# Nucleon tomography through the study of exclusive processes

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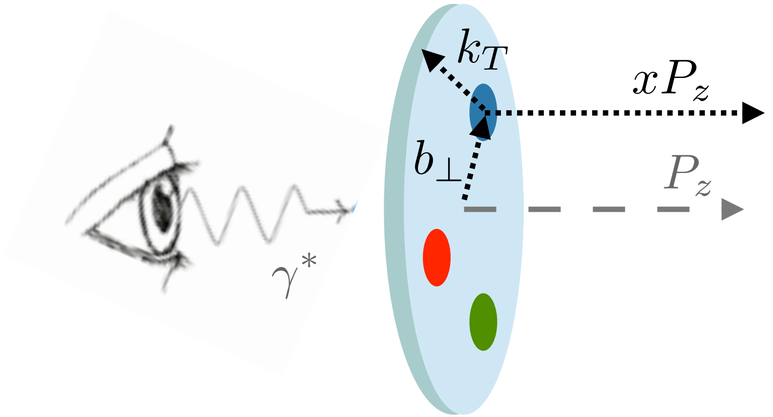
VUB

ODYSSEUS Top science in Flanders fwo

NFQCD
October 12 – November 13, 2026
YITP, Kyoto, Japan

# The various dimensions of the nucleon

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$



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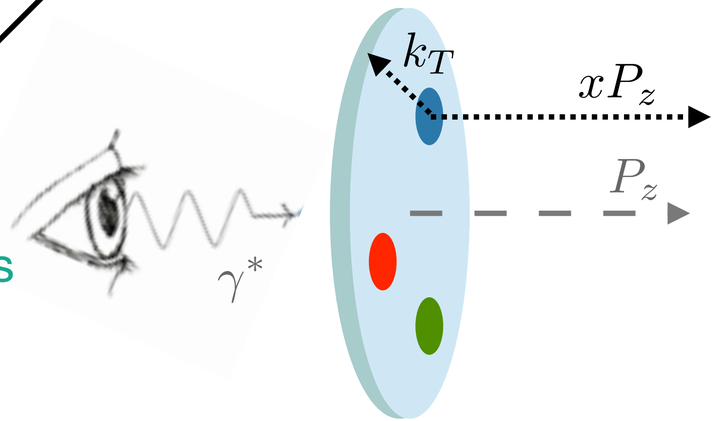
transverse-momentum dependent (TMD) parton distribution functions (PDFs)



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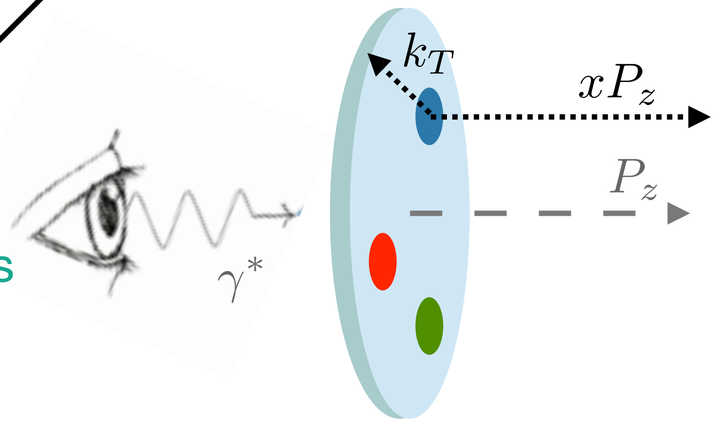
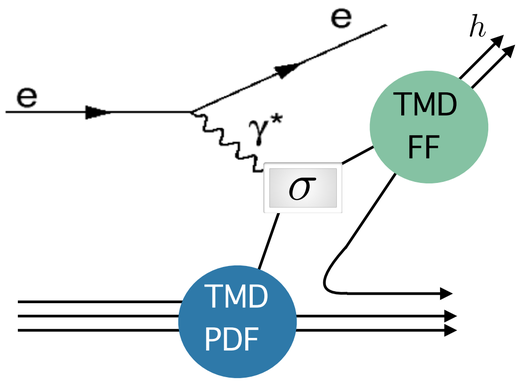



Semi-inclusive processes



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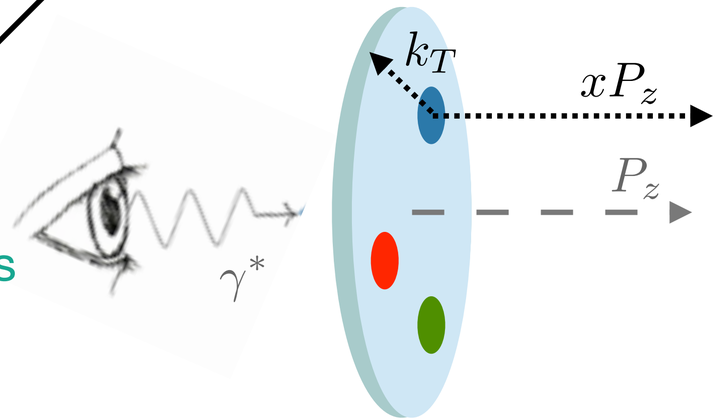


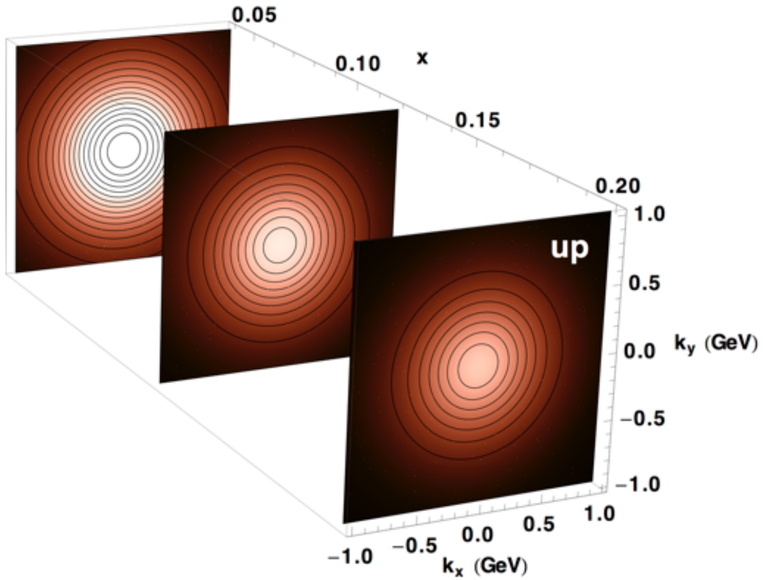

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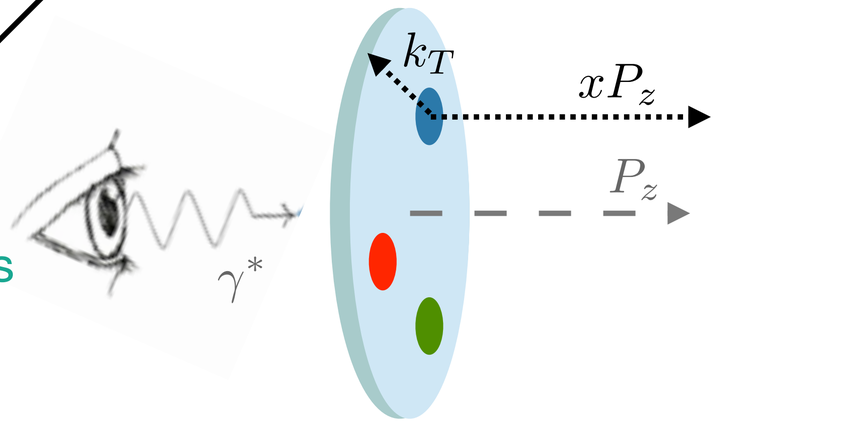


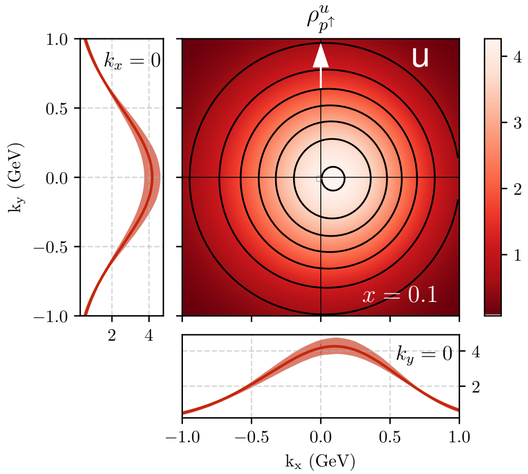


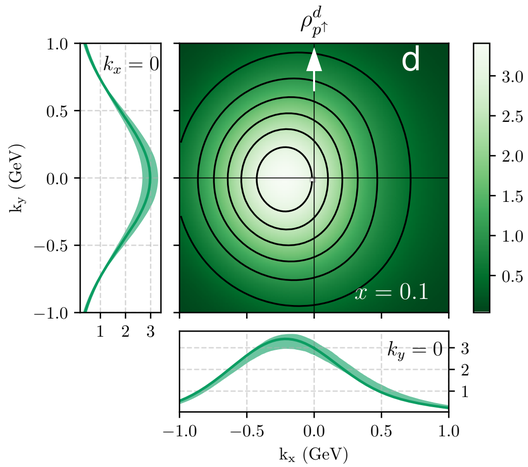

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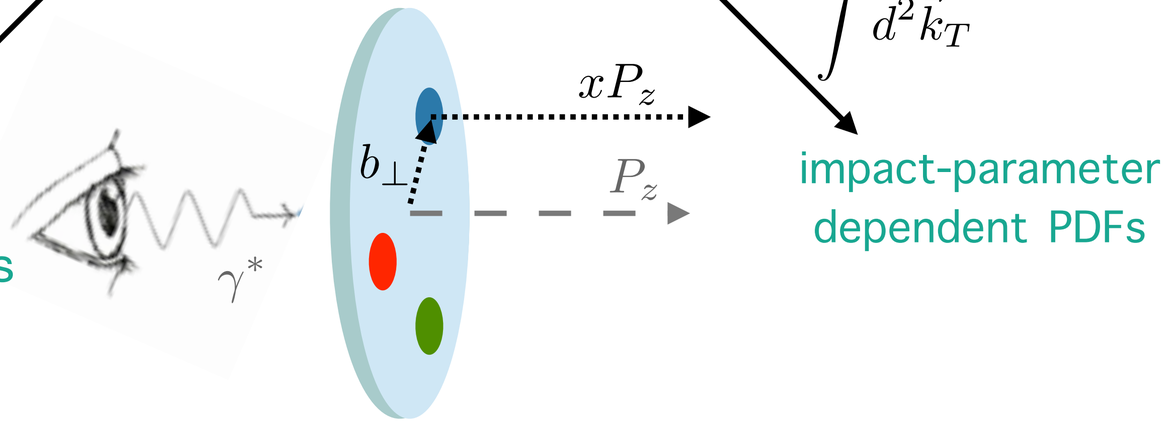


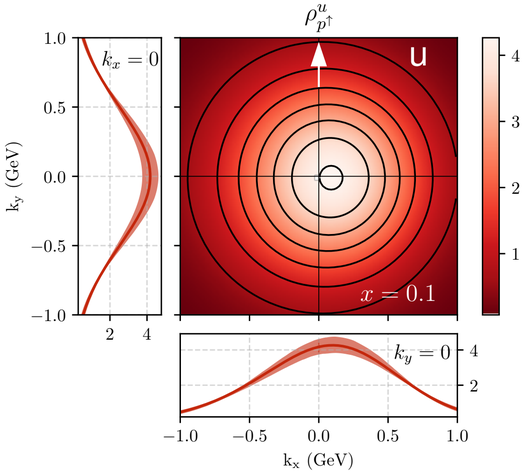


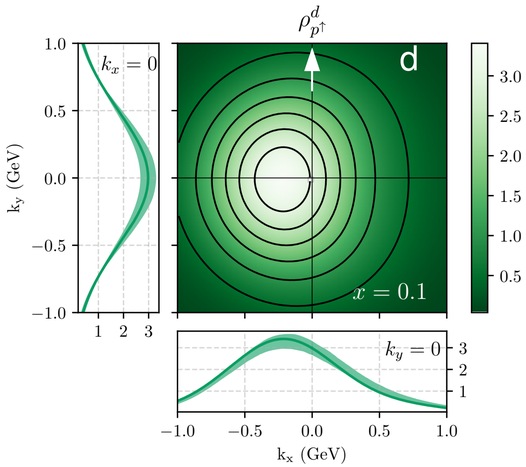

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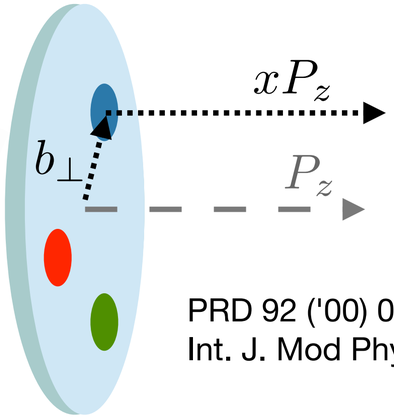


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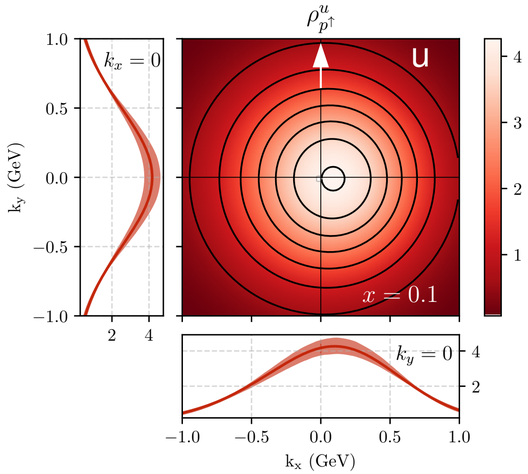
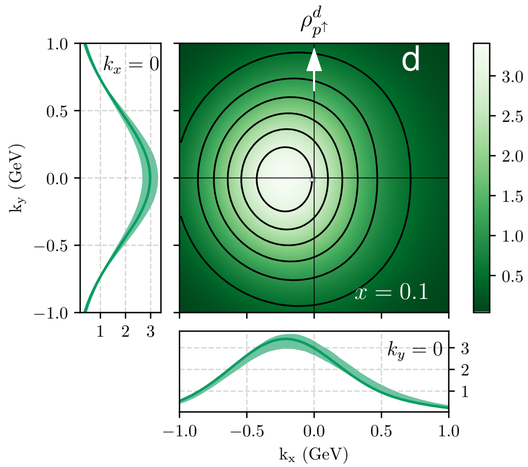
PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

Fourier transform

generalised parton distributions (GPDs)



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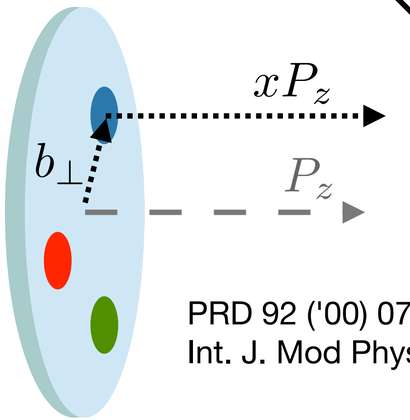


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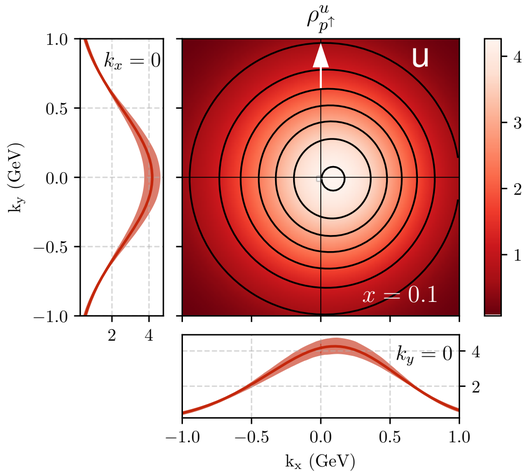
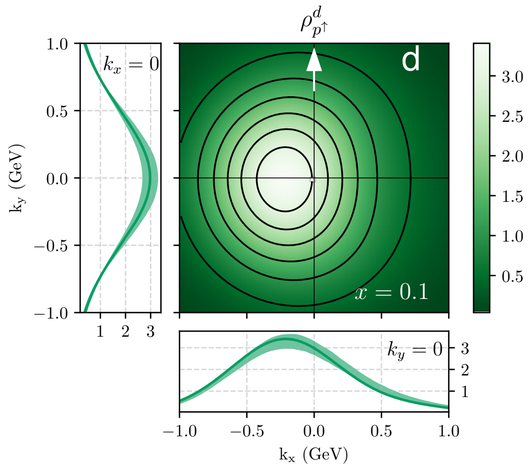
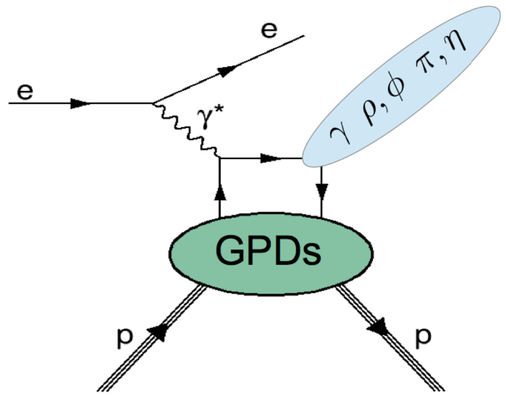



Exclusive processes



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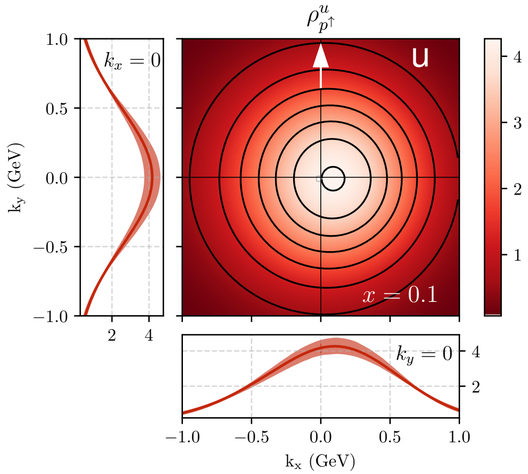


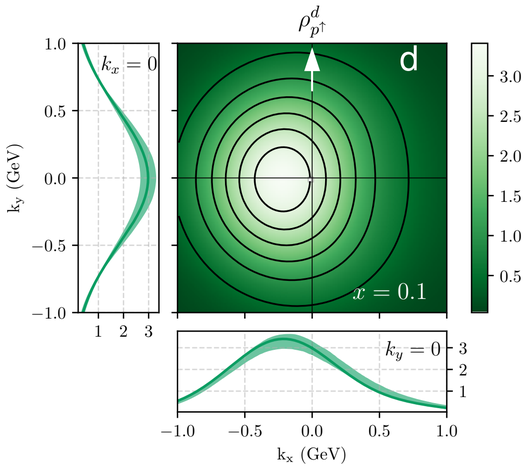


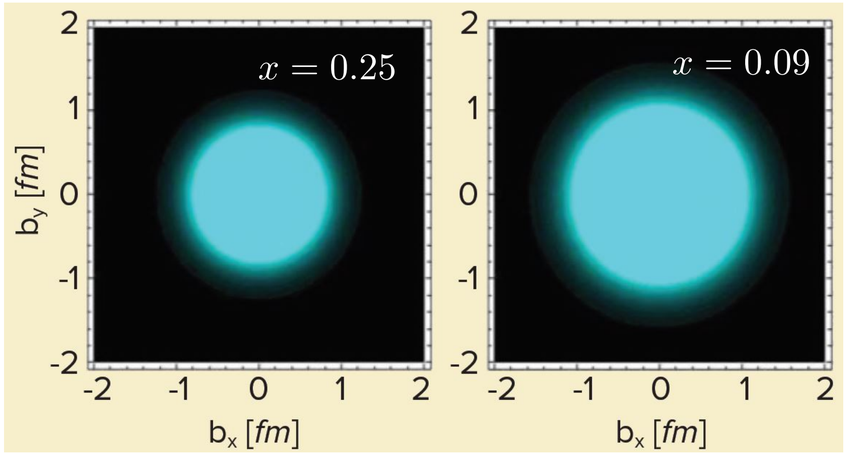

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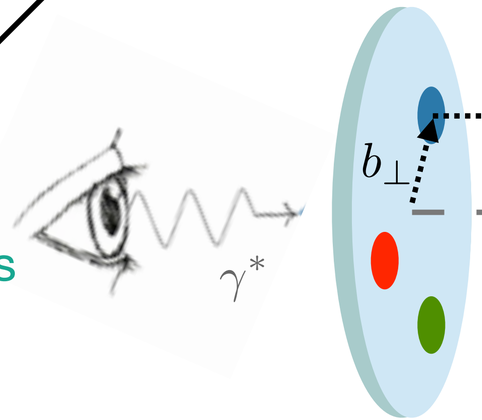


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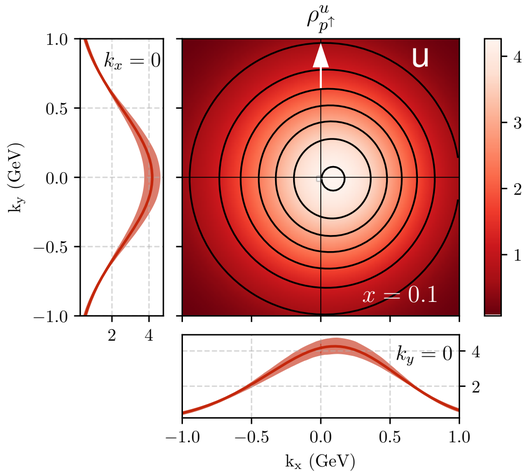


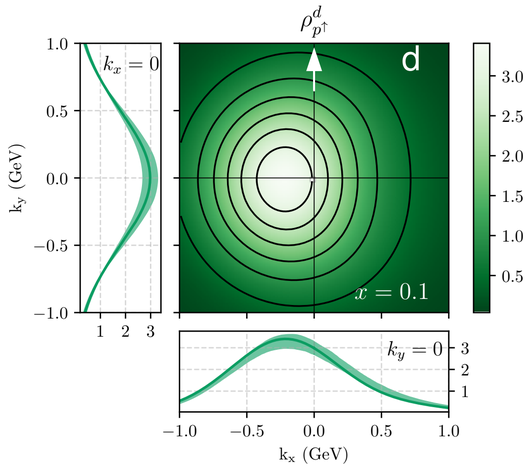


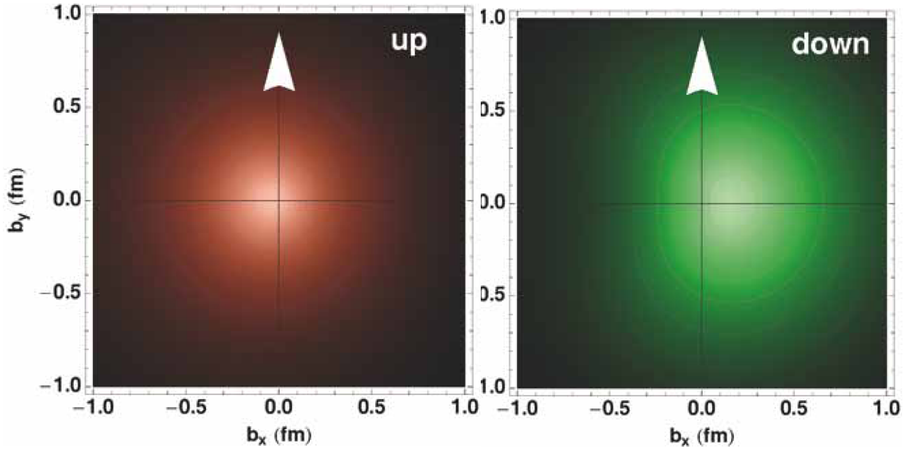

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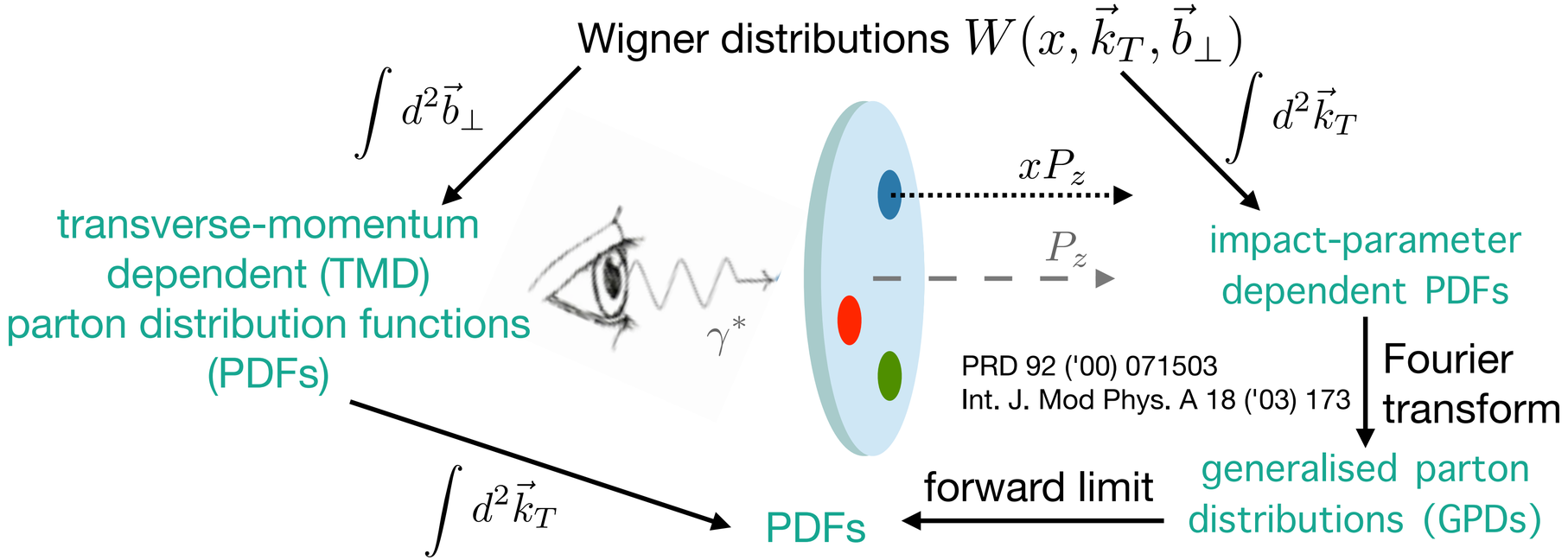


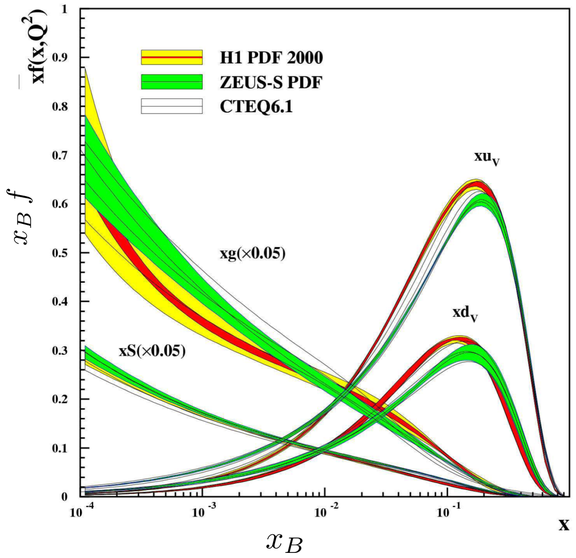

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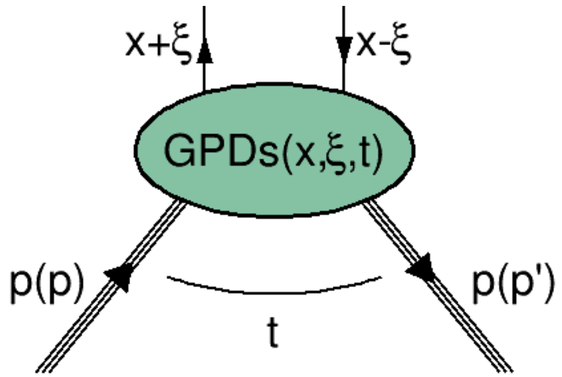


- x=average longitudinal momentum fraction
- 2ξ=longitudinal momentum transfer
- t=squared momentum transfer to hadron

- experimental access to t and ξ (related to Bjorken-x)
- in general: no experimental access to x

- dependence on scale $Q^2$

for spin-1/2 hadron:

Four parton helicity-conserving twist-2 GPDs

| | | |
|---|---|---|
| $H(x,\xi,t)$ | $E(x,\xi,t)$ | parton-spin independent |
| $\tilde{H}(x,\xi,t)$ | $\tilde{E}(x,\xi,t)$ | parton-spin dependent |
| proton helicity non flip | proton helicity flip | |

Four parton helicity-flip twist-2 GPDs

| | |
|---|---|
| $H_T(x,\xi,t)$ | $E_T(x,\xi,t)$ |
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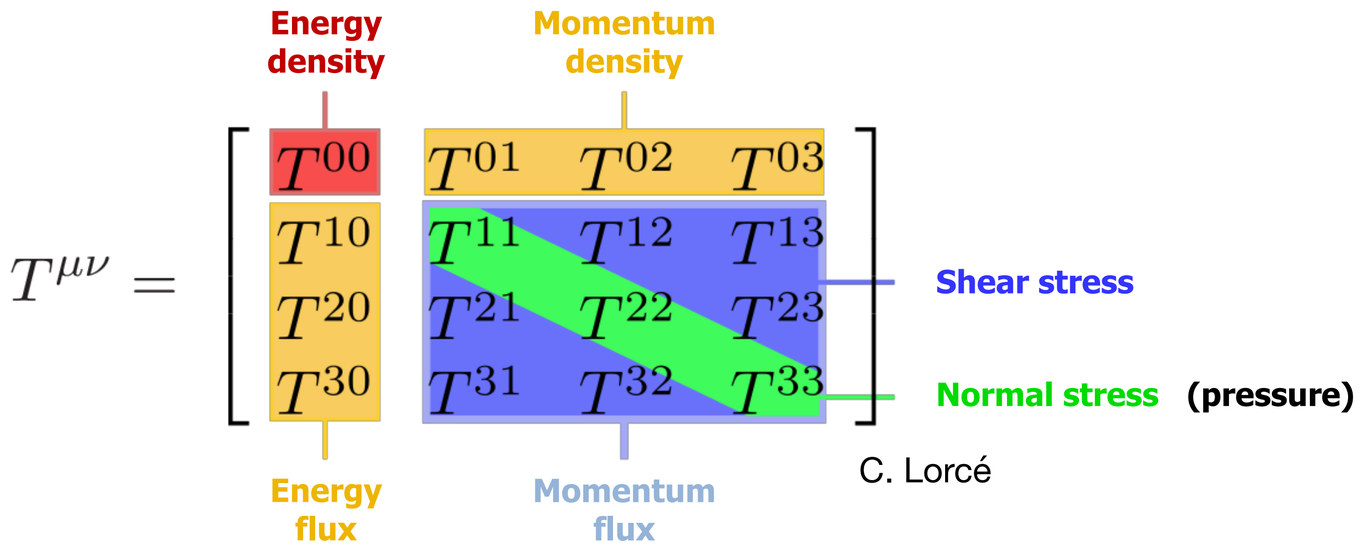
# The mechanical properties of the nucleon




C. Lorcé, H. Moutarde, A. P. Trawiński EPJ. C **79** ('19) 89

$$\left\langle p',s'\middle|T_a^{\mu\nu}(0)\middle|p,s\right\rangle = \bar{u}(p',s')\left\{\frac{P^\mu P^\nu}{M}A_a(t)+\frac{\Delta^\mu\Delta^\nu-\eta^{\mu\nu}\Delta^2}{M}C_a(t)+M\eta^{\mu\nu}\bar{C}_a(t)\right.$$
$$\left.+\frac{P^{\{\mu}i\sigma^{\nu\}\Delta}}{4M}\left[A_a(t)+B_a(t)\right]+\frac{P^{[\mu}i\sigma^{\nu]\Delta}}{4M}D_a(t)\right\}u(p,s)$$

$a = q, g$

$P = \frac{p'+p}{2};\ \Delta = p'-p;\ t = \Delta^2$

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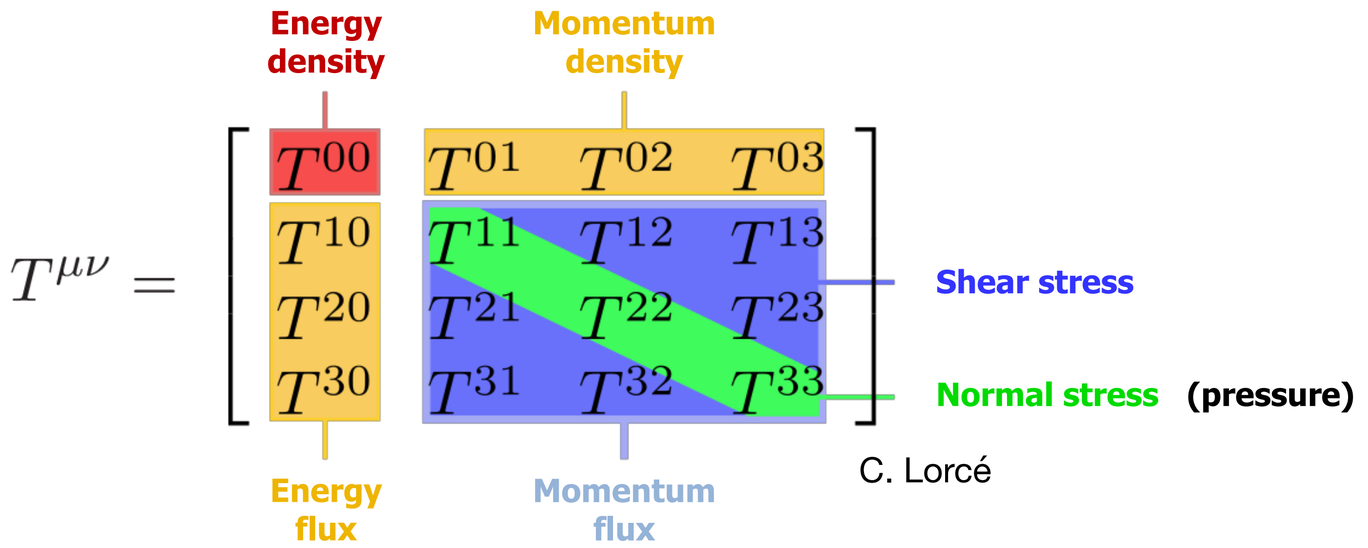


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Gravitational form factors

# GPDs and the mechanical properties of the nucleon

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$$\mathrm{Re}\mathcal{H}(\xi,t) \overset{\mathrm{lo}}{=} D(t) + \mathcal{P}\int_{-1}^{1} \mathrm{d}x \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(x,t)$$

from fits to experimental data

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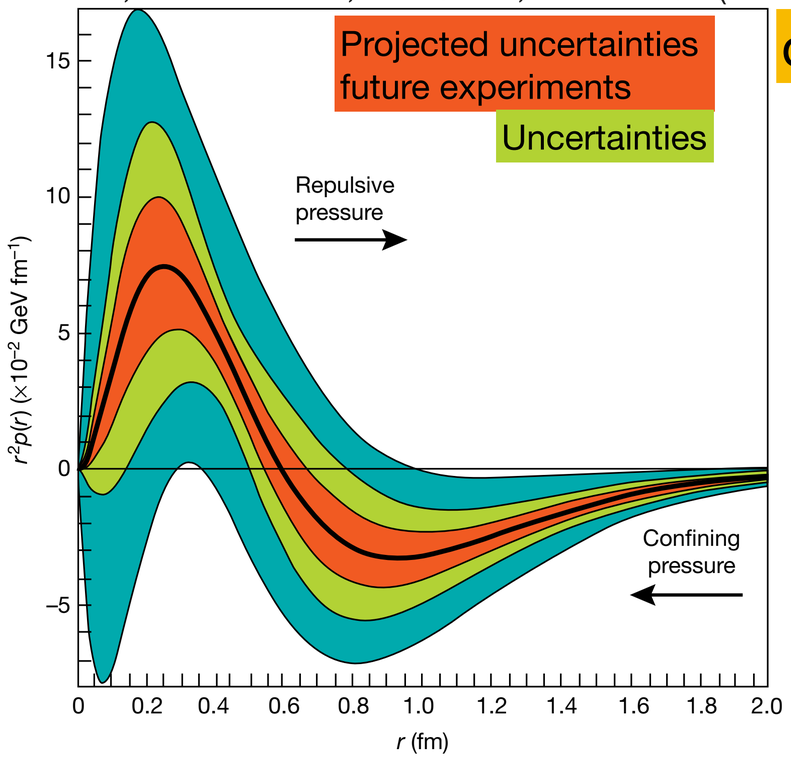


quarks only

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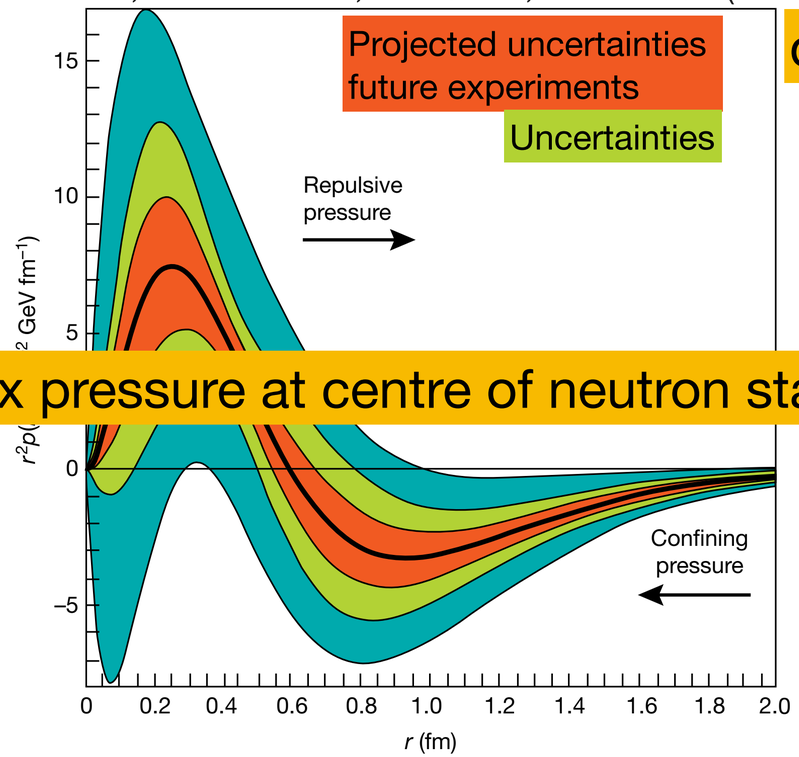


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10x pressure at centre of neutron stars!

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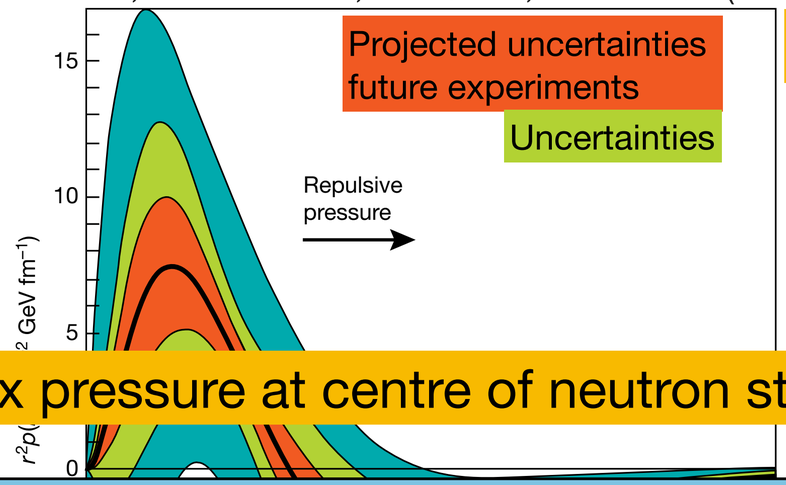


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K. Kumerički, *Nature* **570** (2019) E1–E2:
quark pressure consistent with zero
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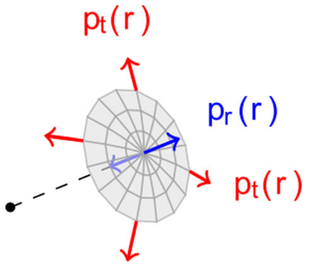


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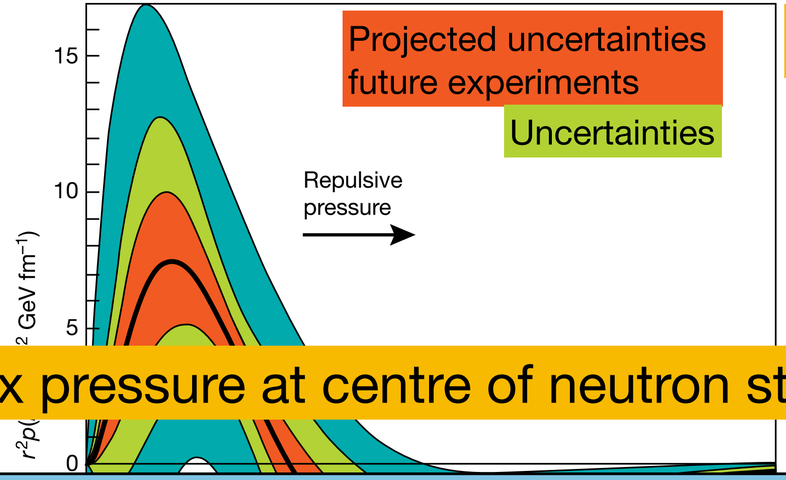


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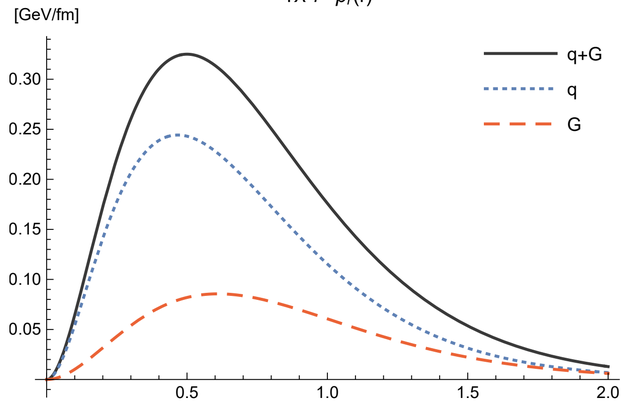
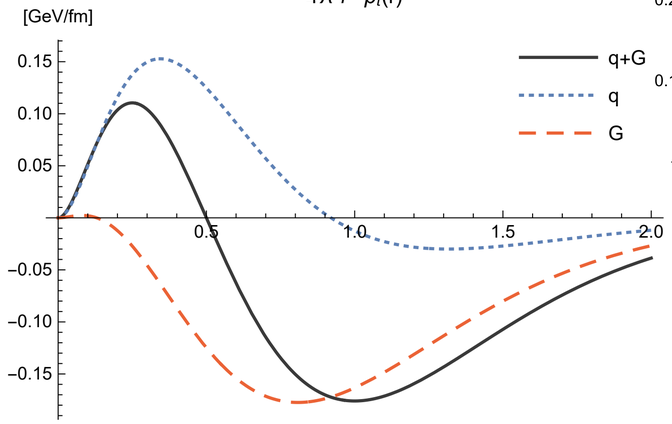
radial pressure

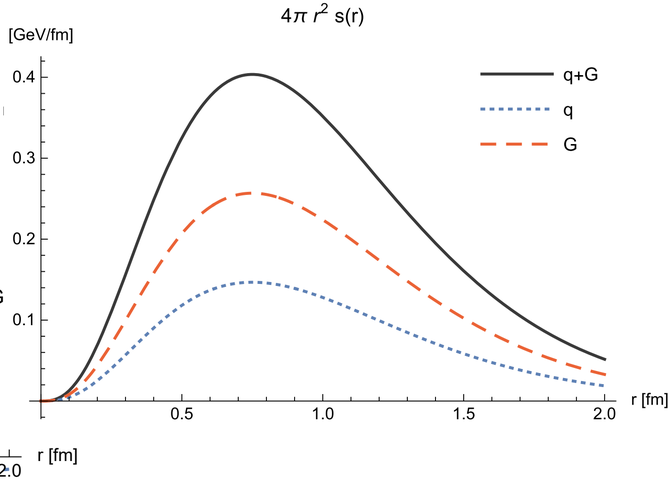



tangential pressure




pressure anisotropy

$$s(r) = p_r(r) - p_t(r)$$

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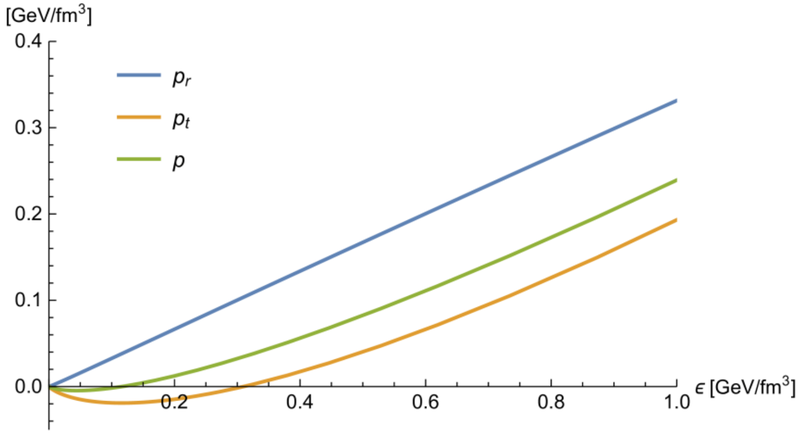
# The nucleon and compact stars

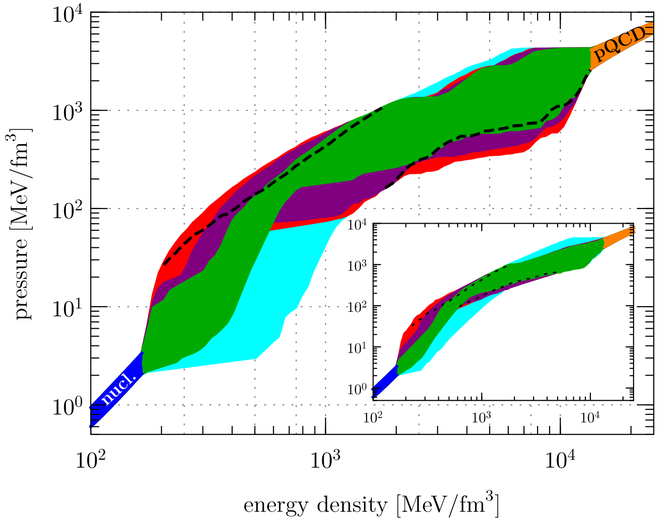
**Nucleon**  **Neutron star**

C. Lorcé, H. Moutarde, A. P. Trawiński EPJ. C **79** ('19) 89

E. Annala et al., Phys. Rev. Lett. **120** (2018) 172703 (2018)

Equation of state



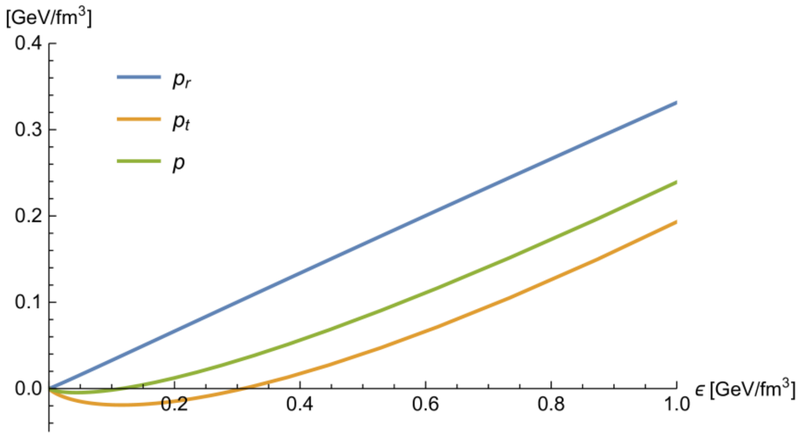
# The nucleon and compact stars

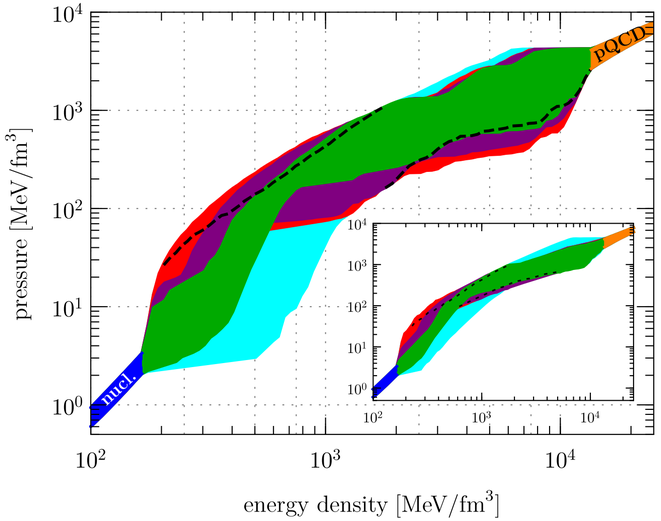
**Nucleon**  **Neutron star**

C. Lorcé, H. Moutarde, A. P. Trawiński EPJ. C **79** ('19) 89

E. Annala et al., Phys. Rev. Lett. **120** (2018) 172703 (2018)

## Equation of state




**Nucleon**  **Neutron star**

## Stability constraints

$$\varepsilon(0) < \infty,\ p(0) < \infty \text{ and } s(0) = 0;$$

$$\varepsilon(r) > 0 \text{ and } p_r(r) > 0;$$

$$\frac{\mathrm{d}\varepsilon(r)}{\mathrm{d}r} < 0 \text{ and } \frac{\mathrm{d}p_r(r)}{\mathrm{d}r} < 0.$$

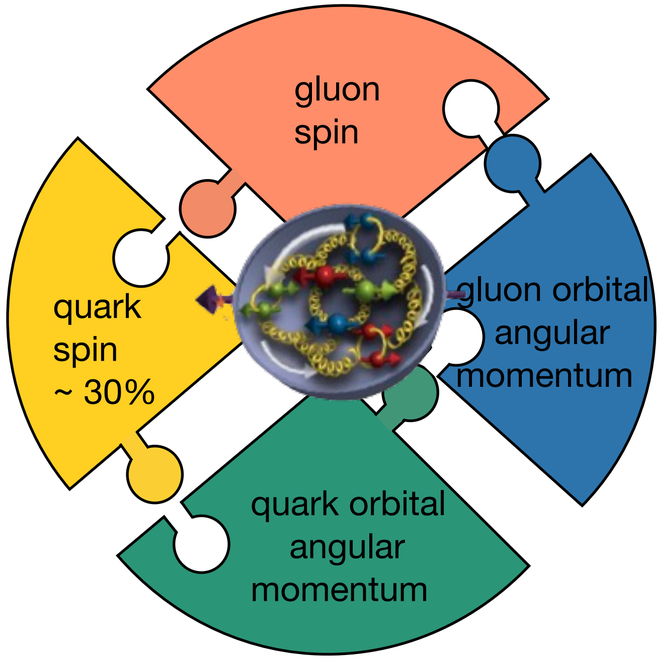
$$0 \leq v_{sr}^2(r) \leq 1 \text{ and } 0 \leq v_{st}^2(r) \leq 1;$$

$$|v_{st}^2(r) - v_{sr}^2(r)| \leq 1;$$

$$\Gamma(r) = \frac{\varepsilon(r) + p_r(r)}{p_r(r)}\, v_{sr}^2 > \frac{4}{3}.$$

$$\begin{aligned}
&\text{NEC} && \varepsilon(r) + p_i(r) \geq 0, && \\
&\text{WEC} && \varepsilon(r) + p_i(r) \geq 0 && \text{and} \quad \varepsilon(r) \geq 0, \\
&\text{SEC} && \varepsilon(r) + p_i(r) \geq 0 && \text{and} \quad \varepsilon(r) + 3\,p(r) \geq 0, \\
&\text{DEC} && \varepsilon(r) \geq |p_i(r)| &&
\end{aligned}$$

# GPDs and the nucleon-spin decomposition




proton spin decomposition (Ji)

