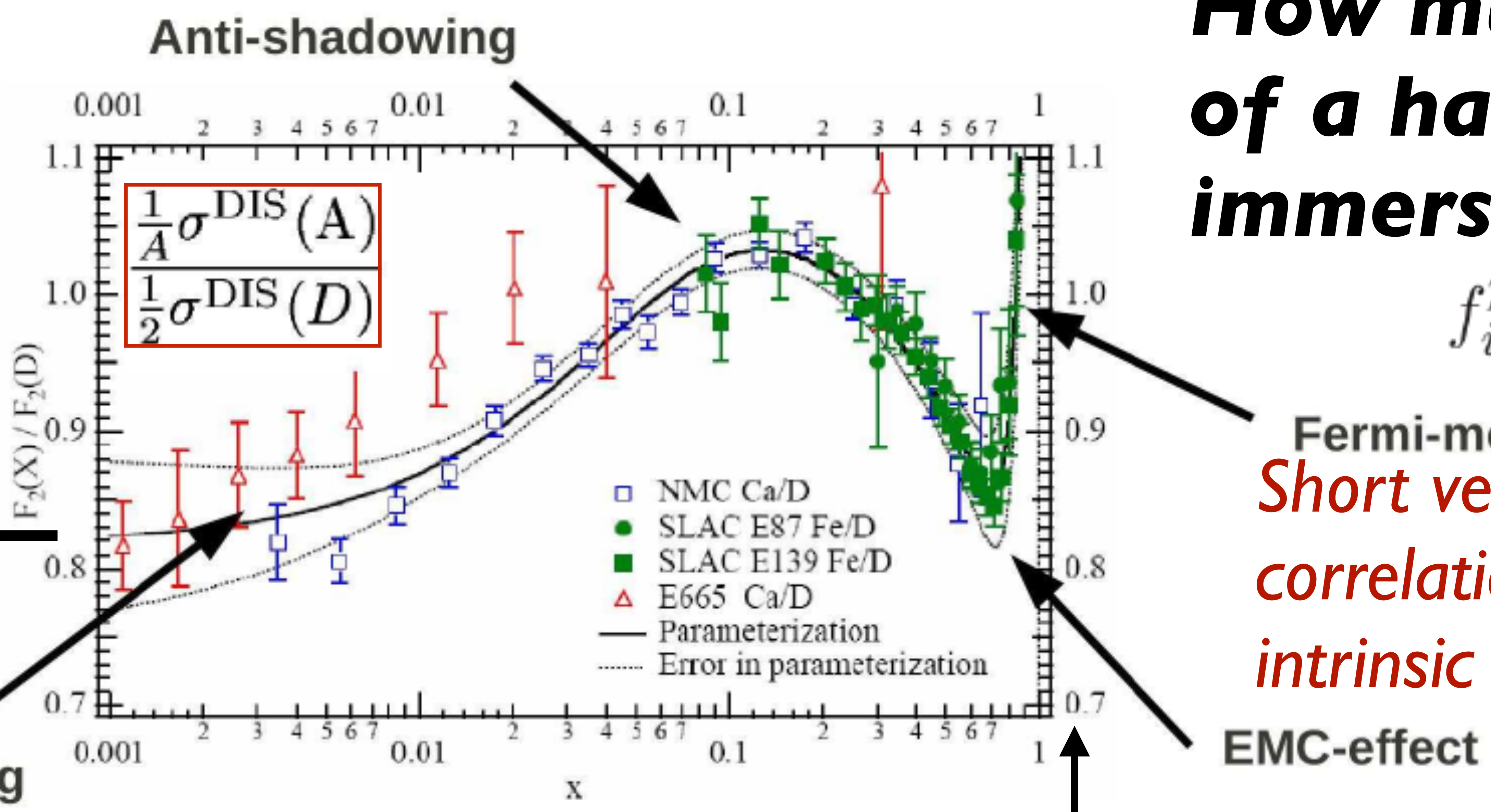
# Motivation:

*Flavour dependence?; relation with shadowing and coherence*

ePb at LHeC/ FCC-he

eAu at EIC

*Multiple scattering, saturation,…; high-energy QCD*




***How much does the structure of a hadron change when it is immersed in a nuclear medium?***

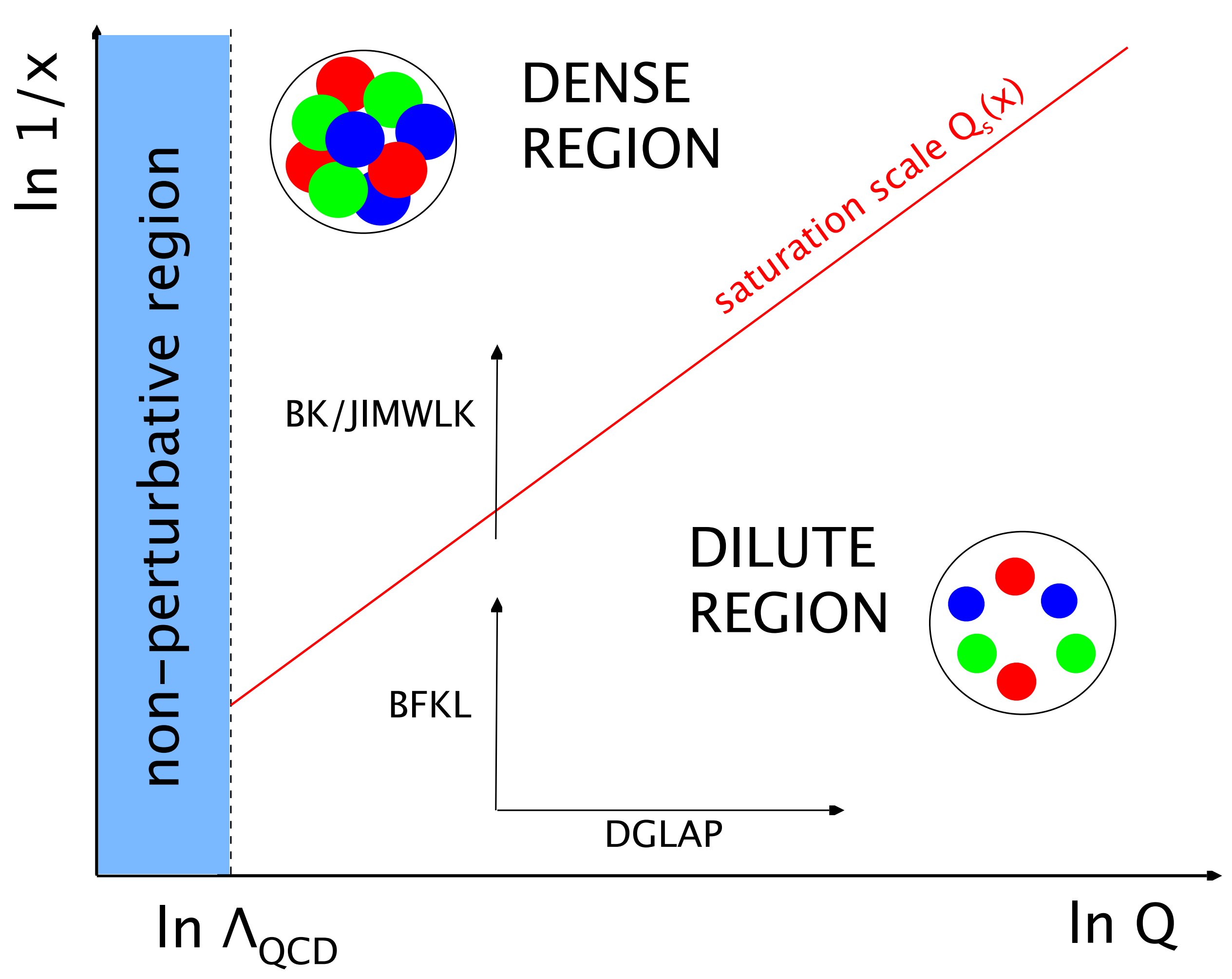
$$f_i^{p,A}(x,Q^2) = \boxed{R_i^A(x,Q^2)} f_i^p(x,Q^2)$$

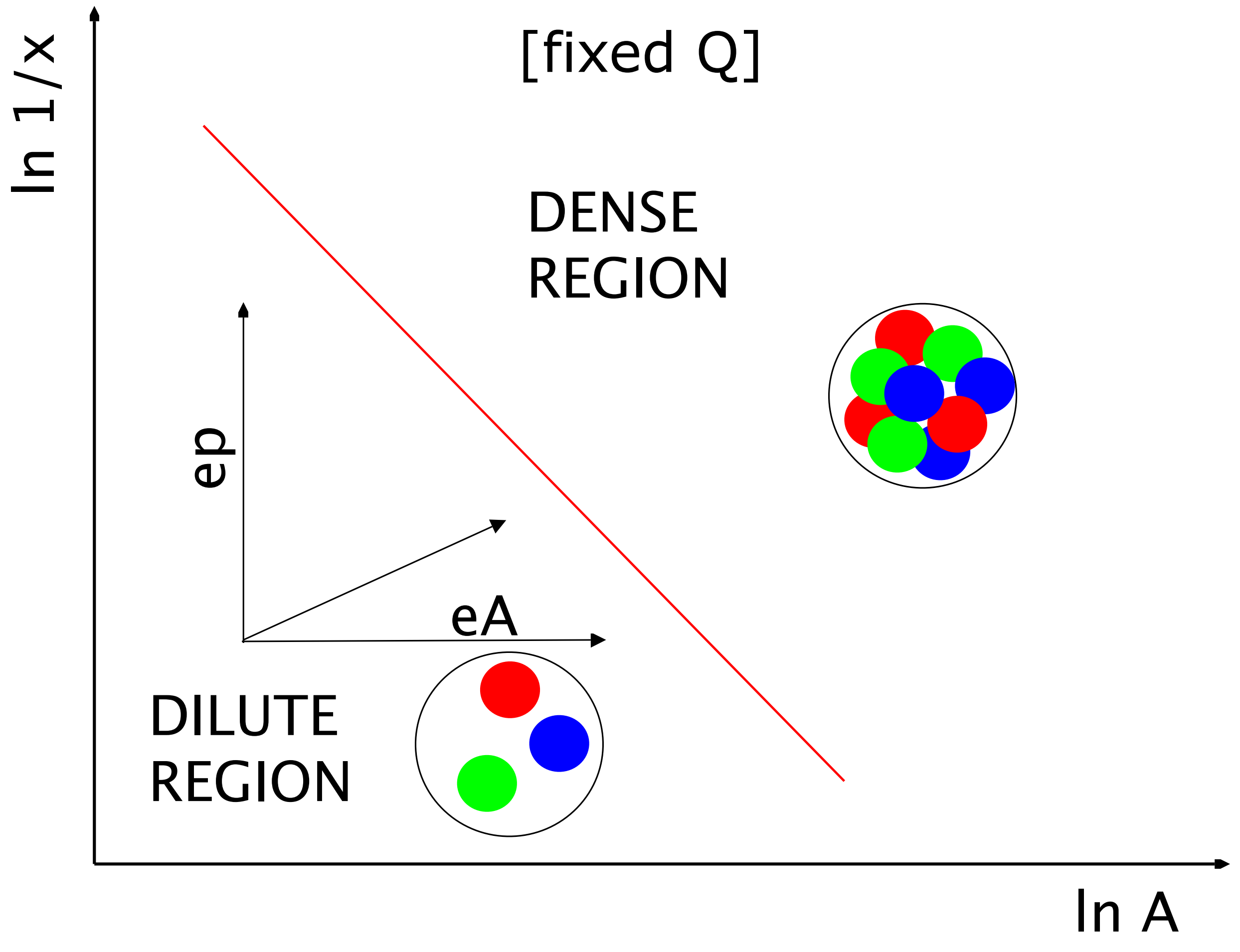
*Short versus long range correlations, pion cloud, intrinsic charm,…*

Superfast quarks

$$\boxed{\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}}$$

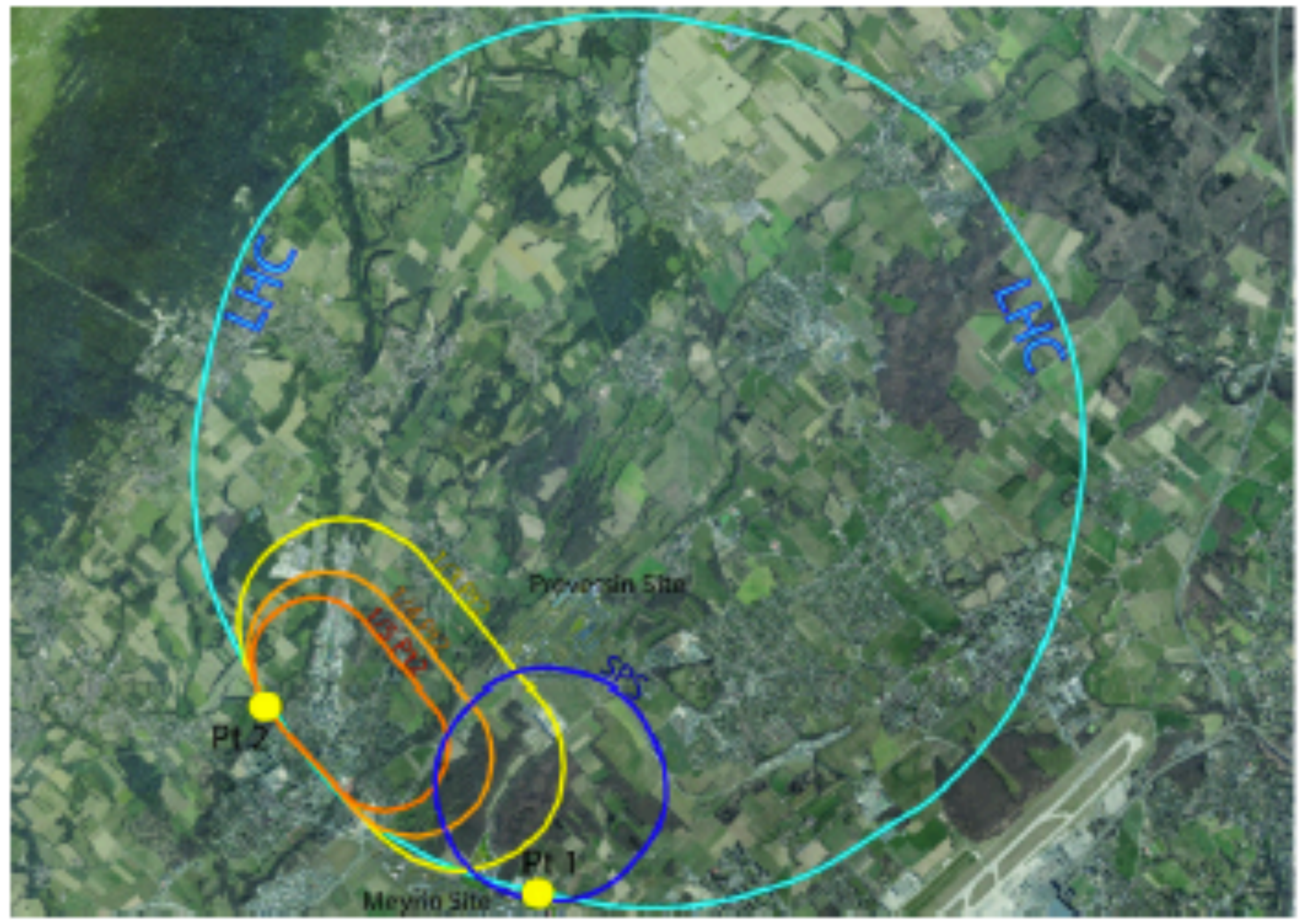
***Where is the novel non-linear regime of QCD that leads to the saturation of parton densities?***



# Accelerators:

M Klein, O Bruening on LoIs for future ep:
Snowmass Meeting on TeV Colliders
8 July 2020, for the LHeC+PERLE+FCCeh




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 $10^{34}$ $cm^{-2}s^{-1}$, for Higgs, BSM

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

CERN-ACC-Note-2020-0002 →arXiv (July)

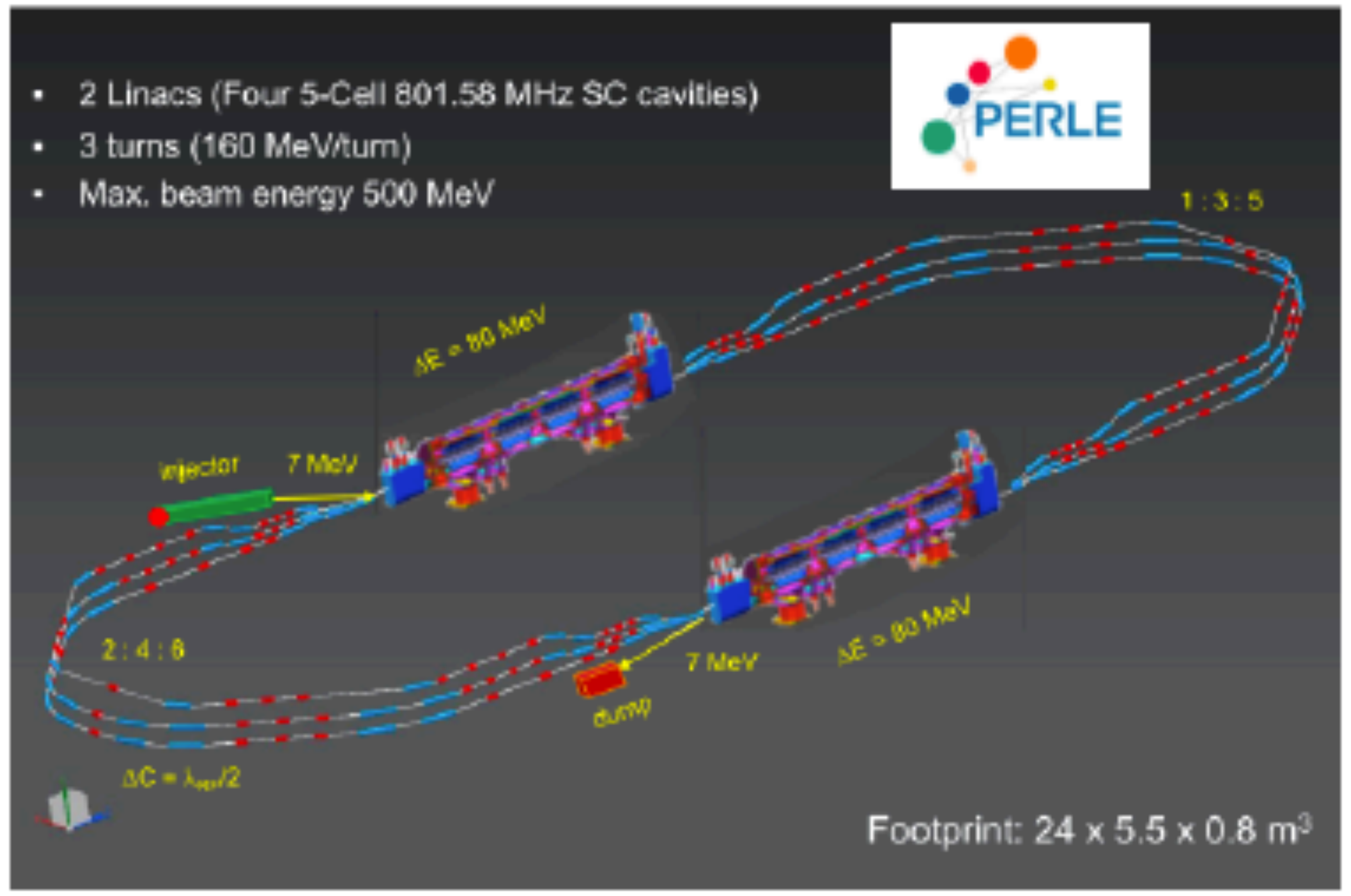
## LHeC, PERLE and FCC-eh

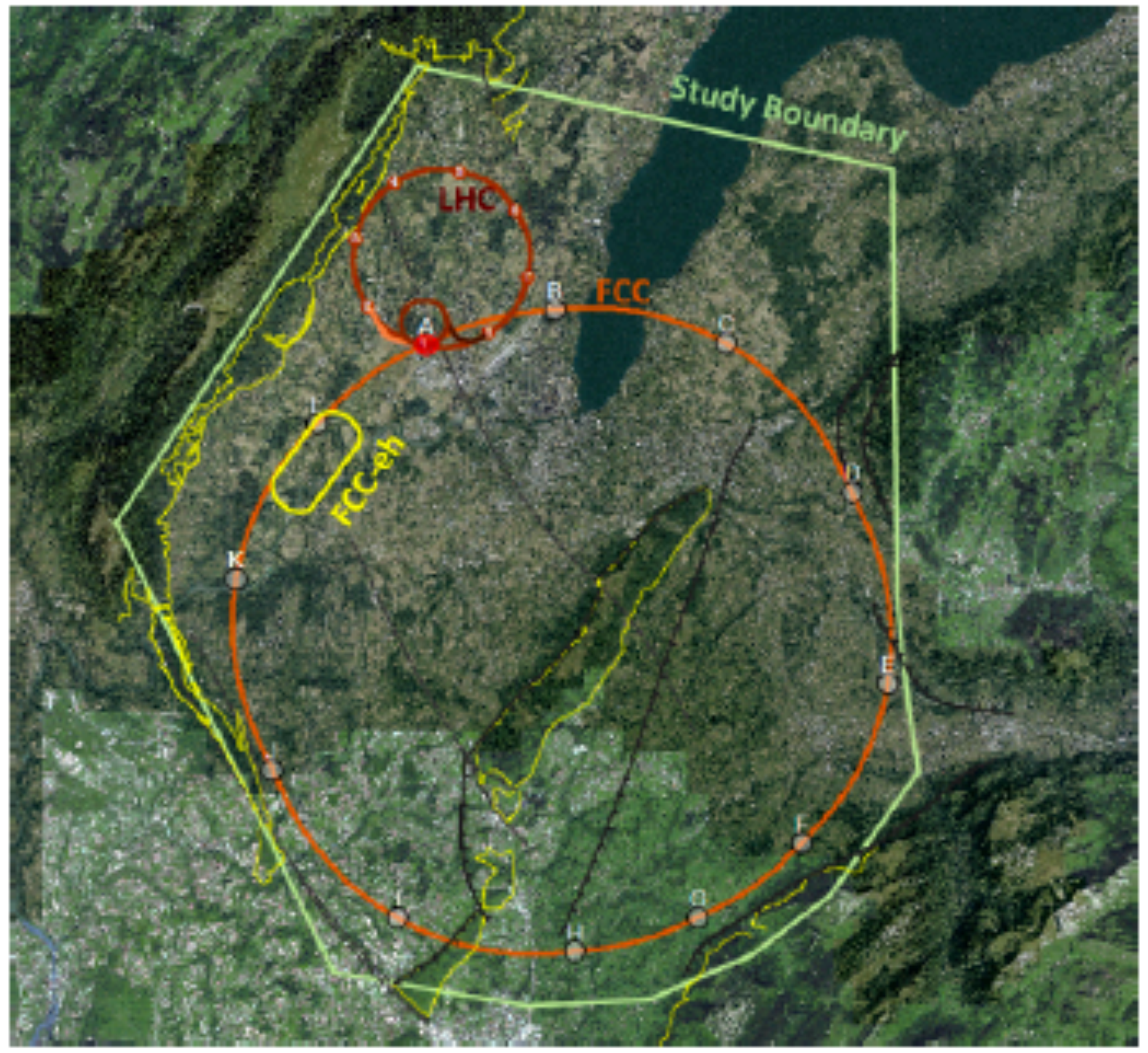
Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESSP)

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

LHeC ERL Parameters and Configuration
$I_e$=20mA, 802 MHz SRF, 3 turns →
$E_e$=500 MeV → 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+

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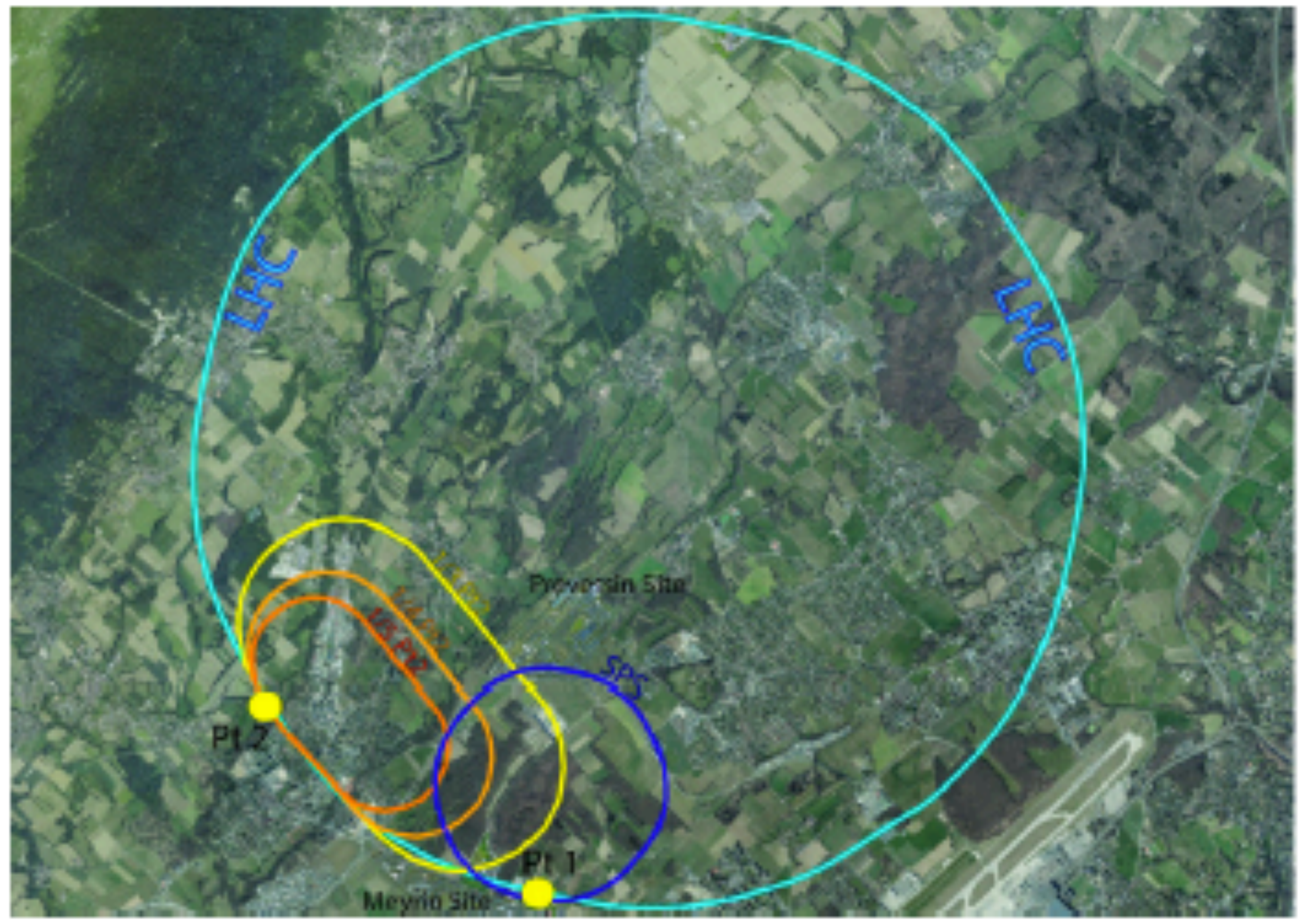


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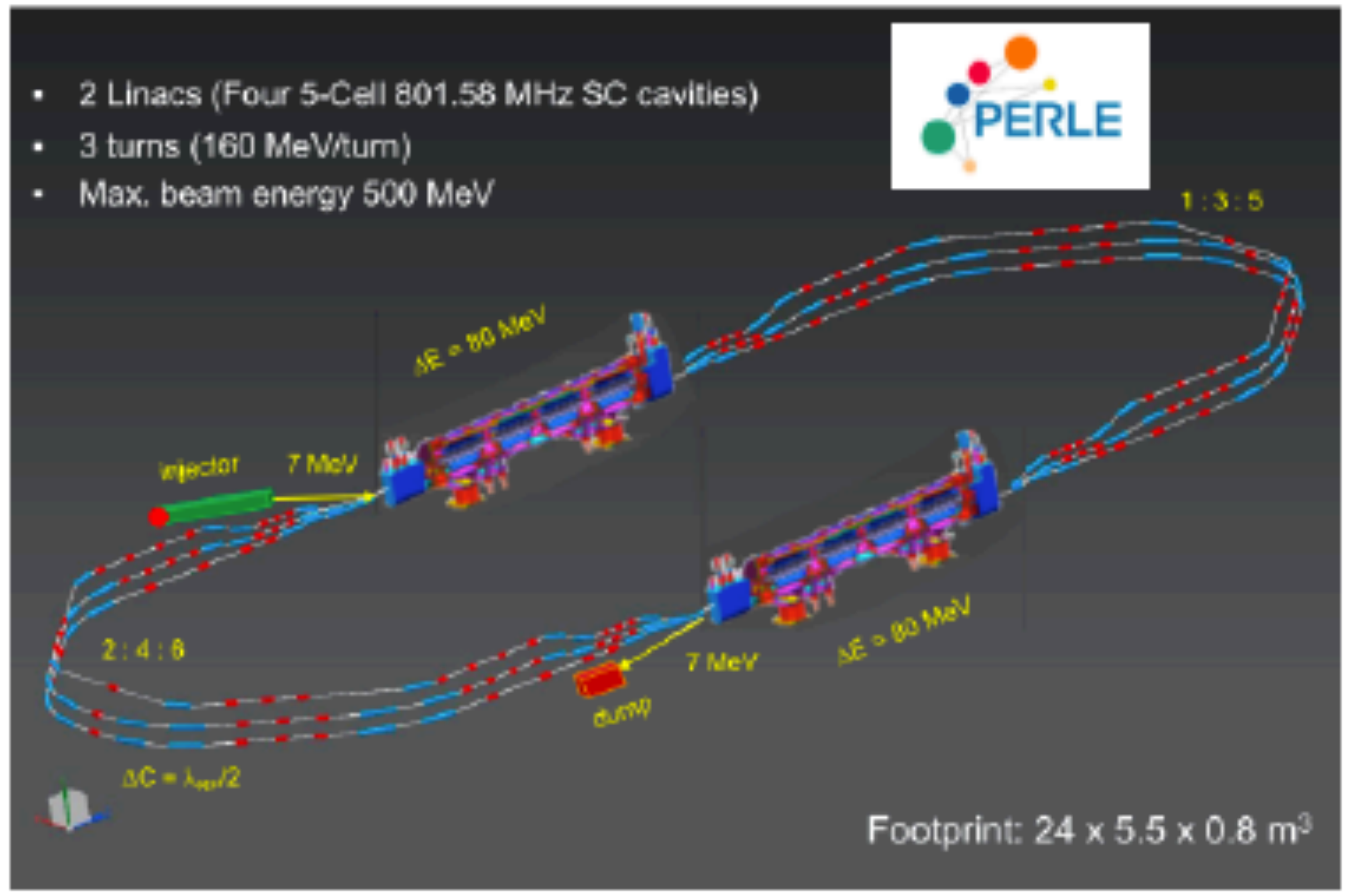


| parameter [unit] | LHeC (HL-LHC) | eA at HE-LHC | FCC-he |
|---|---|---|---|
| $E_{Pb}$ [PeV] | 0.574 | 1.03 | 4.1 |
| $E_e$ [GeV] | 60 | 60 | 60 |
| $\sqrt{s_{eN}}$ electron-nucleon [TeV] | 0.8 | 1.1 | 2.2 |
| Bunch spacing [ns] | 50 | 50 | 100 |
| No. of bunches | 1200 | 1200 | 2072 |
| Ions per bunch [$10^8$] | 1.8 | 1.8 | 1.8 |
| $\gamma\epsilon_A$ [$\mu$m] | 1.5 | 1.0 | 0.9 |
| Electrons per bunch [$10^9$] | 4.67 | 6.2 | 12.5 |
| Electron current [mA] | 15 | 20 | 20 |
| IP beta function $\beta_A^*$ [cm] | 7 | 10 | 15 |
| Hourglass factor $H_{geom}$ | 0.9 | 0.9 | 0.9 |
| Pinch factor $H_{b-b}$ | 1.3 | 1.3 | 1.3 |
| Bunch filling $H_{coll}$ | 0.8 | 0.8 | 0.8 |
| Luminosity [$10^{32}$ $cm^{-2}s^{-1}$] | 7 | 18 | 54 |

**ePb**

60 x 50000 GeV²: 3.5 TeV ep collider

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Concurrent Operation with FCC-hh

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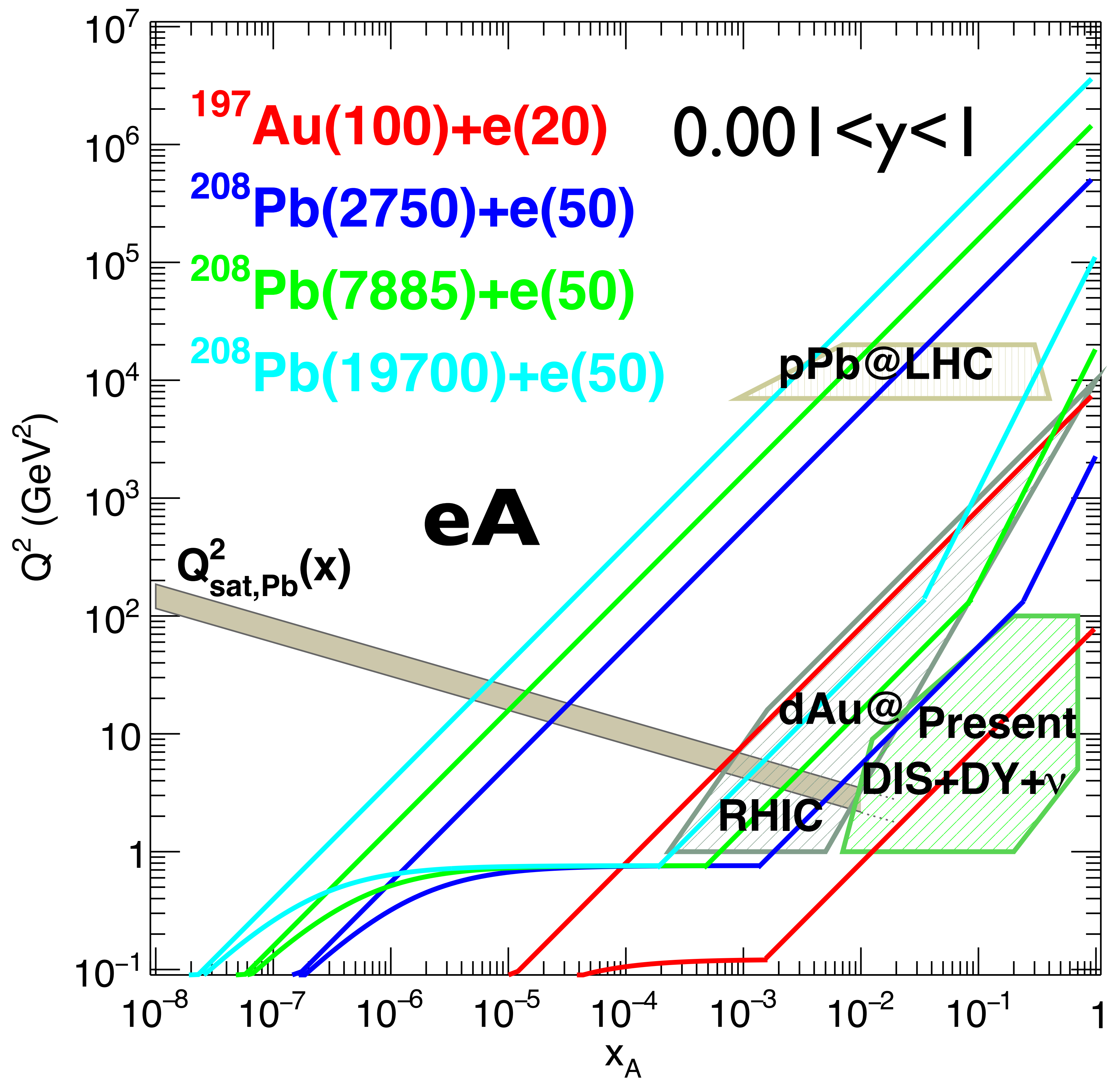
*Eur.Phys.J.ST* 228 (2019) 4, 755 FCC-hh/eh

