UPC and far-forward detection

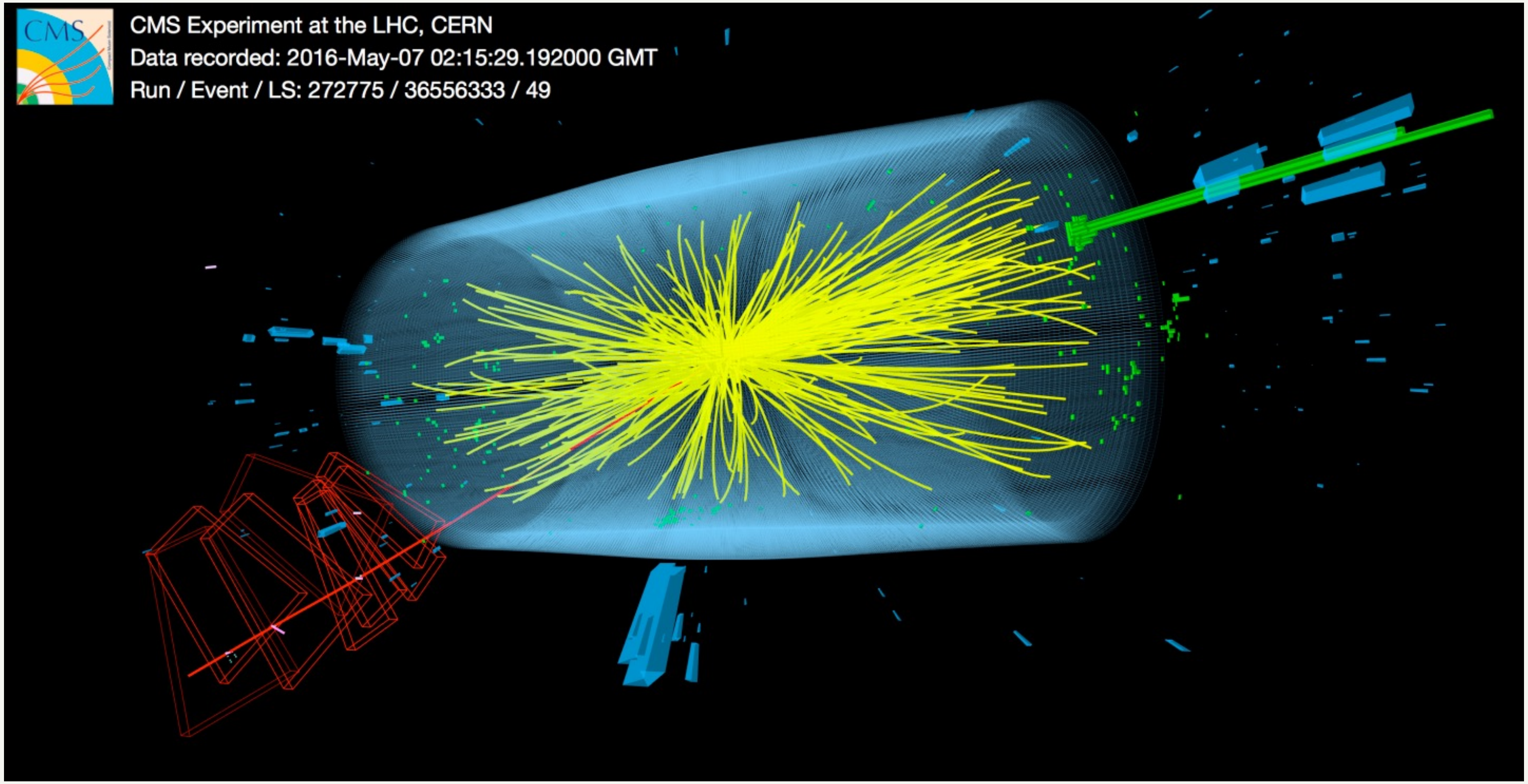
Ronan McNulty

Quarkonia as Tools, Aussois,
Jan 6-10 2024

Overview

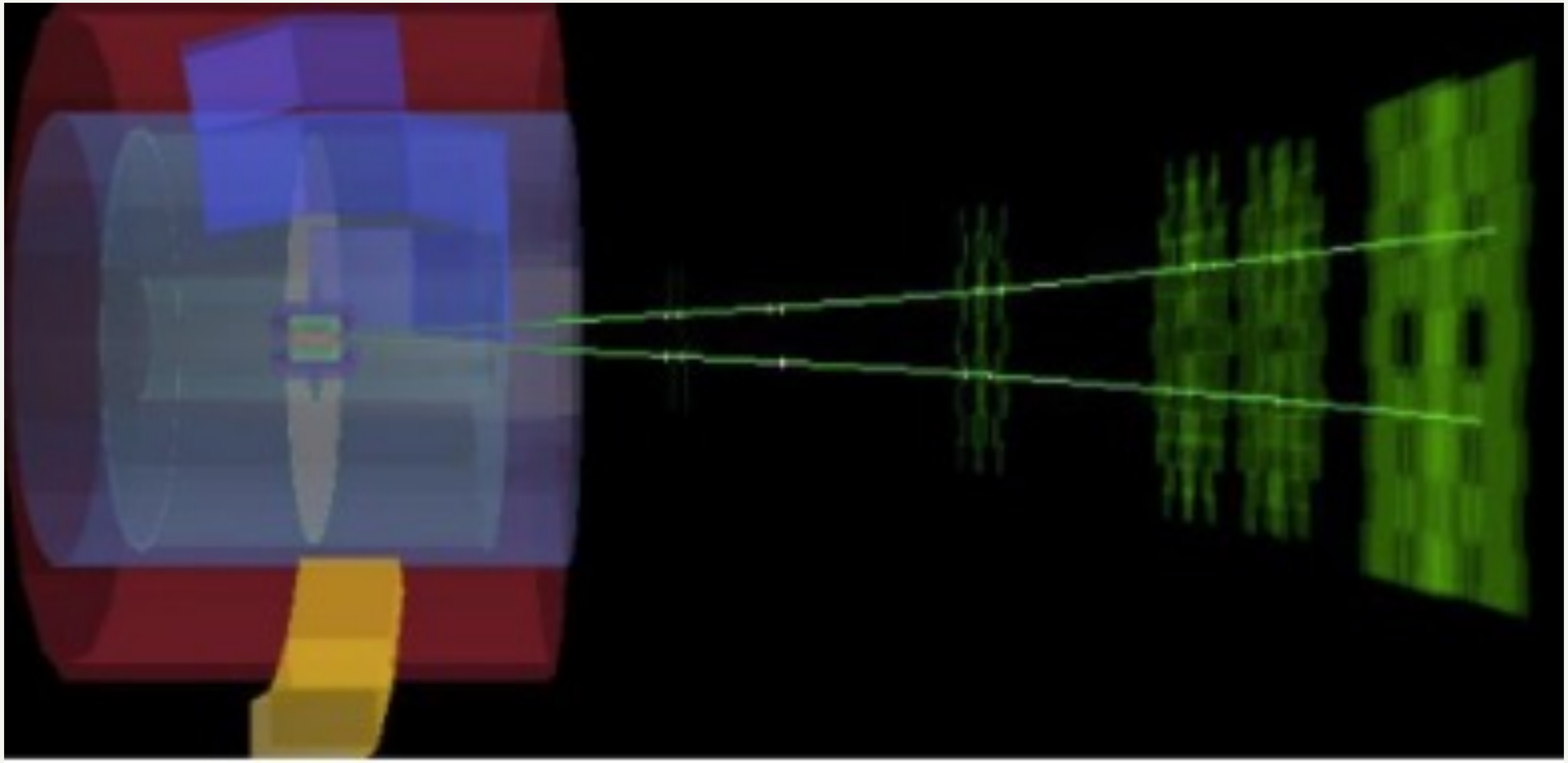
- Introduction to UPC
- (Comments on Odderon at LHC)
- Search for saturation
- Far-forward detection in UPC

pp collision



Most collisions at the LHC, pp, pA, AA have enormous multiplicities due to colour flow. However, when colourless propagators are involved, multiplicities are low and events have large **rapidity gaps**.

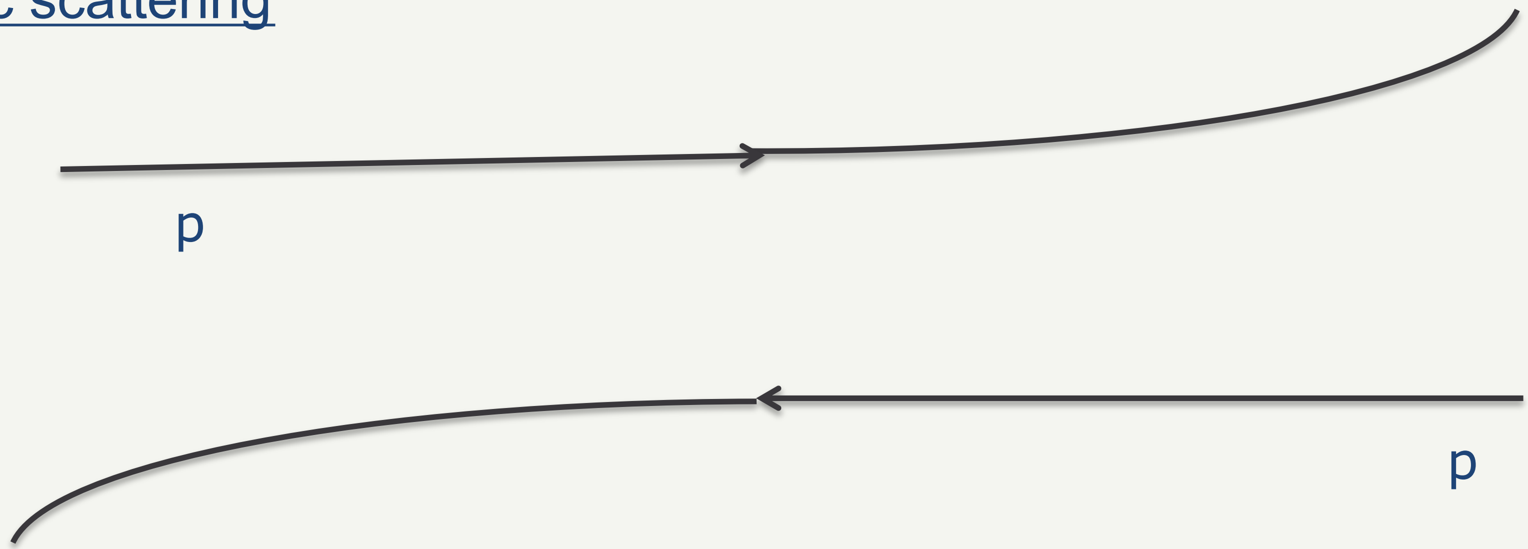
UPC J/ψ at forward rapidity in ALICE PbPb data



(from Evgeny Kryshen talk at INT workshop)

Physics of the Vacuum

Elastic scattering

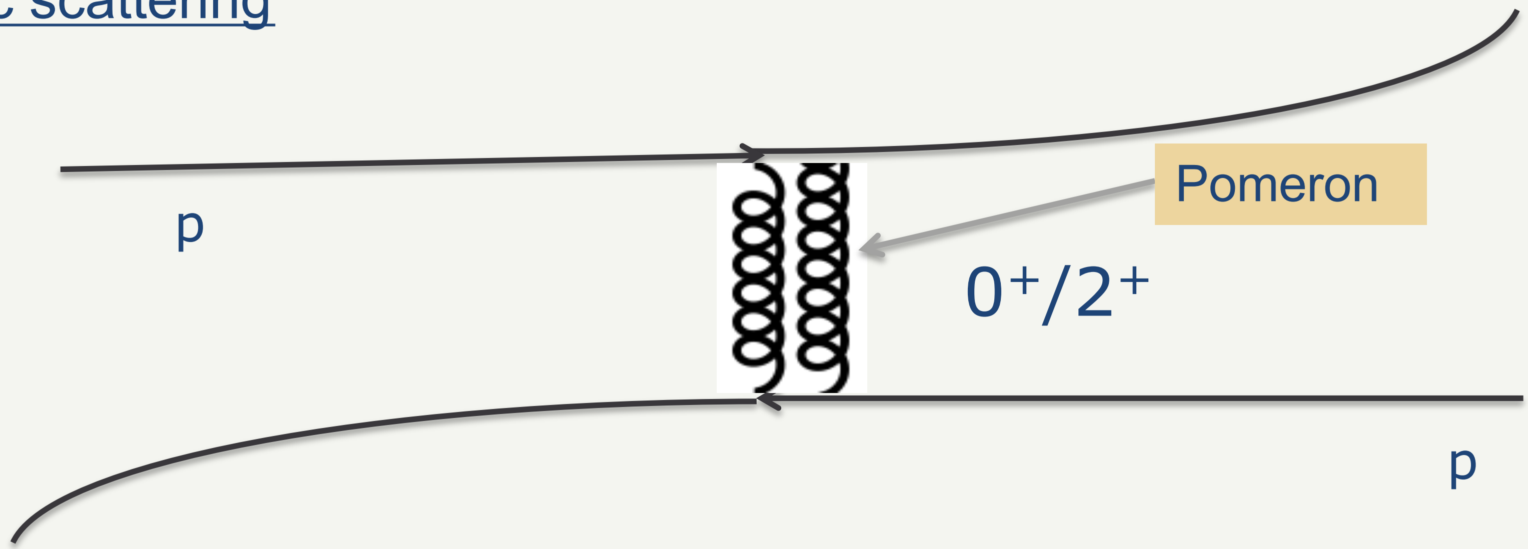


It's QCD – but not as we normally see it. It's colour-free

$\sigma_{elastic} \approx 40mb$
$\sigma_{diffractive} \approx 10mb$
$\sigma_{inelastic} \approx 60mb$

Physics of the Vacuum

Elastic scattering



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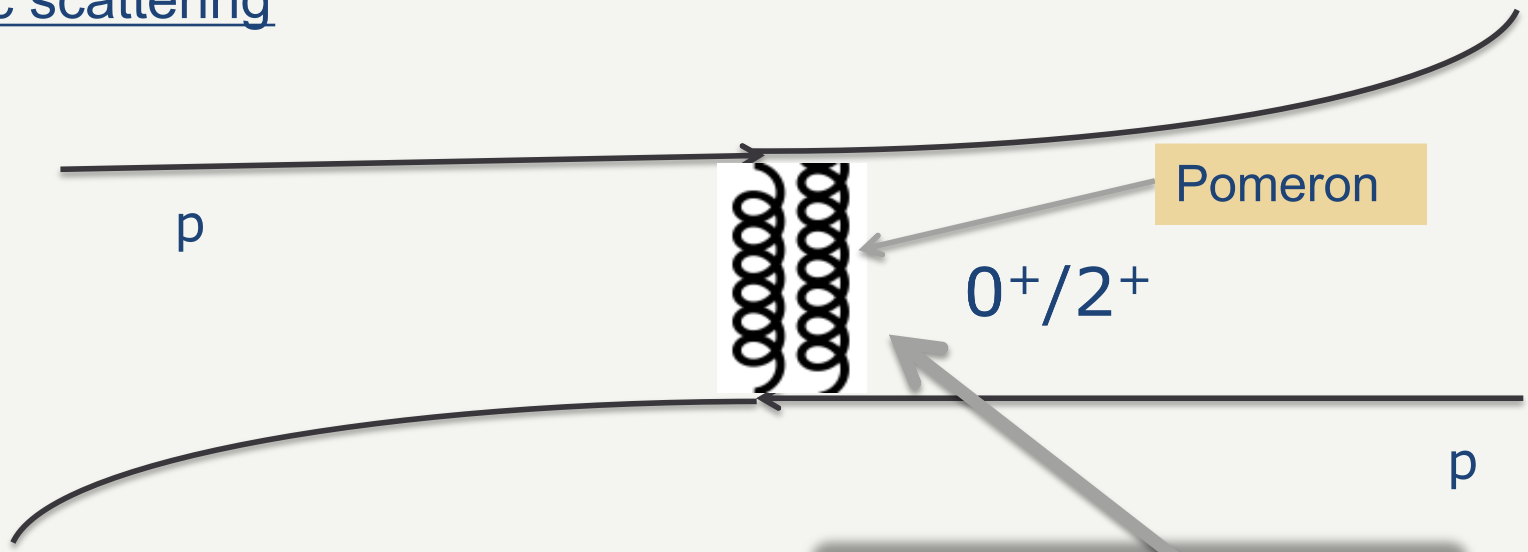
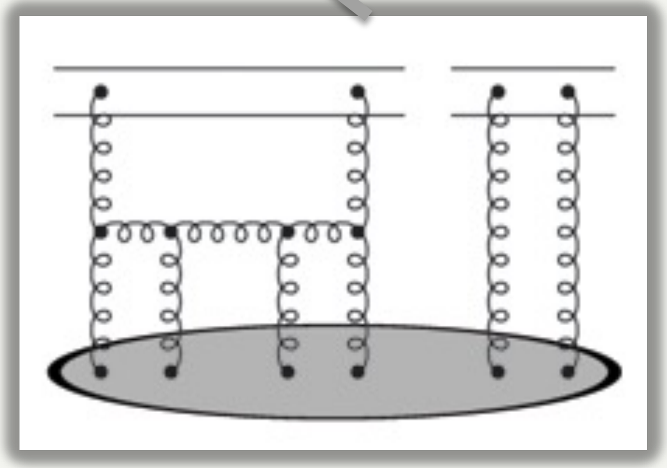


