Hard Probes 2018

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Resolving the Partonic Structure of Nuclei through Energy-Frontier eA Scattering

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for the LHeC/FCC-eh Study group, http://lhec.web.cern.ch/

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- ➜ Pseudodata (M. Klein).
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- ➜ xFitter analysis (P. Agostini, NA).

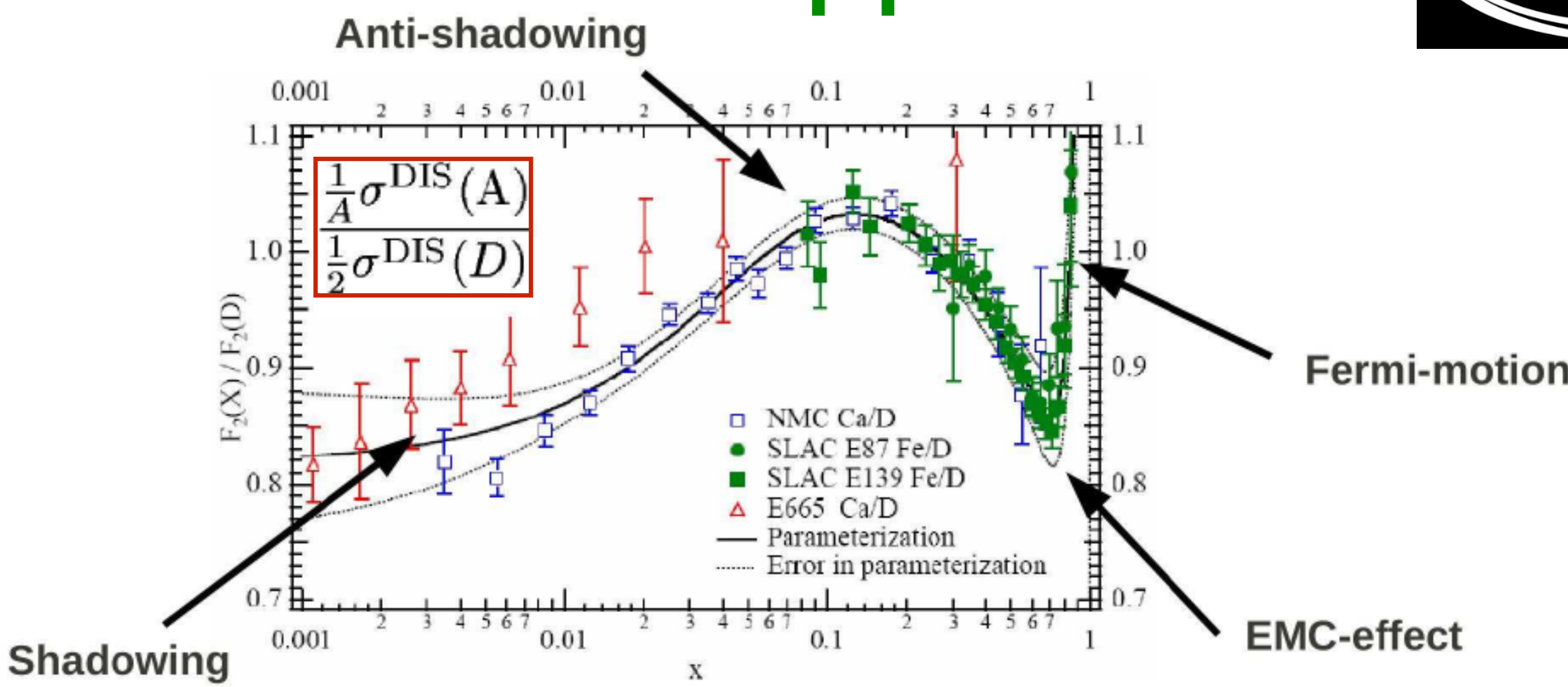
3. Diffractive PDFs at the LHeC and FCC-eh (NA, P. Newman, W. Slominski, A. Stasto):

- ➜ Pseudodata.
- ➜ Method.
- ➜ Results.

4. Summary.

See the talks by Hannu Paukkunen, Heikki Mäntysaari, Thomas Peitzmann, Rabah Abdul Khalek, Hyunchul Kim, Amal Sarkar, Jakub Kremer, Ilkka Helenius, Yeonju Go, Petja Paakinen, Aleksander Kusina and Max Klein.
LHeC/FCC-eh: CDR J. Phys. G39 (2012) 075001, arXiv:1206.2913 [physics.acc-ph]; 2018 workshop, https://indico.cern.ch/event/698368/.

Collinear approach:



- Bound nucleon≠free nucleon: search for process independent nPDFs that realise this condition, assuming 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

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

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

Collinear approach:

Anti-shadowing

- At an energy-frontier ep/eA collider:
  ➜ PDFs 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.

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

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\overline{q},g} \underbrace{f_i^A(\mu^2)}_{\text{Nuclear PDFs, obeying the standard DGLAP}} \otimes \underbrace{\hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)}_{\text{Usual perturbative coefficient functions}}$$

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

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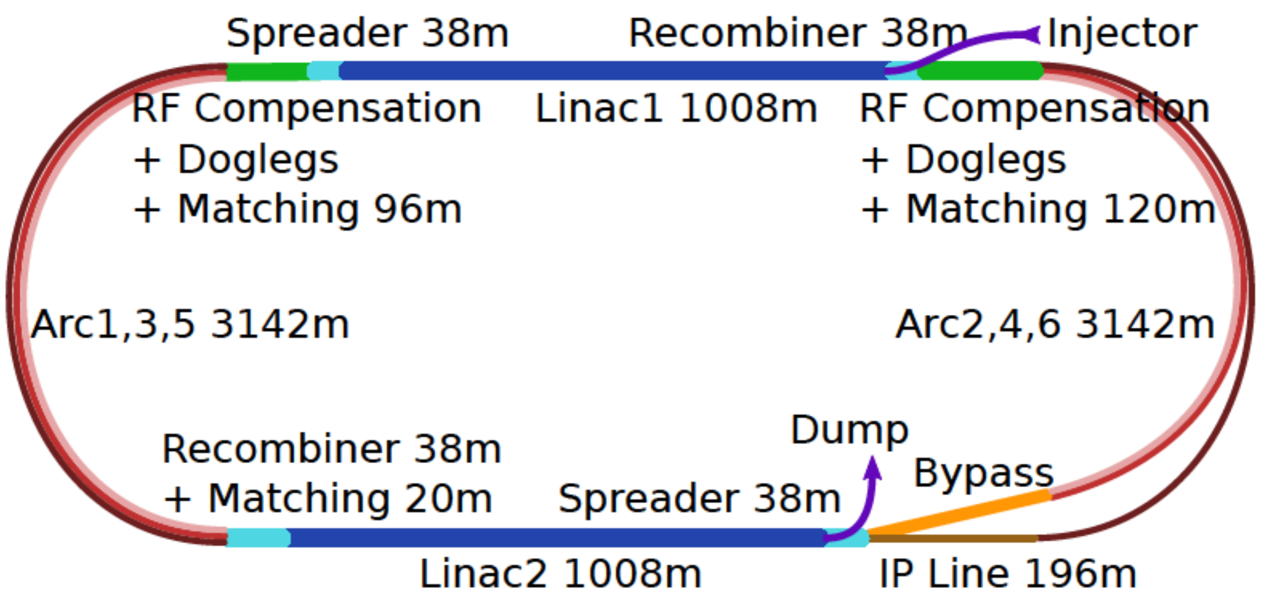
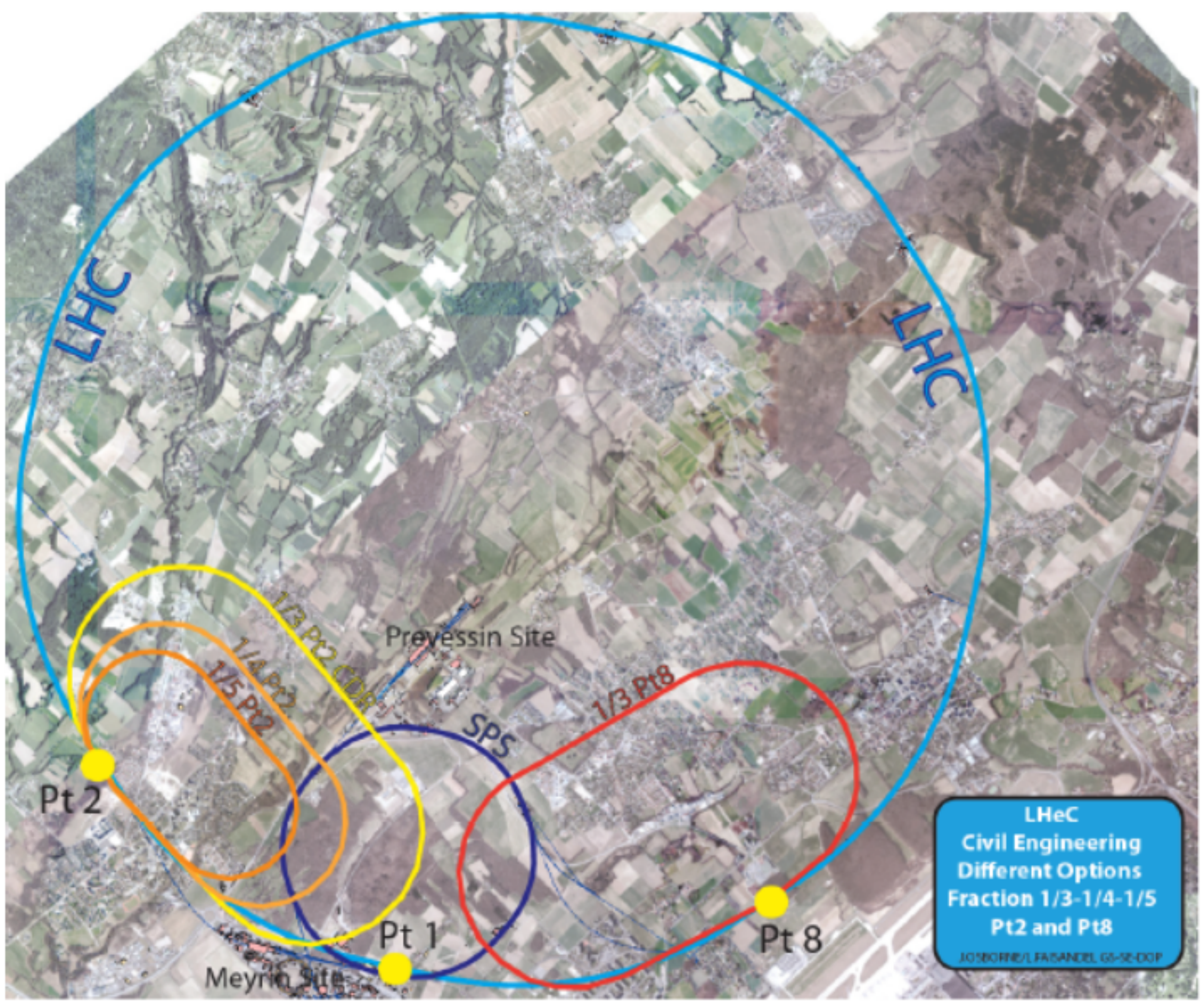
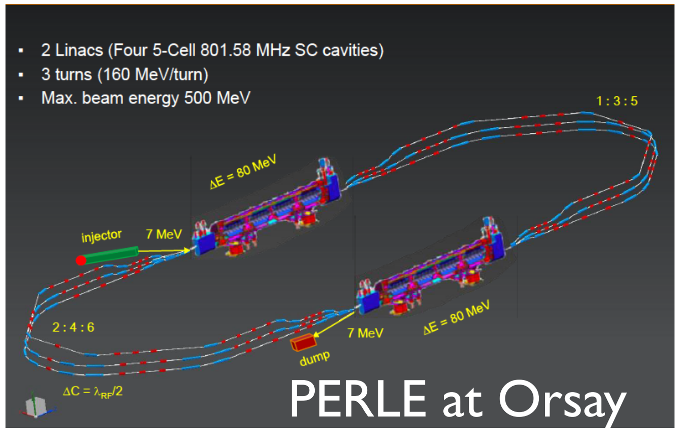
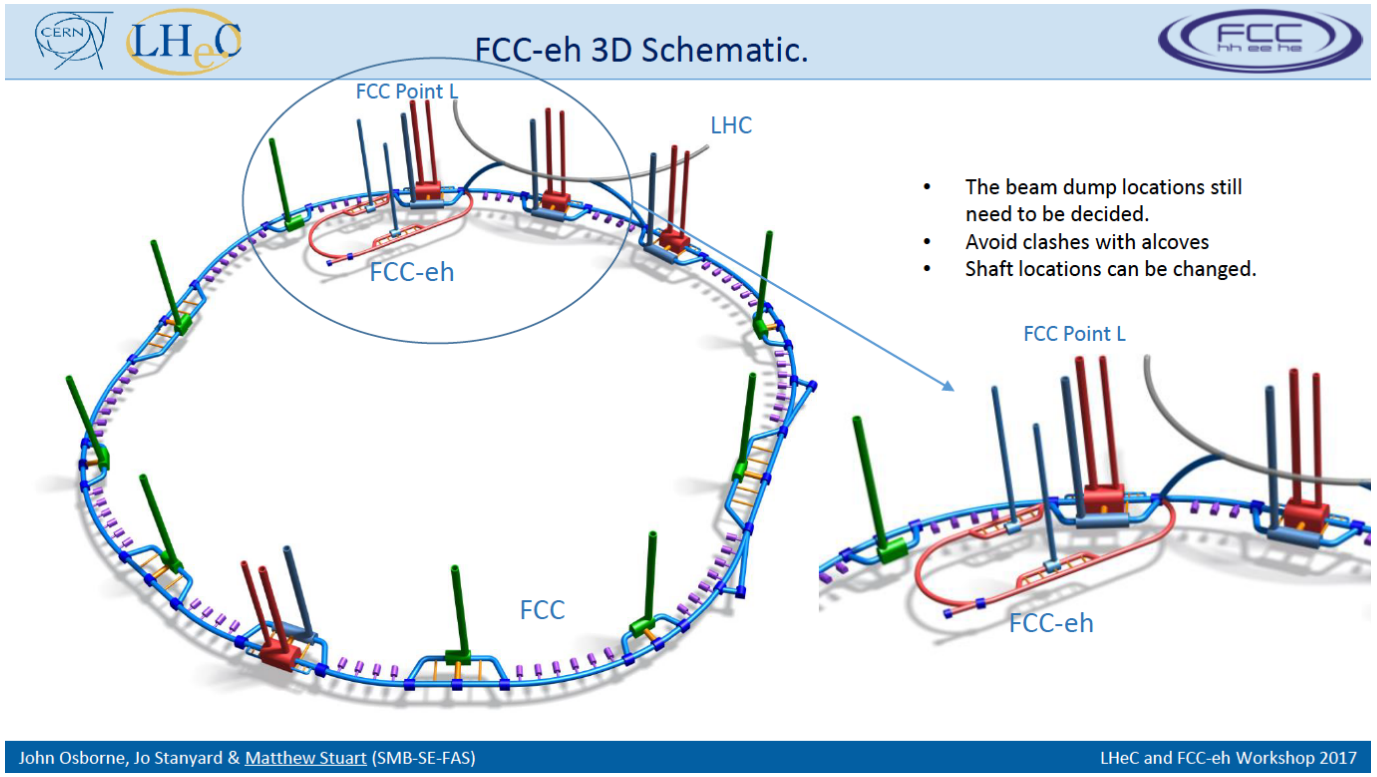
Machines:



- 60 GeV e$^-$ (ERL) against the (HL/HE-)LHC/FCC hadron beams: eA to run either concurrently with pA/AA or in dedicated mode.







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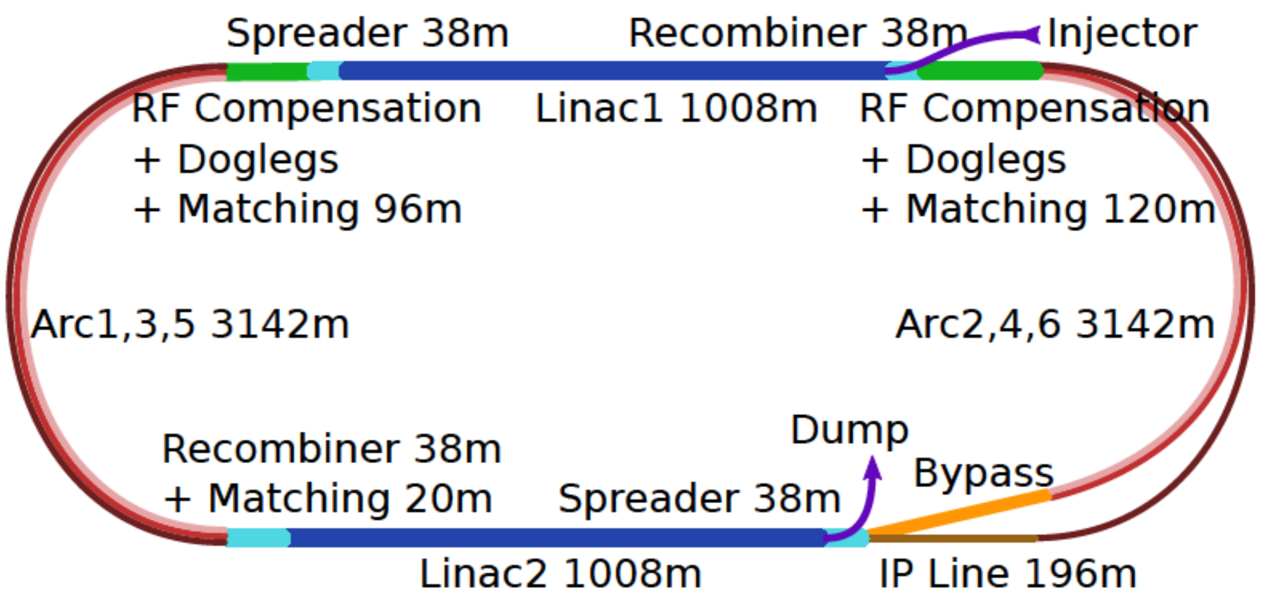


- 60 GeV e- (ERL) against the (HL/HE-)LHC/FCC hadron beams: eA to run either concurrently with pA/AA or in dedicated mode.

