Synergies between UPCs at the LHC and the EIC

AdT

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ePIC and EIC Physics Readiness Workshop
Cosenza, Italy
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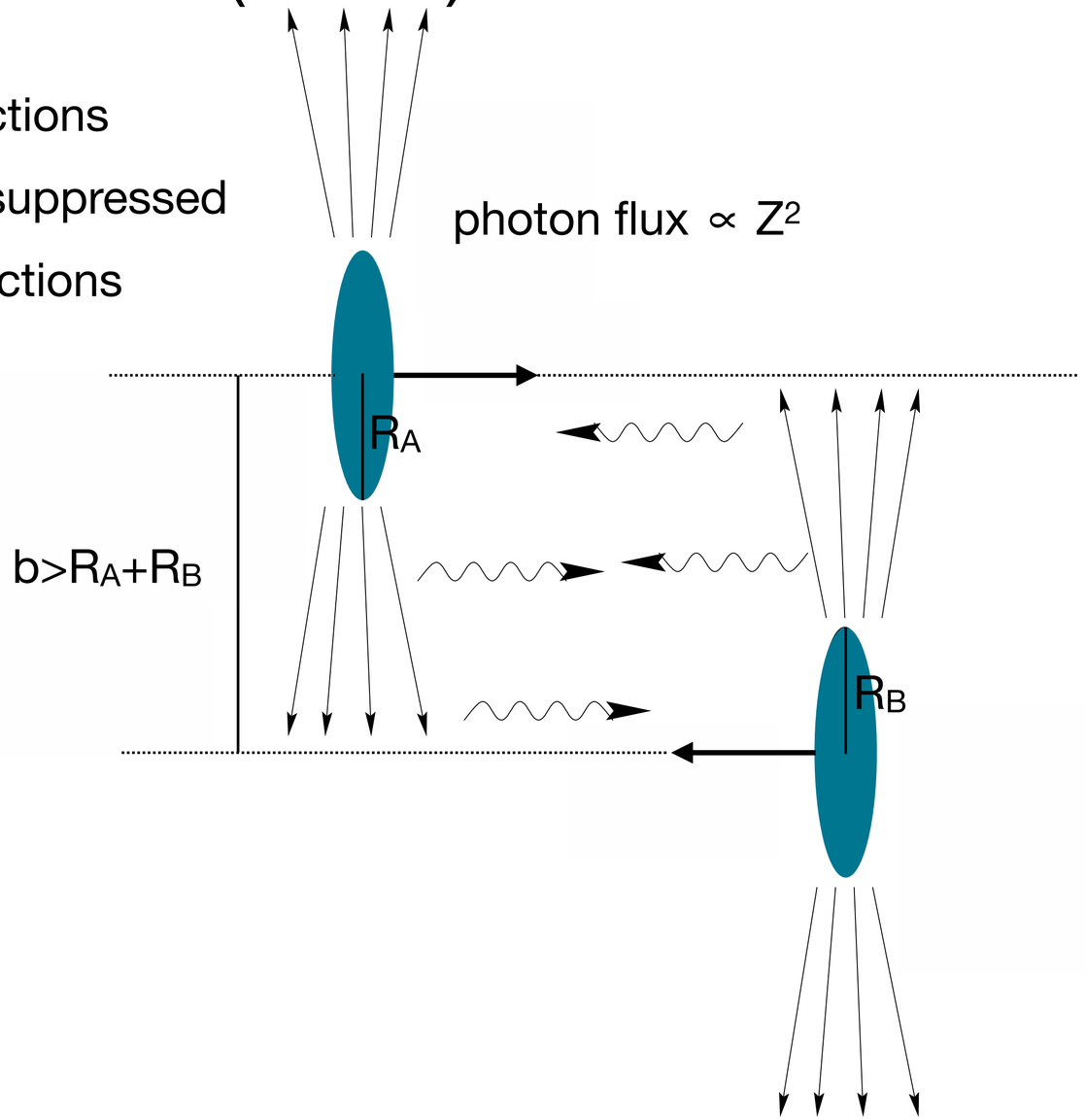
Ultra-peripheral collisions (UPCs)

large–impact-parameter interactions

hadronic interactions strongly suppressed

instead: electromagnetic interactions



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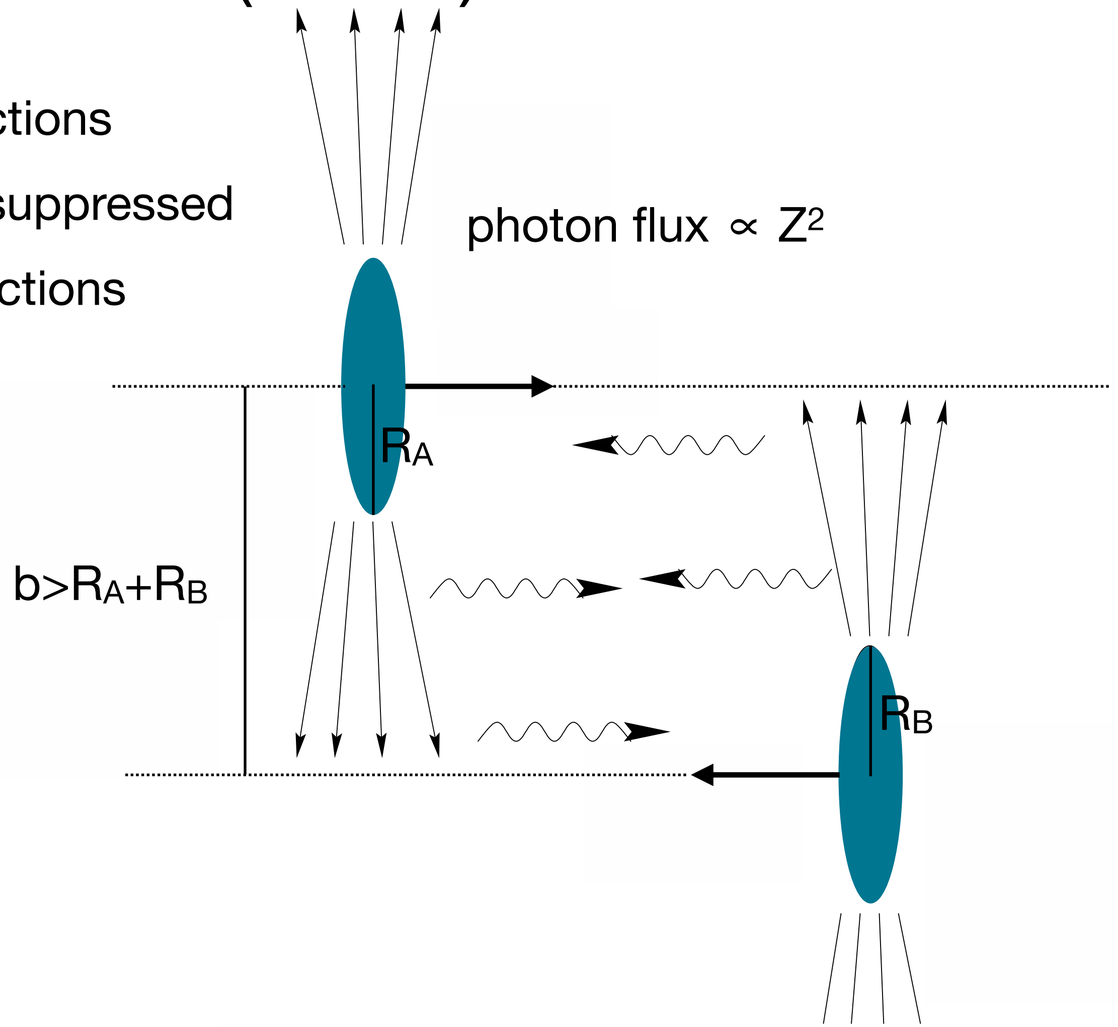


photon virtuality $Q^2 < \left(\frac{\hbar c}{R_A}\right)^2$

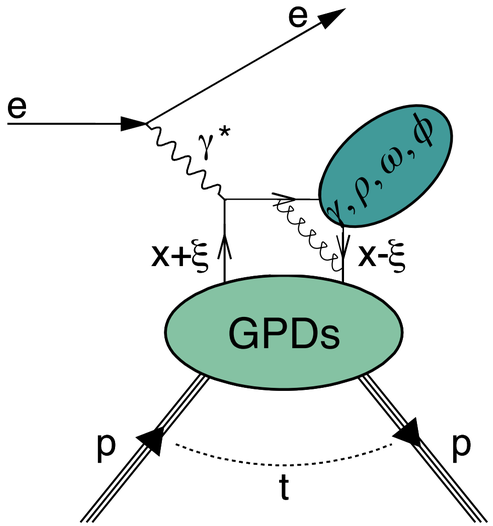
→ quasi-real photons

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

System	$\sqrt{s_{AB}}$	E_A	E_B	(a) $\gamma_{A\leftrightarrow B}$	(b) $E_{\gamma Max}$	(c) $E^{rest}_{\gamma Max}$	(d) $W^{max}_{\gamma p}$
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

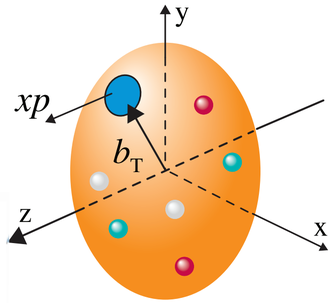
table: K. Lynch

Exclusive processes



Hard exclusive meson production

Hard scale=large Q^2



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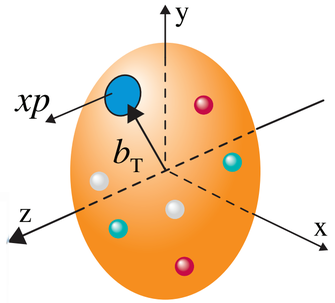

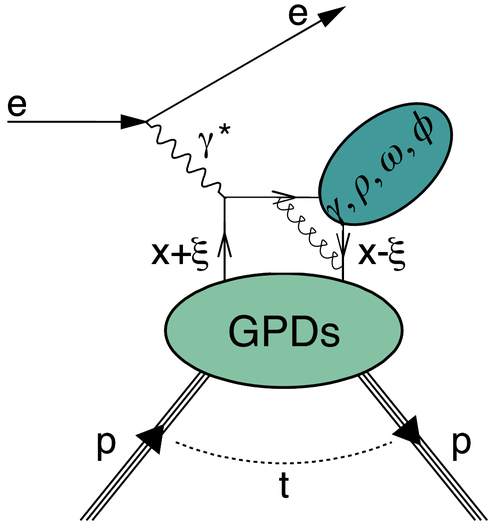

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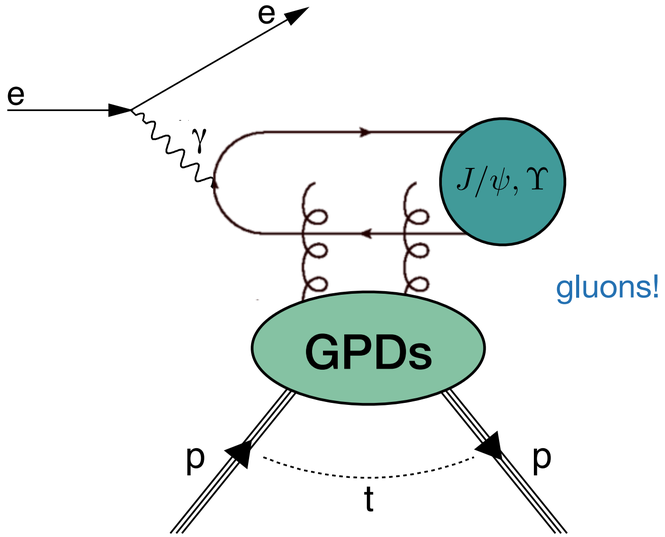

gluons!

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

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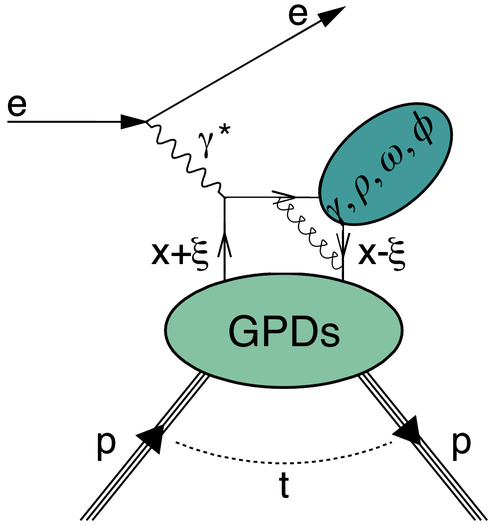

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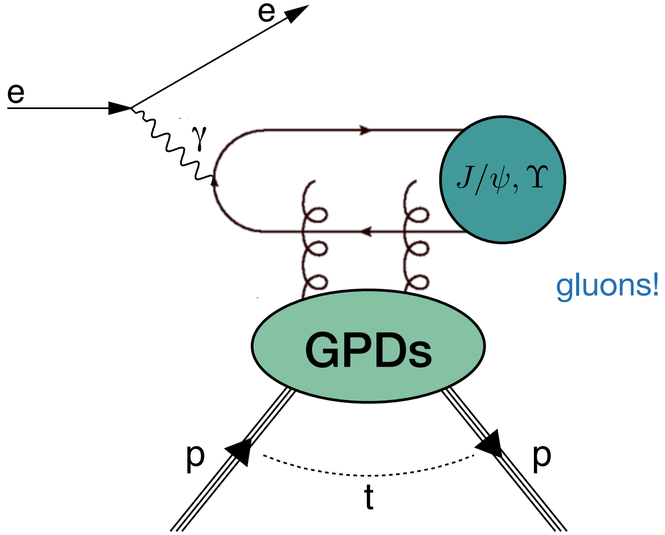

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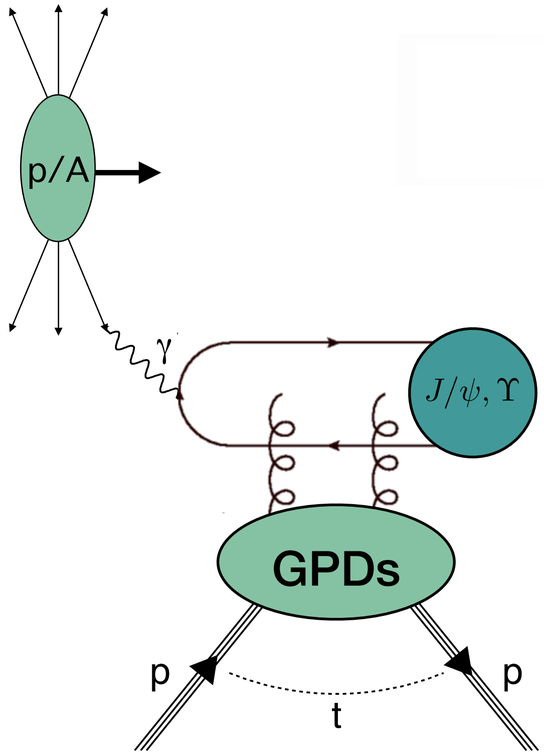

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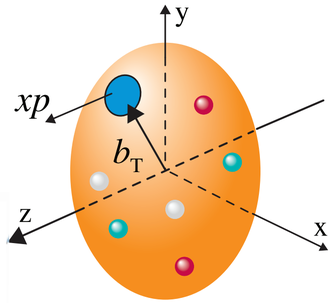

Exclusive processes at the LHC: kinematic coverage

- 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

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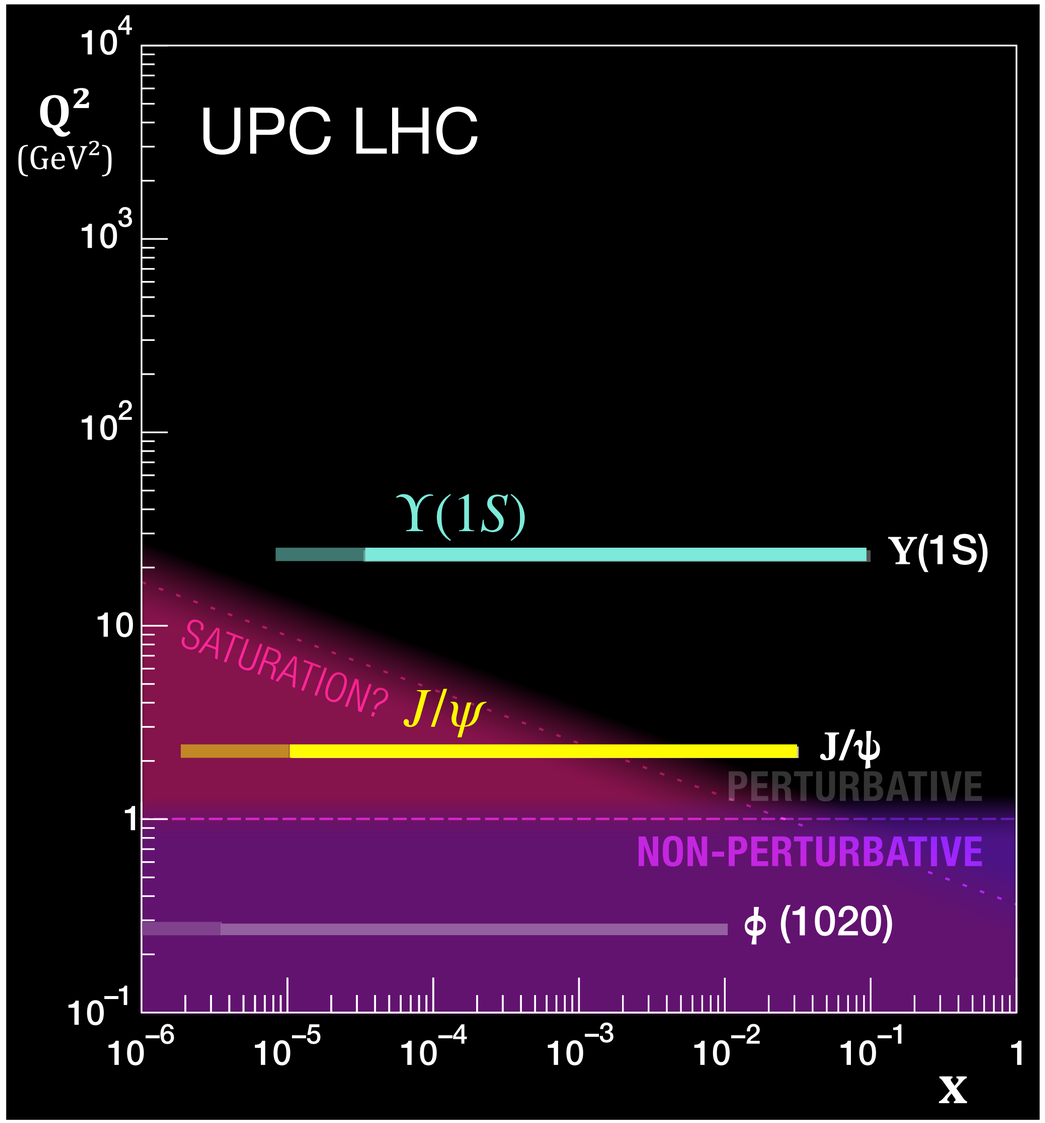

Figure adapted from Jordan Lang | Quarkonia as Tools 2026 | 6 January 2026

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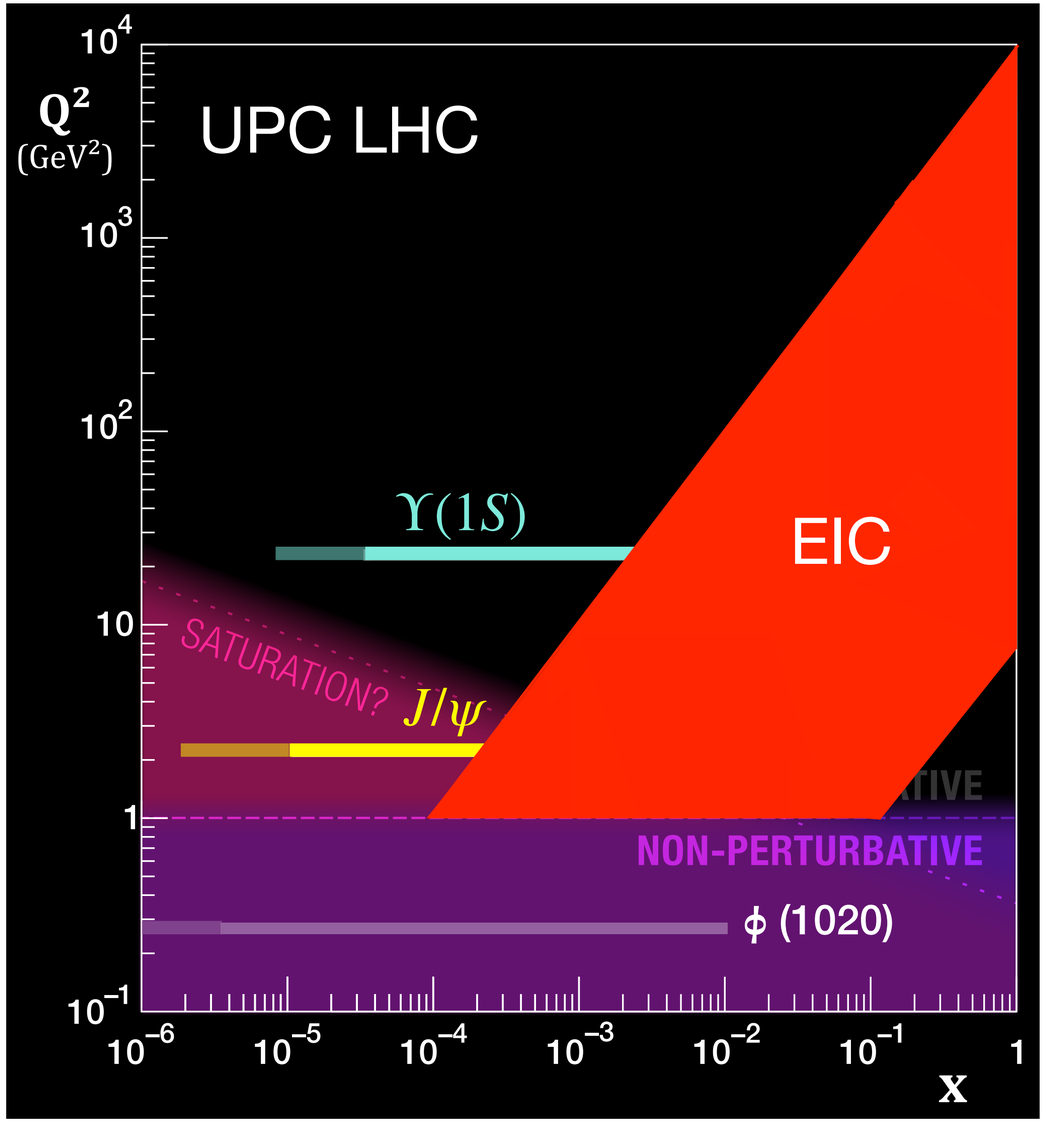

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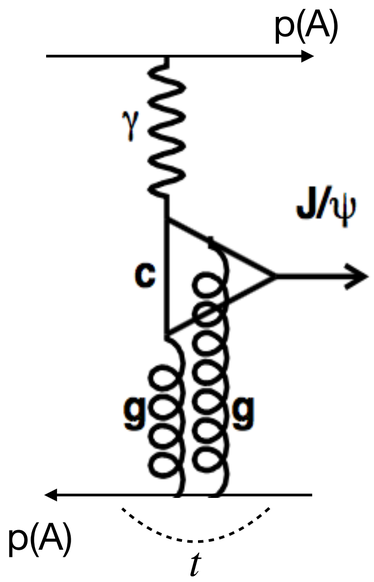
Experimental signature



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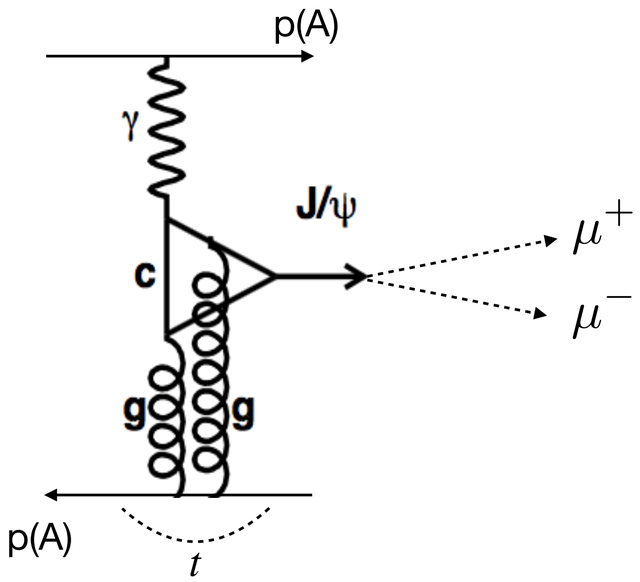

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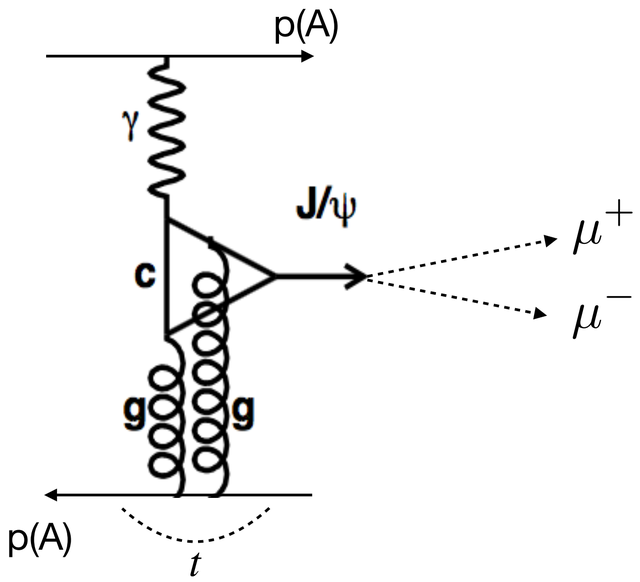

in detector

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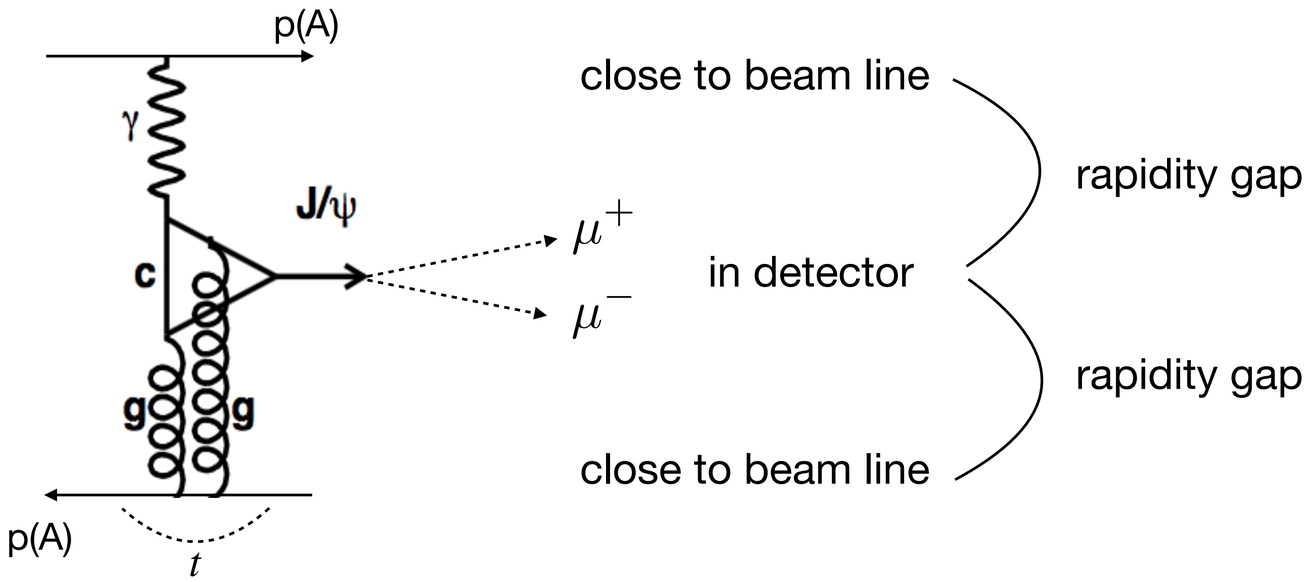

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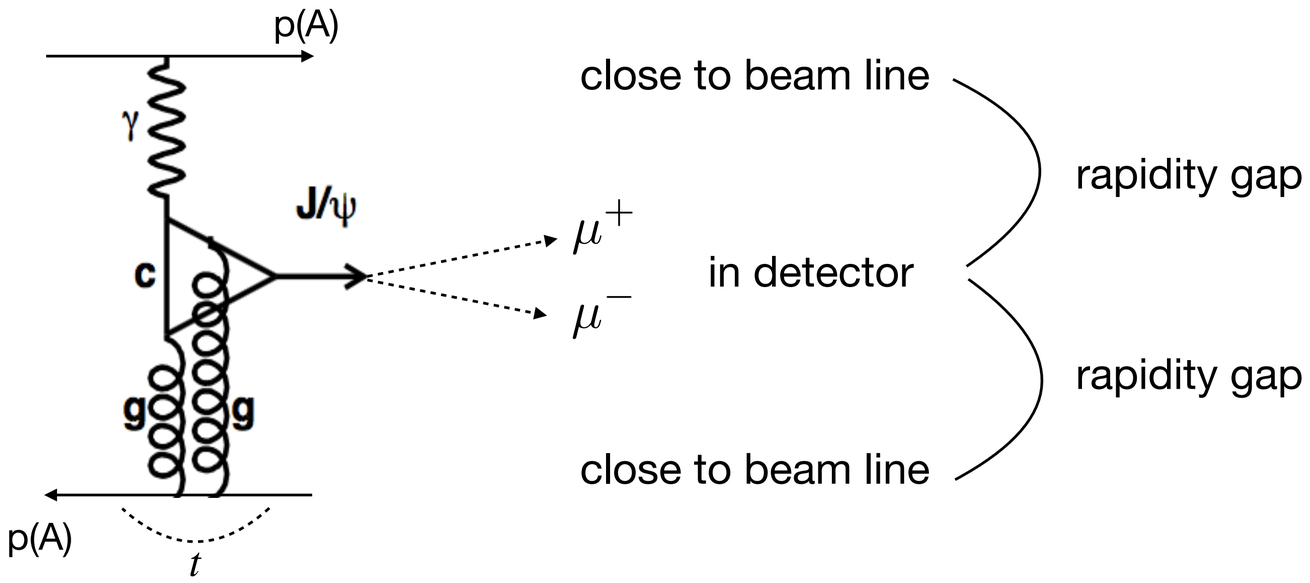


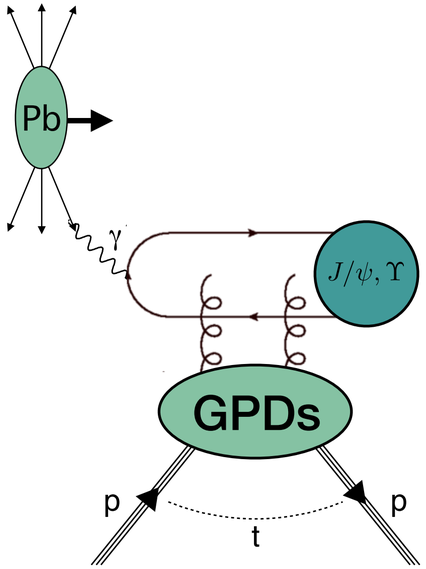
No detection of beam particles

- 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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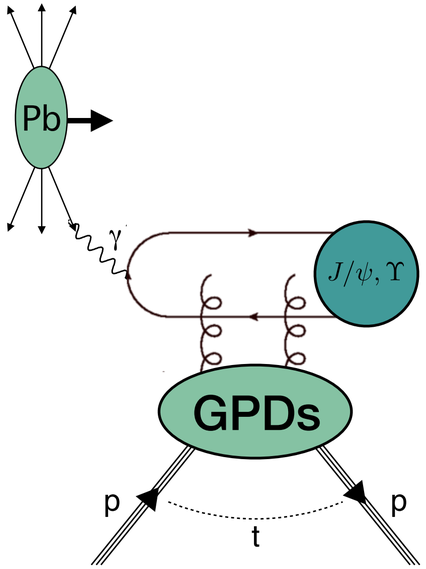

