Indian Summer School of Physics
Phenomenology of Hot and Dense Matter for Future Accelerators
Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University
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Hadron structure phenomenology at an EIC

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Contents:

Bibliography:

- R. Devenish and A. Cooper-Sarker, *Deep Inelastic Scattering*, Oxford University Press 2004.
- G. P. Salam, *Elements of QCD for hadron colliders*, CERN Yellow Report CERN-2010-002, 45-100, arXiv:1011.5131 [hep-ph].
- J. L. Abelleira Fernandez et al., *A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector*, J. Phys. G39 (2012) 075001, arXiv:1206.2913 [physics.acc-ph].
- A. Accardi et al., *Electron Ion Collider: The Next QCD Frontier : Understanding the glue that binds us all*, Eur. Phys. J. A52 (2016) no.9, 268, arXiv:1212.1701 [nucl-ex].

Contents:

1. Basics of DIS.
2. Determination of (n)PDFs.
3. Inclusive and exclusive diffraction.
4. Spin.
5. Small-x physics in DIS.
6. Outlook.

Conventional, wide implications, inclusive Xsections. (→ 2)

Less conventional, differential information, more exclusive Xsections. (→ 3)

I will show very little 🙏. (→ 4)

See Tuomas' lectures. (→ 5)

Just a little discussion about future projects. (→ 6)

Bibliography:

- R. Devenish and A. Cooper-Sarker, *Deep Inelastic Scattering*, Oxford University Press 2004.
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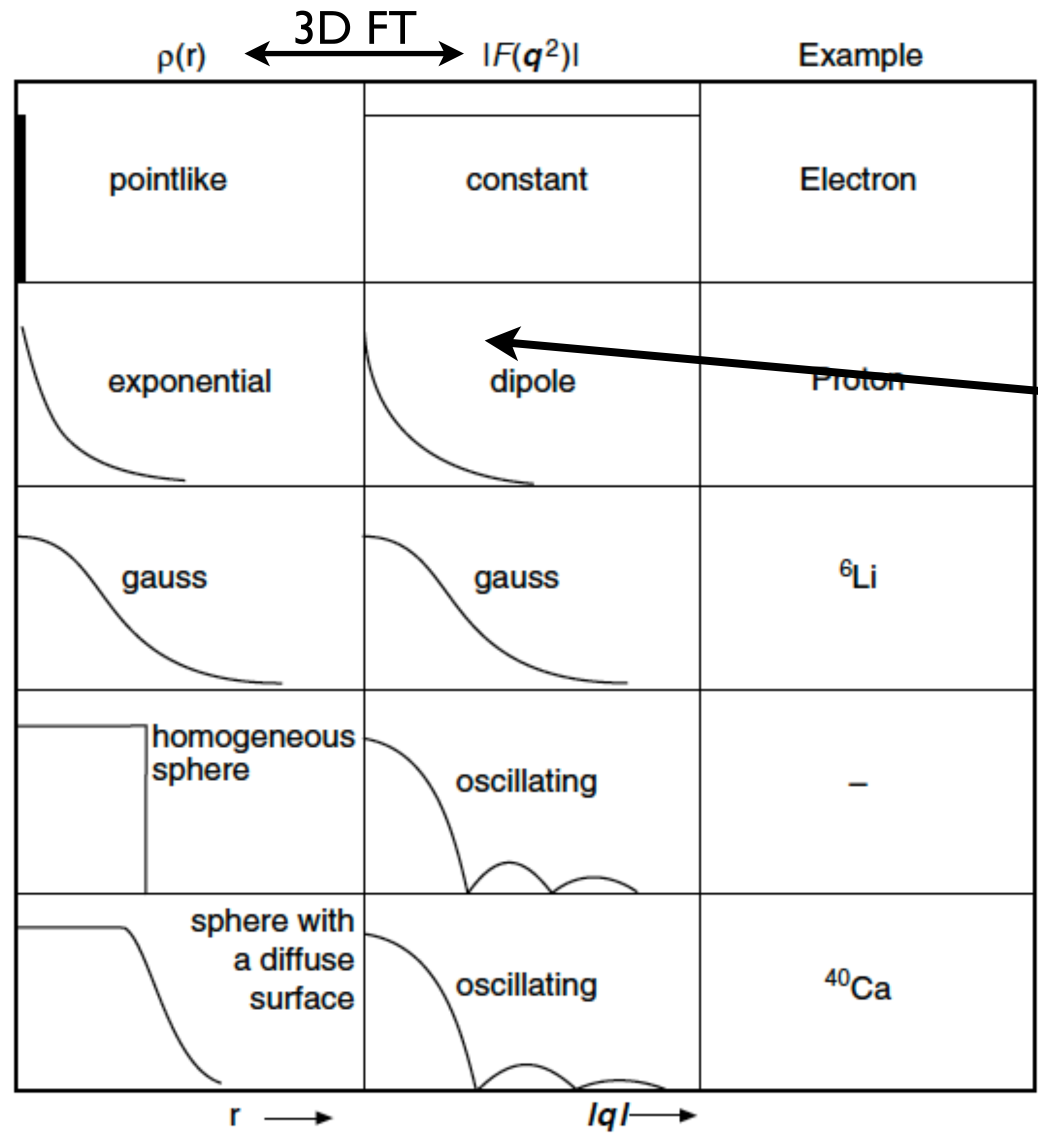
DIS: proton substructure

➜ Let us compare elastic scattering (x=1) on a pointlike s=1/2 particle with that on a proton and the inelastic one (for x~$\mathcal{O}$(1)):



$$\left(\frac{d\sigma}{d\Omega}\right)_{\substack{\text{point}\\ \text{spin } 1/2}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \cdot \left[1 + 2\tau \tan^2\frac{\theta}{2}\right]$$

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \cdot \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}\right]$$

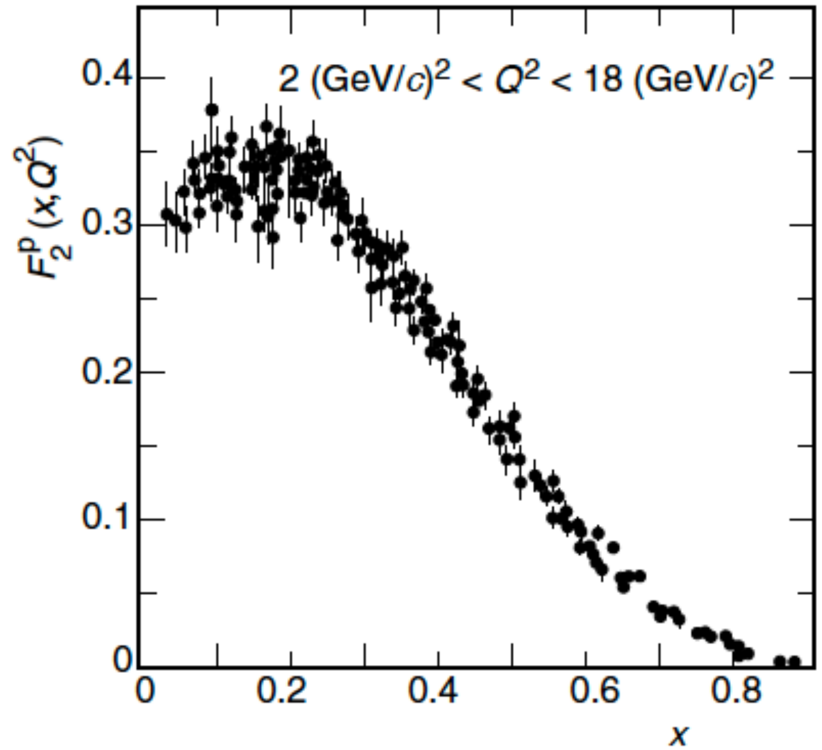
$$\frac{d^2\sigma}{d\Omega\, dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left[W_2(Q^2,\nu) + 2W_1(Q^2,\nu)\tan^2\frac{\theta}{2}\right]$$

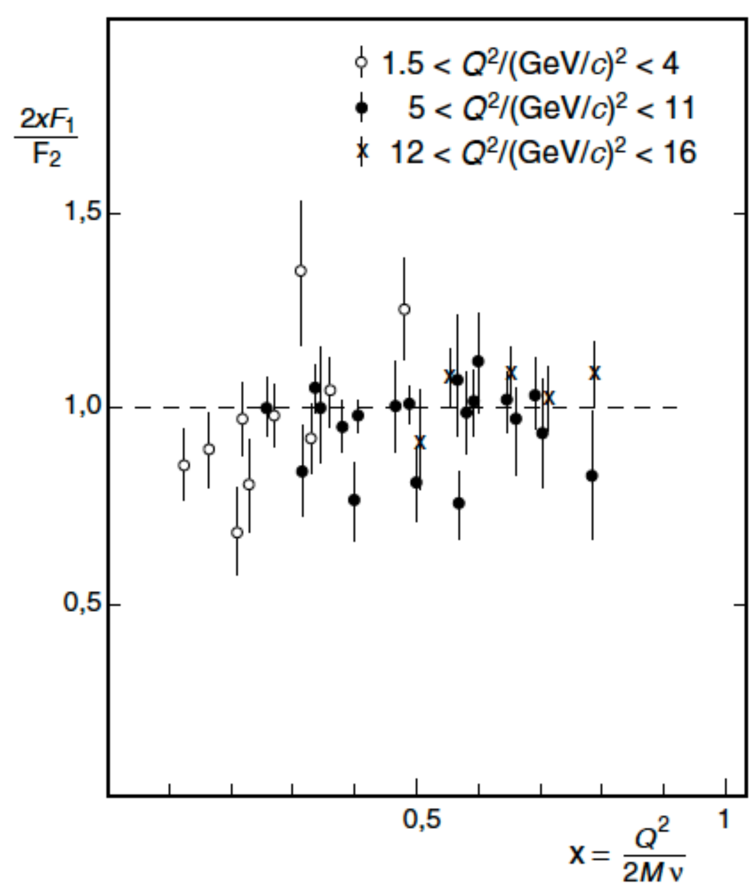
$$F_1(x,Q^2) = Mc^2\, W_1(Q^2,\nu)$$
$$F_2(x,Q^2) = \nu\, W_2(Q^2,\nu)\,.$$

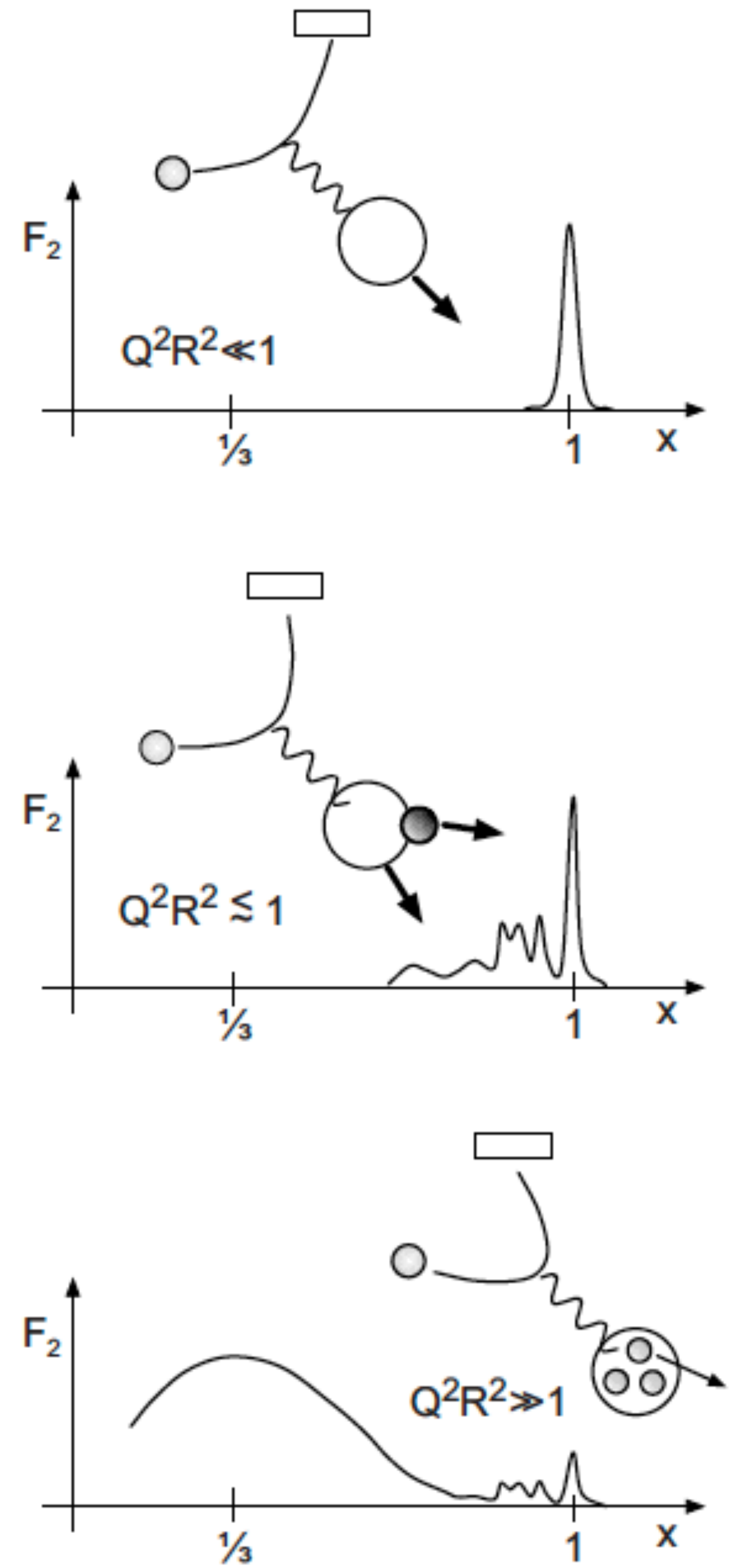
➜ For fixed x, $F_{1,2}$ roughly independent of Q (note $1/Q^4$ behaviour of proton form factors): Bjorken scaling, pointlike scatterers.

➜ $2xF_1=F_2$: Callan-Gross relation, spin-1/2 scatterers.

DIS: proton substructure

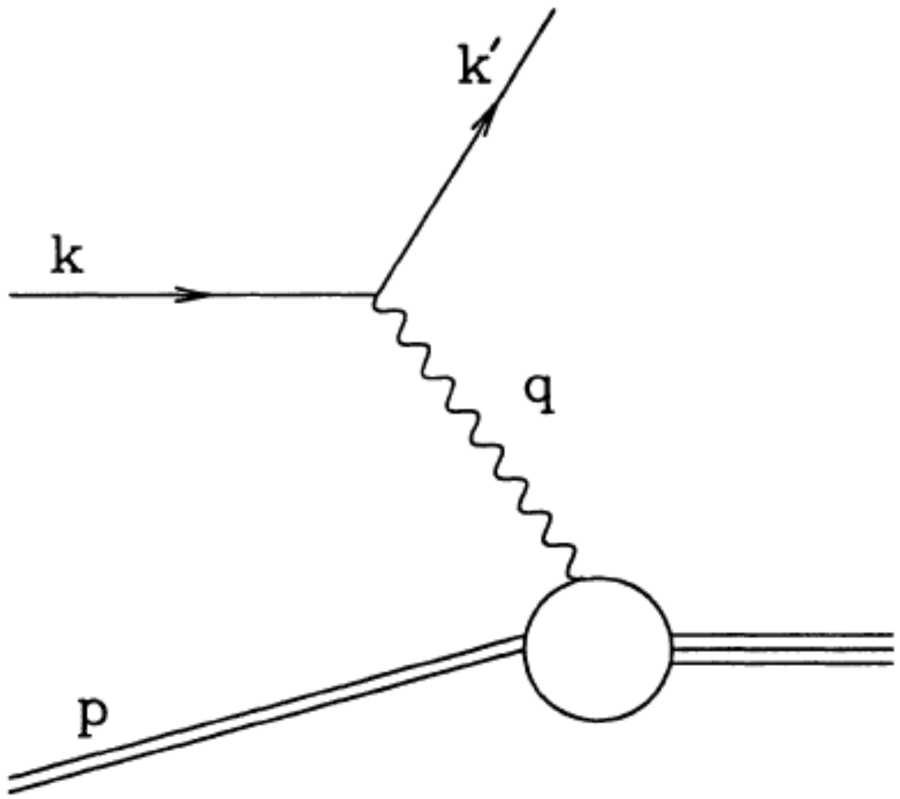






DIS: basics

➜ Consider the process of lepton (e, μ, ν) scattering on a proton (or neutron or nucleus): equivalent to the Rutherford experiment.



Standard DIS variables:

electron-proton cms energy squared:

$$s = (k+p)^2$$

photon-proton cms energy squared:

$$W^2 = (q+p)^2$$

inelasticity

$$y = \frac{p \cdot q}{p \cdot k}$$

Bjorken x

$$x = \frac{-q^2}{2p \cdot q}$$

(minus) photon virtuality

$$Q^2 = -q^2$$

➜ For charged lepton scattering and neglecting Z exchange,

$$\frac{d^2\sigma}{dQ^2\,dx} = \frac{4\pi\alpha^2}{Q^4 x}\left[(1-y)F_2(x,Q^2) + xy^2F_1(x,Q^2)\right]$$

F_1, F_2: structure functions of the hadron

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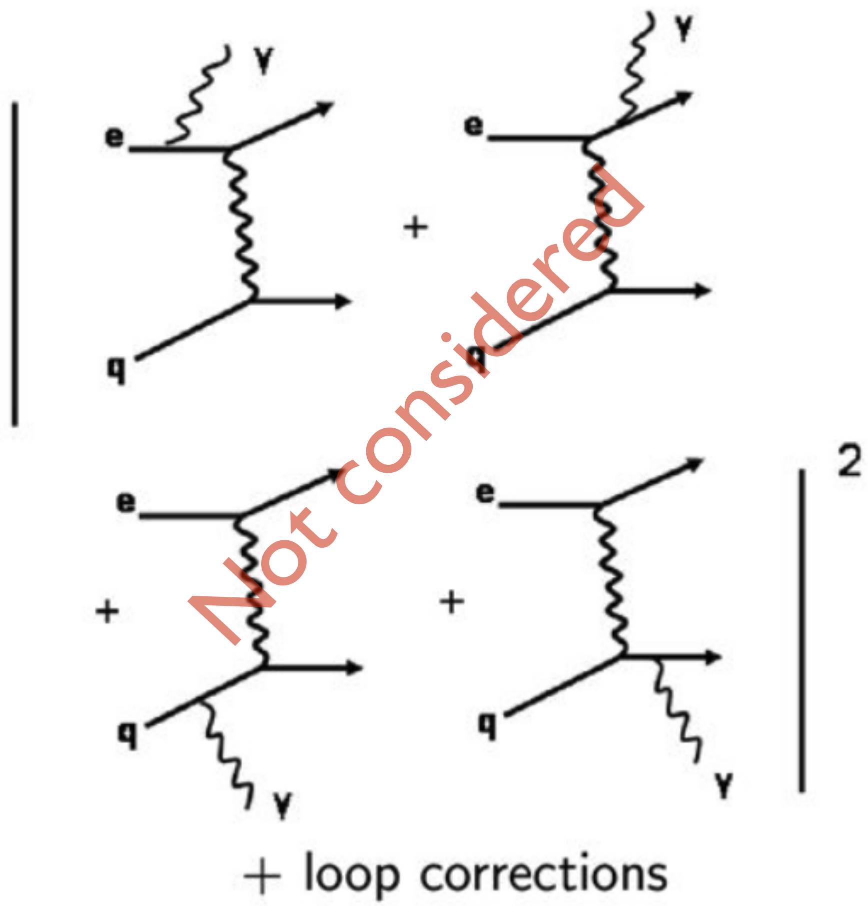

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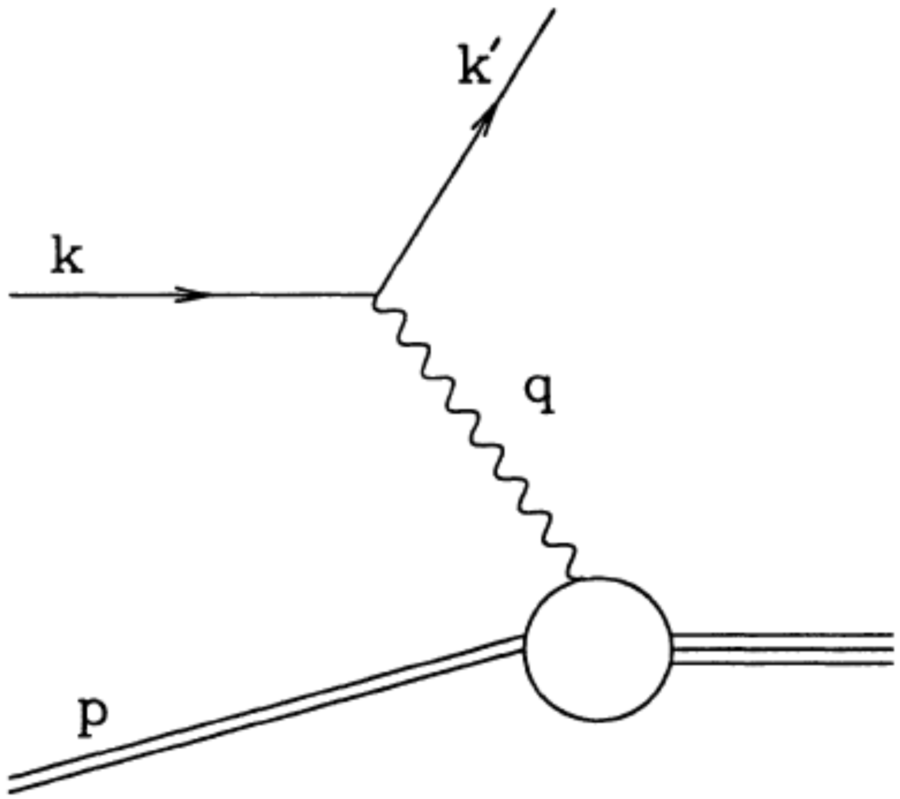

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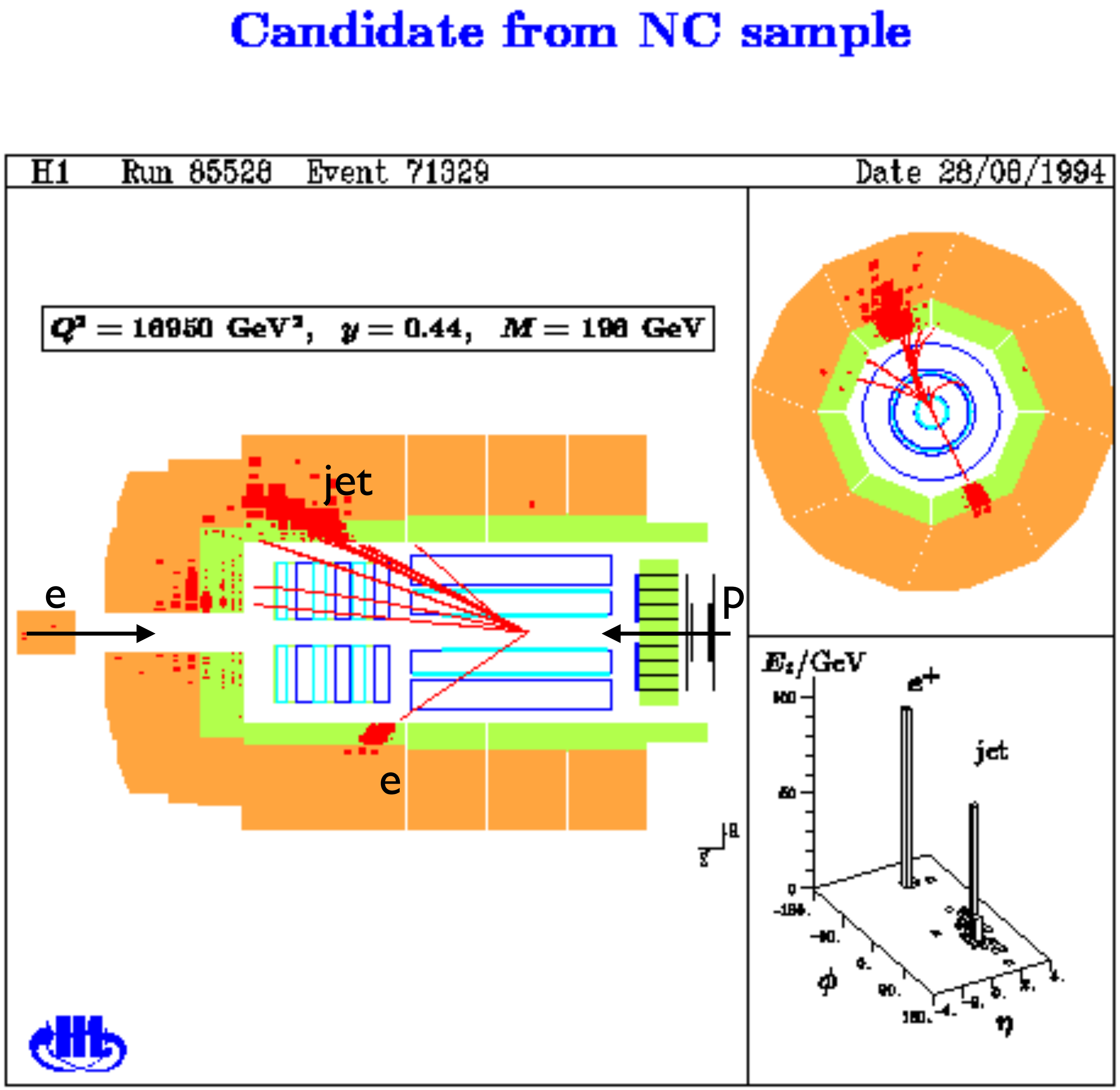
F_1, F_2: structure functions of the hadron

Experiment:



HERA: e±(27.5) + p(920), √s=318 GeV

Lepton method

$$Q_e^2 = 4E_e E_e' \cos^2\left(\frac{\theta_e}{2}\right)$$

$$y_e = 1 - \frac{E_e'}{E_e}\sin^2\left(\frac{\theta_e}{2}\right)$$

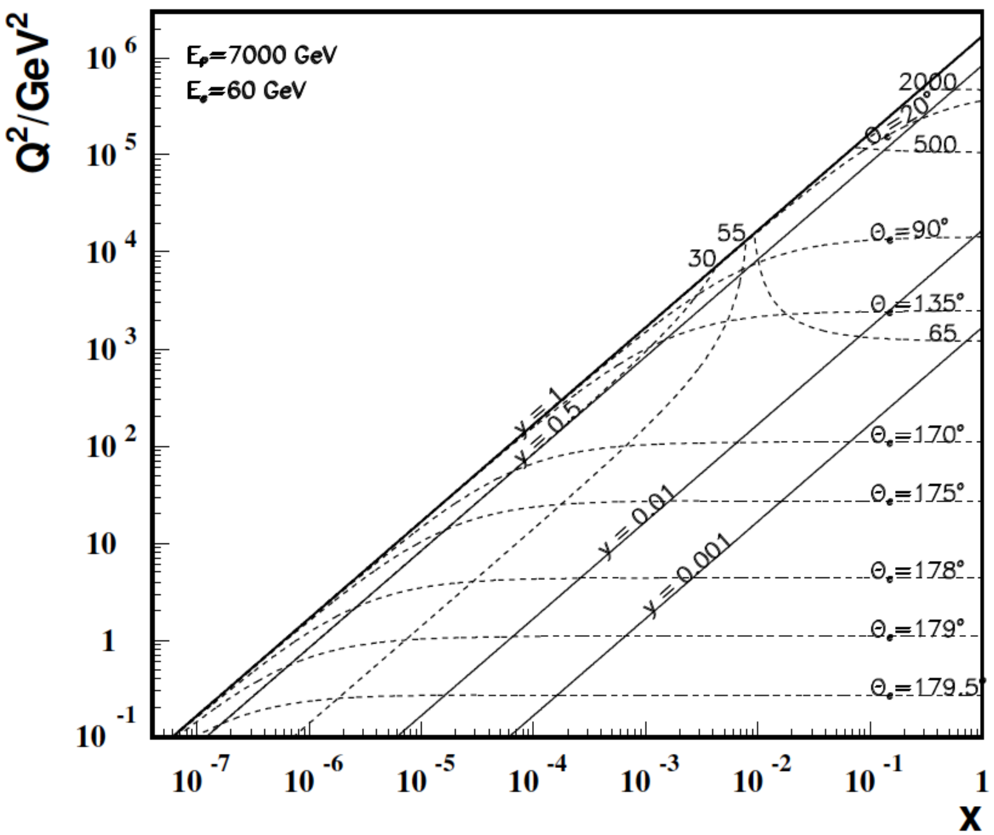
Hadron method

$$Q_h^2 = \frac{1}{1-y_h}\cdot E_h^2 \sin^2(\theta_h)$$

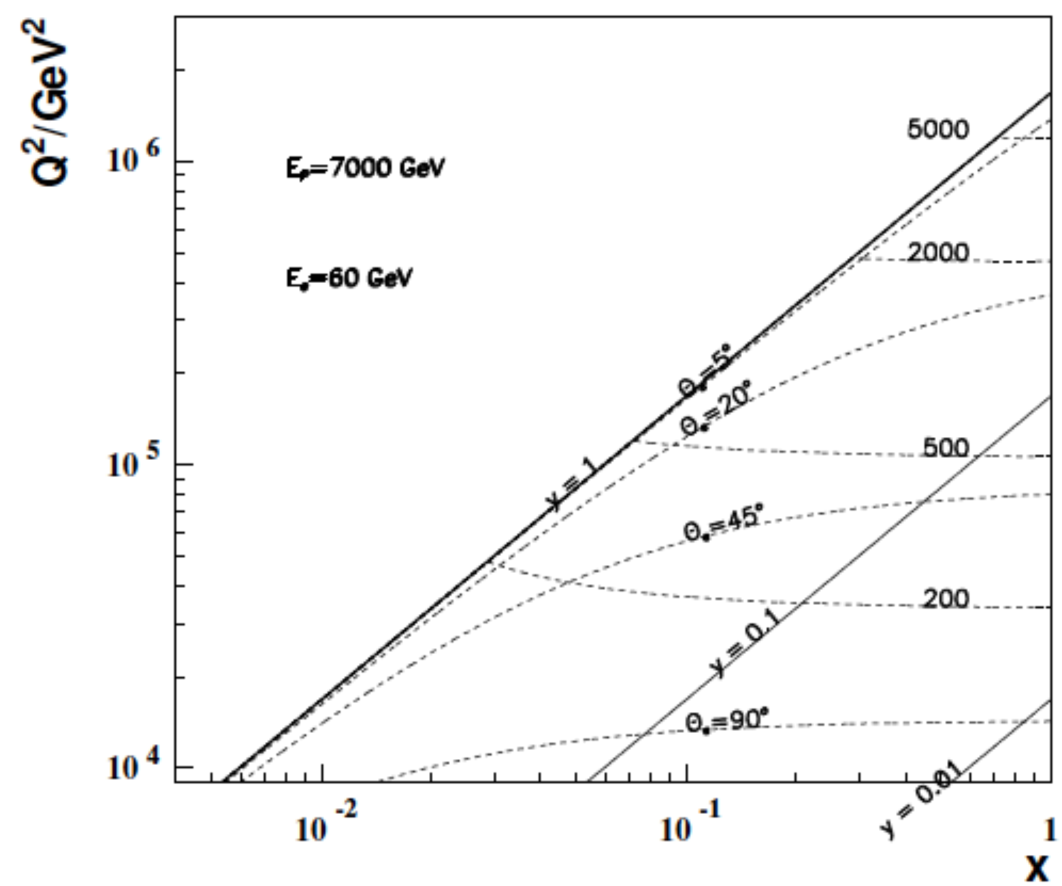
$$y_h = \frac{E_h}{E_e}\sin^2\left(\frac{\theta_h}{2}\right)$$

Note: angles measured with respect to the p direction.

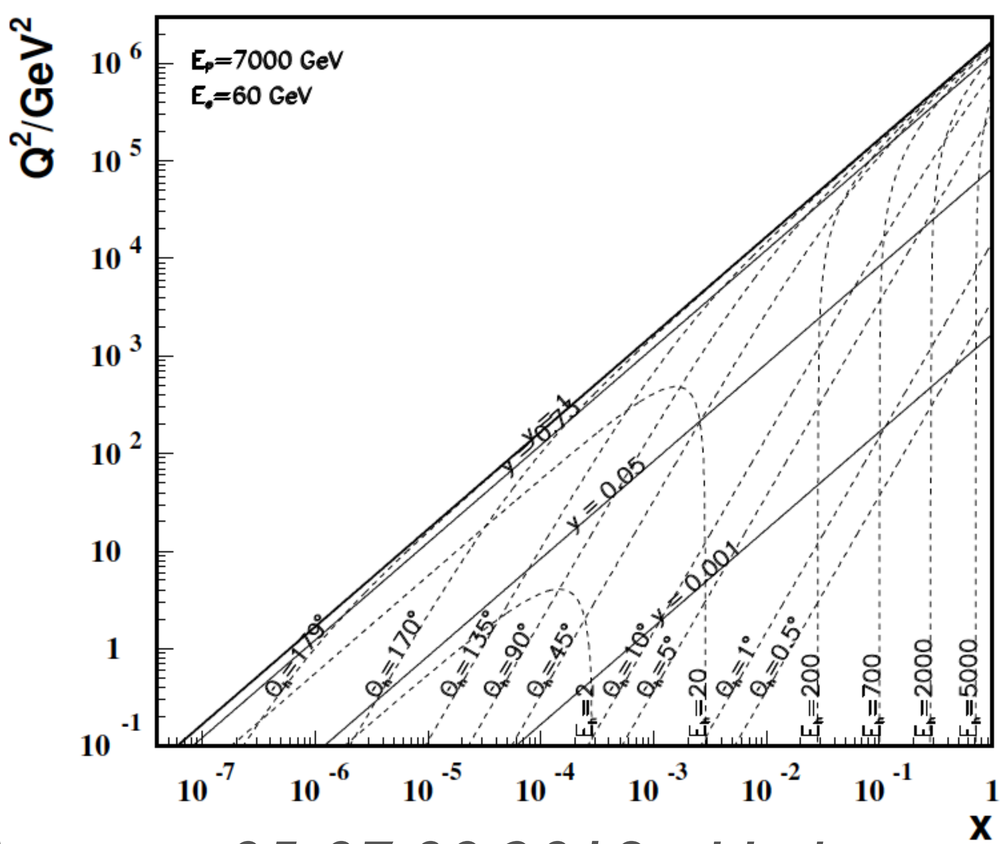
Kinematics:



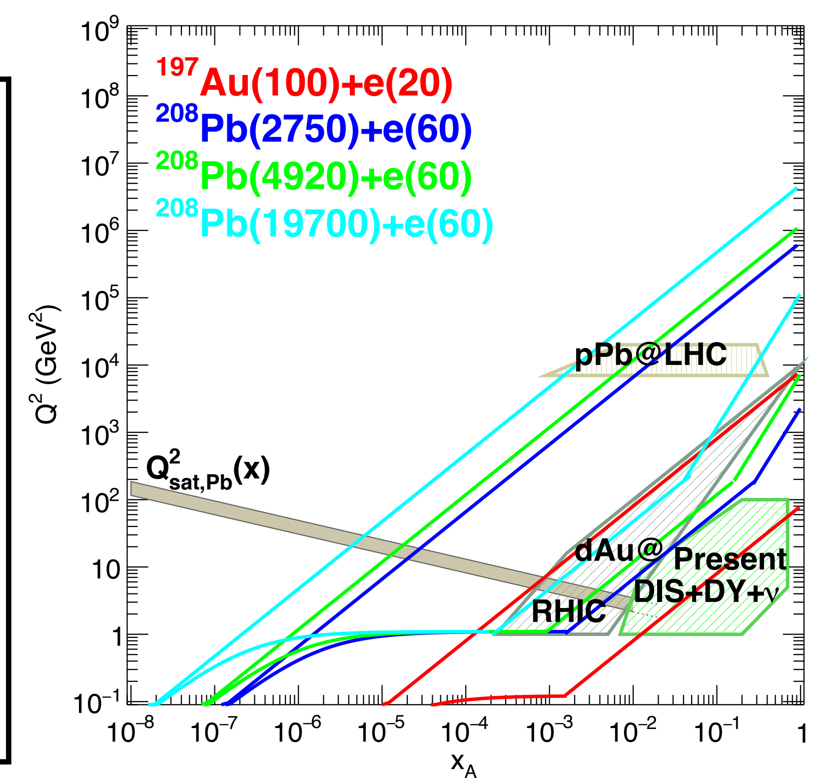
LHeC - electron kinematics



LHeC - hadronic final state kinematics



Large acceptance + excellent EM and HAD calorimetry required.



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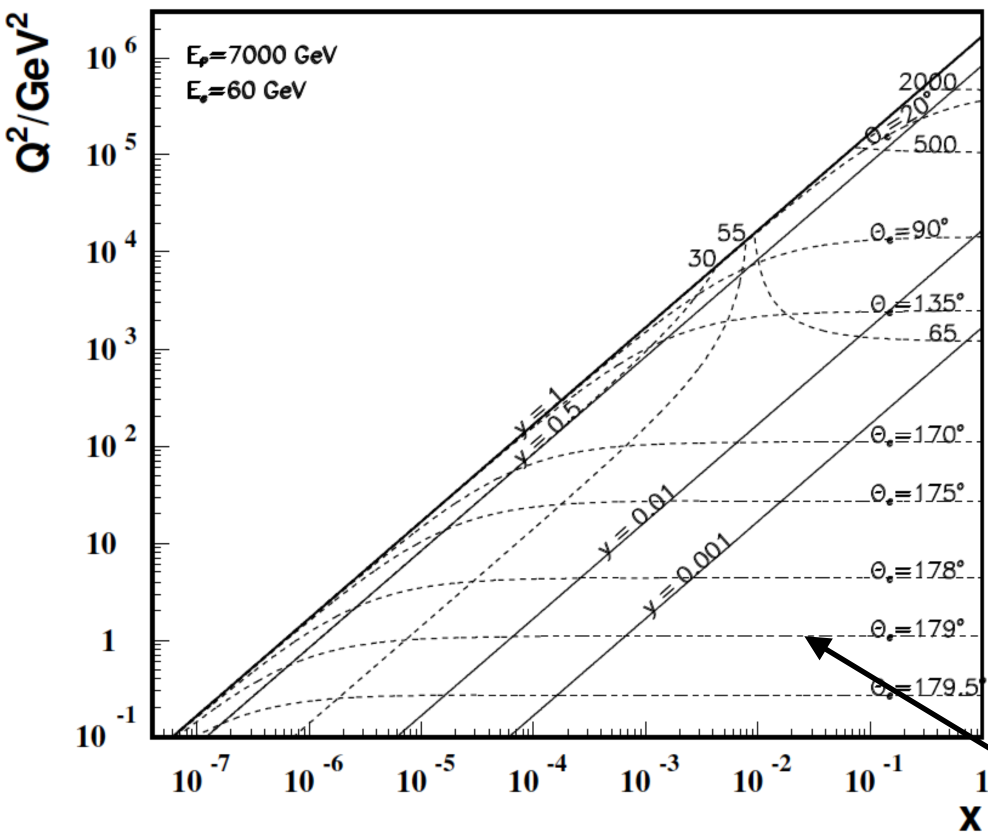
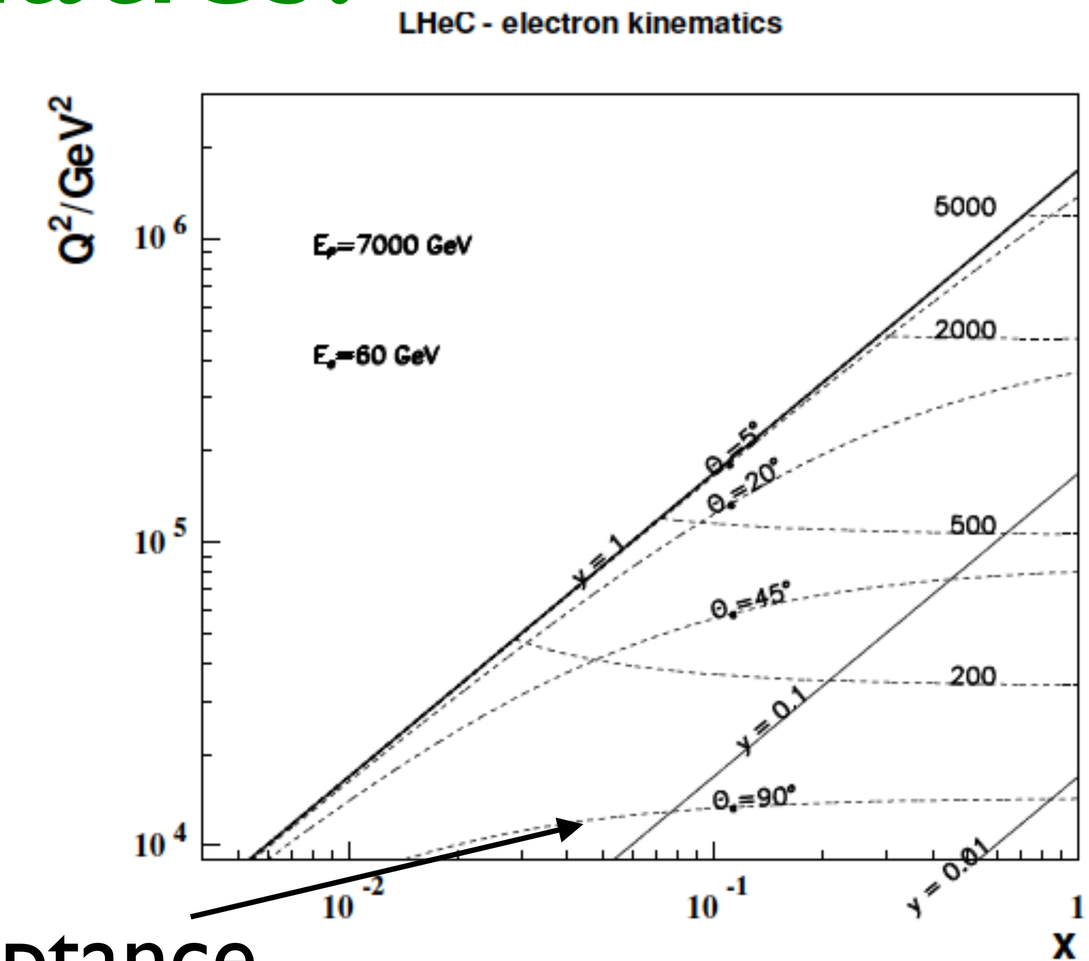
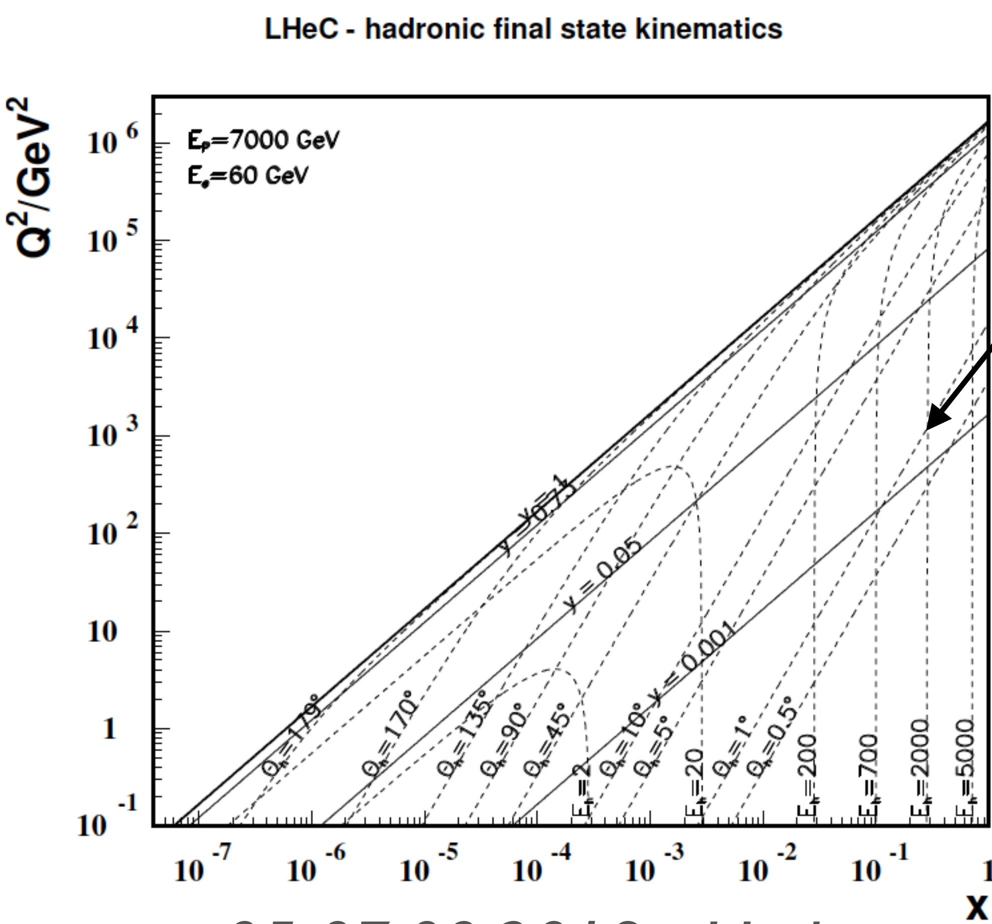




Acceptance



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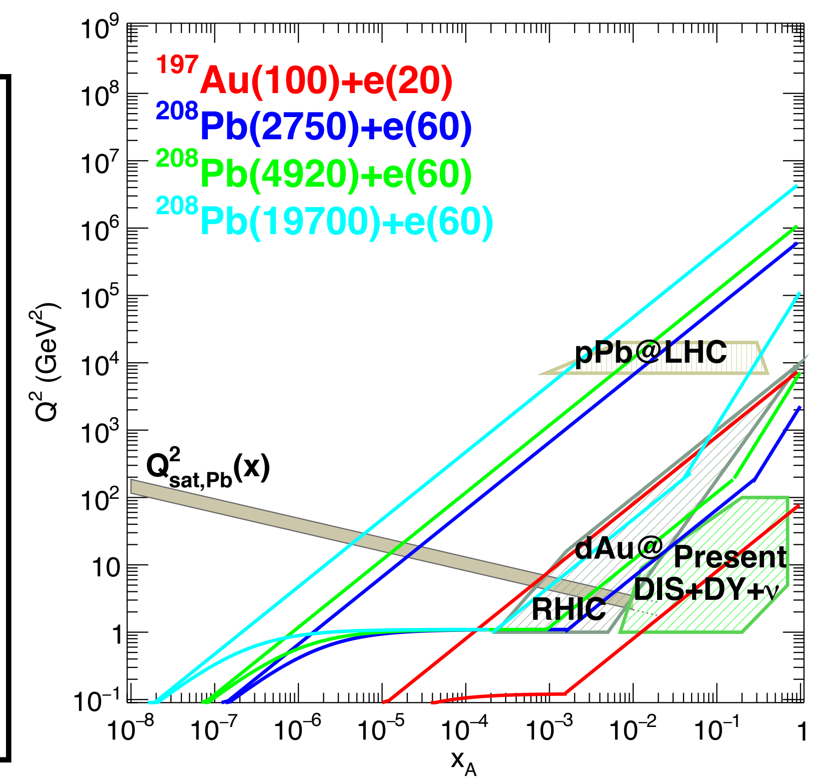

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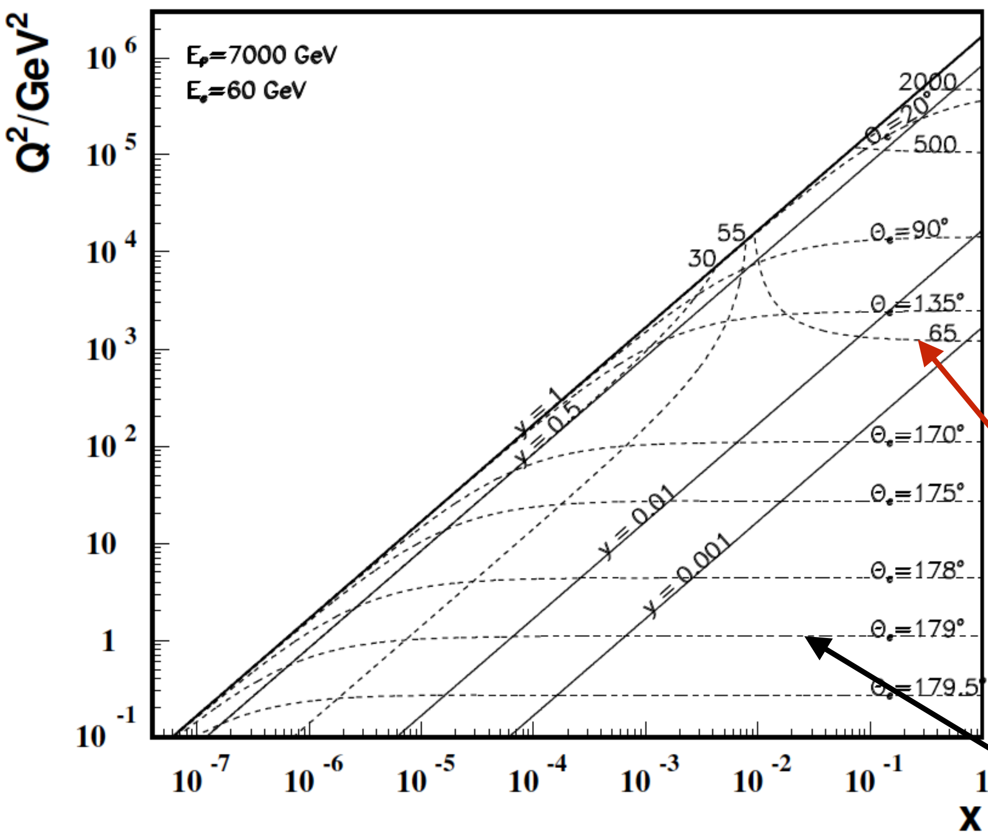
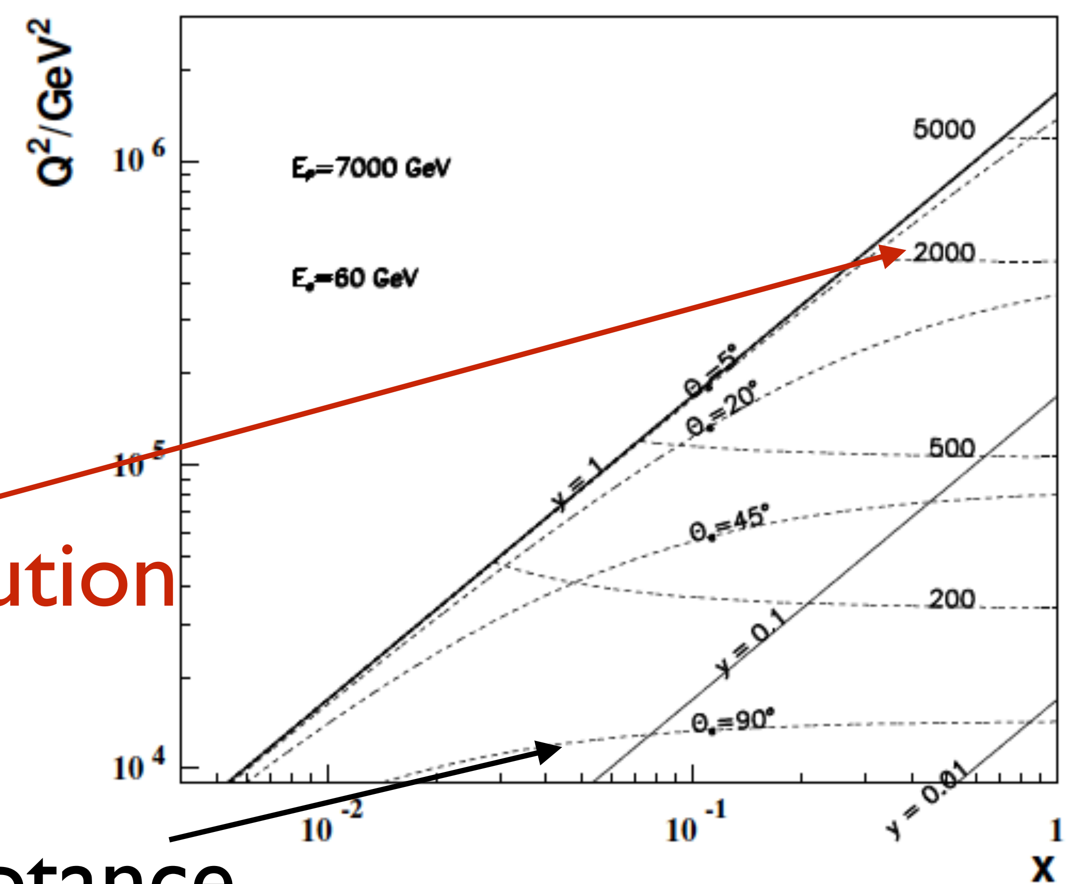


