Weak & strong couplings with inclusive observables at the EIC

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JGU Mainz

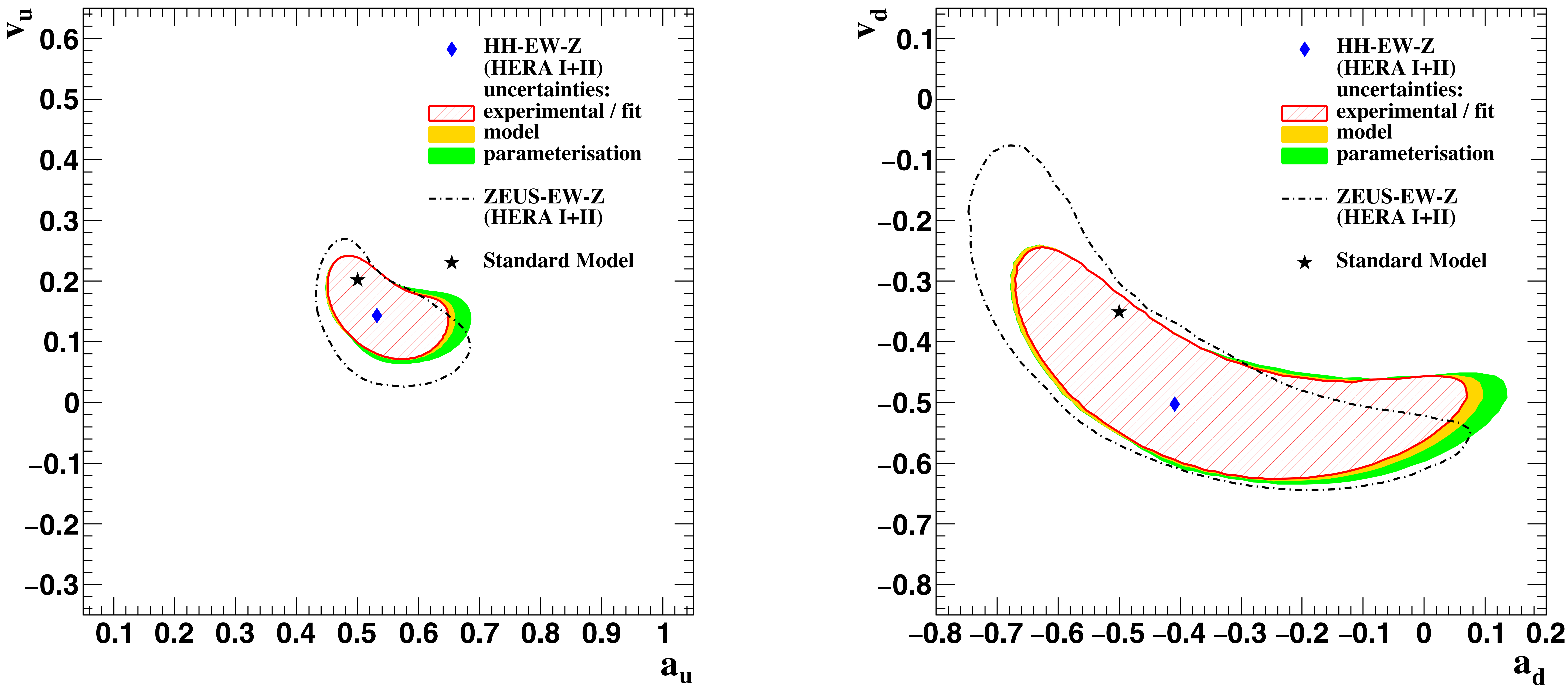
New opportunities for Beyond Standard Model searches at the EIC
July 21-24, 2025

Stony Brook University, NY

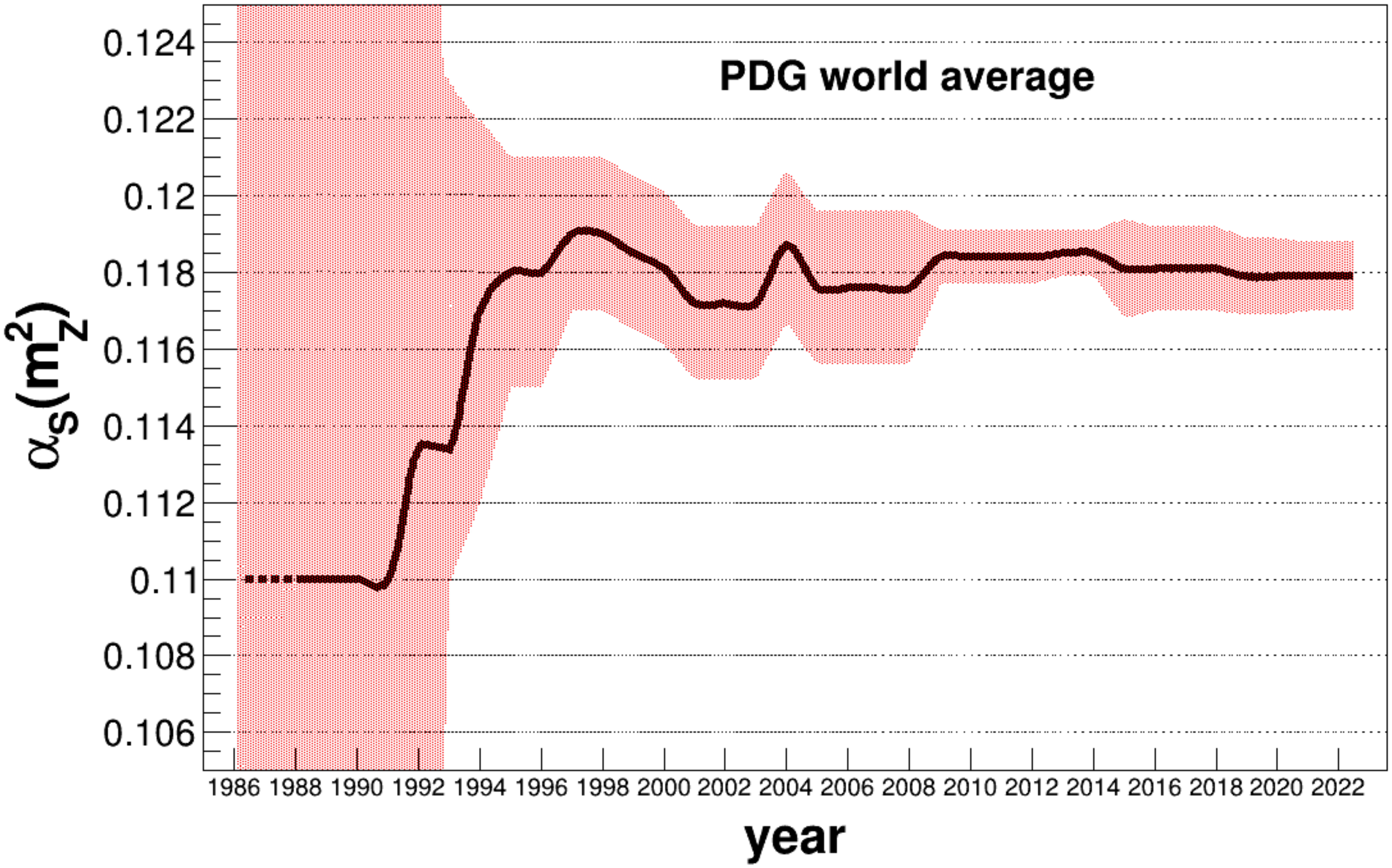
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Light quark electroweak couplings poorly constrained

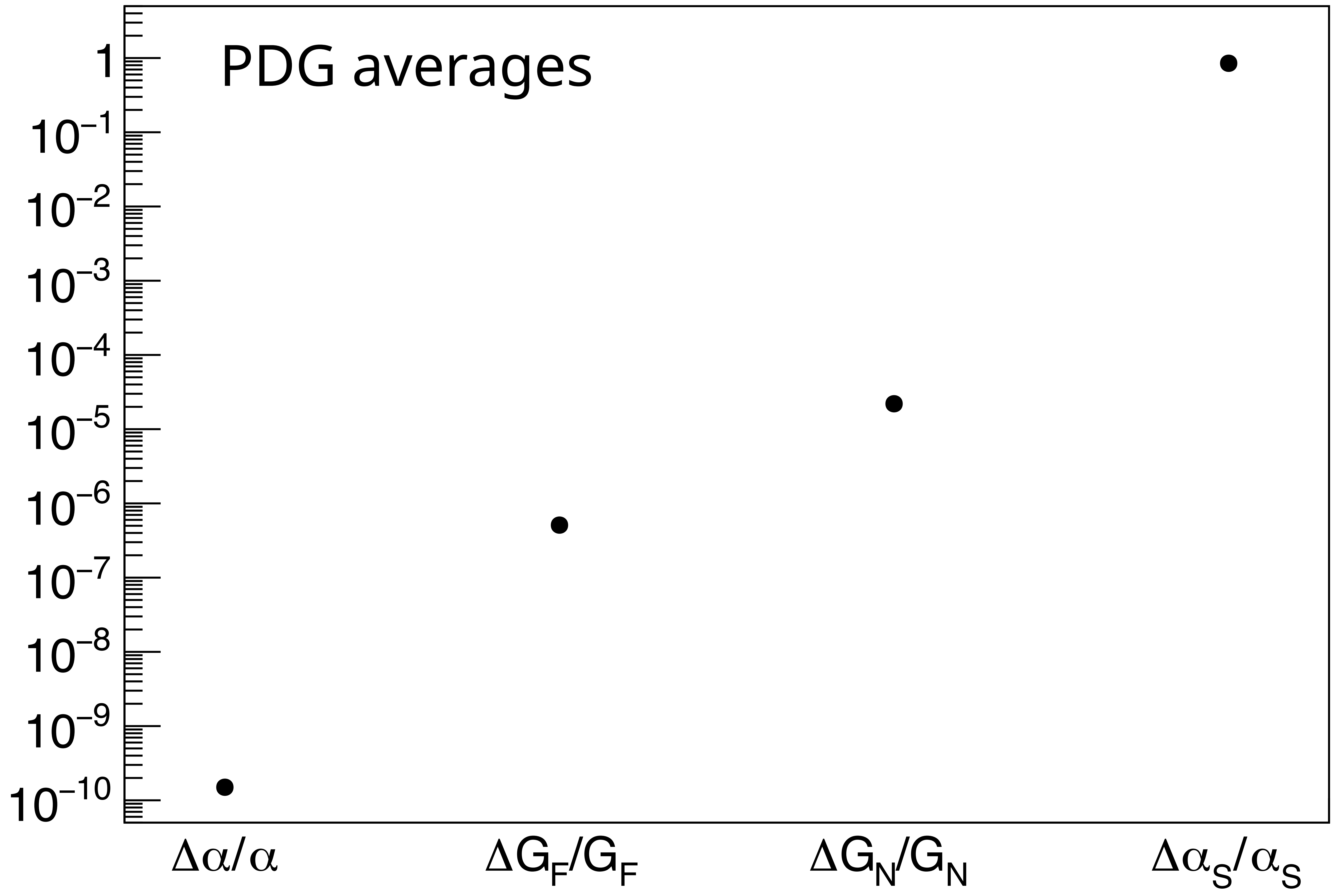
PRD 93, 092002 (2016)



α_S precision has vastly improved in past 3 decades…



…but it remains the most poorly known fundamental force constant



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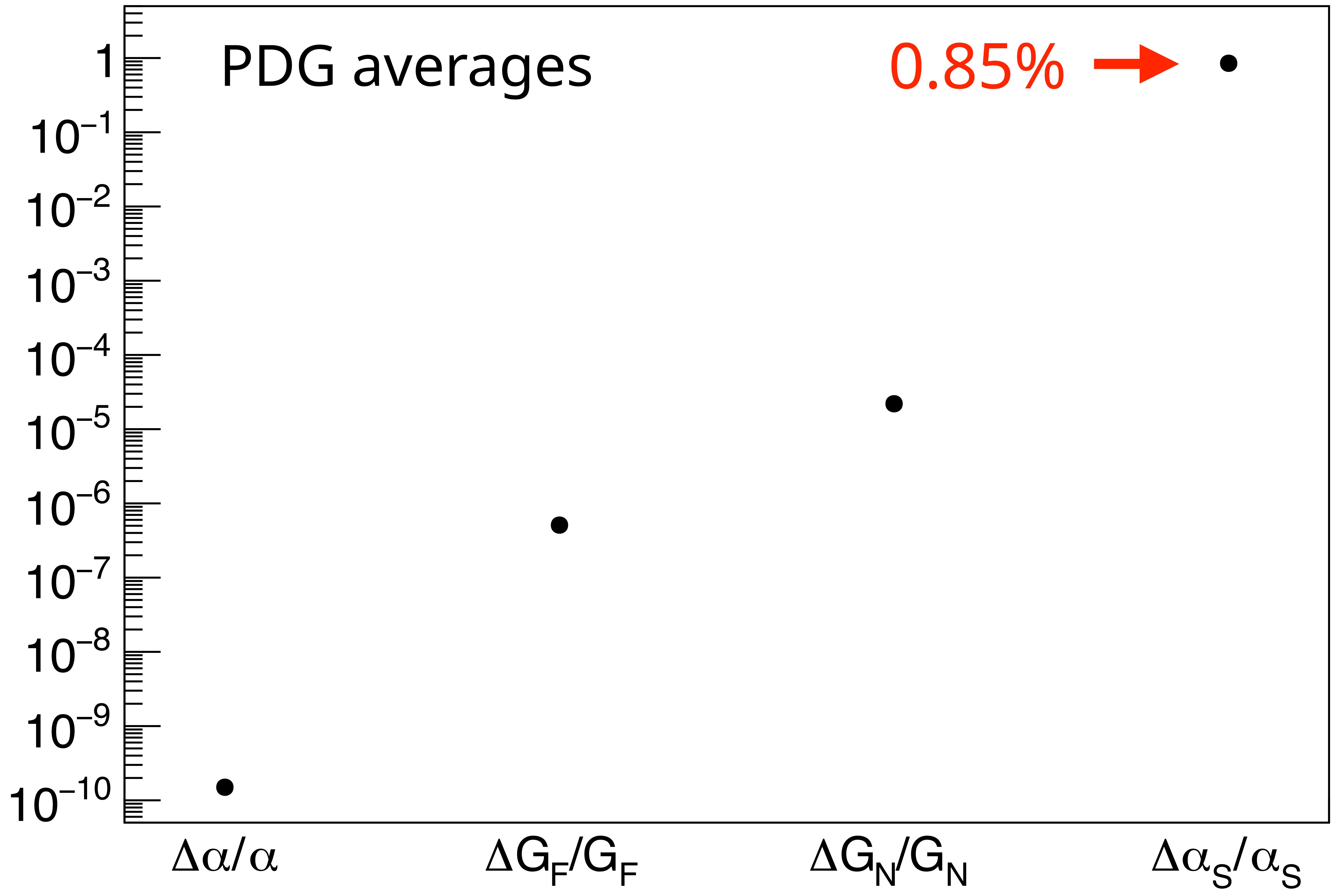

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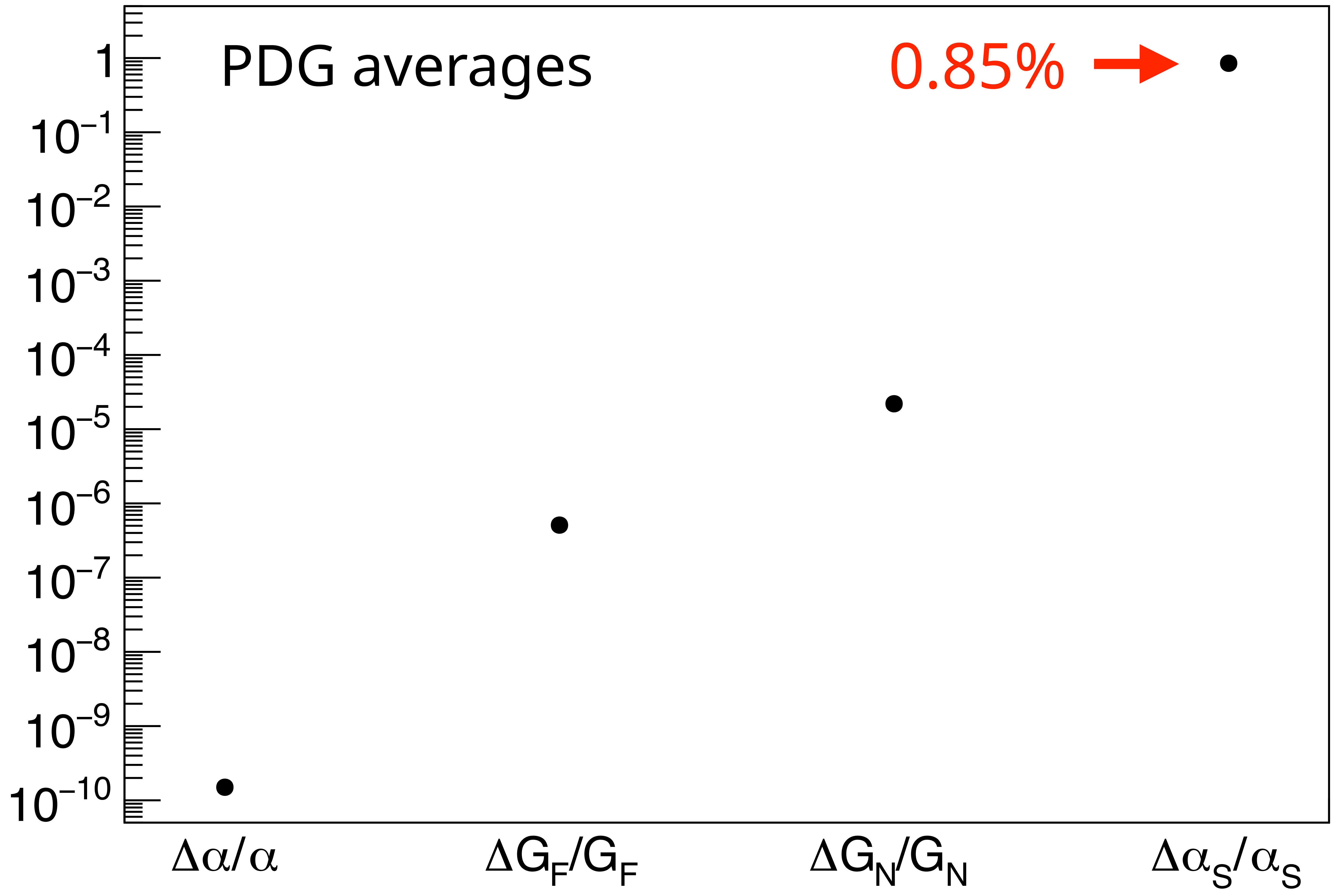

- Limiting factor in precision tests of Standard Model, BSM searches
  - 2-4% uncertainty in Higgs production cross sections, partial decay widths
  - Leading uncertainty in electroweak pseudo-observables

What inclusive observables can constrain these couplings?

Can the EIC improve/go beyond existing measurement of these observables?

What technical challenges are associated with these measurements?

Neutral current DIS

$$\frac{\mathrm{d}\sigma_{NC}^{\pm}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xyQ^4}\left[Y_+\tilde{F}_2 \mp Y_-x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

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

Neutral current DIS

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$$\begin{aligned} \tilde{F}_2^{\pm} &= F_2^{\gamma} - (g_V^e \pm P_e g_A^e)\,\frac{Q^2}{Q^2+M_Z^2}F_2^{\gamma Z}\ldots \\ x\tilde{F}_3^{\pm} &= \quad - (g_A^e \pm P_e g_V^e)\,\frac{Q^2}{Q^2+M_Z^2}xF_3^{\gamma Z}\ldots \end{aligned}$$

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Electron vector &
axial couplings

Neutral current DIS

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$$x\tilde{F}_3^{\pm} \;=\; \;-\; (g_A^e \pm P_e g_V^e)\,\frac{Q^2}{Q^2+M_Z^2}xF_3^{\gamma Z}\ldots$$

Electron vector & axial couplings

$$F_2^{\gamma} = x\sum_q e_q^2\,(q+\overline{q})$$

$$F_2^{\gamma Z} = x\sum_q 2e_q g_V^q\,(q+\overline{q})$$

$$F_3^{\gamma Z} = \sum_q 2e_q g_A^q\,(q-\overline{q})$$

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Quark vector & axial couplings

Cross section difference in polarized DIS

$$\Delta\sigma = \sigma(\lambda_n = -1, \lambda_\ell) - \sigma(\lambda_n = 1, \lambda_\ell)$$

$$\frac{\mathrm{d}\Delta\sigma_{NC}^{\pm}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{8\pi\alpha^2}{yQ^4}\left[-Y_+\tilde{g}_5 \mp Y_-\tilde{g}_1\right]$$

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$$g_1^{\gamma} = \frac{1}{2}\sum_q e_q^2\,(\Delta q + \Delta\overline{q})$$

$$g_1^{\gamma Z} = \sum_q 2e_q g_V^q\,(q + \overline{q})$$

$$g_5^{\gamma Z} = \sum_q e_q g_A^q\,(\Delta q - \Delta\overline{q})$$

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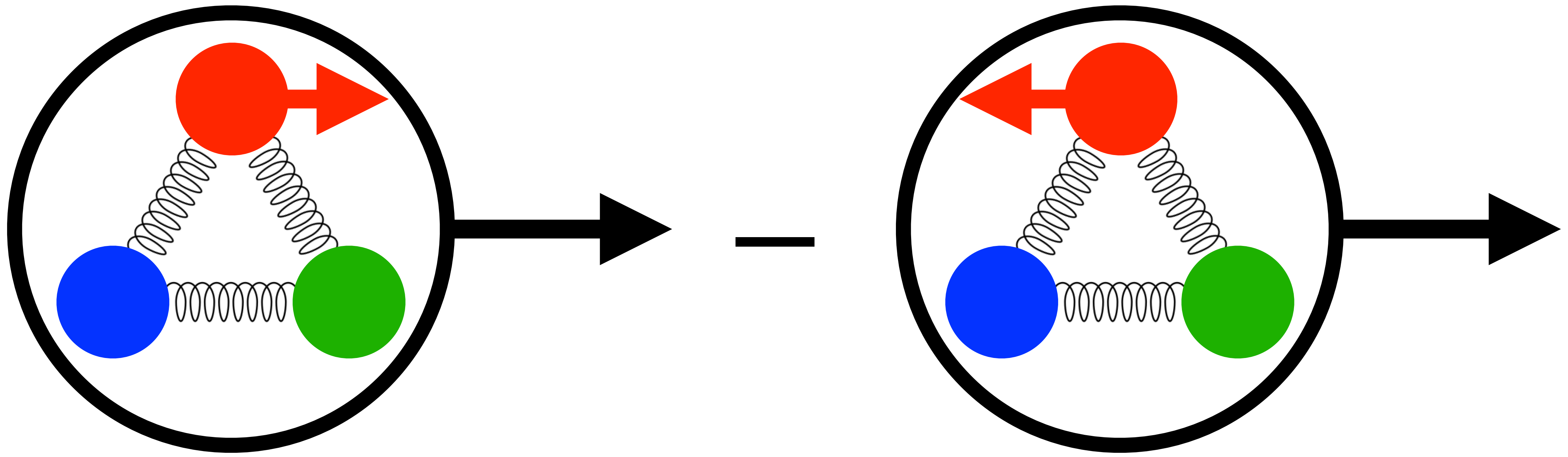
$\Delta q =$ 

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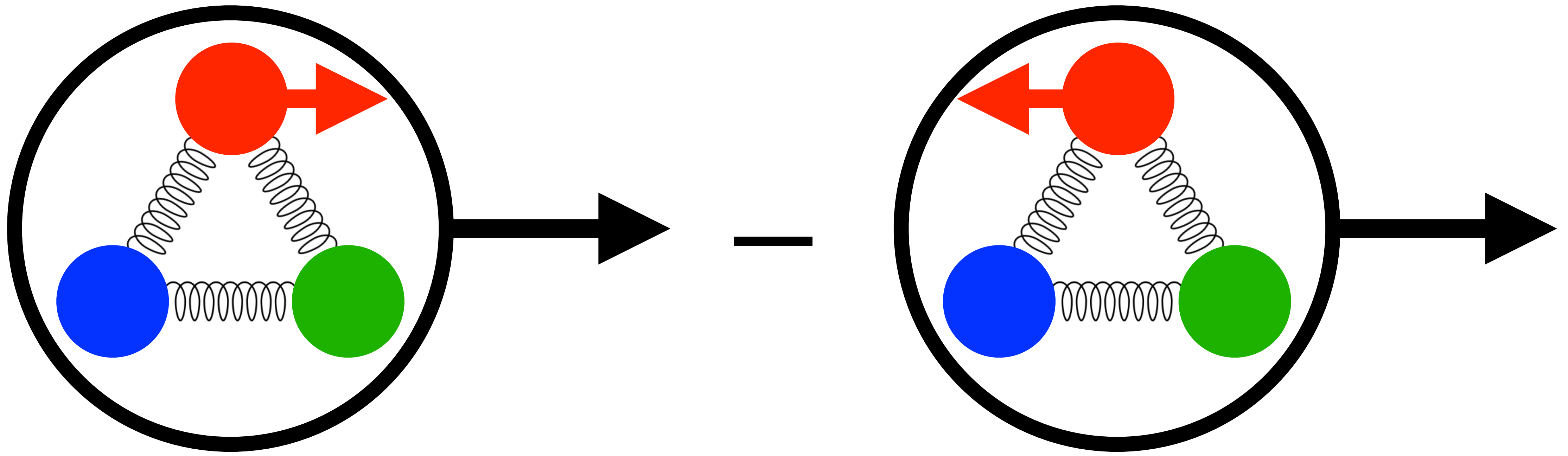
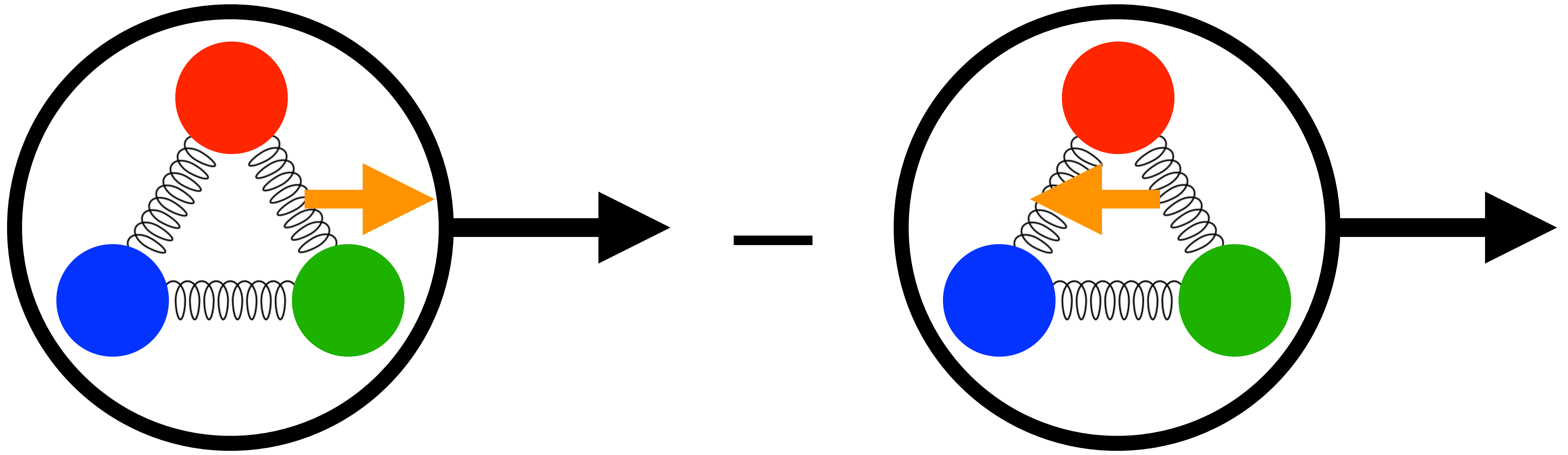


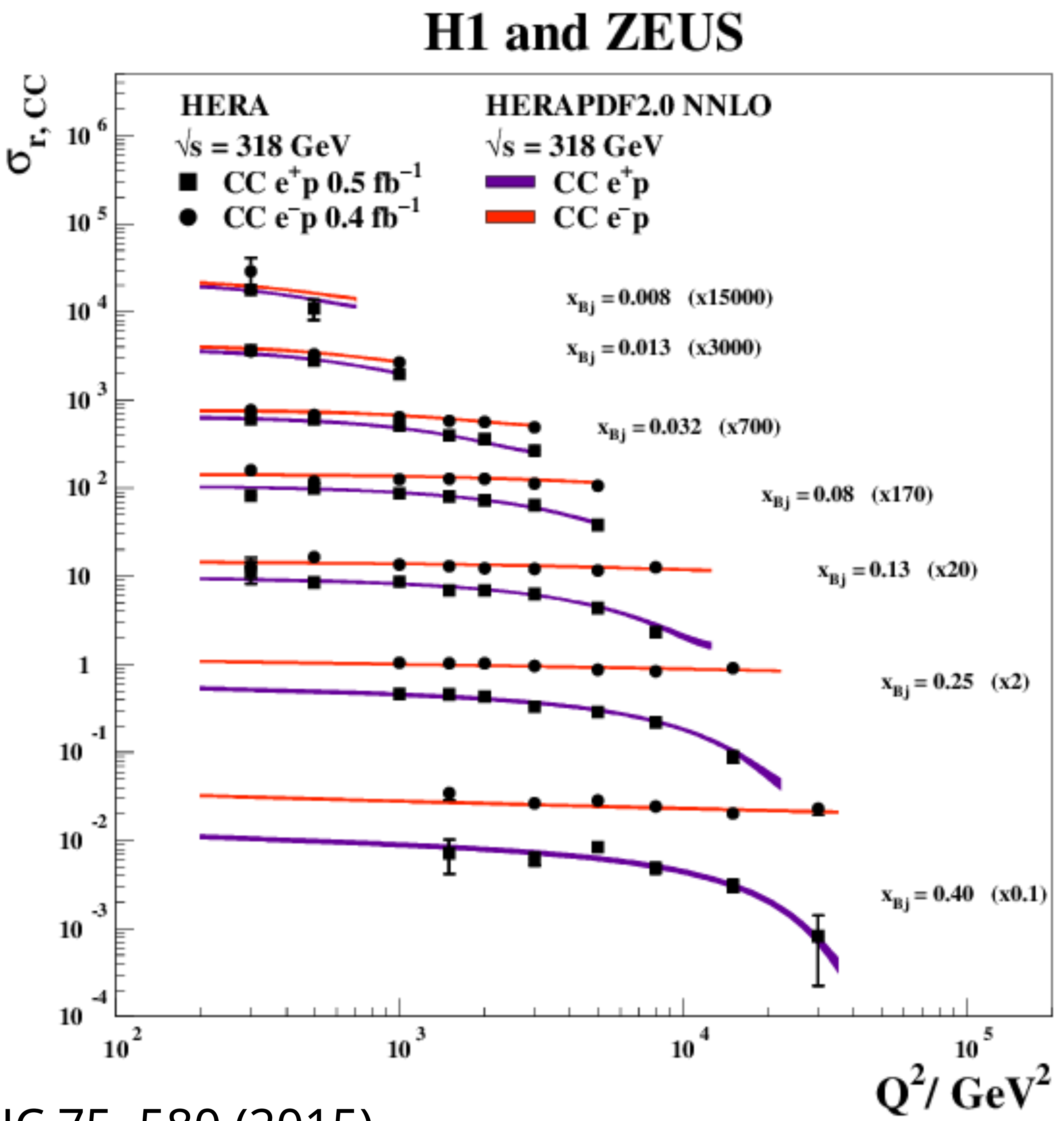
$\Delta g =$



Charged-current structure functions

$$F_2^{W^-} = 2x(u + \bar{d} + \bar{s} + c\dots)$$
$$F_3^{W^-} = 2(u - \bar{d} - \bar{s} + c\dots)$$
$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c\dots)$$
$$g_5^{W^-} = (-\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c\dots)$$

