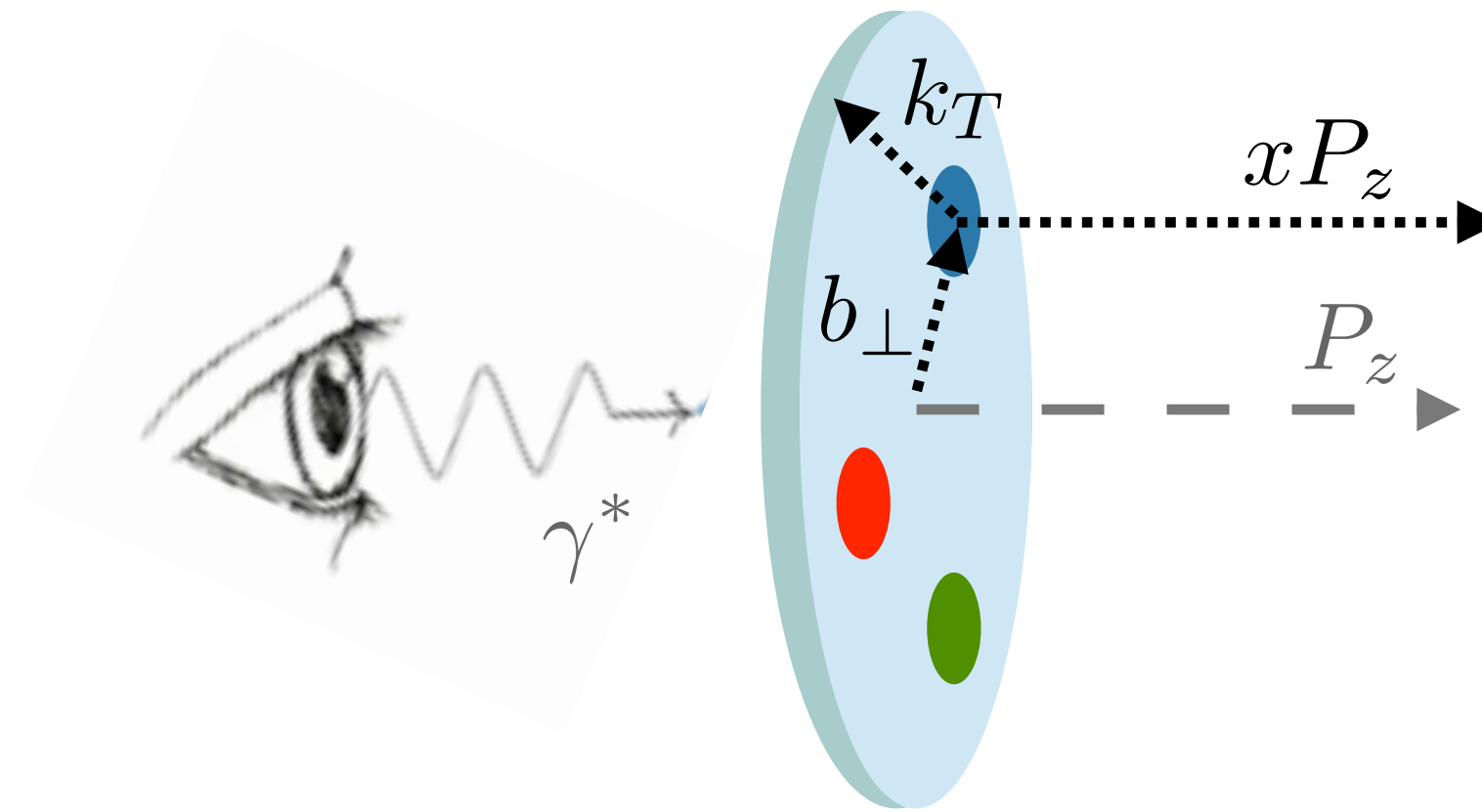


Nucleon tomography through the study of exclusive processes

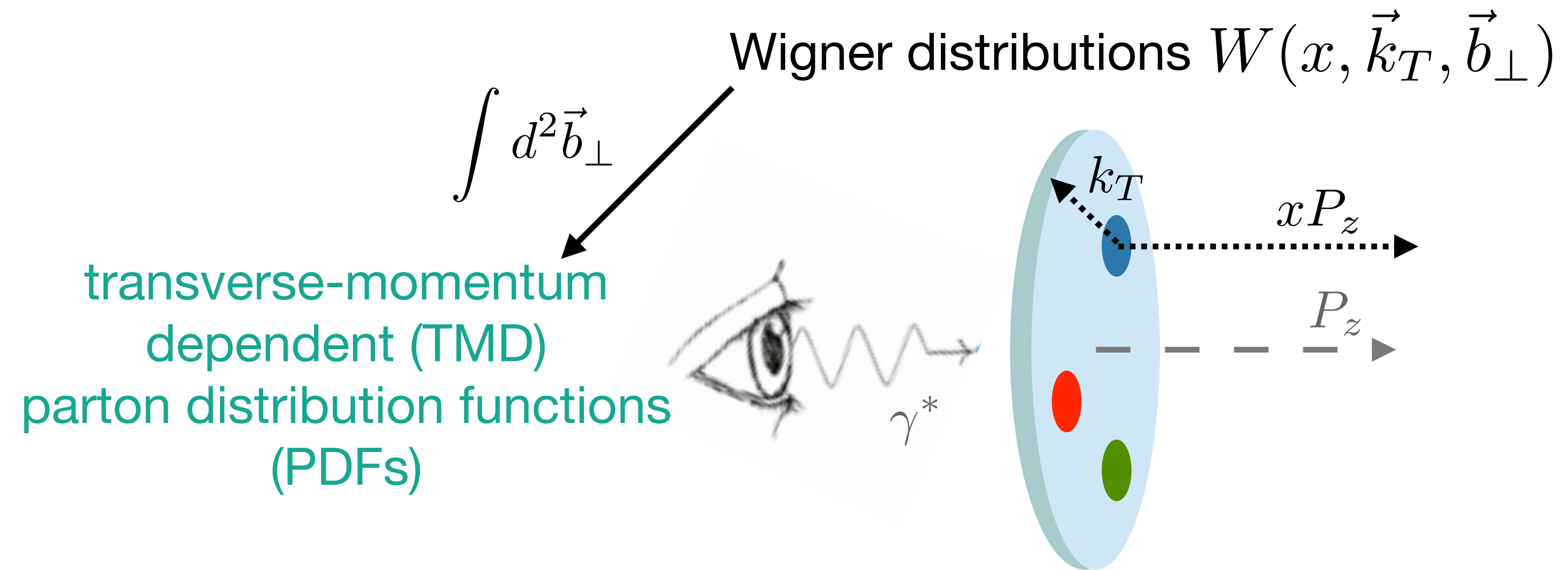
Charlotte Van Hulse
VUB

The various dimensions of the nucleon

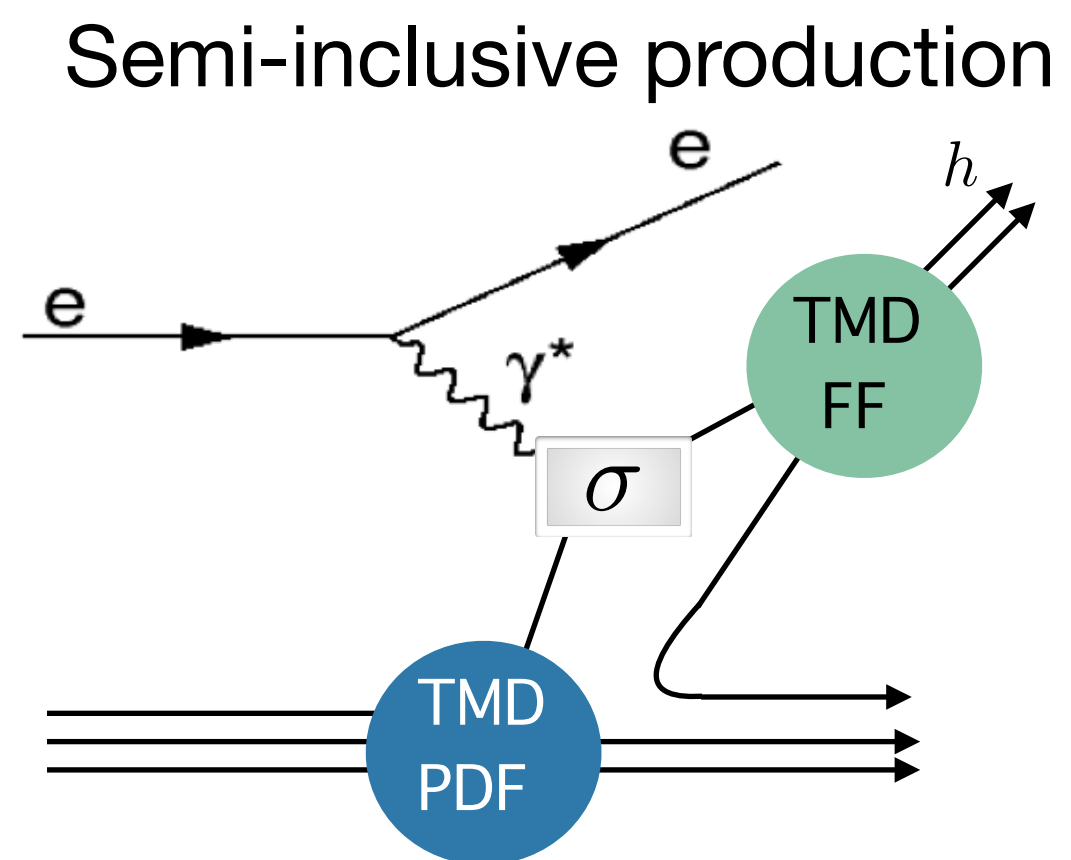
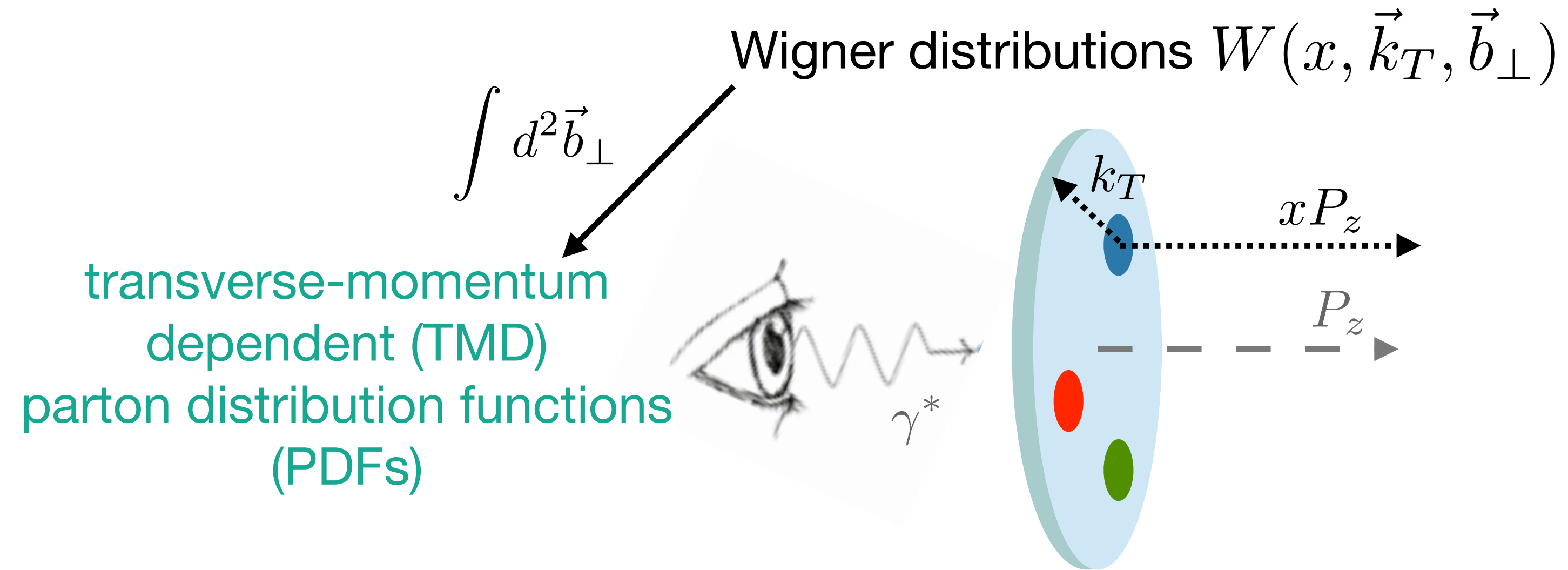
Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$



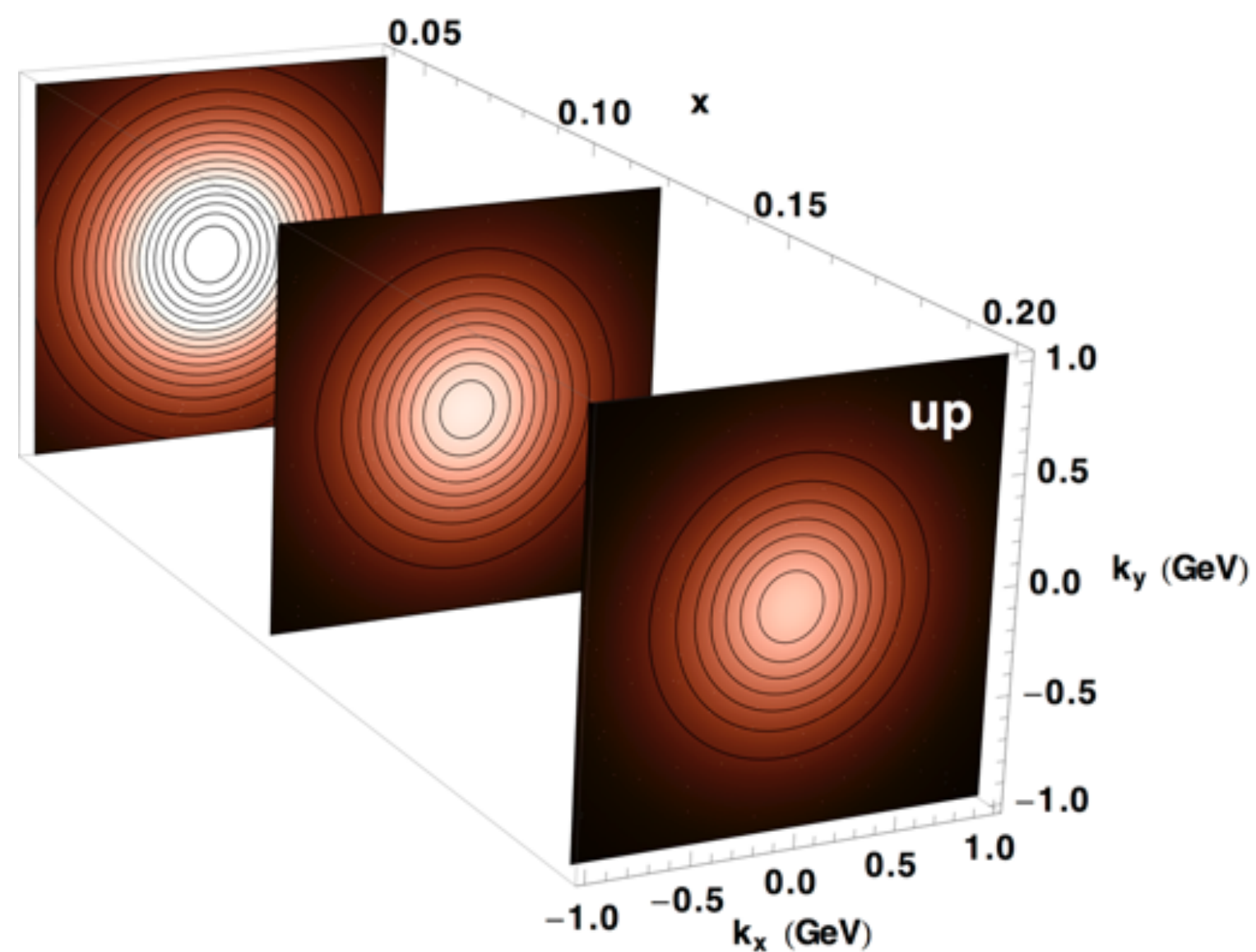
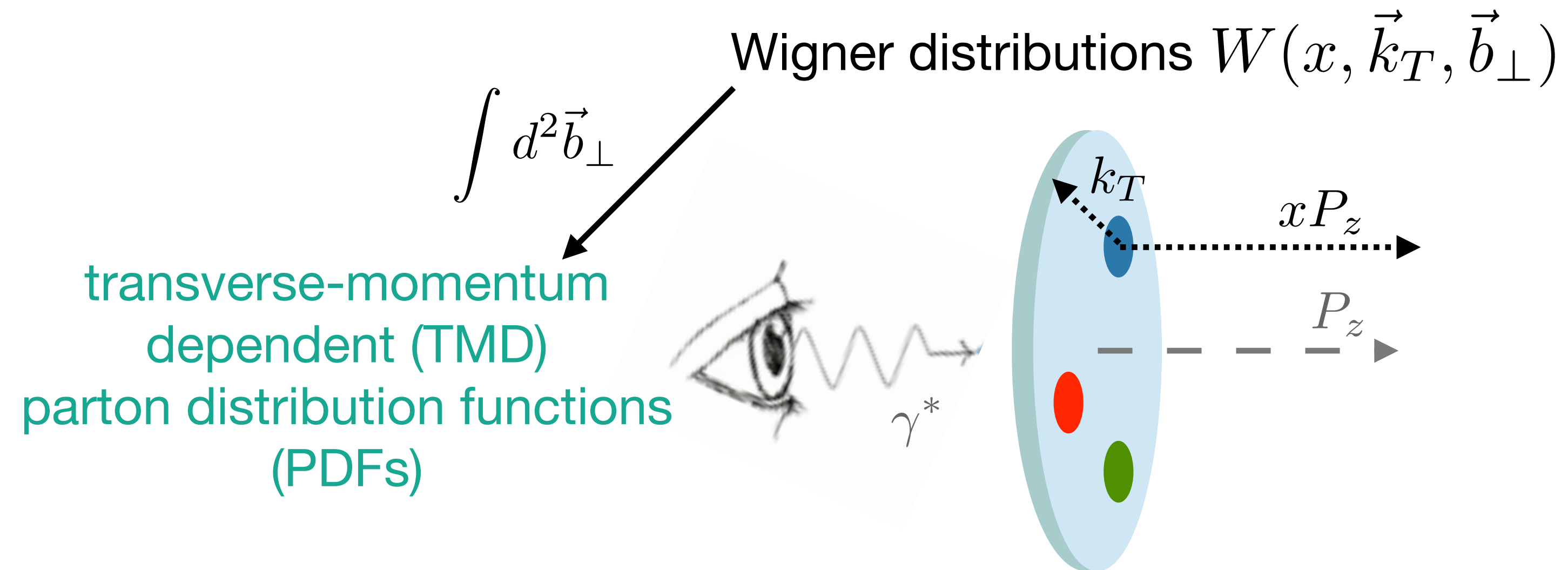
The various dimensions of the nucleon



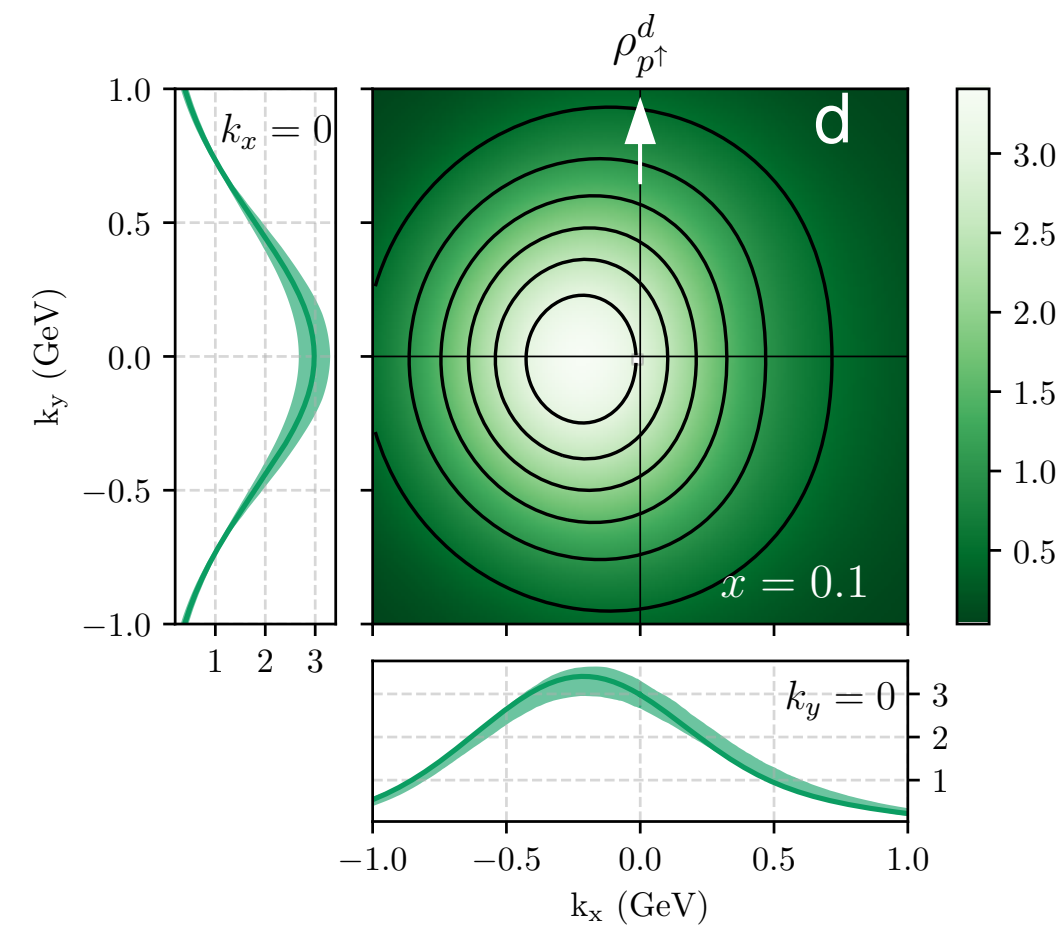
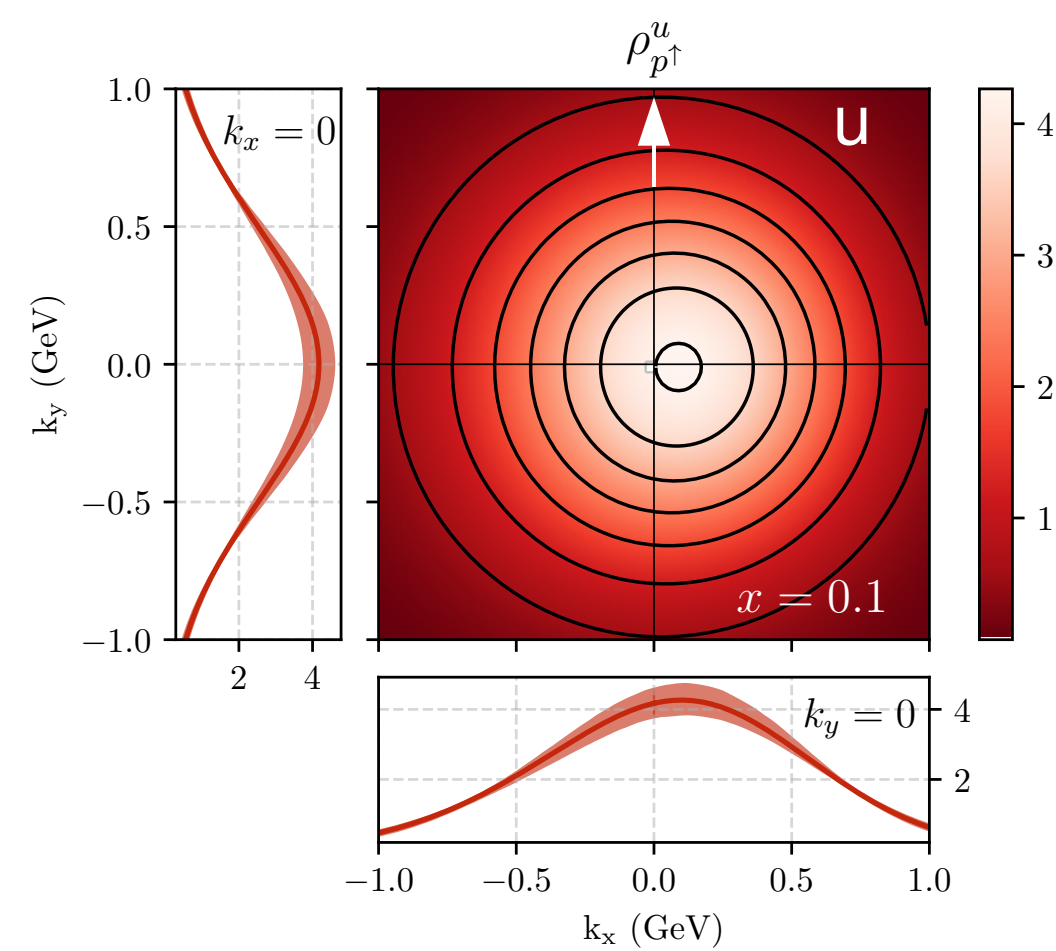
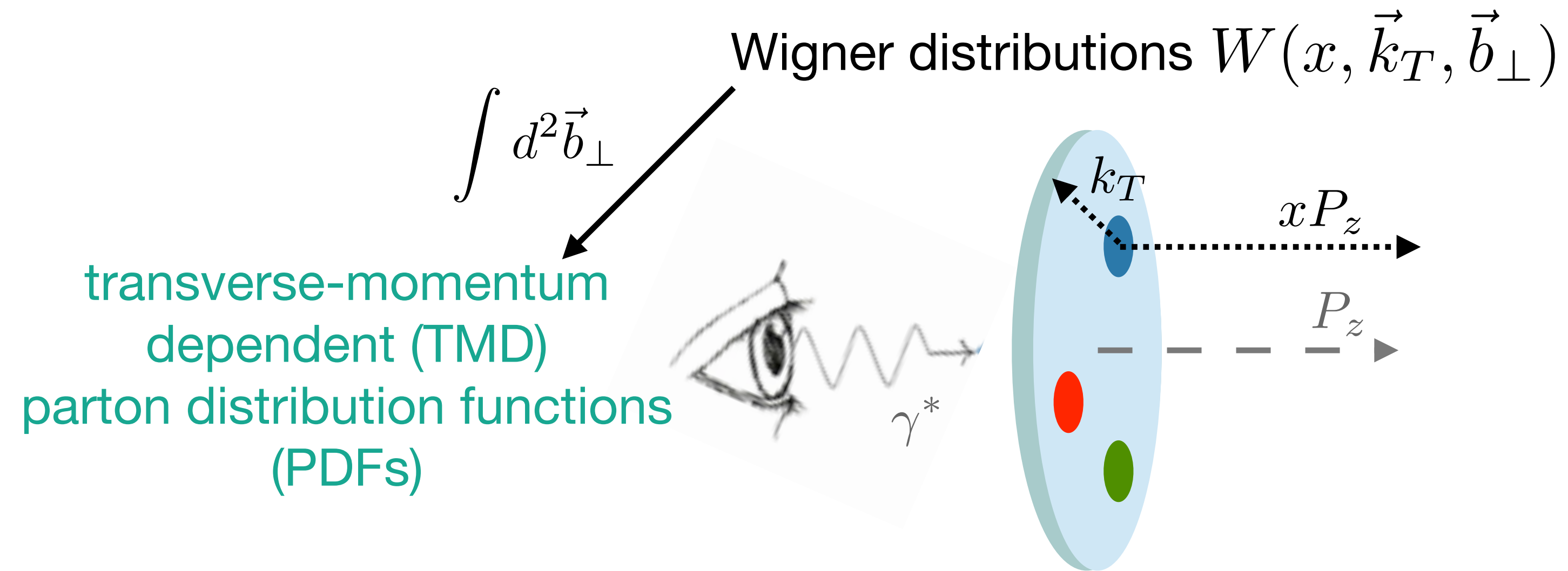
The various dimensions of the nucleon



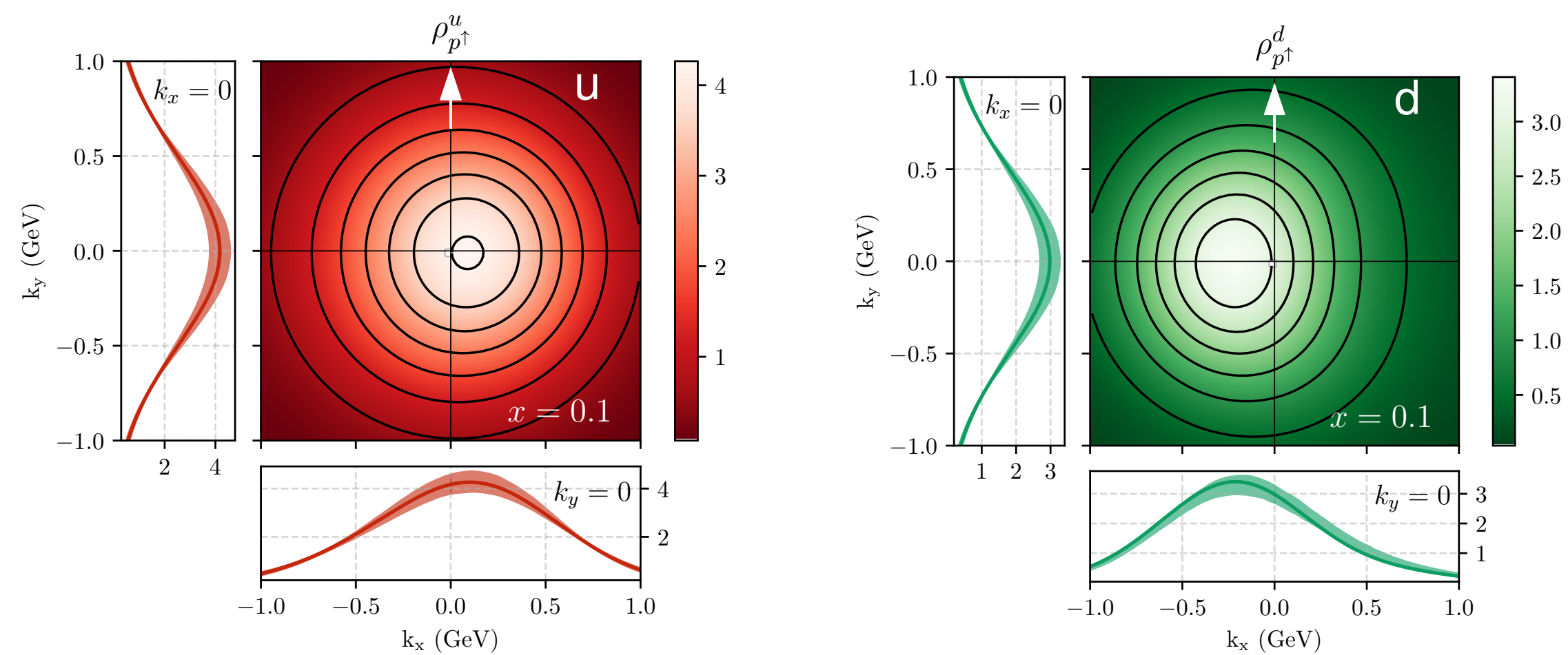
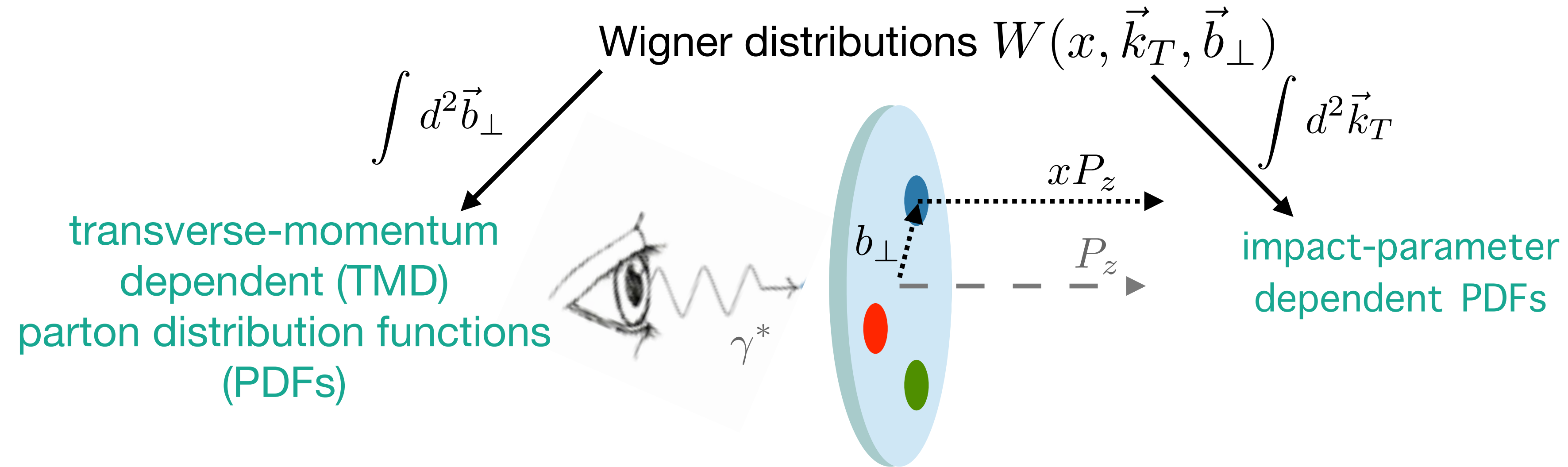
The various dimensions of the nucleon



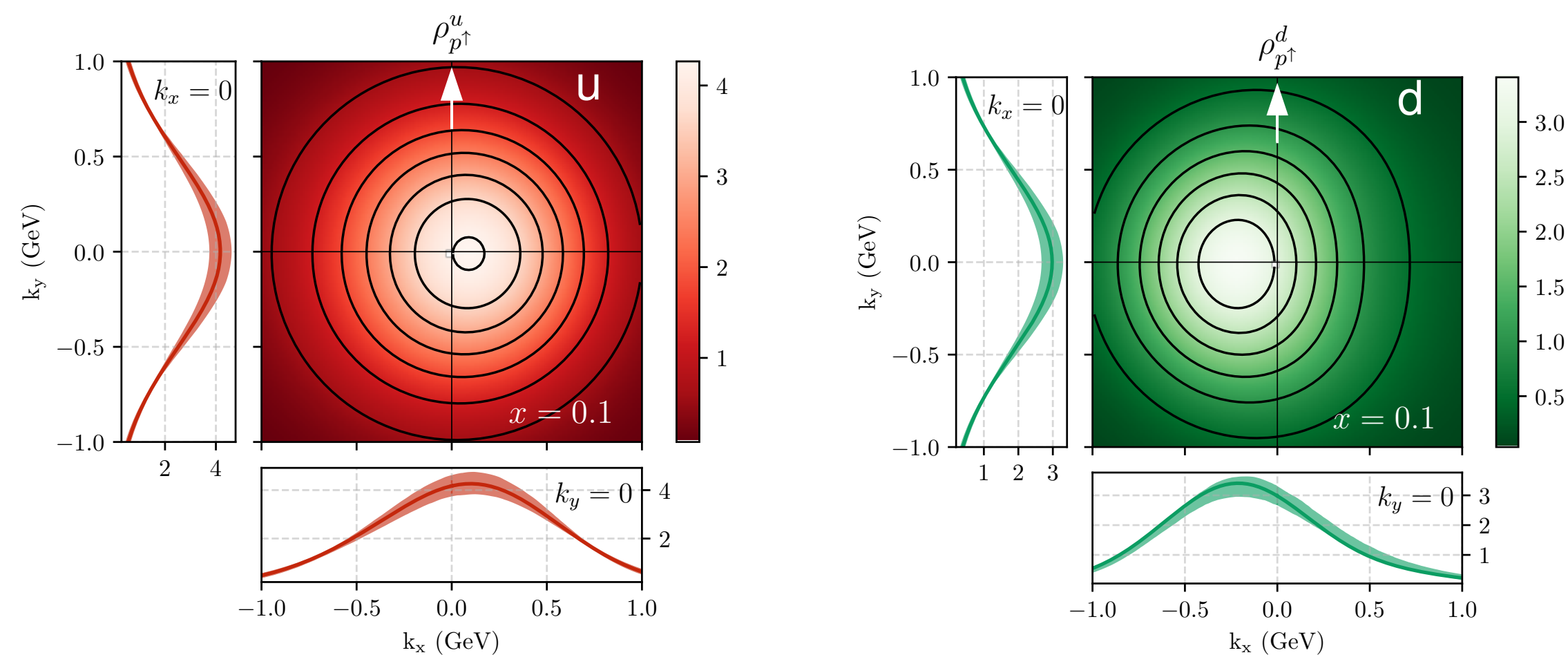
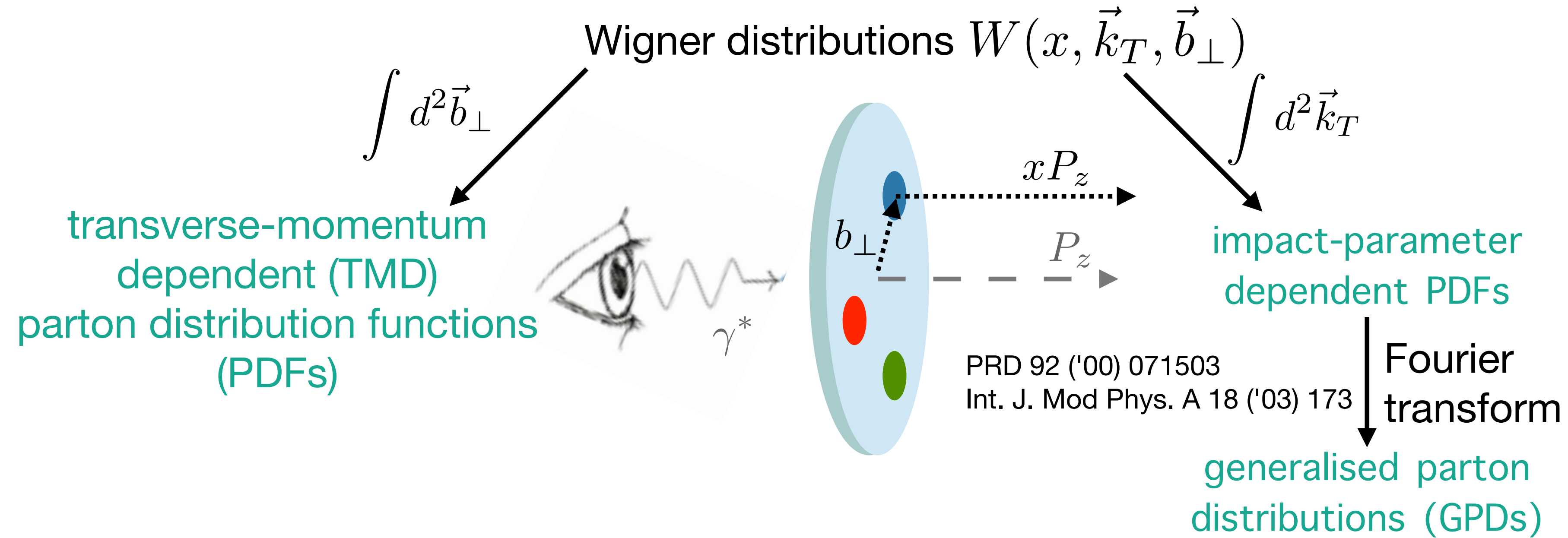
The various dimensions of the nucleon



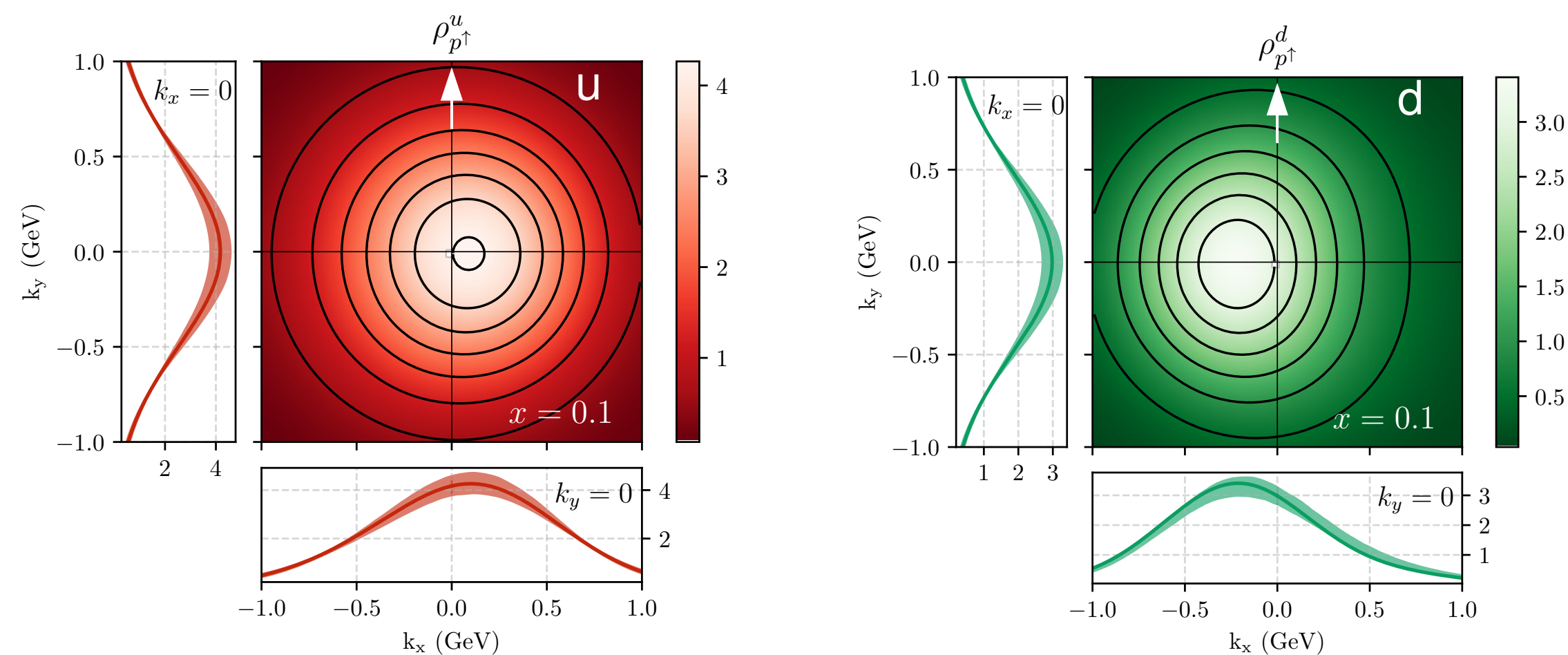
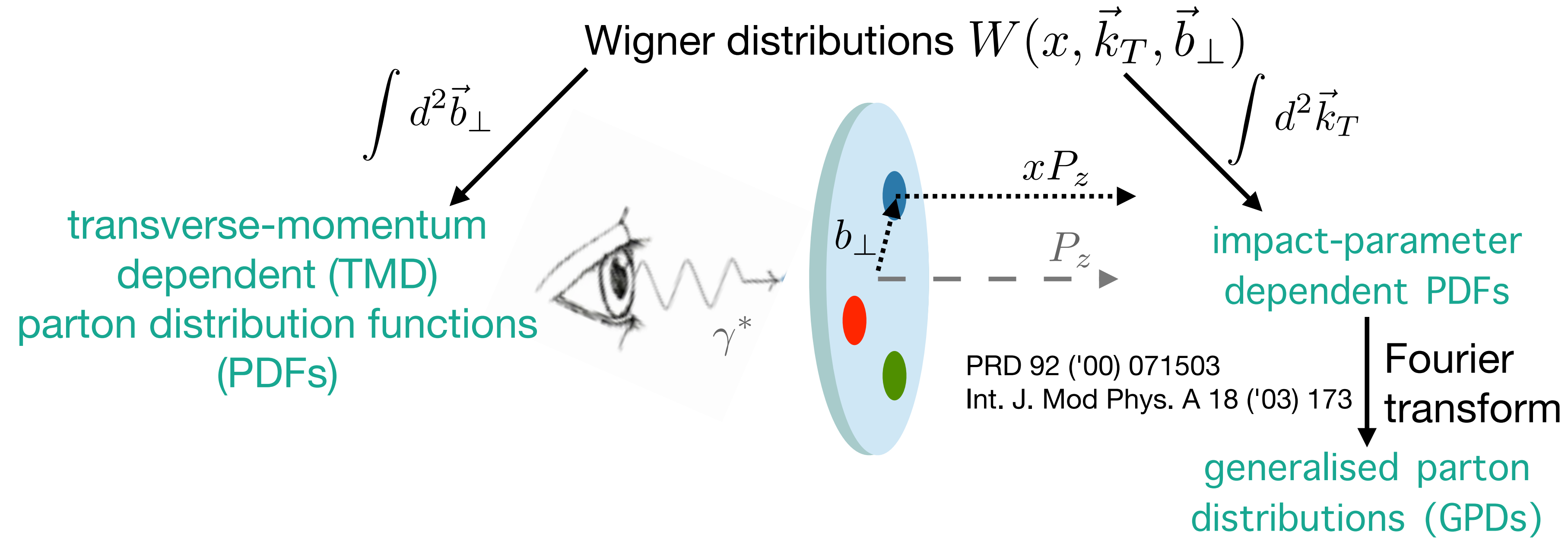
The various dimensions of the nucleon



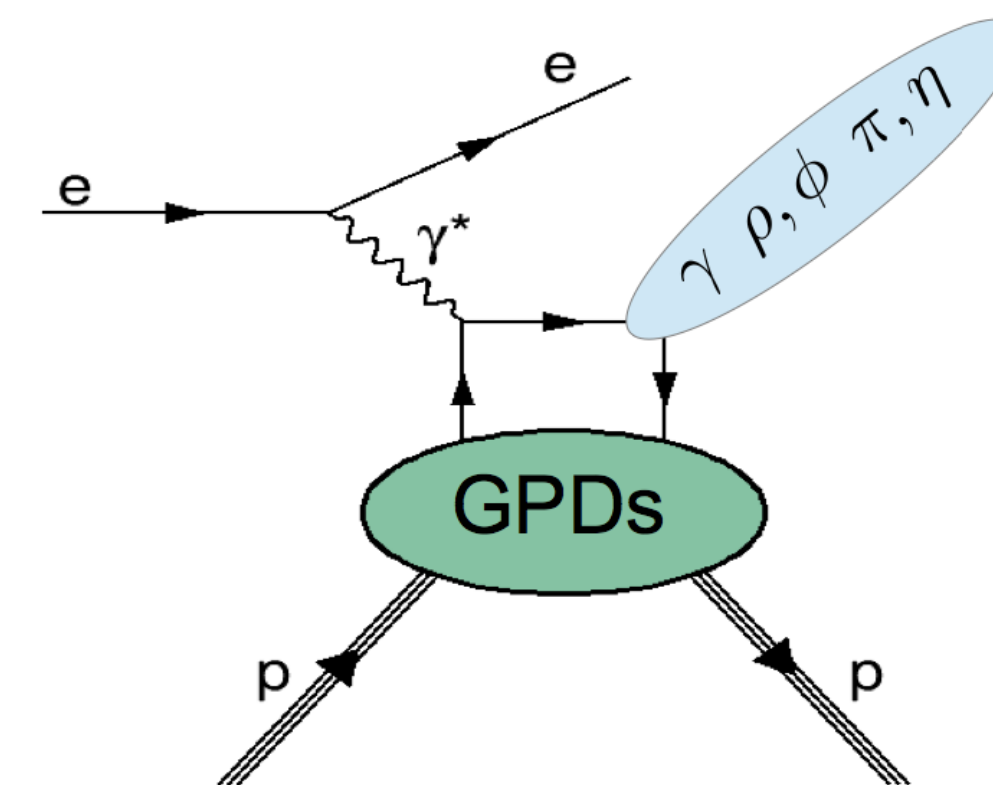
The various dimensions of the nucleon



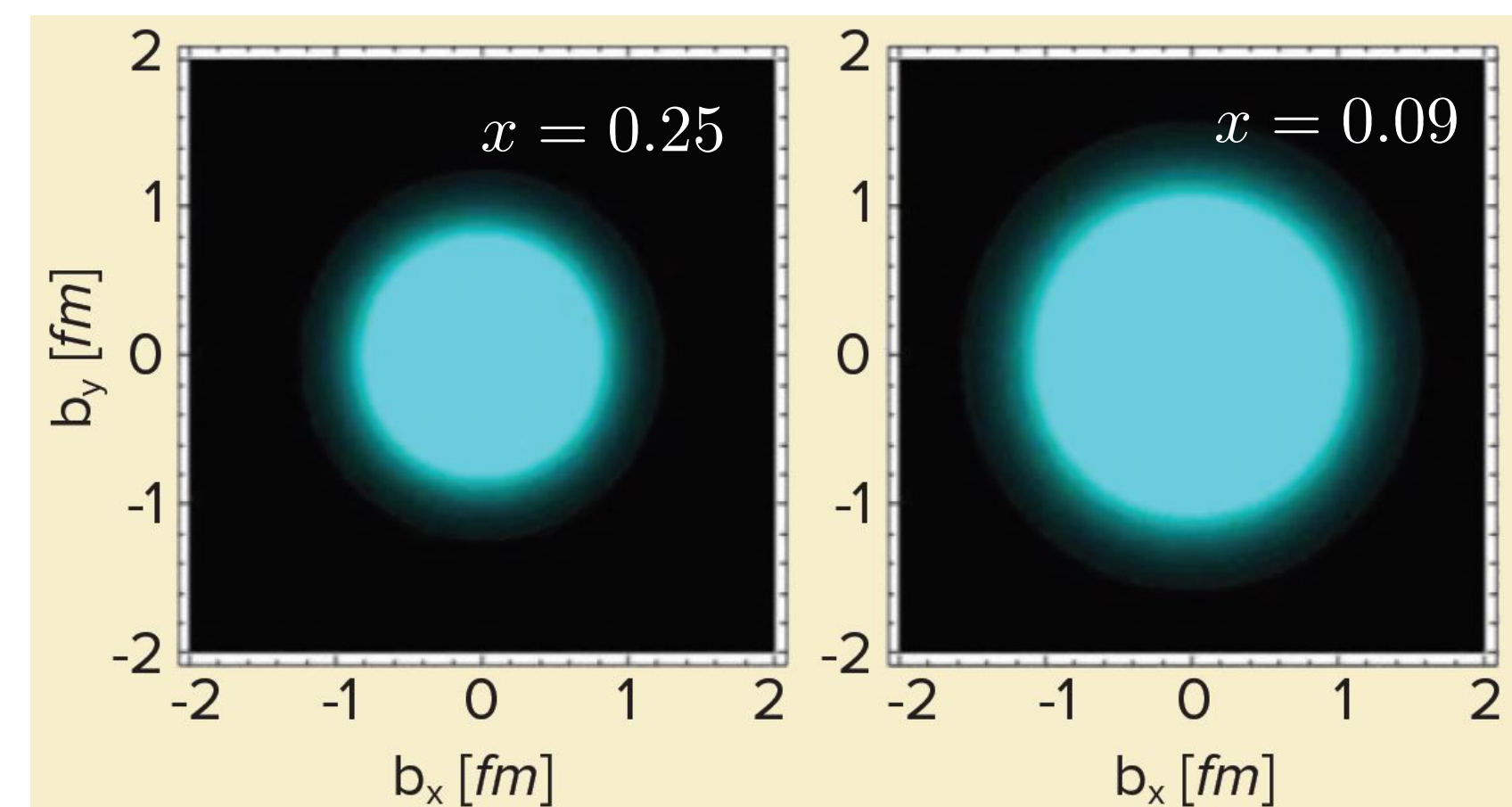
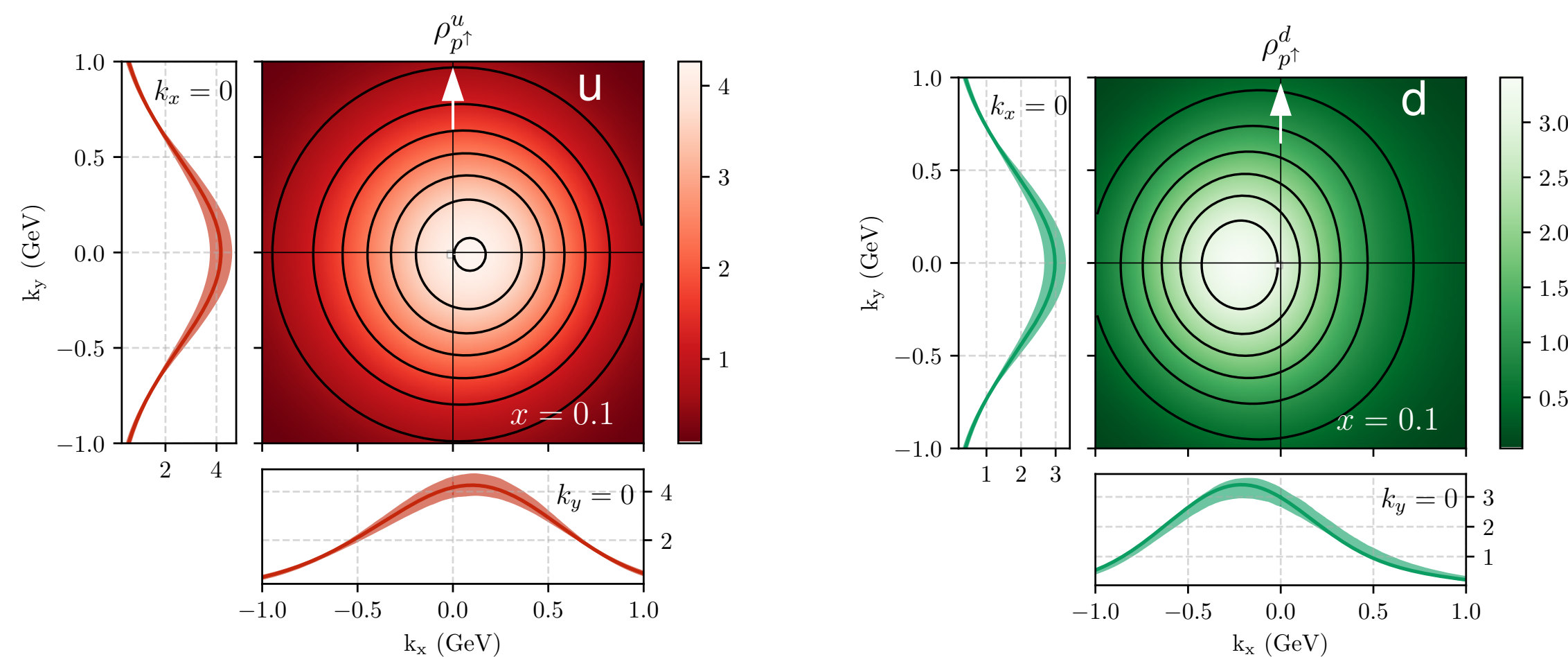
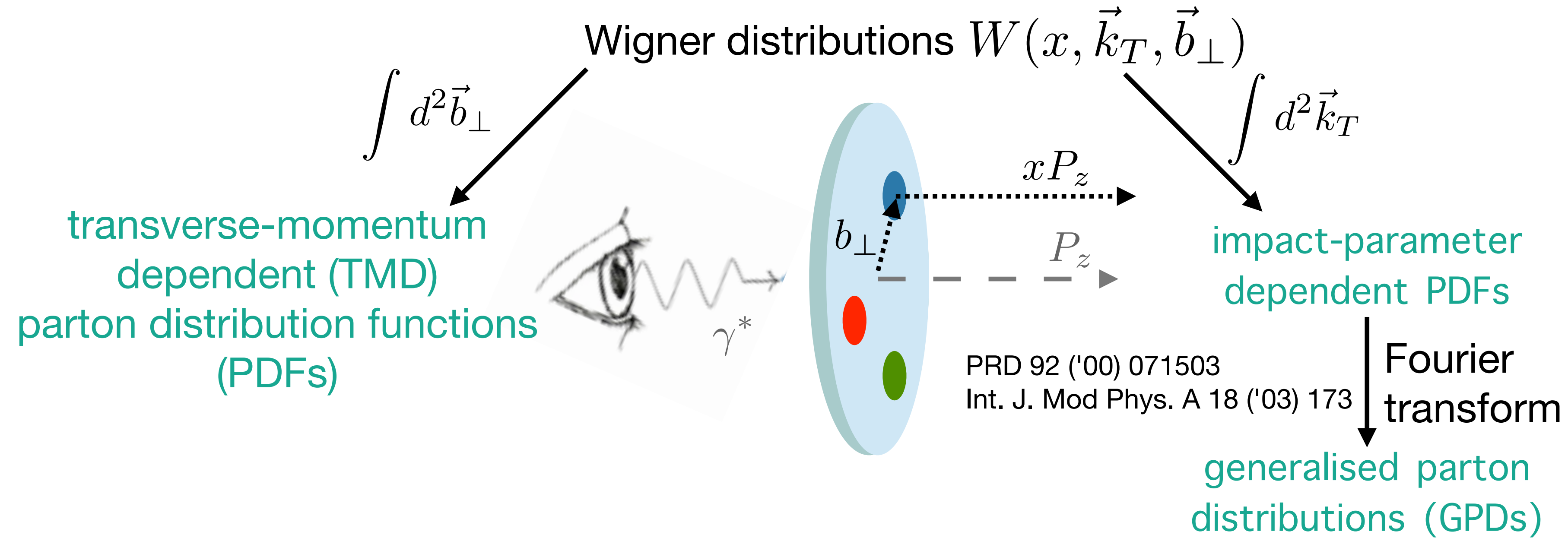
The various dimensions of the nucleon