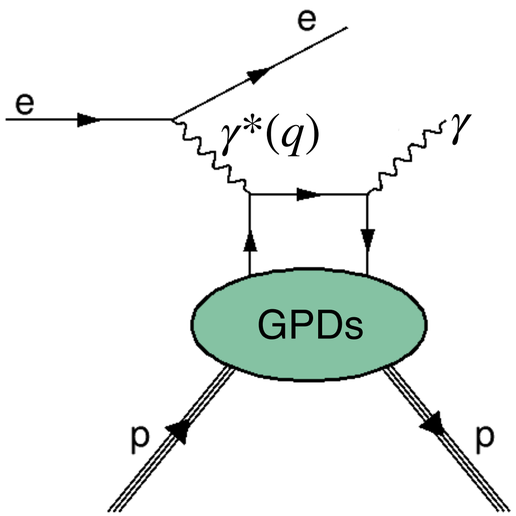
$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \sum_q L^q + J^G$$

30% quark orbital angular momentum gluon angular momentum

$$J = \lim_{t\to 0} \frac{1}{2} \int_{-1}^{1} dx\, x \left[H(x,\xi,t) + E(x,\xi,t)\right]$$

X. Ji, Phys. Rev. Lett. 78 (1997) 610

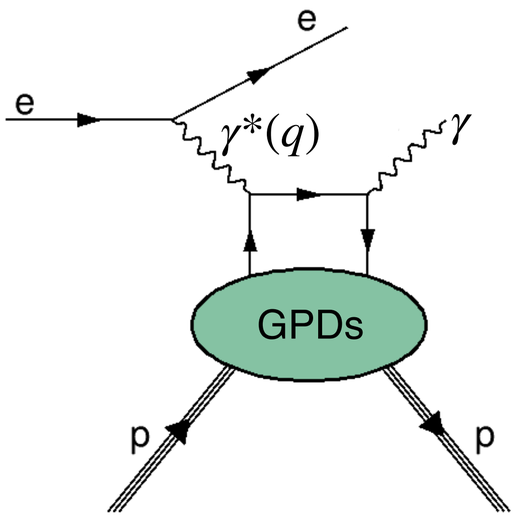
# Experimental access to GPDs via ep interactions




Deeply virtual Compton scattering
(DVCS)
Hard scale=large $Q^2=-q^2$

Theoretically cleanest process

# Experimental access to GPDs via ep interactions




Deeply virtual Compton scattering
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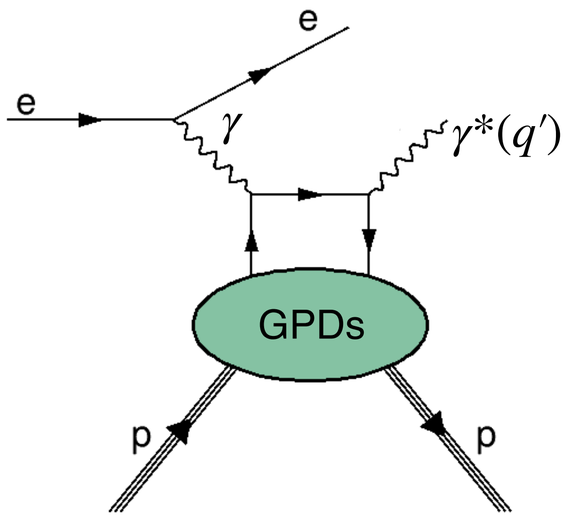
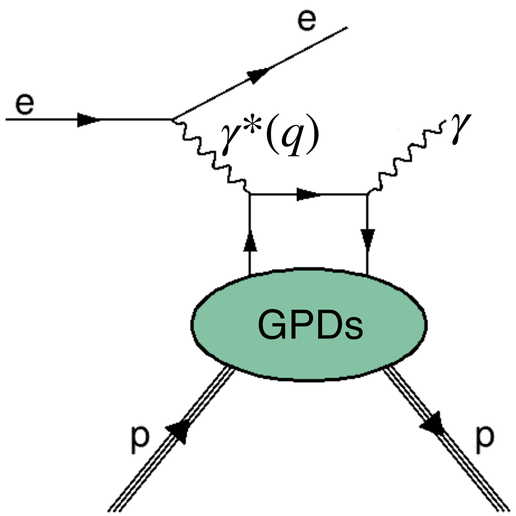



Timelike Compton scattering
(TCS)
Hard scale=large $Q'^2=q'^2$

Theoretically cleanest process

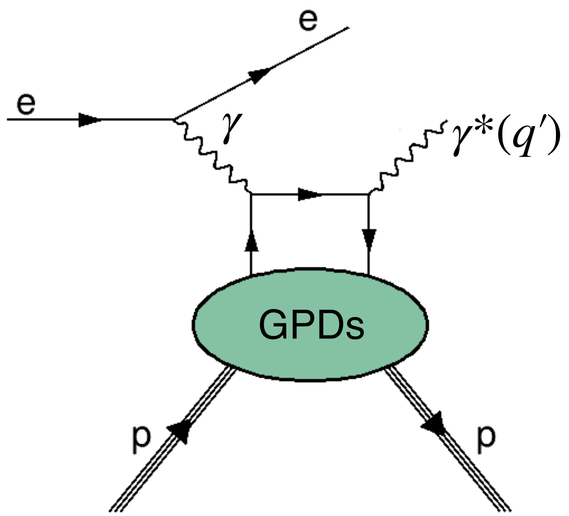
Crucial test for universality of GPDs

# Experimental access to GPDs via ep interactions




Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$

Theoretically cleanest process

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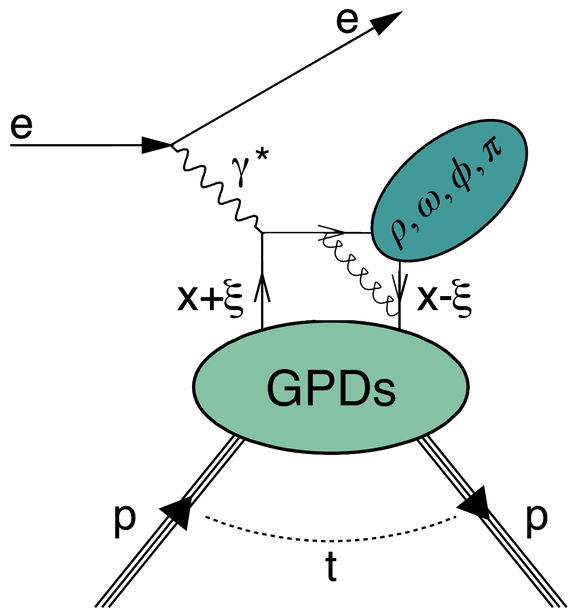
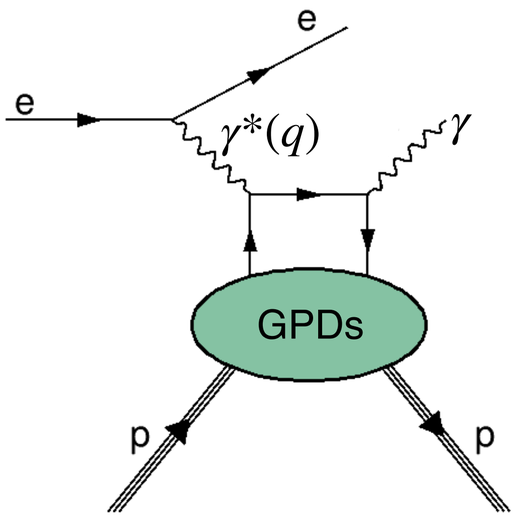
Crucial test for universality of GPDs




Hard exclusive meson production
Hard scale=large $Q^2$

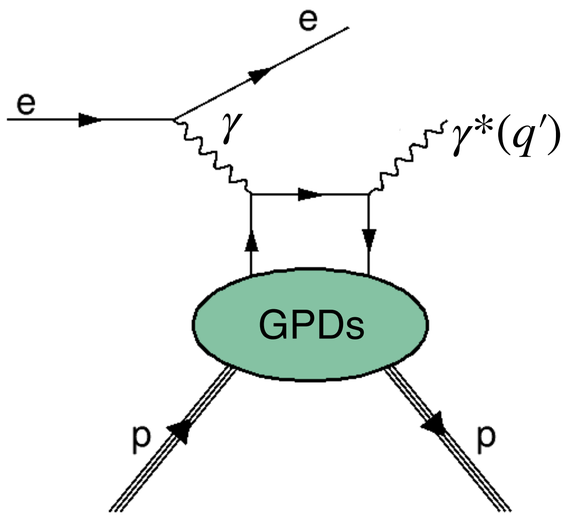
Sensitivity to different GPDs

# Experimental access to GPDs via ep interactions



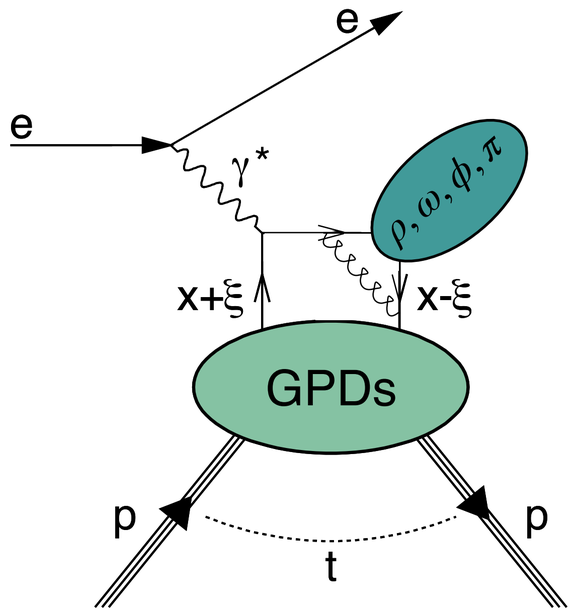

Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$

Theoretically cleanest process



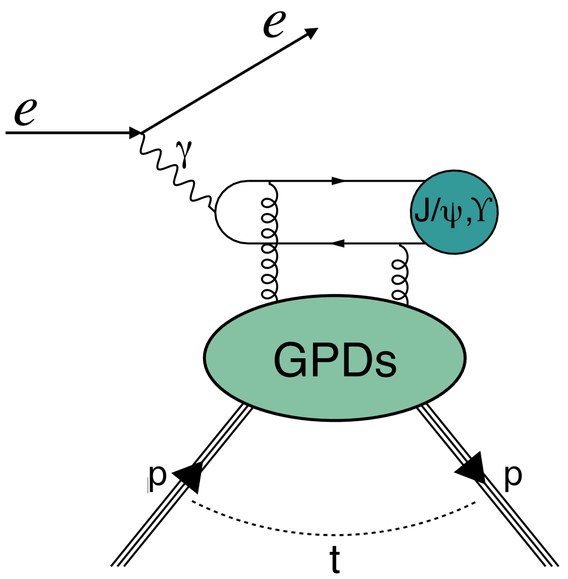

Timelike Compton scattering (TCS)
Hard scale=large $Q'^2=q'^2$

Crucial test for universality of GPDs




Hard exclusive meson production
Hard scale=large $Q^2$

Sensitivity to different GPDs

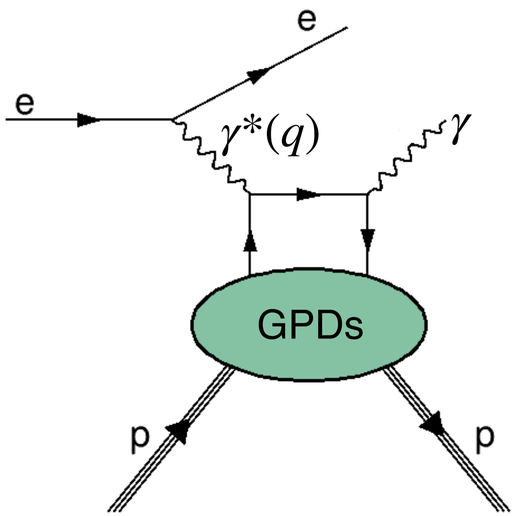



Exclusive meson photoproduction
Hard scale = large c/b-quark mass

Access to gluons

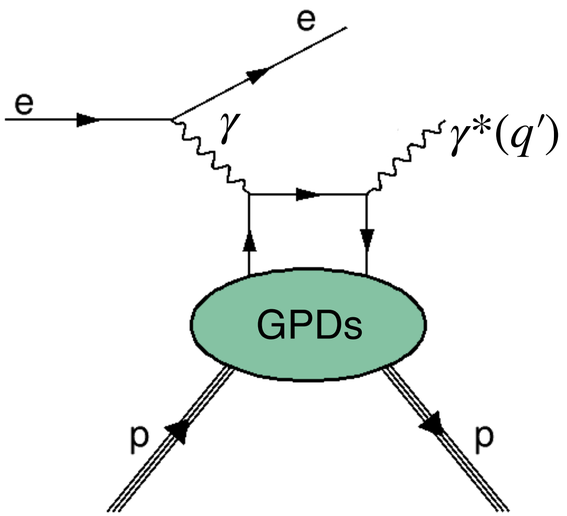
Sensitive to very low $x_B$

# Experimental access to GPDs via ep interactions



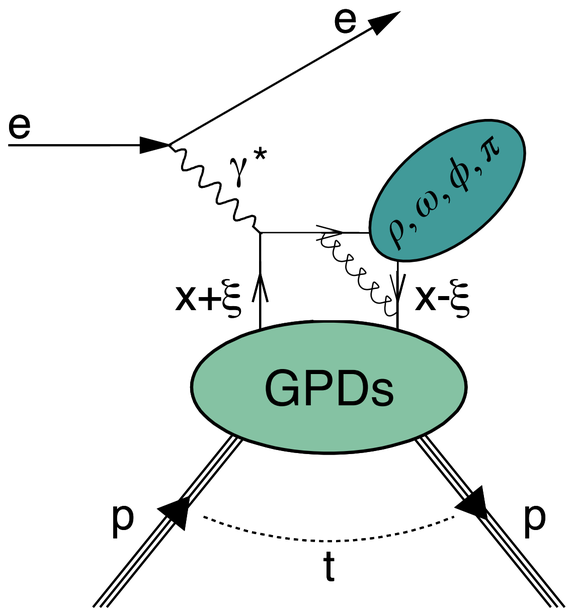

Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$

Theoretically cleanest process



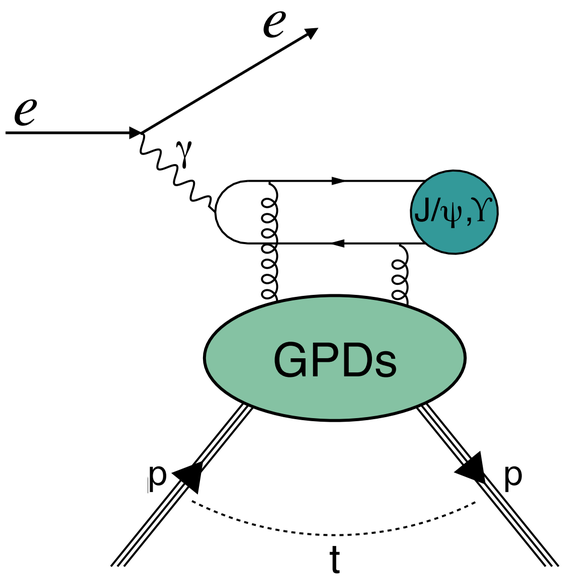

Timelike Compton scattering (TCS)
Hard scale=large $Q'^2=q'^2$

Crucial test for universality of GPDs




Hard exclusive meson production
Hard scale=large $Q^2$

Sensitivity to different GPDs




Exclusive meson photoproduction
Hard scale = large c/b-quark mass

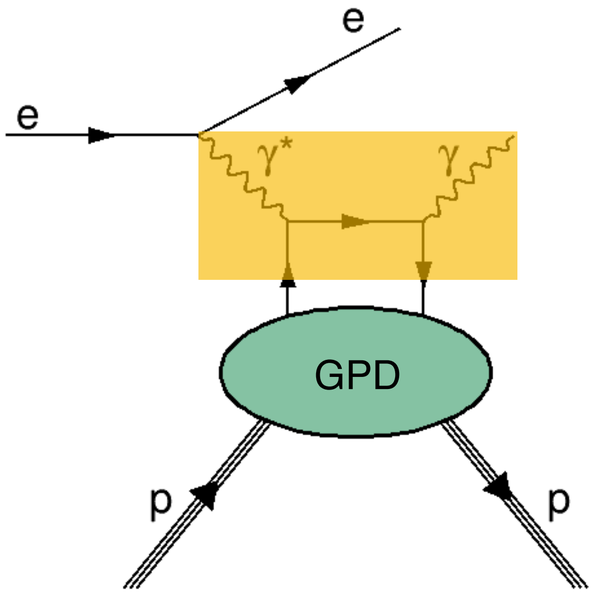
Access to gluons

Sensitive to very low $x_B$

Fixed-target experiments (COMPASS, HERMES, Hall A, B, C at JLab): → medium/large $x_B$ , quarks

Studied at collider experiments (H1 and ZEUS): → low $x_B$ , gluons

# Deeply Virtual Compton Scattering (DVCS)

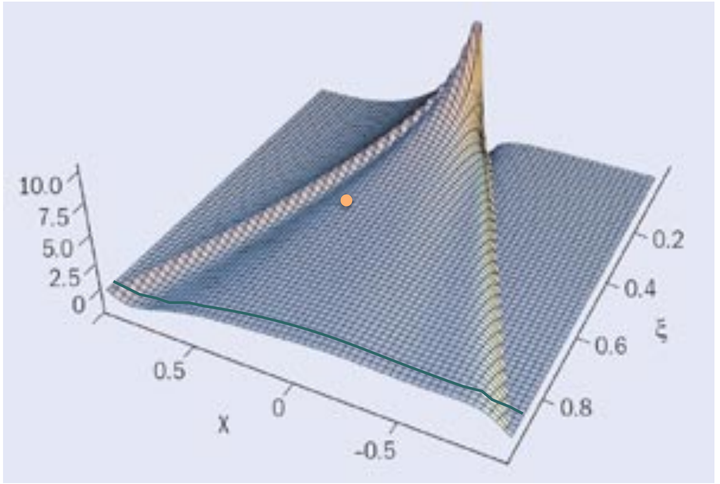



$$\sigma \sim \mathcal{F} = \int_{-1}^{+1} dx \left( \frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) F(x, \xi, t)$$

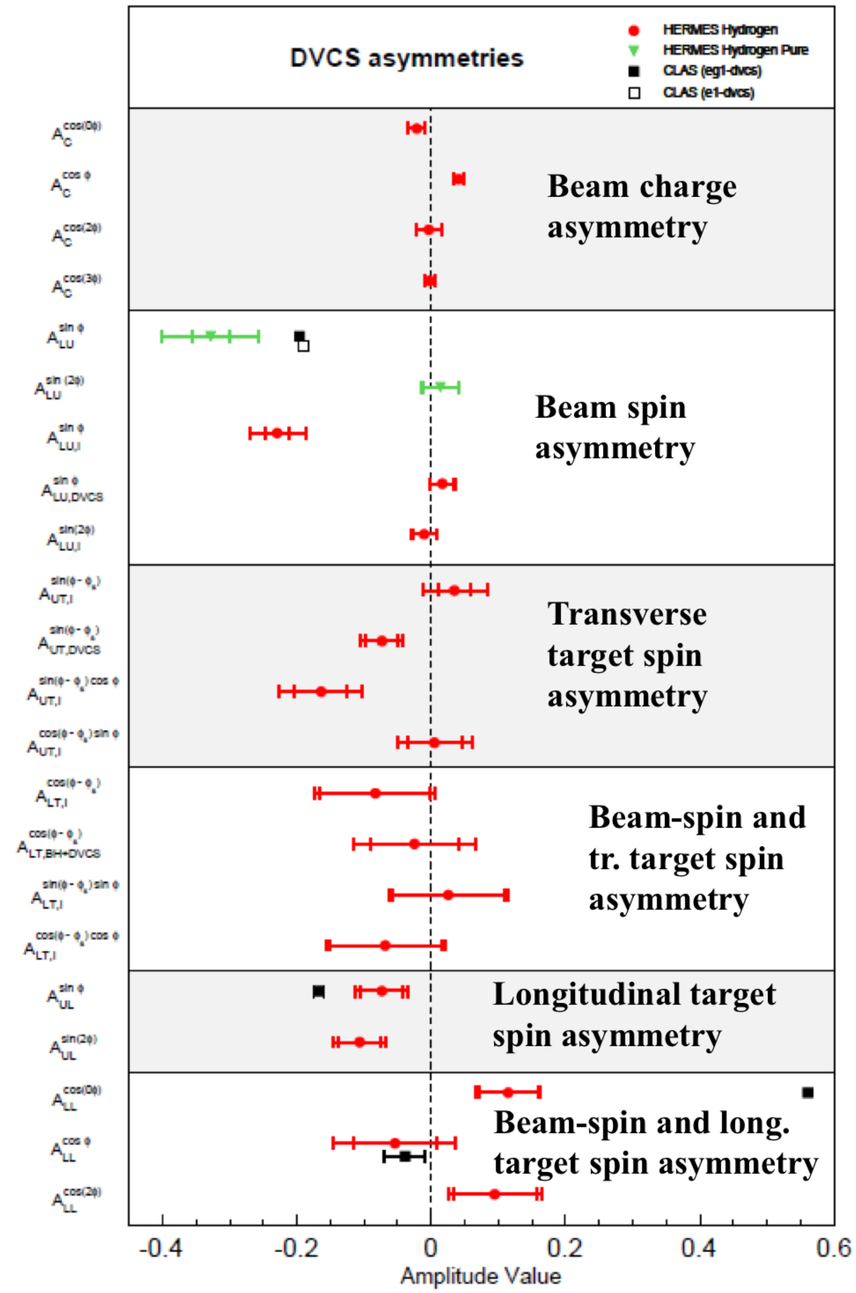
$\mathcal{F}$ : Compton Form Factor (CFF)

$F$ : GPD

| $\Re$(CFF) | $\Im$(CFF) |
|---|---|
| $\sim PV \int_{-1}^{+1} \frac{\text{GPDs}(x, \xi, t)}{x \pm \xi} dx$ | $\pm i\pi\, \text{GPDs}(\pm\xi, \xi, t) + \ldots$ |
| Cross sections<br>Beam-charge asymmetries<br>Double-spin asymmetries | single-spin asymmetries |



# DVCS: pioneering measurements

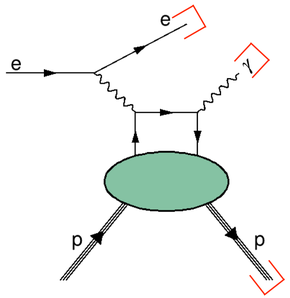



GPD $H$

GPD $E$

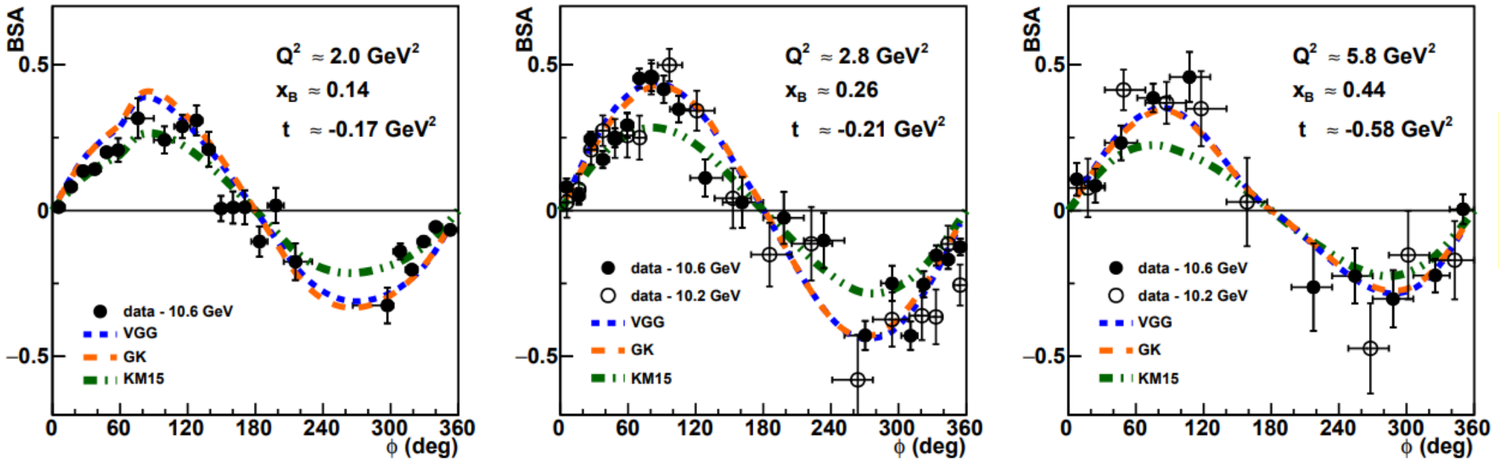
GPD $\tilde{H}$

# DVCS off the proton: CLAS12



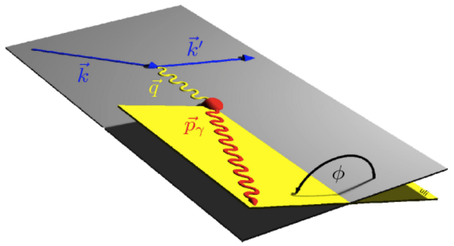

## Beam-spin asymmetry

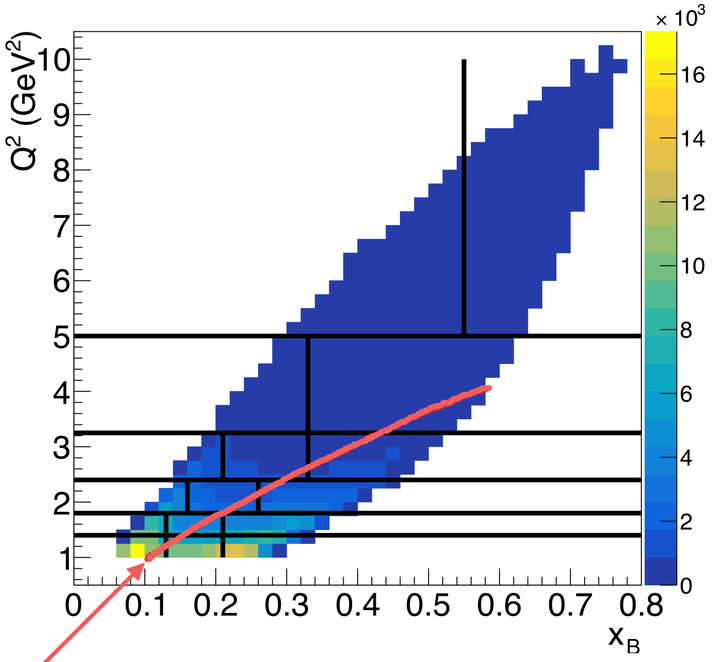
CLAS, Phys. Rev. Lett. **130** (2023), 211902




Vast extension of statistics: 64 bins in $x_B, Q^2, t$

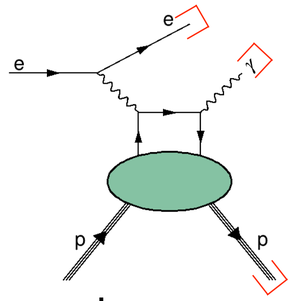
$$\Im m\left[F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M_p^2}F_2\mathcal{E}\right]$$



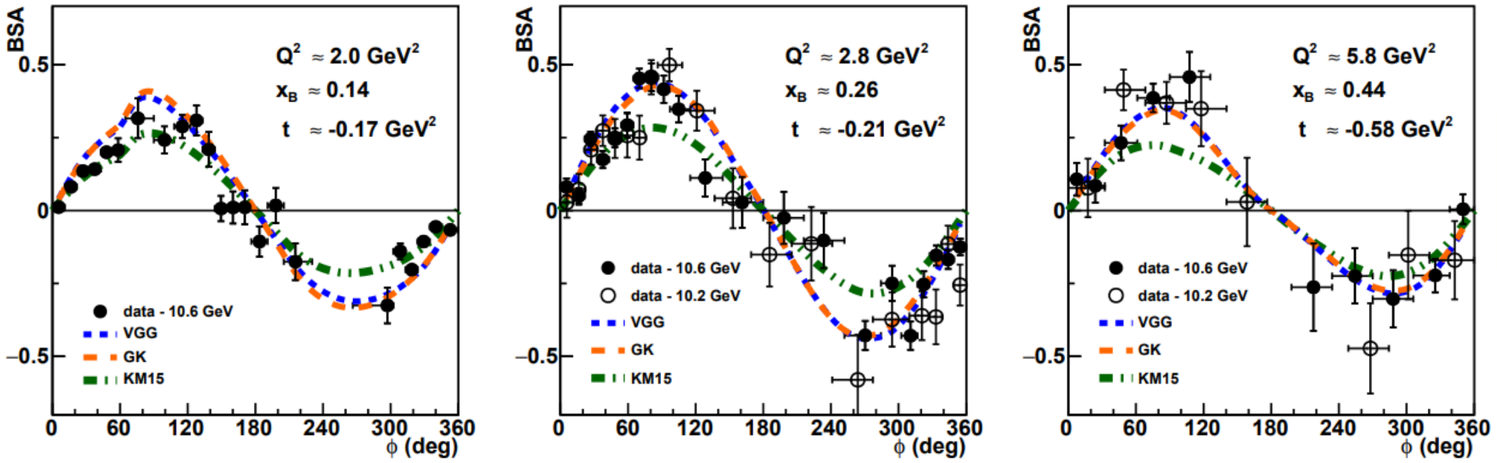

CLAS 6 GeV

# DVCS off the proton: CLAS12




## Beam-spin asymmetry

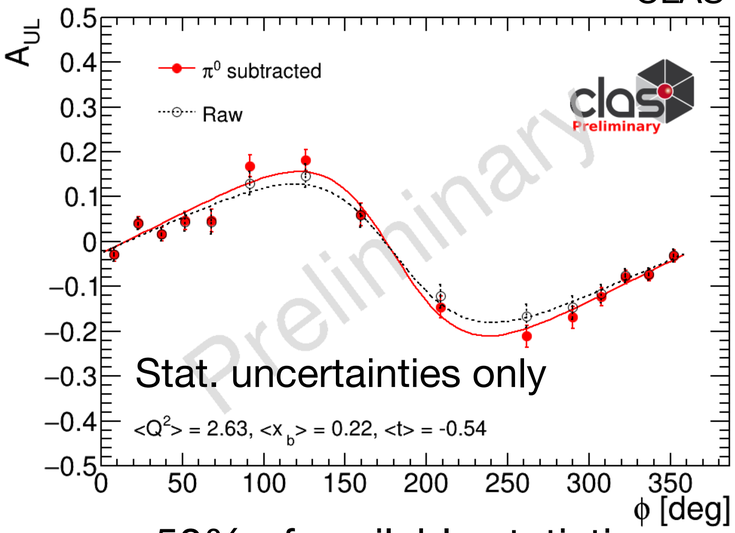
CLAS, Phys. Rev. Lett. **130** (2023), 211902




Vast extension of statistics: 64 bins in $x_B, Q^2, t$

## Longitudinal target-spin asymmetry

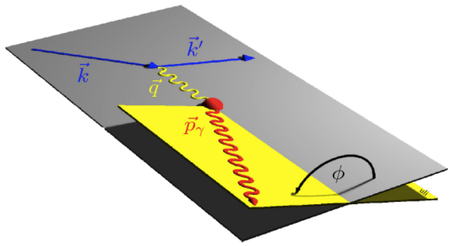
CLAS




50% of available statistics

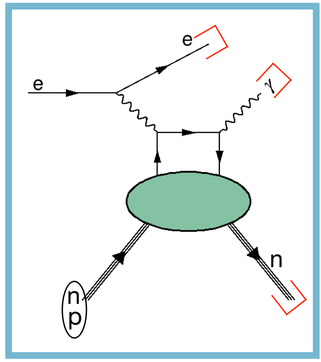
$$\Im m\left[F_1\mathcal{H}+\xi(F_1+F_2)\tilde{\mathcal{H}}-\frac{t}{4M_p^2}F_2\mathcal{E}\right]$$

$$\Im m\left[F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)\left(\mathcal{H}+\frac{x_B}{2}\mathcal{E}\right)-\xi\left(\frac{x_B}{2}F_1+\frac{t}{4M_p^2}F_2\right)\tilde{\mathcal{E}}\right]$$




Combination: clean separation of $\Im m\mathcal{H}$ and $\Im m\tilde{\mathcal{H}}$

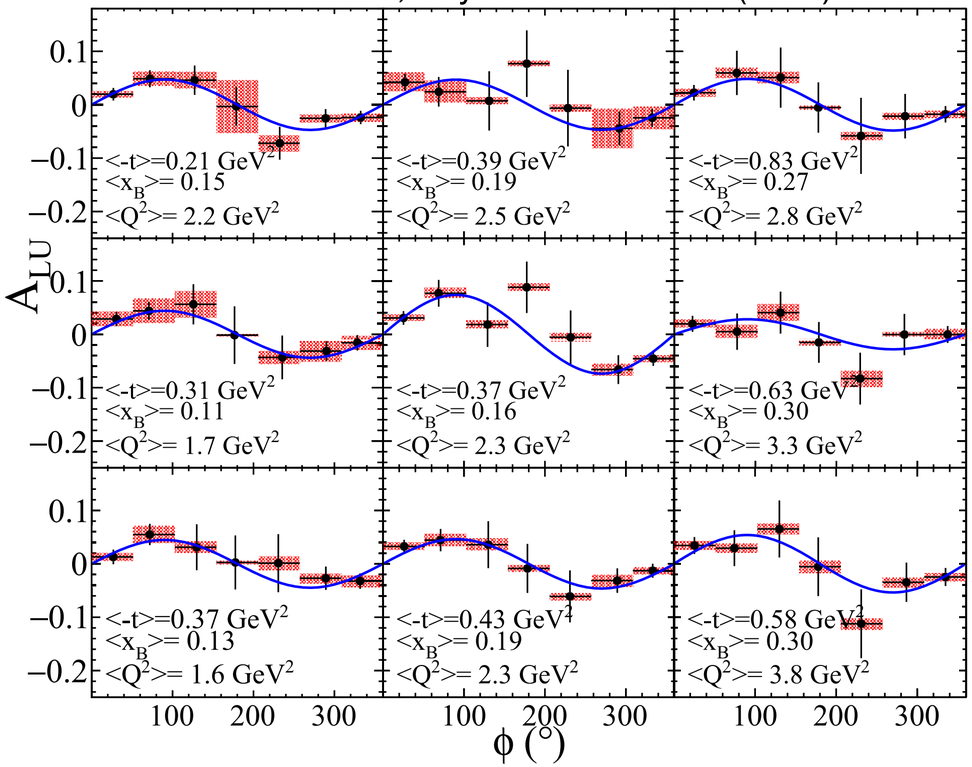
# DVCS off the neutron: CLAS12




First time detection of active neutron

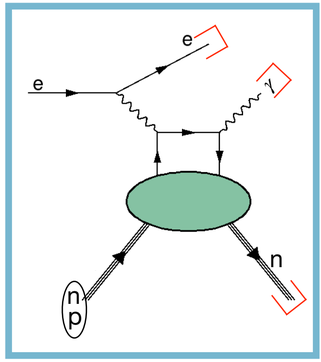
Beam-spin asymmetry

CLAS, Phys. Rev. Lett. **133** (2024) 211903




$$\Im m\left[F_1\mathcal{H} + \xi(F_1+F_2)\mathcal{H} - \frac{t}{4M_n^2}F_2\mathcal{E}\right]$$

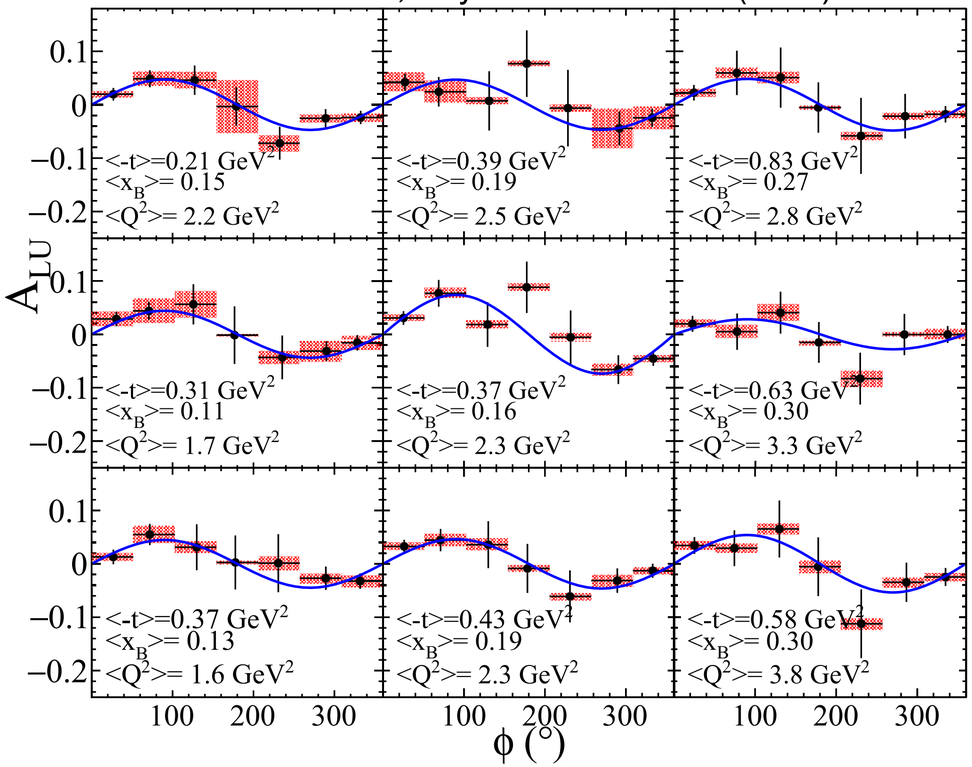
# DVCS off the neutron: CLAS12




First time detection of active neutron

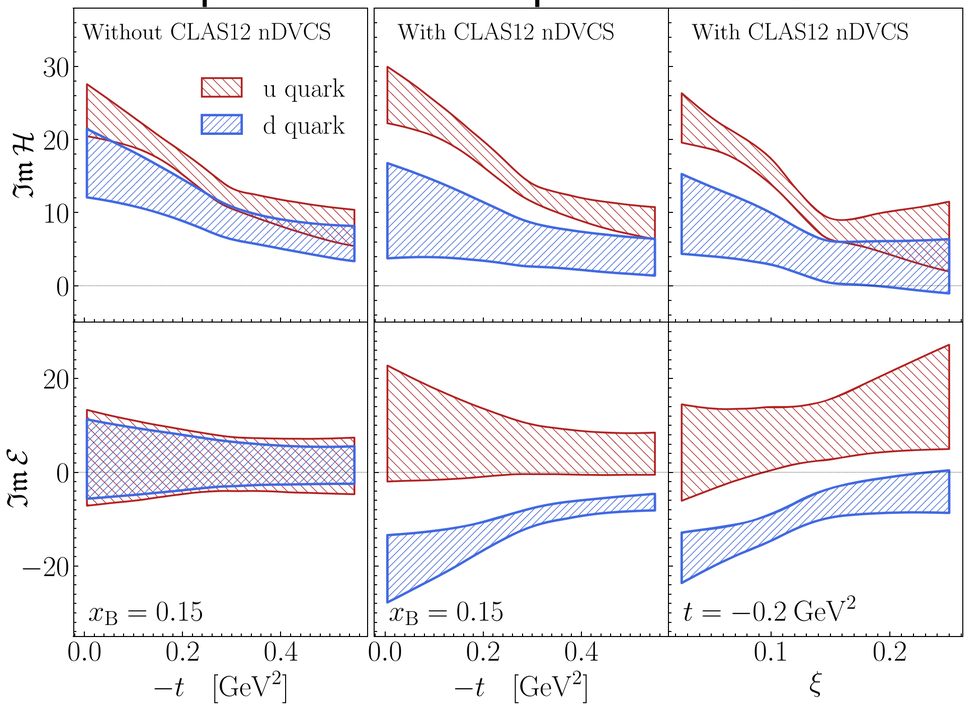
## Beam-spin asymmetry

CLAS, Phys. Rev. Lett. **133** (2024) 211903

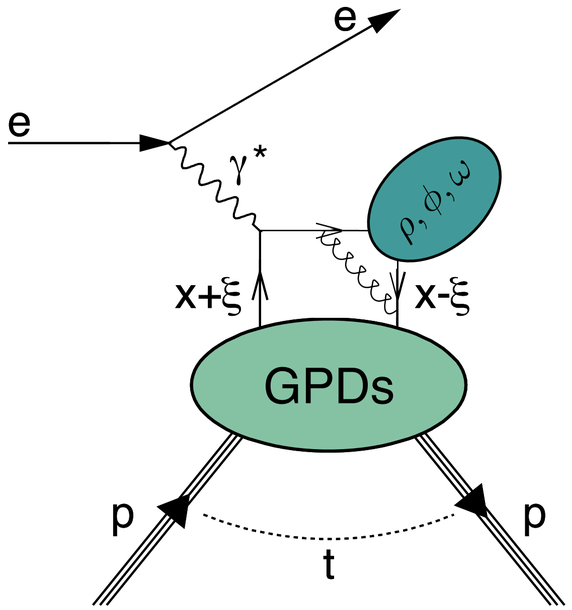



$$\Im m\left[F_1\mathcal{H} + \xi(F_1+F_2)\mathcal{H} - \frac{t}{4M_n^2}F_2\mathcal{E}\right]$$

## Measurements with p and n → quark-flavour separation fo GPDs



# Exclusive vector-meson production

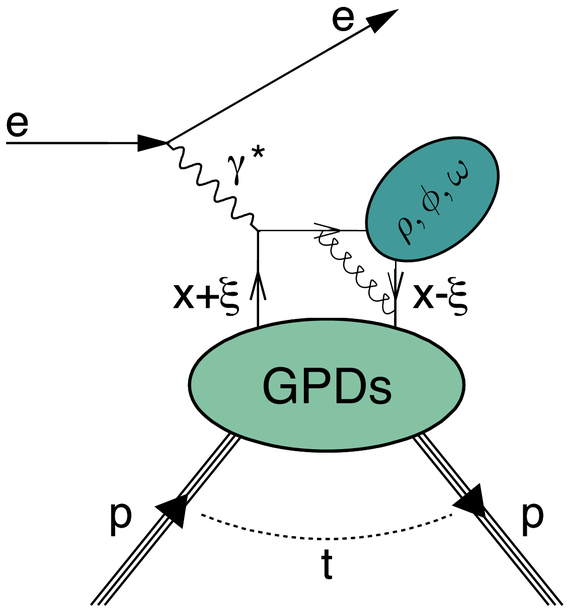


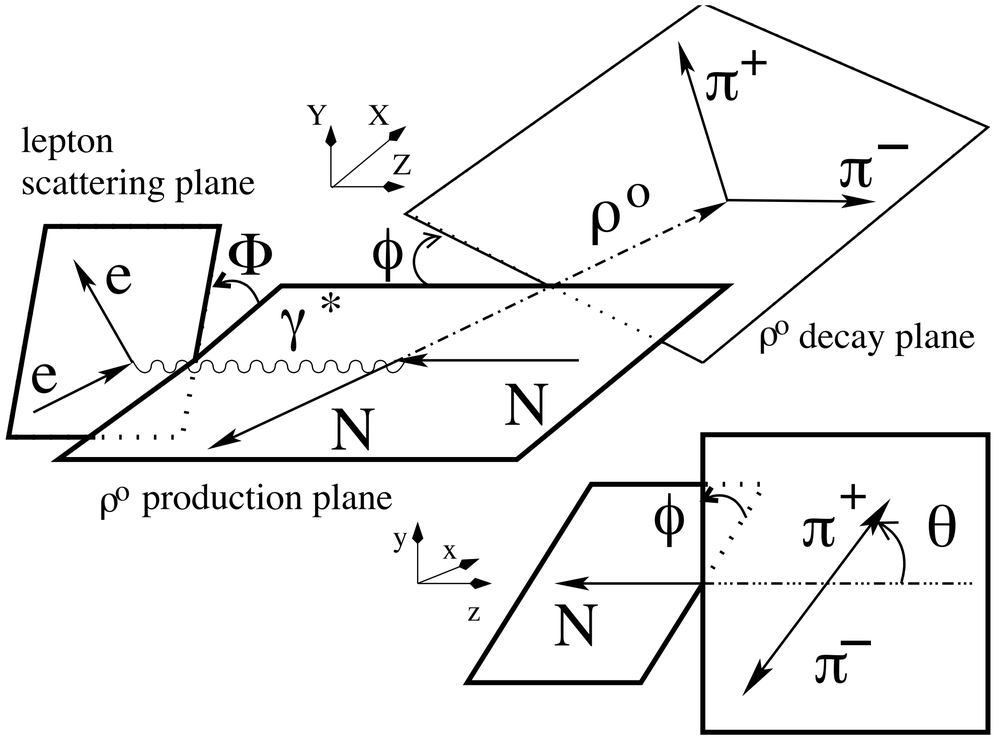

Access to GPDs

$H, E, H_T, \bar{E}_T = 2\tilde{H}_T + E_T$

$\tilde{H}, \tilde{E}$

# Exclusive vector-meson production




Access to GPDs

$H, E, H_T, \bar{E}_T = 2\tilde{H}_T + E_T$

$\tilde{H}, \tilde{E}$

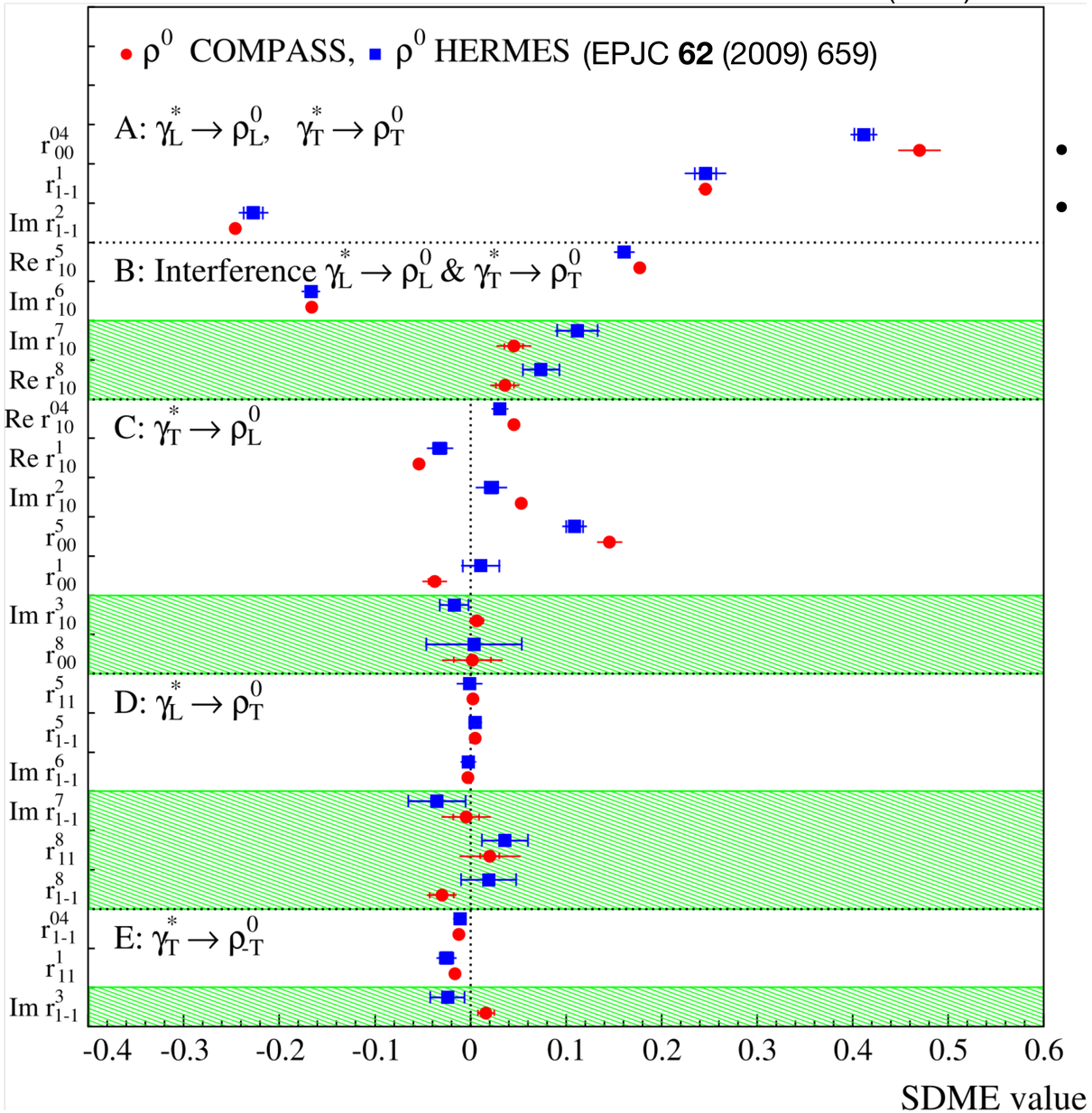
Fit angular distribution of decay pions $\mathcal{W}(\Phi, \phi, \Theta)$ and extract either Spin Density Matrix Elements (SDMEs) or helicity amplitude ratios

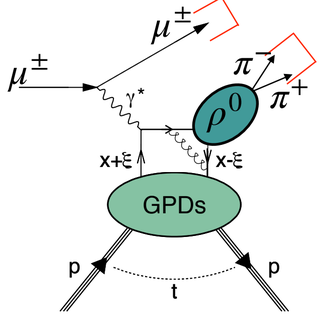
# Exclusive $\rho^0$ production : SDMEs

COMPASS: EPJC **83** (2023) 924

Unpolarised proton target

longitudinally polarised lepton beam




- 5 classes of SDMEs
- unpolarised and polarised SDMEs

HERMES:

$\langle Q^2 \rangle = 1.96$ GeV$^2$

$\langle W \rangle = 4.8$ GeV$^2$

COMPASS:

$\langle Q^2 \rangle = 2.40$ GeV$^2$

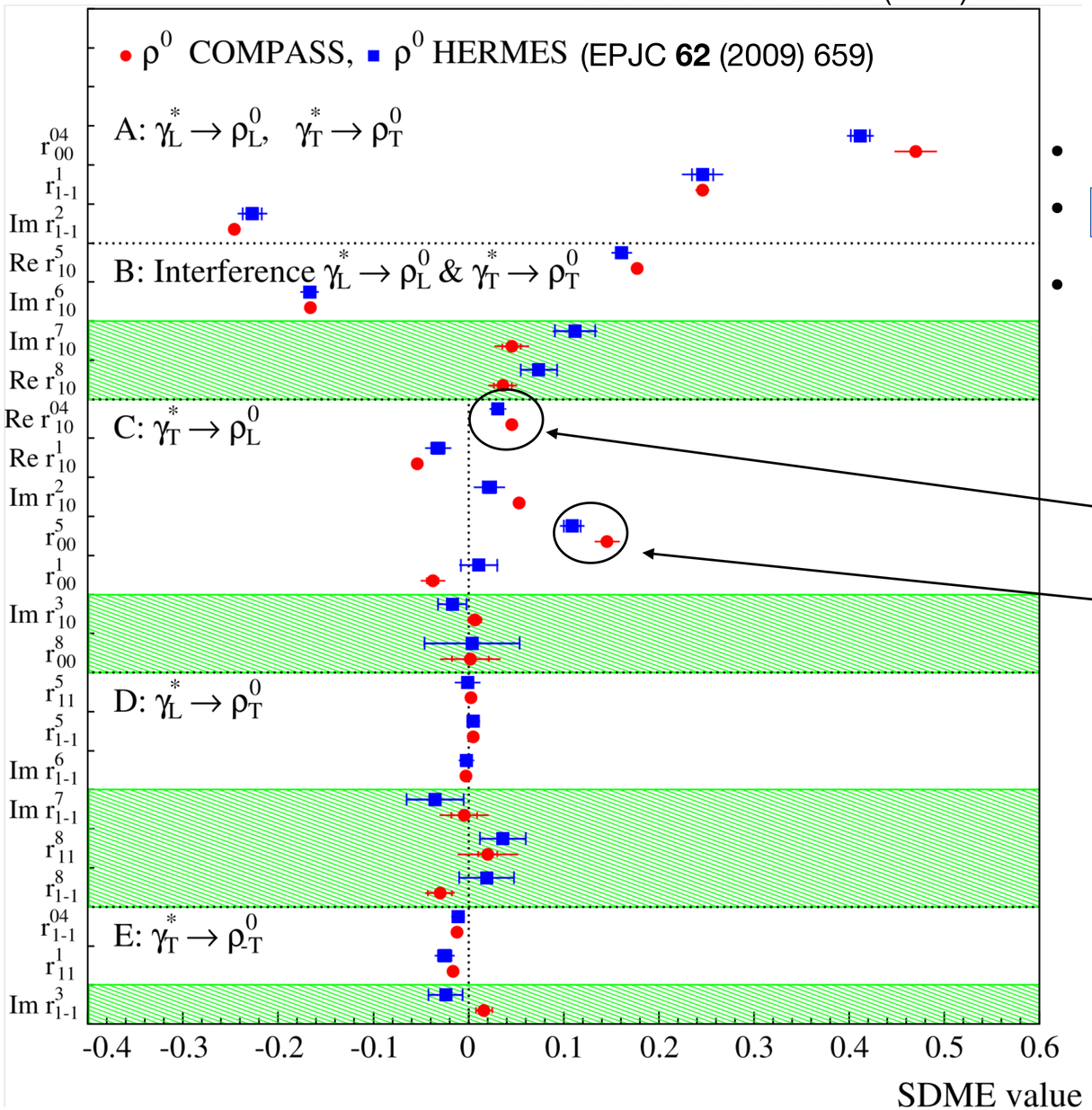
$\langle W \rangle = 9.9$ GeV$^2$

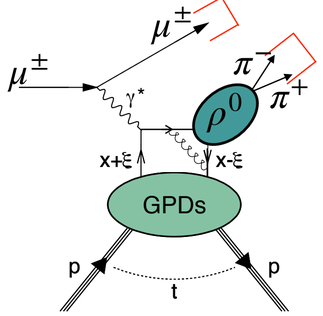
# Exclusive $\rho^0$ production : SDMEs

Unpolarised proton target

longitudinally polarised lepton beam

COMPASS: EPJC **83** (2023) 924




- 5 classes of SDMEs
- unpolarised and polarised SDMEs
- s-channel helicity conservation ($\lambda_{\gamma^*} = \lambda_{\rho^0}$):
  - class A&B: fulfilled
  - class C: strong violation:

$\Re r^{04}_{10} \neq 0$ by $> 4\sigma$

$\Re r^{5}_{00} \neq 0$ by $> 9\sigma$

$H_T, \bar{E}_T = 2\tilde{H}_T + E_T$

(In Goloskokov-Kroll model: $k_\perp$ factorisation assumed)

HERMES:

$\langle Q^2 \rangle = 1.96$ GeV$^2$

$\langle W \rangle = 4.8$ GeV$^2$

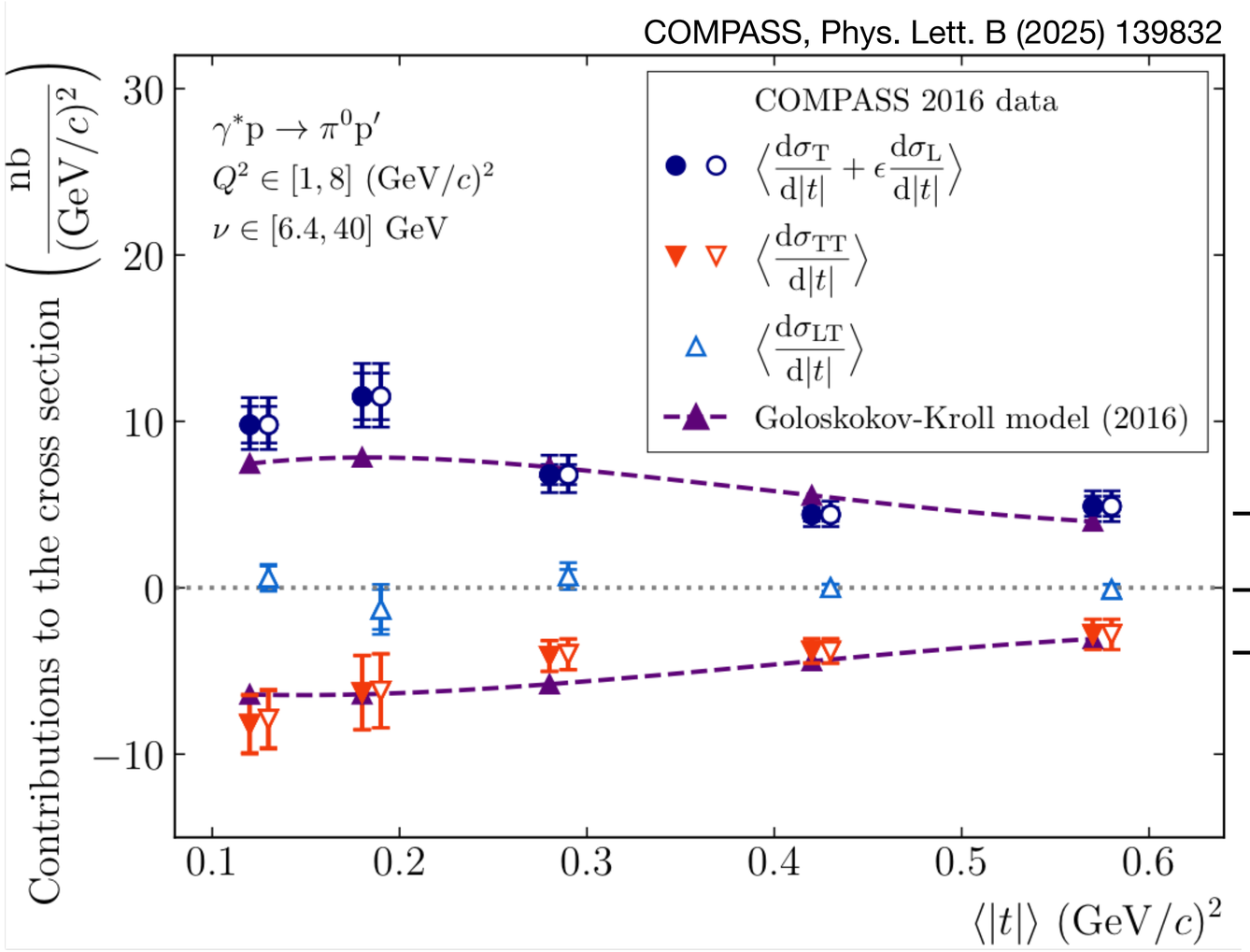
COMPASS:

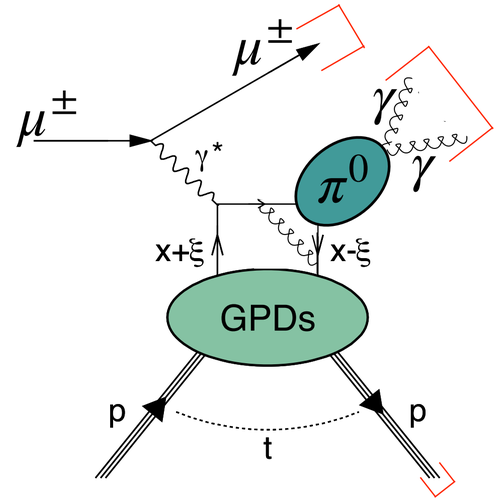
$\langle Q^2 \rangle = 2.40$ GeV$^2$

$\langle W \rangle = 9.9$ GeV$^2$

# Exclusive $\pi^0$ production

Access to transversity GPDs




$\longrightarrow \tilde{H}, \tilde{E}, H_T, \bar{E}_T$

$\longrightarrow H_T, \tilde{E}$

$\longrightarrow \bar{E}_T = 2\tilde{H}_T + E_T$

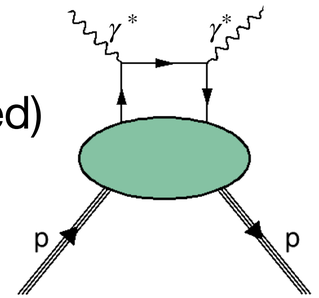
See also:

- JLab Hall A, PRL **117** (2016) 262001
- CLAS, PLB **849** (2024) 138459
- Expected results from JLab Hall C

# Upcoming DIS experiments probing GPDs

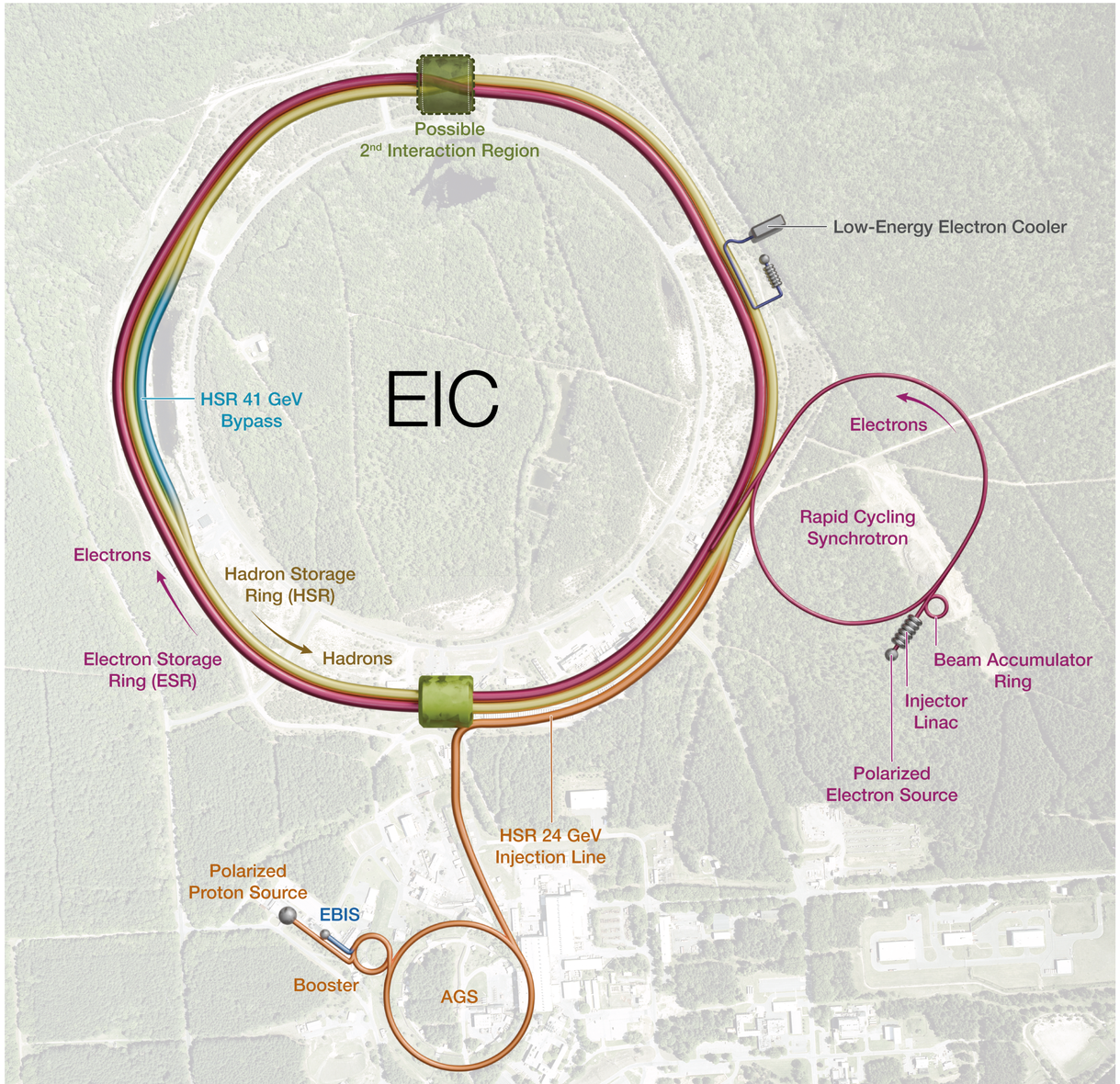
- Jefferson Lab:
  - ALERT at CLAS (analysis ongoing): DVCS and meson production on $^4$He: spin-0 target → only 1 GPD
  - Addition of neutral spectrometer at Hall C: DVCS, exclusive $\pi^0$ off proton (analysis ongoing)
  - Transverse target at CLAS approved (~4 years) → access to GPD $E$
  - Double DVCS at CLAS approved (~5–6 years) and at Hall A with SoLID (C1 approved)

    → access to GPDs at $x \neq \xi$
  - Additional proposals:
    - Positron beam at Jefferson Lab → access to $Re\mathcal{H}$ through beam-charge asymmetry
    - Upgrade to JLab at 22 GeV




- EIC

# Future: the electron-ion collider (EIC)




- Based on RHIC:
  - use exiting hadron storage ring
    energy: 41, 100–275 GeV
  - add electron storage ring in RHIC tunnel
    energy: 5–10 GeV

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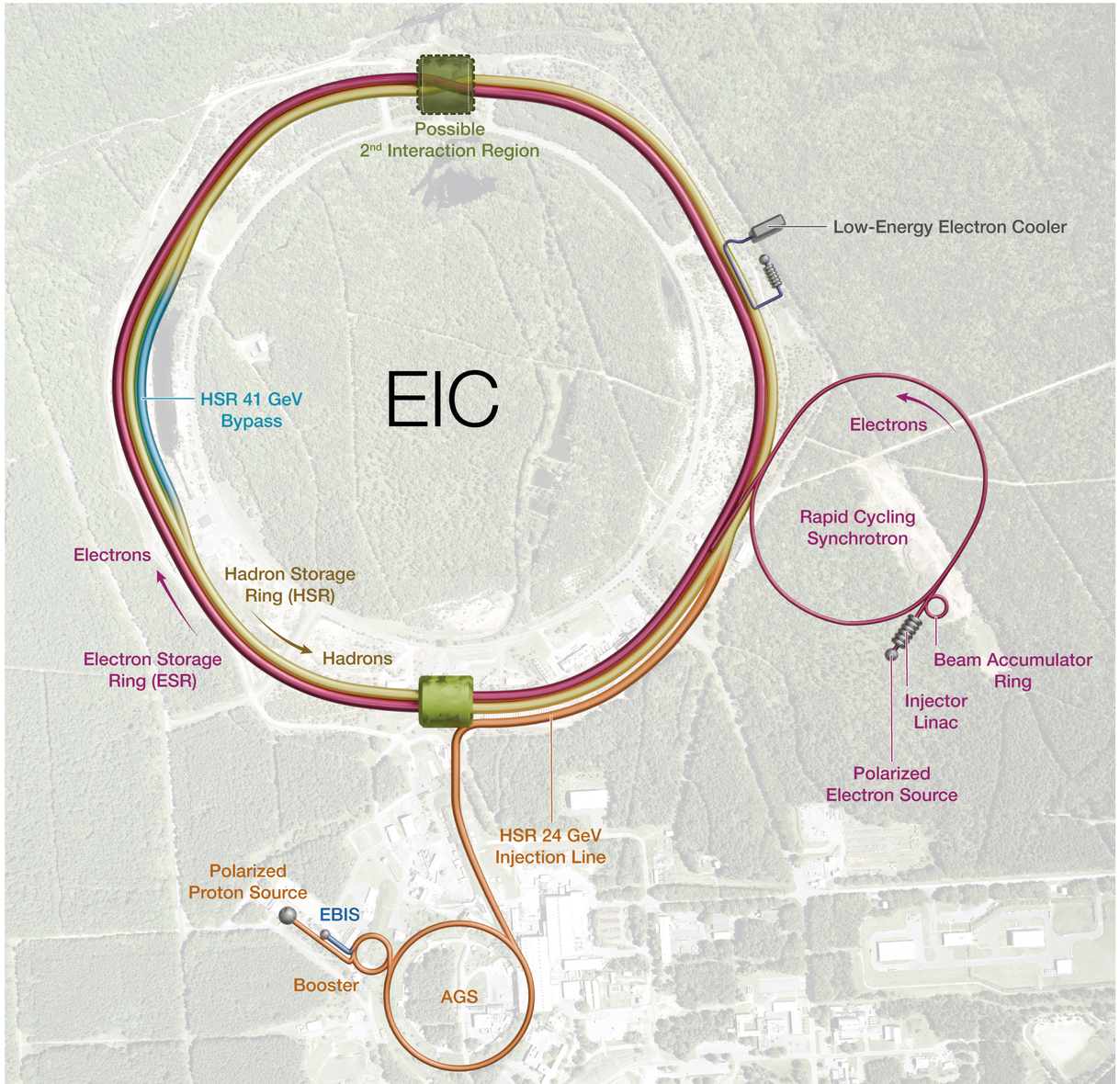


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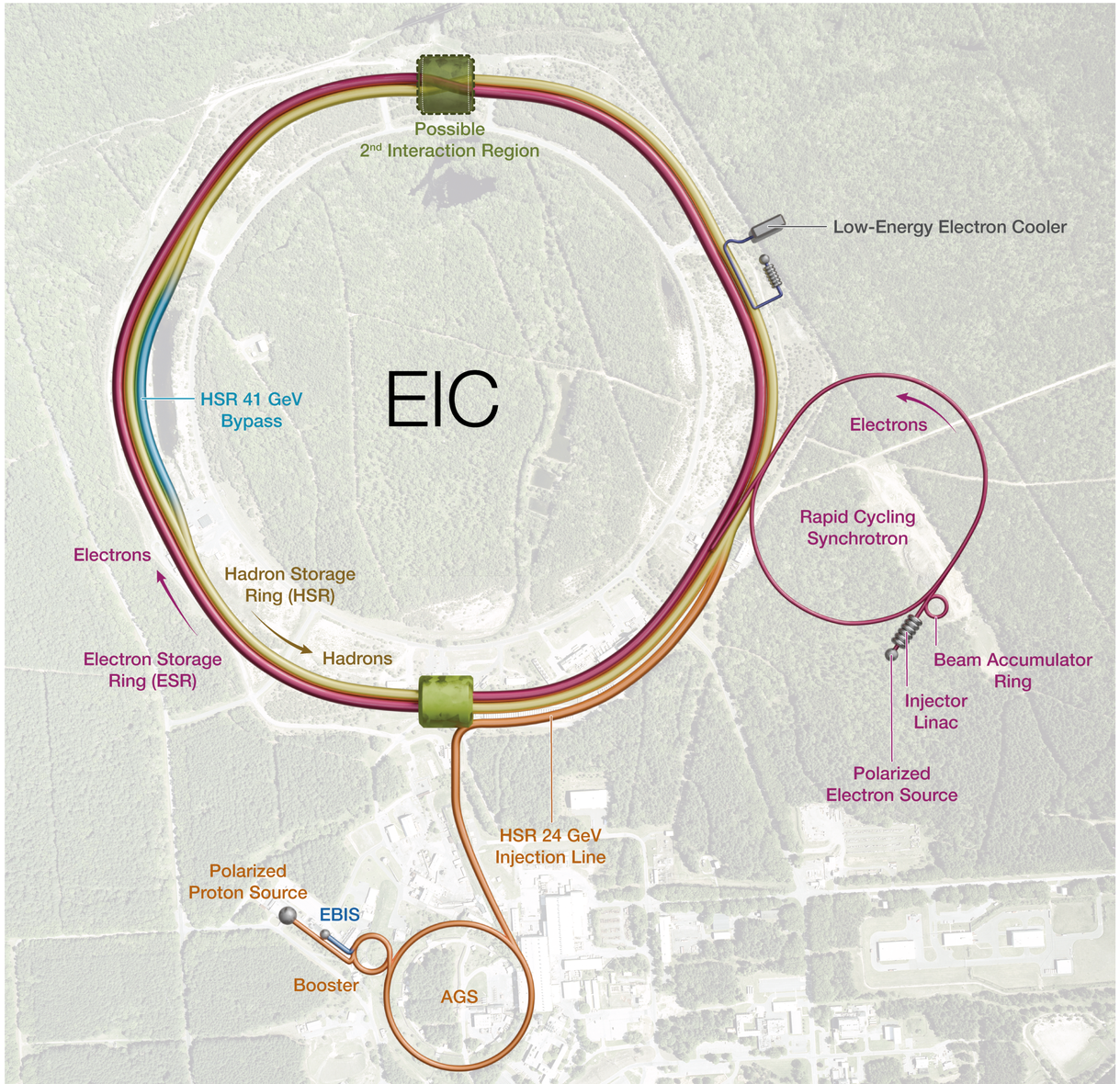


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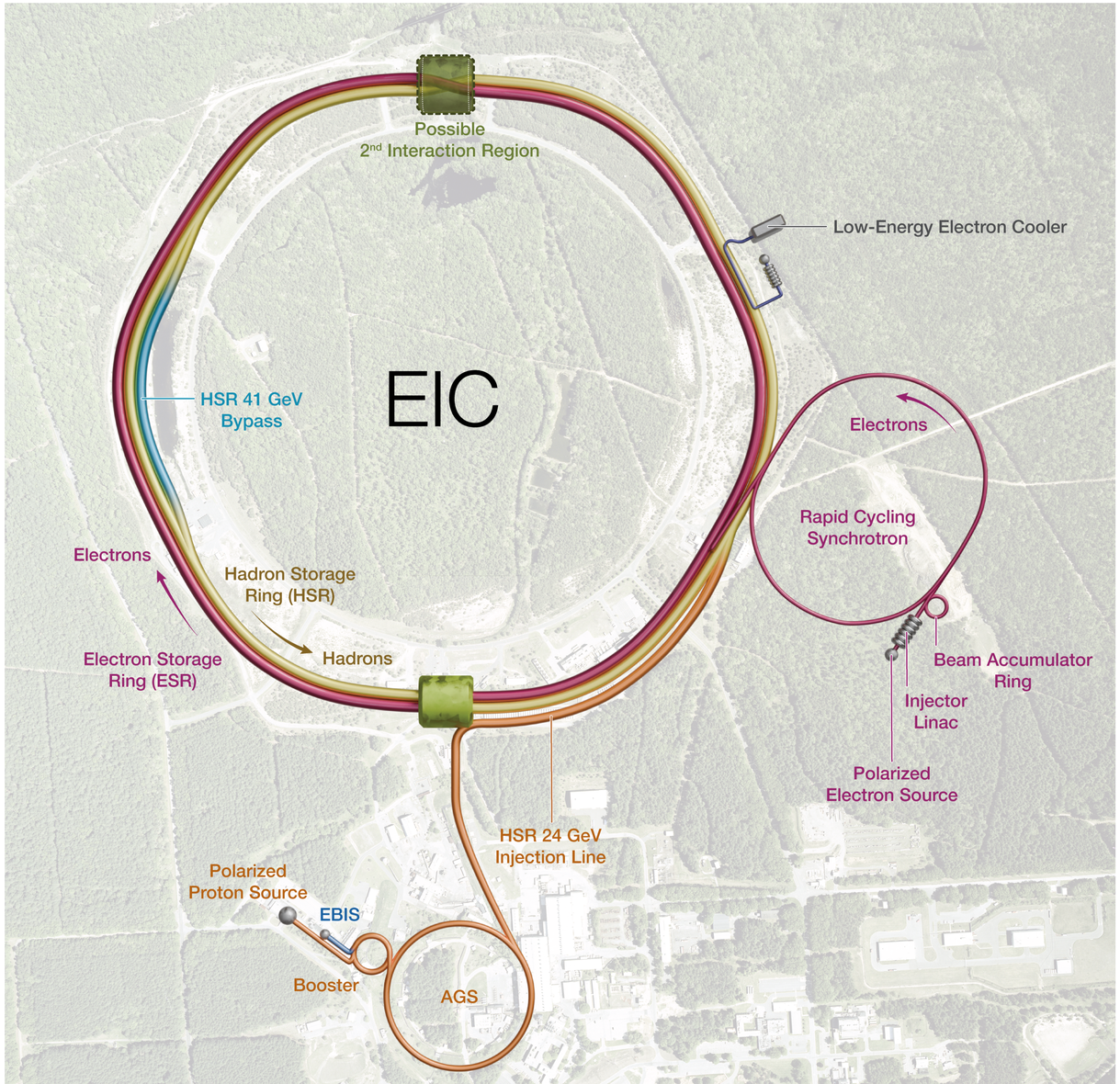


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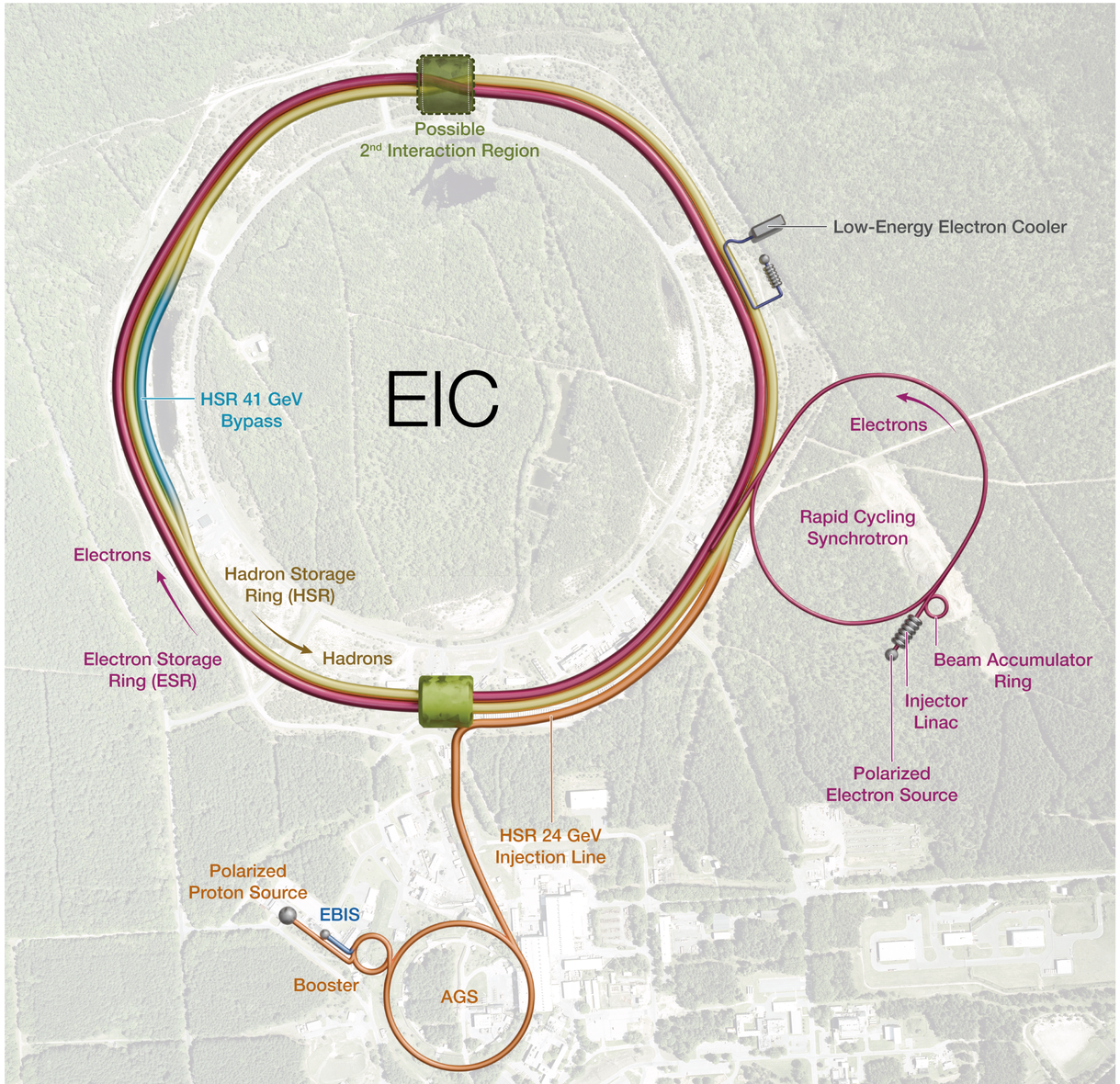


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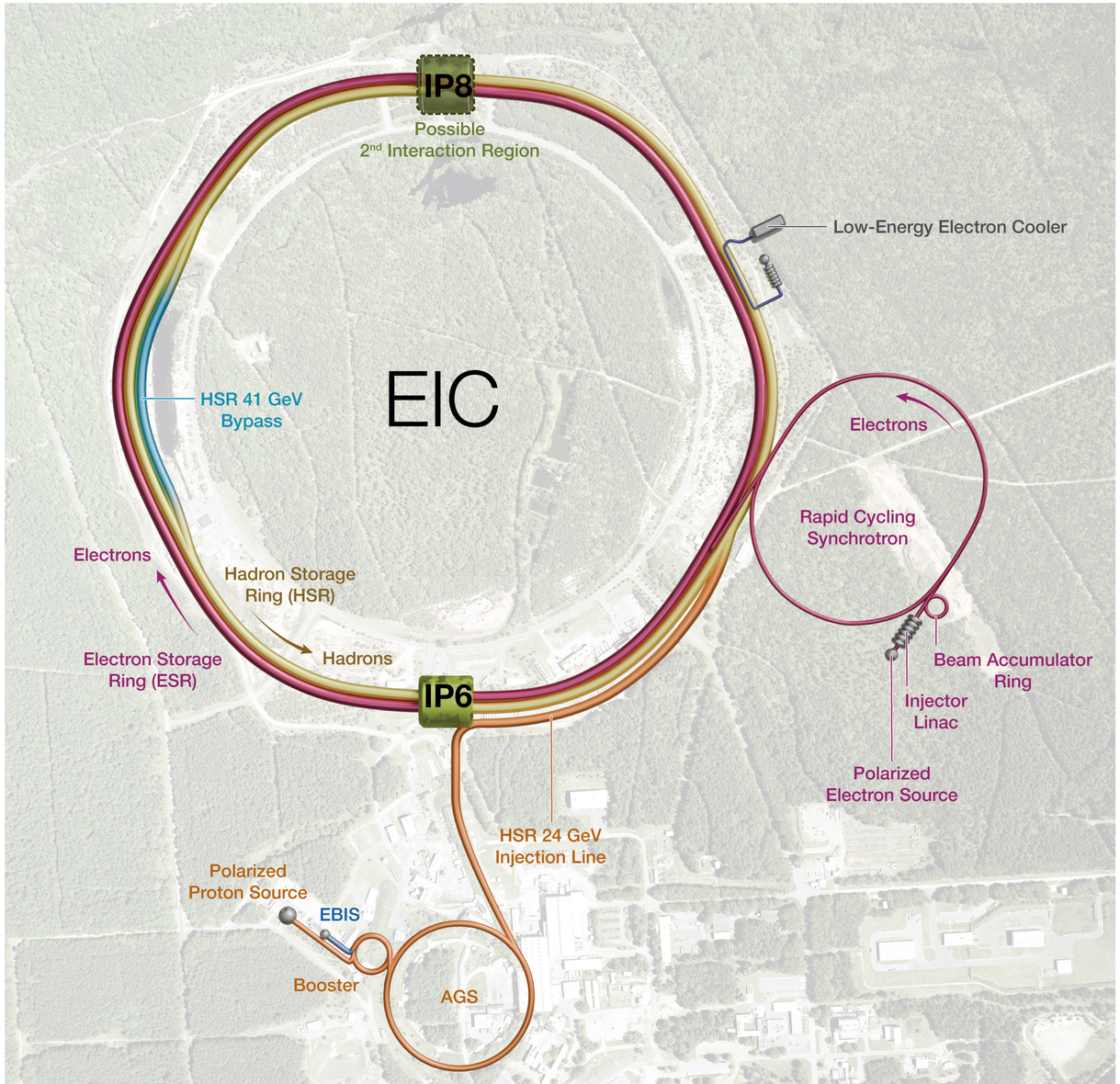


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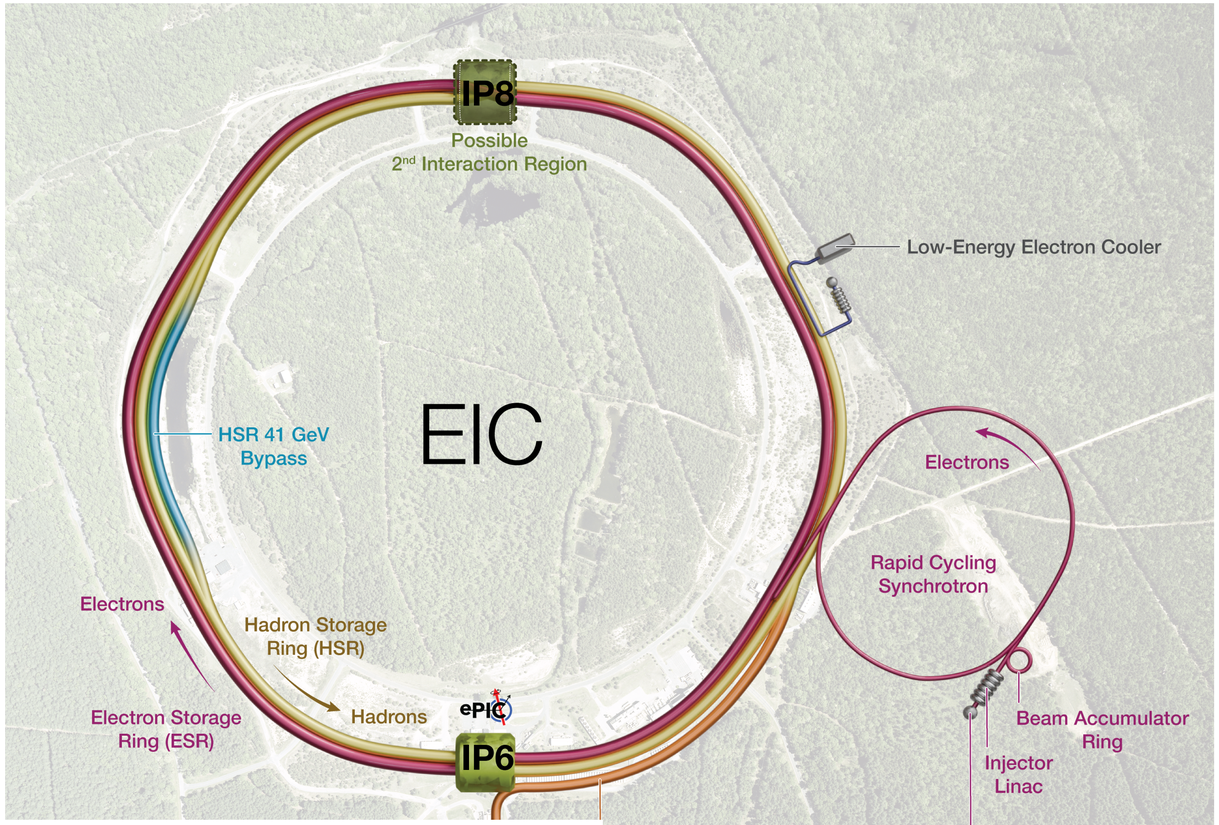


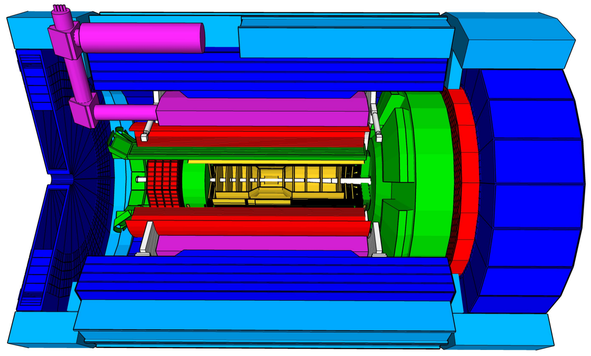

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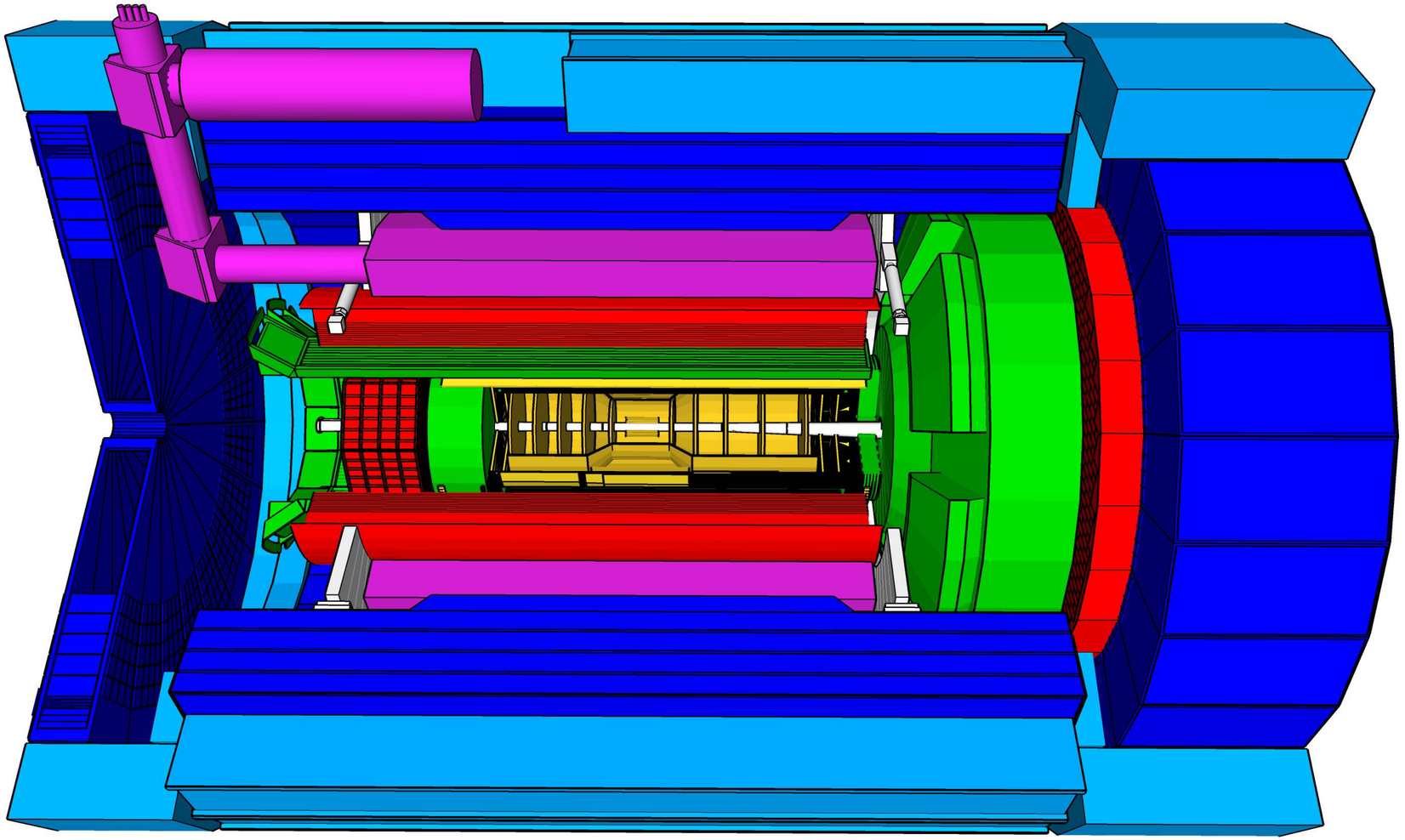

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$0^o \leq \phi \leq 360^o$
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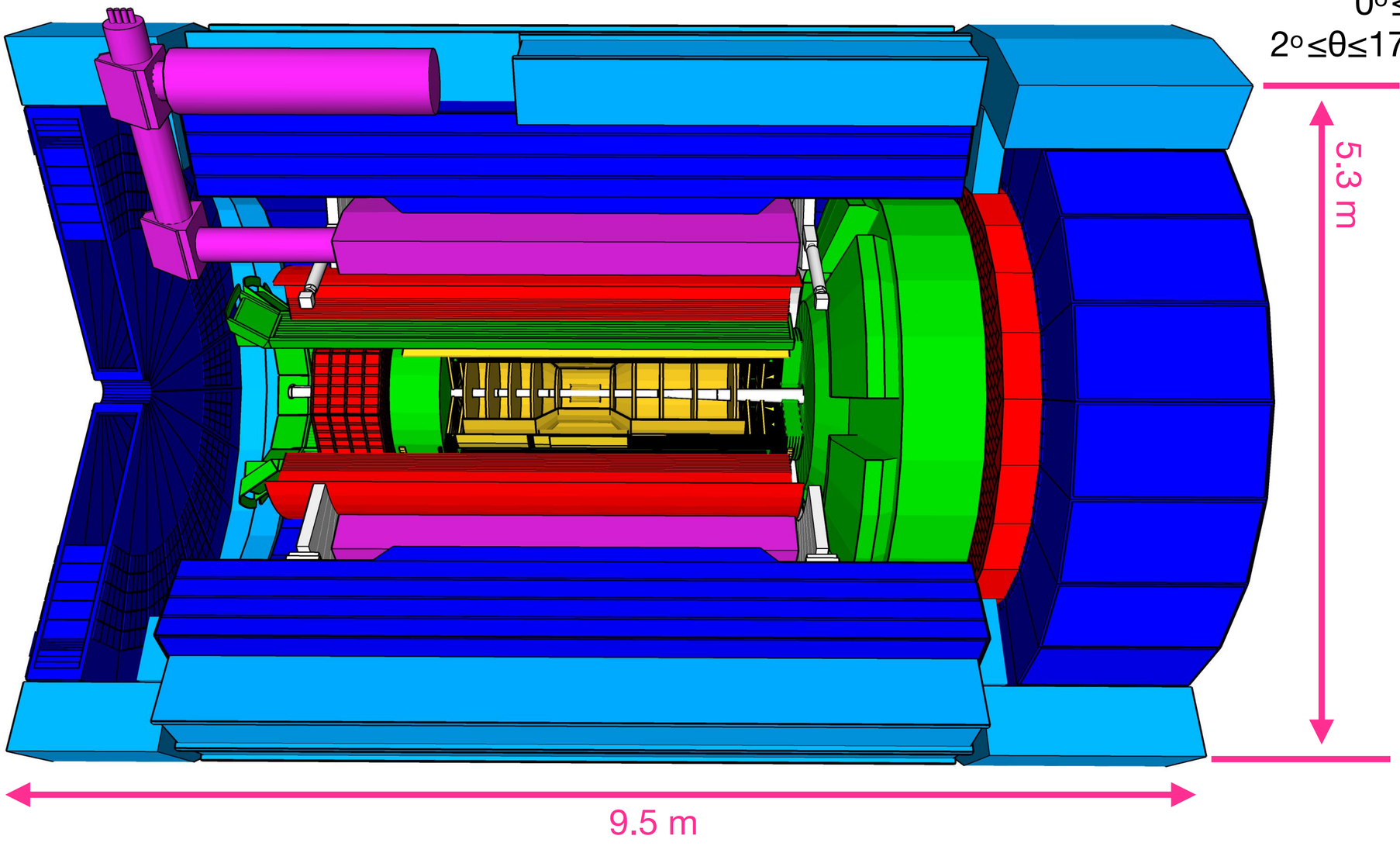

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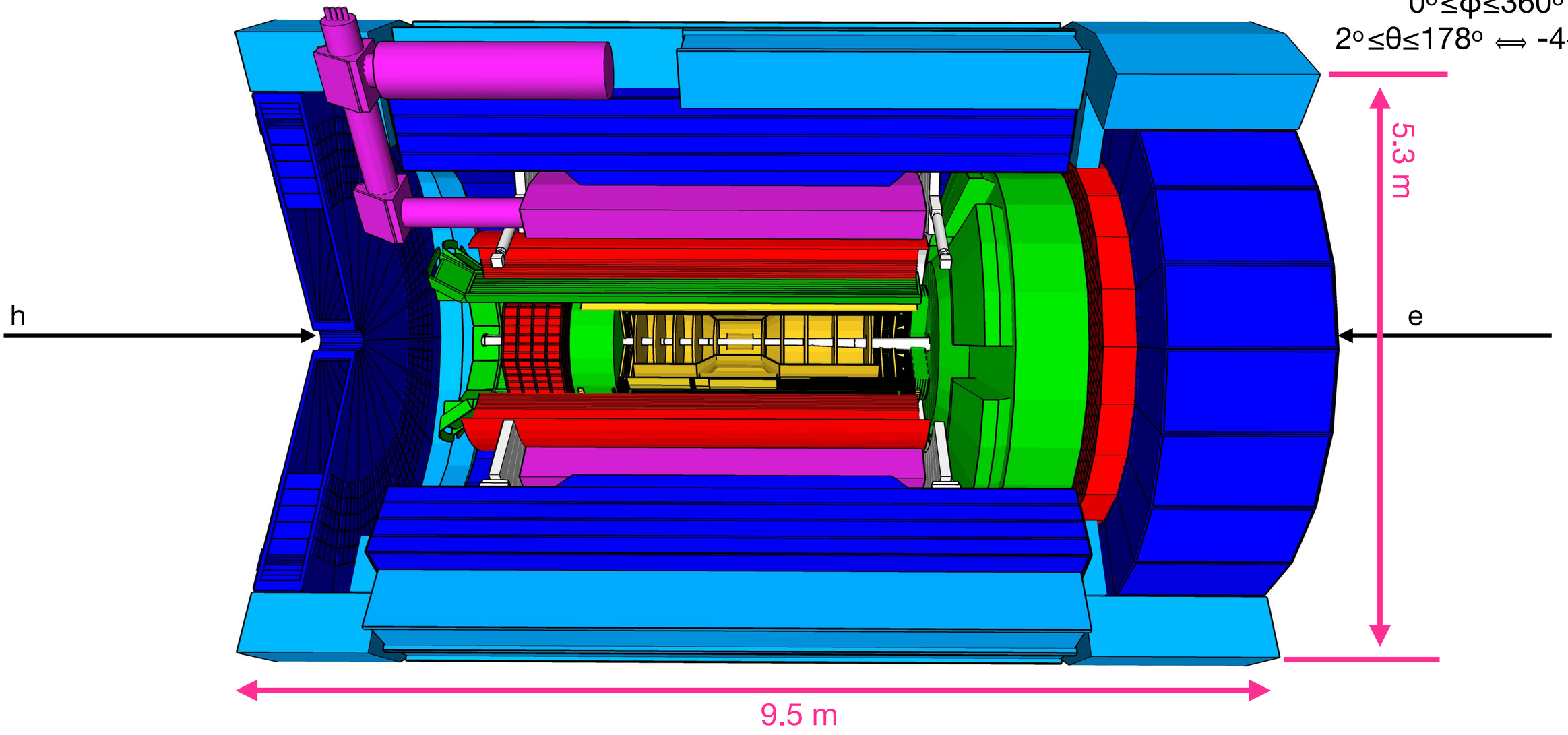

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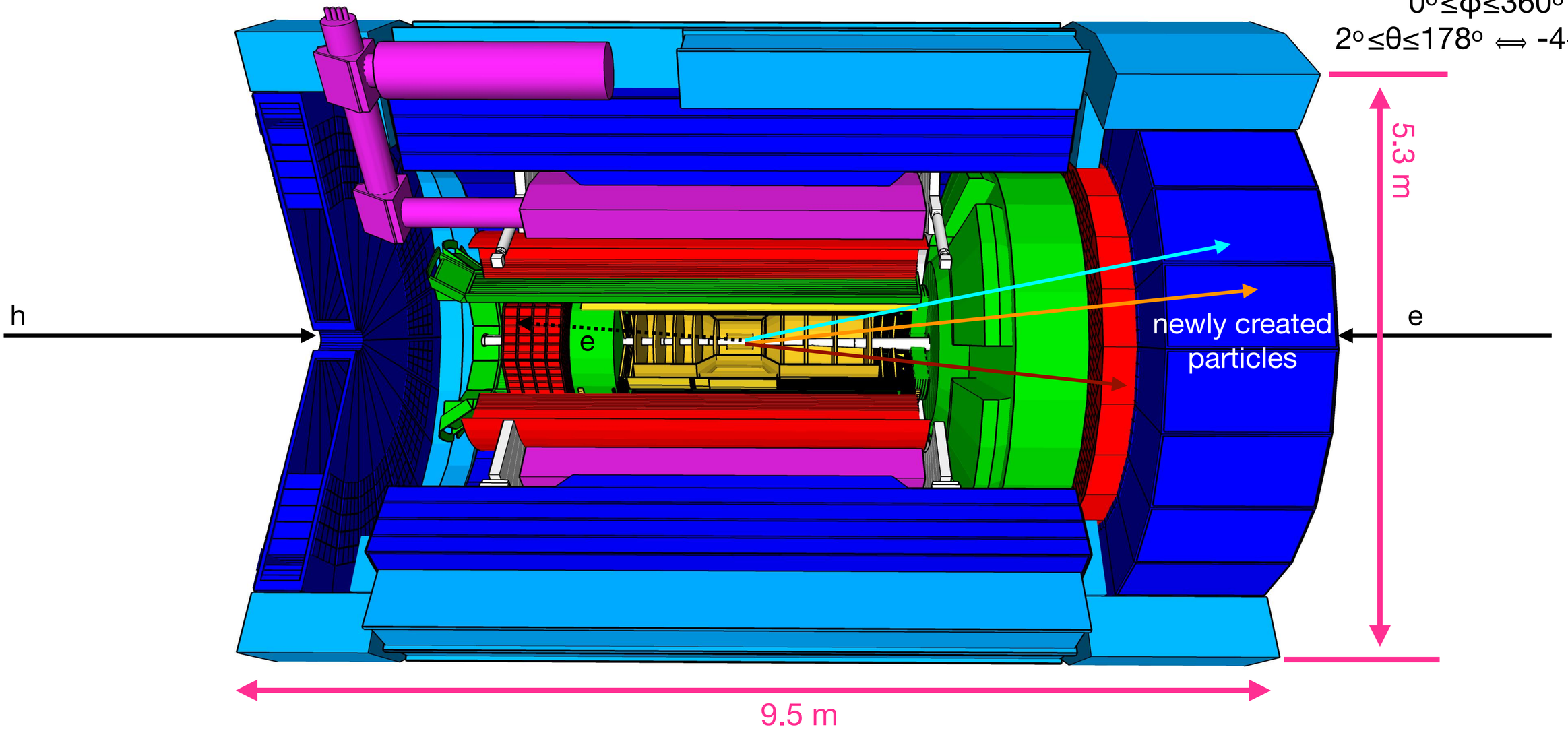

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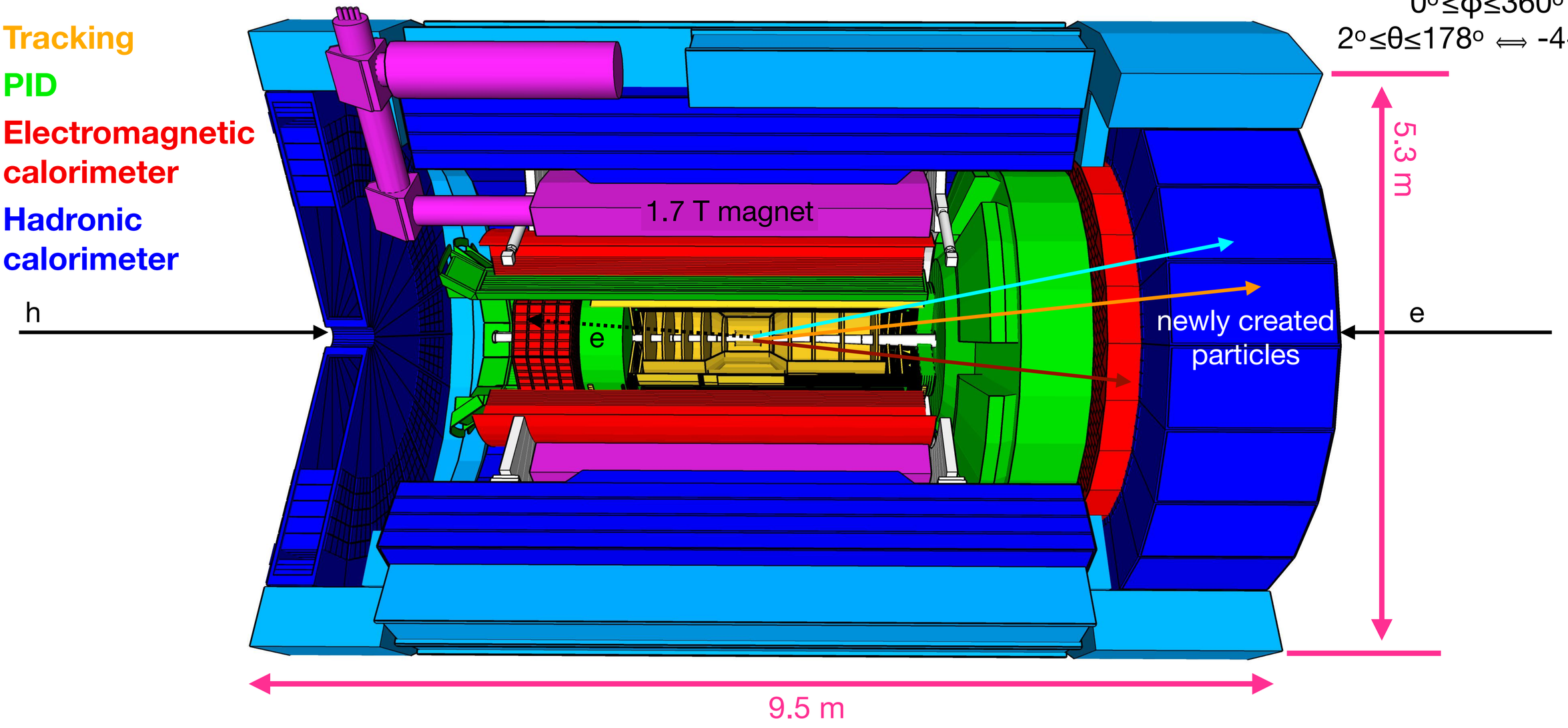

