Describing the proton with electron scattering

Tyler Kutz (JGU Mainz)

Mainz Physics Academy summer school
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What physical characteristics describe an object?

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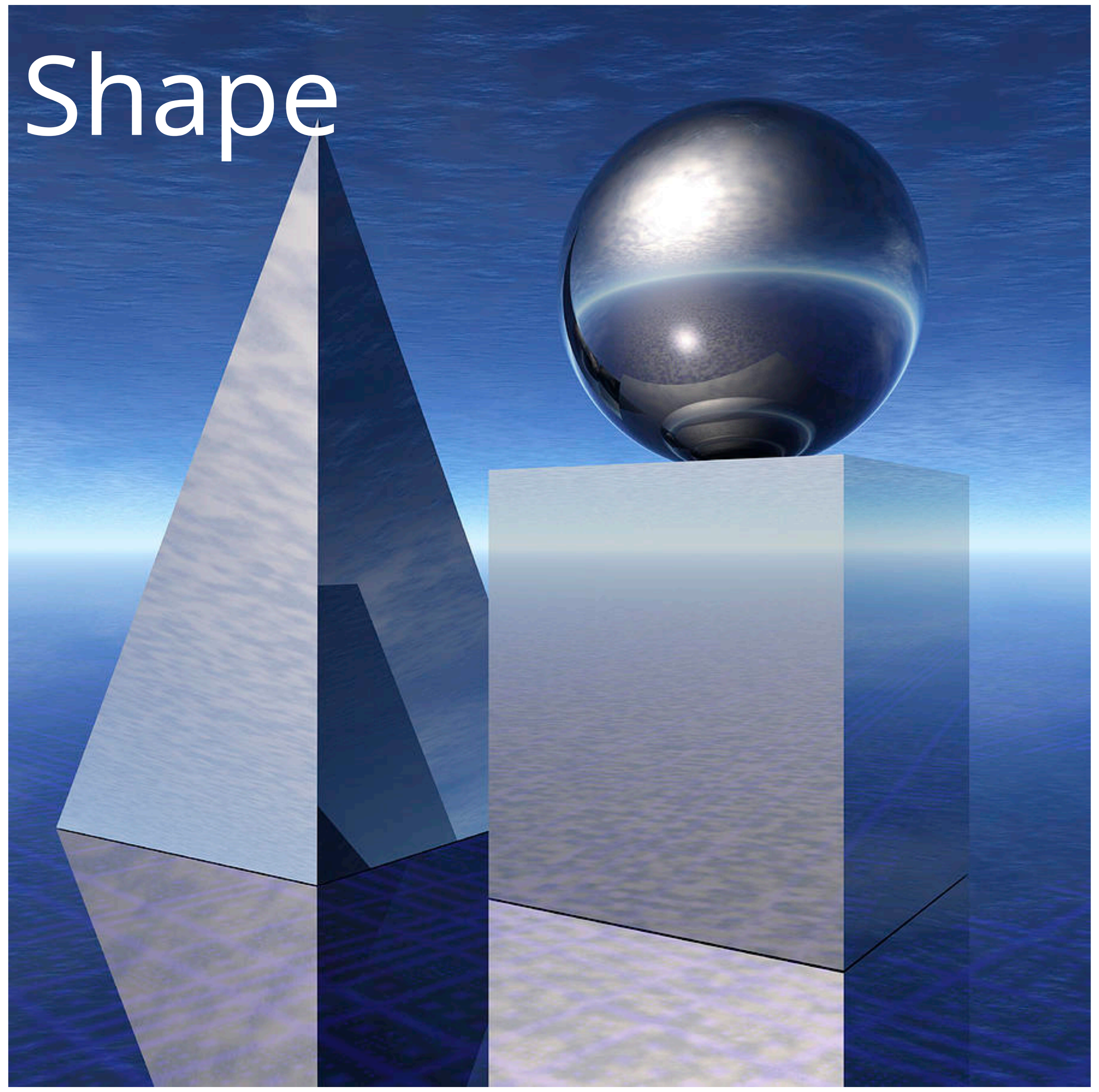
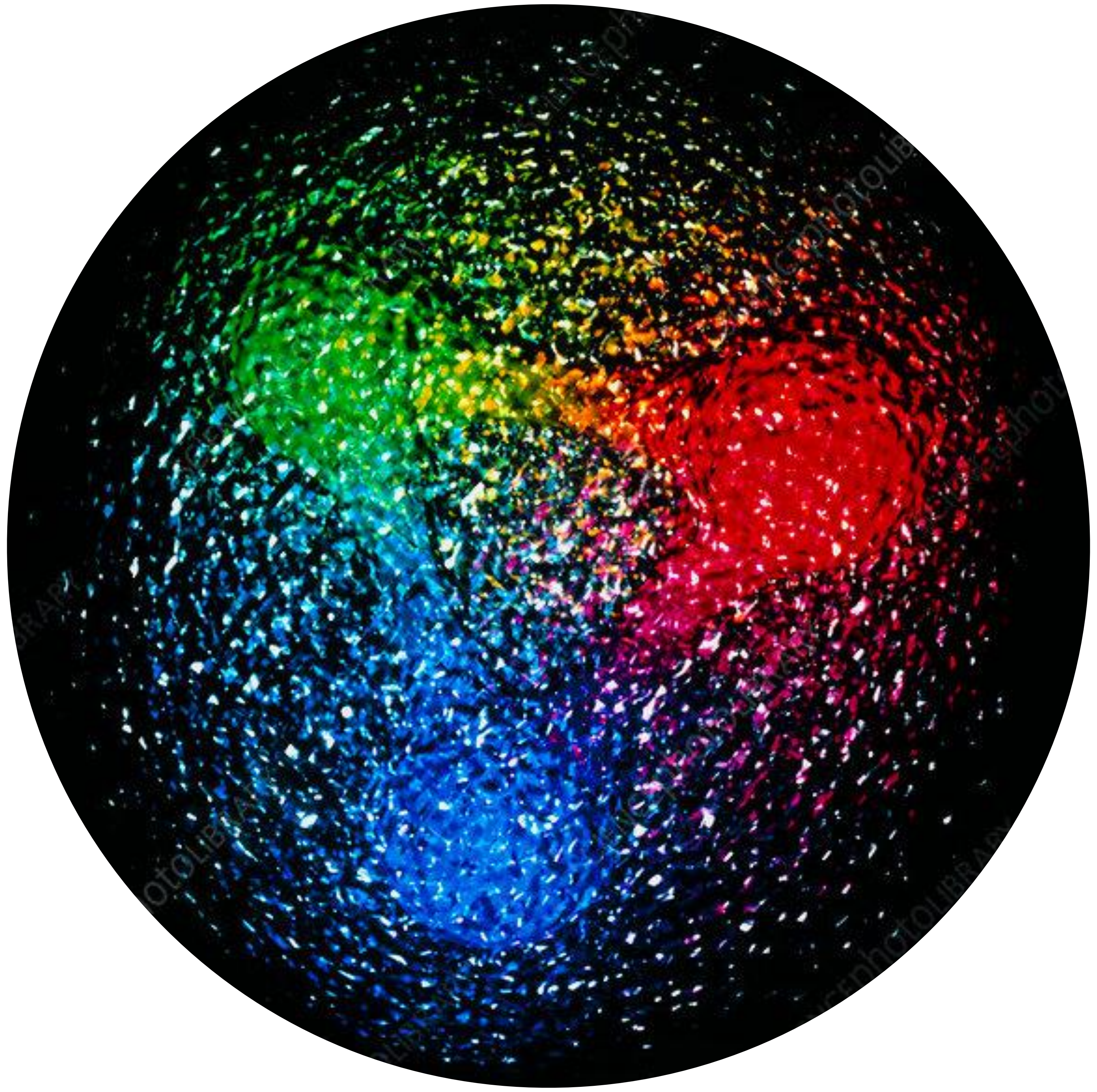


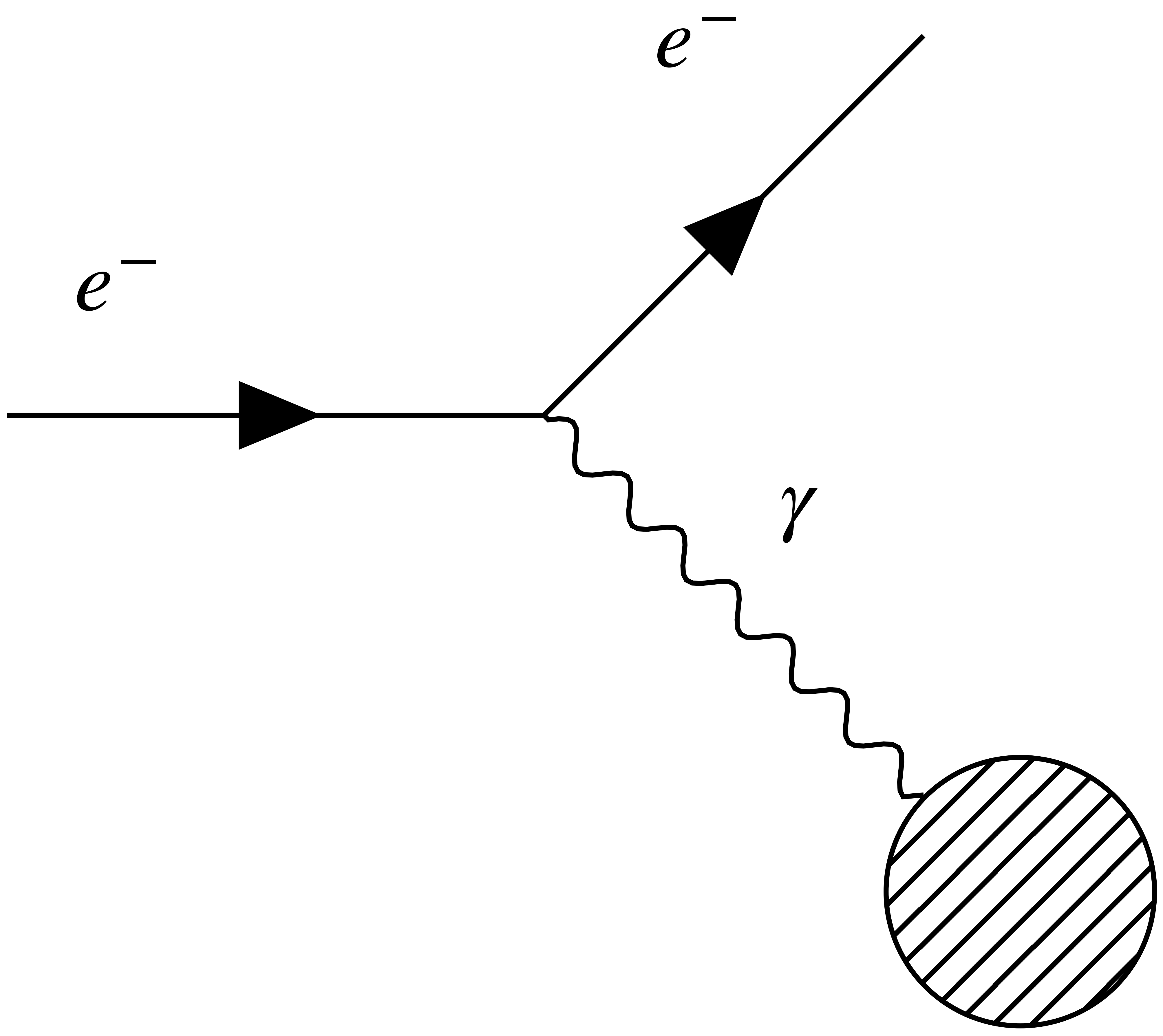
Temperature

Surface

How to describe the proton?

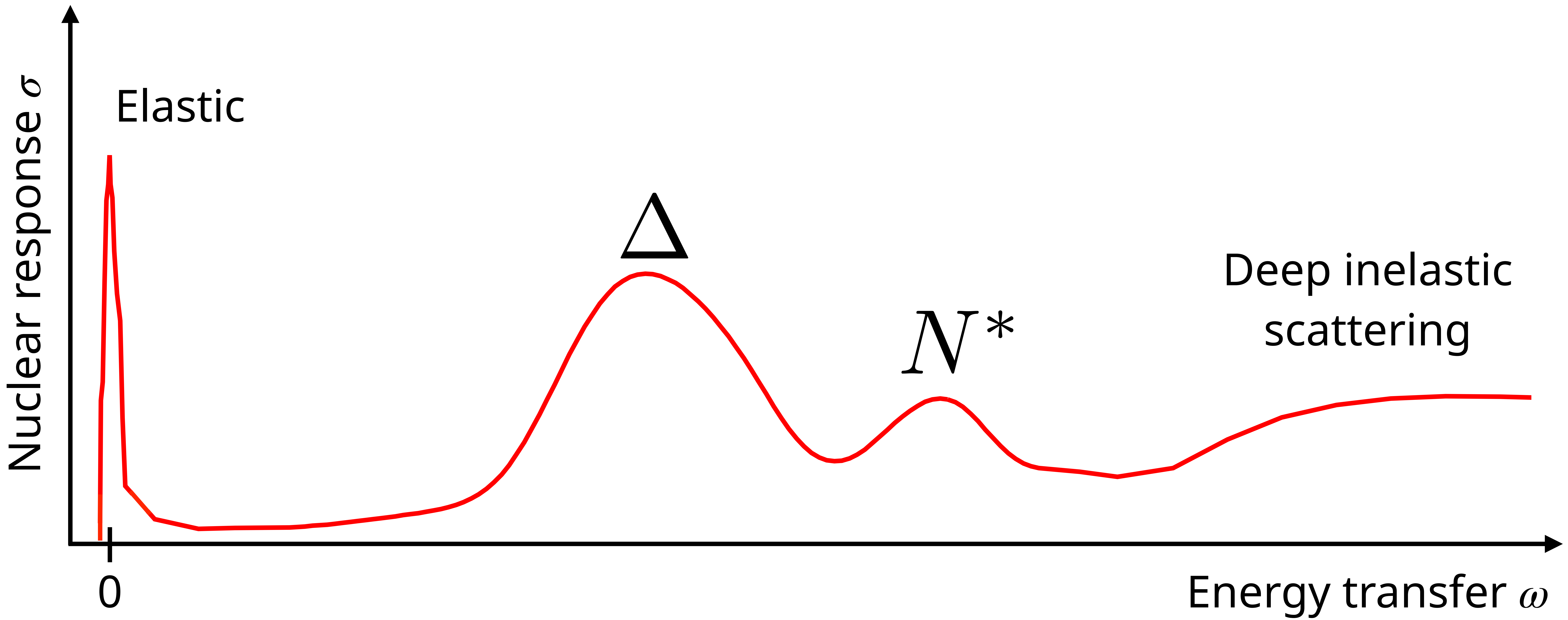


Studying the proton with electron scattering



- Powerful method used since the 1950s
- Electrons are abundant, easy to control and detect
- Typical to assume Born approximation
  - Scattering mediated by single virtual photon
- Clean separation of (known) lepton vertex from (unknown) hadronic vertex

Proton response function



Today’s roadmap

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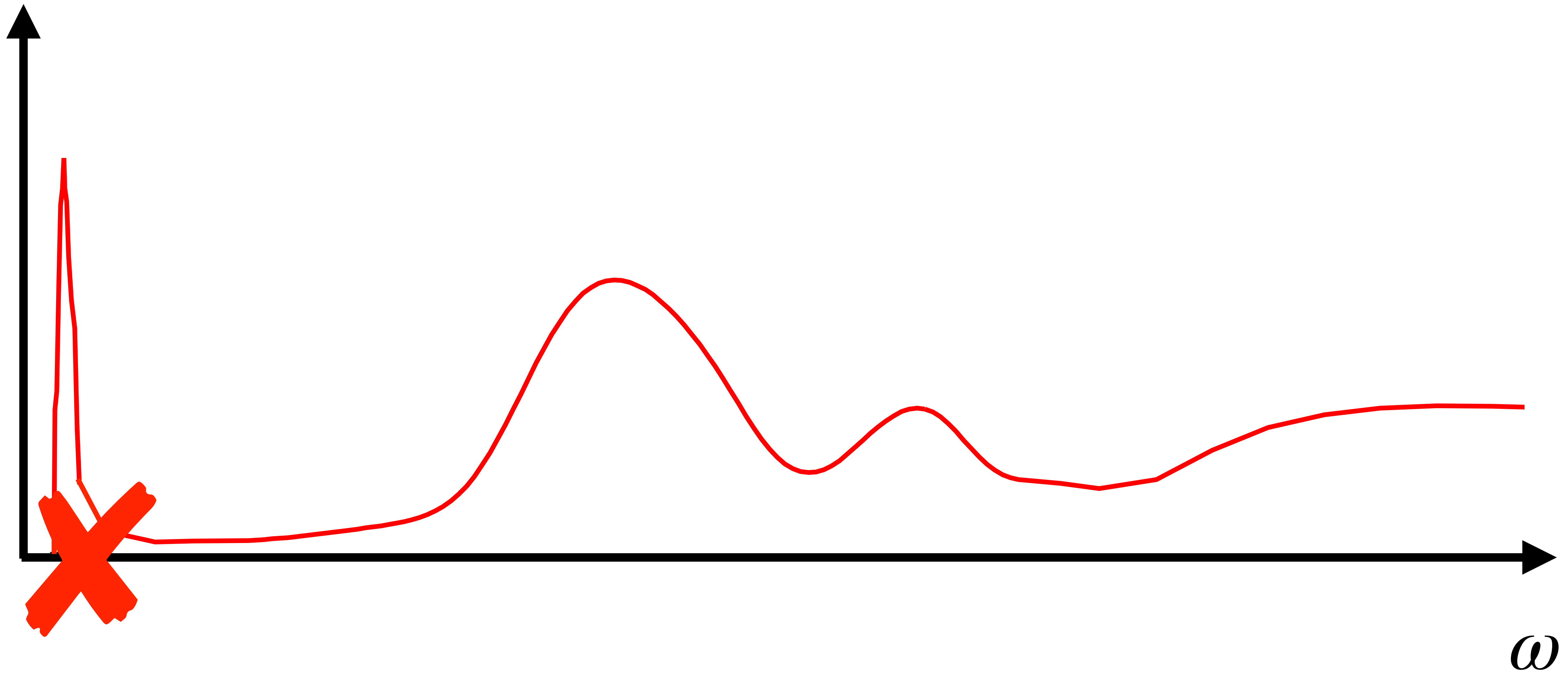
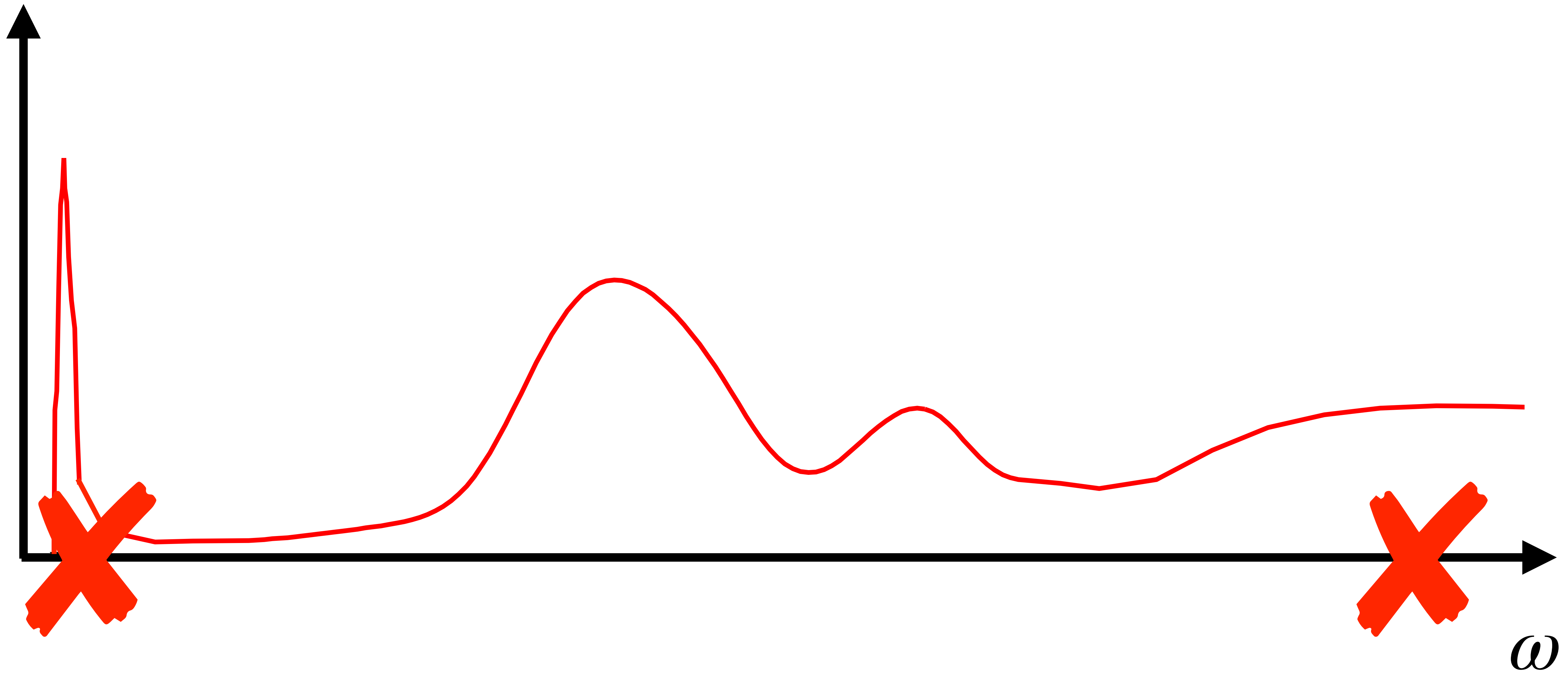


- Elastic scattering:
  - Proton form factor ratio and multi-photon exchange
  - Proton weak charge

Today's roadmap

- Elastic scattering:
  - Proton form factor ratio and multi-photon exchange
  - Proton weak charge
- Deep inelastic scattering
  - Origin of proton spin



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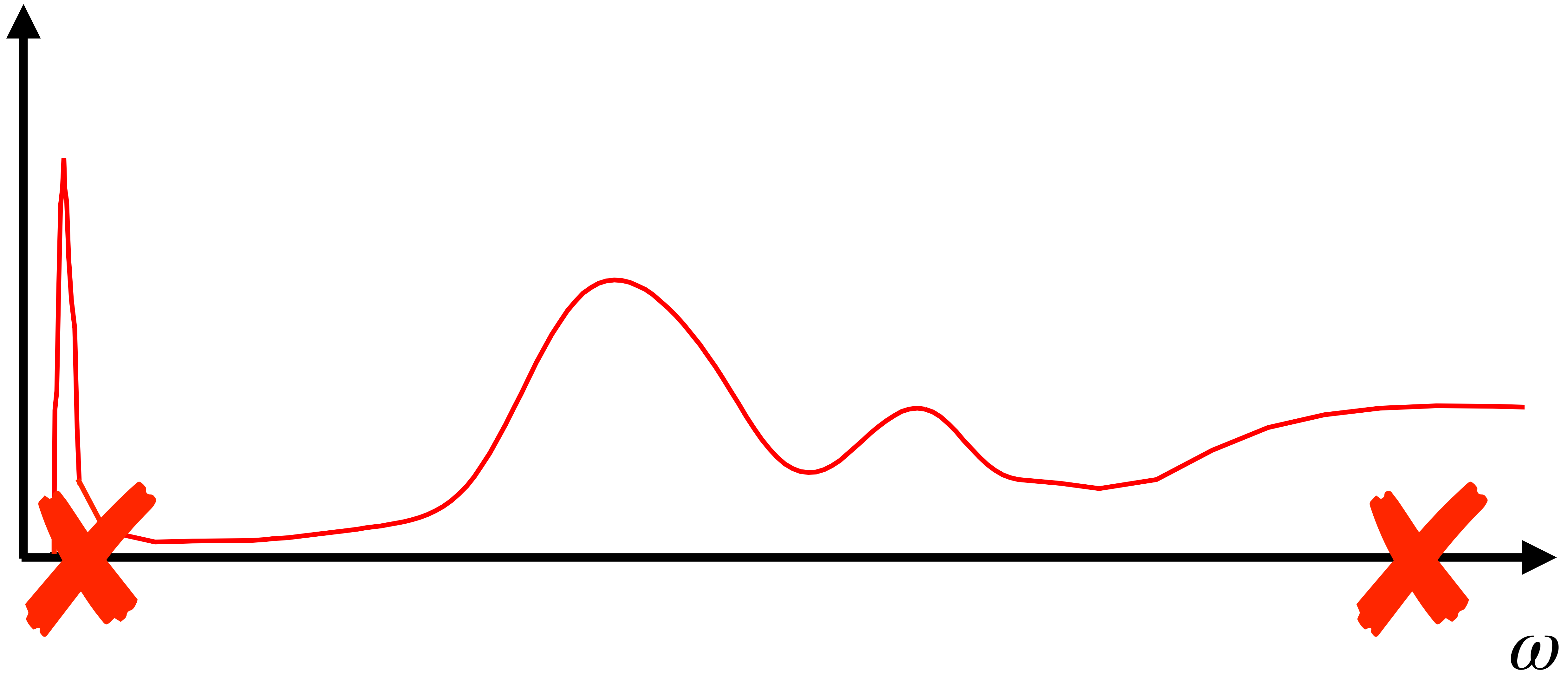

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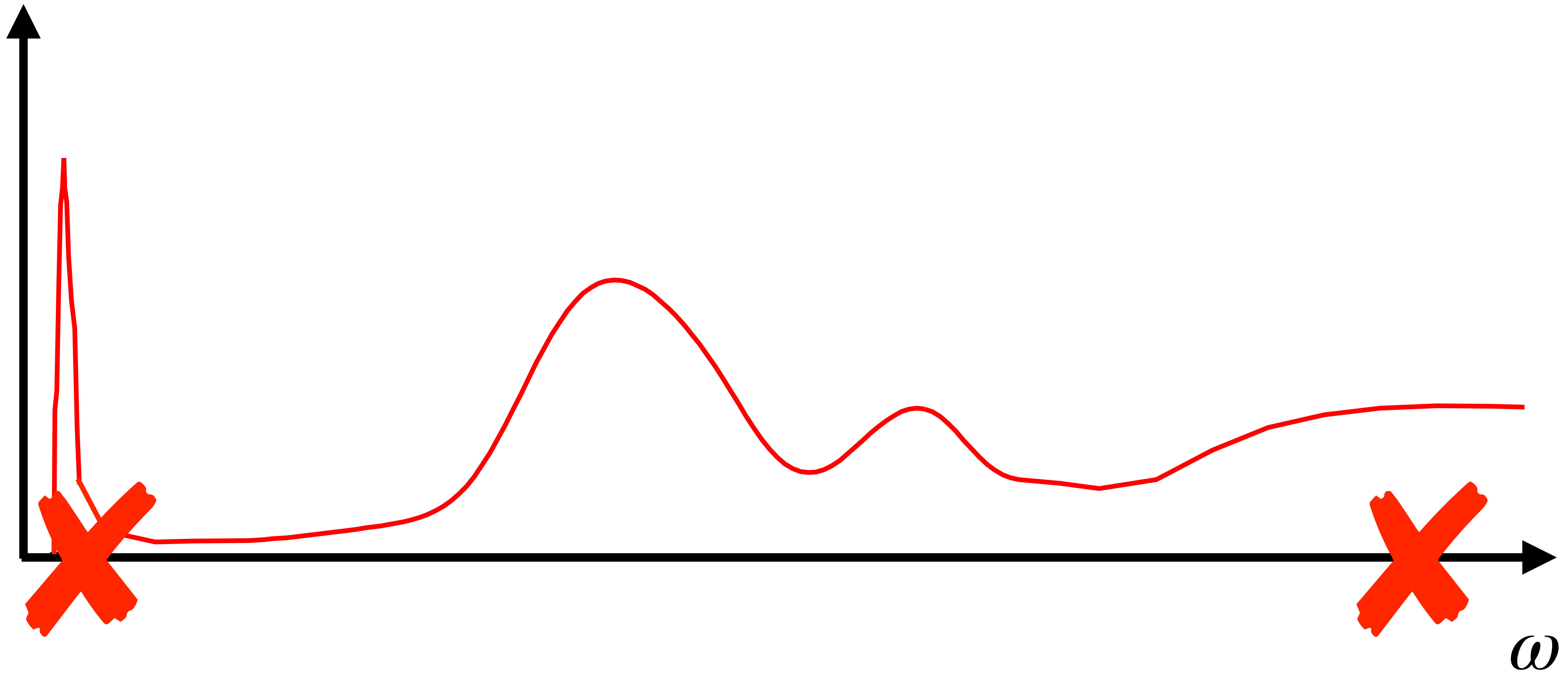

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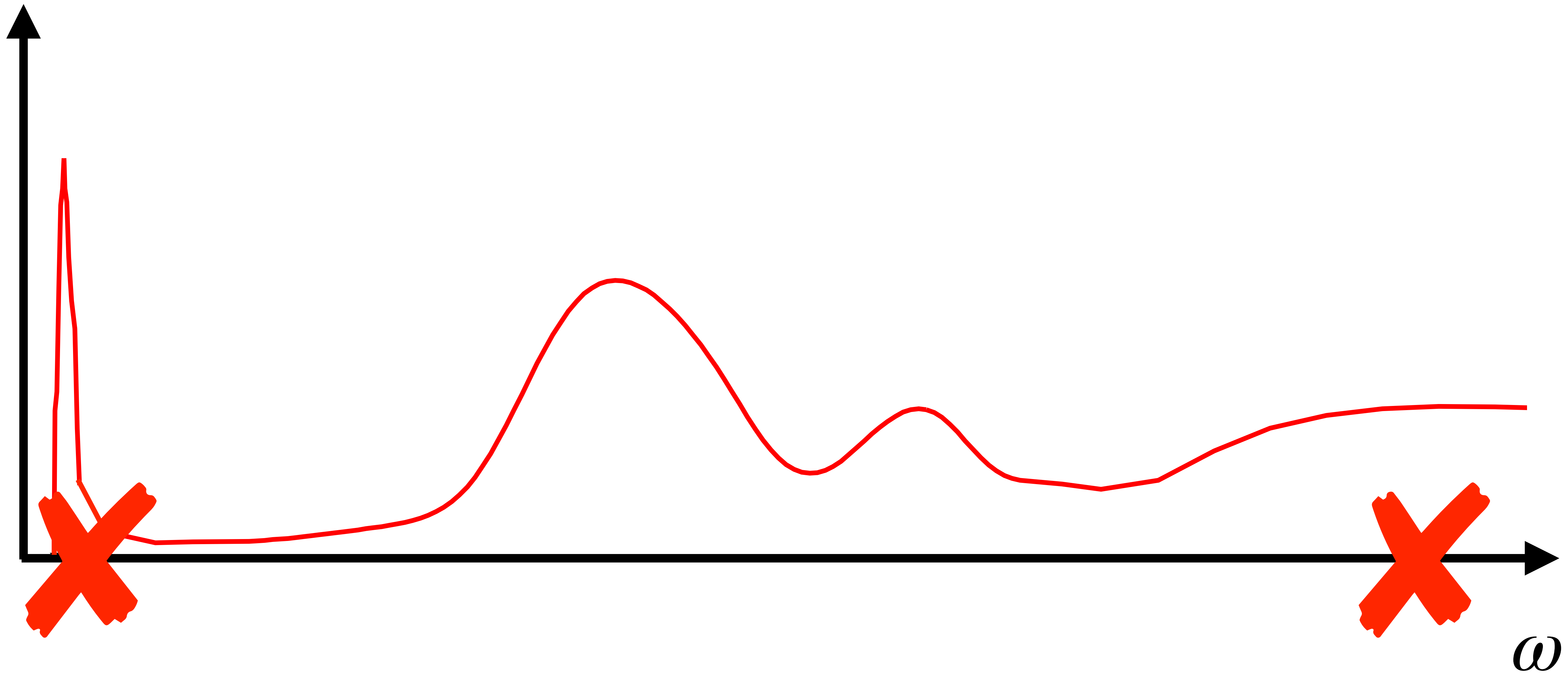

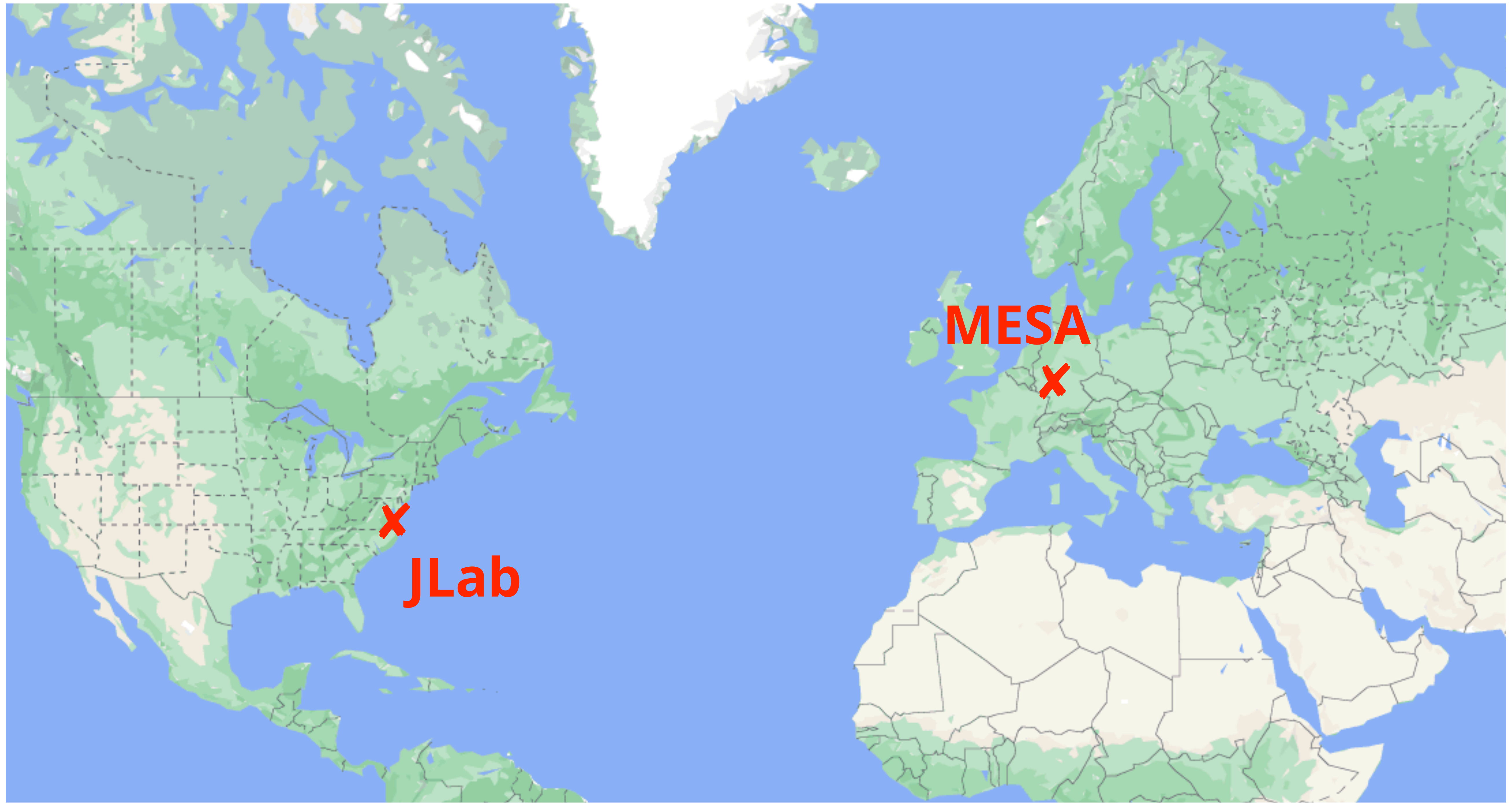

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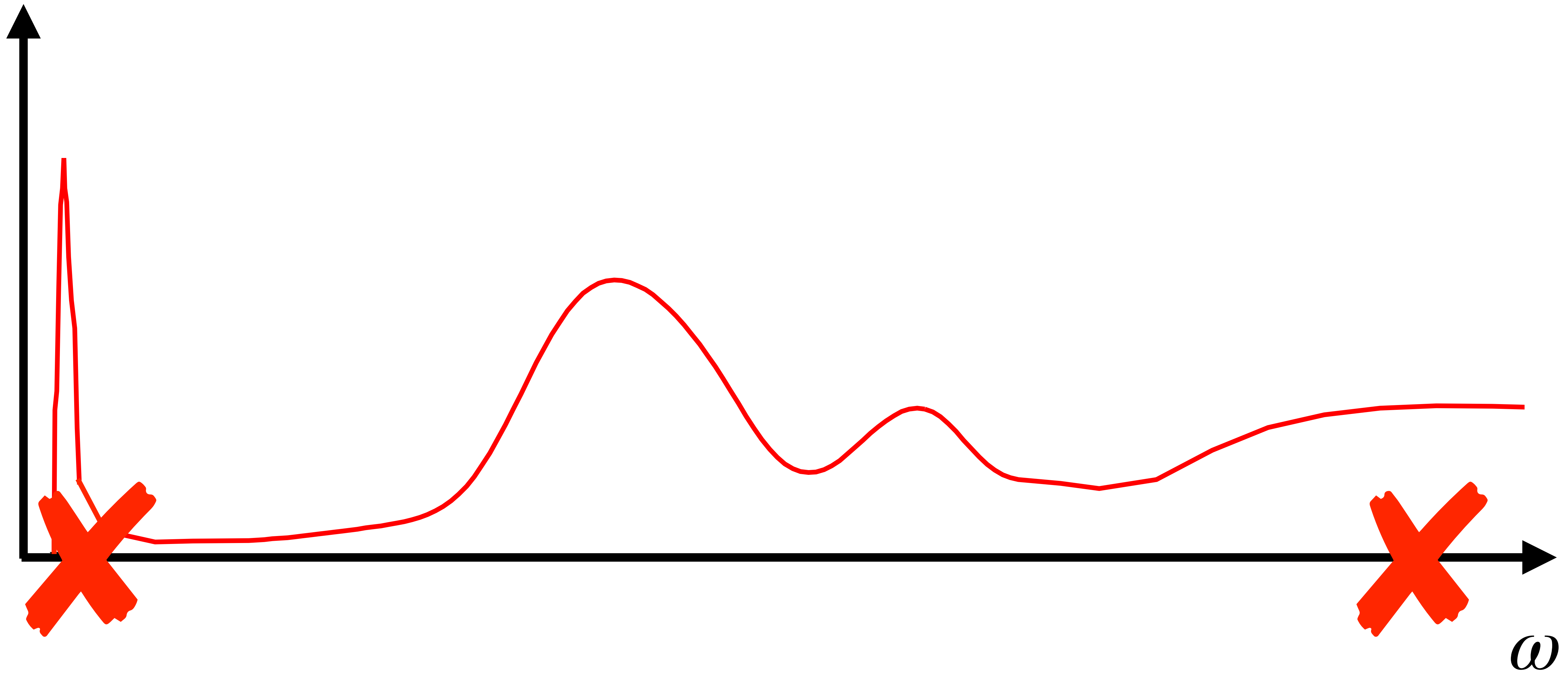

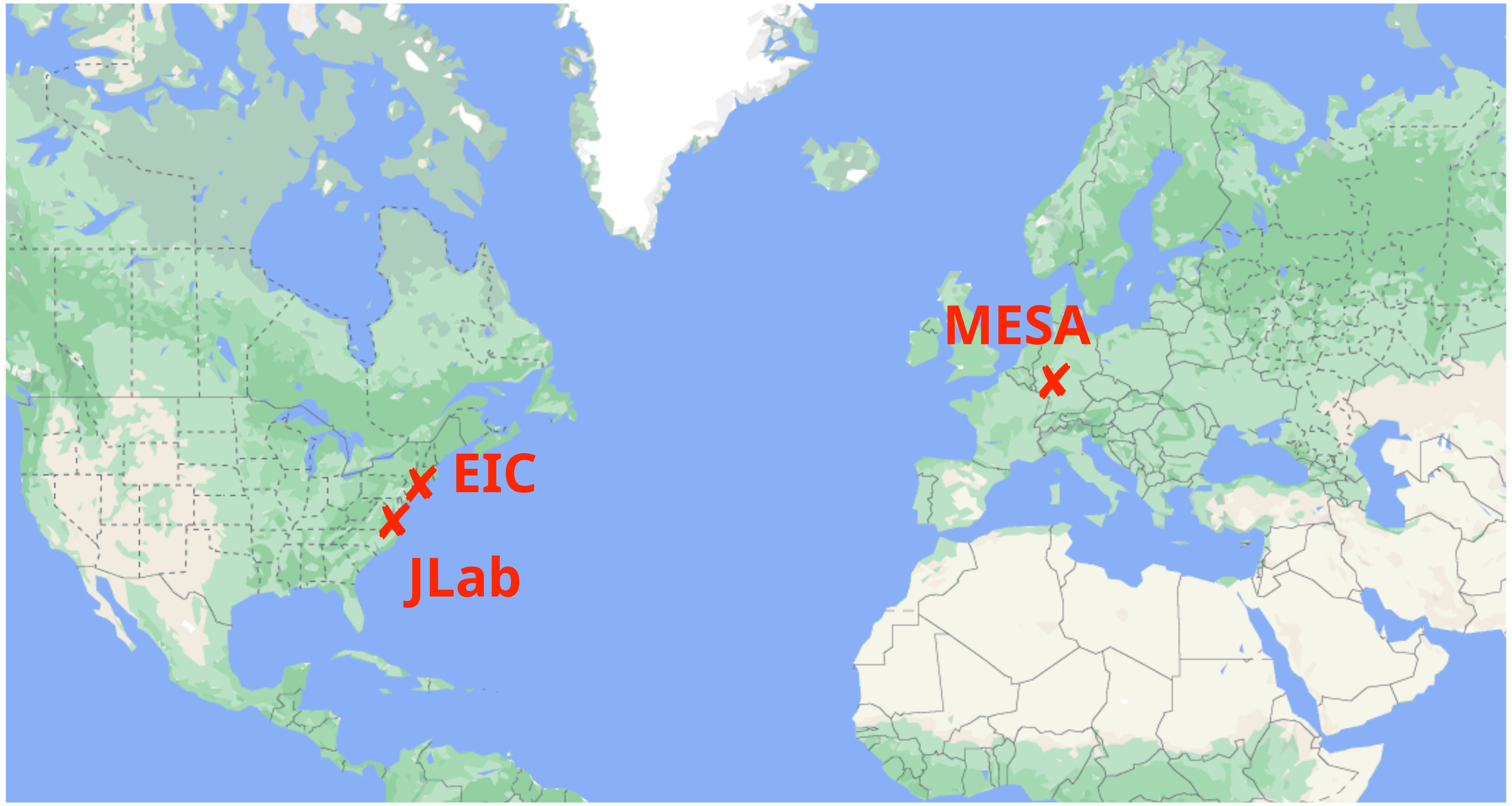

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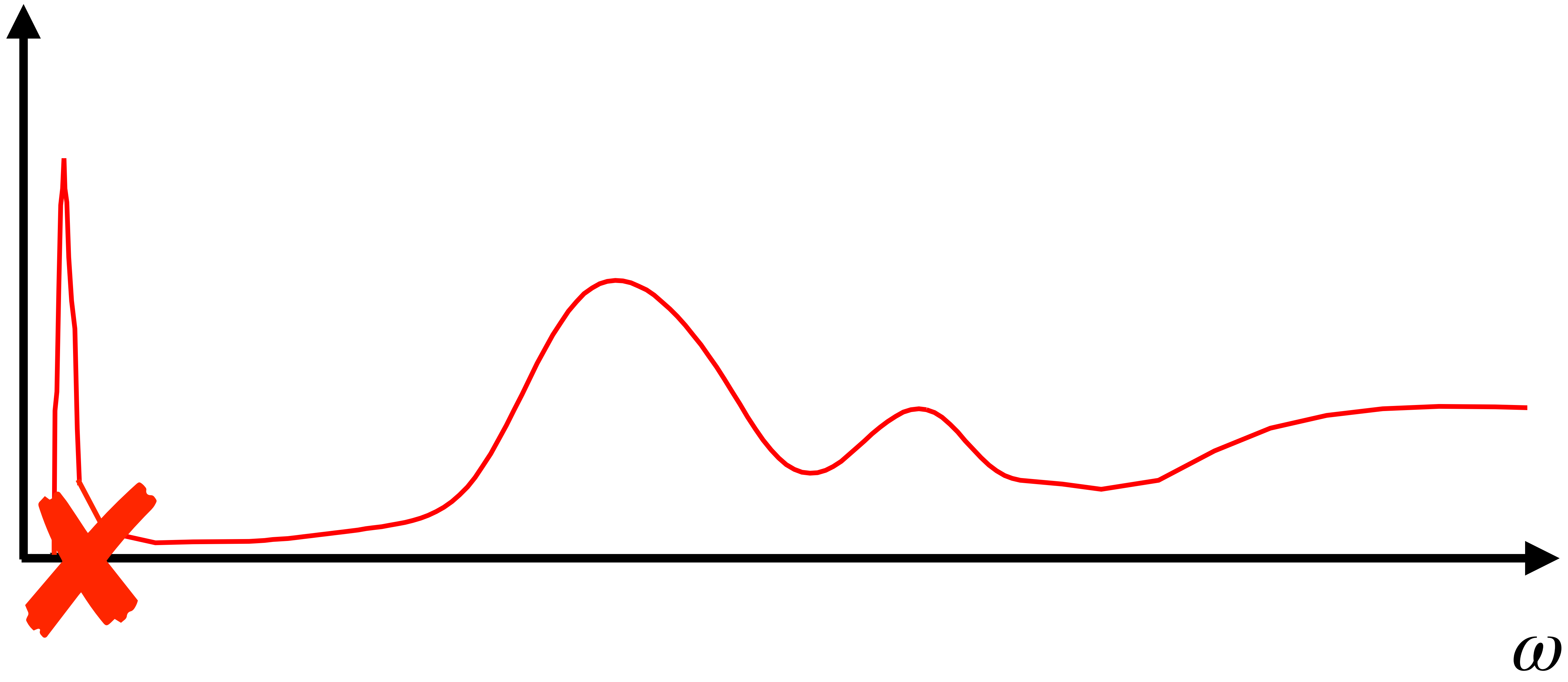

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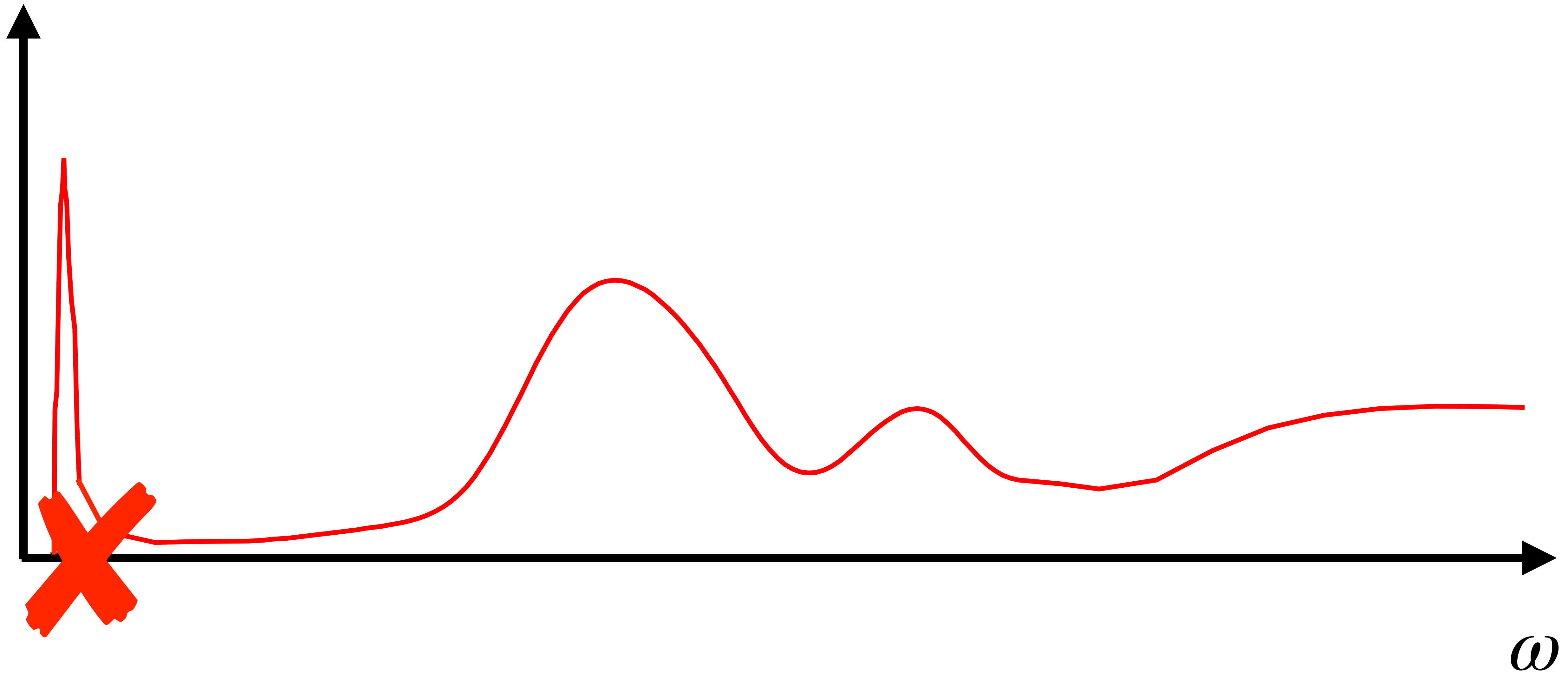
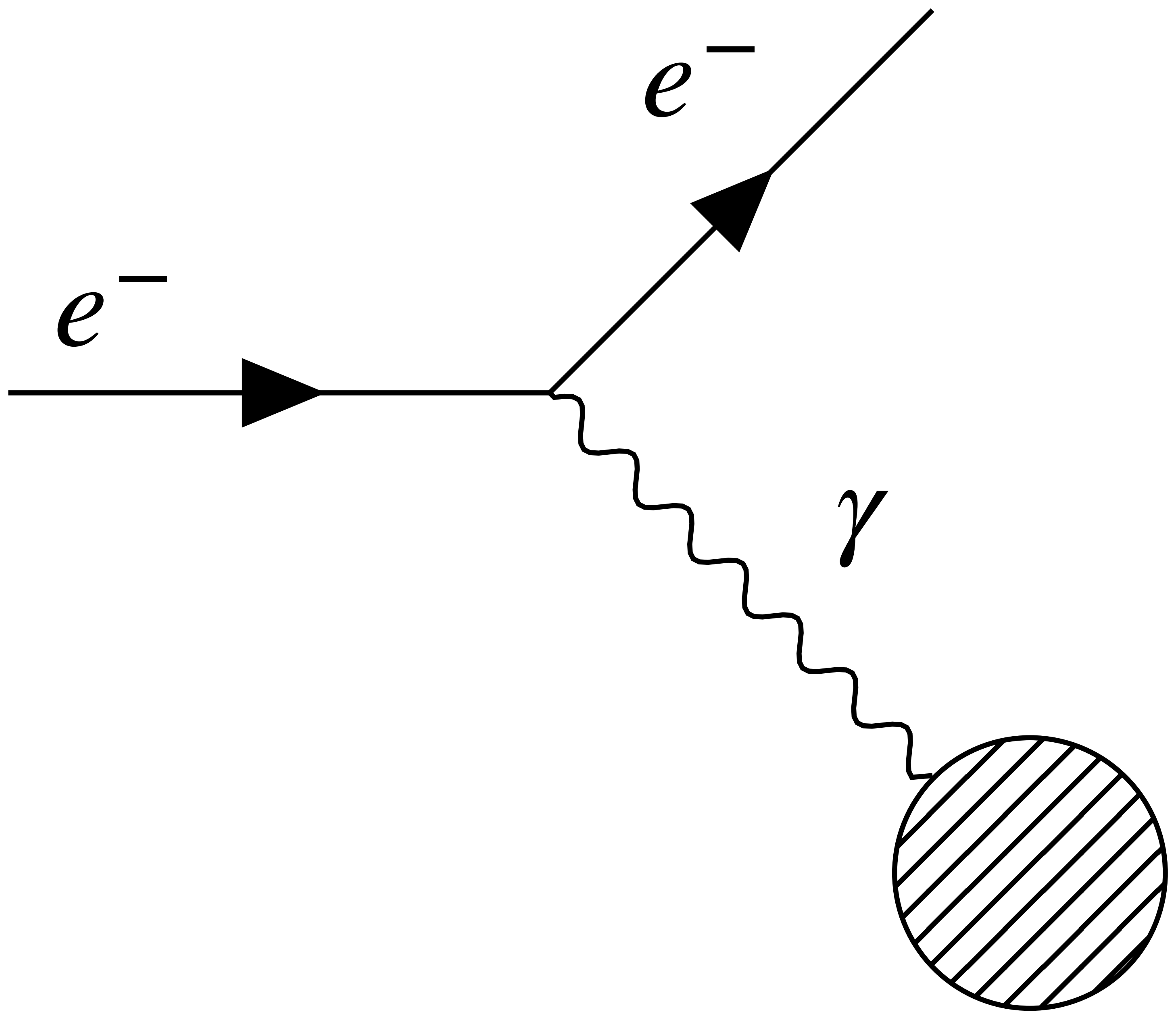


Elastic cross section



Momentum transfer squared

$$Q^2 = -q^2 = 4EE' \sin^2 \frac{\theta}{2}$$

Structureless (pointlike) target

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{4Z^2\alpha^2 E'^2}{Q^4}\frac{E'}{E}\left(1 - \beta^2 \sin^2 \frac{\theta}{2}\right)$$

$$\approx \frac{4Z^2\alpha^2 E'^2}{Q^4}\frac{E'}{E}\cos^2 \frac{\theta}{2}$$

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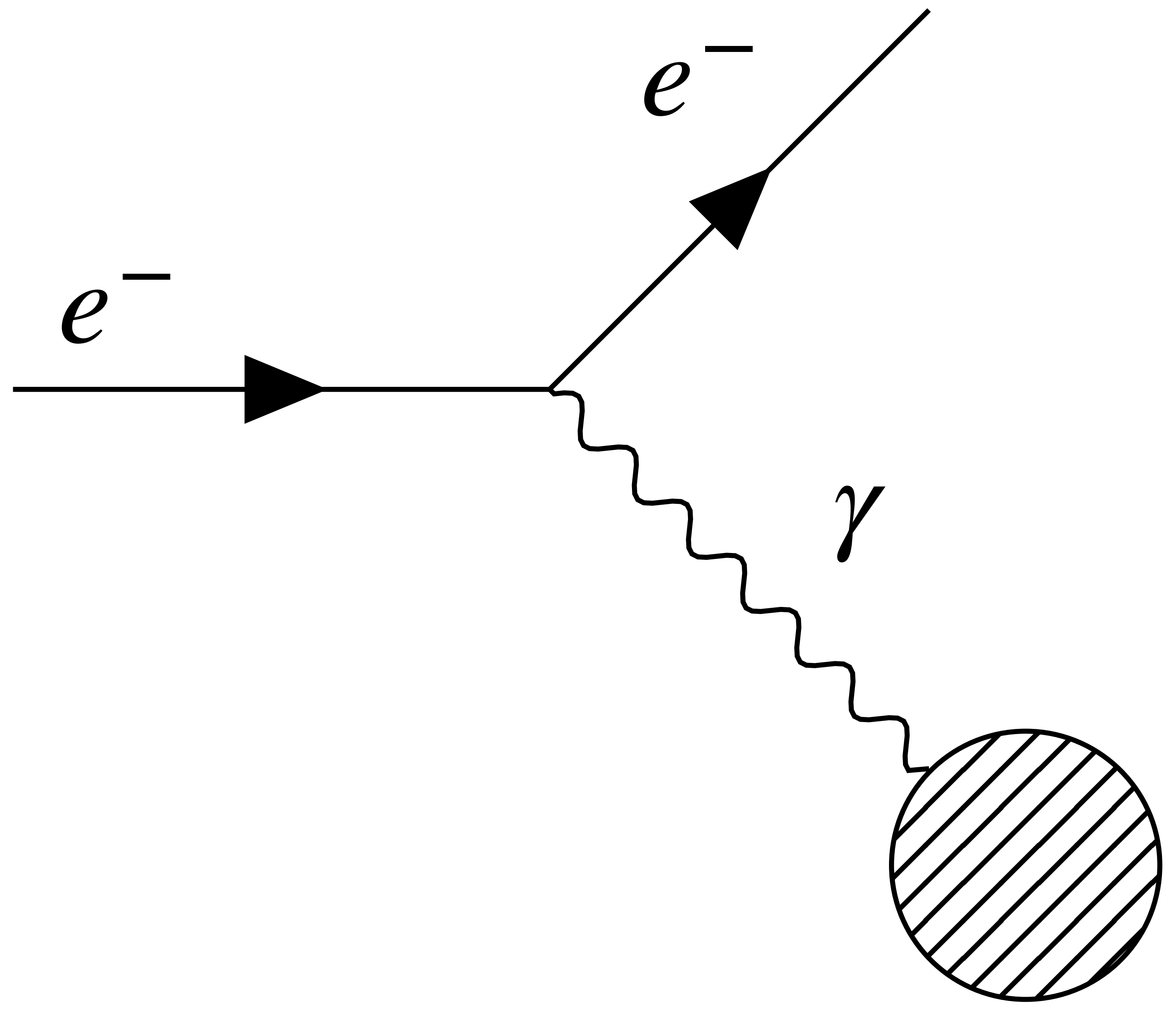

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Extended target

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

$$\tau = Q^2/4M^2 \qquad \varepsilon = \left(1+2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1}$$

Elastic cross section

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

- Structure parameterized with electric and magnetic form factors
  → *Fourier transforms* of charge and current densities

$$G(\mathbf{q}) = \int \rho(\mathbf{x}) e^{i\mathbf{q}\cdot\mathbf{x}}\, d^3x$$

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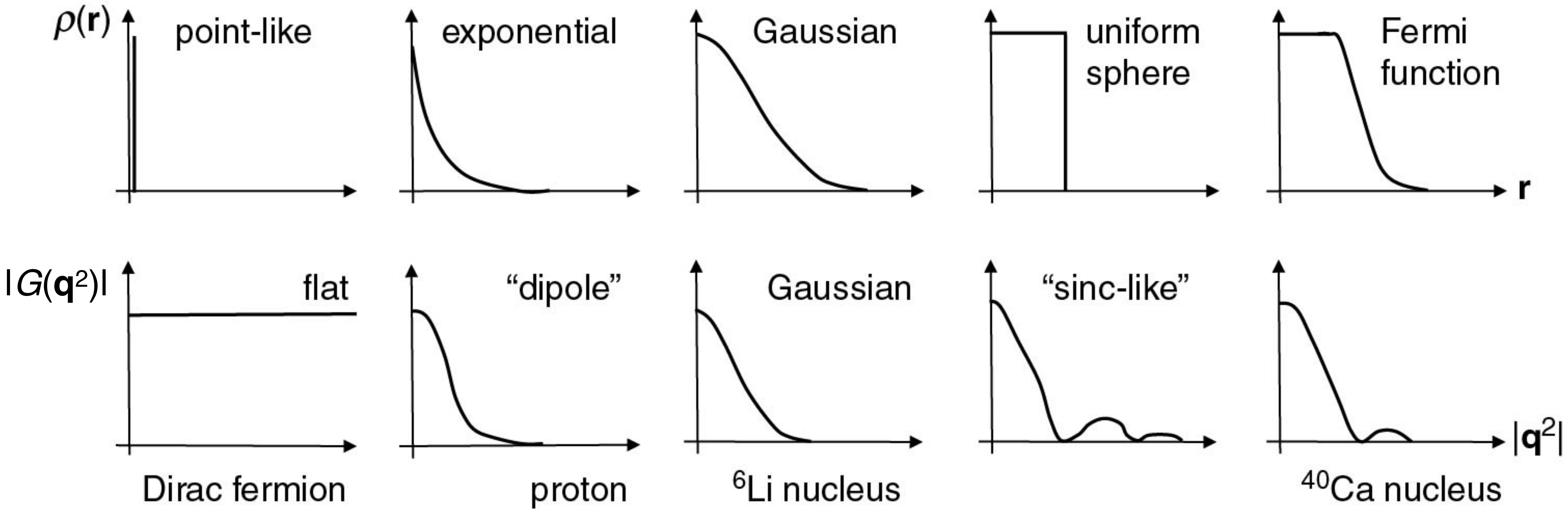

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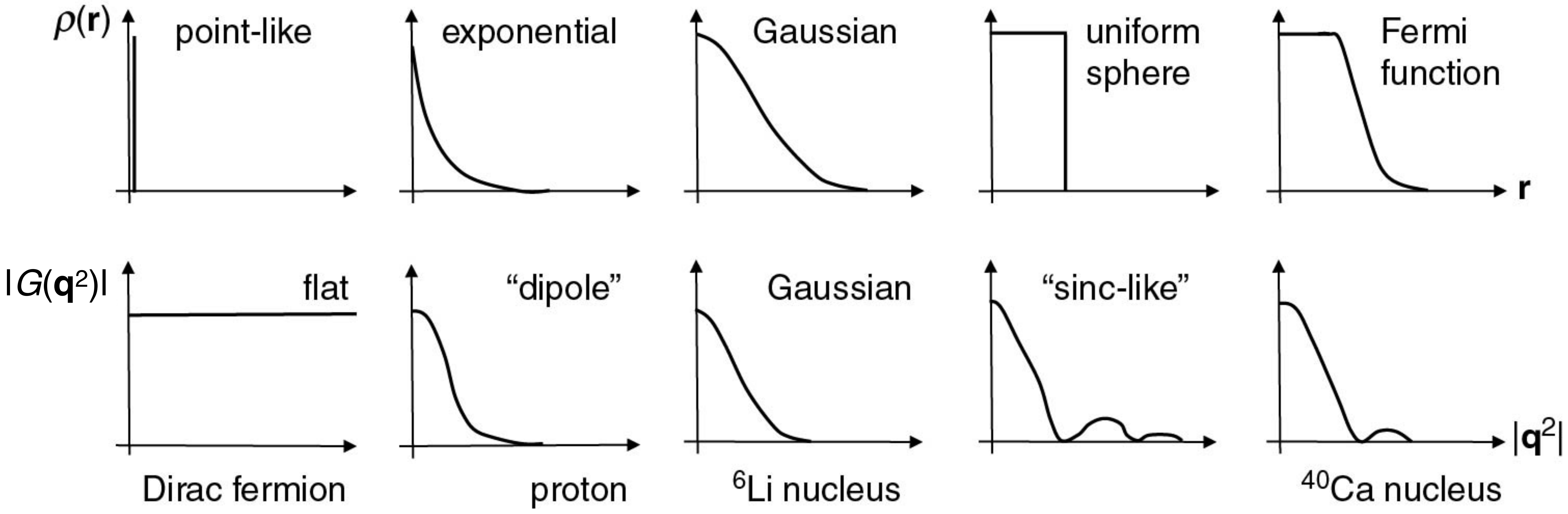


Low Q^2 expansion:

$$\langle r^2 \rangle \approx -6 \frac{dG(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

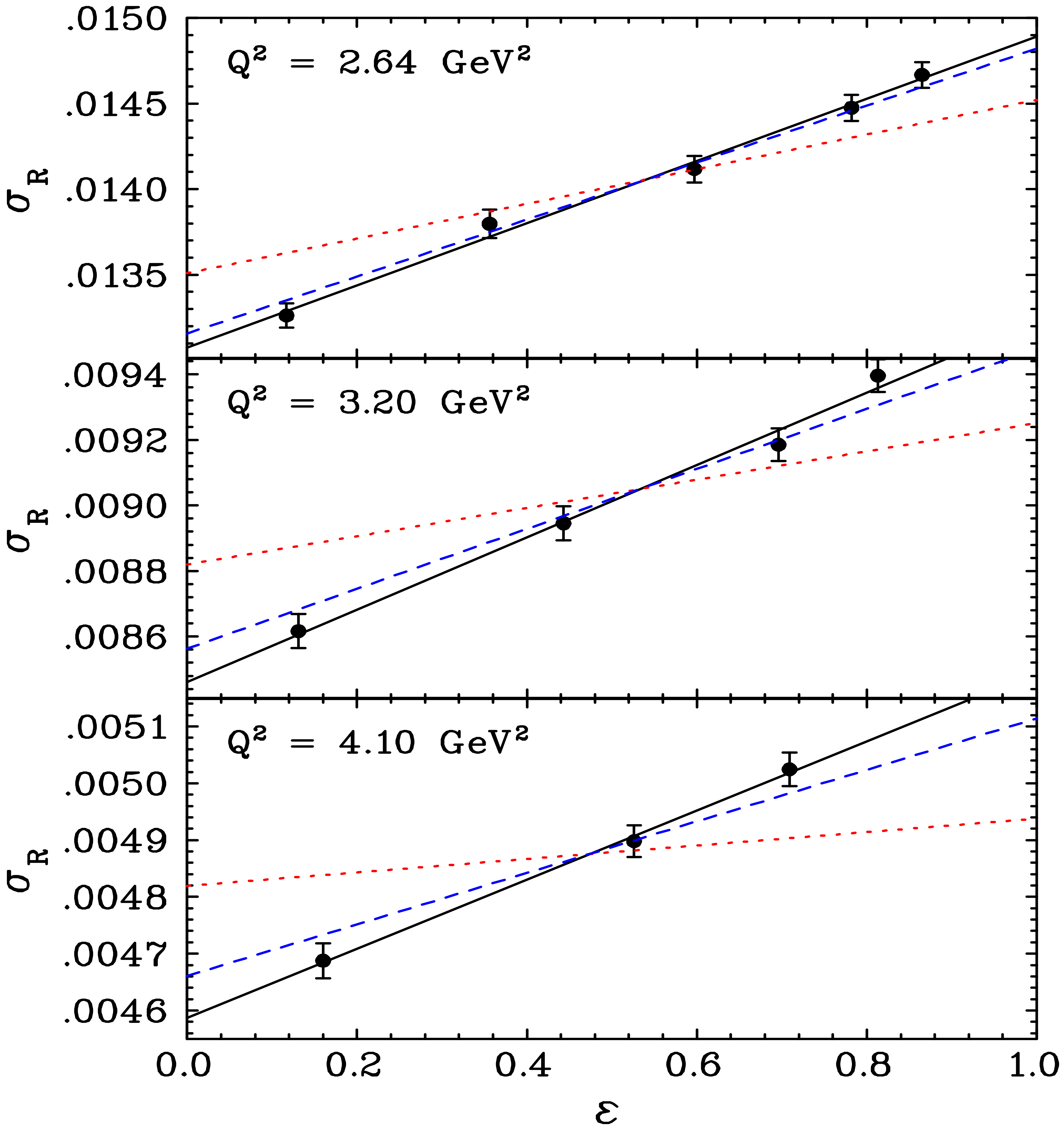
Proton form factors from Rosenbluth separation