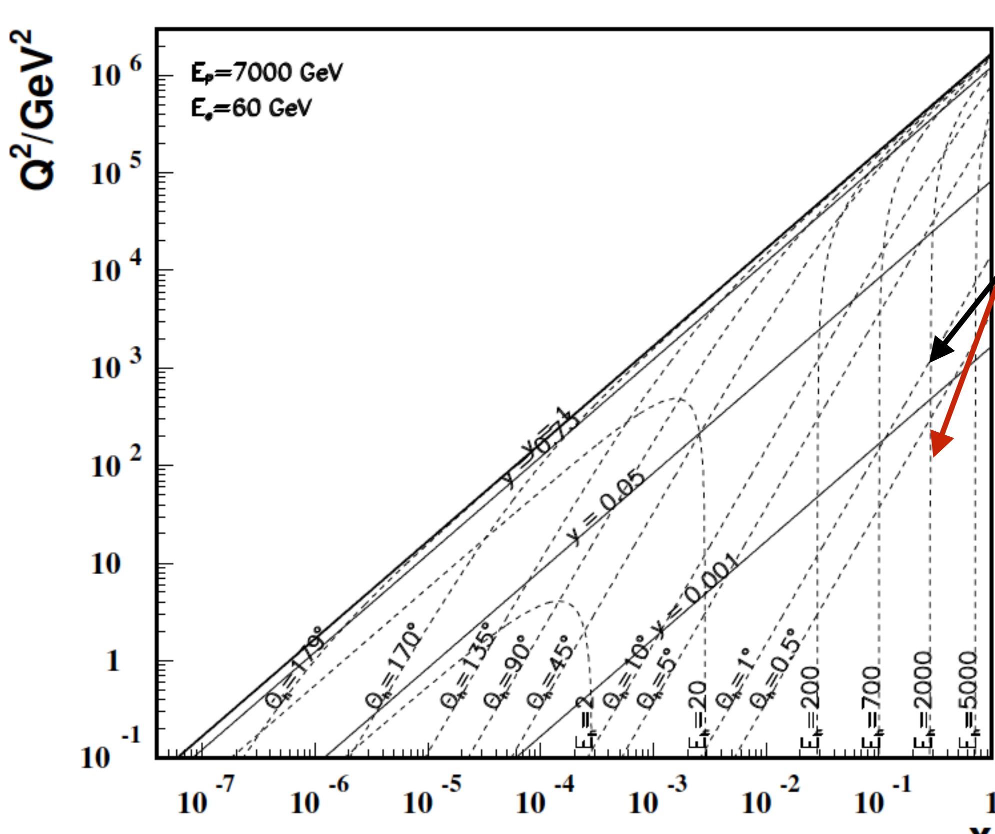
LHeC - electron kinematics



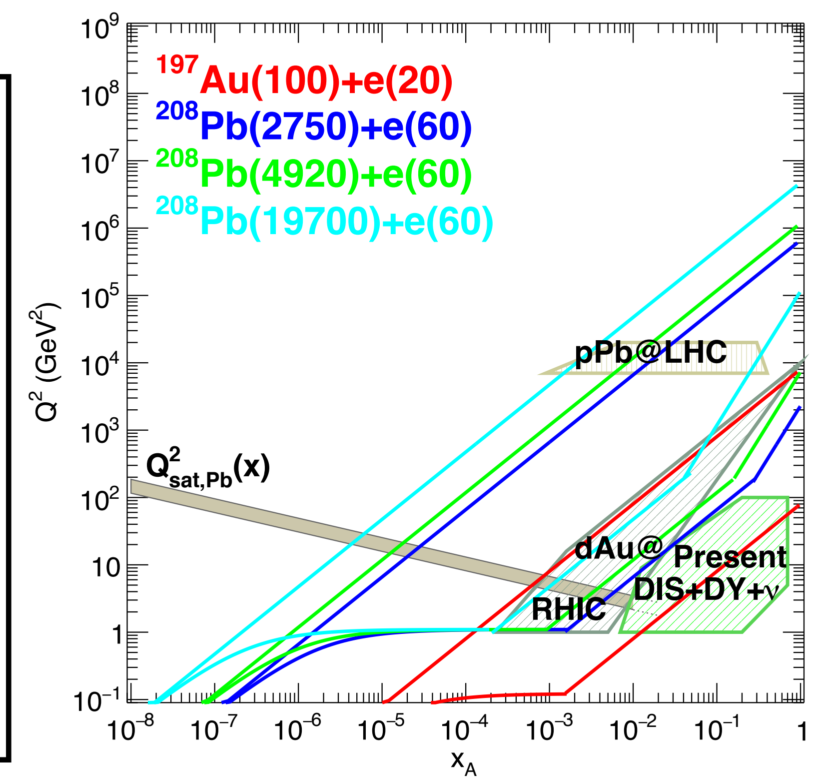
E-resolution

Acceptance

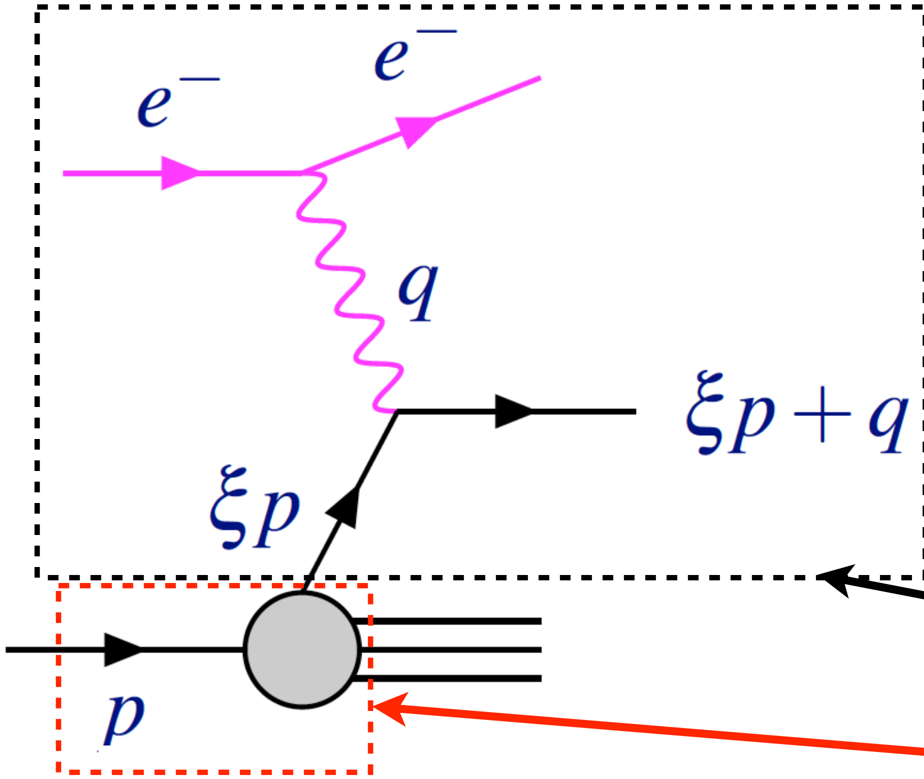
LHeC - hadronic final state kinematics



Large acceptance + excellent EM and HAD calorimetry required.



DIS: parton model



➜ For very large momentum (IMF), the hadron can be considered an incoherent superposition of quanta (partons) during the interaction ($Q \gg \Lambda_{QCD}$): parton model (Feynman, Bjorken, Gribov).

$$\sigma(e^-(k)p(p) \to e^-(k')X) = \int_0^1 d\xi \sum_f f_{q_f}(\xi)\, \sigma(e^-(k)q_f(\xi p) \to e^-(k')\, q_f(\xi p + q))$$

$$F_2(x) = 2xF_1(x) = \sum_{q,\bar{q}} \int_0^1 d\xi\; q(\xi)\; x e_q^2 \delta(x-\xi) + \mathcal{O}(1/Q^2)$$

$$= \sum_{q,\bar{q}} e_q^2\, x q(x)\, .$$

➜ Relation between PDFs for valence and sea quarks and gluons:

$$F_2^{eN}(x) = \frac{5}{18} F_2^{\nu N}(x)$$

electric charges

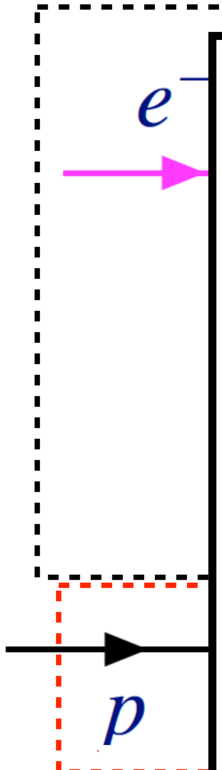
$$F_2^{ep} - F_2^{en} = \frac{1}{3} x(u_v(x) - d_v(x))$$

valence

$$\int_0^1 F_2^{\nu N}(x)dx = \int_0^1 x\left(q(x) + \bar{q}(x)\right)dx = 0.44$$

gluons

DIS: parton model



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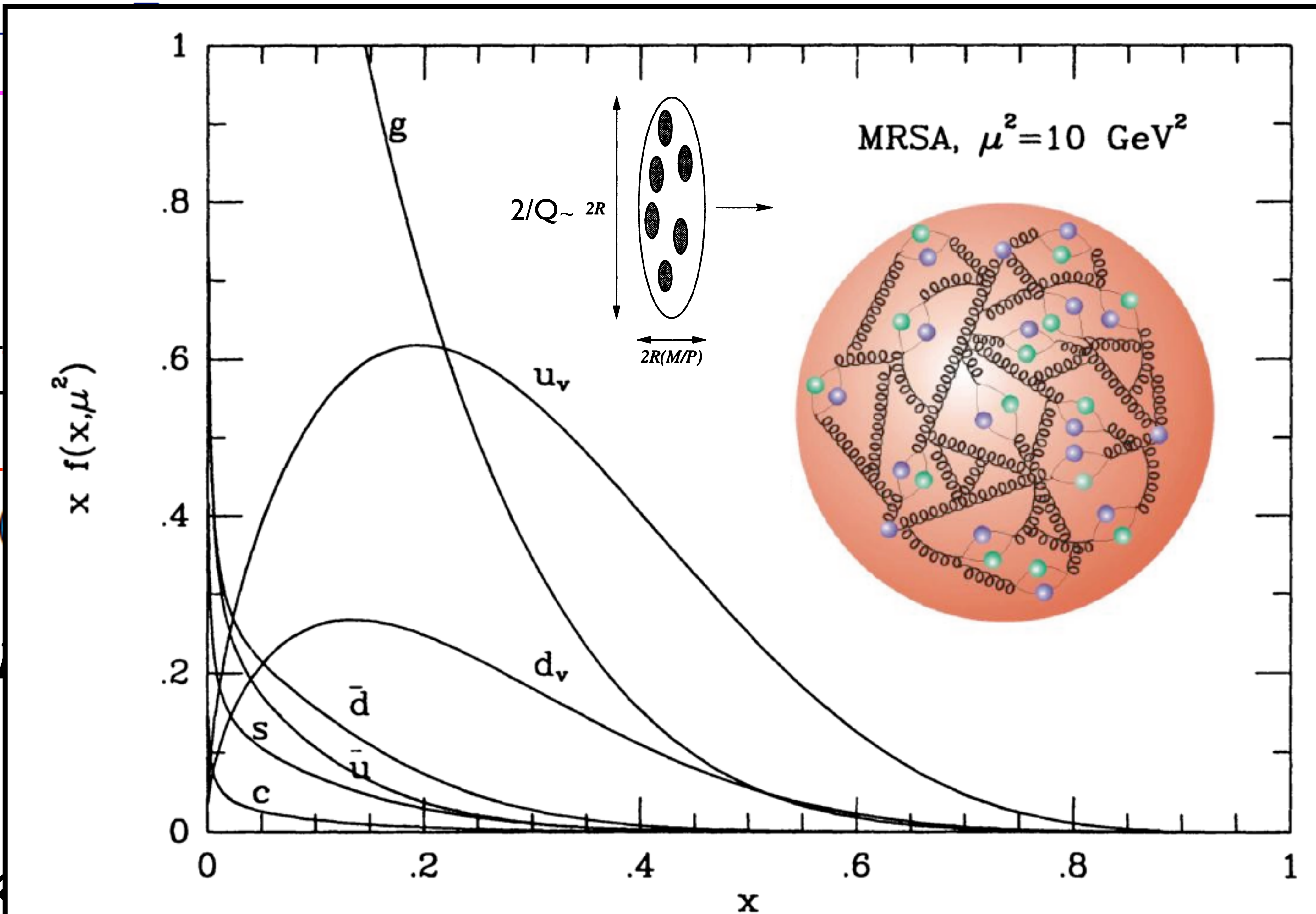
model



$\sigma($ … $p+q))$

… $(1/Q^2)$

➜ Rel… …ons:

$F_2^{eN}(x) = \frac{5}{18} F_2^{\nu N}(x)$

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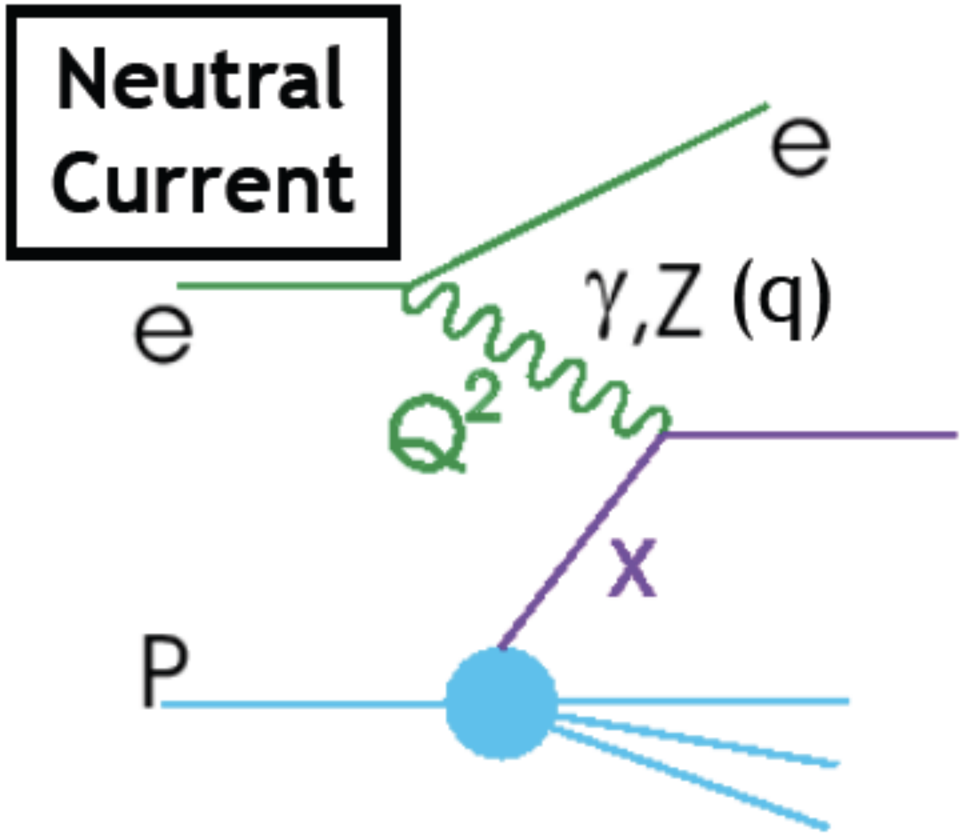
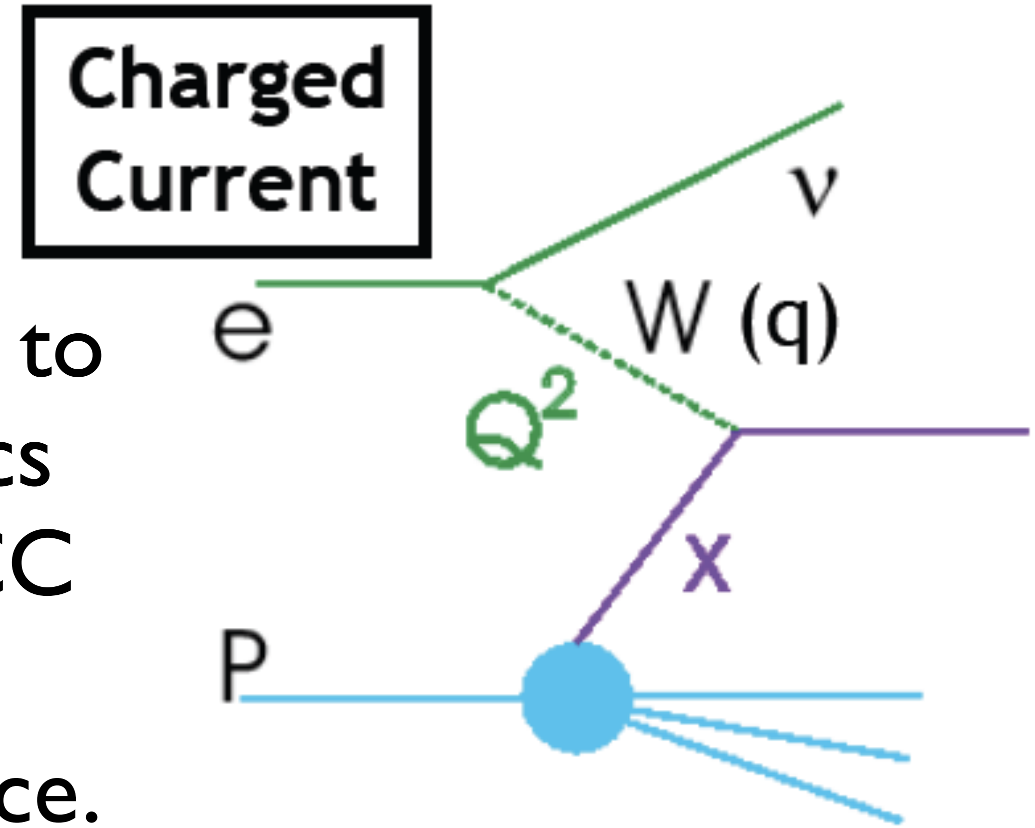
gluons

In more detail:



Sensitivity to EW physics through CC and γZ interference.



$$\frac{d^2\sigma_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x}\cdot\sigma_{r,NC}$$

$$\frac{\mathrm{d}^2\sigma_{CC}^{\pm}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{1\pm P}{2}\cdot\frac{G_F^2}{2\pi x}\cdot\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 Y_+\cdot\sigma_{r,CC}$$

$$\sigma_{r,NC} = \mathbf{F_2} + \frac{Y_-}{Y_+}\mathbf{xF_3} - \frac{y^2}{Y_+}\mathbf{F_L},$$

$$Y_\pm = 1\pm(1-y)^2$$

$$\sigma_{r,CC}^{\pm} = W_2^{\pm} \mp \frac{Y_-}{Y_+}xW_3^{\pm} - \frac{y^2}{Y_+}W_L^{\pm}$$

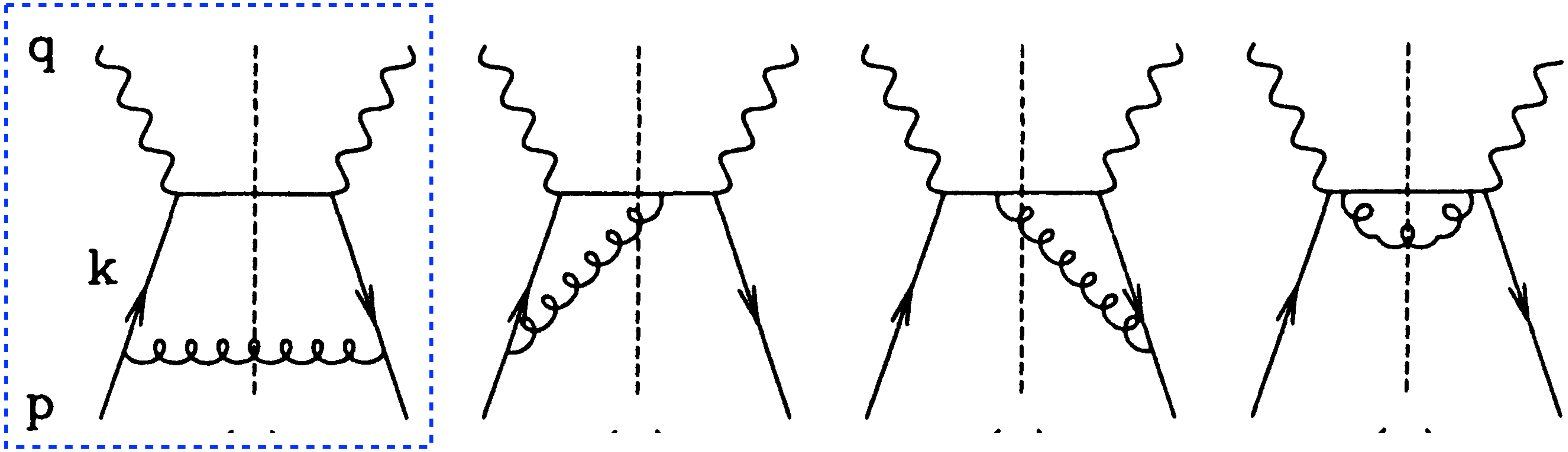
$$\mathbf{F_2^{\pm}} = F_2 + \kappa_Z(-v_e \mp Pa_e)\cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2+a_e^2 \pm 2Pv_e a_e)\cdot F_2^Z$$

$$\mathbf{xF_3^{\pm}} = \kappa_Z(\pm a_e + Pv_e)\cdot xF_3^{\gamma Z} + \kappa_Z^2(\mp 2v_e a_e - P(v_e^2+a_e^2))\cdot xF_3^Z$$

DIS: QCD corrections

➜ The parton model receives corrections from the fact that partons radiate: PDFs evolve with scale Q, DGLAP evolution equations.

only diagram that gives (logarithmic) divergencies (in LC gauge)



$$Q^2\partial_{Q^2}\begin{pmatrix} q_i(x,Q^2) \\ \bar{q}_i(x,Q^2) \\ g(x,Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{d\xi}{\xi}\begin{pmatrix} P_{q_iq_j}\left(\frac{x}{\xi}\right) & 0 & P_{q_ig}\left(\frac{x}{\xi}\right) \\ 0 & P_{q_iq_j}\left(\frac{x}{\xi}\right) & P_{q_ig}\left(\frac{x}{\xi}\right) \\ P_{gq}\left(\frac{x}{\xi}\right) & P_{gq}\left(\frac{x}{\xi}\right) & P_{gg}\left(\frac{x}{\xi}\right) \end{pmatrix}\begin{pmatrix} q_j(x,Q^2) \\ \bar{q}_j(x,Q^2) \\ g(x,Q^2) \end{pmatrix}$$

DGLAP@LO

➜ PDFs are unknown, non-perturbative quantities but we know its perturbative evolution (at leading logarithmic accuracy). They have to be extracted from data.

$$q(x) = \int \frac{d\lambda}{2\pi} e^{i\lambda x}\left\langle P\left|\bar{\psi}(0)\not{n}\psi(\lambda n)\right|P\right\rangle$$

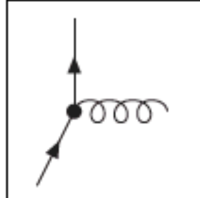
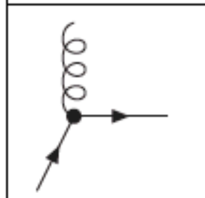
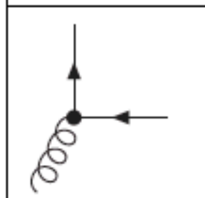
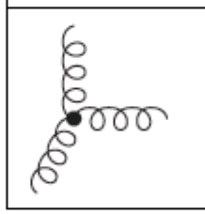
DIS: QCD corrections

➜ The parton mo ... :t that partons radiate: PDFs evol ... quations.

only diagram that gives (logarithmic) divergencies (in LC gauge)

q

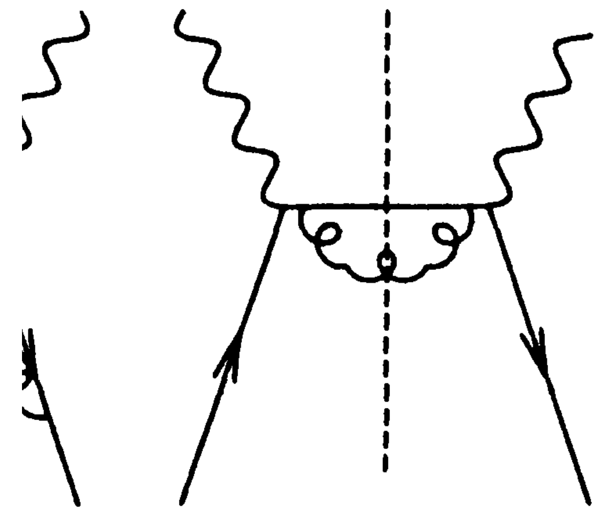
p

Diagram	Splitting
	$P_{qq} = C_F \left[\frac{1+x^2}{(1-x)_+} + \frac{3}{2}\delta(1-x) \right]$
	$P_{gq} = C_F \left[\frac{1+(1-x)^2}{x} \right]$
	$P_{qg} = T_R \left[x^2 + (1-x)^2 \right]$
	$P_{gg} = 2C_A \left[\frac{x}{(1-x)_+} + (1-x)\left(x+\frac{1}{x}\right) \right] + \frac{11C_A - 4n_f T_R}{6}\delta(1-x)$

$T_R=1/2$

$C_F=(N^2-1)/(2N)=4/3$

$C_A=N=3$



$$Q^2 \partial_{Q^2} \begin{pmatrix} q_i(x,Q^2) \\ \bar{q}_i(x,Q^2) \\ g(x,Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{d\xi}{\xi} \begin{pmatrix} P_{q_i q_j}\left(\frac{x}{\xi}\right) & 0 & P_{q_i g}\left(\frac{x}{\xi}\right) \\ 0 & P_{q_i q_j}\left(\frac{x}{\xi}\right) & P_{q_i g}\left(\frac{x}{\xi}\right) \\ P_{gq}\left(\frac{x}{\xi}\right) & P_{gq}\left(\frac{x}{\xi}\right) & P_{gg}\left(\frac{x}{\xi}\right) \end{pmatrix} \begin{pmatrix} q_j(x,Q^2) \\ \bar{q}_j(x,Q^2) \\ g(x,Q^2) \end{pmatrix}$$

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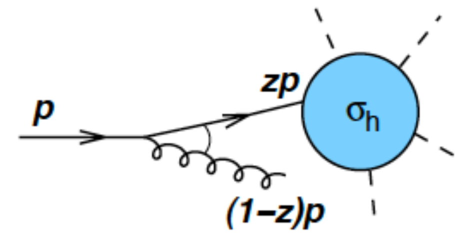
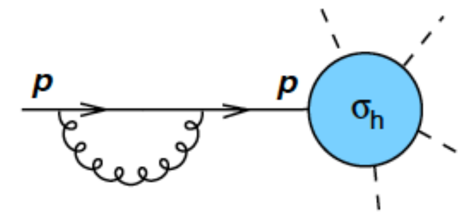
DIS: virtual plus real

➜ When we consider radiation from initial state (before a hard scattering σ_h), both real and virtual correction appear:



$$\sigma_{g+h}(p) \simeq \sigma_h(zp)\frac{\alpha_s C_F}{\pi}\frac{dz}{1-z}\frac{dk_t^2}{k_t^2}$$

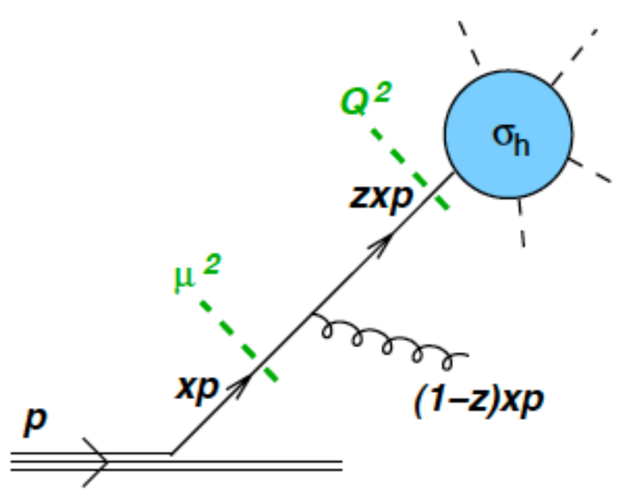


$$\sigma_{V+h}(p) \simeq -\sigma_h(p)\frac{\alpha_s C_F}{\pi}\frac{dz}{1-z}\frac{dk_t^2}{k_t^2}$$

➜ They combine into a IR finite but collinerly divergent cross section:

$$\sigma_{g+h} + \sigma_{V+h} \simeq \frac{\alpha_s C_F}{\pi}\underbrace{\int_0^{Q^2}\frac{dk_t^2}{k_t^2}}_{\text{infinite}}\underbrace{\int_0^1 \frac{dz}{1-z}[\sigma_h(zp)-\sigma_h(p)]}_{\text{finite}}$$

➜ The collinear divergence is absorbed in a redefinition of the PDFs putting a cut-off: the independence of its choice leads to DGLAP.

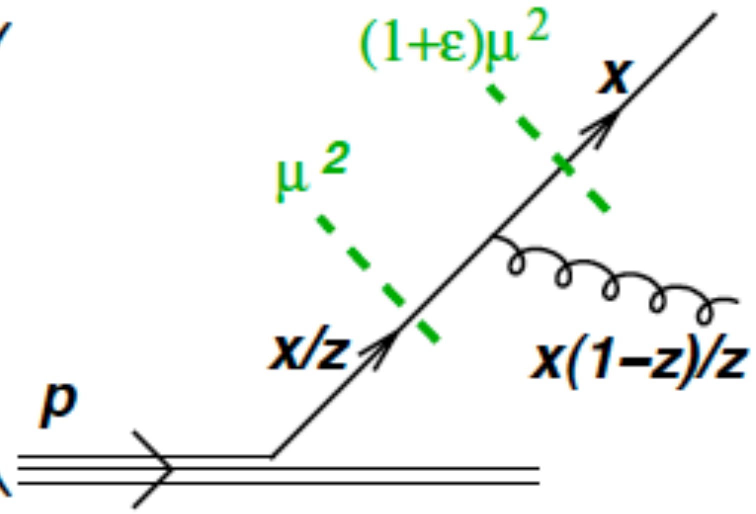


$$\sigma_0 = \int dx\; \sigma_h(xp)\, q(x,\mu_F^2)\,,$$

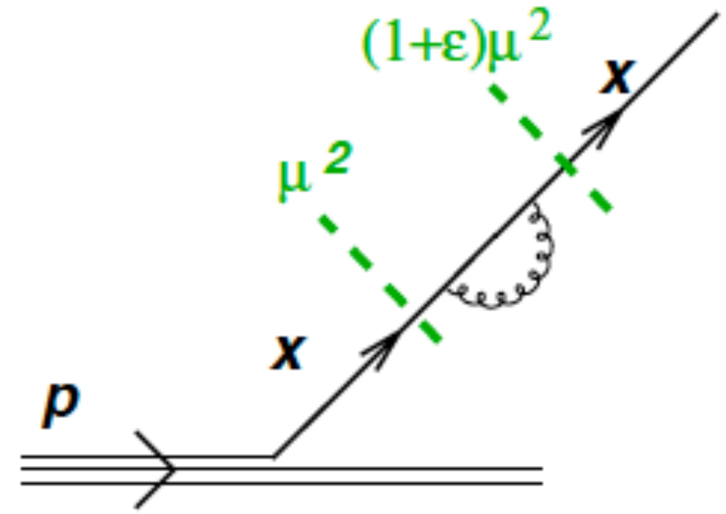
$$\sigma_1 \simeq \frac{\alpha_s C_F}{\pi}\underbrace{\int_{\mu_F^2}^{Q^2}\frac{dk_t^2}{k_t^2}}_{\text{finite (large?)}}\underbrace{\int \frac{dx\,dz}{1-z}\,[\sigma_h(zxp)-\sigma_h(xp)]\, q(x,\mu_F^2)}_{\text{finite}}$$

DIS: virtual plus real

$$\frac{dq(x,\mu_F^2)}{d\ln\mu_F^2} = \frac{1}{\epsilon}\left(\quad + \quad \right)$$



+

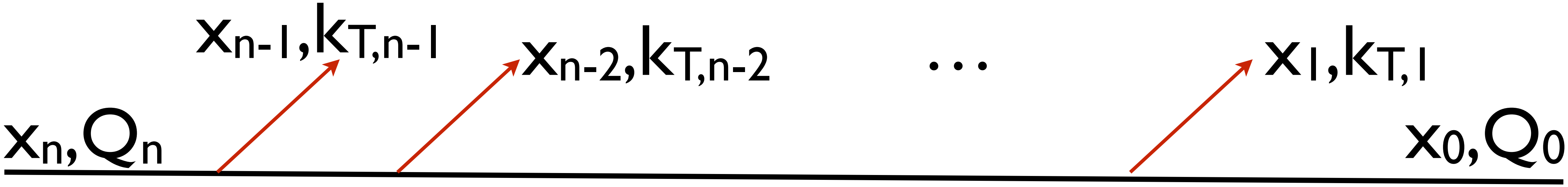


$$= \frac{\alpha_s}{2\pi}\int_x^1 dz\, p_{qq}(z)\,\frac{q(x/z,\mu_F^2)}{z} - \frac{\alpha_s}{2\pi}\int_0^1 dz\, p_{qq}(z)\, q(x,\mu_F^2)$$

$$= \frac{\alpha_s}{2\pi}\underbrace{\int_x^1 dz\, P_{qq}(z)\,\frac{q(x/z,\mu_F^2)}{z}}_{P_{qq}\otimes q}, \qquad P_{qq} = C_F\left(\frac{1+z^2}{1-z}\right)_+$$

$$\int_x^1 dz\,[g(z)]_+\, f(z) = \int_x^1 dz\, g(z)\, f(z) - \int_0^1 dz\, g(z)\, f(1)$$
$$= \int_x^1 dz\, g(z)\,(f(z)-f(1)) - \int_0^x dz\, g(z)\, f(1)$$

Radiation: DGLAP vs. BFKL



$$dP_i \propto \frac{dx_i}{x_i}\frac{d\theta_i}{\theta_i},\ \omega_i = x_i E,\ \theta_i \simeq \frac{k_{T,i}}{\omega_i} \qquad x_n \ll x_{n-1} \ll x_{n-2} \ll \ldots \ll x_1 \ll x_0$$

A) DGLAP, moderate x: $Q_n^2 \gg k_{T,n-1}^2 \gg k_{T,n-2}^2 \gg \ldots \gg k_{T,1}^2 \gg Q_0^2$

$$\int_{Q_0}^{Q_n} dP_{n-1} \int_{Q_0}^{k_{T,n-1}} dP_{n-2} \ldots \int_{Q_0}^{k_{T,2}} dP_1 \propto \left[\frac{\alpha_s N_c}{\pi} \ln \frac{Q_n}{Q_0}\right]^n$$

B) BFKL, small x: $\displaystyle \int_{x_n}^{x_0} dP_{n-1} \int_{x_{n-1}}^{x_0} dP_{n-2} \ldots \int_{x_2}^{x_0} dP_1 \propto \left[\frac{\alpha_s N_c}{\pi} \ln \frac{x_0}{x_n}\right]^n$

- Both of them lead to a gluon distribution at small x behaving like $xg(x,Q^2) \propto x^{-\lambda}$ at fixed Q^2, $\lambda \approx 0.2\text{-}0.3$ in data.

Massive quarks:

- Massive quarks do not have a collinear divergence (dead cone effect).
- The treatment of DGLAP evolution including massive quarks is an open issue, see e.g. 1510.02491.

- FFNS: fixed number of massless species in evolution, HQ generated radiatively, good close to mass threshold, misses $\ln^n(Q^2/m_{HQ}^2)$.

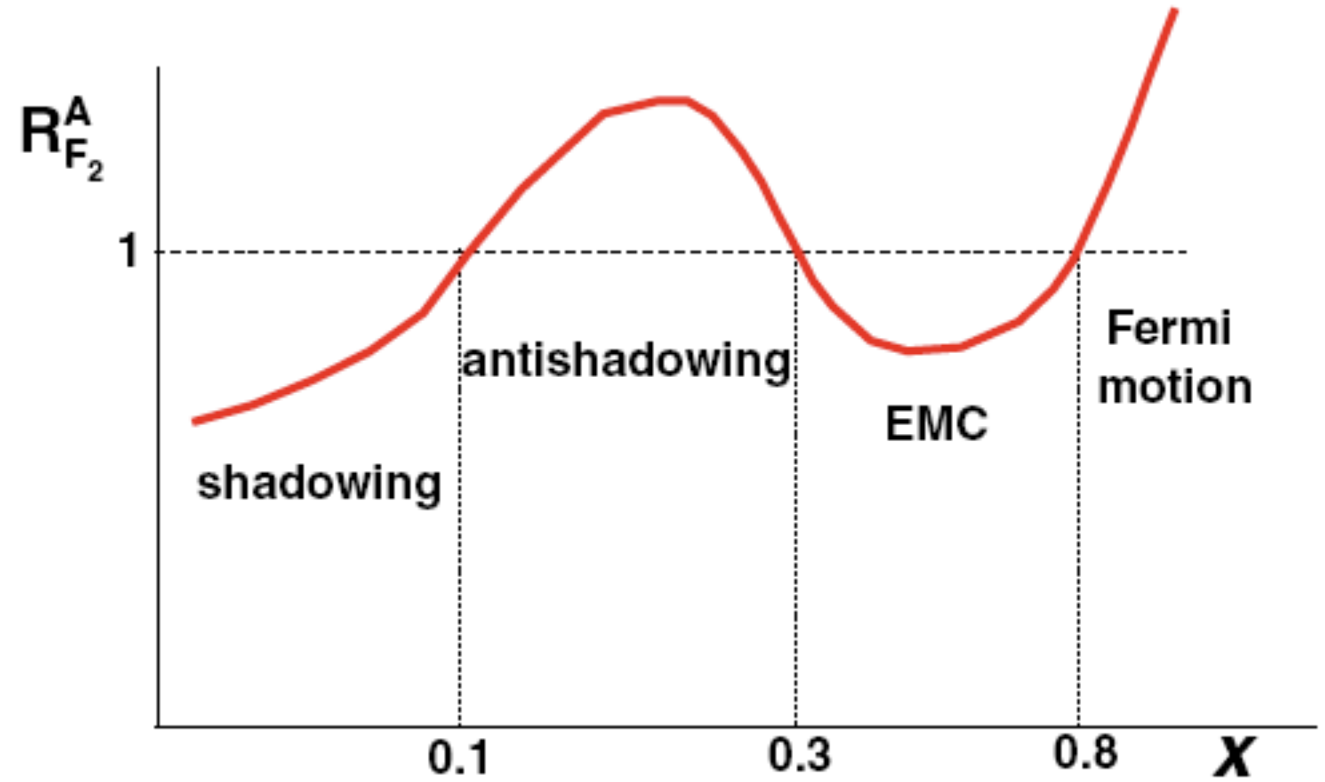
- ZM-VFNS: variable number of massless species in evolution when increasing Q^2, captures $\ln^n(Q^2/m_{HQ}^2)$, bad at threshold.

- Matching of both schemes: GM-VFNS, requires matching between parts that are exactly computed (massive matrix elements) and the massless evolution, several recipes.

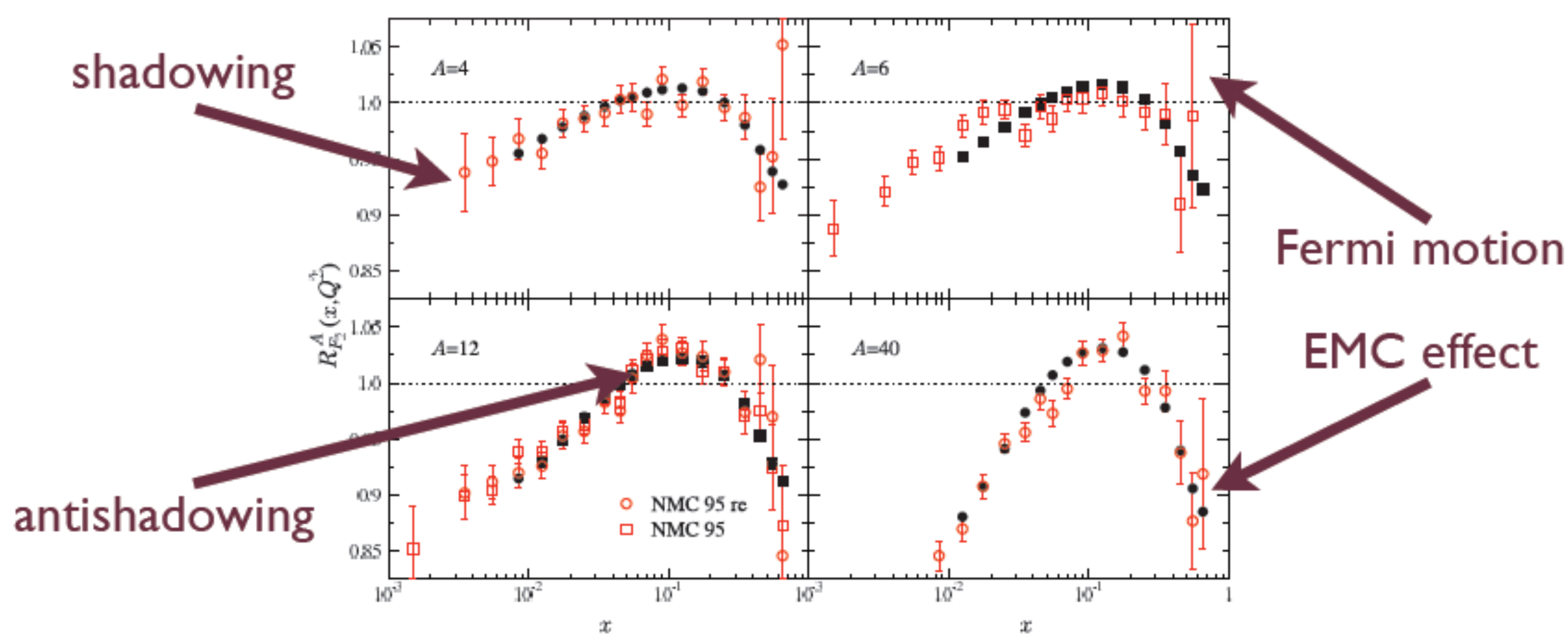
DIS on nuclei:

$$R_{F_2}^A(x,Q^2) = \frac{F_2^A(x,Q^2)}{A F_2^{\rm nucleon}(x,Q^2)}$$

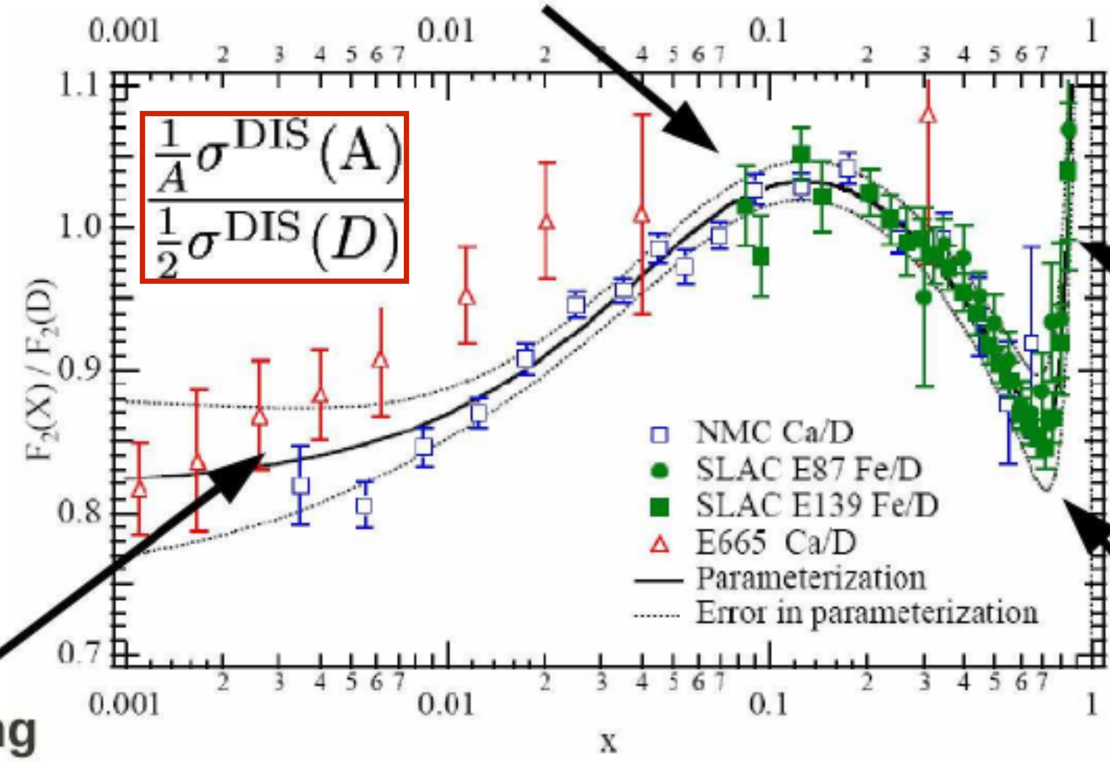
- R=1 indicates the absence of nuclear effects.
- R≠1 discovered in the early 70's, significant beyond isospin effects.
- Each region demands a different explanation.



$$R_{F_2}^A(x,Q^2) = \frac{F_2^A(x,Q^2)}{A F_2^p(x,Q^2)}$$



Collinear approach:



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

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

Nuclear PDFs, obeying the standard DGLAP

Usual perturbative coefficient functions

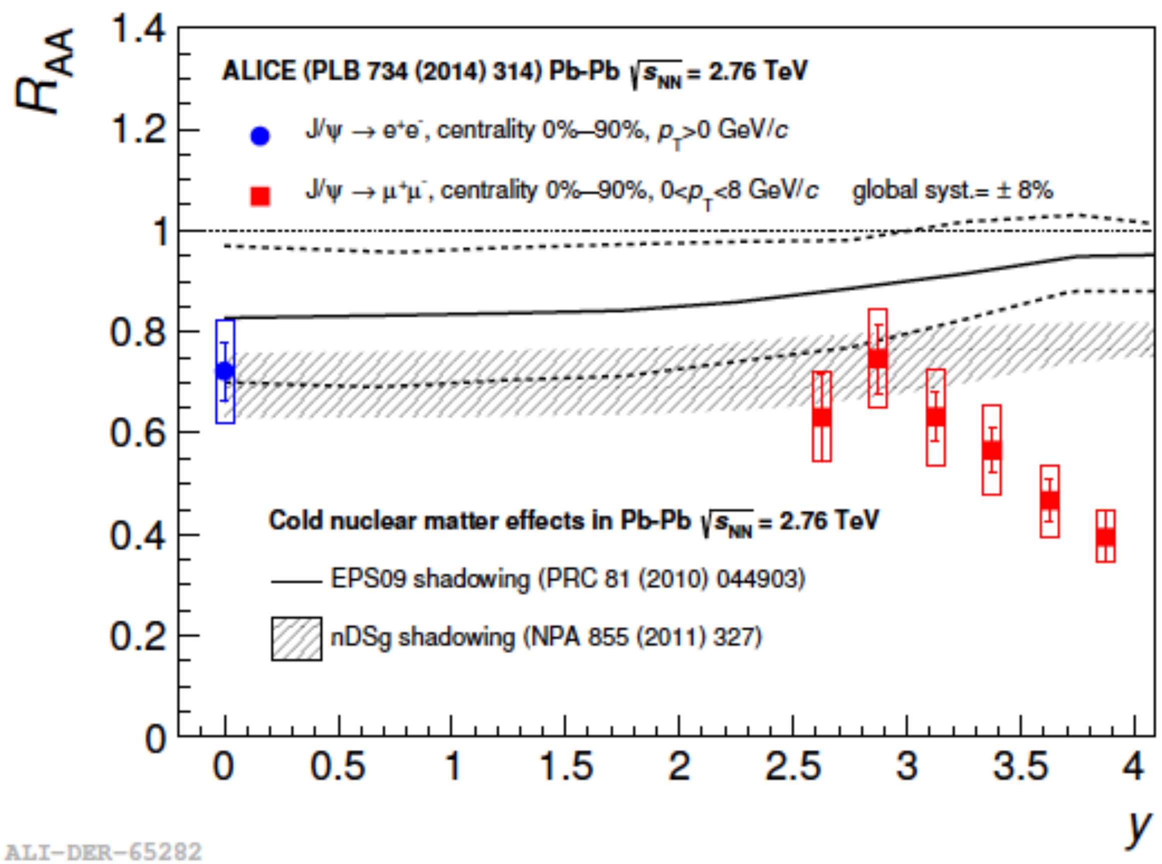
$$f_i^{p,A}(x,Q^2) = \boxed{R_i^A(x,Q^2)} f_i^p(x,Q^2)$$

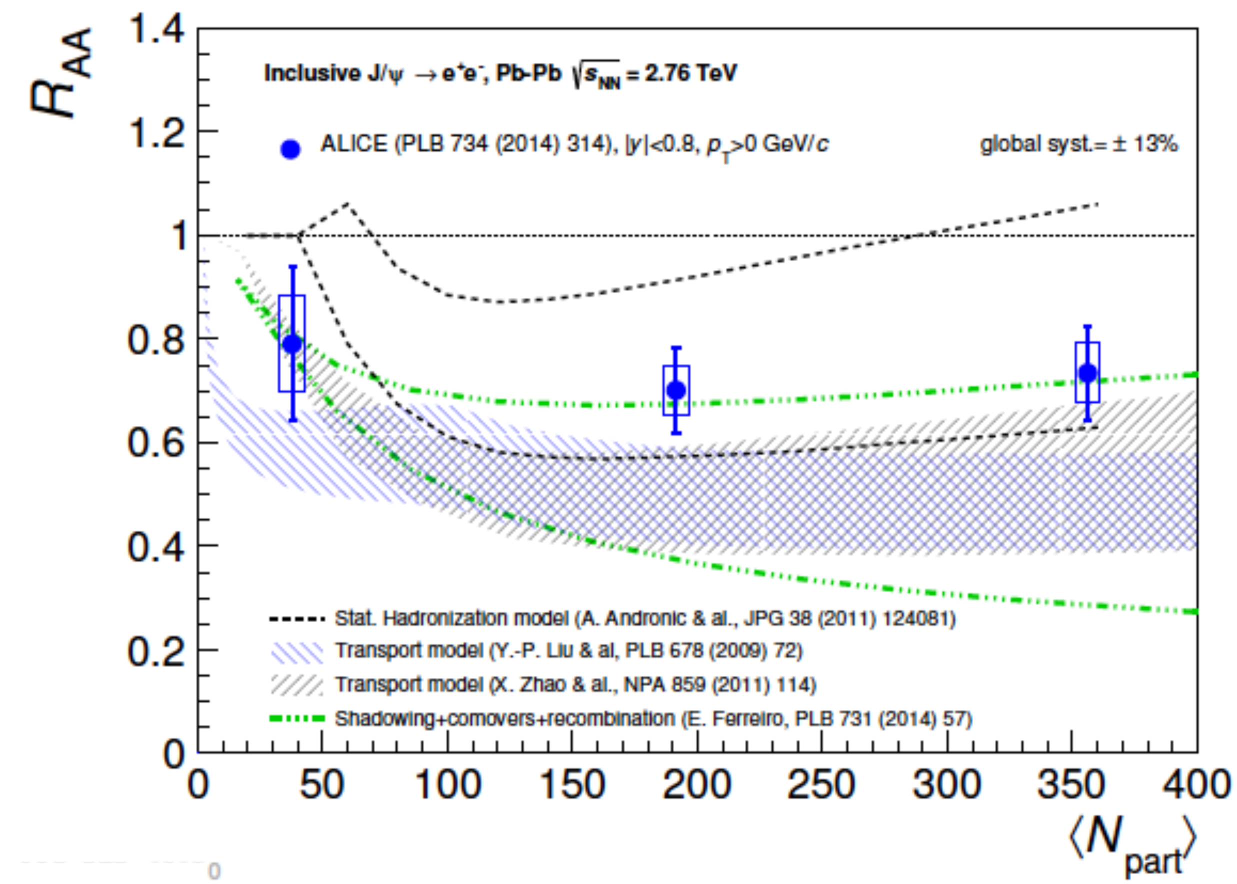
$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

nPDFs for HIC:

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

- Lack of data ⇒ large uncertainties for the nuclear glue at small scales and x: problem for benchmarking in HIC in order to extract 'medium' parameters.