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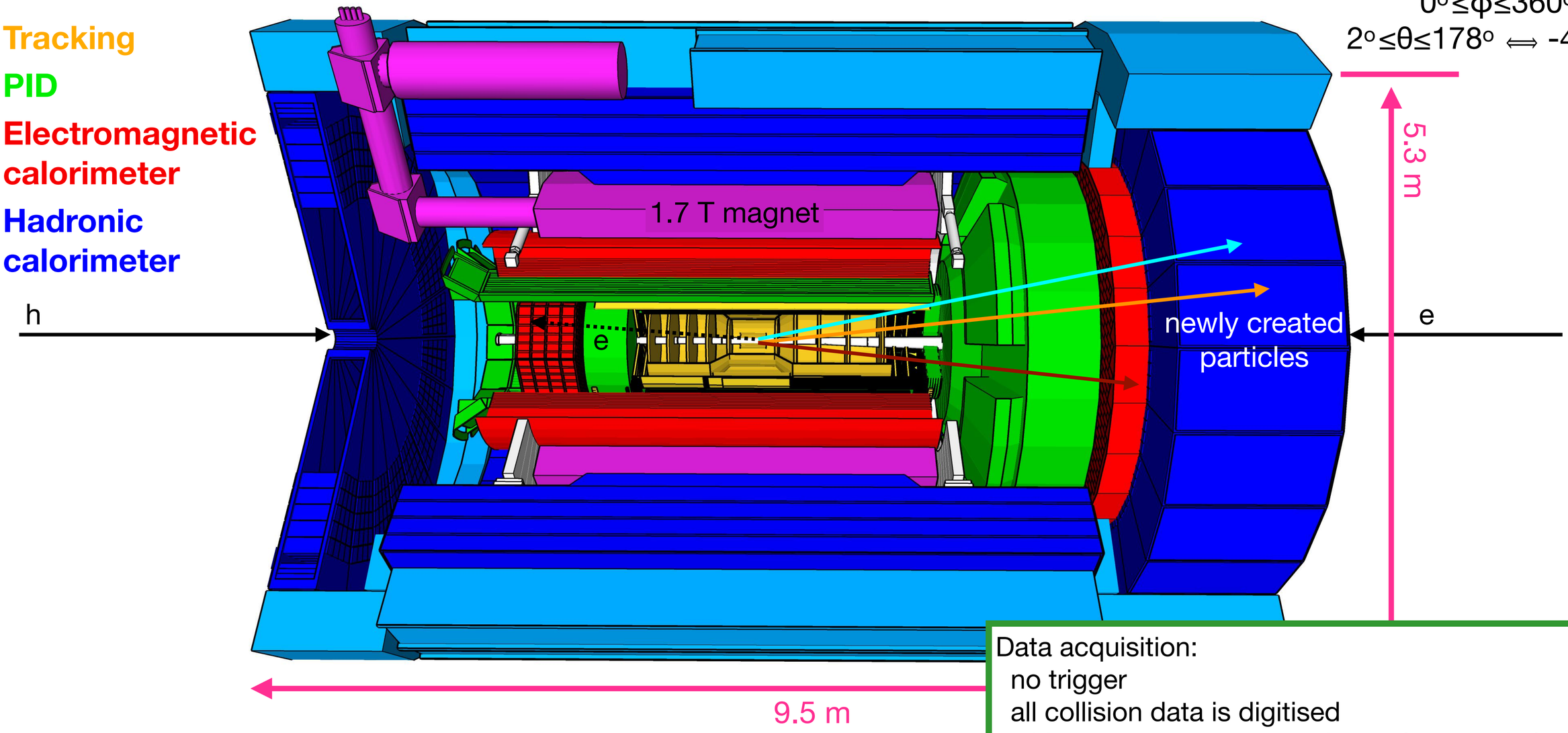
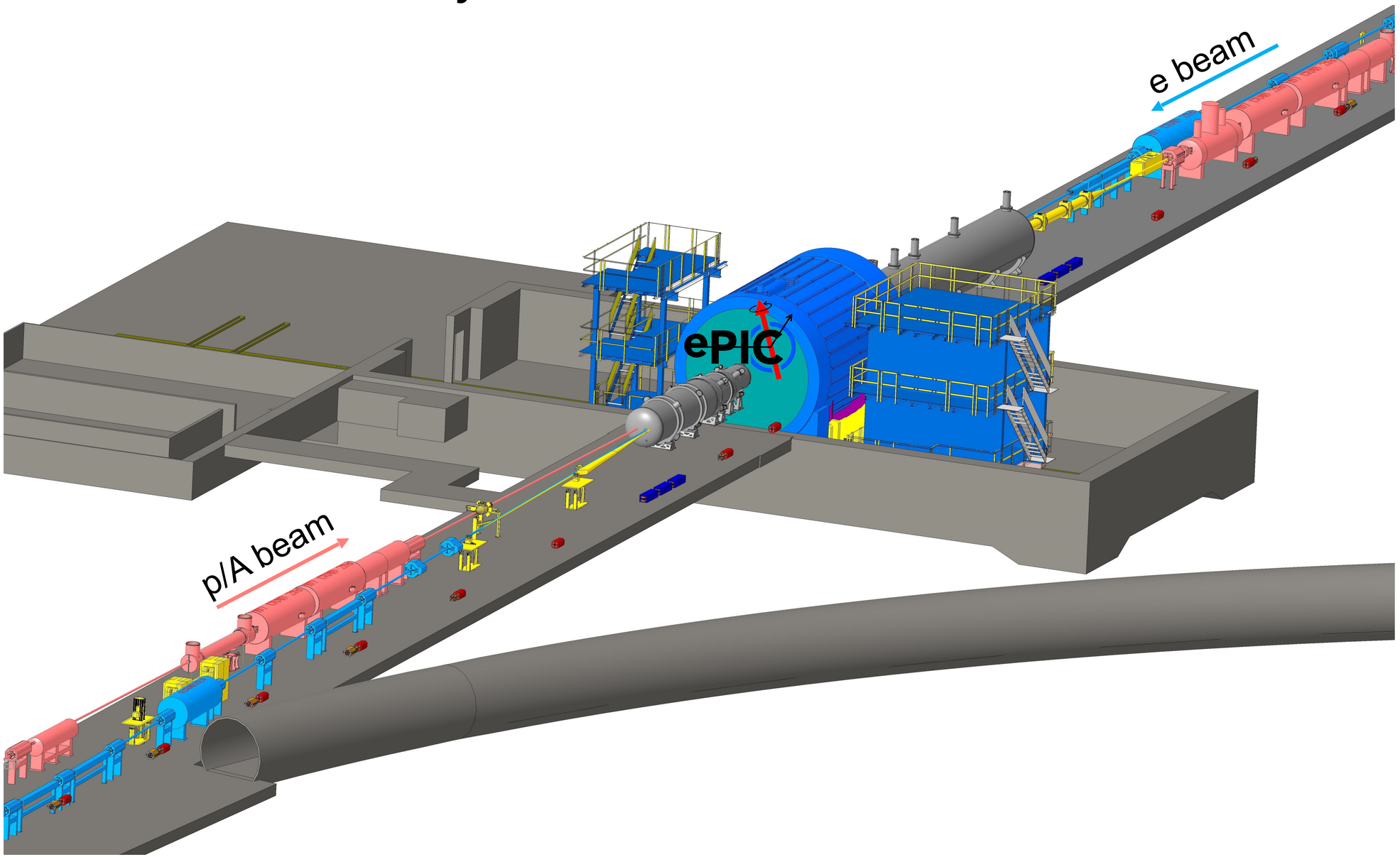



Data acquisition:
no trigger
all collision data is digitised
with strong zero-suppression at front-end electronics

# Far backward/forward systems



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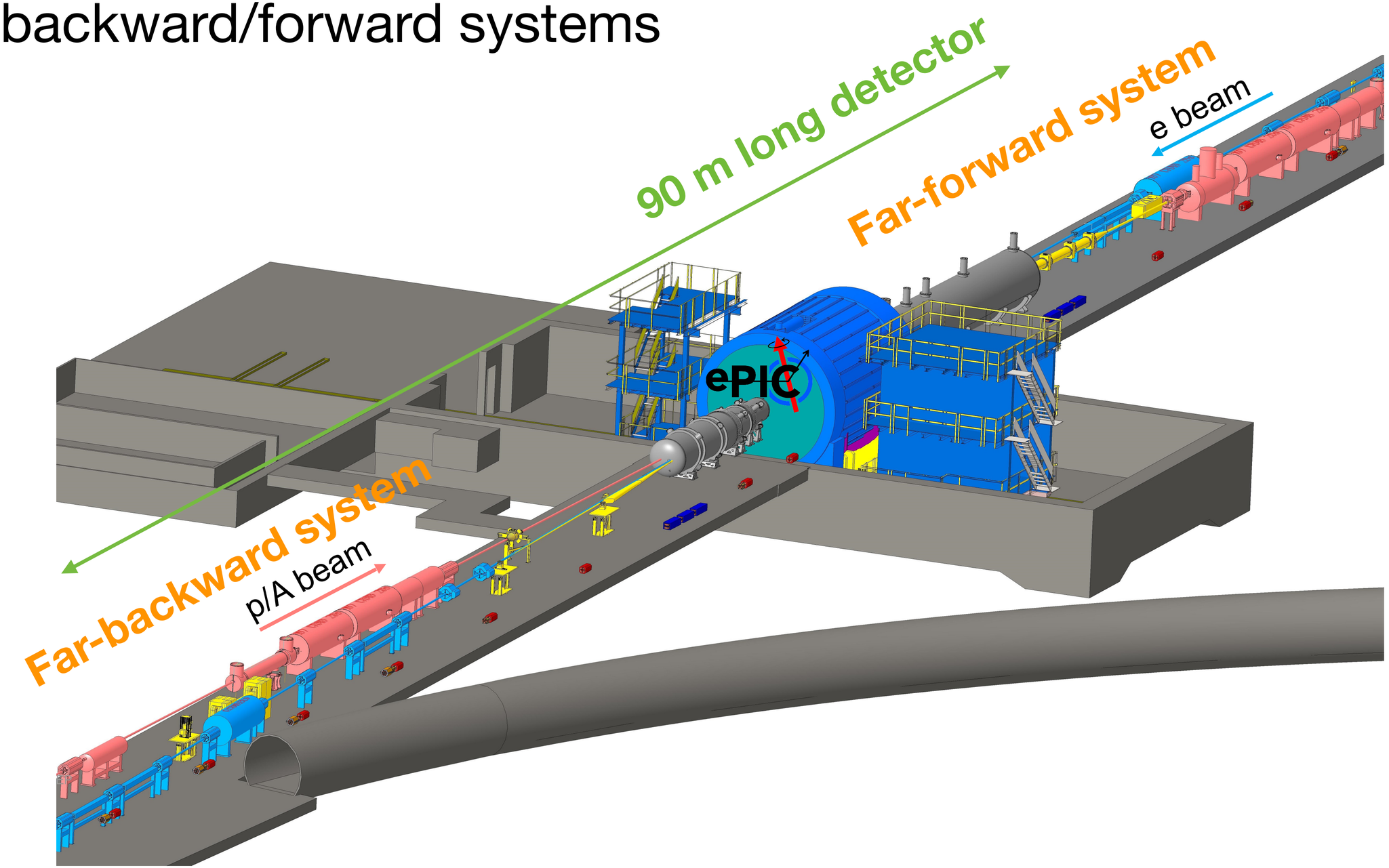

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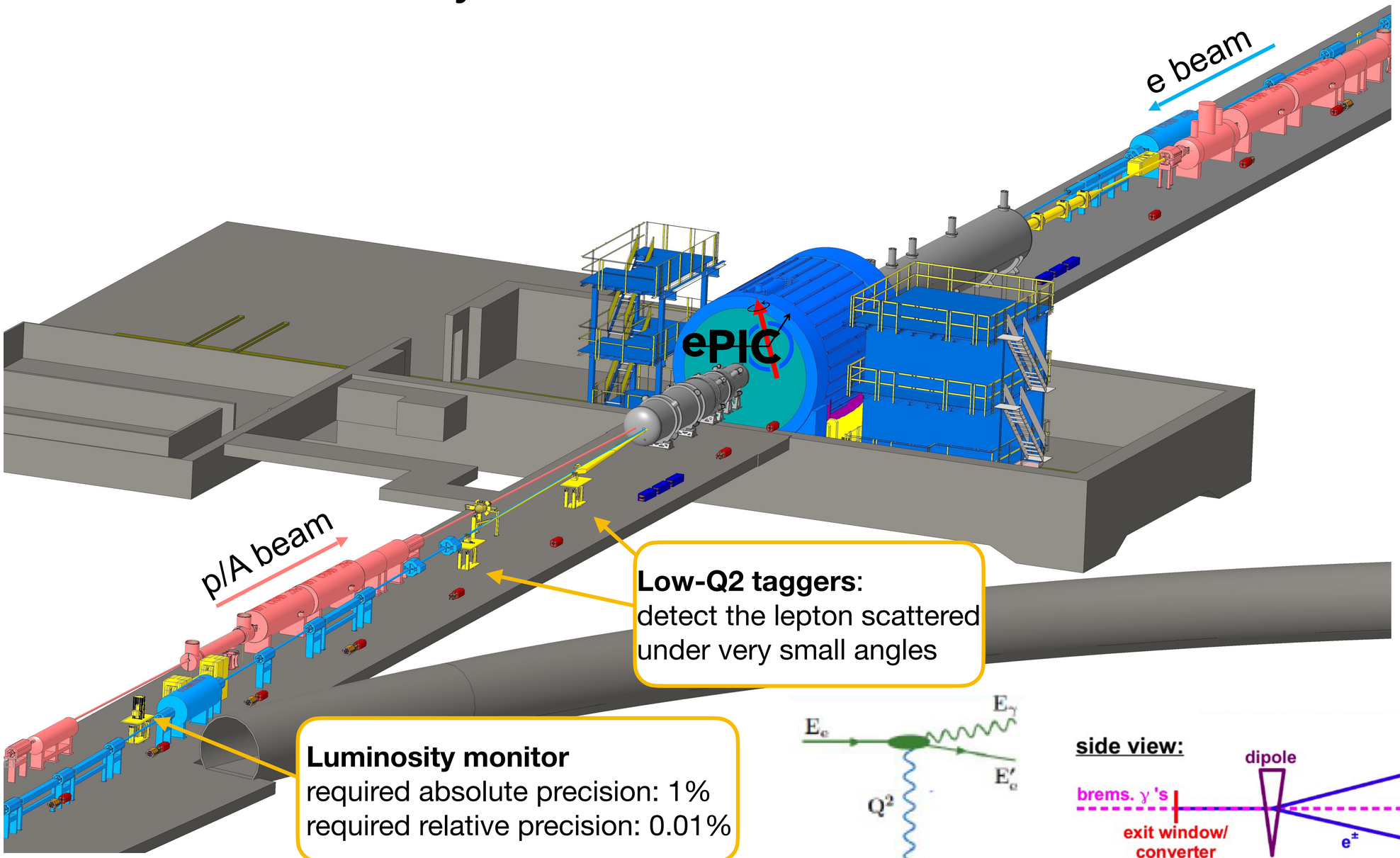


**Low-Q2 taggers**:
detect the lepton scattered under very small angles

**Luminosity monitor**
required absolute precision: 1%
required relative precision: 0.01%

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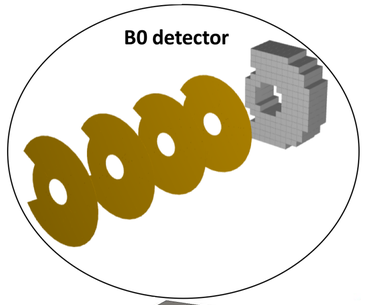
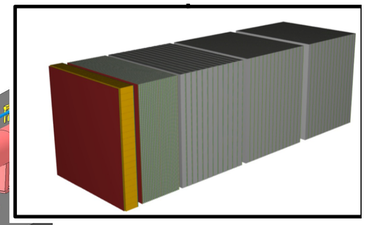
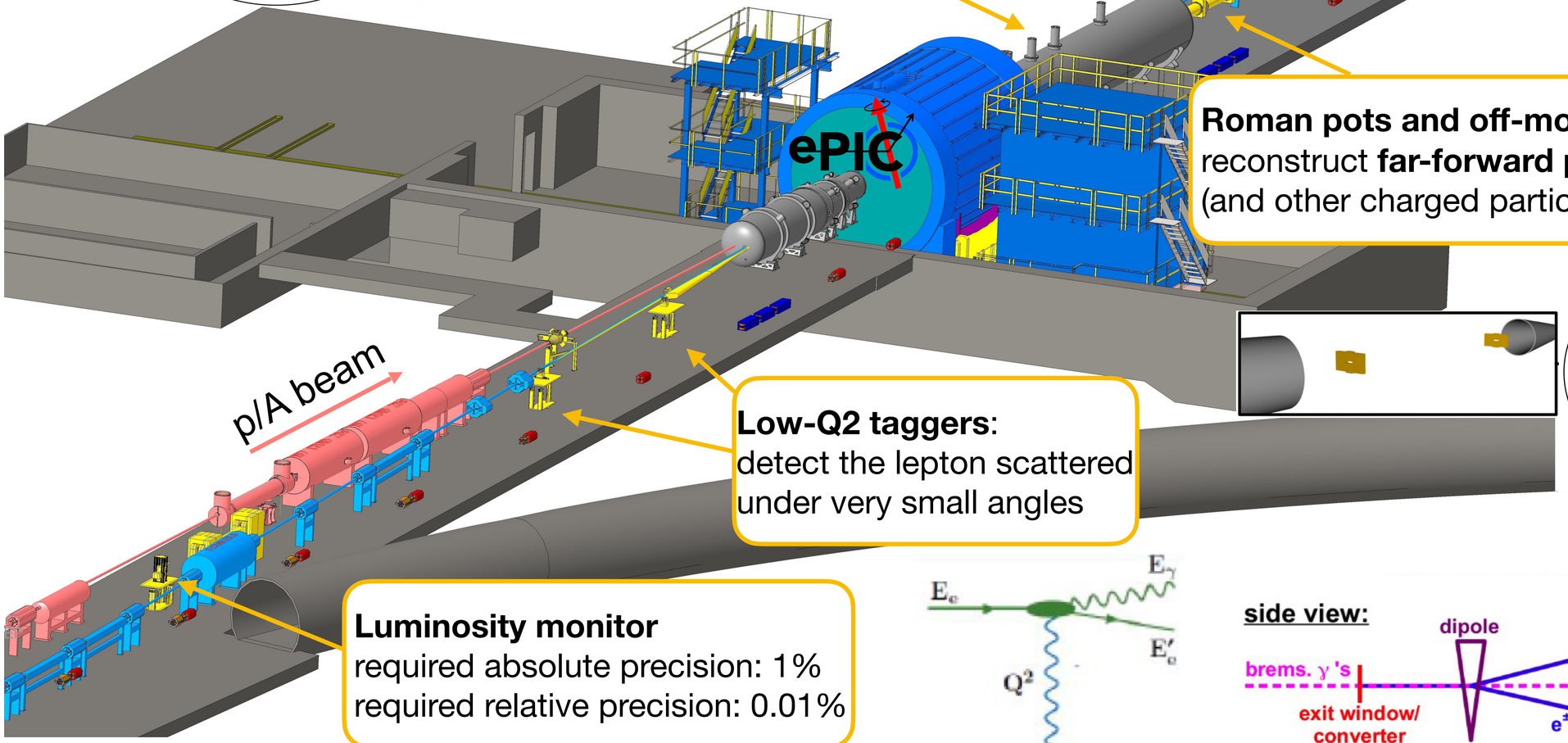


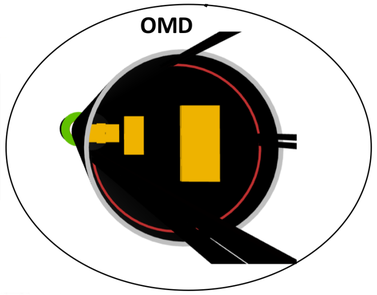

**B0 system**: trackers+electromagnetic calorimeters inside magnetic field to detect **protons and photons**

**Zero-degree calorimeters:** detection of **neutrons and photons**






**Roman pots and off-momentum detectors:** reconstruct **far-forward protons** (and other charged particles+light ions)

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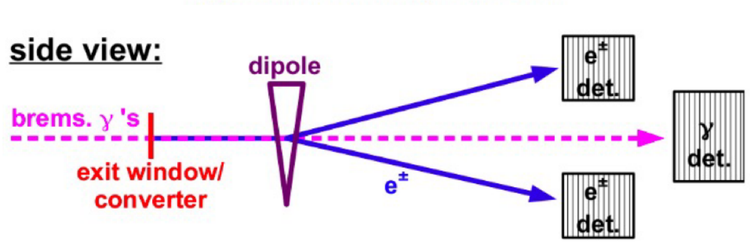

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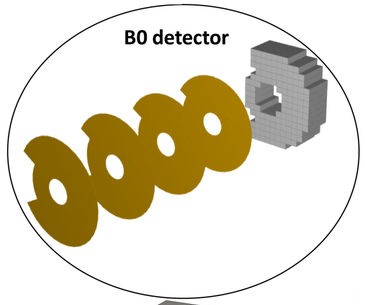


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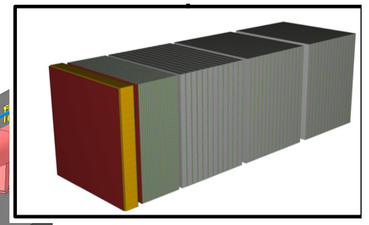

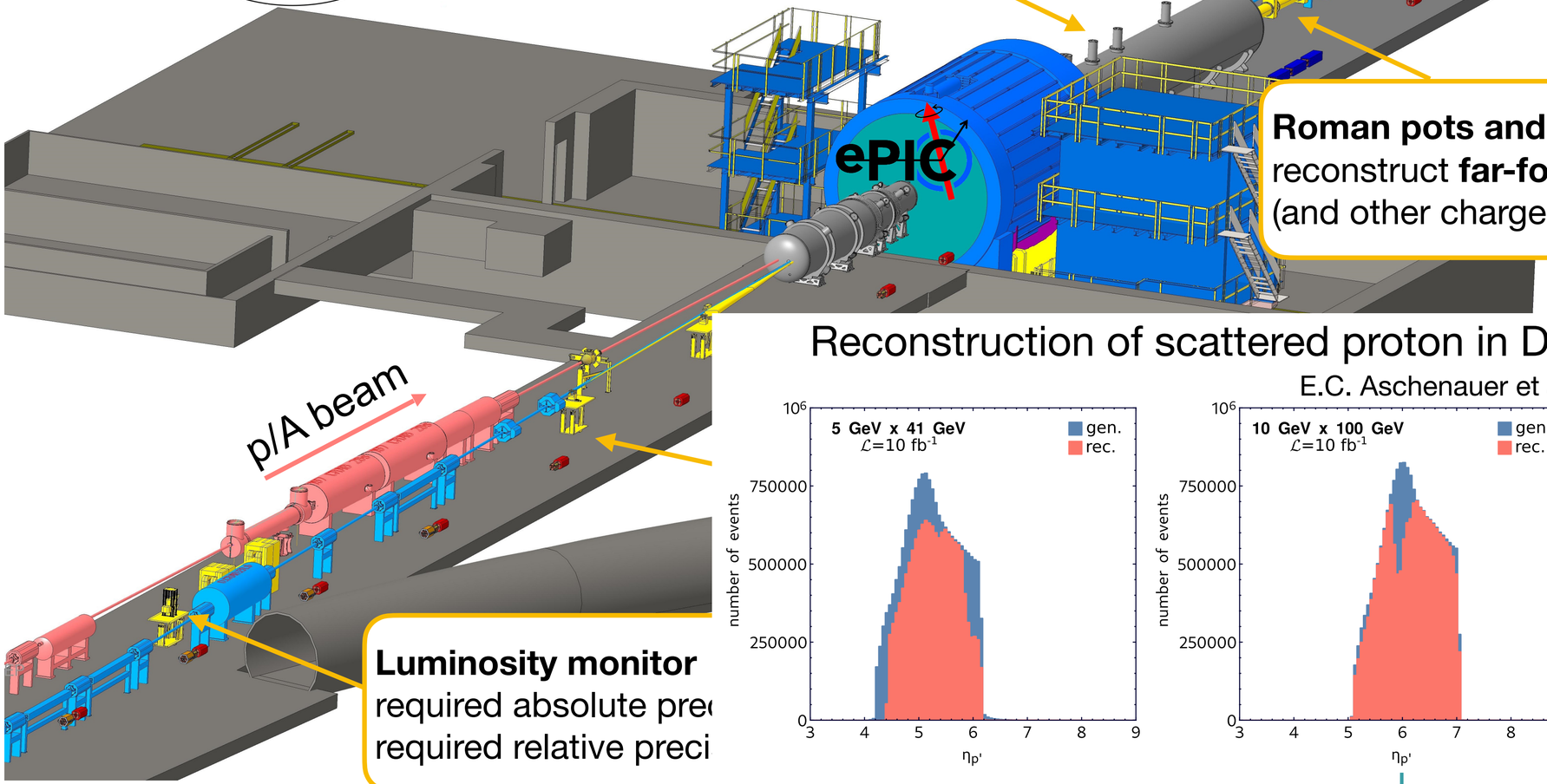


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OMD

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required absolute pre
required relative preci

## Reconstruction of scattered proton in DVCS

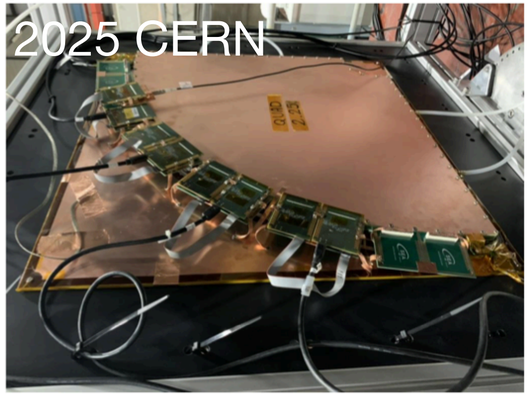
E.C. Aschenauer et al., Phys. Rev. D **112** (2025) 036010



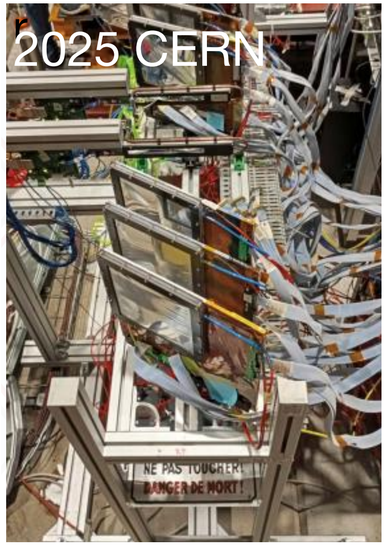

B0 ⟵ ⟶ Roman pots

# Test-beam measurements

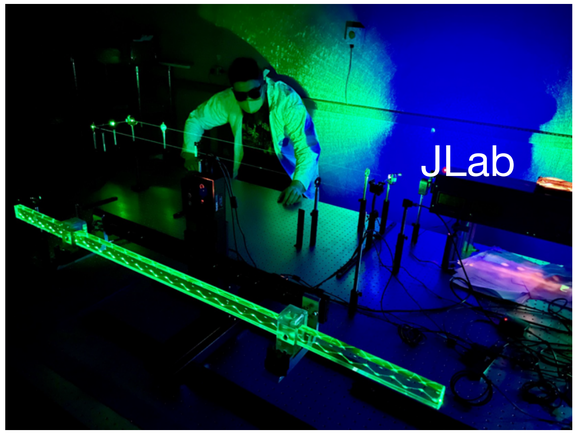
µRWELL-ECT ETAs



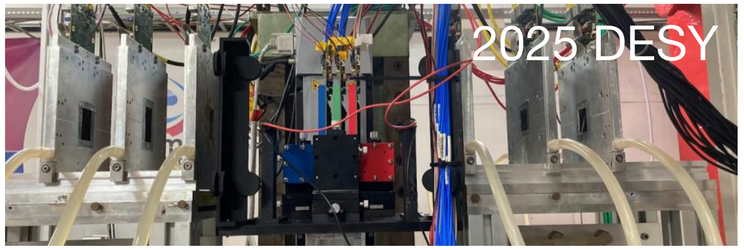

microMegas

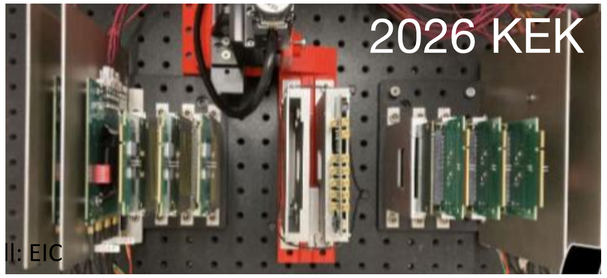



Optical test of
refurbished DIRC

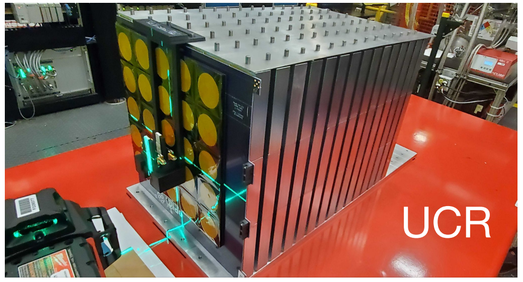



TOF detectors




ZDC




Forward HCAL

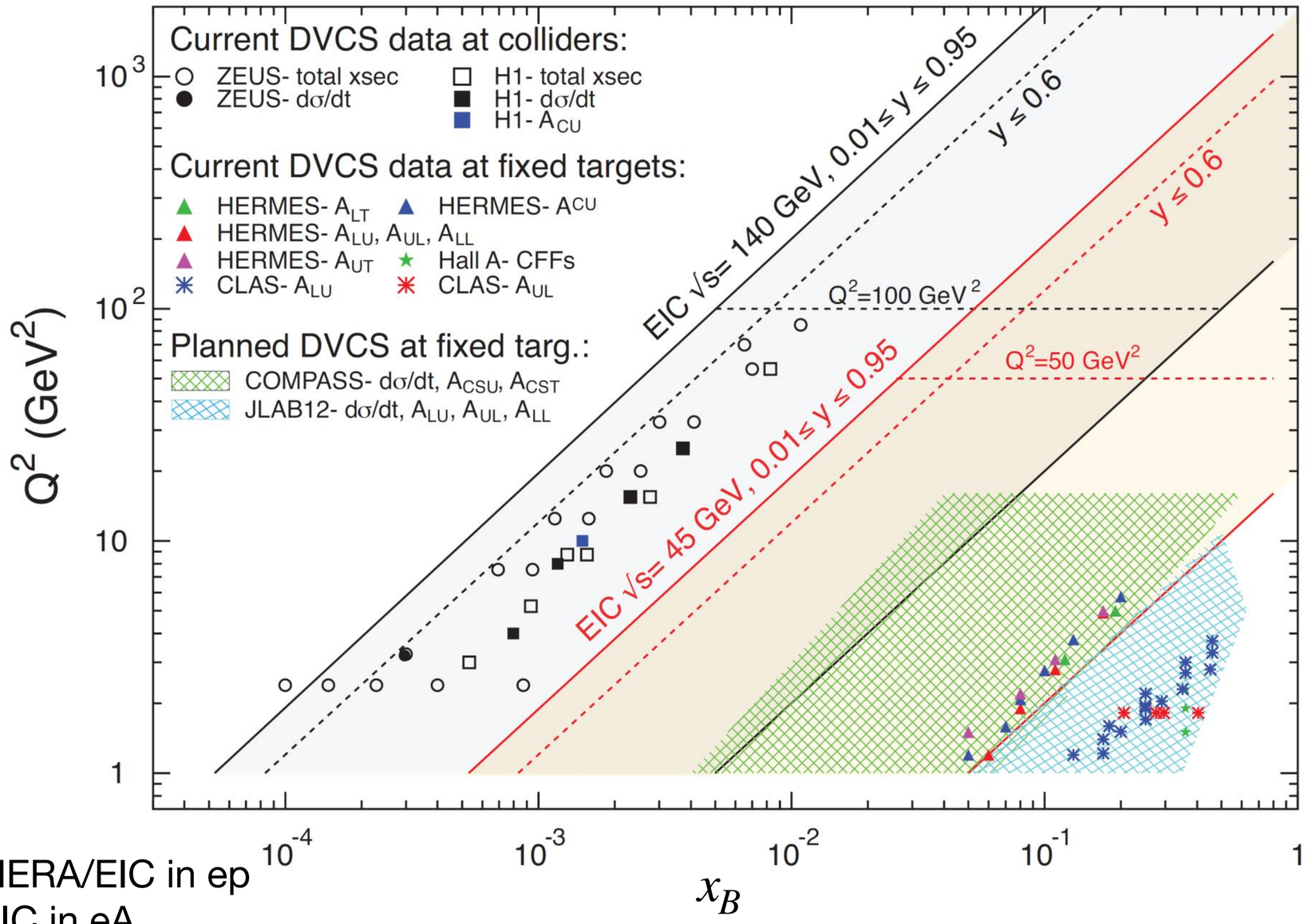



Low-$Q^2$ Tagger





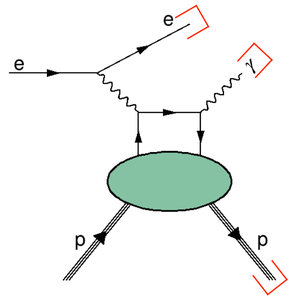

# Kinematic coverage of the EIC



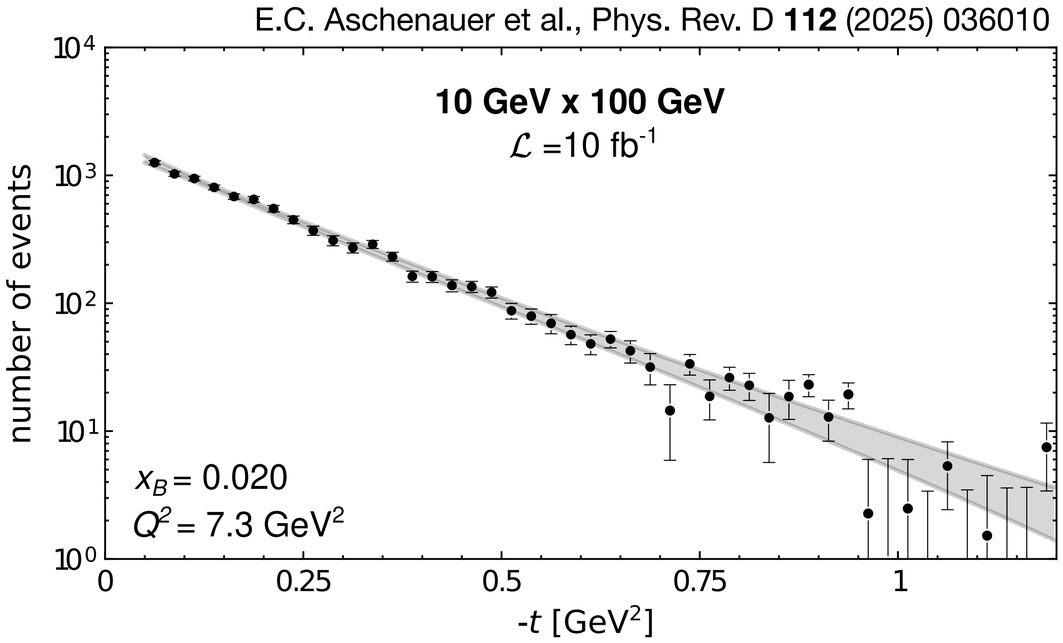

down to $x_B=10^{-4}$ at HERA/EIC in ep

$x_B=10^{-3}$ at EIC in eA

# DVCS at ePIC and impact on determination of CFFs




DVCS after efficiency and acceptance corrections



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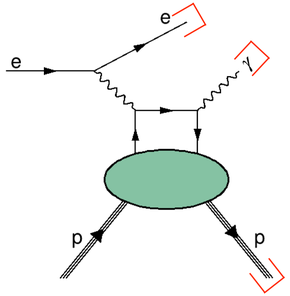


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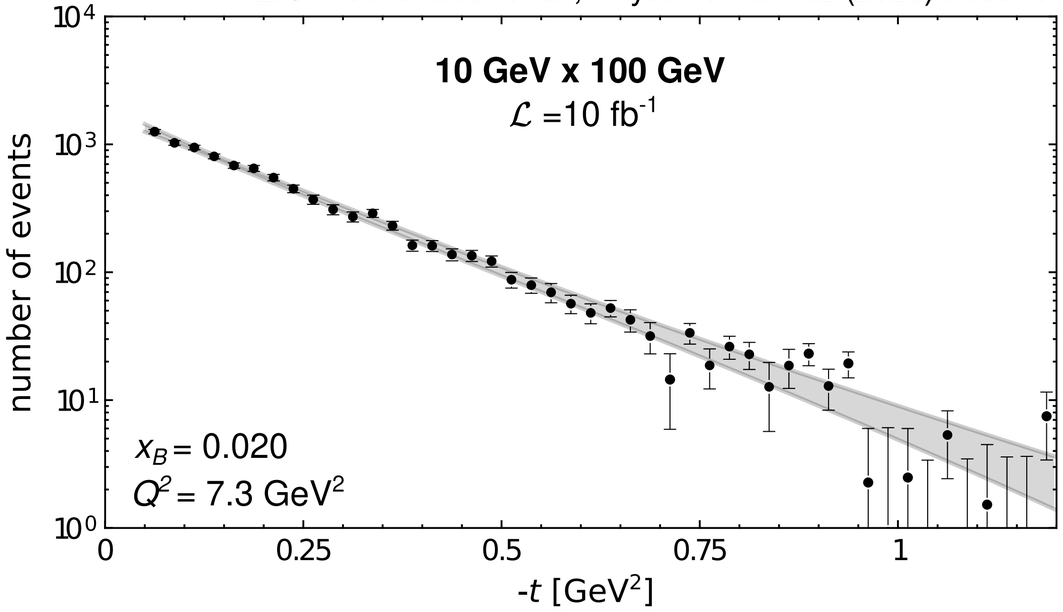
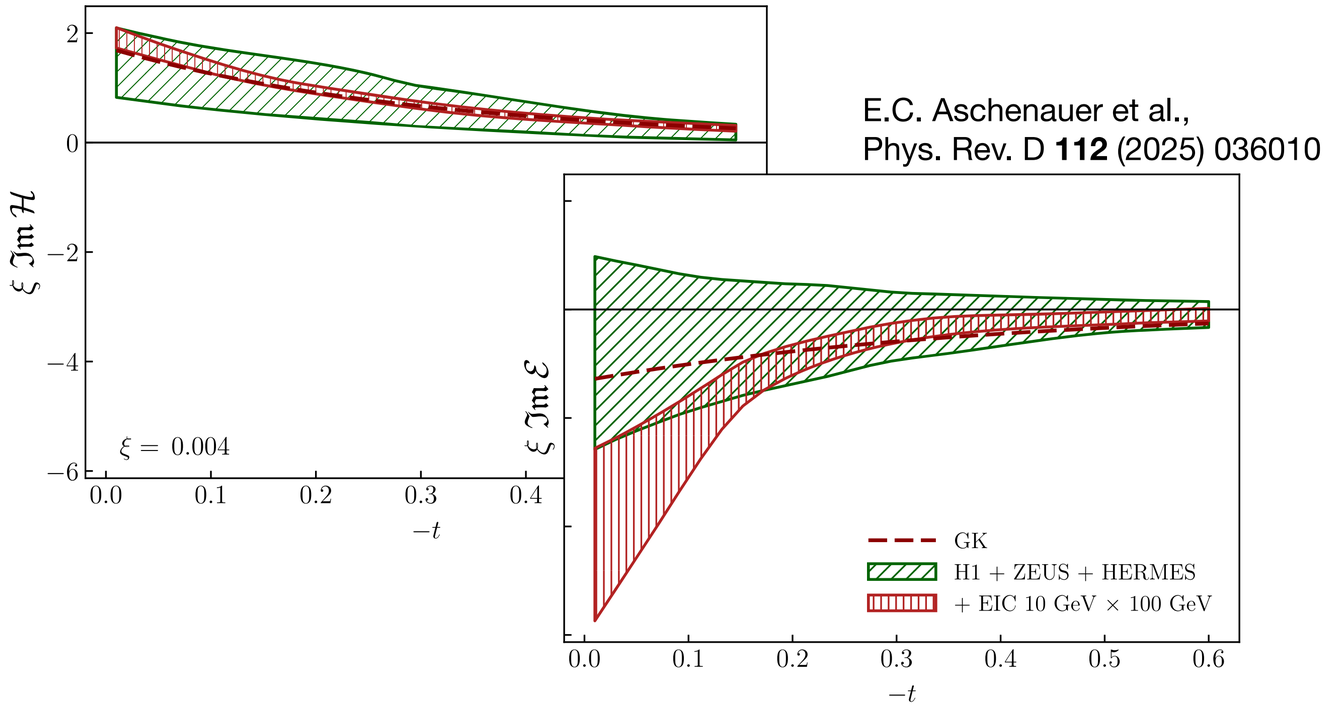
E.C. Aschenauer et al., Phys. Rev. D **112** (2025) 036010



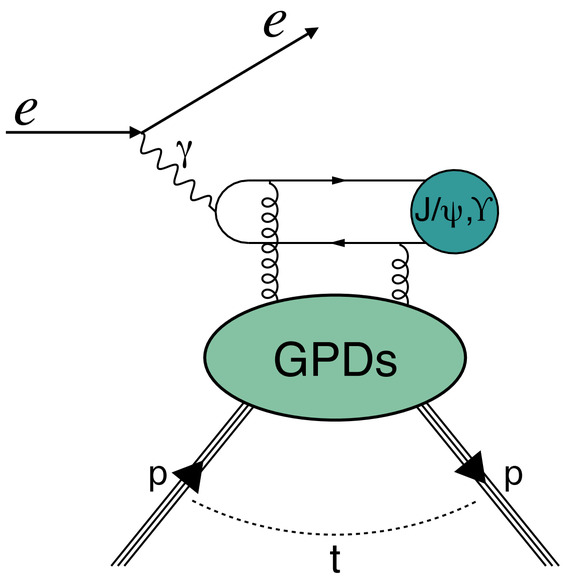

Lepton-beam helicity asymmetry

$$\rightarrow \Im m\left(F_1\mathcal{H} + -\frac{t}{4m^2}F_2\mathcal{E} + \dots\right)$$




E.C. Aschenauer et al.,
Phys. Rev. D **112** (2025) 036010

# Experimental access to GPDs via hadron-hadron interactions




Exclusive meson photoproduction
Hard scale = large c/b-quark mass

Access to gluons

Sensitive to $x_B=10^{-4}$

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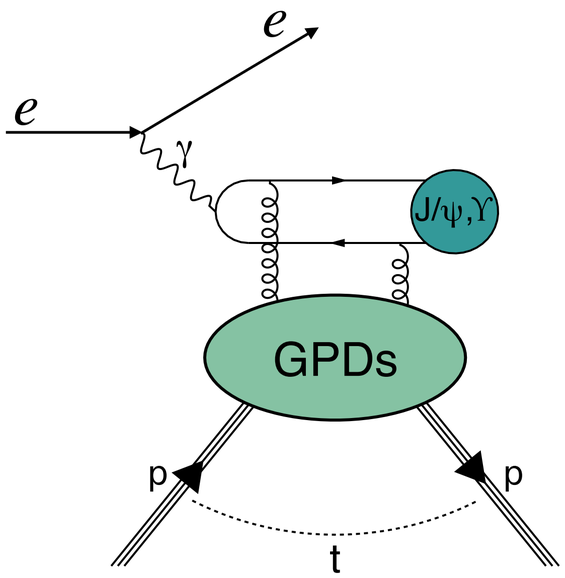


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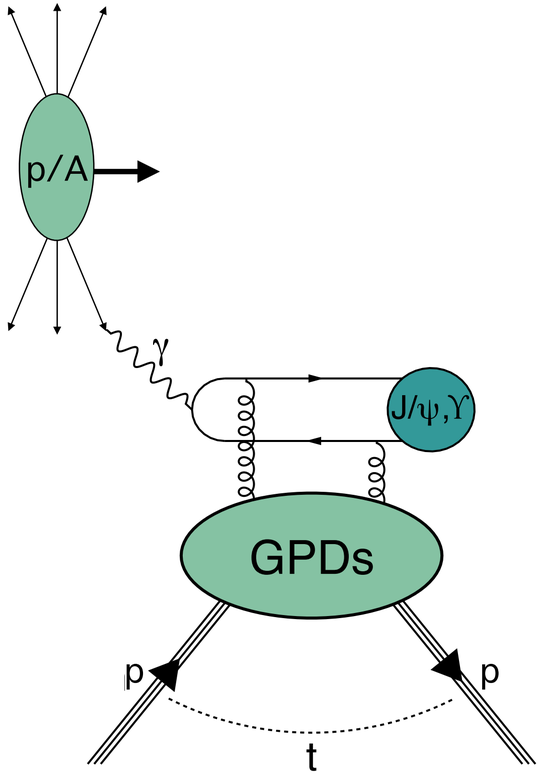


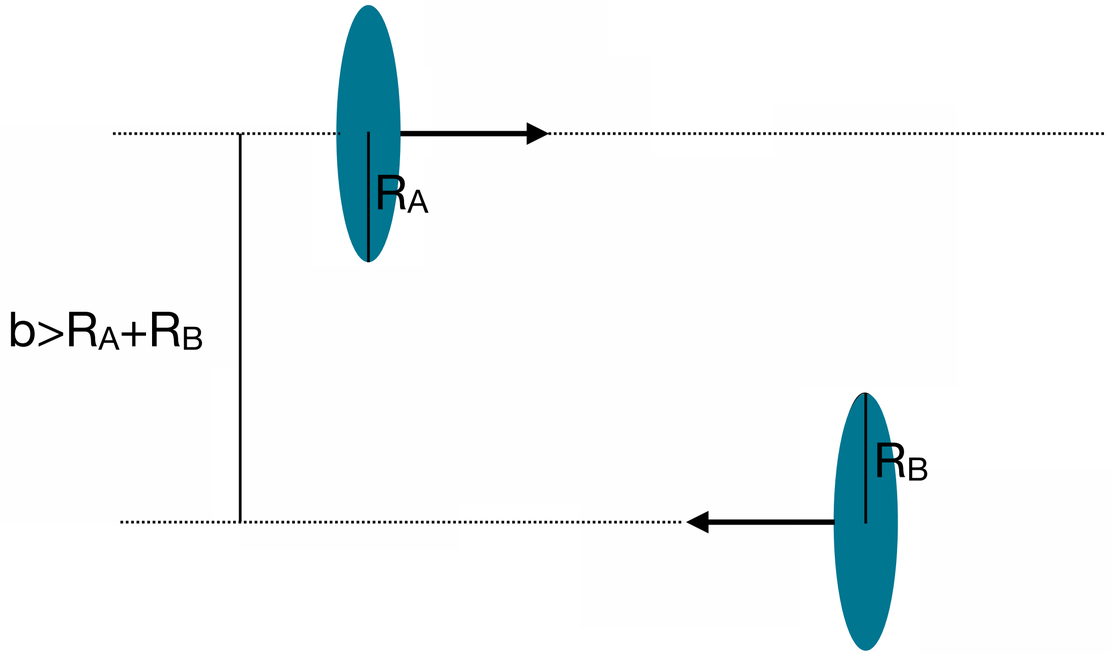

Exclusive meson photoproduction
Hard scale = large c/b-quark mass

Access to gluons

Sensitive to $x_B=10^{-6}$

# Utra-peripheral collisions

large–impact-parameter interactions



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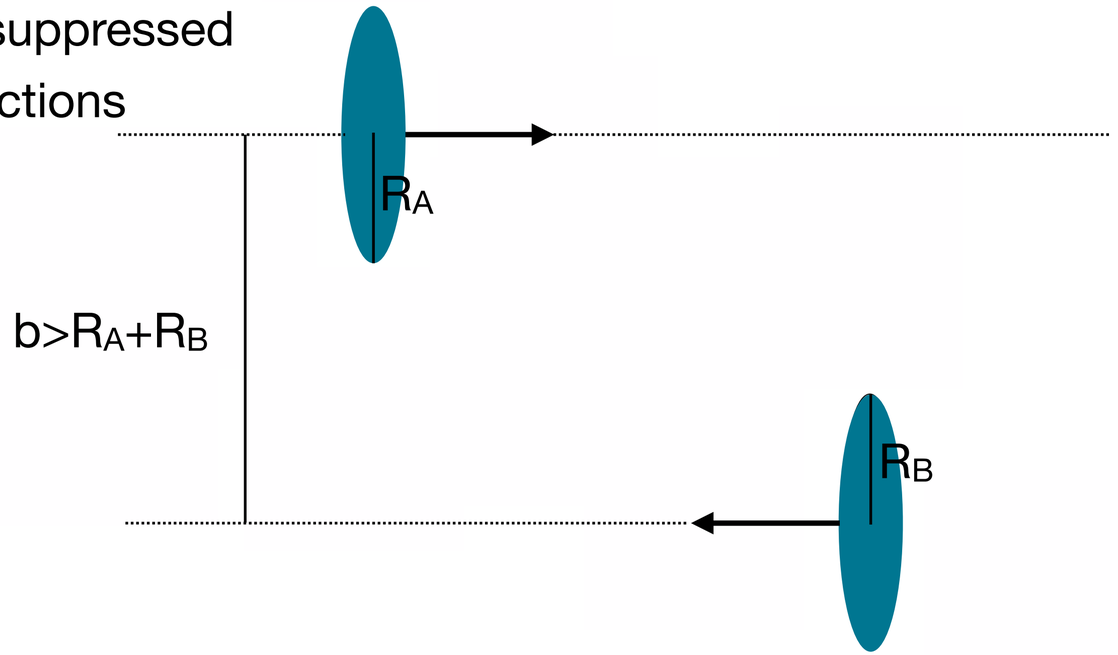
hadronic interactions strongly suppressed

instead: electromagnetic interactions



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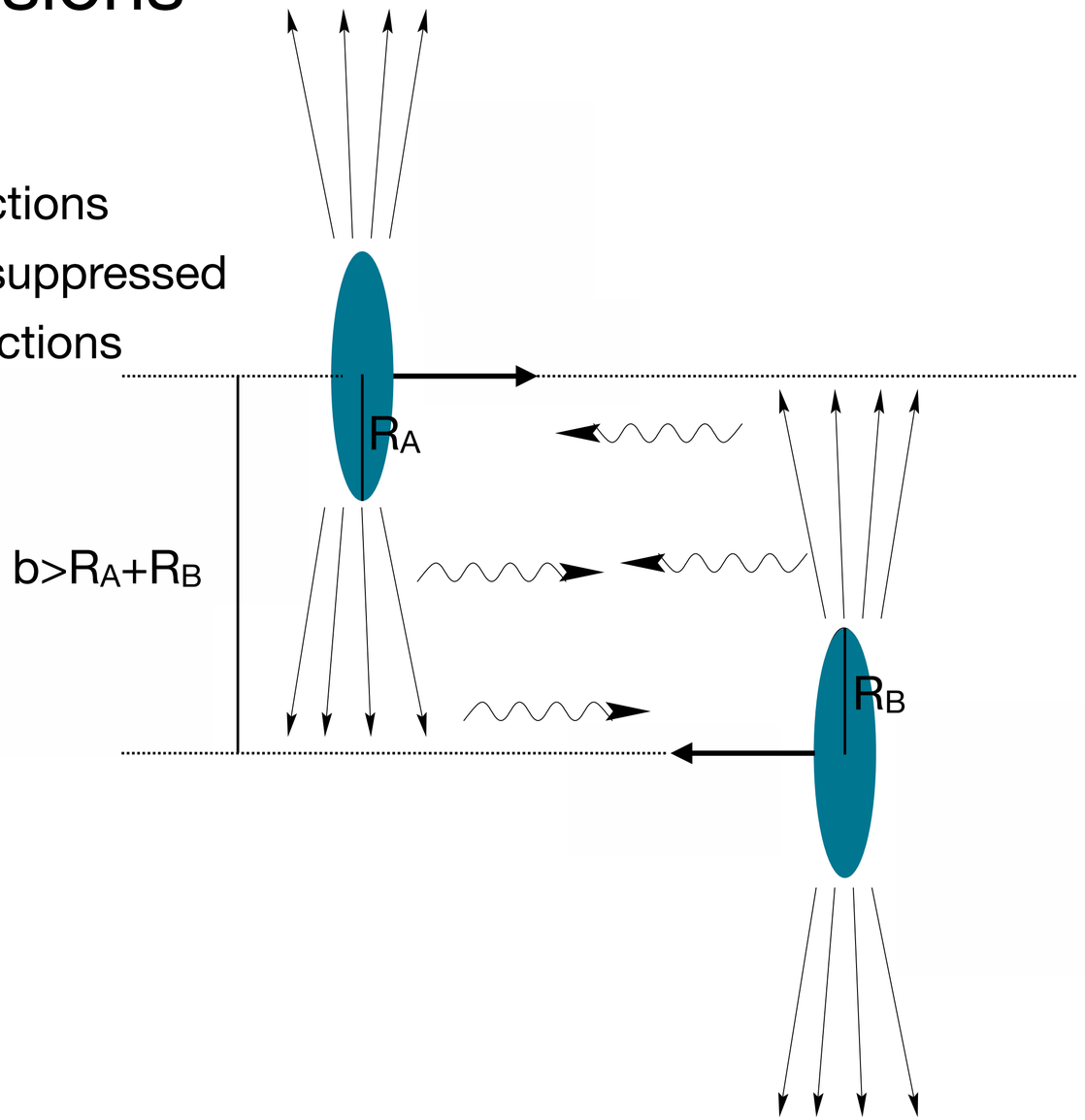