At high energy: $A(s,t)=s^{\alpha(t)}$
$\alpha_P(t)=\alpha_P(0)+\alpha' t$



$\sigma_{elastic} \approx 40mb$
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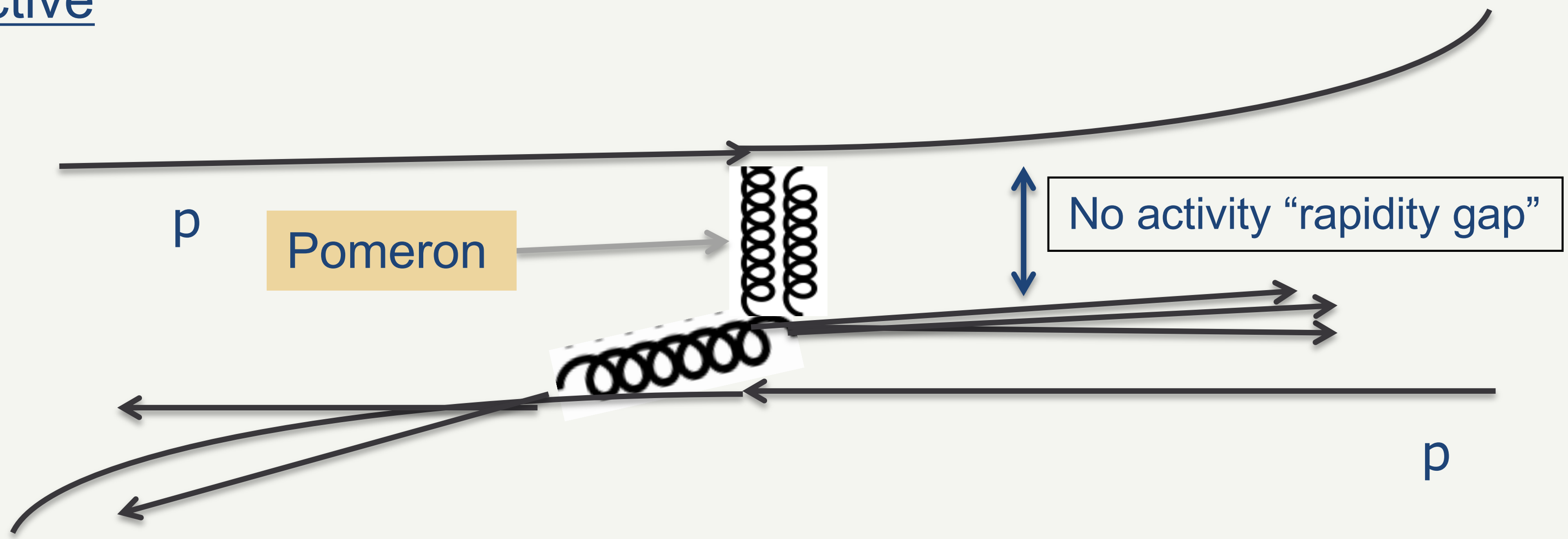
Physics of the Vacuum

Diffractive



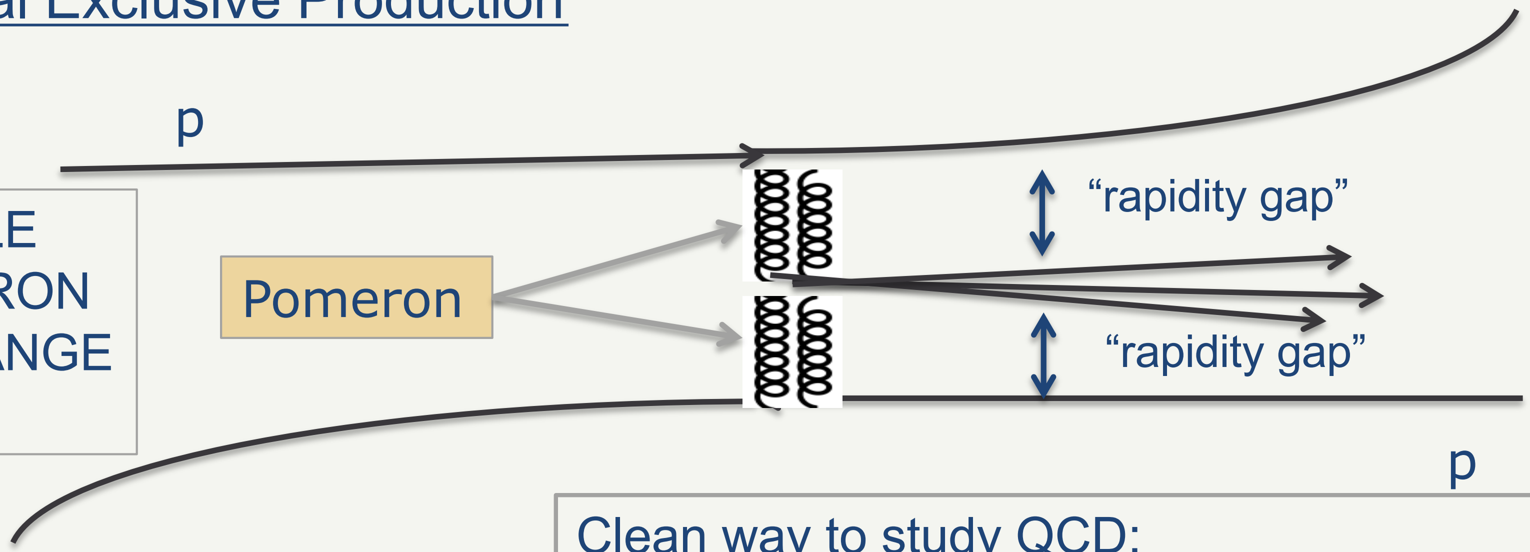
Experimental working definition of diffraction is presence of rapidity gap

$\sigma_{elastic}$ ≈ 40mb
$\sigma_{diffractive}$ ≈ 10mb
$\sigma_{inelastic}$ ≈ 60mb

Physics of the Vacuum

Central Exclusive Production

DOUBLE POMERON EXCHANGE (DPE)



Clean way to study QCD:

- structure of projectiles
- nature of colour-free propagators
- structure of what is produced out of vacuum

$\sigma_{elastic} \approx 40\text{mb}$

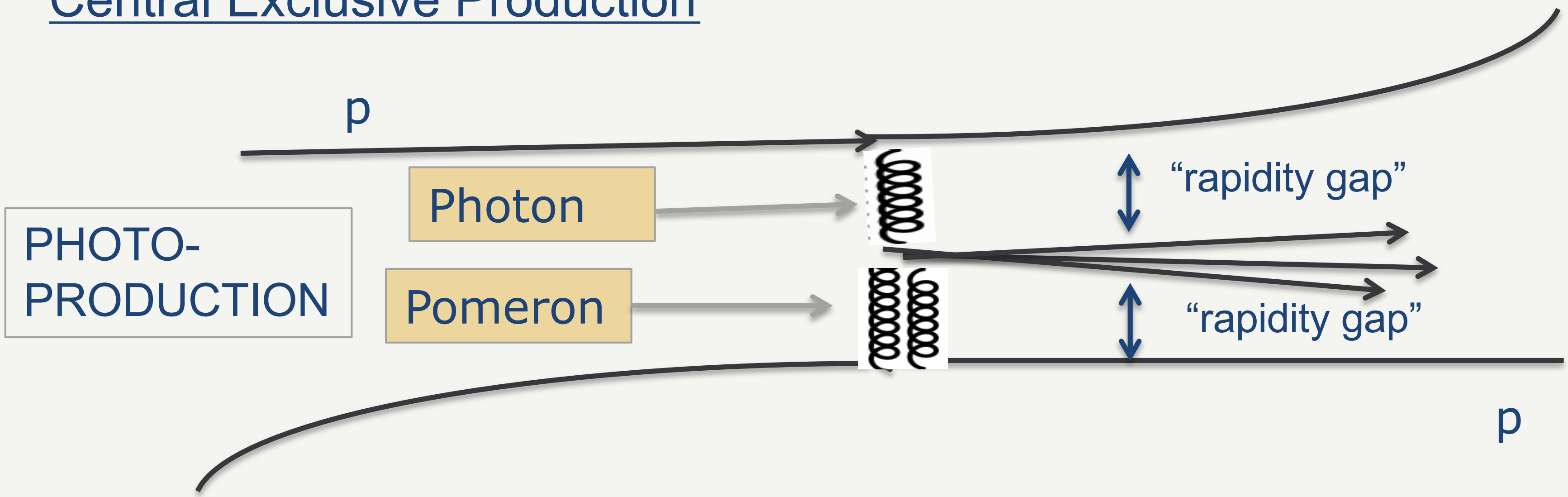
$\sigma_{diffractive} \approx 10\text{mb}$

$\sigma_{inelastic} \approx 60\text{mb}$

100 μb

Physics of the Vacuum

Central Exclusive Production



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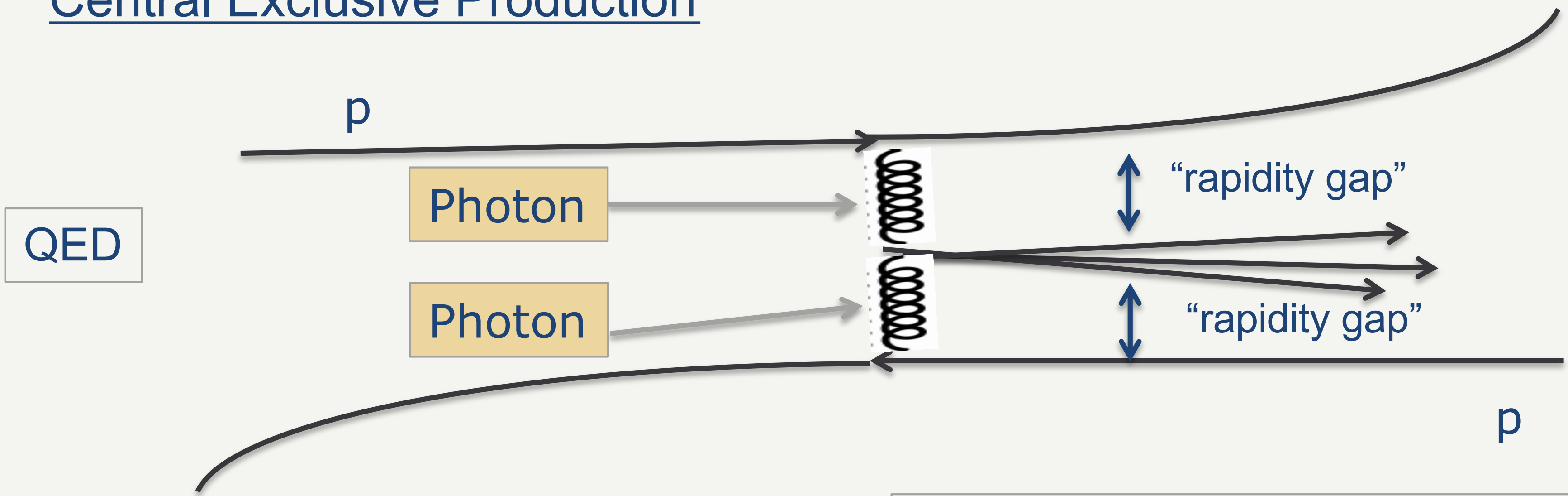
100 μb

Physics of the Vacuum

Central Exclusive Production



CEP is characterised by a rapidity gap all the way to the proton

Detect as large a gap as possible...

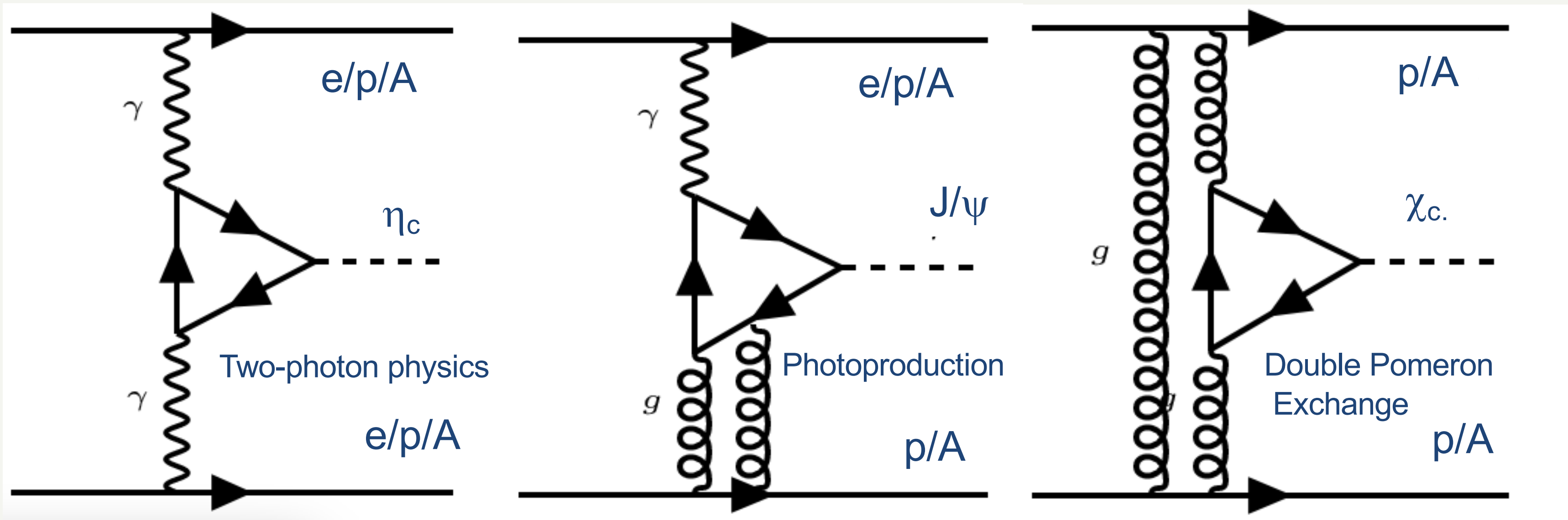
$\sigma_{elastic}$ ≈ 40mb

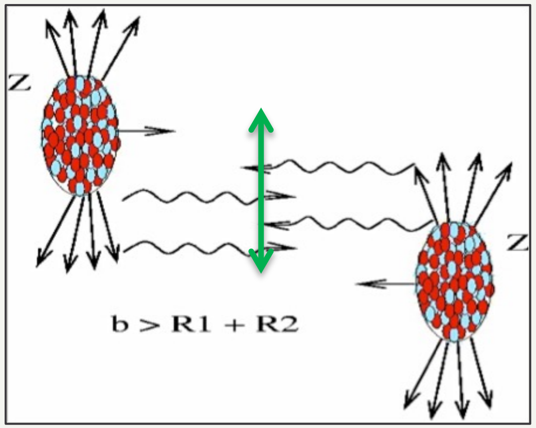
$\sigma_{diffractive}$ ≈ 10mb

$\sigma_{inelastic}$ ≈ 60mb

100 pb

Colourless propagators



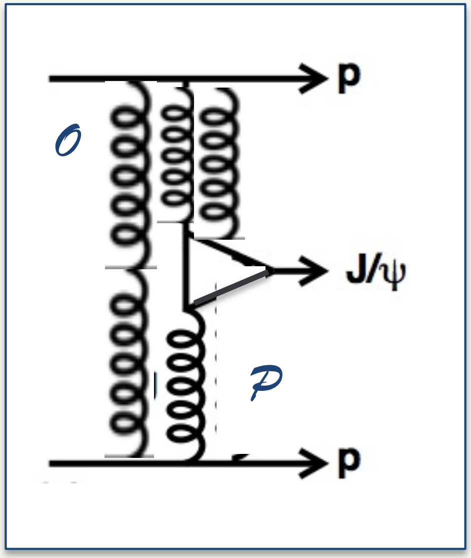


Hadron colliders:
Generally, to ensure no (colourful) QCD interaction, $d>R_1+R_2$ (1.5 - 6 fm).