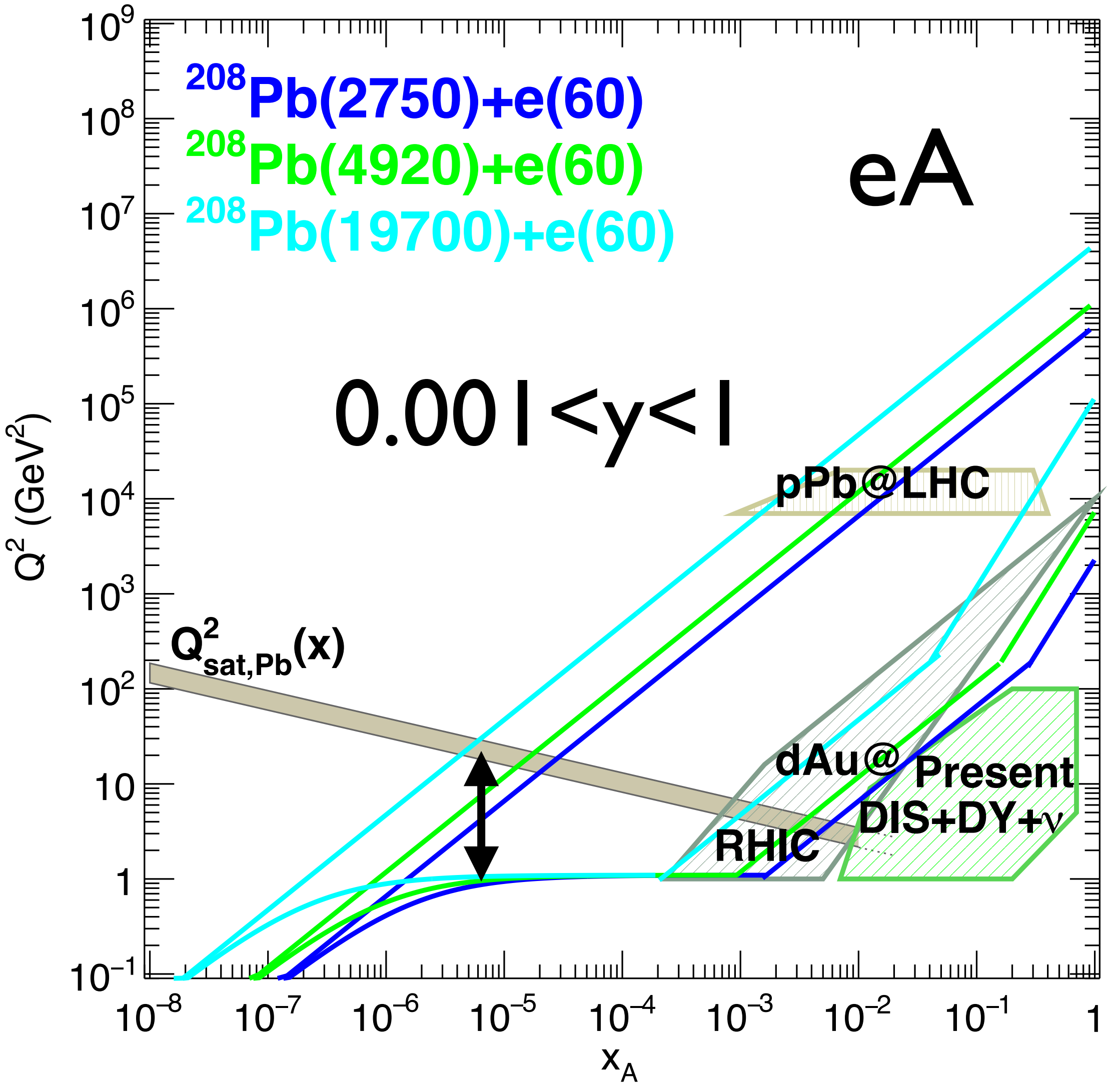
CERN-ACC-2017-0019

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
$\gamma\epsilon_A$ [μm]	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 β_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
Integrated lumi. in 10 y. (fb^{-1}) ~~	6	15	45

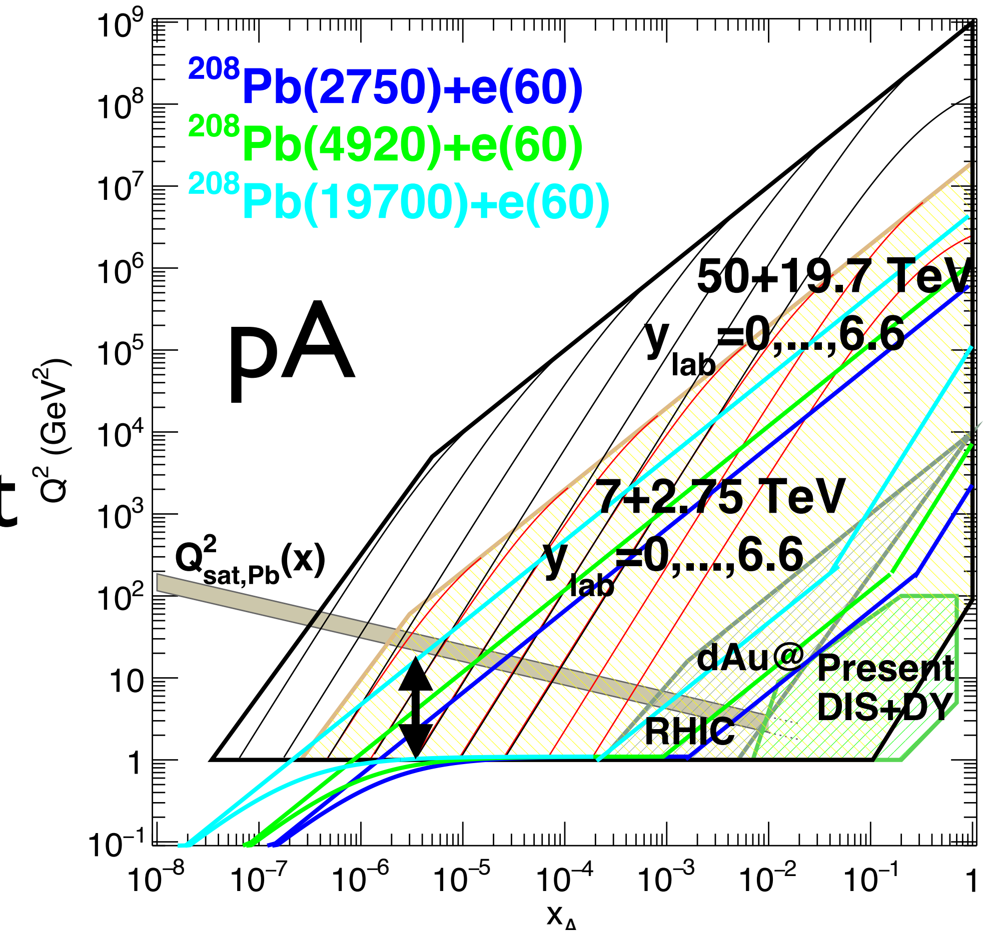
eD at LHEC:
$L_{eN}=AL_{eA}>\sim 3\times 10^{31}$ cm^{-2}s^{-1}
(old CDR number)

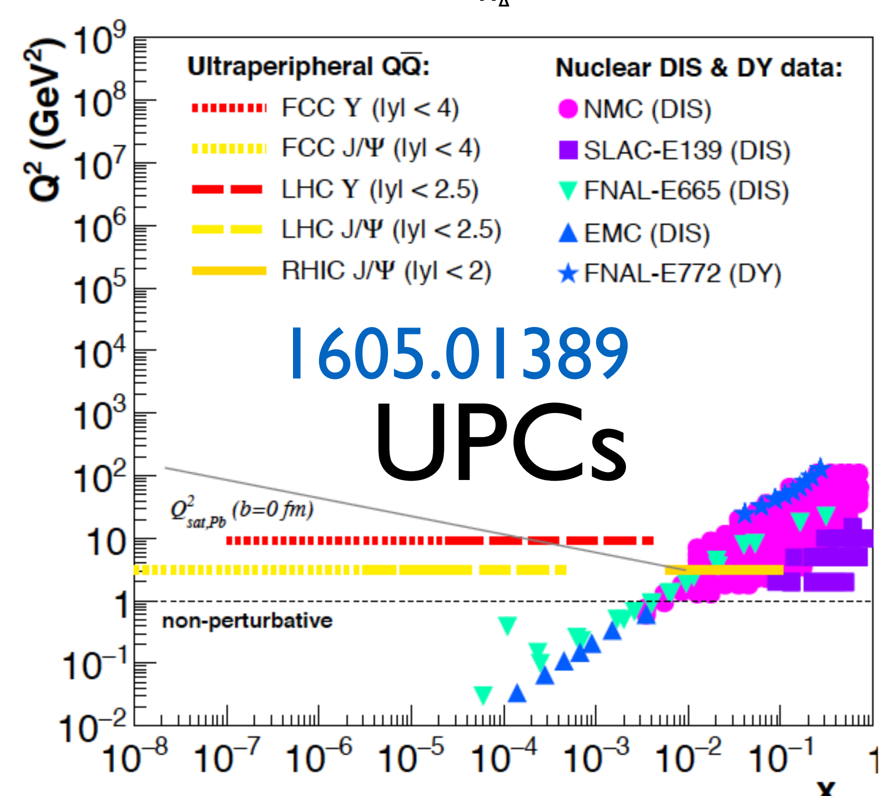
- 100 times larger luminosity than HERA, full HERA integrated luminosity in less than a month.

Kinematics:



- Extension up to 4-5 orders of magnitude in x and Q^2 wrt existing DIS data, ~2-3 wrt JLEIC/eRHIC.



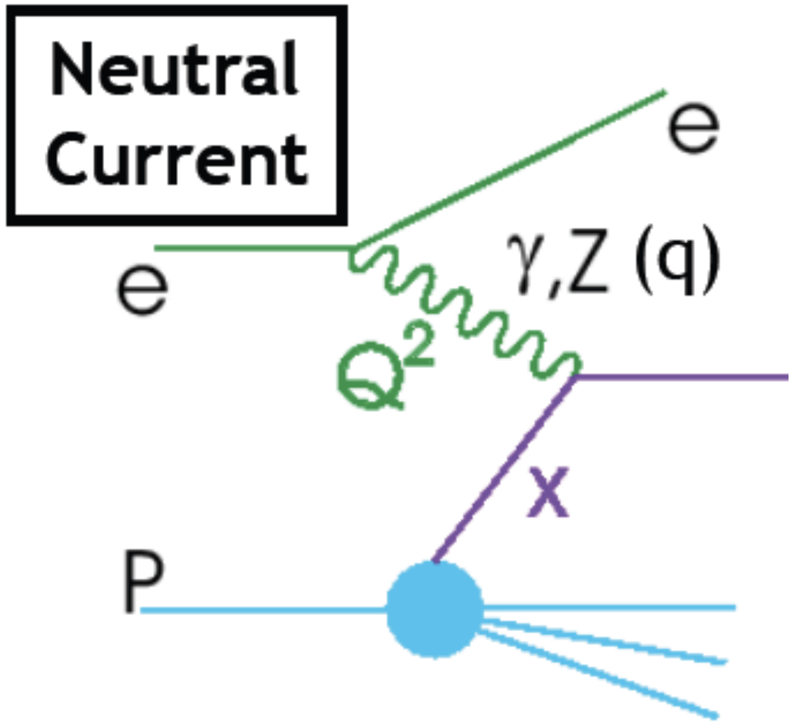


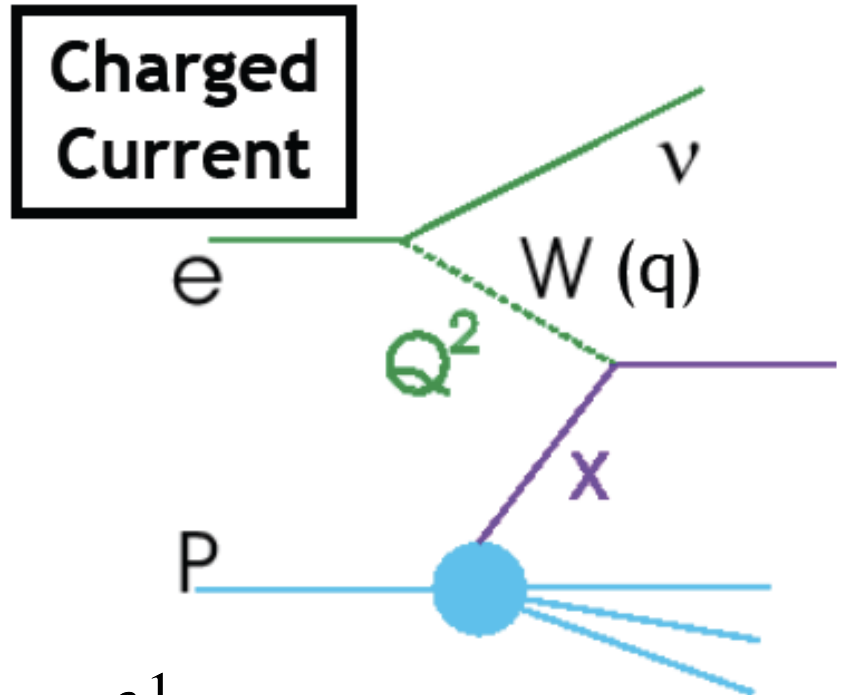
- DIS offers:

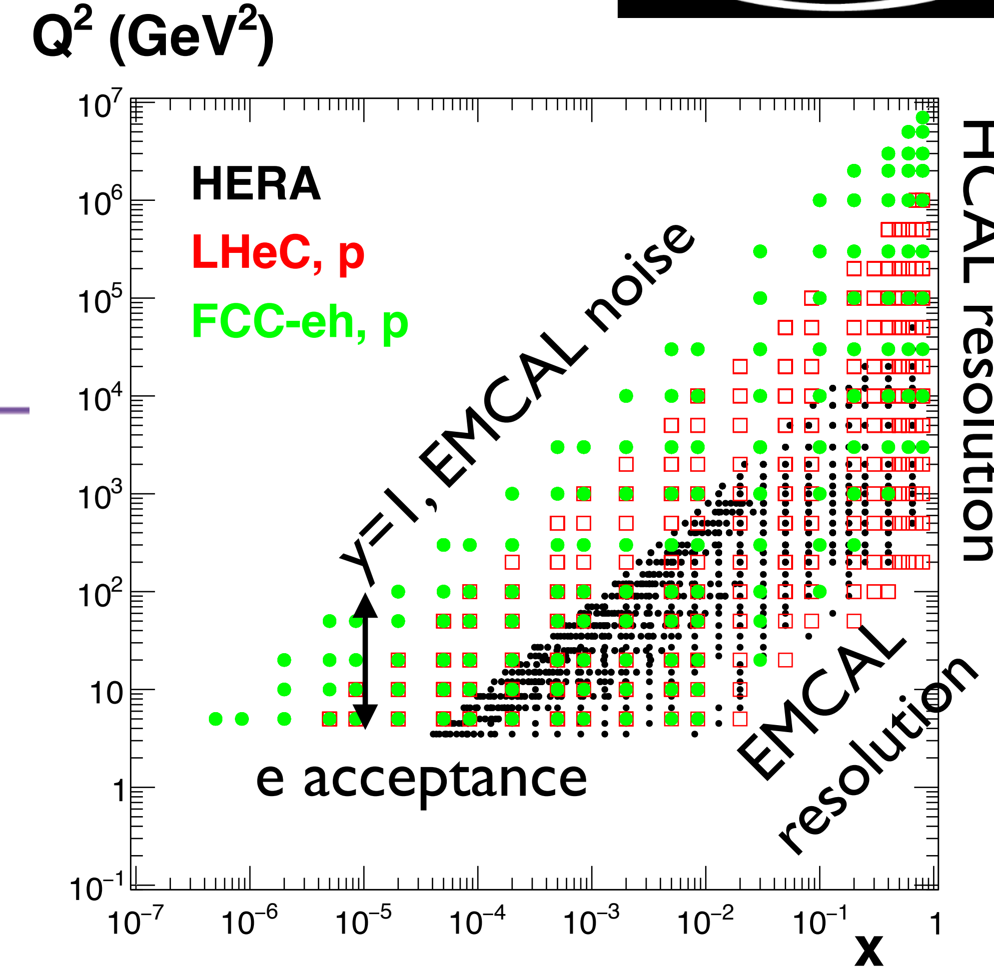
➜ A clean experimental environment: low multiplicity, no pileup, fully constrained kinematics;

➜ A more controlled theoretical setup: many first-principles calculations in collinear and non-collinear frameworks.

Extraction of PDFs:







- Method (DGLAP $\Longrightarrow \int_x^1 \cdots$):

$F_2(x,Q^2) \propto \sum xq(x,Q^2)$: determines directly valence (large x) and sea (low x)

$\frac{\partial F_2(x,Q^2)}{\partial \log Q^2} \propto xg(x,Q^2)$: determines glue via DGLAP, $\mathcal{O}(\alpha_s)$, requires lever arm in Q^2.

$F_L(x,Q^2) \propto xg(x,Q^2) - F_2(x,Q^2)$: determines the glue via DGLAP, $\mathcal{O}(\alpha_s)$, requires lever arm in s (different y at fixed x,Q^2, use σ_{red}).

$F_2^{c,b,t}(x,Q^2)$: determines heavy flavour PDFs, requires HQ ID.

σ_r^{CC} : determines strange PDF, requires HQ ID and measurement of missing energy.

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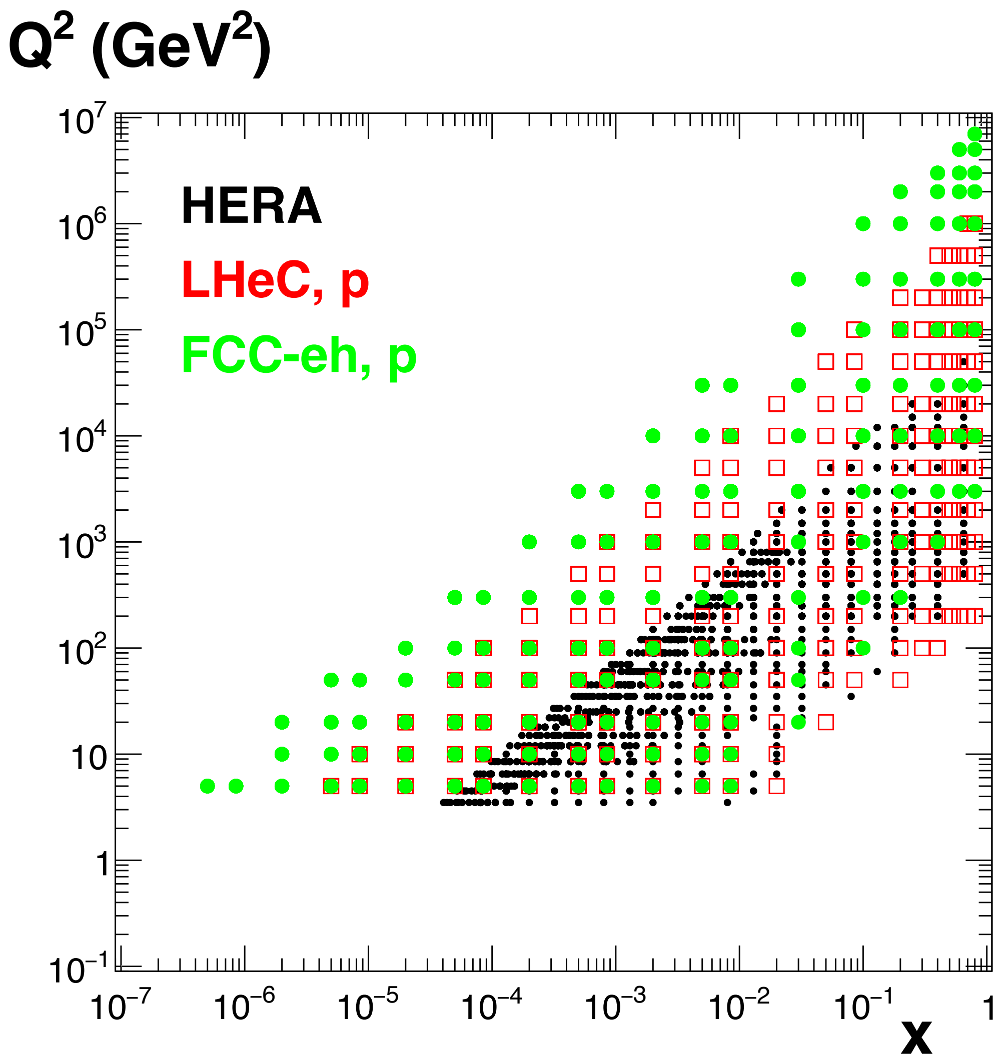
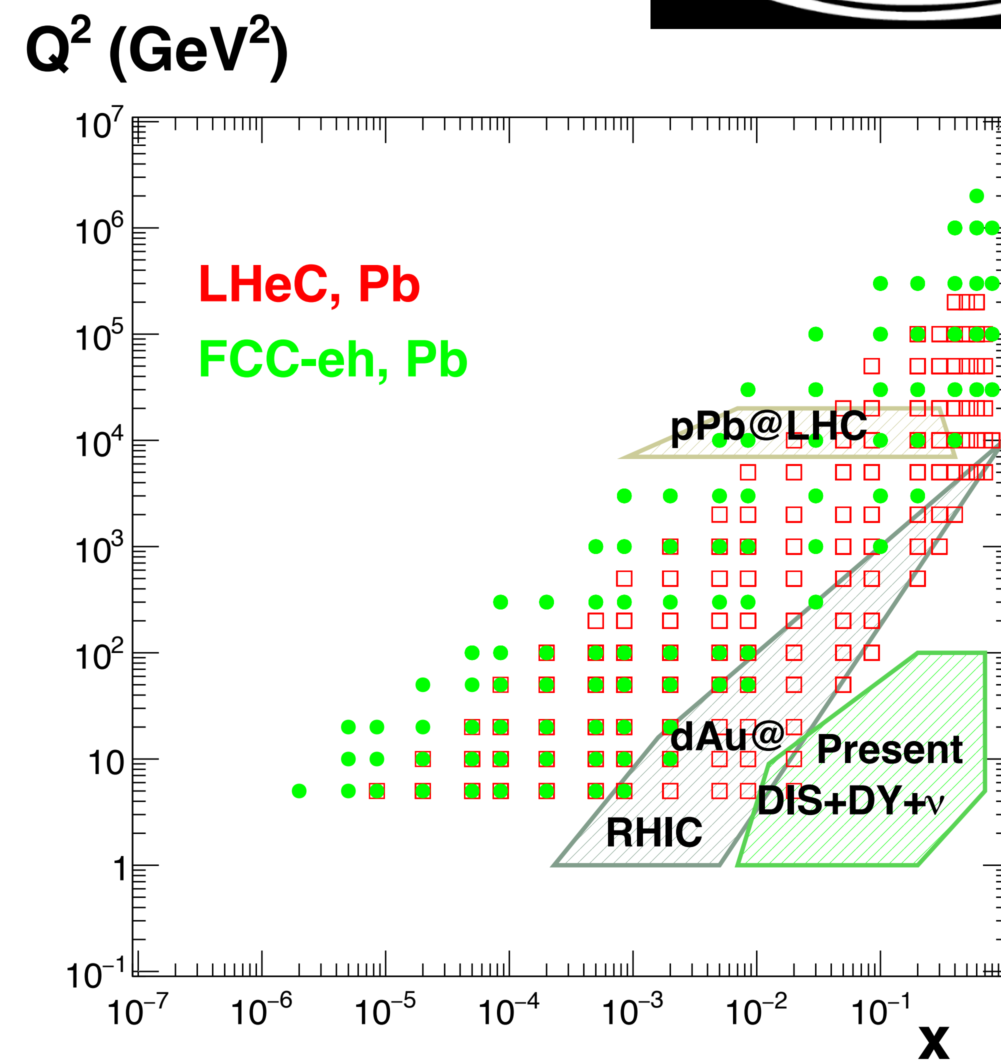
Pseudodata:

	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-eh, 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-eh, 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:



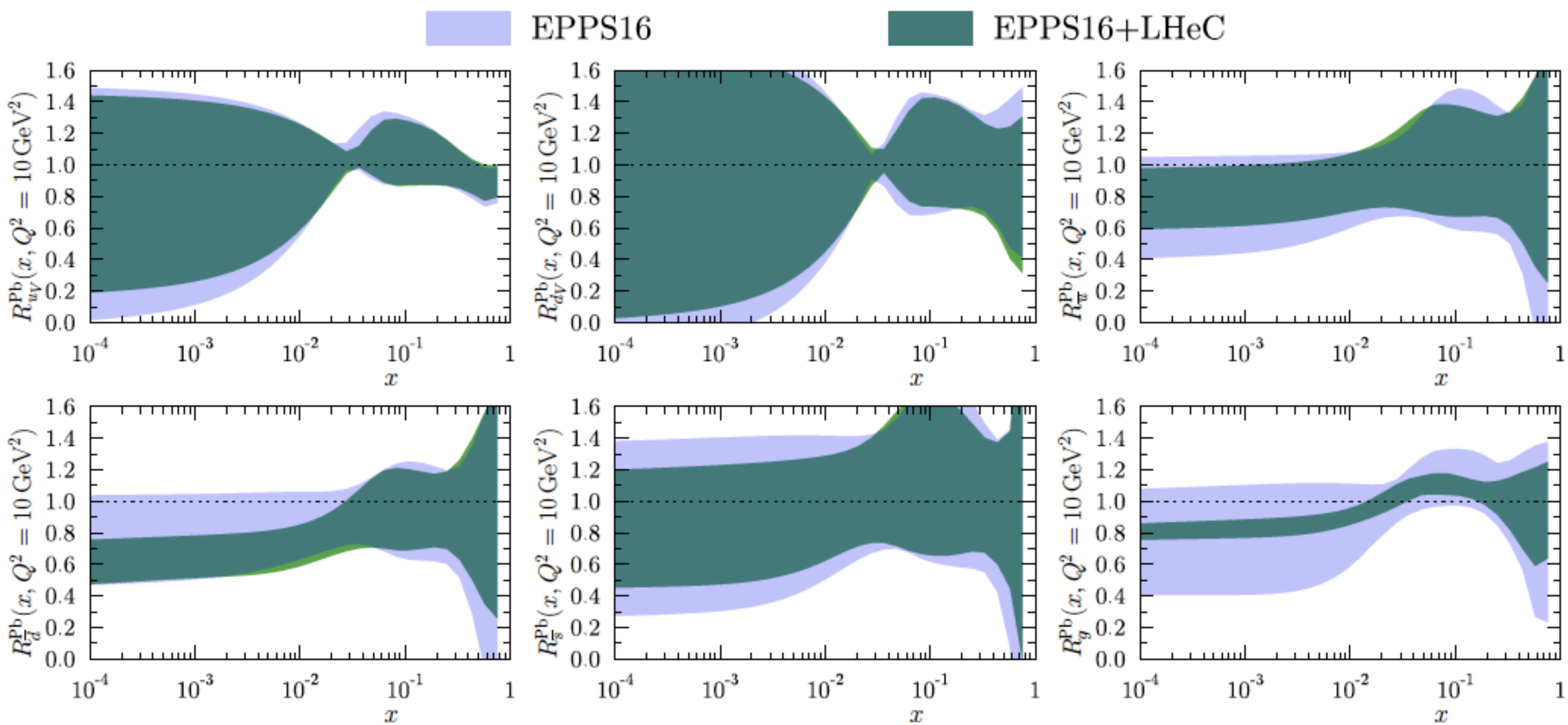


- Pseudodata generated using a code (Max Klein) validated with the H1 MC.
- Cuts: $|\eta_{max}|$=5, 0.95< y< 0.001.
- Error assumptions ~ factor 2 better than at HERA (luminosity uncertainty kept aside).
- Stat./syst. errors (ePb@FCC-eh) from 0.1/1.2% (small x, NC) to 37/6% (large x & Q^2, CC).

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:

- EPPS16-like analysis done previously, with the same data sets plus LHeC NC and CC, the same methods and tolerance ($\Delta\chi^2$=52).
- Limitation on u/d decomposition inherent to almost isospin symmetric nuclei (u/d difference suppressed by 2Z/A-1).



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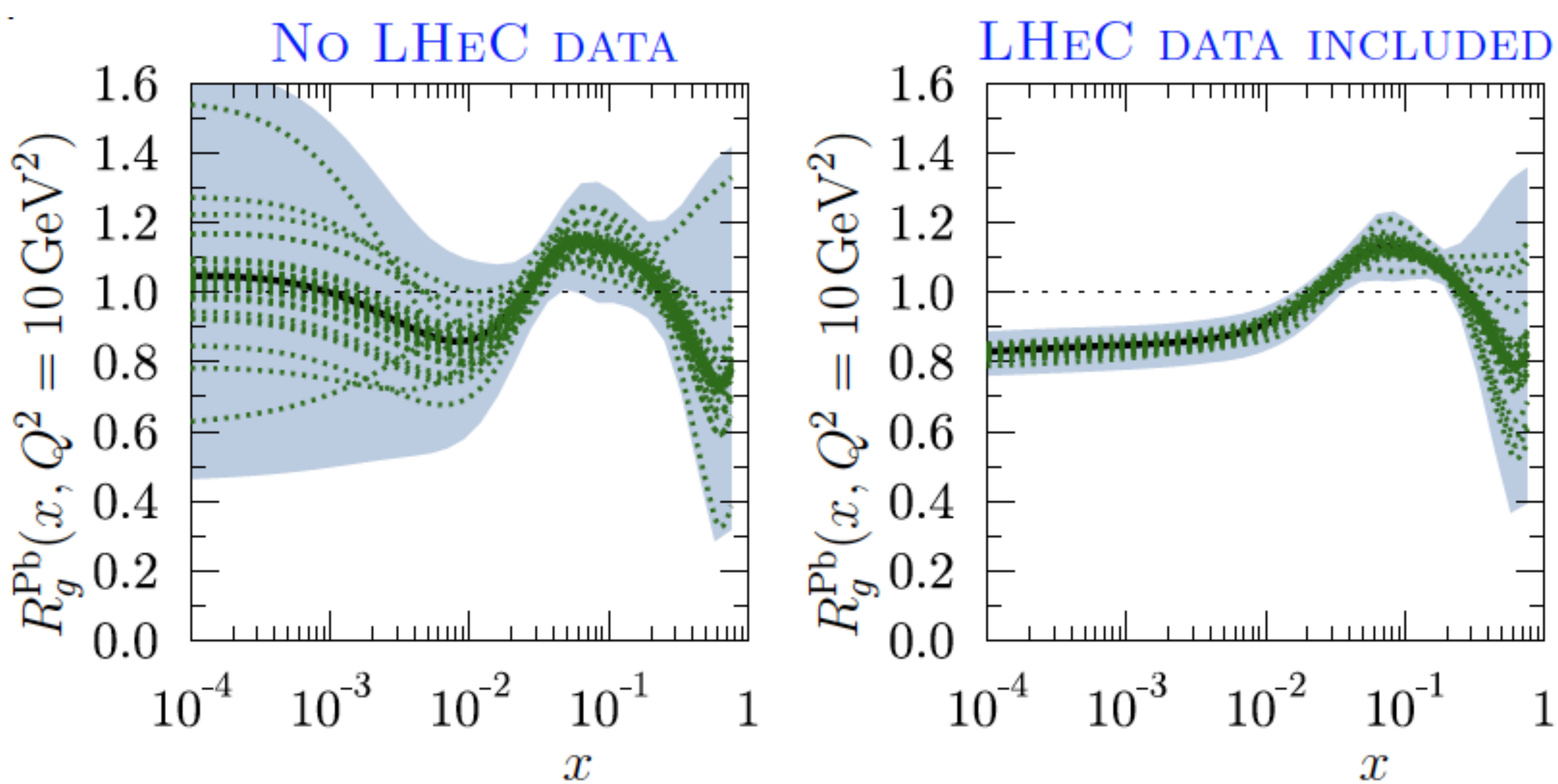
- More flexible parametrisation essayed, require Monte Carlo methods for reliable uncertainty estimation; still visible effects.



xFitter (I):

- Extraction of Pb-only PDFs by fitting pseudodata, using xFitter (1410.4412) 1.2.2 to estimate the 'ultimate' achievable precision:

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

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

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

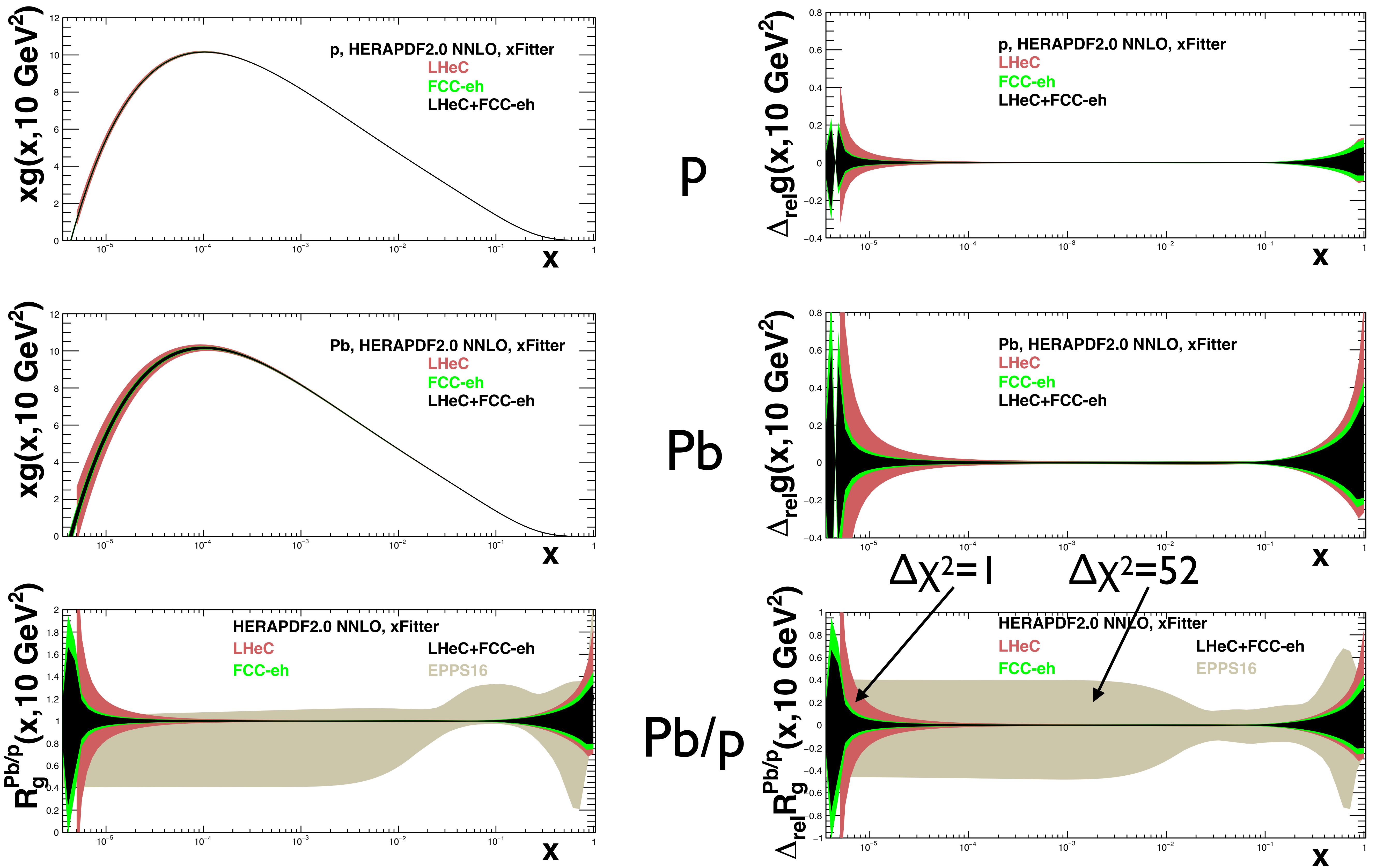
➜ Central pseudodata values from HERAPDF2.0: no parametrisation bias.

➜ Standard xFitter/HERAPDF treatment of correlated/uncorrelated systematics; tolerance $\Delta\chi^2$=1.

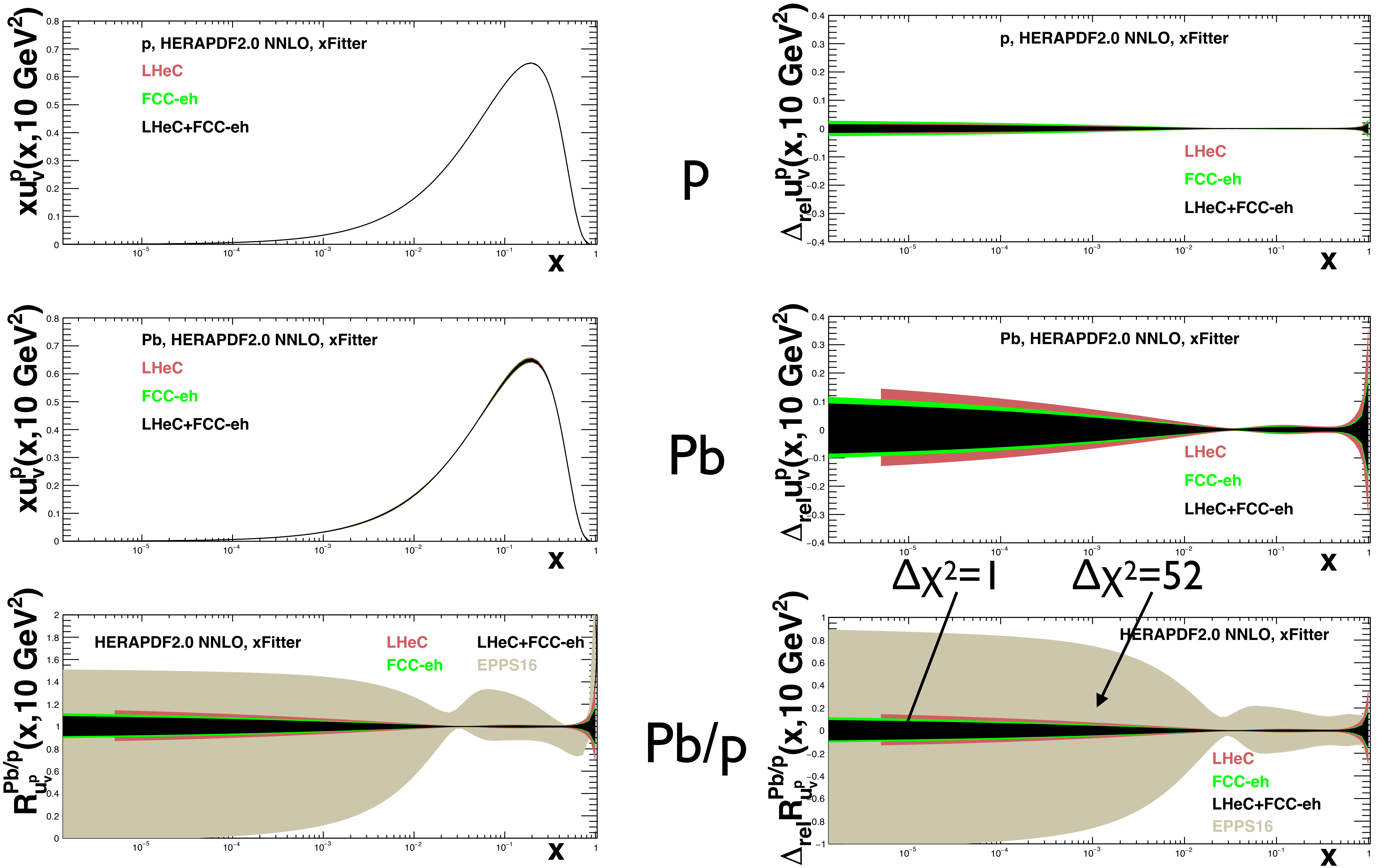
➜ Only data with $Q^2 \geq 3.5$ GeV^2, initial evolution scale 1.9 GeV^2.

➜ Proton PDFs extracted in the same setup for consistency.