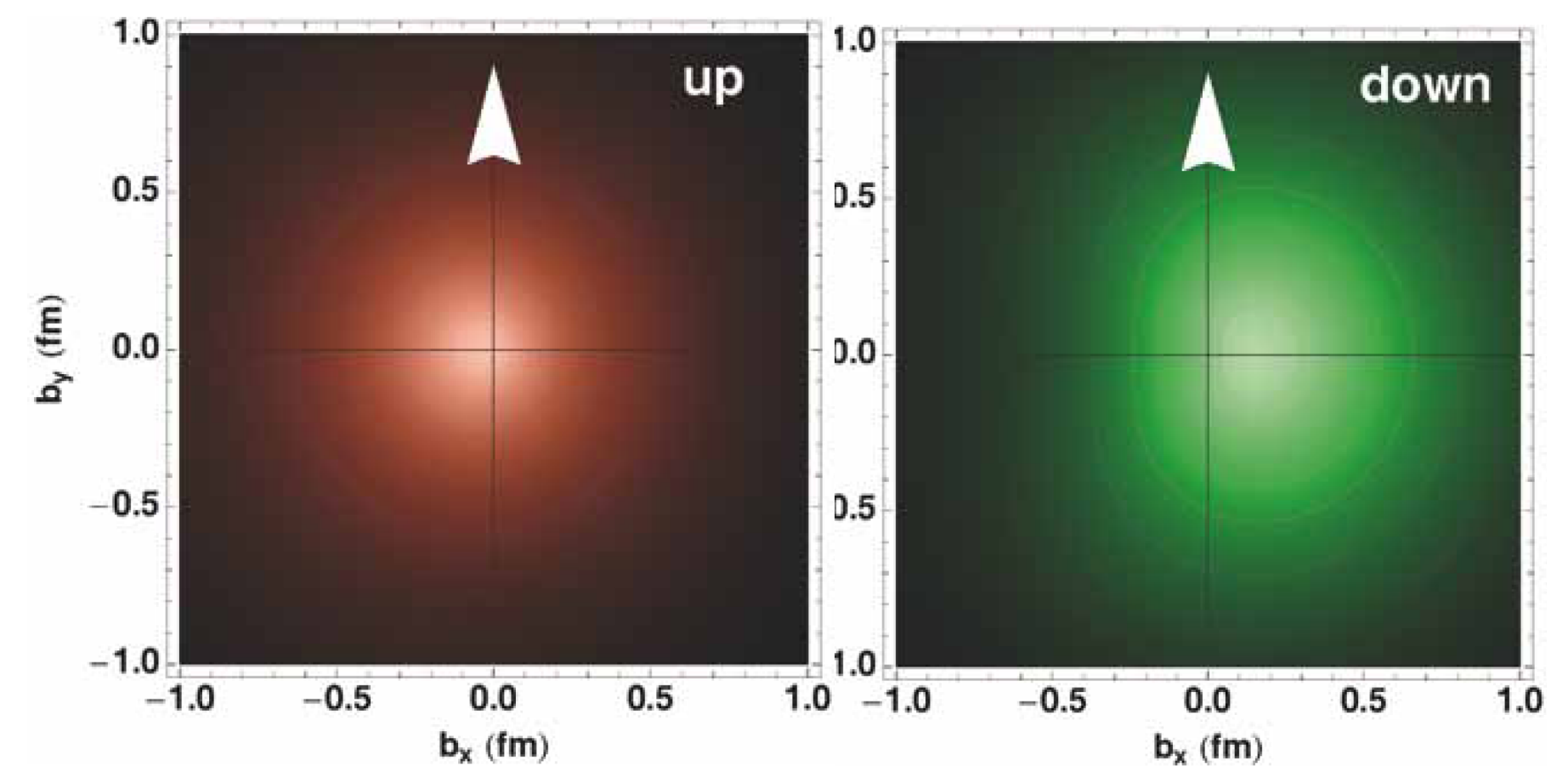
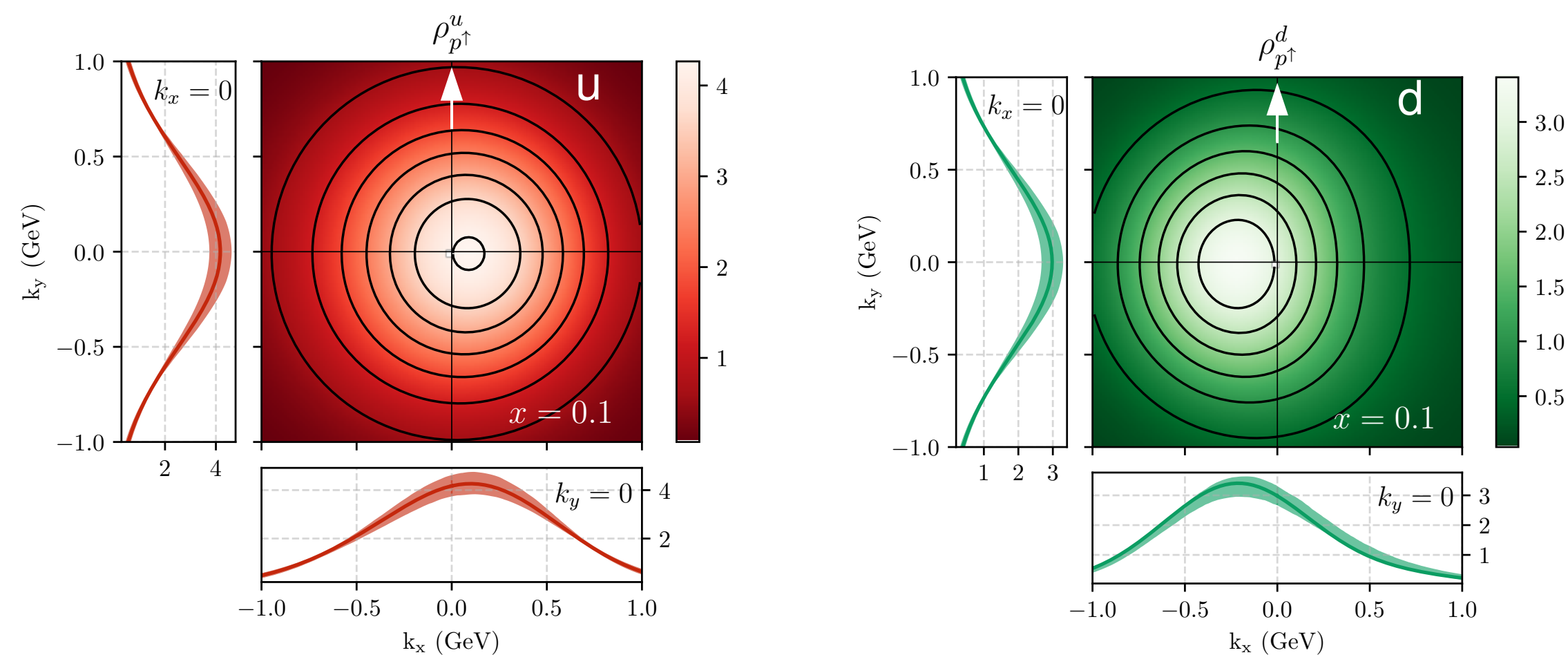
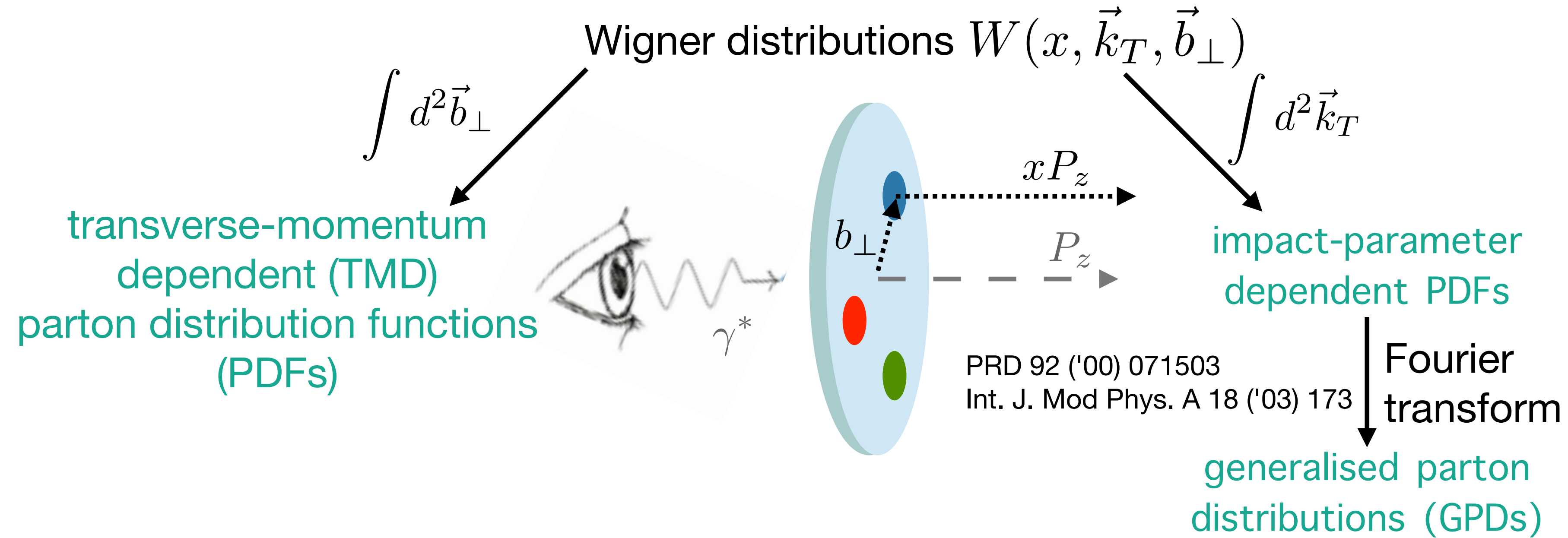
Exclusive production



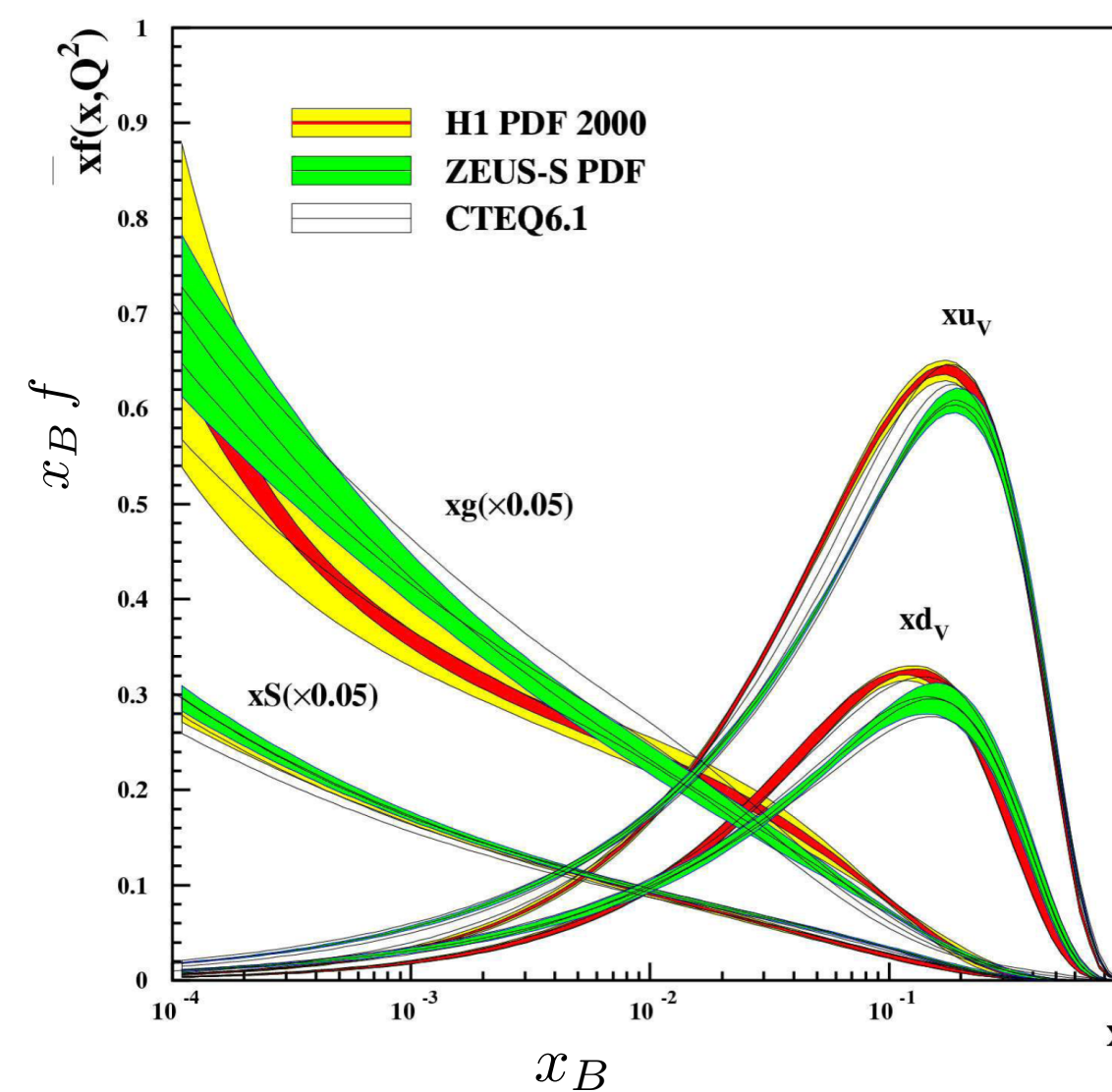
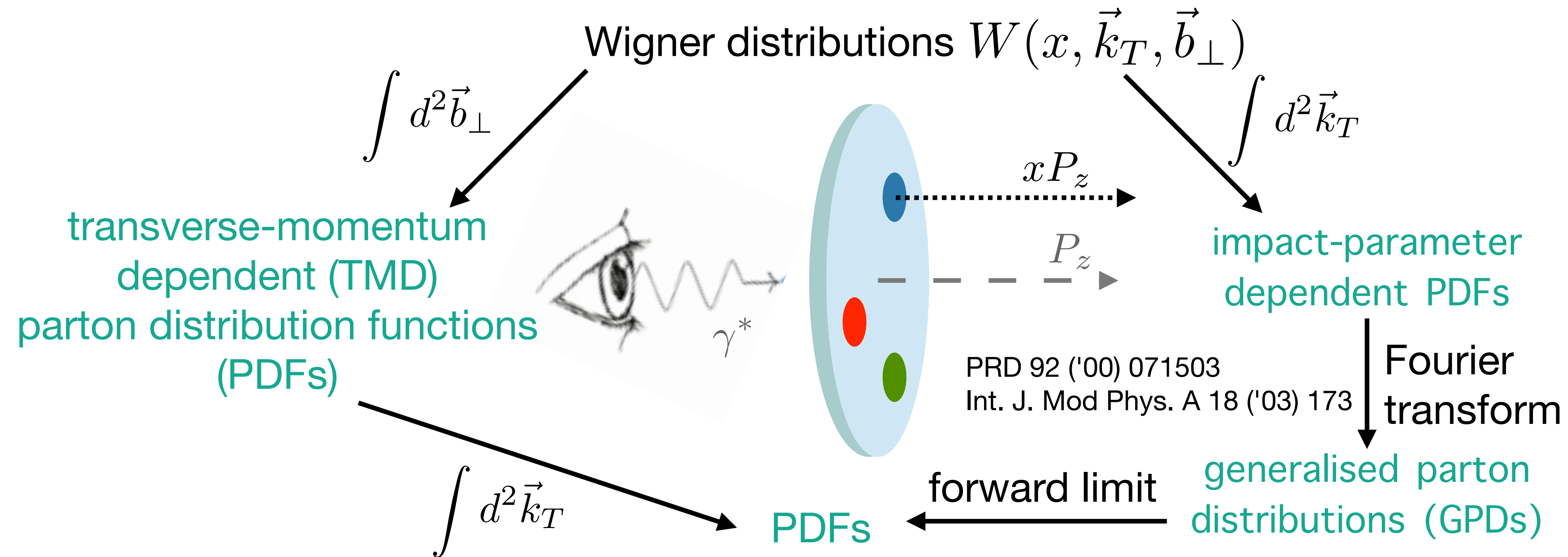
The various dimensions of the nucleon



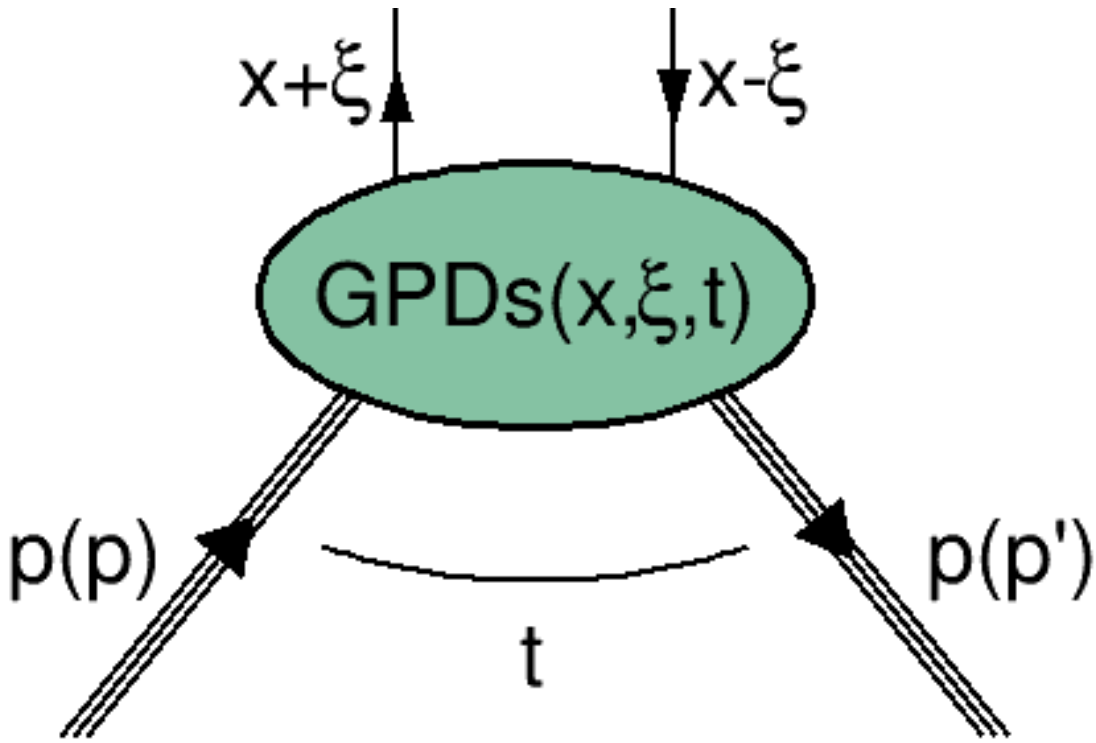
The various dimensions of the nucleon



The various dimensions of the nucleon



Generalised parton distributions (GPDs)



- 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

for spin-1/2 hadron:

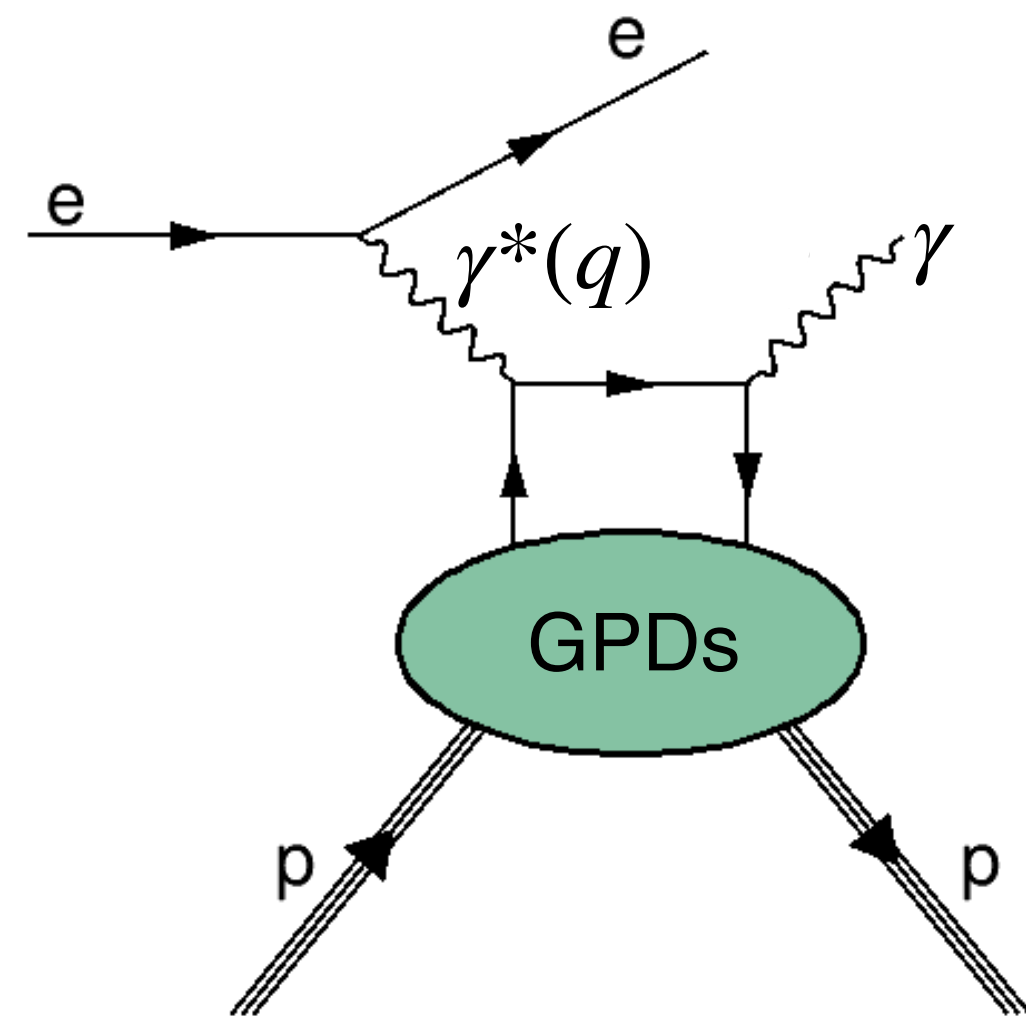
Four parton helicity-conserving twist-2 GPDs

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

Four parton helicity-flip twist-2 GPDs

$H_T(x, \xi, t)$	$E_T(x, \xi, t)$
$\tilde{H}_T(x, \xi, t)$	$\tilde{E}_T(x, \xi, t)$

Experimental access to GPDs via ep interactions

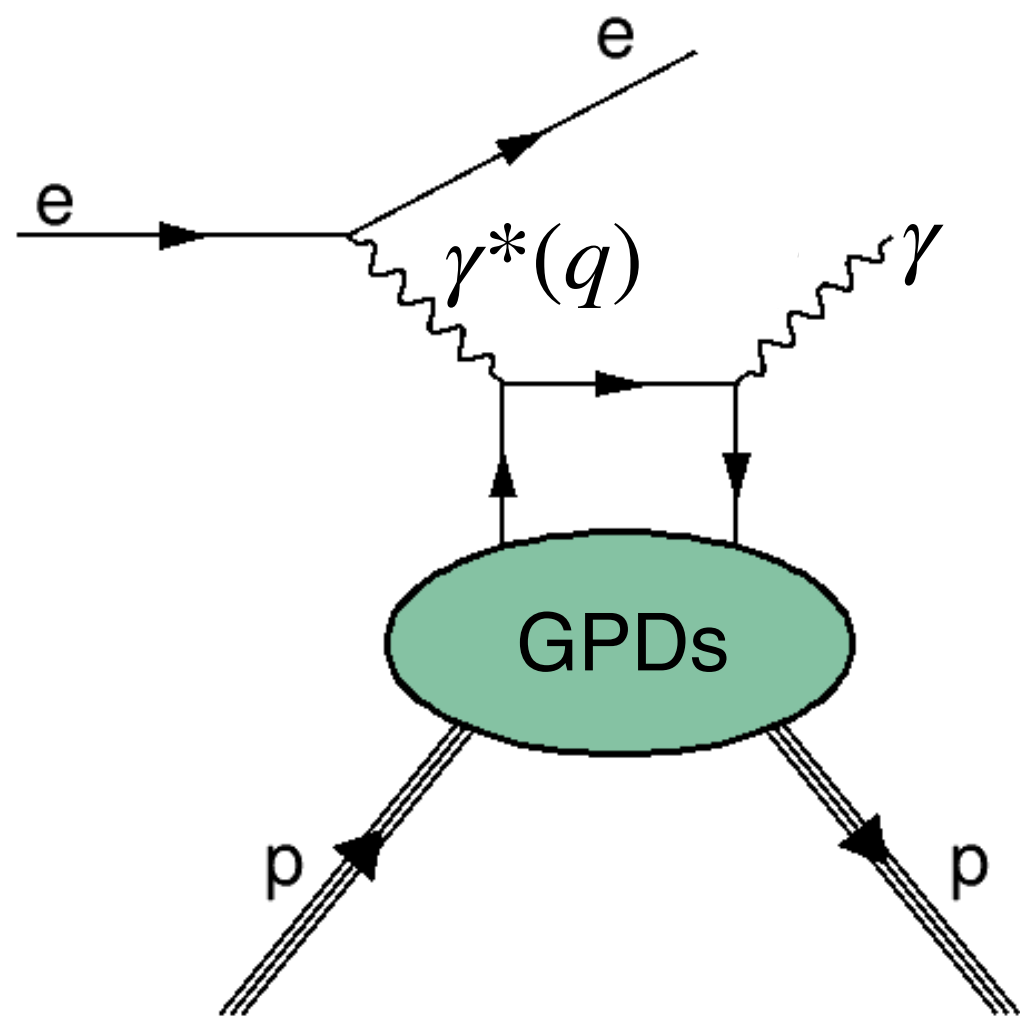


Deeply virtual Compton scattering
(DVCS)

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

Theoretically cleanest process

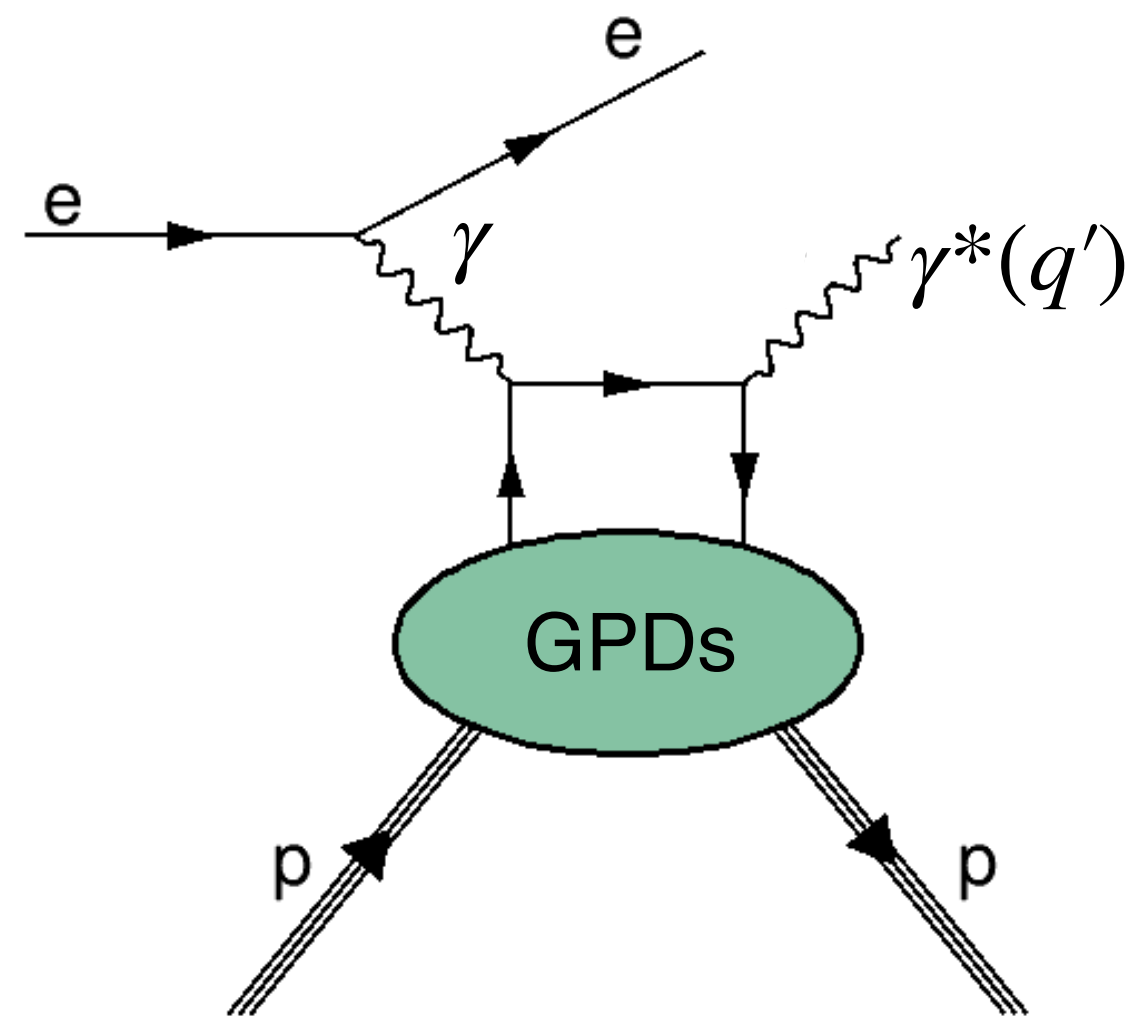
Experimental access to GPDs via ep interactions



Deeply virtual Compton scattering
(DVCS)

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

Theoretically cleanest process

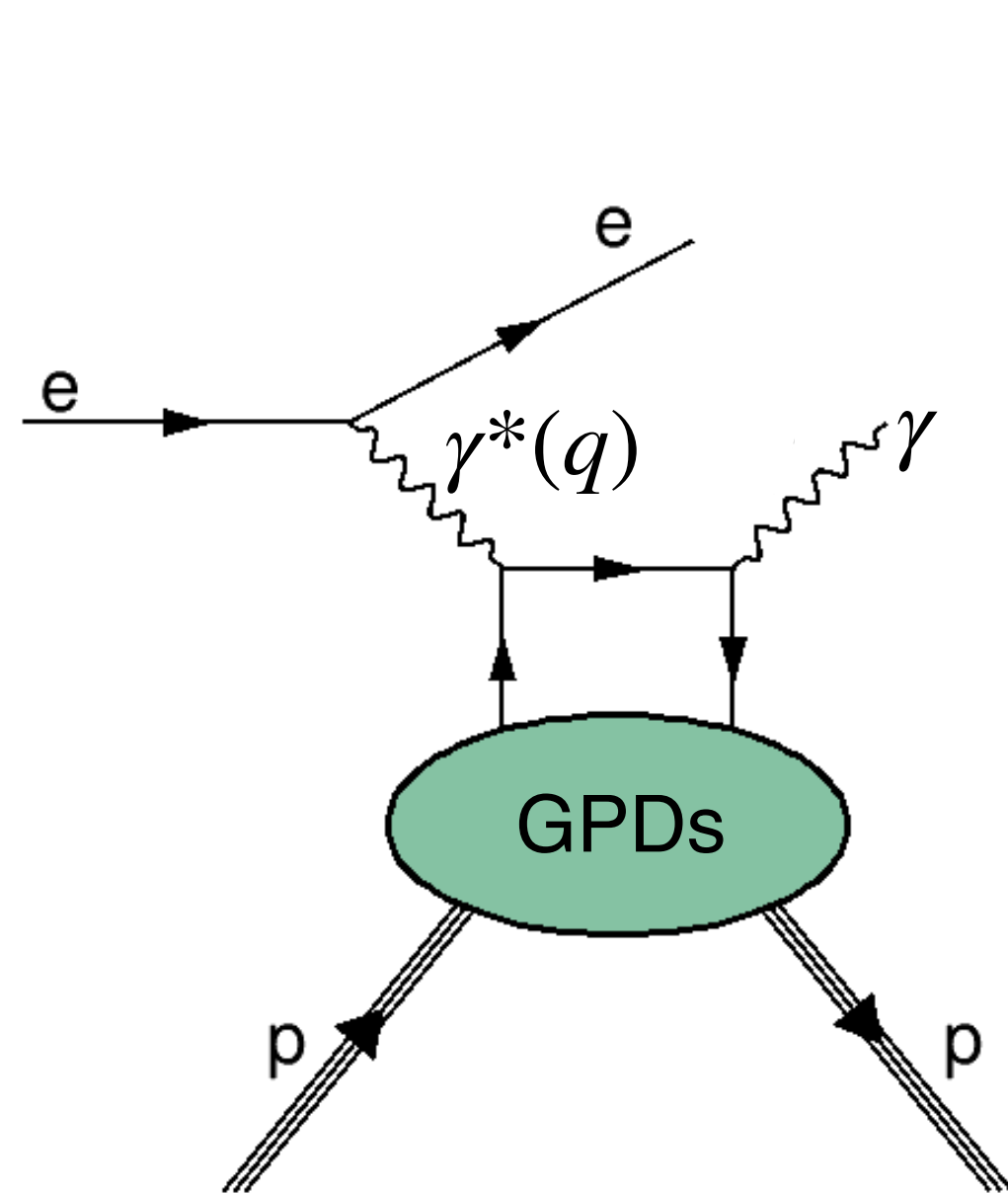


Timelike Compton scattering
(TCS)

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

Crucial test for universality of GPDs

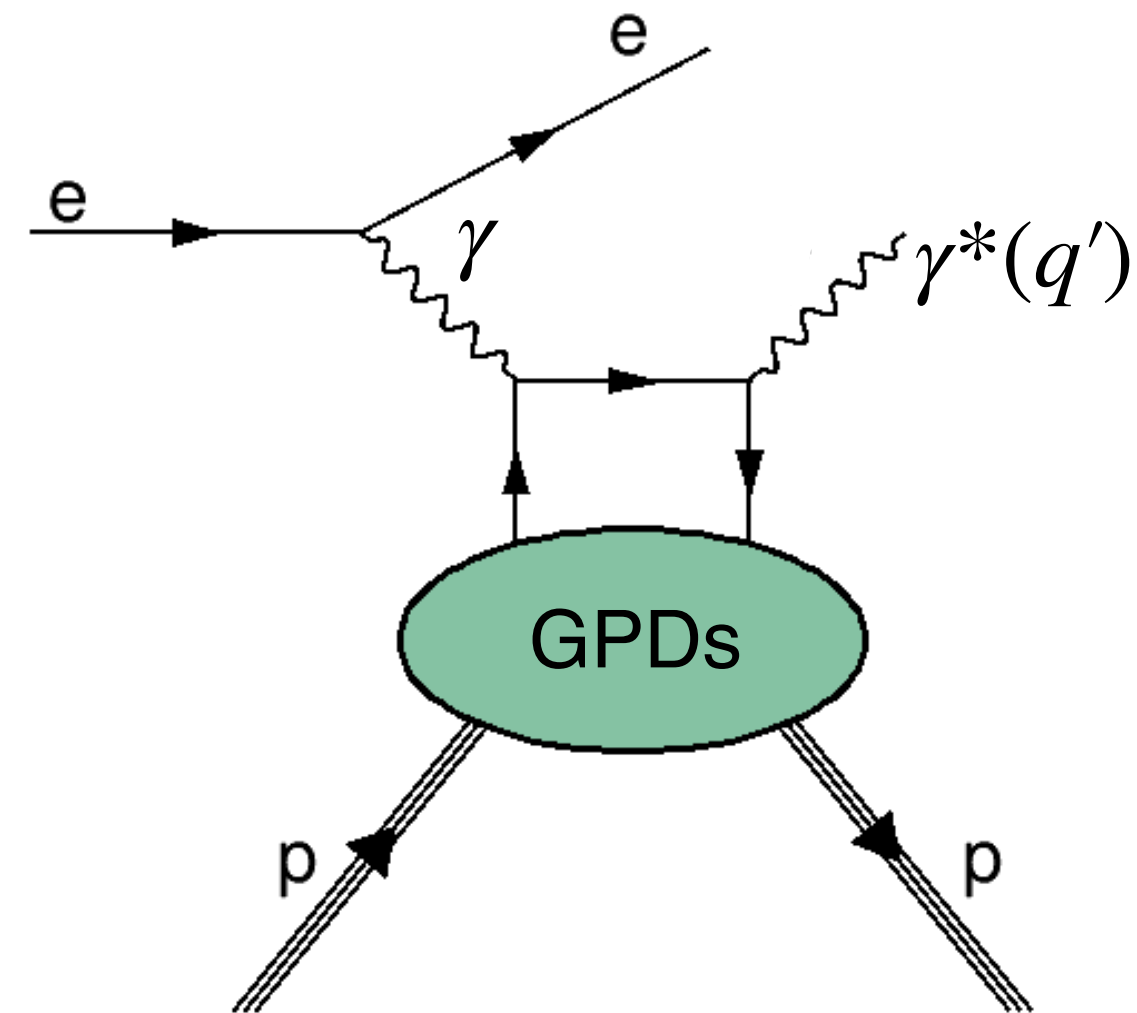
Experimental access to GPDs via ep interactions



Deeply virtual Compton scattering
(DVCS)

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

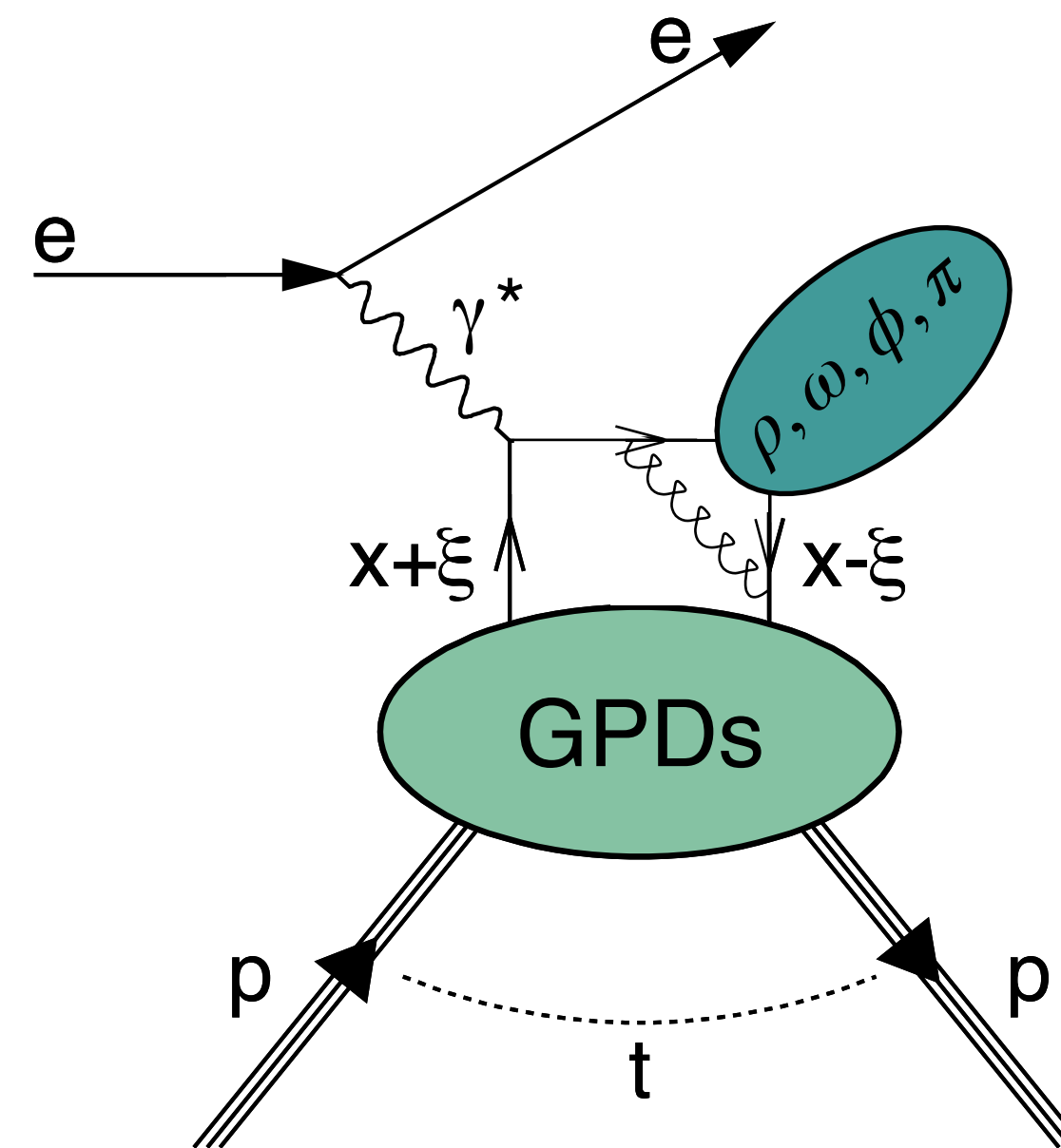
Theoretically cleanest process



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

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

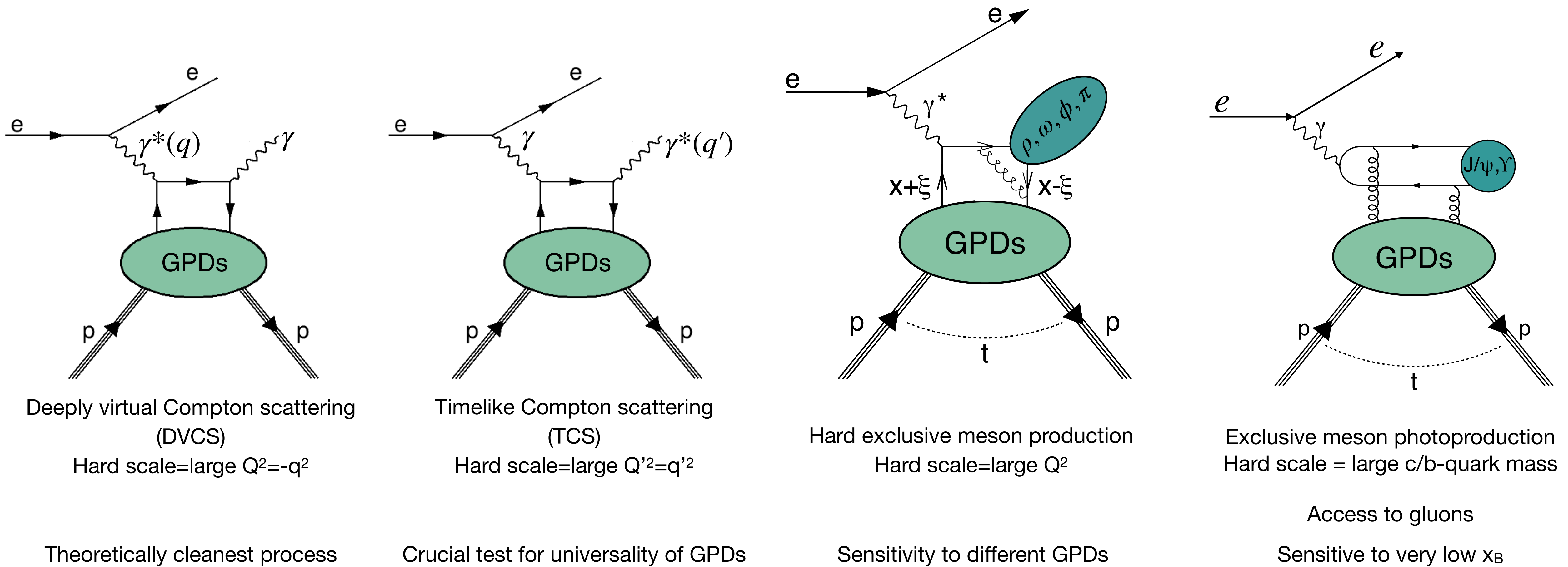
Hard exclusive meson production
Hard scale=large Q^2

Sensitivity to different GPDs

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

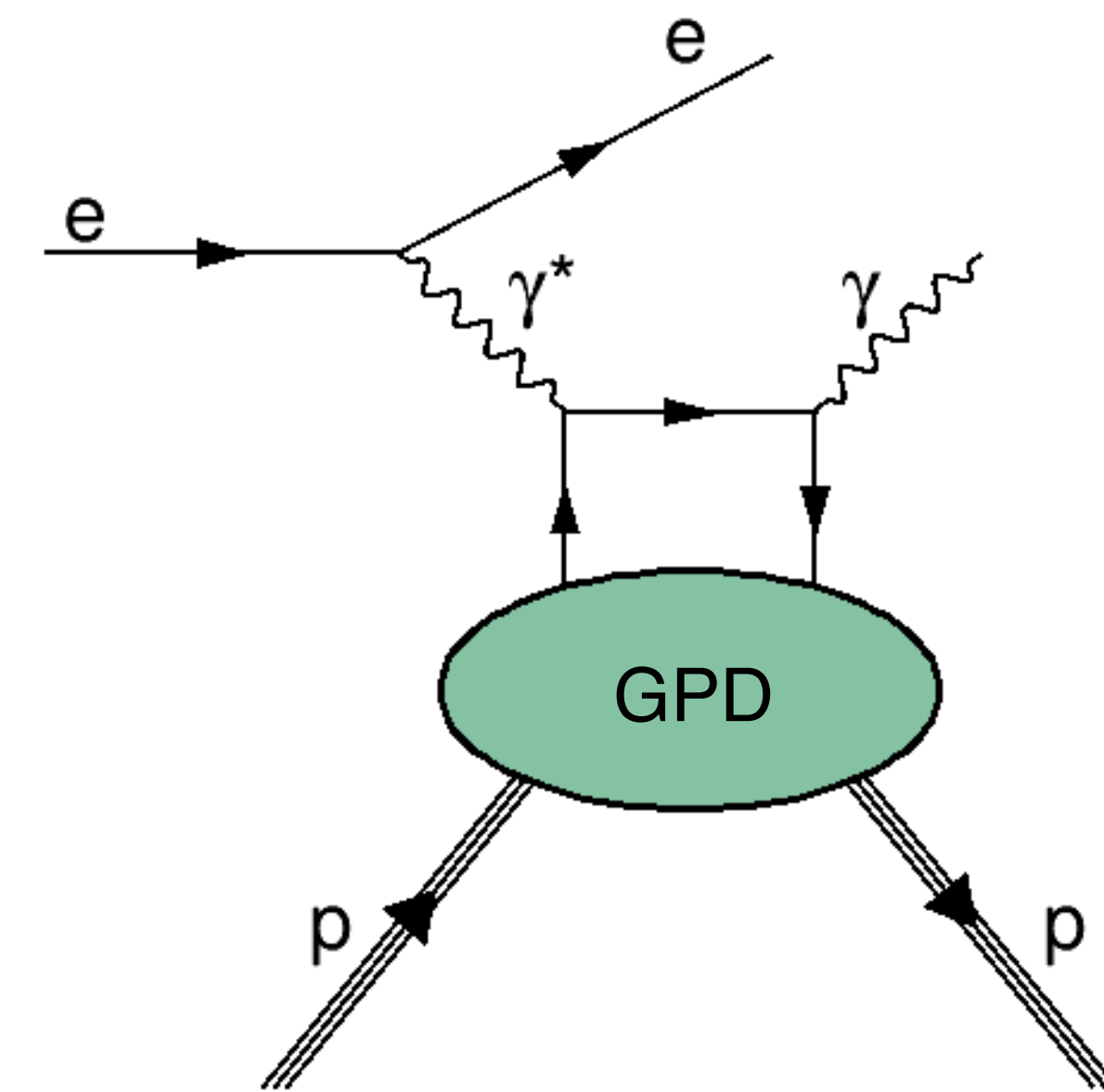
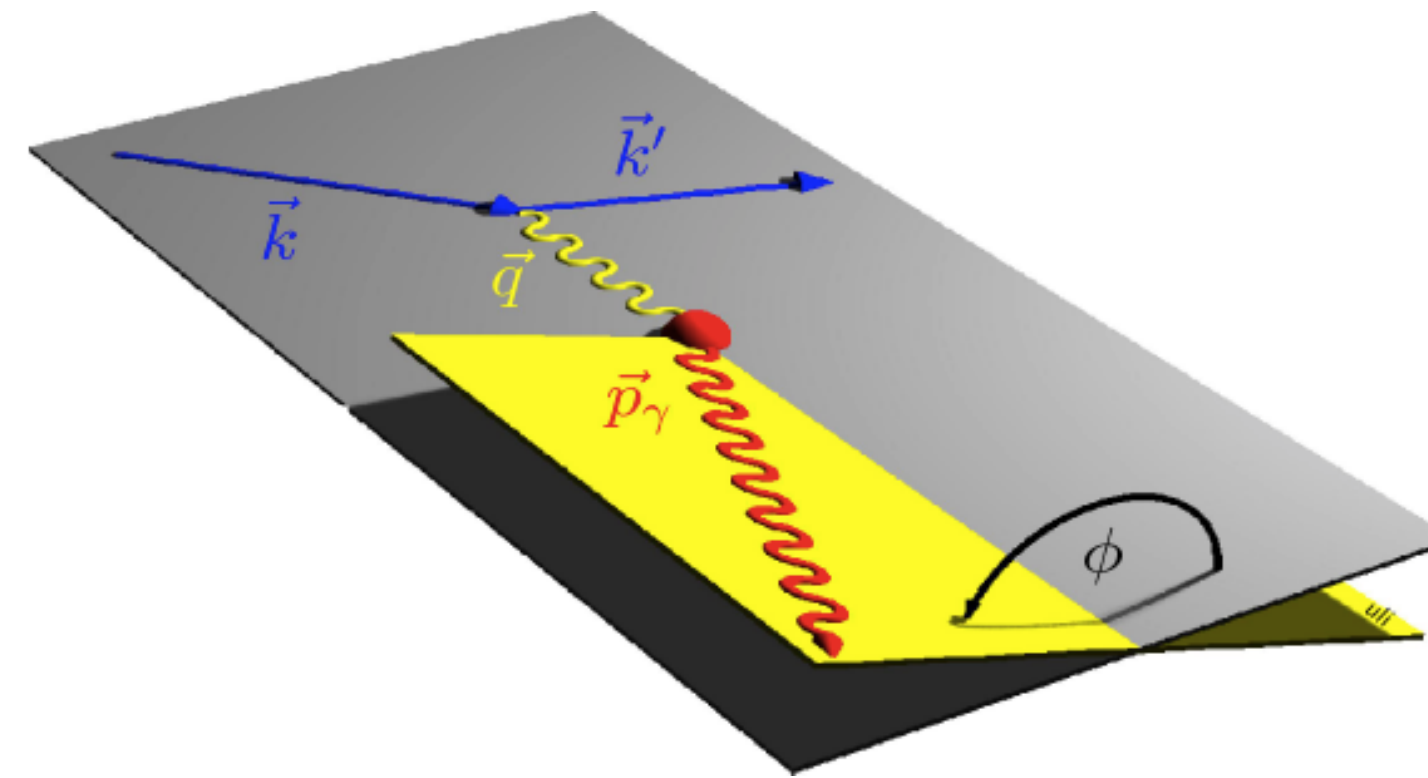
Access to gluons
Sensitive to very low x_B

Experimental access to GPDs via ep interactions



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)



$\Re(\text{CFF})$

$\Im(\text{CFF})$

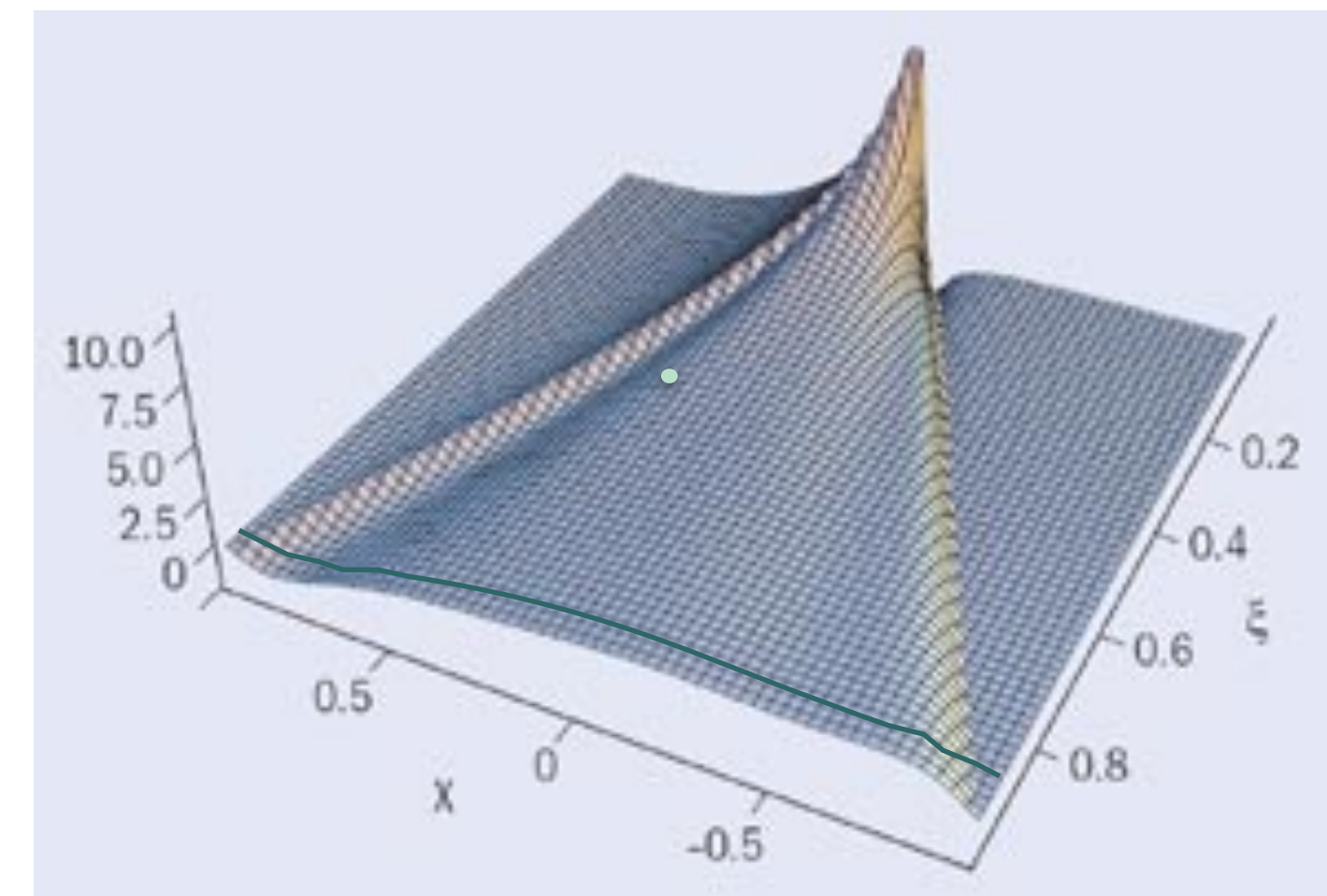
$$\sim PV \int_{-1}^{+1} \frac{\text{GPDs}(x, \xi, t)}{x \pm \xi} dx \pm i\pi \text{GPDs}(\pm\xi, \xi, t) + \dots$$

Cross sections

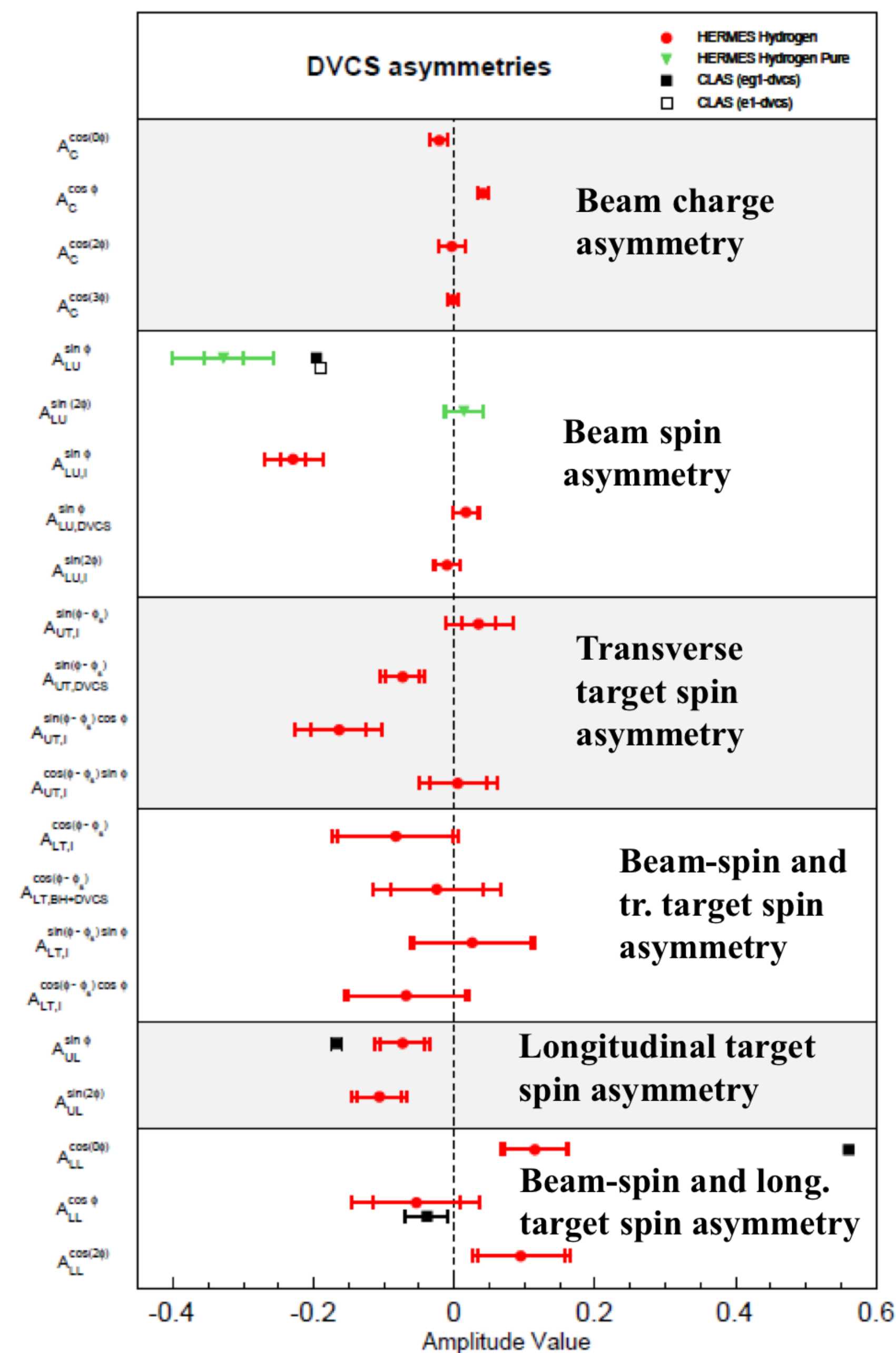
Beam-charge asymmetries

Double-spin asymmetries

single-spin
asymmetries



DVCS: pioneering measurements

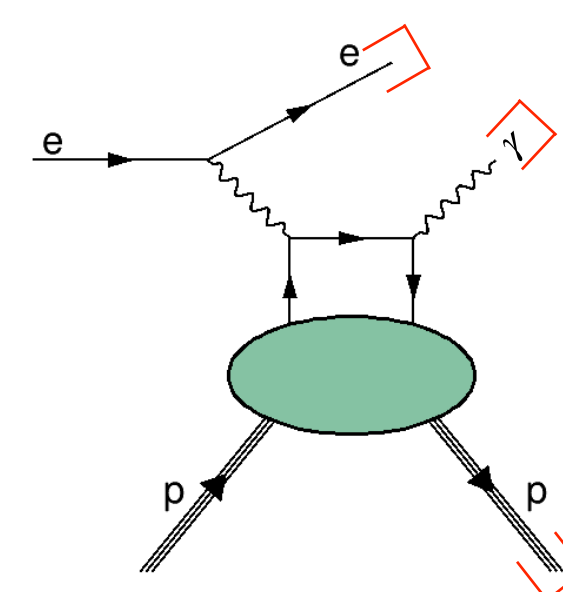


GPD H

GPD E

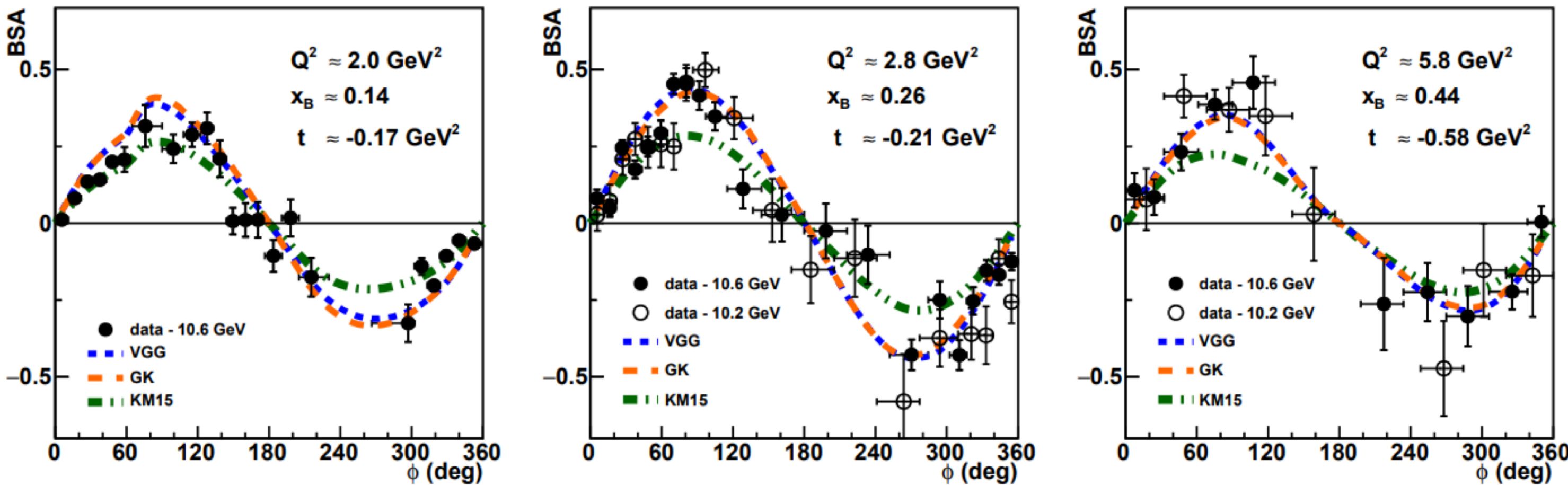
GPD $\tilde{H}$

DVCS off the proton: CLAS12

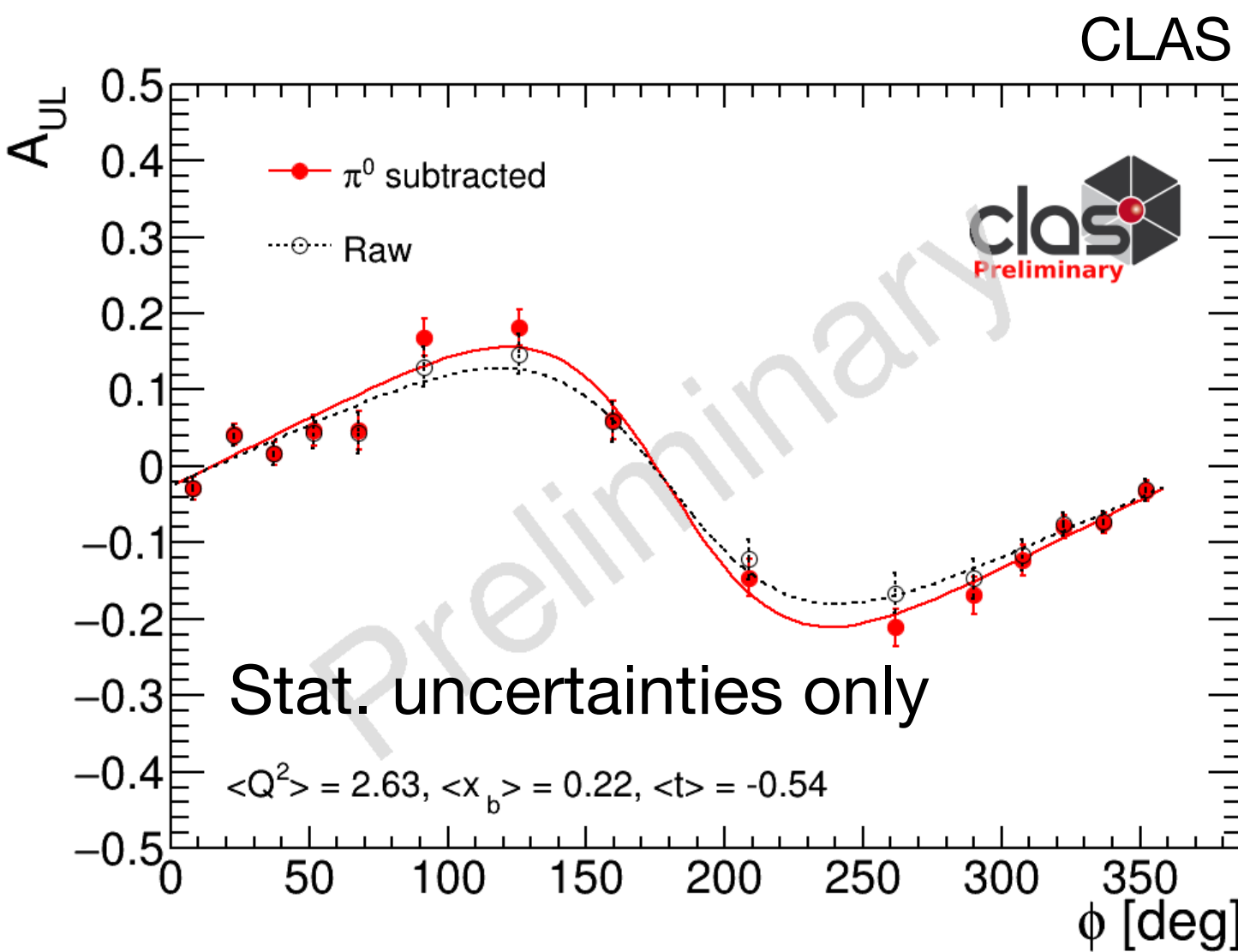


Beam-spin asymmetry

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



Longitudinal target-spin asymmetry

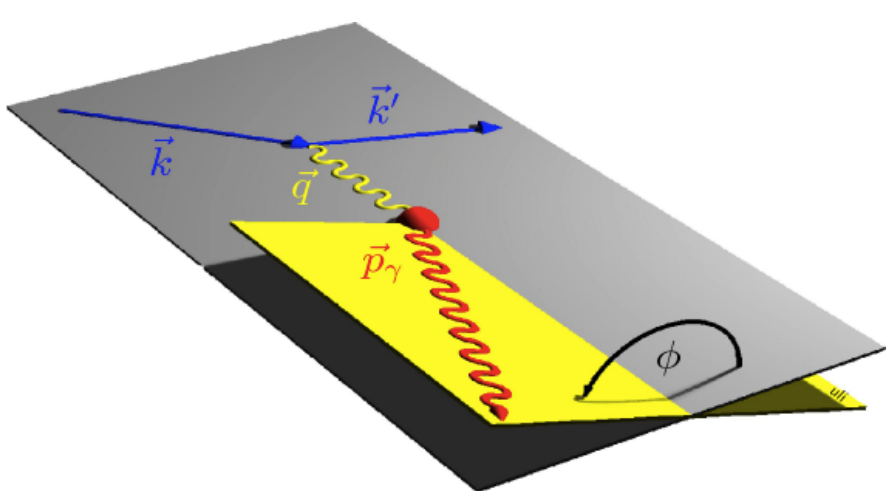


Vast extension of statistics: 64 bins in x_B, Q^2, t

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

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

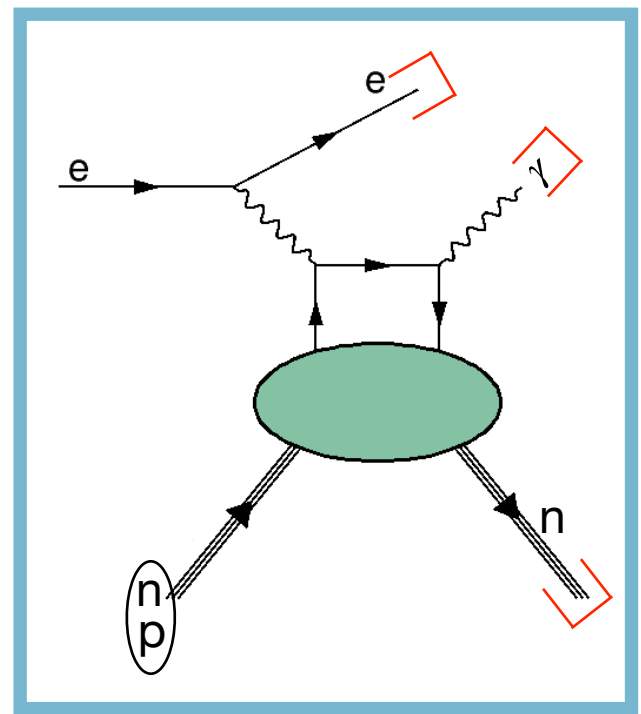
Combination:
clean separation of
 $\Im m \mathcal{H}$ and $\Im m \tilde{\mathcal{H}}$