- Structure functions for W^+ exchange: $u \leftrightarrow d, s \leftrightarrow c$
- Unique combinations of PDFs → flavor separation



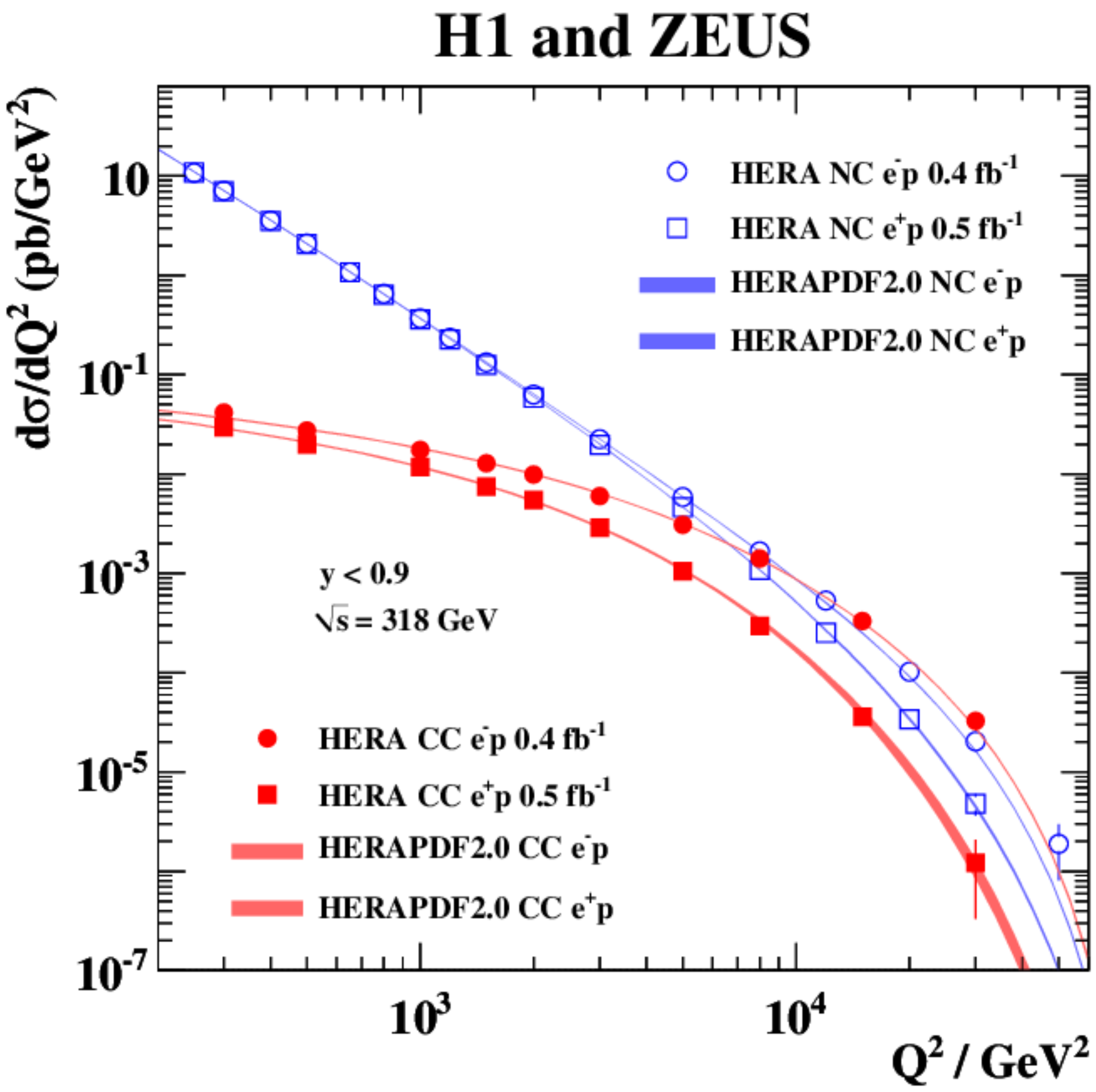
EPJC 75, 580 (2015)

$$\sigma^{+}_{r,CC} \approx \left[x\bar{u} + (1-y)^2 xd\right]$$

$$\sigma^{-}_{r,CC} \approx \left[xu + (1-y)^2 x\bar{d}\right]$$

At fixed x, $y \propto Q^2$

EPJC 75, 580 (2015)



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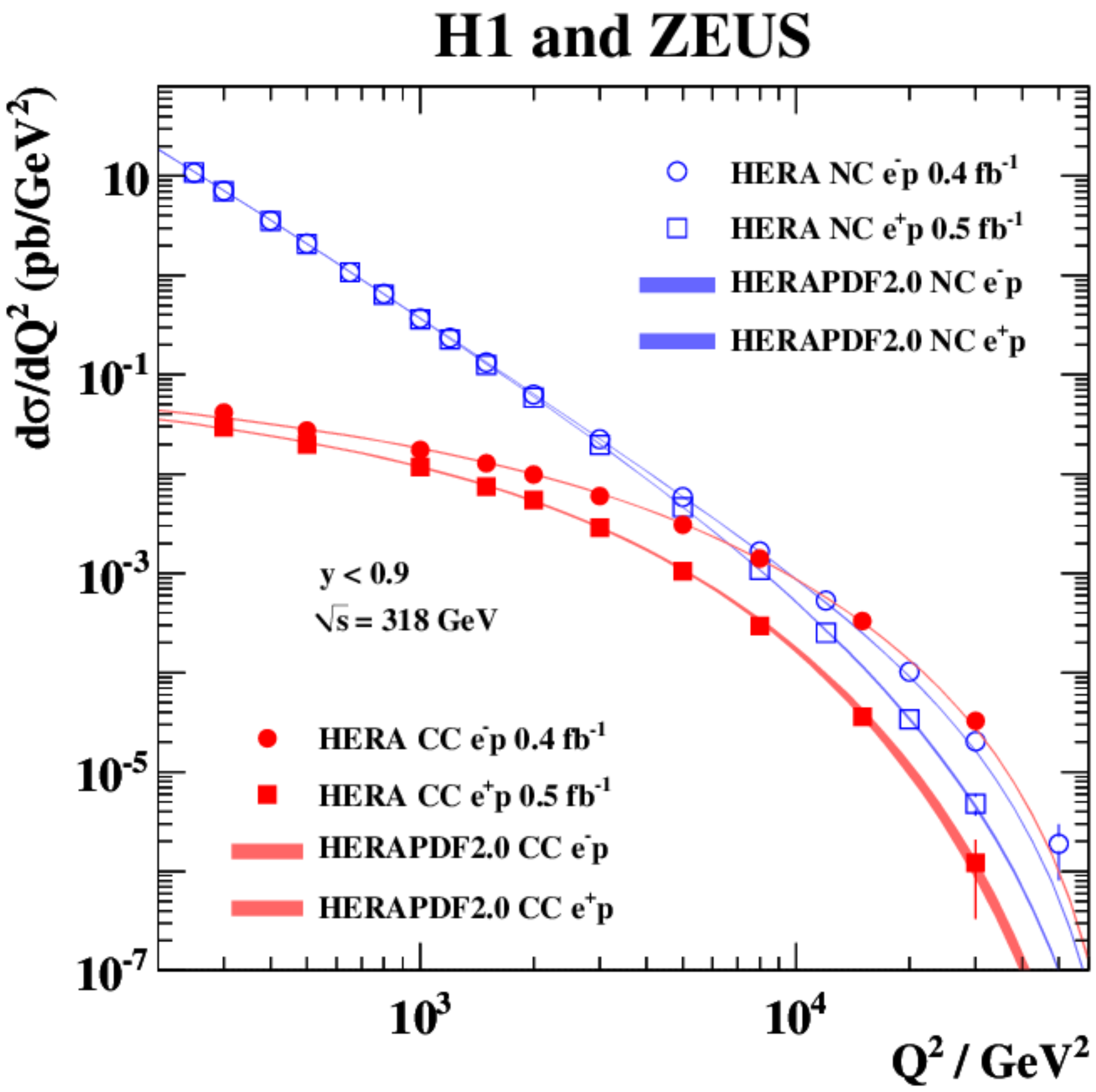
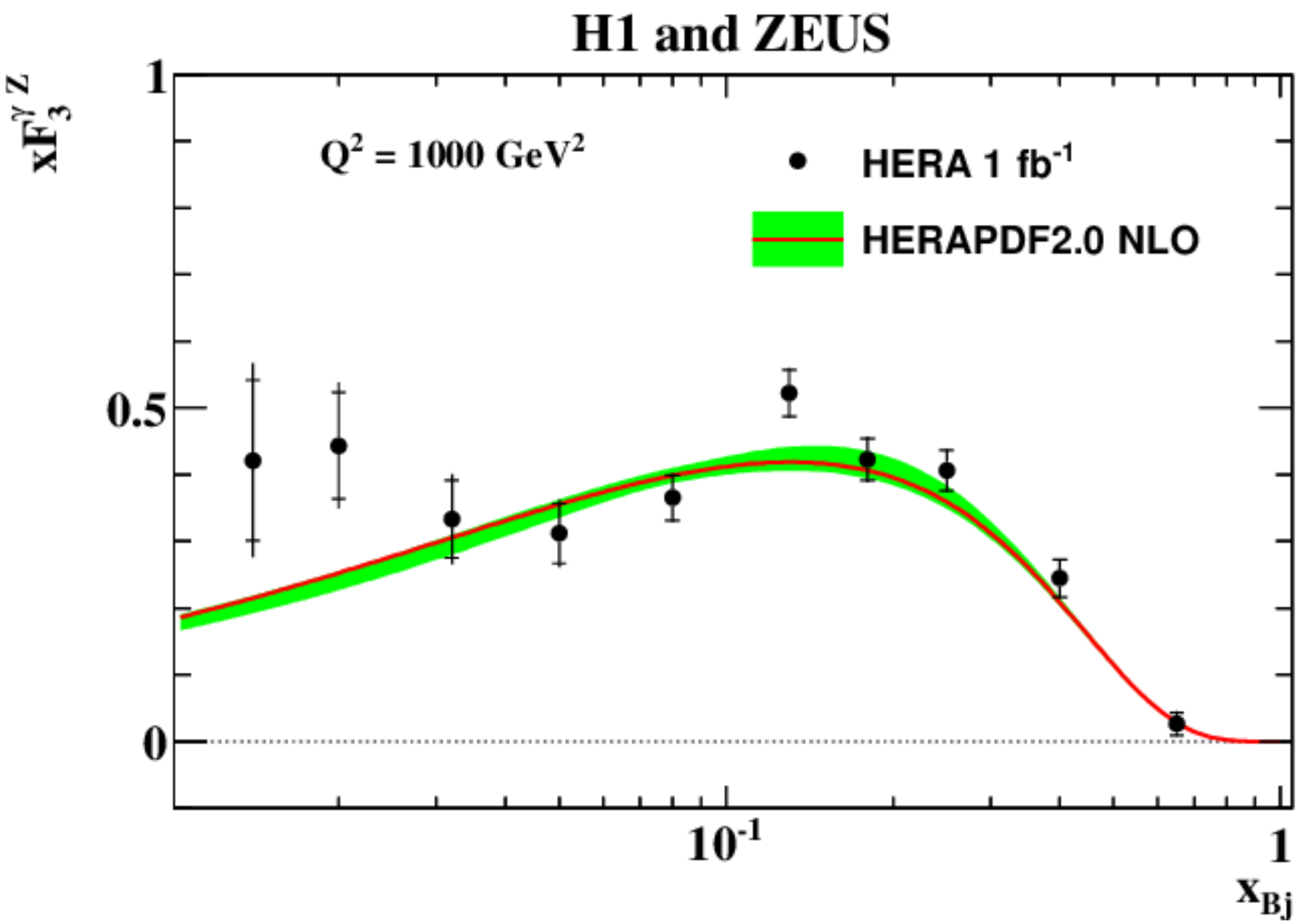
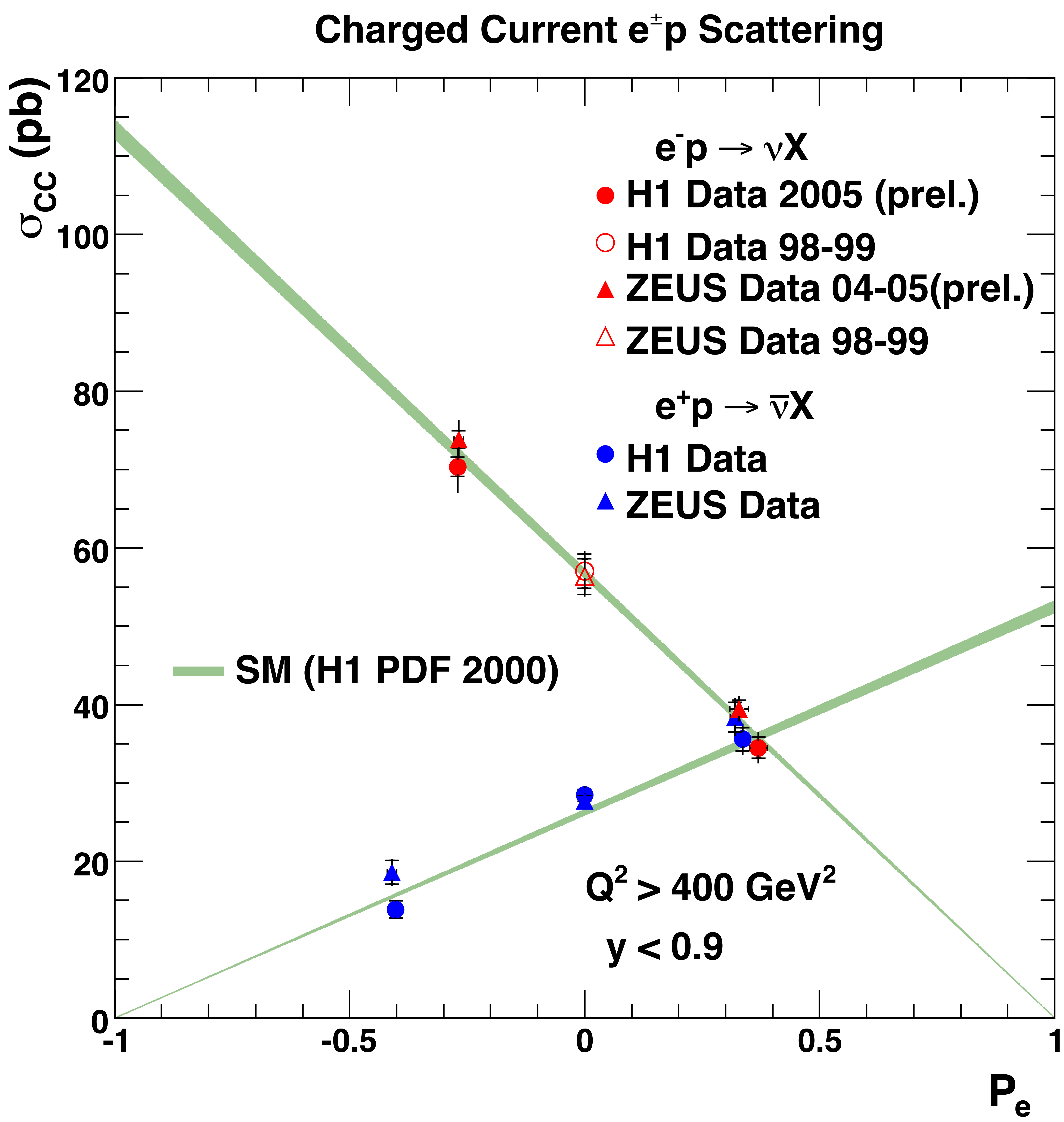


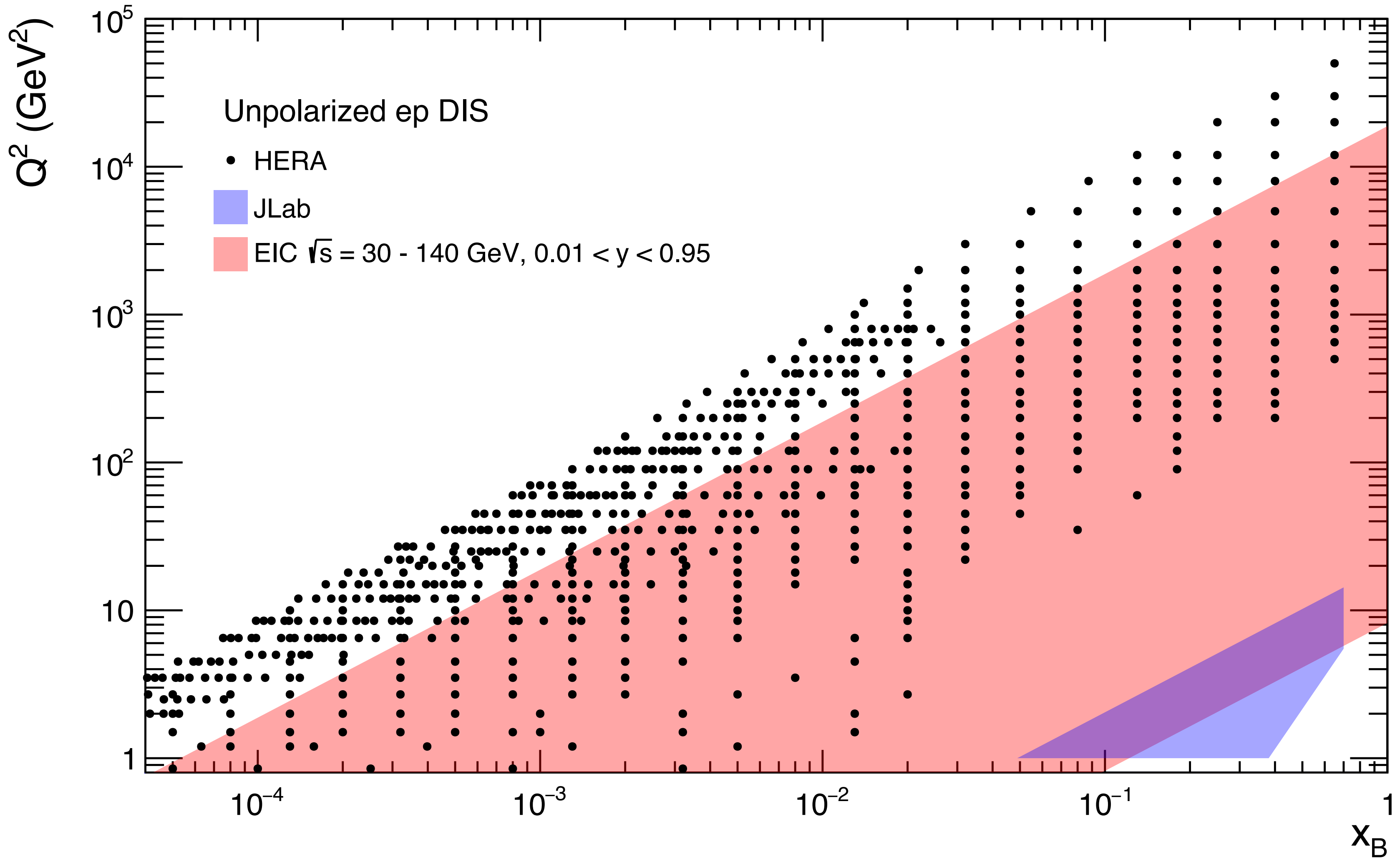




EPJC 75, 580 (2015)

How can inclusive physics at the EIC contribute?

- Limitations: smaller COM energy, no positrons (yet…)
- Advantages: larger luminosity, full polarization, nuclei



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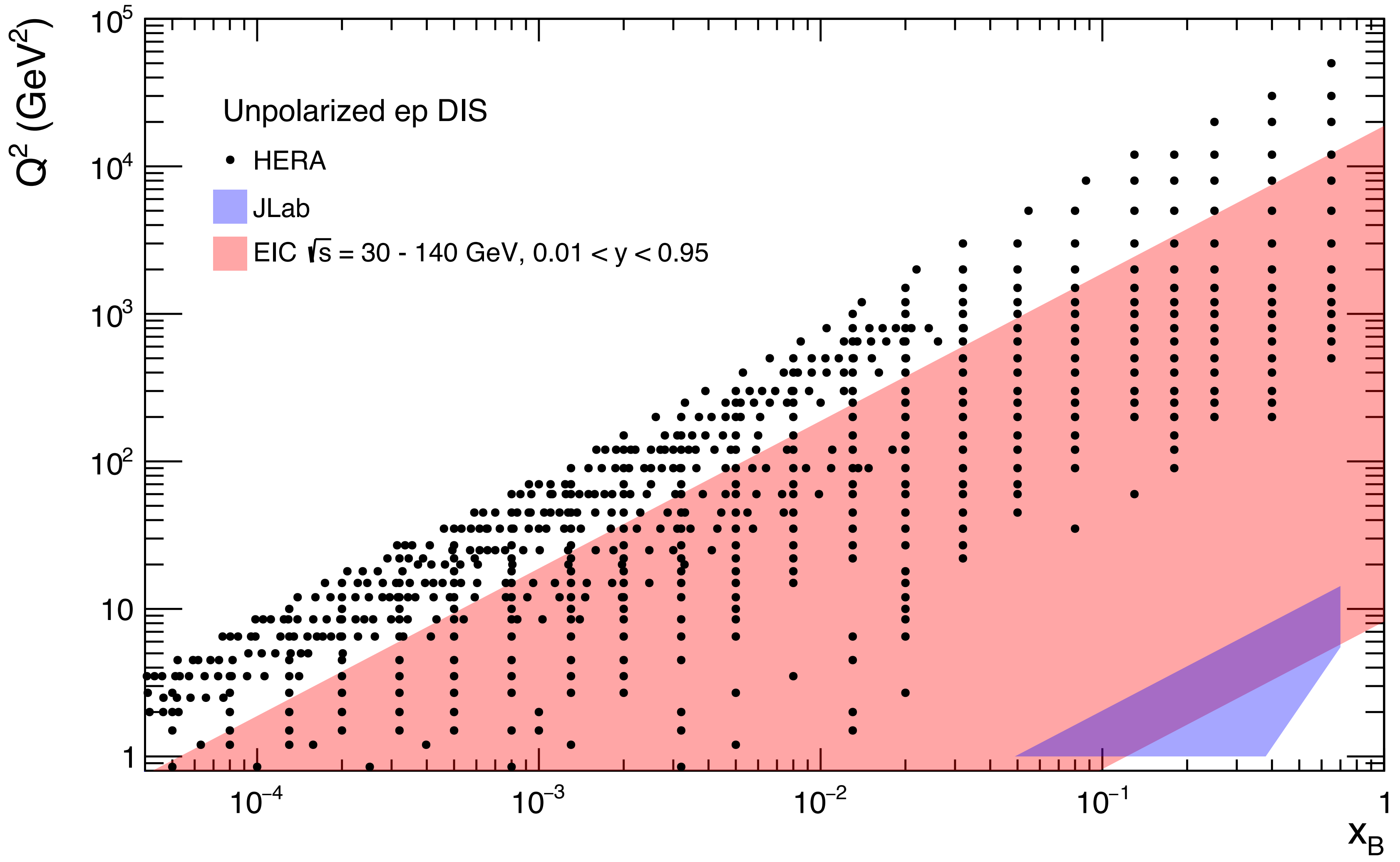

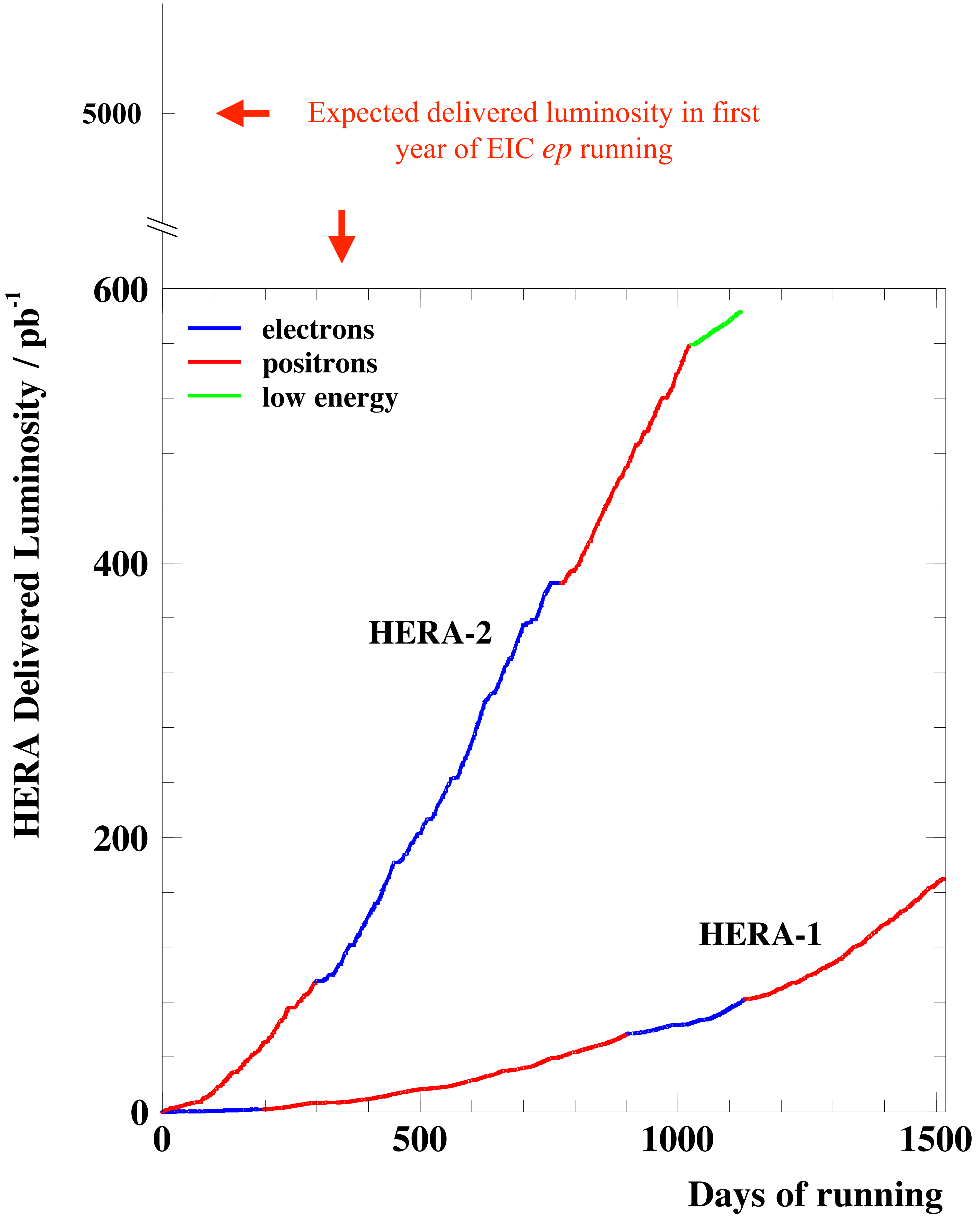

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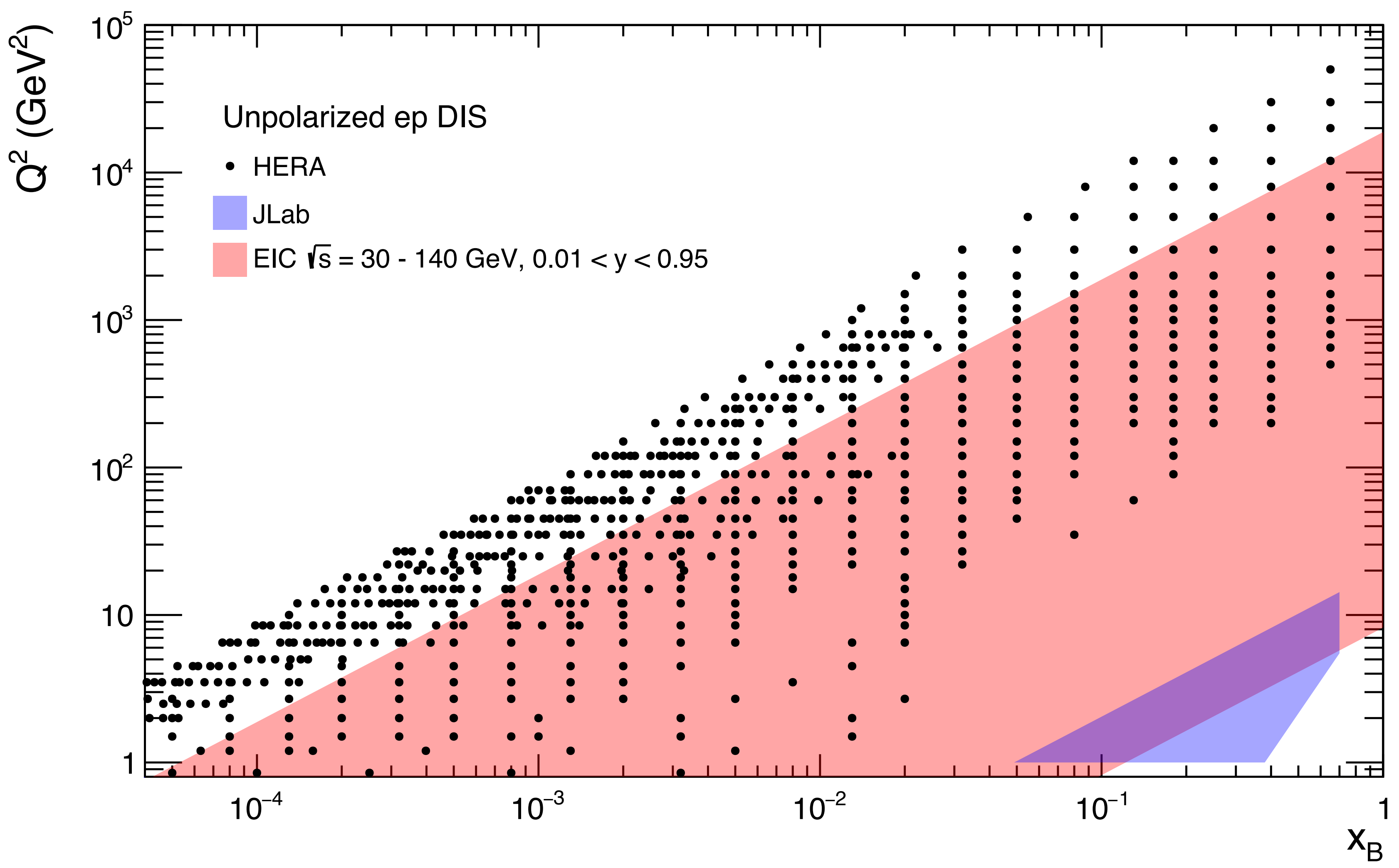