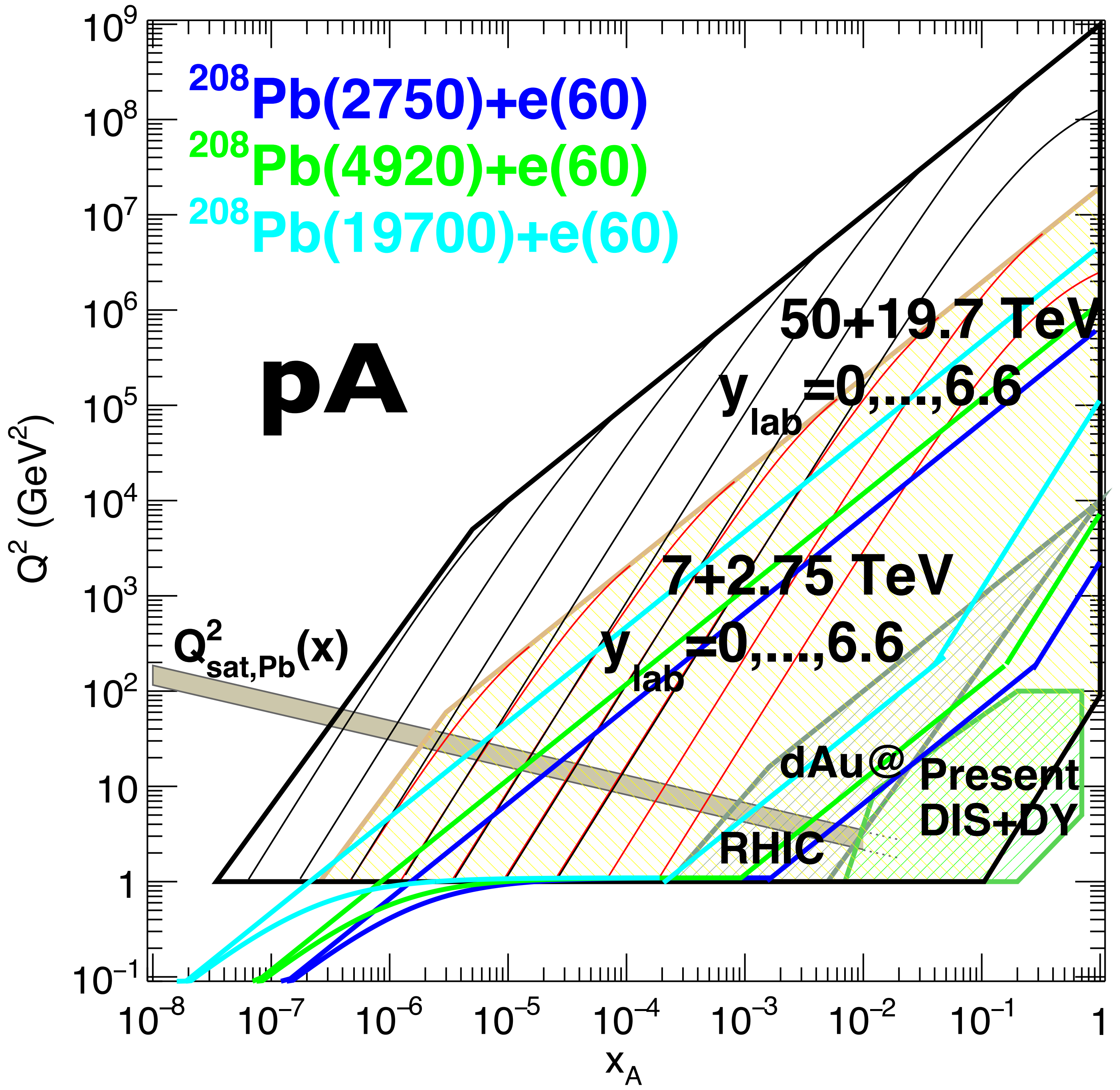
Future CERN Colliders: 1810.13022 Bordry+

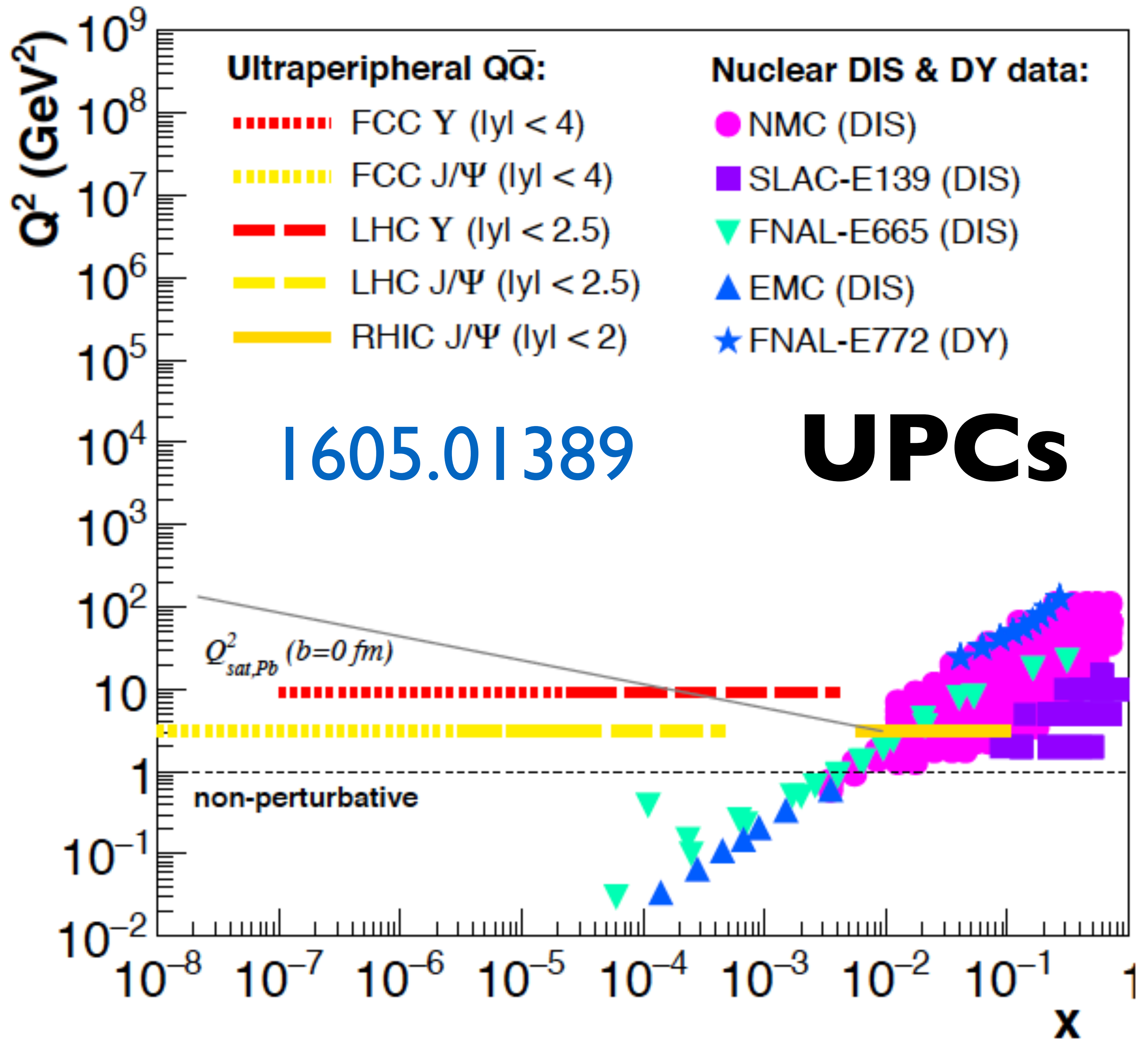
# Kinematics:

- DIS offers:
  - ➜ A clean experimental environment: low multiplicity, no pileup, fully constrained kinematics;
  - ➜ A more controlled theoretical setup: many first-principles calculations in collinear and non-collinear frameworks.




- Extension up to 4-5 orders of magnitude in x and $Q^2$ wrt. existing DIS data; 2-3 wrt. EIC.

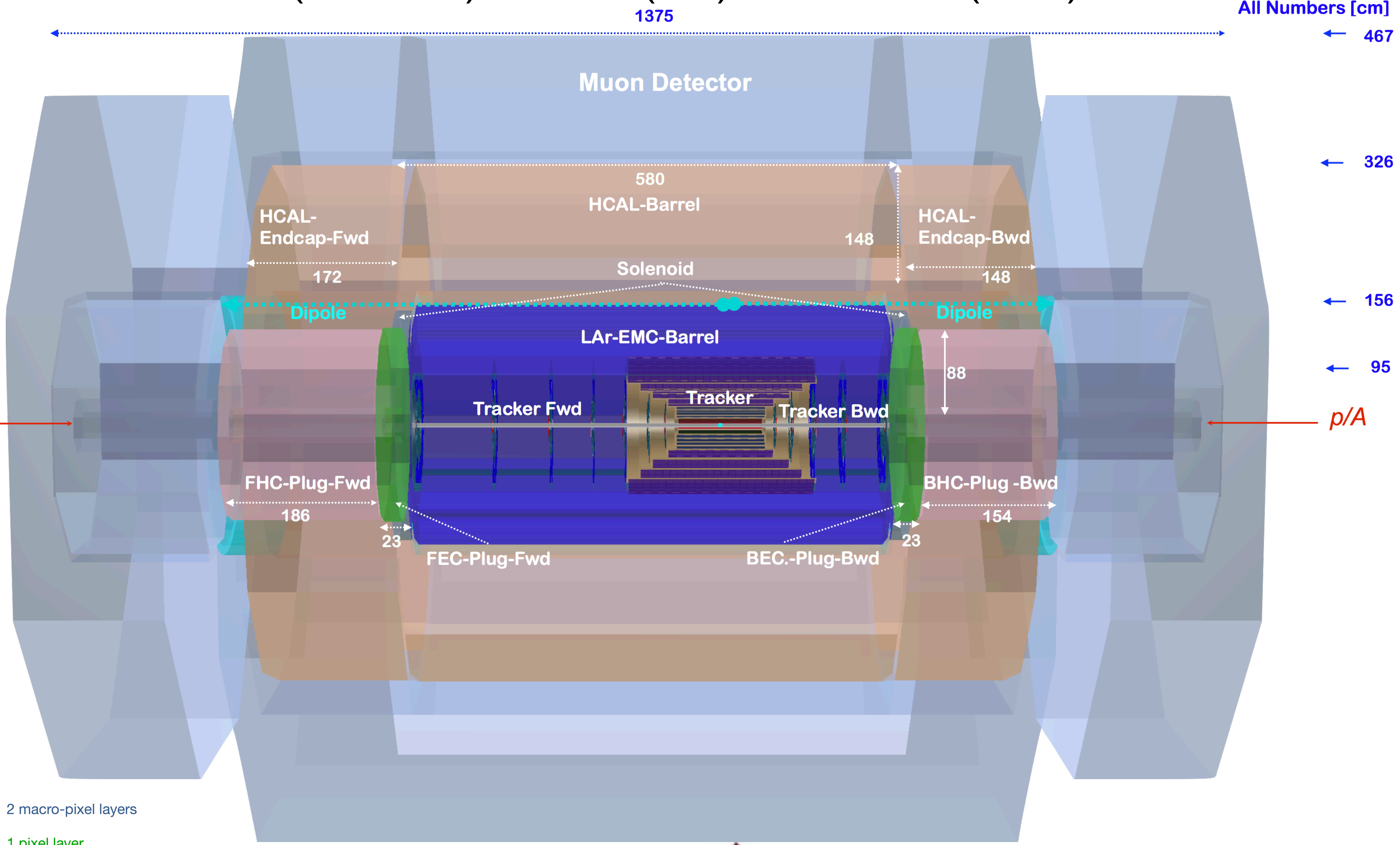


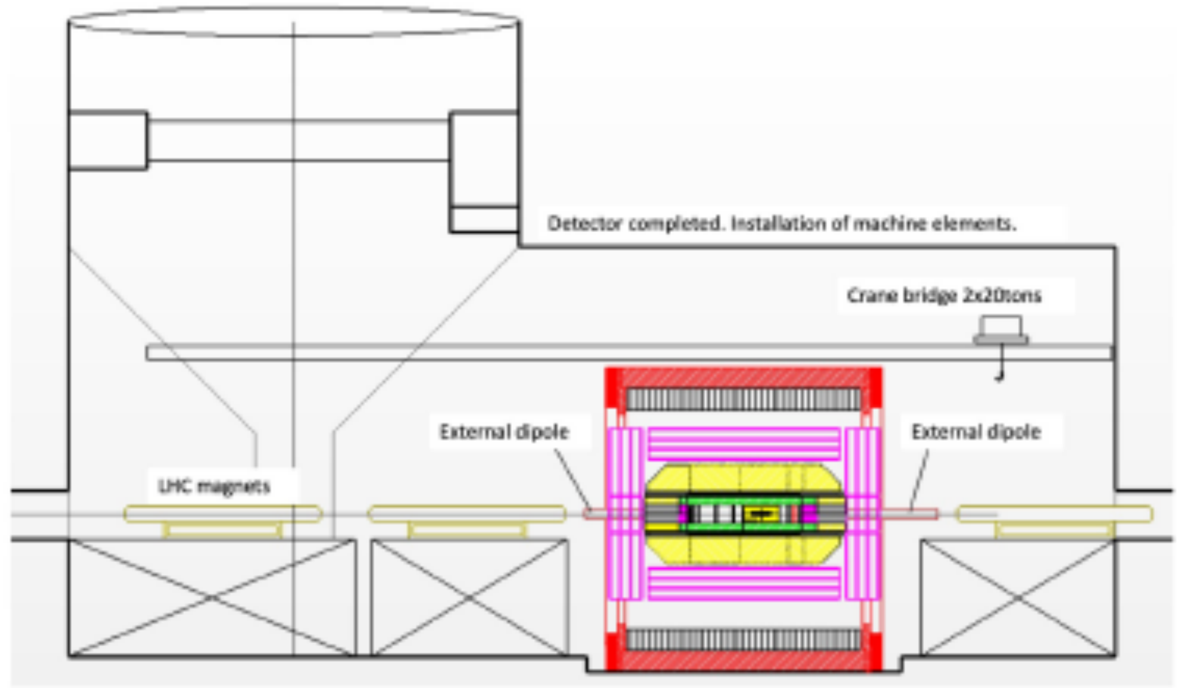



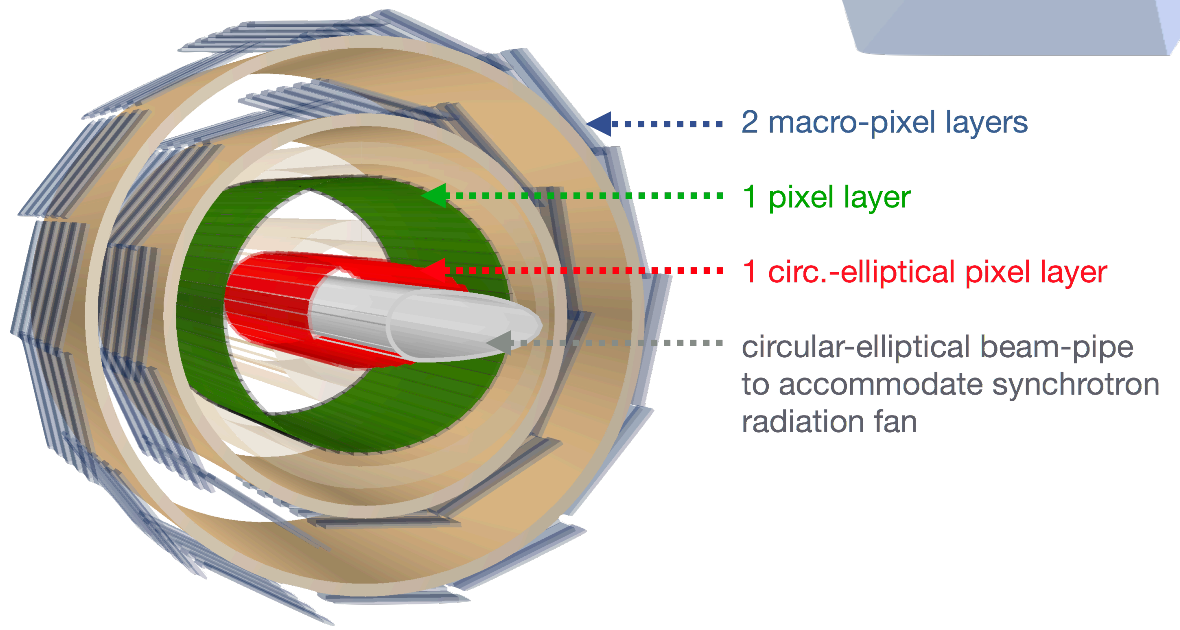
# Detector: ep/eA version

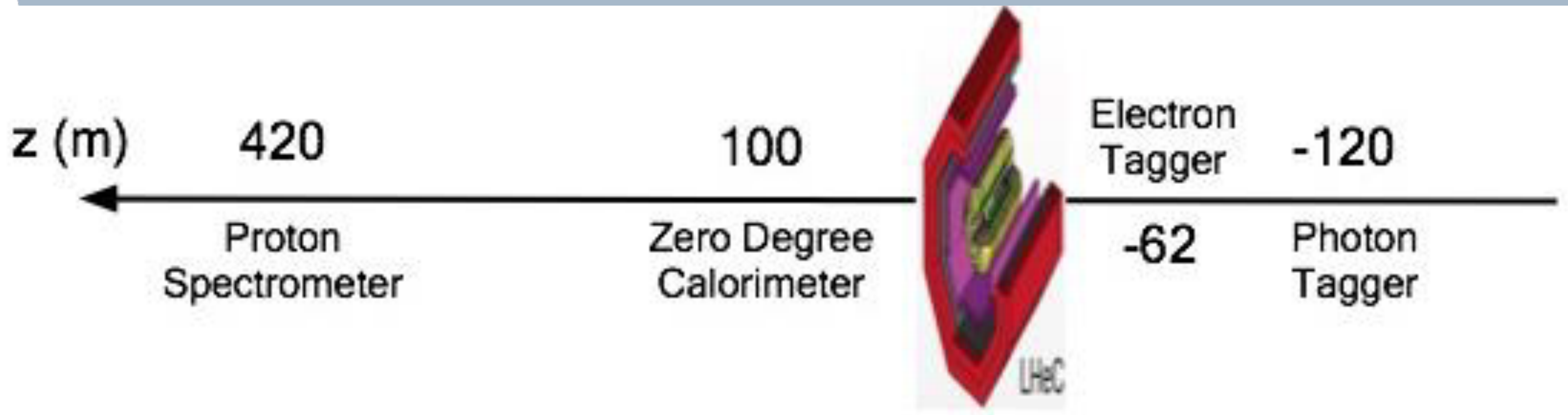
- 1 degree acceptance (|η|<4.7) required for small x and H.
- Central detector: increased tracker radius wrt CDR, radiation level 1/1000 wrt LHC → ideal for CMOS etc.
- Forward/backward detectors: e-, γ-taggers, ZDC, p-spectrometer (FP420).
- Installation in IP2, keeping L3 magnet, feasible in two years.
- FCC: larger tracking, two solenoids?

LHeC (FCC-he): R=4.6 (6.2) m, L=13.6 (19.3) m



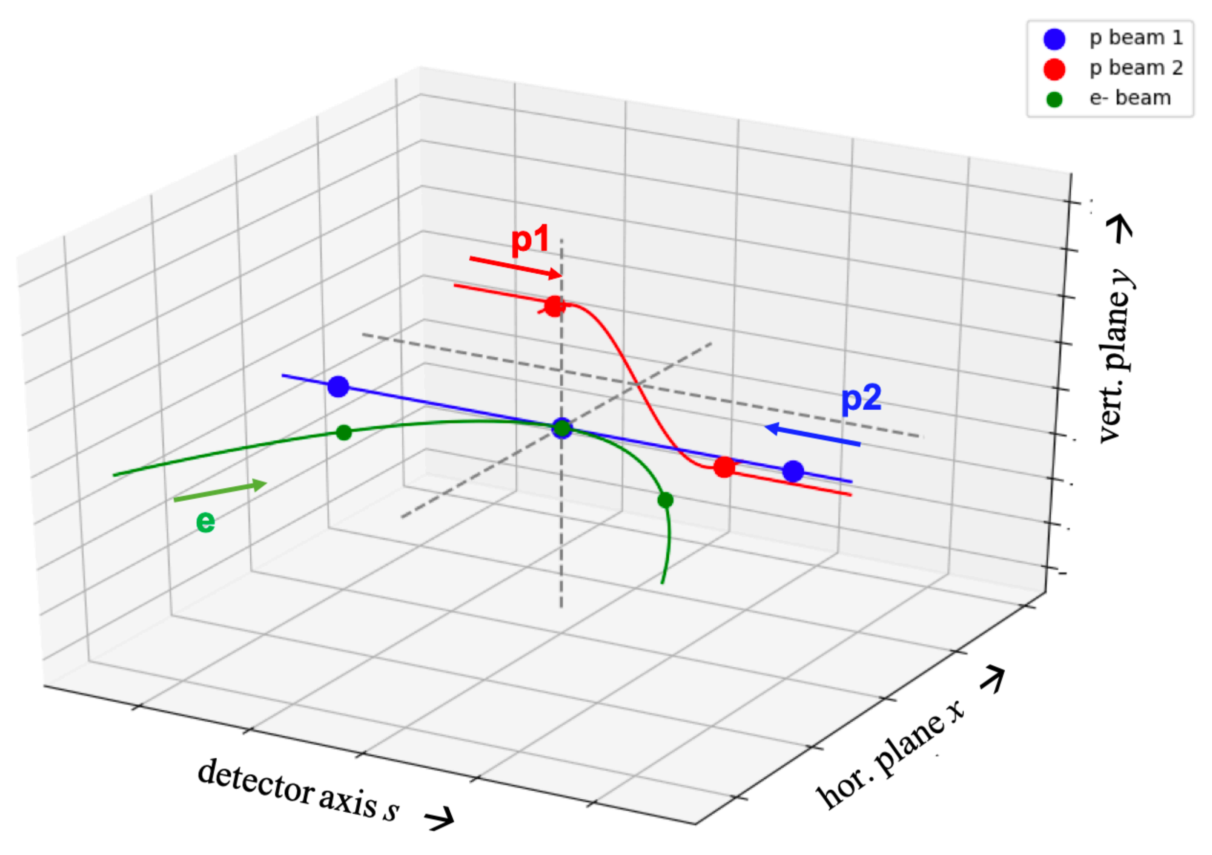



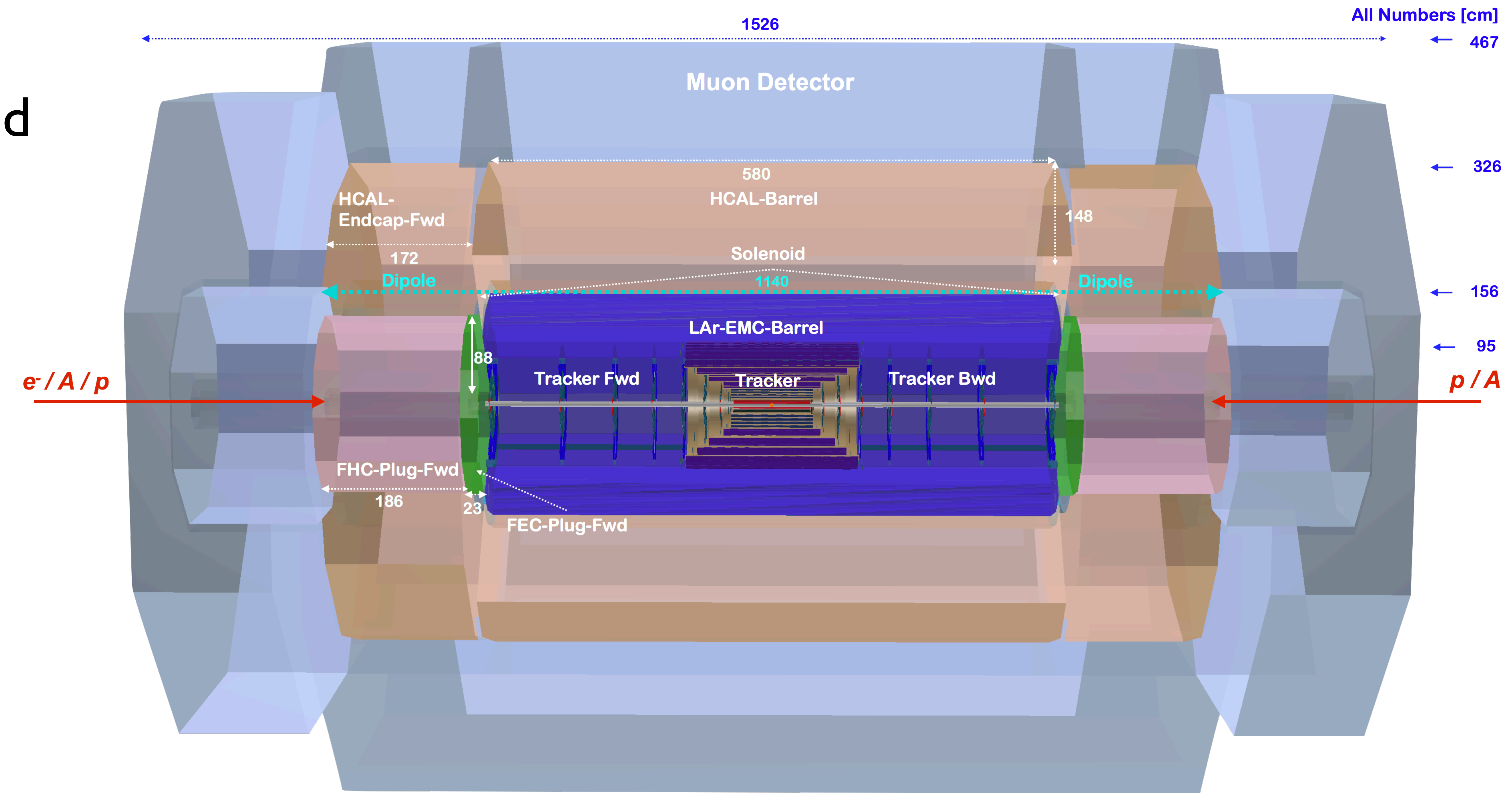
# Detector: eh/hh version

- Accelerator considerations to combine the ALICE3 and LHeC experiments at IP2 of HL-LHC.

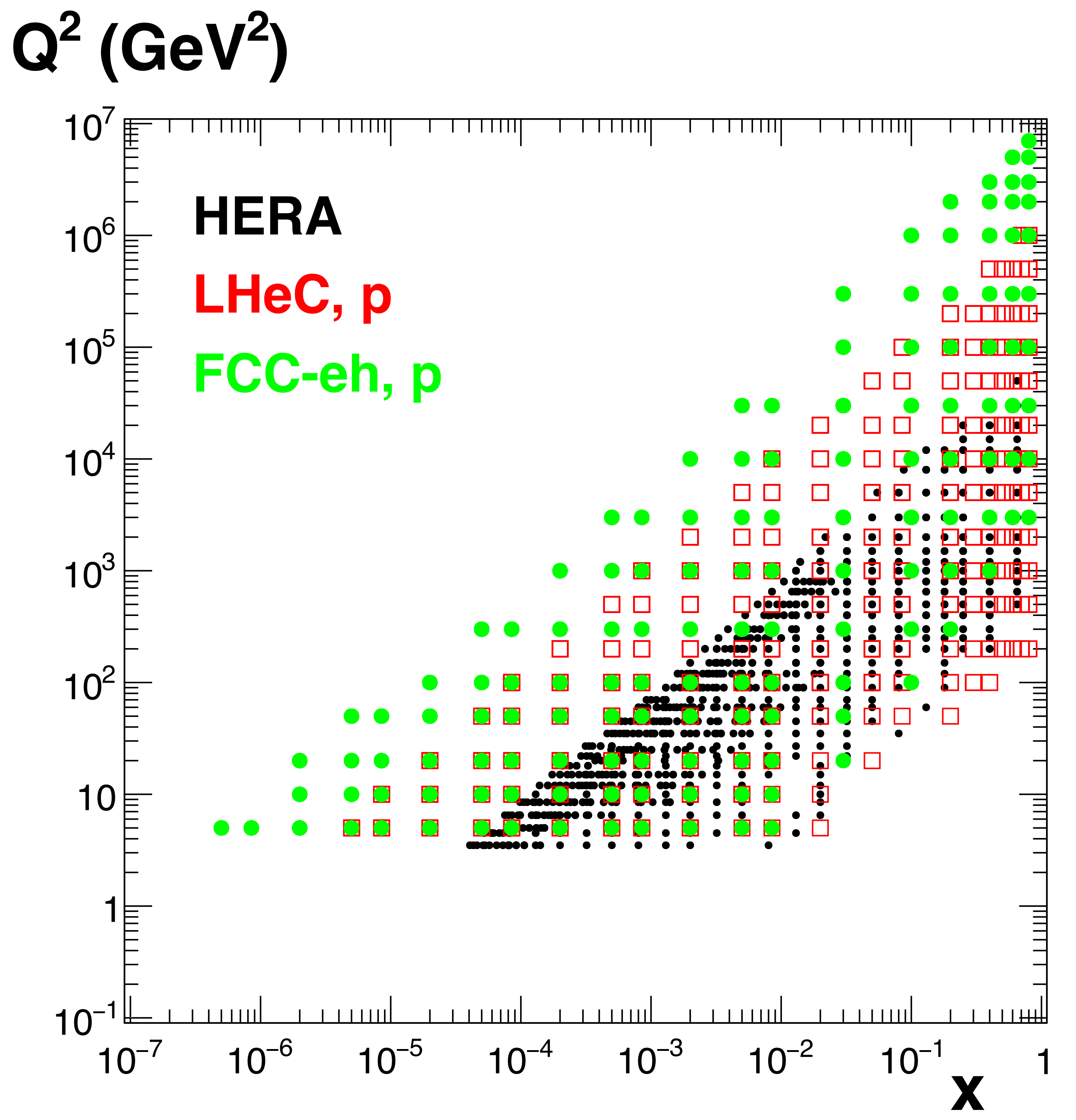
- Two modes of operation:

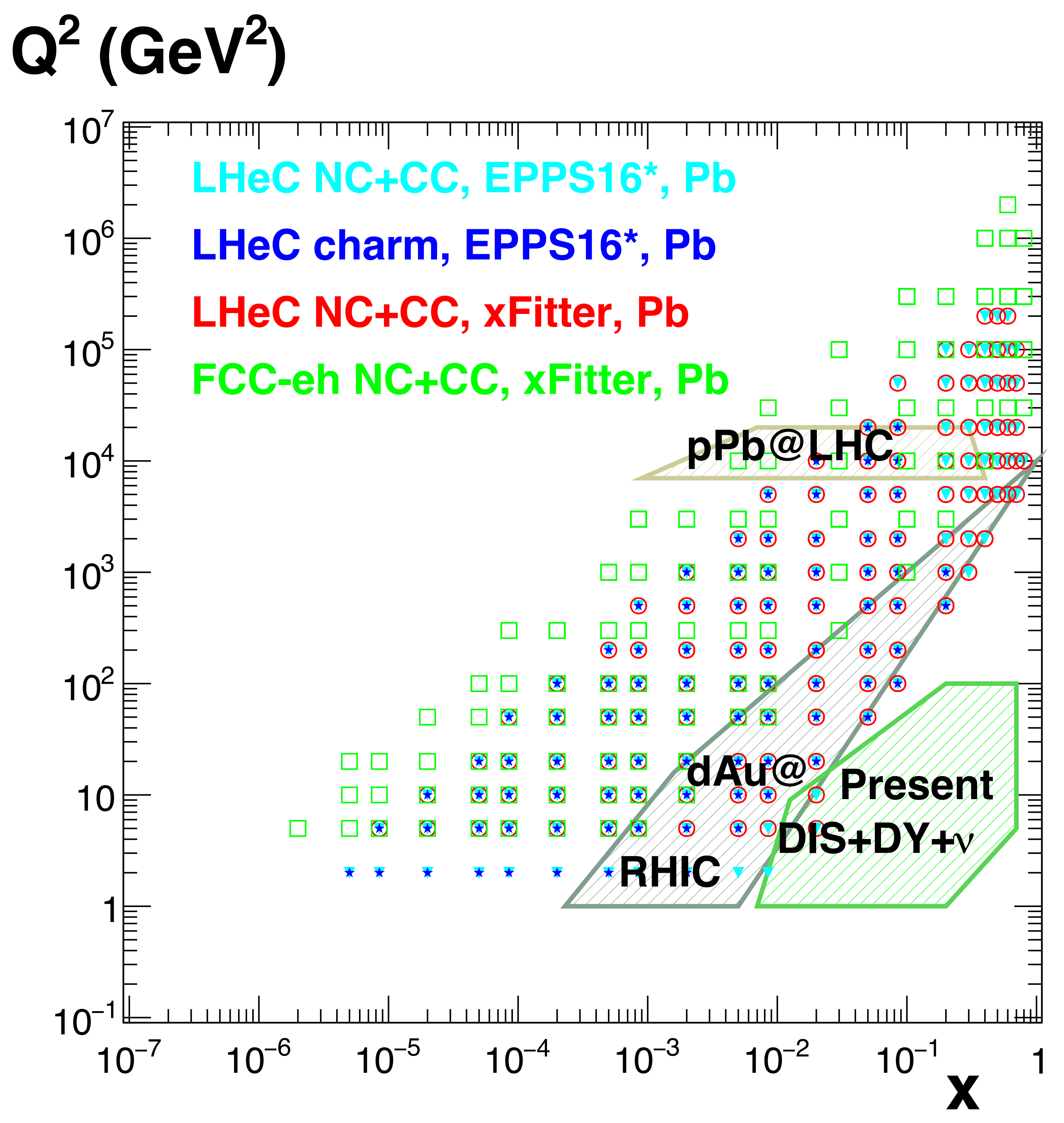
  ➜ hh collisions in IP 1, 2, 5 and 8, no e-beam.
  ➜ eh collisions in IP 2 and hh collisions in IP 1, 5 and 8.

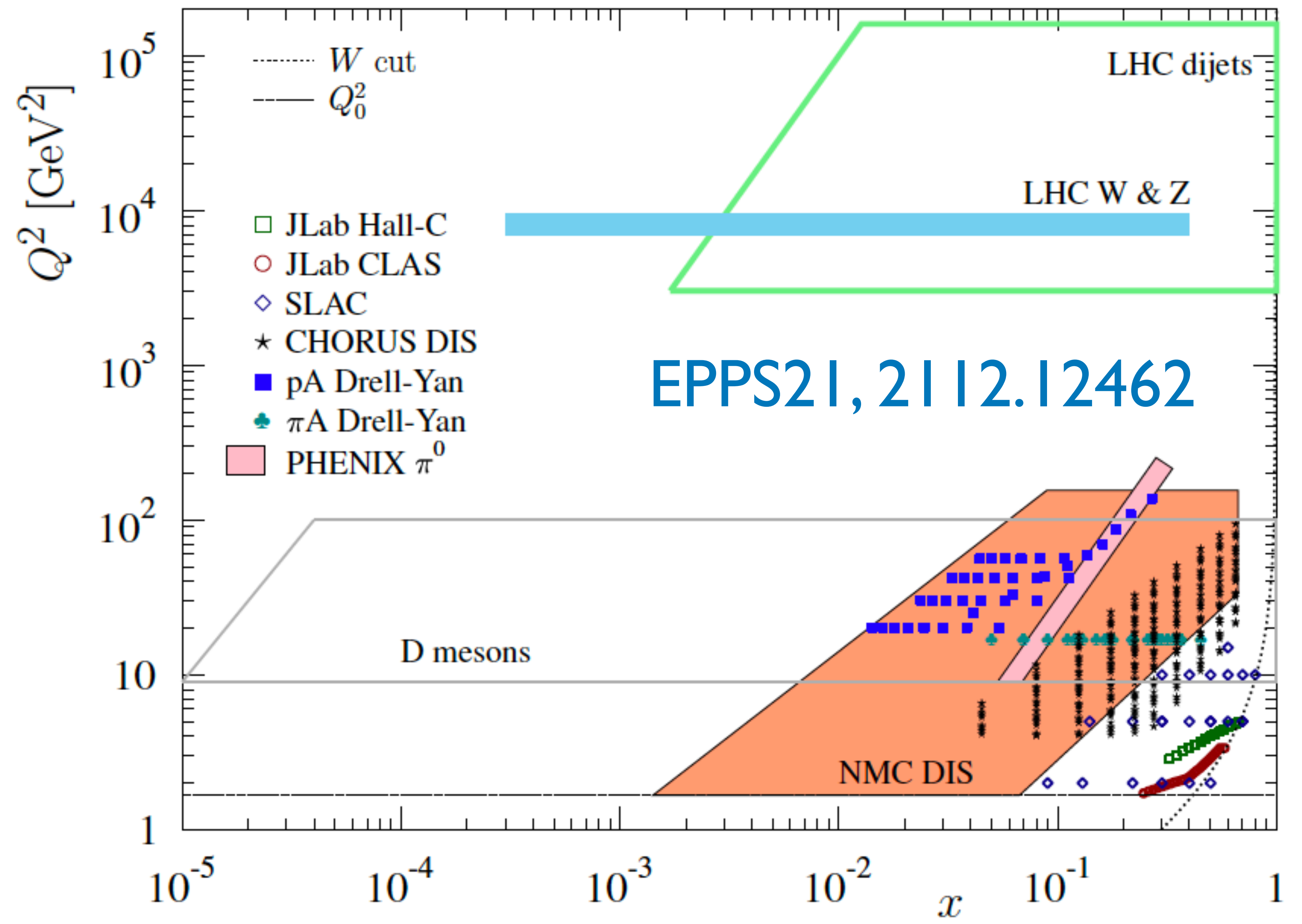


# Pseudodata:




- Pseudodata generated using a code (Max Klein) validated with the H1 MC.
- Cuts: $|\eta_{max}|=5$, 0.95< y< 0.001.
- Error assumptions ~ factor 2 better than at HERA (luminosity uncertainty kept aside).
- Stat./syst. errors (ePb@FCC-he) from 0.1/1.2% (small x, NC) to 37/6% (large x & $Q^2$, CC).