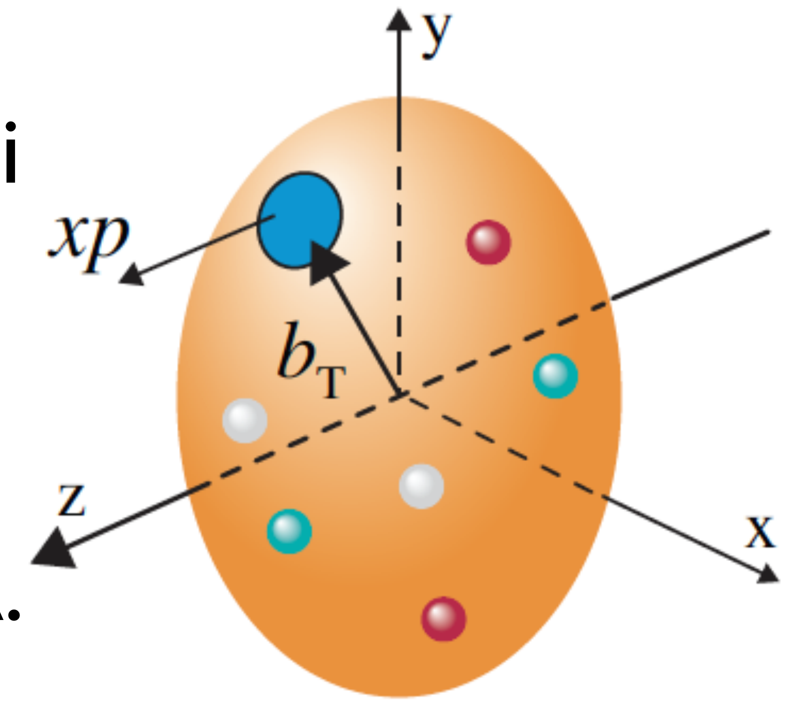


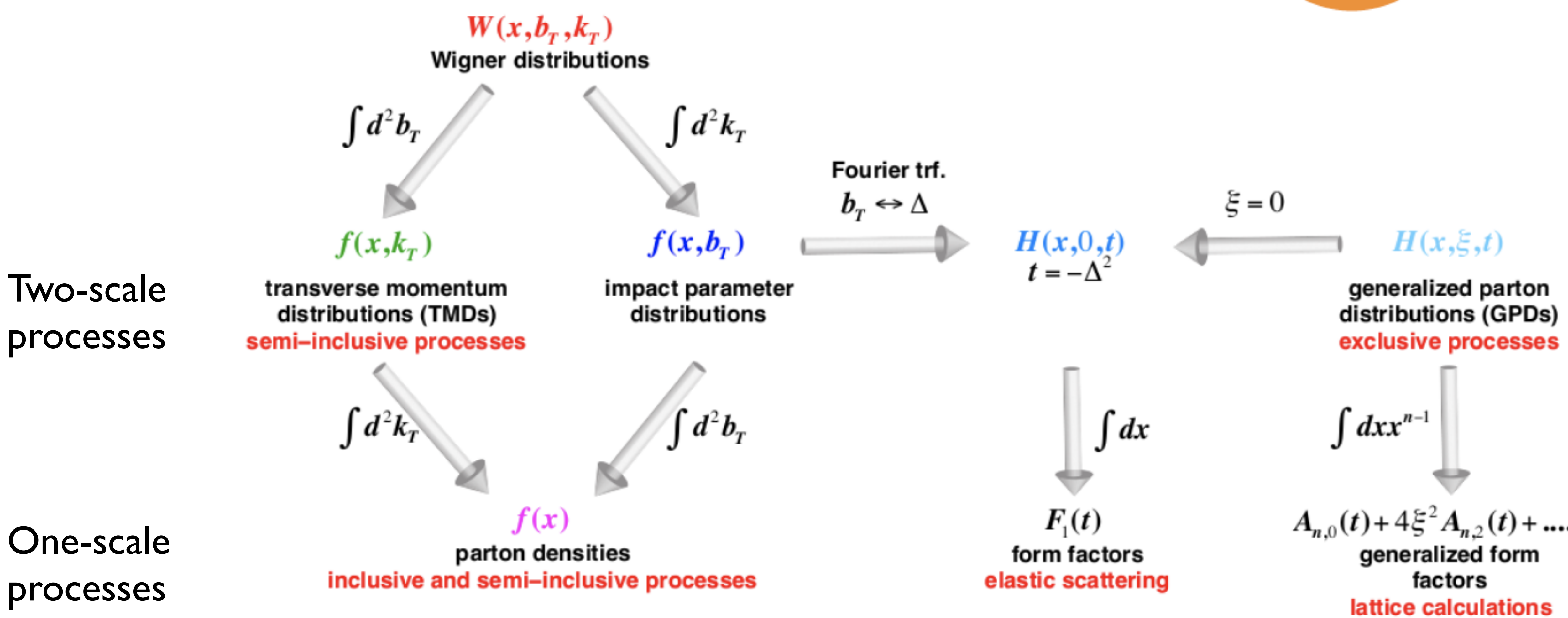
1506.03981

Hadron structure:

- ep/A provides crucial information about:
  → the partonic structure of hadrons and nuclei (lattice, 1711.07916),
  → how particle production depends on such structure (factorisation);

with strong implications on physics in pp/pA/AA.





Contents:

Bibliography:
- R. Devenish and A. Cooper-Sarker, *Deep Inelastic Scattering*, Oxford University Press 2004.
- G. P. Salam, *Elements of QCD for hadron colliders*, CERN Yellow Report CERN-2010-002, 45-100, arXiv:1011.5131 [hep-ph].
- J. L. Abelleira Fernandez et al., *A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector*, J. Phys. G39 (2012) 075001, arXiv:1206.2913 [physics.acc-ph].
- A. Accardi et al., *Electron Ion Collider: The Next QCD Frontier : Understanding the glue that binds us all*, Eur. Phys. J. A52 (2016) no.9, 268, arXiv:1212.1701 [nucl-ex].

Procedure of extraction:

PDFs, or nuclear effects on them, parametrised at initial scale $Q_0 \gg \Lambda_{QCD}$ employing sum rules (parametrisation biases)

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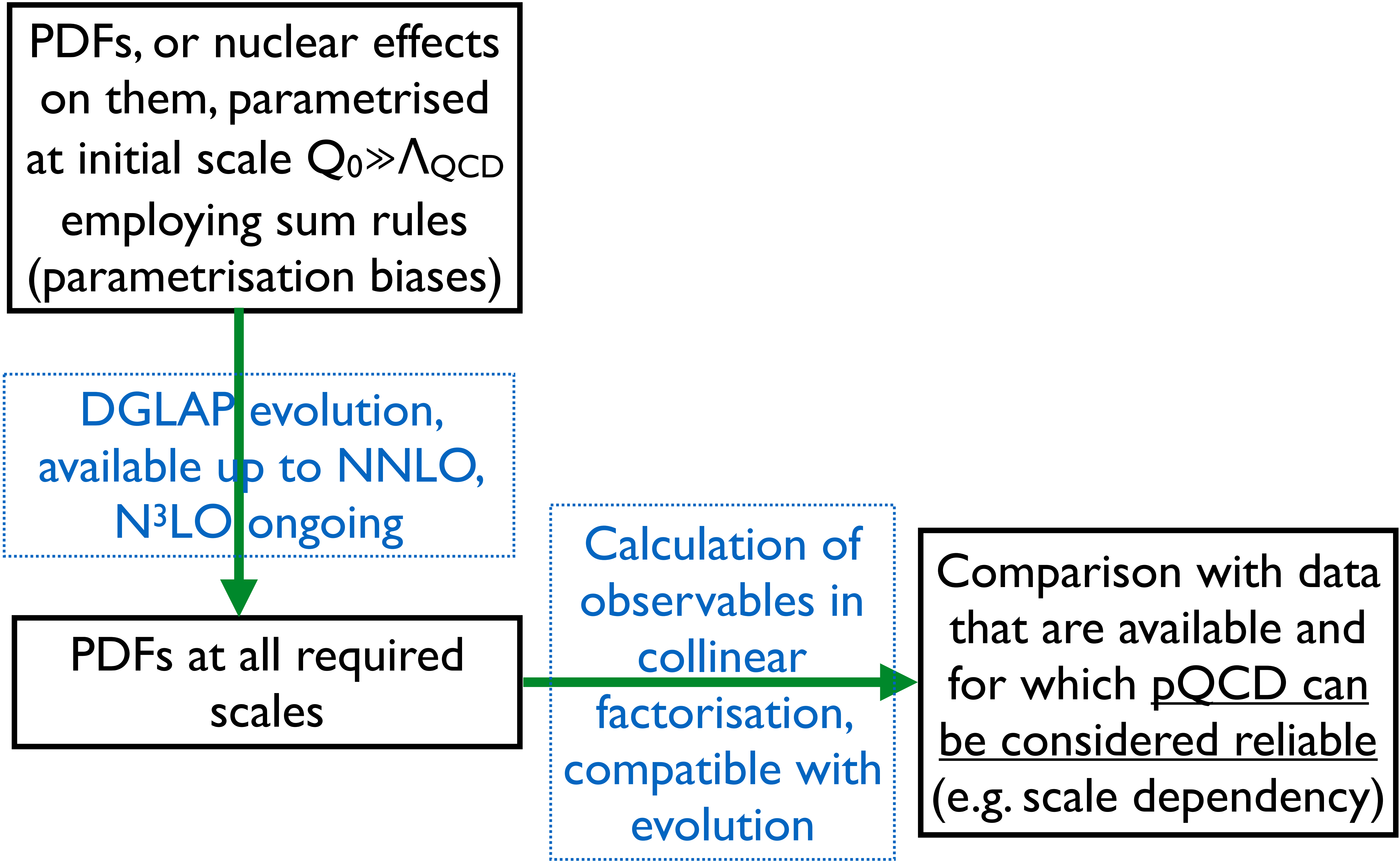
↓

DGLAP evolution, available up to NNLO, N^3LO ongoing

↓

PDFs at all required scales

Procedure of extraction:



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↓ DGLAP evolution, available up to NNLO, N^3LO ongoing

PDFs at all required scales

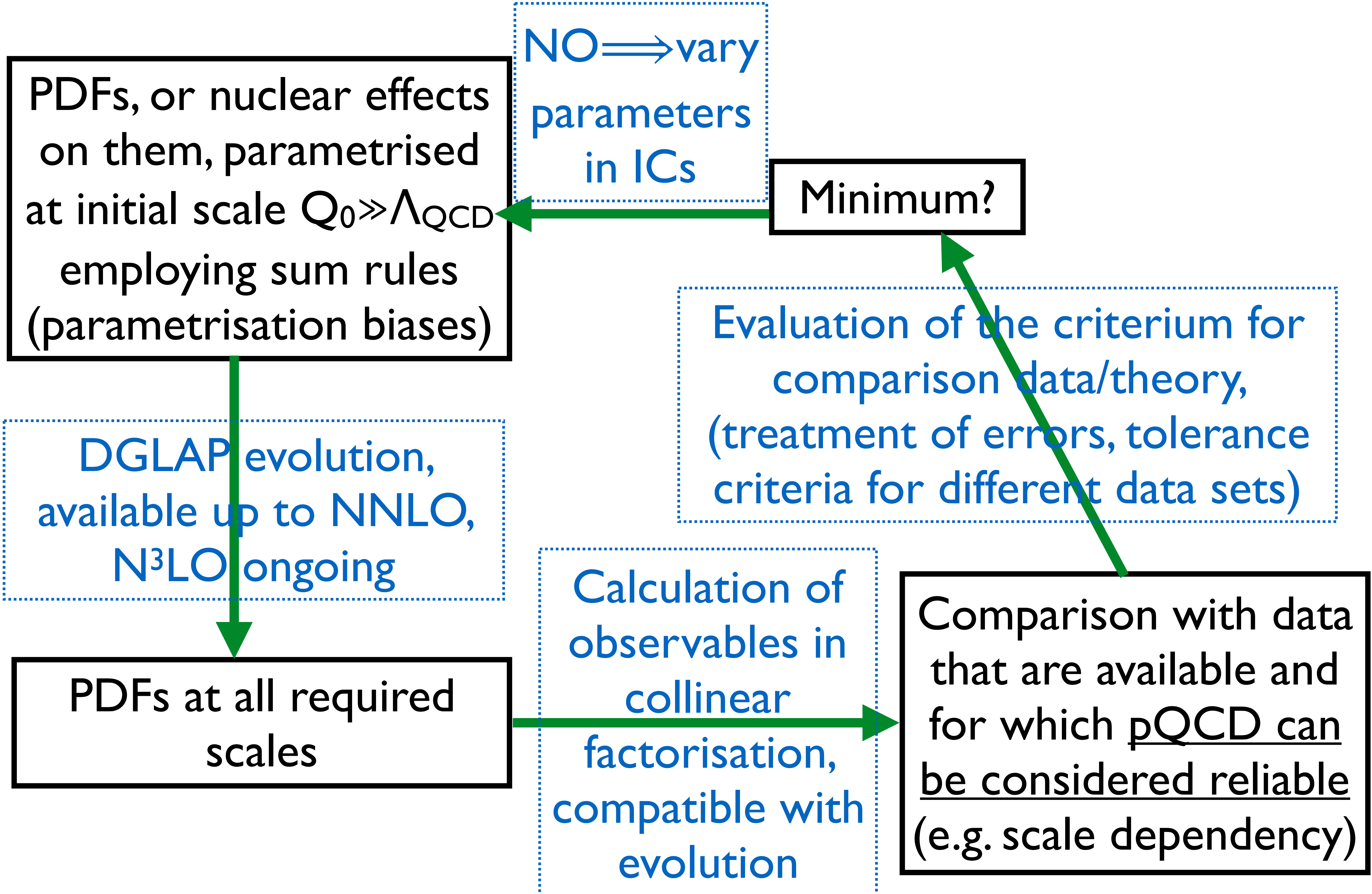
→ Calculation of observables in collinear factorisation, compatible with evolution

Comparison with data that are available and for which <u>pQCD can be considered reliable</u> (e.g. scale dependency)

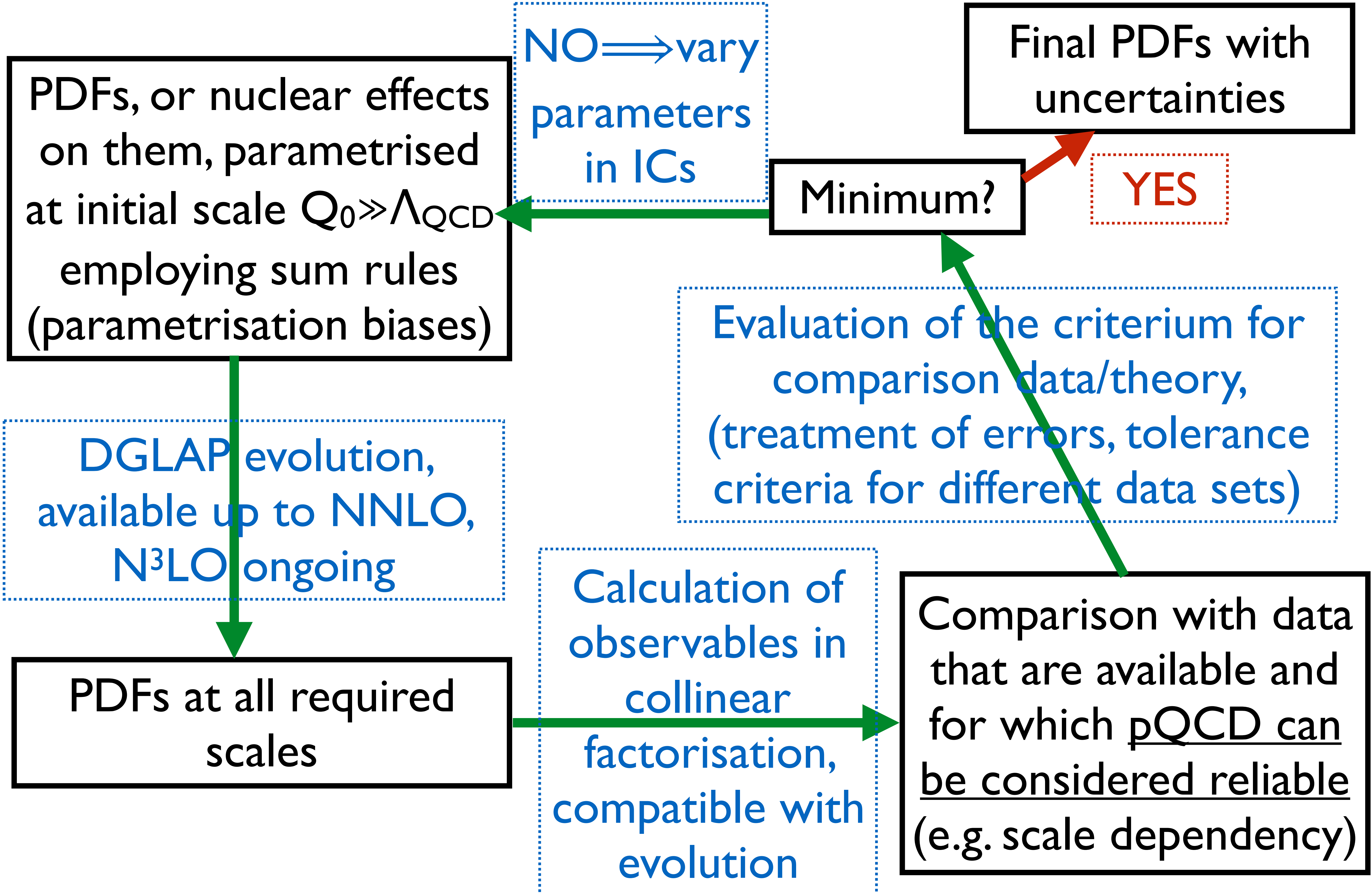
↑ Evaluation of the criterium for comparison data/theory, (treatment of errors, tolerance criteria for different data sets)

Minimum?

Procedure of extraction:



Procedure of extraction:



Procedure of extraction:

- One of the most standard procedures in HEP: development of fast (public) tools for evolution and computation of observables (xFitter, APFEL, ApplGrid,…).
- Problems known by the proton community.
- **Its aim is extracting PDFs from data, assuming that collinear factorisation works**.

(treatment of errors, tolerance criteria for different data sets)

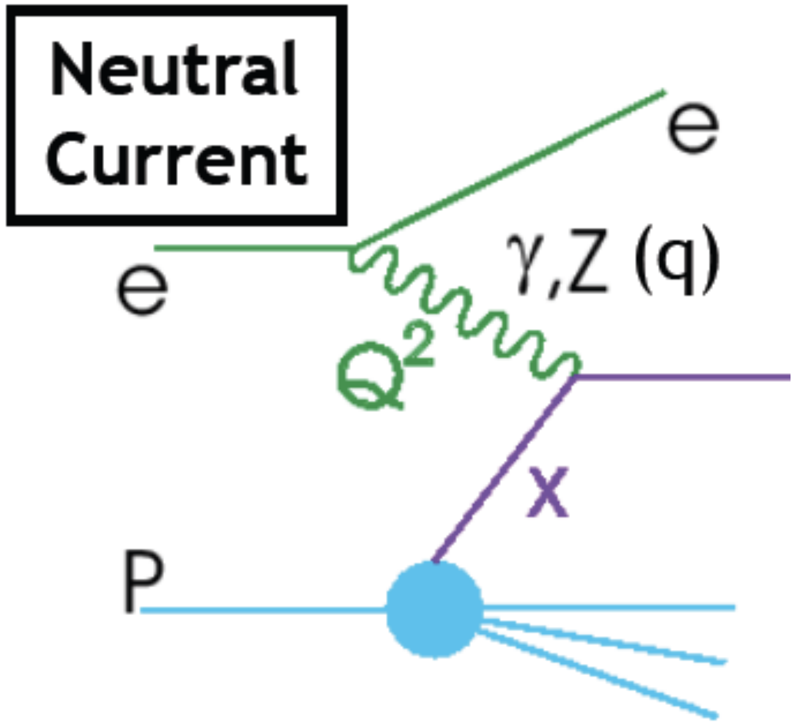
DGLAP evolution, available up to NNLO, N^3LO ongoing

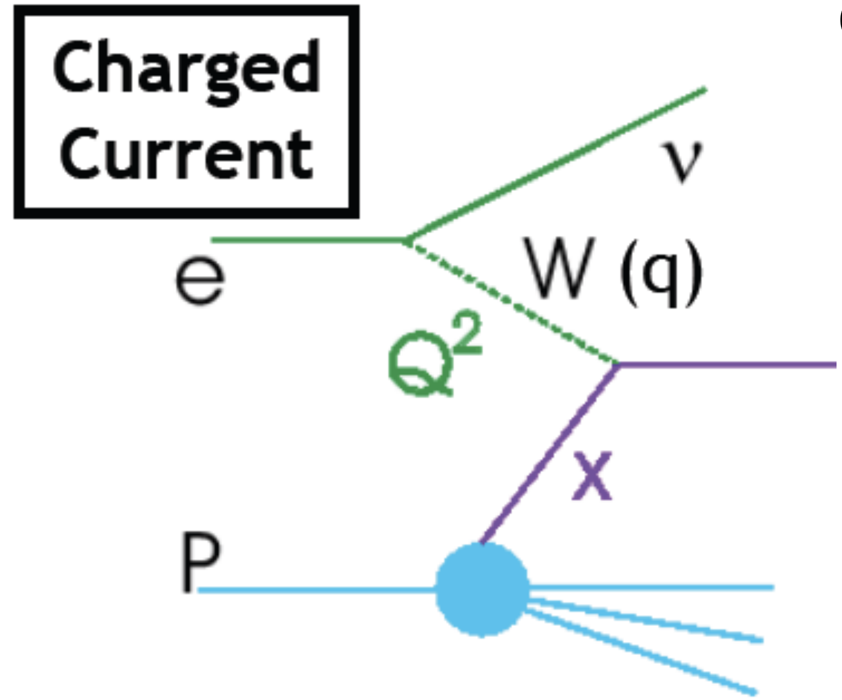
PDFs at all required scales

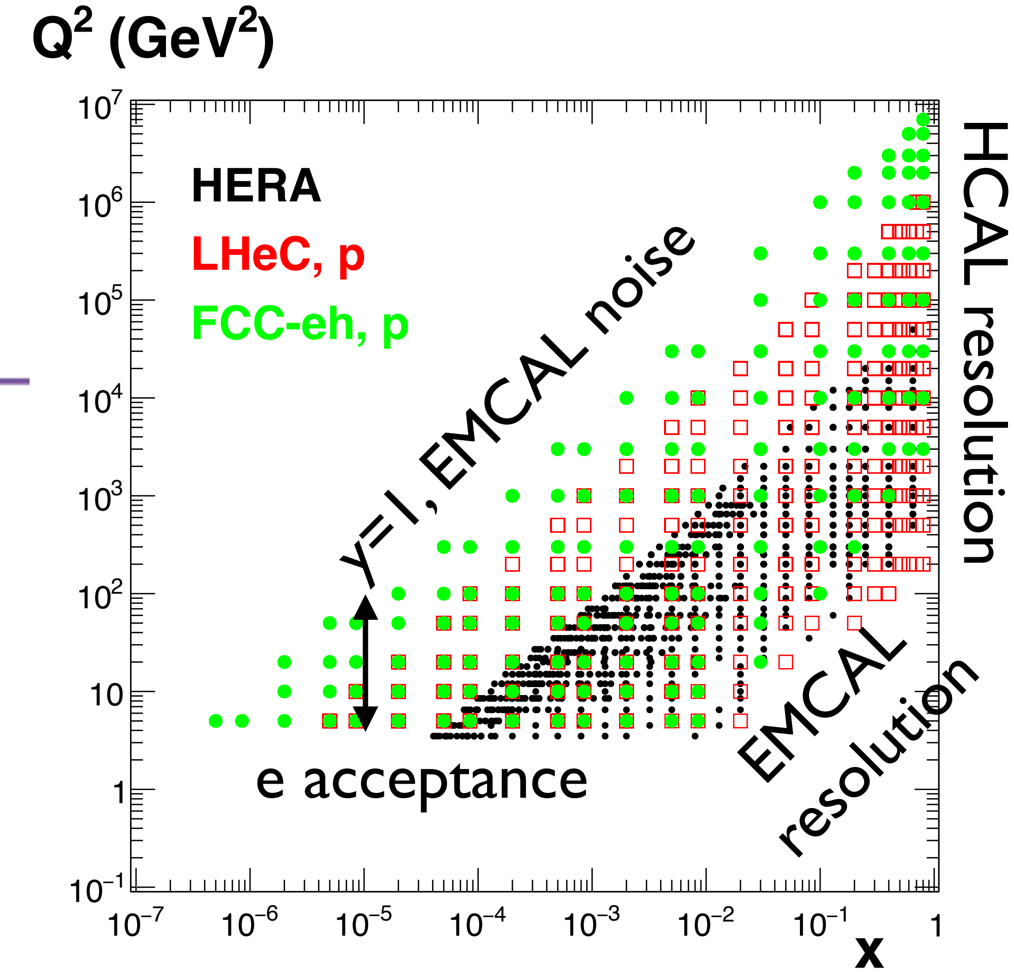
Calculation of observables in collinear factorisation, compatible with evolution

Comparison with data that are available and for which pQCD can be considered reliable (e.g. scale dependency)

Extraction of PDFs:







- Method:

$F_2(x,Q^2) \propto \sum xq(x,Q^2)$: 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 PDFs: requires HQ ID and measurement of missing energy.

Uncertainty estimation:

- Hessian method: first order expansion around minimum χ^2_0.

$$\chi^2 \approx \chi_0^2 + \sum_{ij} \delta a_i H_{ij} \delta a_j \quad H_{ij} \equiv \frac{1}{2} \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}\Big|_{a=a^0} \quad \chi^2 \approx \chi_0^2 + \sum_i z_i^2$$

$$\Delta\chi^2 \equiv \sum_i \frac{\Delta\chi^2(z_i^+) + \Delta\chi^2(z_i^-)}{2N} \approx \sum_i \frac{(z_i^+)^2 + (z_i^-)^2}{2N}$$

$$S_0 = (0, 0, 0, \ldots, 0)$$
$$S_1^\pm = \pm\delta z_1^\pm (1, 0, 0, \ldots, 0)$$
$$S_2^\pm = \pm\delta z_2^\pm (0, 1, 0, \ldots, 0)$$

$$(\Delta X)^2_{\mathrm{extremum}} \approx \Delta\chi^2 \sum_j \left(\frac{\partial X}{\partial z_j}\right)^2$$

$$(\Delta X^+)^2 \approx \sum_k \left[\max\left\{X(S_k^+) - X(S^0), X(S_k^-) - X(S^0), 0\right\}\right]^2$$
$$(\Delta X^-)^2 \approx \sum_k \left[\max\left\{X(S^0) - X(S_k^+), X(S^0) - X(S_k^-), 0\right\}\right]^2$$

- MC method: repeated fits (NN) to many replicas of data.

- Any error analysis is linked to a functional form for the i.c. (NNPDF implies more flexibility, 4 times more paramaters, ~50 to ~400).

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Tolerance to reconcile data sets

$$(\Delta X)^2_{\text{extremum}} \approx \Delta\chi^2 \sum_j \left(\frac{\partial X}{\partial z_j}\right)^2$$

$$(\Delta X^+)^2 \approx \sum_k \left[\max\left\{X(S_k^+) - X(S^0), X(S_k^-) - X(S^0), 0\right\}\right]^2$$
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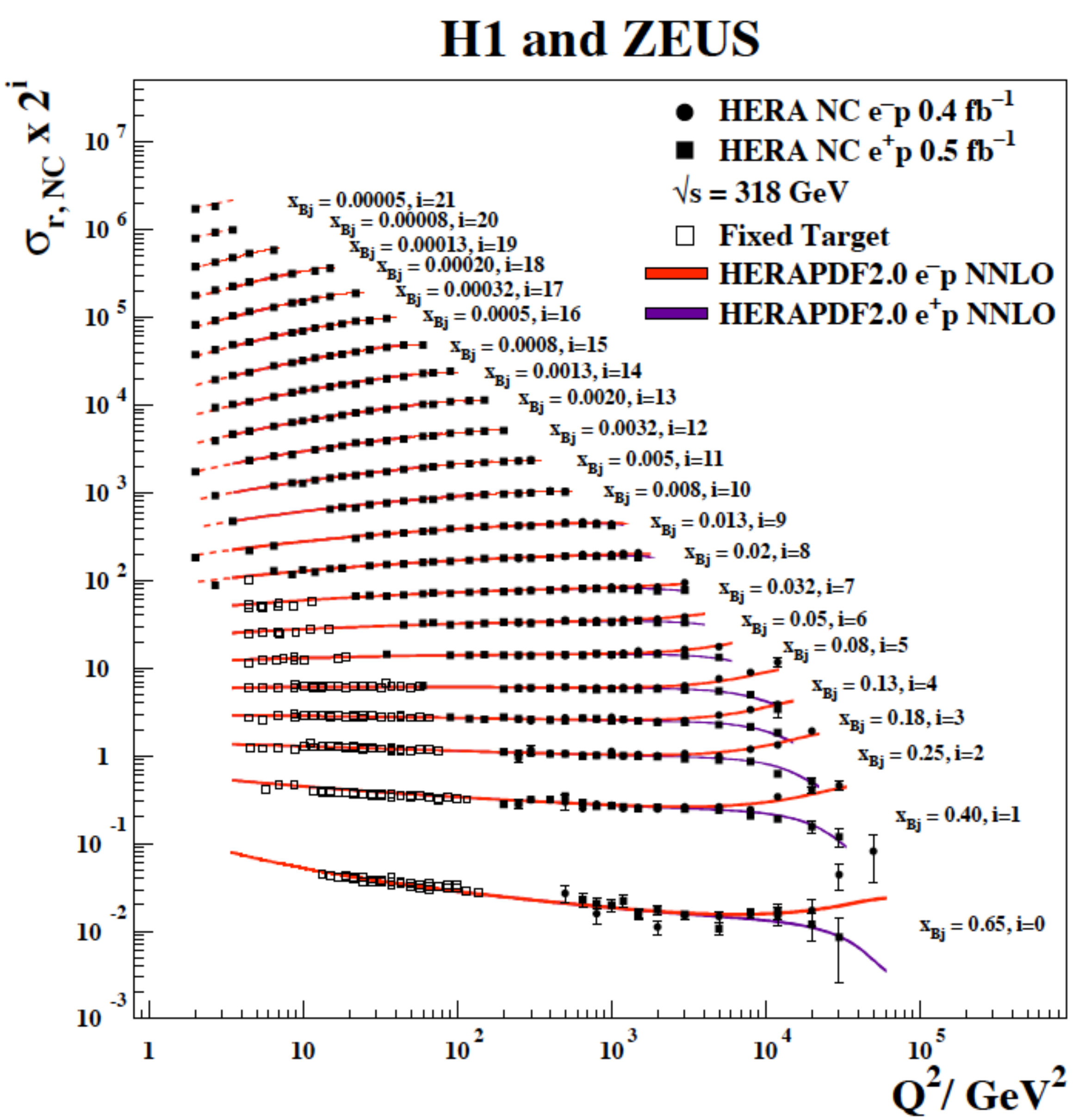
DIS: legacy from HERA

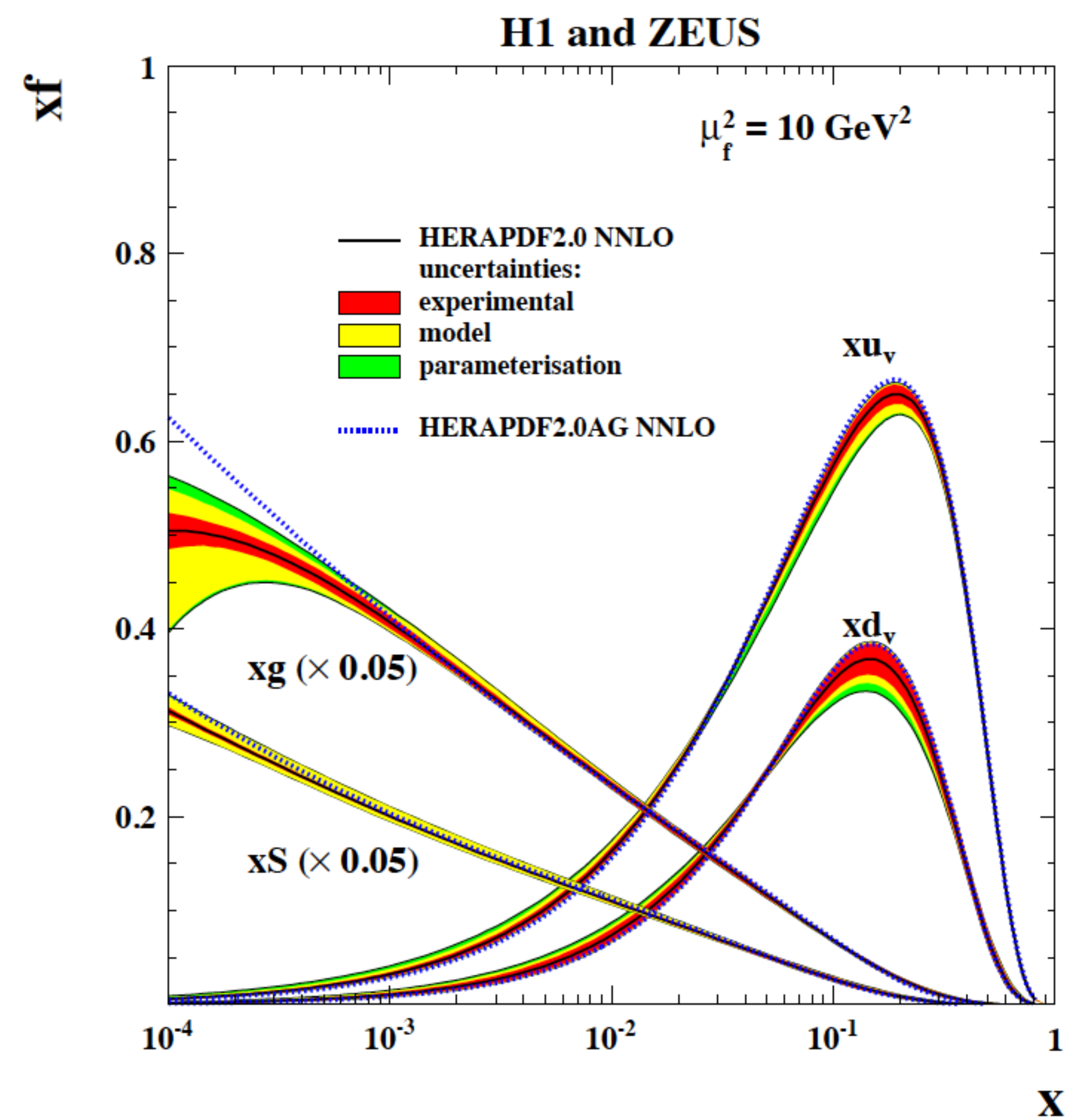
- Three pQCD-based alternatives to describe ep and eA data (differences at moderate $Q^2 (> \Lambda^2_{QCD})$ and small x):

➜ DGLAP evolution (fixed order pQCD).

➜ Resummation schemes (of $[\alpha_s \ln(1/x)]^n$ terms).

➜ Non linear effects: saturation.





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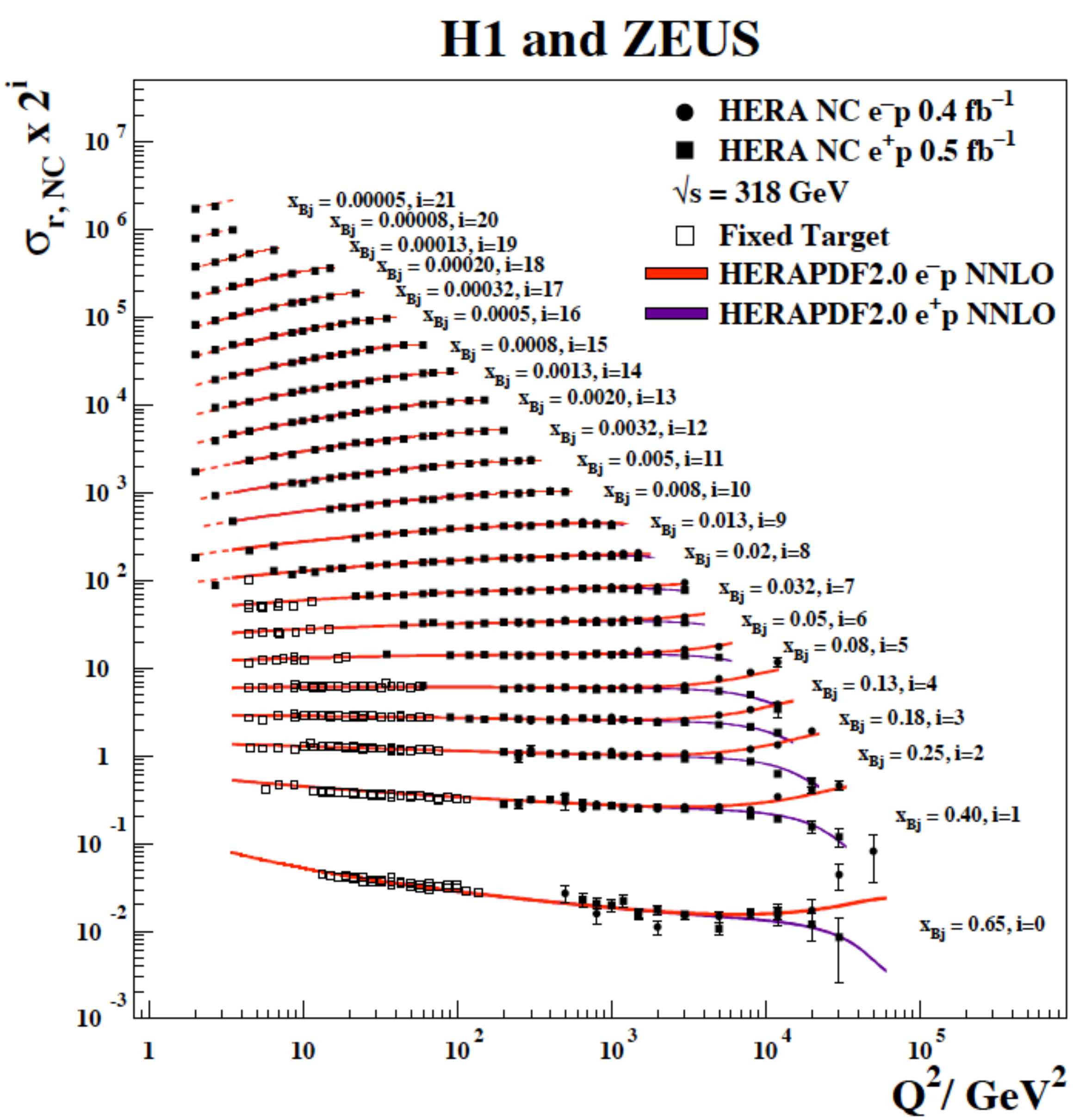
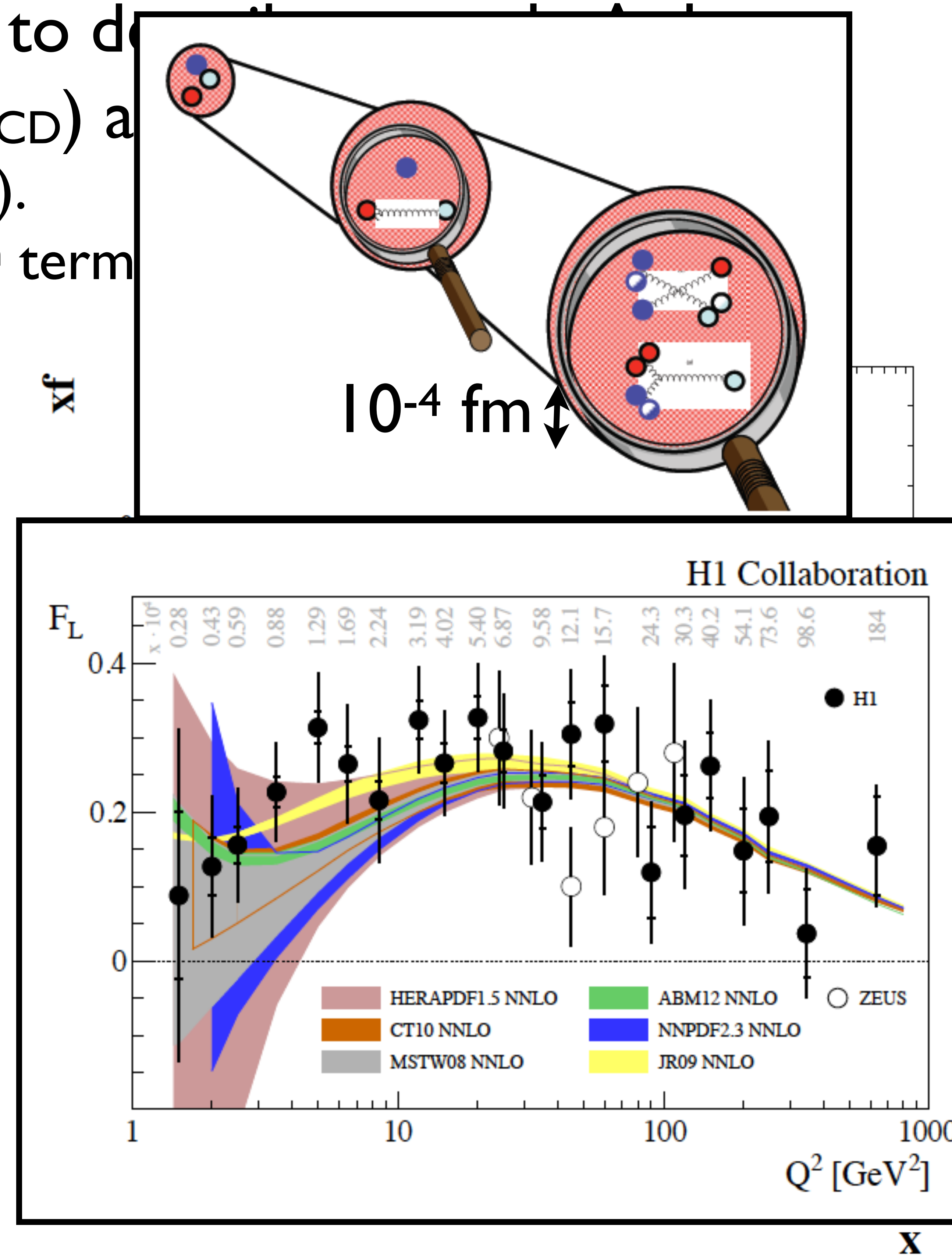
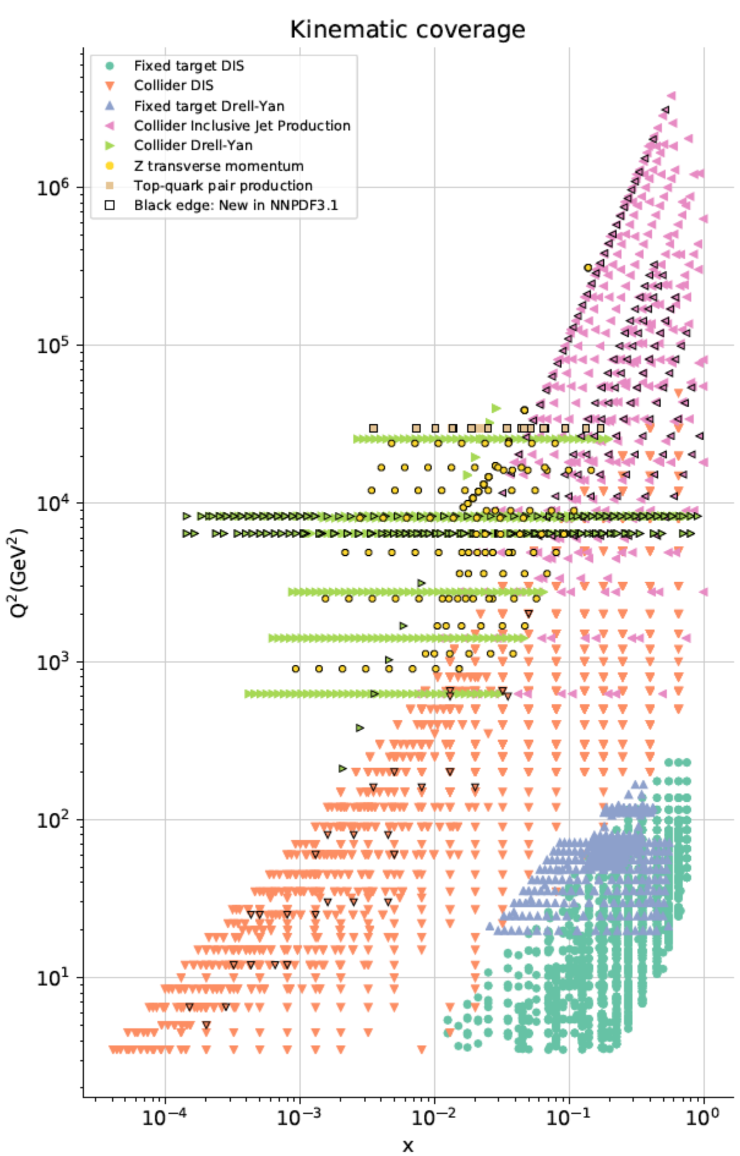




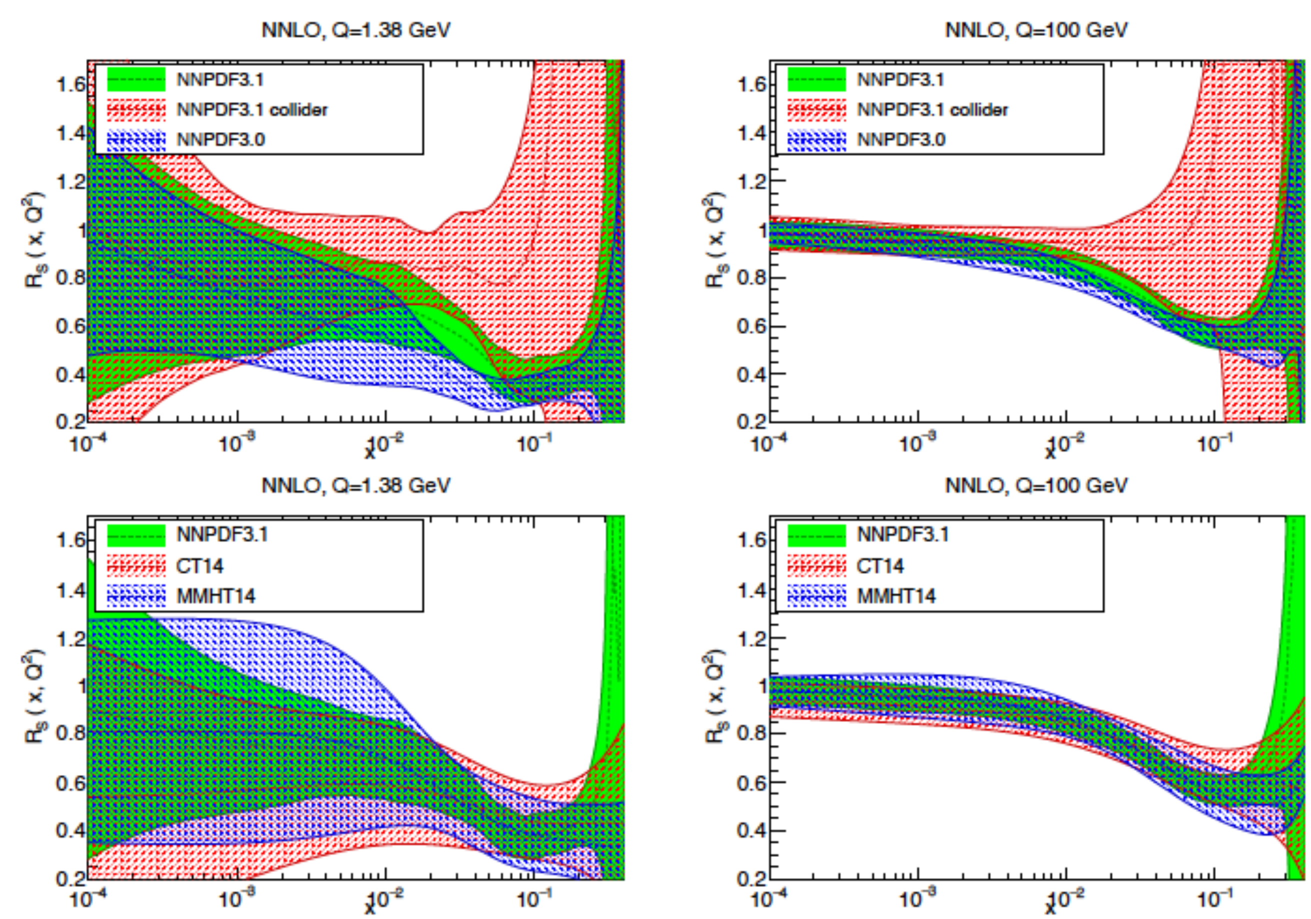
DIS: DGLAP global analysis

➜ Fits to as many data as possible: DIS charged lepton and neutrino data, DY, jets, W/Z/γ… ~4200 points, ~3100 from DIS.
➜ Present accuracy: NNLO for evolution, NLO for all cross sections (NNLO jets not yet employed). Several groups: CT, MMHT, NNPDF, ABJM, HERAPDF,...