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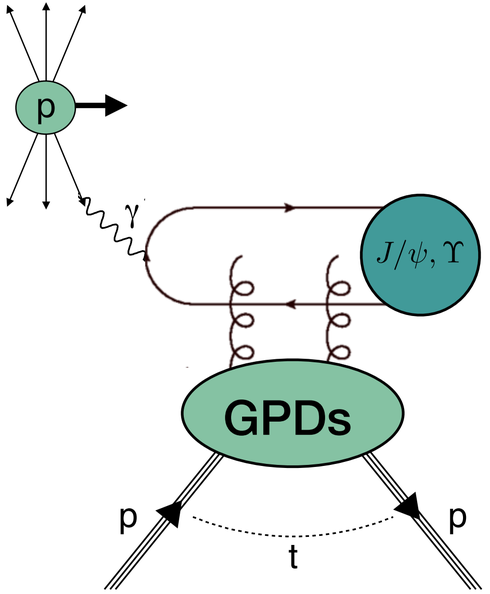


pp: ambiguity in ID of photon emitter

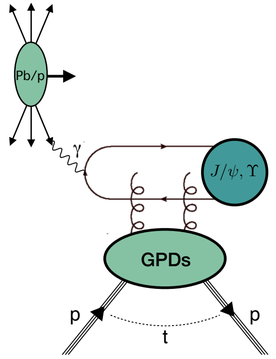
- r = gap survival factor
- $k_{\pm} = \frac{M_{\psi}}{2} e^{\pm y}$ = photon energy
- $\frac{dn}{dk_{\pm}}$ = photon flux
- $W_{\pm}^2 = 2k_{\pm}\sqrt{s}$ = γp invariant mass

relation pp and γp cross section:

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

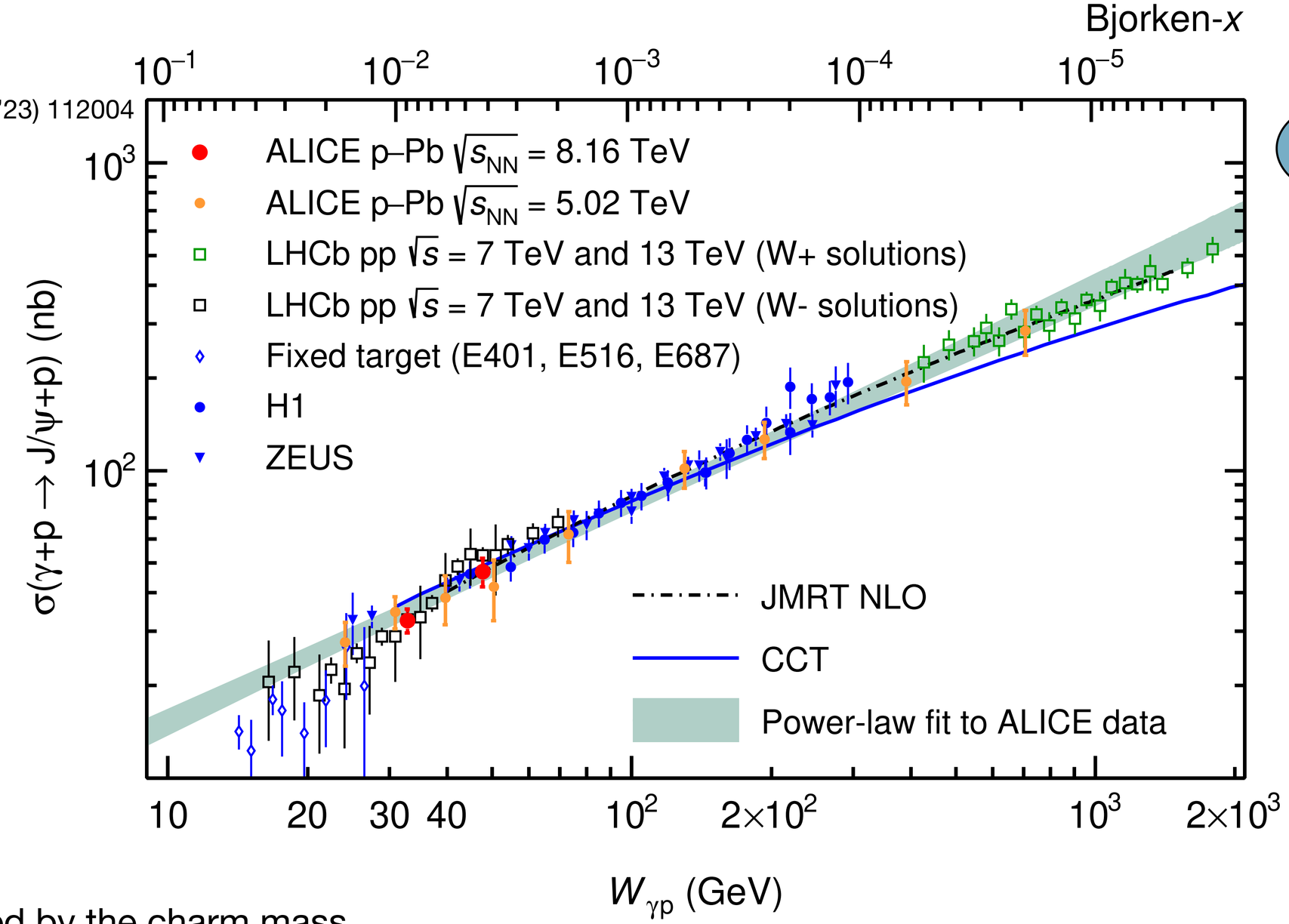
LHCb used HERA data for low-E_γ (W_-) contribution.

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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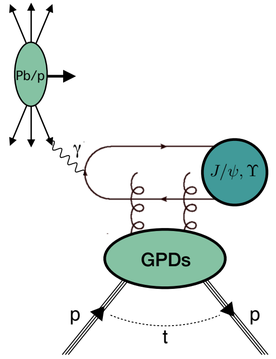

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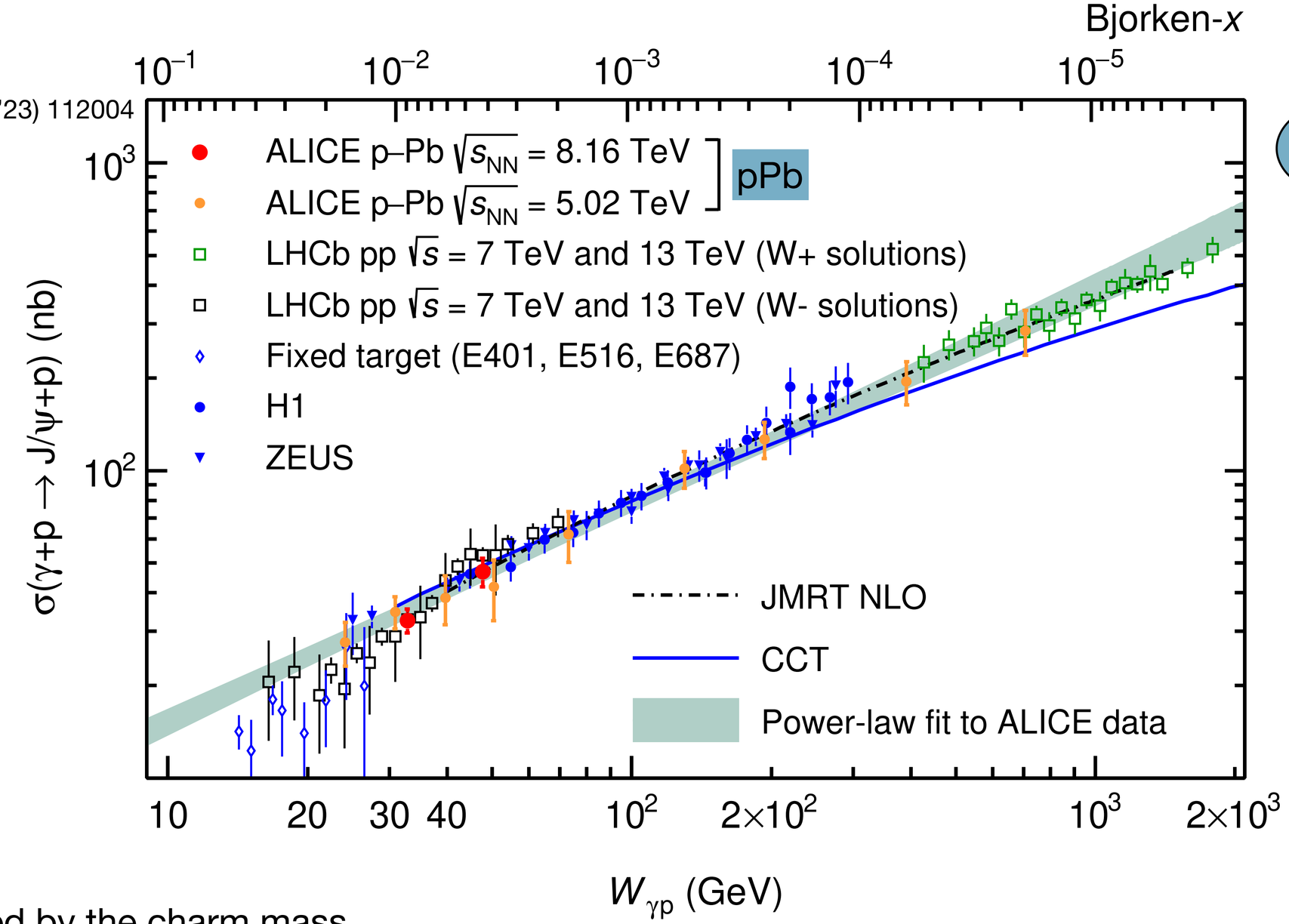

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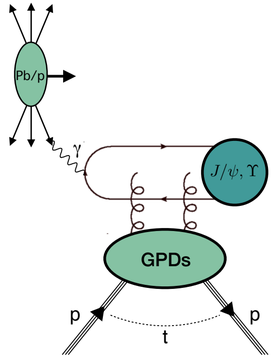

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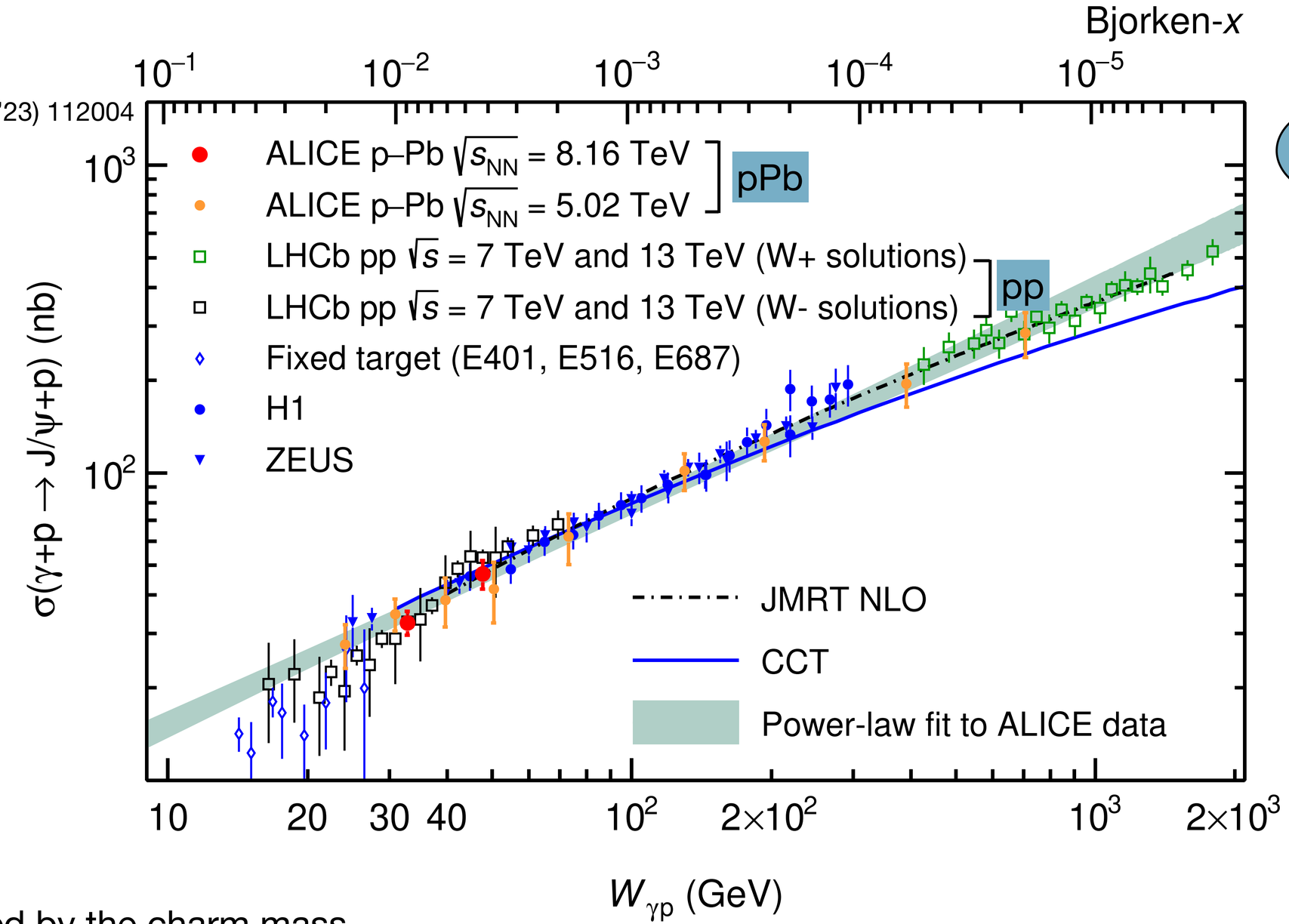

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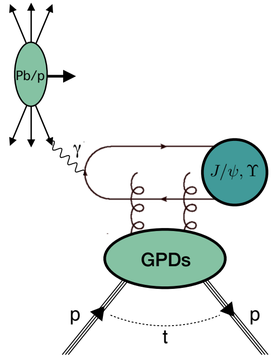

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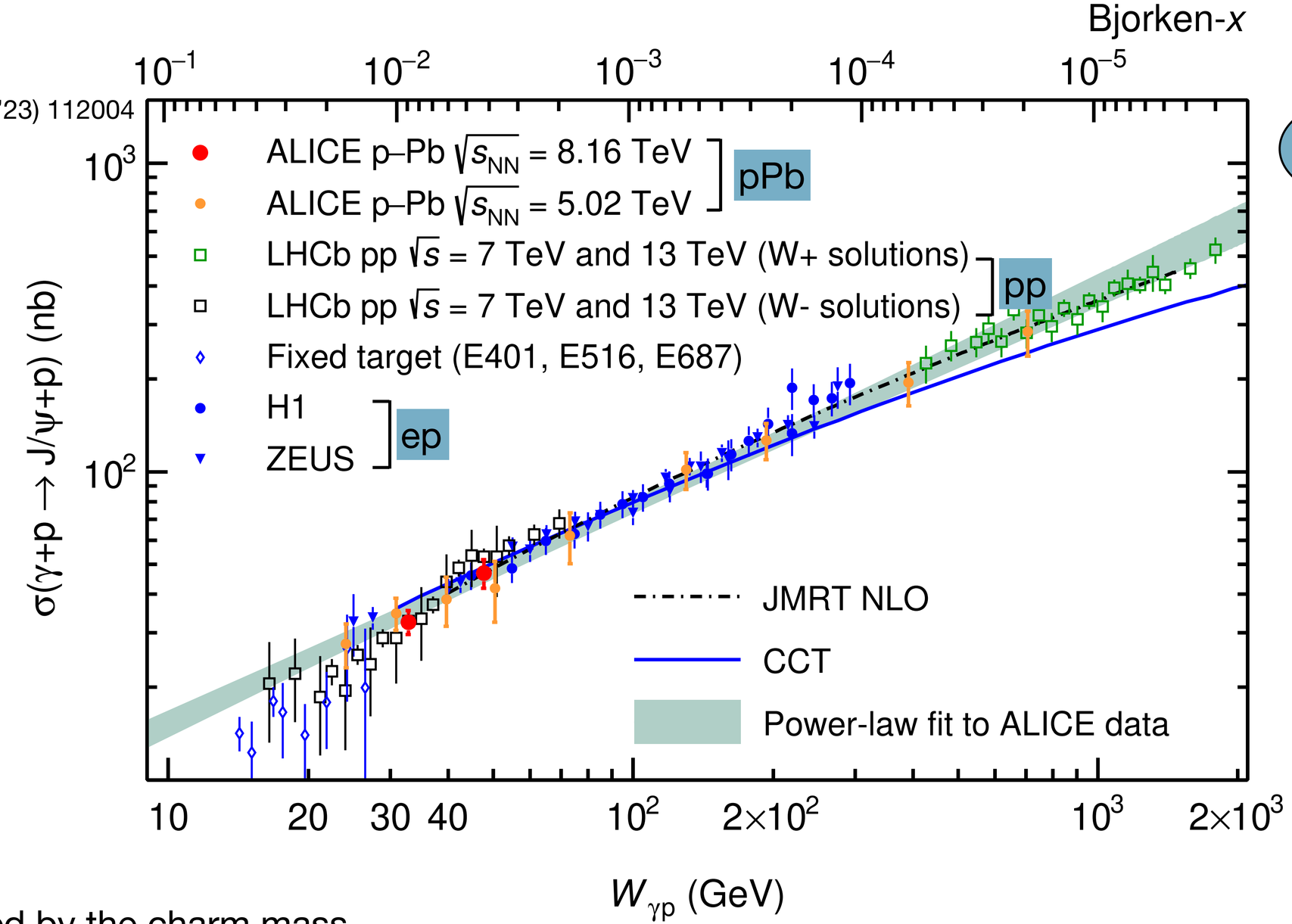

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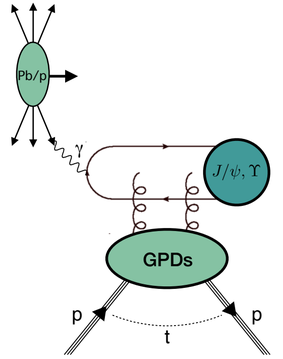

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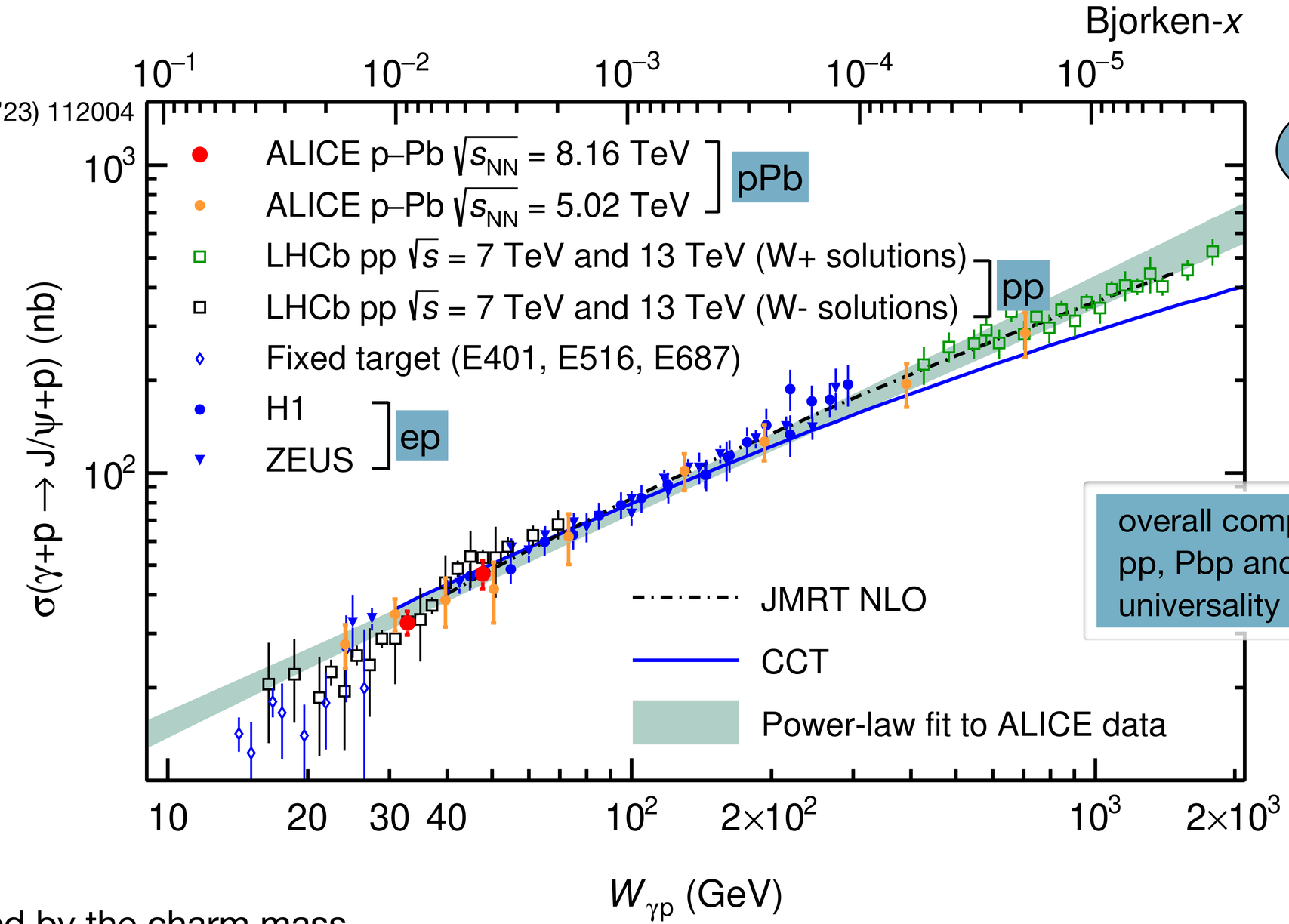

overall compatibility between pp, Pbp and ep data: hint of universality of underlying physics

Hard scale: fixed by the charm mass

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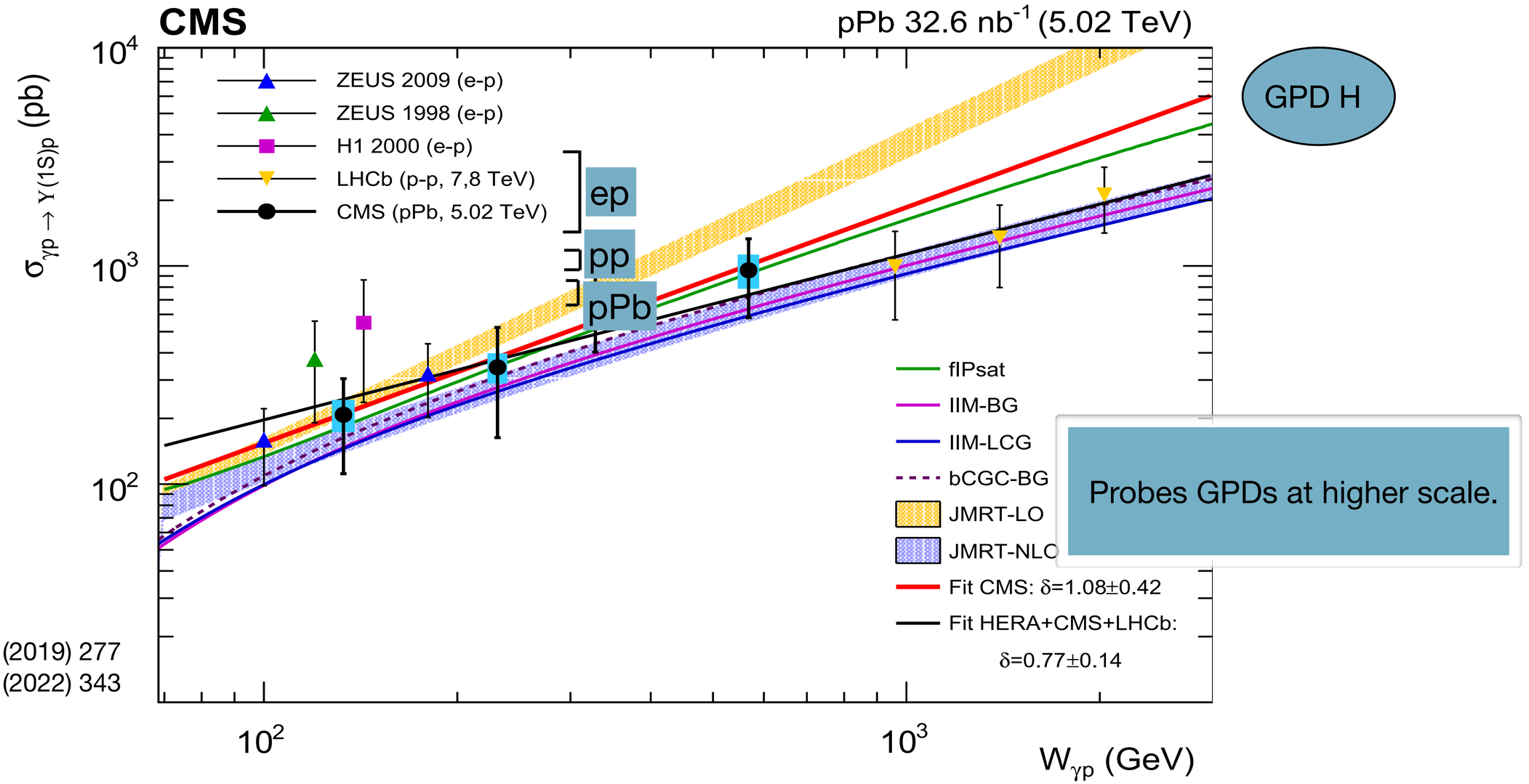
Υ photoproduction cross section



GPD H

Probes GPDs at higher scale.

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

Polarisation and angles

- 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
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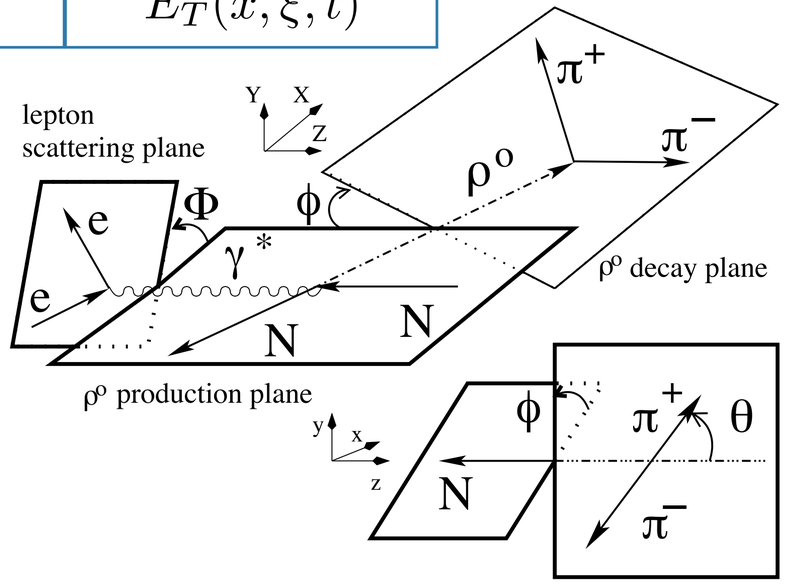
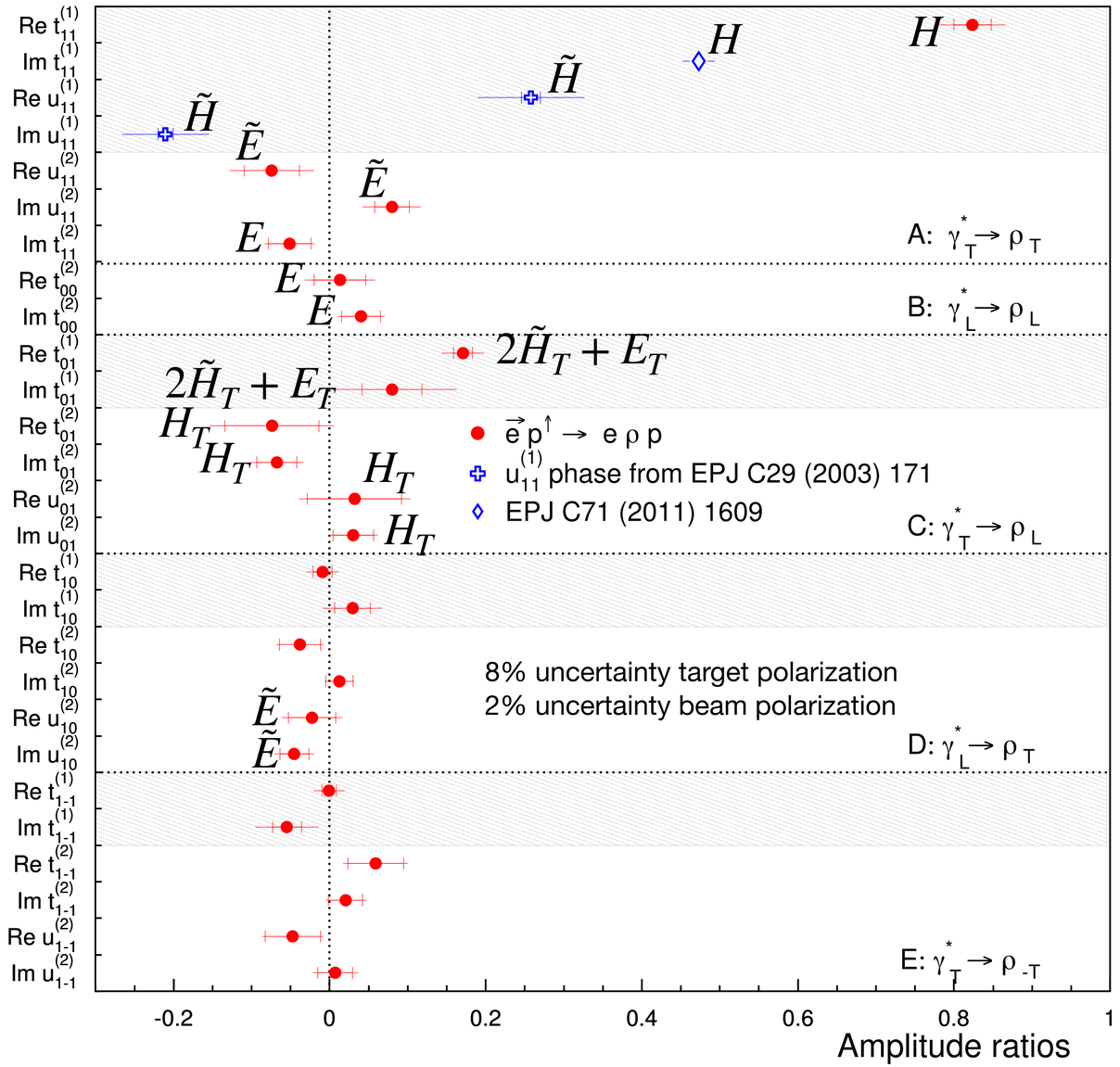


Exclusive ρ on transversely polarised p

Possible at EIC

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



via unpolarised target | via transversely polarised target

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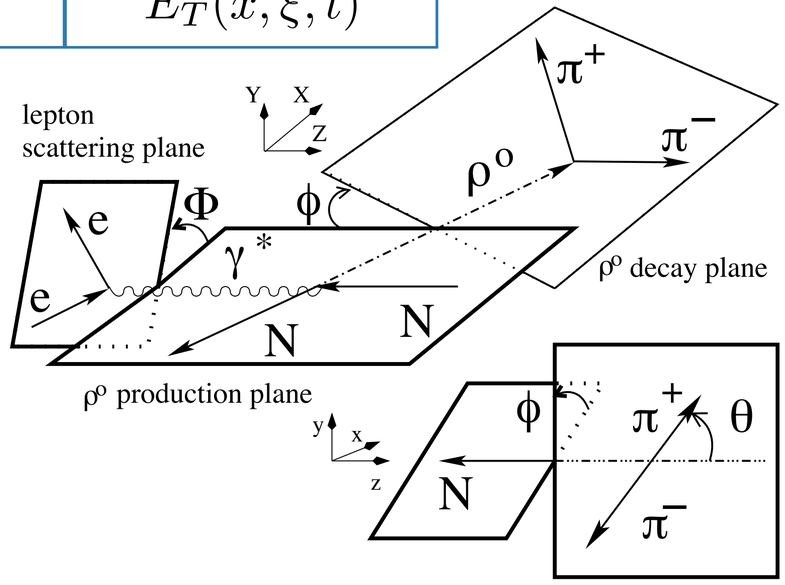