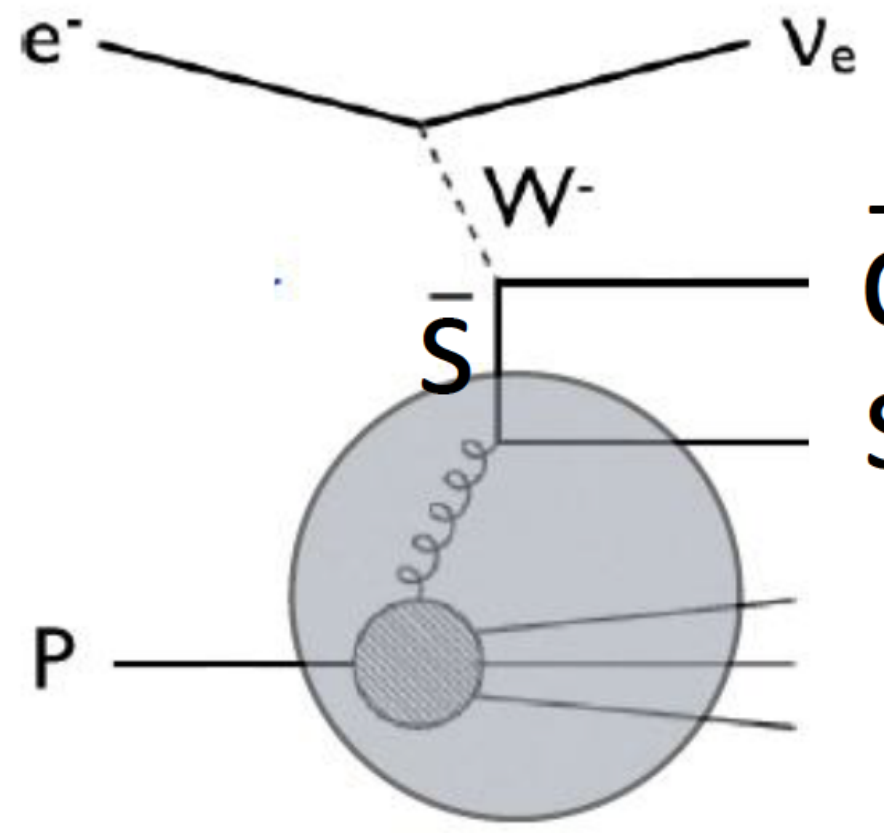
| Source of uncertainty | Error on the source or cross section |
|---|---|
| scattered electron energy scale | 0.1 % |
| scattered electron polar angle | 0.1 mrad |
| hadronic energy scale | 0.5 % |
| calorimeter noise ($y < 0.01$) | 1-3 % |
| radiative corrections | 1-2 % |
| photoproduction background | 1 % |
| global efficiency error | 0.7 % |

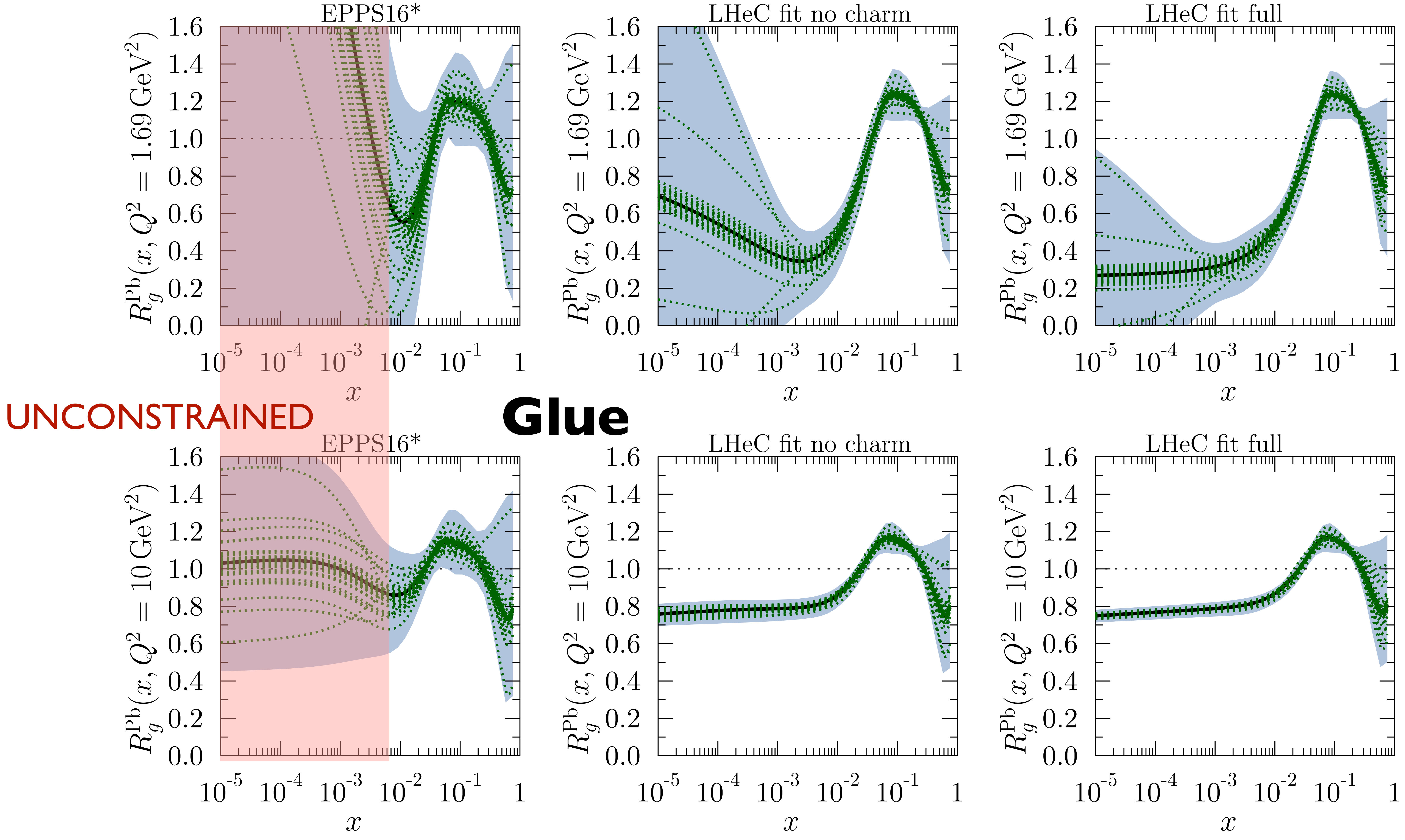
# EPPS16*: results



- Large effect of NC+CC LHeC pseudodata, and of charm on the glue at small x.
- Limitation on u/d decomposition inherent to almost isospin symmetric nuclei (u/d difference suppressed by 2Z/A-1).

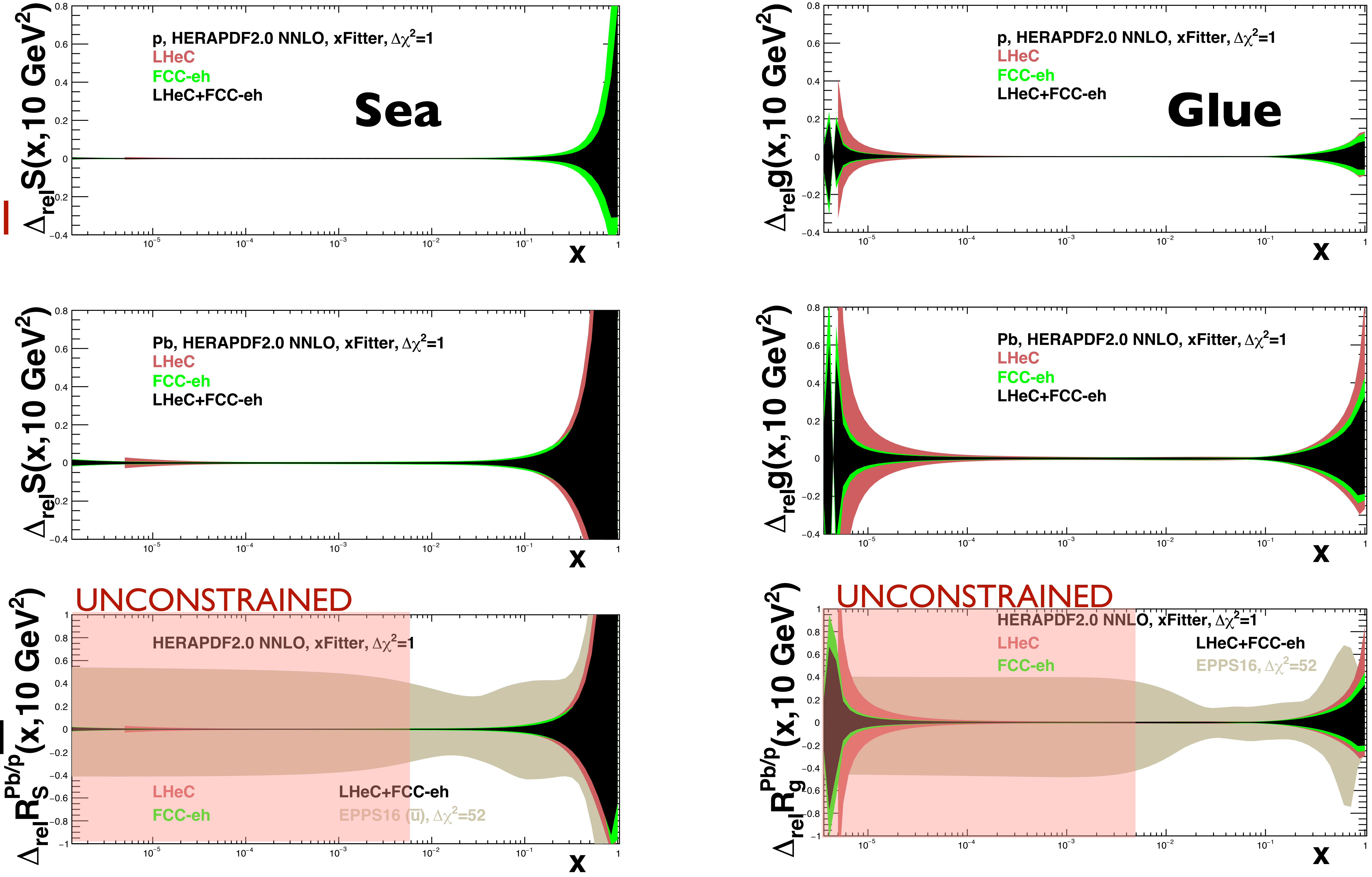
  - Possible further improvements: beauty, c-tagged CC for strange.



# Single nucleus fit: results

- Pb-only PDFs by fitting NC+CC, using xFitter (1410.4412) to estimate uncertainties coming solely from achievable experimental precision.
- Large improvements at all x (glue), but note the different tolerances.
- Fit to a single nucleus possible: no A parametrizations.
- Further: c, b, c-tagged CC for s, more flexible functional forms at small x?
- Test of factorisation in pA.

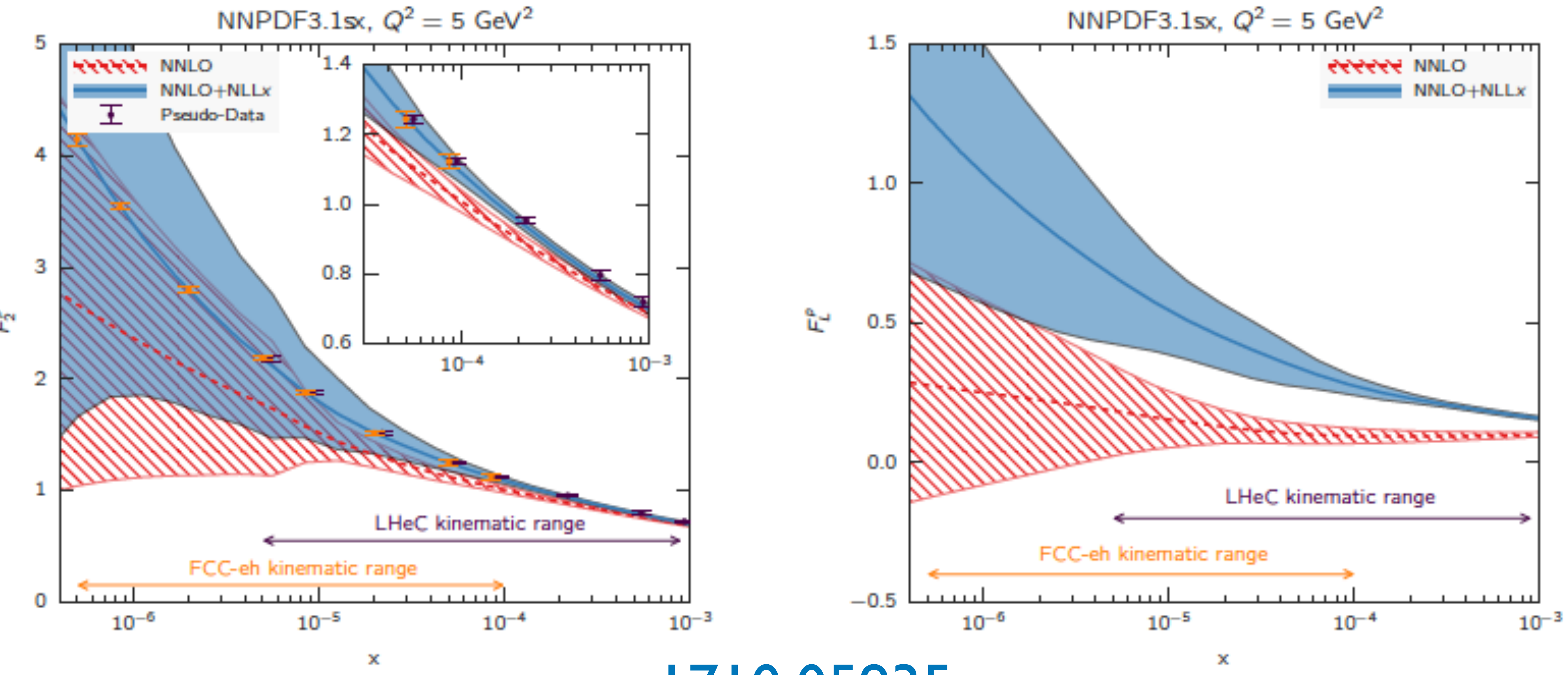


# Saturation: inclusive observables

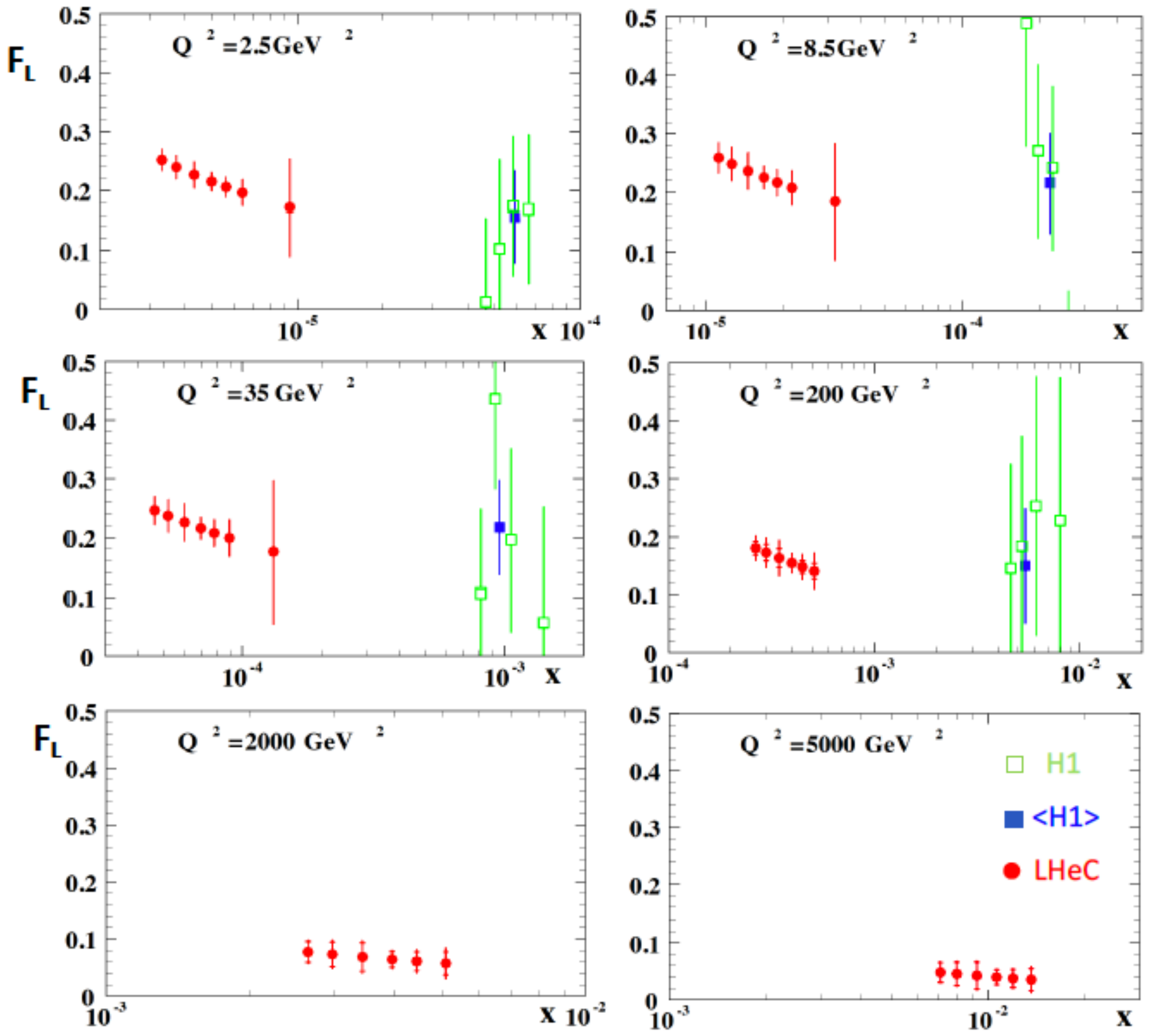
- Searching for this new dynamics requires:

➜ Kinematic reach - lever arm in $Q^2$ at small x to look for the tension between observables ($F_2$, $F_L$, $F_2^{HQ}$): new studies confirm that linear evolution cannot accommodate saturation even at NNLO or NNLO+NLLx. Note that precision at high $Q^2$ helps!

➜ **Varying nuclear size to definitively disentangle resummation from non-linear dynamics** (see 1702.00839 for the need of lever arm!).

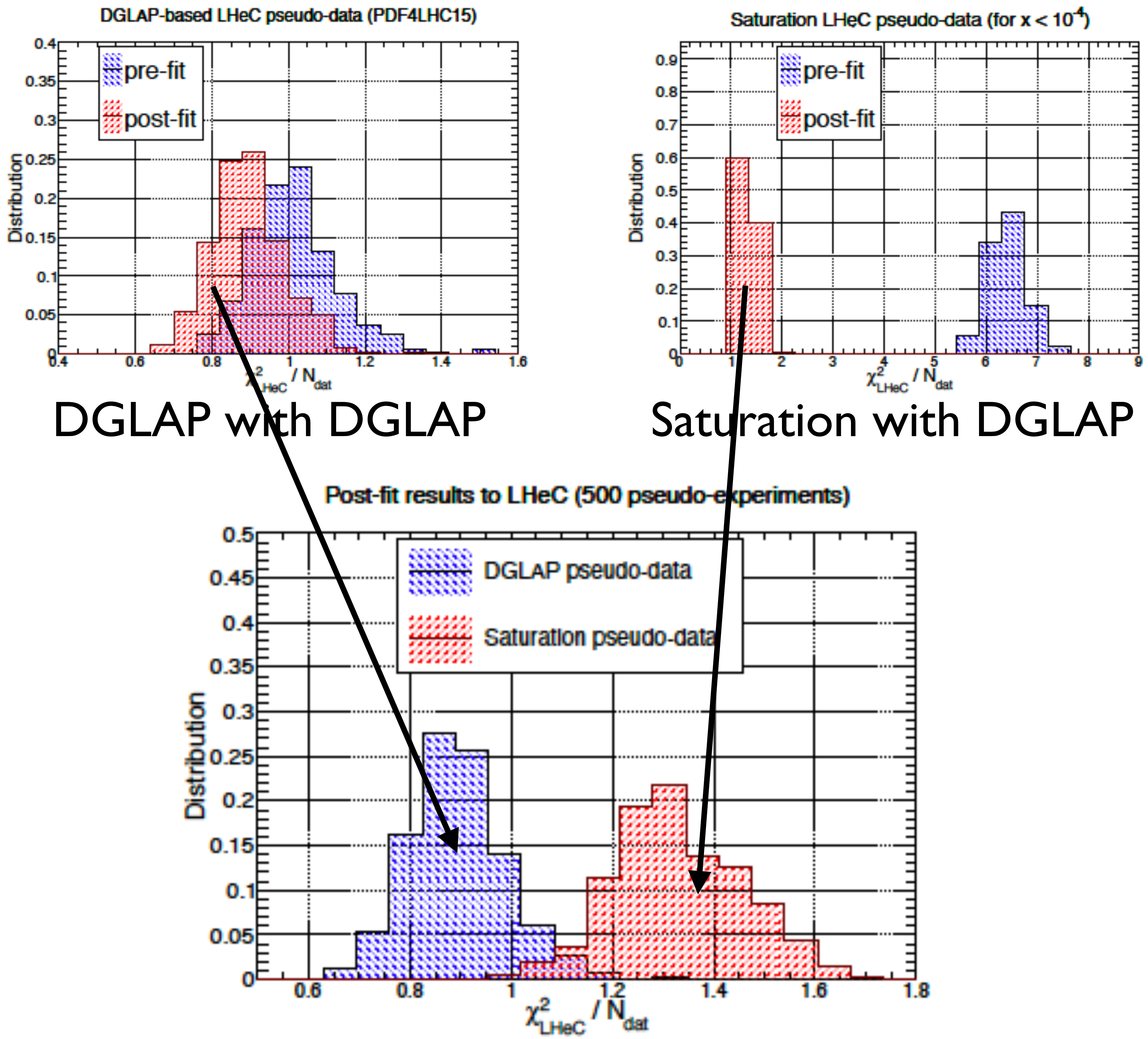


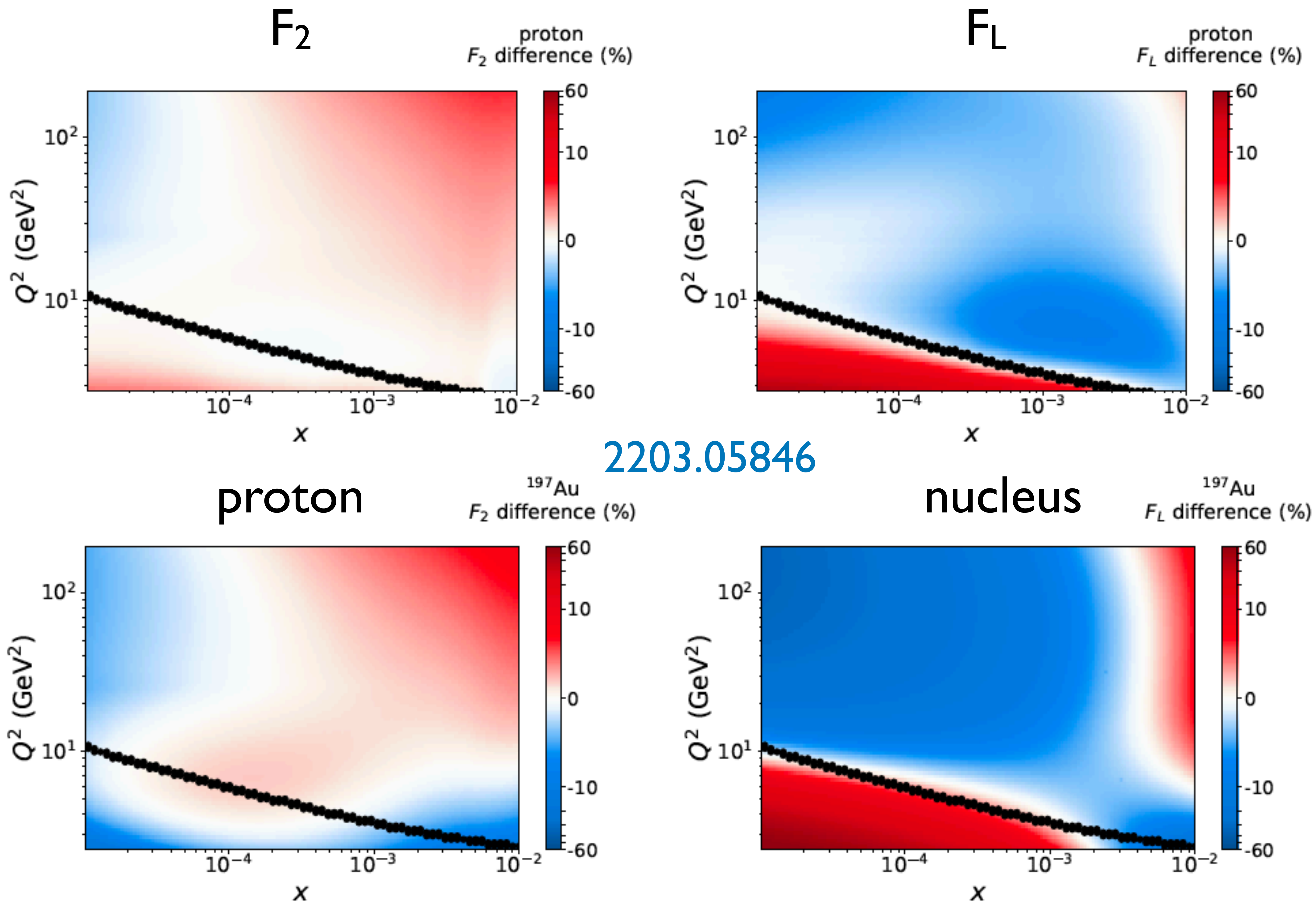

1710.05935



# Looking for non-linear dynamics:

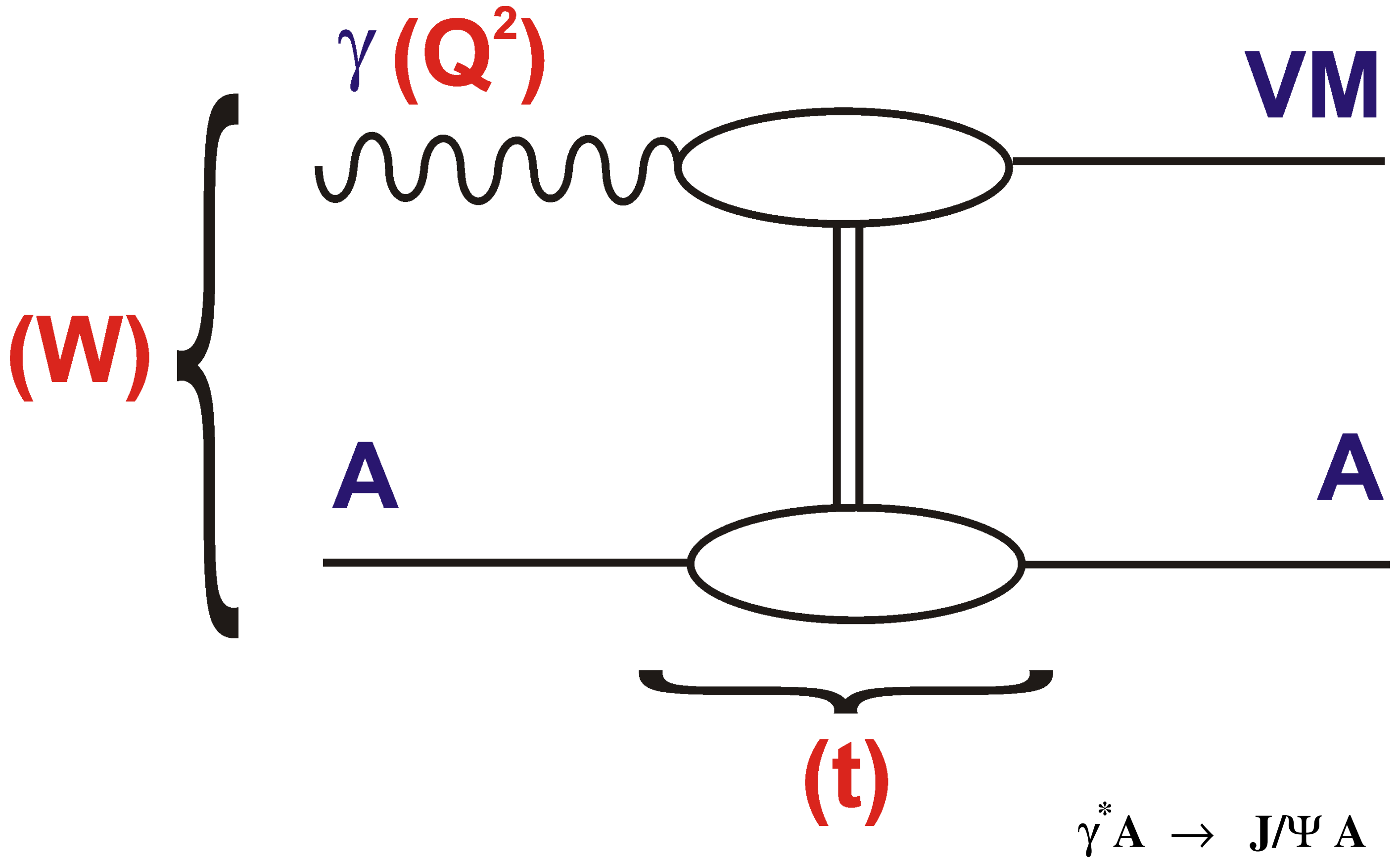
- New studies confirm that linear evolution cannot accommodate saturation even at NNLO or NNLO+NLLx. Note that precision at high $Q^2$ helps!



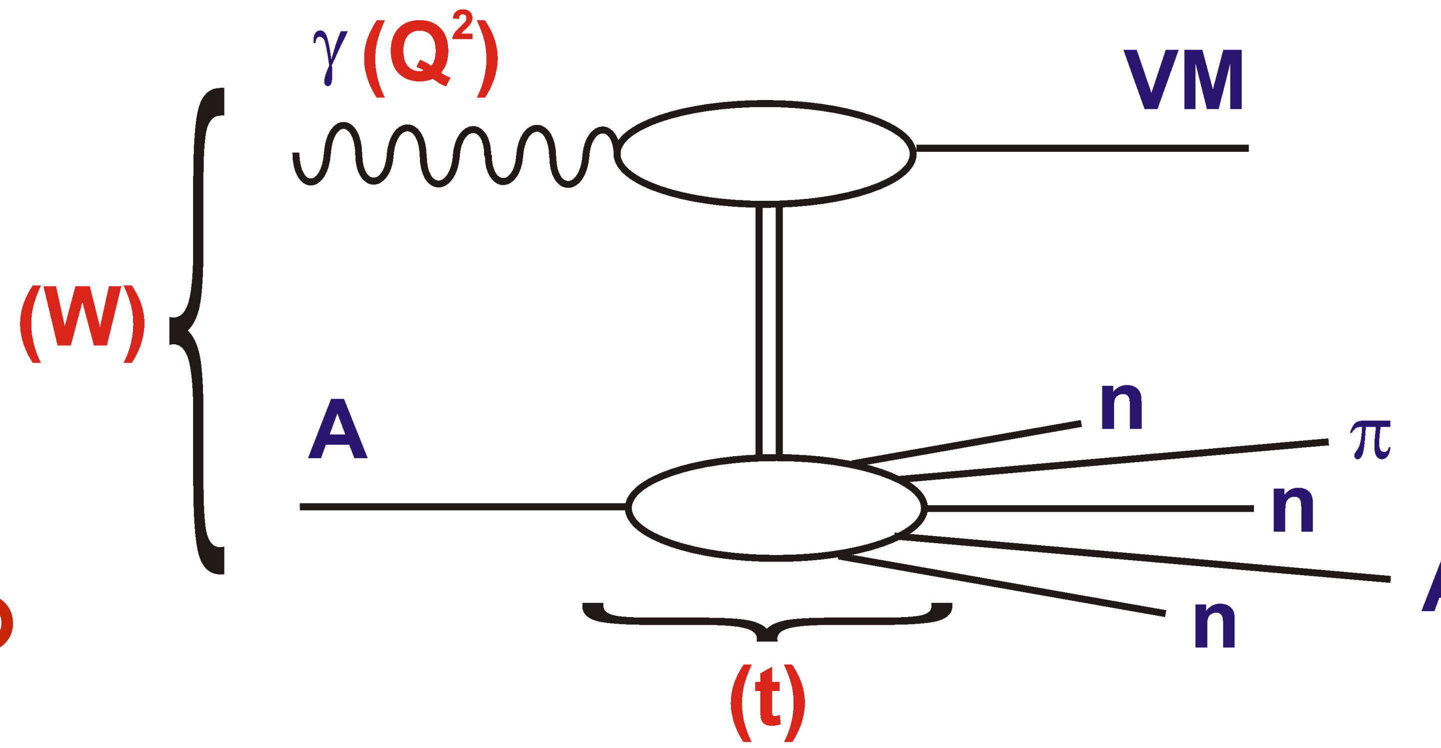



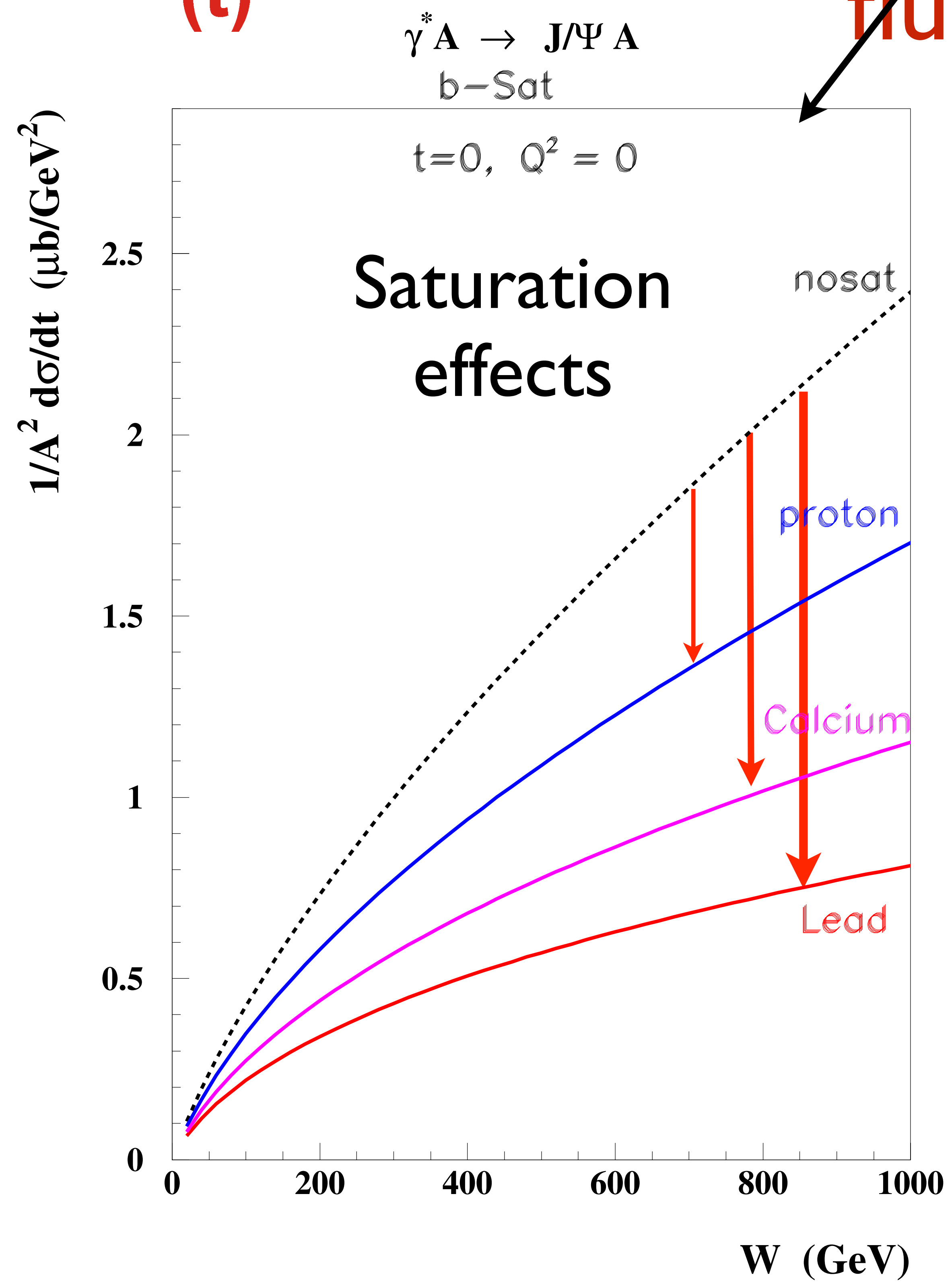
# Elastic VM production:

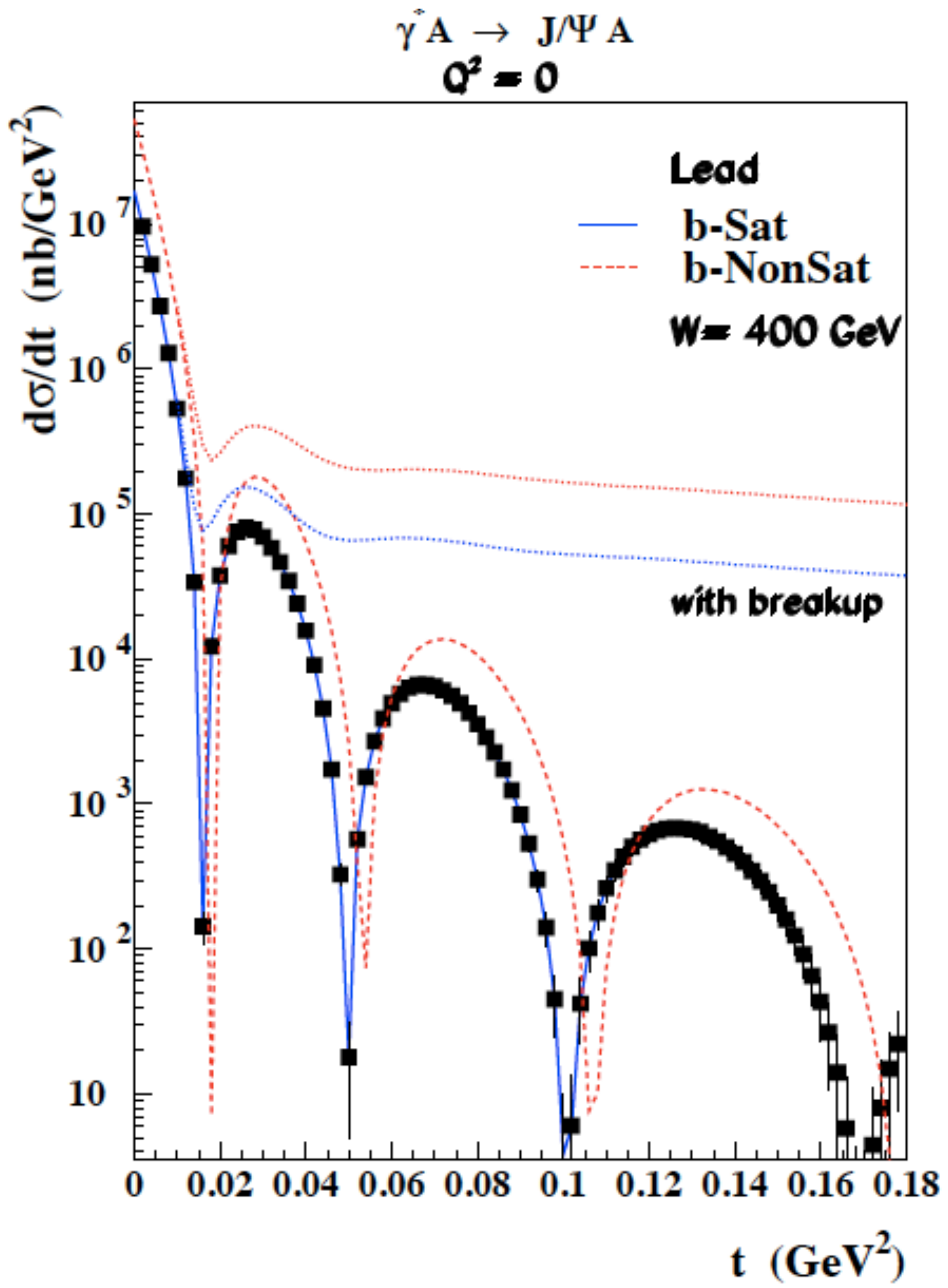





- Challenging experimental problem.
- Coherent case: energy dependence and dips.
- Incoherent case: sensitivity to fluctuations.