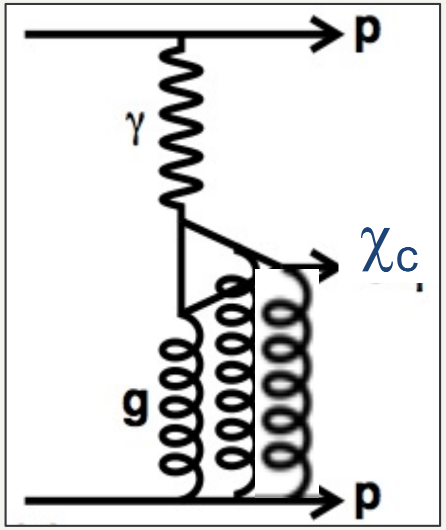
Large impact parameter ↔ Small p_T

Electron-hadron collider:
~70% of total cross-section is diffractive

Odderon search: partner of pomeron



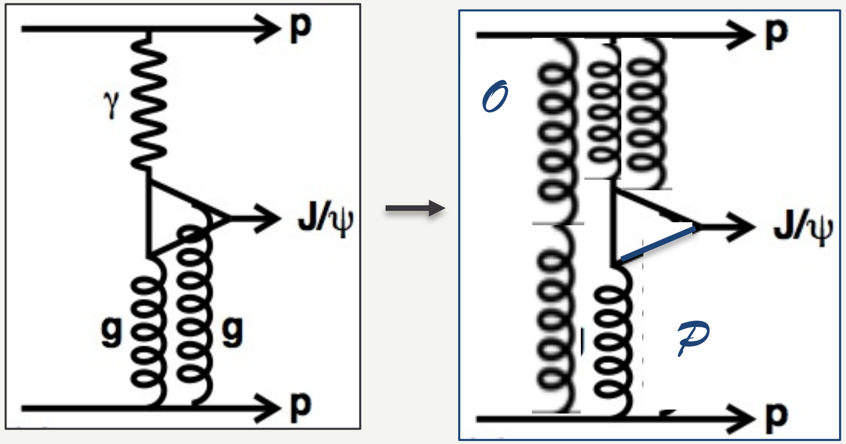
C-odd meson

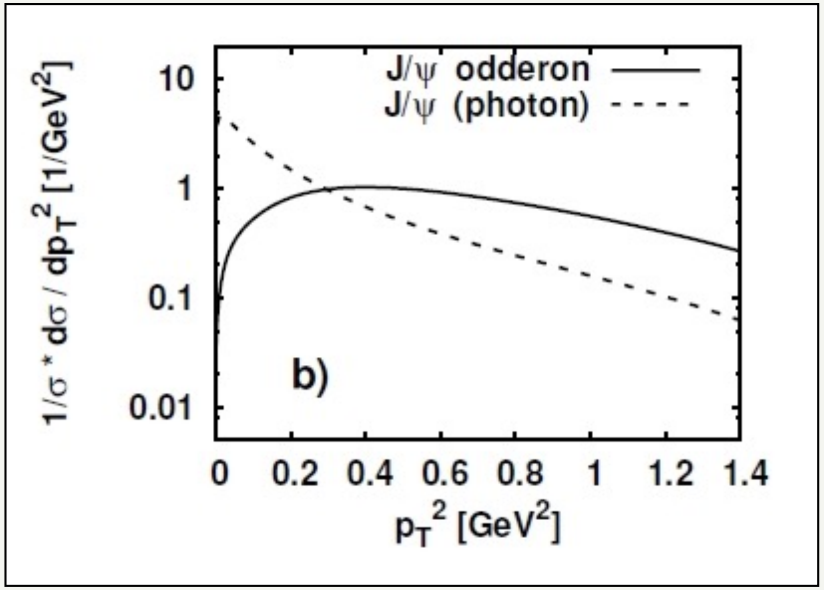


C-even meson

Method 1: High p_T exclusive C- production

Replace γ with $\mathcal{O}$





Bzdak, Motyka, Szymanowski, Cudell PRD 75 (2007) 094023

$$\frac{d\sigma}{dt} \sim e^{bt}$$

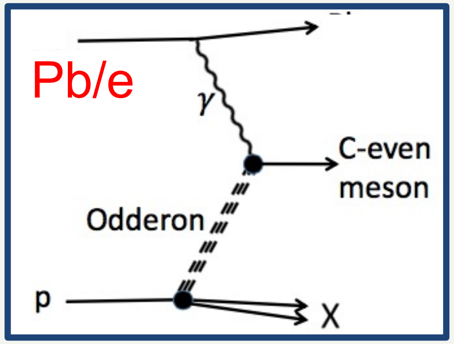
Photoproduction: b~6 GeV^{-2}
Proton dissociation b~1 GeV^{-2}
Odderon b small

$d\sigma^{\mathrm{corr}}/dy$	J/ψ	
	odderon	photon
Tevatron	0.3–1.3–5 nb	0.8–5–9 nb
LHC	0.3–0.9–4 nb	2.4–15–27 nb

Odderon contribution might be 1-10% at LHC and would dominate at high p_T
….. but experimentally this is difficult to see

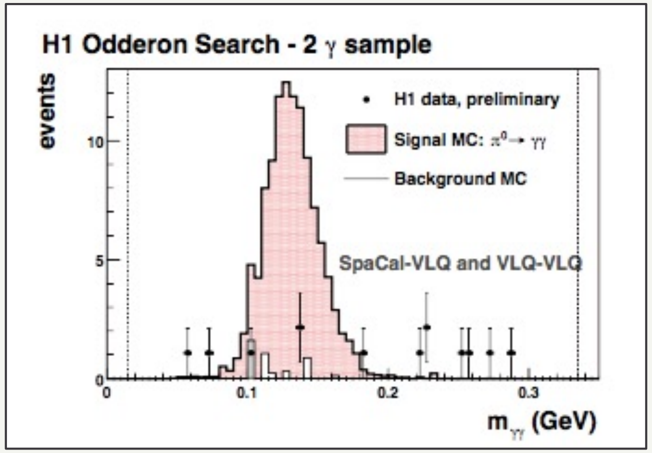
Angular distribution of muons due to polarisation may also differ (R. Schnicker)

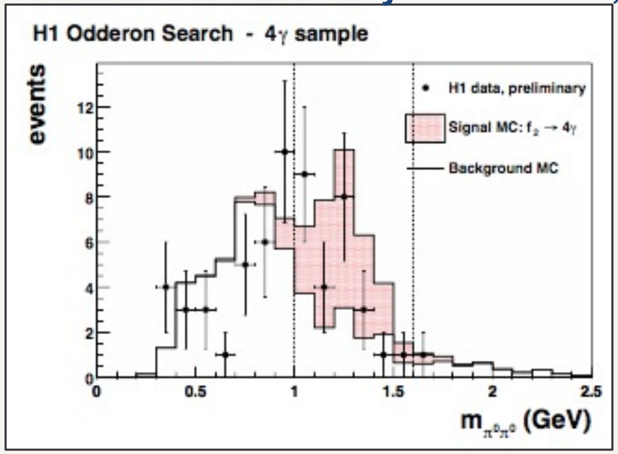
Method 2: Photoproduction of C+

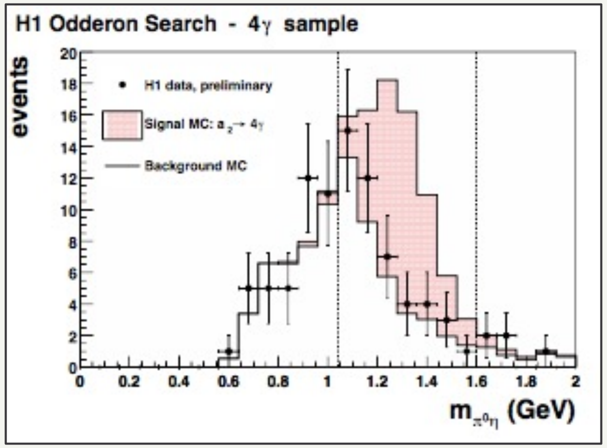


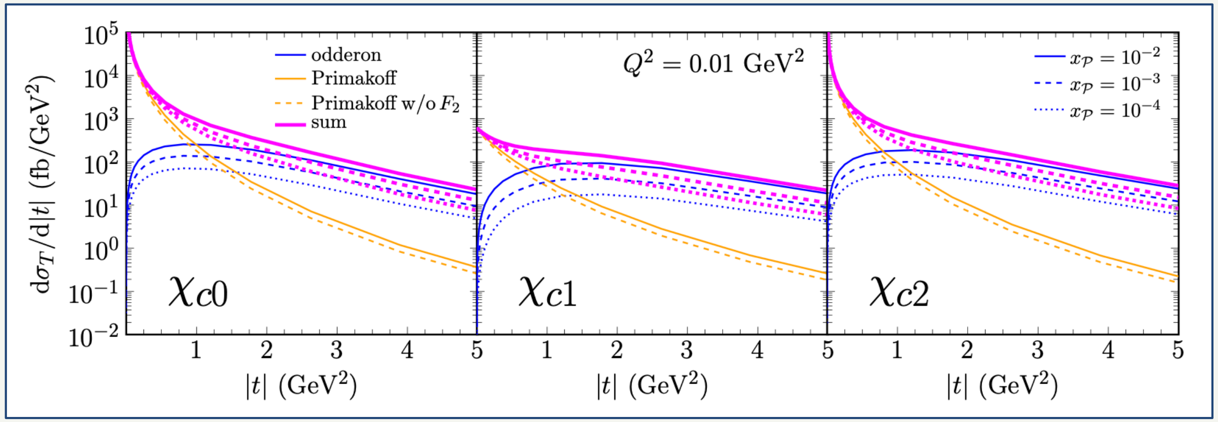
Czyzewski, Kwiecinski, Motyka, PLB398 (1997) 400.
Berger, Donnachie, Dosch, Kilian, Nachtmann, EPJ C9 (1999) 491.
Ryskin EPJ C2 (1998) 339.
Kilian & Nachtmann, EPJ C5 (1998) 317.
Harland-Lang, Khoze, Martin, Ryskin PRD 99 (2019) 3, 034011

Acta Phys. Polon. B33, 3499 (2002). (Conference proceeding.)



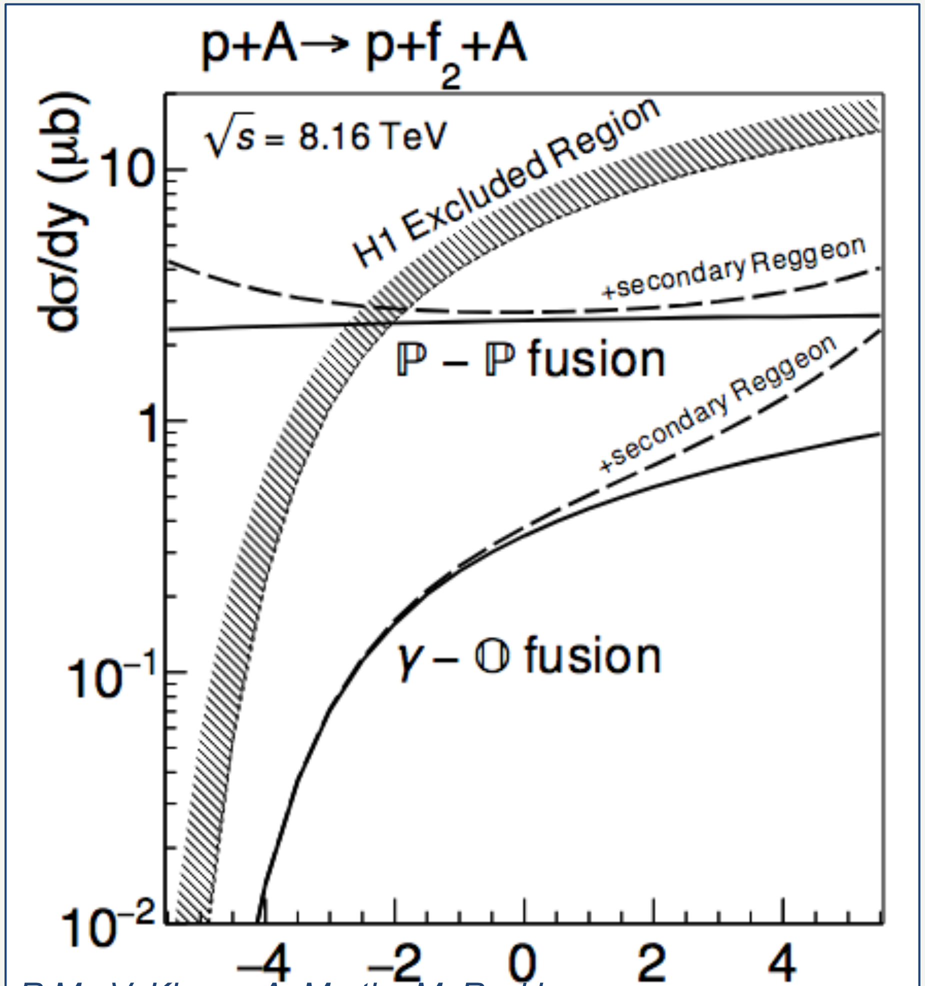




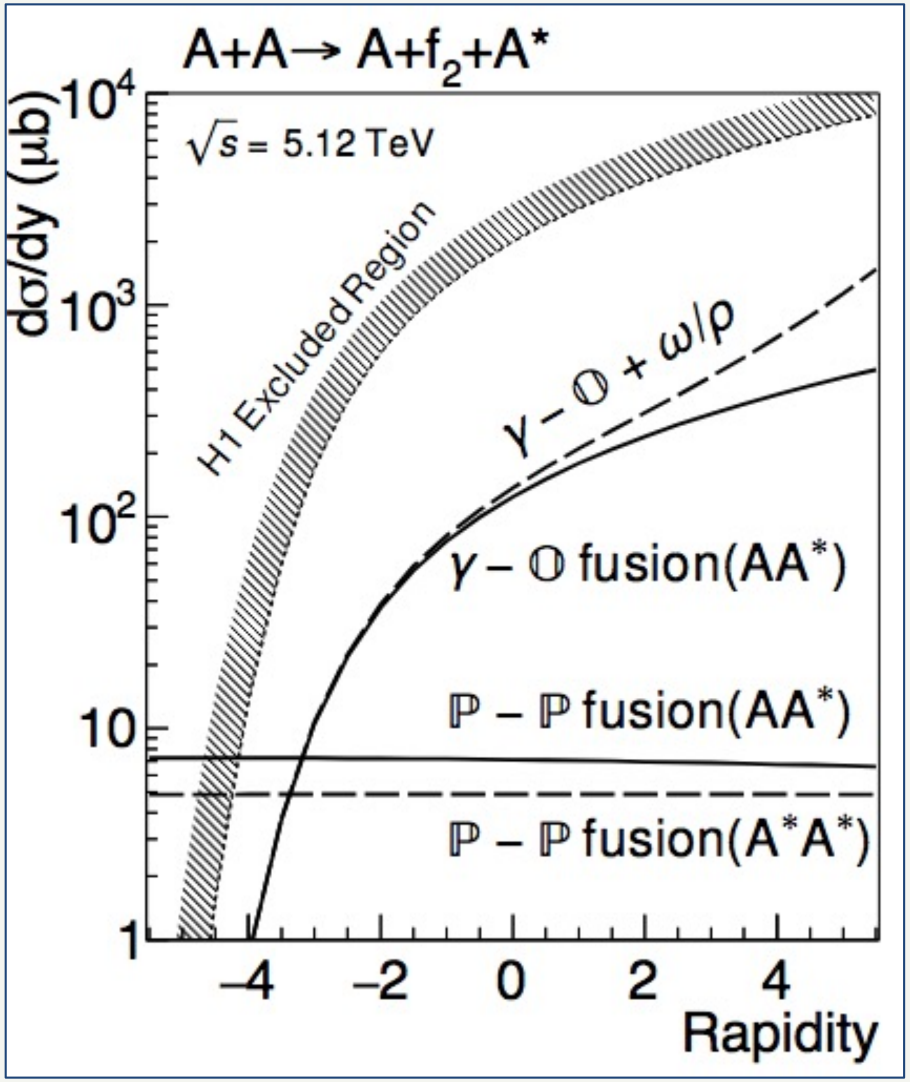


Phys.Rev.D 110 (2024) 1, 014025

Might be seen forward in p-Pb / PbPb



R.M., V. Khoze, A. Martin, M. Ryskin, Eur.Phys.J.C 80 (2020) 3, 288



(Role of survival factors and nuclear break-up important here)

