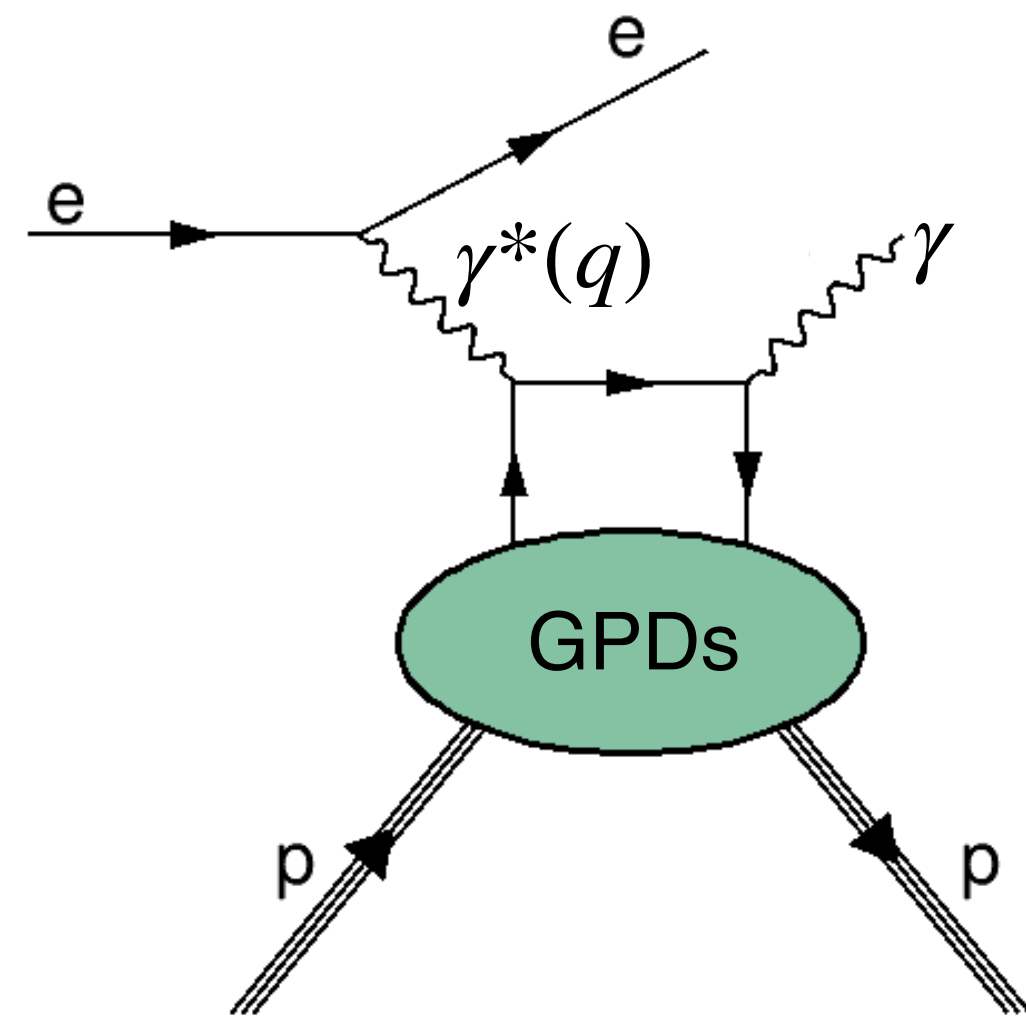


Experimental overview on access to GPDs

Charlotte Van Hulse
VUB

Experimental access to GPDs

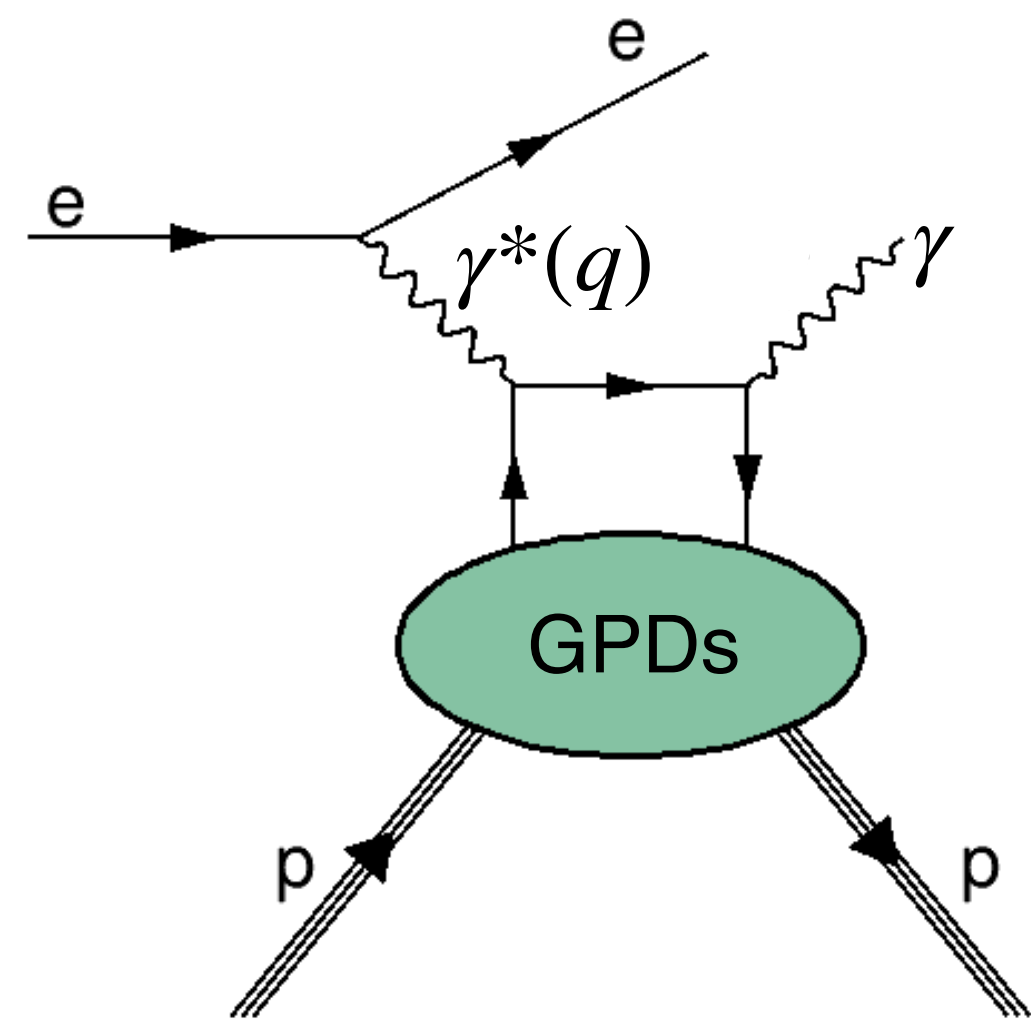


Deeply virtual Compton scattering
(DVCS)

Hard scale=large $Q^2=-q^2$

Theoretically cleanest process

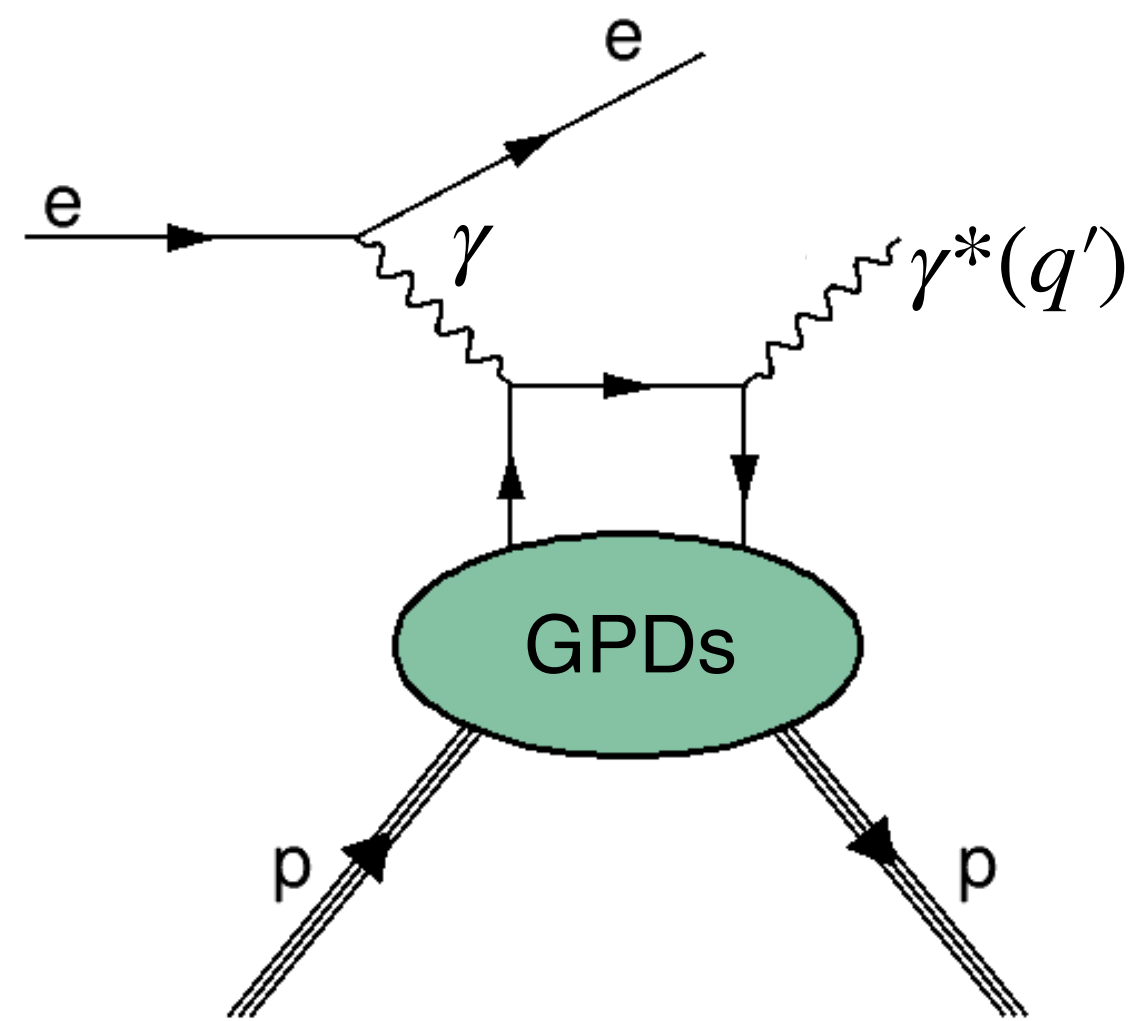
Experimental access to GPDs



Deeply virtual Compton scattering
(DVCS)

Hard scale=large $Q^2=-q^2$

Theoretically cleanest process

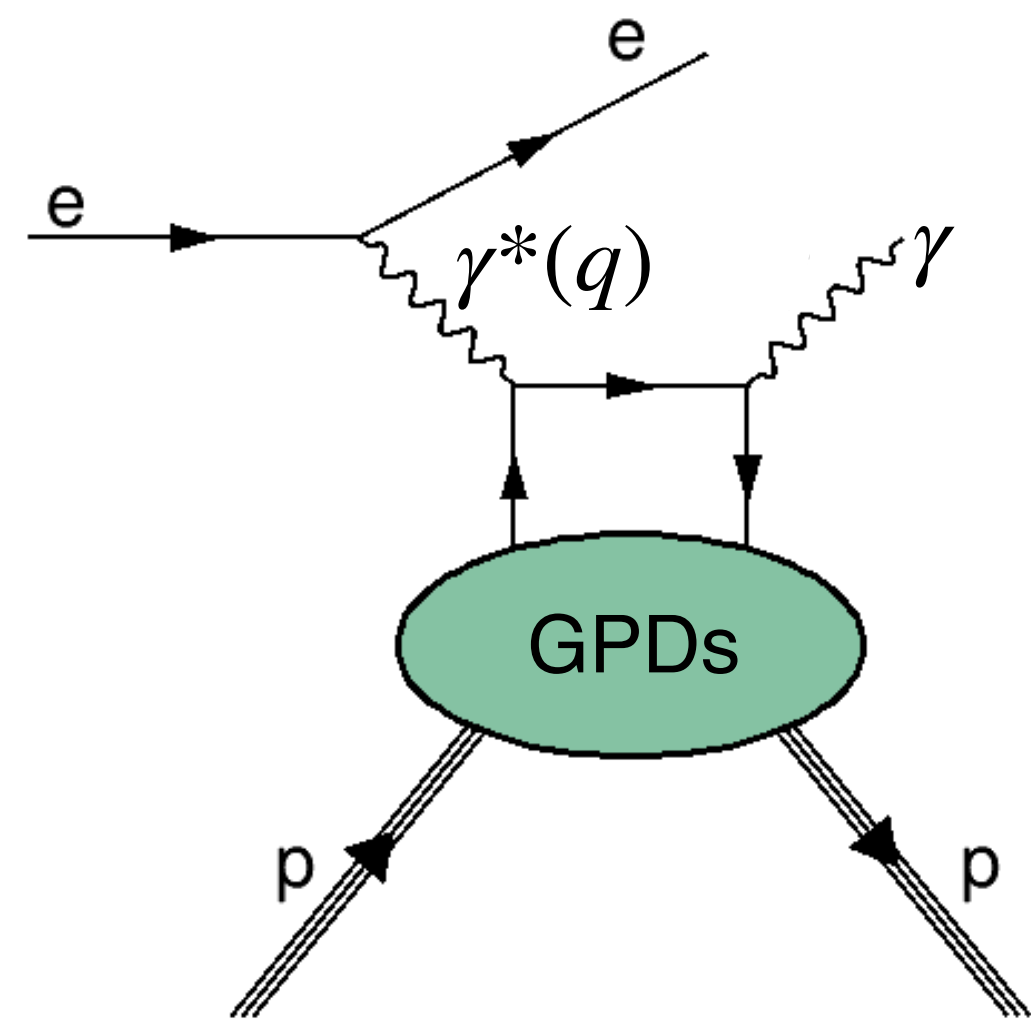


Timelike Compton scattering
(TCS)

Hard scale=large $Q'^2=q'^2$

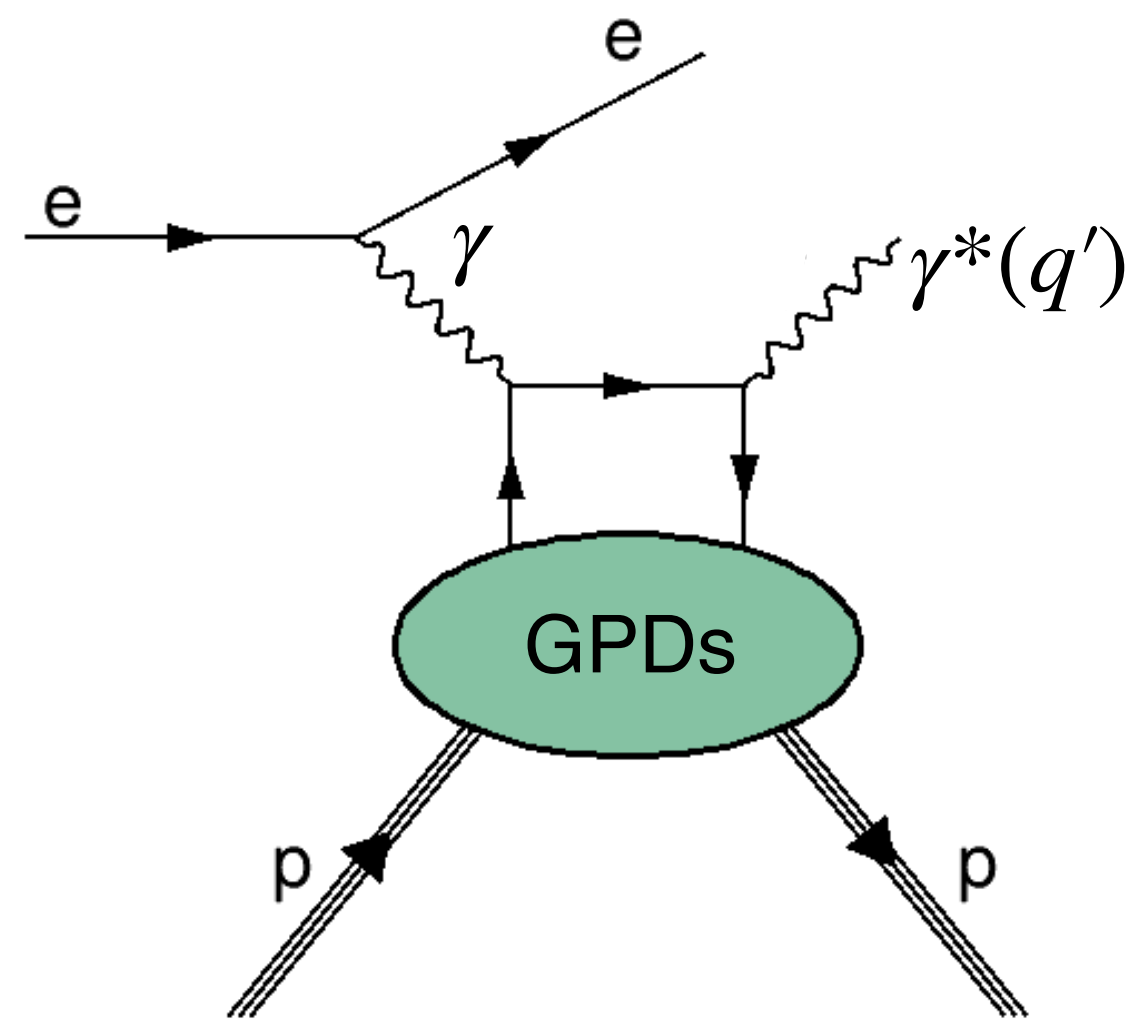
Crucial test for universality of GPDs

Experimental access to GPDs



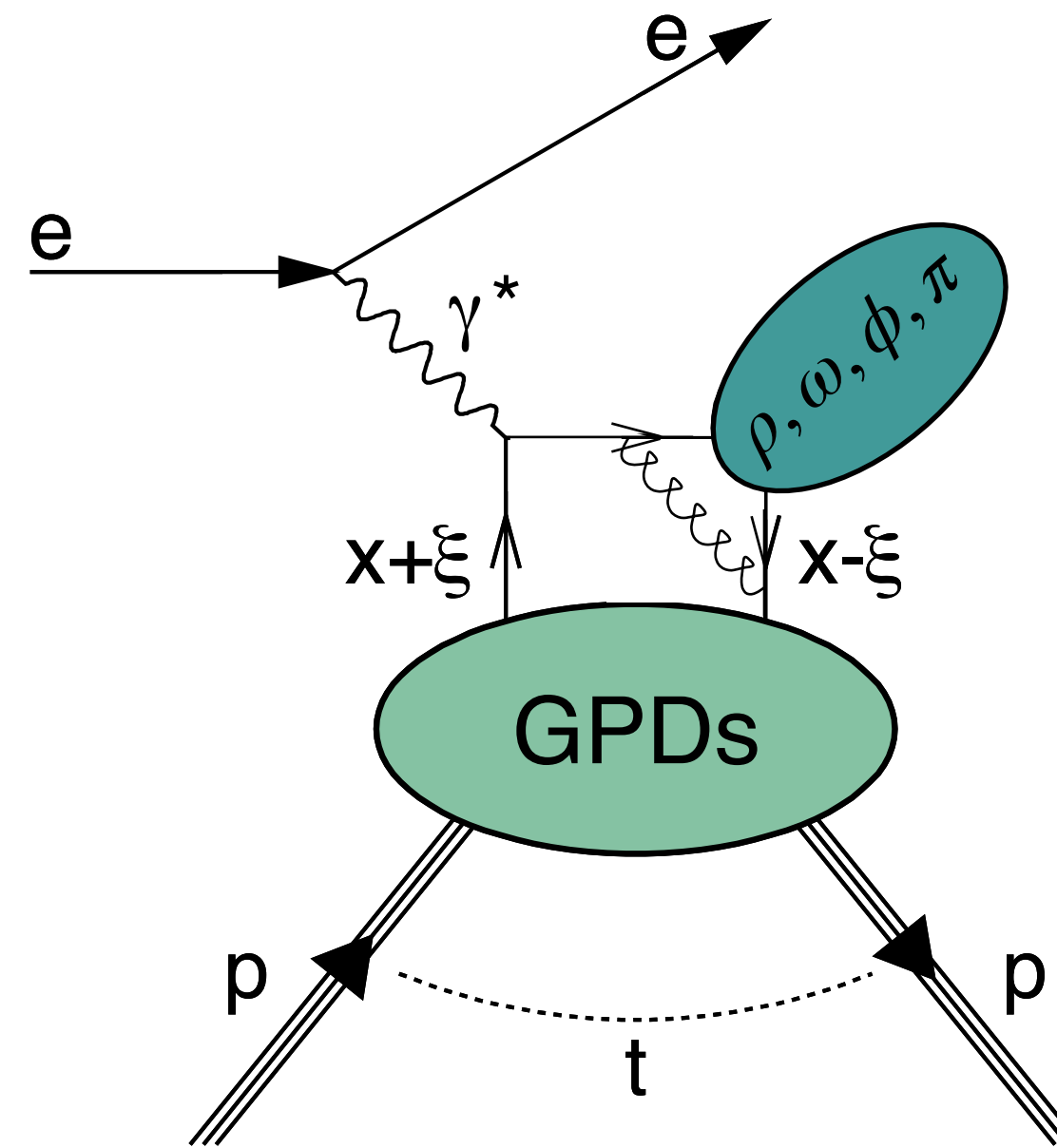
Deeply virtual Compton scattering
(DVCS)
Hard scale=large $Q^2=-q^2$

Theoretically cleanest process



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

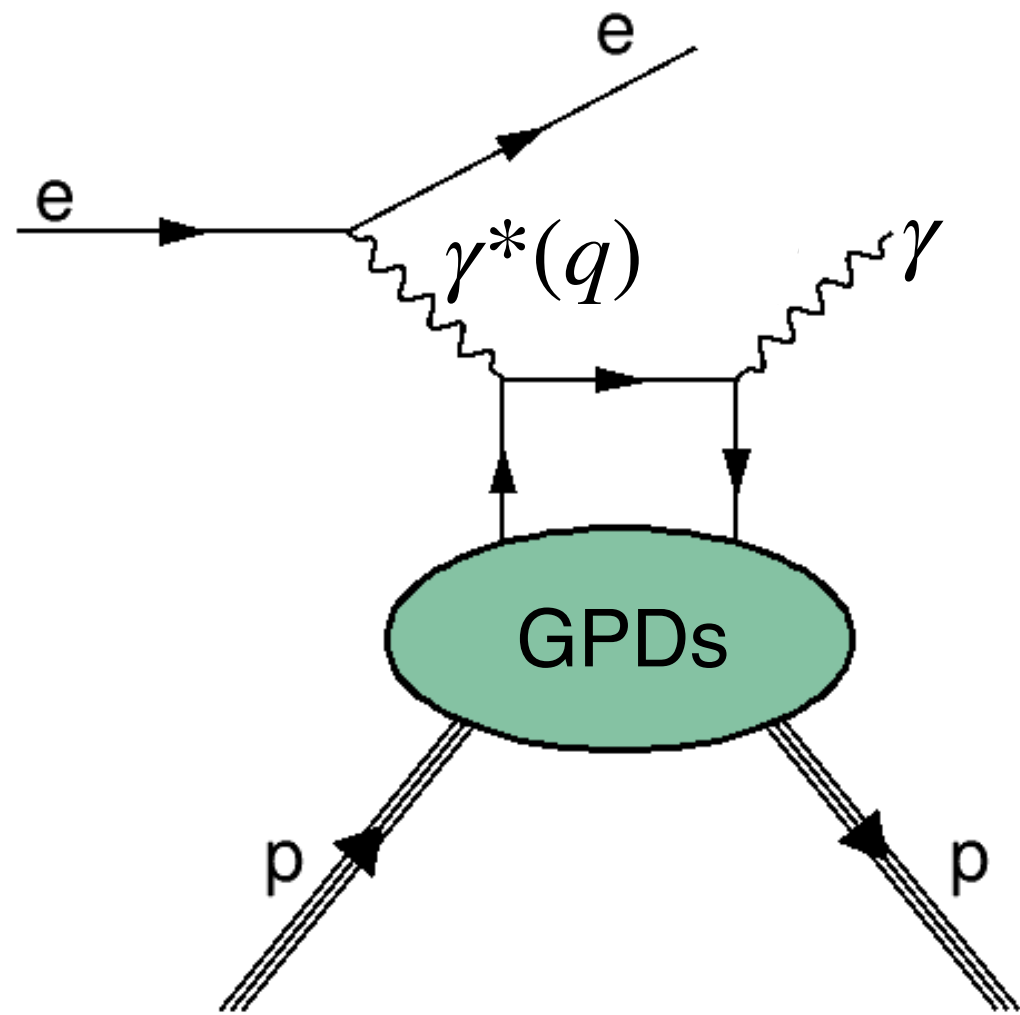
Crucial test for universality of GPDs



Hard exclusive meson production
Hard scale=large Q^2

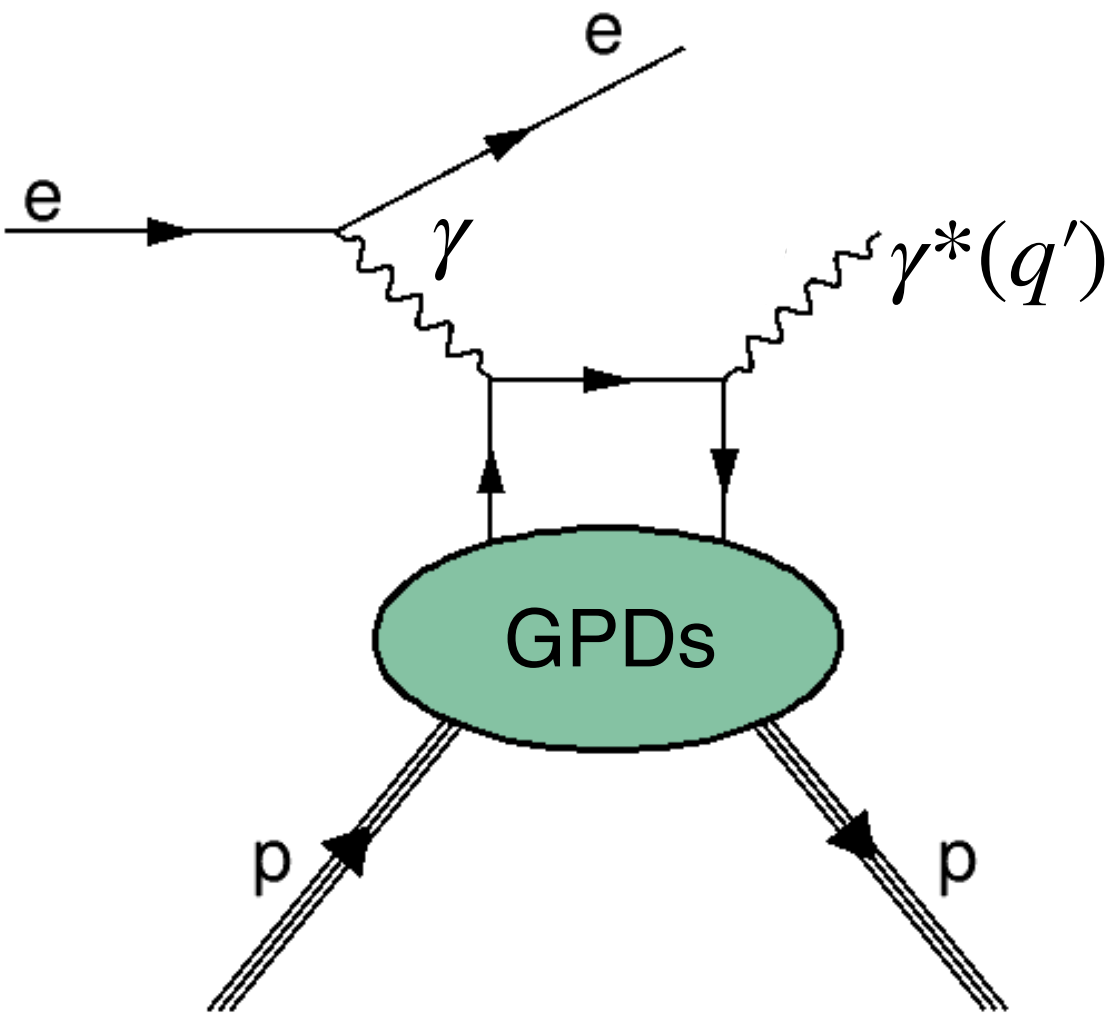
Sensitivity to different GPDs

Experimental access to GPDs



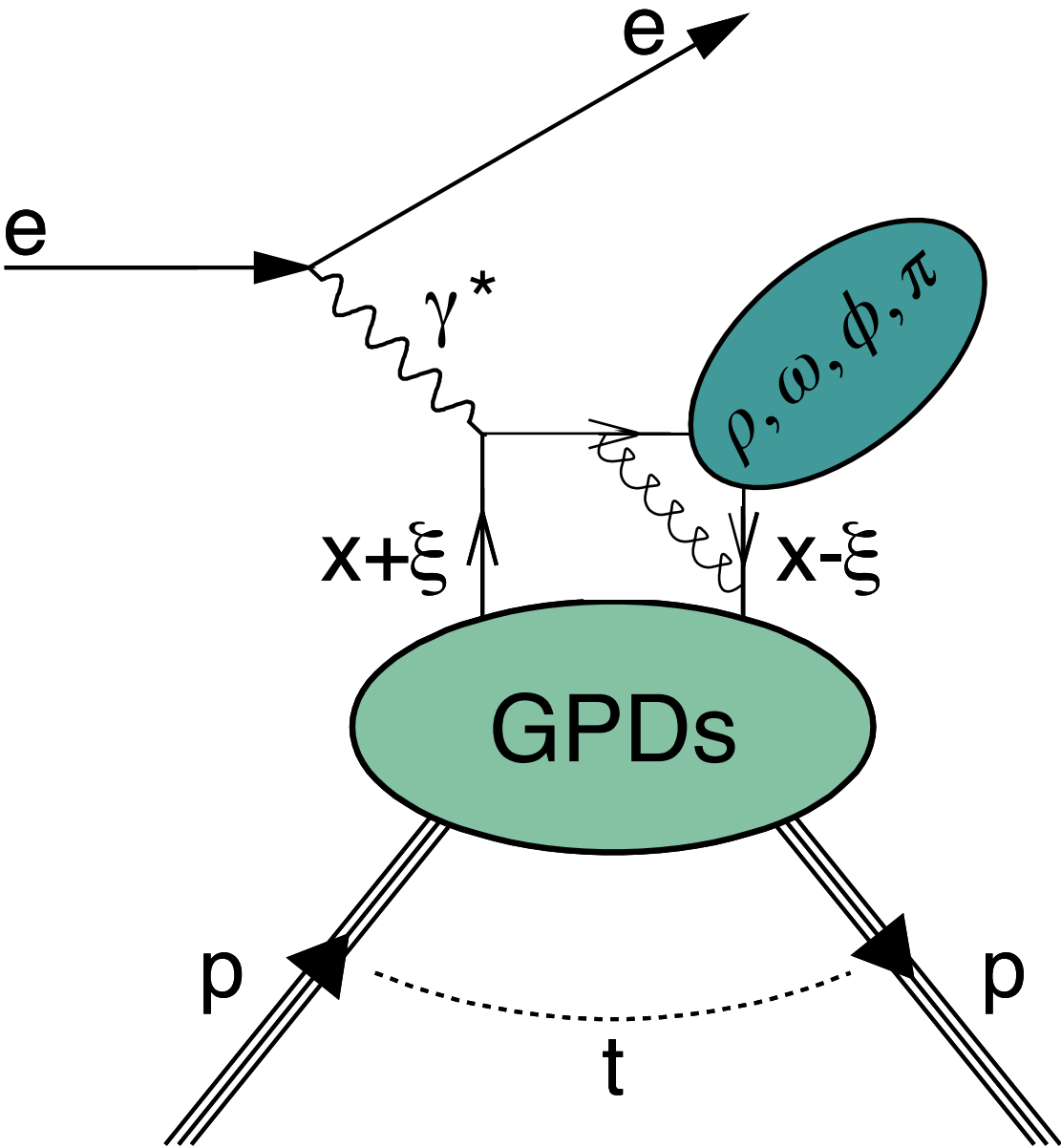
Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$

Theoretically cleanest process



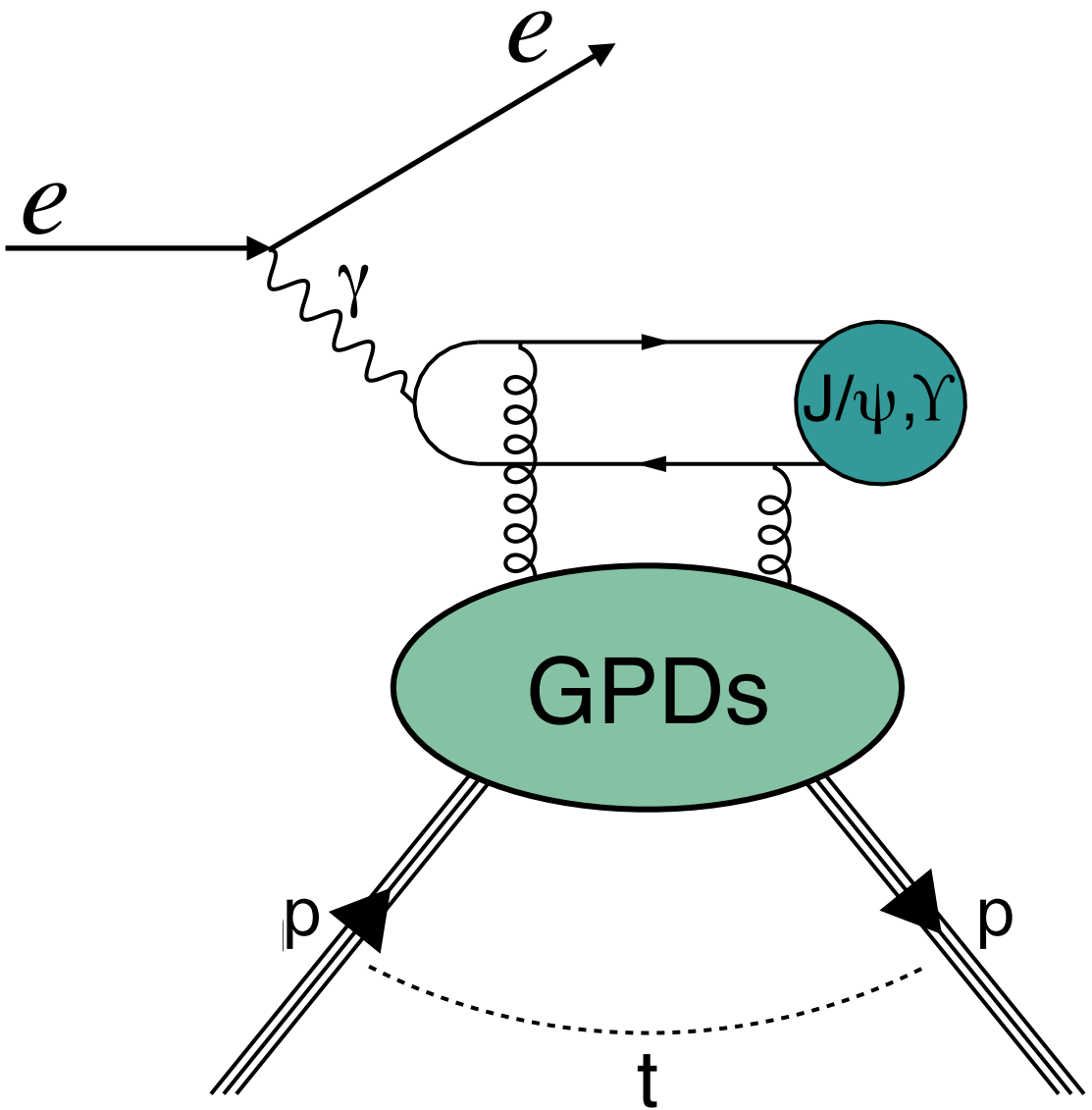
Timelike Compton scattering (TCS)
Hard scale=large $Q'^2=q'^2$

Crucial test for universality of GPDs



Hard exclusive meson production
Hard scale=large Q^2

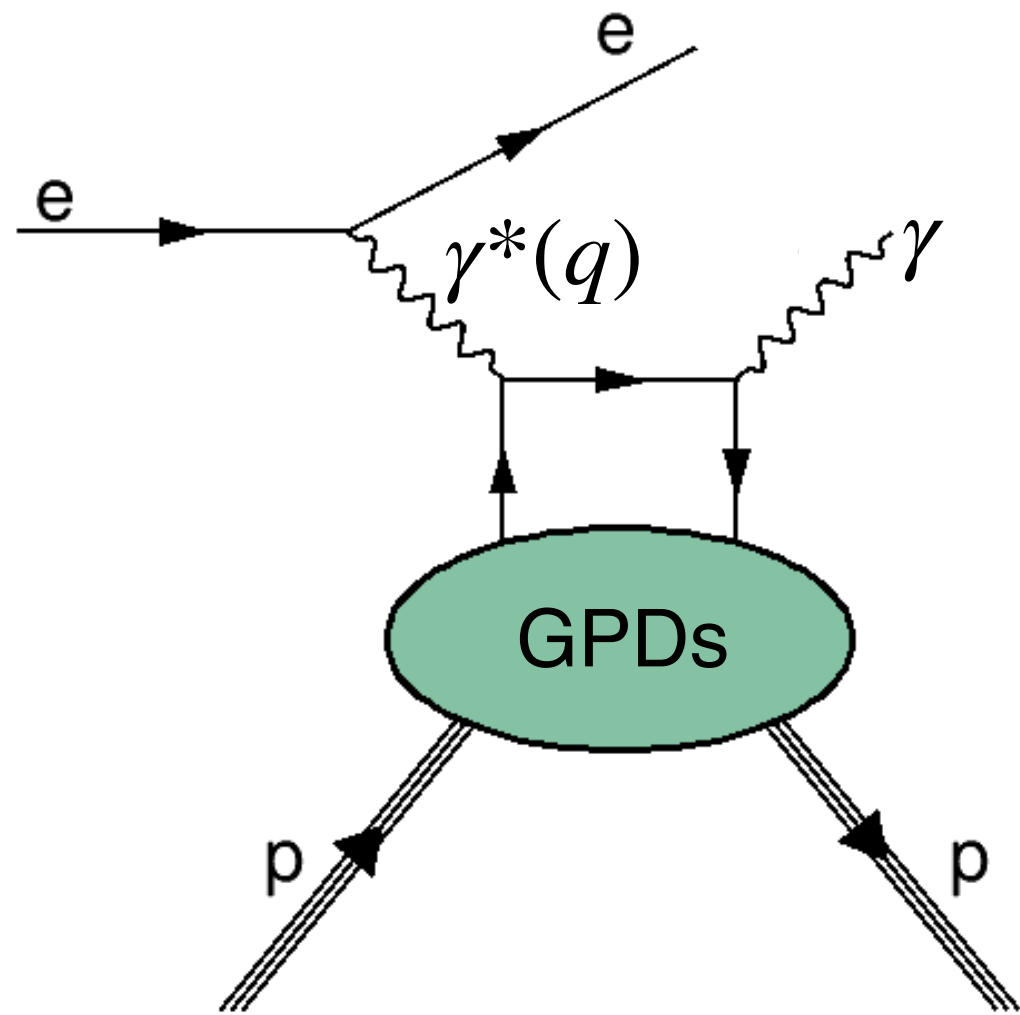
Sensitivity to different GPDs



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

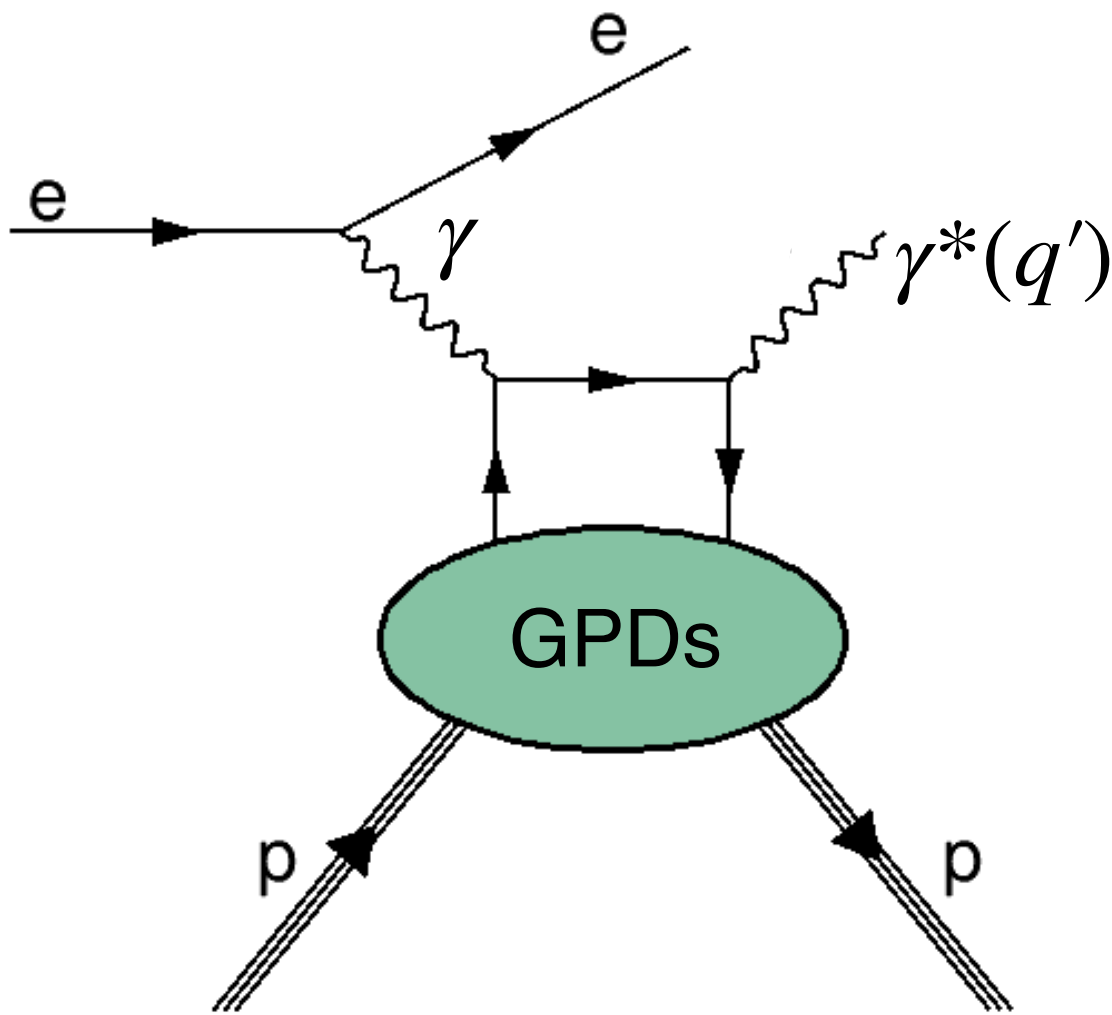
Access to gluons

Experimental access to GPDs



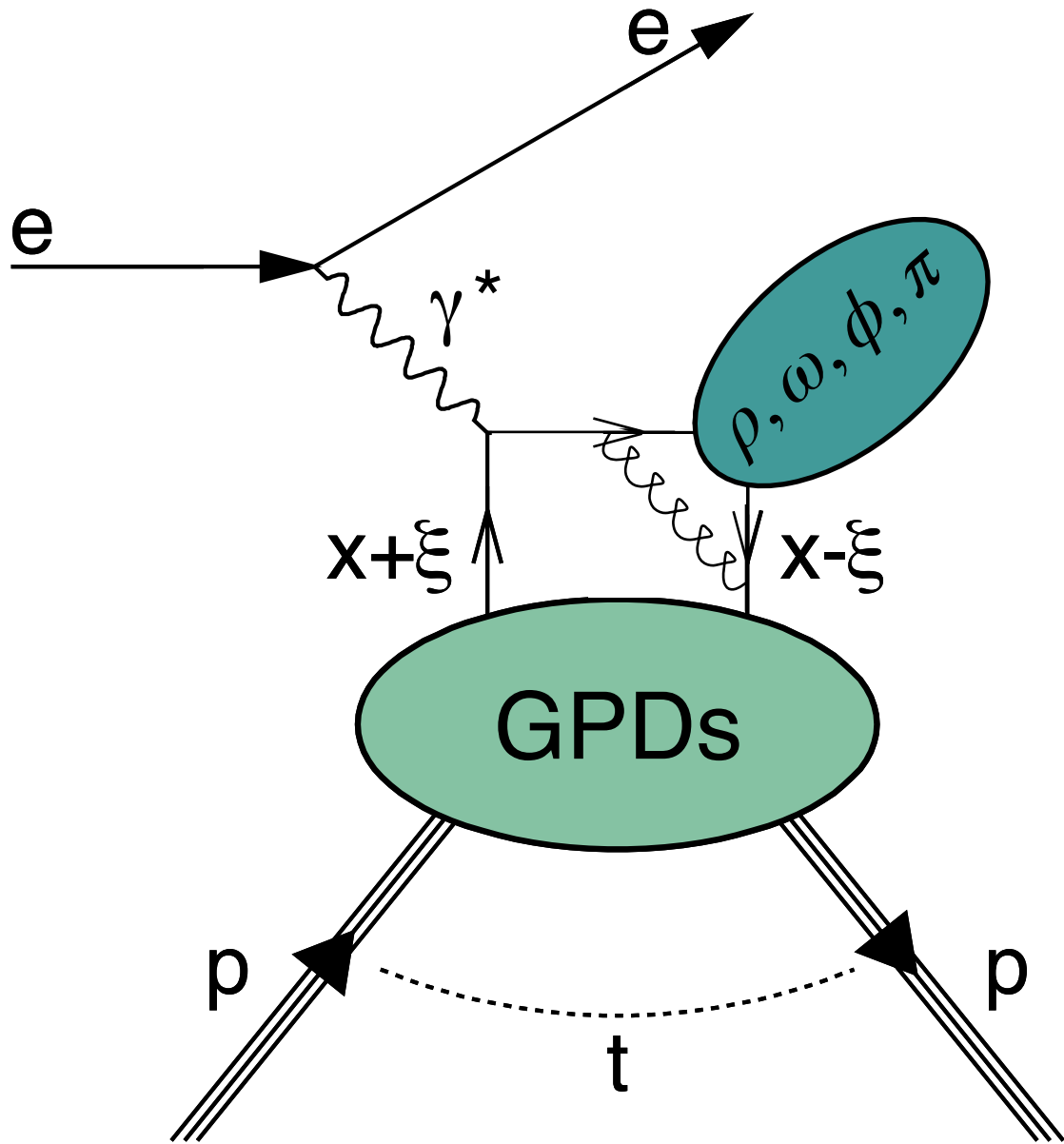
Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$