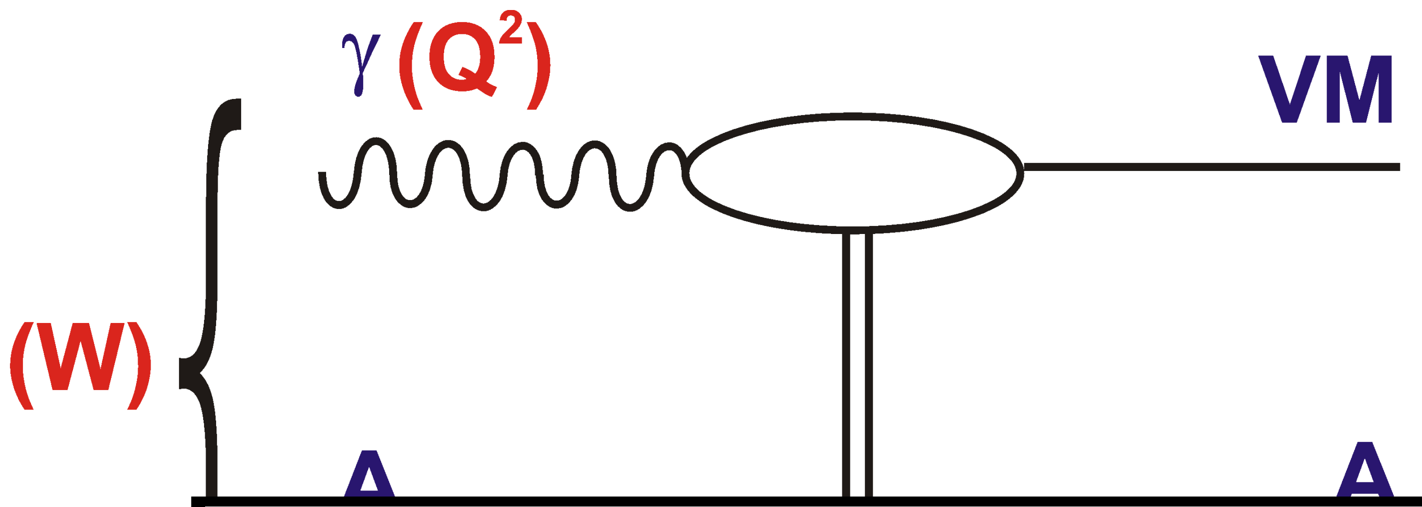




$$\Delta t = 2\sqrt{-t}\Delta p_T(J/\Psi)$$

$$\Delta p_T < 10 \text{ MeV}$$

$$\Delta t < 0.01 \text{ GeV}^2$$

# Elastic VM production:

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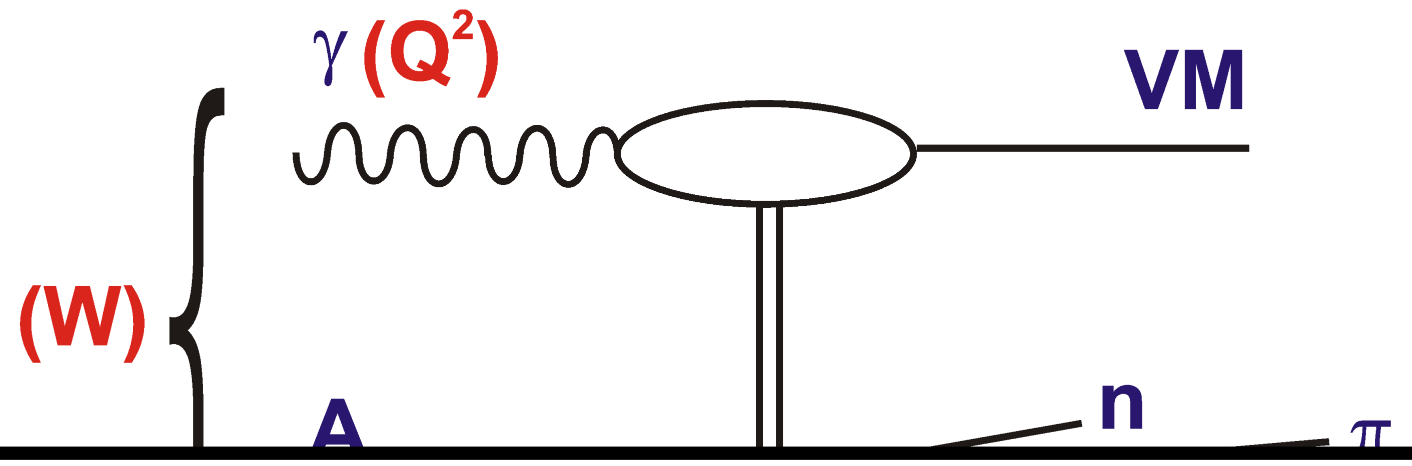
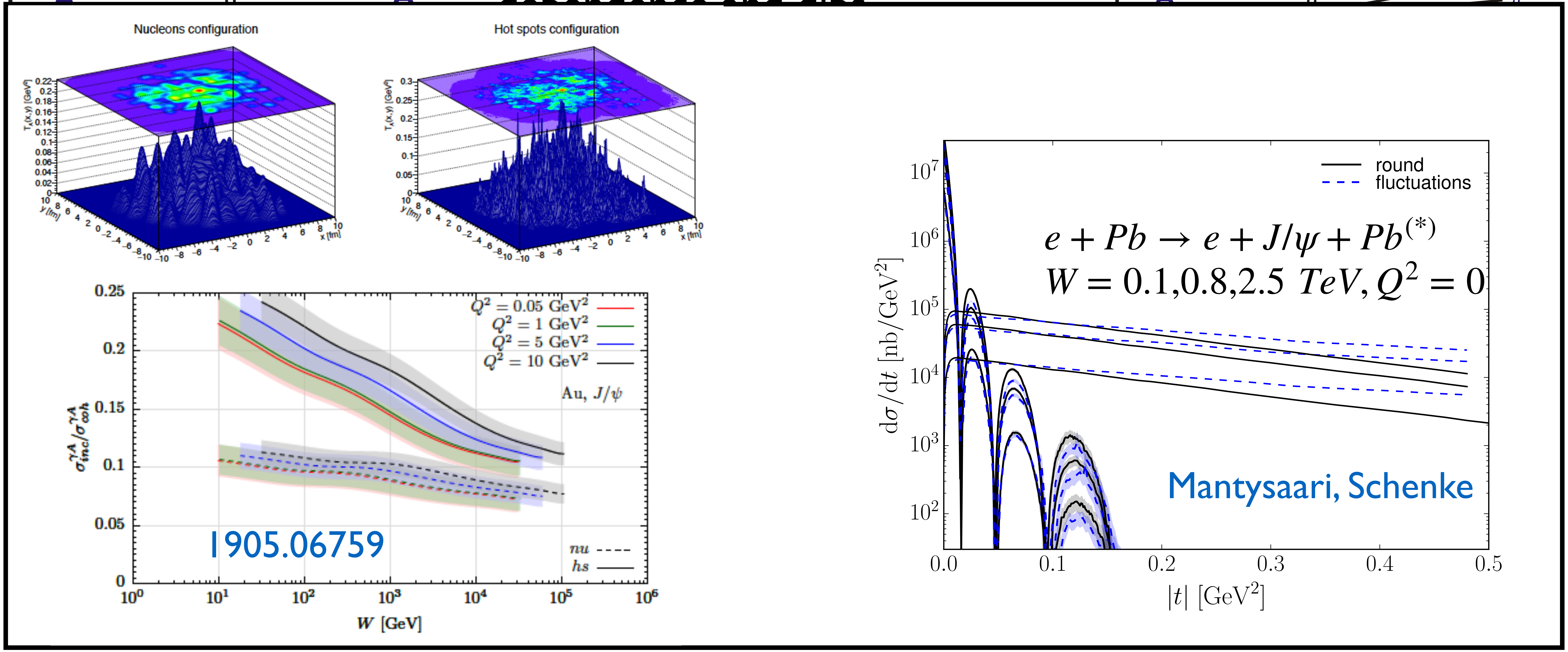


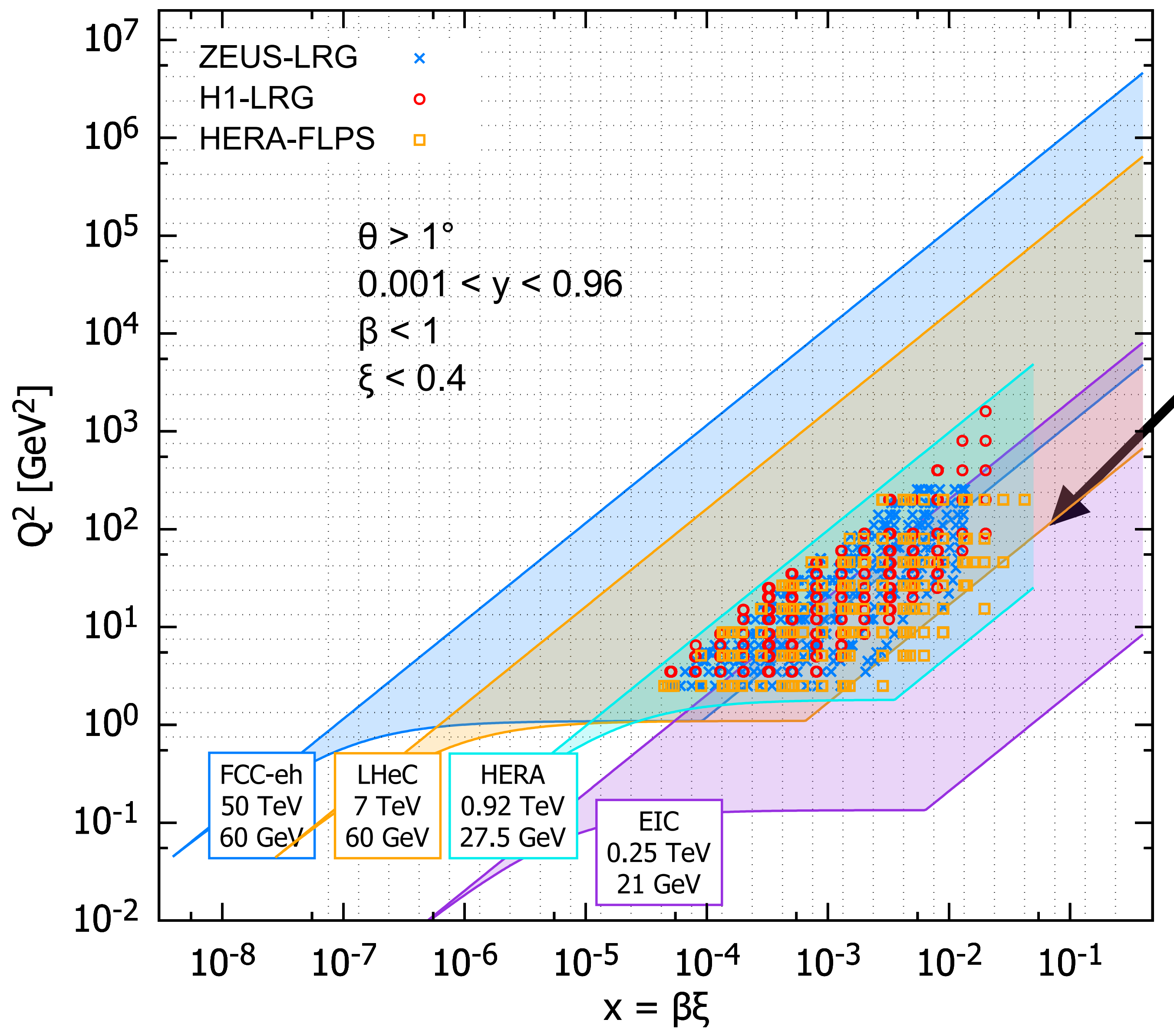
# Nuclear diffractive PDFs:

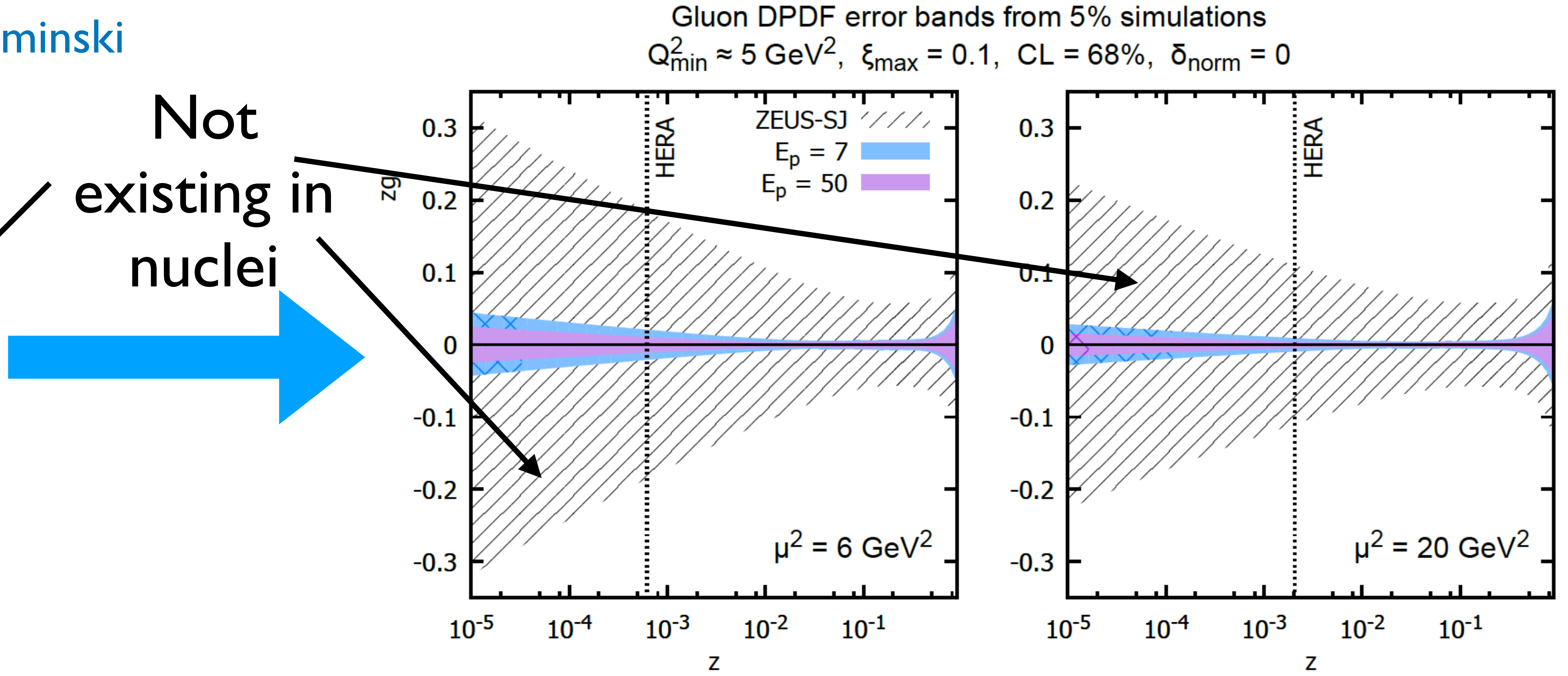
- Diffractive PDFs give the conditional probability of measuring a parton in the hadron with the hadron remaining intact: ~10 % events at HERA are diffractive!
- Never measured in nuclei (enhancement expected), incoherent diffraction dominant above relatively small -t: interplay between multiple scattering and survival probability of the colourless exchange (rapidity gap), relation between diffraction in ep and nuclear shadowing ⇒ MPIs, CEP.

- At the LHeC/FCC-he, **extractable in nuclei with the same accuracy as in proton**.

LHeC/FCC-he, coherent diffraction

1901.09076: NA, PN, AS, Wojtek Slominski

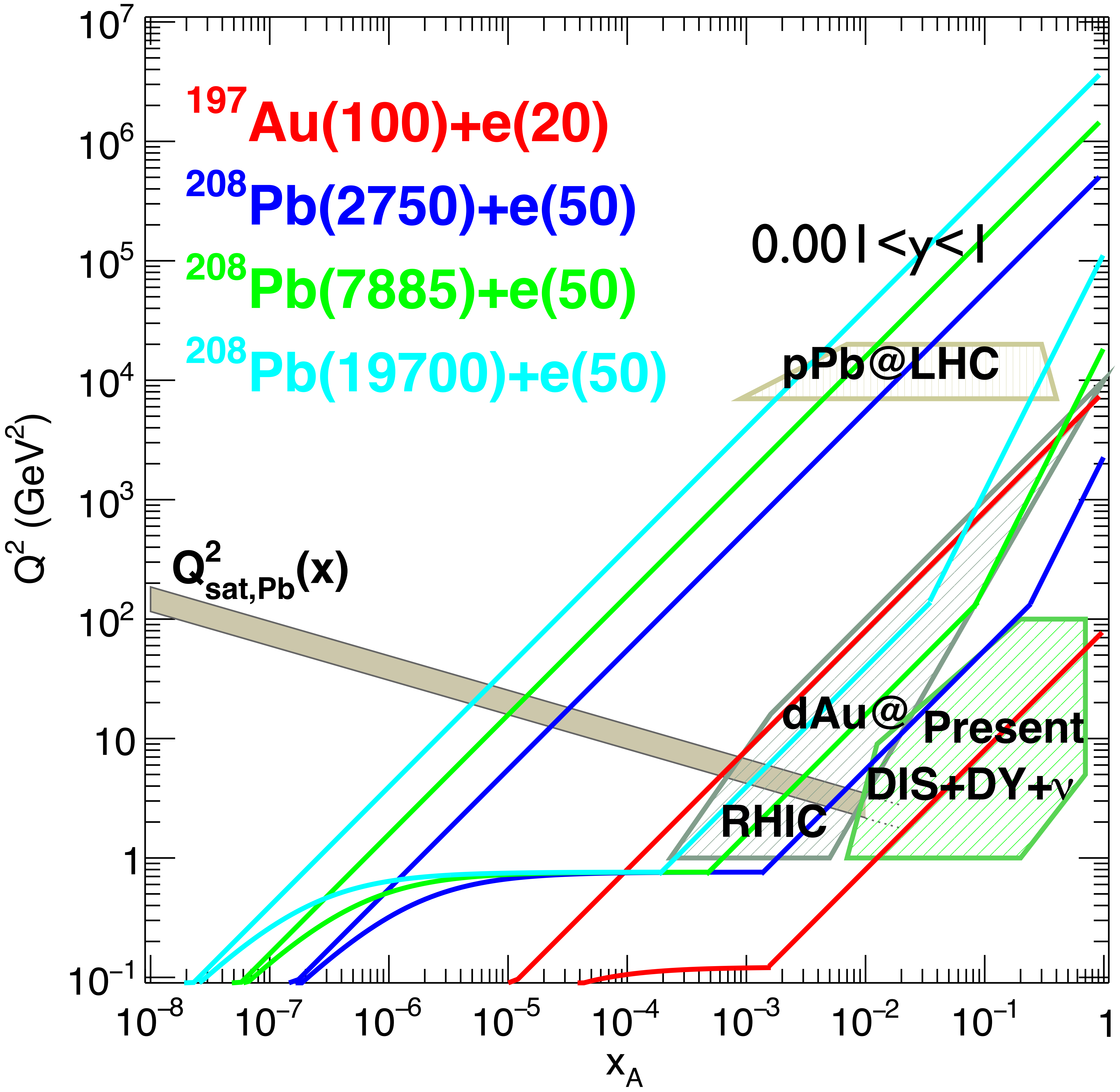


# Summary:

- The LHeC (and the FCC-he) will explore a completely new region in the x-$Q^2$ plane, enlarging the one presently explored in DIS by ~4 orders of magnitude down in x and up in $Q^2$.
  - ➜ A precise determination of nPDFs and nDPDFs will be possible, that cannot be matched at hadron colliders ⇒ factorisation.
  - ➜ Tests of small-x dynamics by studying both ep and eA.
  - ➜ Studies of the transverse structure of p and A.

Therefore: <u>precision</u> (for understanding nuclear structure in a totally new kinematic domain and for its use in present and future pA/AA) & <u>discovery</u> (of a genuinely new regime of QCD).




➜ ***Thanks to the organisers.***
➜ ***Thank you very much for your attention.***

# Backup:

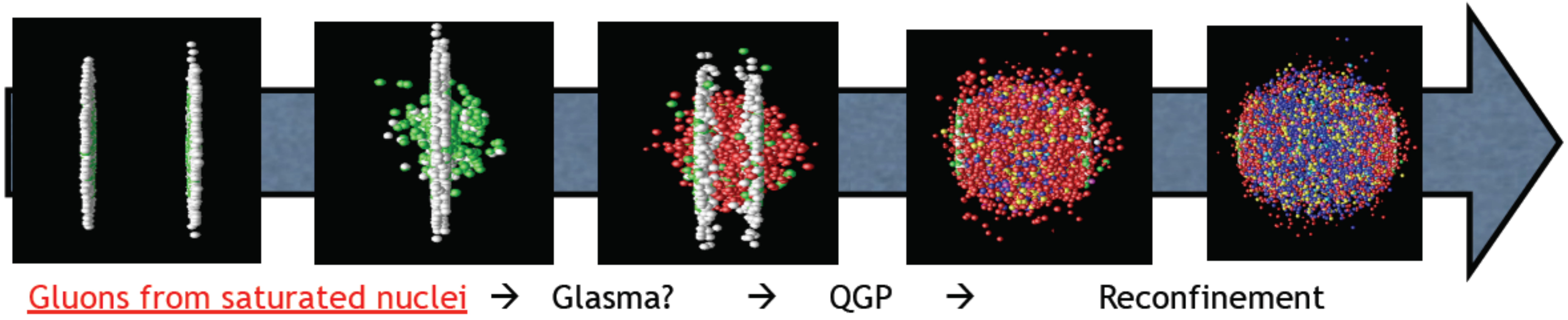
# Dynamics in pA/AA:

- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).

- Medium behaves very early like a low viscosity liquid: macroscopic description.

- Medium is very opaque to coloured particles traversing it.

[B. Cole]




- Lack of information about small-x partons, correlations and transverse structure.
- We do not understand the dense regime.

- How isotropised the system becomes?
- Why is hydro effective so fast, which dynamics?

- Dynamical mechanisms for such opacity? Weak or strong coupling?
- How to extract accurately medium parameters?

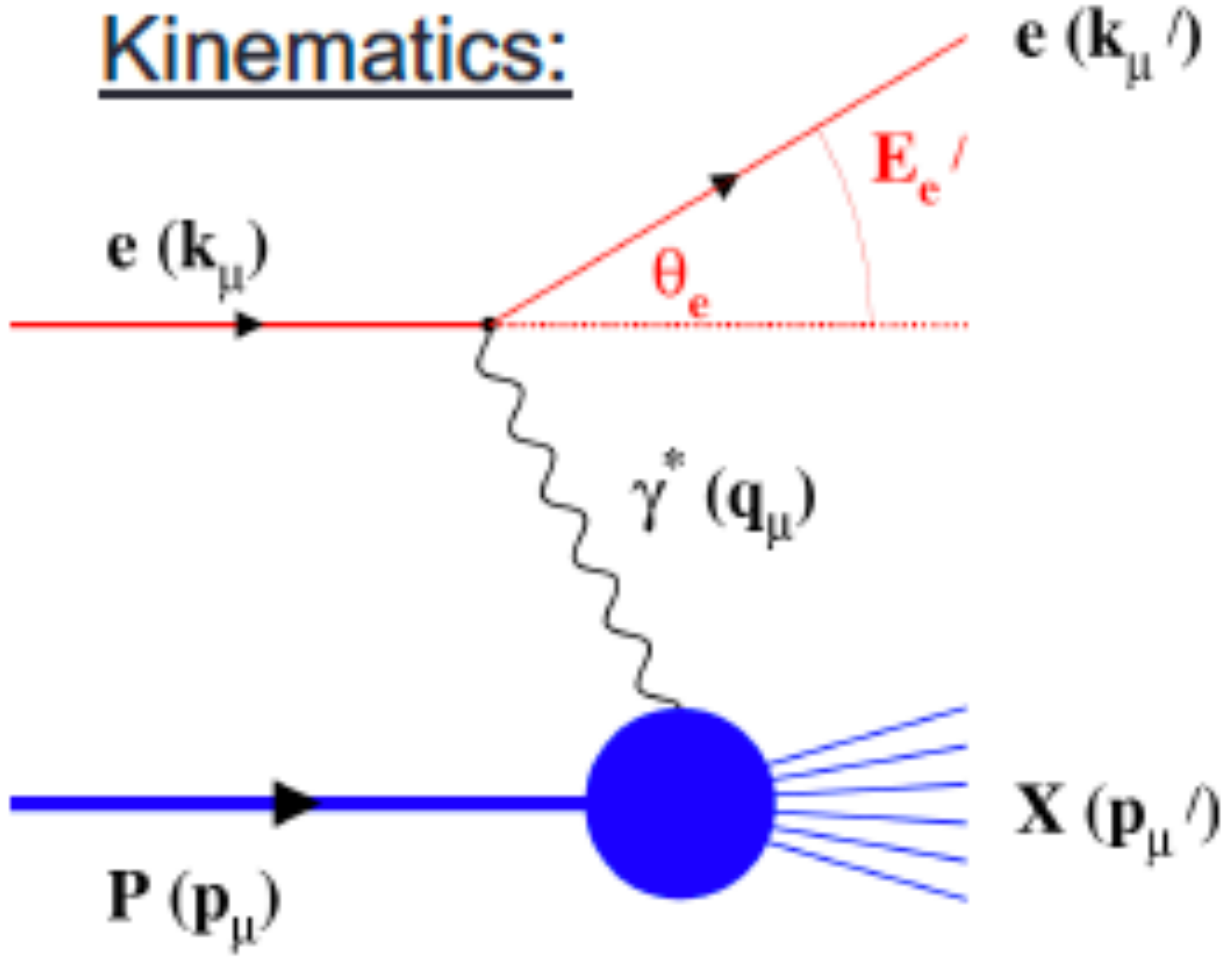
**→ Nuclear WF and mechanism of particle production.**

**→ Initial conditions; how small can a system become and still show "collectivity"?**

**→ In-medium QCD radiation, cold nuclear effects on hard probes.**

# Quick reminder:

Kinematics:




$$Q^2 = -q^2 = -(k_\mu - k_\mu')^2$$

$$Q^2 = 2E_e E_e'(1 - \cos\Theta_{e'})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E_e'}{E_e}\cos^2\left(\frac{\theta_e'}{2}\right)$$

Measure of inelasticity

$$s = 4\,E_t\,E_e$$

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

***Hadron* :**

$$z = \frac{E_h}{\nu};\, p_t$$

with respect to $\gamma$

High lumi & acceptance

**Exclusive DIS**

detect & identify *everything* e+p/A → e'+h(π,K,p,jet)+…

**Semi-inclusive events:**

e+p/A → e'+h(π,K,p,jet)+X

detect the scattered lepton in coincidence with identified hadrons/jets

**Inclusive events:**

e+p/A → e'+X

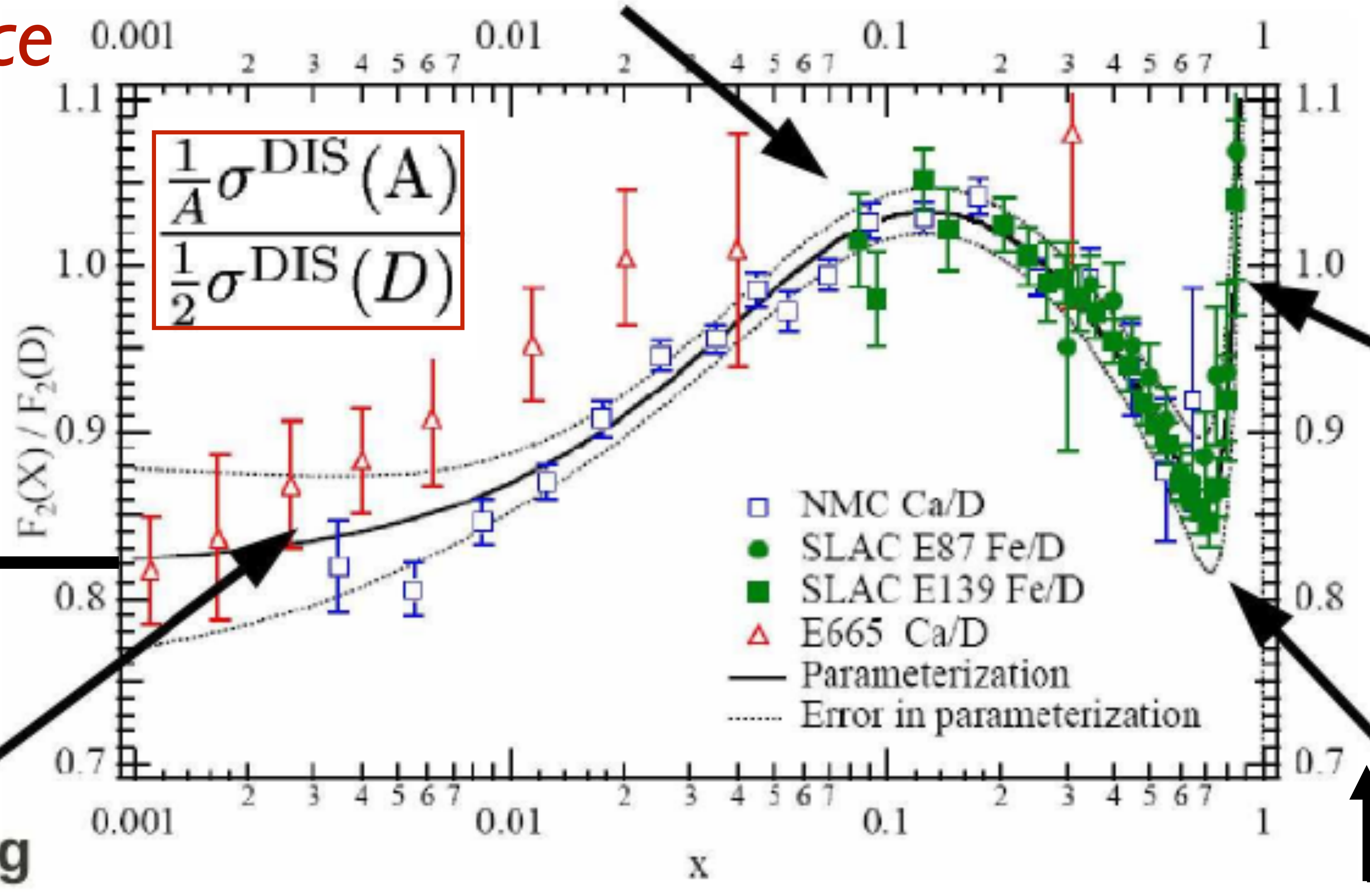
detect *only the scattered lepton* in the detector

Low lumi & acceptance

# Nuclear structure functions:

*Flavour dependence?; relation with shadowing and coherence*

**How much does the structure of a hadron change when it is immersed in a nuclear medium?**




ePb at LHeC/ FCC-he

eAu at EIC

*Multiple scattering, saturation,…; high-energy QCD*

*Short versus long range correlations, pion cloud, intrinsic charm,…*

Superfast quarks

- Bound nucleon $\neq$ free nucleon: search for process independent nPDFs that realise this condition, within collinear factorisation.

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\bar{q},g} f_i^A(\mu^2) \otimes \hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)$$

Nuclear PDFs, obeying the standard DGLAP

Usual perturbative coefficient functions

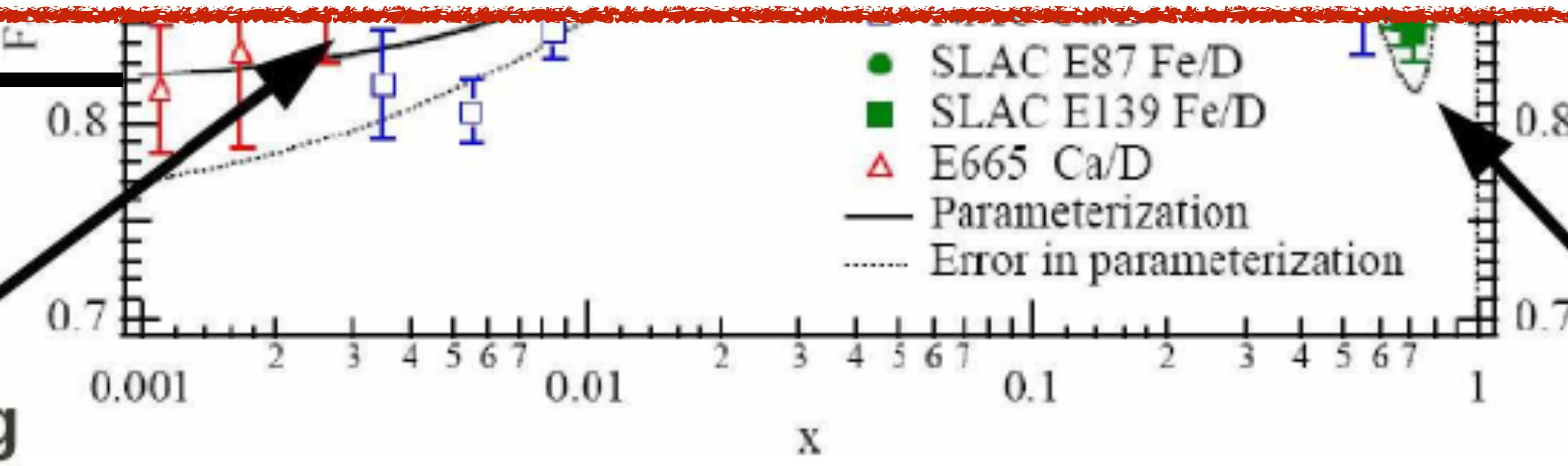
$$f_i^{p,A}(x,Q^2) = R_i^A(x,Q^2)\, f_i^p(x,Q^2)$$

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

# Nuclear structure functions:

- At an ep/eA collider:
  - ➜ PDF of a single nucleus possible, no need of ratios that would be obtained a posteriori.
  - ➜ Same method of extraction in both ep and eA.
  - ➜ Physics beyond standard collinear factorisation can be studied in a single setup, with size effects disentangled from energy effects and a large lever arm in x at perturbative $Q^2$.

EIC




*Multiple scattering, saturation,…; high-energy QCD*

Shadowing

*Short versus long range correlations, pion cloud, intrinsic charm,…*

EMC-effect

Superfast quarks

- Bound nucleon ≠ free nucleon: search for process independent nPDFs that realise this condition, within collinear factorisation.

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\bar{q},g} f_i^A(\mu^2)\otimes\hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)$$

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$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

# Small-x physics:

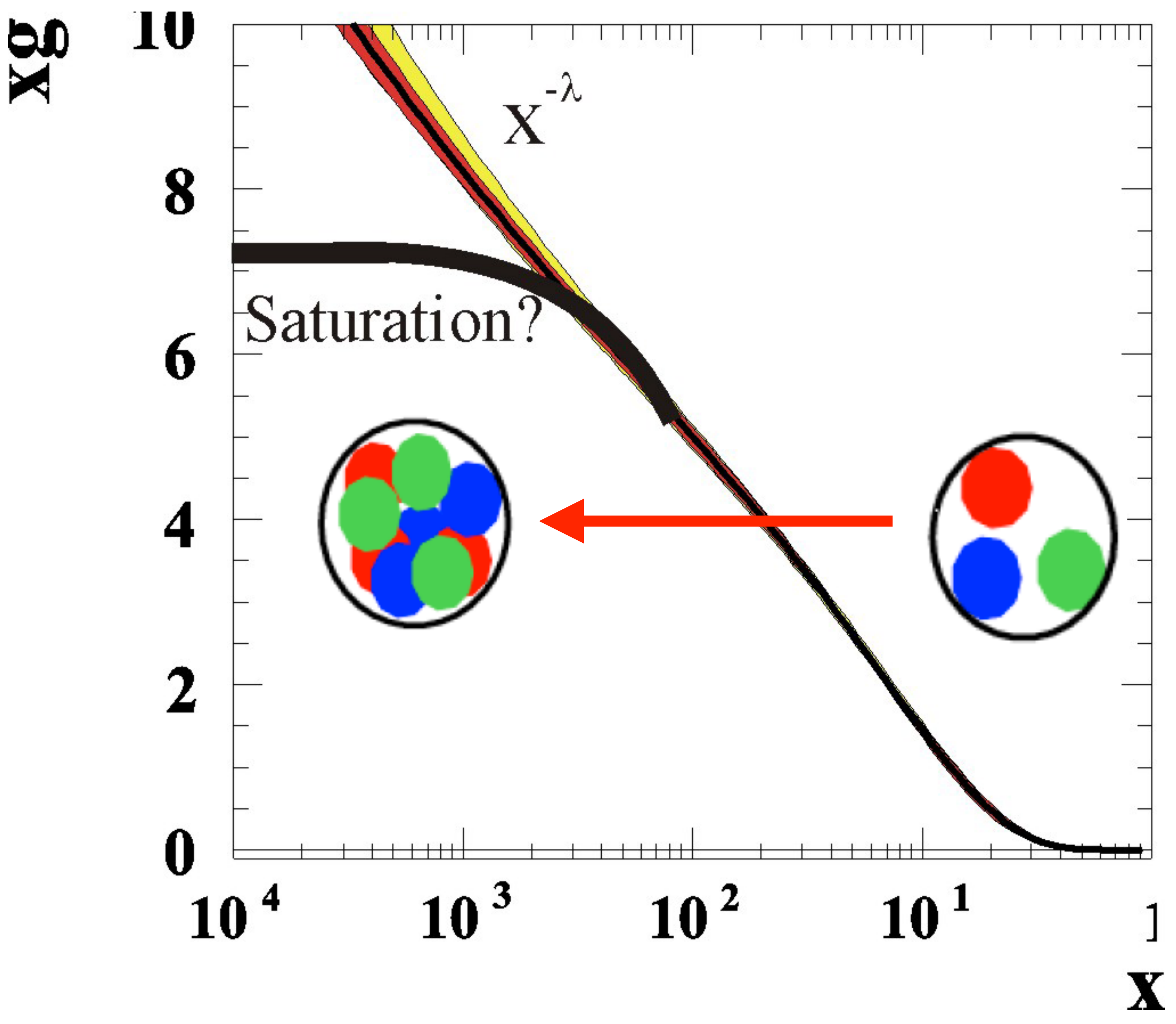


- HERA found xg α $x^{-0.3}$.
- Present data can be described by:
  - ➜ Linear evolution approaches, either DGLAP or resummation at low x.
  - ➜ Non-linear approaches - weak coupling but high density: saturation.