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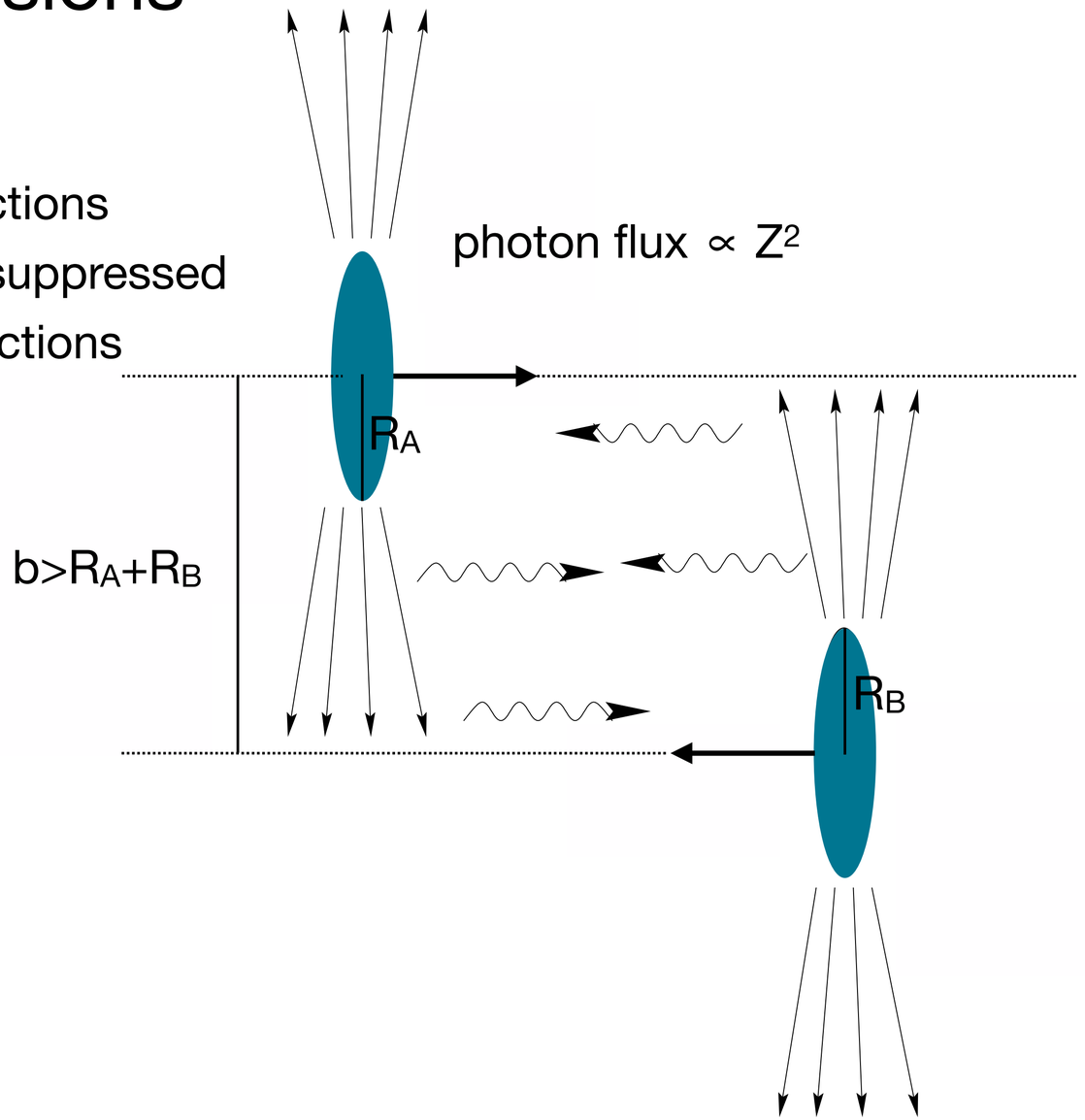

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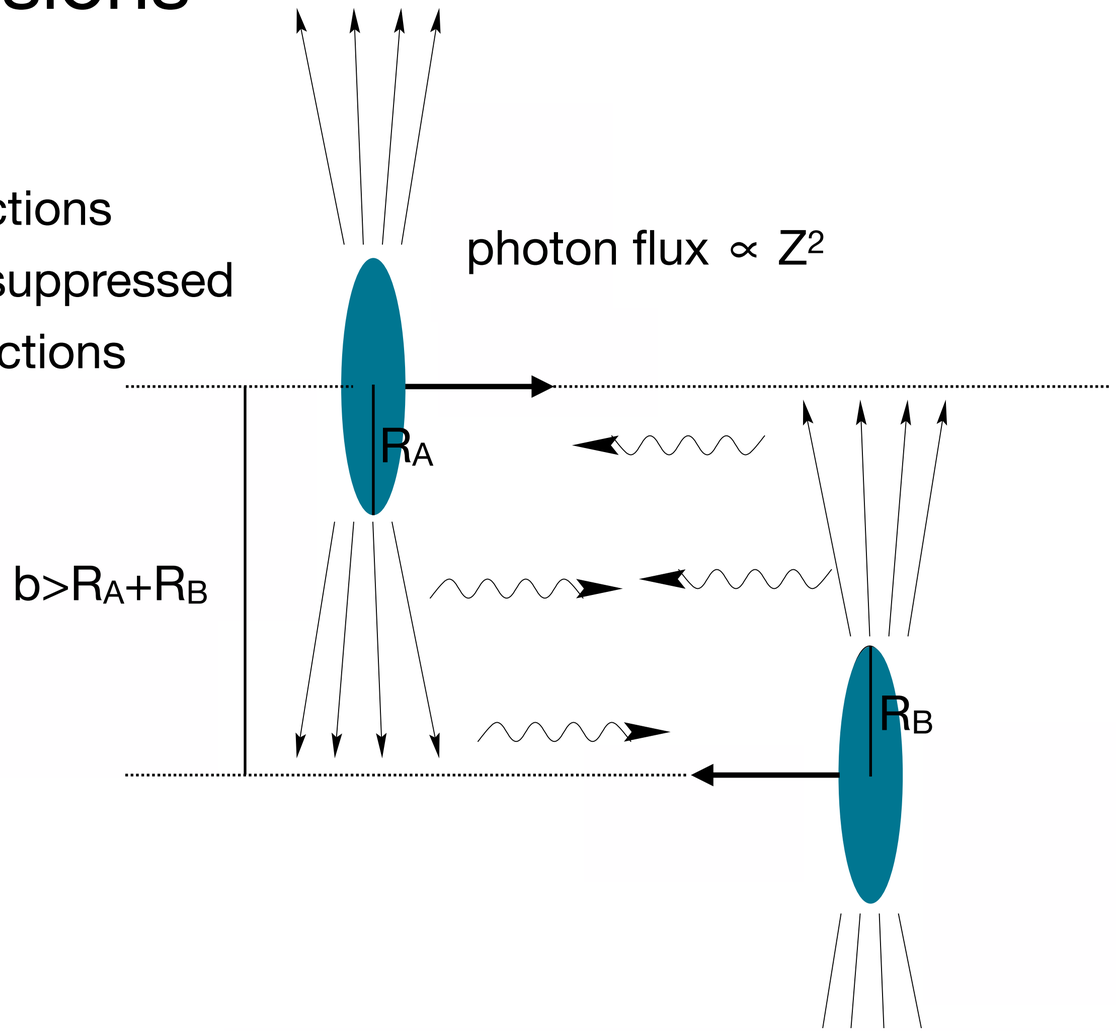


photon virtuality $Q^2 < \left(\frac{\hbar c}{R_A}\right)^2$

→ quasi-real photons

maximum photon energy = $\frac{2\gamma\hbar c}{b_{\min}}$

| System | $\sqrt{s_{AB}}$ | $E_A$ | $E_B$ | (a) $\gamma_{A\leftrightarrow B}$ | (b) $E^{rest}_{\gamma Max}$ | (c) $E_{\gamma Max}$ | (d) $W^{max}_{\gamma p}$ |
|---|---|---|---|---|---|---|---|
| pPb | 5.02 TeV | 4 TeV | 1.567 TeV | $1.43 \times 10^7$ | 28 MeV | 0.4 PeV | 0.86 TeV |
| pPb | 8.16 TeV | 6.5 TeV | 2.56 TeV | $3.78 \times 10^7$ | 28 MeV | 1 PeV | 1.4 TeV |
| pp | 13 TeV | 6.5 TeV | 6.5 TeV | $9.6 \times 10^7$ | 116 MeV | 11 PeV | 4.6 TeV |

table: K. Lynch

# Exclusive processes at the LHC: kinematic coverage

- hard scale of the interaction:

$$\bar{Q}^2 = \frac{Q^2 + M_V^2}{4} = \frac{M_V^2}{4}$$

- Bjorken-x variable:

$$x_B = \frac{Q^2 + M_V^2}{W_{\gamma p}^2 + Q^2} = \frac{M_V^2}{W_{\gamma p}^2}$$

$$= \frac{M_V}{\sqrt{s_{NN}}} e^{\pm y} \approx \frac{2\xi}{1-\xi}$$

photoproduction

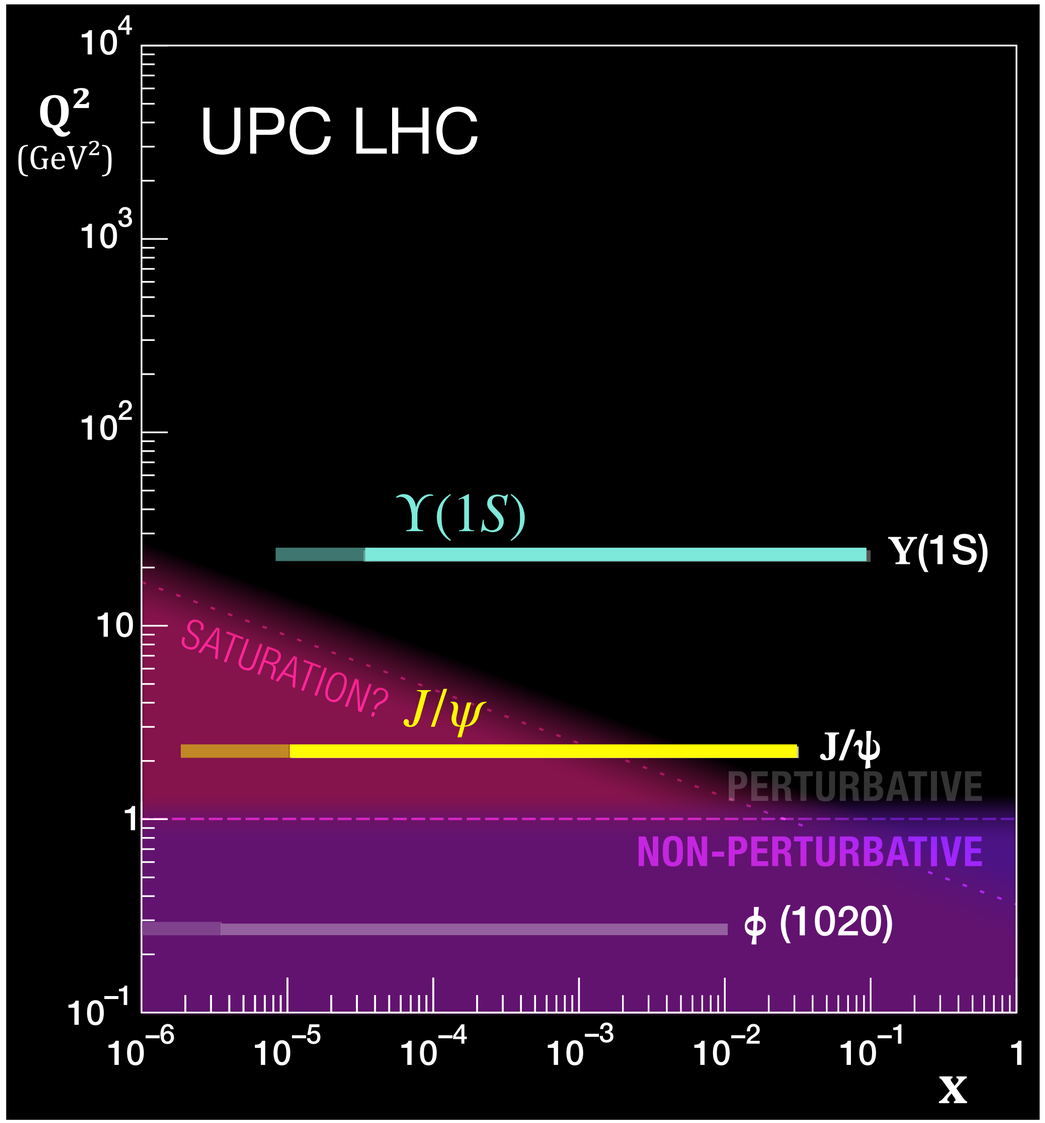


Figure adapted from Jordan Lang | Quarkonia as Tools 2026 | 6 January 2026

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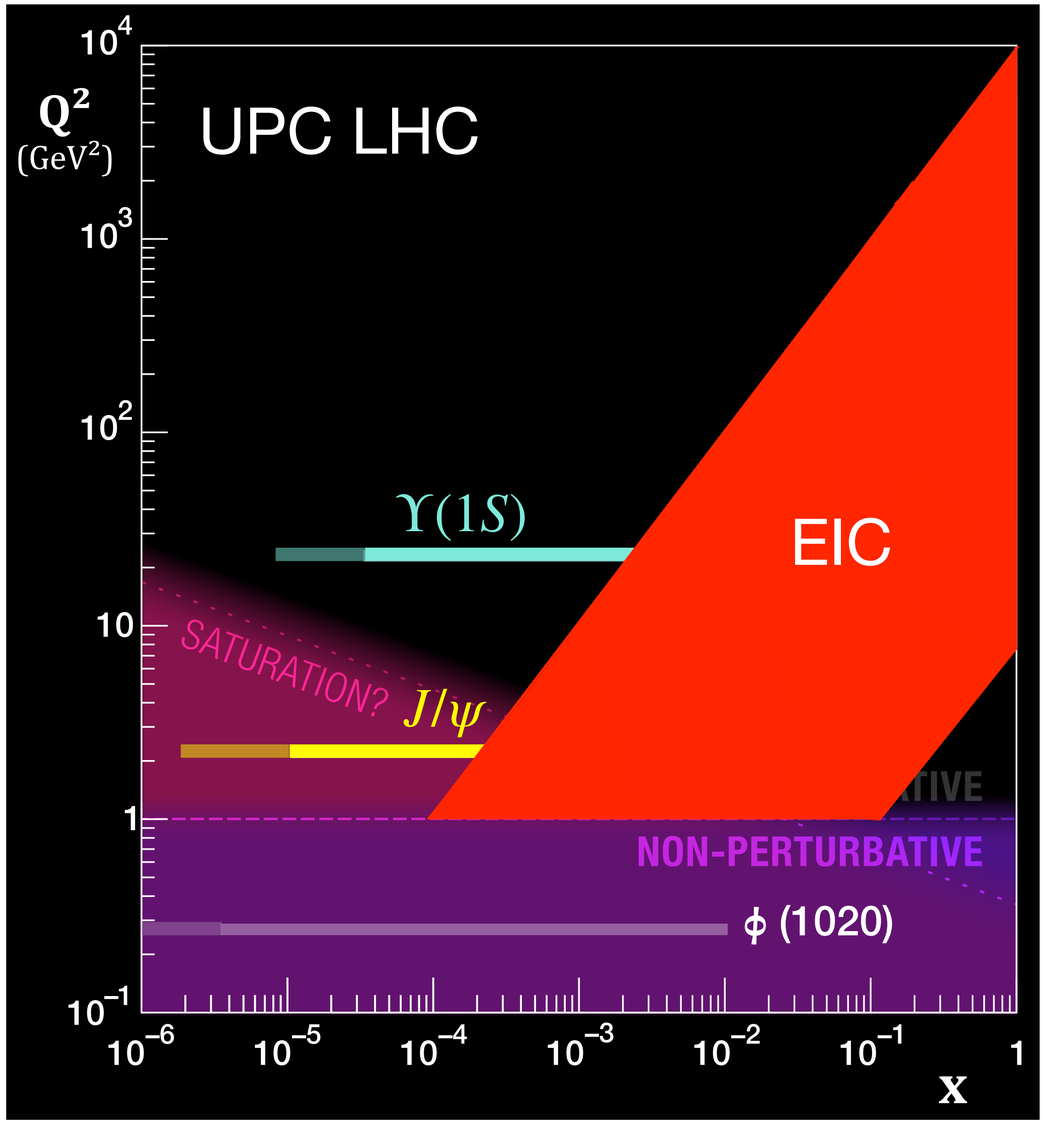


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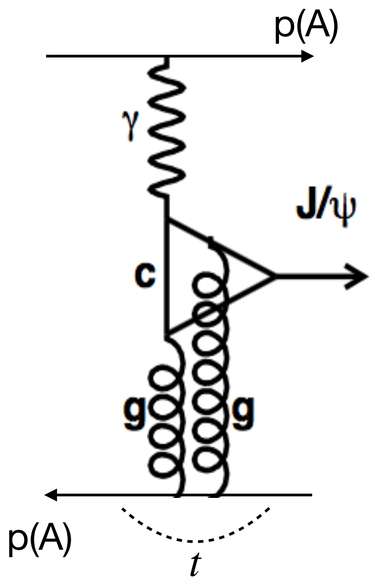
# Experimental signature at the LHC



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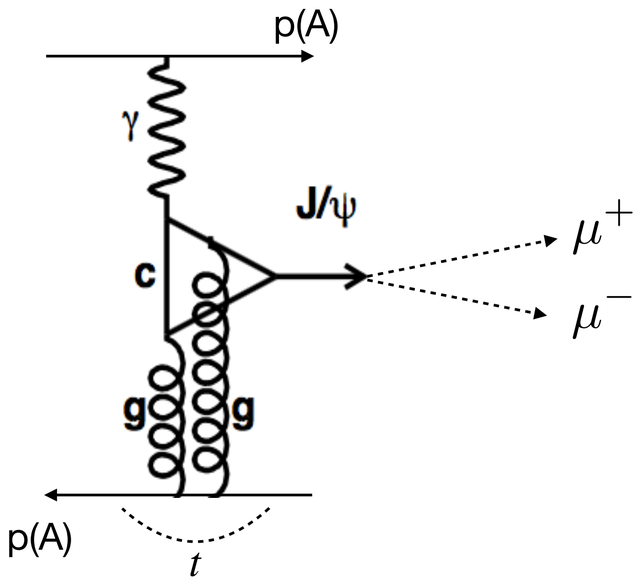

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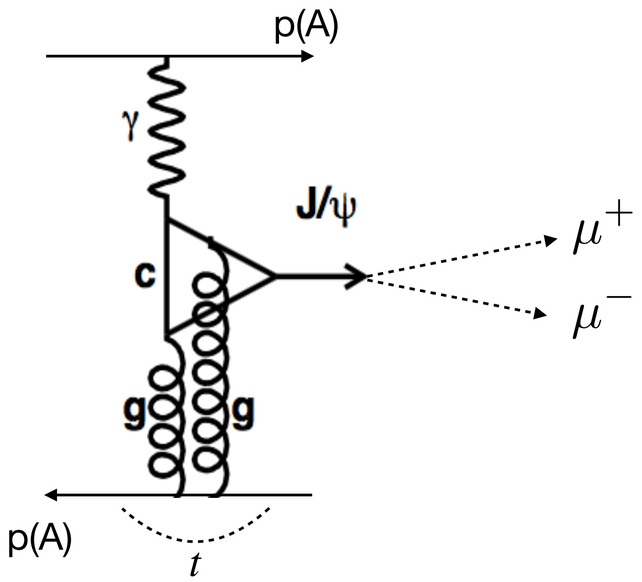
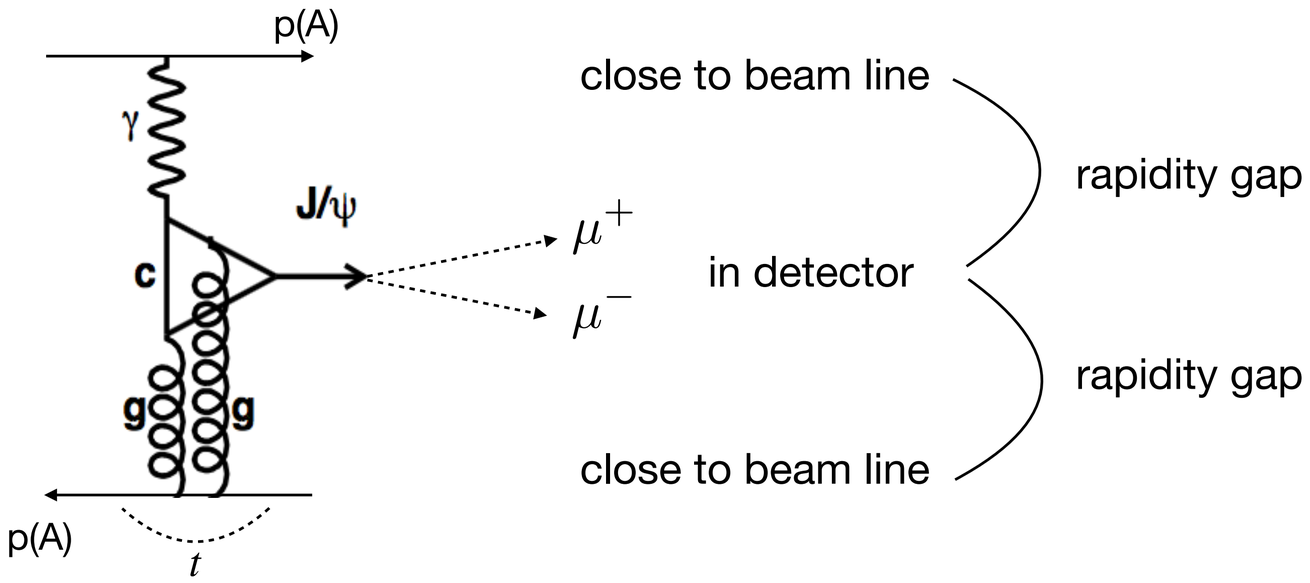



in detector

# Experimental signature at the LHC



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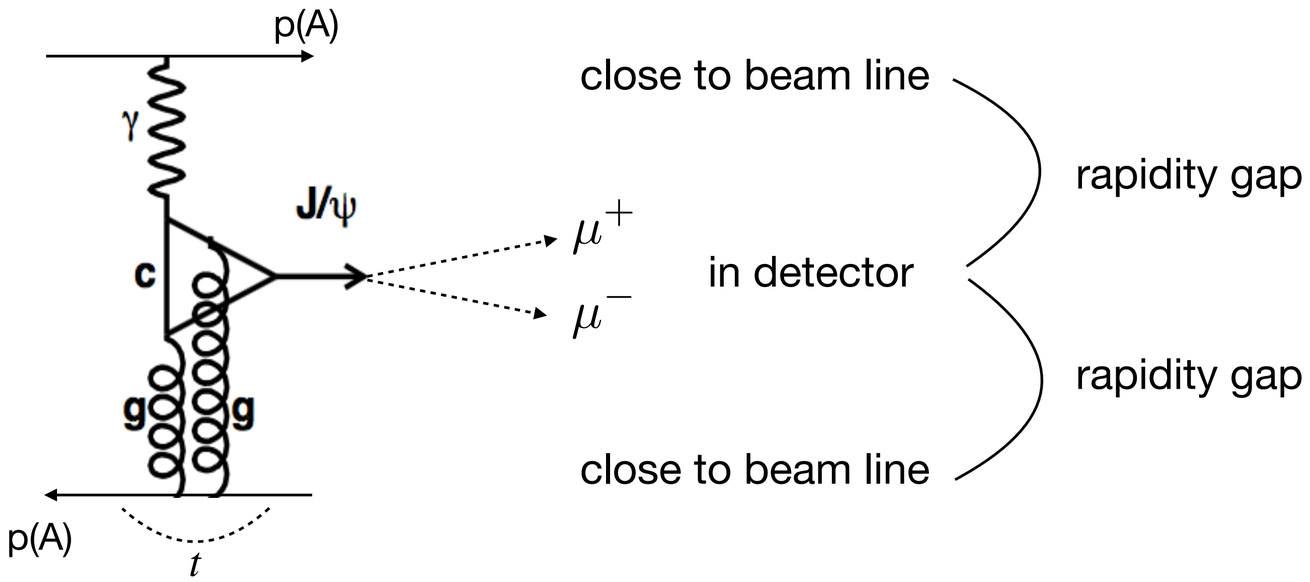


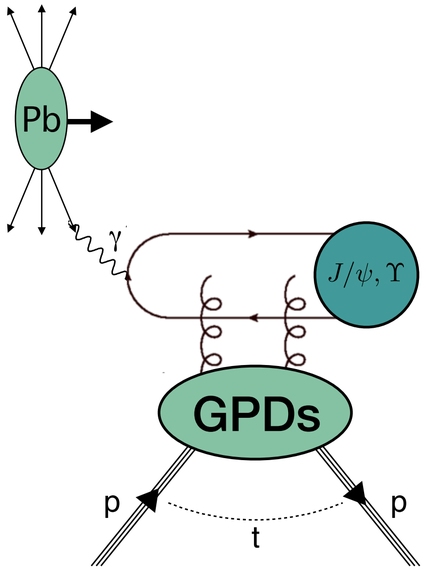

No detection of beam particles

- Mandelstam variable:

$$t = (p - p')^2 \approx -p_{T,J/\psi}^2$$

- (Partial) ambiguity in ID of probed beam particle in symmetric collisions

# Extraction of the J/ψ photoproduction off the proton




pPb: use $Z^2$ dependence of photon flux

→ Pb is predominantly photon emitter

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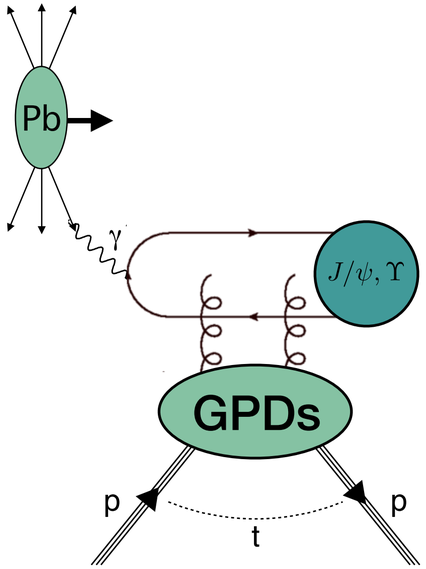


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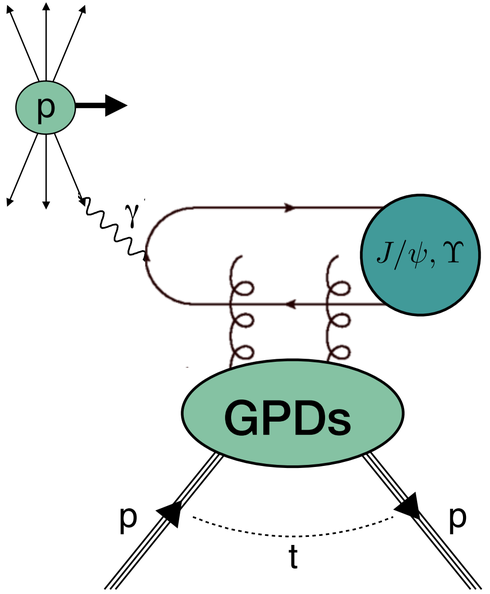



pp: ambiguity in ID of photon emitter

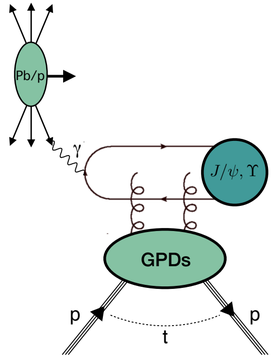
- r = gap survival factor
- $k_{\pm} = \frac{M_{\psi}}{2} e^{\pm y}$ = photon energy
- $\frac{dn}{dk_{\pm}}$ = photon flux
- $W_{\pm}^2 = 2k_{\pm}\sqrt{s}$ = γp invariant mass

relation pp and γp cross section:

$$\sigma_{pp\to p\psi p} = r(W_+)k_+ \frac{\mathrm{d}n}{\mathrm{d}k_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_- \frac{\mathrm{d}n}{\mathrm{d}k_-}\sigma_{\gamma p\to\psi p}(W_-)$$

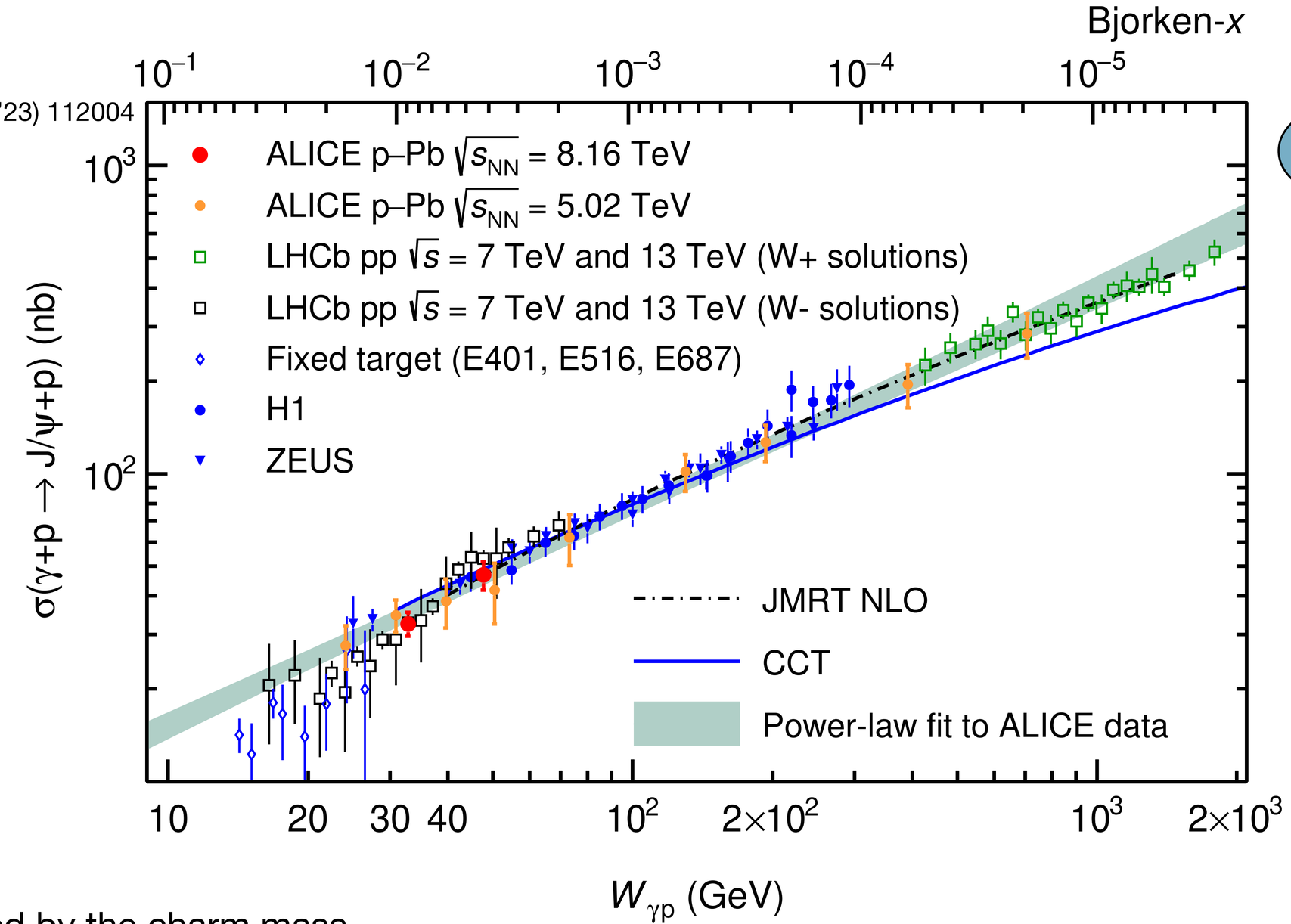
LHCb used HERA data for low-$E_\gamma$ ( $W_-$ ) contribution.

# J/ψ photoproduction cross section off the proton at the LHC




GPD H

Phys. Rev. D **108** ('23) 112004




Hard scale: fixed by the charm mass

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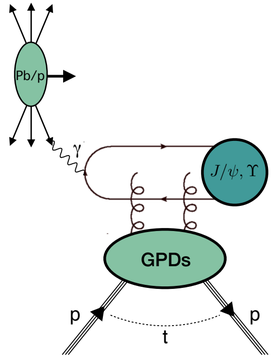


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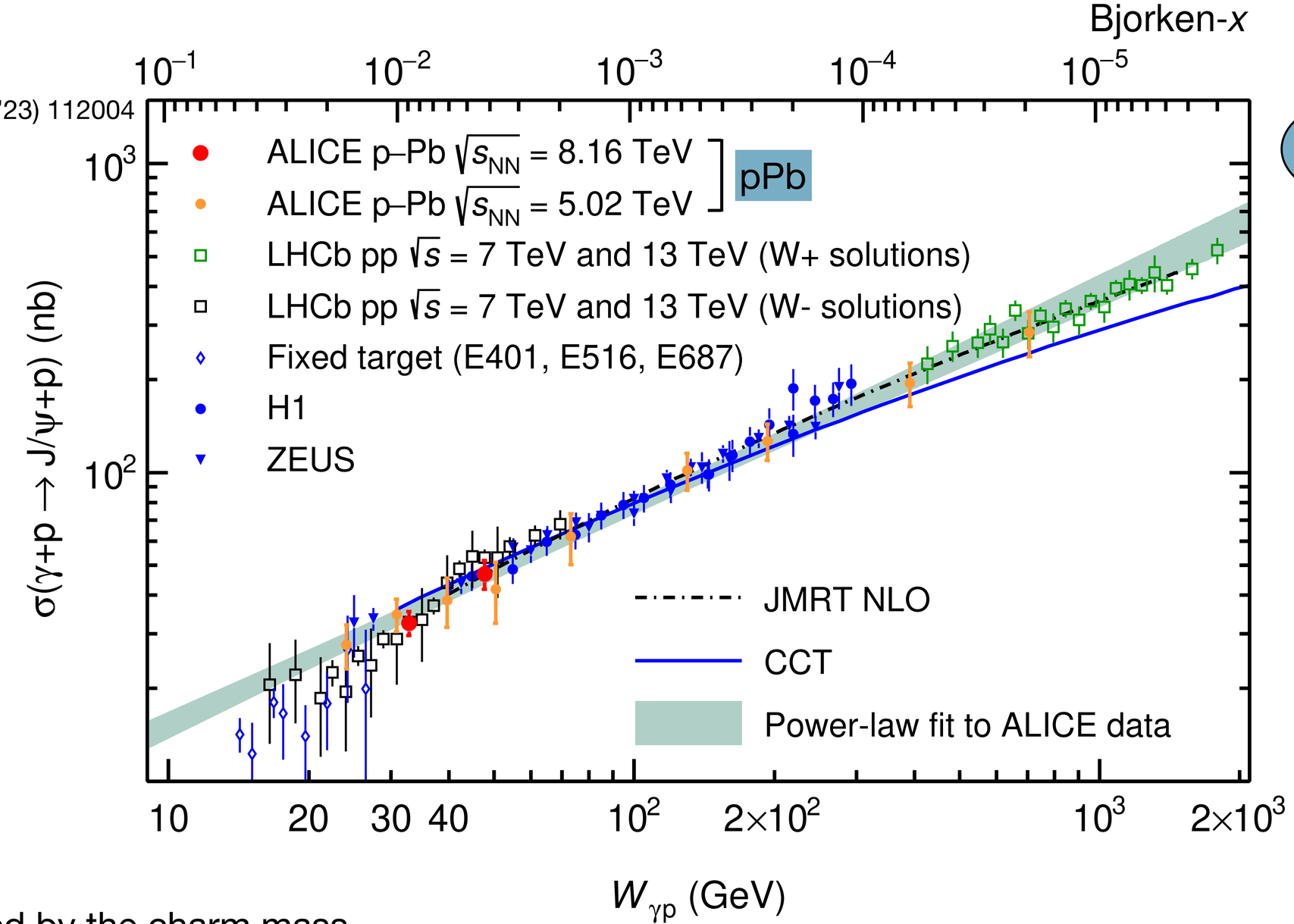


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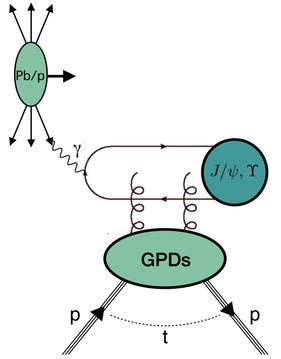


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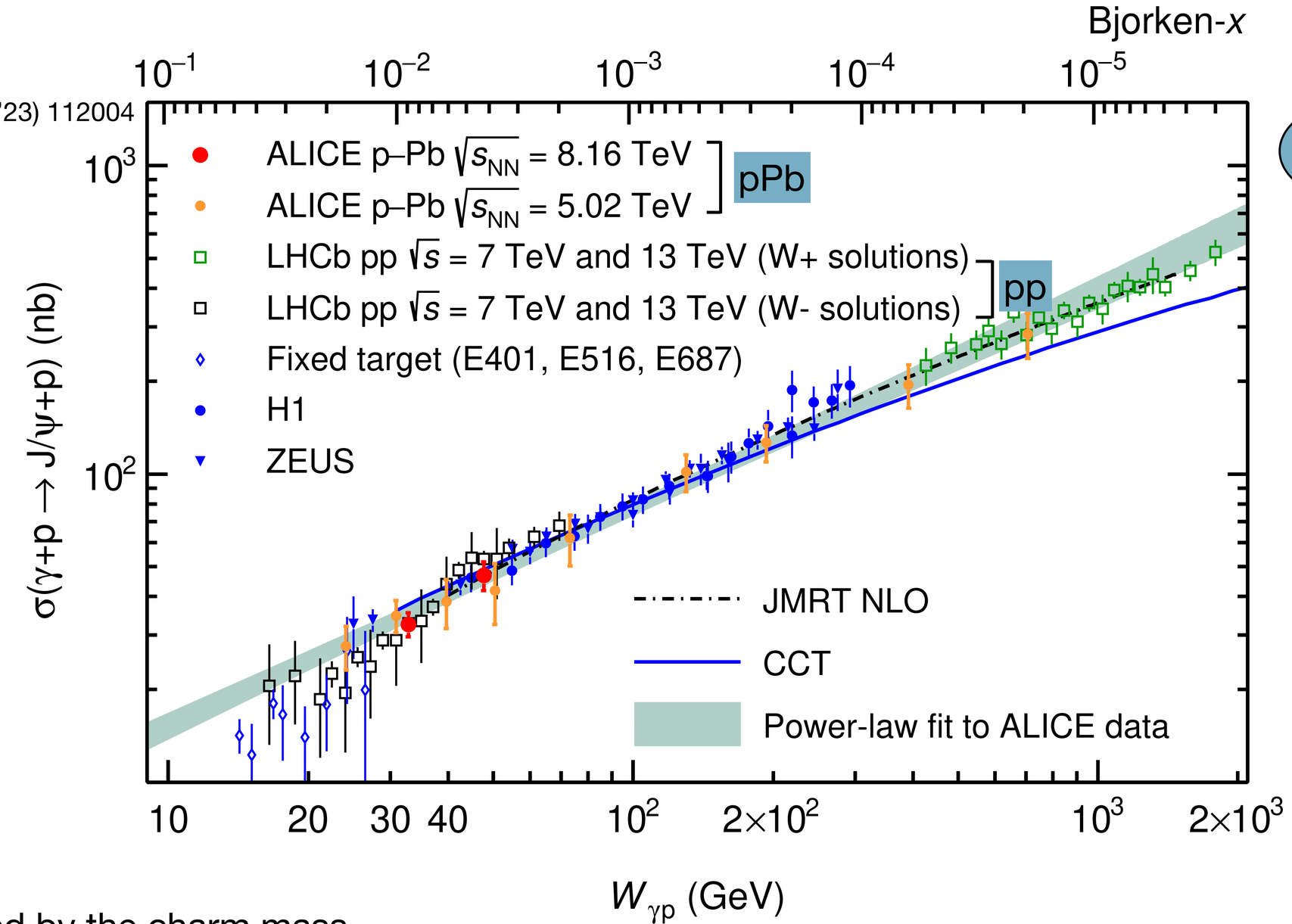


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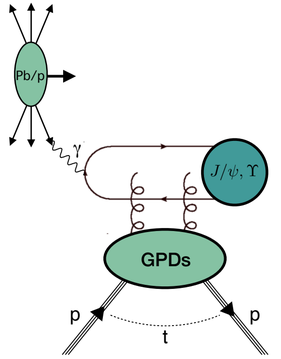


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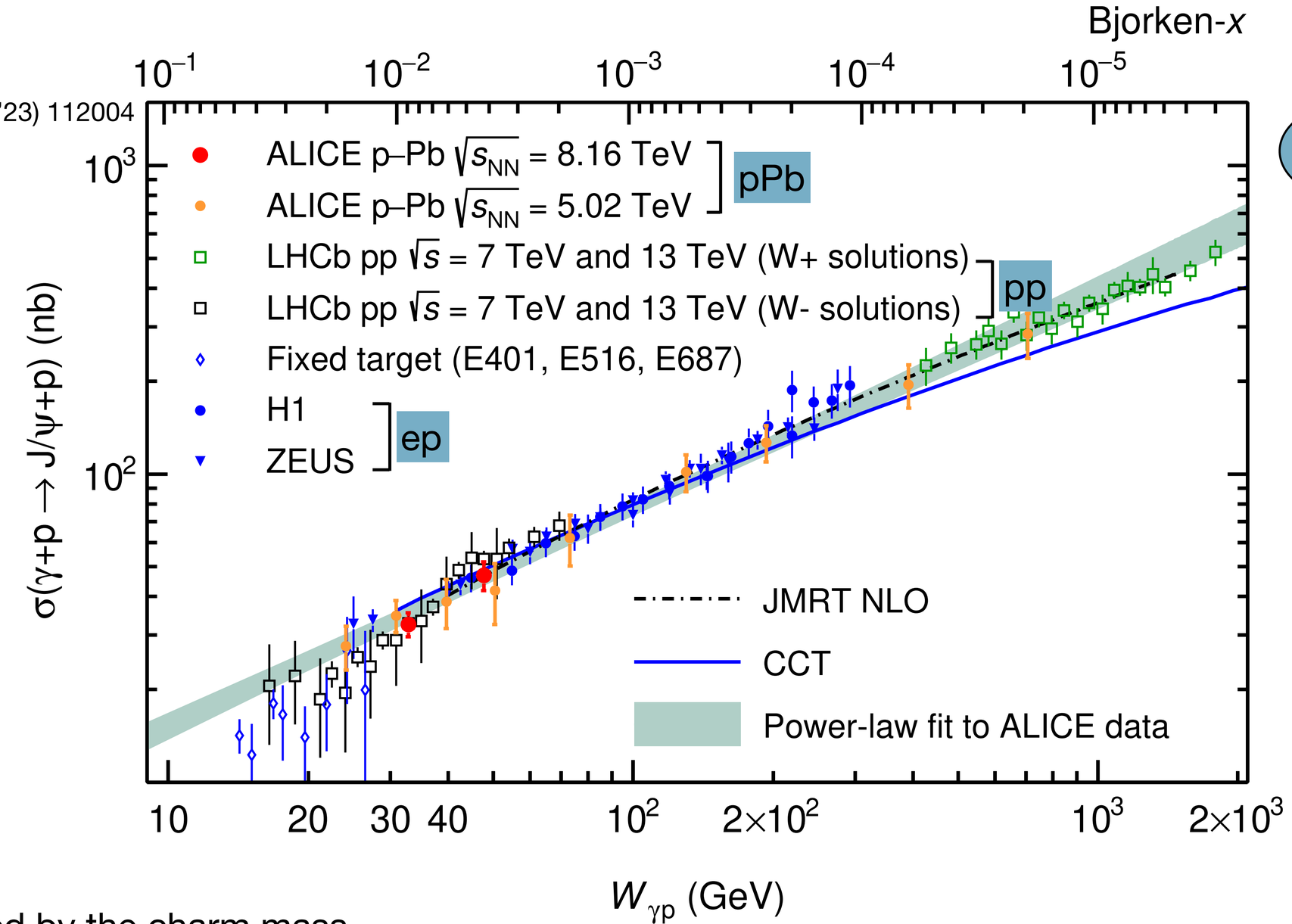


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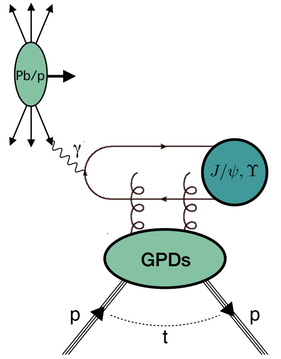


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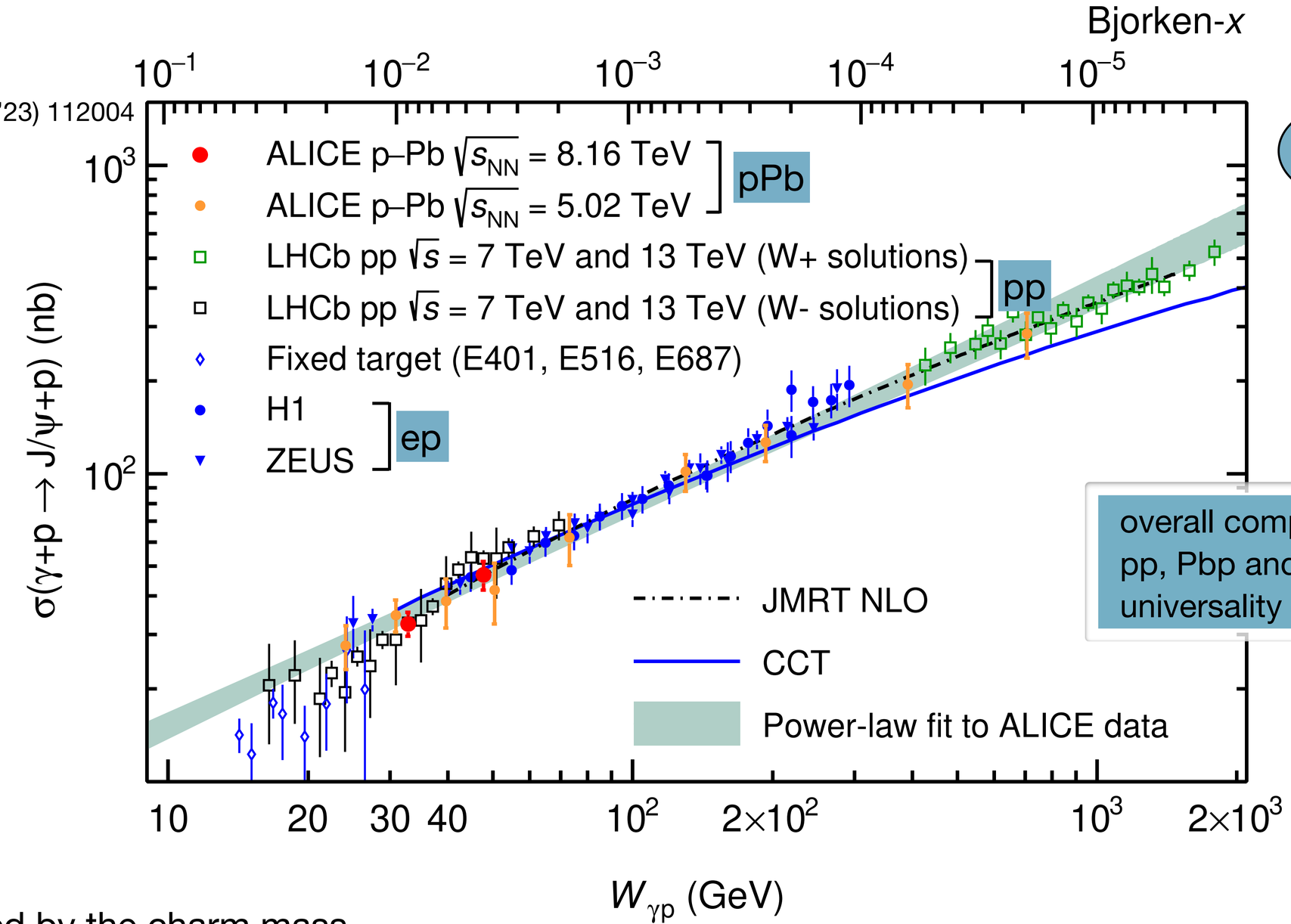
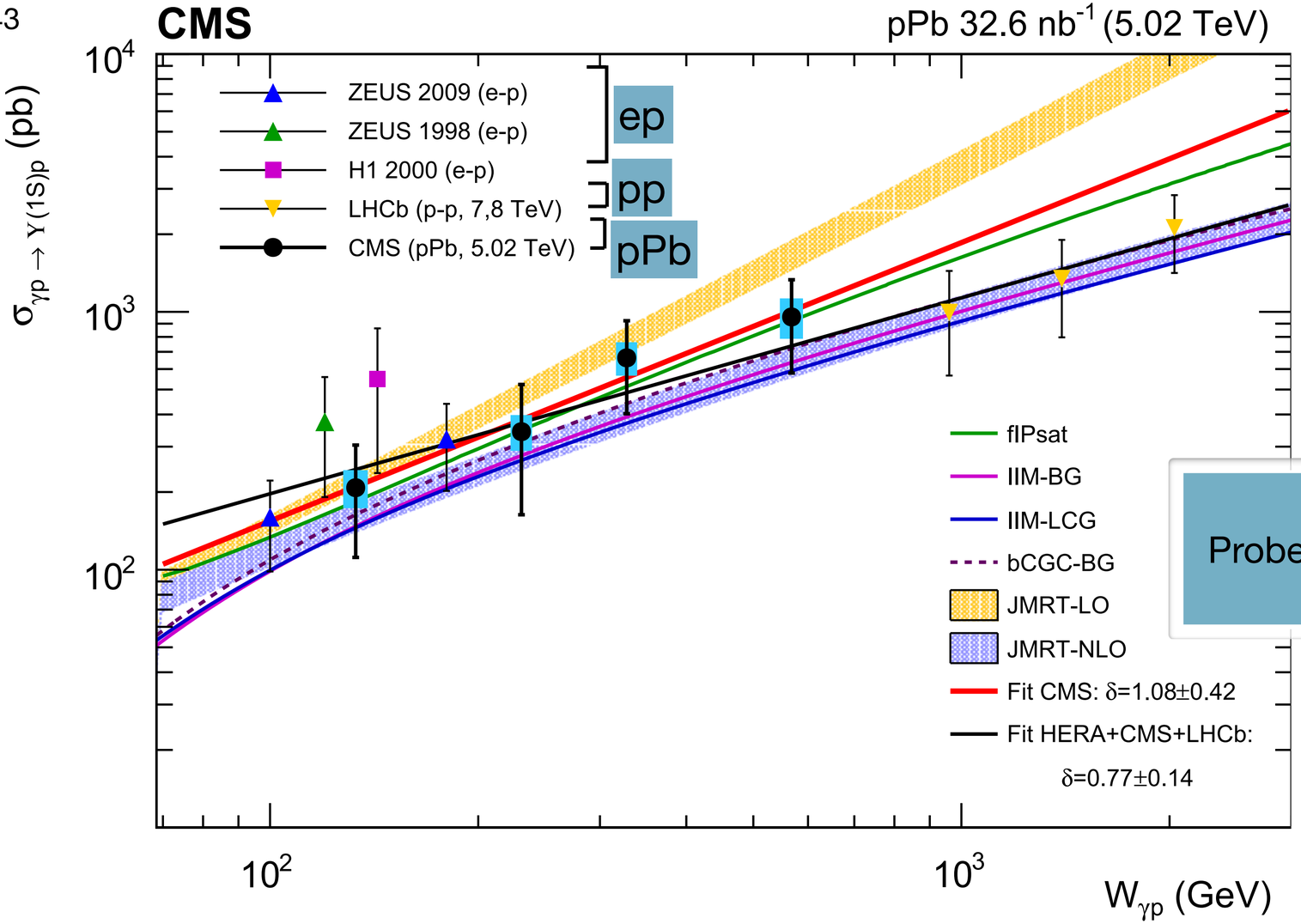


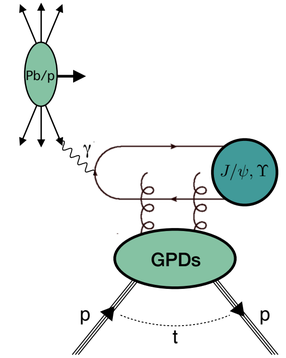

overall compatibility between pp, Pbp and ep data: hint of universality of underlying physics

Hard scale: fixed by the charm mass

# $\Upsilon$ photoproduction cross section

Eur. Phys. J. C **79** (2019) 277
Eur. Phys. J. C **82** (2022) 343




GPD H

Probes GPDs at higher scale.