- Method employed since 1960s
- Reduced cross section:

$$\sigma_R = \left(\frac{d\sigma}{d\Omega} \cdot \varepsilon(1+\tau)\right) \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}}$$

$$= \varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)$$

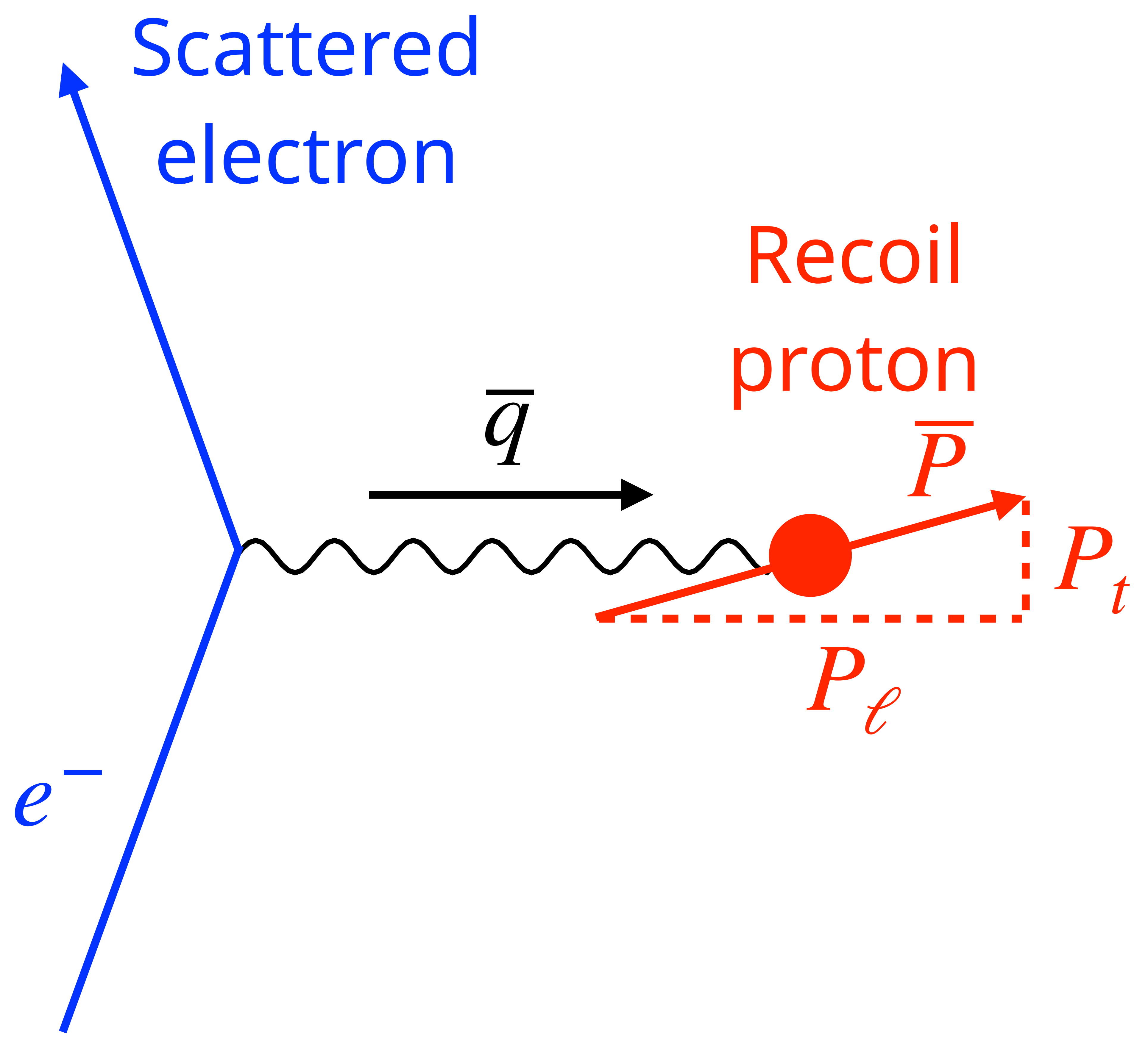
- Measure σ_R at fixed Q^2 for differing ε
- Slope, intercept of linear fit yields G_E, G_M (up to sign)



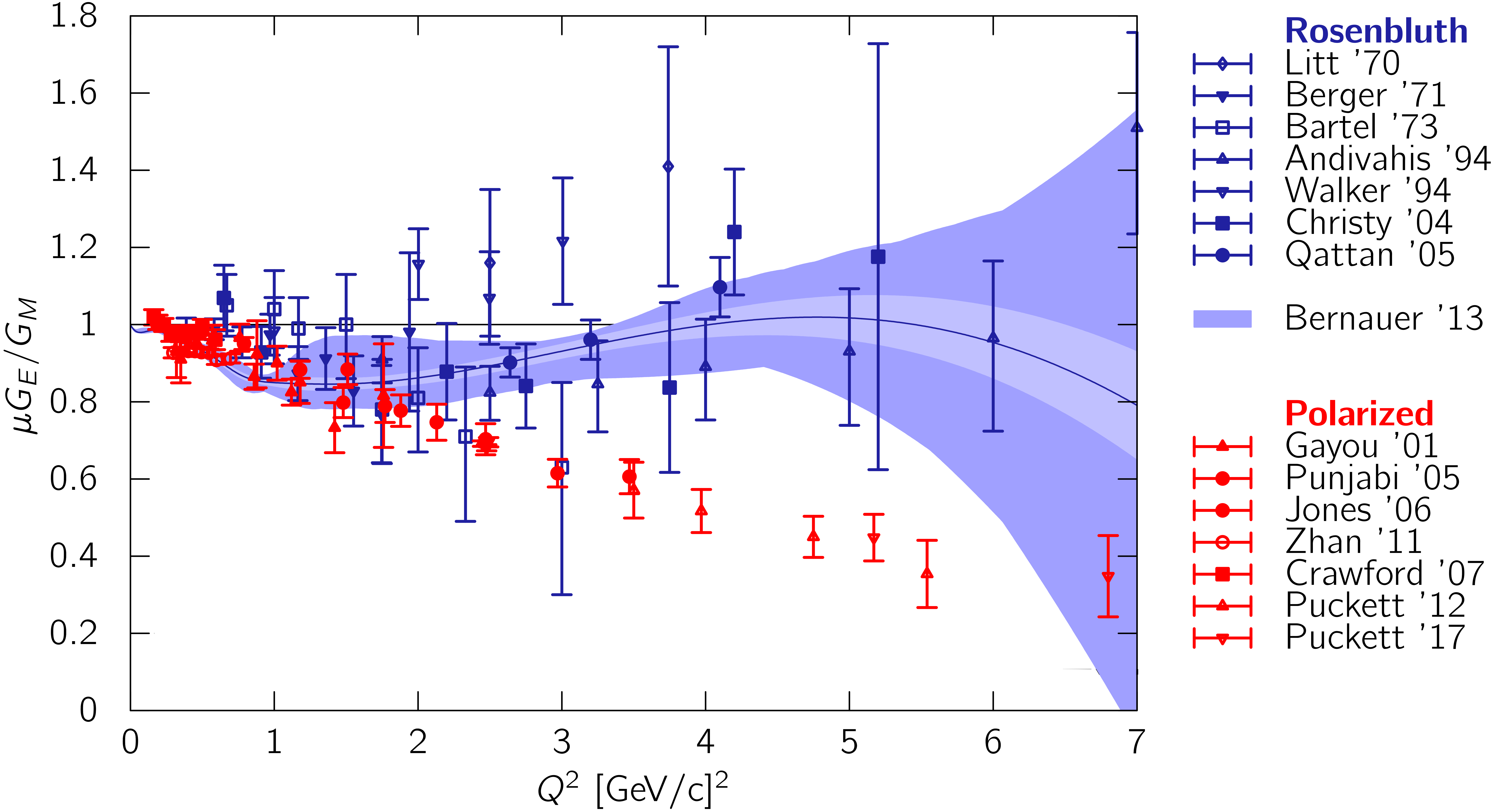
Proton form factor ratio from polarization transfer

- Pioneered at JLab in the 2000s
- Longitudinally polarized electrons on unpolarized protons
- Polarization transferred to the proton
- Detect components of recoil proton polarization $\overline{P}$ (relative to $\overline{q}$)
- Ratio of transverse/longitudinal components directly gives form factor ratio:

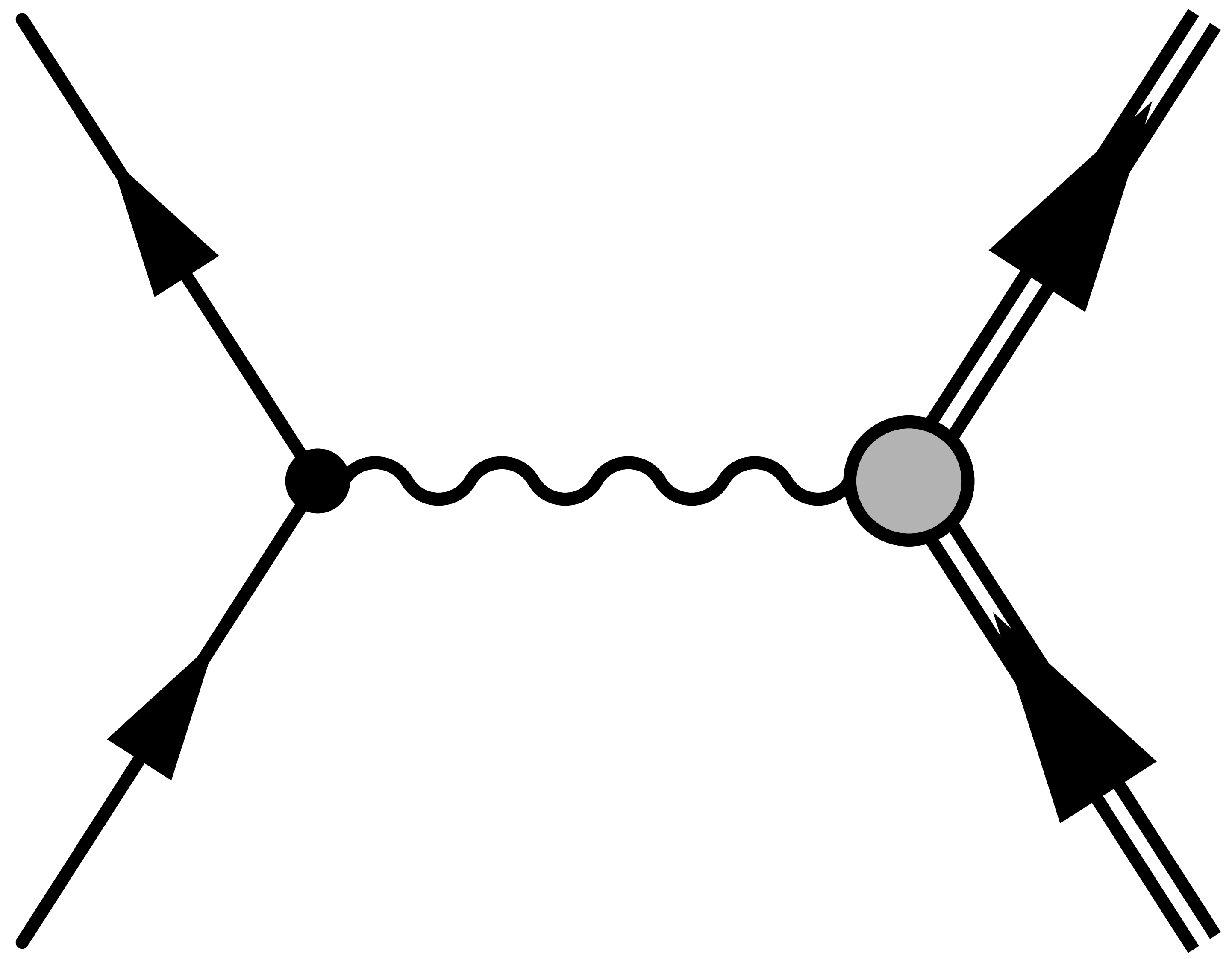
$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}$$



Different methods show discrepancy in form factor ratio



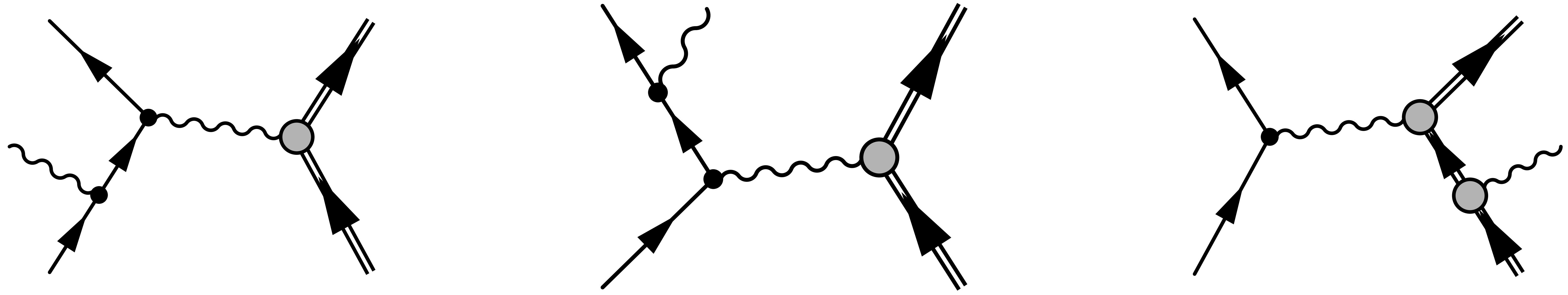
Beyond the Born approximation



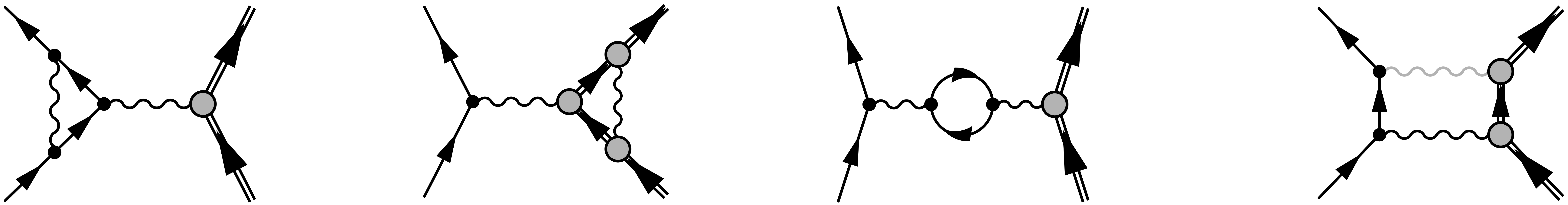
- Single-photon exchange useful picture
- But…this never happens!
- Many higher-order QED contributions to scattering process

Beyond the Born approximation

Bremsstrahlung



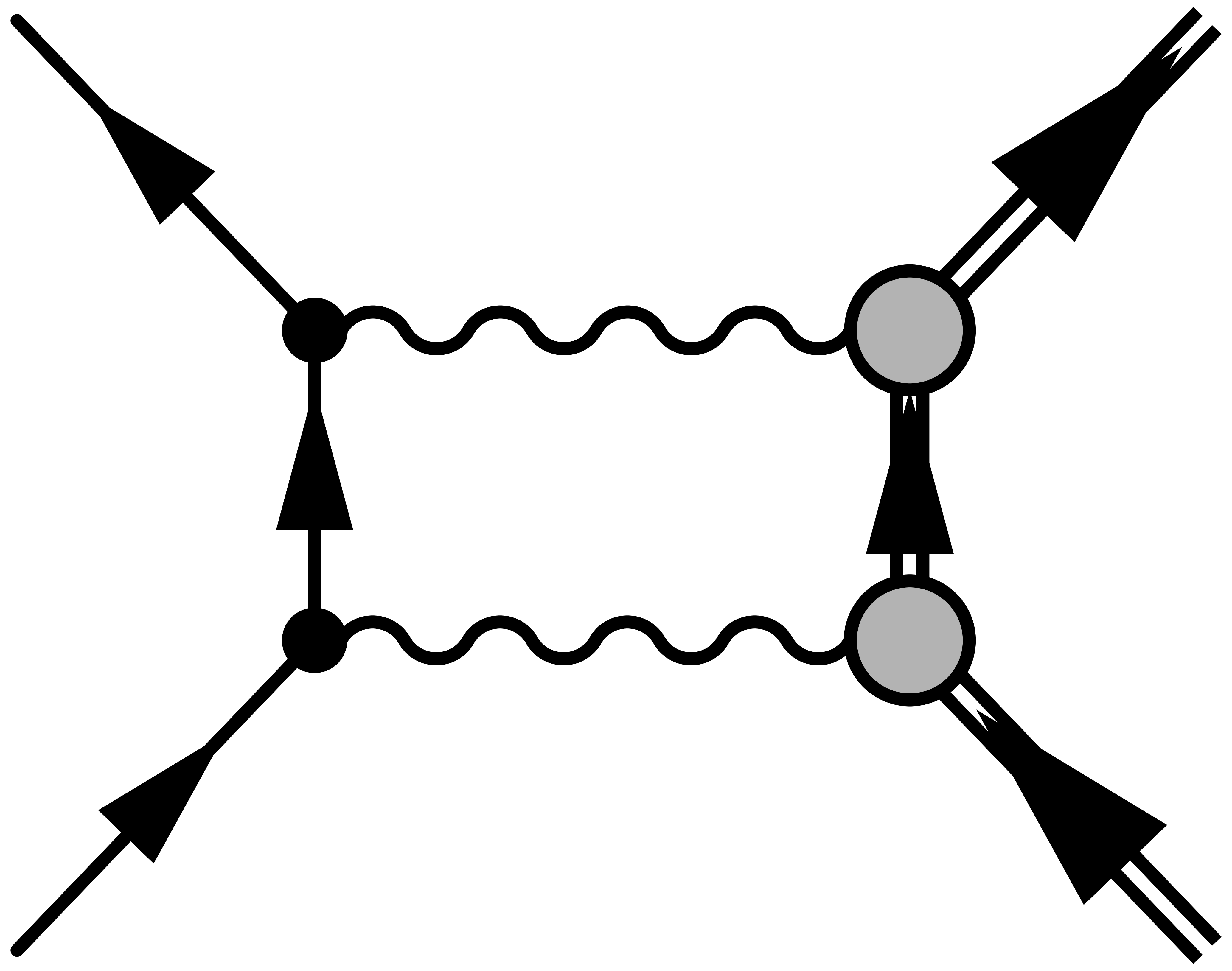
e vertex | *p* vertex | Vacuum polarization | Soft TPE



"Radiative corrections" :

calculate theoretically, subtract from experimental cross section

Missing radiative correction: hard two-photon exchange



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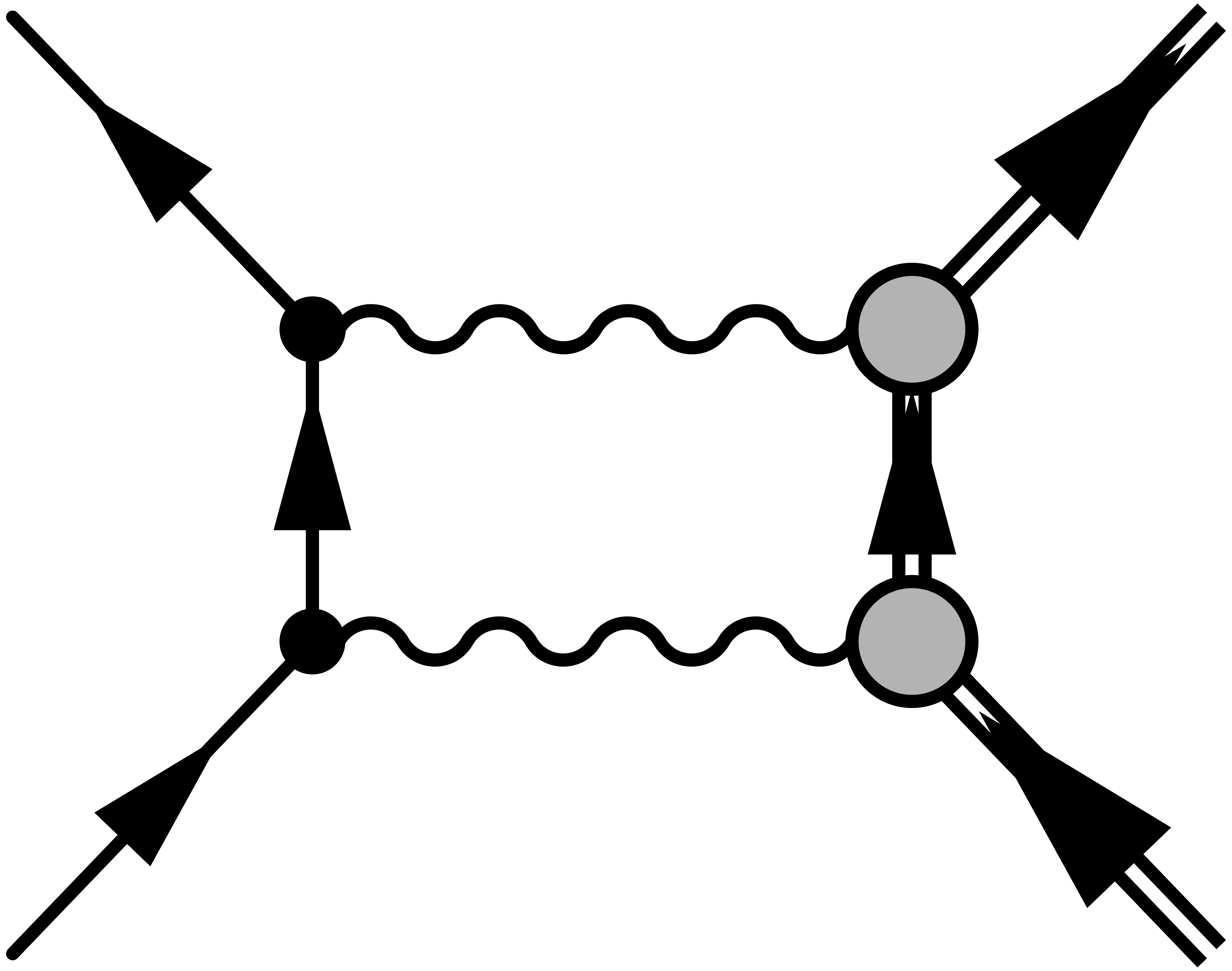

- Hard: both photons carry significant four-momentum
- Unlike other radiative processes, the hadronic vertex does not factorize
- Intrinsically depends on internal structure of the proton!

Calculation of hard TPE model-dependent

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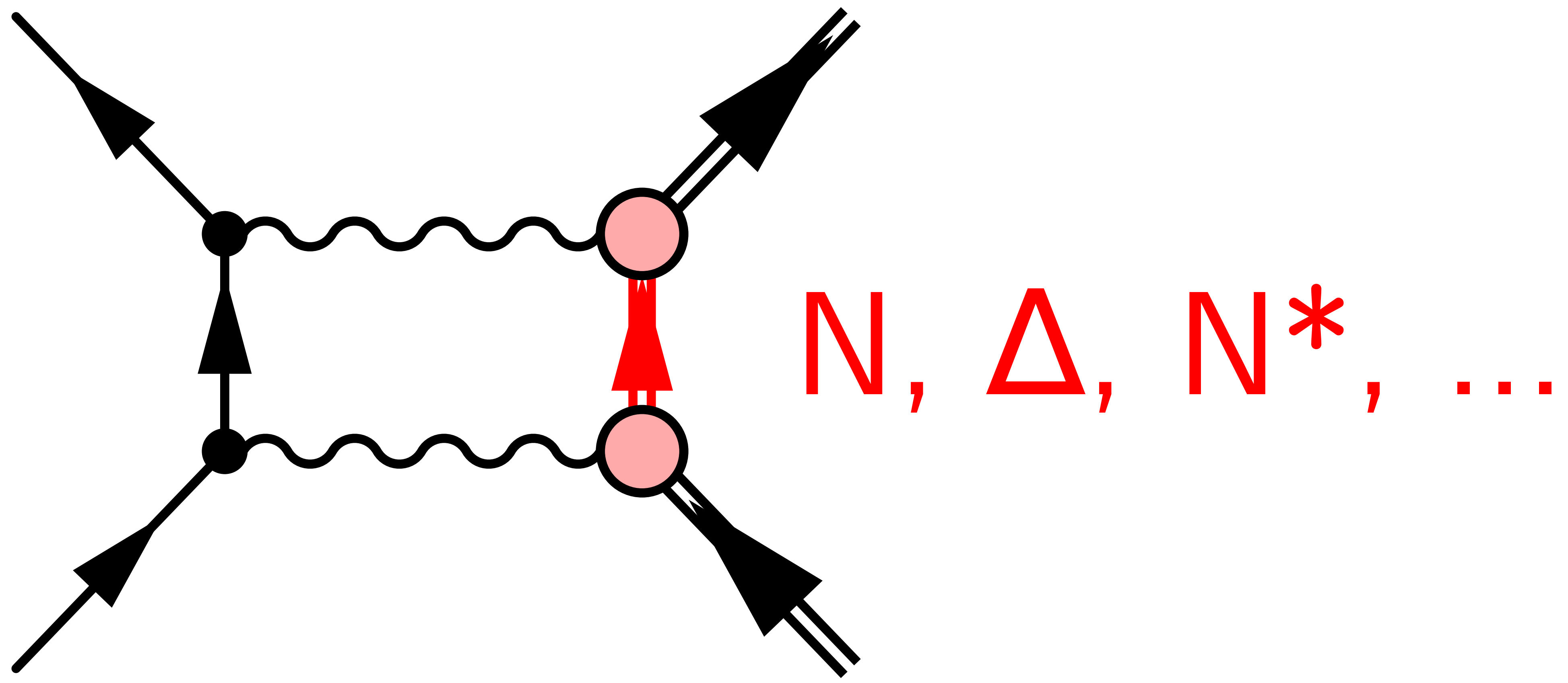
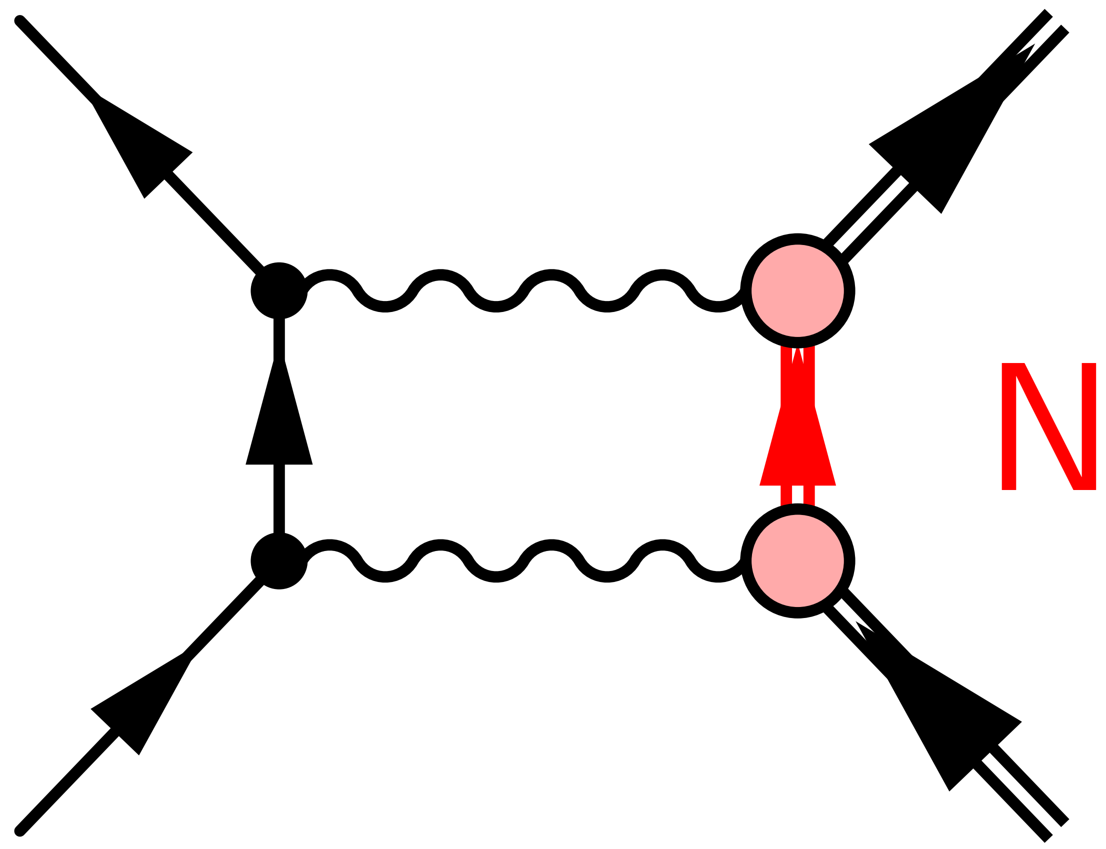


- Sum over intermediate hadronic states e.g. Ahmed, Blunden, Melnitchouk PRC 102, 045205 (2020)
- $Q^2 \lesssim 3$ GeV^2.

Calculation of hard TPE model-dependent



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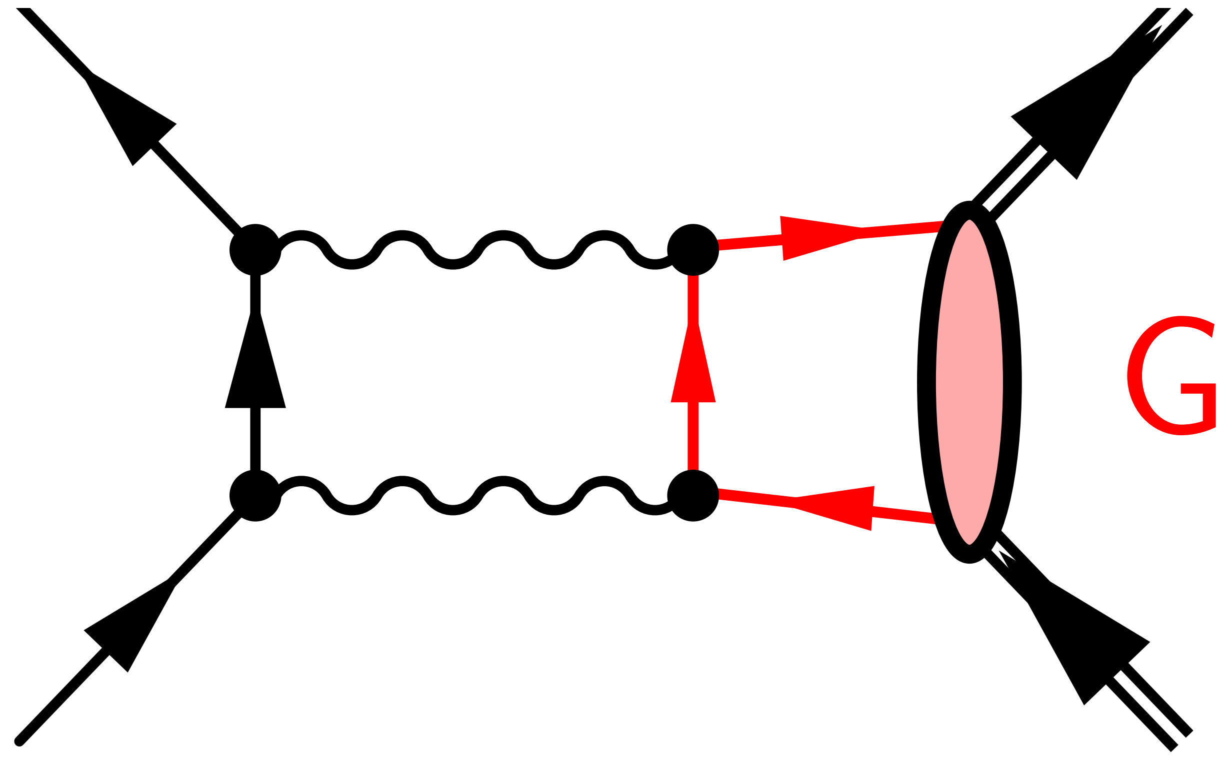

- Treat as $\gamma\gamma$ interaction with quarks described by generalized parton distributions
  e.g. Afanasev et al. PRD 72, 013008 (2005)
- $Q^2 \gtrsim 5$ GeV².

TPE could resolve $\mu G_E/G_M$ discrepancy

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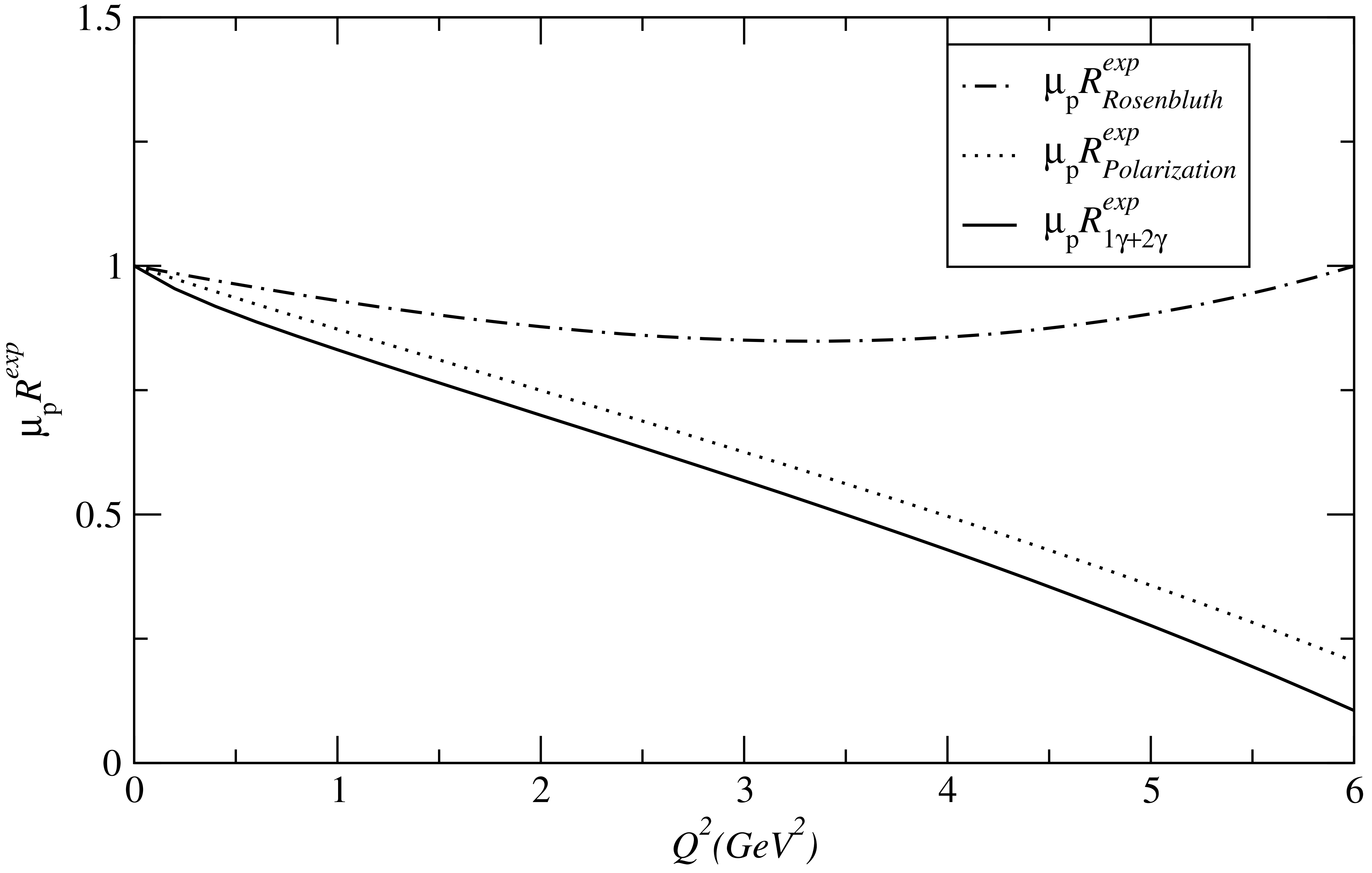
- TPE would have enhanced impact on Rosenbluth separation vs. polarization transfer e.g. Guichon & Vanderhaeghen, PRL 91, 142303 (2003)



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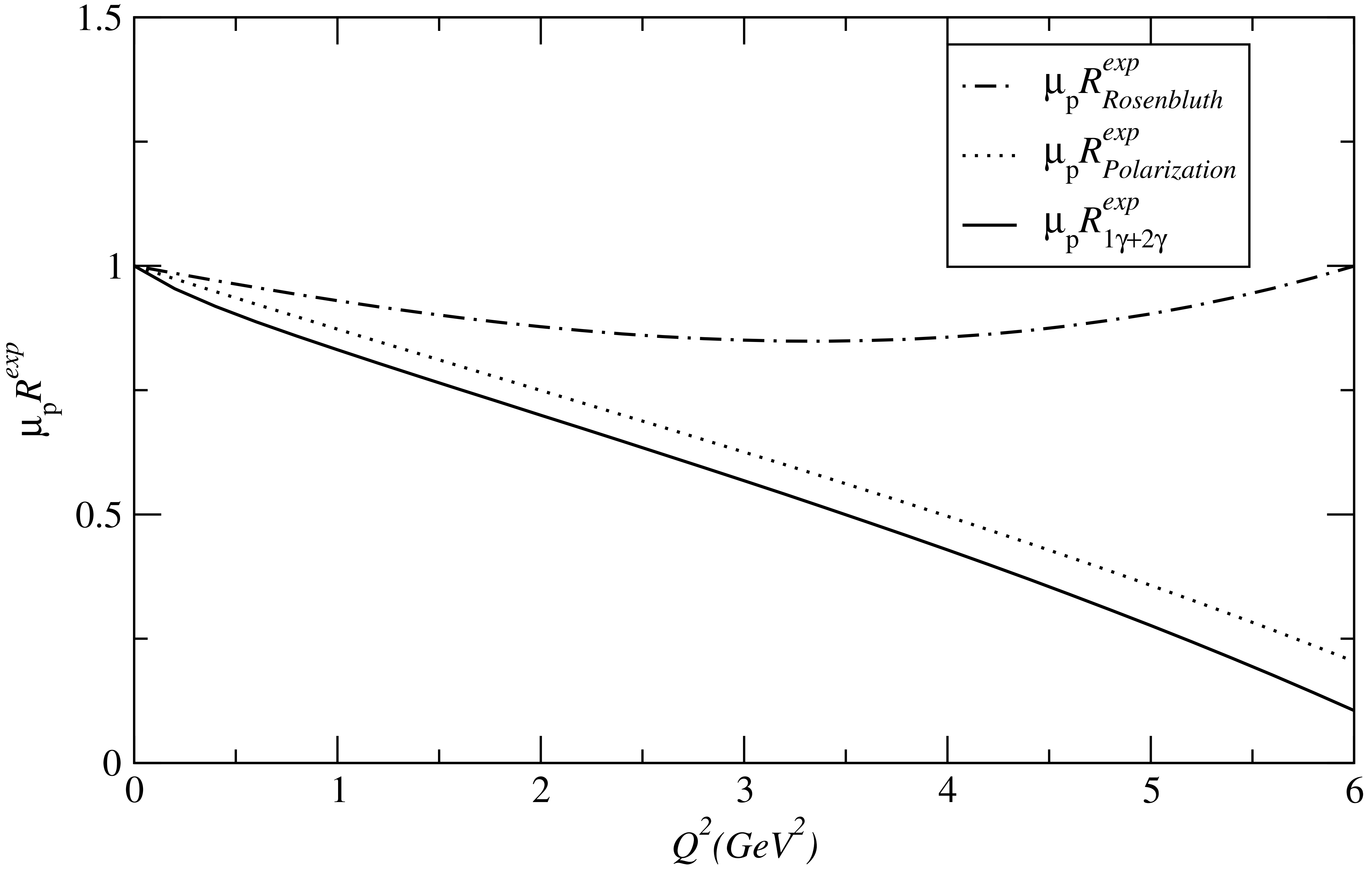
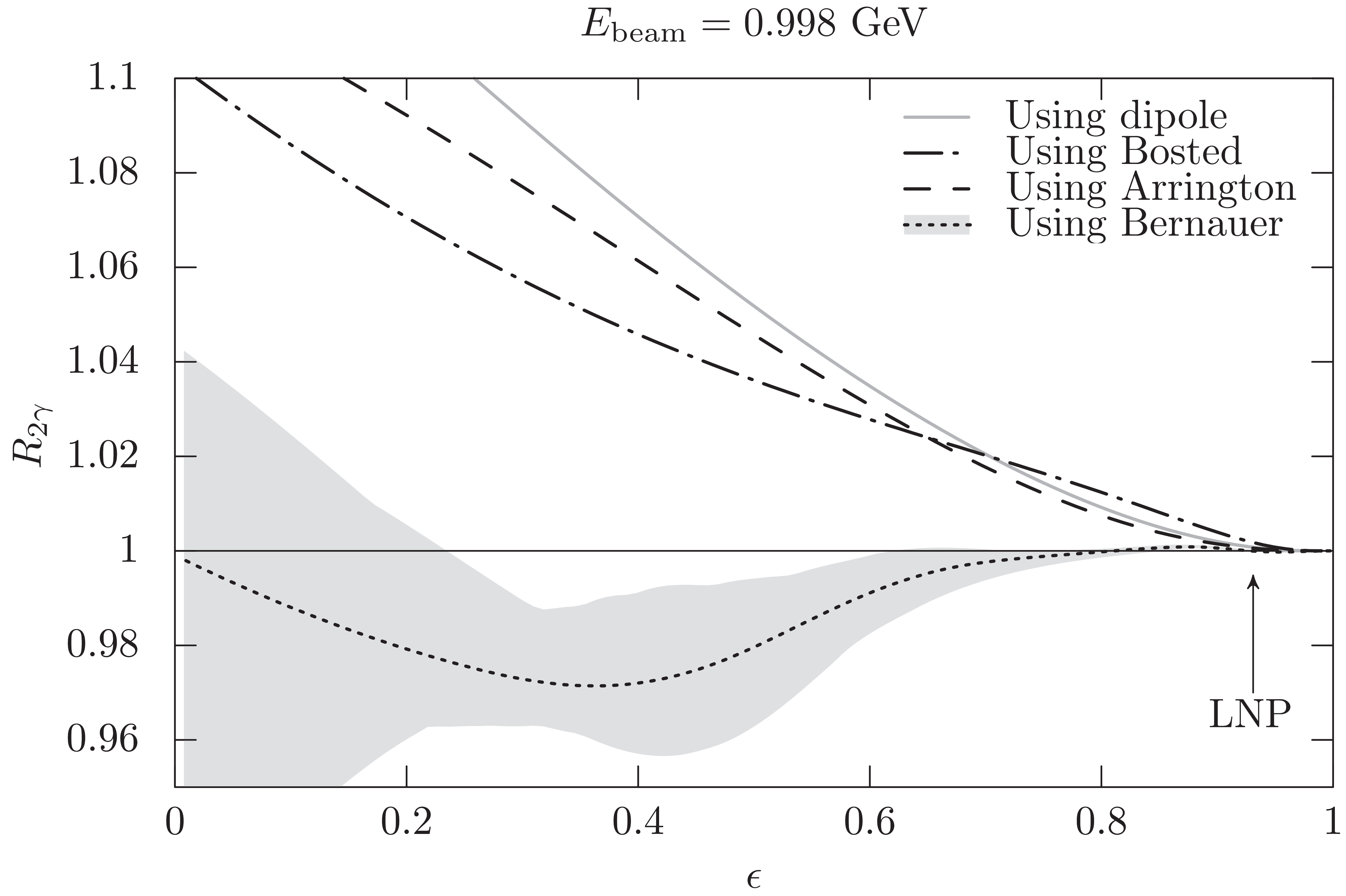
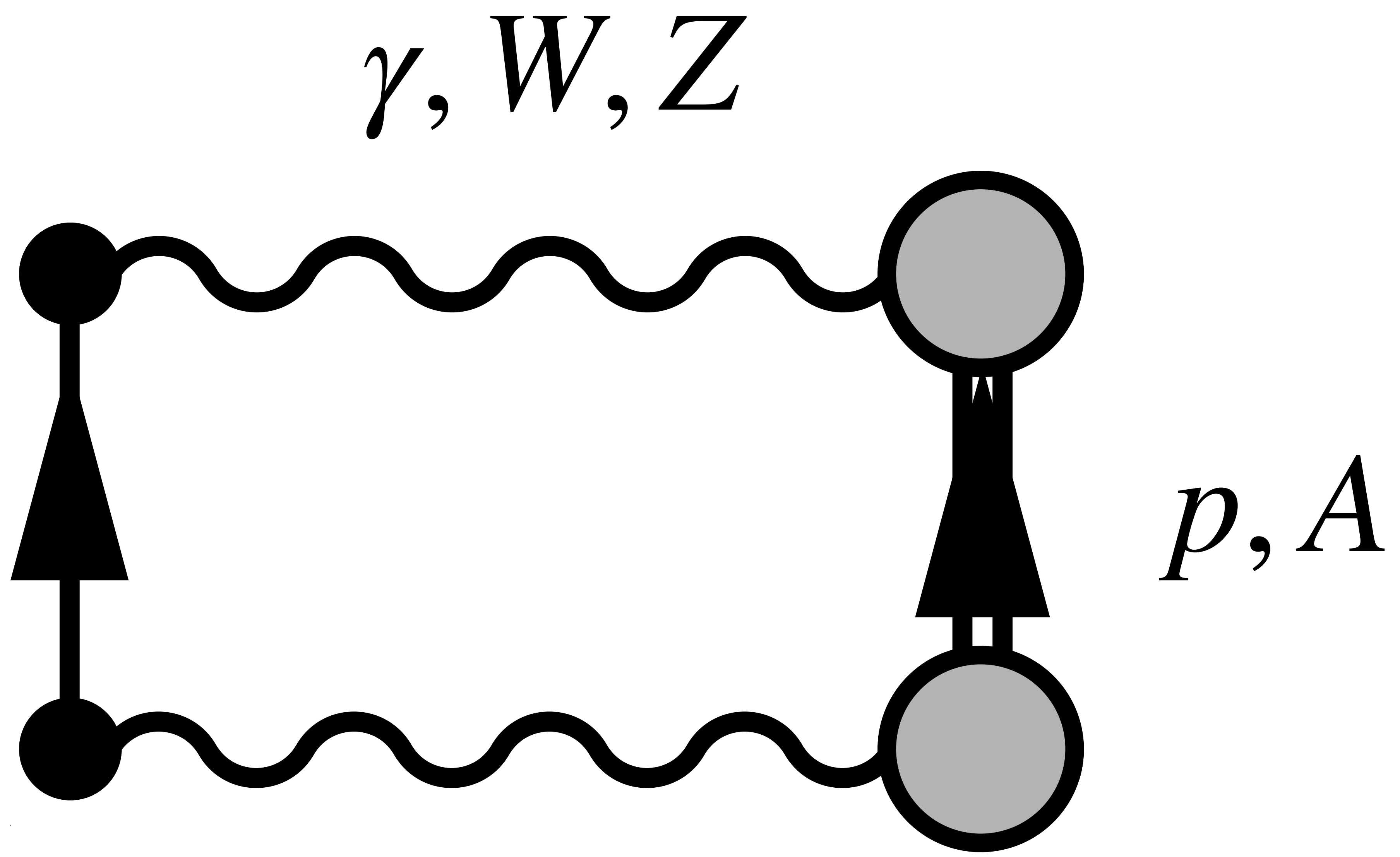
- TPE would have enhanced impact on Rosenbluth separation vs. polarization transfer e.g. Guichon & Vanderhaeghen, PRL 91, 142303 (2003)
- Phenomenological approach: predict size of TPE needed to resolve discrepancy e.g. Schmidt, JPG 47, 055109 (2020)





Hadronic box diagrams a more general challenge as radiative correction to electro(weak) measurements



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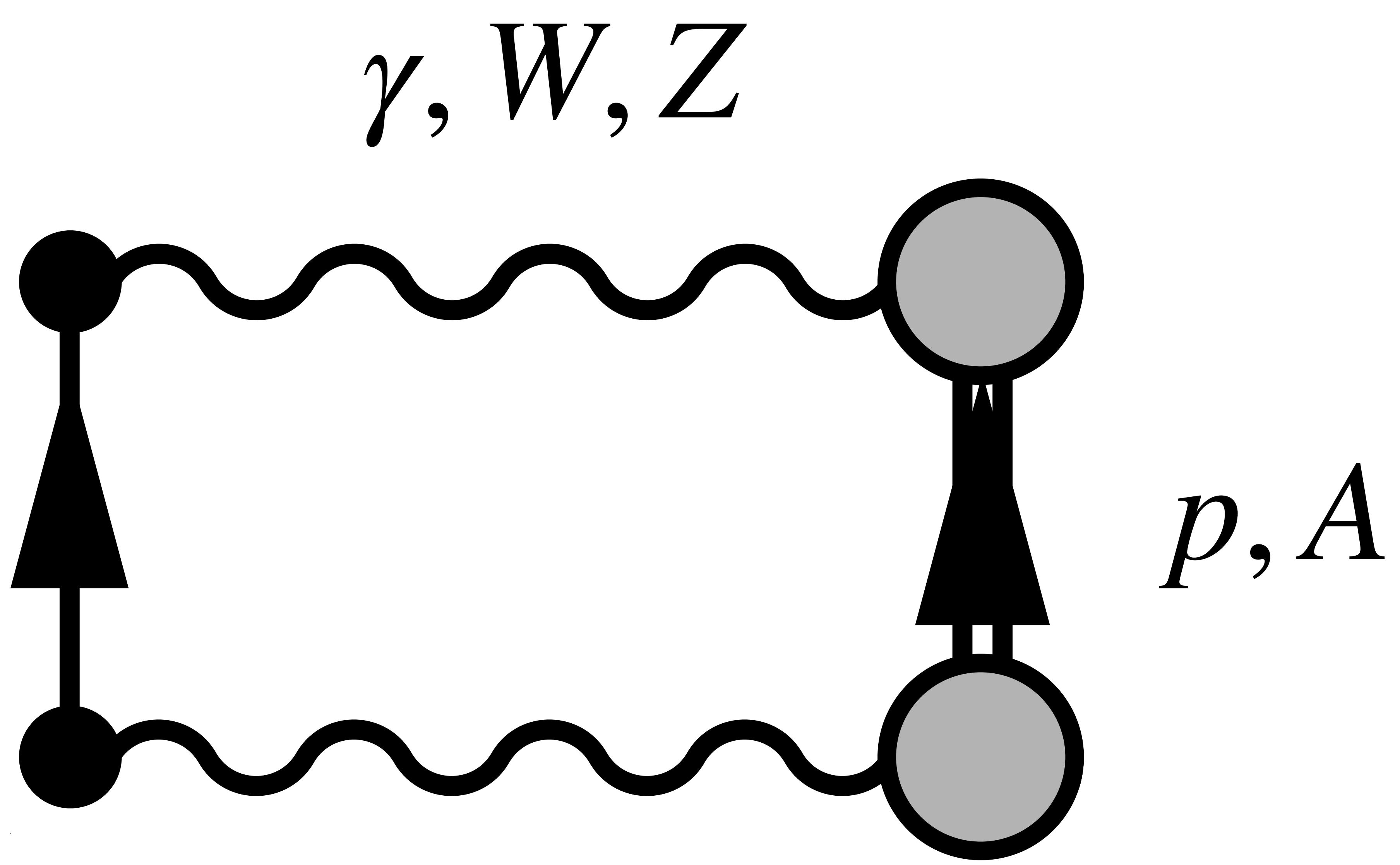
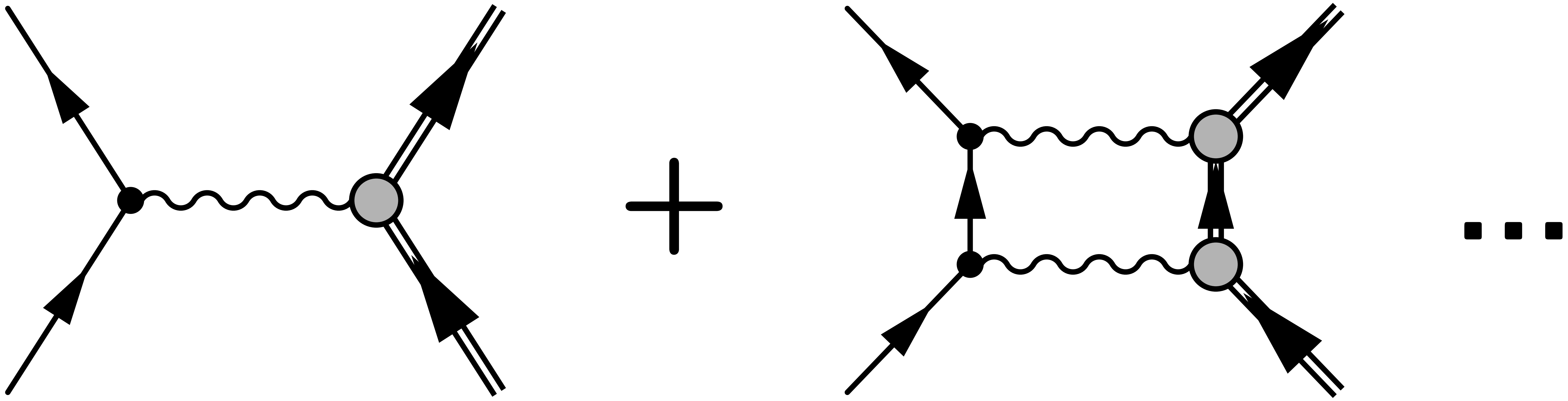


- $\Box_{\gamma\gamma}$: background to parity-violating electron scattering (PVES)
- $\Box_{\gamma Z}$: weak mixing angle extractions from PVES
- $\Box_{\gamma W}$: CKM matrix elements from β-decay

Can observe interference between one- and two-photon exchange

$$\mathcal{M} =$$



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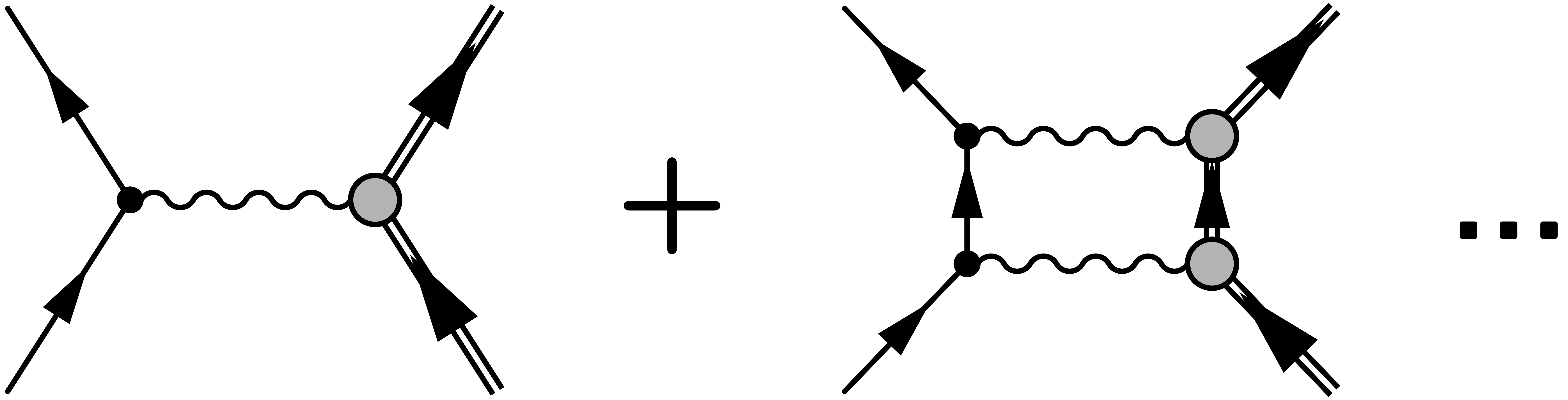

- Normal single-spin asymmetries

$$A_n = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{2\mathcal{I}(\mathcal{M}_{1\gamma}\mathcal{M}^*_{2\gamma})}{|\mathcal{M}_{1\gamma}|^2}$$

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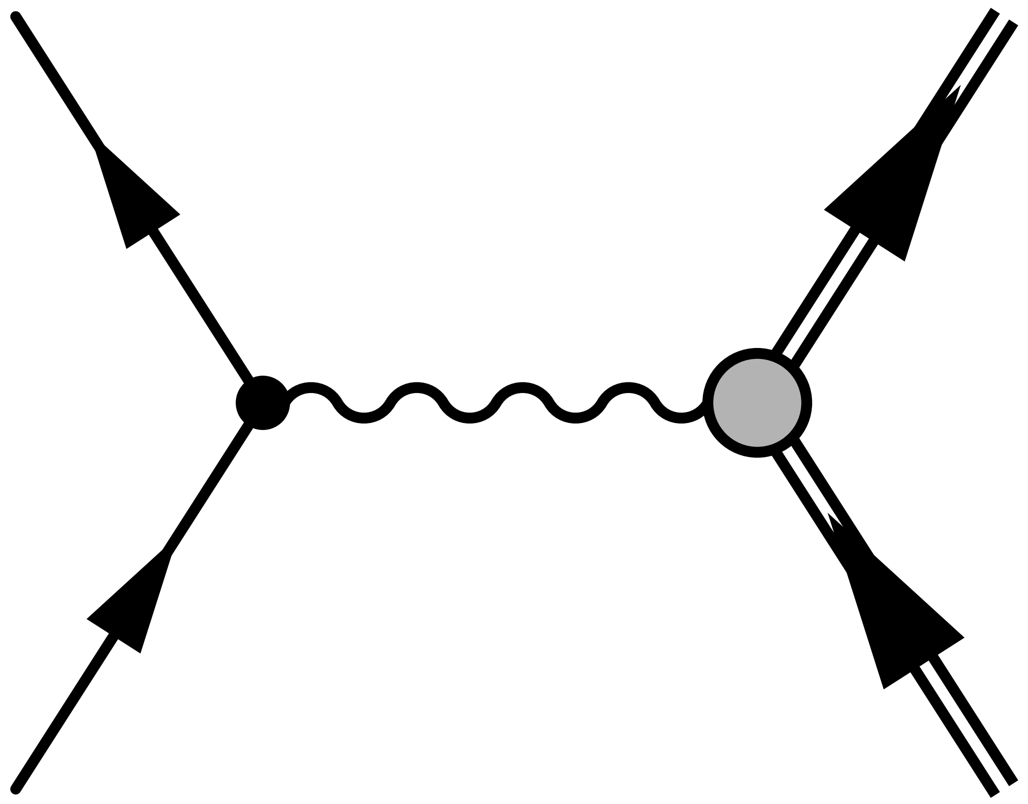

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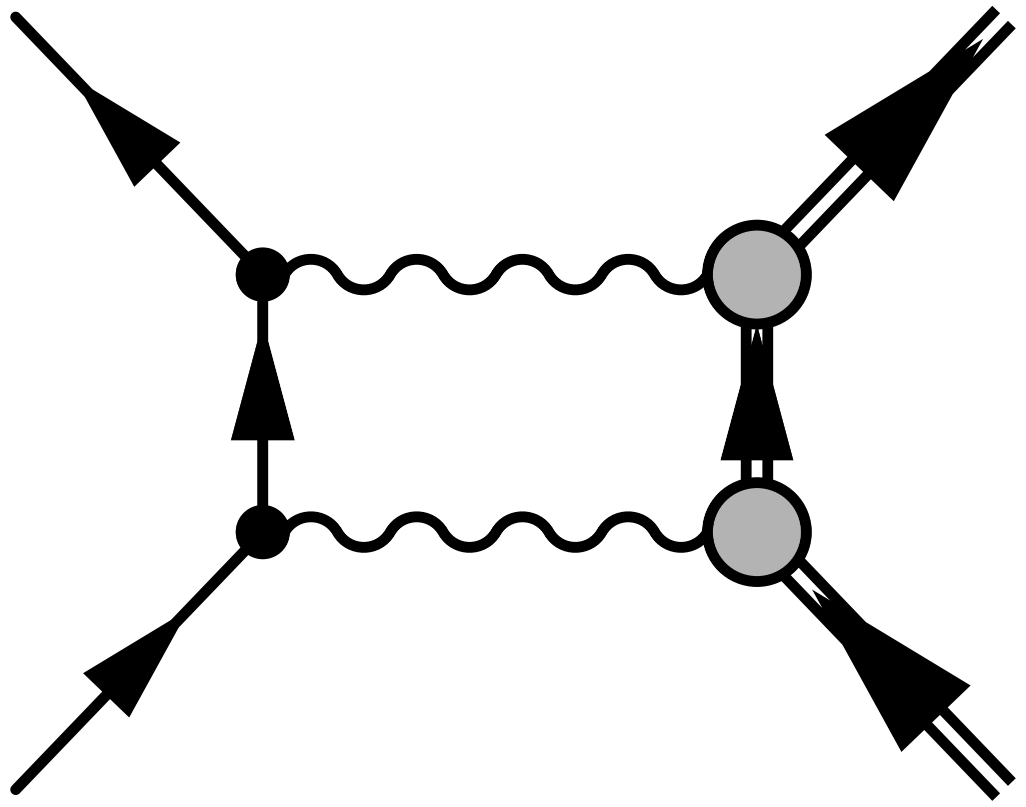

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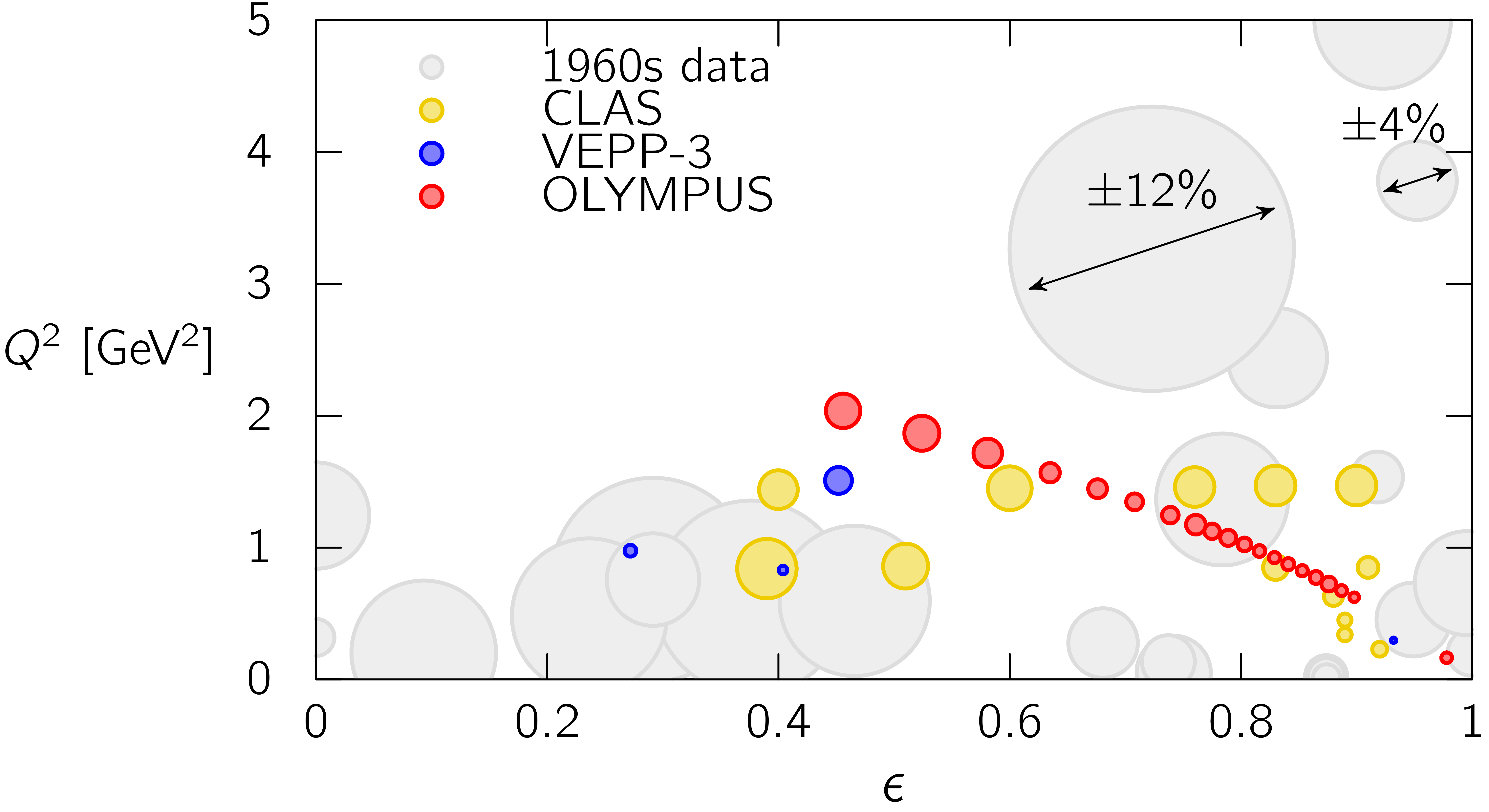
  - Background to PVES

- Positron to electron ratio:

$$R_{2\gamma} = \frac{\sigma_{e^+p}}{\sigma_{e^-p}} = 1 + \frac{4\mathcal{R}(\mathcal{M}_{1\gamma}\mathcal{M}_{2\gamma}^{*})}{|\mathcal{M}_{1\gamma}|^2} + \ldots$$