$$R_s(x,Q^2)=\frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)}$$

PDF set	$R_s(0.023, 1.38 \text{ GeV})$	$R_s(0.023, M_Z)$
NNPDF3.0	0.45±0.09	0.71±0.04
NNPDF3.1	0.59±0.12	0.77±0.05
NNPDF3.1 collider-only	0.82±0.18	0.92±0.09
NNPDF3.1 HERA + ATLAS W, Z	1.03±0.38	1.05±0.240
xFitter HERA + ATLAS W, Z (Ref. [72])	$1.13^{+0.11}_{-0.11}$	-



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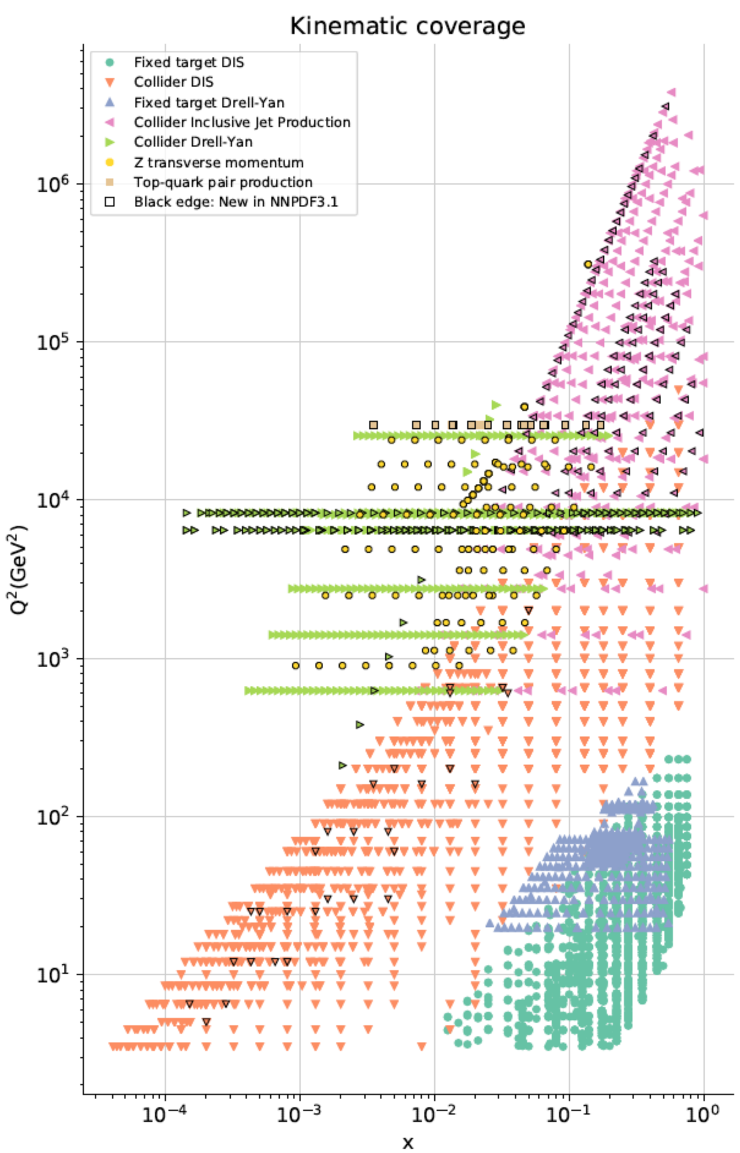
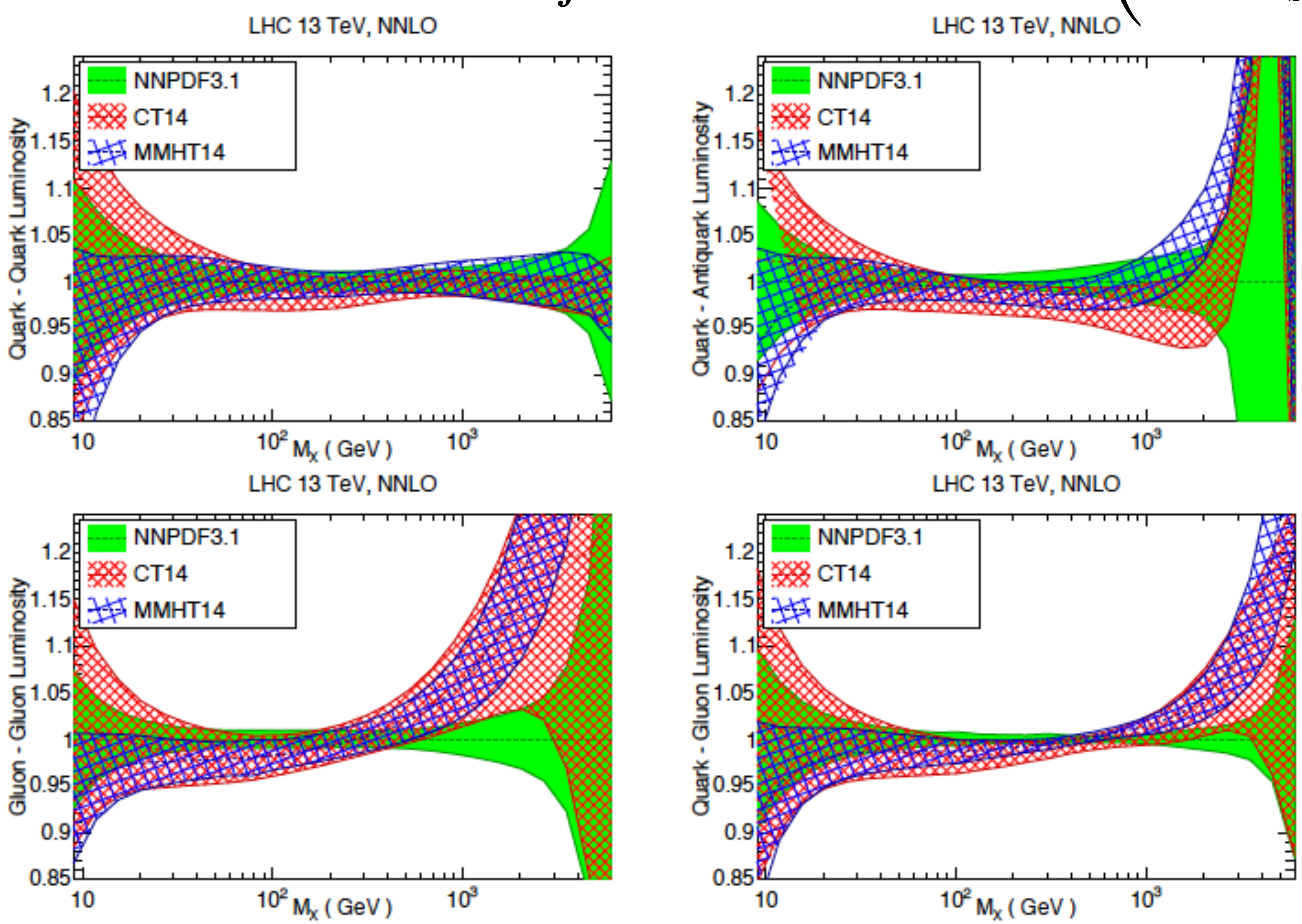
$$\mathcal{L}_{ij}(M_X) = \int dx_i dx_j\, f_i(x_i, M_X^2) f_j(x_j, M_X^2)\, \delta\left(x_i x_j - \frac{M_X^2}{s}\right)$$





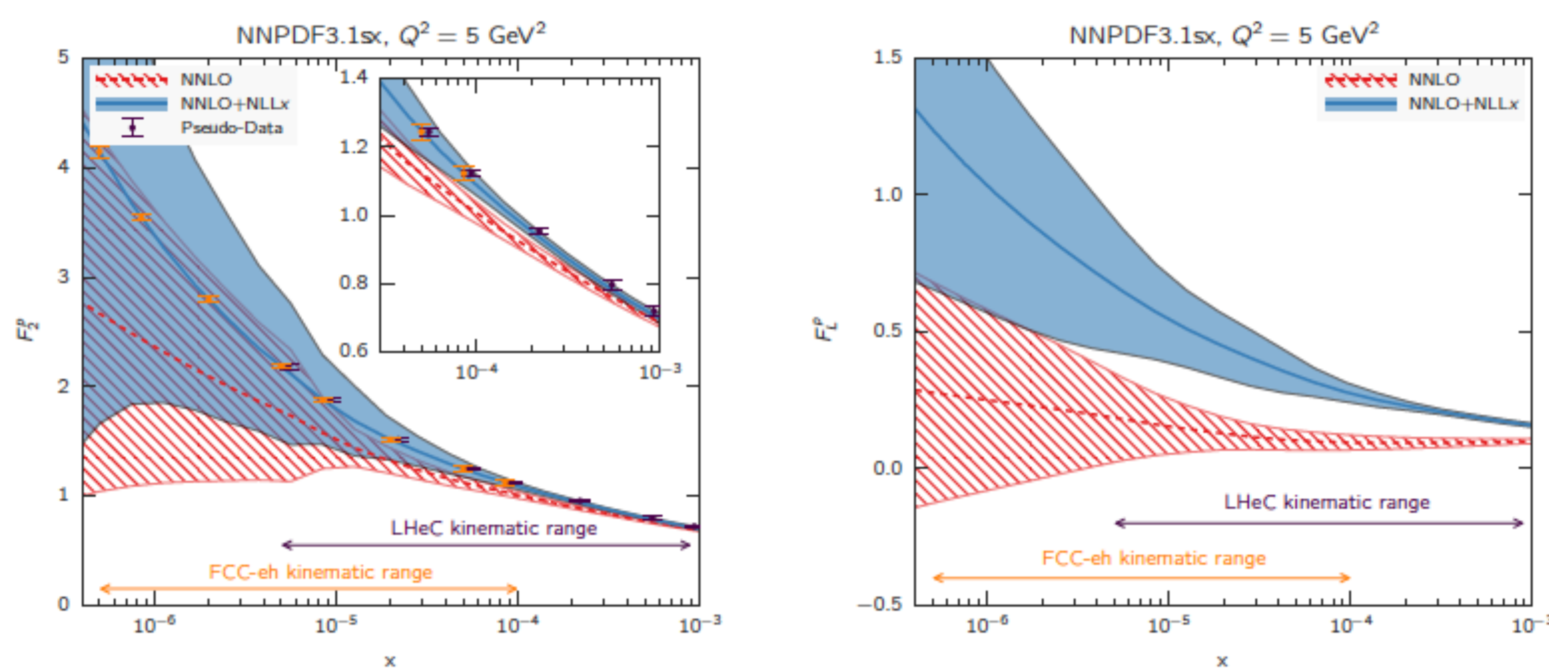
Resummation:

- Resummation has been suggested (1710.05935) to cure the problem seen in HERA data of a worsening of the PDF fit quality with decreasing x and Q^2: the problem lies in F_L.

$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x)$$

$$k = 0,1,2,\ h = 0,1 \text{ at present}$$

- This approach, and saturation, can be checked at smaller x through the tension between observables: F_2, F_L, σ_r^{HQ}.



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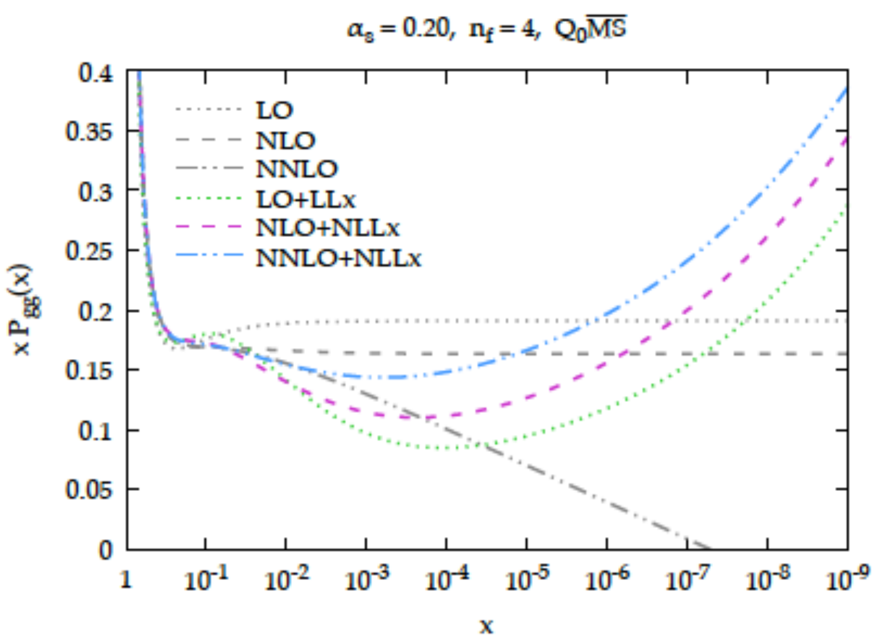

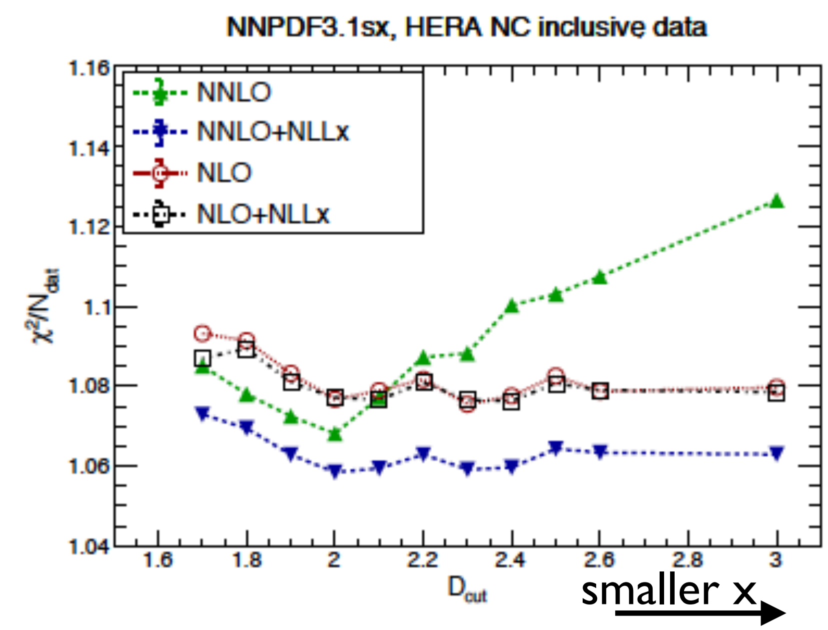

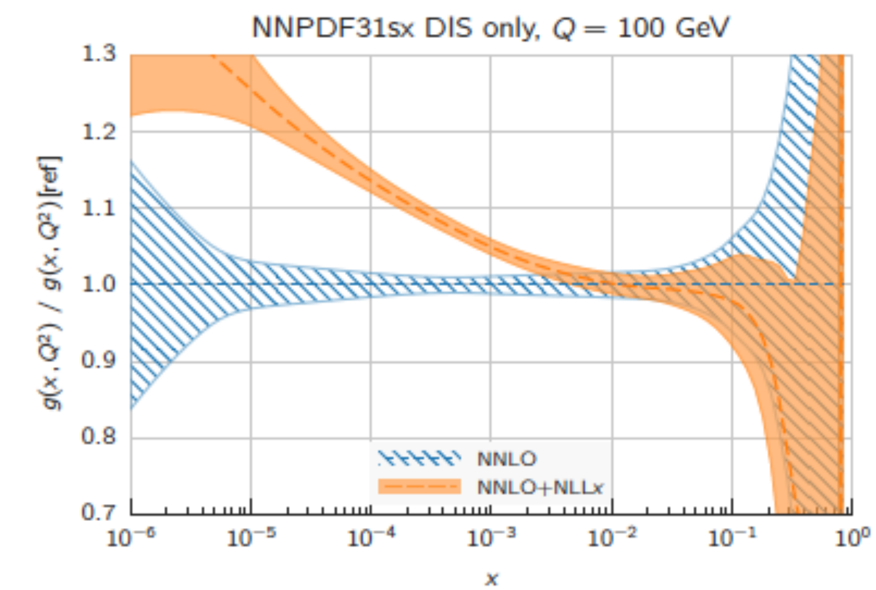

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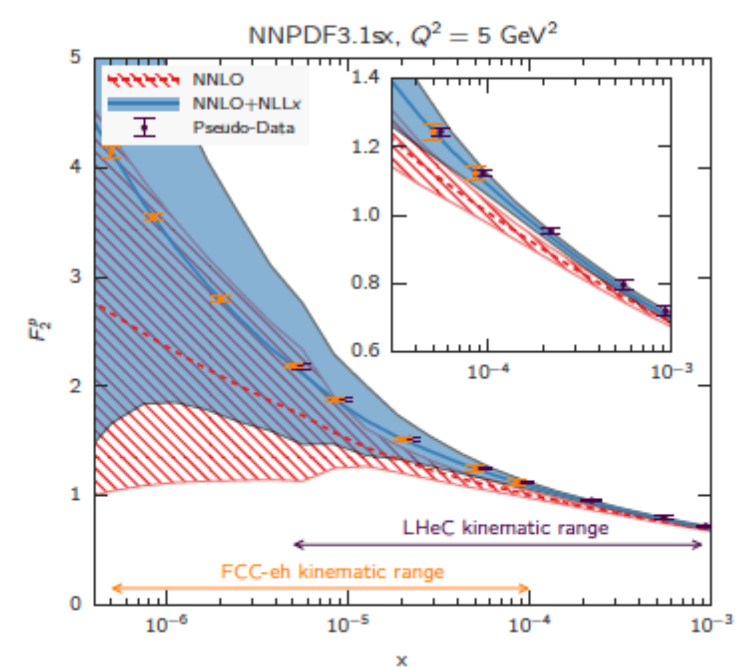
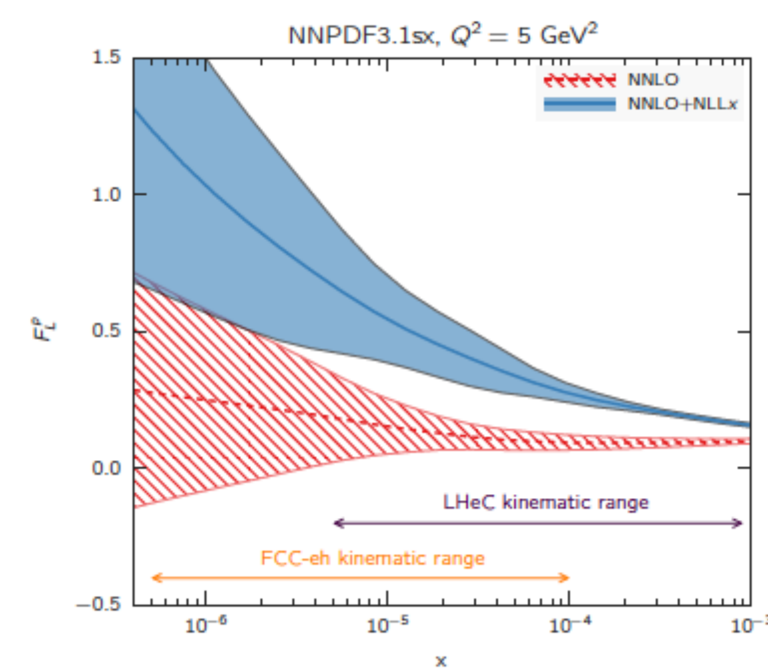
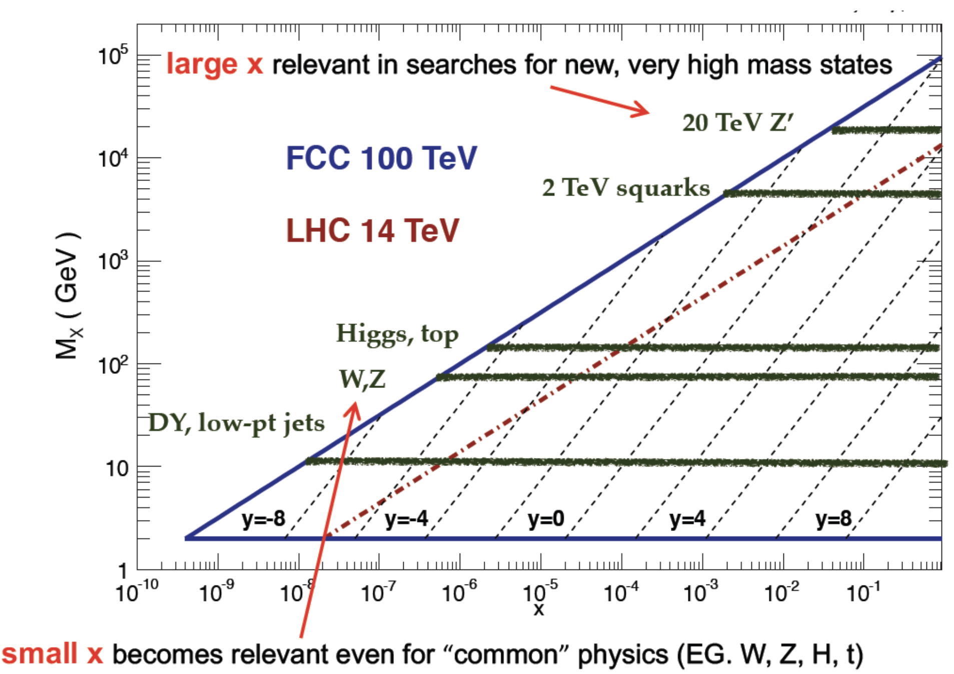


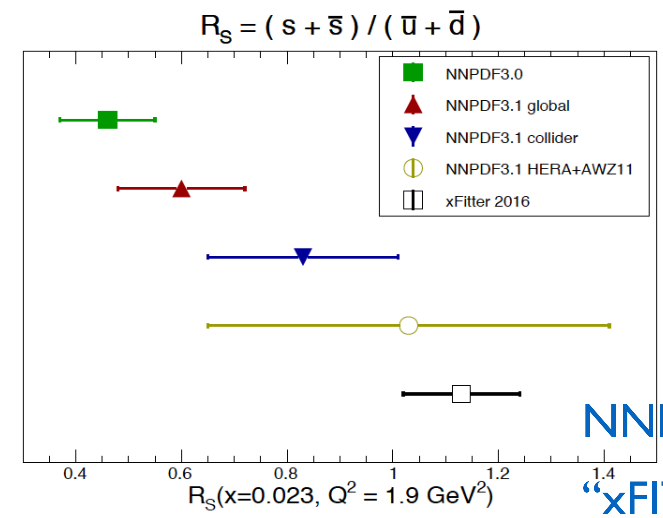


Proton PDFs at EICs:

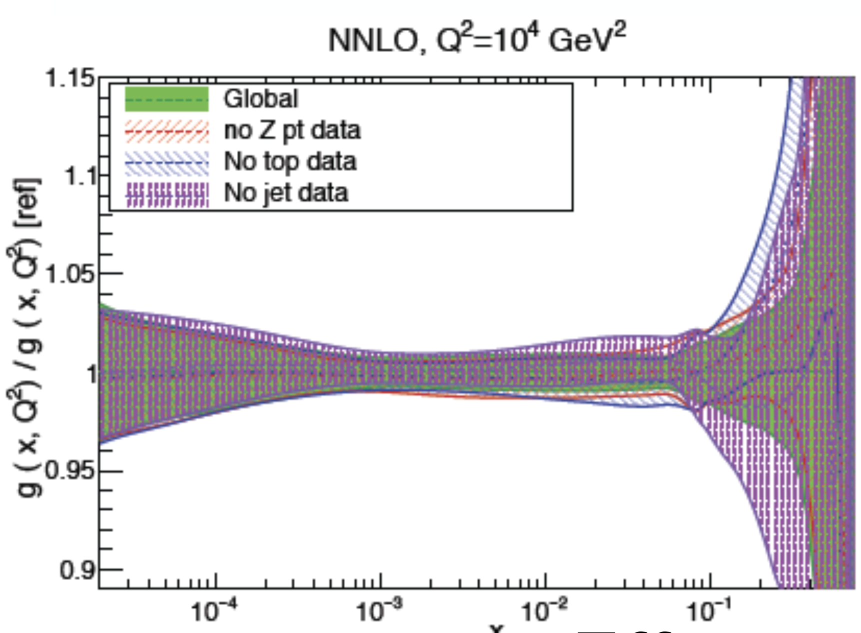
• Unpolarised proton PDFs show large uncertainties in regions of interest for HL-LHC and future hadron colliders.

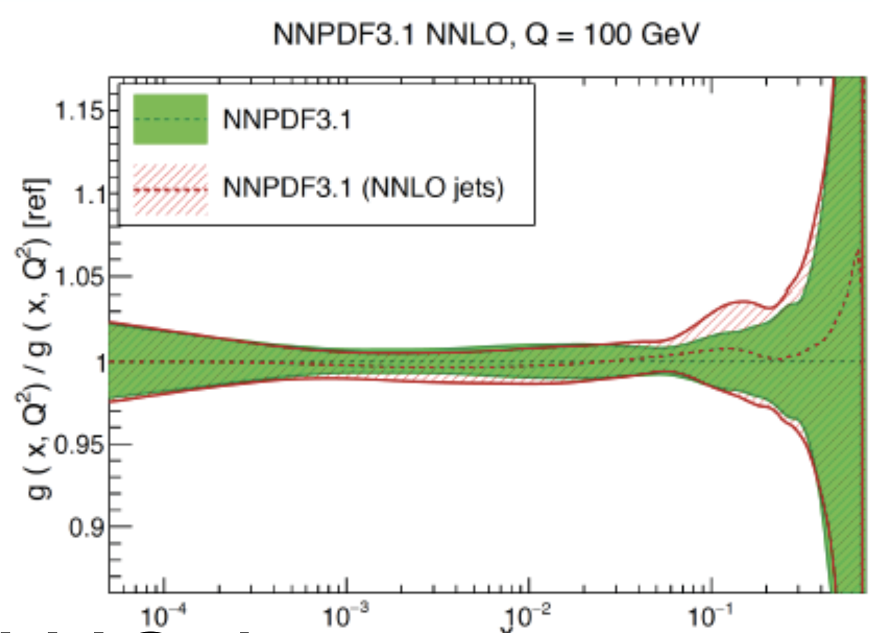


C. Gwenlan at DIS2017; M. Klein at HL/HE-LHC WS 2017



NNPDF3.1 arXiv:1706.00428, note: "xFITTER16" = ATLAS: 1612.0301

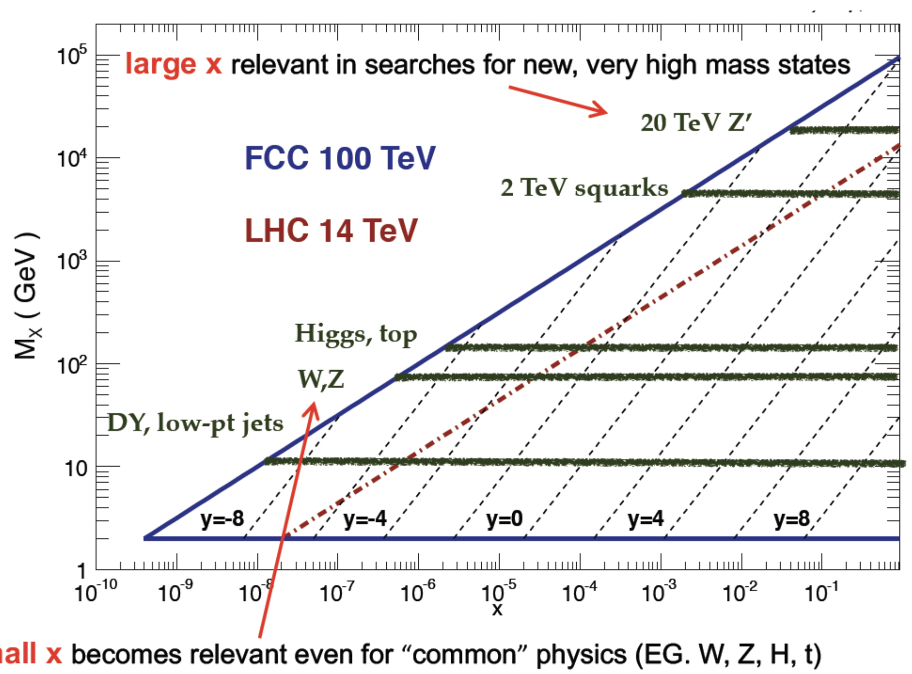




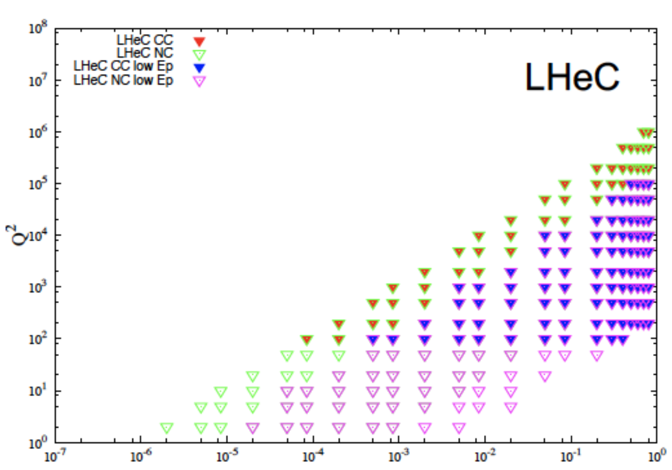
Effect of LHC data

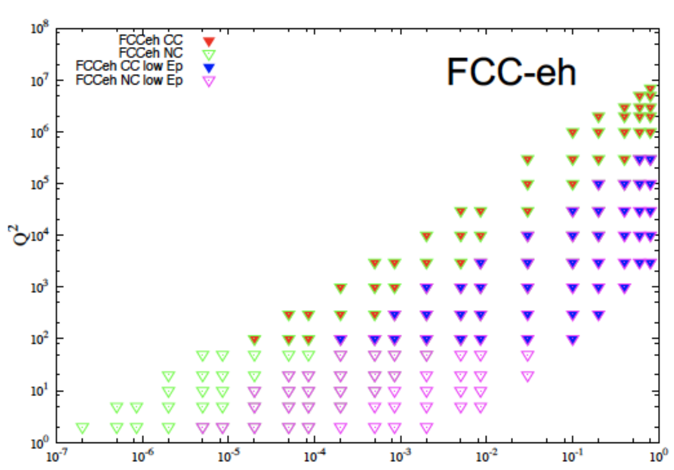
Proton PDFs at EICs:

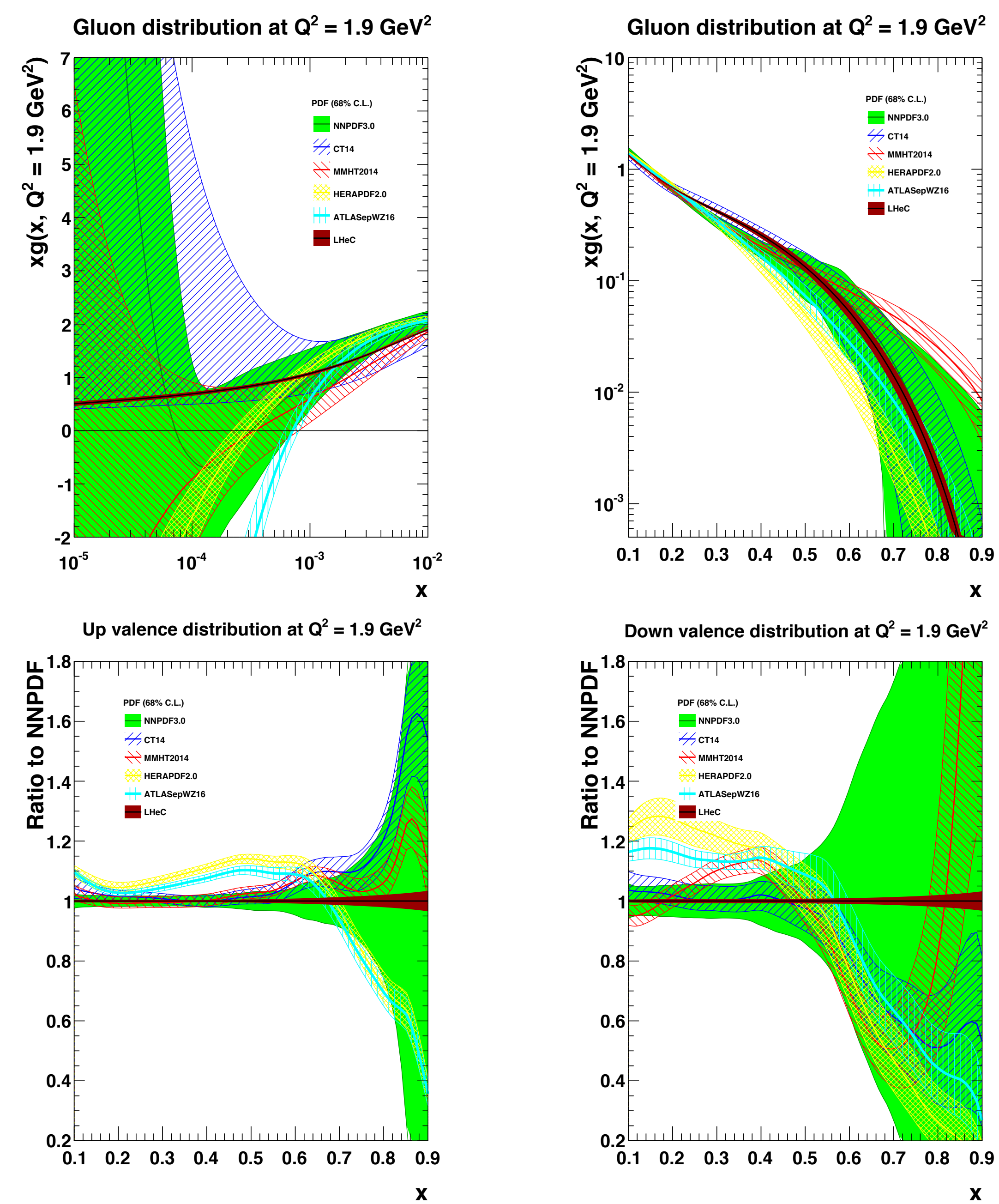
- Unpolarised proton PDFs show large uncertainties in regions of interest for HL-LHC and future hadron colliders.
- Inclusive measurements in ep largely improve the situation, plus new possibilities: full flavour decomposition, top, intrinsic charm,…



C. Gwenlan at DIS2017; M. Klein at HL/HE-LHC WS 2017







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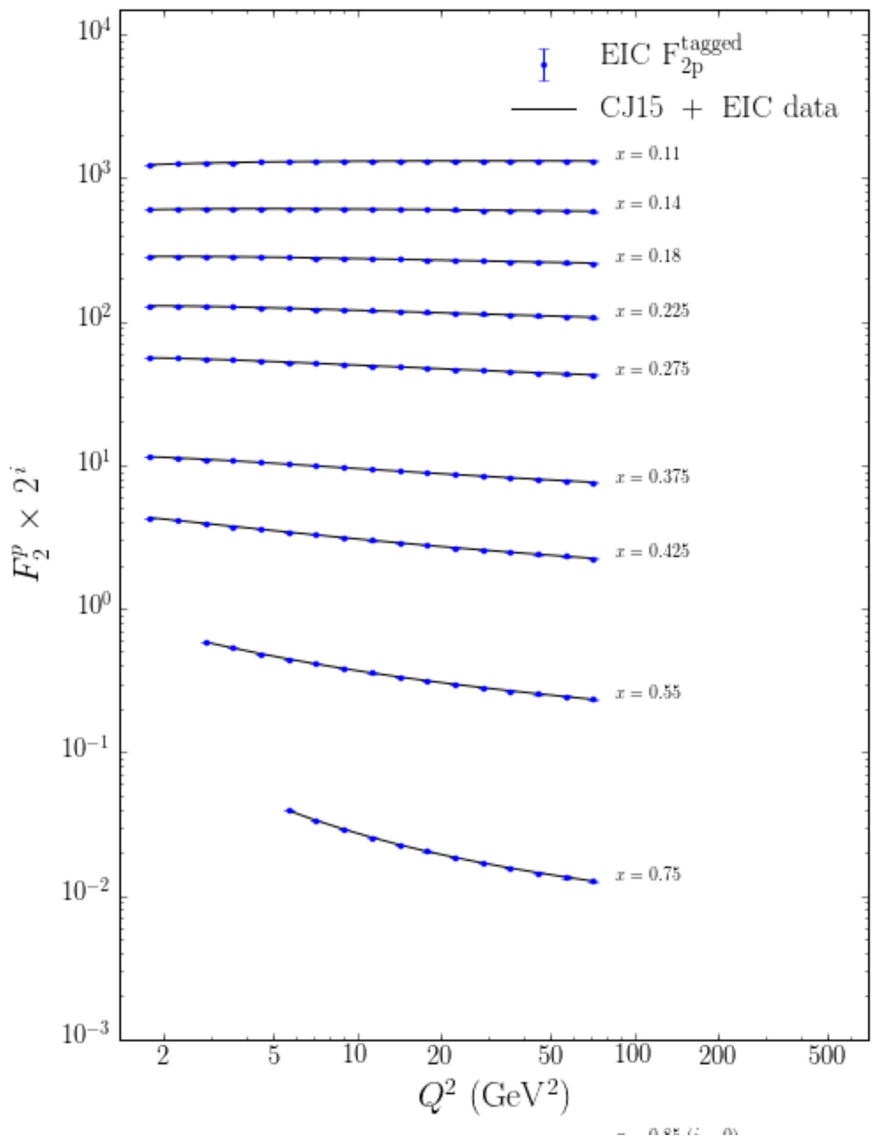
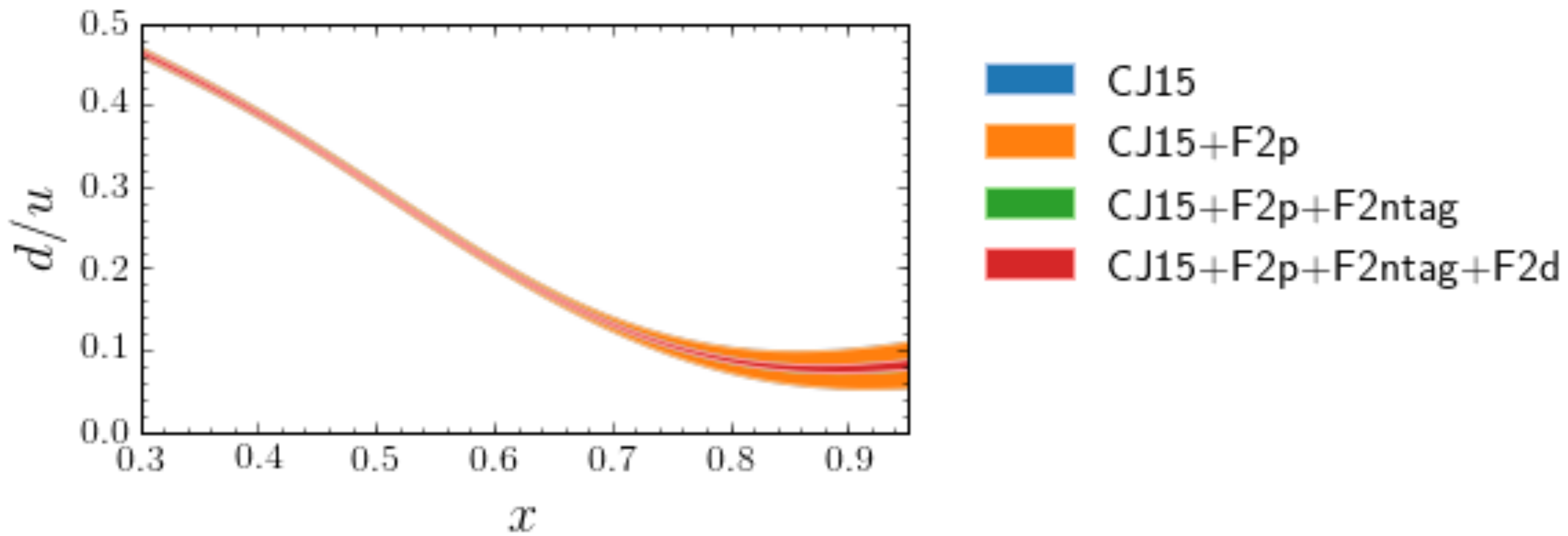


R. Yoshida at DIS2017



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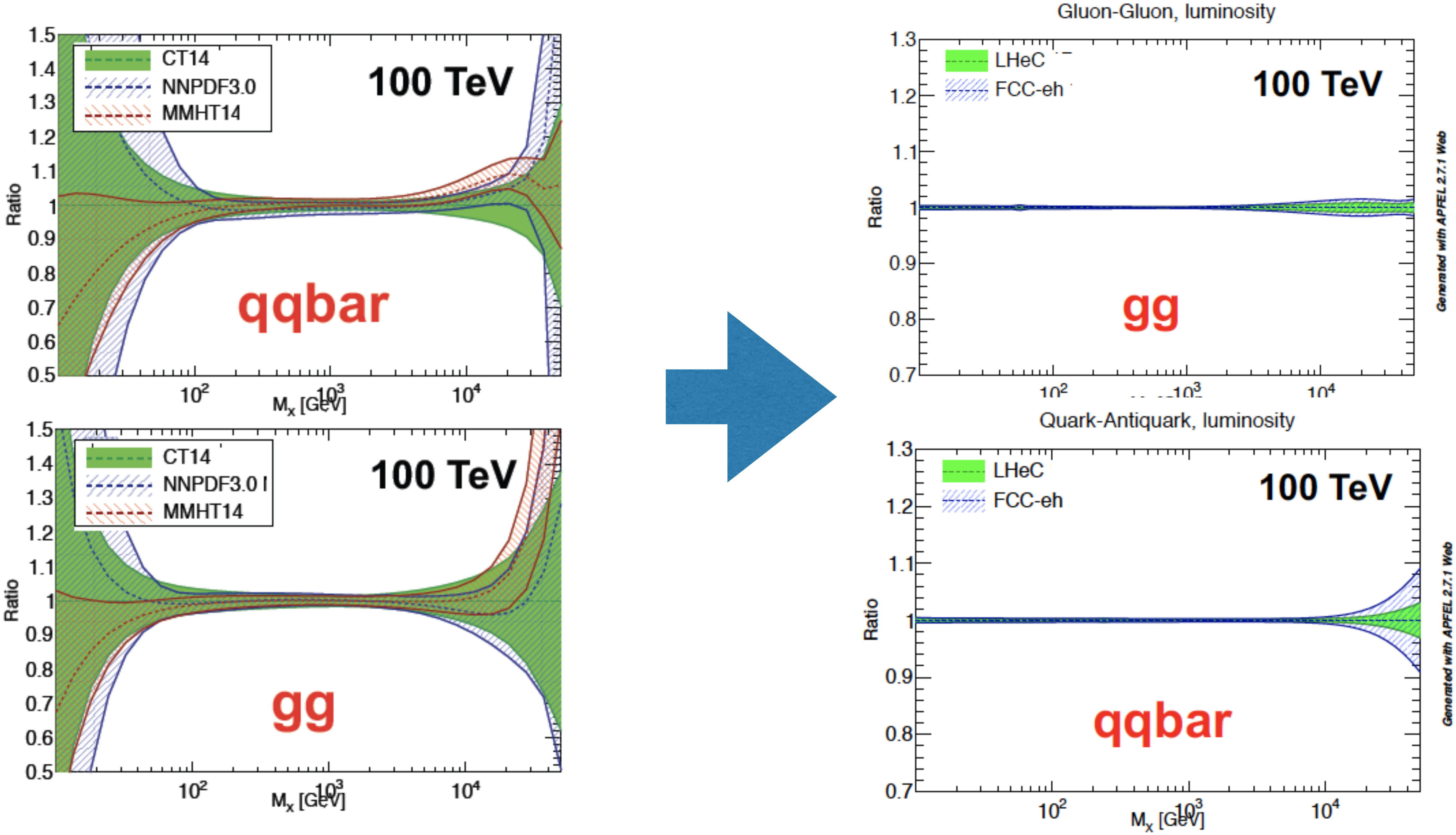
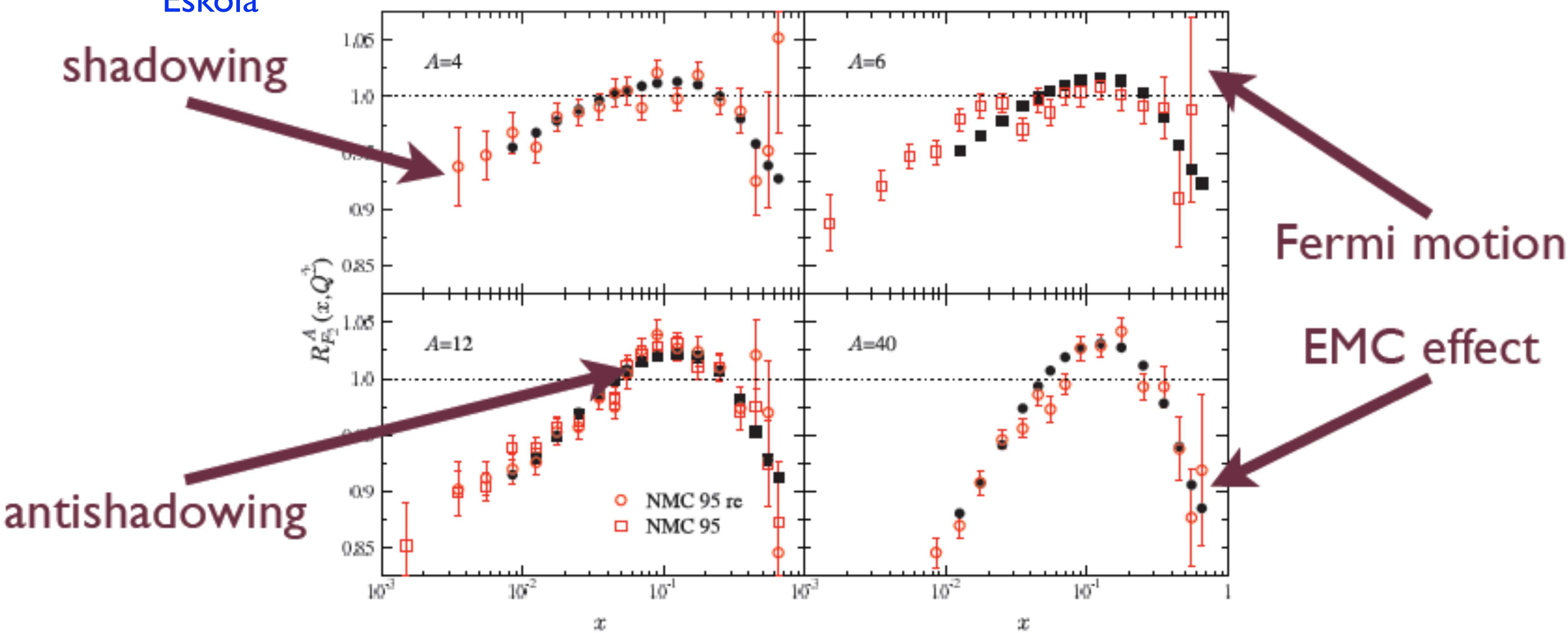


nPDFs:

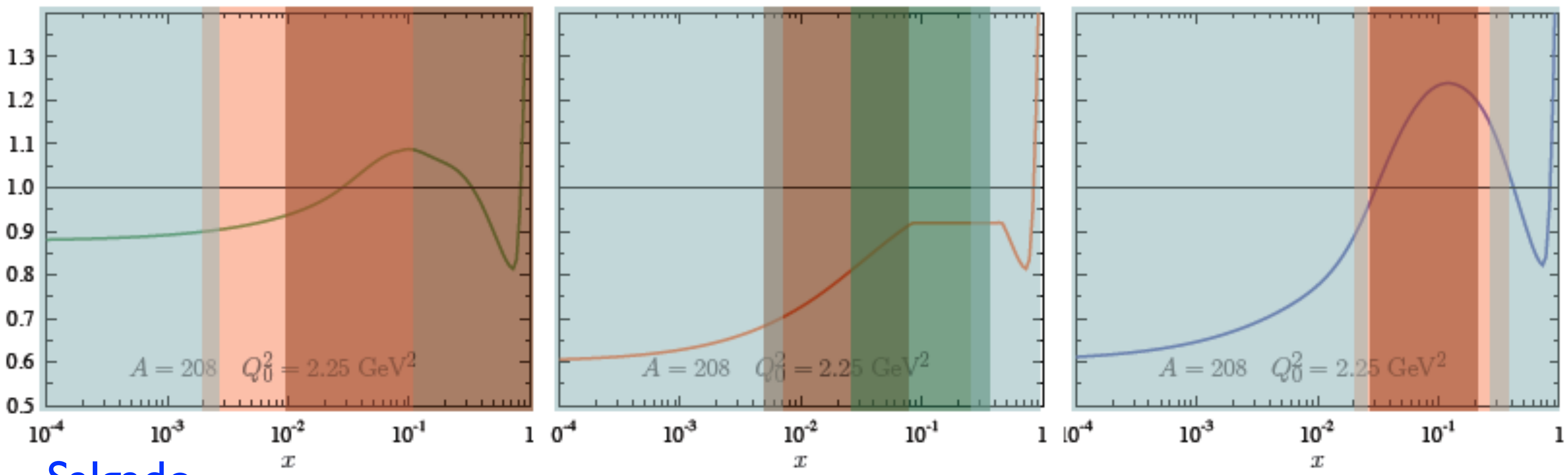
$$R^A_{F_2}(x,Q^2) = \frac{F^A_2(x,Q^2)}{AF^p_2(x,Q^2)}$$