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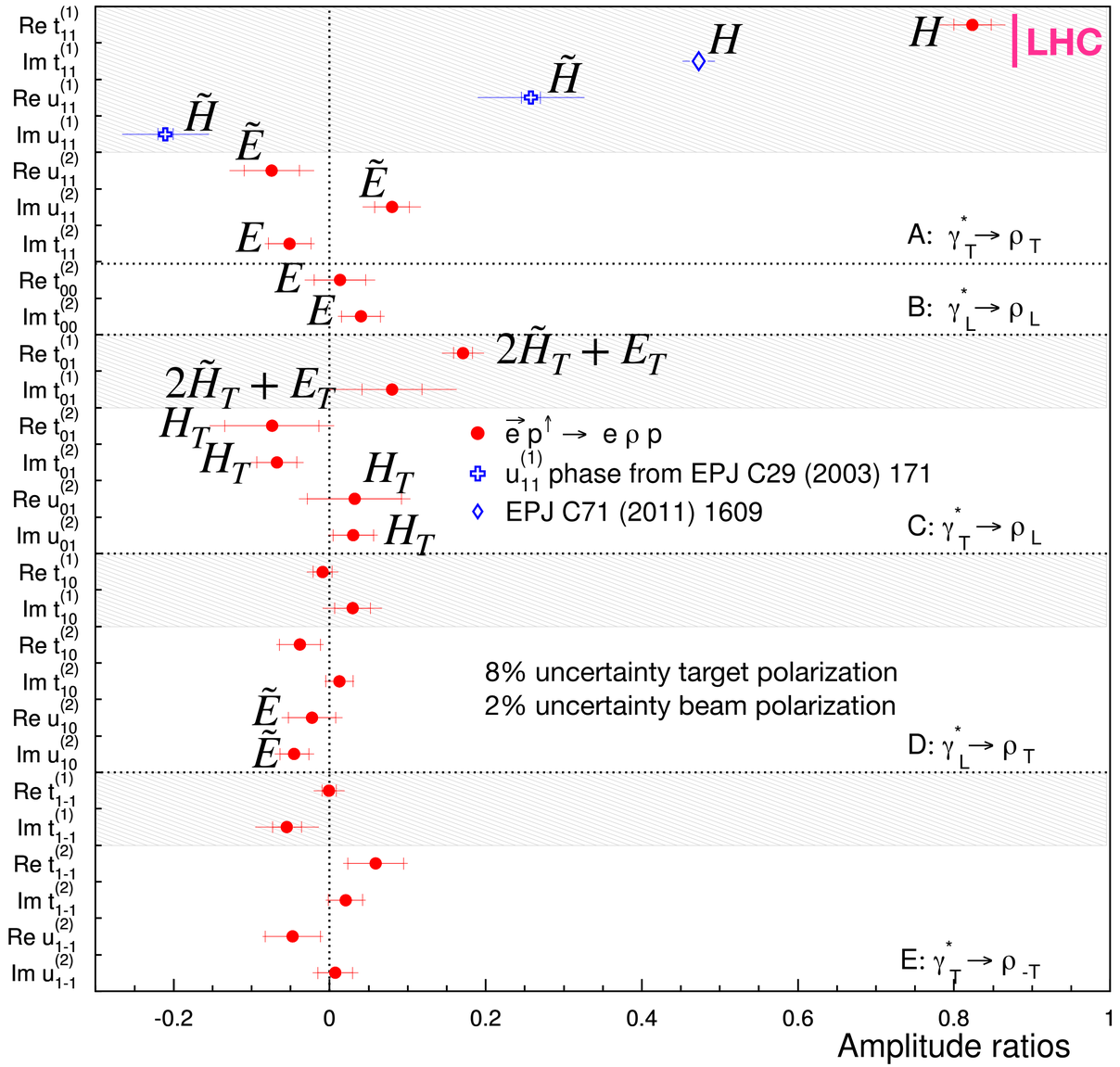

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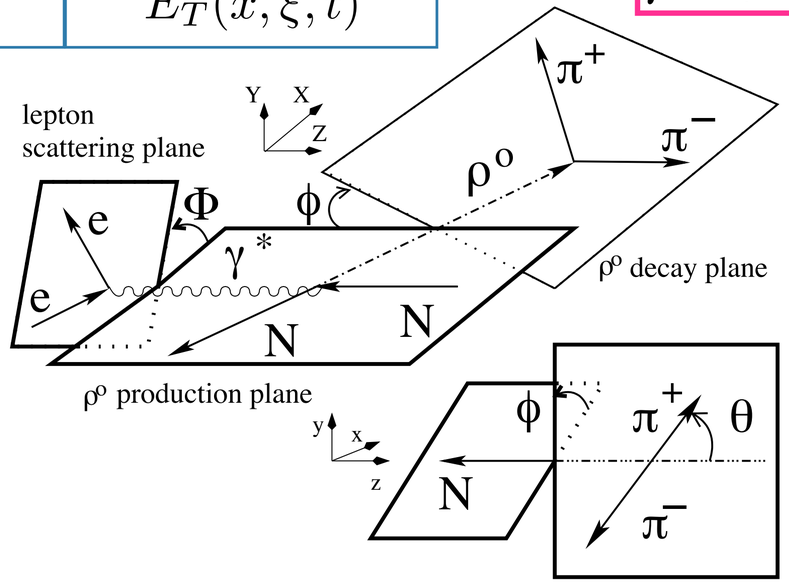

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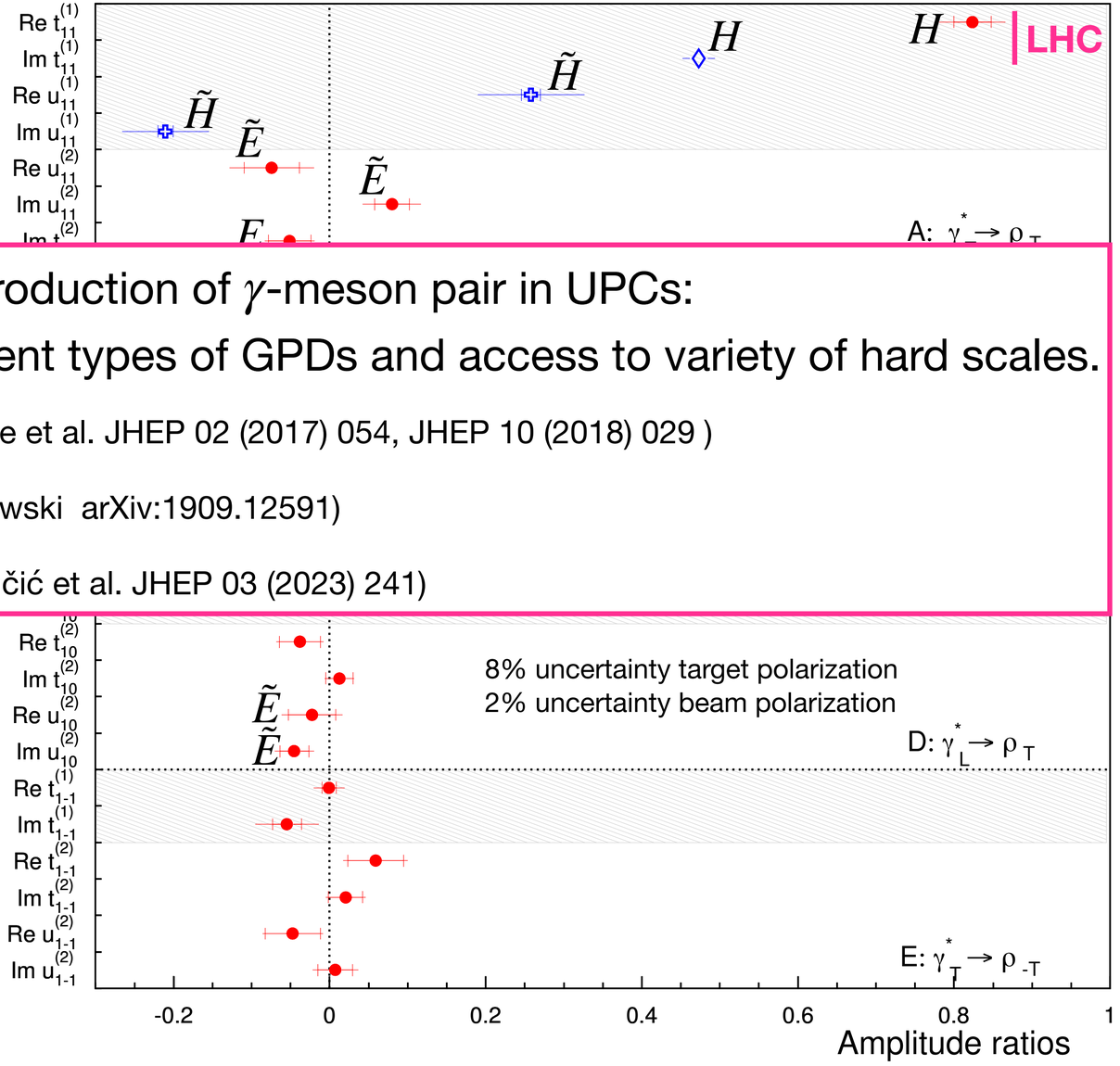

Exclusive production of γ-meson pair in UPCs:

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)

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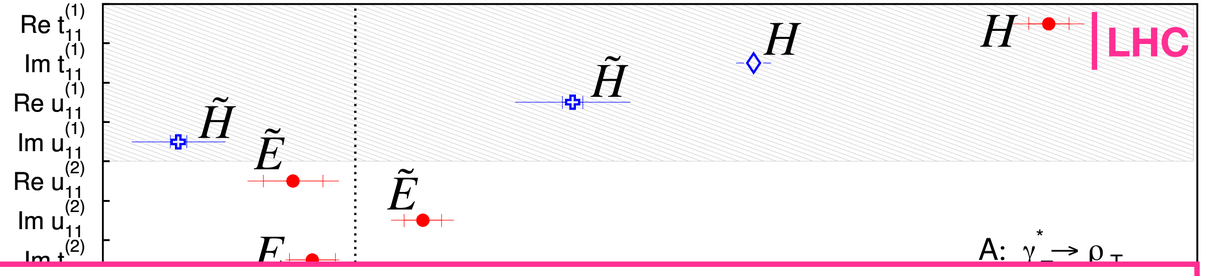

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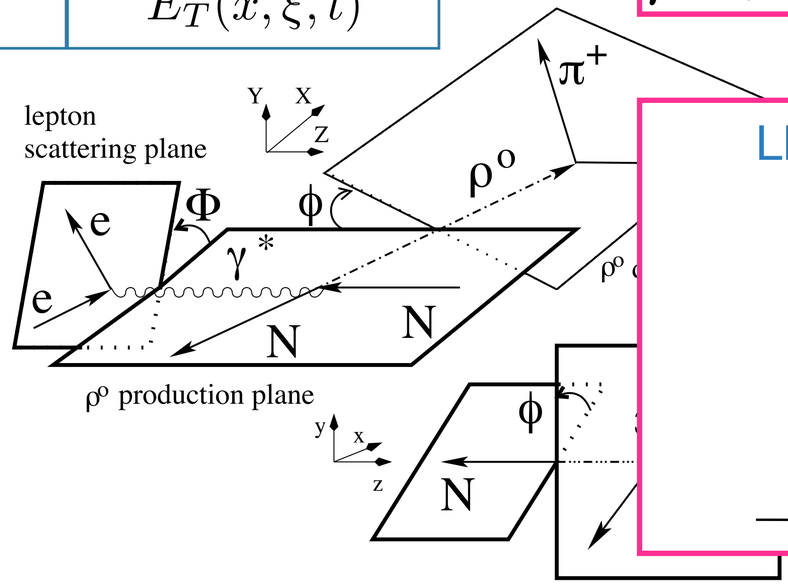
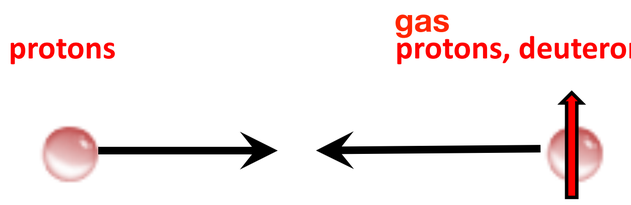


LHCSPIN: transversely polarised gas target



$\sqrt{s_{NN}} = 115$ GeV

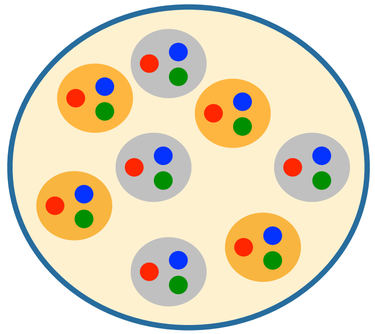
⟶ access to spin-dependent GPDs at the LHC at large x_B

Ultra-peripheral collisions in PbPb

What object are we probing?

Ultra-peripheral collisions in PbPb

What object are we probing?



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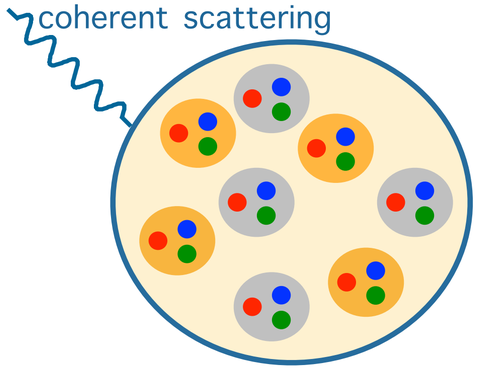
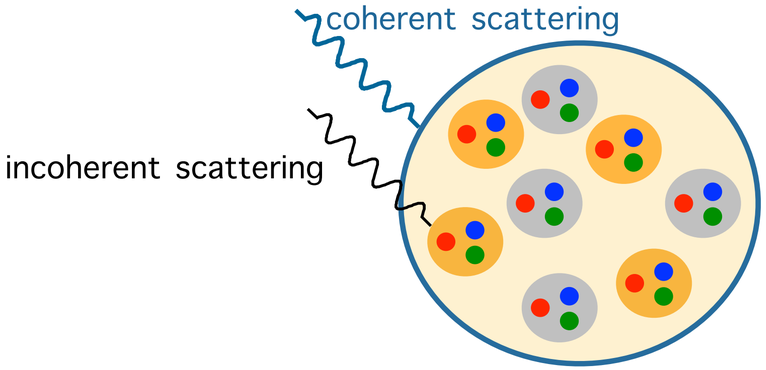


Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

Ultra-peripheral collisions in PbPb

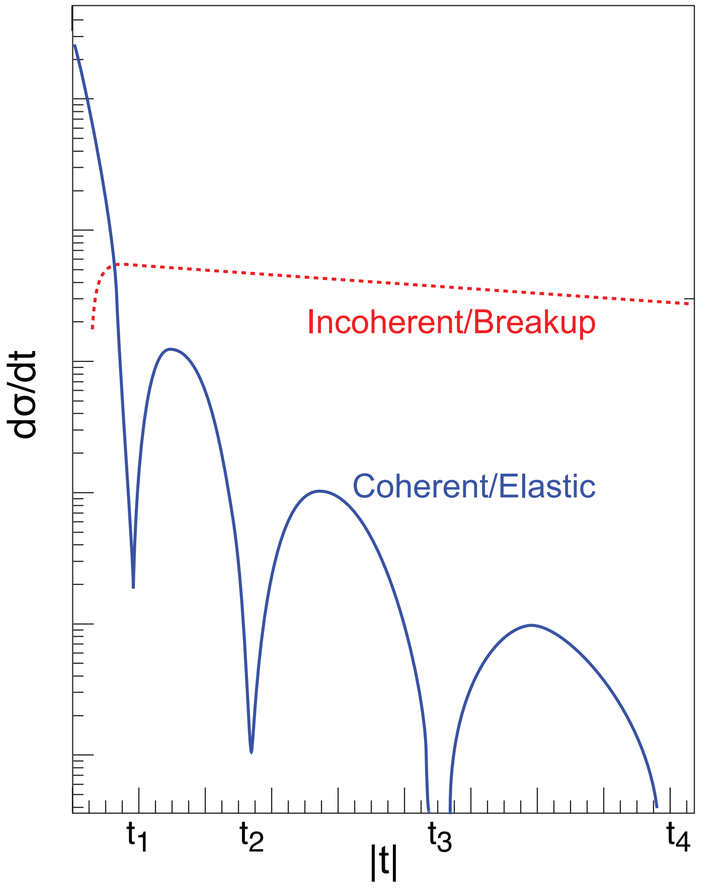
What object are we probing?



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

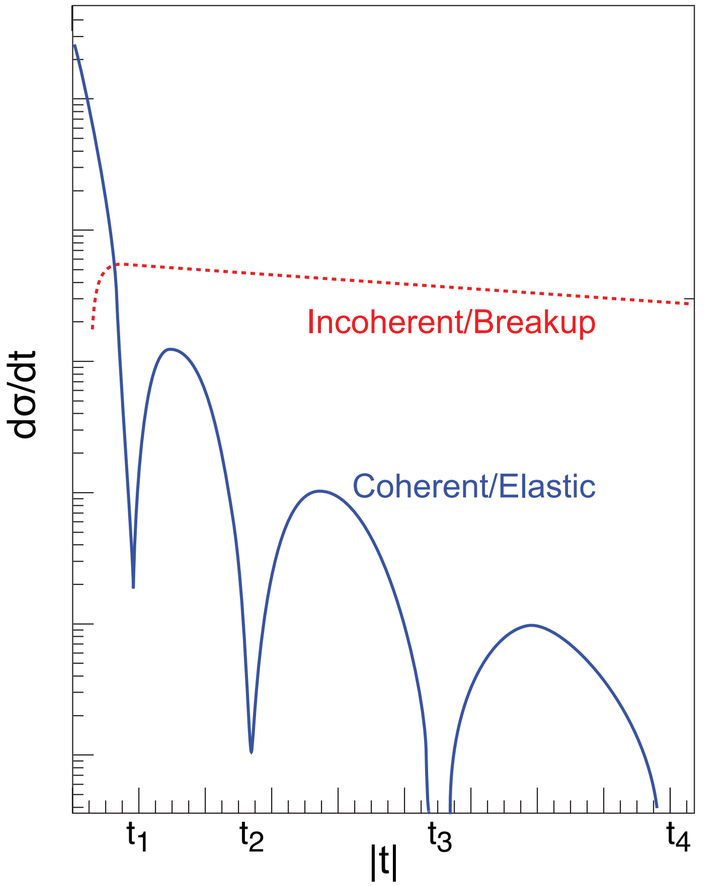
Incoherent interaction: interaction with constituents inside target.
~ target does not remain in same quantum state.
Ex.: target dissociation, excitation

Experimental important points



Experimental important points

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



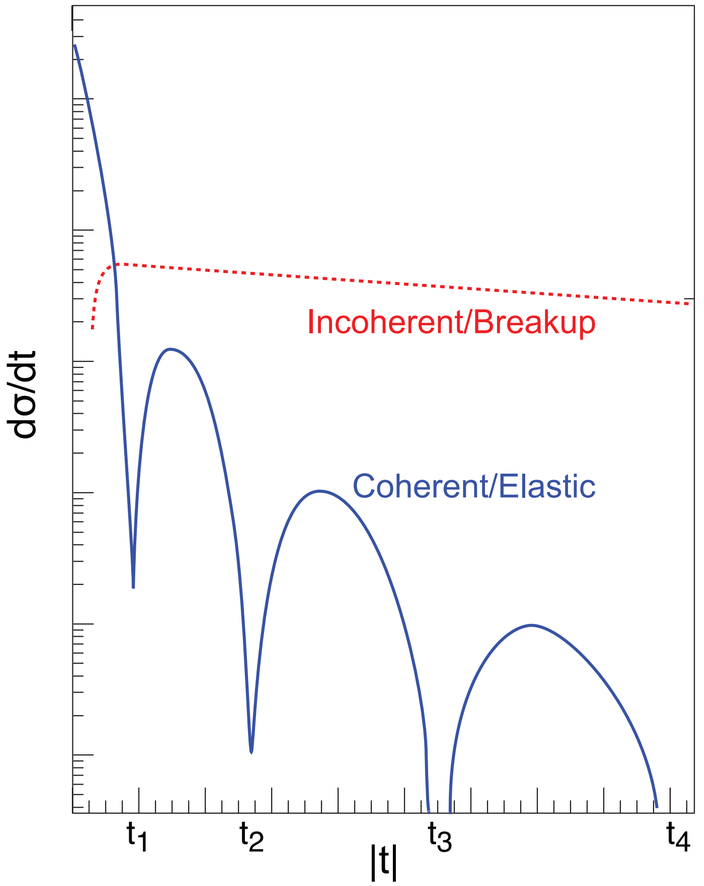
Experimental important points

- 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.
~third diffractive minimum.



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Experimentally limited by maximum transverse momentum.
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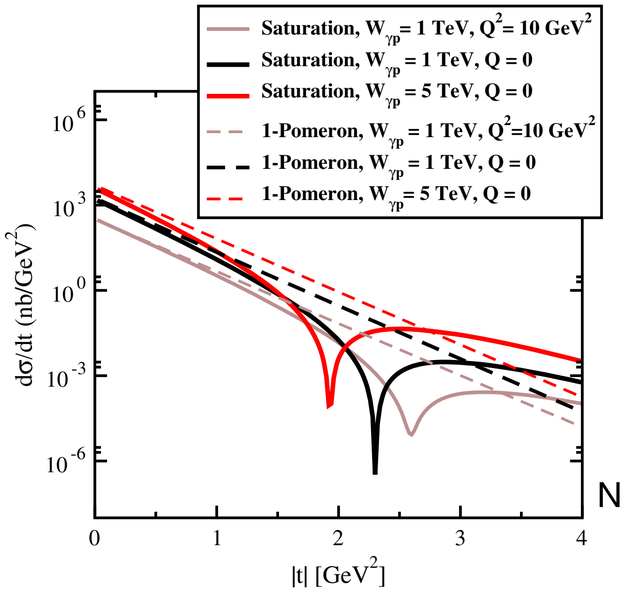
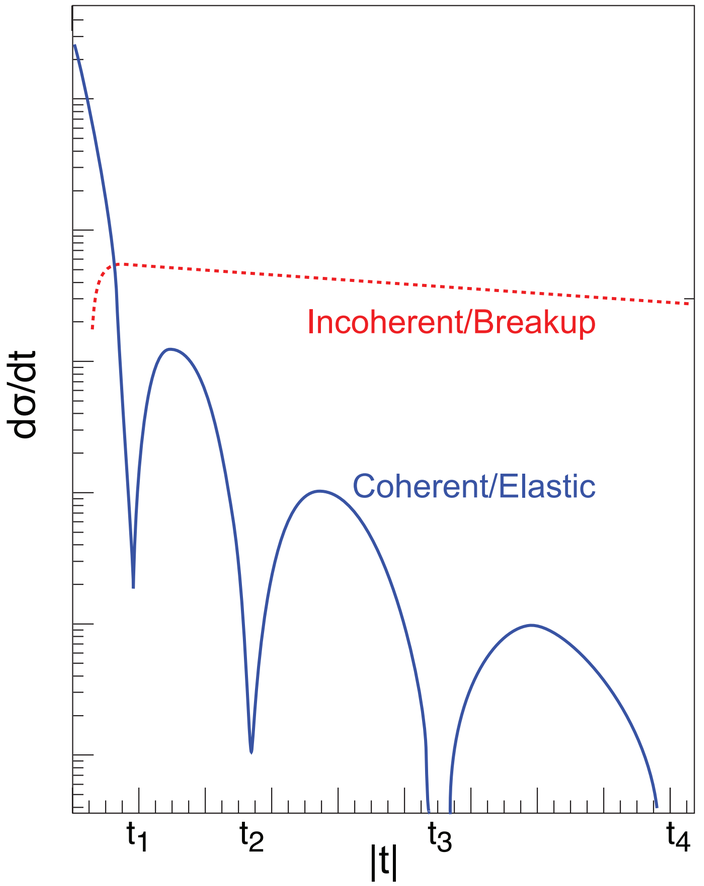
  - Saturation:

determine dip position indirectly
via slope and probe its dependence
With $W_{\gamma p}$

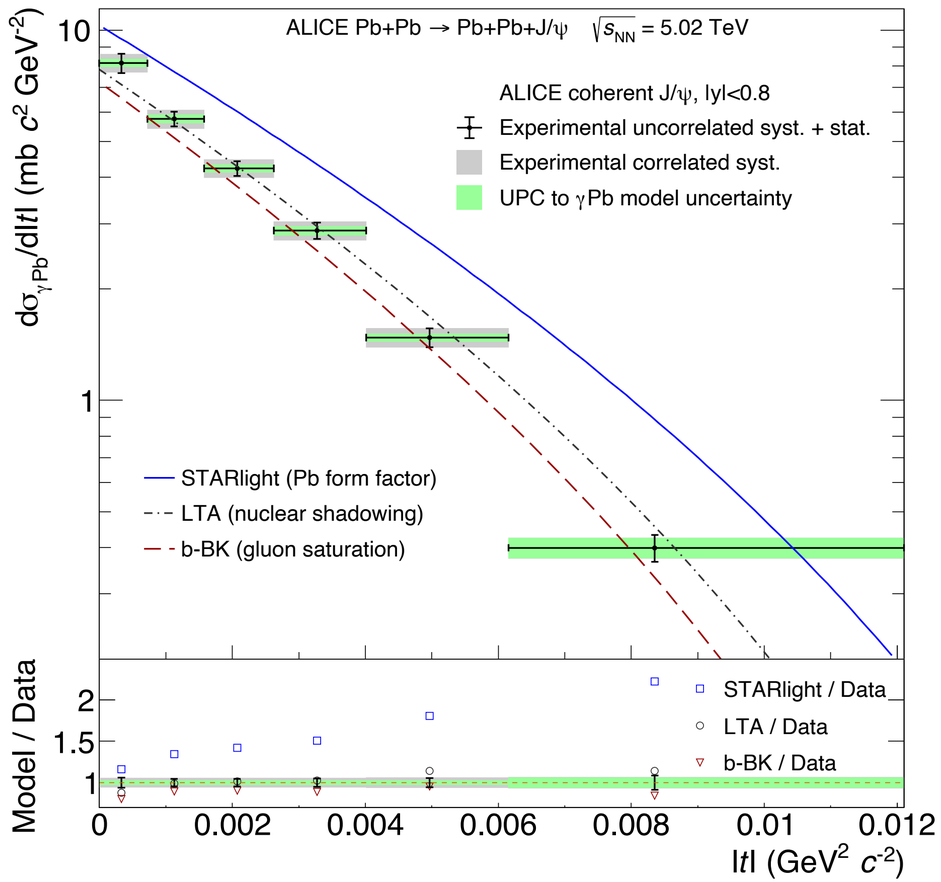




N. Armesto and A. H. Rezaeian, Phys. Rev. D **90** (2014) 054003.

Coherent production in PbPb at ALICE and at the EIC

ALICE, Phys. Lett. B **817** (2021) 136280



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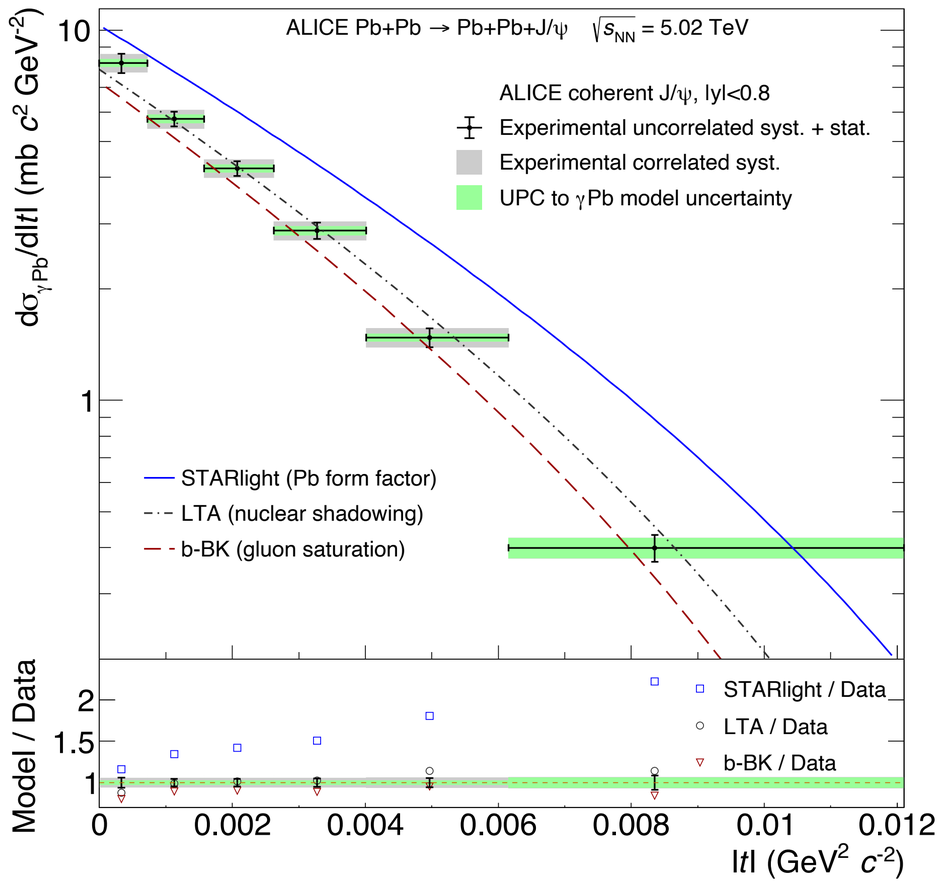
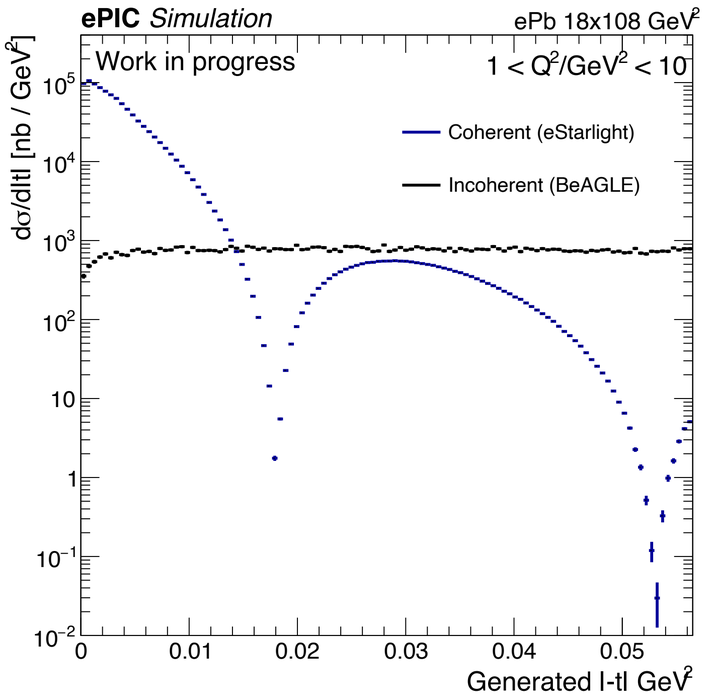
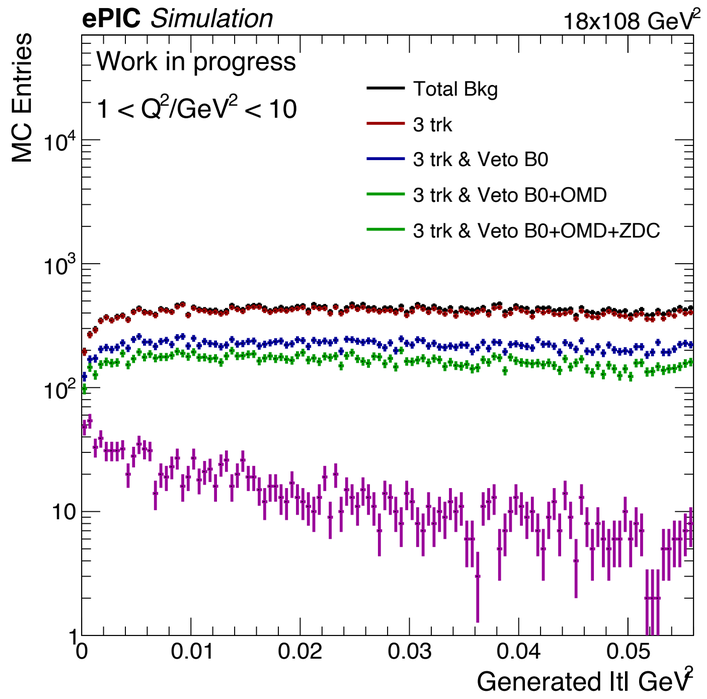
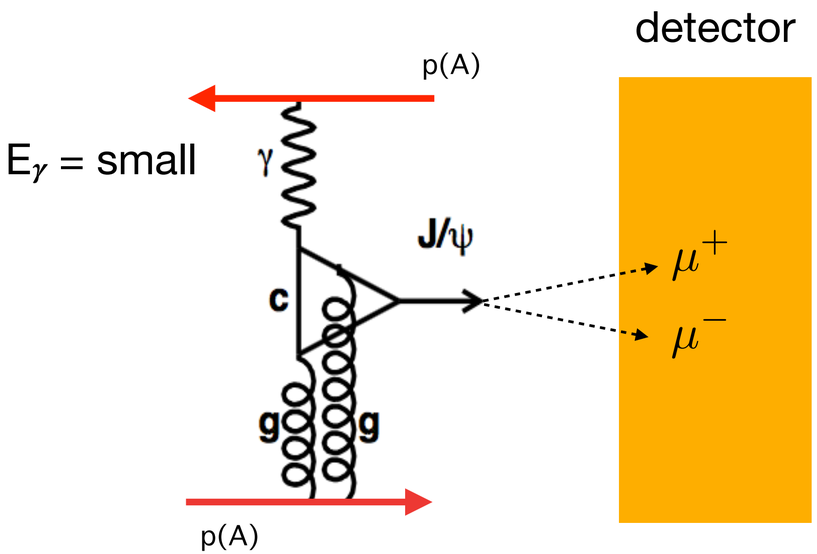