Theoretically cleanest process



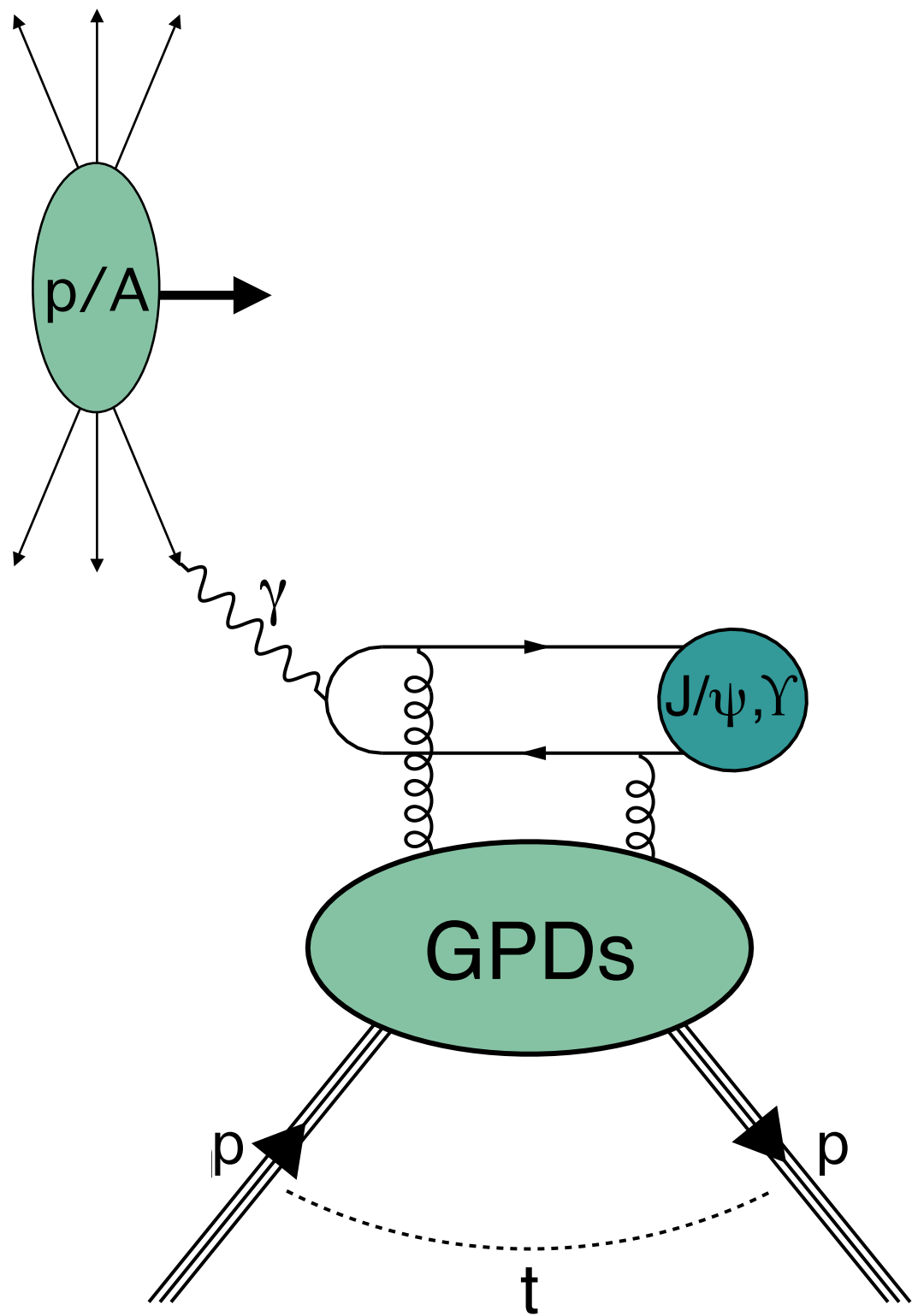
Timelike Compton scattering (TCS)
Hard scale=large $Q'^2=q'^2$

Crucial test for universality of GPDs



Hard exclusive meson production
Hard scale=large Q^2

Sensitivity to different GPDs

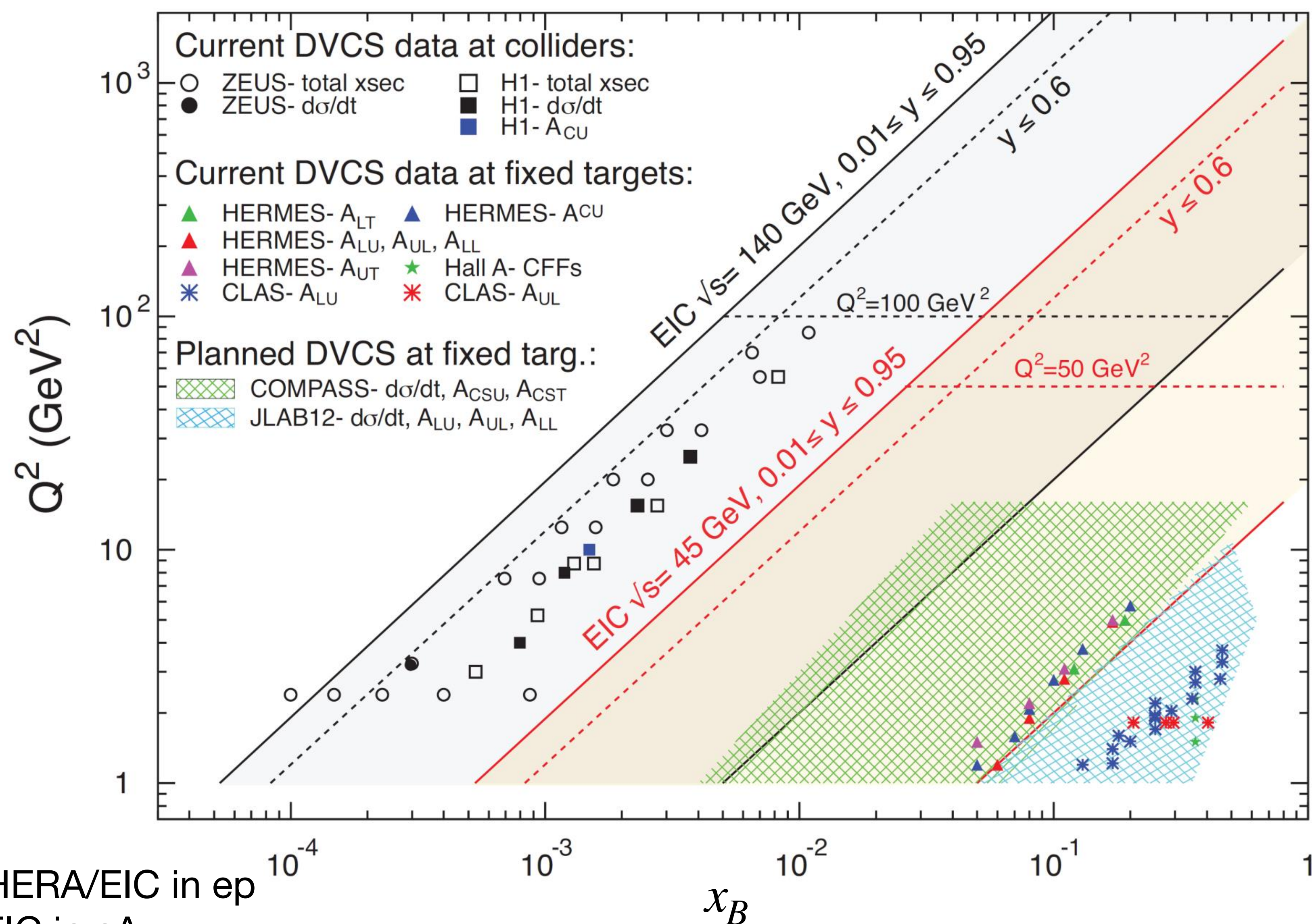


Exclusive meson photoproduction
Hard scale = large c/b-quark mass

Access to gluons

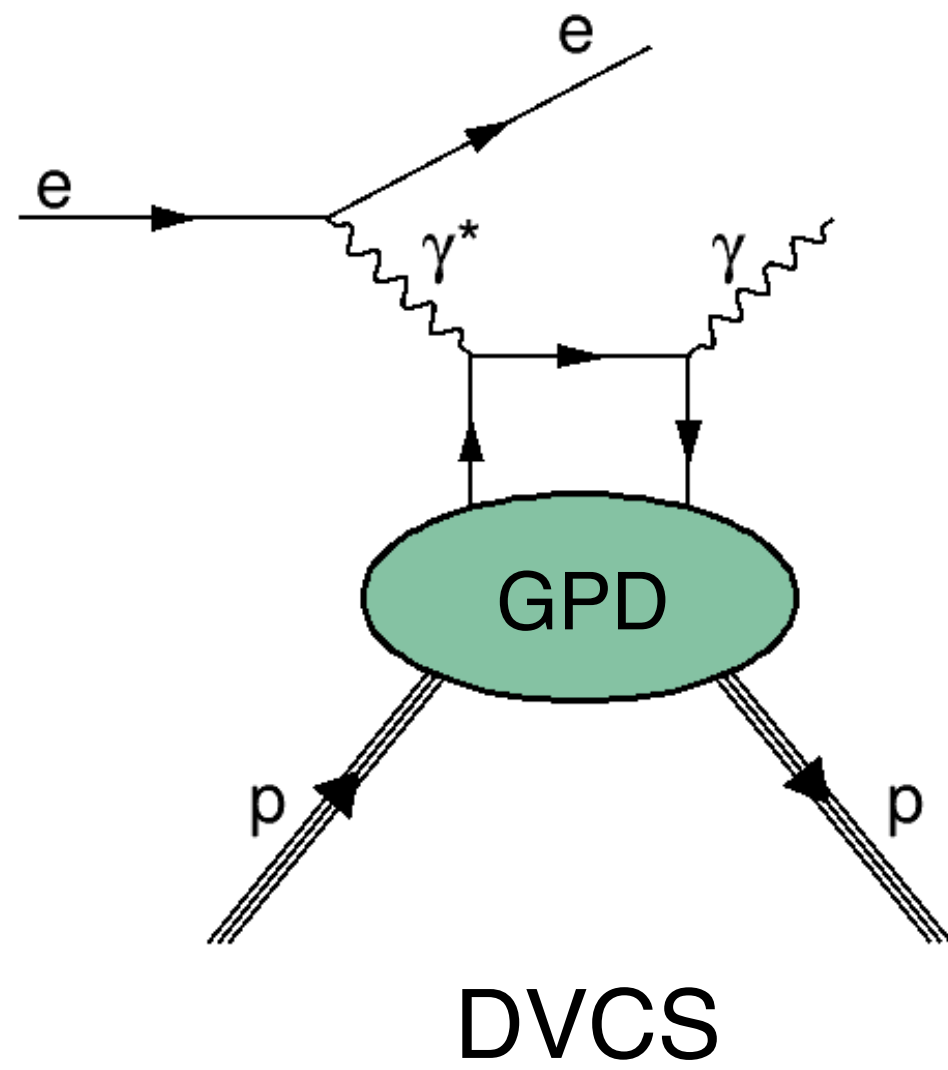
Sensitive to very low x_B

Kinematic coverage DIS experiments

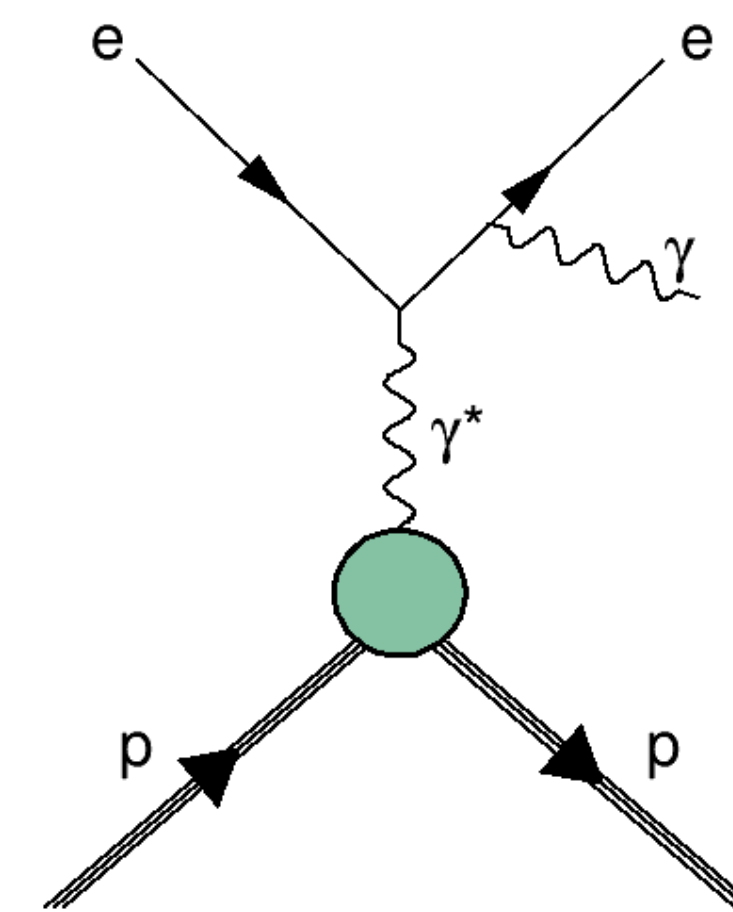
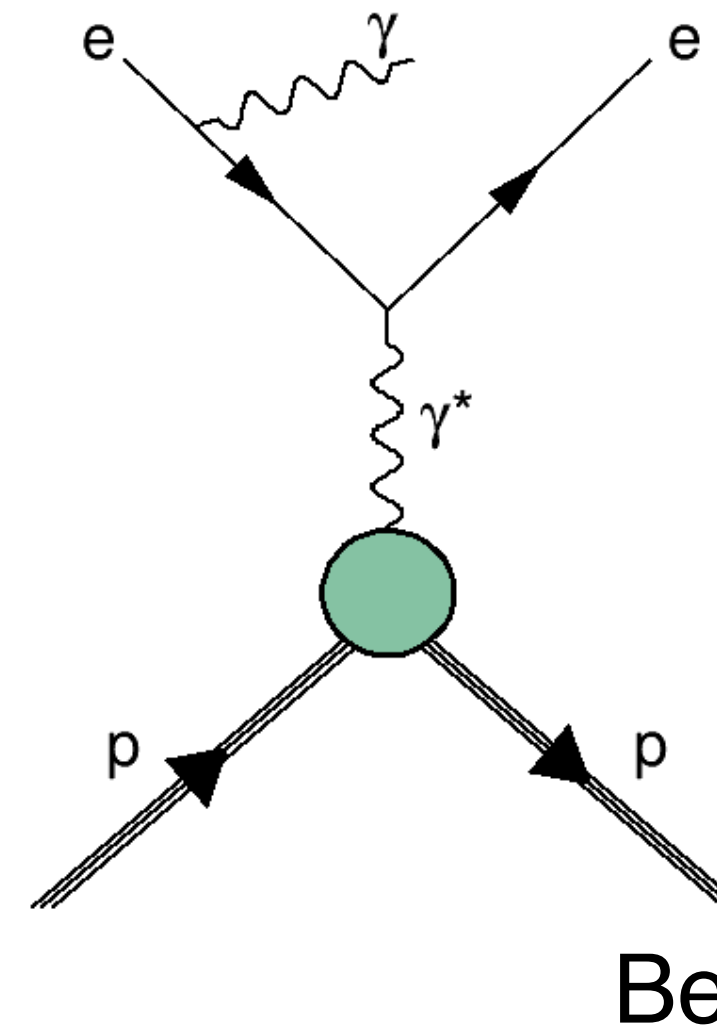
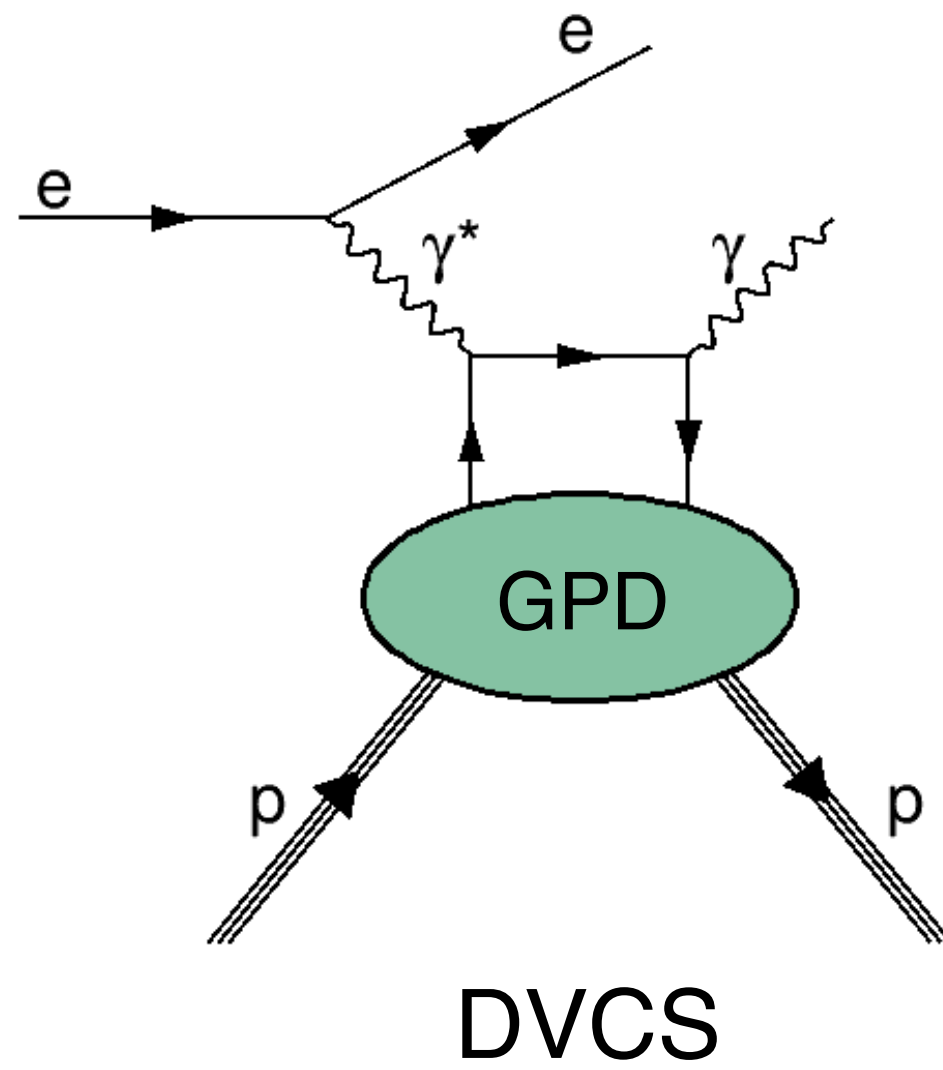


down to $x_B=10^{-4}$ at HERA/EIC in ep
 $x_B=10^{-3}$ at EIC in eA

GPDs and deeply virtual Compton scattering (DVCS)



GPDs and deeply virtual Compton scattering (DVCS)



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

GPDs and deeply virtual Compton scattering (DVCS)

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

$$|\tau_{BH}|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^2 c_n^{BH} \cos(n\phi) \right\} \quad \text{calculable with knowledge Pauli \& Dirac form factors}$$

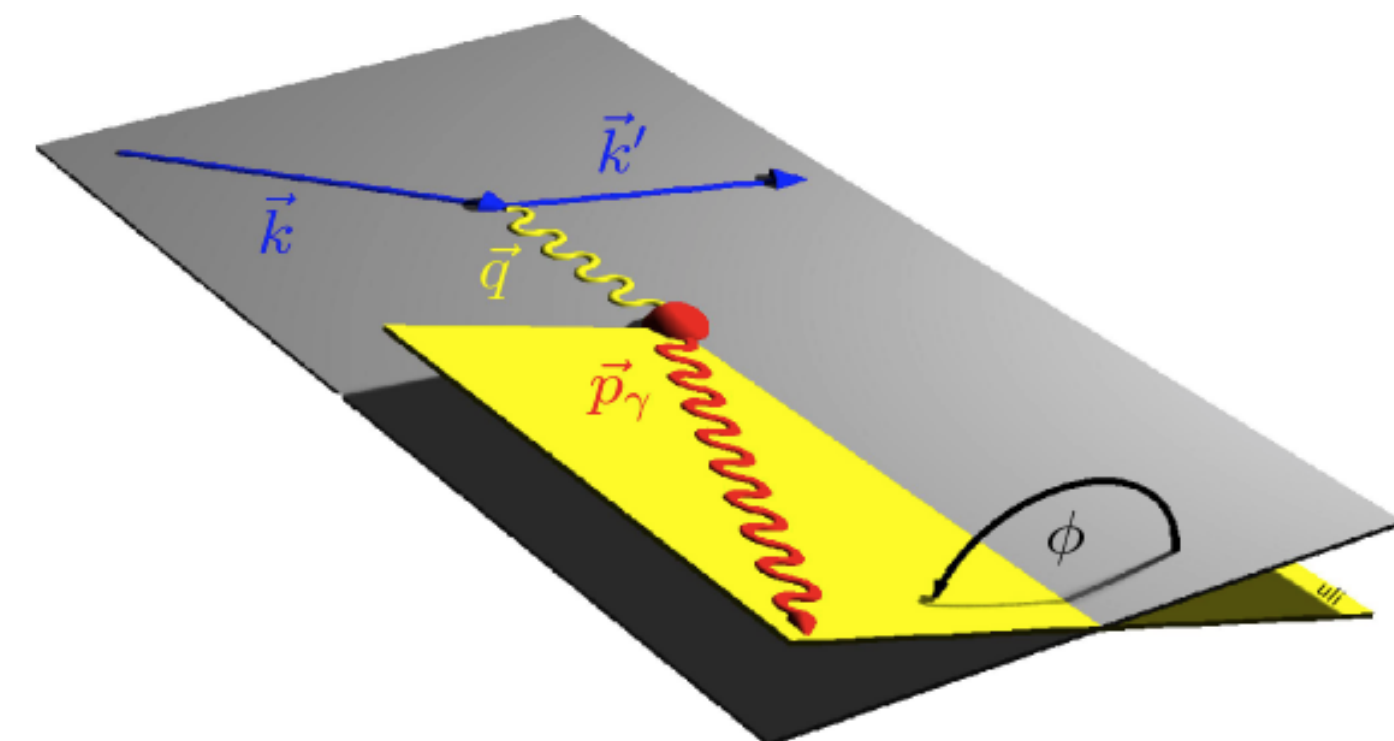
$$|\tau_{DVCS}|^2 = \frac{1}{Q^2} \left\{ \sum_{n=0}^2 c_n^{DVCS} \cos(n\phi) + \lambda s_1^{DVCS} \sin(\phi) \right\} \quad \text{coefficients: bilinear in GPDs}$$

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

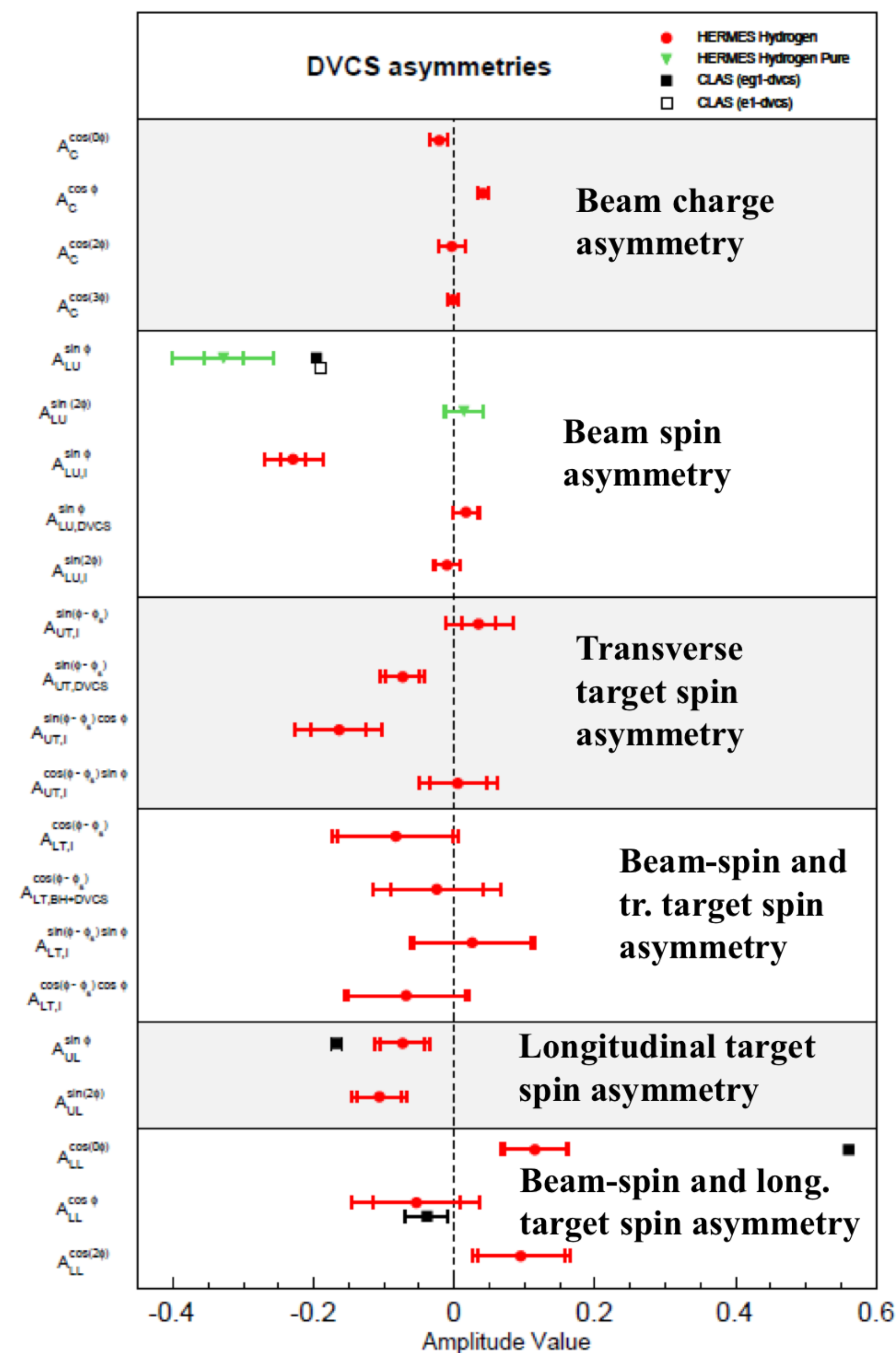
beam
charge

beam
polarization

Unpolarized nucleon
Longitudinally polarized lepton beam



DVCS: pioneering measurements

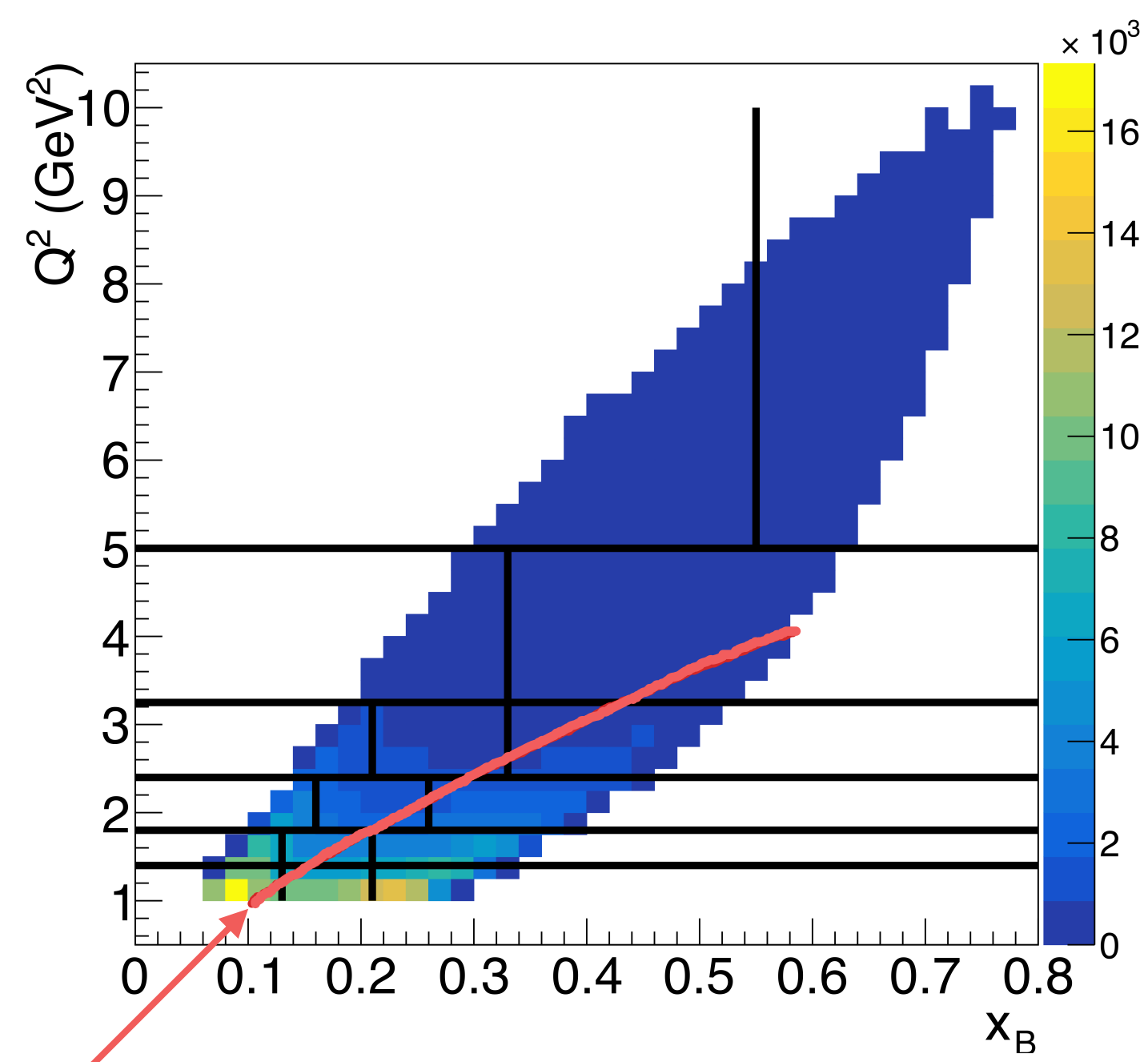
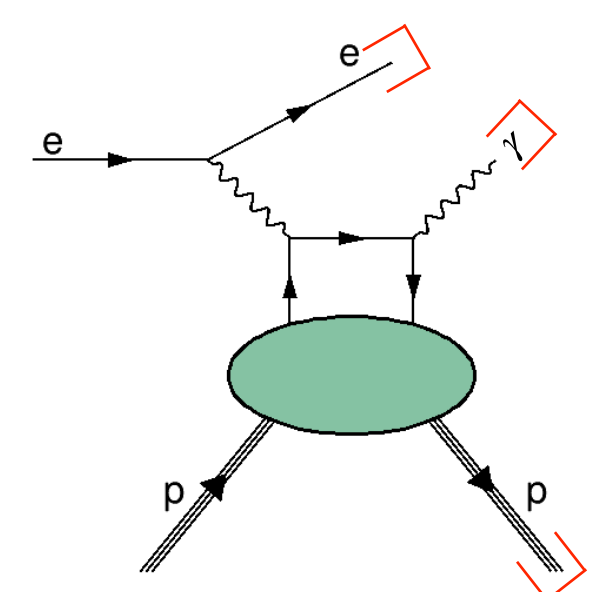


GPD H

GPD E

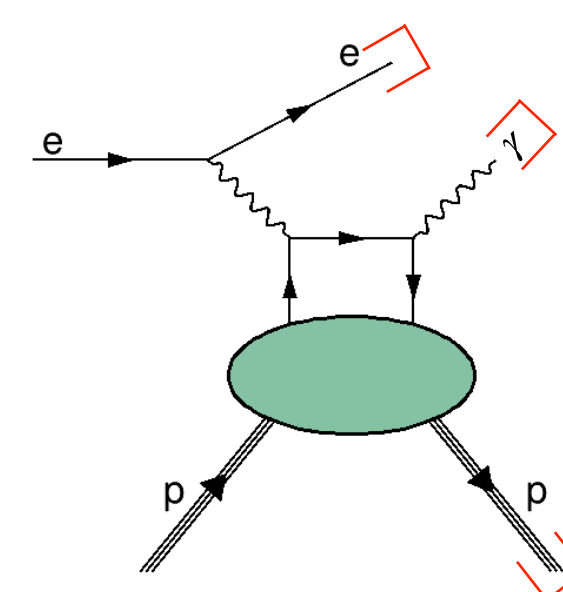
GPD $\tilde{H}$

DVCS off the proton: CLAS12



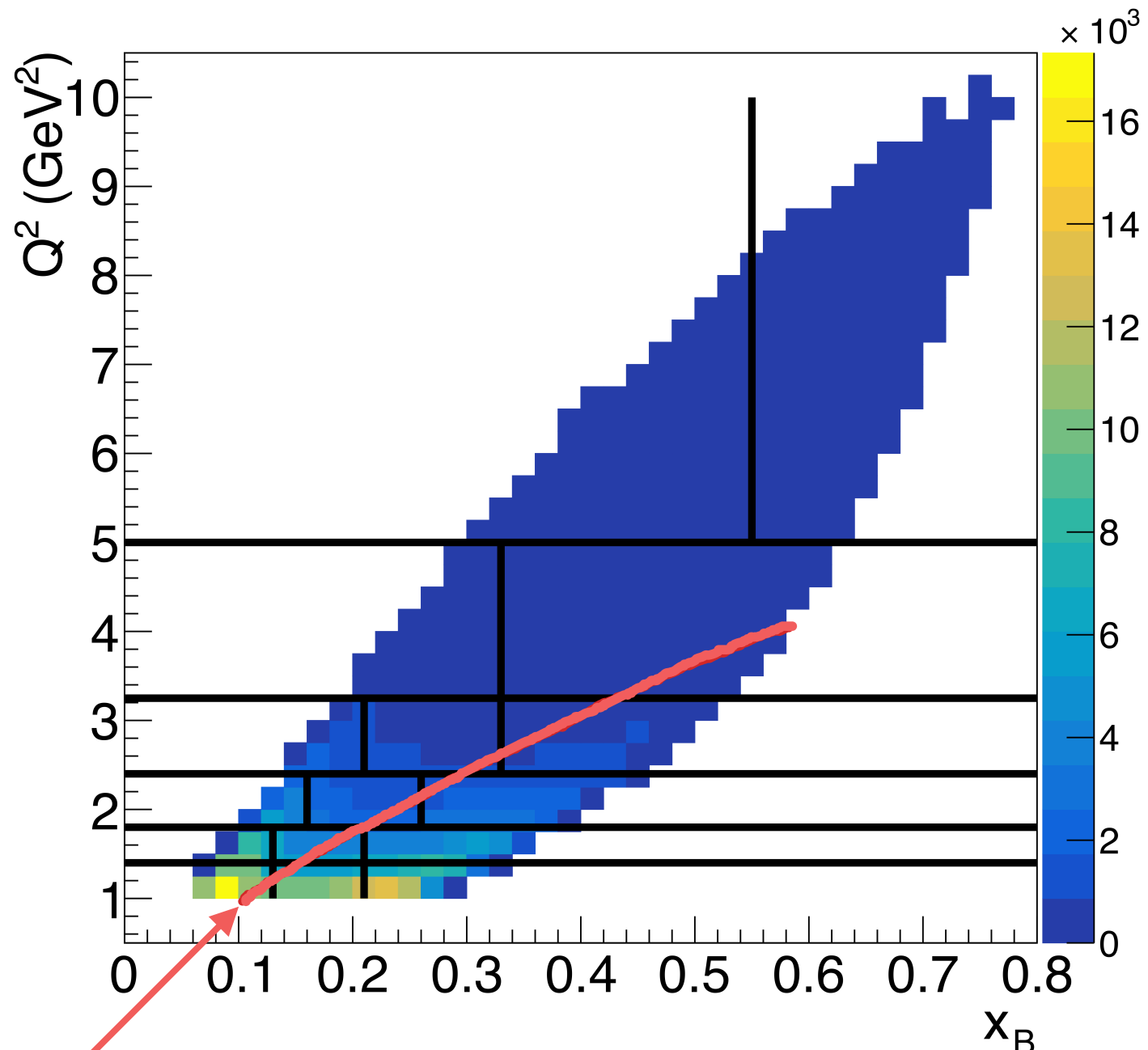
CLAS 6 GeV

DVCS off the proton: CLAS12

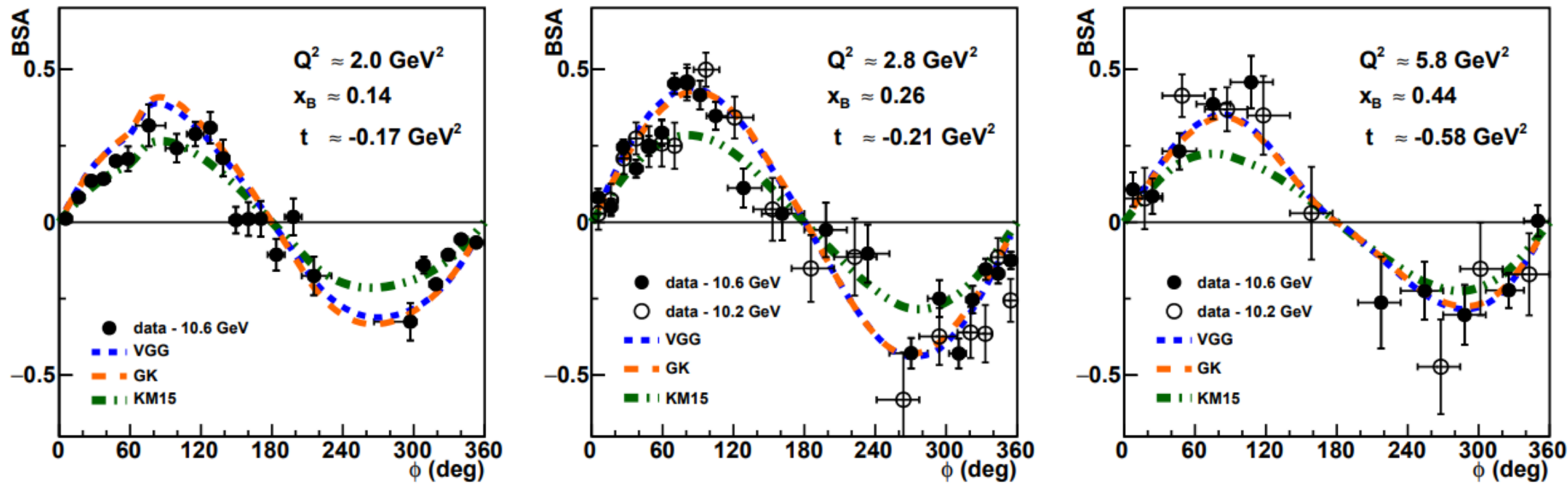


Beam-spin asymmetry

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

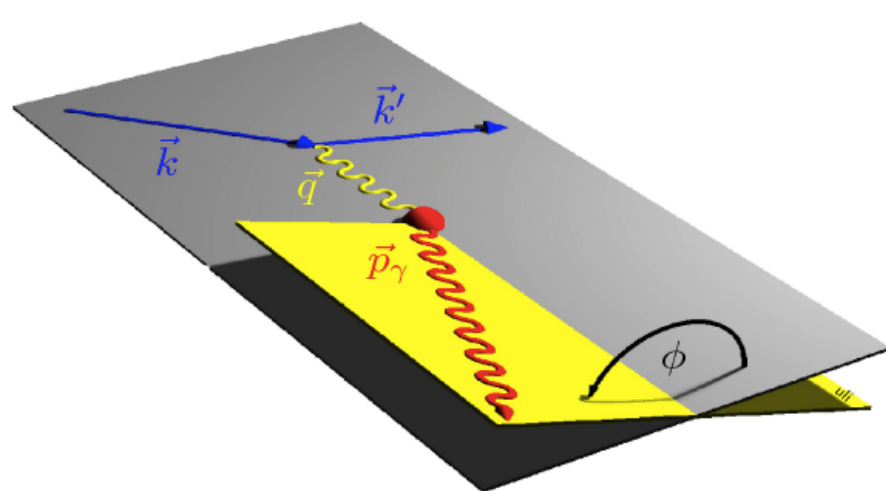


CLAS 6 GeV

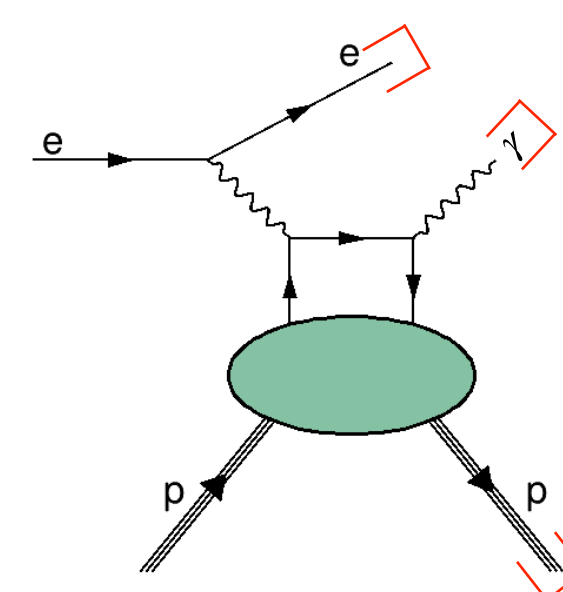


Vast extension of statistics: 64 bins in x_B, Q^2, t

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

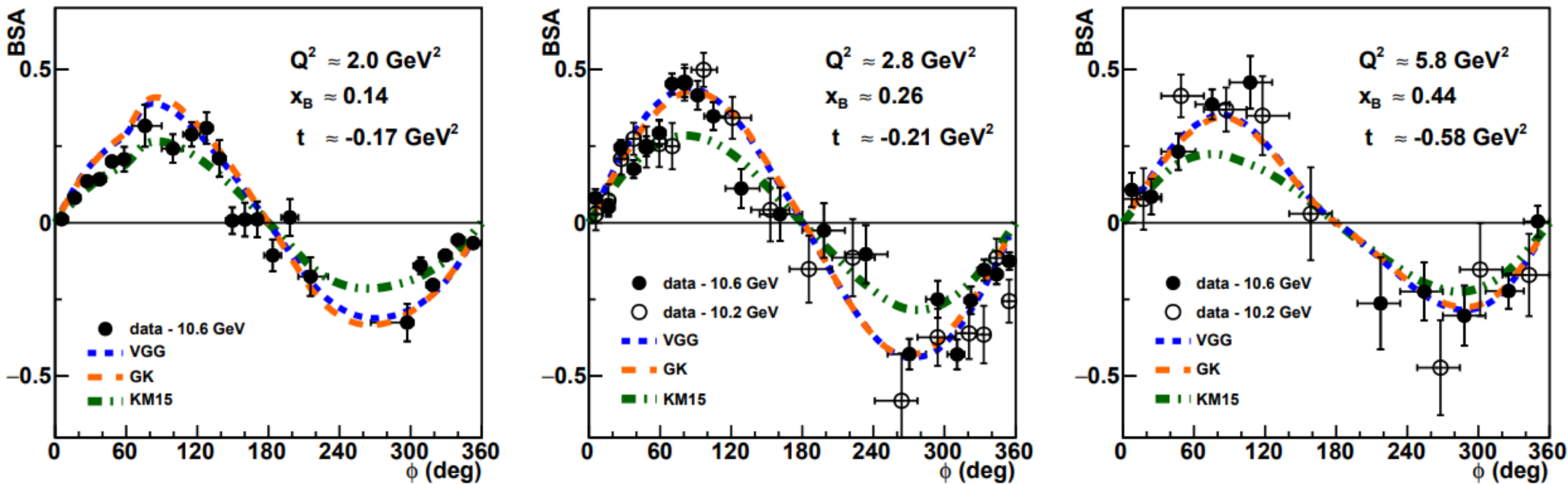


DVCS off the proton: CLAS12

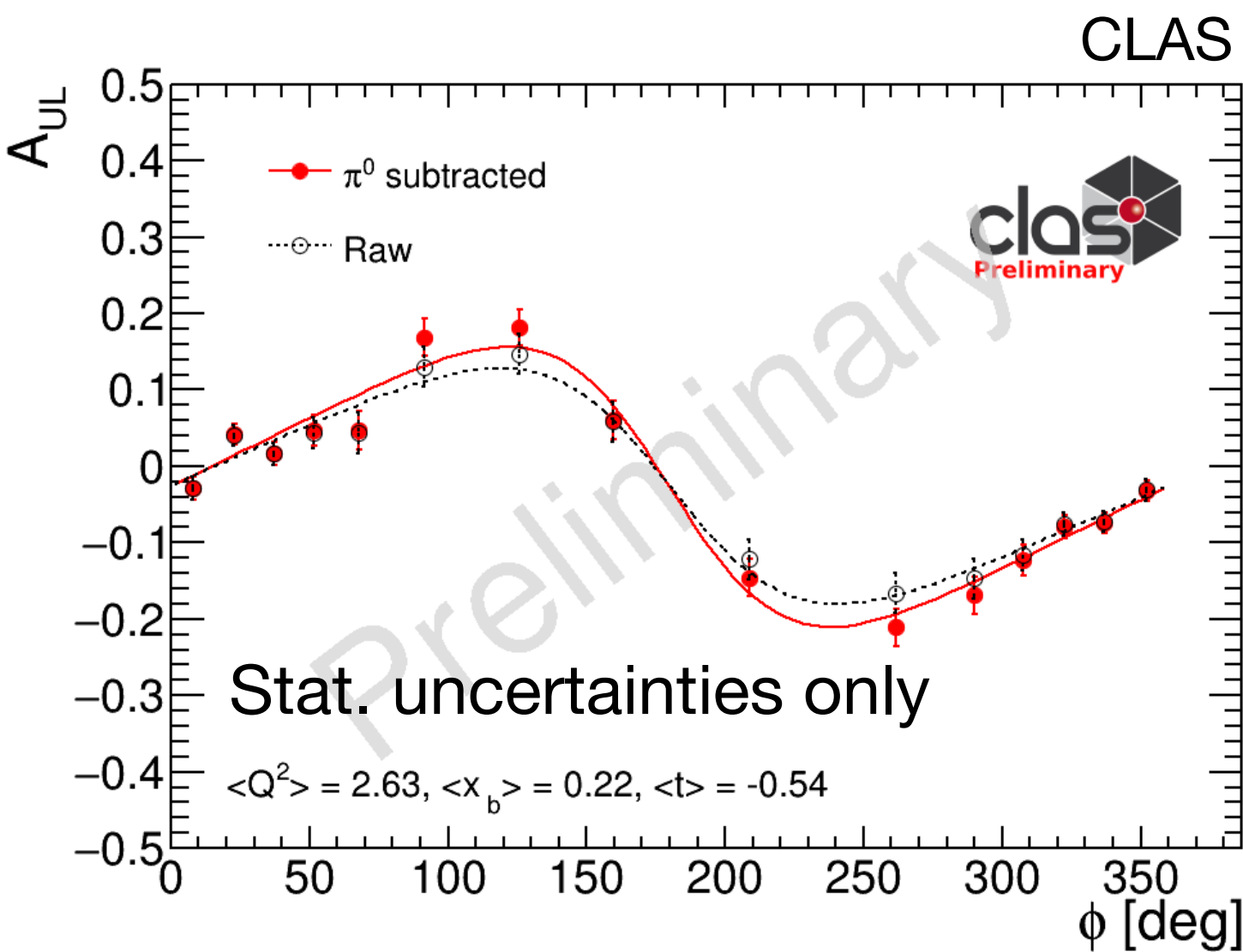


Beam-spin asymmetry

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



Longitudinal target-spin asymmetry

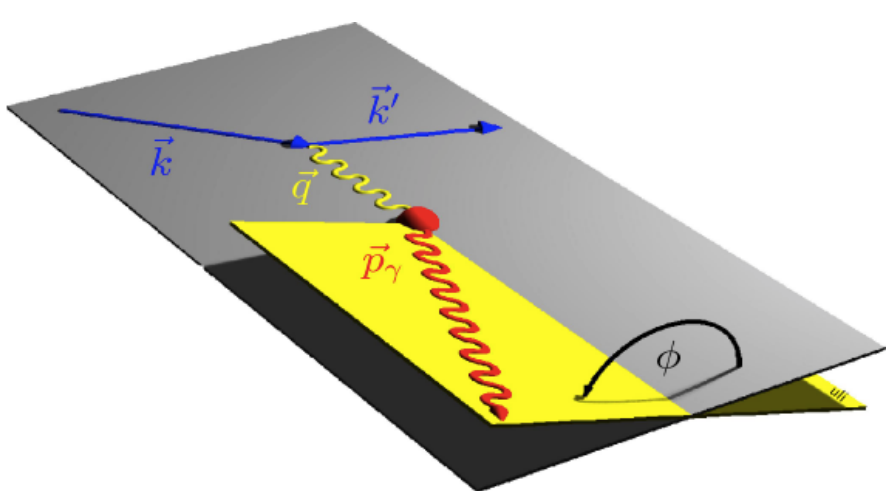


Vast extension of statistics: 64 bins in x_B, Q^2, t

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

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

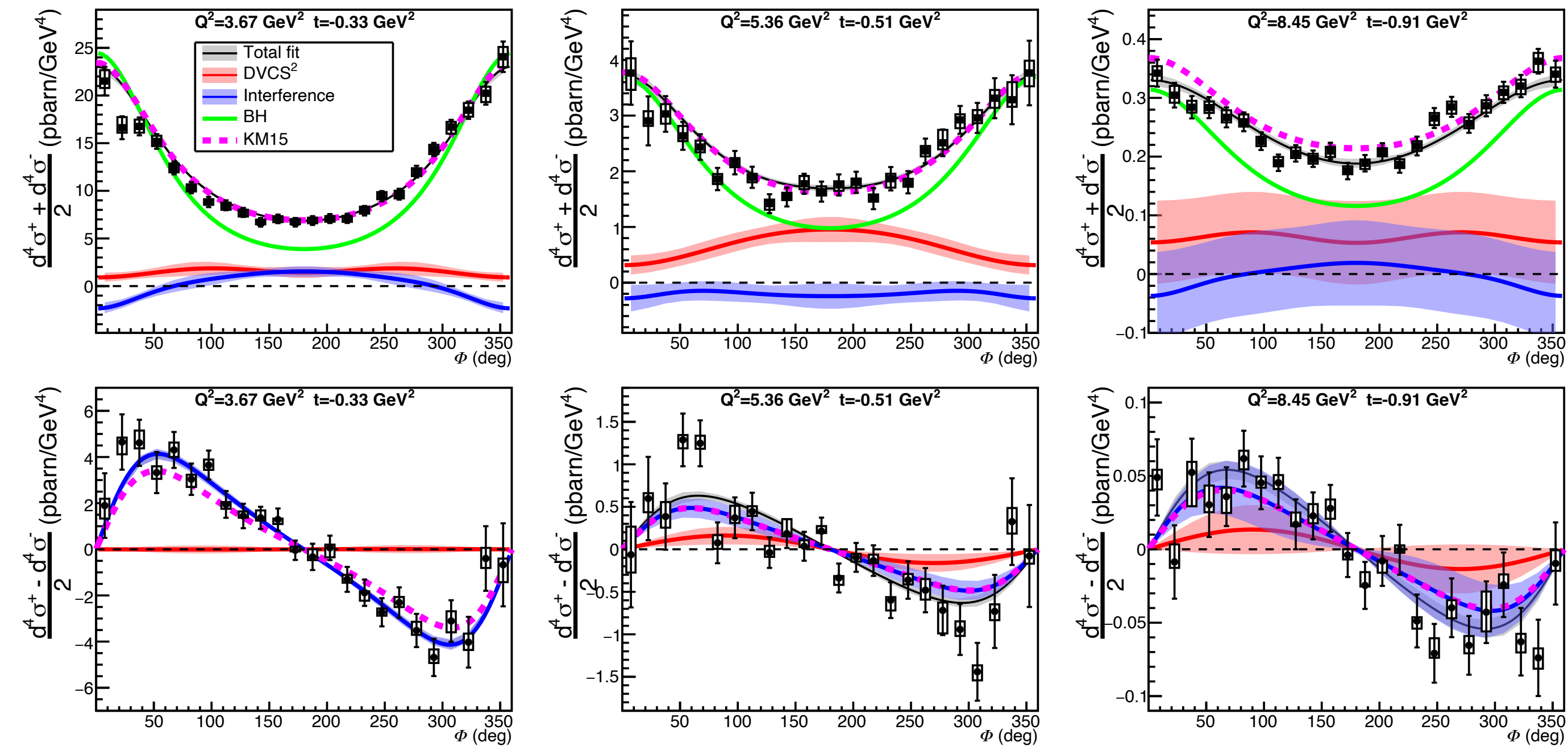
Combination:
clean separation of
 $\Im m \mathcal{H}$ and $\Im m \tilde{\mathcal{H}}$