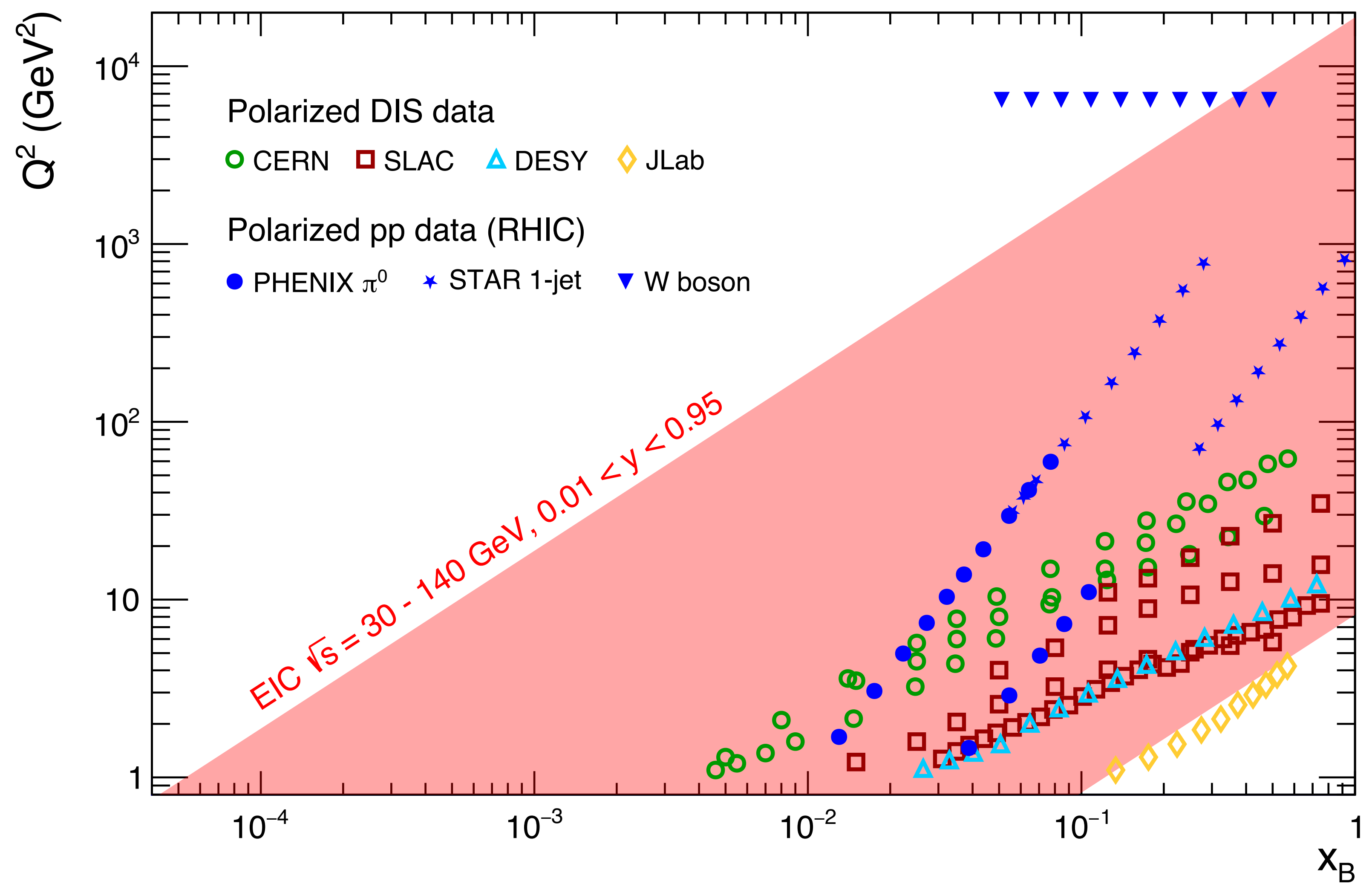

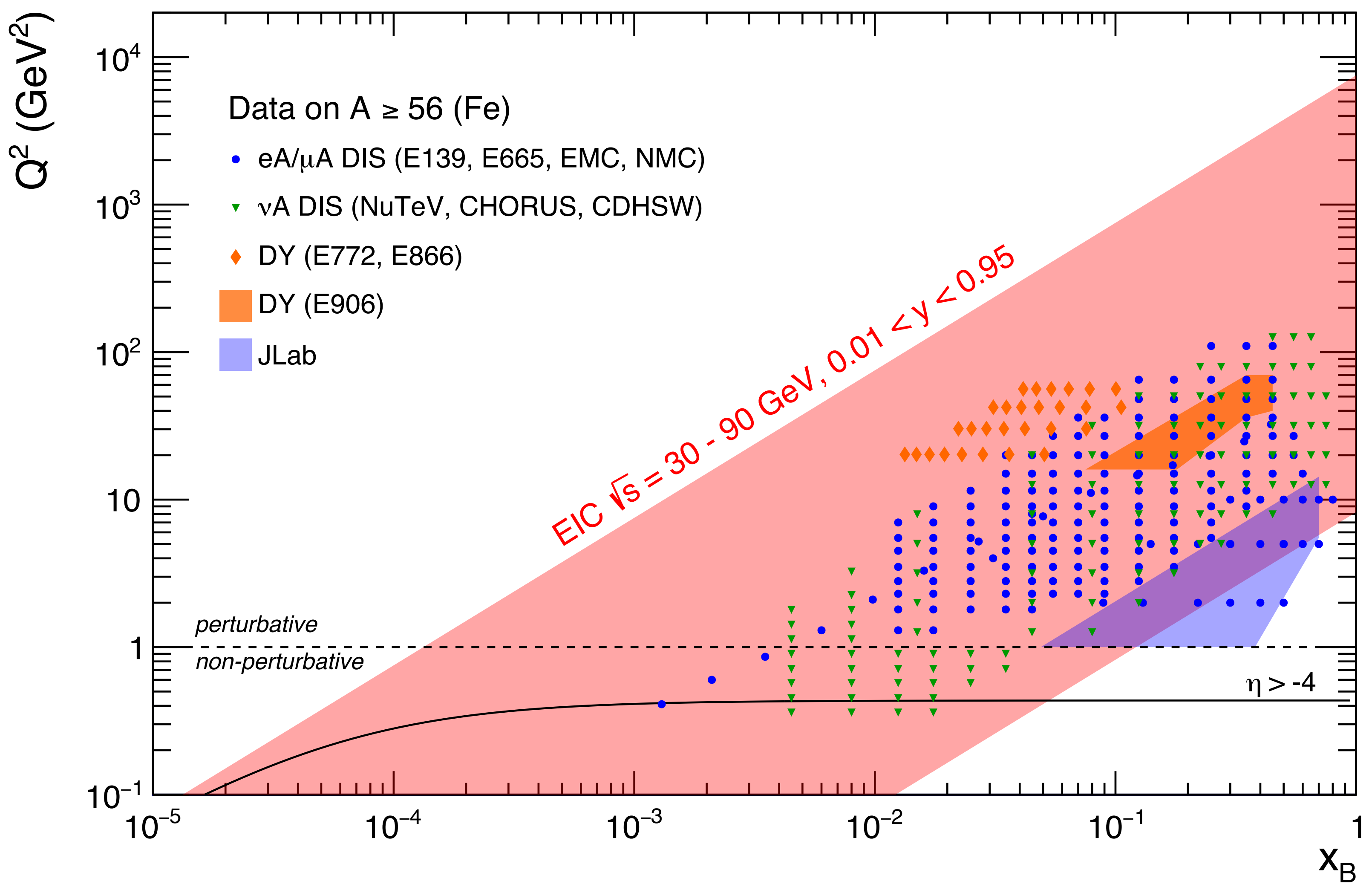

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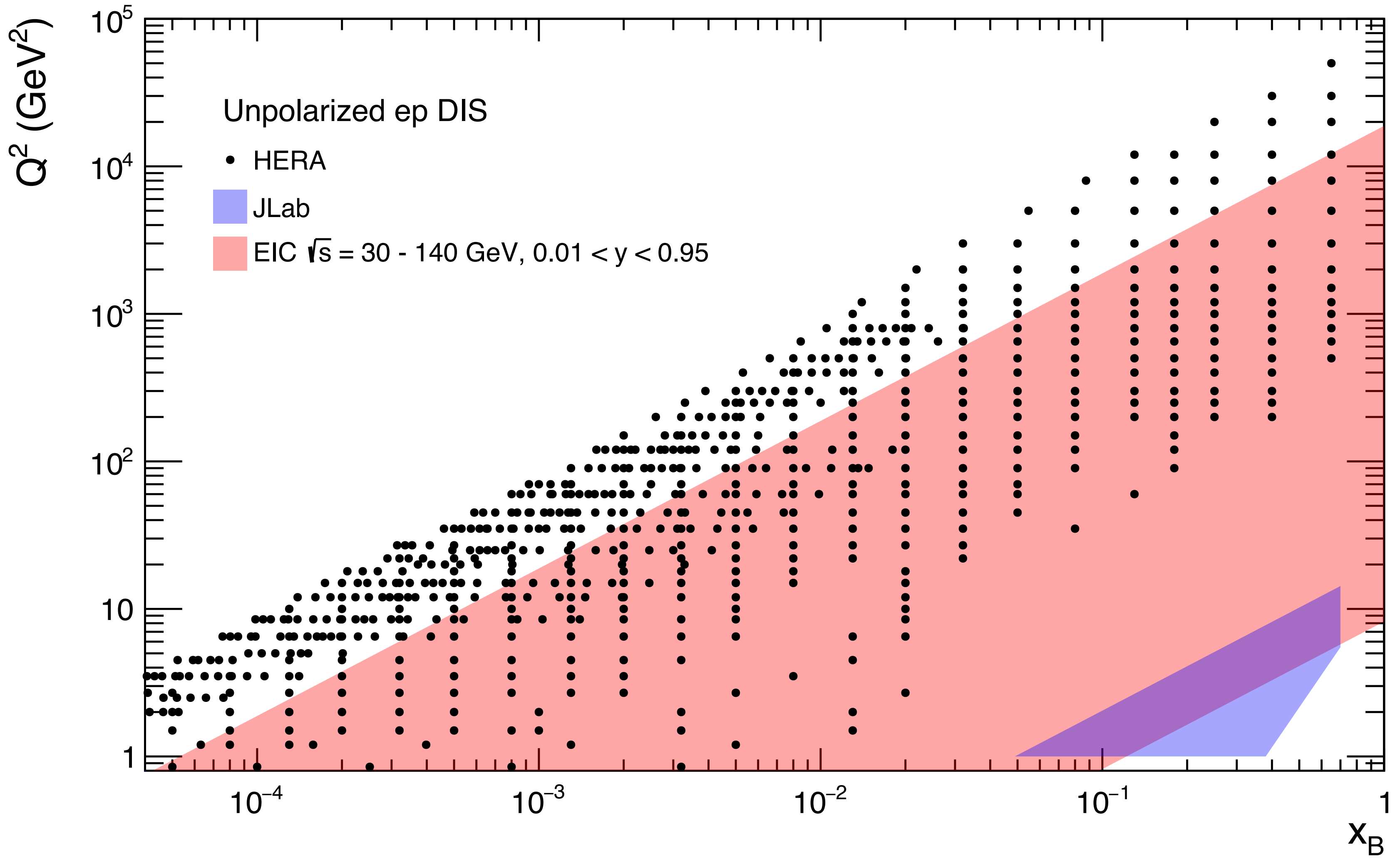
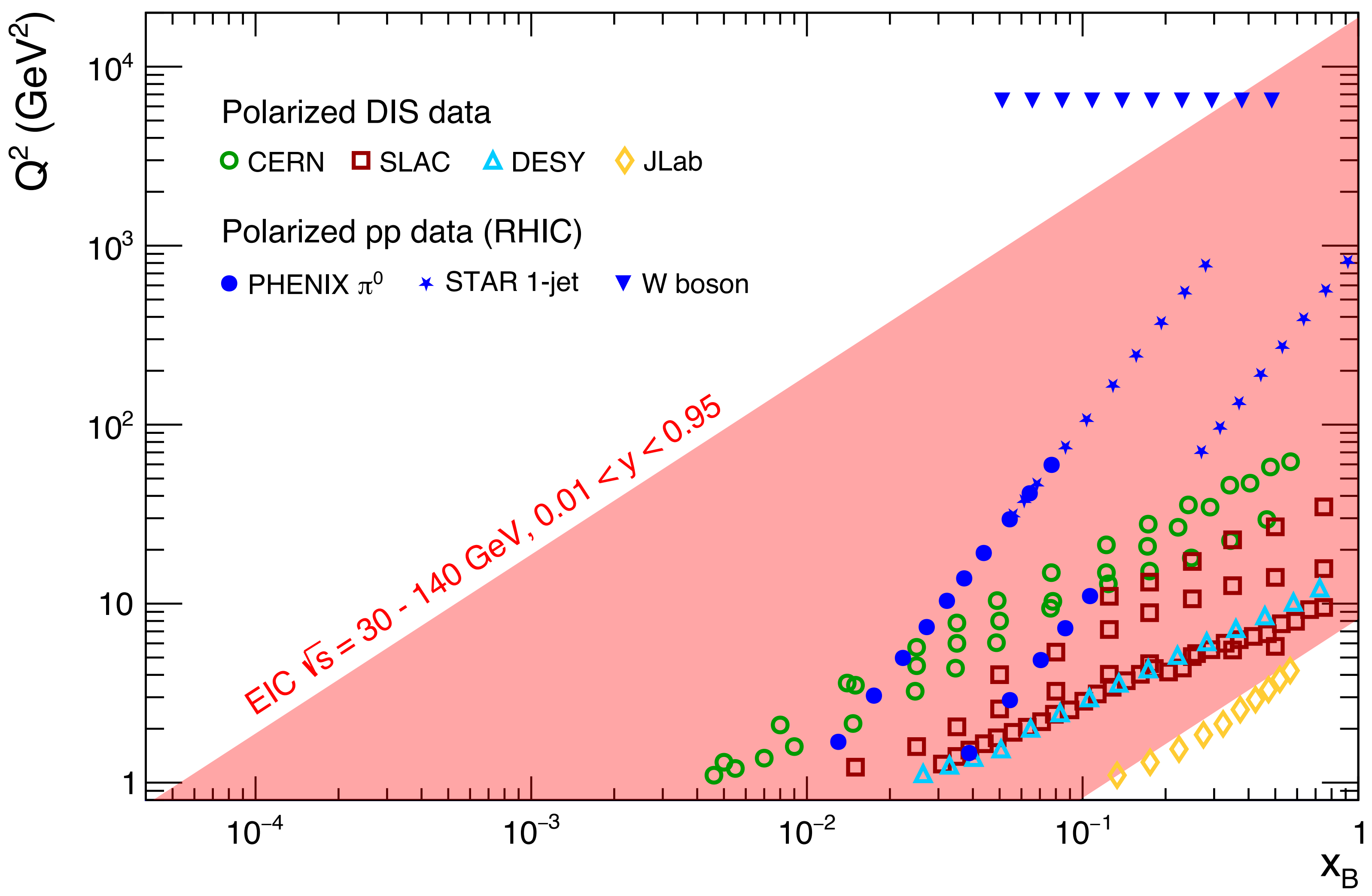
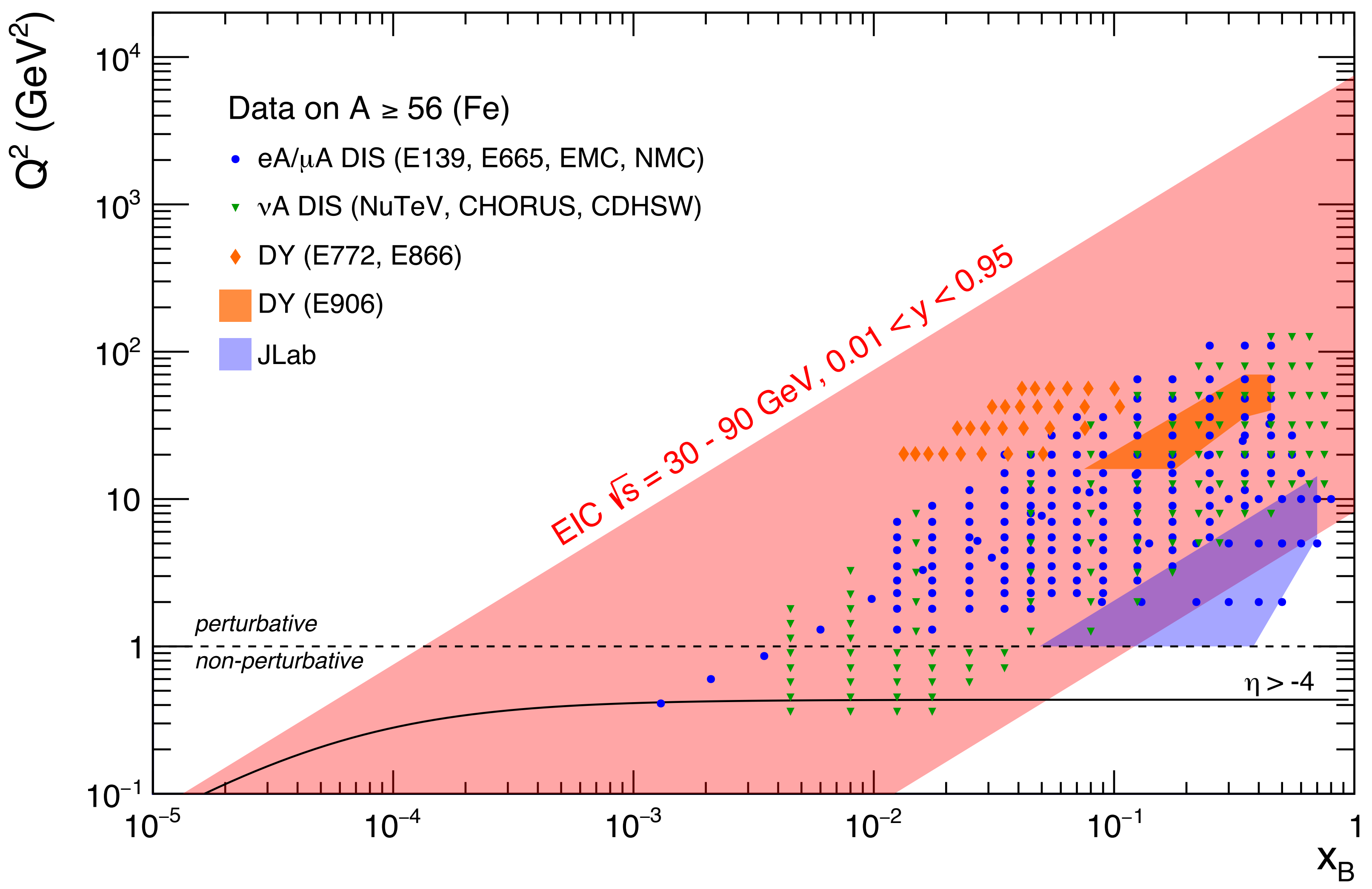


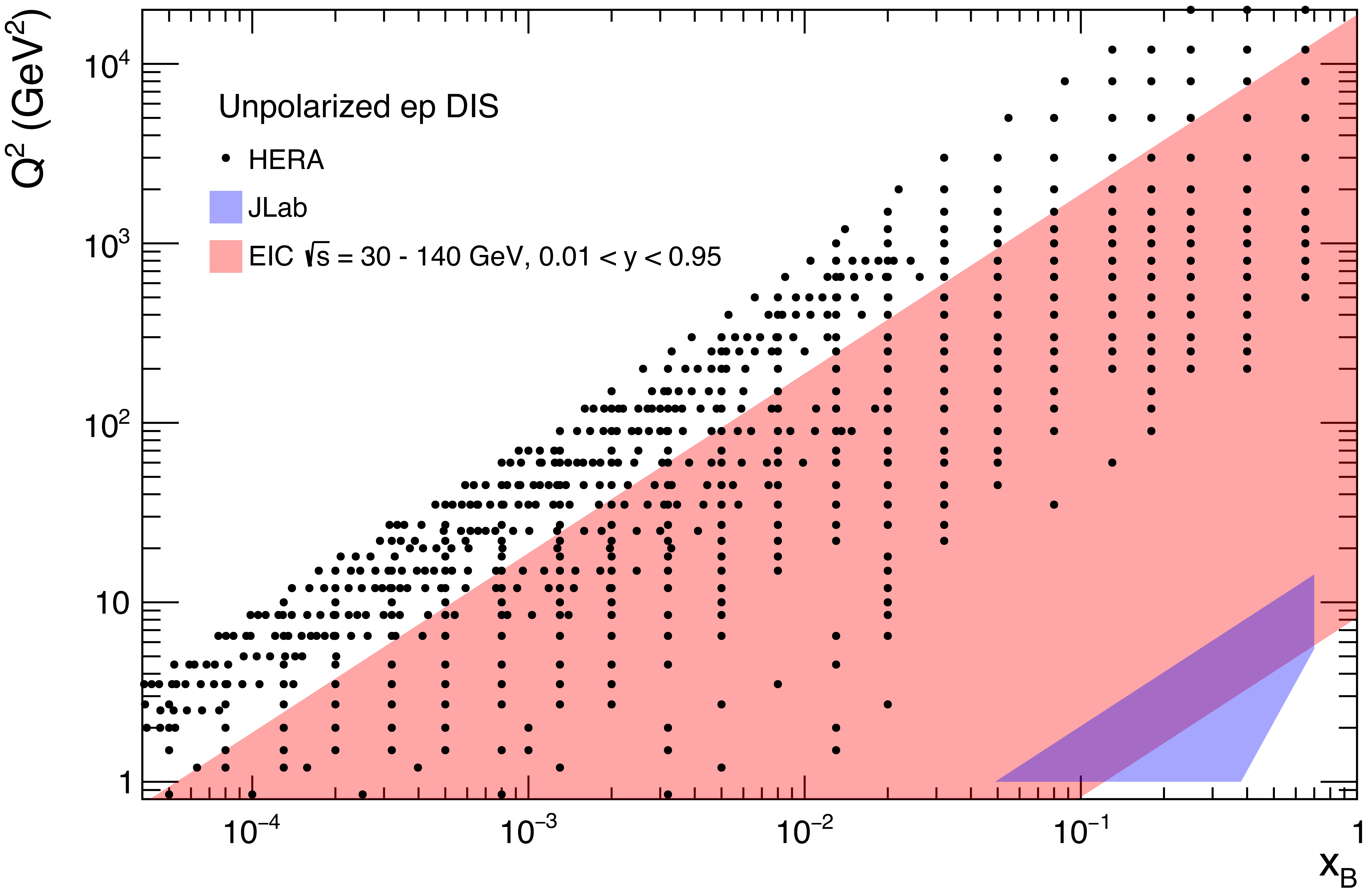




<u>Inclusive observables:</u>

- Neutral current cross sections
- Charge-current cross sections
- Double-spin asymmetries
- Parity-violating asymmetries (see Mike's talk tomorrow)