# Access to GPDs: LHC and EIC

- for spin-1/2 hadron:

Four parton helicity-conserving twist-2 GPDs

| | | |
|---|---|---|
| $H(x,\xi,t)$ | $E(x,\xi,t)$ | parton-spin independent |
| $\tilde{H}(x,\xi,t)$ | $\tilde{E}(x,\xi,t)$ | parton-spin dependent |
| proton helicity non flip | proton helicity flip | |

Four parton helicity-flip twist-2 GPDs

| | |
|---|---|
| $H_T(x,\xi,t)$ | $E_T(x,\xi,t)$ |
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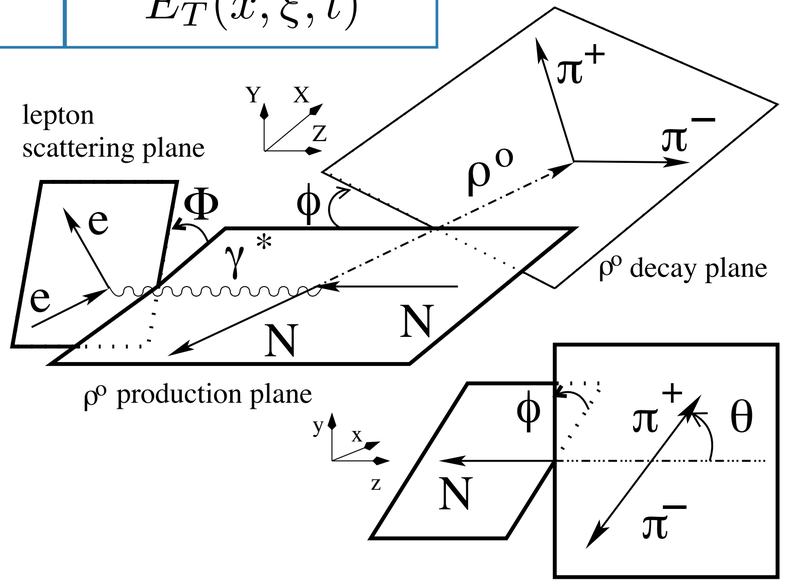
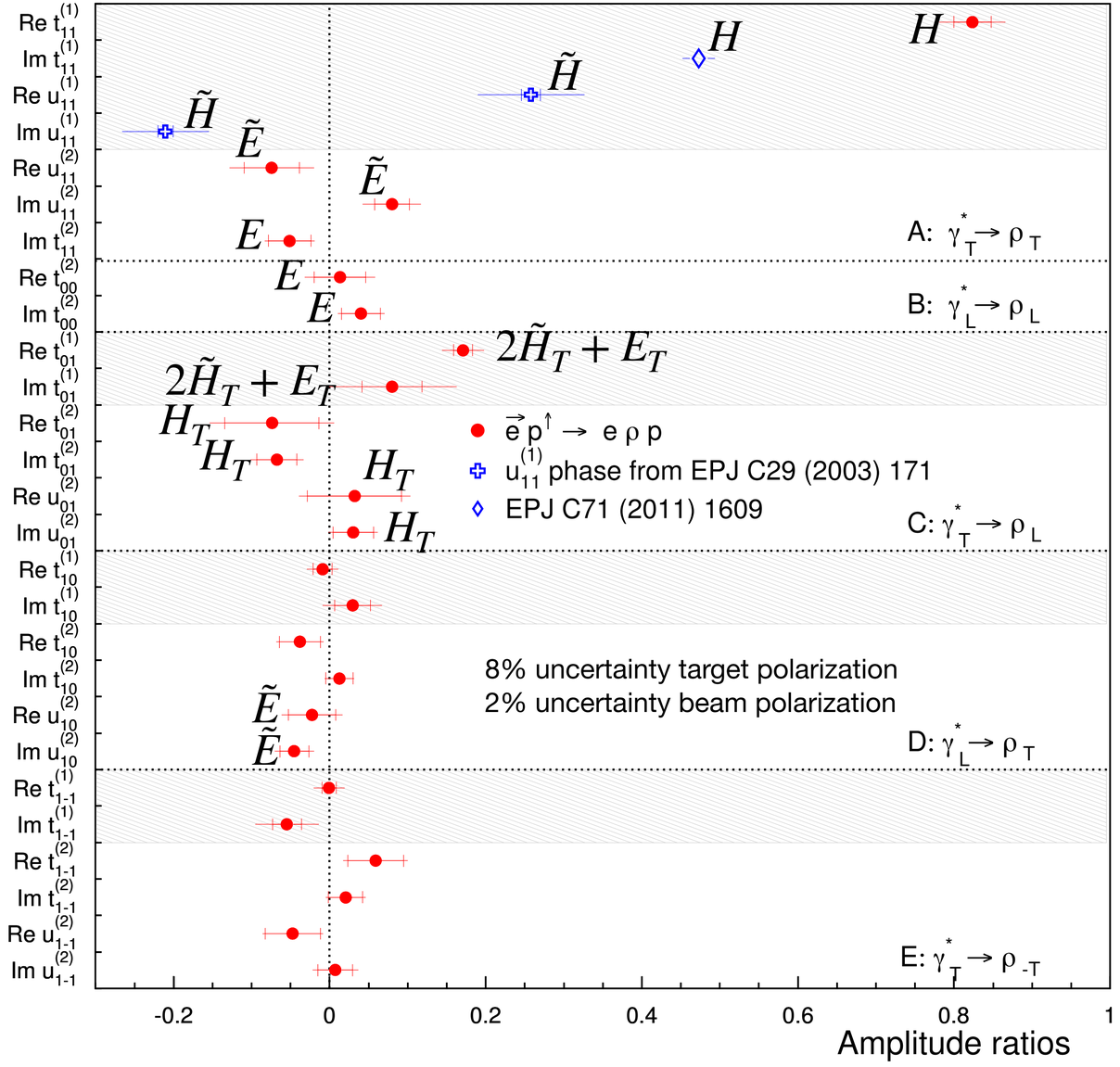



Exclusive $\rho$ on transversely polarised p

**Possible at EIC**

HERMES, Eur. Phys. J. C **77** (2017) 378




via unpolarised target | via transversely polarised target

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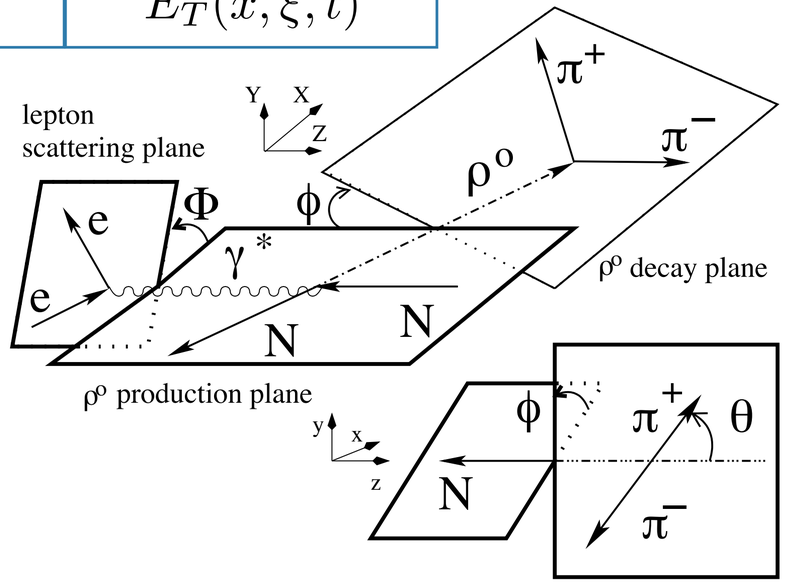


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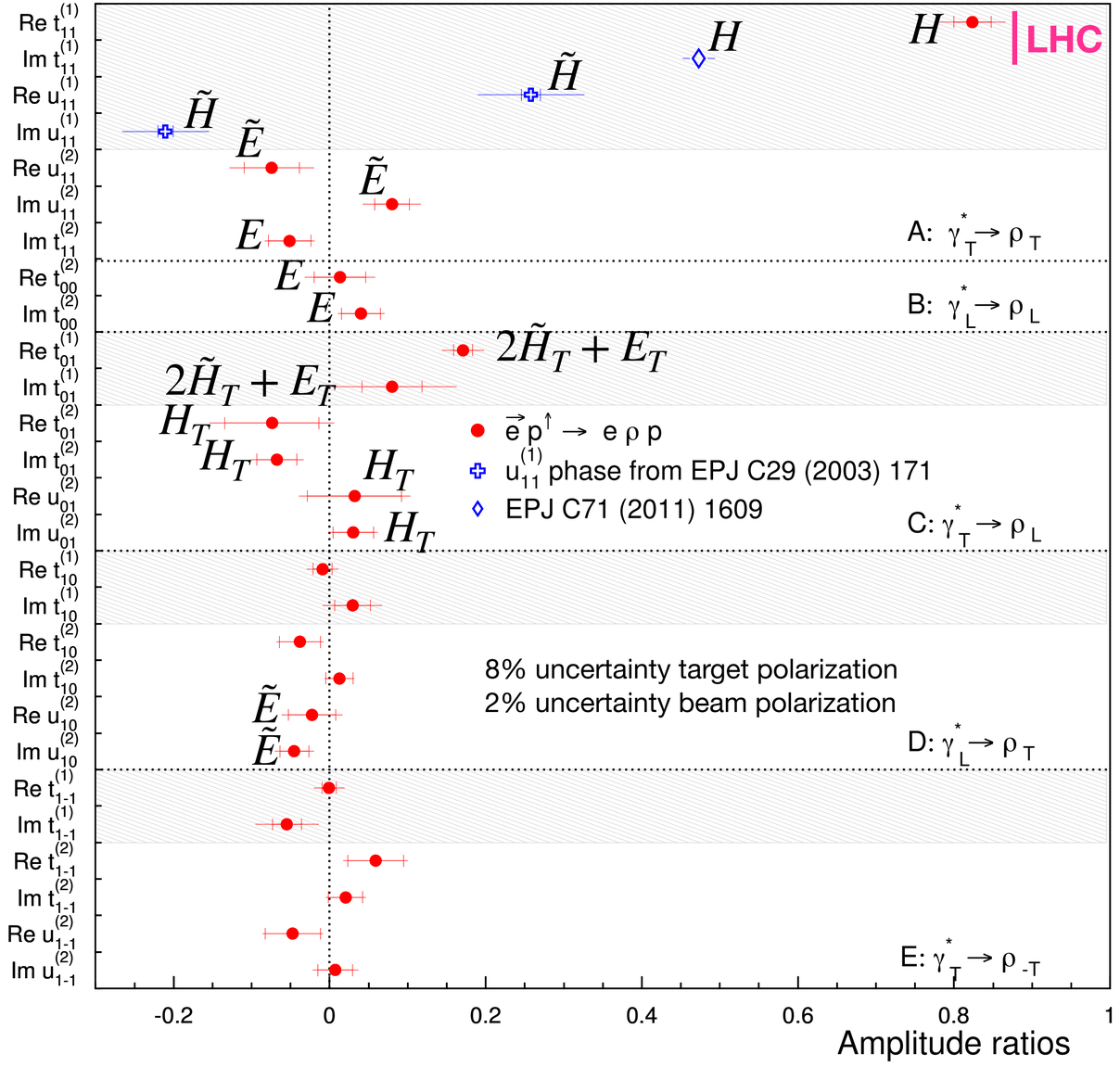


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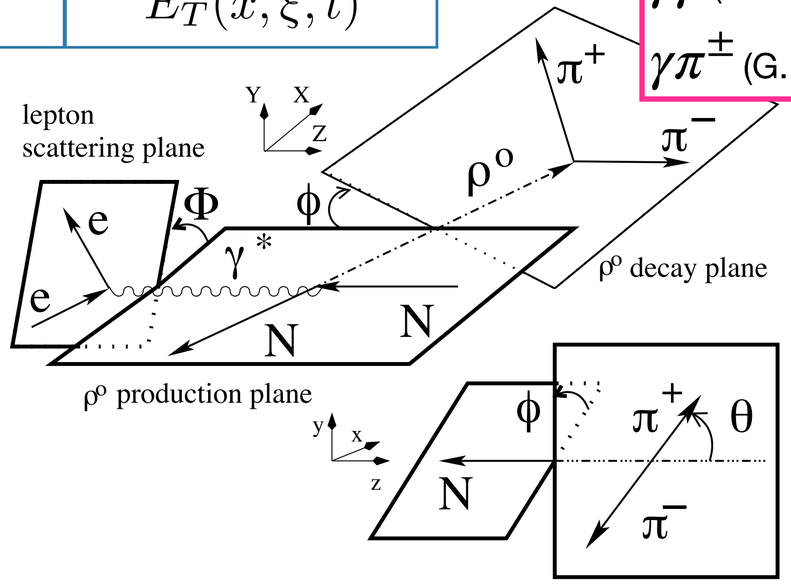


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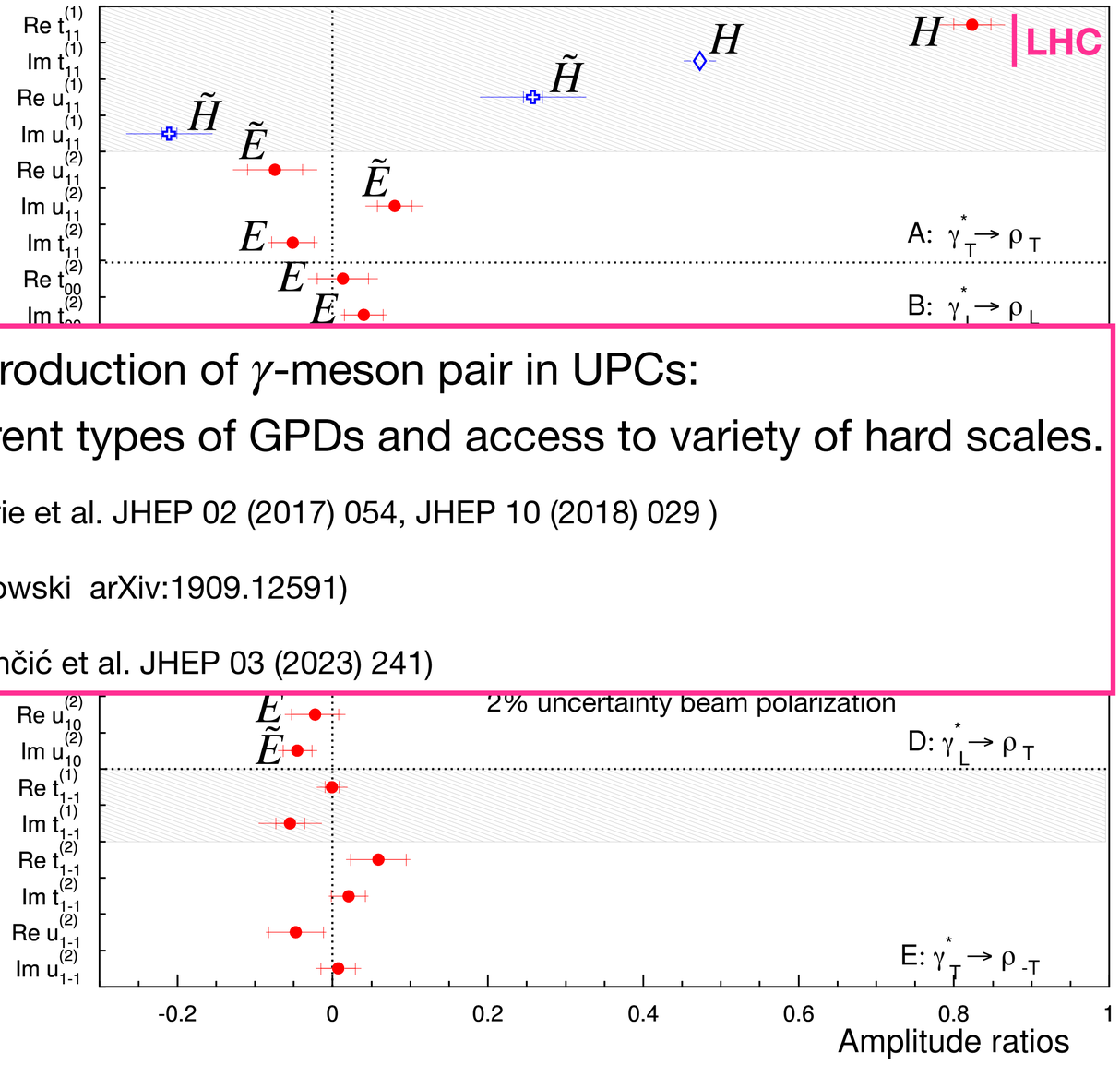



Exclusive production of $\gamma$-meson pair in UPCs:

probe different types of GPDs and access to variety of hard scales.

$\gamma\rho$ (R. Boussarie et al. JHEP 02 (2017) 054, JHEP 10 (2018) 029 )

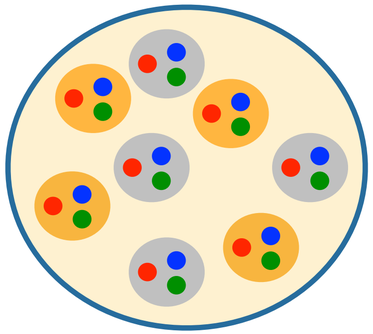
$\gamma\gamma$ (L. Szymanowski arXiv:1909.12591)

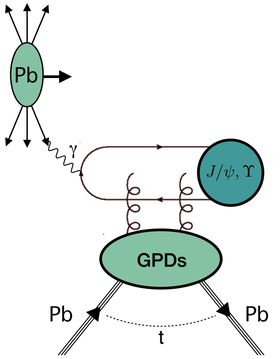
$\gamma\pi^{\pm}$ (G. Duplančić et al. JHEP 03 (2023) 241)

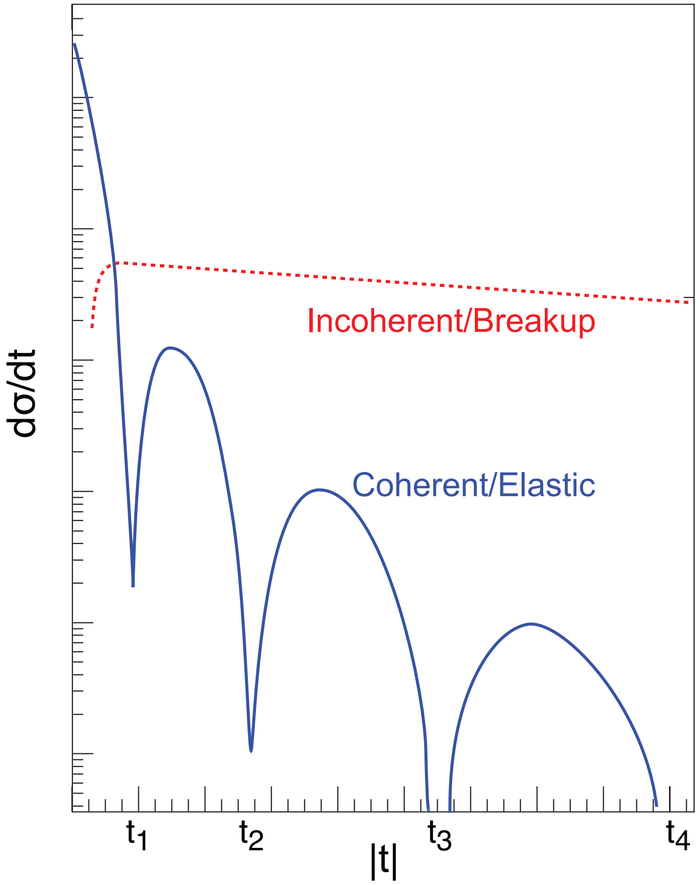
via unpolarised target | via transversely polarised target

# Probing ions

What object are we probing?





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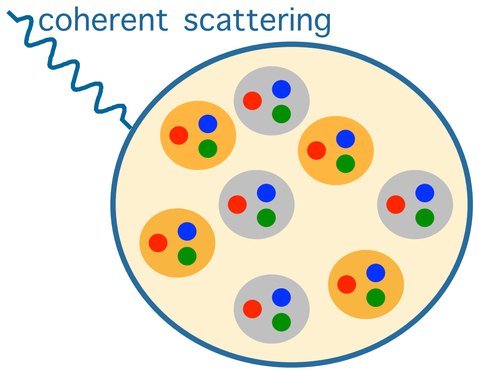
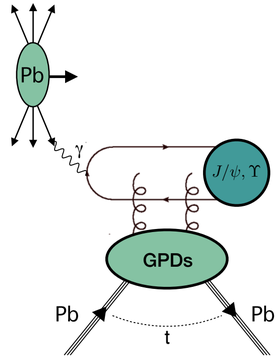
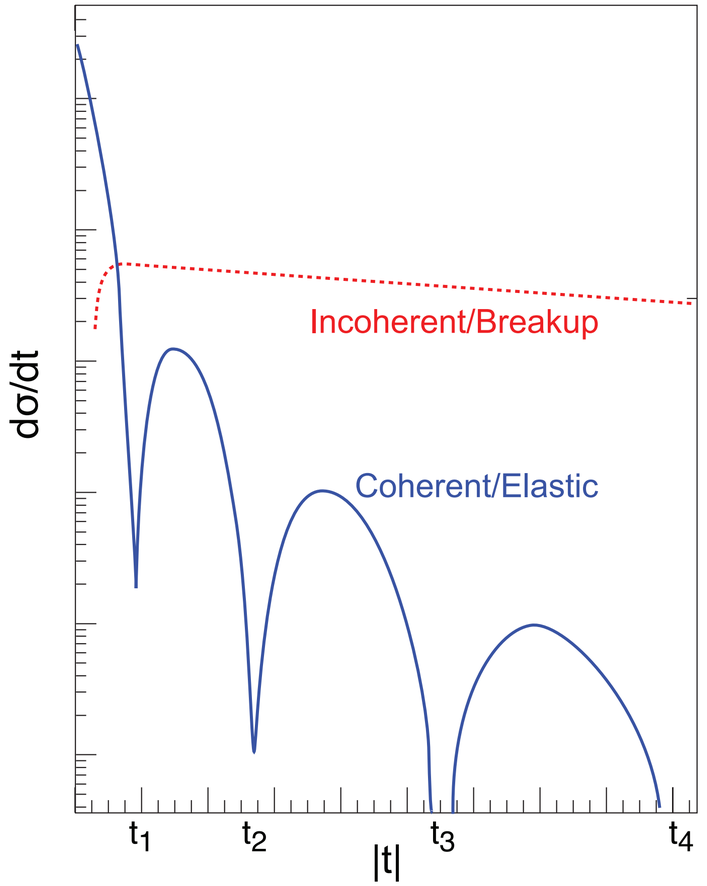
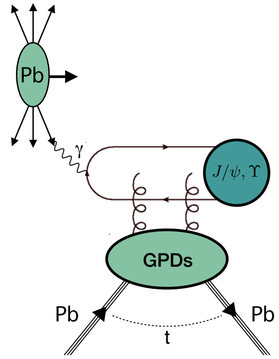



Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.



# Probing ions

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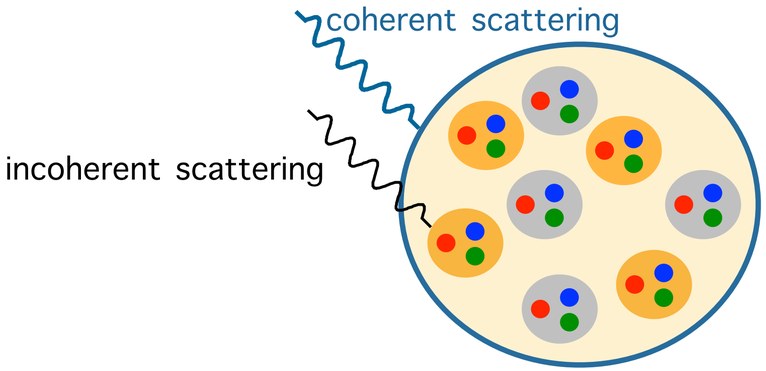
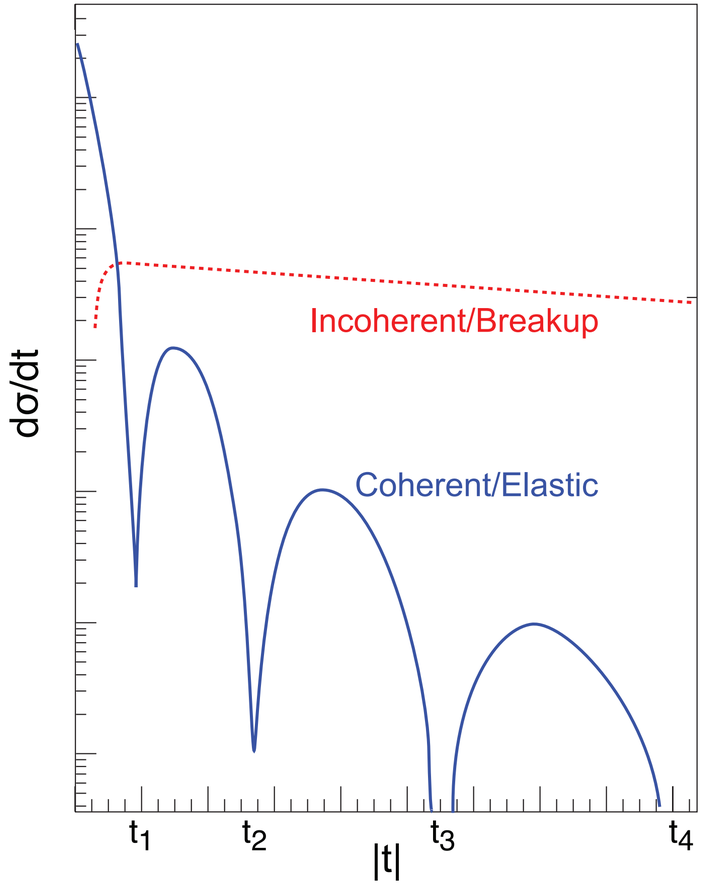
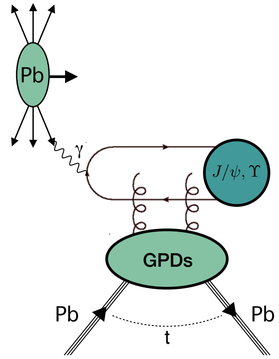


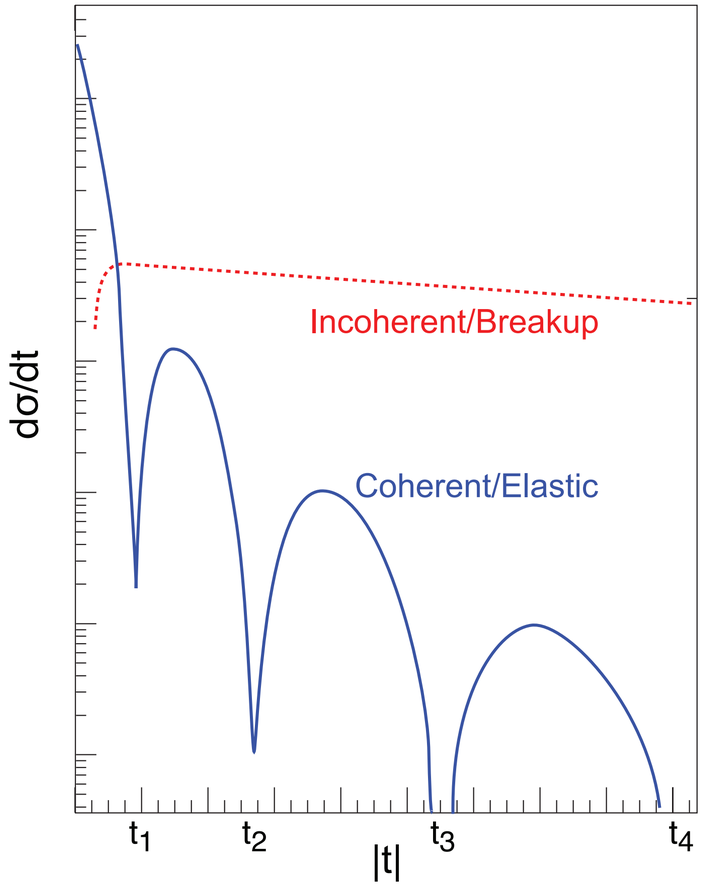

Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

Incoherent interaction: interaction with constituents inside target
~ target does not remain in same quantum state.
Ex.: target dissociation, excitation

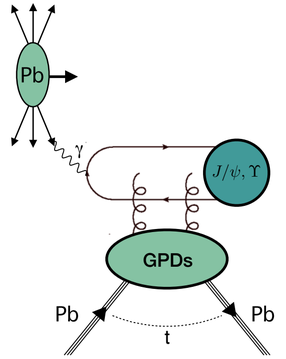
# Experimentally important points




- Good separation of coherent and incoherent production: not easy!



# Experimentally important points

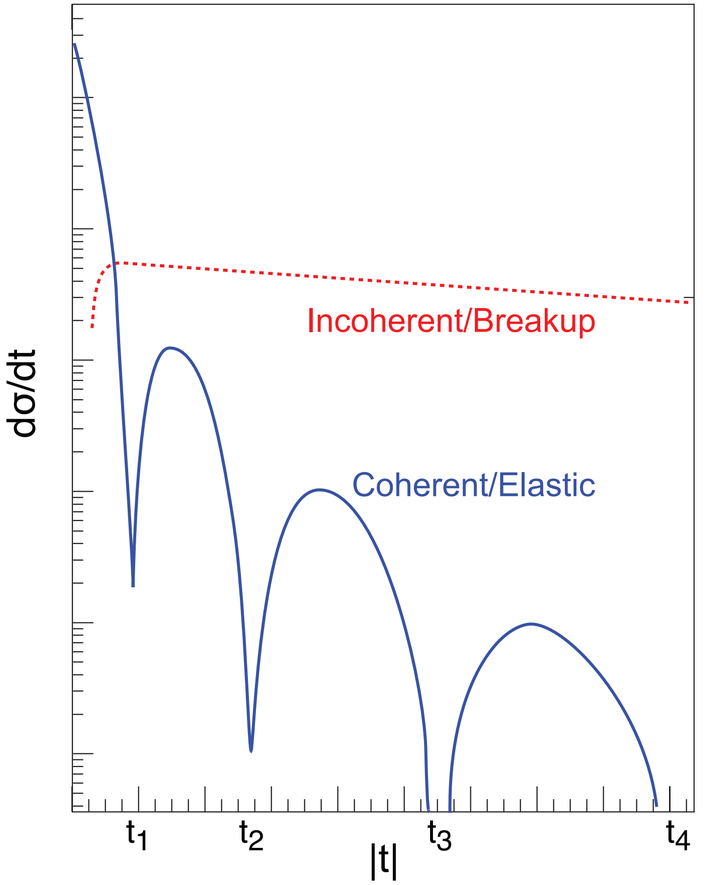



- Good separation of coherent and incoherent production: not easy!

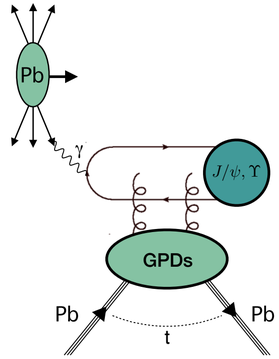
- Coherent production: measurements up to large t:
  - 3D or 2D (x independent) transverse position

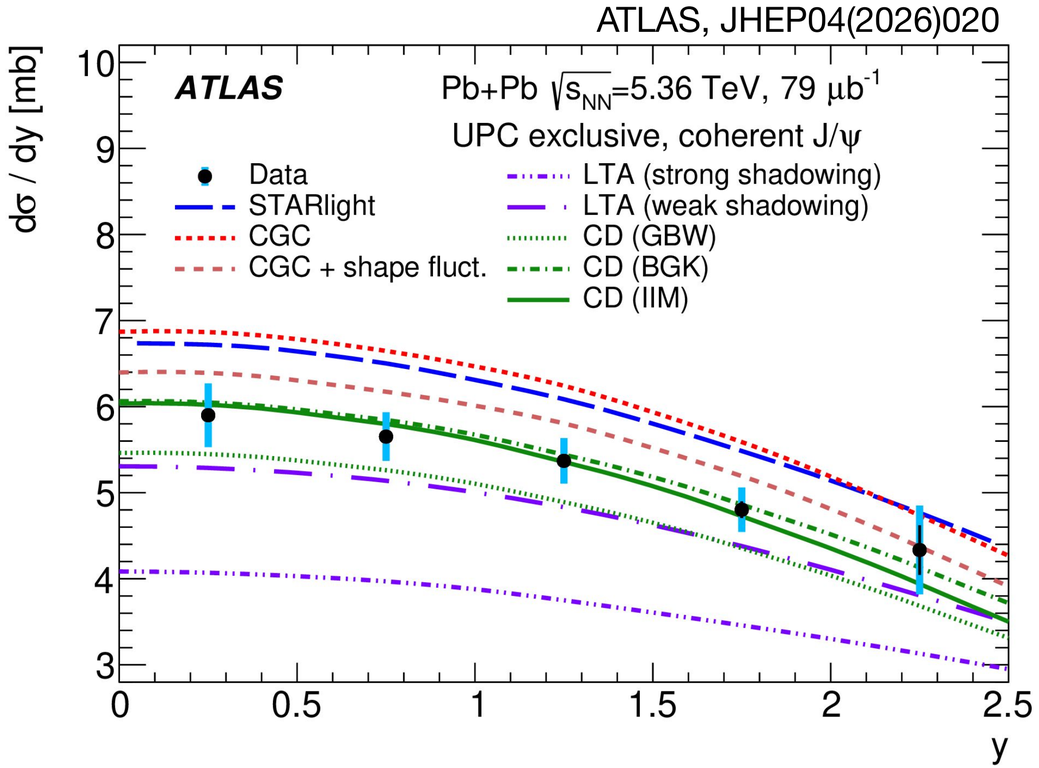
$$\int_0^{\infty} d\Delta_\perp \; \mathrm{GPD}(x, 0, \Delta_\perp)\; e^{-ib_\perp \Delta_\perp}$$

Experimentally limited by maximum transverse momentum.
Need to extend $p_T$ range as much as possible in measurement.
~second/third diffractive minimum.



# Coherent $J/\psi$ production in PbPb collisions at the LHC

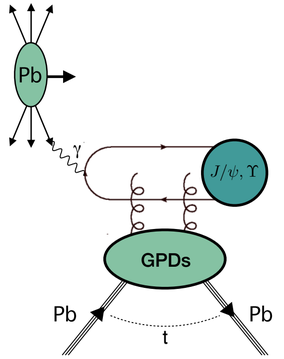


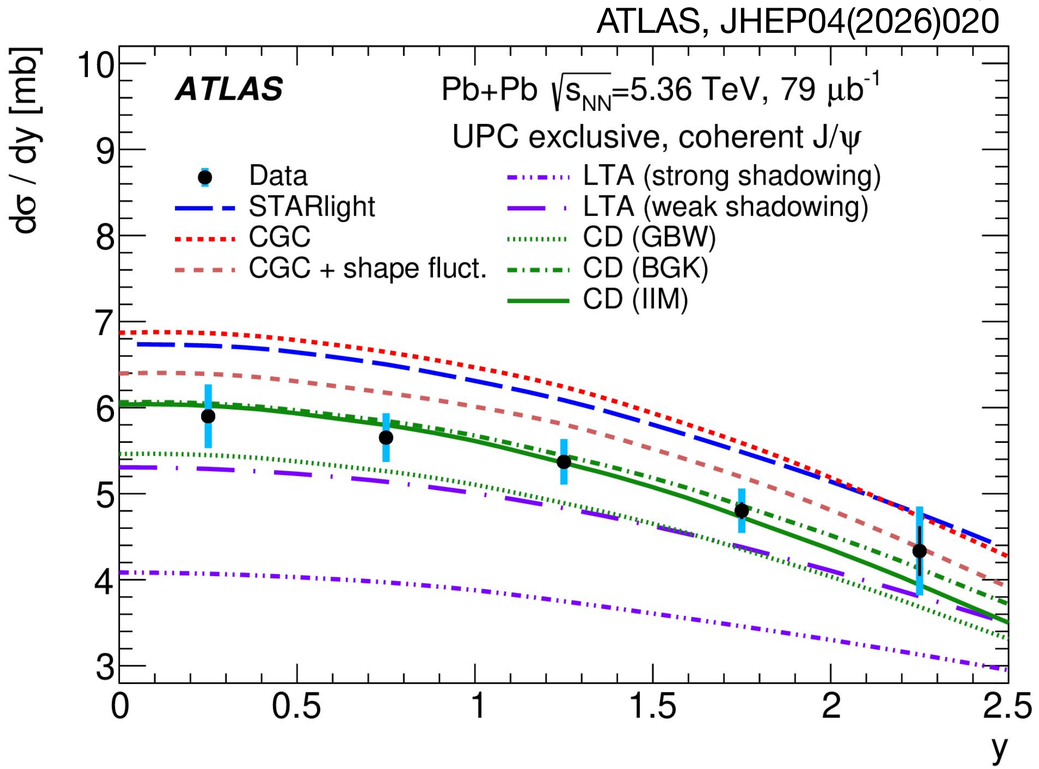

Results indicate significant nuclear shadowing

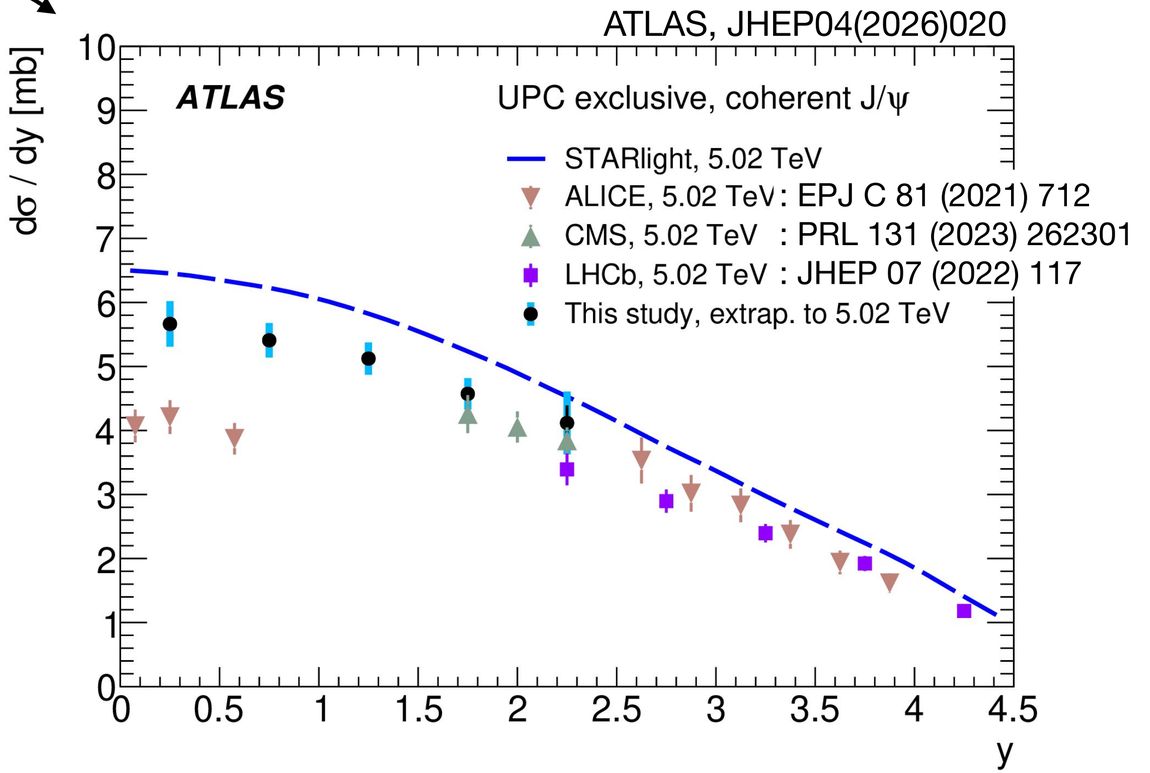
See also:
Preliminary results ALICE at $\sqrt{s_{NN}}$ 5.36 TeV

# Coherent $J/\psi$ production in PbPb collisions at the LHC




Scaling of the data to $\sqrt{s_{NN}} = 5.02$ TeV
with STARlight

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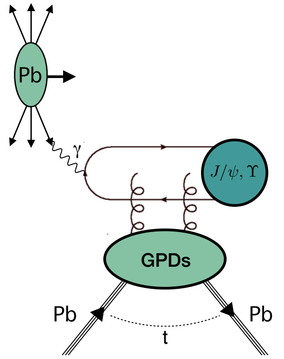


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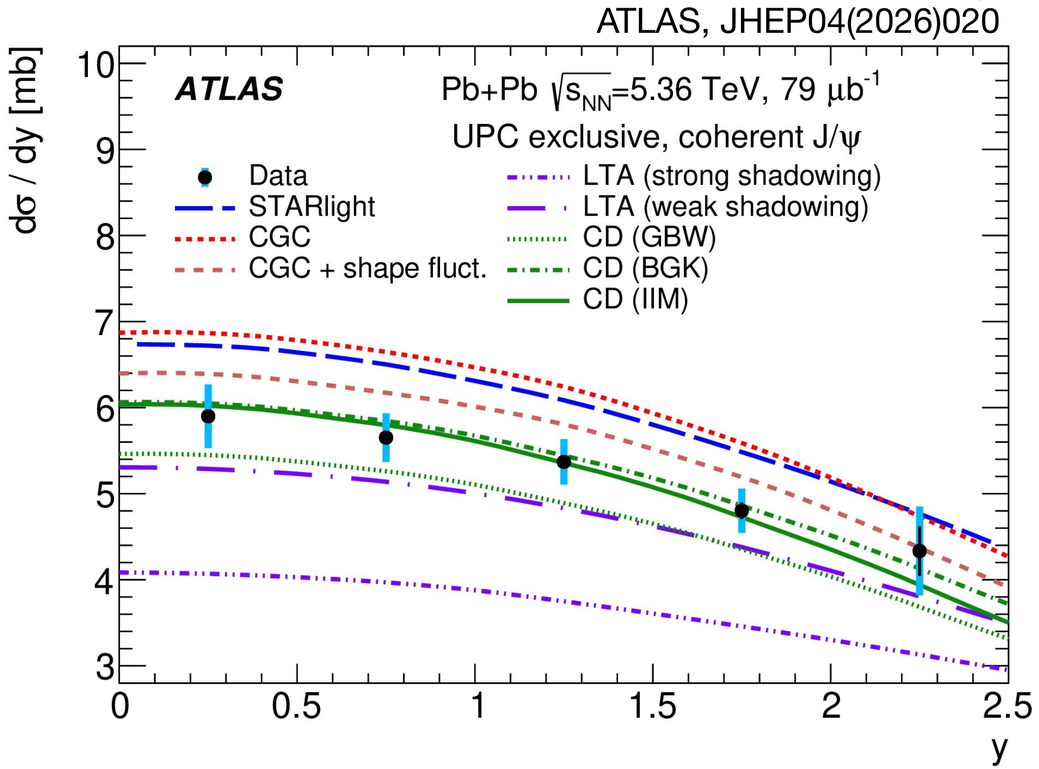


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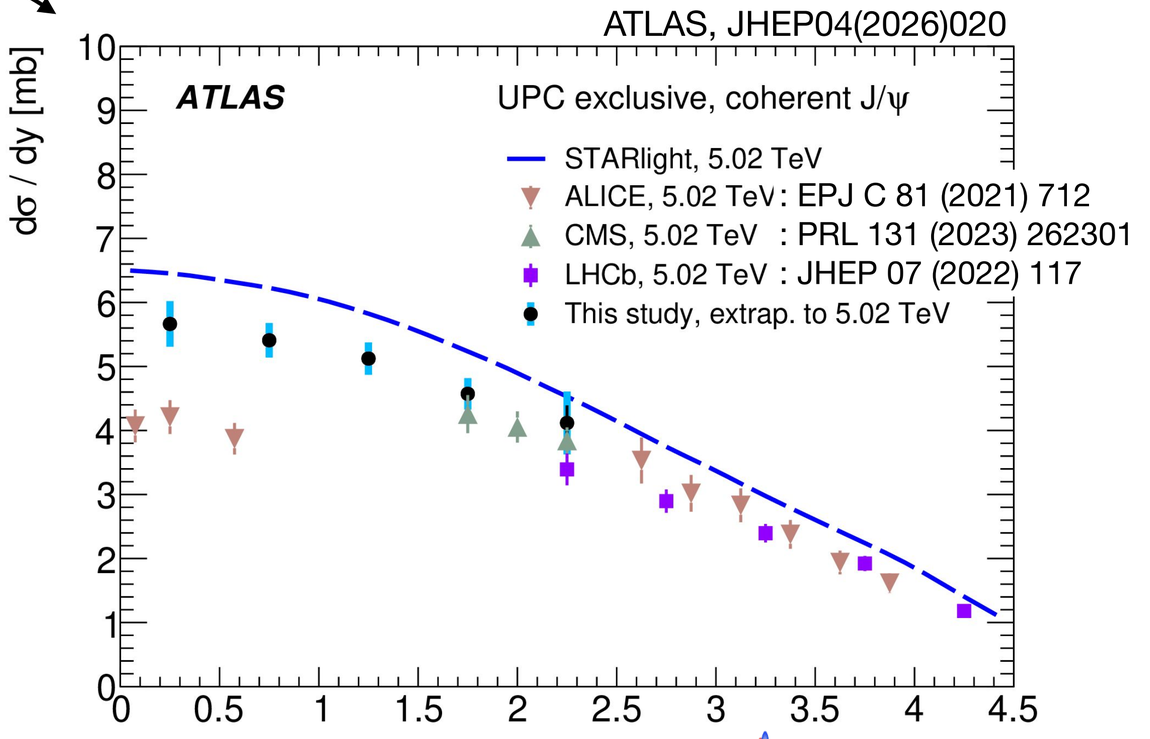
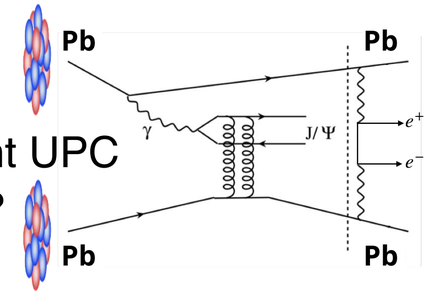
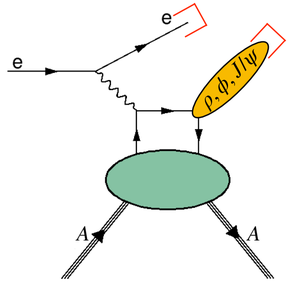



- Tension with ALICE results
- Potential contribution from coincident UPC $e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$ pair production?