  - Leading TPE correction to unpolarized ep scattering

Existing positron measurements inconclusive on $\mu G_E/G_M$ discrepancy



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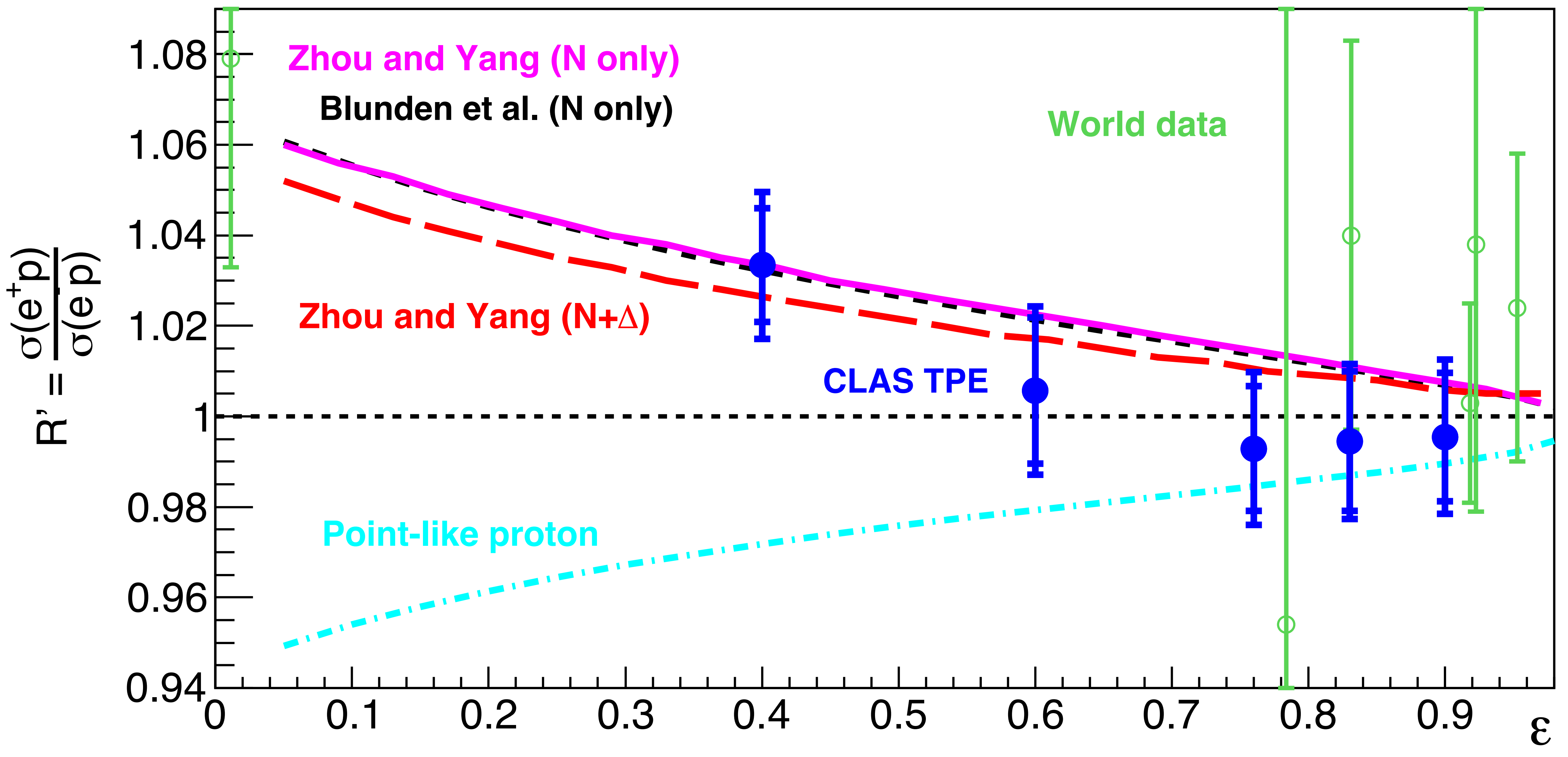
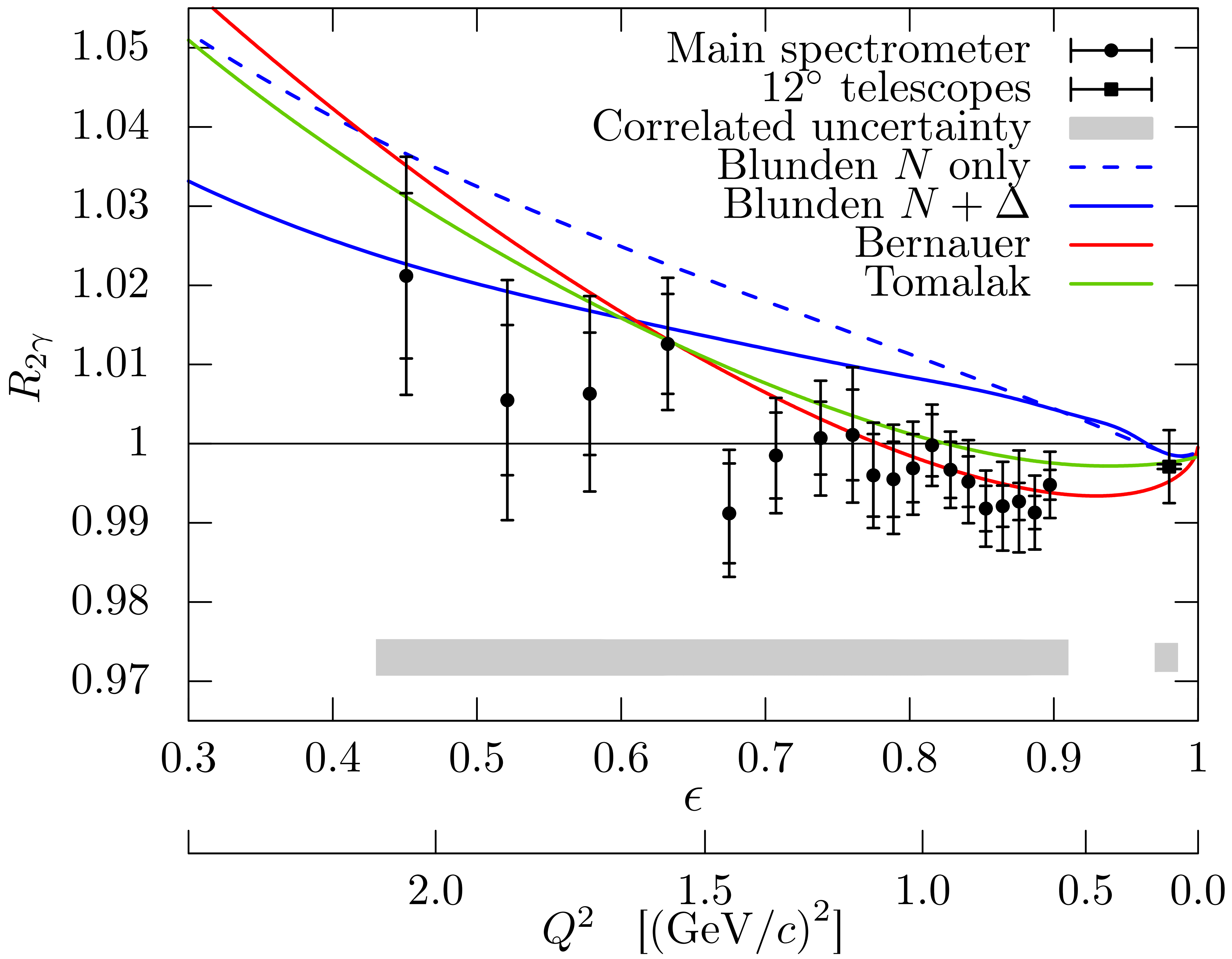
CLAS, PRL 114, 062003 (2015)

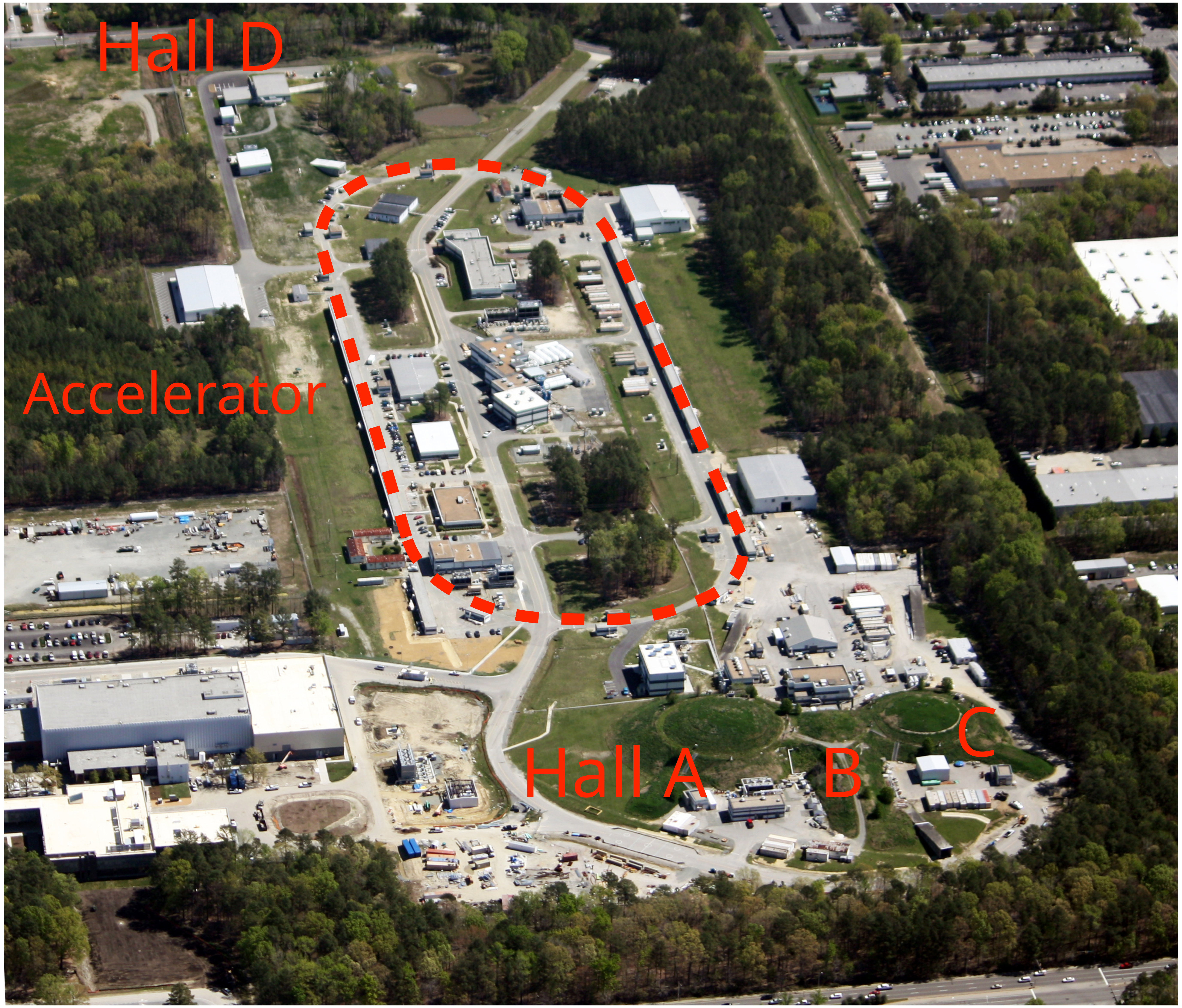


OLYMPUS, PRL 118, 092501 (2017)



See also: Rachek et al. PRL 114, 062005 (2015)

Jefferson Lab



- Located in Newport News, Virginia
- CEBAF: Polarized electron beams up to 12 GeV, 150 μA
- Four experimental halls with complementary instrumentation:
  - High-resolution spectrometers (A & C)
  - Large-acceptance multipurpose detector (B)
  - Real photon beam (D)

Efforts to develop positron program at JLab

- Recent interest in development of positron source for possible JLab upgrade
- Currently being pursued in conjunction with possible 22 GeV upgrade
- Physics case:
  - Driven by multi-photon exchange and 3D nucleon imaging (DVCS)
  - Summarized by community in EPJA special issue
  - Several positron proposals submitted/approved by JLab program committee

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PR12+23-008 “Direct Measurement of Hard Two-Photon Exchange with Electrons and Positrons at CLAS12”

CLAS12 in Hall B

Forward detector

3.5 T torus magnet, 5° < θ < 35°

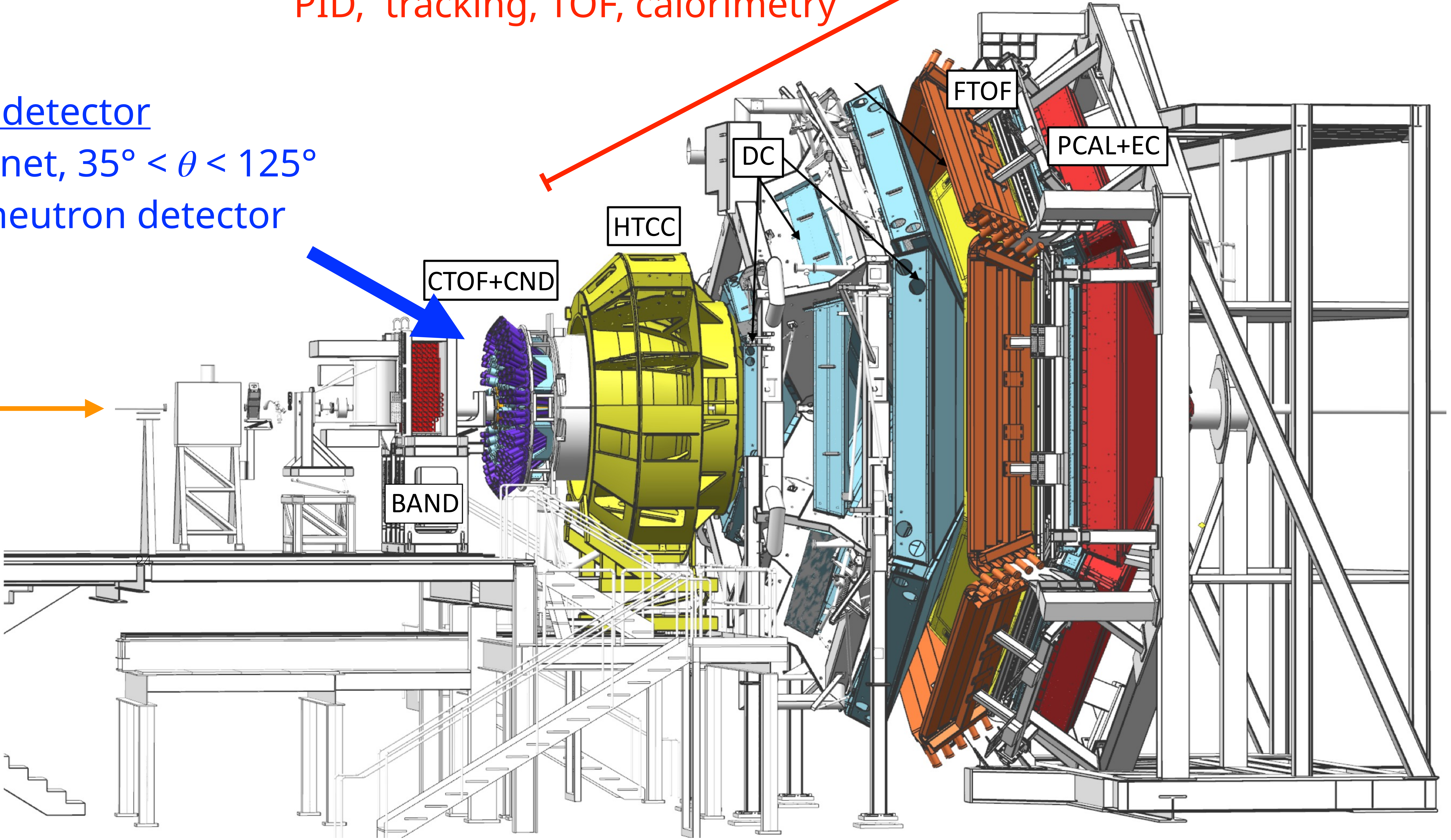
PID, tracking, TOF, calorimetry

Central detector

5 T solenoid magnet, 35° < θ < 125°

Tracking, TOF, neutron detector

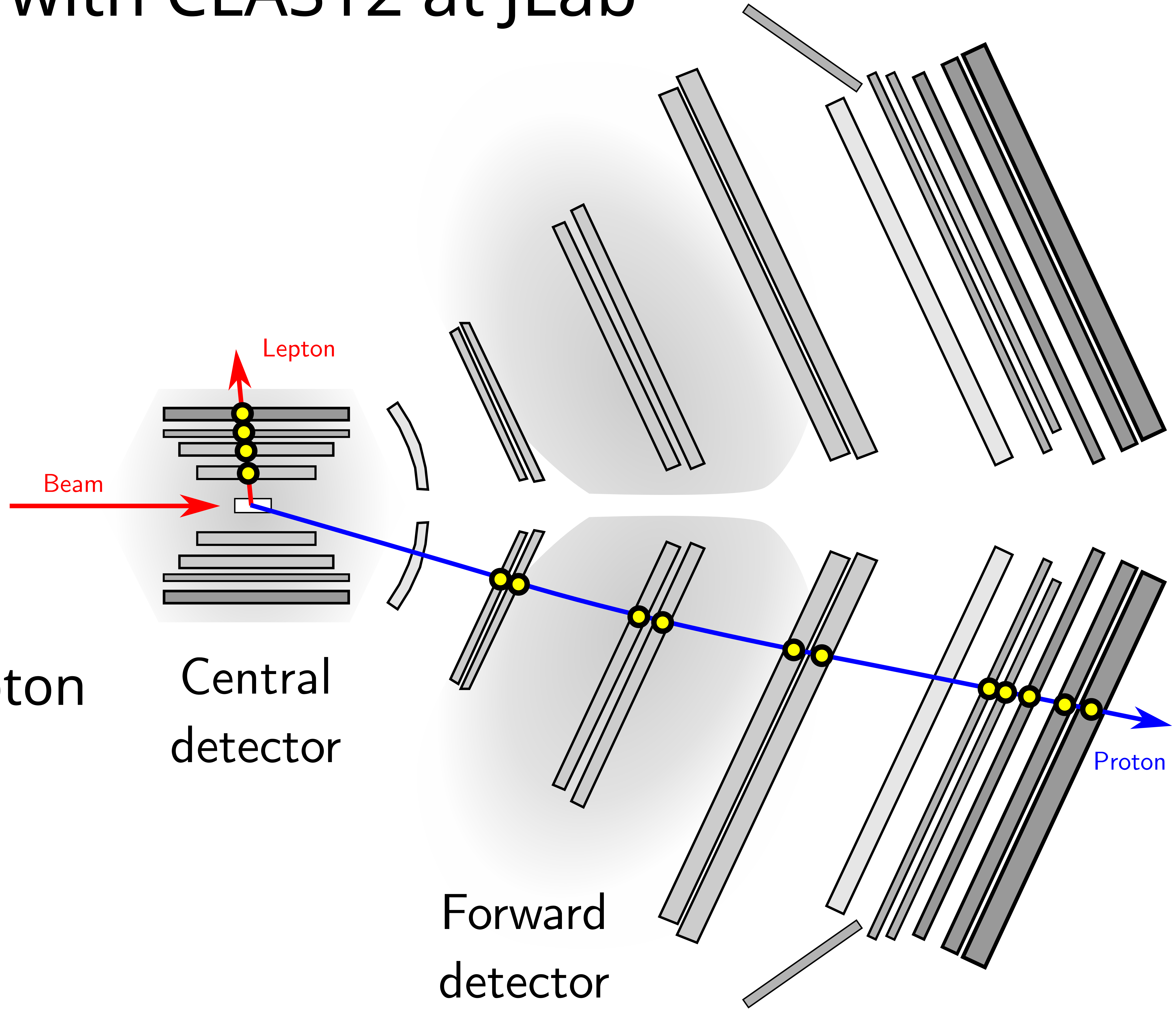
Beam



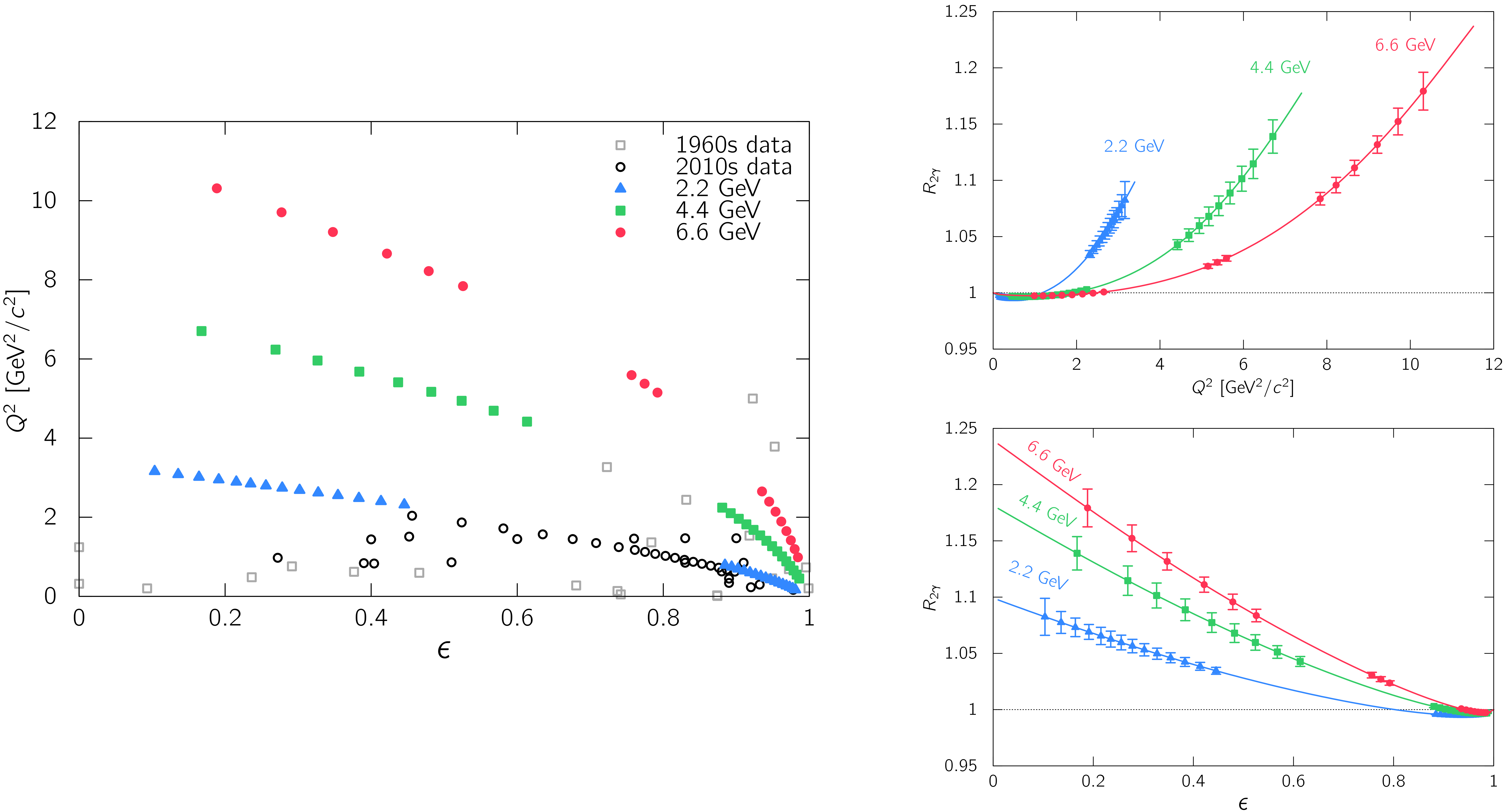
V.D. Burkert et al., NIM A 959, 163419 (2020)

Proposed measurement with CLAS12 at JLab

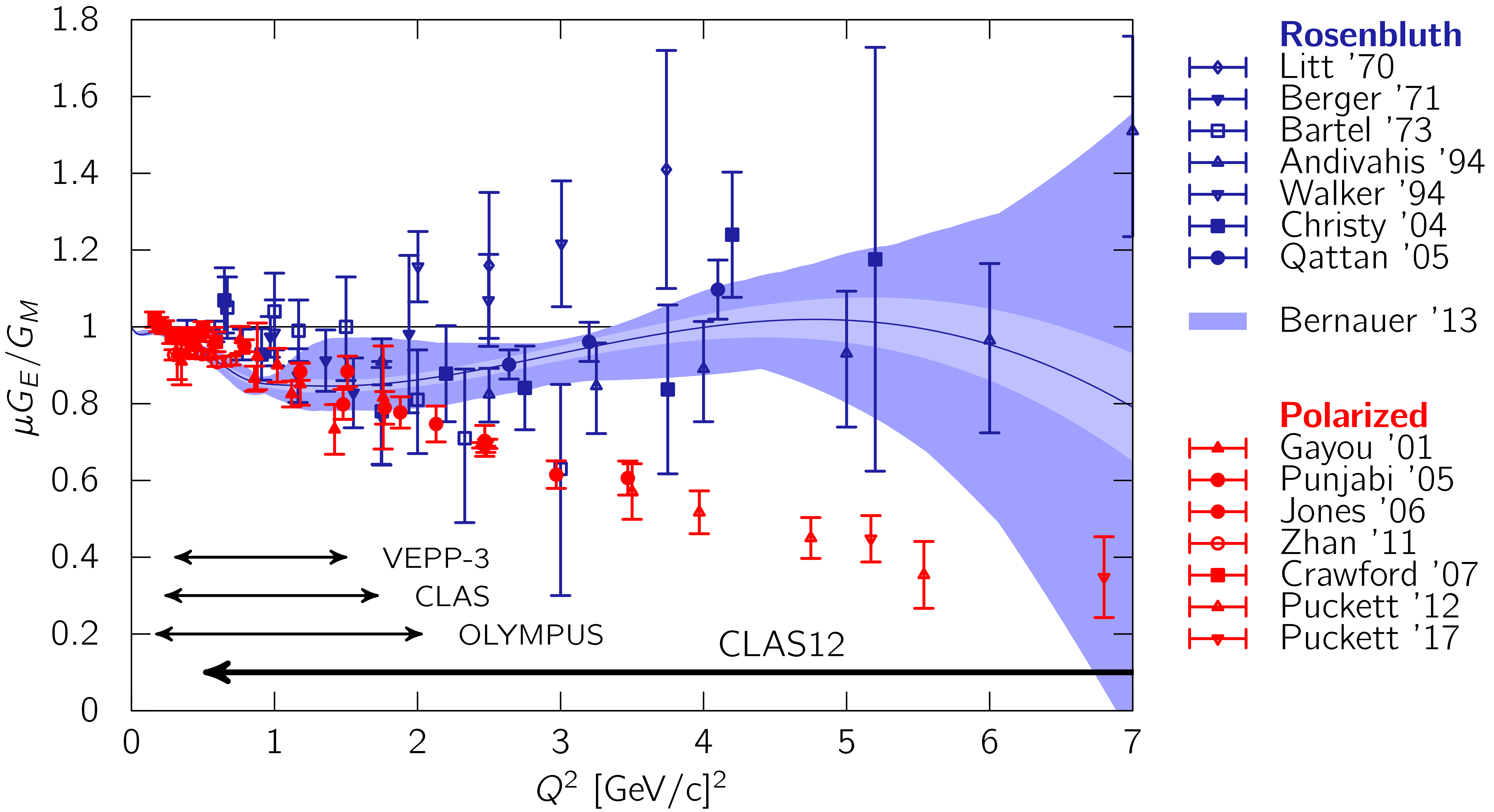
- Measure e^+p/e^-p ratio
- E_{beam} = 2.2, 4.4, 6.6 GeV
- High Q^2, low ϵ requires
  $\rightarrow$ forward proton, central lepton



CLAS12 ideal for mapping TPE over wide phase space



Definitive answer to whether TPE causes discrepancy



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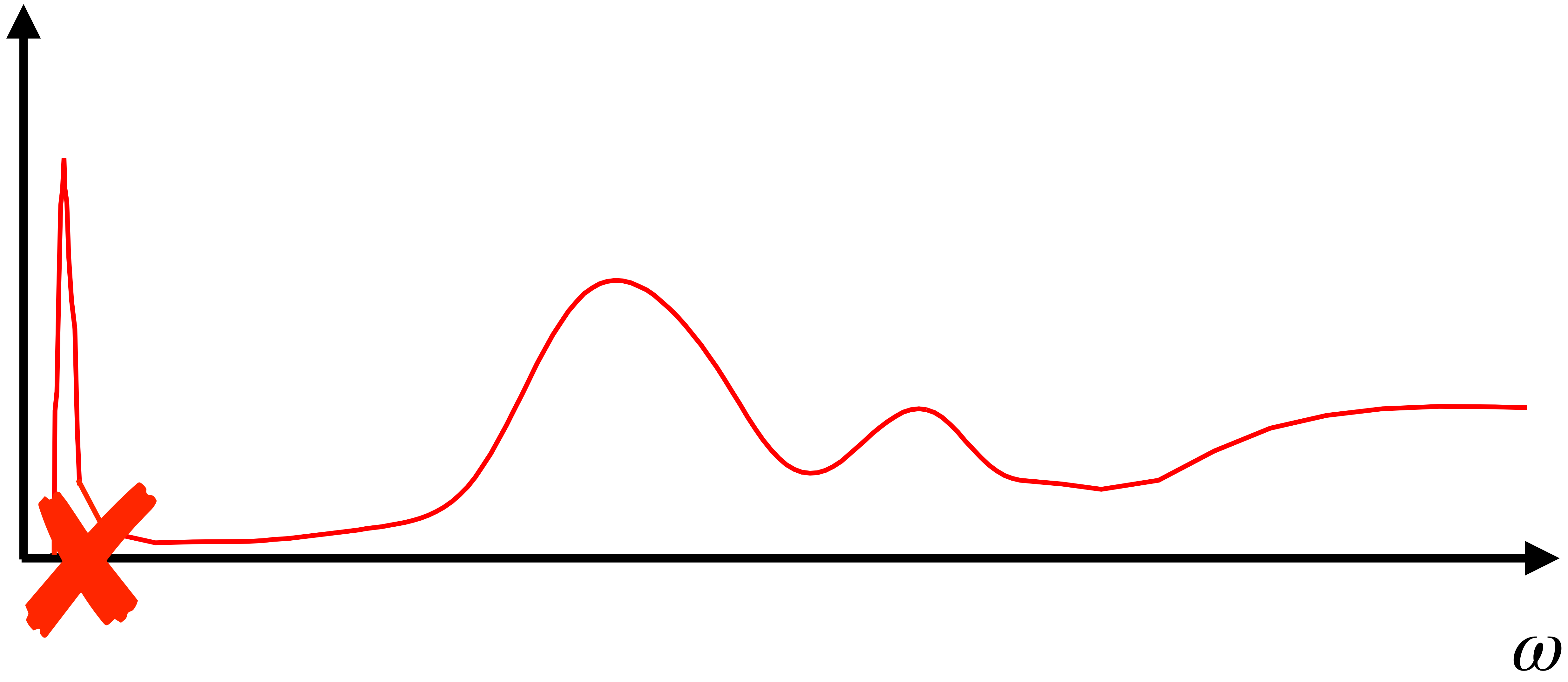

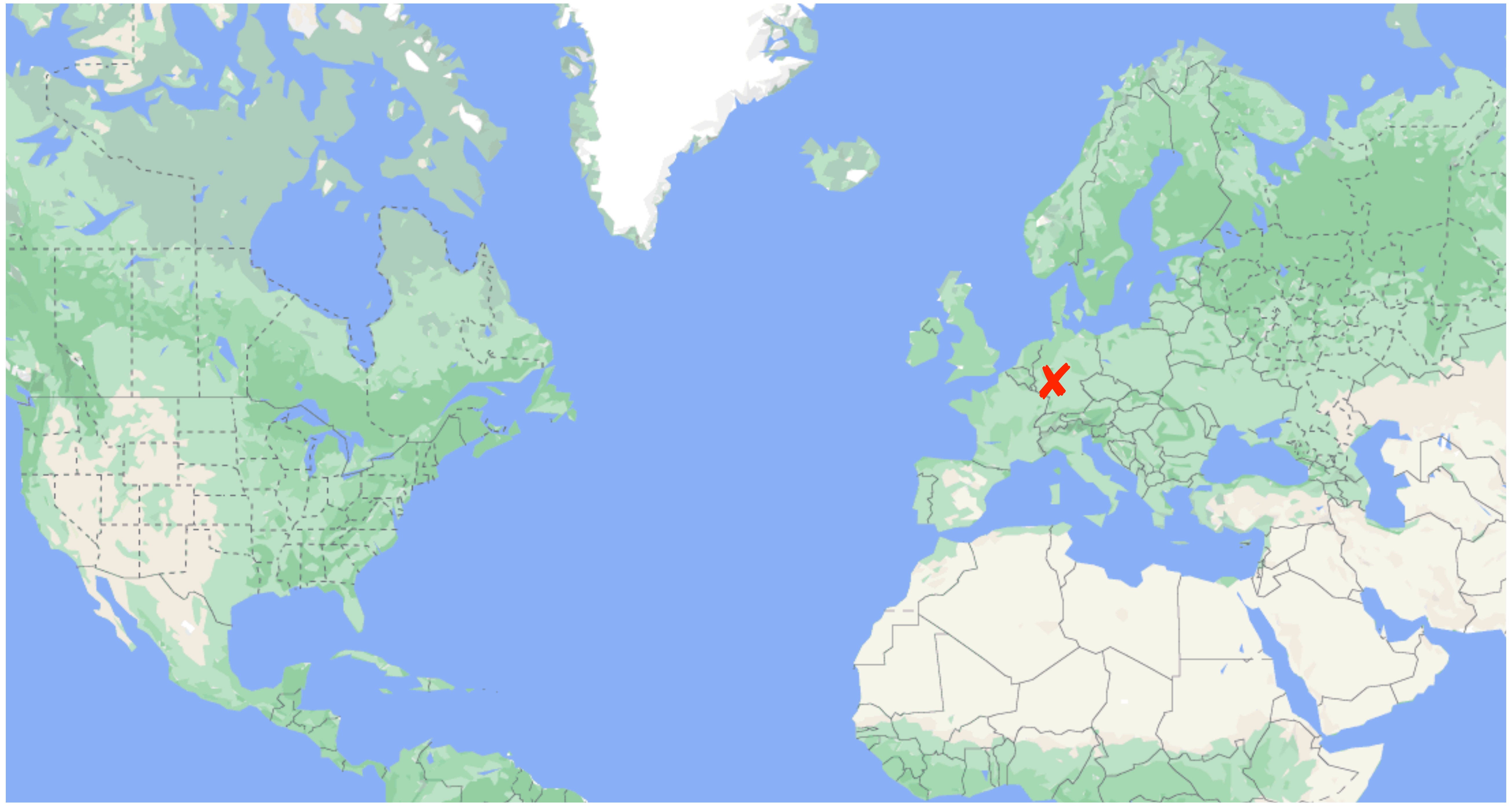

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  - Proton weak charge
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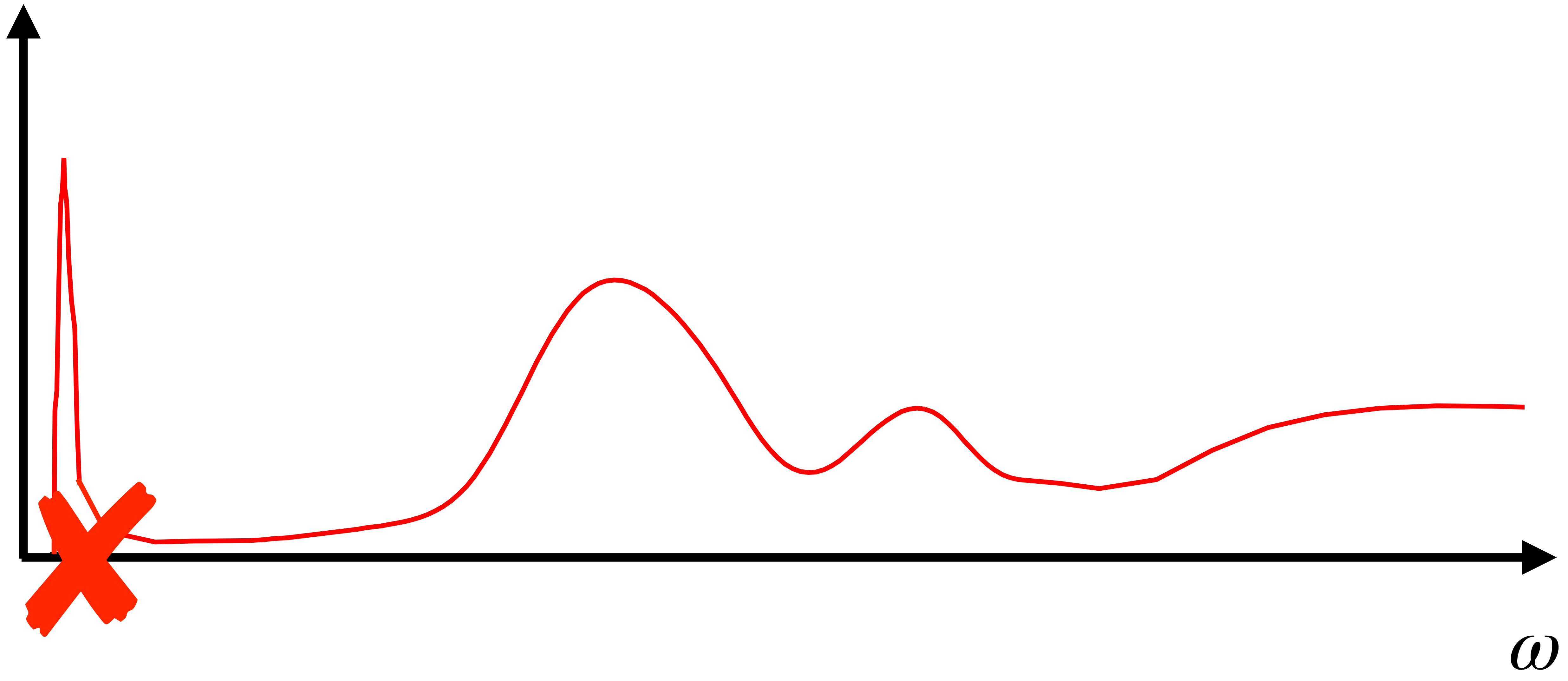
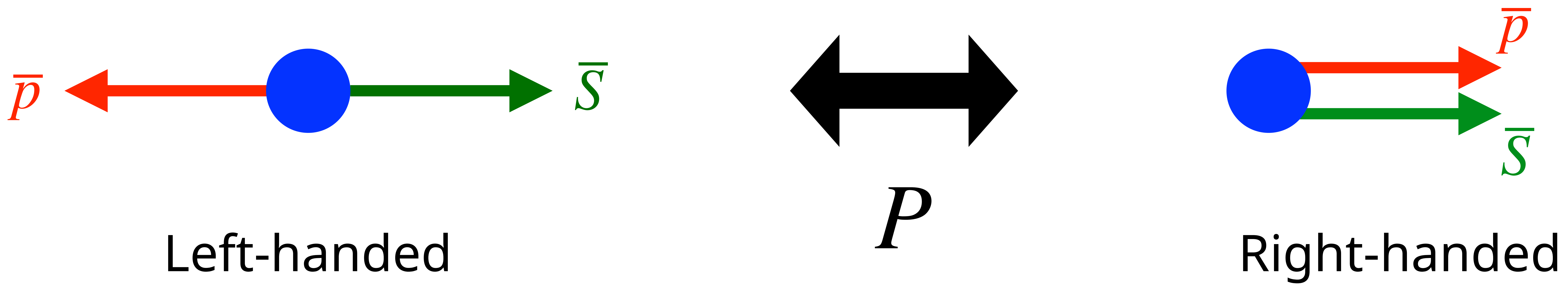
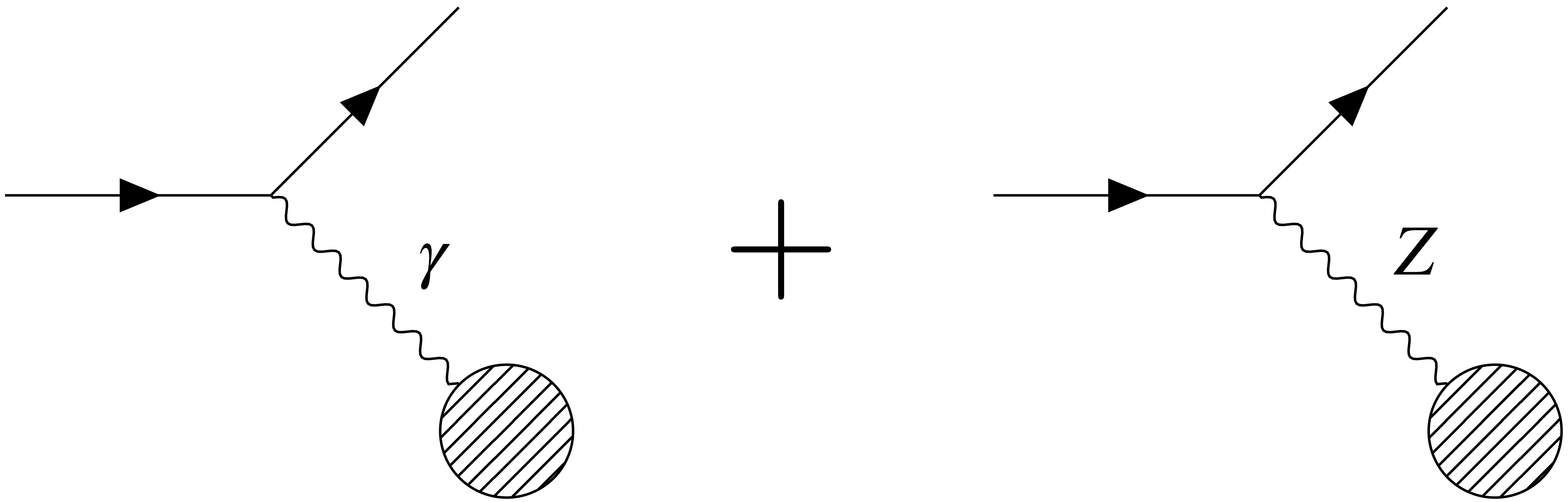


The weak interaction violates parity

- Parity transformation $P : (x, y\ z) \rightarrow (-x,\ -y,\ -z)$
- Parity violation in weak interactions:
    - Theorized by Lee & Yang in 1956
    - Discovered by C.S. Wu in 1957



Parity-violating electron scattering



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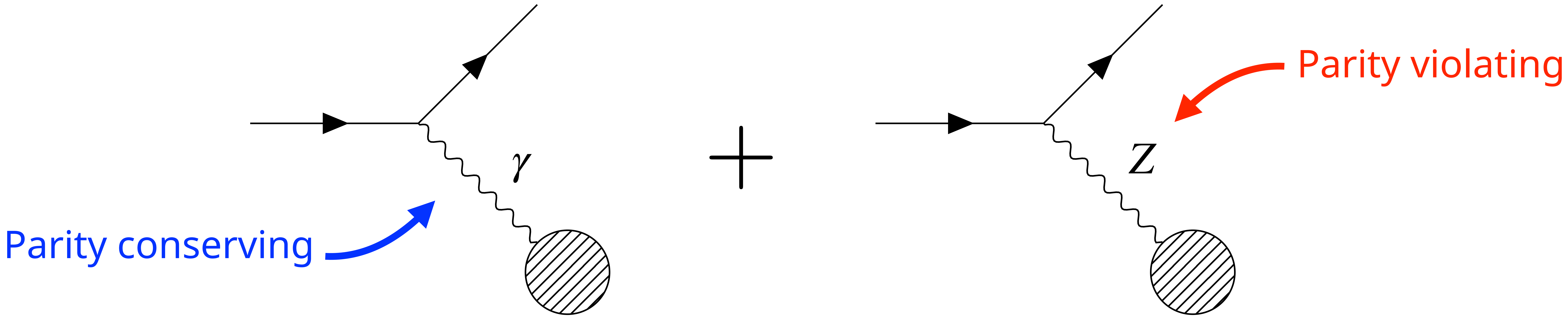

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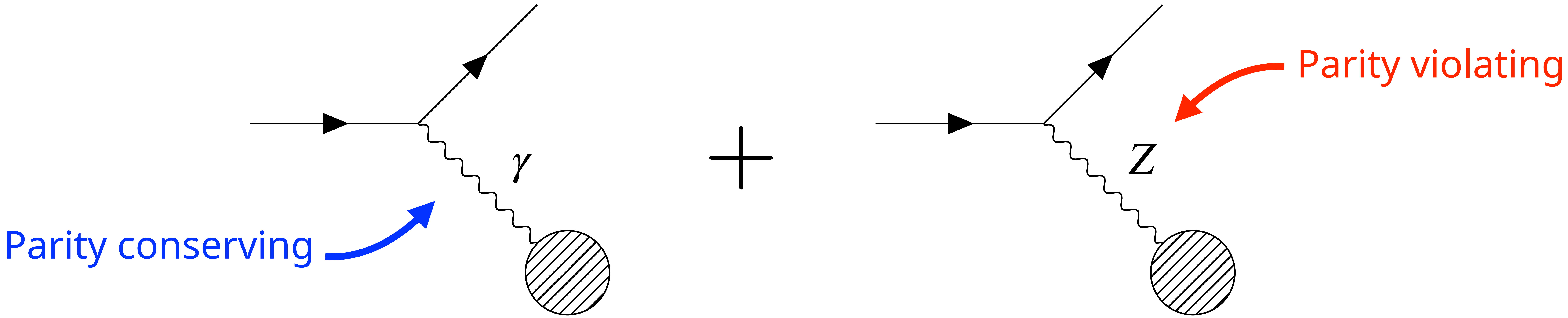

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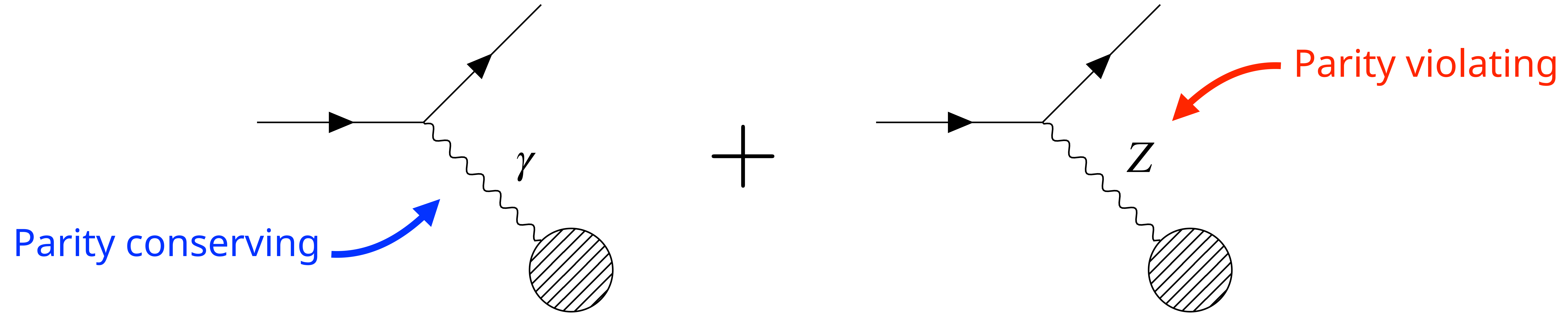

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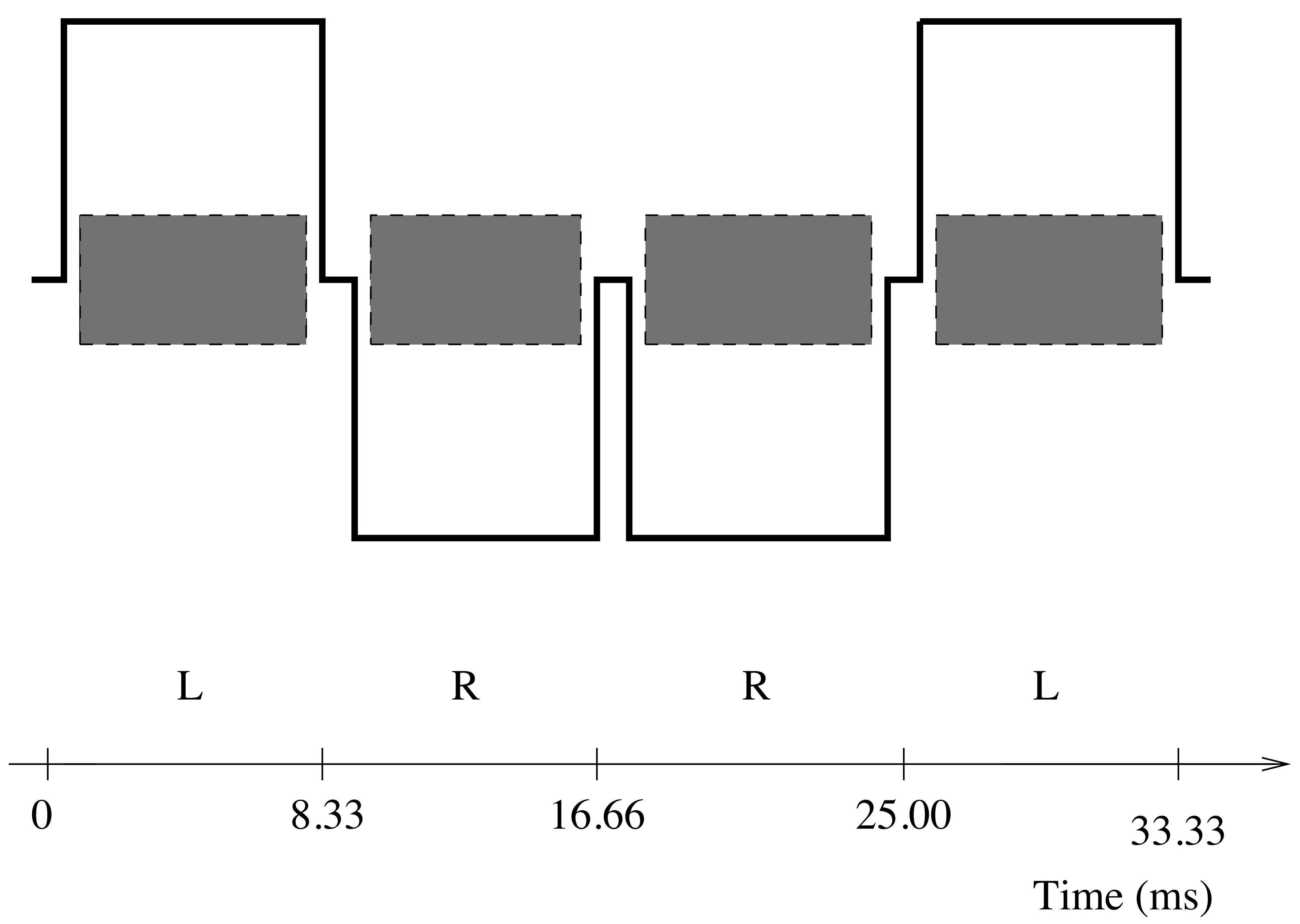
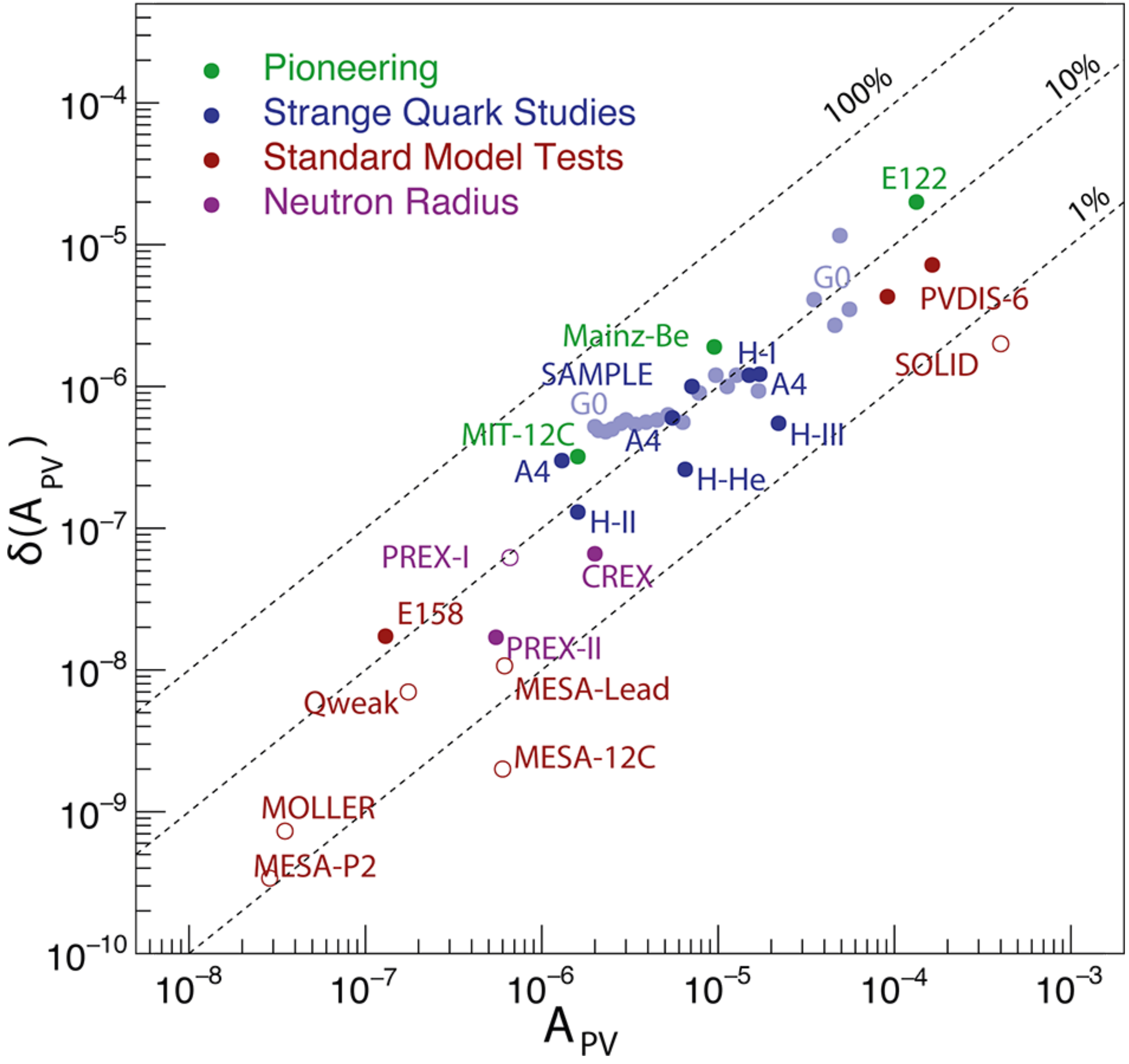
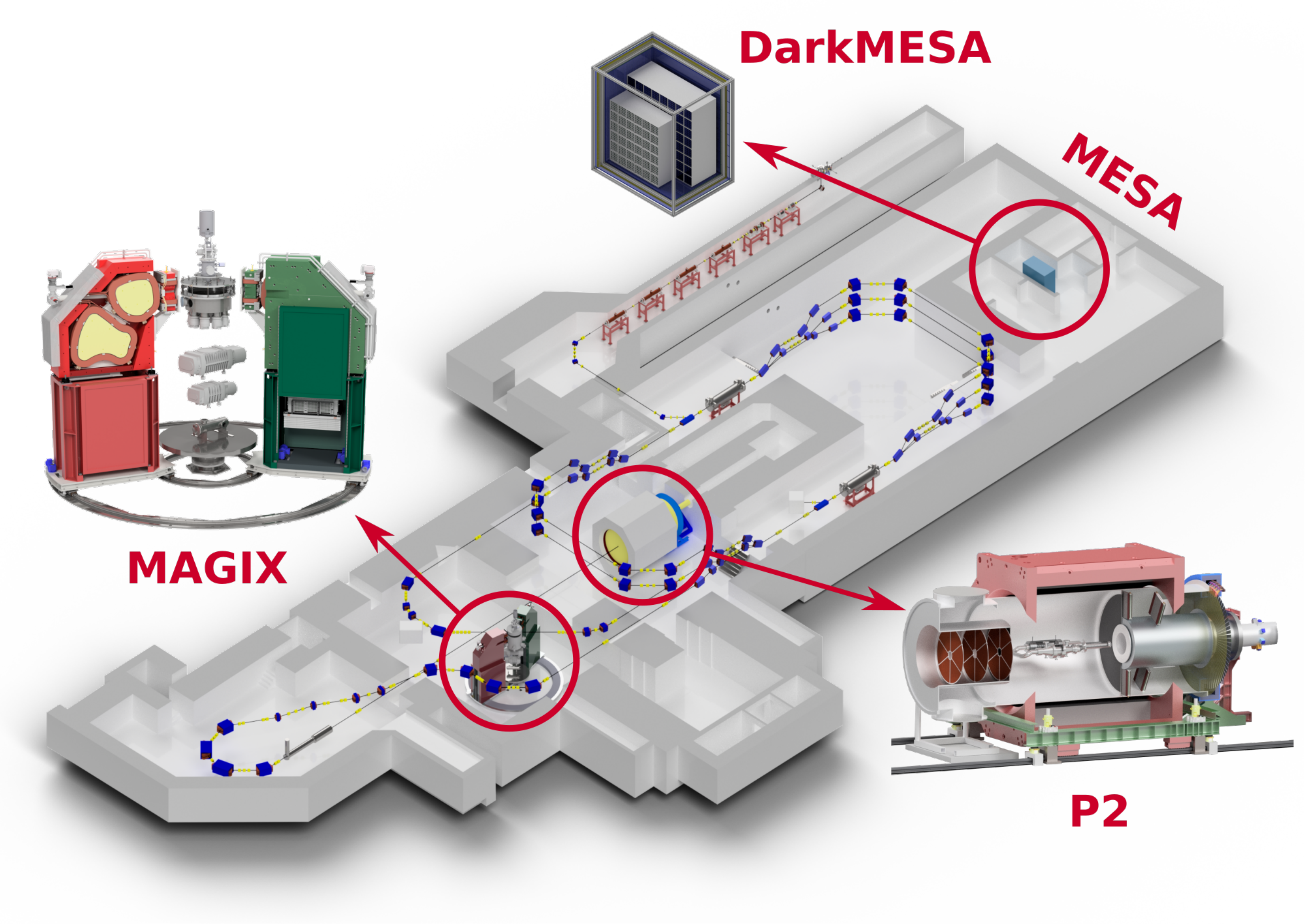


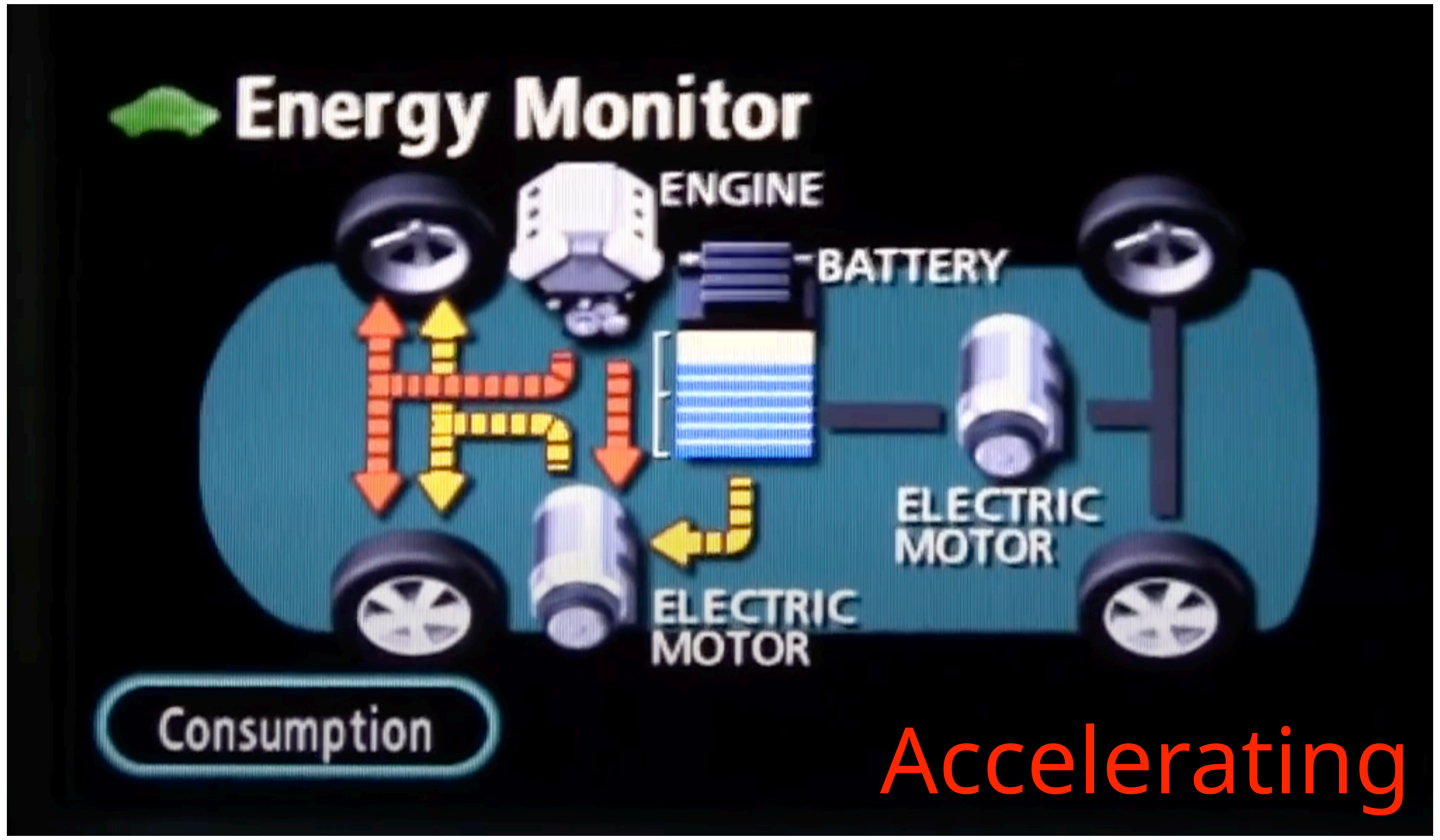
- History of PVES: continuous improvement in accelerator and detector technology
- State of the art: sub-ppb statistical reach and control of systematics



Mainz Energy-recovery Superconducting Accelerator (MESA)



What is energy recovery?