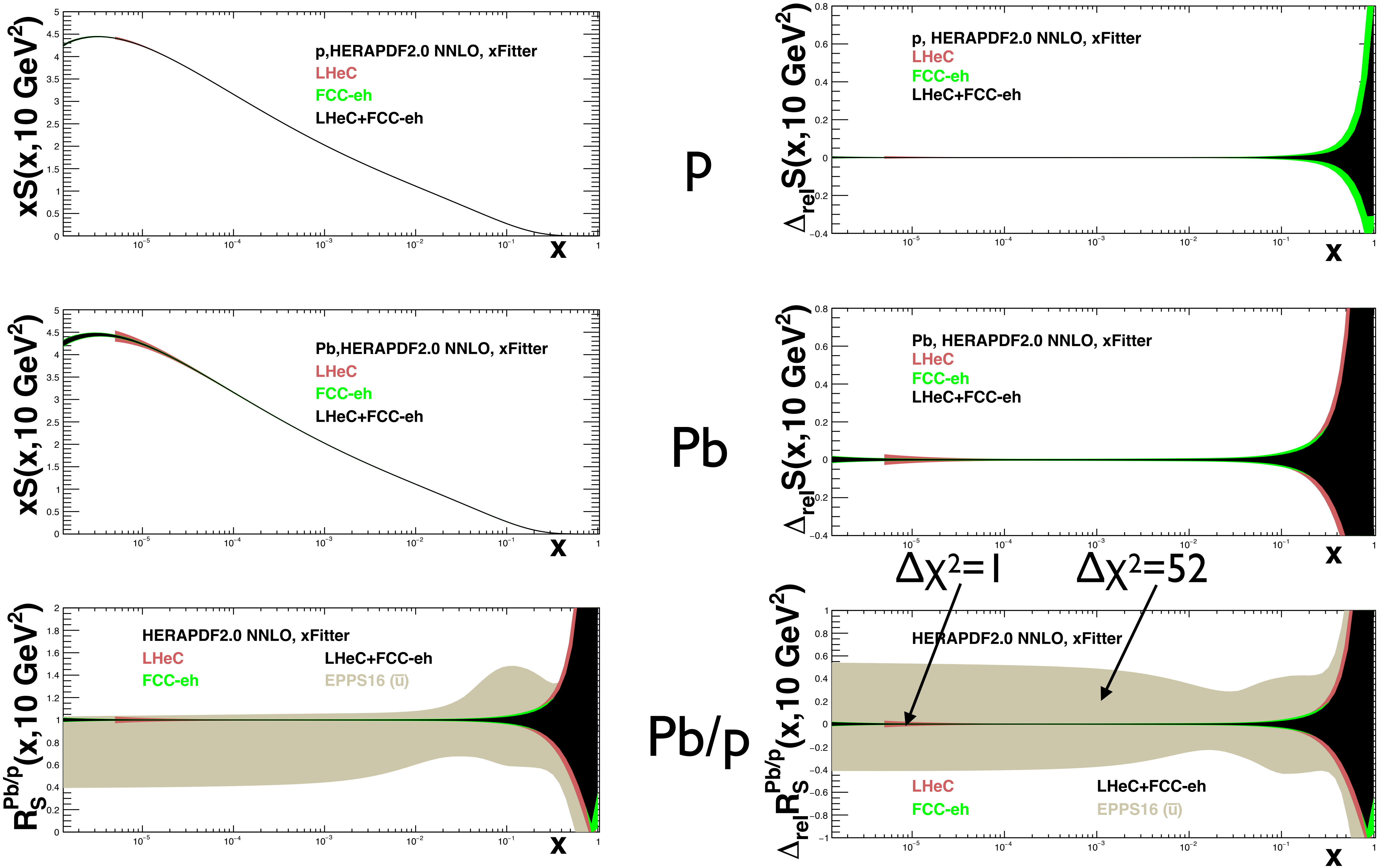
xFitter: gluon



xFitter: valence



xFitter: sea



p,HERAPDF2.0 NNLO, xFitter
LHeC
FCC-eh
LHeC+FCC-eh
xS(x,10 GeV²)
x
p
p, HERAPDF2.0 NNLO, xFitter
LHeC
FCC-eh
LHeC+FCC-eh
Δ_rel S(x,10 GeV²)
x
Pb,HERAPDF2.0 NNLO, xFitter
LHeC
FCC-eh
LHeC+FCC-eh
xS(x,10 GeV²)
x
Pb
Pb, HERAPDF2.0 NNLO, xFitter
LHeC
FCC-eh
LHeC+FCC-eh
Δ_rel S(x,10 GeV²)
x
Δχ²=1
Δχ²=52
HERAPDF2.0 NNLO, xFitter
LHeC
FCC-eh
LHeC+FCC-eh
EPPS16 (ū)
R_S^Pb/p(x,10 GeV²)
x
Pb/p
HERAPDF2.0 NNLO, xFitter
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EPPS16 (ū)
Δ_rel R_S^Pb/p(x,10 GeV²)
x

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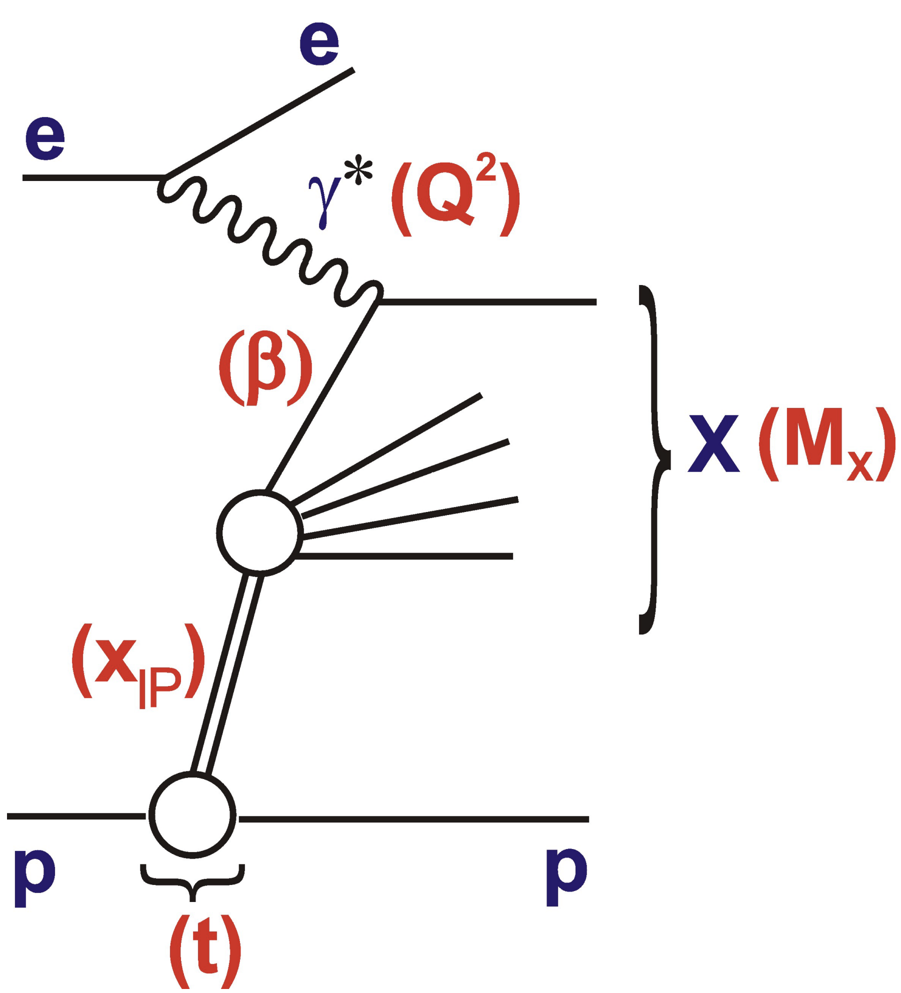
DPDFs and factorisation:



$$\frac{d^3\sigma^D}{dx_{IP}\,dx\,dQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4} Y_+ \,\sigma_r^{D(3)}(x_{IP}, x, Q^2)$$

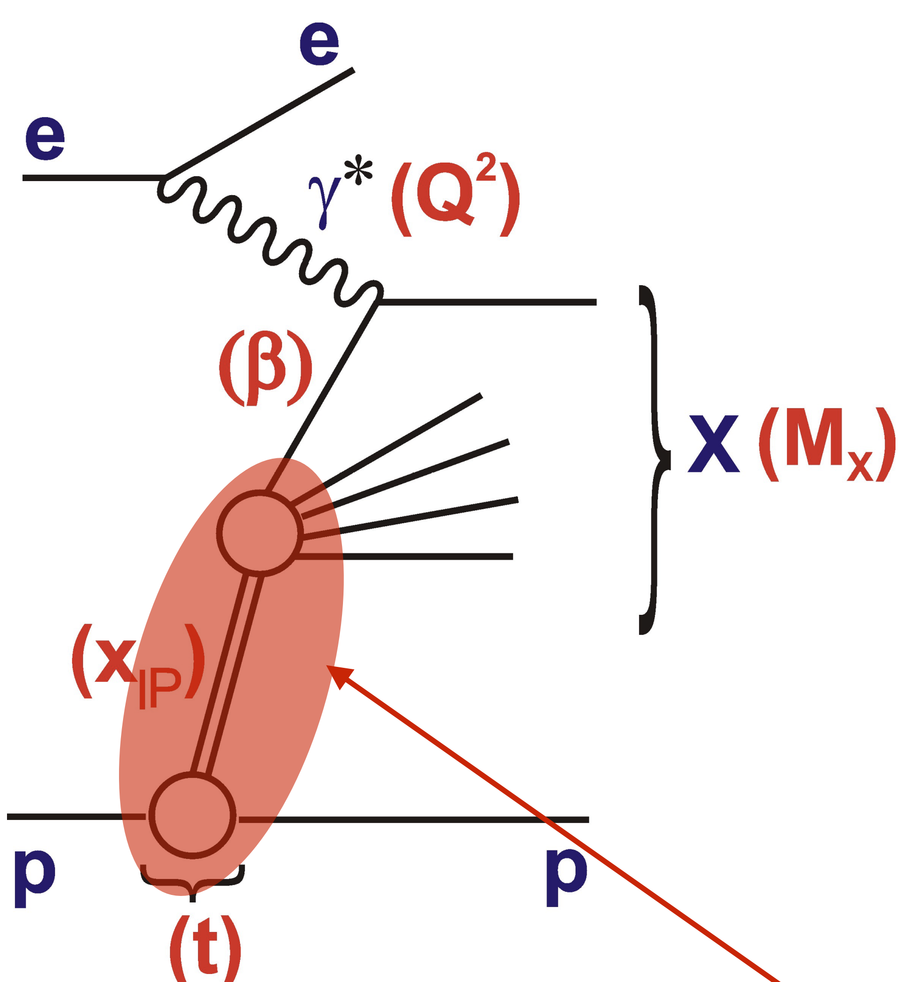
$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{Y_+} F_L^{D(3)}$$

$$Y_+ = 1 + (1-y)^2$$

$$F_{T,L}^{D(3)}(x, Q^2, x_{IP}) = \int_{-\infty}^{0} dt F_{T,L}^{D(4)}(x, Q^2, x_{IP}, t)$$

$$F_2^{D(4)} = F_T^{D(4)} + F_L^{D(4)}$$

DPDFs and factorisation:



$$\frac{d^3\sigma^D}{dx_{IP}\,dx\,dQ^2} = \frac{2\pi\alpha_{\rm em}^2}{xQ^4} Y_+ \, \sigma_r^{D(3)}(x_{IP}, x, Q^2)$$

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$$F_2^{D(4)} = F_T^{D(4)} + F_L^{D(4)}$$

- For fixed t, x_P, collinear factorisation holds (Collins): diffractive PDFs expressing the conditional probability of finding a parton with momentum fraction β with the proton remaining intact.

$$d\sigma^{ep\to eXY}(x, Q^2, x_{IP}, t) = \sum_i f_i^D \otimes d\hat{\sigma}^{ei} + \mathcal{O}(\Lambda^2/Q^2)$$

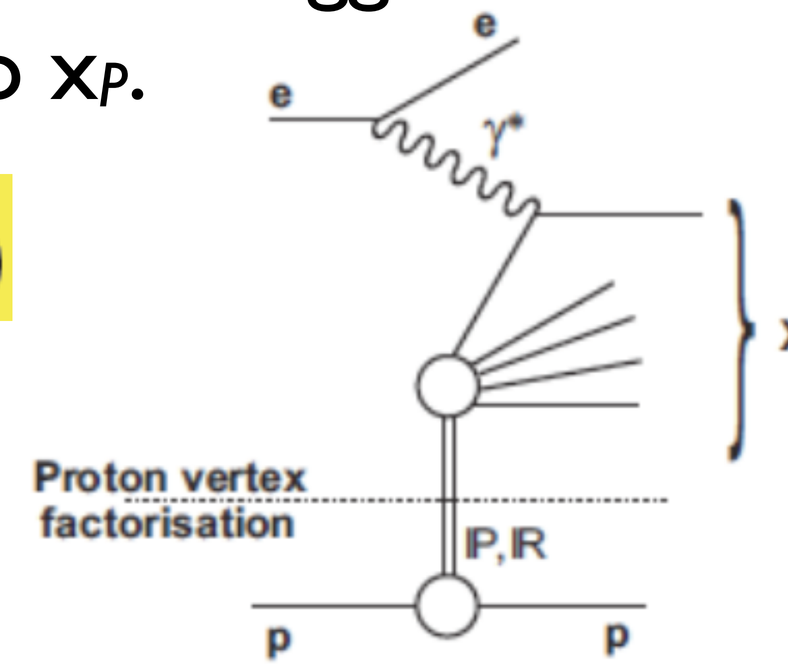
Extraction of DPDFs:

- To extract DPDFs, an additional assumption is made: Regge factorisation that seems to work for not large too x_P.

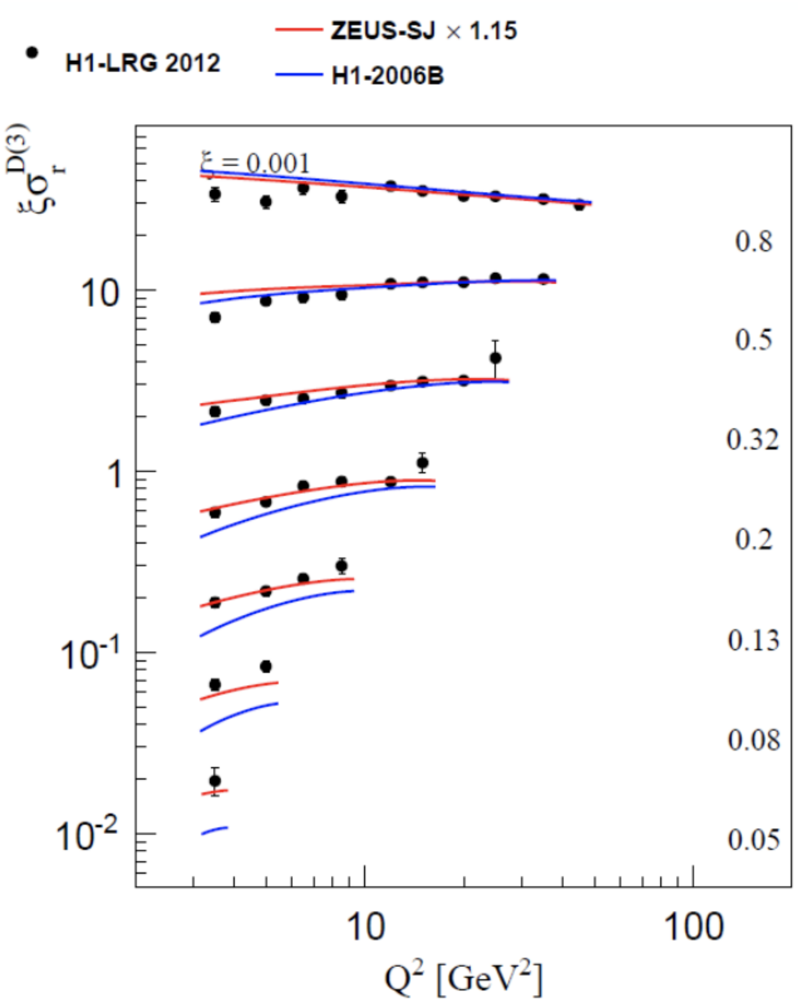
$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t)\, f_i(\beta = x/x_{IP}, Q^2)$$

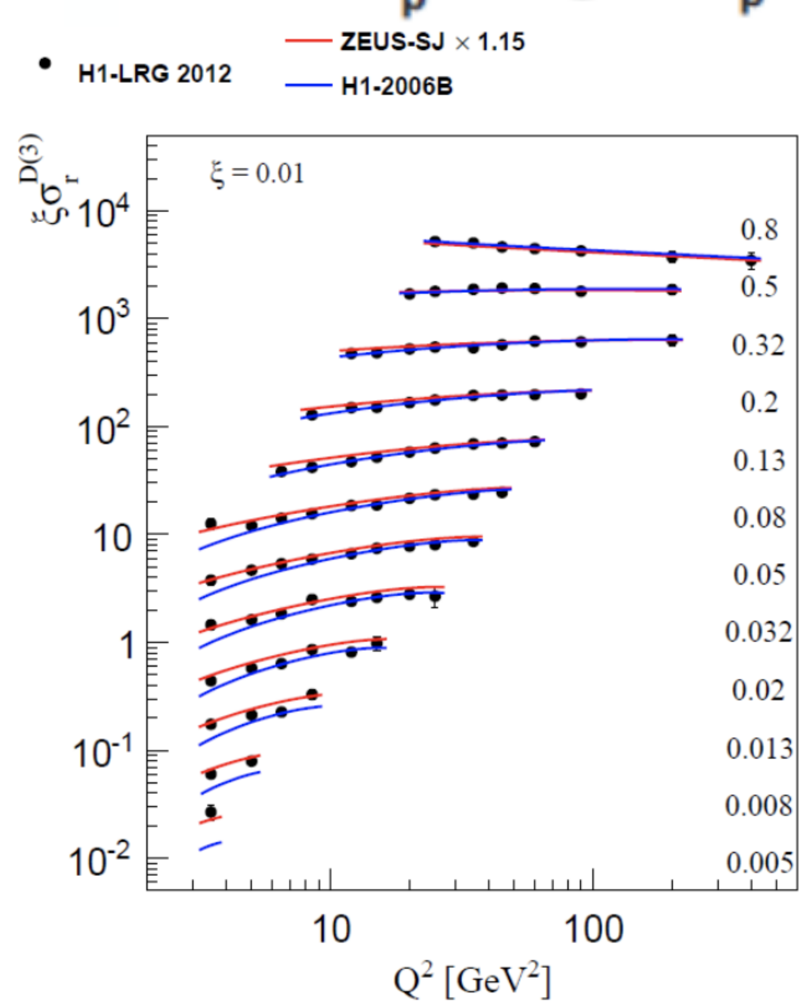
Pomeron flux

$$f_{IP/p}(x_{IP}, t) = A_{IP} \frac{e^{B_{IP} t}}{x^{2\alpha_{IP}(t)-1}}$$



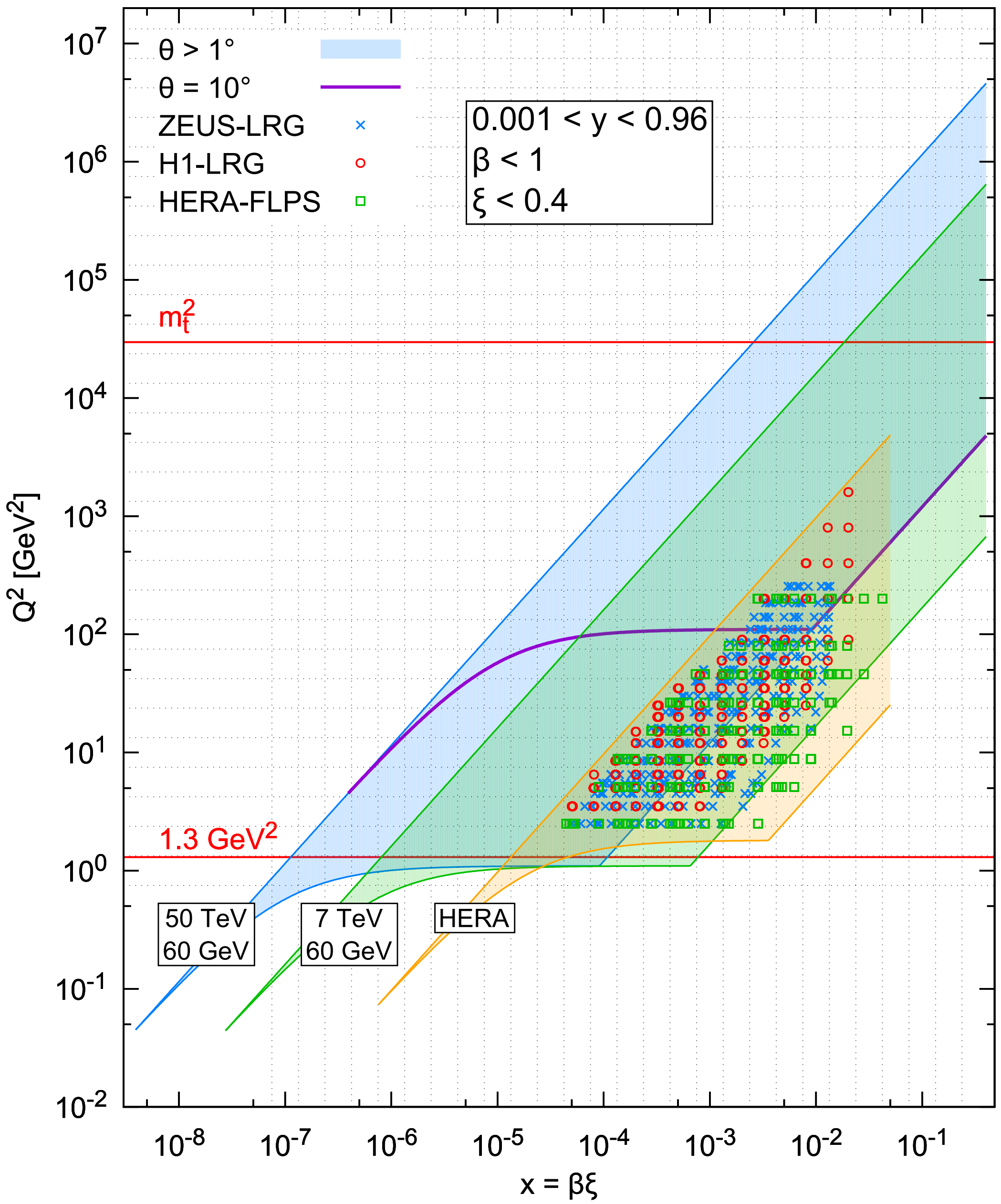
$f_i(\beta, Q^2)$ evolve with DGLAP evolution equations: fits to HERA data (additional contributions at large x_P=ξ and small β).