Unpolarized NC cross sections



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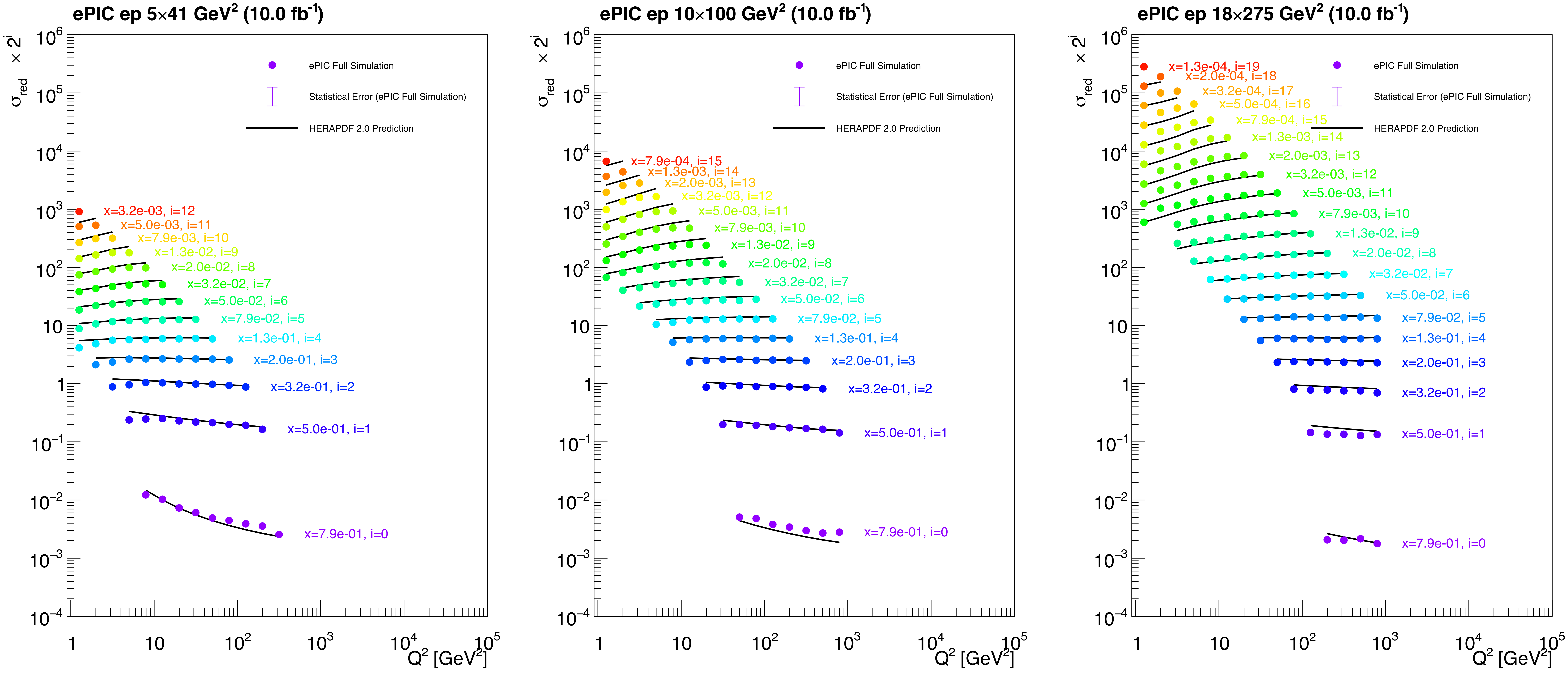
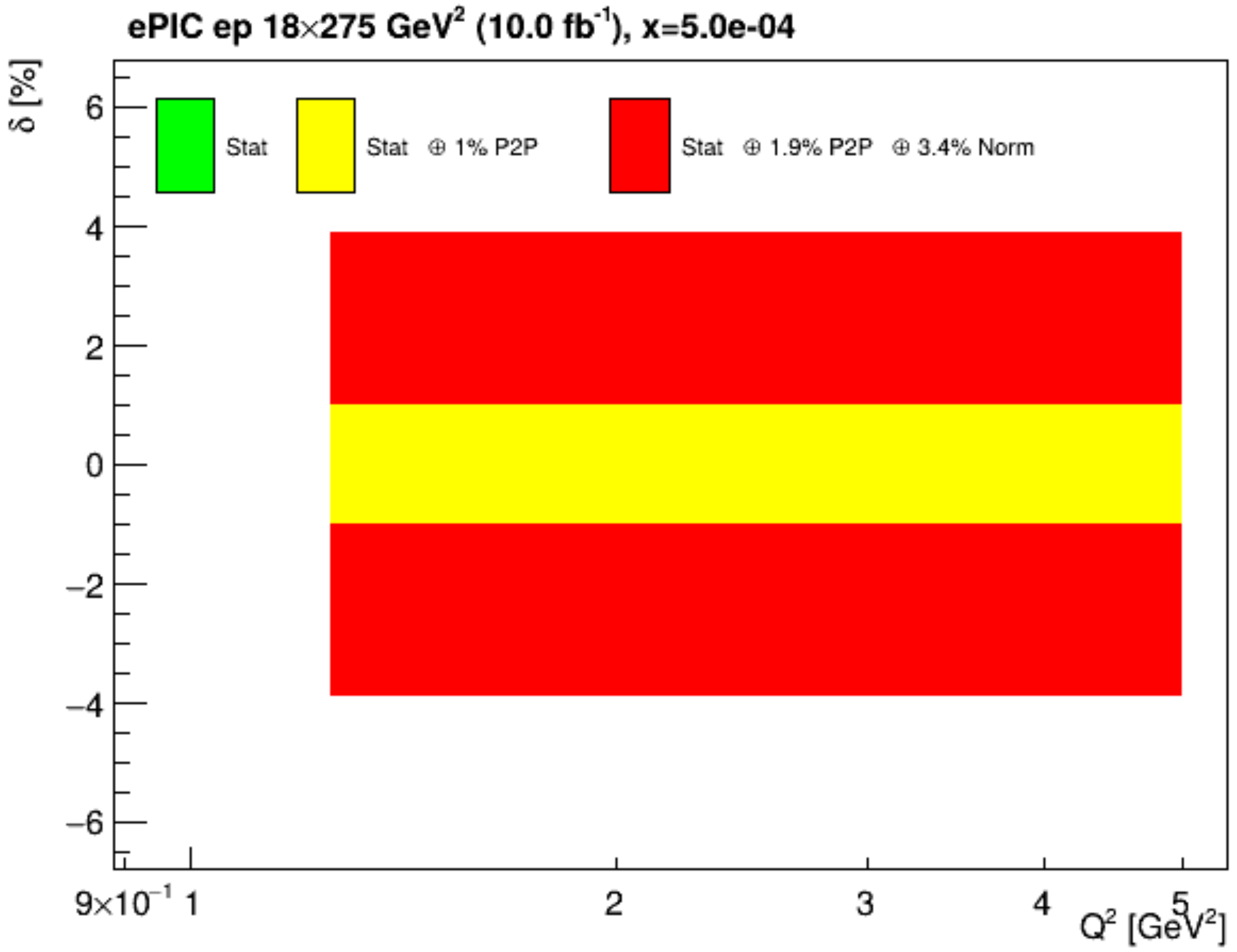
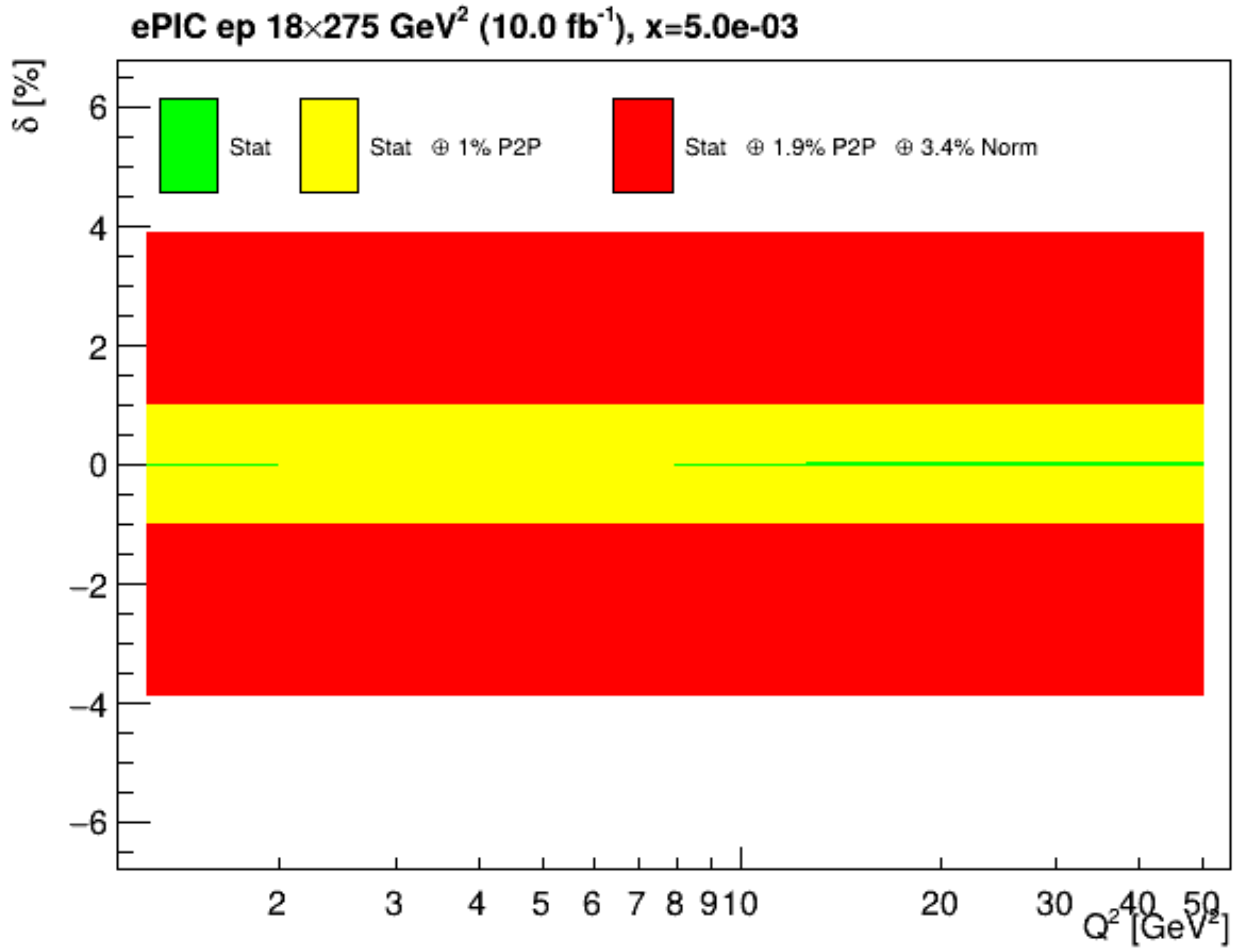
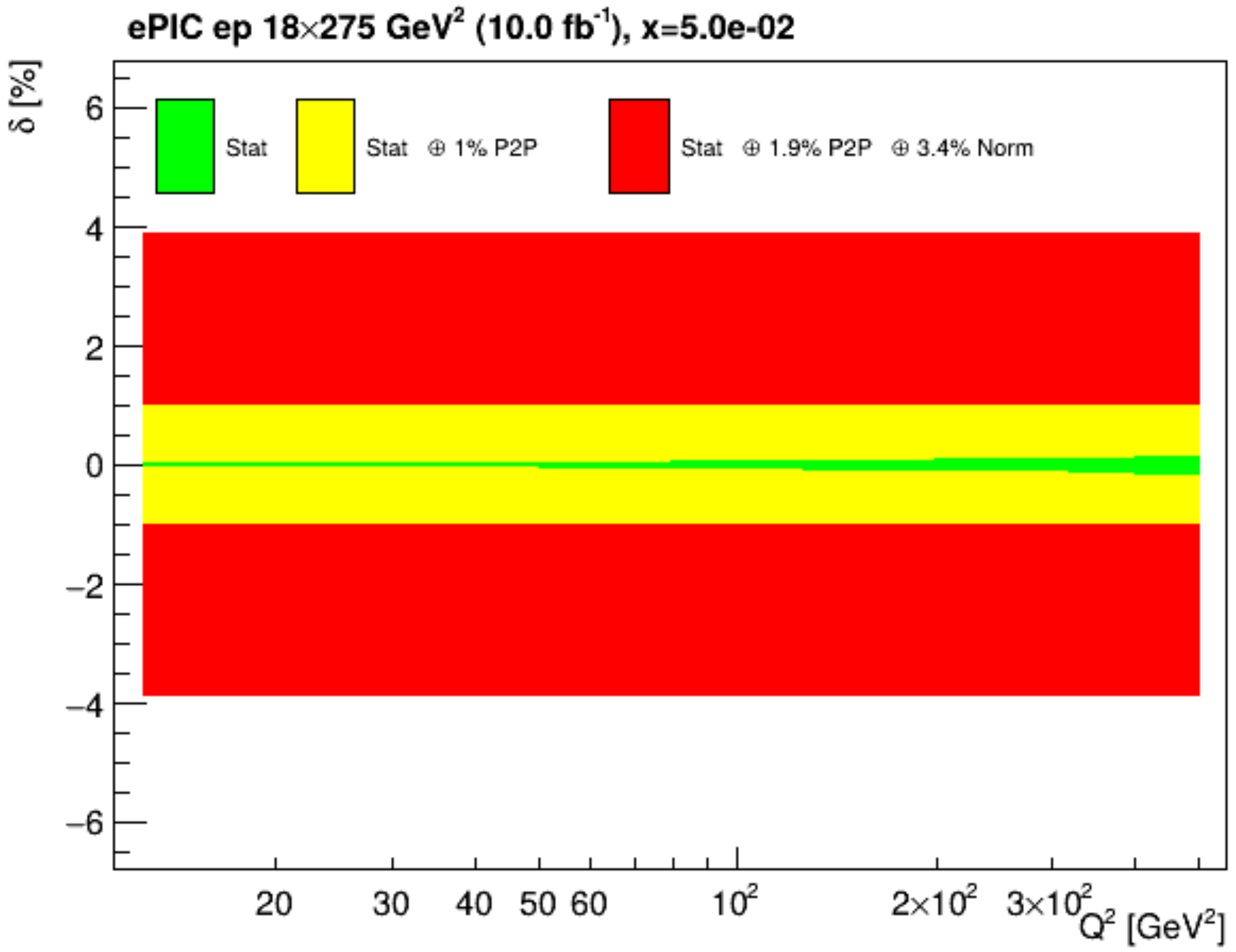
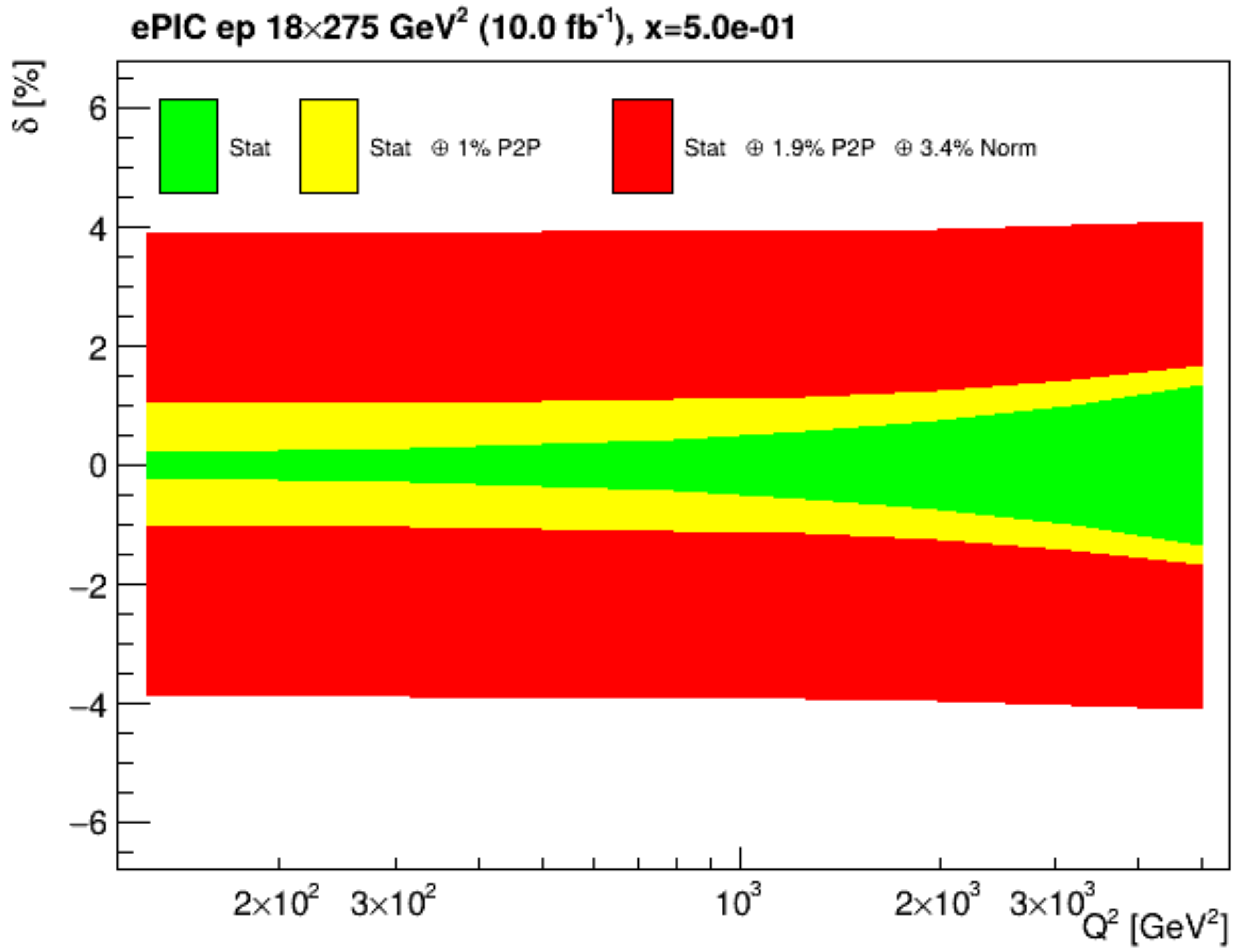


Unpolarized NC cross section precision



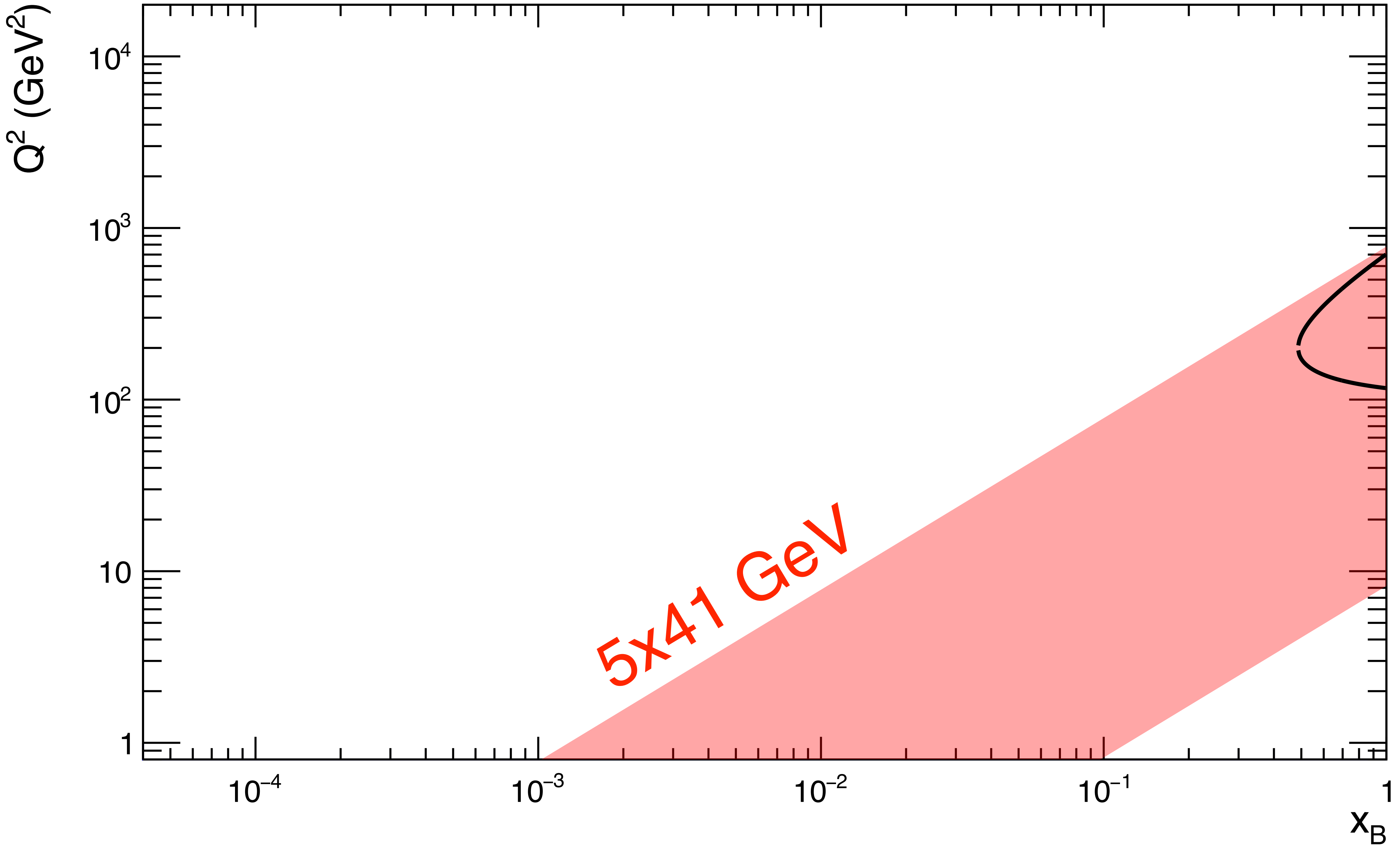


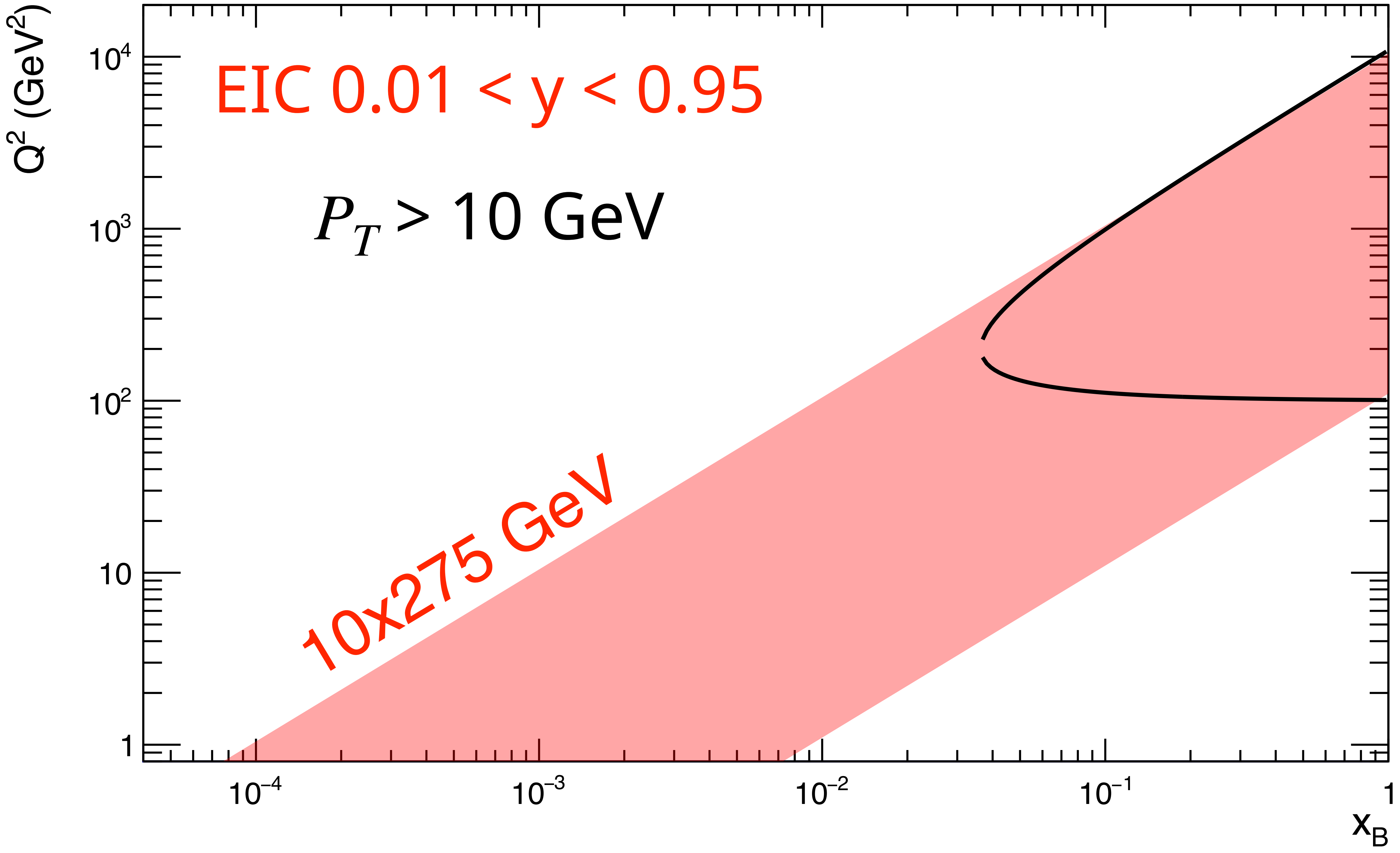


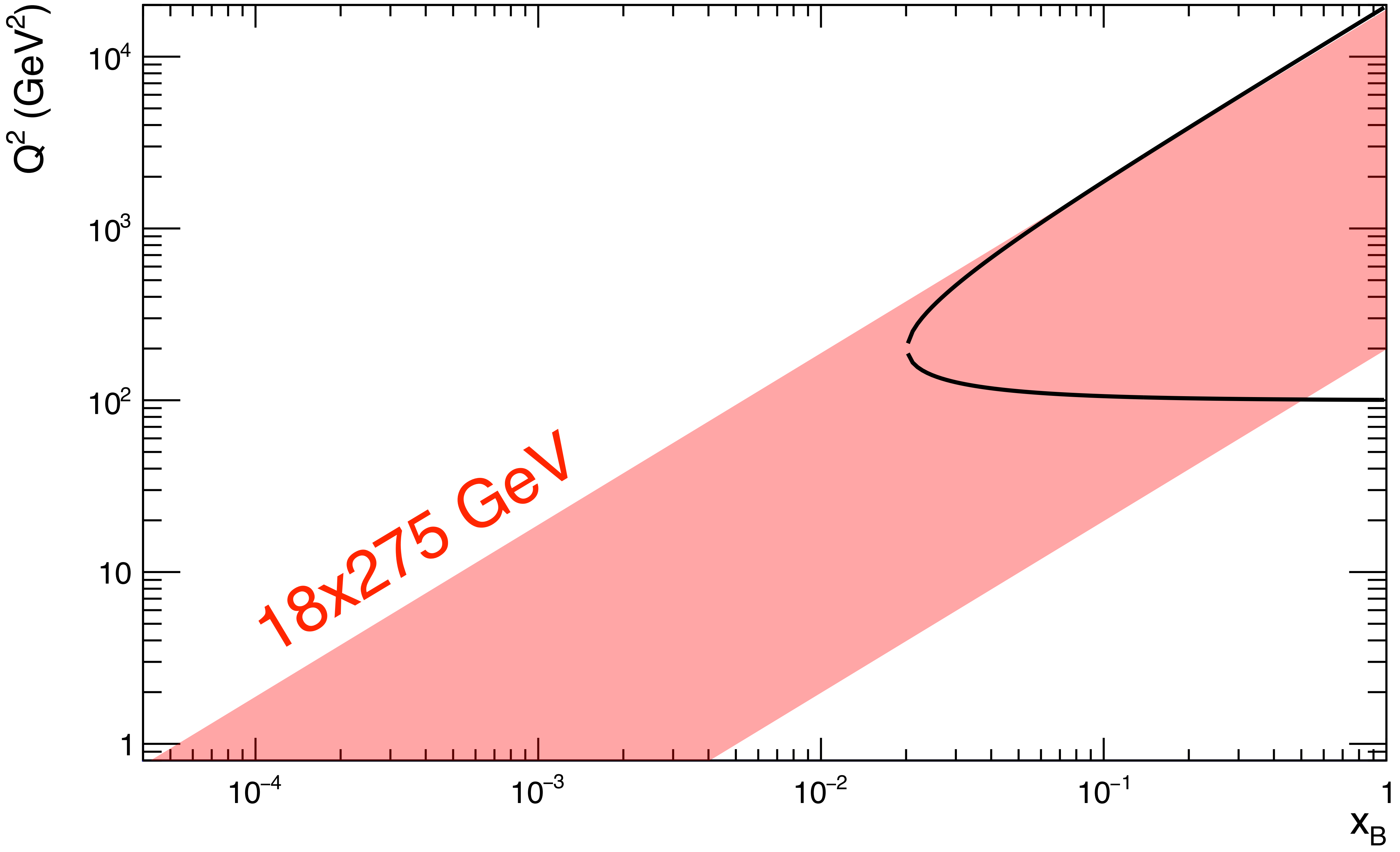


CC at EIC

- Not feasible at lowest COM energy
- Largest phase space at 18x275 GeV
- Peak luminosity at 10x275 GeV







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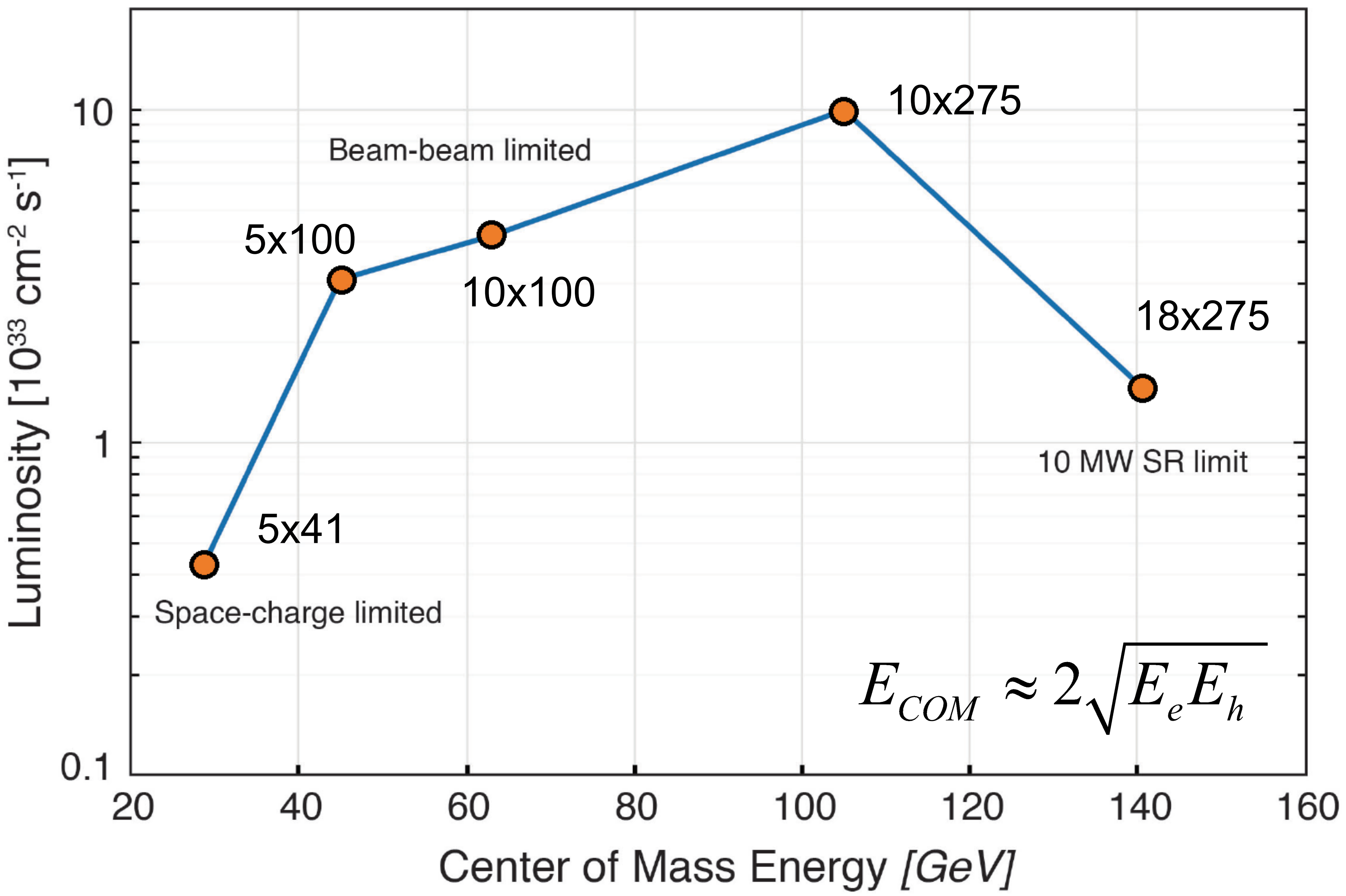