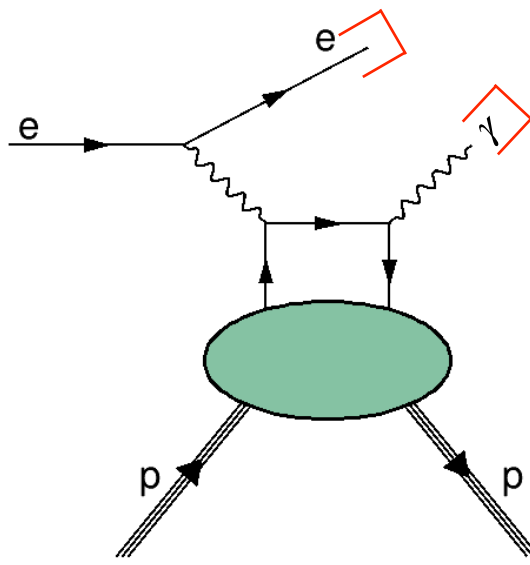
DVCS off the proton: Hall A and C

Hall A, Phys. Rev. Lett. 128 (2022) 25, 252002

Unpolarised cross section



Beam-spin asymmetry

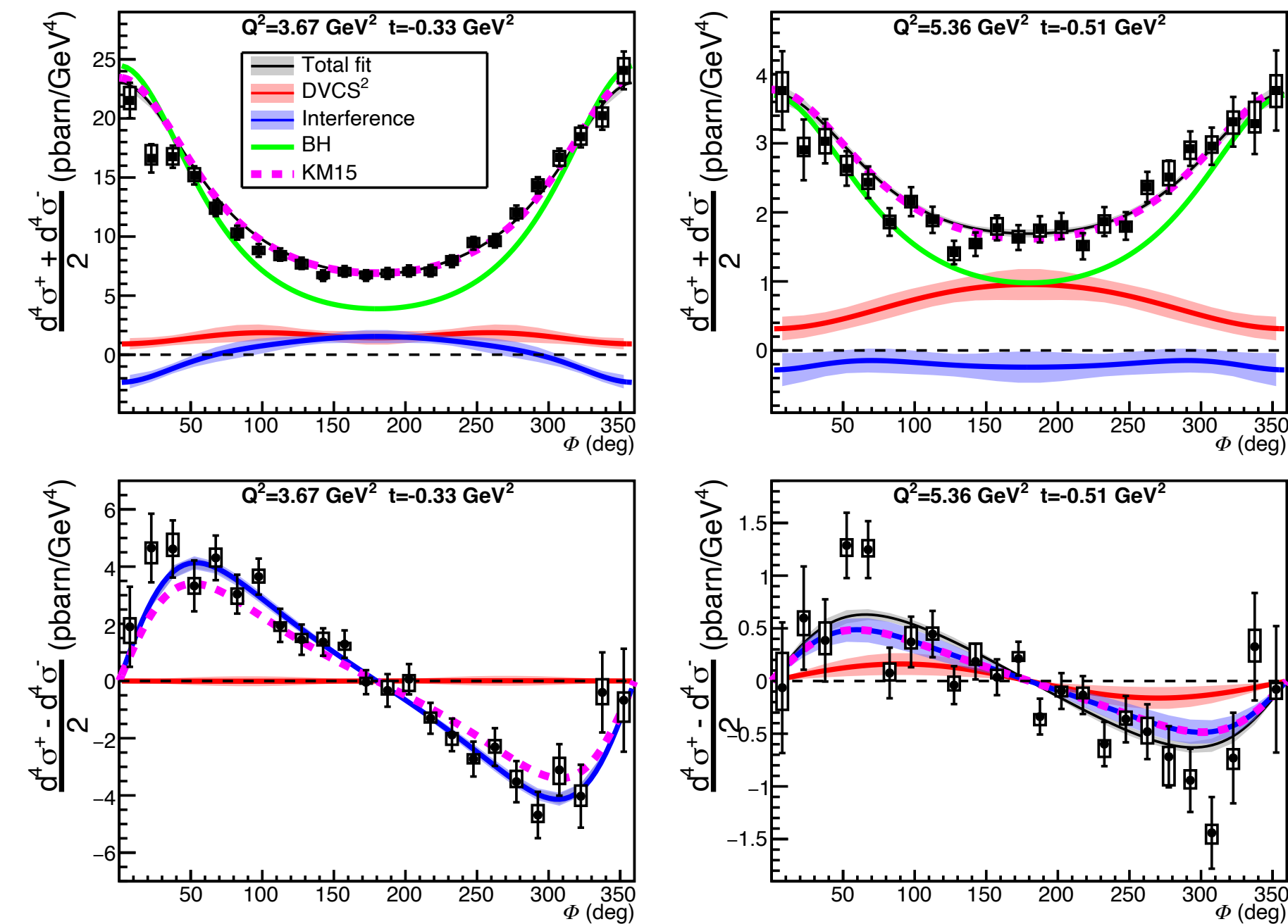


- Measurement with 3 beam energies
- Separation of BH, DVCS and interference terms
- Simultaneous extraction of all 4 chiral-even CFFs

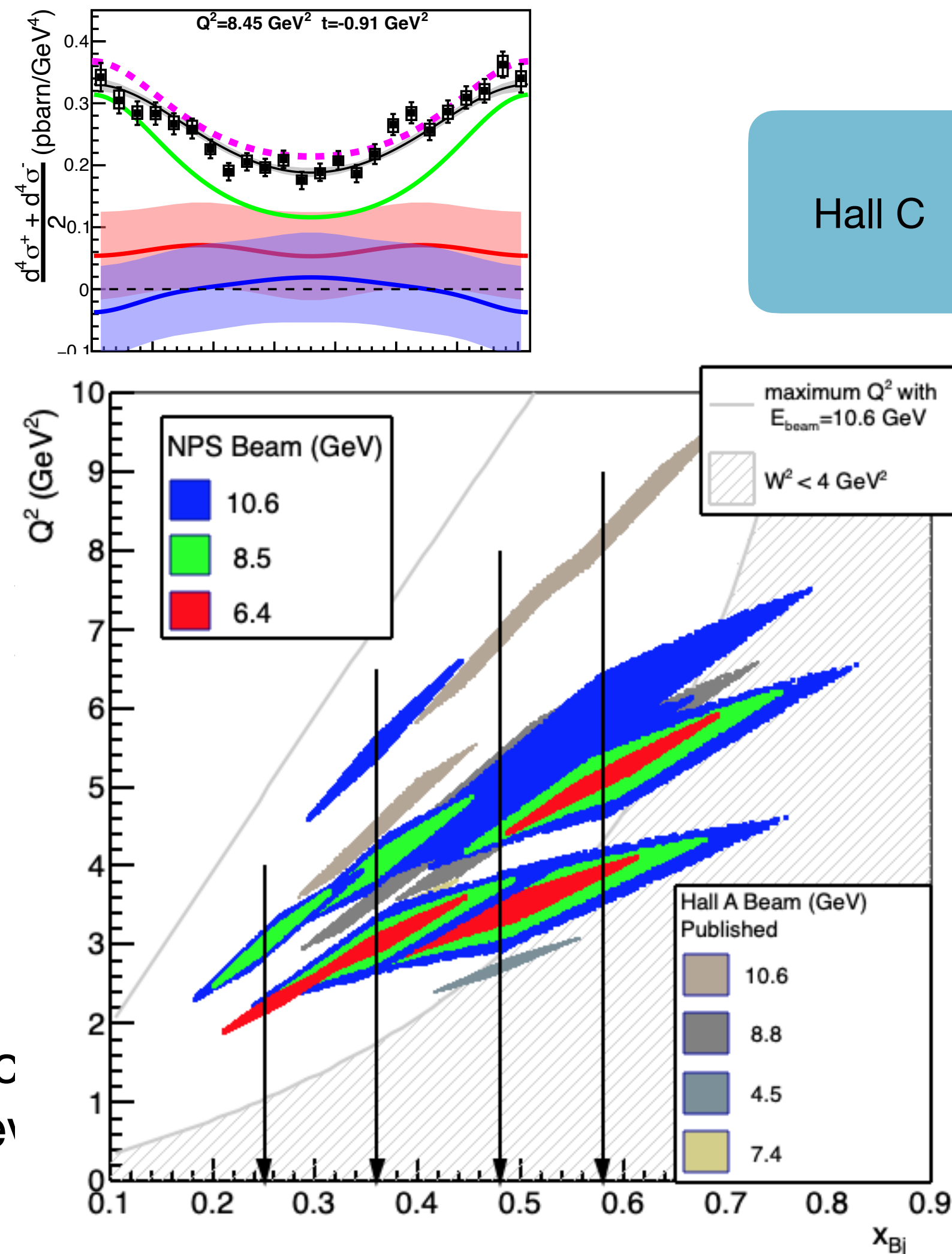
DVCS off the proton: Hall A and C

Hall A, Phys. Rev. Lett. 128 (2022) 25, 252002

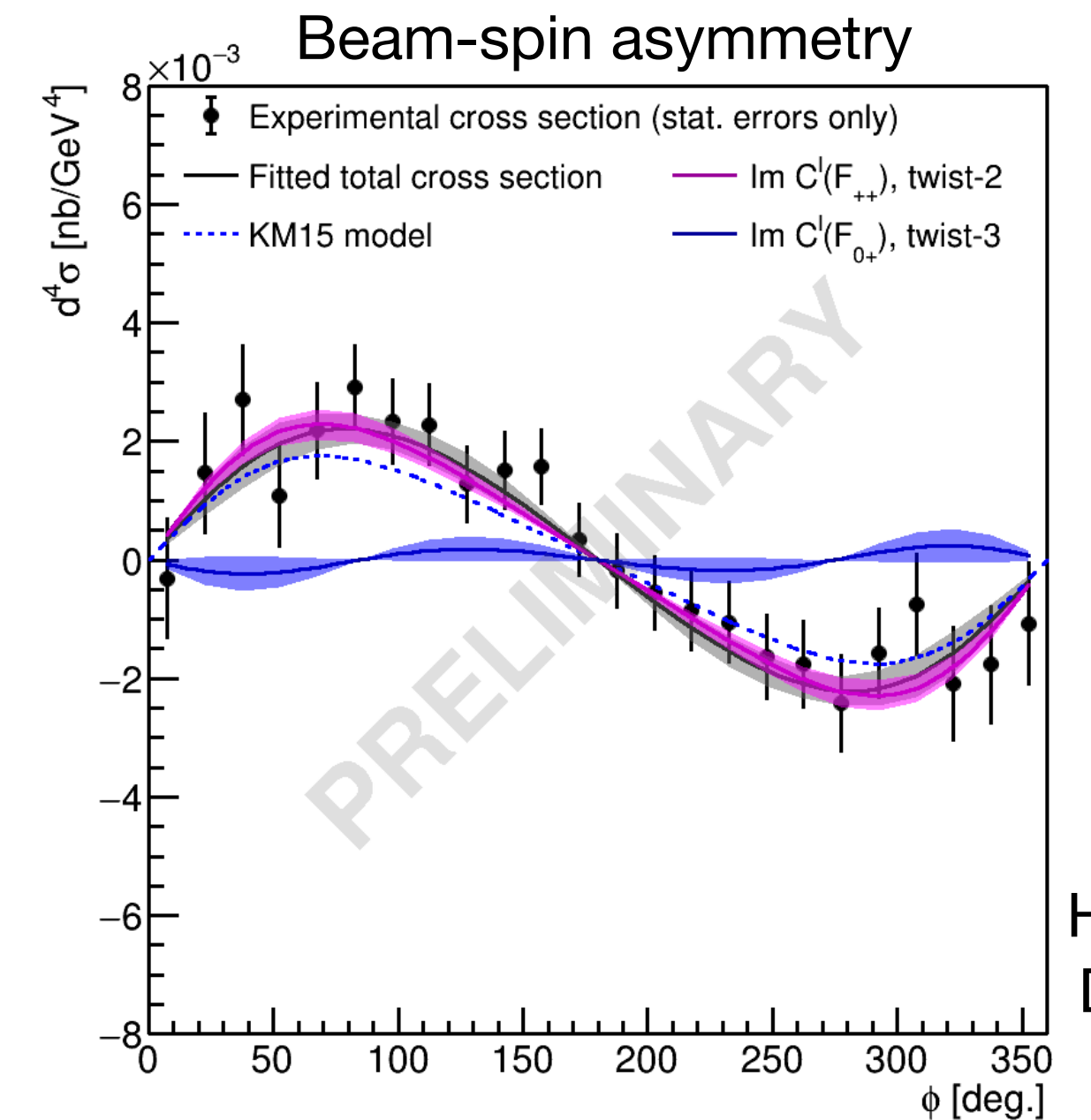
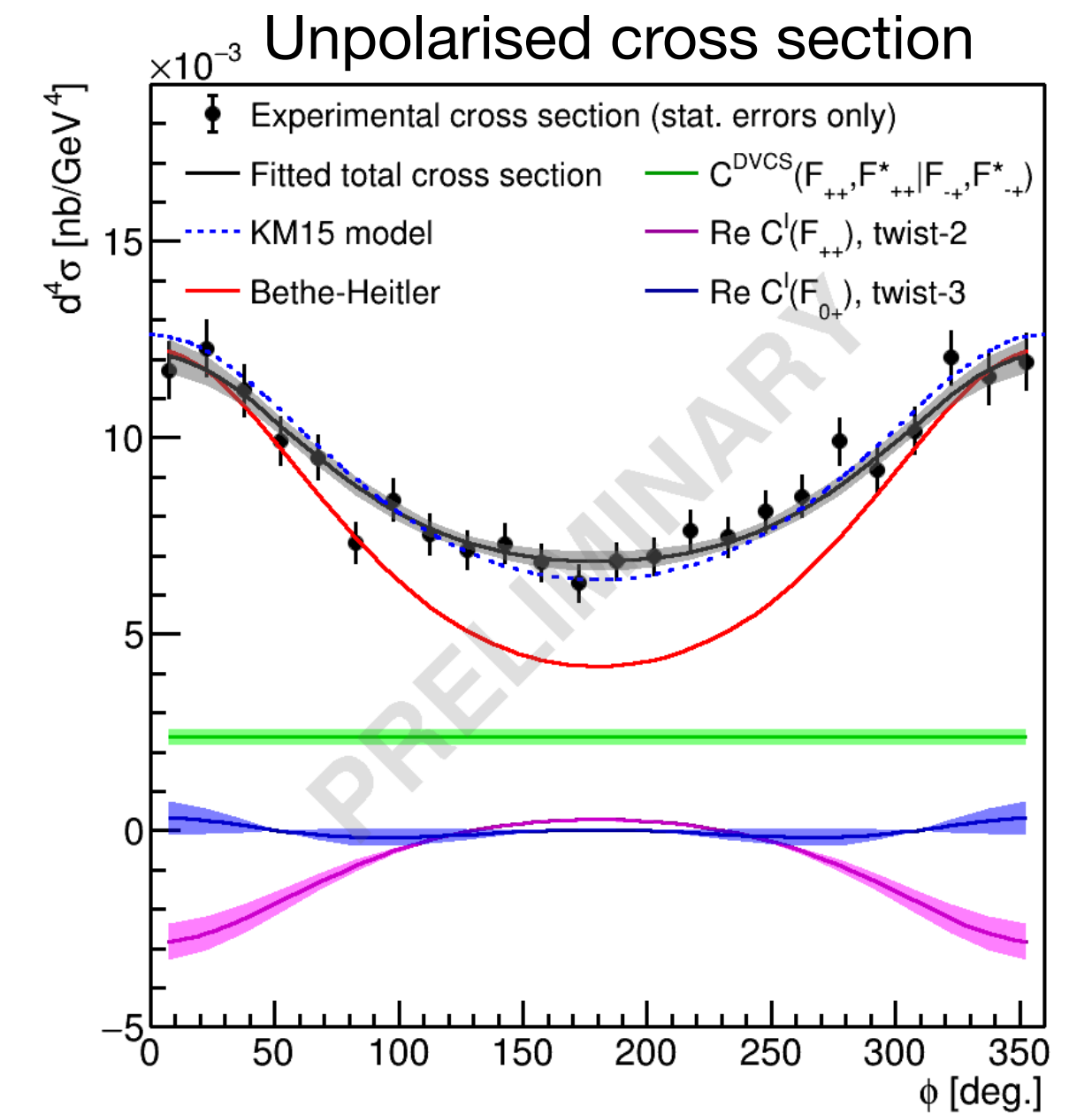
Unpolarised cross section



Beam-spin asymmetry



Hall C

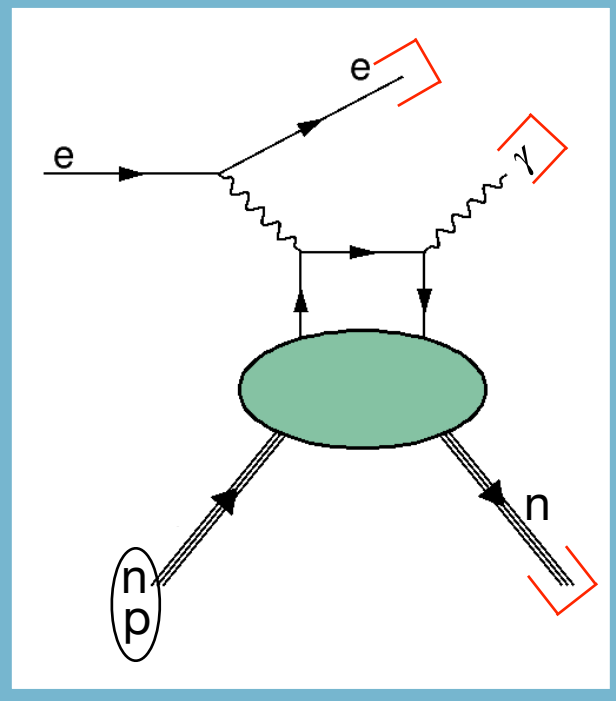


- Measurement with 3 beam energies
- Separation of BH, DVCS and interference
- Simultaneous extraction of all 4 chiral-e

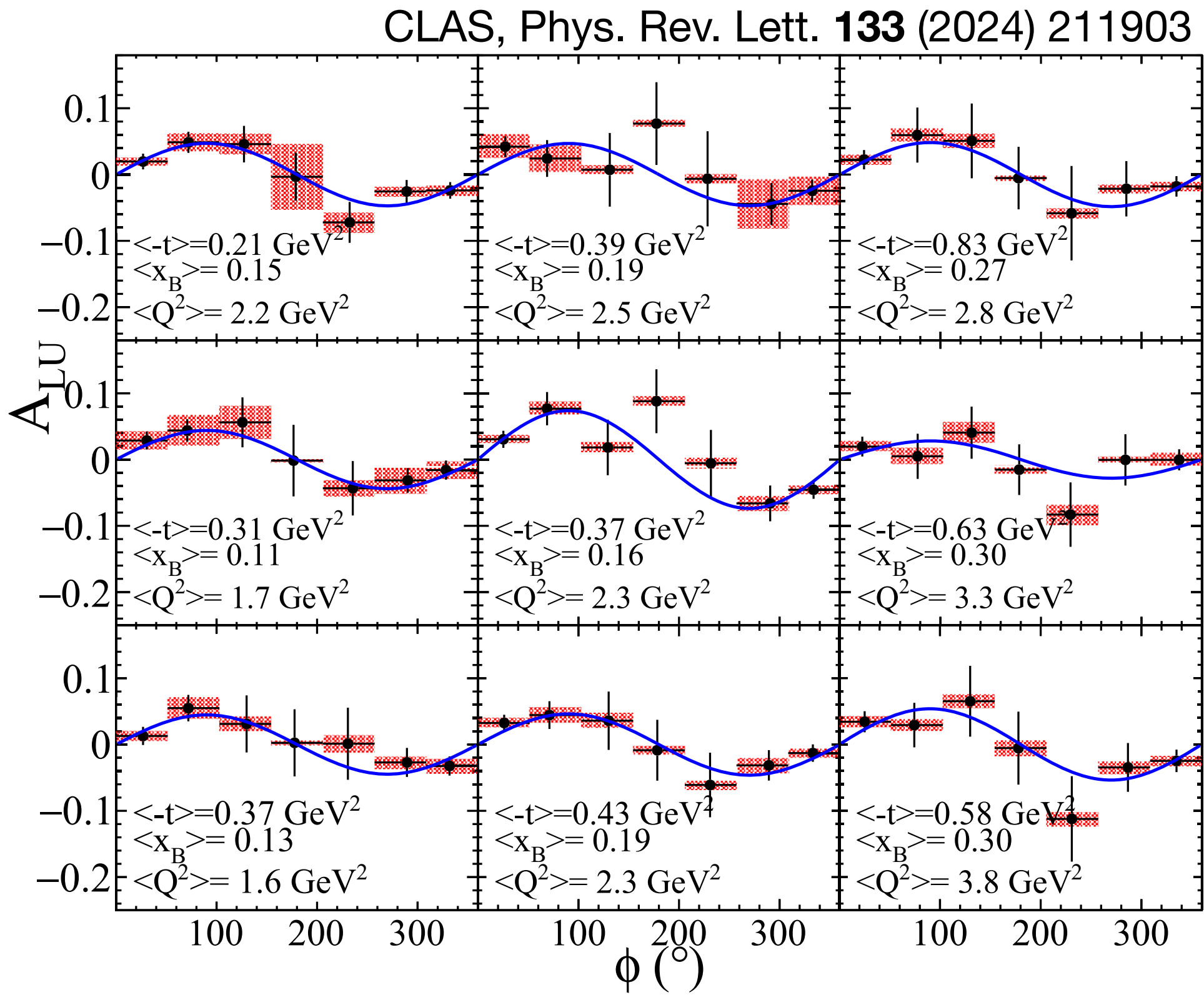
H. Huang
DIS2026

DVCS off the neutron: CLAS12

First time detection of active neutron



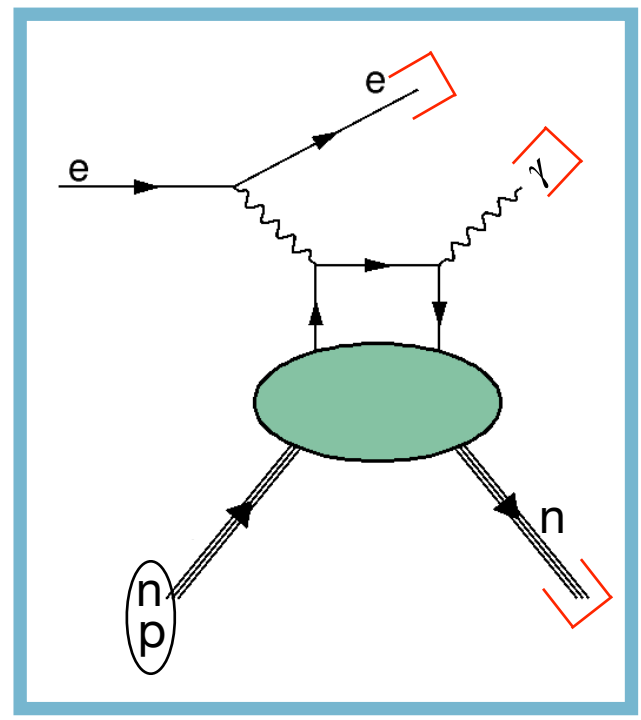
Beam-spin asymmetry



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

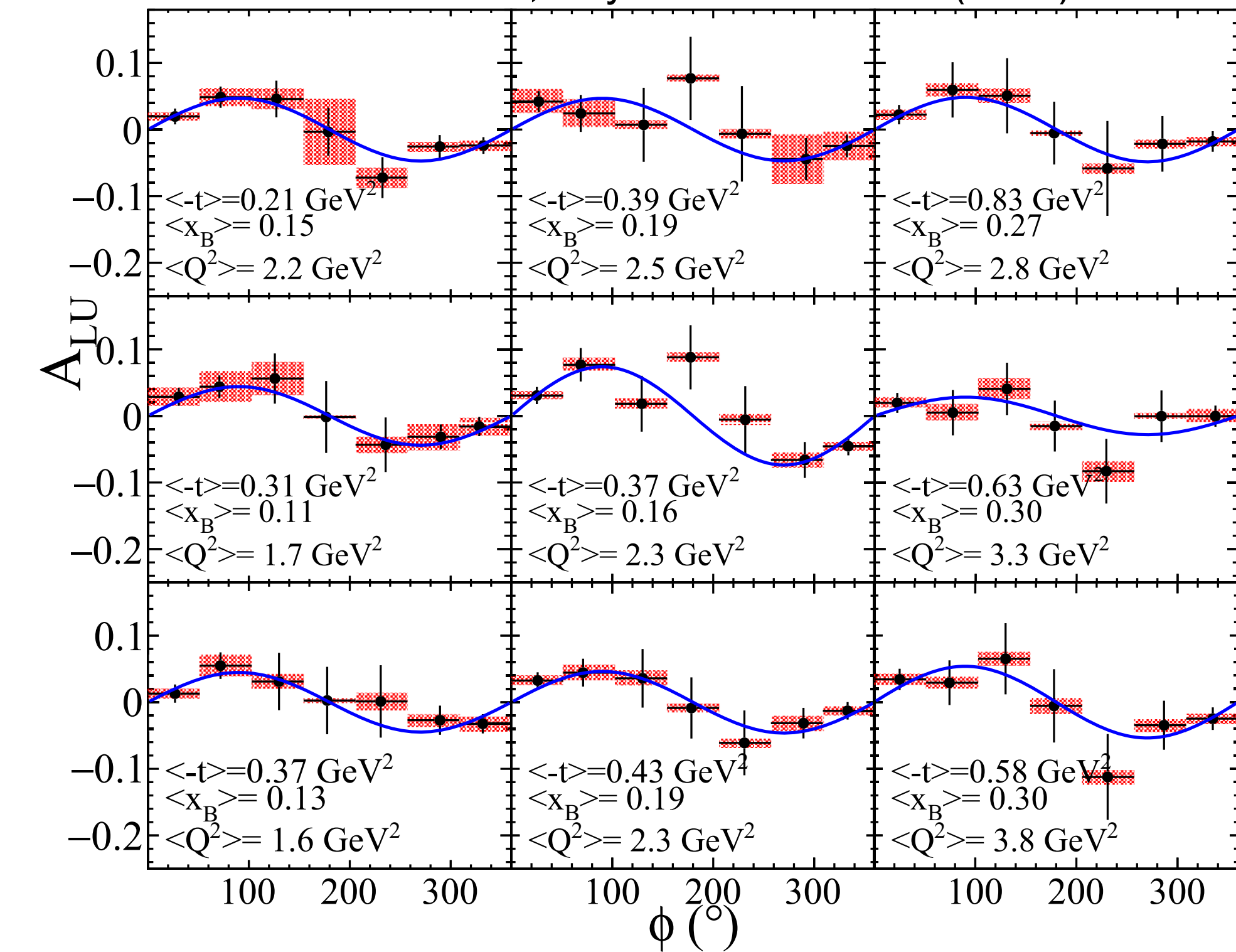
DVCS off the neutron: CLAS12

First time detection of active neutron



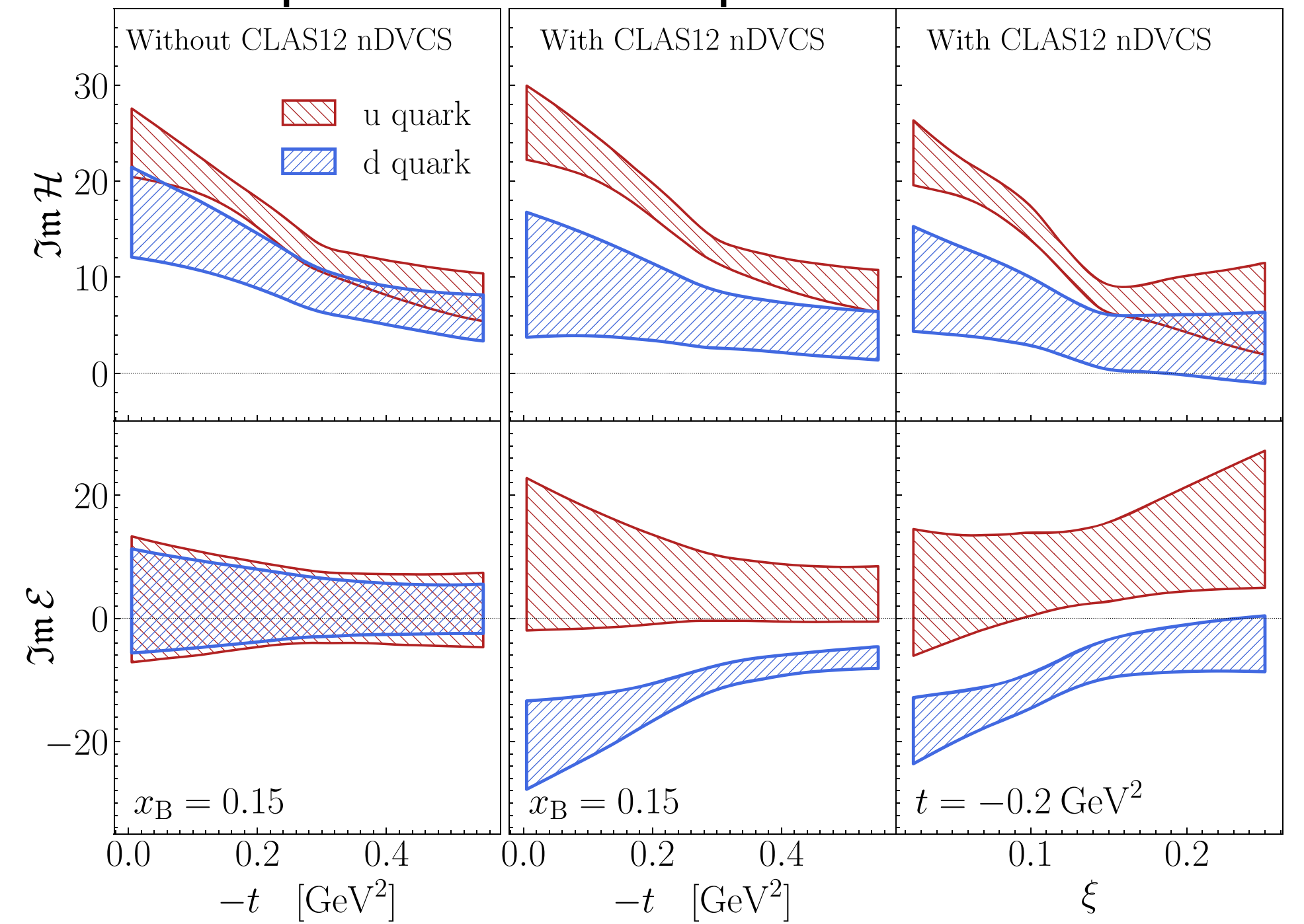
Beam-spin asymmetry

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



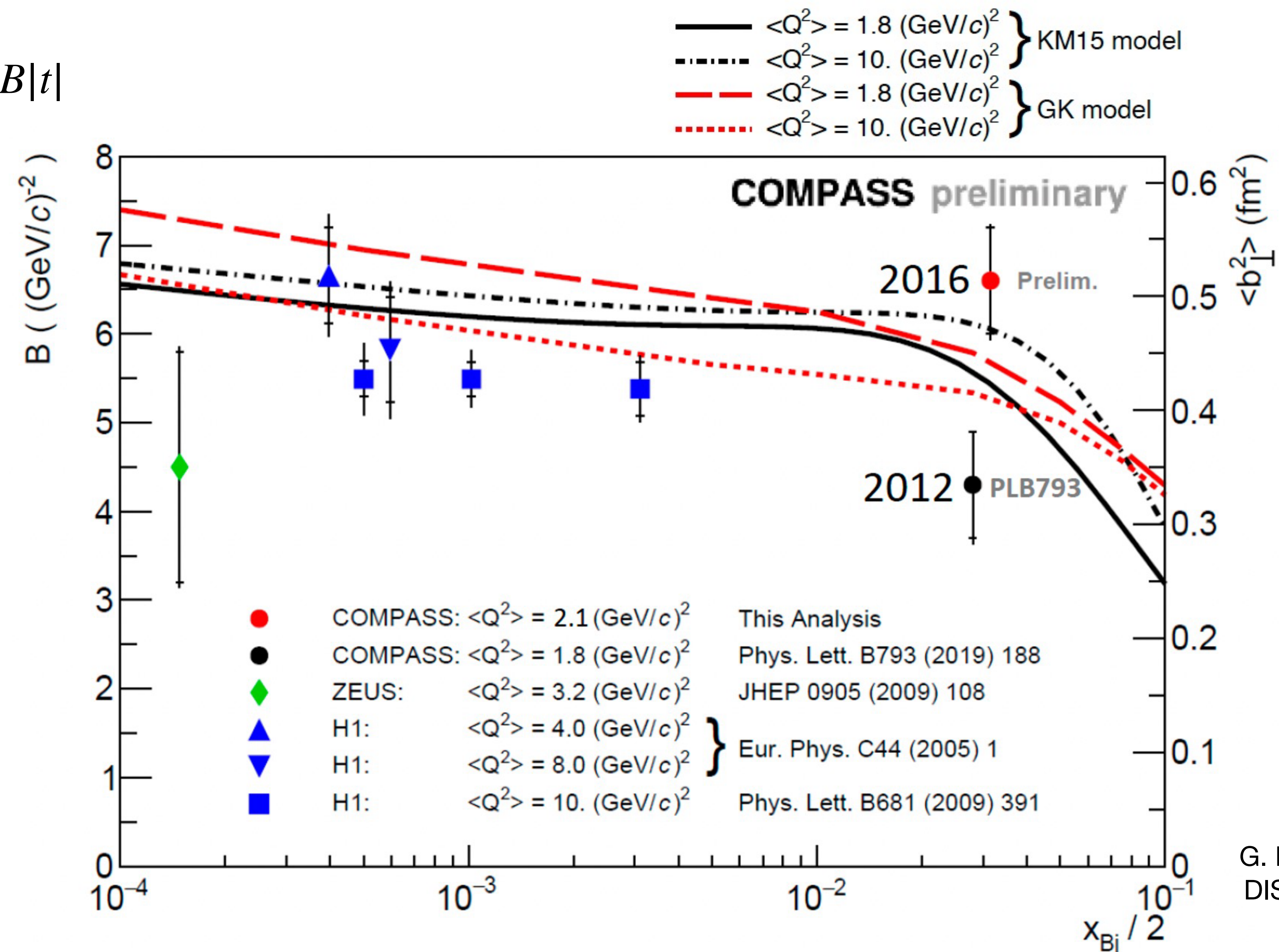
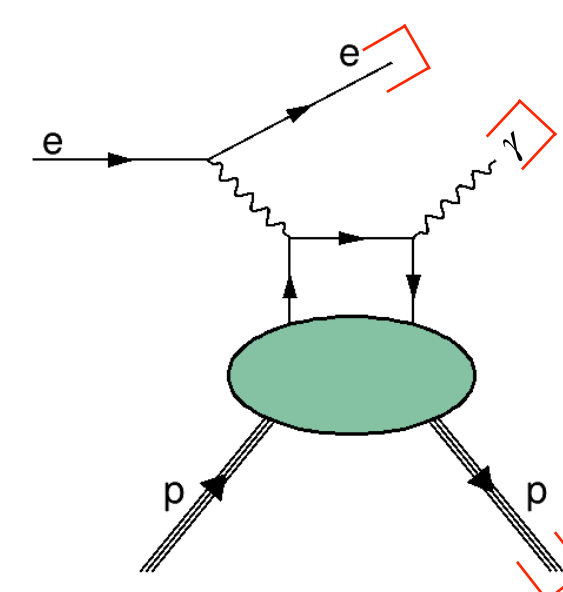
$$\Im m \left[F_1 \mathcal{H} + \xi (F_1 + F_2) \mathcal{H} - \frac{t}{4M_n^2} F_2 \mathcal{E} \right]$$