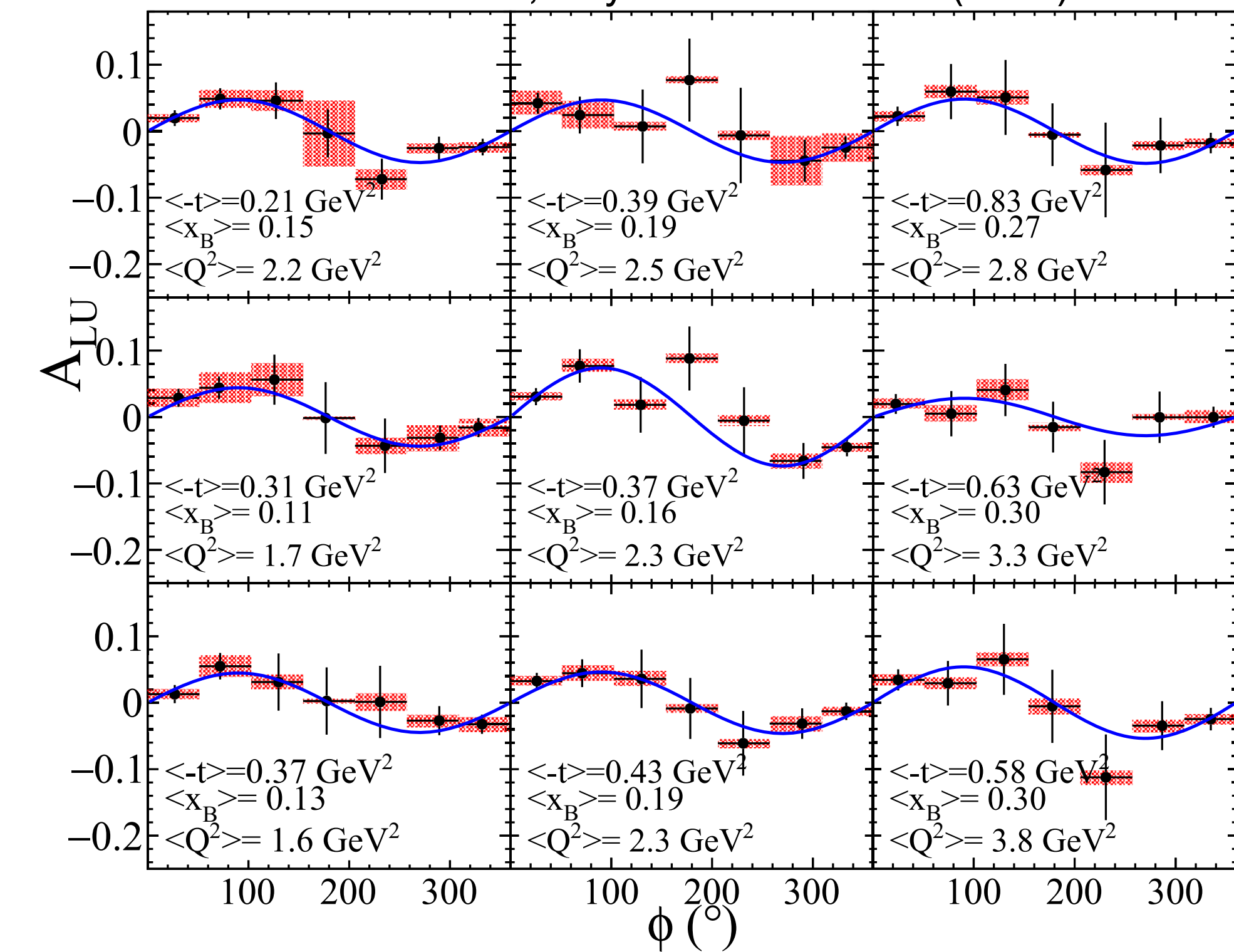
DVCS off the neutron: CLAS12

First time detection of active neutron

Beam-spin asymmetry



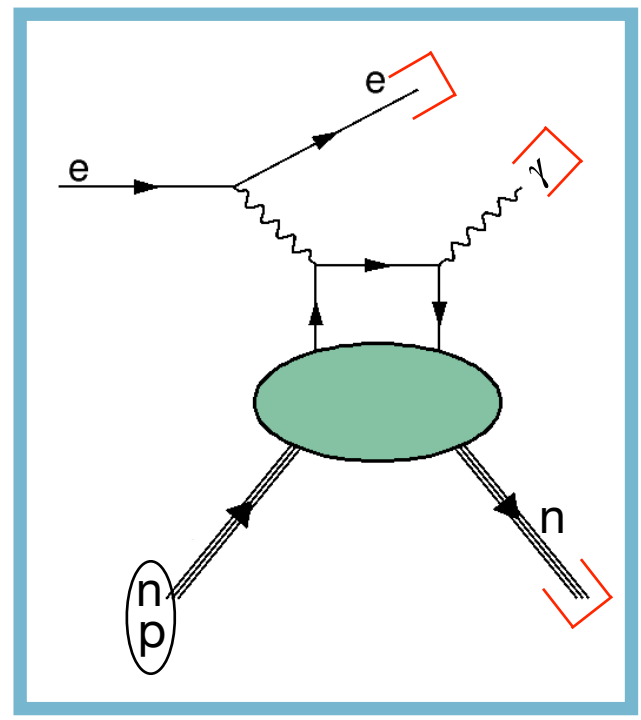
CLAS, Phys. Rev. Lett. **133** (2024) 211903



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

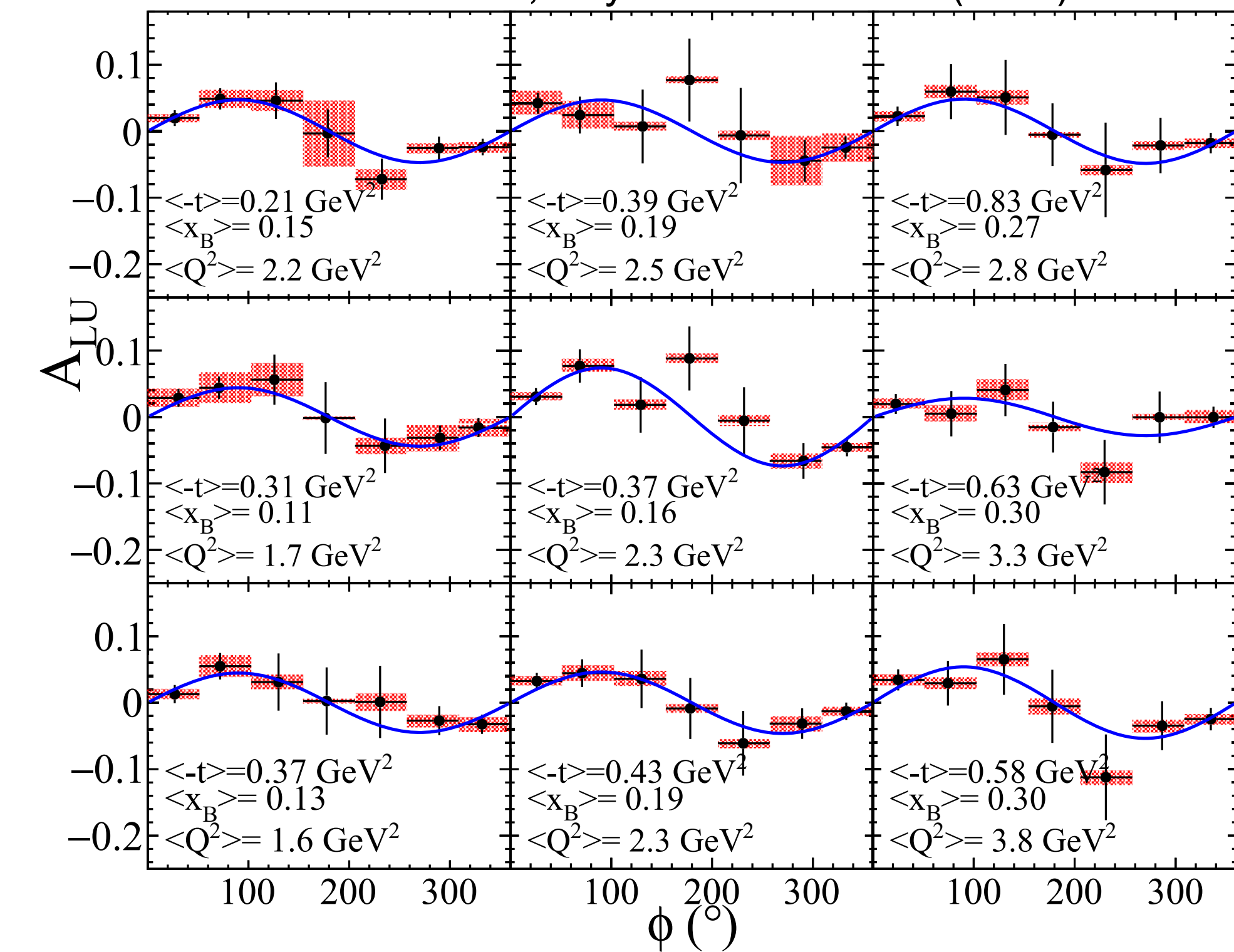
DVCS off the neutron: CLAS12

First time detection of active neutron



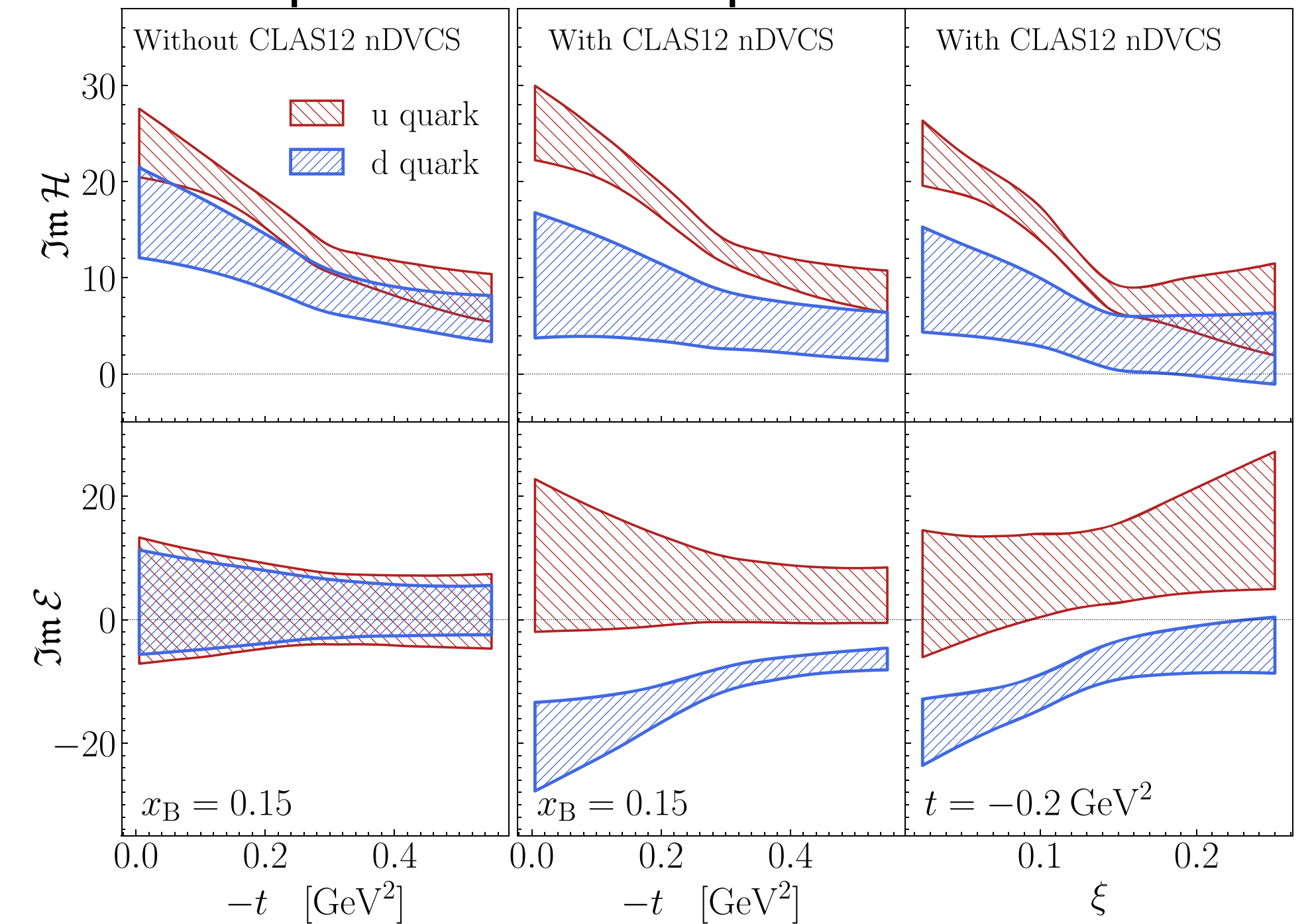
Beam-spin asymmetry

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



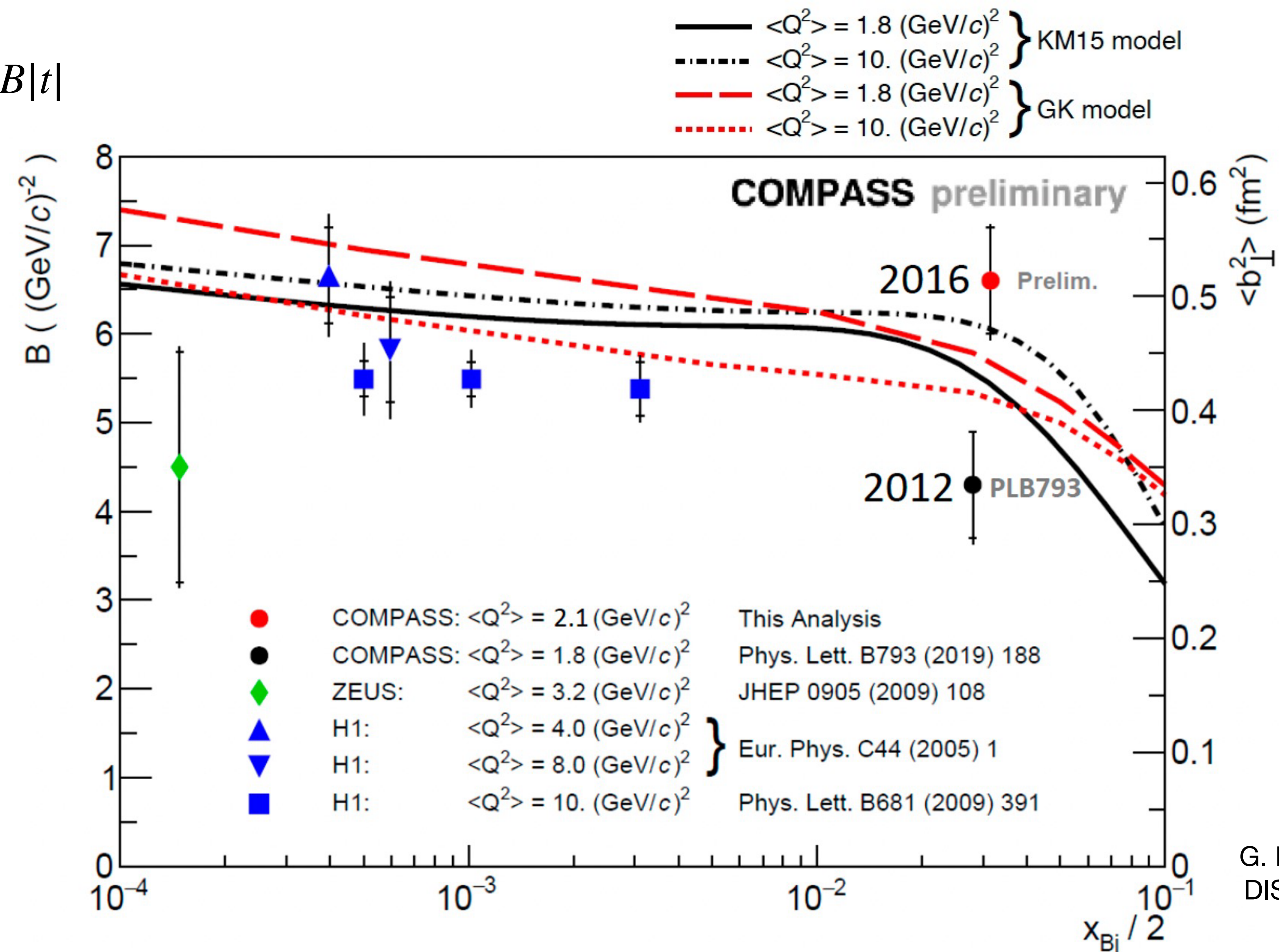
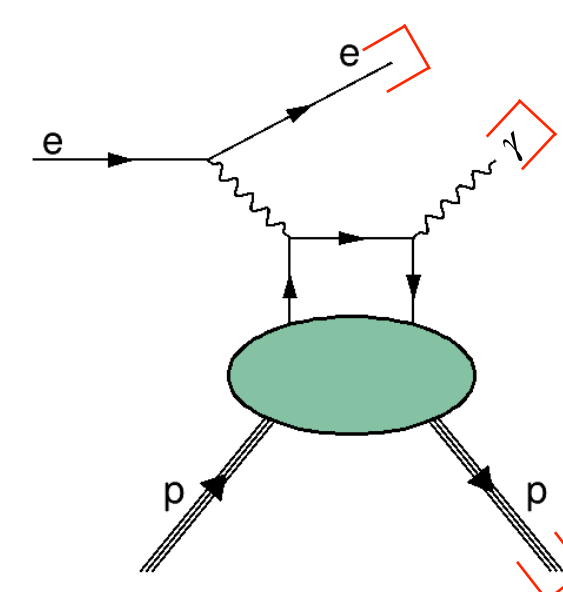
$$\Im m \left[F_1 \mathcal{H} + \xi (F_1 + F_2) \mathcal{H} - \frac{t}{4M_n^2} F_2 \mathcal{E} \right]$$

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



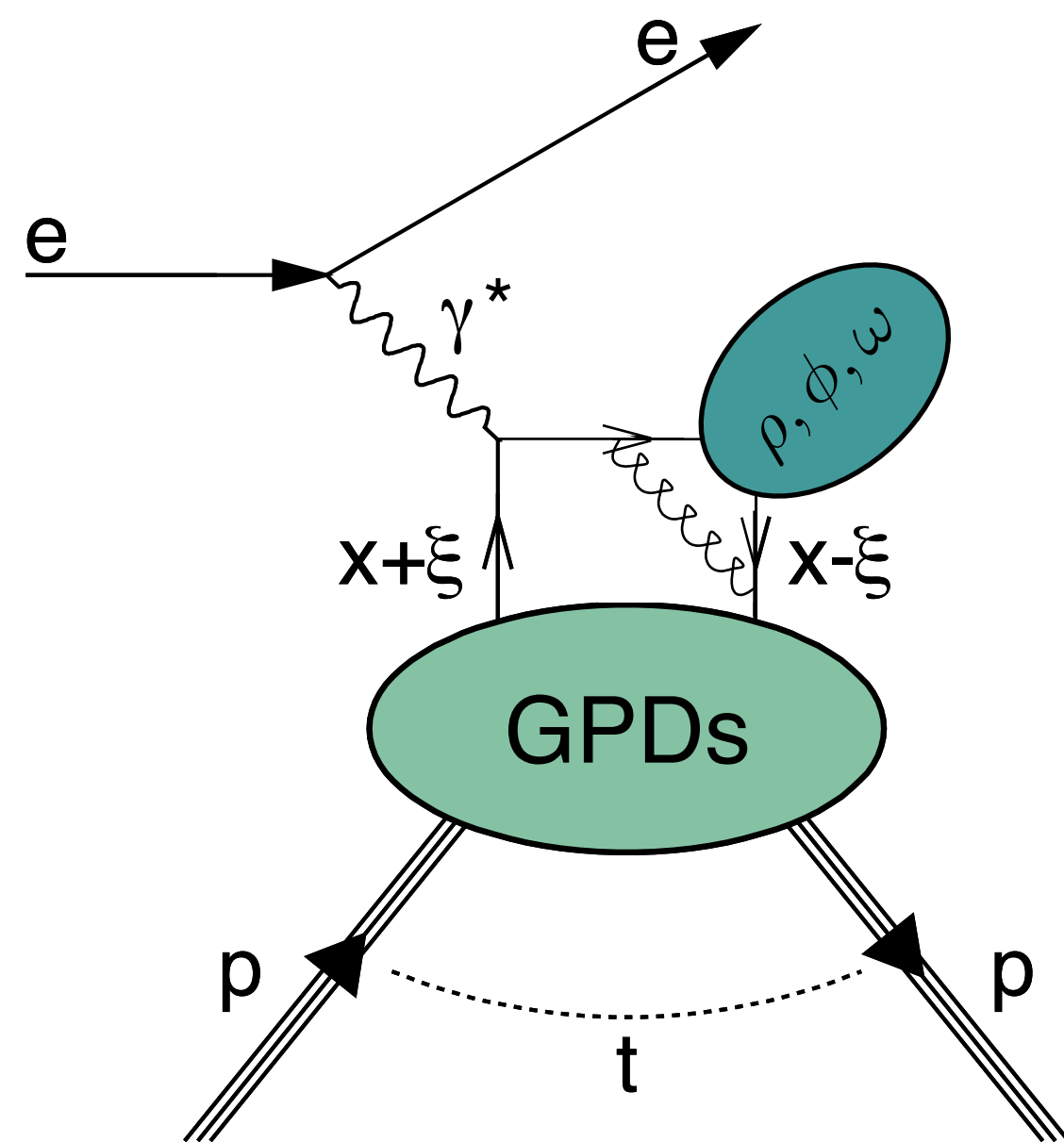
DVCS off the proton: COMPASS

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



G. Kainth
DIS2026

Exclusive vector-meson production

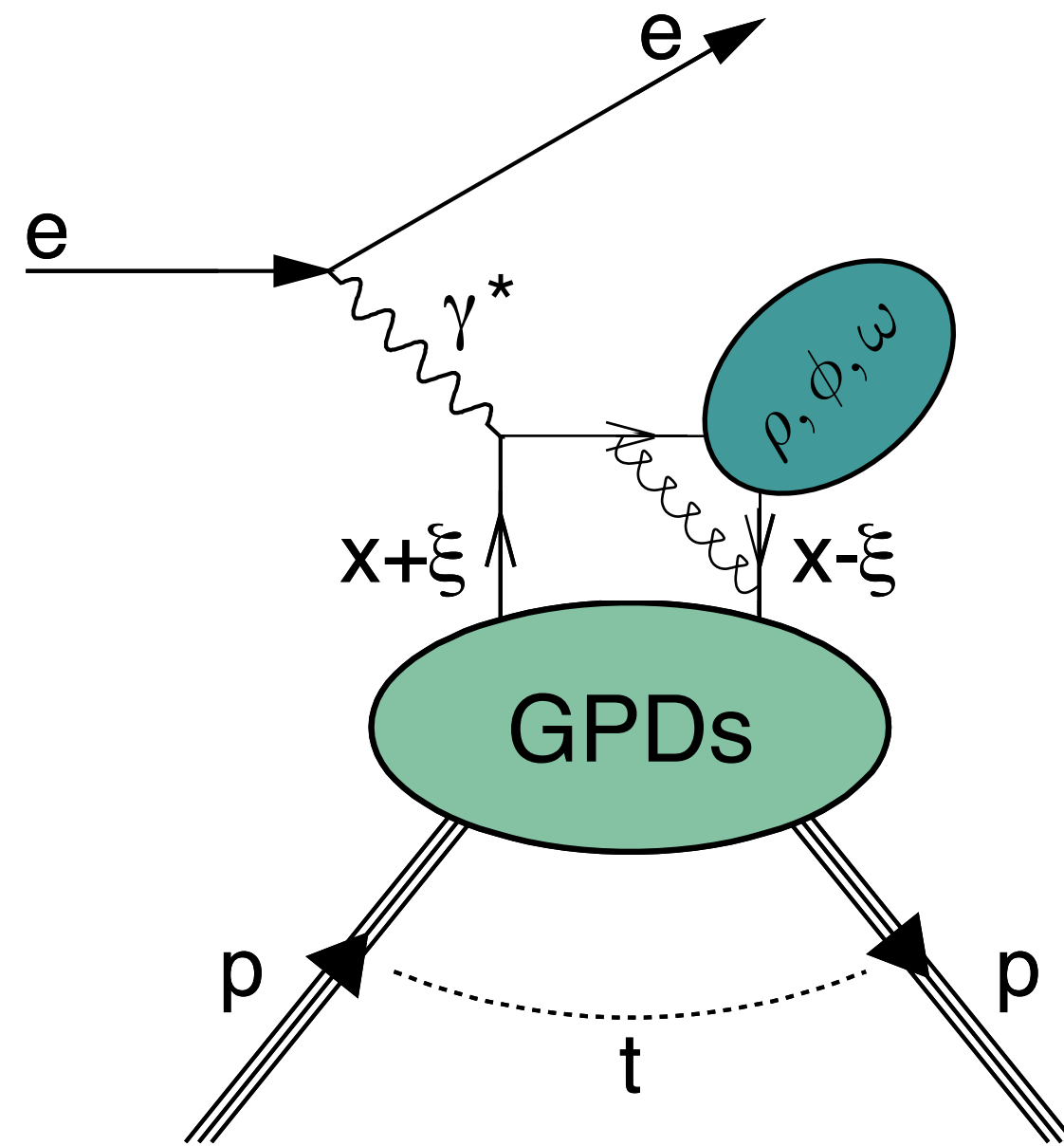


Access to GPDs

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

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

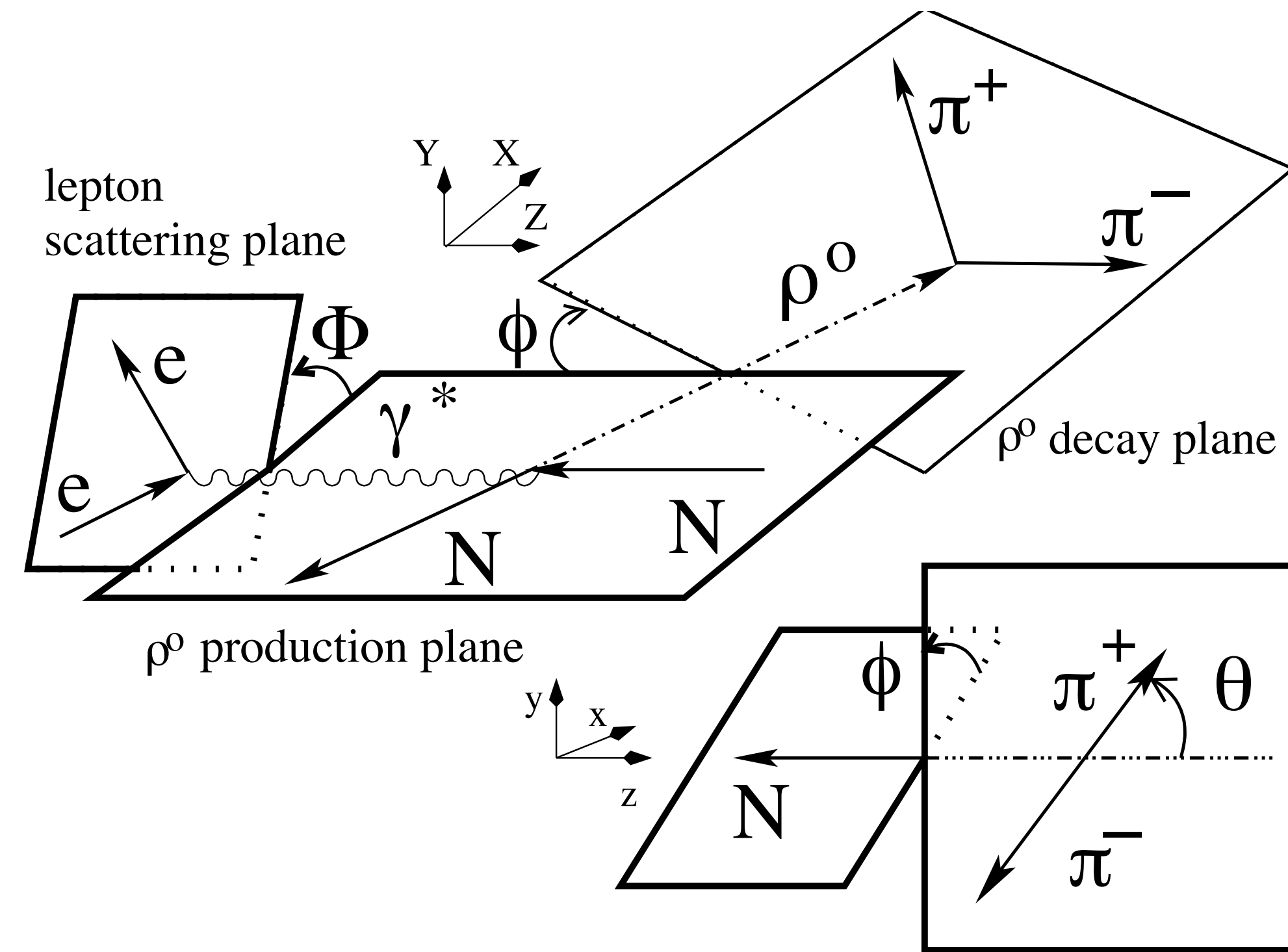
Exclusive vector-meson production



Access to GPDs

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

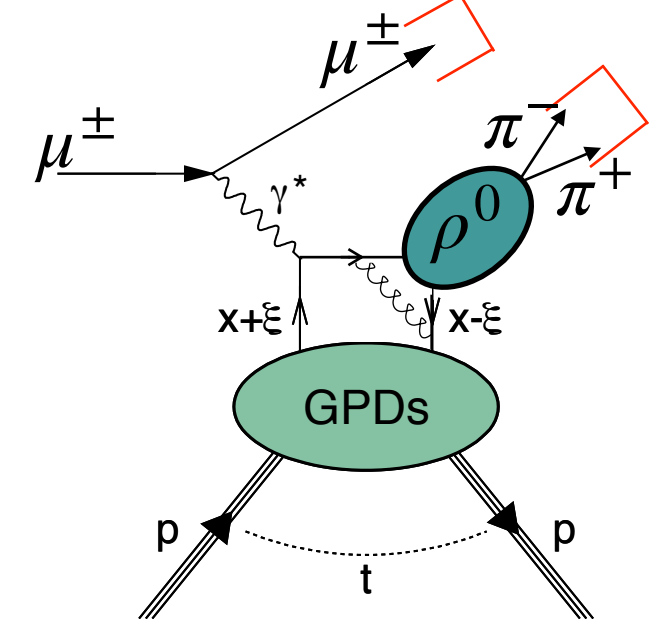
$$\tilde{H}, \tilde{E}$$



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

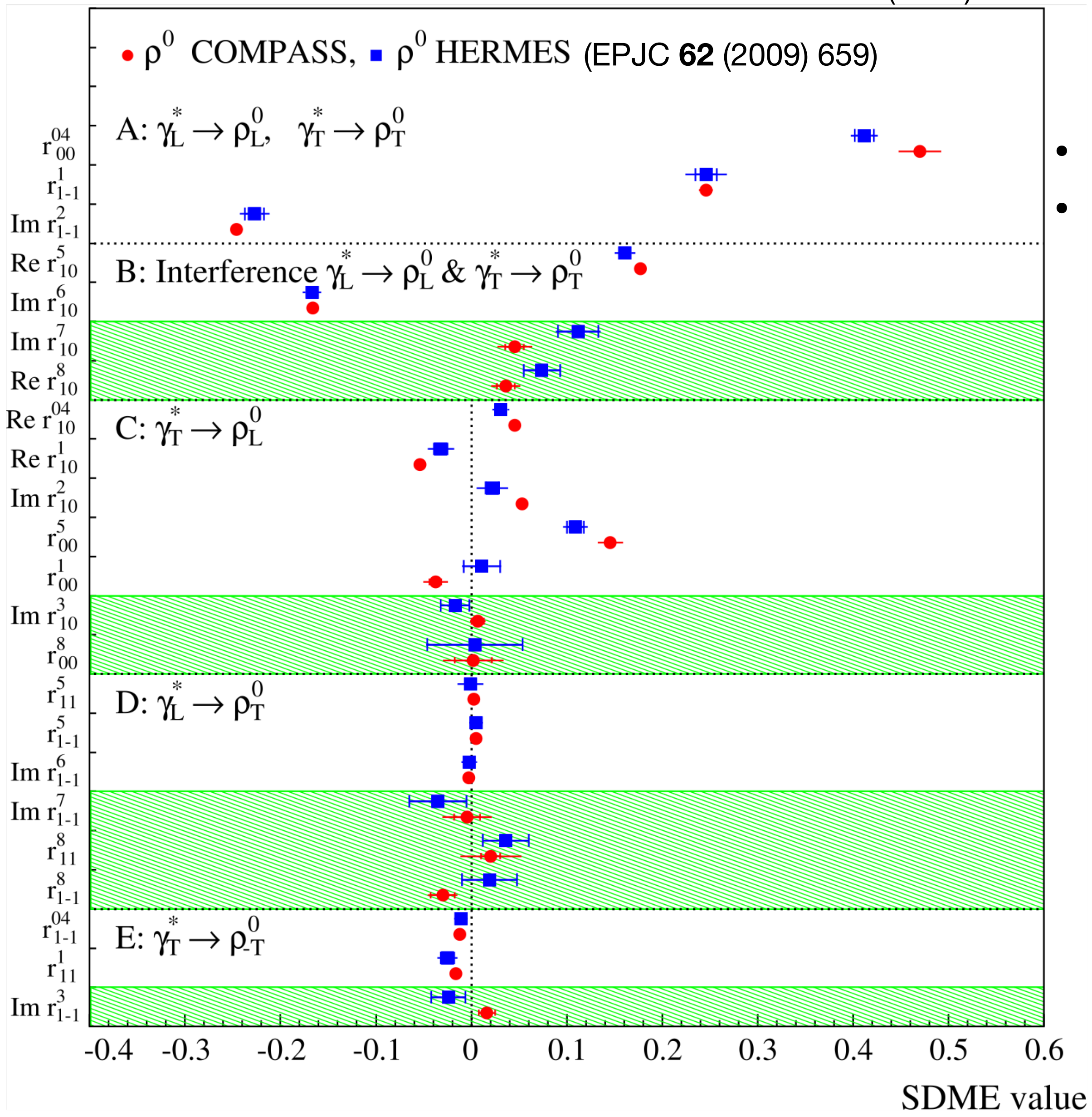


Unpolarised proton target
longitudinally polarised lepton
beam

- 5 classes of SDMEs
- unpolarised and polarised SDMEs

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

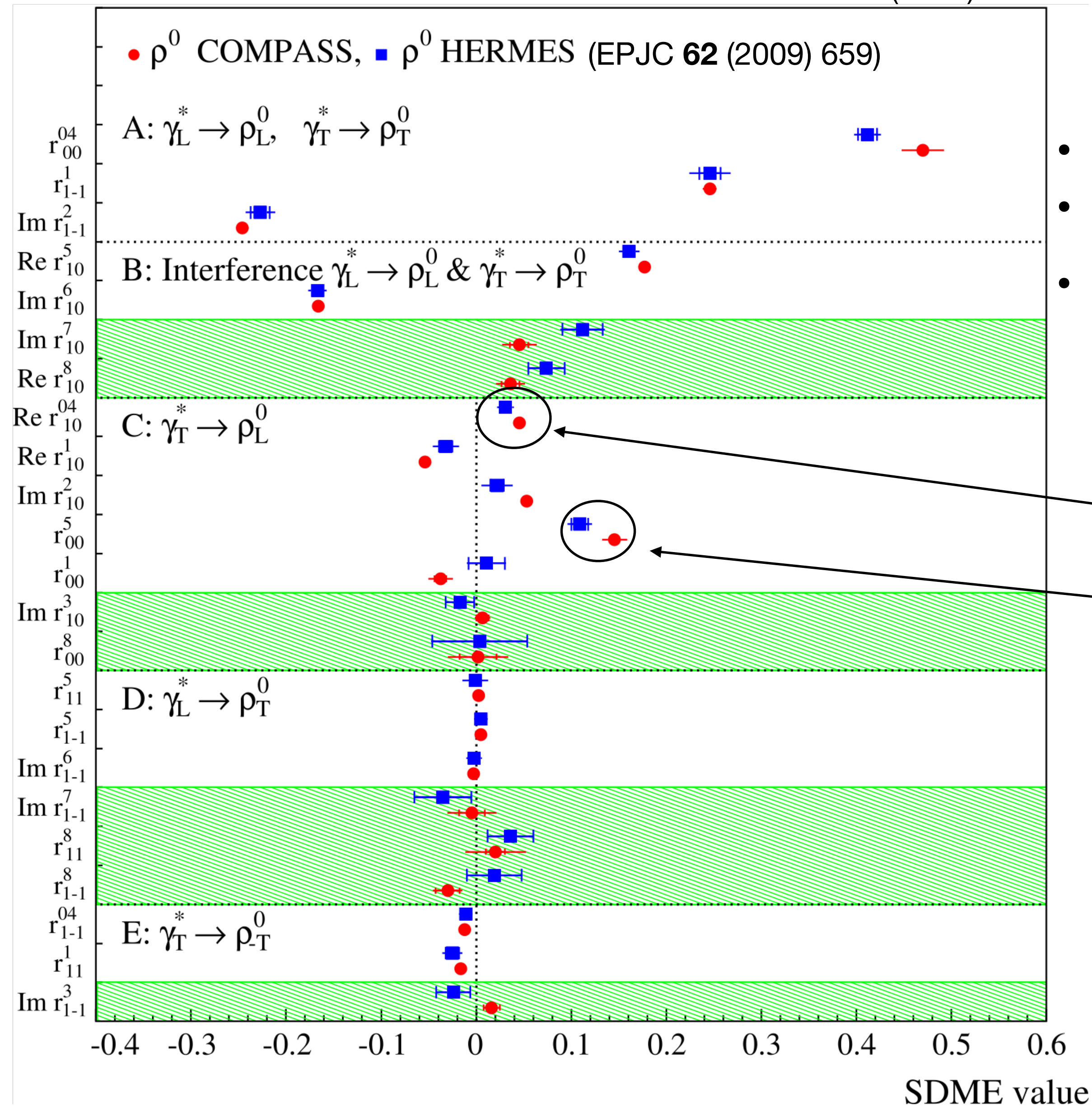
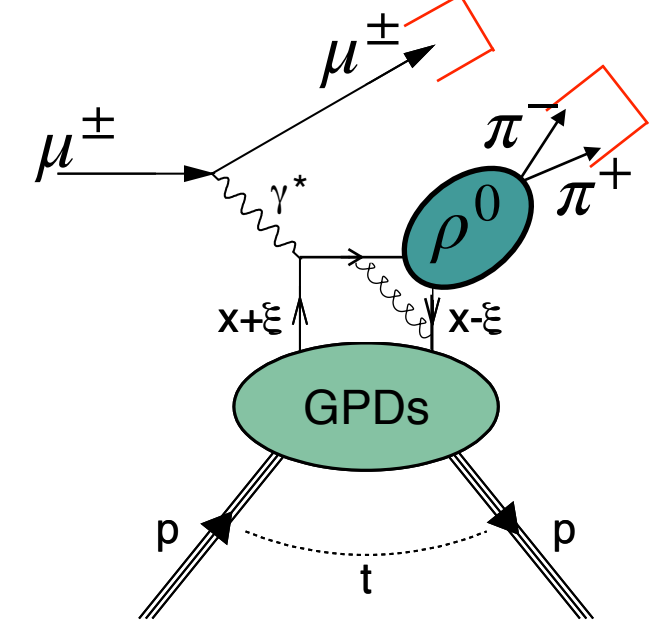
COMPASS:
 $\langle Q^2 \rangle = 2.40 \text{ GeV}^2$
 $\langle W \rangle = 9.9 \text{ GeV}^2$



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:

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

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

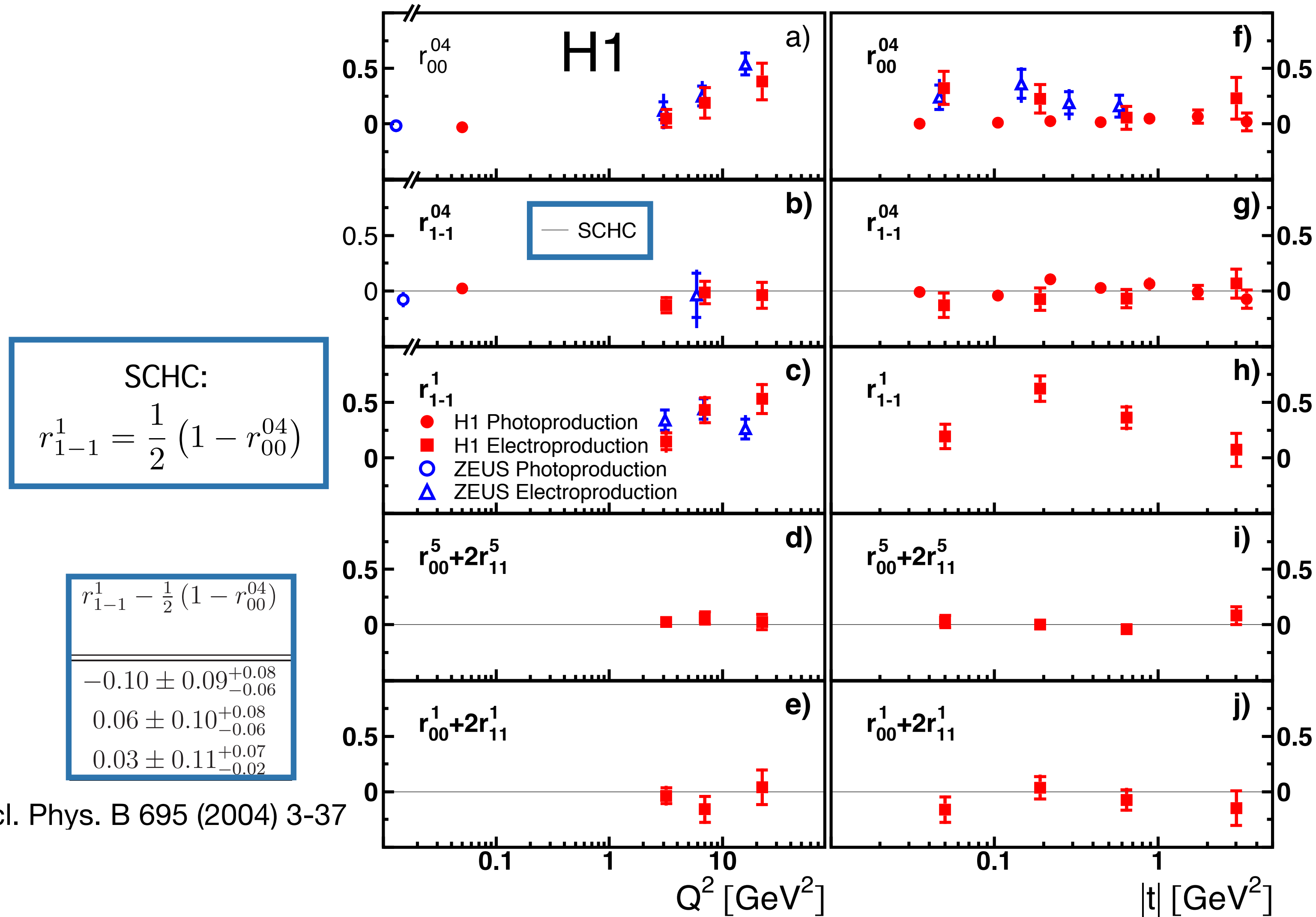
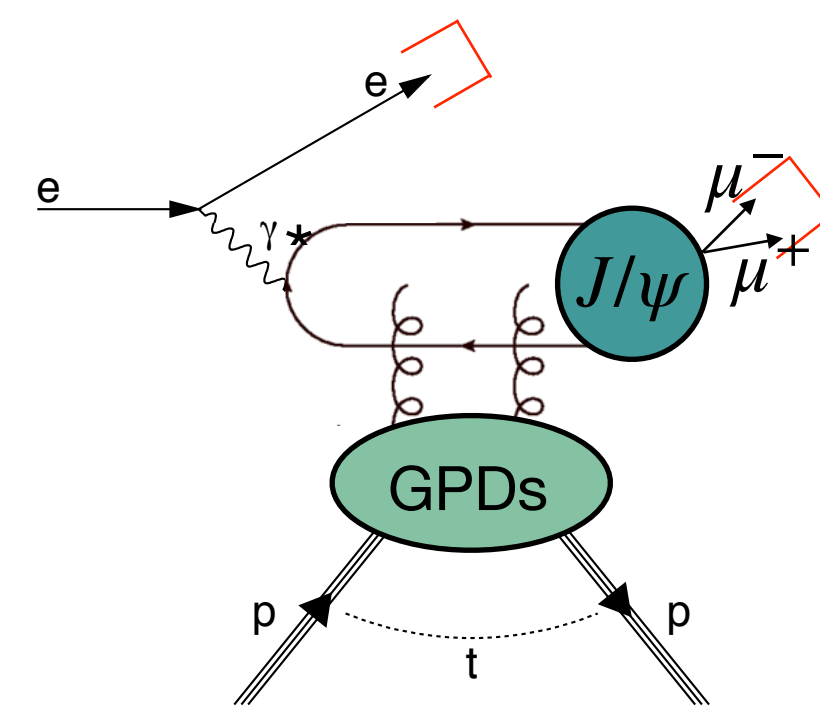
$$H_T, \bar{E}_T = 2\tilde{H}_T + E_T$$

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

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

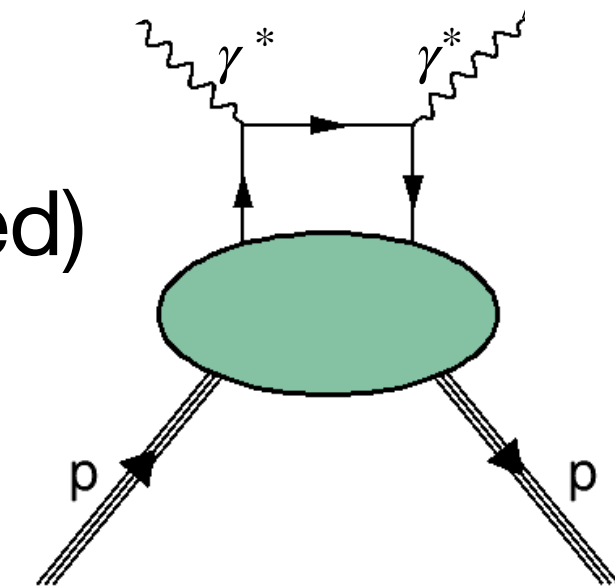
COMPASS:
 $\langle Q^2 \rangle = 2.40 \text{ GeV}^2$
 $\langle W \rangle = 9.9 \text{ GeV}^2$

Exclusive J/ψ production : SDMEs



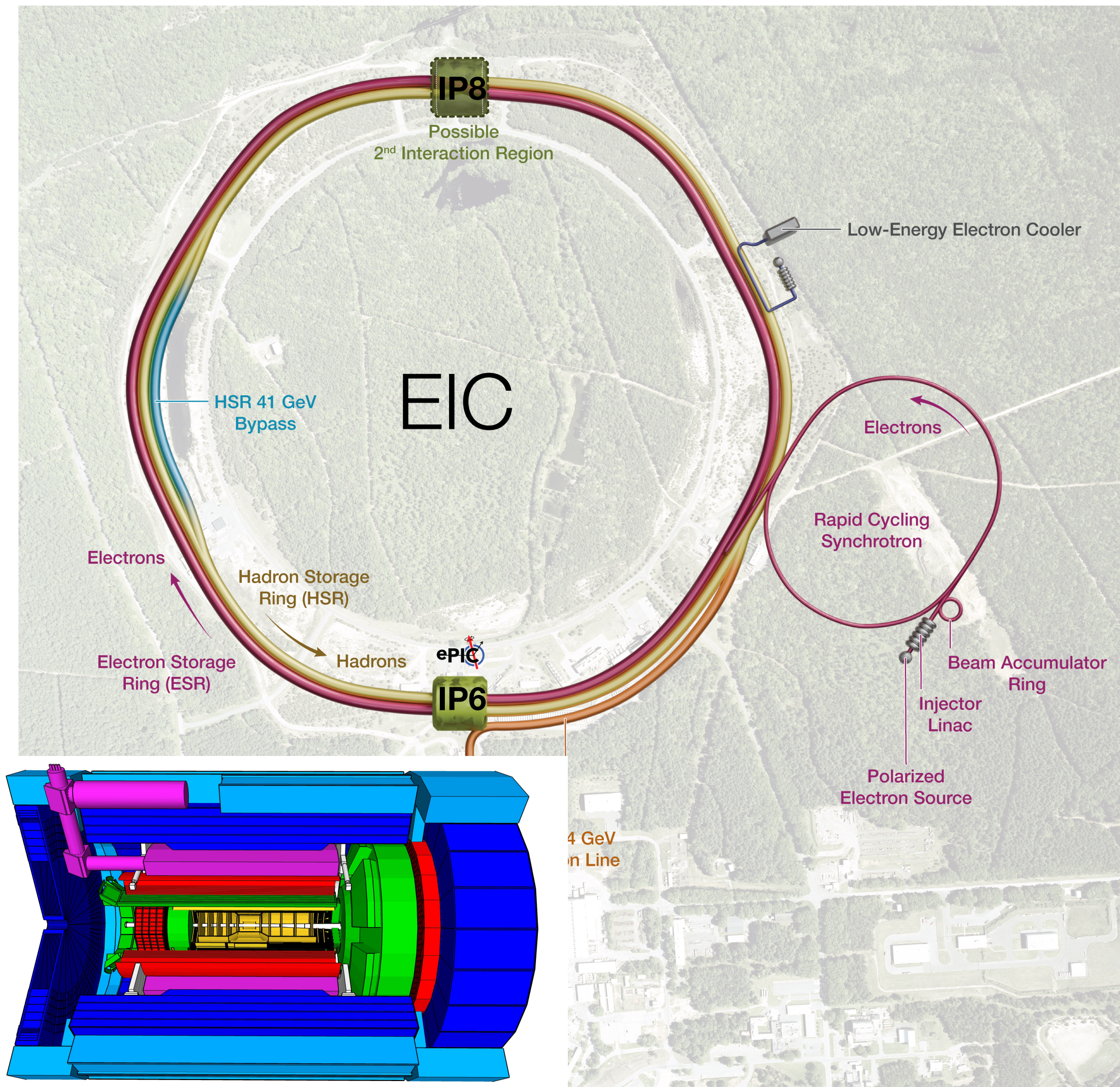
Upcoming DIS experiments probing GPDs

- 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



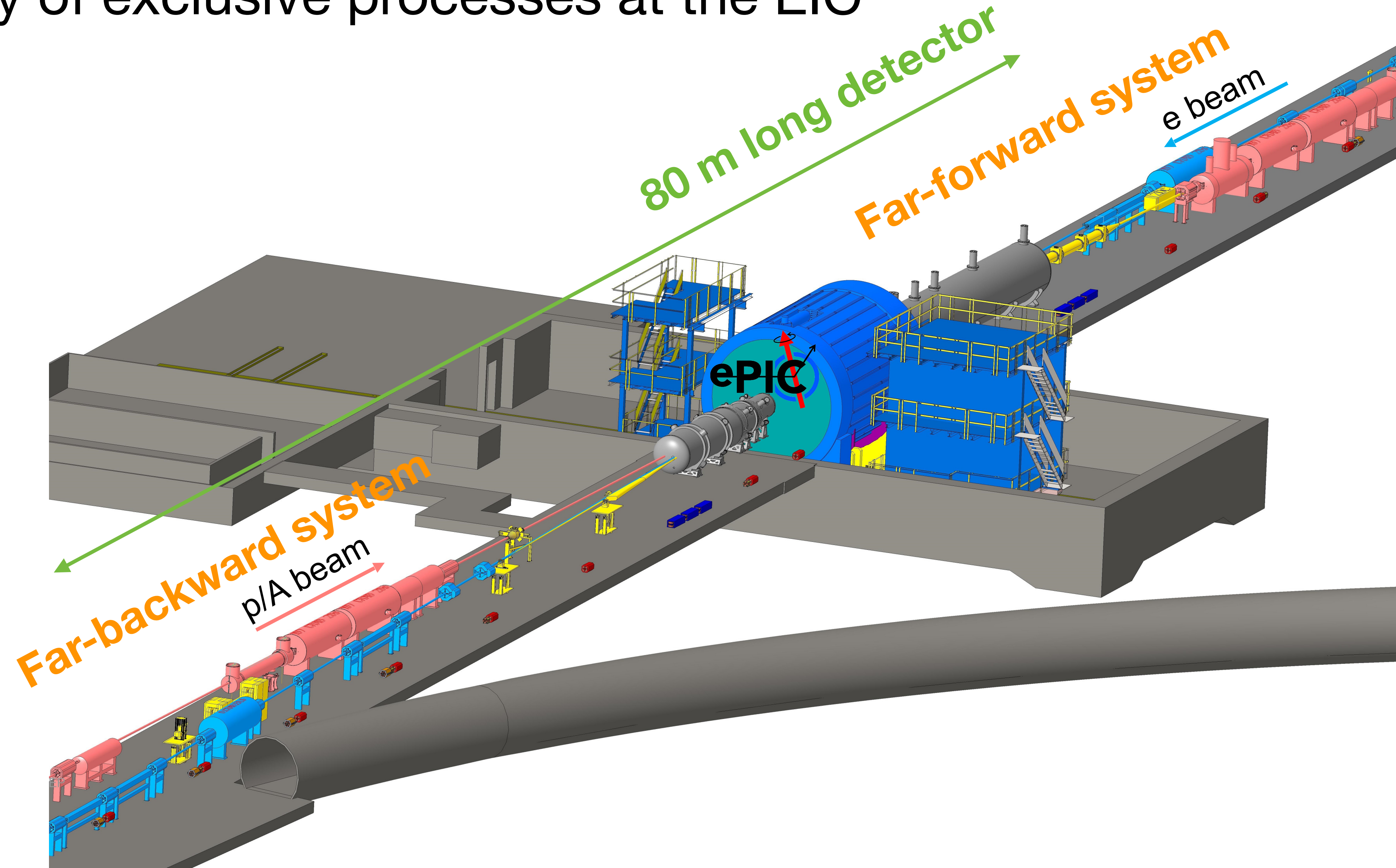
- EIC

Future: the electron-ion collider (EIC)