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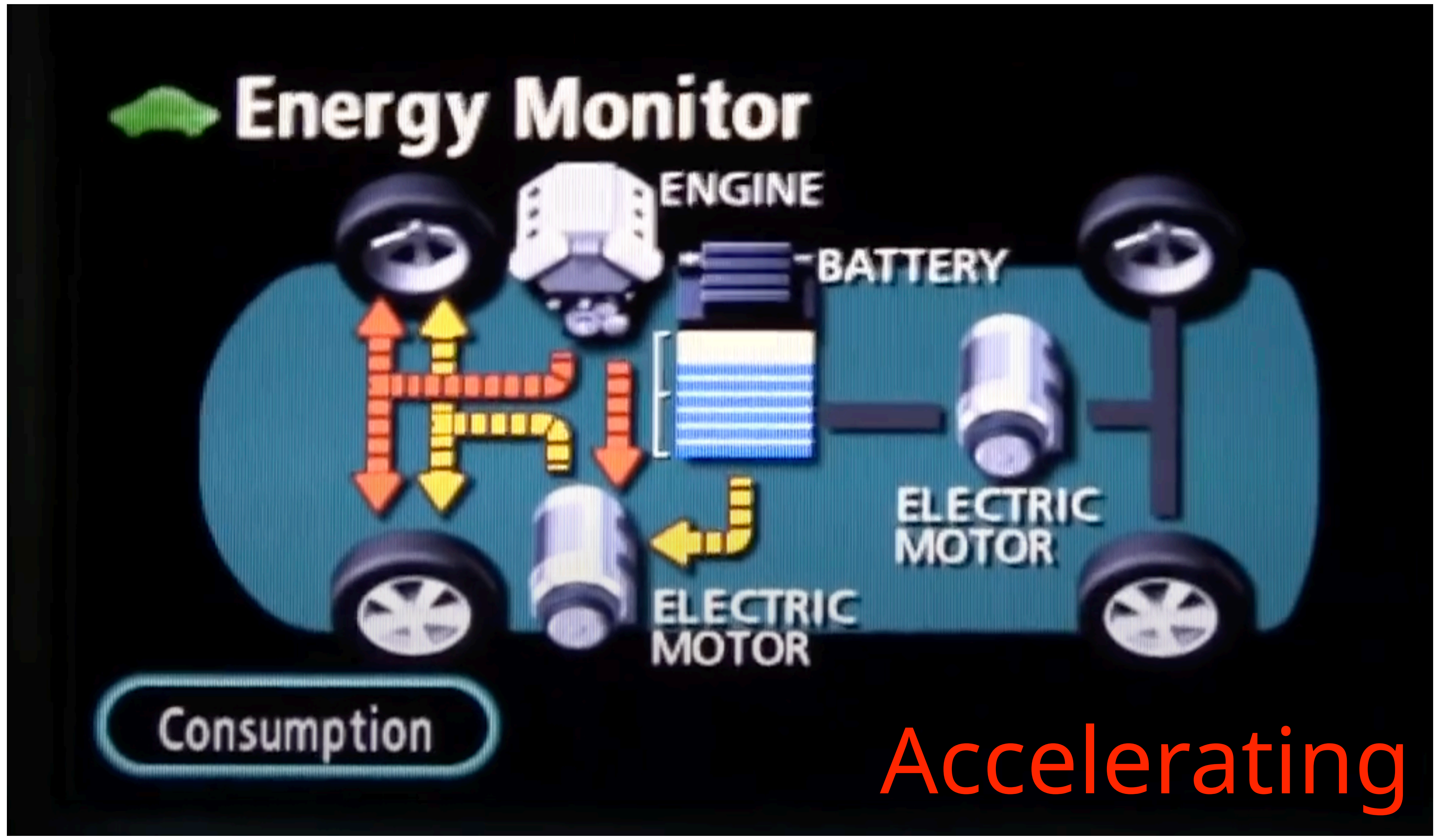

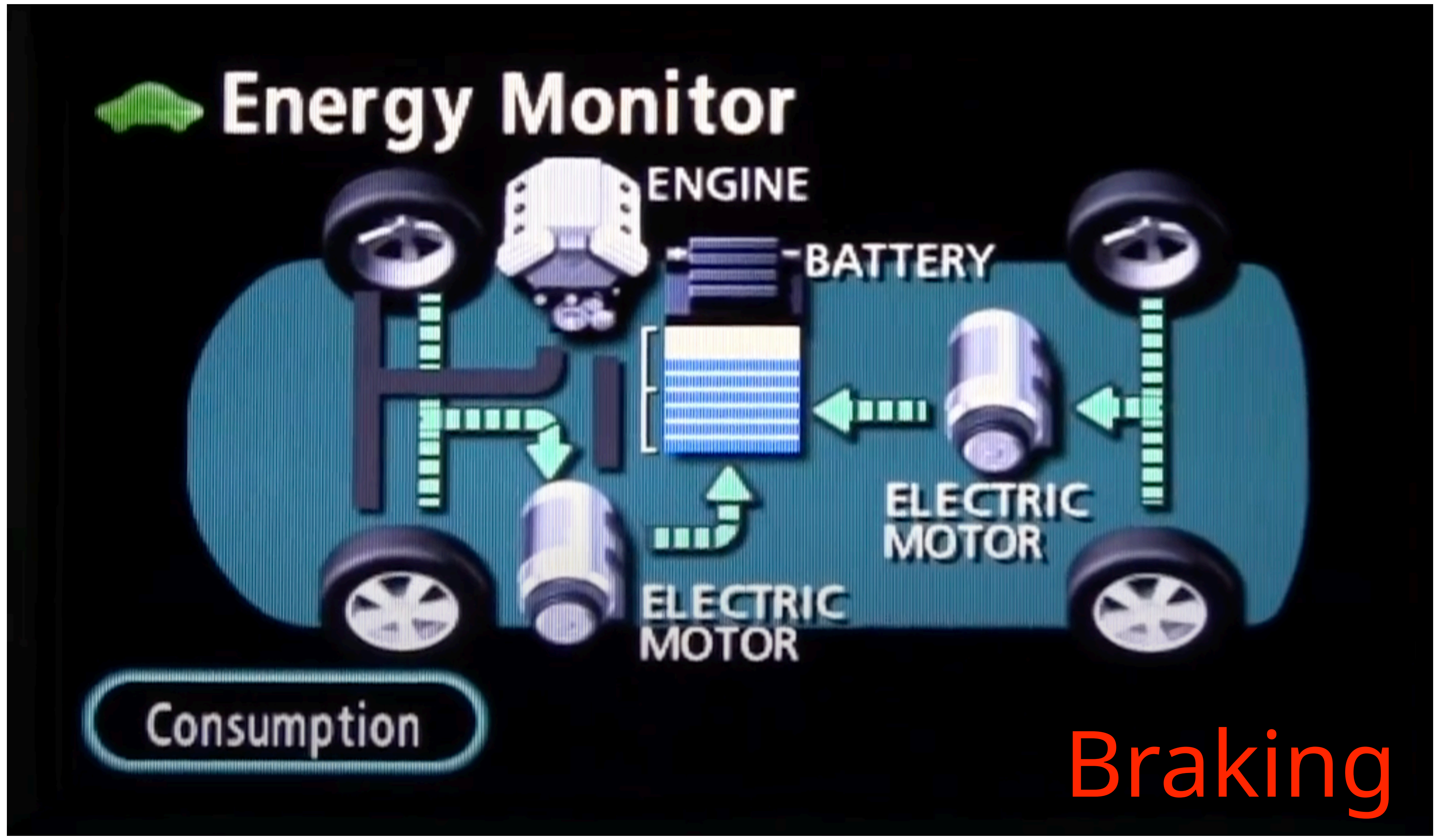

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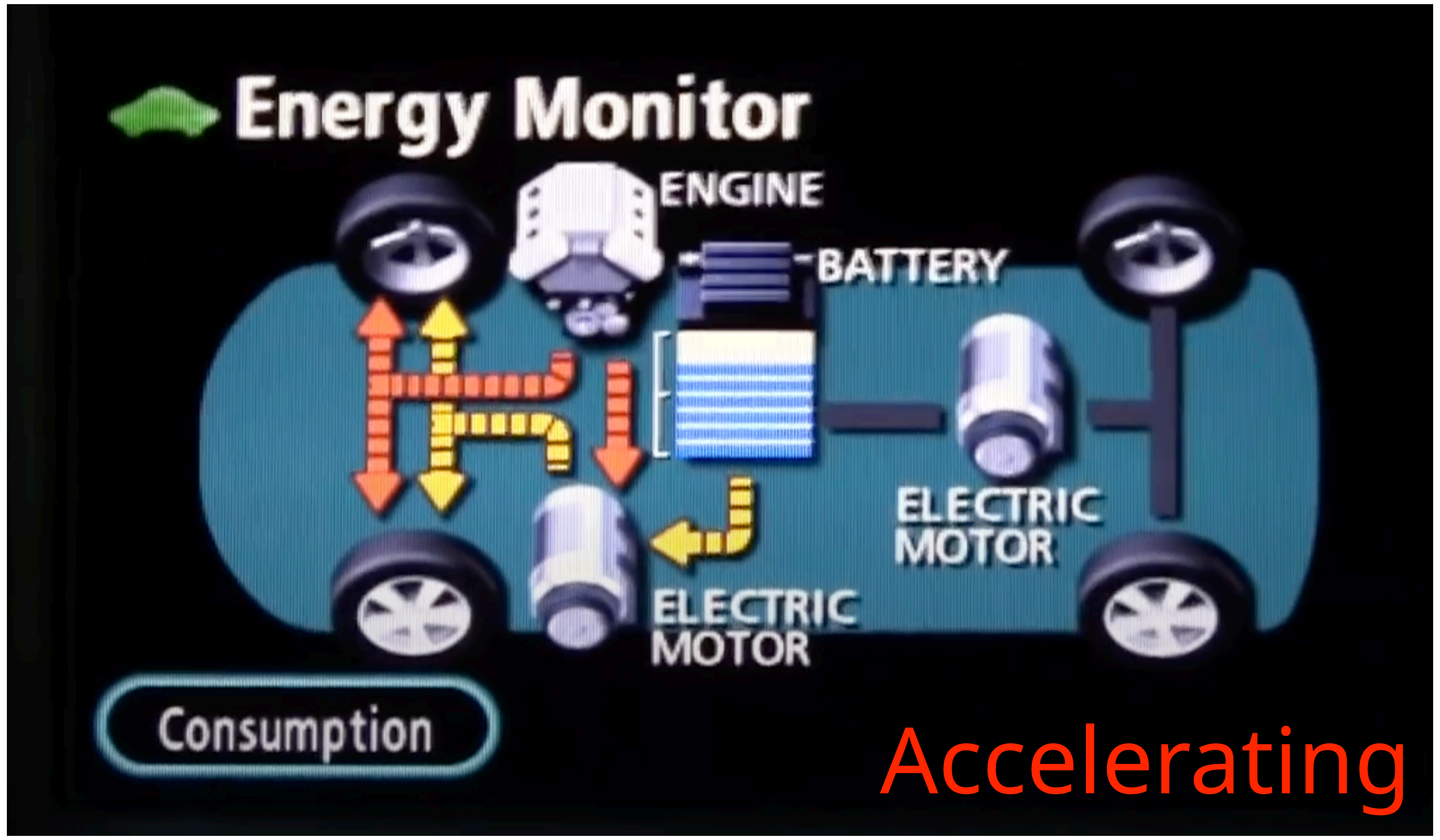
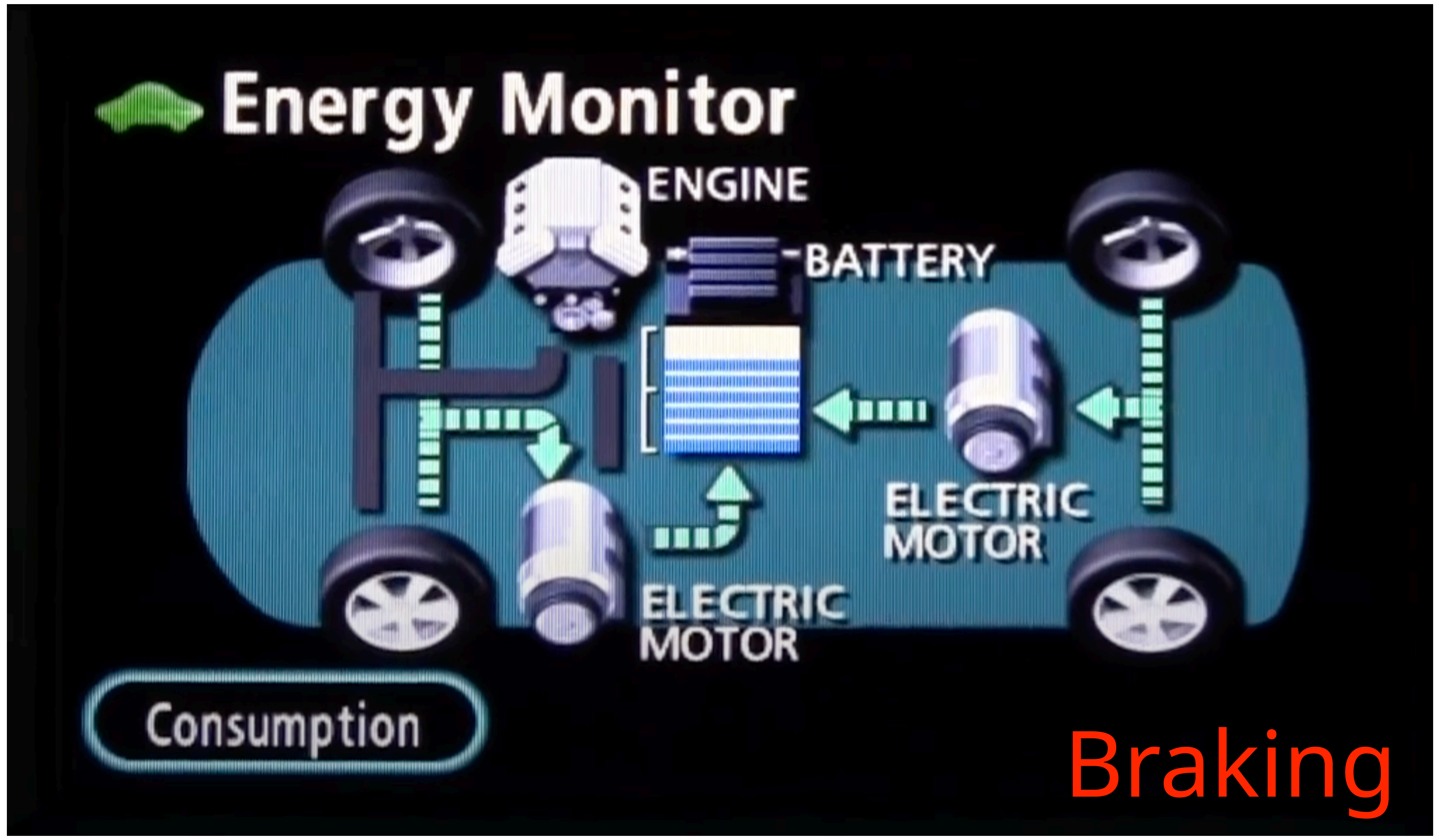
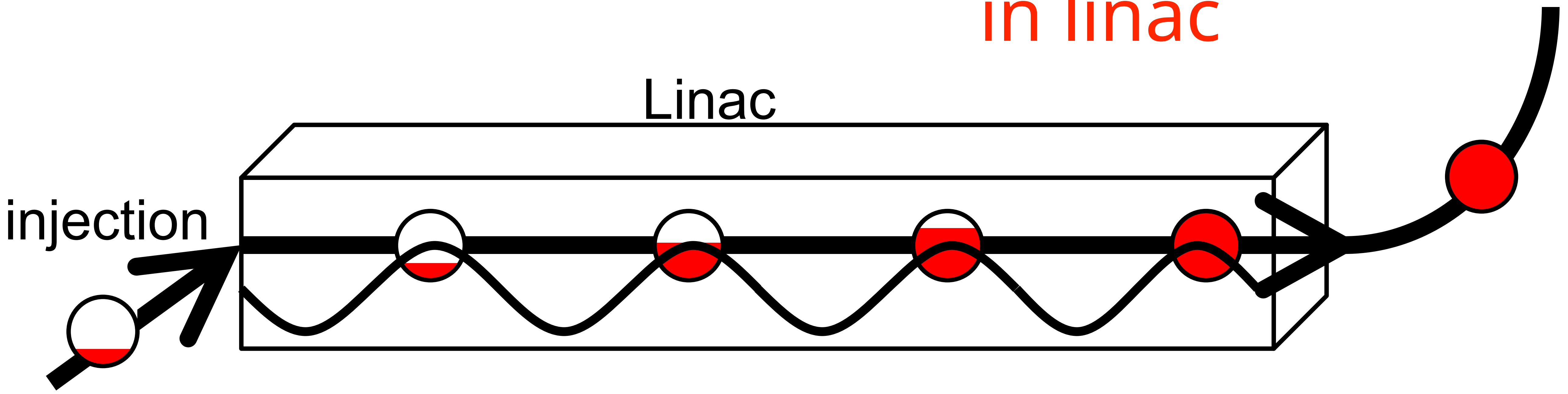




Electron accelerated in linac



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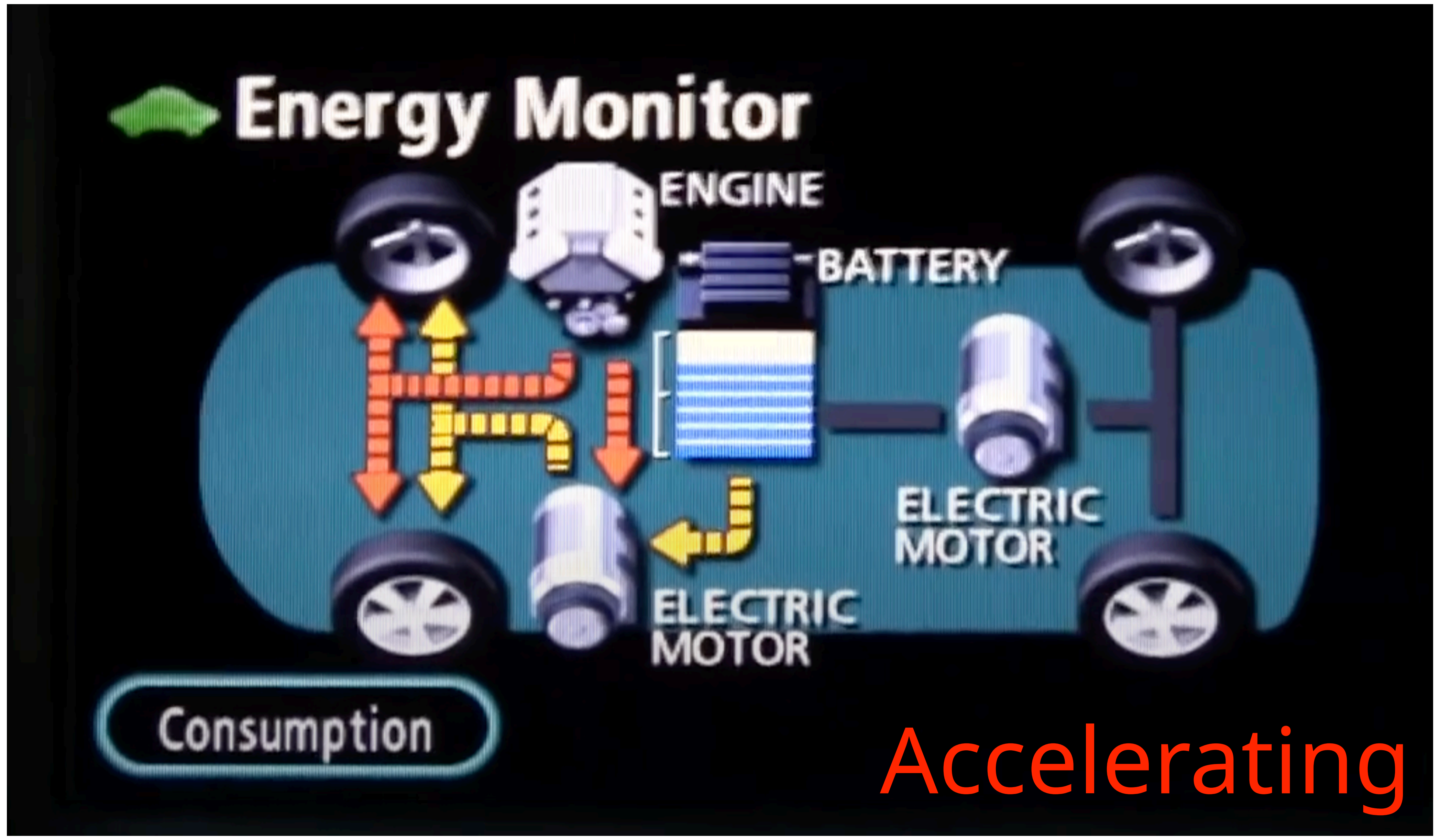
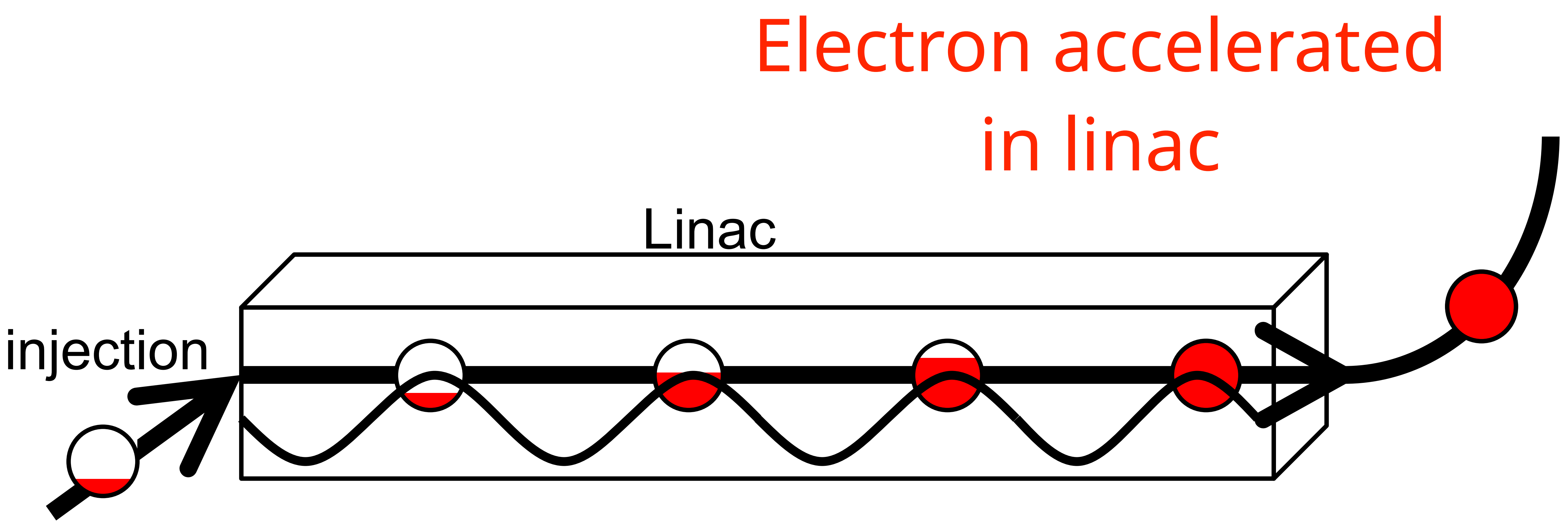
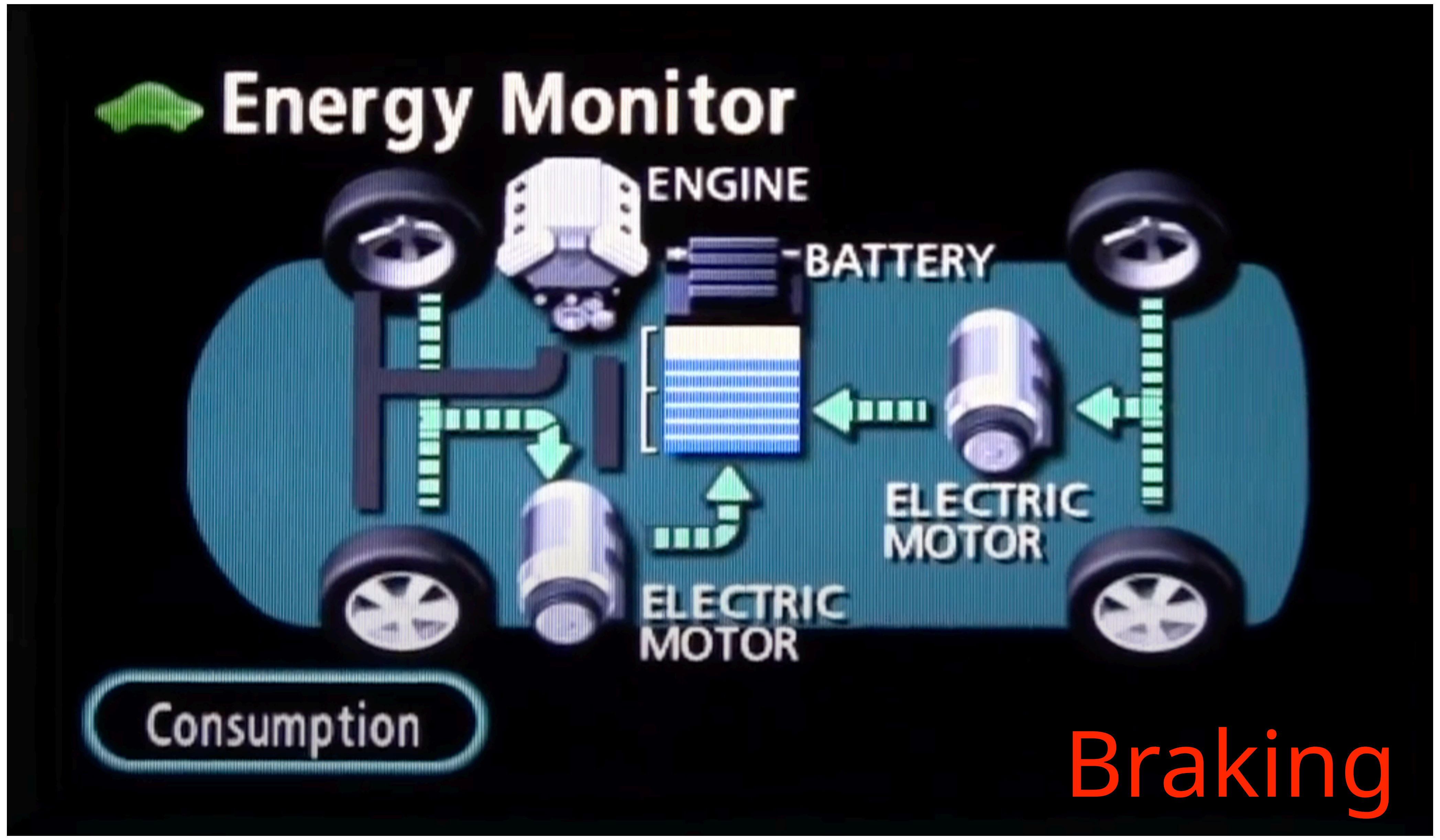
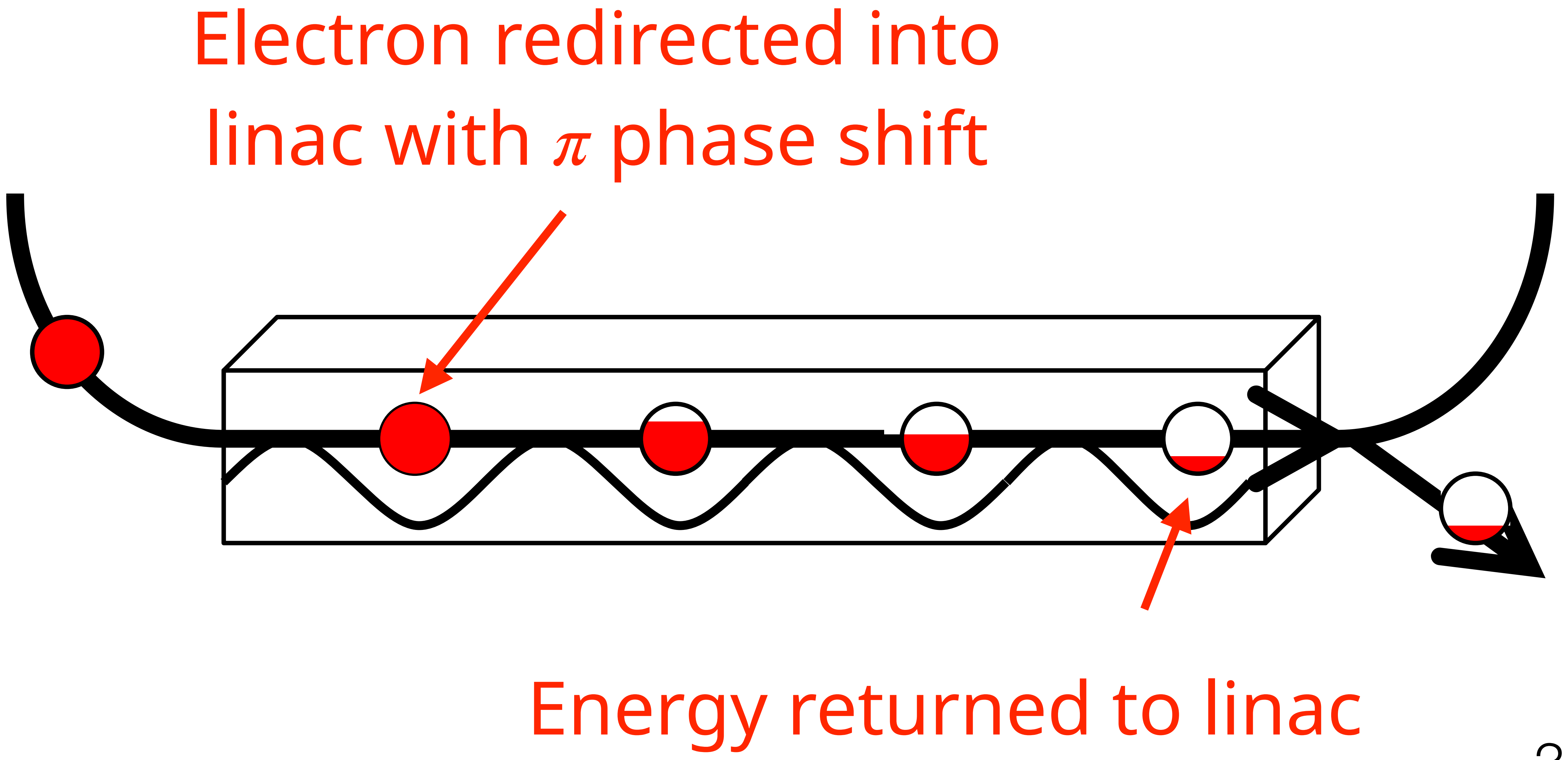


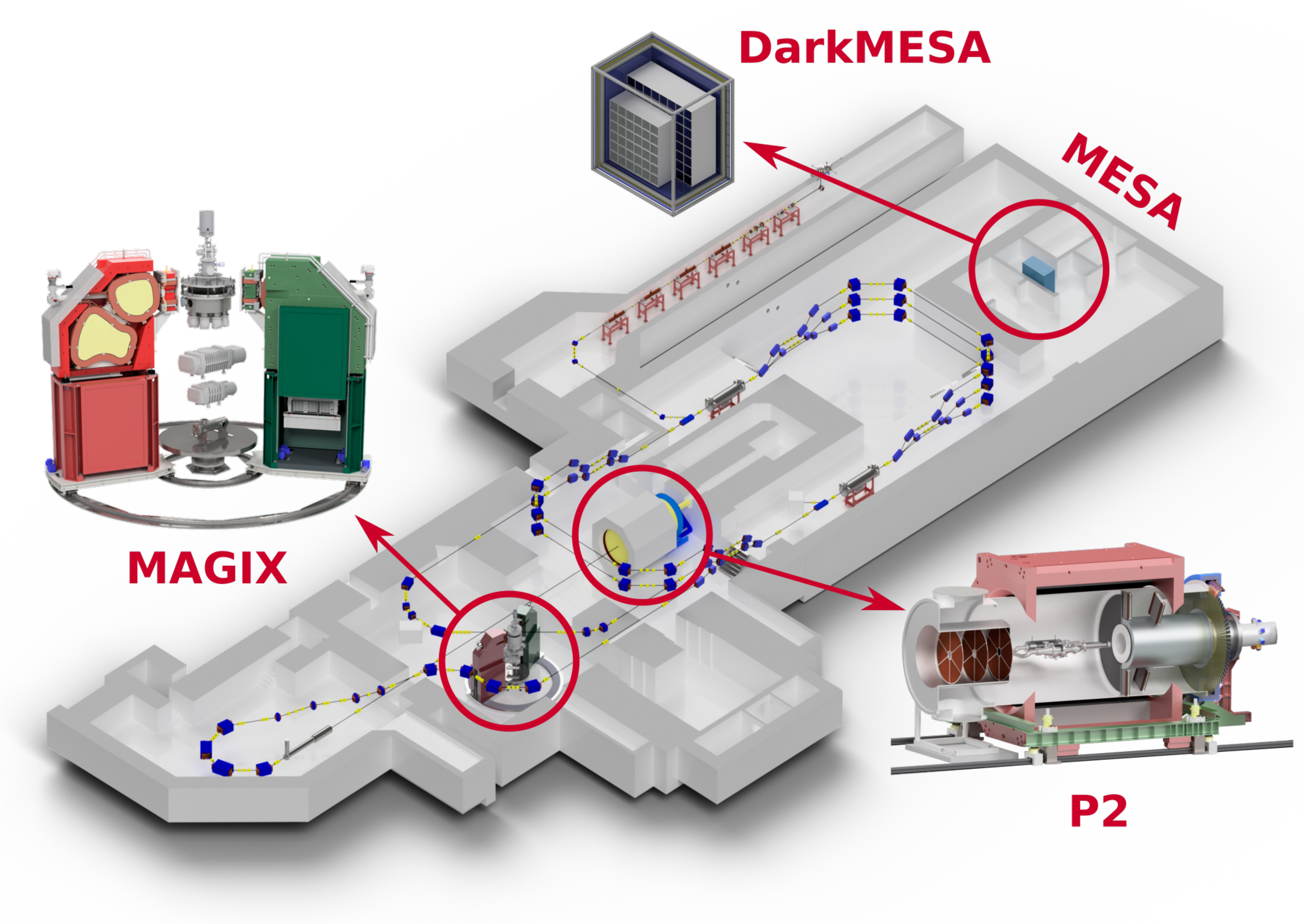






MESA

- In *energy-recovery mode:*
  - Energy up to 105 MeV
  - Currents over *1000 μA*



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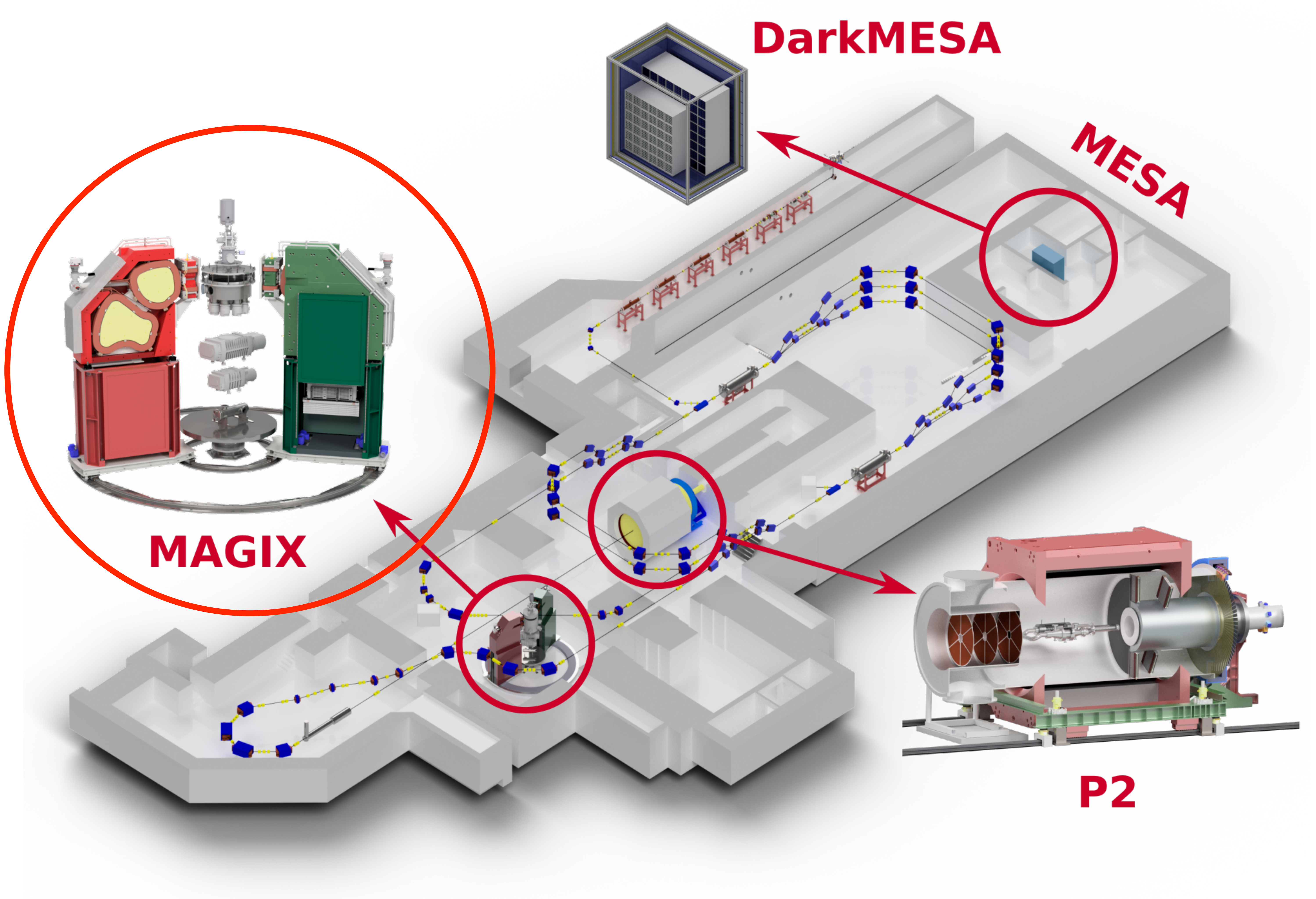

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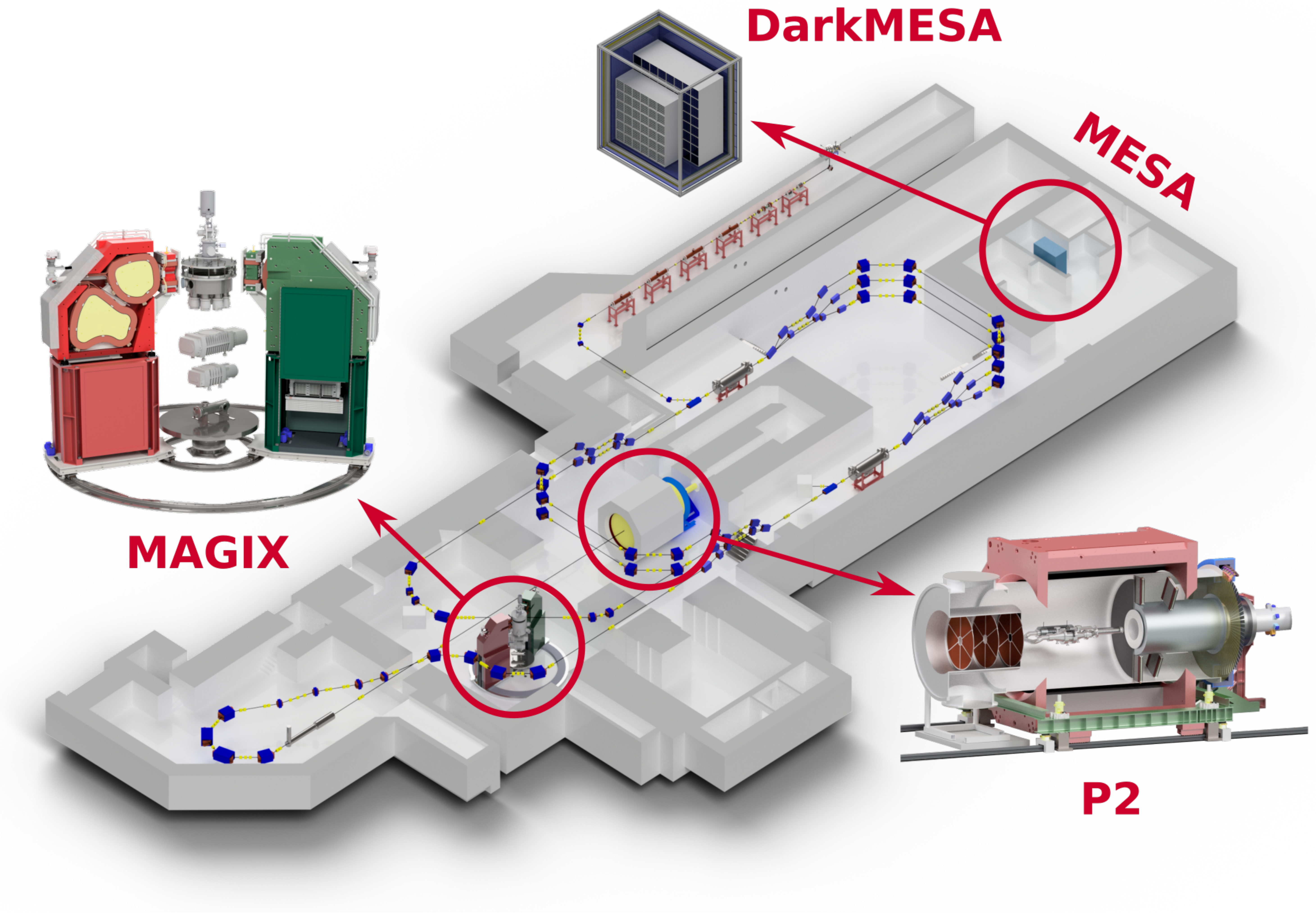
  - Current up to 150 μA
  - Polarization up to 80%



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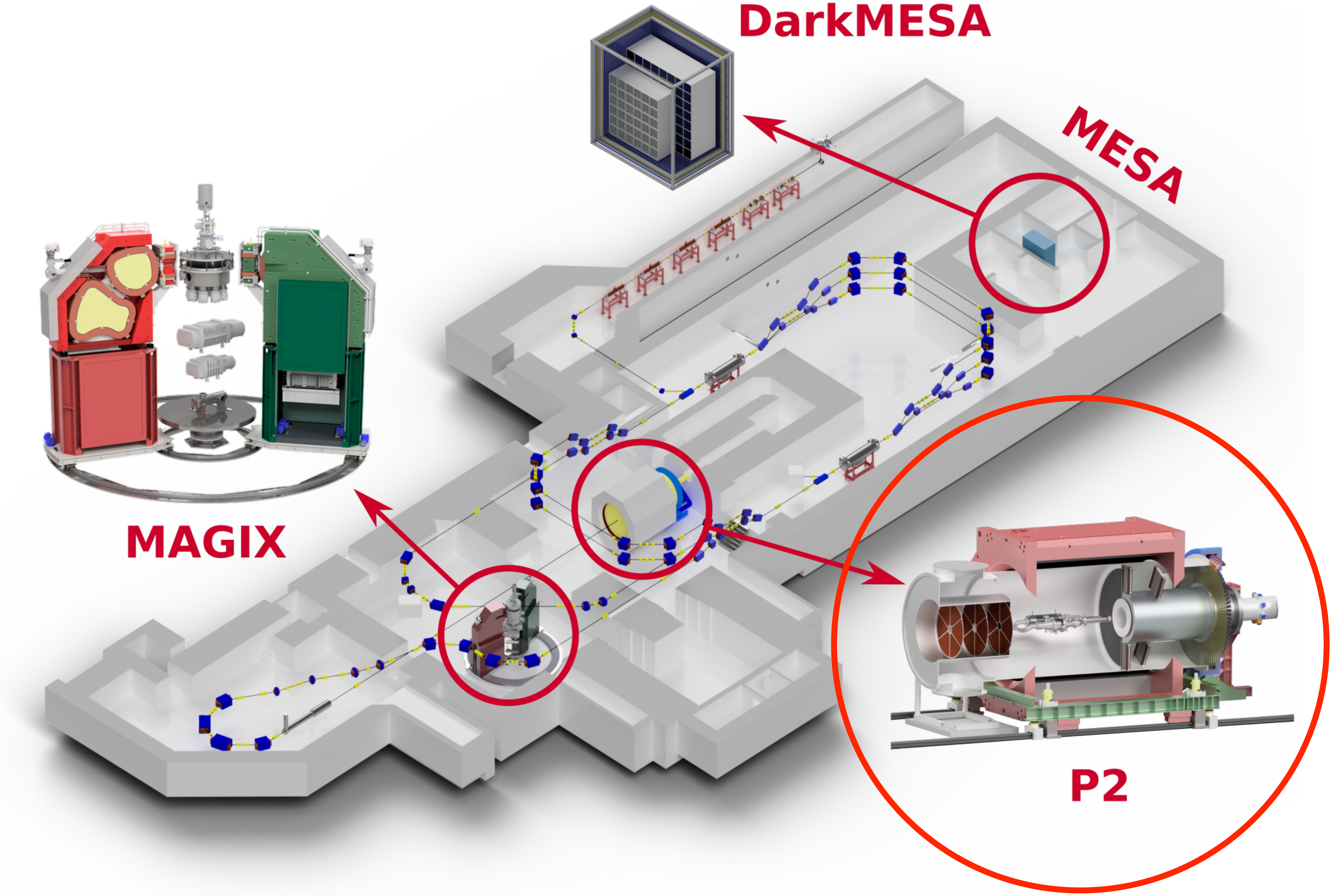

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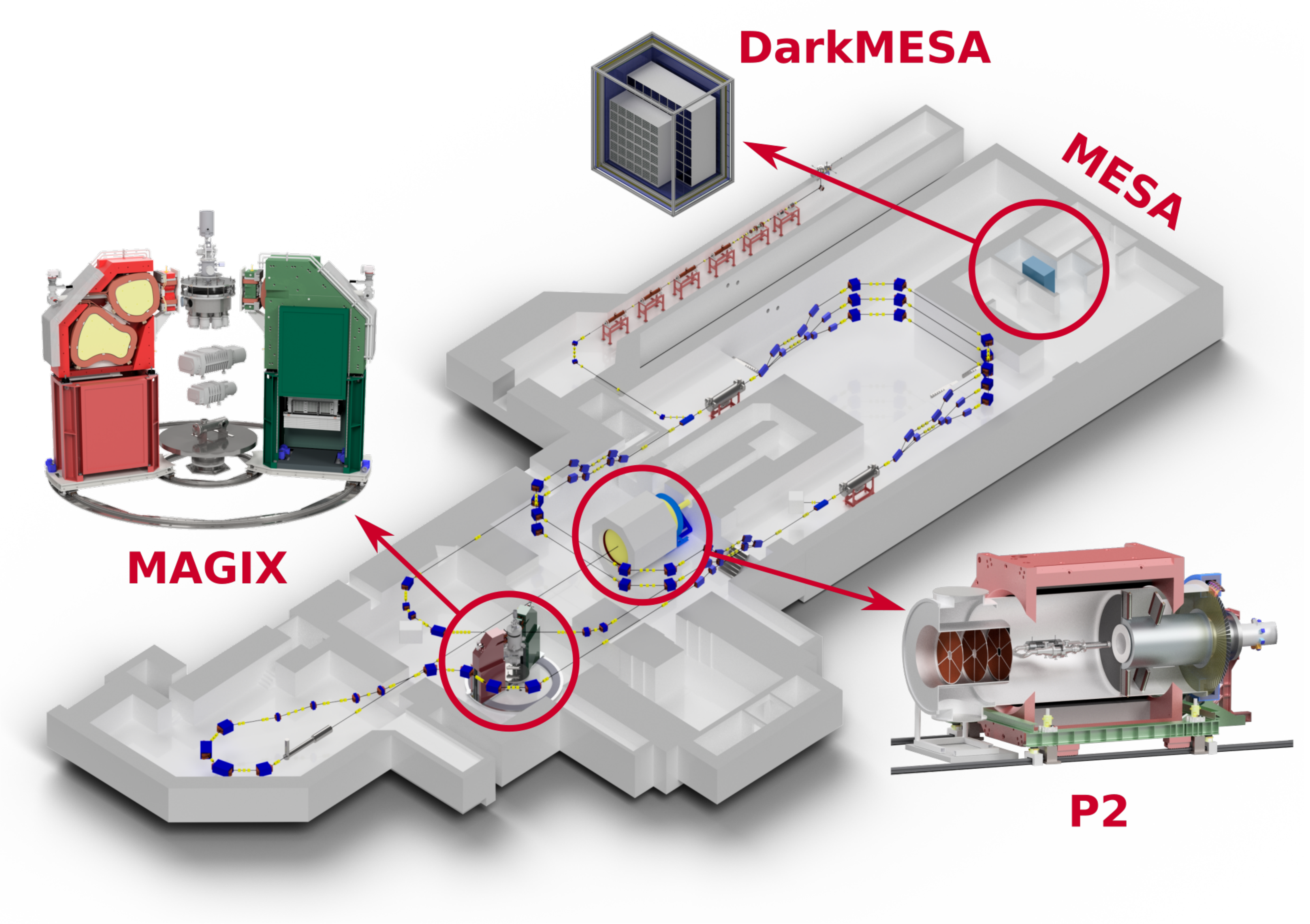
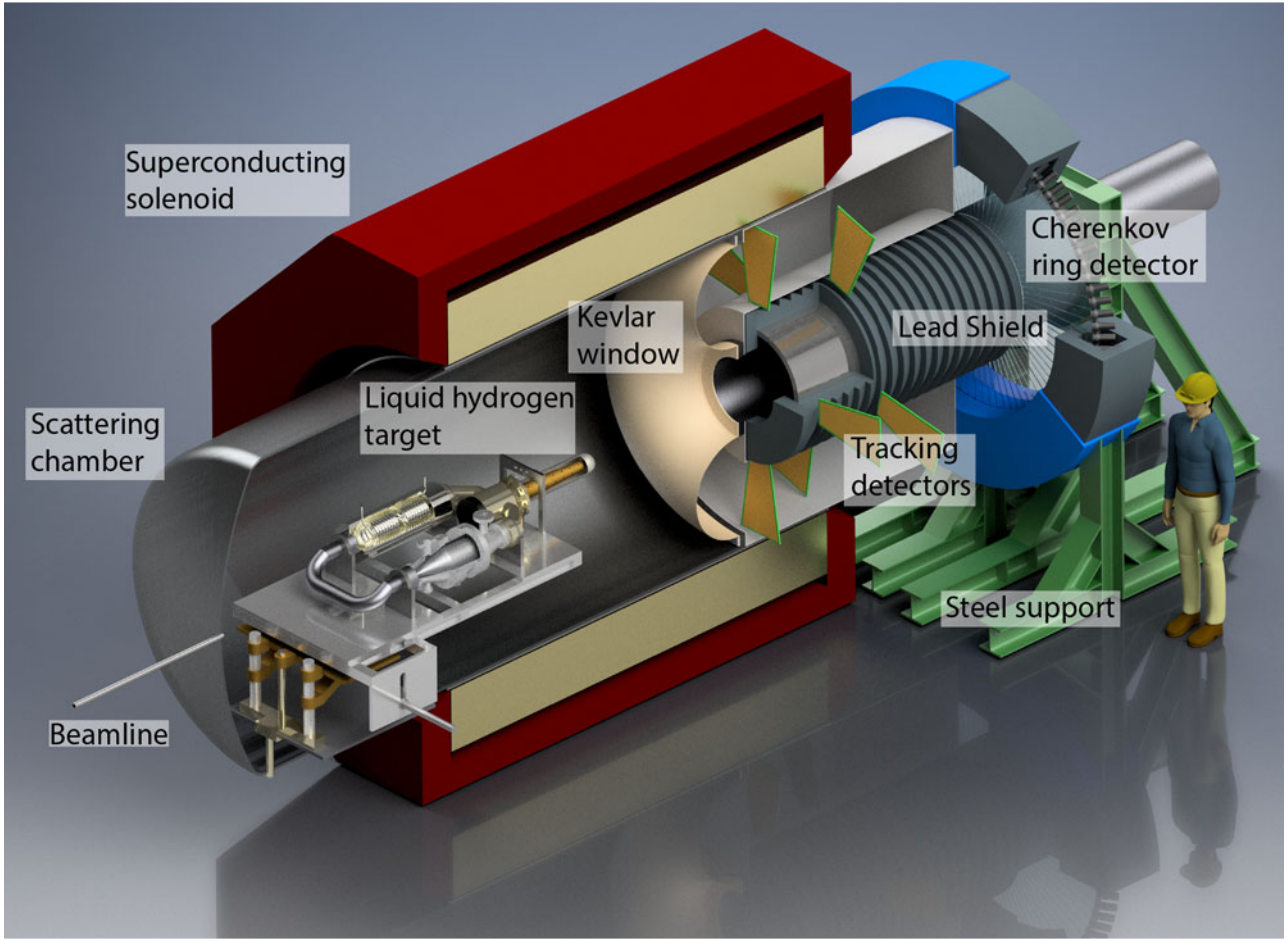


The P2 experiment



- Measure parity violating asymmetry in elastic ep scattering
- Extracted beam mode:
  - E = 155 MeV, I = 150 μA
- 60 cm LH target
- Solenoidal spectrometer with full azimuthal acceptance
- Central θ_e = 35°

Delivery of the P2 solenoid (November 2024)

Measuring the weak charge of the proton

- In *ep* scattering:

$$A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p - F(E, Q^2) \right]$$

$$Q_W^p = 1 - 4\sin^2\theta_W$$

- Precision extraction of weak mixing angle at low Q^2
- Sensitivity to BSM physics parameterized by effective interactions (e.g. SMEFT)

P2 experiment at MESA:
Goal of 40 ppb ± 0.57 ppm
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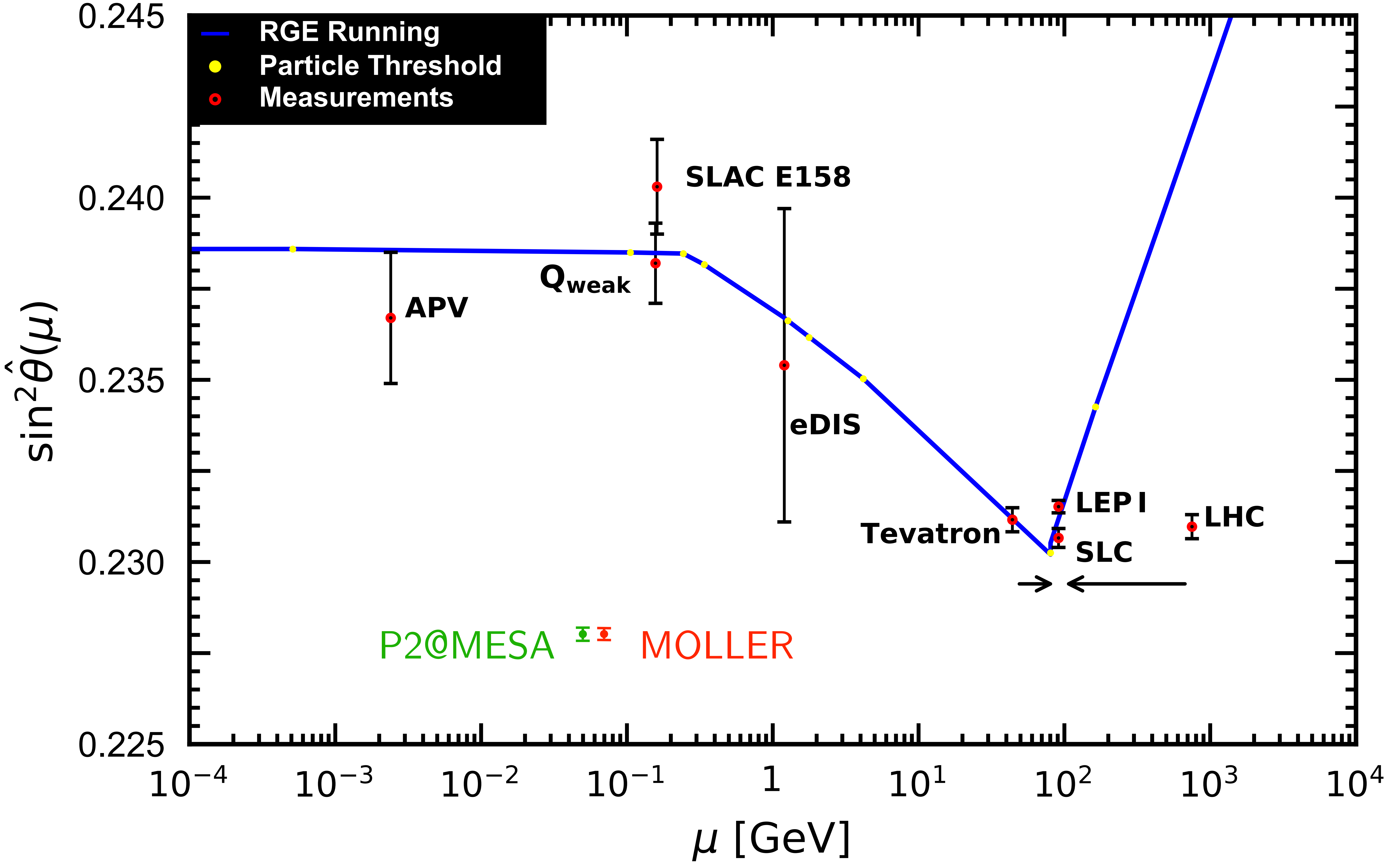

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Challenges in the precision frontier...

- Sub-ppb precision requires enormous statistics

$$\frac{1}{\sqrt{N}} < 0.57 \text{ ppb} \rightarrow N > 10^{18}$$

- Assuming counting detector rate of 100 MHz = over *100 years* of data collection
  → need *100s of GHz* event rates

- This requirement creates significant experimental demands:
  - Large beam currents on thick targets
  - High rate detectors

High-power targets

- Large power deposition (up to several kW) can quickly lead to target instability, degradation
  - Solid targets: melting, holes
  - Liquid targets: density fluctuations, boiling

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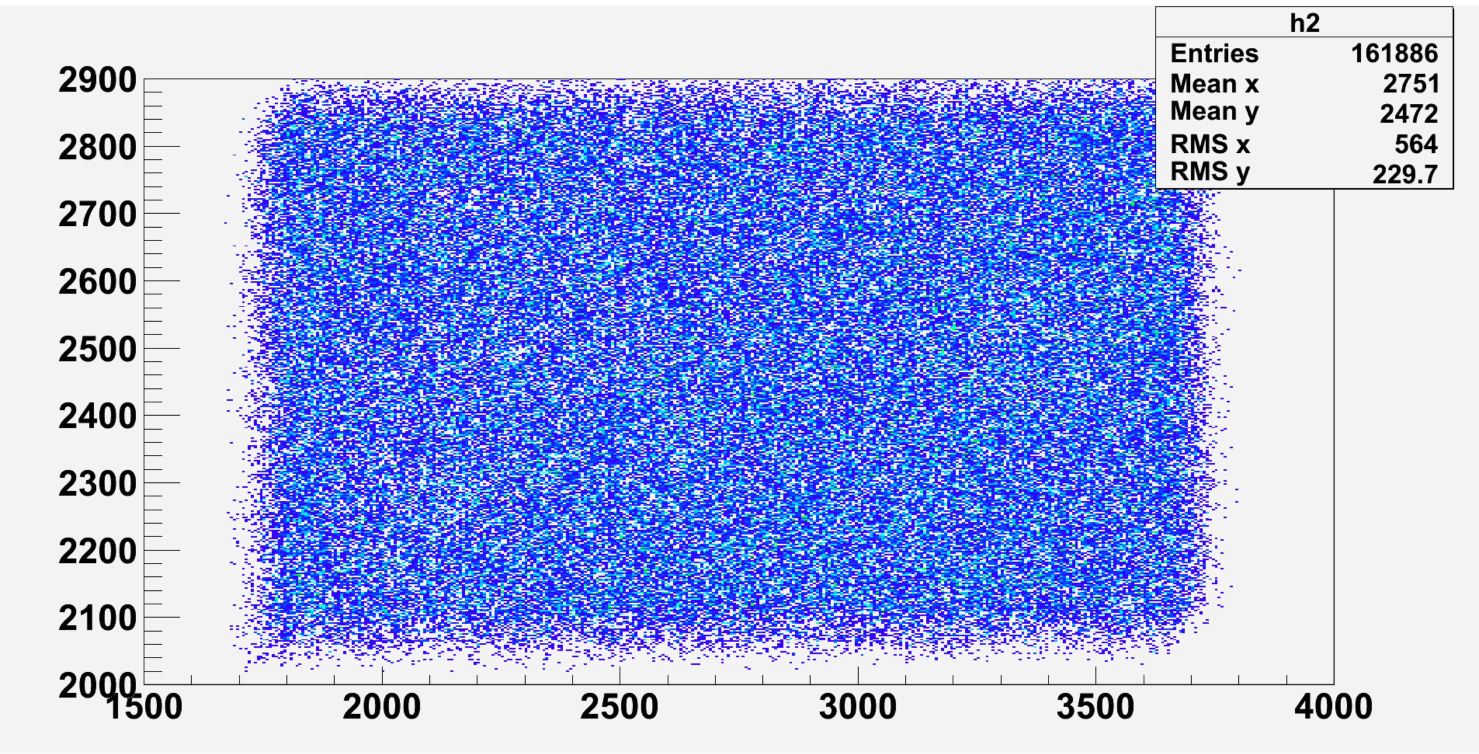
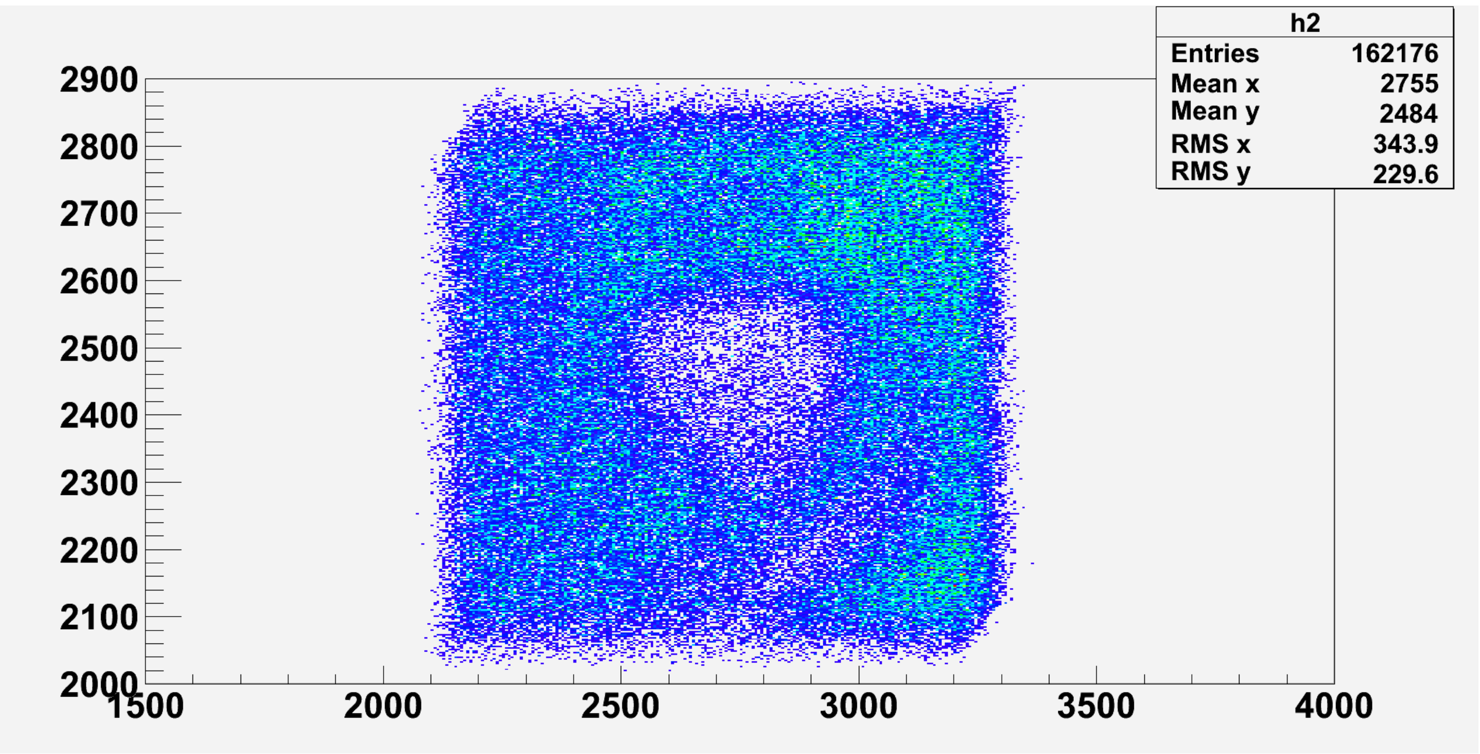
From PREX at JLab

New ^{208}Pb target

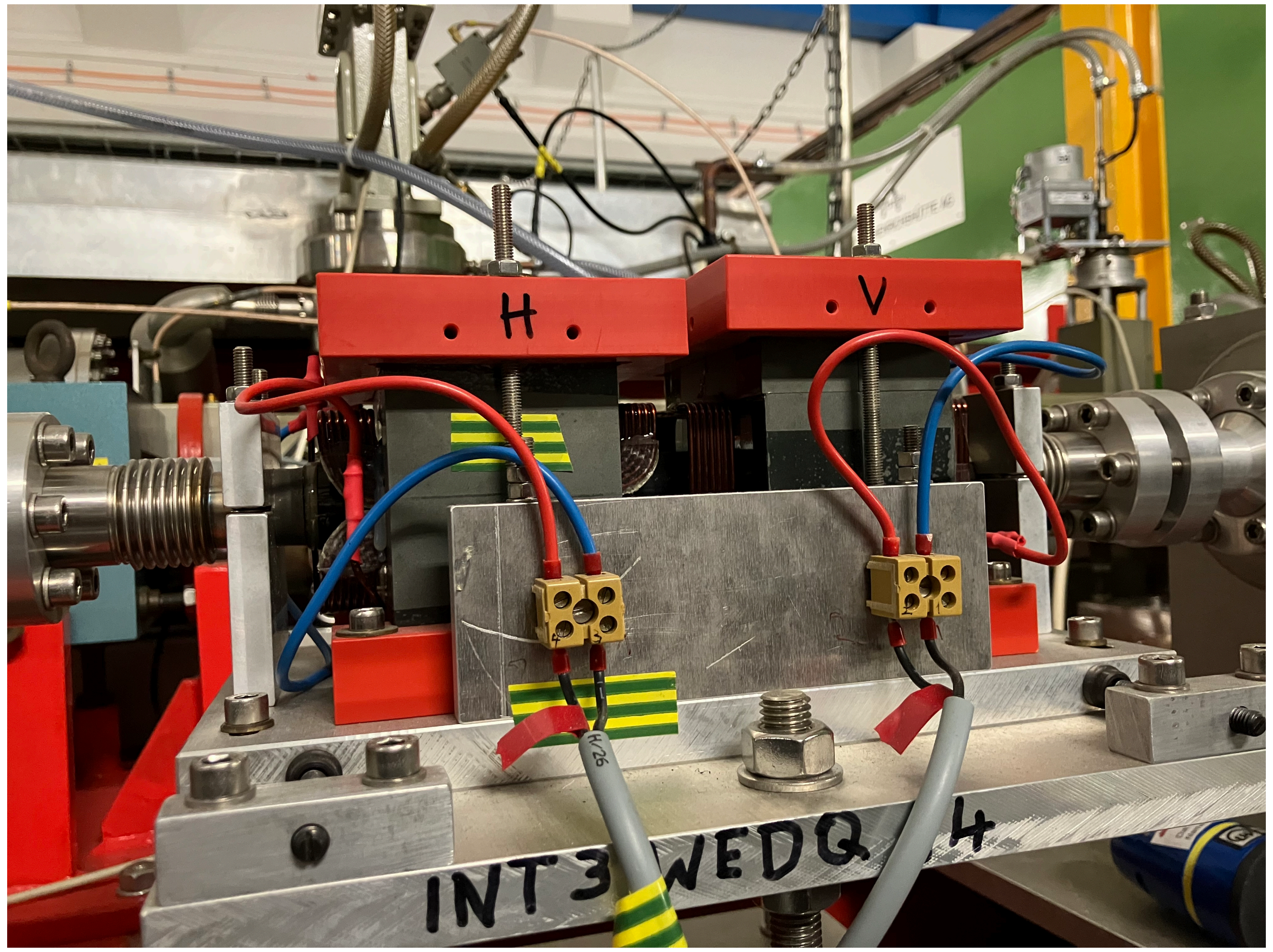


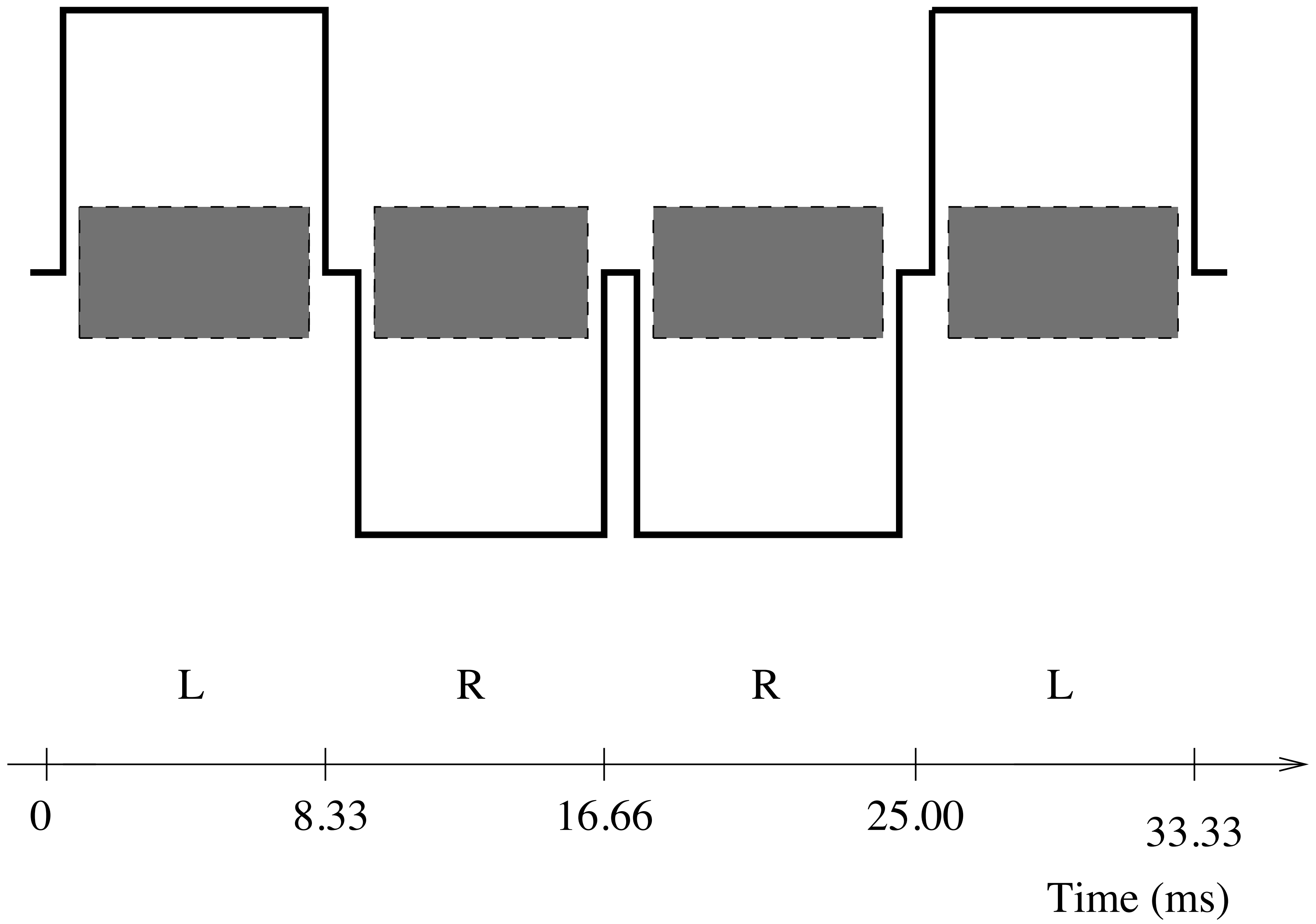
After 1 week at 70 μA

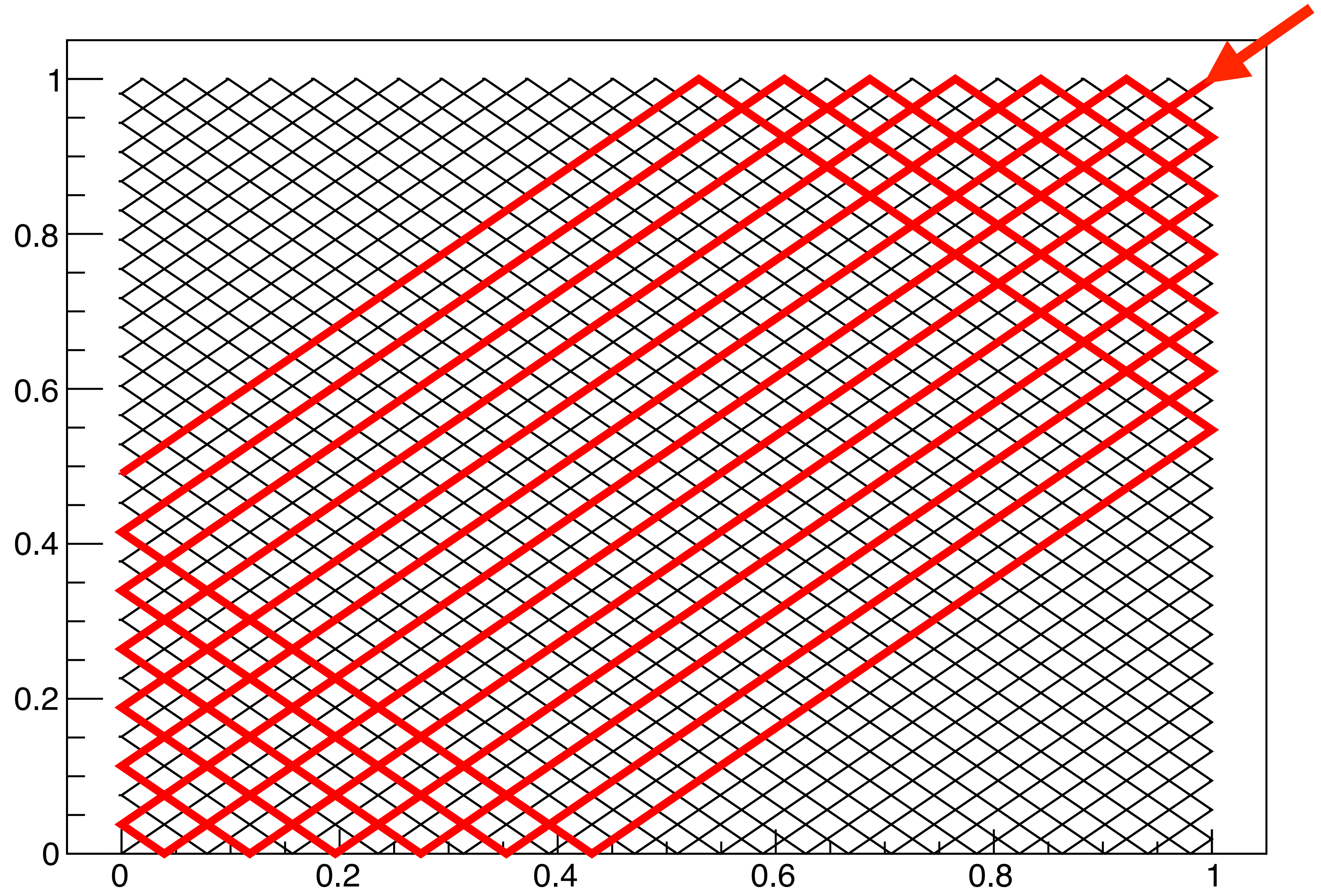


Beam rastering

- Fast-steering magnets raster beam on target
- Distributes power, reducing target degradation
- *Pattern must be carefully synchronized with beam helicity to reduce systematics!*