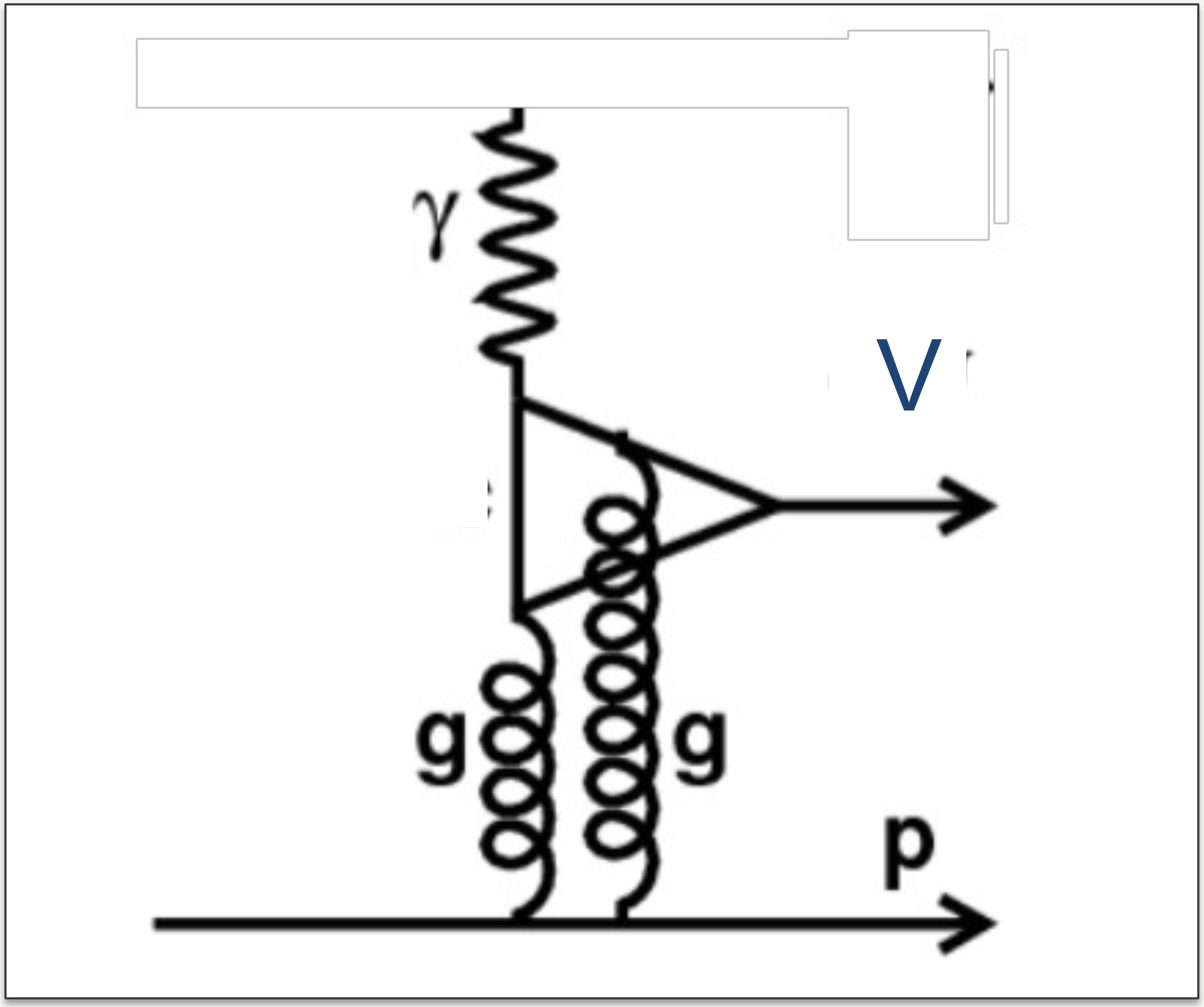
Gluon recombination (saturation)

Fractional momentum of the parton

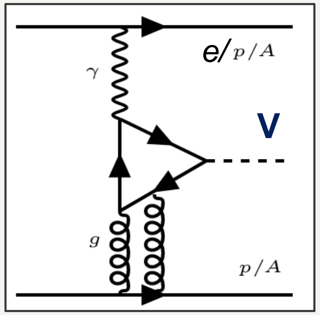
Energy Scale

Ridzikova Alexandra FNSPE CTU PRAGUE

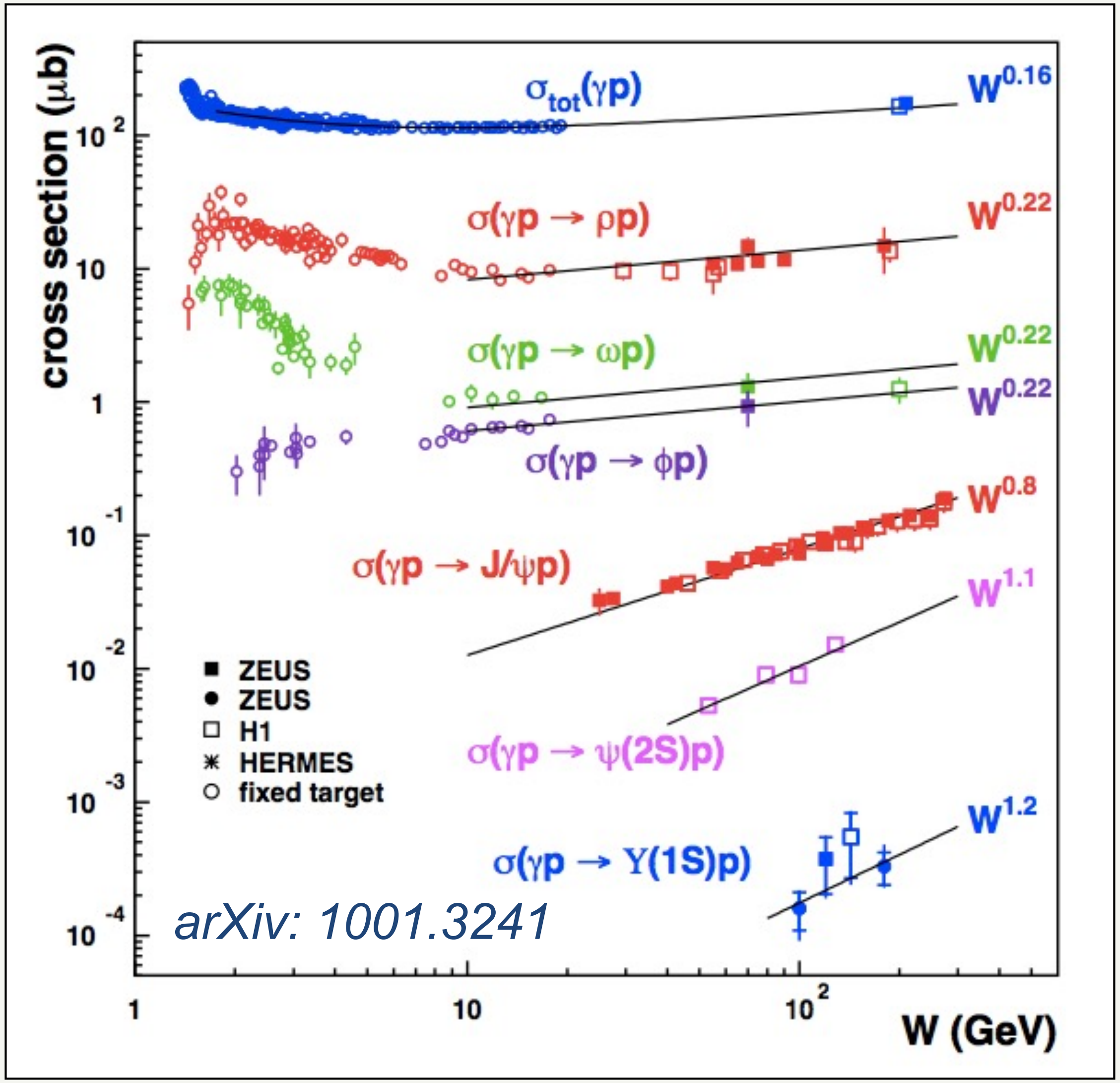
Photoproduction

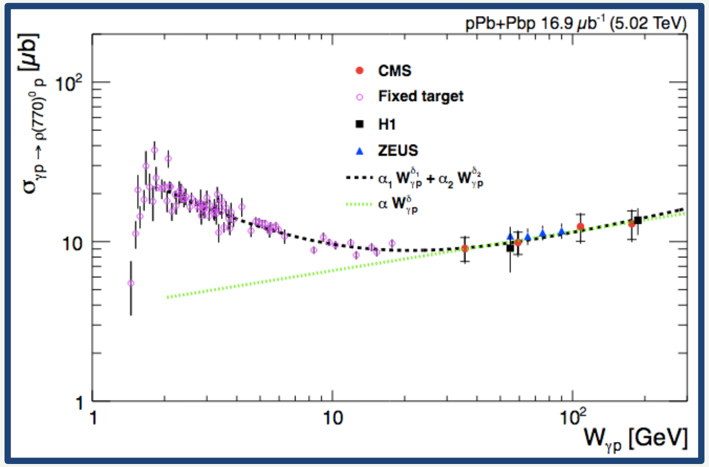


Photoproduction



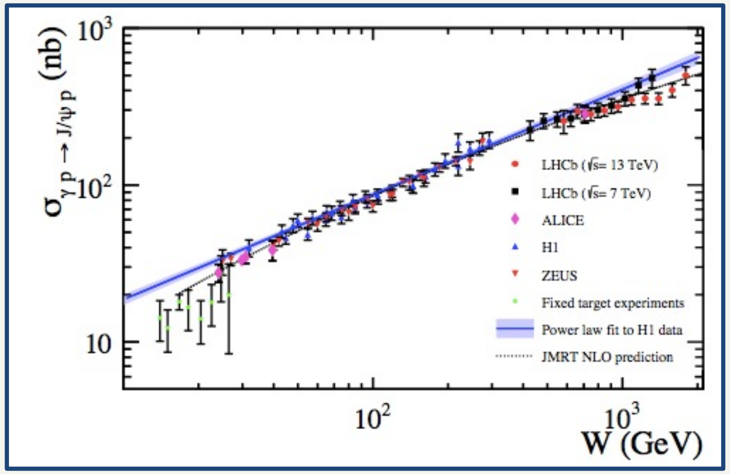
- Rise in σ related to Pomeron intercept
  - $\sigma \sim W^{\delta}$
  - $\delta = 4(\alpha_P(t) - 1)$
  - $\alpha_P(t) = \alpha_P(0) + \alpha' t$
- Compare slopes ρ,ω,ϕ to J/ψ,ψ',Υ
- Extract $g(x,Q^2)$





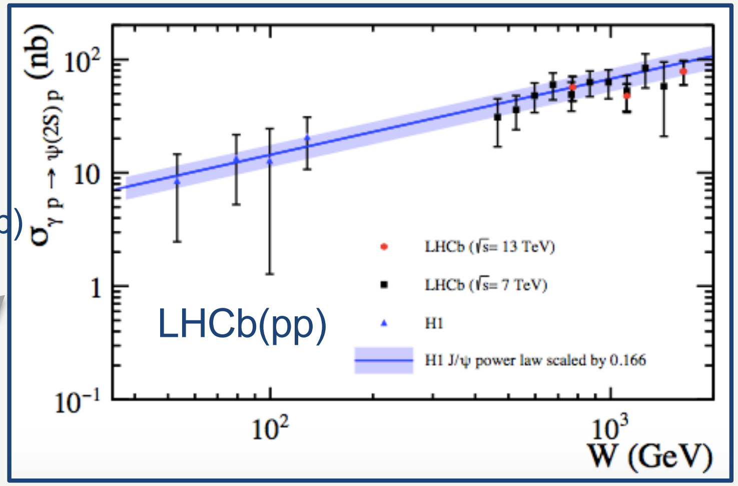
CMS (pPb) ALICE (XeXe, PbPb)

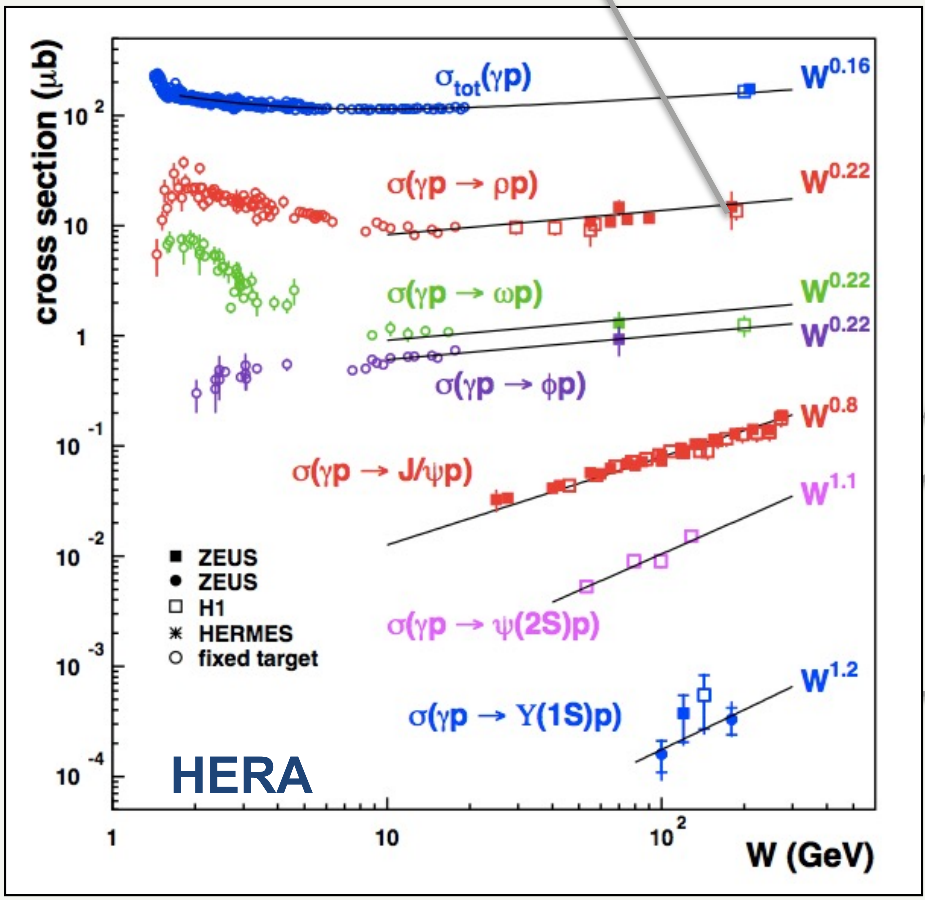
ALICE (pPb, PbPb)
LHCb (pp, PbPb)



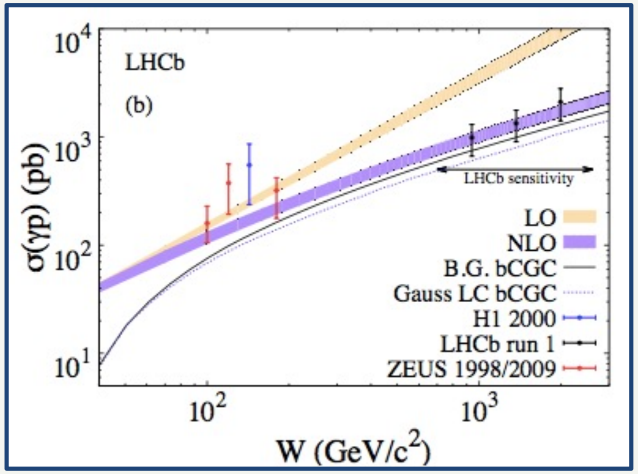
Central region
$W_{LHC} \sim W_{HERA}$
Forward
$W_{LHC} >> W_{HERA}$

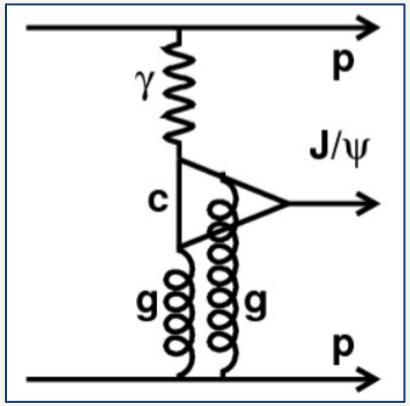
LHCb
(pp, PbPb)