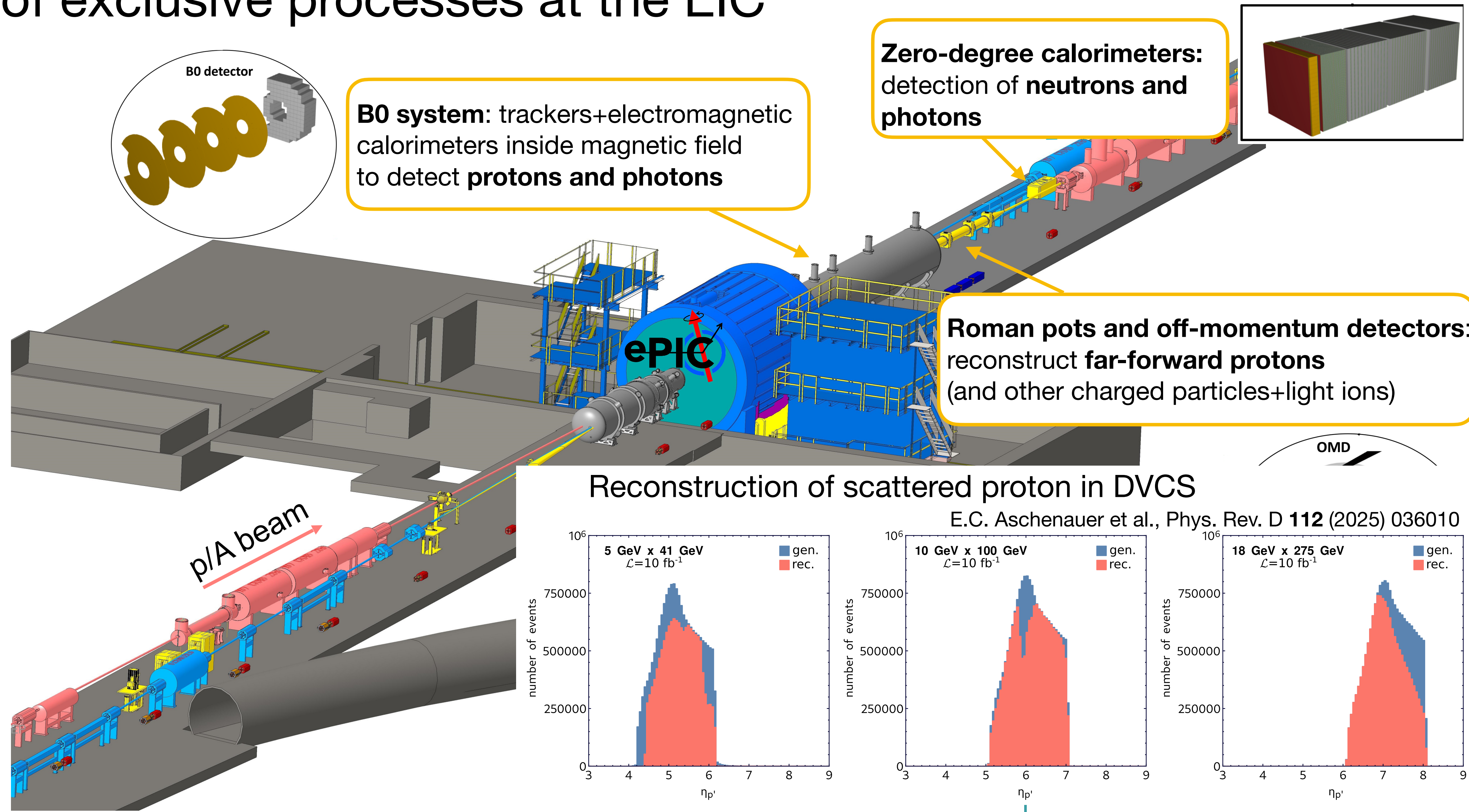


- Based on RHIC:
 - use exiting hadron storage ring
energy: 41, 100–275 GeV
 - add electron storage ring in RHIC tunnel
energy: 5–10 GeV
- $\sqrt{s} = 29 - 100 \text{ GeV}$ (140 GeV upgradable)
- $\vec{e} + \vec{p}^\uparrow, \overrightarrow{He}^\uparrow$
- ~ 70% polarisation
- + heavier, unpolarised ions, up to Uranium
- $\mathcal{L} = 10^{33-34} \text{ cm}^{-2} \text{ s}^{-1}$
- ↔ $\mathcal{L}_{\text{int}} = 10 - 100 \text{ fb}^{-1}/\text{year}$

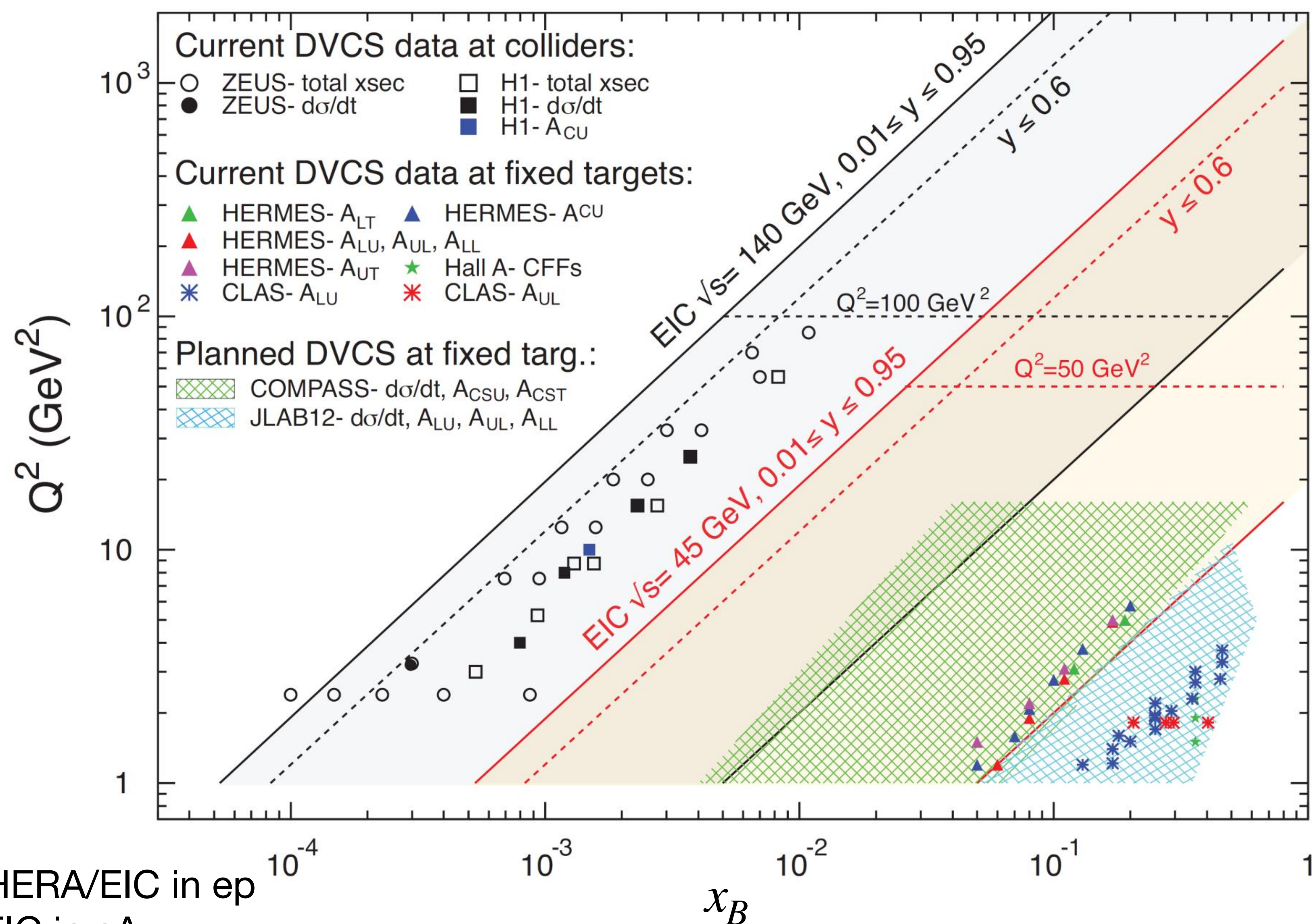
Study of exclusive processes at the EIC



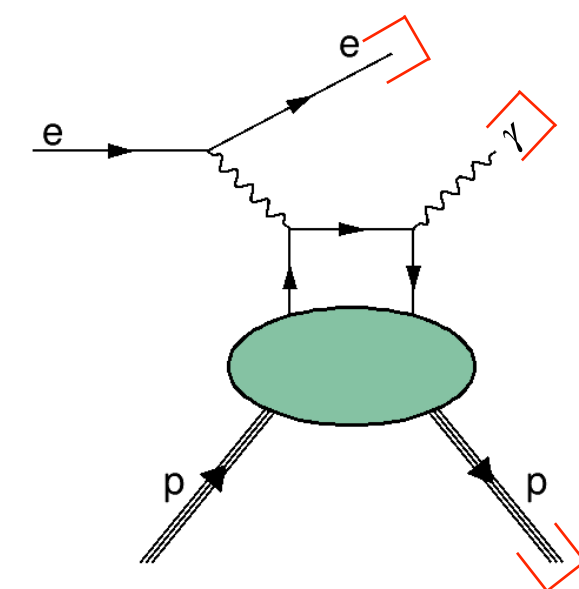
Study of exclusive processes at the EIC



Kinematic coverage of the EIC



DVCS at ePIC and impact on determination of CFFs

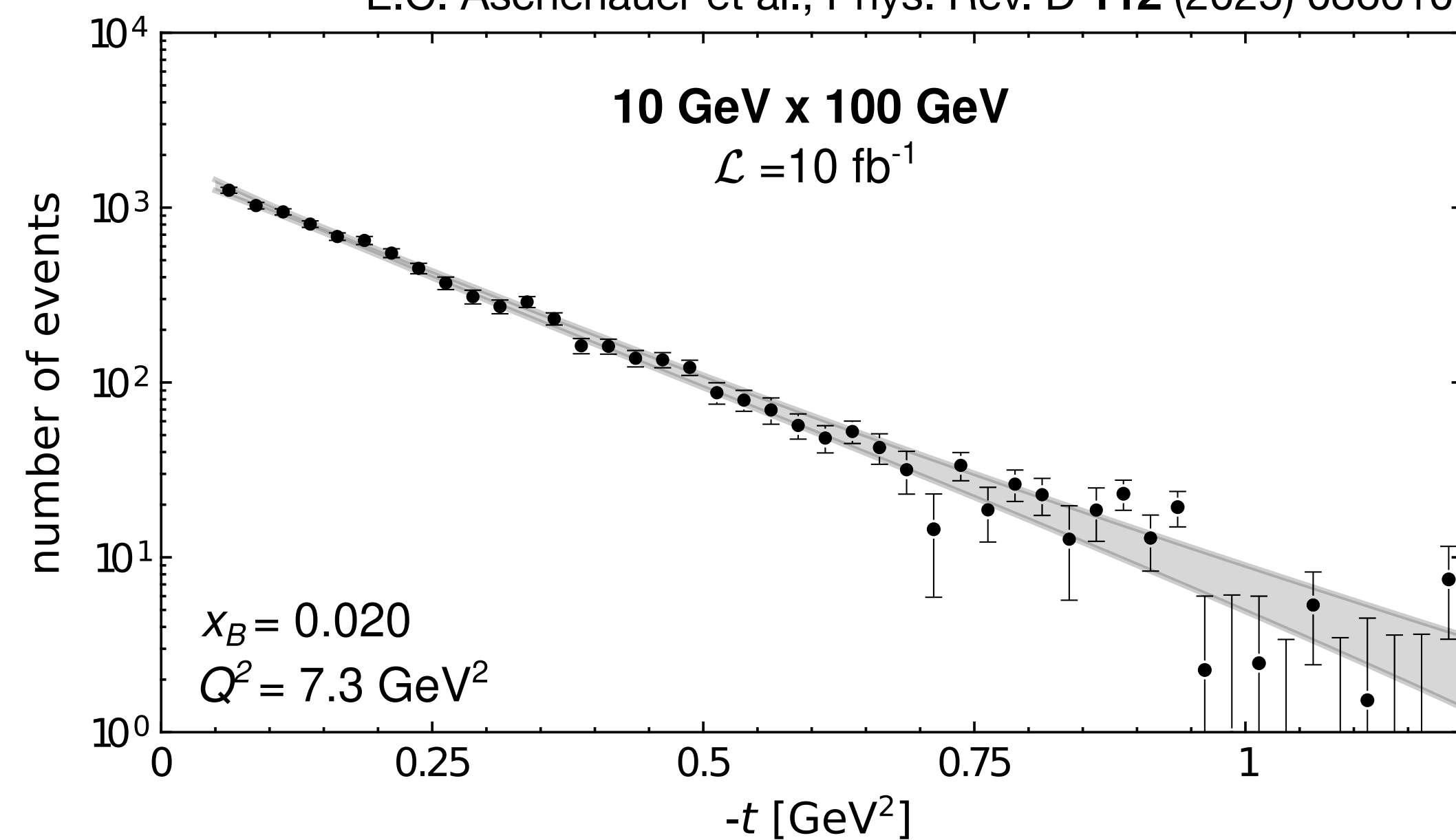


DVCS after efficiency and acceptance corrections

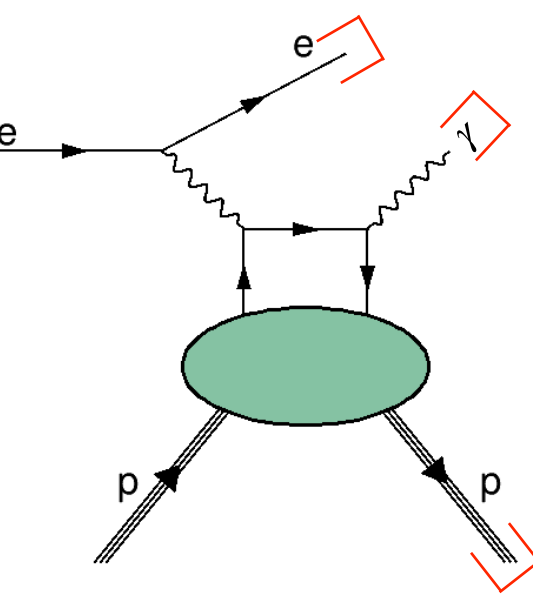
E.C. Aschenauer et al., Phys. Rev. D **112** (2025) 036010

10 GeV x 100 GeV

$\mathcal{L} = 10 \text{ fb}^{-1}$



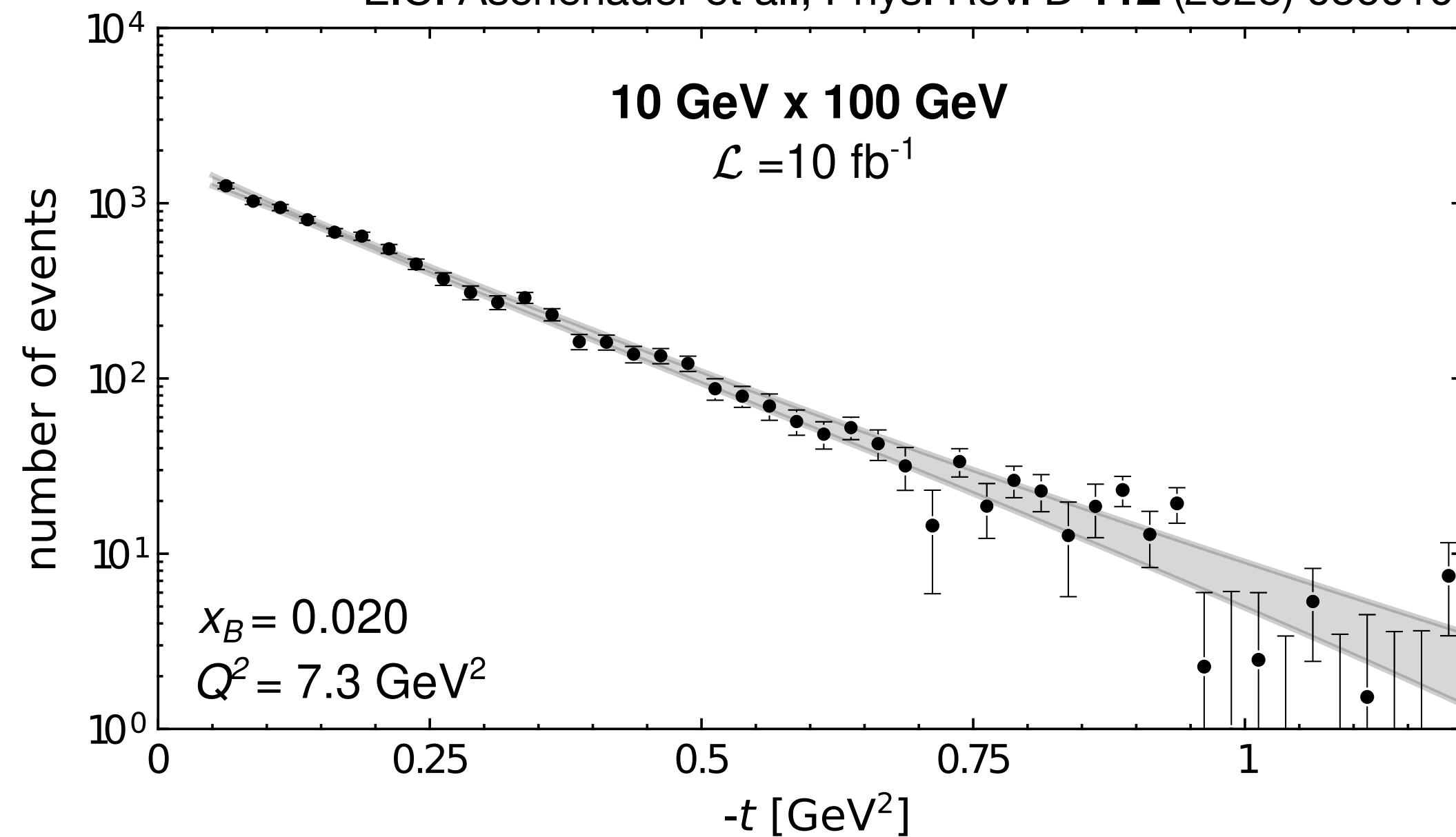
DVCS at ePIC and impact on determination of CFFs



DVCS after efficiency and acceptance corrections

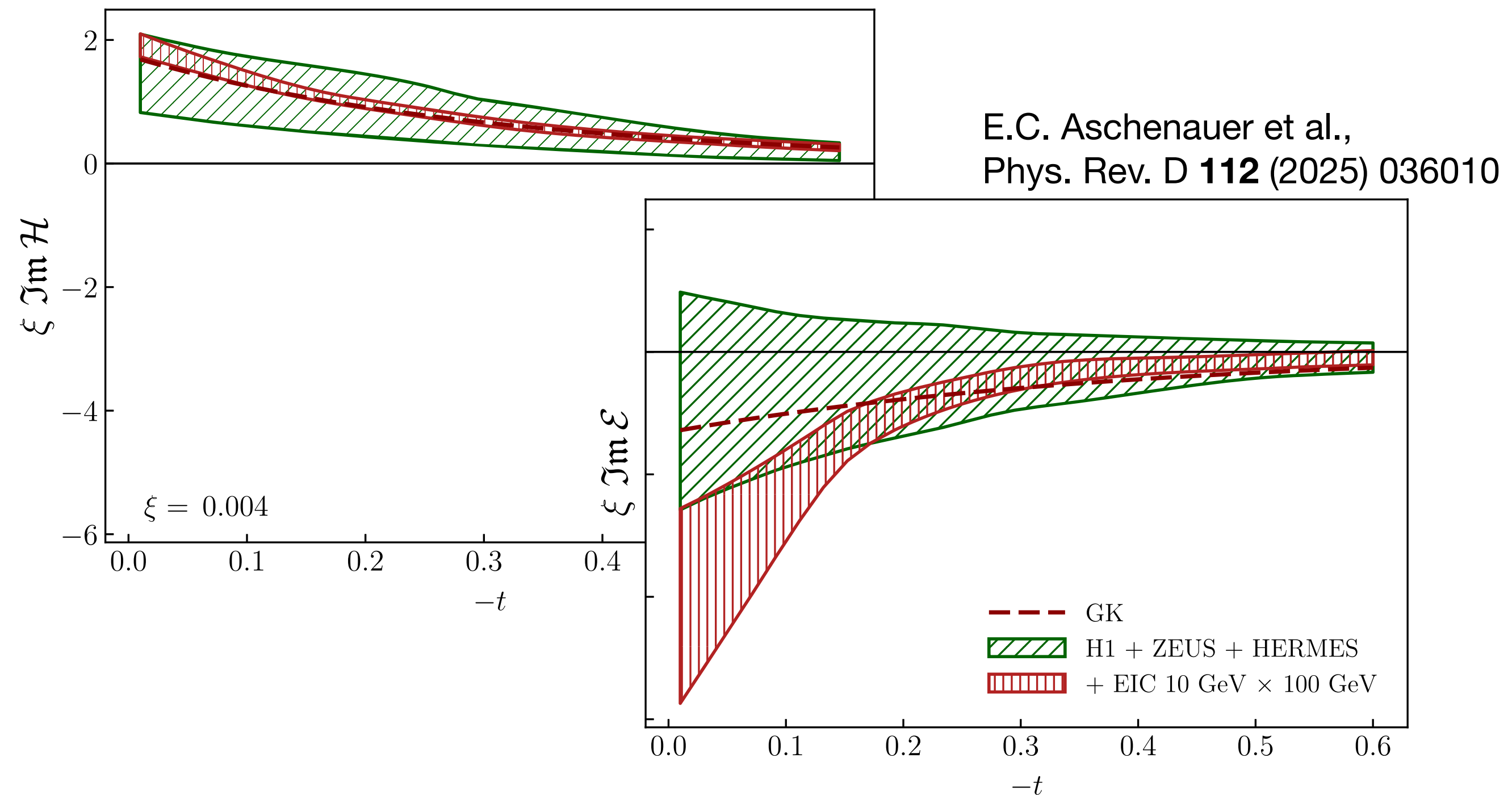
E.C. Aschenauer et al., Phys. Rev. D **112** (2025) 036010

10 GeV x 100 GeV
 $\mathcal{L} = 10 \text{ fb}^{-1}$

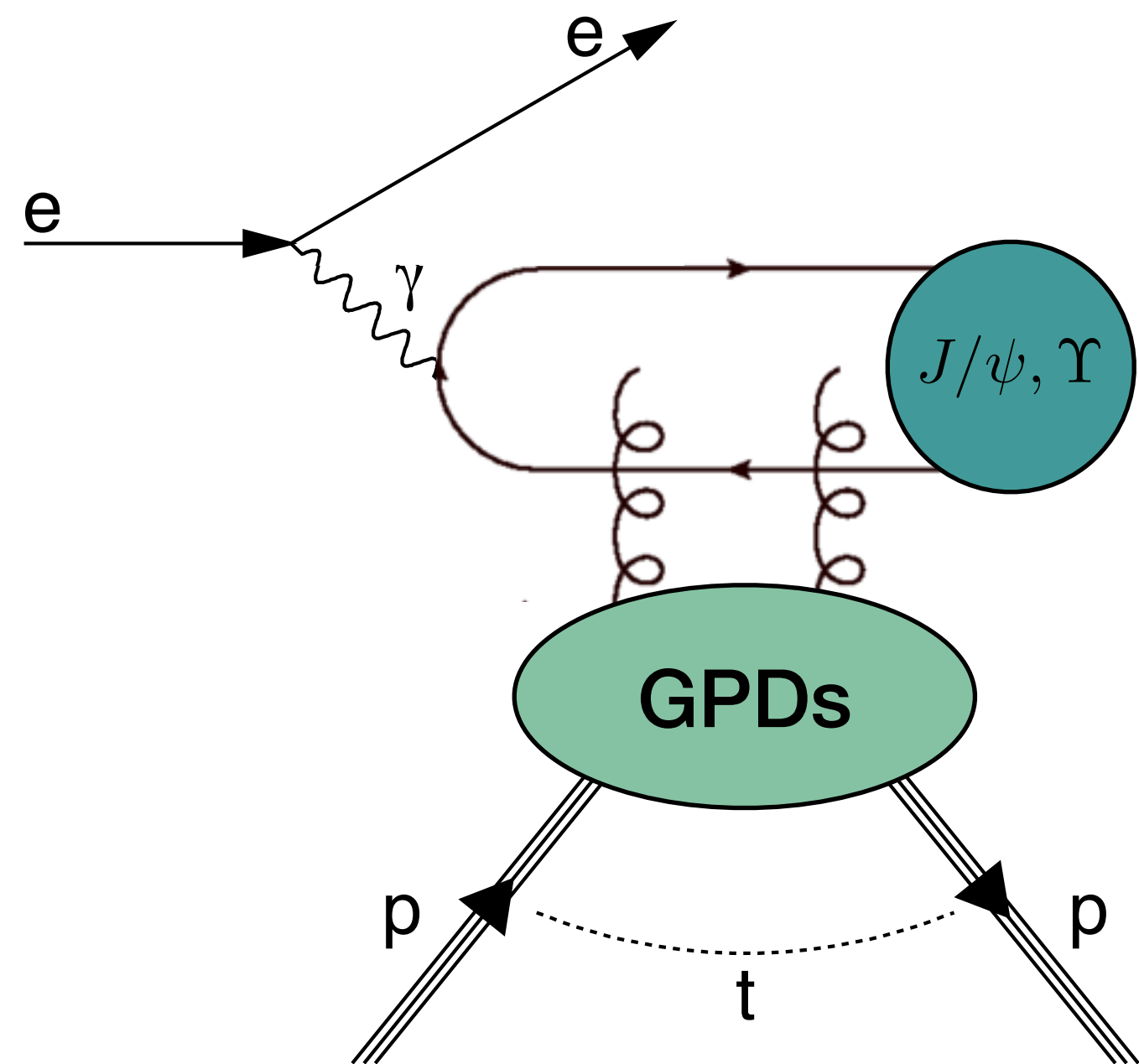


Lepton-beam helicity asymmetry

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



Experimental access to GPDs: photoproduction



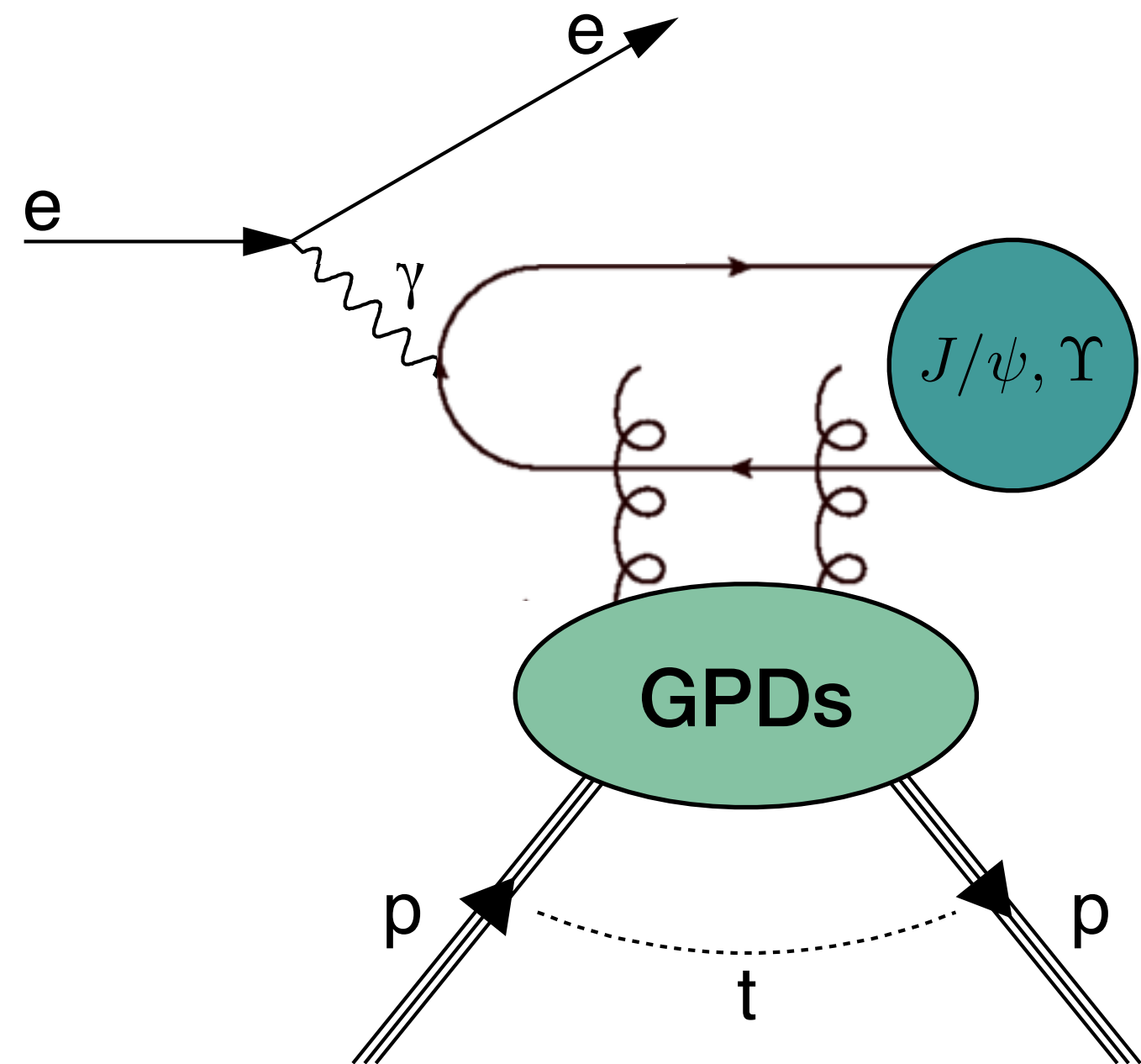
Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

H1 – EPJ C 46 ('06) 585; 73 ('13) 2466; PLB 541 ('02) 251
ZEUS – Nucl. Phys. B 695 ('04) 3; PLB 680 ('09) 4

$$W_{\gamma p} = [30, 300] \text{ GeV}$$

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

Experimental access to GPDs: photoproduction

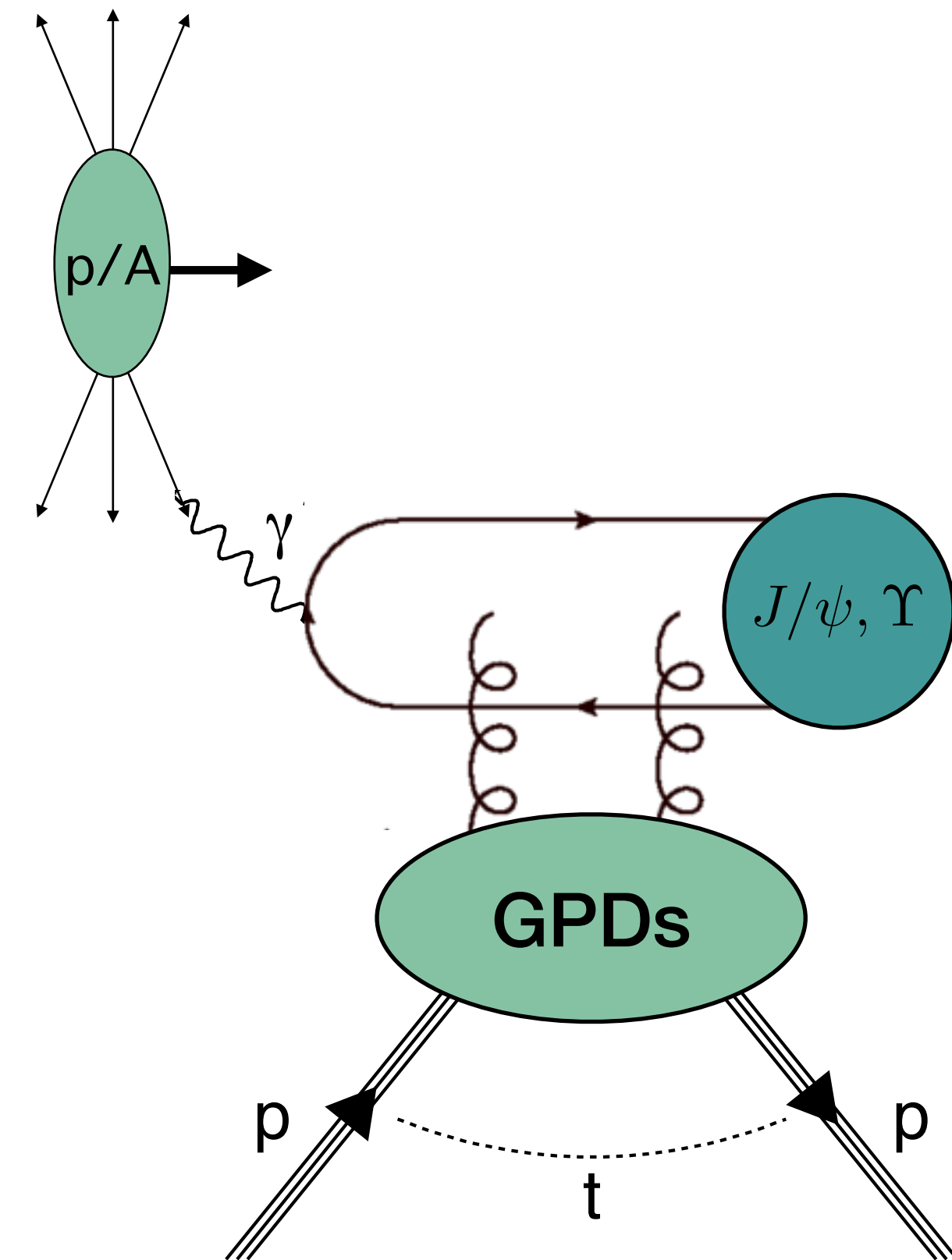


Exclusive meson photoproduction
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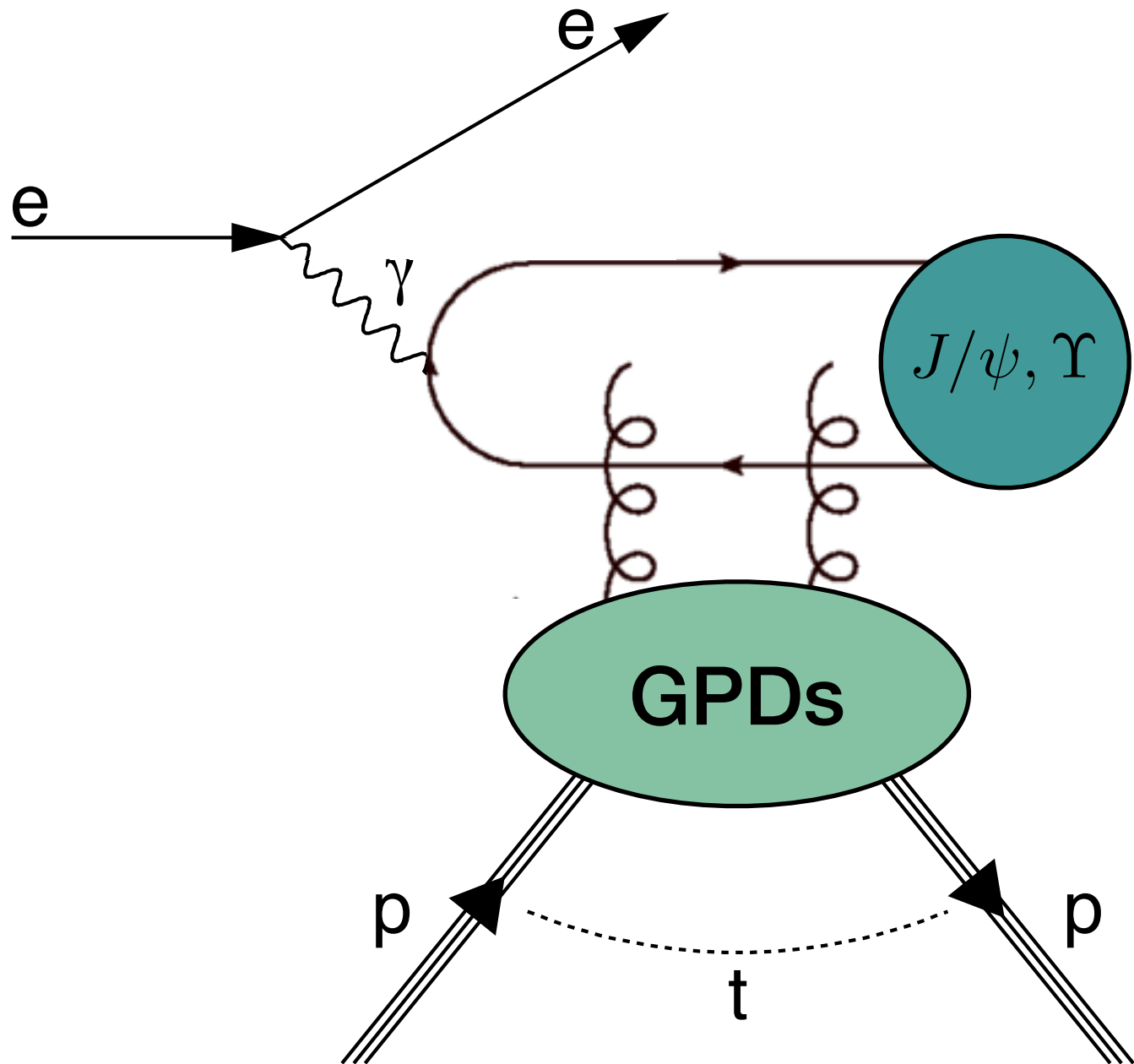
H1 – EPJ C 46 ('06) 585; 73 ('13) 2466; PLB 541 ('02) 251
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Experimental access to GPDs: photoproduction

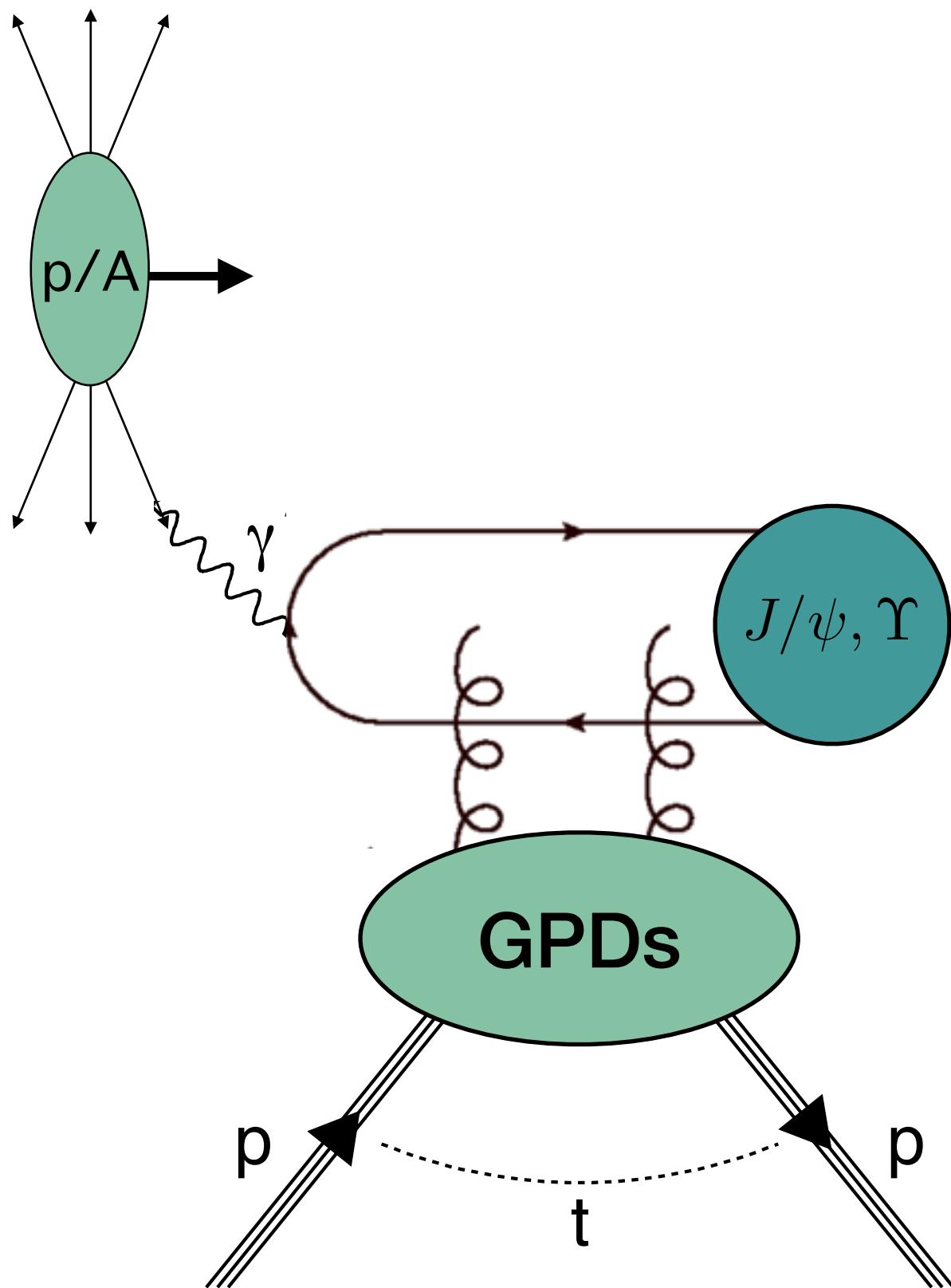


Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

H1 – EPJ C 46 ('06) 585; 73 ('13) 2466; PLB 541 ('02) 251
ZEUS – Nucl. Phys. B 695 ('04) 3; PLB 680 ('09) 4

$W_{\gamma p} = [30, 300] \text{ GeV}$

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



$W_{\gamma N}^{\text{max}} = 34 \text{ GeV}$

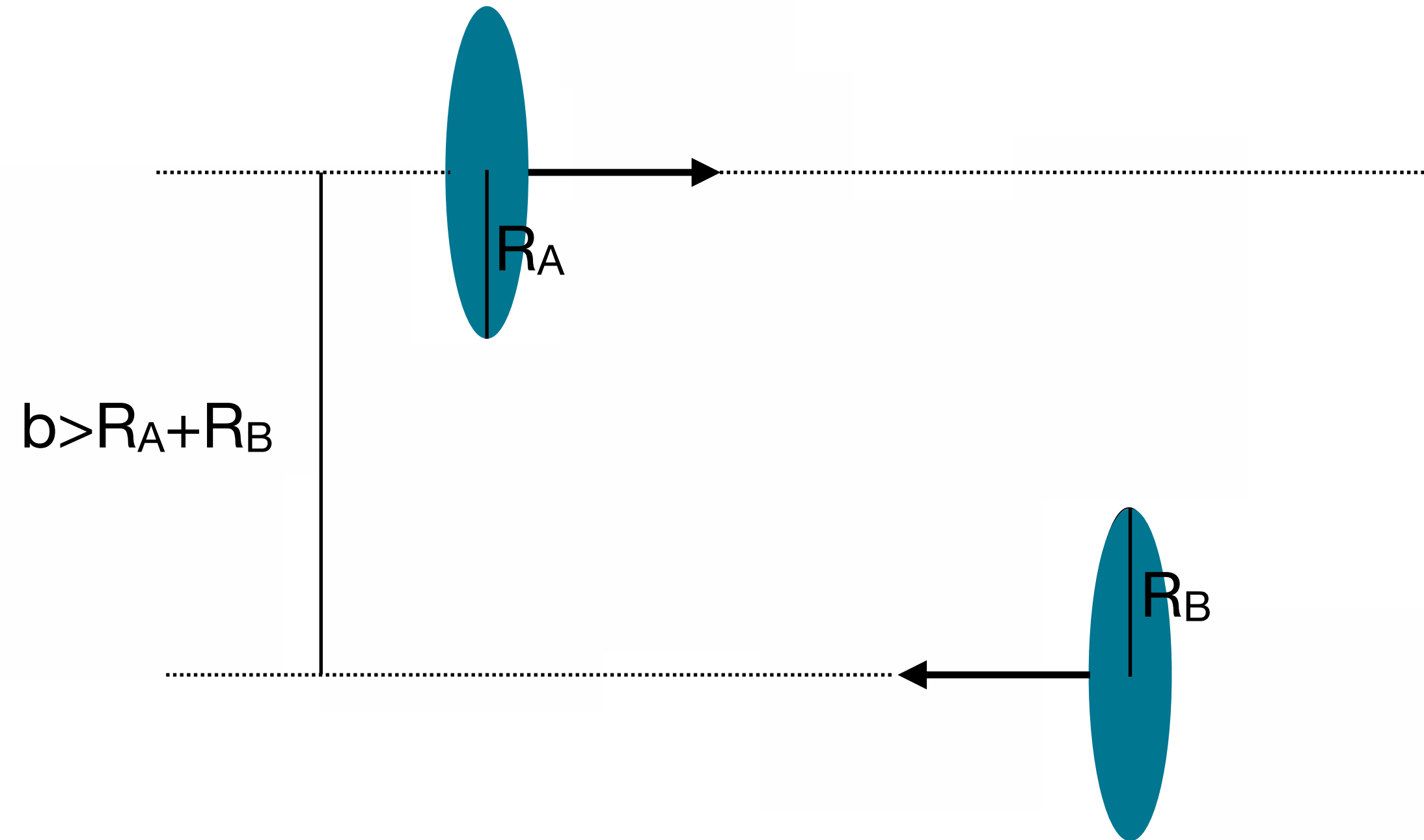
PHENIX: Au-Au – Phys. Lett. B **679** ('09) 321
CDF: p- $\bar{p}$ – Phys. Rev. Lett. **102** ('09) 242001
CMS, PbPb: Phys. Lett. B **772** ('17) 489
CMS, pPb: Eur. Phys. J. C **79** ('19) 277
ALICE: Pb-Pb – Eur. Phys. J. C **73** ('13) 2617; Phys. Lett. B **718** ('13) 1273;
Phys. Lett. B **751** ('15) 358; Phys. Lett. B **798** ('19) 134926.
ALICE: p-Pb – Phys. Rev. Lett. **113** ('14) 232504; Eur. Phys. J. C **79** ('19) 402
LHCb: PbPb – CERN-LHCb-CONF-2018-003
LHCb: pp – J. Phys. G: Nucl. Part. Phys. **40** ('13) 045001; **41** ('14) 055002;
JHEP 1509 ('15) 084); JHEP10('18)167

$W_{\gamma p}^{\text{max}} = 1.5 \text{ TeV}$

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

Ultra-peripheral collisions

large-impact-parameter interactions

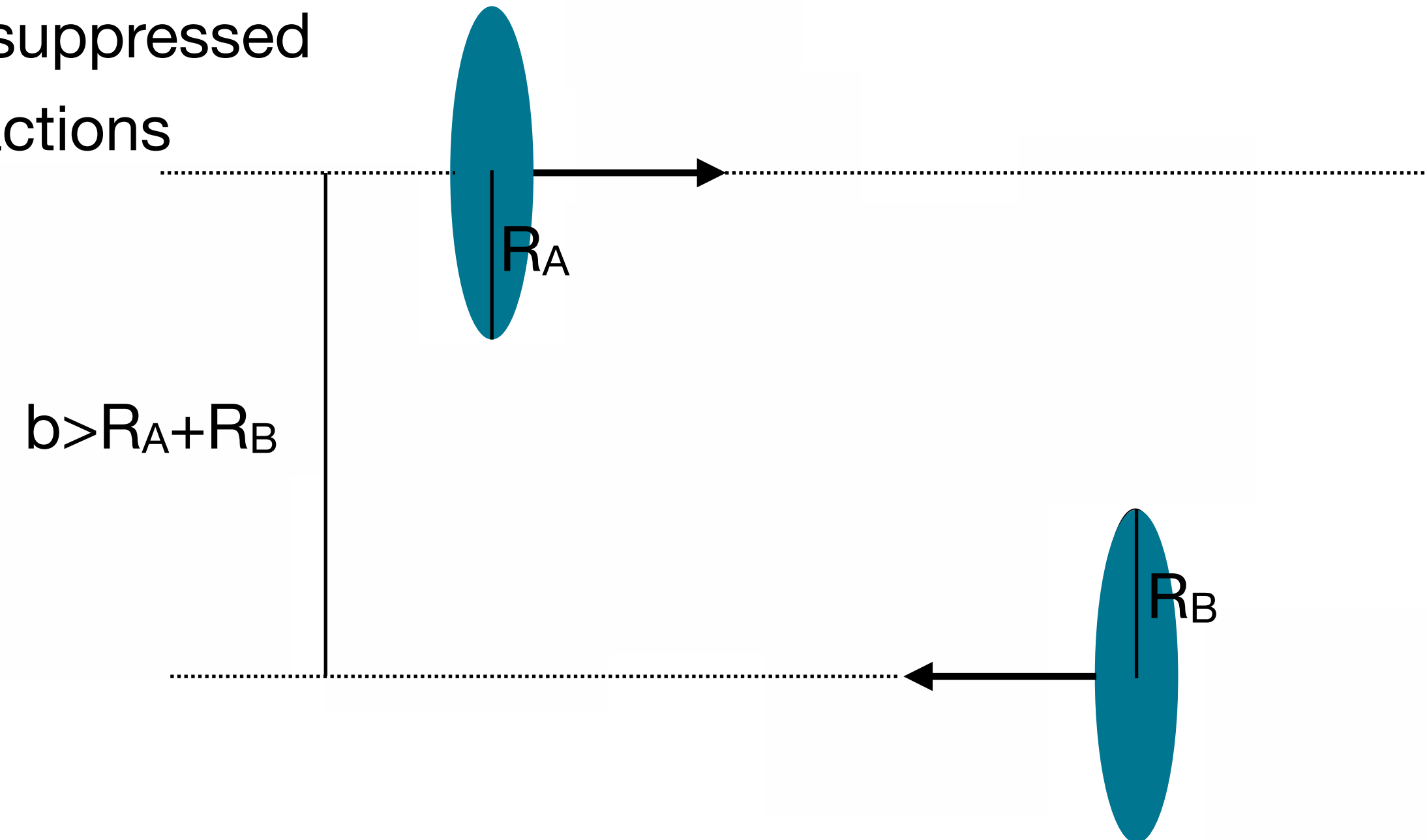


Ultra-peripheral collisions

large-impact-parameter interactions

hadronic interactions strongly suppressed

instead: electromagnetic interactions

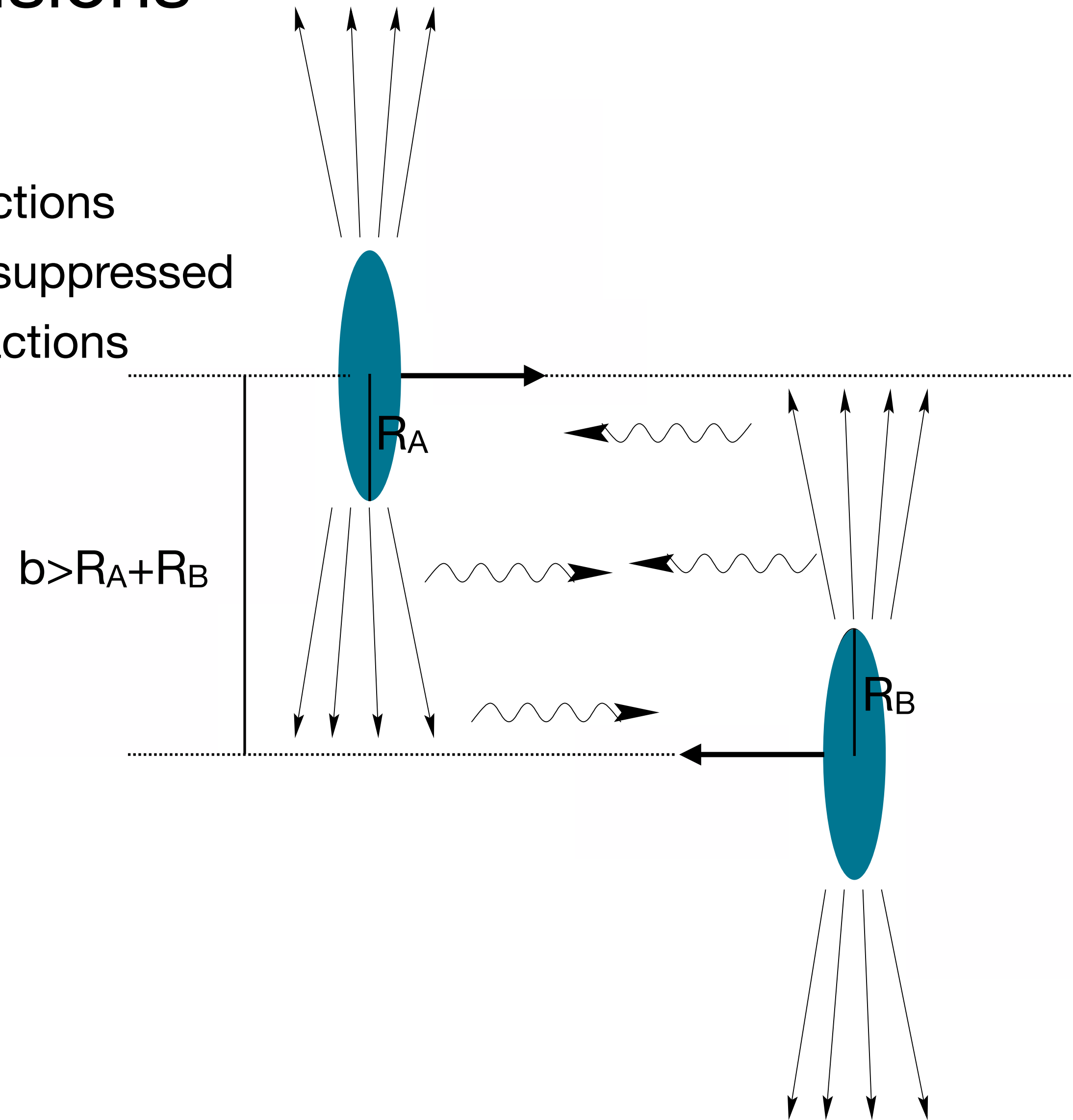


Ultra-peripheral collisions

large-impact-parameter interactions

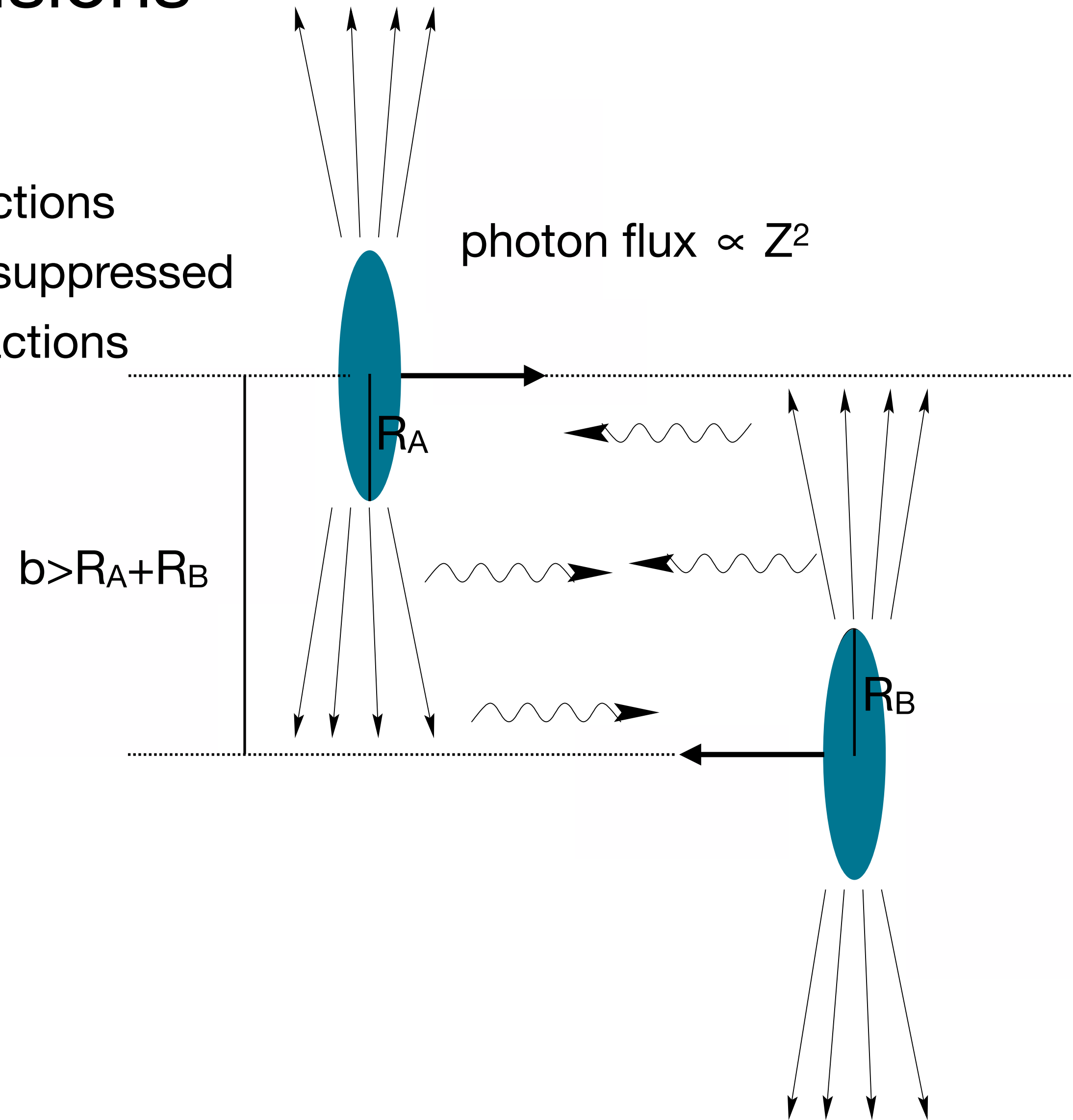
hadronic interactions strongly suppressed

instead: electromagnetic interactions



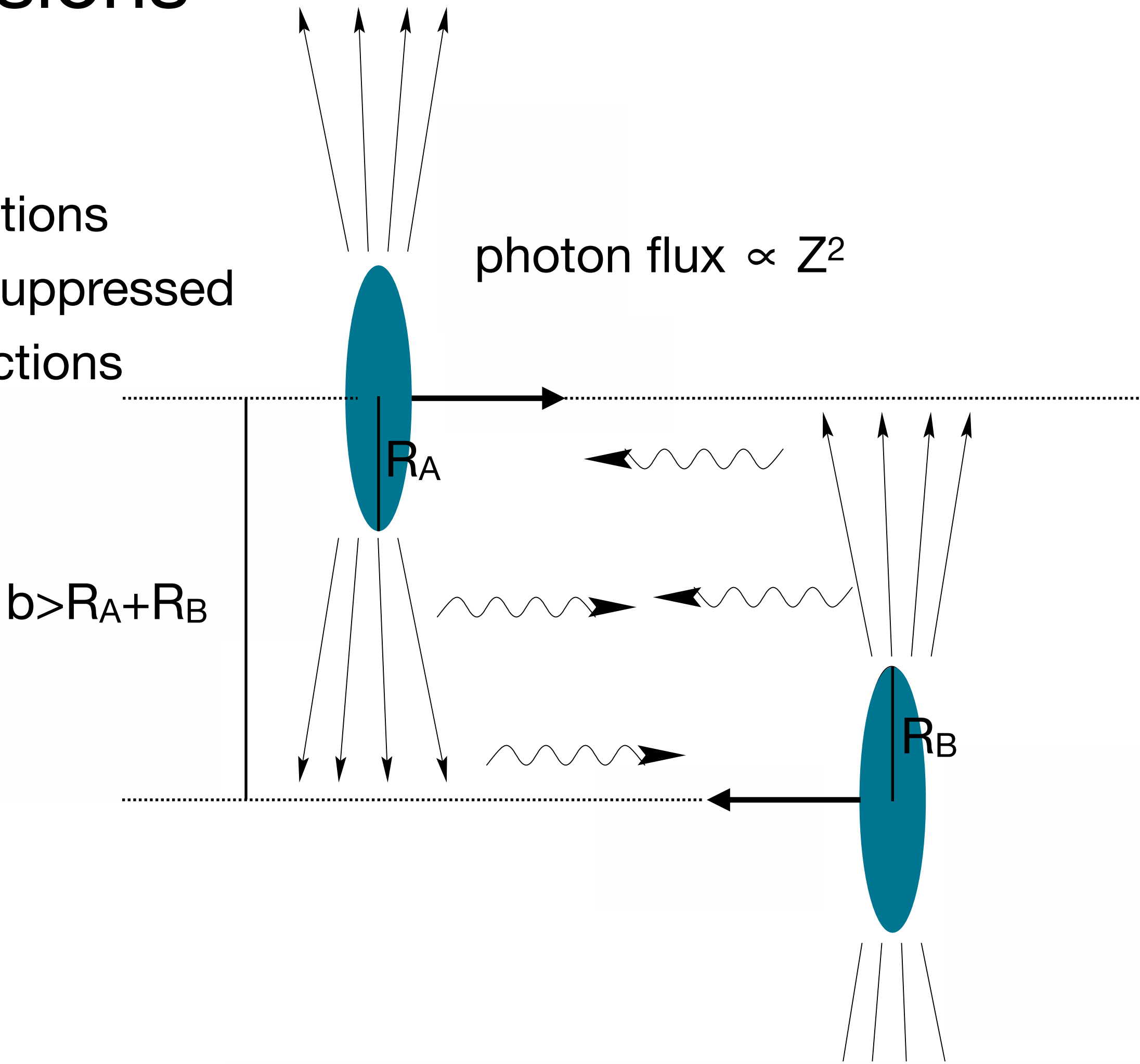
Ultra-peripheral collisions

large-impact-parameter interactions
hadronic interactions strongly suppressed
instead: electromagnetic interactions