Detector requirements

- Insensitive to low-energy background

  → Pure Cherenkov detector

- Accommodate 100+ GHz event rates to achieve required statistics

  → Radiation-hard material

  → Integrate signal from many simultaneous events (no "counting")

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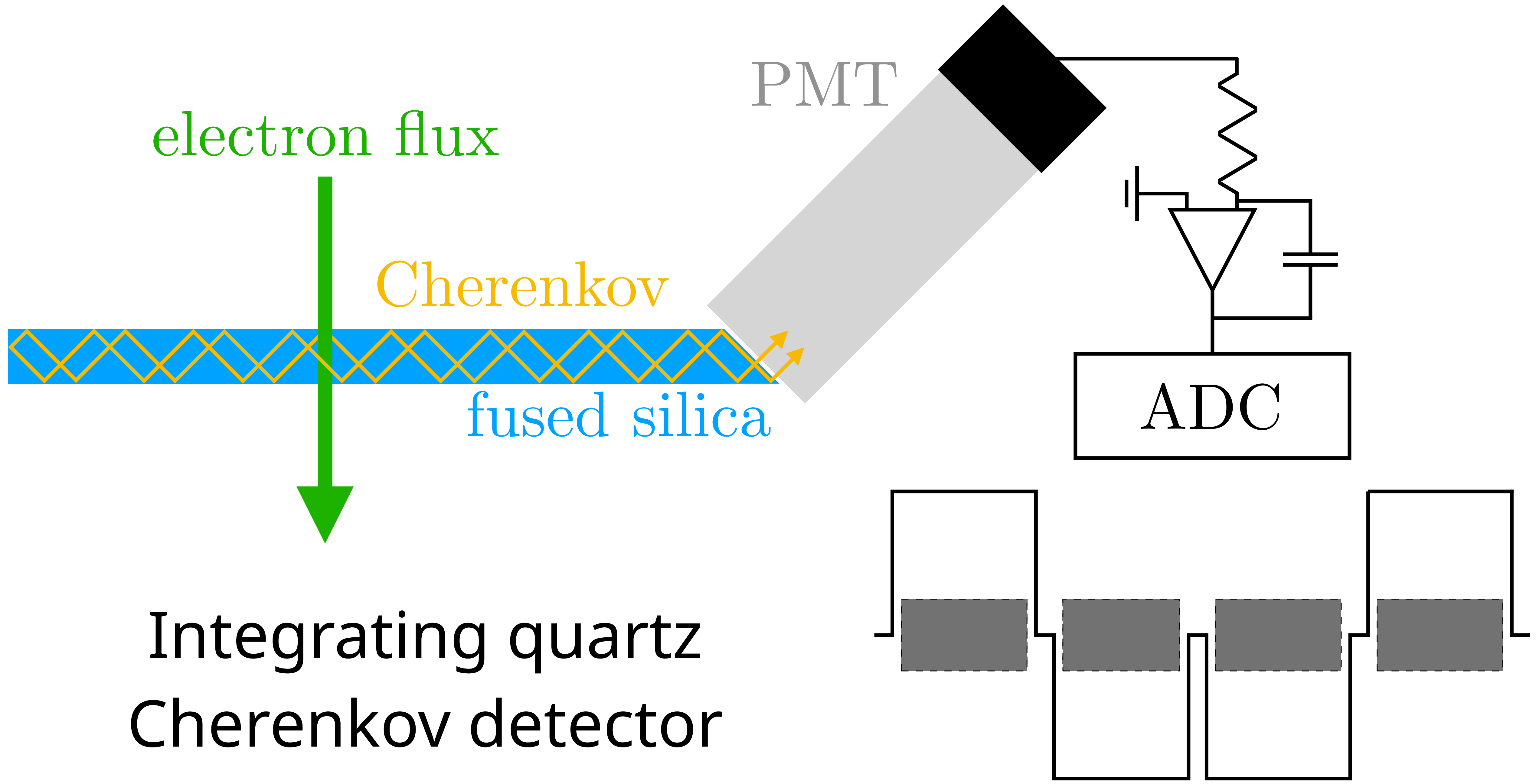

Integrating quartz Cherenkov detector

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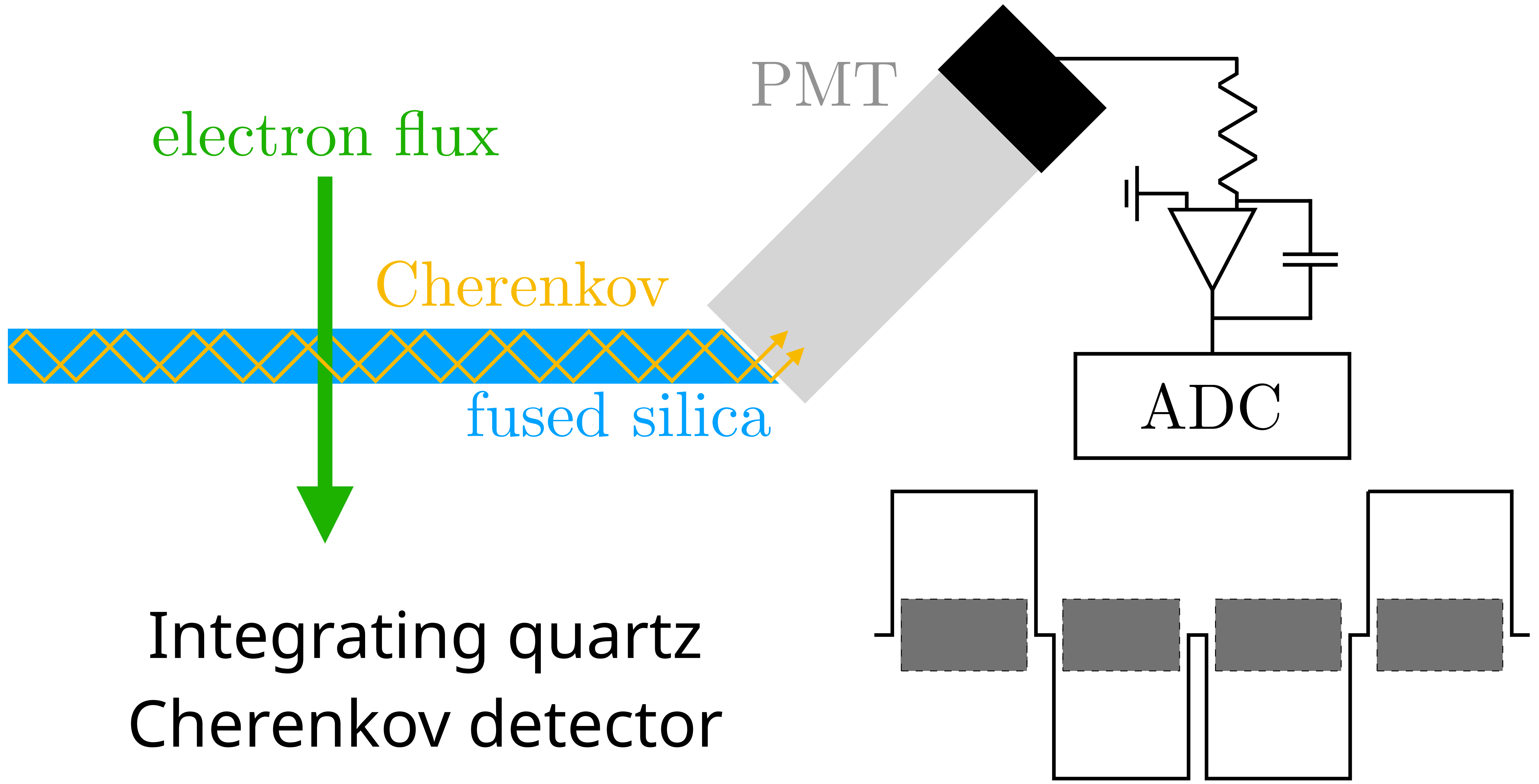

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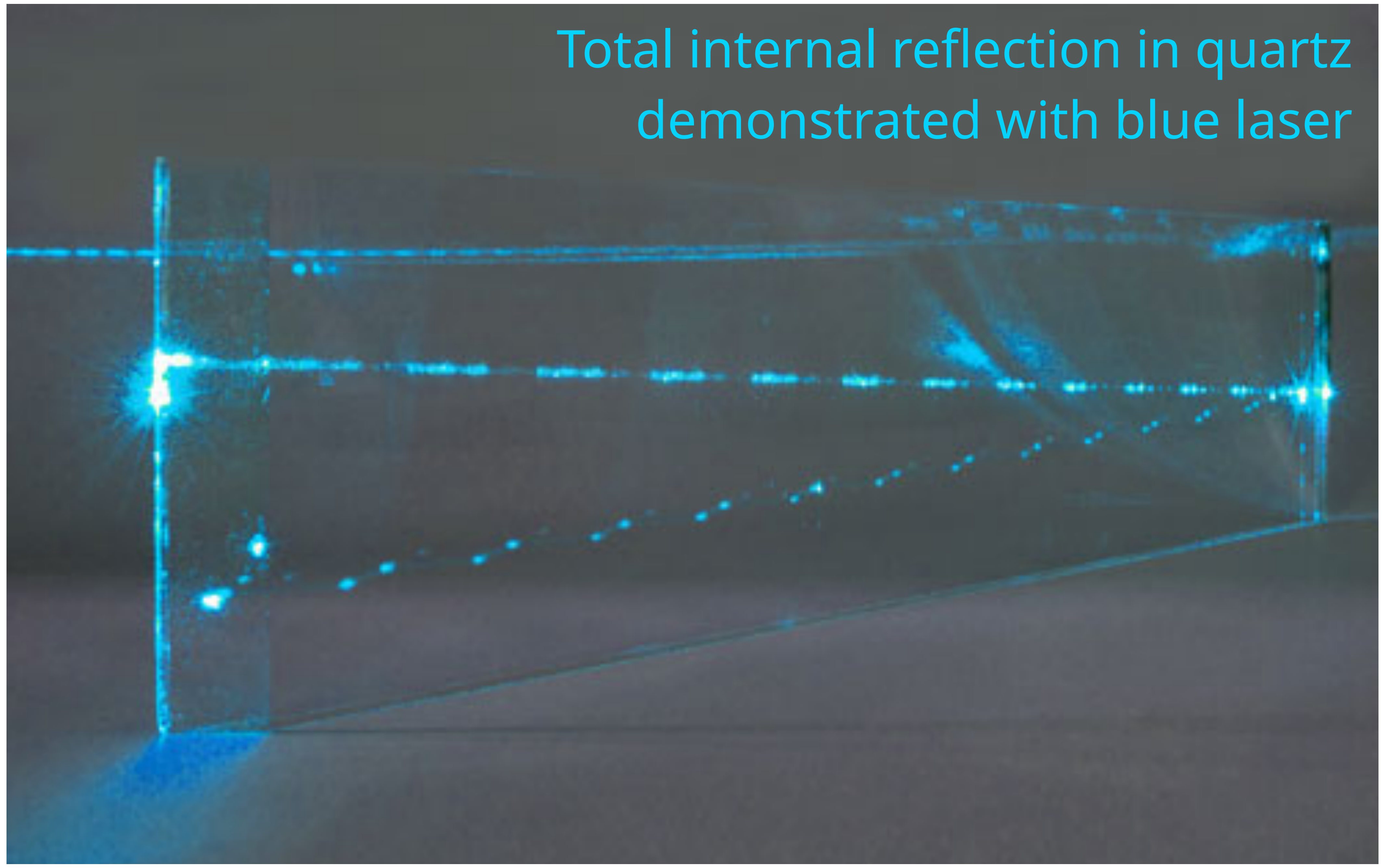
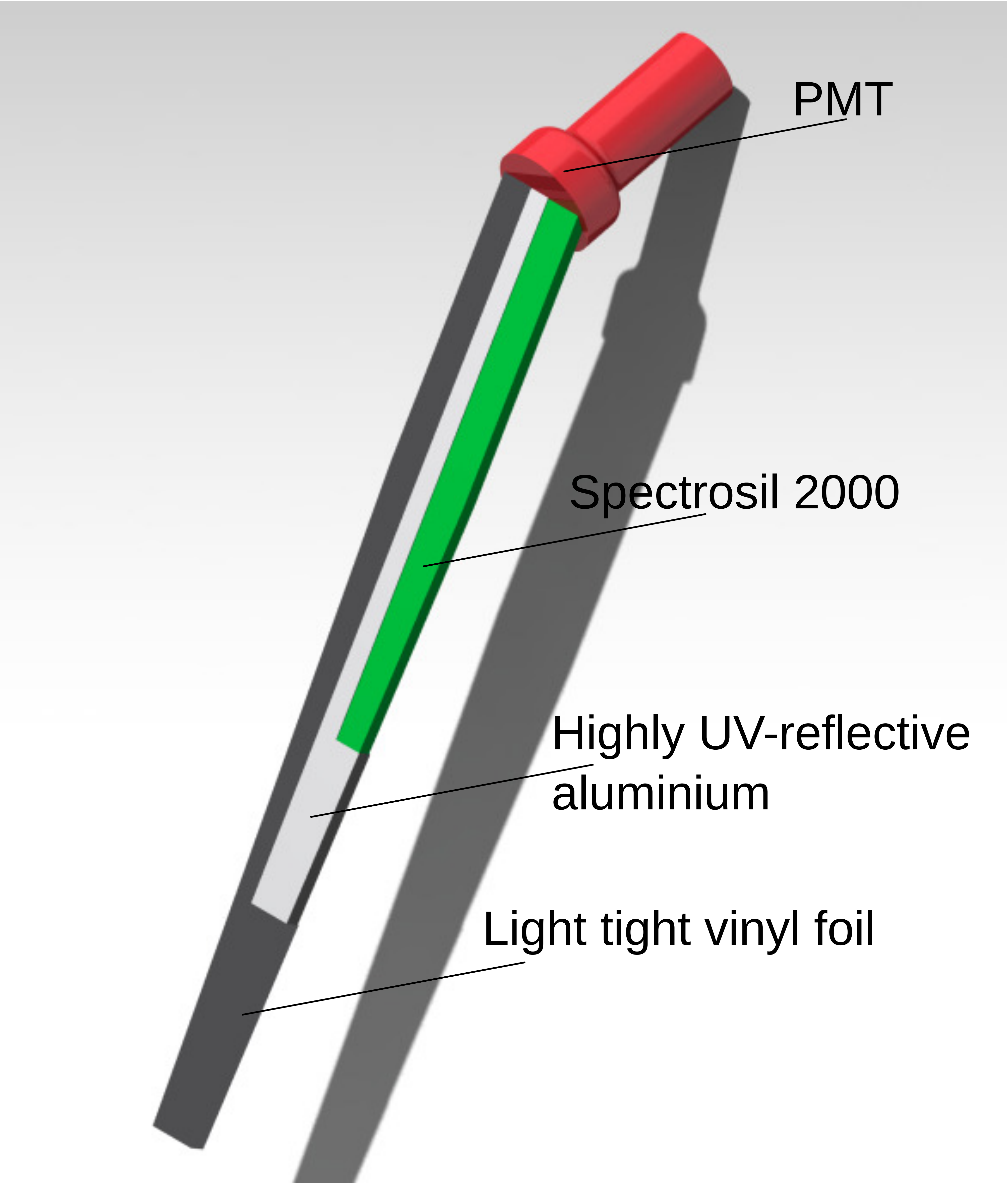
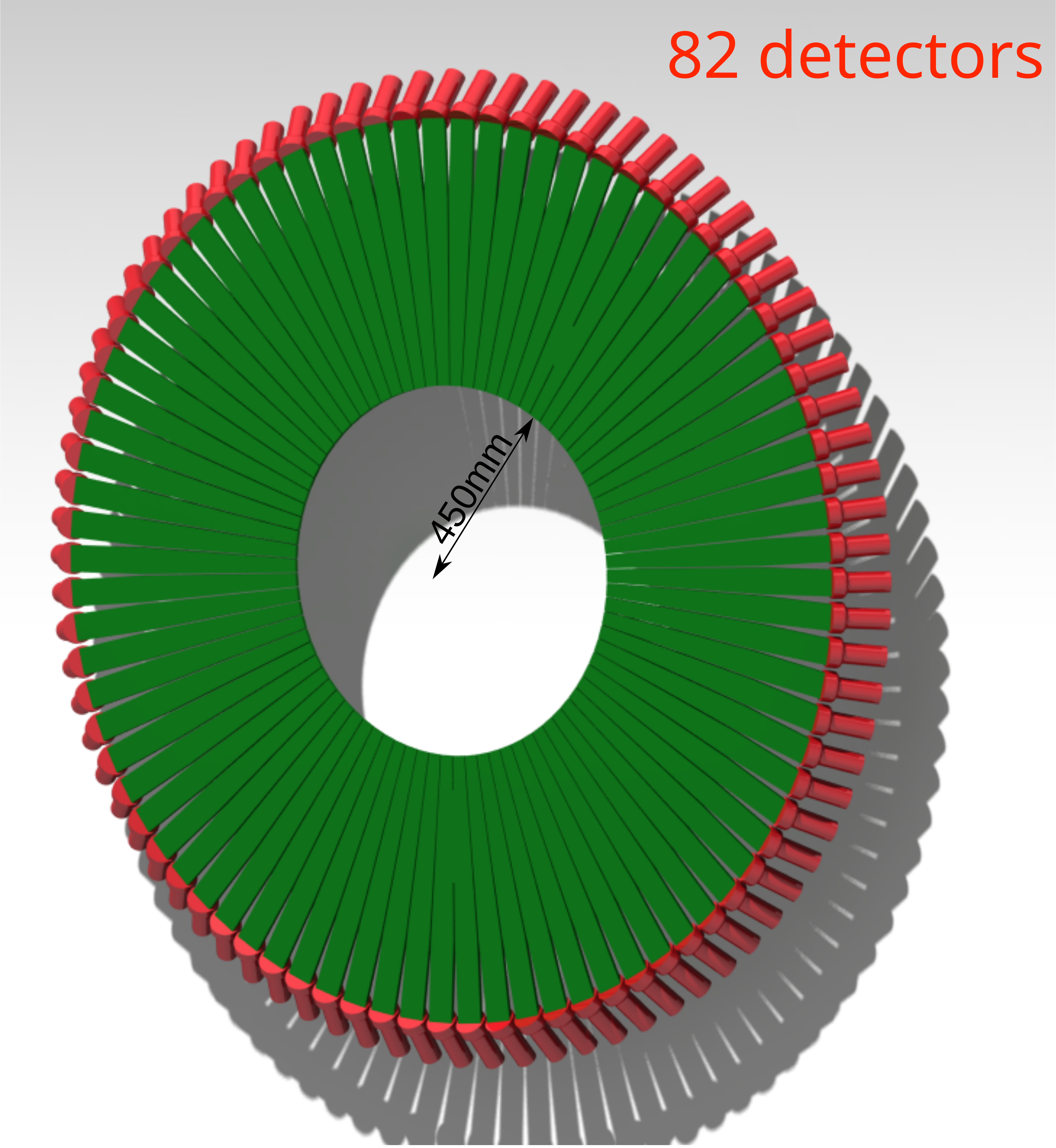


P2 detector ring





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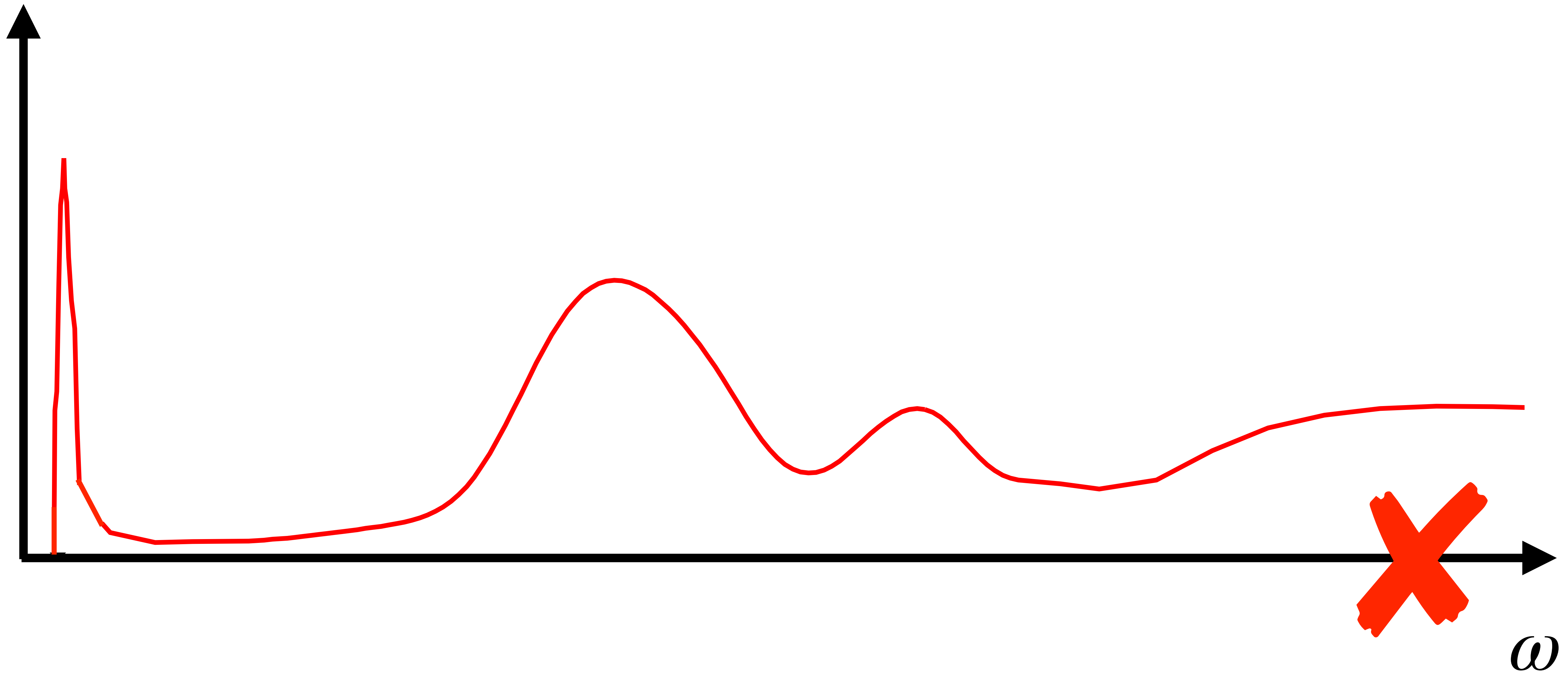

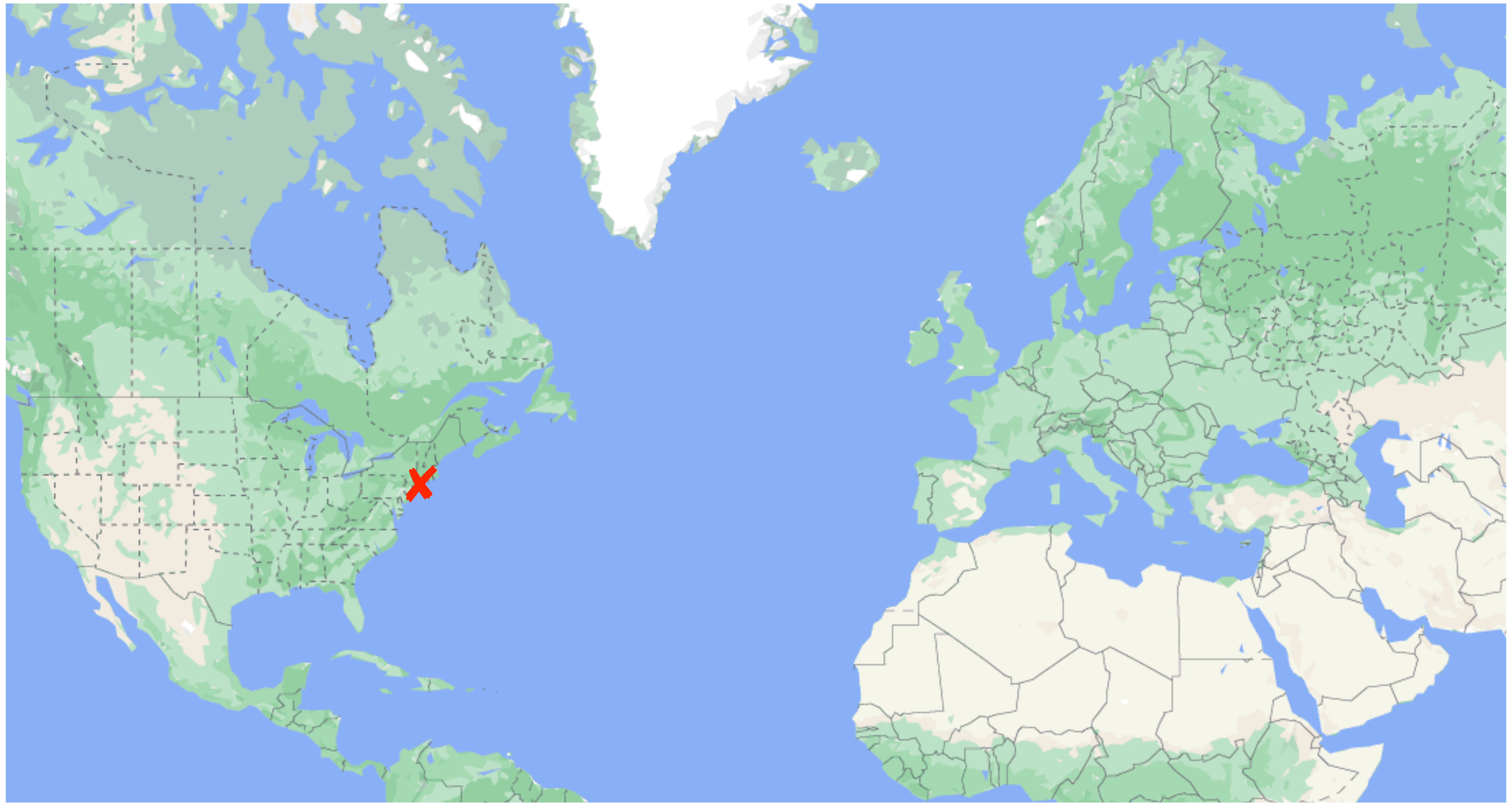

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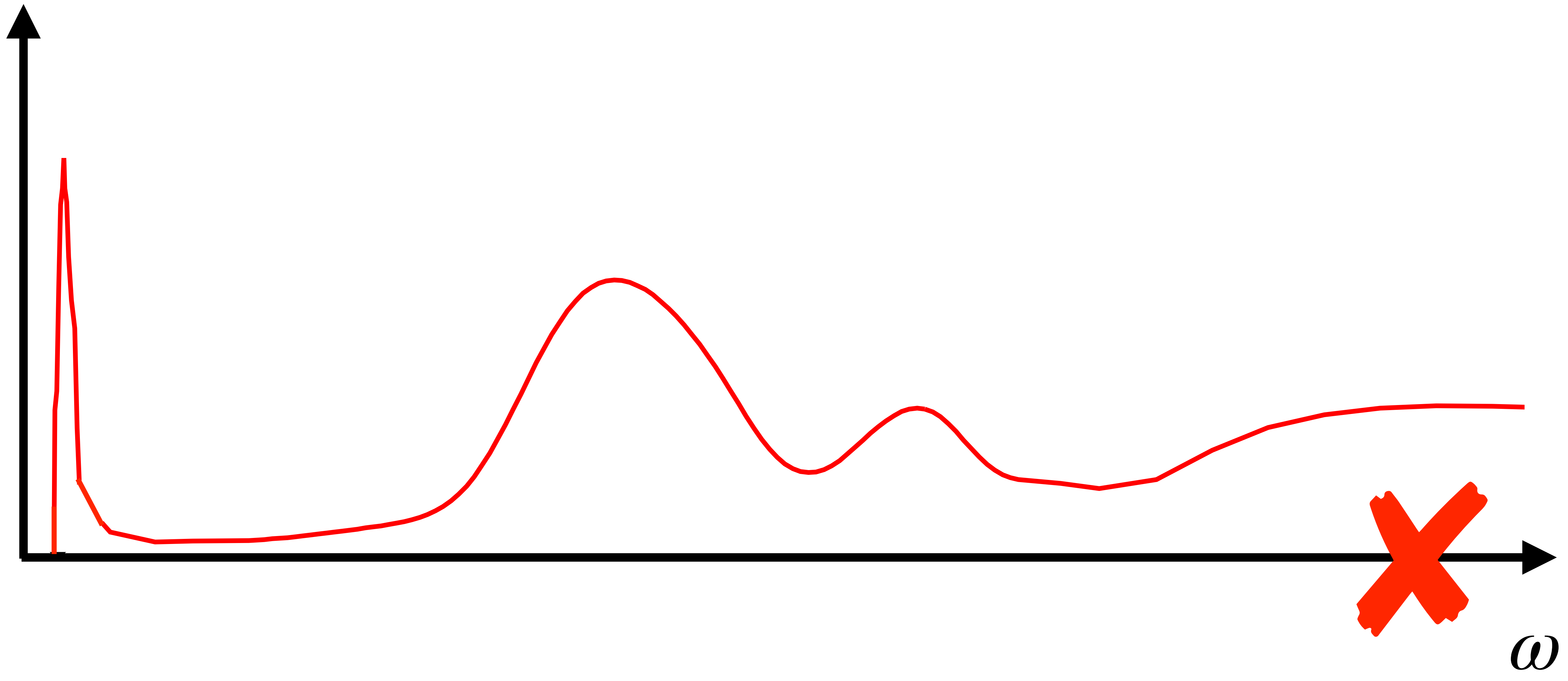
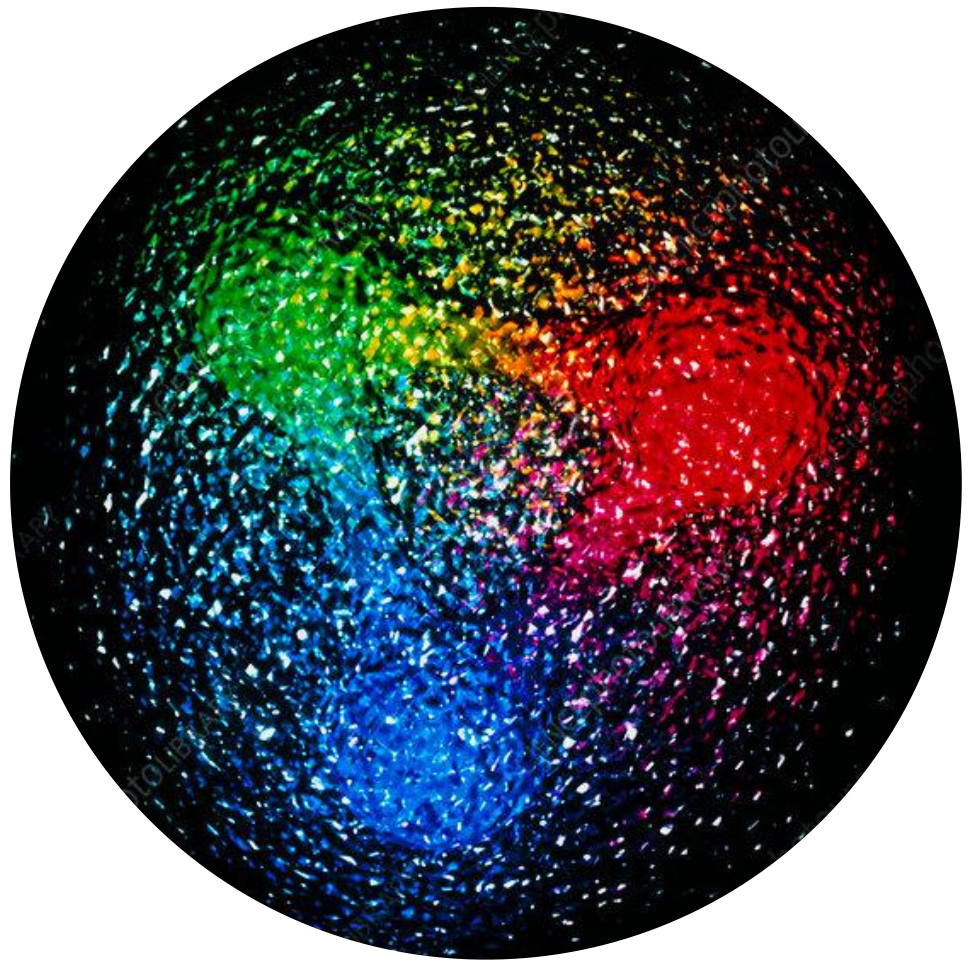


The quarks in the proton



- *Protons & neutrons* account for most visible mass in the universe
- Most of this mass is *dynamically generated* by the constituent *quarks & gluons*

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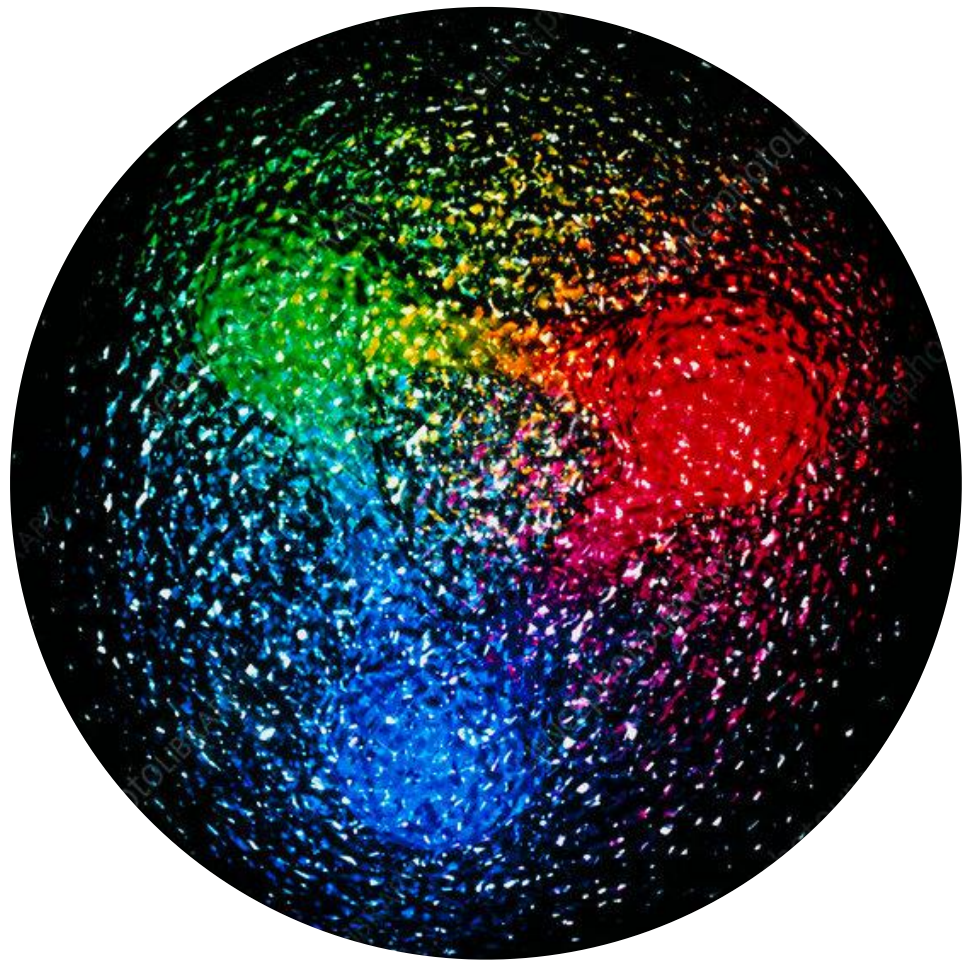

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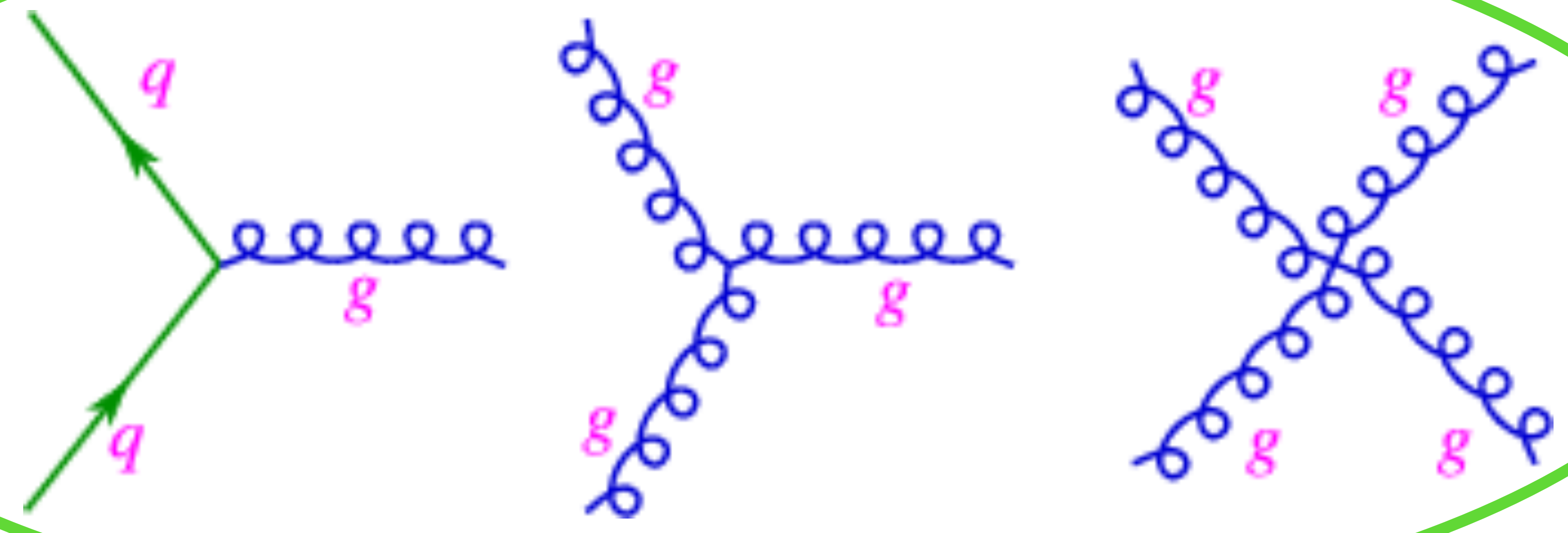

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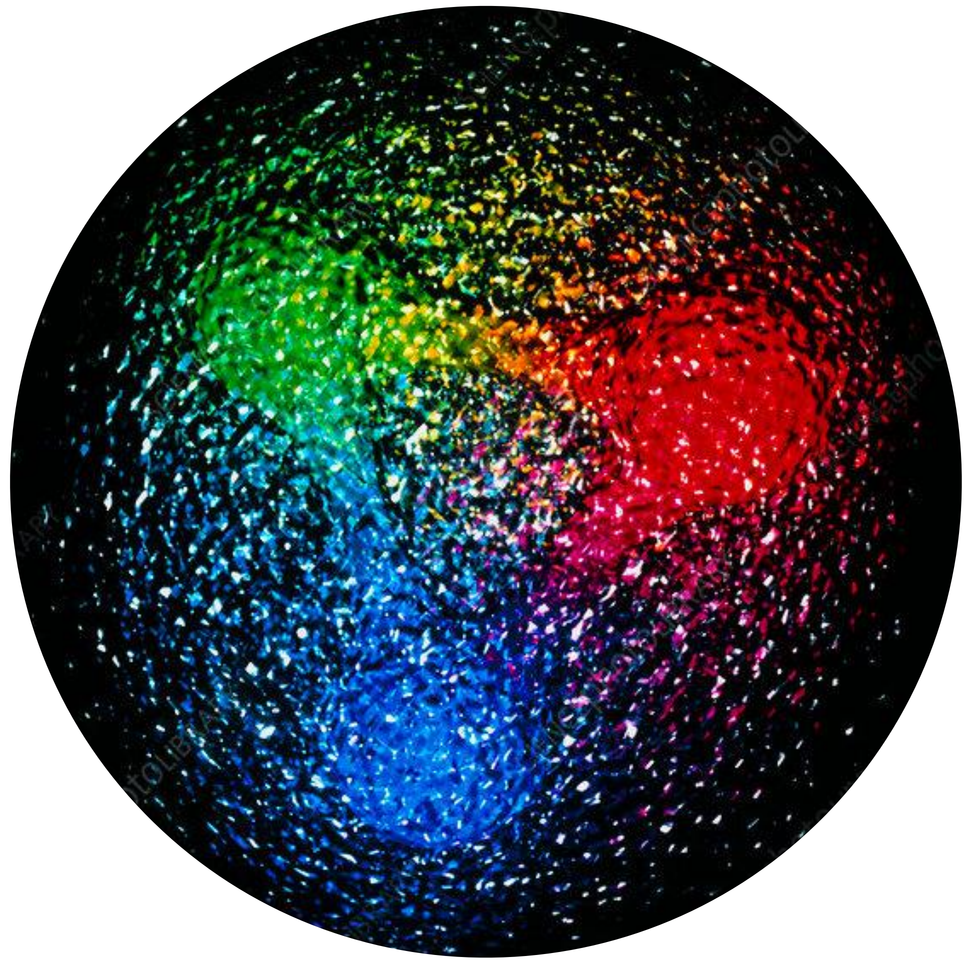

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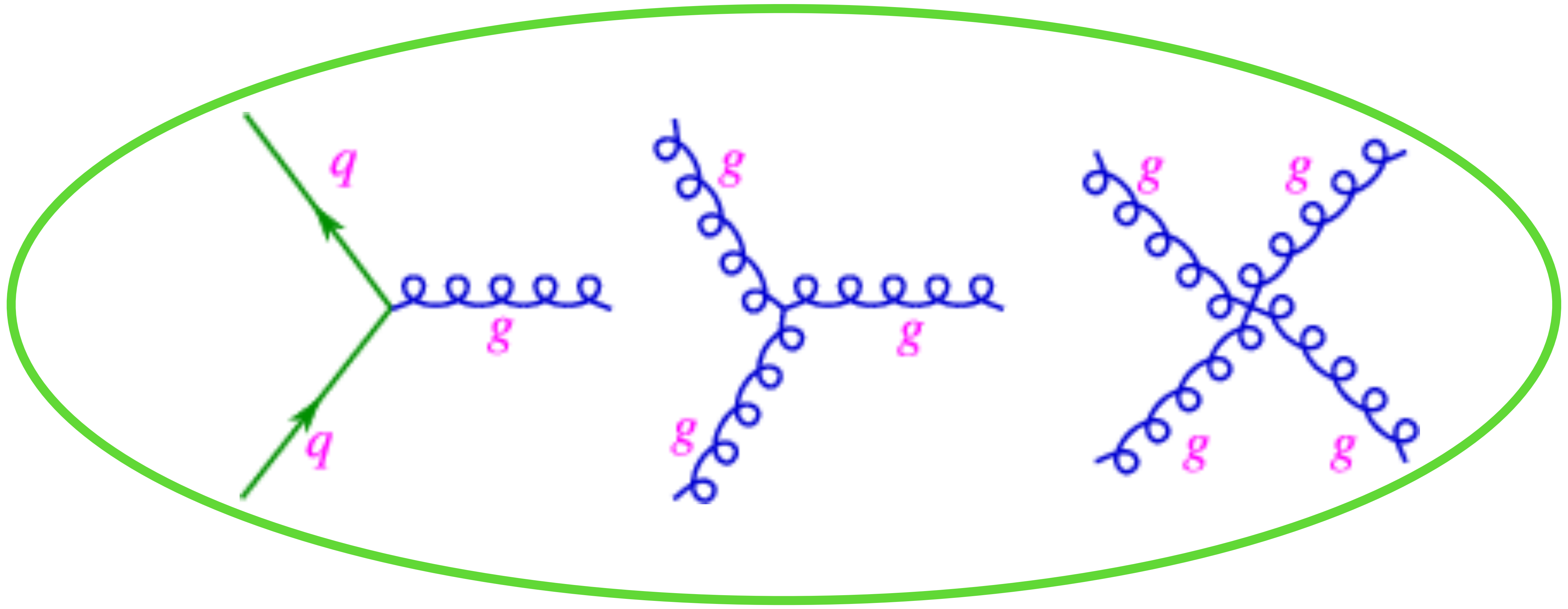
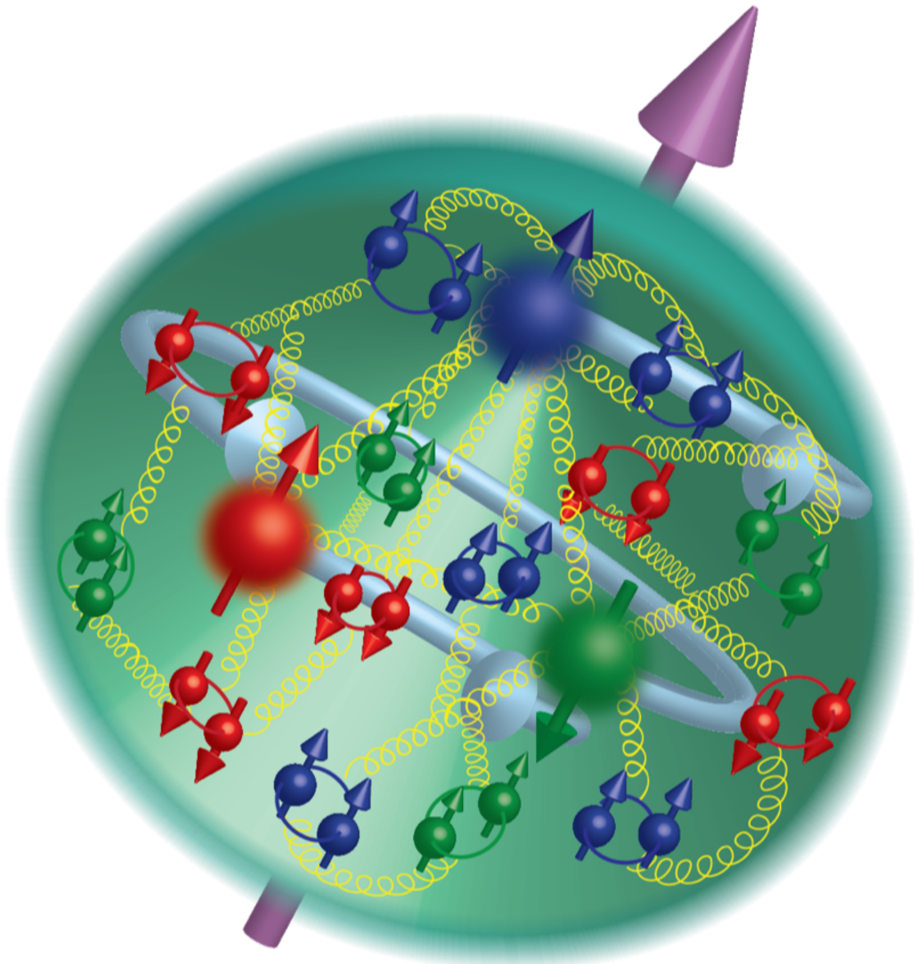
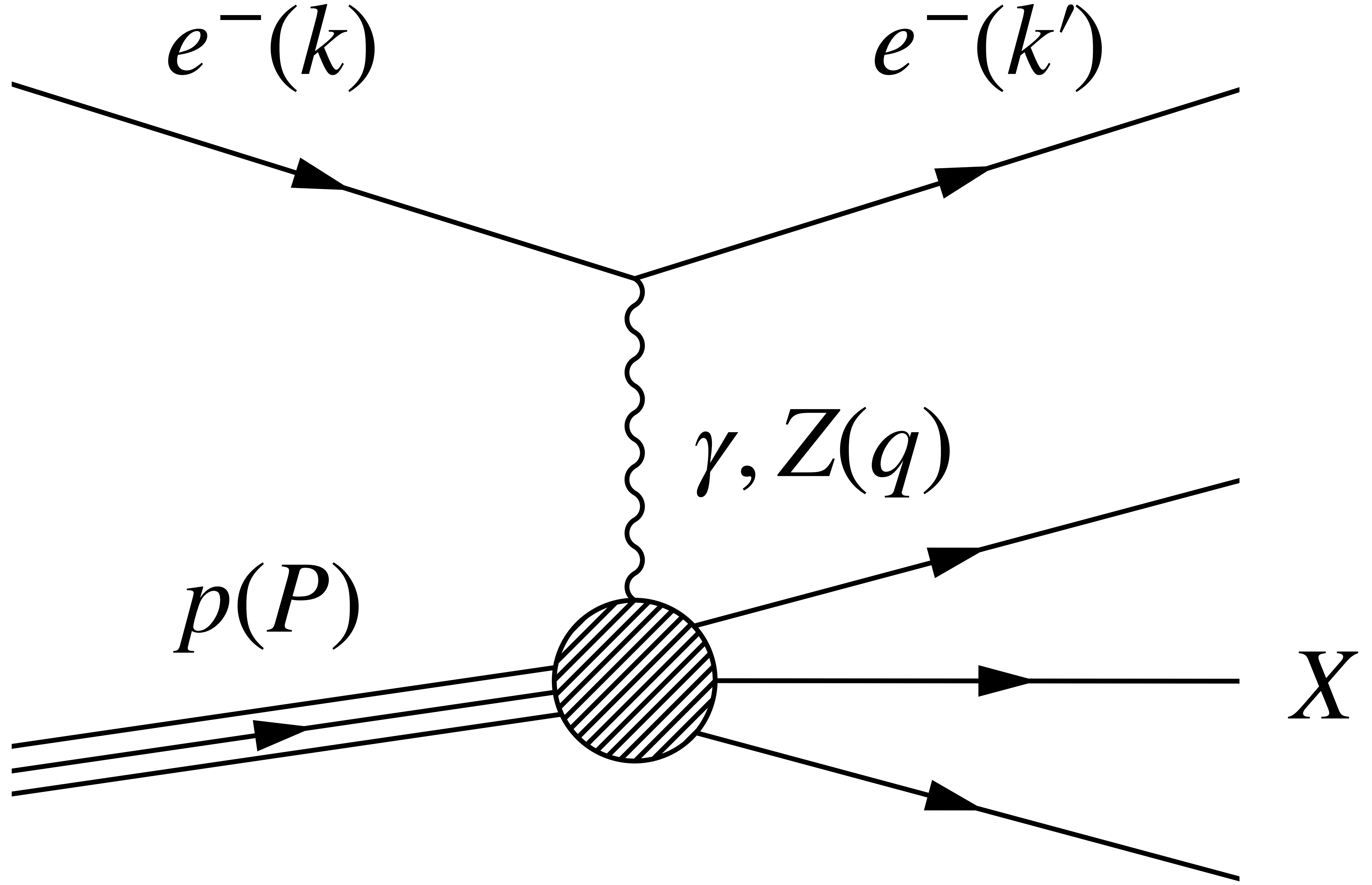




Emergent proton properties?

Quarks probed with deep inelastic scattering



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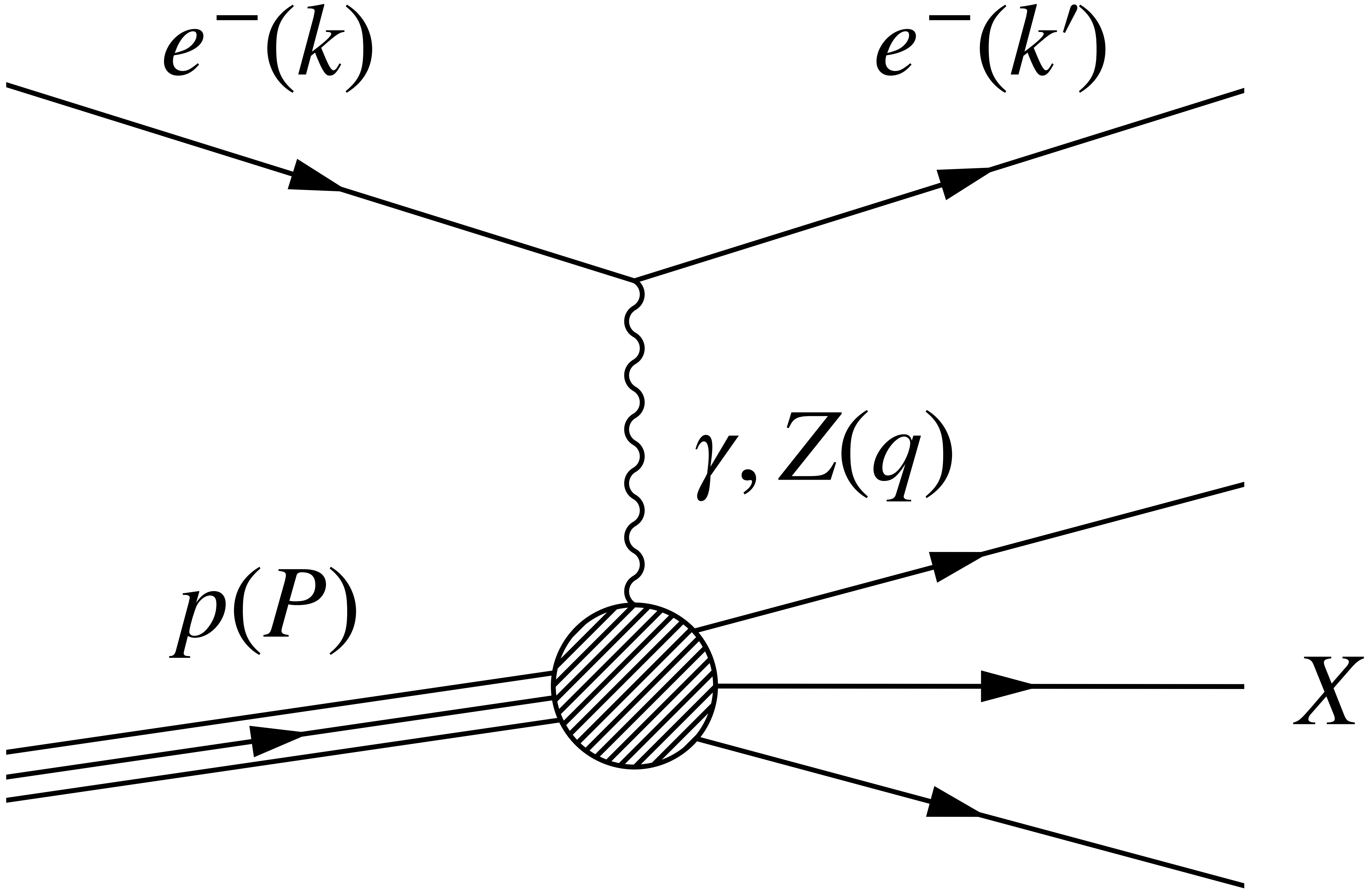

Detect scattered electron

$$Q^2 = -q^2 = (k' - k)^2$$

$$x_B = \frac{Q^2}{2P \cdot q}$$

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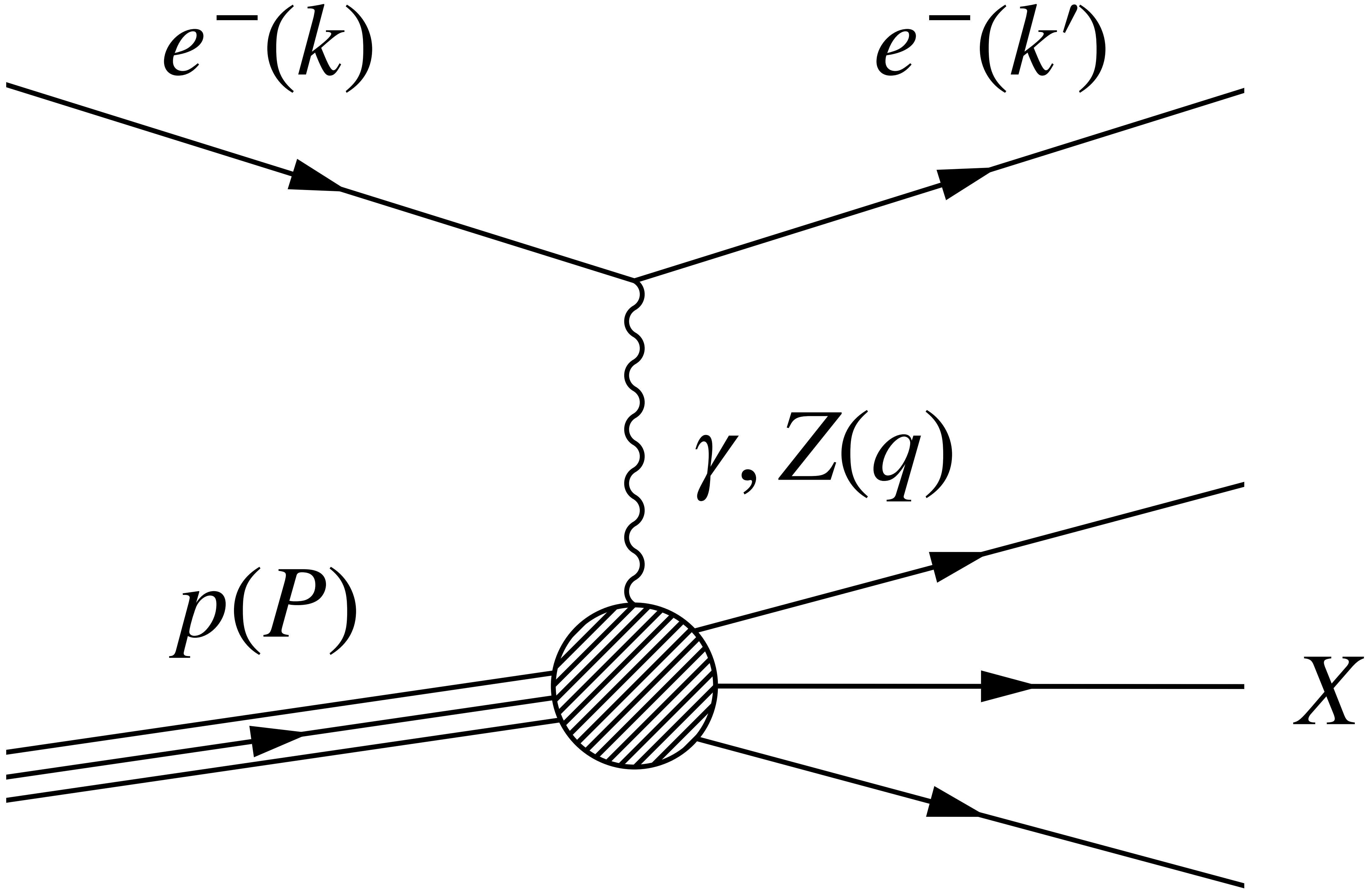

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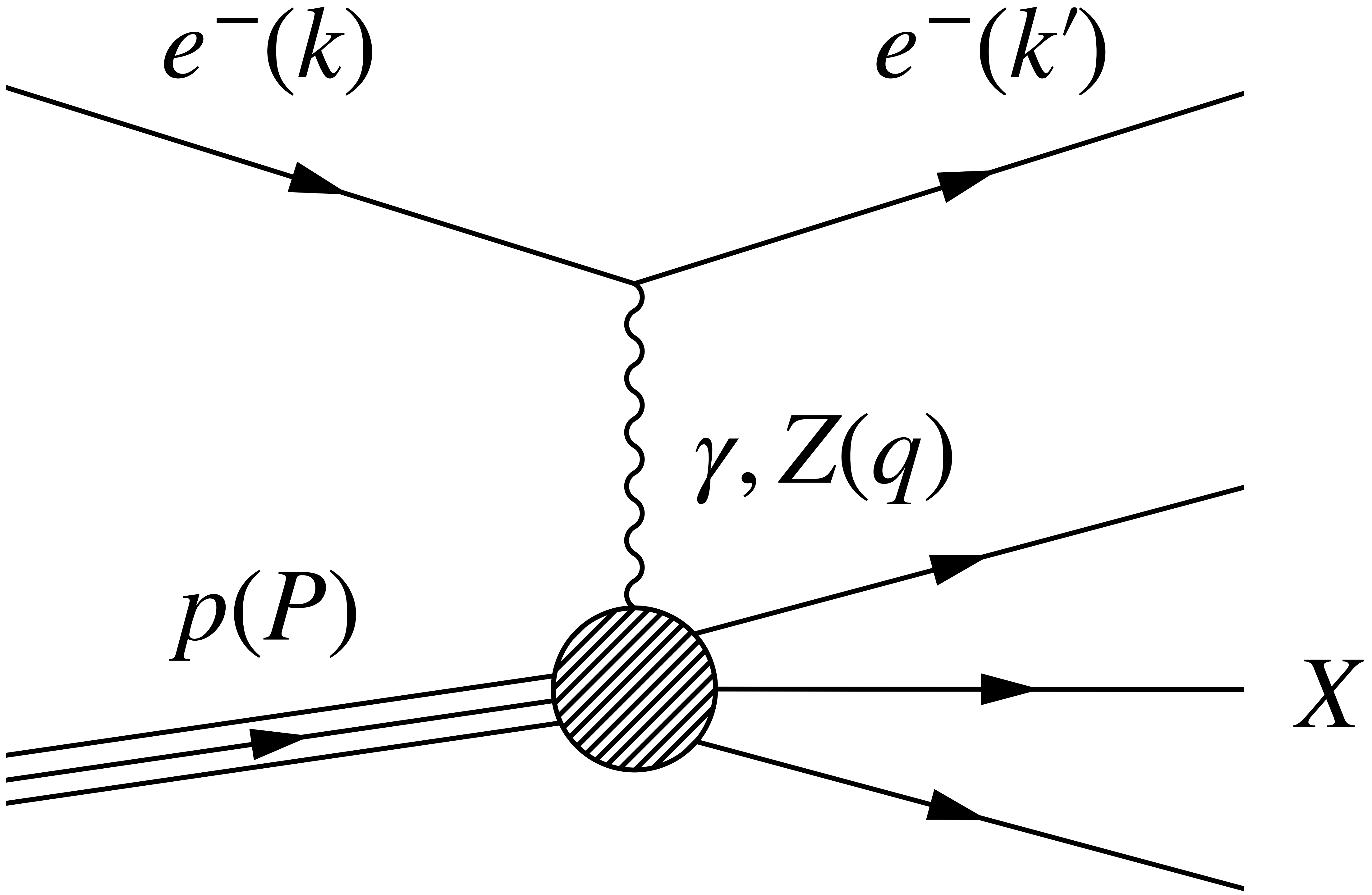

