Exclusive quarkonium production at the EIC and LHC

Charlotte Van Hulse
VUB

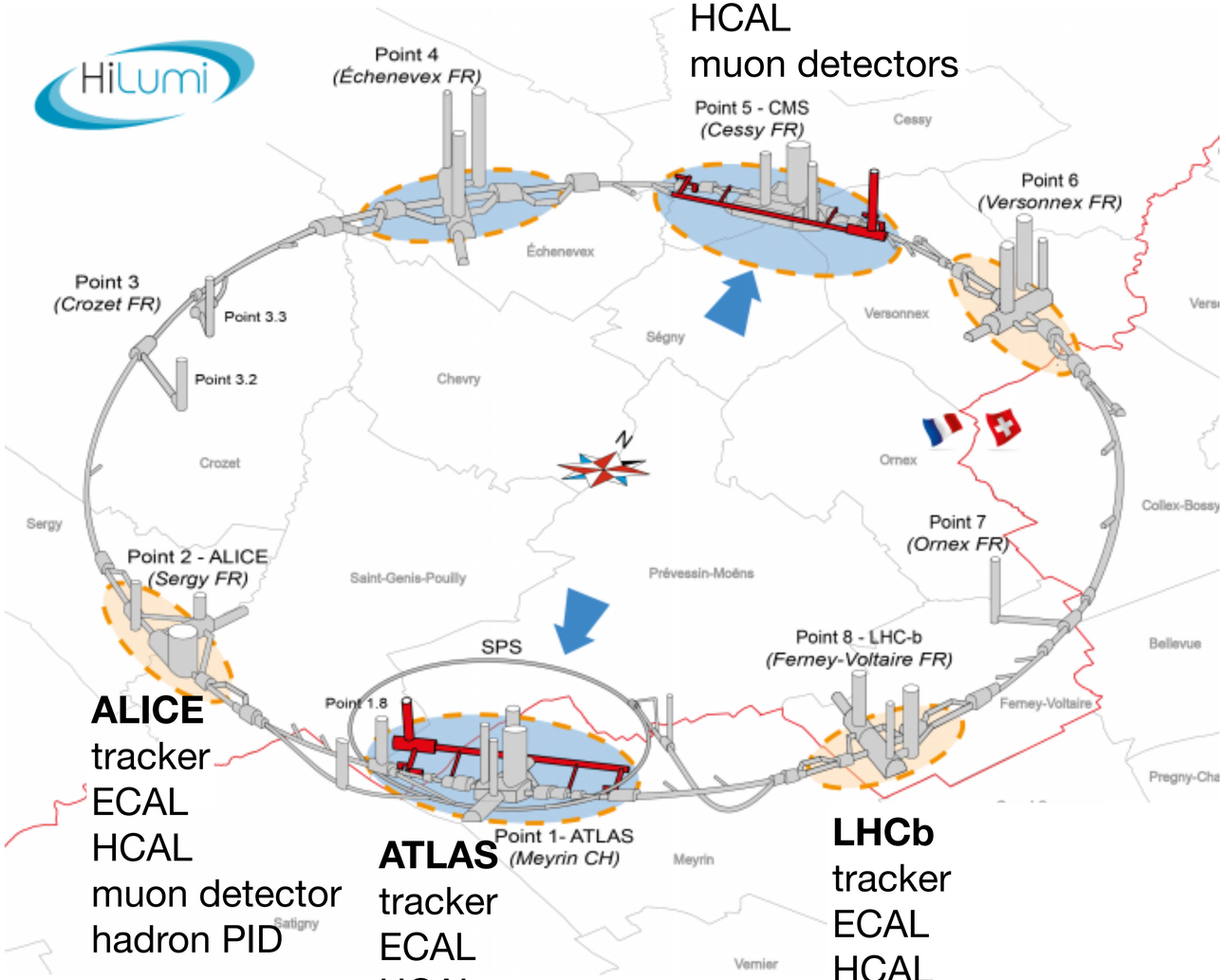
ODYSSEUS Top science in Flanders fwo

Workshop on the Physics Program with High Luminosity Facilities
October 5 – 9, 2026
Jefferson Lab

The high-lumi LHC

A. Dainese et al., CERN Yellow Reports: Vol. 7 (2019)

CMS
tracker
ECAL
HCAL
muon detectors



ALICE
tracker
ECAL
HCAL
muon detector
hadron PID

ATLAS
tracker
ECAL
HCAL
muon detector

LHCb
tracker
ECAL
HCAL
muon detector
hadron PID

pp collisions

$\sqrt{s} = 14$ TeV

ATLAS/CMS $\mathscr{L} : 5 \cdot 10^{34}$ cm^{-2} s^{-1} $\rightarrow \mathscr{L}_{\text{int}} : 3000$ fb^{-1}

LHCb $\mathscr{L} : 2 \cdot 10^{33}/2 \cdot 10^{34}$ cm^{-2} s^{-1} $\rightarrow \mathscr{L}_{\text{int}} : 300$ fb^{-1}

PbPb collisions

$\sqrt{s_{NN}} = 5.5$ TeV

ALICE/ATLAS/CMS RUN4: $\mathscr{L}_{\text{int}} : 6.8$ nb^{-1}

LHCb RUN4: $\mathscr{L}_{\text{int}} : 1.0$ nb^{-1}

pPb collisions

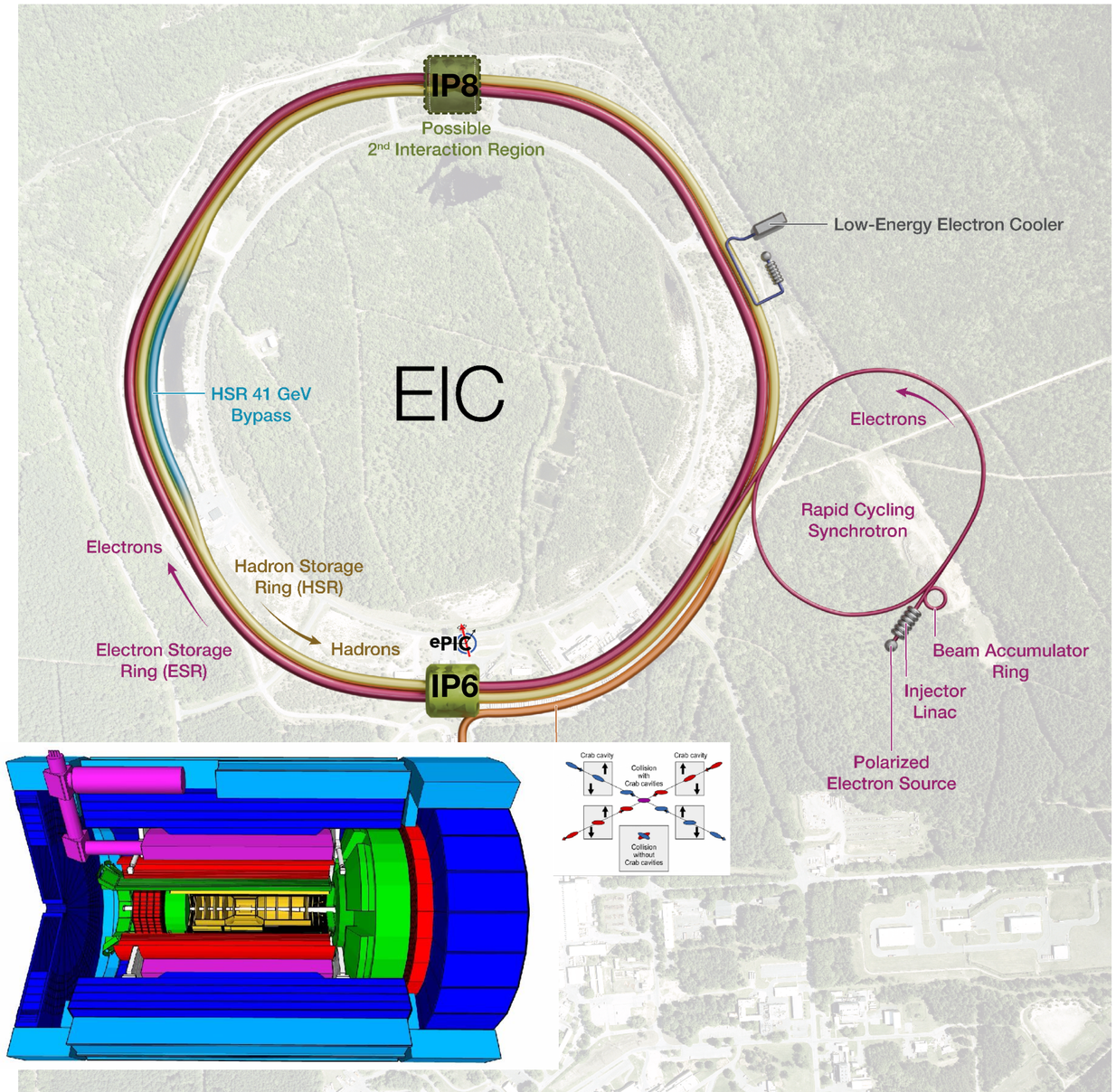
$\sqrt{s_{NN}} = 8.8$ TeV

ATLAS/CMS RUN4: $\mathscr{L}_{\text{int}} : 0.6$ pb^{-1}

ALICE/LHCb RUN4: $\mathscr{L}_{\text{int}} : 0.3$ pb^{-1}

Also pO and OO runs and possibly other intermediate-mass nuclei such as Ar-Ar

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

  $\rightarrow \sqrt{s} = 29 - 100$ GeV (140 GeV upgradable)

- $\mathscr{L} = 10^{33} - 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

  $\rightarrow \mathscr{L}_{\mathrm{int}} = 10 - 100\ \mathrm{fb}^{-1}/\mathrm{year}$

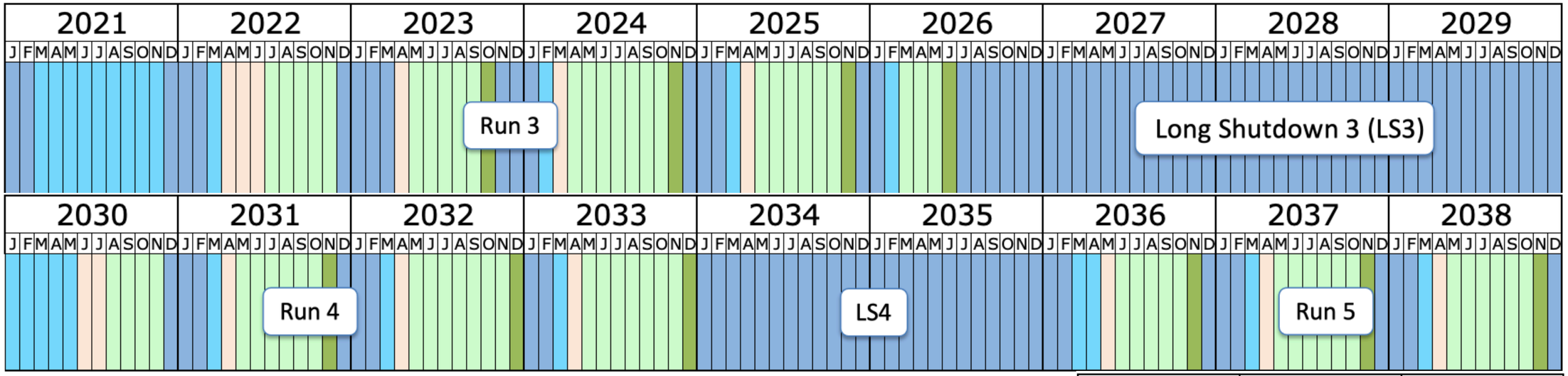
- $\vec{e} + \vec{p}^{\uparrow},\ \overrightarrow{He}^{\uparrow}$

  ~ 70% polarisation

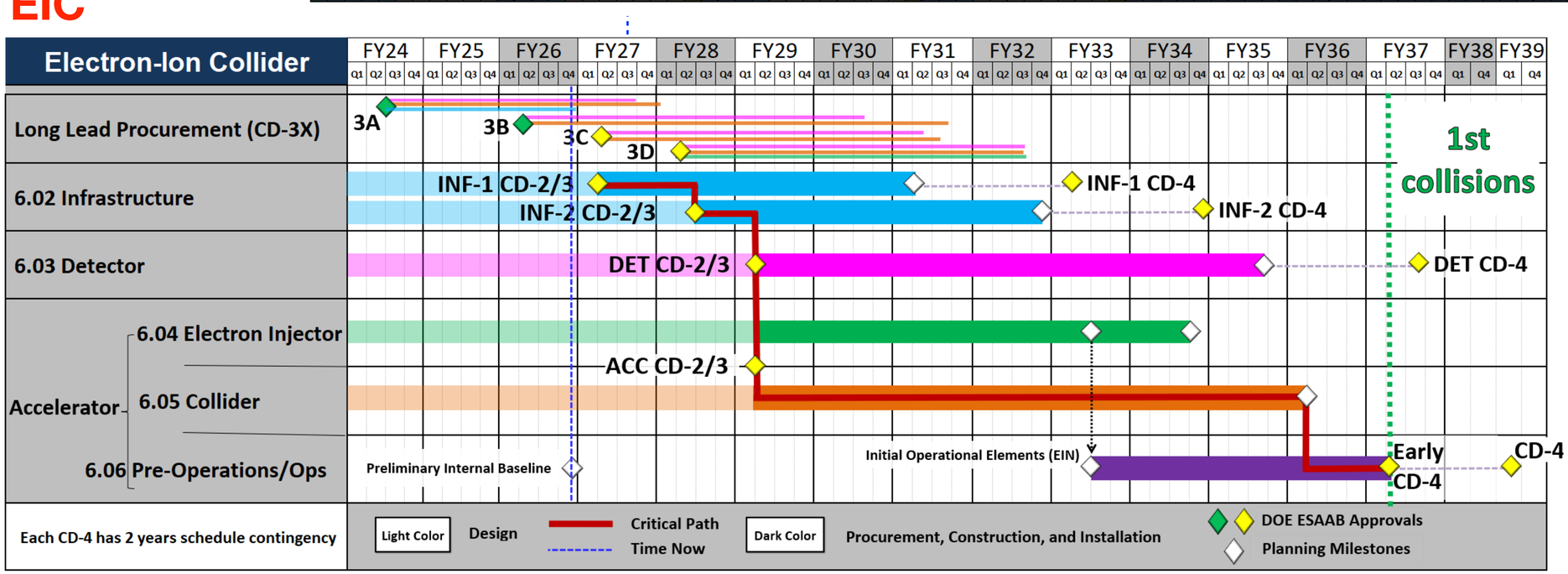
  + heavier, unpolarised ions, up to Uranium

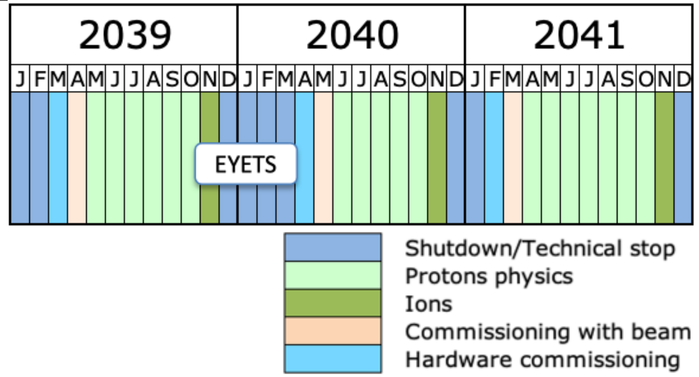
Timelines

LHC

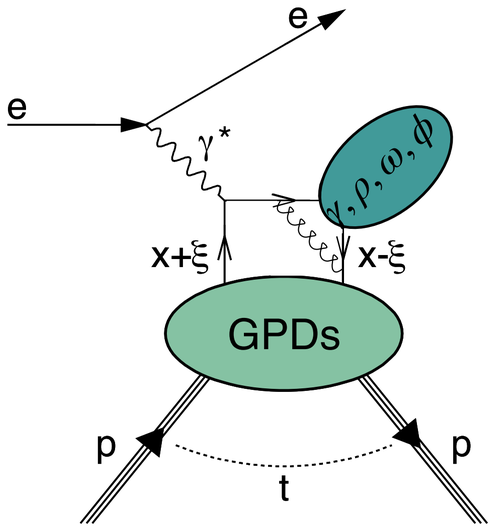


EIC



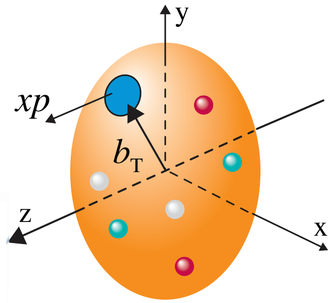


Exclusive processes

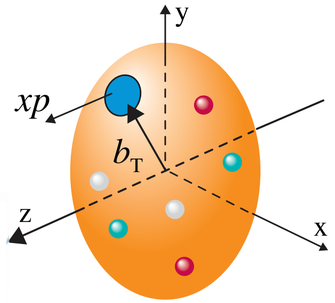


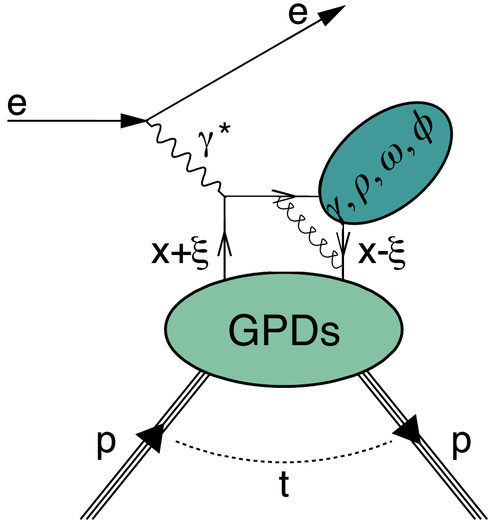
Hard exclusive meson production

Hard scale=large Q^2

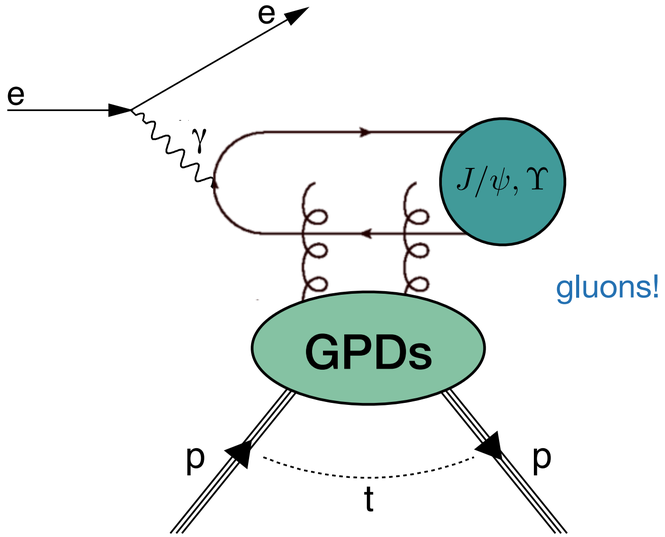


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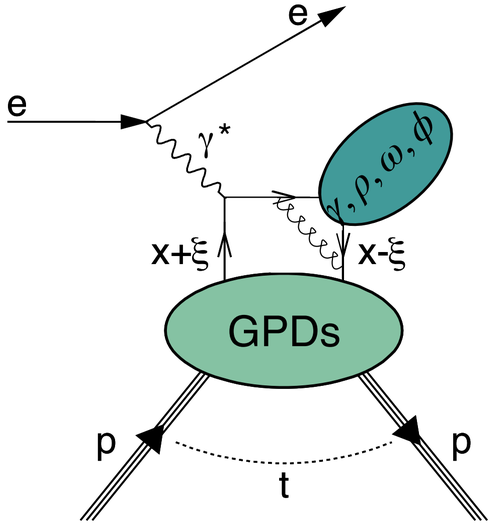
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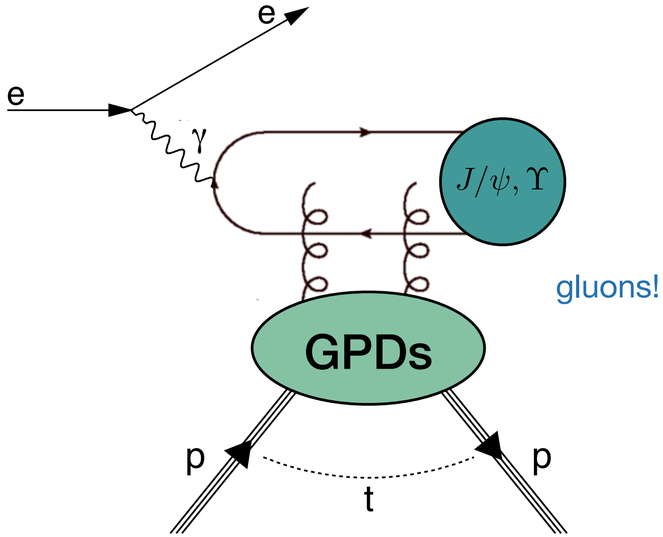
gluons!

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

Exclusive processes

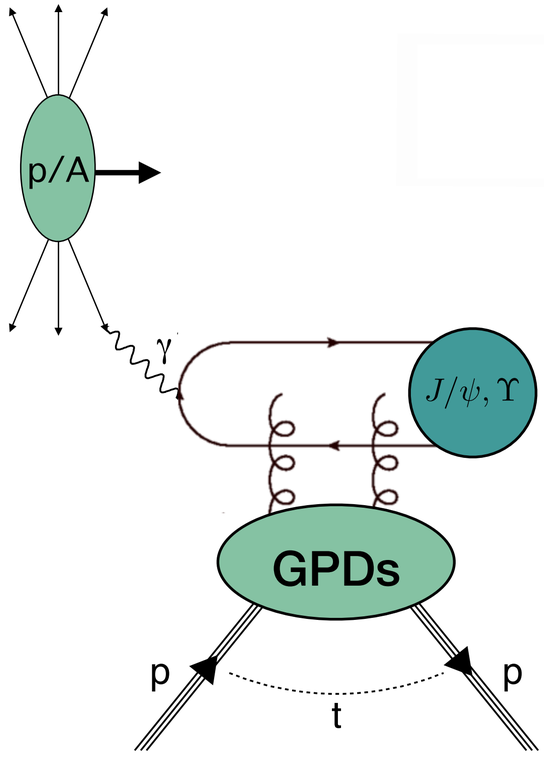


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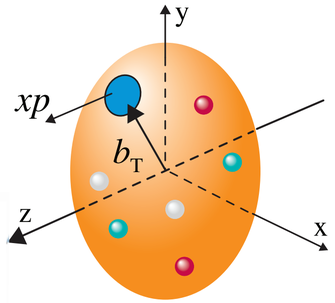


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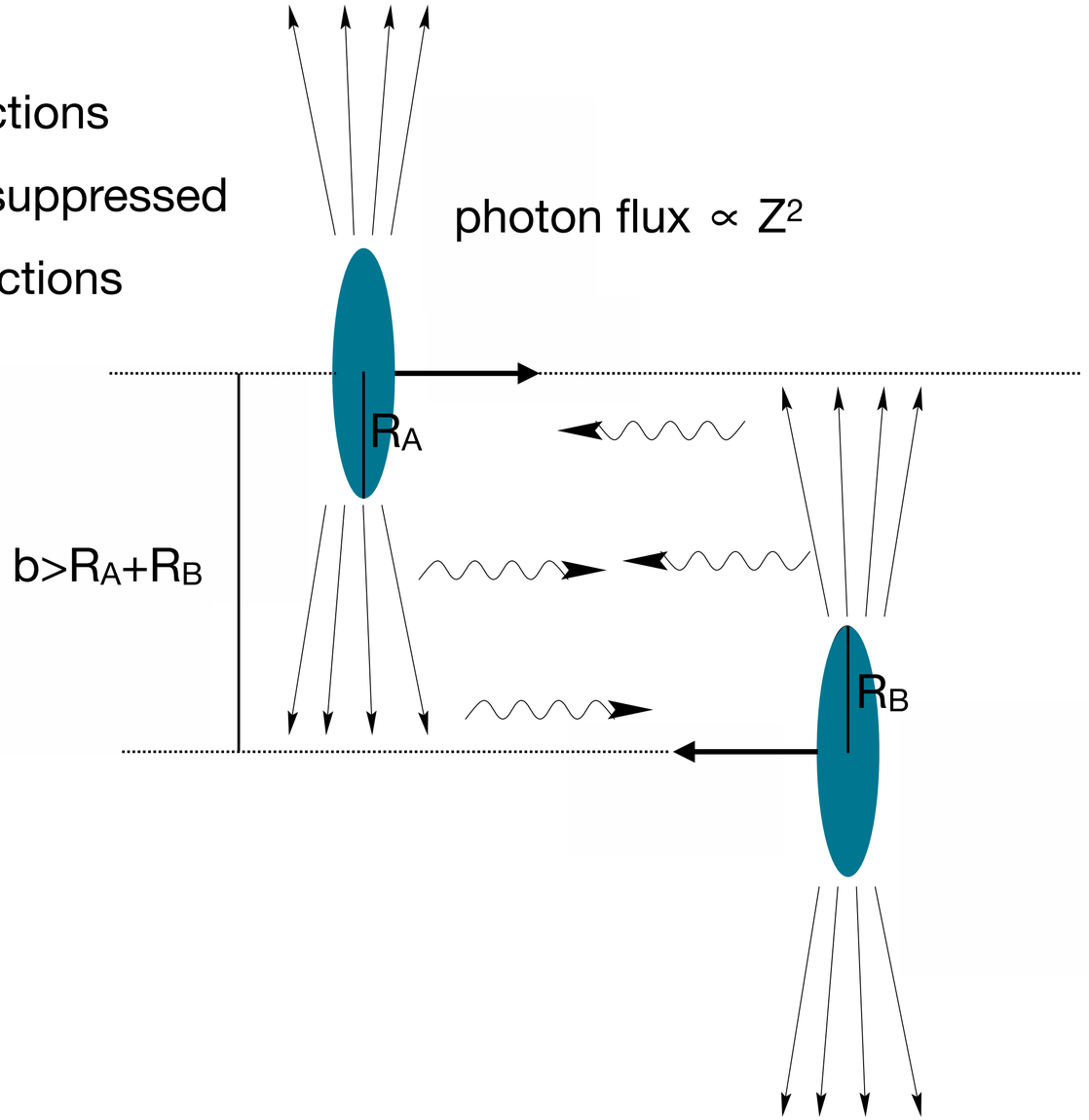