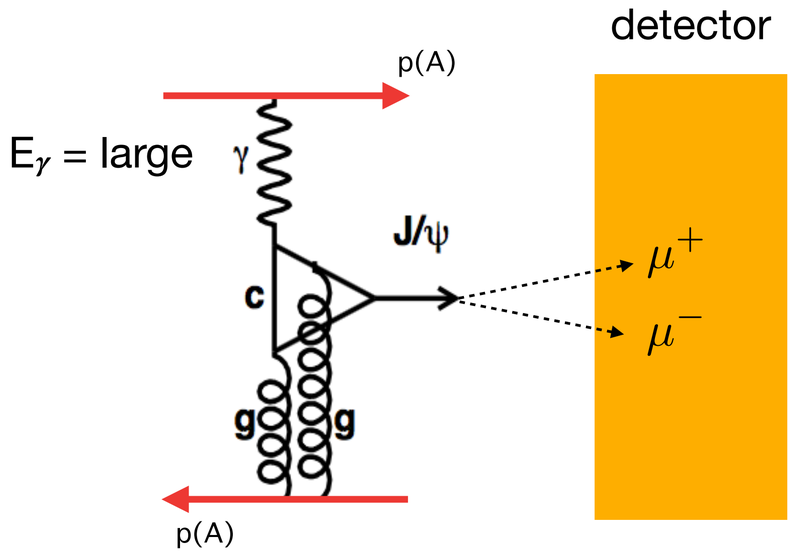




Disentangling the ambiguity on the ID of the γ emitter



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



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

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

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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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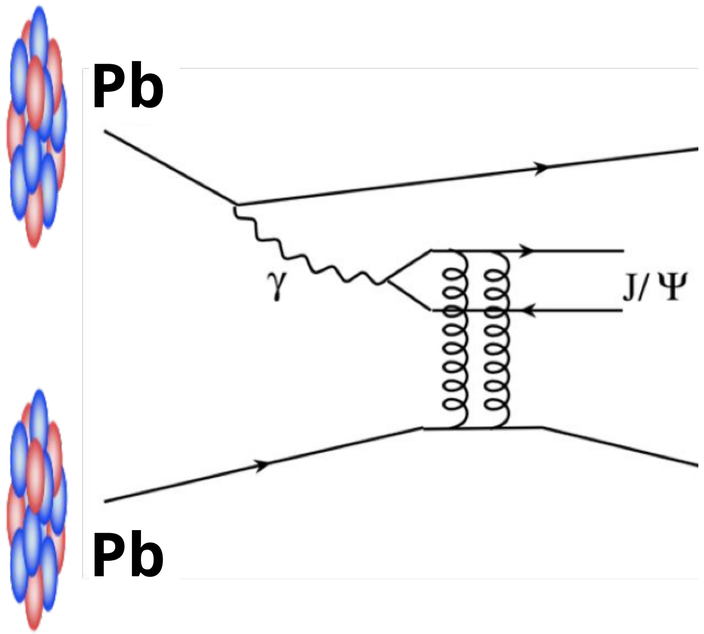

Picture from André Ståhl

Disentangling the ambiguity on the ID of the γ emitter

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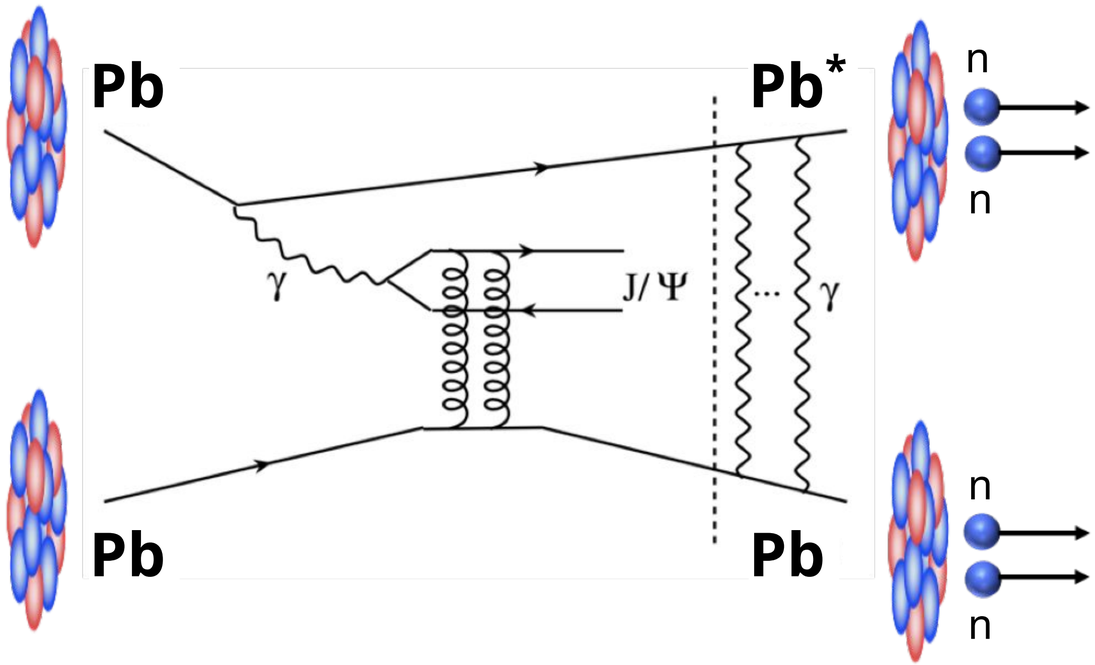
Small impact parameter, b ⟶ higher probability for exciting ($\propto 1/b^2$) ⟶ higher probability to emit neutrons.



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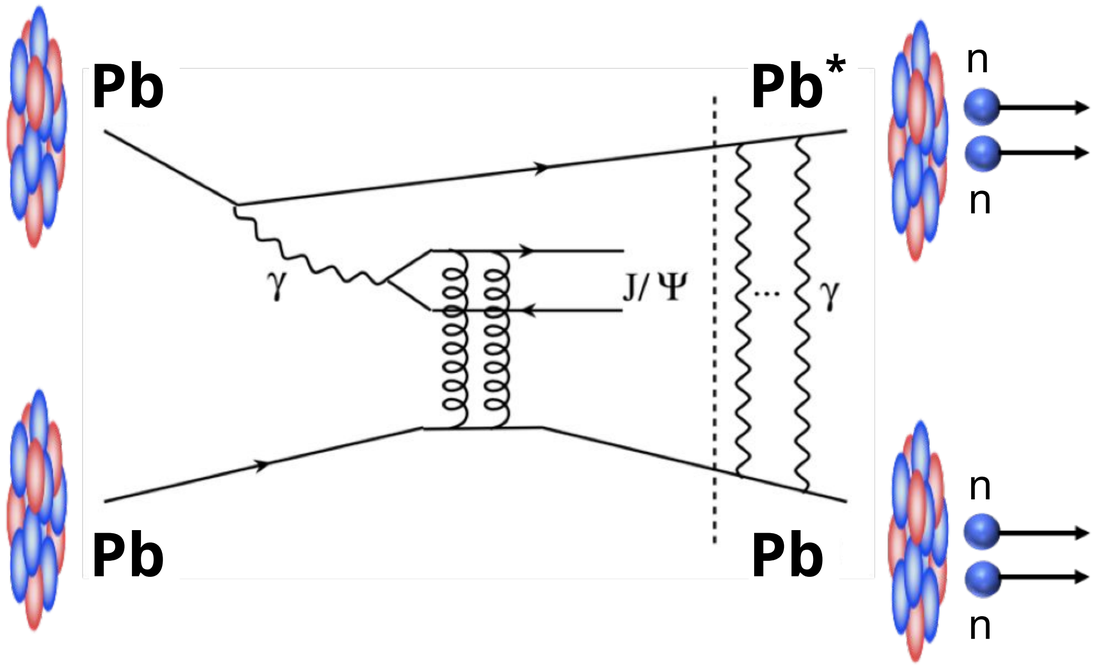
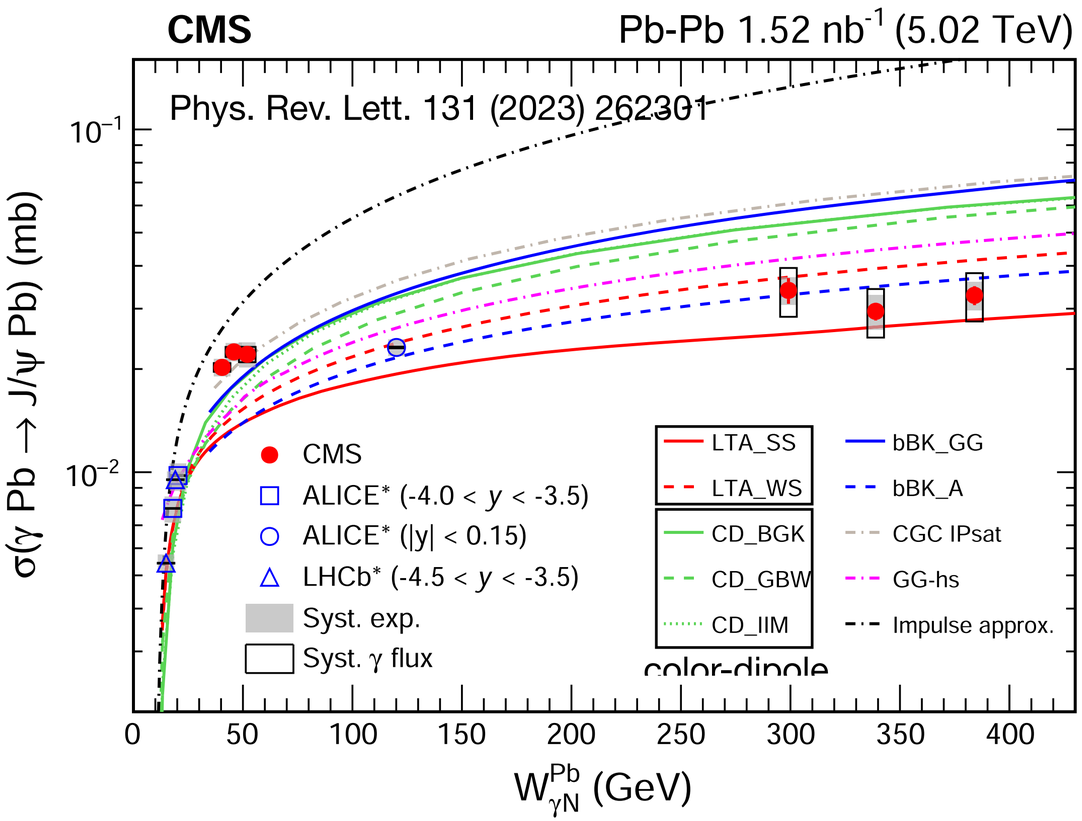
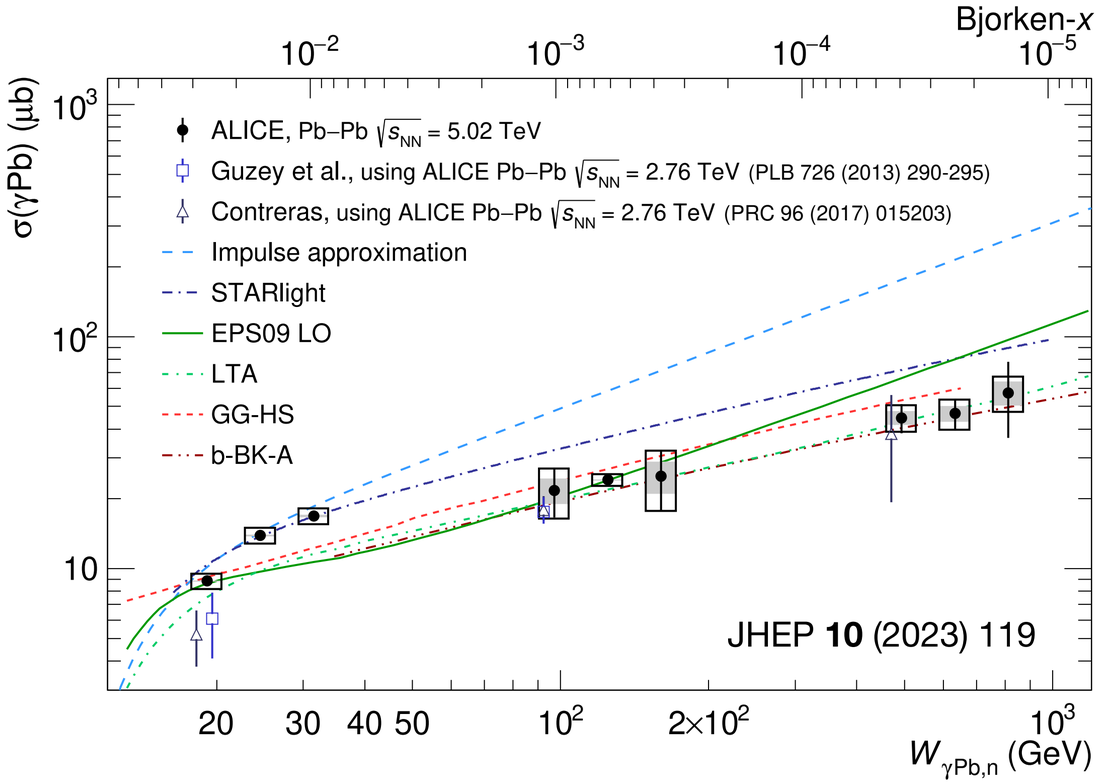


⟶ Make measurement with possibility to detect neutrons

Picture from André Ståhl

CMS: γPb cross section, energy dependence

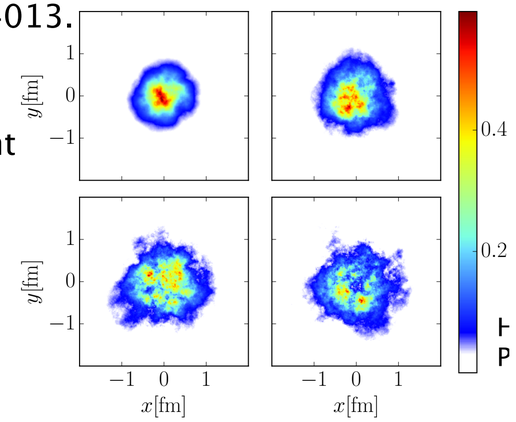




Dissociative production measured by ALICE

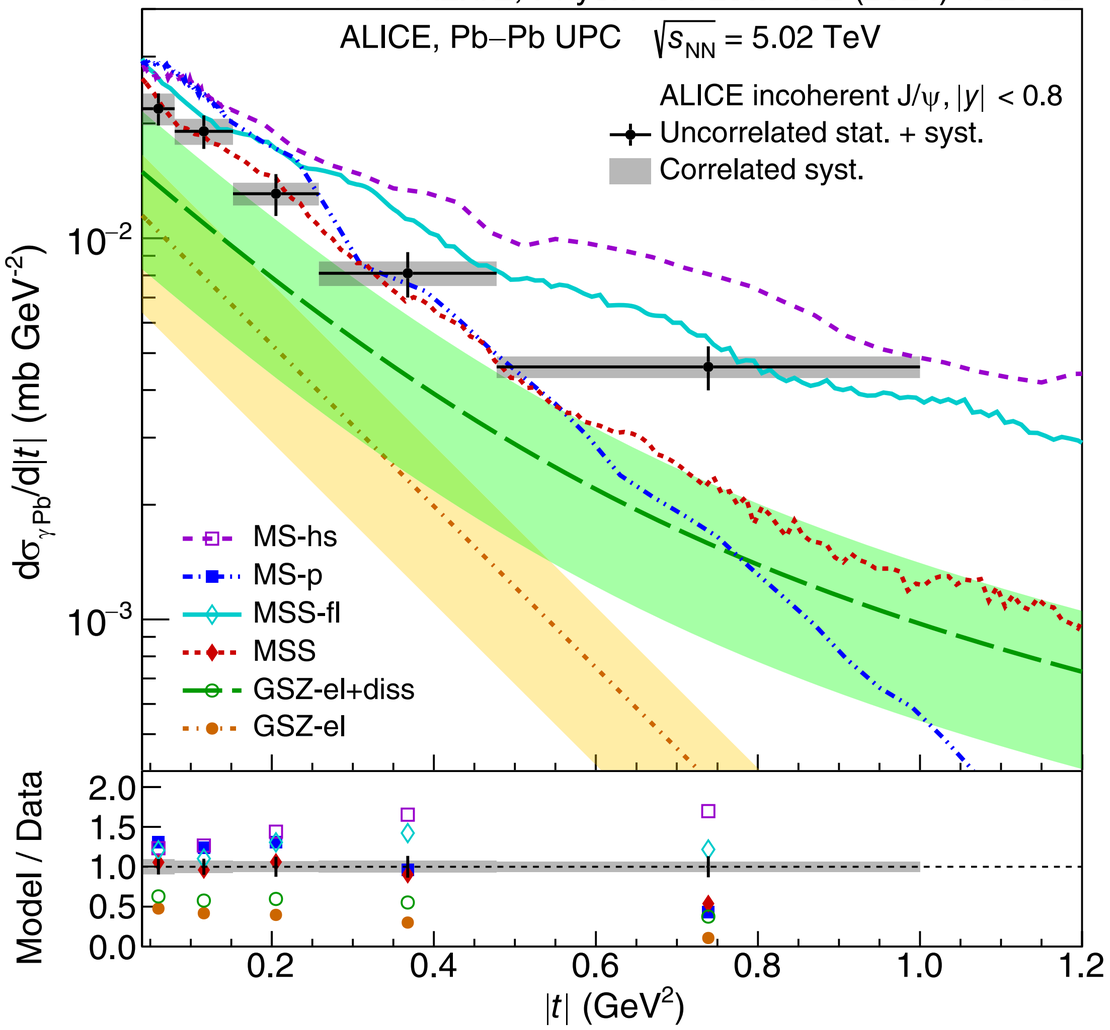
H. Mäntysaari and B. Schenke.
PRD 98 (2018) 034013.

Event-by-event fluctuations



PbPb

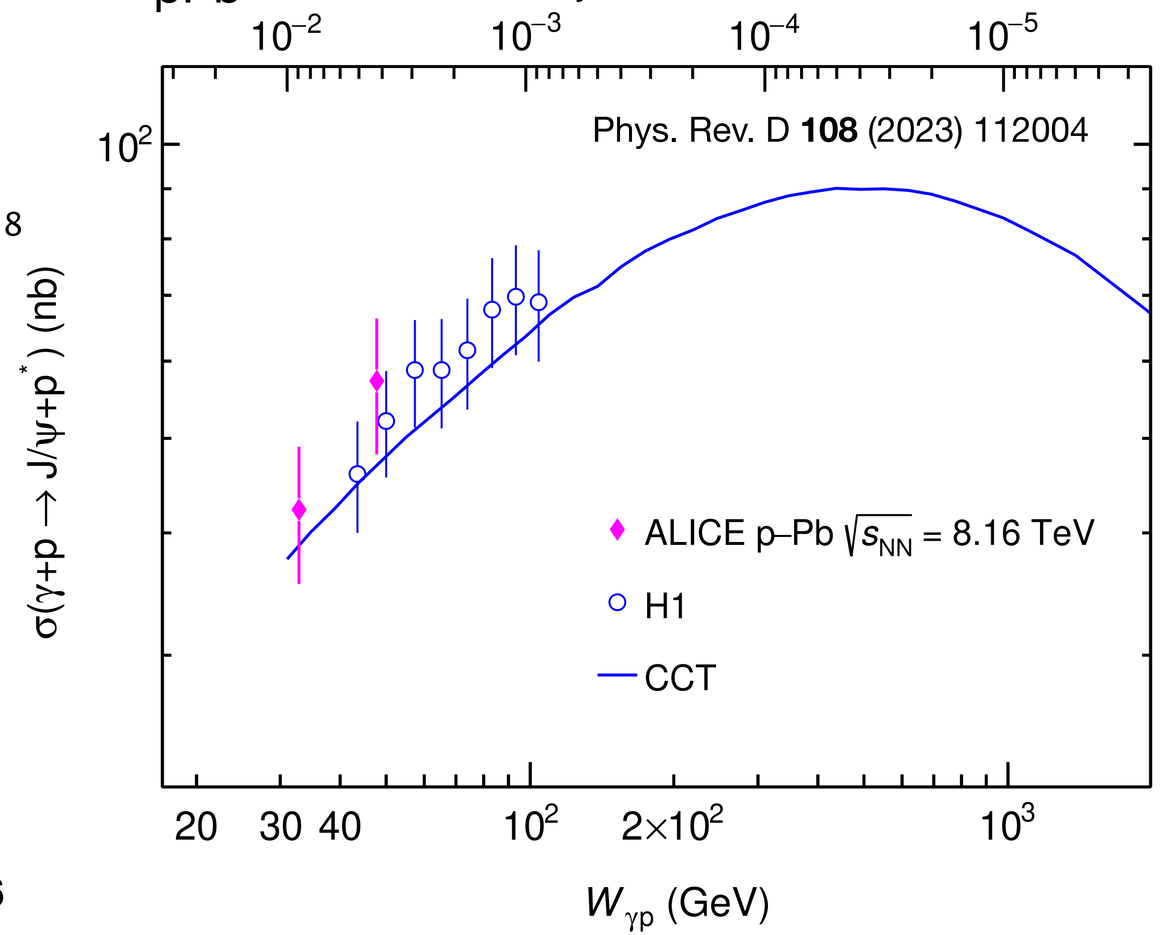
ALICE, Phys. Rev. Lett. 132 (2024) 162302



2018

pPb

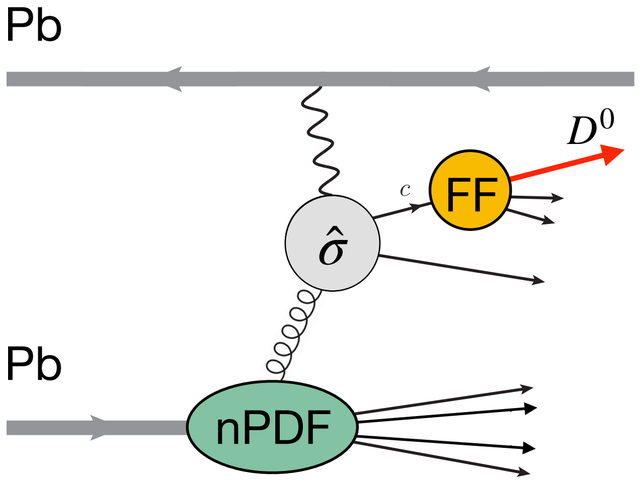
Bjorken-x



Inclusive D^0 photoproduction

First measurement by CMS:

PbPb at $\sqrt{s_{NN}} = 5.36$ TeV



Study nuclear gluon PDFs in new kinematic region

Inclusive D^0 photoproduction: kinematic coverage

- hard scale of the interaction:

$$Q^2 = p_{T,c}^2 + m_c^2$$

- Bjorken-x variable:

$$x_B = \frac{Q}{\sqrt{s_{NN}}} e^{-y_c}$$

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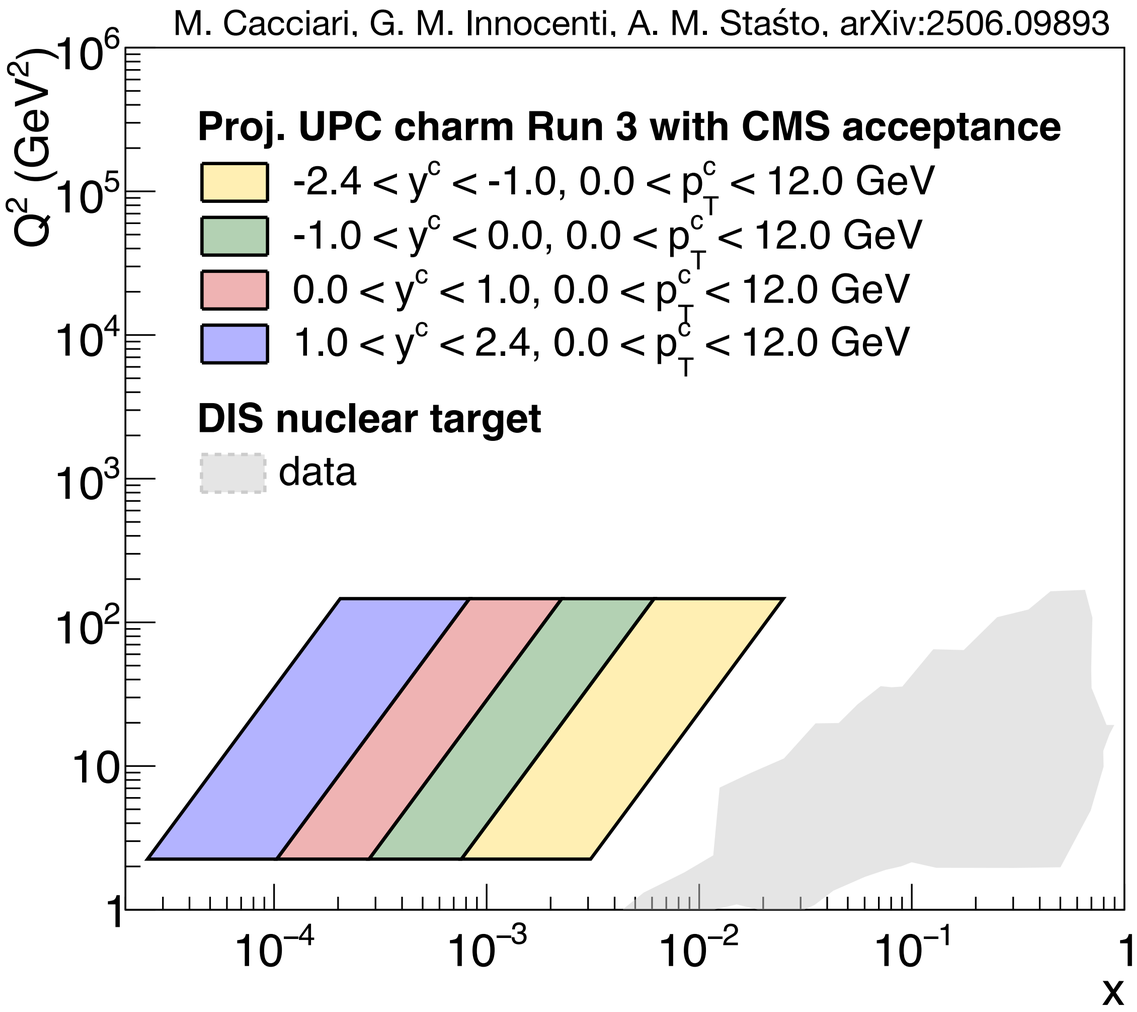

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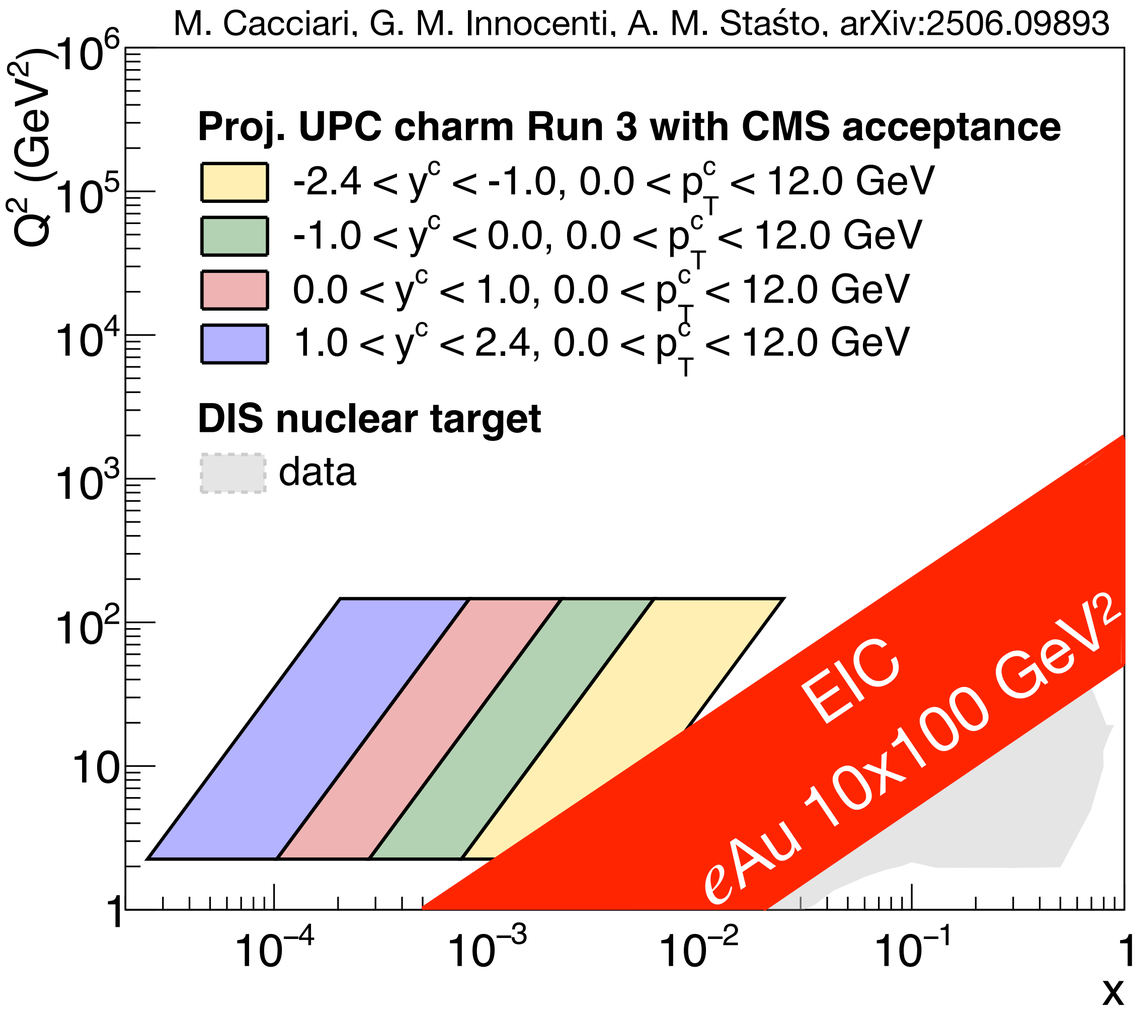
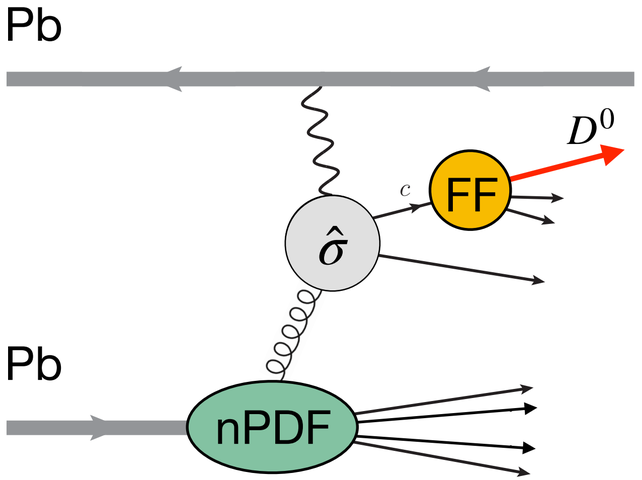