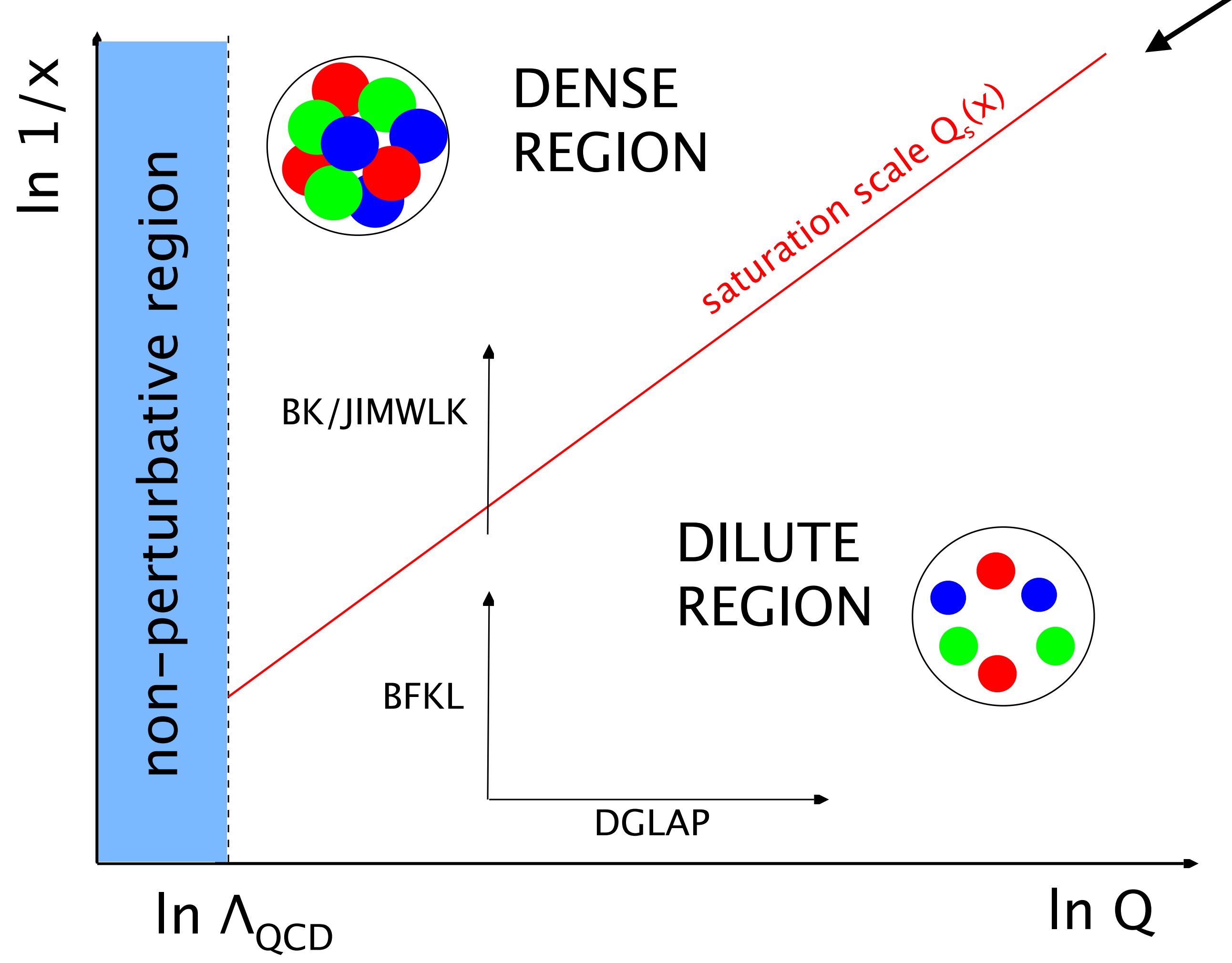
- Theory: at high energies (i.e. small x), non-linear dynamics must be present. **Where is it?** At HERA:
  - ➜ Hints of failure of DGLAP at small x, $Q^2$, resummation?
  - ➜ No ridge azimuthal structures yet found.

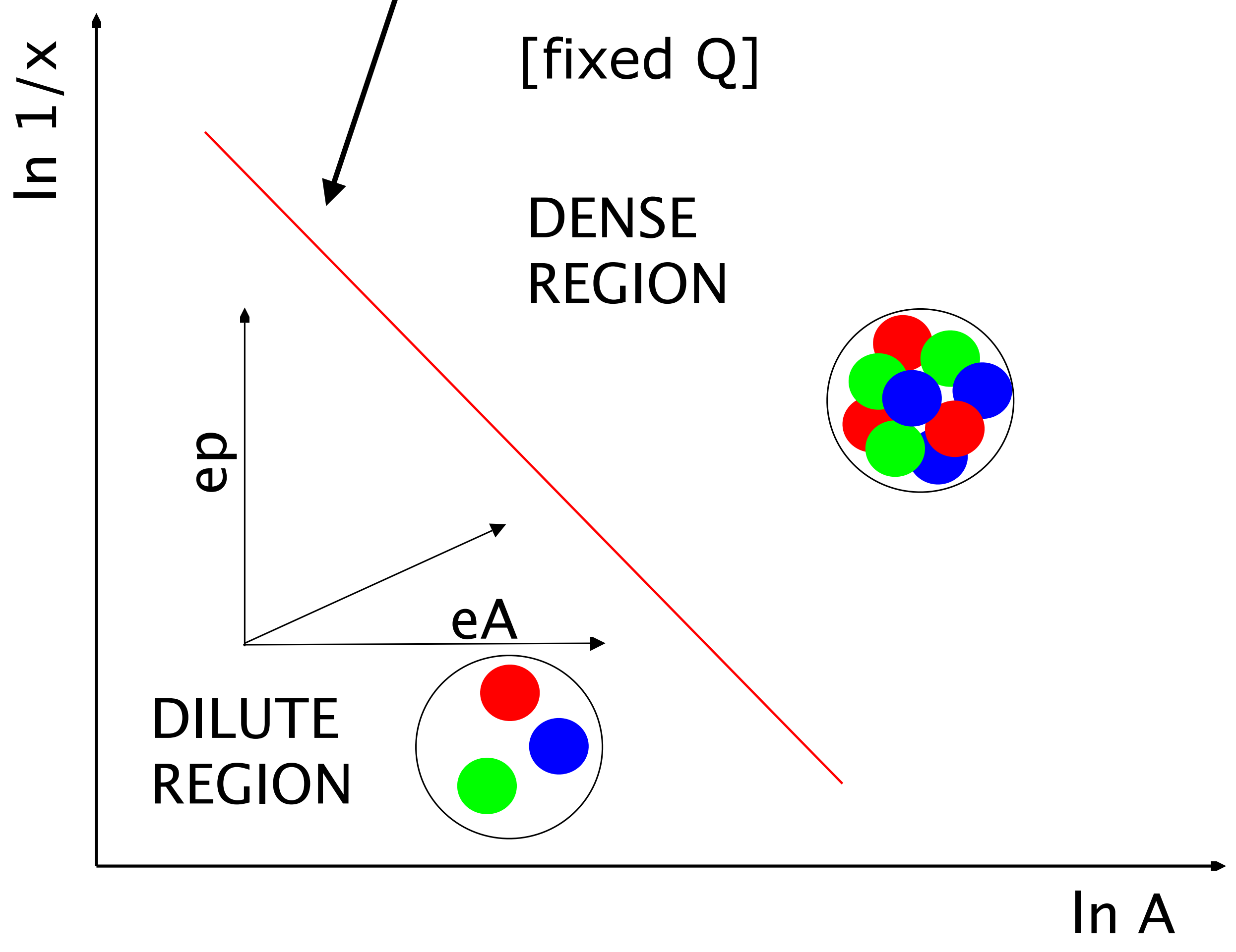
- Saturation is density-driven: ↓x/↑A ⇒

**ep&eA + range in 1/x & $Q^2$ essential for full understanding.**




$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$

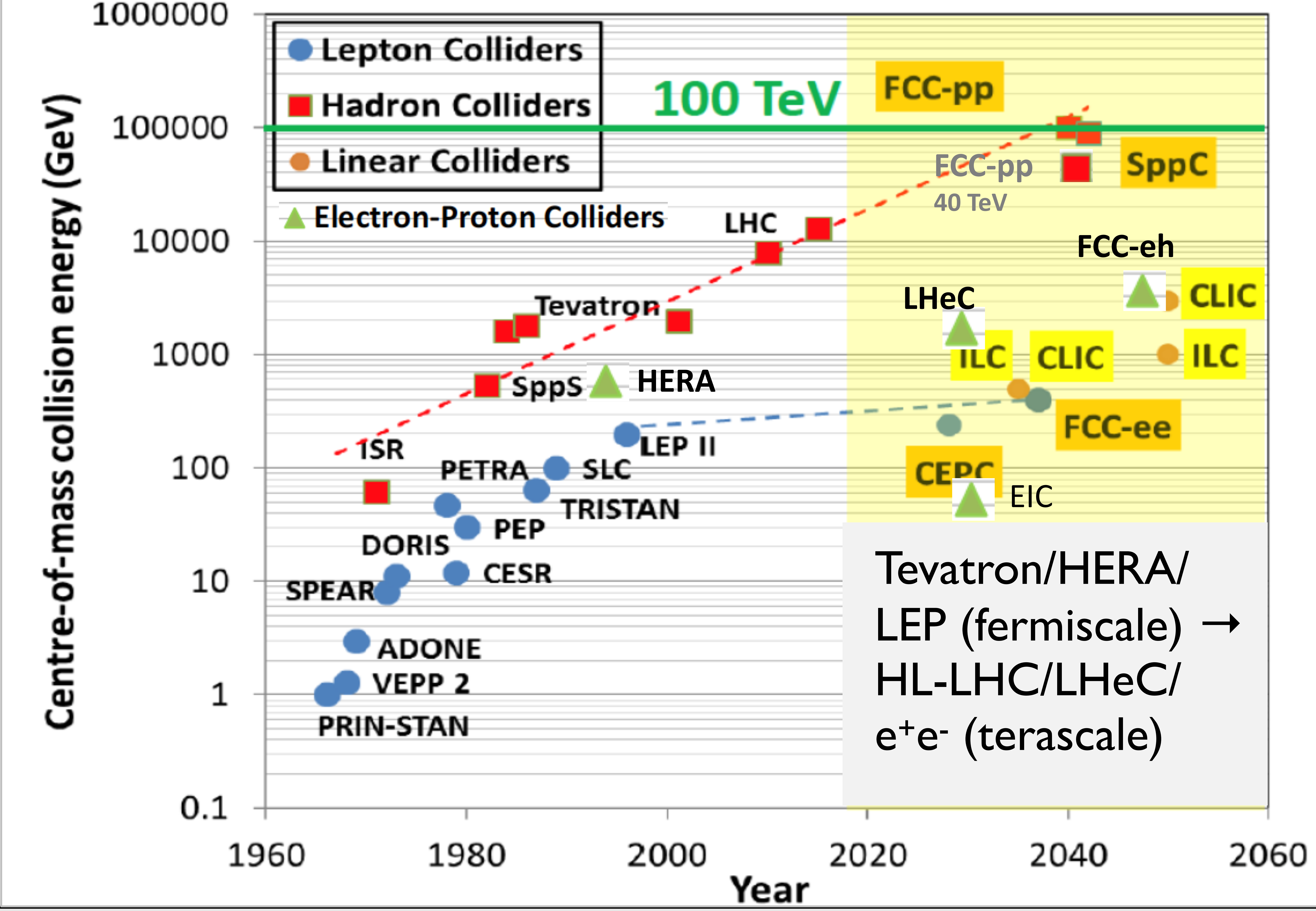


# Accelerators:

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

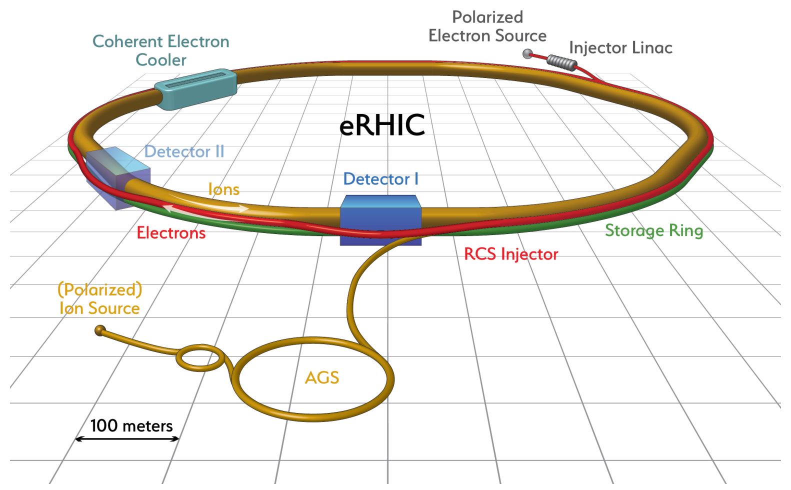
- **It must be able to run concurrently with pp** (also FCC-he), plus limitations on power consumption, high luminosity for Higgs studies,… ⇒ energy recovery linac as baseline.

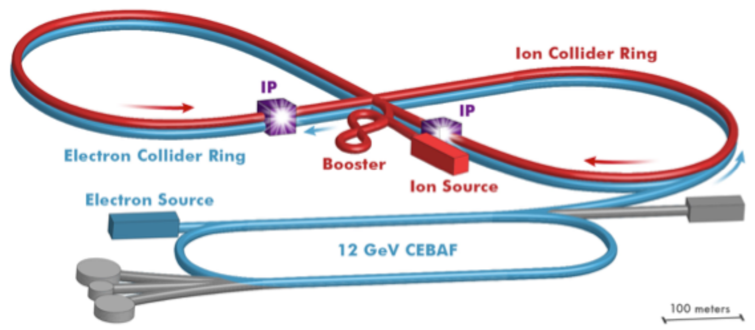



Tevatron/HERA/LEP (fermiscale) → HL-LHC/LHeC/$e^+e^-$ (terascale)

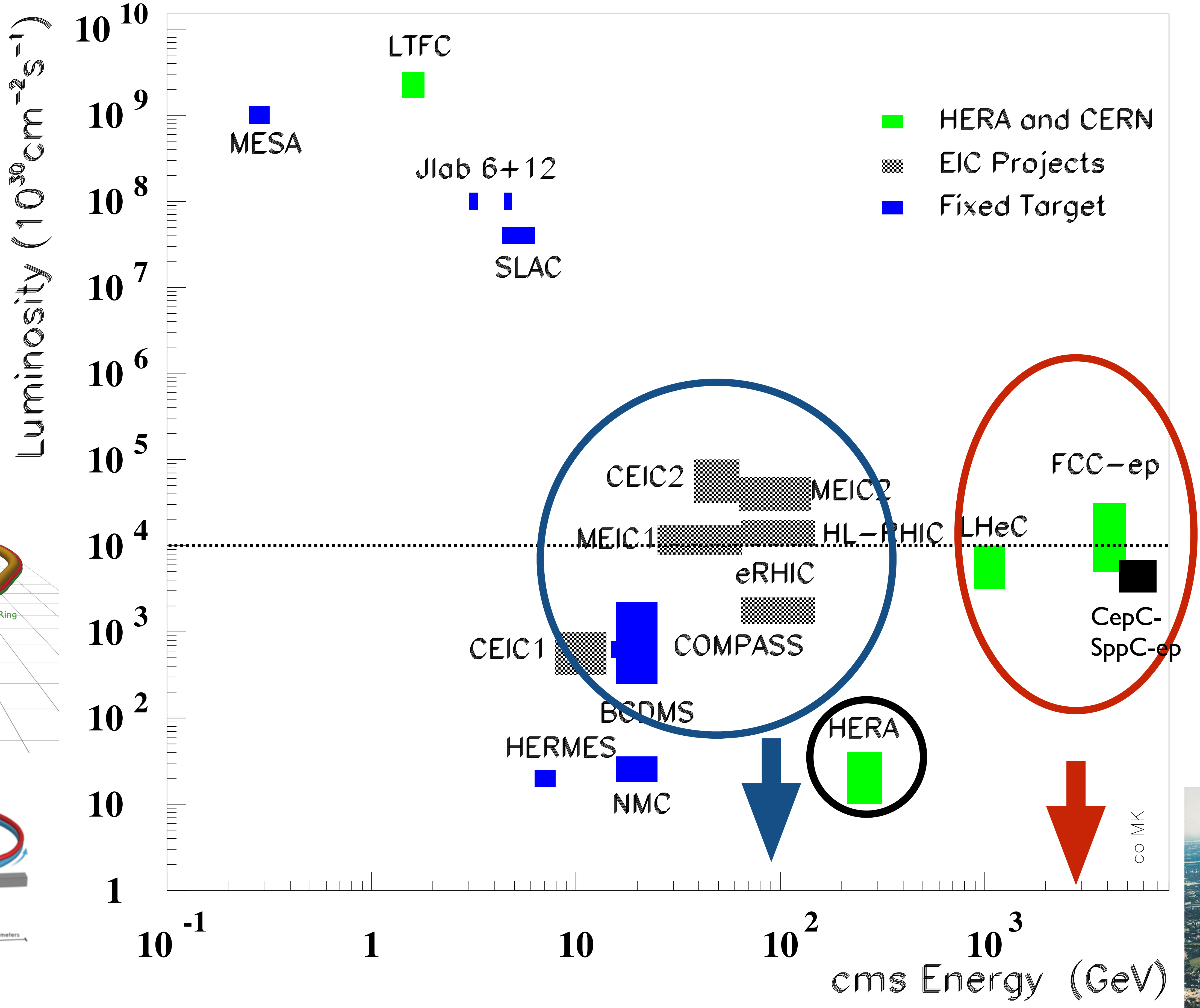
# Machines: ep/eA

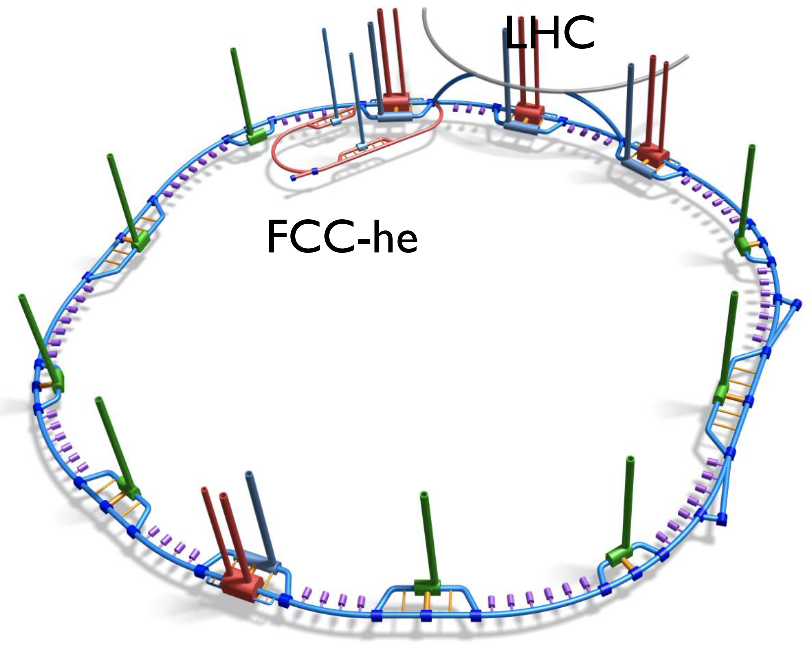
- Projects of eA colliders with $E_{cm}$ ~ $\mathcal{O}(0.1)$ TeV/A (EICs at US and China) and $\mathcal{O}(1)$ TeV/A (LHeC and FCC-he at CERN) addressing different physics.

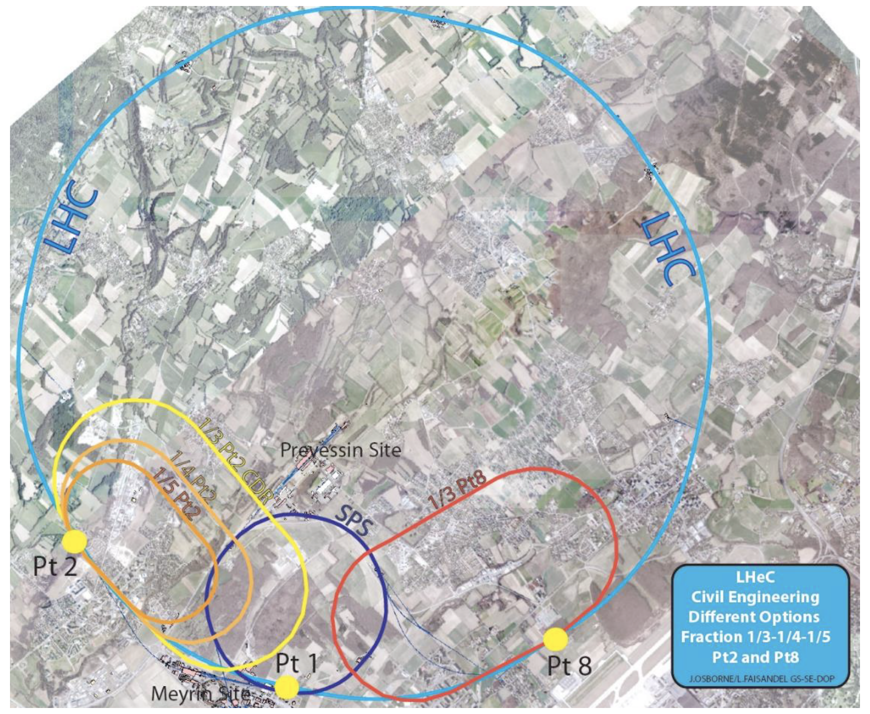


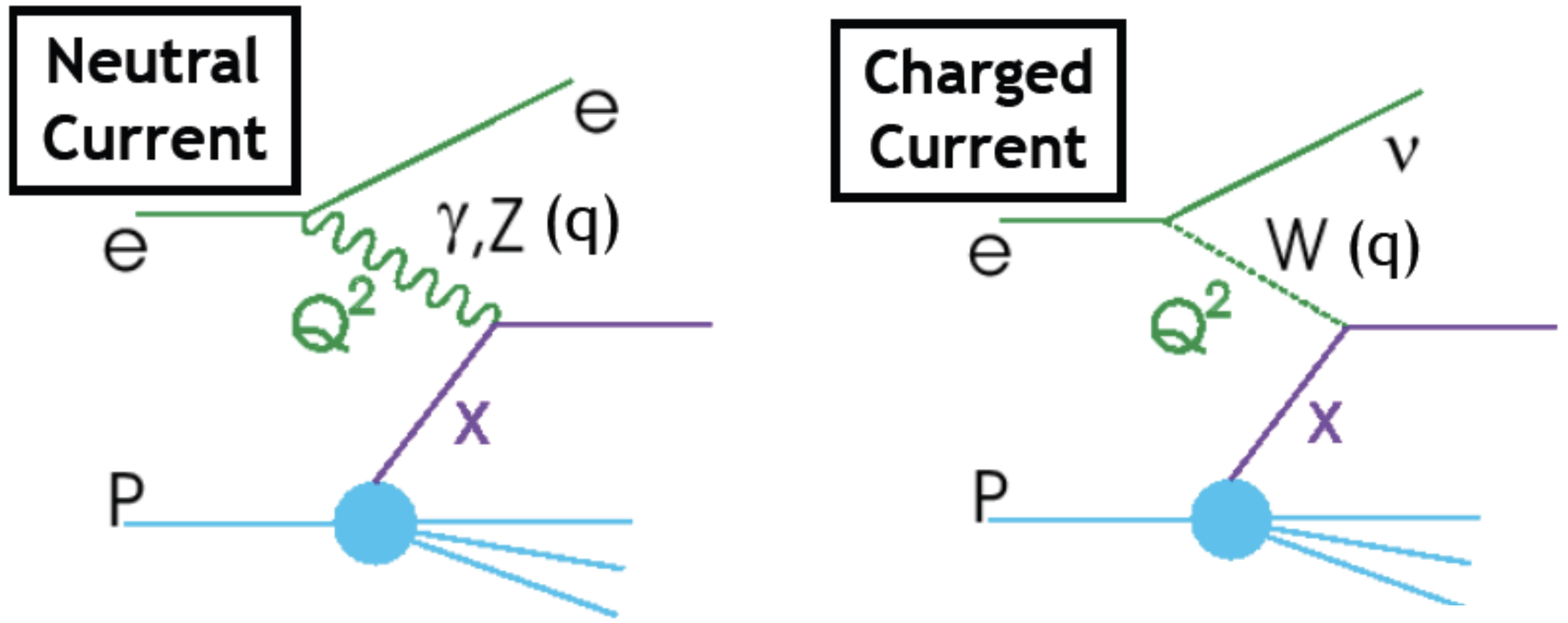

Lepton-proton/nucleus scattering facilities

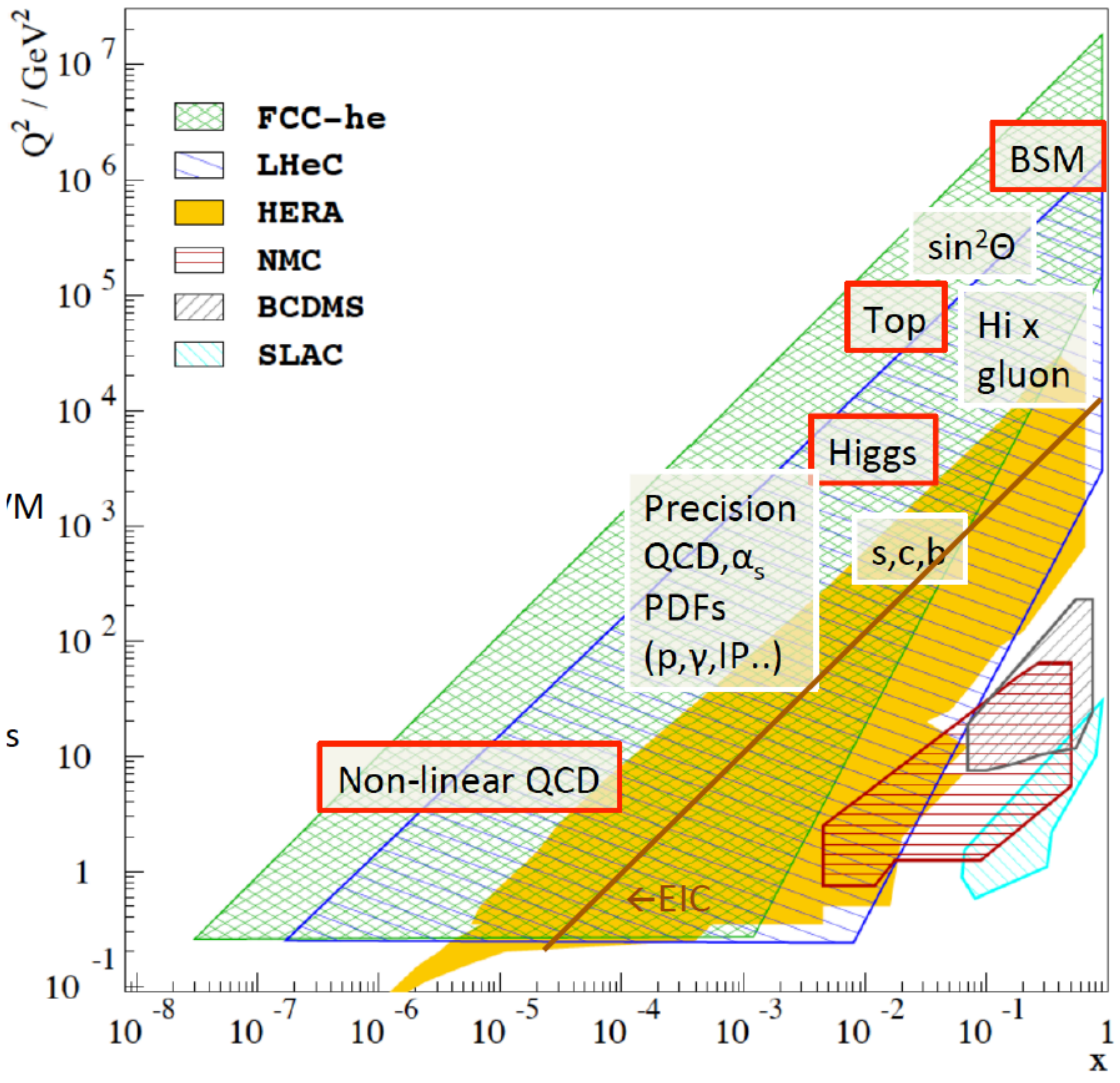



# Summary of physics:




- 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. PDF, EW measurements).
- Transform the LHC into a high precision Higgs facility.
- Has unique and complementary discovery potential of BSM particles (prompt and long-lived).
- **Overall: a unique Particle and Nuclear Physics Facility.**

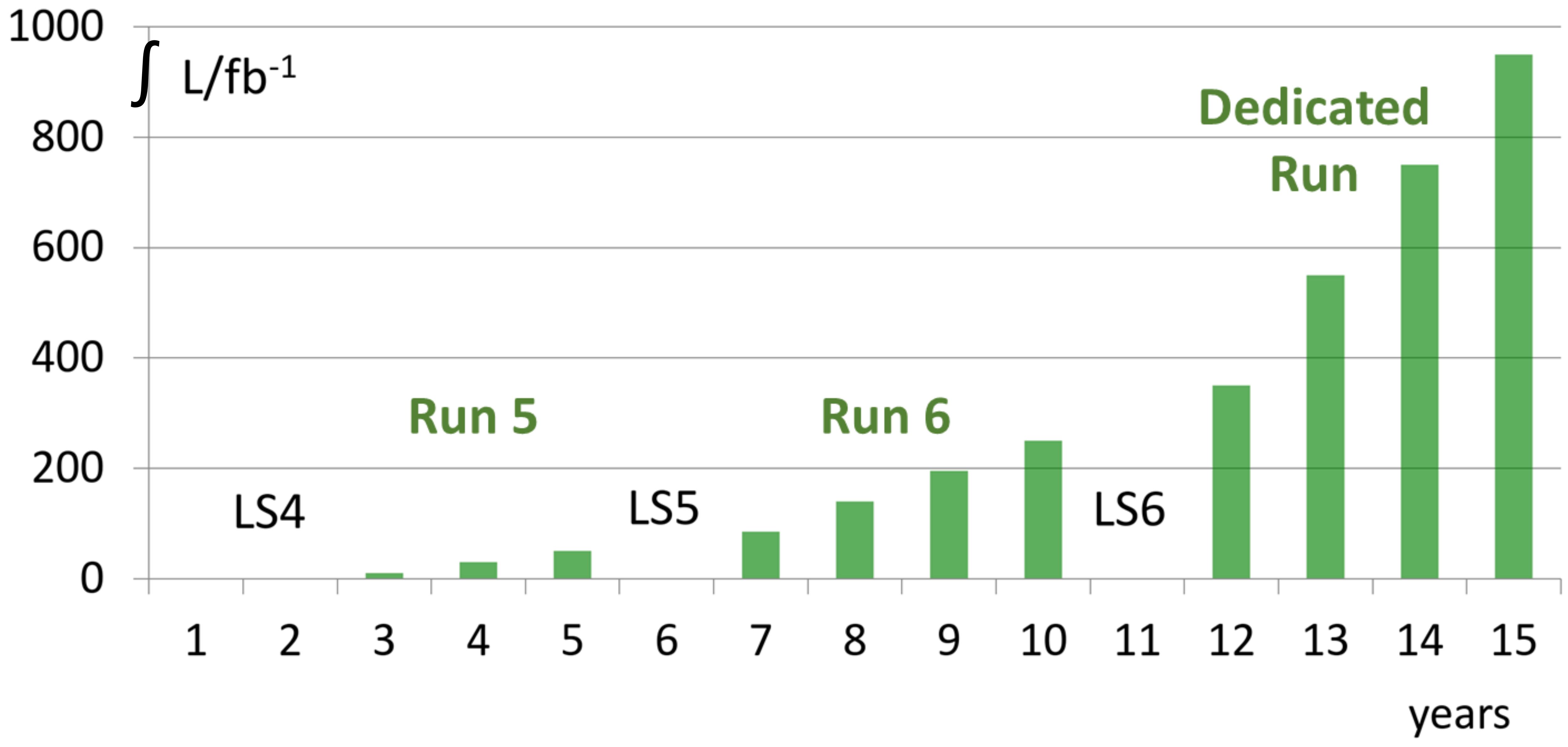
# Luminosities:

| Parameter [unit] | LHeC CDR | ep at HL-LHC | ep at HE-LHC | FCC-he |
|---|---|---|---|---|
| $E_p$ [TeV] | 7 | 7 | 13.5 | 50 |
| $E_e$ [GeV] | 60 | 60 | 60 | 60 |
| $\sqrt{s}$ [TeV] | 1.3 | 1.3 | 1.7 | 3.5 |
| Bunch spacing [ns] | 25 | 25 | 25 | 25 |
| Protons per bunch [$10^{11}$] | 1.7 | 2.2 | 2.5 | 1 |
| $\gamma\varepsilon_p$ [$\mu$m] | 3.7 | 2 | 2.5 | 2.2 |
| Electrons per bunch [$10^9$] | 1 | 2.3 | 3.0 | 3.0 |
| Electron current [mA] | 6.4 | 15 | 20 | 20 |
| IP beta function $\beta_p^*$ [cm] | 10 | 7 | 10 | 15 |
| Hourglass factor $H_{geom}$ | 0.9 | 0.9 | 0.9 | 0.9 |
| Pinch factor $H_{b-b}$ | 1.3 | 1.3 | 1.3 | 1.3 |
| Proton filling $H_{coll}$ | 0.8 | 0.8 | 0.8 | 0.8 |
| Luminosity [$10^{33}$ cm$^{-2}$s$^{-1}$] | 1 | 8 | 12 | 15 |

**ep**

| parameter [unit] | LHeC (HL-LHC) | eA at HE-LHC | FCC-he |
|---|---|---|---|
| $E_{Pb}$ [PeV] | 0.574 | 1.03 | 4.1 |
| $E_e$ [GeV] | 60 | 60 | 60 |
| $\sqrt{s_{eN}}$ electron-nucleon [TeV] | 0.8 | 1.1 | 2.2 |
| Bunch spacing [ns] | 50 | 50 | 100 |
| No. of bunches | 1200 | 1200 | 2072 |
| Ions per bunch [$10^8$] | 1.8 | 1.8 | 1.8 |
| $\gamma\epsilon_A$ [$\mu$m] | 1.5 | 1.0 | 0.9 |
| Electrons per bunch [$10^9$] | 4.67 | 6.2 | 12.5 |
| Electron current [mA] | 15 | 20 | 20 |
| IP beta function $\beta_A^*$ [cm] | 7 | 10 | 15 |
| Hourglass factor $H_{geom}$ | 0.9 | 0.9 | 0.9 |
| Pinch factor $H_{b-b}$ | 1.3 | 1.3 | 1.3 |
| Bunch filling $H_{coll}$ | 0.8 | 0.8 | 0.8 |
| Luminosity [$10^{32}$ cm$^{-2}$s$^{-1}$] | 7 | 18 | 54 |