Ultra-peripheral collisions (UPCs)

large–impact-parameter interactions

hadronic interactions strongly suppressed

instead: electromagnetic interactions

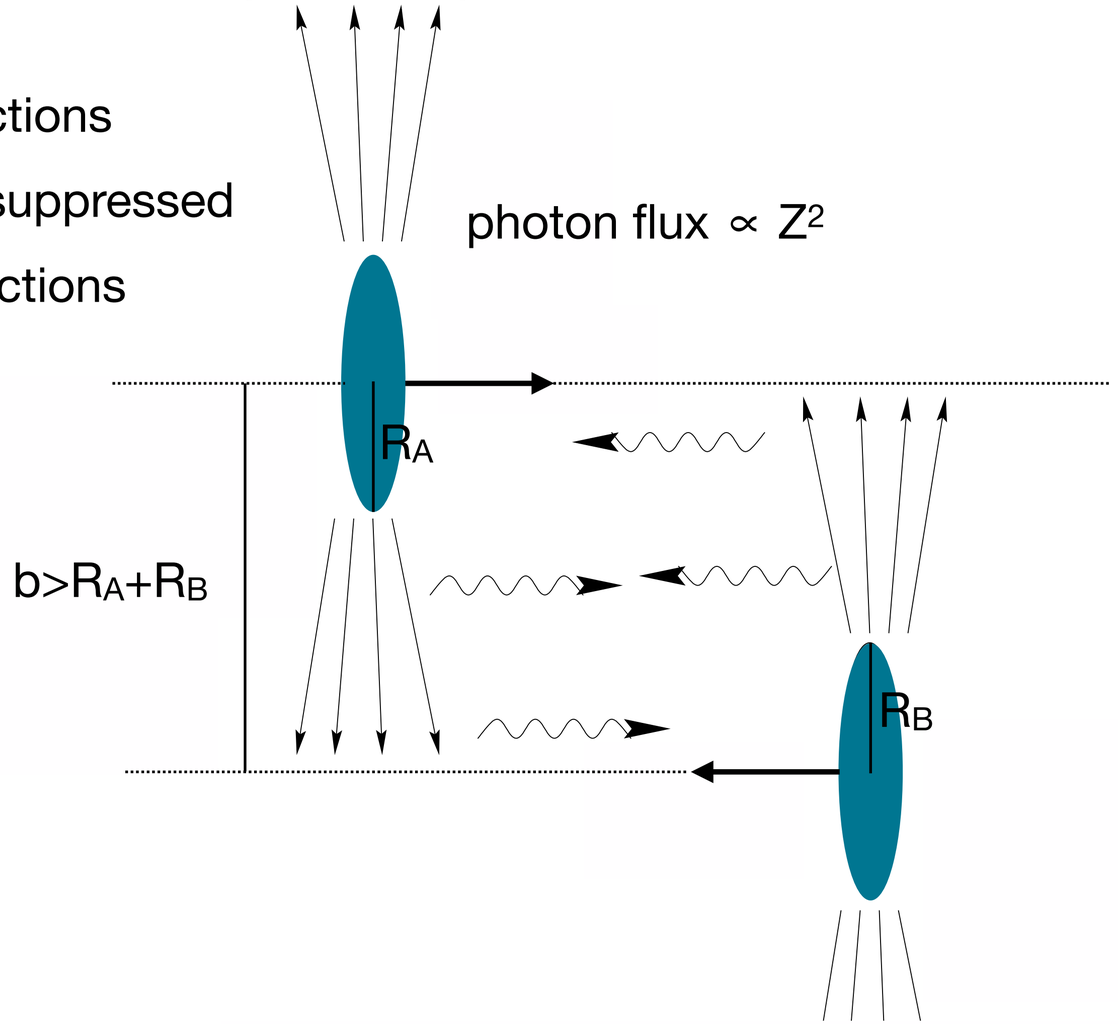


Ultra-peripheral collisions (UPCs)

large–impact-parameter interactions

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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) $E_{\gamma Max}$	(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

Kinematic coverage

- hard scale of the interaction:

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

photoproduction

- Bjorken-x variable:

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

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

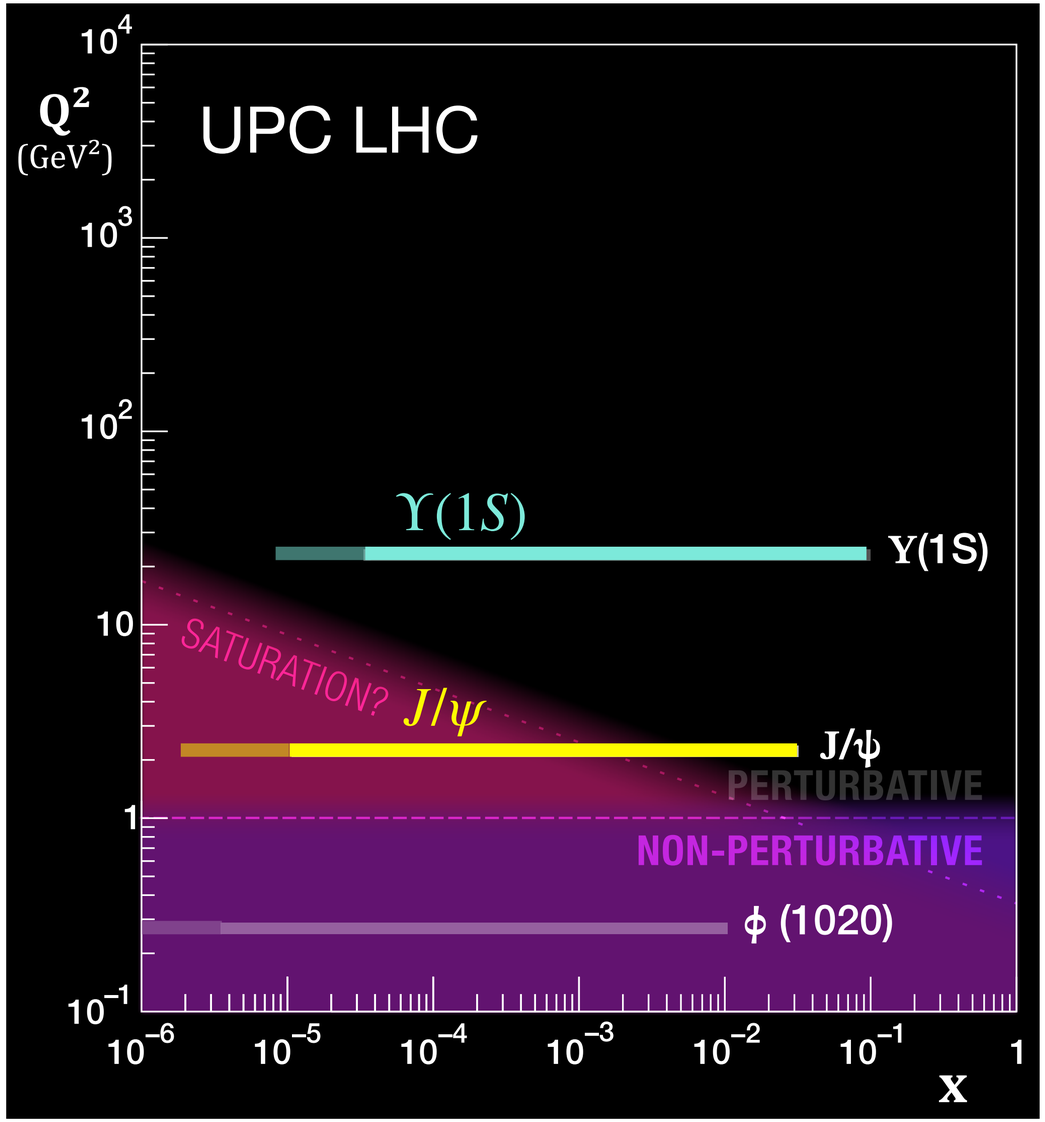


Figure adapted from Jordan Lang | Quarkonia as Tools 2026 | 6 January 2026

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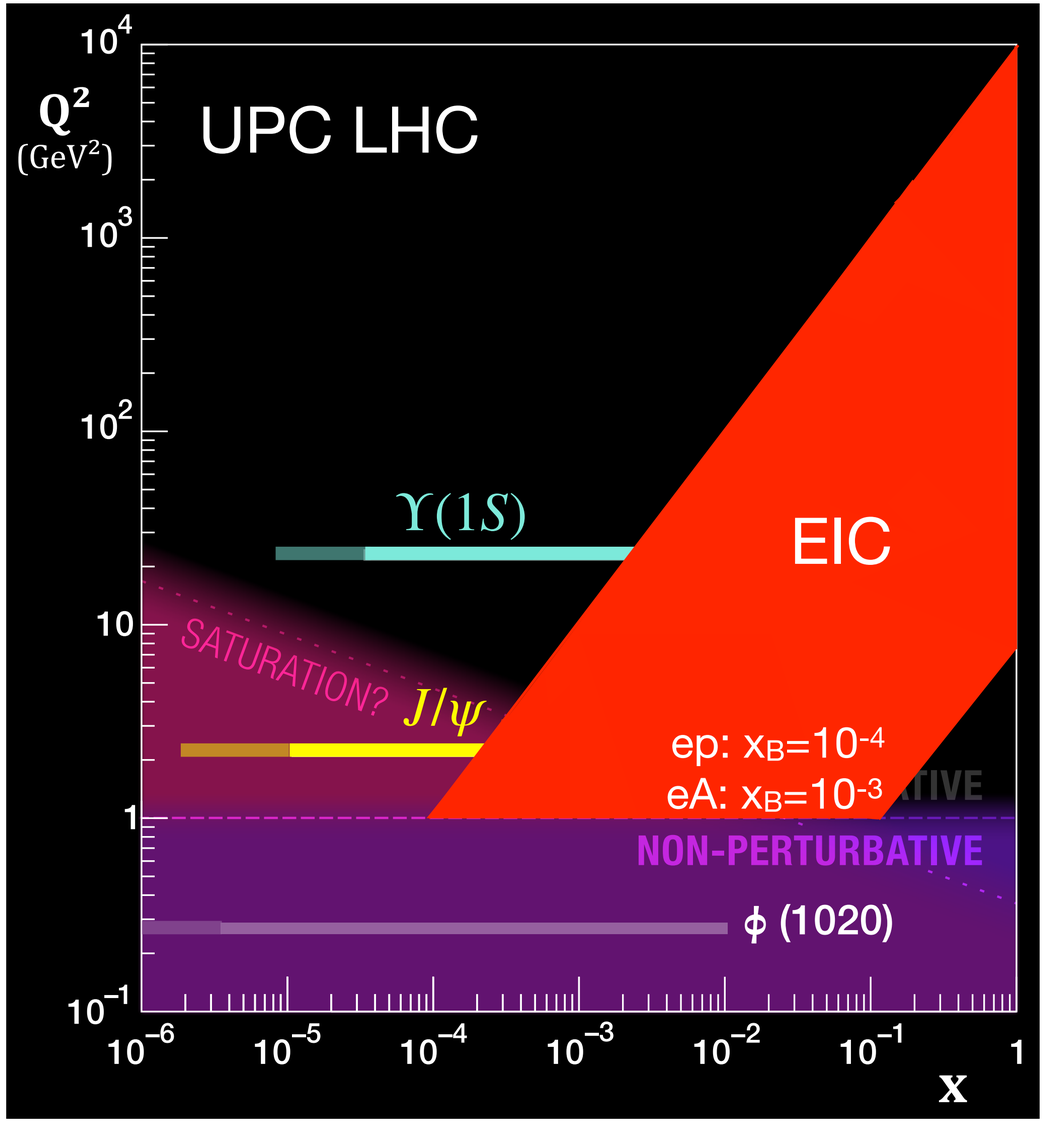
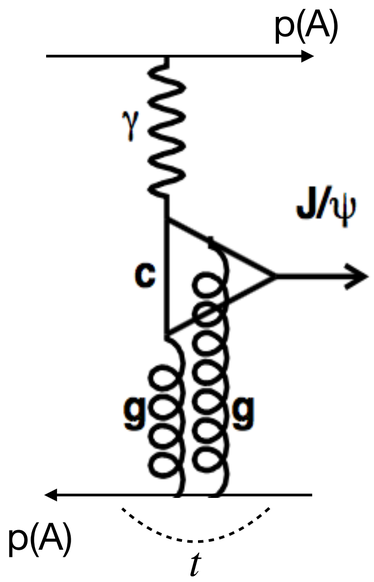
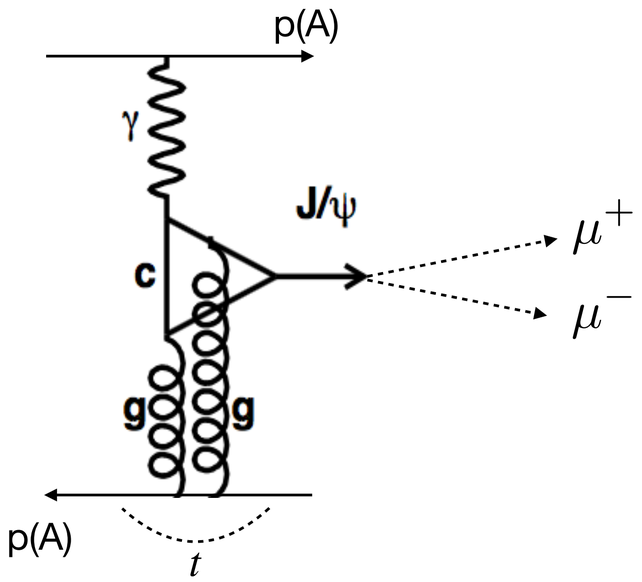


Figure adapted from Jordan Lang | Quarkonia as Tools 2026 | 6 January 2026

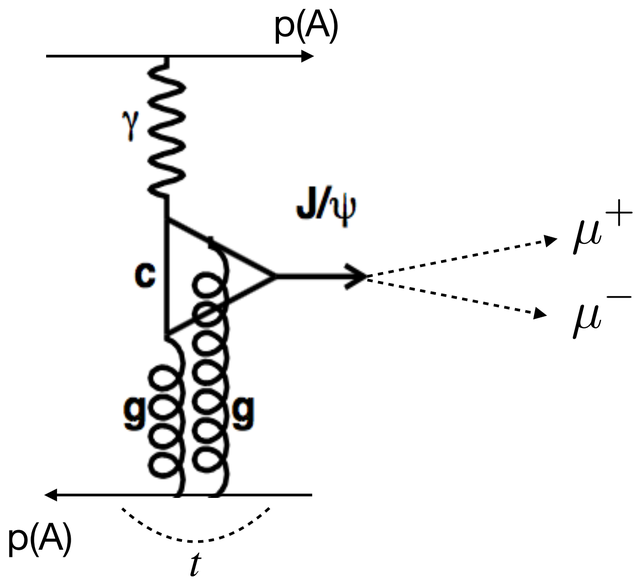
Experimental signature at the LHC



Experimental signature at the LHC

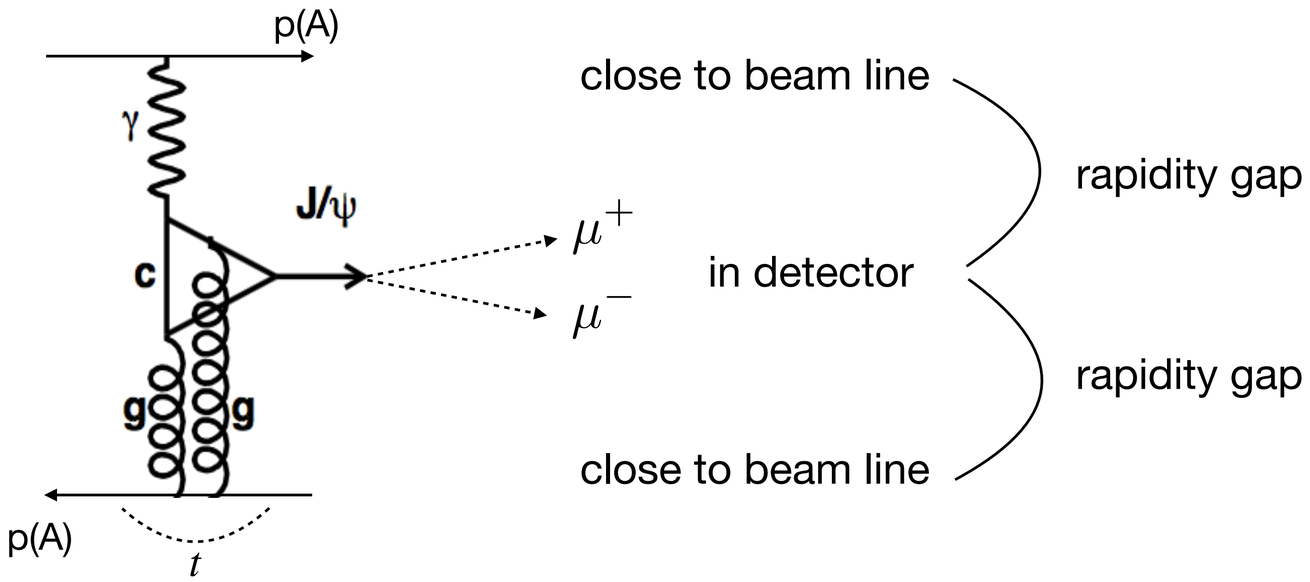


Experimental signature at the LHC

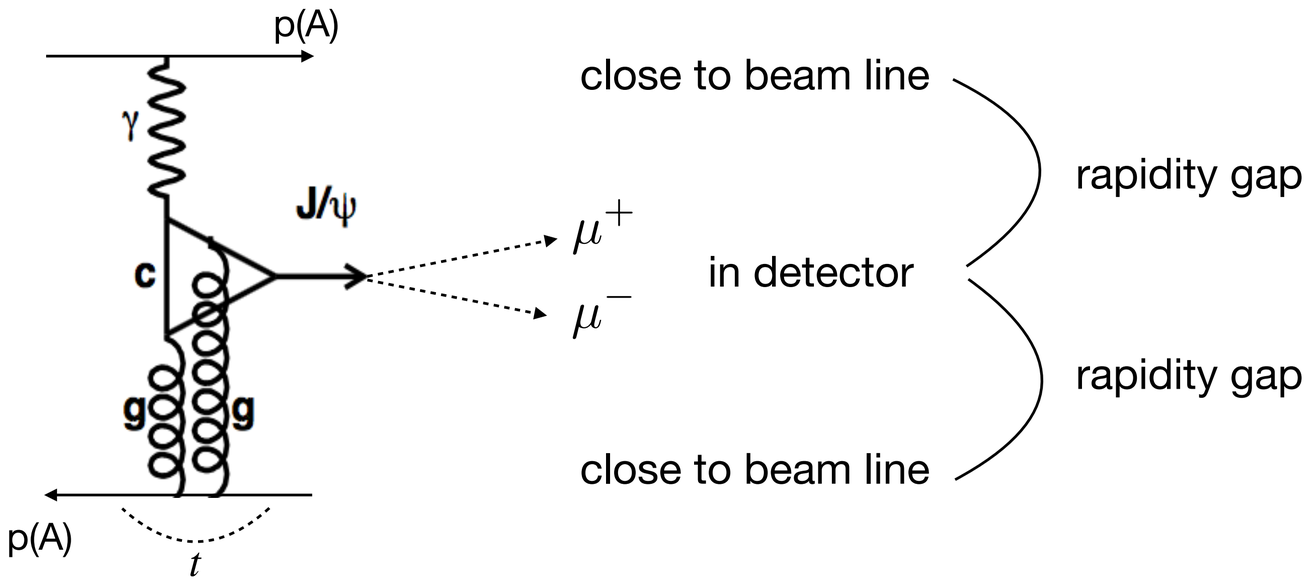


in detector

Experimental signature at the LHC



Experimental signature at the LHC



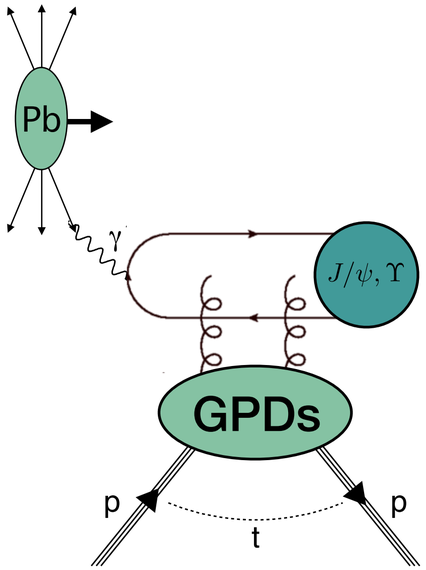
No detection of beam particles

- Mandelstam variable:

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

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

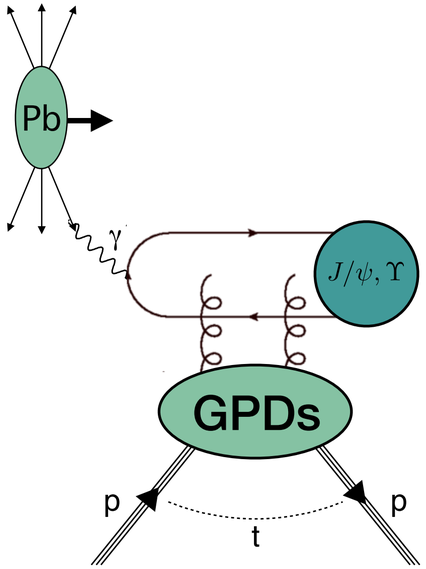
Extraction of the J/ψ photoproduction off the proton



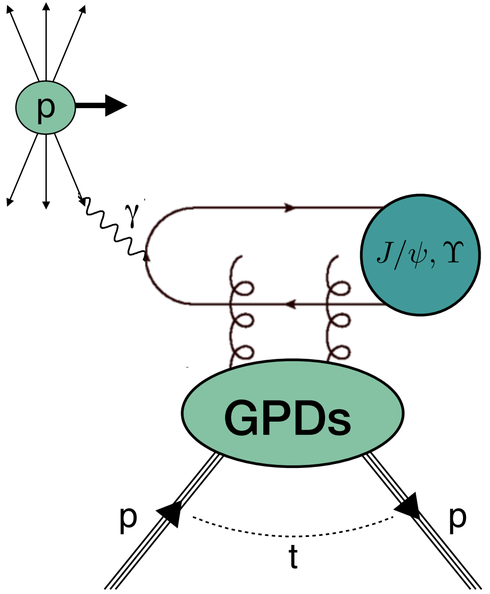
pPb: use Z^2 dependence of photon flux

→ Pb is predominantly photon emitter

Extraction of the J/ψ photoproduction off the proton



pPb: use Z^2 dependence of photon flux
→ Pb is predominantly photon emitter



pp: ambiguity in ID of photon emitter

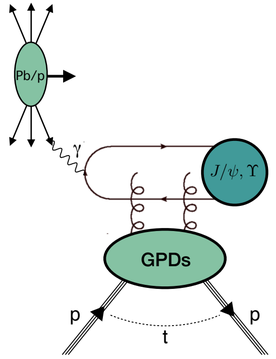
- r = gap survival factor
- $k_{\pm} = \frac{M_{\psi}}{2} e^{\pm y}$ = photon energy
- $\frac{dn}{dk_{\pm}}$ = photon flux
- $W_{\pm}^2 = 2k_{\pm}\sqrt{s}$ = γp invariant mass

relation pp and γp cross section:

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

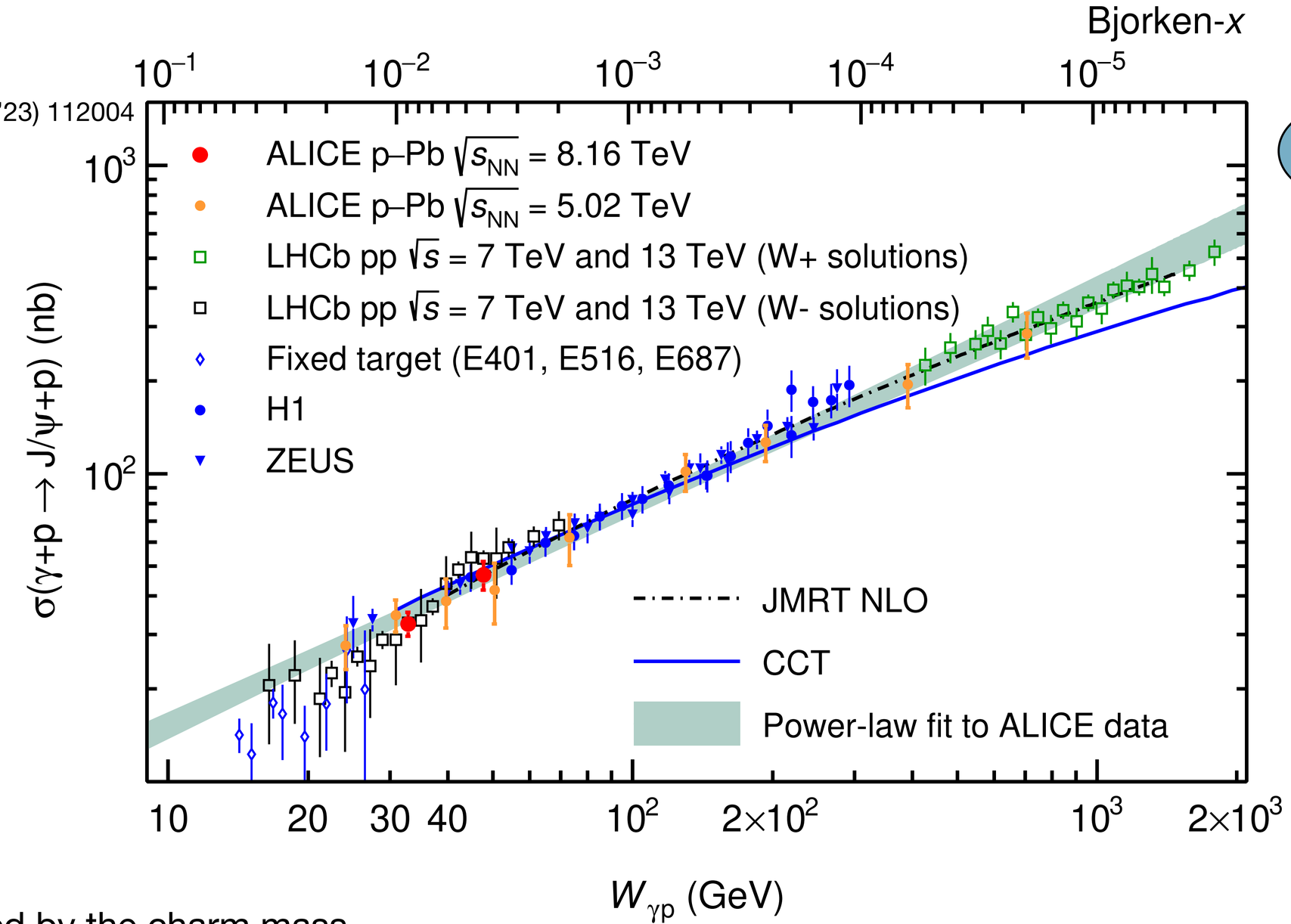
LHCb used HERA data for low-E_γ (W_-) contribution.