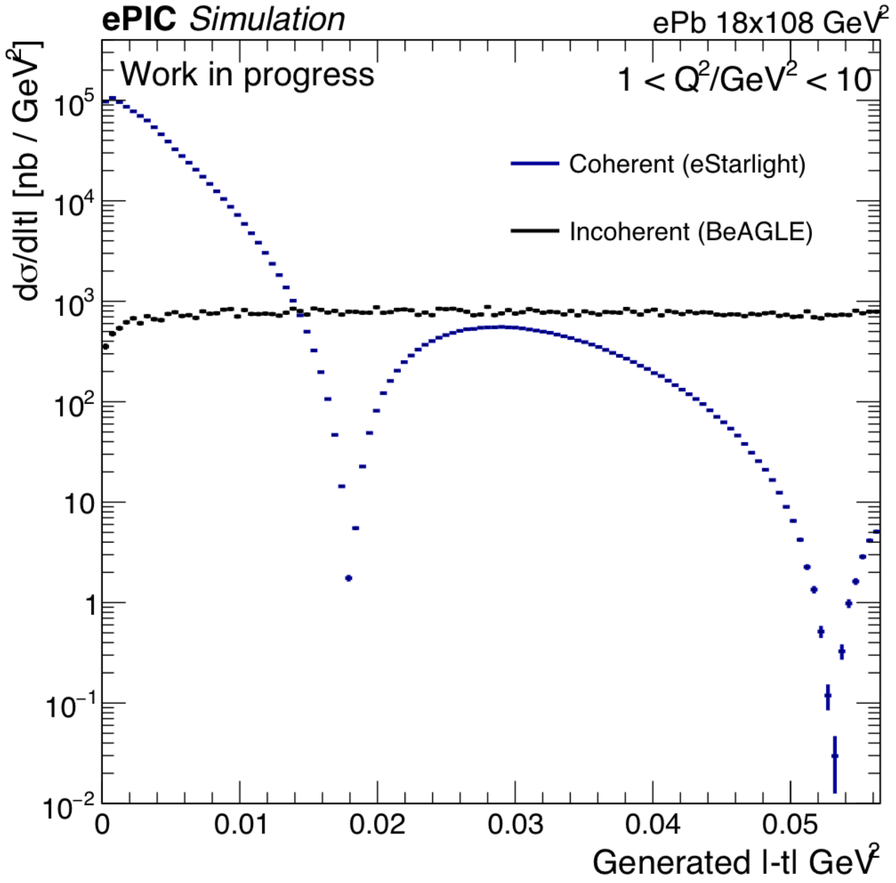



See also:
Preliminary results ALICE at $\sqrt{s_{NN}}$ 5.36 TeV

# Exclusive vector-meson production off nuclei in ePIC

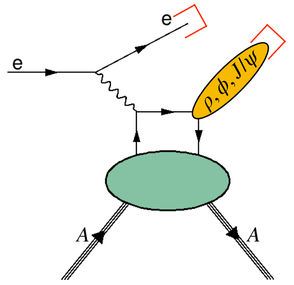



Separation of coherent and incoherent signal




Simulated coherent and incoherent signal

# Exclusive vector-meson production off nuclei in ePIC

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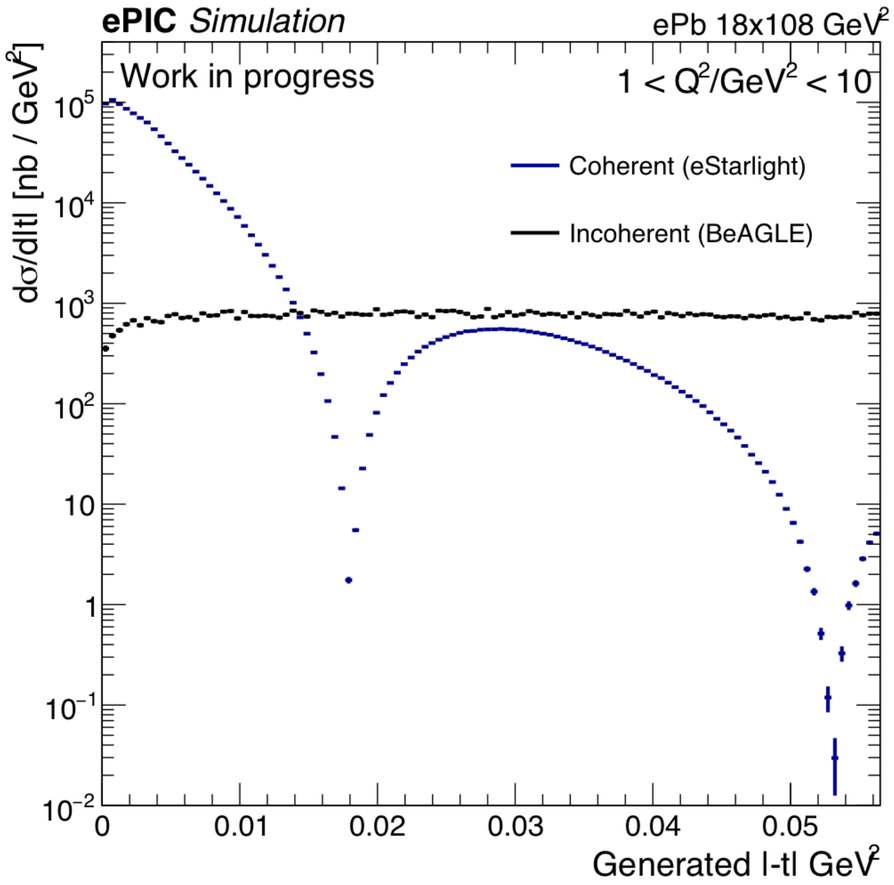


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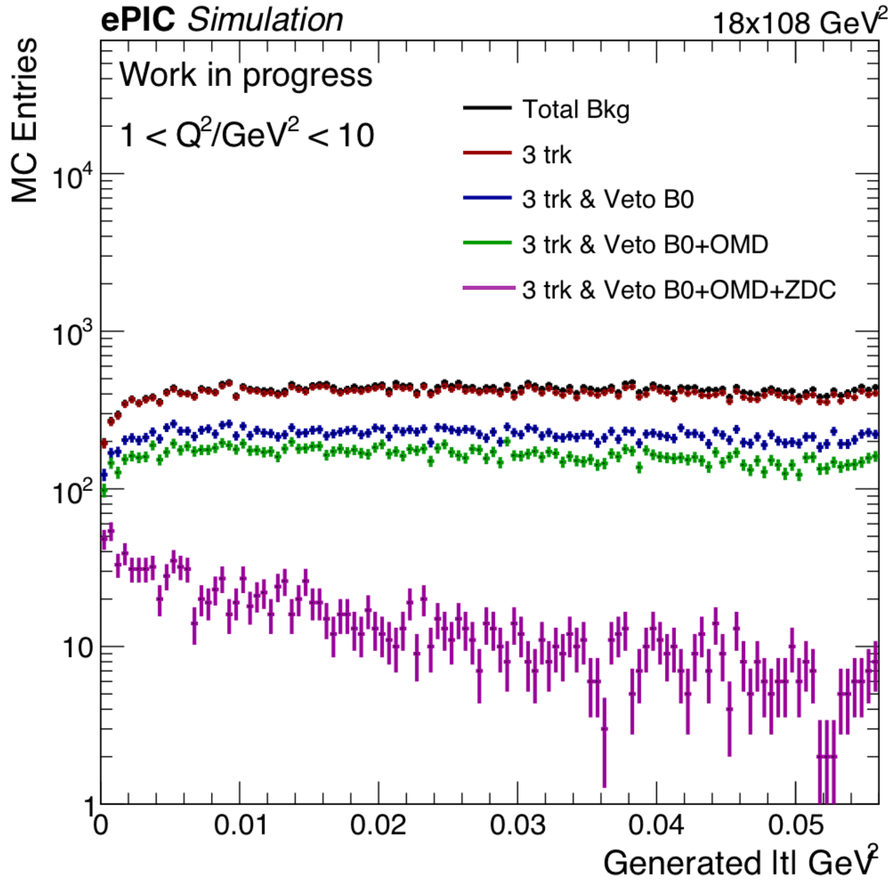
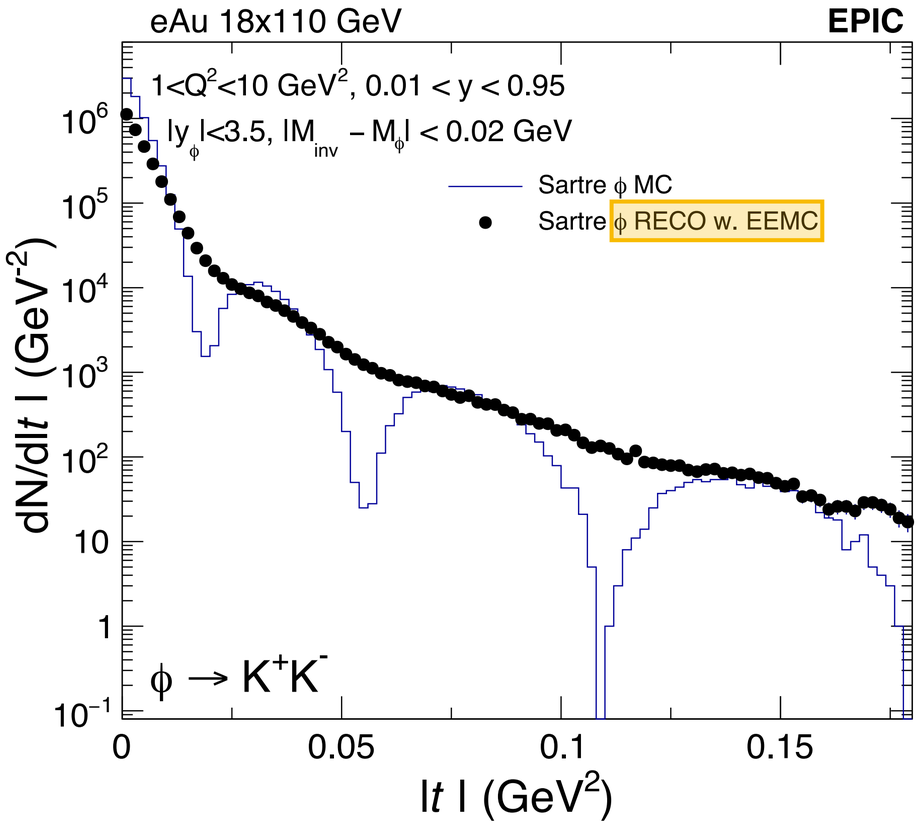
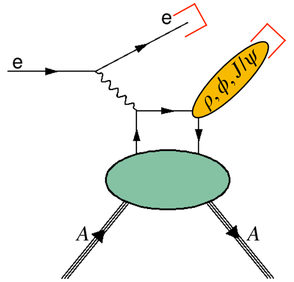



Suppression of incoherent signal using detector system

# Resolution in t



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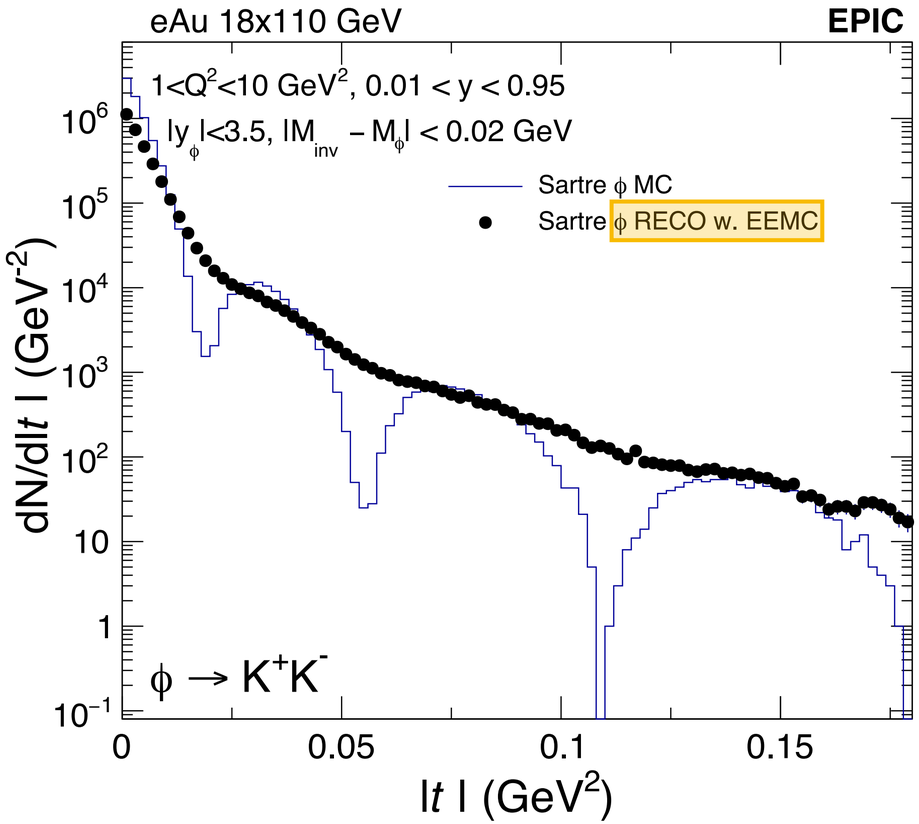
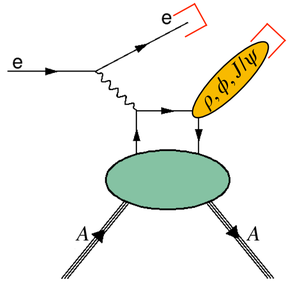
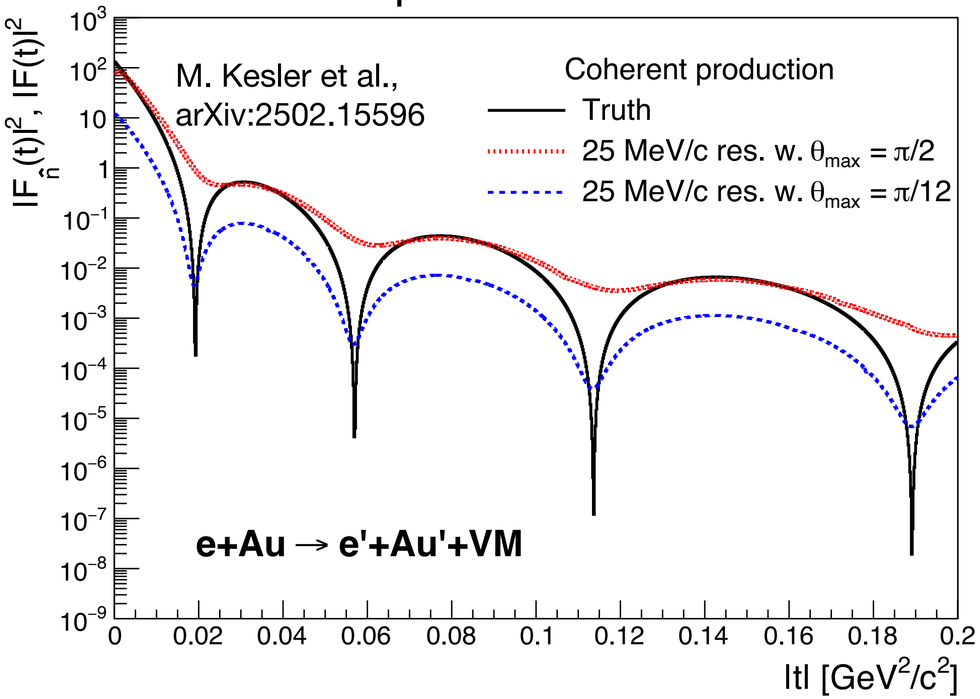
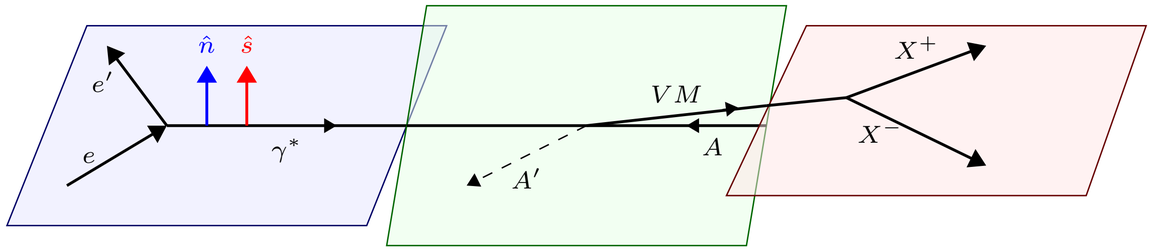



## Development of new method




Scattering Plane | Production Plane | Decay Plane




project $t$ along $\hat{n}$

# Summary

- Valence region at Jefferson Lab: full GPD programme at high precision to extract chiral-even and chiral-odd GPDs using polarised electron beam and unpolarised, longitudinally and transversely polarised proton targets as well as light nuclei.

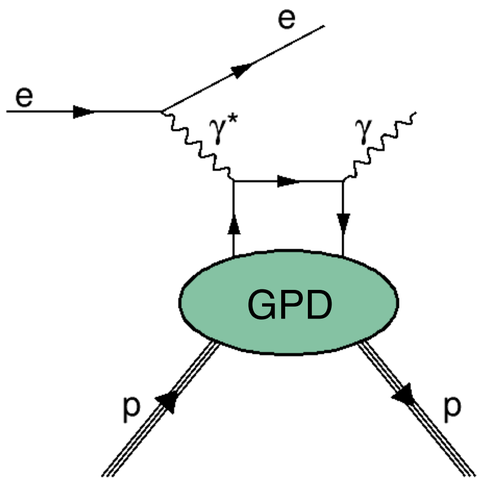
- Sea-quarks at COMPASS: measurements of DVCS and hard exclusive meson production off unpolarised proton are ongoing.

- Sea-quarks and gluons at the EIC: full GPD programme, at unrivalled precision down to $x_B=10^{-4}$, using polarised electron beam and polarised nucleons as well as entire series of unpolarised nuclei.

- LHC:
  - Spin-independent, highest-energy measurements with proton and lead ions: test of universality of GPDs and access to lowest region in $x_B$, down to $10^{-6}$.
  - Fixed target with proton and noble gasses for high-$x_B$ region. Plans for transversely polarised target.

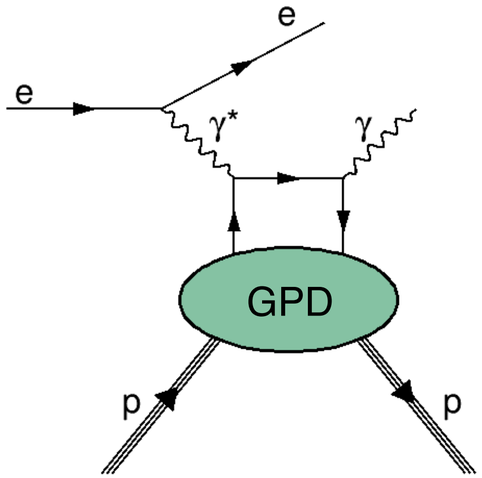
# Back up

# GPDs and deeply virtual Compton scattering (DVCS)

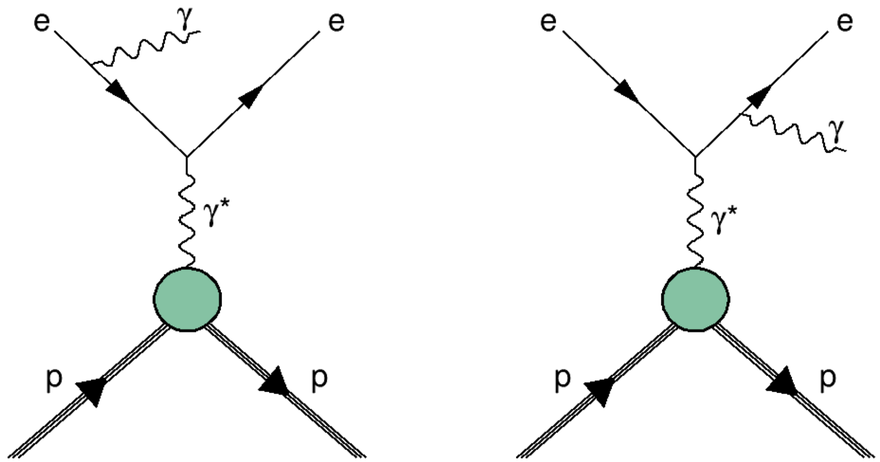



DVCS

# GPDs and deeply virtual Compton scattering (DVCS)




DVCS




Bethe-Heitler

$$d\sigma = |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH}$$

# GPDs and deeply virtual Compton scattering (DVCS)

$$d\sigma = |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{DVCS}\tau_{BH}^{*} + \tau_{DVCS}^{*}\tau_{BH}$$

$$|\tau_{BH}|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{2} c_n^{BH} \cos(n\phi) \right\}$$

calculable with knowledge Pauli & Dirac form factors

$$|\tau_{DVCS}|^2 = \frac{1}{Q^2} \left\{ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + \lambda\, s_1^{DVCS} \sin(\phi) \right\}$$

coefficients: bilinear in GPDs

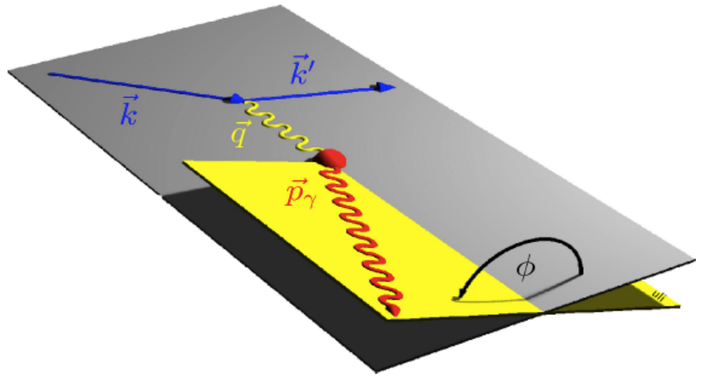
$$\mathcal{I} = \frac{-e_l\, K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right\}$$

coefficients: linear in GPDs

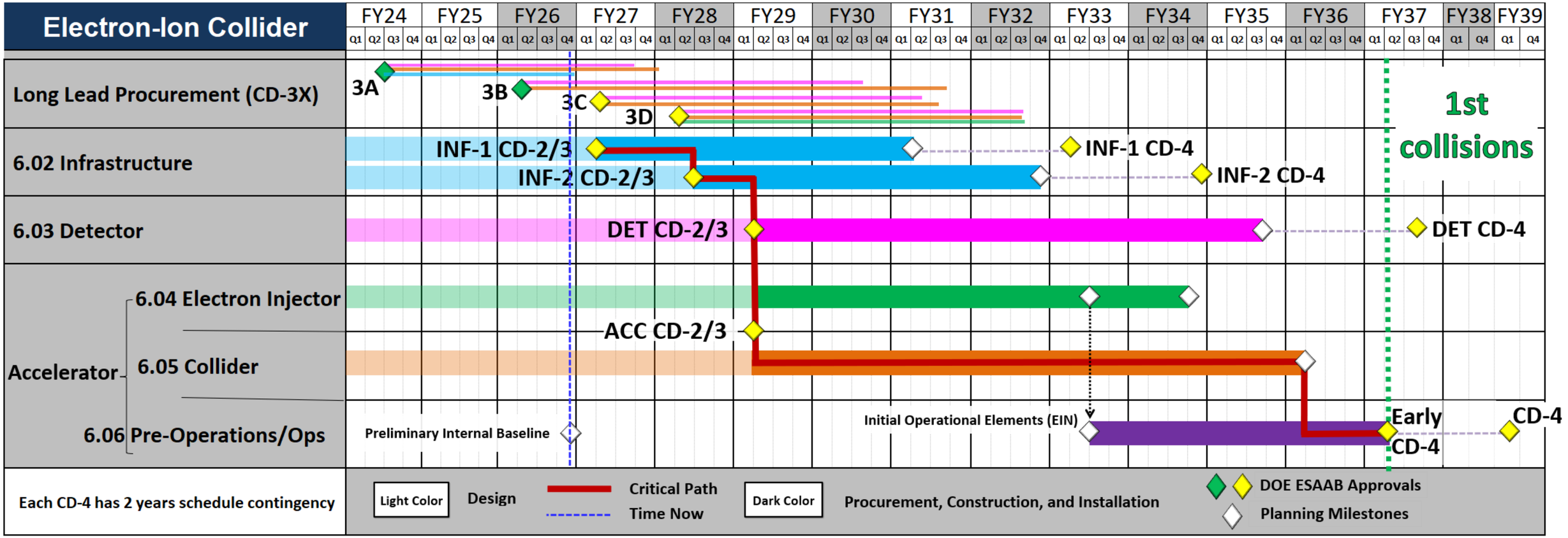
beam charge

beam polarization

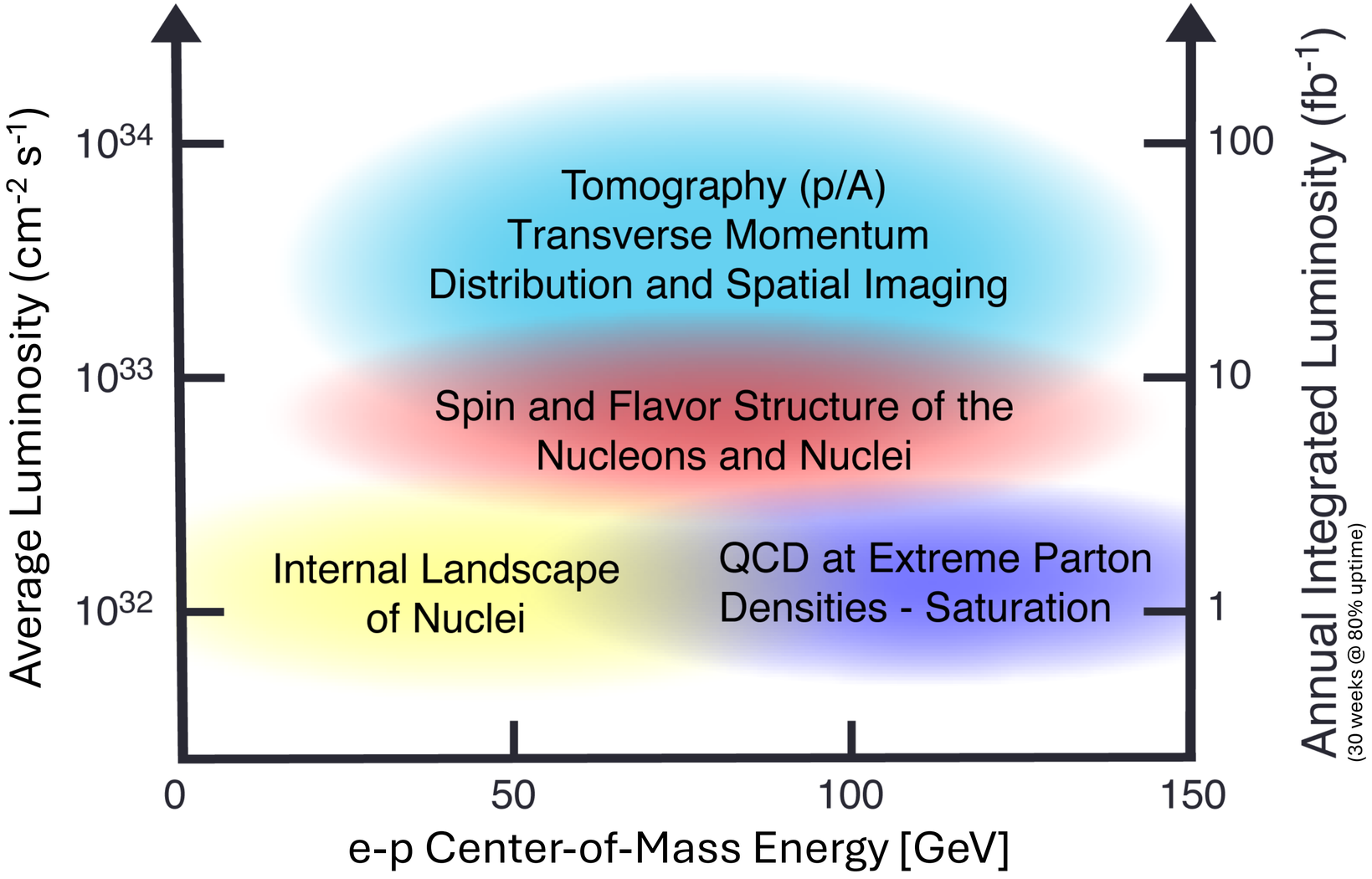
Unpolarized nucleon
Longitudinally polarized lepton beam



# Timeline EIC



# The various data-collection stages



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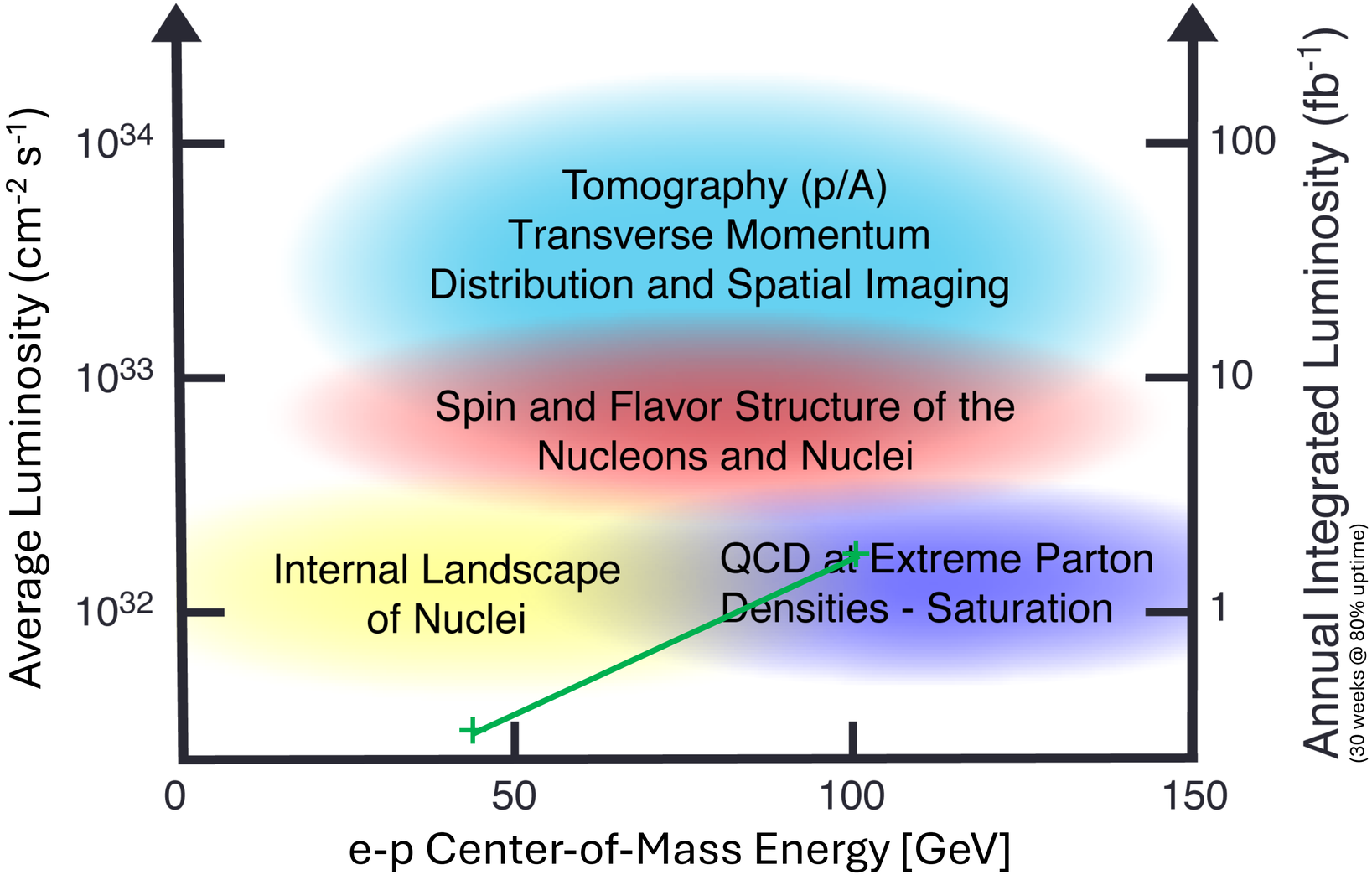
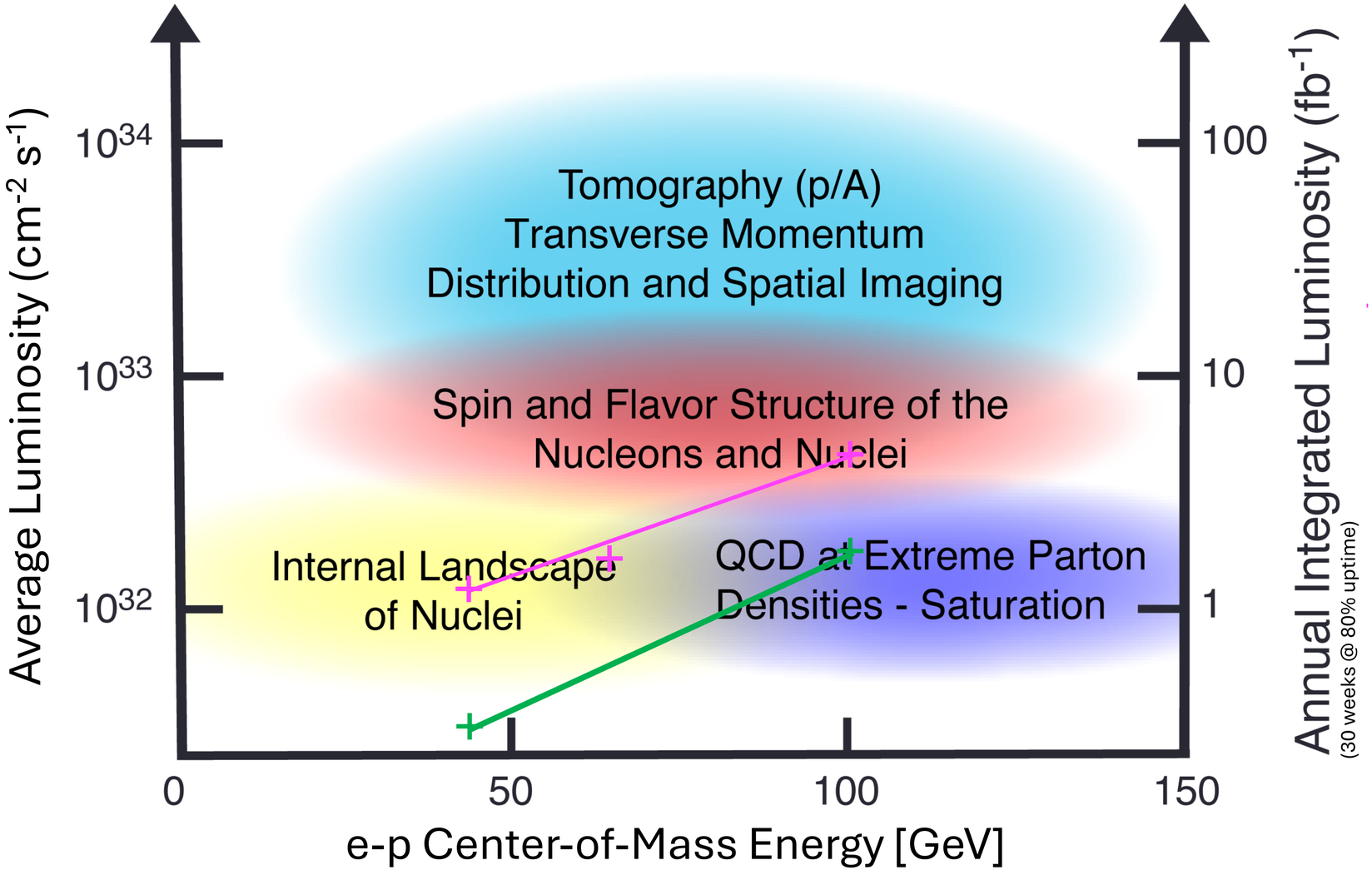



+ EIC
  - SRF for 7nC/bunch
  - no 394 MHz crab cavities
  - no low energy cooling
  - no 41 GeV bypass

# The various data-collection stages

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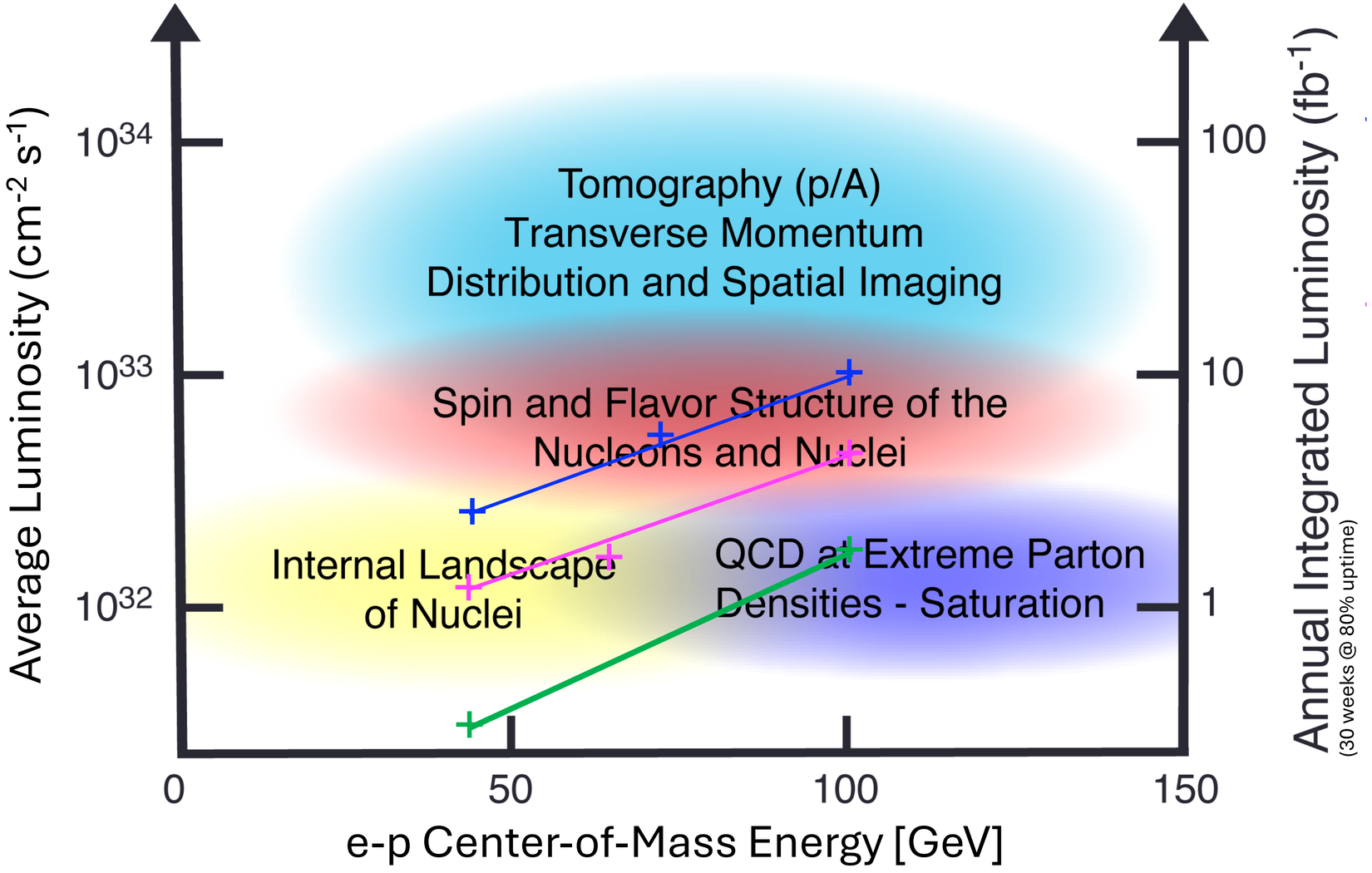


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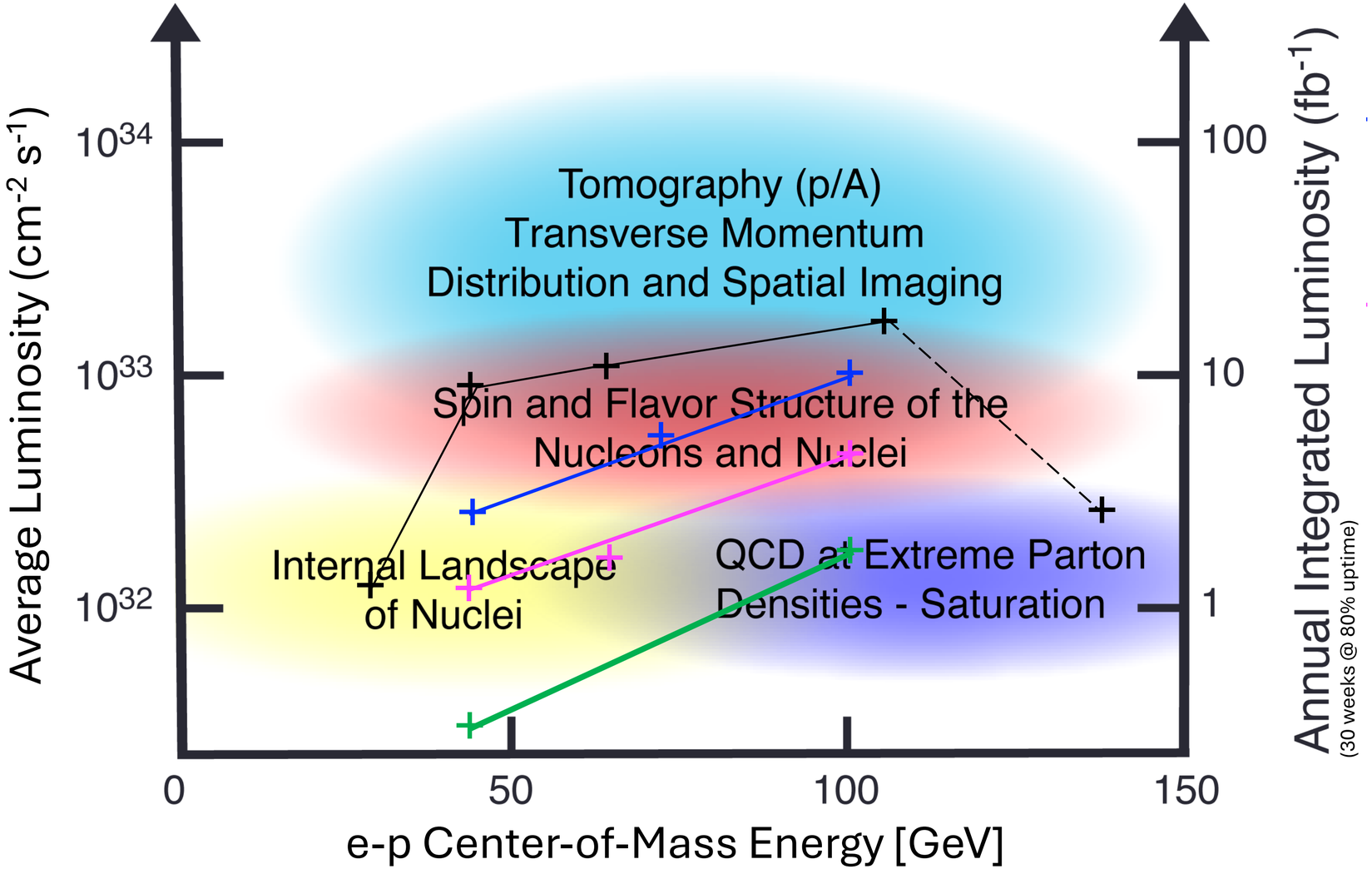


+ EIC Full Capability
  - - - 140 GeV (upgrade)

+ EIC
  - SRF for 7nC/bunch
  - no 41 GeV bypass

+ EIC
  - SRF for 7nC/bunch
  - no 394 MHz crab cavities
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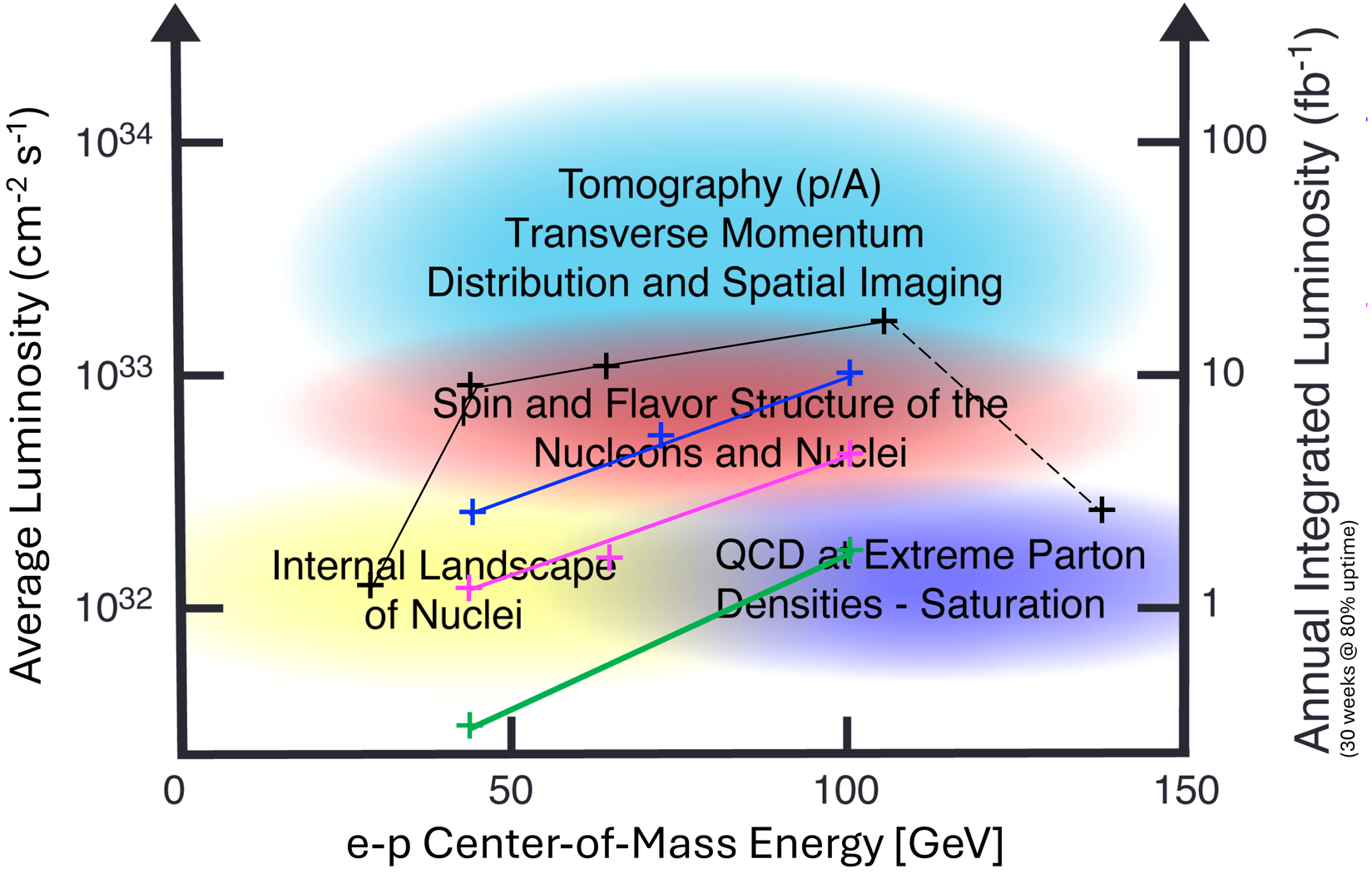


Plans for strong hadron cooling to further increase luminosity

+ EIC Full Capability
  - - - 140 GeV (upgrade)

+ EIC
  - SRF for 7nC/bunch
  - no 41 GeV bypass

+ EIC
  - SRF for 7nC/bunch
  - no 394 MHz crab cavities
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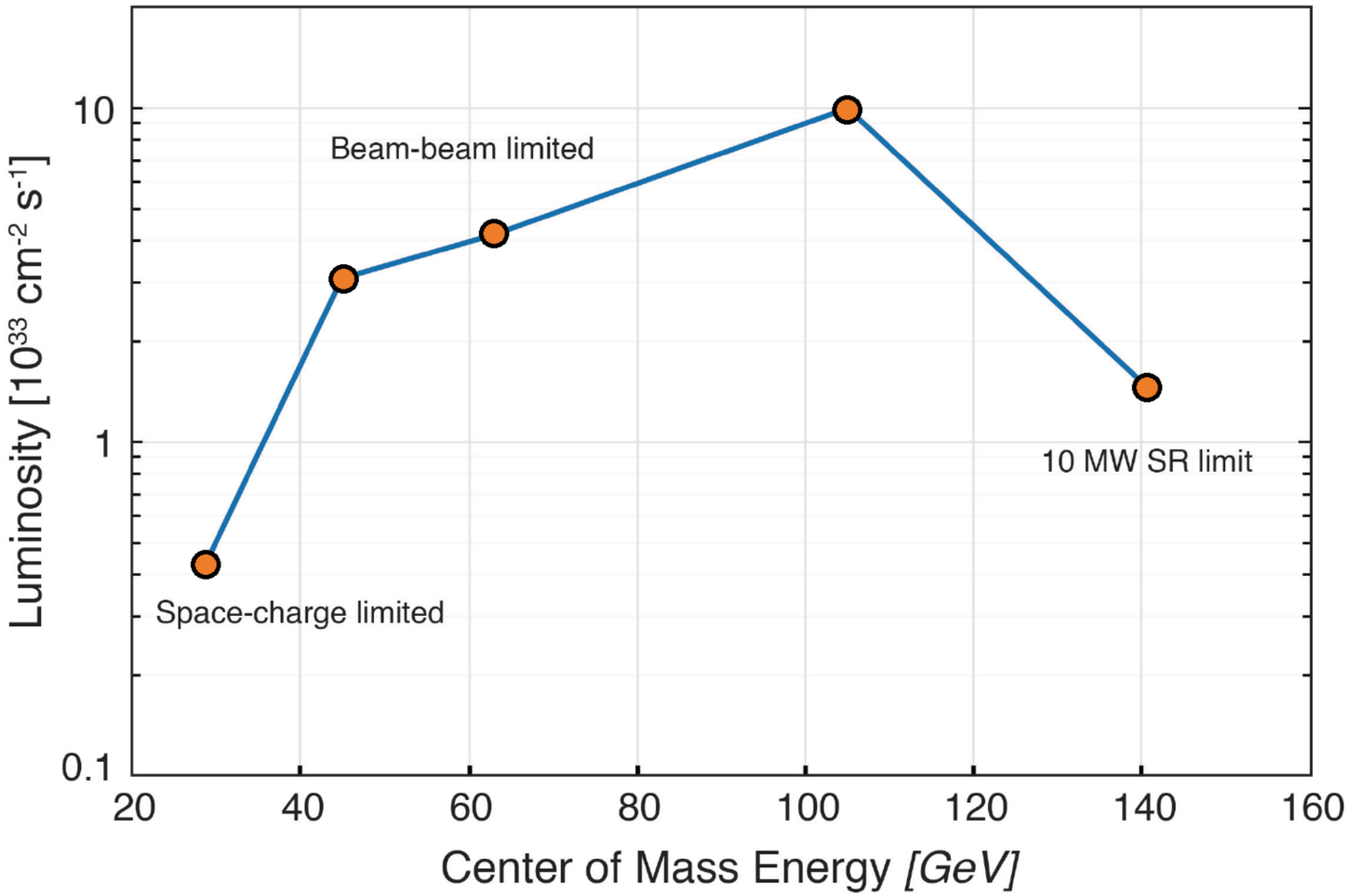
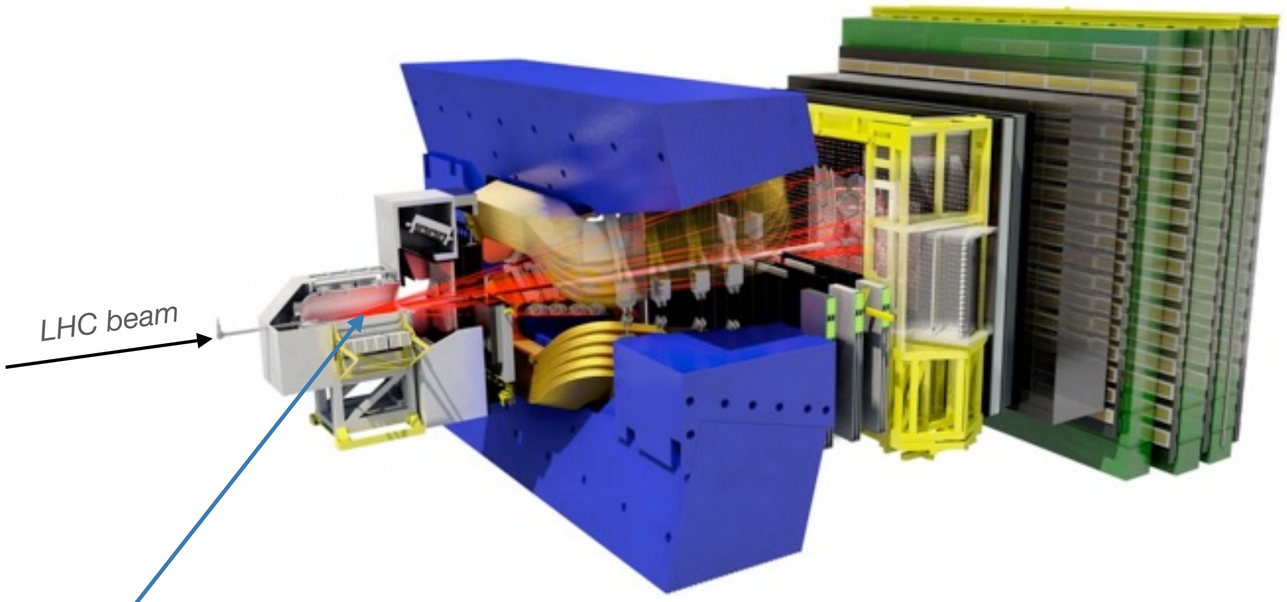
+ EIC
  - SRF for 7nC/bunch
  - no 394 MHz crab cavities
  - no low energy cooling
  - no 41 GeV bypass