**ePb**



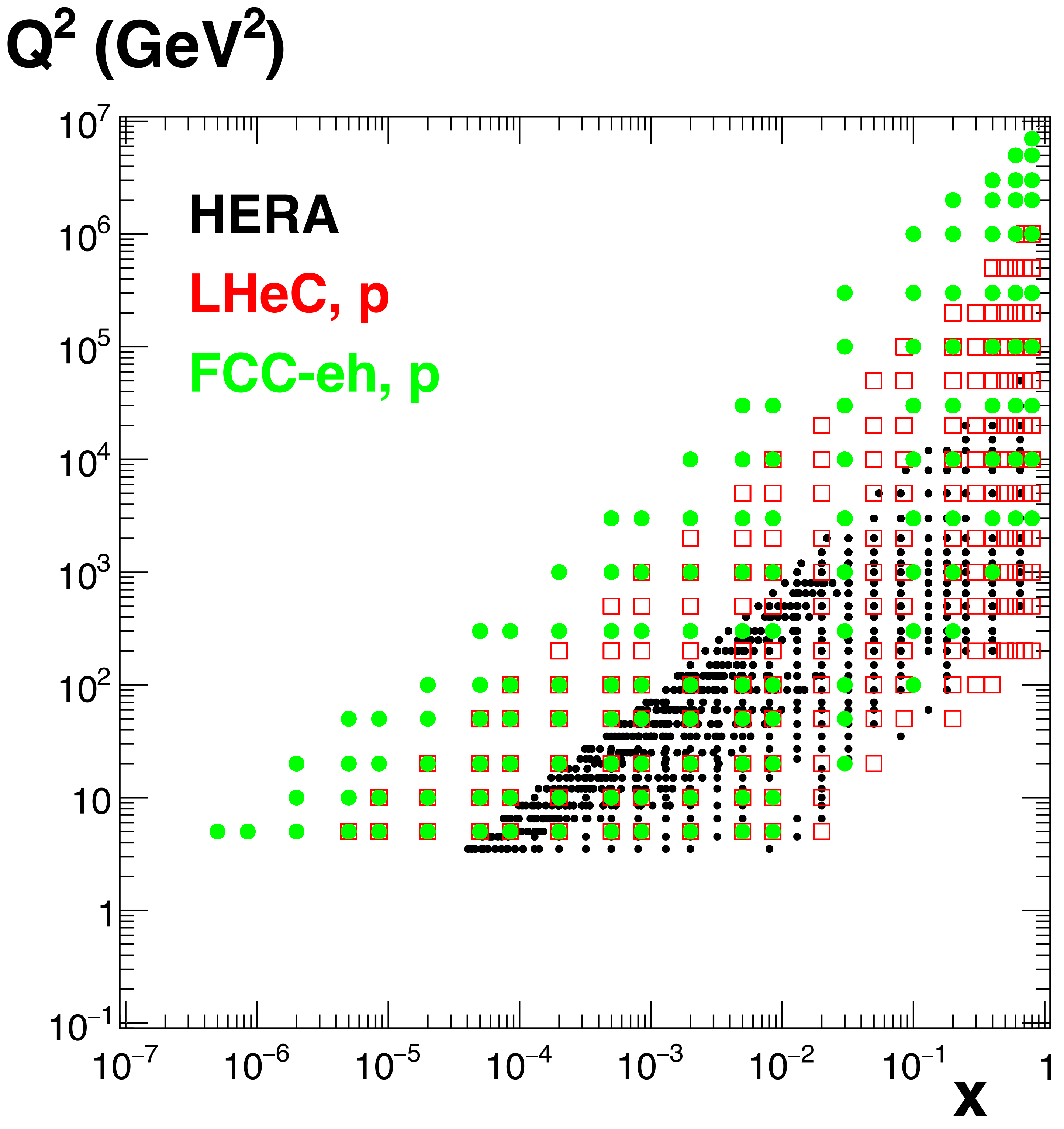

1810.13022; O. Brüning at EPS-HEP 2019 and talk here

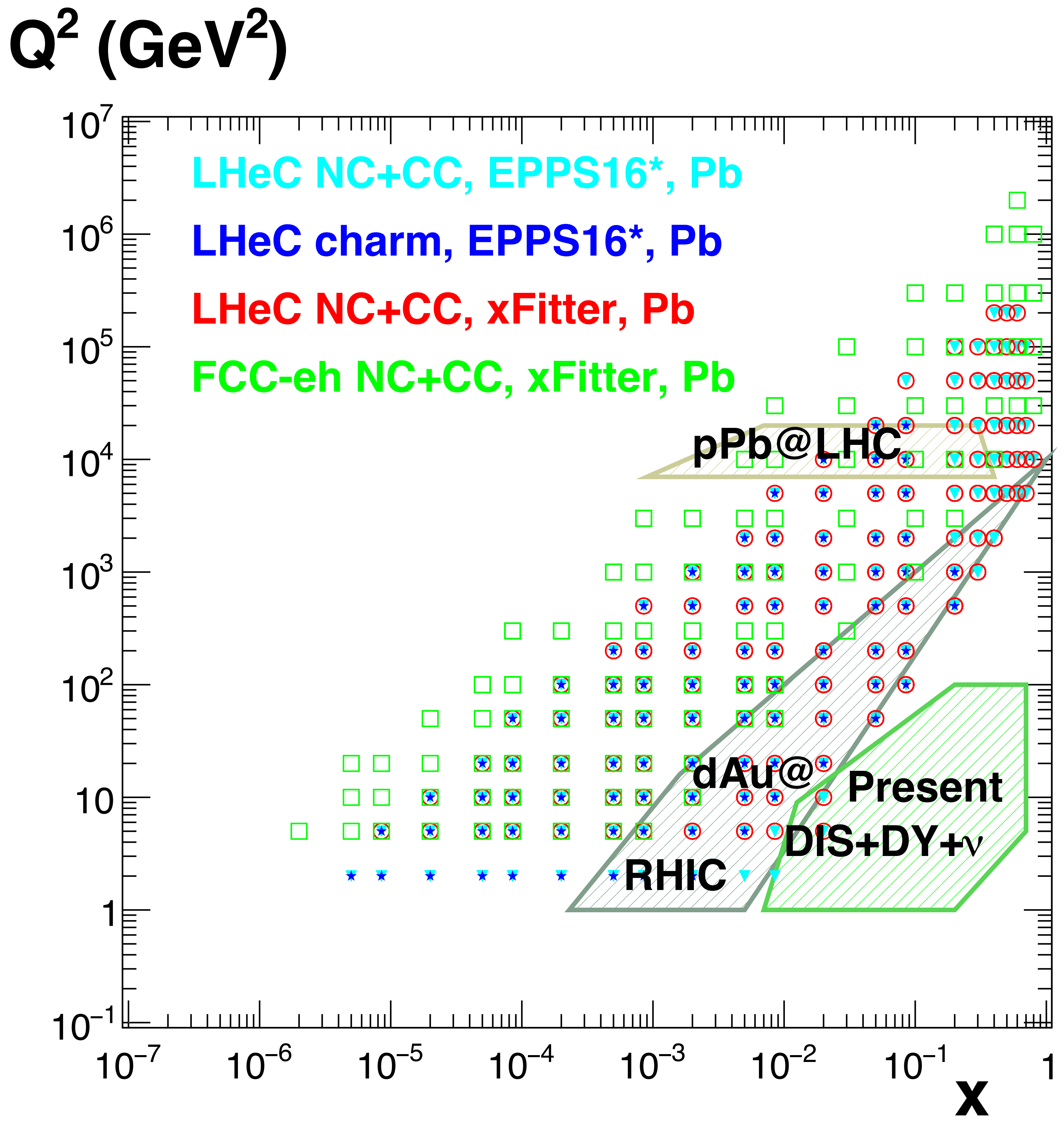
- P=±0.8 (electrons).
- Positrons: P=0, 1/100 luminosity.
- FCC-he could deliver integrated luminosities ~2 ab$^{-1}$, depending on pp operation.
- ePb integrated luminosities can be estimated 1/100 those in ep (~10 times smaller luminosity times ~10 times smaller running time).

# Pseudodata:

| | $E_e$ (GeV) | $E_h$ (TeV/nucleon) | Polarisation | Luminosity ($fb^{-1}$) | NC/CC | # data |
|---|---|---|---|---|---|---|
| **ep@LHeC**, 1005 data points for $Q^2 \geq 3.5$ $GeV^2$ | 60 ($e^-$) | 1 (p) | 0 | 100 | CC | 93 |
| | 60 ($e^-$) | 1 (p) | 0 | 100 | NC | 136 |
| | 60 ($e^-$) | 7 (p) | -0.8 | 1000 | CC | 114 |
| | 60 ($e^-$) | 7 (p) | 0.8 | 300 | CC | 113 |
| | 60 ($e^+$) | 7 (p) | 0 | 100 | CC | 109 |
| | 60 ($e^-$) | 7 (p) | -0.8 | 1000 | NC | 159 |
| | 60 ($e^-$) | 7 (p) | 0.8 | 300 | NC | 159 |
| | 60 ($e^+$) | 7 (p) | 0 | 100 | NC | 157 |
| **ePb@LHeC**, 484 data points for $Q^2 \geq 3.5$ $GeV^2$ | 20 ($e^-$) | 2.75 (Pb) | -0.8 | 0.03 | CC | 51 |
| | 20 ($e^-$) | 2.75 (Pb) | -0.8 | 0.03 | NC | 93 |
| | 26.9 ($e^-$) | 2.75 (Pb) | -0.8 | 0.02 | CC | 55 |
| | 26.9 ($e^-$) | 2.75 (Pb) | -0.8 | 0.02 | NC | 98 |
| | 60 ($e^-$) | 2.75 (Pb) | -0.8 | 1 | CC | 85 |
| | 60 ($e^-$) | 2.75 (Pb) | -0.8 | 1 | NC | 129 |
| **ep@FCC-he**, 619 data points for $Q^2 \geq 3.5$ $GeV^2$ | 20 ($e^-$) | 7 (p) | 0 | 100 | CC | 46 |
| | 20 ($e^-$) | 7 (p) | 0 | 100 | NC | 89 |
| | 60 ($e^-$) | 50 (p) | -0.8 | 1000 | CC | 67 |
| | 60 ($e^-$) | 50 (p) | 0.8 | 300 | CC | 65 |
| | 60 ($e^+$) | 50 (p) | 0 | 100 | CC | 60 |
| | 60 ($e^-$) | 50 (p) | -0.8 | 1000 | NC | 111 |
| | 60 ($e^-$) | 50 (p) | 0.8 | 300 | NC | 110 |
| | 60 ($e^+$) | 50 (p) | 0 | 100 | NC | 107 |
| **ePb@FCC-he**, 150 data points for $Q^2 \geq 3.5$ $GeV^2$ | 60 ($e^-$) | 20 (Pb) | -0.8 | 10 | CC | 58 |
| | 60 ($e^-$) | 20 (Pb) | -0.8 | 10 | NC | 101 |

# Pseudodata:

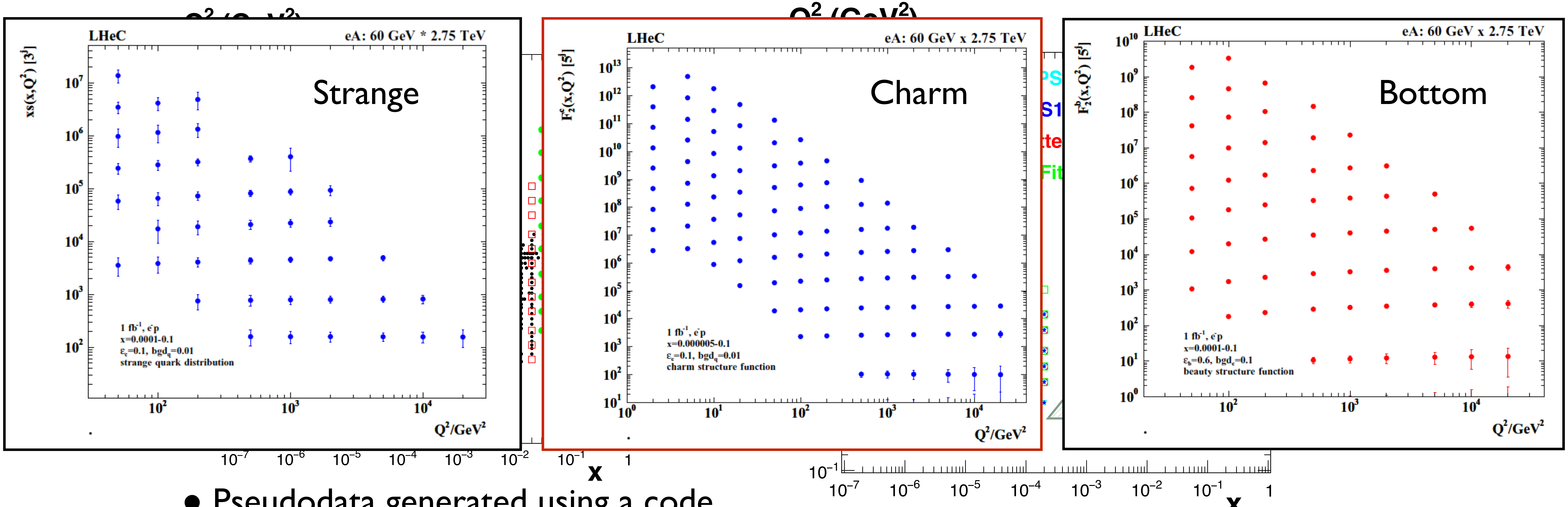



- Pseudodata generated using a code (Max Klein) validated with the H1 MC.
- Cuts: $|\eta_{max}|$=5, 0.95< y< 0.001.
- Error assumptions ~ factor 2 better than at HERA (luminosity uncertainty kept aside).

| Source of uncertainty | Error on the source or cross section |
|---|---|
| scattered electron energy scale | 0.1 % |
| scattered electron polar angle | 0.1 mrad |
| hadronic energy scale | 0.5 % |
| calorimeter noise ($y < 0.01$) | 1-3 % |
| radiative corrections | 1-2 % |
| photoproduction background | 1 % |
| global efficiency error | 0.7 % |

# Pseudodata:

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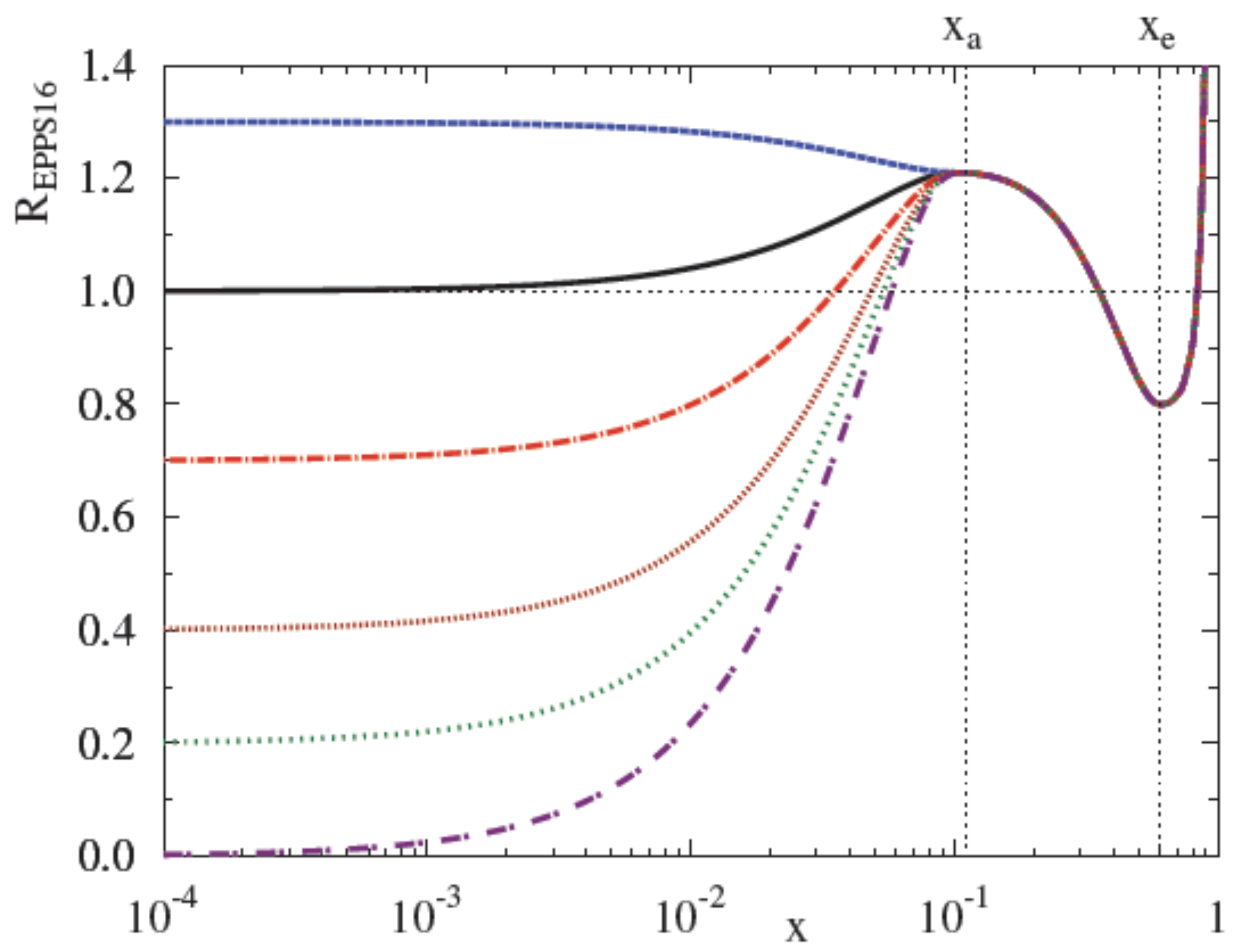
| radiative corrections | 1-2 % |
| photoproduction background | 1 % |
| global efficiency error | 0.7 % |

# EPPS16*: setup

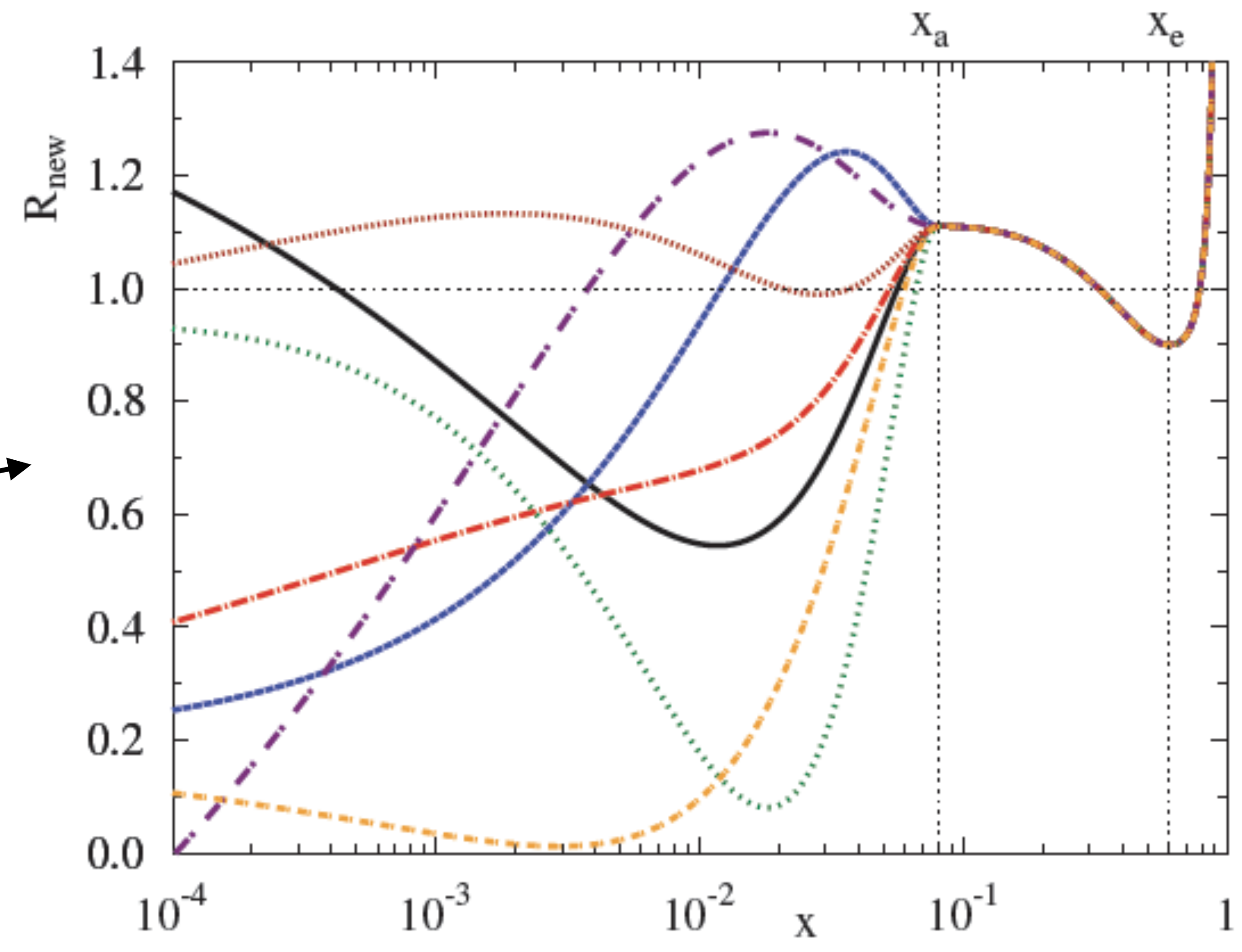


- EPPS16-like analysis updated, with the same data sets plus LHeC NC, CC and charm reduced cross sections.
- Central values generated using EPS09.
- Same methods and tolerance ($\Delta\chi^2$=52) as in EPPS16, but more flexible functional form at small x.

$$R_{\rm EPPS16}(x) = \begin{cases} a_0 + a_1(x-x_a)^2 & x \le x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1. \end{cases}$$

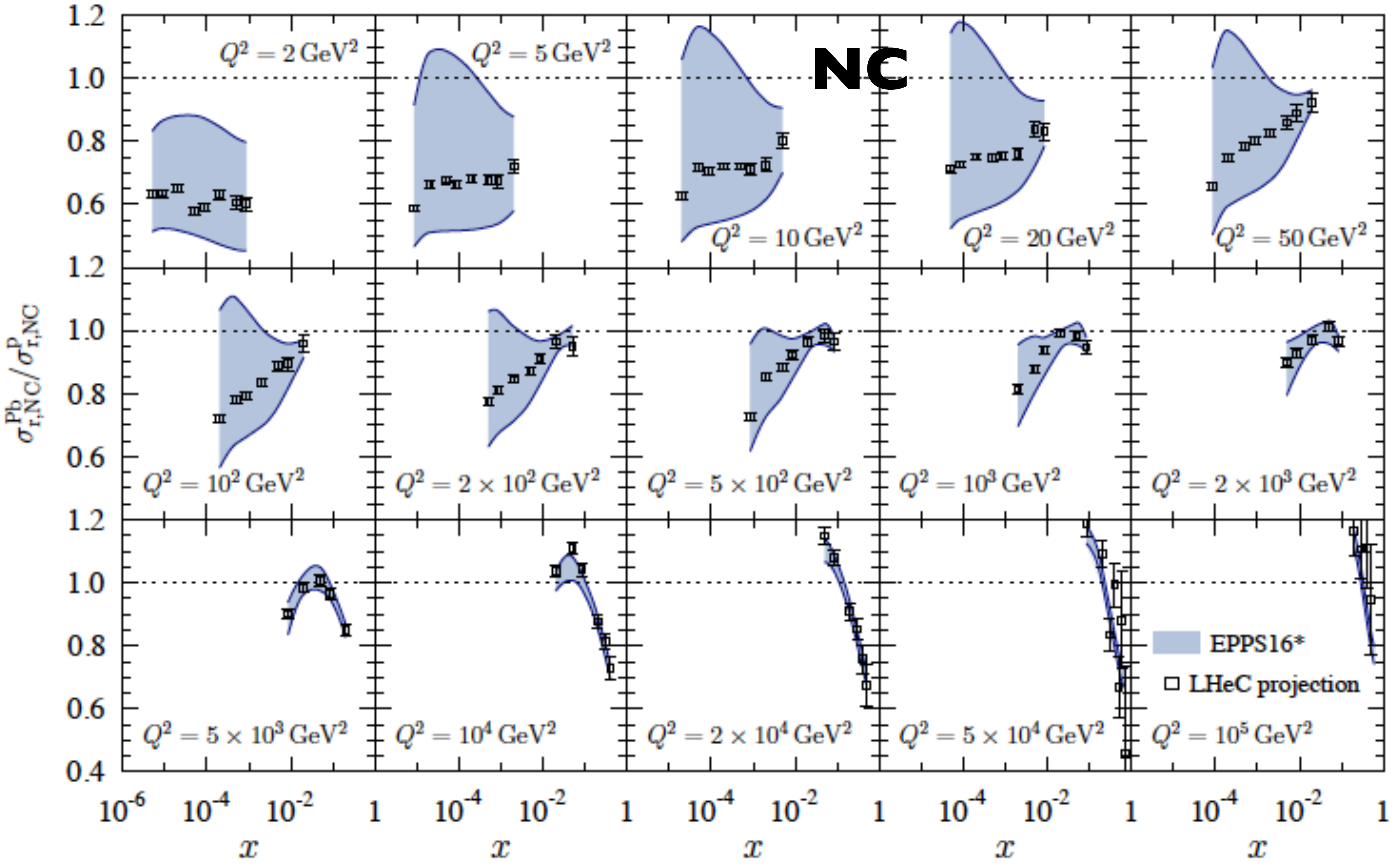



$$R_{\rm new}(x \le x_a) = a_0 + (x-x_a)^2 \left[ a_1 + \sum_{k=1}^{2} a_{k+2} x^{k/4} \right]$$



# EPPS16*: results

- Large effect of NC+CC LHeC pseudodata, and of charm on the glue at small x.
- Limitation on u/d decomposition inherent to almost isospin symmetric nuclei (u/d difference suppressed by 2Z/A-1).



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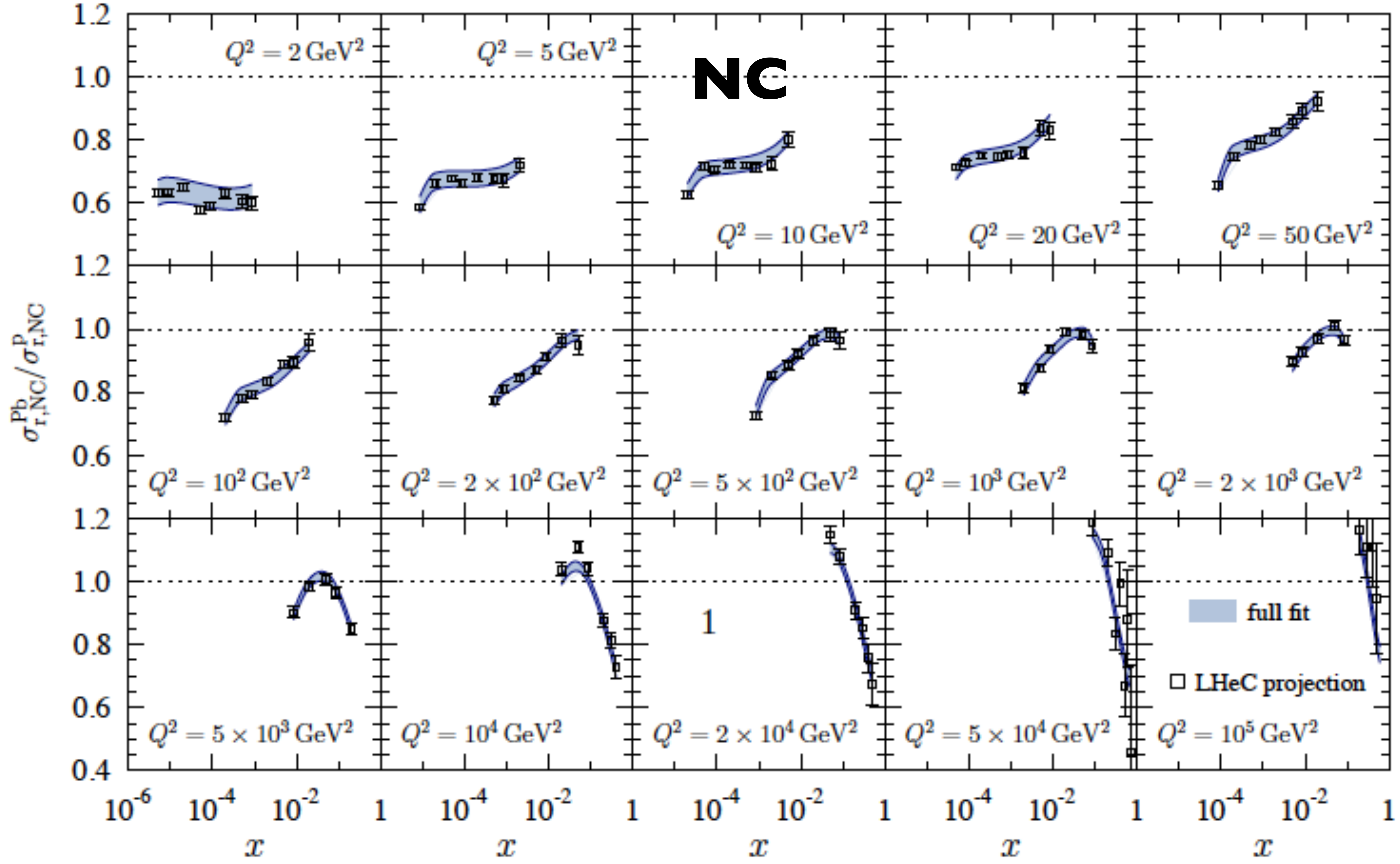

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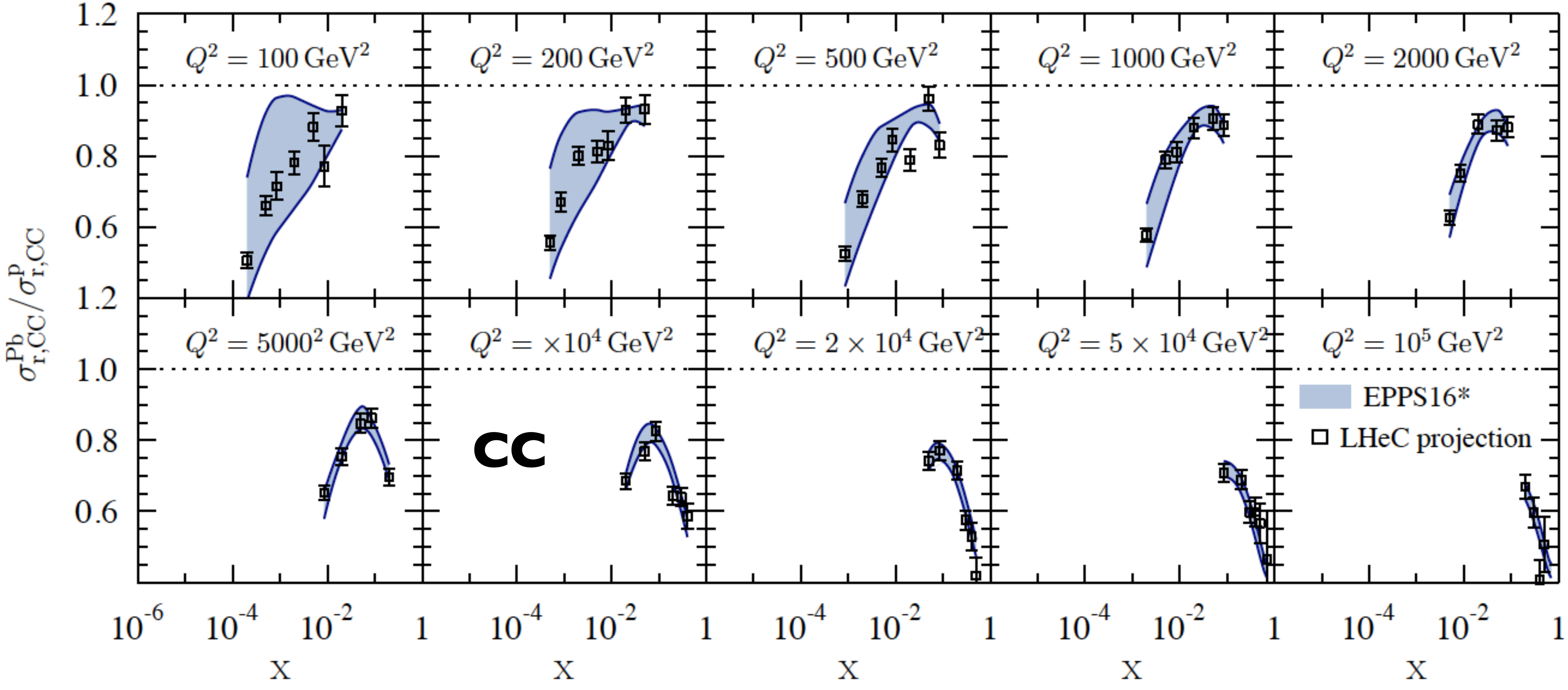

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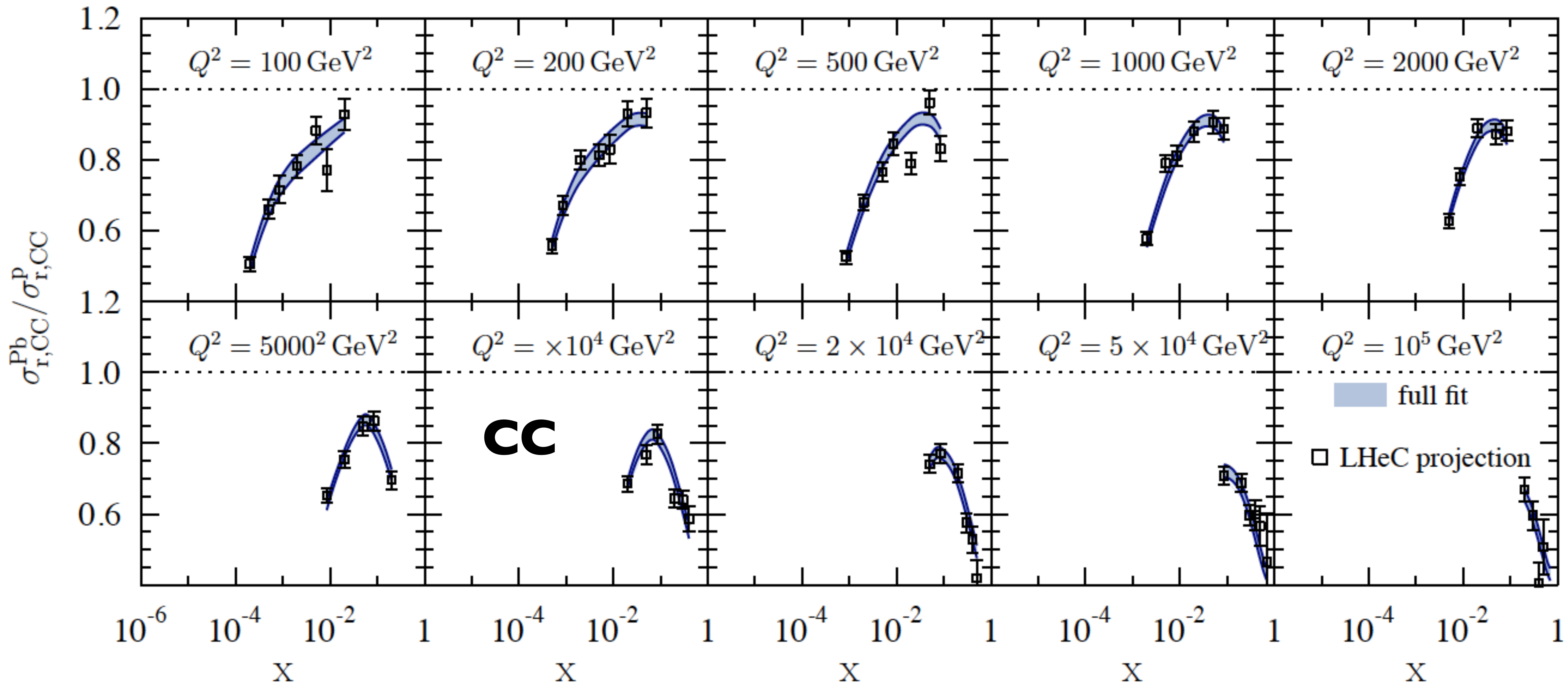

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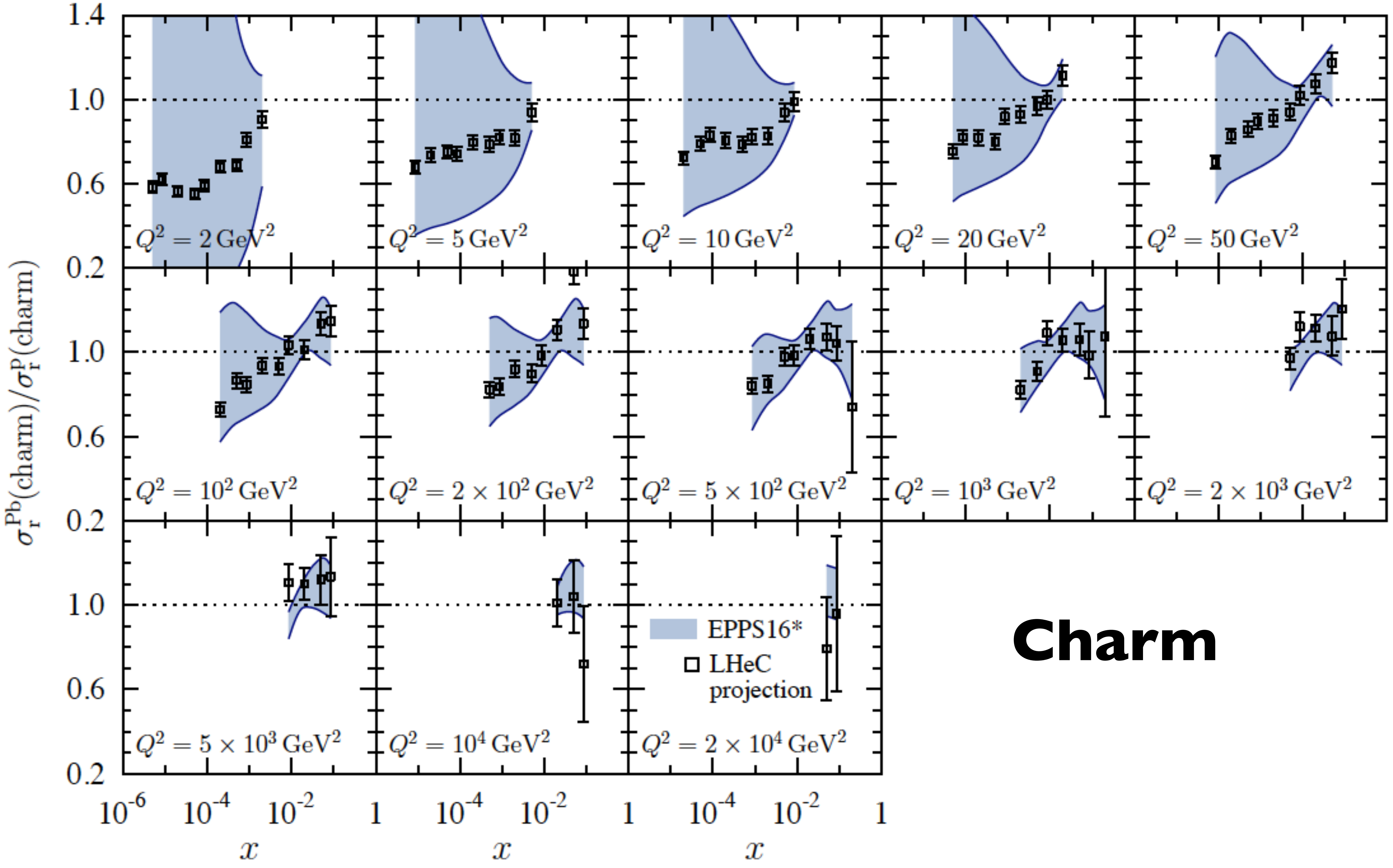