Ultra-peripheral collisions

large–impact-parameter interactions
hadronic interactions strongly suppressed
instead: electromagnetic interactions

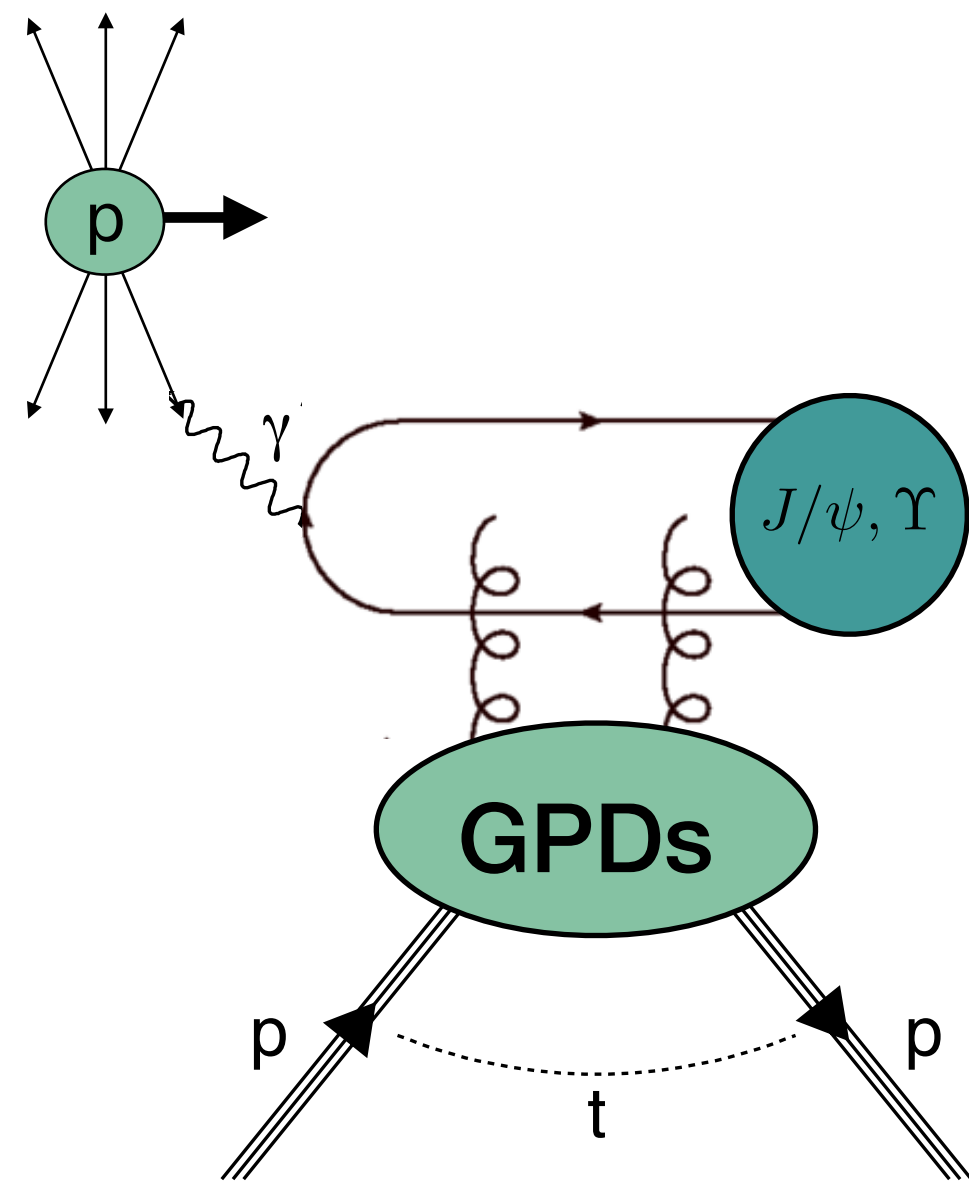


photon virtuality $Q^2 < \left(\frac{\hbar c}{R_A}\right)^2$
→ quasi-real photons
maximum photon energy = $\frac{2\gamma\hbar c}{b_{\min}}$

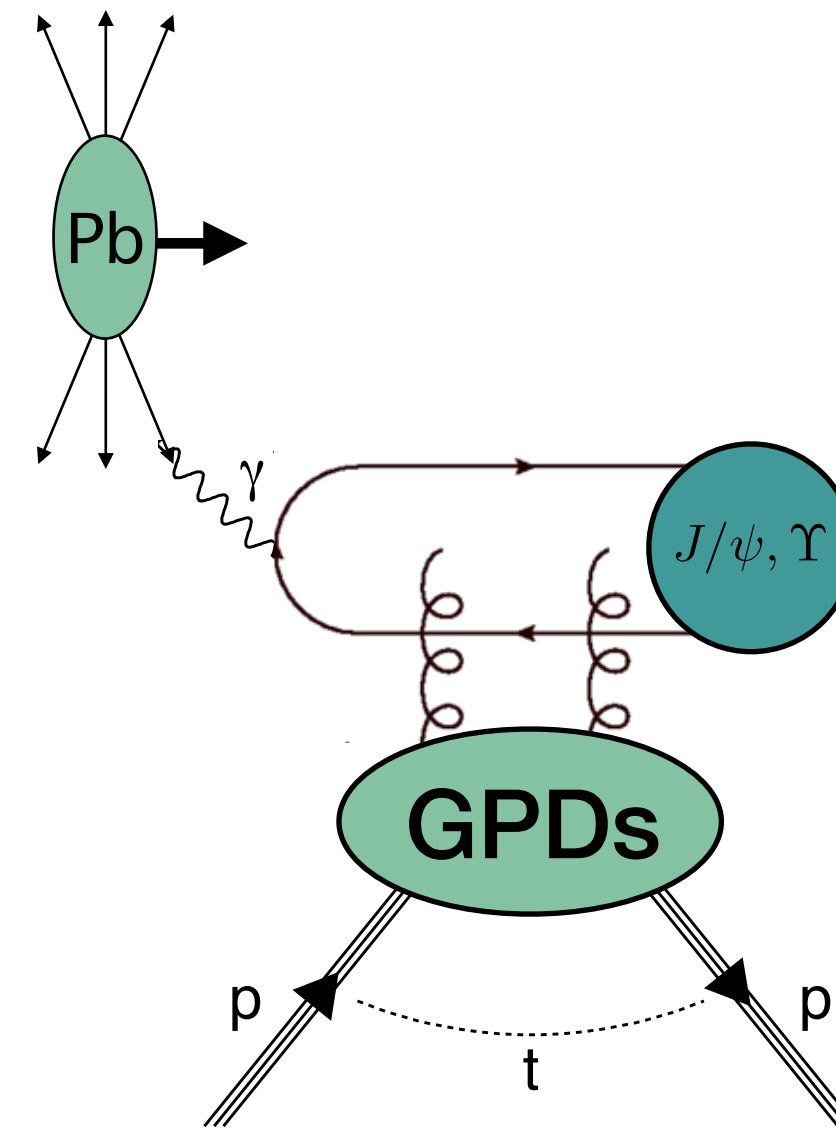
System	$\sqrt{s_{AB}}$	E_A	E_B	(a) $\gamma_{A\leftrightarrow B}$	(b) $E_{\gamma Max}^{rest}$	(c) $E_{\gamma Max}$	(d) $W_{\gamma p}^{max}$
pPb	5.02 TeV	4 TeV	1.567 TeV	1.43×10^7	28 MeV	0.4 PeV	0.86 TeV
pPb	8.16 TeV	6.5 TeV	2.56 TeV	3.78×10^7	28 MeV	1 PeV	1.4 TeV
pp	13 TeV	6.5 TeV	6.5 TeV	9.6×10^7	116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

table: K. Lynch

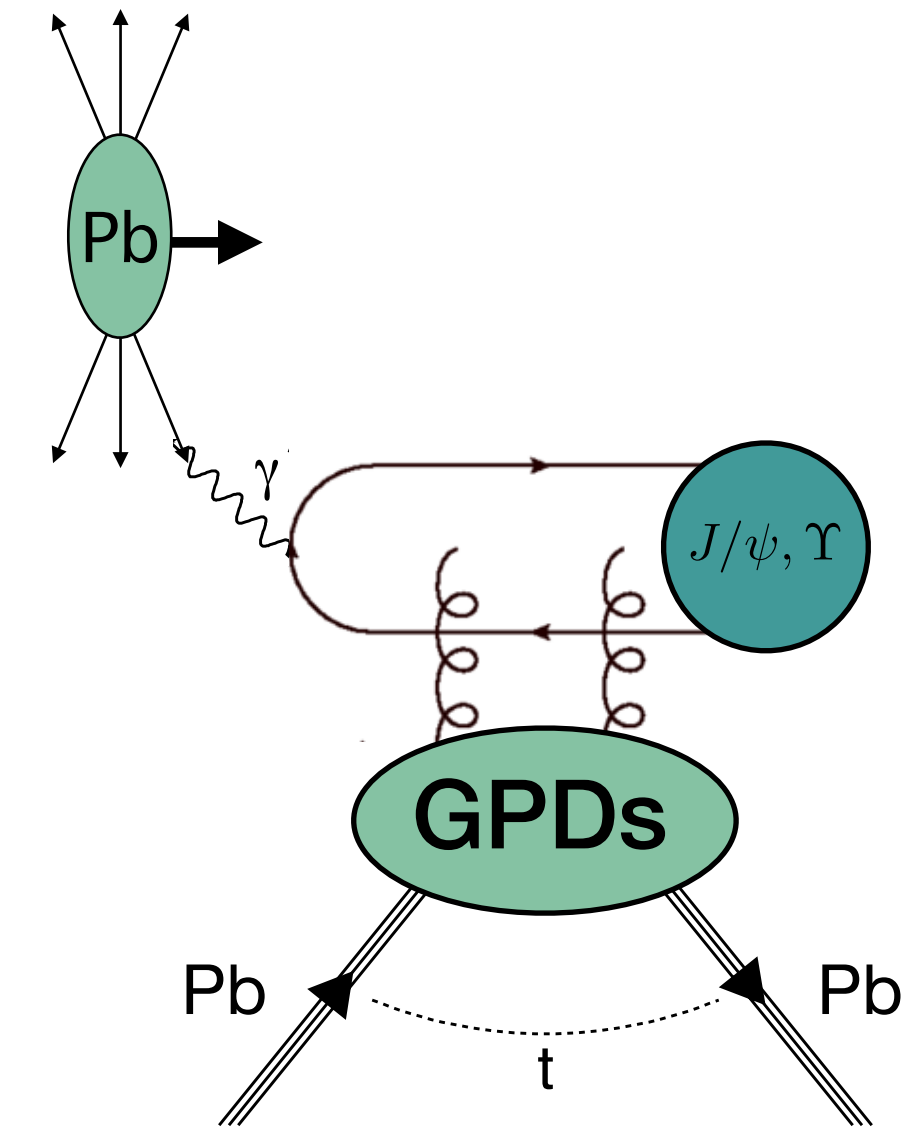
Ultra-peripheral hadron-hadron collisions



pp: ambiguity in ID of photon emitter



pPb: use Z^2 dependence of photon flux
 → 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

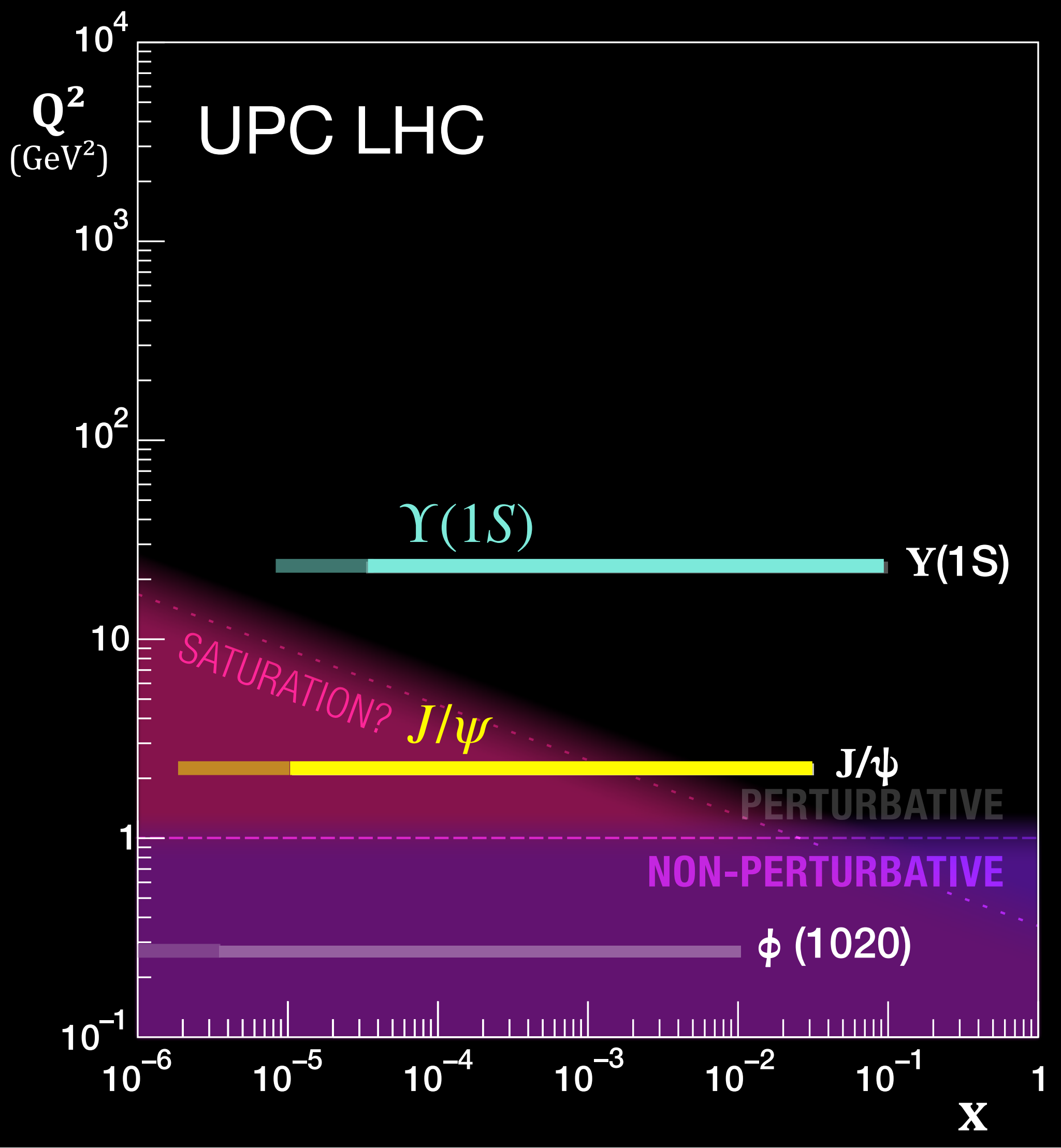


Figure adapted from Jordan Lang | Quarkonia as Tools 2026 | 6 January 2026

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photoproduction

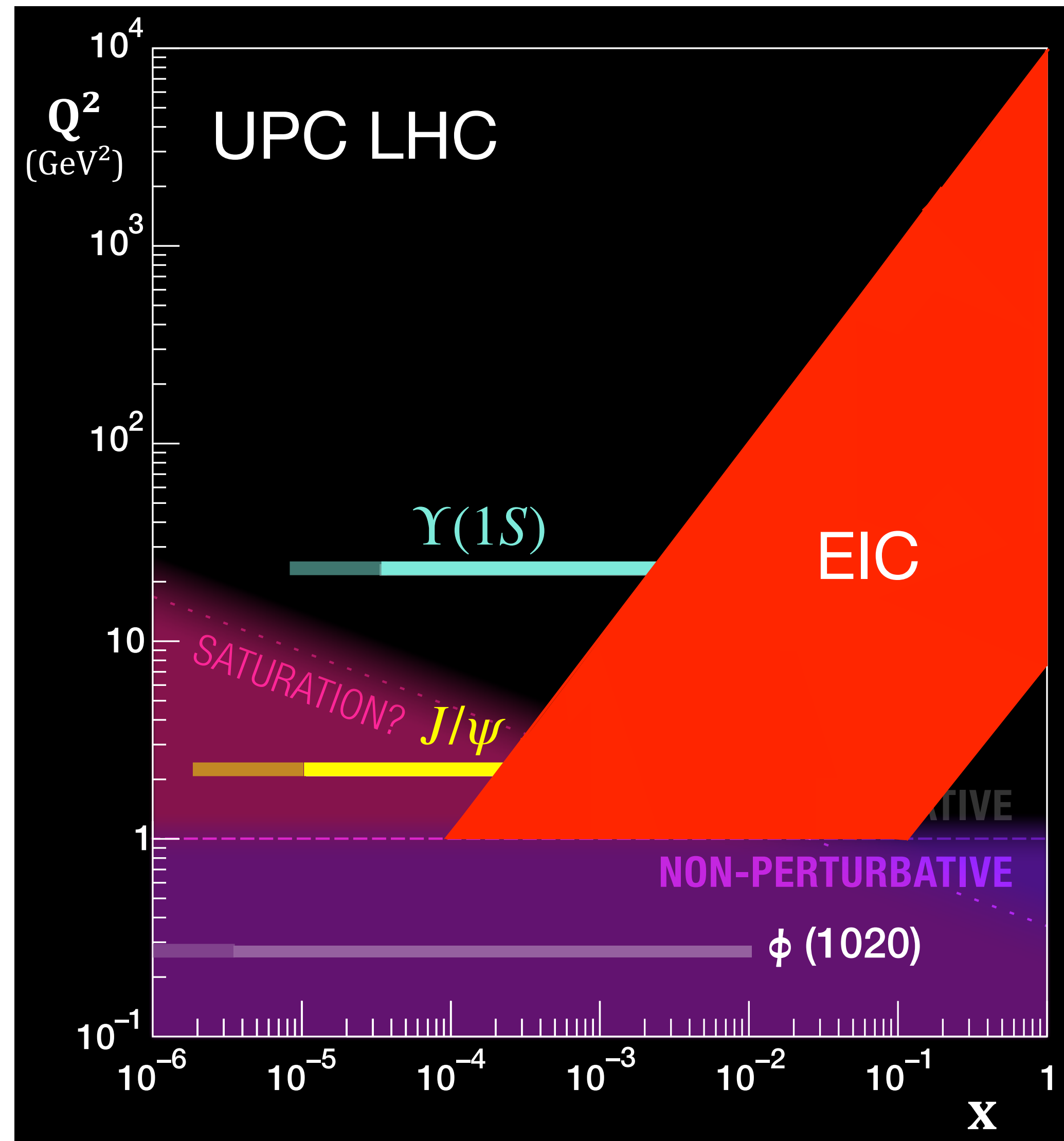
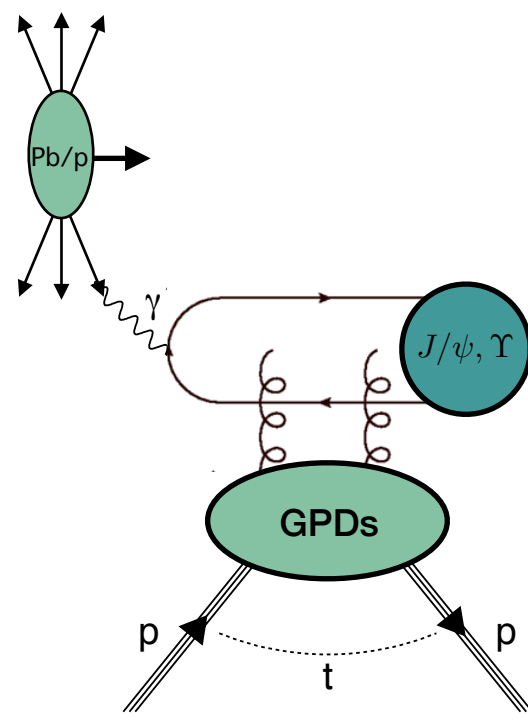
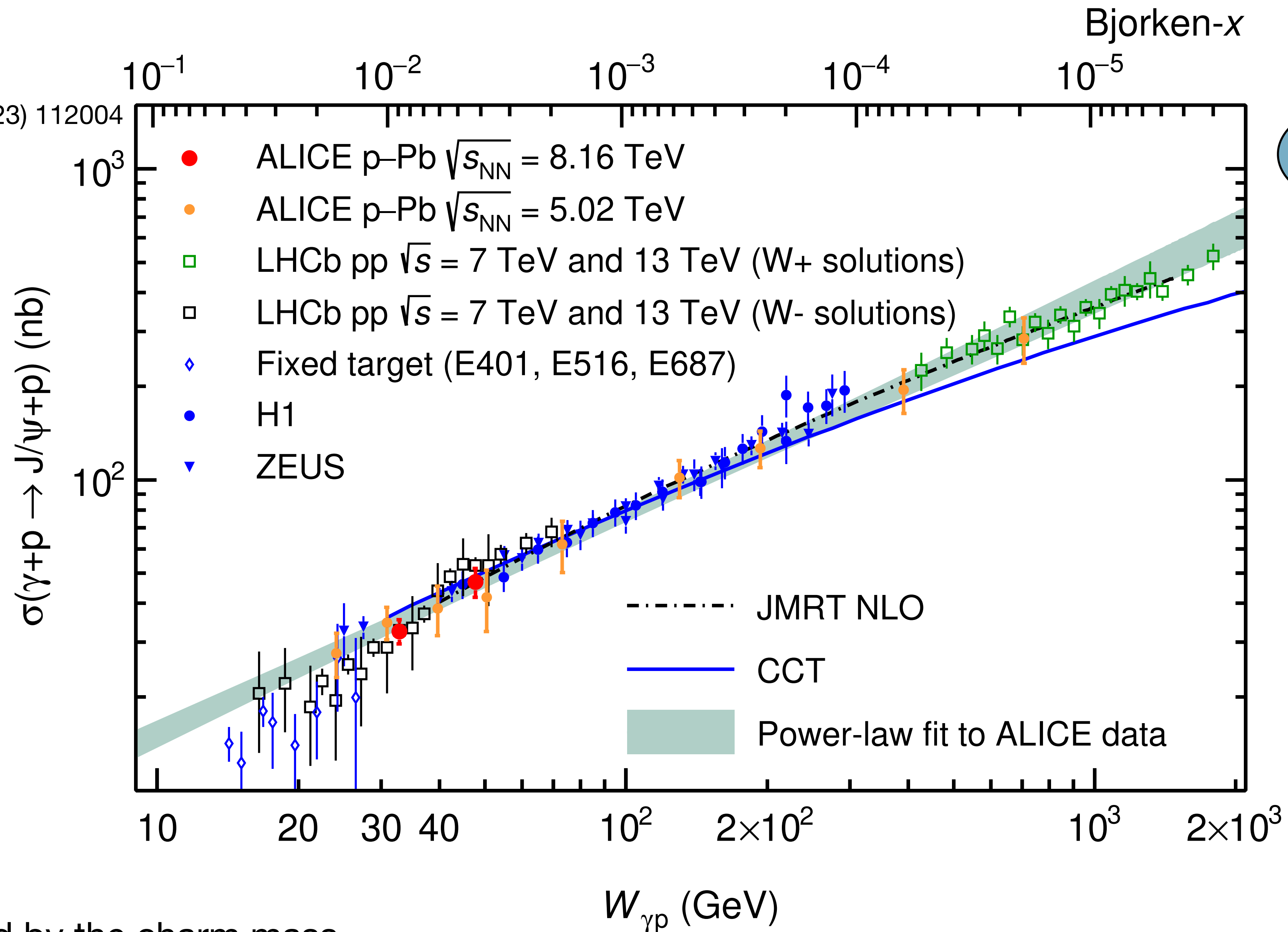


Figure adapted from Jordan Lang | Quarkonia as Tools 2026 | 6 January 2026

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

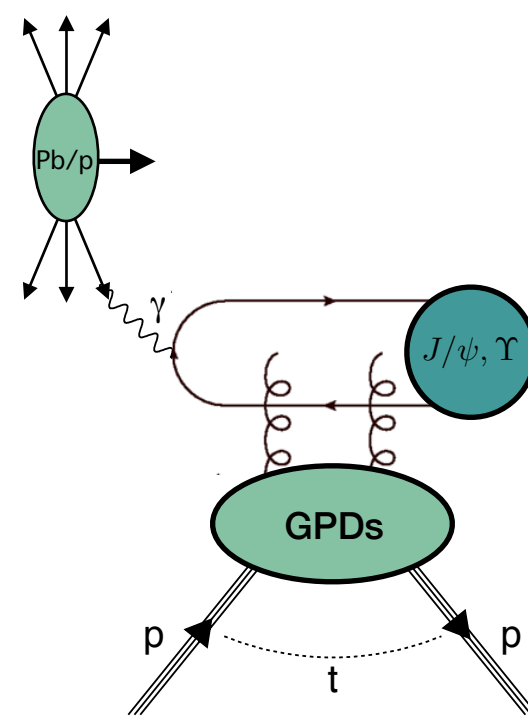
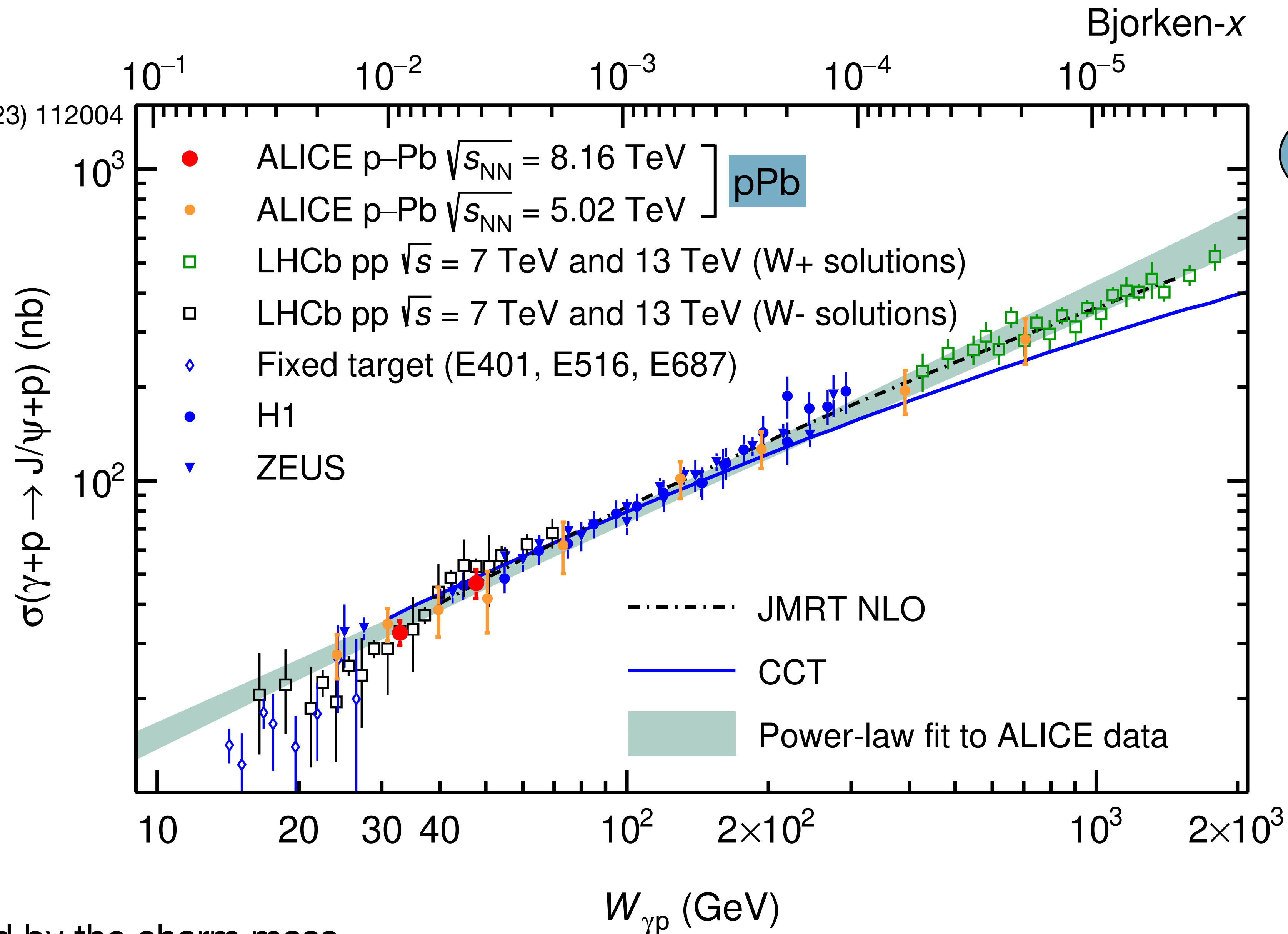
Phys. Rev. D **108** ('23) 112004



Hard scale: fixed by the charm mass

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

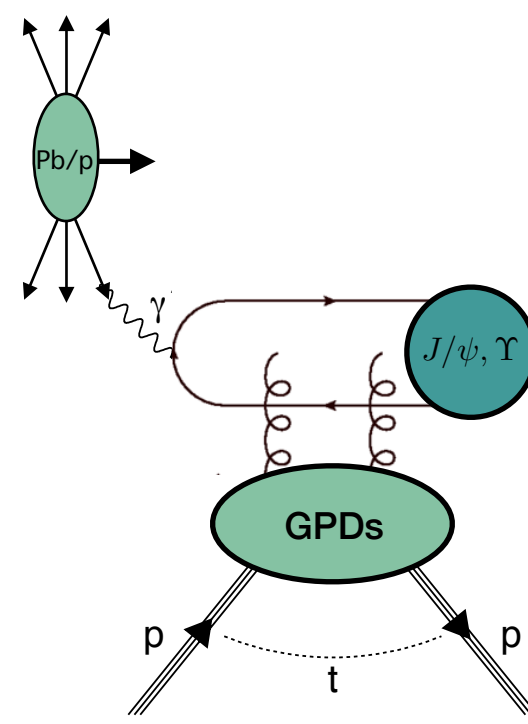
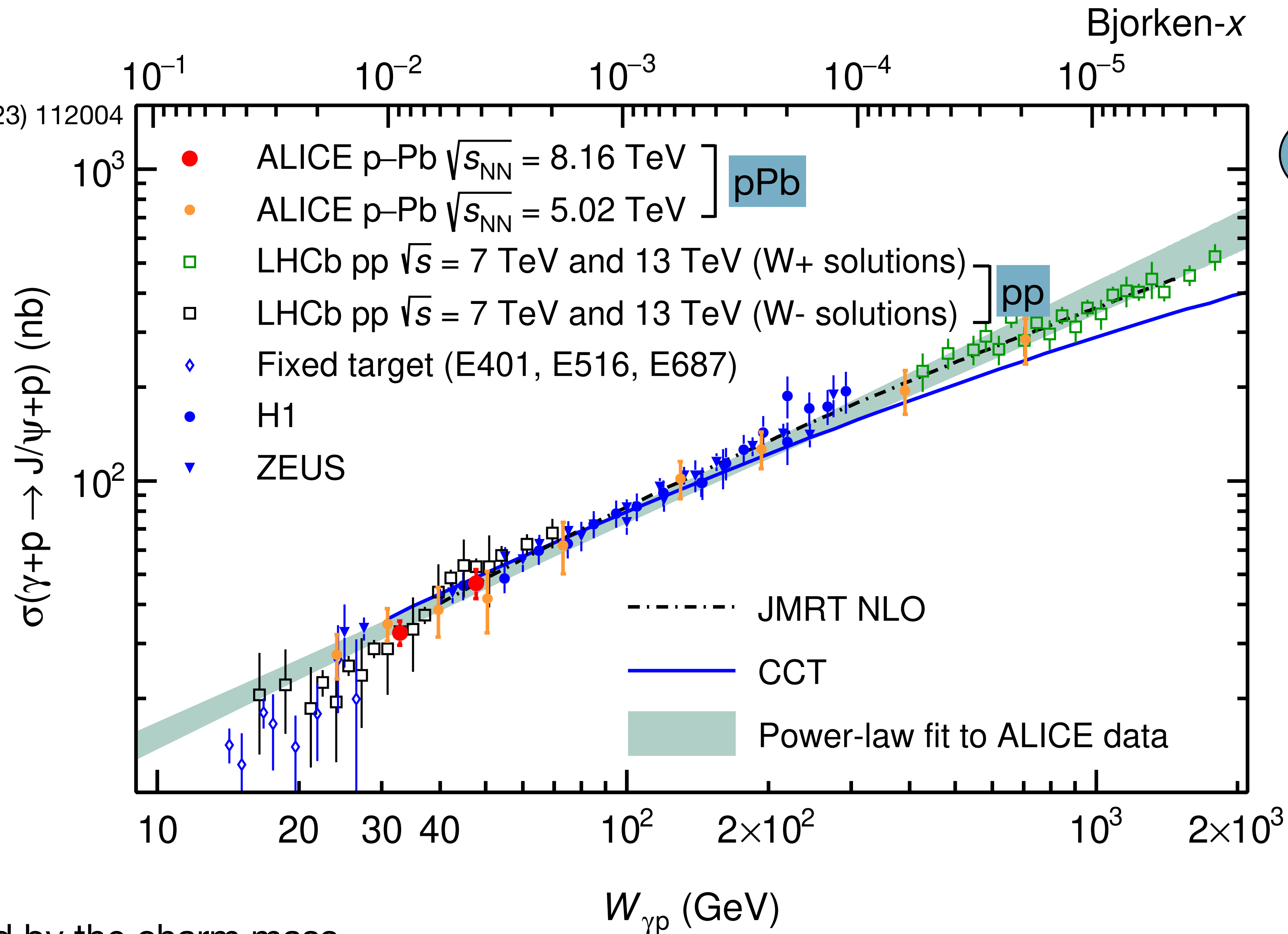
Phys. Rev. D **108** ('23) 112004



Hard scale: fixed by the charm mass

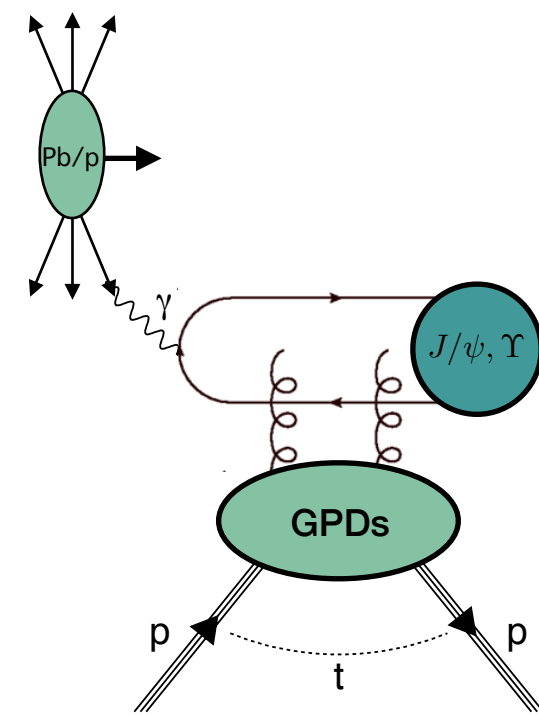
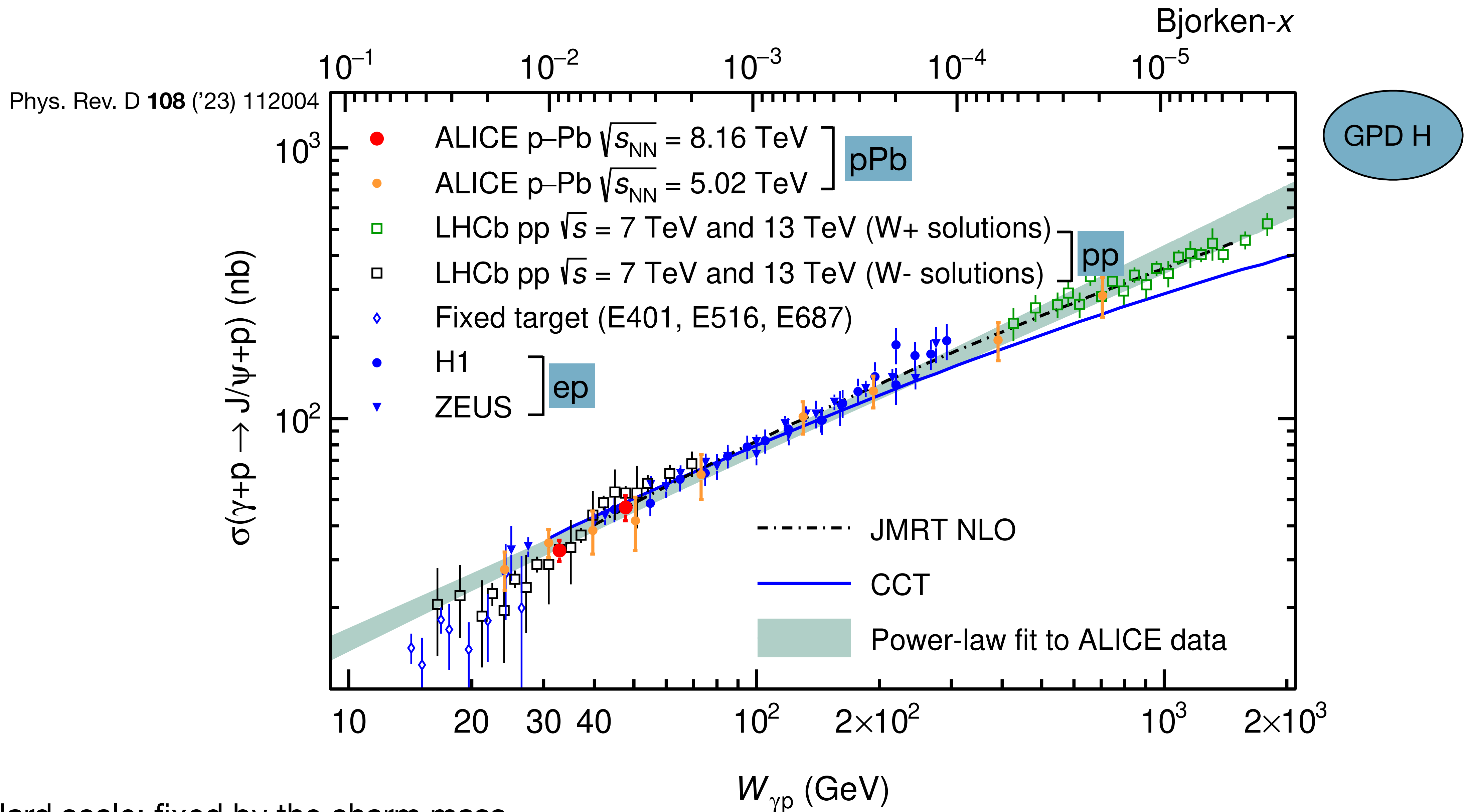
J/ψ photoproduction cross section off the proton at the LHC

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



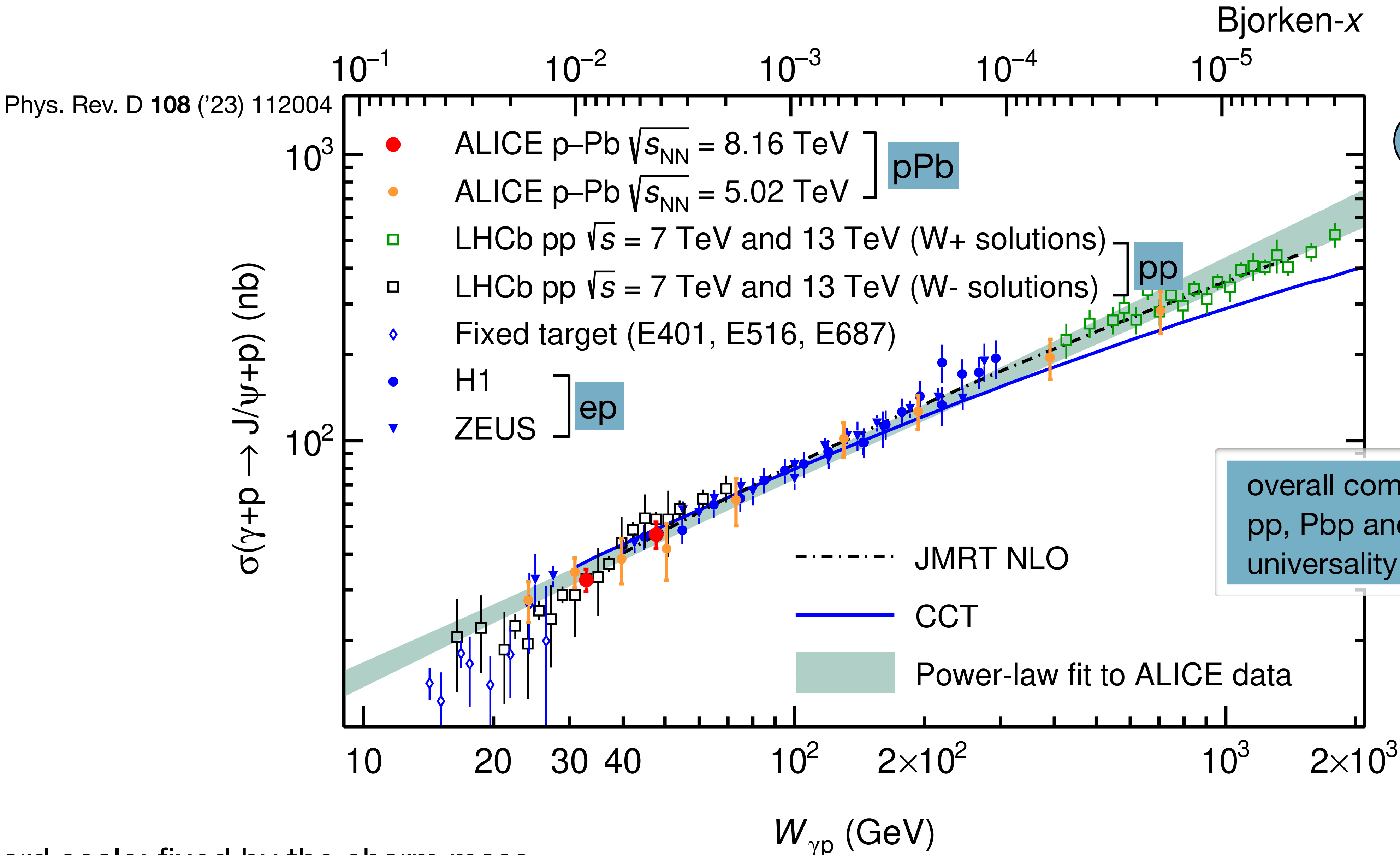
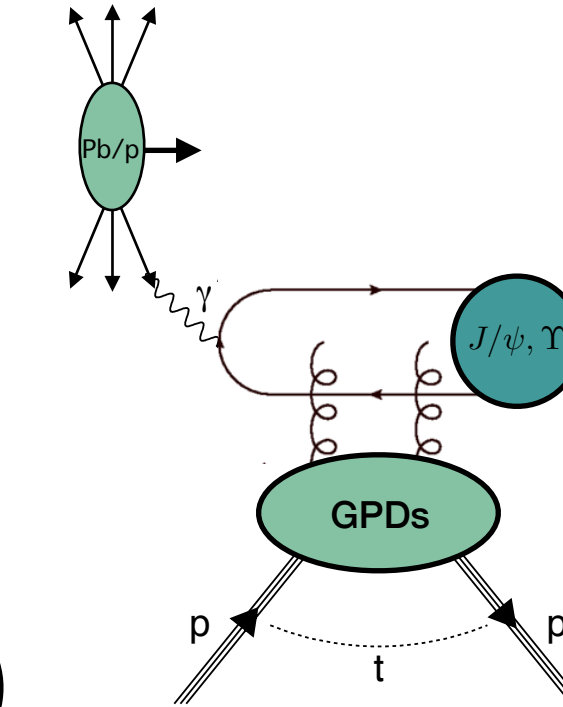
Hard scale: fixed by the charm mass

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

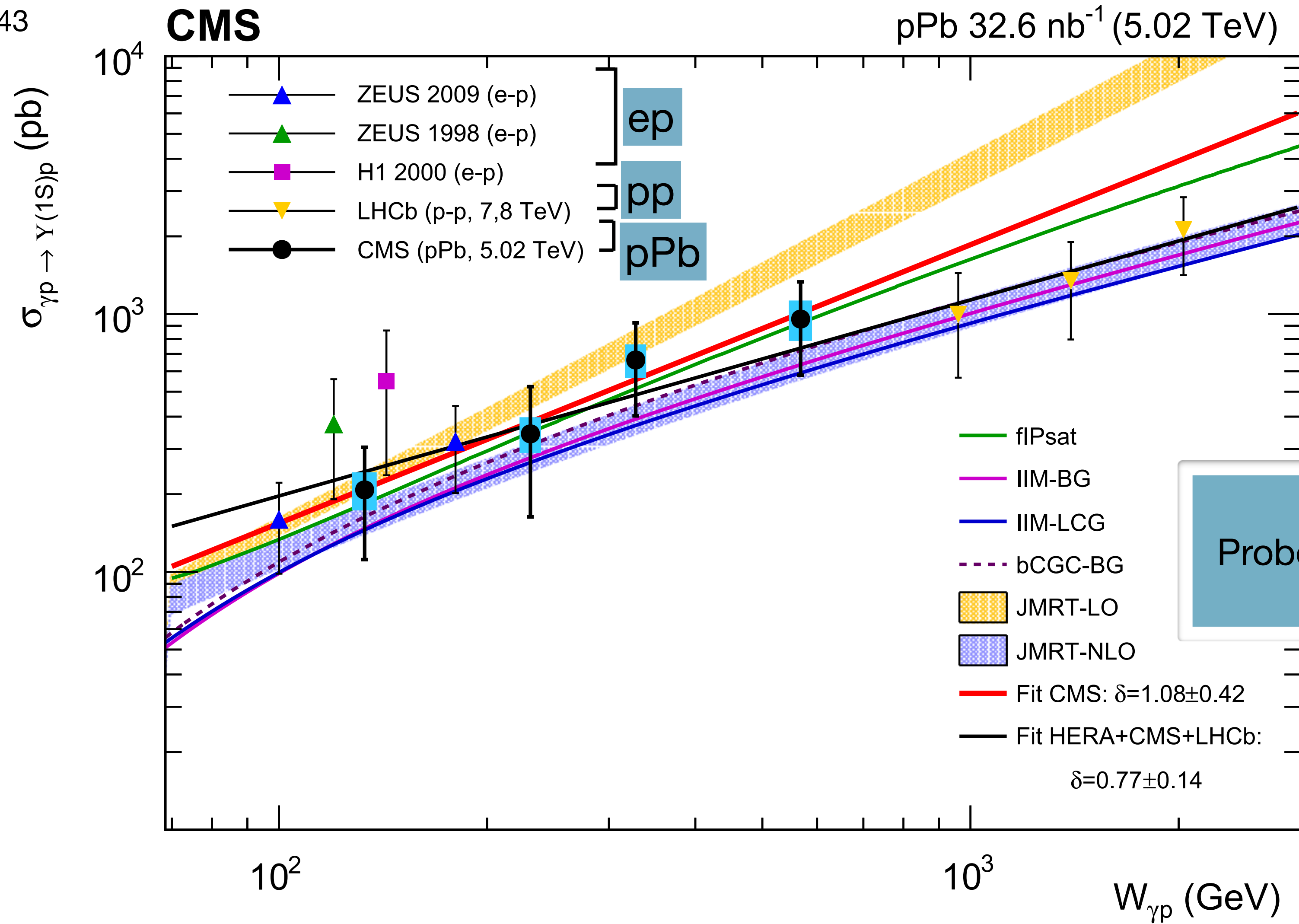


Hard scale: fixed by the charm mass

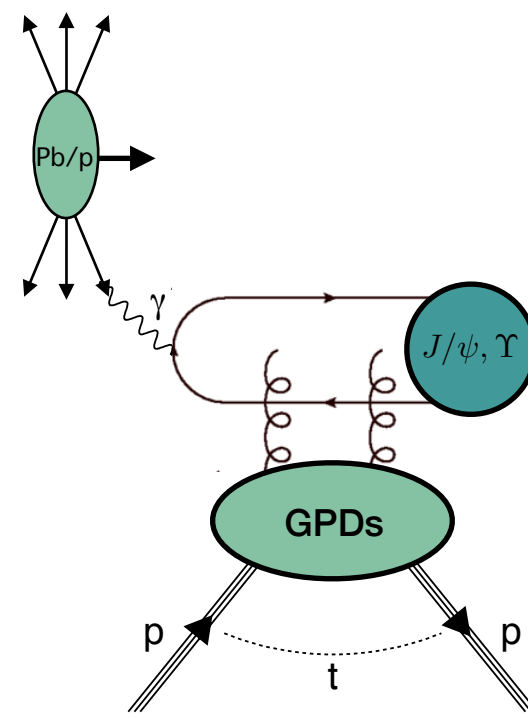
Υ photoproduction cross section

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

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



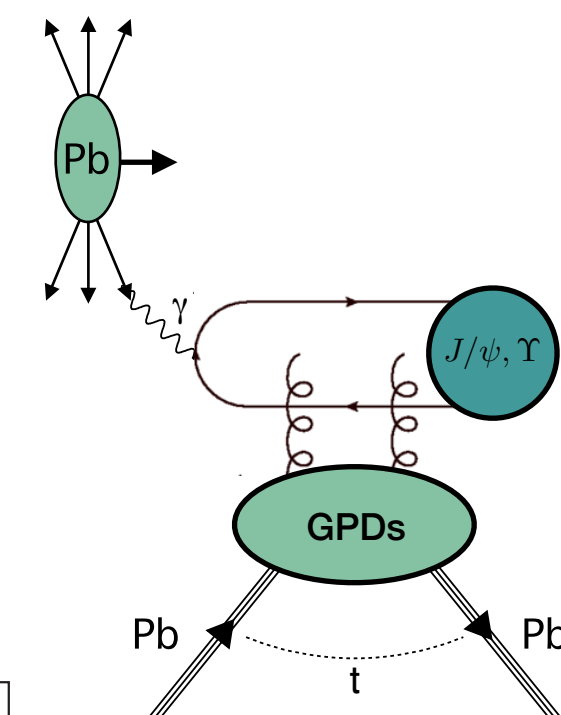
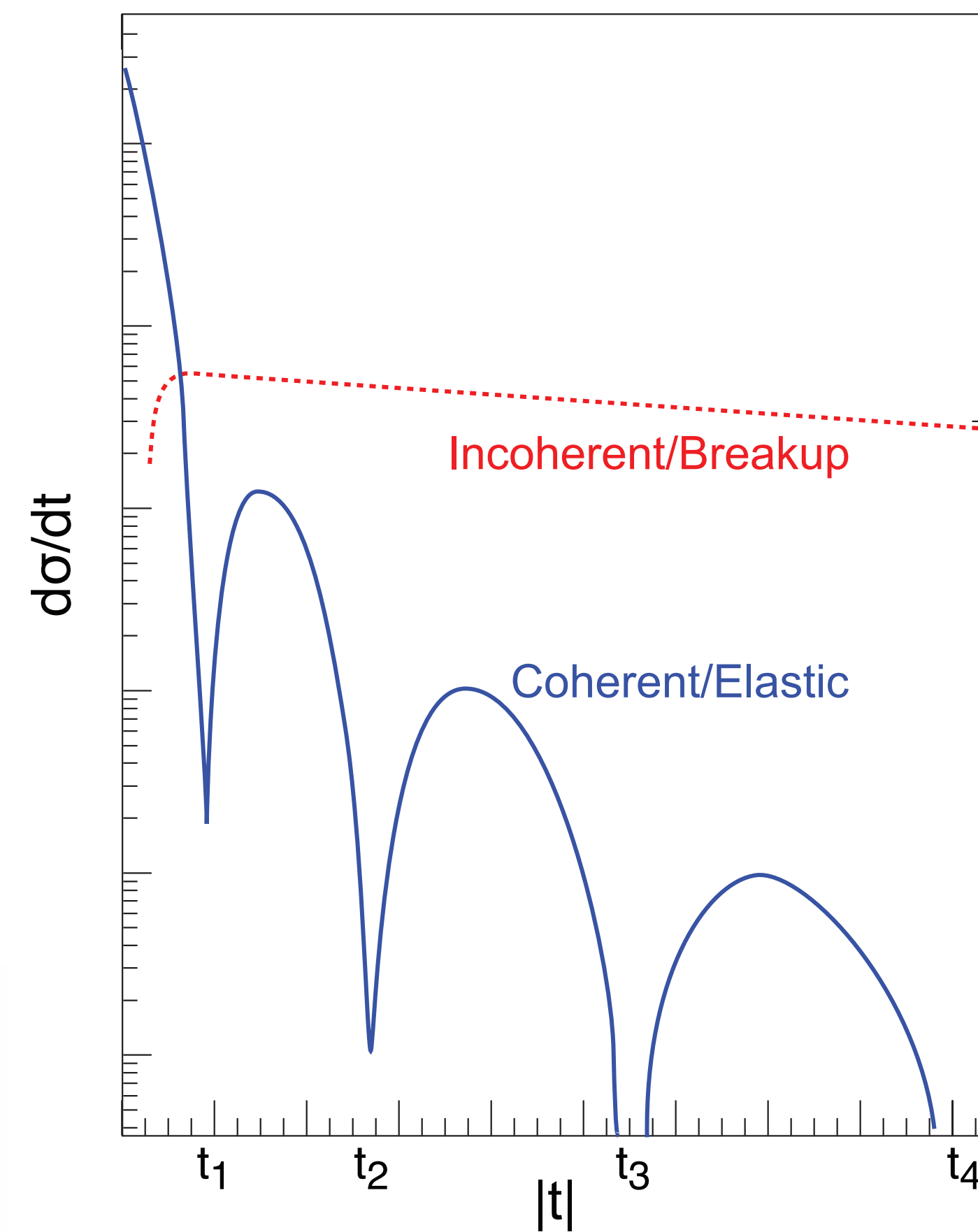
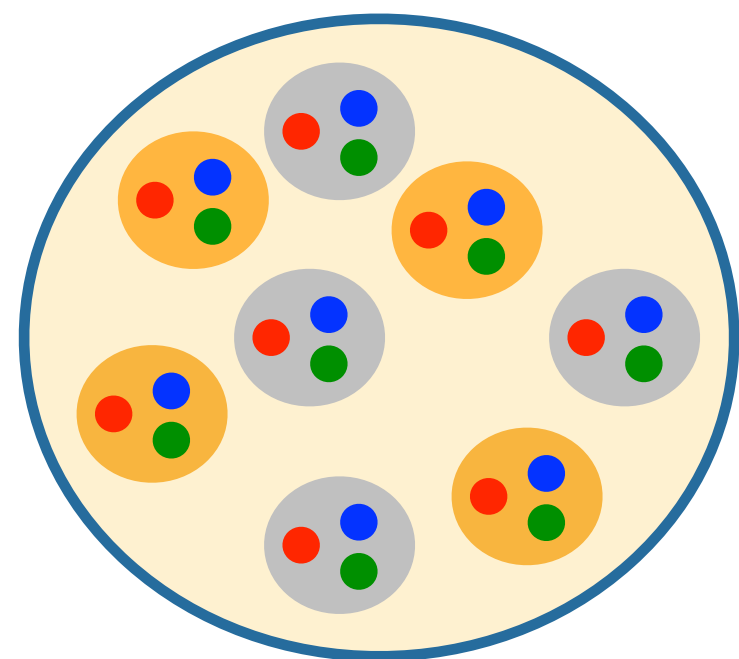
GPD H



Probes GPDs at higher scale.

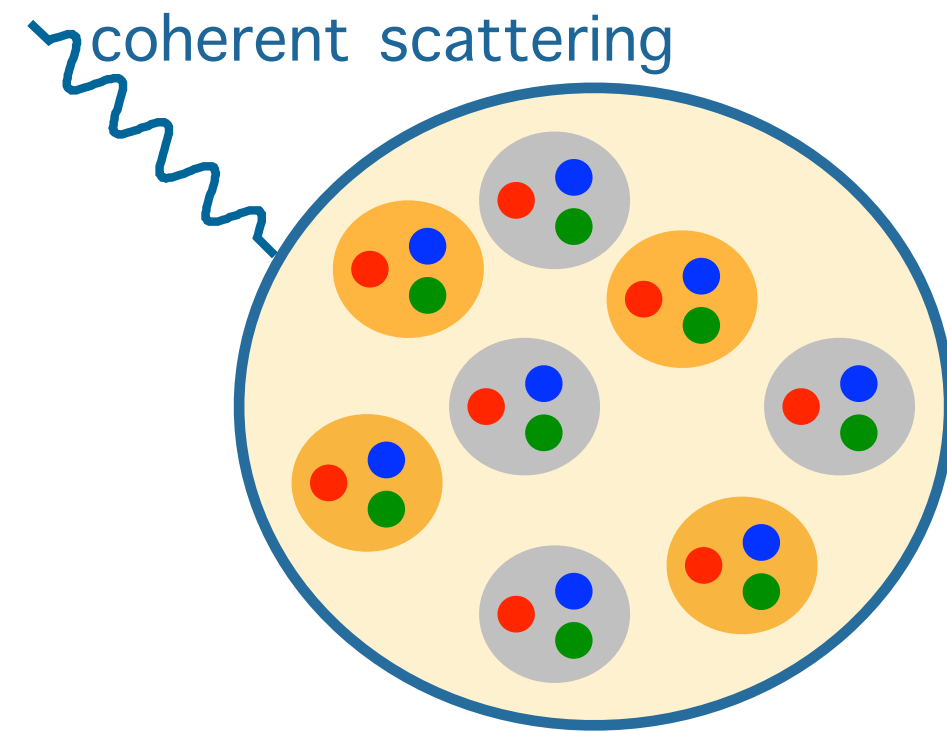
Ultrapерipheral PbPb collisions

What object are we probing?

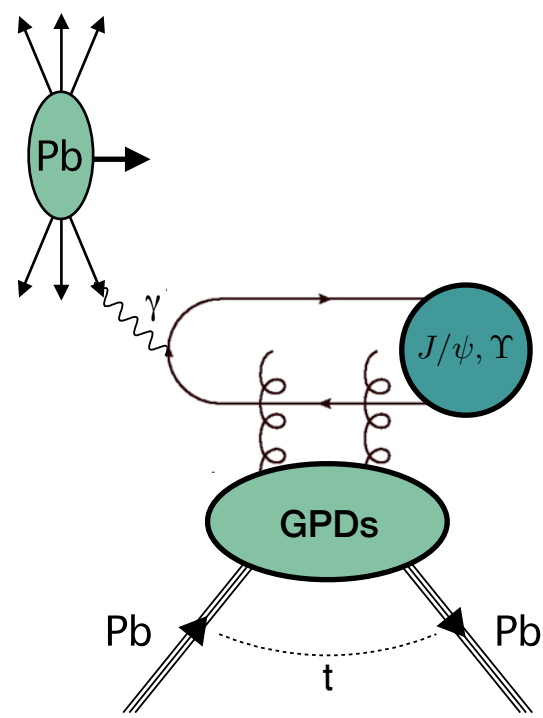
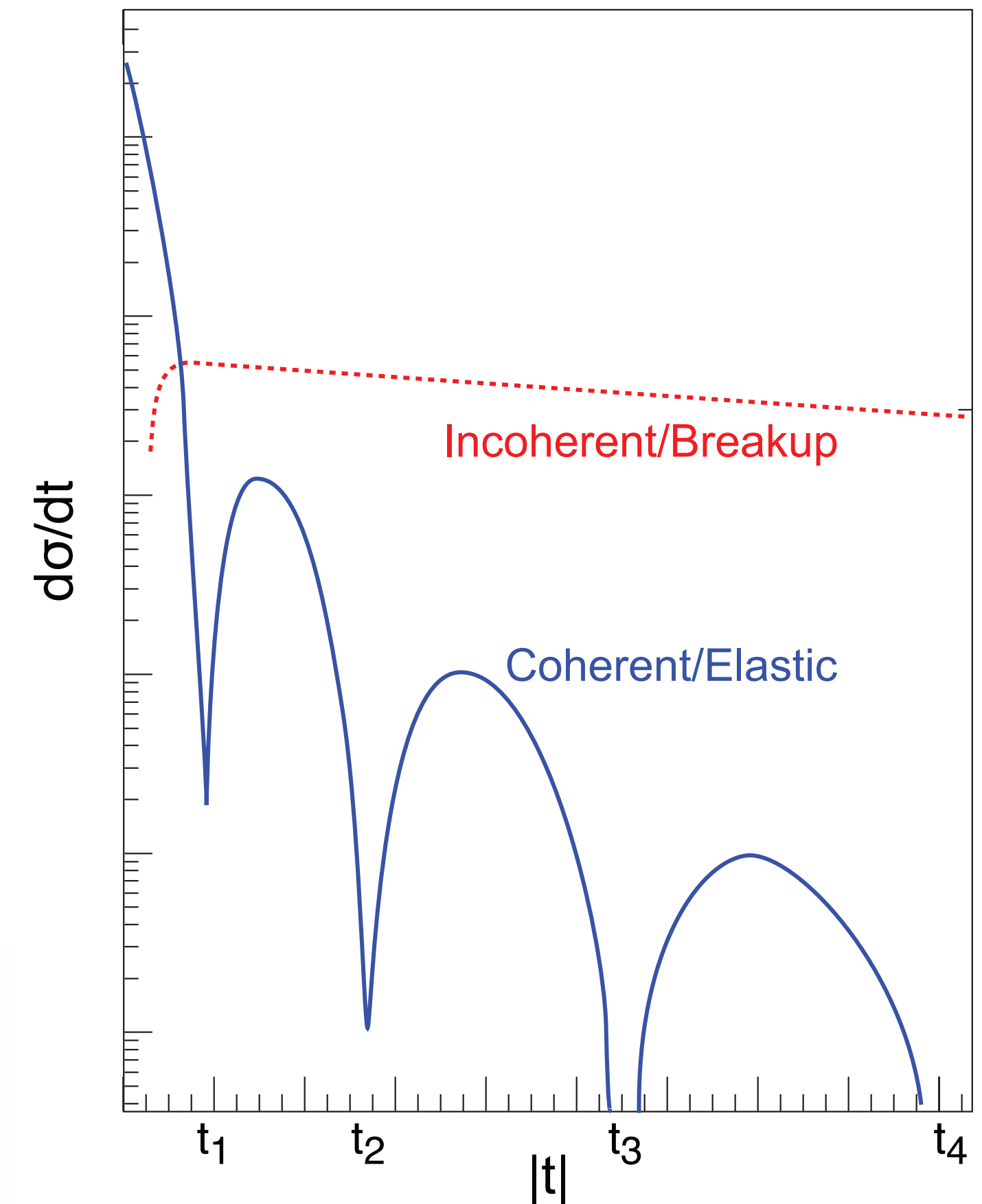


Ultrapерipheral PbPb collisions

What object are we probing?