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



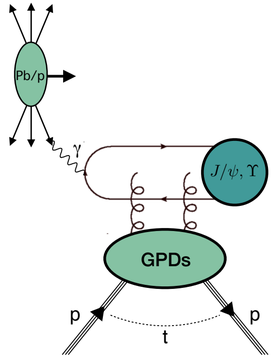
GPD H

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



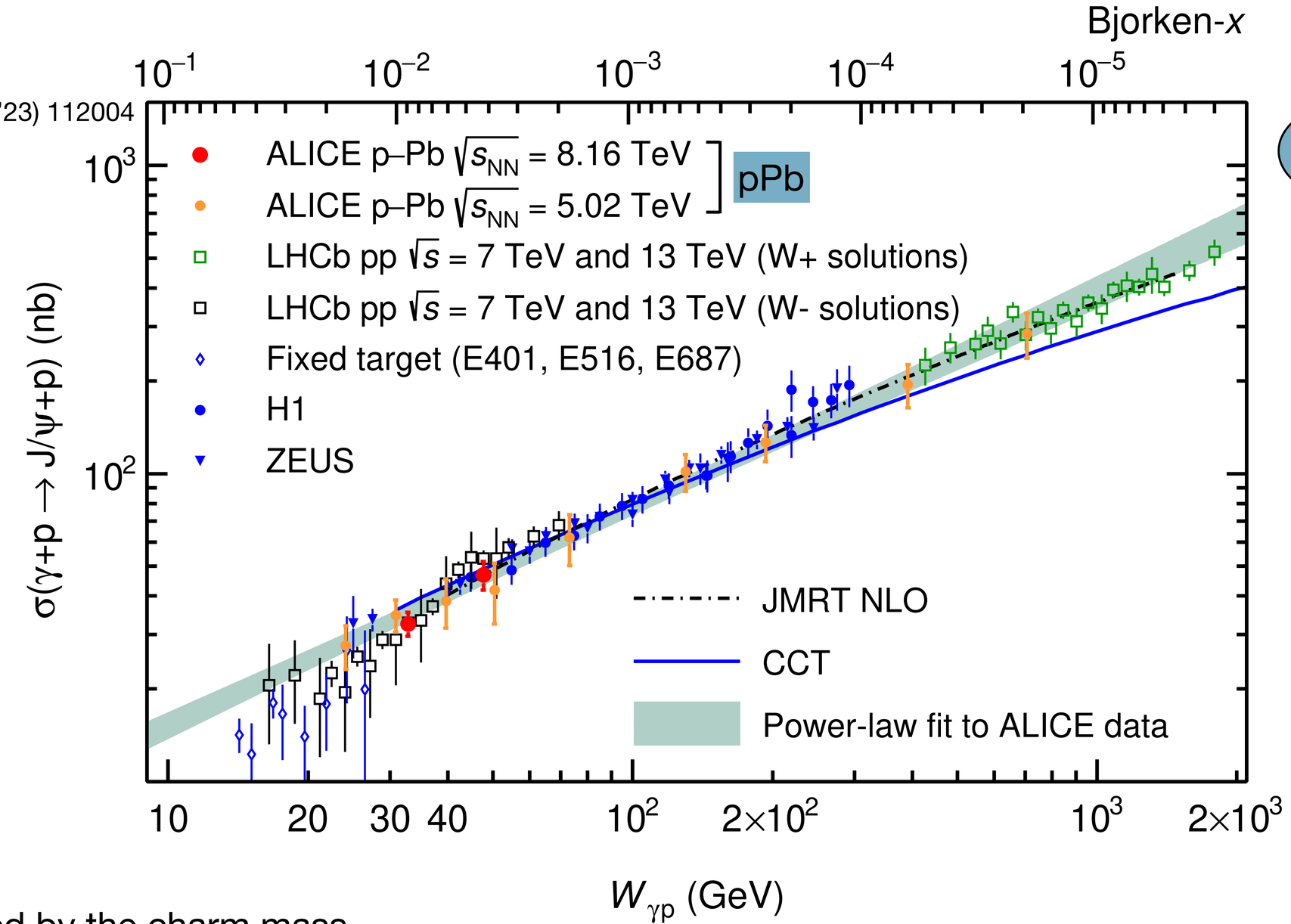
Hard scale: fixed by the charm mass

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



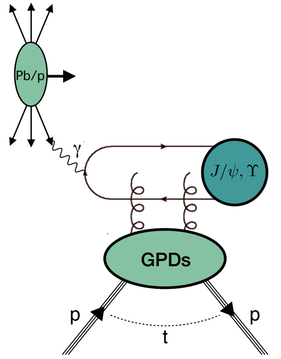
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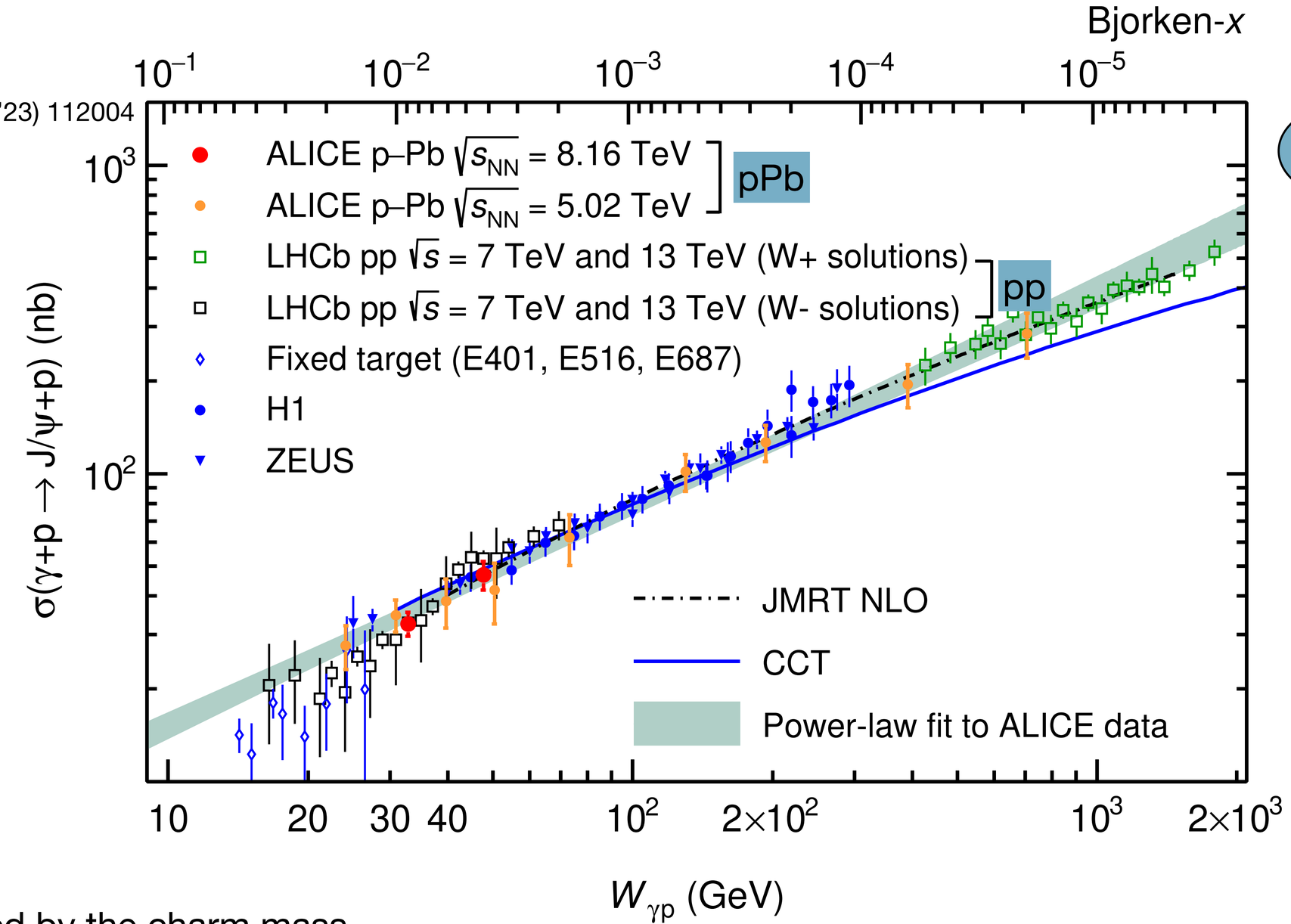
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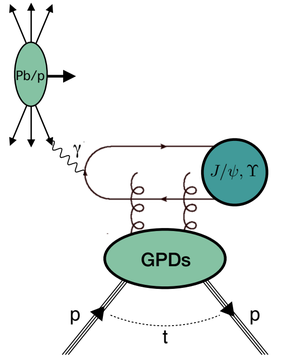
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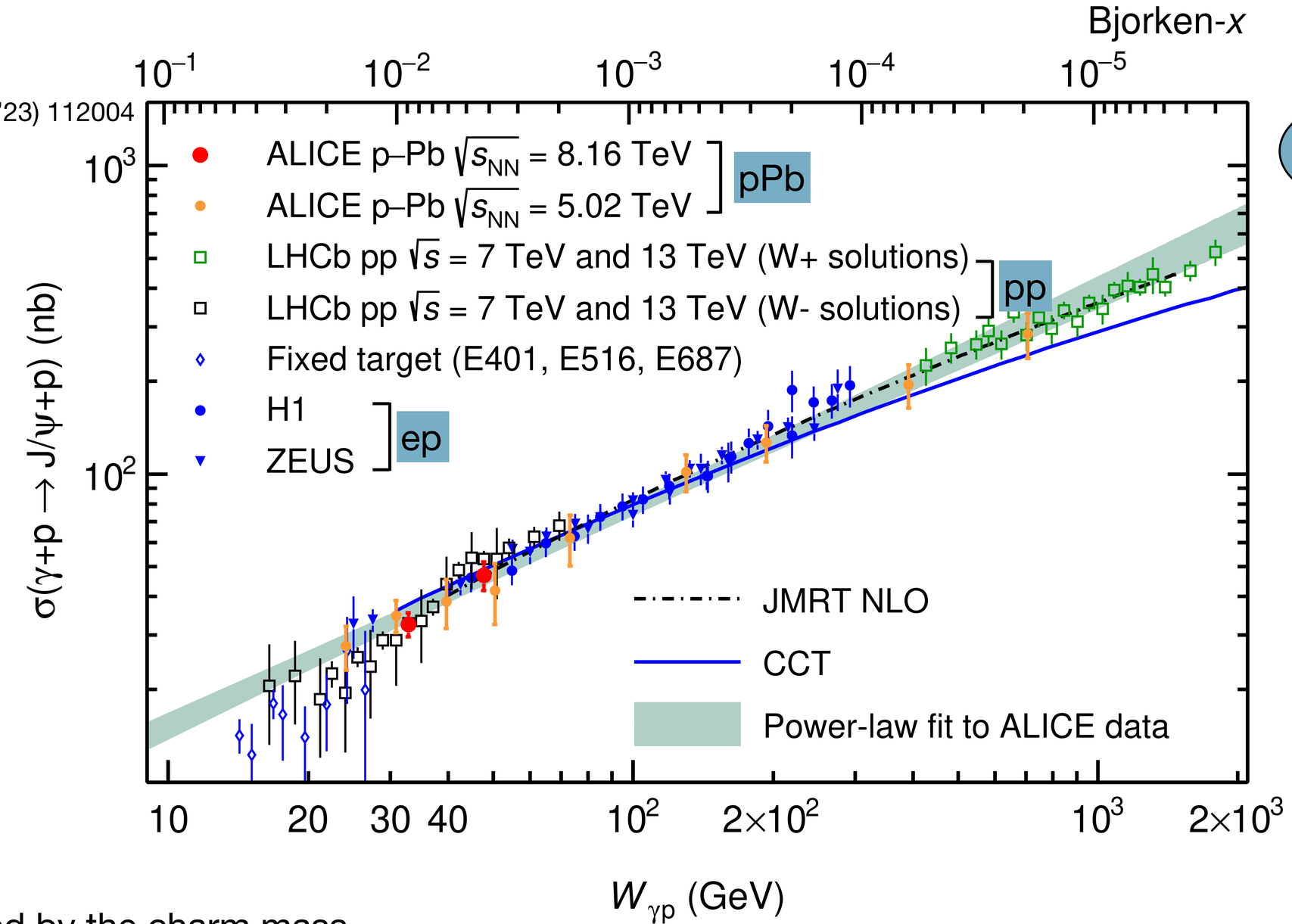
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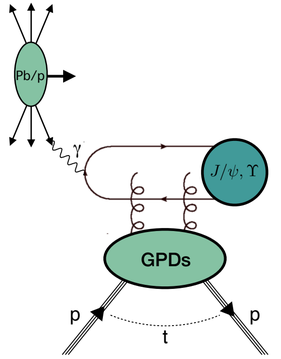
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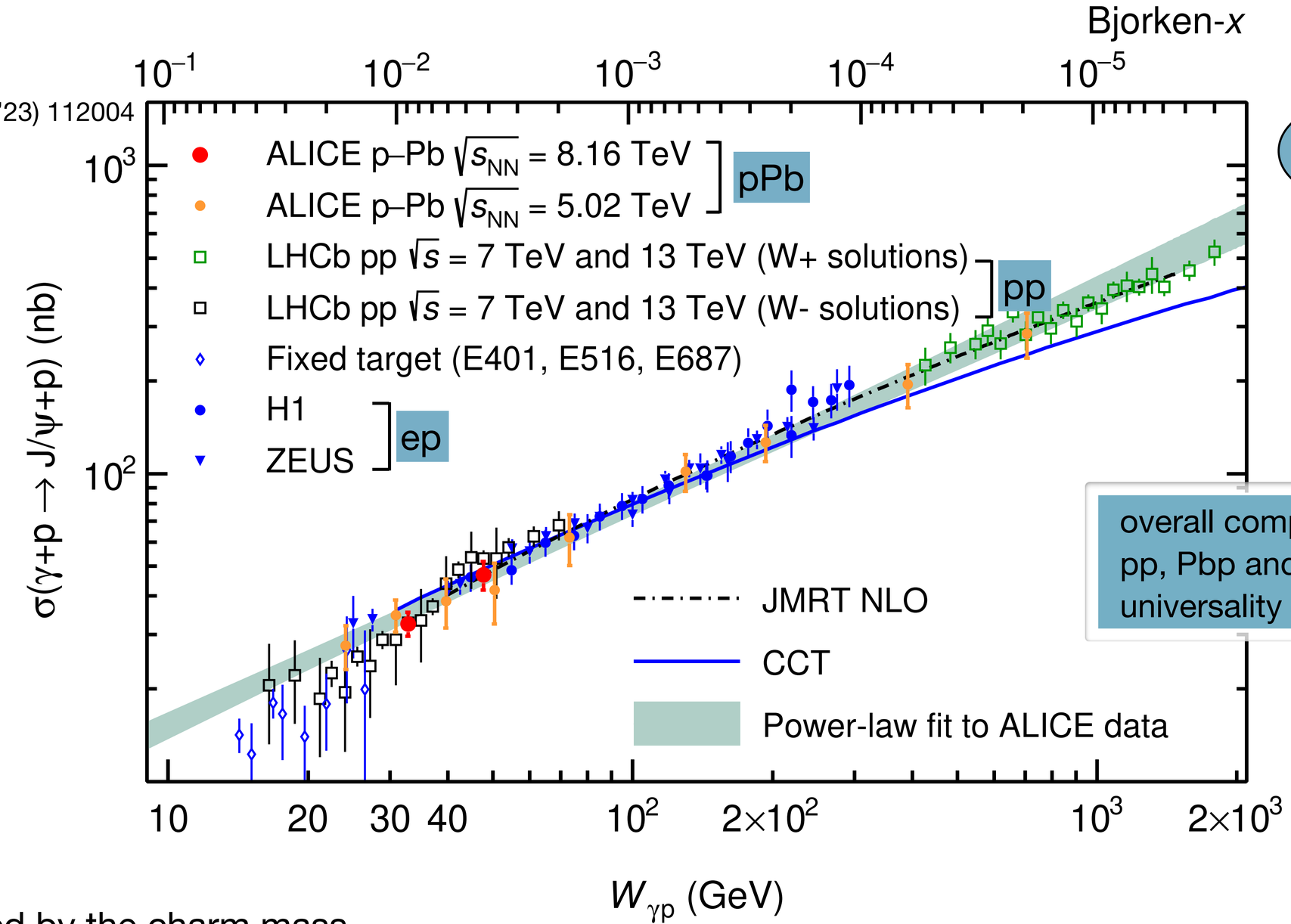
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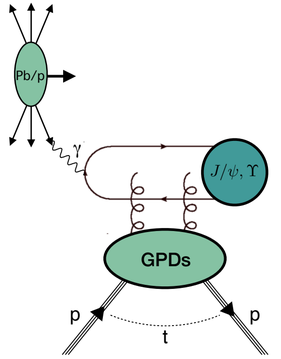
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overall compatibility between pp, Pbp and ep data: hint of universality of underlying physics

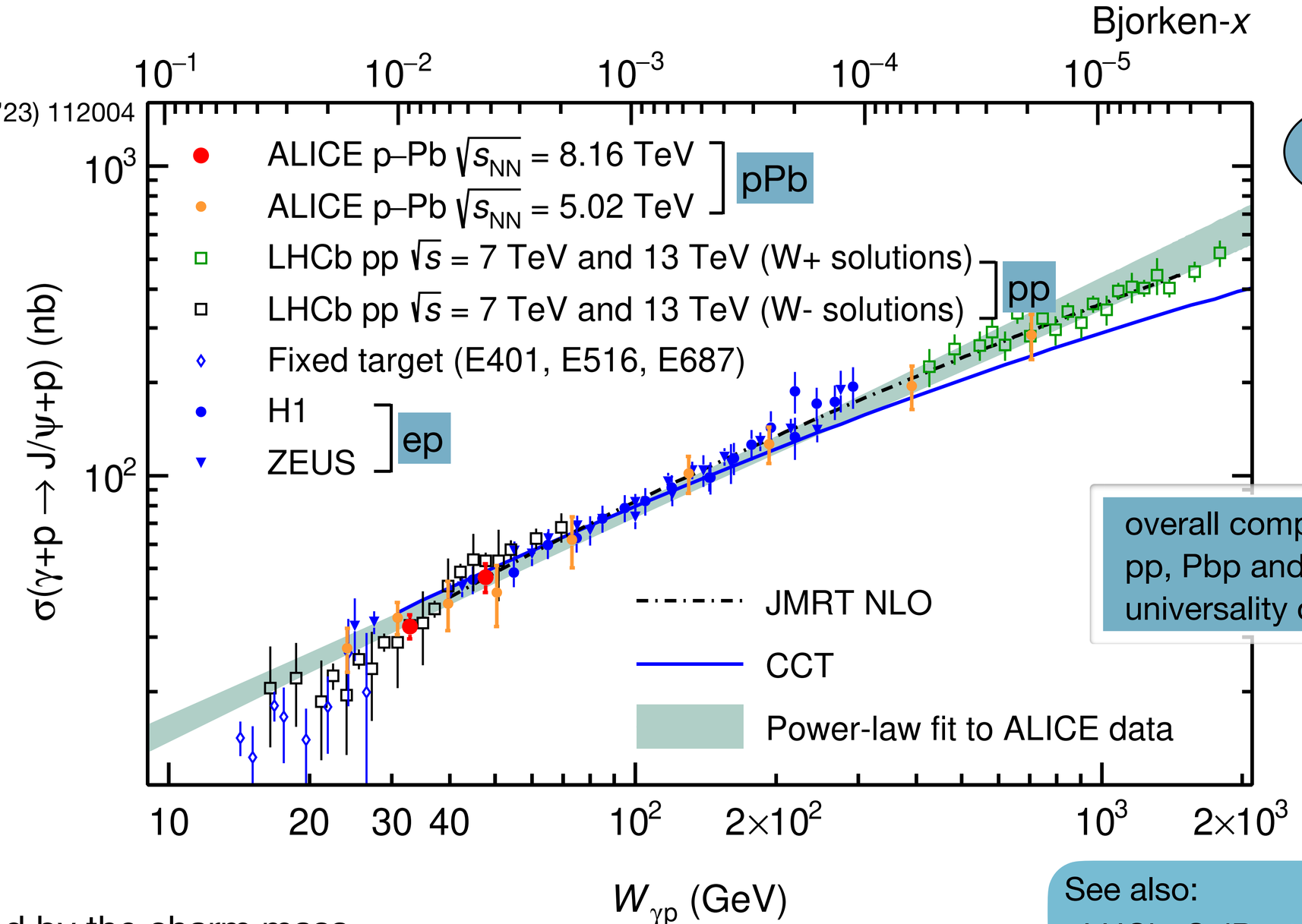
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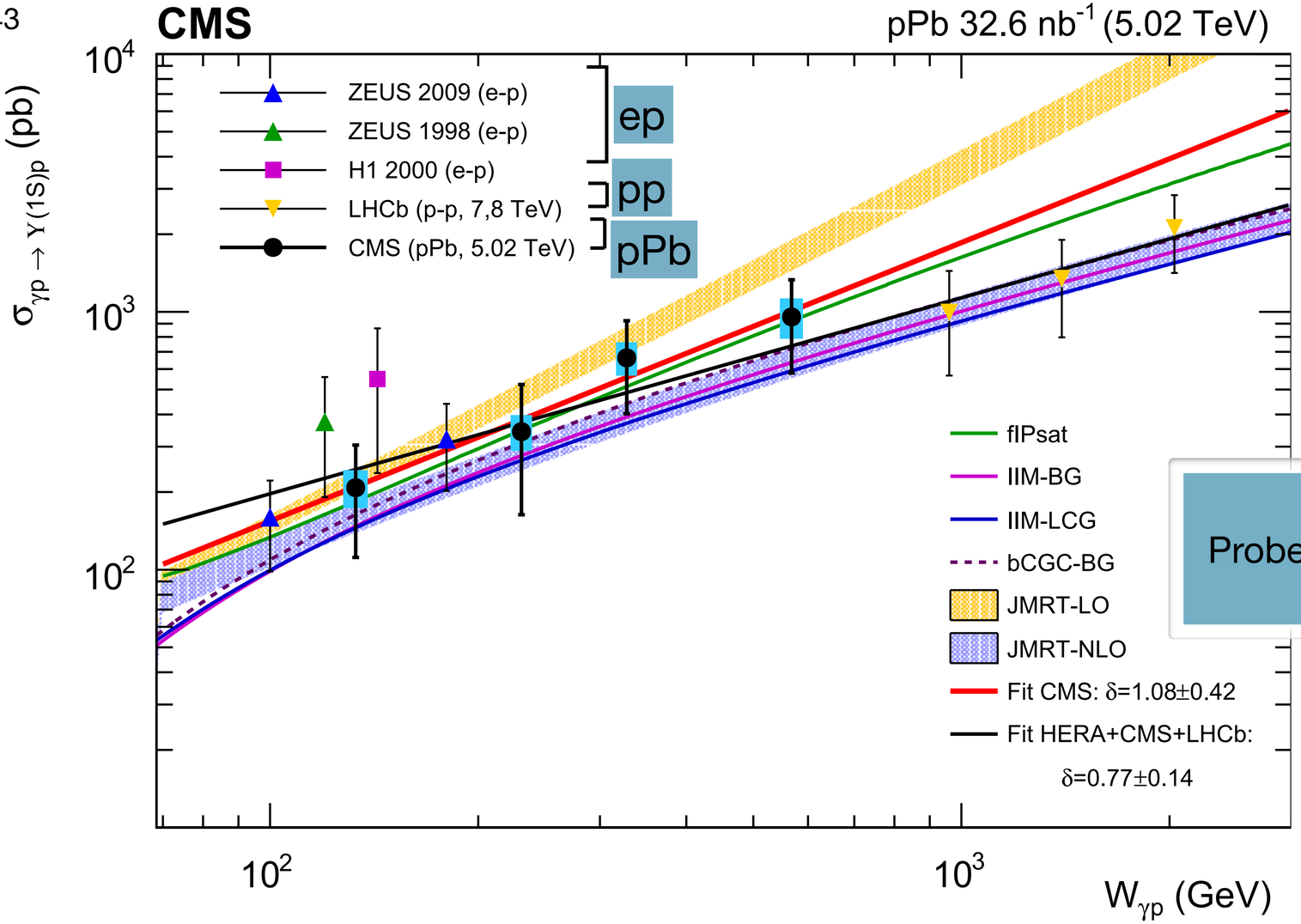
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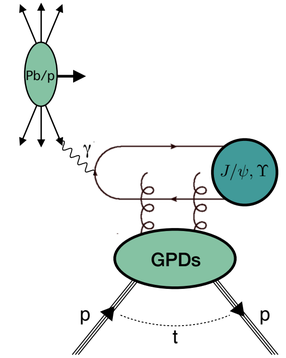
Hard scale: fixed by the charm mass

See also:
- LHCb, SciPost Phys. 18 (2025) 071

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.