Experimental signature



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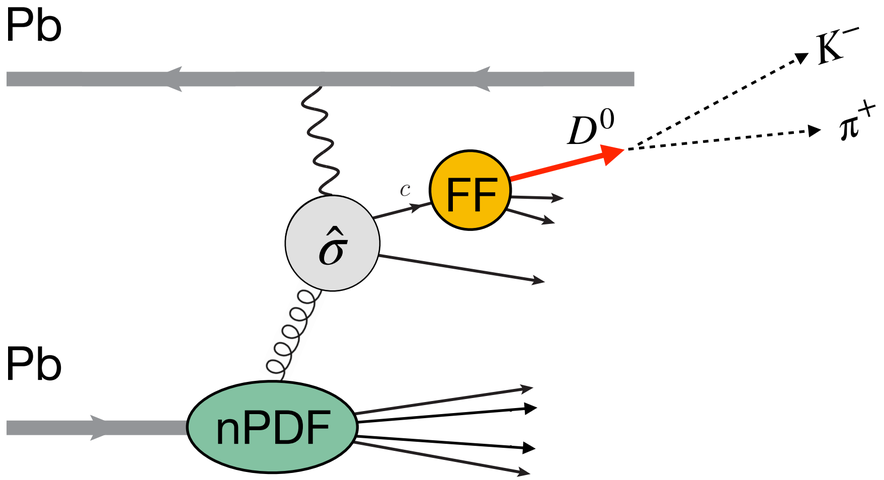

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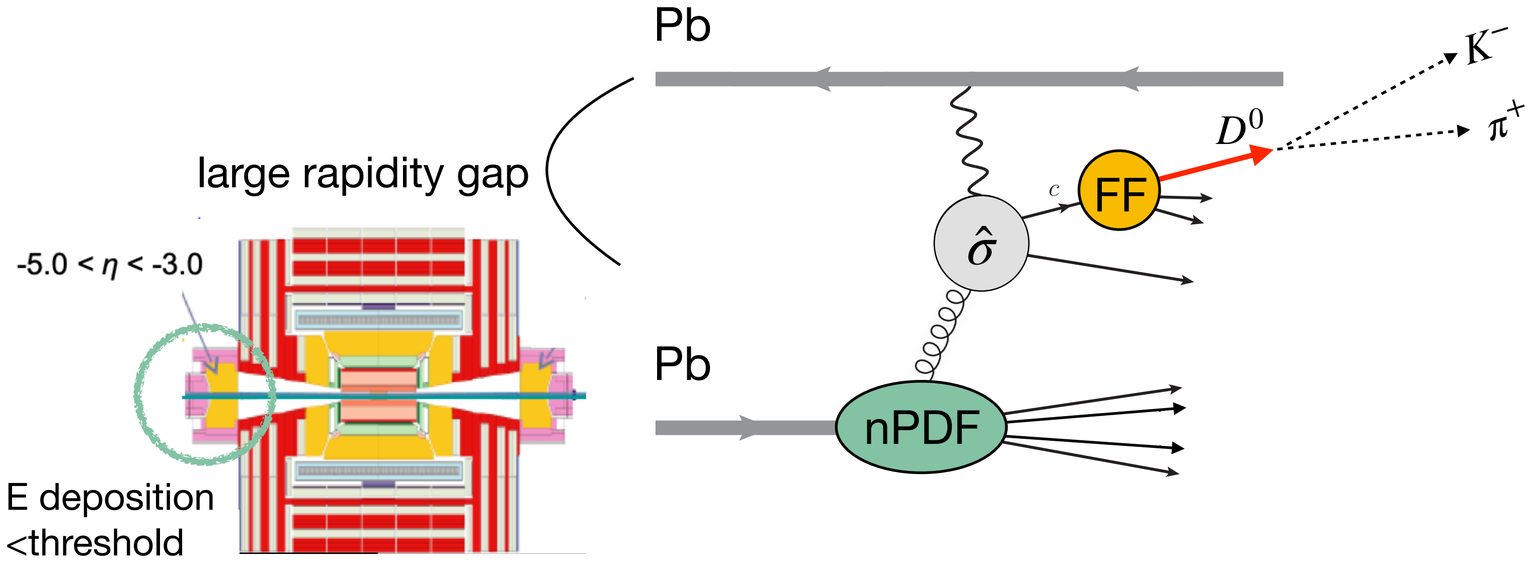

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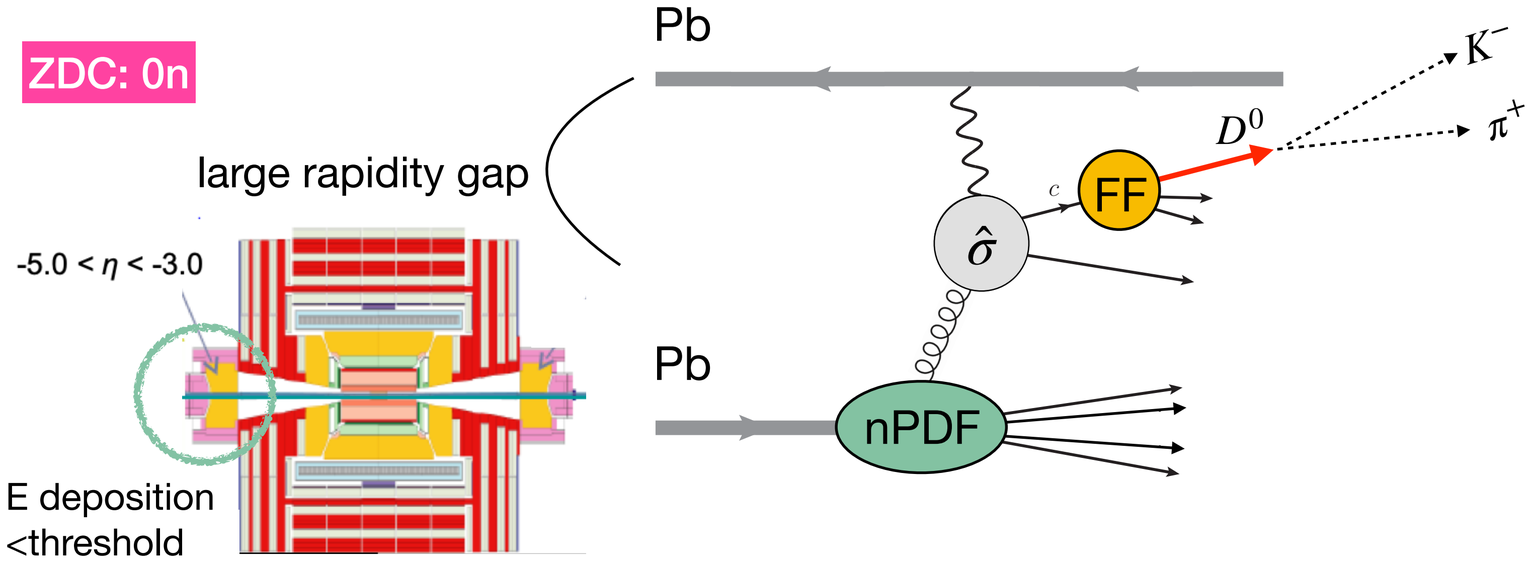

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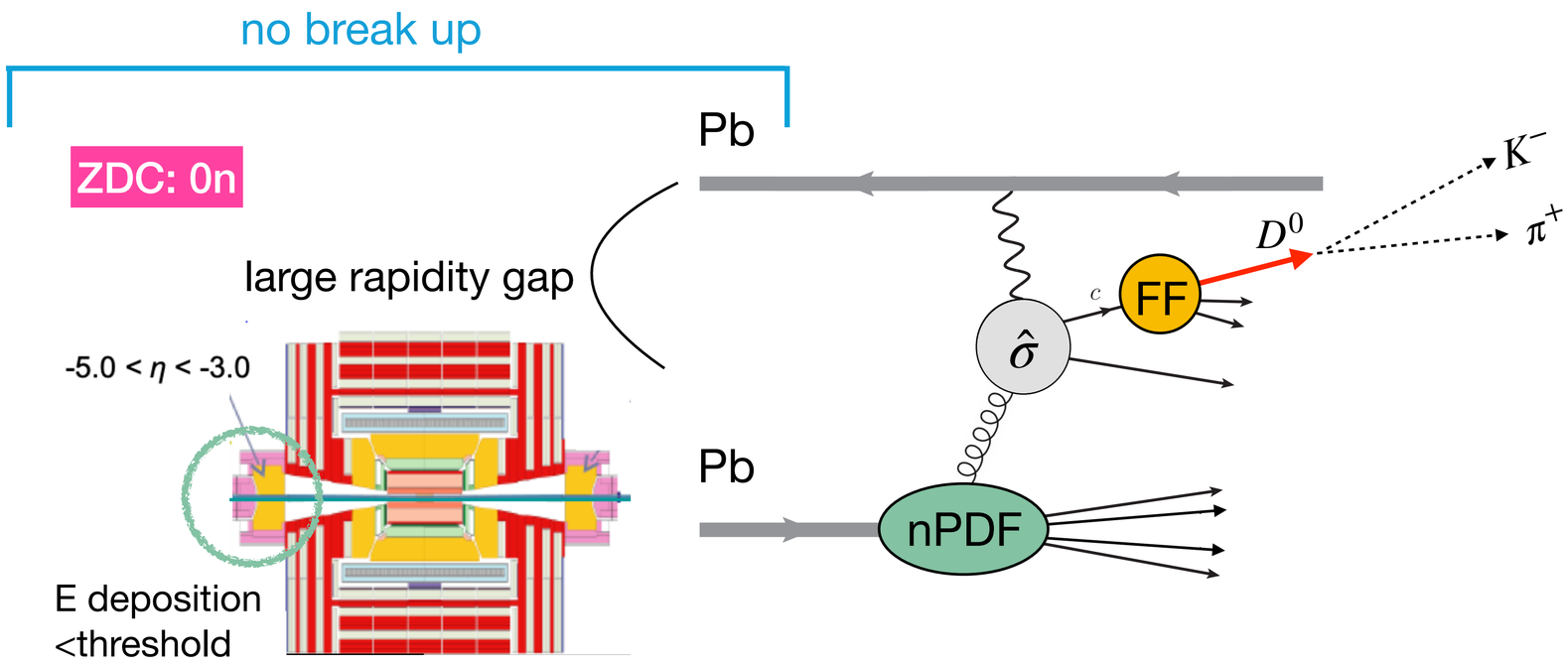

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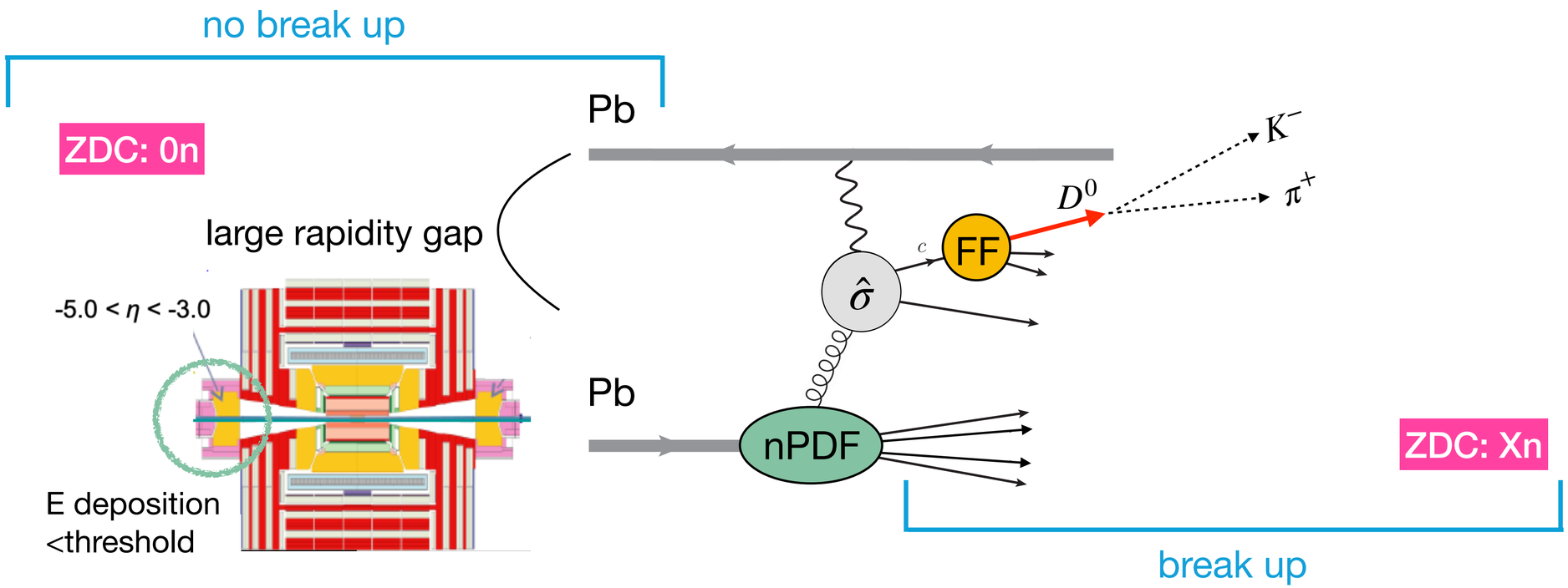
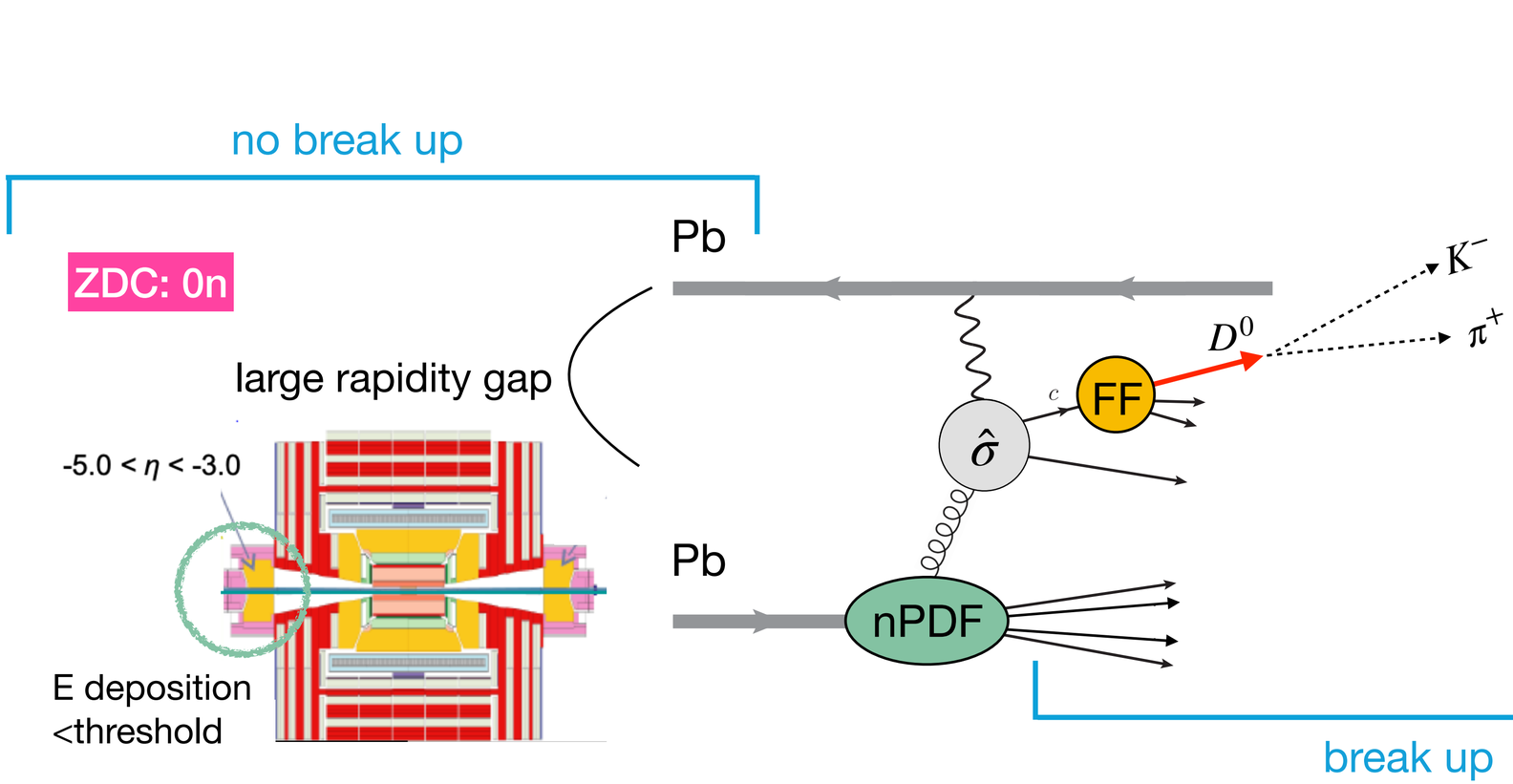
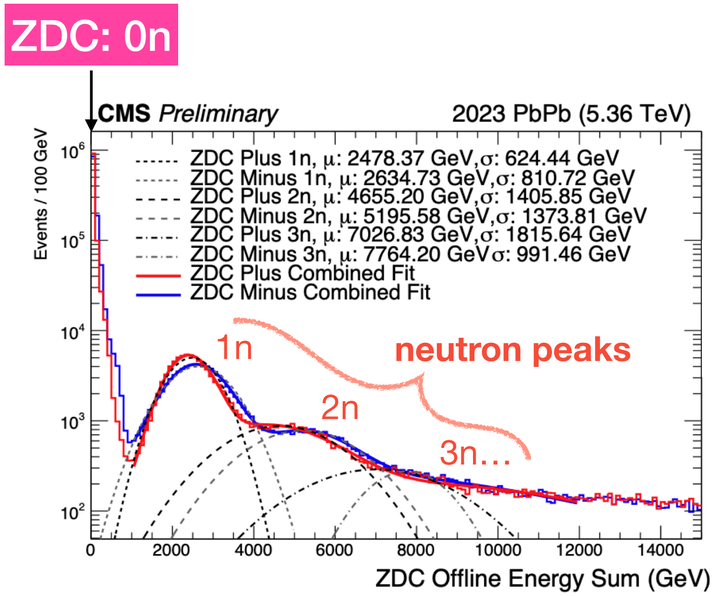


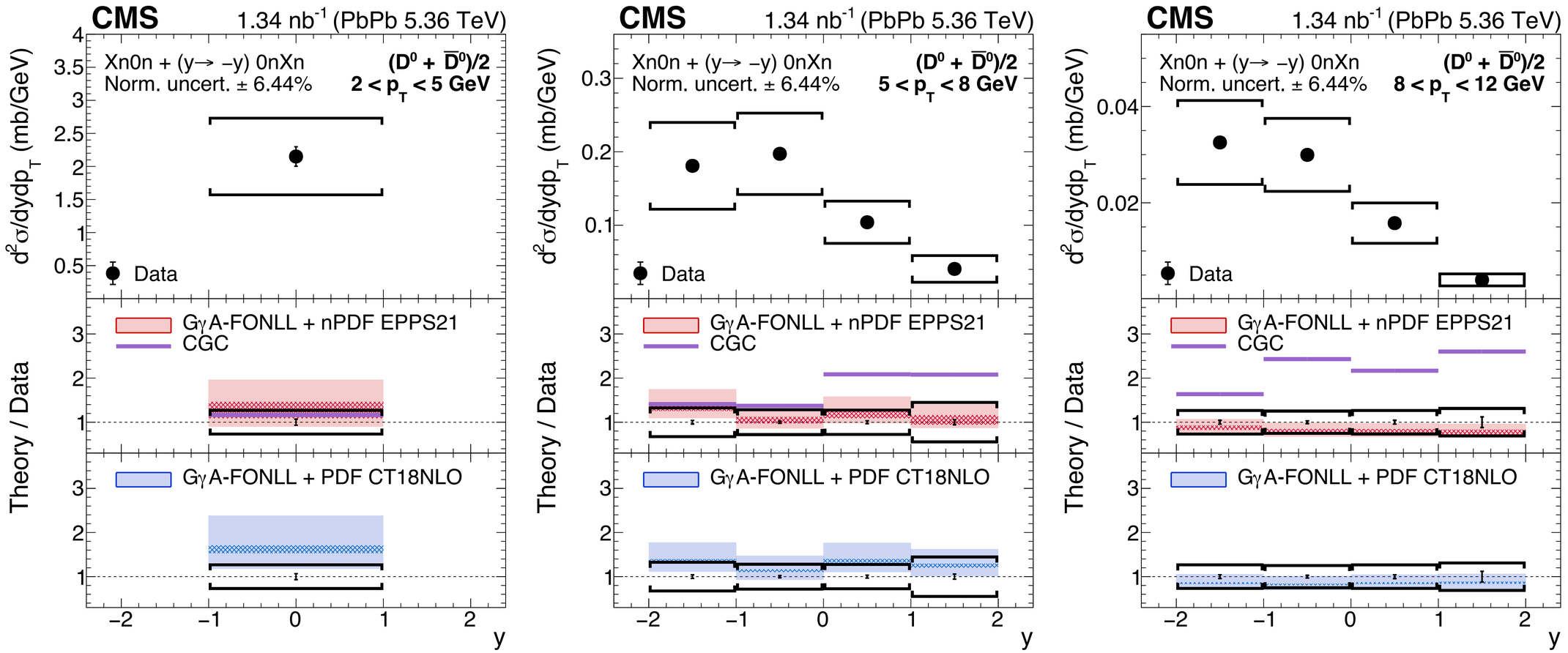
Experimental signature





Results

CMS, arXiv:2509.08626



high x_B ← → low x_B

cross section reflects
photon flux and nPDFs

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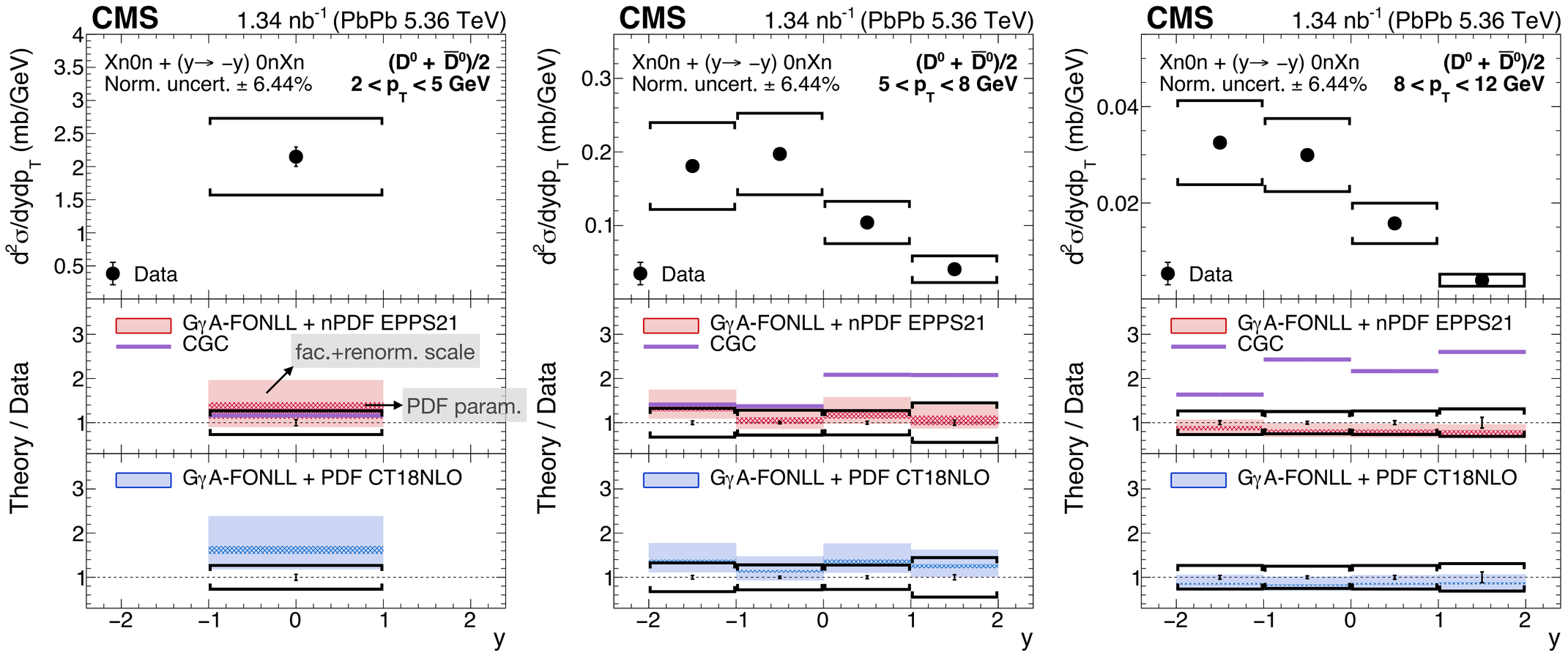
CMS, arXiv:2509.08626



high x_B ← → low x_B

cross section reflects
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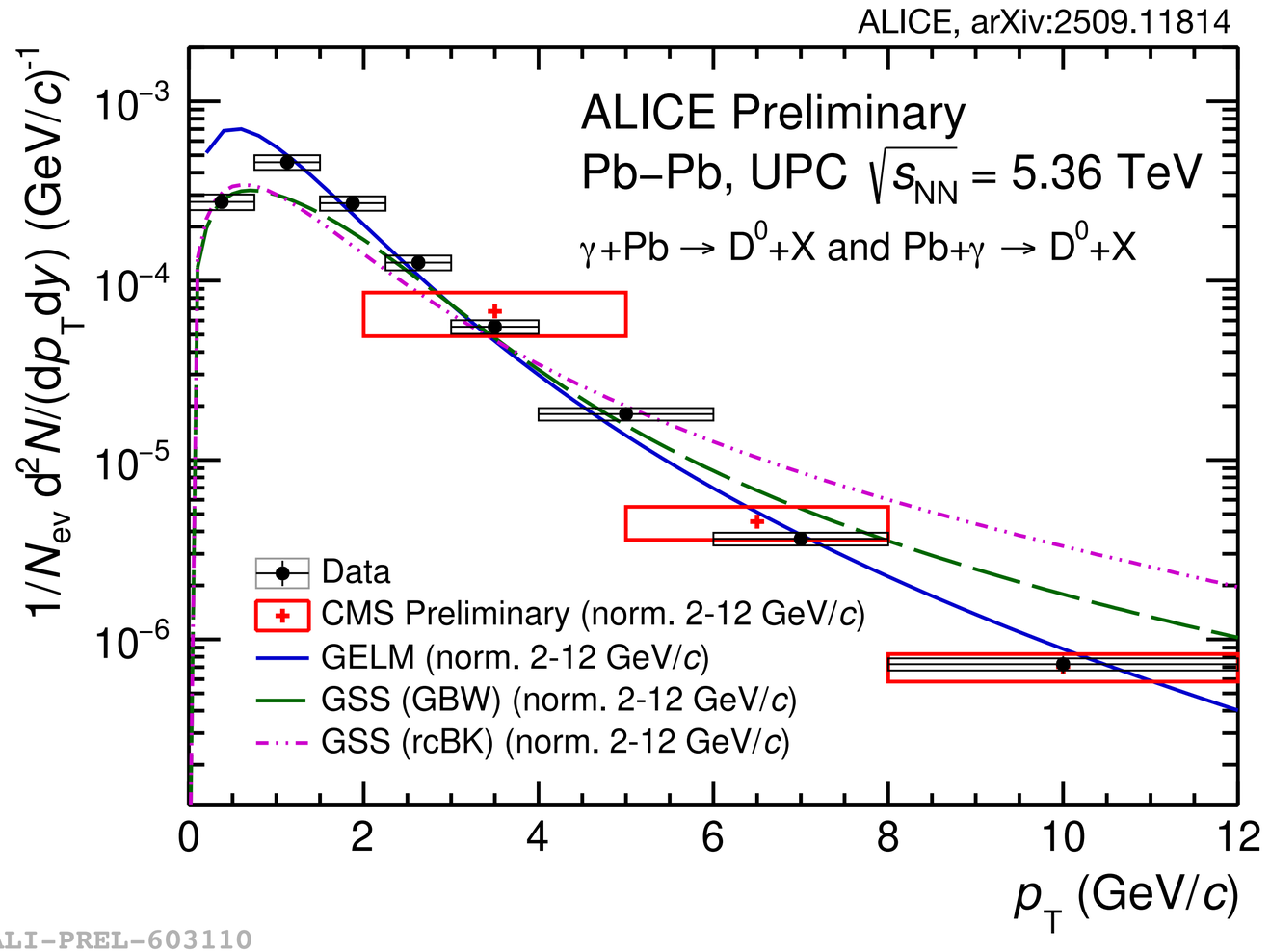
Inclusive D^0 photoproduction at ALICE

More restricted x_B coverage.
p_T down to 0!

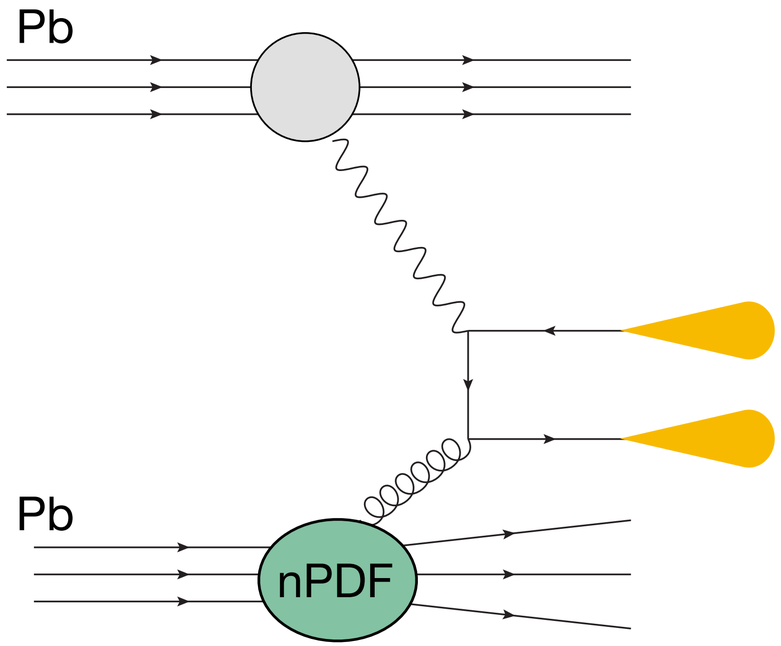
ALICE and CMS agree well.