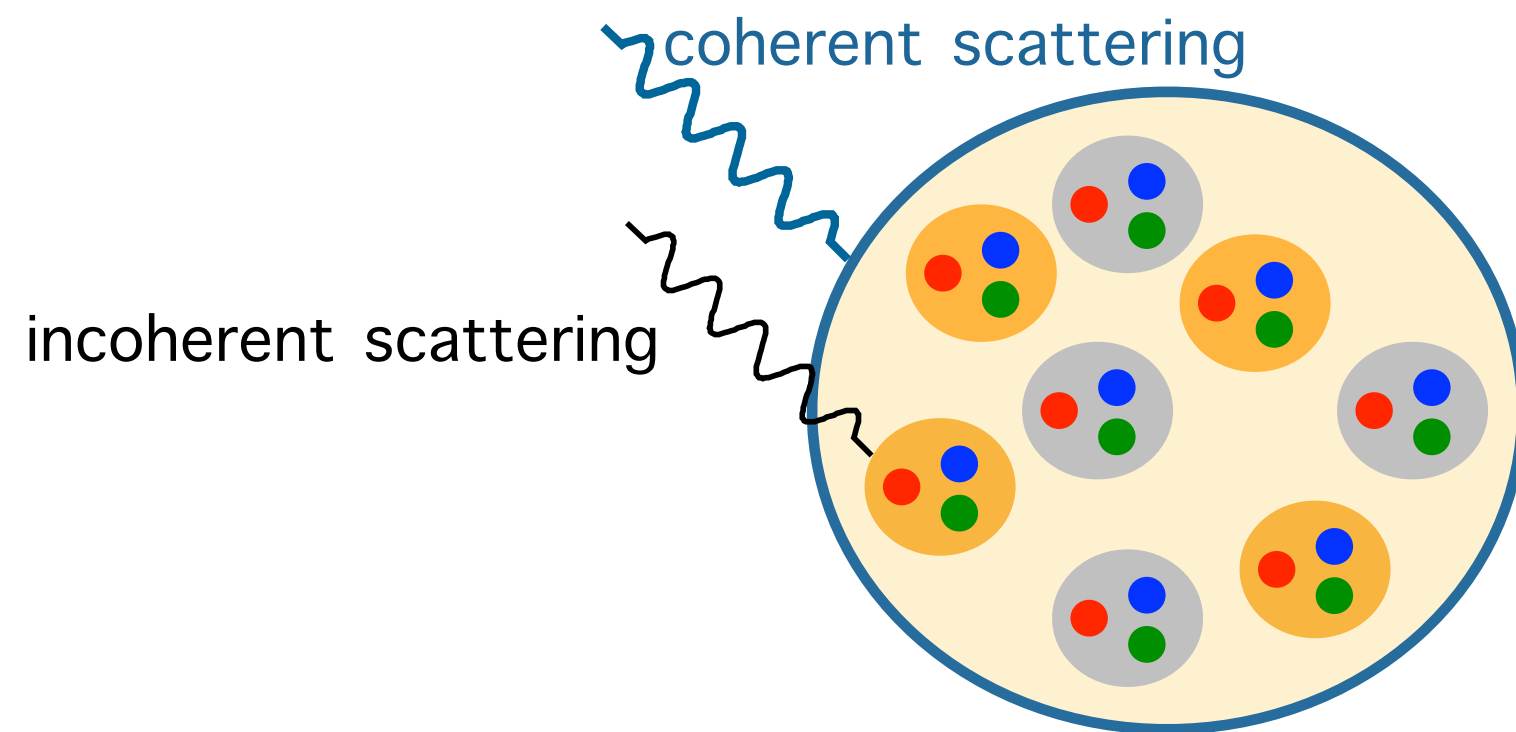


Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.



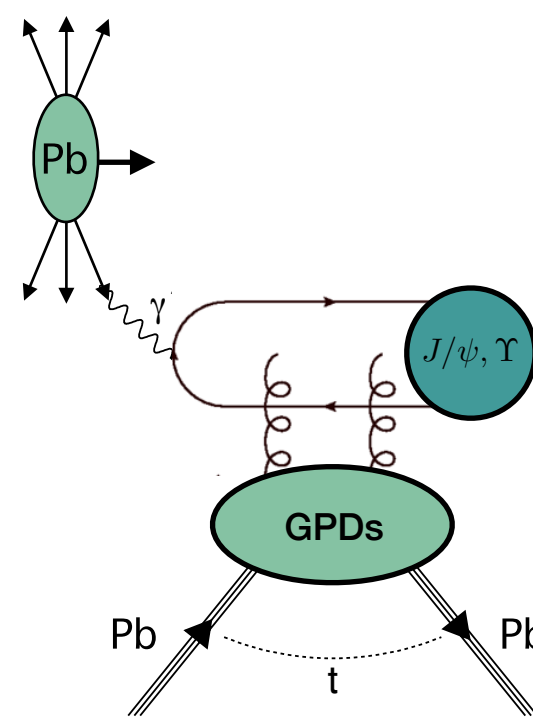
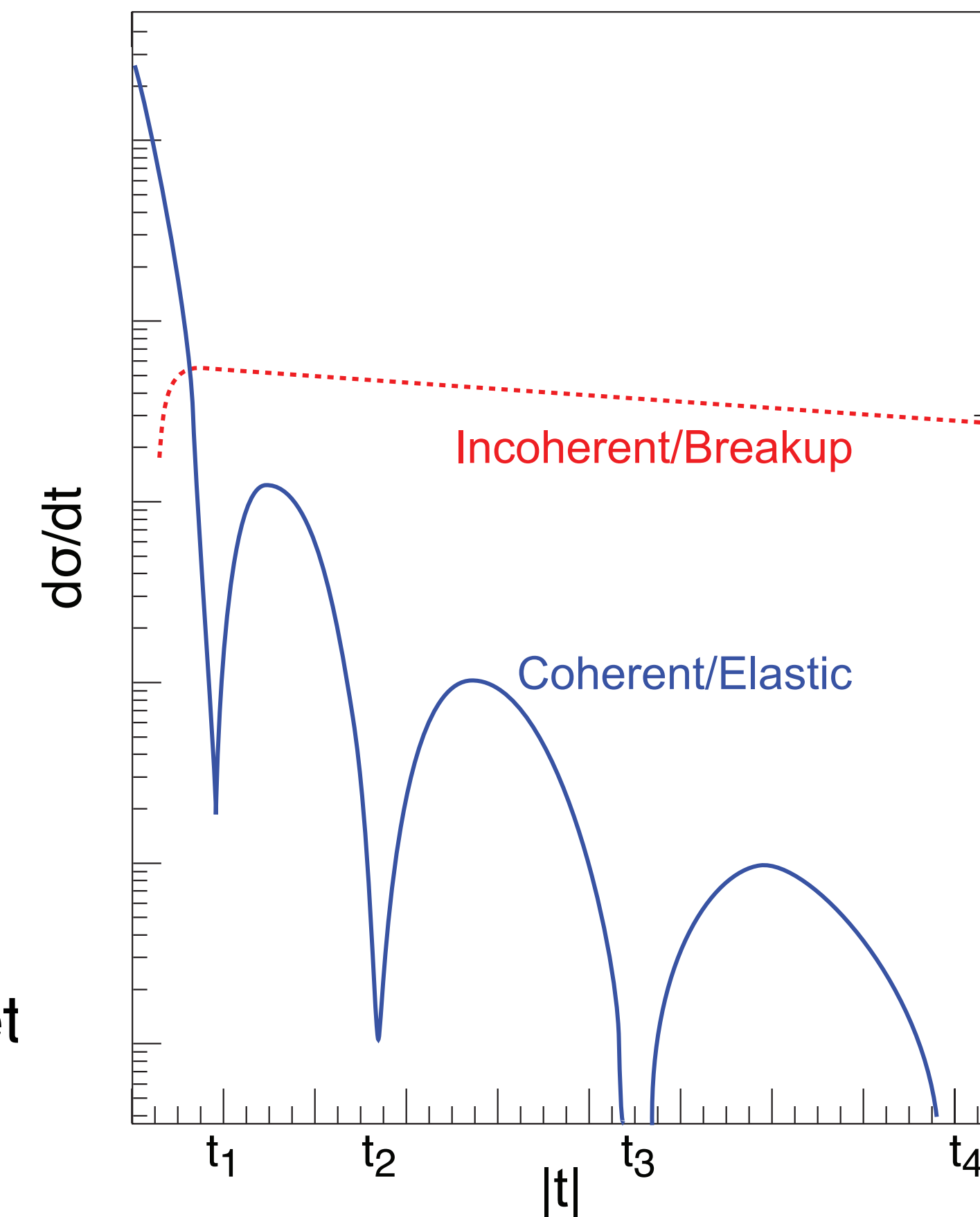
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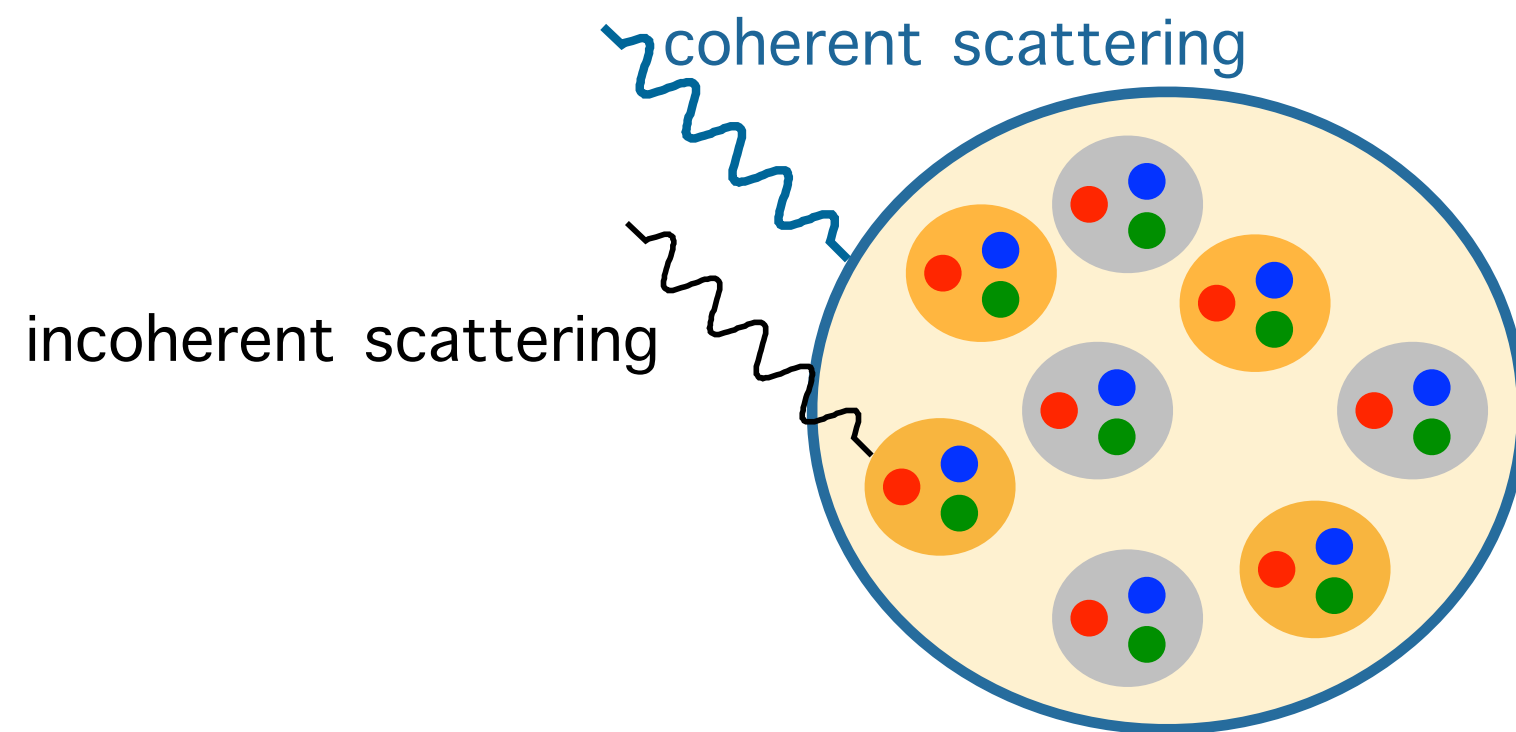
Coherent interaction: interaction with target as a whole.
 ~ target remains in same quantum state.

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



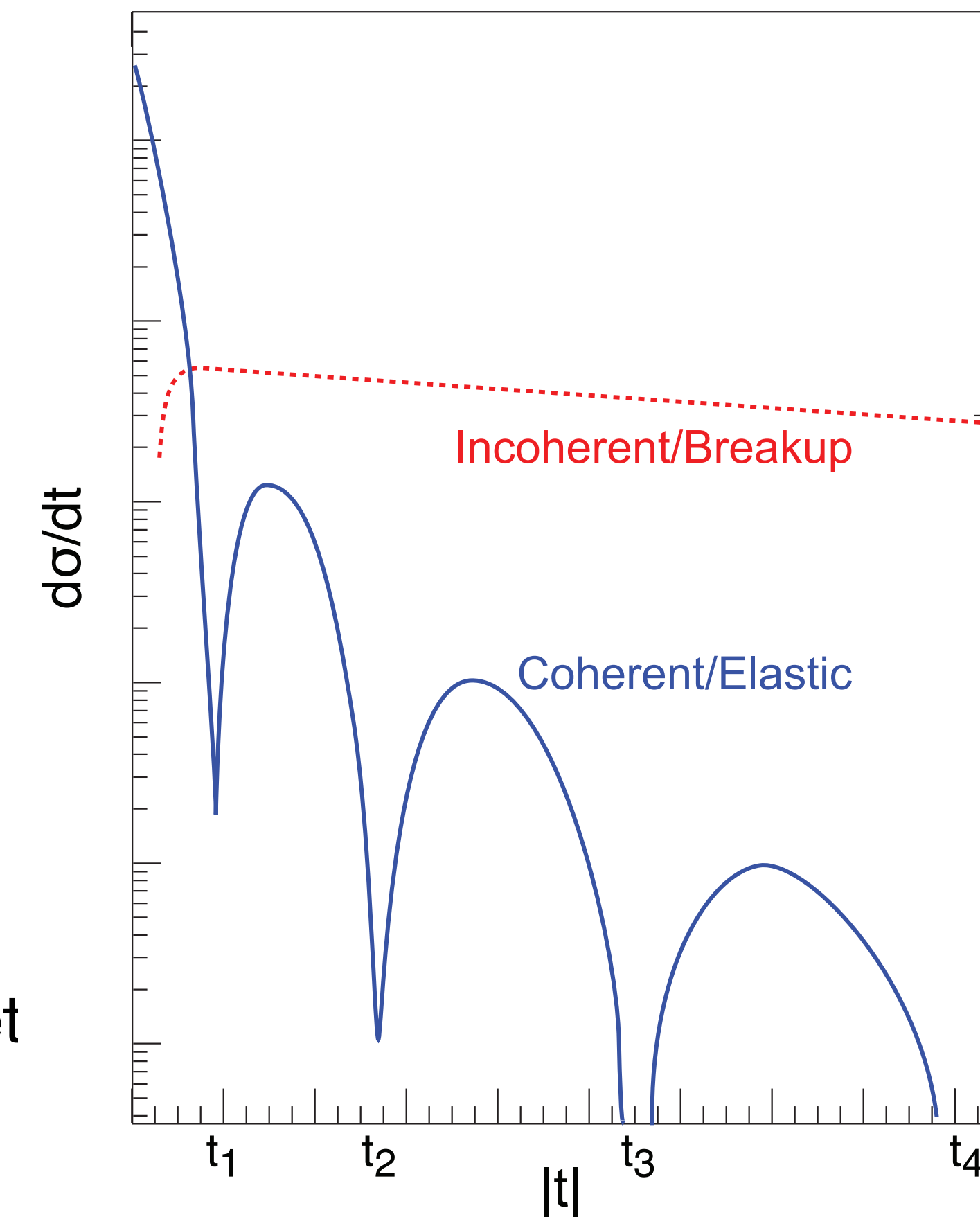
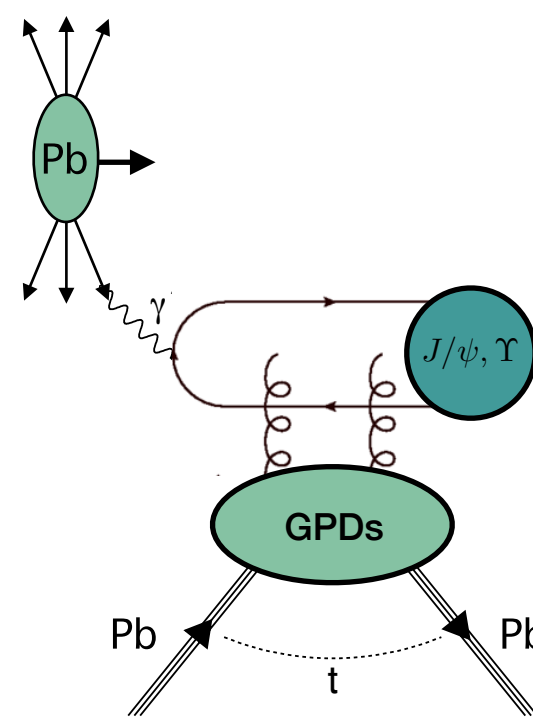
Ultrapерipheral PbPb collisions

What object are we probing?



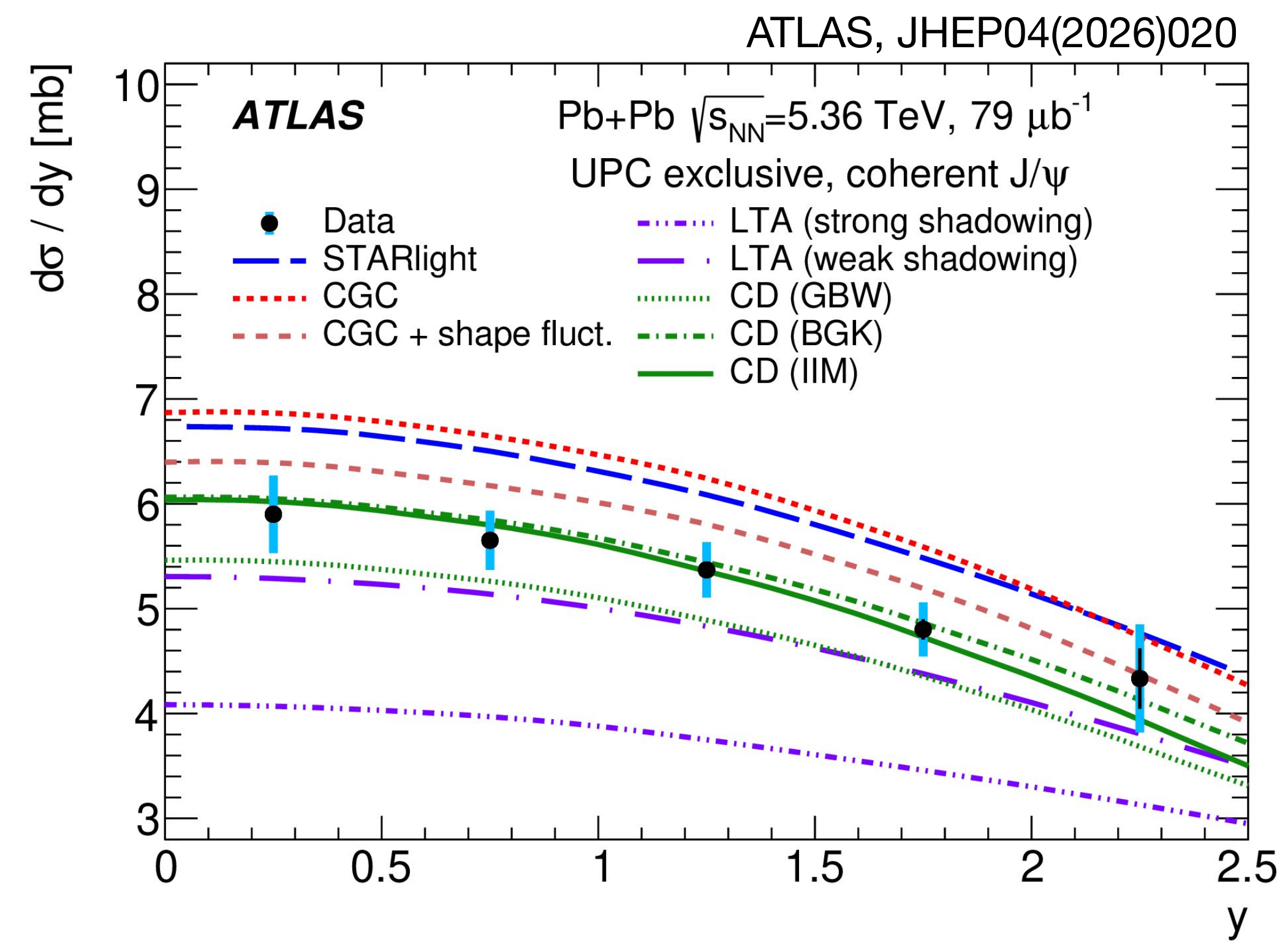
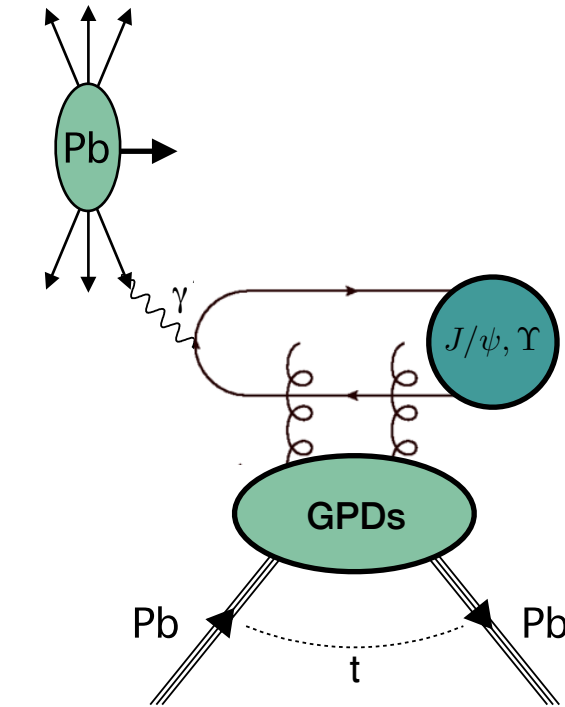
Coherent interaction: interaction with target as a whole.
 ~ target remains in same quantum state.

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



Good separation of coherent/incoherent:
 not easy!

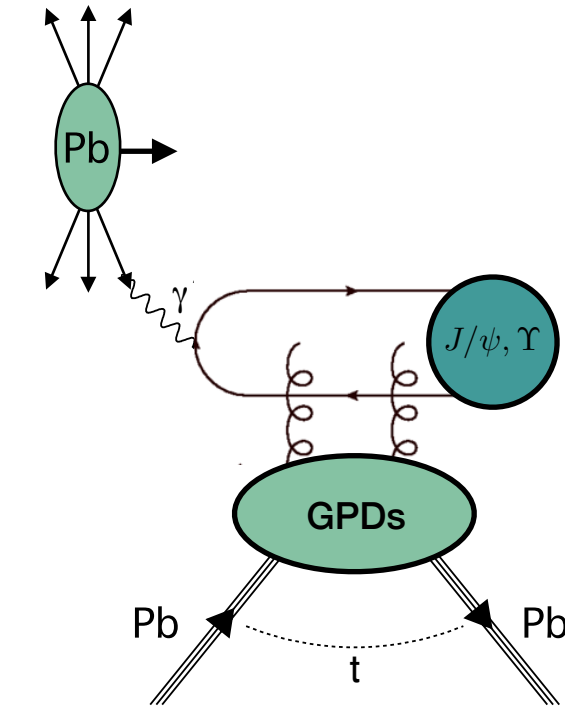
Coherent J/ψ production in PbPb collisions at the LHC



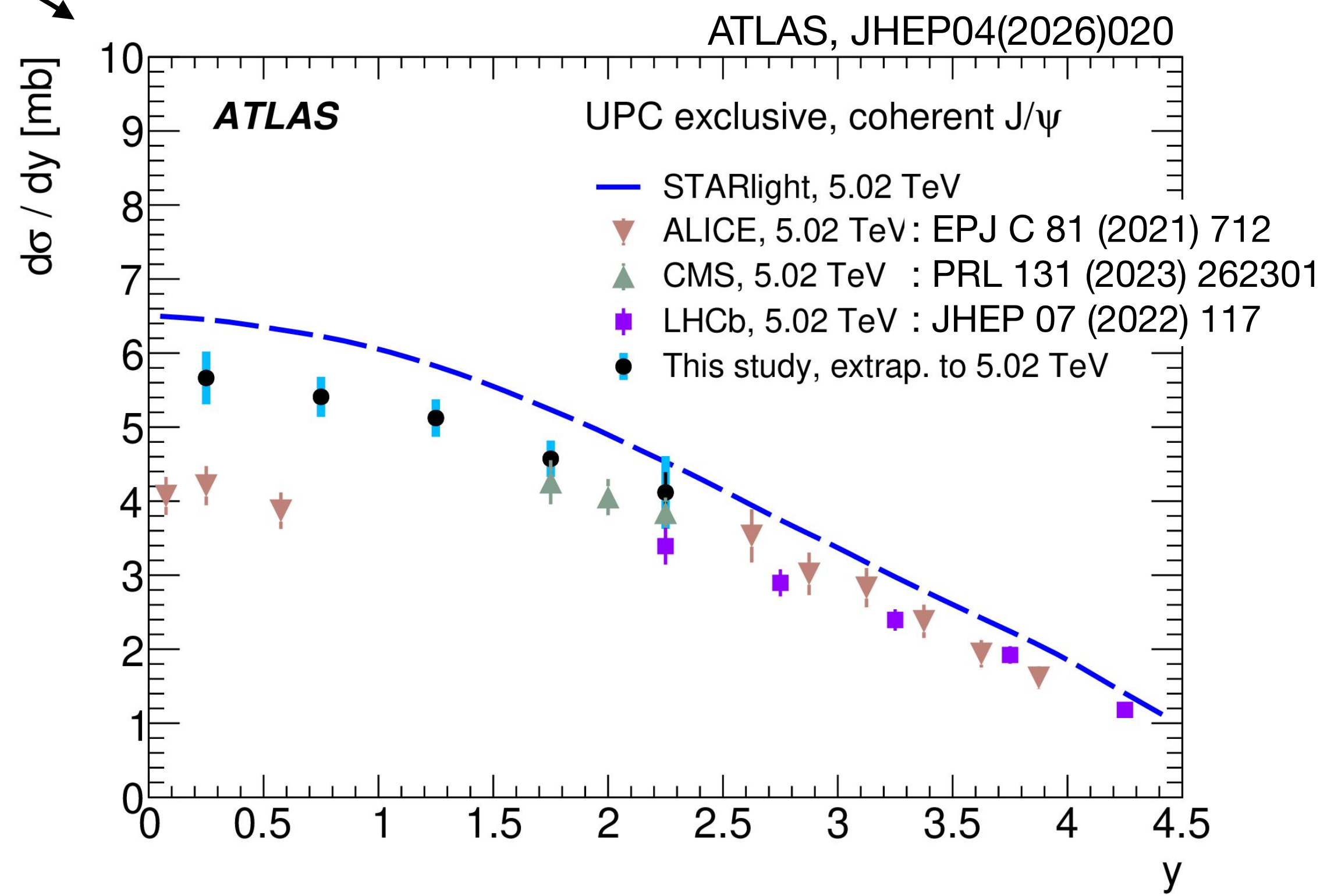
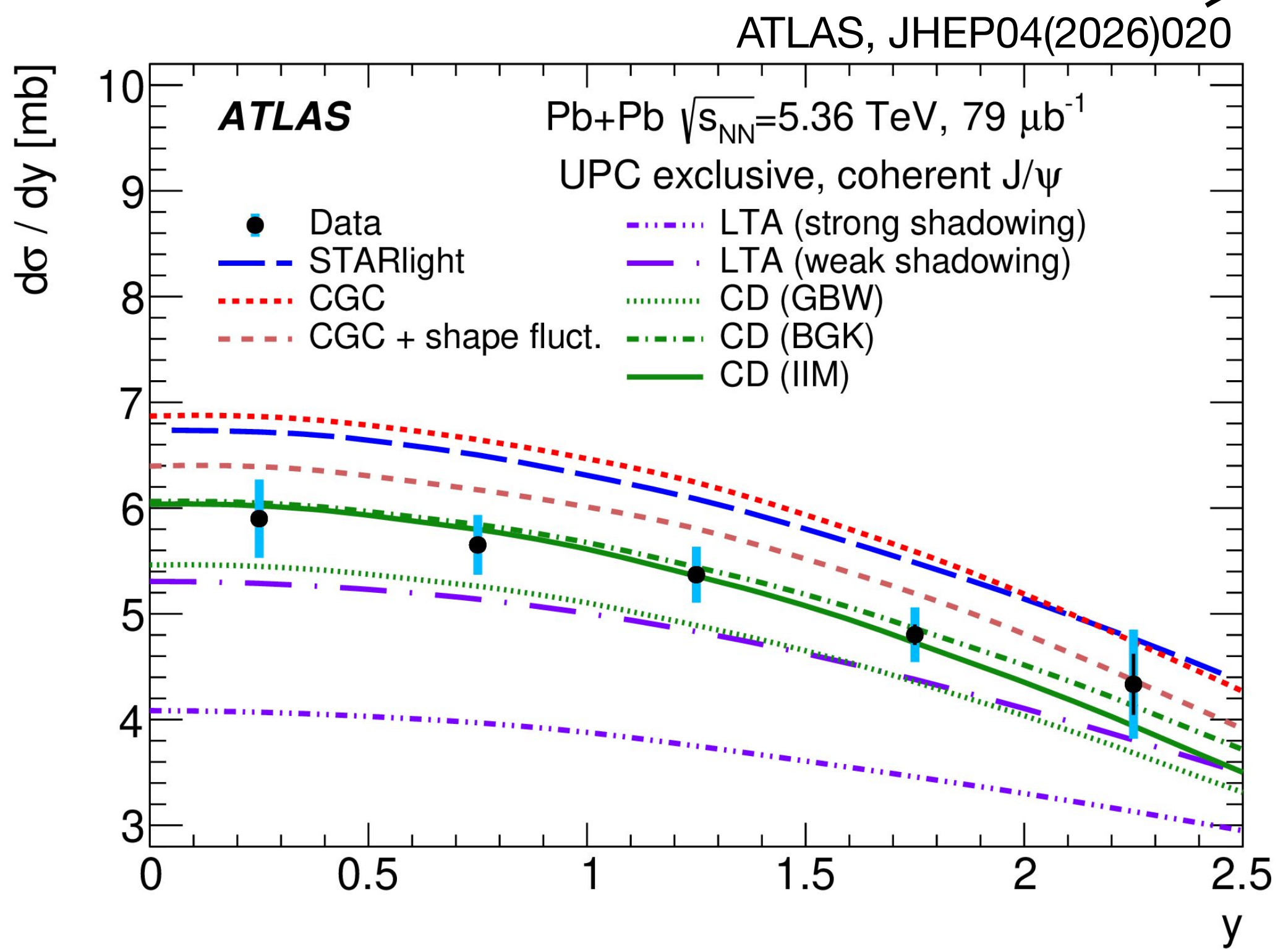
Results indicate significant nuclear shadowing

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

Coherent J/ψ production in PbPb collisions at the LHC



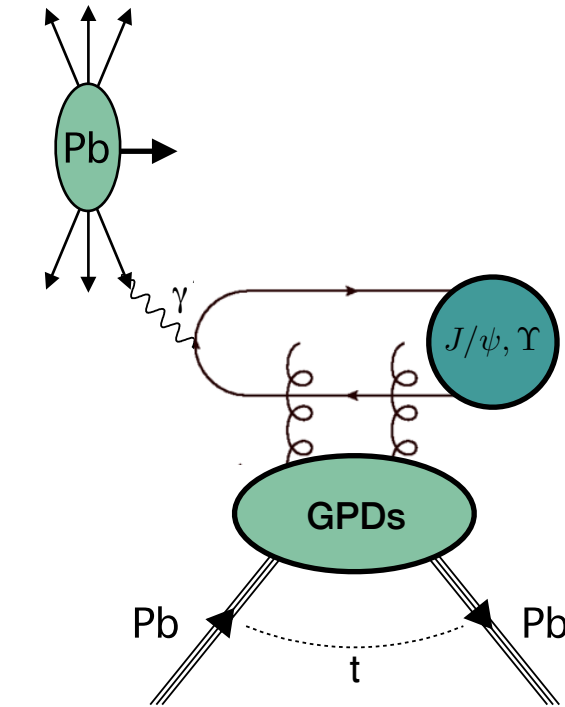
Scaling of the data to $\sqrt{s_{NN}} = 5.02$ TeV
with STARlight



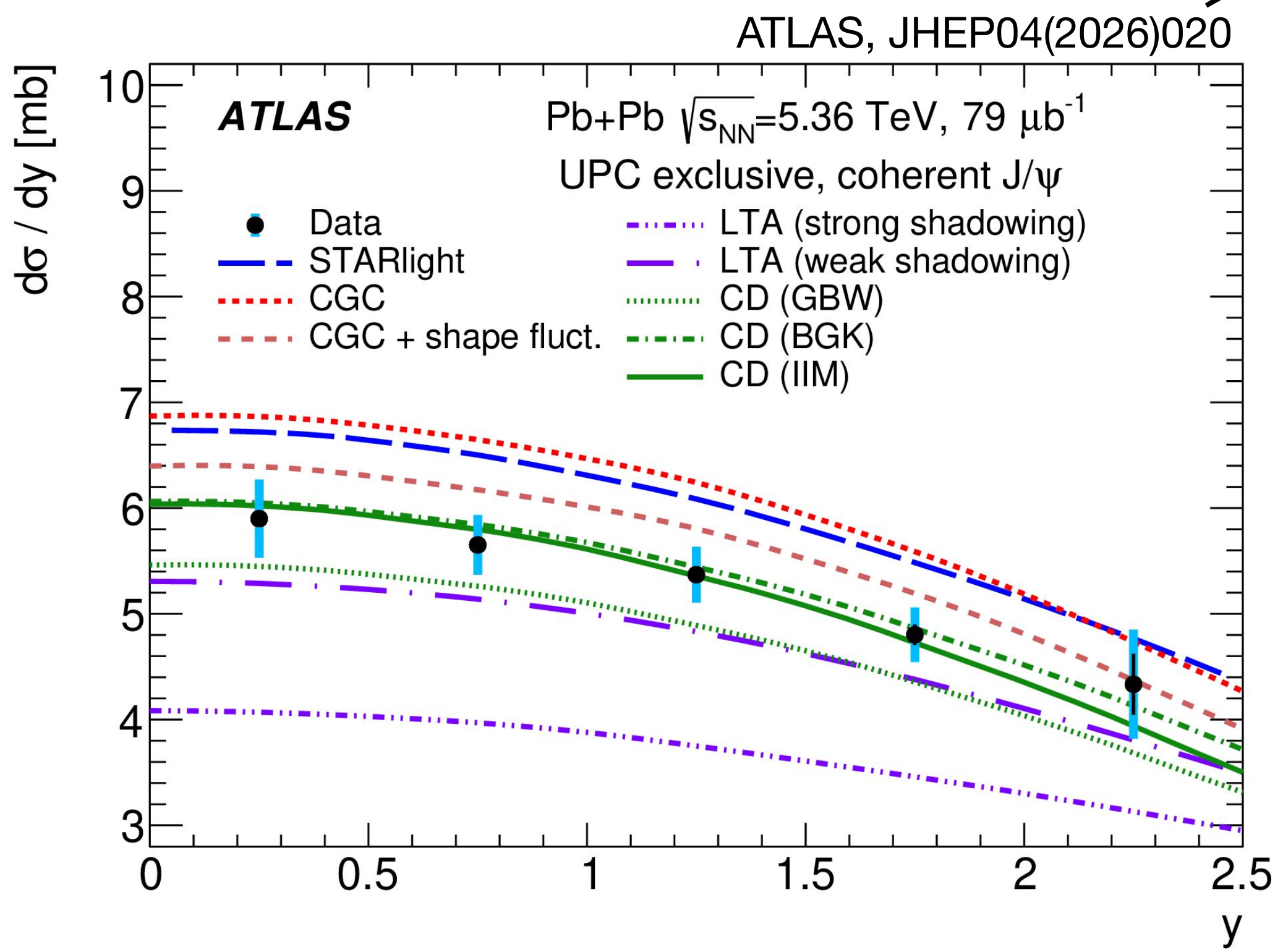
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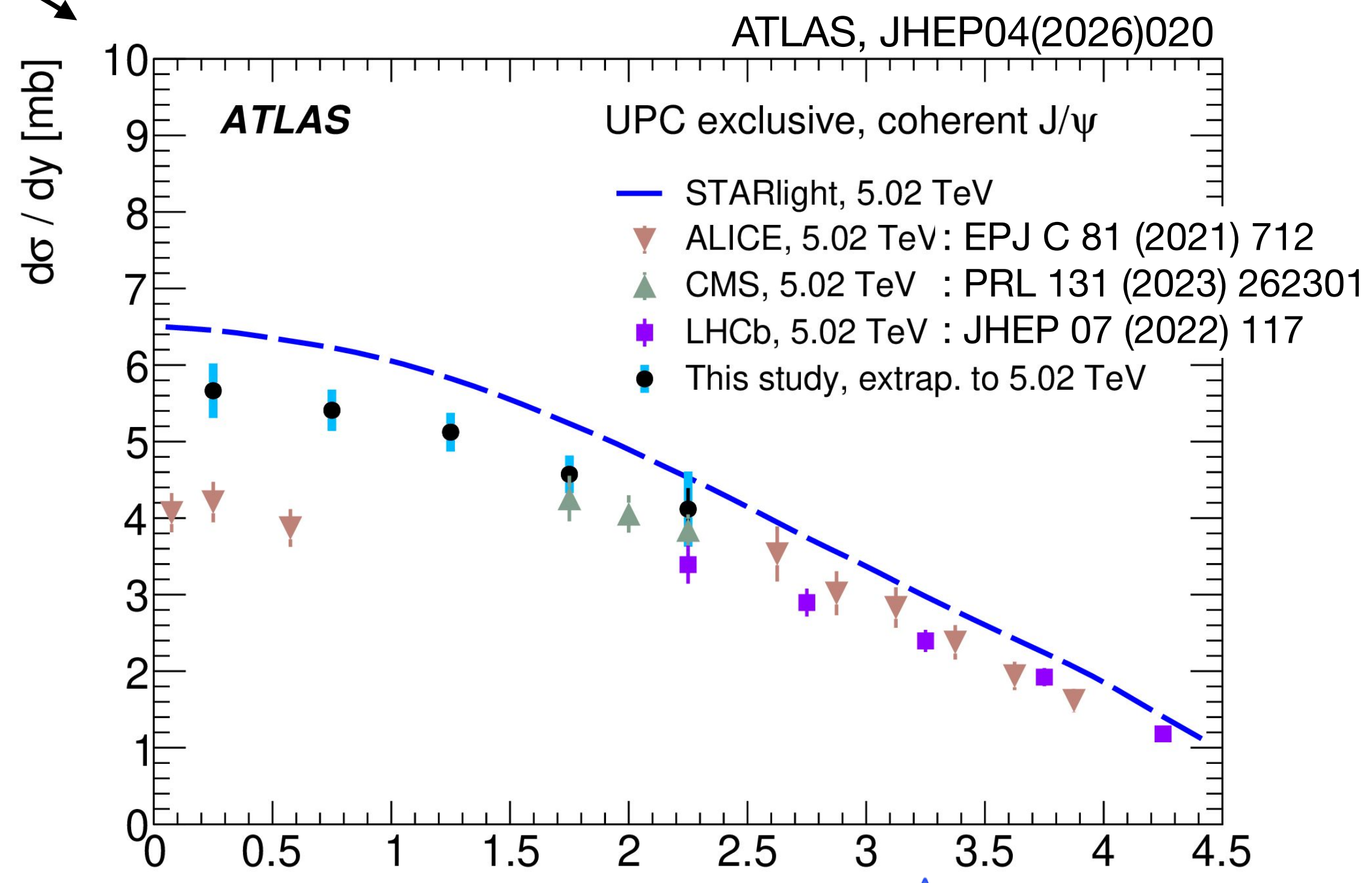
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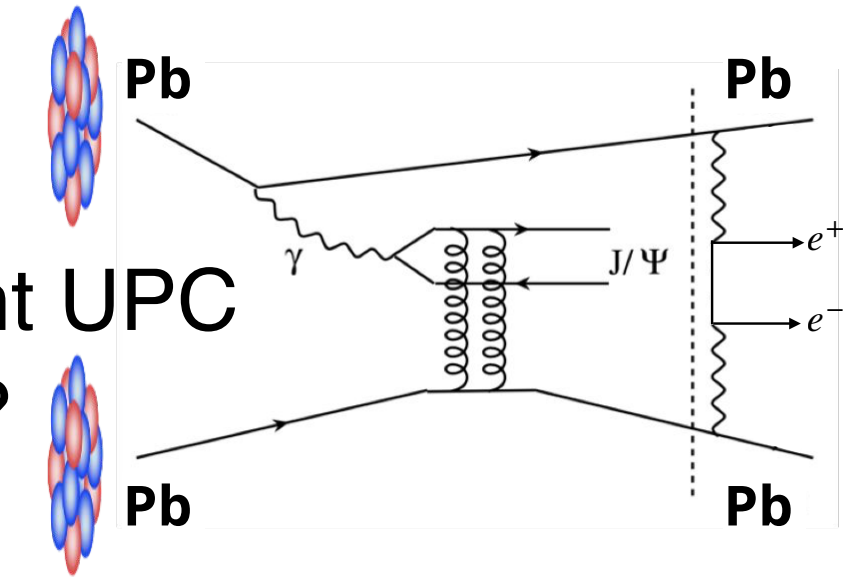
Scaling of the data to $\sqrt{s_{NN}} = 5.02$ TeV
with STARlight



Results indicate significant nuclear shadowing



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



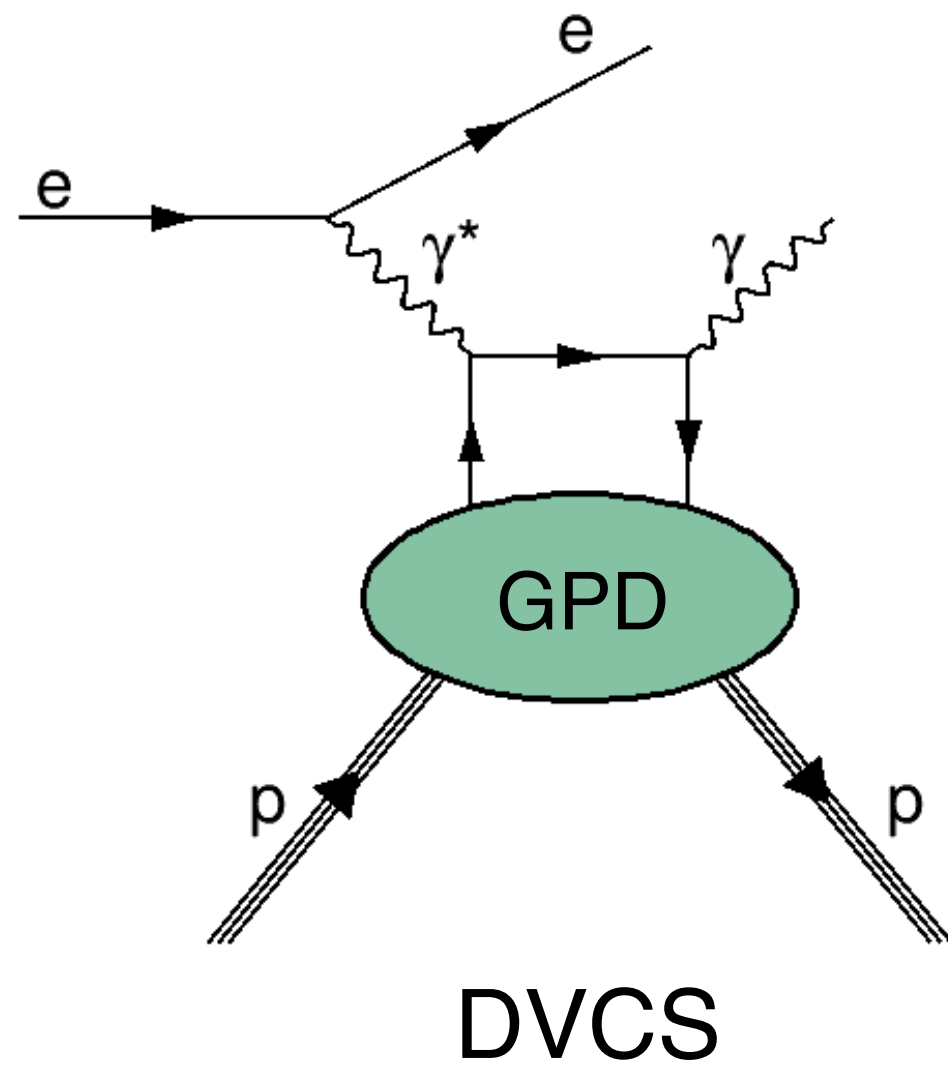
See also:
Preliminary results ALICE at $\sqrt{s_{NN}} 5.36$ TeV

Summary

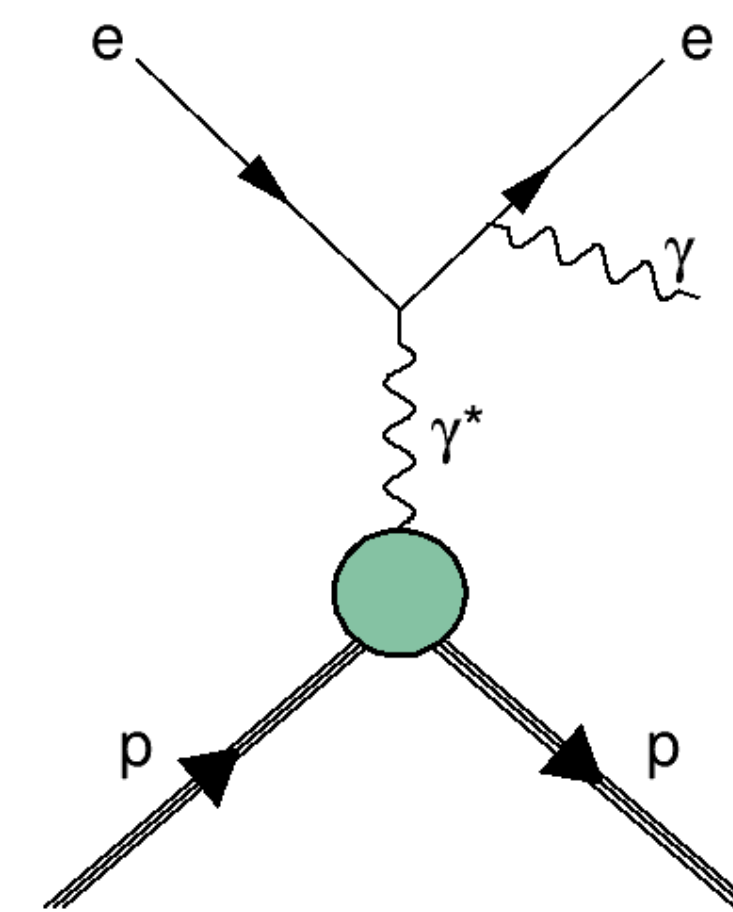
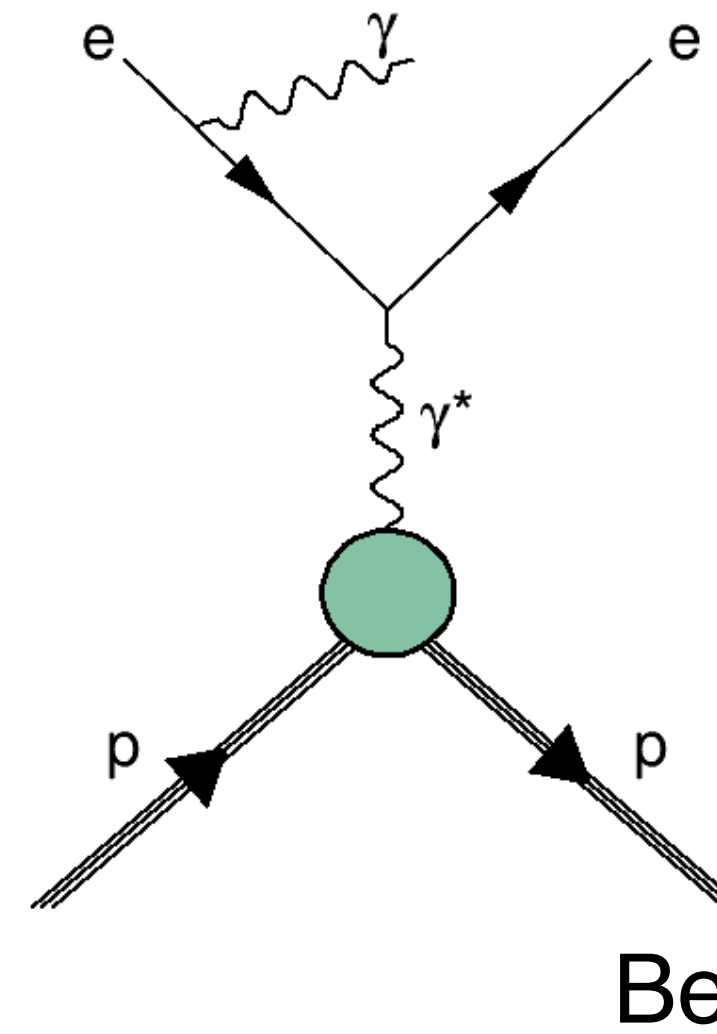
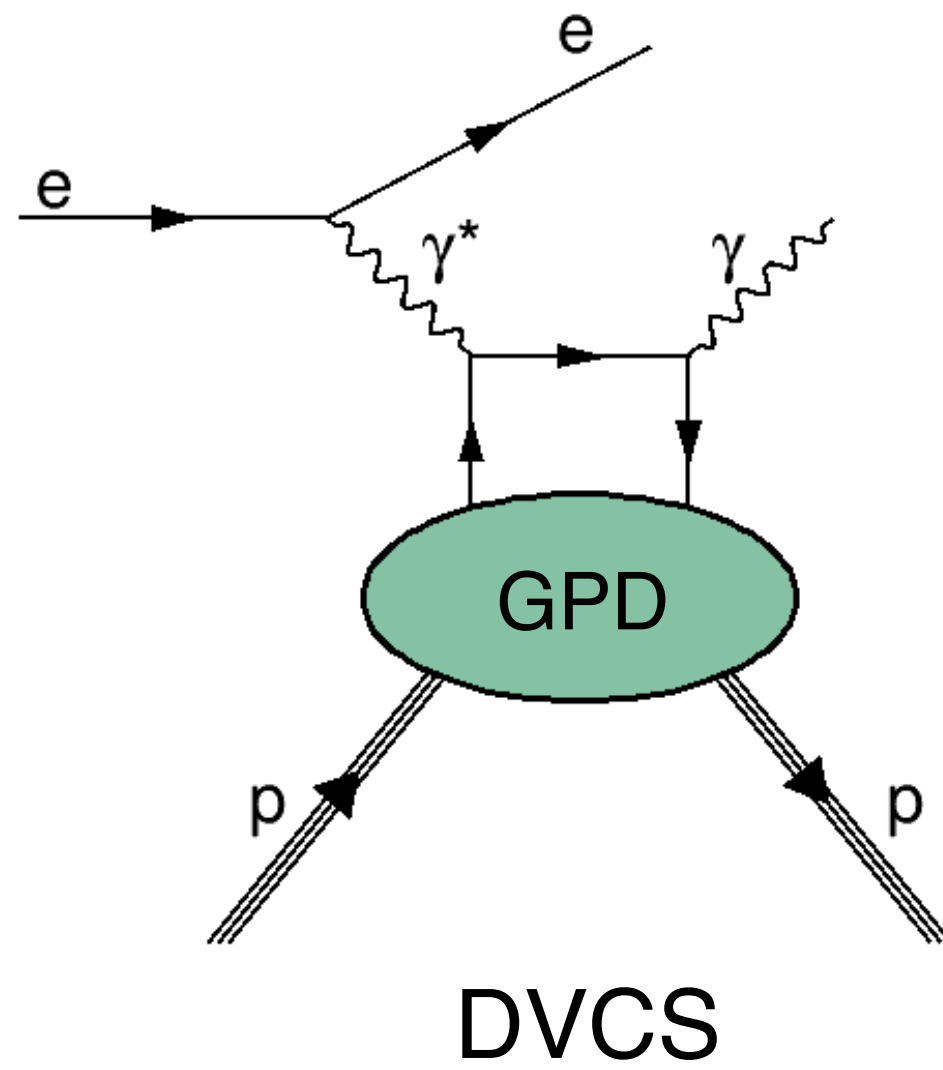
- Valence region at Jefferson Lab: full GPD programme at high precision to extract chiral-even and chiral-odd GPDs using polarised electron beam and unpolarised, longitudinally and transversely polarised proton targets as well as light nuclei.
- Sea-quarks at COMPASS: measurements of DVCS and hard exclusive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

Back up

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)

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

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

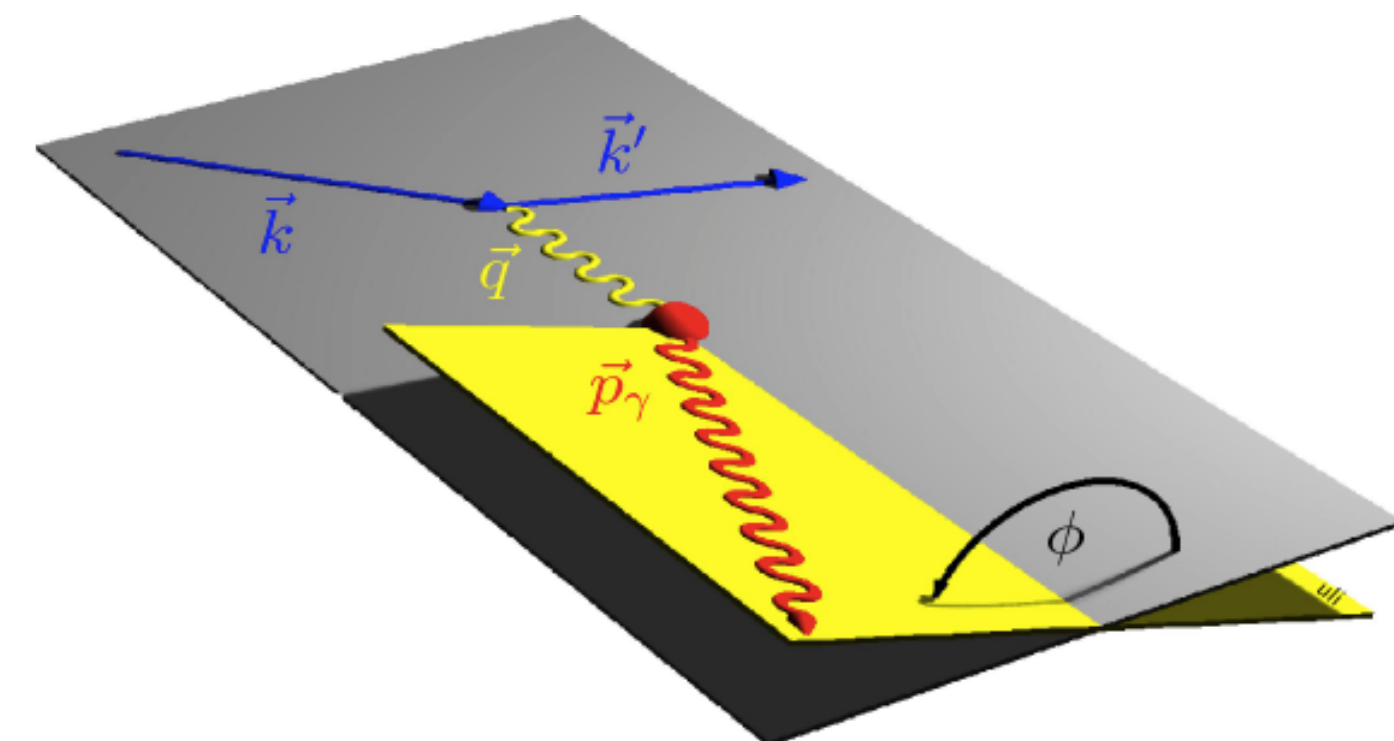
$$|\tau_{DVCS}|^2 = \frac{1}{Q^2} \left\{ \sum_{n=0}^2 c_n^{DVCS} \cos(n\phi) + \lambda s_1^{DVCS} \sin(\phi) \right\} \quad \text{coefficients: bilinear in GPDs}$$

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

beam
charge

beam
polarization

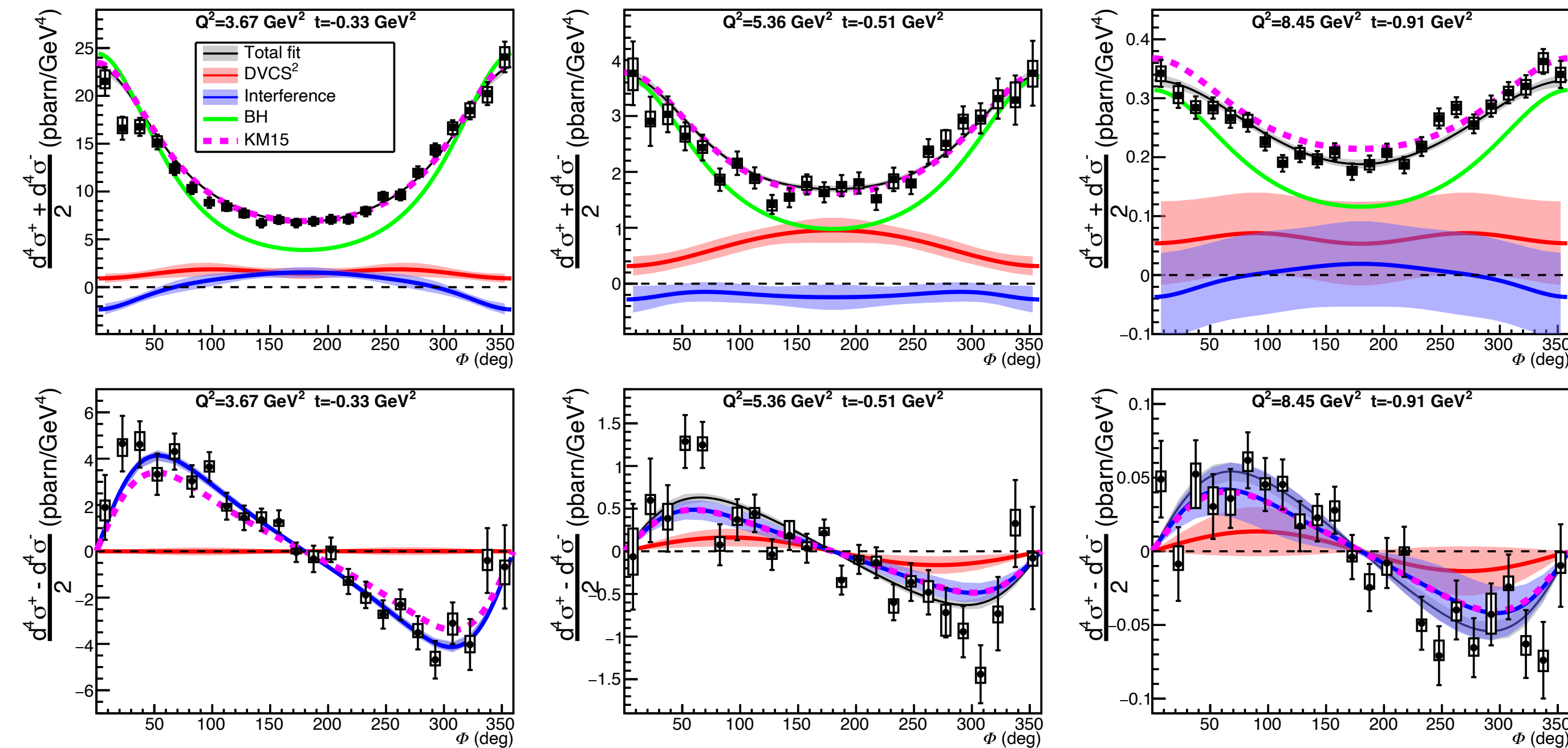
Unpolarized nucleon
Longitudinally polarized lepton beam