Access to GPDs: LHC and EIC

- for spin-1/2 hadron:

Four parton helicity-conserving twist-2 GPDs

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

Four parton helicity-flip twist-2 GPDs

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

Access to GPDs: LHC and EIC

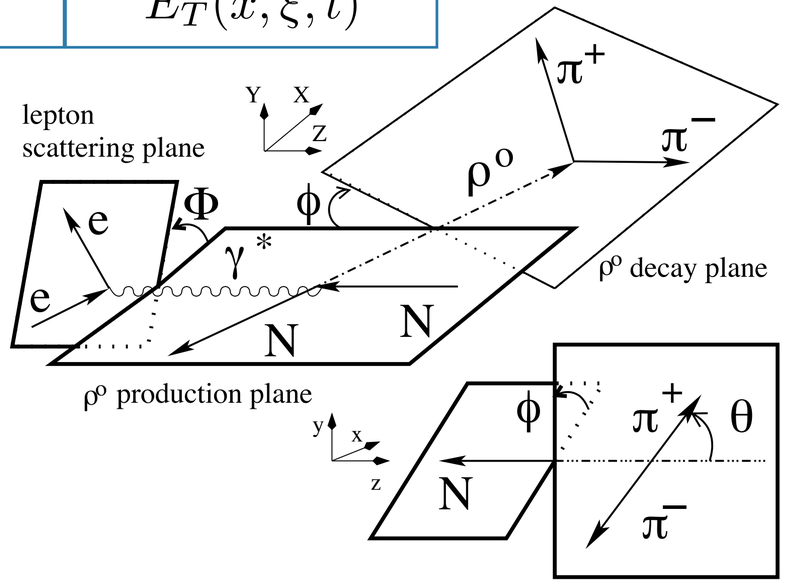
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Four parton helicity-flip twist-2 GPDs

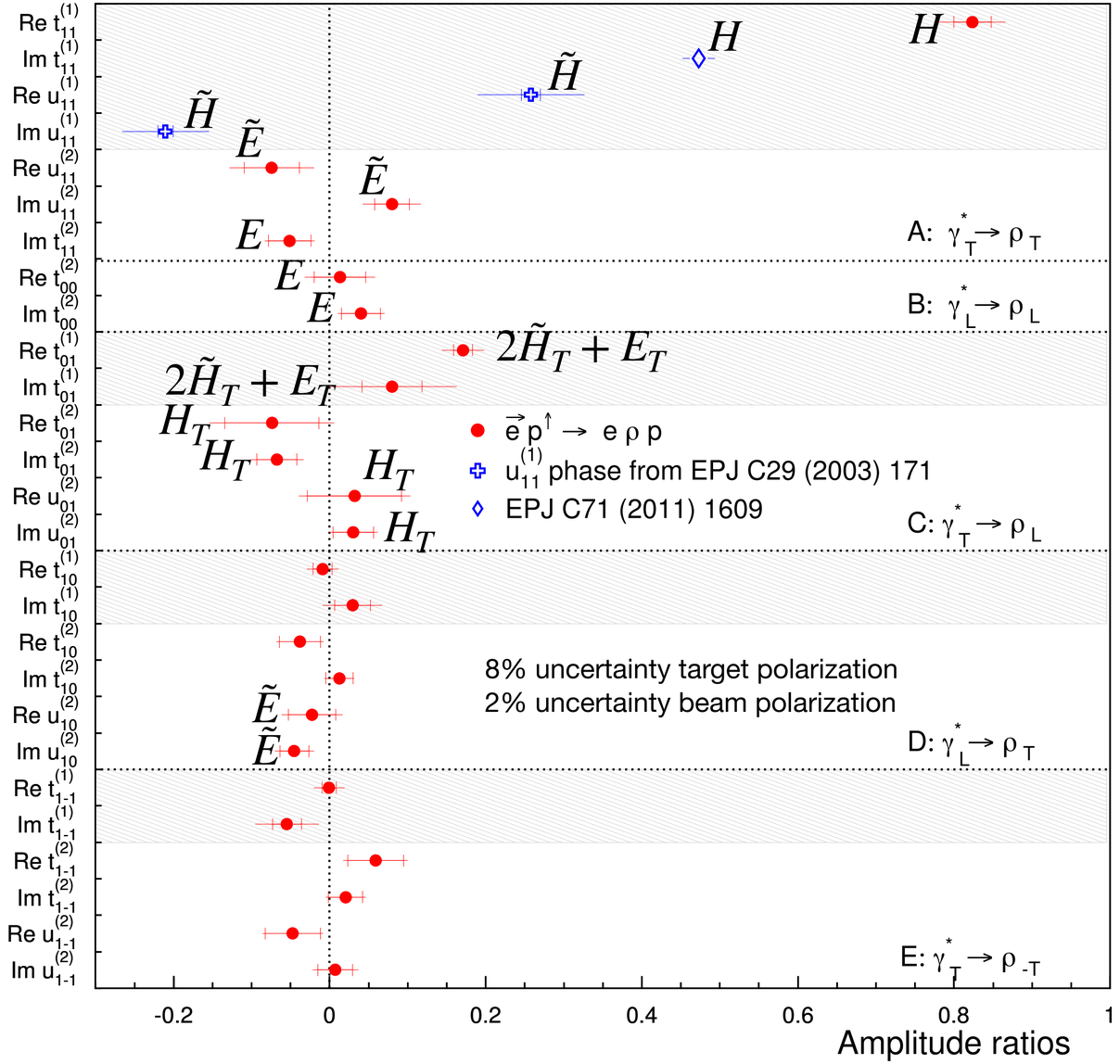
$H_T(x,\xi,t)$	$E_T(x,\xi,t)$
$\tilde{H}_T(x,\xi,t)$	$\tilde{E}_T(x,\xi,t)$



Exclusive ρ on transversely polarised p

Possible at EIC

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



via unpolarised target | via transversely polarised target

Access to GPDs: LHC and EIC

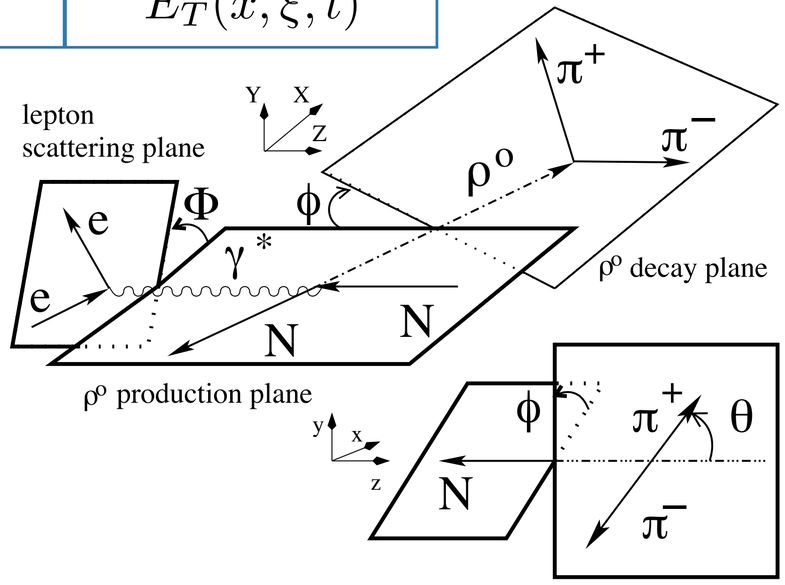
- for spin-1/2 hadron:

Four parton helicity-conserving twist-2 GPDs

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

Four parton helicity-flip twist-2 GPDs

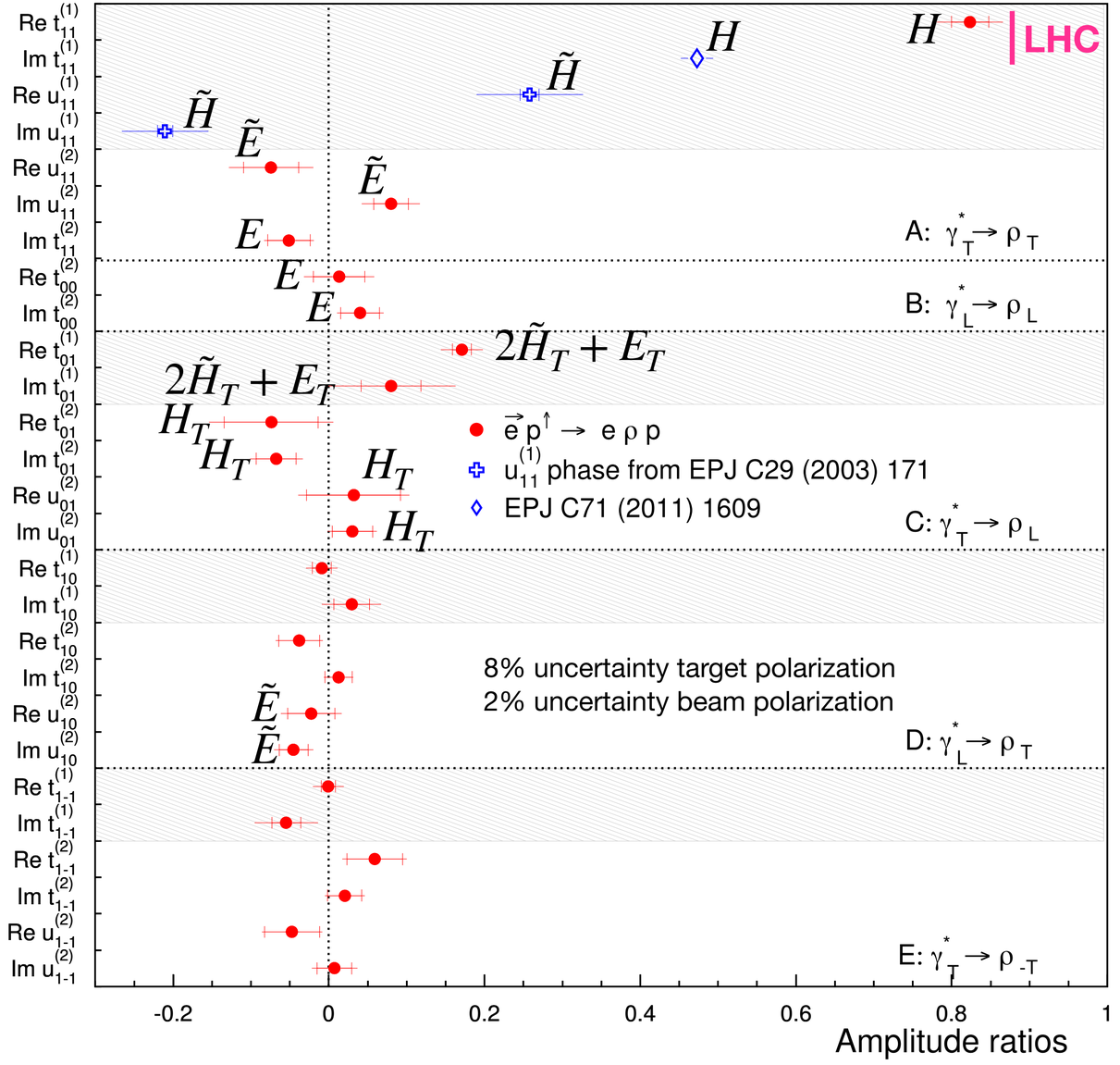
$H_T(x,\xi,t)$	$E_T(x,\xi,t)$
$\tilde{H}_T(x,\xi,t)$	$\tilde{E}_T(x,\xi,t)$



Exclusive ρ on transversely polarised p

Possible at EIC

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



via unpolarised target | via transversely polarised target

Access to GPDs: LHC and EIC

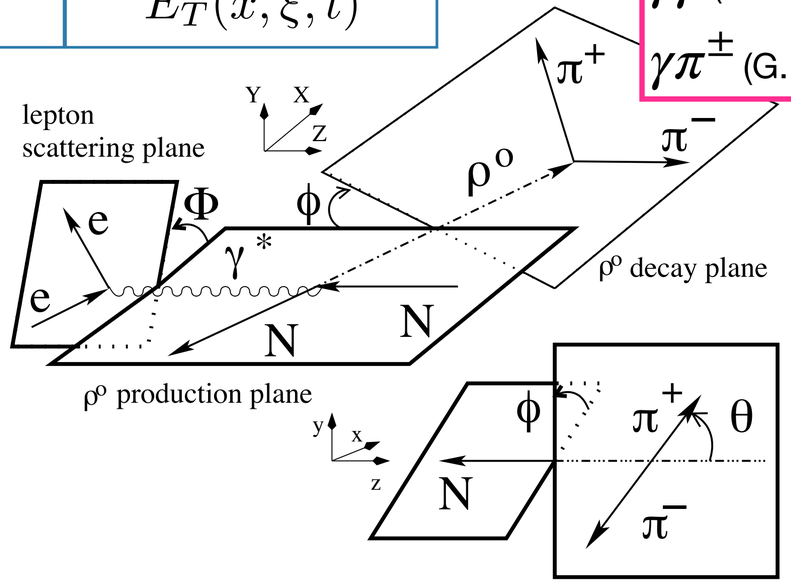
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Four parton helicity-flip twist-2 GPDs

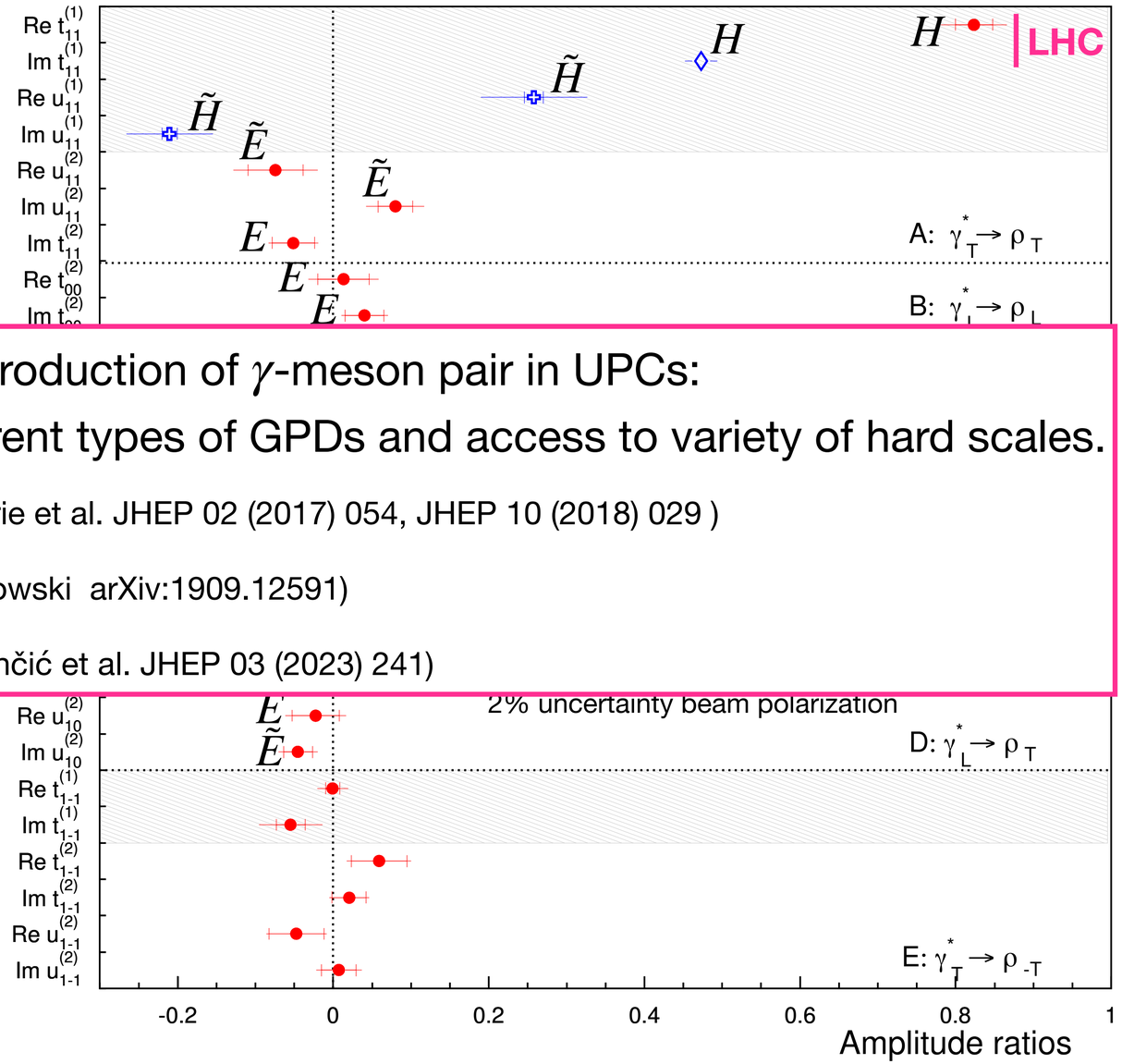
$H_T(x,\xi,t)$	$E_T(x,\xi,t)$
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Exclusive ρ on transversely polarised p

Possible at EIC

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Exclusive production of γ-meson pair in UPCs:

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

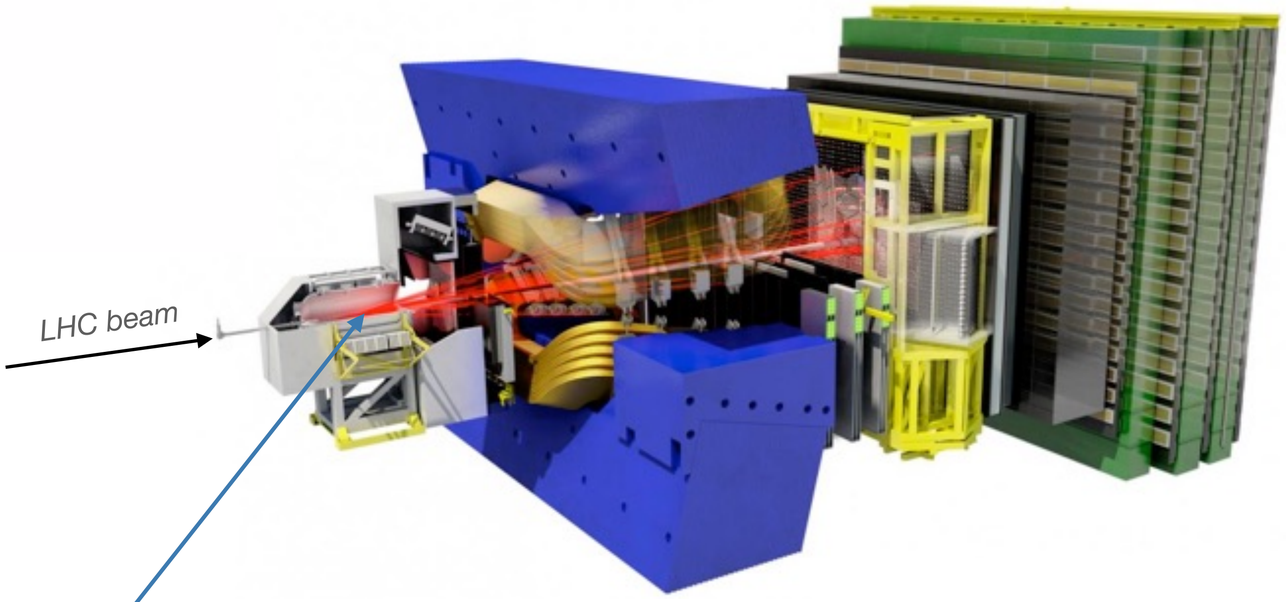
$\gamma\rho$ (R. Boussarie et al. JHEP 02 (2017) 054, JHEP 10 (2018) 029)

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

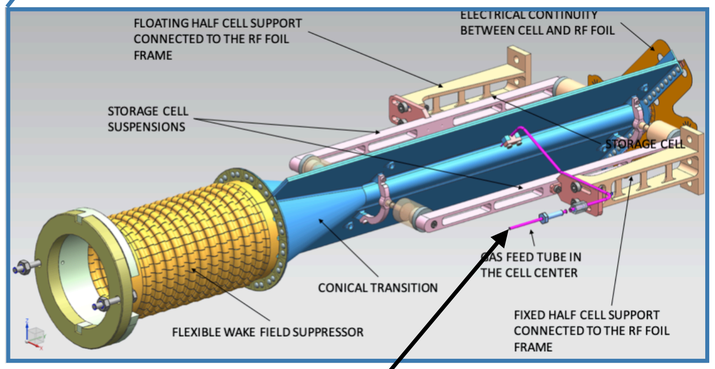
$\gamma\pi^{\pm}$ (G. Duplančić et al. JHEP 03 (2023) 241)