Eskola



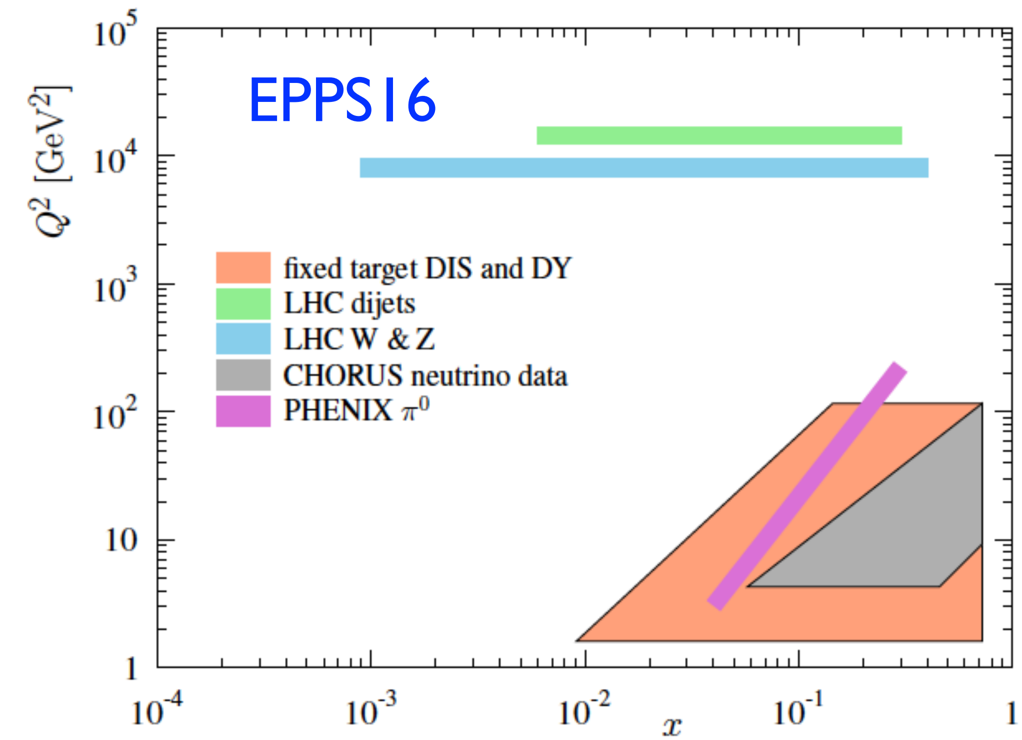
nPDFs:

Valence | Sea quarks | Gluons



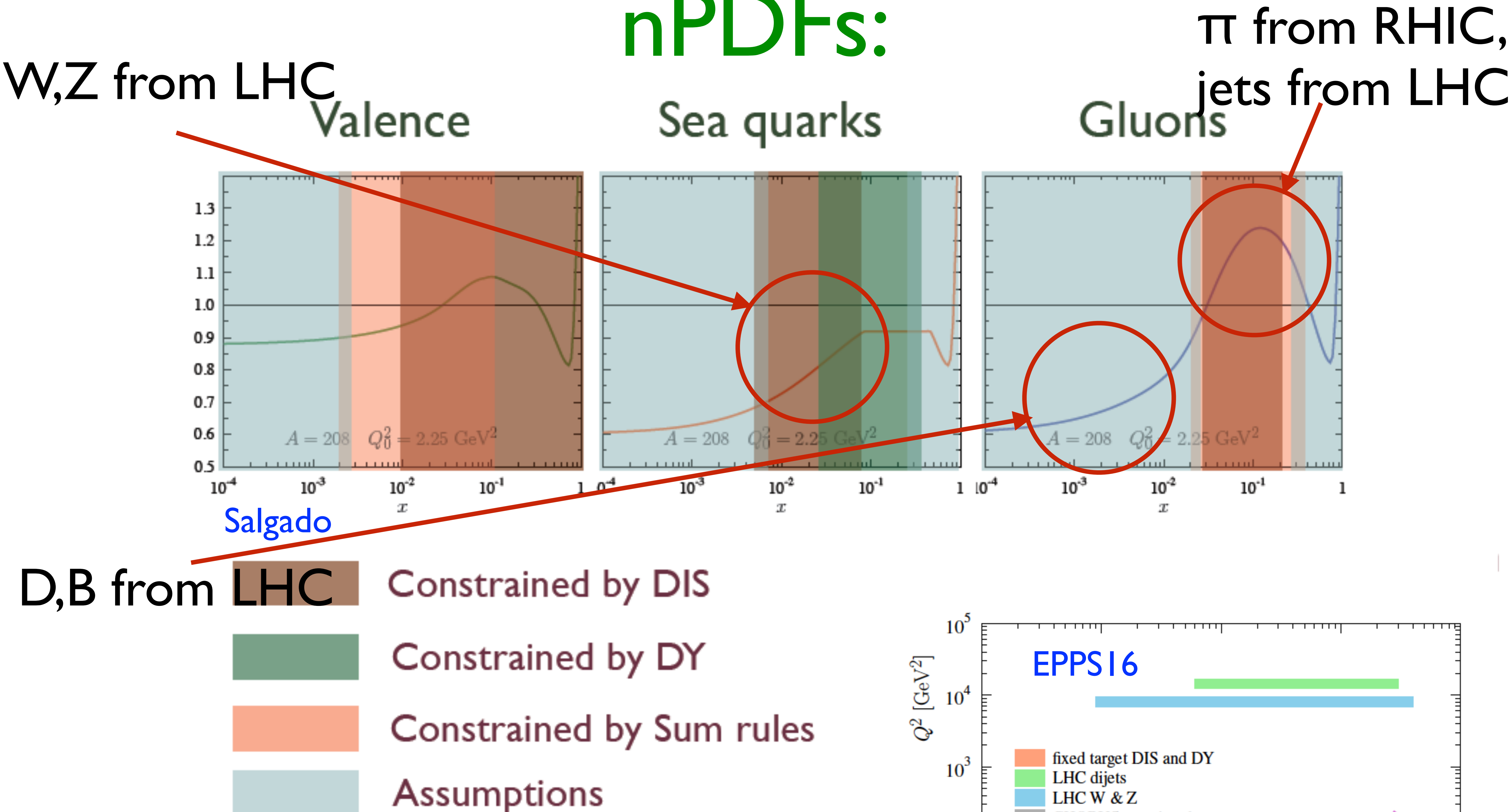
Salgado

- Constrained by DIS
- Constrained by DY
- Constrained by Sum rules
- Assumptions



- Lack of experimental data makes the small-x region unconstrained ⇒ uncertainties on observables.

nPDFs:



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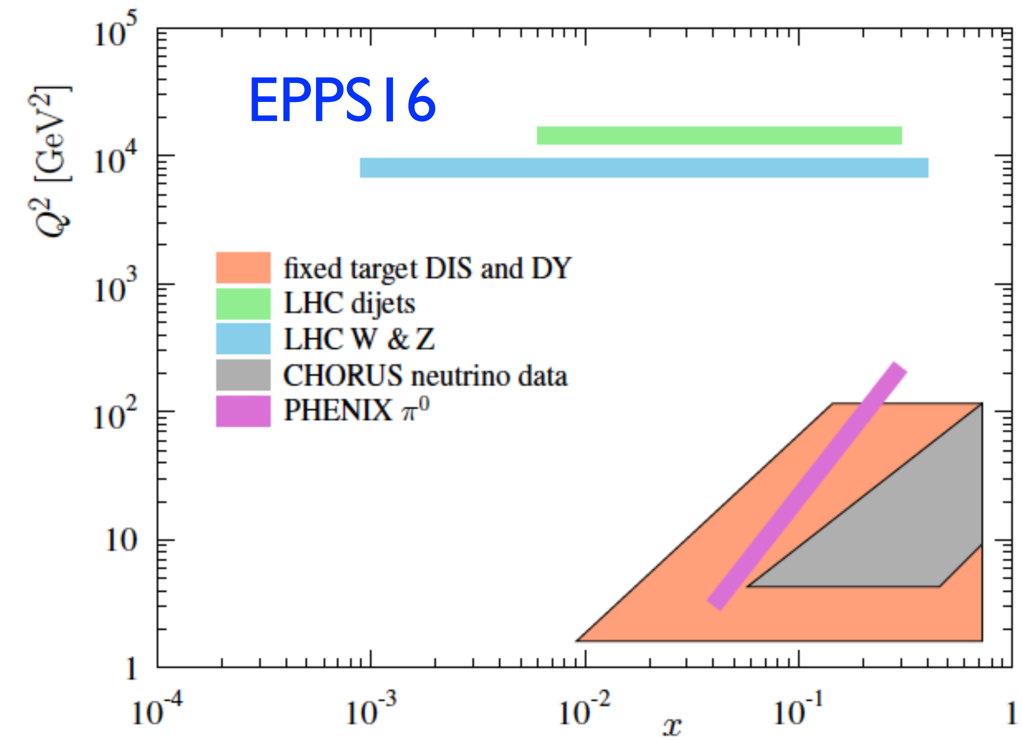

Available sets:

SET		HKN07 PRC76 (2007) 065207	EPS09 JHEP 0904 (2009) 065	DSSZ PRD85 (2012) 074028	nCTEQ15 PRD93 (2016) 085037	KA15 PRD93 (2016) 014036	EPPS16 EPJC C77 (2017)163
data	eDIS	✔	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔	✔
	π^0	✘	✔	✔	✔	✘	✔
	νDIS	✘	✘	✔	✘	✘	✔
	pPb	✘	✘	✘	✘	✘	✔
# data		1241	929	1579	740	1479	1811
order		NLO	NLO	NLO	NLO	NNLO	NLO
proton PDF		MRST98	CTEQ6.1	MSTW2008	~CTEQ6.1	JR09	CT14NLO
mass scheme		ZM-VFNS	ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS
comments		$\Delta\chi^2$=13.7, ratios, <u>no EMC for gluons</u>	$\Delta\chi^2$=50, ratios, <u>huge shadowing-antishadowing</u>	$\Delta\chi^2$=30, ratios, <u>medium-modified FFs for π^0</u>	$\Delta\chi^2$=35, PDFs, valence <u>flavour sep., not enough sensitivity</u>	PDFs, <u>deuteron data included</u>	$\Delta\chi^2$=52 flavour sep., ratios, <u>LHC pPb data</u>

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			✔	✔	✔	✔
			✔	✔	✔	✔
			✔	✔	✘	✔
			✔	✘	✘	✔
			✘	✘	✘	✔
			1579	740	1479	1811
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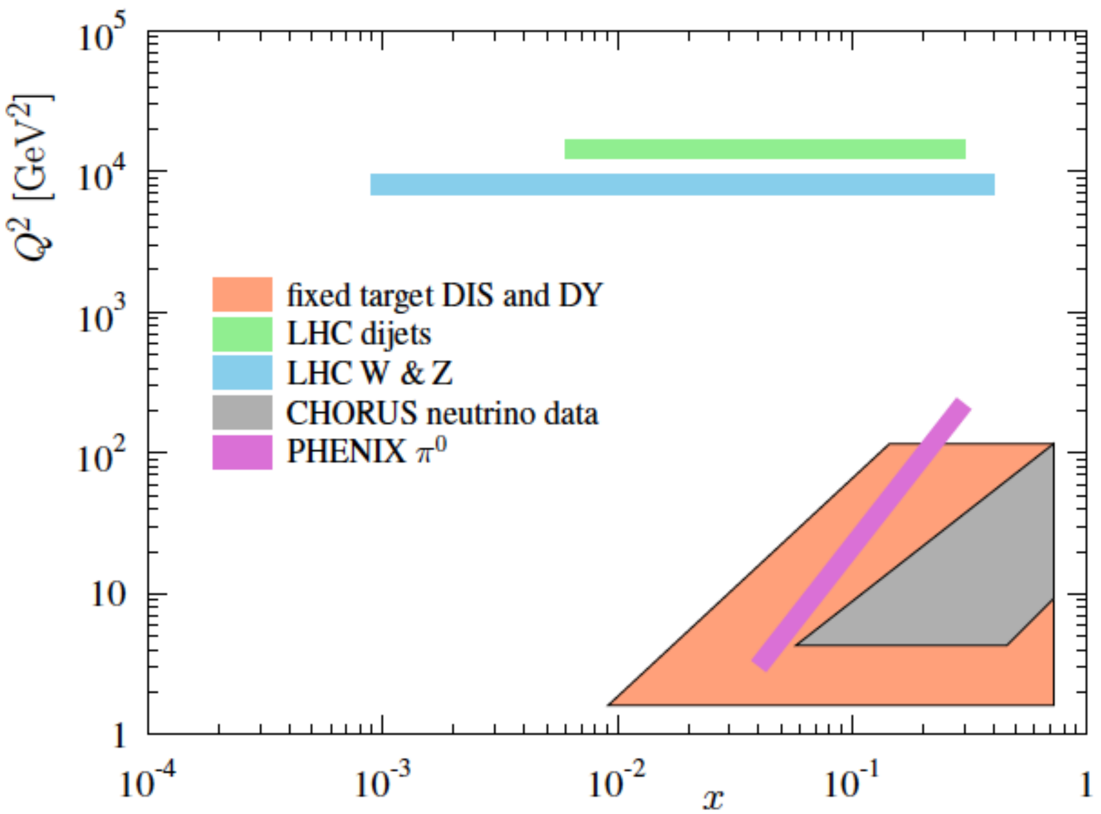
- Centrality dependence (EPS09s) not from data but from the A-dependence of the parameters.
- Several models provide it: Vogt et al., FGS, Ferreiro et al.,…

EPPS16:



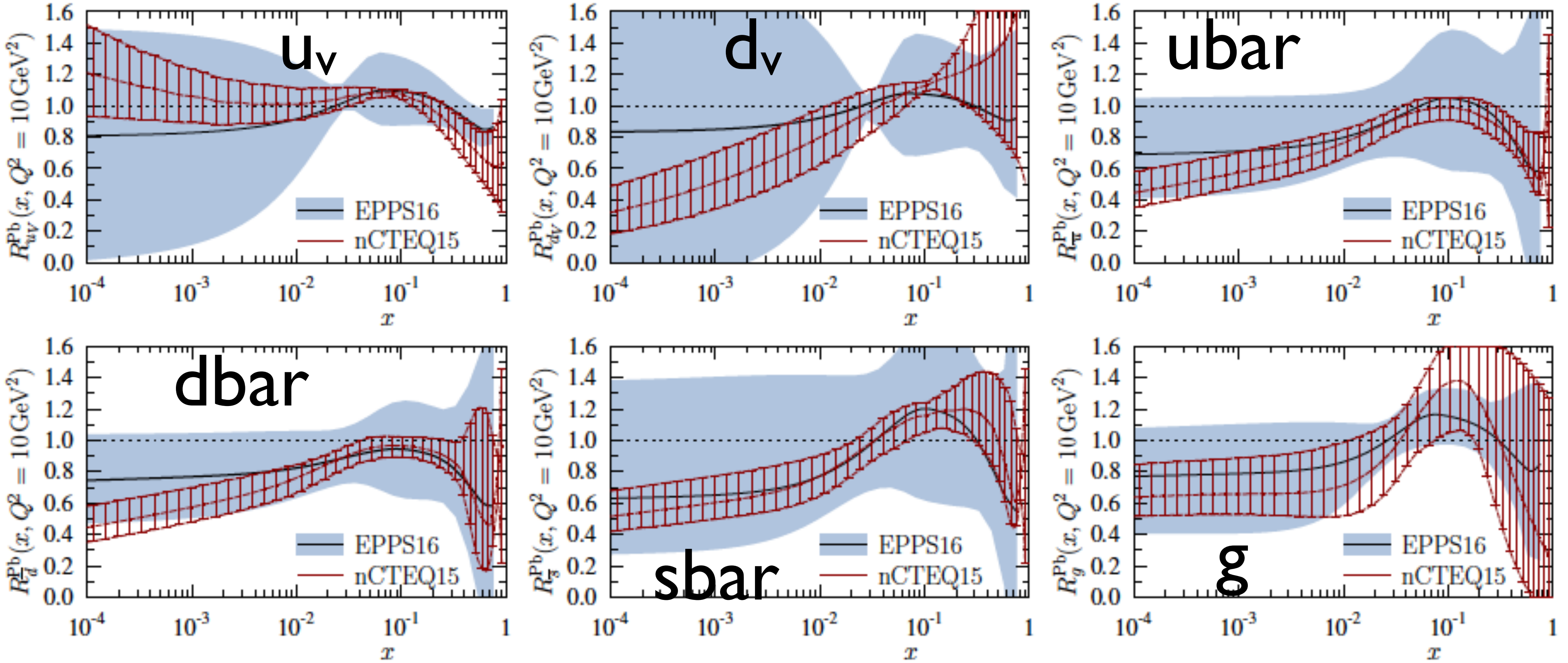
- Most Pb data from CHORUS, 30 Pb points from pPb@LHC: fit for a single nucleus not possible.

Experiment	Observable	Collisions	Data points	χ^2	Ref.
SLAC E139	DIS	e^-He(4), e^-D	21	12.2	[69]
CERN NMC 95, re.	DIS	μ^-He(4), μ^-D	16	18.0	[70]
CERN NMC 95	DIS	μ^-Li(6), μ^-D	15	18.4	[71]
CERN NMC 95, Q^2 dep.	DIS	μ^-Li(6), μ^-D	153	161.2	[71]
SLAC E139	DIS	e^-Be(9), e^-D	20	12.9	[69]
CERN NMC 96	DIS	μ^-Be(9), μ^-C	15	4.4	[72]
SLAC E139	DIS	e^-C(12), e^-D	7	6.4	[69]
CERN NMC 95	DIS	μ^-C(12), μ^-D	15	9.0	[71]
CERN NMC 95, Q^2 dep.	DIS	μ^-C(12), μ^-D	165	133.6	[71]
CERN NMC 95, re.	DIS	μ^-C(12), μ^-D	16	16.7	[70]
CERN NMC 95, re.	DIS	μ^-C(12), μ^-Li(6)	20	27.9	[70]
FNAL E772	DY	pC(12), pD	9	11.3	[73]
SLAC E139	DIS	e^-Al(27), e^-D	20	13.7	[69]
CERN NMC 96	DIS	μ^-Al(27), μ^-C(12)	15	5.6	[72]
SLAC E139	DIS	e^-Ca(40), e^-D	7	4.8	[69]
FNAL E772	DY	pCa(40), pD	9	3.33	[73]
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-D	15	27.6	[70]
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-Li(6)	20	19.5	[70]
CERN NMC 96	DIS	μ^-Ca(40), μ^-C(12)	15	6.4	[72]
SLAC E139	DIS	e^-Fe(56), e^-D	26	22.6	[69]
FNAL E772	DY	e^-Fe(56), e^-D	9	3.0	[73]
CERN NMC 96	DIS	μ^-Fe(56), μ^-C(12)	15	10.8	[72]
FNAL E866	DY	pFe(56), pBe(9)	28	20.1	[74]
CERN EMC	DIS	μ^-Cu(64), μ^-D	19	15.4	[75]
SLAC E139	DIS	e^-Ag(108), e^-D	7	8.0	[69]
CERN NMC 96	DIS	μ^-Sn(117), μ^-C(12)	15	12.5	[72]
CERN NMC 96, Q^2 dep.	DIS	μ^-Sn(117), μ^-C(12)	144	87.6	[76]
FNAL E772	DY	pW(184), pD	9	7.2	[73]
FNAL E866	DY	pW(184), pBe(9)	28	26.1	[74]
CERN NA10★	DY	π^-W(184), π^-D	10	11.6	[49]
FNAL E615★	DY	π^+W(184), π^-W(184)	11	10.2	[50]
CERN NA3★	DY	π^-Pt(195), π^-H	7	4.6	[48]
SLAC E139	DIS	e^-Au(197), e^-D	21	8.4	[69]
RHIC PHENIX	π^0	dAu(197), pp	20	6.9	[28]
CERN NMC 96	DIS	μ^-Pb(207), μ^-C(12)	15	4.1	[72]
CERN CMS★	$W^\pm$	pPb(208)	10	8.8	[43]
CERN CMS★	Z	pPb(208)	6	5.8	[45]
CERN ATLAS★	Z	pPb(208)	7	9.6	[46]
CERN CMS★	dijet	pPb(208)	7	5.5	[34]
CERN CHORUS★	DIS	νPb(208), $\bar{\nu}$Pb(208)	824	998.6	[47]
Total			1811	1789	

EPPS16:

Q^2=10 GeV^2

- nCTEQ15 vs. EPPS16: note the parametrisation bias.

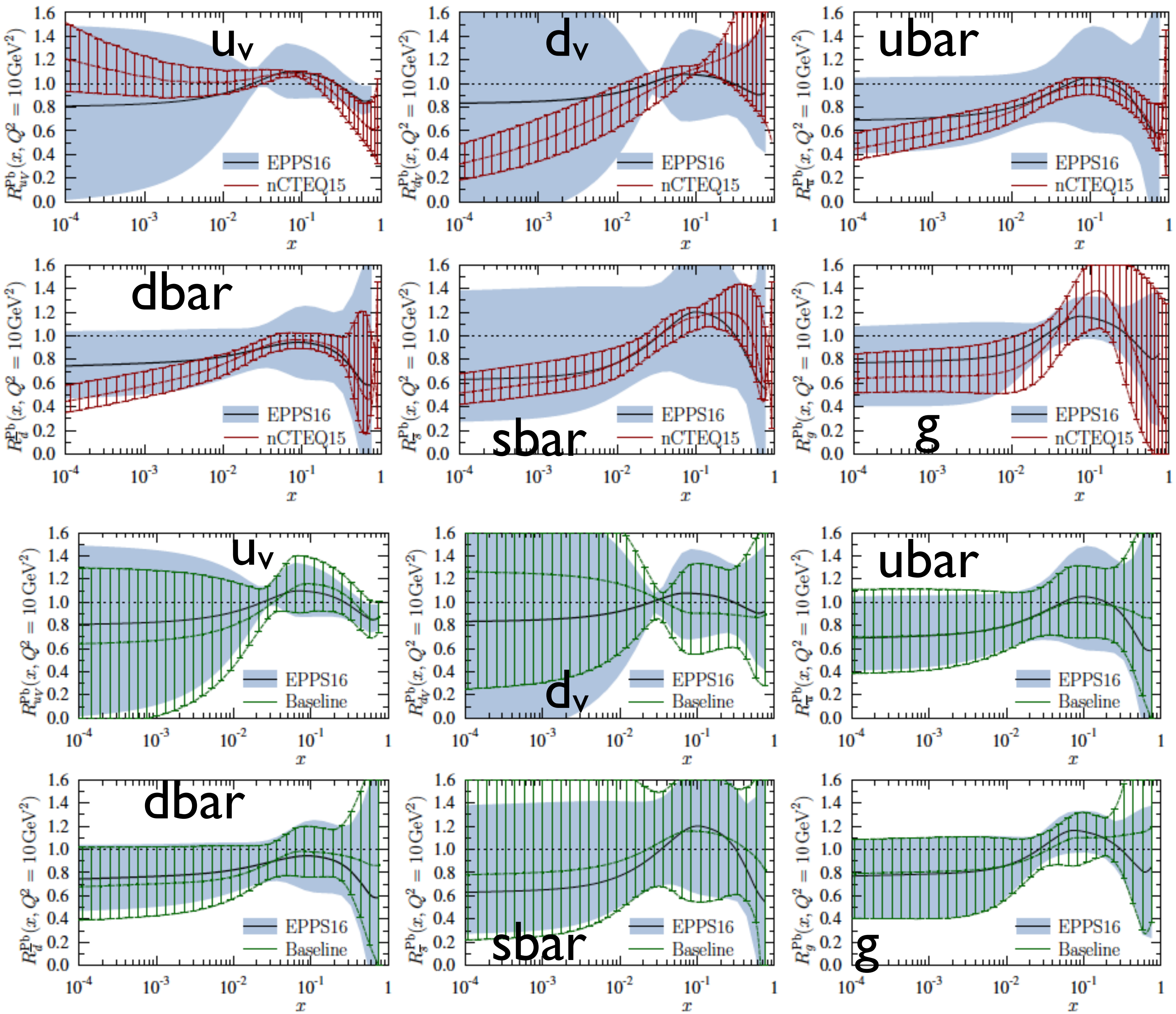


EPPS16:

Q^2=10 GeV^2

- nCTEQ15 vs. EPPS16: note the parametrisation bias.

- Presently available LHC data seem not to have a large effect: large-x glue (baseline=no ν, no LHC data).



Nuclear PDFs at EICs:

- Unpolarised nuclear PDFs are very poorly known, particularly for $x<10^{-2}$.
- Inclusive measurements in eA largely improve the situation, plus new possibilities: flavour decomposition (but u-d challenging), fits for a single nucleus, release assumptions in unknown regions,…

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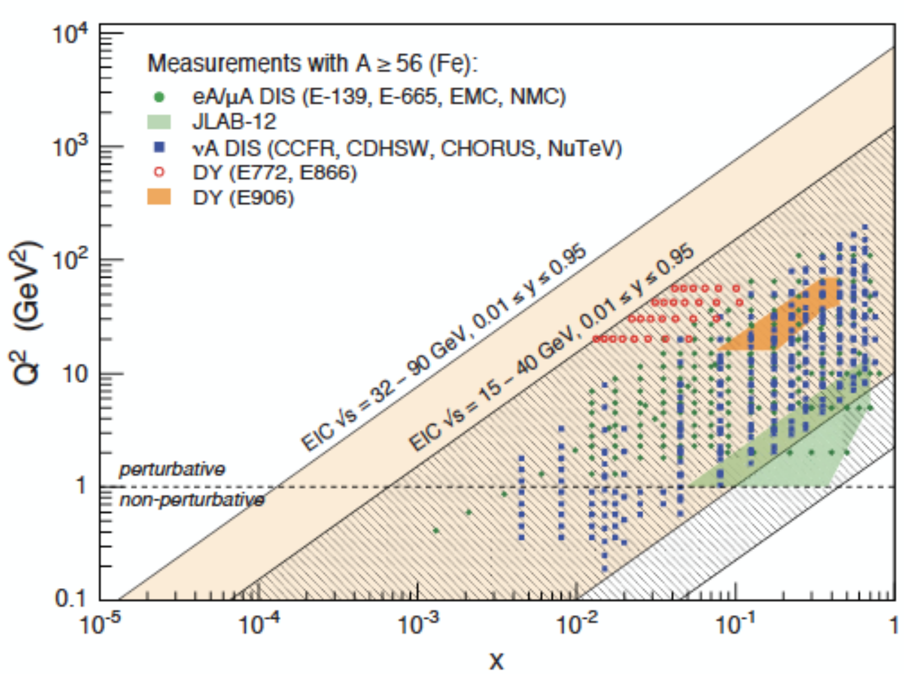

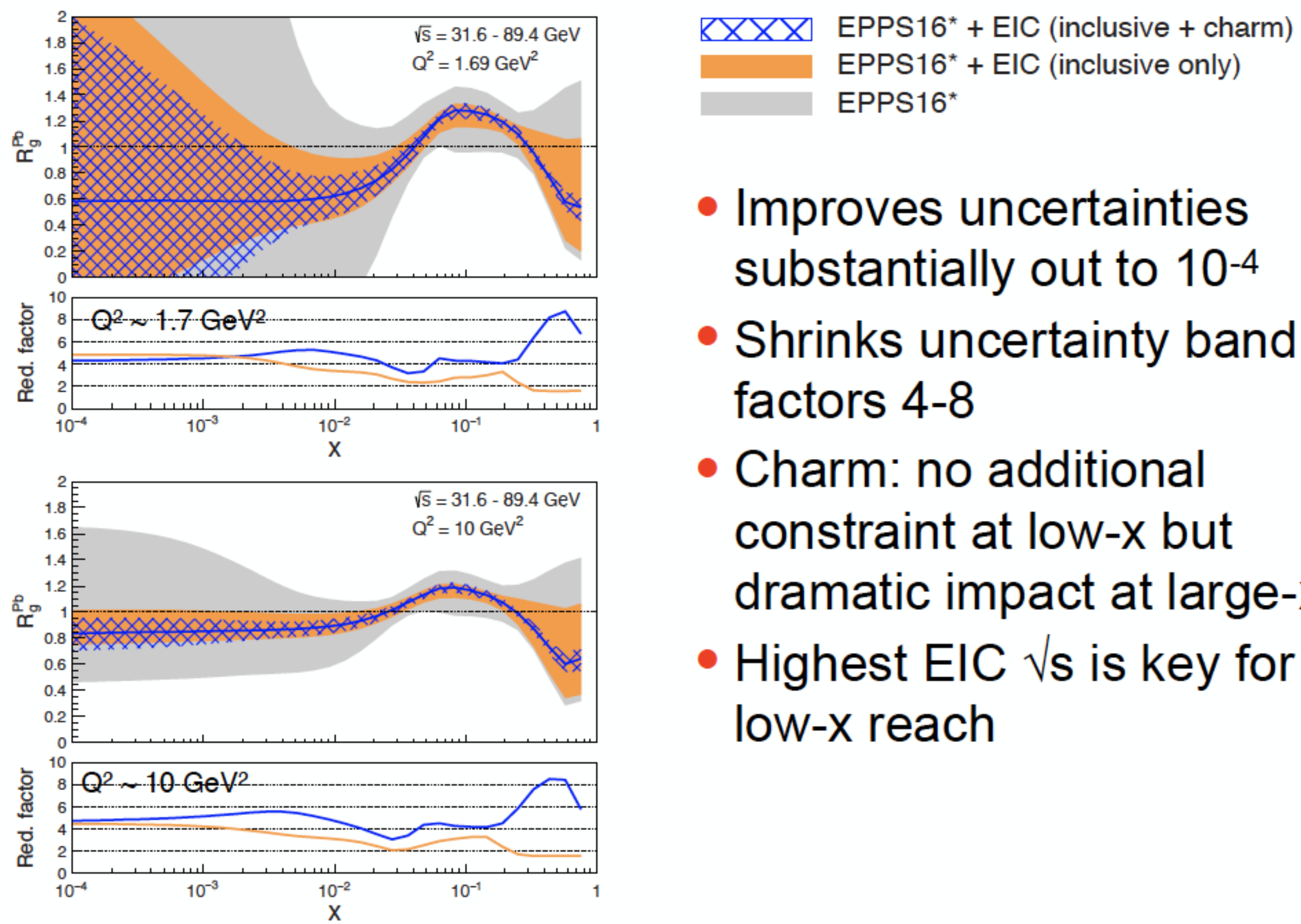

- Improves uncertainties substantially out to 10^{-4}
- Shrinks uncertainty band by factors 4-8
- Charm: no additional constraint at low-x but dramatic impact at large-x
- Highest EIC √s is key for low-x reach

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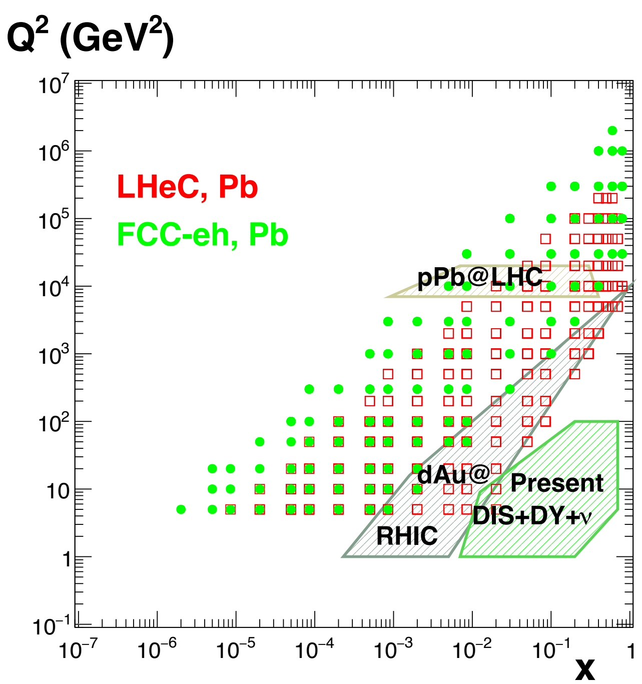
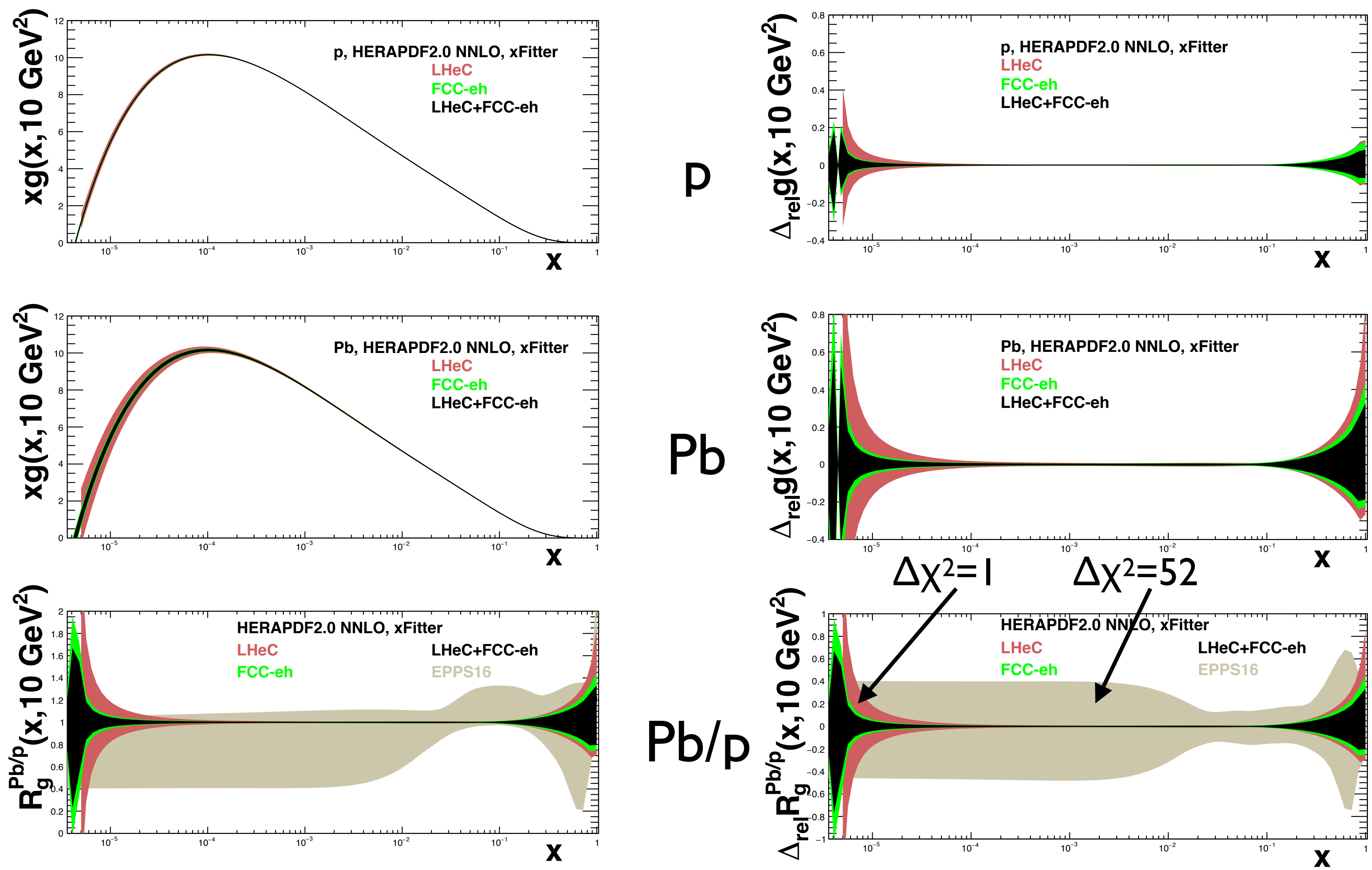
xFitter study of Pb PDFs at the LHeC





u-d separation in eA:

The effect of LHeC pseudodata

H. Paukkunen

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

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

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

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

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

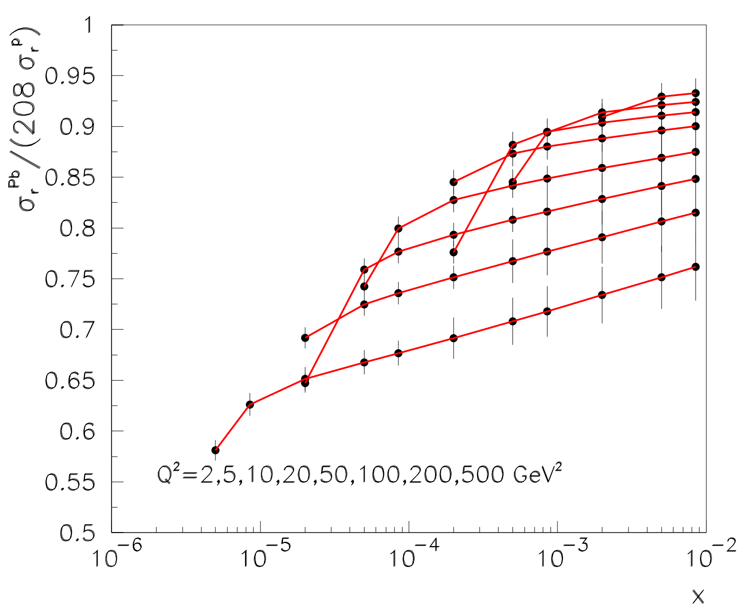
Leading term "Correction term"

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

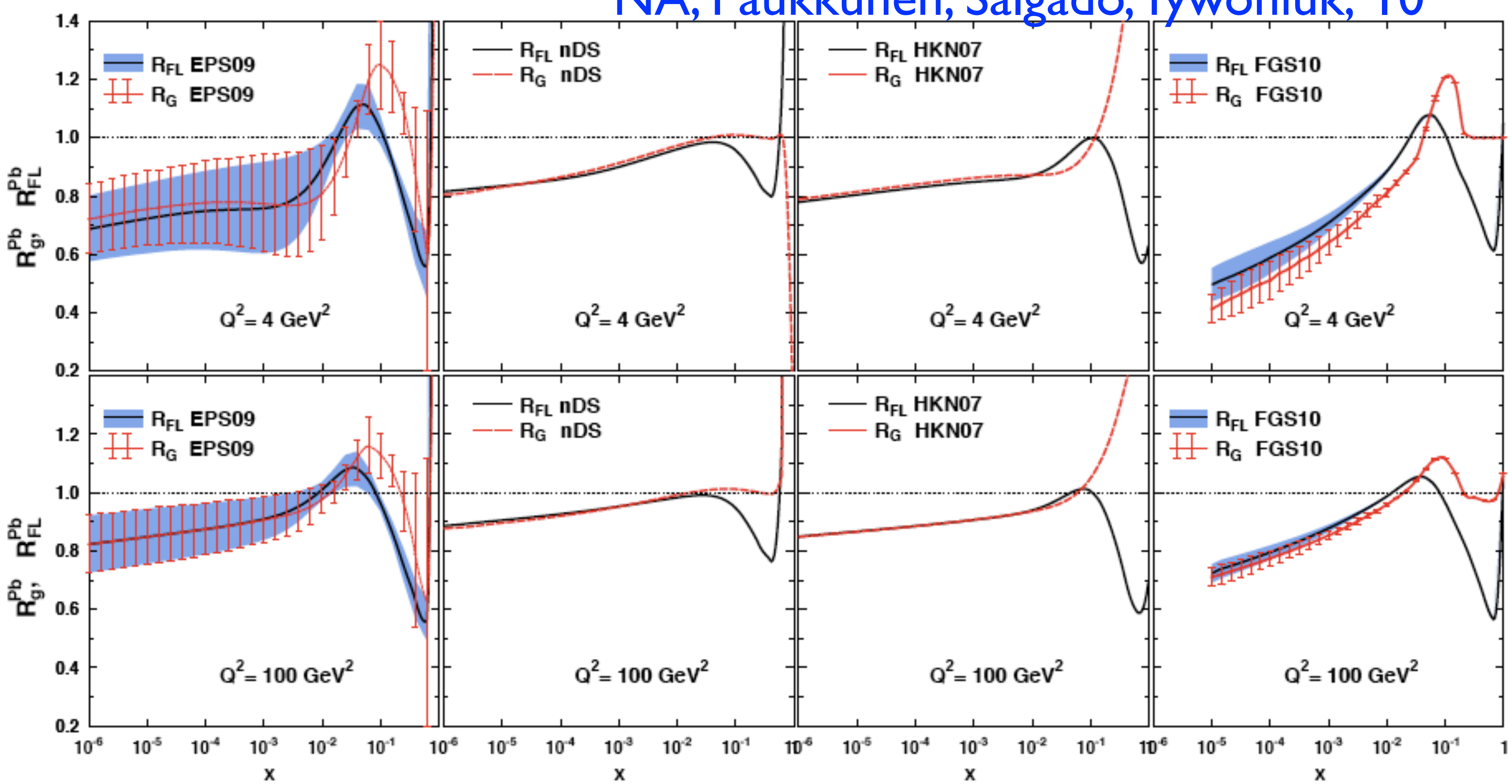
F_L in eA:

$$\sigma_r^{NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{NC}}{dx dQ^2} = F_2 \left[1 - \frac{y^2}{Y_+}\frac{F_L}{F_2}\right], \qquad Y_+ = 1 + (1-y)^2$$

- F_L traces the nuclear effects on the glue (Cazarotto et al '08): most sensitive to deviations wrt fixed order perturbation theory.
- Uncertainties in the extraction of F_2 due to the unknown nuclear effects on F_L of order 5 % (> stat.+syst.) ⇒ either measure F_L or use the reduced cross section (but then ratios at two energies...).



NA, Paukkunen, Salgado, Tywoniuk, '10



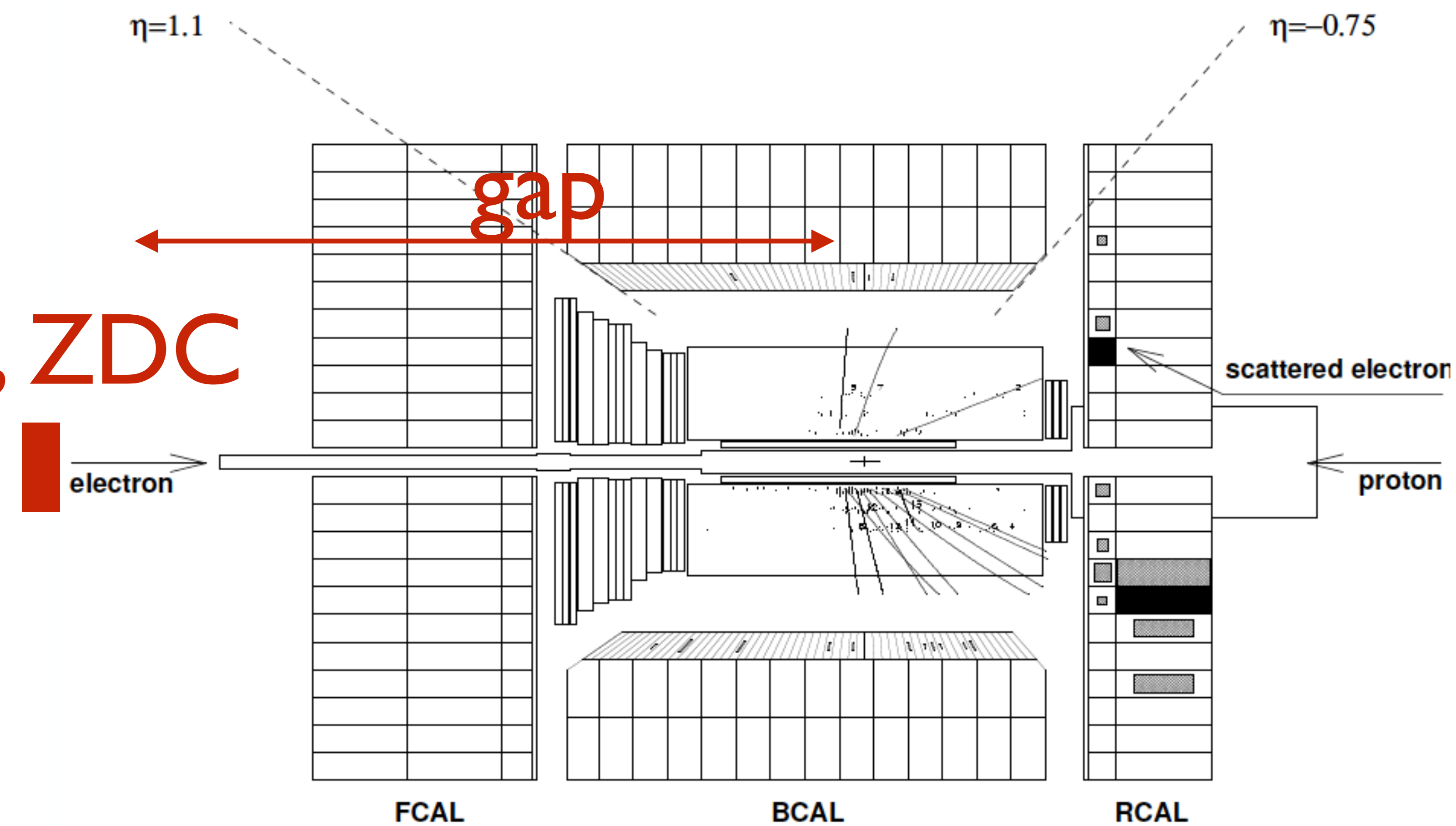
Contents:

Bibliography:
- R. Devenish and A. Cooper-Sarker, *Deep Inelastic Scattering*, Oxford University Press 2004.
- G. P. Salam, *Elements of QCD for hadron colliders*, CERN Yellow Report CERN-2010-002, 45-100, arXiv:1011.5131 [hep-ph].
- J. L. Abelleira Fernandez et al., *A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector*, J. Phys. G39 (2012) 075001, arXiv:1206.2913 [physics.acc-ph].
- A. Accardi et al., *Electron Ion Collider: The Next QCD Frontier : Understanding the glue that binds us all*, Eur. Phys. J. A52 (2016) no.9, 268, arXiv:1212.1701 [nucl-ex].

Diffraction:

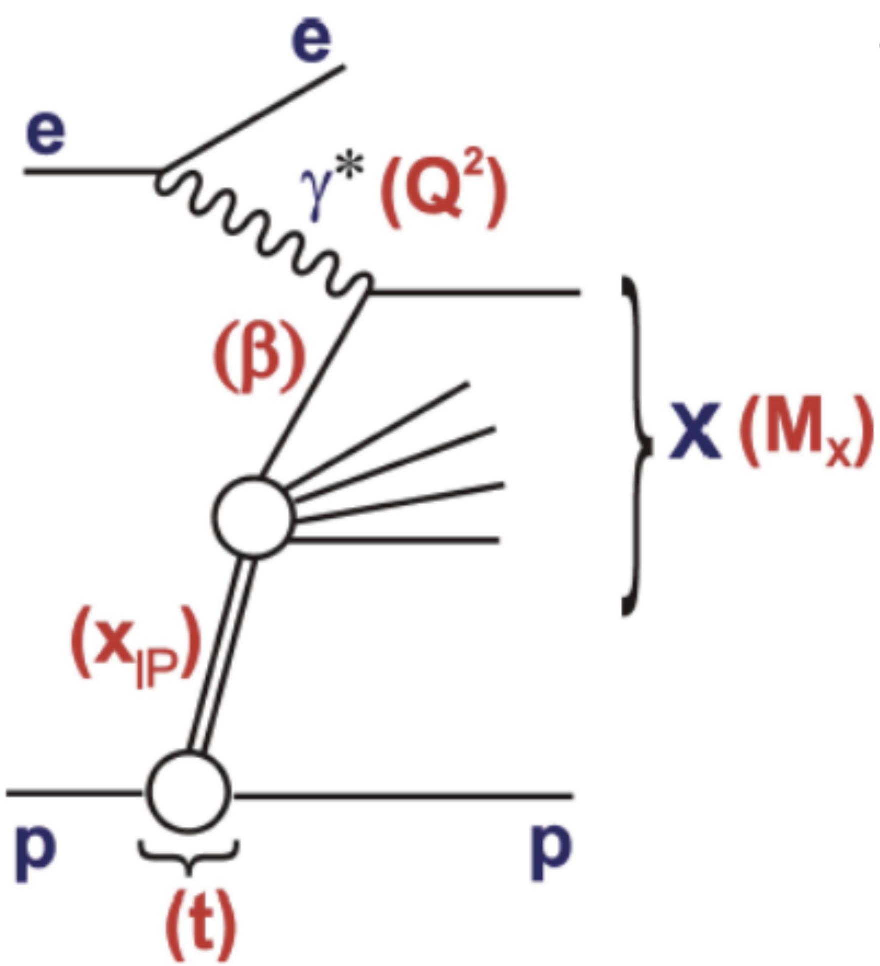
- At HERA, ~10 % of the events have a pseudorapidity gap in hadronic activity (or intact detected proton): **diffractive**.

- They measure the probability of the proton to remain intact in the scattering, while producing some activity far from the proton: exchange of a colourless object, called *Pomeron*.