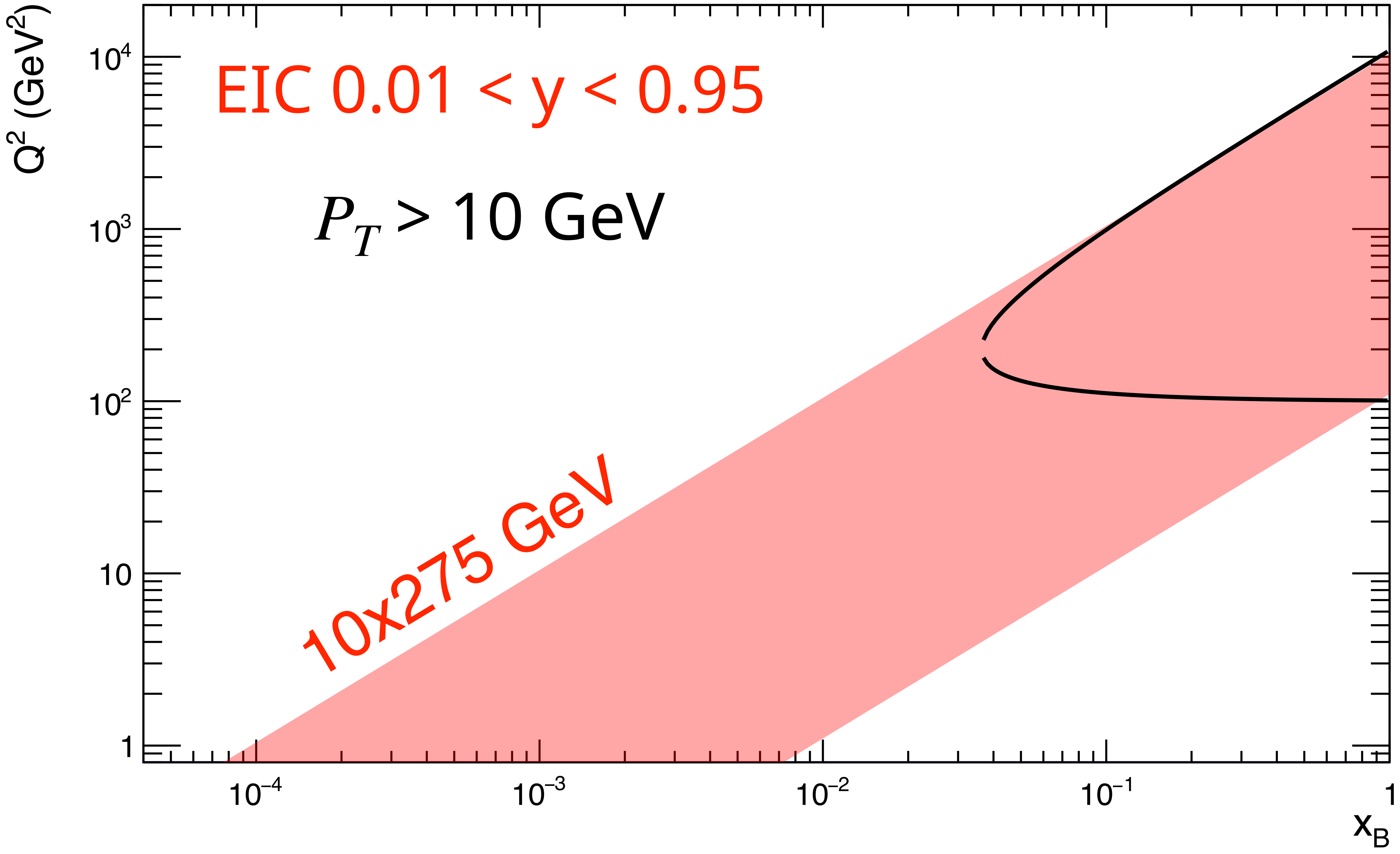

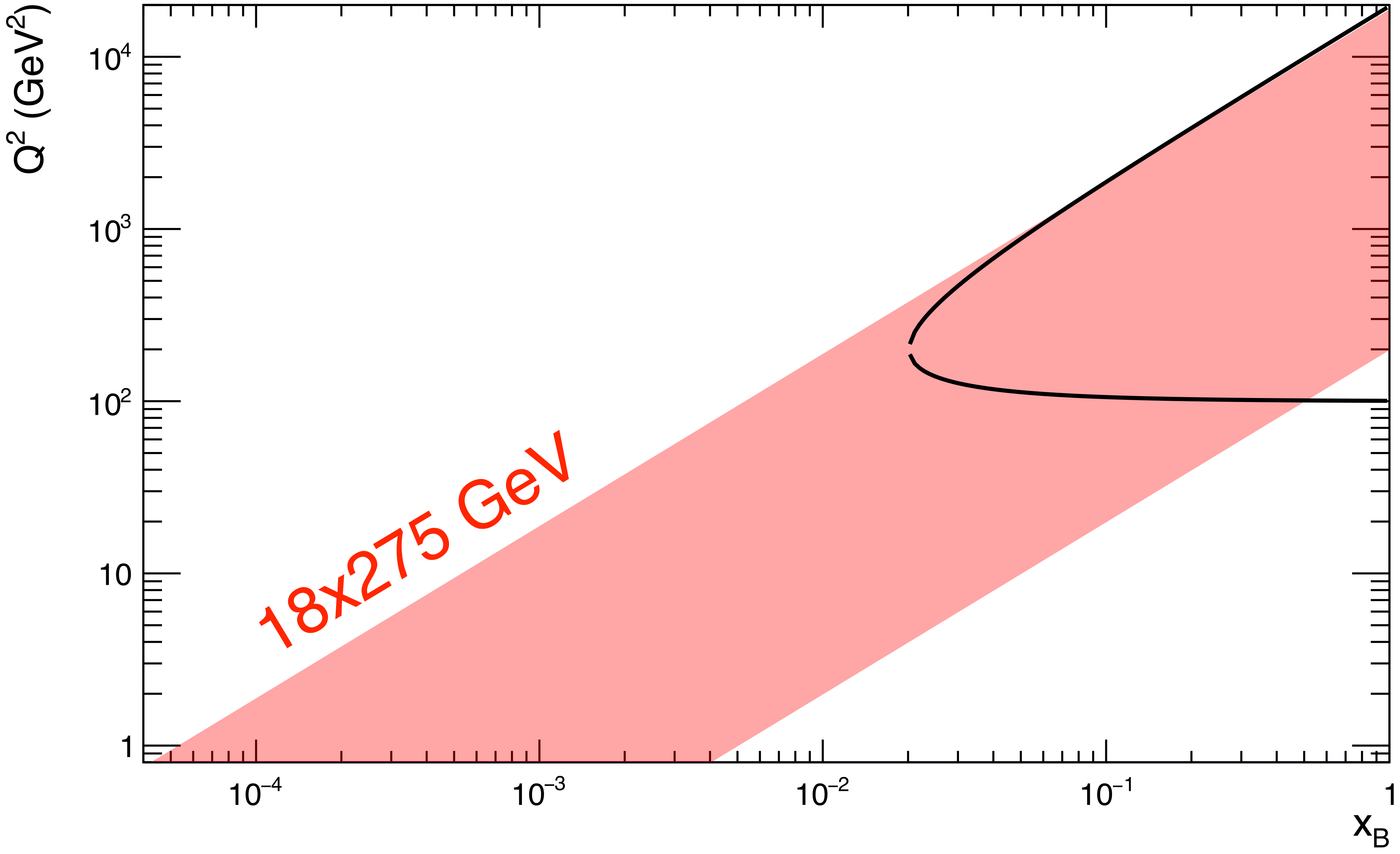

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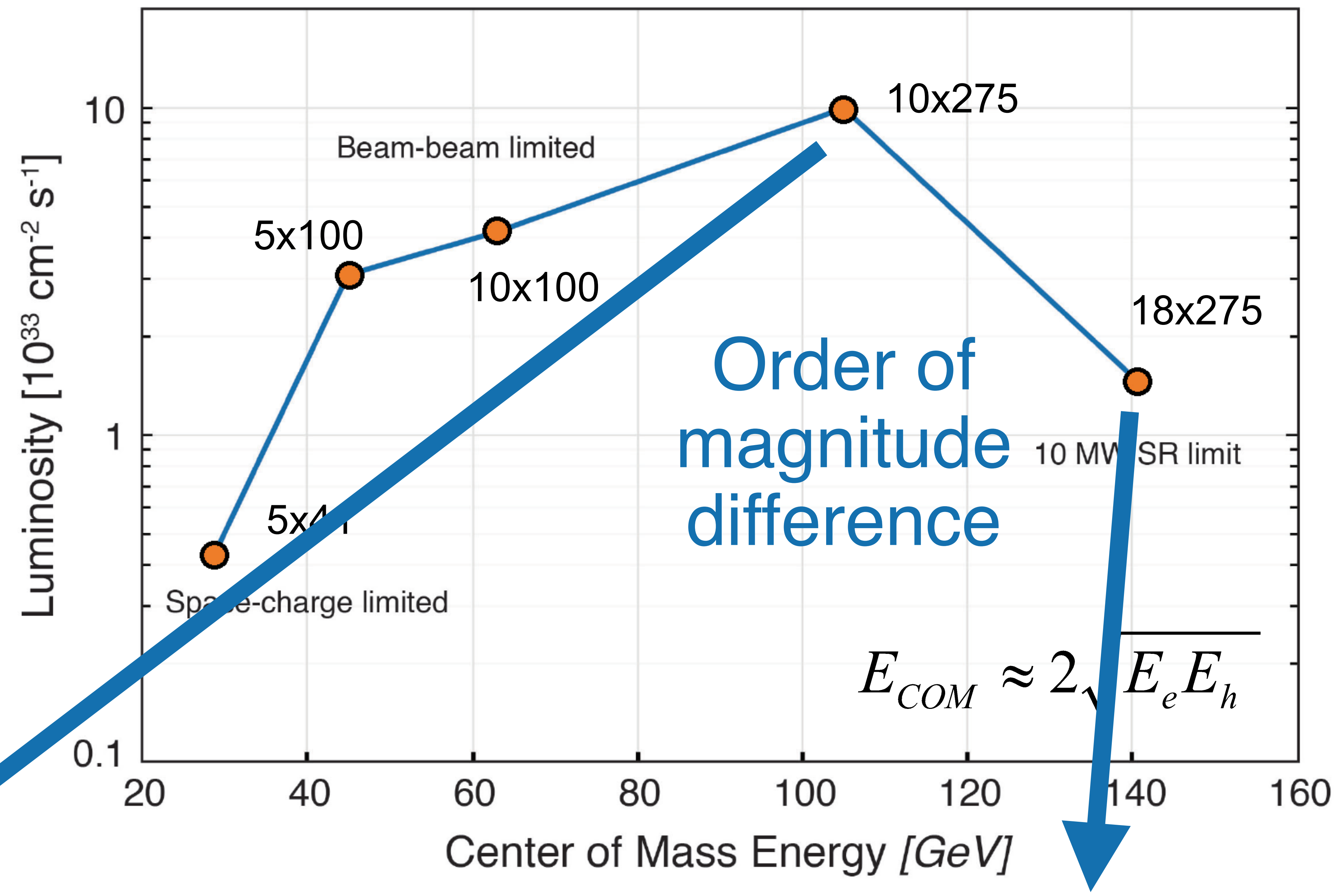

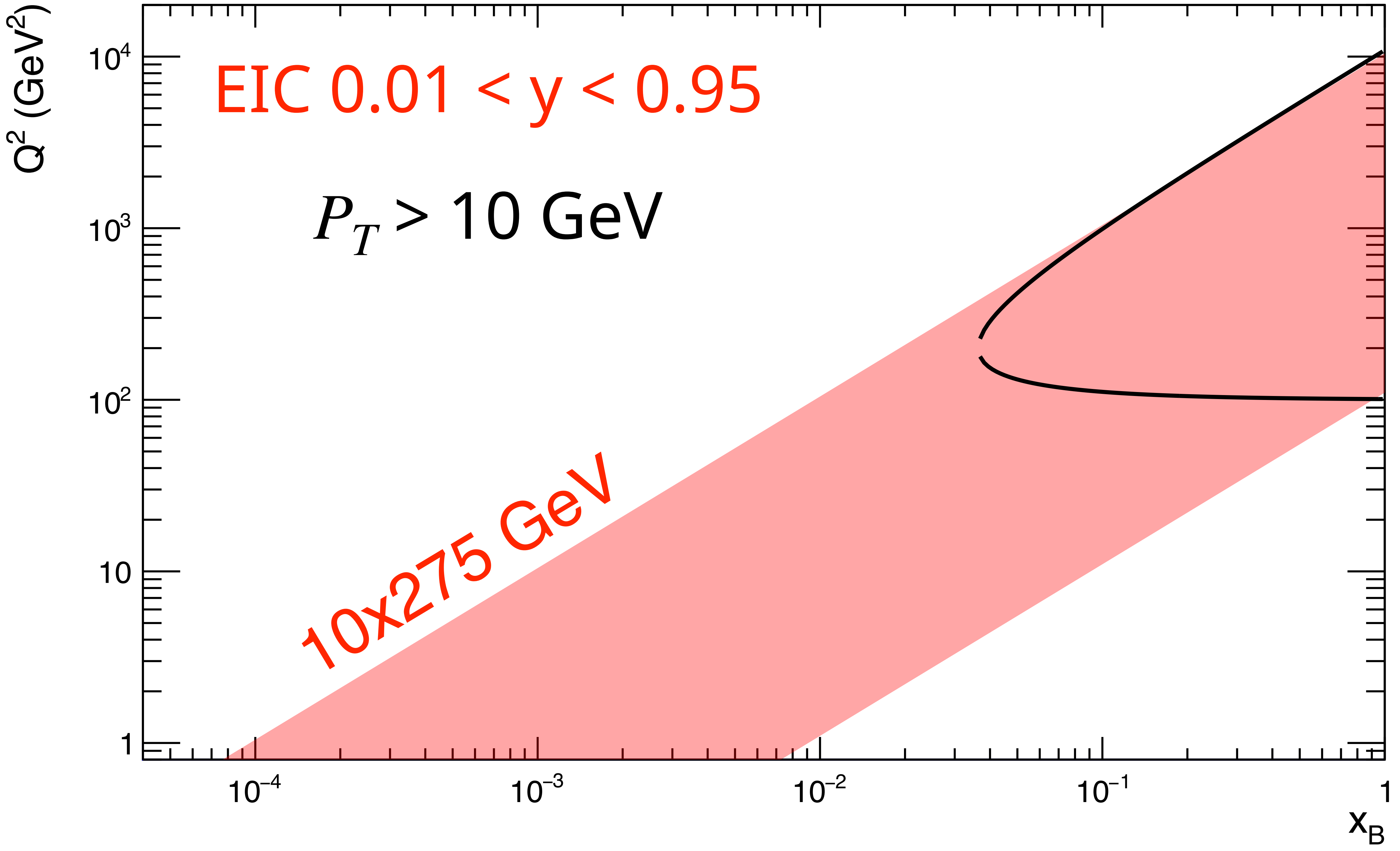

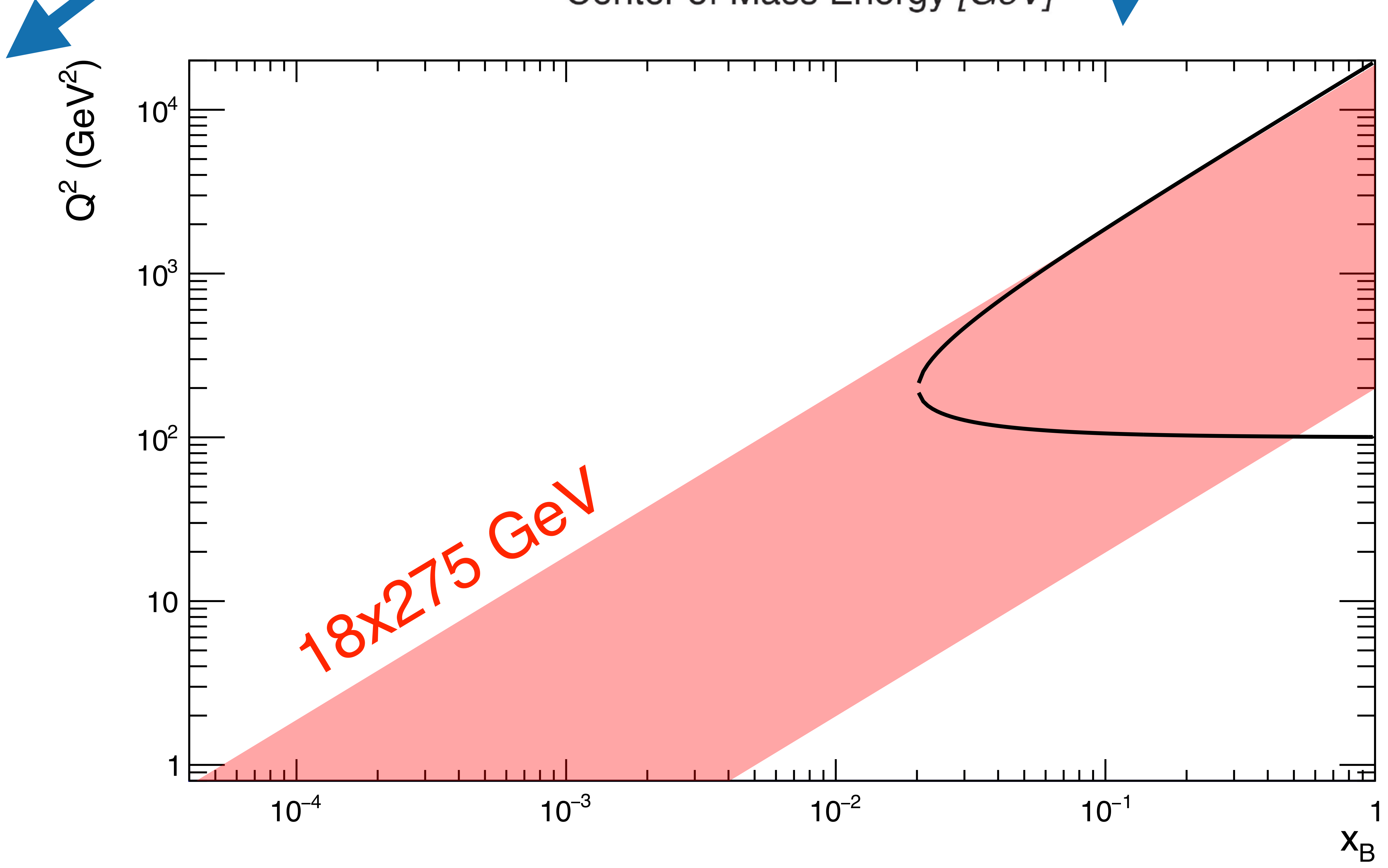

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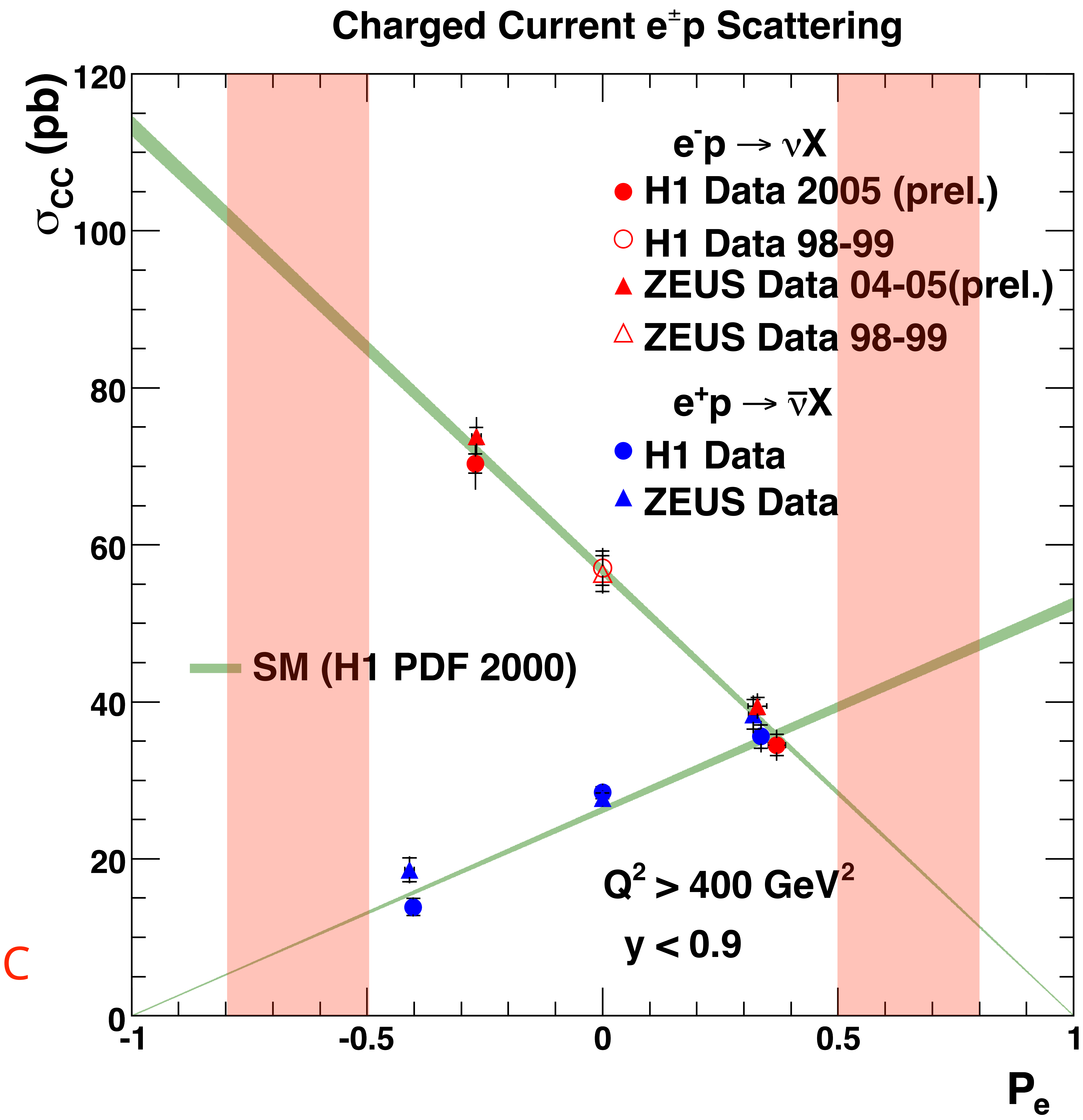

Larger polarization at EIC

Light quark couplings at future facilities

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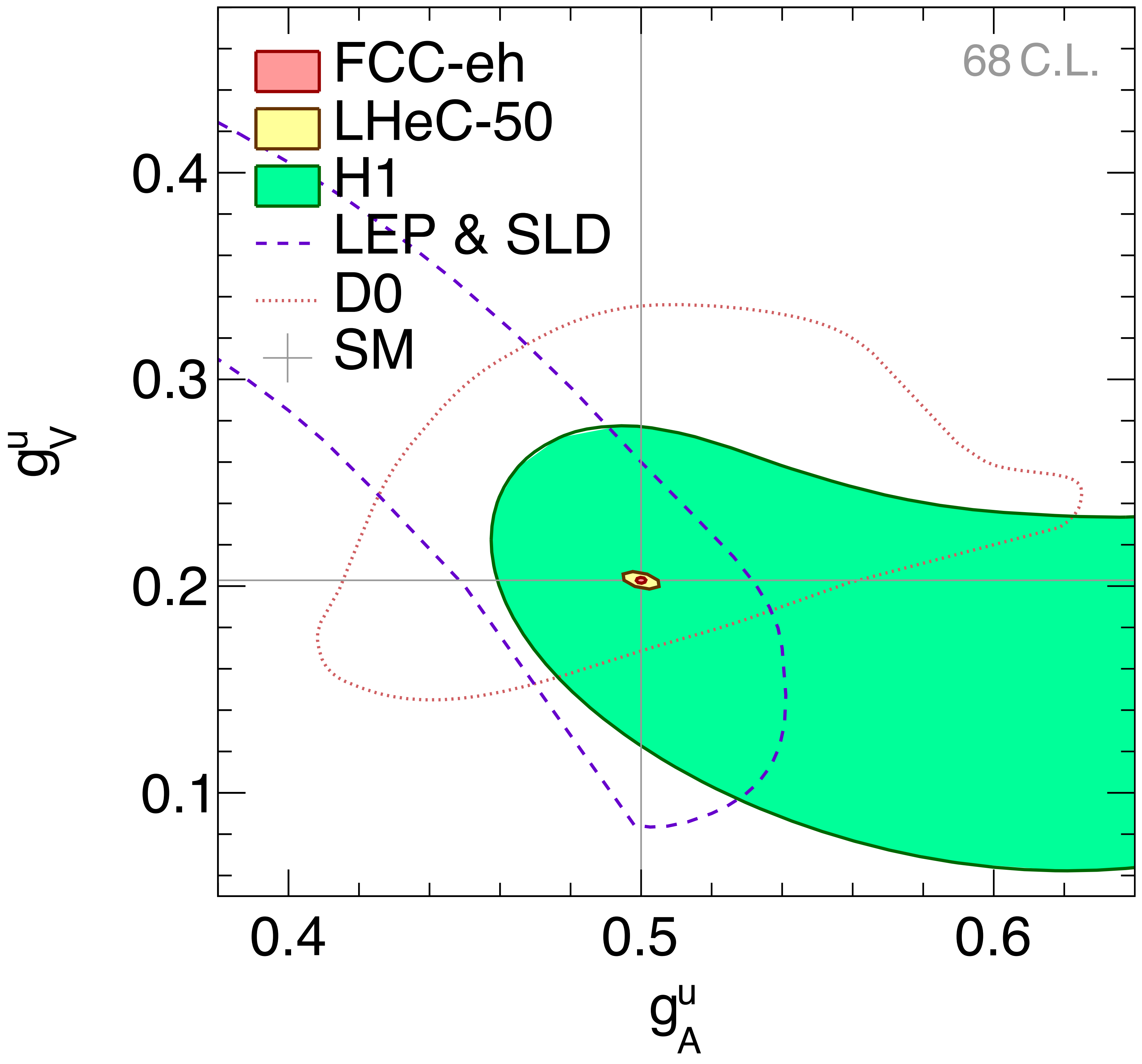

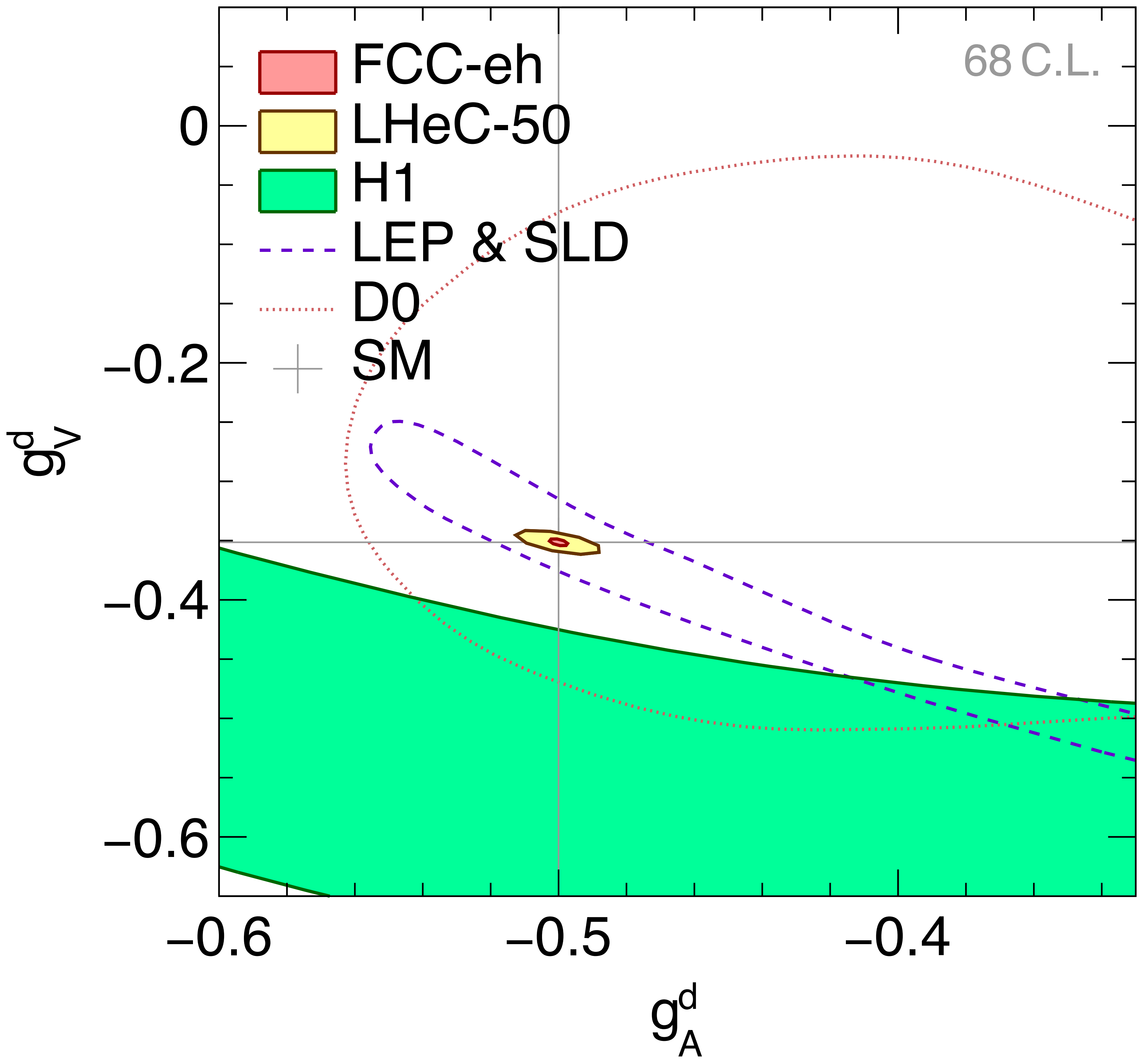

- FCC-eh, LHeC: high $\sqrt{s}$, ab^{-1} luminosity, positrons...
- EIC can't compete, but it is much closer to being realized... can it contribute to existing constraints from HERA?

Origin of proton spin

$$\Delta\Sigma/2 + \Delta G + L_q + L_g = \frac{1}{2}$$

Origin of proton spin

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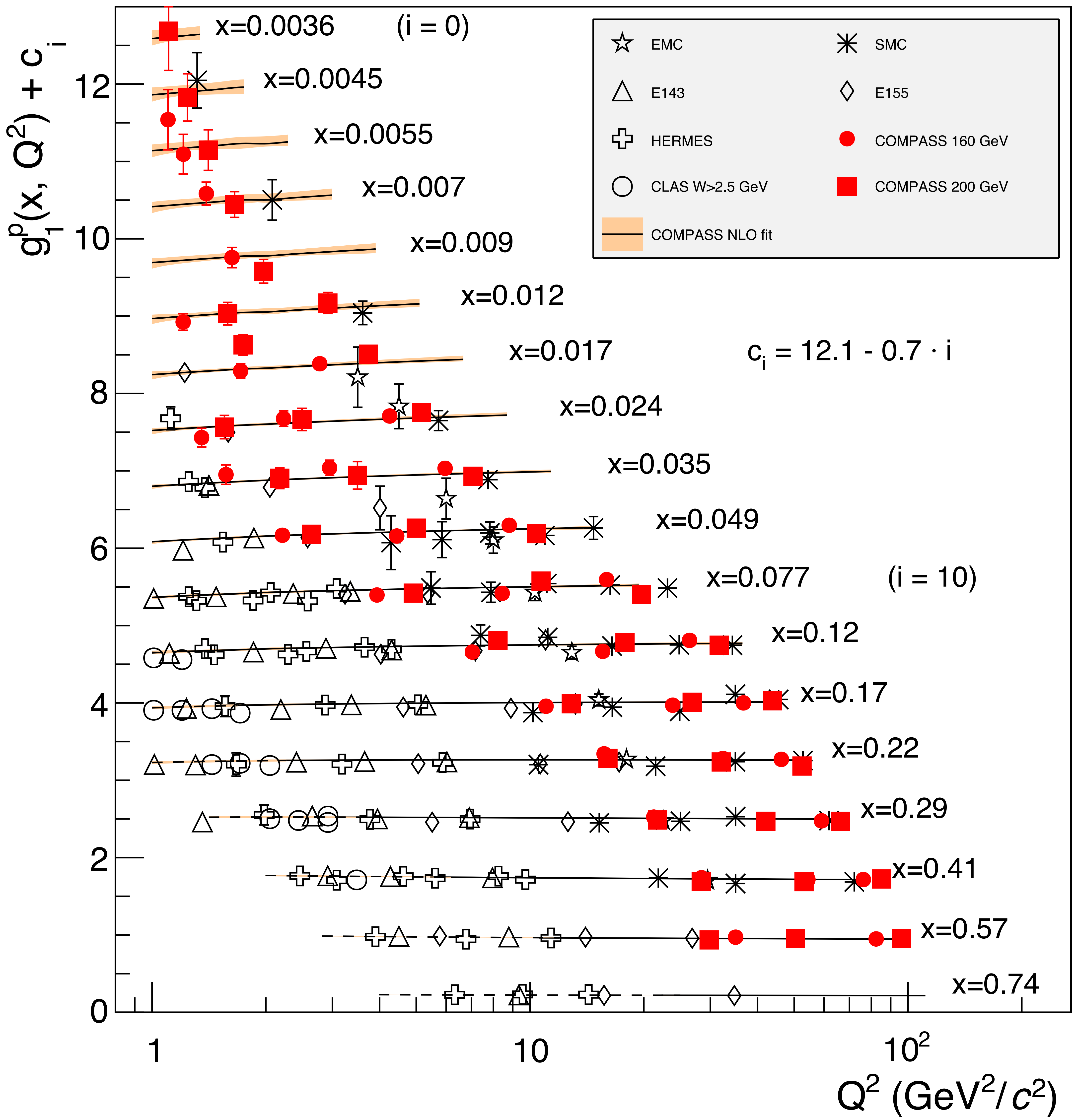
COMPASS PLB 753, 18 (2016)

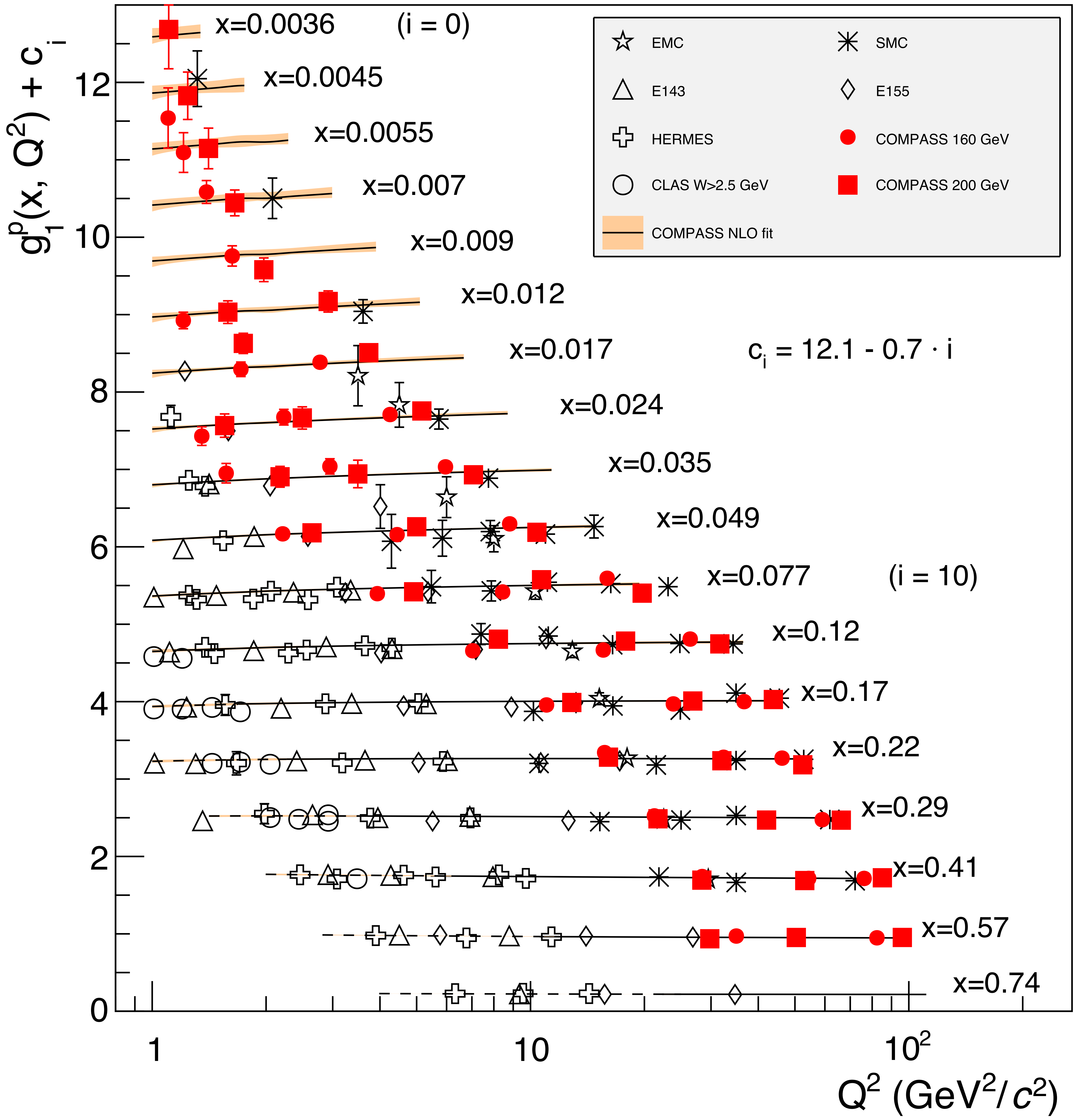


Origin of proton spin

$$\Delta\Sigma/2 + \Delta G + L_q + L_g = \frac{1}{2}$$

$\approx 30\%$

COMPASS PLB 753, 18 (2016)