via unpolarised target | via transversely polarised target

Fixed target at LHCb



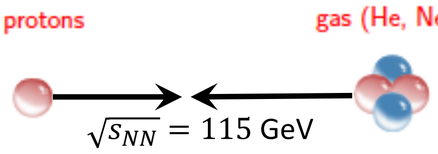
LHC RUN 3



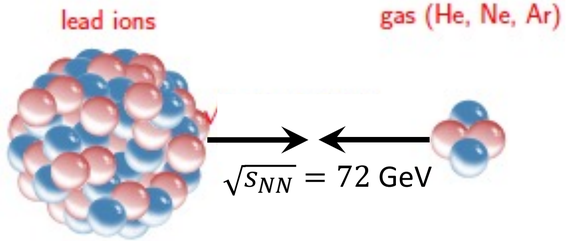
inject gas: He, Ne, Ar, and H_2, D_2

Fixed target – SMOG2

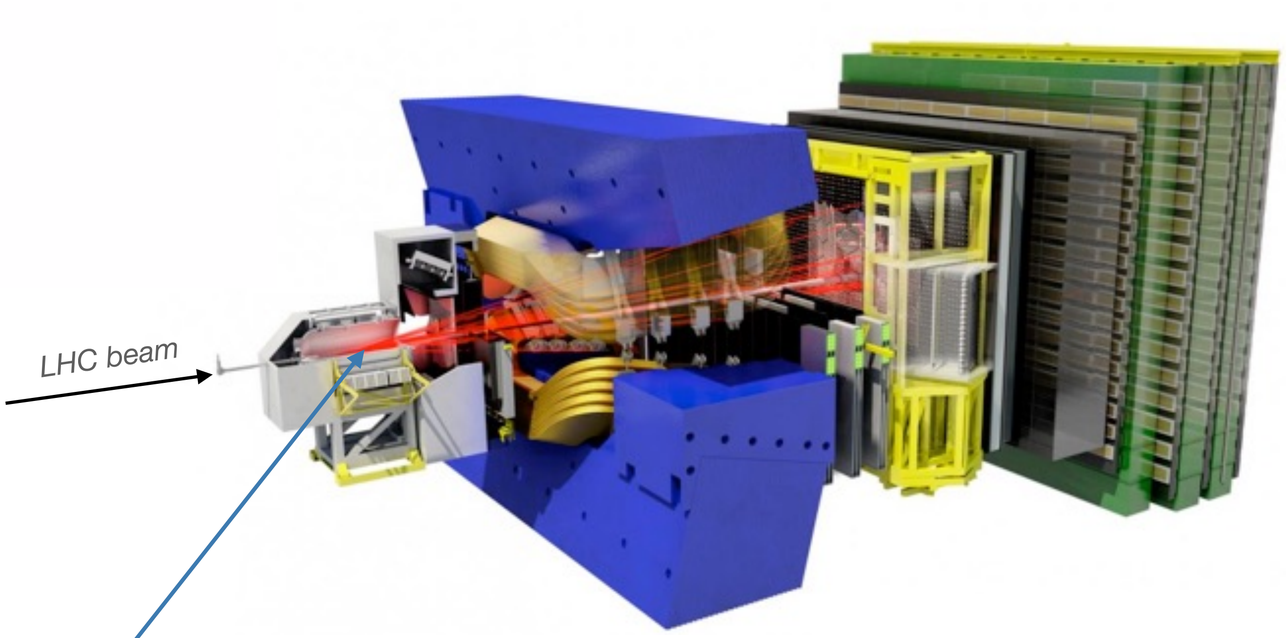
p beam



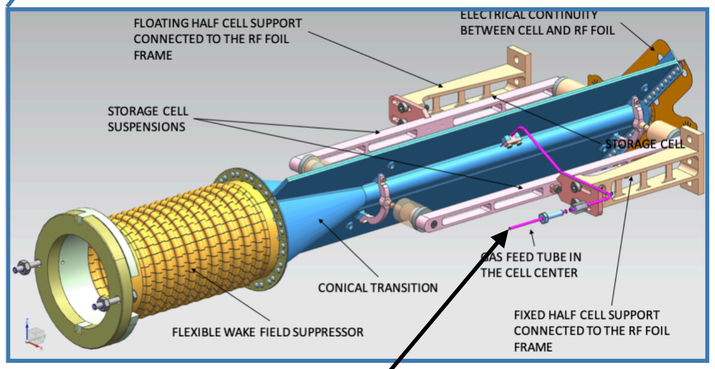
Pb beam



Fixed target at LHCb

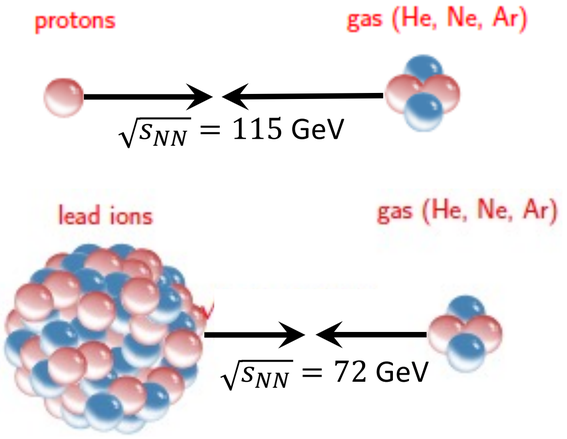


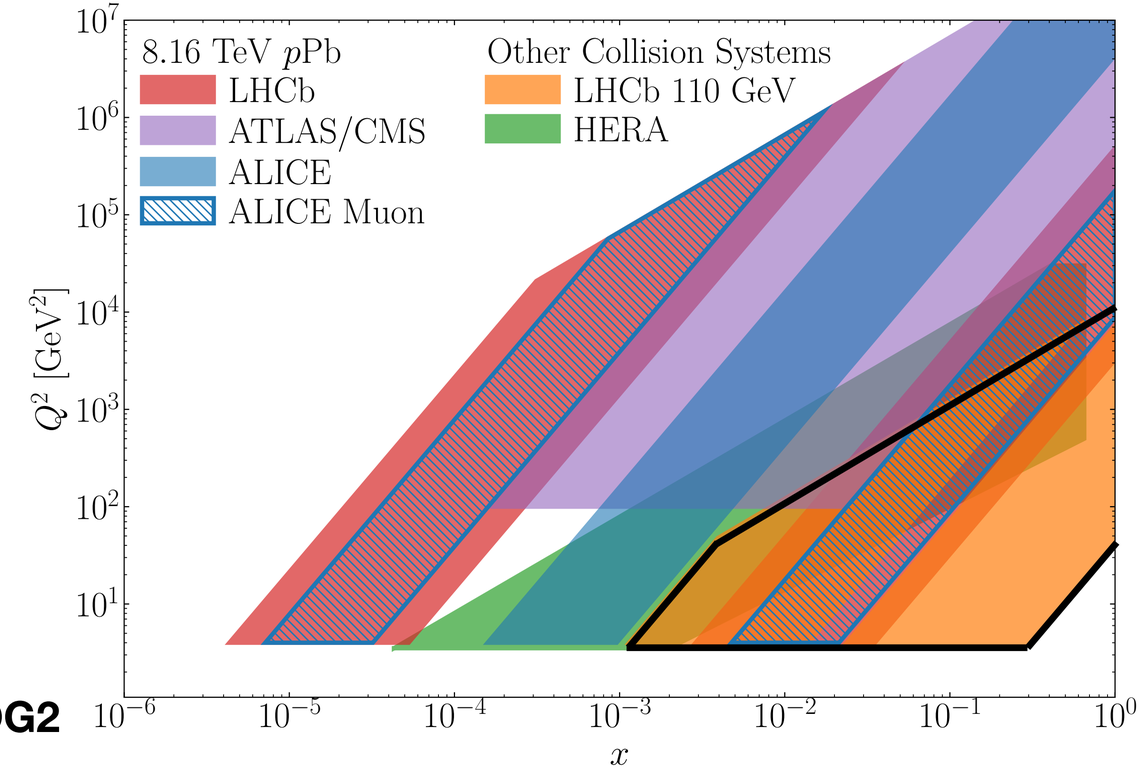
LHC RUN 3



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

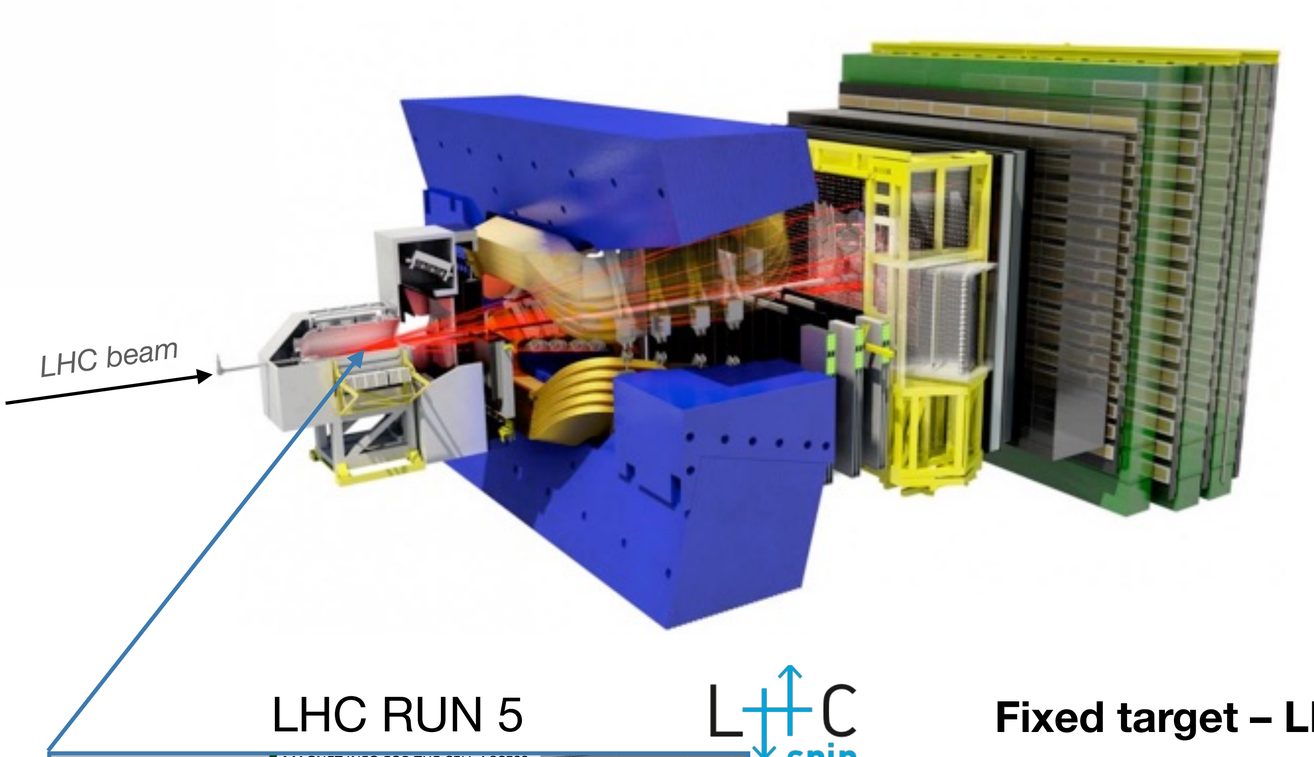
Fixed target – SMOG2

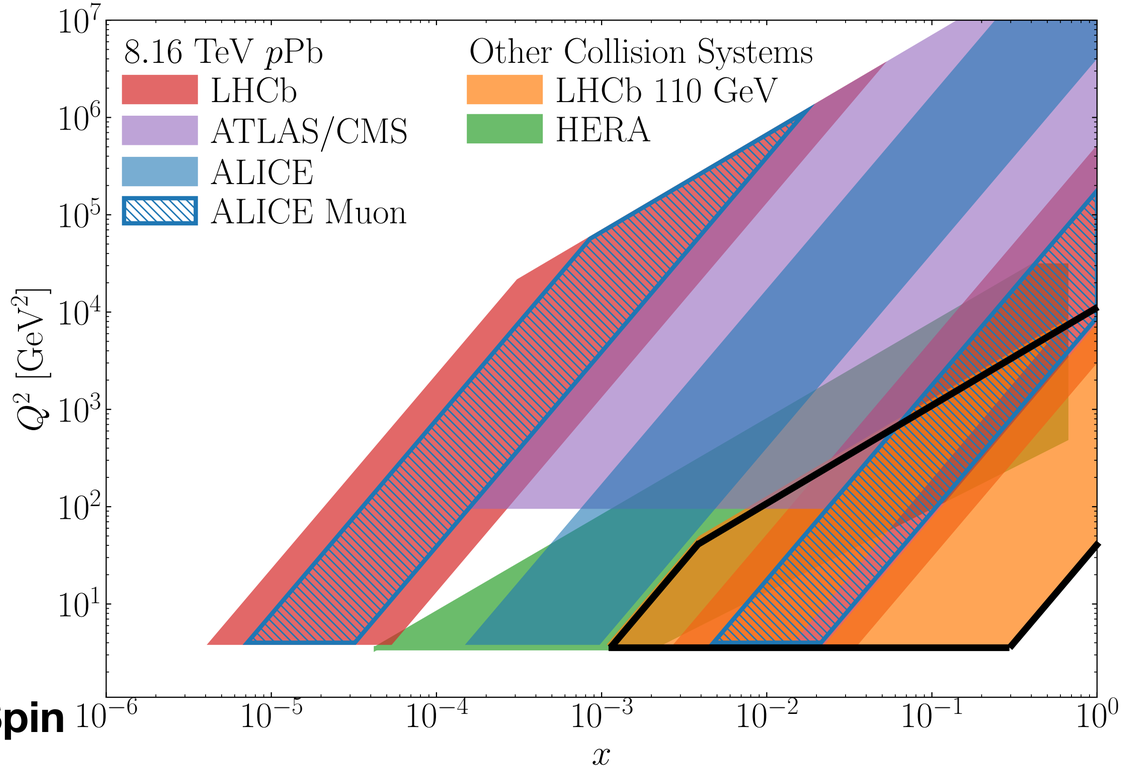




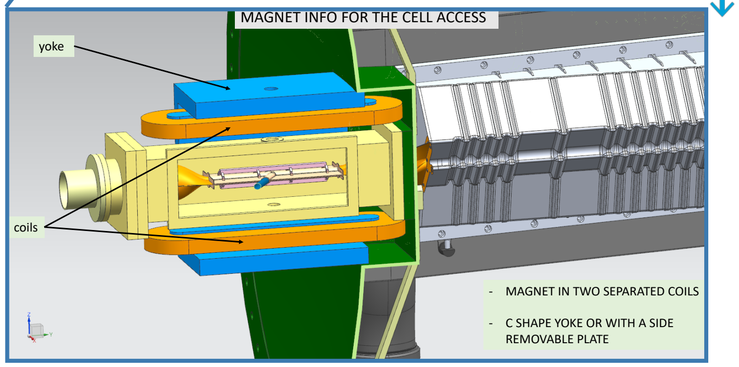
Access to high x

Fixed target at LHCb



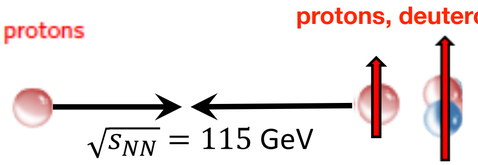


LHC RUN 5

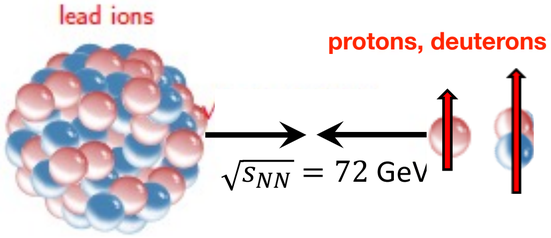


Fixed target – LHCSpin

p beam

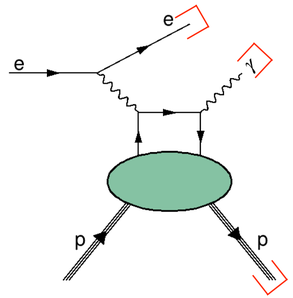


Pb beam

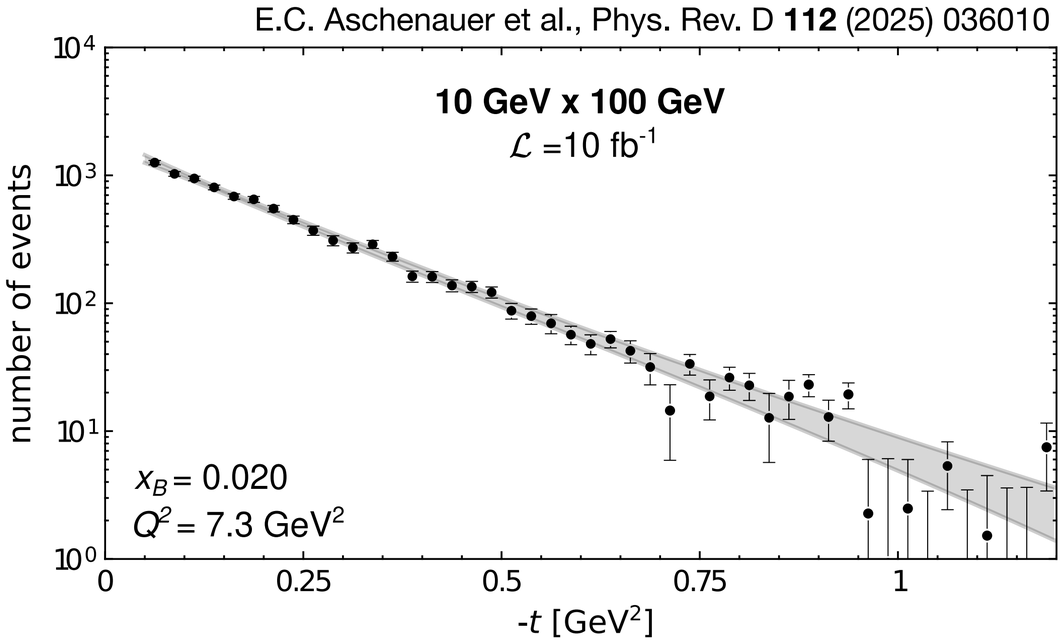


Access to high x

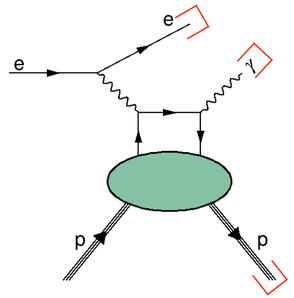
DVCS at ePIC and impact on determination of CFFs



DVCS after efficiency and acceptance corrections

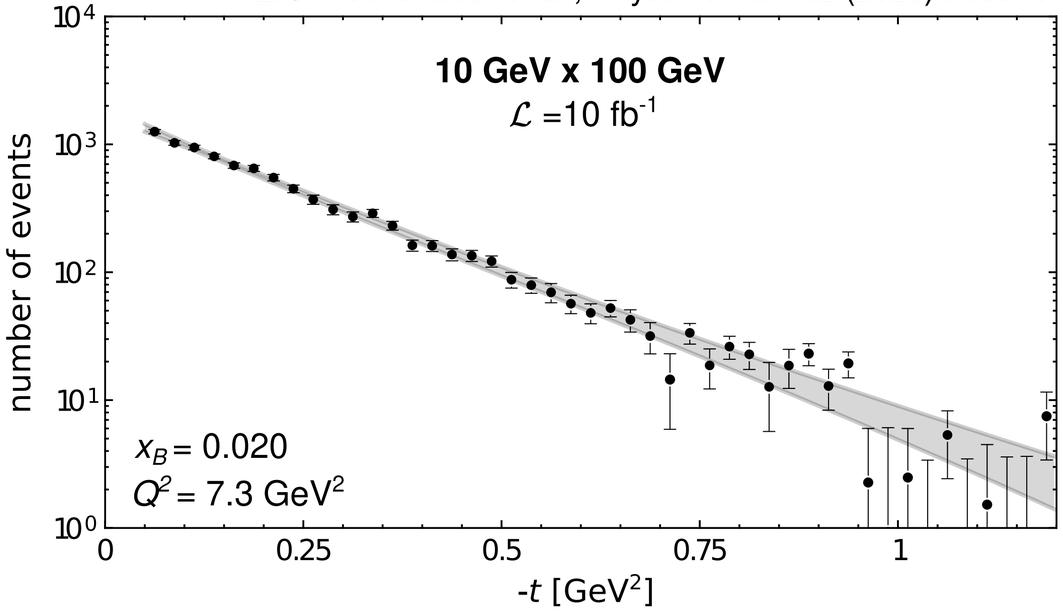


DVCS at ePIC and impact on determination of CFFs



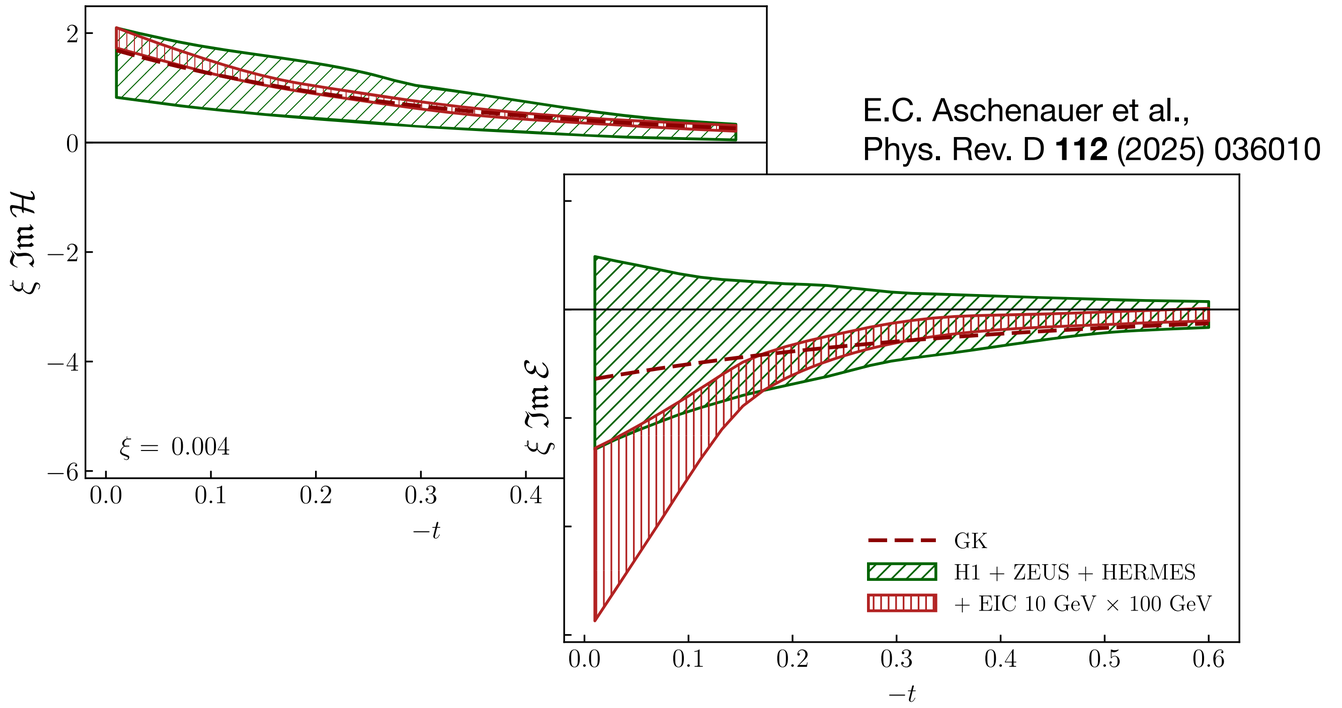
DVCS after efficiency and acceptance corrections

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



Lepton-beam helicity asymmetry

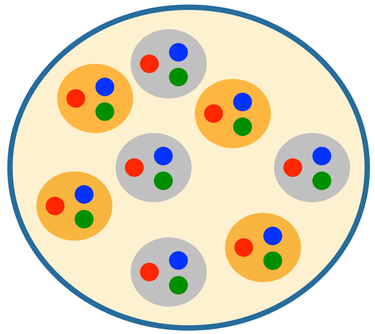
$$\rightarrow \Im m\left(F_1\mathcal{H} + -\frac{t}{4m^2}F_2\mathcal{E} + \dots\right)$$

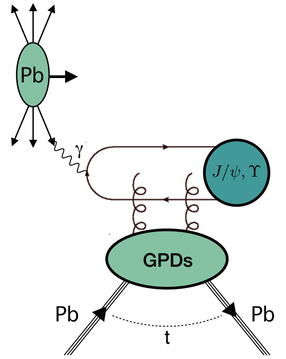


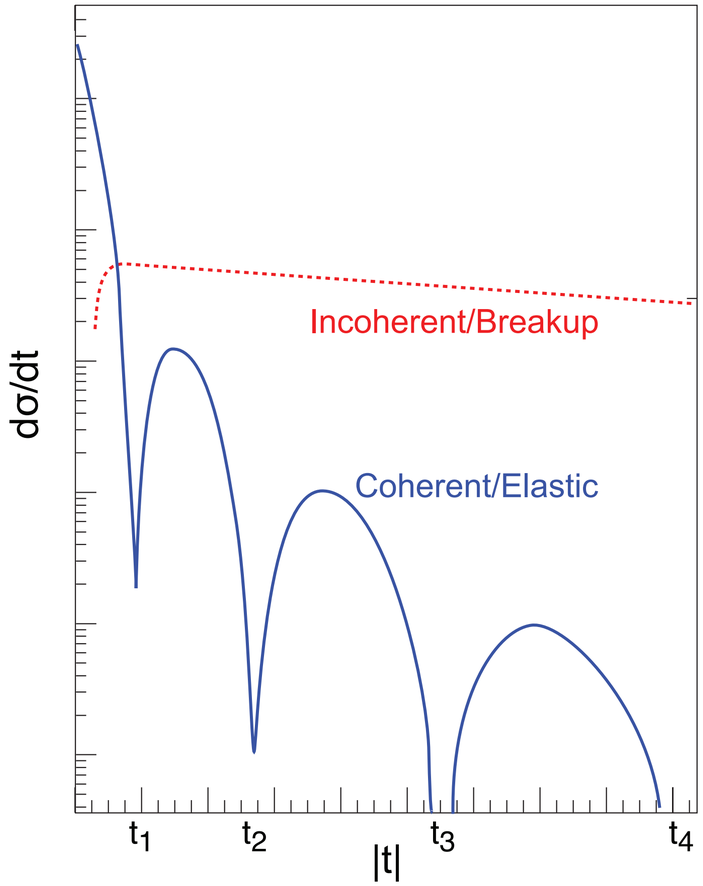
E.C. Aschenauer et al.,
Phys. Rev. D **112** (2025) 036010

Probing ions

What object are we probing?