**Charm**

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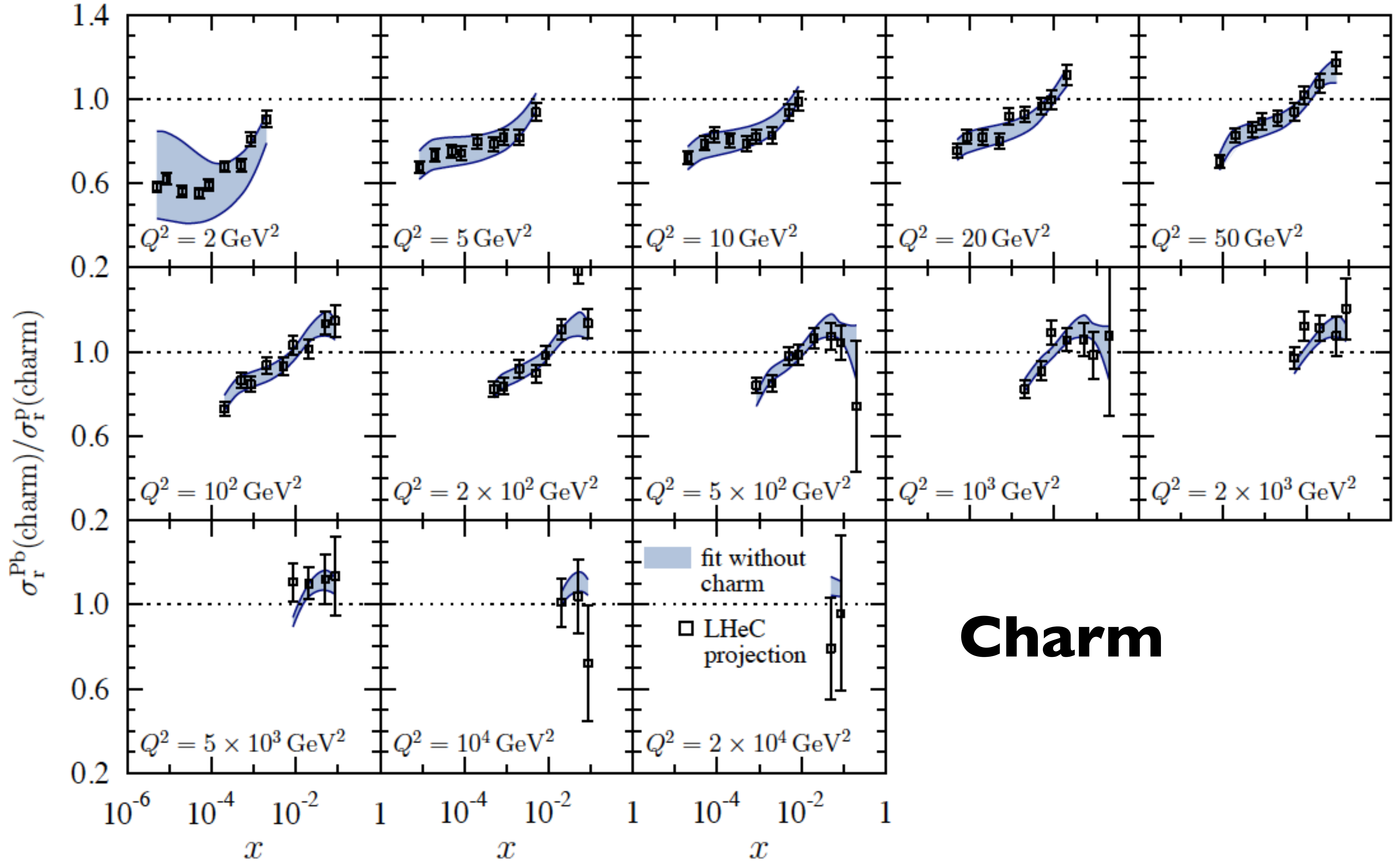


**Charm**

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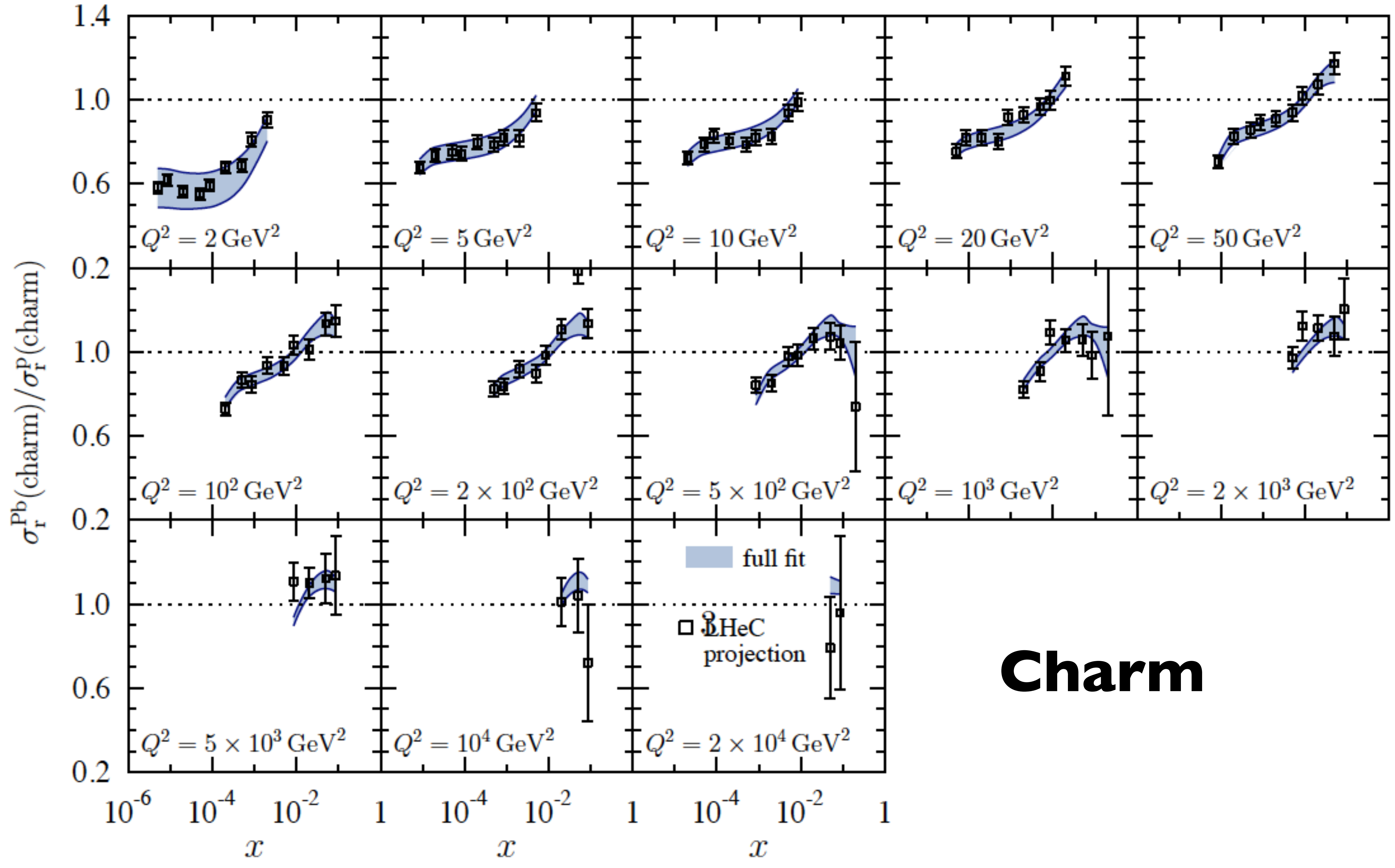


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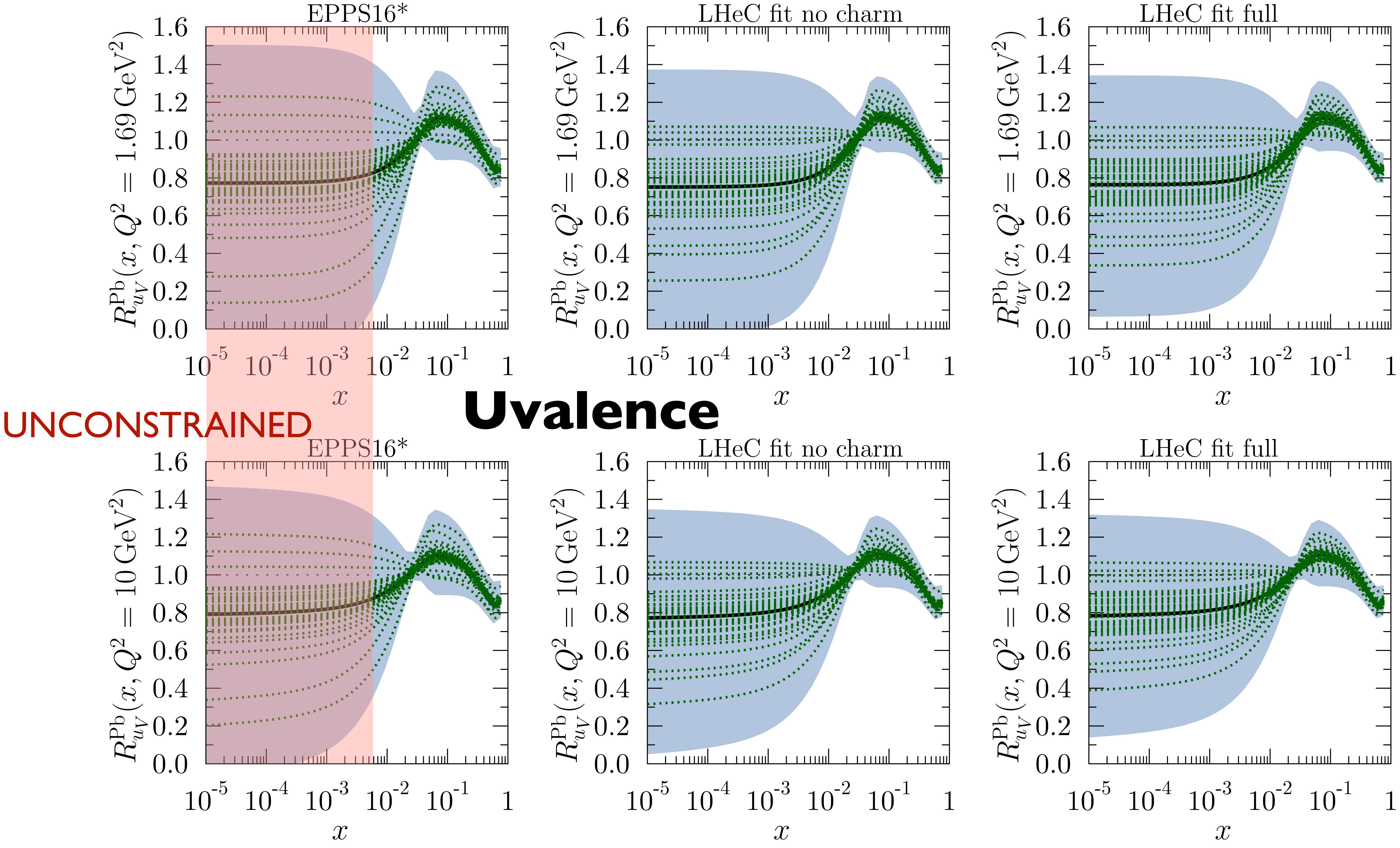

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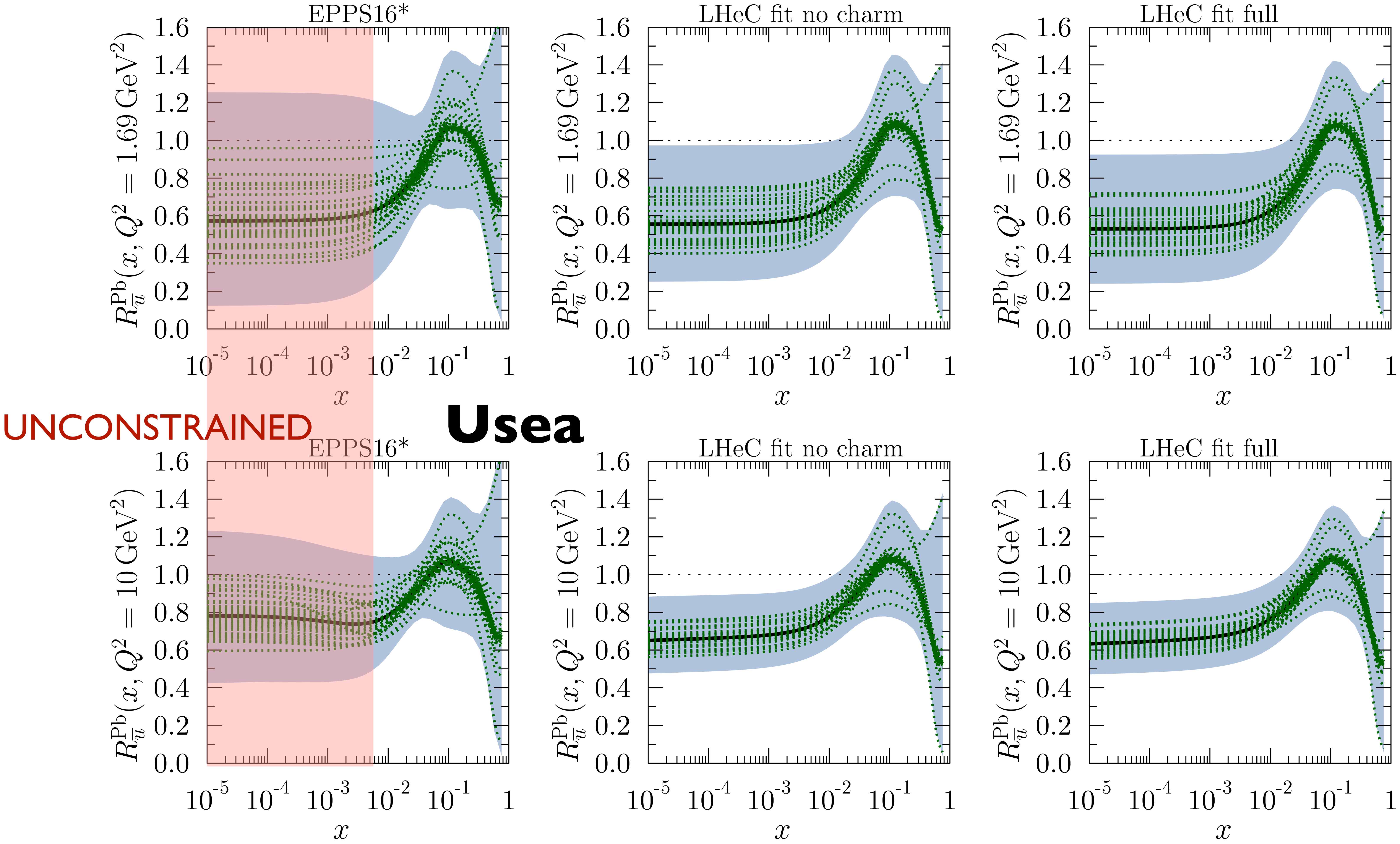

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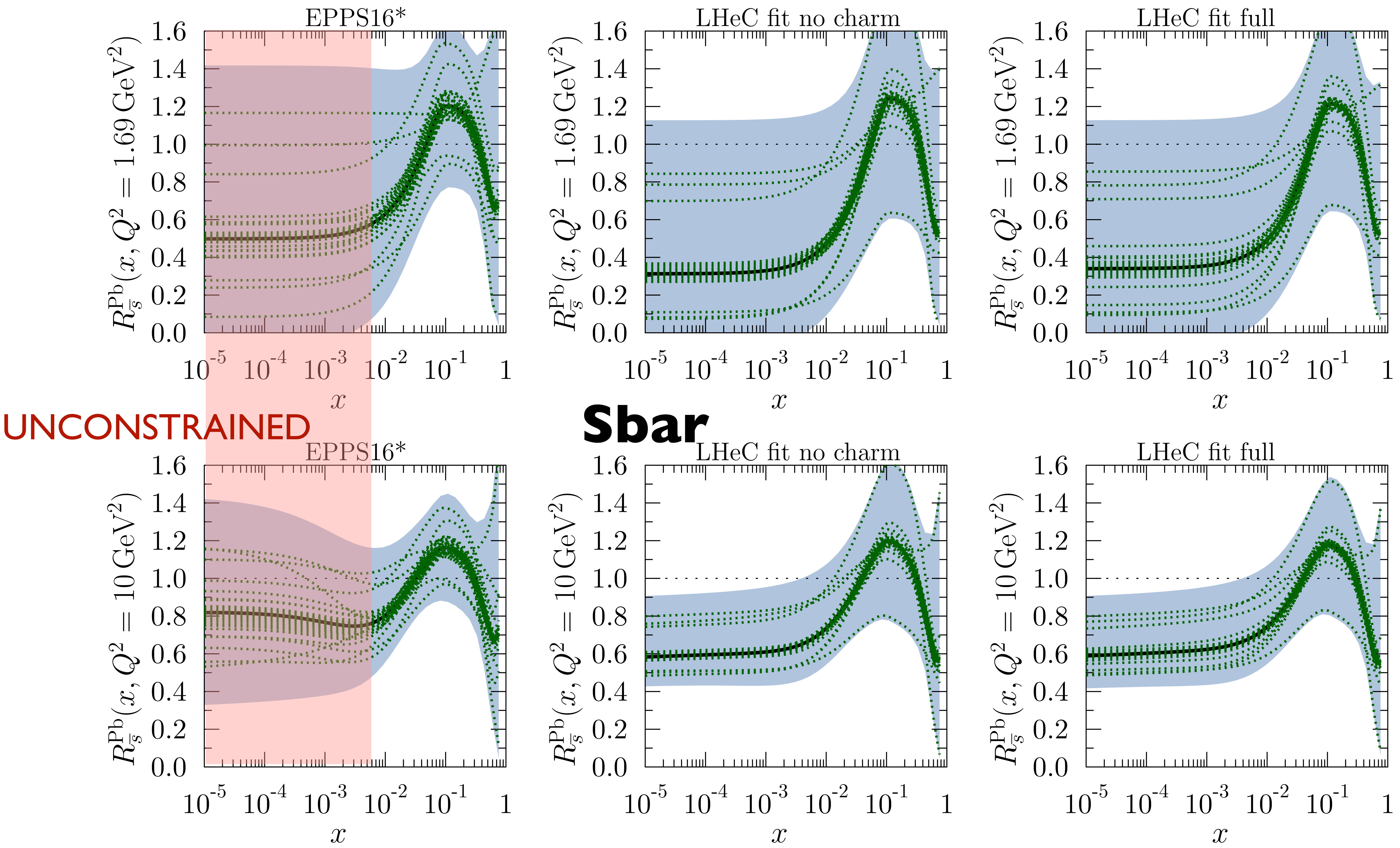

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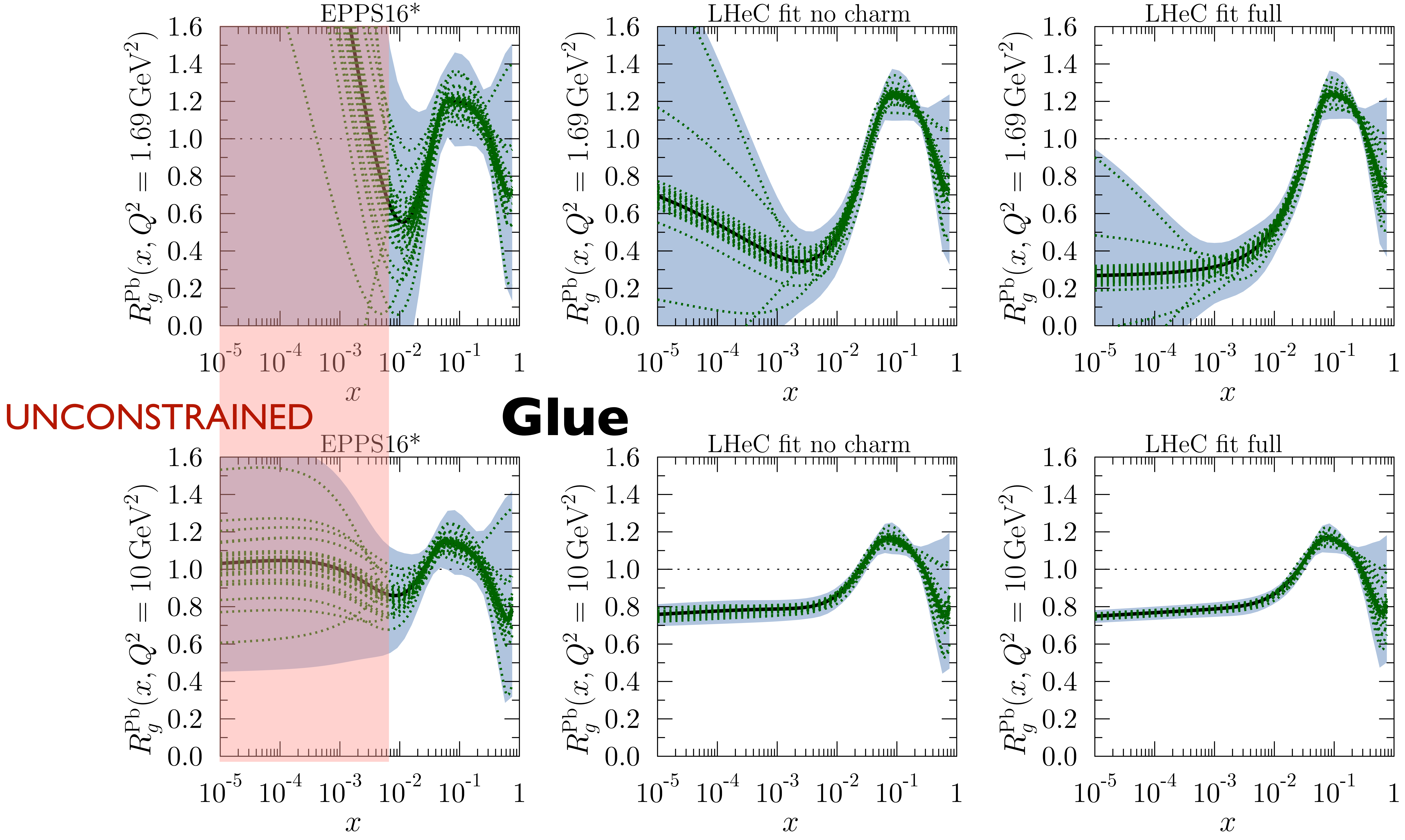

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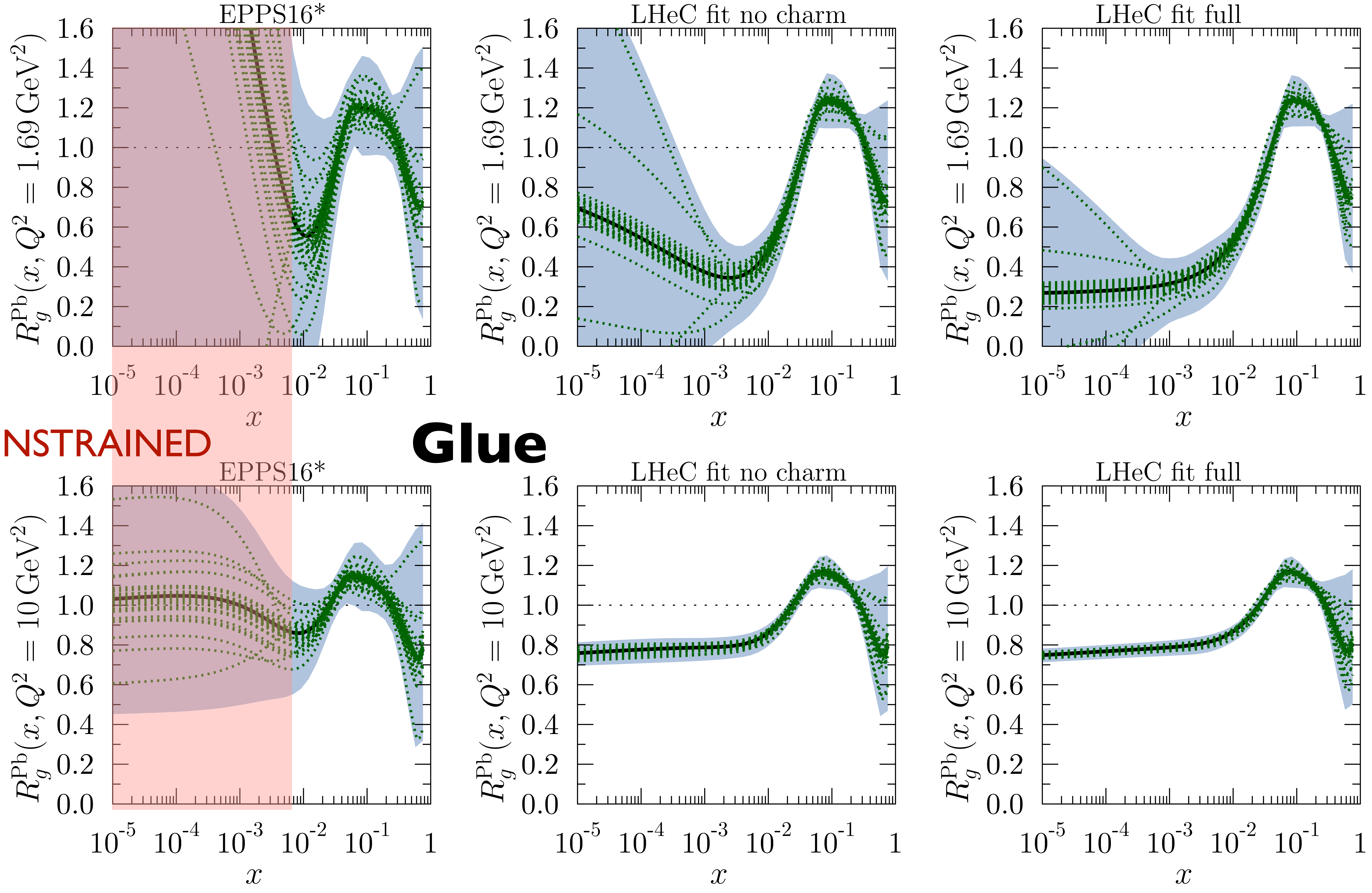
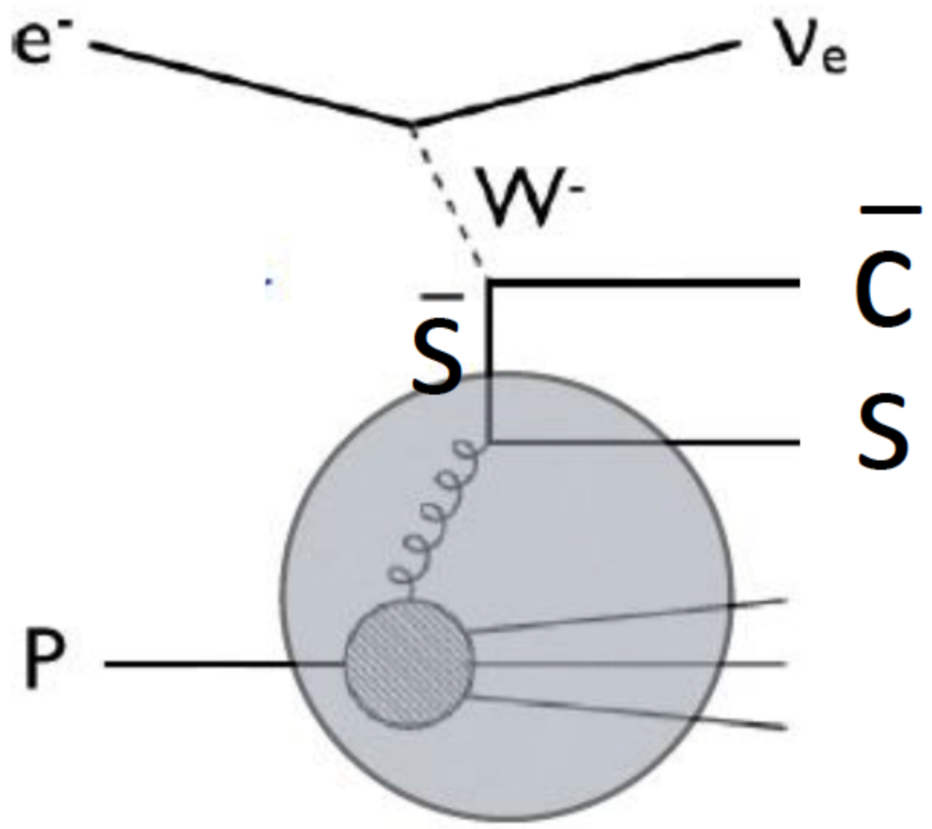



- Possible further improvements: beauty, c-tagged CC for strange.



# xFitter: method

● Extraction of **Pb-only** PDFs by fitting NC+CC pseudodata, using xFitter (1410.4412)1.2.2 to estimate the uncertainties coming solely from the achievable experimental precision.

➜ HERAPDF2.0-type parametrisation (1506.06042, 14 parameters), NNLO evolution, RTOPT mass scheme, $\alpha_s$=0.118.

$$xU = xu + xc\,, \qquad x\bar{U} = x\bar{u} + x\bar{c}\,, \qquad xD = xd + xs\,, \qquad x\bar{D} = x\bar{d} + x\bar{s}$$

$$\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right),\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1 + D_{\bar{U}}x\right),\\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}$$

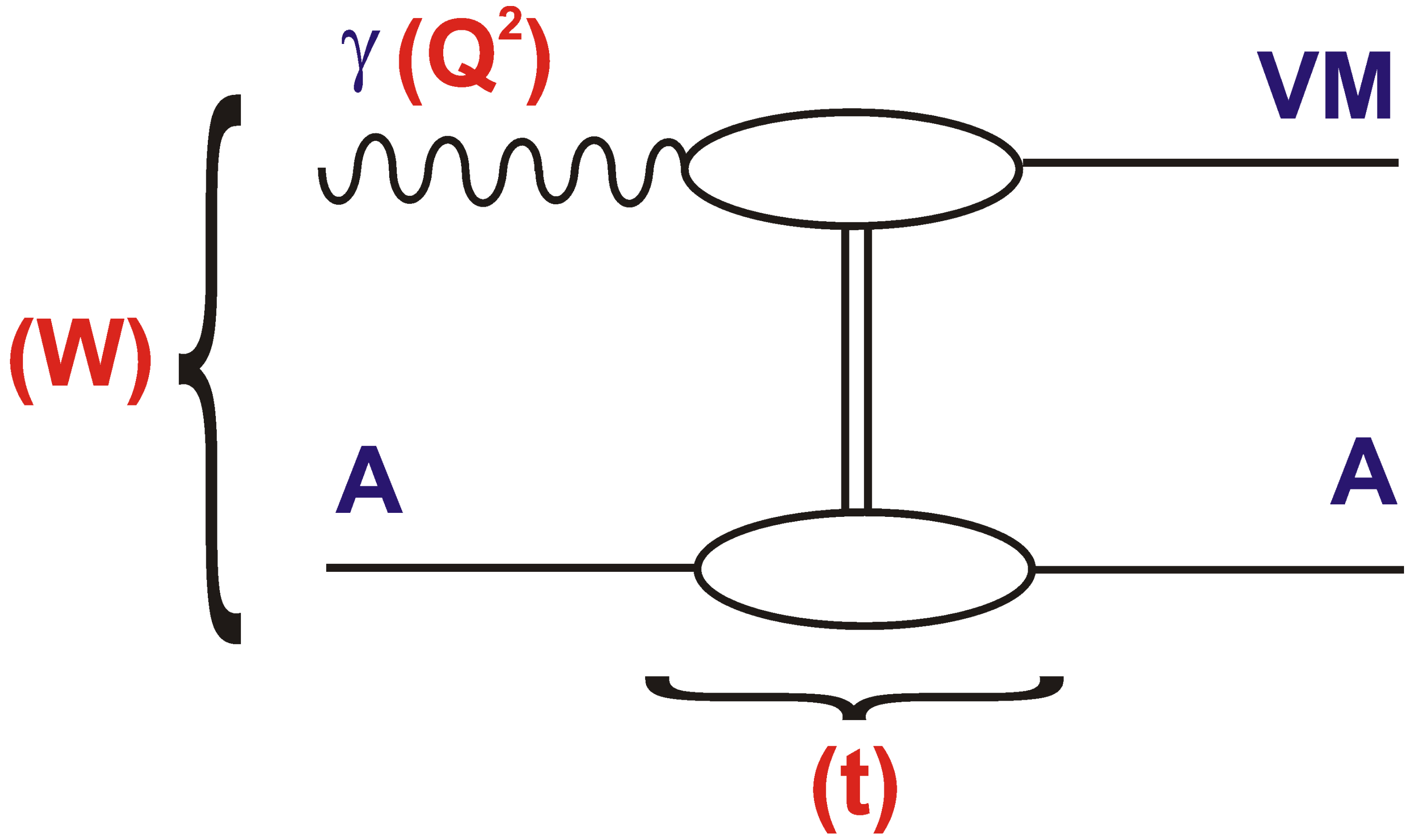
➜ Central pseudodata values from HERAPDF2.0: neither parametrisation bias nor theory uncertainties.

➜ Standard xFitter/HERAPDF treatment of correlated/uncorrelated systematics; tolerance $\Delta\chi^2$=1 (note $\Delta\chi^2$=52 in EPPS16*).

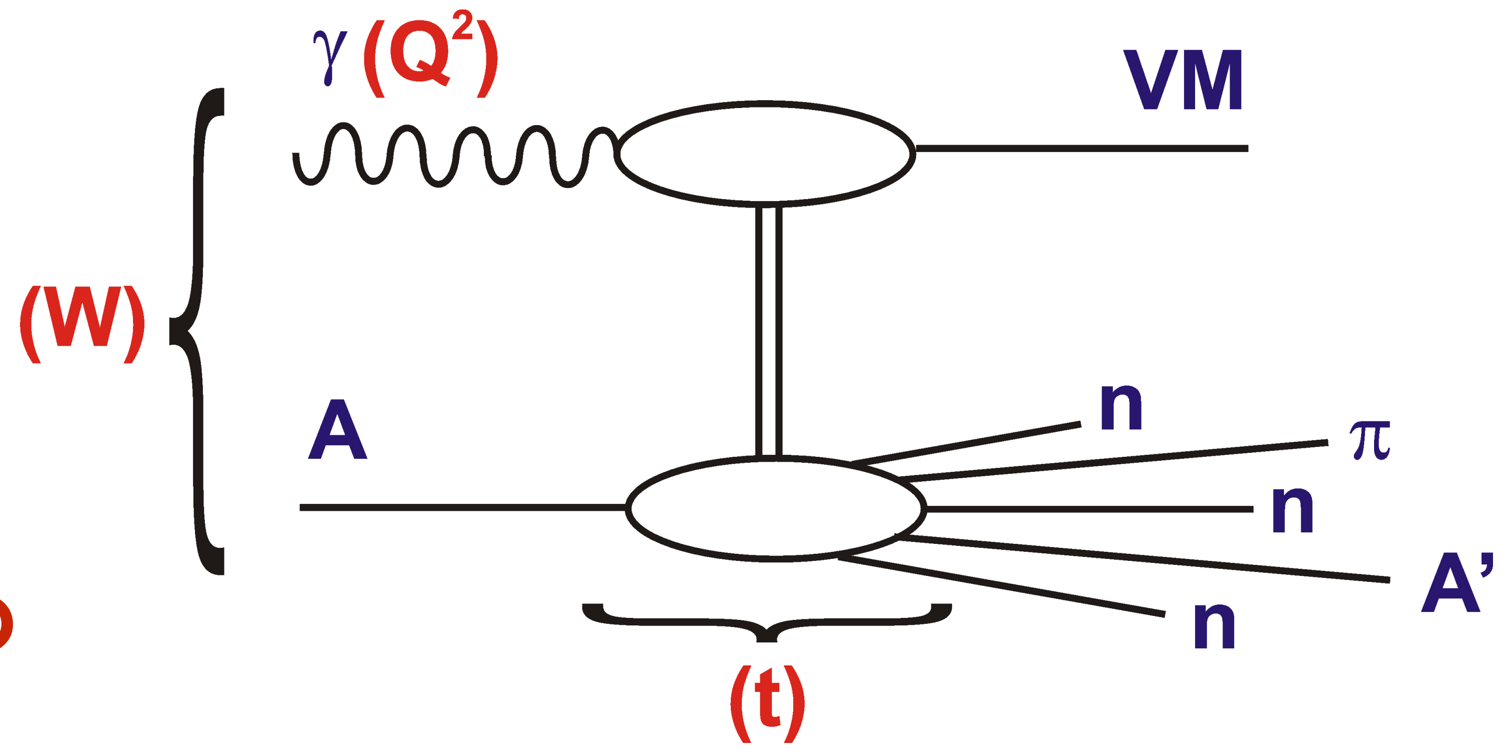
➜ Only data with $Q^2 \geq 3.5$ GeV$^2$, initial evolution scale 1.9 GeV$^2$.