Diffractive event in ZEUS at HERA

Diffraction:



$$x_{Bj} = x_{IP}\beta$$

Standard DIS variables:

electron-proton
cms energy squared:

$$s = (k+p)^2$$

photon-proton
cms energy squared:

$$W^2 = (q+p)^2$$

inelasticity

$$y = \frac{p \cdot q}{p \cdot k}$$

Bjorken x

$$x = \frac{-q^2}{2p \cdot q}$$

(minus) photon virtuality

$$Q^2 = -q^2$$

Diffractive DIS variables:

$$\xi \equiv x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$

momentum fraction of
the Pomeron w.r.t hadron

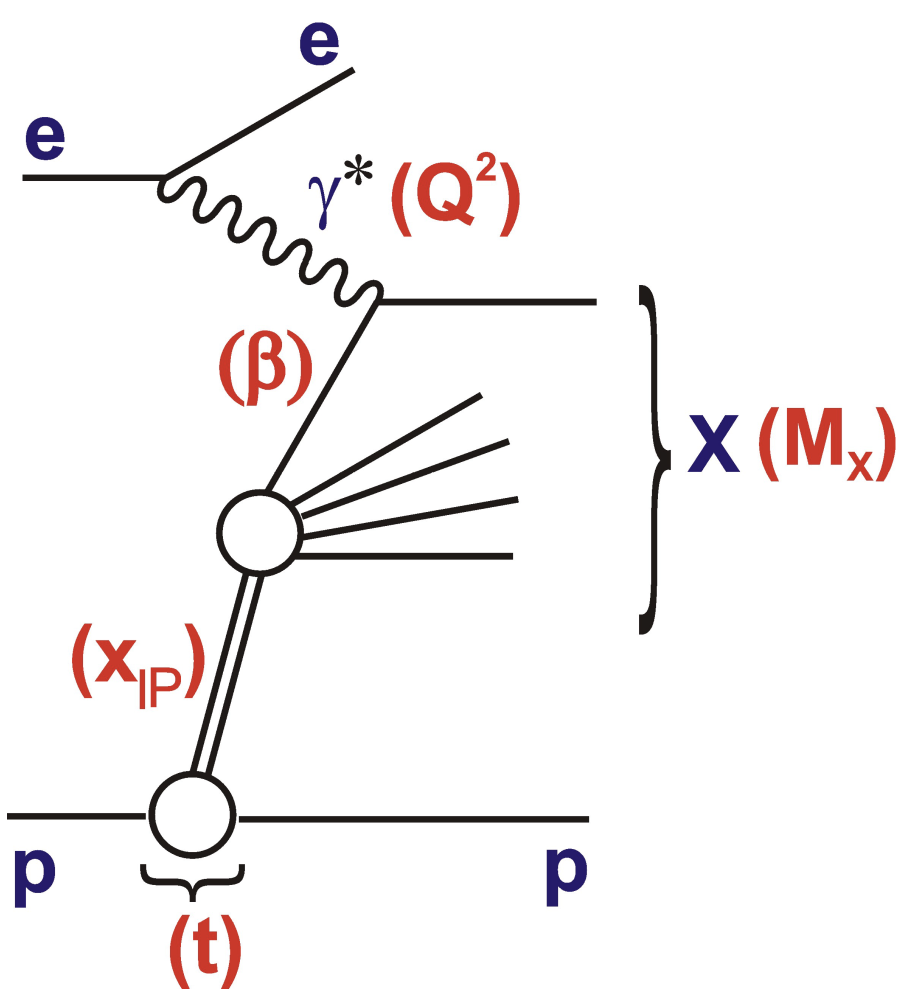
$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

momentum fraction of
parton w.r.t Pomeron

$$t = (p - p')^2$$

4-momentum transfer squared

Diffractive SF and factorisation:



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

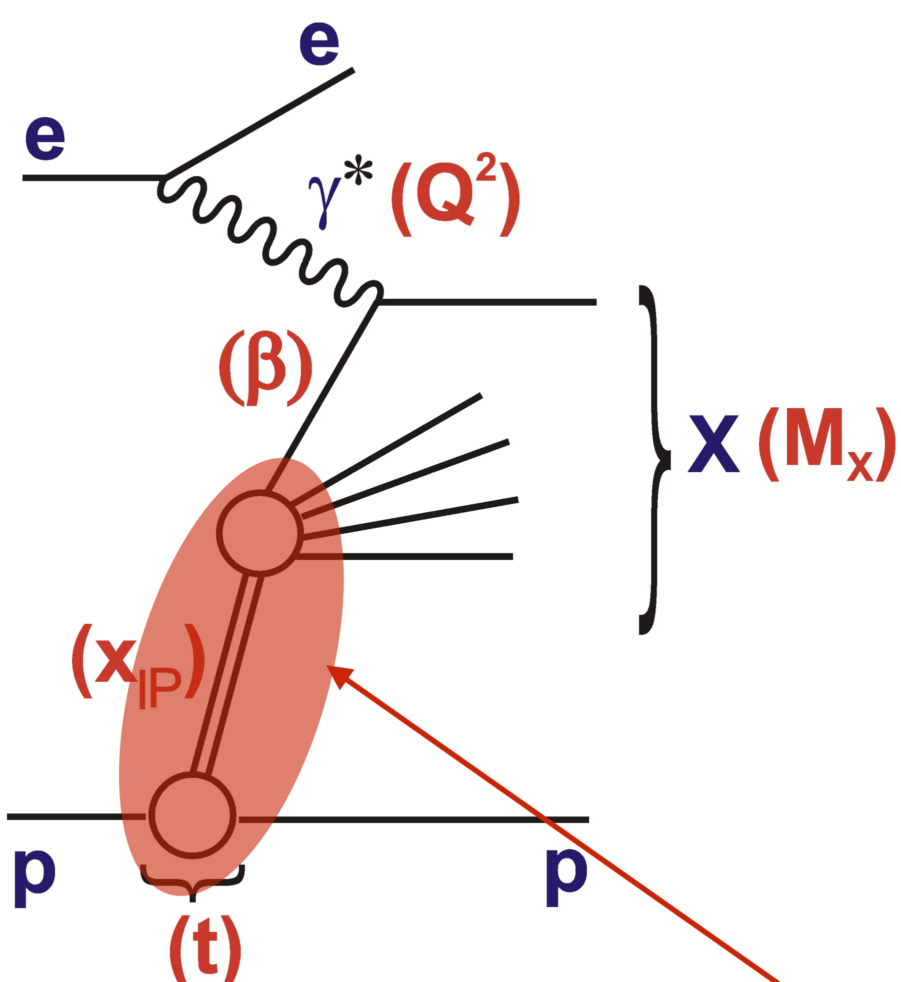
$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{Y_+}F_L^{D(3)}$$

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

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

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

Diffractive SF and factorisation:



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

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

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

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

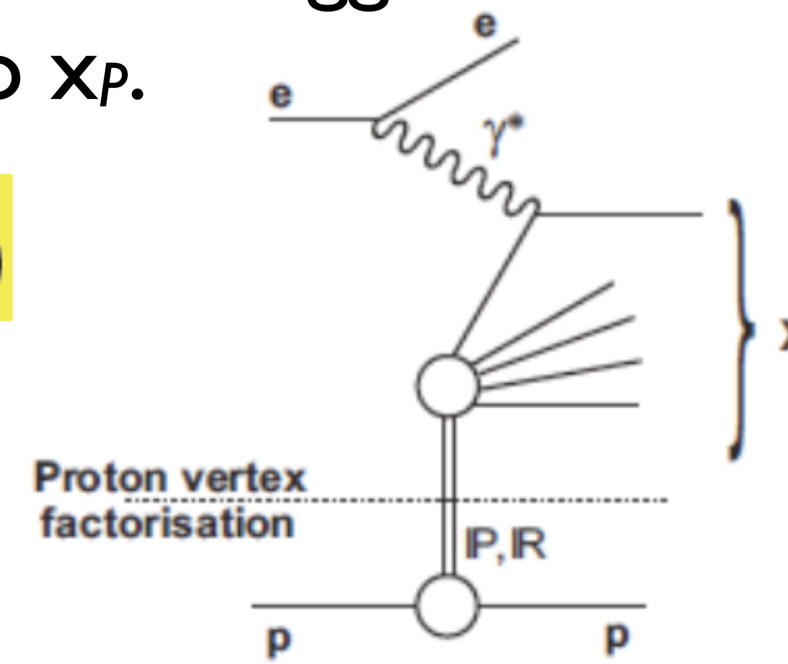
$$F_2^{D(4)} = F_T^{D(4)} + F_L^{D(4)}$$

• 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.

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

Diffractive PDFs:

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

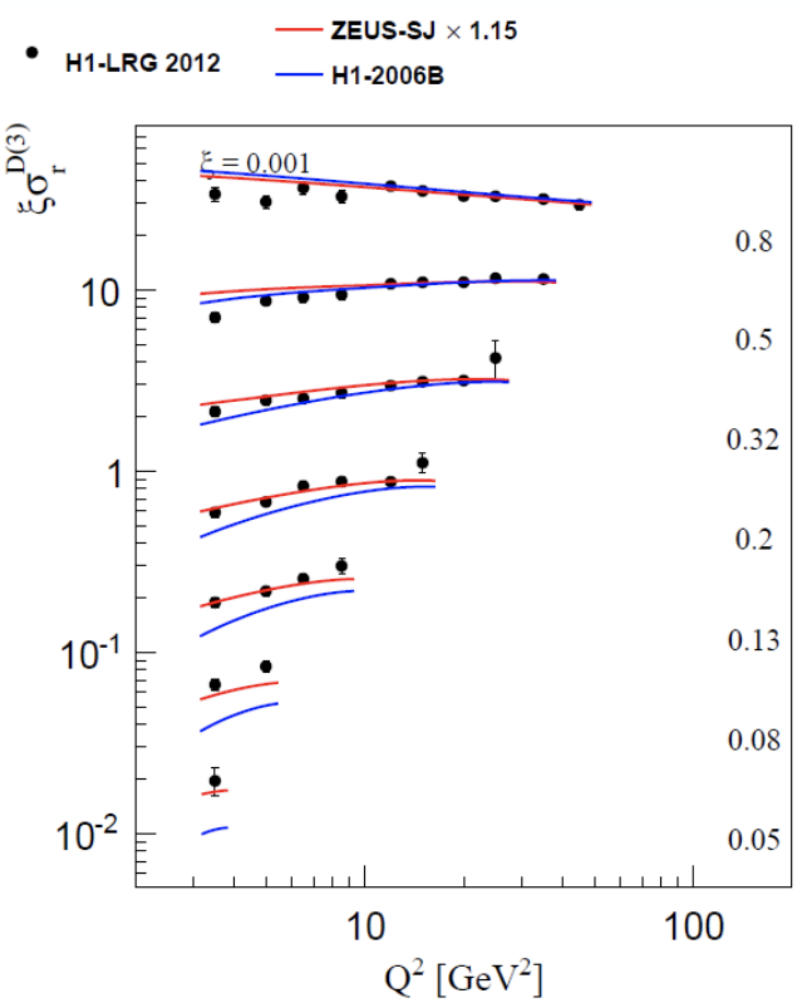


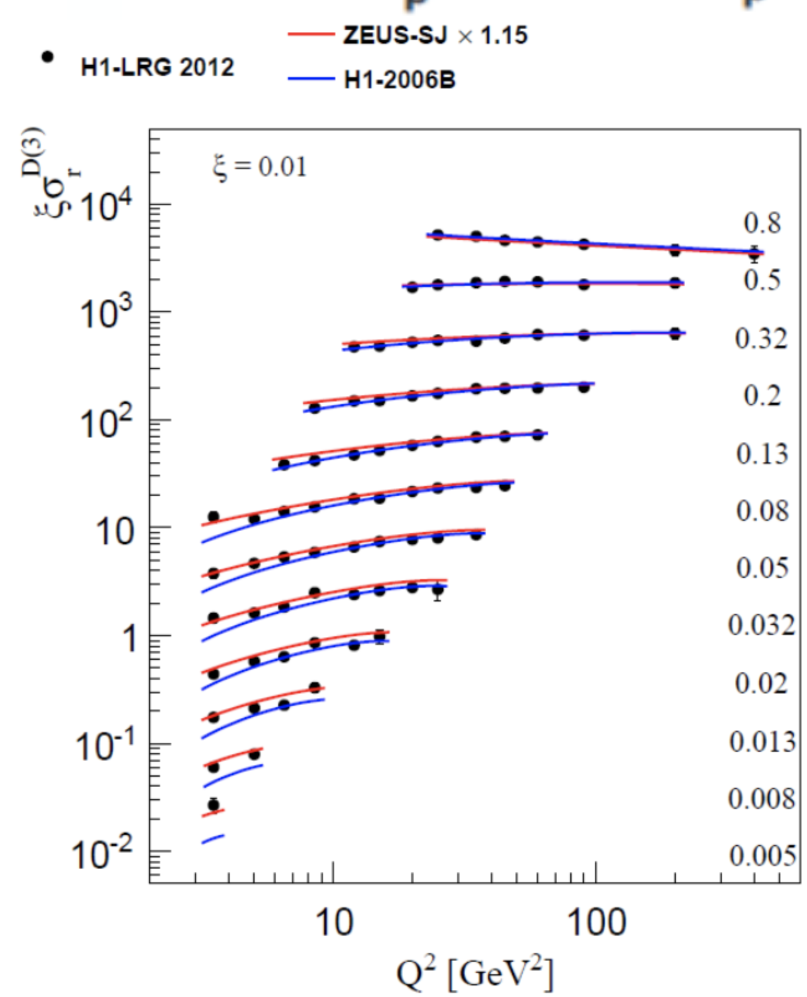
$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t)\, f_i(\beta = x/x_{IP}, Q^2)$$

Pomeron flux

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

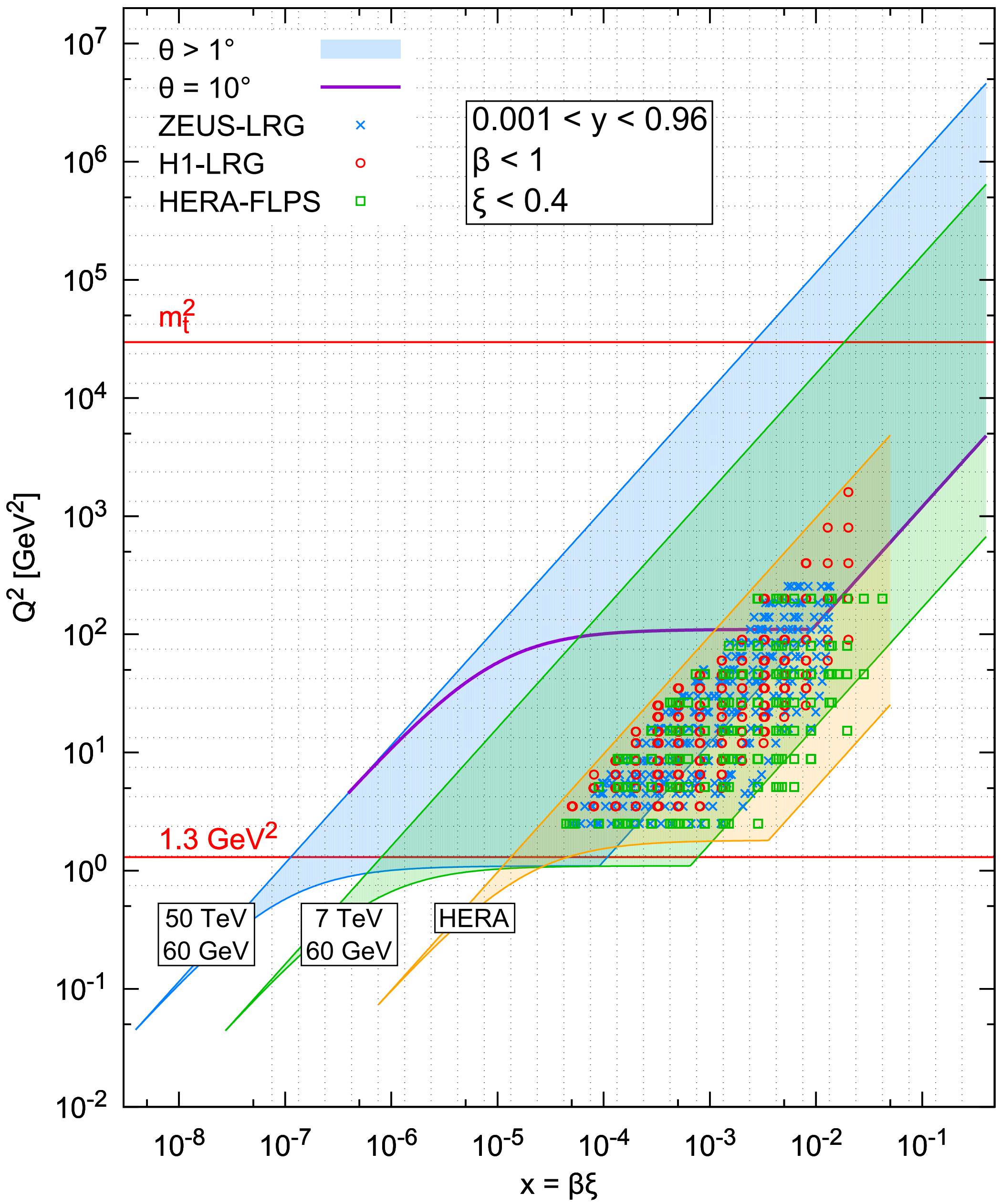
$f_i(\beta, Q^2)$ evolve with DGLAP evolution equations: fits to HERA data (additional contributions at large x_P=ξ and small β).

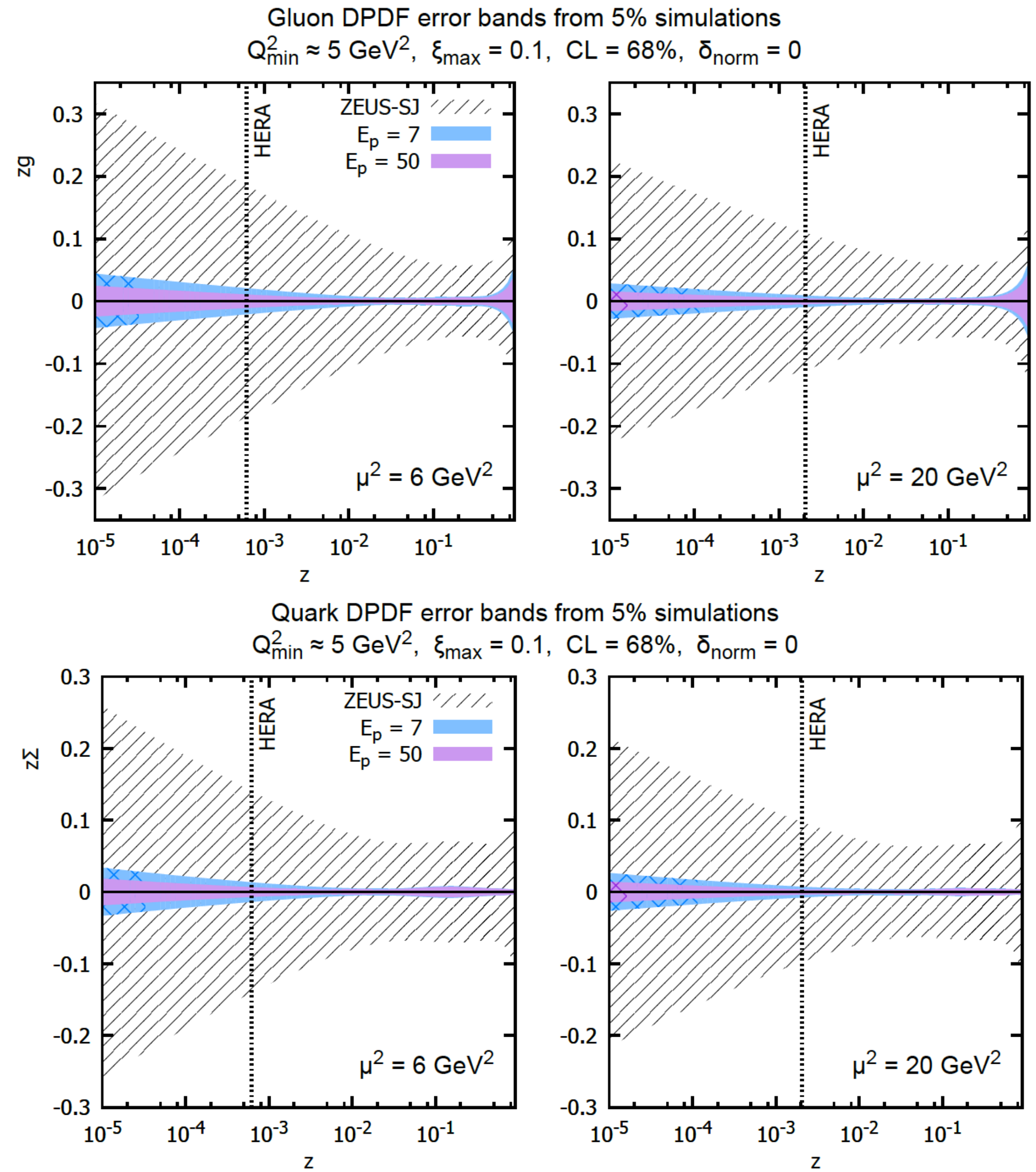




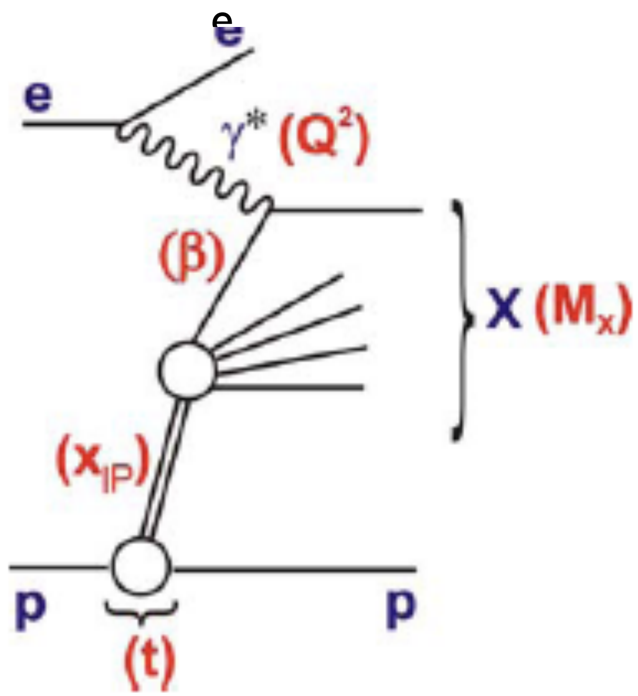
DPDFs at EICs:

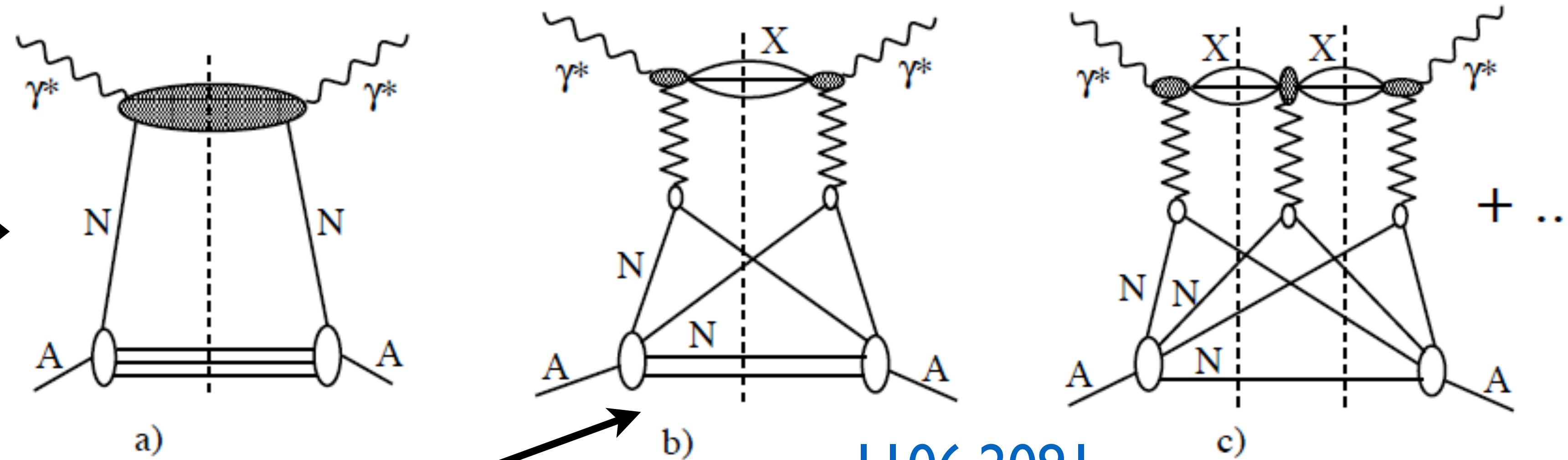
- Limitations at HERA (check of Regge factorisation, size and shape of the diffractive glue) can be overcome with EICs:





Diffraction in ep and shadowing:





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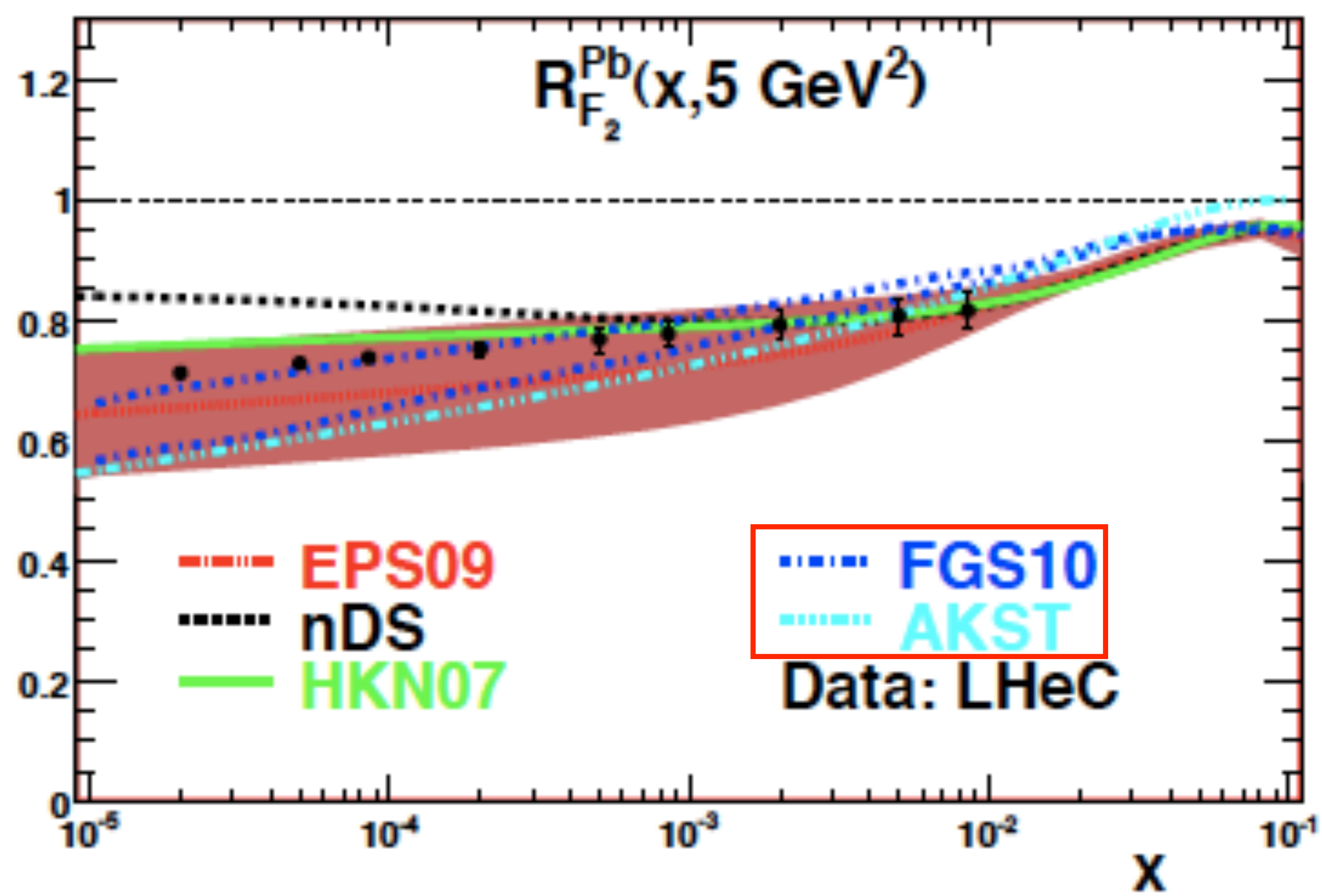
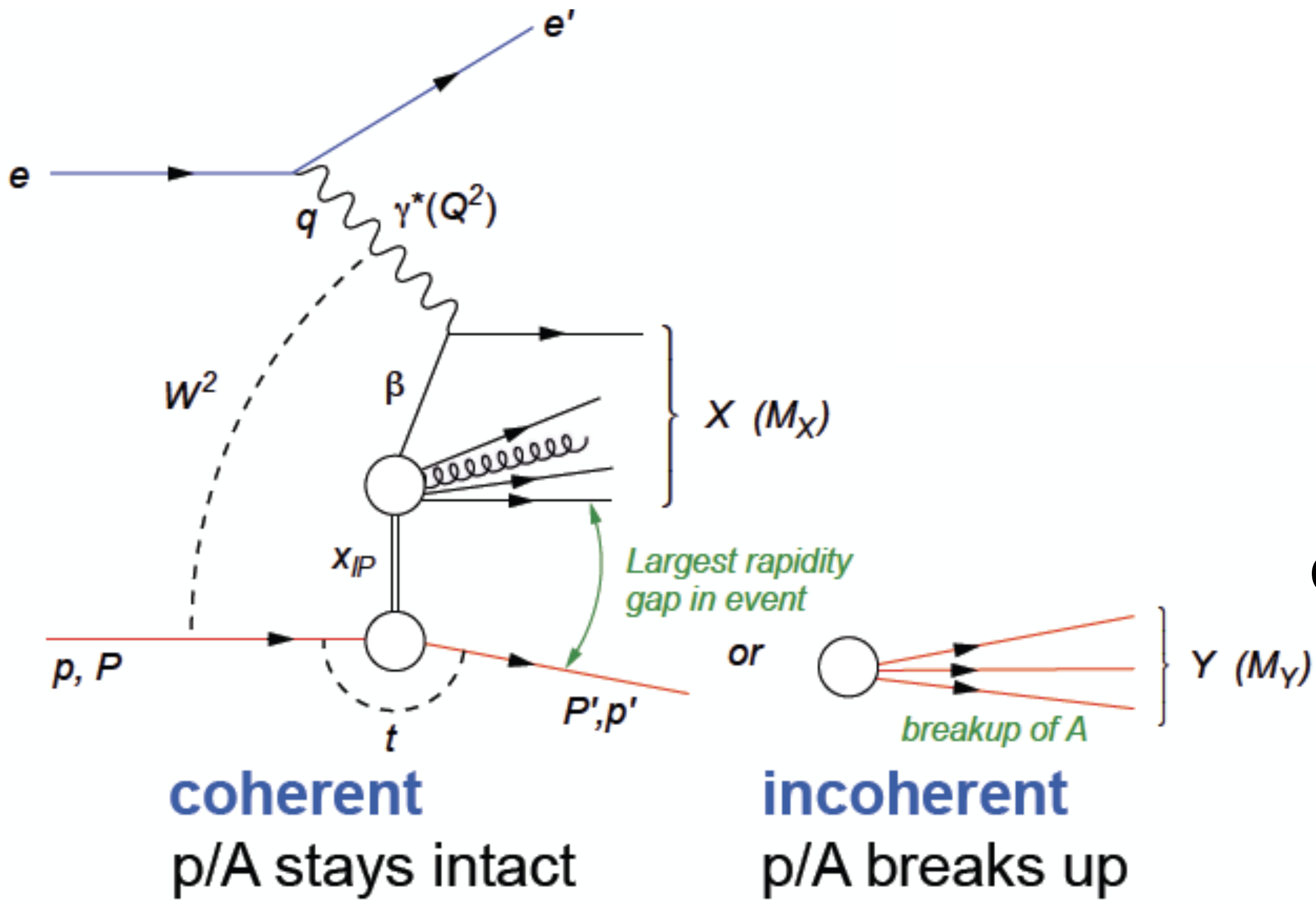


- Diffraction in ep is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the 'benchmark' for new effects.

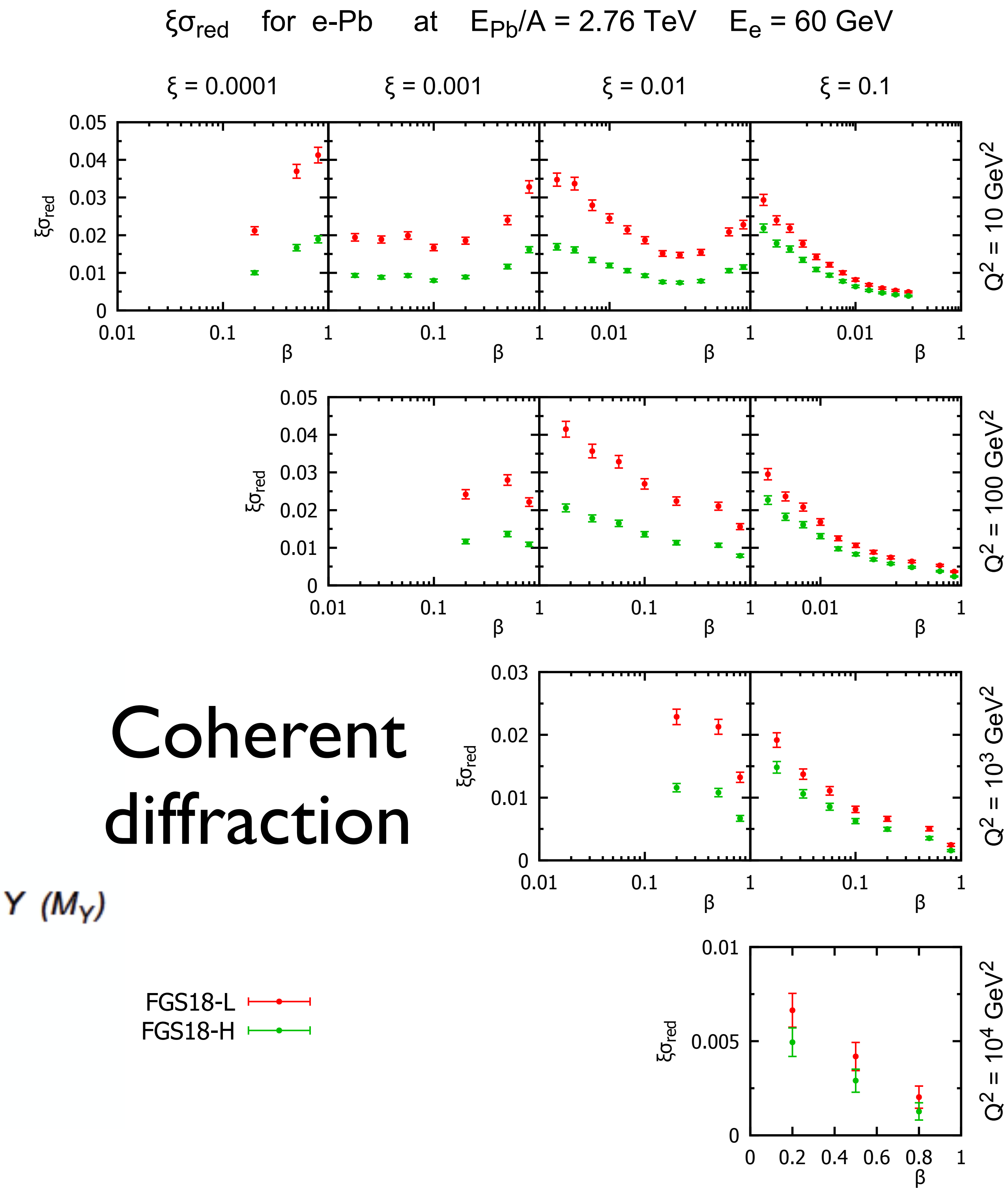
nDPDFs at EICs:

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

- Challenging experimental problem (LPS + ZDC?).

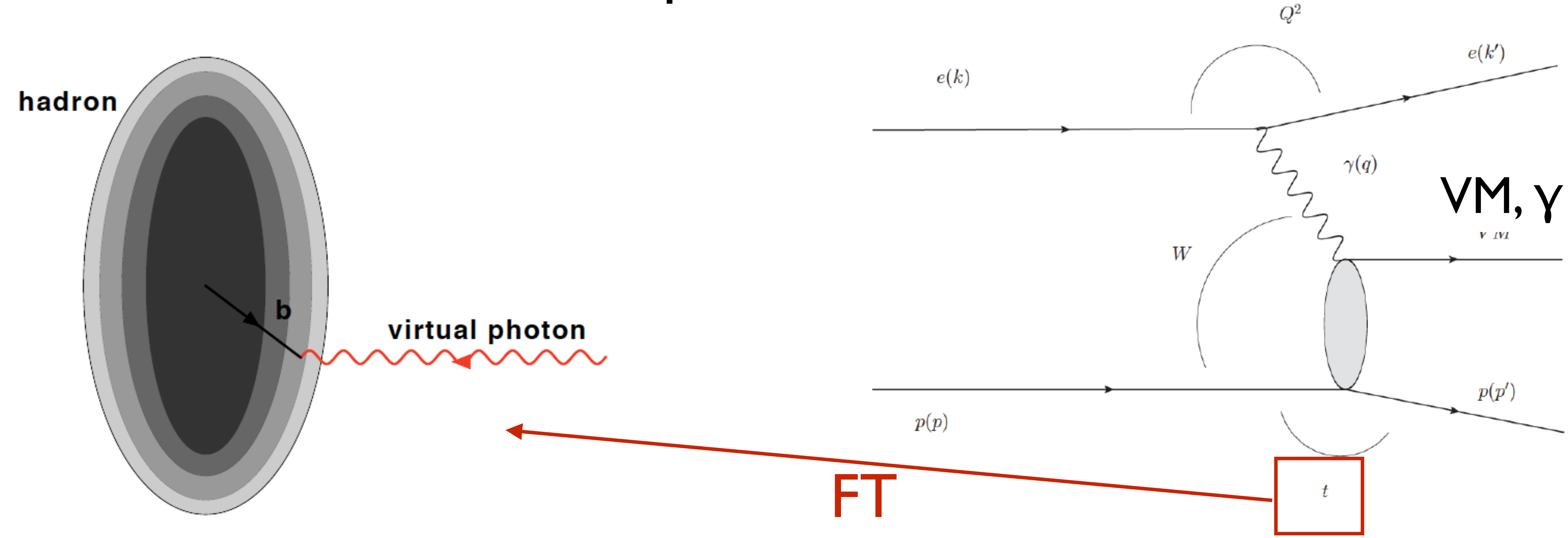


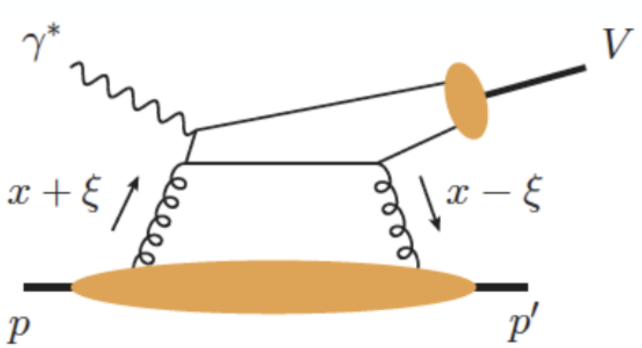
Coherent diffraction



Exclusive production:

- Exclusive production gives a 3D scan of the hadron/nucleus: gluon GPDs with vector mesons, quark GPDs with DVCS. It can be studied for Q=0 in UPCs, precision and O>0 in EICs.





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

Off-diagonal matrix elements, appear in amplitudes.

Exclusive production:

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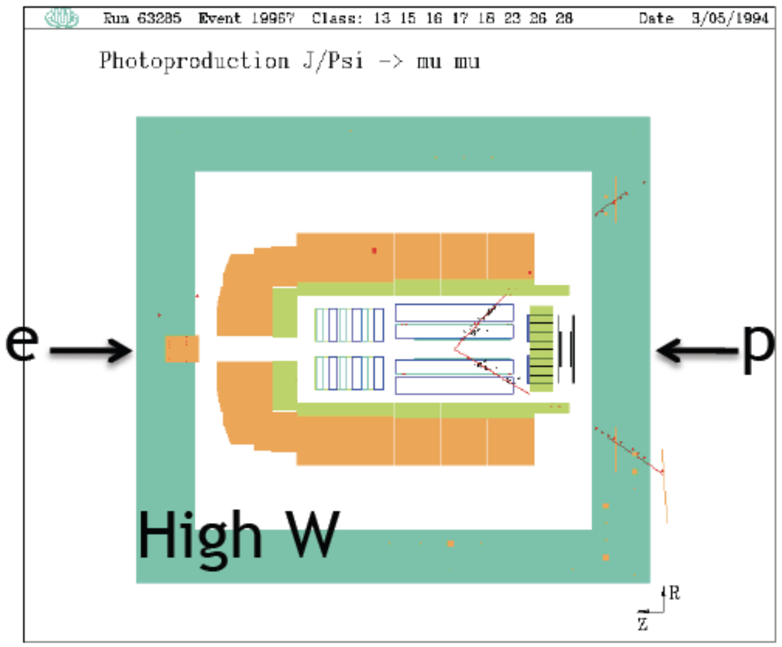
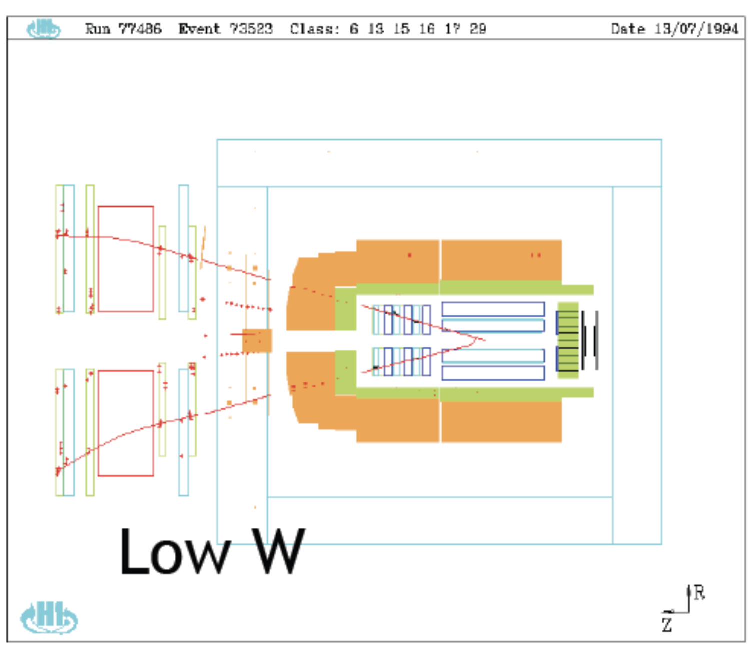
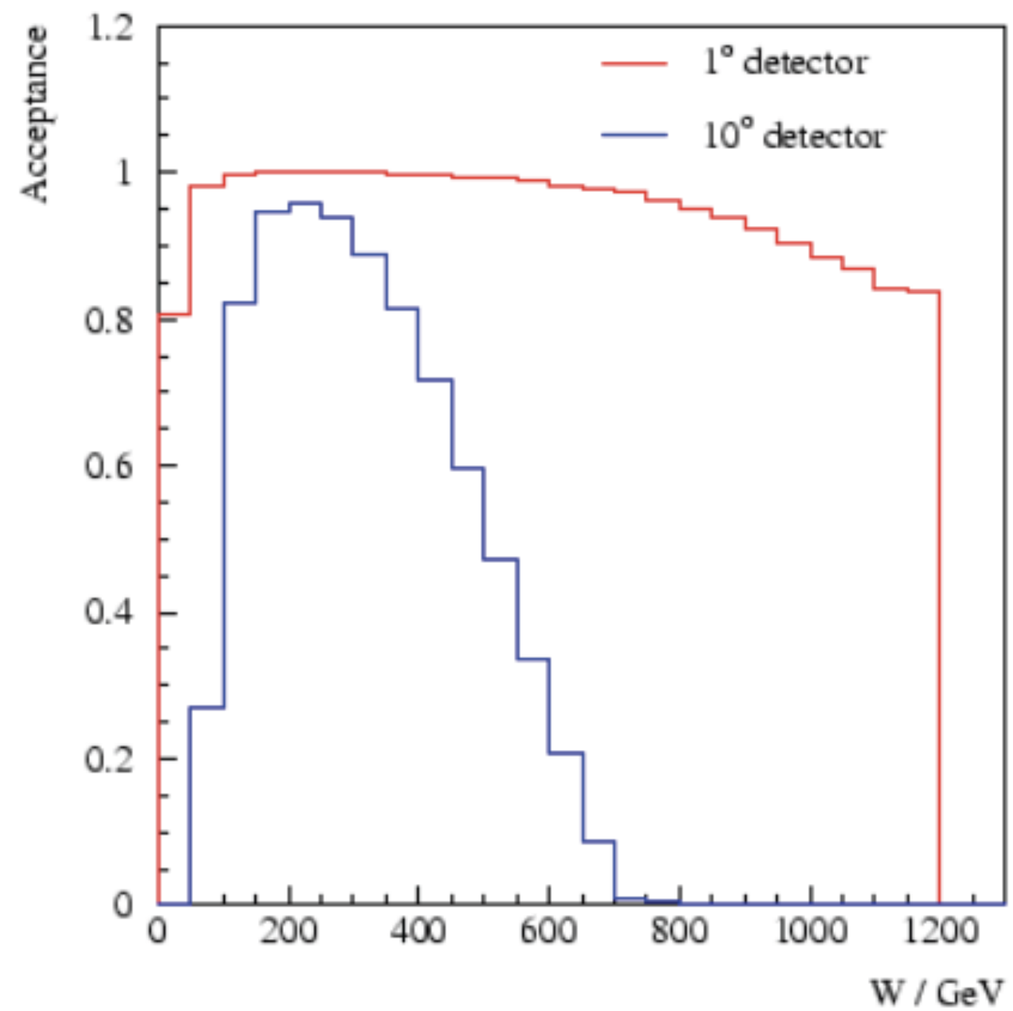
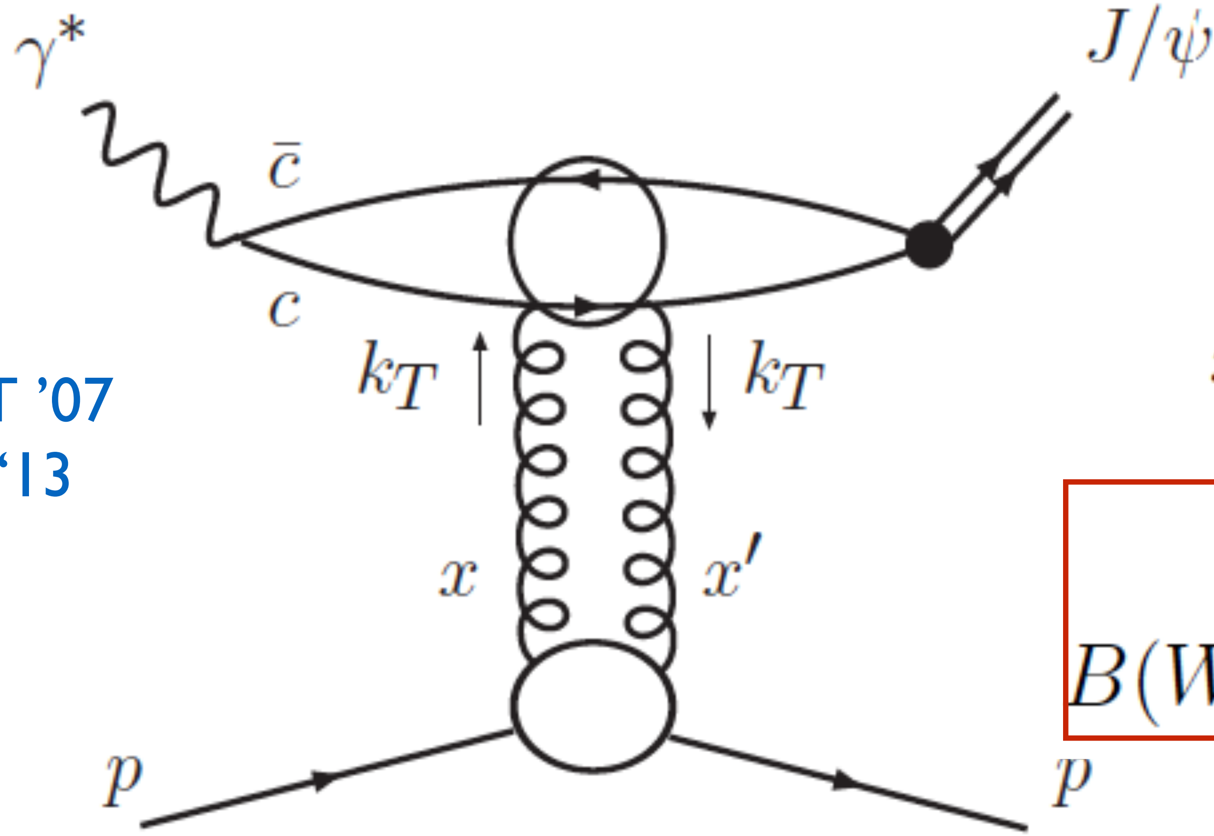






High acceptance essential!!!

pQCD for ep→eJ/ψp:



MNRT '07
JMRT '13

$$\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4$$

$$x = (Q^2 + M_{J/\psi}^2)/(W^2 + Q^2)$$

$$\sigma \sim \exp(-Bt)$$

$$B(W) = (4.9 + 4\alpha' \ln(W/W_0)) \ \mathrm{GeV}^{-2}$$

by hand (Regge)

LO

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right)$$

NR WF

- It should not be the gluon PDF but the GPD:

$$R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + \frac{5}{2})}{\Gamma(\lambda + 4)}$$

$$\lambda(Q^2) = \partial\left[\ln(xg)\right]/\partial \ln(1/x)$$

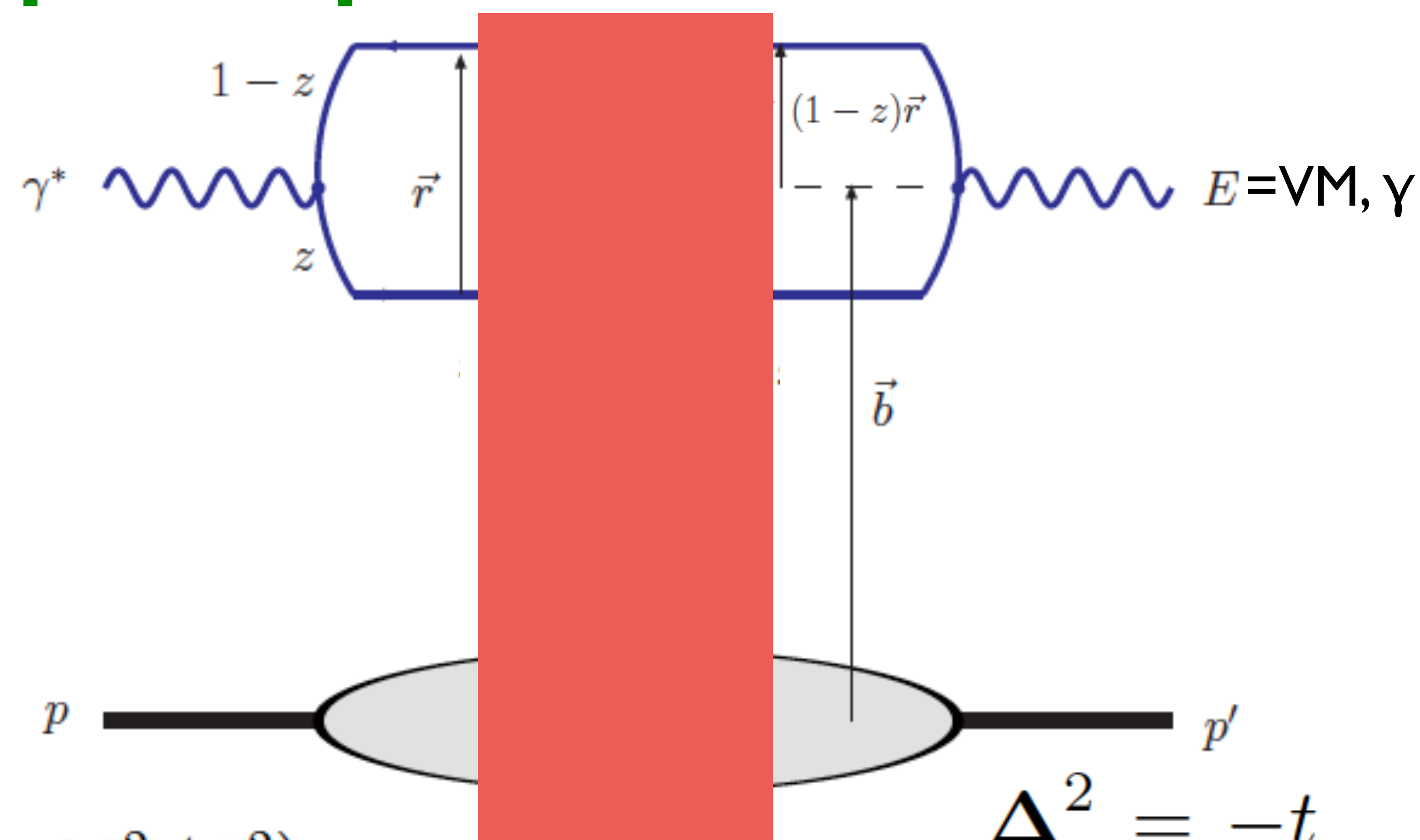
- NLO estimated, not complete.
- Real part via dispersion relations:

$$\frac{\mathrm{Re}A}{\mathrm{Im}A} \simeq \frac{\pi}{2}\lambda$$

The dipole picture:

- Long-lived (virtual) photon fluctuation, $x<(2m_N R)^{-1}$.