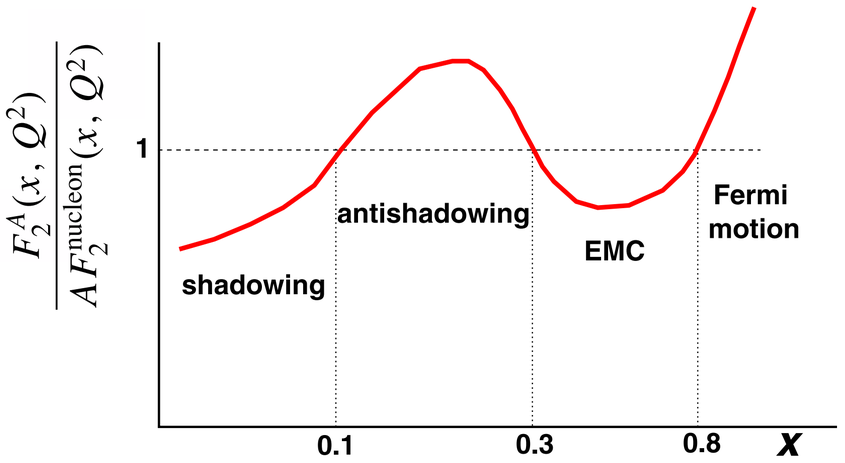


Inclusive jet photoproduction

First inclusive UPC measurement: ATLAS

PbPb at $\sqrt{s_{NN}} = 5.02$ TeV





Probe nuclear PDFs in shadowing and anti-shadowing regions

Inclusive jet photoproduction: kinematic coverage

- hard scale of the interaction:

$$H_T = \sum_{\text{jet}} p_{T,jet} \xrightarrow{2\to2} 2Q$$

- Bjorken-x variable:

$$x_A = \frac{M_J}{\sqrt{s}} e^{-y_J}$$

$$M_J = \sqrt{\left(\sum_{\text{jet}} E_{\text{jet}}\right)^2 - \left|\sum_{\text{jet}} \vec{p}_{\text{jet}}\right|^2}$$

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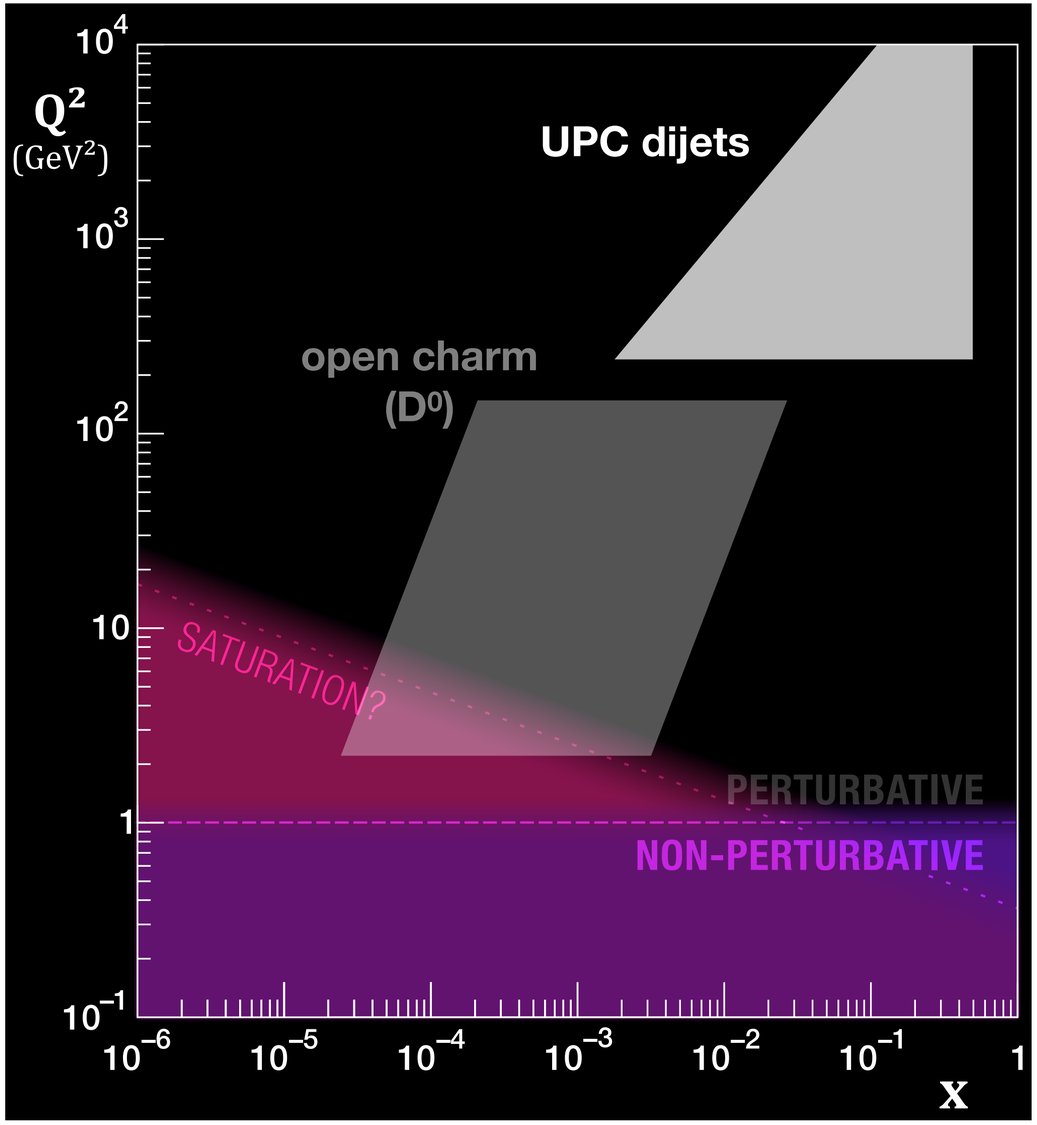

Figure from Jordan Lang | Quarkonia as Tools 2026 | 6 January 2026

Inclusive jet photoproduction: kinematic coverage

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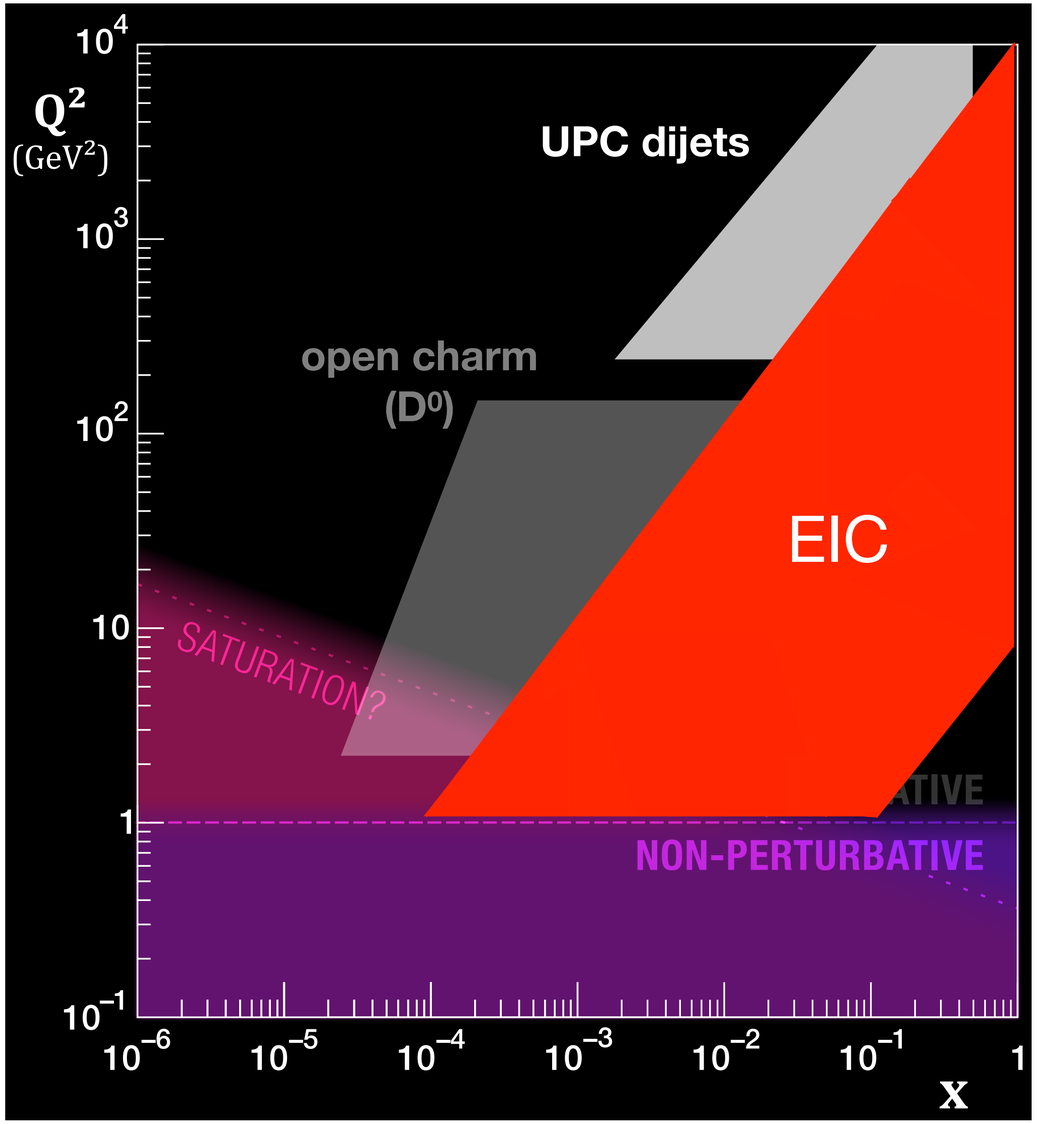
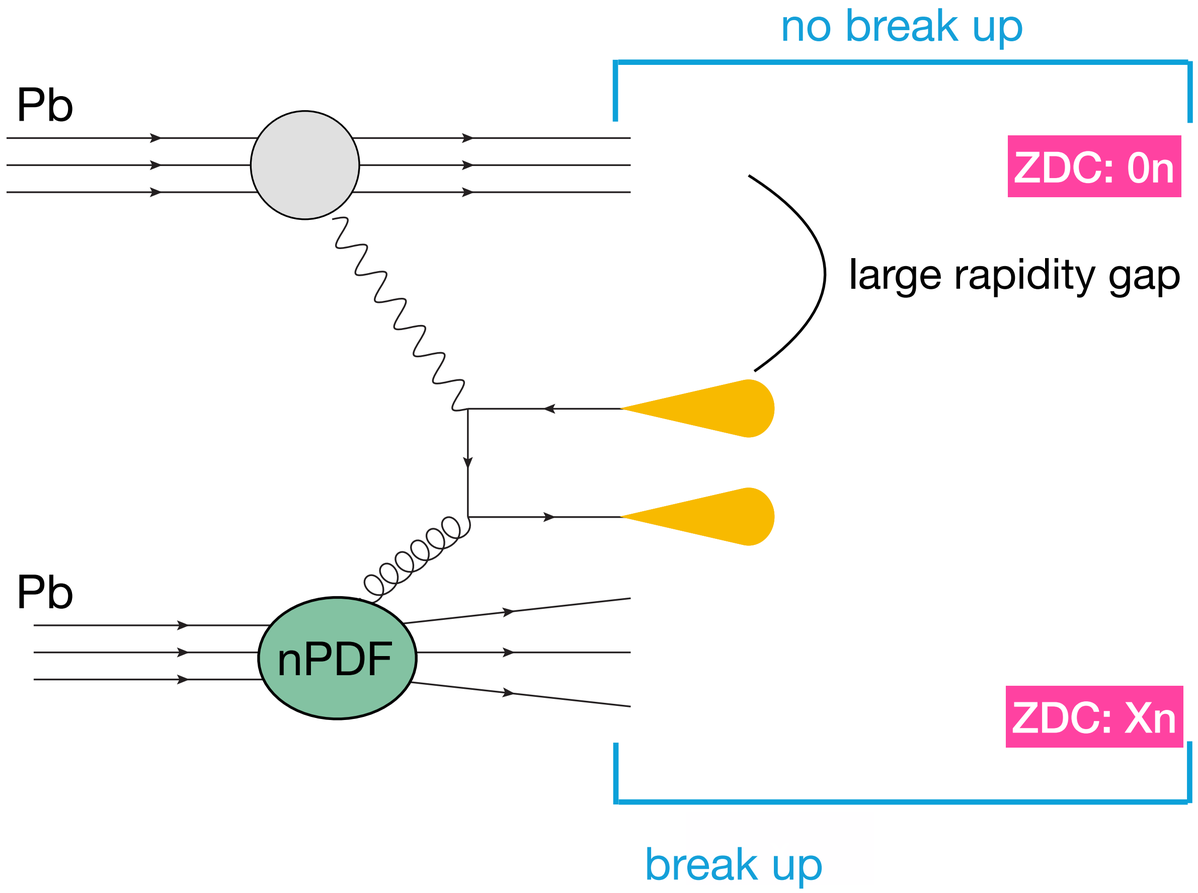


Figure from Jordan Lang | Quarkonia as Tools 2026 | 6 January 2026

Experimental signature



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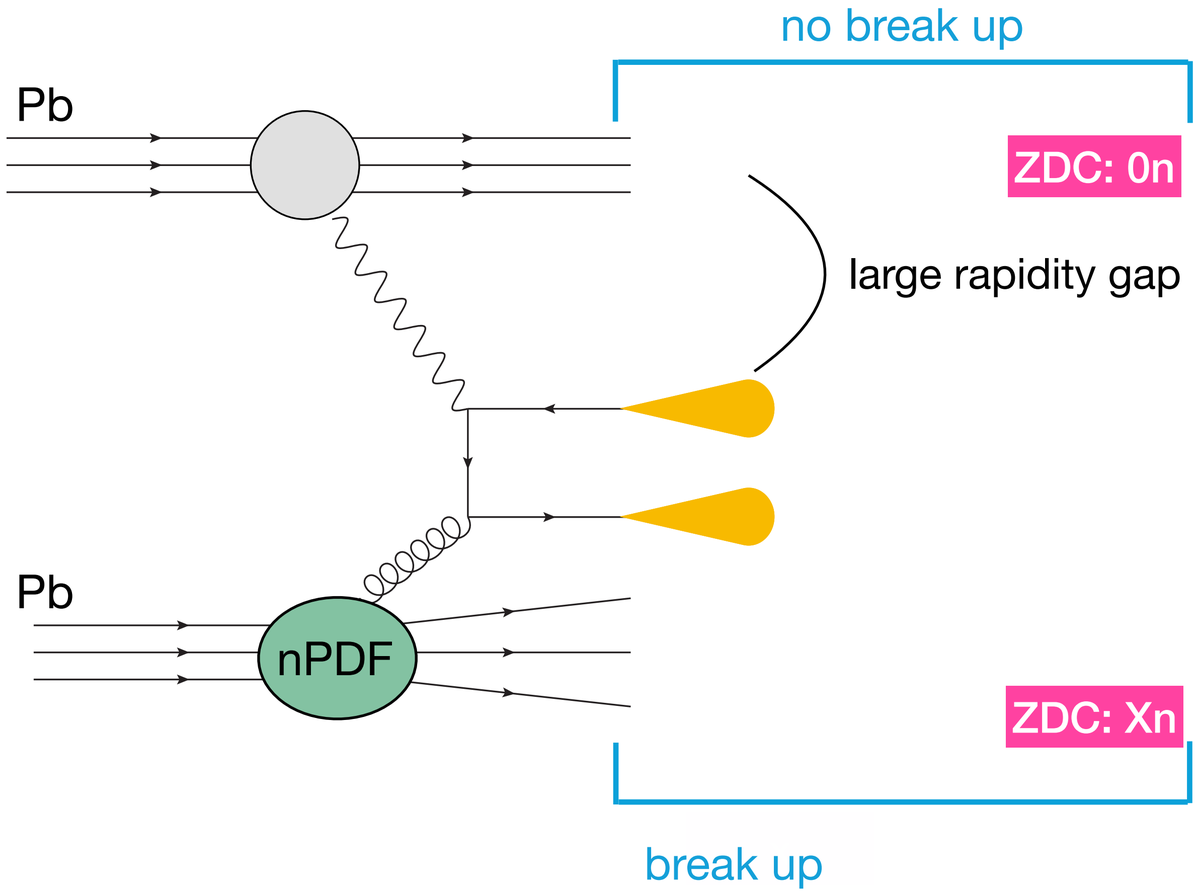
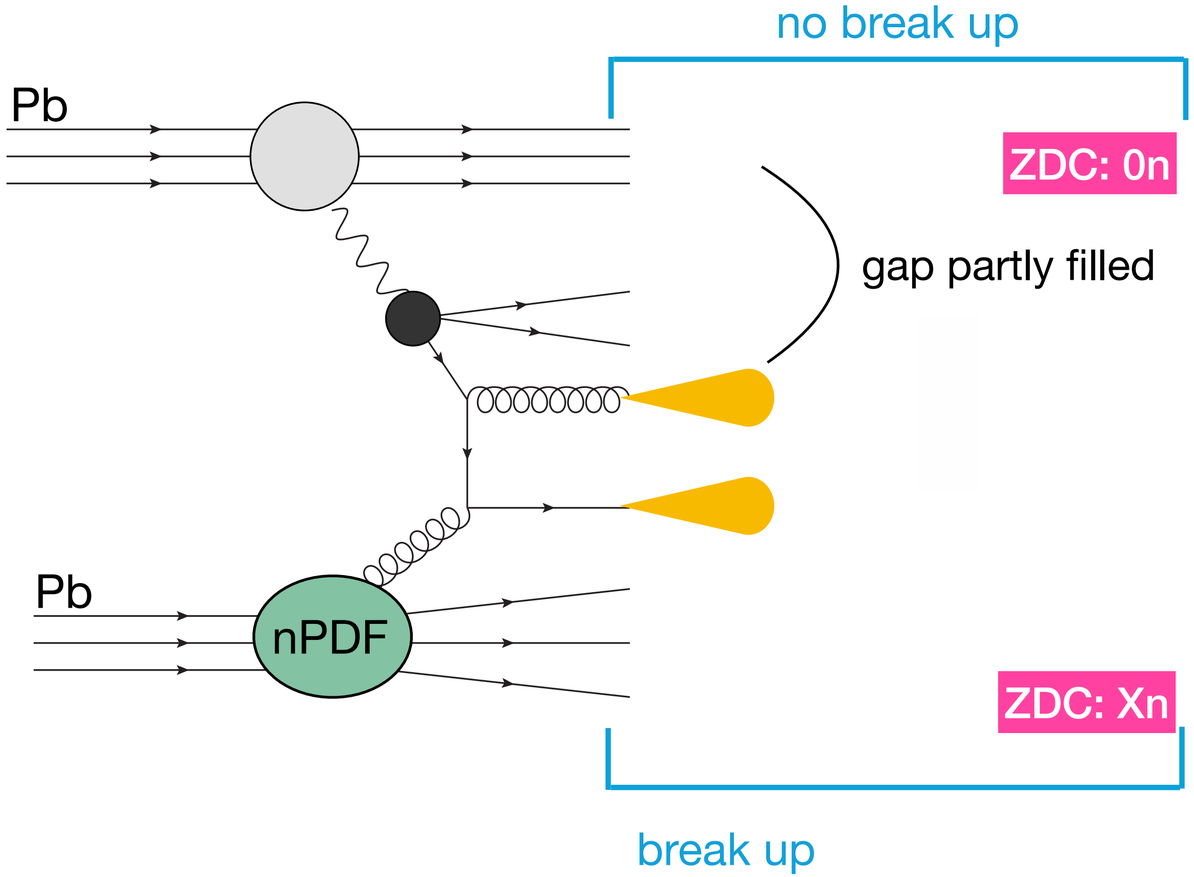


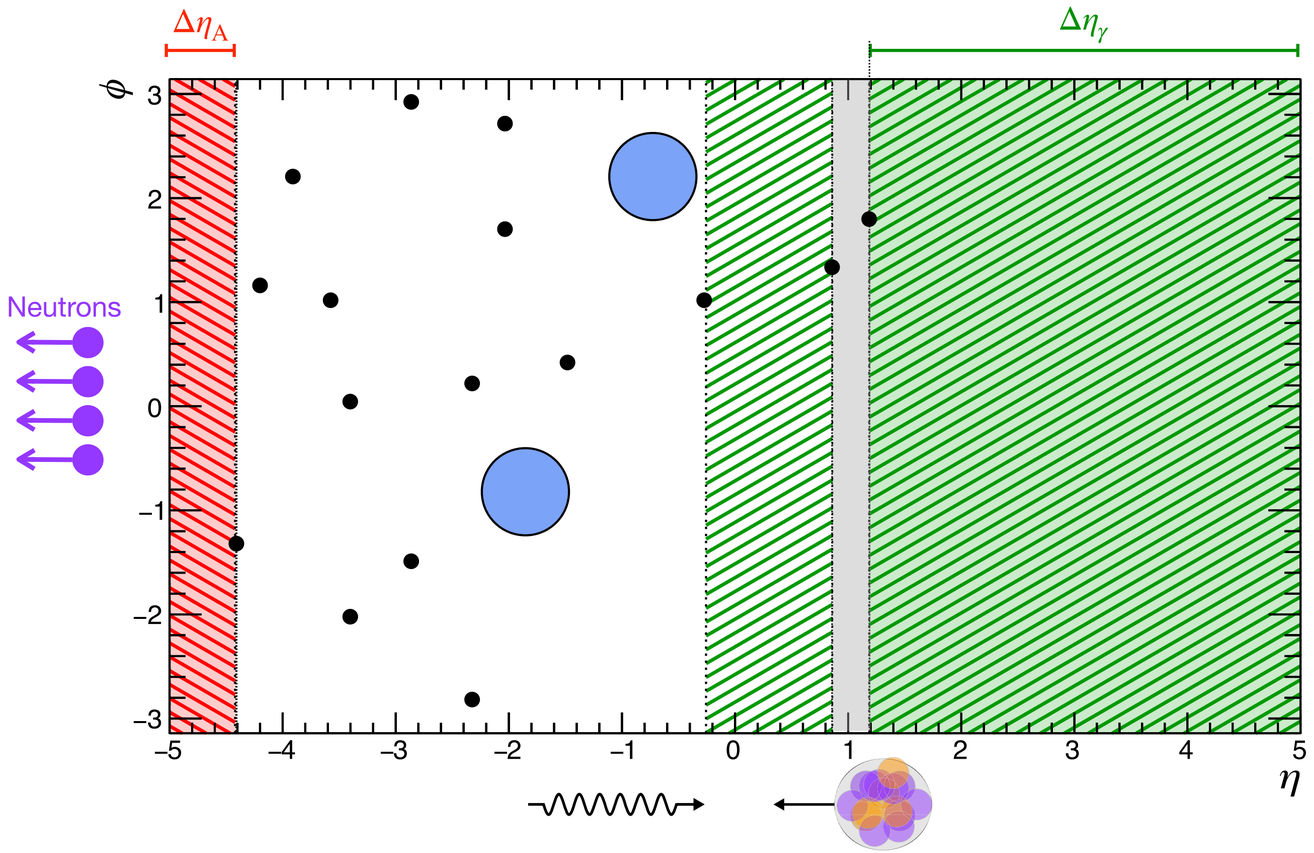
direct photon



resolved photon

access to partonic structure of photon.

Experimental signature: activity in detector



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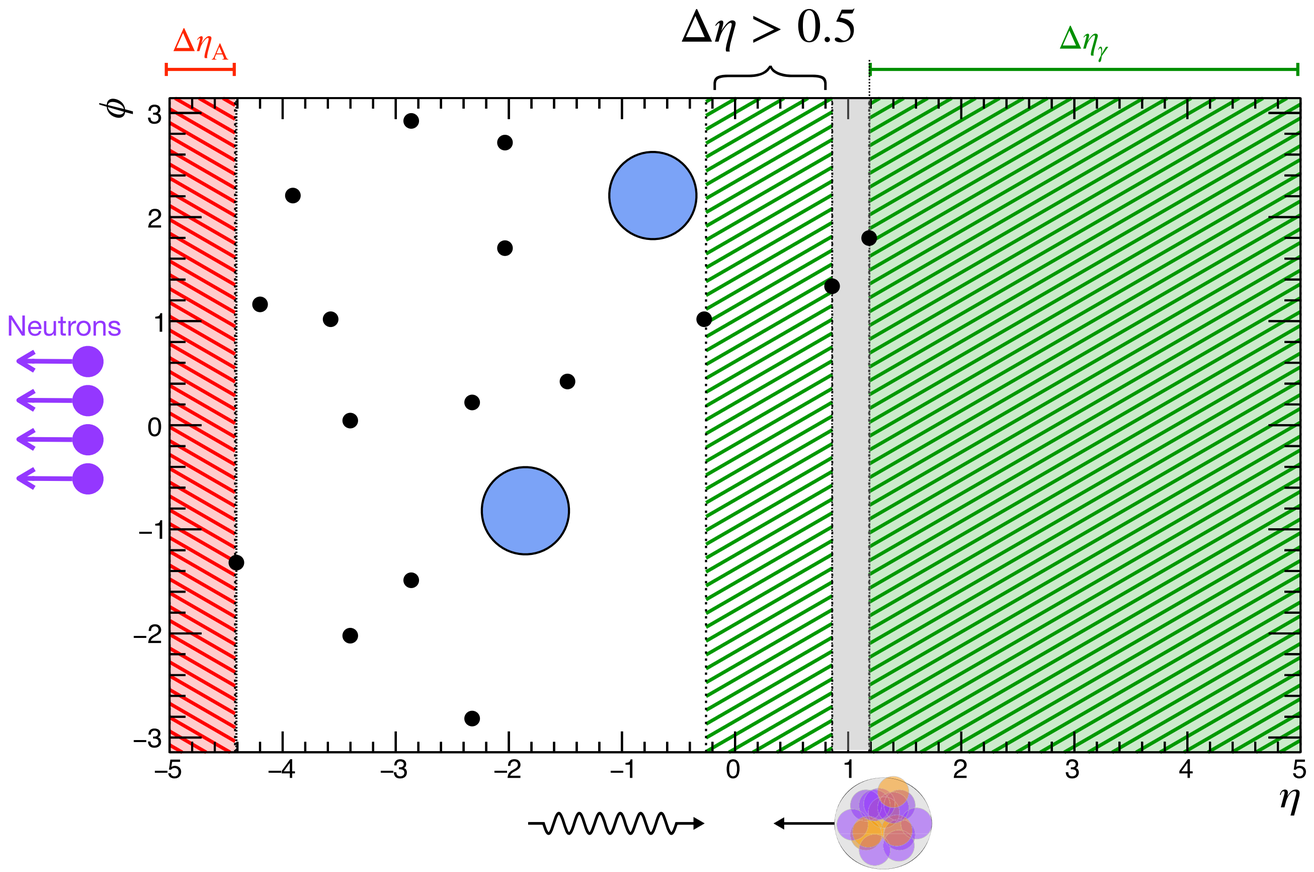
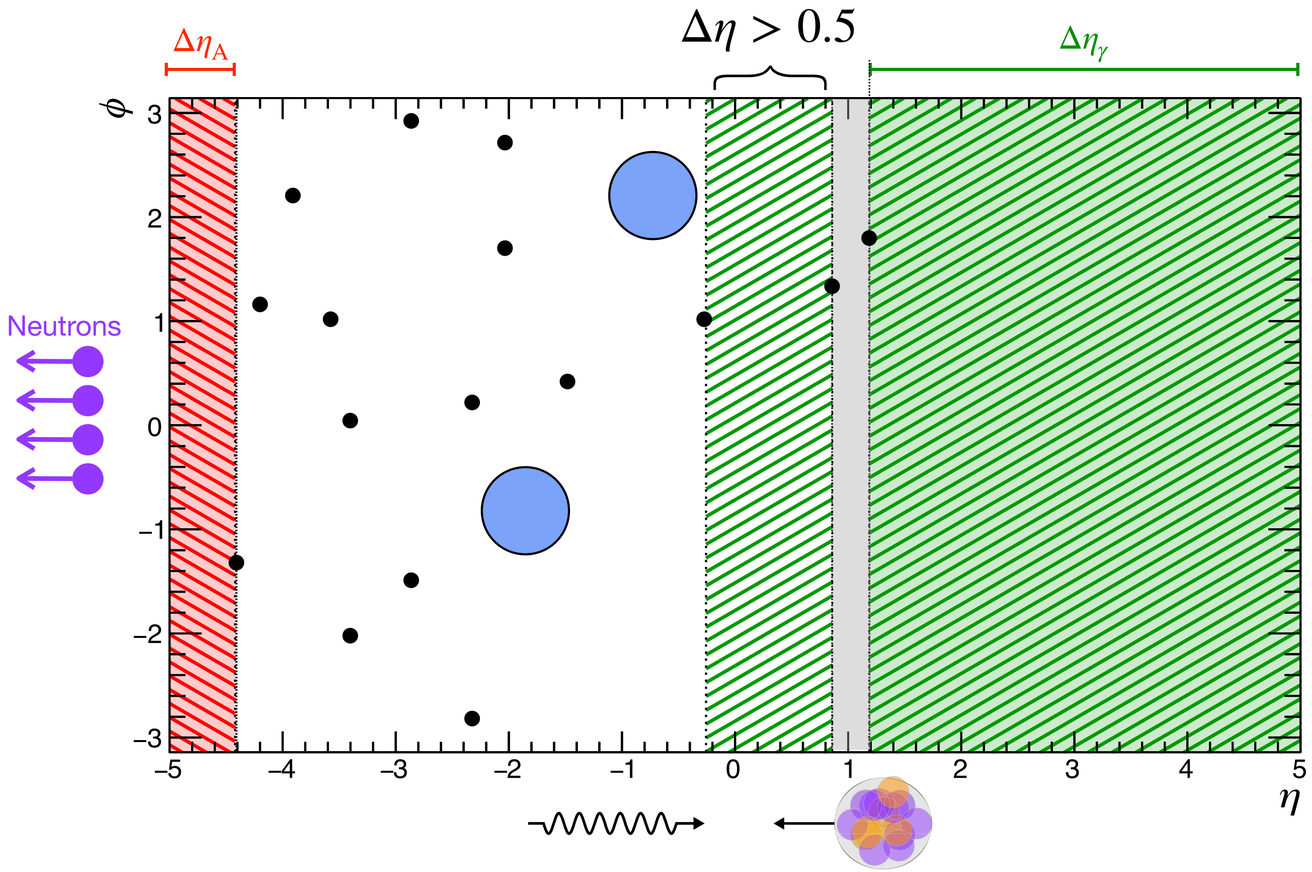


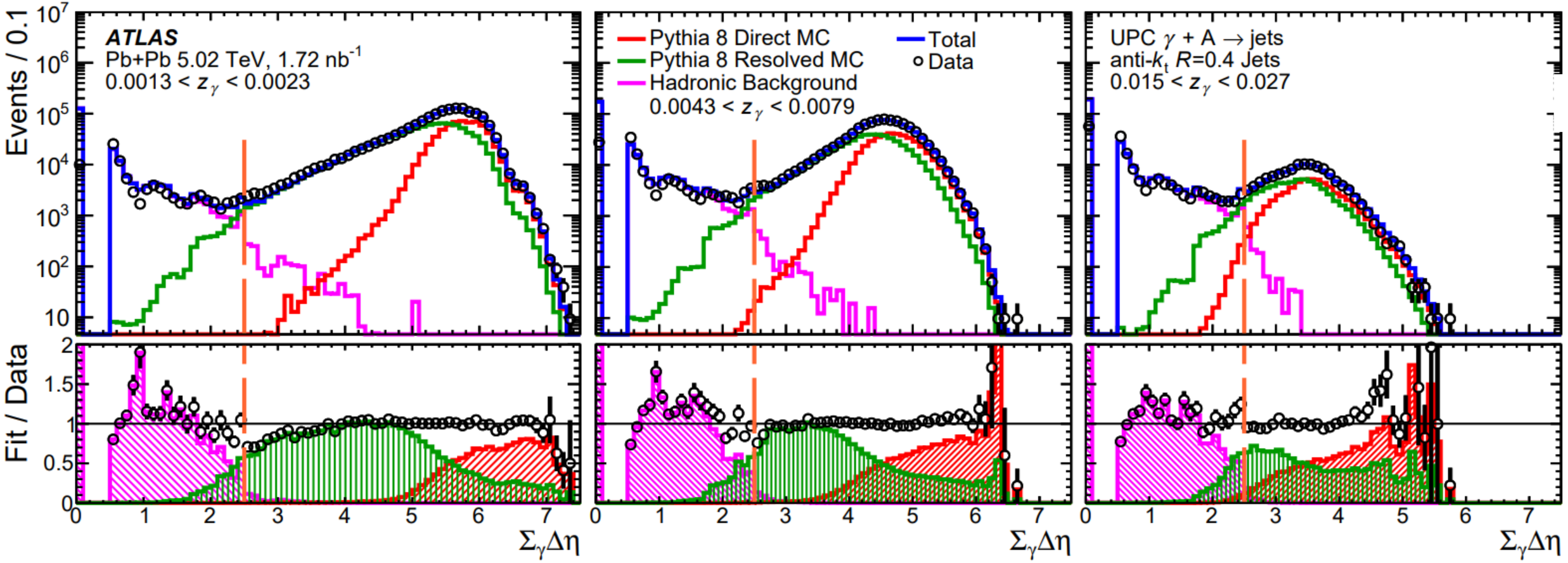
Experimental signature: activity in detector