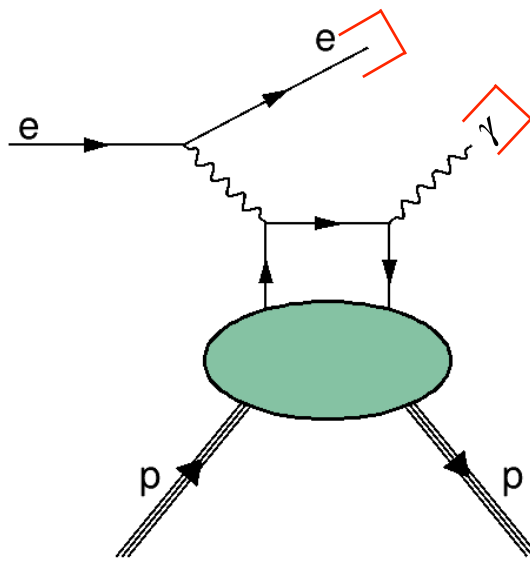
DVCS off the proton: Hall A and C

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

Unpolarised cross section



Beam-spin asymmetry

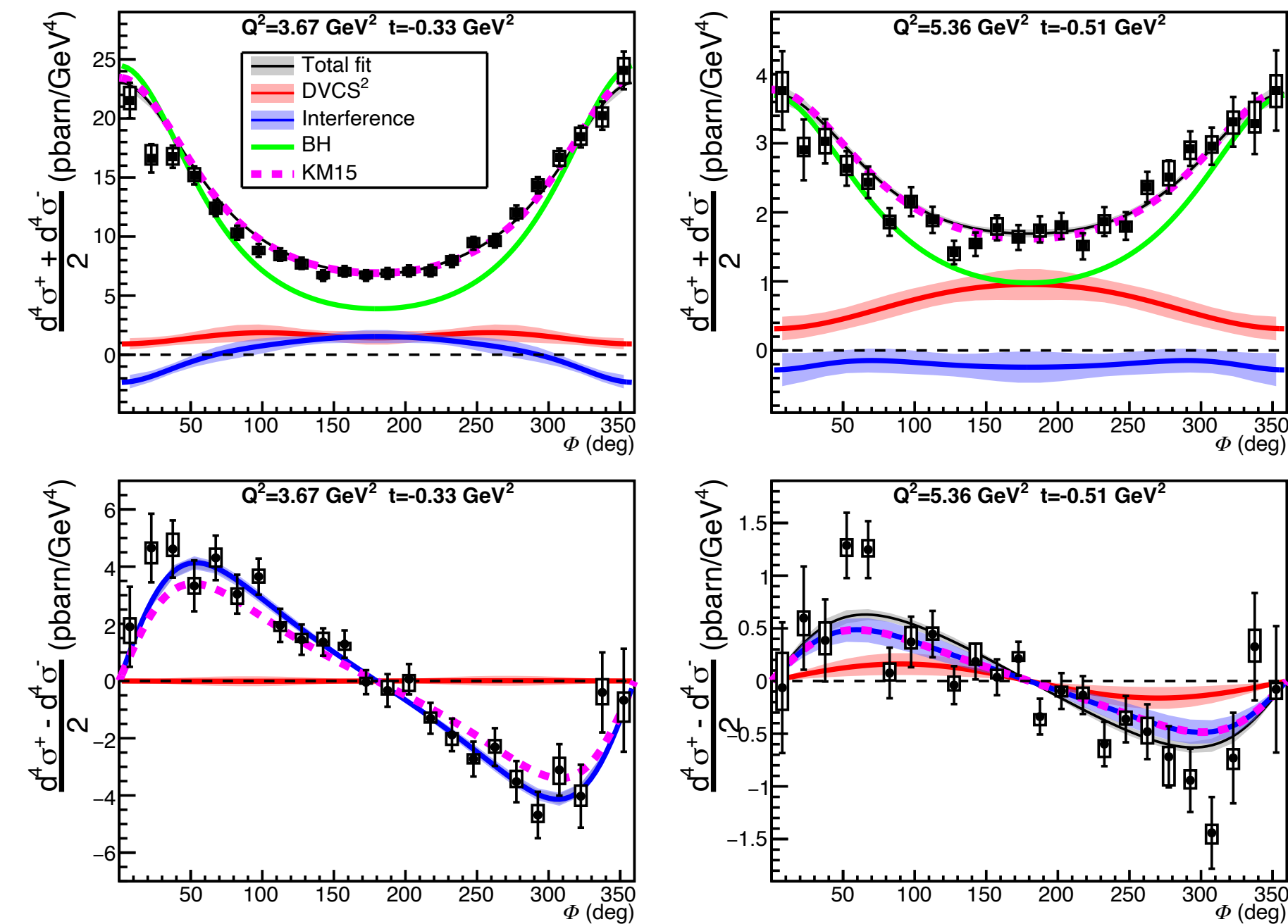


- Measurement with 3 beam energies
- Separation of BH, DVCS and interference terms
- Simultaneous extraction of all 4 chiral-even CFFs

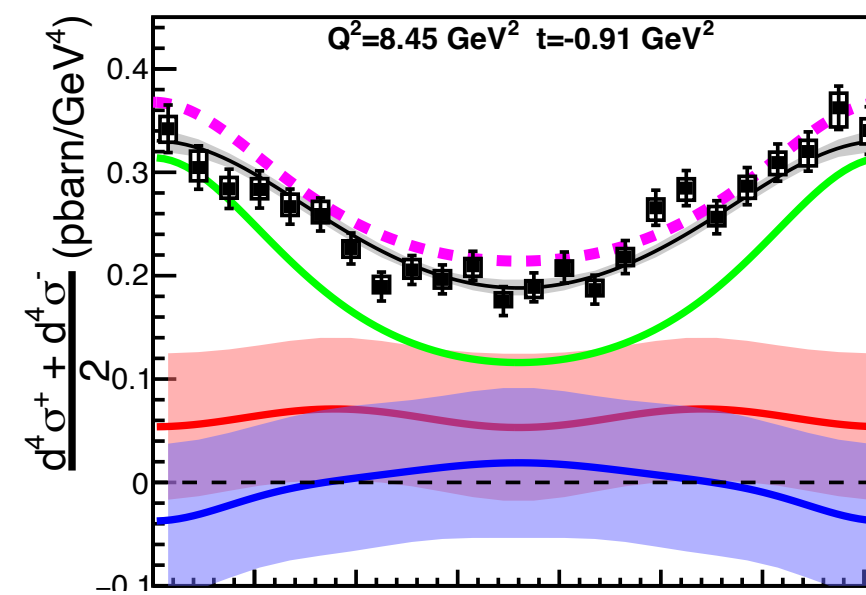
DVCS off the proton: Hall A and C

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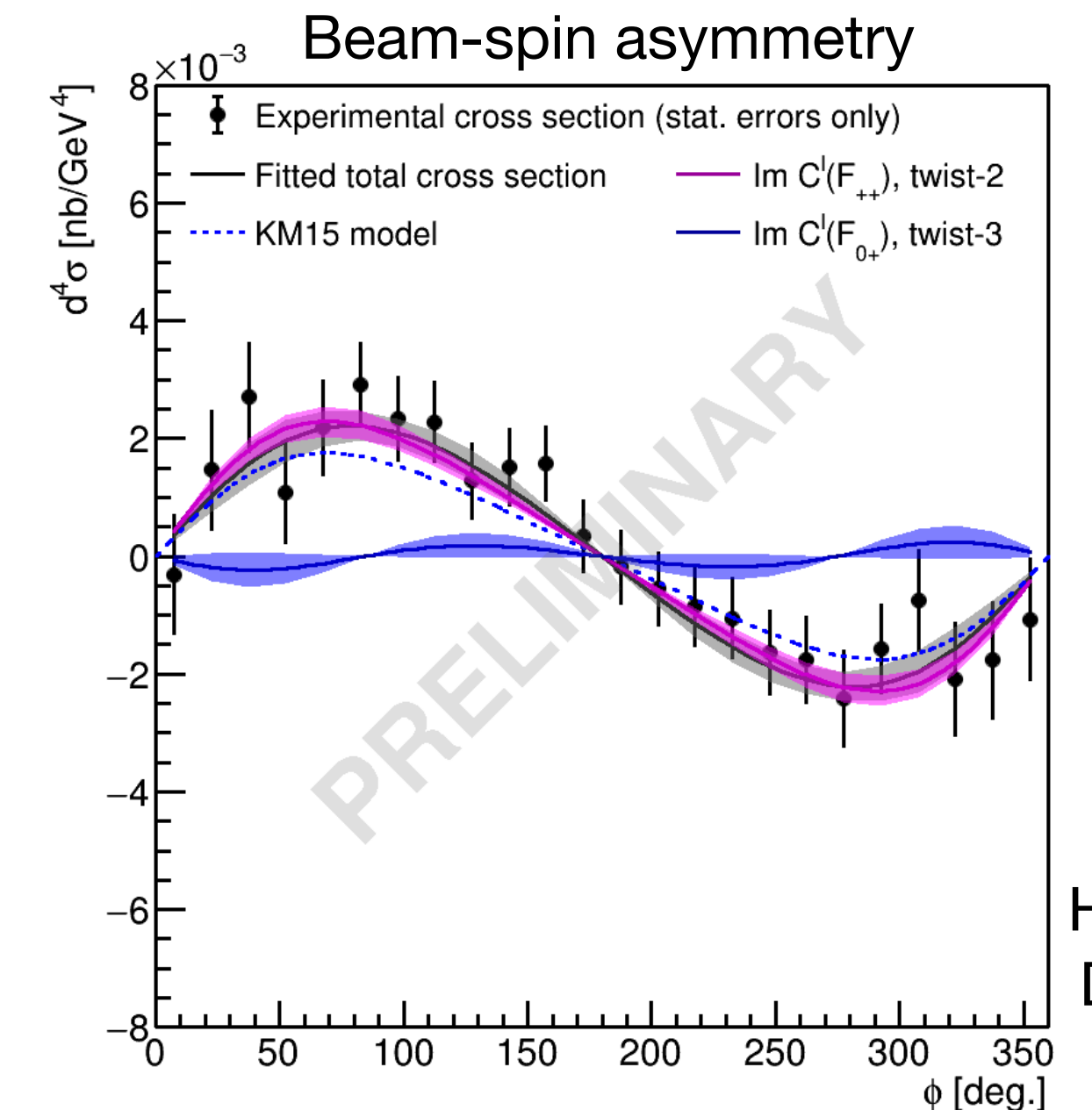
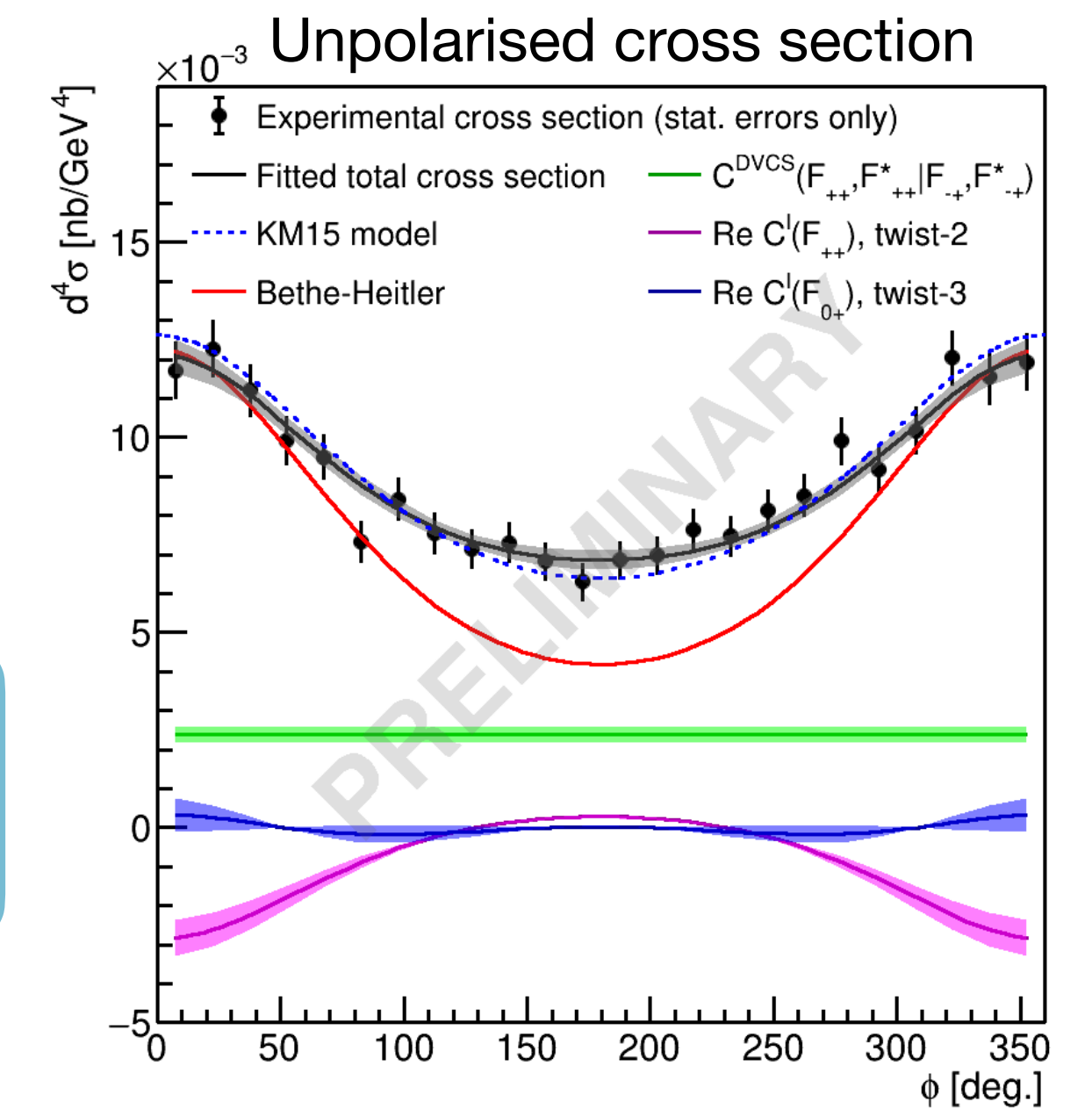
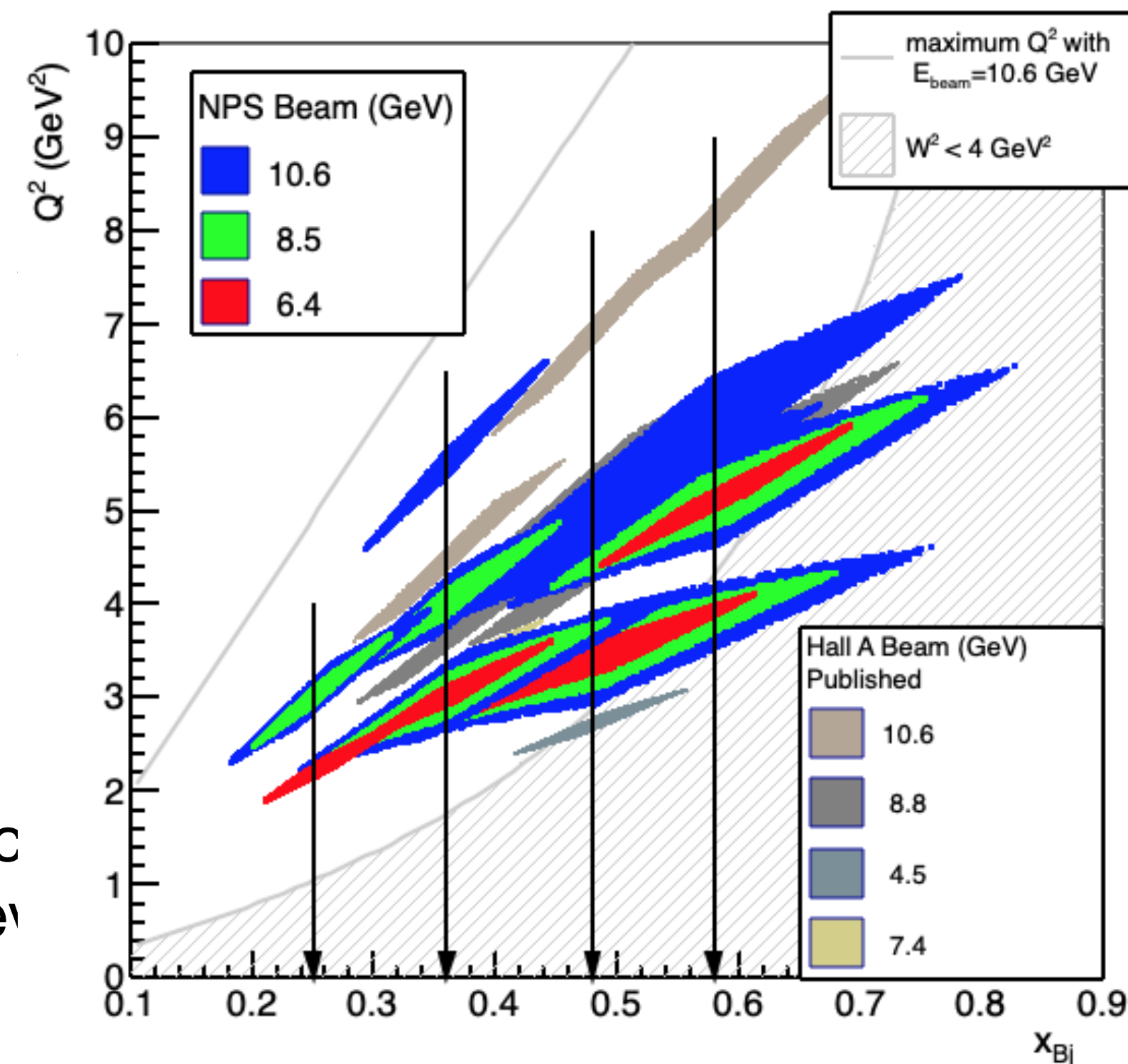
Unpolarised cross section



Beam-spin asymmetry



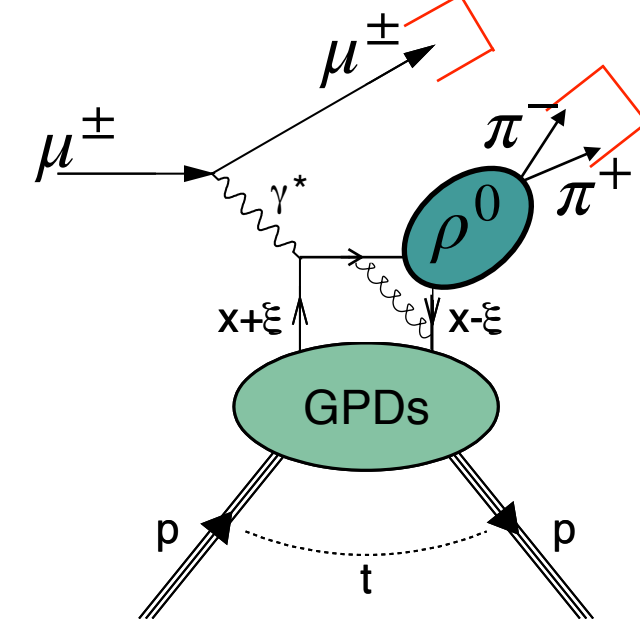
Hall C



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

Exclusive ρ^0 production : SDMEs

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

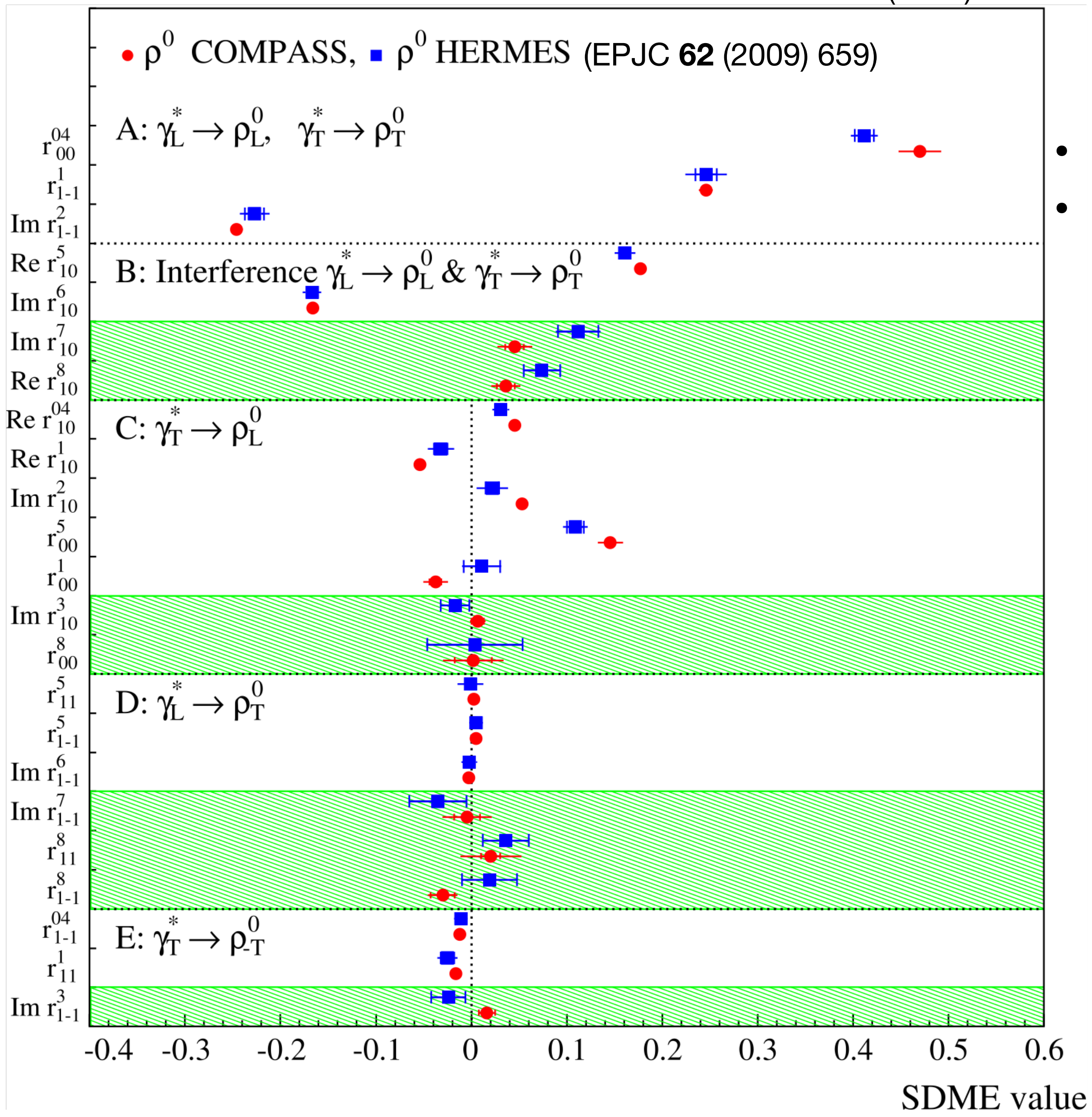


Unpolarised proton target
longitudinally polarised lepton
beam

- 5 classes of SDMEs
- unpolarised and polarised SDMEs

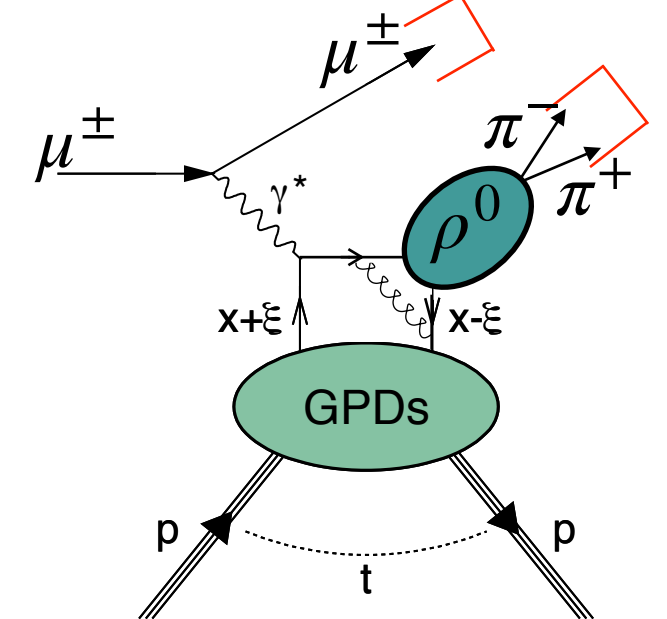
HERMES:
 $\langle Q^2 \rangle = 1.96 \text{ GeV}^2$
 $\langle W \rangle = 4.8 \text{ GeV}^2$

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

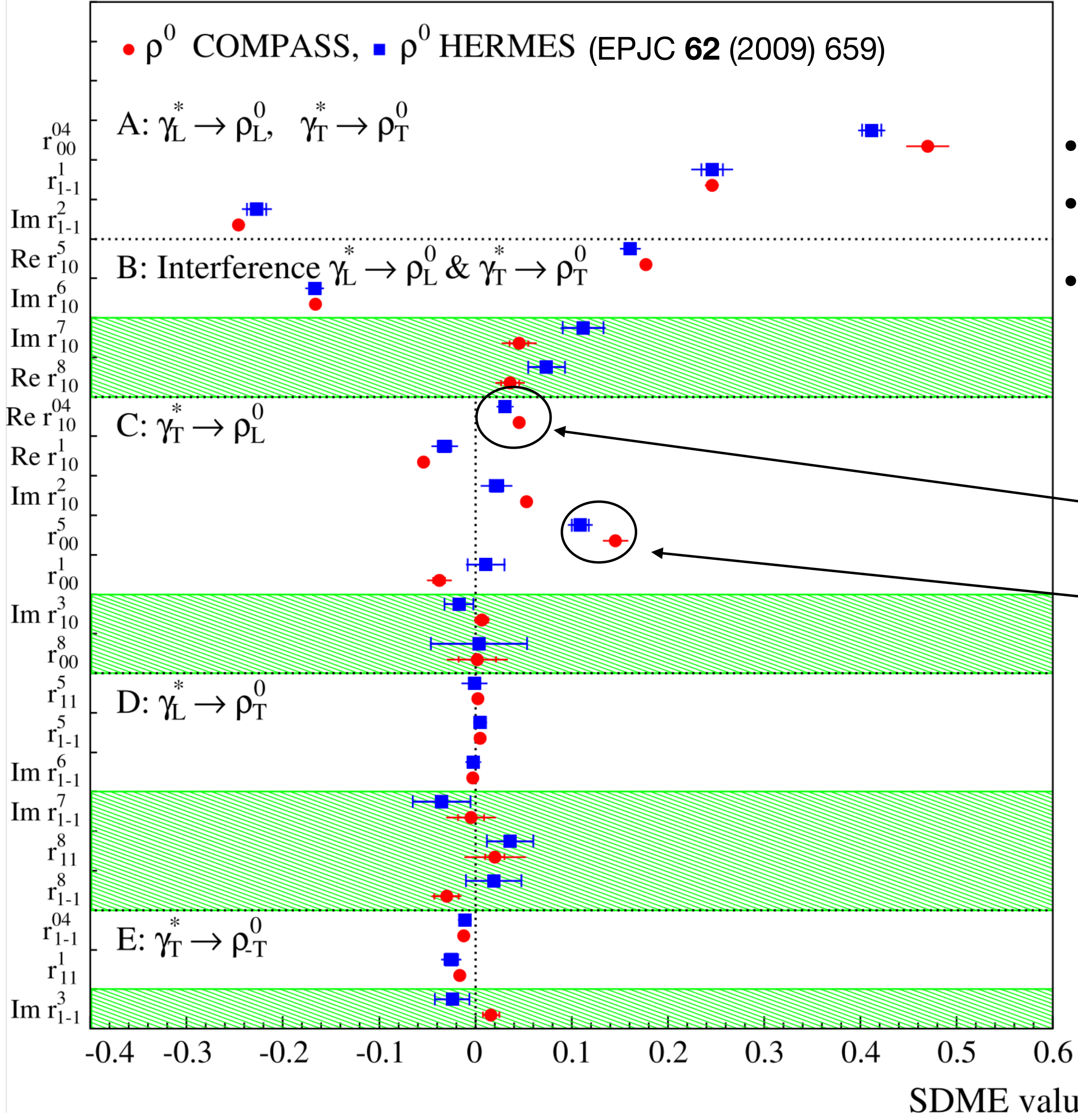


Exclusive ρ^0 production : SDMEs

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



Unpolarised proton target
longitudinally polarised lepton beam



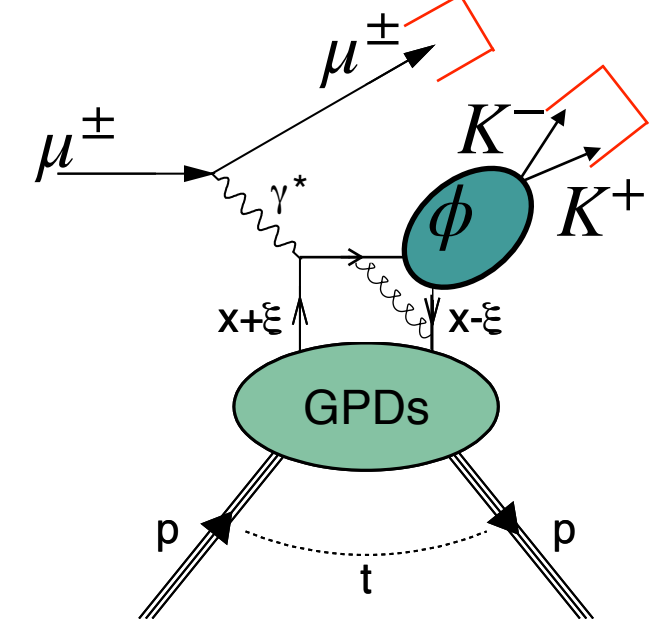
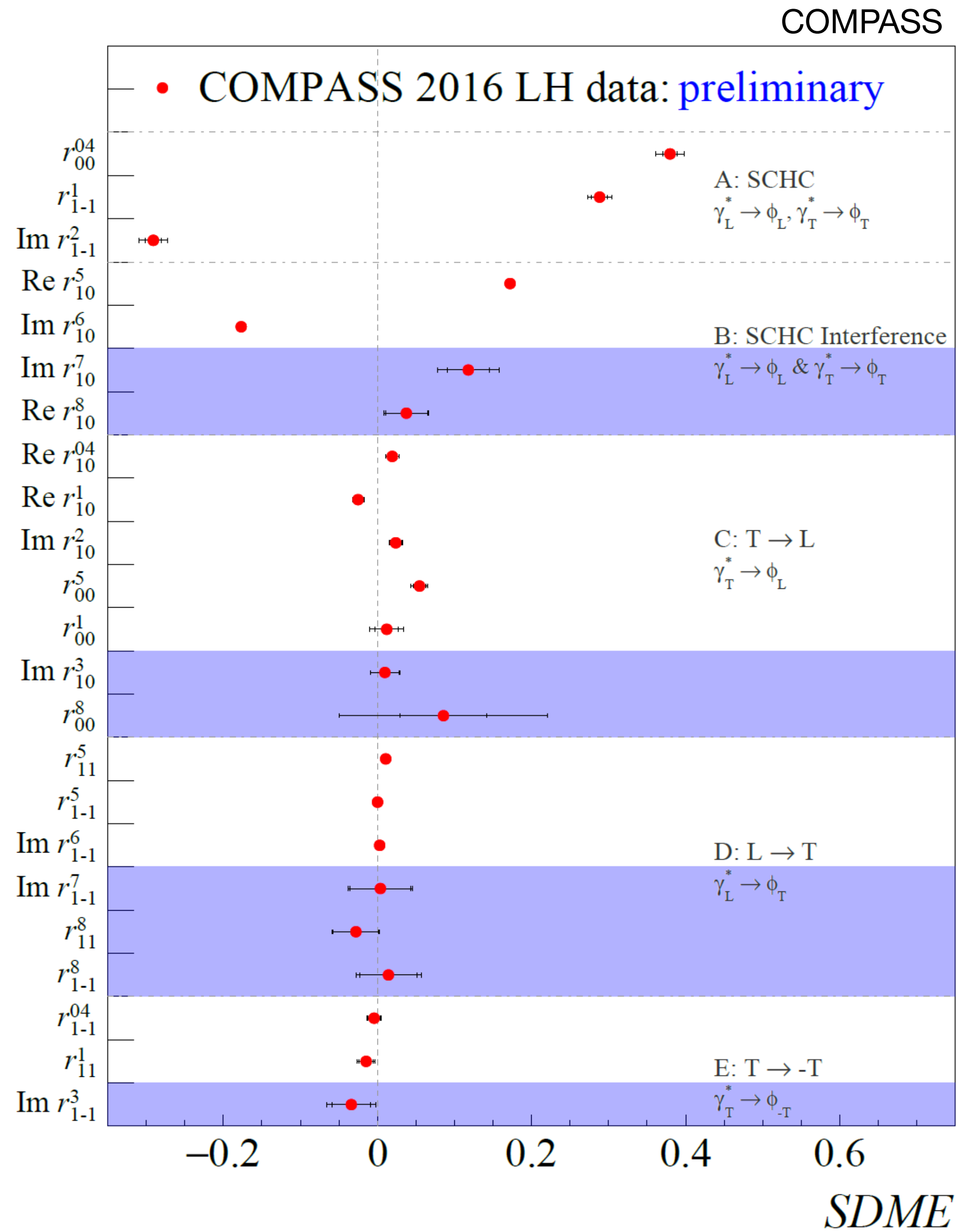
- 5 classes of SDMEs
 - unpolarised and polarised SDMEs
 - s-channel helicity conservation ($\lambda_{\gamma^*} = \lambda_{\rho^0}$):
 - class A&B: fulfilled
 - class C: strong violation:
 - $\Re r_{10}^{04} \neq 0$ by $> 4\sigma$
 - $\Re r_{00}^5 \neq 0$ by $> 9\sigma$
- $H_T, \bar{E}_T = 2\tilde{H}_T + E_T$
(In Goloskokov-Kroll model:
 $k_{\perp}$ factorisation assumed)

HERMES:
 $\langle Q^2 \rangle = 1.96 \text{ GeV}^2$
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Exclusive ϕ production : SDMEs

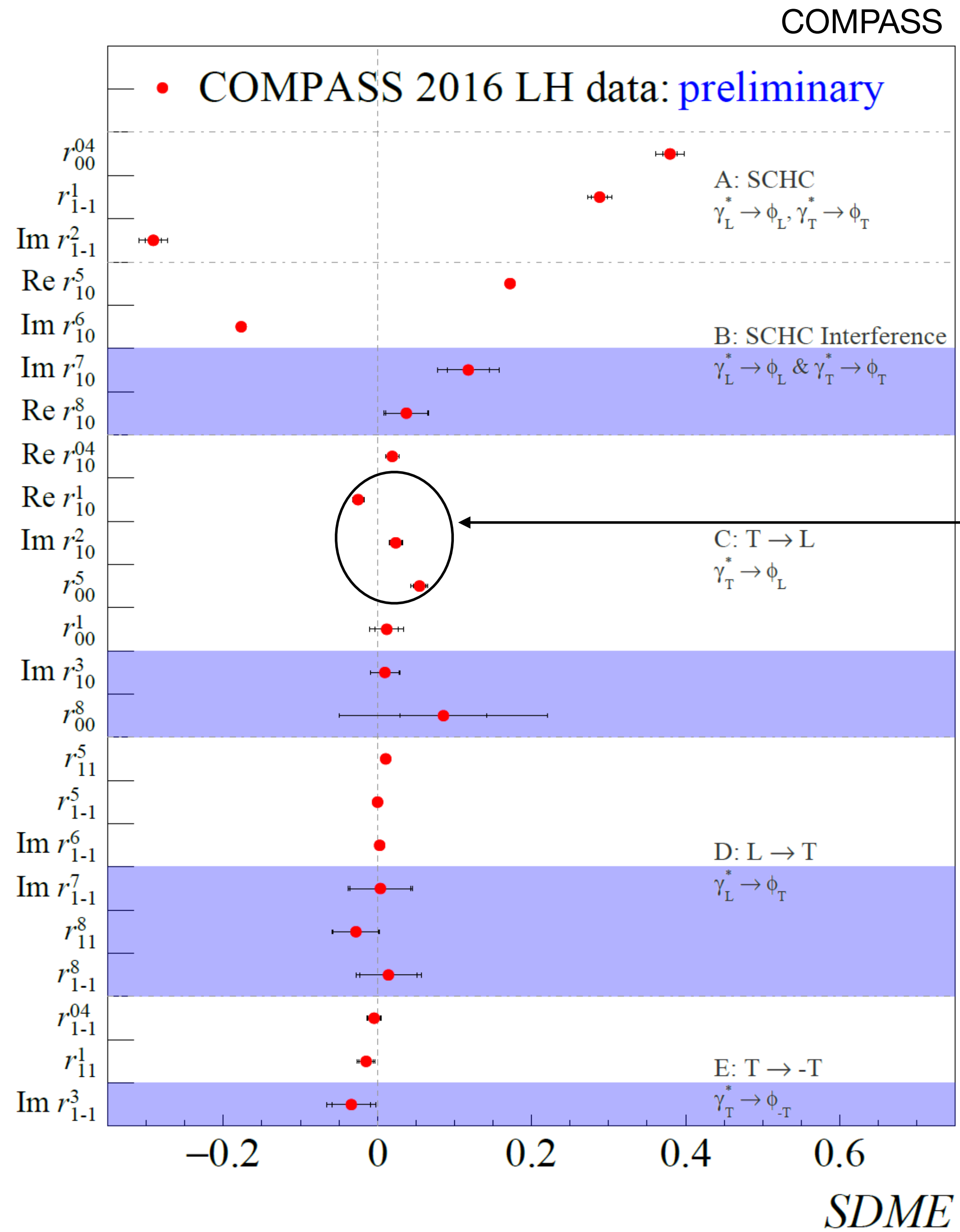
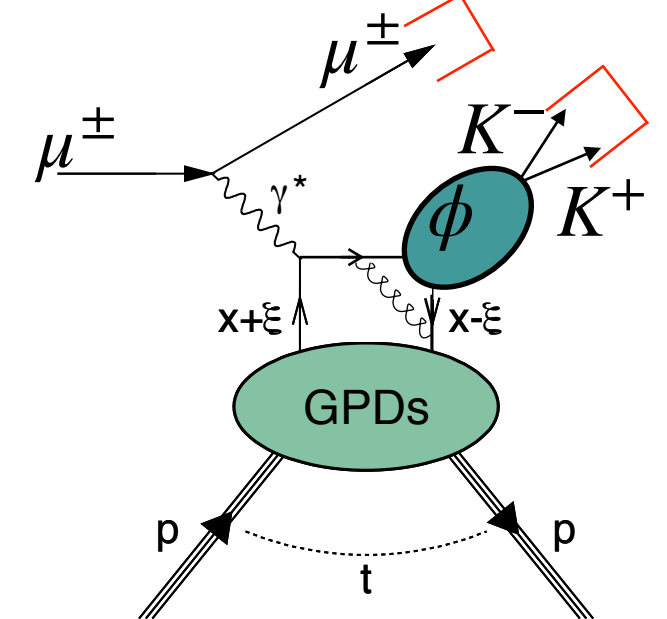
Unpolarised proton target
longitudinally polarised lepton beam



- 5 classes of SDMEs
- unpolarised and polarised SDMEs

Exclusive ϕ production : SDMEs

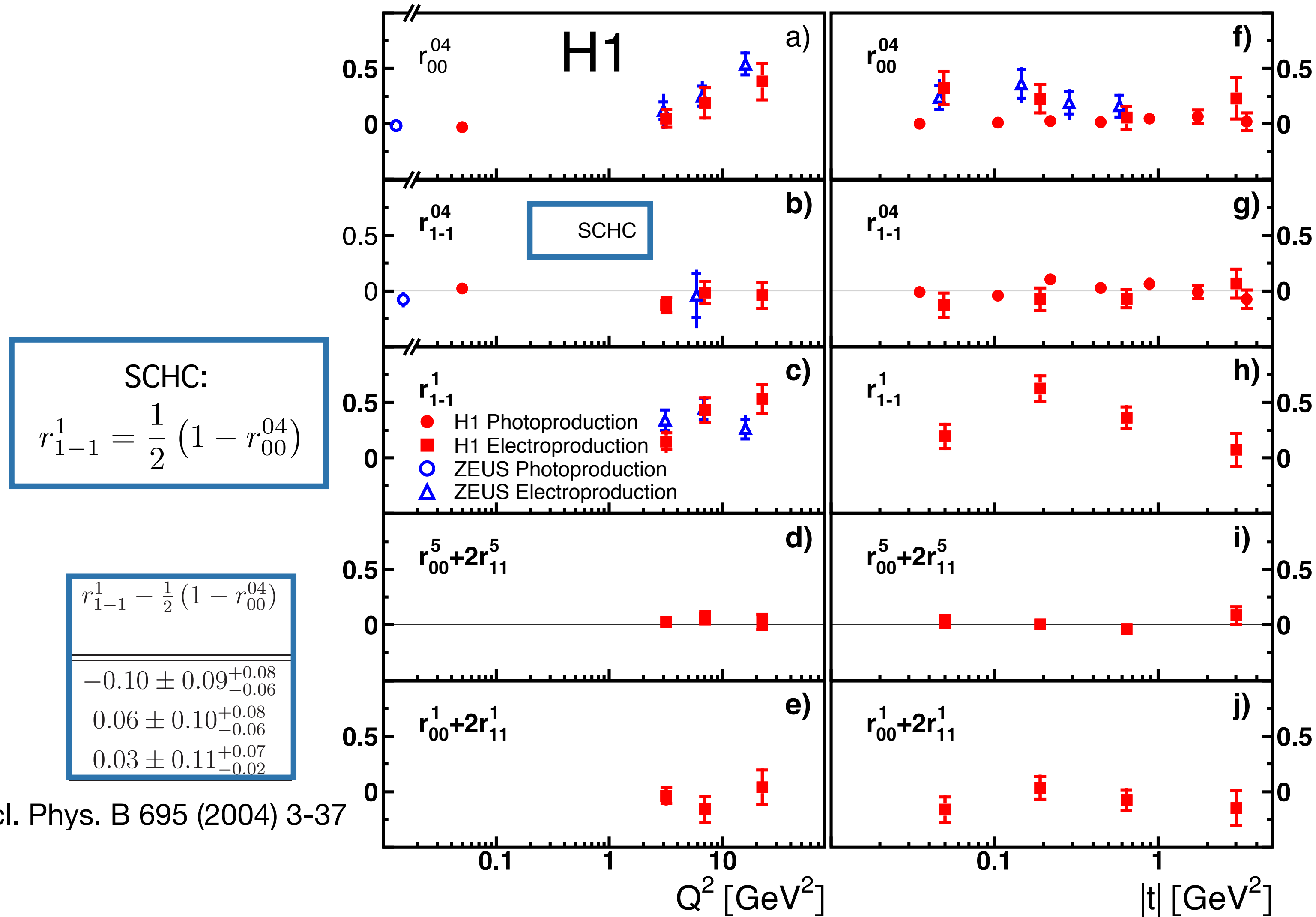
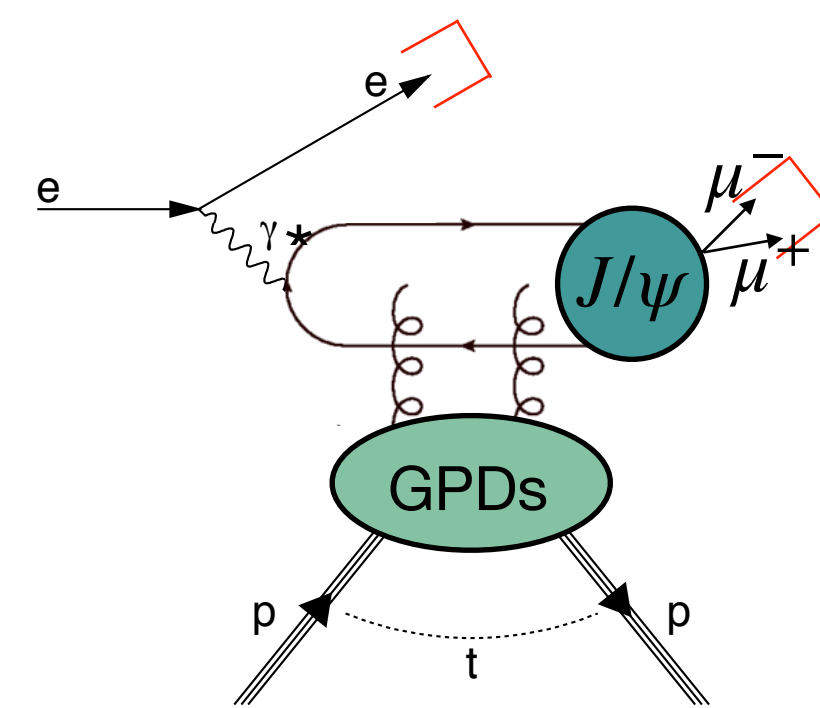
Unpolarised proton target
longitudinally polarised lepton beam



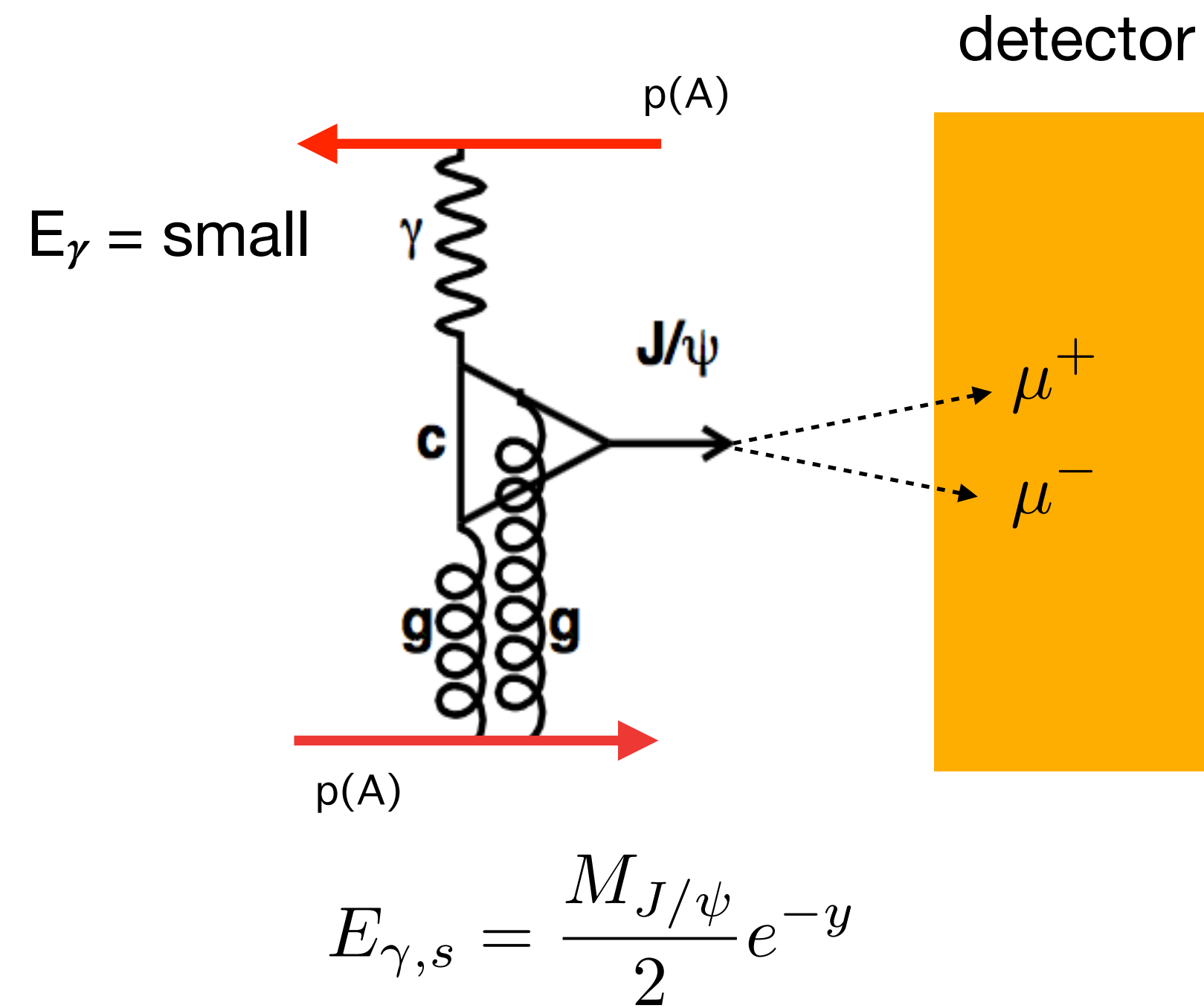
- 5 classes of SDMEs
- unpolarised and polarised SDMEs
- s-channel helicity conservation ($\lambda_{\gamma^*} = \lambda_{\rho^0}$):
 - class A: fulfilled
 - class B: small tensions
 - class C: violation:

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

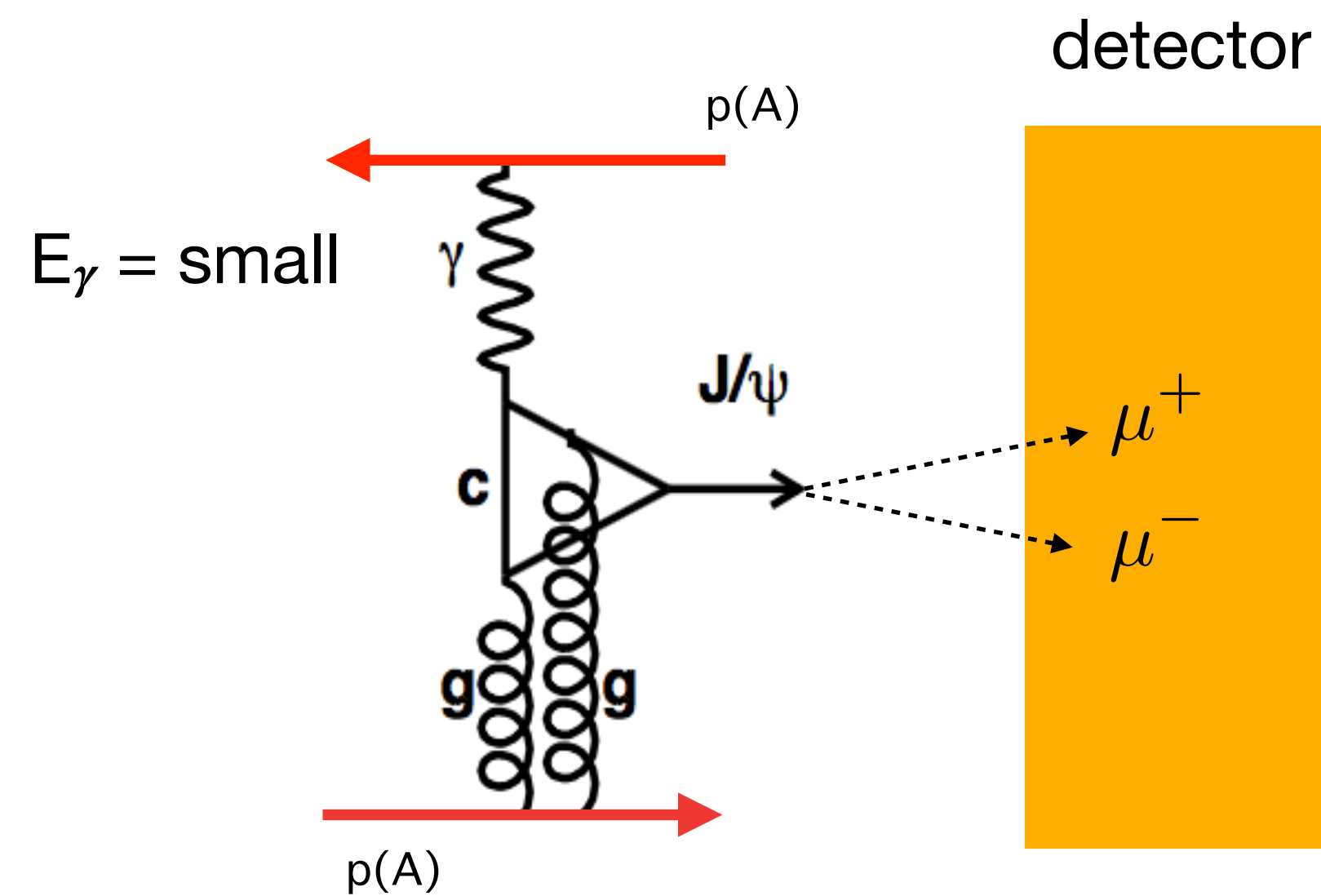
Exclusive J/ψ production : SDMEs



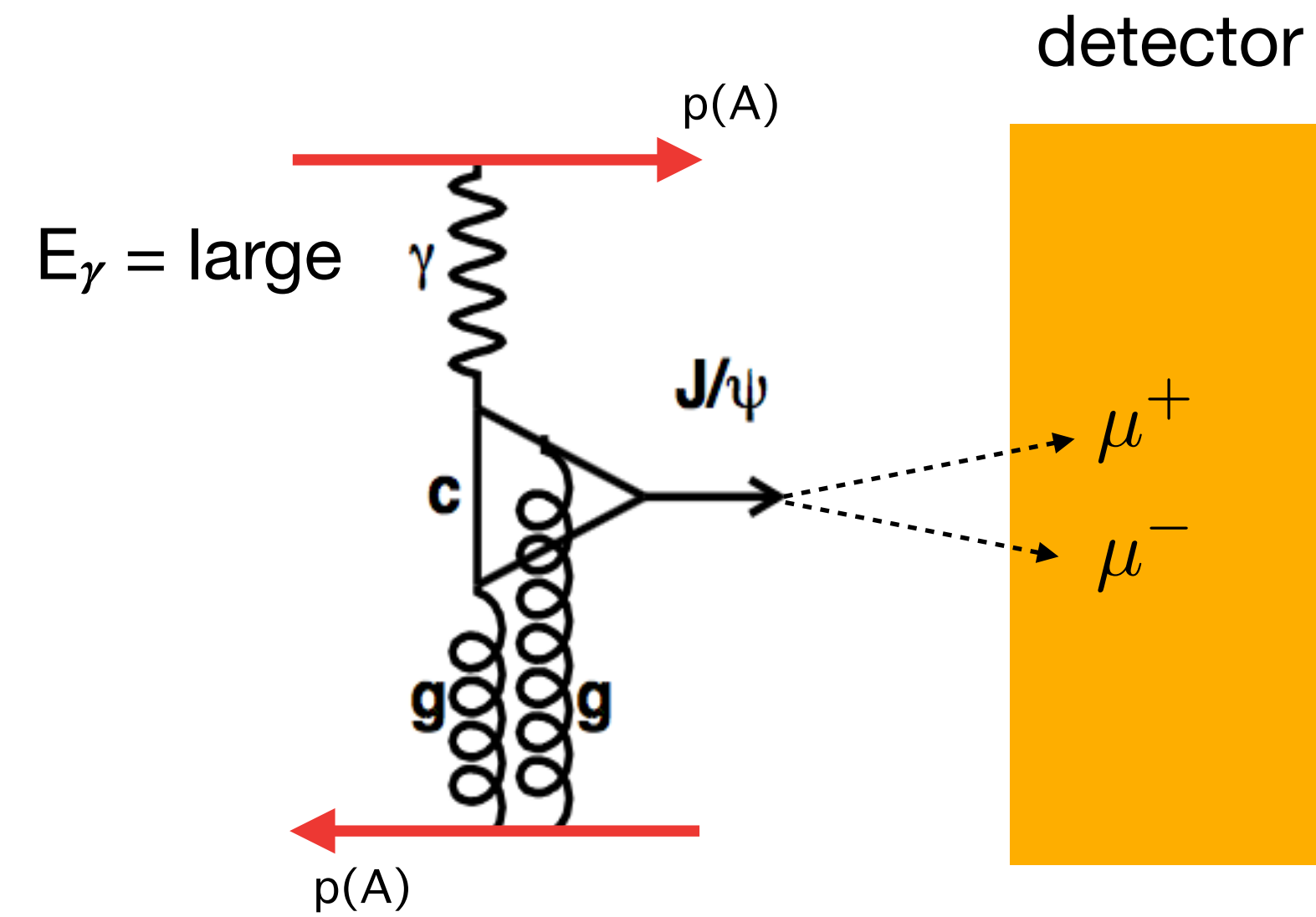
Disentangling the ambiguity on the ID of the γ emitter