Measurements with p and n $\rightarrow$ quark-flavour separation fo GPDs



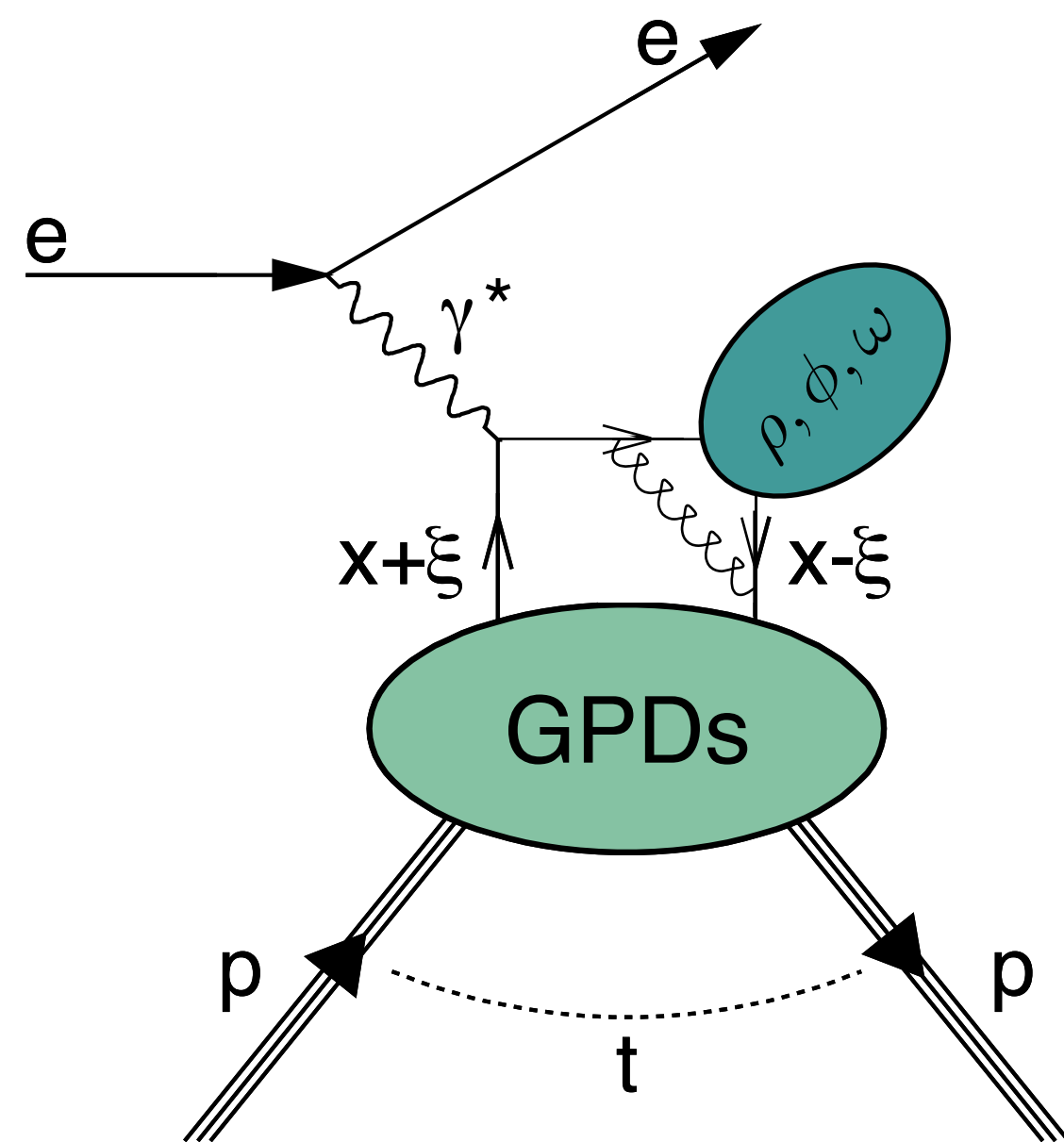
DVCS off the proton: COMPASS

$$\frac{d\sigma^{DVCS}}{dt} \sim e^{-B|t|}$$



G. Kainth
DIS2026

Exclusive vector-meson production

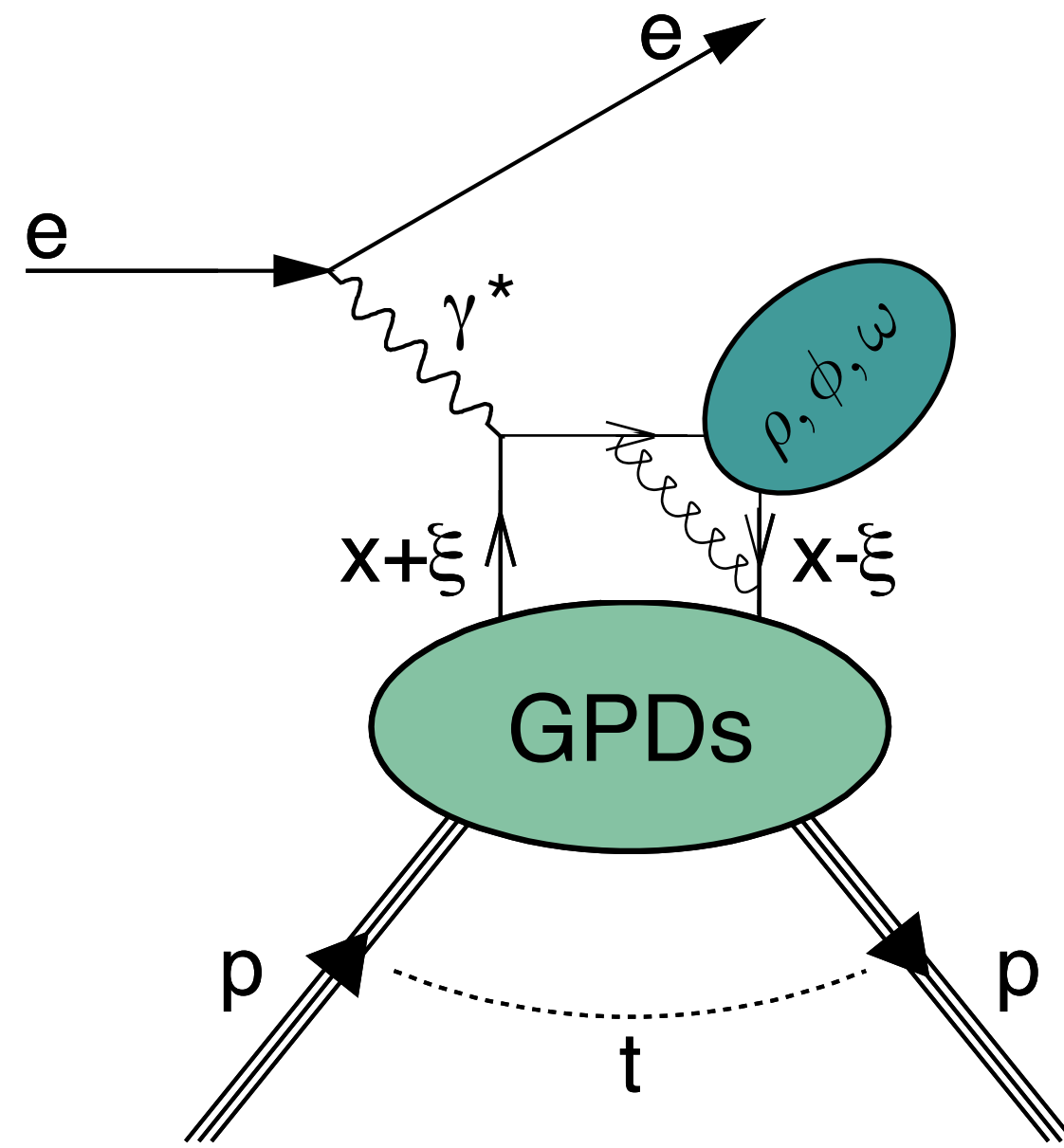


Access to GPDs

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

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

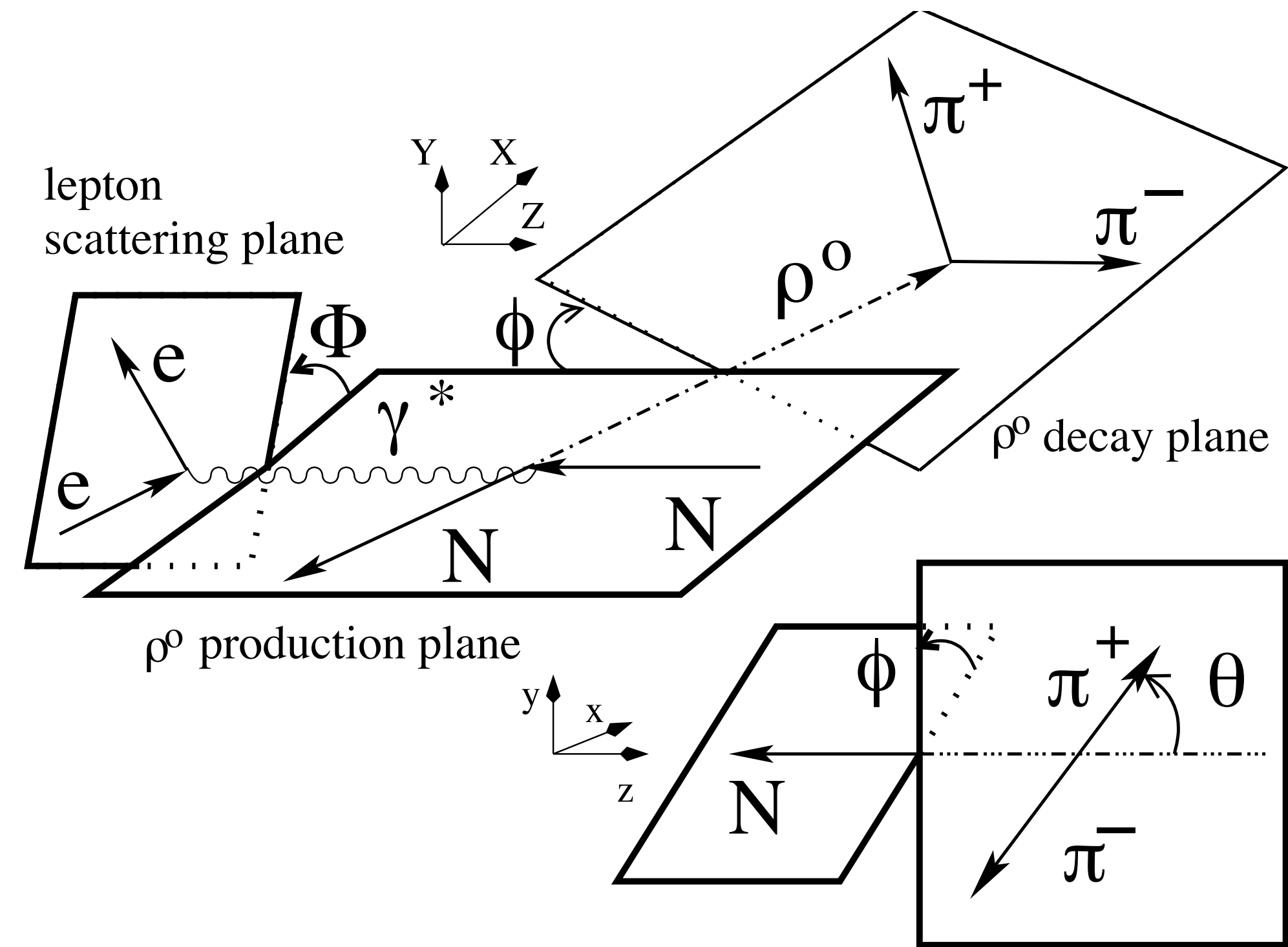
Exclusive vector-meson production



Access to GPDs

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

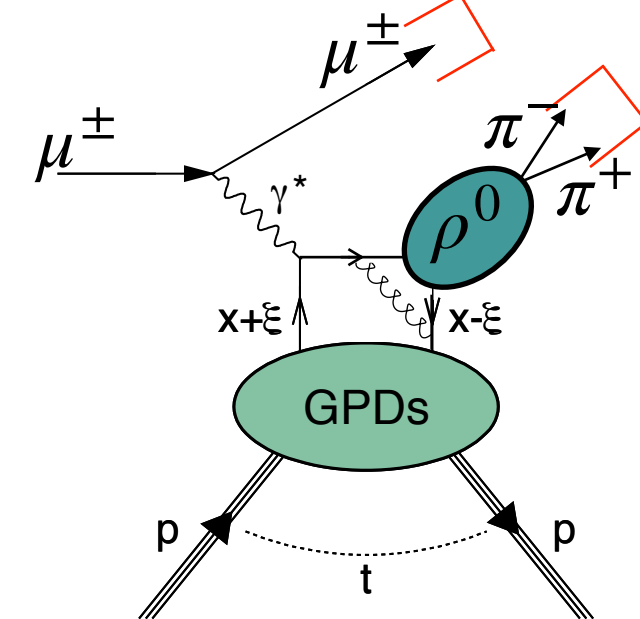
$$\tilde{H}, \tilde{E}$$



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

Exclusive ρ^0 production : SDMEs

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

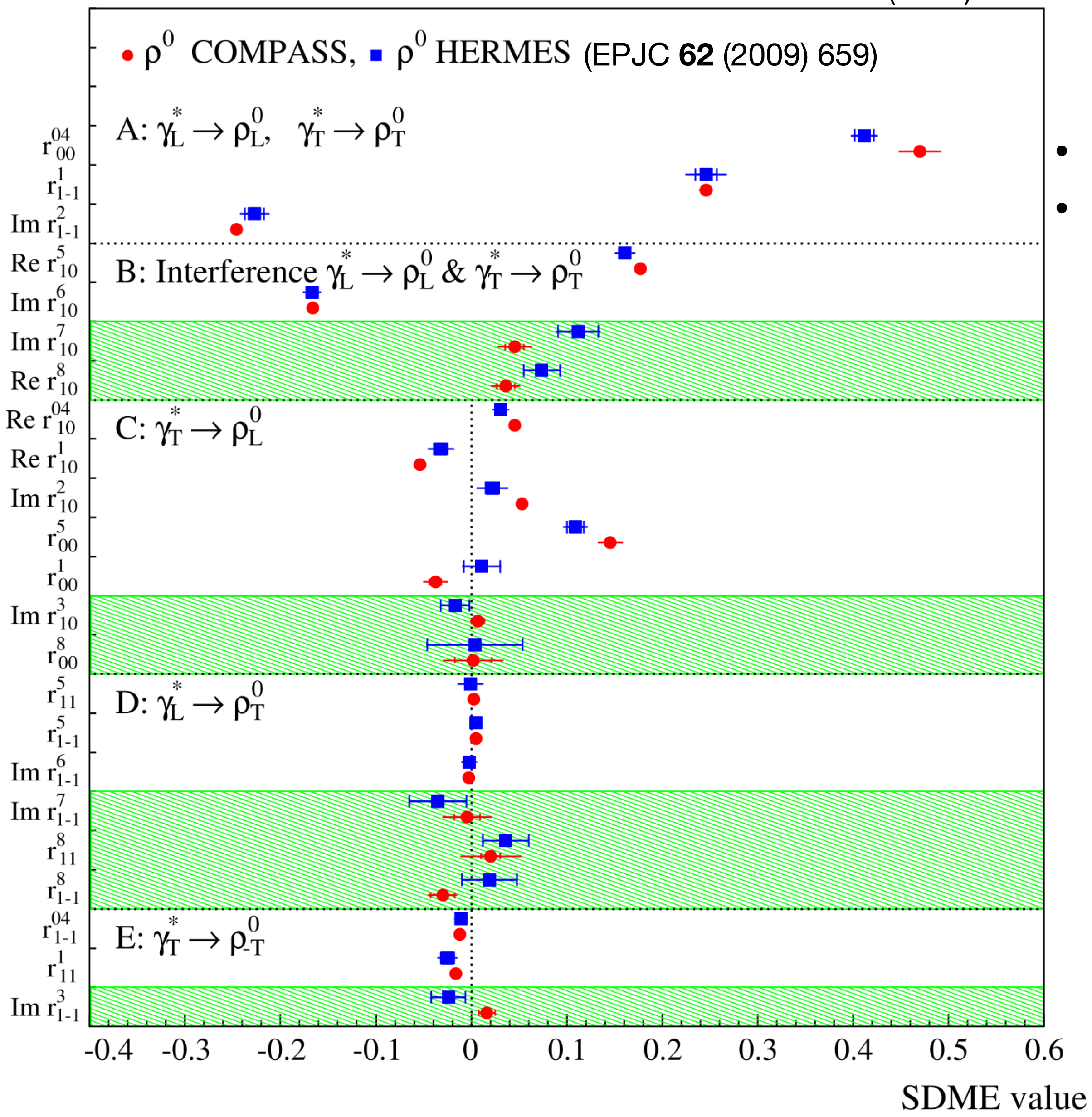


Unpolarised proton target
longitudinally polarised lepton
beam

- 5 classes of SDMEs
- unpolarised and polarised SDMEs

HERMES:
 $\langle Q^2 \rangle = 1.96 \text{ GeV}^2$
 $\langle W \rangle = 4.8 \text{ GeV}^2$

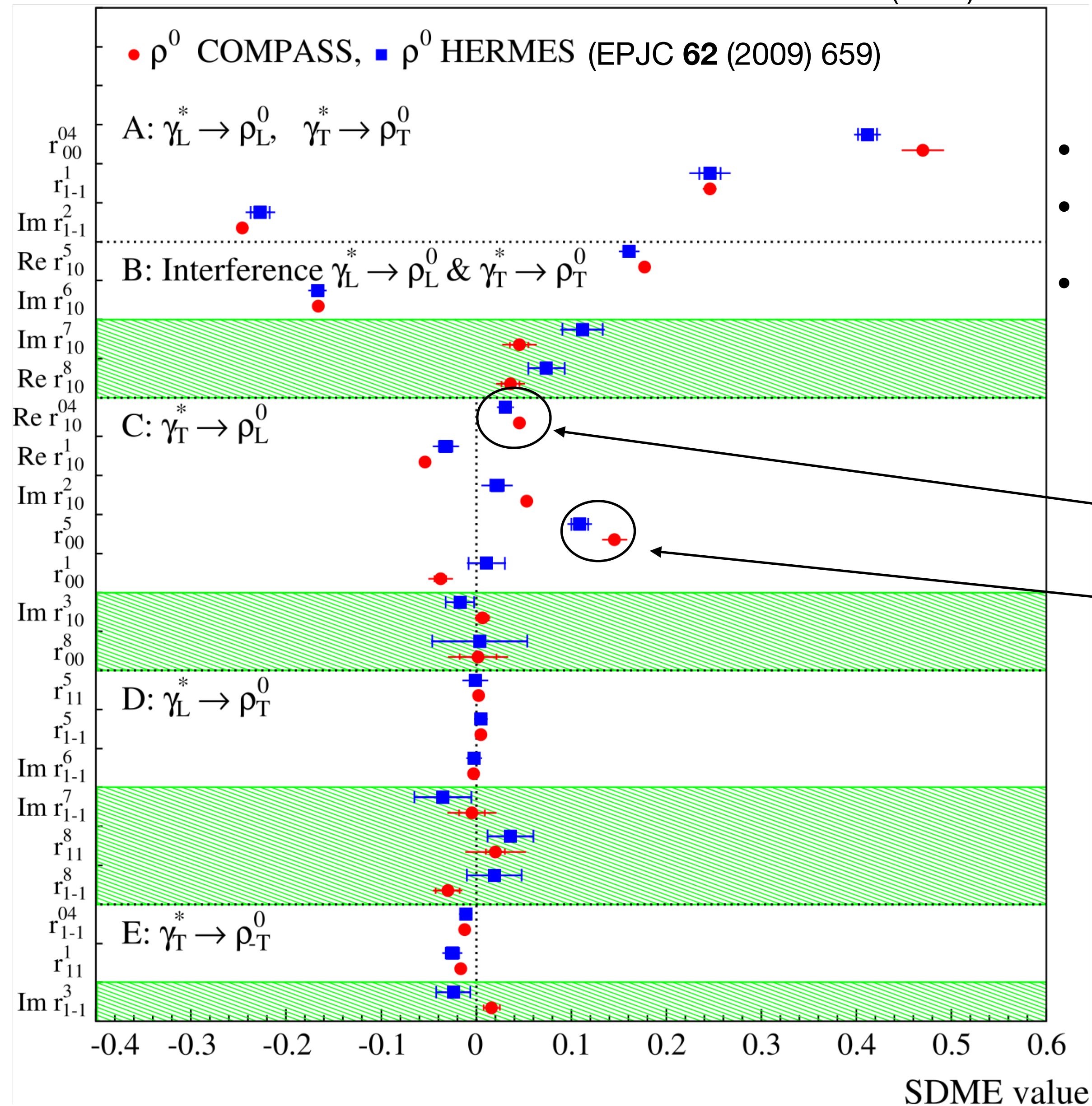
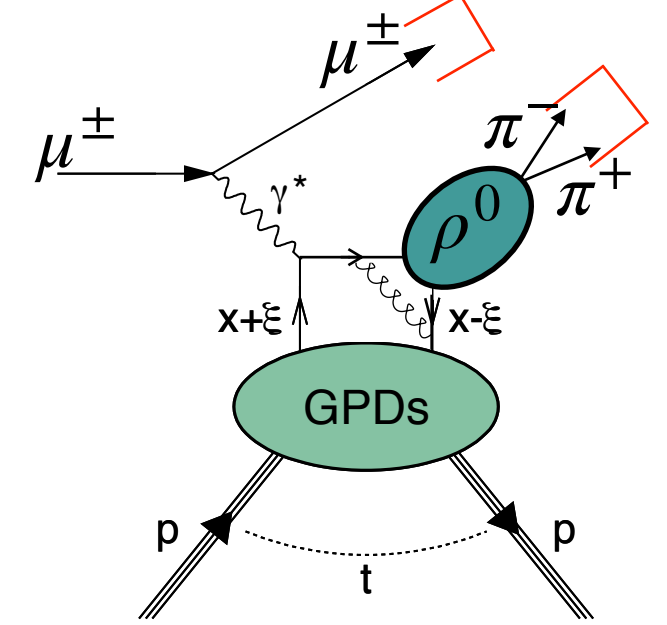
COMPASS:
 $\langle Q^2 \rangle = 2.40 \text{ GeV}^2$
 $\langle W \rangle = 9.9 \text{ GeV}^2$



Exclusive ρ^0 production : SDMEs

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

Unpolarised proton target
longitudinally polarised lepton beam



- 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:

$$\Re r_{10}^{04} \neq 0 \text{ by } > 4\sigma$$

$$\Re r_{00}^5 \neq 0 \text{ by } > 9\sigma$$

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

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

HERMES:

$$\langle Q^2 \rangle = 1.96 \text{ GeV}^2$$

$$\langle W \rangle = 4.8 \text{ GeV}^2$$

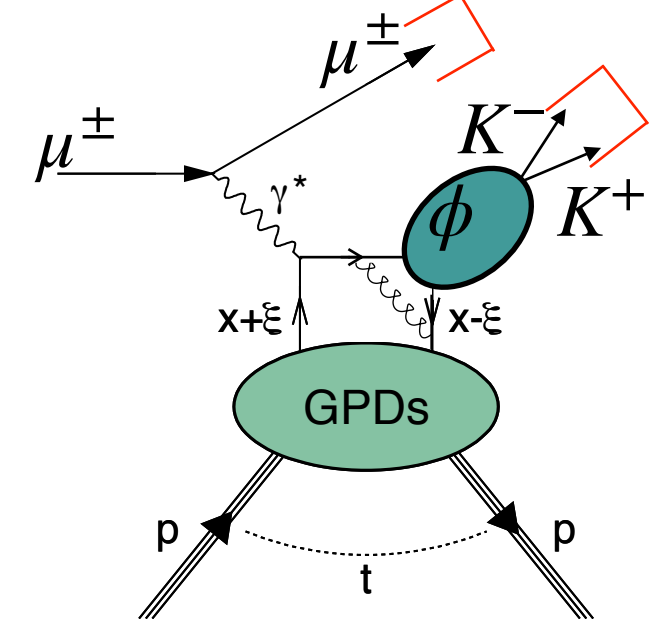
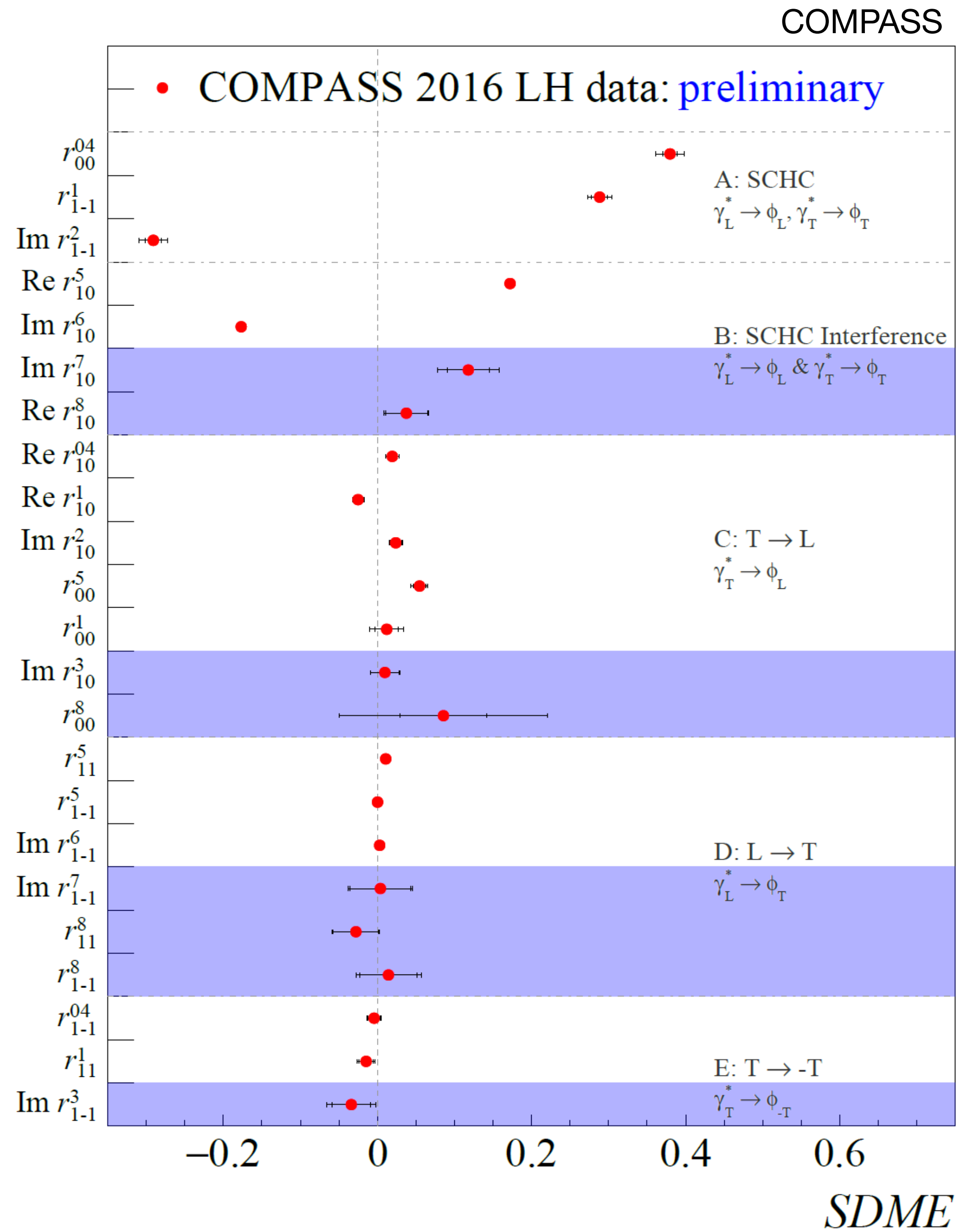
COMPASS:

$$\langle Q^2 \rangle = 2.40 \text{ GeV}^2$$

$$\langle W \rangle = 9.9 \text{ GeV}^2$$

Exclusive ϕ production : SDMEs

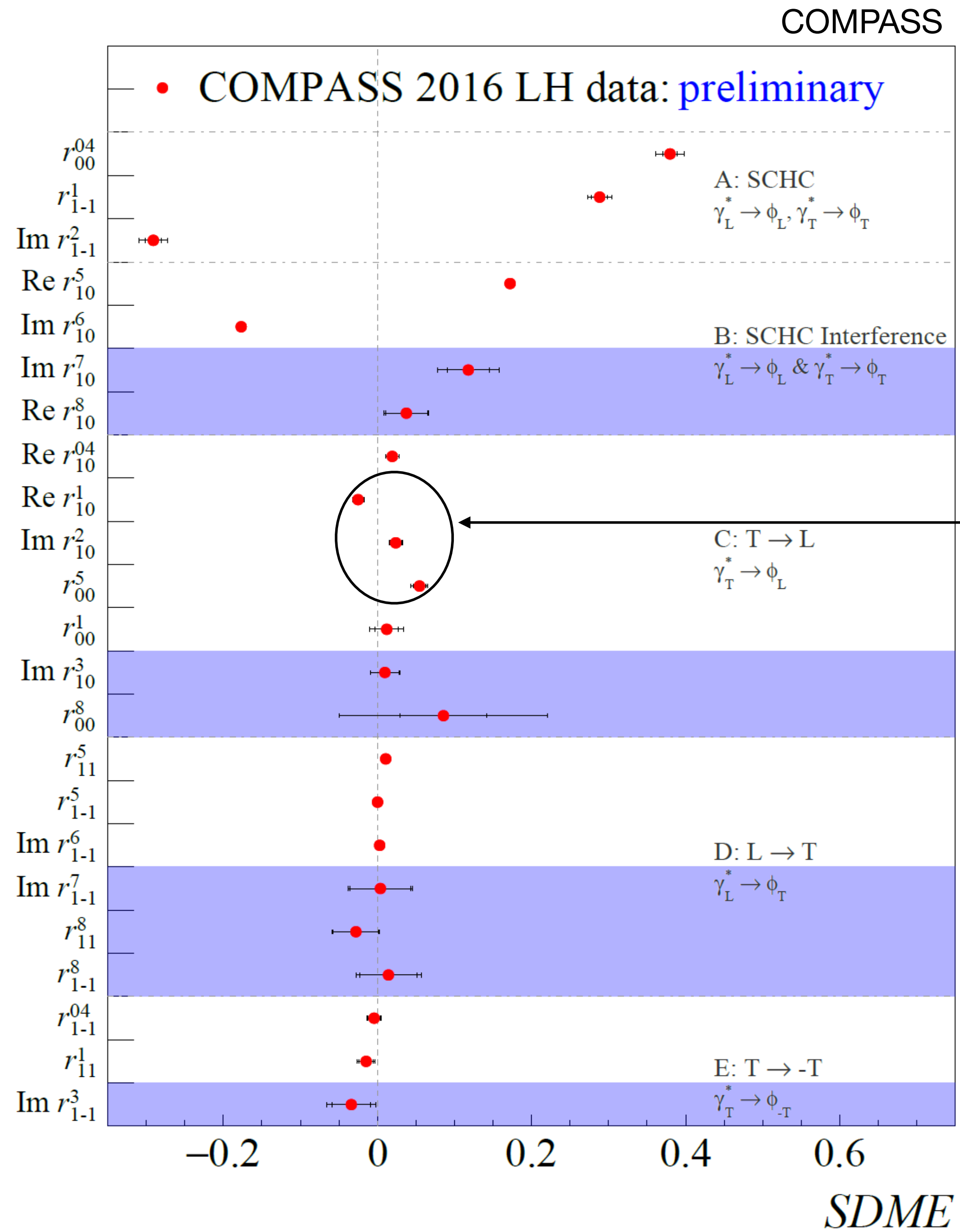
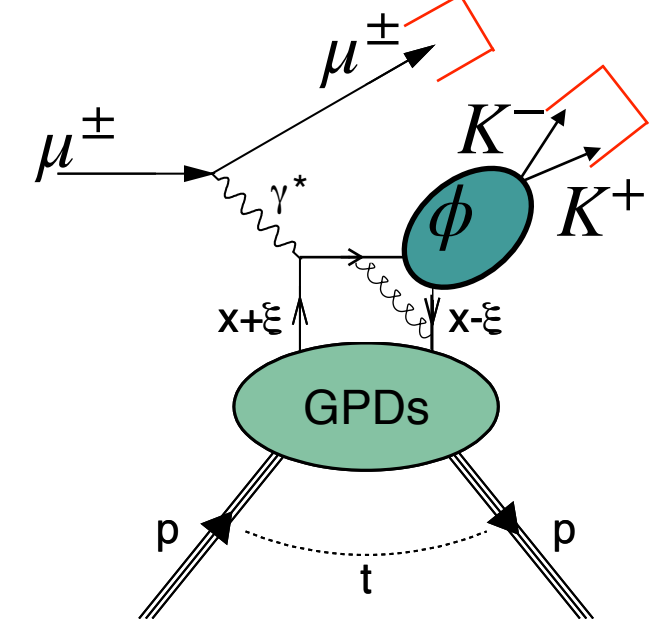
Unpolarised proton target
longitudinally polarised lepton beam



- 5 classes of SDMEs
- unpolarised and polarised SDMEs

Exclusive ϕ production : SDMEs

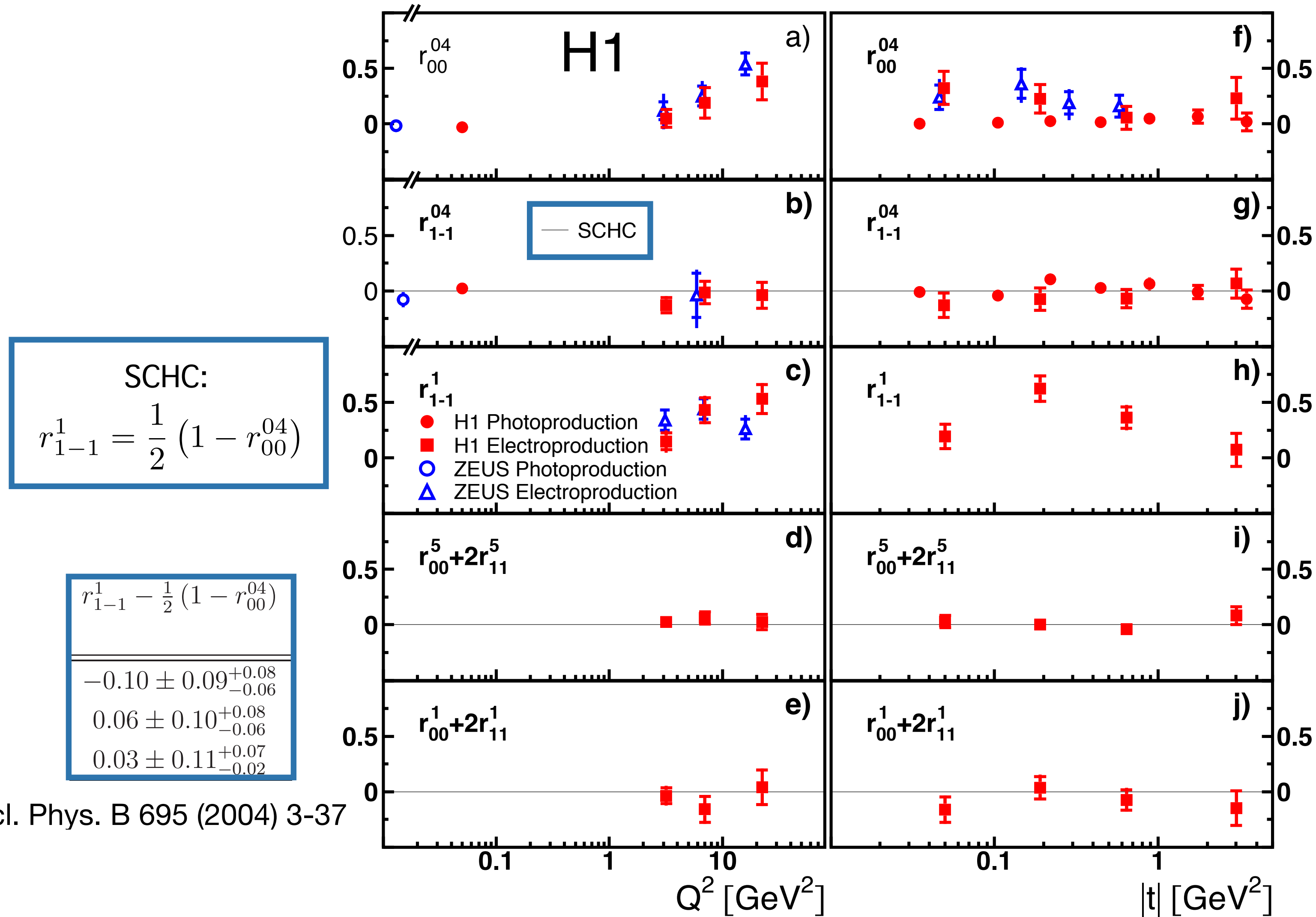
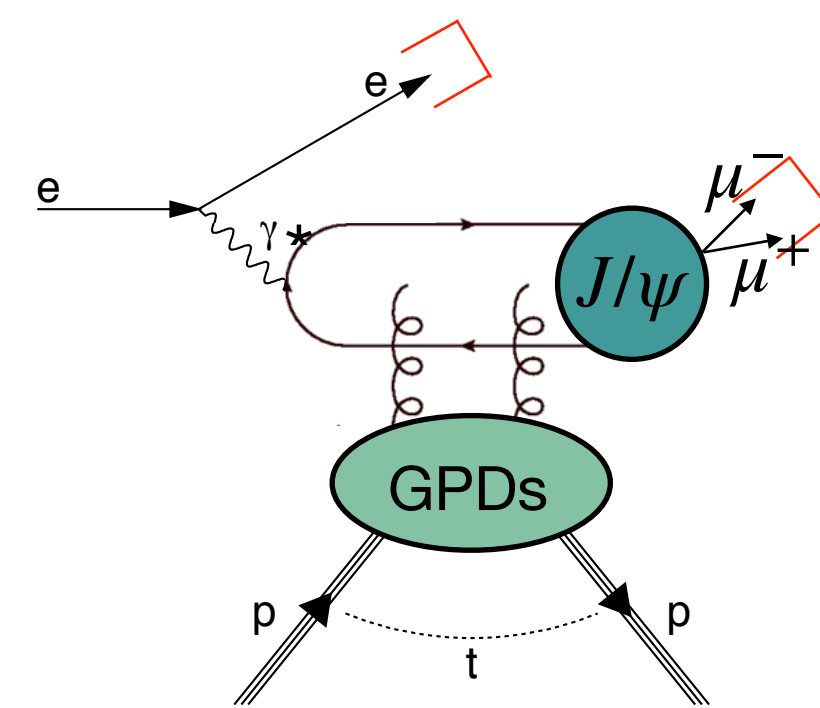
Unpolarised proton target
longitudinally polarised lepton beam



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

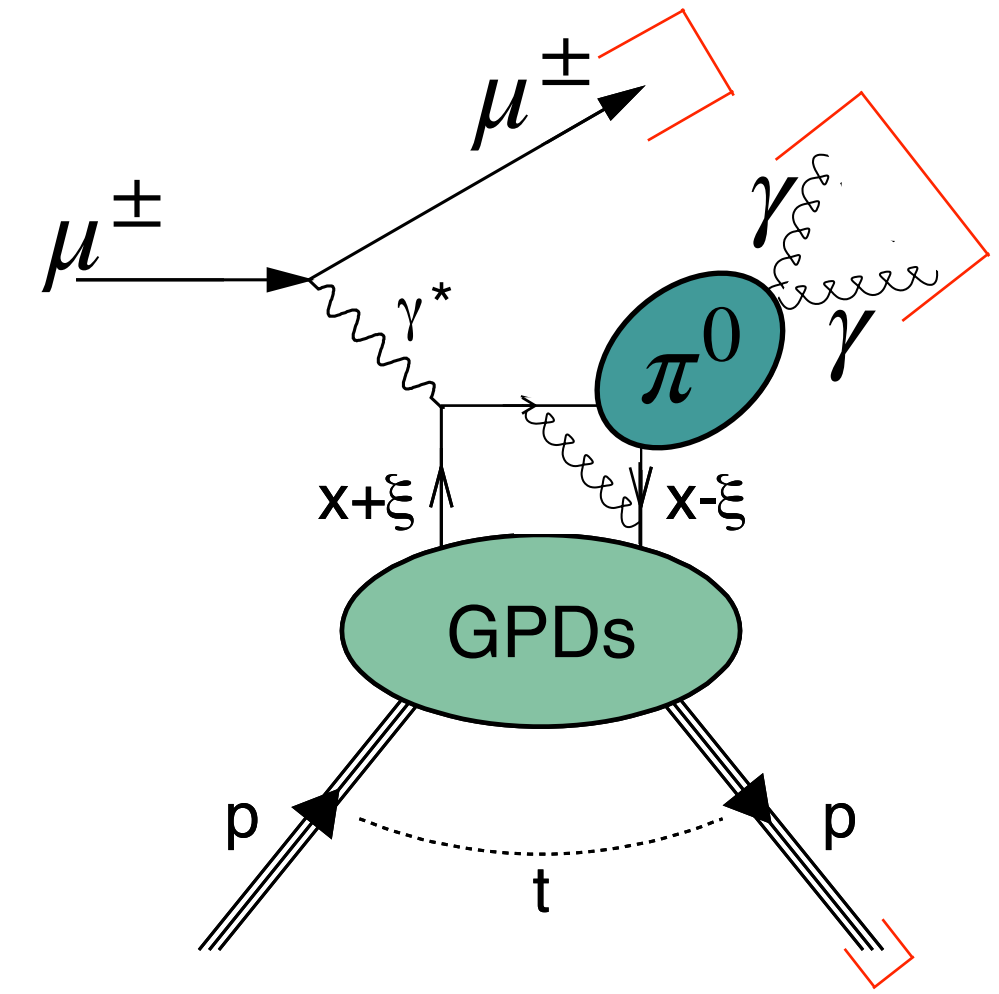
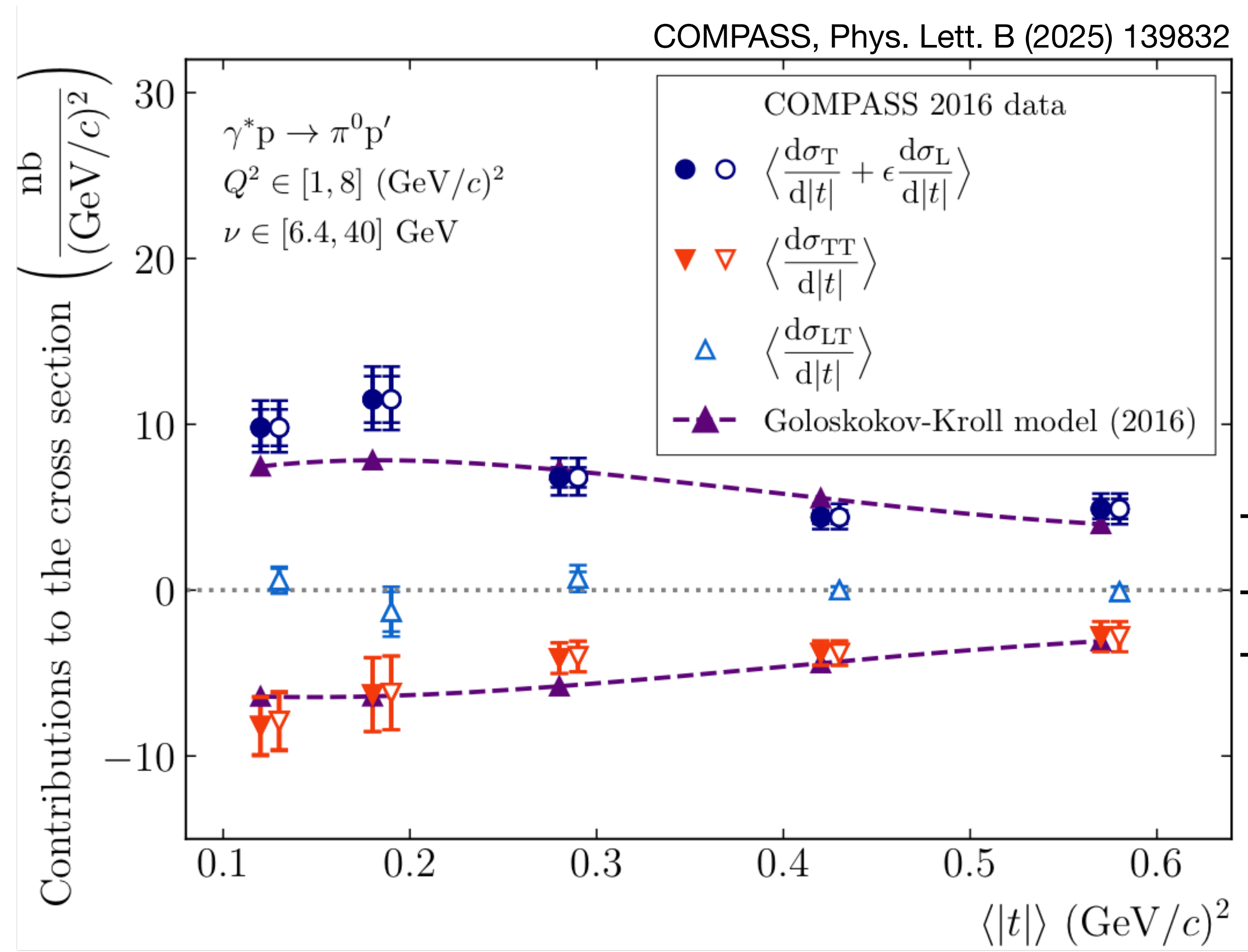
$H_T, \bar{E}_T = 2\tilde{H}_T + E_T$
(In Goloskokov-Kroll model:
 $k_{\perp}$ factorisation assumed)

Exclusive J/ψ production : SDMEs



Exclusive π^0 production

Access to transversity GPDs



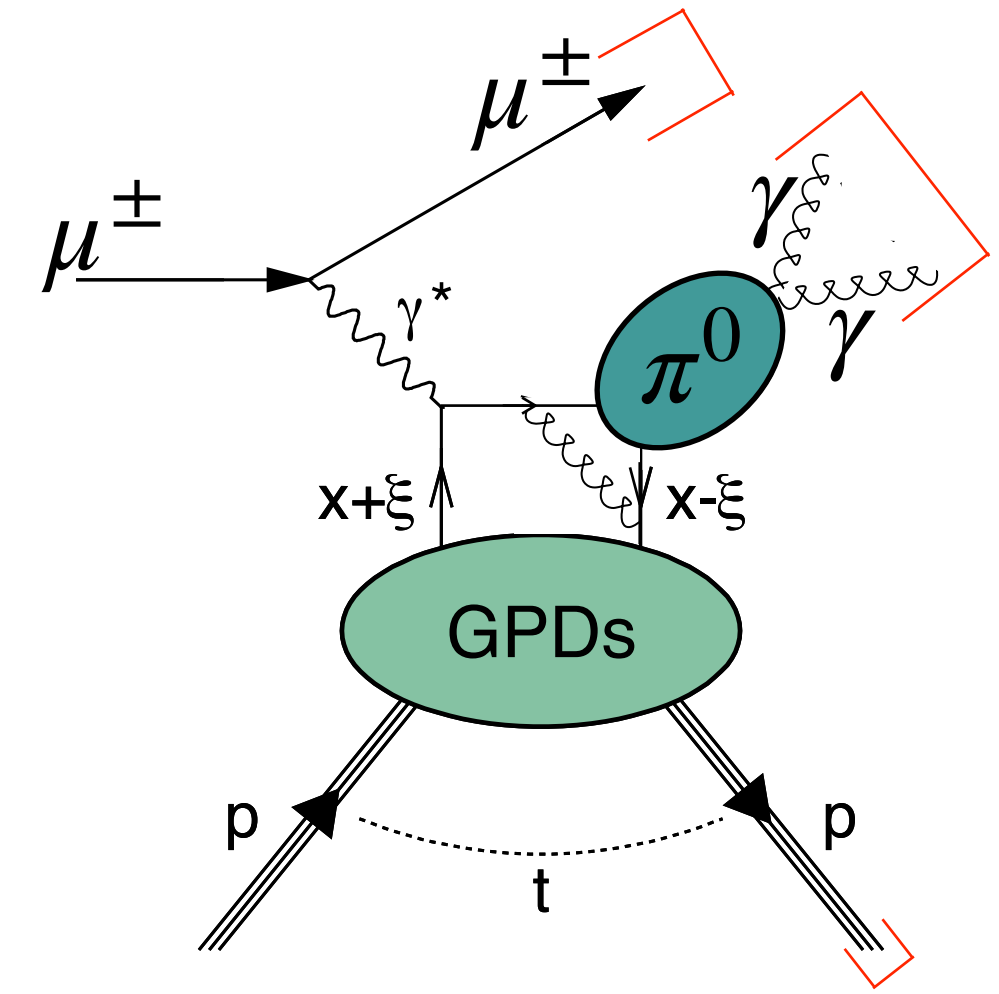
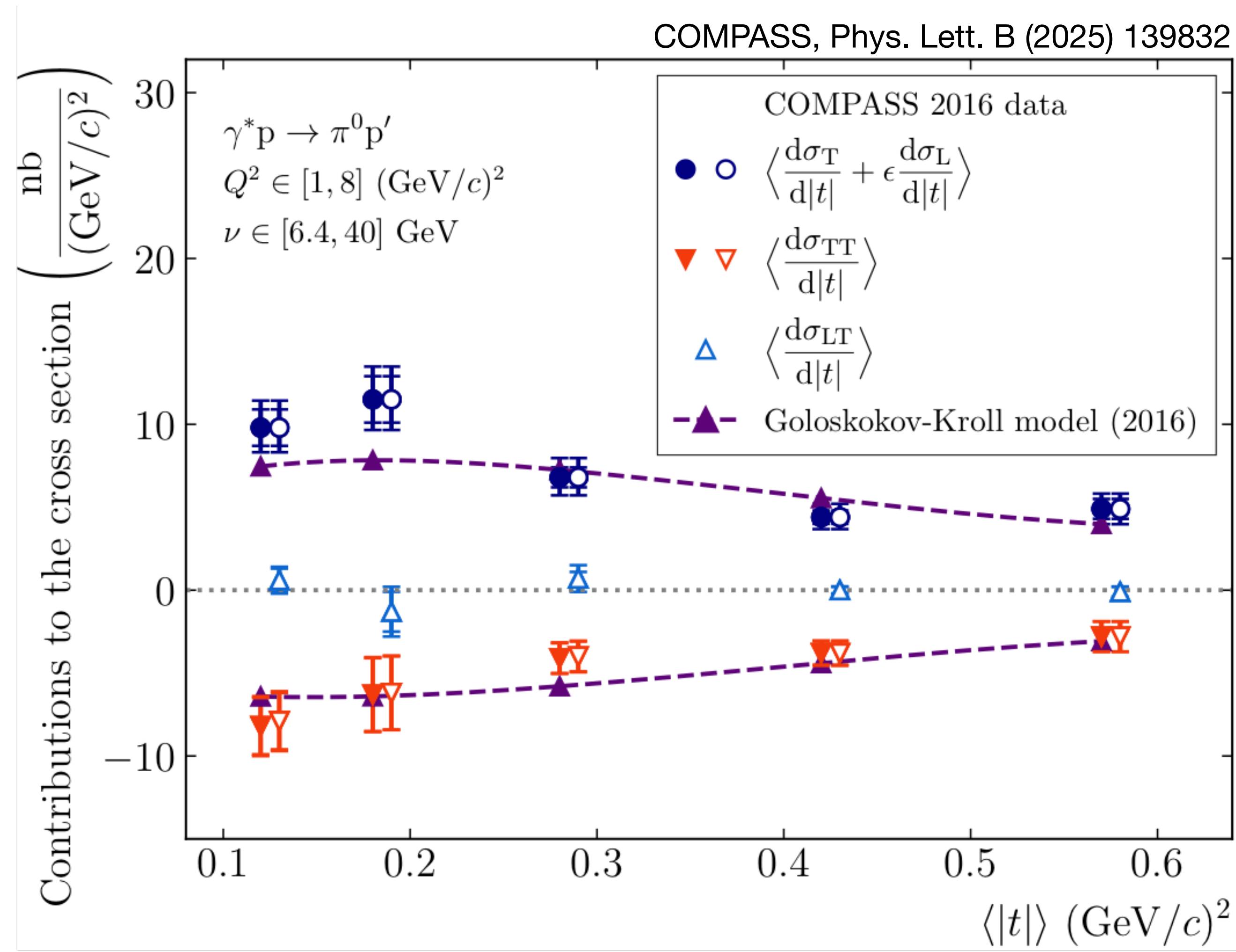
$\tilde{H}, \tilde{E}, H_T, \bar{E}_T$

$H_T, \tilde{E}$

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

Exclusive π^0 production

Access to transversity GPDs



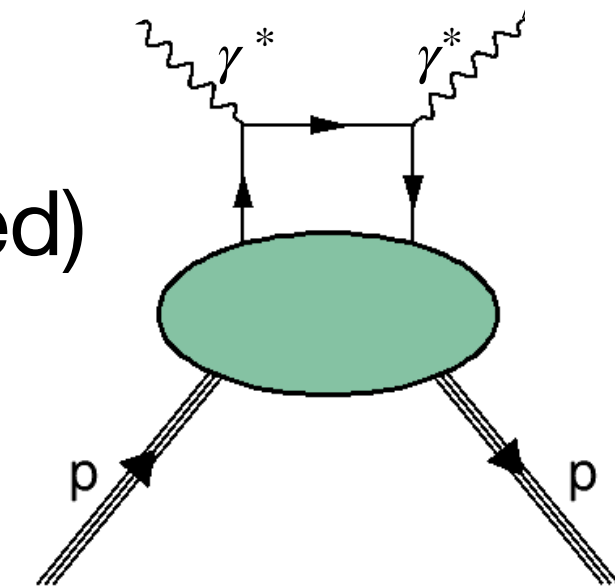
$\tilde{H}, \tilde{E}, H_T, \bar{E}_T$
 $H_T, \tilde{E}$
 $\bar{E}_T = 2\tilde{H}_T + E_T$

See also:

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

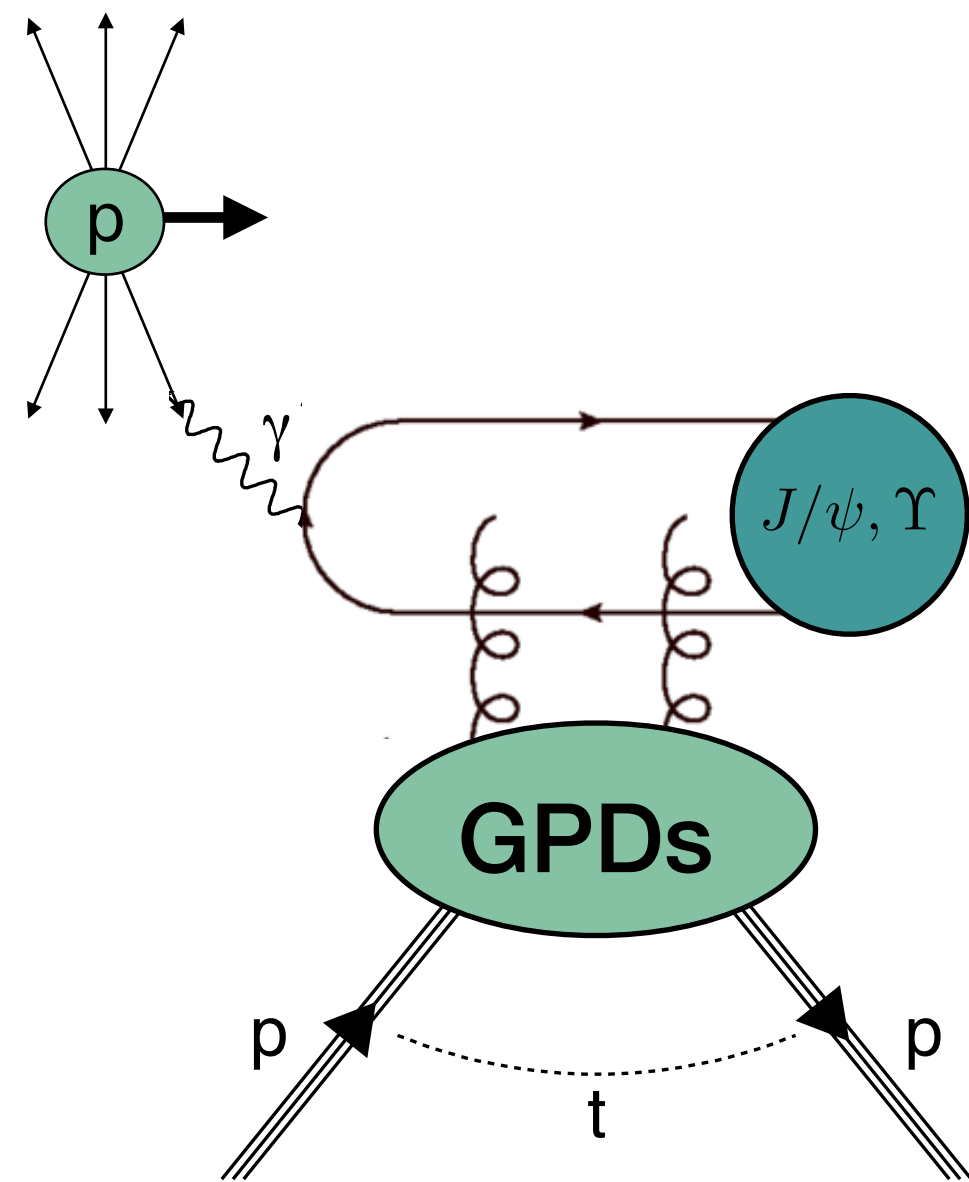
Upcoming DIS experiments probing GPDs

- Jefferson Lab:
 - ALERT at CLAS (analysis ongoing): DVCS and meson production on ^4He : spin-0 target $\rightarrow$ only 1 GPD
 - Addition of neutral spectrometer at Hall C: DVCS, exclusive π^0 off proton (analysis ongoing)
 - Transverse target at CLAS approved (~ 4 years) $\rightarrow$ access to GPD E
 - Double DVCS at CLAS approved ($\sim 5\text{--}6$ years) and at Hall A with SoLID (C1 approved)
 $\rightarrow$ access to GPDs at $x \neq \xi$
 - Additional proposals:
 - Positron beam at Jefferson Lab $\rightarrow$ access to $Re\mathcal{H}$ through beam-charge asymmetry
 - Upgrade to JLab at 22 GeV

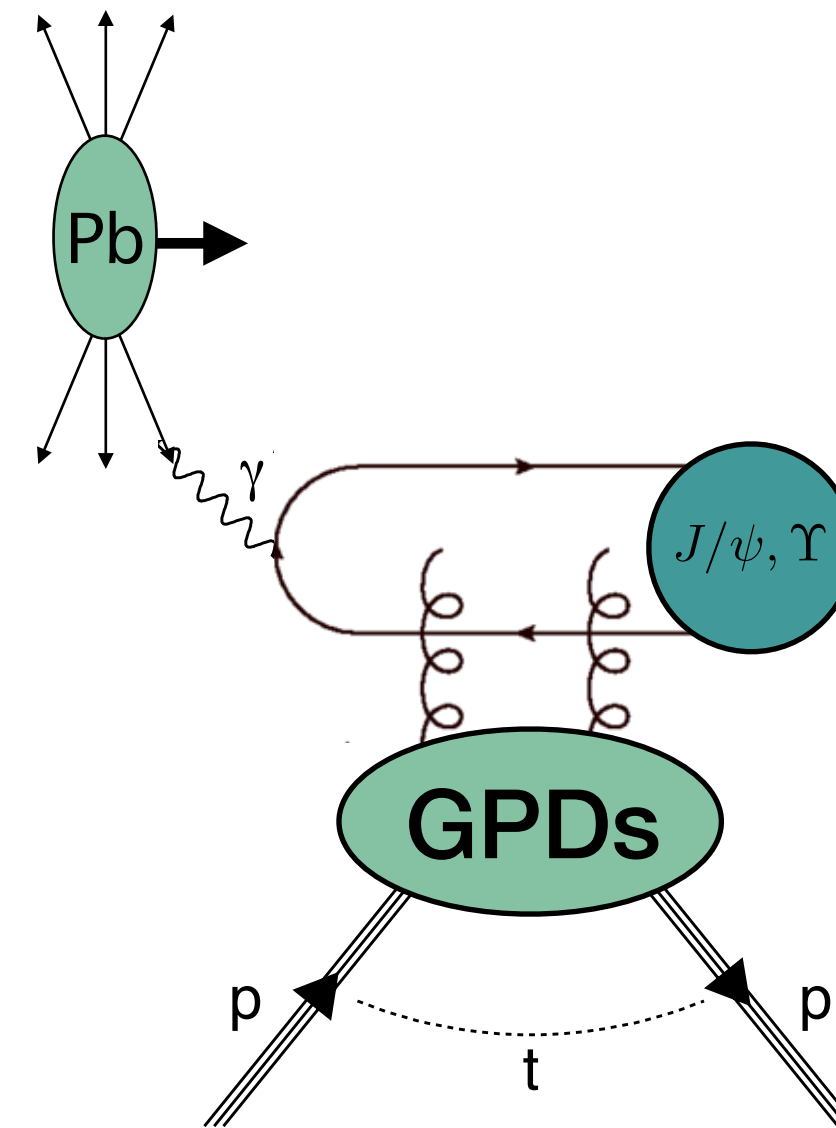


- EIC

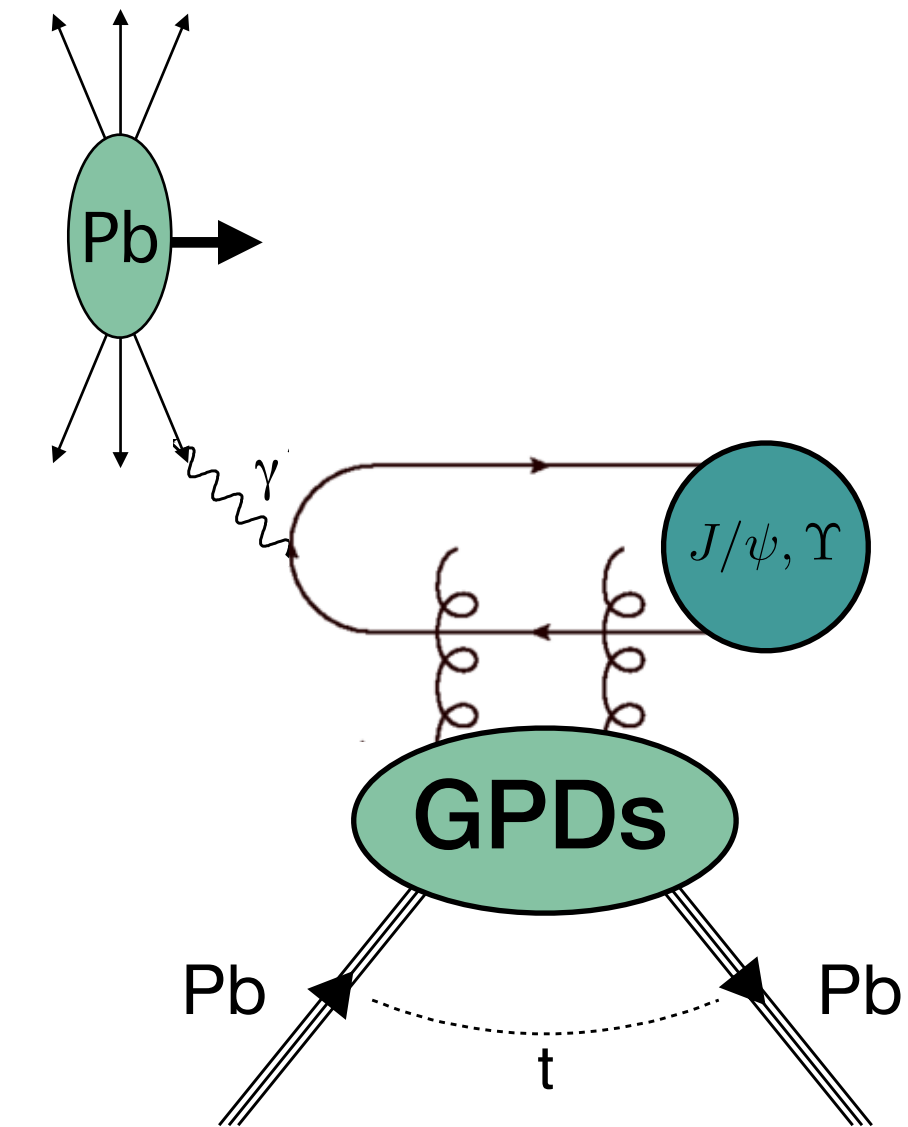
Ultra-peripheral hadron-hadron collisions



pp: ambiguity in ID of photon emitter



pPb: use Z^2 dependence of photon flux
 $\rightarrow$ Pb is predominantly photon emitter



PbPb: probing nuclear GPDs
 Ambiguity in ID of probed ion
 can be lifted with ZDCs

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

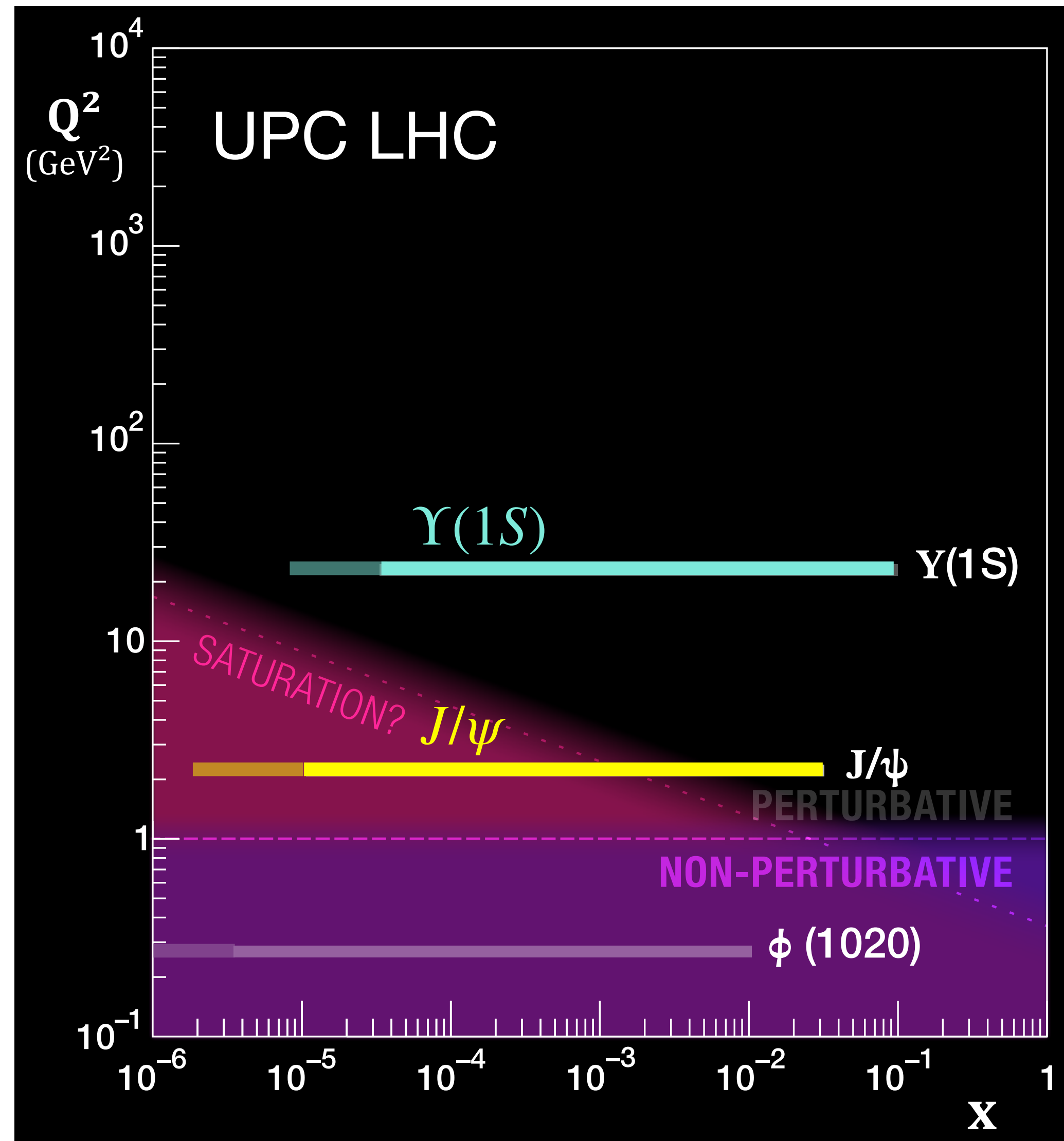


Figure adapted from Jordan Lang | Quarkonia as Tools 2026 | 6 January 2026

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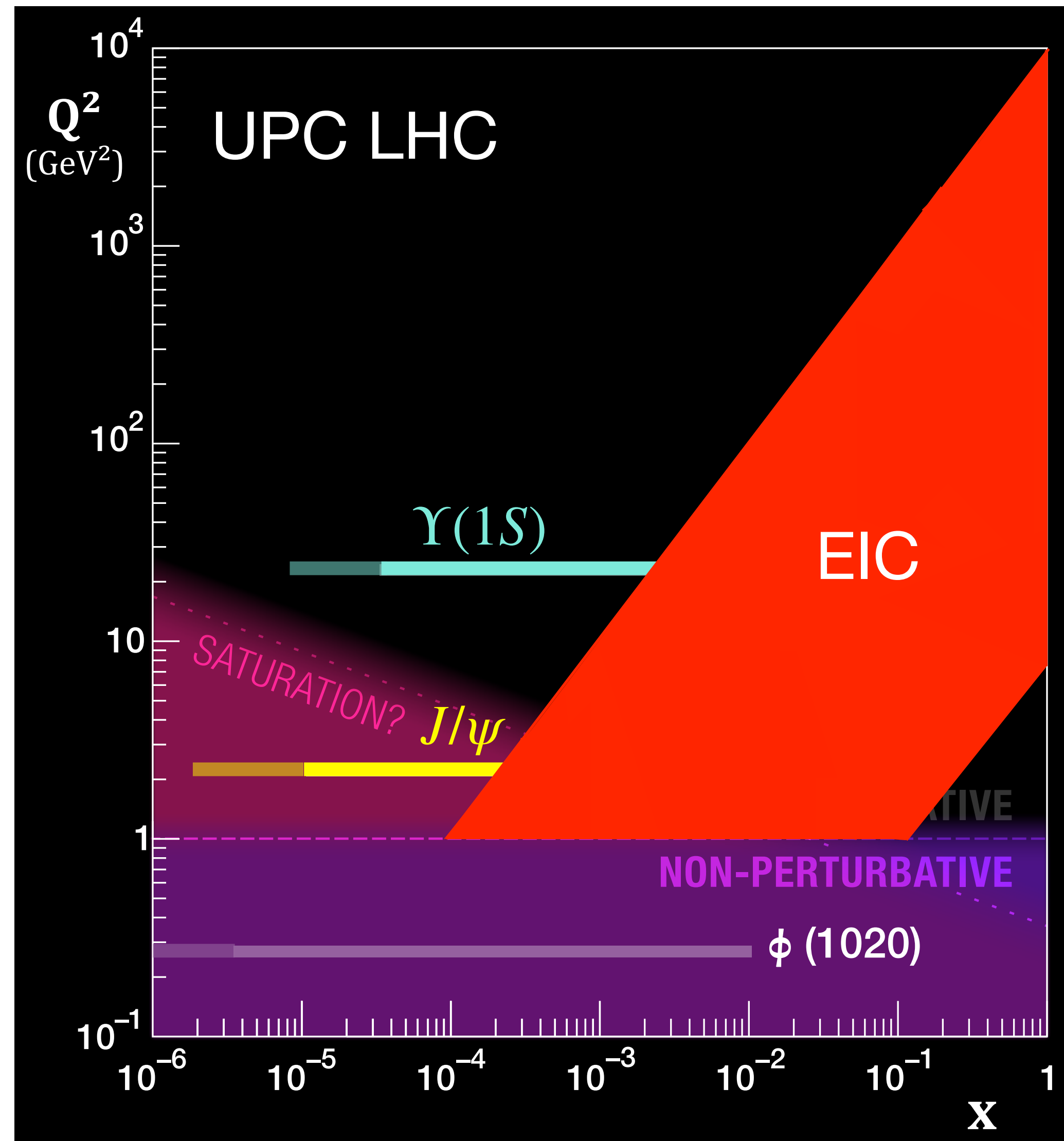
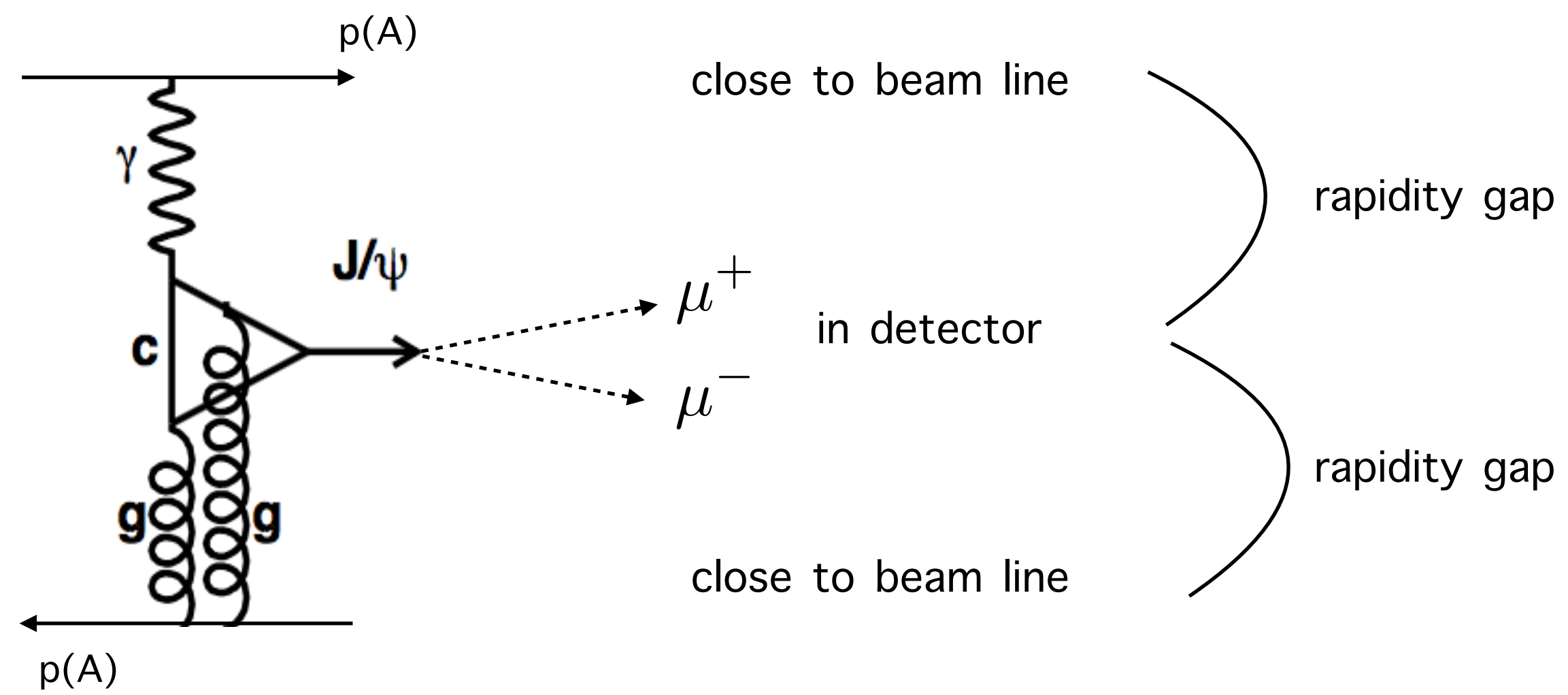


Figure adapted from Jordan Lang | Quarkonia as Tools 2026 | 6 January 2026

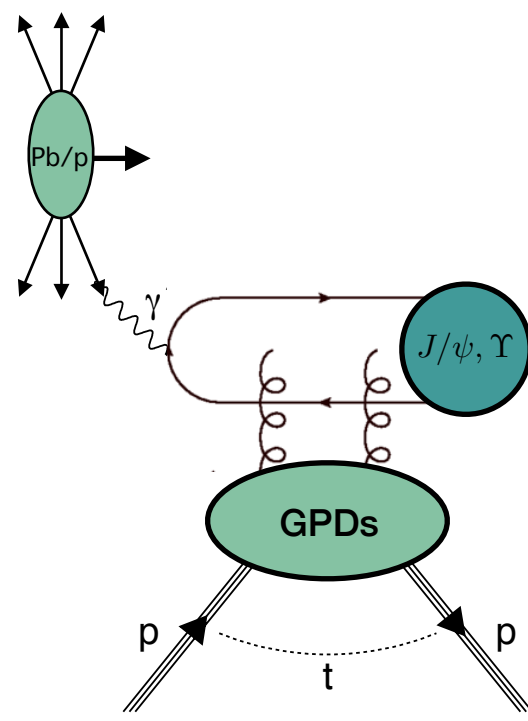
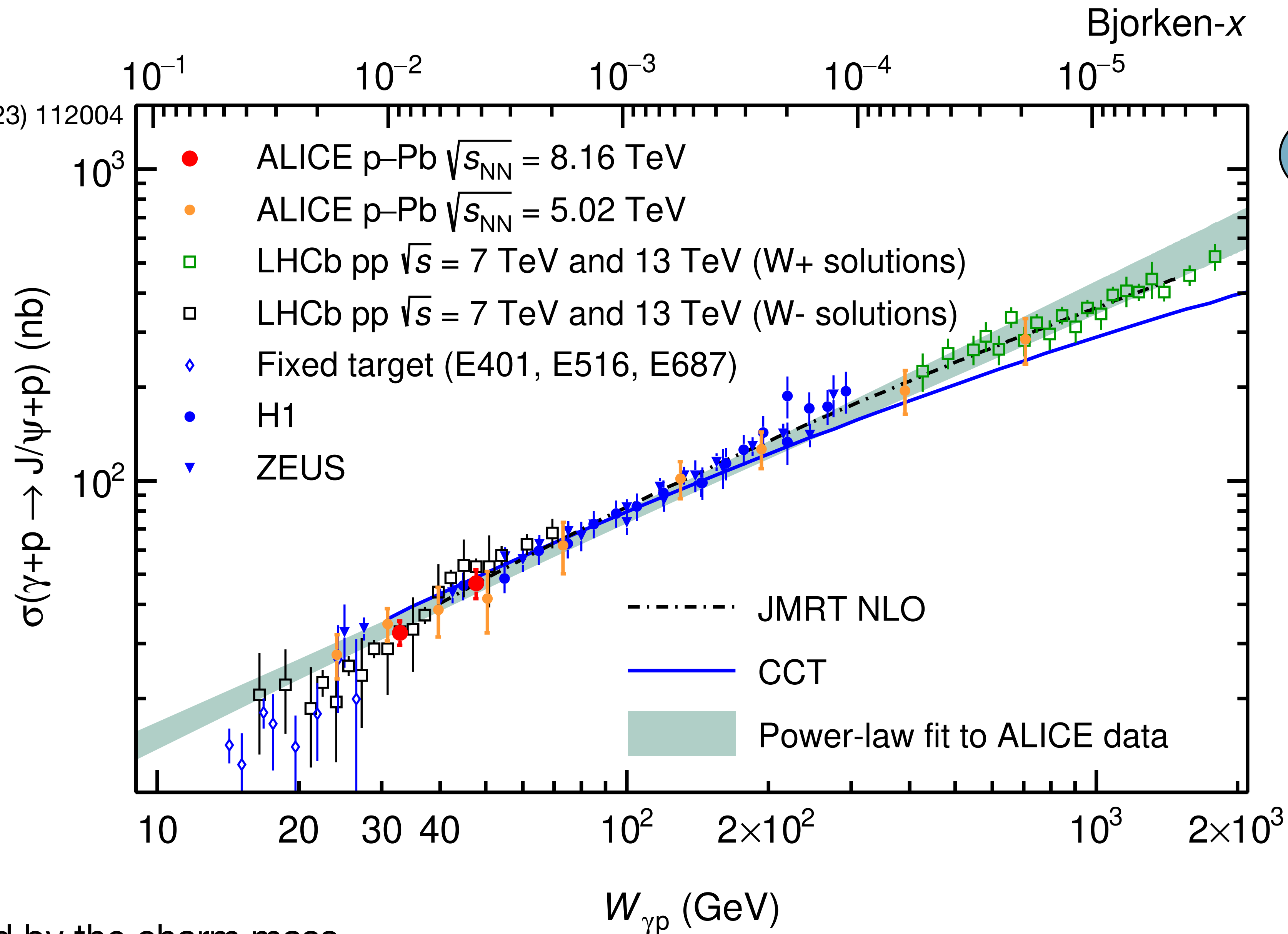
Experimental signature



$$-t \approx p_{T,\mu\mu}^2$$

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

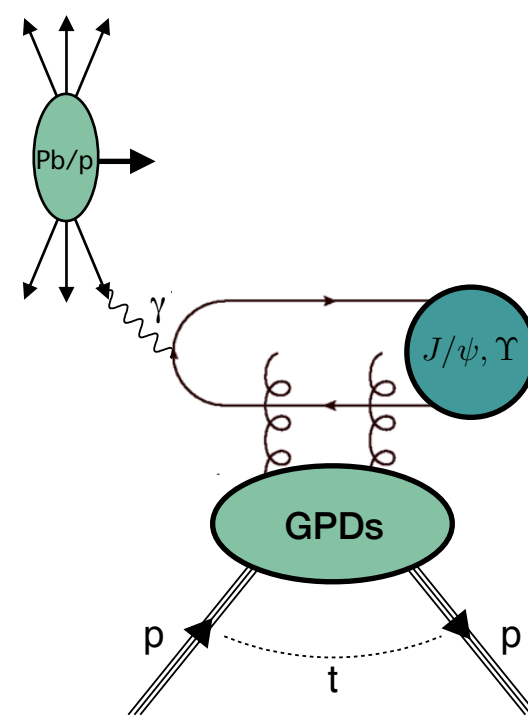
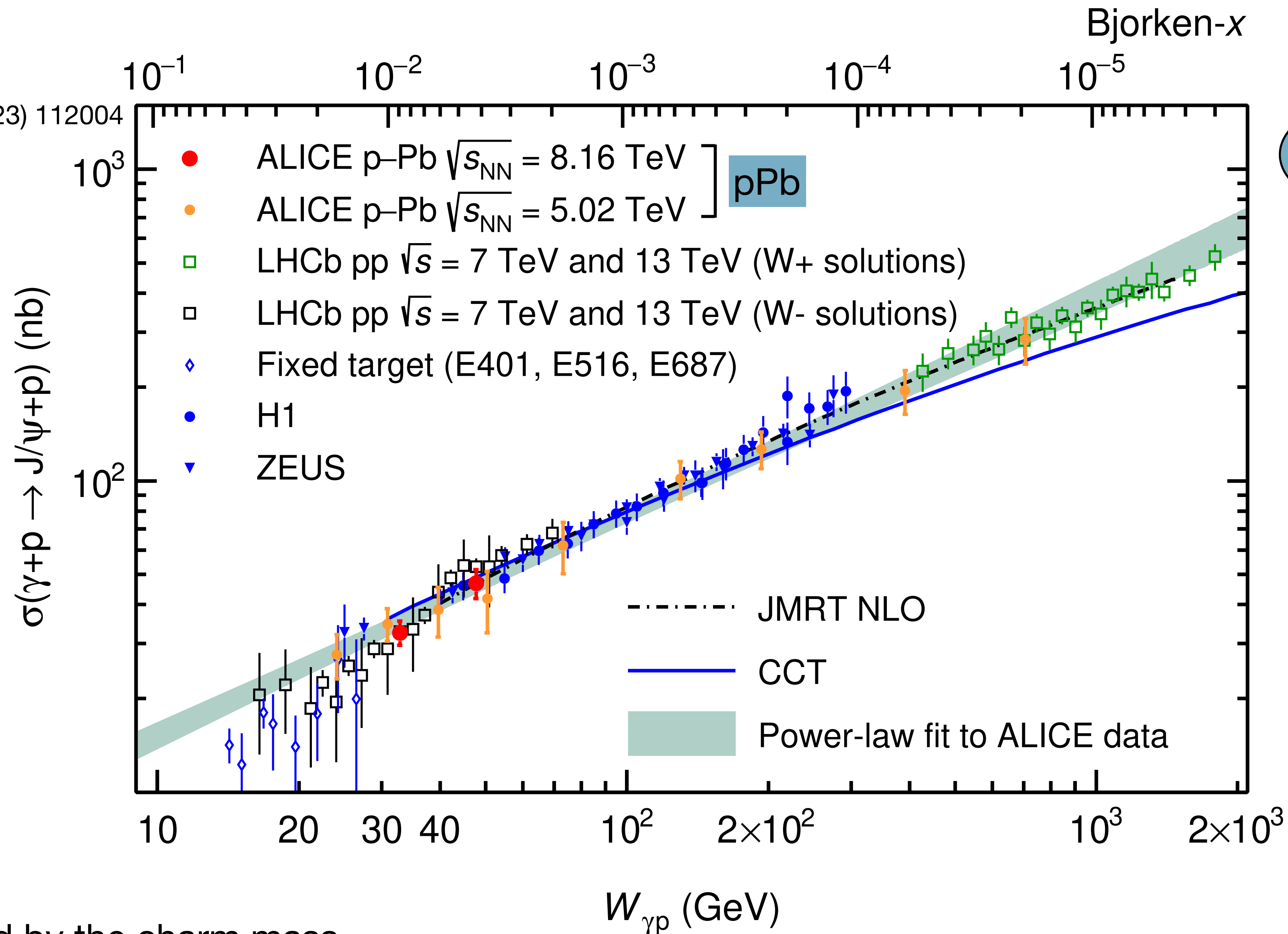
Phys. Rev. D **108** ('23) 112004



Hard scale: fixed by the charm mass

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

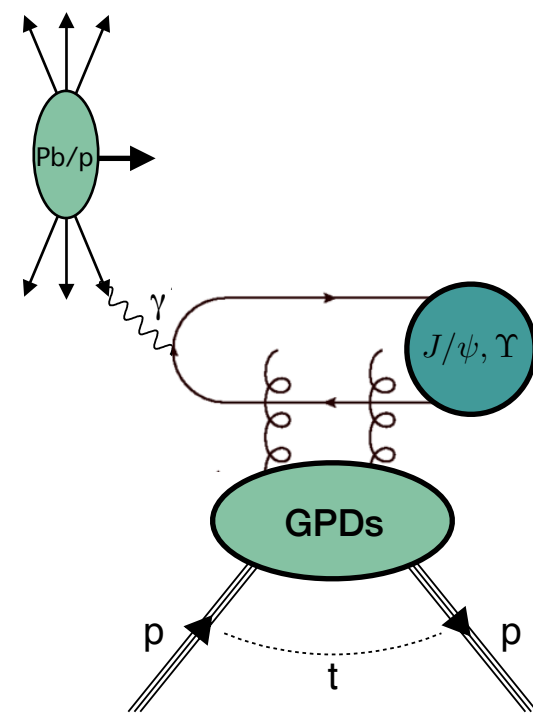
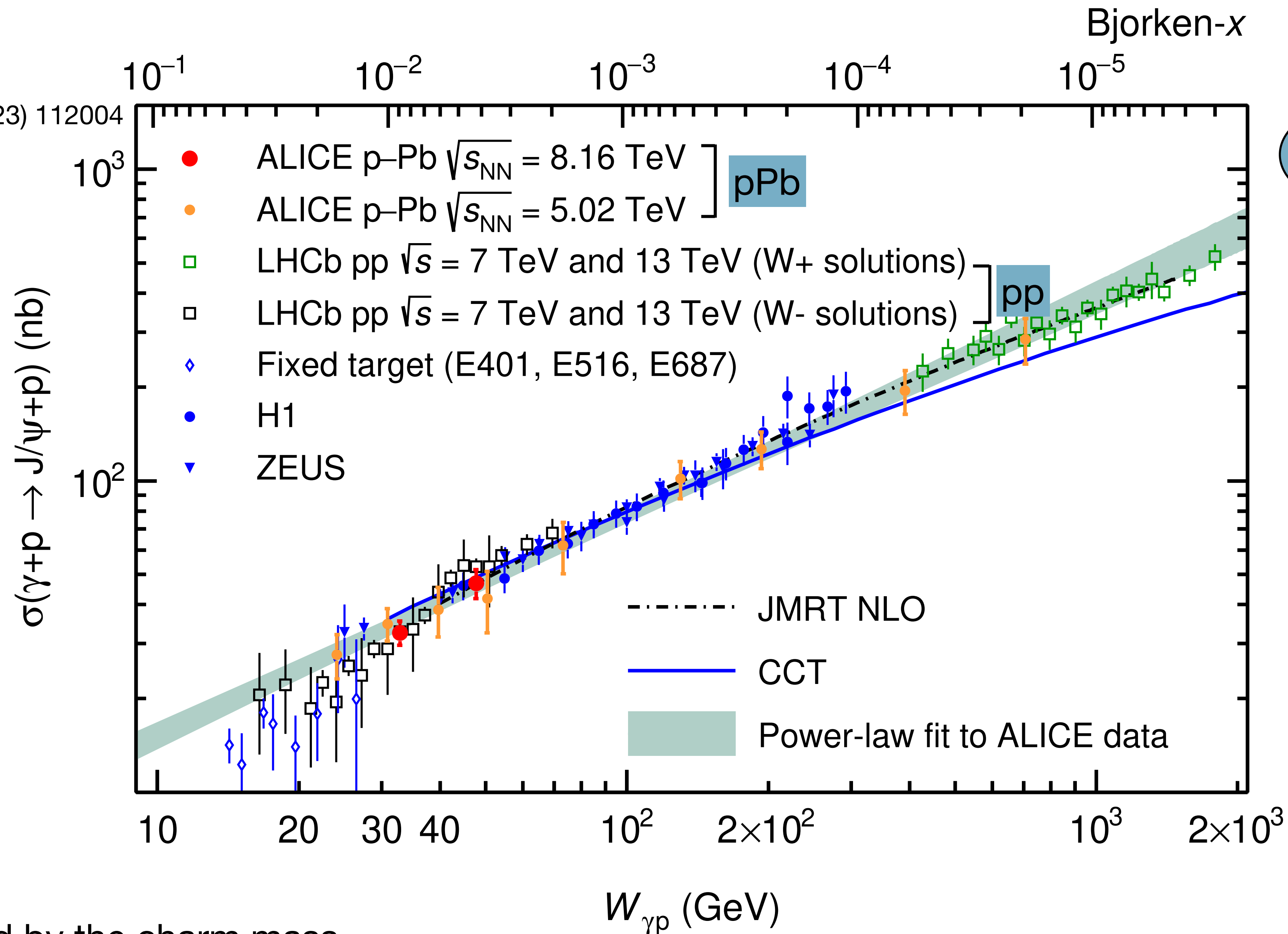
Phys. Rev. D **108** ('23) 112004



Hard scale: fixed by the charm mass

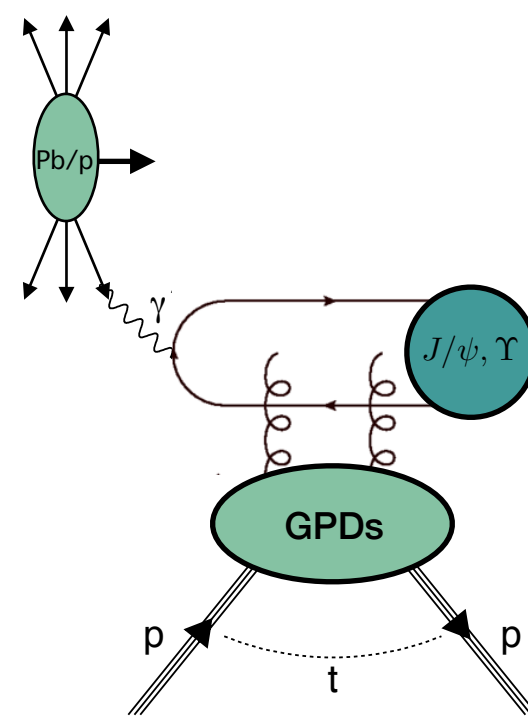
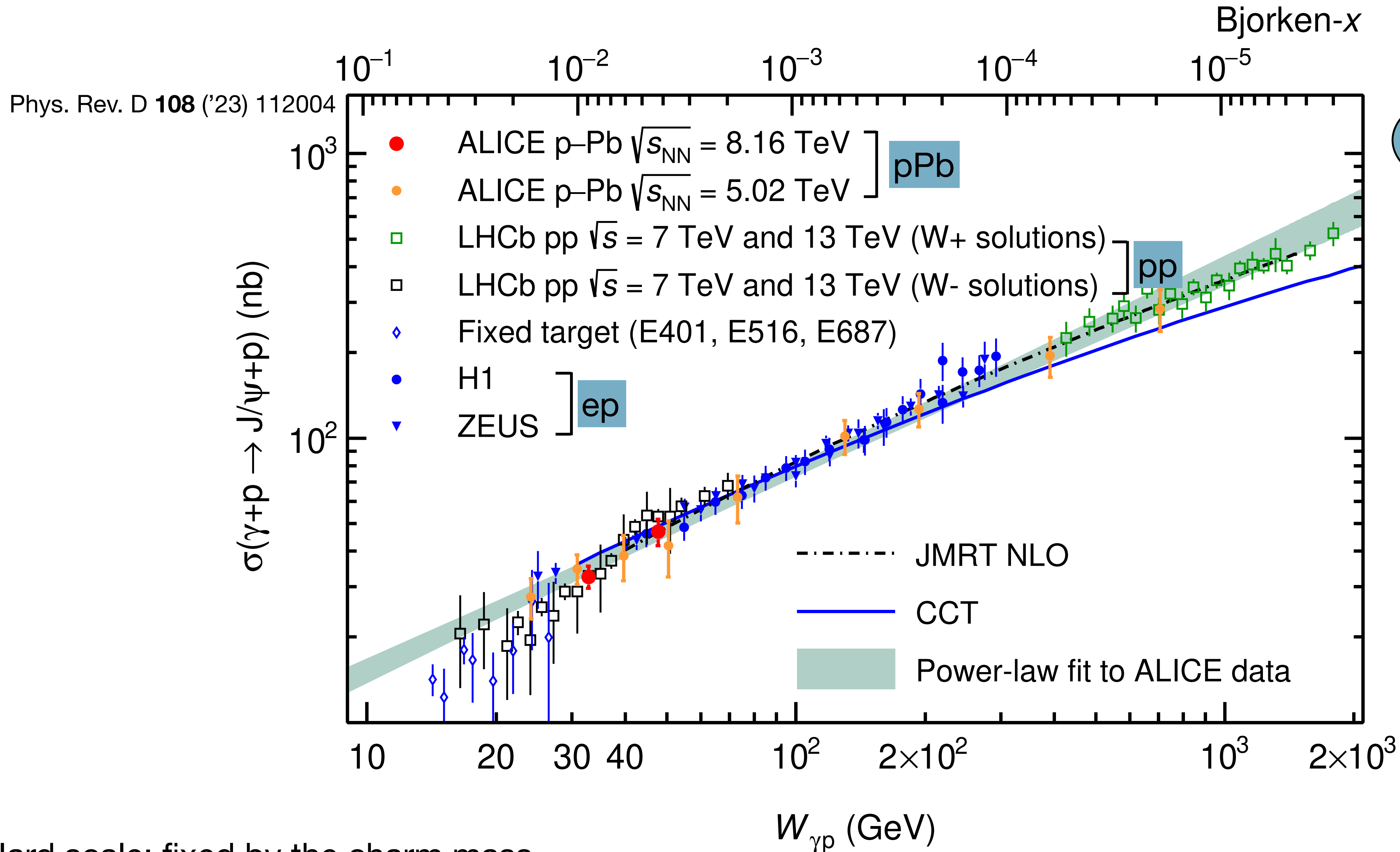
J/ψ photoproduction cross section off the proton at the LHC

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



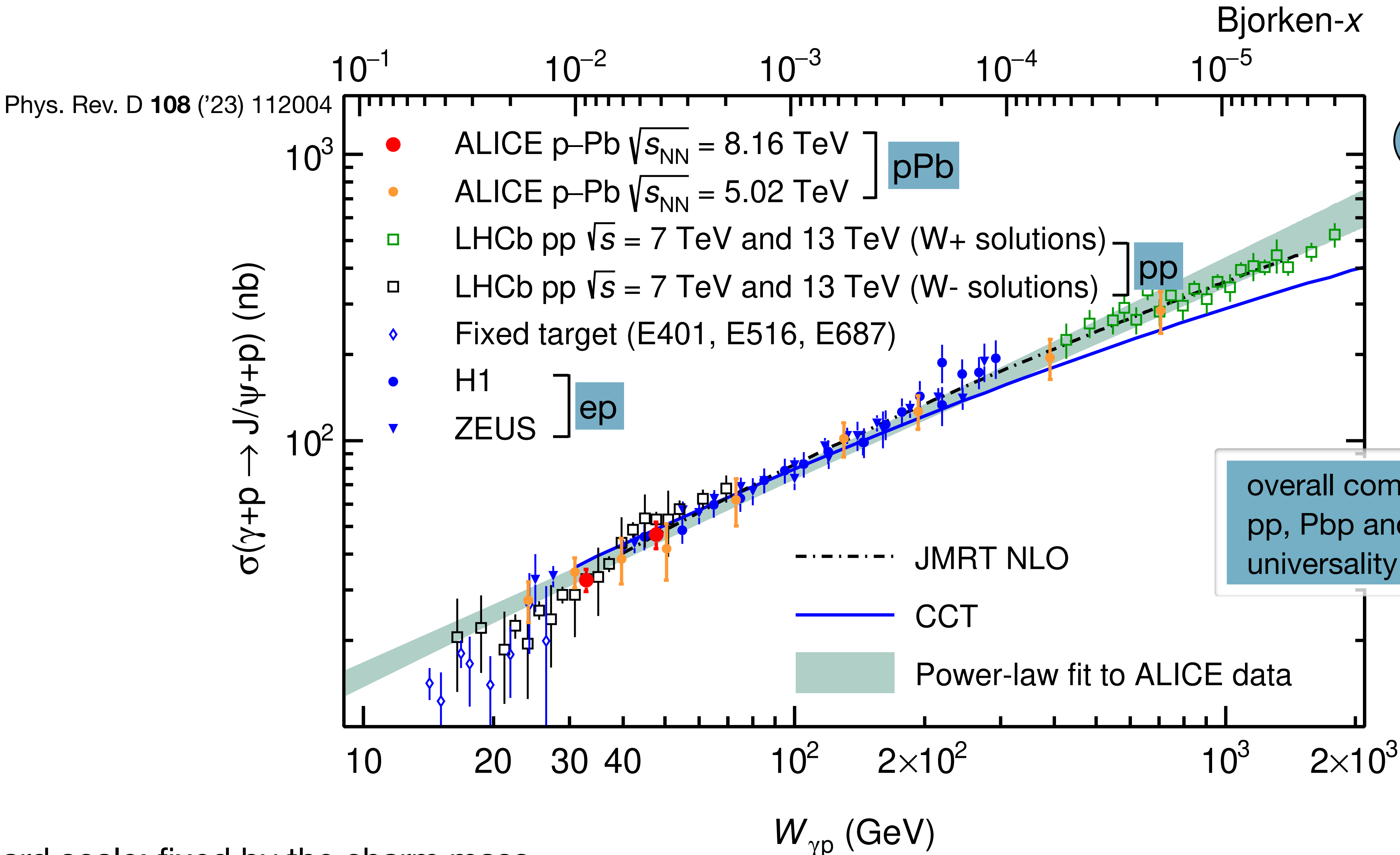
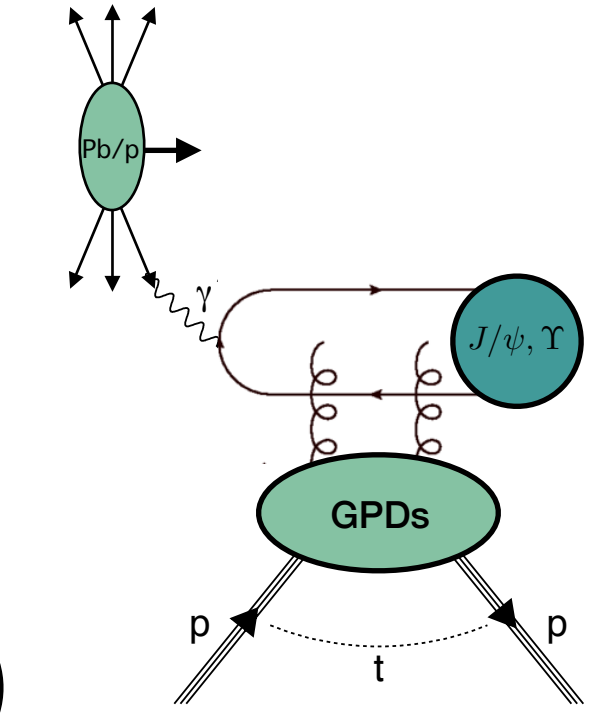
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J/ψ photoproduction cross section off the proton at the LHC