Origin of proton spin

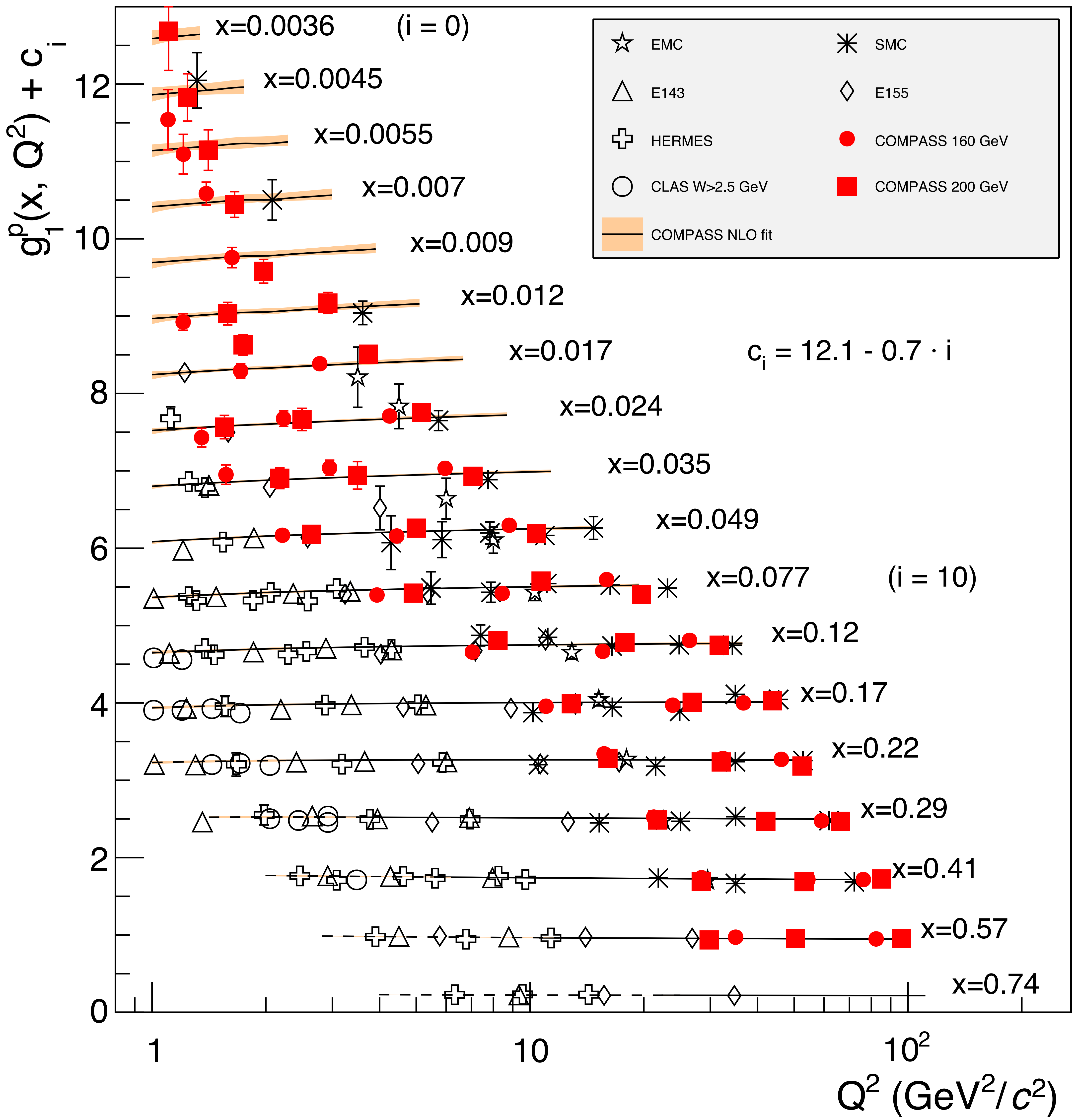
$$\Delta\Sigma/2 + \Delta G + L_q + L_g = \frac{1}{2}$$

≈ 30%

≈ 40%

Large uncertainty!

COMPASS PLB 753, 18 (2016)



Origin of proton spin

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≈ 30%

≈ 40%

Large uncertainty!

?%

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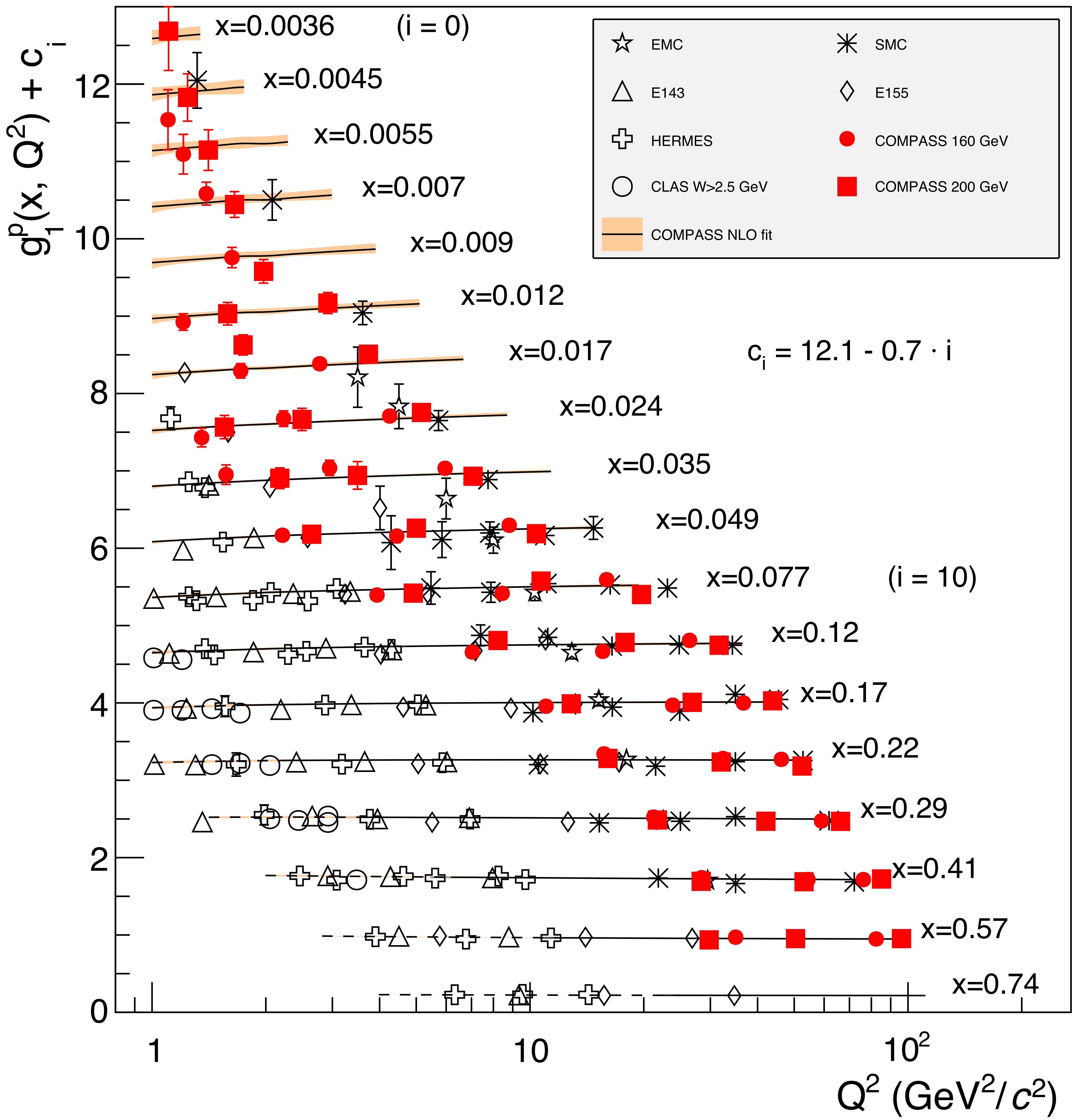
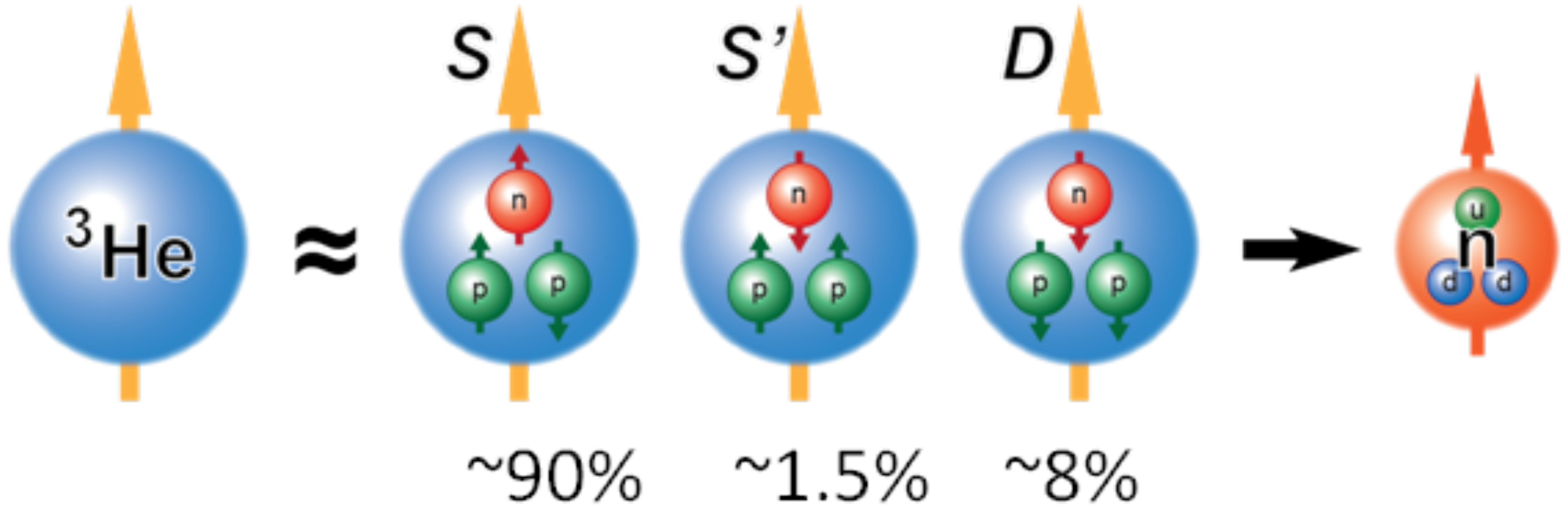


Spin structure functions from double-spin asymmetries

$$A_1 = \frac{A_\parallel}{D(1+\eta\xi)} - \frac{\eta A_\perp}{d(1+\eta\xi)}$$

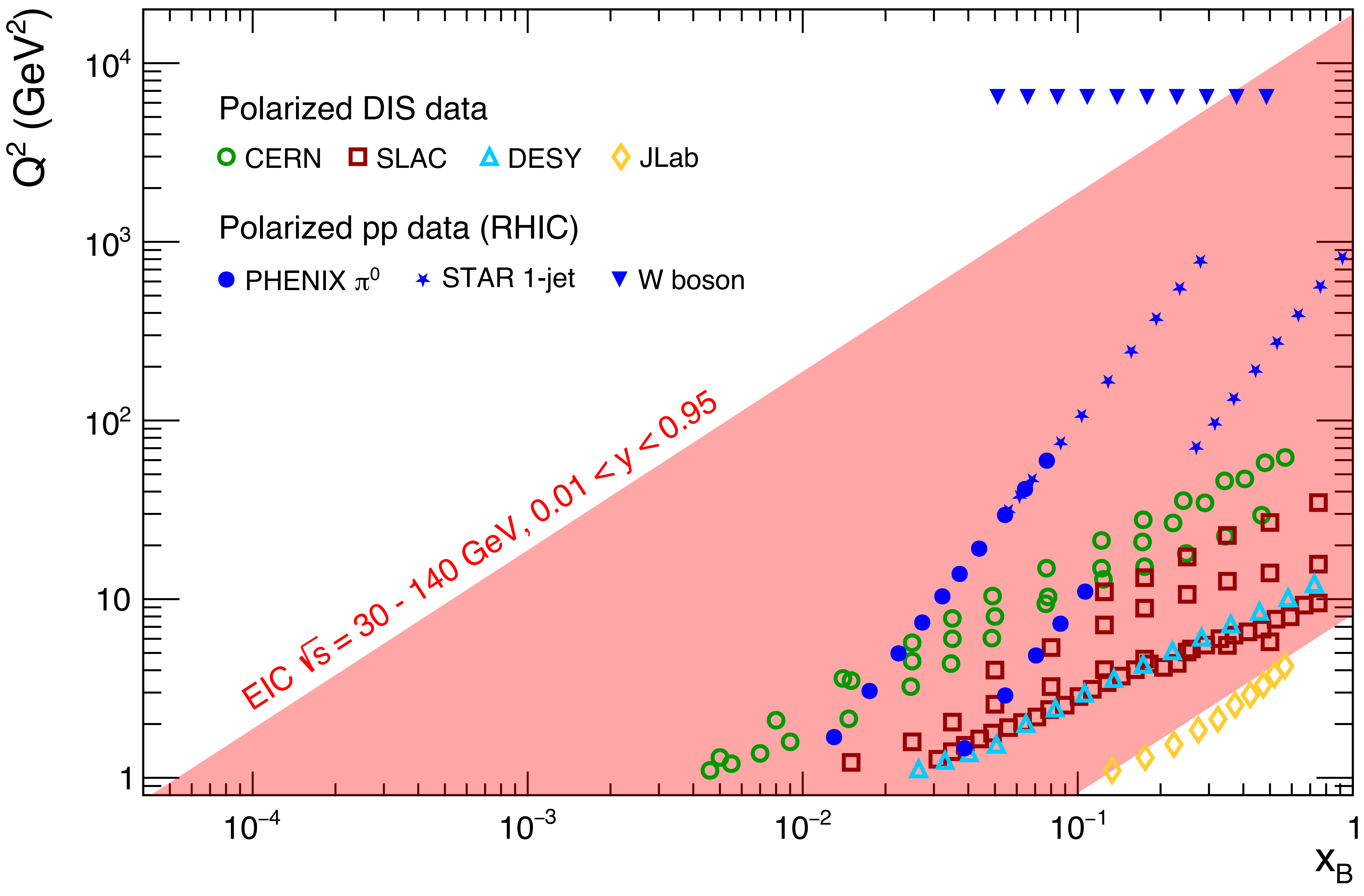
$$\approx g_1 / F_1$$

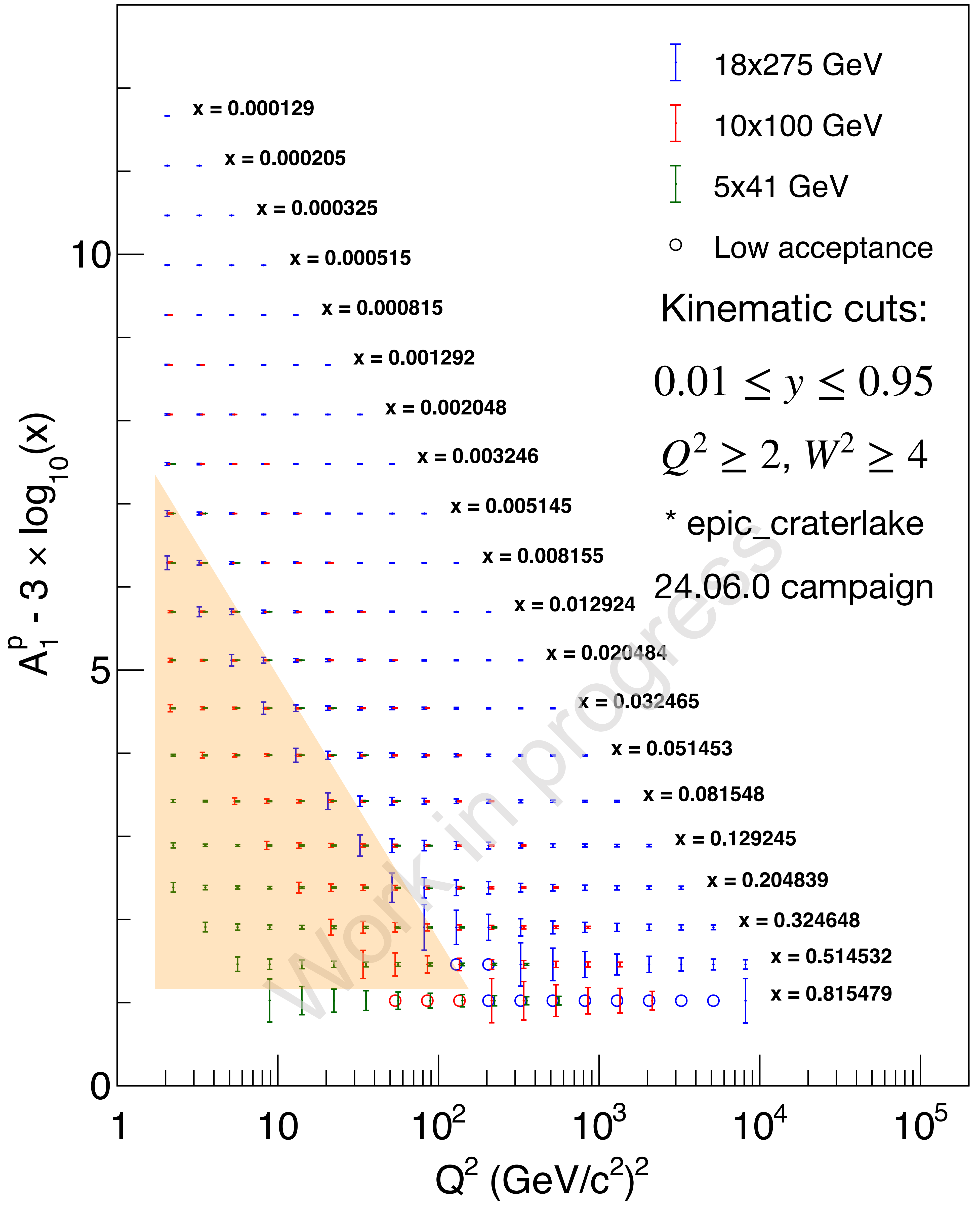
$$A_\parallel = \frac{\sigma^{\leftrightarrows} - \sigma^{\rightrightarrows}}{\sigma^{\leftrightarrows} + \sigma^{\rightrightarrows}} \quad \text{and} \quad A_\perp = \frac{\sigma^{\rightarrow\uparrow} - \sigma^{\rightarrow\downarrow}}{\sigma^{\rightarrow\uparrow} + \sigma^{\rightarrow\downarrow}}$$



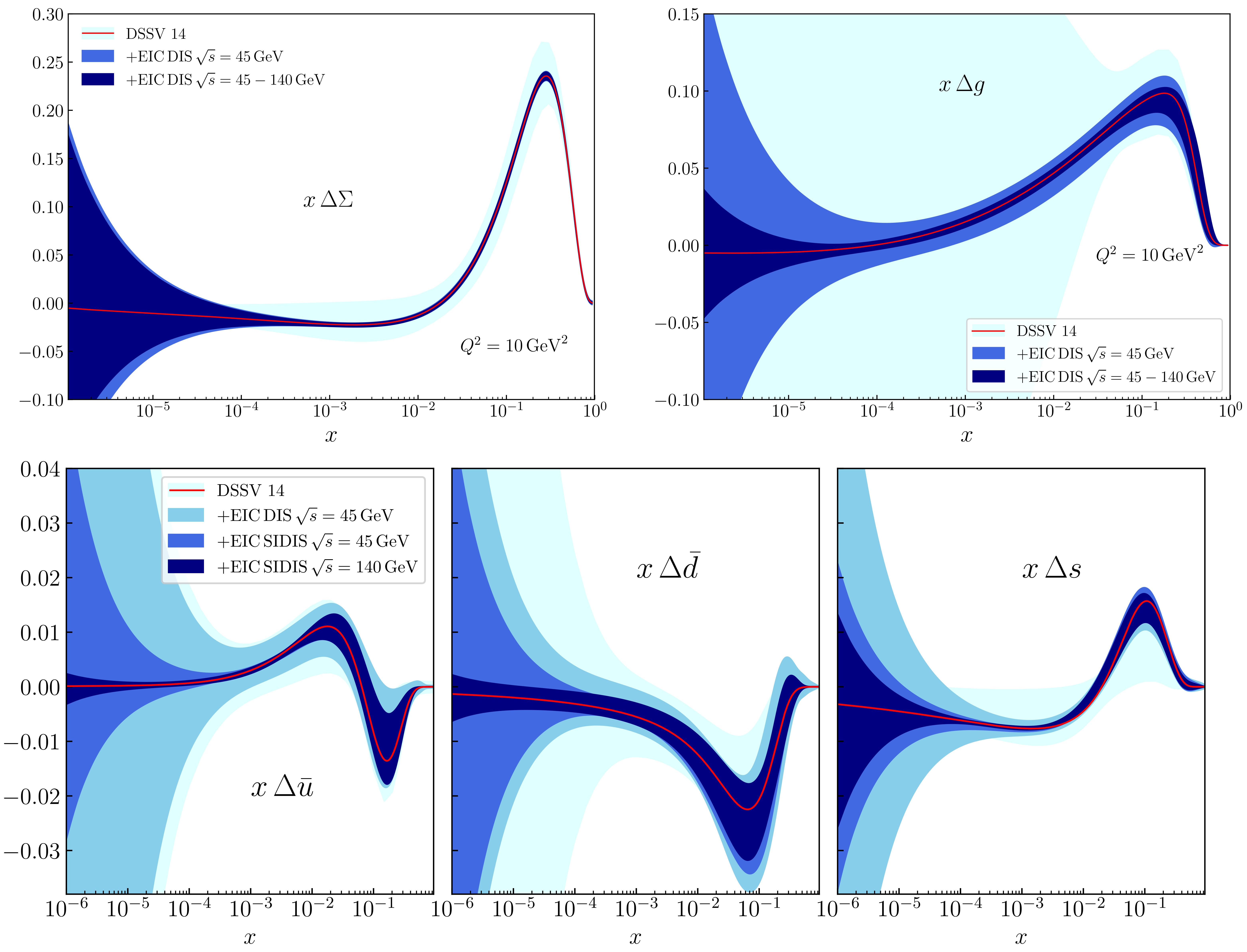
- Access g_1^p directly from A_1^p
- Access g_1^n from helium-3
  - Traditional method: measure A_1^p, $A_1^{^3He}$ and apply nuclear corrections
  - Possible EIC method: “tag” neutron scattering with two spectator protons in far-forward detector

EIC will make major contribution to ΔG at low-x





Impact of EIC measurements



From Yellow report…. working towards ePIC-specific impact plots

α_S at the EIC

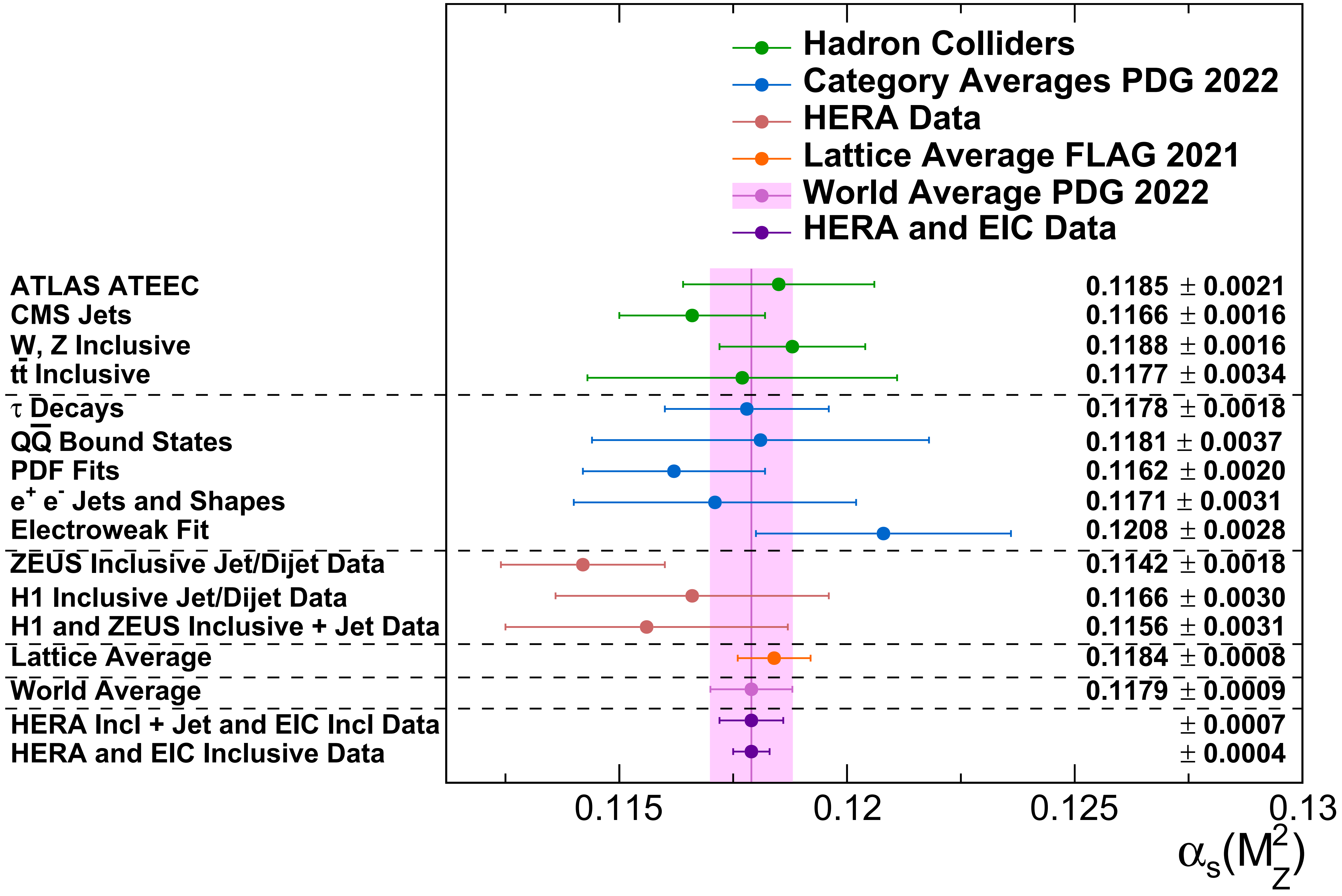
- Simultaneous fit of α_S, PDFs on unpolarized cross sections
- Extract α_S from proton/neutron g_1 using Bjorken sum rule:

$$\Gamma_1^{\mathrm{p-n}} \equiv \int_0^{1^-} (g_1^{\mathrm{p}} - g_1^{\mathrm{n}})\, dx$$

Infinite Q^2: $$\Gamma_1^{\mathrm{p-n}}(Q^2)\Big|_{Q^2\to\infty} = \frac{g_A}{6}$$

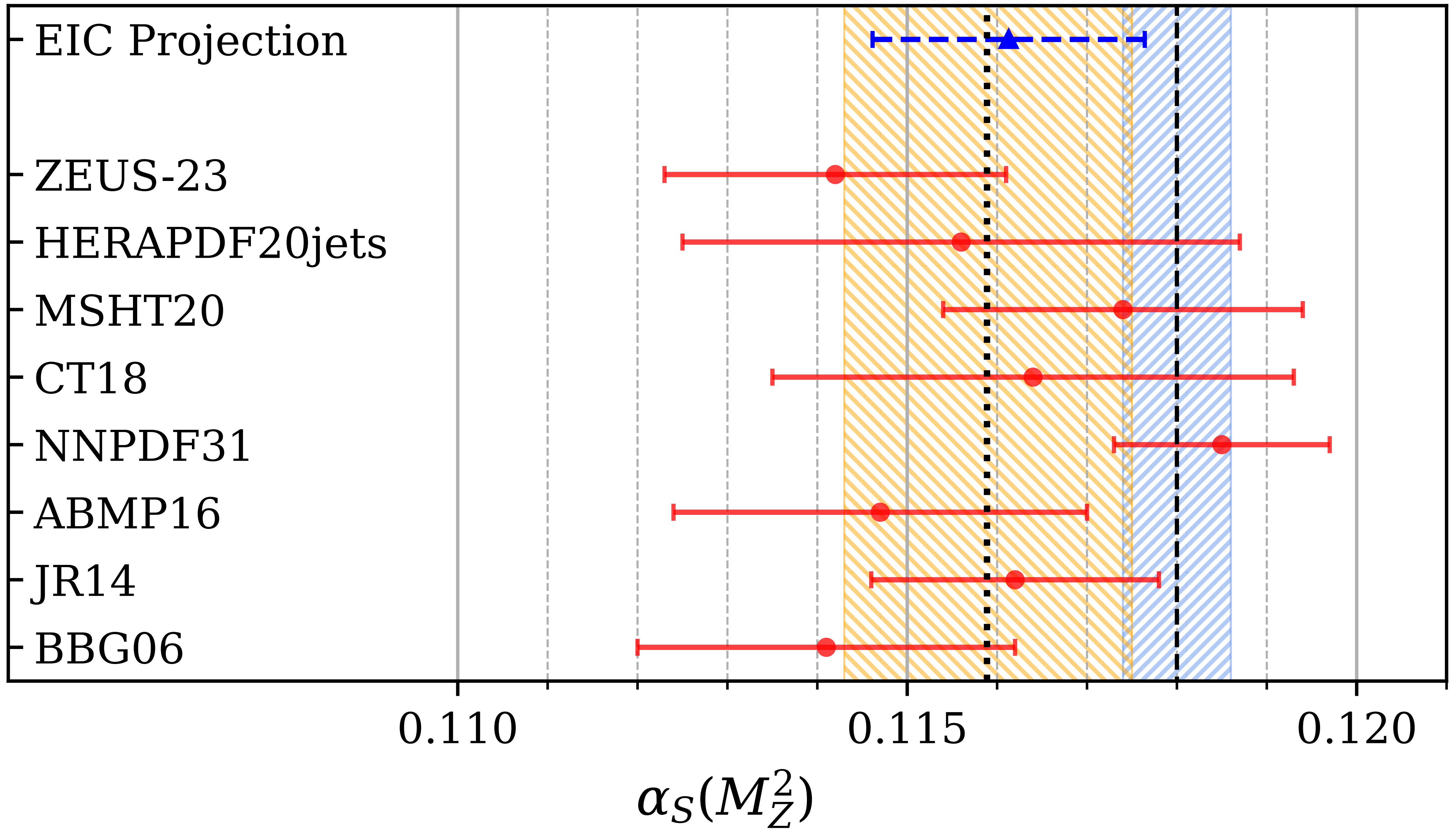
Finite Q^2: $$\Gamma_1^{\mathrm{p-n}}(\alpha_s) = \frac{g_{\mathrm{A}}}{6}\left[1 - \frac{\alpha_s(Q^2)}{\pi} - 3.58\left(\frac{\alpha_s(Q^2)}{\pi}\right)^2 \ldots\right]$$