Disentangling the ambiguity on the ID of the γ emitter

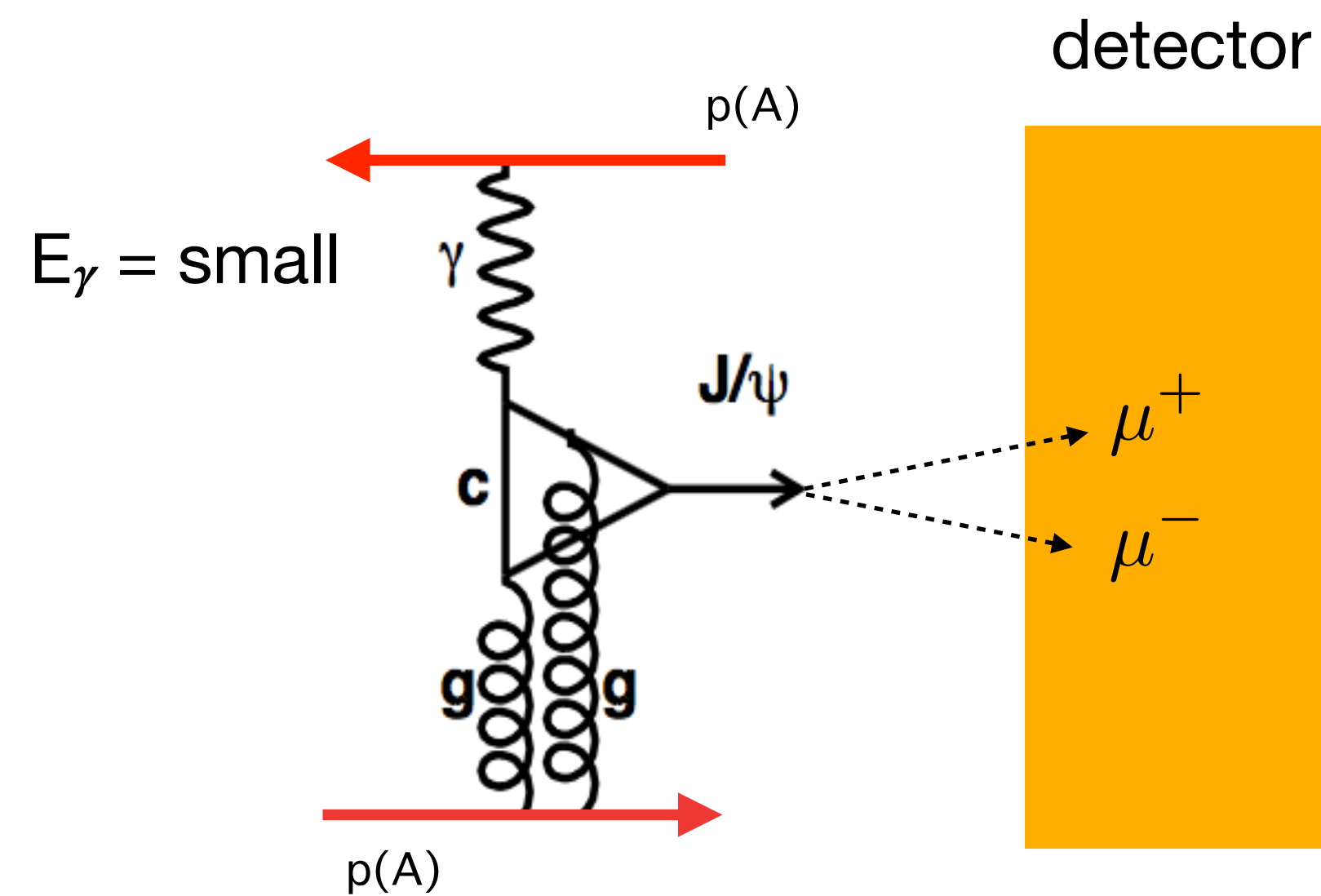


$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$

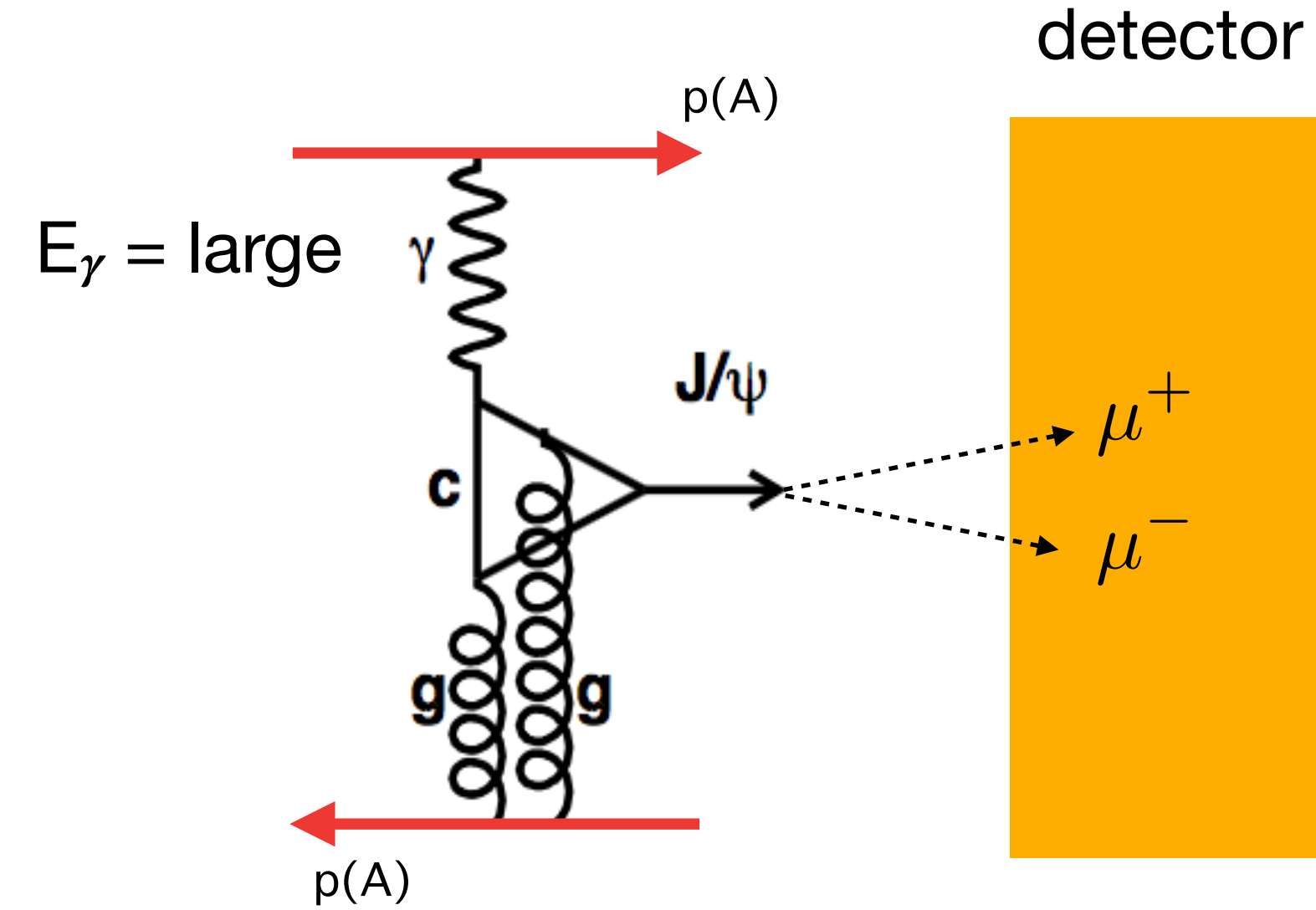


$$E_{\gamma,l} = \frac{M_{J/\psi}}{2} e^{+y}$$

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

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

Disentangling the ambiguity on the ID of the γ emitter

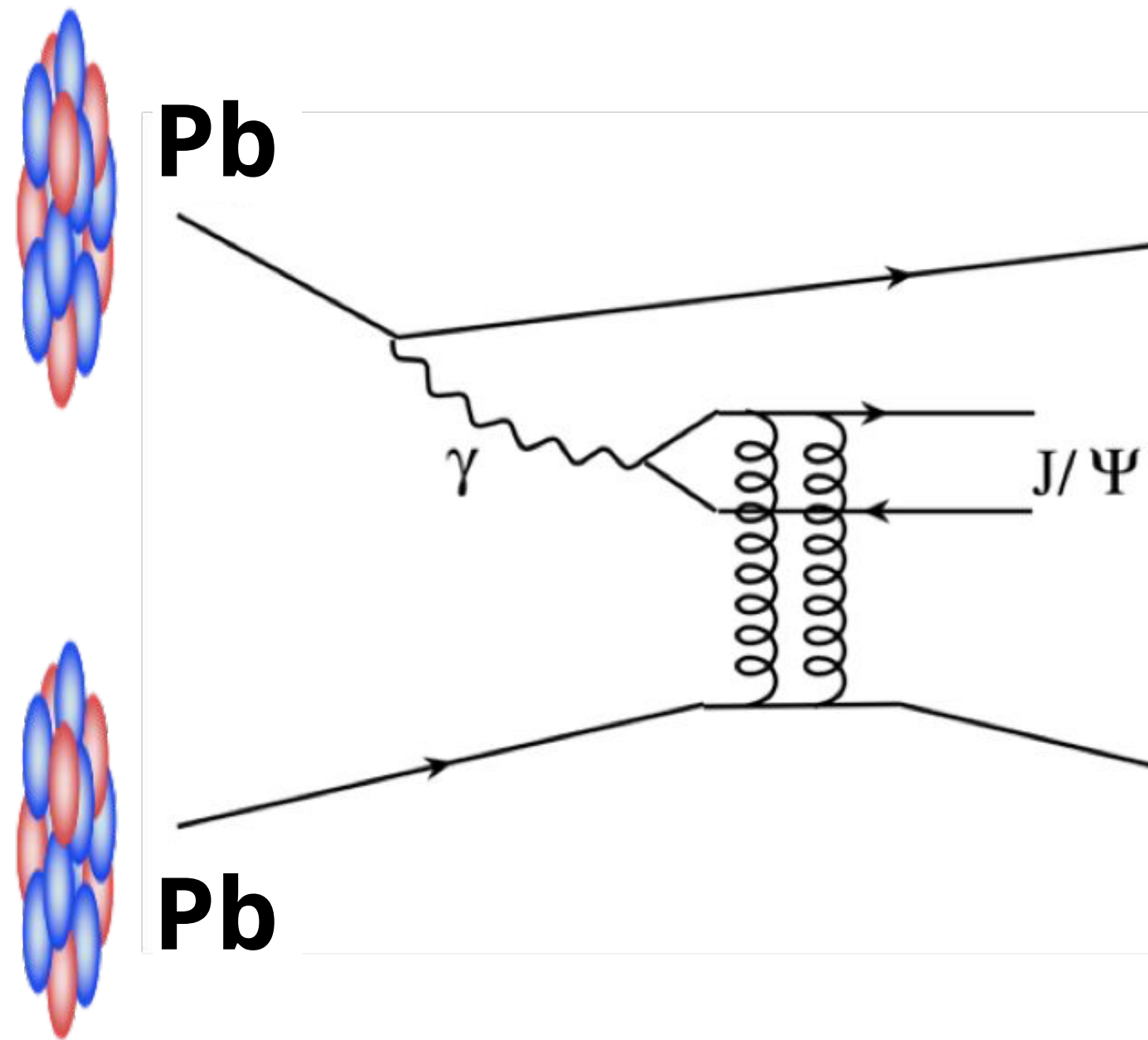
$$\sigma(y) = N_{\gamma/A}(E_{\gamma,s}) \sigma_{J/\psi}(E_{\gamma,s}) + N_{\gamma/A}(E_{\gamma,l}) \sigma_{J/\psi}(E_{\gamma,l})$$

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

Disentangling the ambiguity on the ID of the γ emitter

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

Photon flux $N_{\gamma/A}(E_{\gamma})$ is function of impact parameter:
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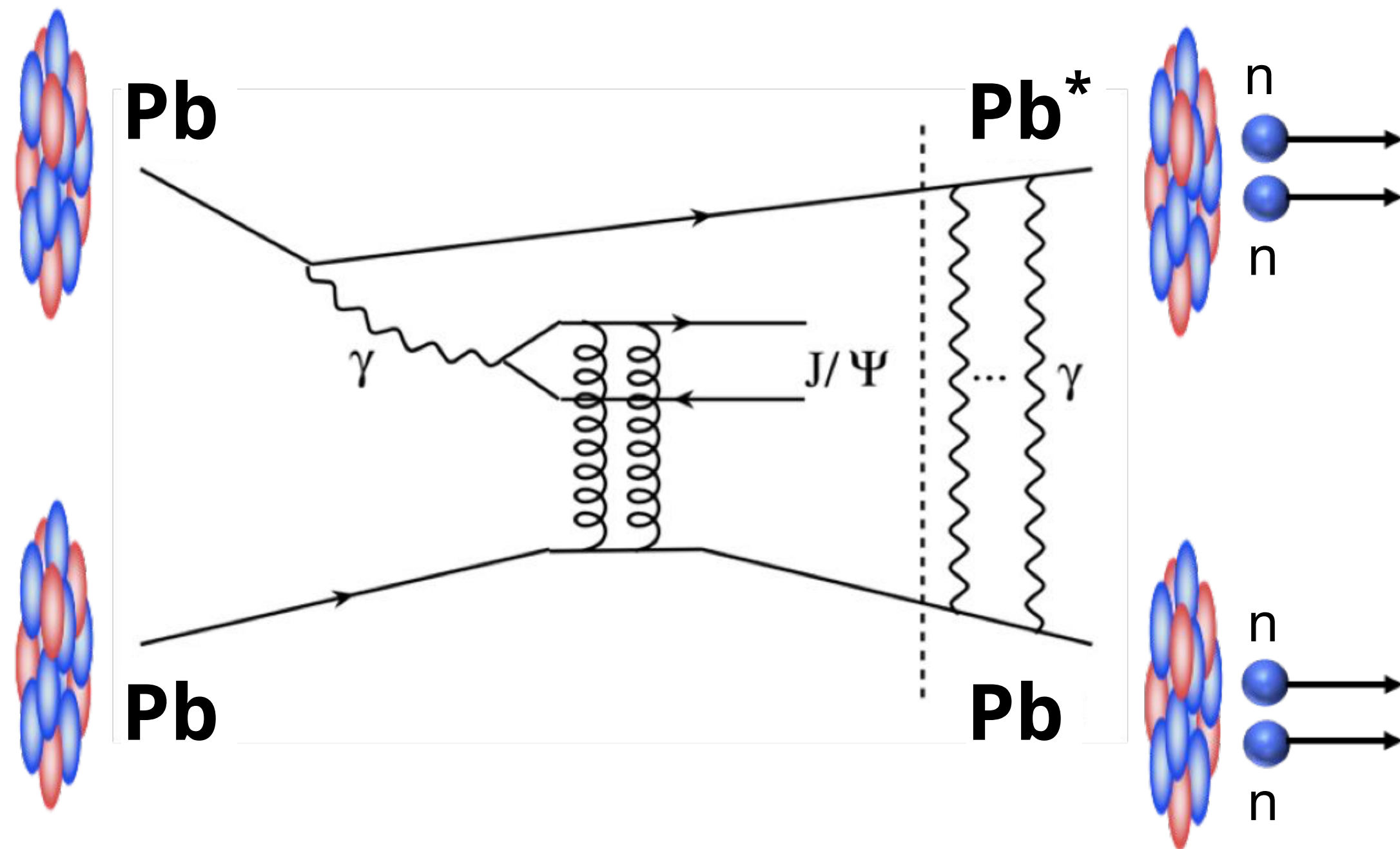


Disentangling the ambiguity on the ID of the γ emitter

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

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

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

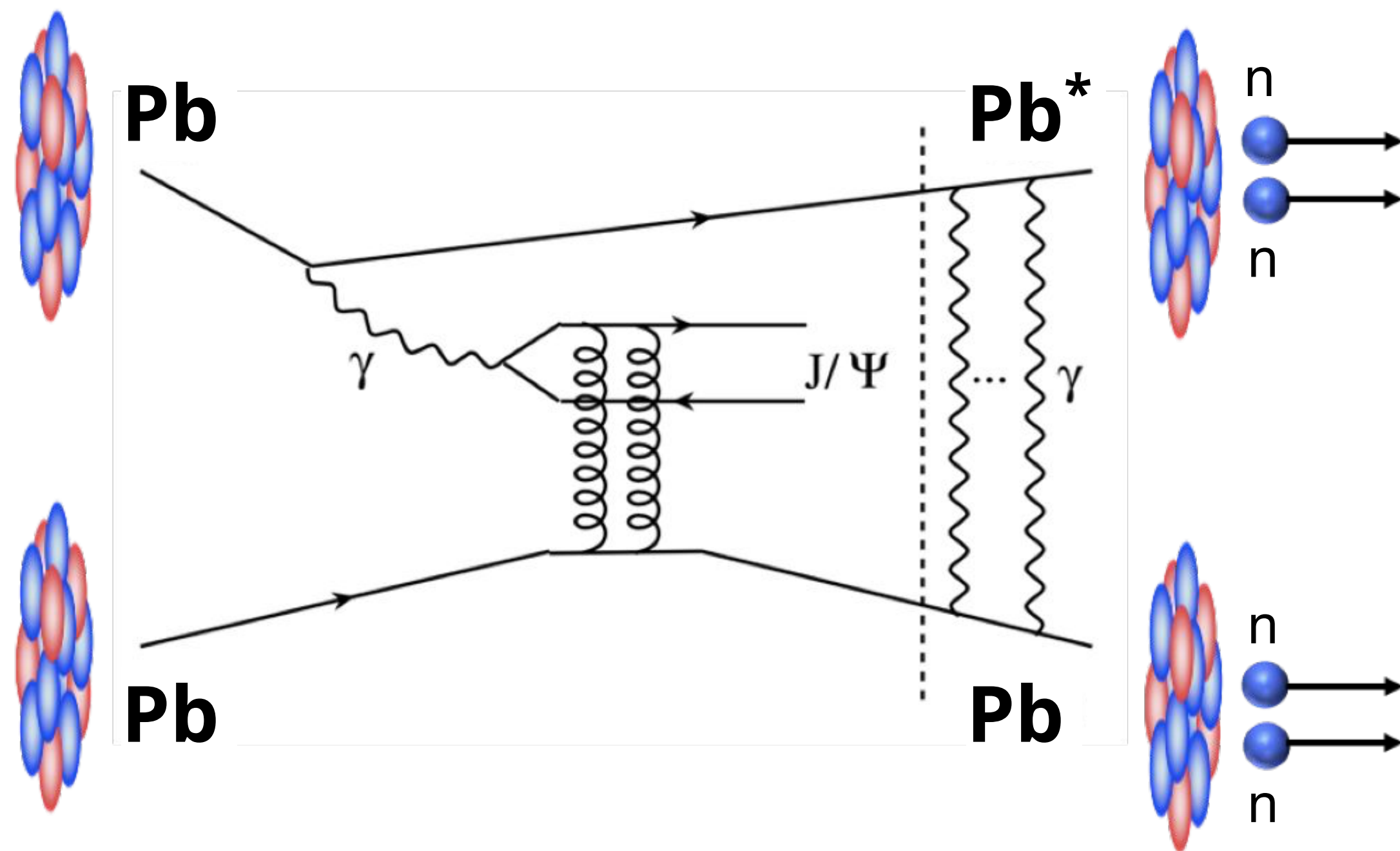


Disentangling the ambiguity on the ID of the γ emitter

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

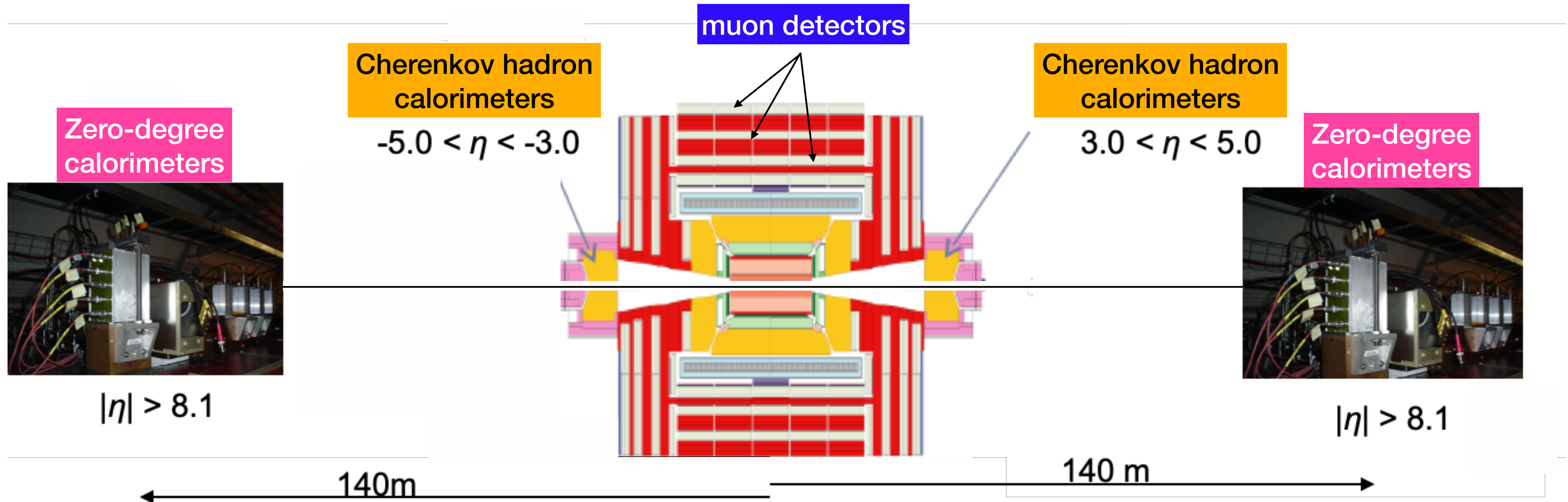
Photon flux $N_{\gamma/A}(E_{\gamma})$ is function of impact parameter:
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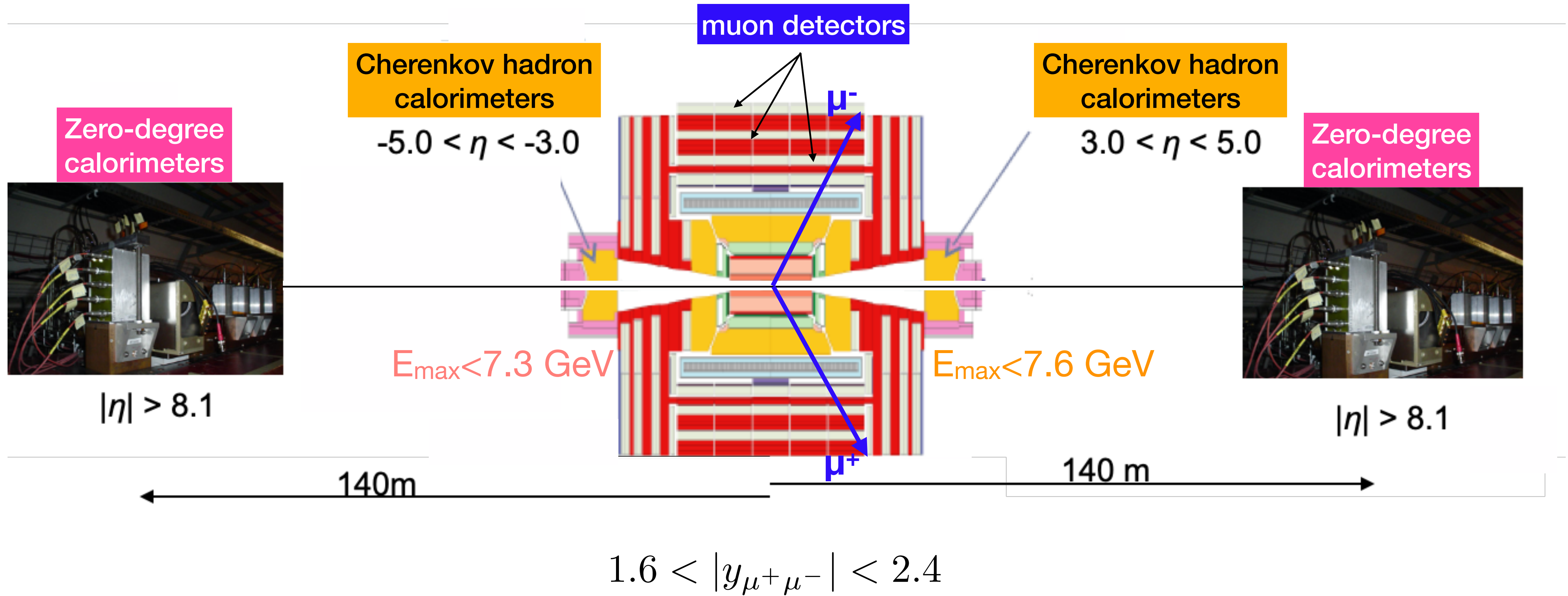


Make measurement with
possibility to detect neutrons

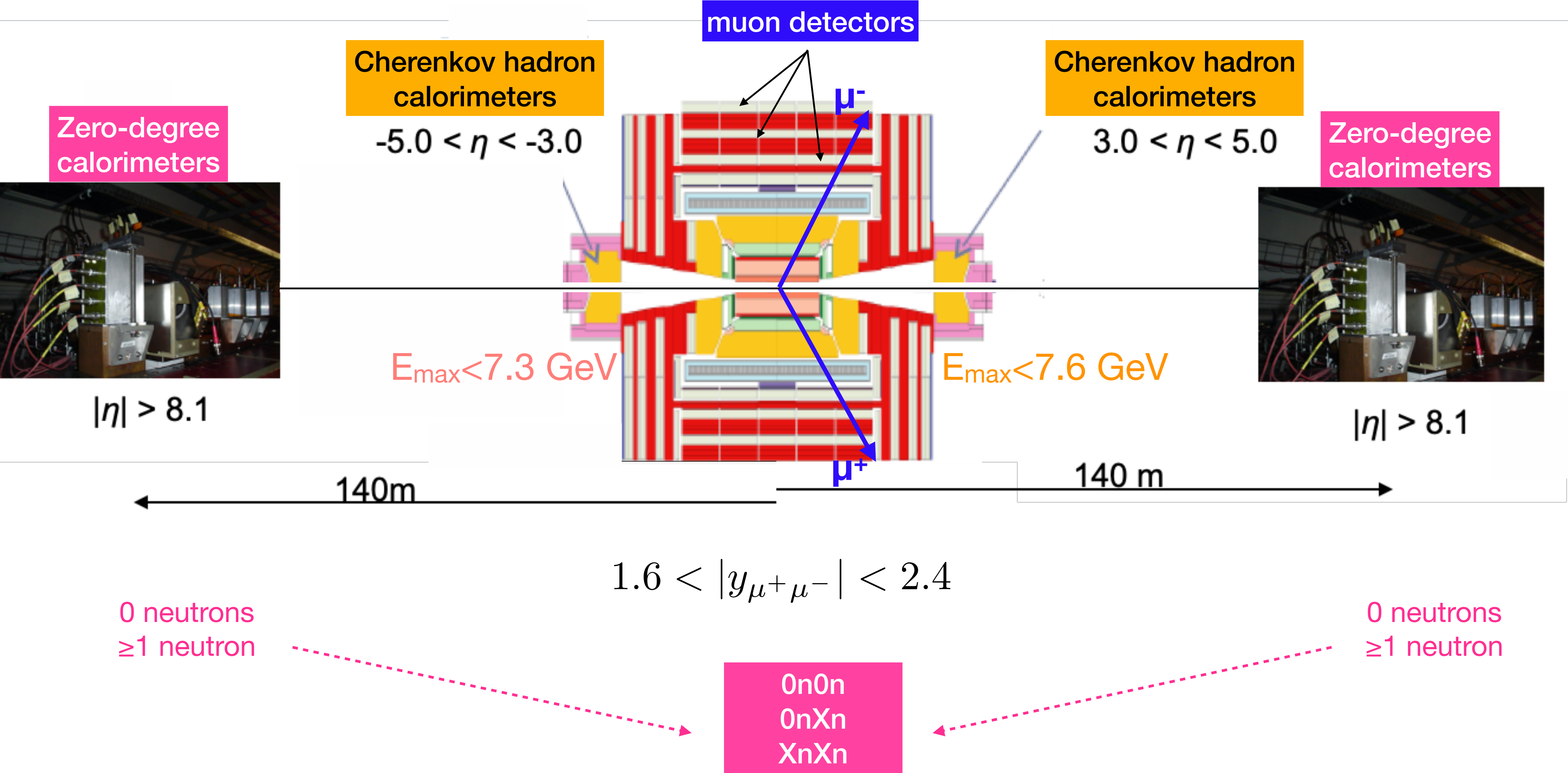
CMS central detector and the (far-)forward region



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

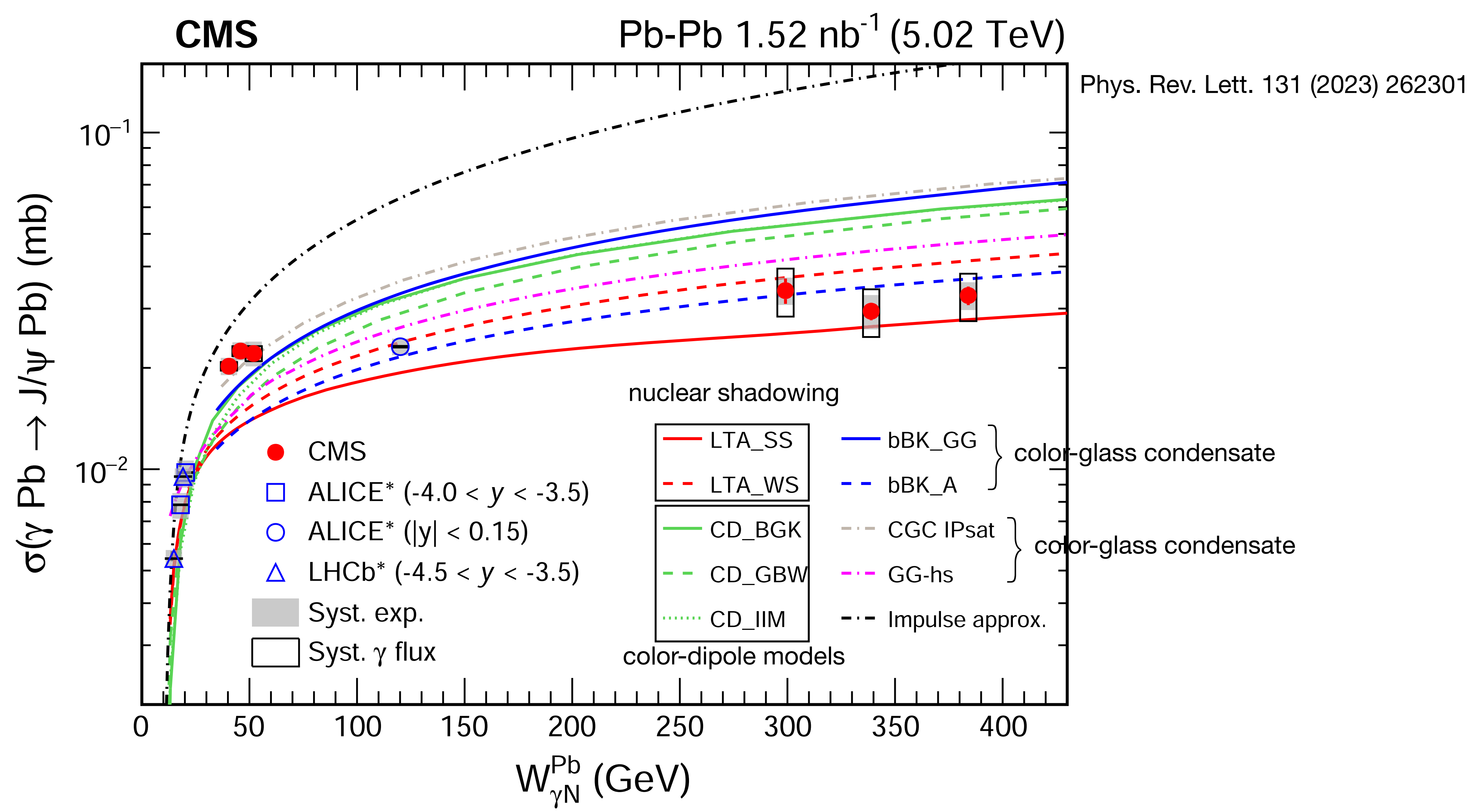
Disentangling the ambiguity on the ID of the γ emitter

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

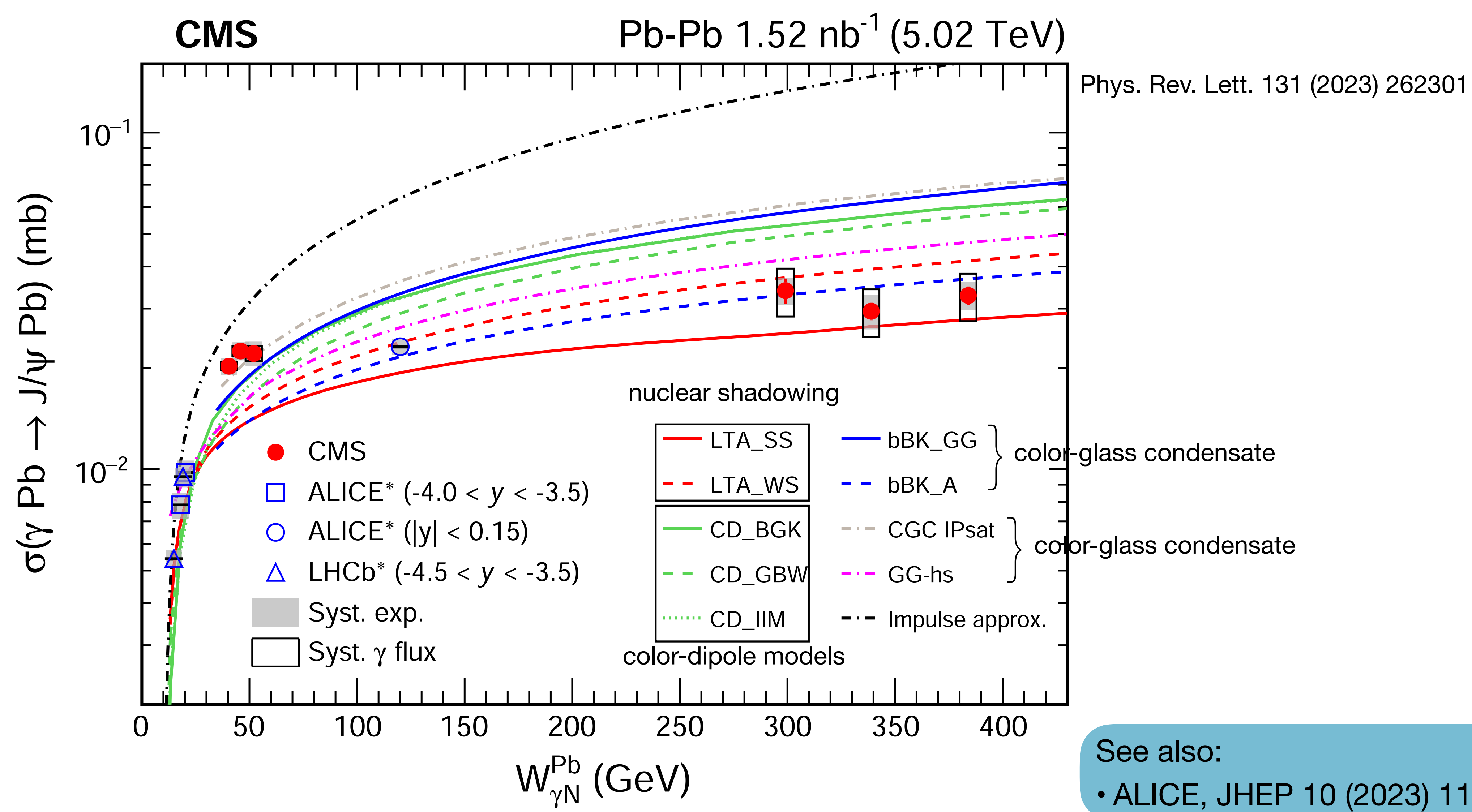
Disentangling the ambiguity on the ID of the γ emitter

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

CMS: γ Pb cross section, energy dependence

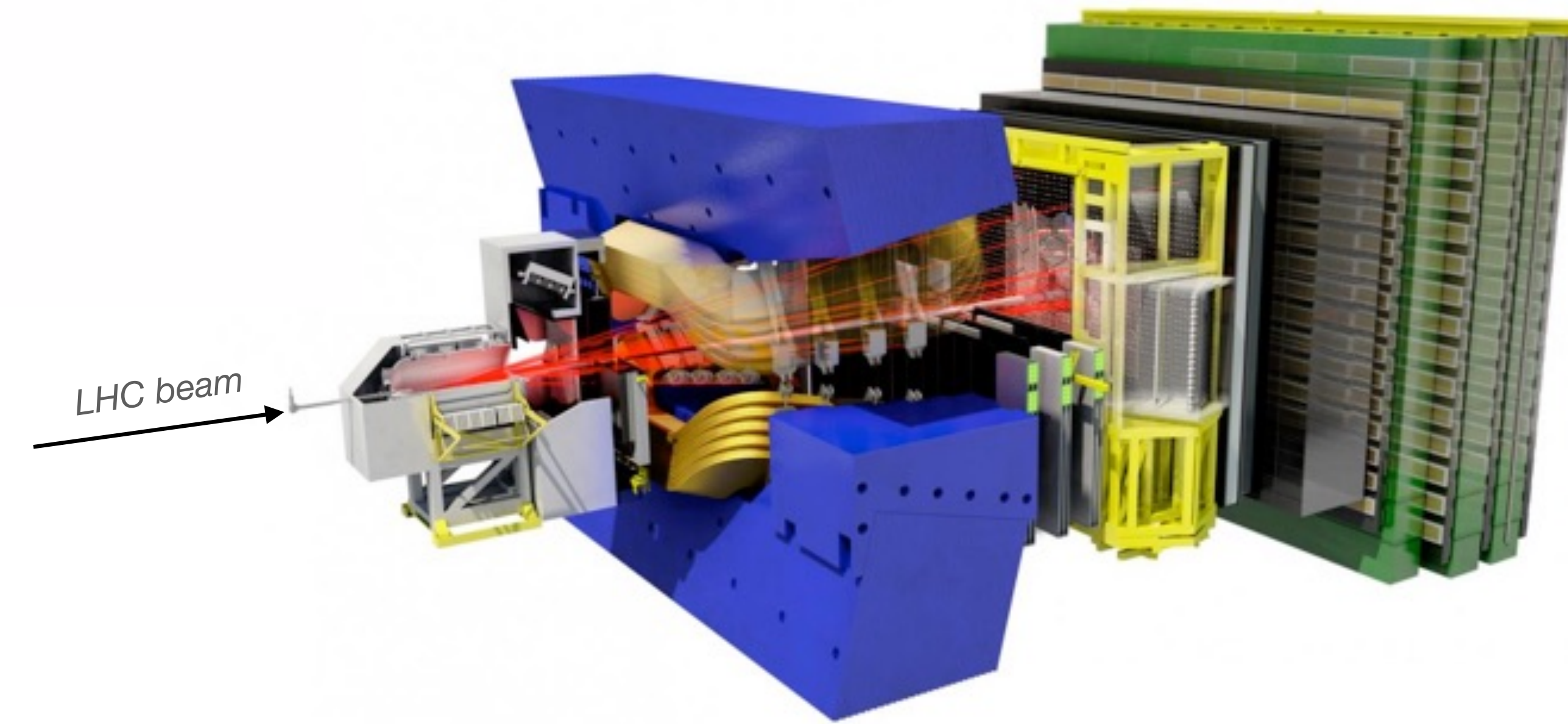


CMS: γ Pb cross section, energy dependence

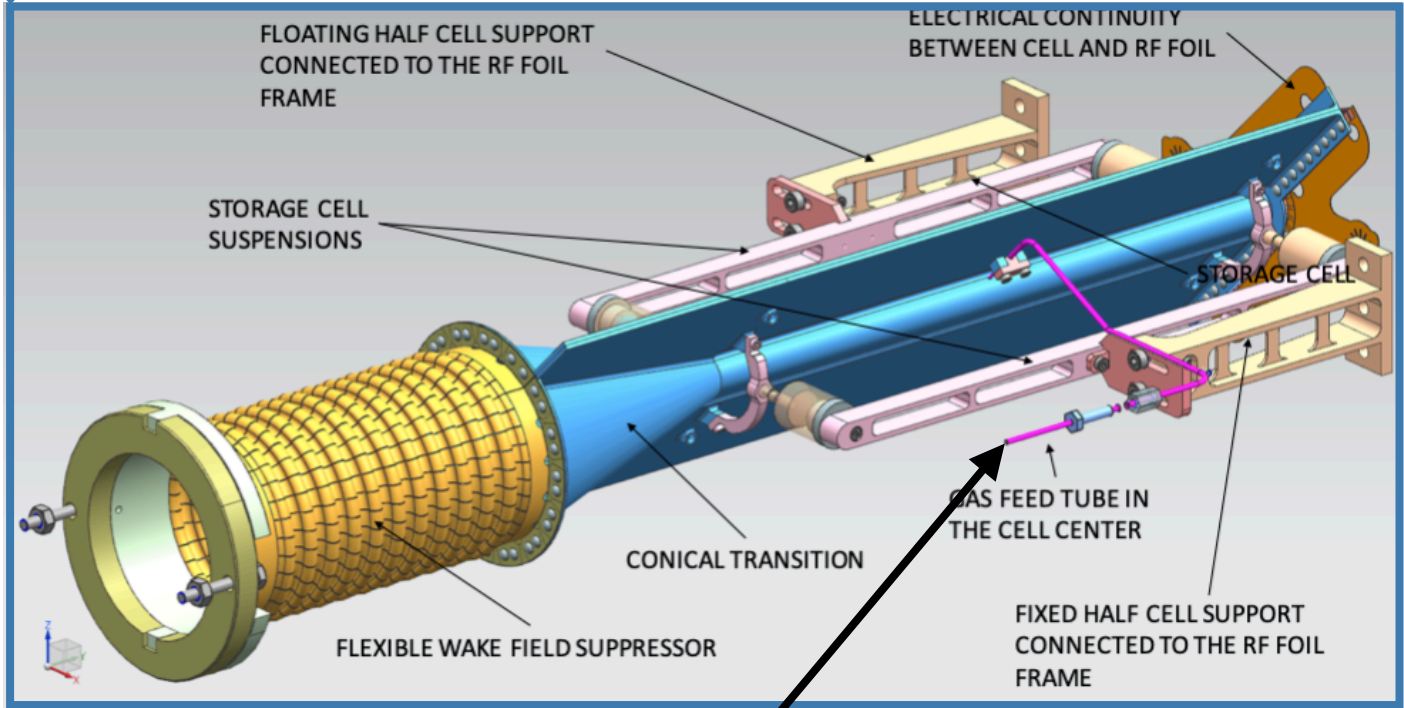
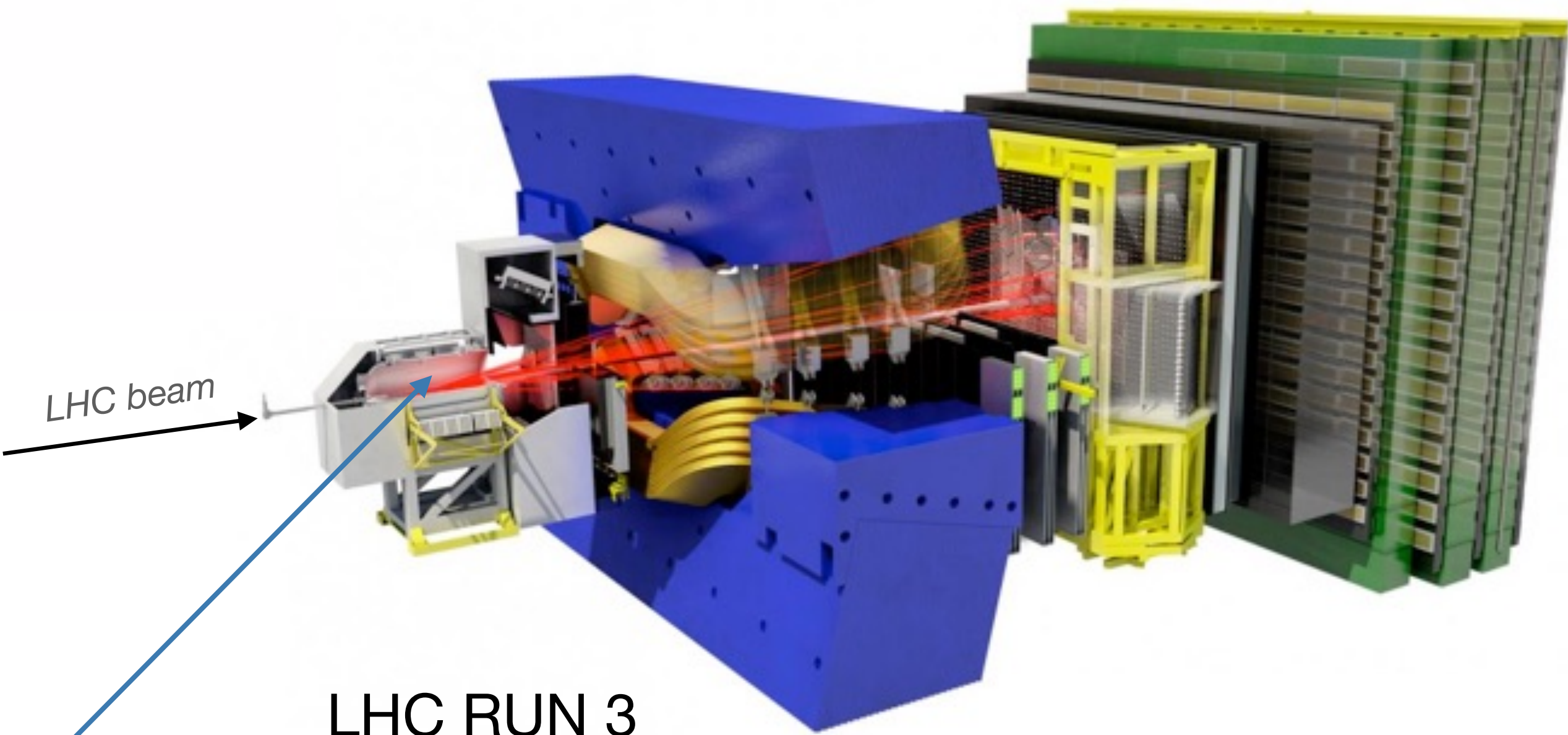


See also:
• ALICE, JHEP 10 (2023) 119

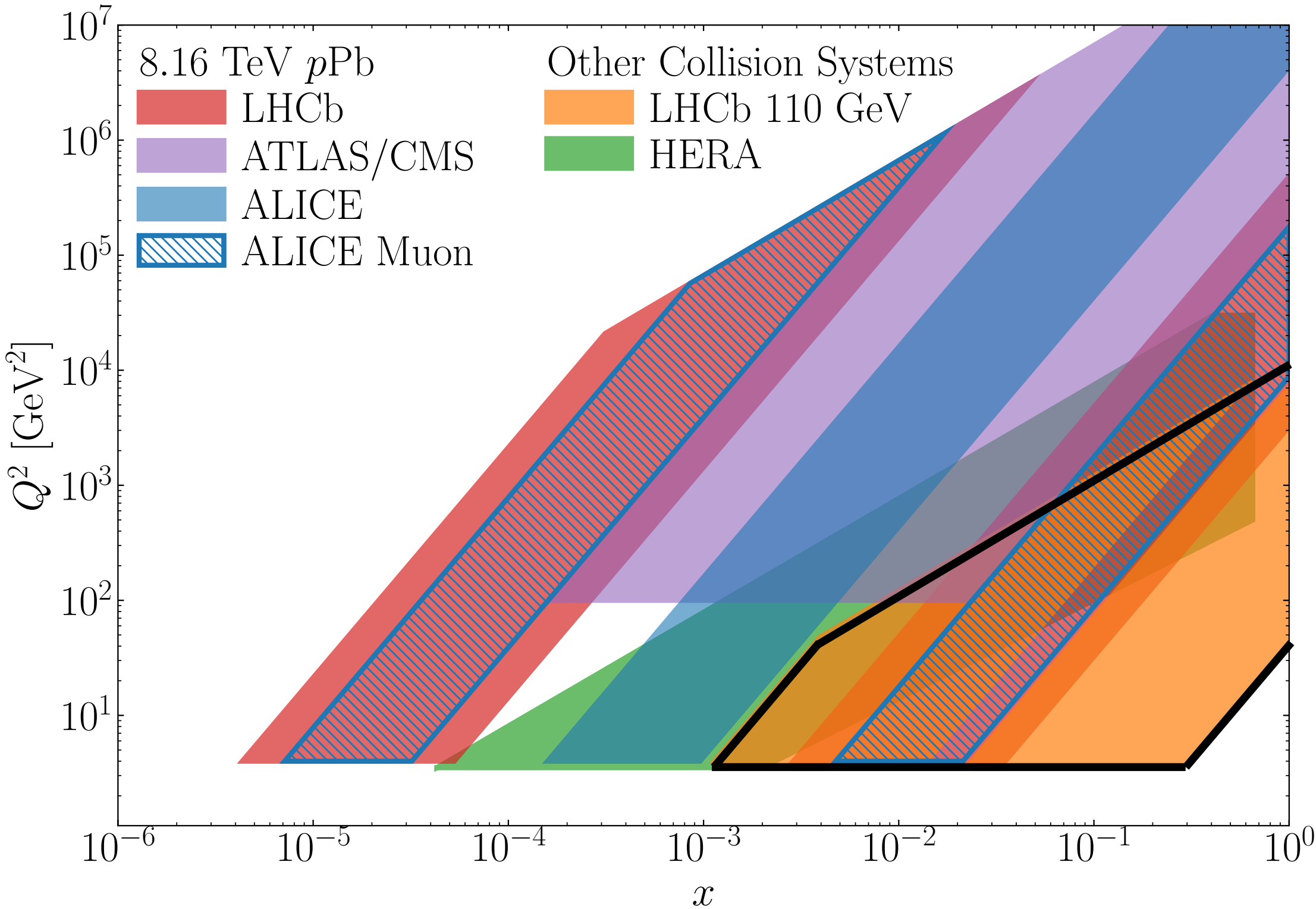
Fixed target at LHCb



Fixed target at LHCb

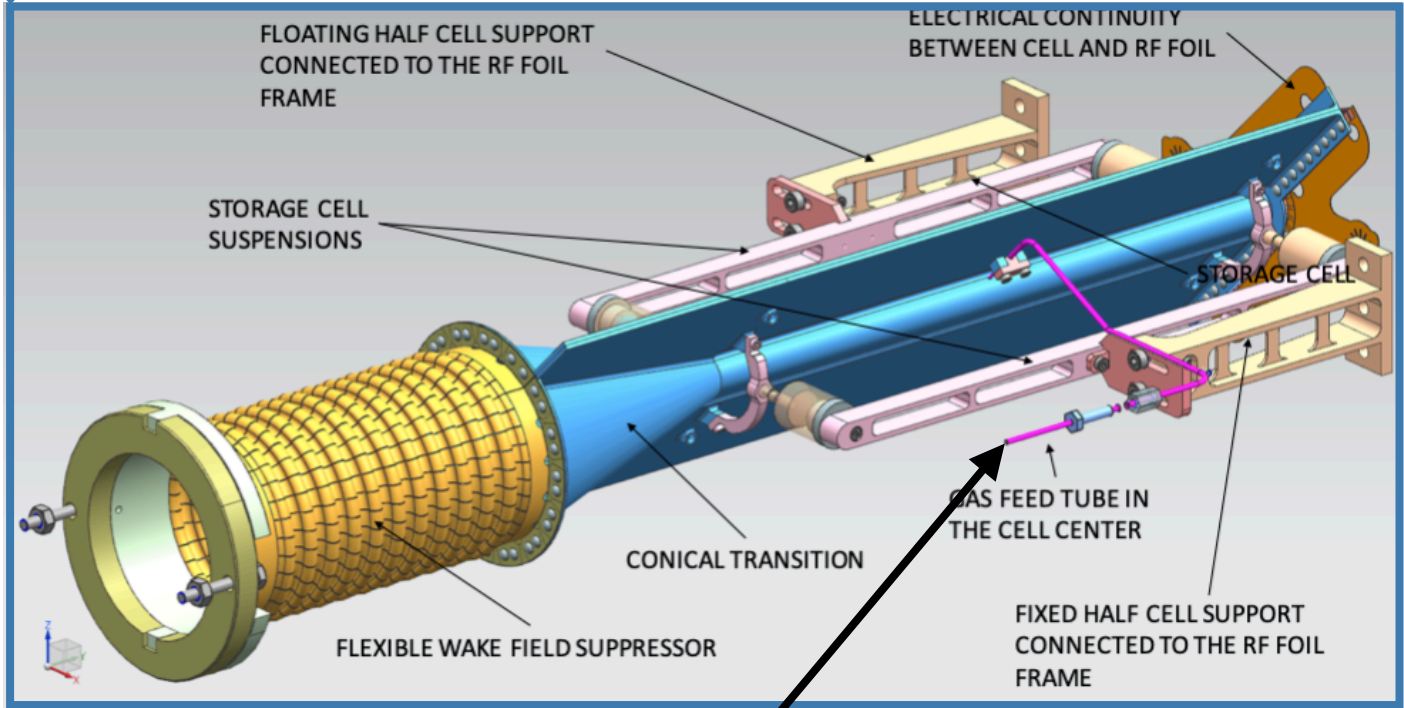
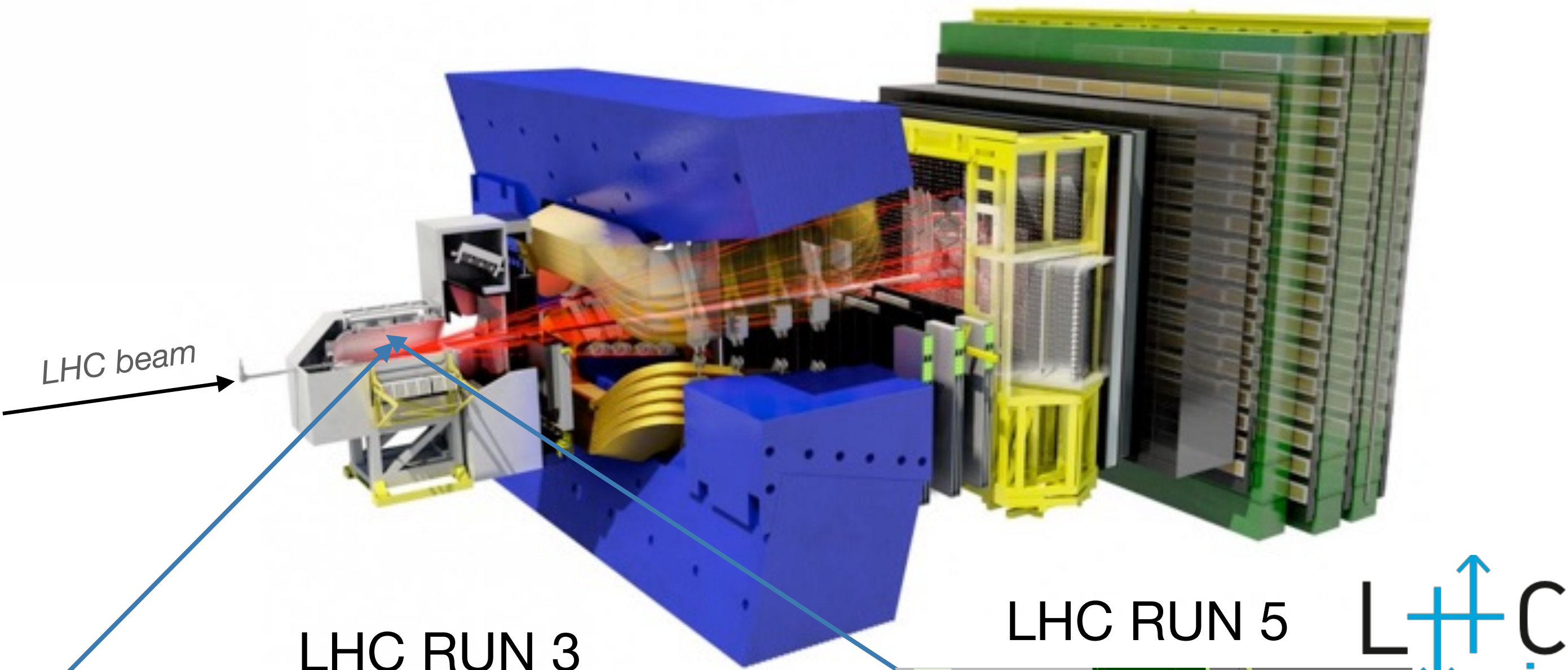


inject gas: He, Ne, Ar, and H₂, D₂

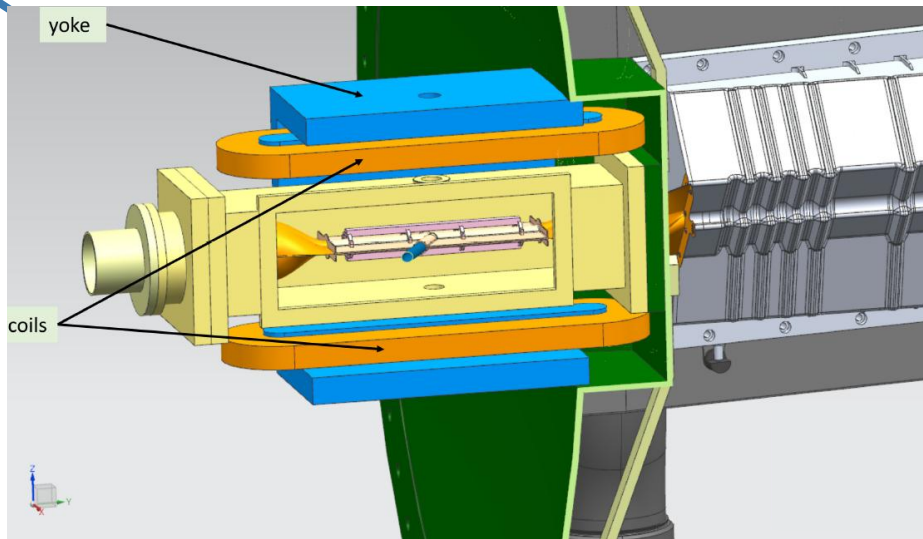


Access to **high x**

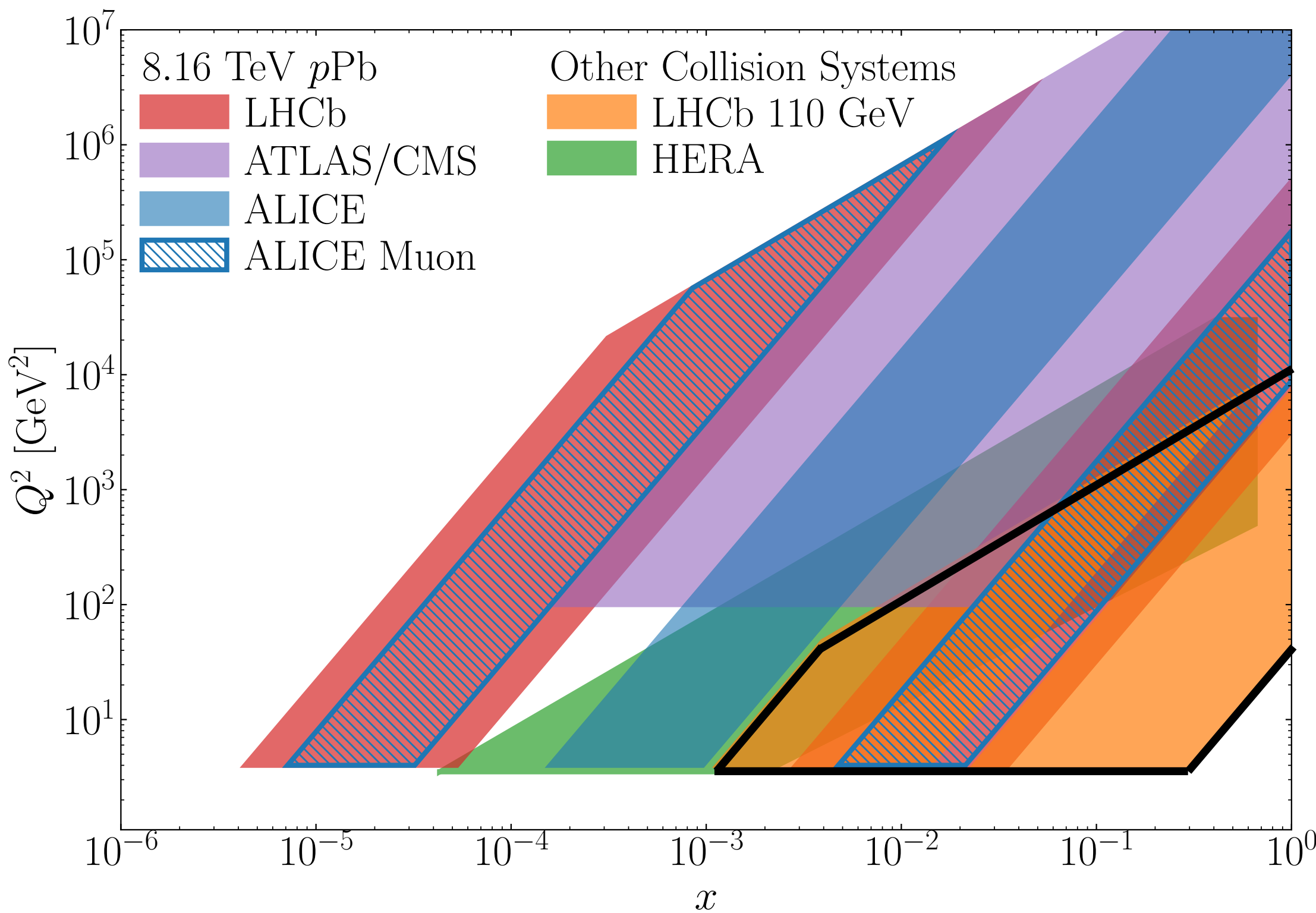
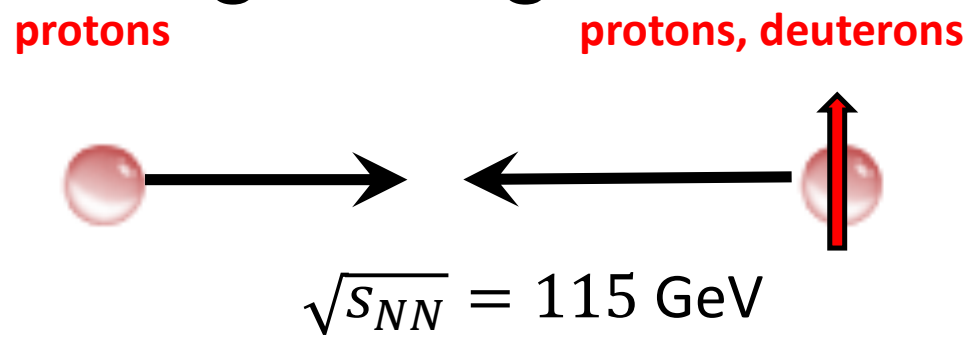
Fixed target at LHCb



inject gas: He, Ne, Ar, and H₂, D₂



transversely polarised
gas target



Access to **high x**