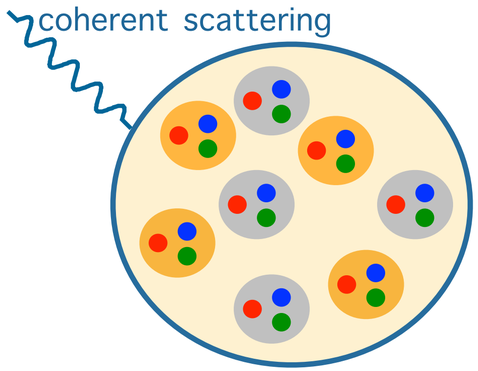


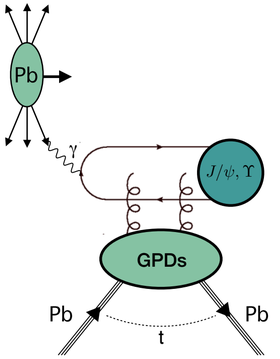


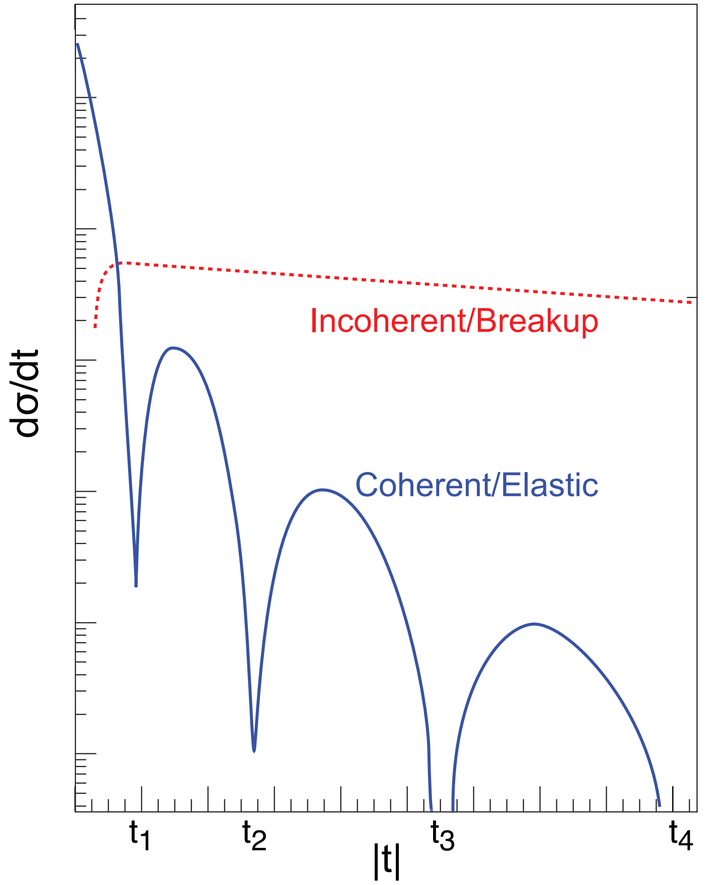


Probing ions

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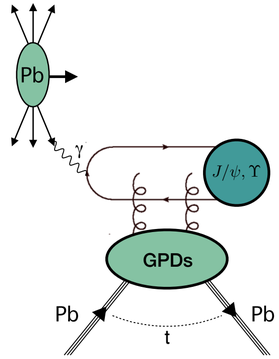




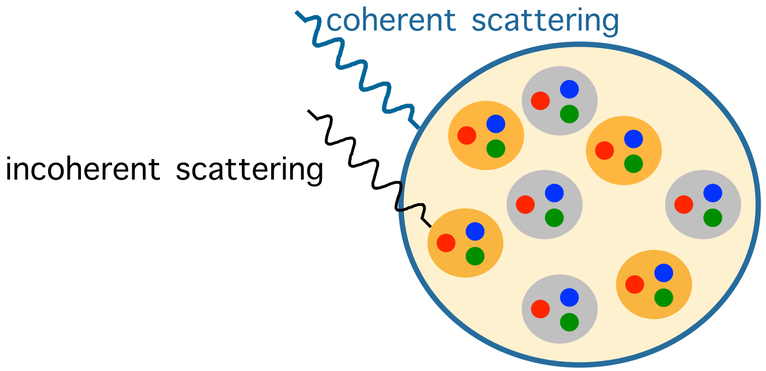


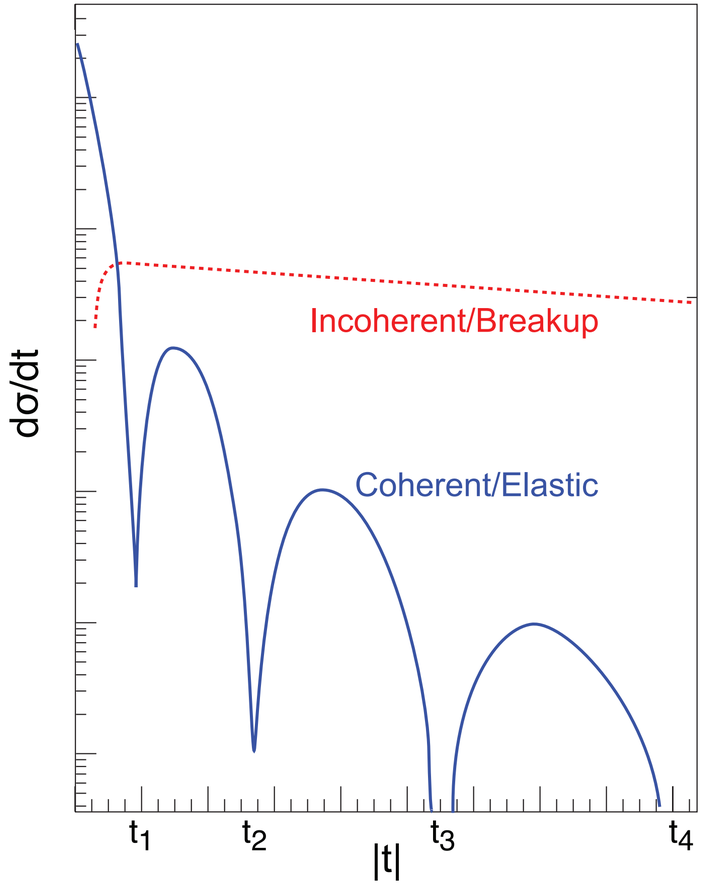
Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

Probing ions



What object are we probing?

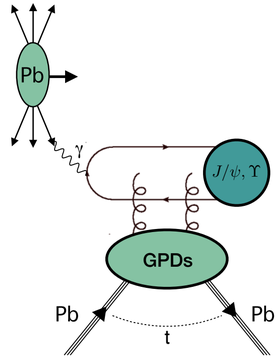




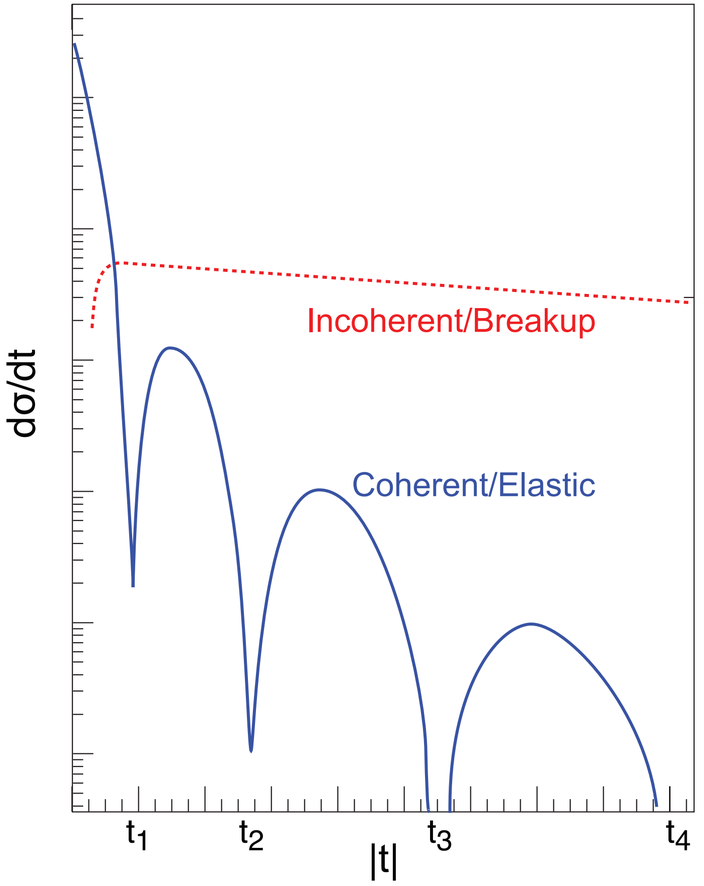
Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

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

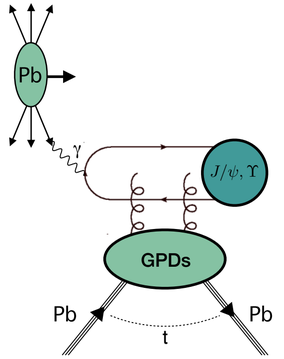
Experimentally important points



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



Experimentally important points

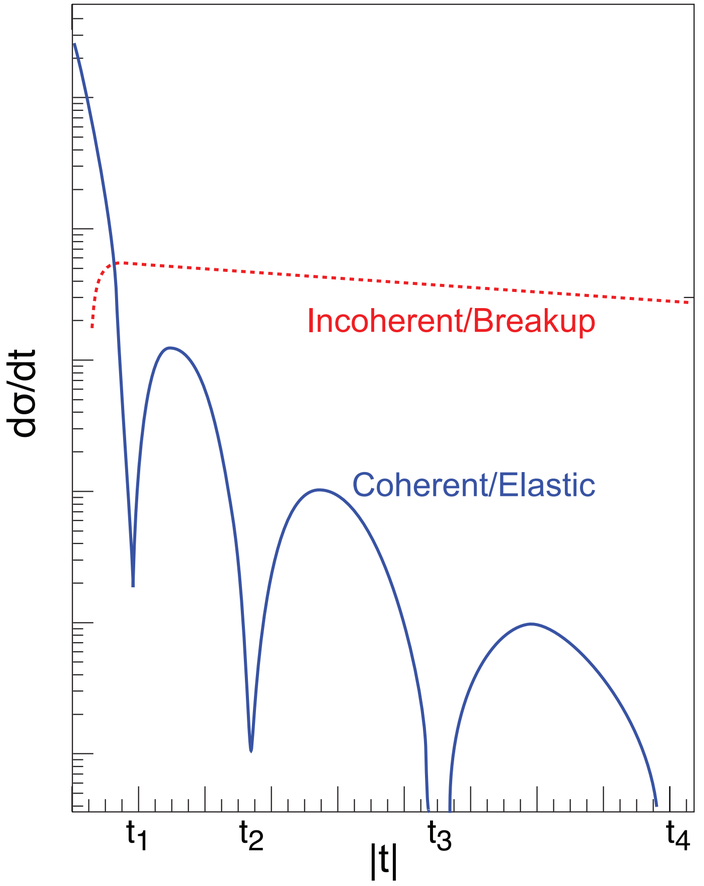


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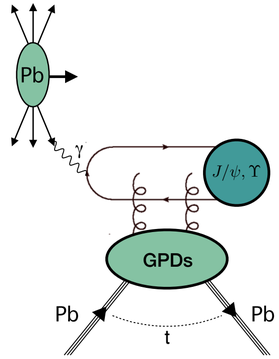
- Coherent production: measurements up to large t:
  - 3D or 2D (x independent) transverse position

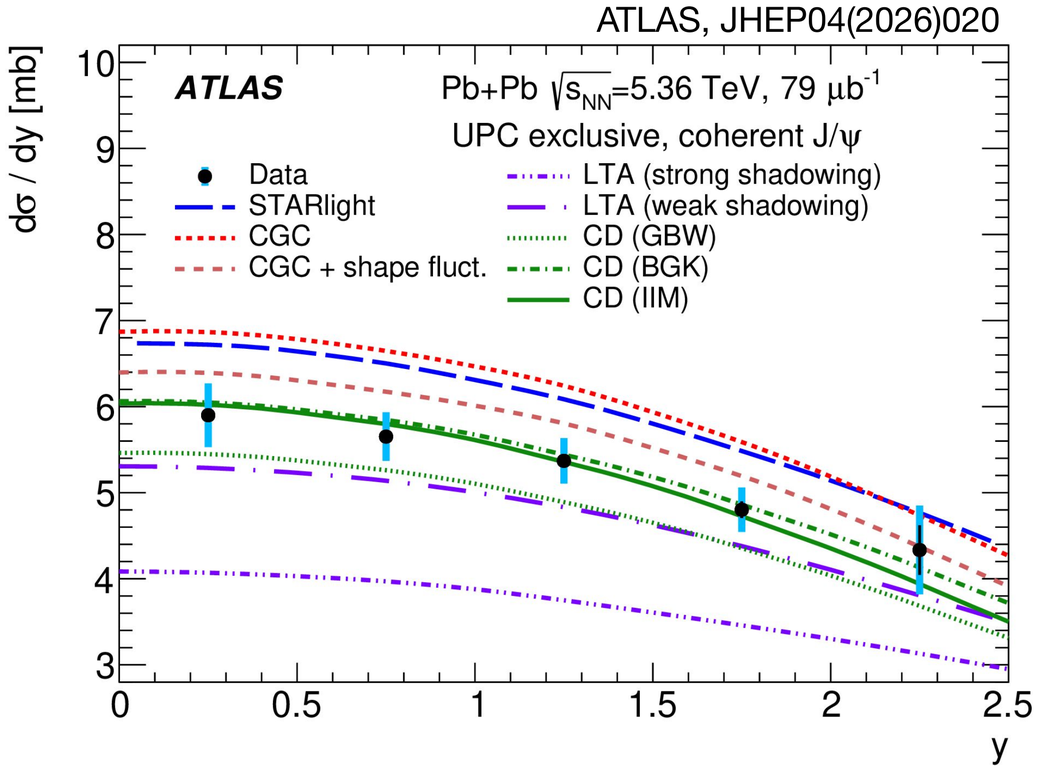
$$\int_0^{\infty} d\Delta_\perp \; \mathrm{GPD}(x, 0, \Delta_\perp)\; e^{-ib_\perp \Delta_\perp}$$

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



Coherent J/ψ production in PbPb collisions at the LHC

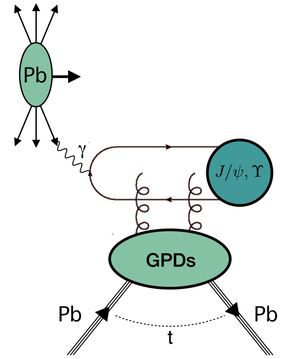




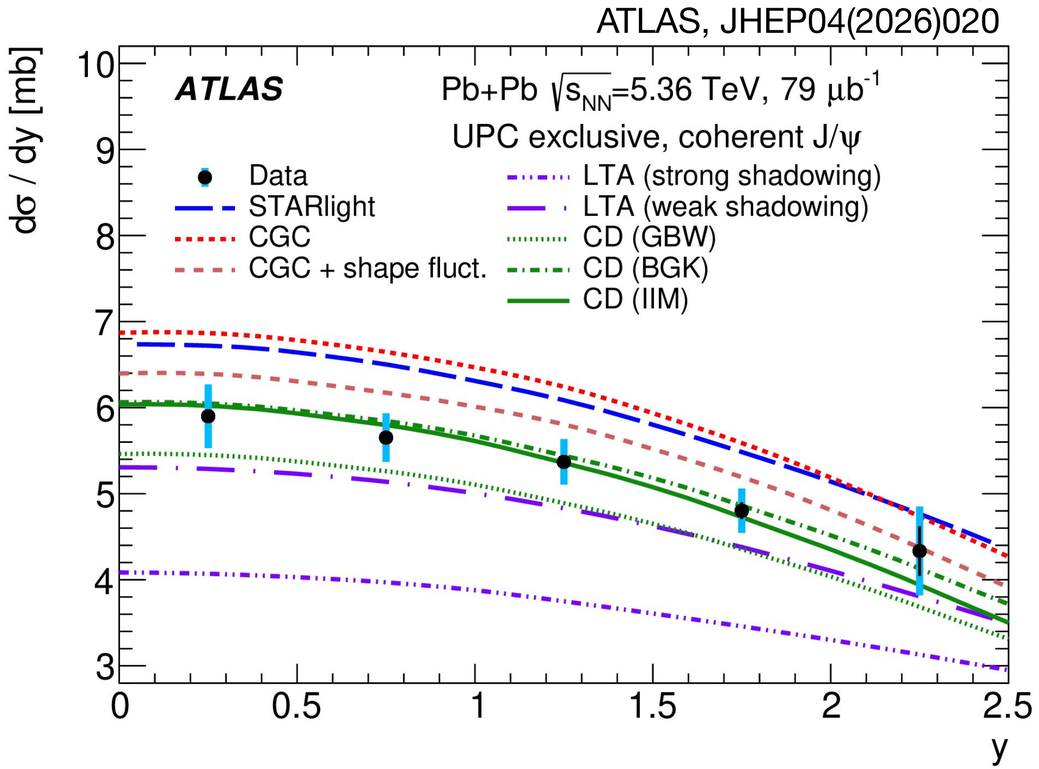
Results indicate significant nuclear shadowing

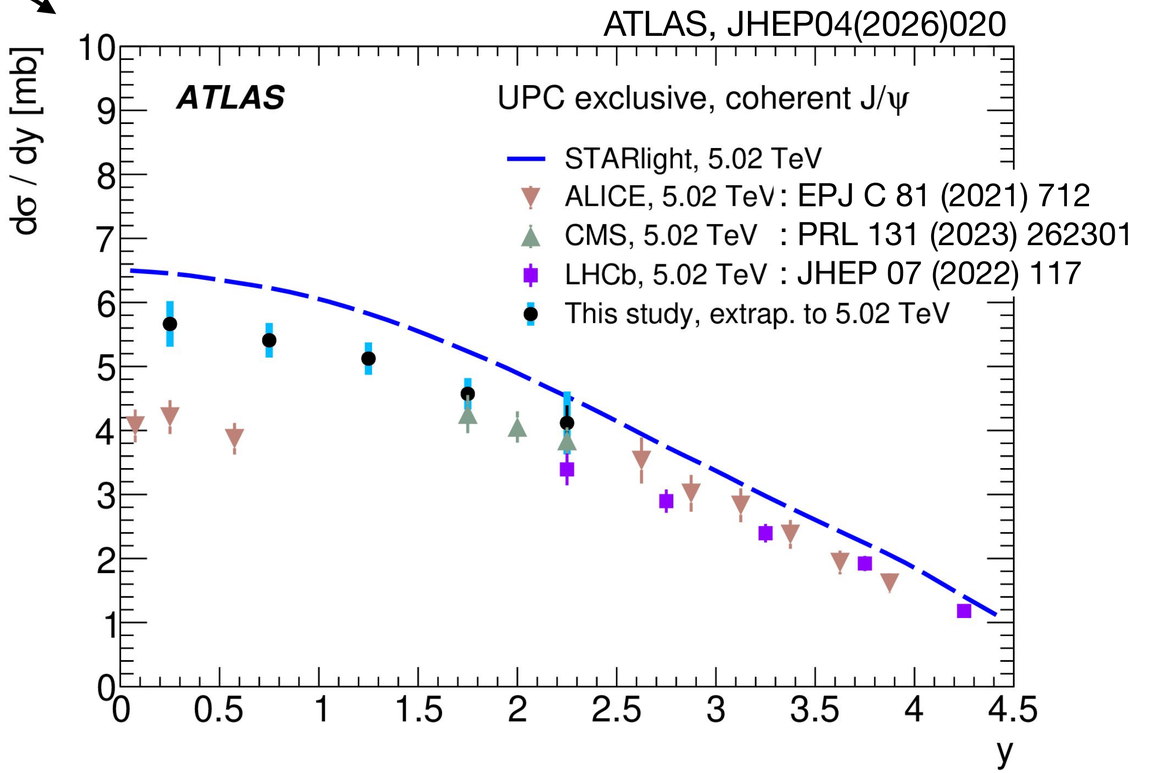
See also:
Preliminary results ALICE at $\sqrt{s_{NN}}$ 5.36 TeV

Coherent J/ψ production in PbPb collisions at the LHC



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

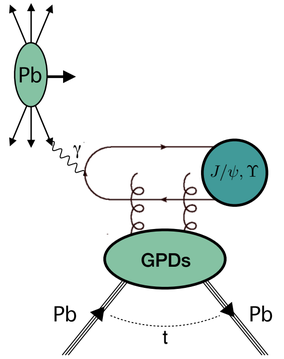




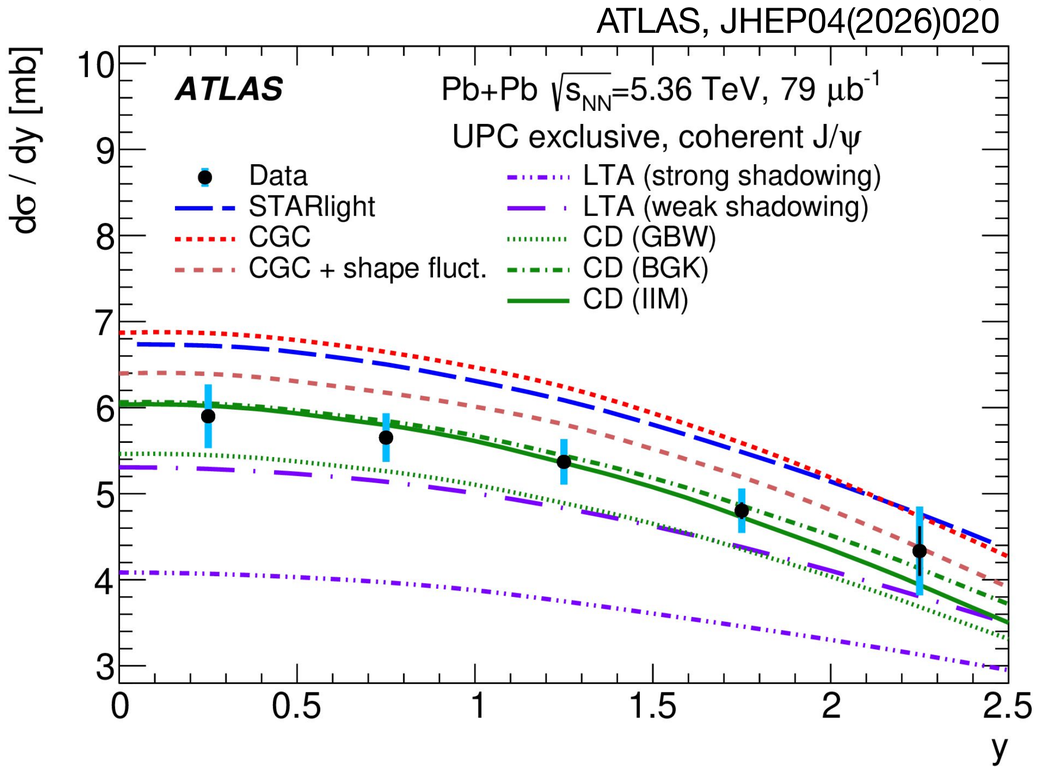
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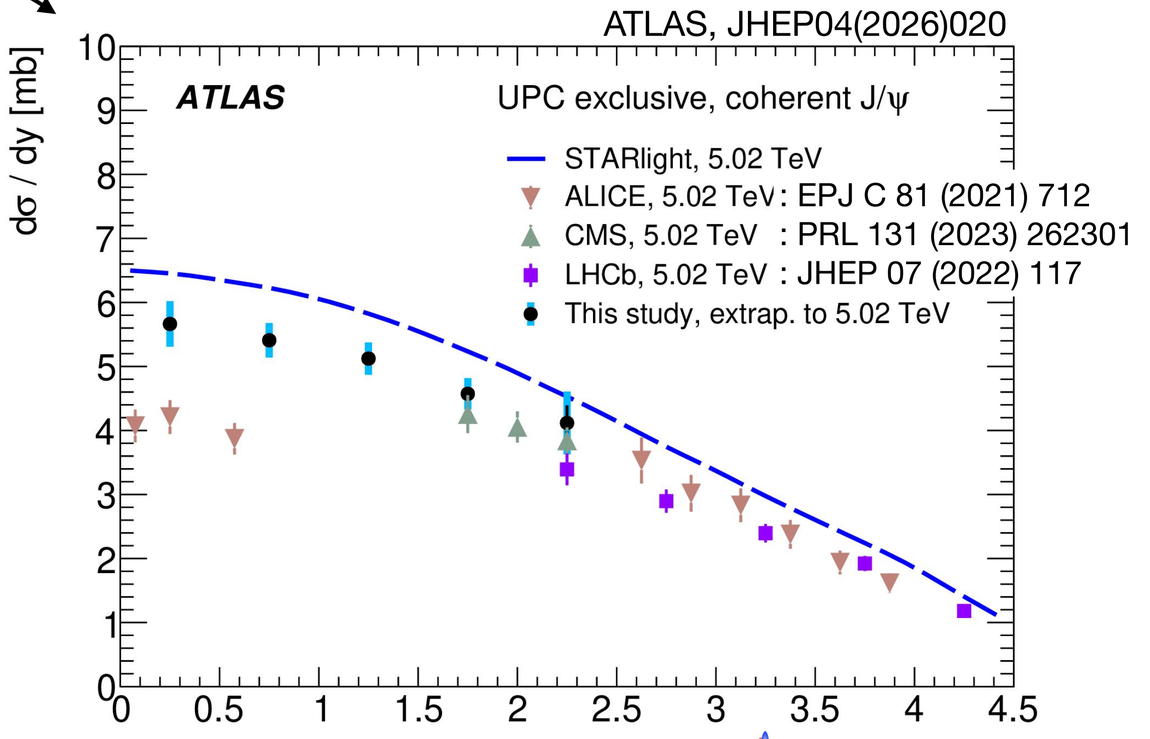
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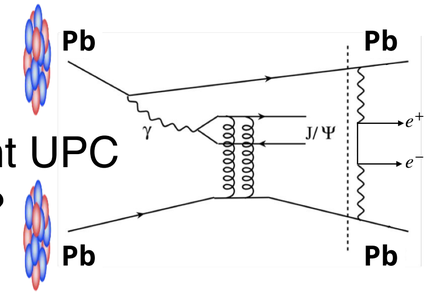
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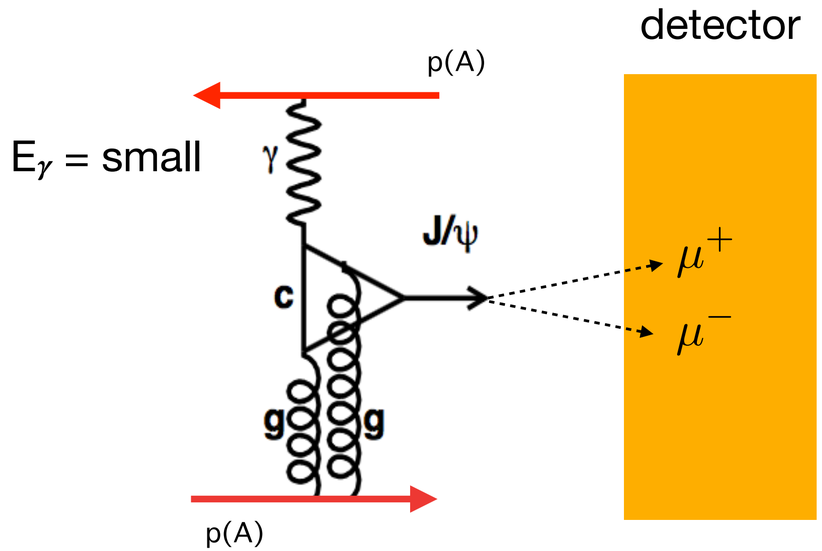


- Tension with ALICE results
- Potential contribution from coincident UPC e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ pair production?