LHCb (pp)
CMS (pPb)





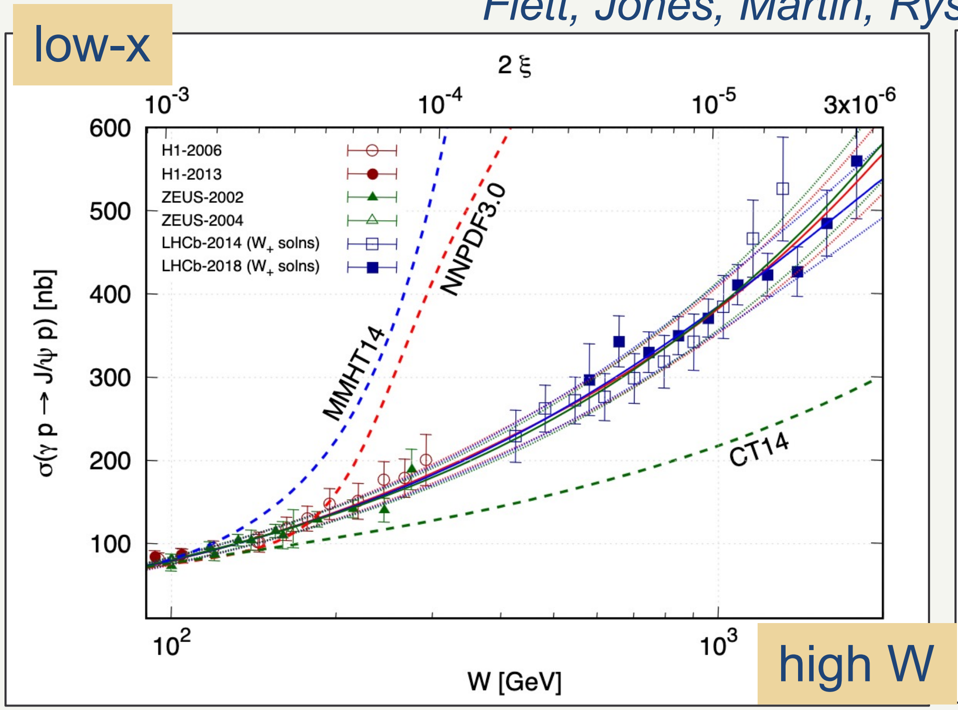
Implications: GPDs and PDF

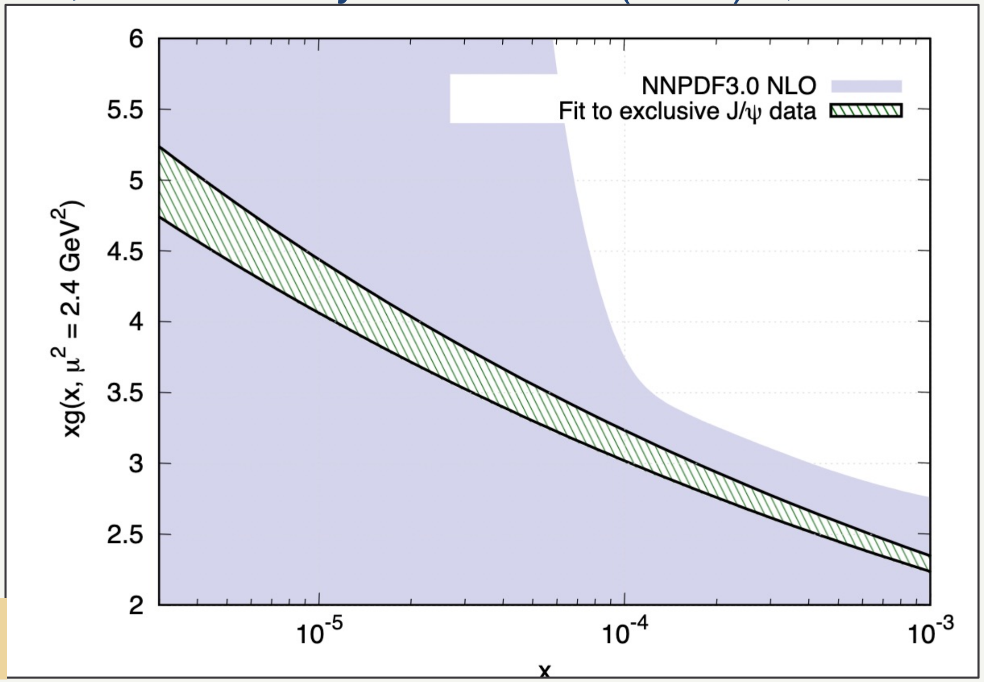
Ryskin, Z. Phys. C 57 (1993) 89

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M^3_{J/\psi}\pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4}xg(x,\bar{Q}^2)\right]^2\left(1+\frac{Q^2}{M^2_{J/\psi}}\right)$$

Flett, Martin, Ryskin, Teubner. Phys.Rev.D 102 (2020) 114021

Flett, Jones, Martin, Ryskin, Teubner. Phys.Rev.D 101 (2020) 9, 094011





makes use of Shuvaev transform to relate GPDs and PDFs

$$H_q(X,\xi) = \int_{-1}^{1} dx' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{ds}{y(s)\sqrt{1-y(s)x'}}\right]\frac{d}{dx'}\left(\frac{q(x')}{|x'|}\right),$$

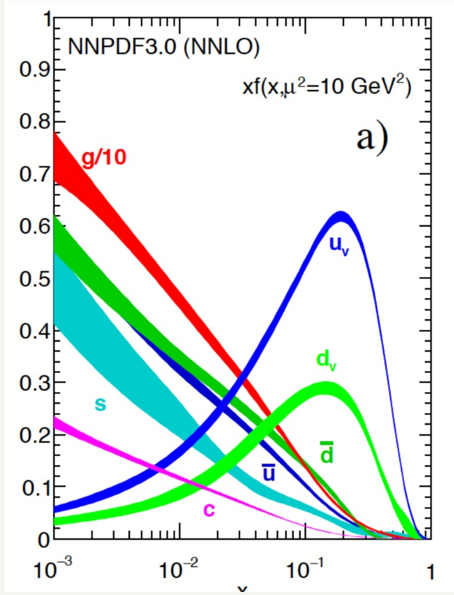
$$H_g(X,\xi) = \int_{-1}^{1} dx' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{ds\ (X+\xi(1-2s))}{y(s)\sqrt{1-y(s)x'}}\right]\frac{d}{dx'}\left(\frac{g(x')}{|x'|}\right),$$

where the transform kernel,

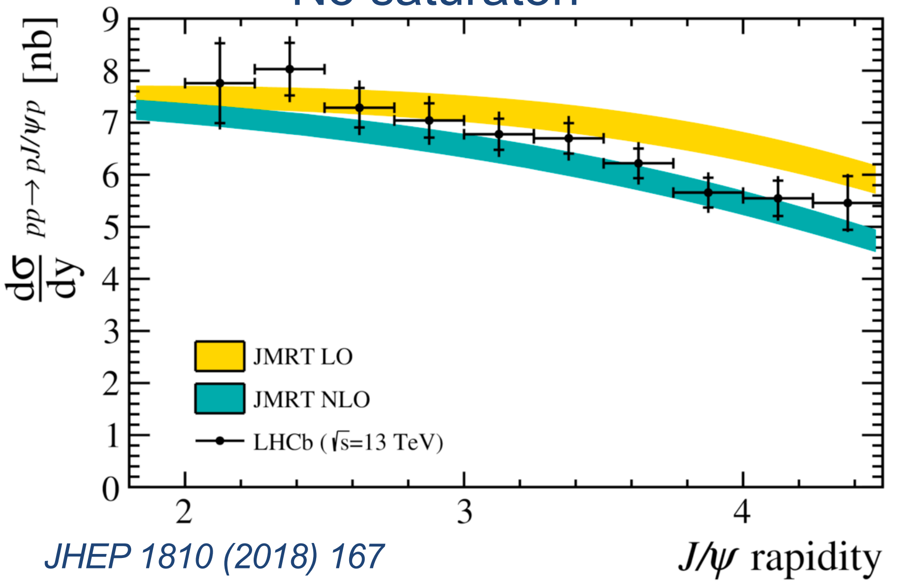
$$y(s) = \frac{4s(1-s)}{(X+\xi(1-2s))}.$$

Implications: Saturation

Saturation effects become visible at low-x.
Onset of saturation expected to scale with nucleon density ~ $A^{1/3}$ so
may be easier to see in nuclear collisions

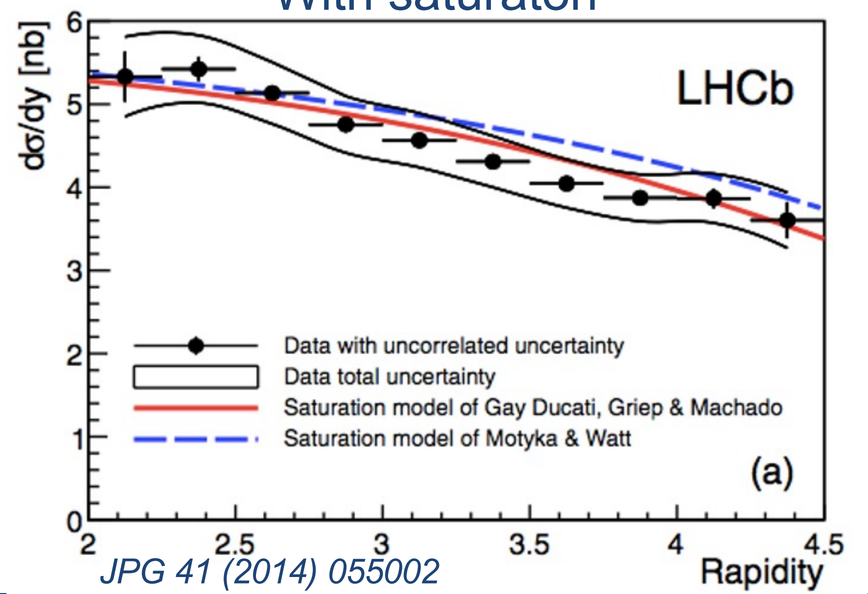


No saturaton



JHEP 1810 (2018) 167

With saturaton



JPG 41 (2014) 055002

Saturation is not inconsistent with the data, but is also not required.

Looking for saturation in nuclear collisions

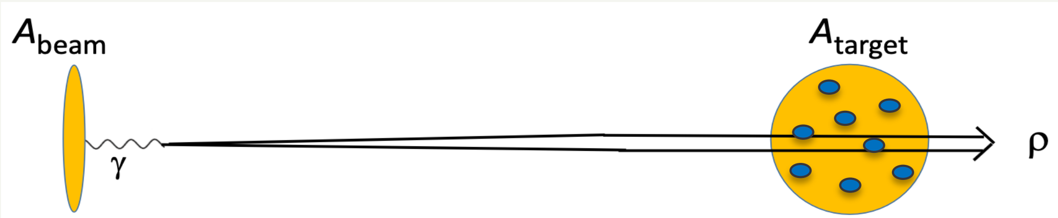
Coherent interaction: all nucleons behave as one.

- b ~ 2R=13.2 fm so p_T~15 MeV
- nucleus remains intact*.

*additional EMD can excite or break nucleus

All things being equal, $\sigma_{\gamma A \to VA} = N_A \, \sigma_{\gamma p \to Vp}$

Saturation would decrease cross-section at high-W (low-x)
Nuclear suppression observed...
How much is due to saturation and how much to 'nuclear effects'?



$$\mathcal{A}_{\rho n}(b) = i(1 - e^{-\Omega(b)/2})$$

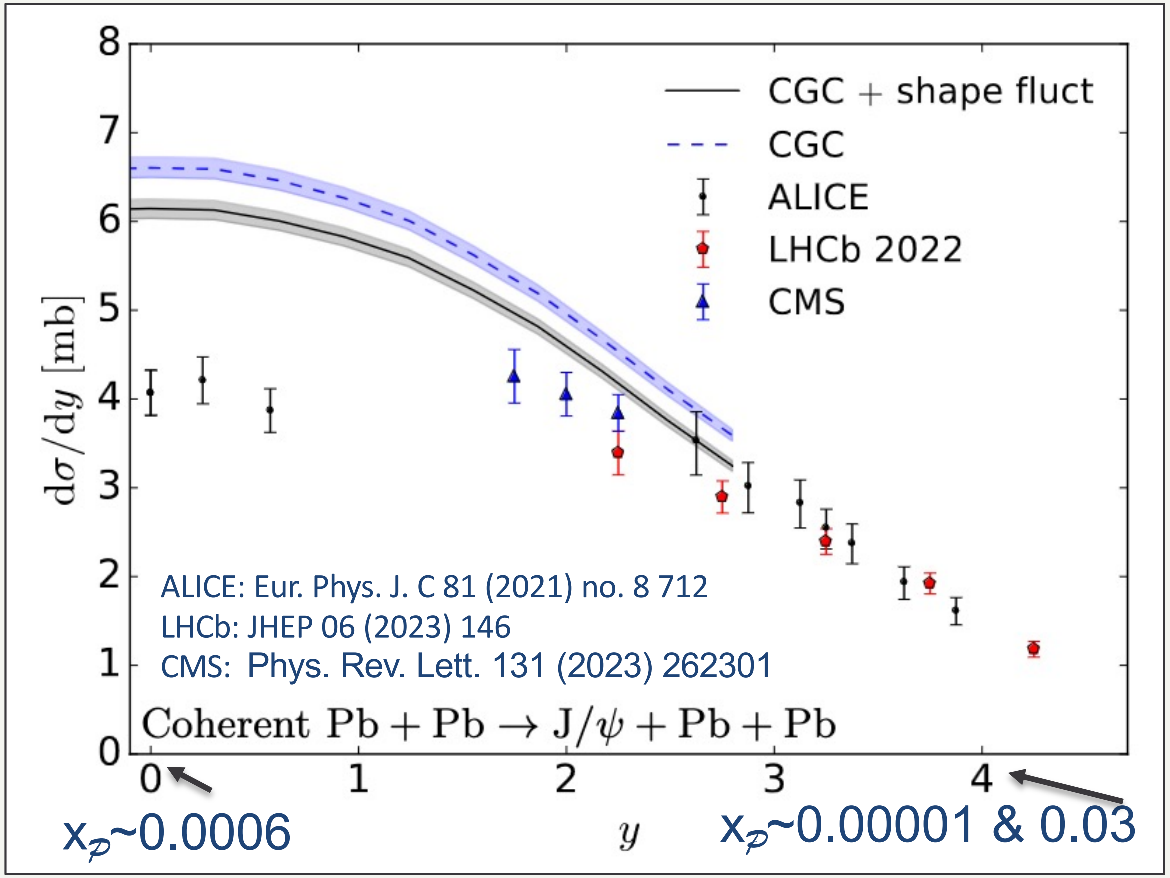
$$\Omega(b) = T_A(b)\sigma_{\rho n}\eta$$

Glauber eikonal approx.

Incoherent interaction with nucleon or parton

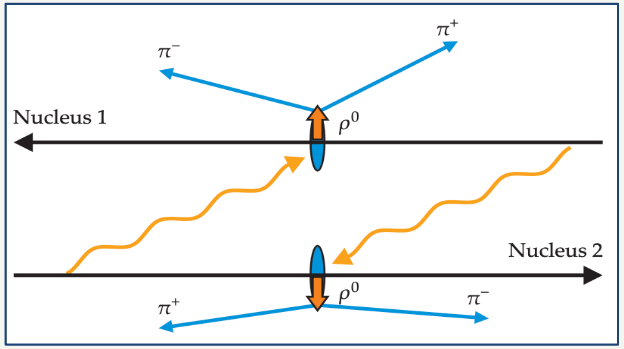
- p_T distribution follows exp(bt) b smaller than for coherent
- break-up is observed
- sensitive to smaller structures – saturation gives deviations from isotropy.

Coherent J/ψ in PbPb



H. Mäntysaari, F. Salazar, B. Schenke: Phys.Rev.D 109 (2024) 7, L071504

"We predict strong saturation-driven nuclear suppression at high energies, while LHC data prefers even stronger suppression."