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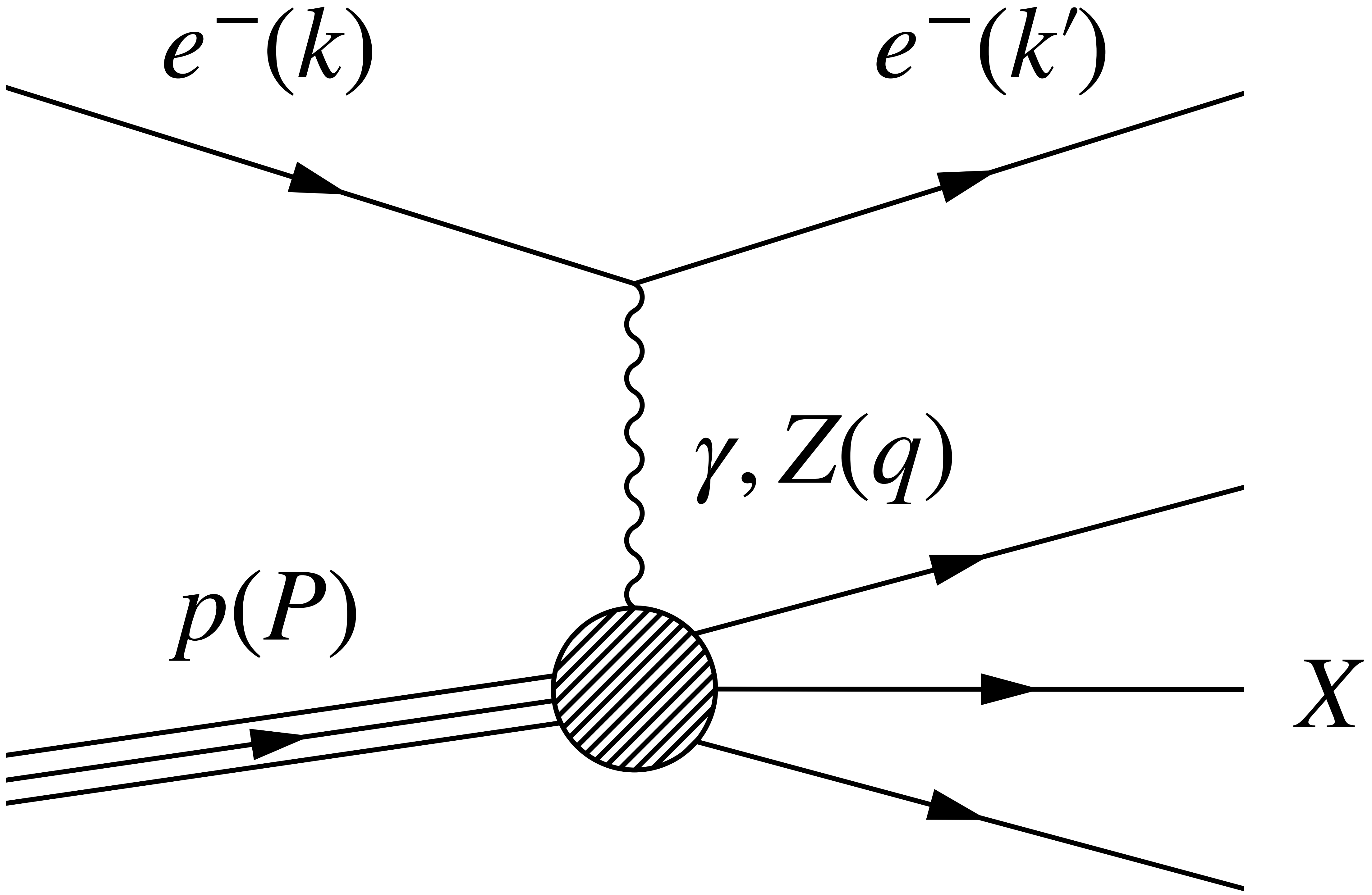

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Neutral current DIS in naive quark-pardon model

- Hard scattering off non-interacting quarks
- Structure independent of Q^2 ("scaling" → prediction for pioneering DIS experiments at SLAC)
- No transverse momentum

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

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$$\begin{aligned}
\tilde{F}_2^{\pm} &= F_2^{\gamma} - (g_V^e \pm \lambda_e g_A^e)\,\eta_{\gamma Z} F_2^{\gamma Z}\ldots \\
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\end{aligned}$$

$$\eta_{\gamma Z} = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2 + M_Z^2}\right)$$

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

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

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

$$\begin{aligned}\tilde{F}_2^{\pm} &= F_2^{\gamma} - (g_V^e \pm \lambda_e g_A^e)\,\eta_{\gamma Z}F_2^{\gamma Z}\ldots\\ x\tilde{F}_3^{\pm} &= \quad\; - (g_A^e \pm \lambda_e g_V^e)\,\eta_{\gamma Z}xF_3^{\gamma Z}\ldots\end{aligned}$$

$$\eta_{\gamma Z} = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2+M_Z^2}\right)$$

Neutral current DIS in naive quark-pardon model

- Hard scattering off non-interacting quarks
- Structure independent of Q^2 ("scaling" → prediction for pioneering DIS experiments at SLAC)
- No transverse momentum

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

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$$\eta_{\gamma Z} = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2+M_Z^2}\right)$$

Parton distribution functions (PDFs): Probability to find (anti)quark carrying momentum fraction x_B

$q = u(x_B), d(x_B), s(x_B)\dots$

Cross section difference in polarized DIS

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

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

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

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

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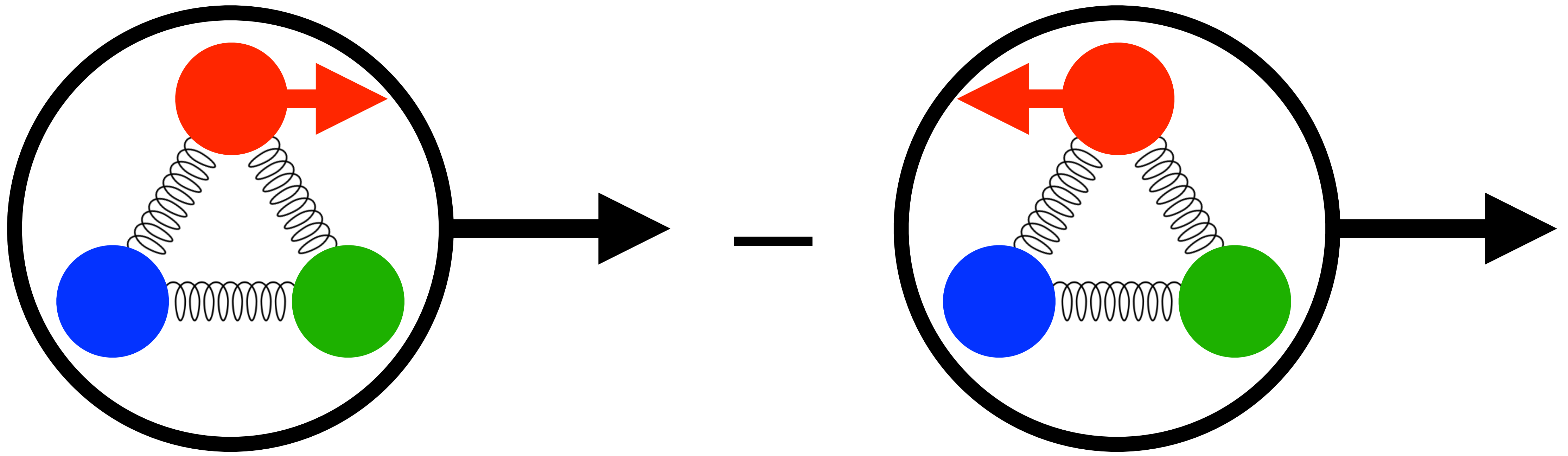
$\Delta q =$ 

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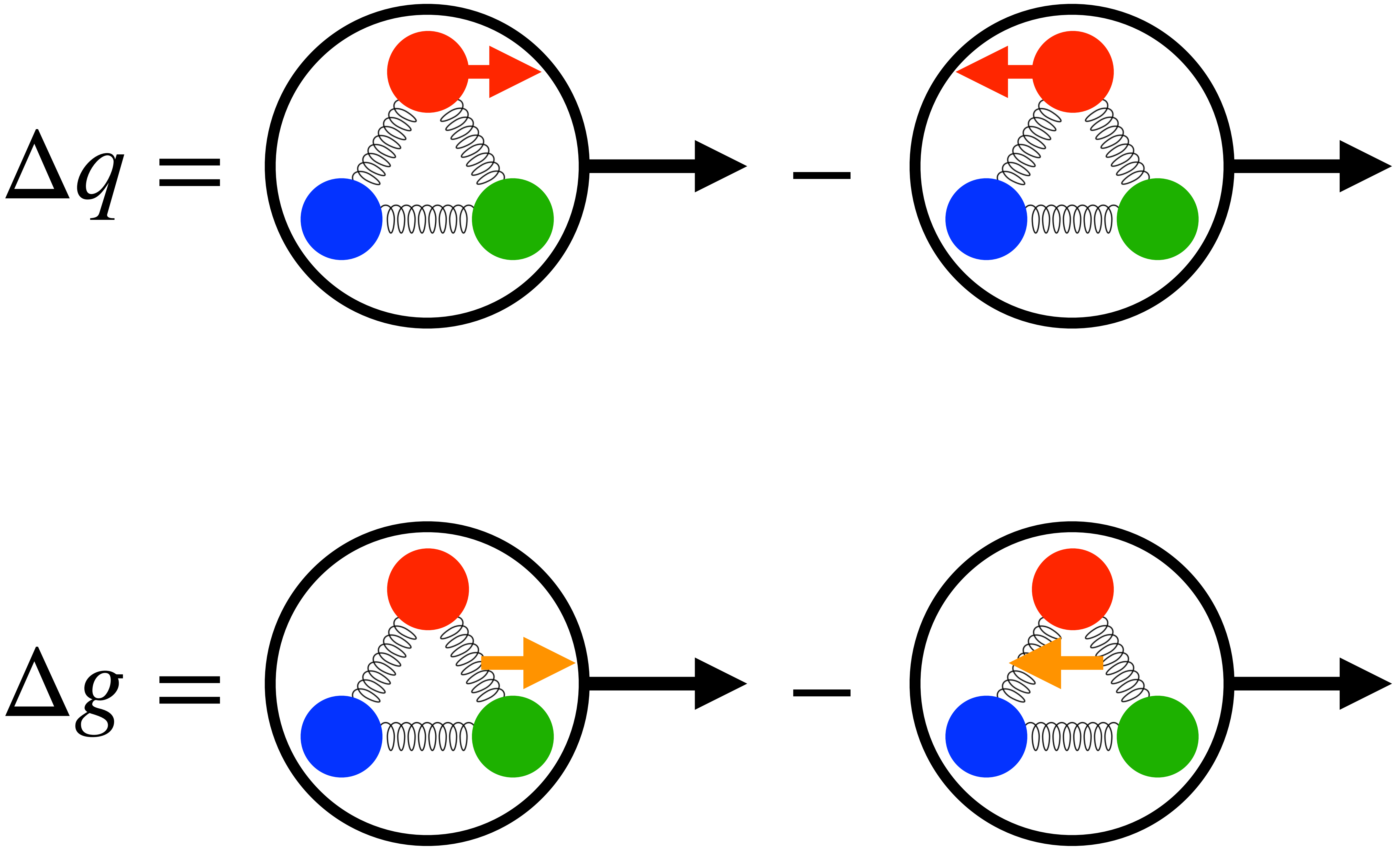
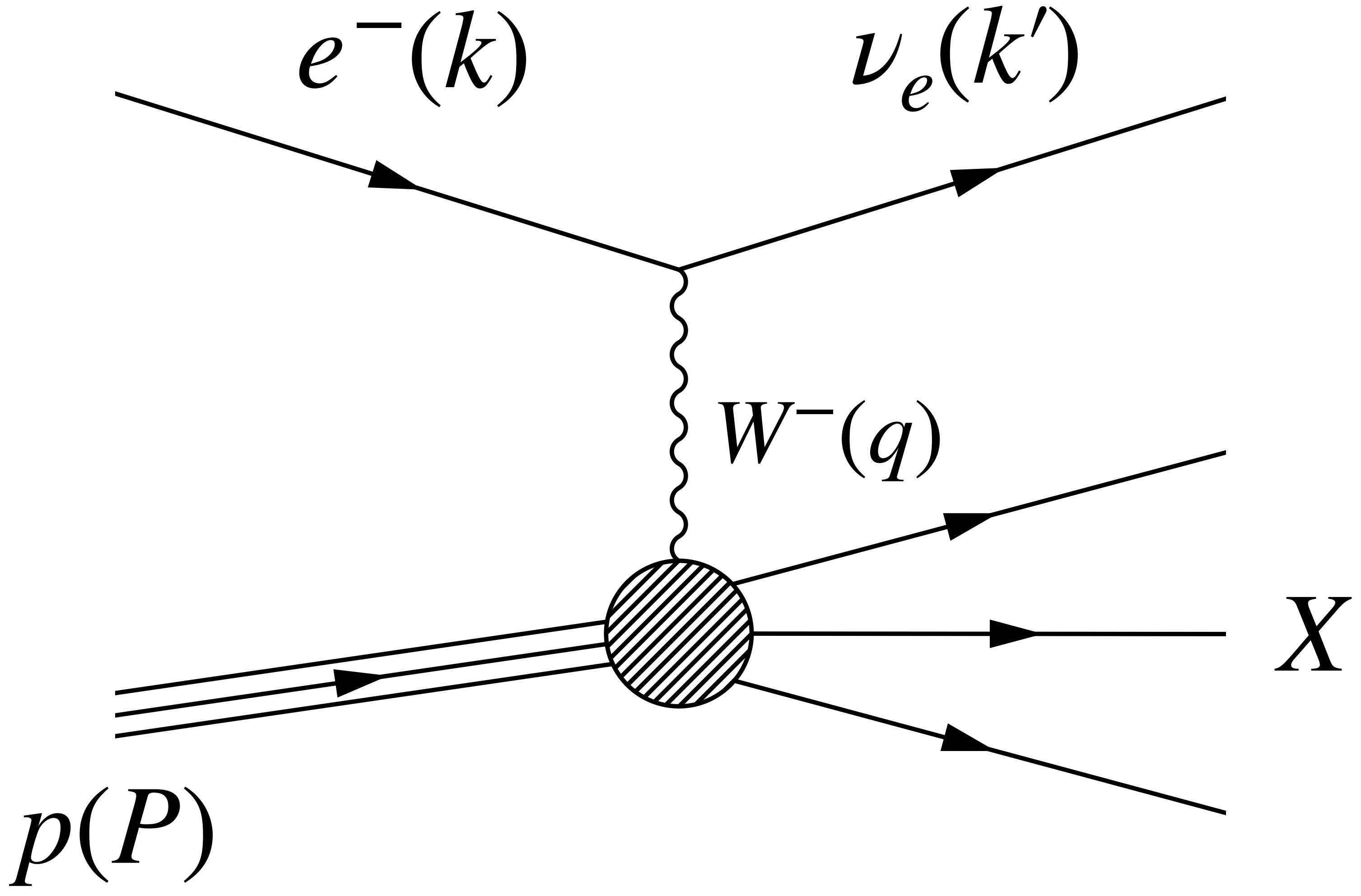


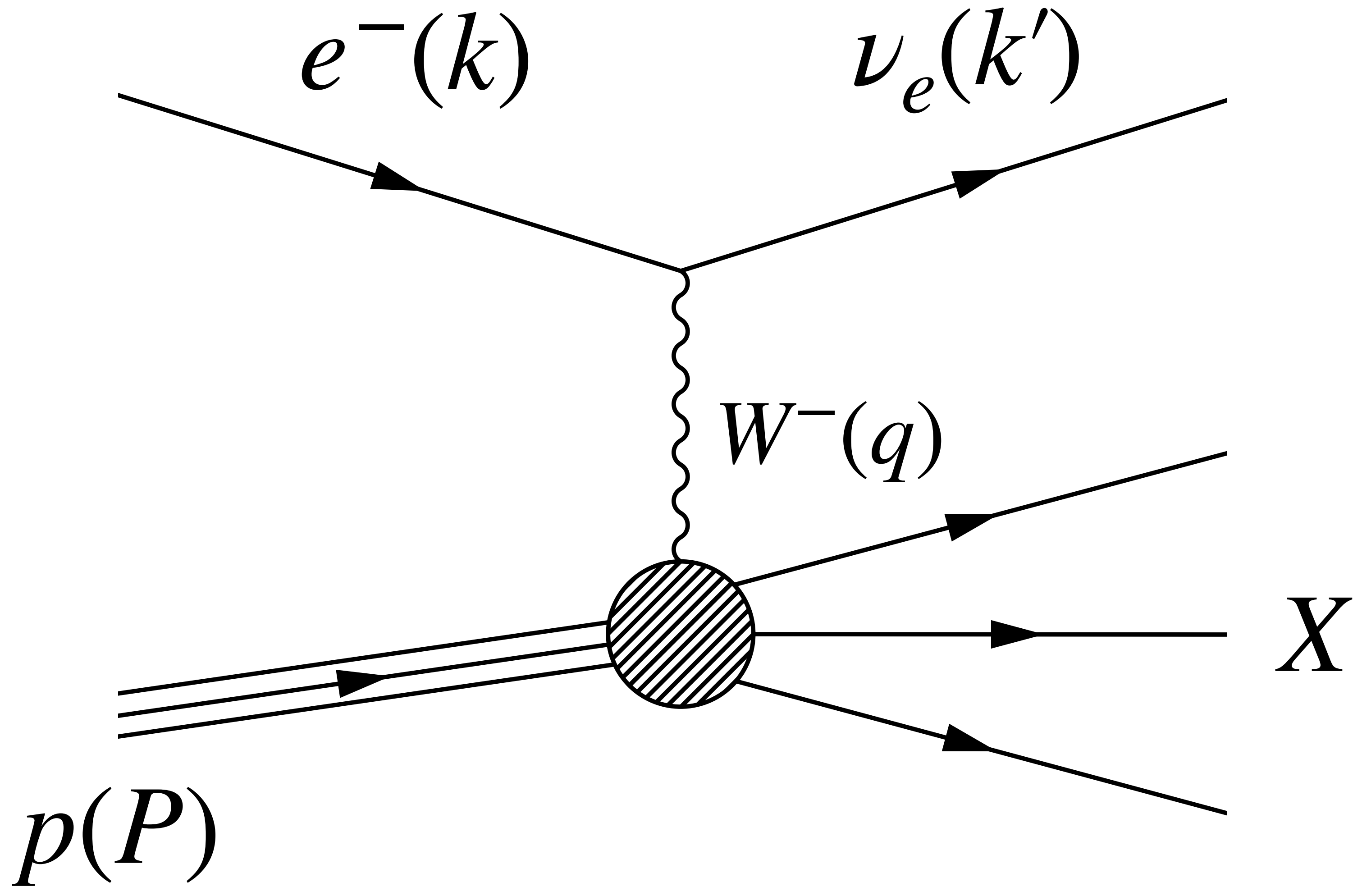
Charged-current DIS



$$\frac{\mathrm{d}\sigma_{CC}^{\pm}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xyQ^4}(1 \pm \lambda_e)\eta_W \left[Y_+ F_2^W \mp Y_- x F_3^W - y^2 F_L^W\right]$$

$$\eta_W = \frac{1}{2}\left(\frac{G_F M_Z^2}{4\pi\alpha}\frac{Q^2}{Q^2 + M_W^2}\right)^2$$

Charged-current DIS



$$\frac{\mathrm{d}\sigma^{\pm}_{CC}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xyQ^4}(1 \pm \lambda_e)\eta_W \left[Y_+ F_2^W \mp Y_- x F_3^W - y^2 F_L^W\right]$$

$$\eta_W = \frac{1}{2}\left(\frac{G_F M_Z^2}{4\pi\alpha}\frac{Q^2}{Q^2 + M_W^2}\right)^2$$

$$F_2^{W^-} = 2x(u + \bar{d} + \bar{s} + c \ldots)$$

$$F_3^{W^-} = 2(u - \bar{d} - \bar{s} + c \ldots)$$

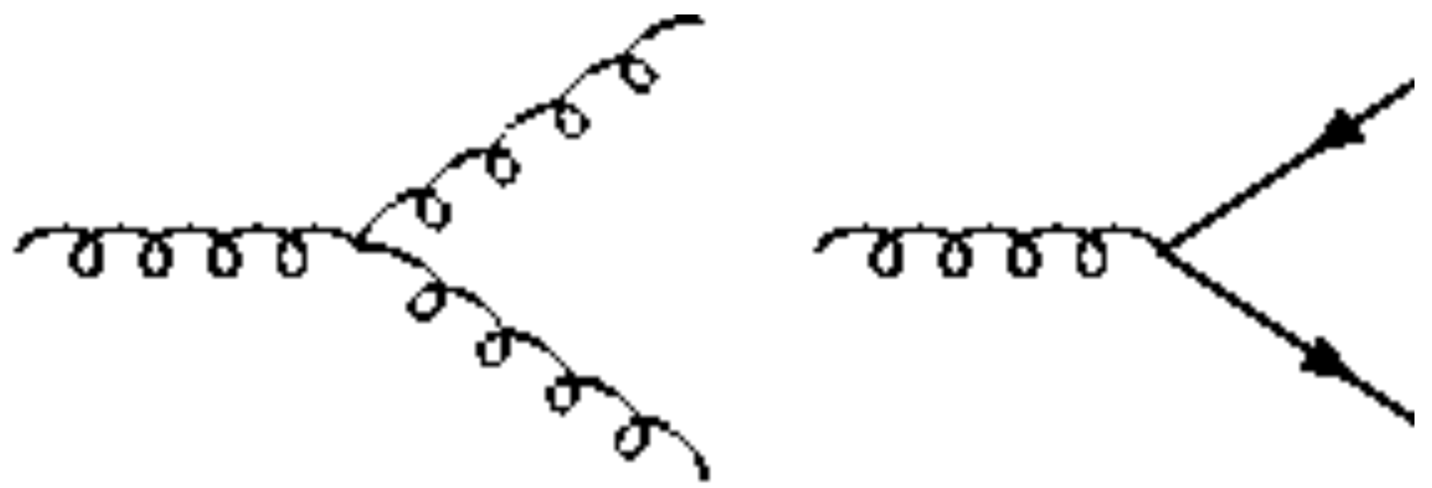
$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c \ldots)$$

$$g_5^{W^-} = (-\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c \ldots)$$

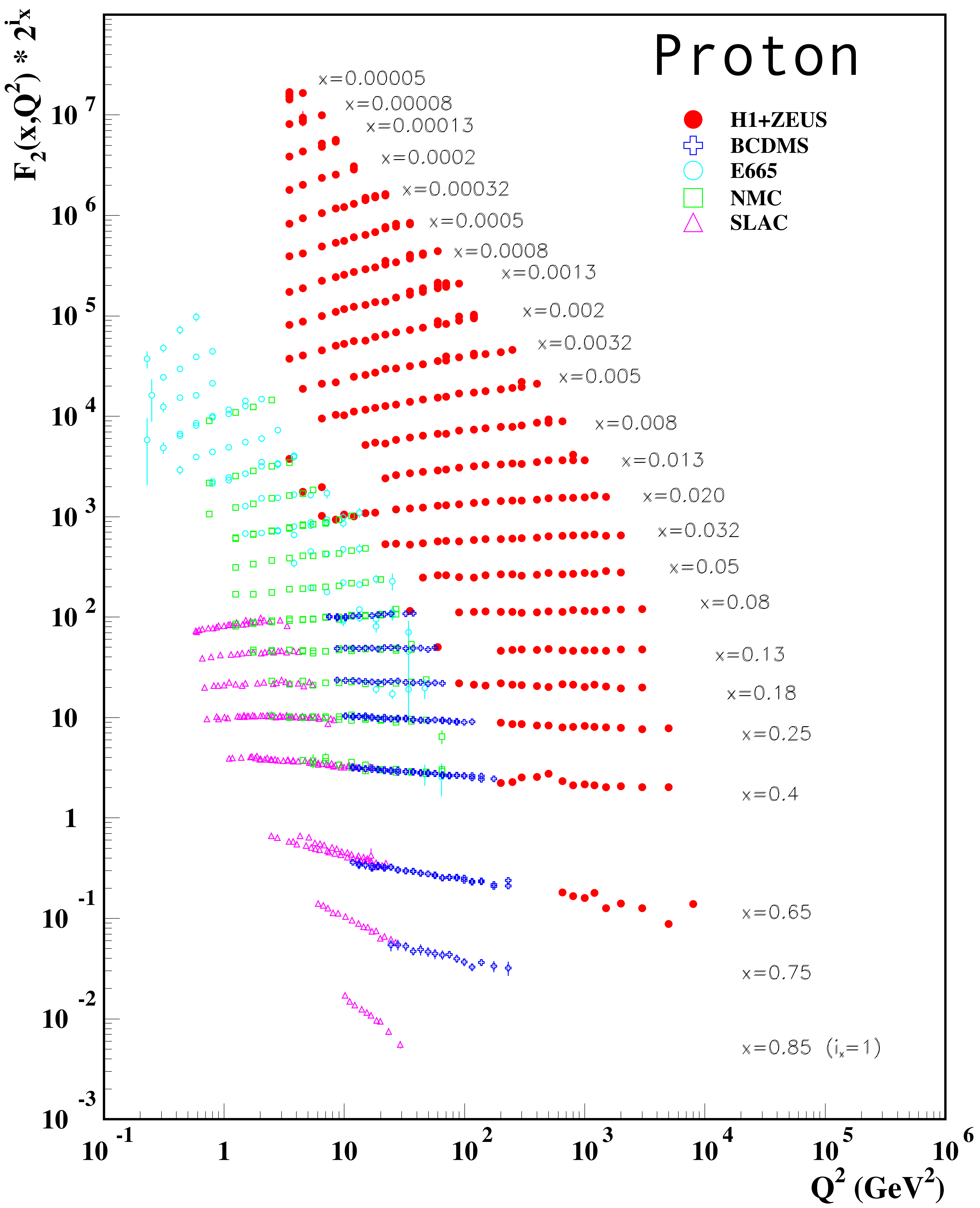
- Structure functions for W^+ exchange: $u \leftrightarrow d, s \leftrightarrow c$
- Unique combinations of PDFs → flavor separation

Real world: QCD violates scaling

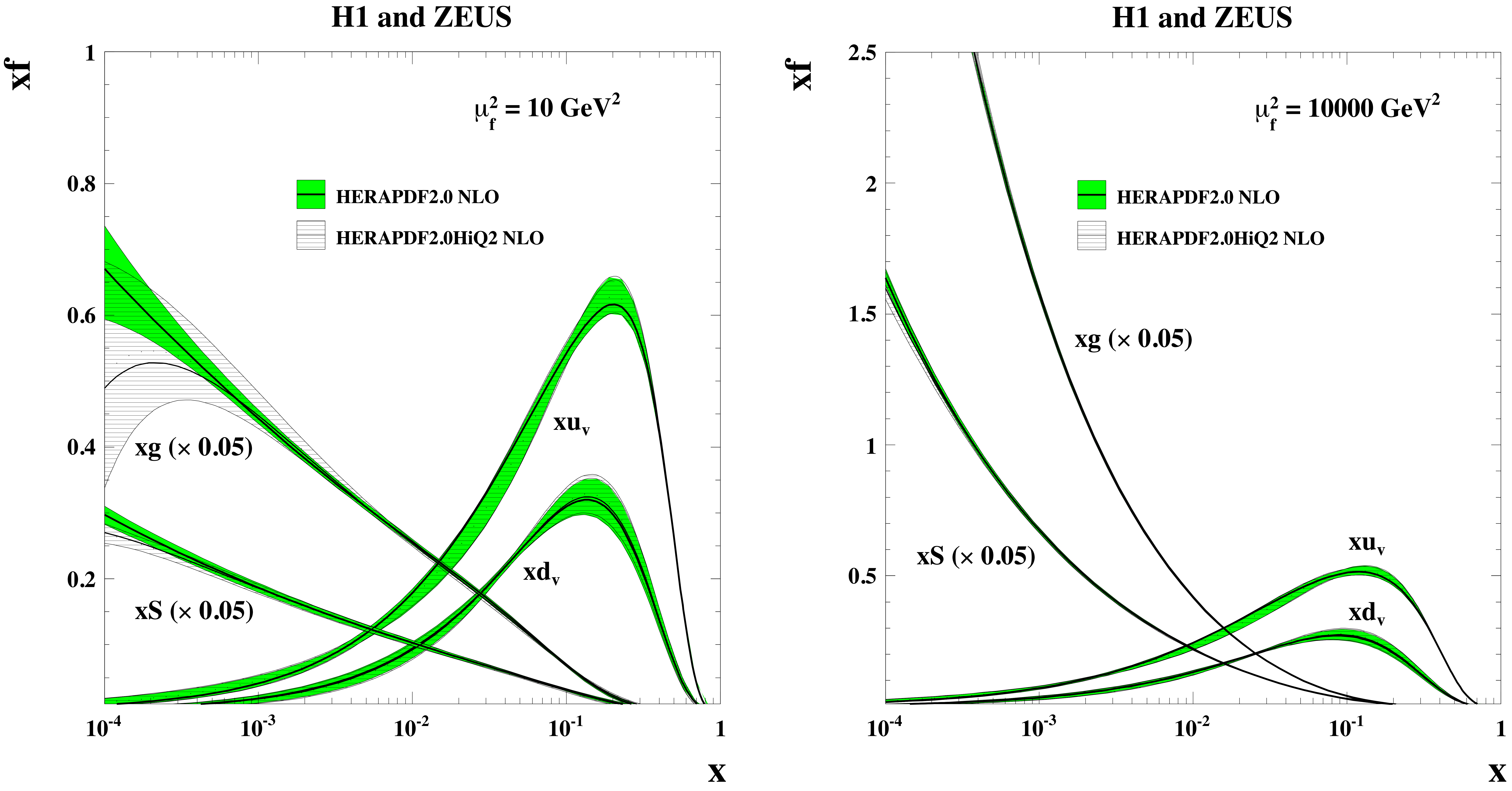
- *The quark-parton model ignores gluons!*
- Gluonic processes lead to large Q^2 dependence of cross sections, PDFs



- DGLAP equations beautifully describe evolution of PDFs with Q^2
  ...but cannot predict PDFs *a priori*



Scale dependence of PDFs



- High x_B dominated by valence quarks
- Low x_B, high Q^2 dominated by gluons (and sea quarks)

[Visualizing the proton]

Most of proton spin unaccounted for!

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

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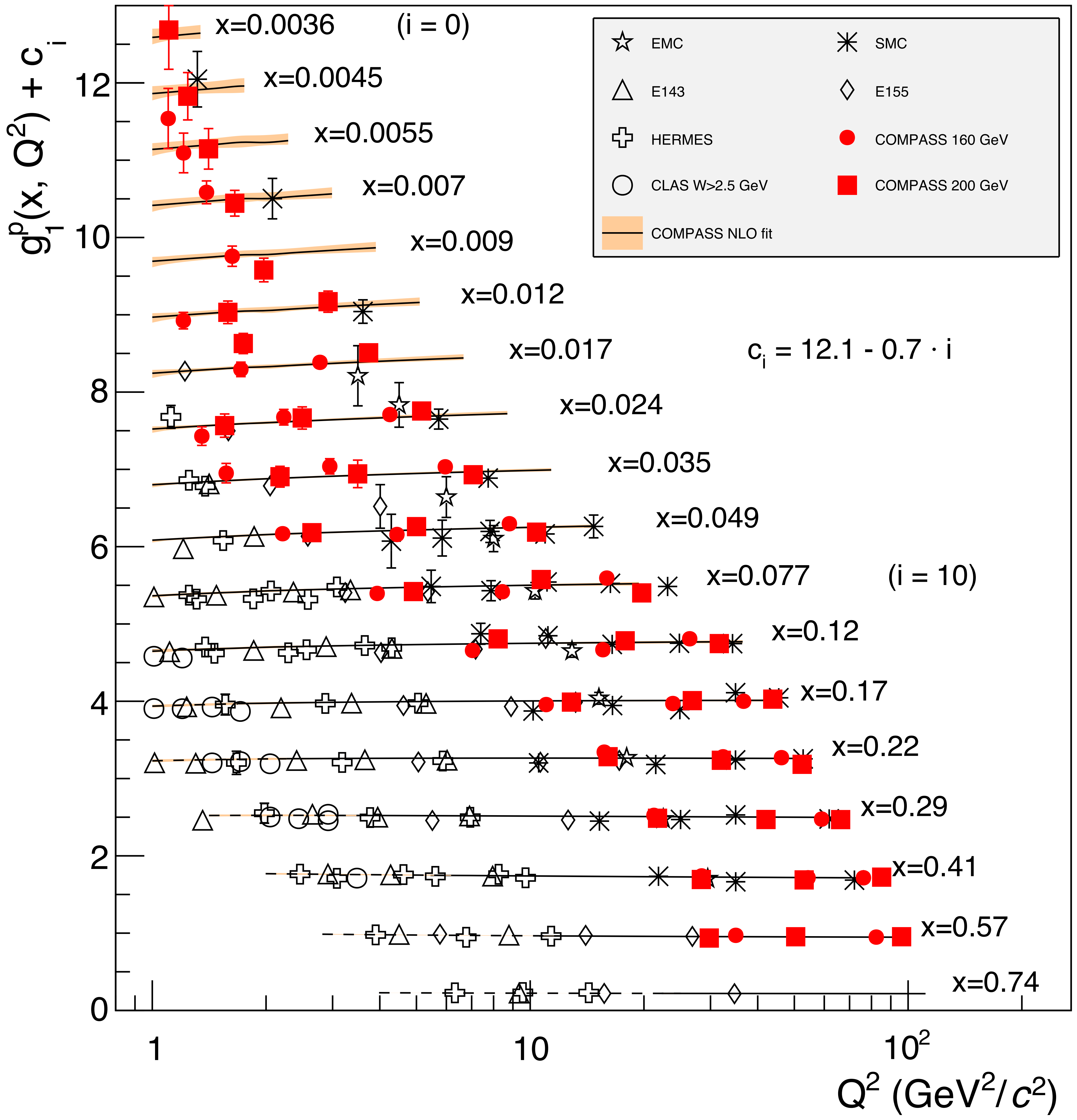
$$\Delta\Sigma/2 + \Delta G + L_q + L_g = \frac{1}{2}$$

COMPASS PLB 753, 18 (2016)



Most of proton spin unaccounted for!

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

≈ 30%

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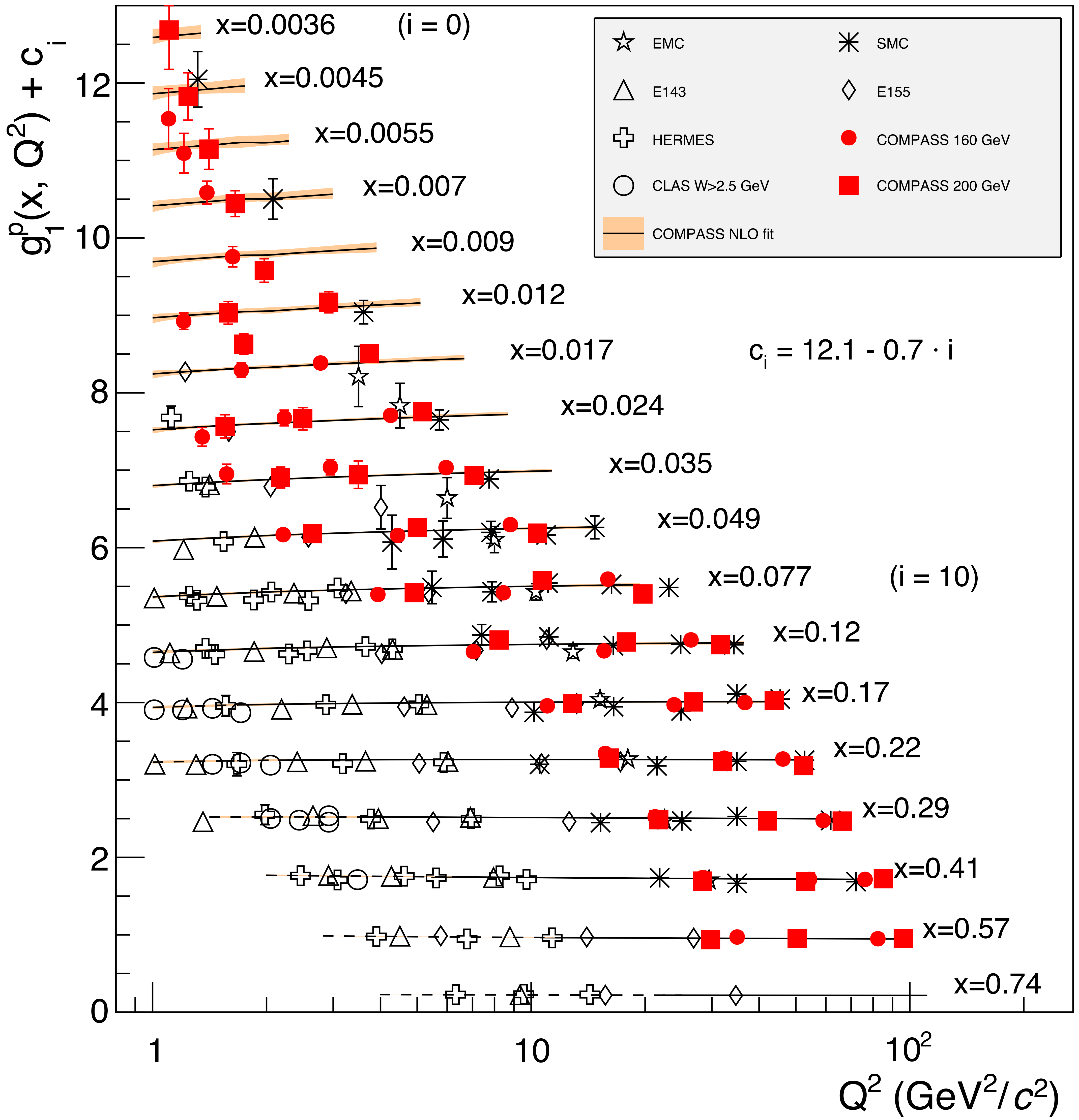

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≈ 40%?
Large
uncertainty!

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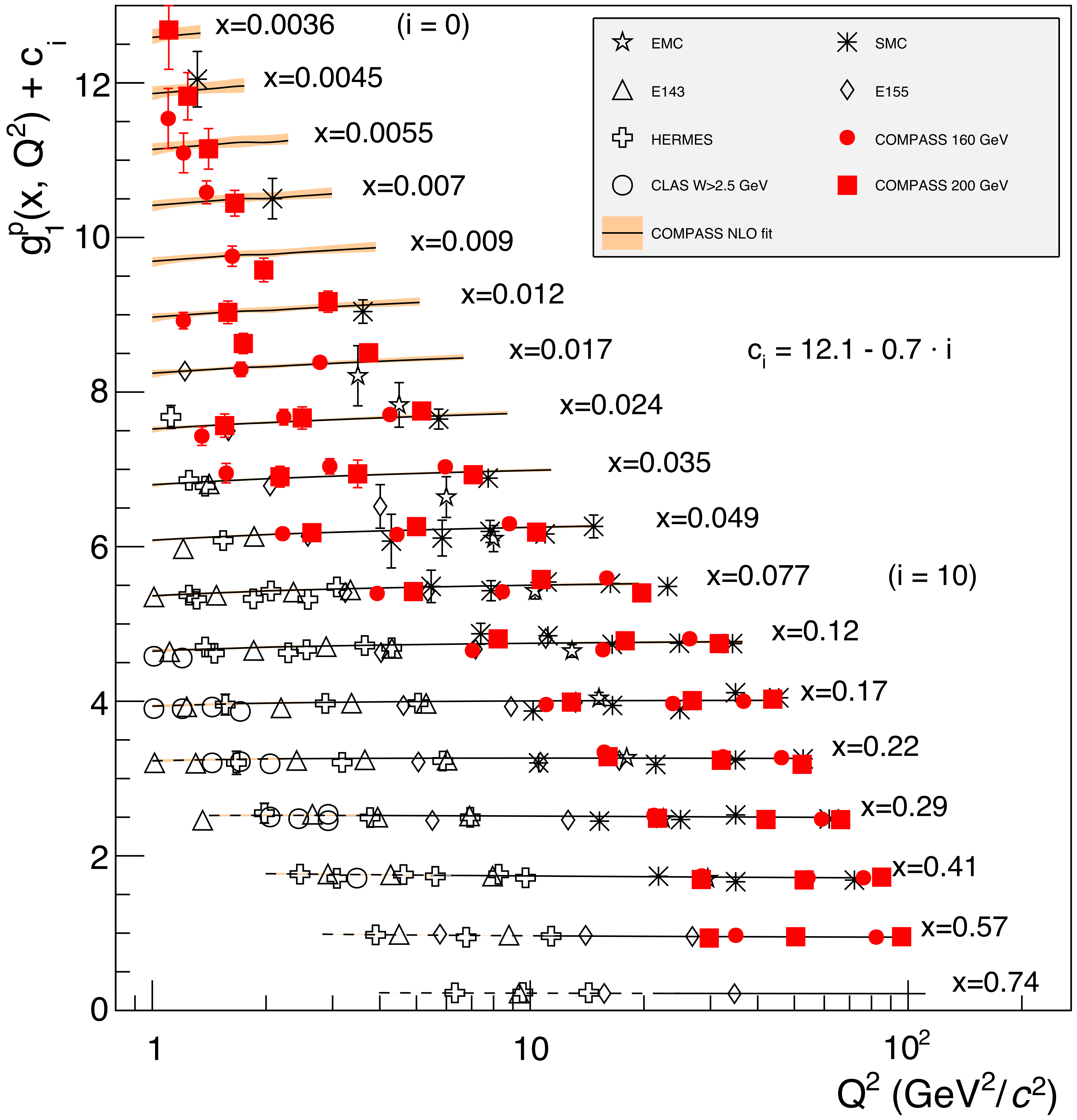

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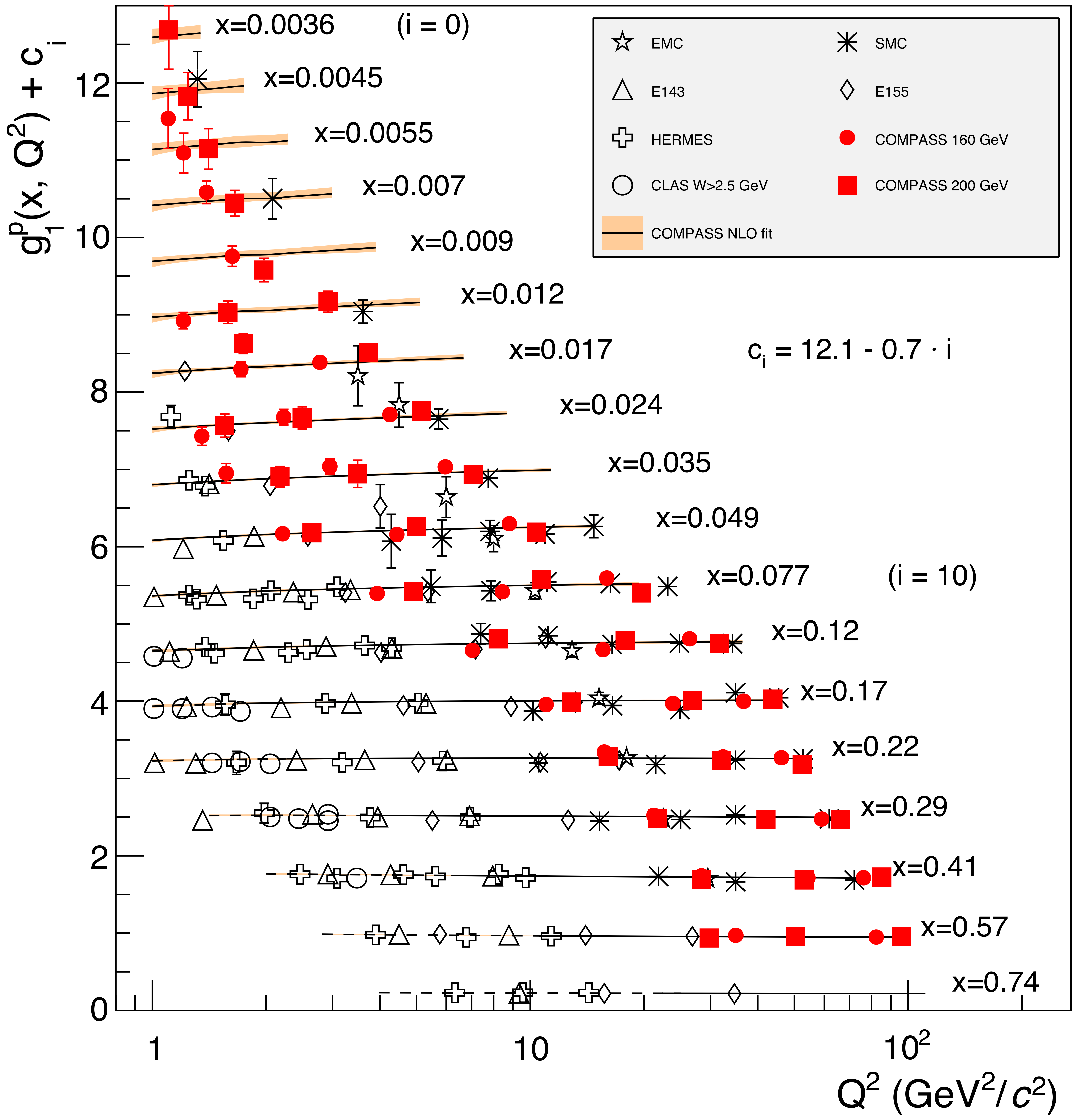

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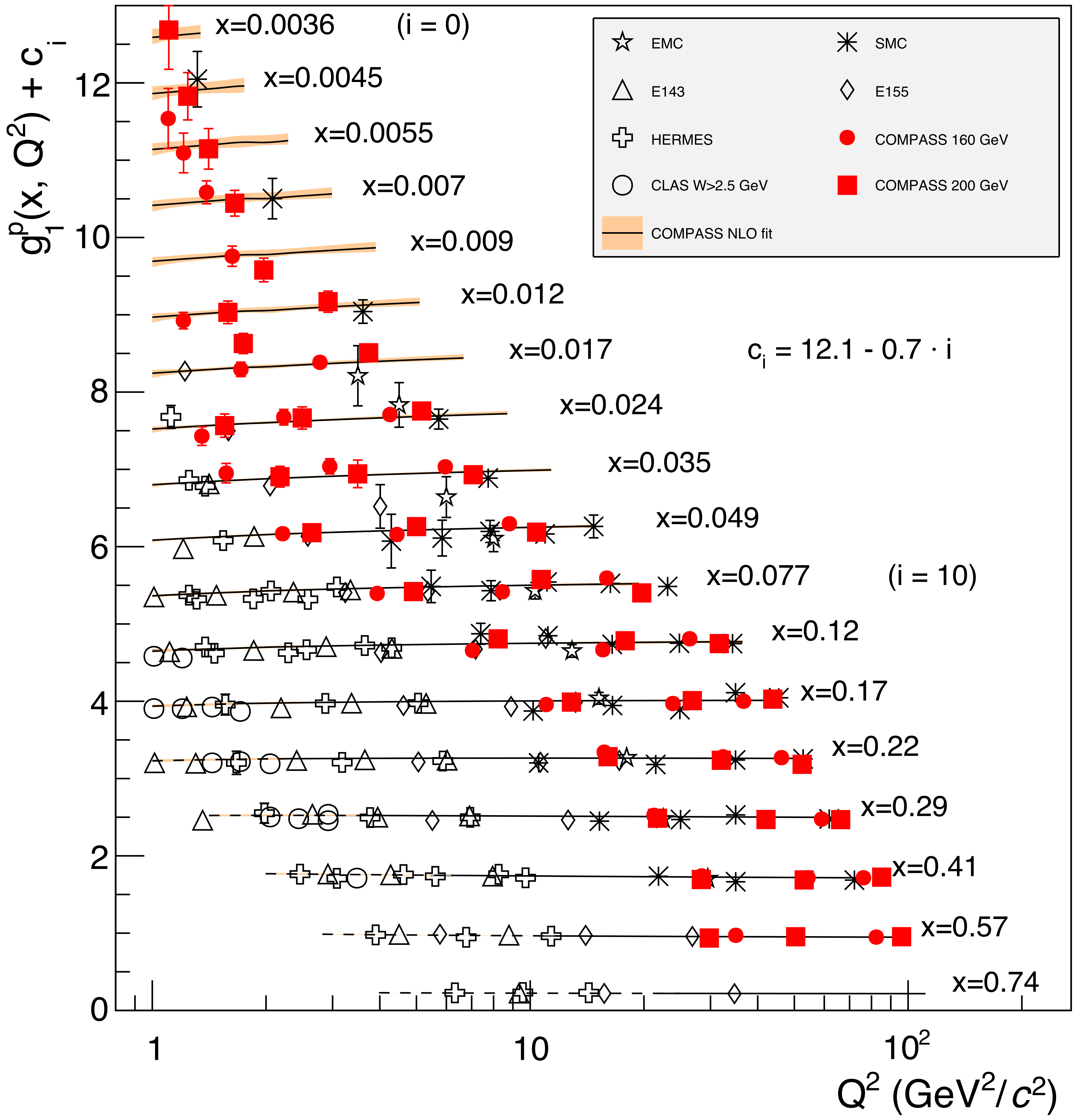
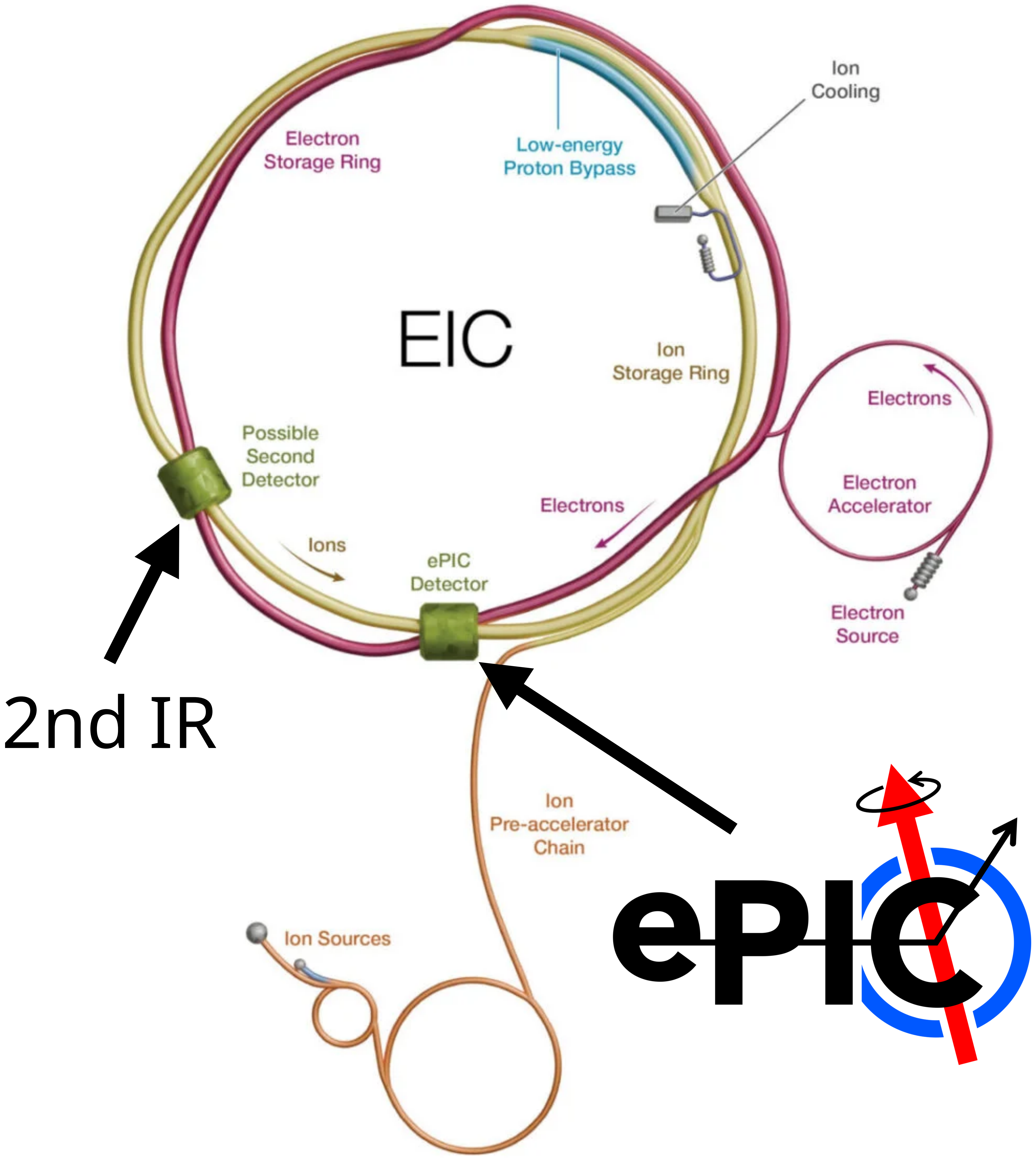
"Proton spin crisis"

COMPASS PLB 753, 18 (2016)

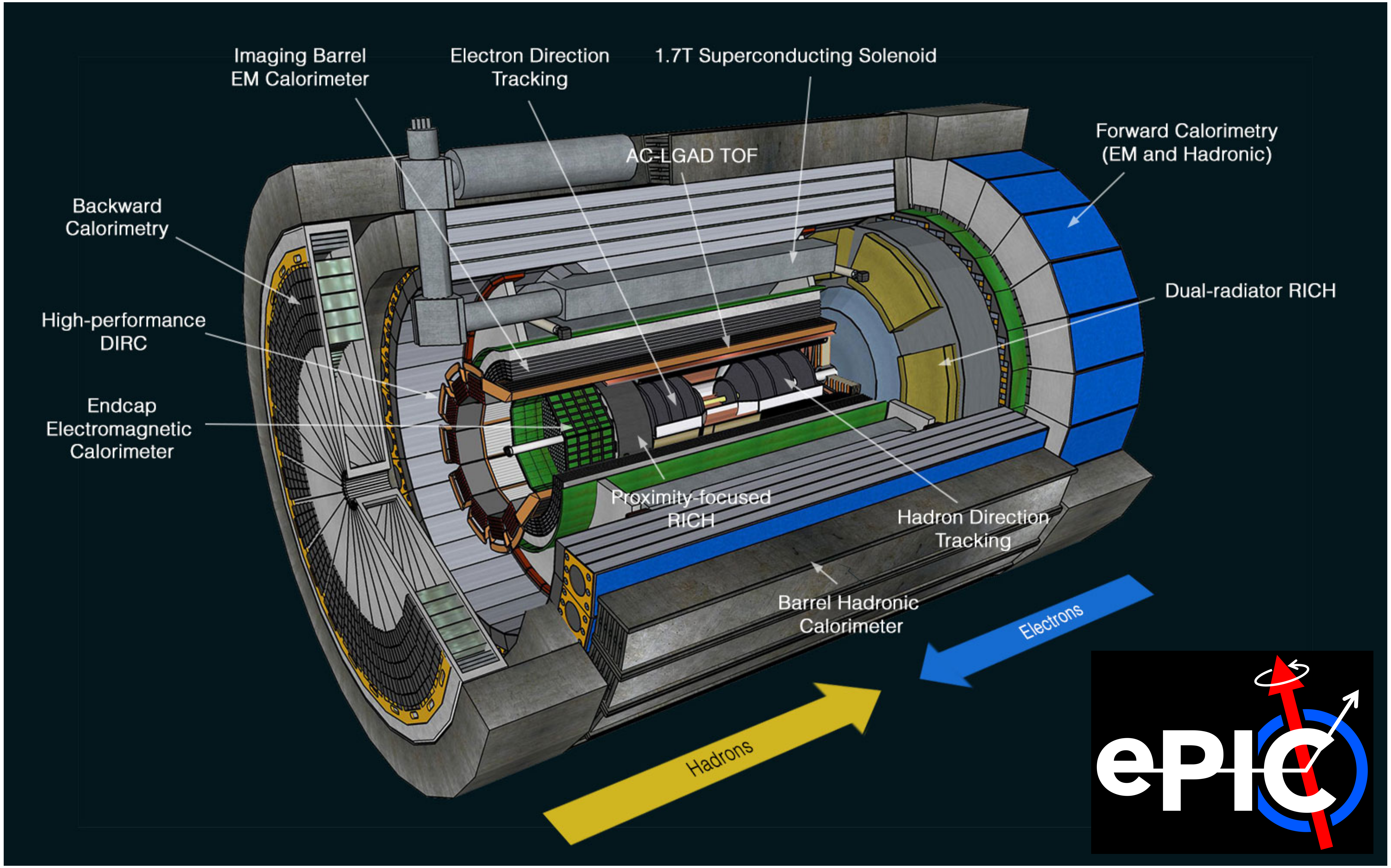


Electron-ion collider (Long Island, New York)

- Under construction at Brookhaven National Lab
- Fully polarized ep and eA collisions
- High luminosity!
- $20 < \sqrt{s} < 140$ GeV → wide range of x_B, Q^2!
- ePIC detector (project detector) under development
- Second interaction region for complementary detector



The ePIC detector



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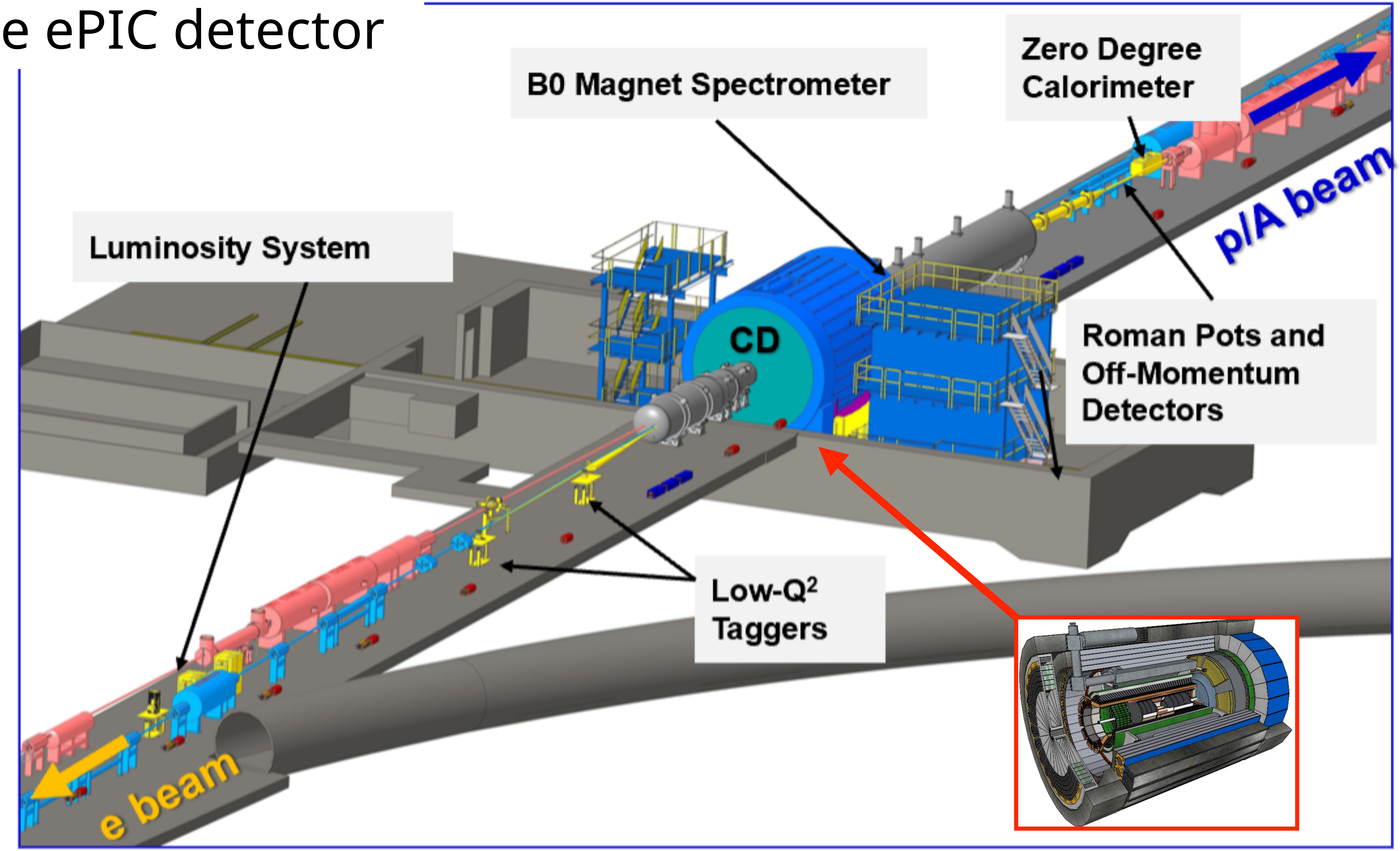
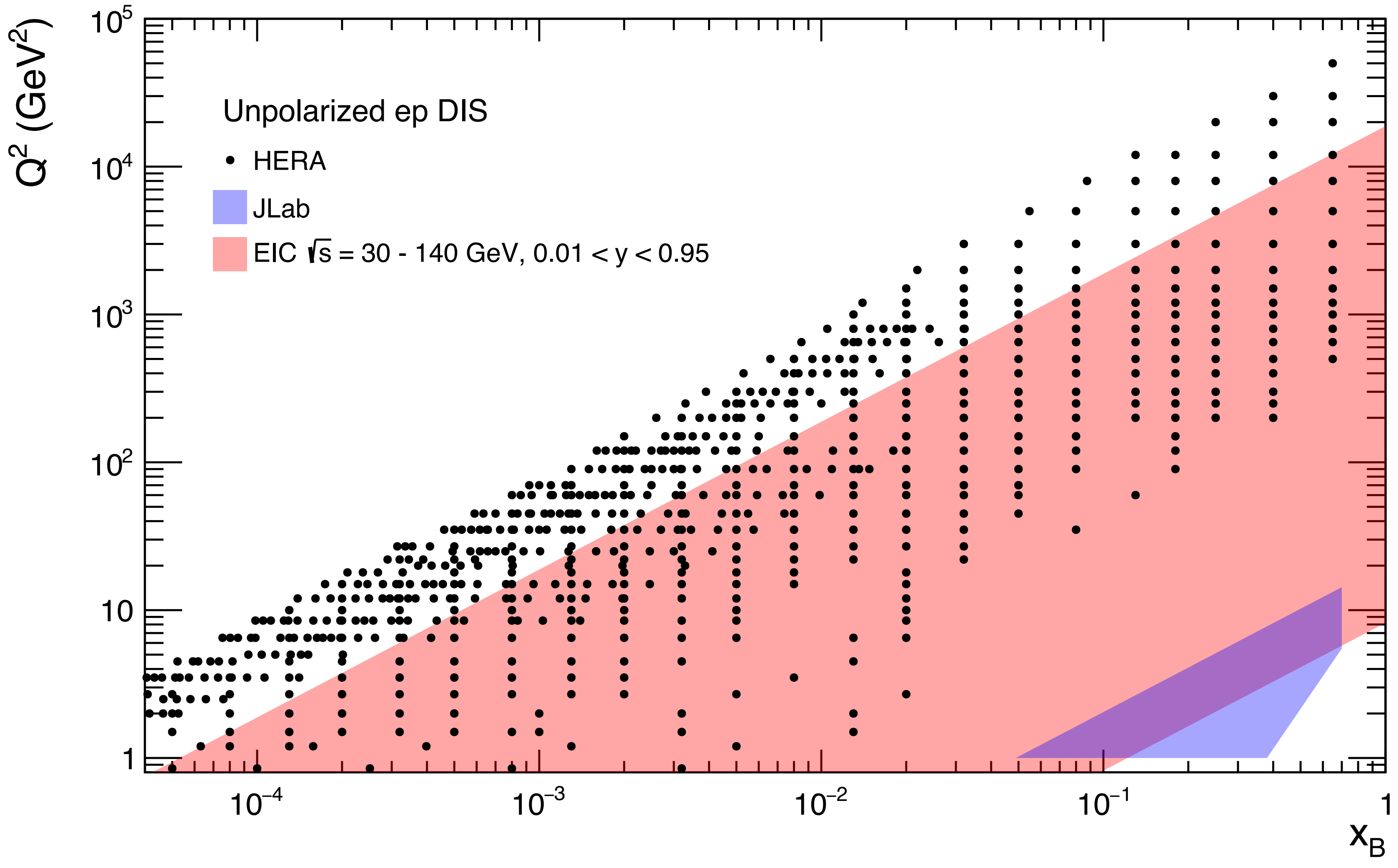


What can EIC add to the discussion?