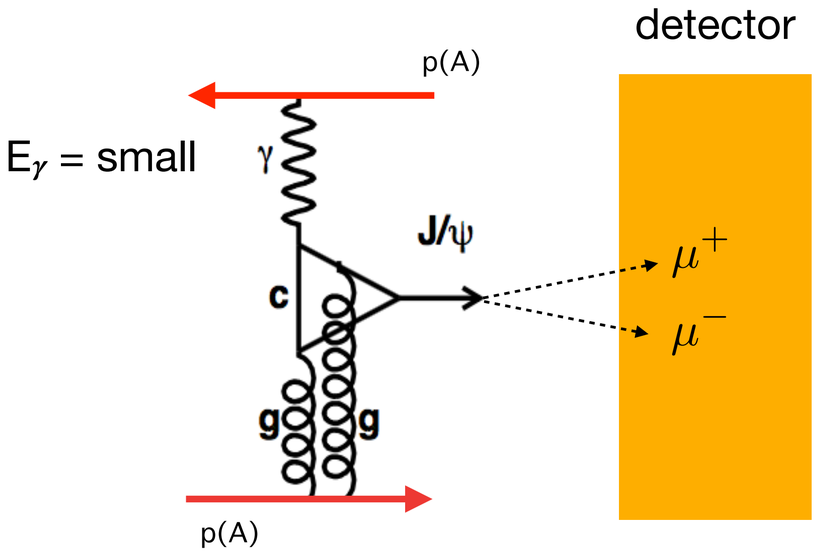
See also:
Preliminary results ALICE at $\sqrt{s_{NN}}$ 5.36 TeV

Disentangling the ambiguity on the ID of the γ emitter

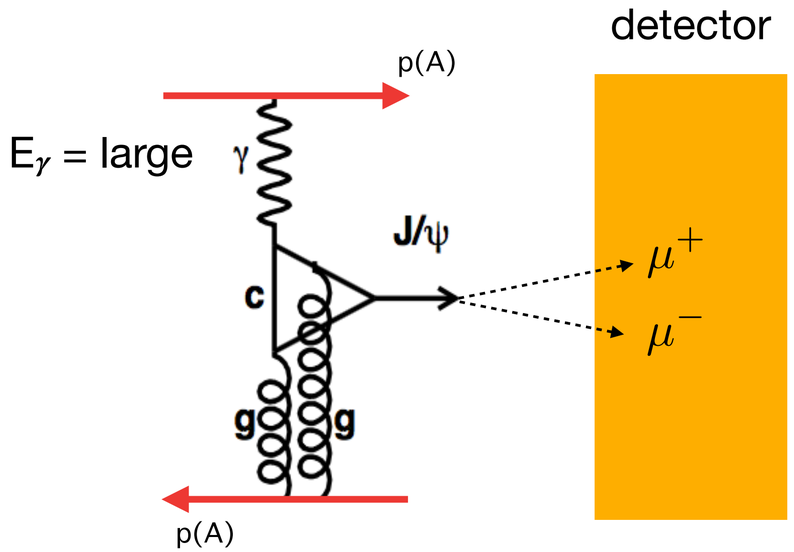


$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$

Disentangling the ambiguity on the ID of the γ emitter

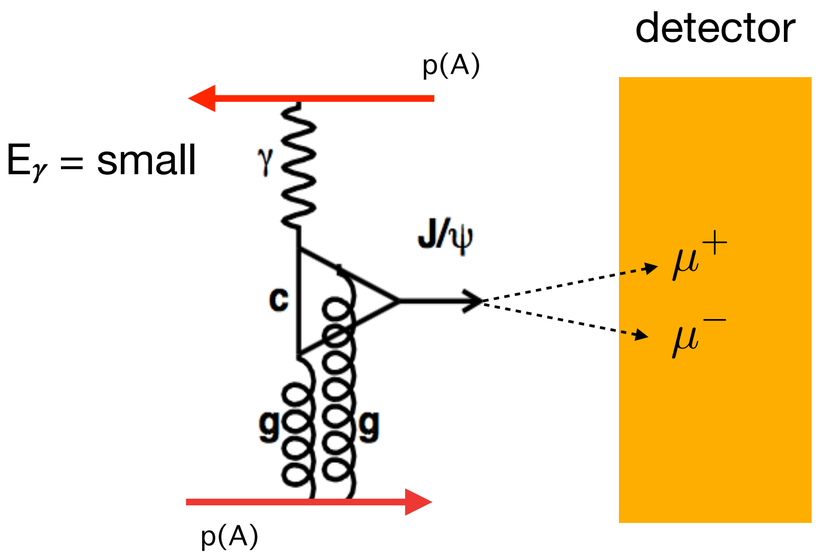


$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$

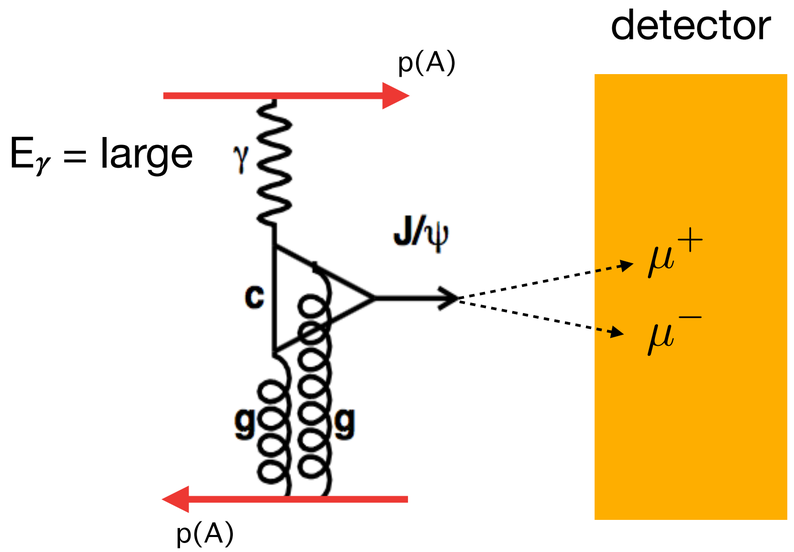


$$E_{\gamma,l} = \frac{M_{J/\psi}}{2} e^{+y}$$

Disentangling the ambiguity on the ID of the γ emitter



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



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

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

Disentangling the ambiguity on the ID of the γ emitter

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

Disentangling the ambiguity on the ID of the γ emitter

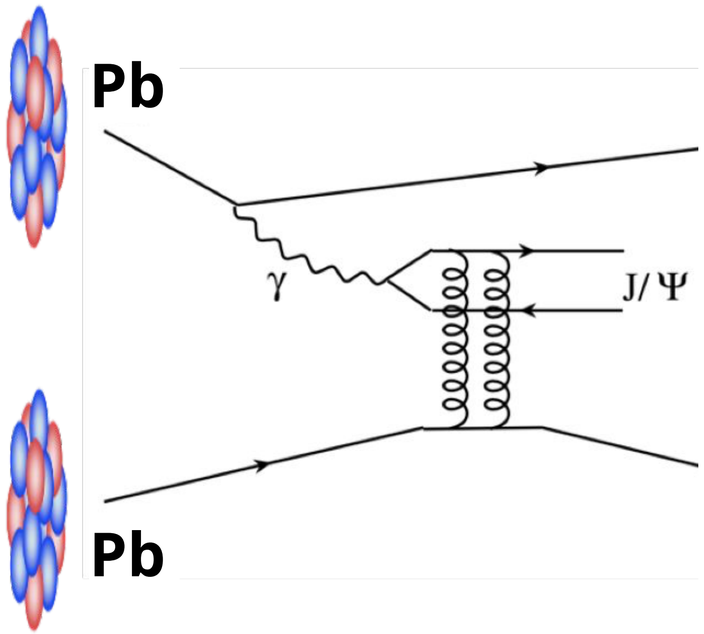
$$\sigma(y) = N_{\gamma/A}(E_{\gamma,s})\ \sigma_{J/\psi}(E_{\gamma,s}) + N_{\gamma/A}(E_{\gamma,l})\ \sigma_{J/\psi}(E_{\gamma,l})$$

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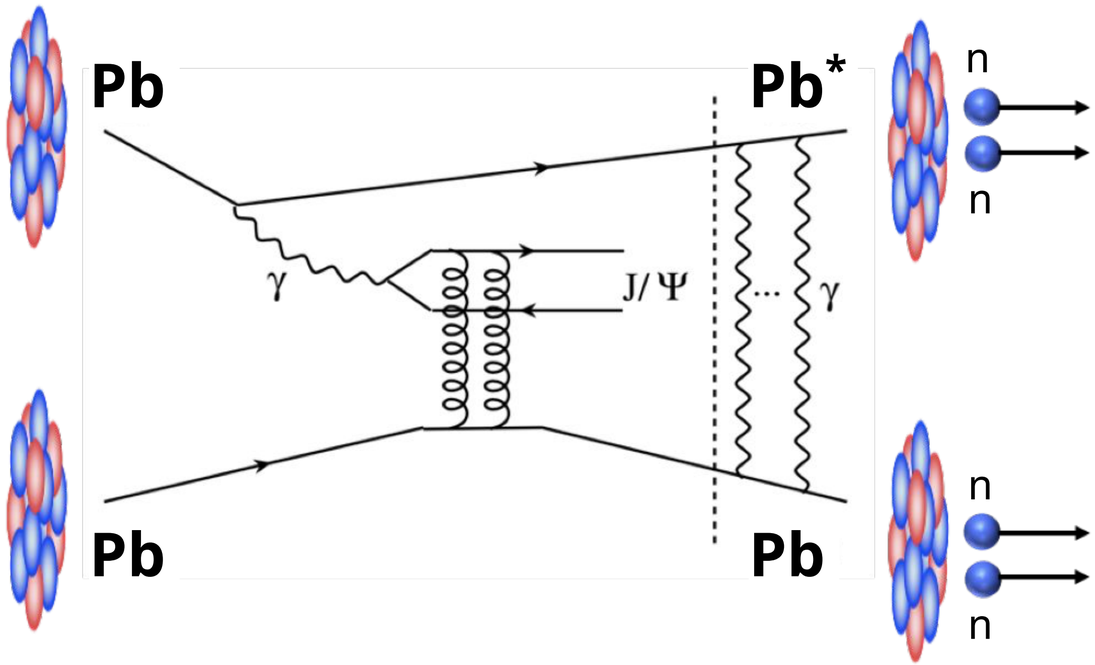
Picture from André Ståhl

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



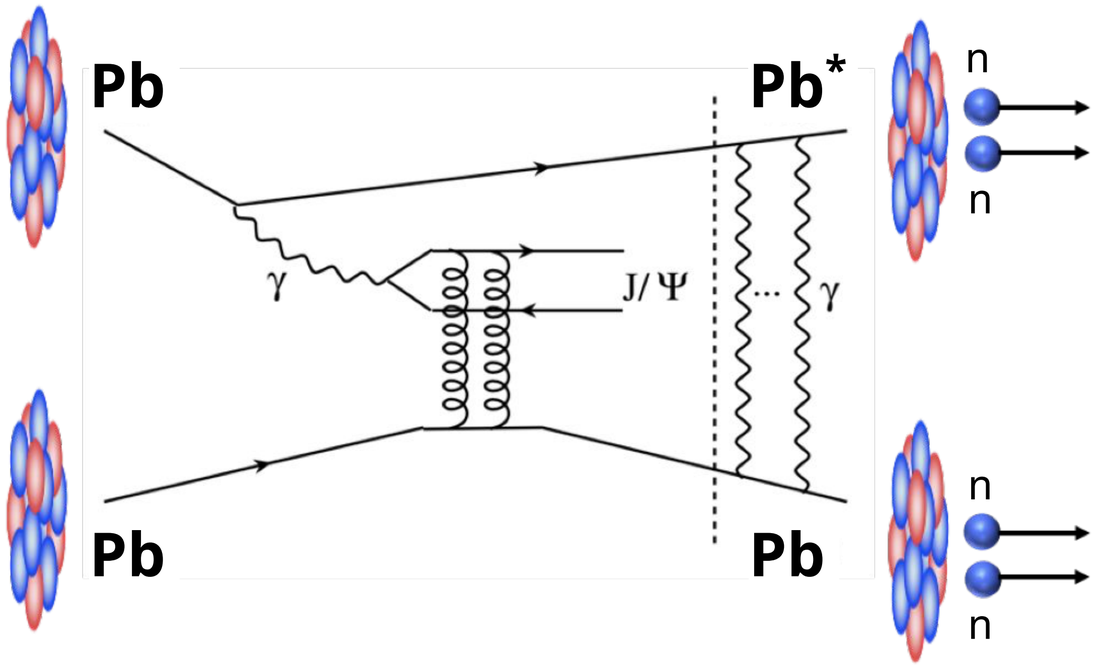
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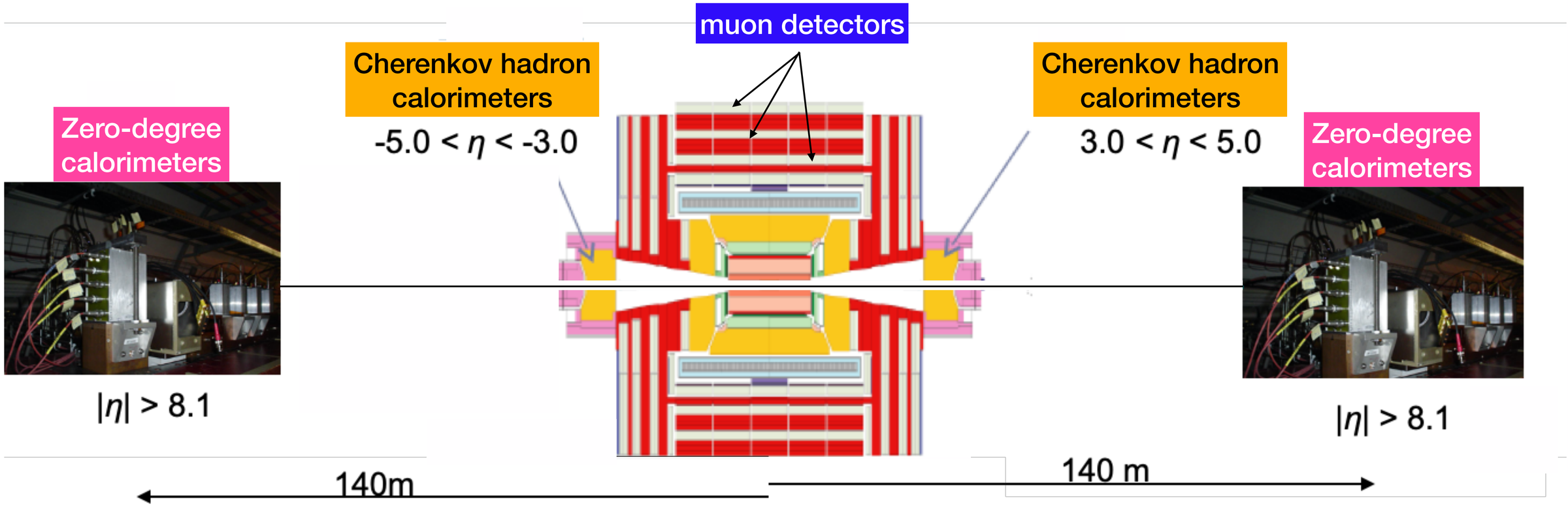
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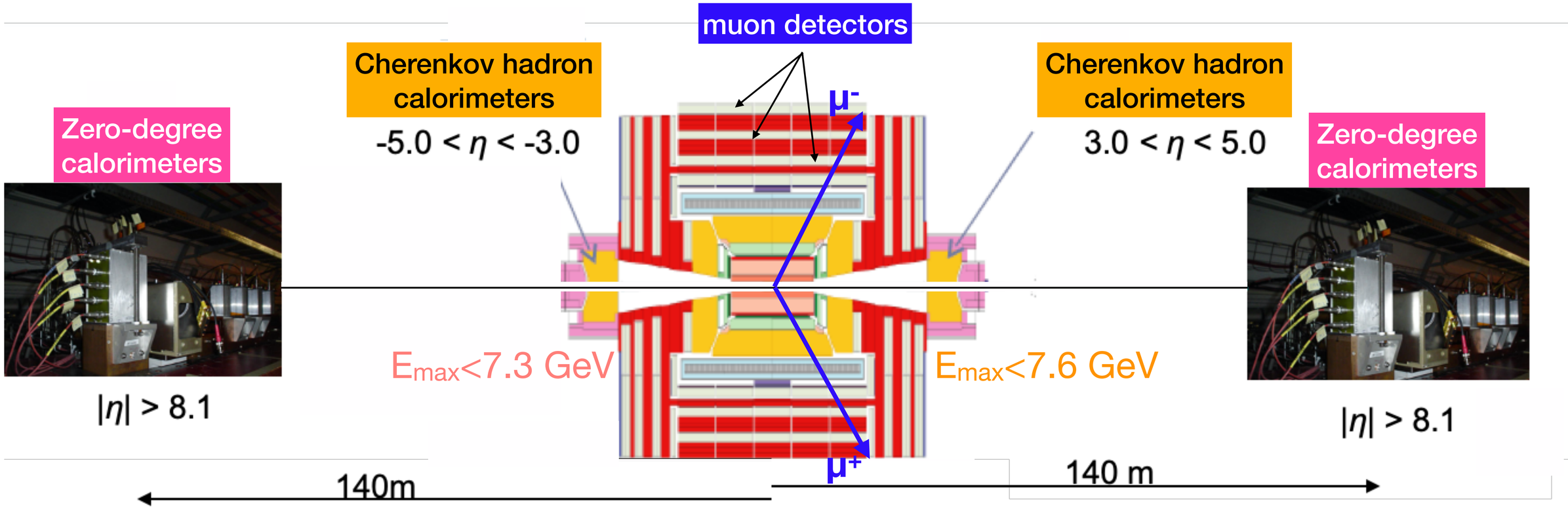
⟶ Make measurement with possibility to detect neutrons

Picture from André Ståhl

CMS central detector and the (far-)forward region

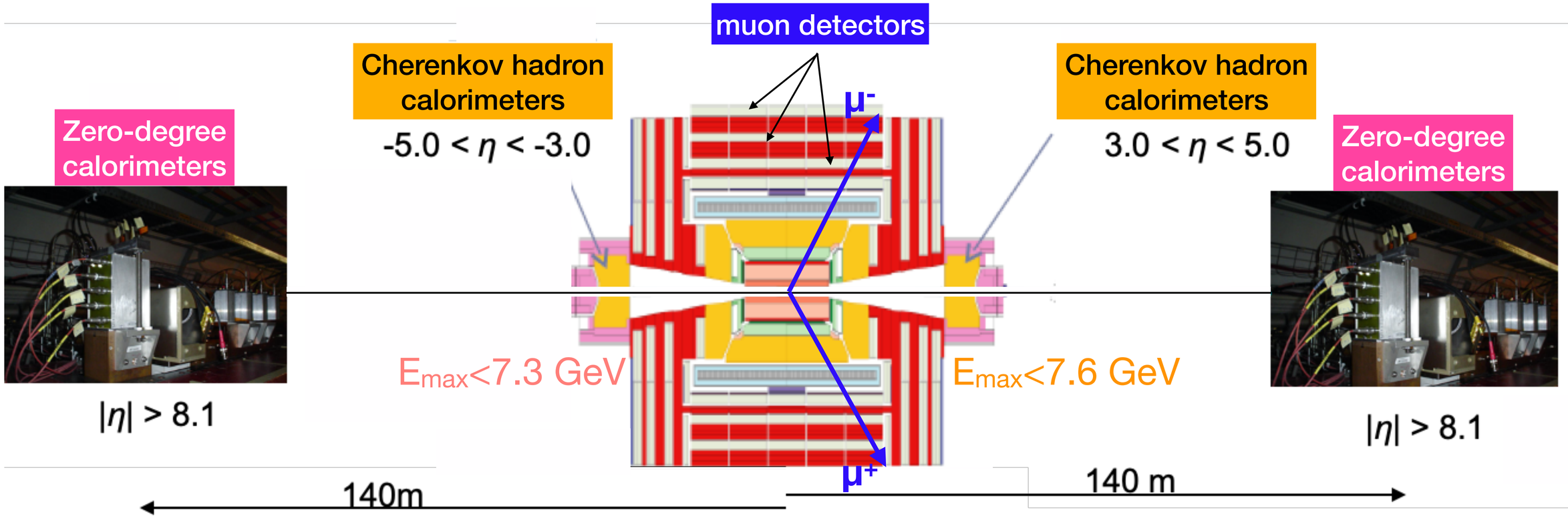


CMS central detector and the (far-)forward region



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

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

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

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

measured

Disentangling the ambiguity on the ID of the γ emitter

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

Disentangling the ambiguity on the ID of the γ emitter

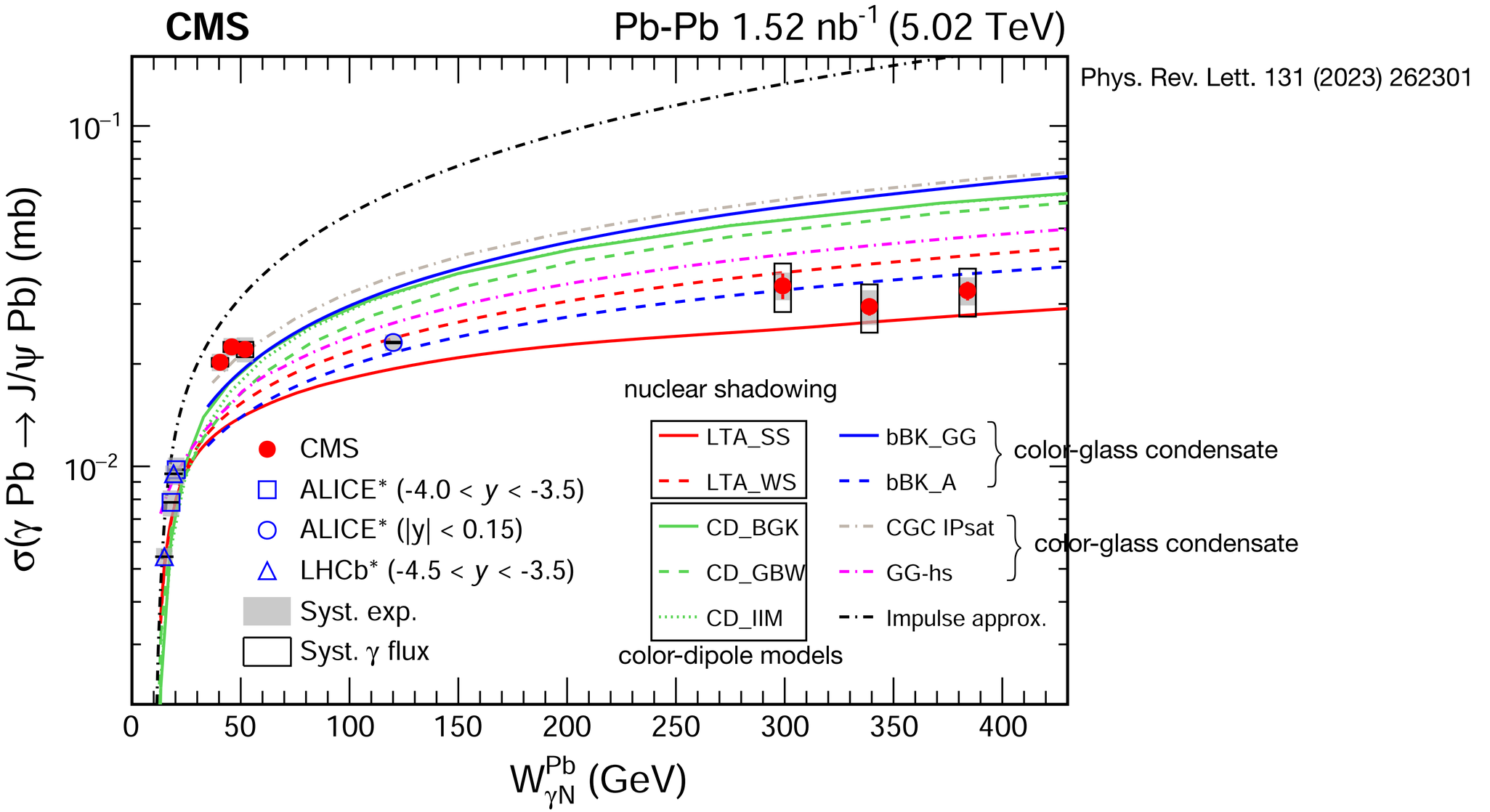
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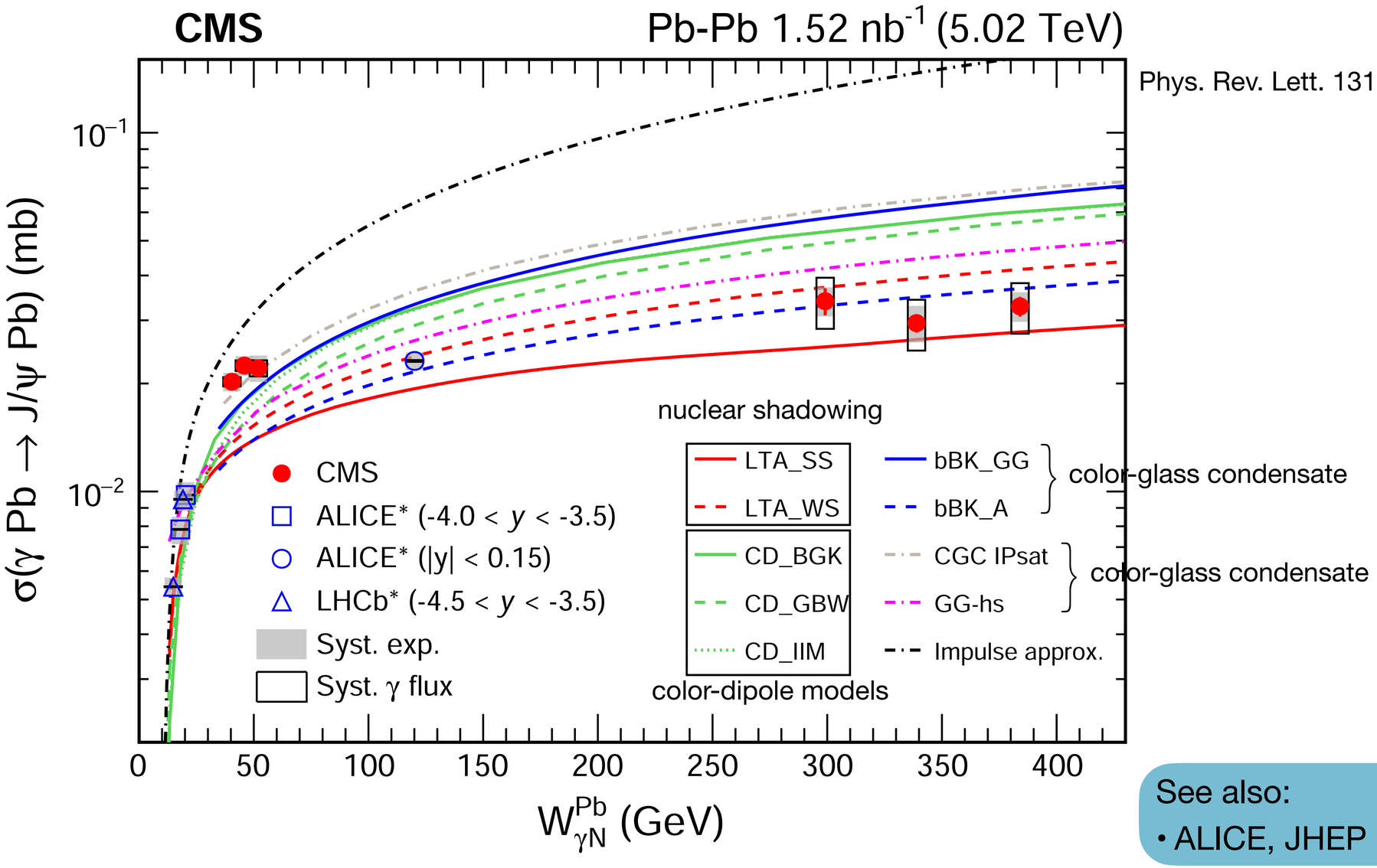
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measured | **computed (StarLight)** | **extracted** | **computed (StarLight)** | **extracted**