EPJC 83, 1011 (2023)



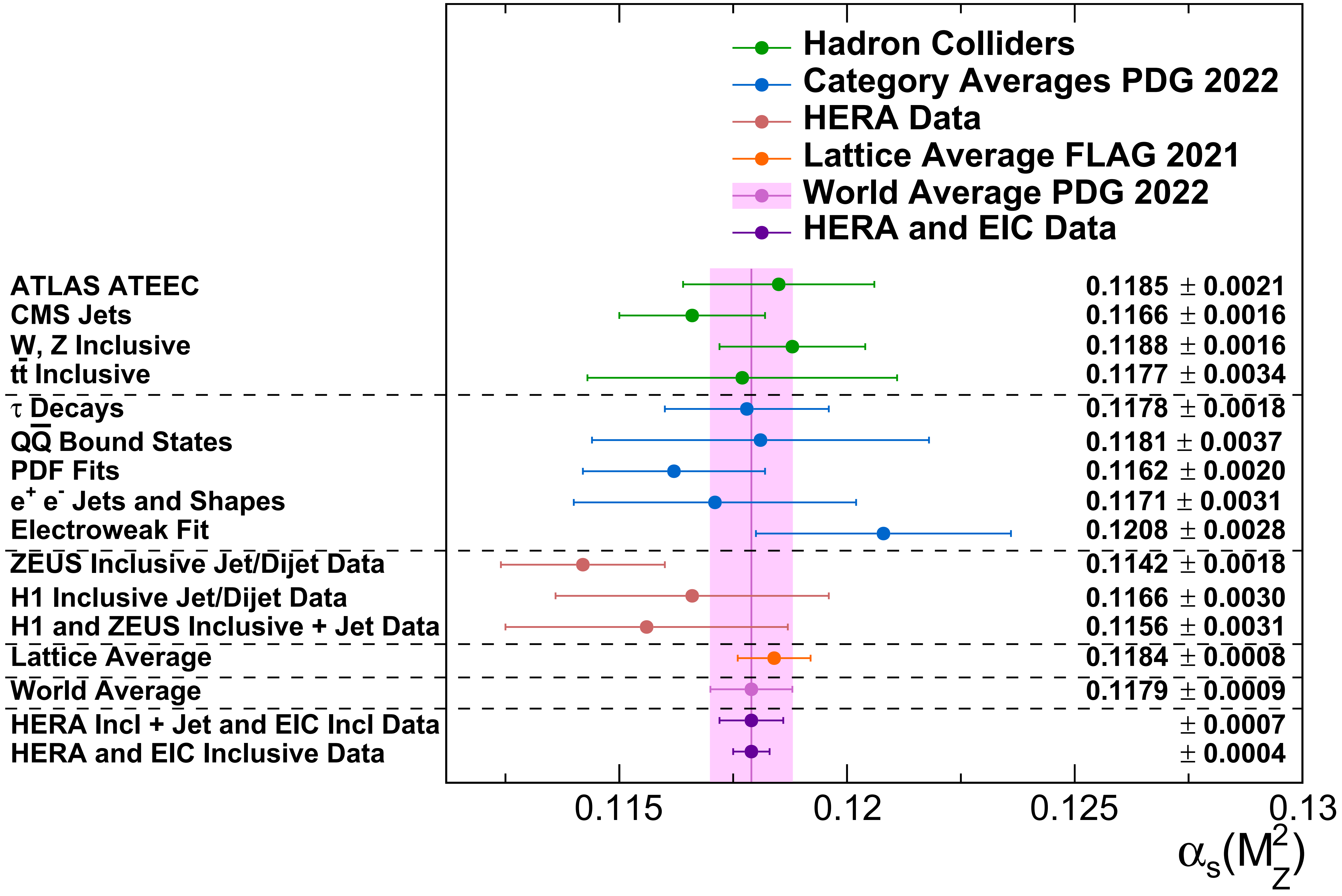
Unpolarized cross sections

PRD 110, 074004 (2024)



Bjorken sum rule

EPJC 83, 1011 (2023)



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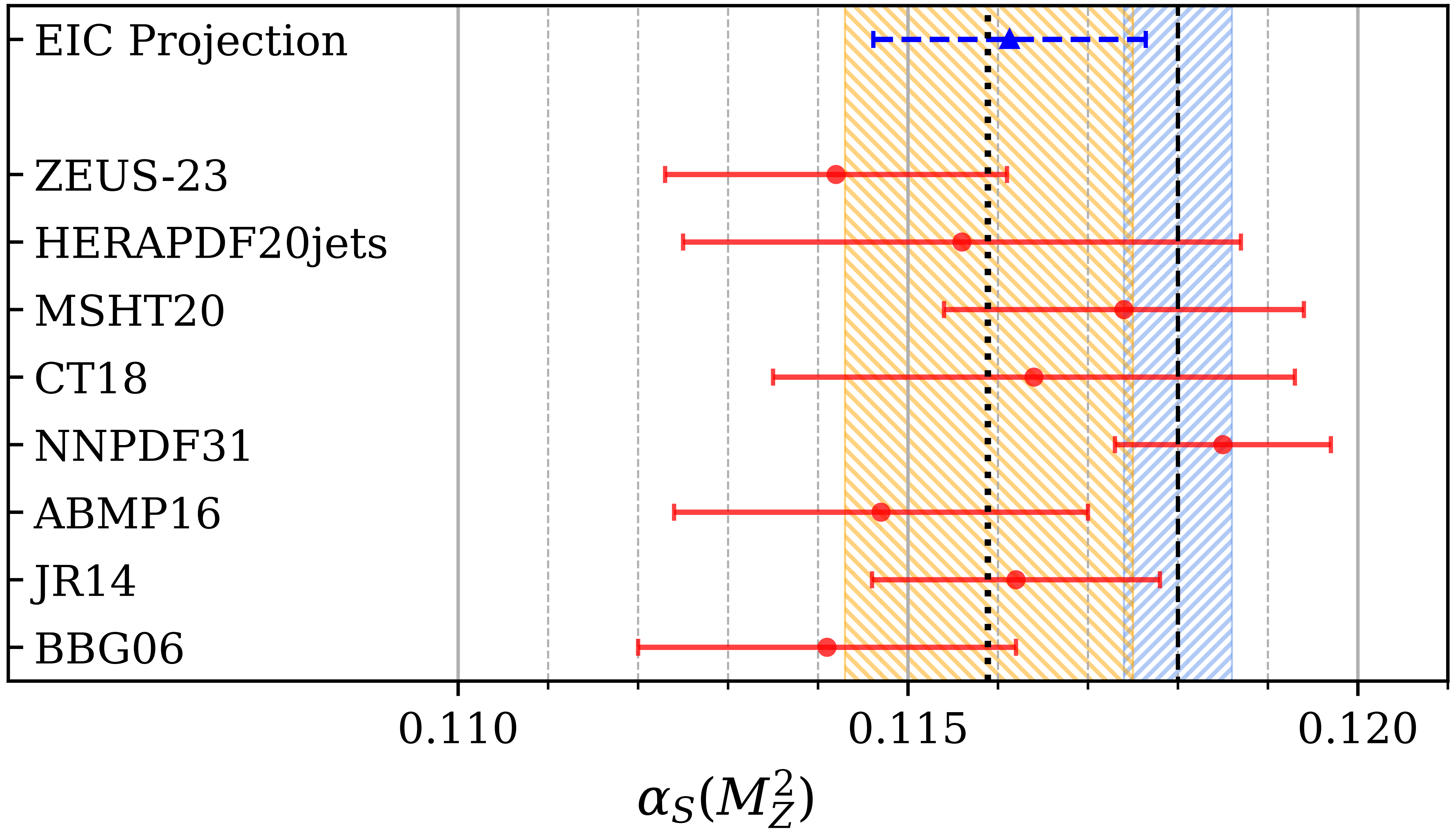


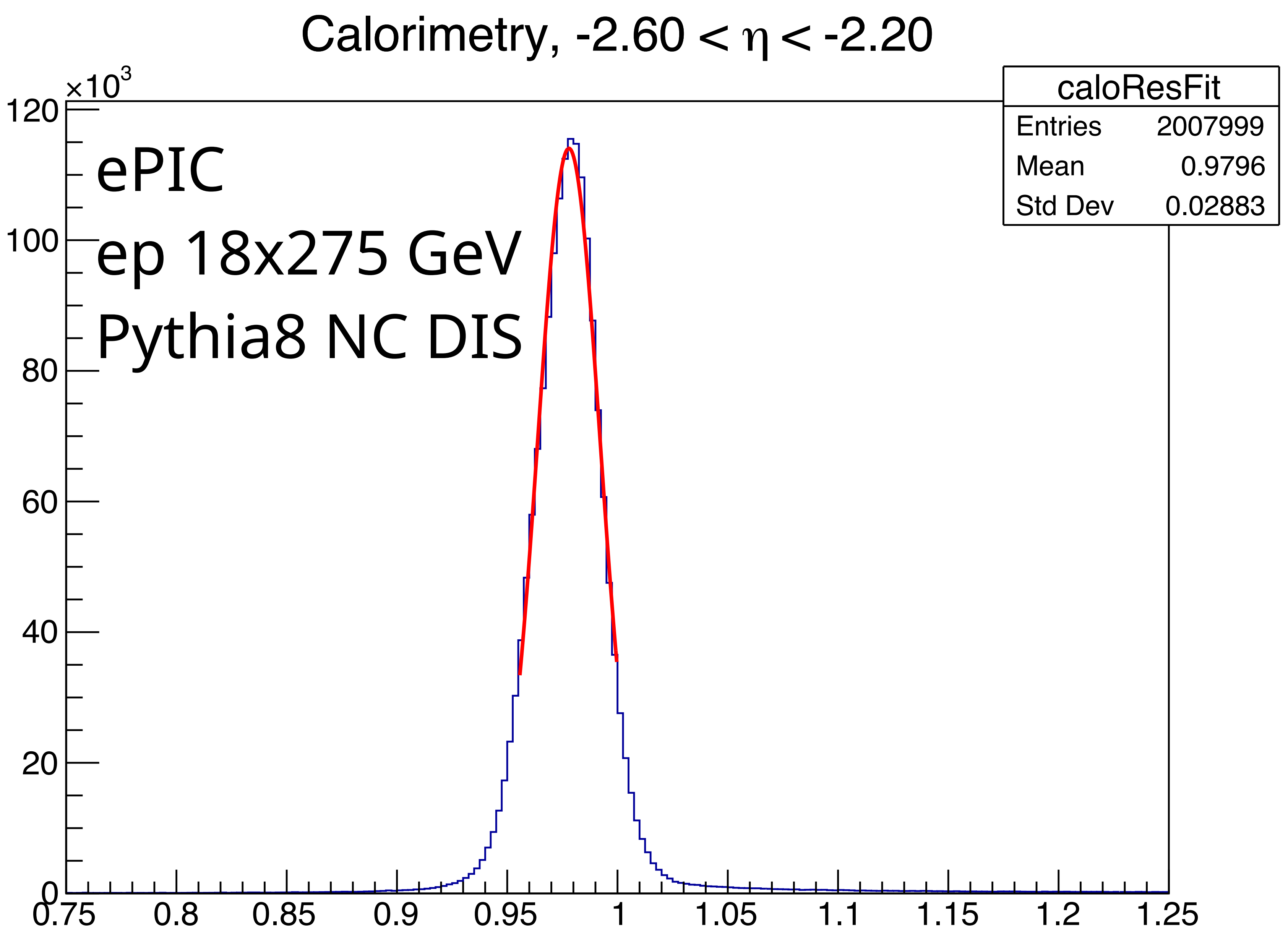
Bjorken sum rule

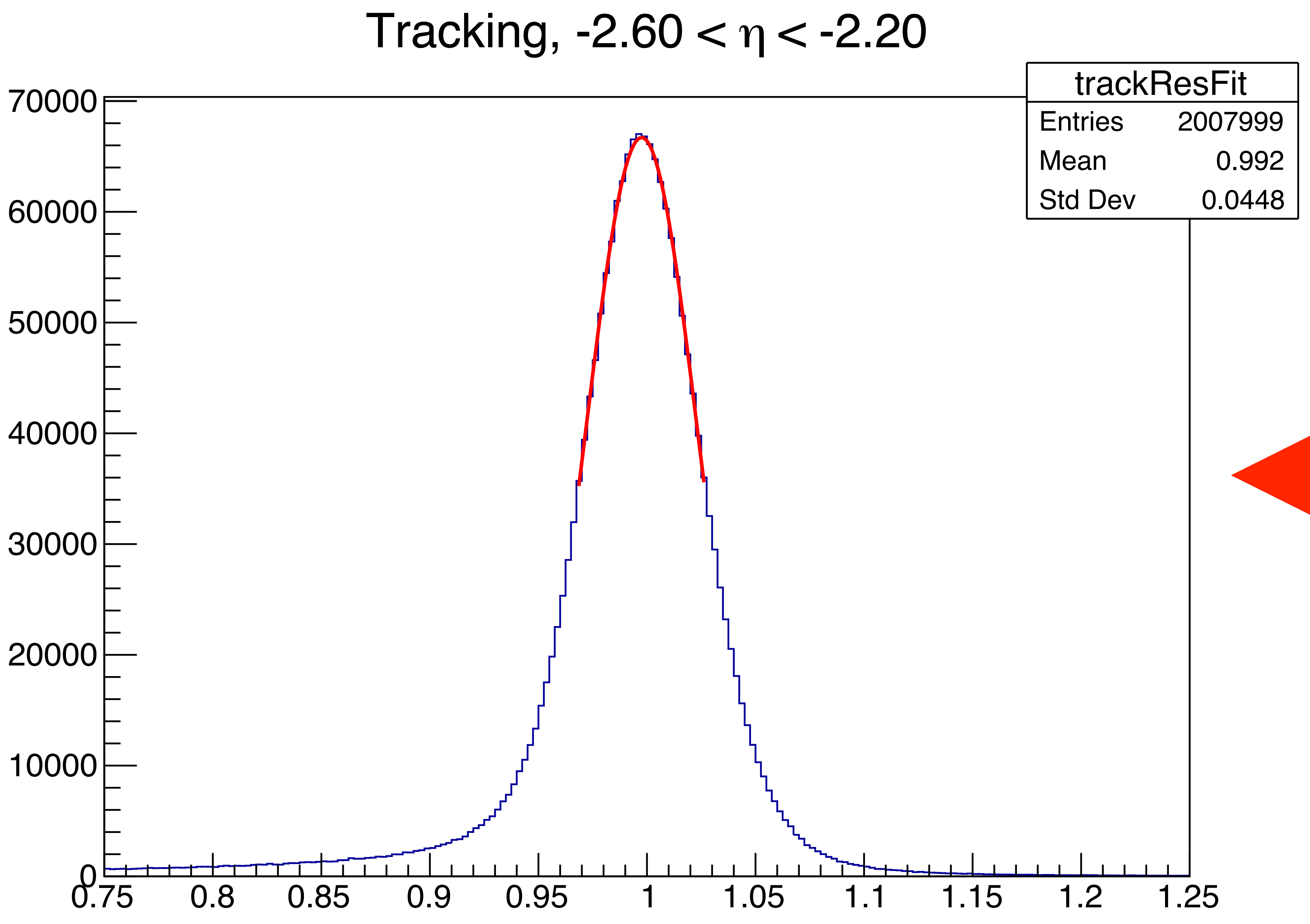
Global fit of unpolarized, polarized observables? (Win Lin, SBU)

Requirements for high-precision cross sections and asymmetries

- Kinematic reconstruction
- Electron identification
- Luminosity monitoring

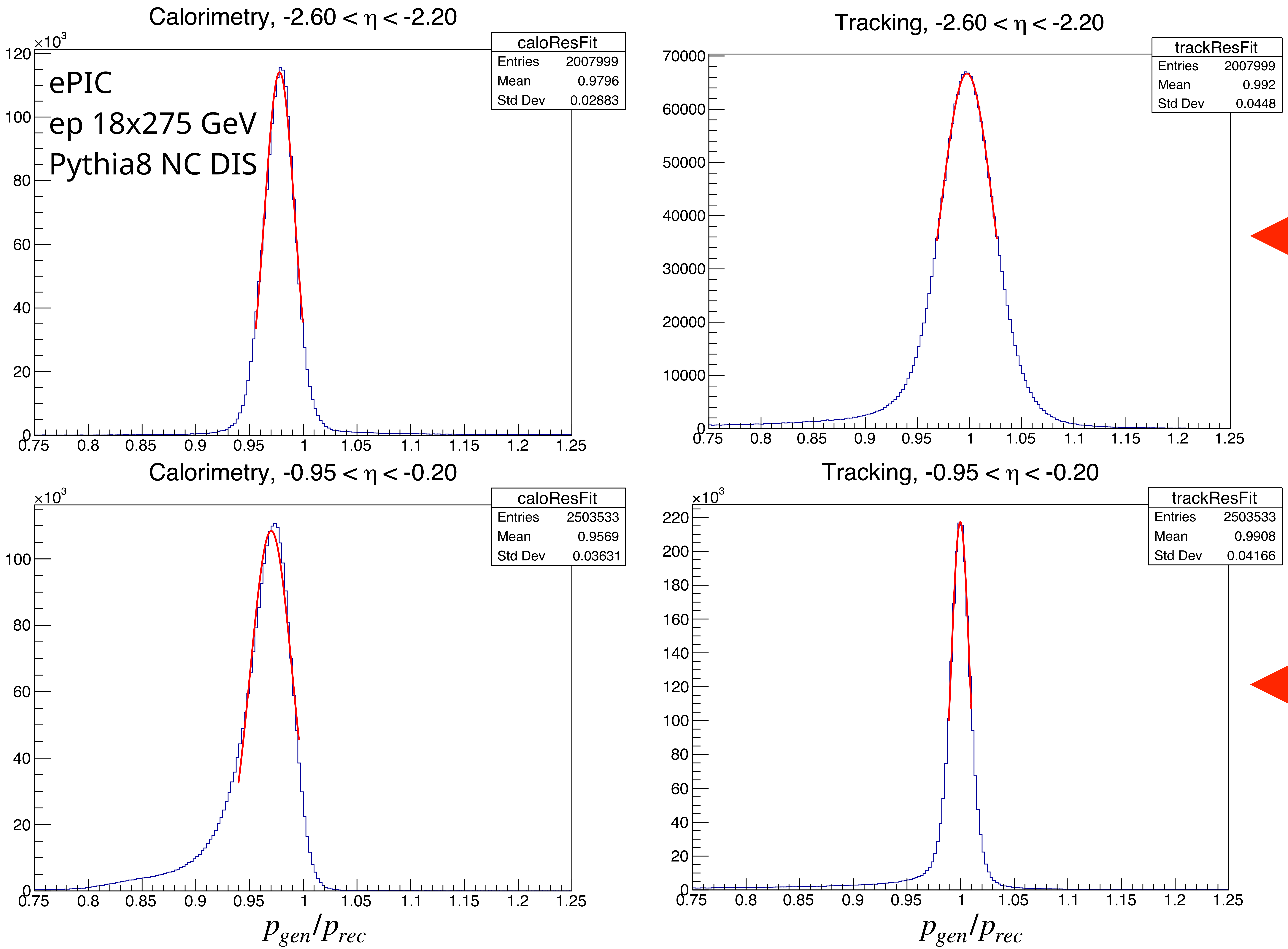
Electron momentum resolutions





Calorimeter resolution better in endcap

Electron momentum resolutions



Calorimeter resolution better in endcap

Tracking resolution better in barrel

Traditional reconstruction methods use subset of lepton, hadron quantities

Lepton

E'_e, θ_e

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Lepton

E'_e, θ_e

- Electron
  $Q^2\left(E'_e, \theta_e\right), y\left(E'_e, \theta_e\right)$

Traditional reconstruction methods use subset of lepton, hadron quantities

Lepton

$$E'_e, \theta_e$$

Hadron

$$\delta_h = \sum_i (E_i - p_{z,i})$$

$$p_{T,h} = \sqrt{\left(\sum_i p_{x,i}\right)^2 + \left(\sum_i p_{y,i}\right)^2}$$

$$\cos\gamma_h = \frac{p_{T,h}^2 - \delta_h^2}{p_{T,h}^2 + \delta_h^2}$$

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  $Q^2\left(\delta_h, p_{T,h}\right), y\left(\delta_h, p_{T,h}\right)$

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- $e\Sigma$
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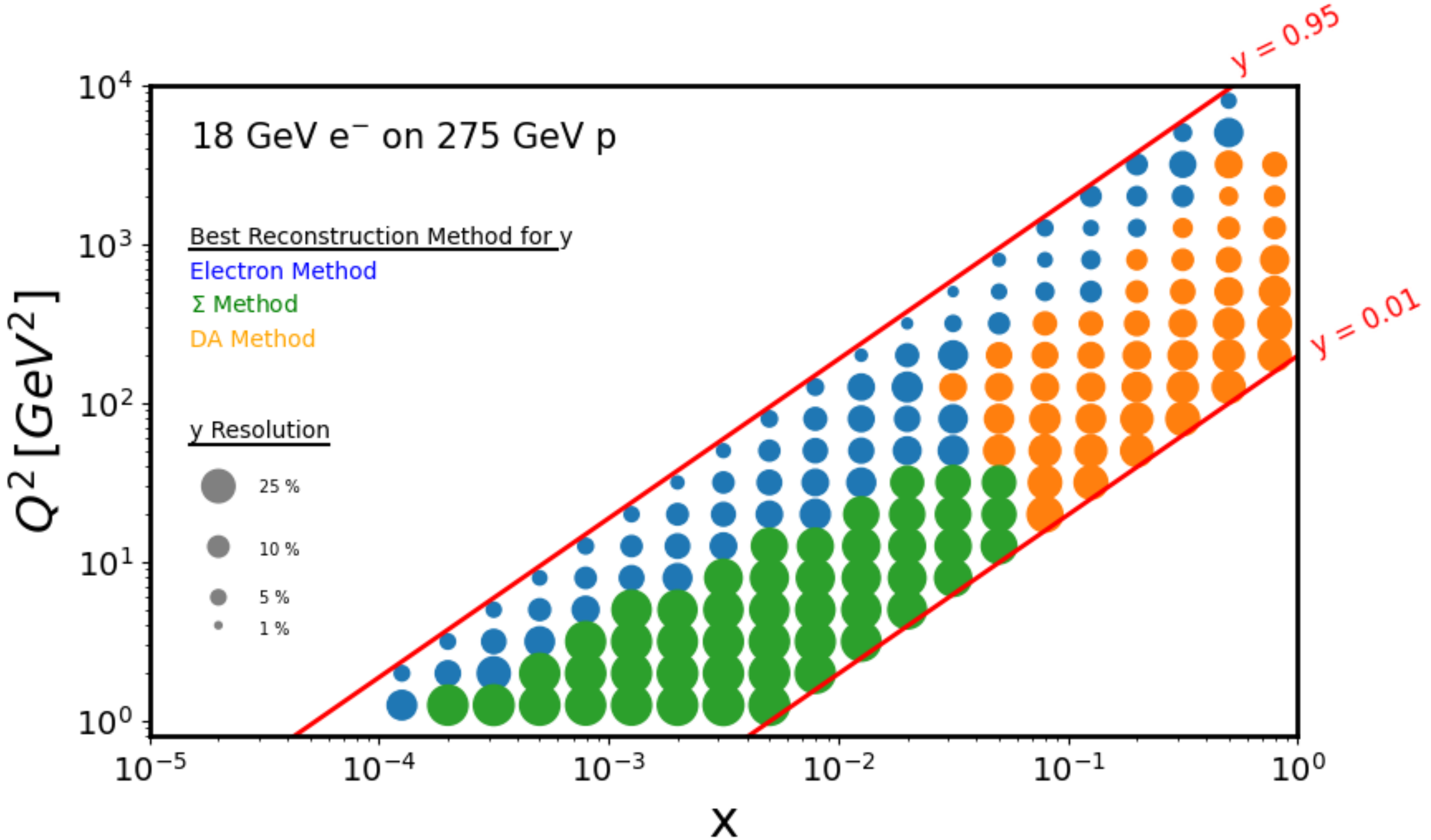
- Neutral-current analyses can leverage over-constrained kinematics to optimize resolution
- Jacquet-Blondel *only* option for charged-current analyses

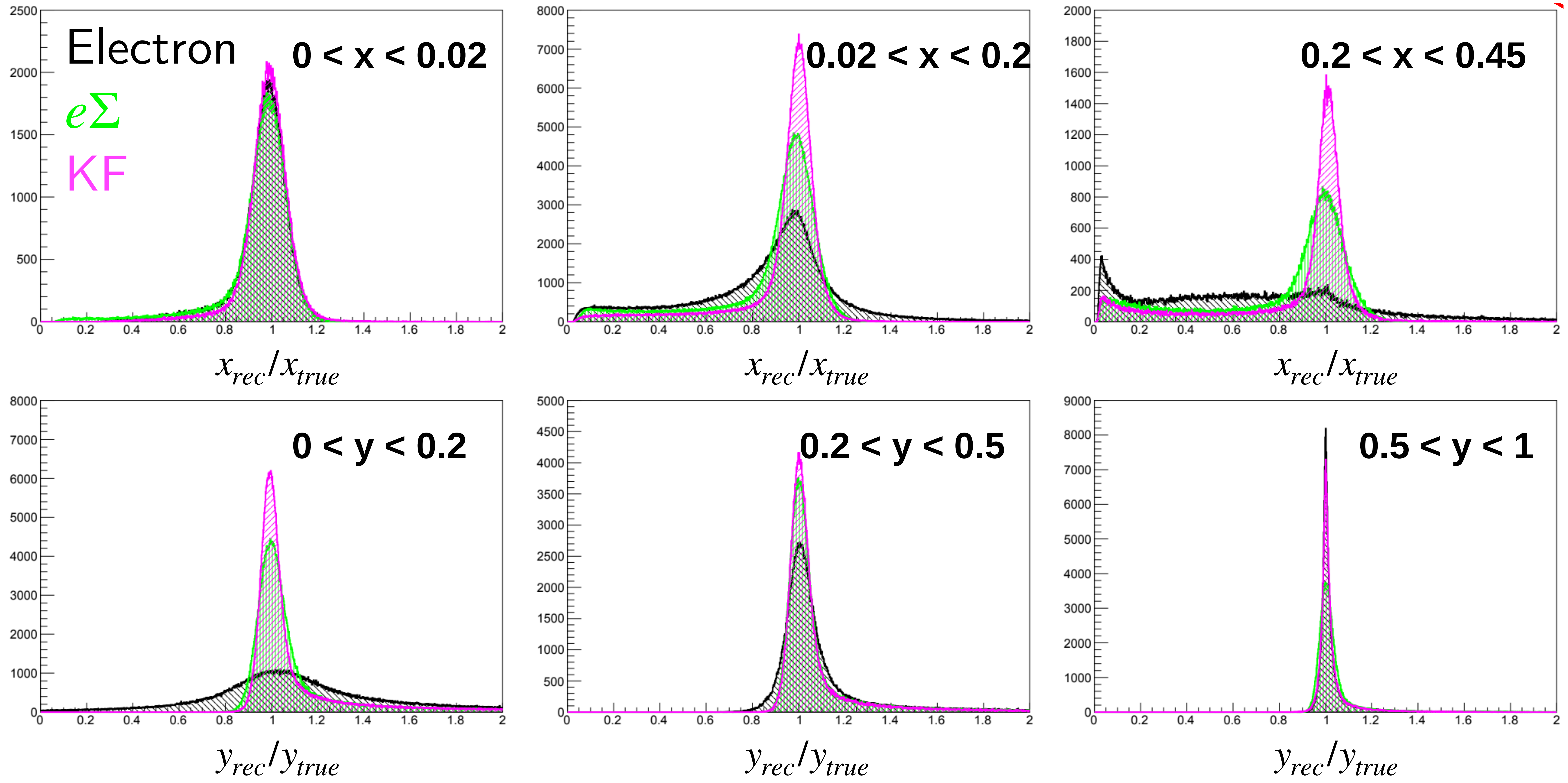

18 GeV e⁻ on 275 GeV p
Best Reconstruction Method for y
Electron Method
Σ Method
DA Method
y Resolution
25 %
10 %
5 %
1 %
y = 0.95
y = 0.01
$Q^2\,[GeV^2]$
x
10^0
10^1
10^2
10^3
10^4
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0

More advanced reconstruction methods

More advanced reconstruction methods

- Kinematic fitting: reconstruct $\bar{\lambda} = \{x_B, y, E_\gamma\}$ from $\overline{D} = \{E'_e, \theta'_e, \delta_h, p_{T,h}\}$ using likelihood function (Stephen Maple, et al.)

Proof of concept: Smeared DJANGOH events with ISR



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- Machine learning: use simulation to train neural network (M. Diefenthaler, A. Farhat, A. Verbytskyi and Y. Xu)
- Particle-flow: optimize combination of all detector information (Derek Anderson, et al.)