$\sum_\gamma \Delta\eta > 2.5 \longrightarrow$ rapidity gap

allow for direct & resolved photon contributions

Experimental signature: activity in detector



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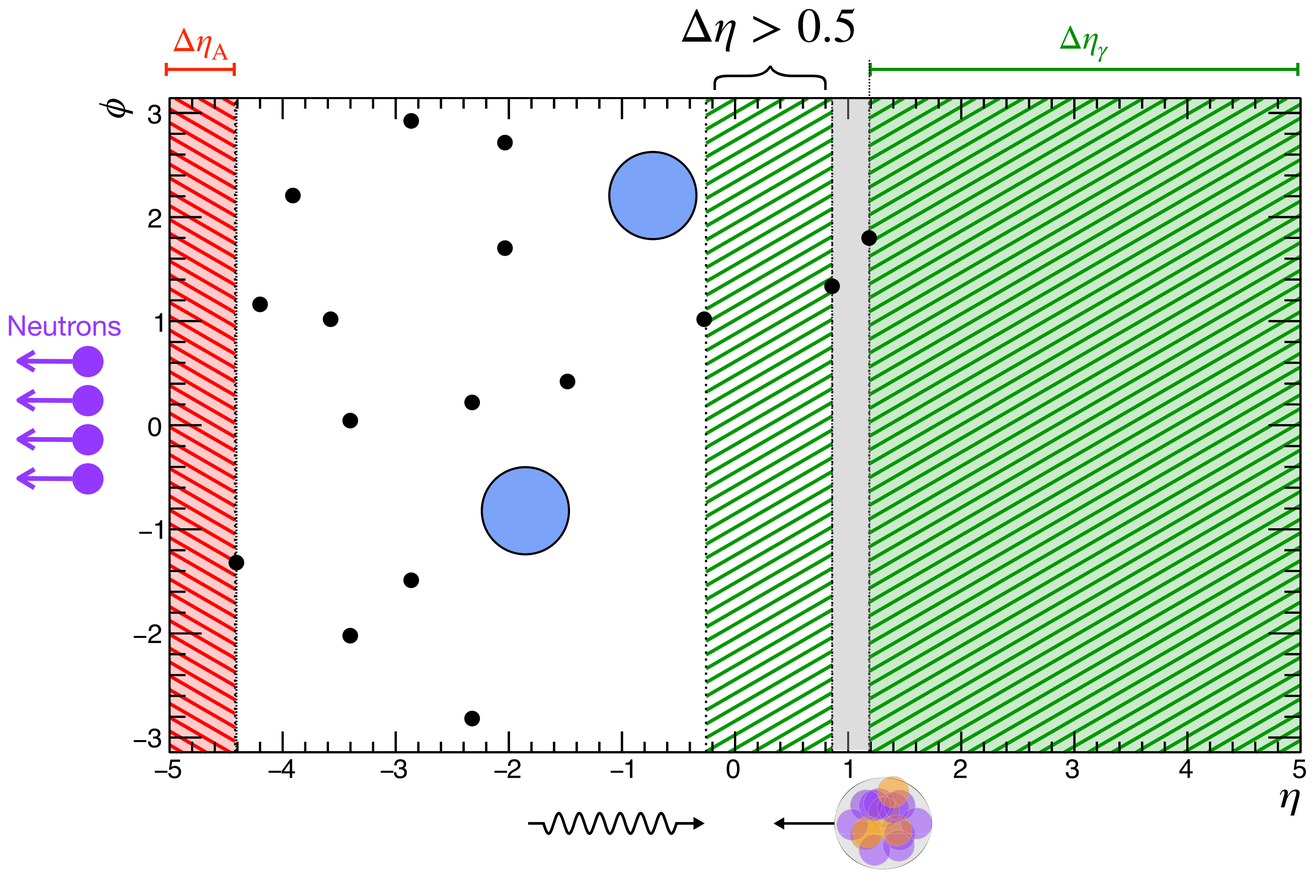
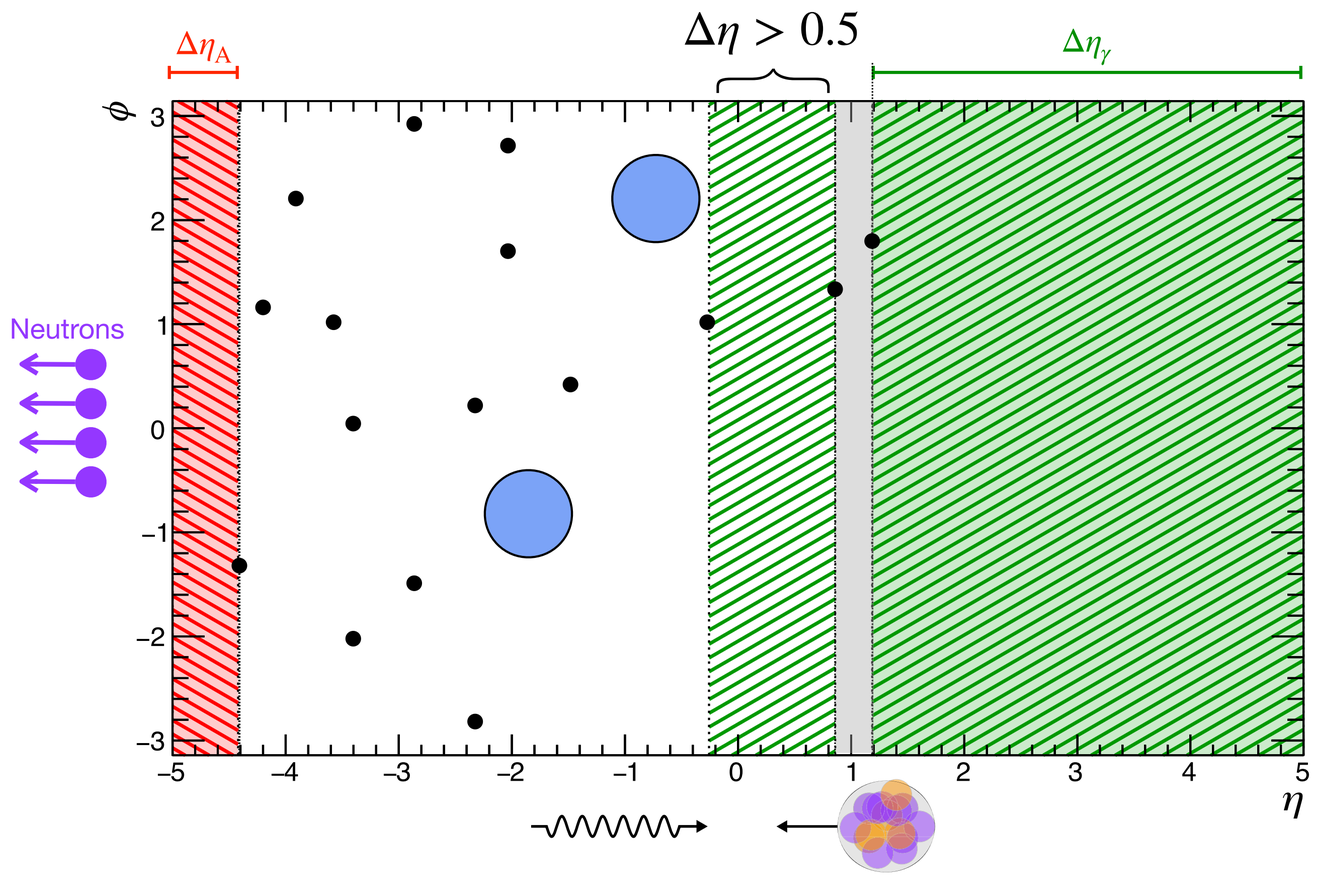


$\Delta\eta_A < 3$ ⟶ break up

$\sum_\gamma \Delta\eta > 2.5$ ⟶ rapidity gap

allow for direct & resolved photon contributions

Experimental signature: activity in detector



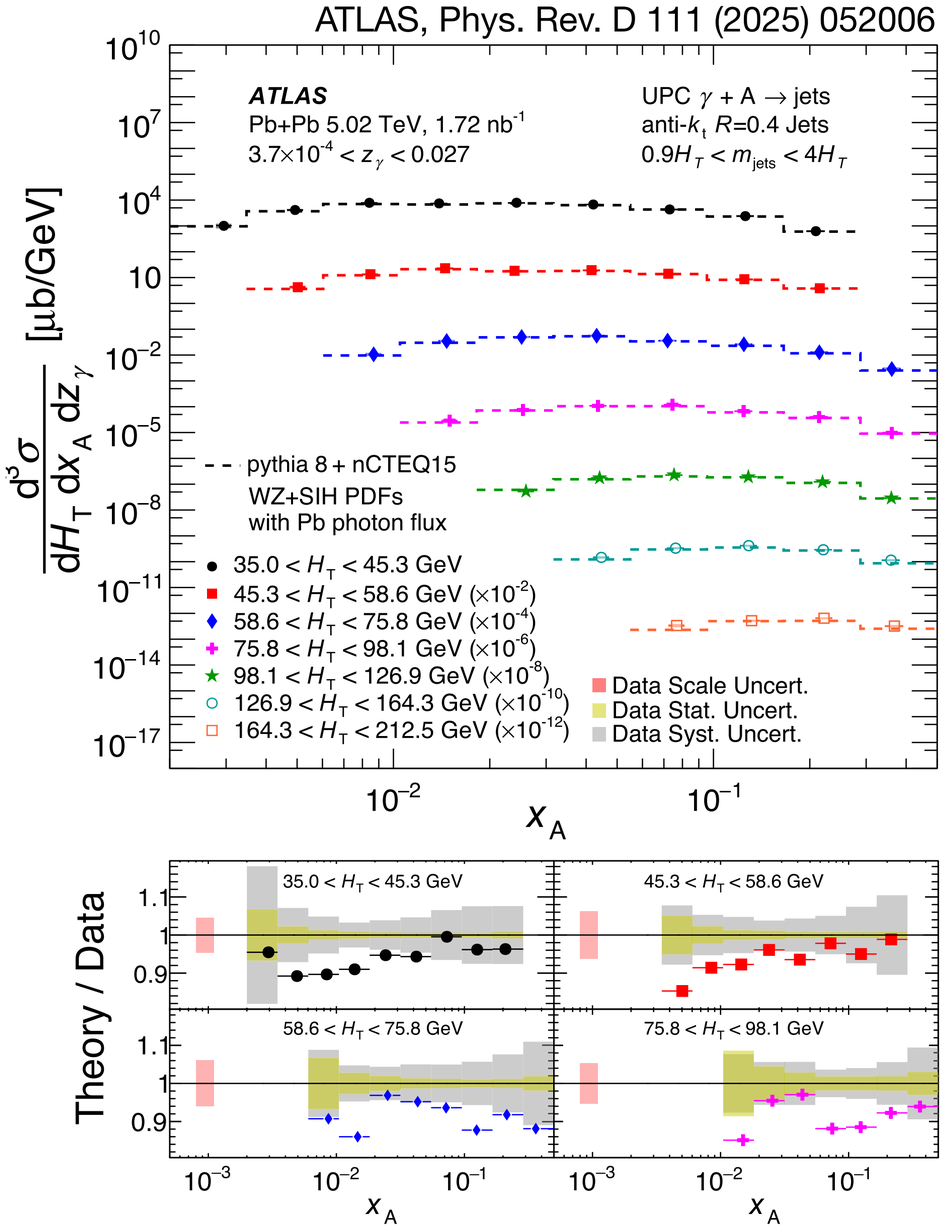
$\Delta\eta_A < 3$ ⟶ break up

$\sum_\gamma \Delta\eta > 2.5$ ⟶ rapidity gap

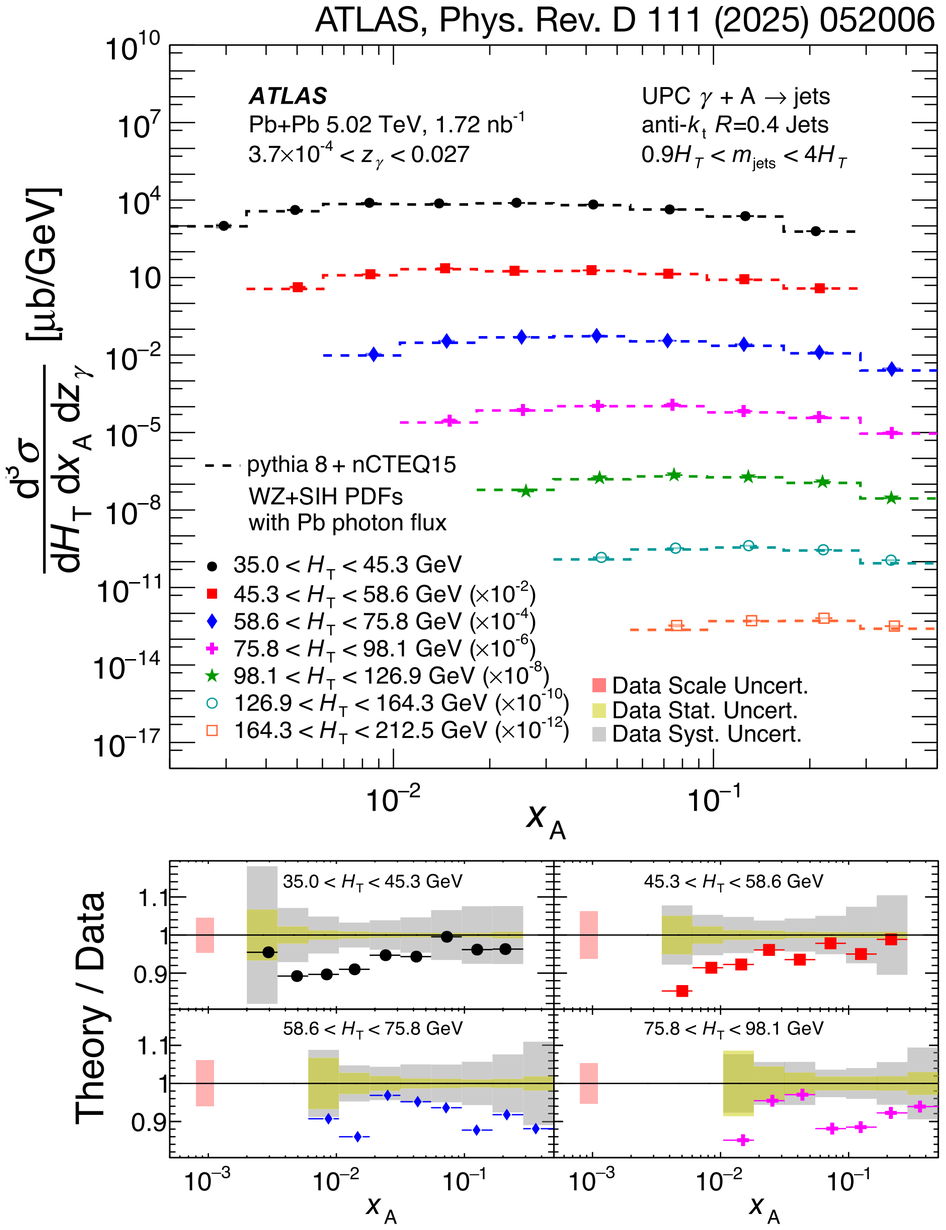
allow for direct & resolved photon contributions

$\sum \Delta\eta < 9$: suppress $\gamma\gamma \to e^+e^-$

Results


ATLAS, Phys. Rev. D 111 (2025) 052006
ATLAS
Pb+Pb 5.02 TeV, 1.72 nb-1
3.7×10-4 < zγ < 0.027
UPC γ + A → jets
anti-kt R=0.4 Jets
0.9HT < mjets < 4HT
pythia 8 + nCTEQ15
WZ+SIH PDFs
with Pb photon flux
35.0 < HT < 45.3 GeV
45.3 < HT < 58.6 GeV (×10-2)
58.6 < HT < 75.8 GeV (×10-4)
75.8 < HT < 98.1 GeV (×10-6)
98.1 < HT < 126.9 GeV (×10-8)
126.9 < HT < 164.3 GeV (×10-10)
164.3 < HT < 212.5 GeV (×10-12)
Data Scale Uncert.
Data Stat. Uncert.
Data Syst. Uncert.
d3σ / dHT dxA dzγ [μb/GeV]
xA
Theory / Data
35.0 < HT < 45.3 GeV
45.3 < HT < 58.6 GeV
58.6 < HT < 75.8 GeV
75.8 < HT < 98.1 GeV

Results

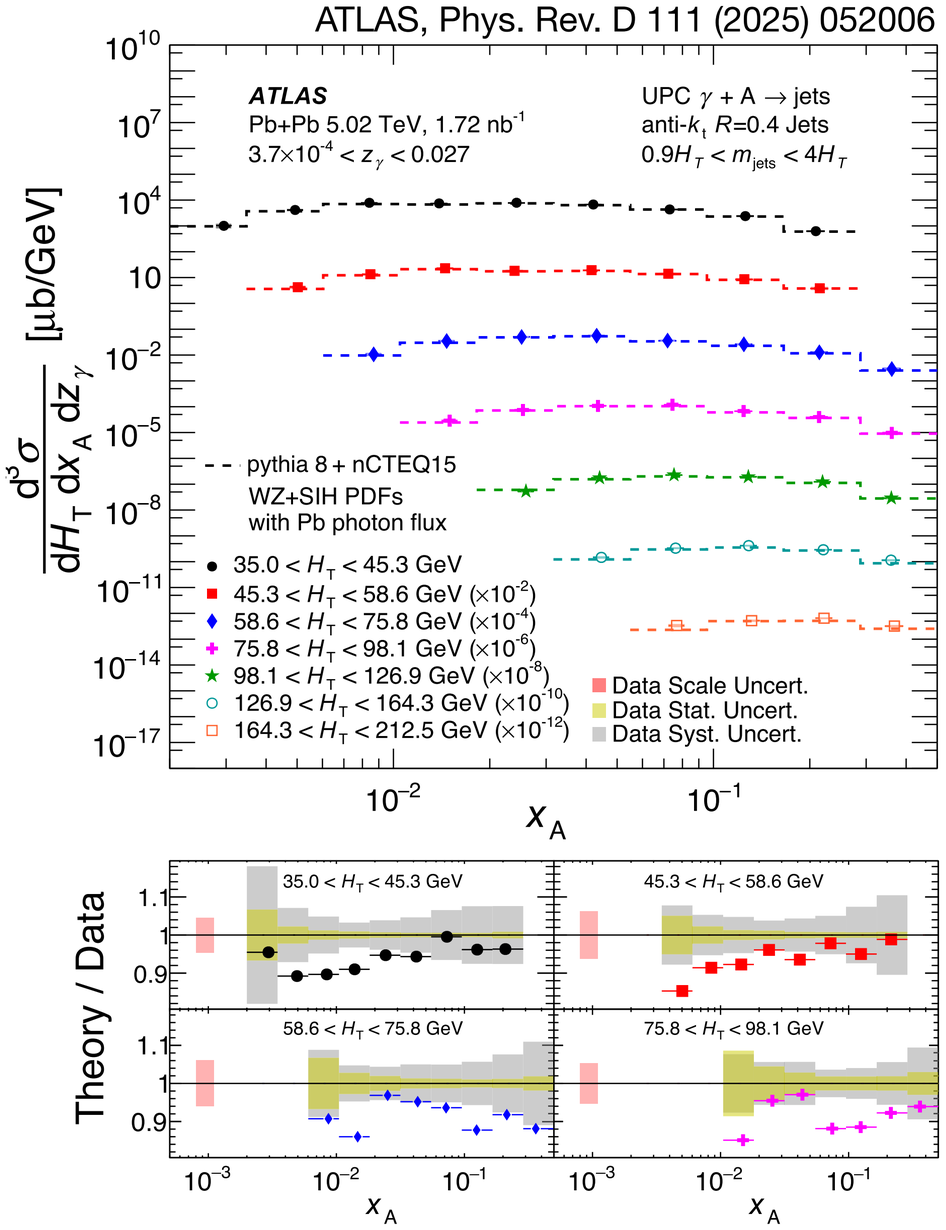


z_γ ~ emitted photon energy fraction

Results also differential in z_γ

→ more robust separation of correlated systematic uncertainties.

Results



z_γ ~ emitted photon energy fraction

Results also differential in z_γ

→ more robust separation of correlated systematic uncertainties.

Theory LO pythia(nCTEQ15)+reweighting for Pb flux:

- underpredicts data in shadowing region.
- better agreement at higher x_A.

With NLO pQCD calculations and PS corrections

→ include data in global nPDF fits.

Summary

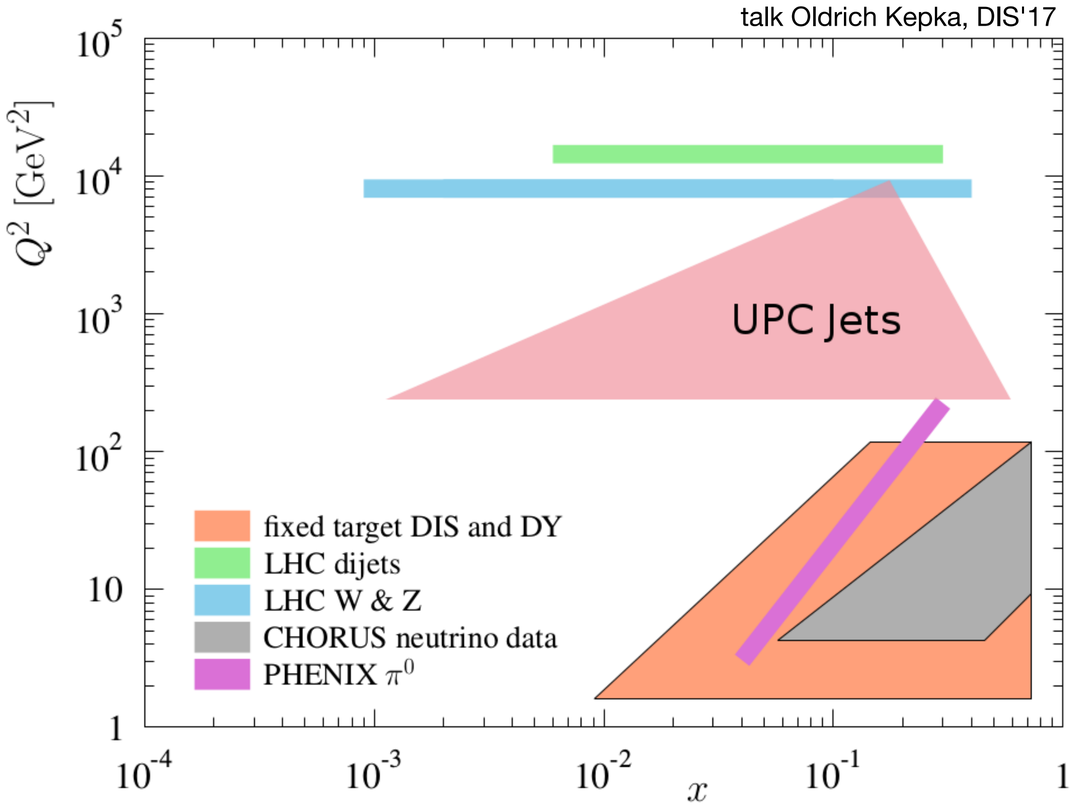
- Vast complementarity between LHC UPC and EIC measurements:
  - EIC provides high precision and polarisation
  - LHC covers otherwise unaccessible low-x_B region
  - Potential pQCD UPC measurements at (polarised) fixed target: coverage of large-x_B region

- EIC: large variety of nuclei

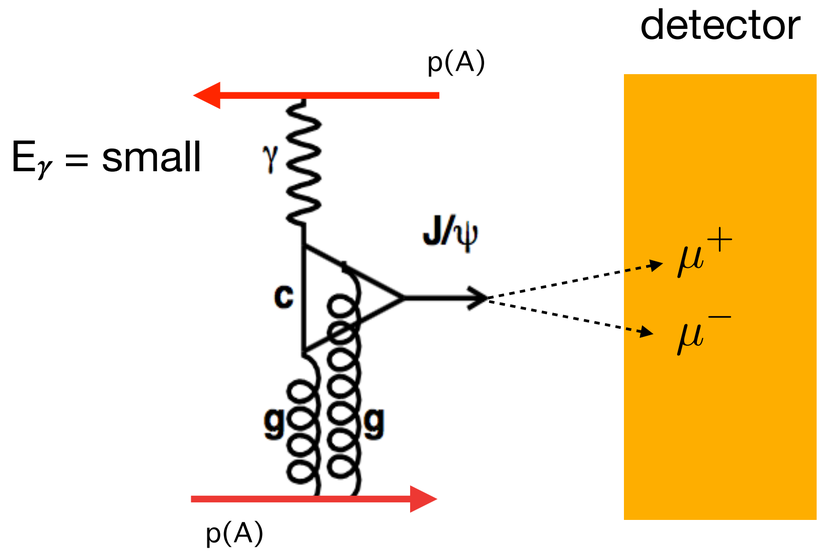
  —> valuable for study of nuclear effects
- Fixed target also covers variety of nuclei, at large x_B —> complementary channel

Back up

Kinematic coverage jets

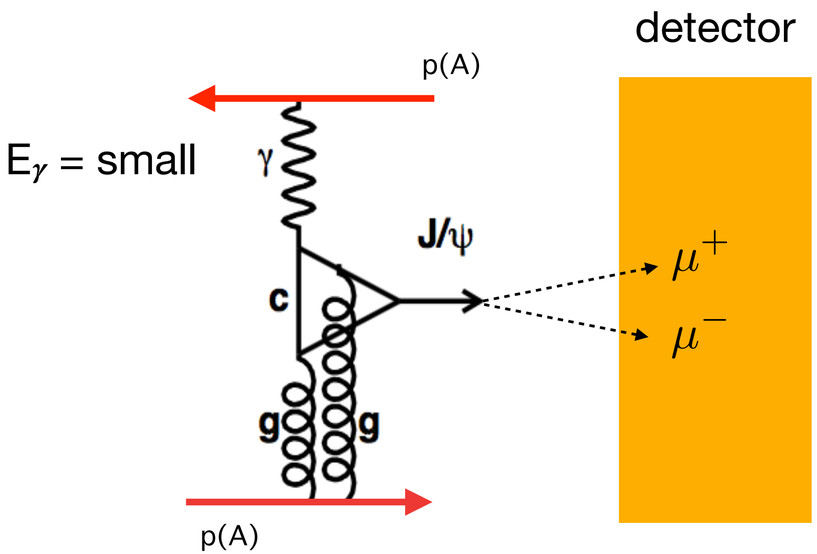


Disentangling the ambiguity on the ID of the γ emitter



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

Disentangling the ambiguity on the ID of the γ emitter



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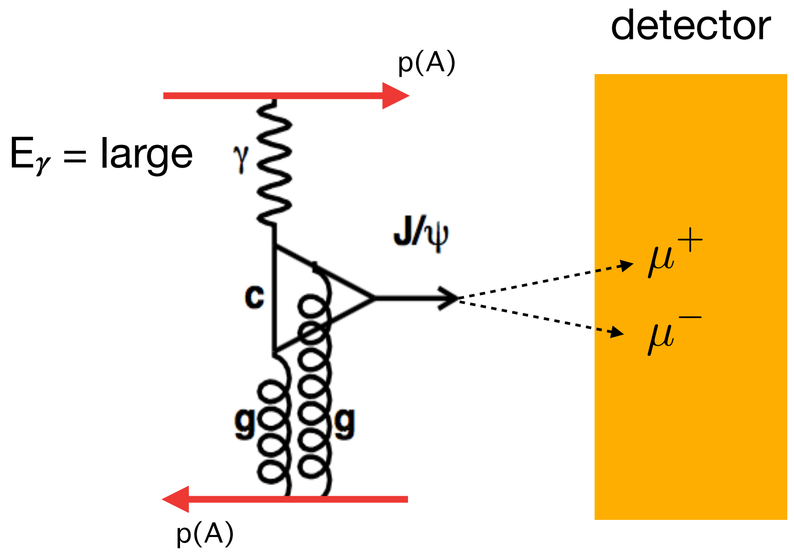

$$E_{\gamma,l} = \frac{M_{J/\psi}}{2} e^{+y}$$

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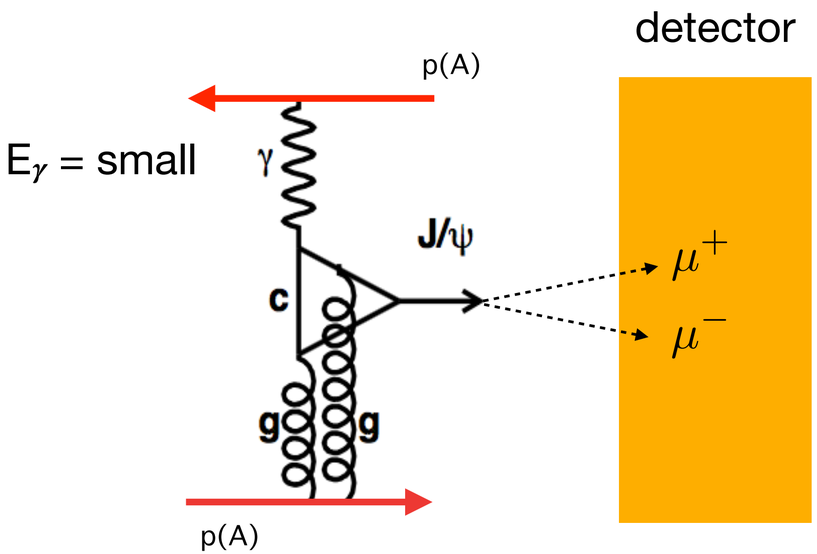

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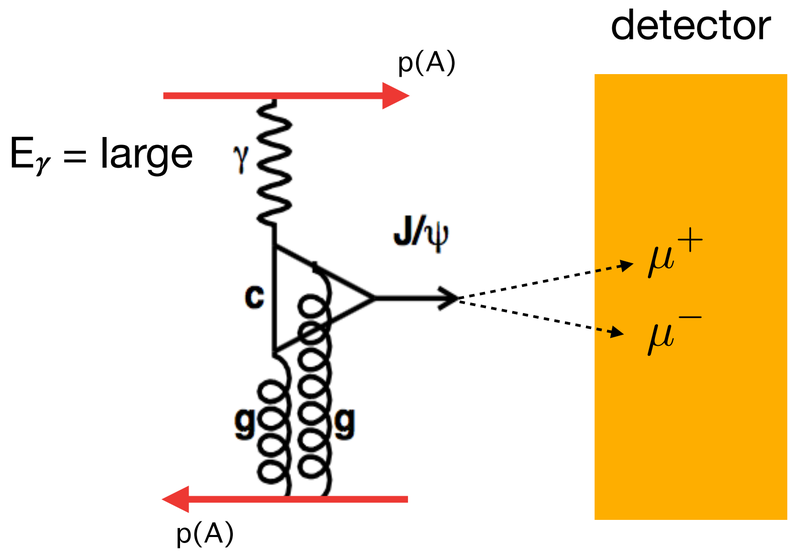

$$E_{\gamma,l} = \frac{M_{J/\psi}}{2} e^{+y}$$

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

Disentangling the ambiguity on the ID of the γ emitter

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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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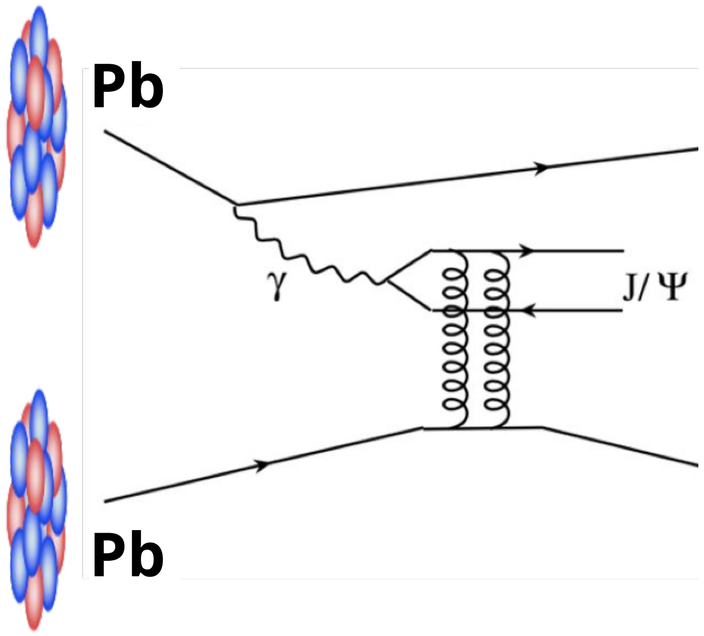

Picture from André Ståhl

Disentangling the ambiguity on the ID of the γ emitter

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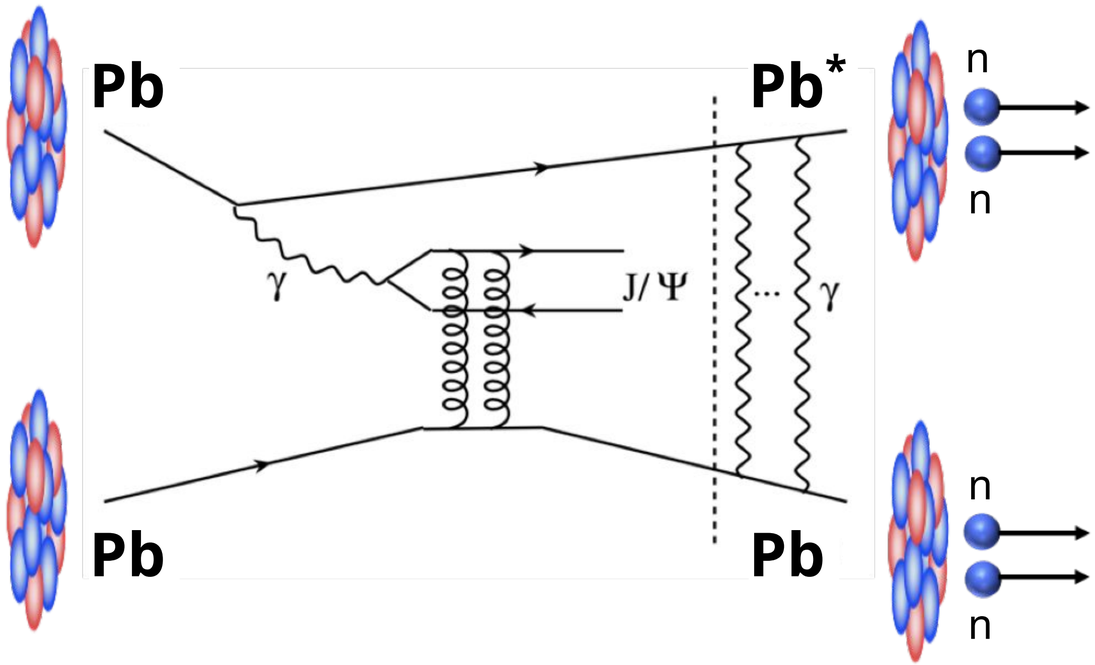
Small impact parameter, b ⟶ higher probability for exciting ($\propto 1/b^2$) ⟶ higher probability to emit neutrons.