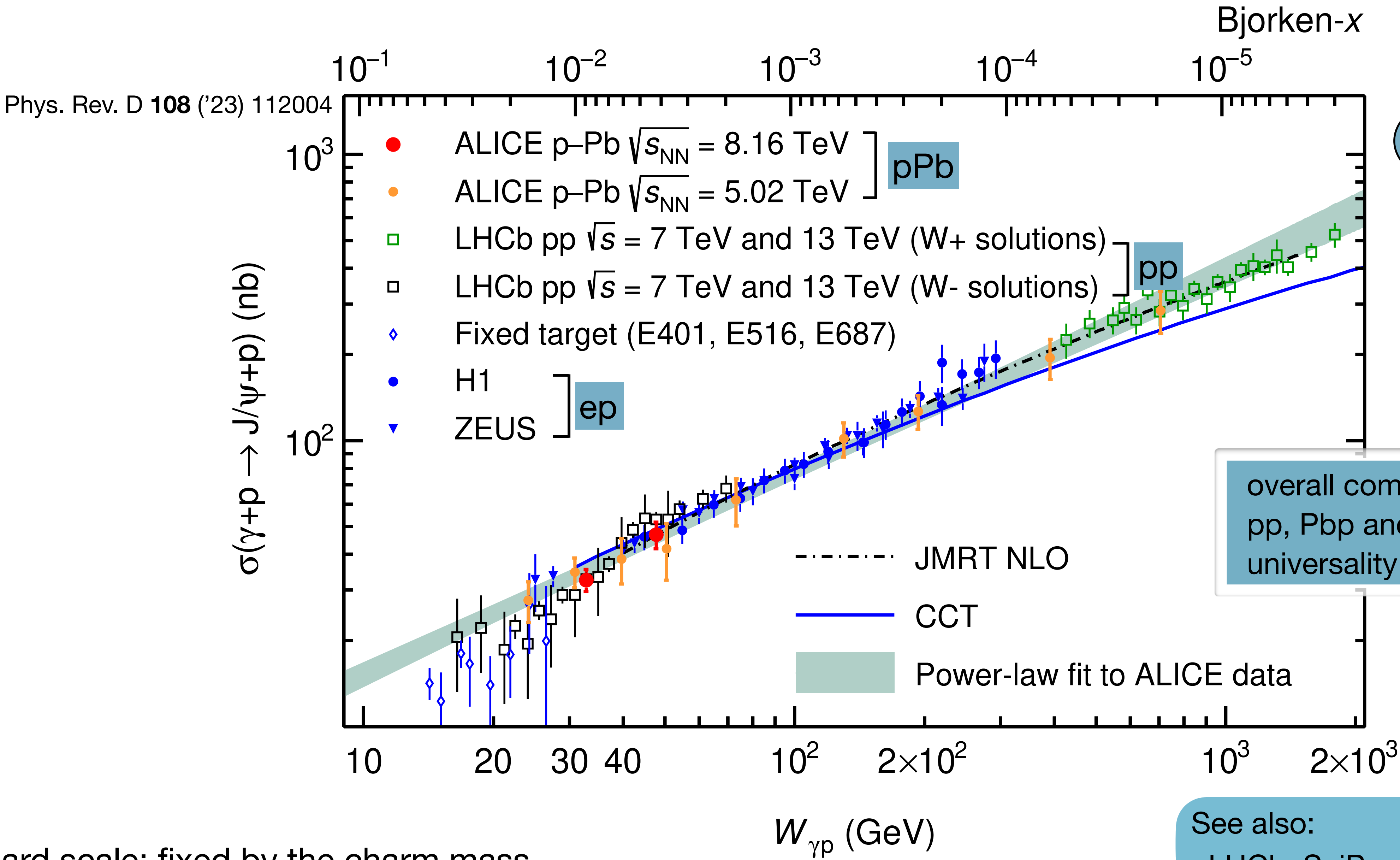
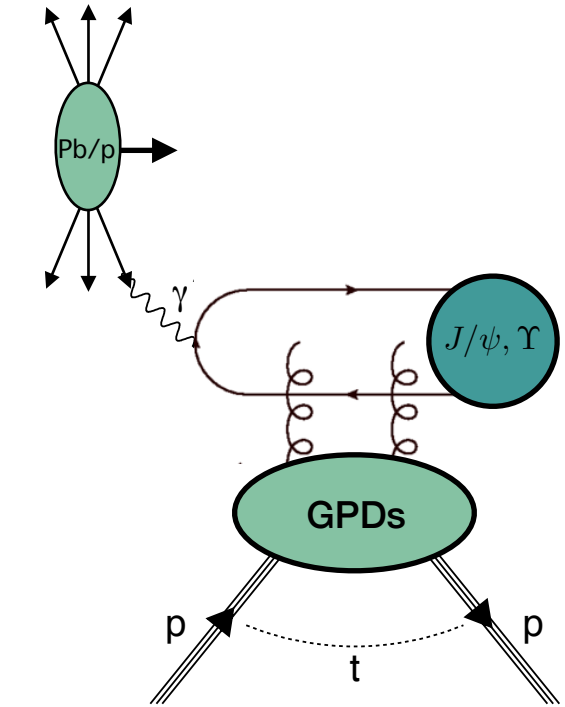
Hard scale: fixed by the charm mass

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



Hard scale: fixed by the charm mass

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

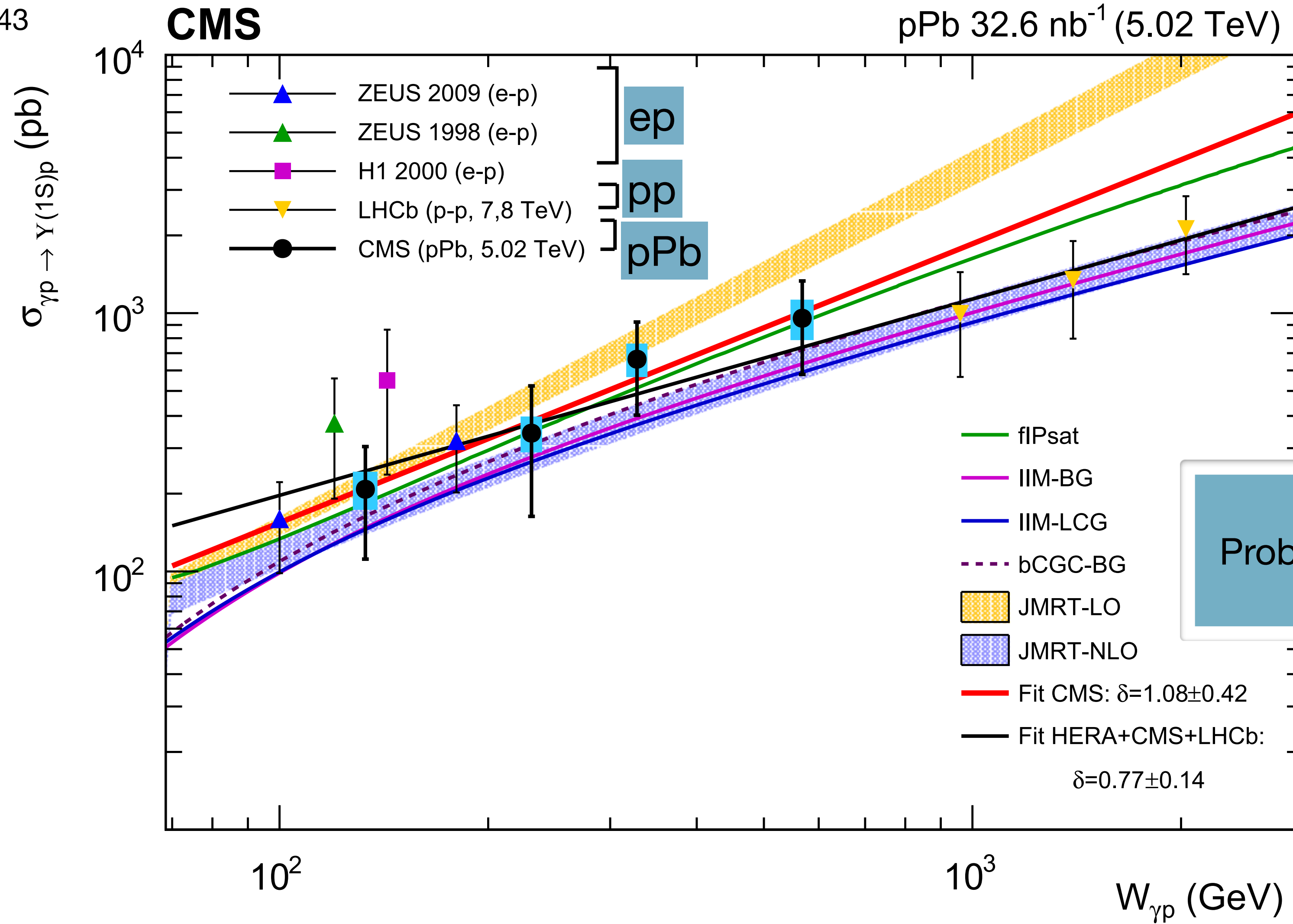


Hard scale: fixed by the charm mass

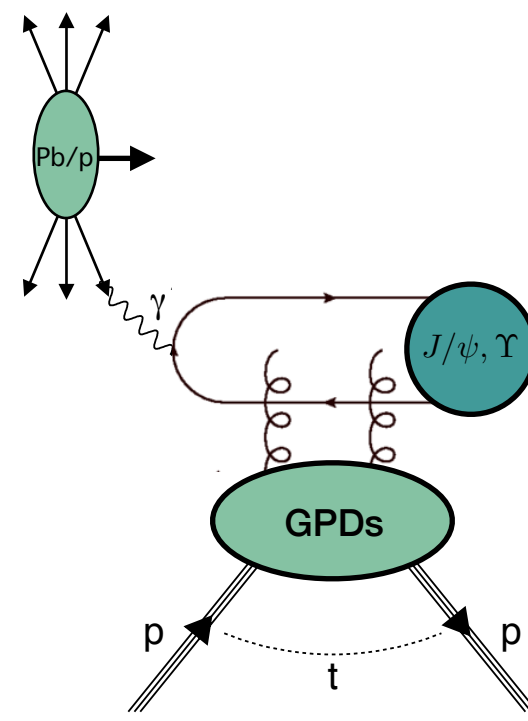
Υ photoproduction cross section

Eur. Phys. J. C **79** (2019) 277

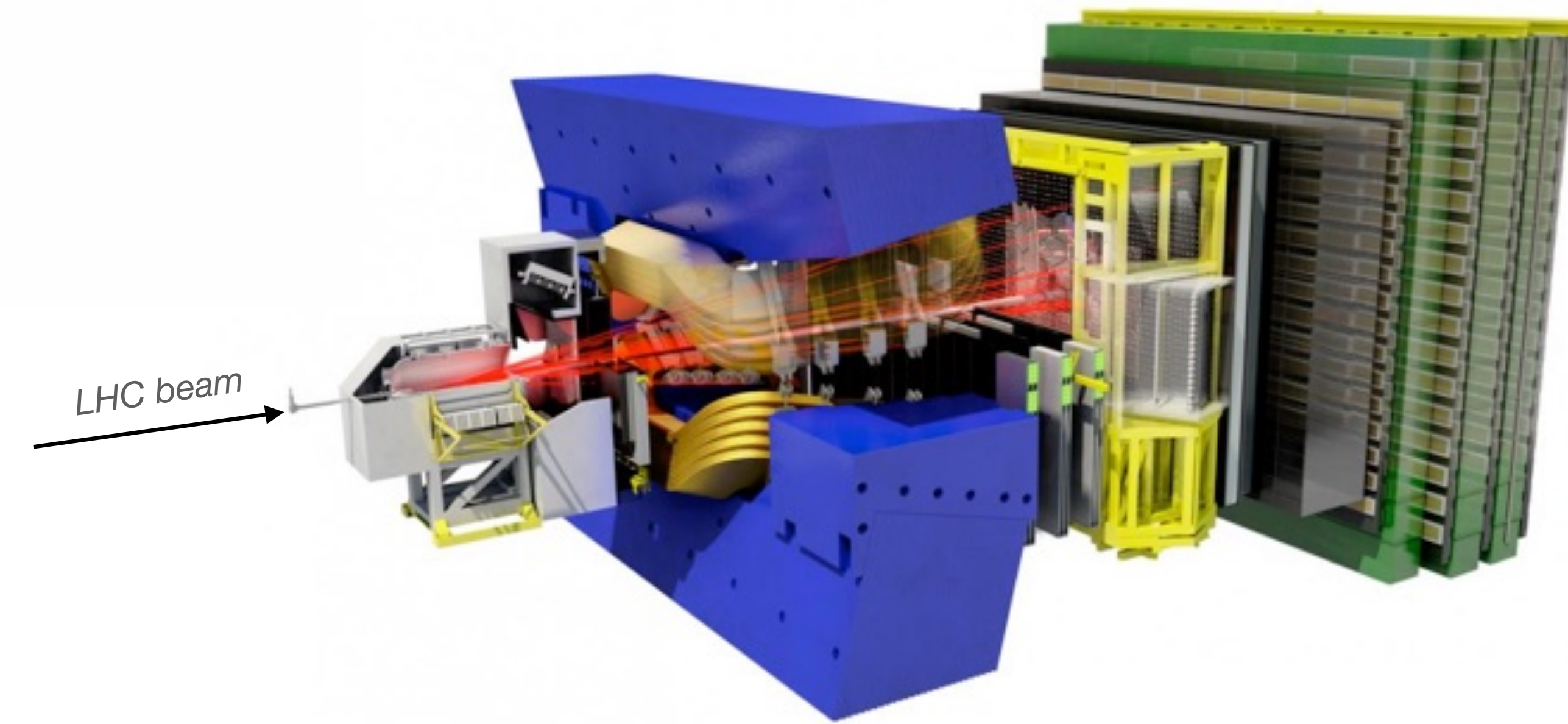
Eur. Phys. J. C **82** (2022) 343



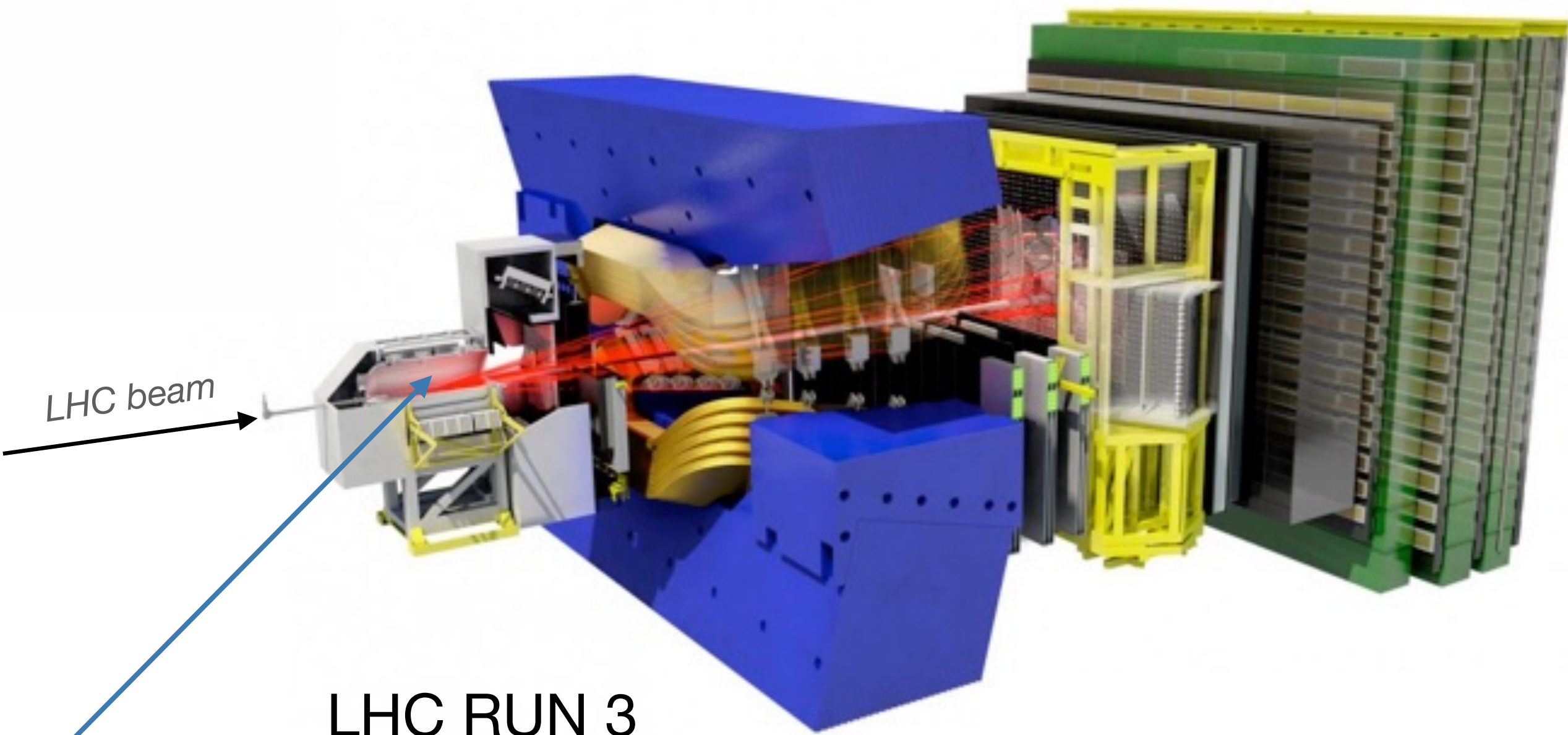
GPD H



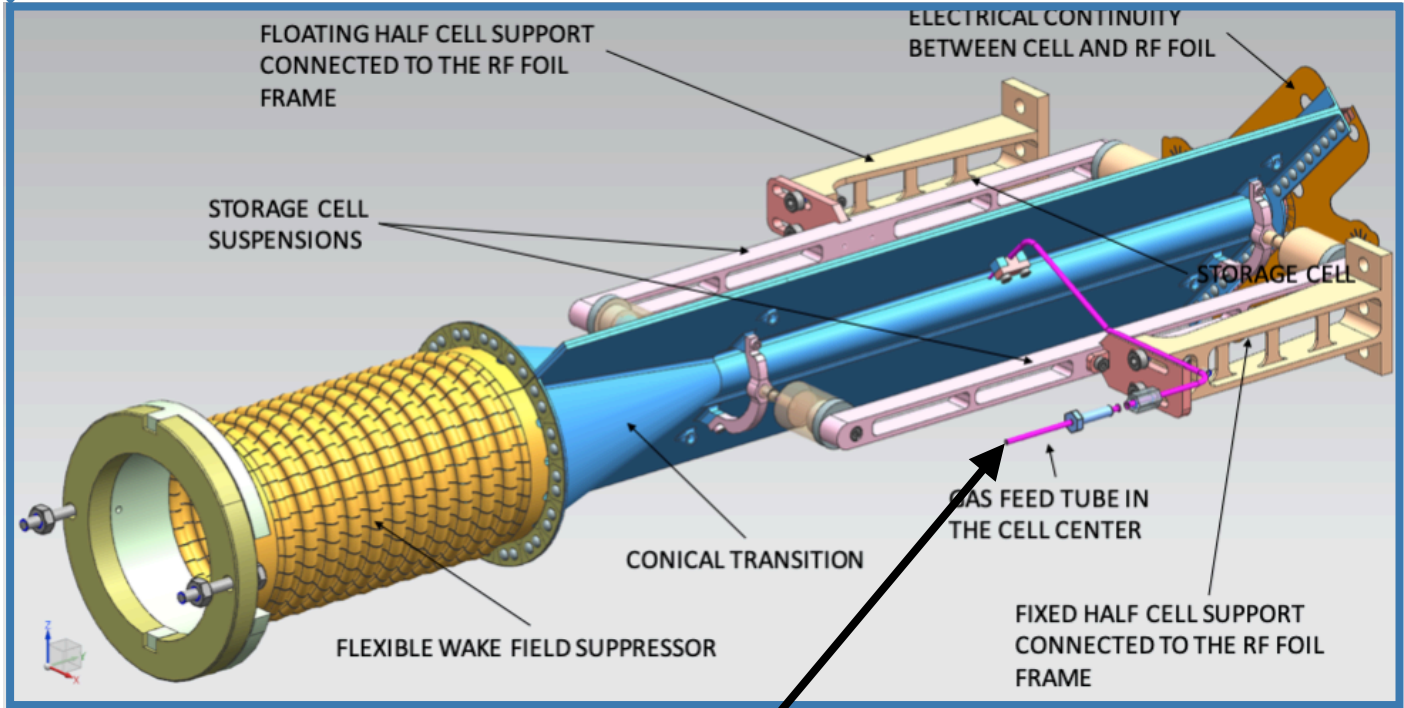
Fixed target at LHCb



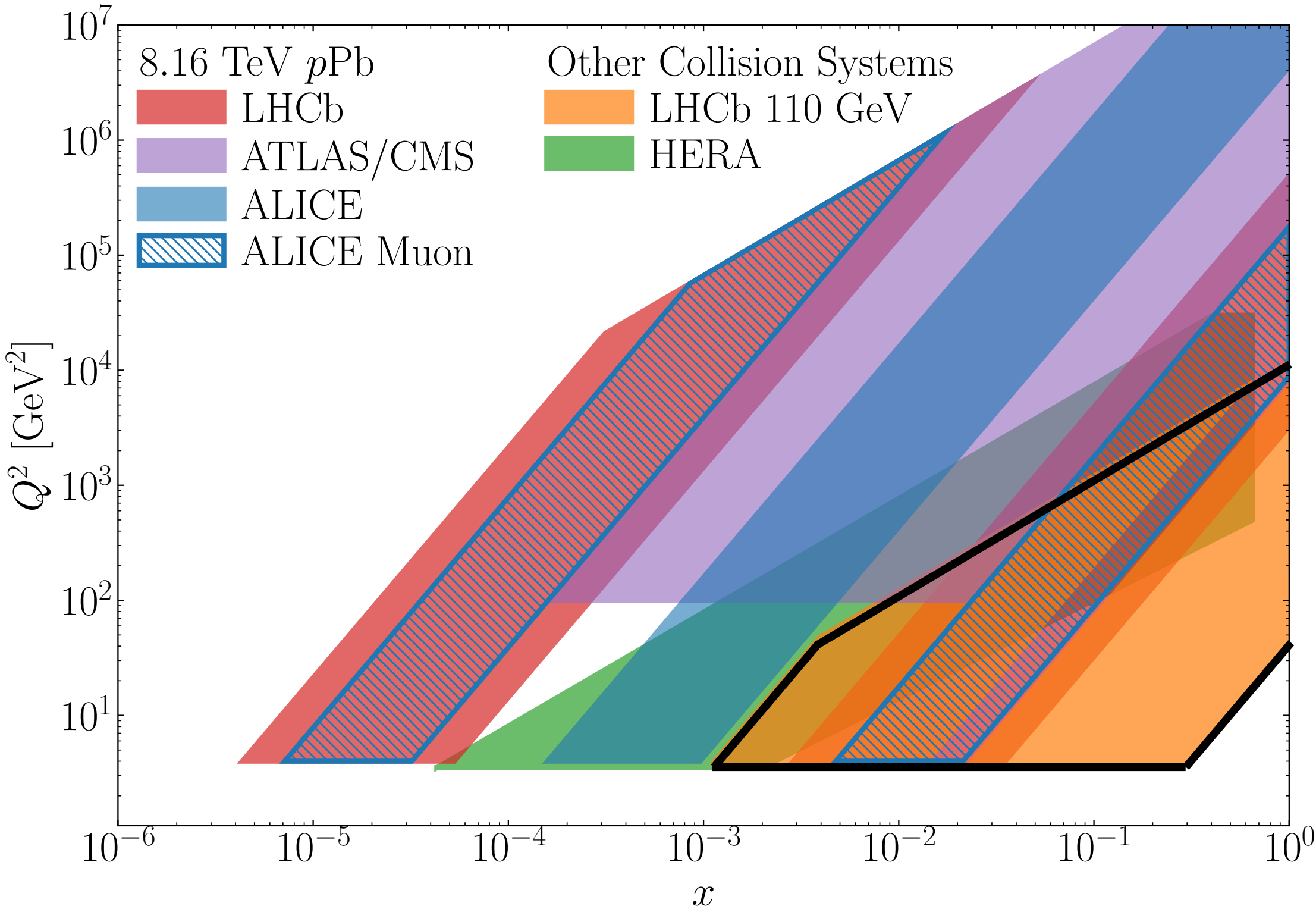
Fixed target at LHCb



LHC RUN 3

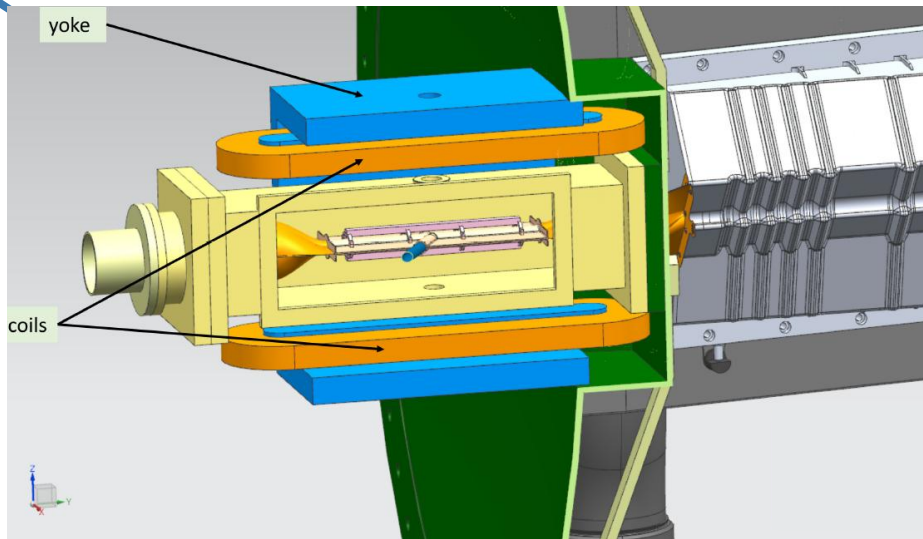
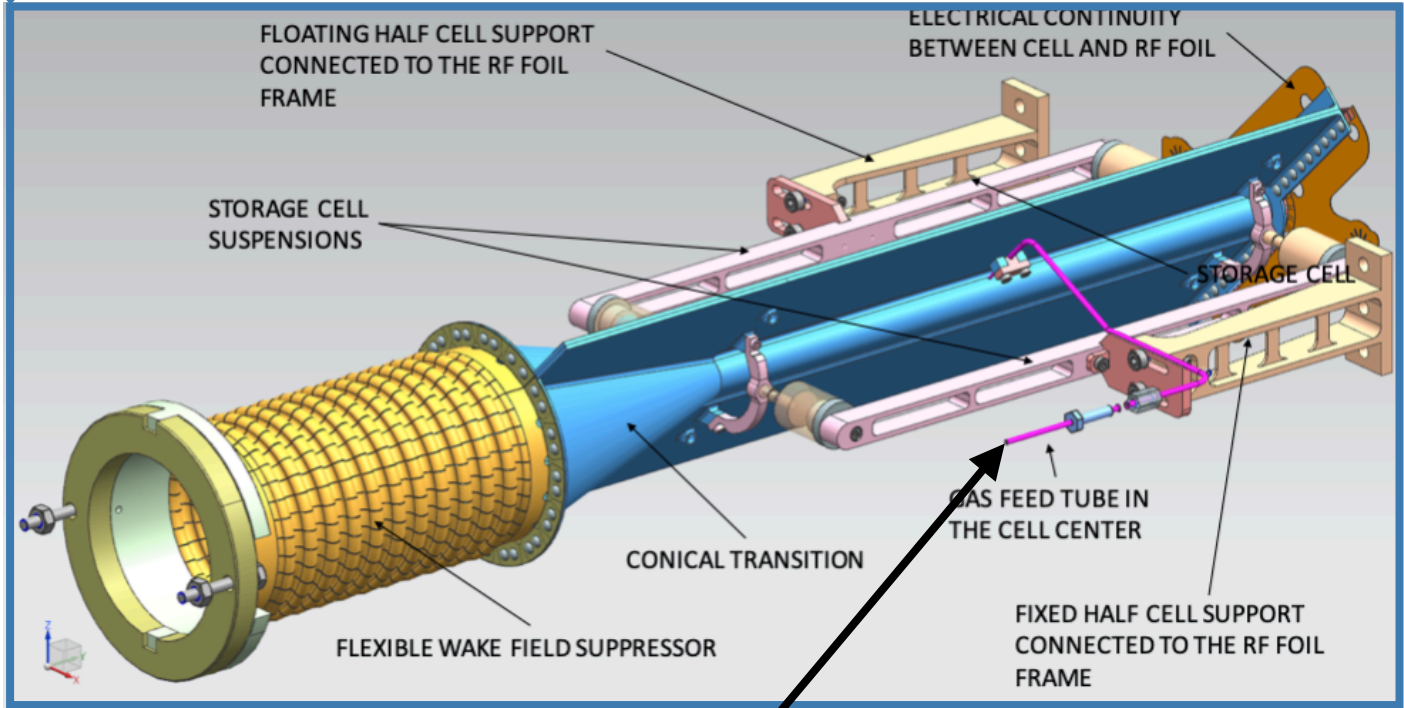
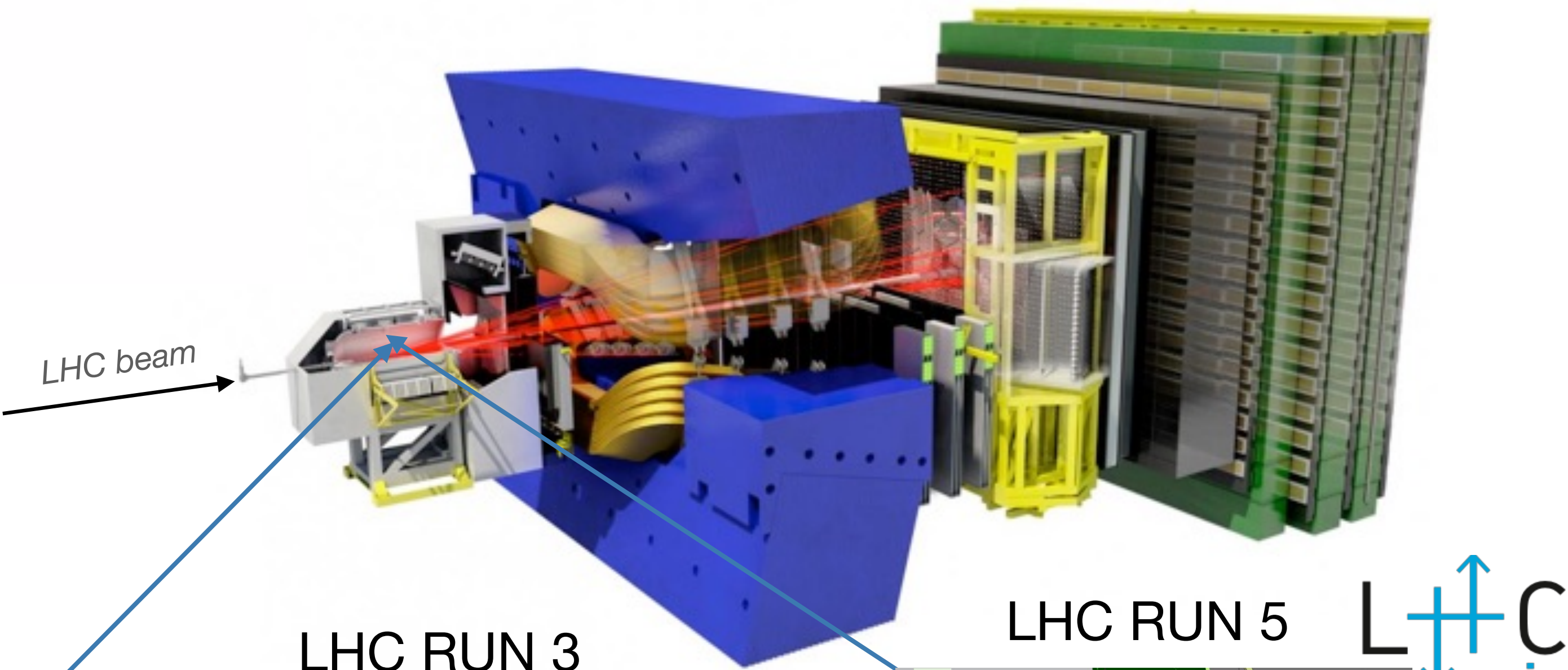


inject gas: He, Ne, Ar, and H₂, D₂



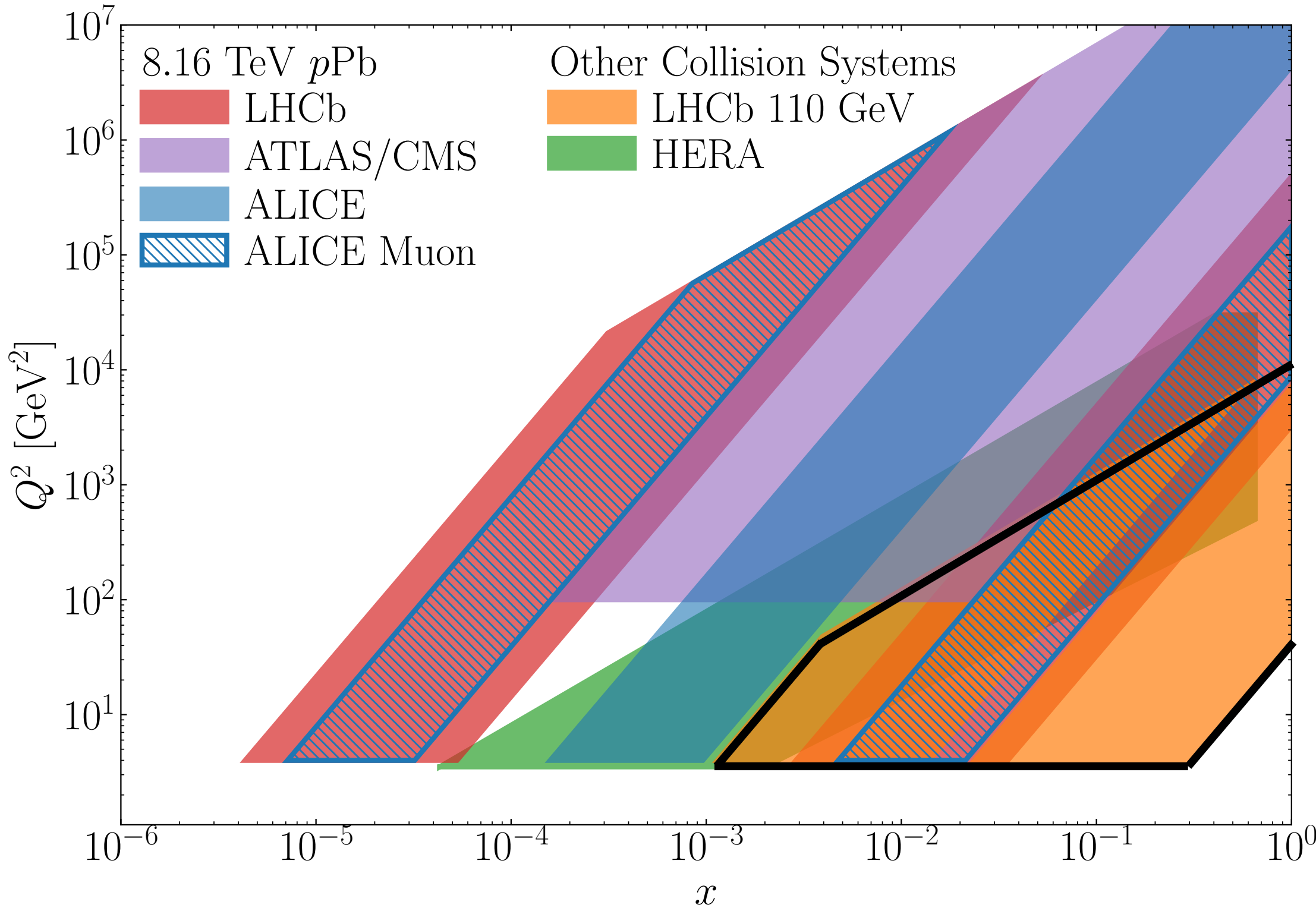
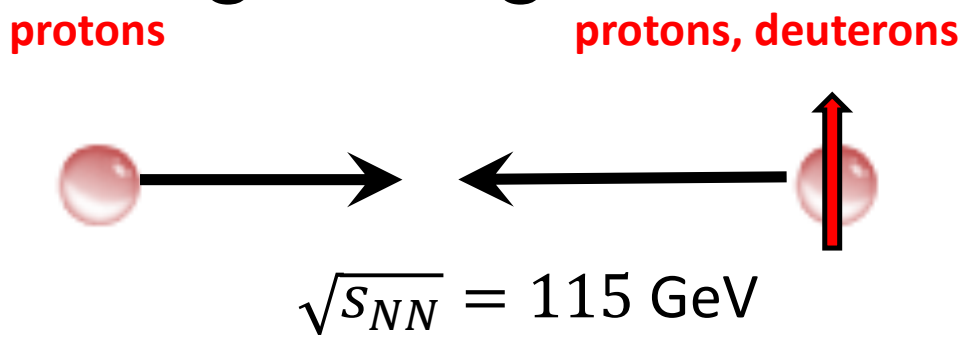
Access to **high x**

Fixed target at LHCb



transversely polarised
gas target

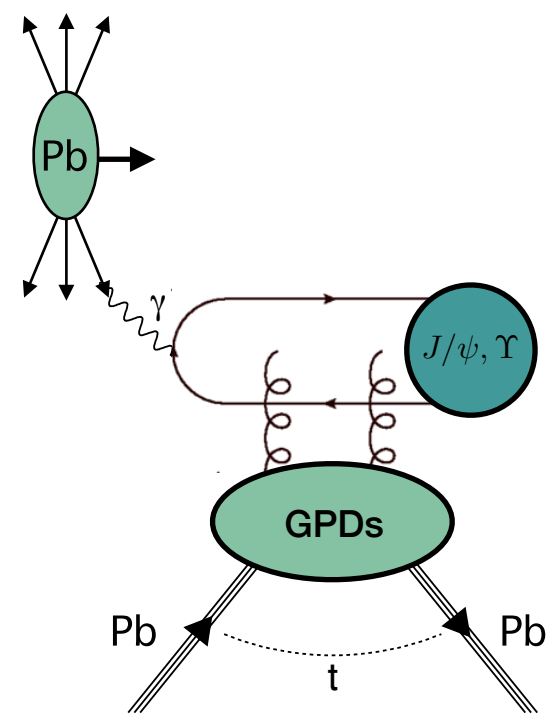
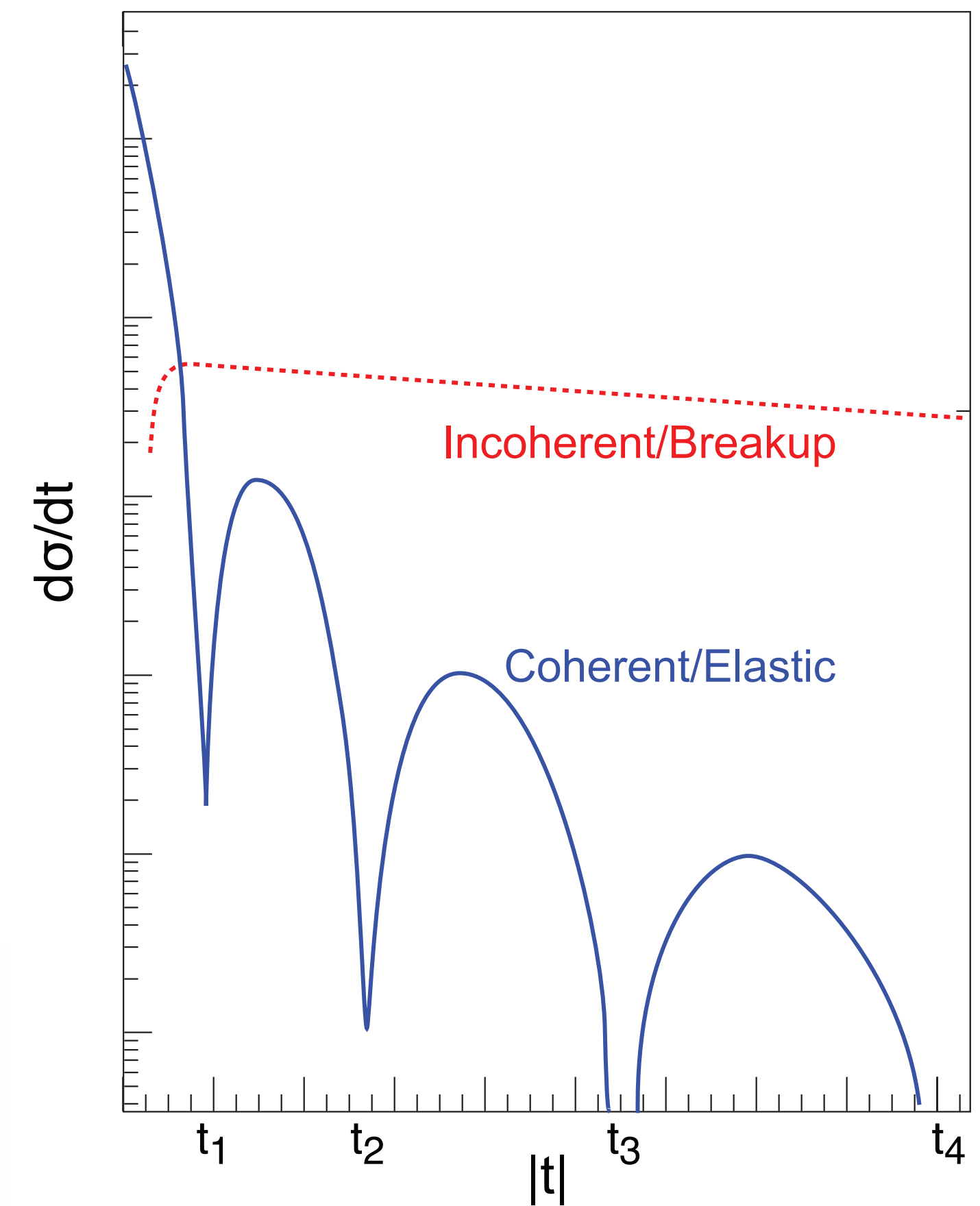
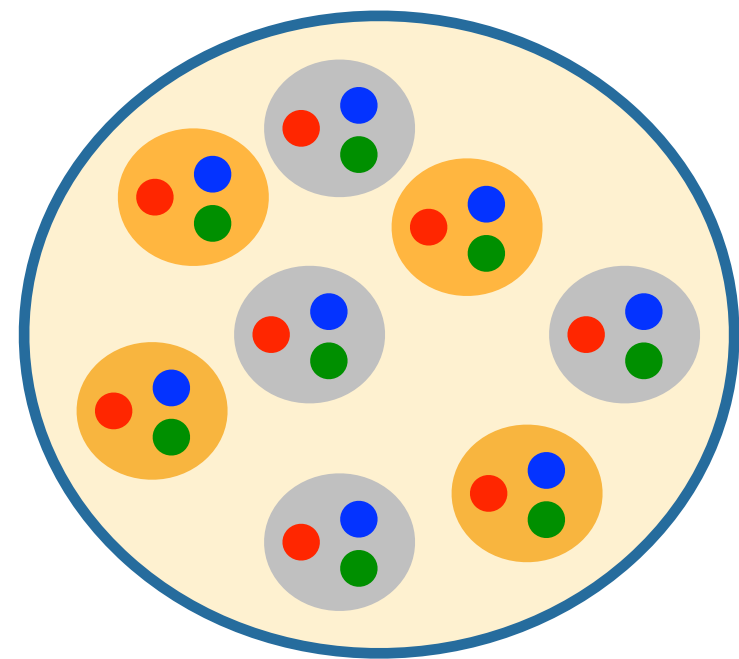
inject gas: He, Ne, Ar, and H₂, D₂



Access to **high x**

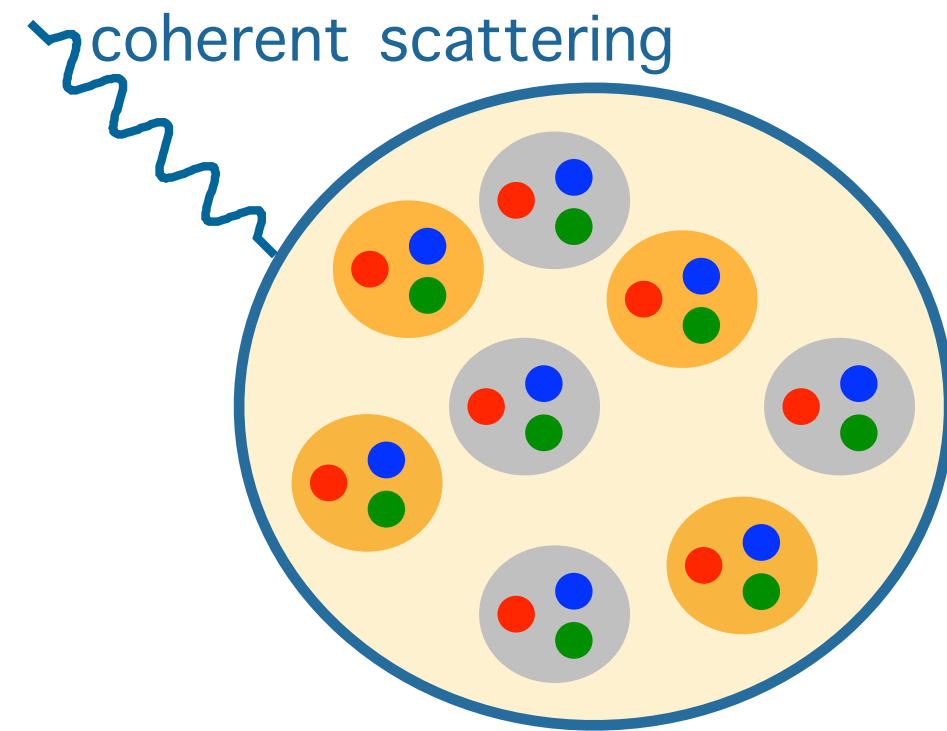
Ultrapерipheral PbPb collisions

What object are we probing?