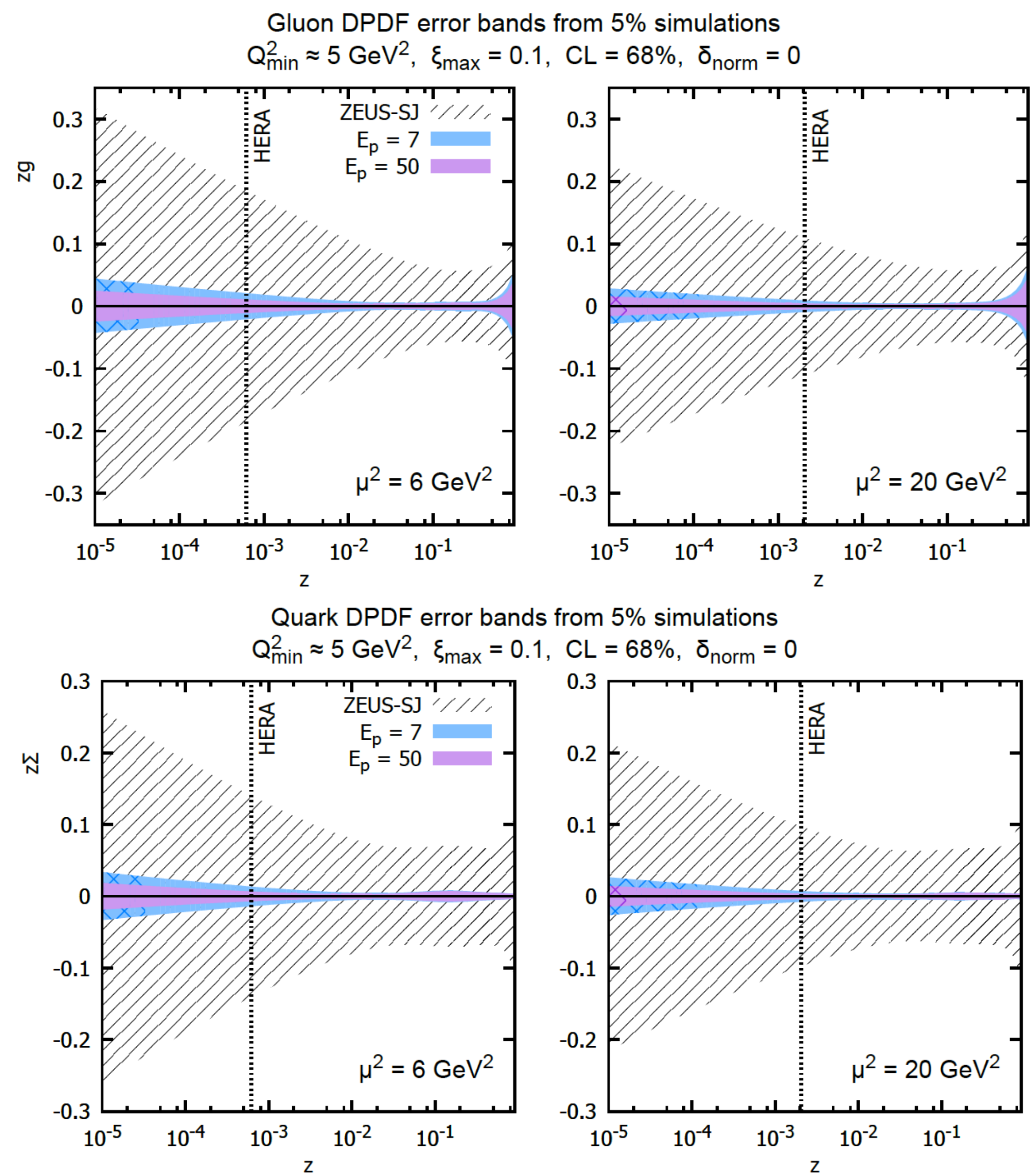




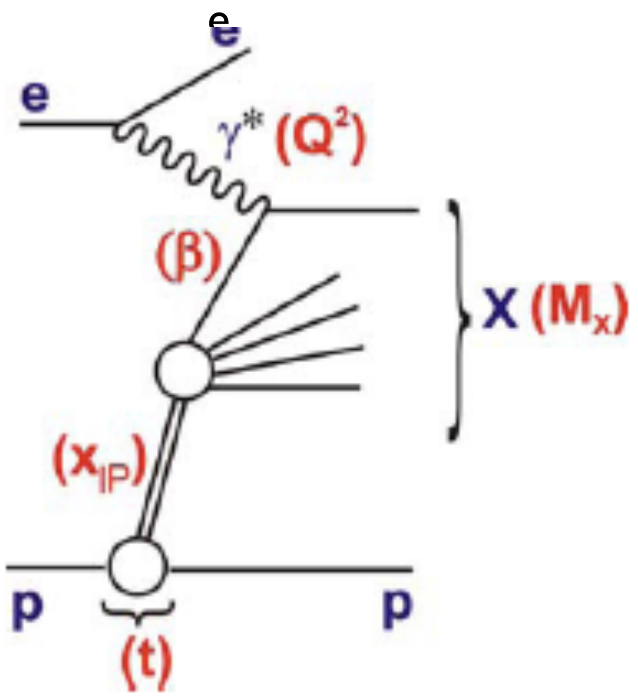
DPDFs at LHeC/FCC-eh:

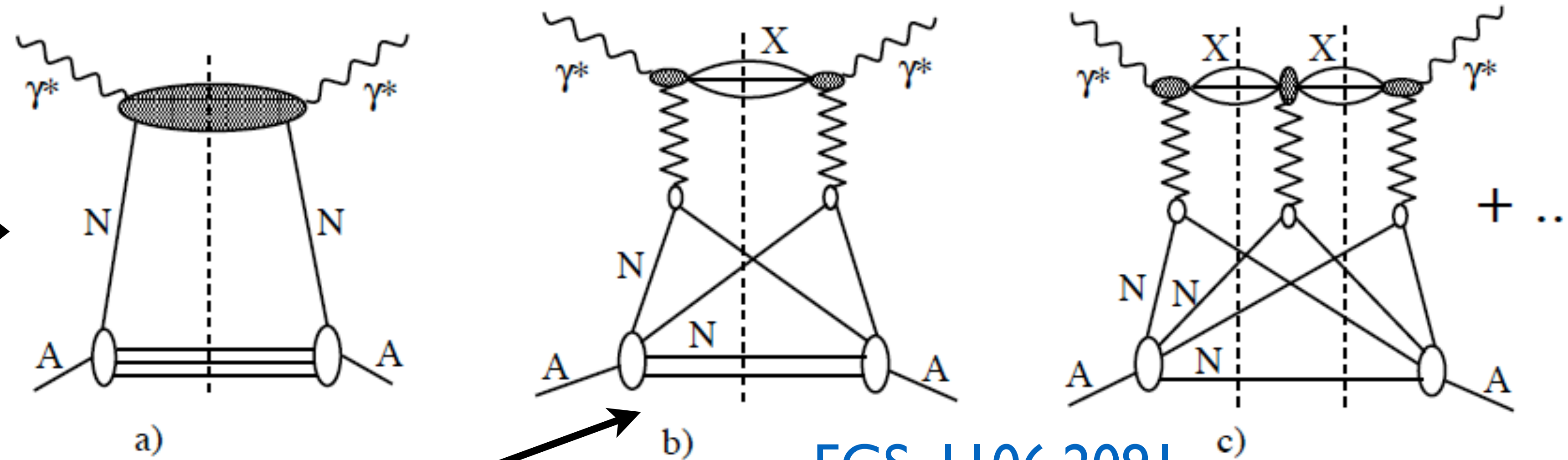
- Limitations at HERA (check of Regge factorisation, size and shape of the diffractive glue) can be overcome with LHeC/FCC-eh:





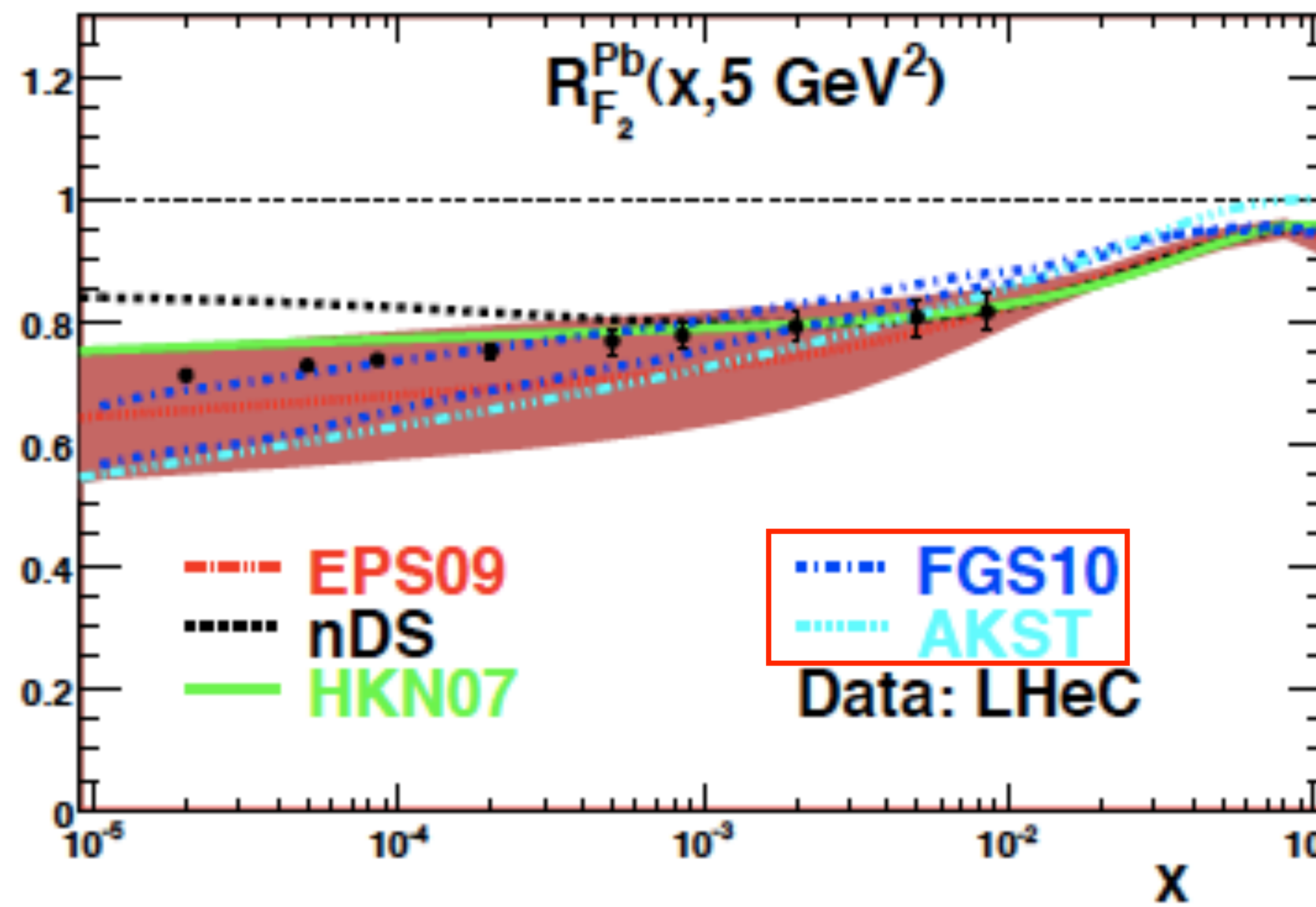
Diffraction & shadowing:





FGS, 1106.2091

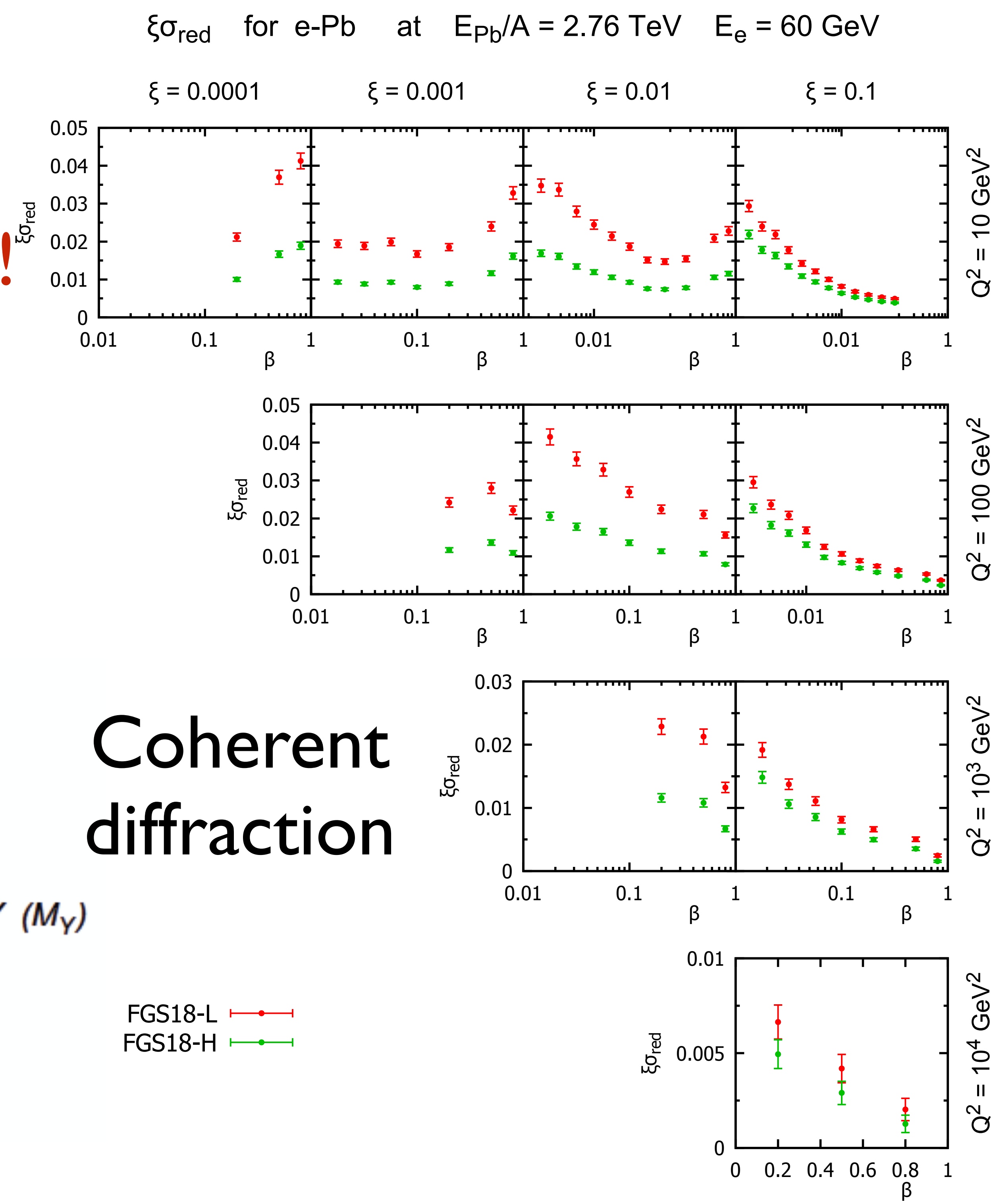
- Diffraction in ep is linked to nuclear shadowing through basic QFT (Gribov): system size and impact parameter dependence. eD to test and set the 'benchmark' for new effects.



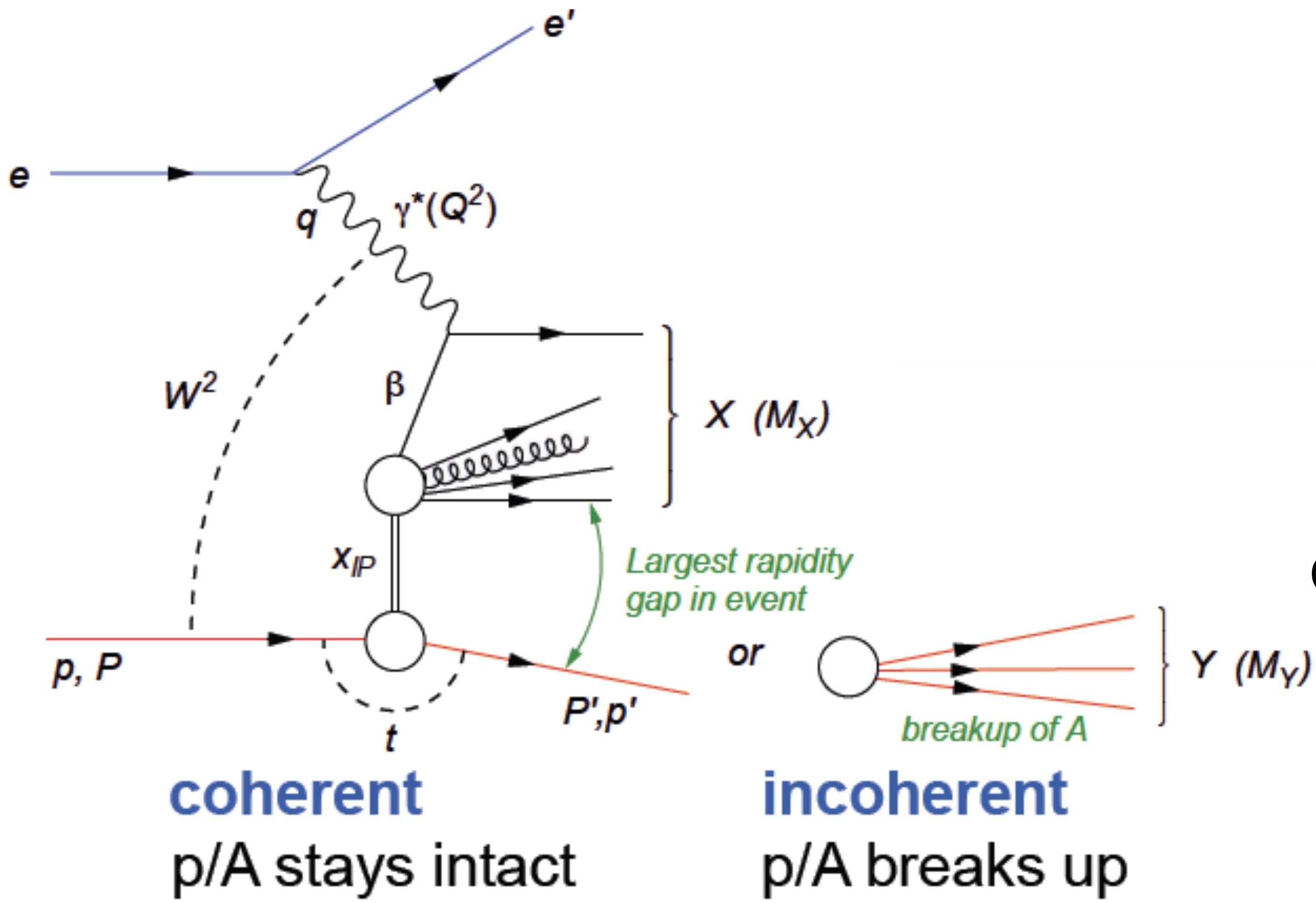
nDPDFs at LHeC:

- Diffractive PDFs have never been measured in nuclei, where incoherent diffraction becomes dominant above relatively small -t.

- Challenging experimental problem (LPS + ZDC?).
- Extraction of nDPDFs possible!