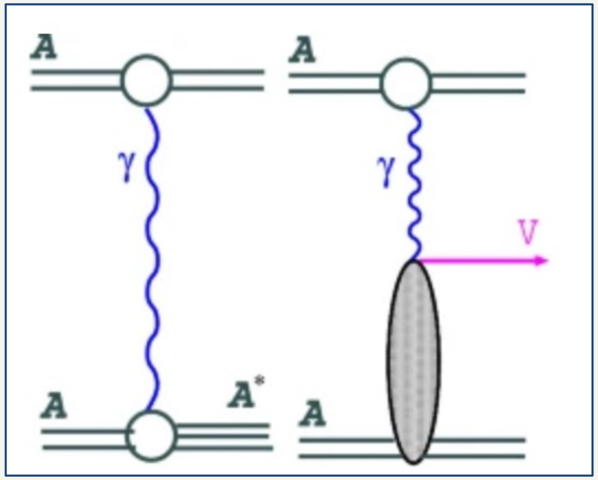


S. Klein, J. Nystrand, Physics Today 70, (2017) 40.

However, away from y=0, there is a two-fold ambiguity in the photon emitter and two-fold ambiguity in the value of W.

$$\frac{d\sigma_{PbPb\to PbJ/\psi Pb}}{dy} = \left(k\frac{dN_\gamma}{dk}\right)^{+}\sigma_{\gamma Pb\to J/\psi Pb}(W^+) + \left(k\frac{dN_\gamma}{dk}\right)^{-}\sigma_{\gamma Pb\to J/\psi Pb}(W^-)$$

Electromagnetic ‘pile-up’ interactions



The electromagnetic field of the nucleus is so intense that long-range photon interactions often occur in addition to hadronic interactions.

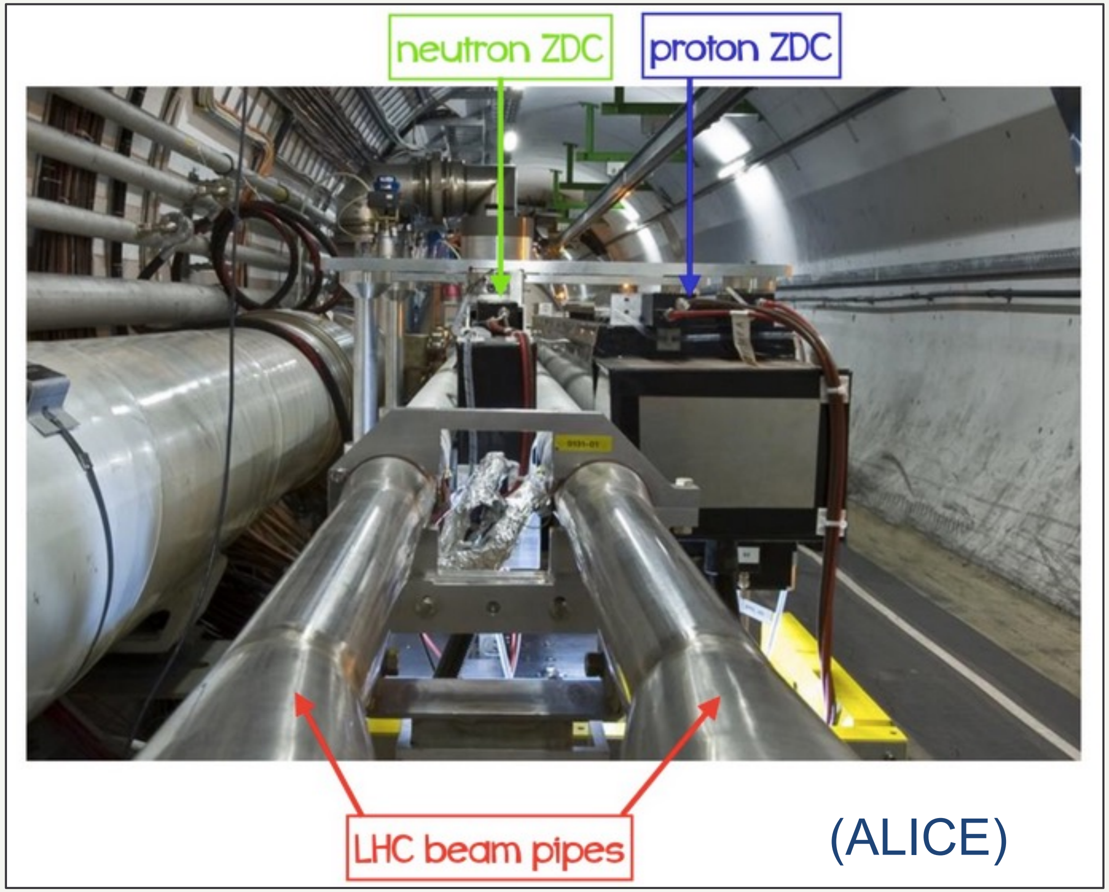
Excites the nucleus.
Can lead to Electomagnetic Dissociation (EMD) of the nucleus.
This is more probable at low impact parameter, *b*, and photon flux depends on *b*

Emission of one or more neutrons

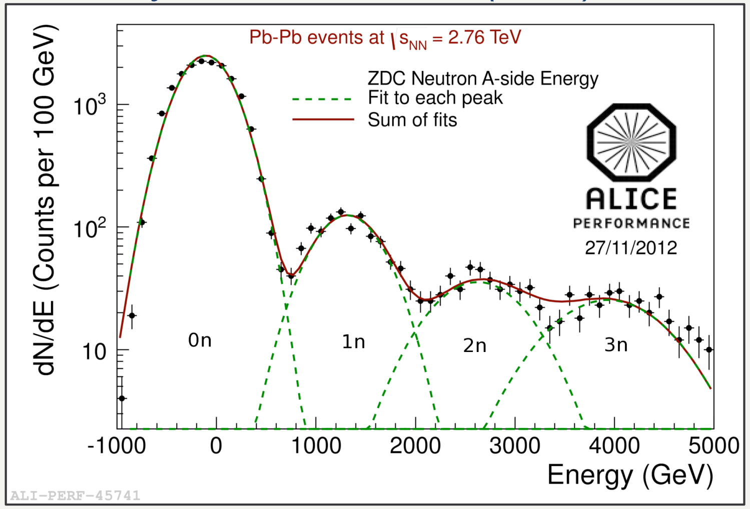
- Possibly proton emission too
- Nuclear break-up

Need far-forward detectors to see these.

ZDC calorimeters installed in CMS, ALICE, STAR



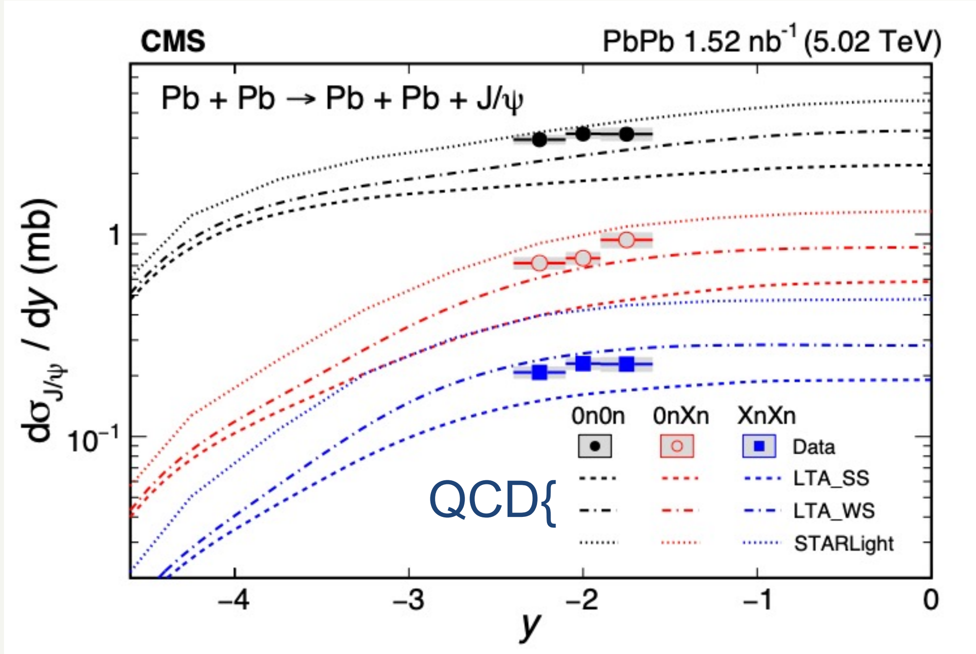
J. Phys.: Conf. Ser. 455 (2013) 012010



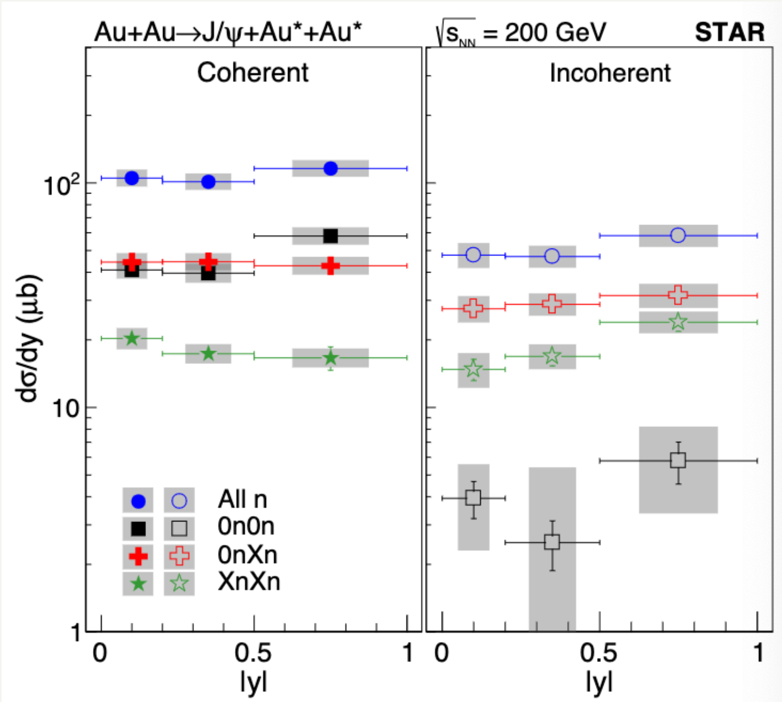
Detection of neutrons when ion breaks up allows identification of Electromagnetic Dissociation (EMD)

Resolving the two-fold ambiguity in PbPb

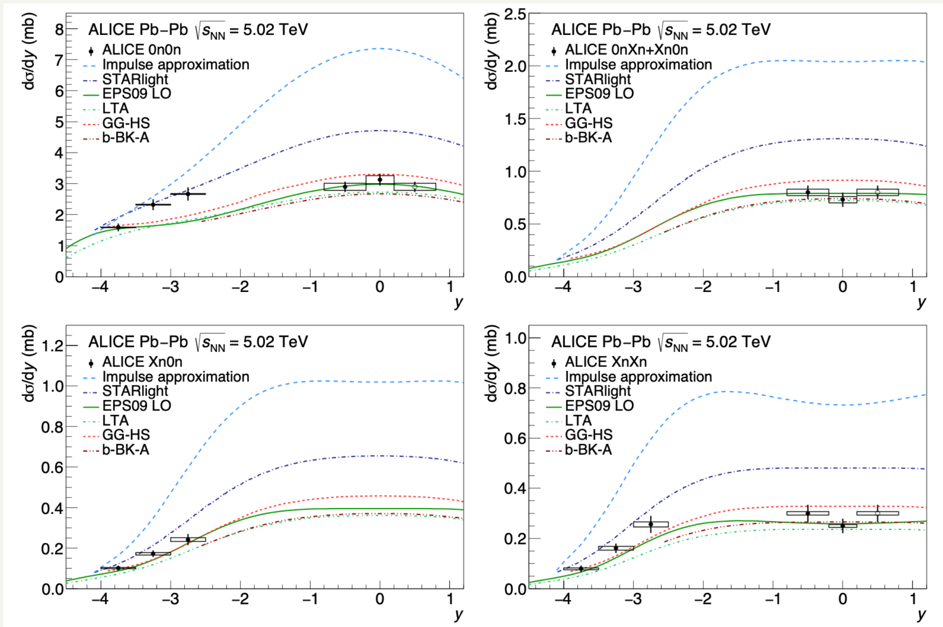
EMD is more likely at small impact parameters.
So fluxes for 0n and (X>=1)n different.



Phys. Rev. Lett. 131 (2023) 262301

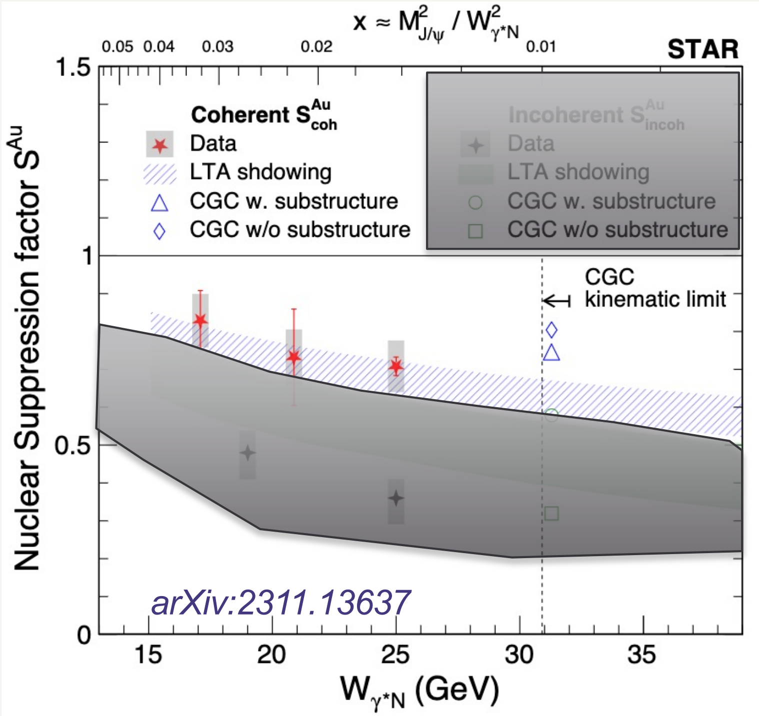


arXiv: 2311.13632

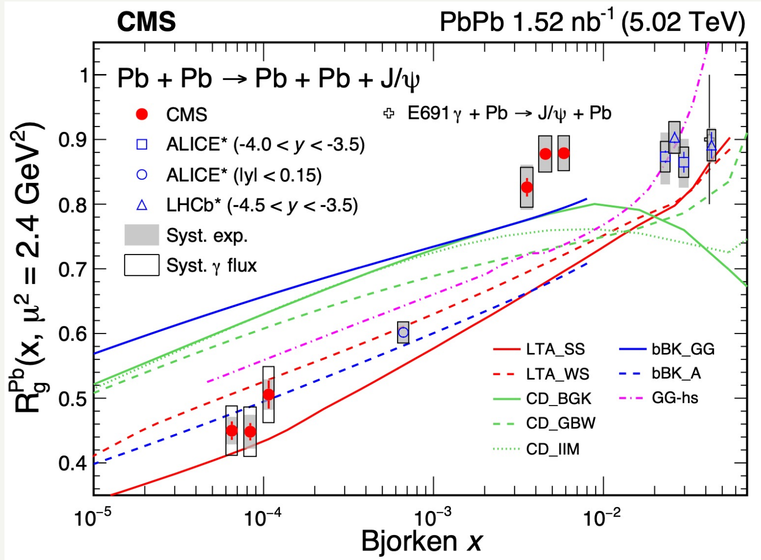


JHEP 10 (2023) 119

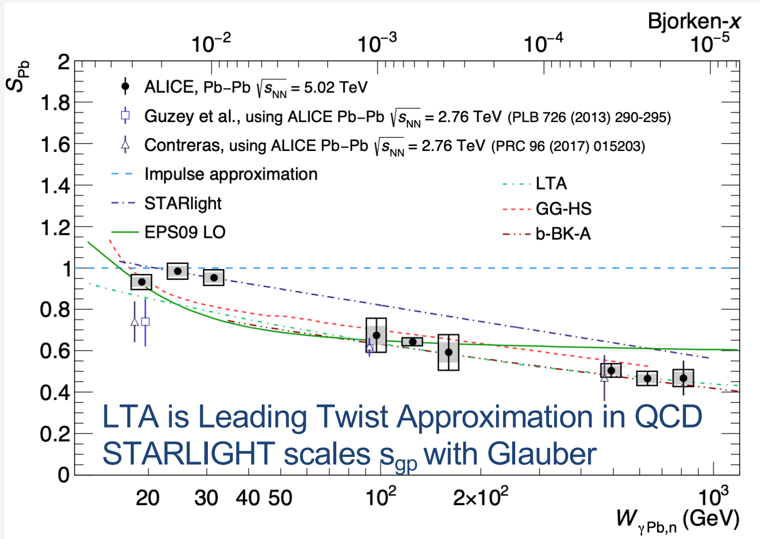
Re-expressed in terms of nuclear suppression factors