- Unified description of inclusive, diffractive and exclusive processes.



$$\boldsymbol{\Delta}^2 = -t$$

$$x = x_{Bj}\left(1 + M_V^2/Q^2\right)$$

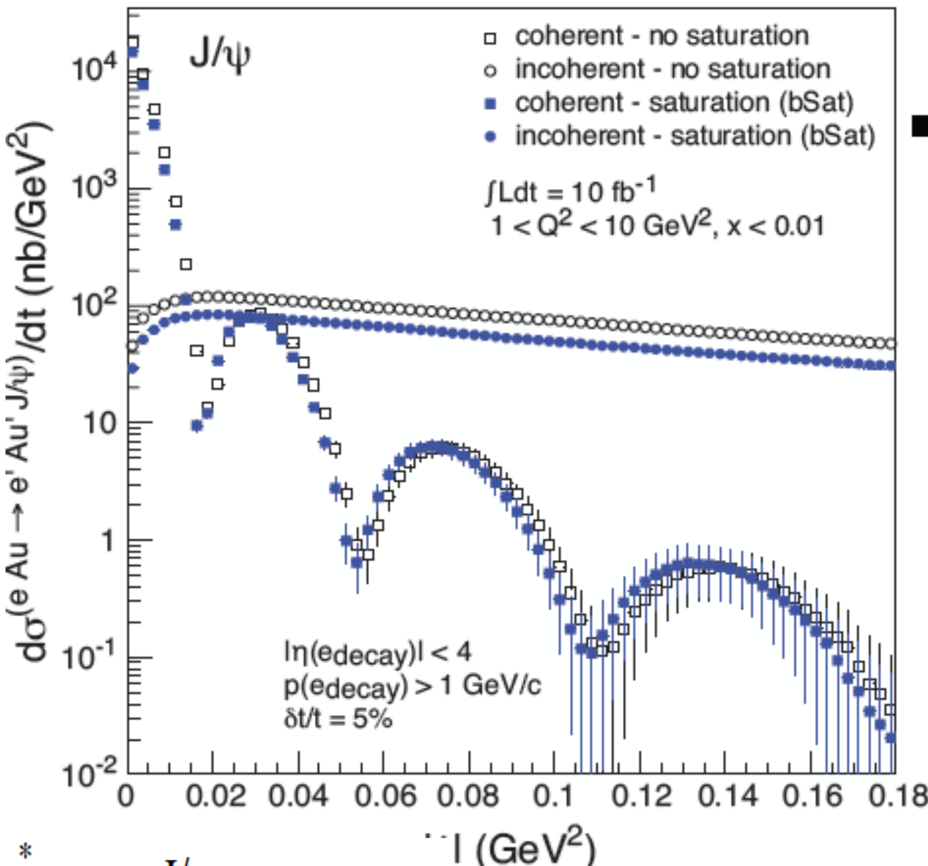
$$\frac{d\sigma_{T,L}^{\gamma^* p\to Ep}}{dt} = \frac{1}{16\pi}\left|\mathcal{A}_{T,L}^{\gamma^* p\to Ep}\right|^2 (1+\beta^2)R_g^2 \qquad \beta = \tan\left(\frac{\pi\lambda}{2}\right), \quad \lambda \equiv \frac{\partial \ln\left(\mathcal{A}_{T,L}^{\gamma^* p\to Ep}\right)}{\partial \ln(1/x)}$$

$$\mathcal{A}_{T,L}^{\gamma^* p\to Ep} = 2i\int d^2\boldsymbol{r}\int_0^1 dz \int d^2\boldsymbol{b}\,(\Psi_E^*\Psi)_{T,L}\, e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\mathcal{N}(x,r,b)$$

- Correction to non-diagonal gluon PDF (skewedness) introduced.
- Boosted Gaussian VM WF fitted to leptonic decays.
- qqbarg component in diffraction, not yet in exclusive VM.

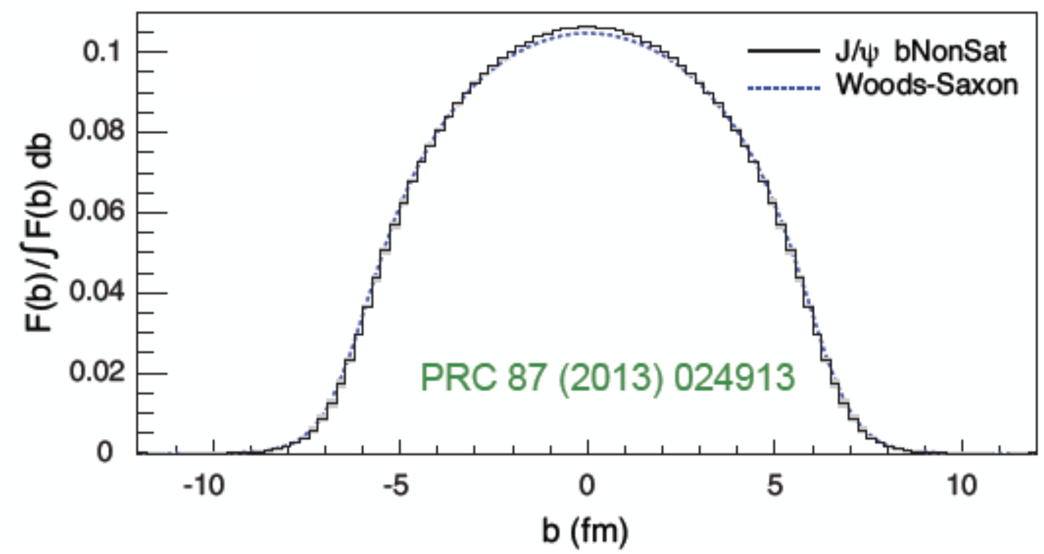
Elastic vector mesons (I):

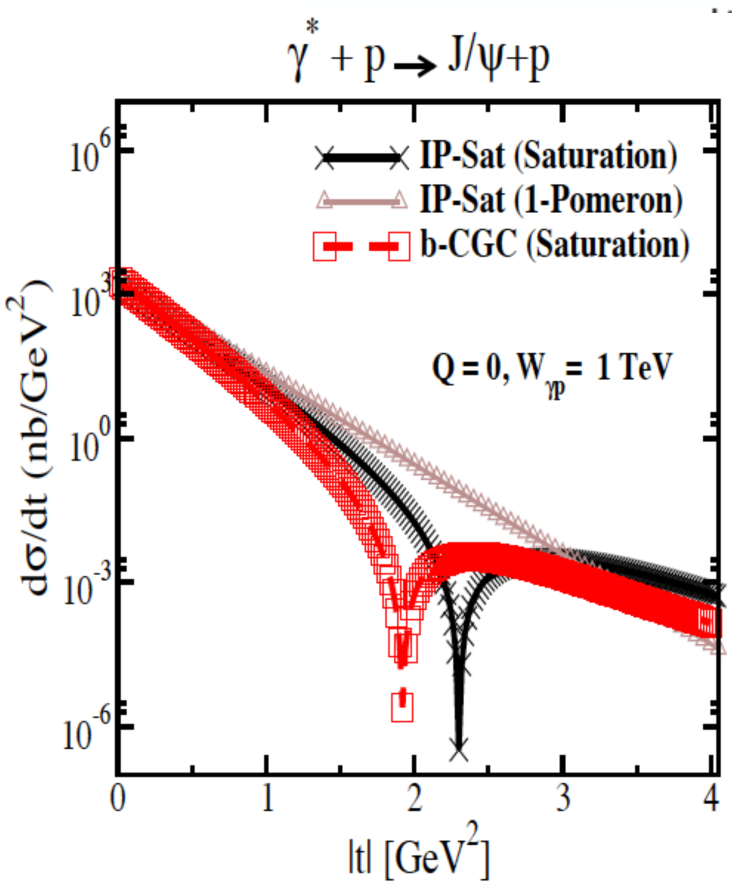
$$e + Au \to e + J/\psi + Au^{(*)}$$

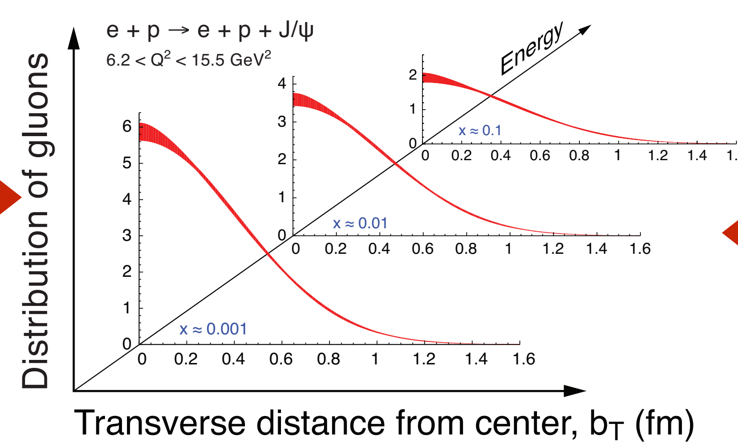


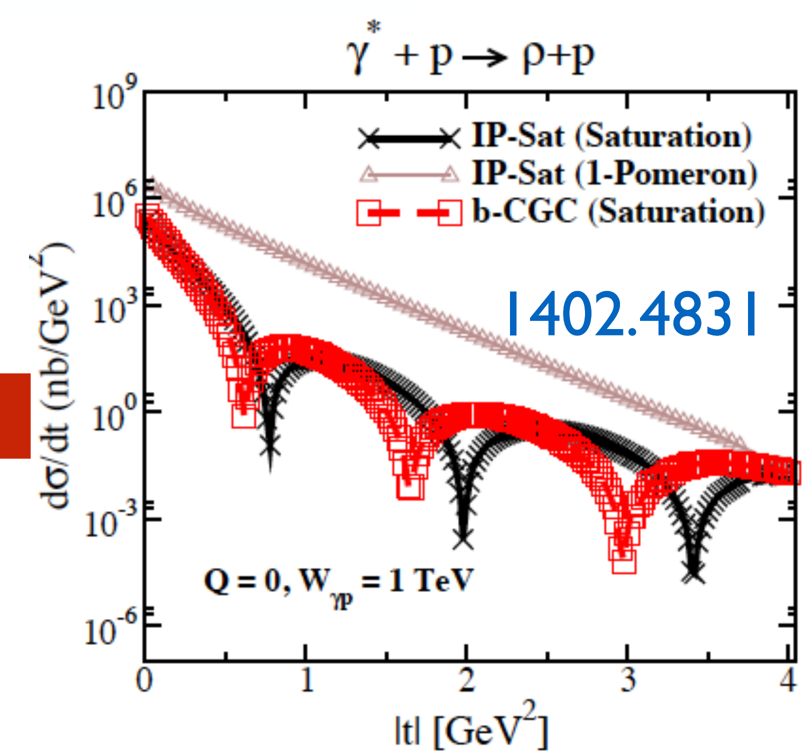
$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

$t = \Delta^2/(1-x) \approx \Delta^2$







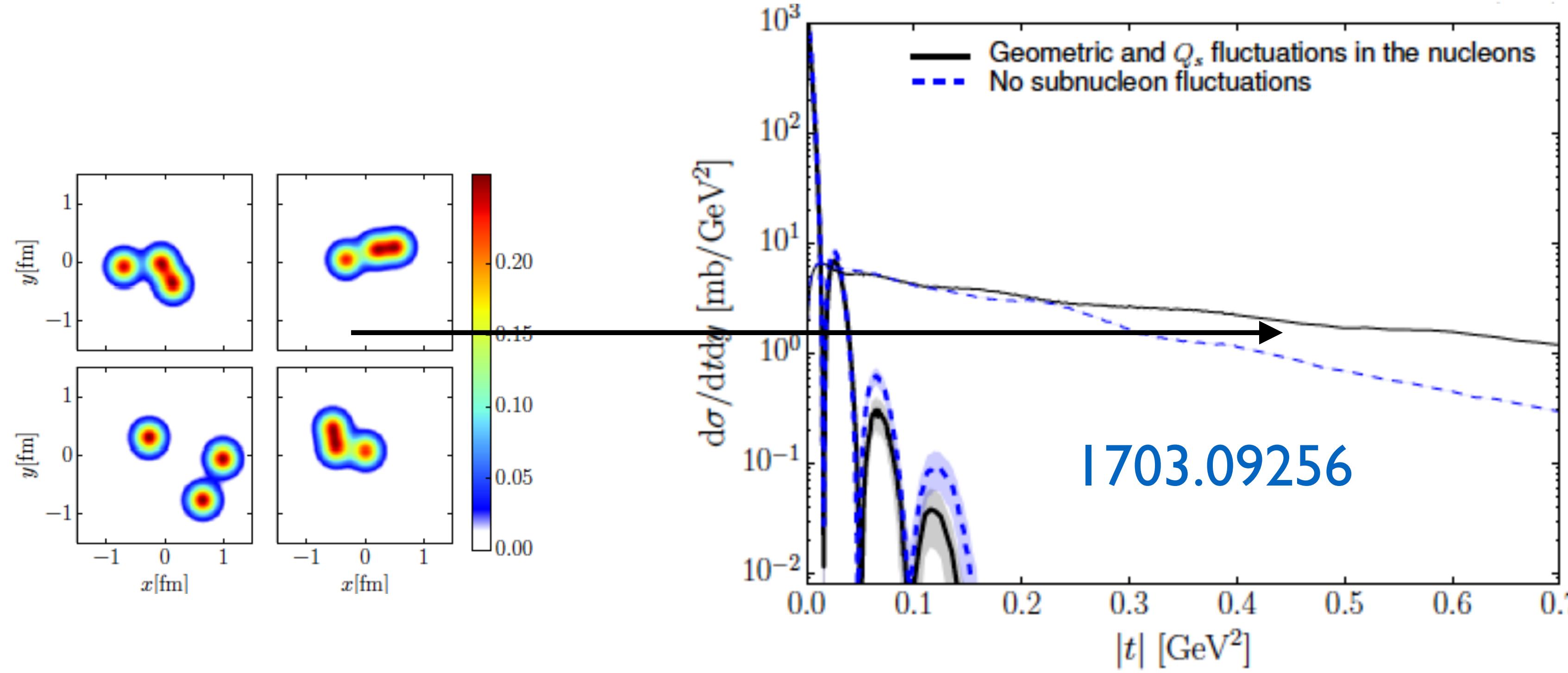


Elastic vector mesons (II):

- Incoherent diffraction sensitive to fluctuations: hot spots? that determine the initial stage of HIC, the distribution of MPIs, ...

$$\left.\frac{d\sigma(\gamma p \to \mathrm{J}/\psi p)}{dt}\right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi}\left|\left\langle A(x,Q^2,\vec{\Delta})_{T,L}\right\rangle\right|^2$$

$$\left.\frac{d\sigma(\gamma p \to \mathrm{J}/\psi Y)}{dt}\right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})_{T,L}\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})_{T,L}\right\rangle\right|^2\right)$$



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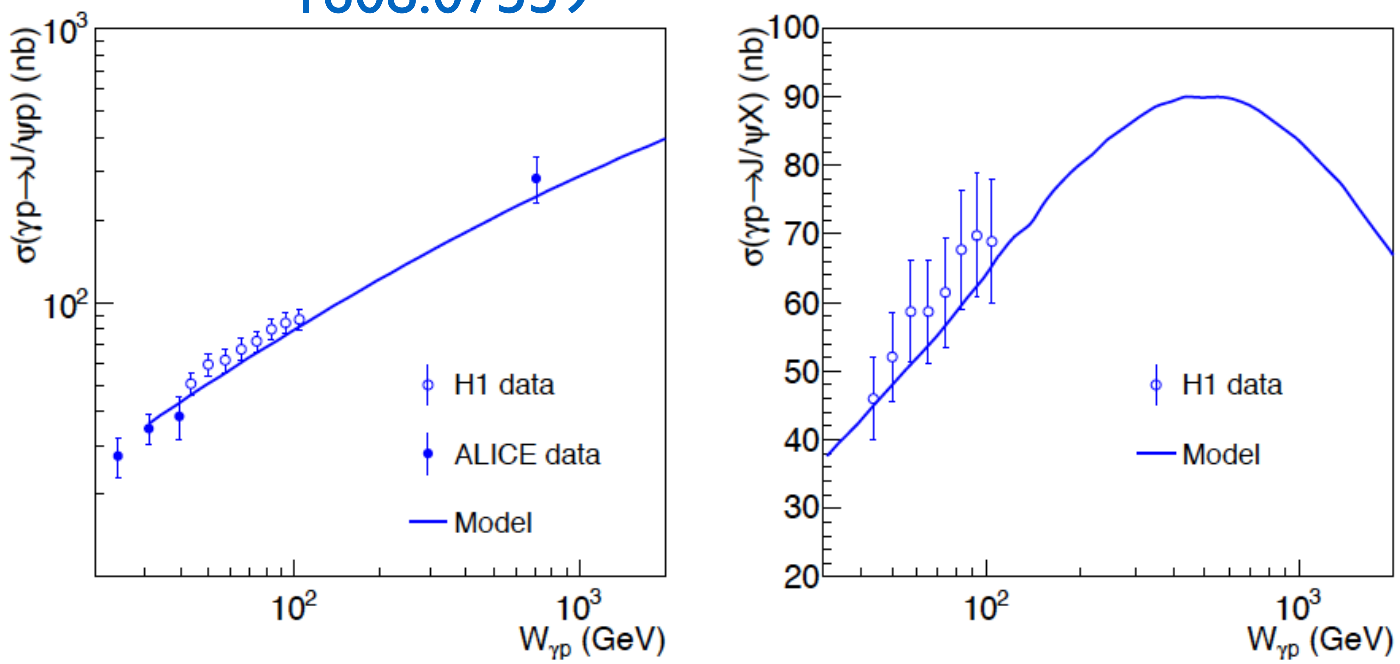


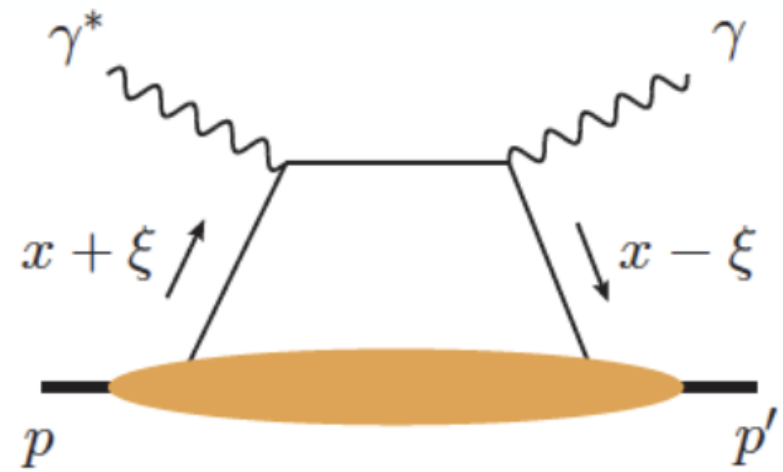
$$T(\vec{b}) = \frac{1}{N_{hs}}\sum_{i=1}^{N_{hs}} T_{hs}(\vec{b}-\vec{b_i})$$

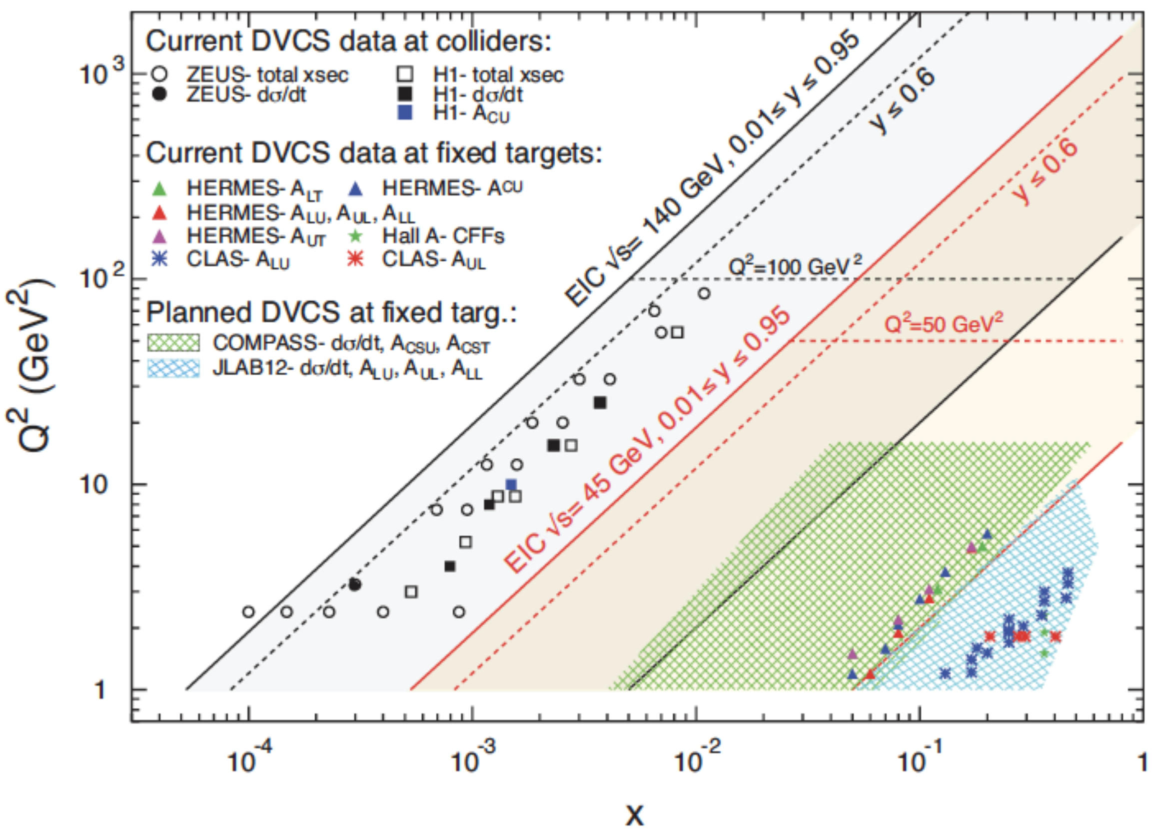
$$T_{hs}(\vec{b}-\vec{b_i}) = \frac{1}{2\pi B_{hs}} e^{-\frac{(\vec{b}-\vec{b_i})^2}{2B_{hs}}}$$

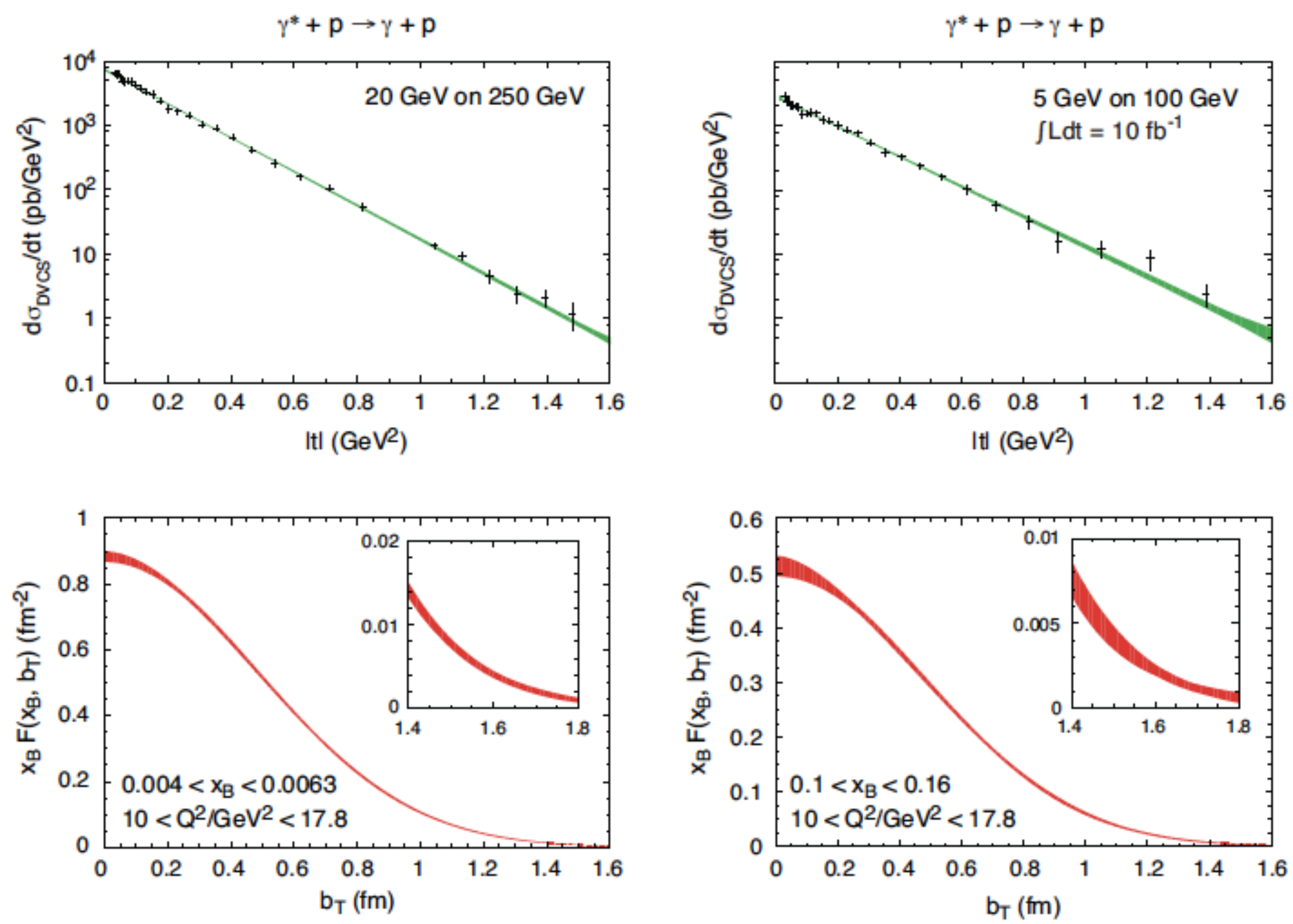
$$N_{hs}(x) = p_0 x^{p_1}(1+p_2\sqrt{x})$$

DVCS:

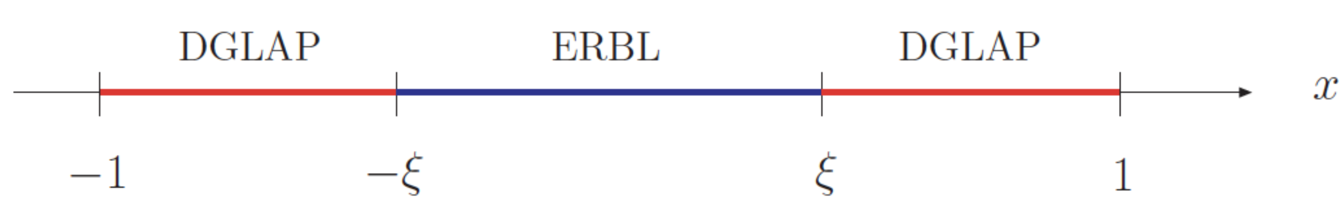
- Quark GPDs can be studied in DVCS.







- The evolution equations for TMDs and GPDs could be tested at the EICs.

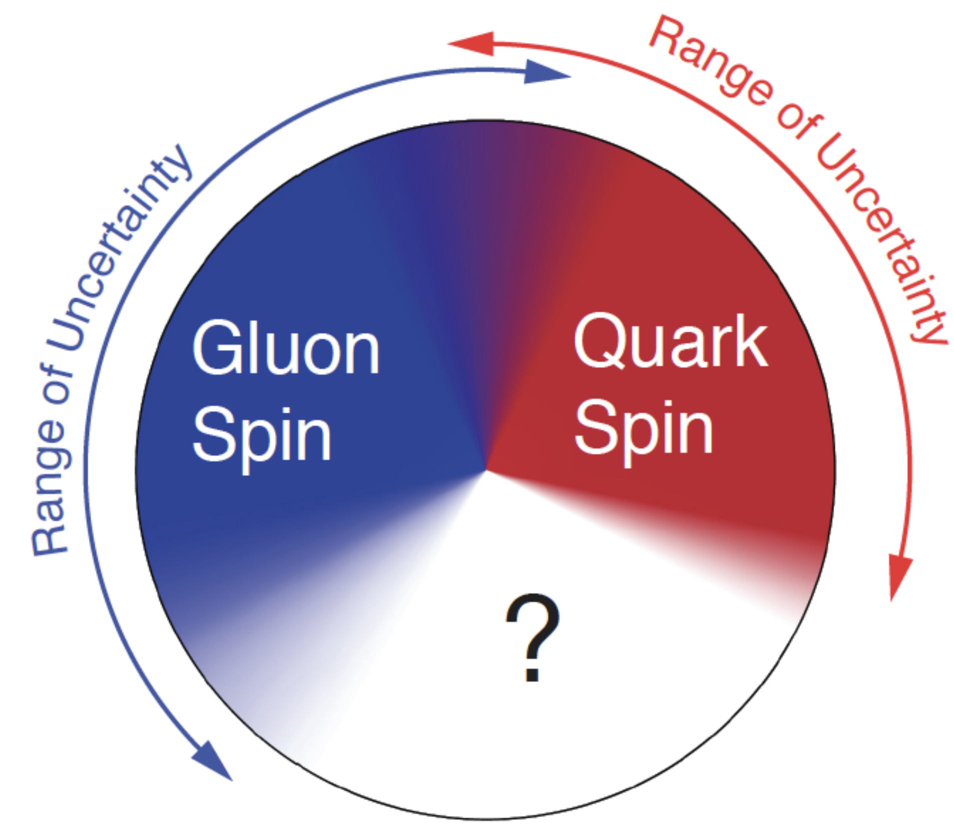


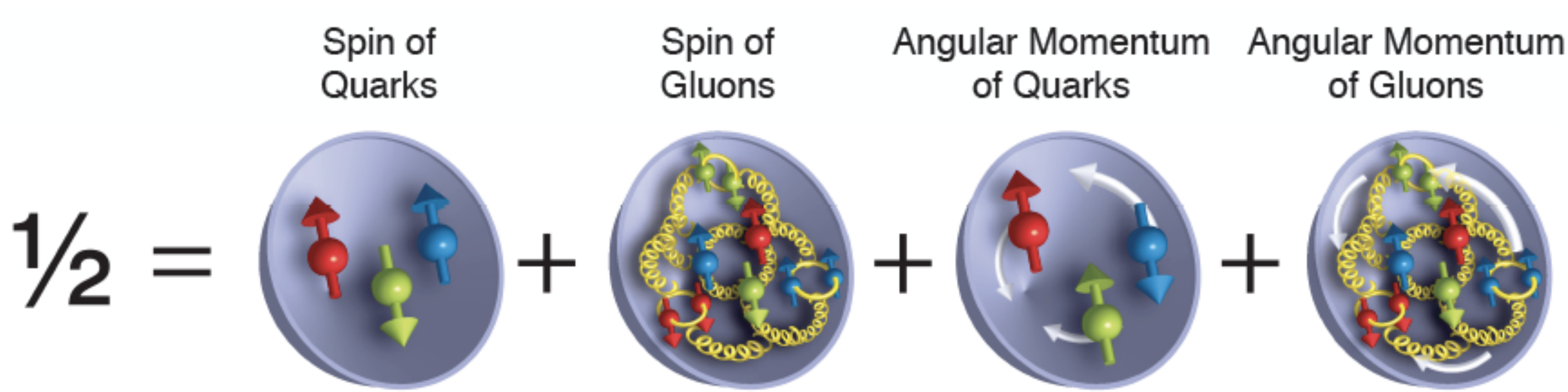
Contents:

Bibliography:
- R. Devenish and A. Cooper-Sarker, *Deep Inelastic Scattering*, Oxford University Press 2004.
- G. P. Salam, *Elements of QCD for hadron colliders*, CERN Yellow Report CERN-2010-002, 45-100, arXiv:1011.5131 [hep-ph].
- J. L. Abelleira Fernandez et al., *A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector*, J. Phys. G39 (2012) 075001, arXiv:1206.2913 [physics.acc-ph].
- A. Accardi et al., *Electron Ion Collider: The Next QCD Frontier : Understanding the glue that binds us all*, Eur. Phys. J. A52 (2016) no.9, 268, arXiv:1212.1701 [nucl-ex].

Spin physics:

- The origin of proton spin has been an open issue for several decades: schematically speaking, quarks account for ~30 %, gluons for ~ 20 % (known in a limited x-range), the rest?





1509.06489,
1206.6014,
1212.1701

Spin physics:

- Inclusive measurements with both e and p polarised (**EIC**): huge improvement at low x.

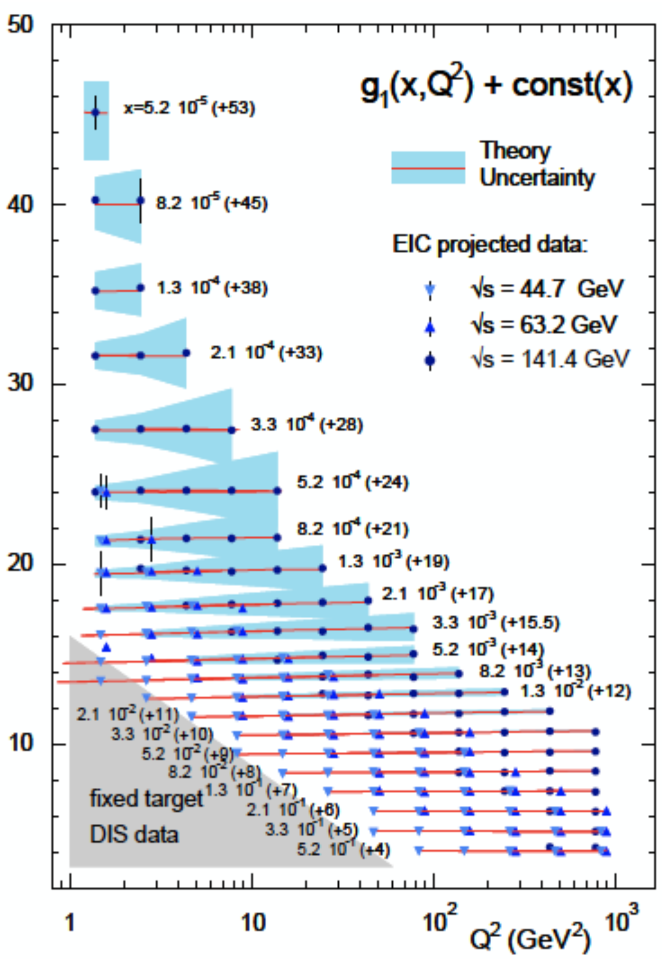
Inclusive Measurement: $\frac{1}{2}\left[\frac{d^2\sigma^{\rightleftarrows}}{dx\,dQ^2}-\frac{d^2\sigma^{\rightrightarrows}}{dx\,dQ^2}\right]\simeq\frac{4\pi\,\alpha^2}{Q^4}y\,(2-y)\,g_1(x,Q^2)$

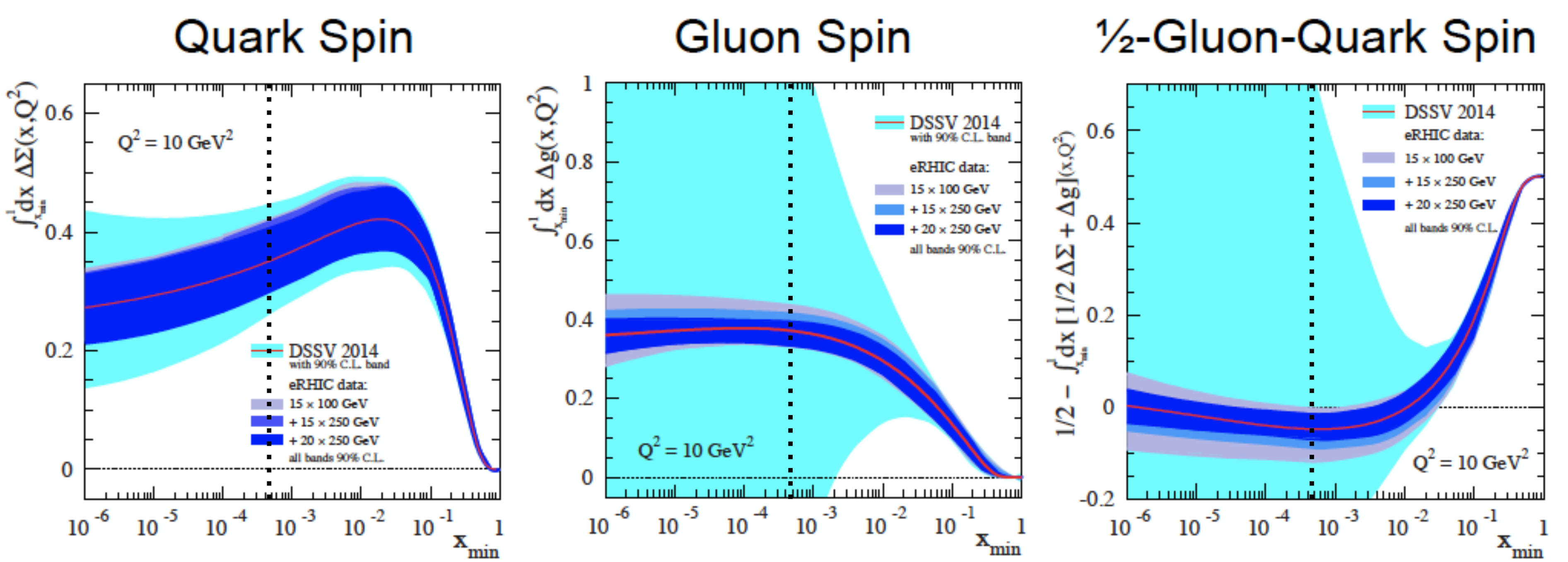
e+p → e′+X

Leading Order: $g_1(x,Q^2)=\frac{1}{2}\sum e_q^2\,[\Delta q(x,Q^2)+\Delta\bar{q}(x,Q^2)]$

$\Delta\Sigma(Q^2)=\int_0^1 dx\;g_1(x,Q^2)$ (Quark Spin)

Higher Order: $\frac{dg_1}{d\log Q^2}\propto\Delta g(x,Q^2)$ (Gluon Spin)





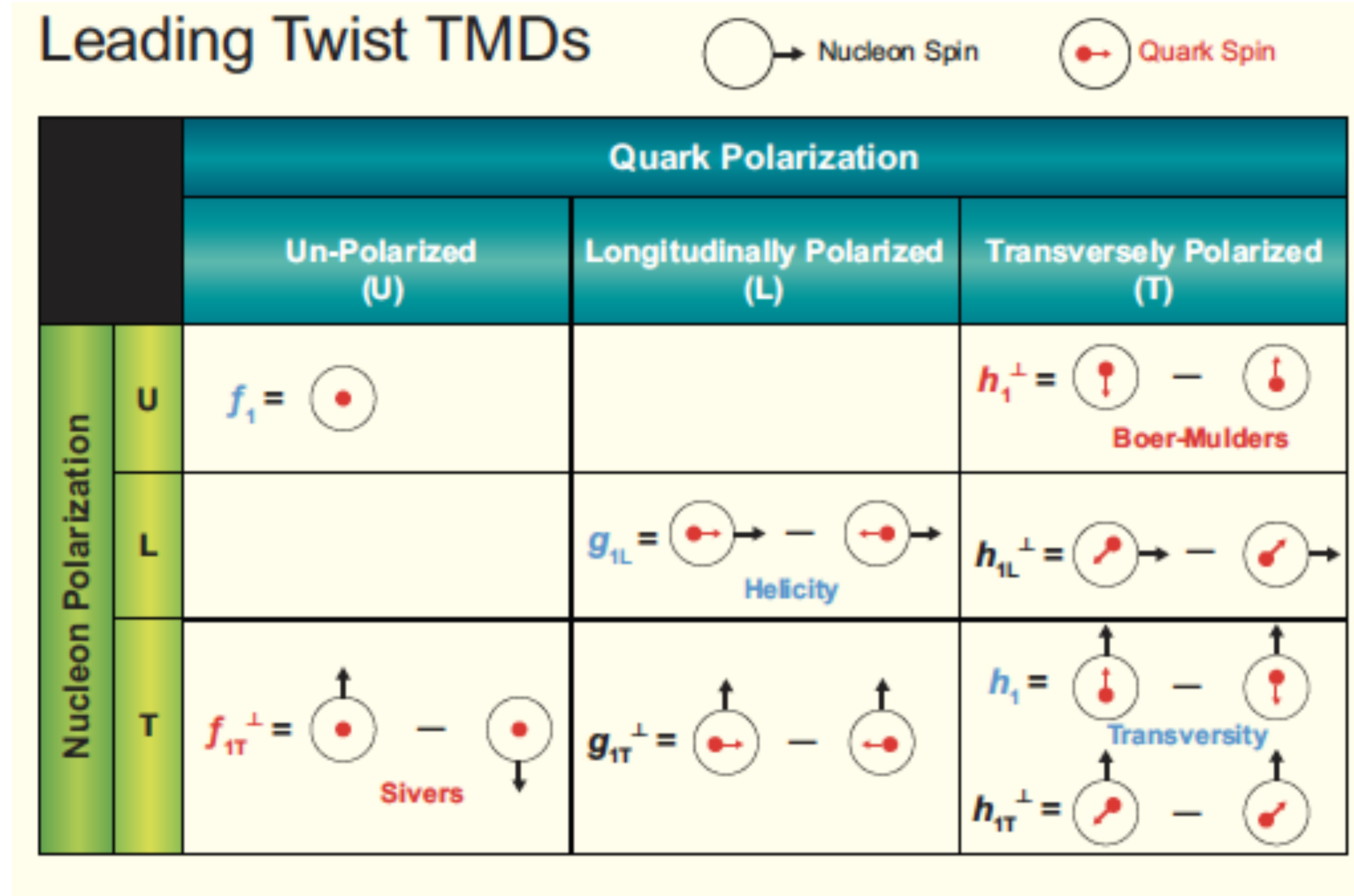
1509.06489, 1206.6014, 1212.1701

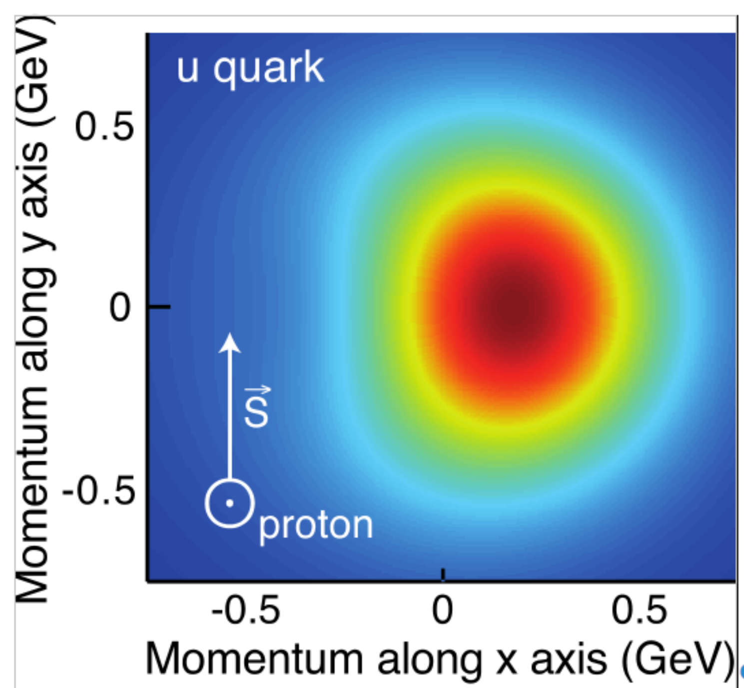
Spin physics:

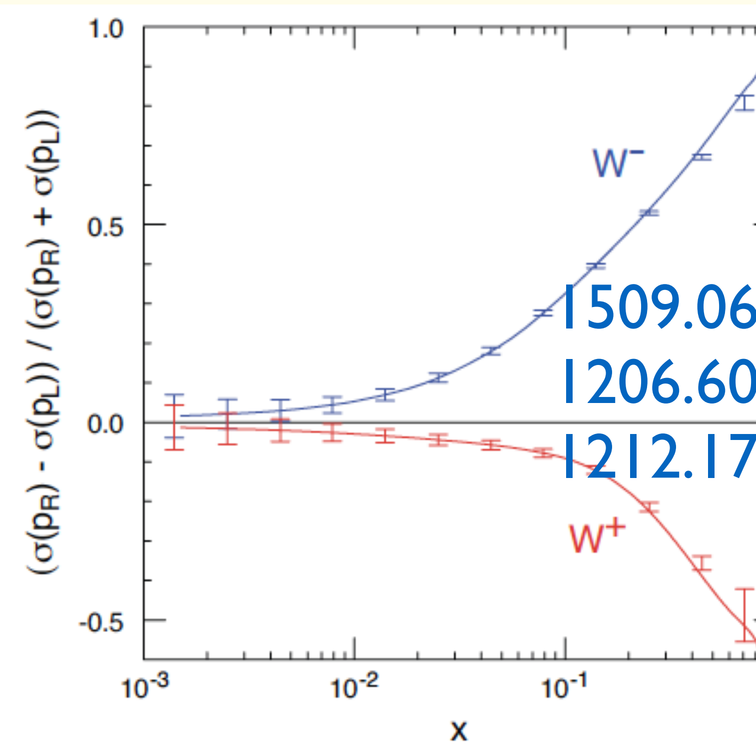
- Several TMDs to be determined by different observables.

- Beyond inclusive DIS, further possibilities are SIDIS (FFs required), CC,…
- Besides, polarised light nuclei, diffraction,…

- TMD factorisation can be tested in non-polarised collisions: dijets, charm,… Relation at small x with CGC.







1509.06489, 1206.6014, 1212.1701

Contents:

1. Basics of DIS.
2. Determination of (n)PDFs.
3. Inclusive and exclusive diffraction.
4. Spin.
5. Small-x physics in DIS.
6. Outlook.

Bibliography:
- R. Devenish and A. Cooper-Sarker, *Deep Inelastic Scattering*, Oxford University Press 2004.
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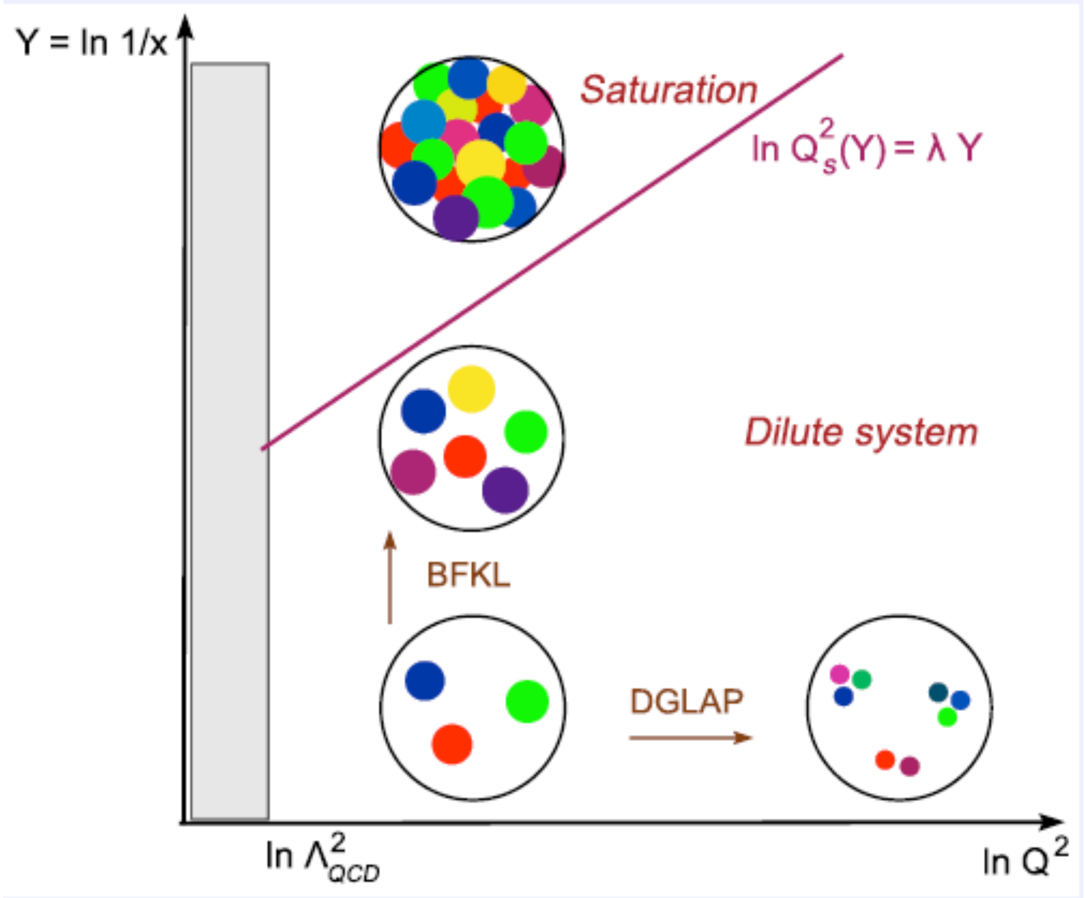
Why:

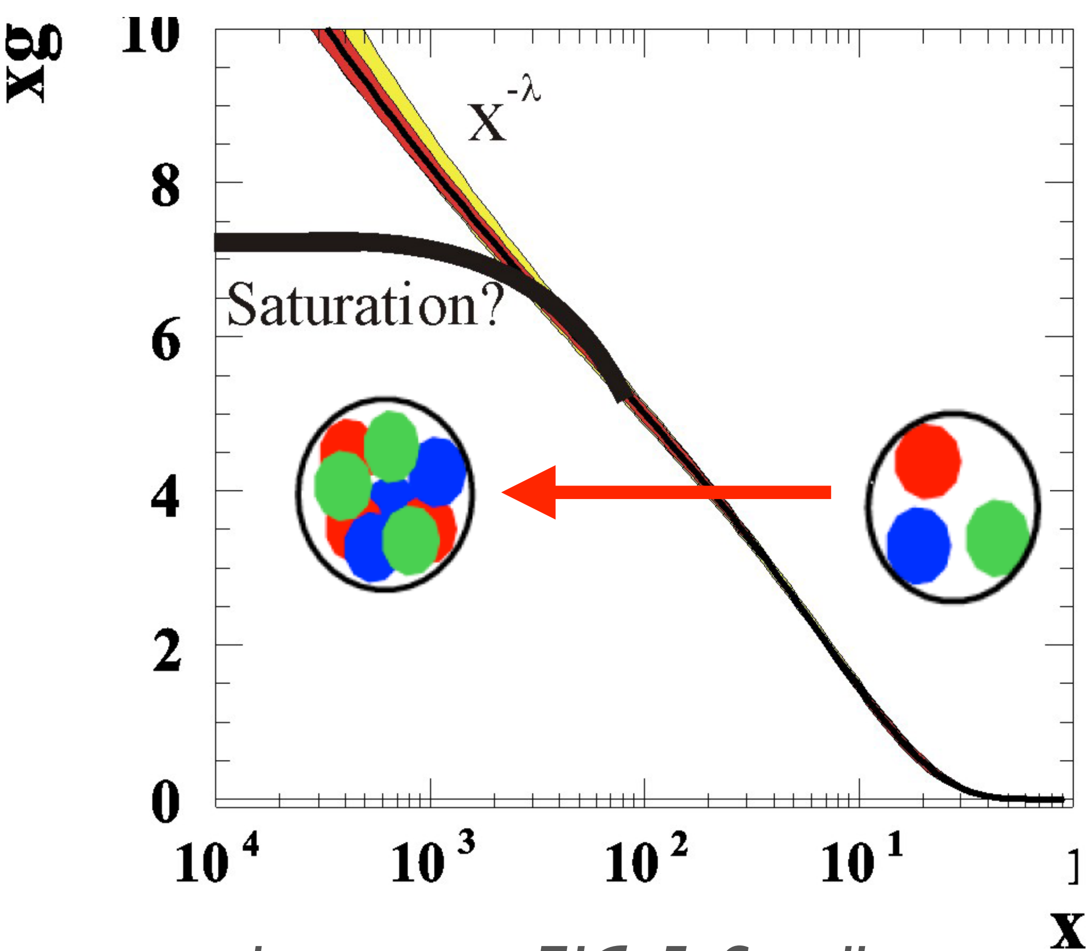
• Standard fixed-order perturbation theory (DGLAP, linear evolution) must eventually fail:

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

➜ High density ⇒ linear evolution must not hold: saturation, either perturbative (CGC) or non-perturbative.