Impact of pion contamination on observables

- Pions passing all electron ID cuts give contamination $f_{\pi/e}$
- Contamination can be corrected or treated as dilution

Cross sections
(correct contamination):

$$\left(\frac{\Delta\left(\sigma^{r,NC}\right)}{\sigma^{r,NC}}\right)_{\pi^-} = \Delta f_{\pi/e}$$

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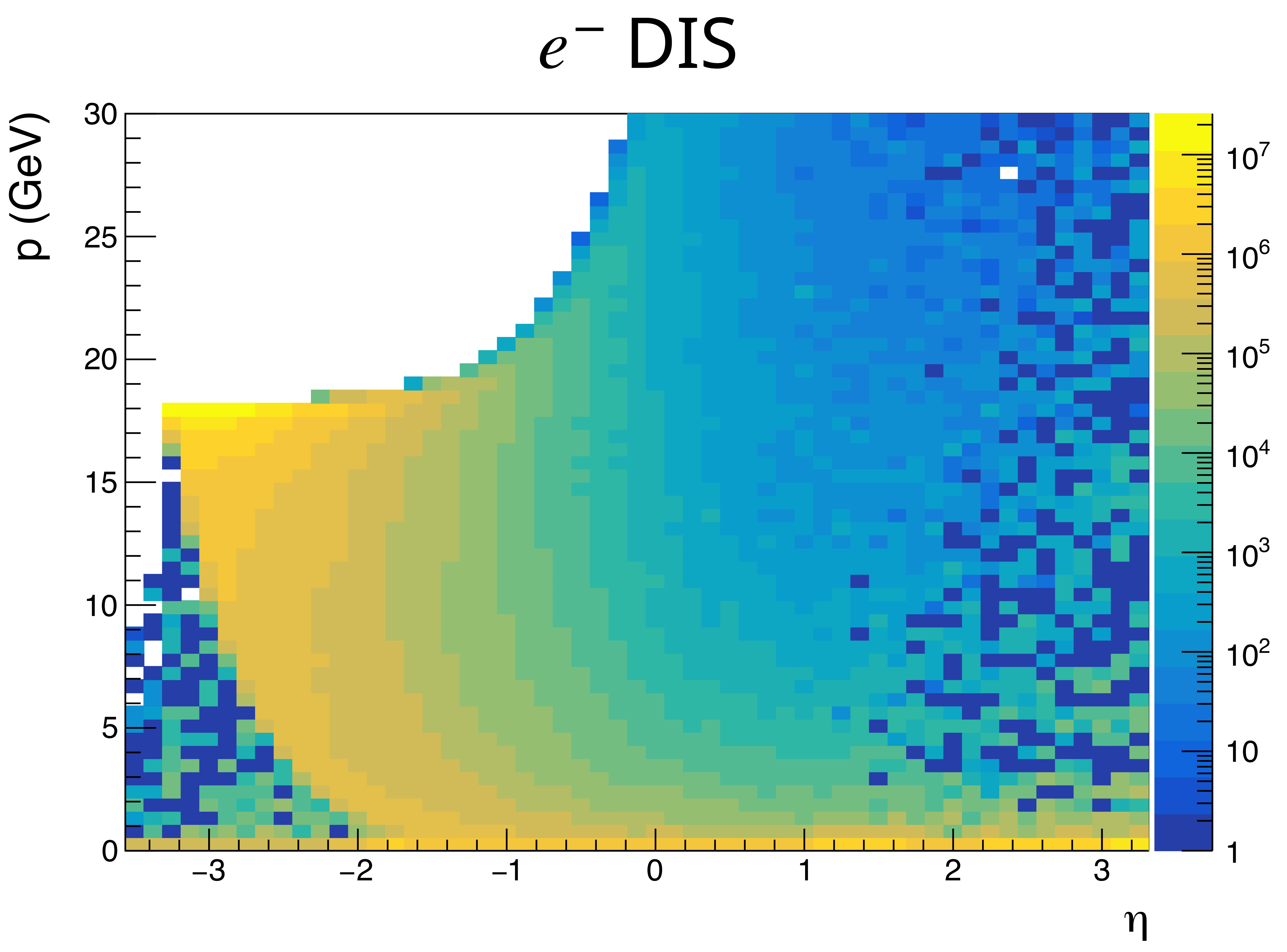
$$\approx 0.1 \times f_{\pi/e} \ldots 1 \times f_{\pi/e}$$

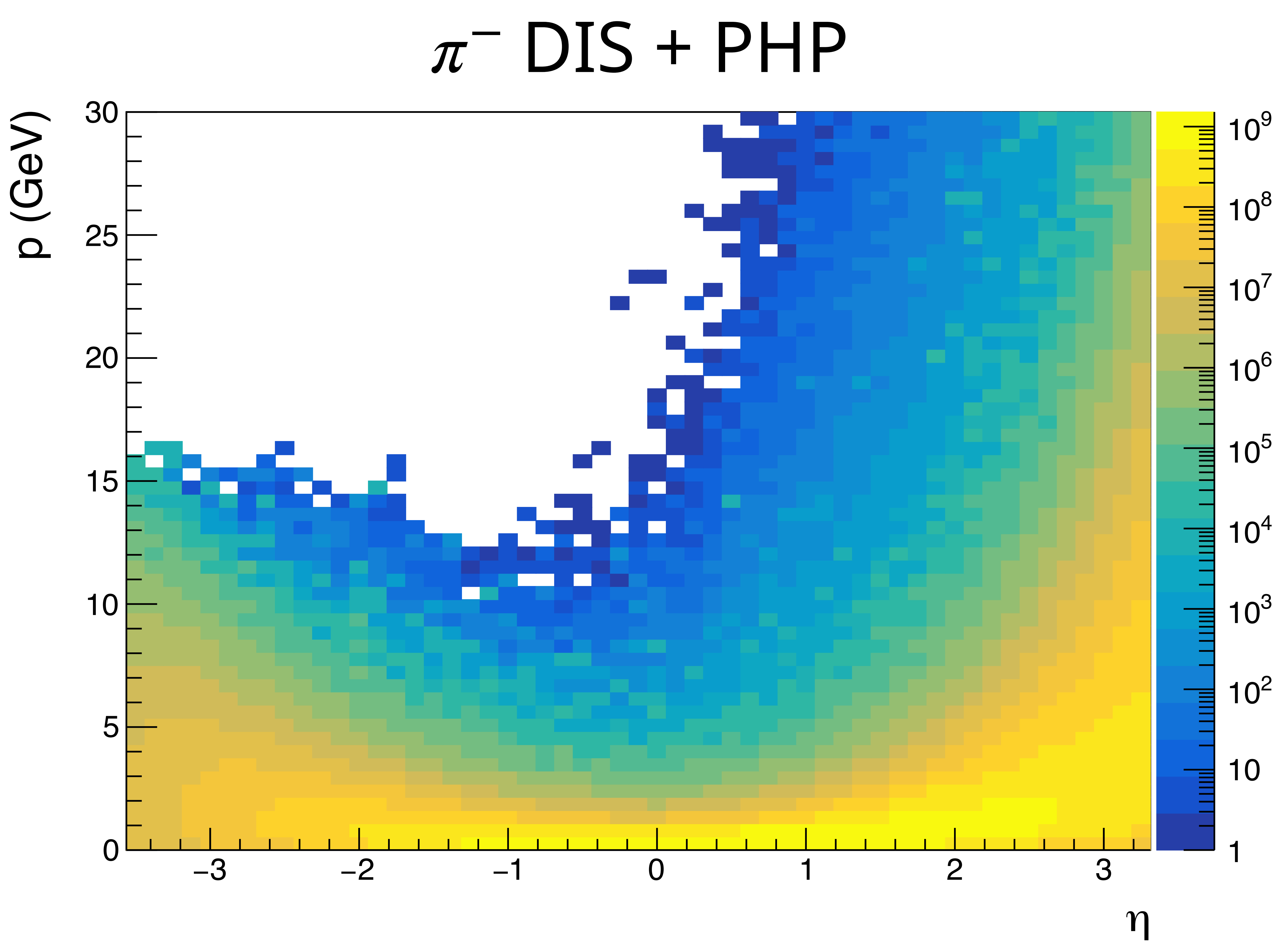
Two regimes:

Large A^e, nonzero $|A^\pi| < A^e$

Small A^e, $|A^\pi| \approx 0$

Electron to pion ratios

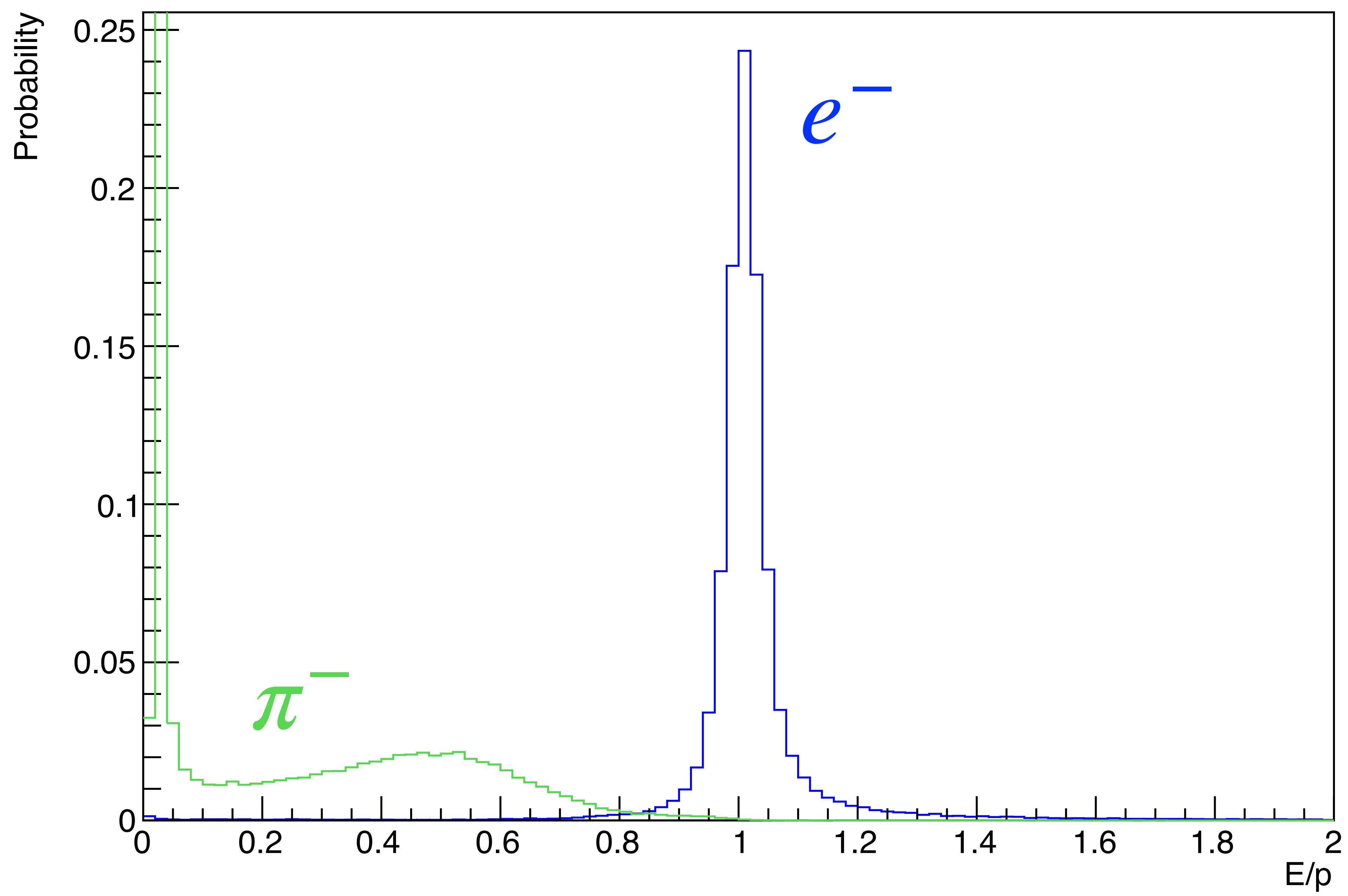


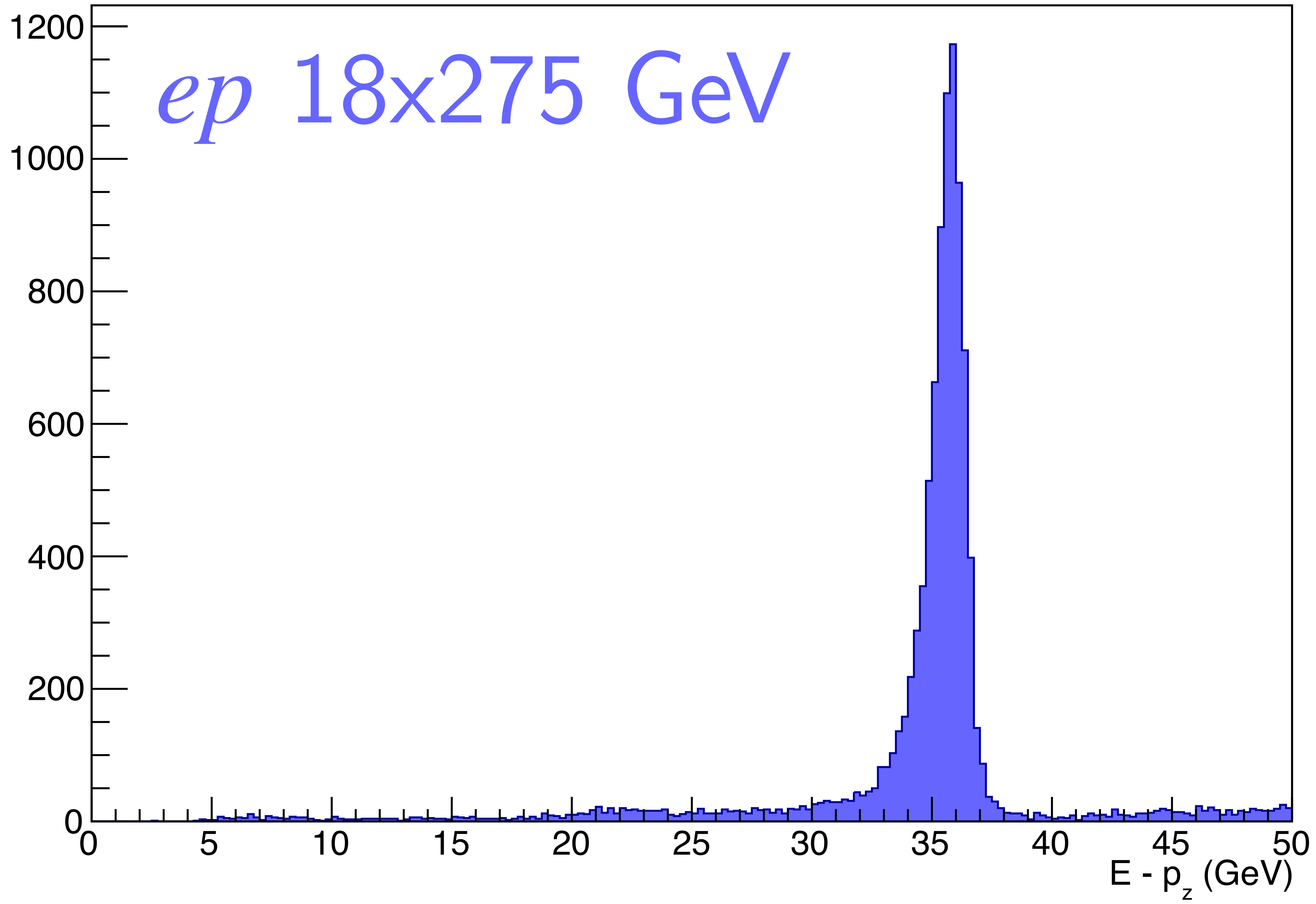


- Signal e^- from DJANGOH DIS
- Background π^- from DJANGOH DIS, Pythia6 photoproduction (Q^2 < 2 GeV²)

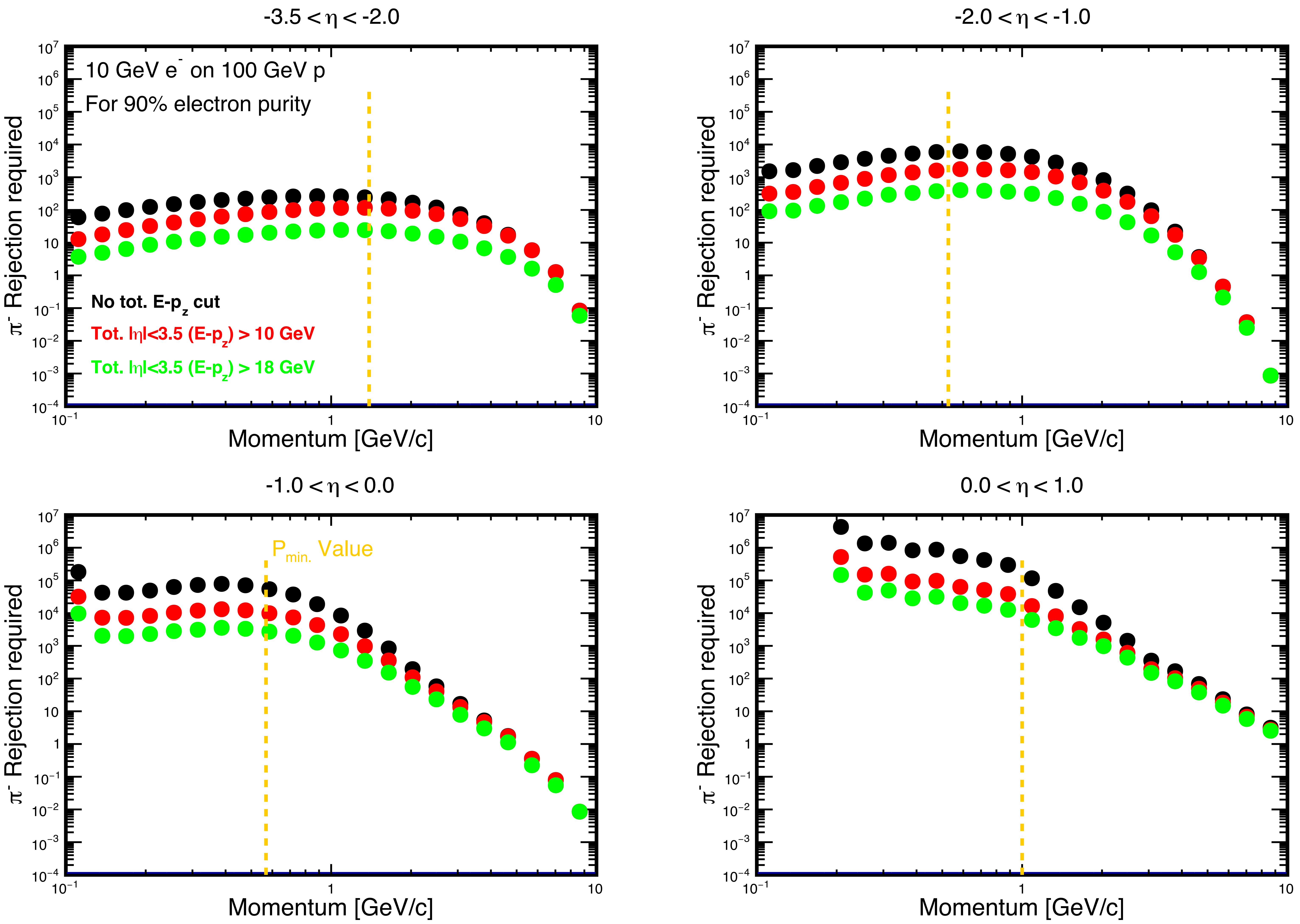
Pion suppression cuts

- $E/p \approx 1$
- $\delta = \sum_i (E_i - p_{z,i}) = 2E_e$
  - Effective veto of photoproduction, ISR
- PID (hpDIRC, pfRICH, dRICH, ToF)
  - Critical rejection at low momentum
- Shower shape
  - Imaging barrel calorimeter





Required suppression for 90% purity



- $E - p_z$ cut can reduce required suppression by up to 20x
- Tightness of cut depends on resolution of hadronic final state
- Barrel critical region due to large raw π^-/e^- ratio

HERA demonstrated luminosity measurement with bremsstrahlung

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- Pure QED process with large, precisely calculable cross section
- Precision:
    - 1% at HERA-I, 1.7% at HERA-II
    - EIC goal: $\leq$ 1% (abs.), 10^{-4} (rel. bunch-to-bunch)

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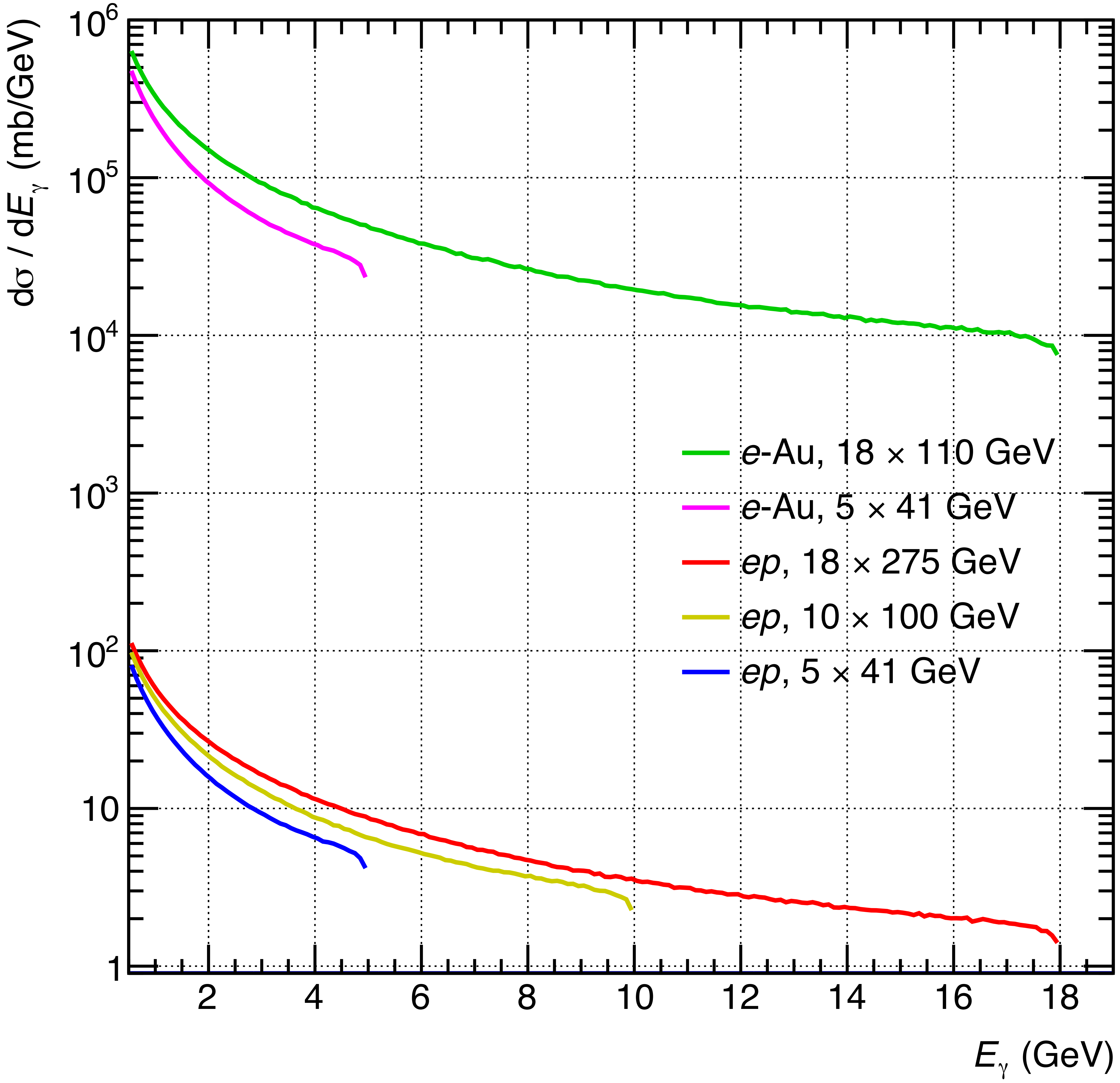
  - 1% at HERA-I, 1.7% at HERA-II
  - EIC goal: ≤ 1% (abs.), 10^{-4} (rel. bunch-to-bunch)

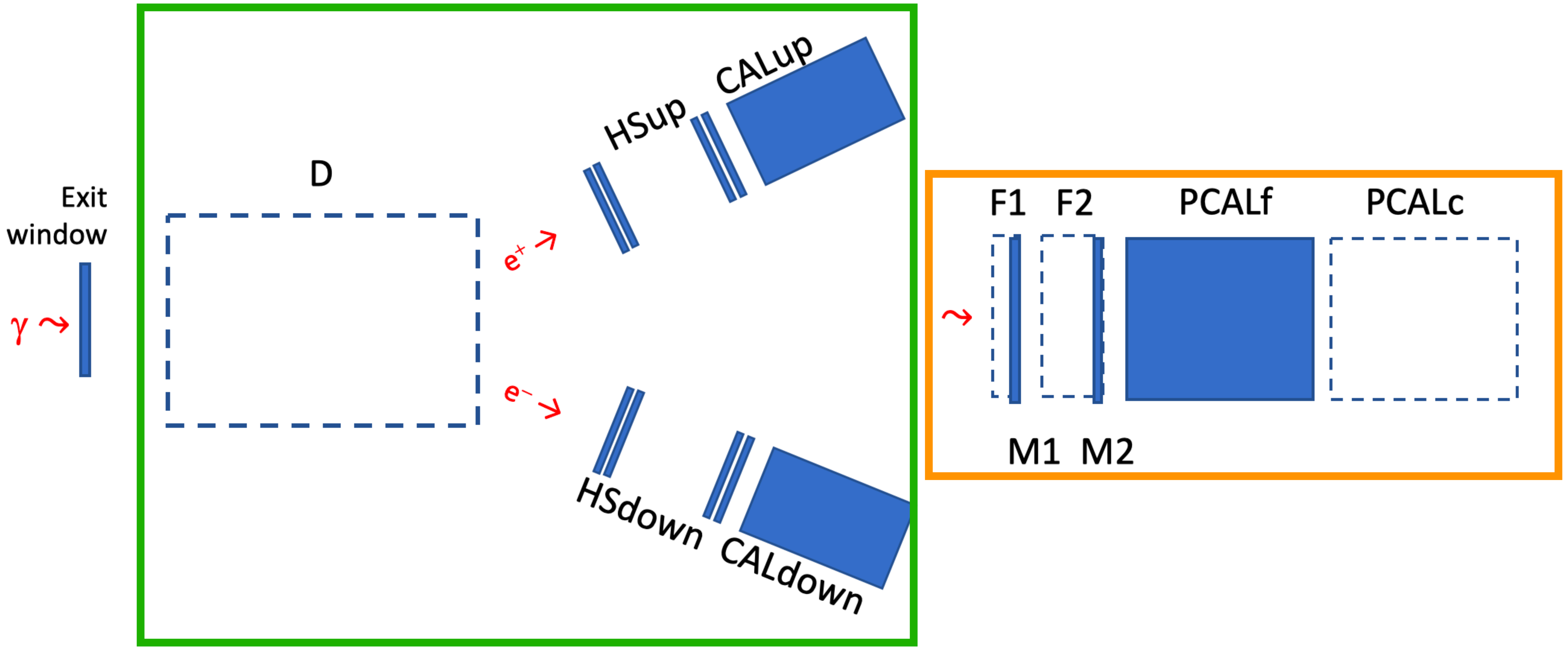
Challenges at EIC:

- Event pileup, even worse for heavy ions ($\sigma_{Brem} \propto Z^2$)
- Increased synchrotron radiation background
- Large integrated doses
- High bunch rate requires fast timing/readout



Address challenges with two-detector luminosity monitor

Pair spectrometer: detect $e^{\pm}$ pairs produced in exit window



Direct photon detector: detect bremsstrahlung photons

Address challenges with two-detector luminosity monitor

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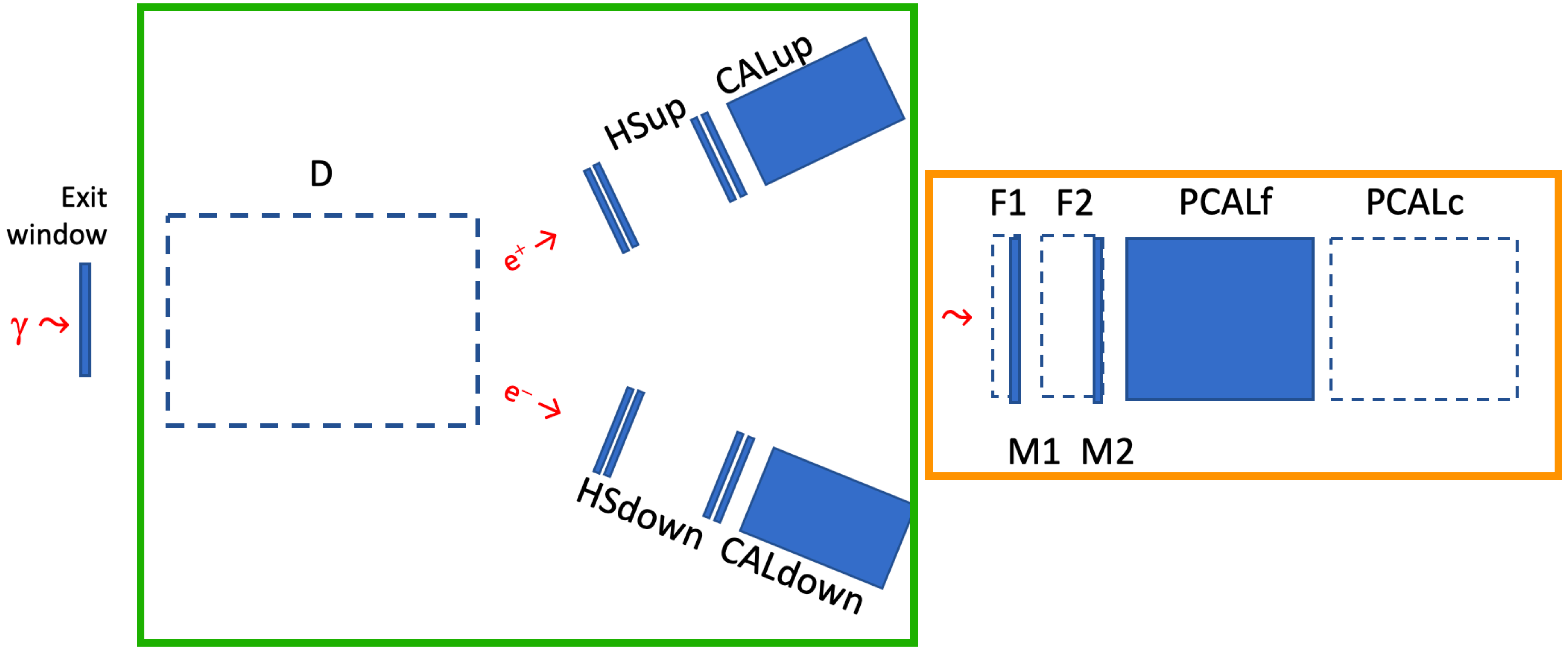

Direct photon detector: detect bremsstrahlung photons

- Both systems to use tungsten/fiber-array calorimeters
- Fibers read out with silicon photomultipliers (SiPM)
- Mesh design allows shower profile reconstruction
  → better disentangle multi-hit events

Theory systematics

experiment

$$\sigma(x_B, Q^2) = \frac{N - B}{\mathcal{L} \cdot \mathcal{A}} \cdot \mathcal{C} \cdot (1 + \Delta)$$

theory

- Bin-centering $\mathcal{C}$
- Radiative corrections Δ
    - Efforts to unify QED radiative effects with QCD radiation
      Liu, Melnitchouk, Qiu, Sato [PRD 104, 094033 (2021)]
      Cammarota, Qiu, Watanabe, Zhang [arXiv:2505.23487]
    - Electroweak radiation…
- Binned *unfolding* of experiment vs. event-by-event *folding* of theory

Summary

- Inclusive reactions are the “bread and butter” of the EIC
- Beyond core EIC science, inclusive physics can contribute to EW and BSM physics searches
- High-precision extractions of α_S can be performed with EIC measurements
- Polarized and charged-current measurement at the EIC are sensitive to EW couplings, but sensitivity studies are needed