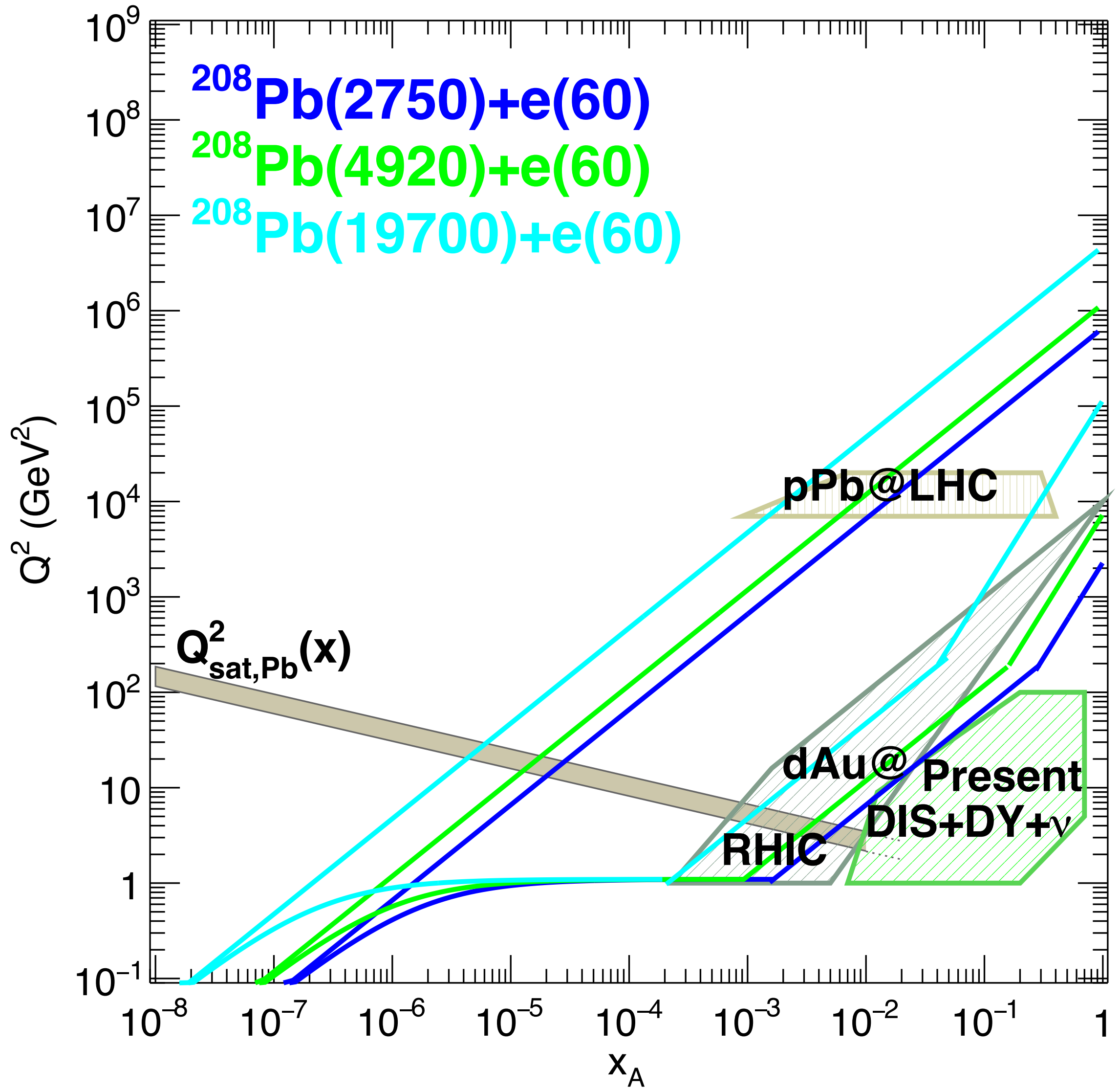
Coherent diffraction



Summary:

- The LHeC & FCC-eh will explore a completely new region in the x-Q^2 plane, enlarging the one presently explored in DIS by ~3-4 orders of magnitude down in x and up in Q^2.

http://lhec.web.cern.ch/



- A precise determination of nuclear inclusive and diffractive PDFs will be possible, that cannot be matched at hadron colliders: PDFs for a single nuclei in a single experiment.

- Work in progress (to be ready for the CDR next February):
  - ➜ Determination of nPDFs in EPPS16 (Hannu Paukkunen) including c,b.
  - ➜ Radiative corrections in ep and eA.
  - ➜ Nuclear diffractive PDFs (Wojtek Slominski).
  - ➜ Implications of DPDF on nuclear shadowing (Vadim Guzey)?

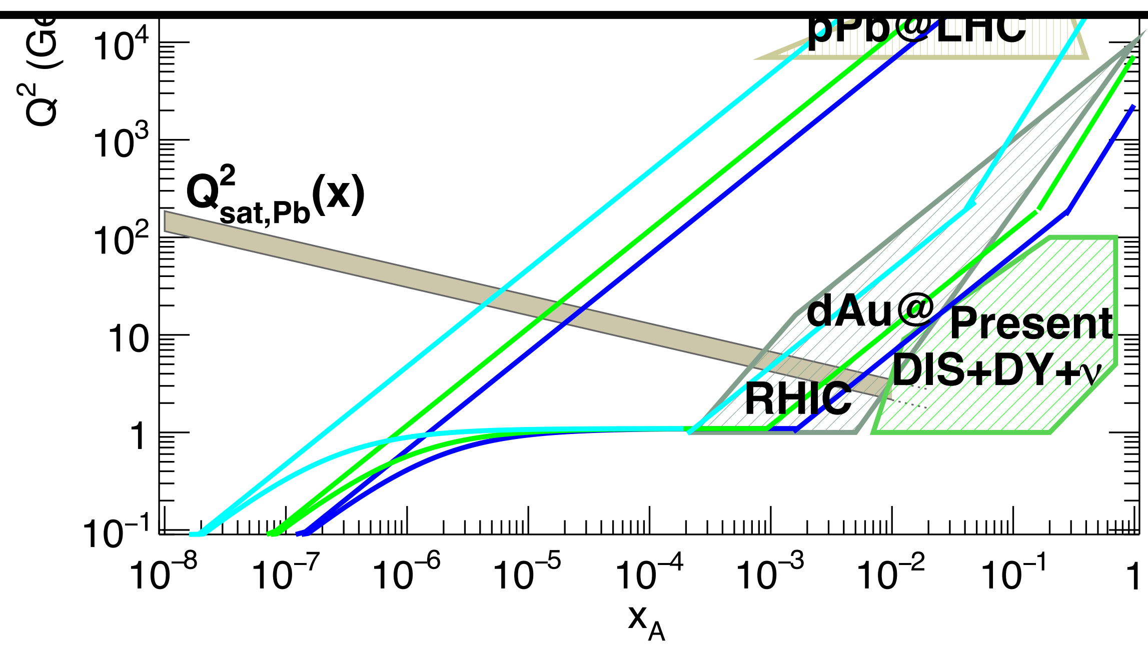
Summary:

- The LHeC & FCC-eh will explore

http://lhec.web.cern.ch/

→ Thanks to Max Klein, Hannu Paukkunen and Pía Zurita for comments, and to Voica Radescu for help with xFitter.

→ Thank you very much for your attention!!!



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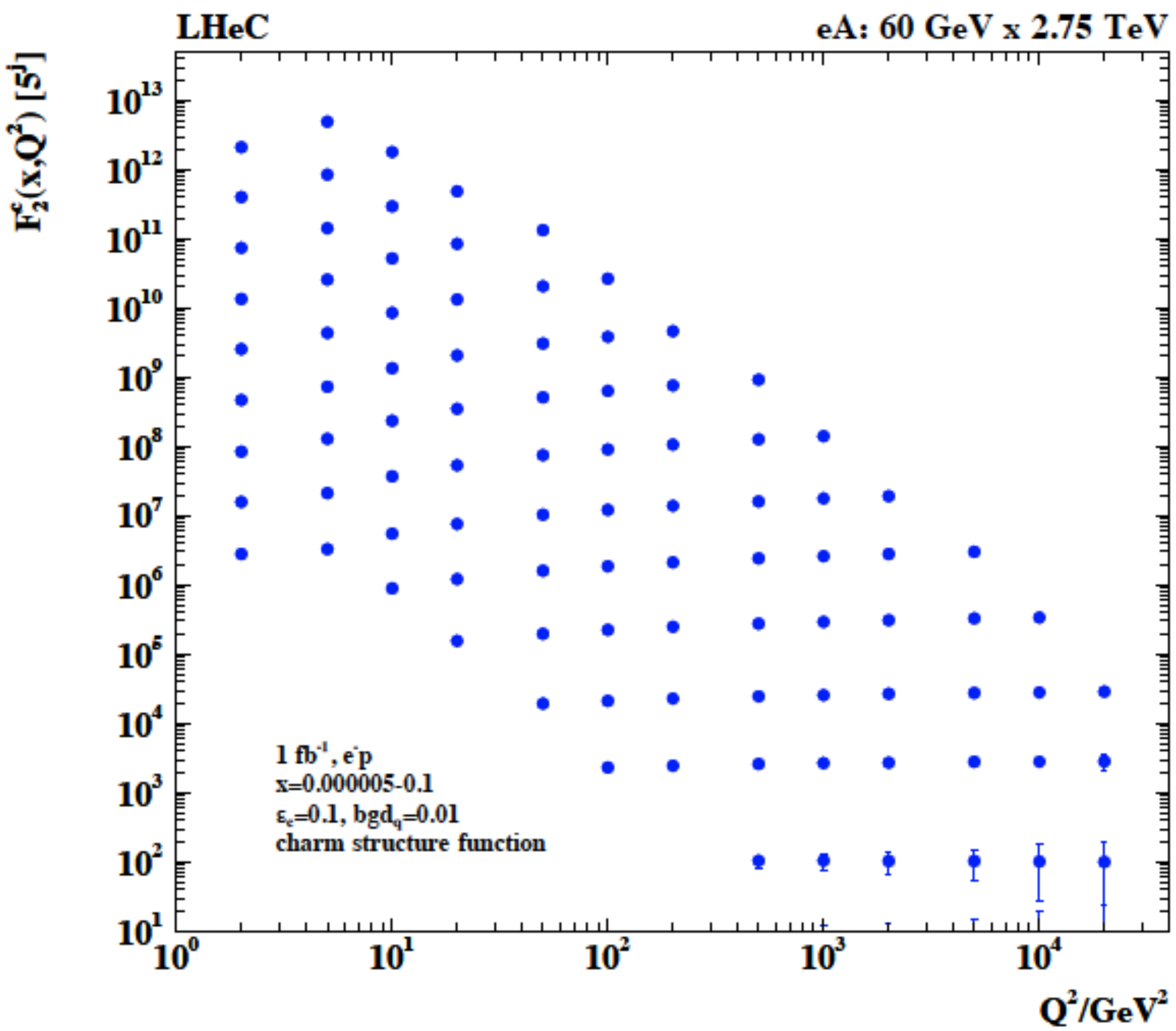
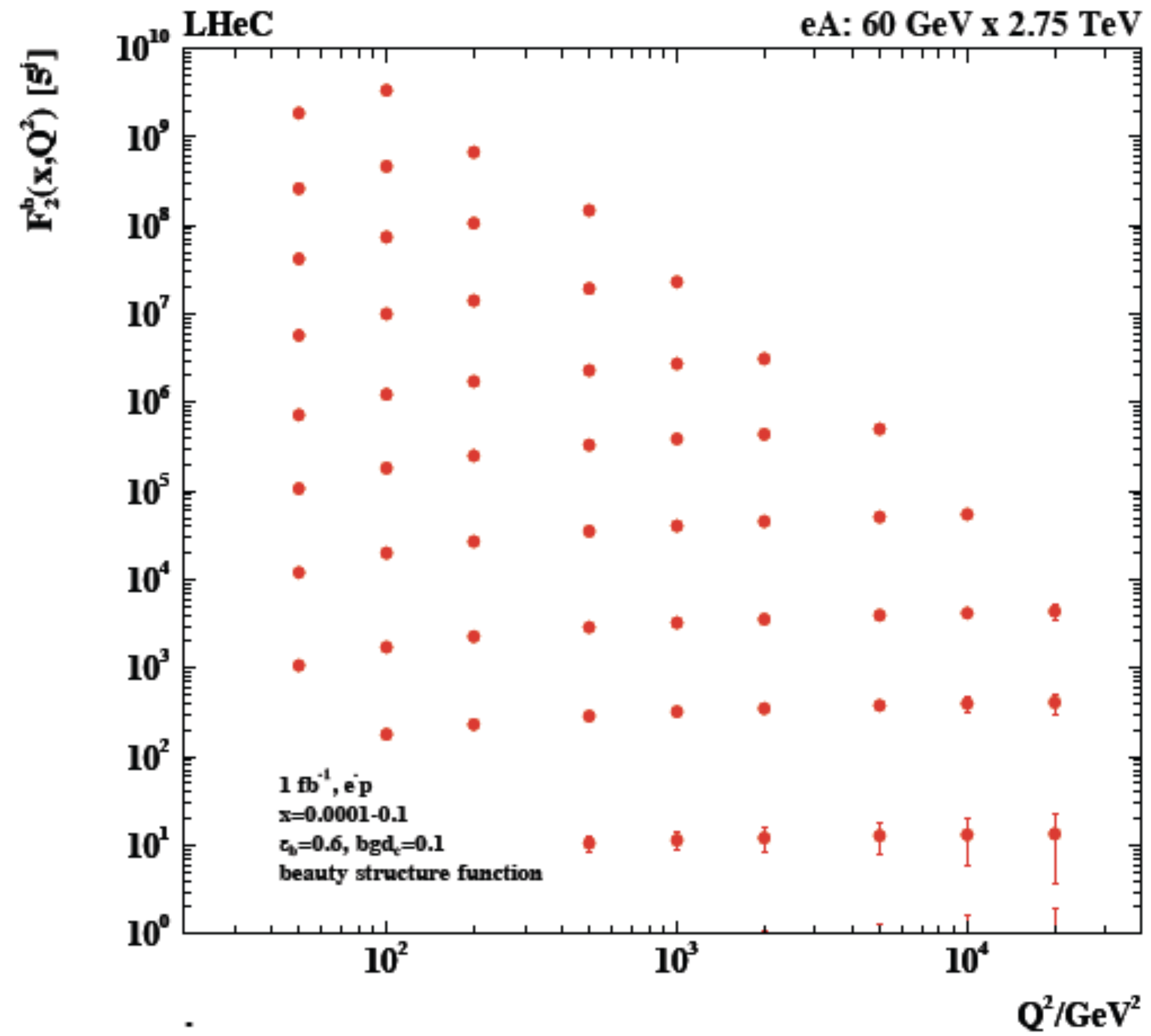
Heavy flavours at LHeC:

Charm in ePb



Beauty in ePb



M. Klein, DOI: 10.1051/epjconf/201611203002

Backup:

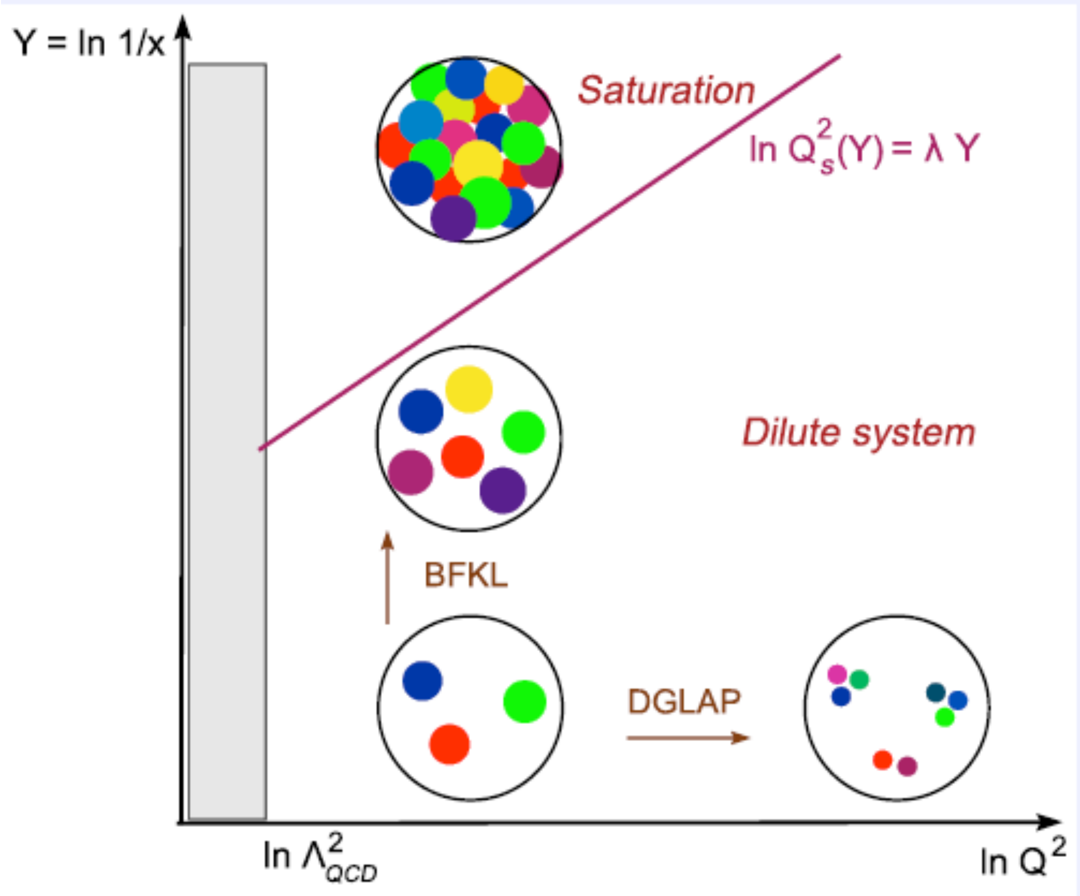
h/A wave function:

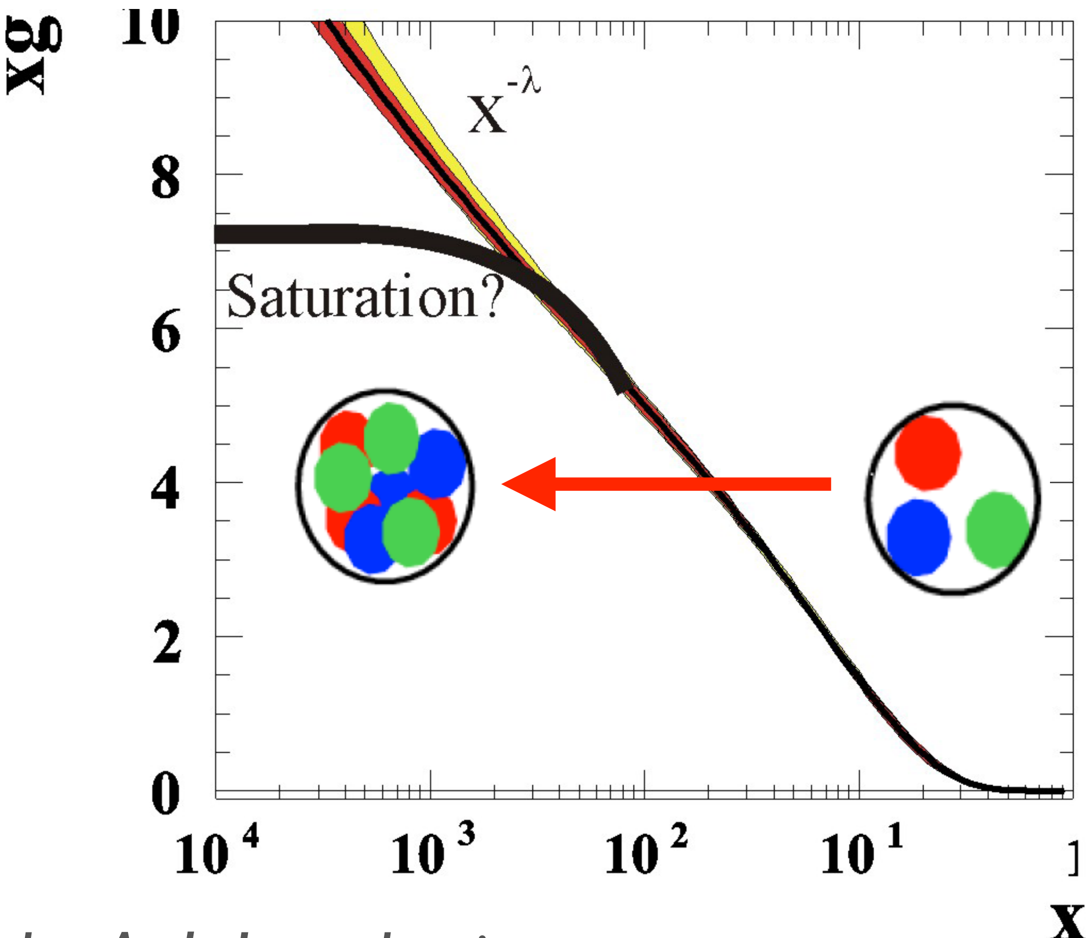
• Standard fixed-order perturbation theory (DGLAP, linear evolution) must eventually fail:

➜ Large logs e.g. $\alpha_s \ln(1/x) \sim 1$: resummation (BFKL,CCFM,ABF,CCSS).