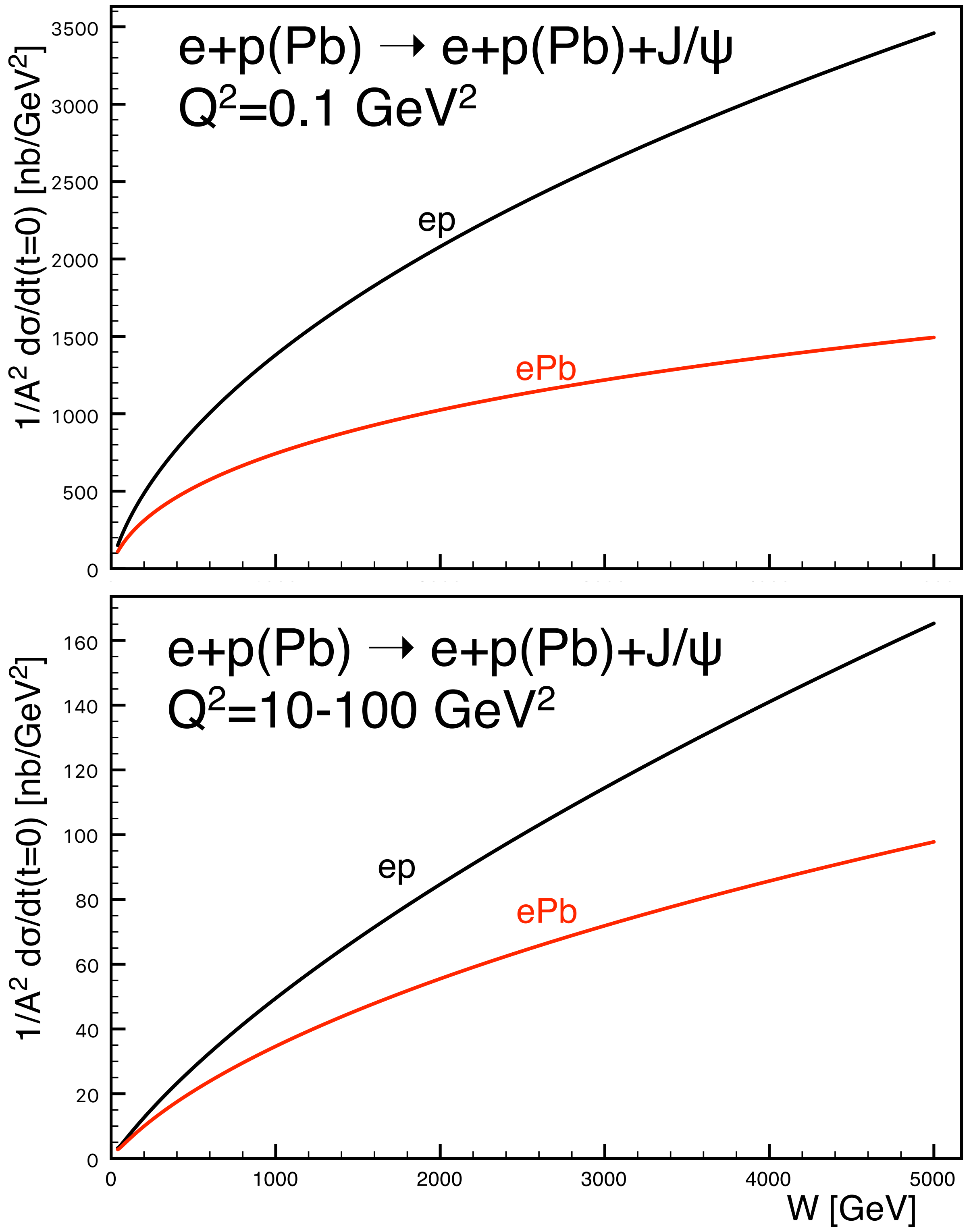
➜ Proton PDFs extracted in the same setup for consistency.

# Elastic VM production:

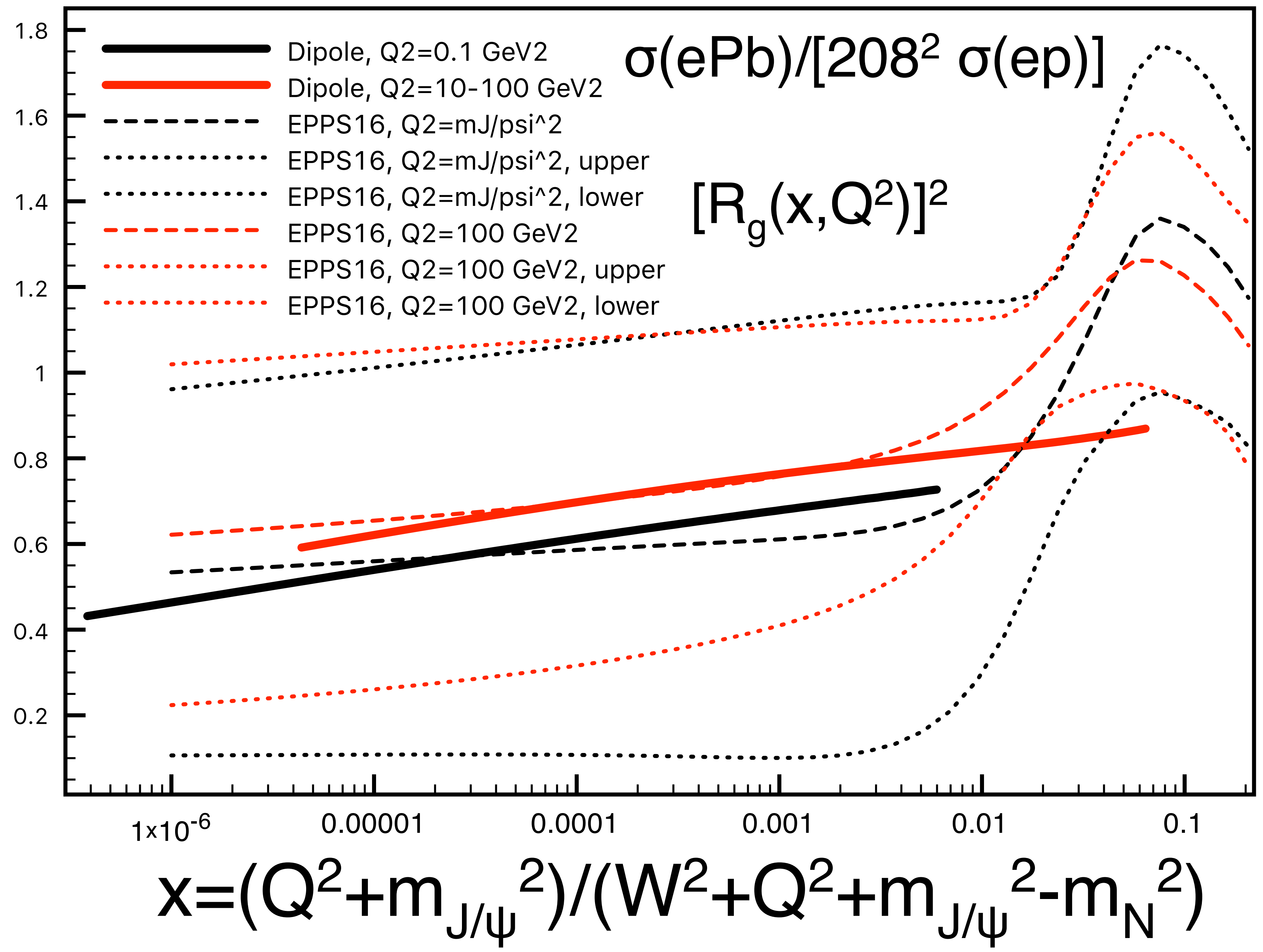



- Challenging experimental problem.
- Coherent case: energy dependence and dips.
- Incoherent case: sensitivity to fluctuations.



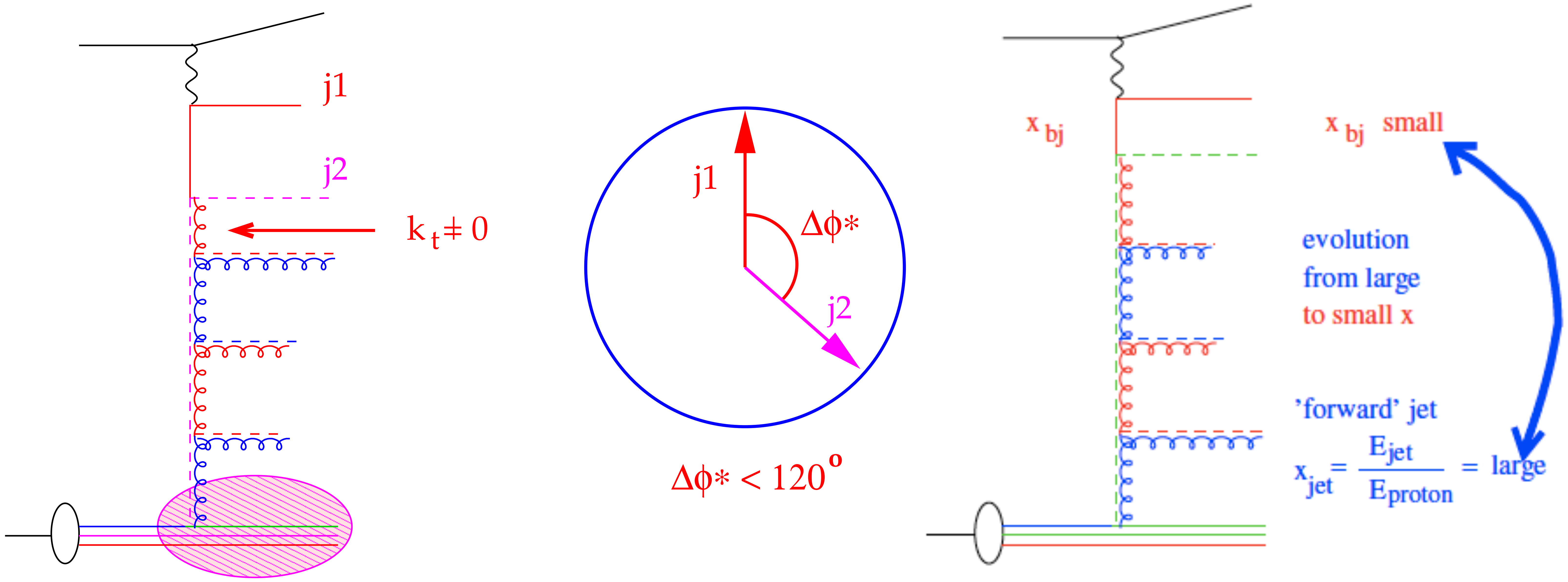

- Will nuclear effects alone disentangle saturation?




Mantysaari, Paukkunen

# Azimuthal correlations (II):

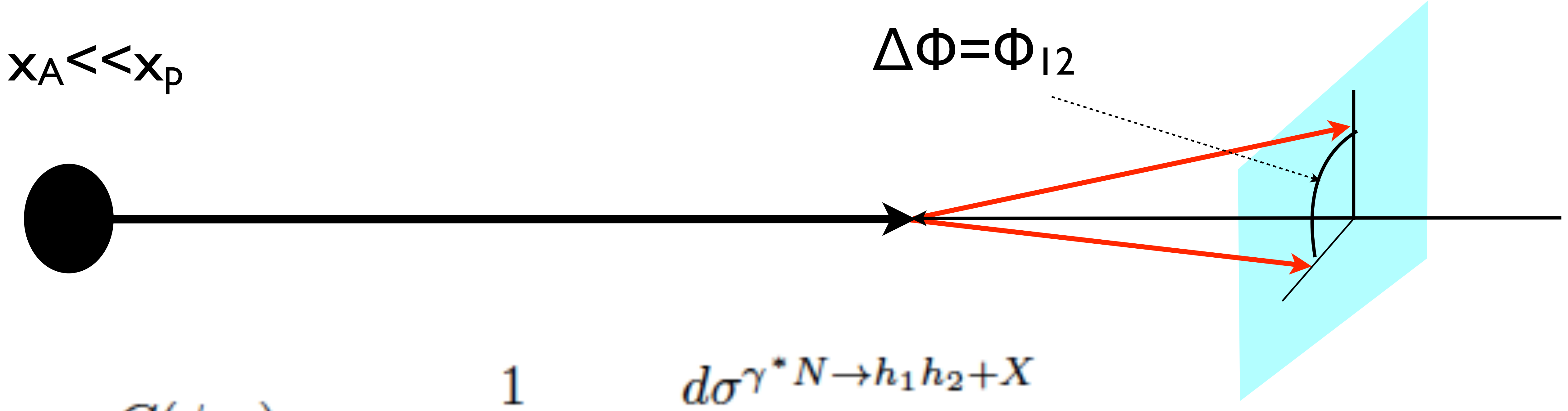
- Studying dijet azimuthal decorrelation or forward jets ($p_T \sim Q$) in ep/eA/pp/pA would allow to understand the mechanism of radiation:
  - ➜ $k_T$-ordered: DGLAP.
  - ➜ $k_T$-disordered: BFKL.
  - ➜ Saturation?
- Further imposing a rapidity gap (diffractive jets) is most interesting.



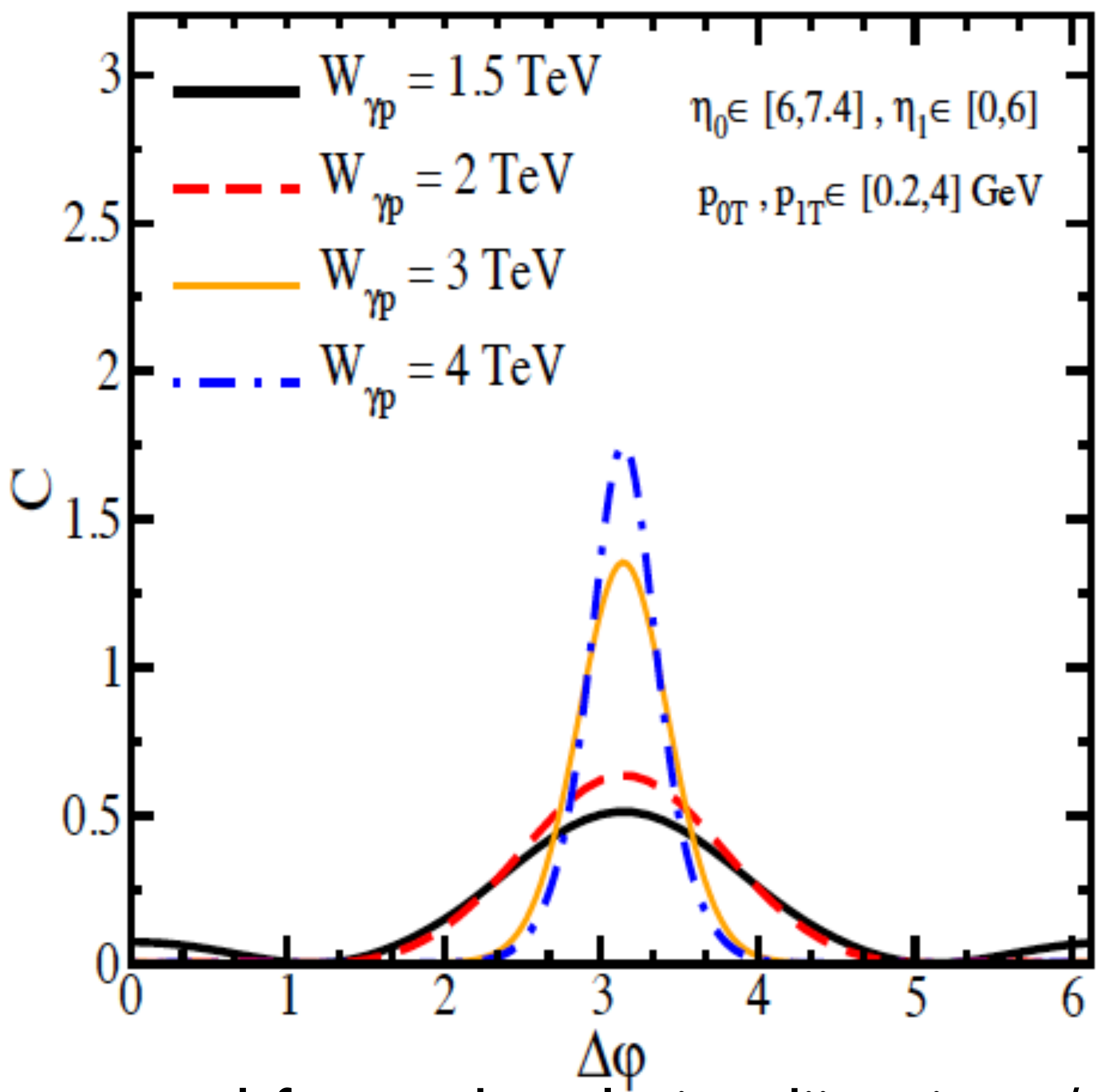

- **Nuclear and saturation effects on usual BFKL signals** (e.g. dijet azimuthal decorrelation, Mueller-Navelet jets) has not been extensively addressed (Kovchegov-Jalilian-Marian, see also A. Ramnath et al., K. Kutak et al.): A-dependence?

# Azimuthal correlations:

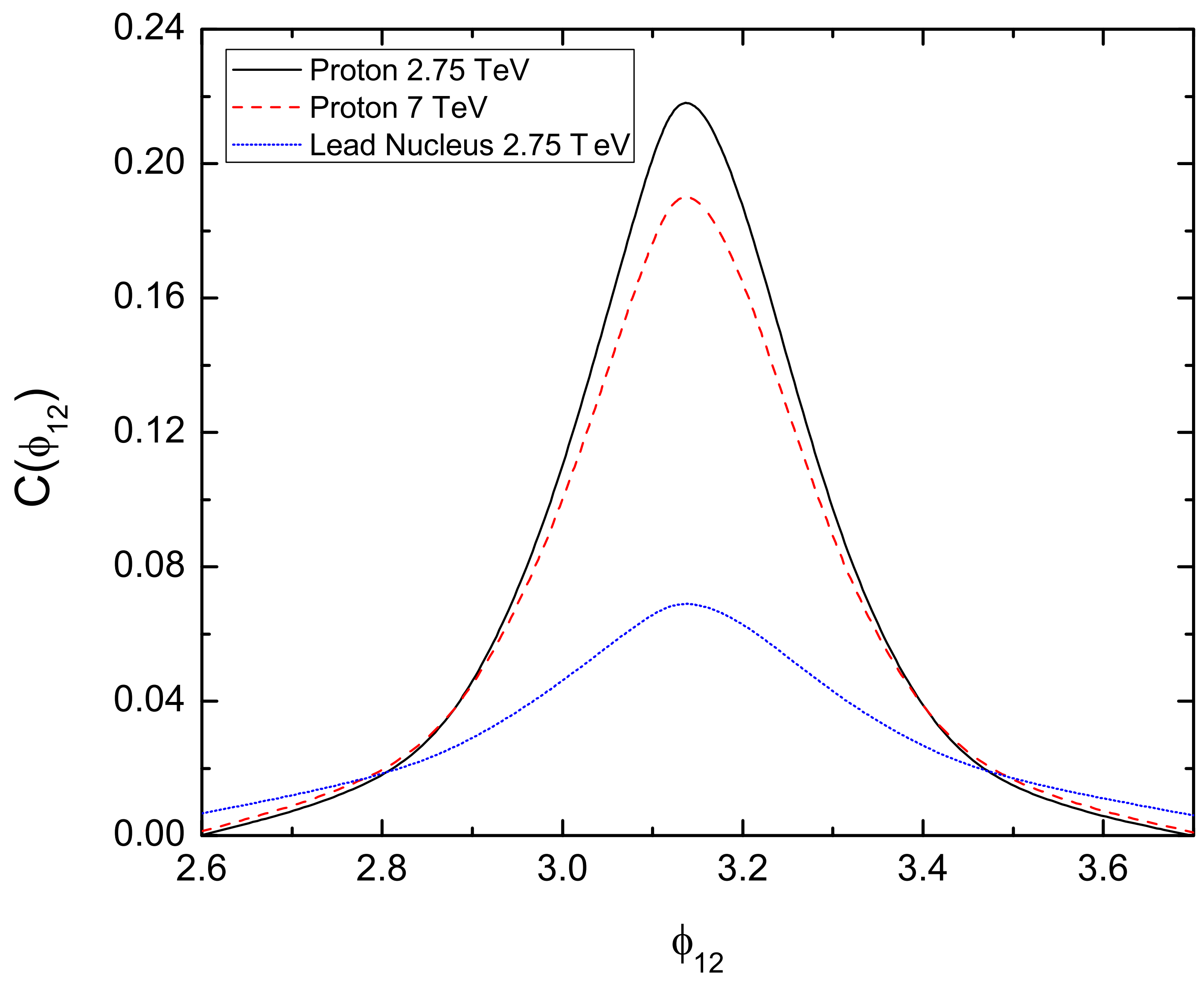
- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- To be studied far from kinematical limits.




$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N \to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d\phi_{12}}$$




central-forward exclusive dijets in ep/eA, 1511.07452

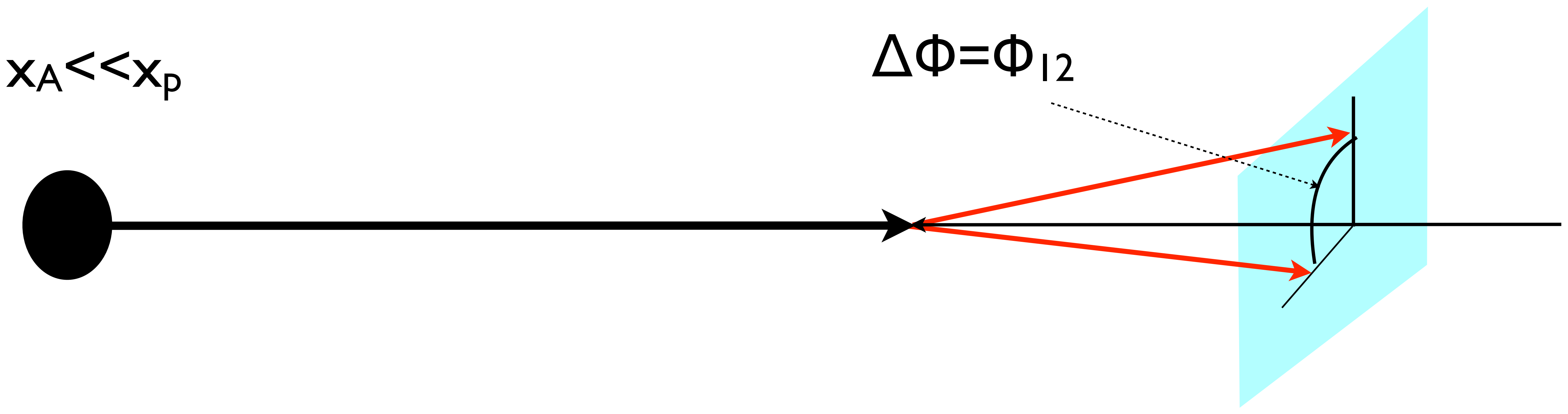



h-h in ePb

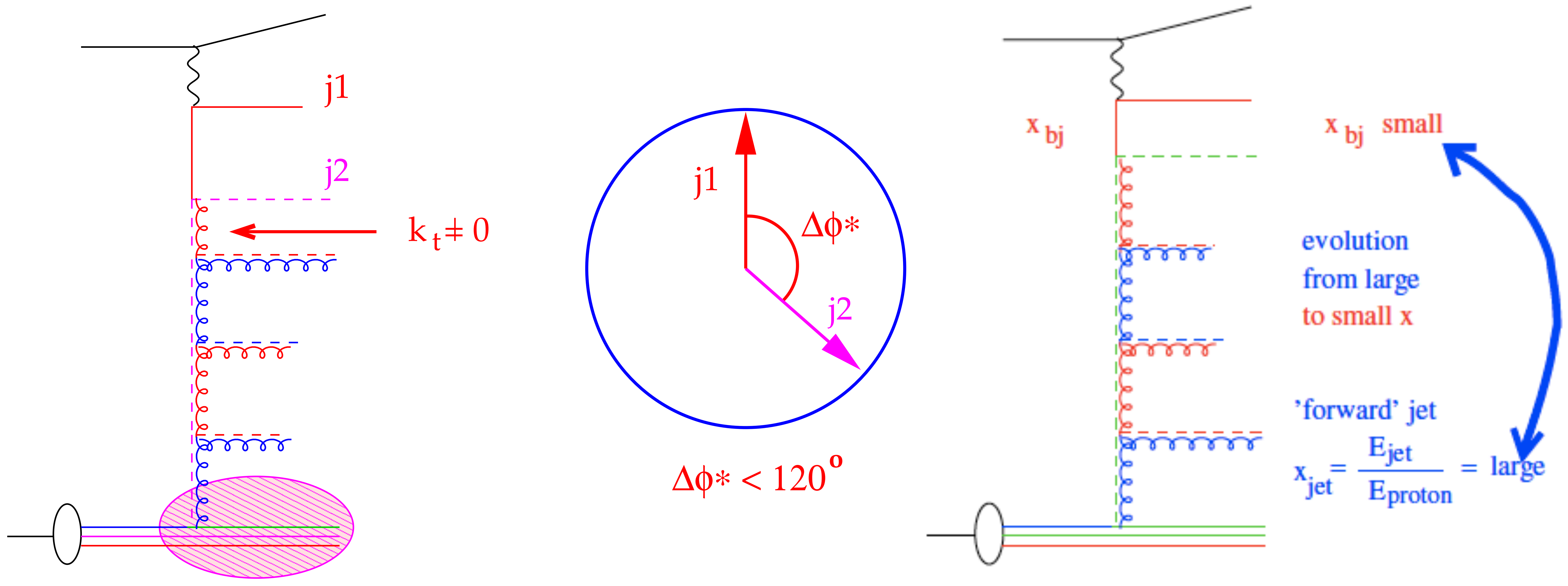
$p_T^{lead}$>3 GeV
$p_T^{ass}$>2 GeV
$z_{lead}=z_{ass}$=0.3
y=0.7
$Q^2$=4 GeV$^2$

# Azimuthal correlations:

- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- To be studied far from kinematical limits.




- **Nuclear and saturation effects on usual BFKL signals** (e.g. dijet azimuthal decorrelation, Mueller-Navelet jets) has not been extensively addressed in pA, less in DIS: A-dependence?

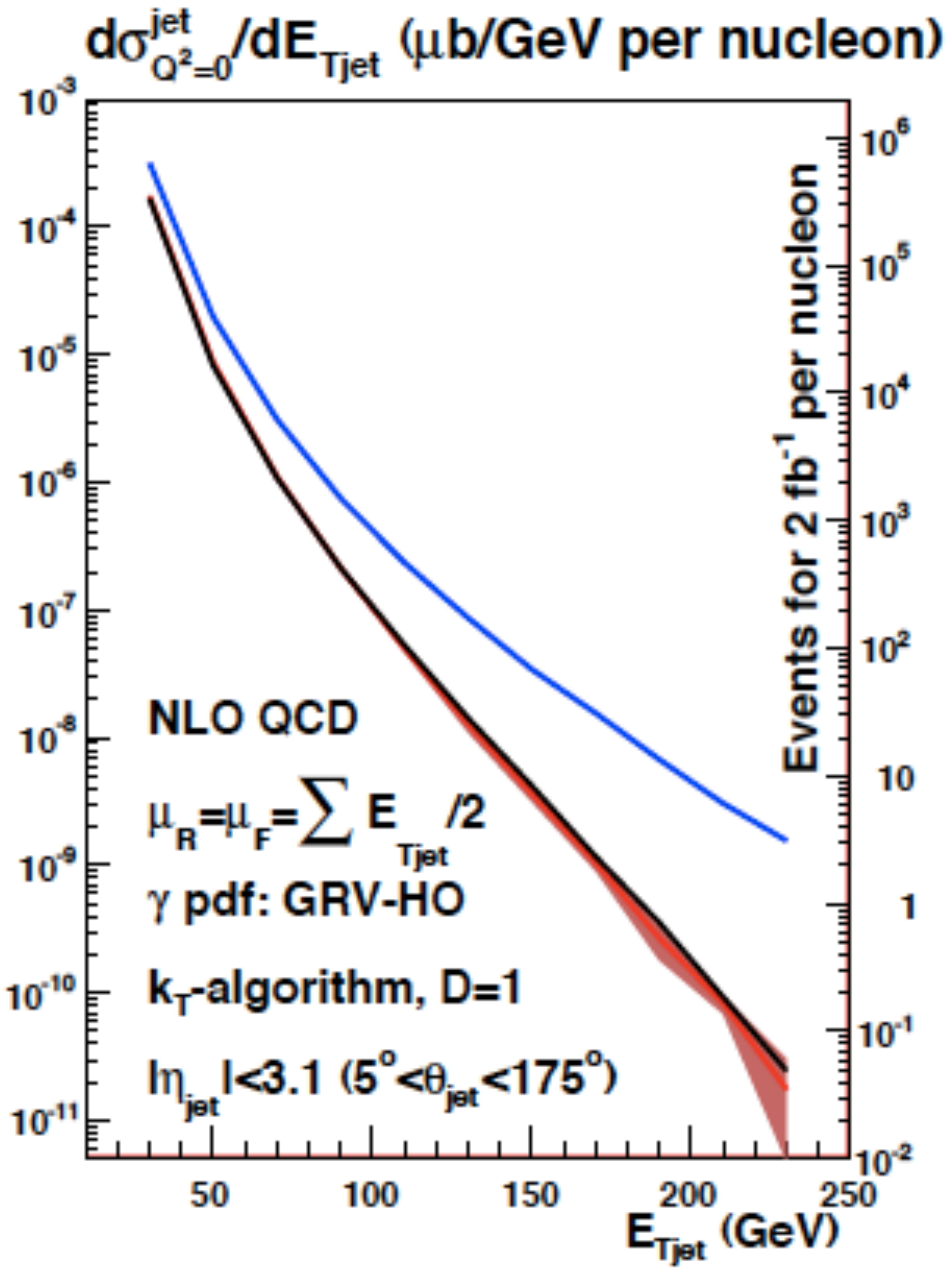


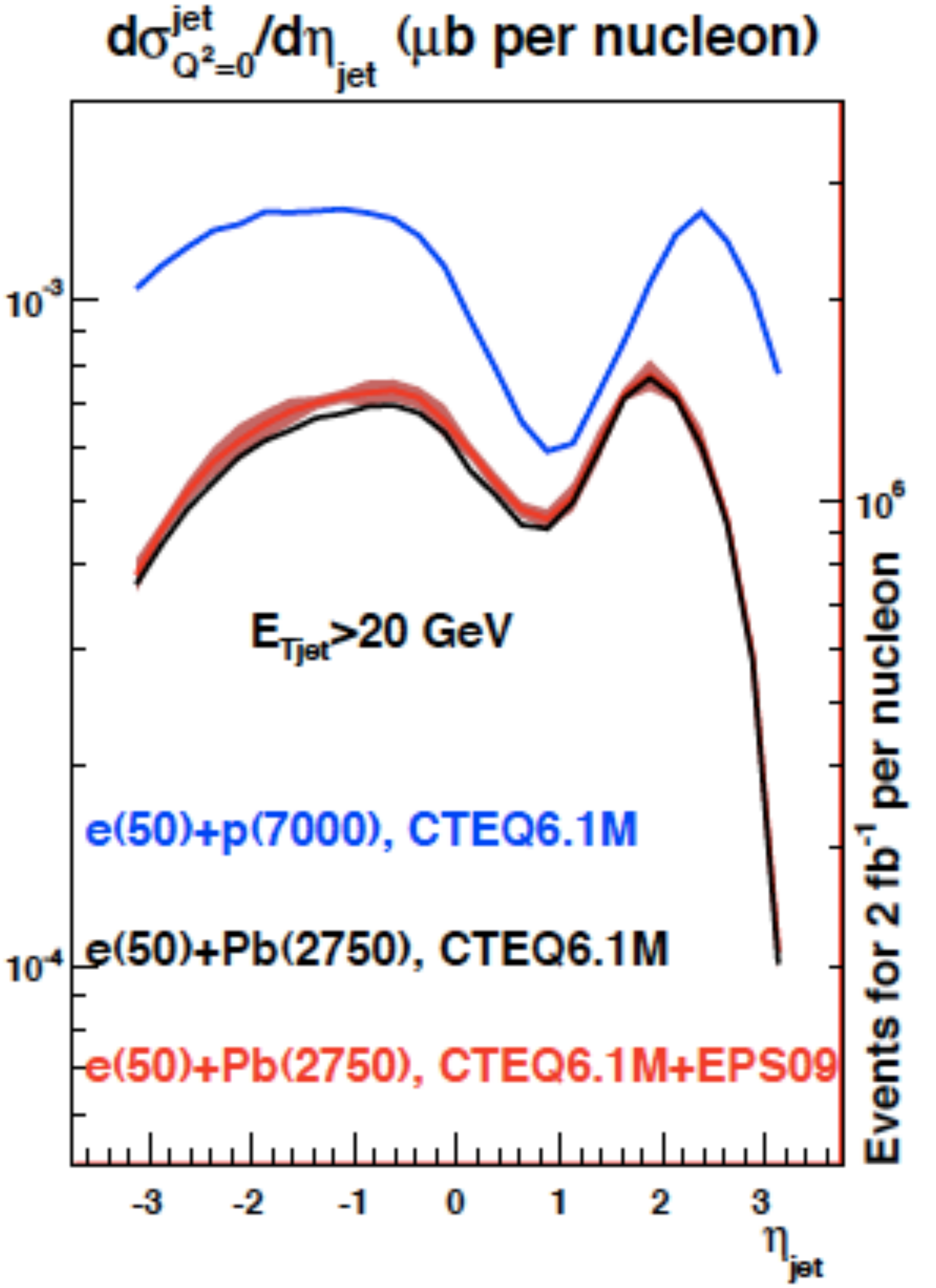
# Jets:

- Jet observables in AA: energy loss + response of the medium must be disentangled for characterisation of the medium.
- Jets not suppressed in pPb @ LHC: compatibility with softer observables? → **small systems**.
- Jets (inclusive and diffractive) abundantly produced in eA up to sizeable $E_T$, they can be used to **test factorisation and for precision studies of changes of QCD radiation in the nuclear environment ⇒**

**hard probes of the QGP.**

LHeC CDR 1206.2913

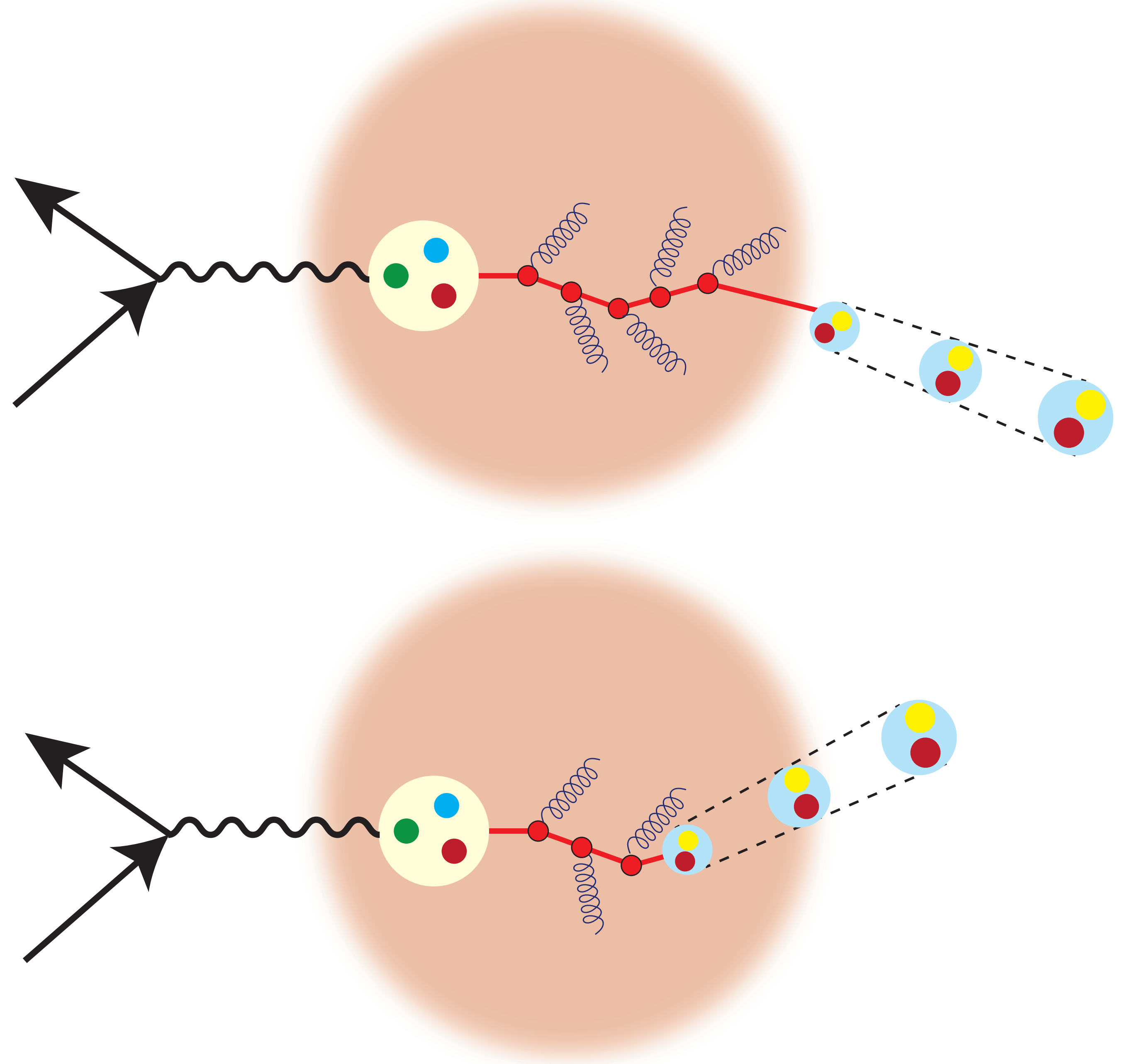


# Fragmentation functions:

- eA: dynamics of QCD radiation and hadronization for light and heavy particles (energy loss of light and heavy, and quarkonium production and suppression), **relevant for particle production off nuclei** (nPDF determination in pA) **and for QGP analysis in AA.**

➜ High energy: partonic evolution altered in the nuclear medium.



➜ Low energy: hadronization inside → formation time, (pre-)hadronic absorption,...

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$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{dN_A^h(z,\nu)}{d\nu\, dz} \Bigg/ \frac{1}{N_D^e}\frac{dN_D^h(z,\nu)}{d\nu\, dz}$$