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





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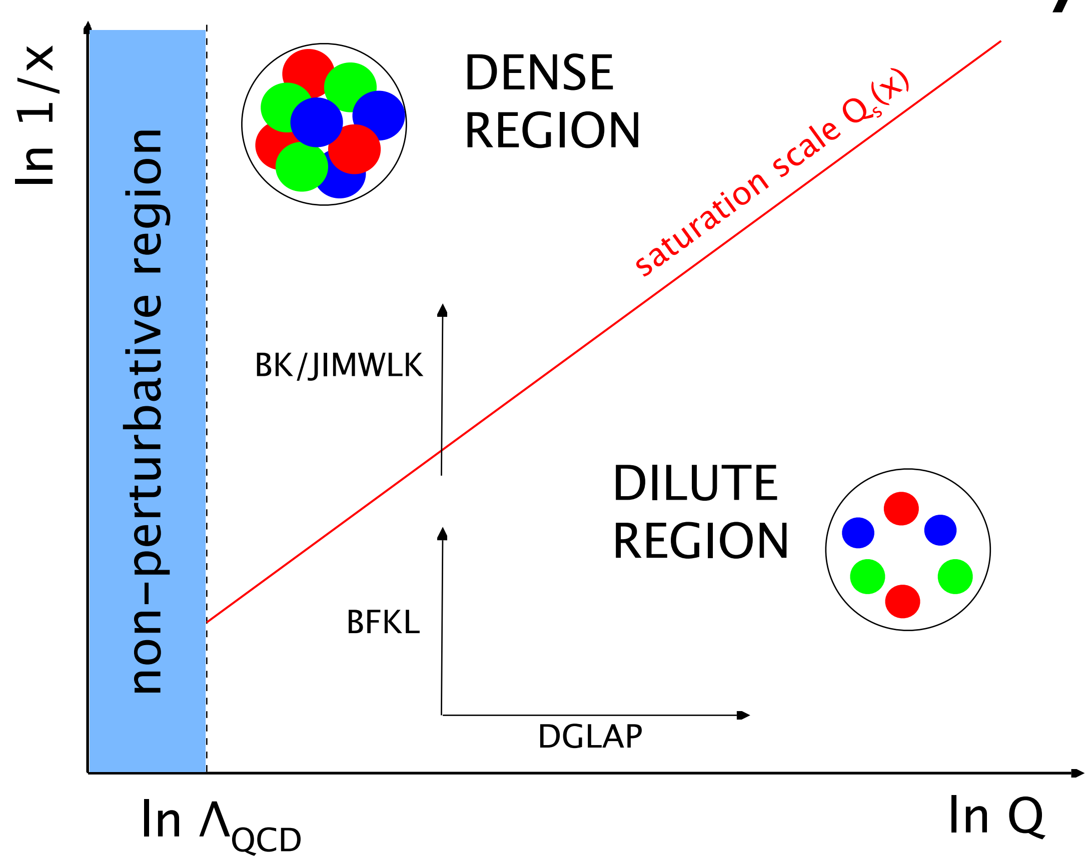
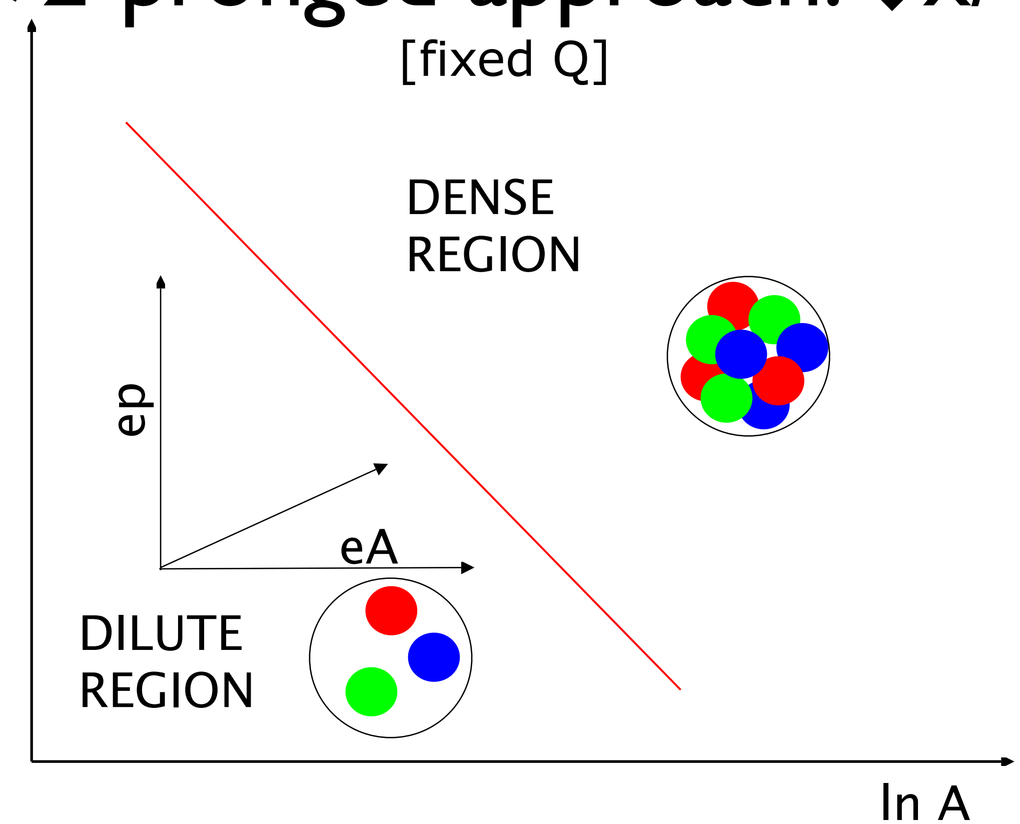
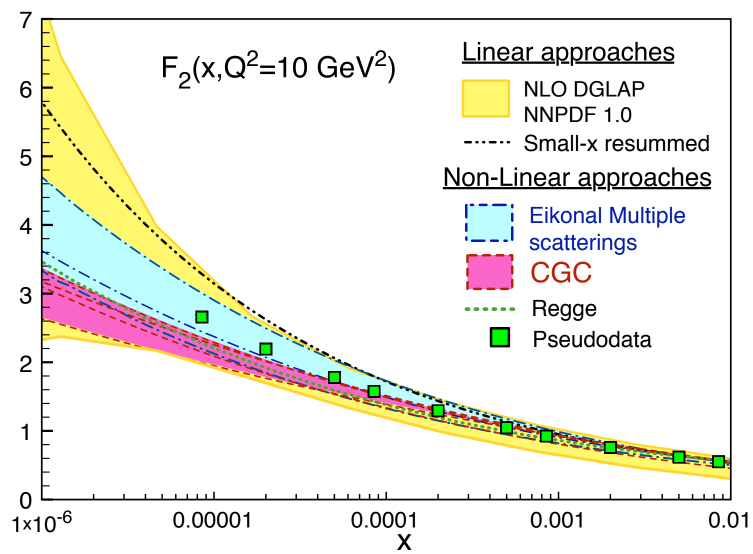
- Non-linear effects driven by density⇒2-pronged approach: ↓x/↑A.

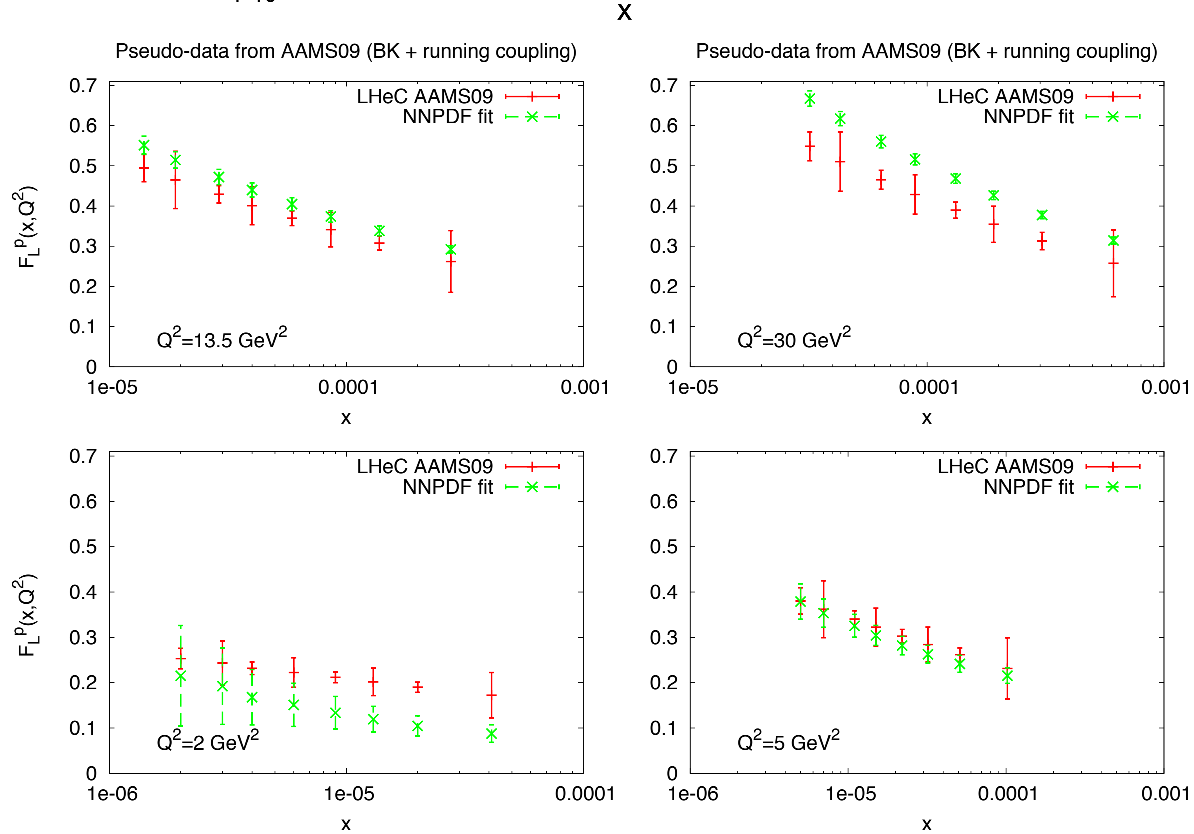


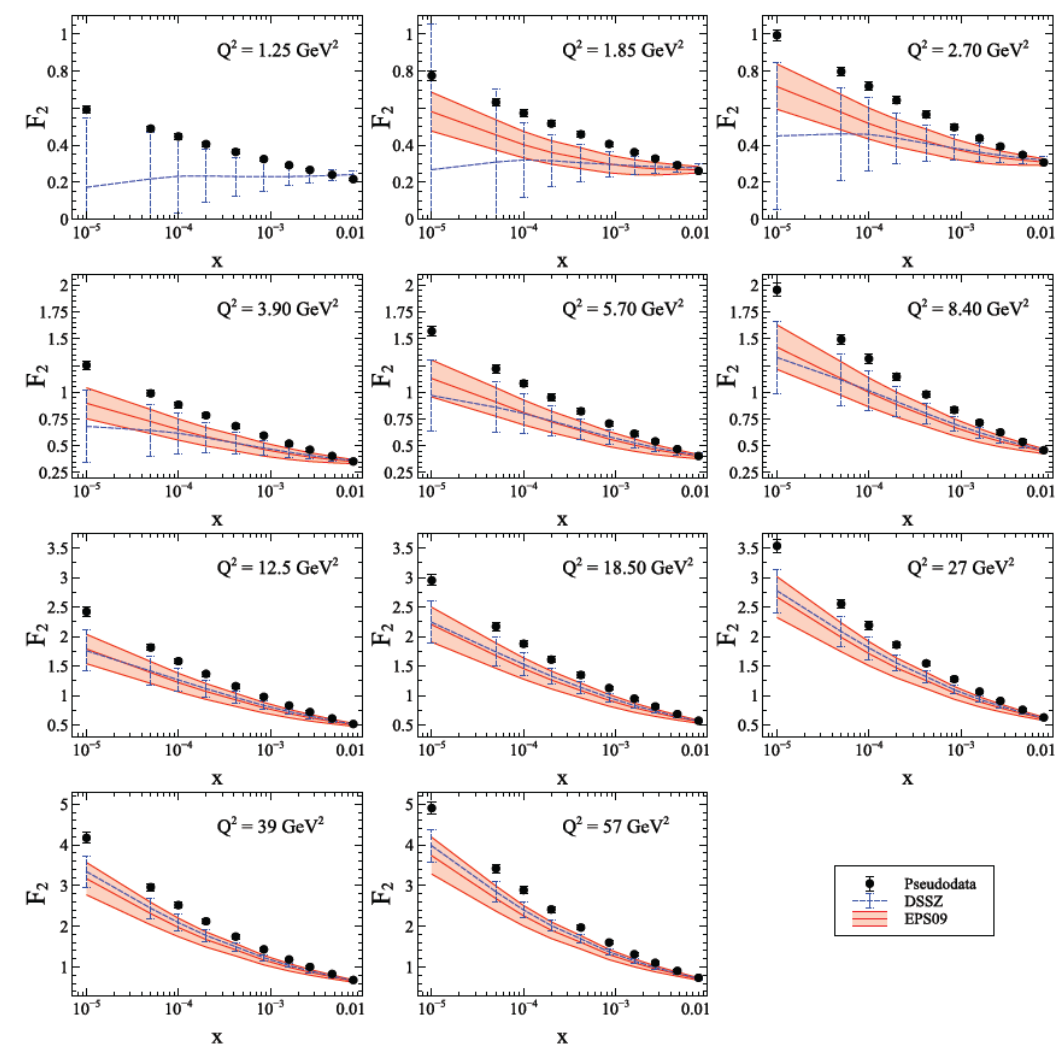


Small x: inclusive observables

- Simultaneous description of different inclusive observables (with different sensitivities to the gluon and the sea) in DGLAP may show tensions e.g. F_2 and F_L or σ_r^{HQ} if enough lever arm in Q^2 is available.







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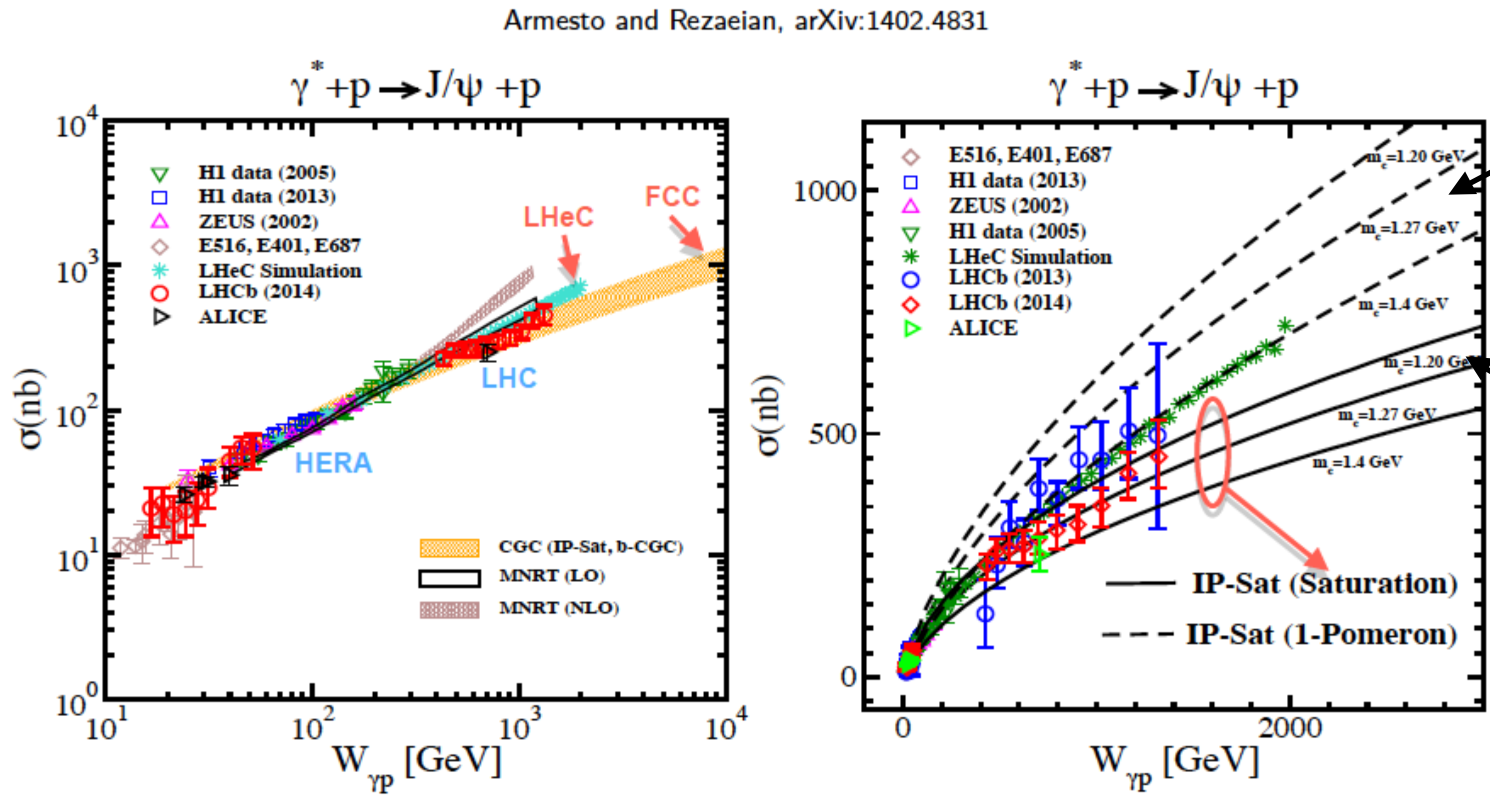
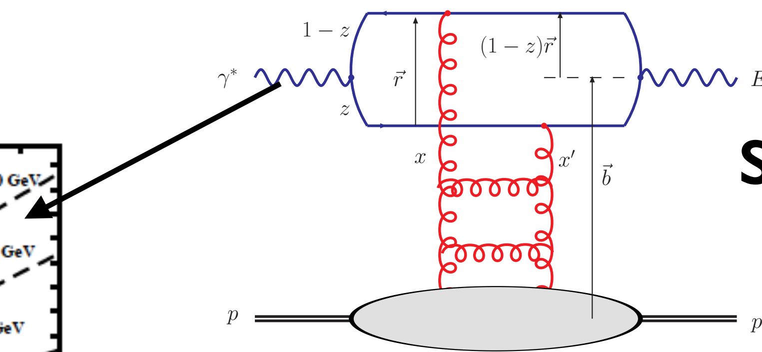
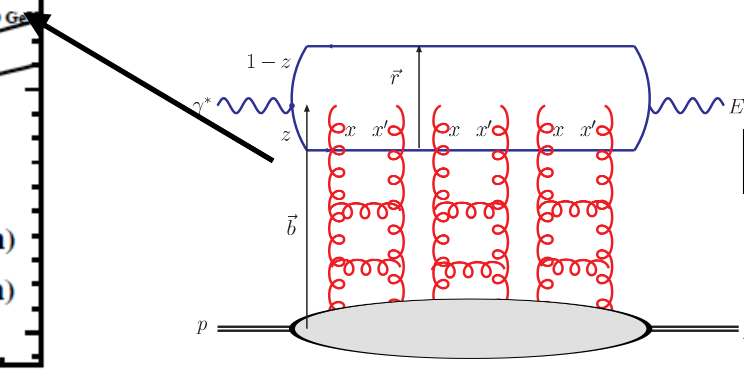
Small-x: diffraction

- Diffraction is a promising observable, but uncertainties exist.





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



Non-linear, saturation.

Small-x: diffraction

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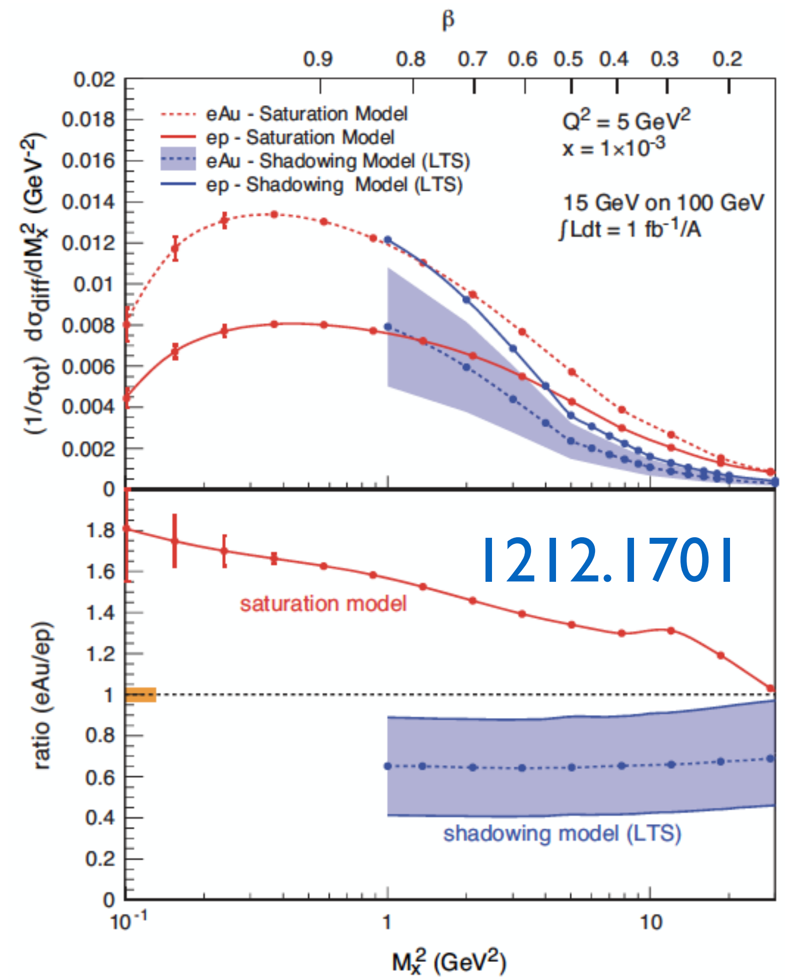
- Present saturation models lead to a blackening of the hadron (shrinking of the diffractive peak) and a larger total diffractive cross section in eA.



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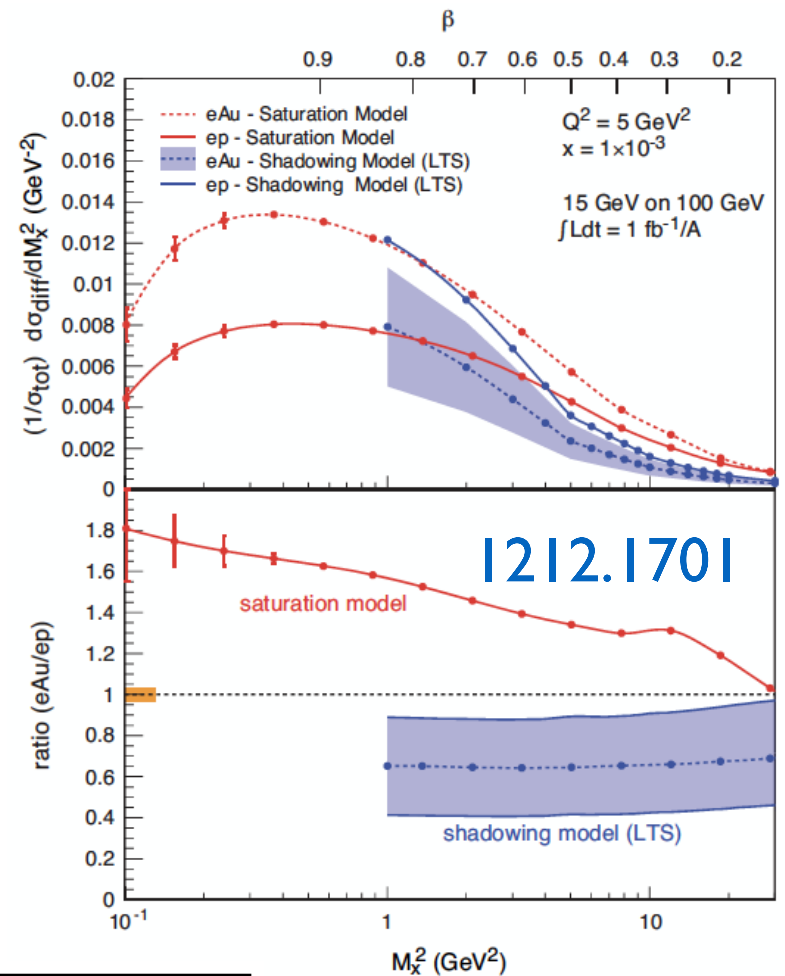

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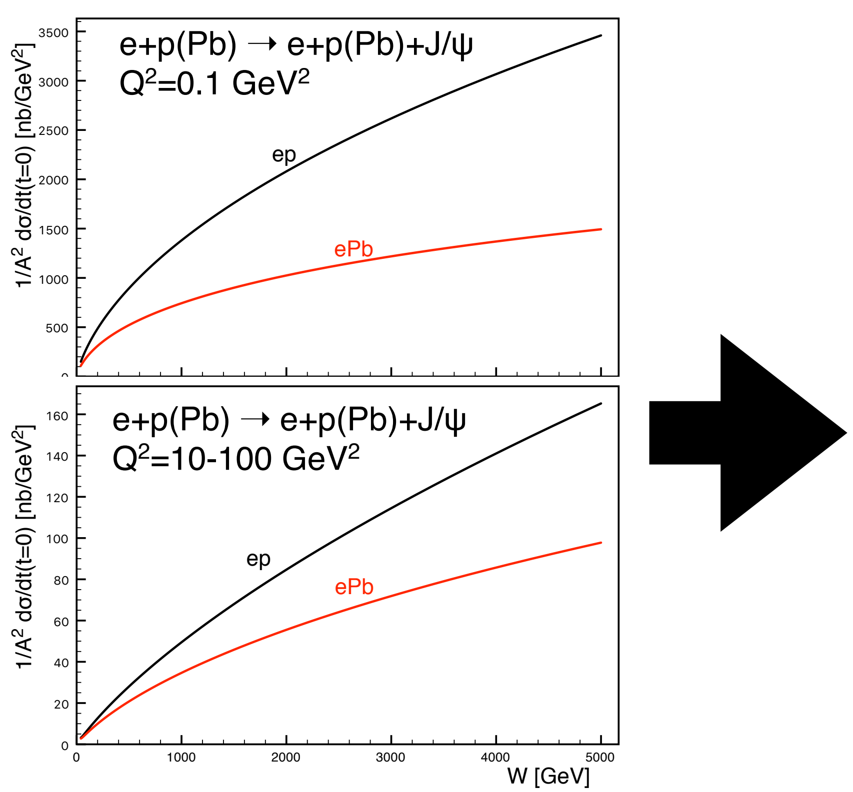
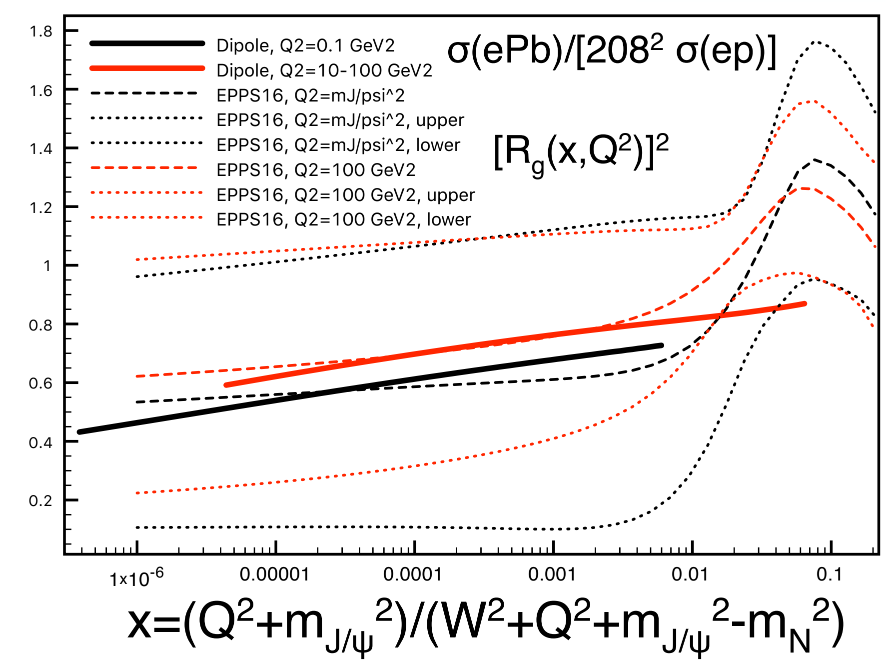




Mantysaari, Paukkunen

The small system puzzle:

Collective hadronisation

Collective expansion (hydro-like)

Direct photons

Final state interactions (non-hydro)

Observable or effect	PbPb	pPb (high mult.)	pp (high mult.)	Refs.
Low p_T spectra ("radial flow")	yes	yes	yes	[1–10]
Intermed. p_T ("recombination")	yes	yes	yes	[5, 6, 10–15]
Particle ratios	GC level	GC level except Ω	GC level except Ω	[8, 9, 16, 17]
Statistical model	$\gamma_s^{GC} = 1$, 10–30%	$\gamma_s^{GC} \approx 1$, 20–40%	$\gamma_s^{C} < 1$, 20–40%	[9, 18, 19]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[20–28]
Azimuthal anisotropy (v_n) (from two part. correlations)	$v_1 - v_7$	$v_1 - v_5$	v_2, v_3	[29–31] [32–39, 39–43]
Characteristic mass dependence	$v_2 - v_5$	v_2, v_3	v_2	[39, 42–48]
Directed flow (from spectators)	yes	no	no	[49]
Charge dependent flow (CME, CMW)	yes	yes	not observed	[50–54]
Higher order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ"	[39, 55–64, 64–69]
Weak η dependence	yes	yes	not measured	[41, 65, 67, 70–76]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[40, 77, 78]
Event-by-event v_n distributions	$n = 2 - 4$	not measured	not measured	[79, 80]
Event plane and v_n correlations	yes	yes	yes	[81–84]
Direct photons at low p_T	yes	not measured	yes	[85, 86]
Jet quenching	yes	not observed	not observed	[87–107]
Heavy flavor anisotropy	yes	yes [108]	not measured	[108–118]
Quarkonia	$J/\psi \uparrow$, $\Upsilon \downarrow$	suppressed	not measured	[108, 118–125, 125–138]

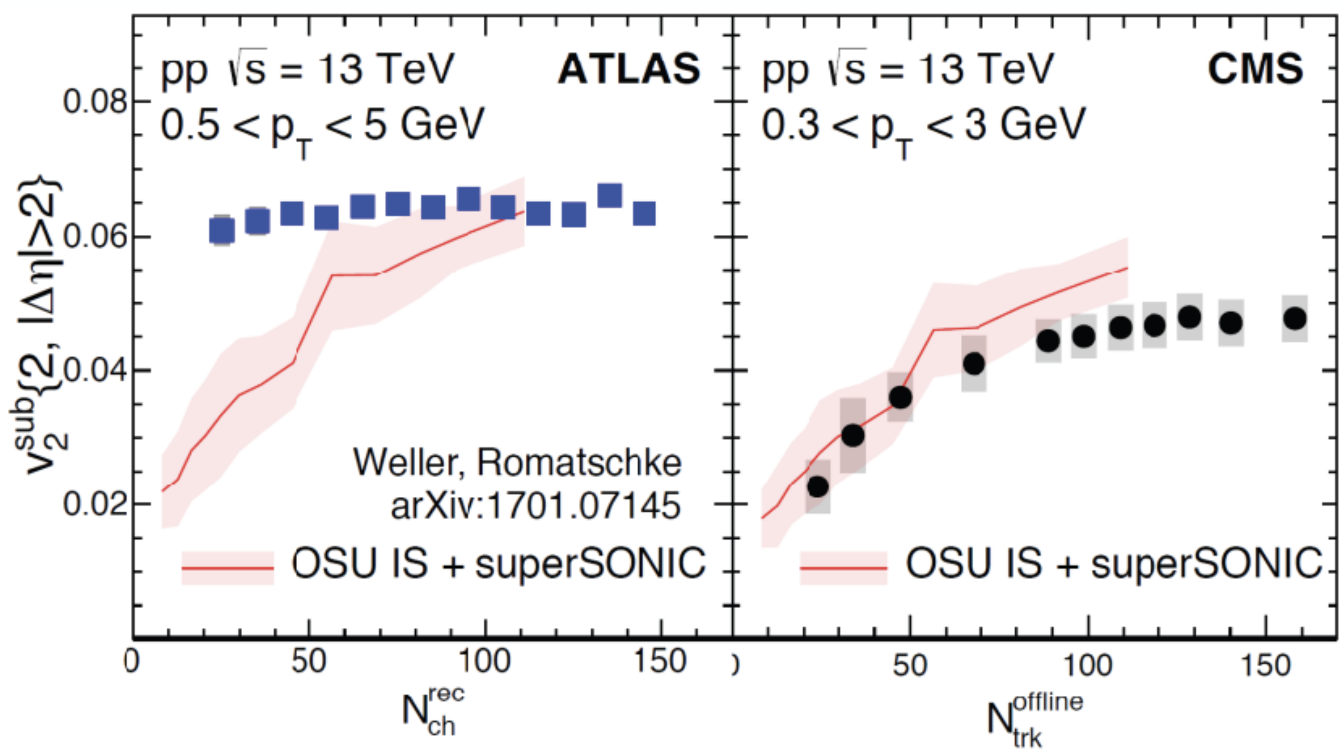
HL/HE-LHC workshops, preliminary, to be published

The small system puzzle:

- Azimuthal correlations extended in η (the ridge) are found in all systems from almost minimum bias pp (10) to central AA (2000) and are describable by viscous relativistic hydro (with suitable ICs):

  ➜ Final state interactions, so QGP-like physics in all systems?

  ➜ Correlations already present in the hadron or nucleus wave functions, as in CGC calculations?



- One way to proceed: go to even smaller systems, ep/eA, down to a point where final state interactions cannot be justified.

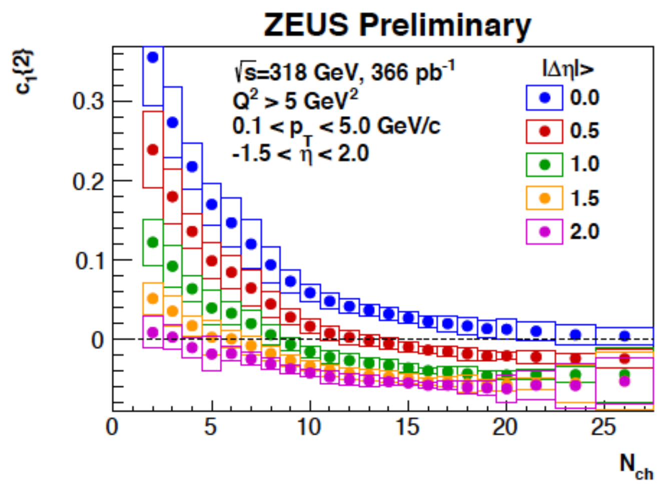
  ➜ Correlations appear (e.g. in eA, CGC): evidence of initial state effects?

  ➜ No correlations: evidence of final state interactions?

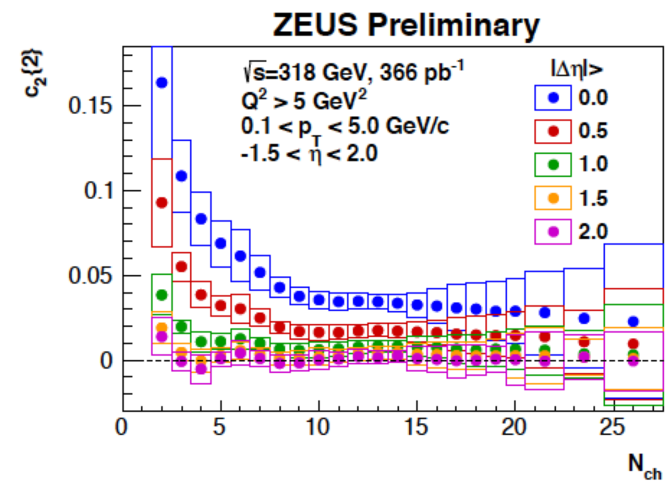
- Note: preliminary analysis by ZEUS and ALEPH put strong limits on azimuthal 2-particle correlations in ep at HERA and e^+e^- at LEP.

The small system puzzle:

Multiplicity-dependent $c_1\{2\}$ and $c_2\{2\}$ with increasing η-separation



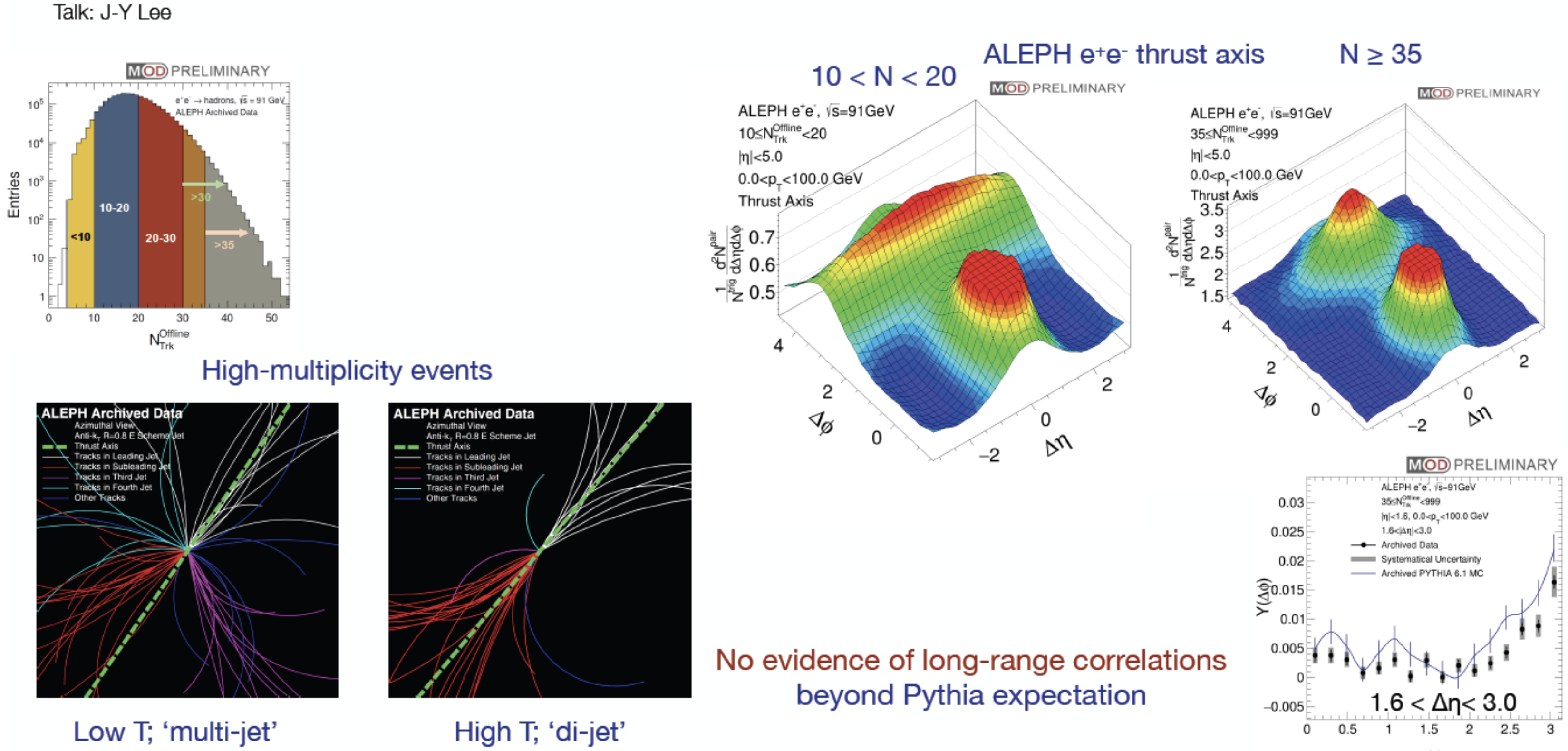
$|\Delta\eta| > 2.0$: $c_1\{2\}$ changes sign
→ consistent with momentum conservation.



$|\Delta\eta| > 2.0$: $c_2\{2\}$ consistent with zero.

Switching off the flow: e^+e^-

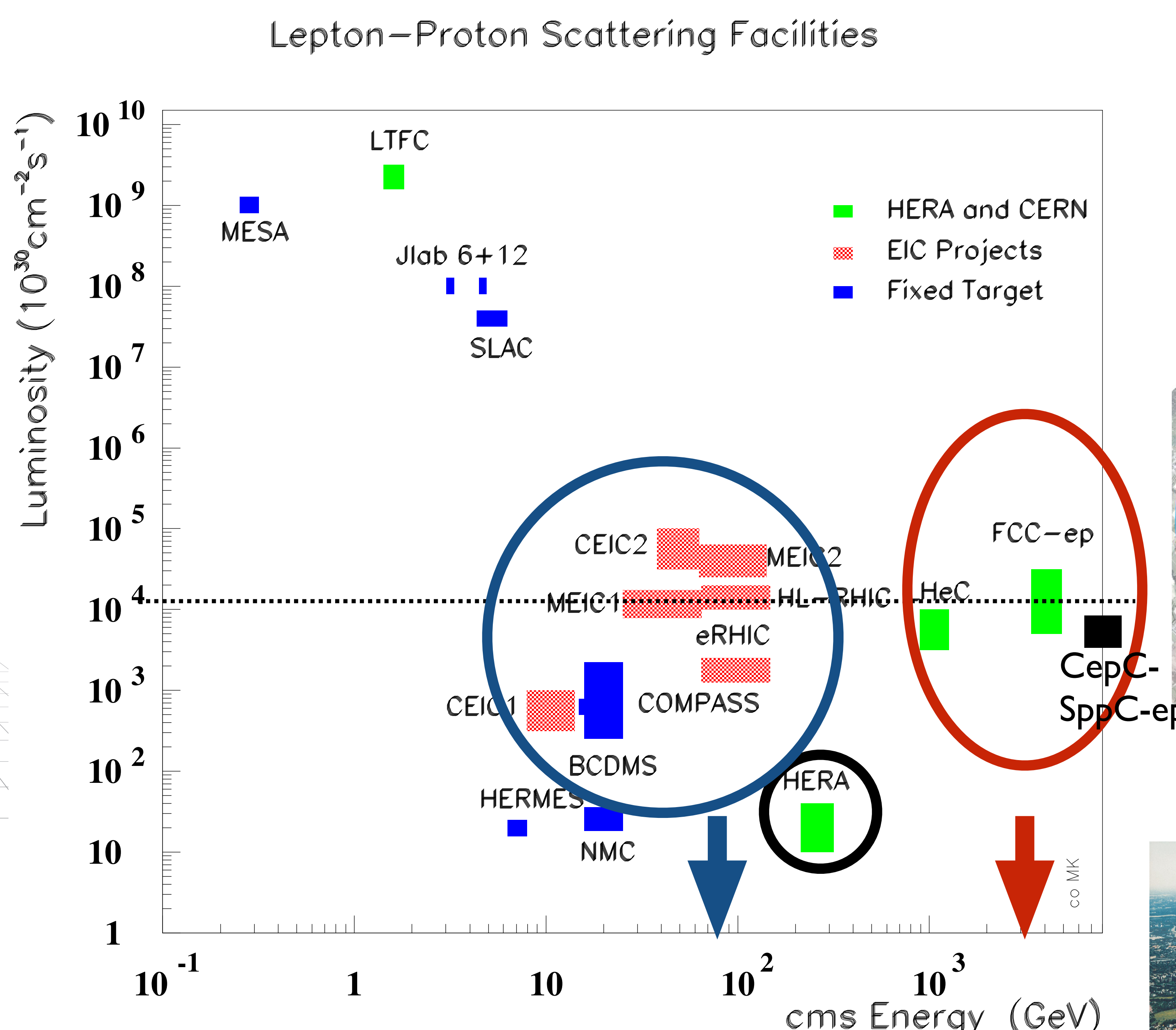
Talk: J-Y Lee



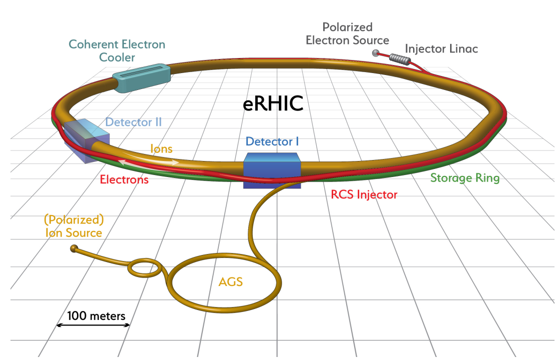
Contents:

Bibliography:
- R. Devenish and A. Cooper-Sarker, *Deep Inelastic Scattering*, Oxford University Press 2004.
- G. P. Salam, *Elements of QCD for hadron colliders*, CERN Yellow Report CERN-2010-002, 45-100, arXiv:1011.5131 [hep-ph].
- J. L. Abelleira Fernandez et al., *A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector*, J. Phys. G39 (2012) 075001, arXiv:1206.2913 [physics.acc-ph].
- A. Accardi et al., *Electron Ion Collider: The Next QCD Frontier : Understanding the glue that binds us all*, Eur. Phys. J. A52 (2016) no.9, 268, arXiv:1212.1701 [nucl-ex].

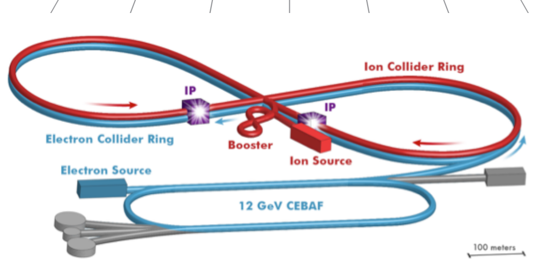
Finally:



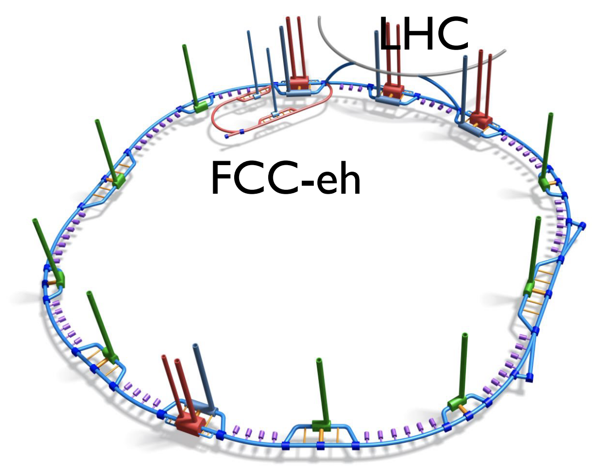
Lepton–Proton Scattering Facilities
Luminosity (10^{30}cm^{-2}s^{-1})
cms Energy (GeV)
HERA and CERN
EIC Projects
Fixed Target
LTFC
MESA
Jlab 6+12
SLAC
CEIC2
MEIC2
MEIC1
HL–RHIC
eRHIC
CEIC1
COMPASS
BCDMS
HERMES
NMC
HERA
HeC
FCC–ep
CepC-
SppC-ep
co MK



Coherent Electron Cooler
Polarized Electron Source
Injector Linac
eRHIC
Detector II
Detector I
Ions
Electrons
Storage Ring
RCS Injector
(Polarized) Ion Source
AGS
100 meters



Ion Collider Ring
IP
Electron Collider Ring
Booster
Ion Source
Electron Source
12 GeV CEBAF
100 meters



LHC
FCC-eh

LHC
Prevessin Site
SPS
Pt 2
Pt 1
Pt 8
Meyrin Site
LHeC
Civil Engineering
Different Options
Fraction 1/3-1/4-1/5
Pt2 and Pt8

HERA
PETRA
N
O
S
W

Finally:

Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33} cm^{-2} s^{-1}$)	Ions	Polarization
EIC (eRHIC)	$> 2025 - 2030$	30 - 140	2 - 15	p $\to$ U	e, p, ^{3}He, Li
EIC(JLEIC)	$> 2025 - 2030$	20 - 100 $\to$ 140	2 - 50	p $\to$ U	e, p, d, ^{3}He, Li
EIC in China	> 2028	16 - 34	1 $\to$ 100	p $\to$ Pb	e, p, light nuclei
LHeC	> 2030	1300	10	depends on LHC	e possible
PEPIC	$> 2025 - 2030$	530 $\to$ 1400	$< 10^{-3}$	depends on LHC	depends on source
VHEeP	> 2030	1000-9000	$10^{-5} - 10^{-4}$	depends on LHC	depends on source
FCC-eh	> 2044	3500	15	depends on FCC-hh	e possible