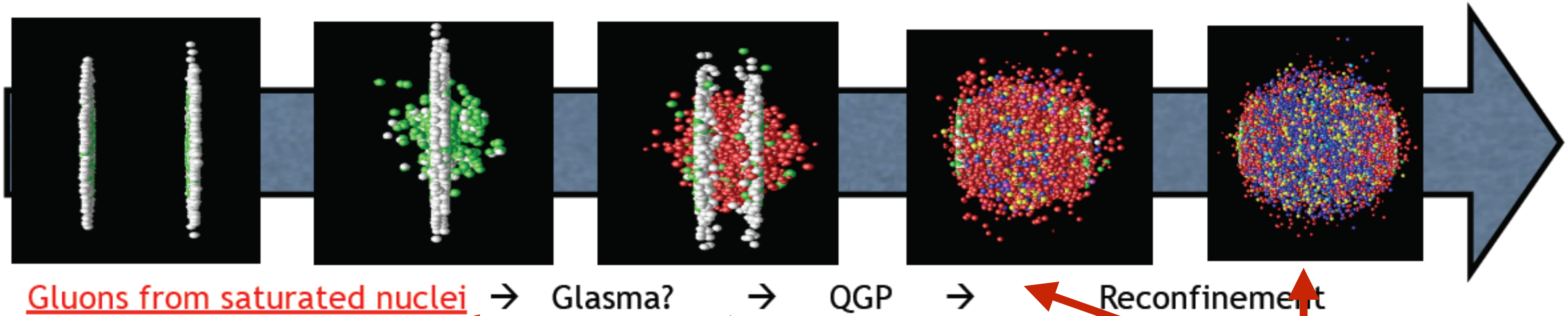
➜ High-density: x↓, A↑ ⇒ non-linear regime, recombination balancing splitting: saturation, perturbative (CGC) or non.

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





Relevance for HIC:



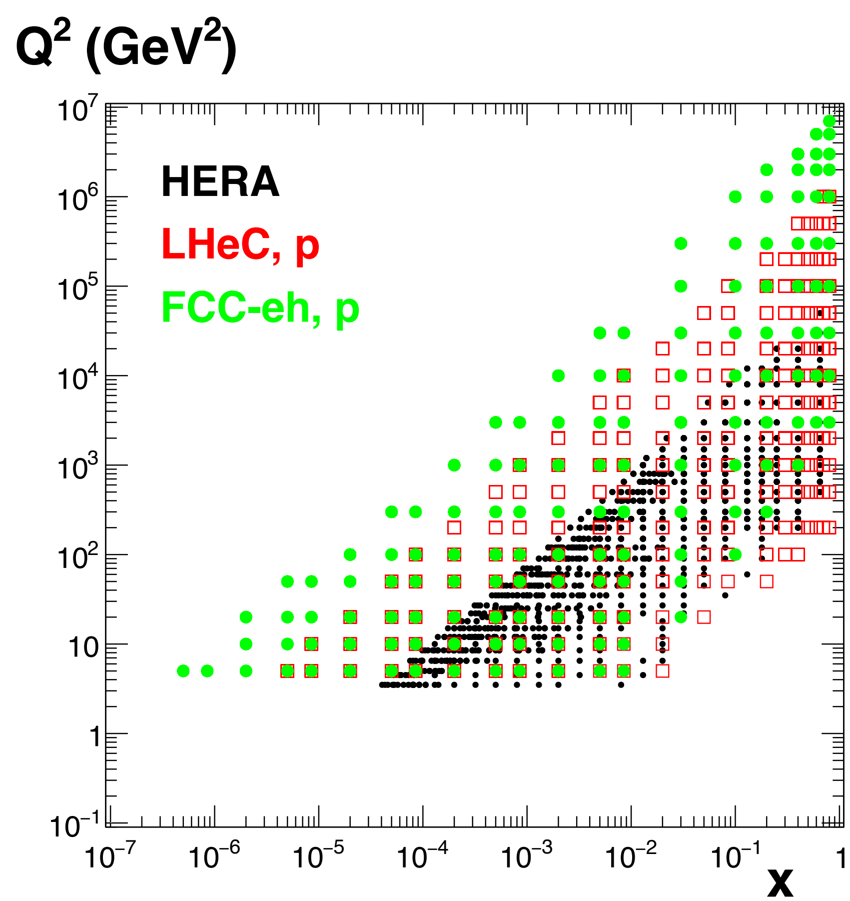
- Nuclear wave function at small x: **nuclear structure functions.**

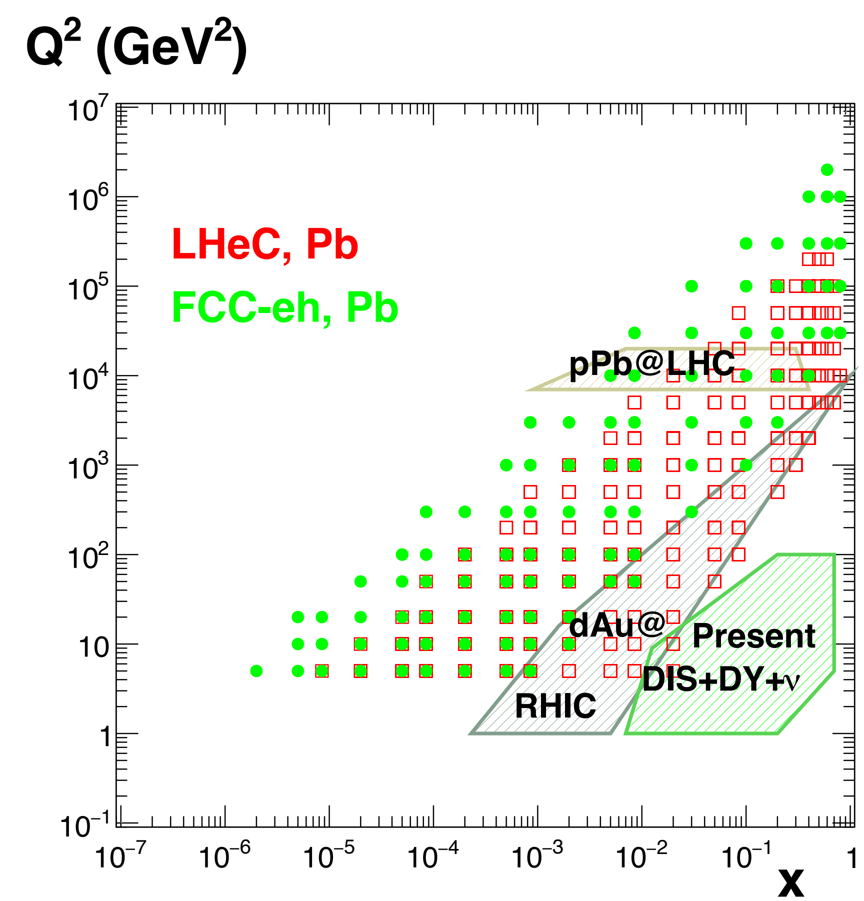
- Particle production at the very beginning: which factorisation in eA?

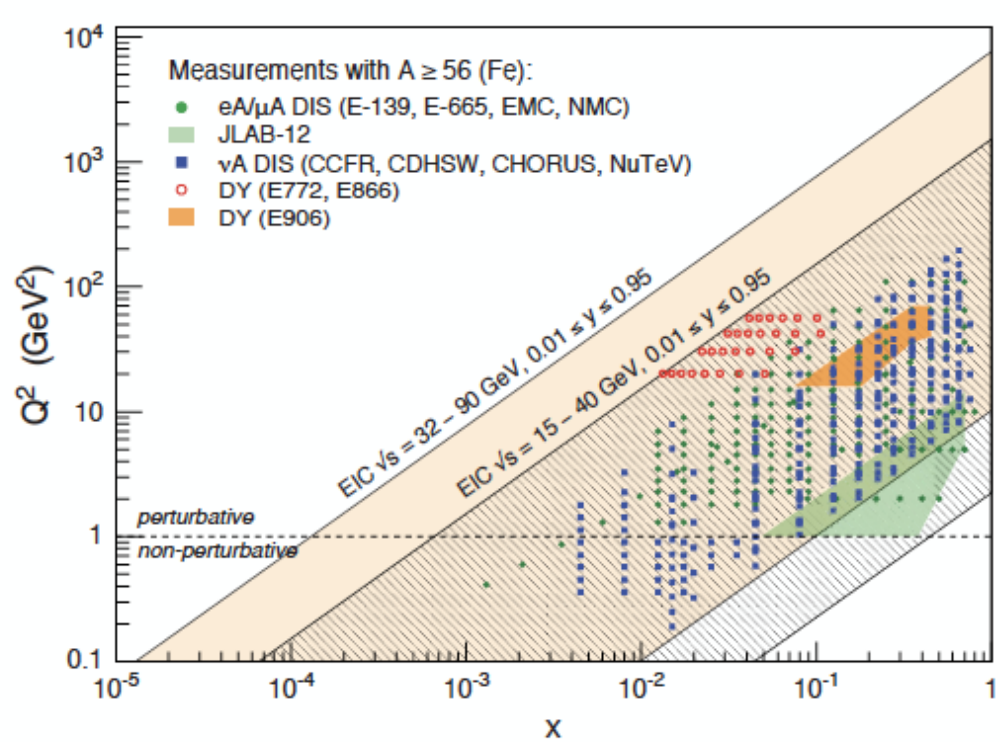
- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

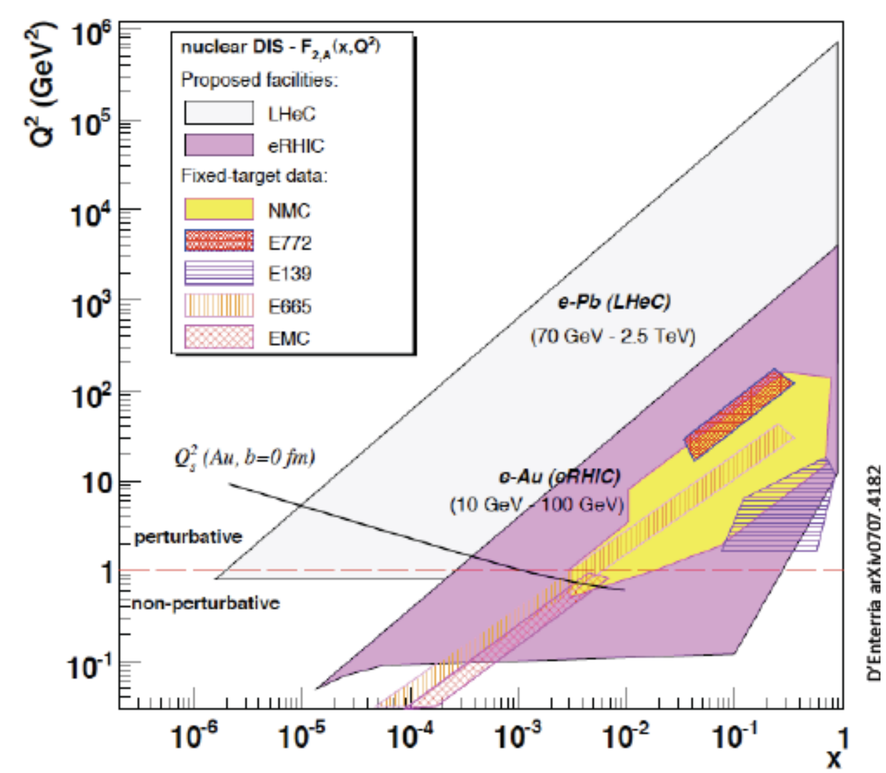
- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

LHeC/FCC-eh vs. EIC:









EPPS16 (I):

The LHeC pseudodata

- Assume $\mathcal{L}_{\rm ep} = 10\,{\rm fb}$, $\mathcal{L}_{\rm ePb} = 1\,{\rm fb}$ (per nucleon)
- The assumed energy configs: $\sqrt{s_{\rm p}} = 7\,{\rm TeV}$, $\sqrt{s_{\rm Pb}} = 2.75\,{\rm TeV}$ (per nucleon) on $E_e = 60\,{\rm GeV}$ electrons.
- The pseudodata are here obtained from ratios of reduced cross sections σ^i and relative point-to-point ($\delta^i_{\rm uncor.}$) and normalization ($\delta^i_{\rm uncor.}$) uncertainties as

$$R_i = R_i(EPS09) \times \left[1 + \delta^i_{\rm uncor.} r^i + \delta_{\rm norm.} r^{\rm norm.}\right]$$

where

$$R_i(EPS09) = \frac{\sigma^i_{\rm ePb}(CTEQ6.6 + EPS09)}{\sigma^i_{\rm ep}(CTEQ6.6)},$$

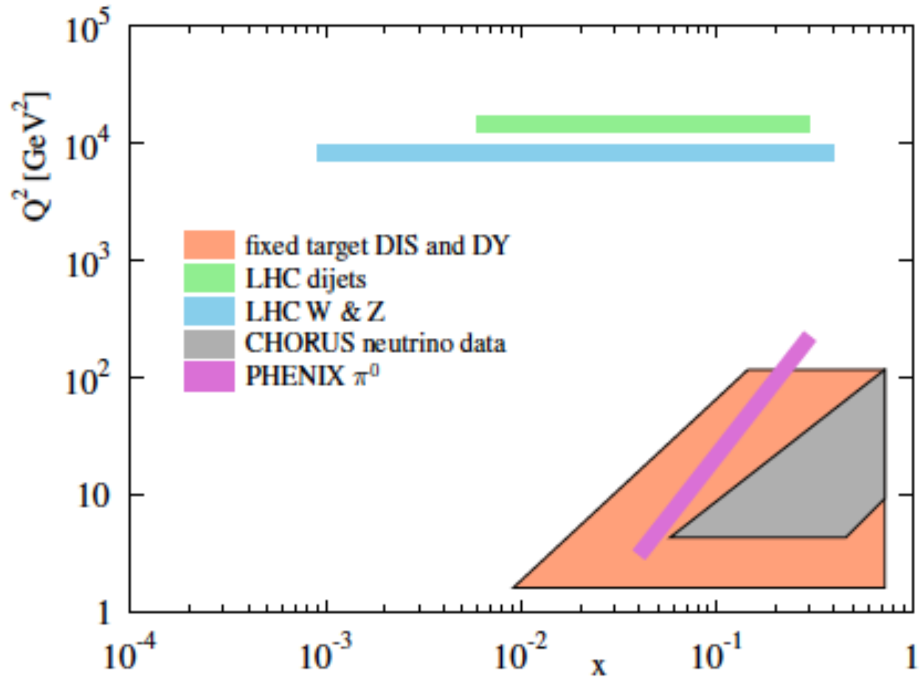
and r^i and $r^{\rm norm.}$ are Gaussian random numbers.

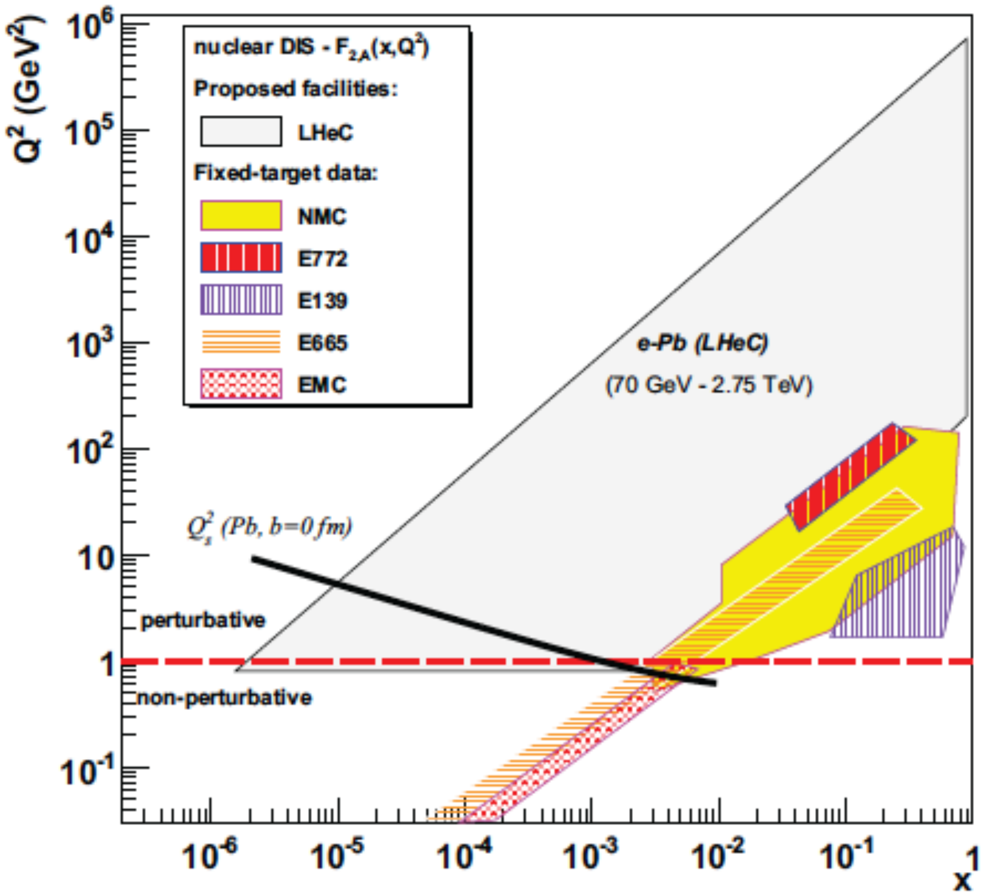
- In EPS09 $R_{u_{\rm V}} \approx R_{d_{\rm V}}$, $R_{\overline{u}} \approx R_{\overline{d}} \approx R_{\overline{s}}$ (free in EPPS16, but would not expect large deviations from this)

EPPS16 (I):

The analysis framework

- The fit framework same as in the EPPS16 analysis [EPJ C77, 163]
- Include the same data as in EPPS16 plus LHeC (NC and CC) pseudo data.
- Hessian uncertainty analysis with $\Delta\chi^2 = 52$ (as in EPPS16)

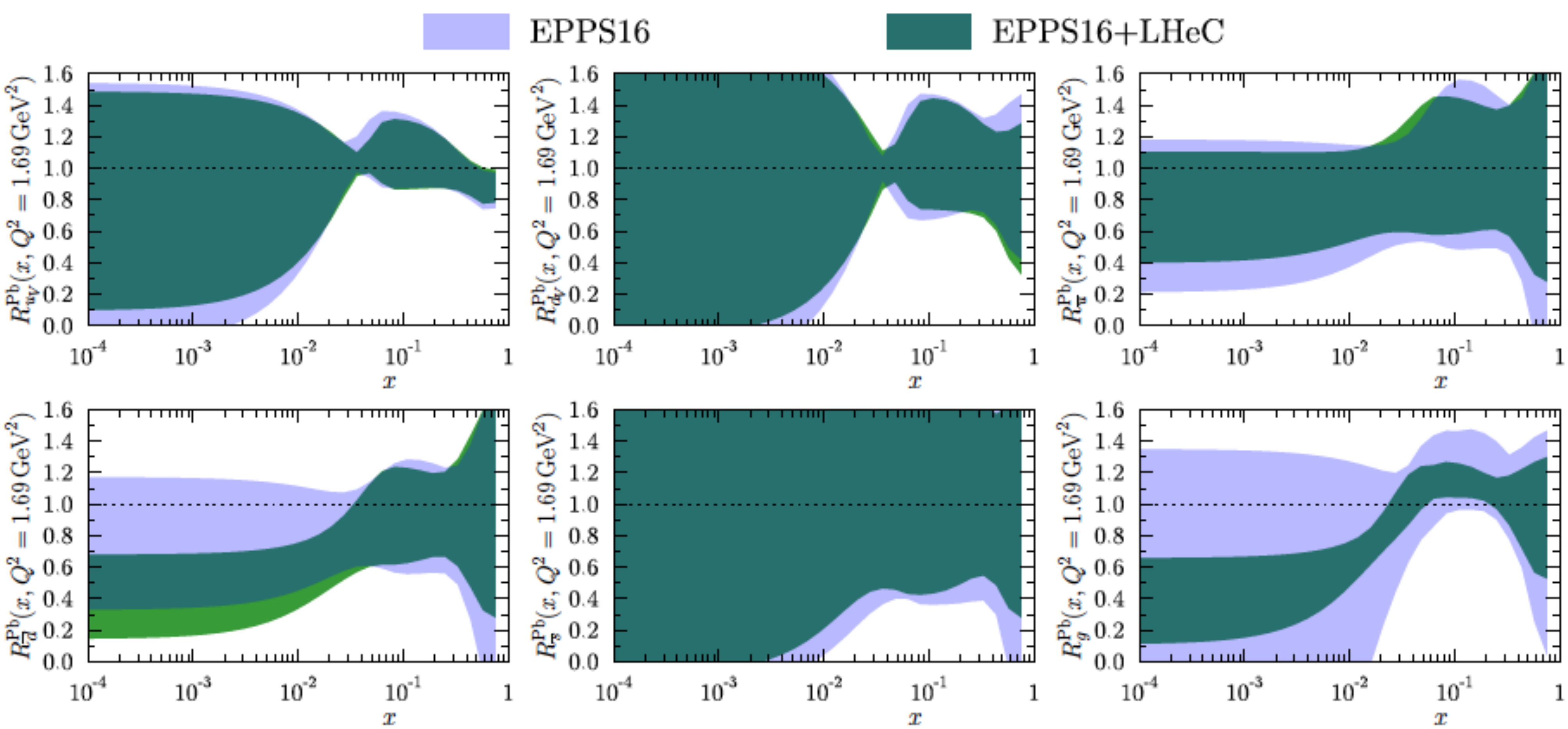




EPPS16 (I):