arXiv:2311.13637



Phys. Rev. Lett. 131 (2023) 262301



LTA is Leading Twist Approximation in QCD
STARLIGHT scales s_{gp} with Glauber

JHEP 10 (2023) 119

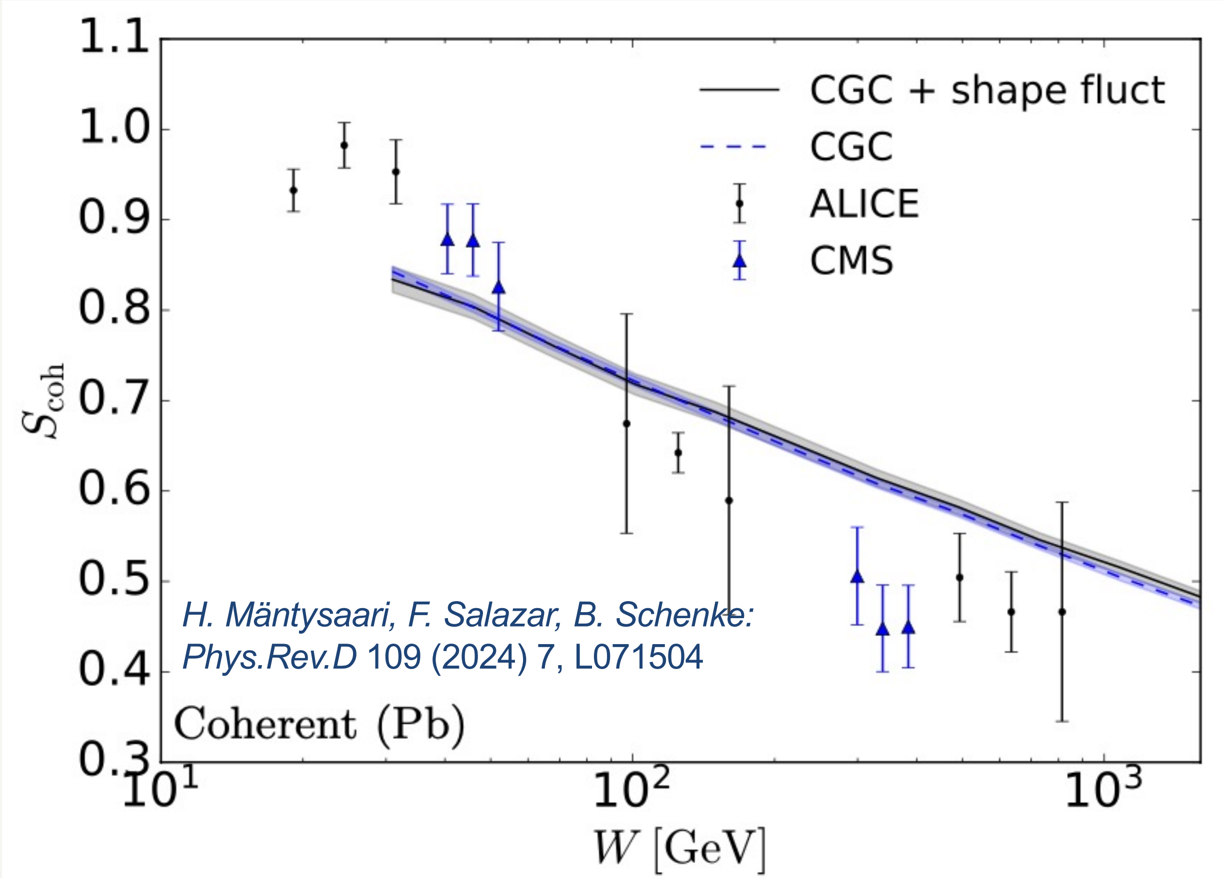
$$S_{\mathrm{coh}} = \sqrt{\frac{\sigma^{\gamma A}}{\sigma^{\mathrm{IA}}}}$$

IA is simple N_A scaling of $\sigma_{\gamma p}$

None of the models does a perfect job.
QCD/Starlight not too bad.
Models with saturation also reasonable

The case for saturation....

$$S_{\mathrm{coh}} = \sqrt{\frac{\sigma^{\gamma A}}{\sigma^{\mathrm{IA}}}}$$



Comment: Would be nice to plot LTA too

Results may be similar, which begs the question about how to separate saturation from higher-order QCD effects.

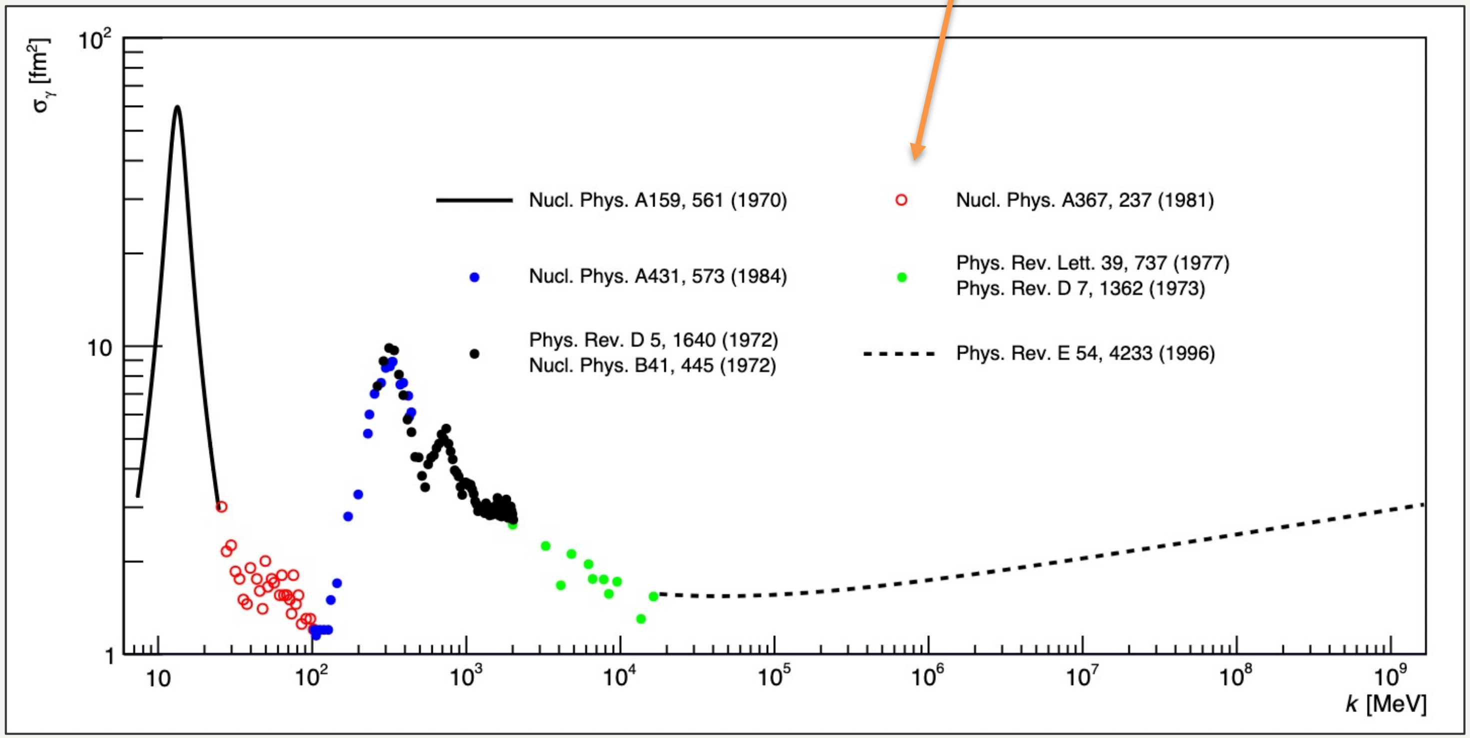
Require precise photon fluxes for 0,1,2... neutron emissions

Calculated eg. in NooN generator *Comput.Phys.Commun.* 253 (2020) 107181

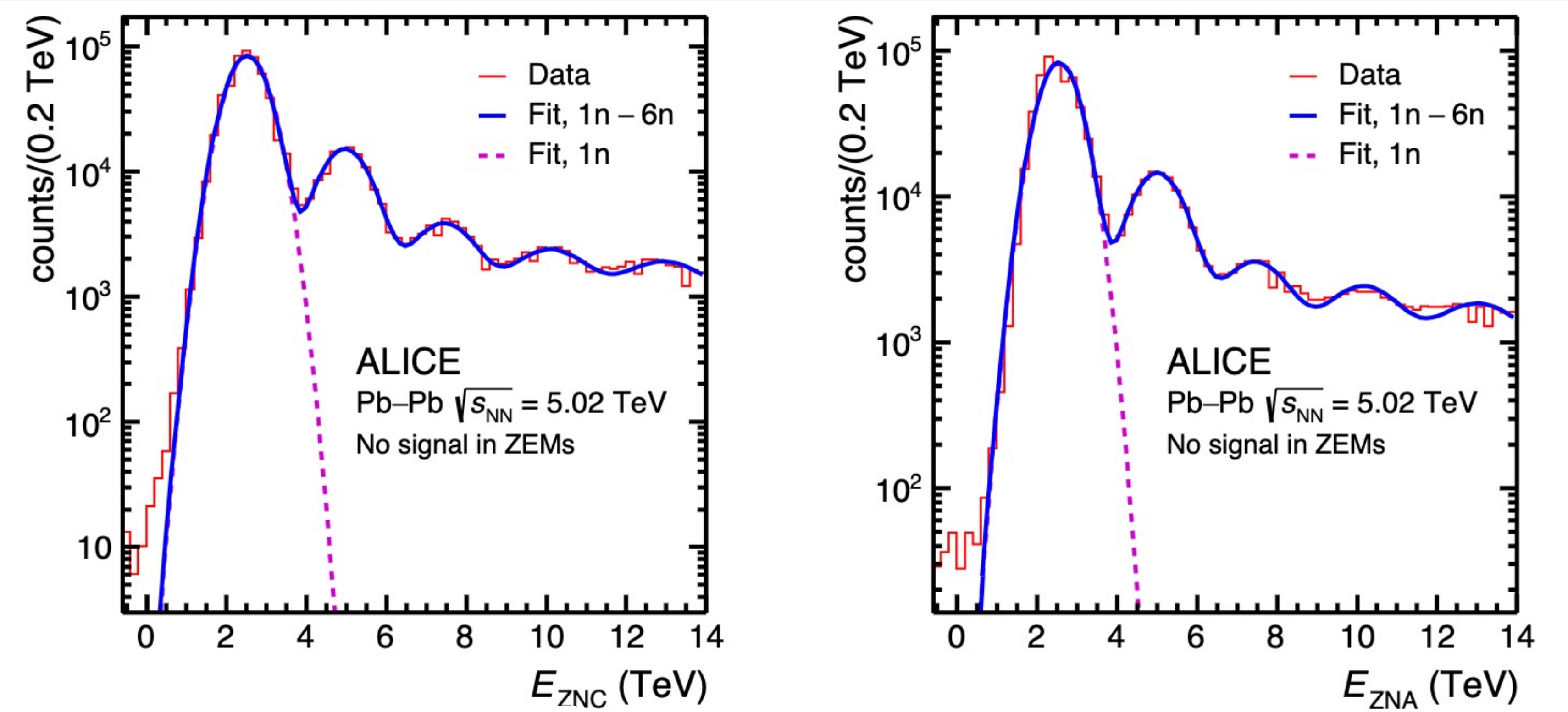
Mean number of Coulomb excitations emitting >=1 neutron

$$P^{1}_{\mathrm{Xn}}(b) = \int dk \frac{d^3n(b,k)}{dk d^2b} \sigma_{\gamma A \to A' + \mathrm{Xn}}(k)$$

Photon flux at energy *k* and distance *b*



Emission of neutrons



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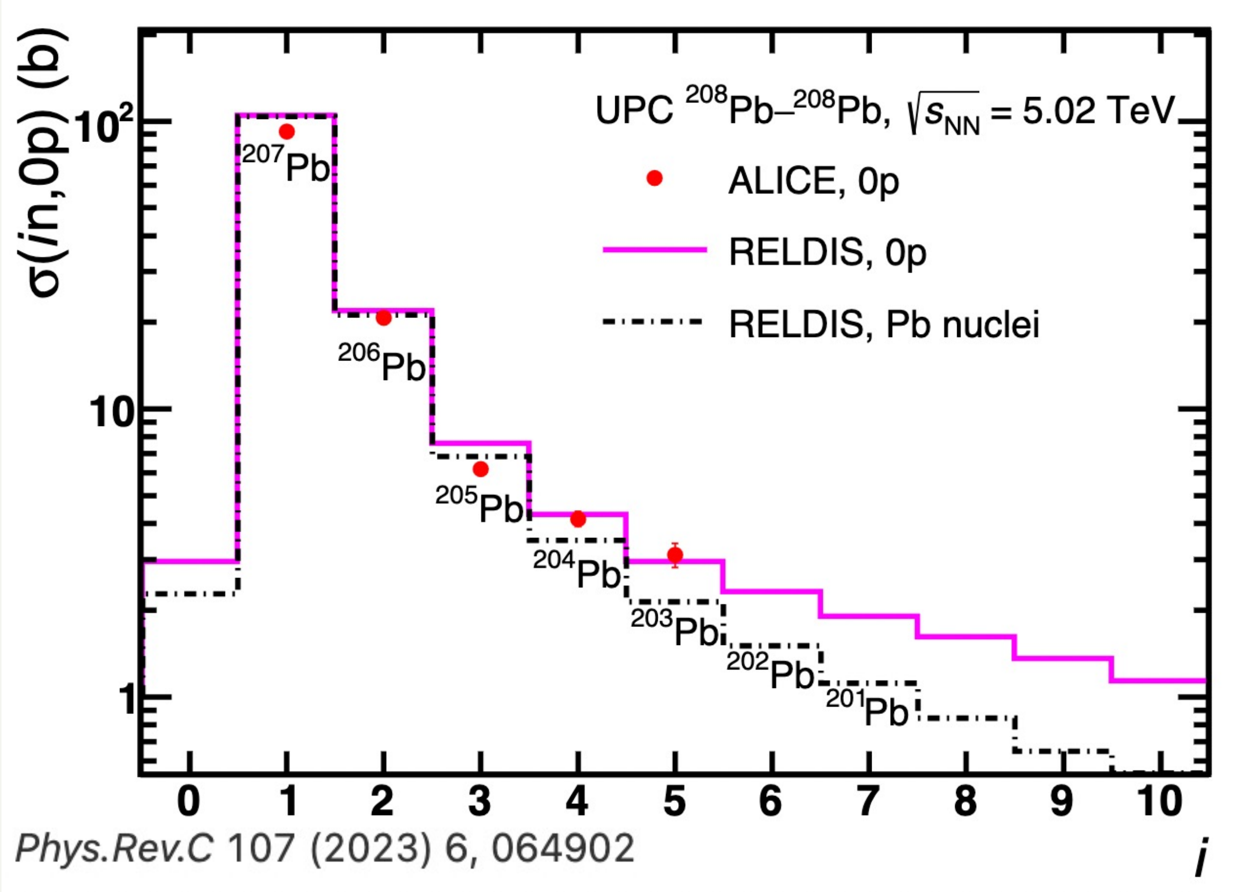
Analysis for rho photoproduction just considered 00, 0X, X0, XX emissions.

But you can count the number of neutrons on either side....