# Luminosity and centre-of-mass energy: ep collisions

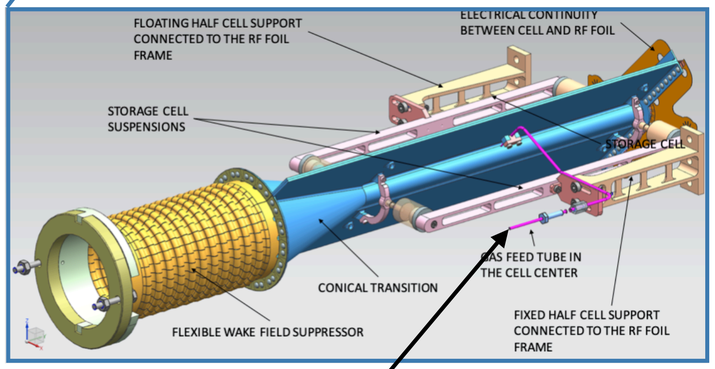



Luminosity for eA similar within factor 2–3

# Fixed target at LHCb



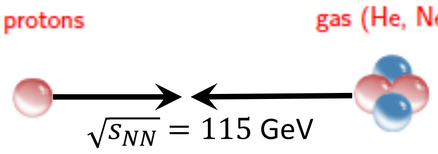

LHC RUN 3



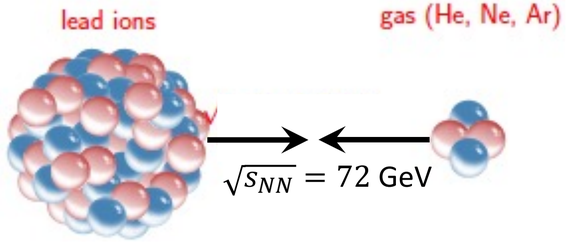

inject gas: He, Ne, Ar, and $H_2$, $D_2$

**Fixed target – SMOG2**

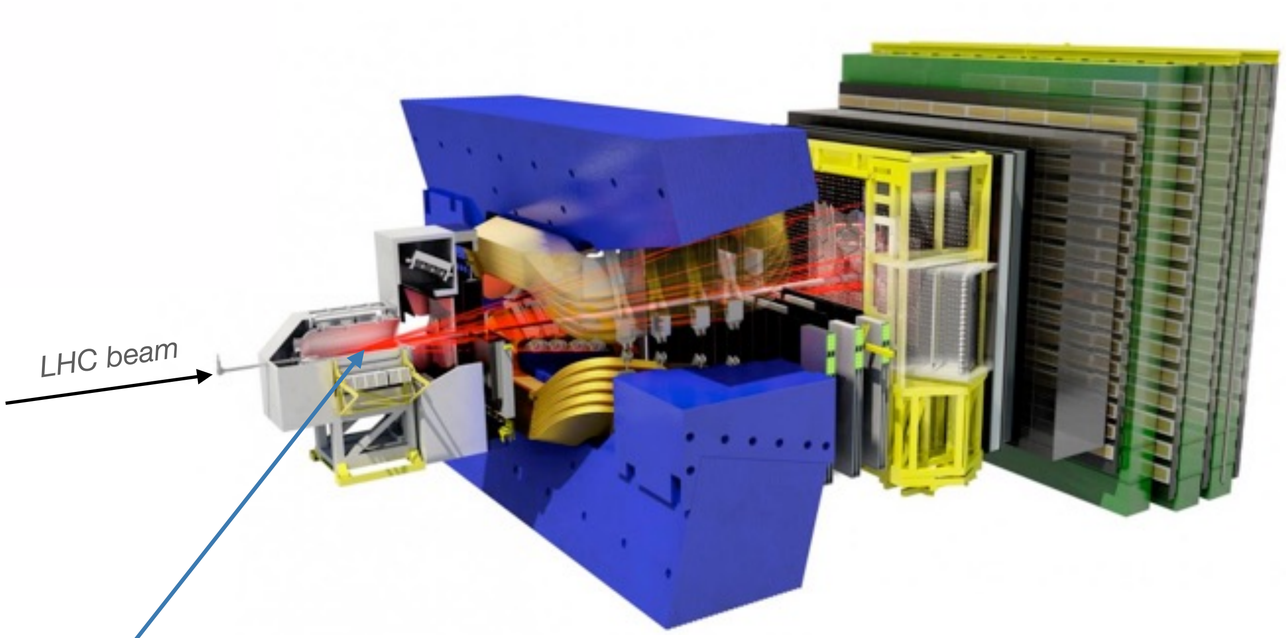
p beam



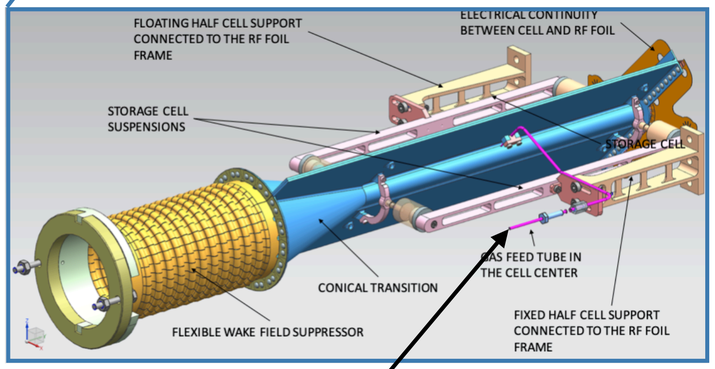

Pb beam



# Fixed target at LHCb

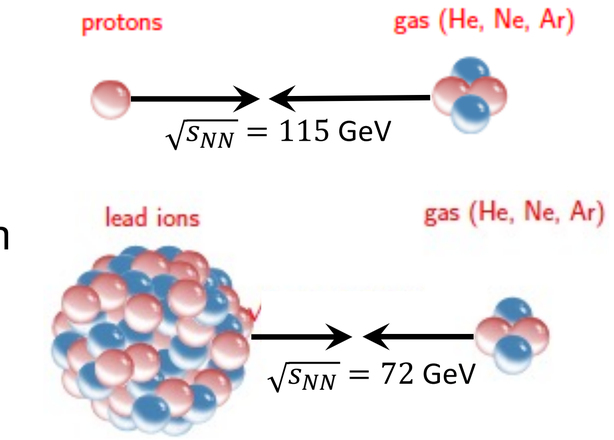


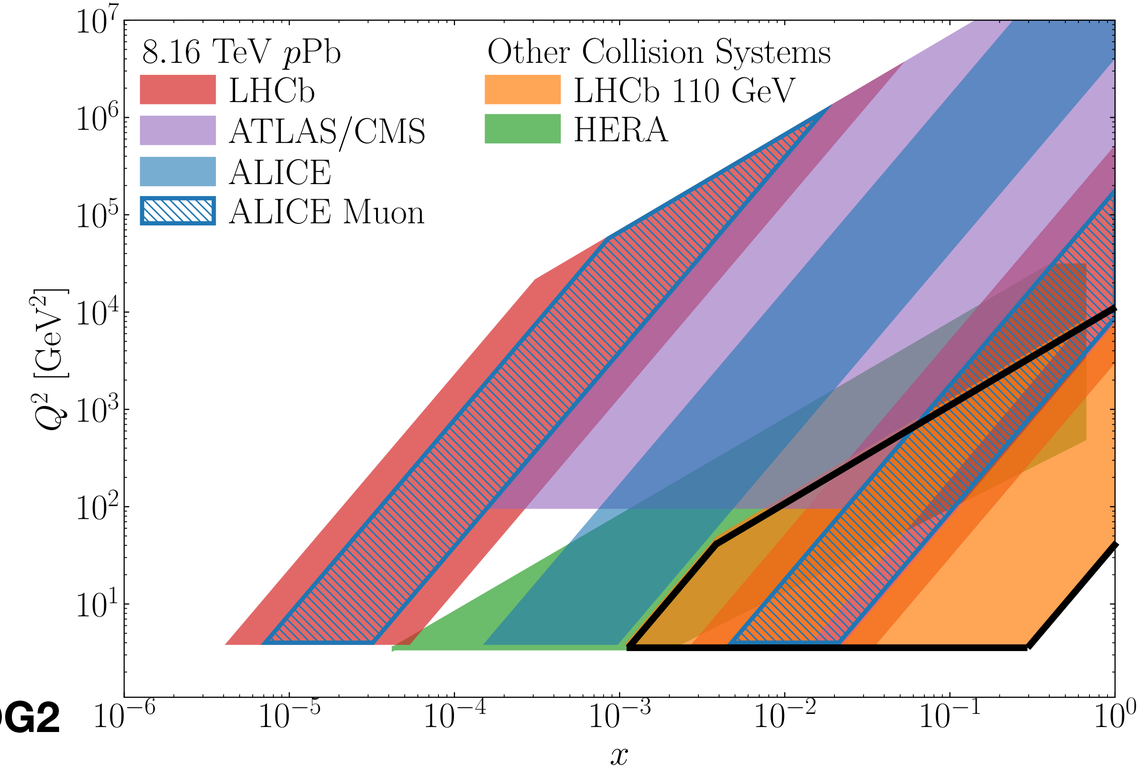

LHC RUN 3




inject gas: He, Ne, Ar, and $H_2$, $D_2$

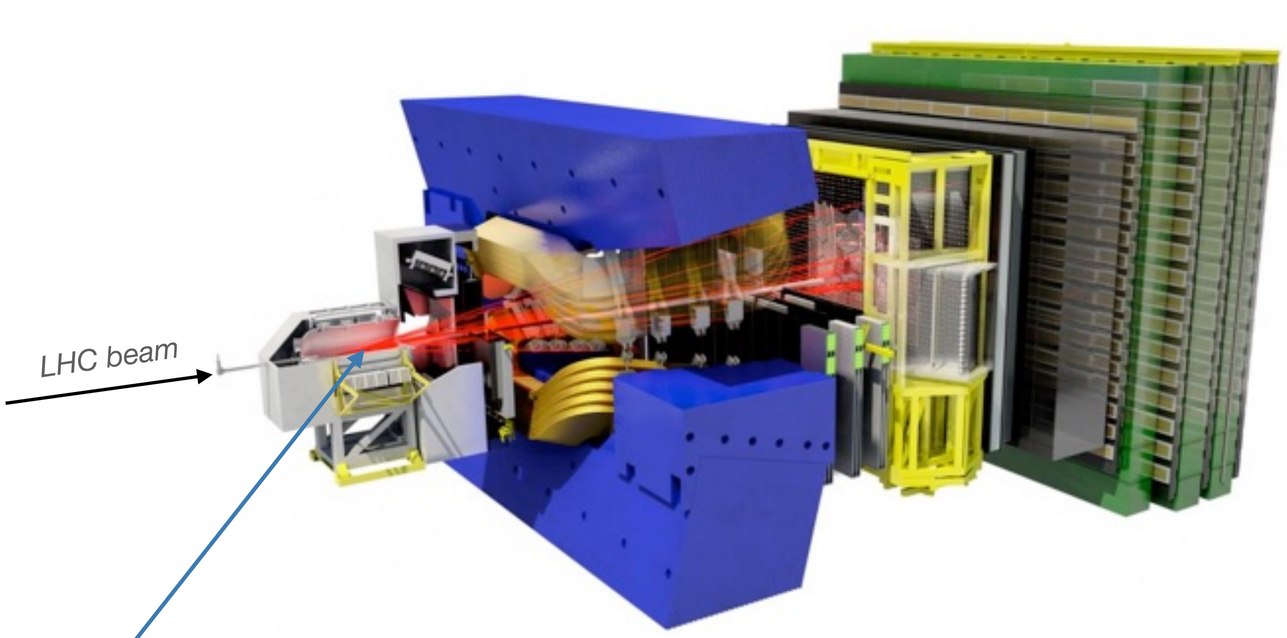
**Fixed target – SMOG2**

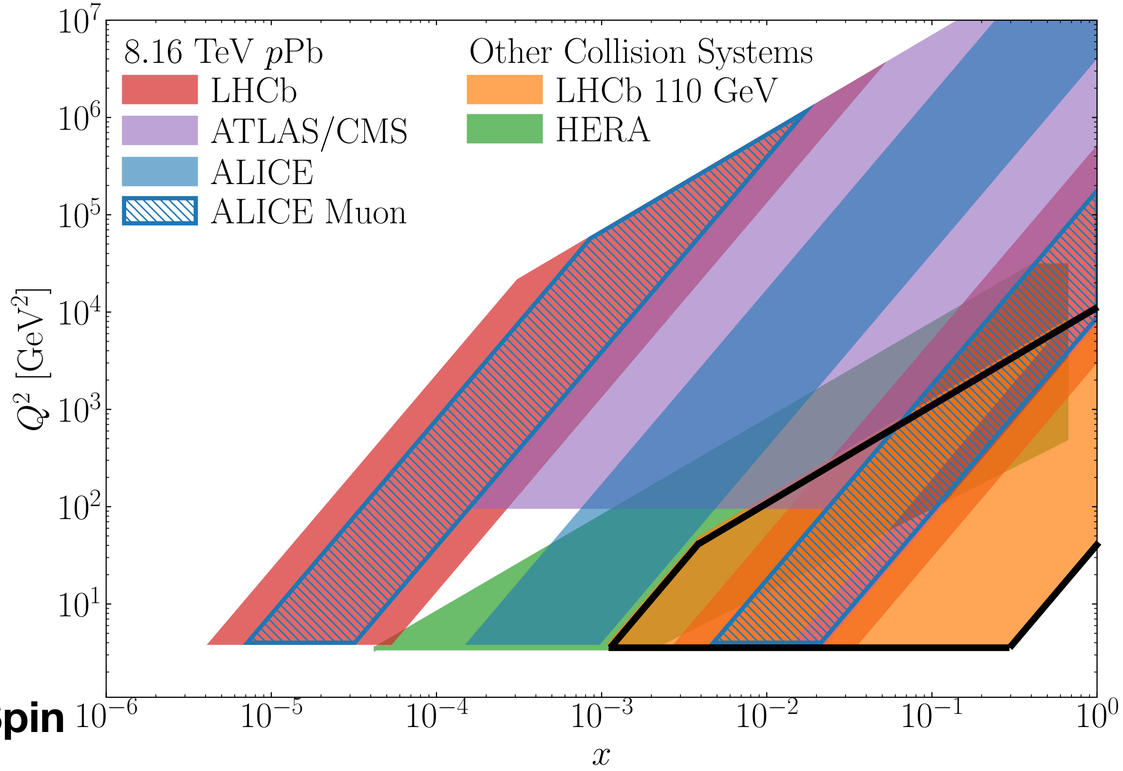


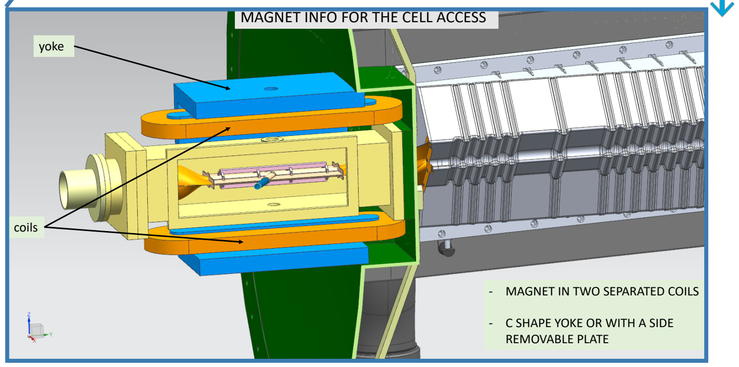

Access to high $x$

# Fixed target at LHCb



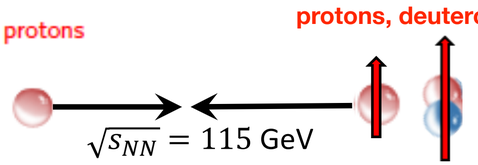




LHC RUN 5

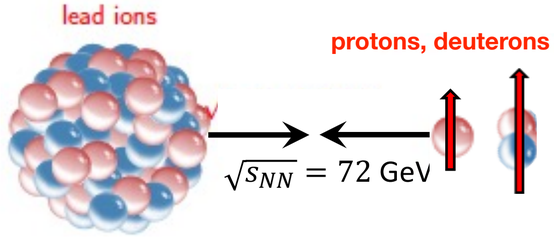



**Fixed target – LHCSpin**

p beam

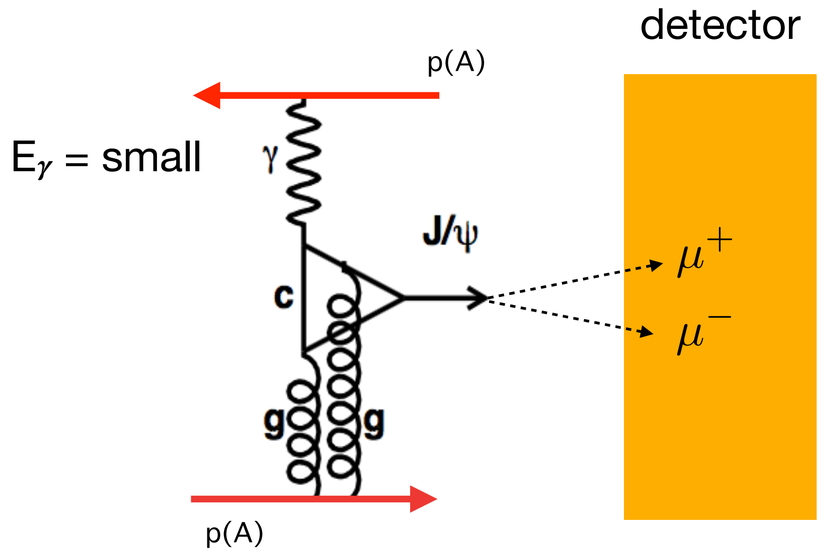



Pb beam



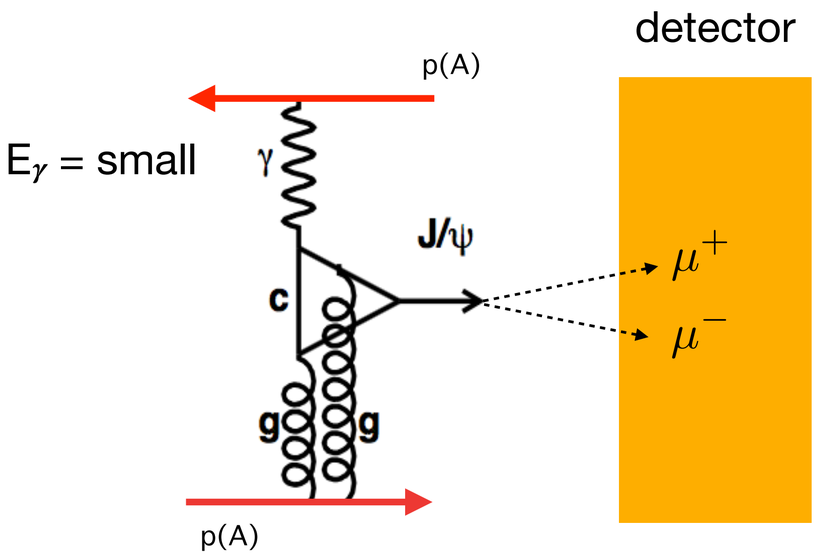

Access to high $x$

# Disentangling the ambiguity on the ID of the $\gamma$ emitter

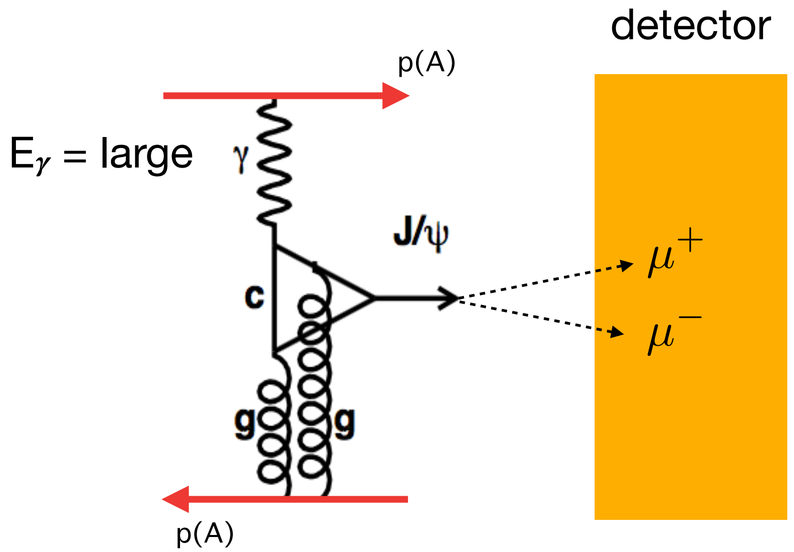



$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$

# Disentangling the ambiguity on the ID of the $\gamma$ emitter

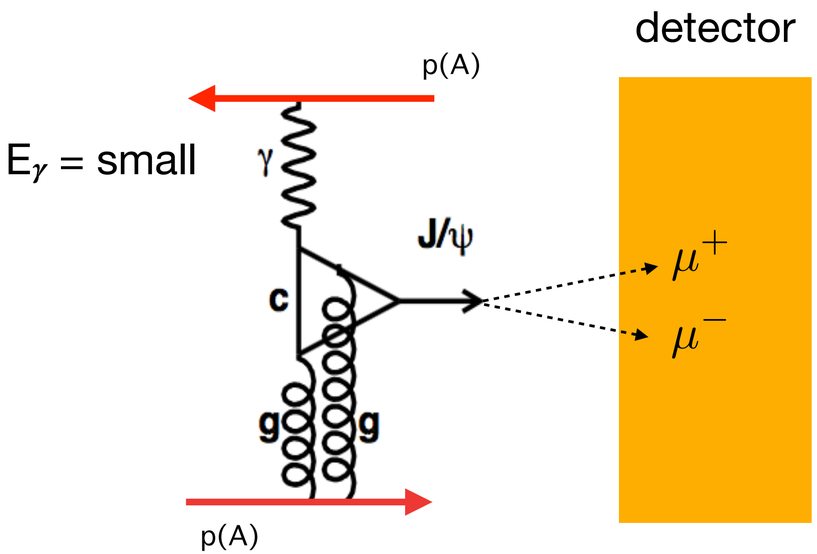



$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$

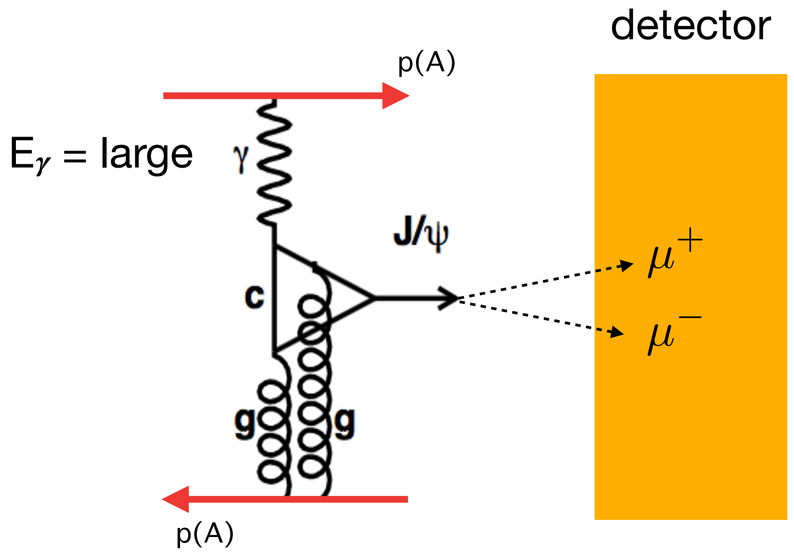



$$E_{\gamma,l} = \frac{M_{J/\psi}}{2} e^{+y}$$

# Disentangling the ambiguity on the ID of the $\gamma$ emitter




$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$




$$E_{\gamma,l} = \frac{M_{J/\psi}}{2} e^{+y}$$

$$\sigma(y) = N_{\gamma/A}(E_{\gamma,s})\ \sigma_{J/\psi}(E_{\gamma,s}) + N_{\gamma/A}(E_{\gamma,l})\ \sigma_{J/\psi}(E_{\gamma,l})$$

# Disentangling the ambiguity on the ID of the $\gamma$ emitter

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Photon flux $N_{\gamma/A}(E_\gamma)$ is function of impact parameter:
enhanced for large $E_\gamma$ at small impact parameter.

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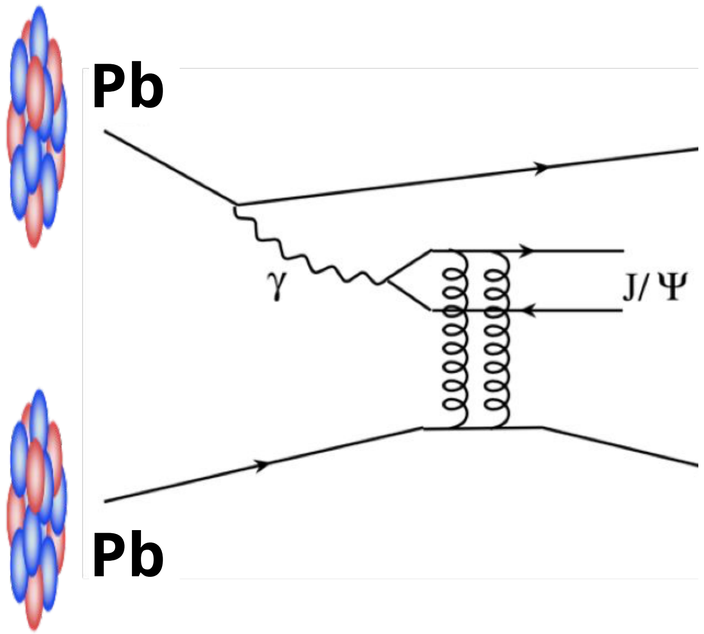


Picture from André Ståhl

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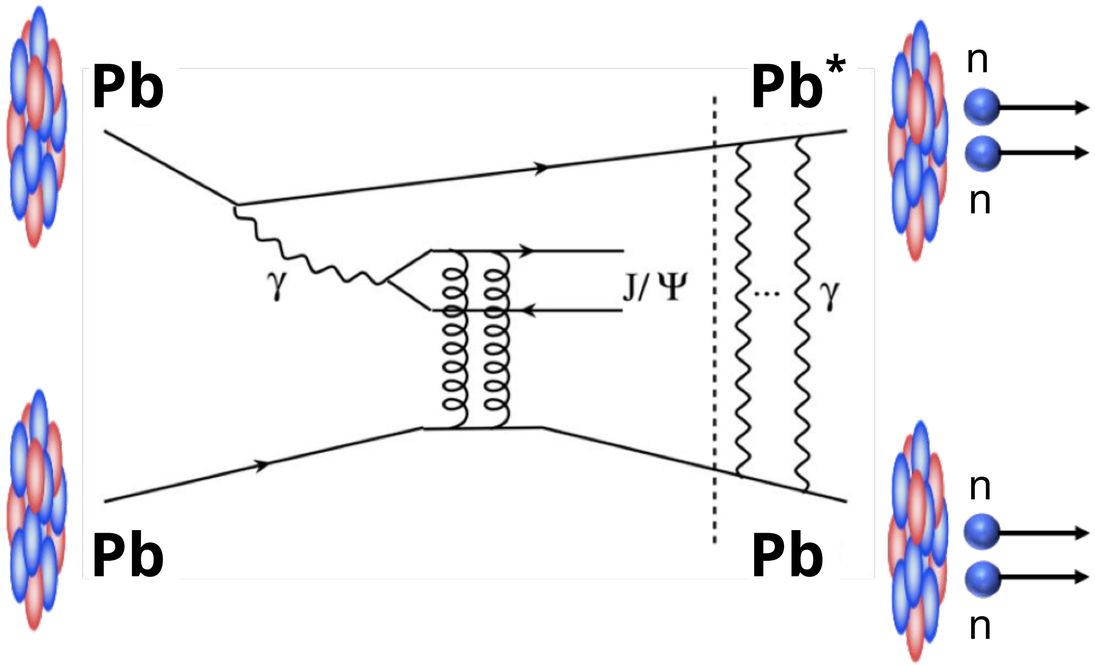
Photon flux $N_{\gamma/A}(E_\gamma)$ is function of impact parameter:
enhanced for large $E_\gamma$ at small impact parameter.

Small impact parameter, b ⟶ higher probability for exciting ($\propto 1/b^2$) ⟶ higher probability to emit neutrons.




Picture from André Ståhl

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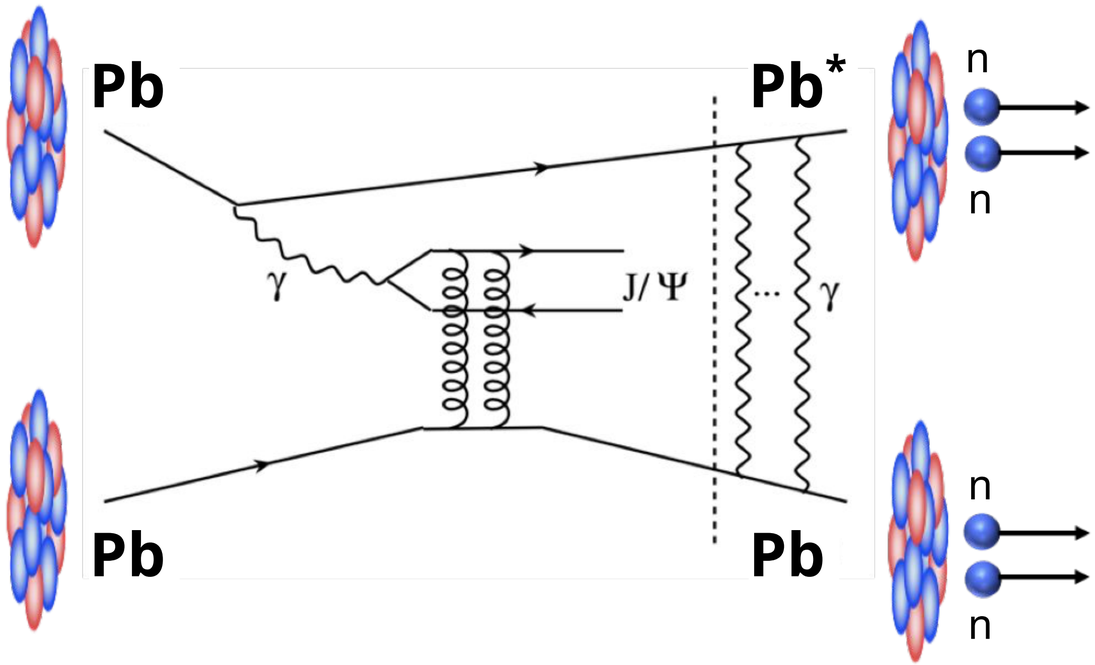
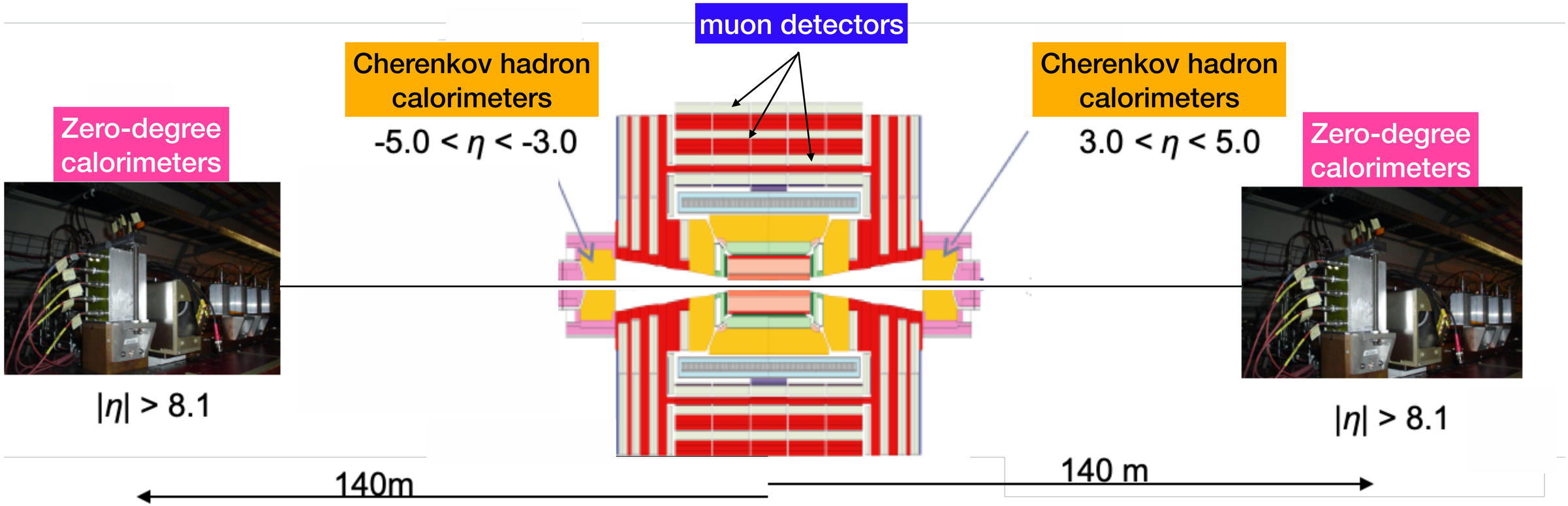


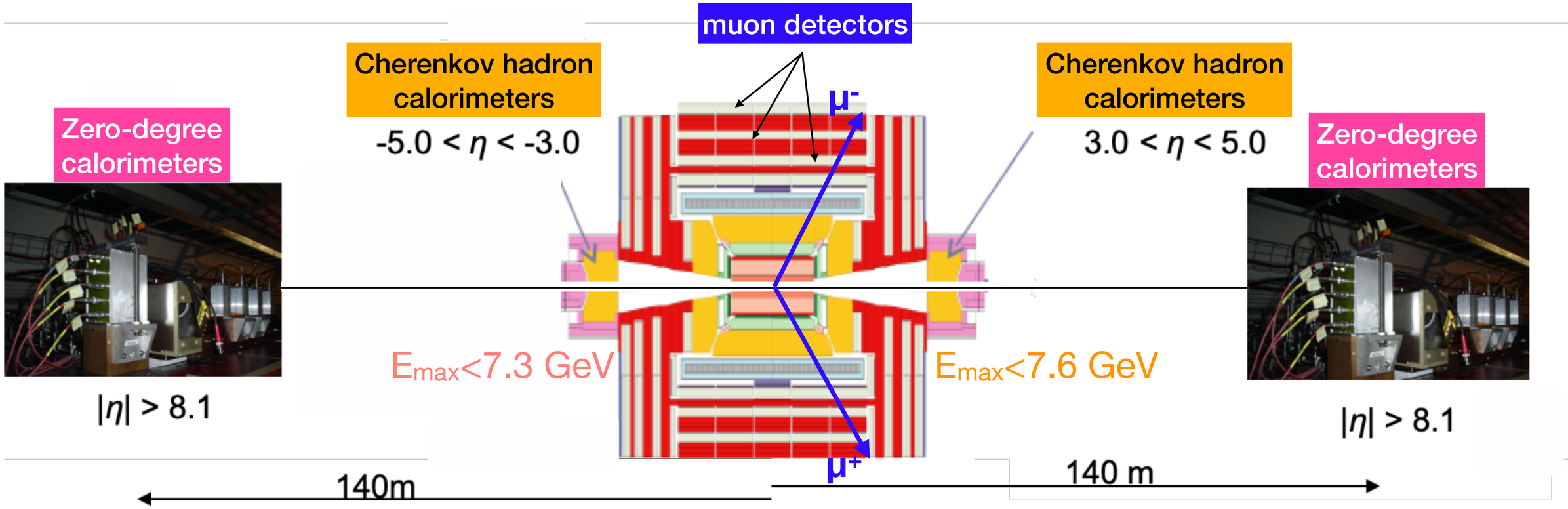

⟶ Make measurement with possibility to detect neutrons

Picture from André Ståhl

# CMS central detector and the (far-)forward region

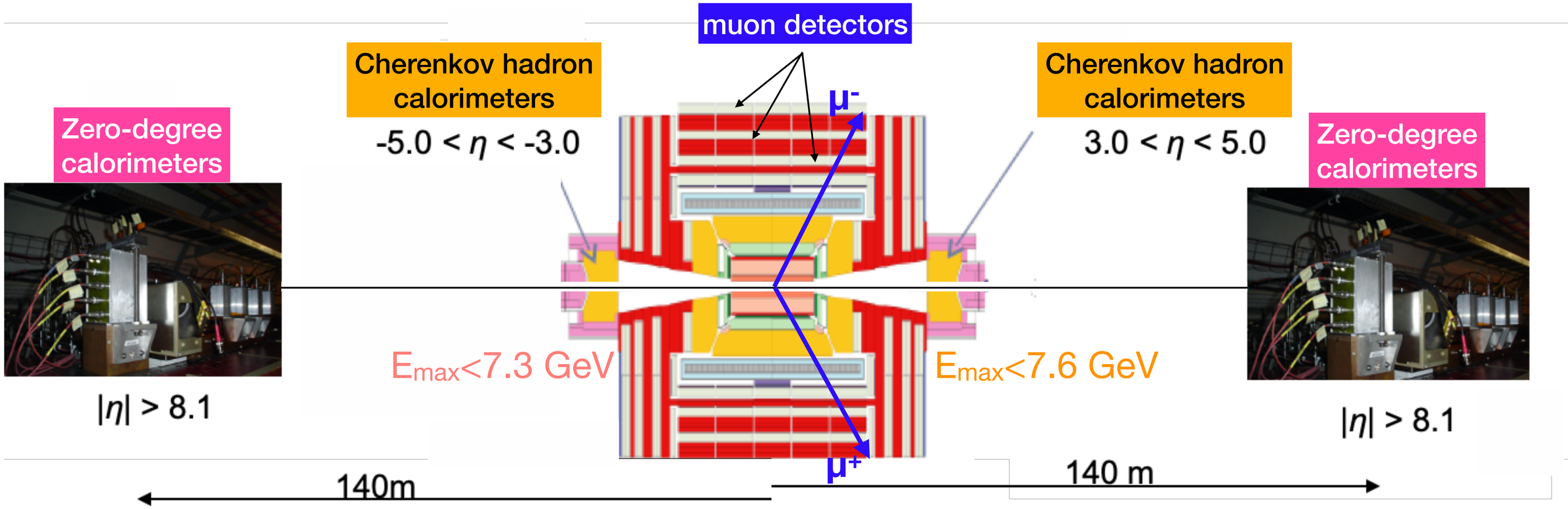


# CMS central detector and the (far-)forward region




$$1.6 < |y_{\mu^+\mu^-}| < 2.4$$

# CMS central detector and the (far-)forward region




$$1.6 < |y_{\mu^+\mu^-}| < 2.4$$

0 neutrons
≥1 neutron

0n0n
0nXn
XnXn

0 neutrons
≥1 neutron

# Disentangling the ambiguity on the ID of the $\gamma$ emitter

$$\sigma^{0n0n}(y) = N^{0n0n}_{\gamma/A}(E_{\gamma,s})\ \sigma_{J/\psi}(E_{\gamma,s}) + N^{0n0n}_{\gamma/A}(E_{\gamma,l})\ \sigma_{J/\psi}(E_{\gamma,l})$$

$$\sigma^{0nXn}(y) = N^{0nXn}_{\gamma/A}(E_{\gamma,s})\ \sigma_{J/\psi}(E_{\gamma,s}) + N^{0nXn}_{\gamma/A}(E_{\gamma,l})\ \sigma_{J/\psi}(E_{\gamma,l})$$

$$\sigma^{XnXn}(y) = N^{XnXn}_{\gamma/A}(E_{\gamma,s})\ \sigma_{J/\psi}(E_{\gamma,s}) + N^{XnXn}_{\gamma/A}(E_{\gamma,l})\ \sigma_{J/\psi}(E_{\gamma,l})$$

**measured**

# Disentangling the ambiguity on the ID of the $\gamma$ emitter

$$\sigma^{0n0n}(y) = N^{0n0n}_{\gamma/A}(E_{\gamma,s})\,\sigma_{J/\psi}(E_{\gamma,s}) + N^{0n0n}_{\gamma/A}(E_{\gamma,l})\,\sigma_{J/\psi}(E_{\gamma,l})$$

$$\sigma^{0nXn}(y) = N^{0nXn}_{\gamma/A}(E_{\gamma,s})\,\sigma_{J/\psi}(E_{\gamma,s}) + N^{0nXn}_{\gamma/A}(E_{\gamma,l})\,\sigma_{J/\psi}(E_{\gamma,l})$$

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**measured** — **computed (StarLight)** — **computed (StarLight)**

# Disentangling the ambiguity on the ID of the $\gamma$ emitter

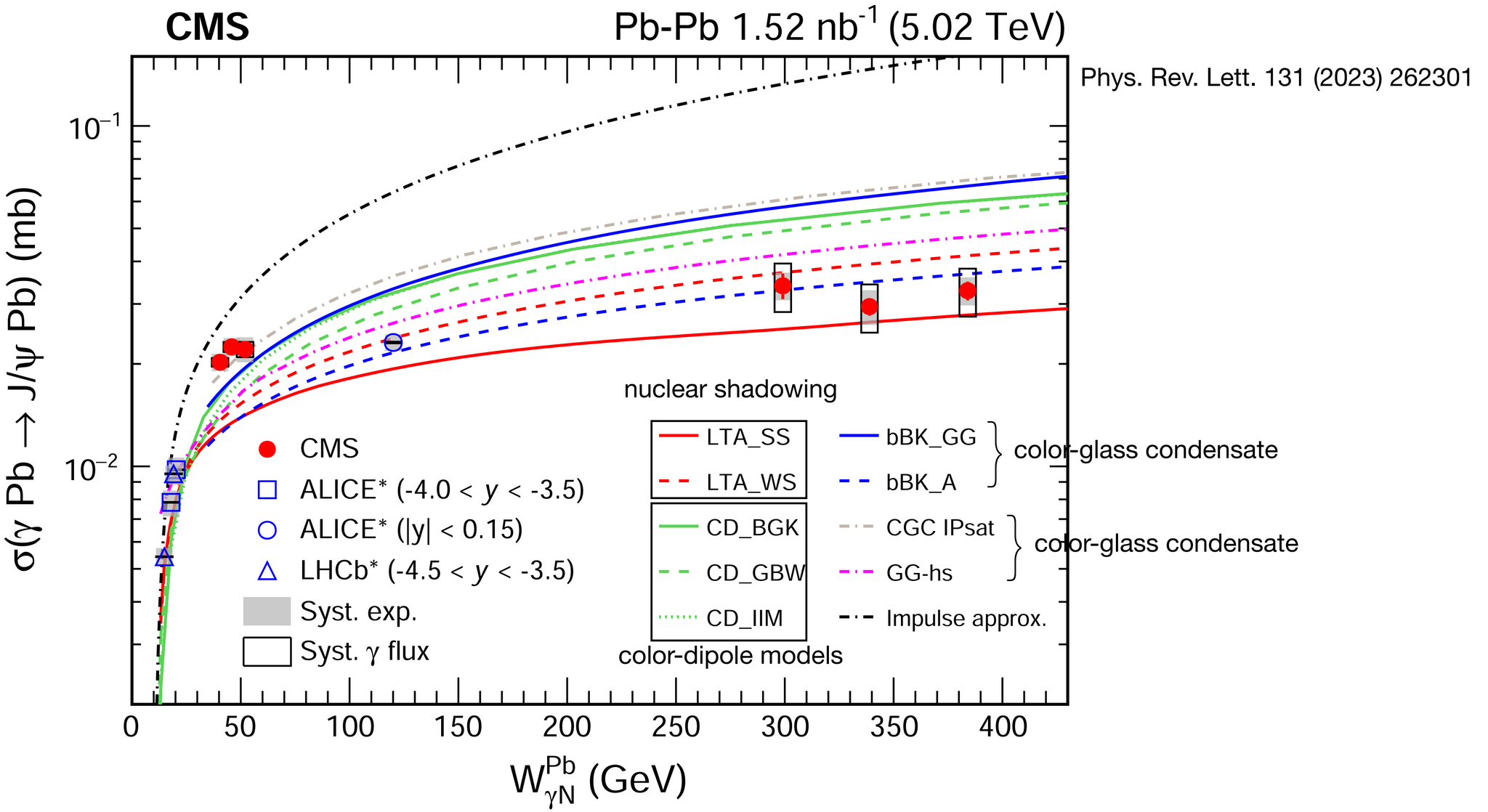
$$\sigma^{0n0n}(y) = N^{0n0n}_{\gamma/A}(E_{\gamma,s})\,\sigma_{J/\psi}(E_{\gamma,s}) + N^{0n0n}_{\gamma/A}(E_{\gamma,l})\,\sigma_{J/\psi}(E_{\gamma,l})$$

$$\sigma^{0nXn}(y) = N^{0nXn}_{\gamma/A}(E_{\gamma,s})\,\sigma_{J/\psi}(E_{\gamma,s}) + N^{0nXn}_{\gamma/A}(E_{\gamma,l})\,\sigma_{J/\psi}(E_{\gamma,l})$$

$$\sigma^{XnXn}(y) = N^{XnXn}_{\gamma/A}(E_{\gamma,s})\,\sigma_{J/\psi}(E_{\gamma,s}) + N^{XnXn}_{\gamma/A}(E_{\gamma,l})\,\sigma_{J/\psi}(E_{\gamma,l})$$

**measured** | **computed (StarLight)** | **extracted** | **computed (StarLight)** | **extracted**

# CMS: $\gamma$Pb cross section, energy dependence



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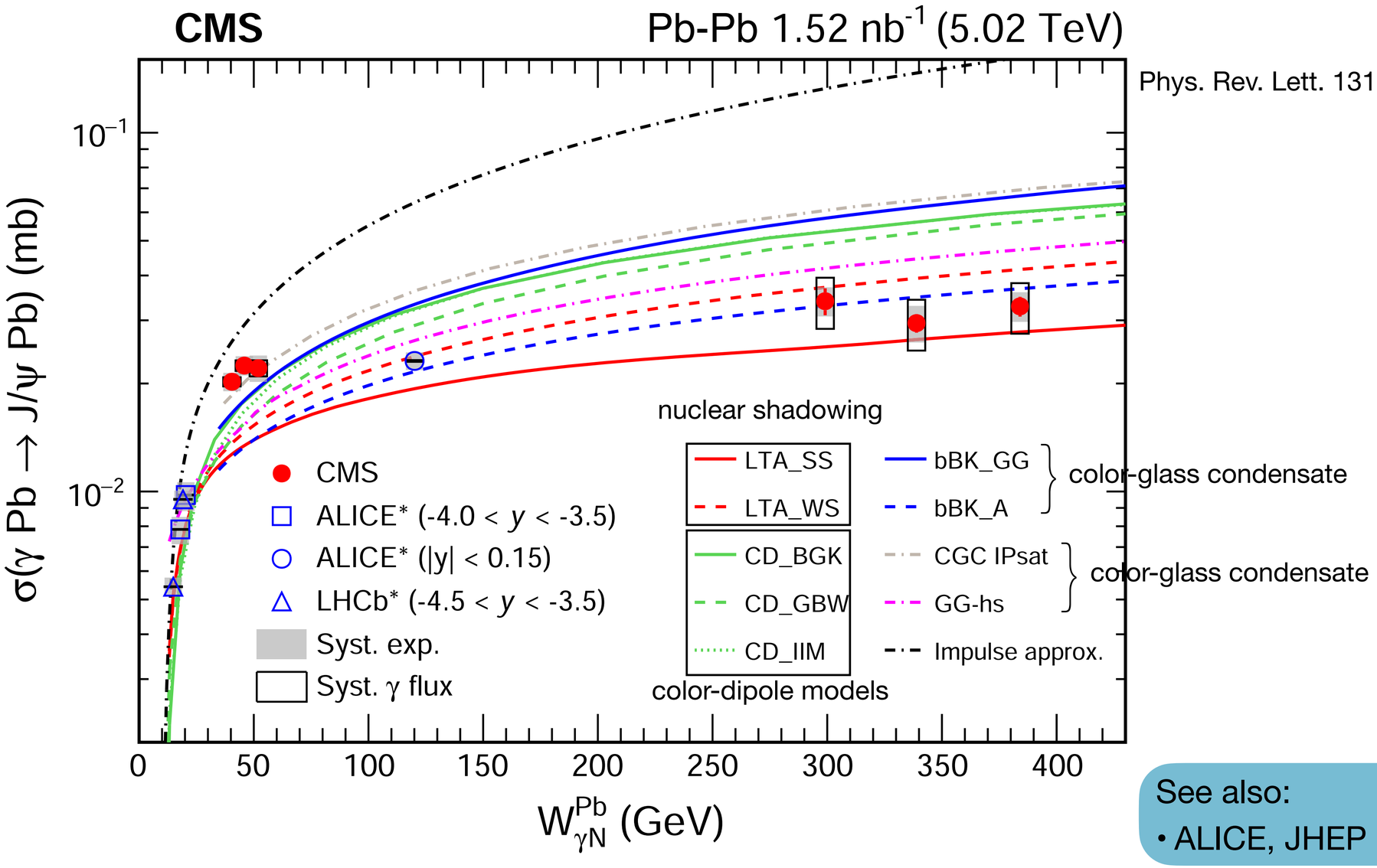
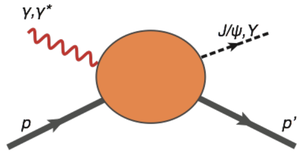


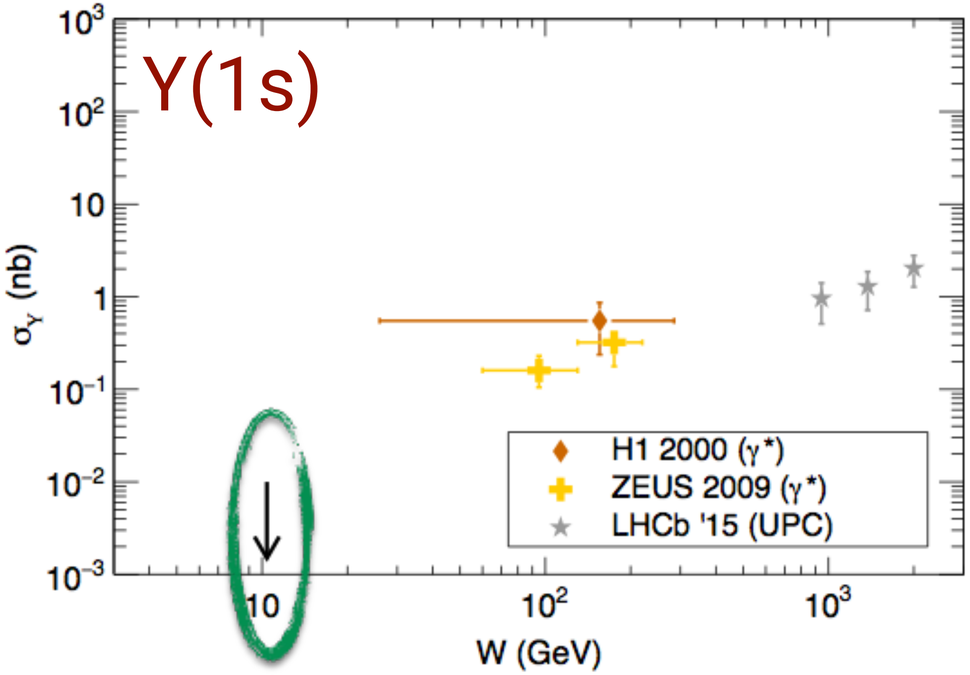

Phys. Rev. Lett. 131 (2023) 262301

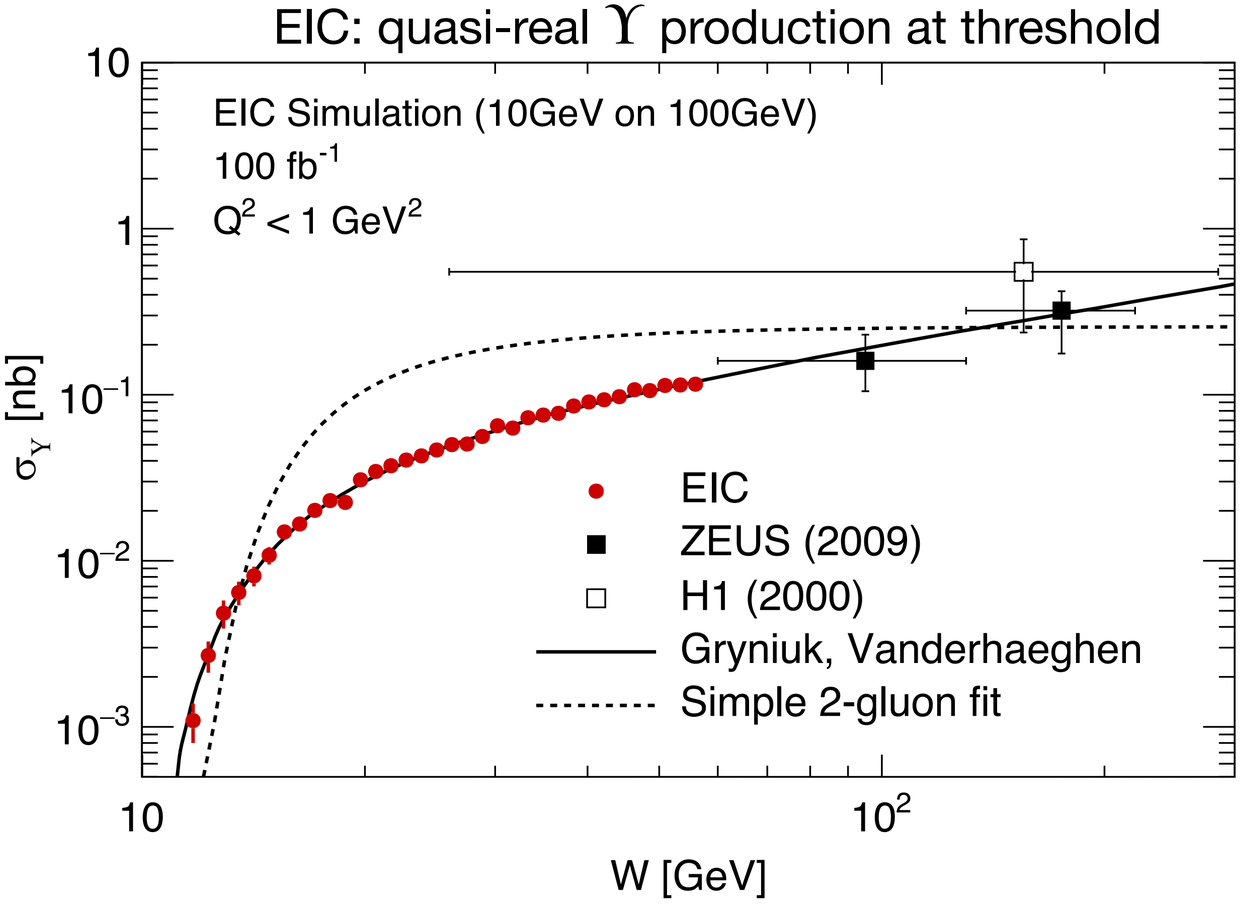
See also:
- ALICE, JHEP 10 (2023) 119

# Quarkonium threshold production




Information on gluon trace anomaly




Figures from Z.-E. Meziani (3rd proton mass workshop: origin and perspective, 16 Jan 2021) and S. Joosten