The effect of LHeC pseudodata

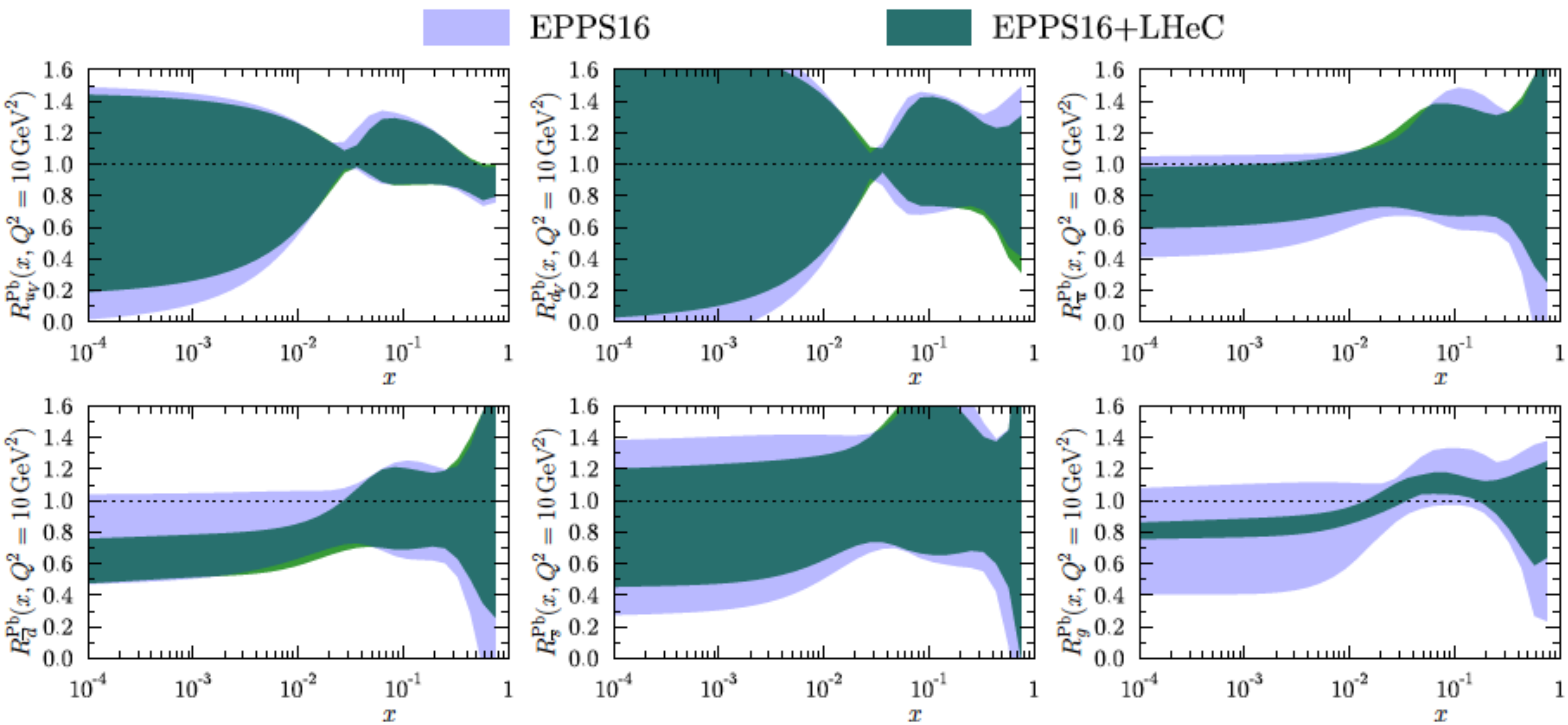
- The improvement after adding the LHeC data ($Q^2 = 1.69\,\mathrm{GeV}^2$)



EPPS16 (I):

The effect of LHeC pseudodata

- The improvement after adding the LHeC data ($Q^2 = 10\,\mathrm{GeV}^2$)



EPPS16 (II):

The effect of LHeC pseudodata

- Why it's so hard to pin down the flavor dependence?
- Take the valence up-quark distribution u_V^A as an example:

$$u_V^A = \frac{Z}{A} R_{u_V}\, u_V^{\rm proton} + \frac{A-Z}{A} R_{d_V}\, d_V^{\rm proton}$$

- Write this in terms of average modification R_V and the difference δR_V

$$R_V \equiv \frac{R_{u_V}\, u_V^{\rm proton} + R_{d_V}\, d_V^{\rm proton}}{u_V^{\rm proton} + d_V^{\rm proton}}, \qquad \delta R_V \equiv R_{u_V} - R_{d_V}$$

$$u_V^A = R_V \left(\frac{Z}{A} u_V^{\rm proton} + \frac{A-Z}{A} d_V^{\rm proton} \right) + \delta R_V \left(\frac{2Z}{A} - 1 \right) \frac{u_V^{\rm proton}}{1 + u_V^{\rm proton}/d_V^{\rm proton}}$$

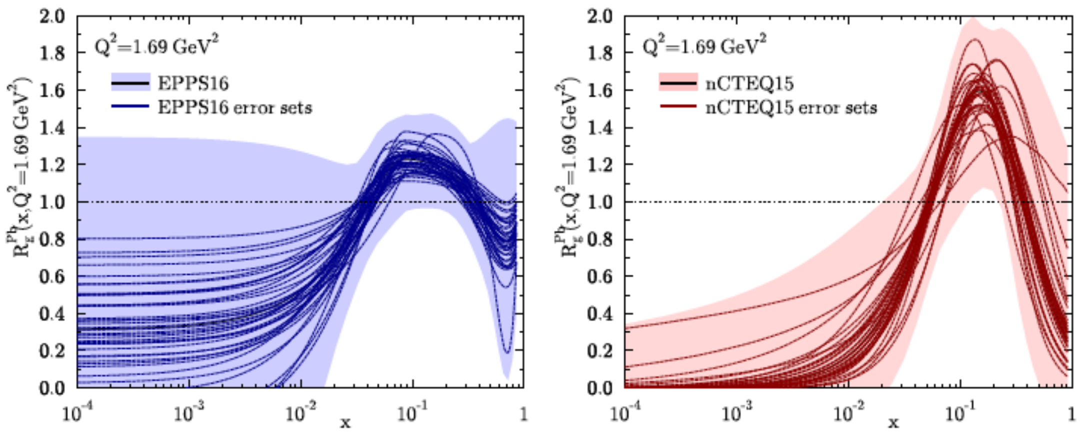
Leading term (first term) — "Correction term" (second term)

- The effects of flavour separation (i.e. δR_V here) are suppressed in cross sections — but also so in most of the nPDF applications.

EPPS16 (II):

$$R^{\rm EPS09}(x) = \begin{cases} a_0 + a_1 (x - x_a)^2 & x \le x_a \\ b_0 + b_1 x^\alpha + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

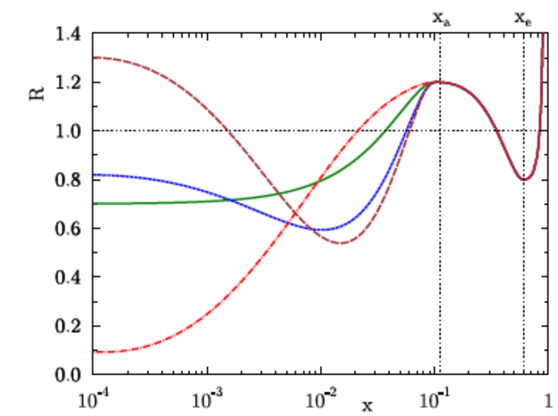
$$R^{\rm nCTEQ15}(x) = \left[c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}\right] / f^p(x)$$



$$R(x \le x_a) = a_0 + a_1 (x - x_a)^2 + \sqrt{x}(x_a - x)\left[a_2 \log\left(\frac{x}{x_a}\right) + a_3 \log^2\left(\frac{x}{x_a}\right) + a_4 \log^3\left(\frac{x}{x_a}\right) + \ldots\right]$$

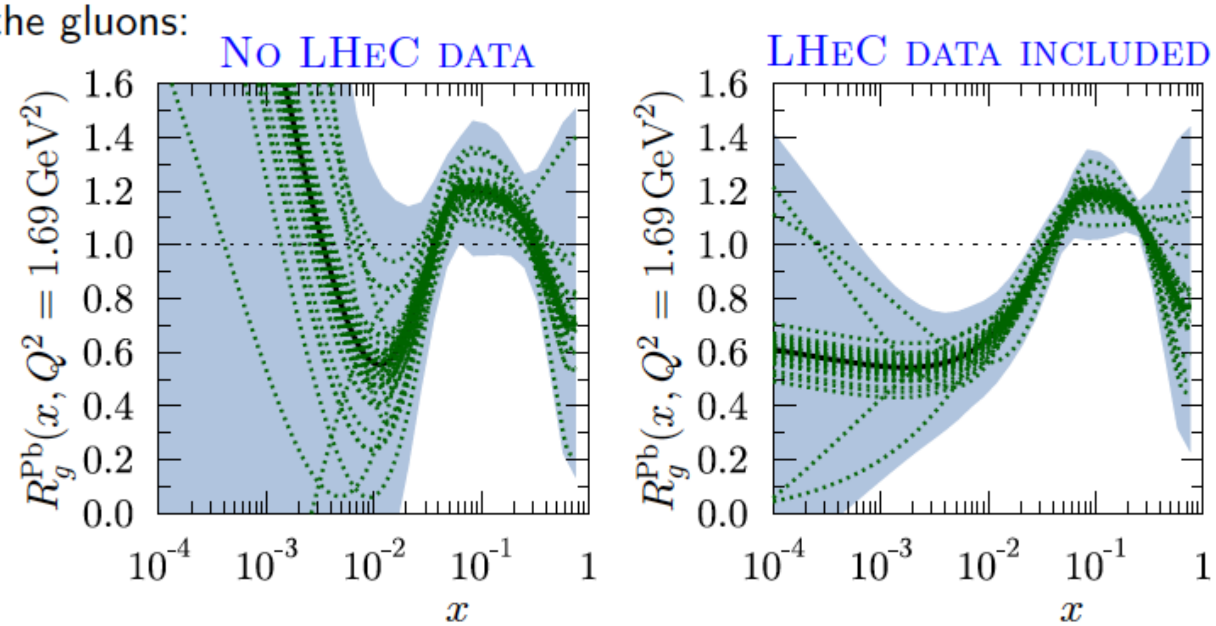
or

$$R(x \le x_a) = a_0 + (x - x_a)^2 \left[a_1 + a_2 x^\alpha + a_3 x^{2\alpha} + a_4 x^{3\alpha} + \ldots\right], \quad \alpha \ll 1$$

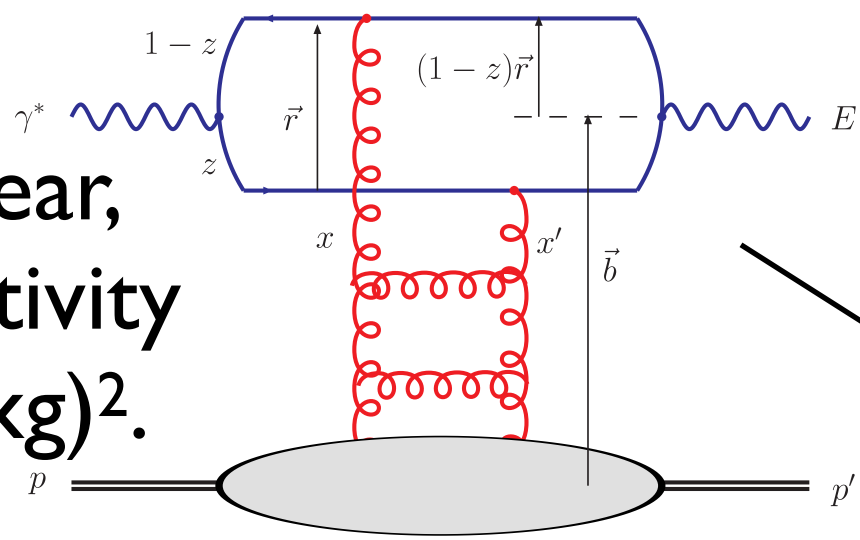


- Would need Monte-Carlo methods to more reliably map the uncertainties

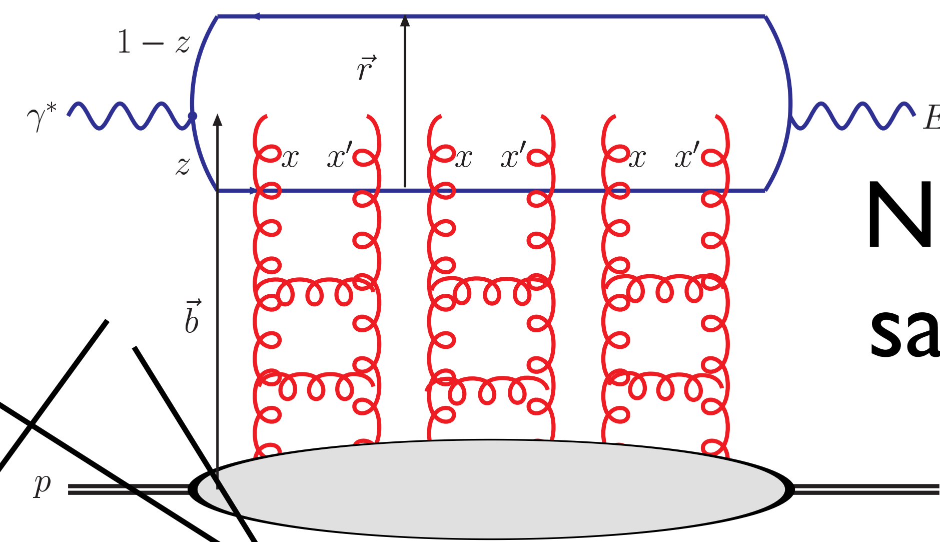
  $\Longrightarrow$ Further work needed
- Despite all the shortcomings, a typical result using a more flexible form for the gluons:



Exclusive VMs:

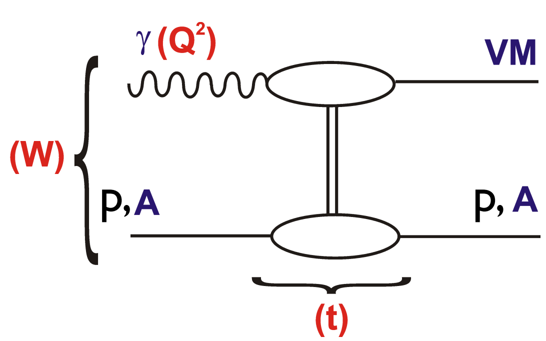


Linear, sensitivity to $(xg)^2$.

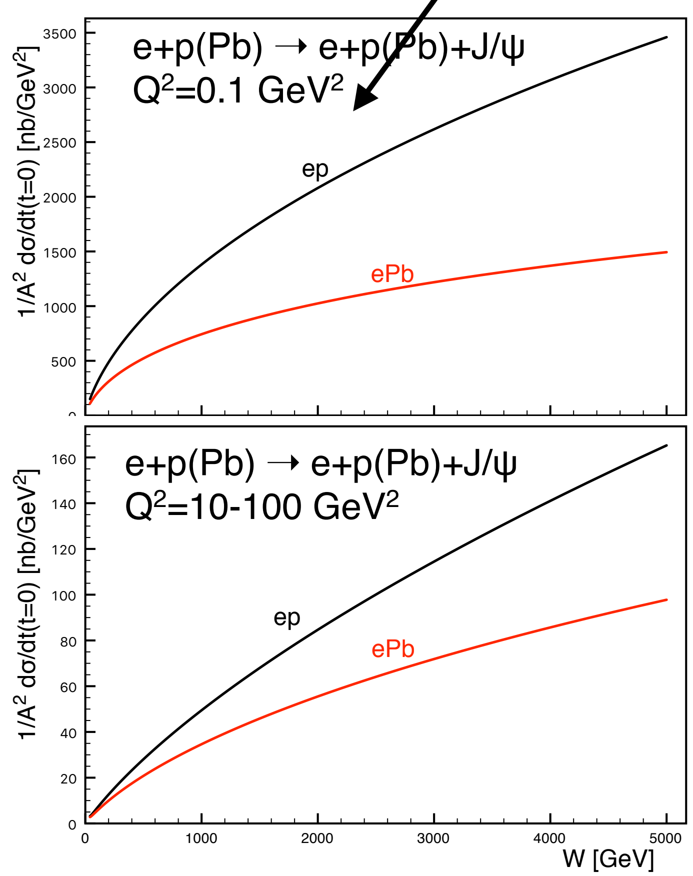


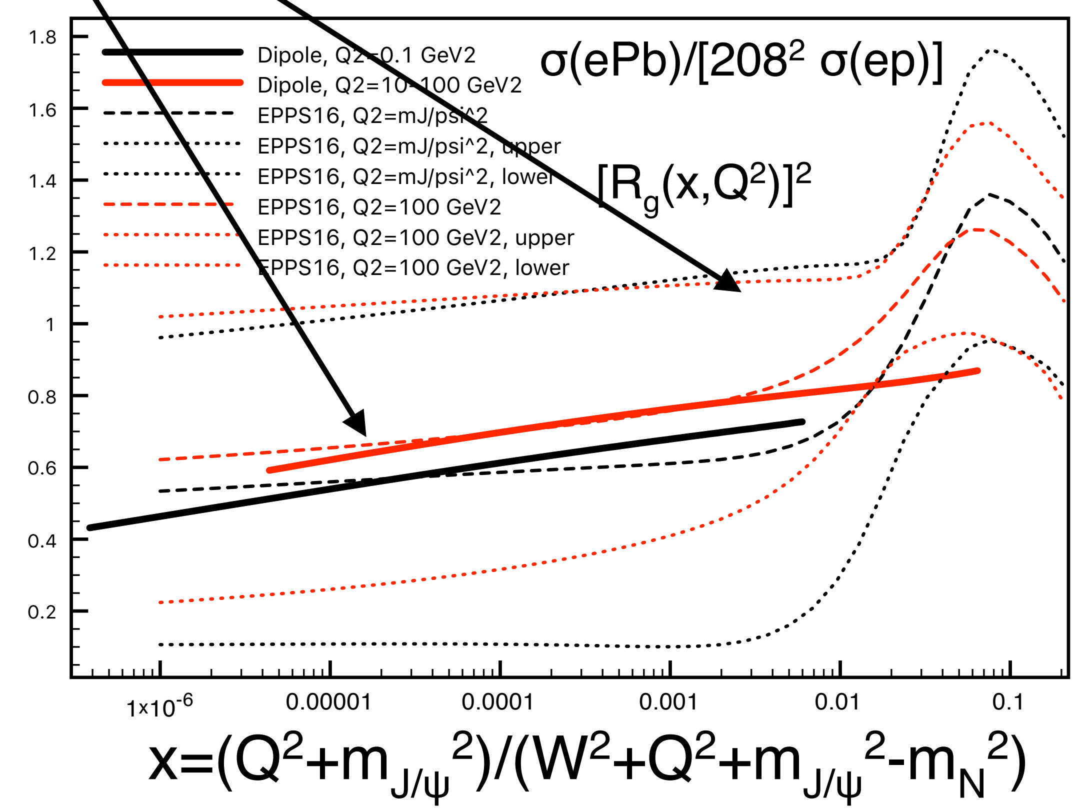
Non-linear, saturation.

- The magnitude of nuclear shadowing needs not be different in collinear and non-collinear approaches.



Coherent diffractive VM production





Mantysaari, Paukkunen