- HERA was the original lepton-proton collider
- EIC limitations: smaller COM energy, no positrons (yet…)
- EIC advantages: larger luminosity, full polarization, heavy nuclei



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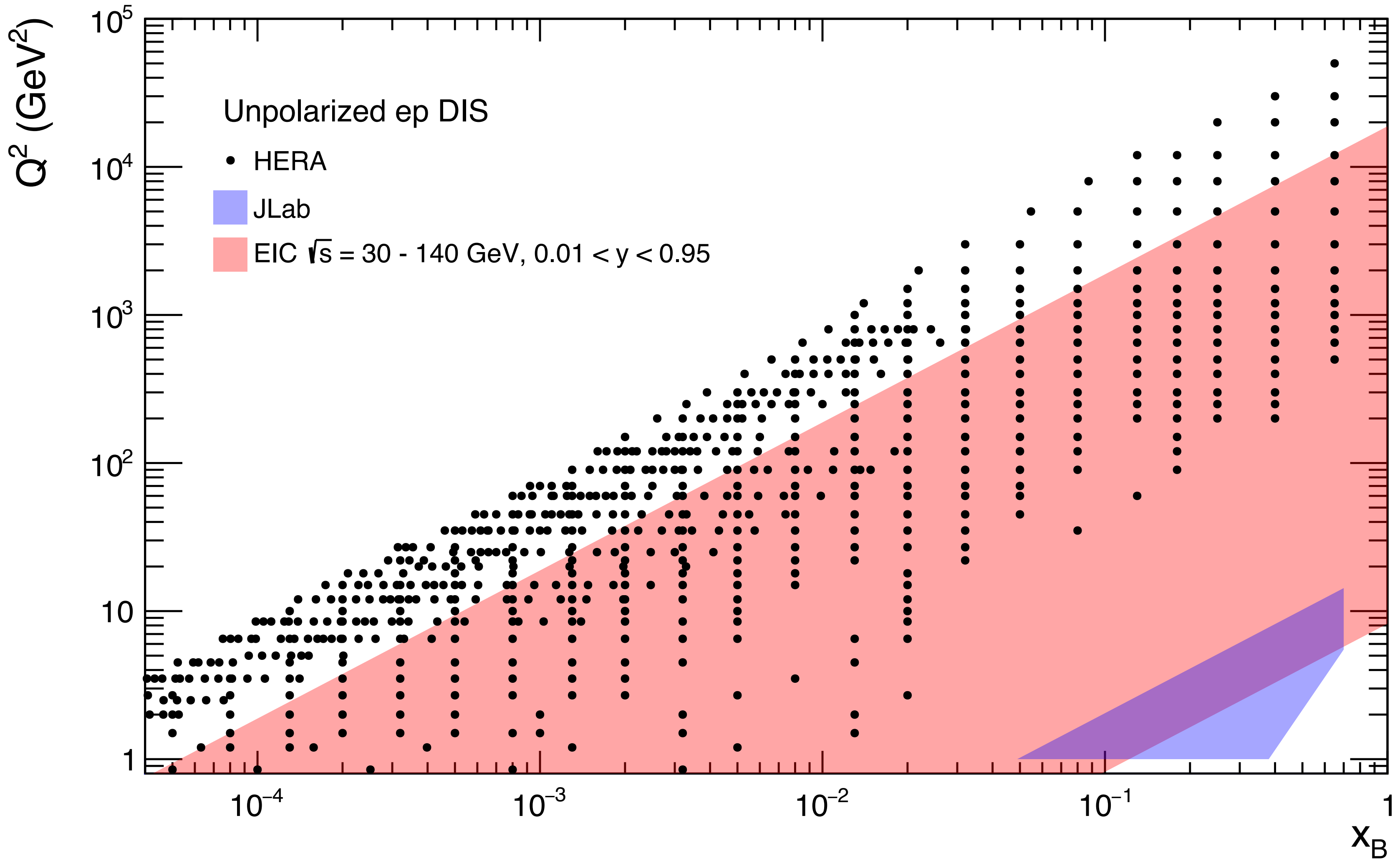

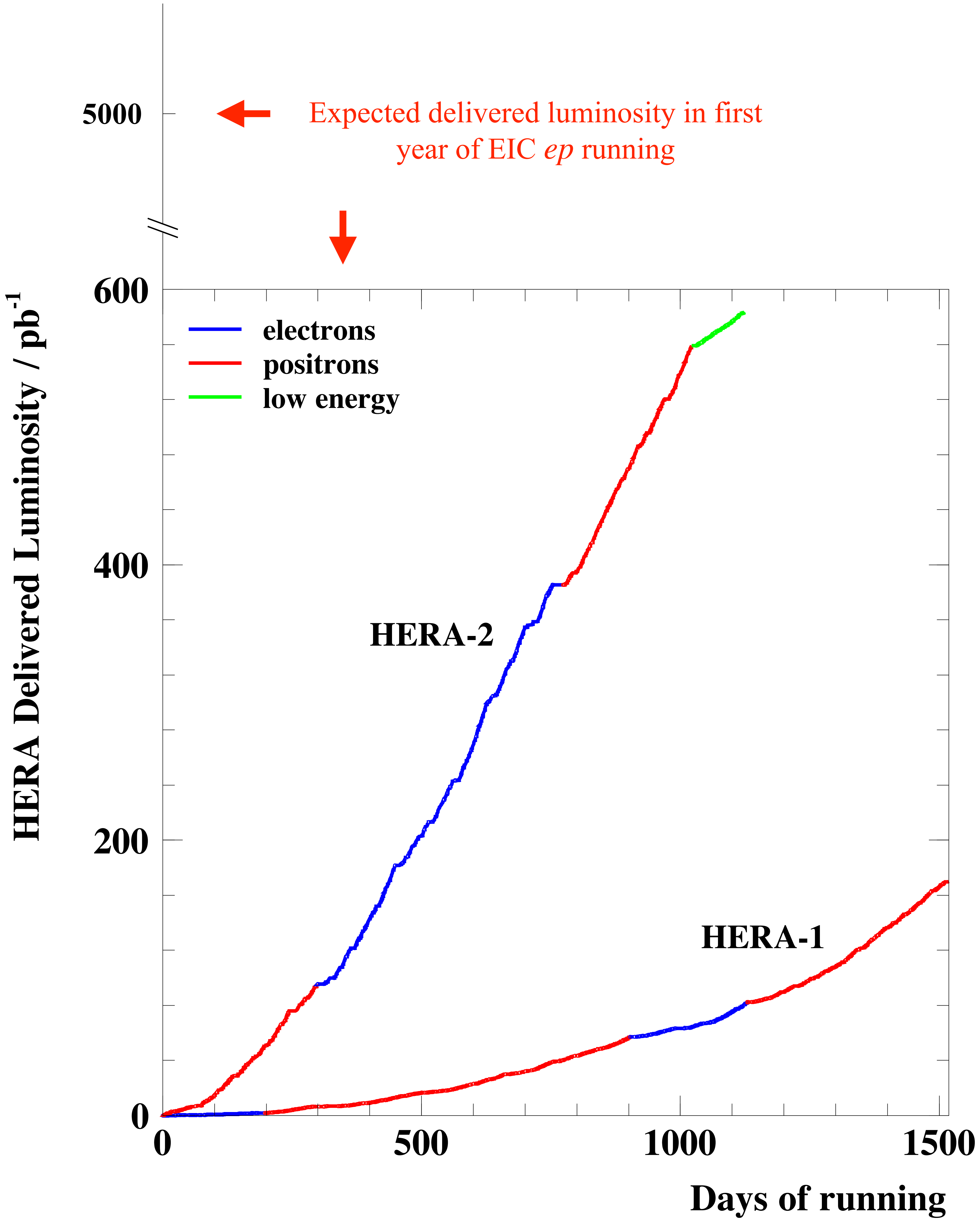

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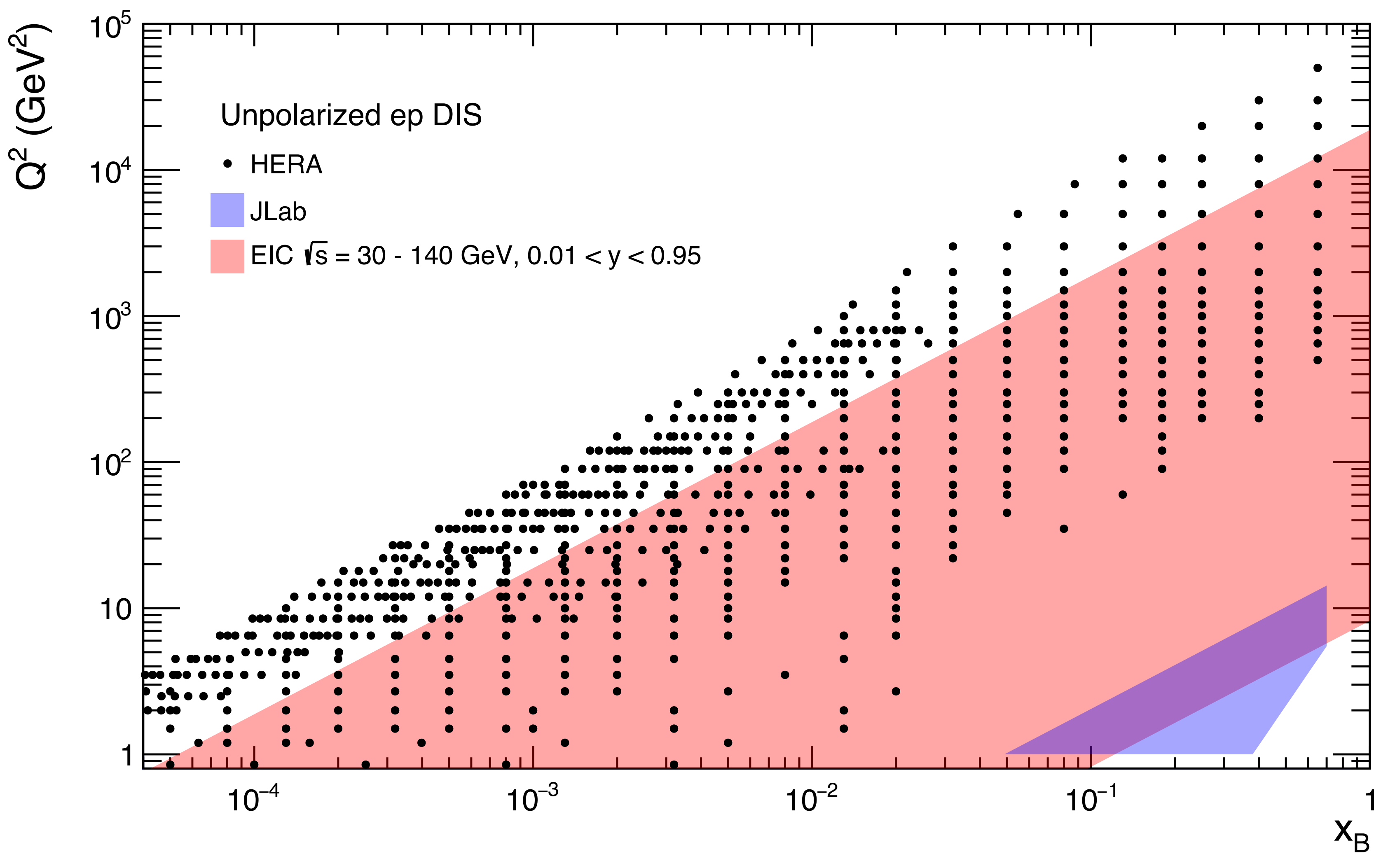
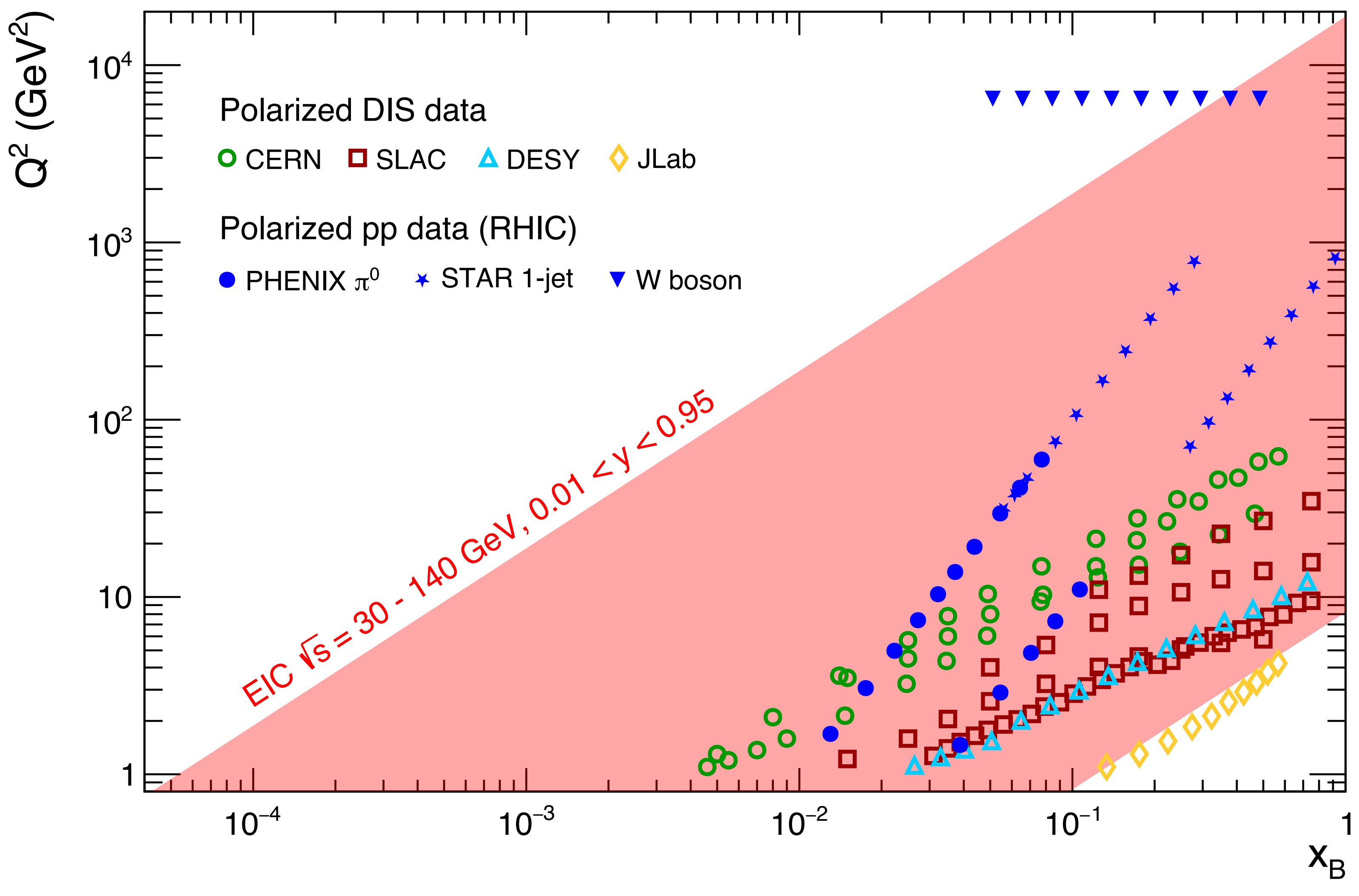
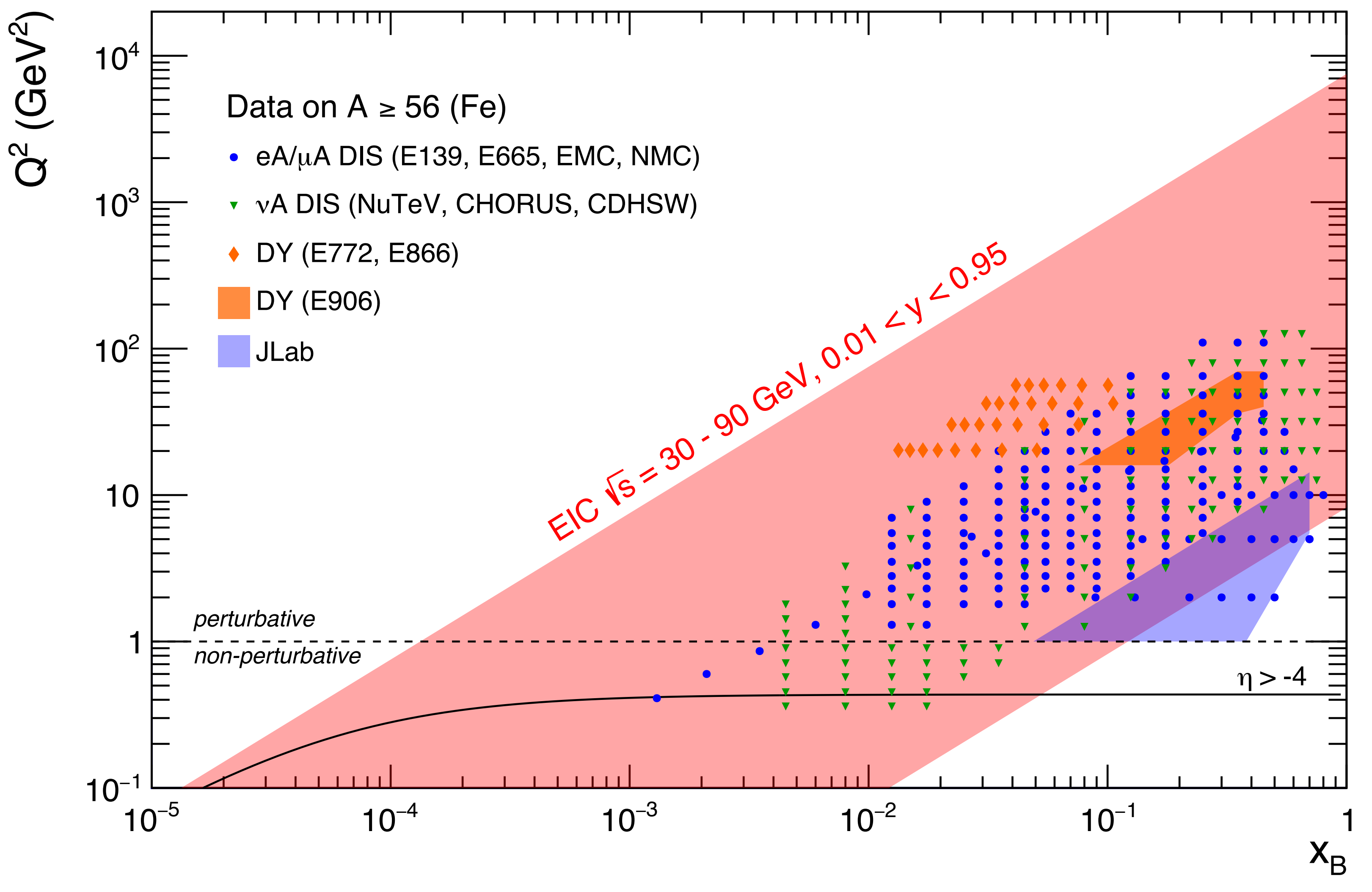
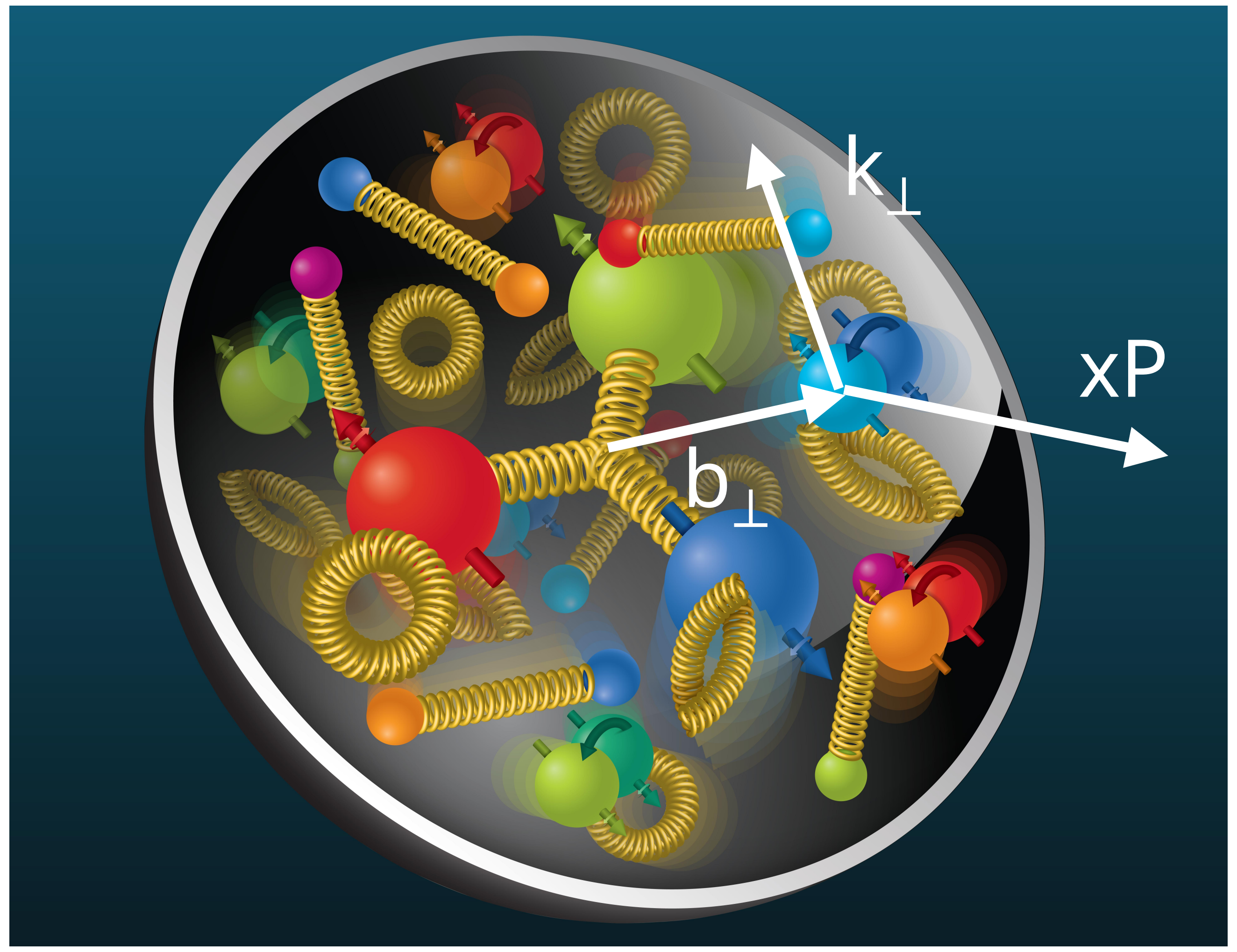


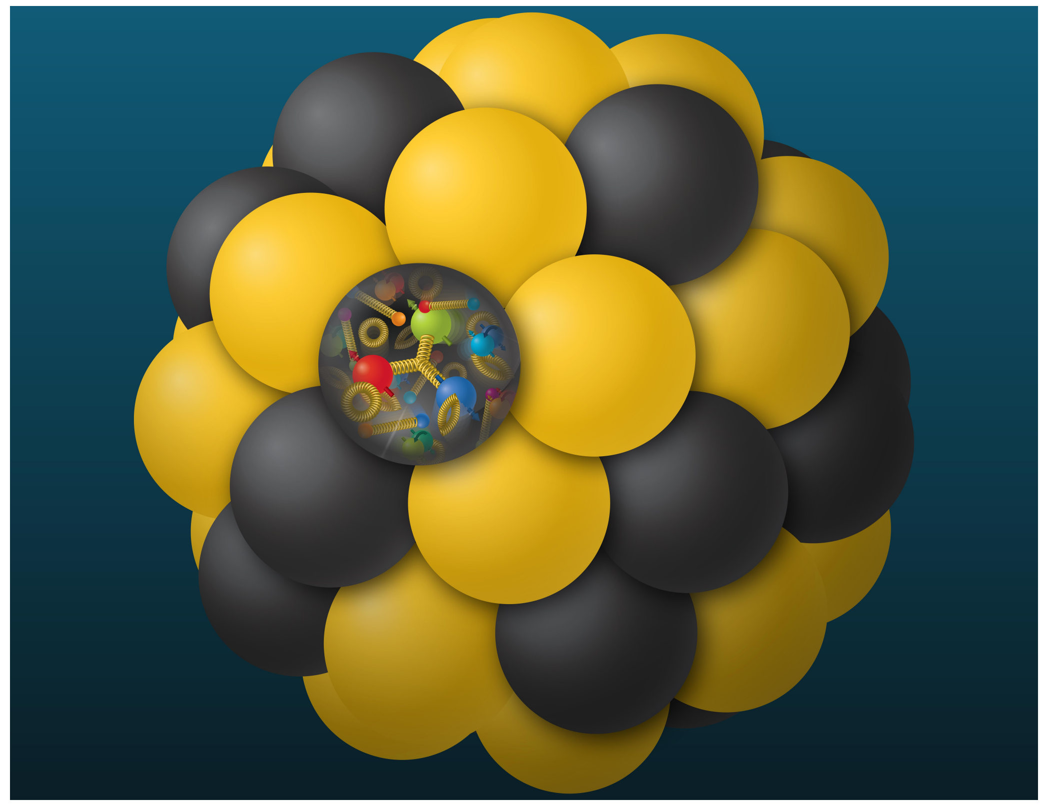


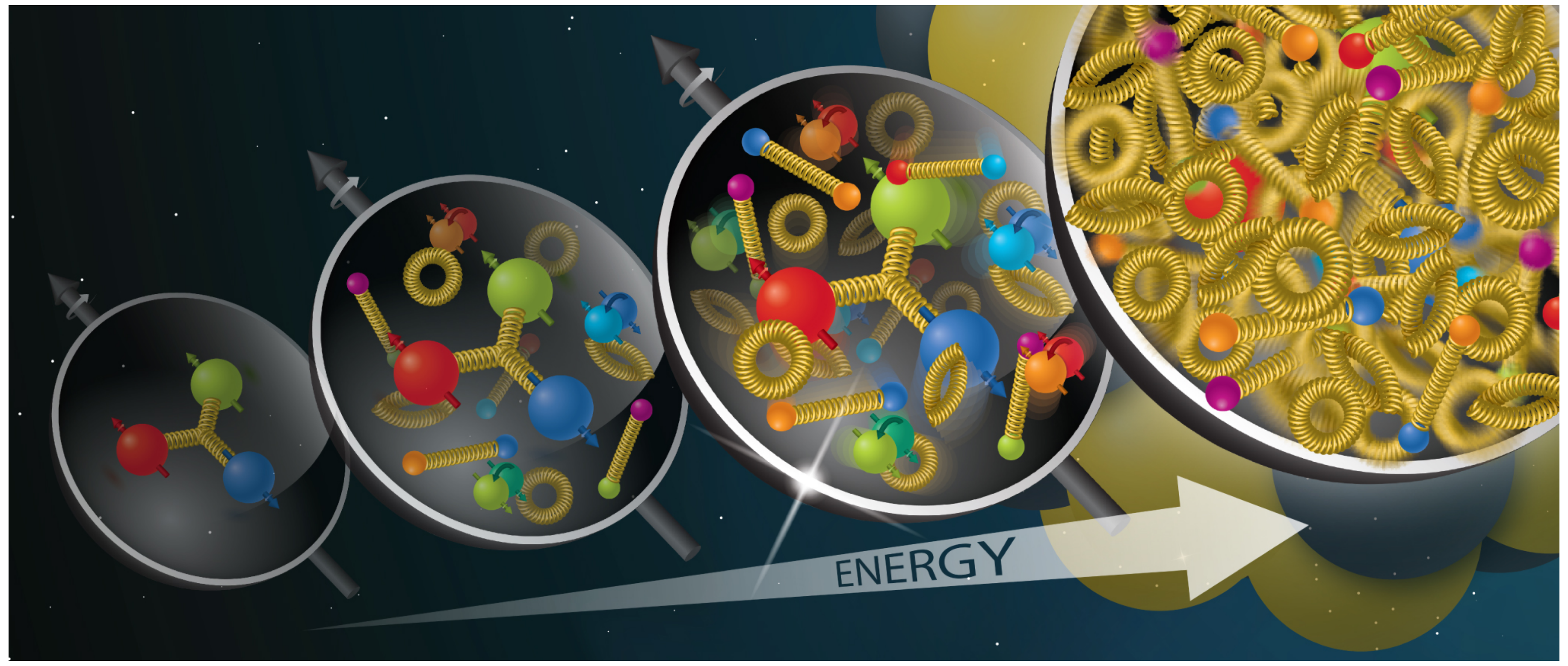


Physics goals of the EIC

- Origin of proton mass and spin
- 3D imaging of the nucleon
- Nuclear modification
- Gluon saturation







Probing proton spin with double-spin asymmetries

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

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

$$\approx g_1 / F_1 \propto \sum_q e_q^2 \left(\Delta q + \Delta\overline{q}\right)$$

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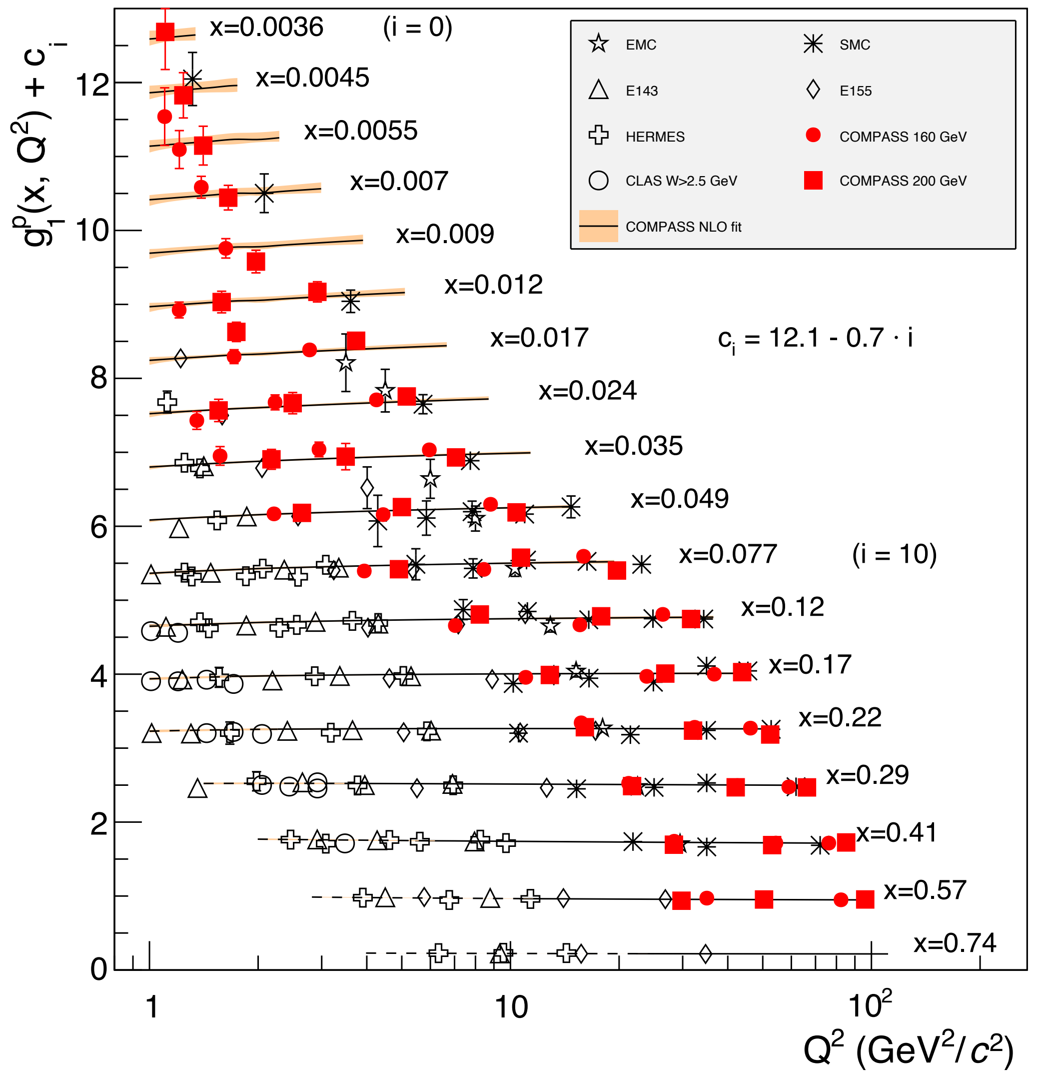
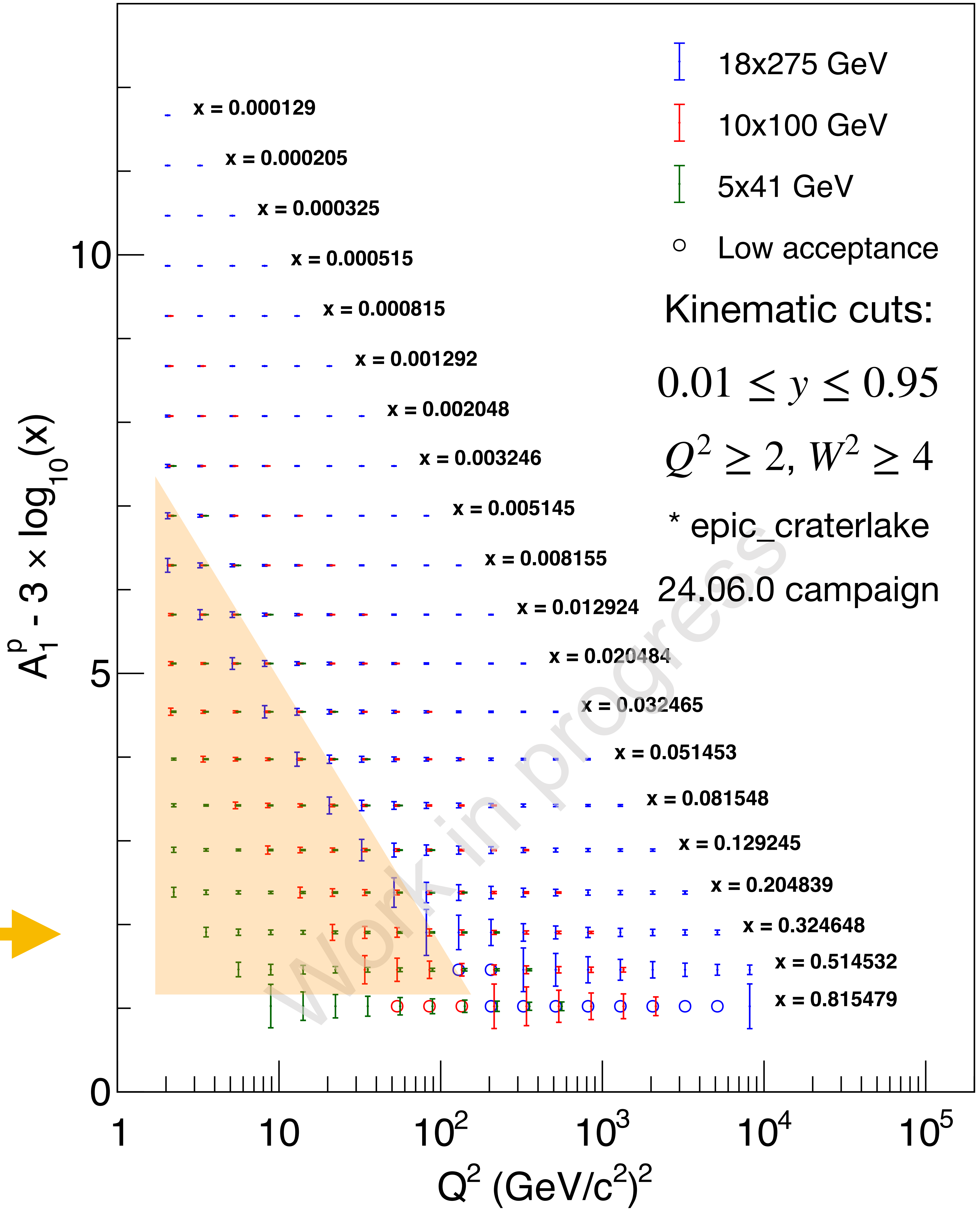
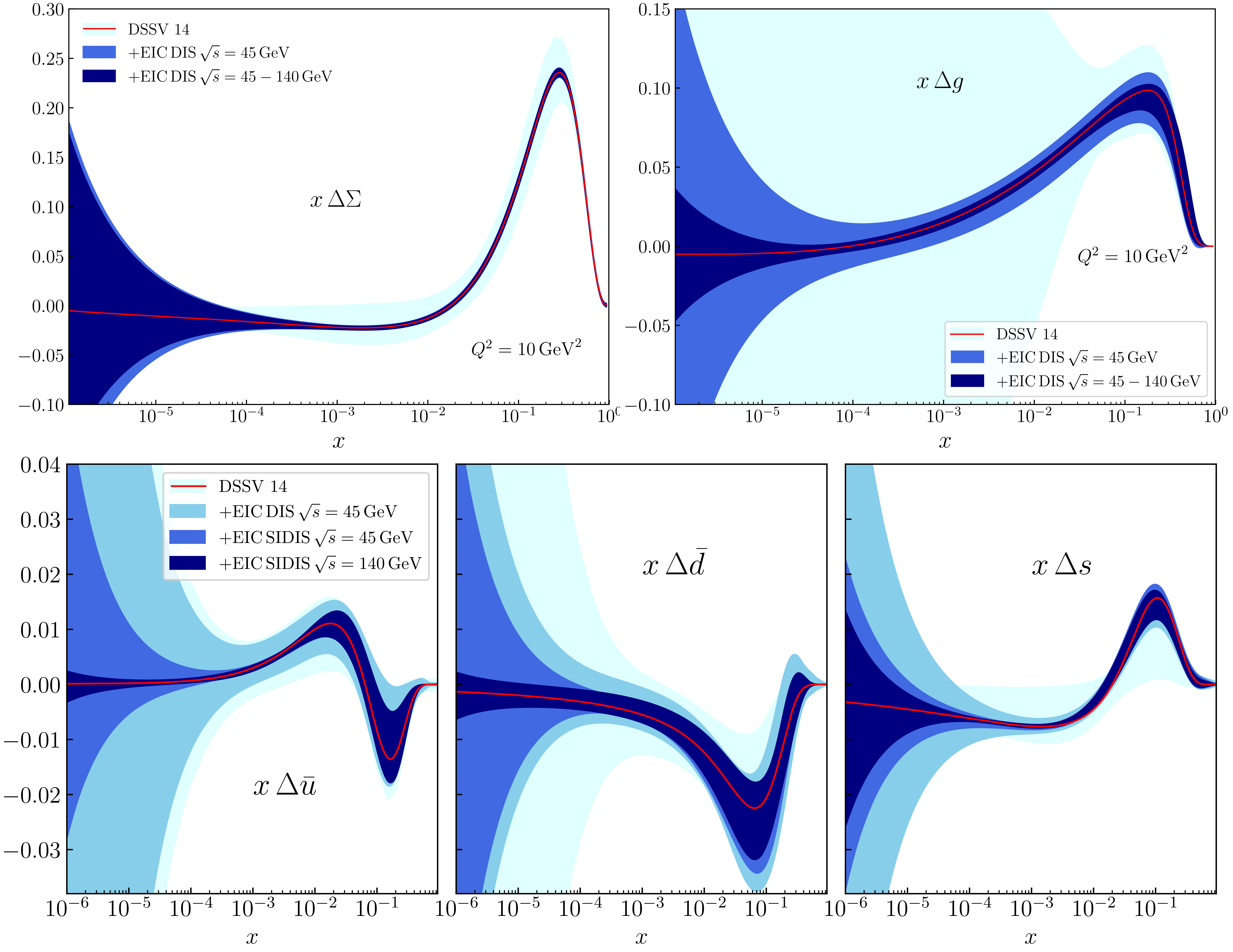




Impact of EIC measurements

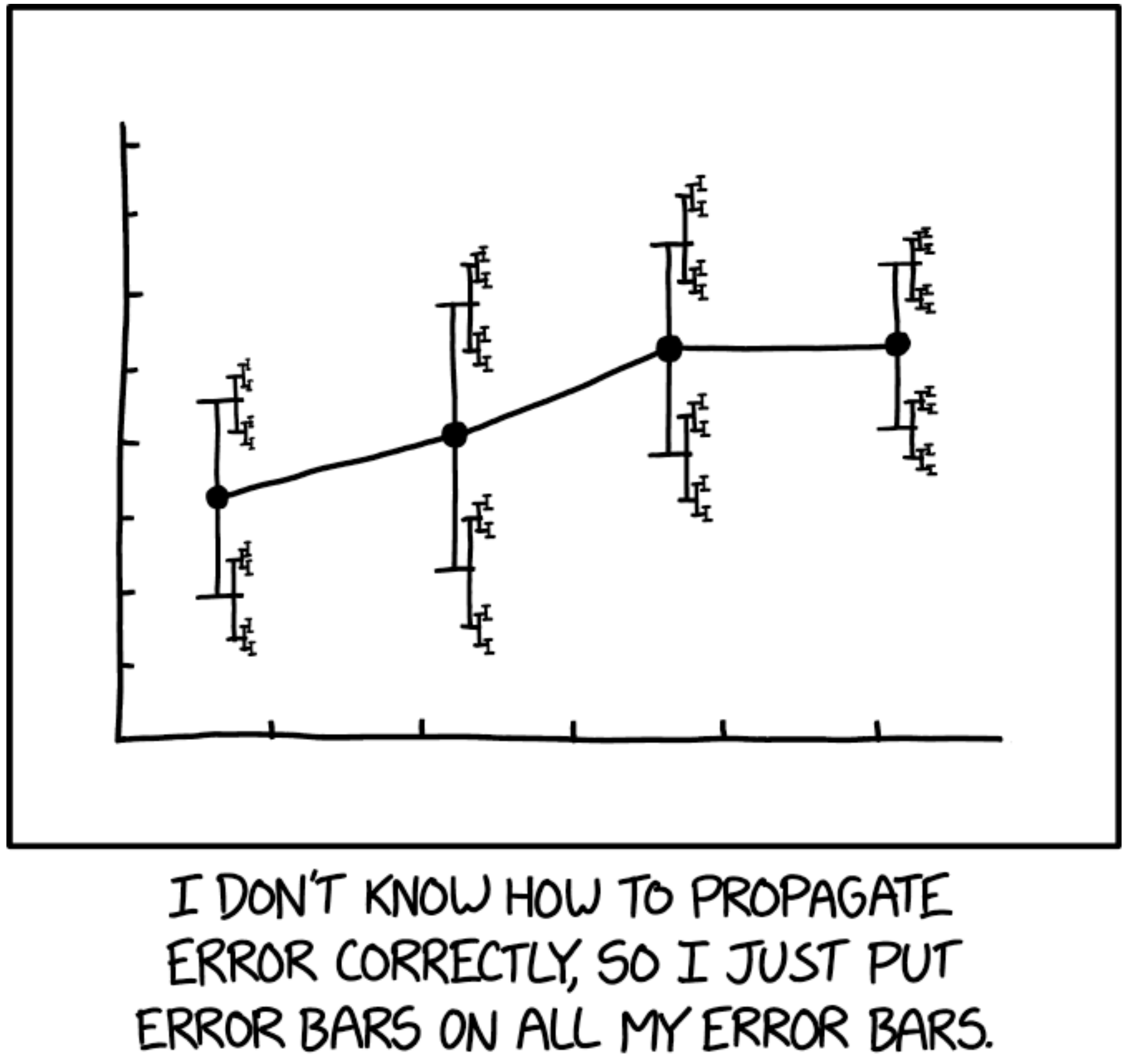


EIC will be *systematics limited*

- High luminosity means that statistical uncertainty will be negligible
- Physics impact will be limited by control of systematics

Key sources of systematics

- Kinematic reconstruction
  - Need high-resolution reconstruction of y, Q^2
- Electron identification
  - Minimize pion contamination
  - Reduce contamination in CC analyses



Hermetic detector allows reconstruction from entire final state

$$Q^2 = sxy, \quad s = (P+k)^2$$

Lepton

$E'_{e'}, \theta_e$

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Hermetic detector allows reconstruction from entire final state

$$Q^2 = sxy, \qquad s = (P+k)^2$$

Lepton

$$E'_e,\ \theta_e$$

Hadron

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

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

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

- Electron: $y_{elec} = \frac{P \cdot q}{P \cdot k}$ $\quad Q^2_{elec} = -(k-k')^2$
- Jacquet-Blondel: $y_{JB} = \frac{\delta_h}{2E_e}$ $\quad Q^2_{JB} = \frac{p_{T,h}^2}{1 - y_{JB}}$

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- Double-angle:

$$y_{DA} = \frac{\tan\left(\frac{\gamma_h}{2}\right)}{\tan\left(\frac{\theta_e}{2}\right) + \tan\left(\frac{\gamma_h}{2}\right)} \qquad Q^2_{JB} = \frac{4E_e^2 \cot\left(\frac{\theta_e}{2}\right)}{\tan\left(\frac{\theta_e}{2}\right) + \tan\left(\frac{\gamma_h}{2}\right)}$$

Hermetic detector allows reconstruction from entire final state

$$Q^2 = sxy, \quad s = (P+k)^2$$

Lepton

$$E'_e, \ \theta_e$$

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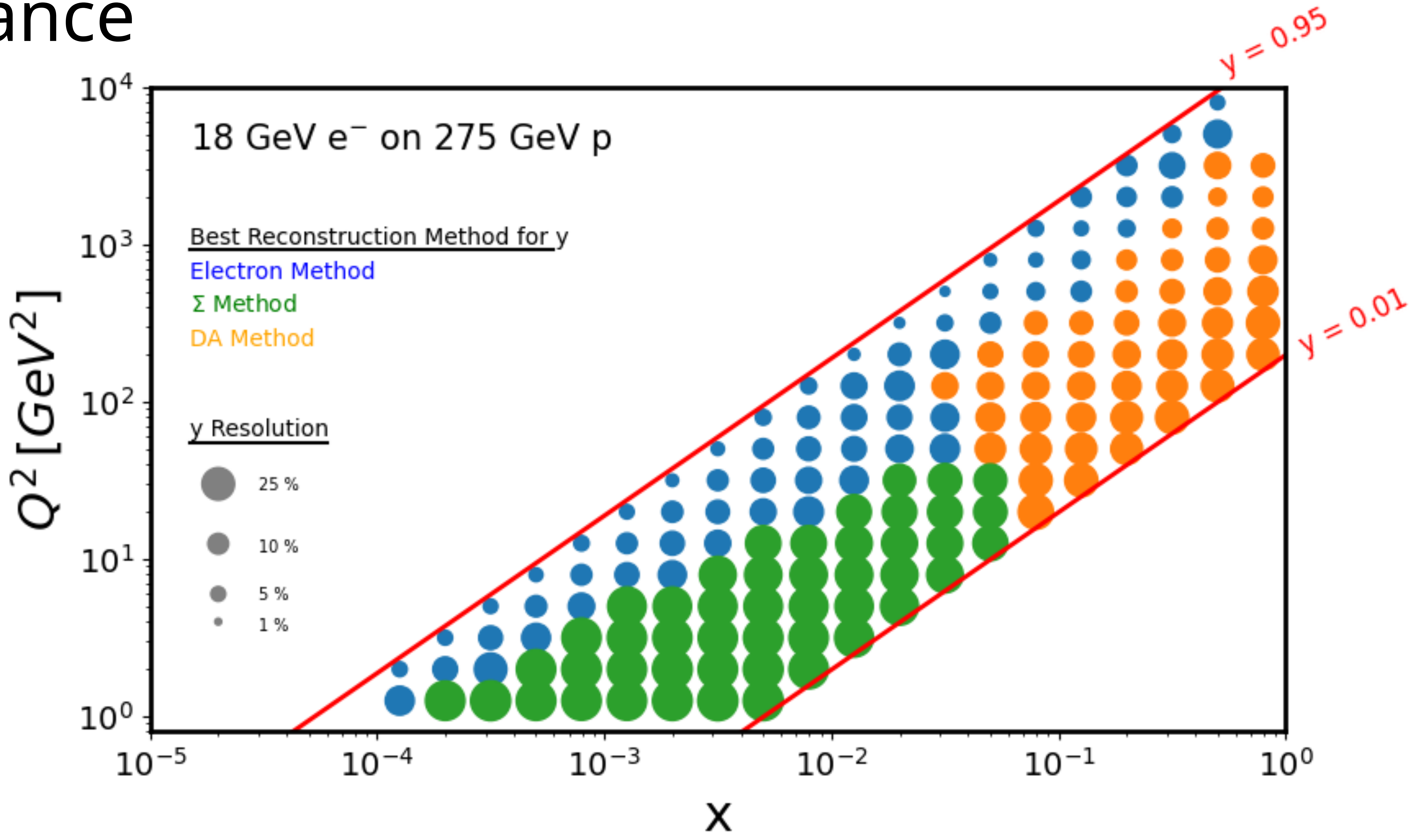
- $e\Sigma$: $y_\Sigma = \frac{\delta_h}{\delta_h + E'_e(1-\cos\theta_e)}$ $\quad Q^2_\Sigma = \frac{(E'_e \sin\theta_e)^2}{1-y_\Sigma}$

NC: leverage over-constrained kinematics to optimize performance



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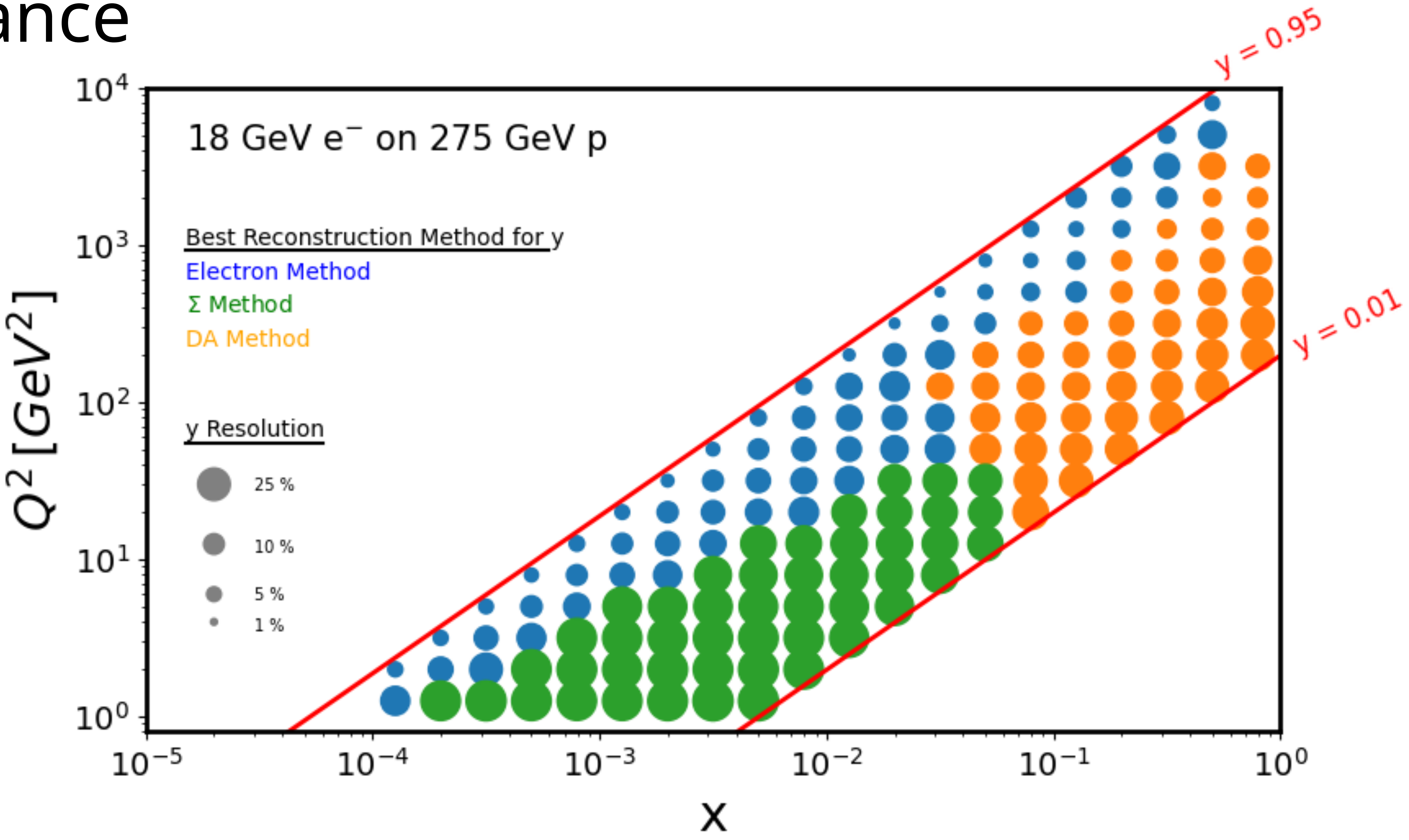
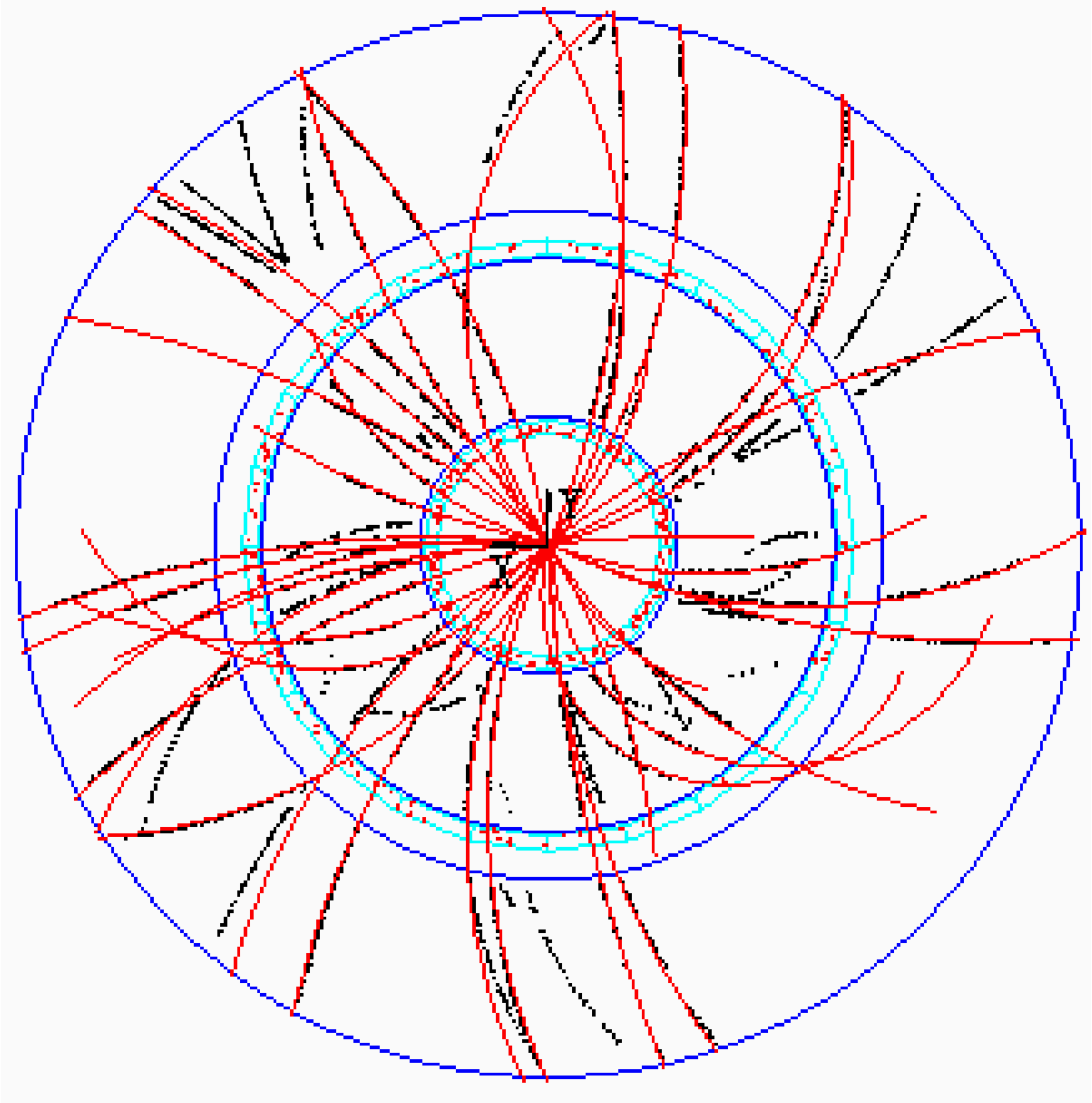


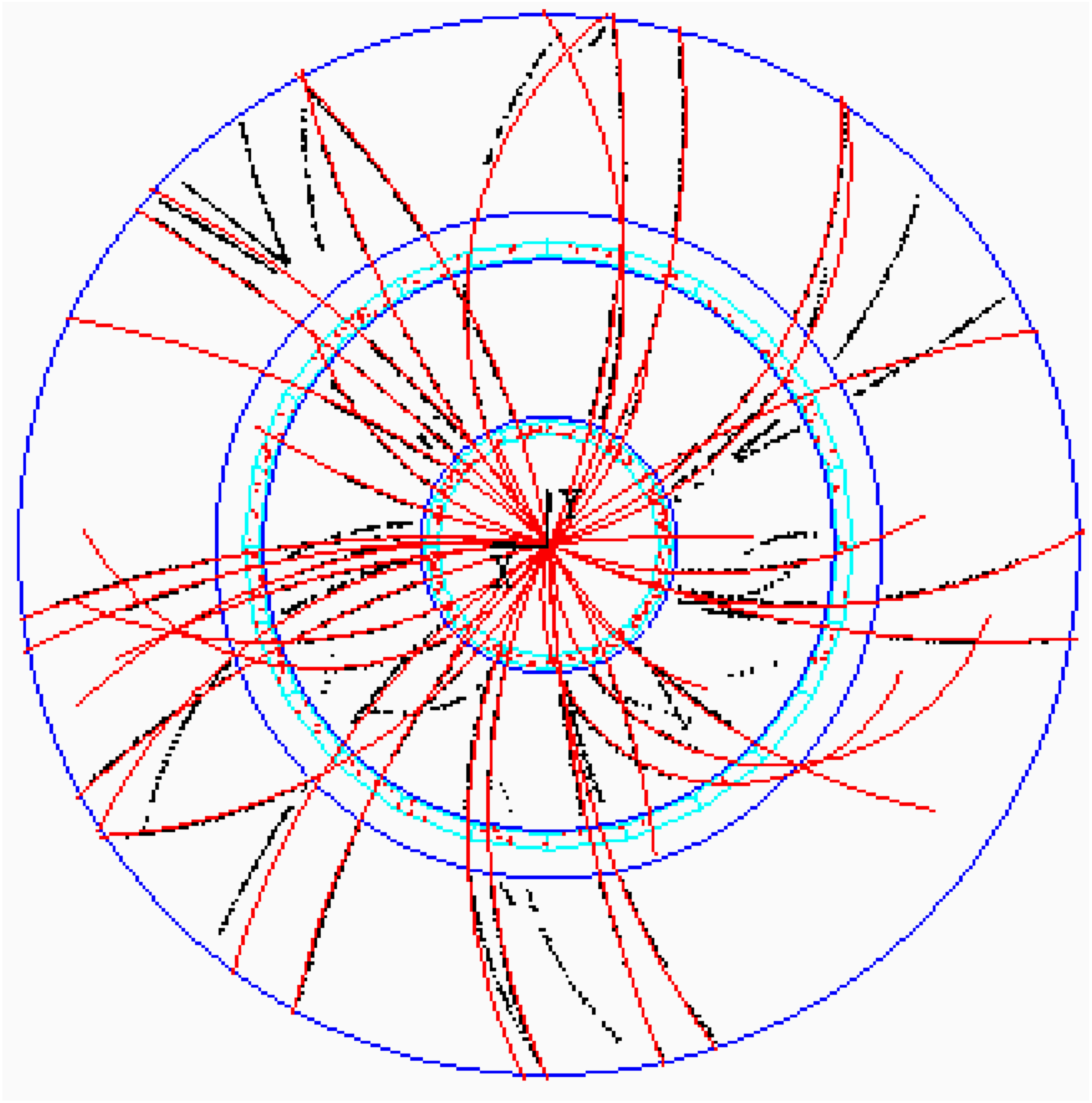
JB method only option for CC analyses

Electron identification



Electron identification

- Electrons will leave negative tracks
    - Eliminate neutral, positive particles



Electron identification

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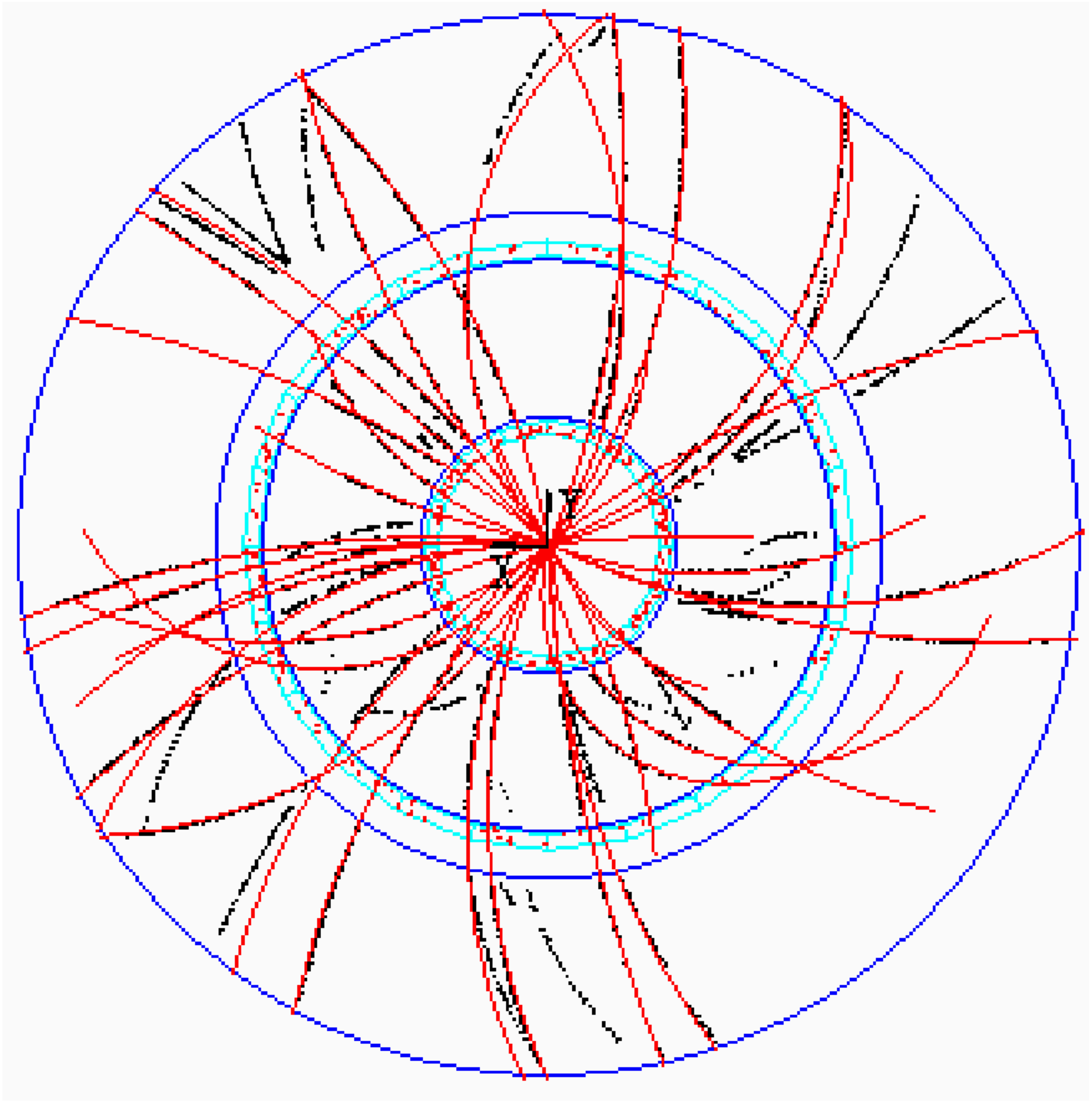
    - Still need to contend with π^-



Electron identification

- Electrons will leave negative tracks
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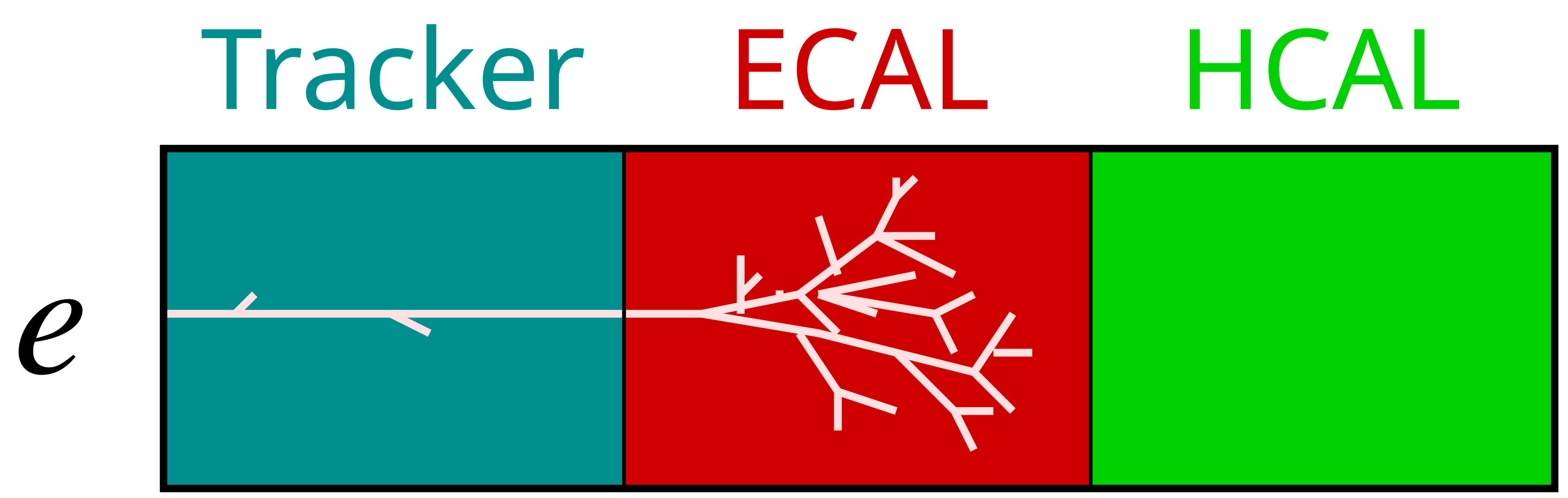
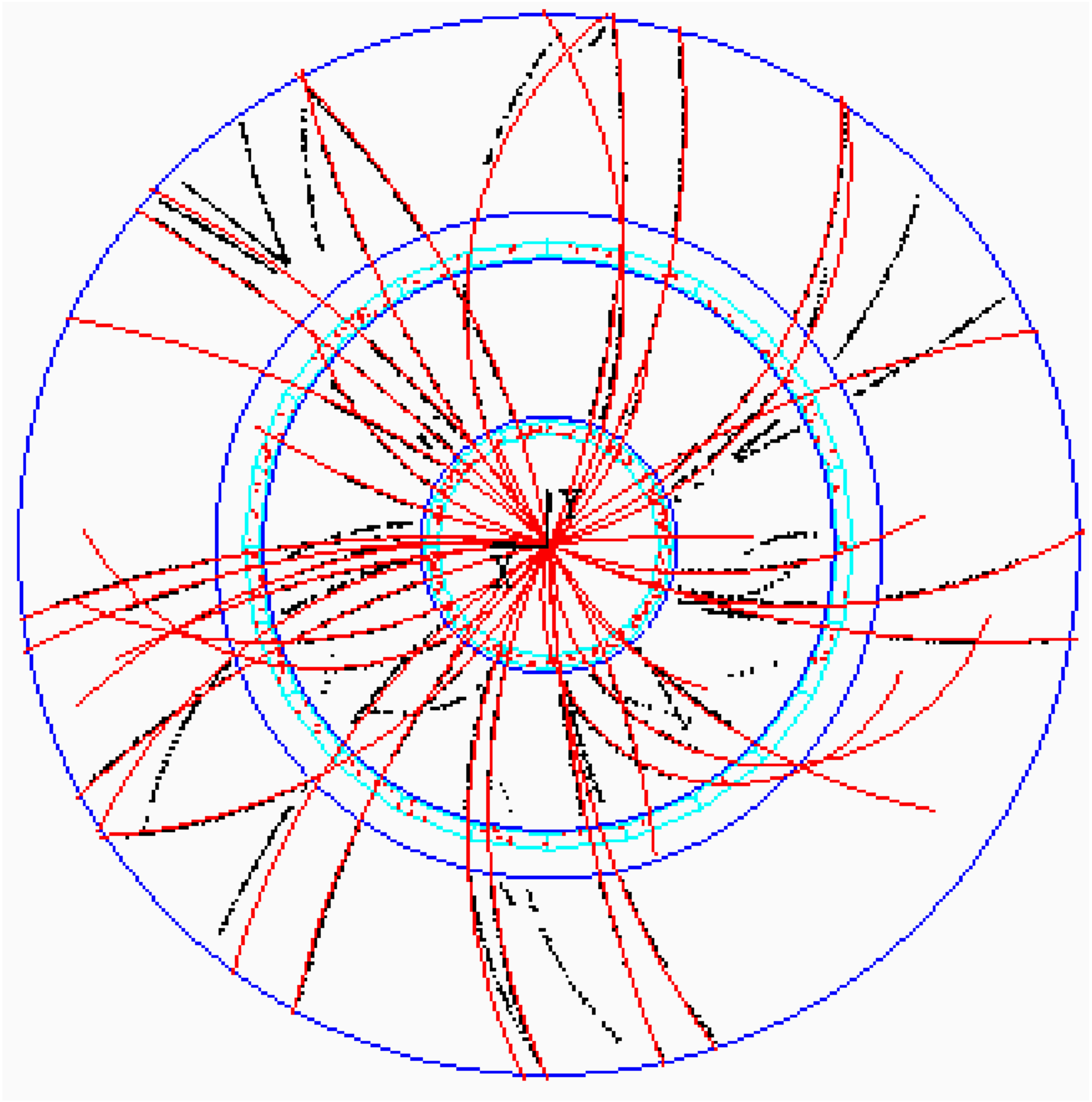
- Electrons typically deposit all their energy in electromagnetic calorimeter