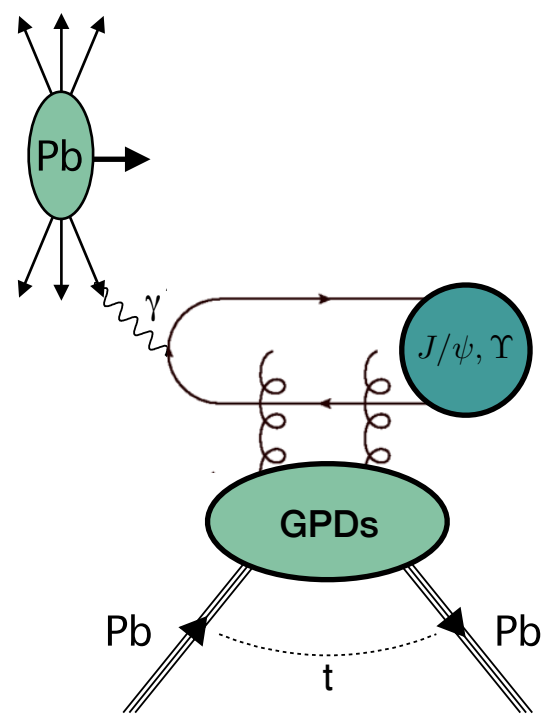
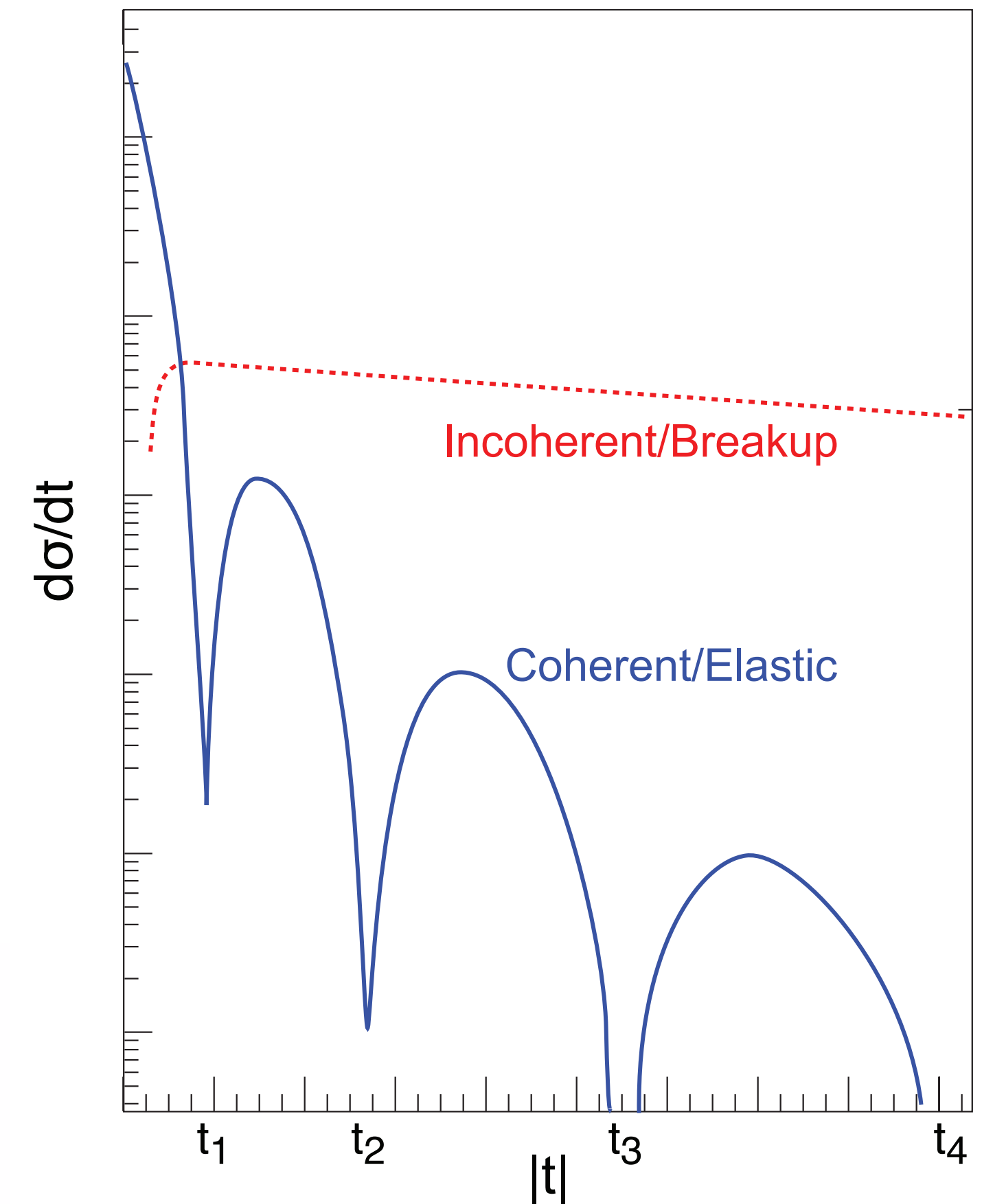


Ultrapерipheral PbPb collisions

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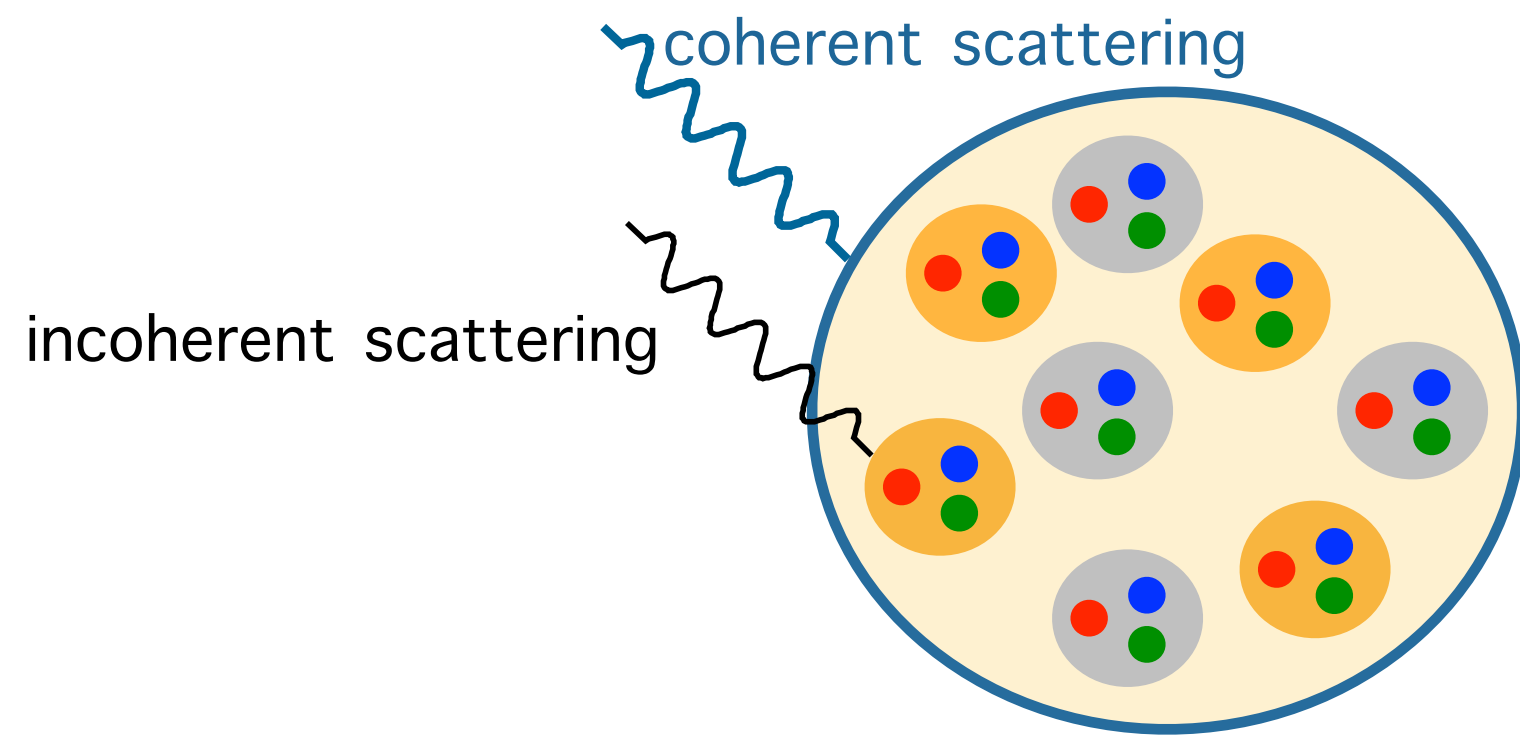


Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.



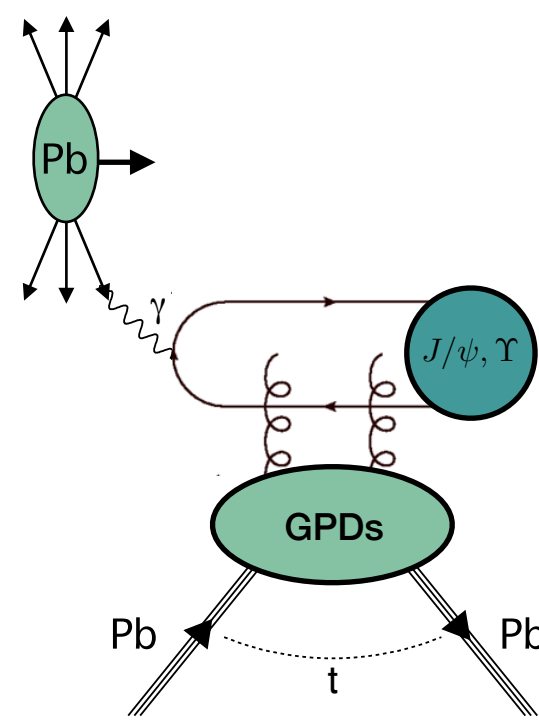
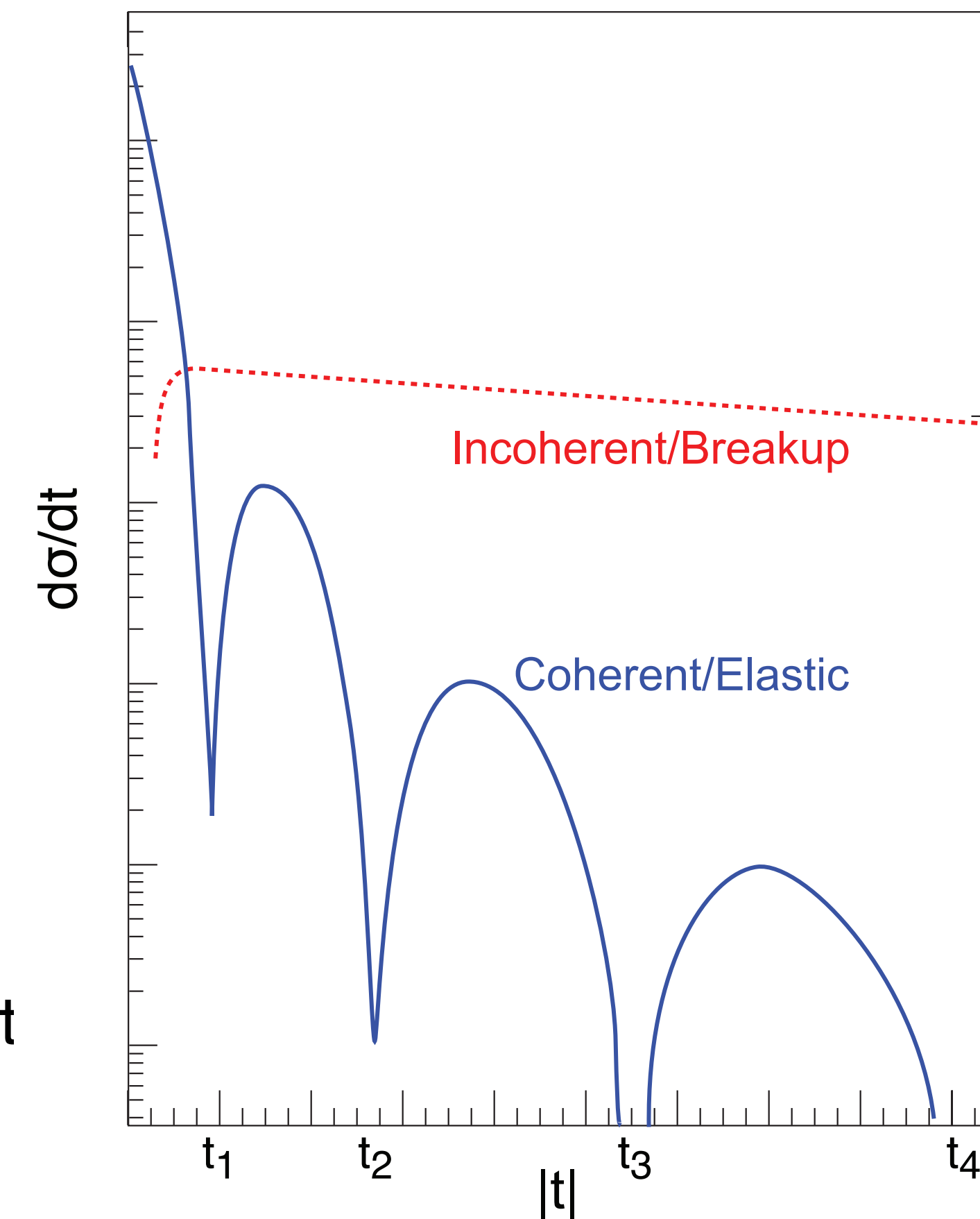
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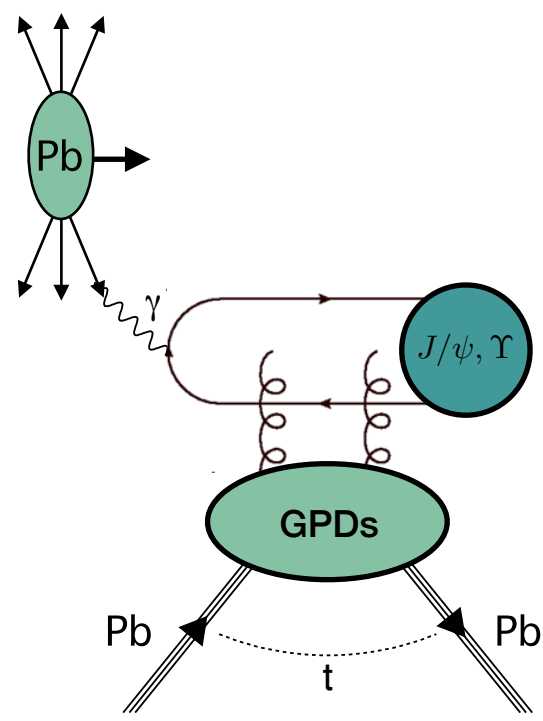
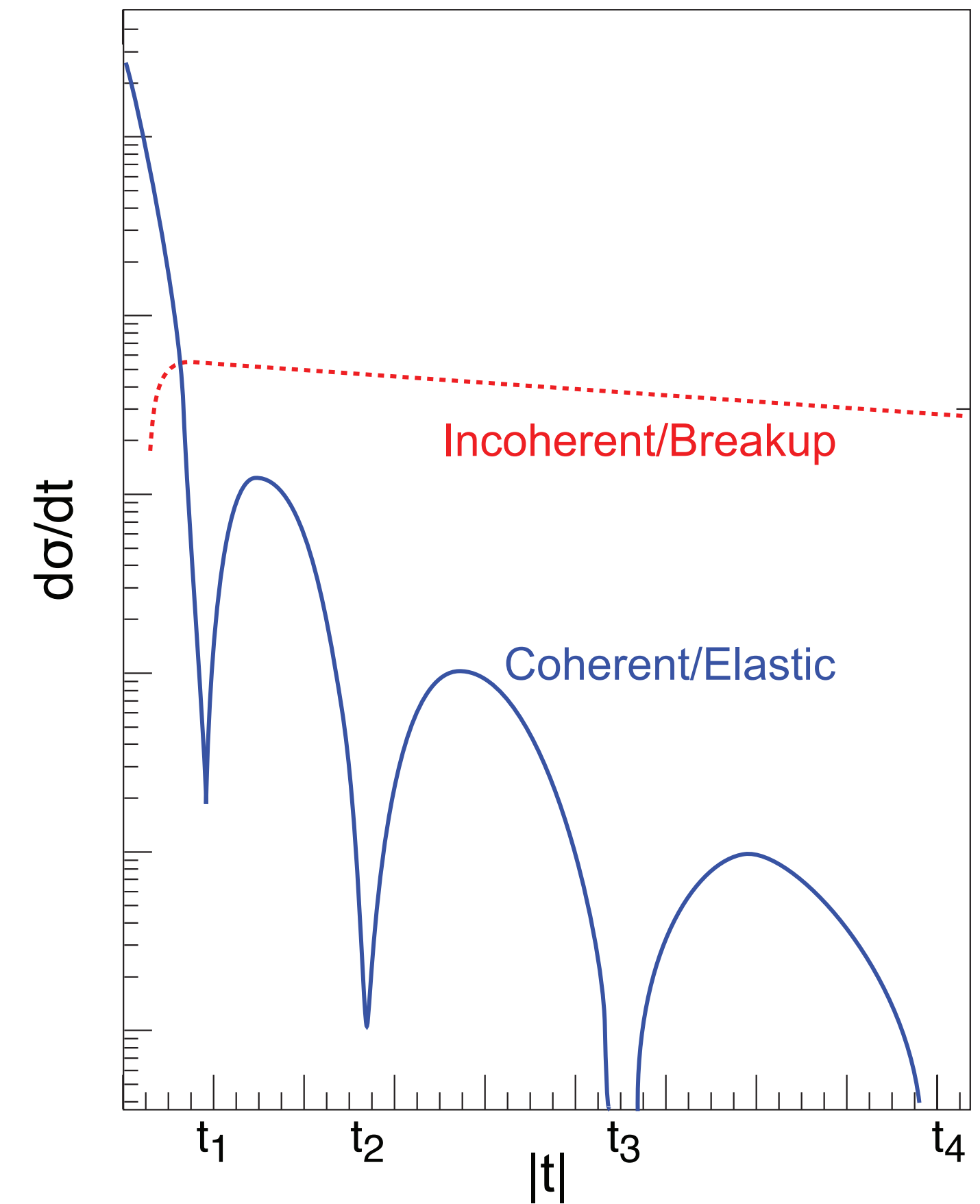
Coherent interaction: interaction with target as a whole.
 ~ target remains in same quantum state.

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!

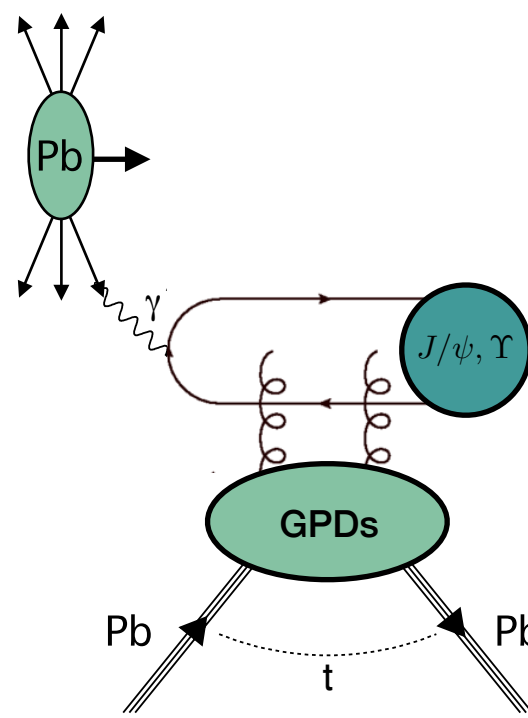
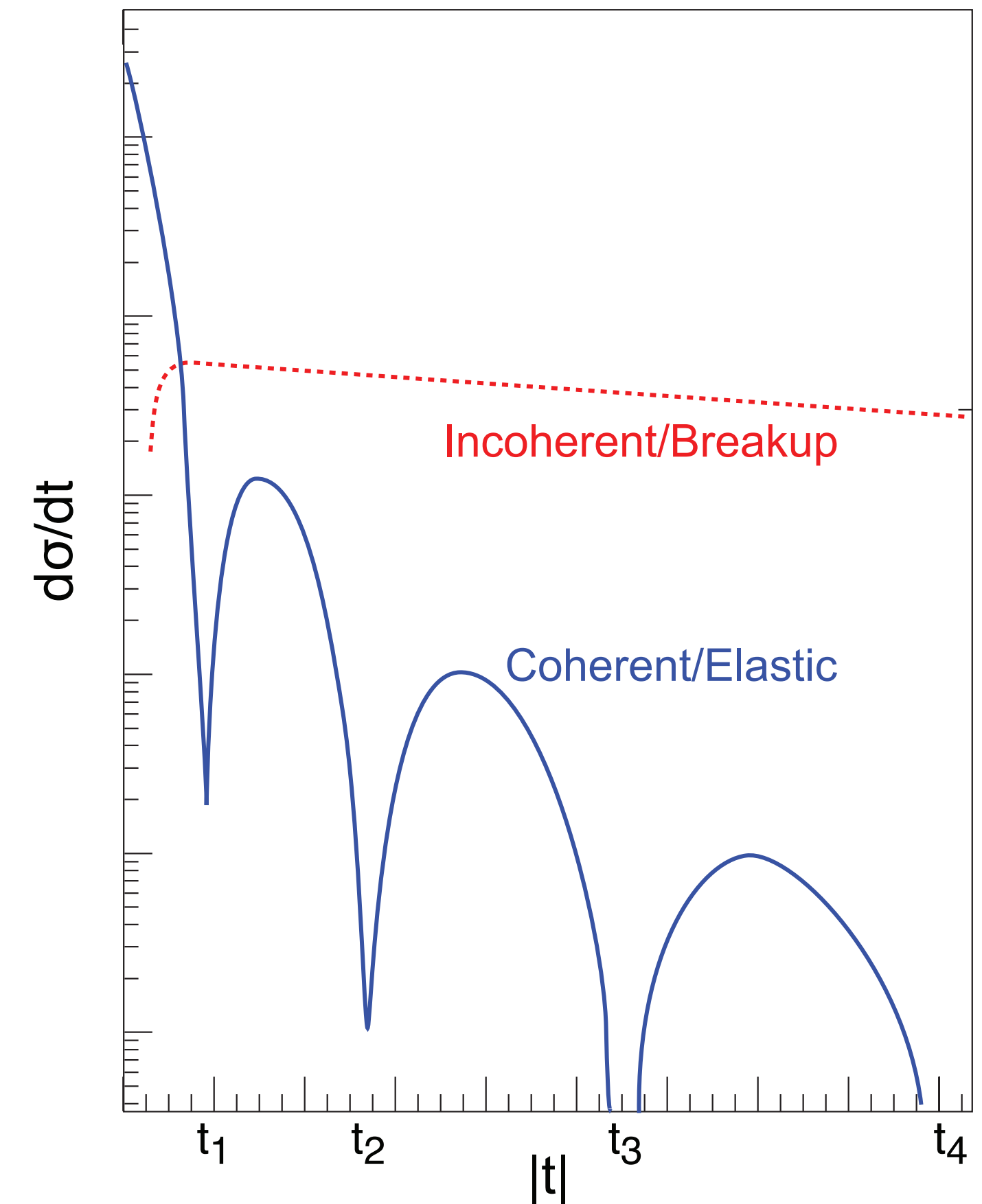


Experimentally important points

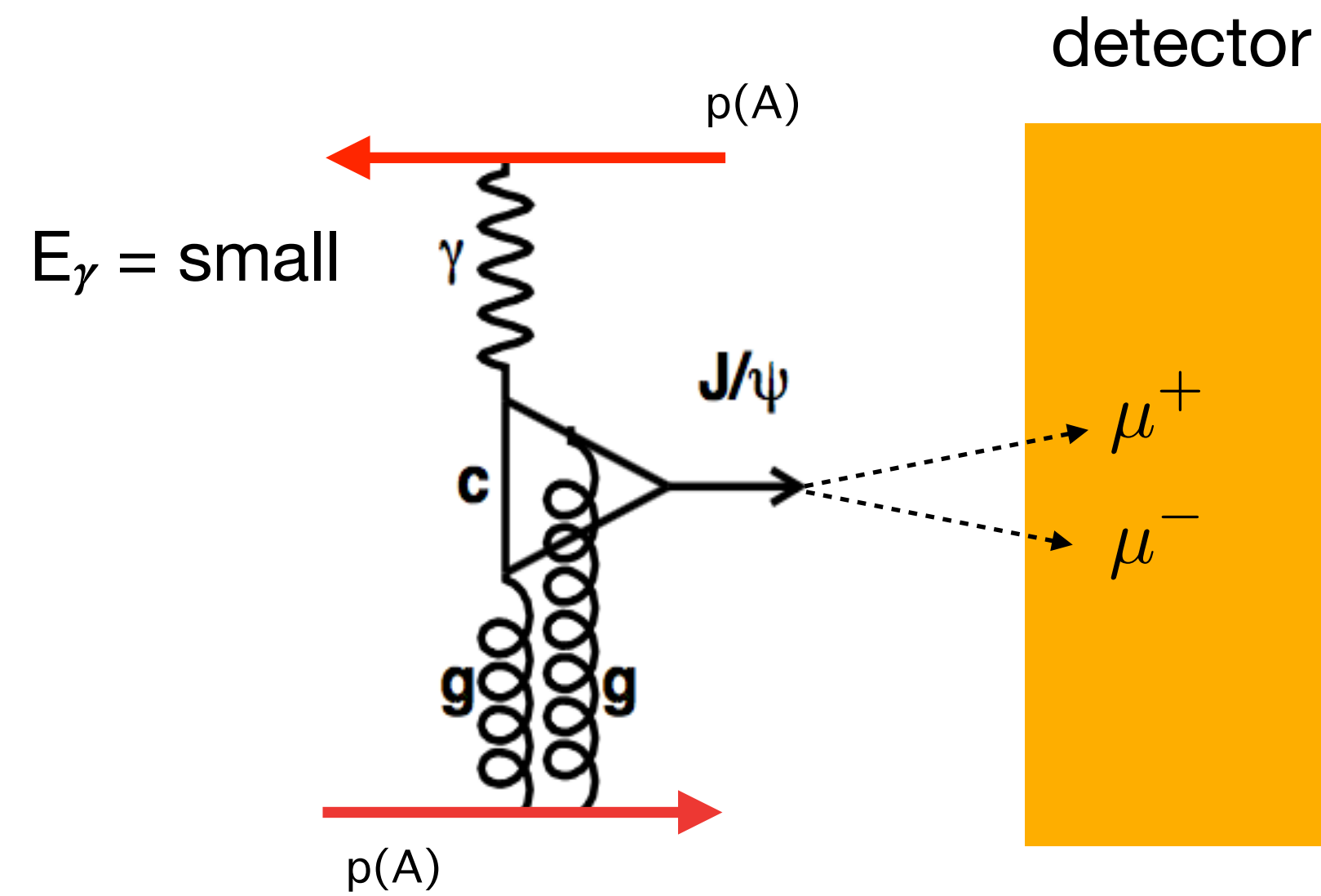
- Good separation of coherent and incoherent production: not easy!
- Coherent production: measurements up to large t :
 - 3D or 2D (x independent) transverse position

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

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

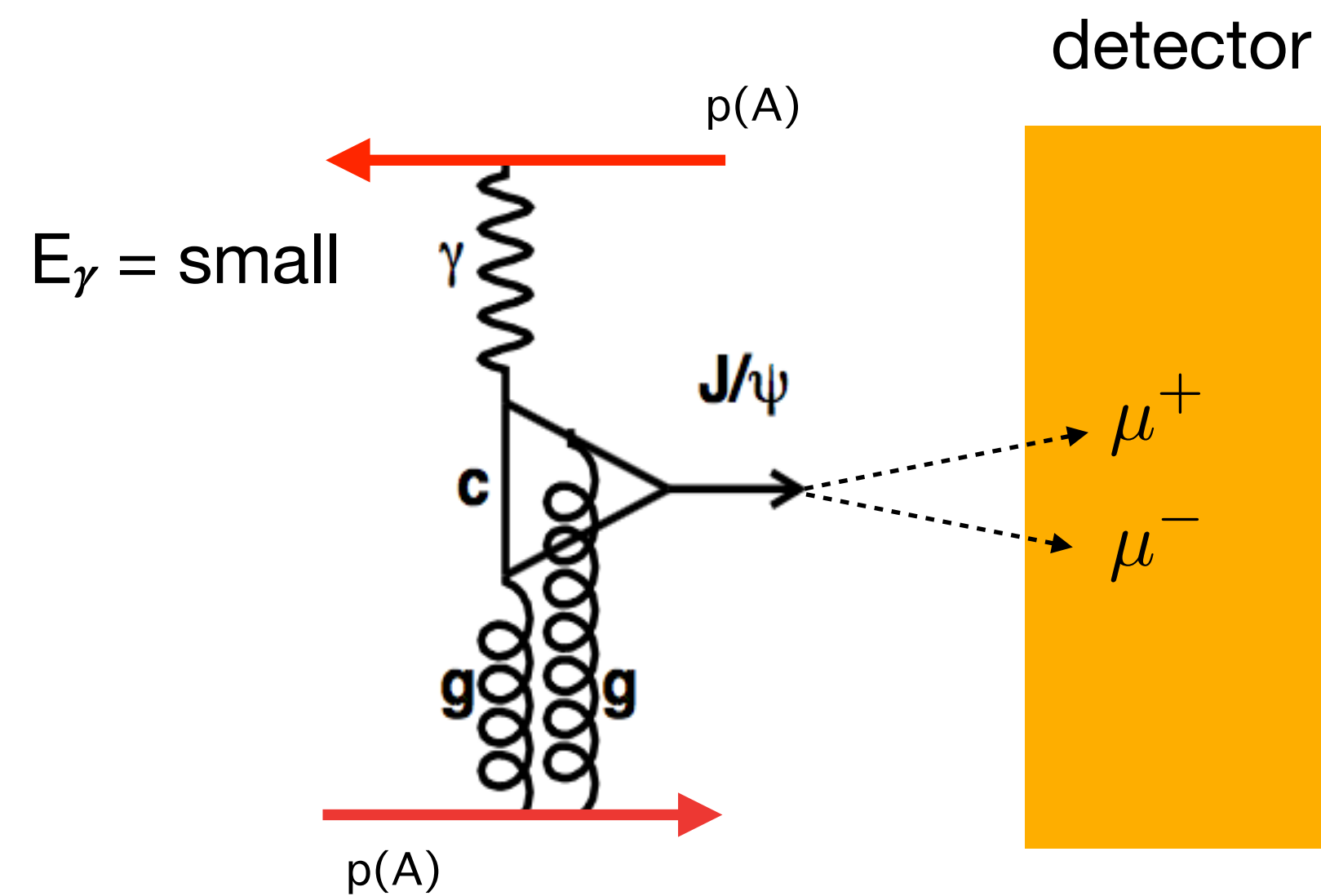


Disentangling the ambiguity on the ID of the γ emitter

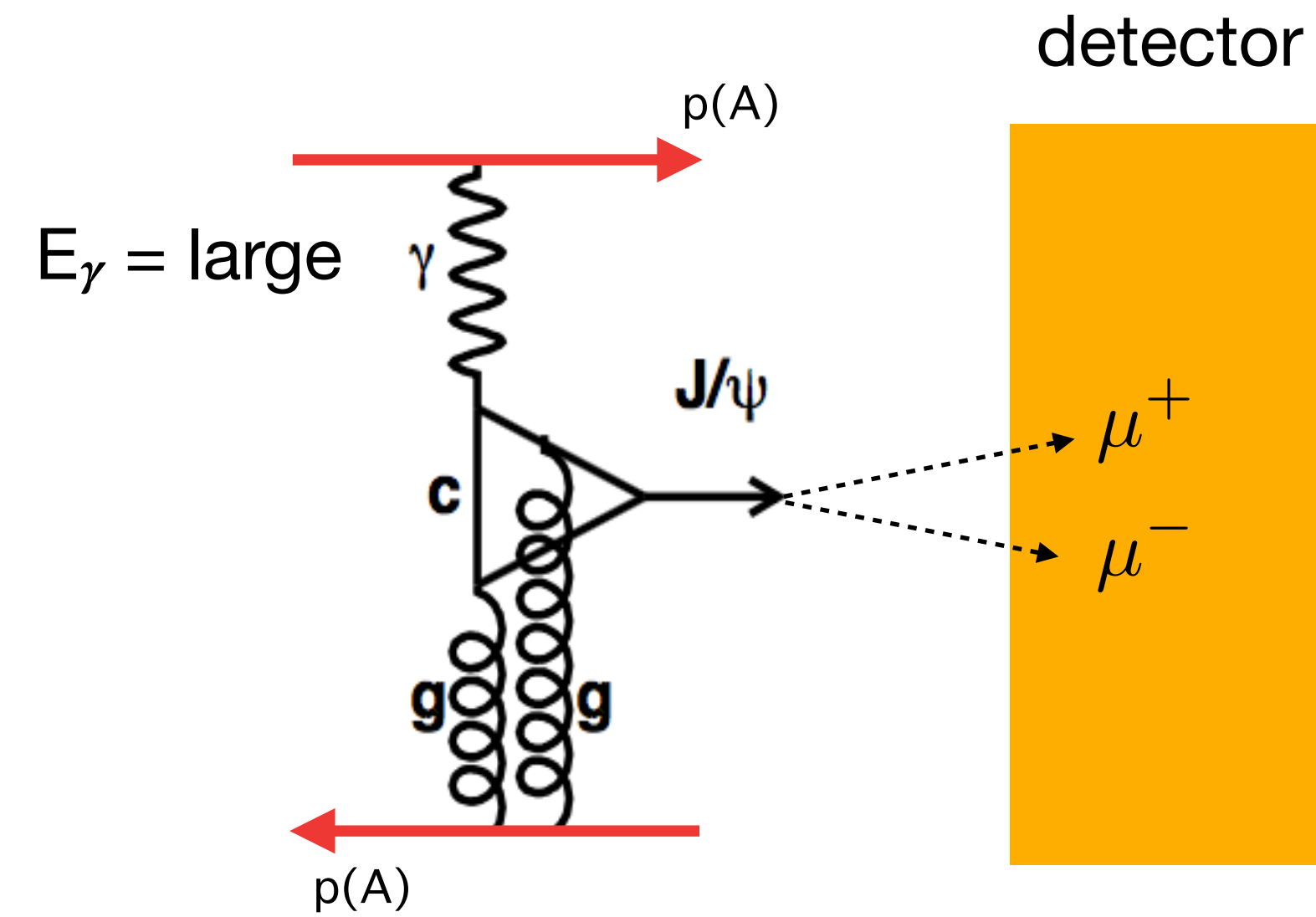


$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$

Disentangling the ambiguity on the ID of the γ emitter

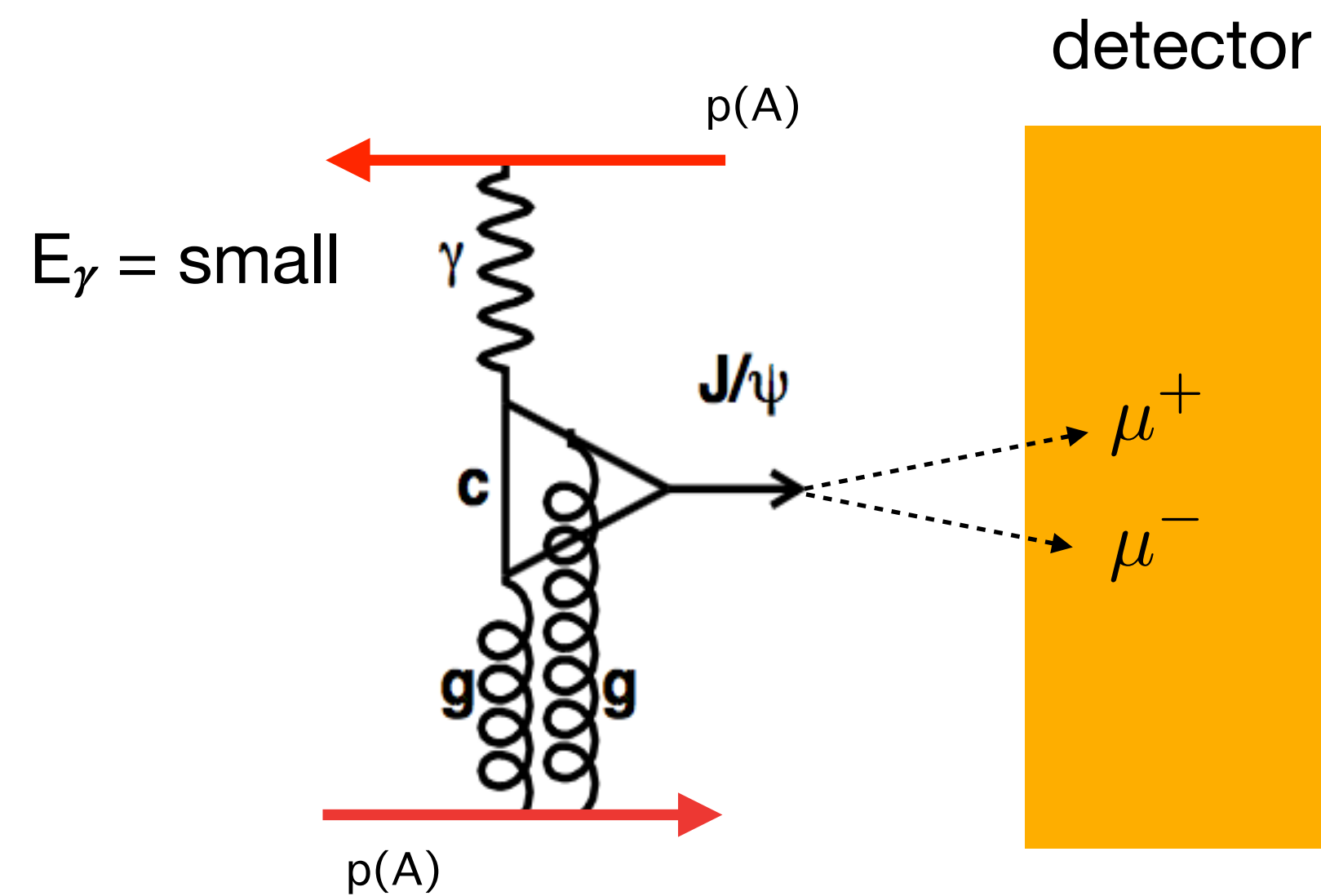


$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$

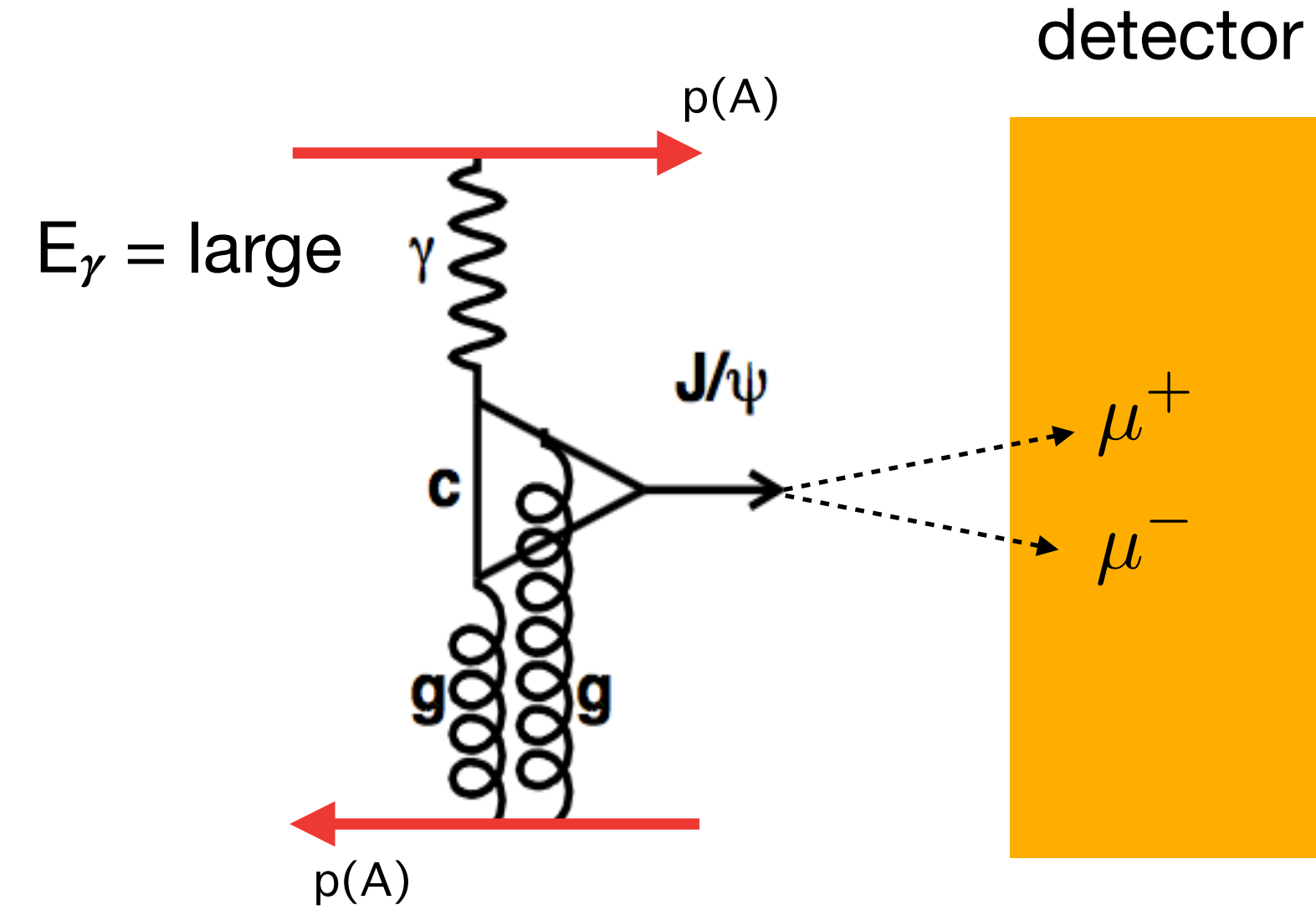


$$E_{\gamma,l} = \frac{M_{J/\psi}}{2} e^{+y}$$

Disentangling the ambiguity on the ID of the γ 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 γ emitter

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Disentangling the ambiguity on the ID of the γ emitter

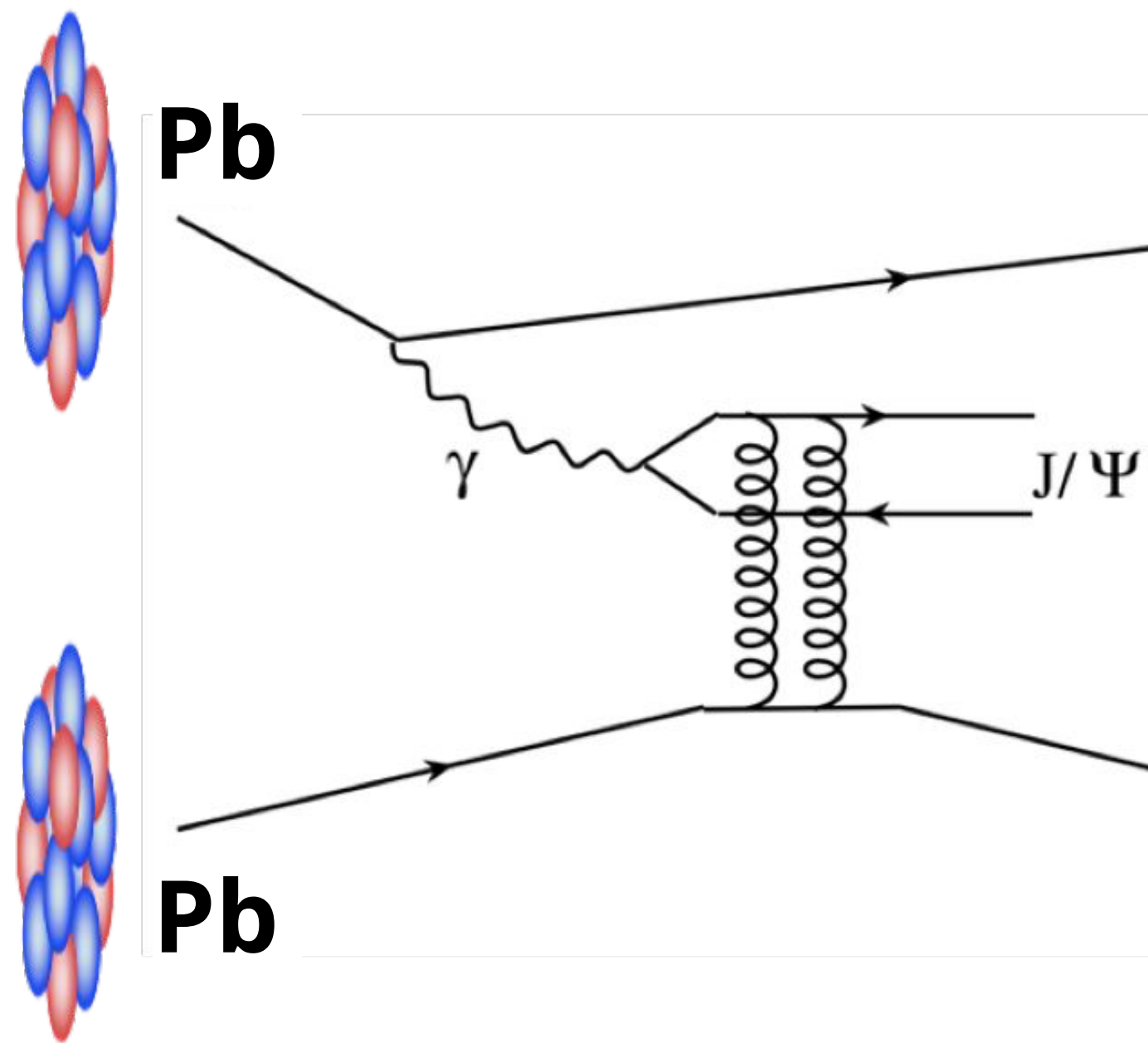
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Photon flux $N_{\gamma/A}(E_{\gamma})$ is function of impact parameter:
enhanced for large E_{γ} at small impact parameter.

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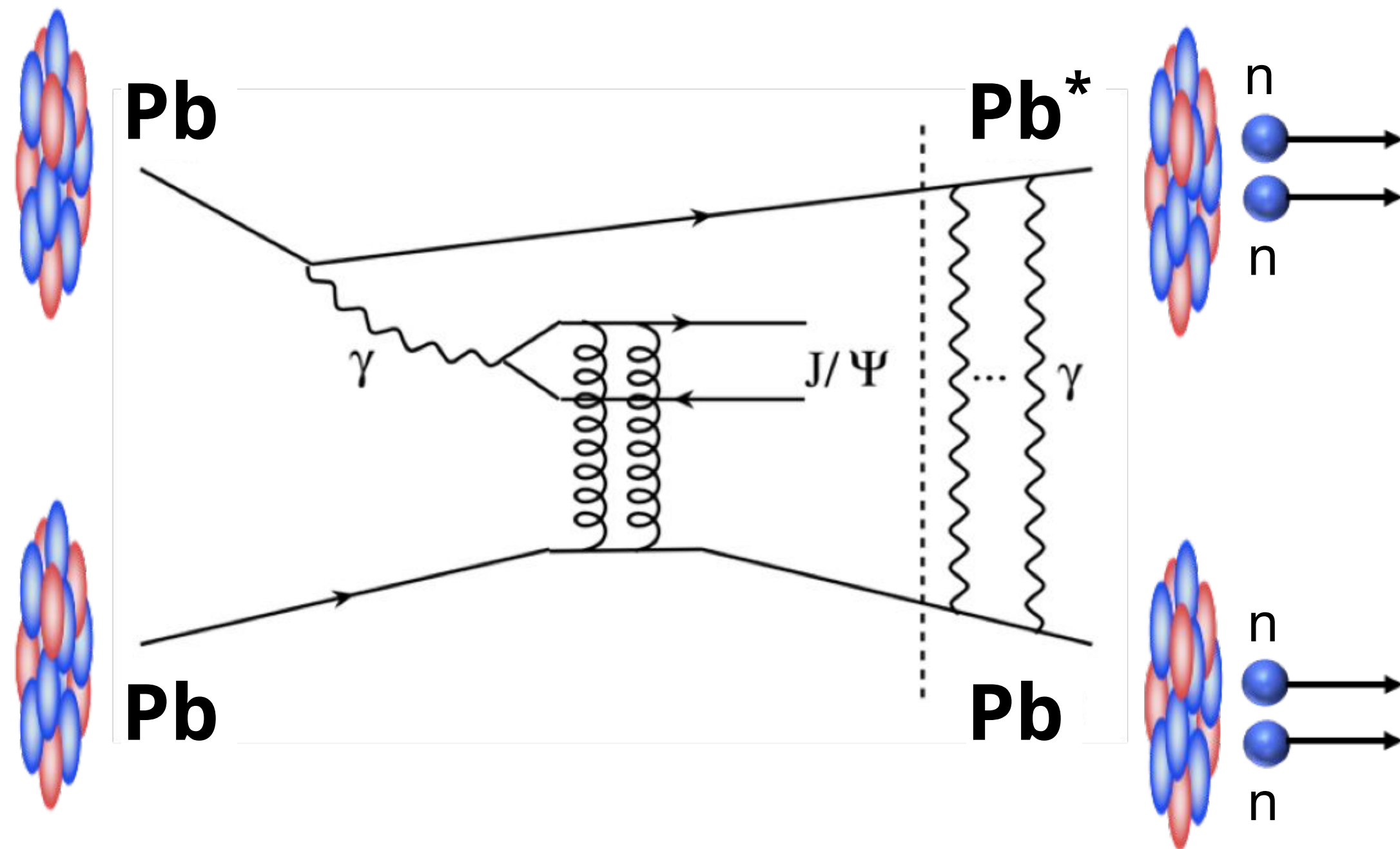


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Small impact parameter, $b \longrightarrow$ higher probability for exciting ($\propto 1/b^2$) $\longrightarrow$ higher probability to emit neutrons.