CMS: γPb cross section, energy dependence



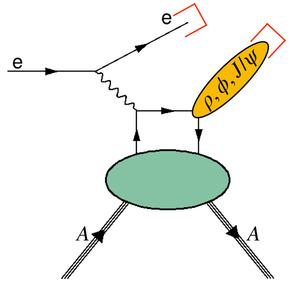
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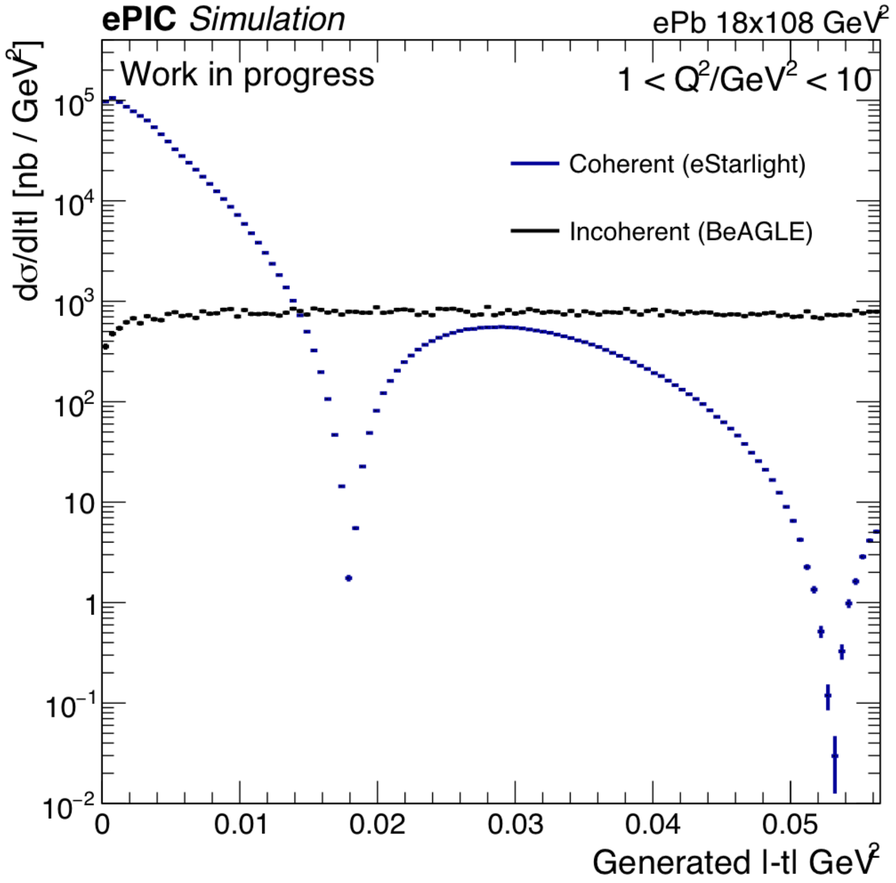
Phys. Rev. Lett. 131 (2023) 262301

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

Exclusive vector-meson production off nuclei in ePIC

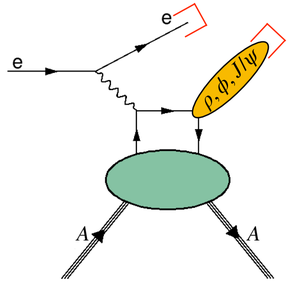


Separation of coherent and incoherent signal

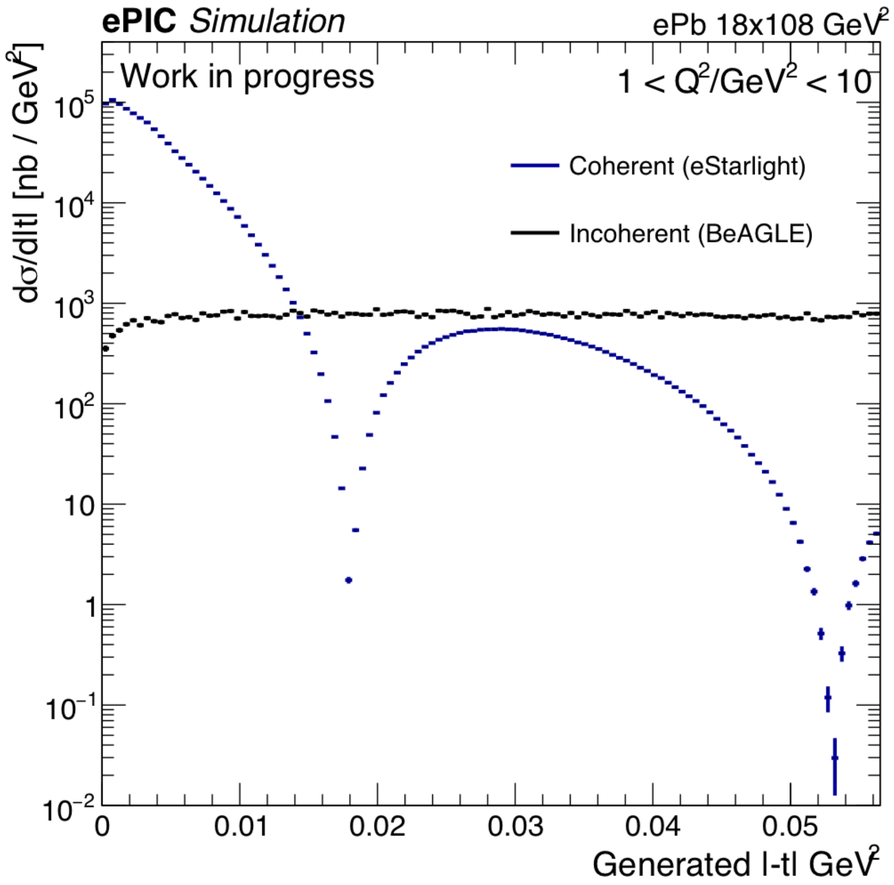


Simulated coherent and incoherent signal

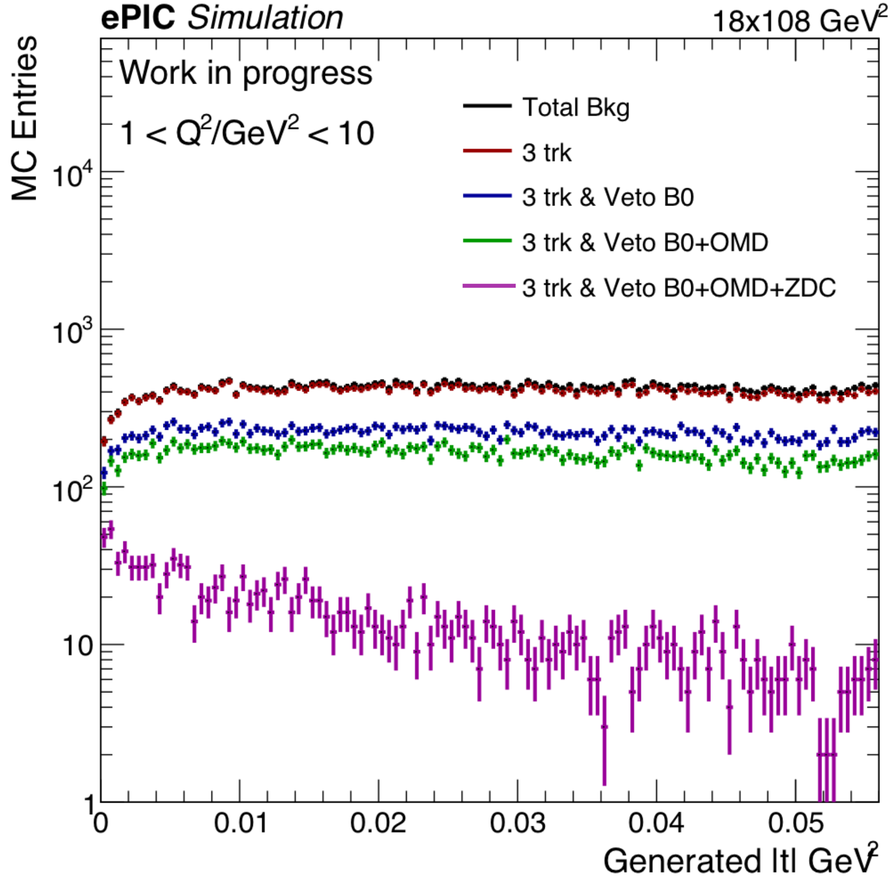
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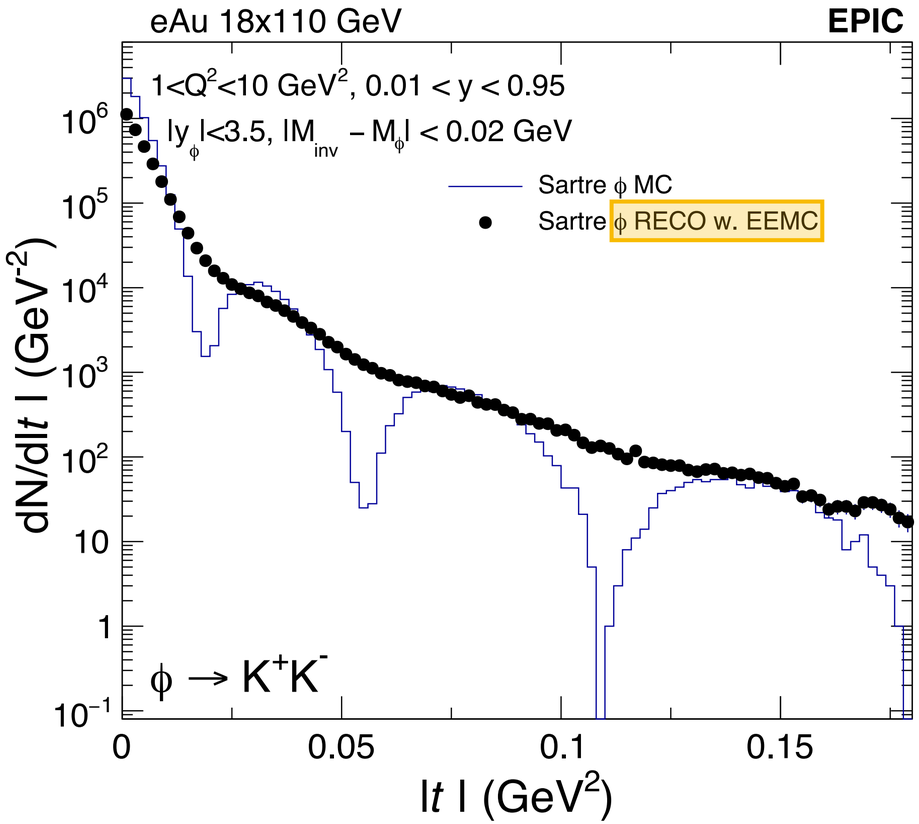


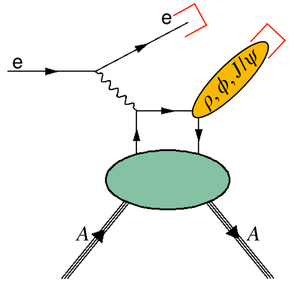
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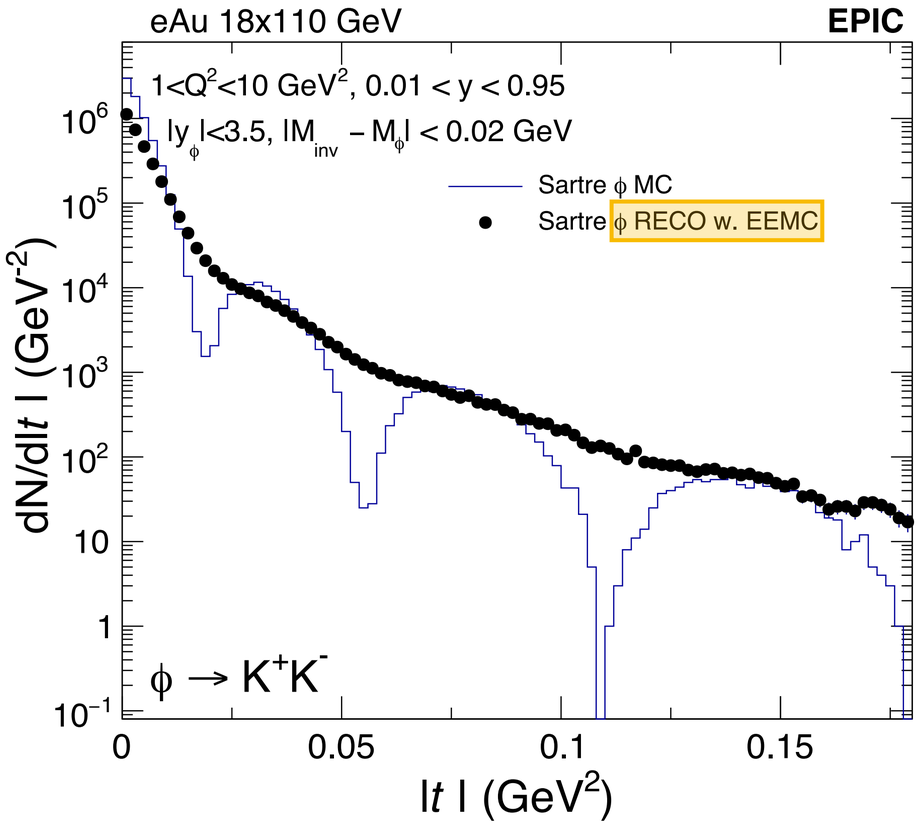
Suppression of incoherent signal using detector system

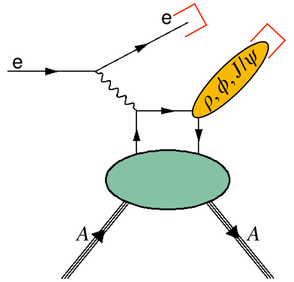
Resolution in t



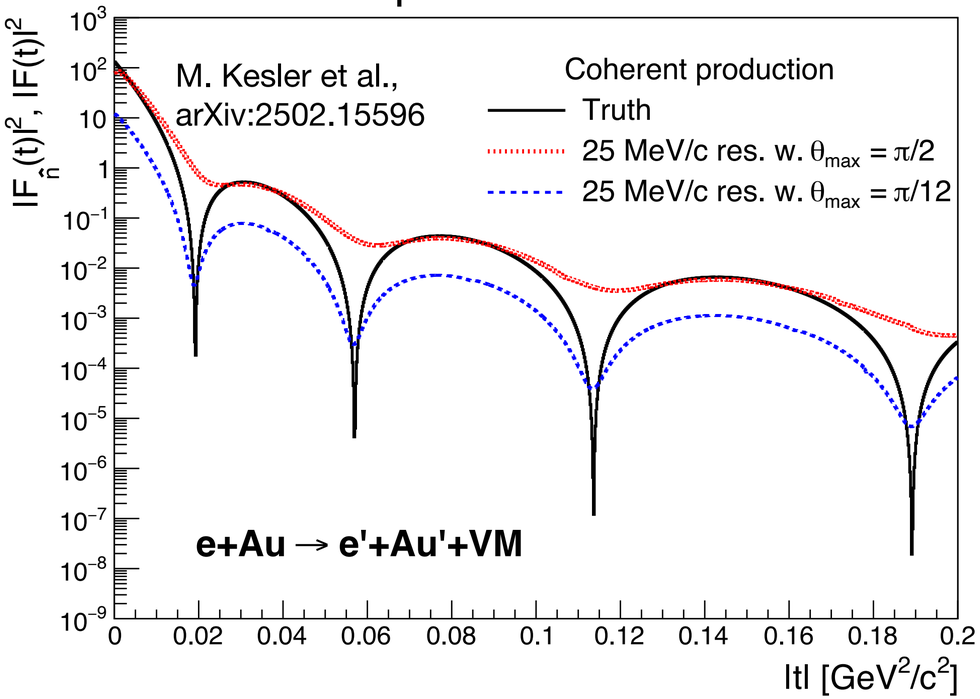


Resolution in t

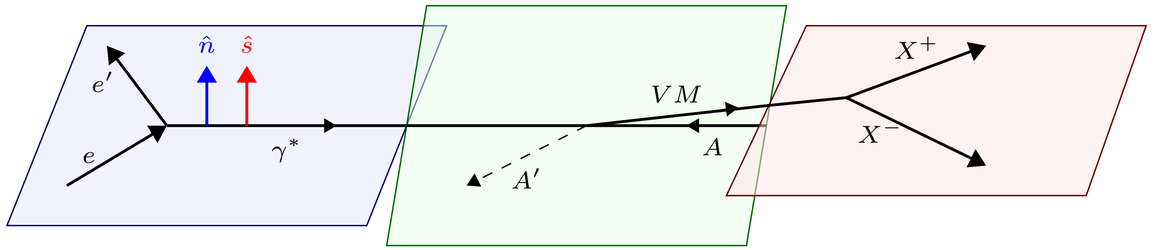




Development of new method

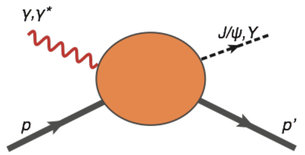


Scattering Plane | Production Plane | Decay Plane

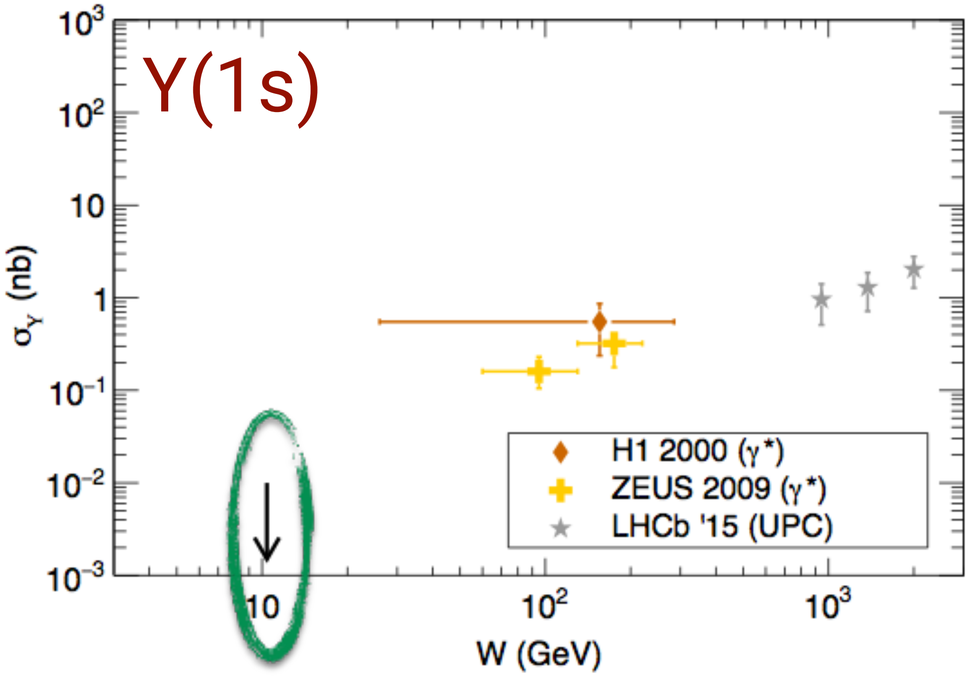


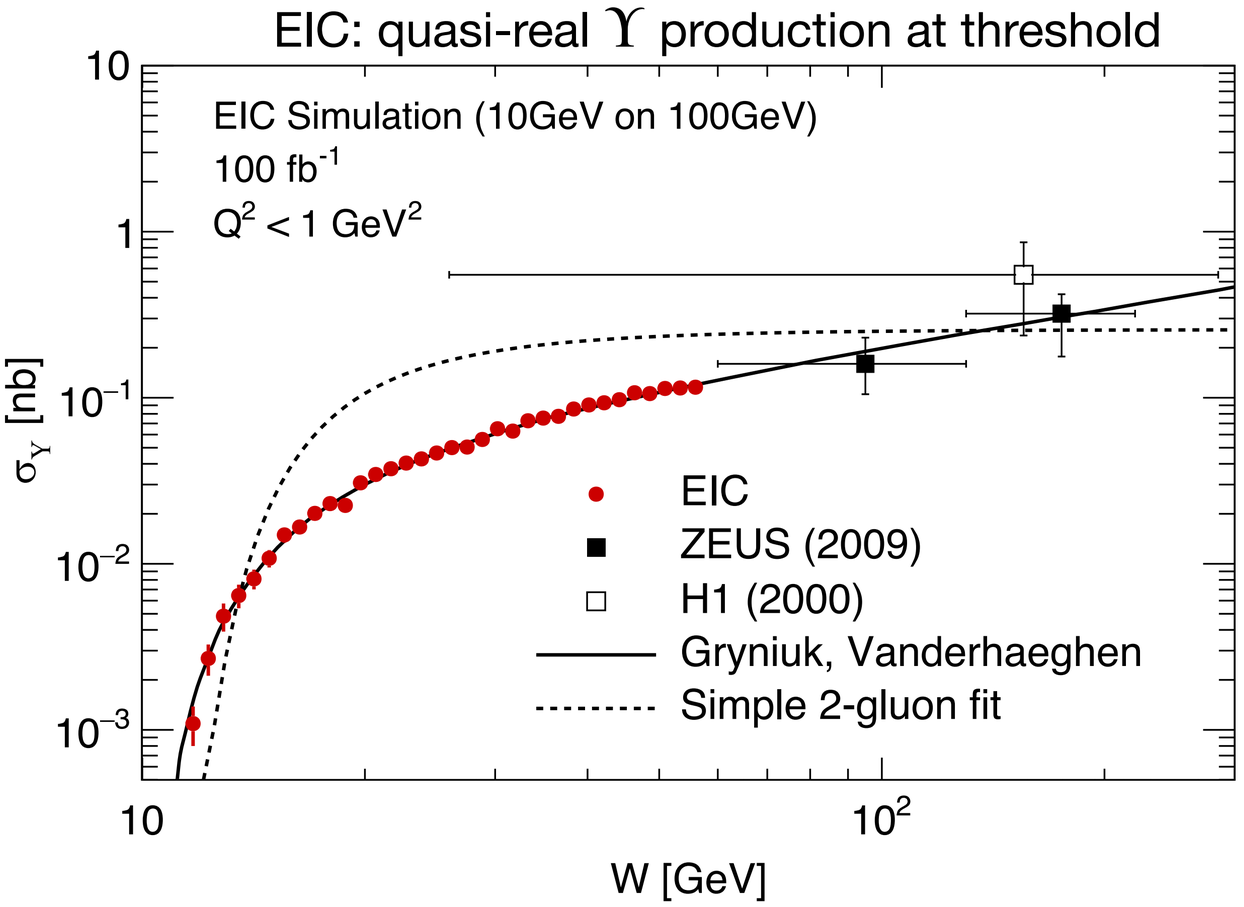
project t along $\hat{n}$

Quarkonium threshold production



Information on gluon trace anomaly





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

Summary

- 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, complementary to JLab.
  - Plans for transversely polarised target.

- EIC:
  - Down to $x_B=10^{-4}$, polarised beams and entire series of unpolarised nuclei.
  - Study with high precision of gluon GPDs
  - Threshold production: Υ complementary to J/ψ JLab studies