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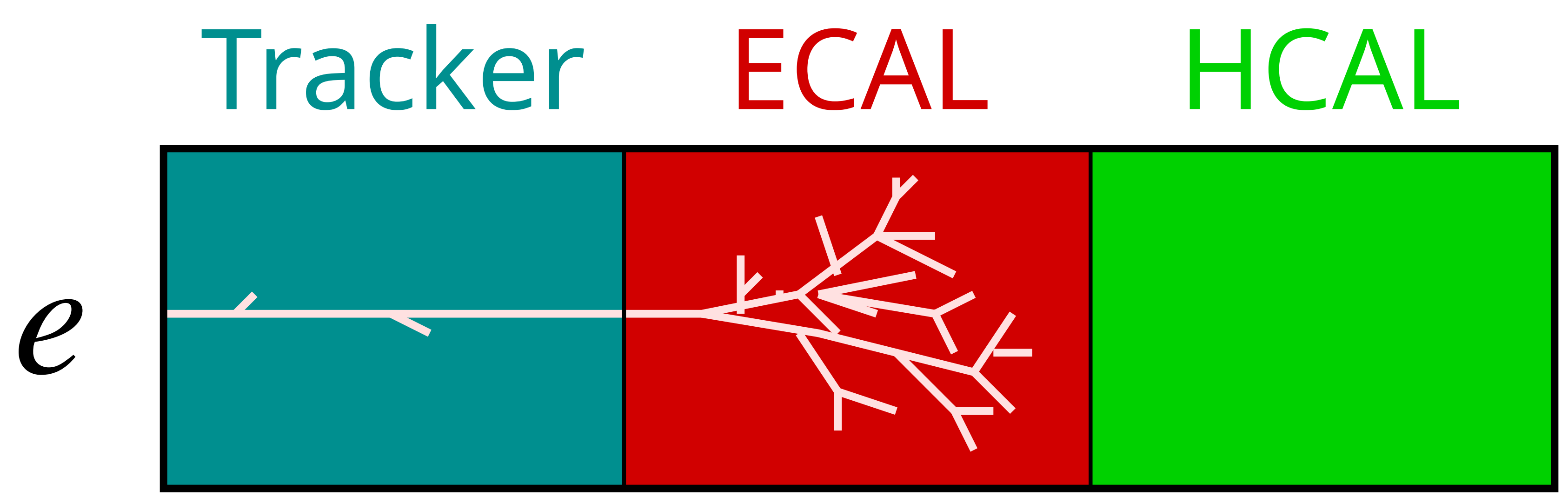

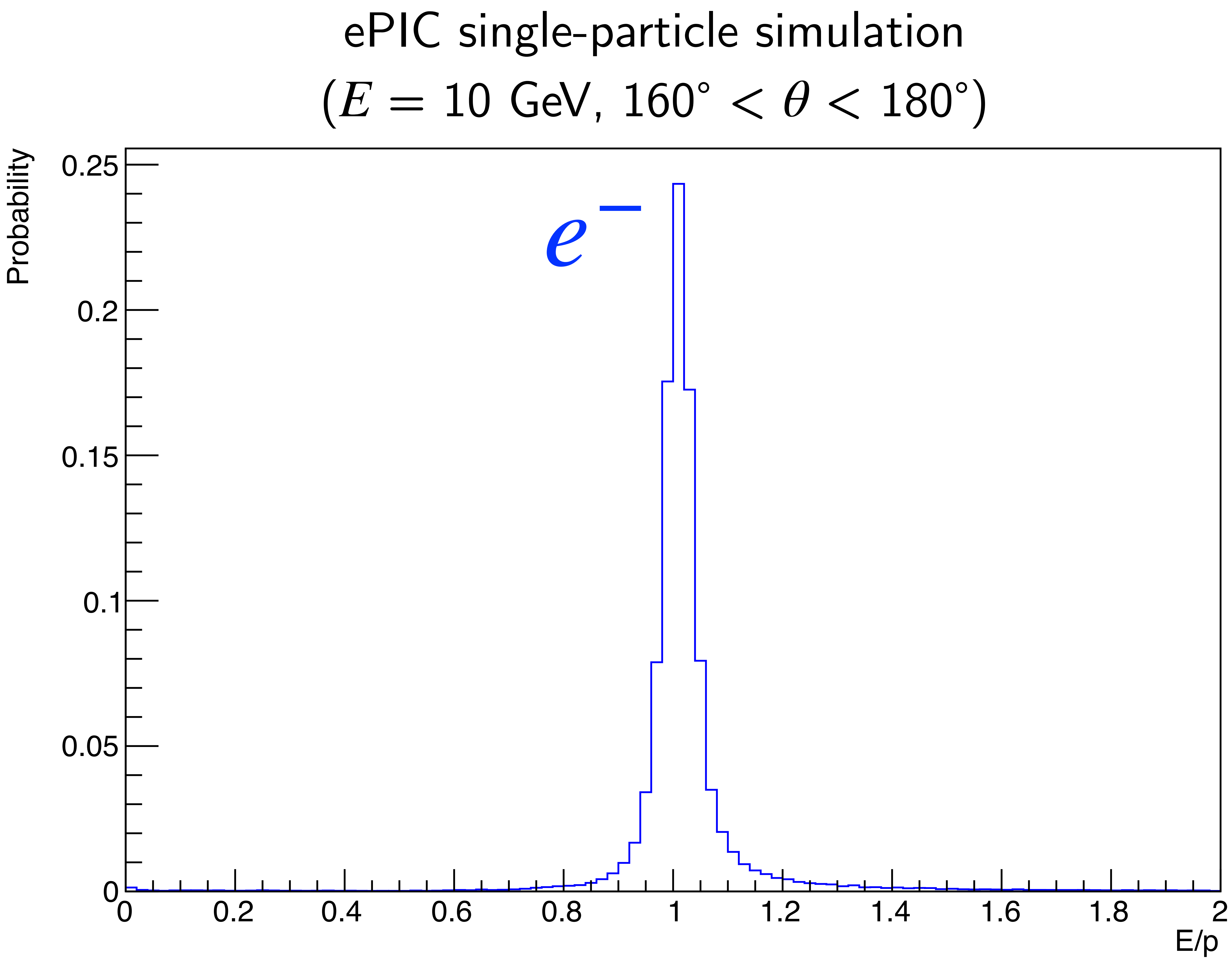

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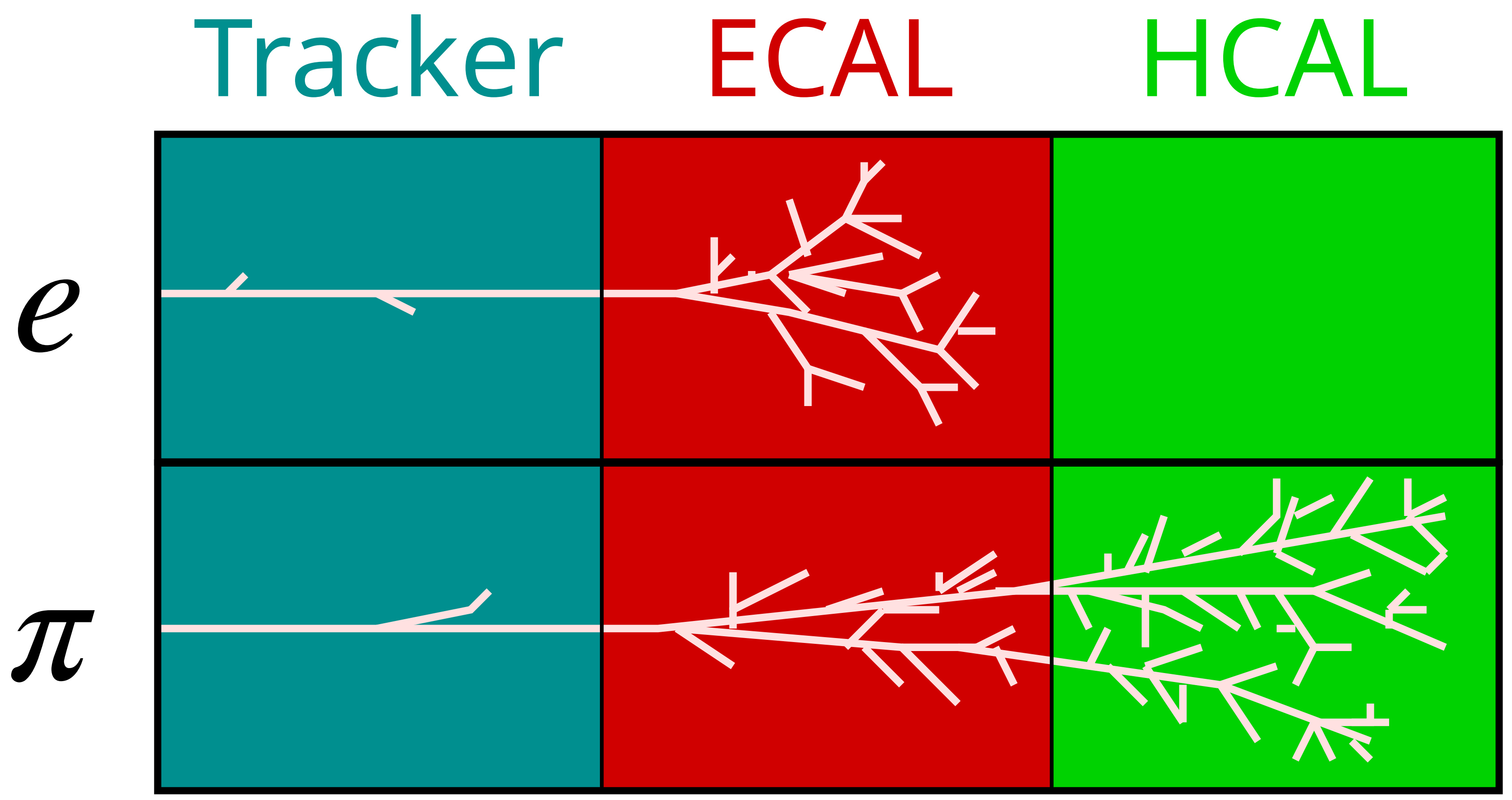

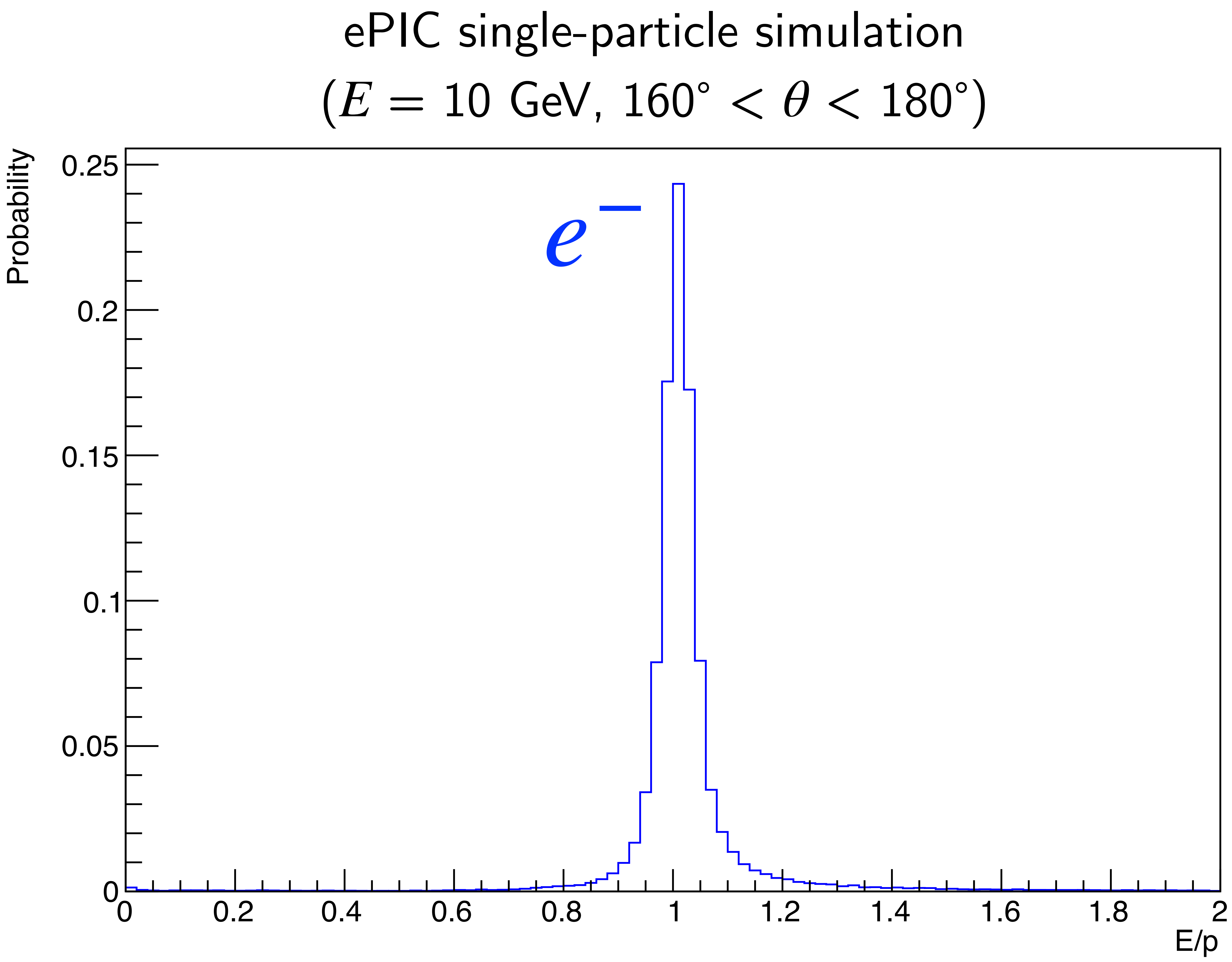

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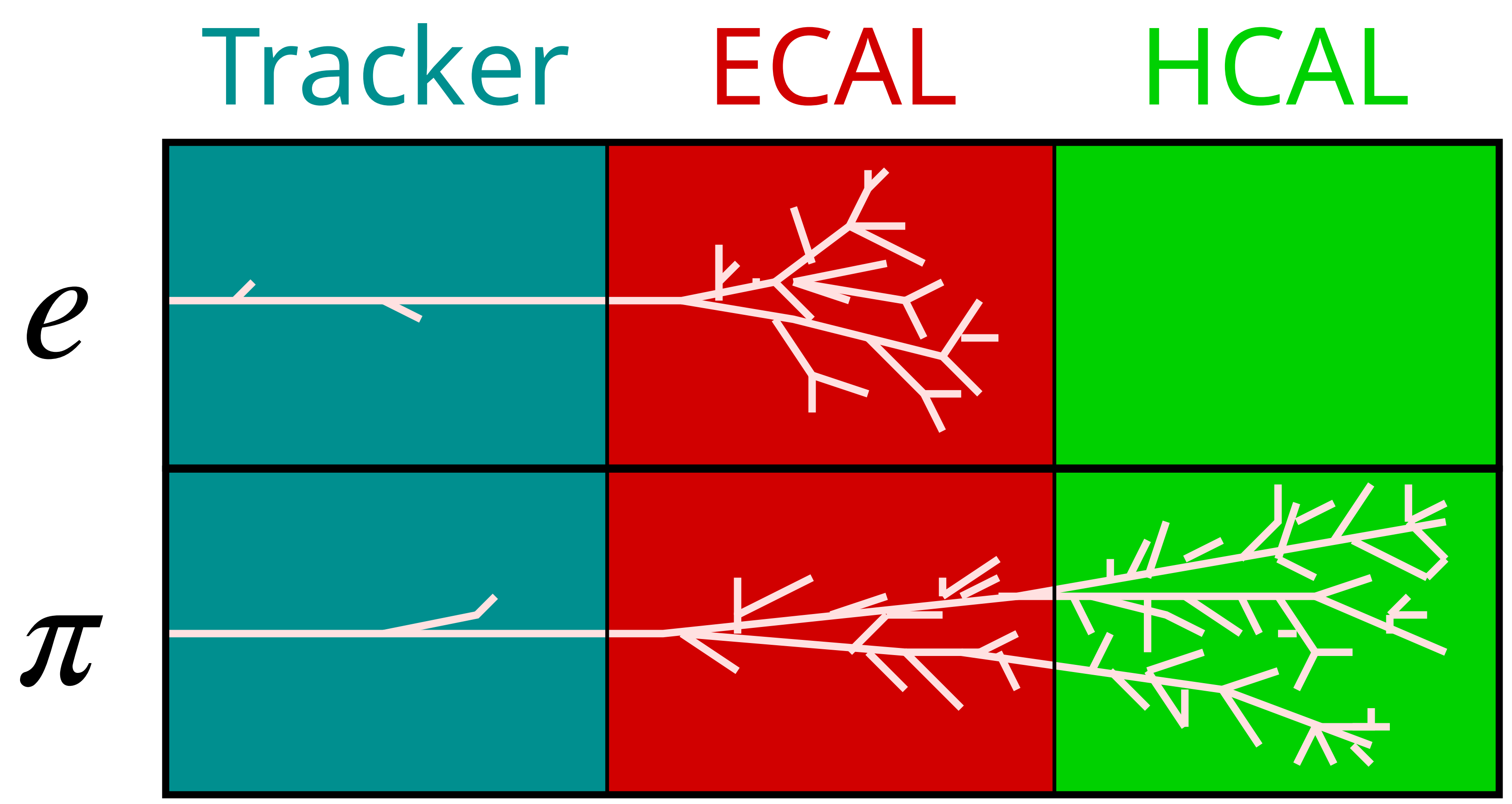

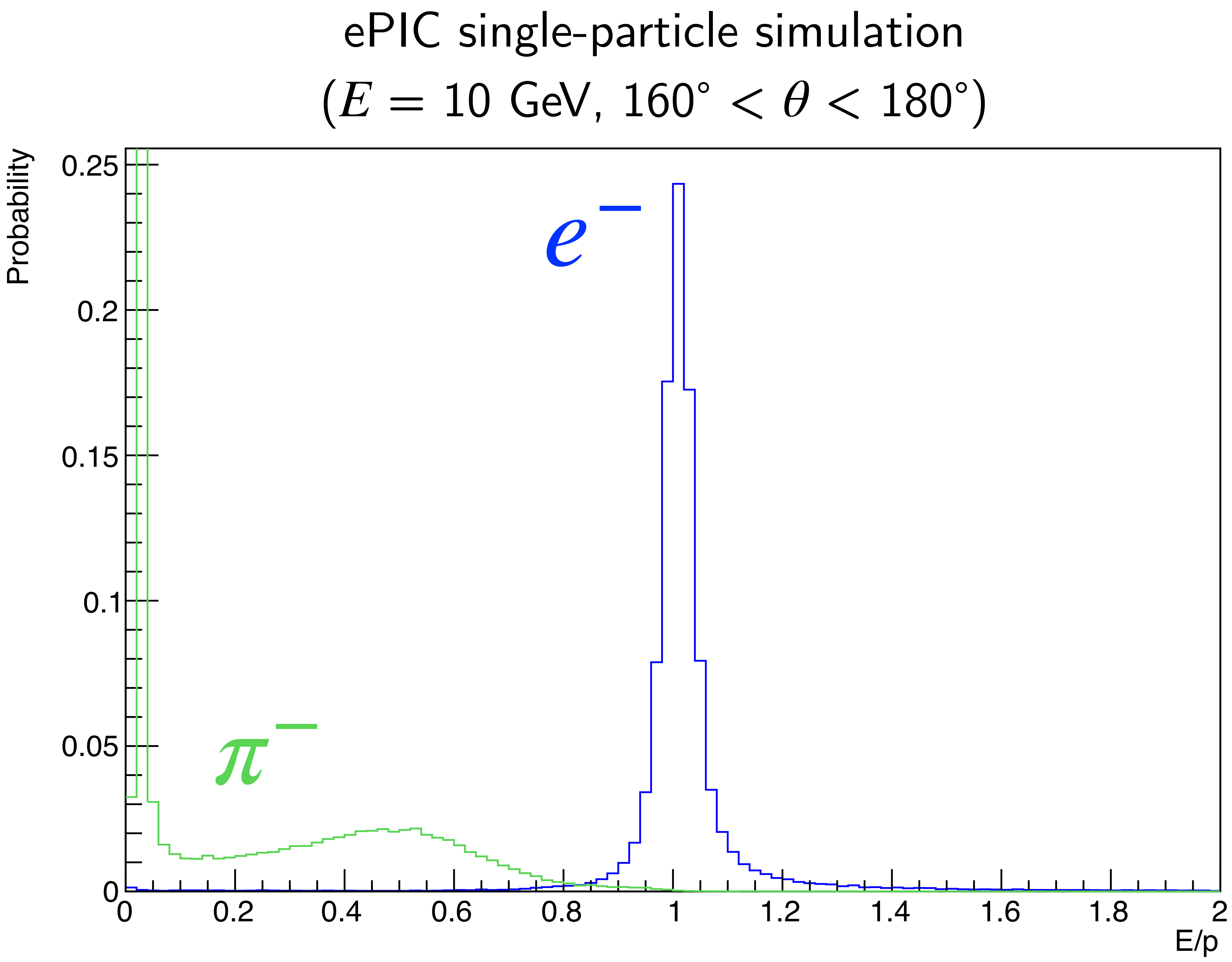

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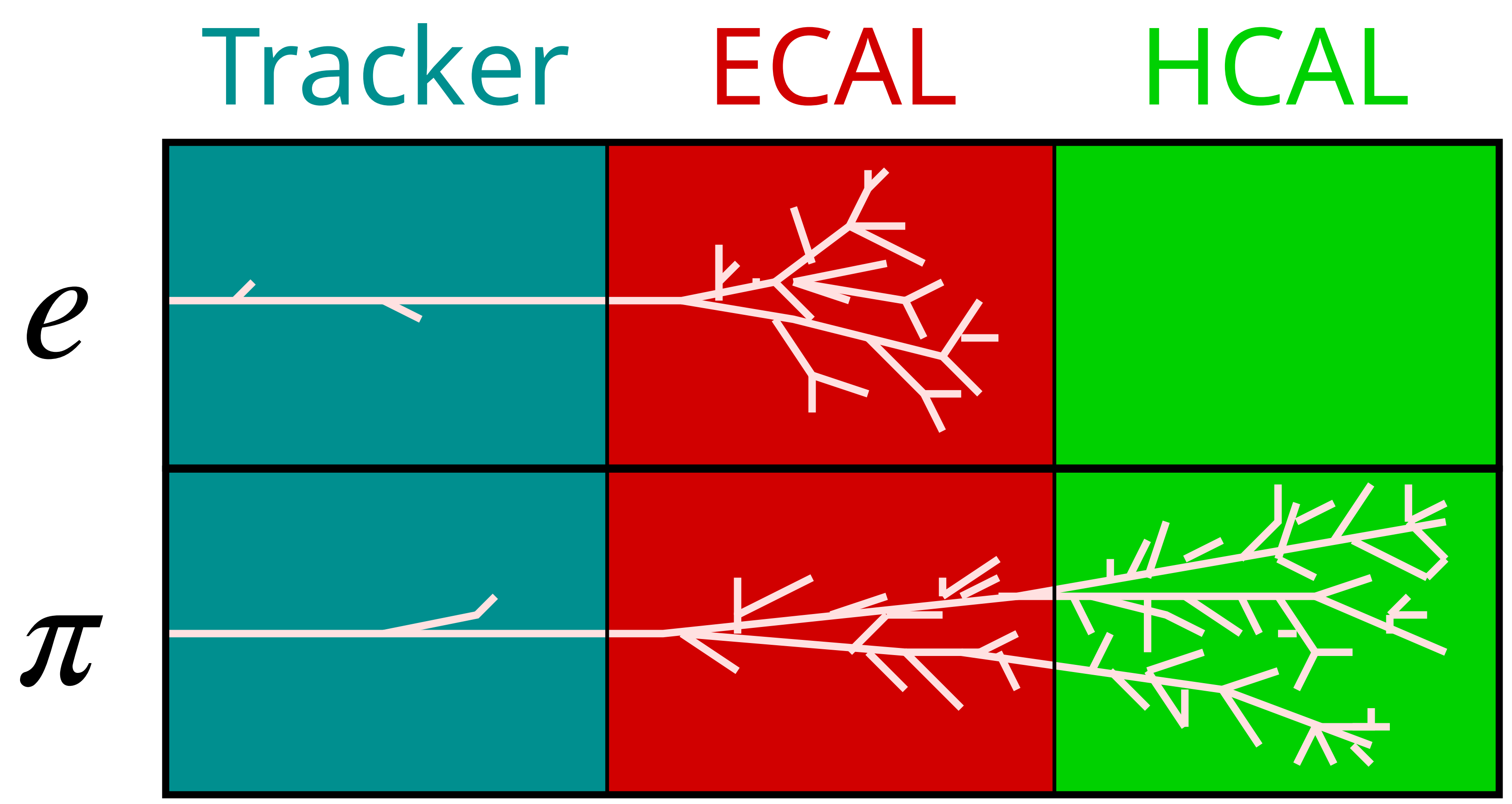

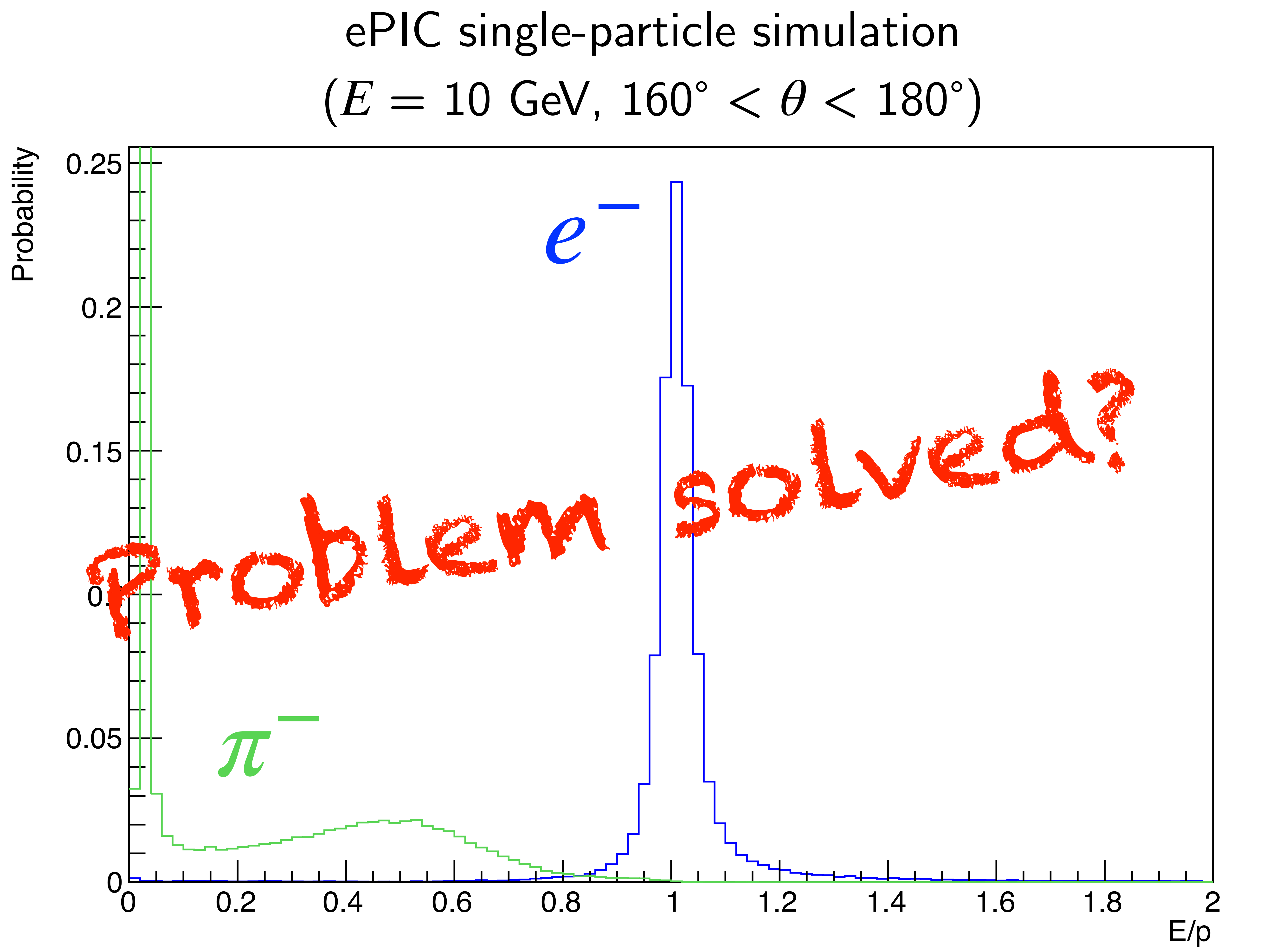

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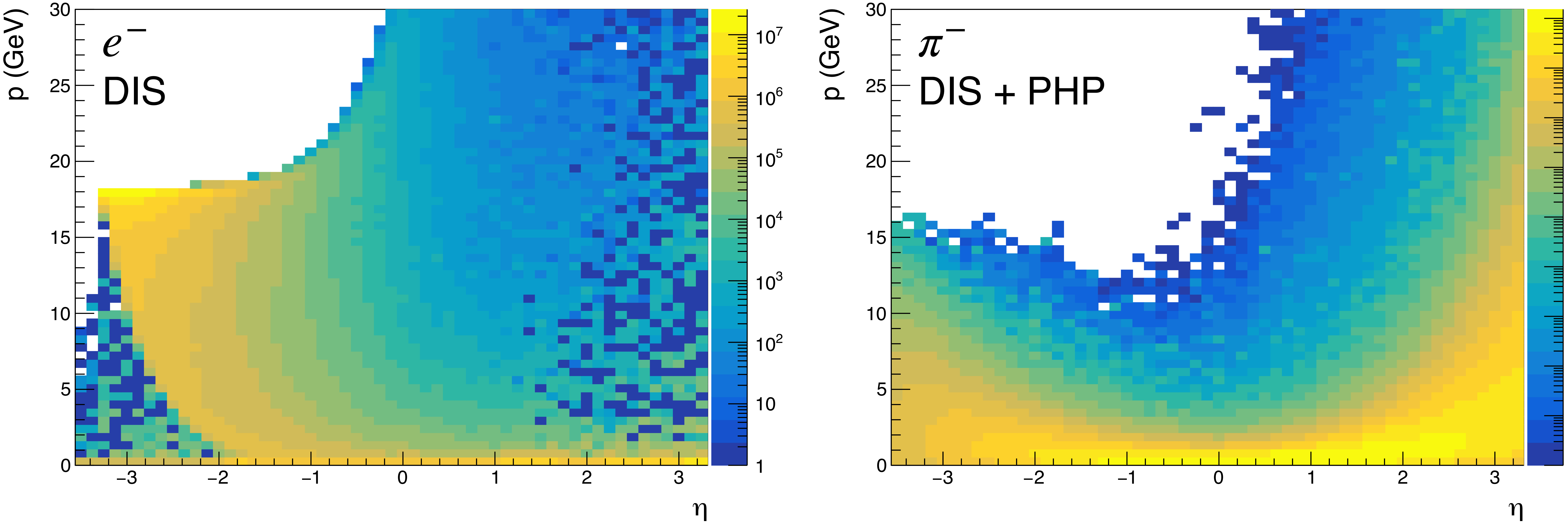

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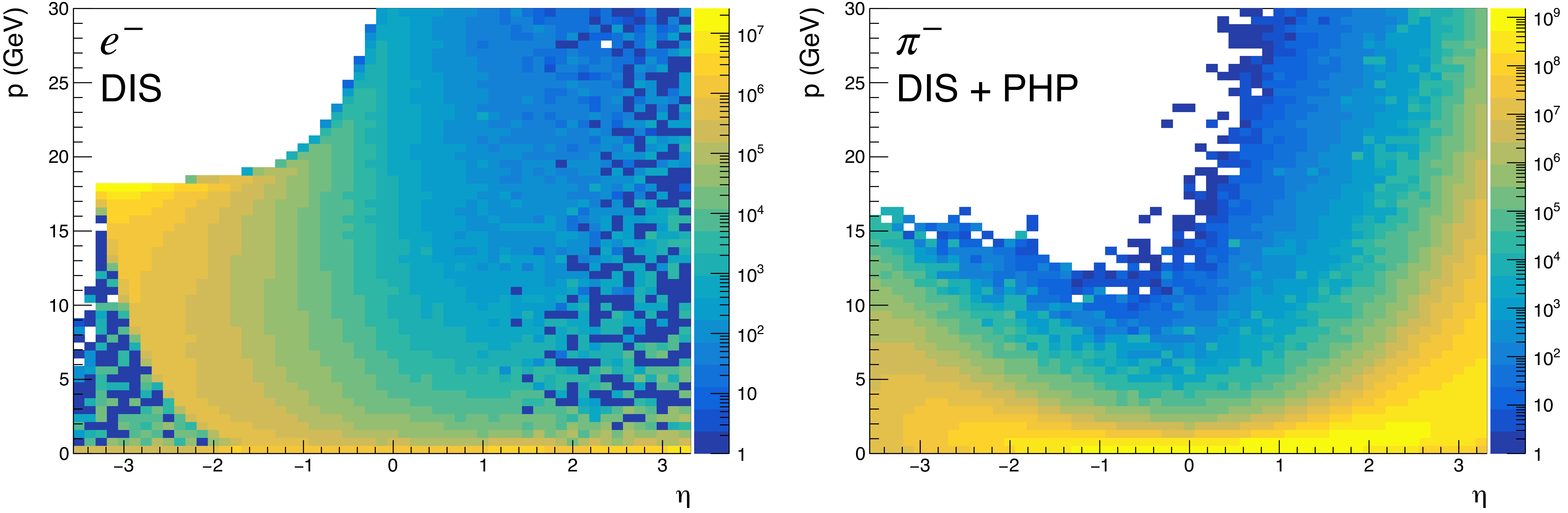

Cannot rely on E/p alone

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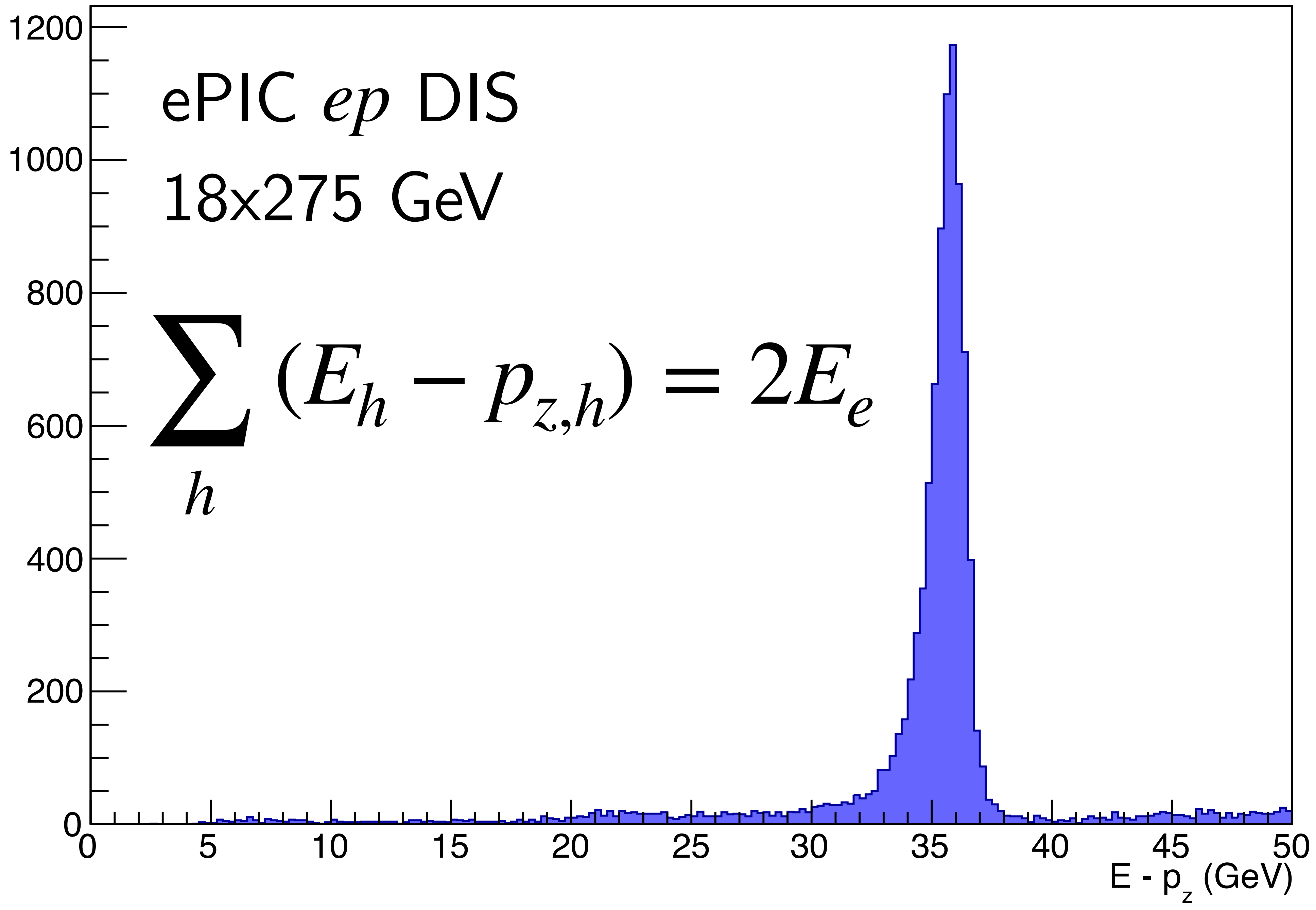

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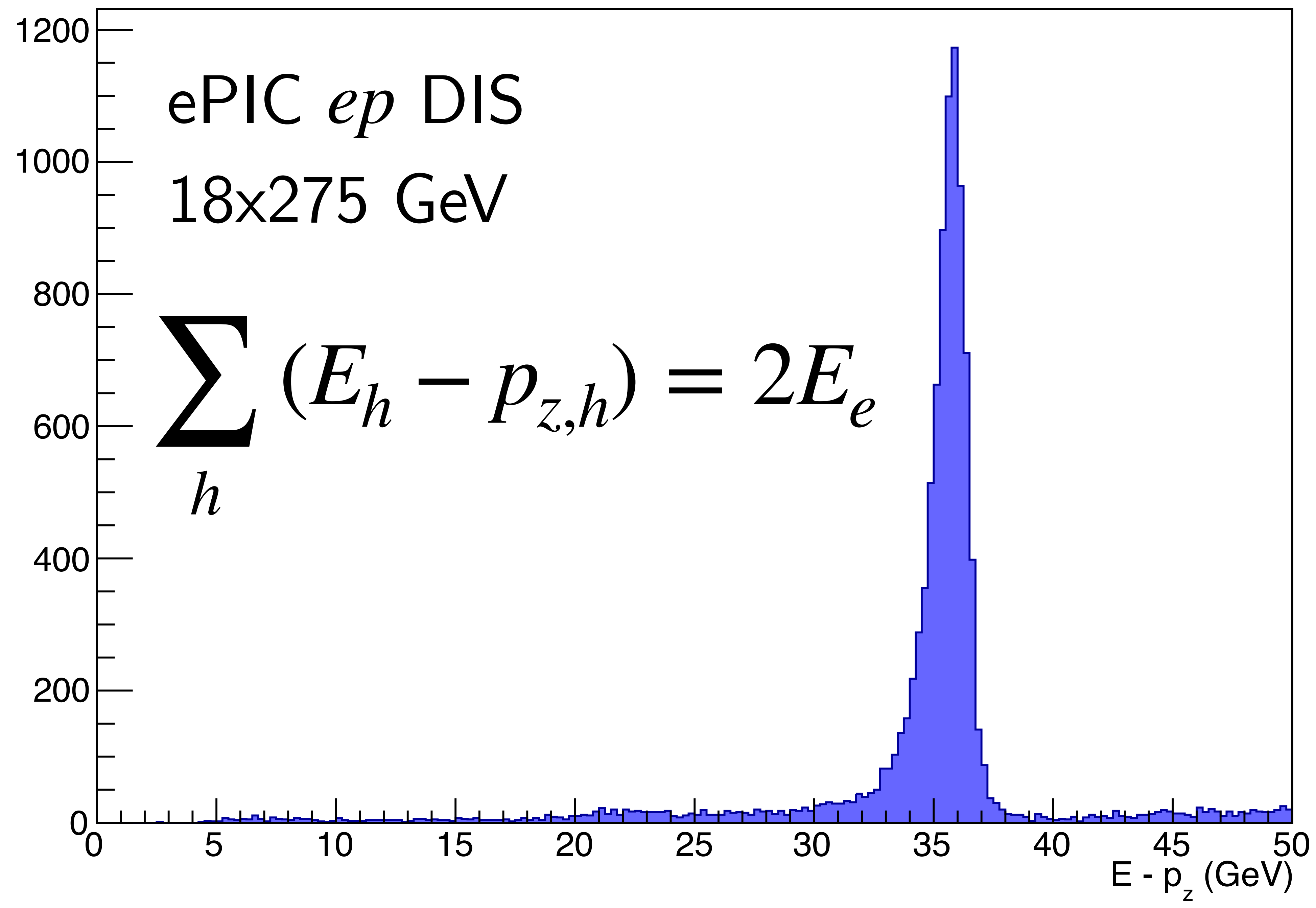

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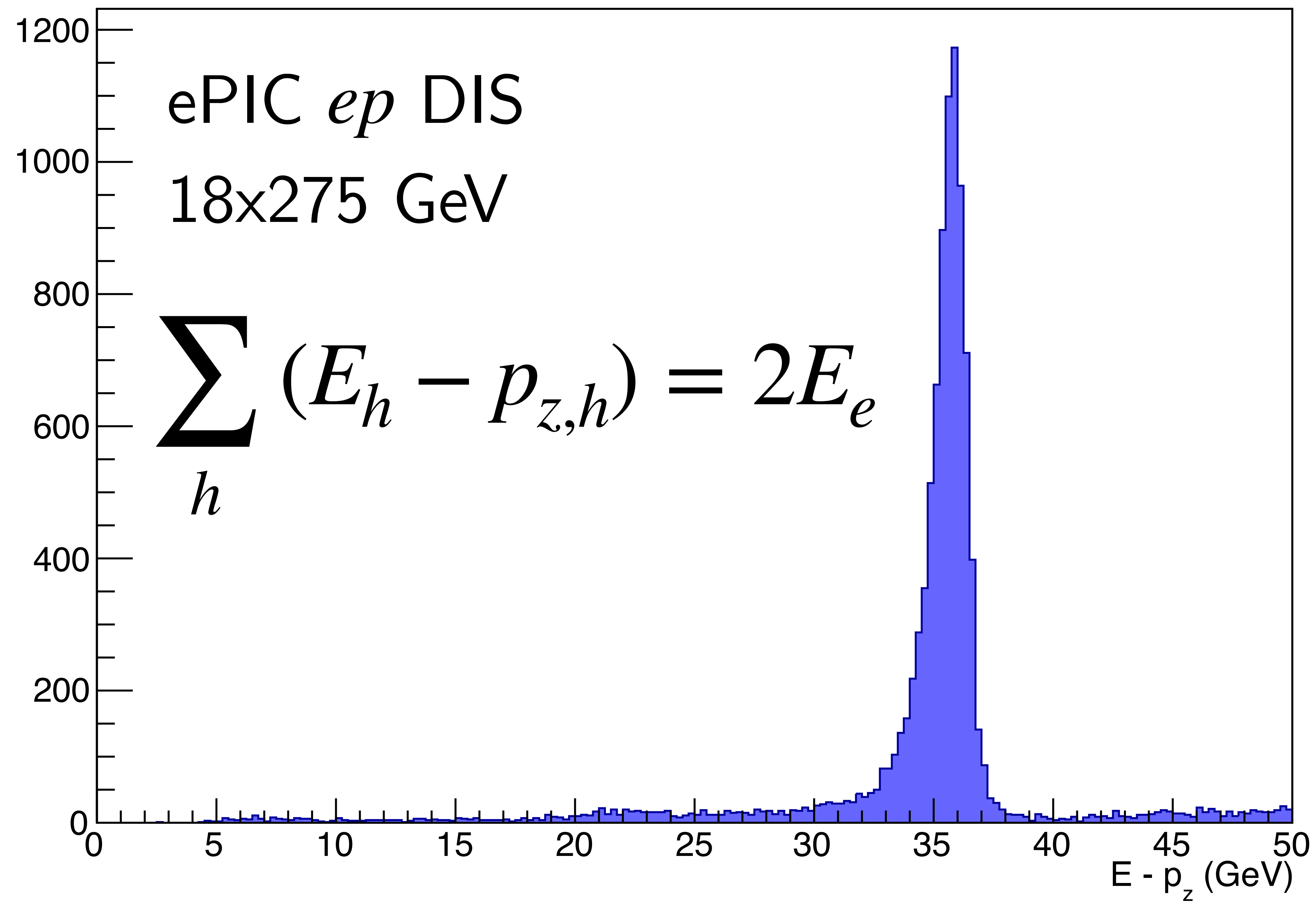

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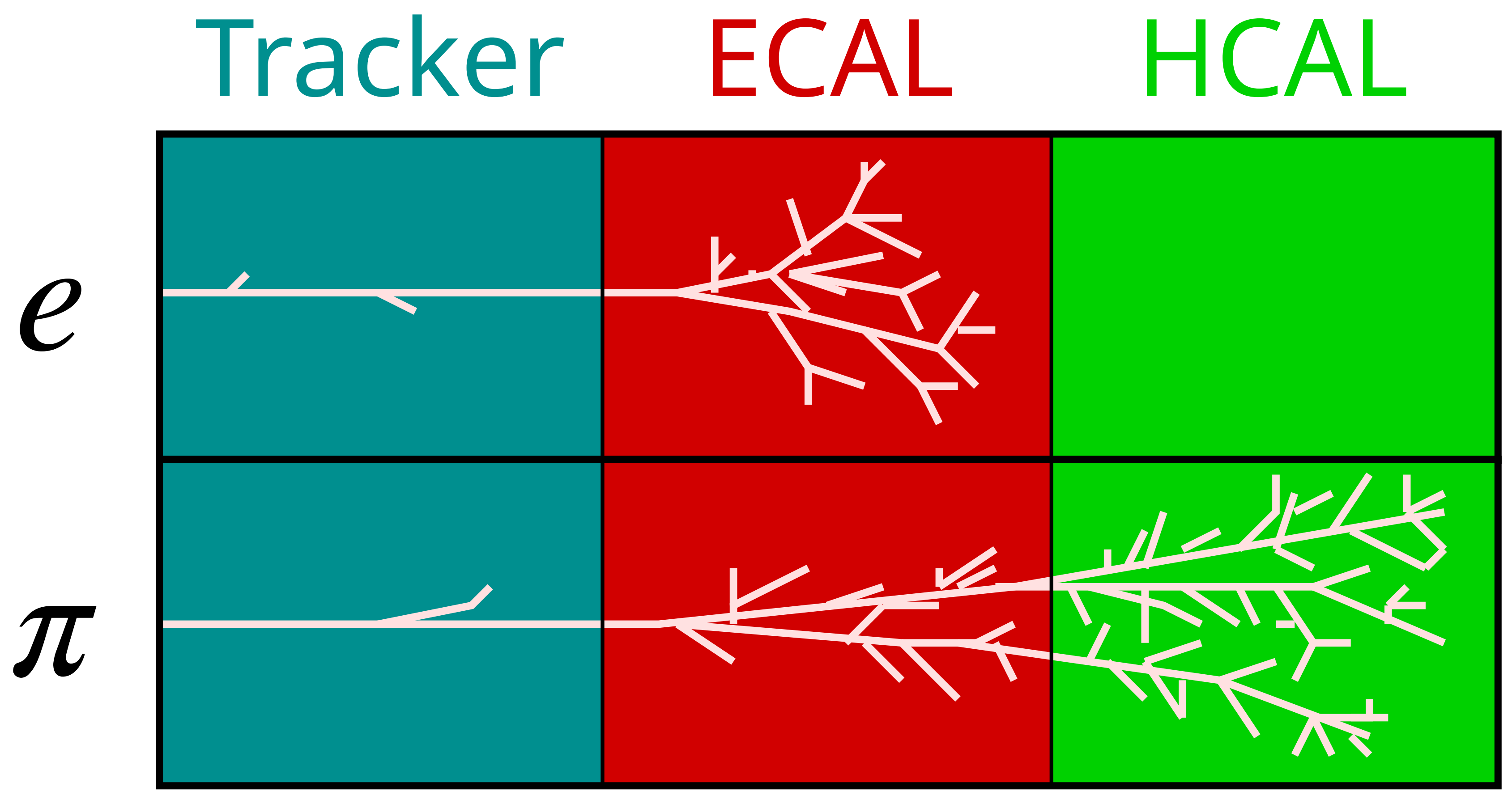

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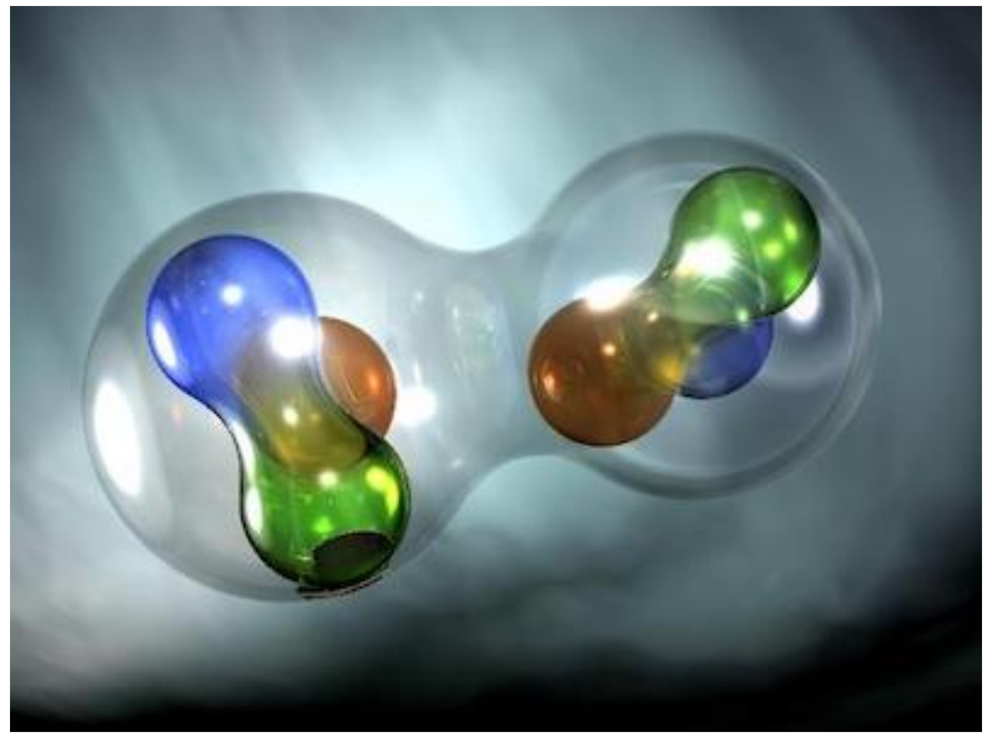

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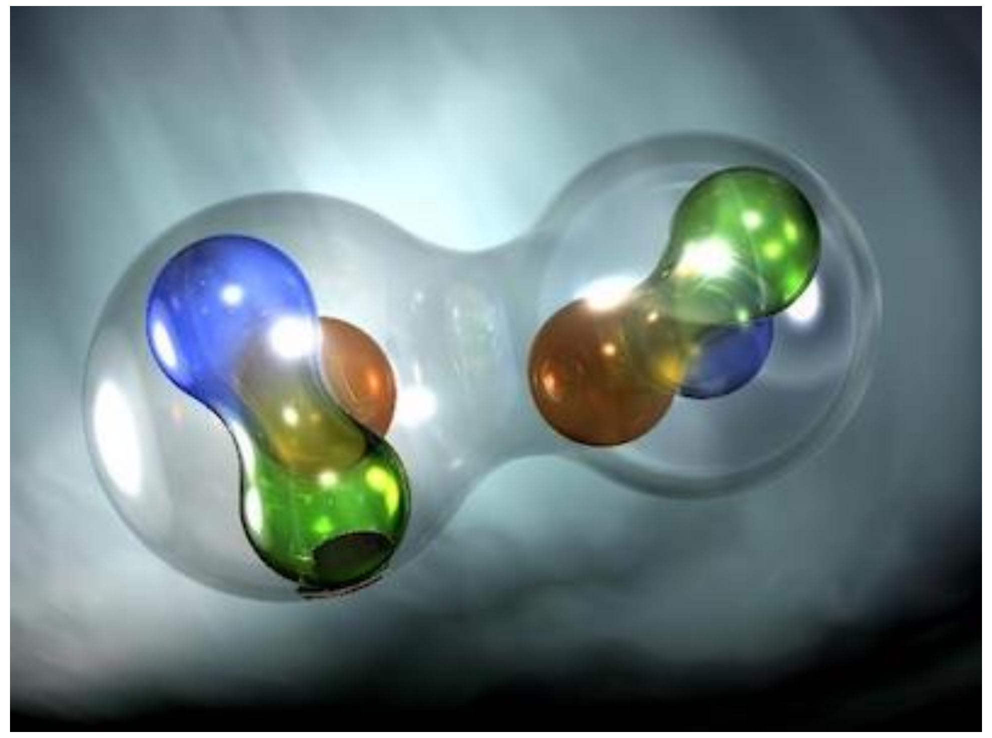

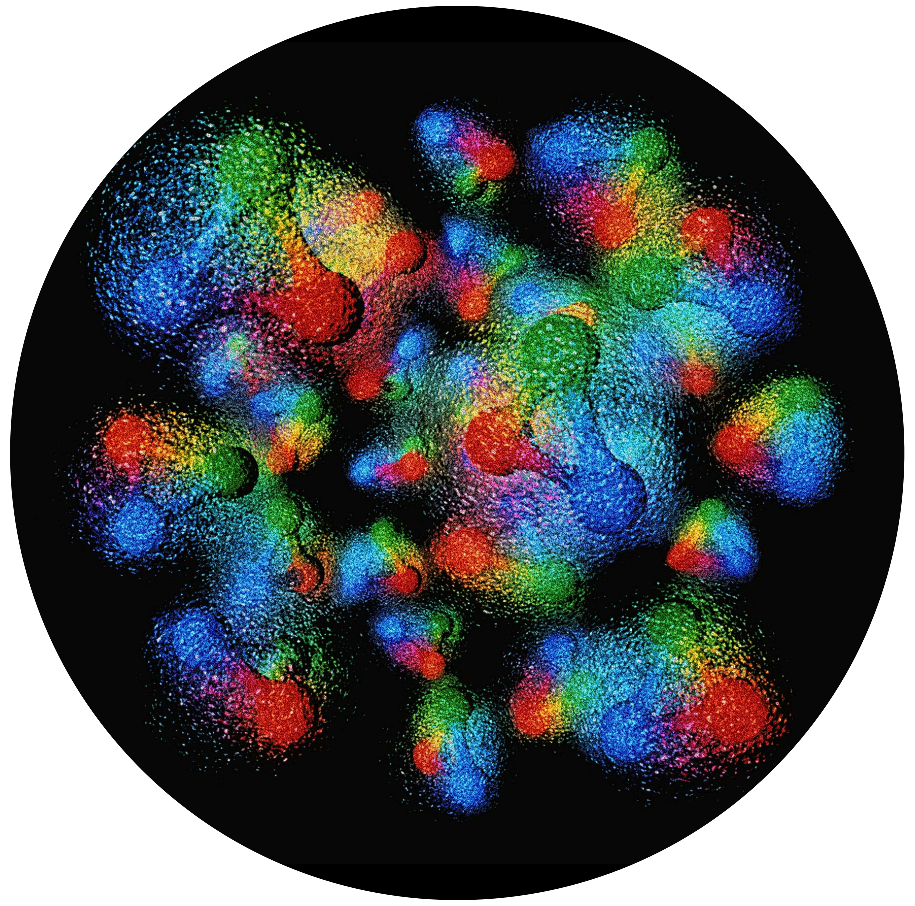

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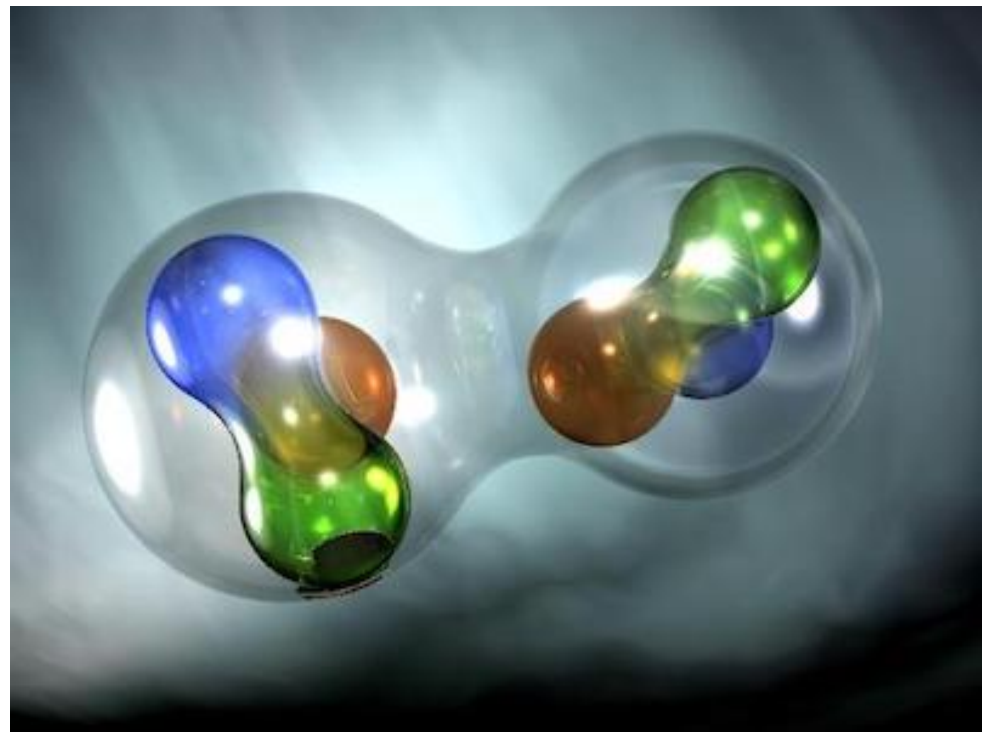

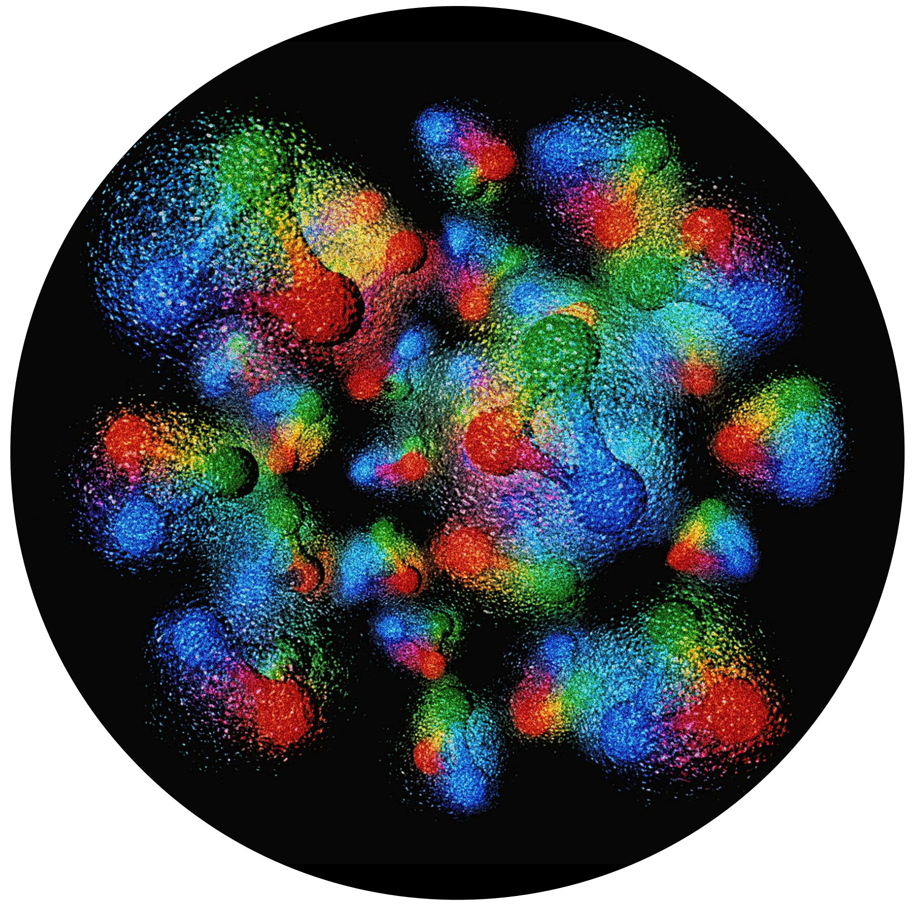

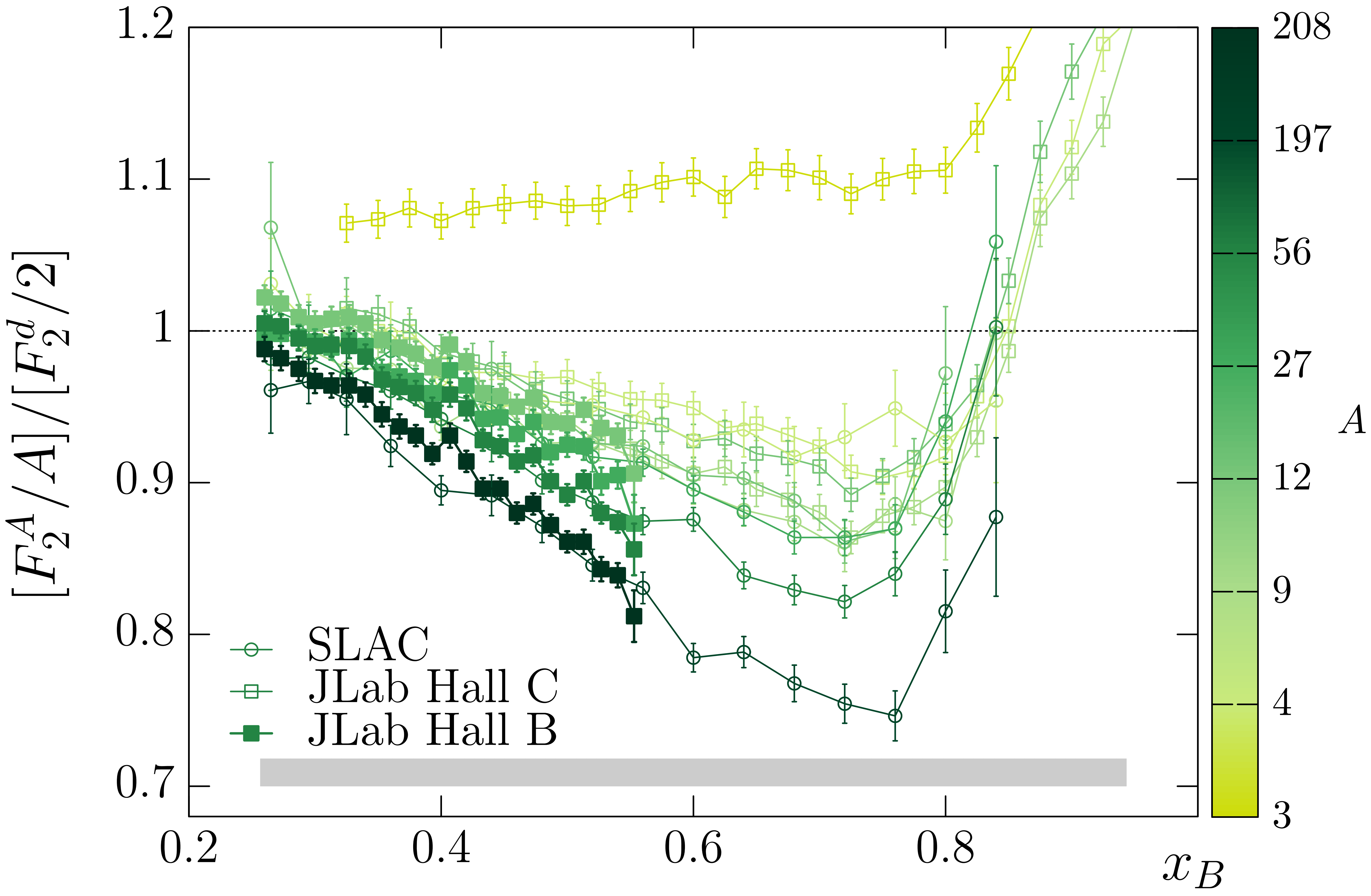

Summary and outlook

- Electron scattering is an old tool, but continues to be invaluable for studying nuclear physics
- Despite being extensively studied, the proton still contains many mysteries!

- JLab: active 12 GeV electron program, with possible positron and 22 GeV upgrades in the next decade
- MESA: under construction, first beam expected next year
- EIC: under construction, first collisions expected mid-2030s