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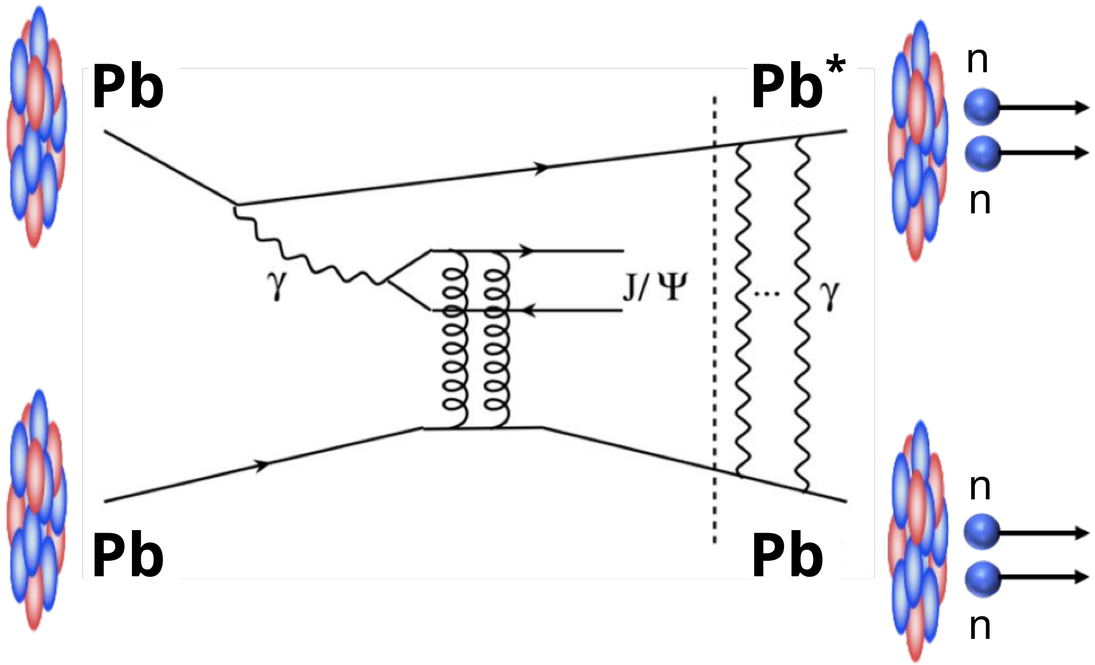
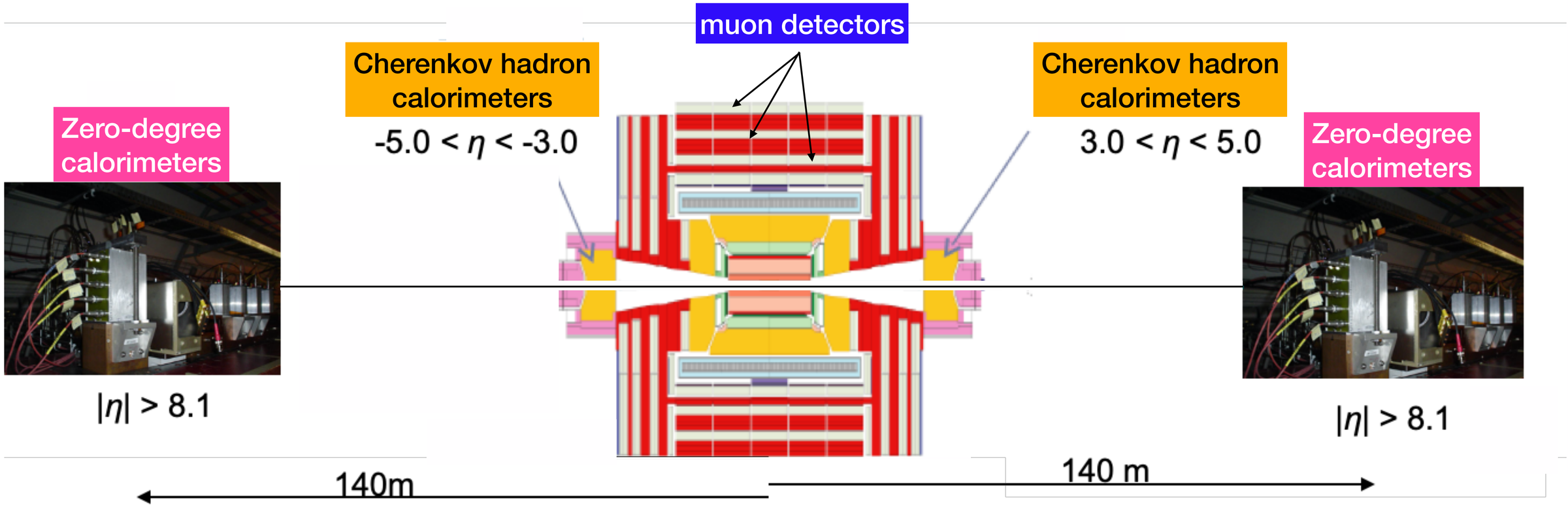


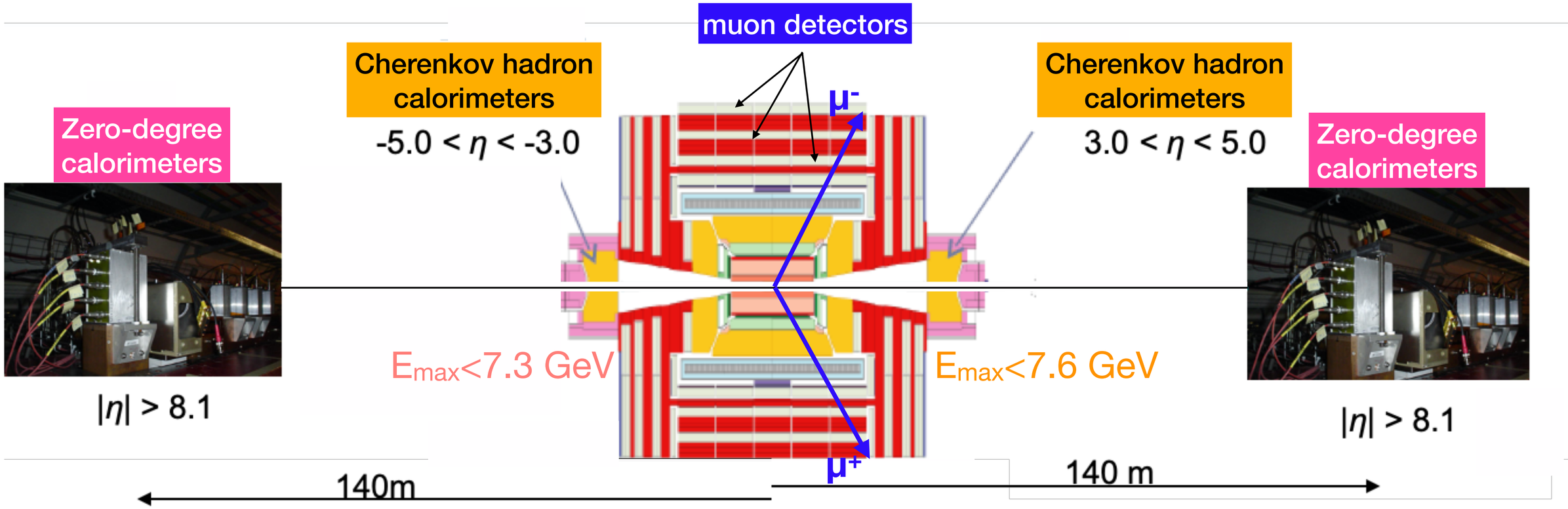
⟶ Make measurement with possibility to detect neutrons

Picture from André Ståhl

CMS central detector and the (far-)forward region

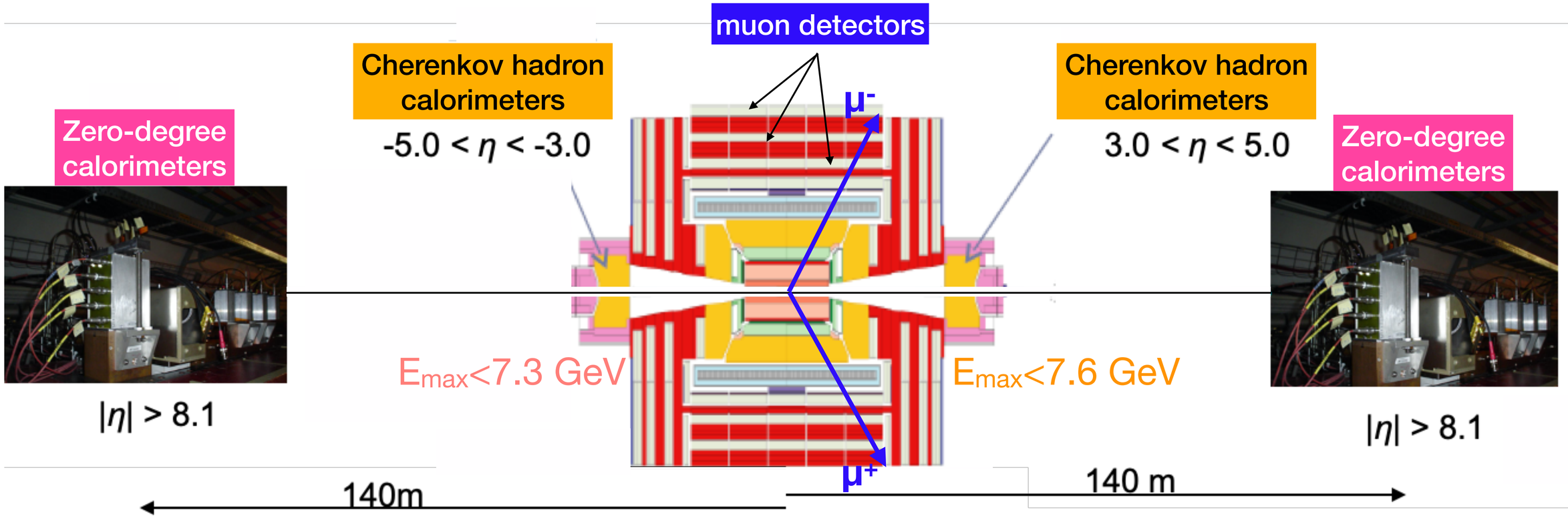


CMS central detector and the (far-)forward region



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

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 γ 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 γ emitter

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

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measured

computed (StarLight)

computed (StarLight)

Disentangling the ambiguity on the ID of the γ emitter

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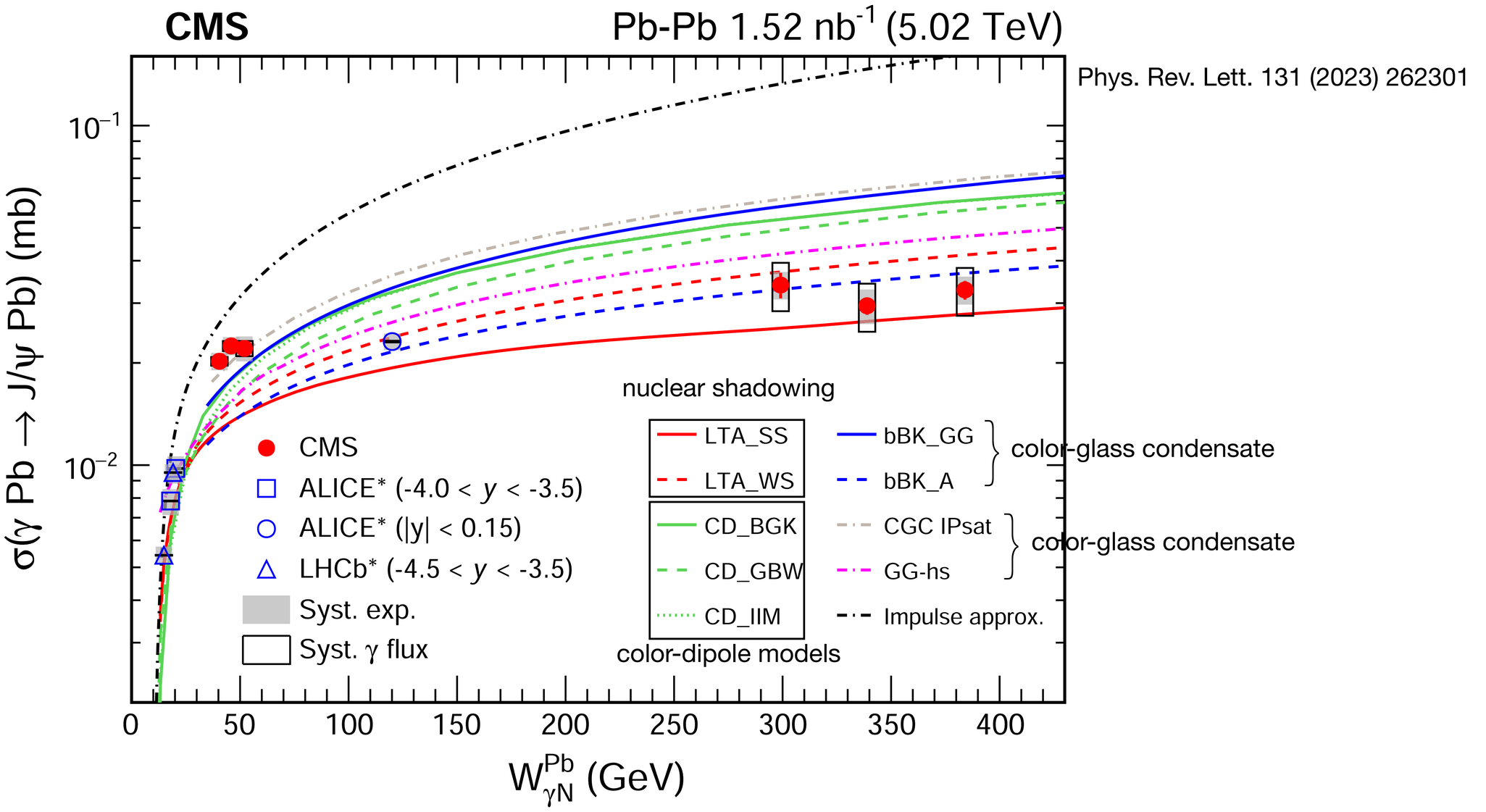
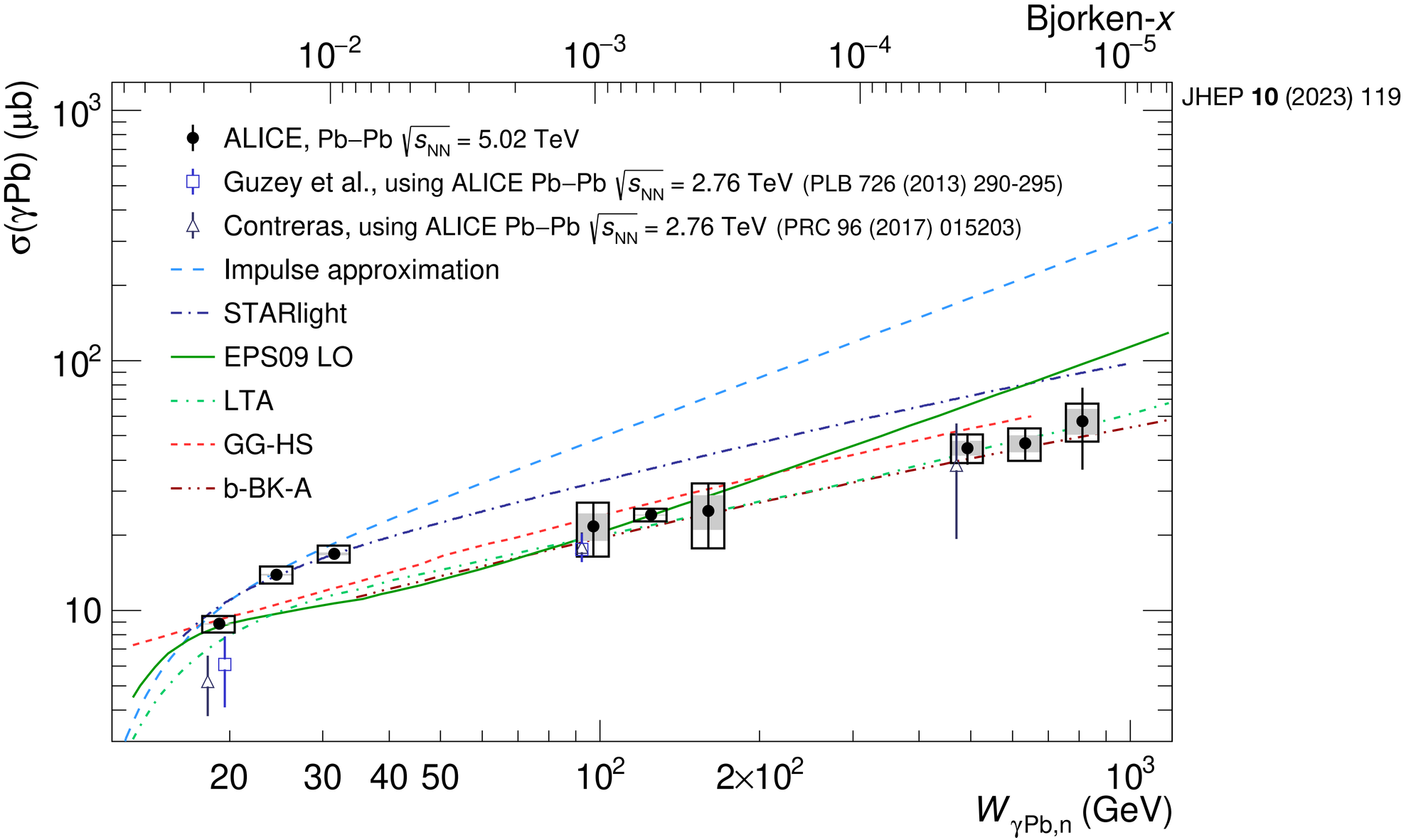
measured | **computed (StarLight)** | **extracted** | **computed (StarLight)** | **extracted**

CMS: γPb cross section, energy dependence



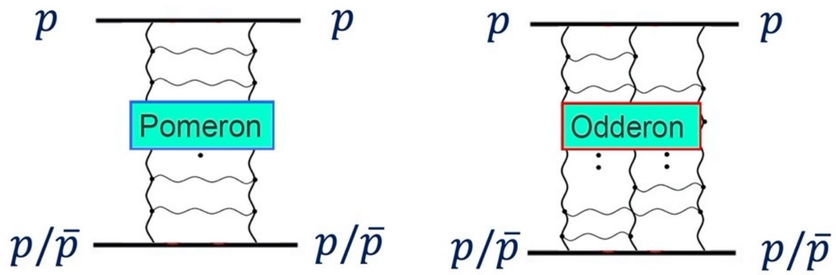
ALICE: γPb cross section, energy dependence



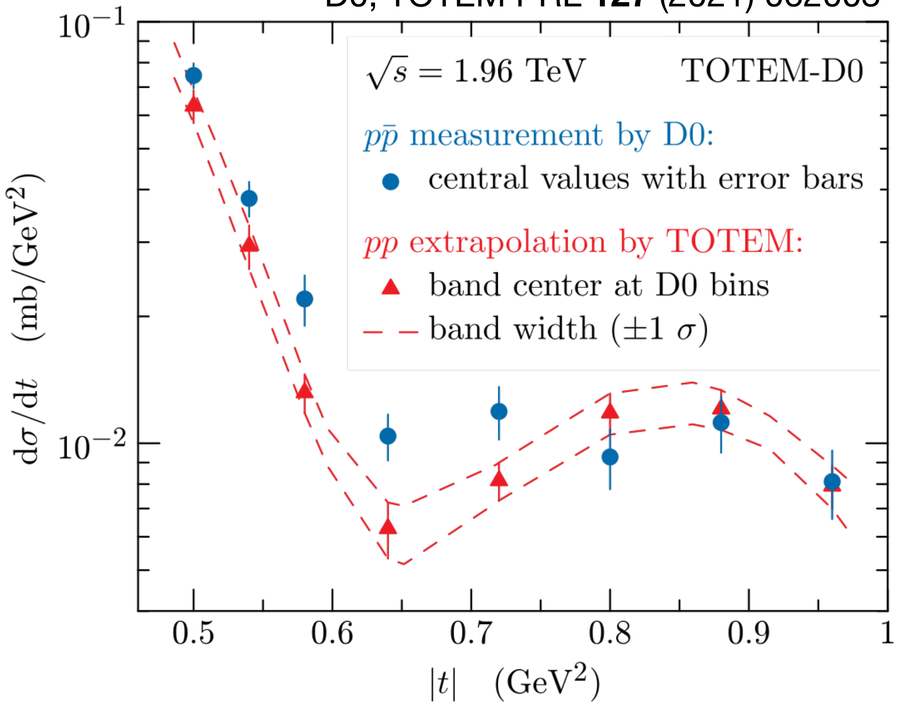
JHEP **10** (2023) 119

Search for the Odderon

hadron-hadron collisions



D0, TOTEM PRL **127** (2021) 062003



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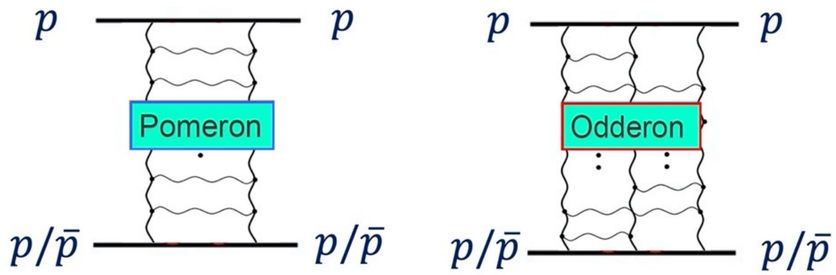

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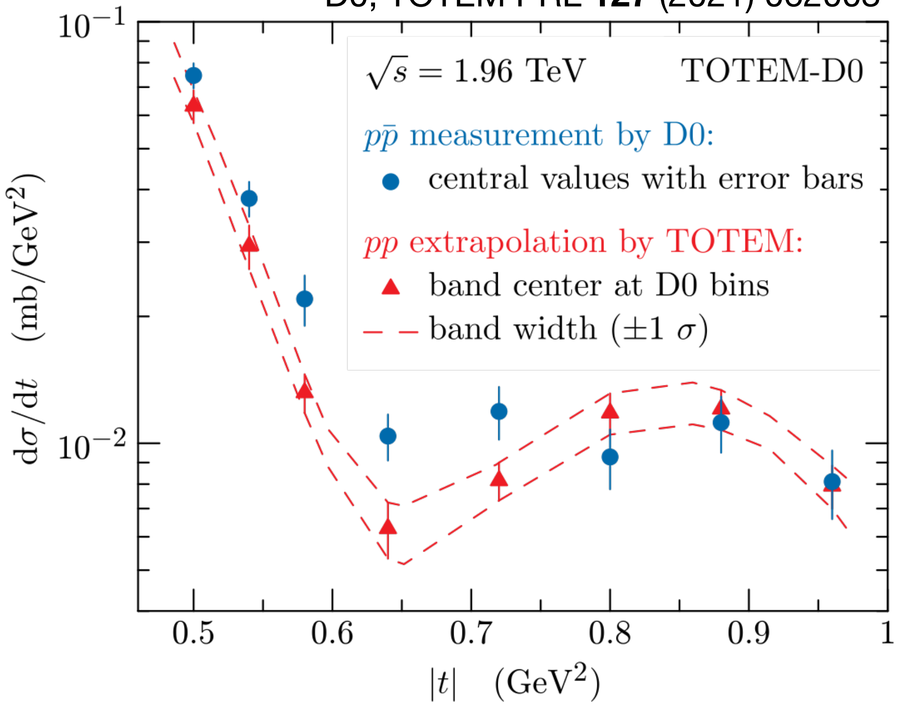

also e.g., f_2 in pA and AA collisions

R. McNulty et al., EPJC **80** (2020) 288

Search for the Odderon

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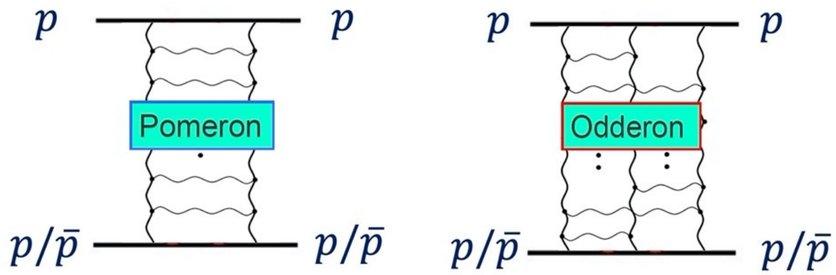

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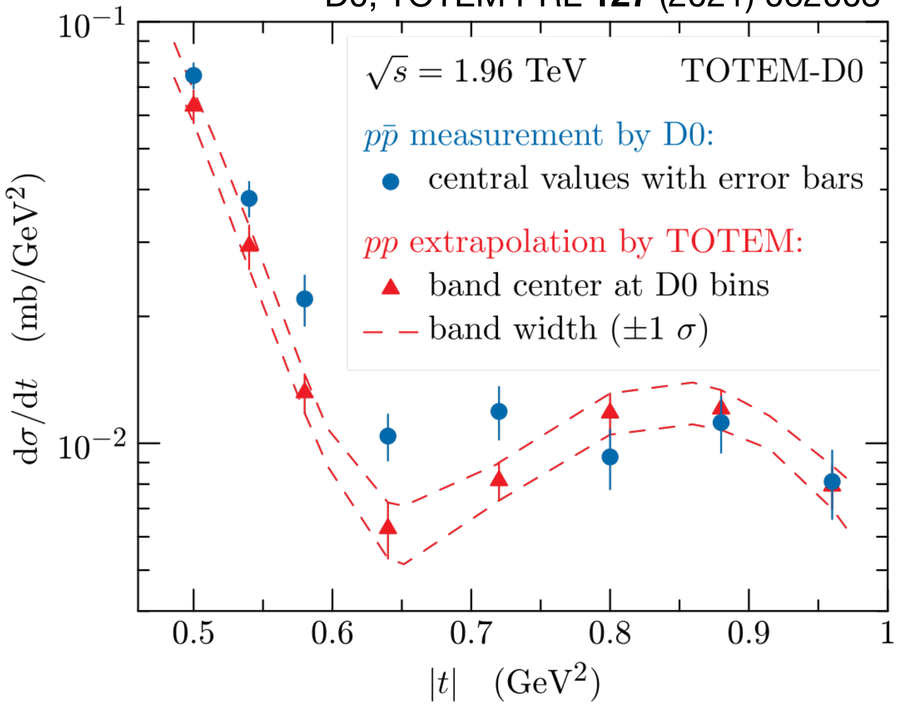

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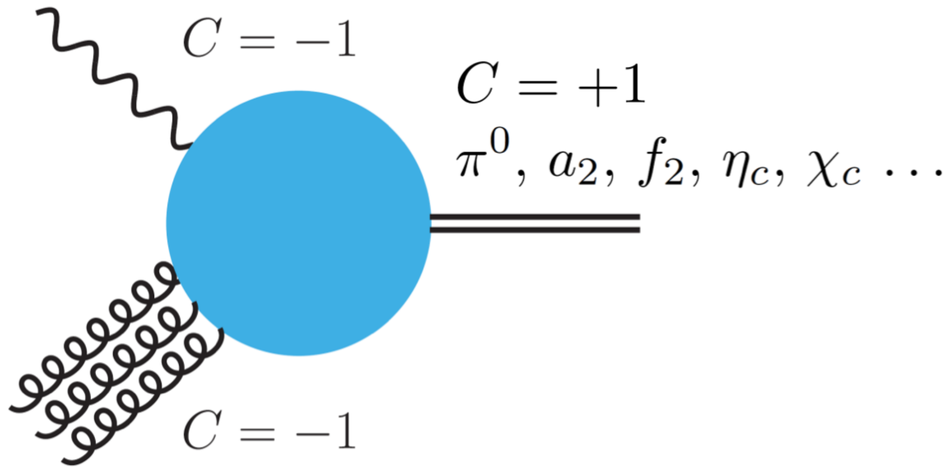
R. McNulty et al., EPJC **80** (2020) 288

deep-inelastic scattering



offers more theoretical control

Measurement by H1

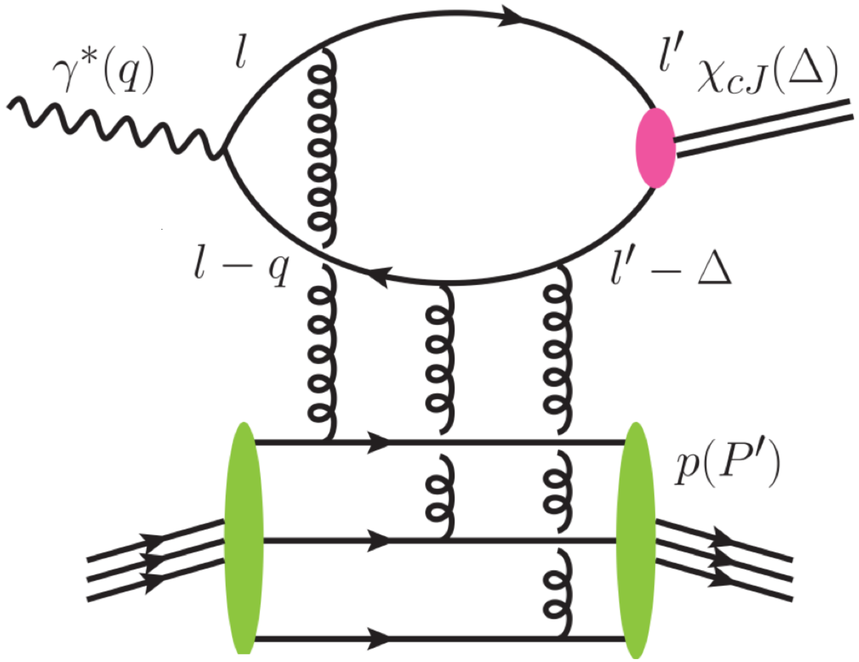
Phys. Lett. B **544** (2002) 35–43

$\sigma(\gamma^* p \to \pi^0 N^*) < 39$ nb

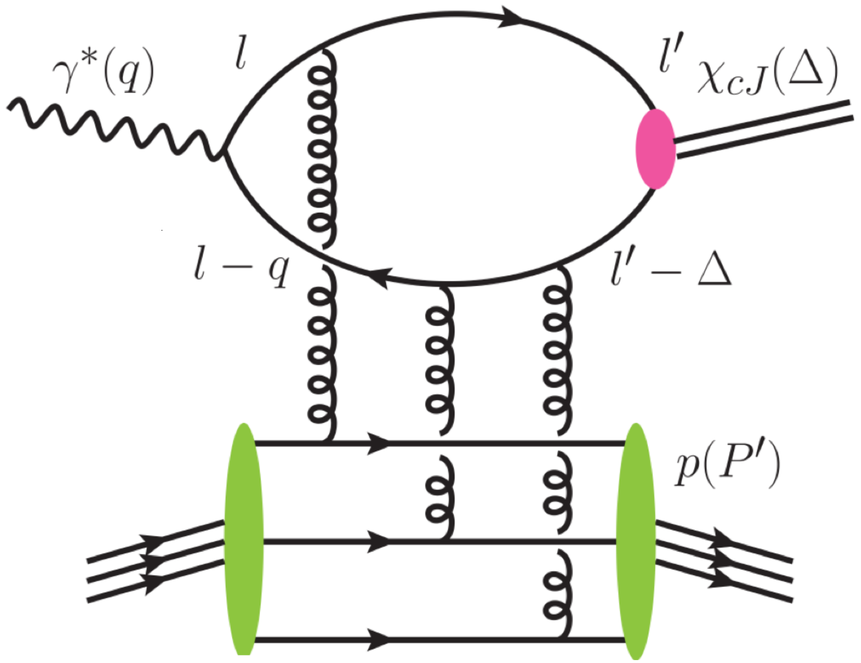
$\sigma(\gamma^* p \to f_2 X) < 16$ nb

$\sigma(\gamma^* p \to a_2 X) < 96$ nb

Search for the Odderon at the EIC



Search for the Odderon at the EIC



S. Beníc et al., arXiv:2402.19134