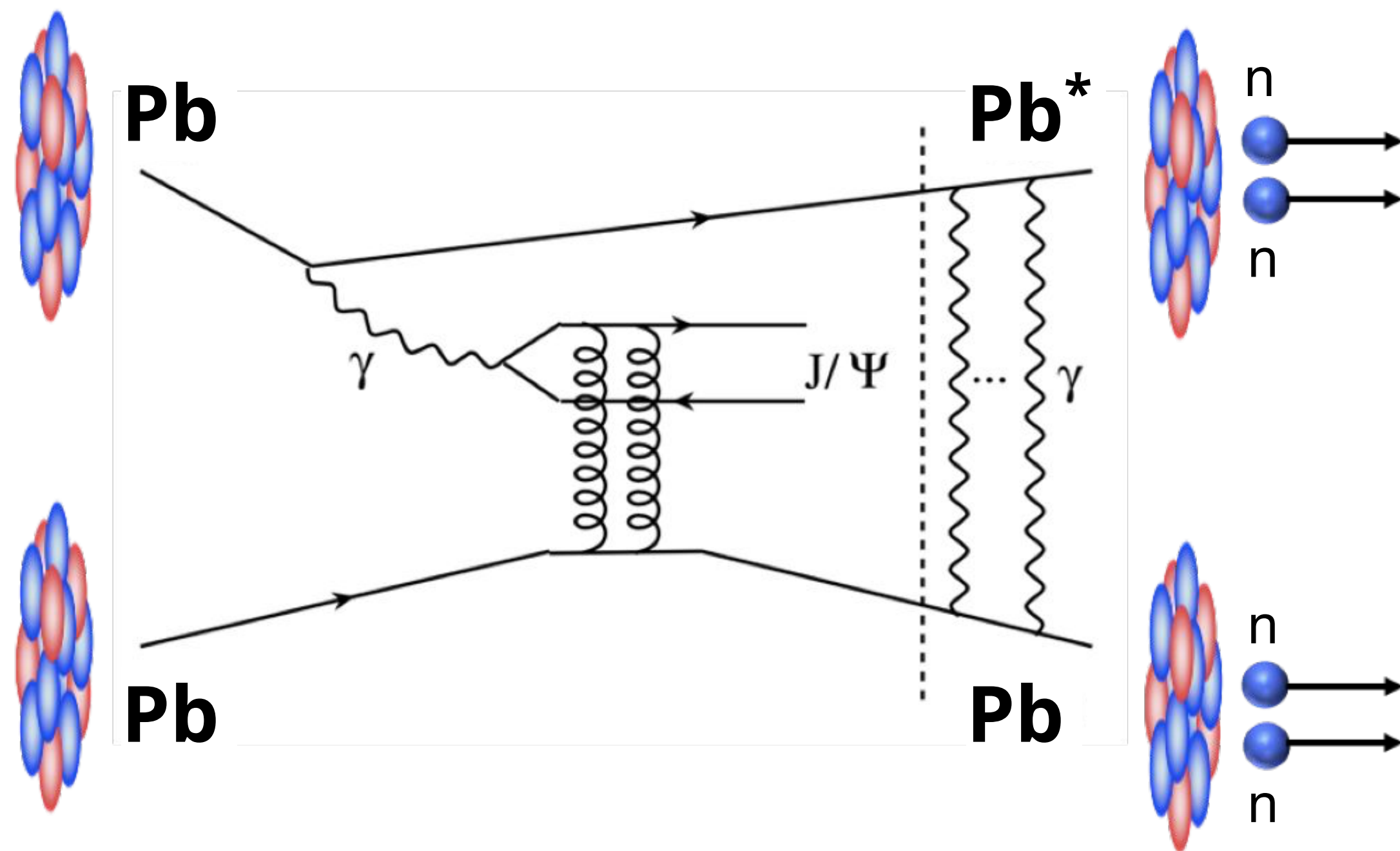


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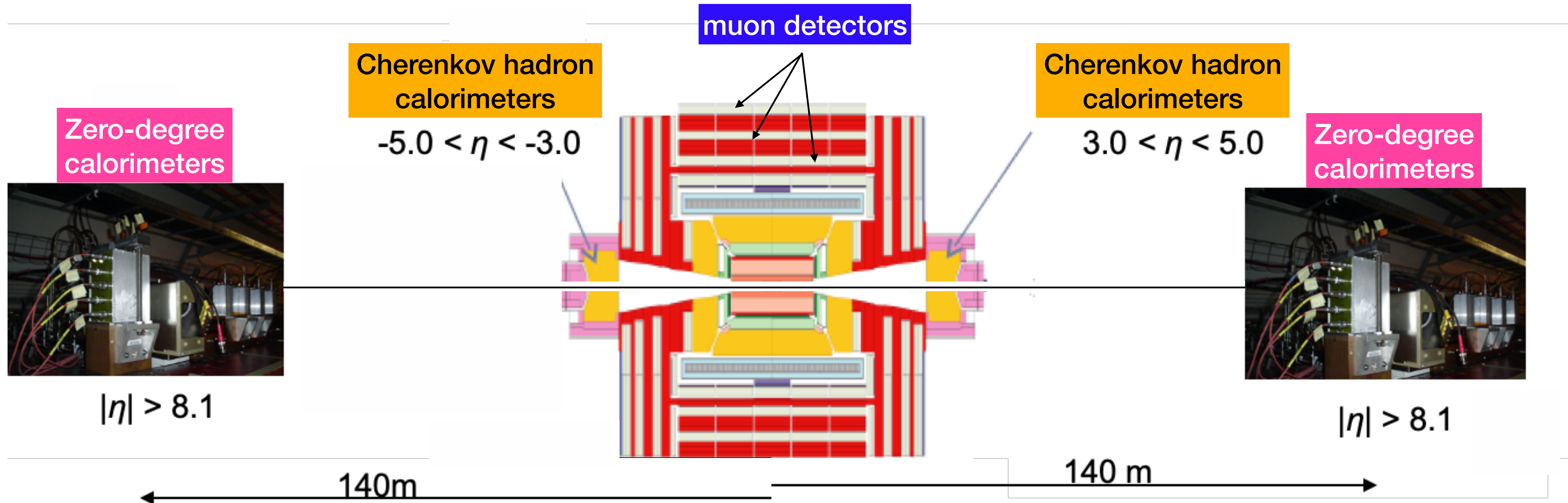
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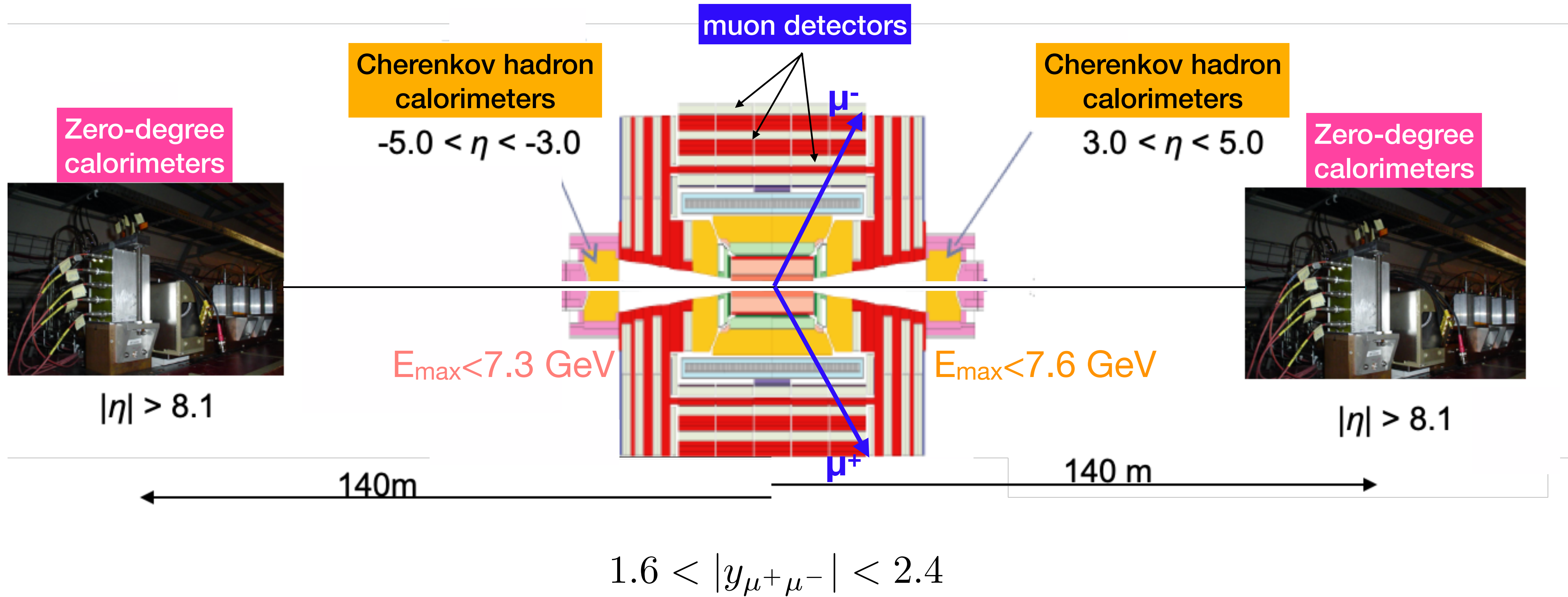


Make measurement with
possibility to detect neutrons

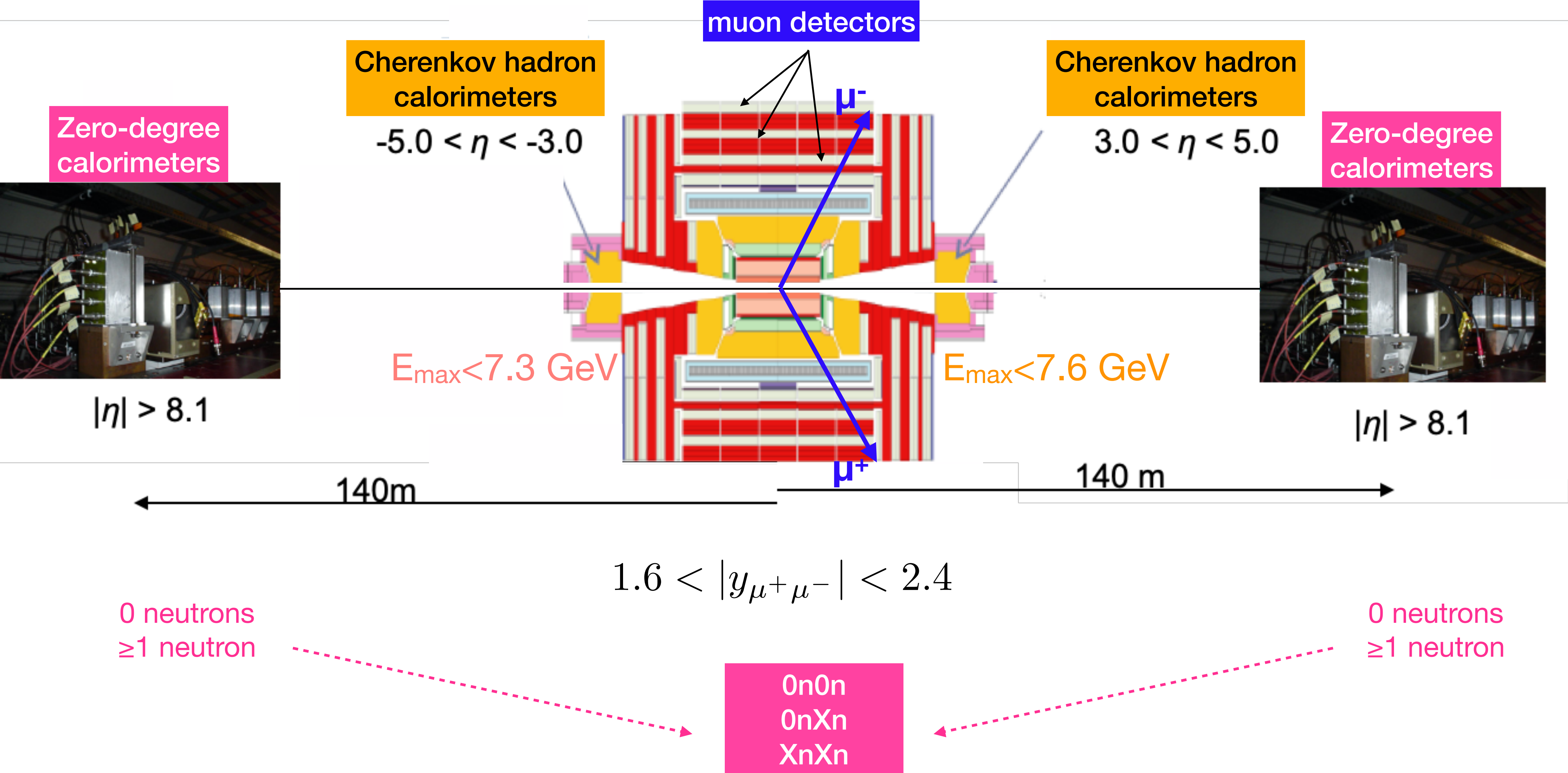
CMS central detector and the (far-)forward region



CMS central detector and the (far-)forward region



CMS central detector and the (far-)forward region



Disentangling the ambiguity on the ID of the γ emitter

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

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

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

measured

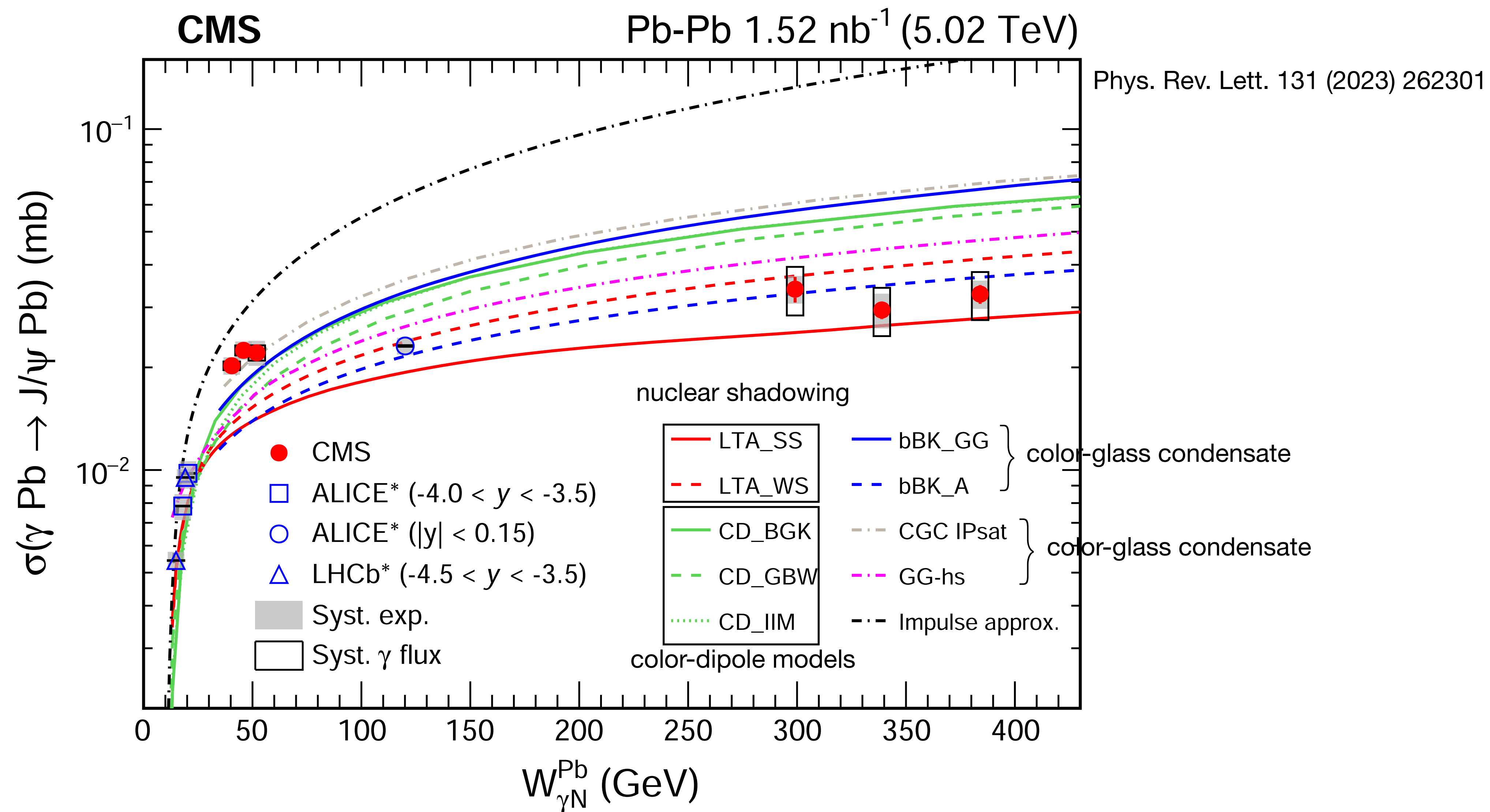
Disentangling the ambiguity on the ID of the γ emitter

$\sigma^{0n0n}(y)$	=	$N_{\gamma/A}^{0n0n}(E_{\gamma,s}) \sigma_{J/\psi}(E_{\gamma,s})$	+	$N_{\gamma/A}^{0n0n}(E_{\gamma,l}) \sigma_{J/\psi}(E_{\gamma,l})$
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measured		computed (StarLight)		computed (StarLight)

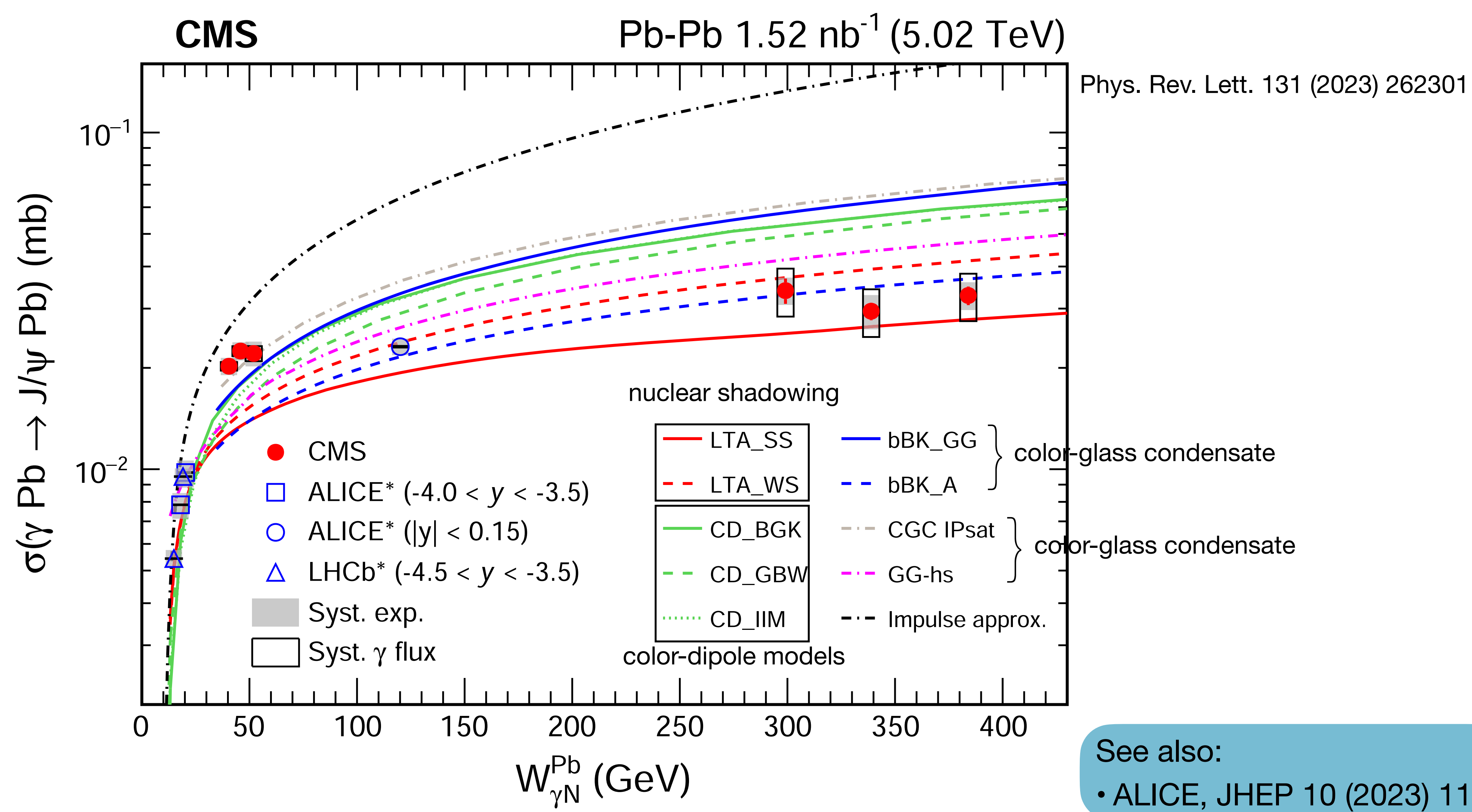
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$\sigma^{XnXn}(y)$	=	$N_{\gamma/A}^{XnXn}(E_{\gamma,s})$	$\sigma_{J/\psi}(E_{\gamma,s})$	+	$N_{\gamma/A}^{XnXn}(E_{\gamma,l})$	$\sigma_{J/\psi}(E_{\gamma,l})$
measured		computed (StarLight)	extracted		computed (StarLight)	extracted

CMS: γ Pb cross section, energy dependence

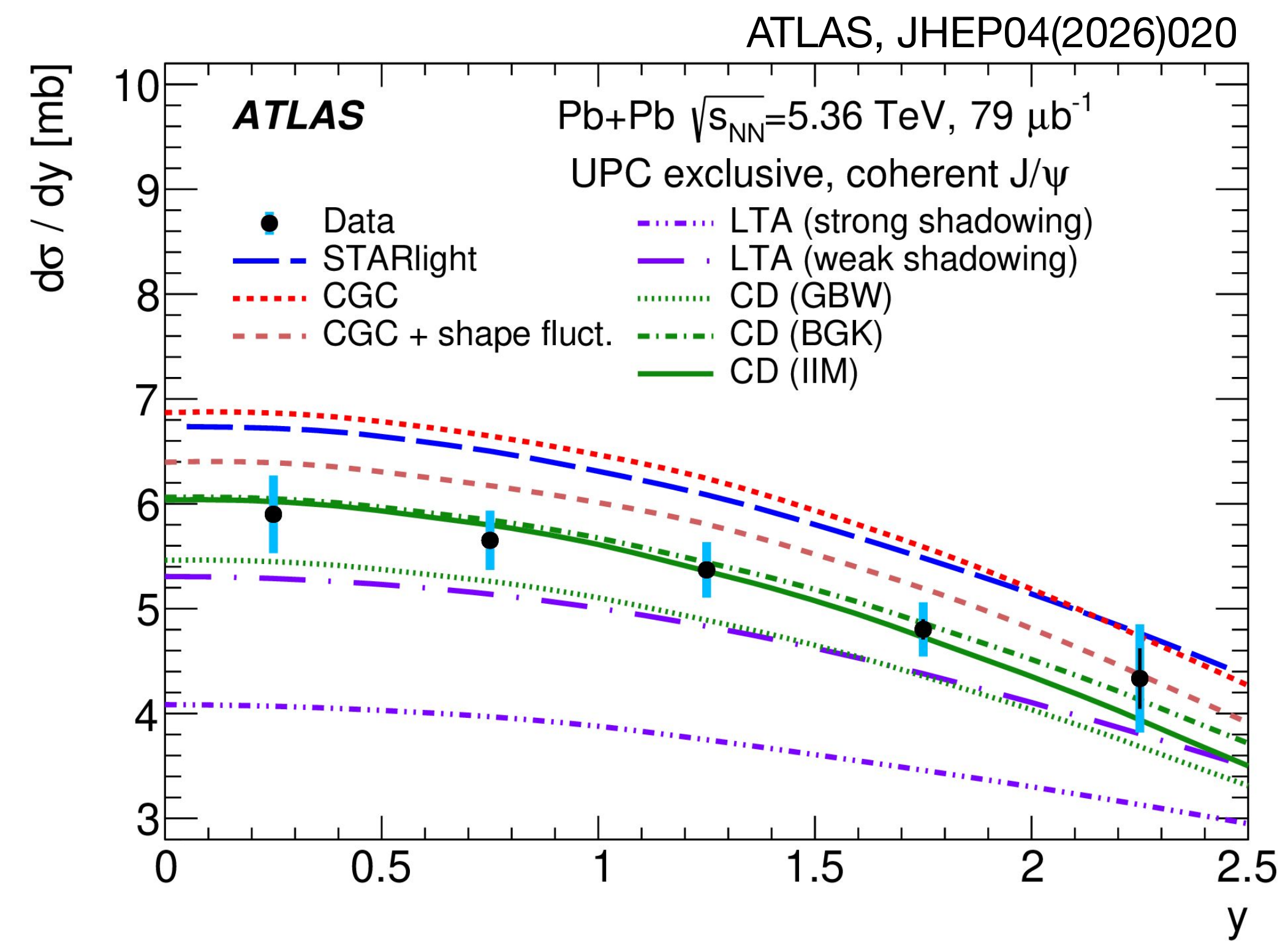
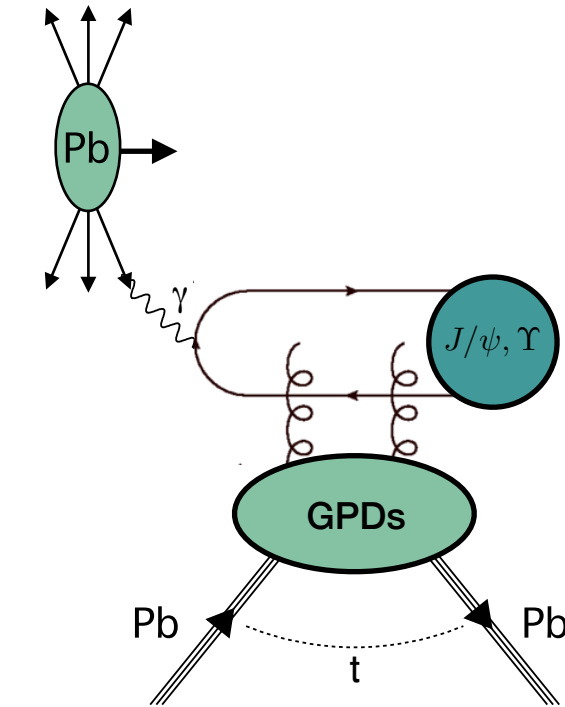


CMS: γ Pb cross section, energy dependence



See also:
• ALICE, JHEP 10 (2023) 119

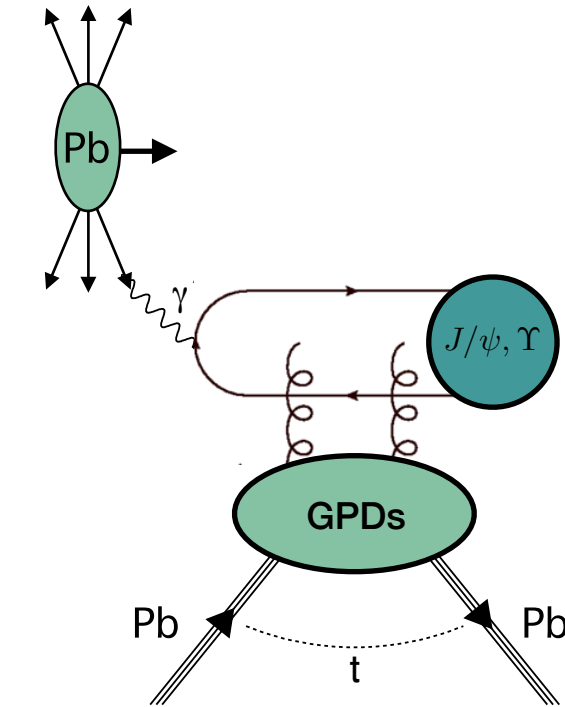
Coherent J/ψ production in PbPb collisions at the LHC



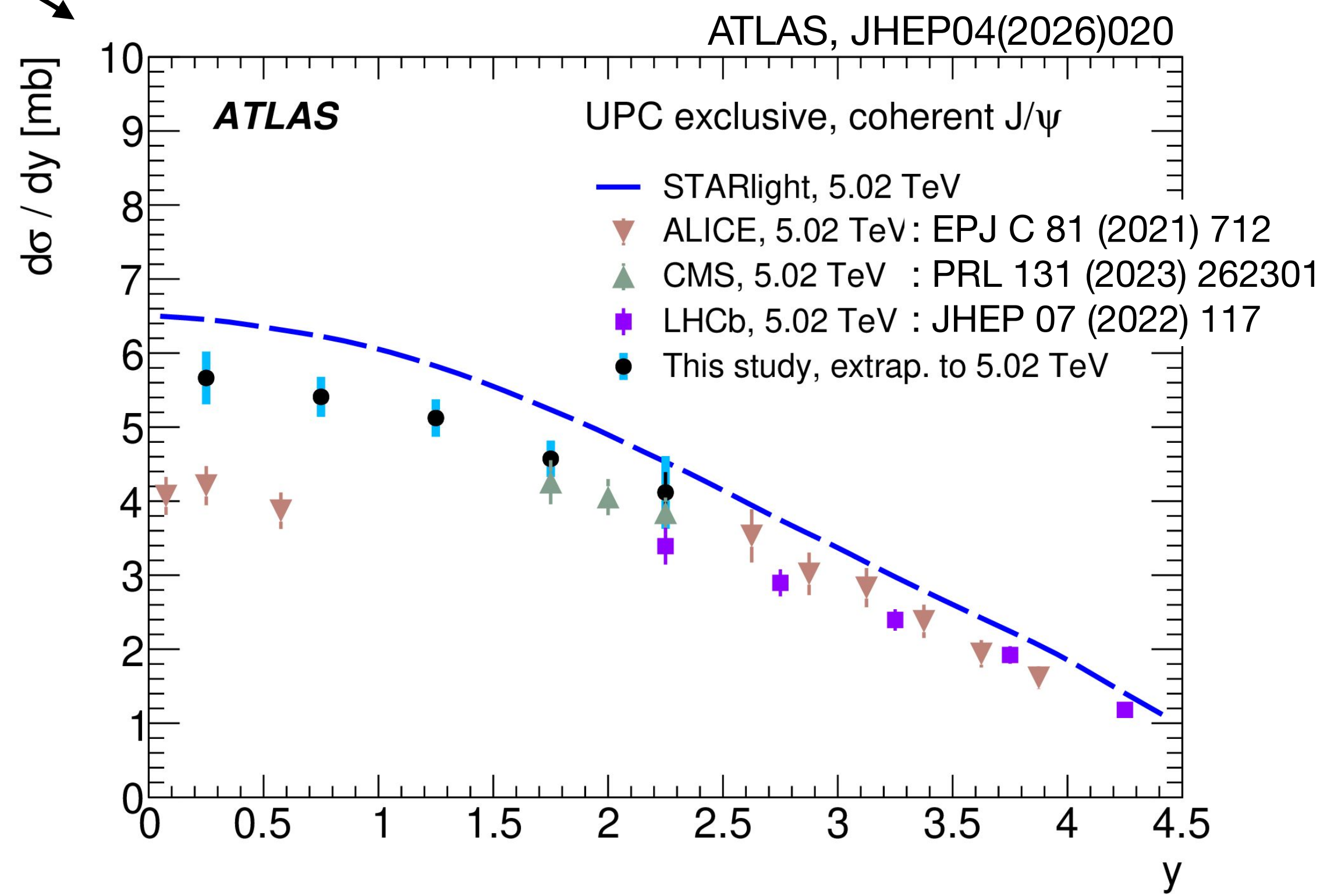
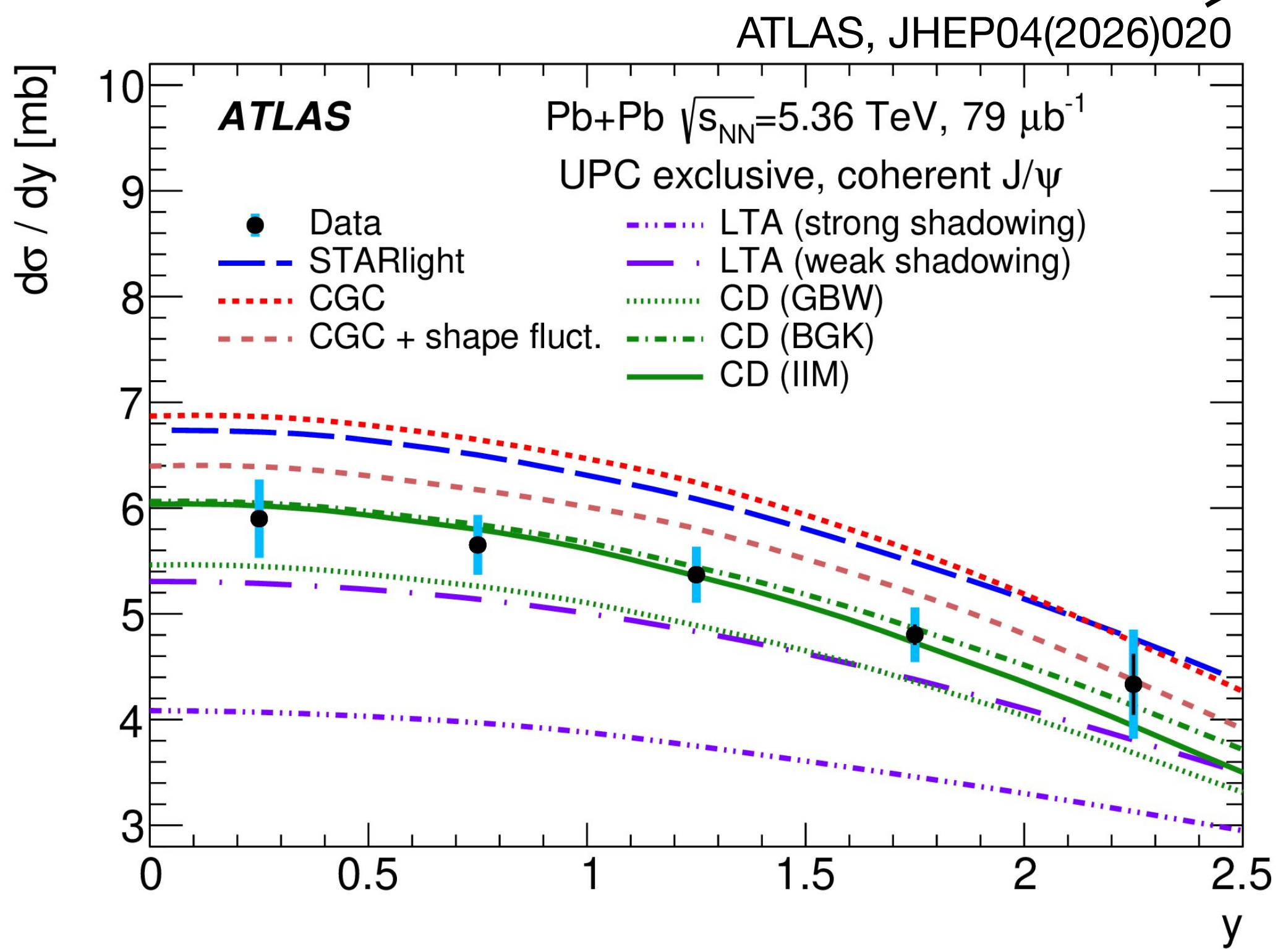
Results indicate significant nuclear shadowing

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

Coherent J/ψ production in PbPb collisions at the LHC



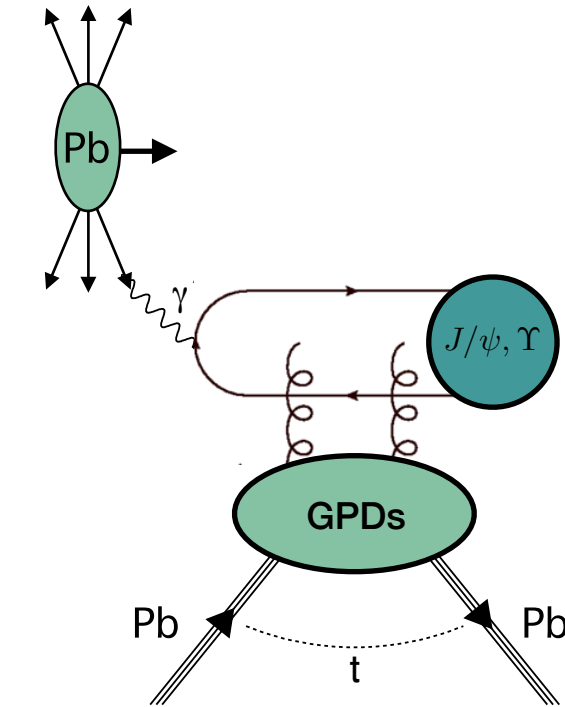
Scaling of the data to $\sqrt{s_{NN}} = 5.02$ TeV
with STARlight



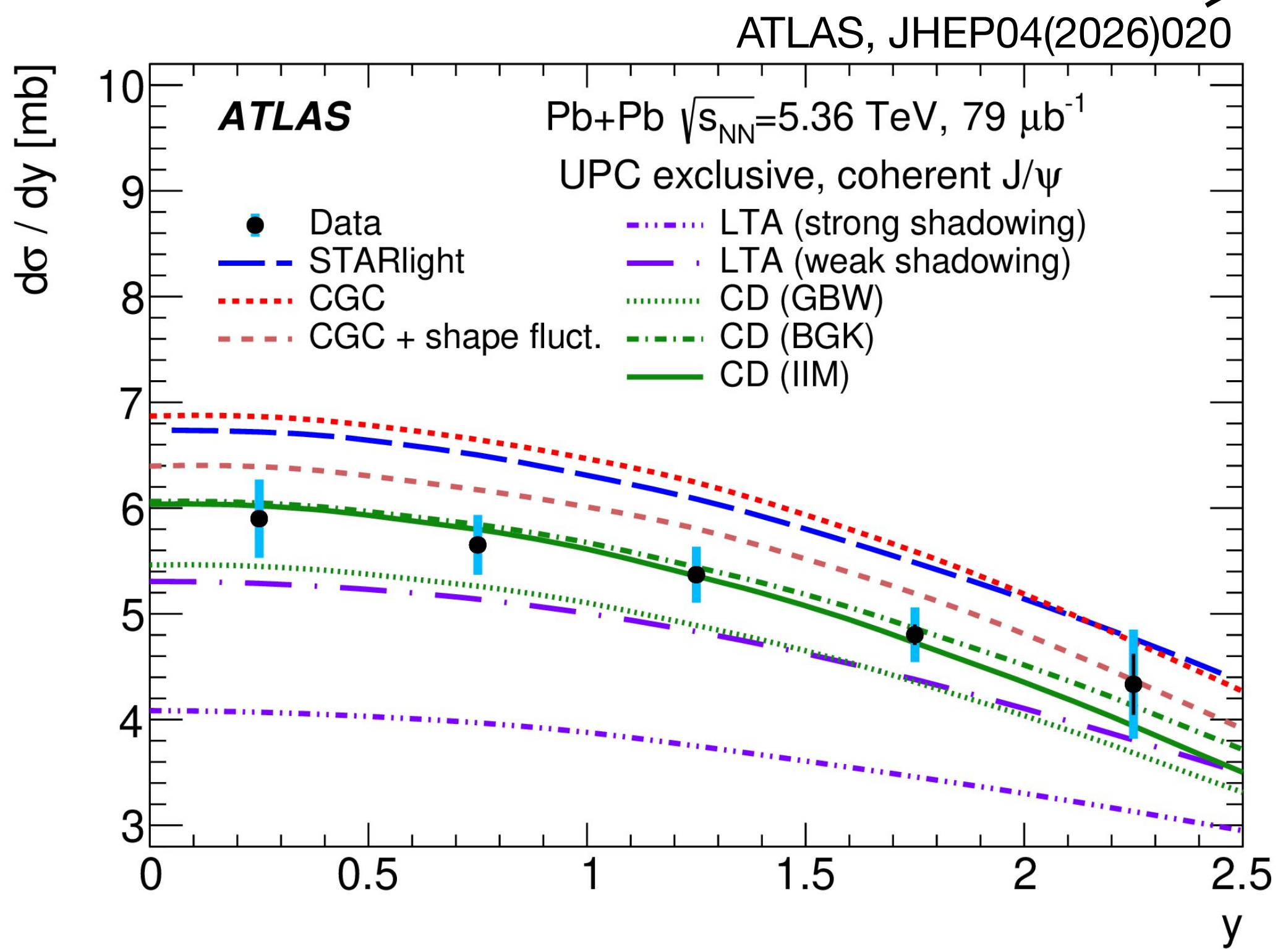
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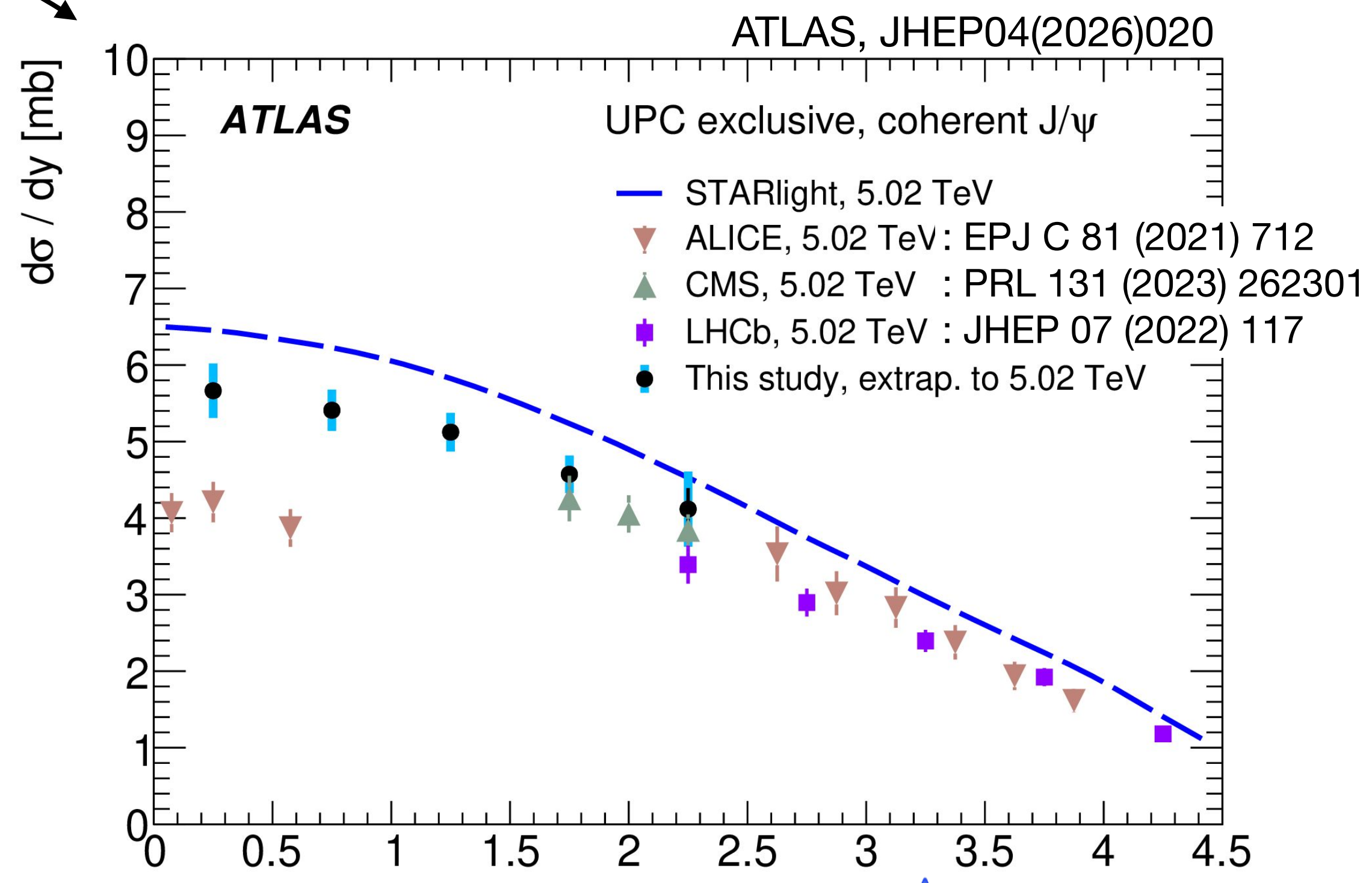
Coherent J/ψ production in PbPb collisions at the LHC



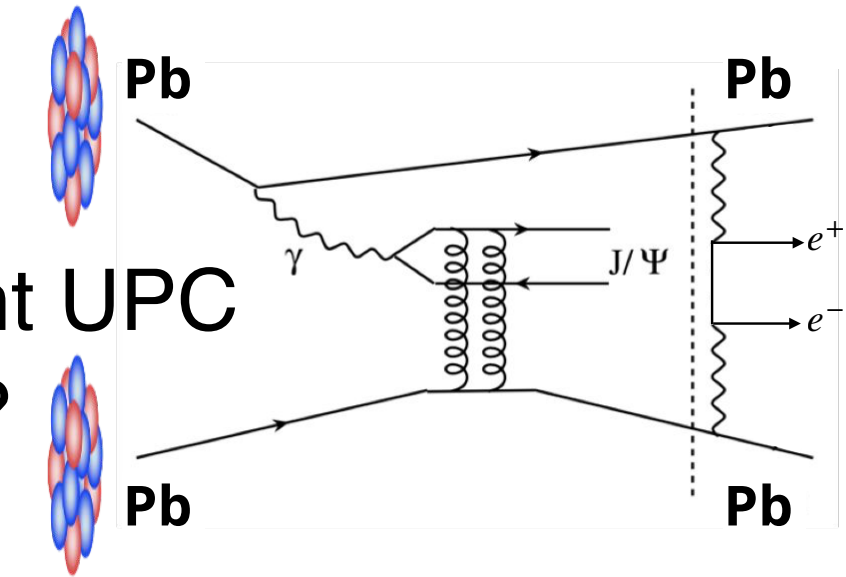
Scaling of the data to $\sqrt{s_{NN}} = 5.02$ TeV
with STARlight



Results indicate significant nuclear shadowing



- 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

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.