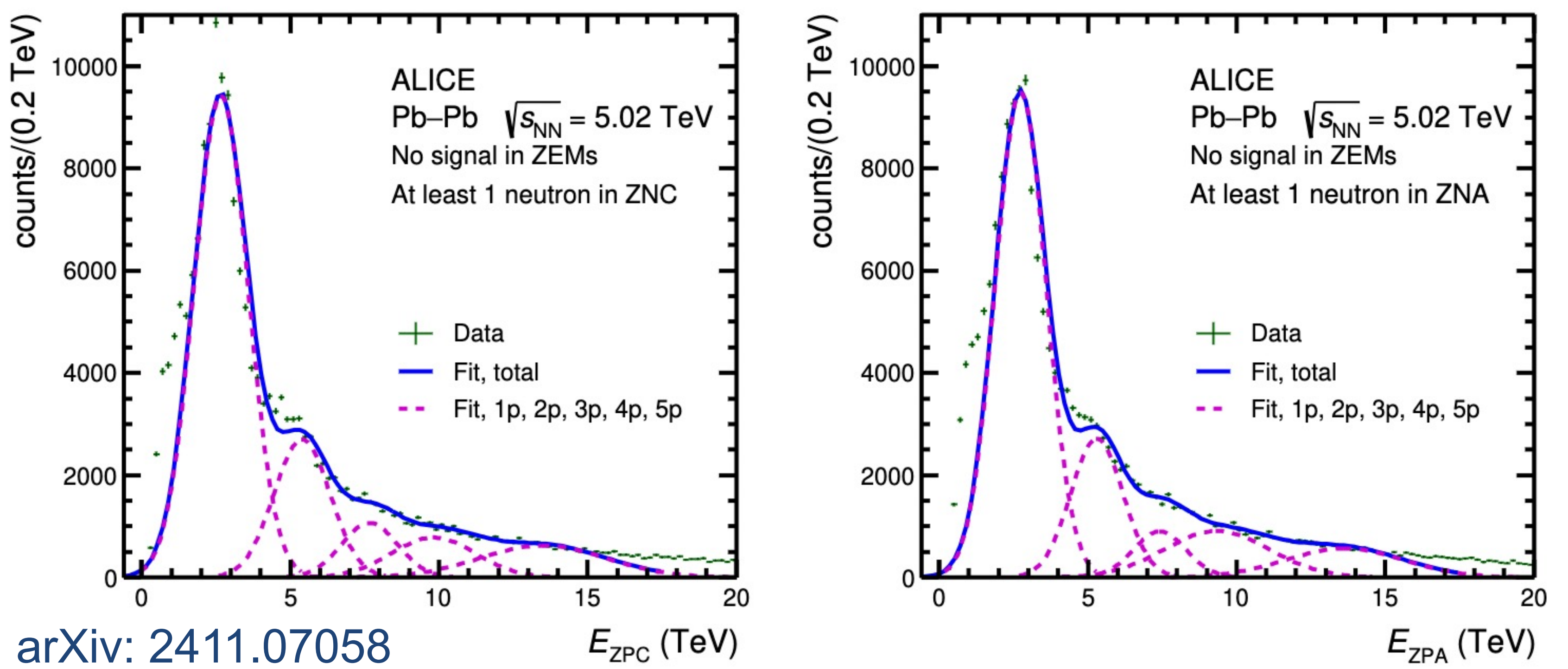
Cross-section for emission of just neutrons

Vetoing on the response in the proton ZDC....



(Validation of the models used for the photoproduction analysis)

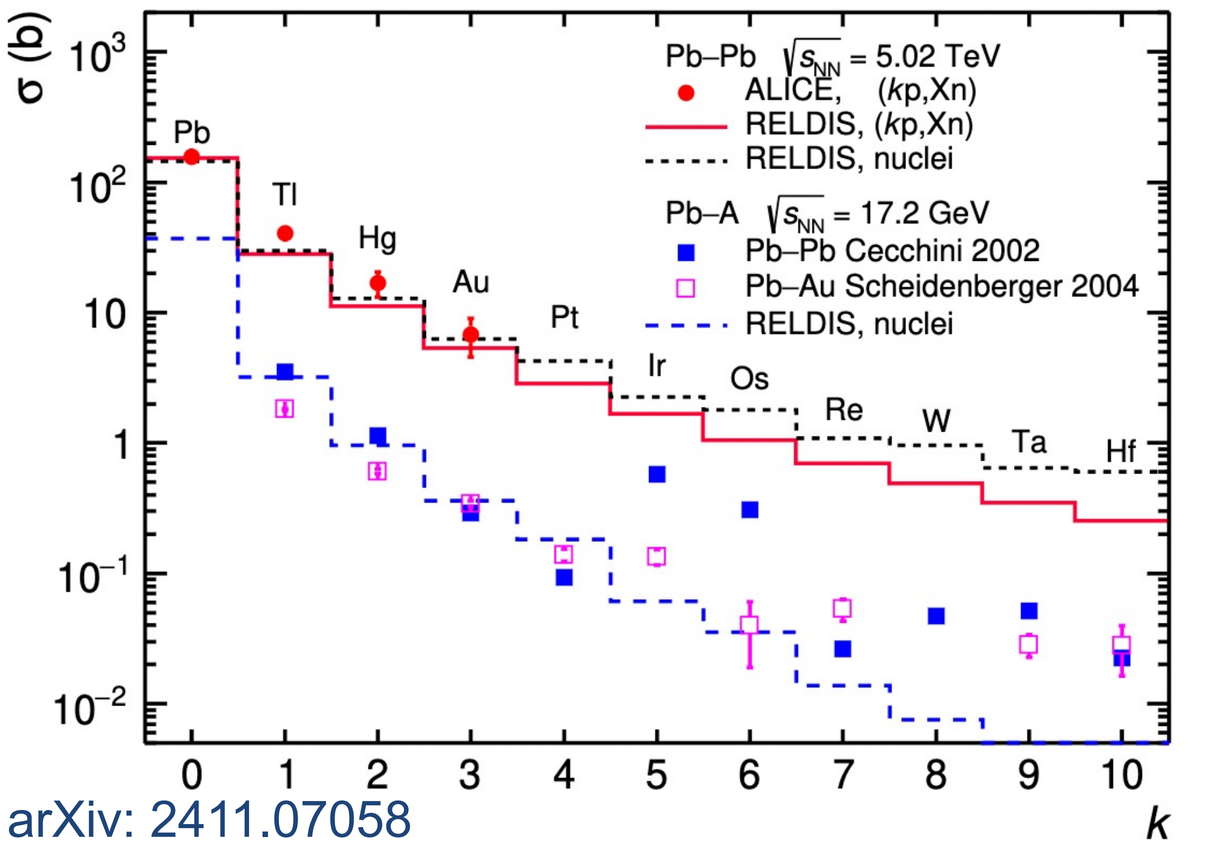
Emission of protons



arXiv: 2411.07058

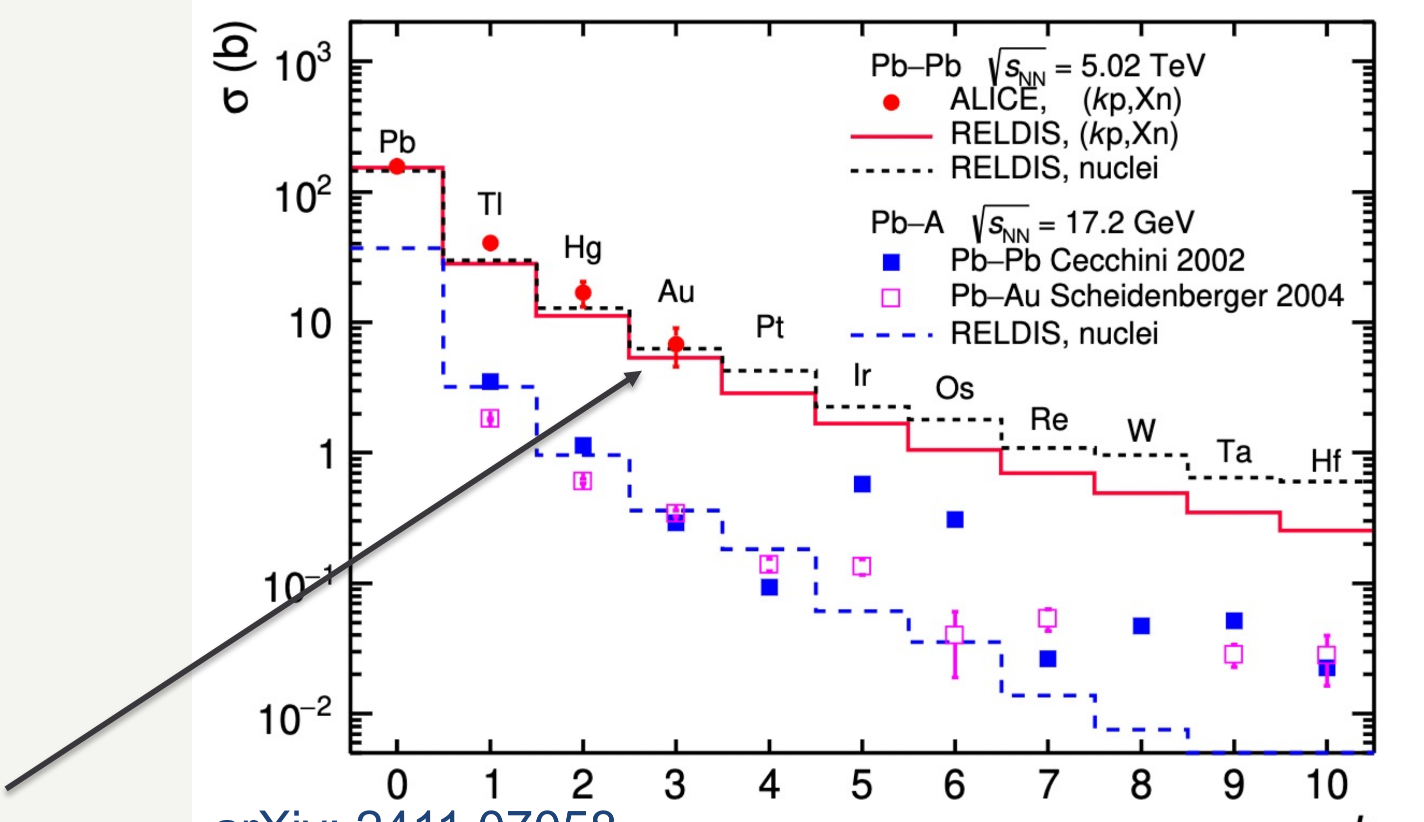
You can count the number of protons on either side....

Cross-section for emission of *k* protons and >0 neutrons



arXiv: 2411.07058

Cross-section for emission of *k* protons and >0 neutrons



arXiv: 2411.07058

Thus turning lead into gold....

Conclusions

- Far forward detection at the LHC allows first measurements of EDM of Pb nuclei
- Can then be used as a tool to lift the two-fold ambiguity in symmetric collisions
- Relate photoproduction on the proton to photoproduction on the nucleus
- .....and search for saturation

backup

Incoherent scatters also interesting

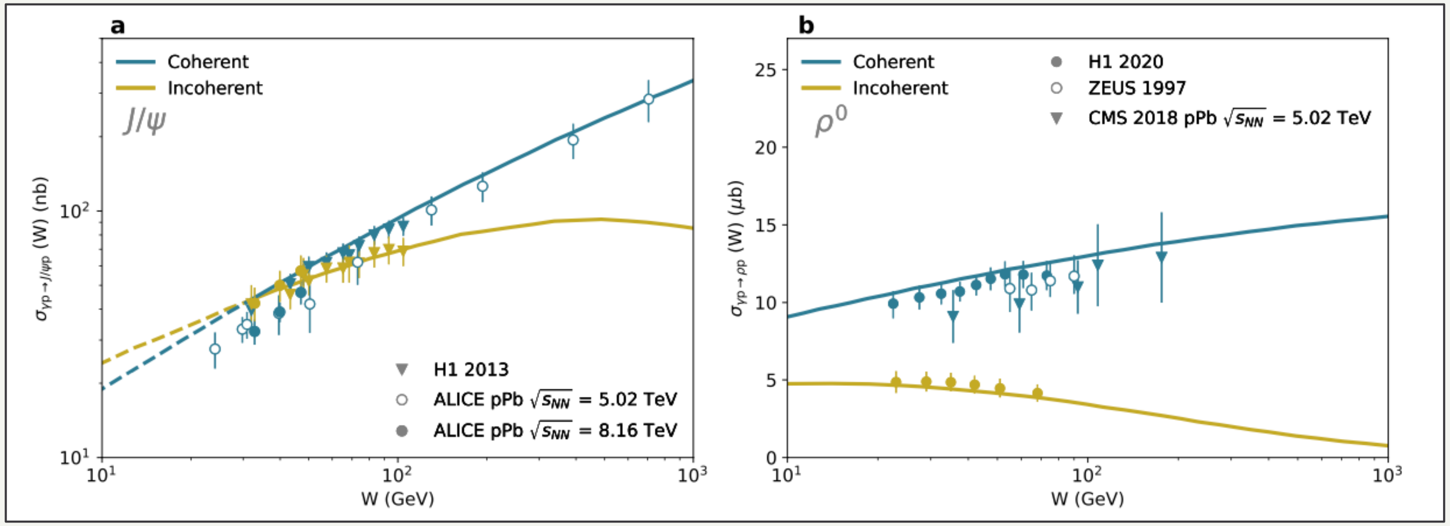
Intact target: sensitive to **average** colour
Breakup: sensitive to fluctuations (**rms**)

$$\frac{d\sigma^{\gamma^* p \to J/\Psi p}}{dt} = \frac{1}{16\pi} \left| \langle A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \rangle \right|^2$$

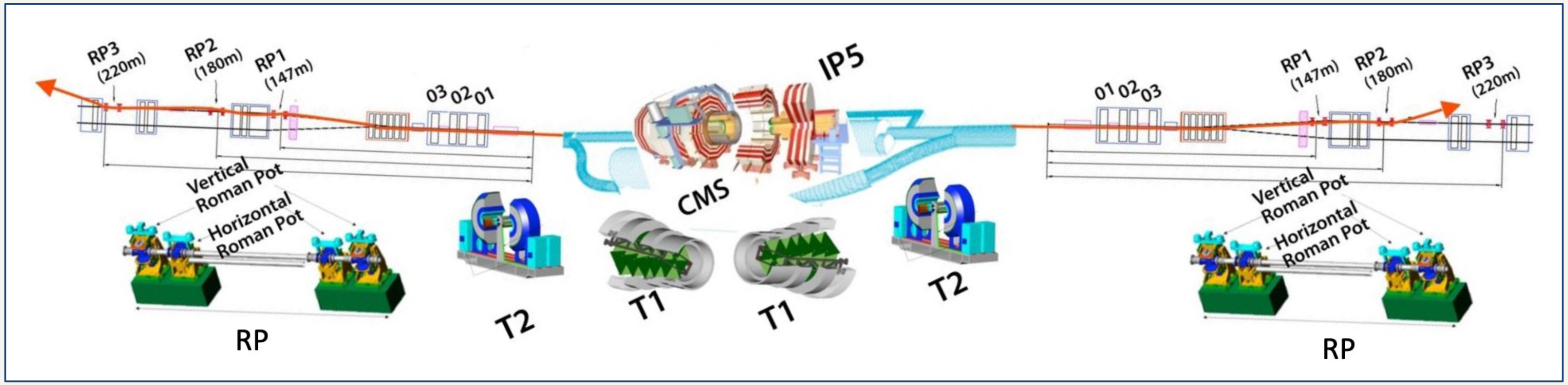
$$\frac{d\sigma^{\gamma^* N \to J/\Psi N^*}}{dt} = \frac{1}{16\pi} \left(\left\langle \left| A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \right|^2 - \left| \langle A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \rangle \right|^2 \right) \right.$$

Mäntysaari, Schenke, Phys. Rev. Lett. 117, 052301 (2016)

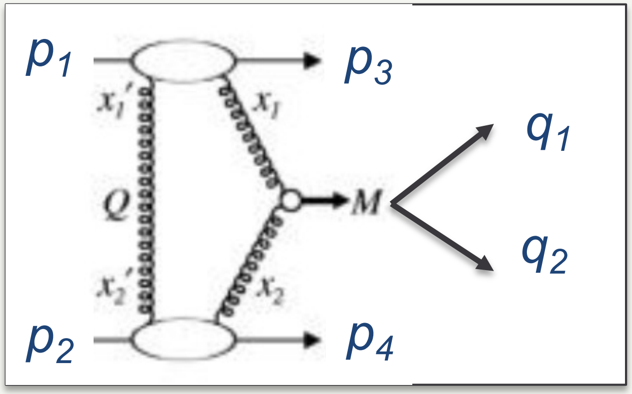
- Original model based on gluonic fluctuations around three hot-spots (valence quarks)
- Hot-spot evolution model (
- Energy-dependent hot-spots (J. Cepila, J. G. Contreras, J. D. Tapia Takaki Phys. Lett. B766 (2017) 186–191)
- The onset of saturation? (J. Cepilaa, J. G. Contrerasa, M. Matasa, A. Ridzikova, arXiv:2313.11320)



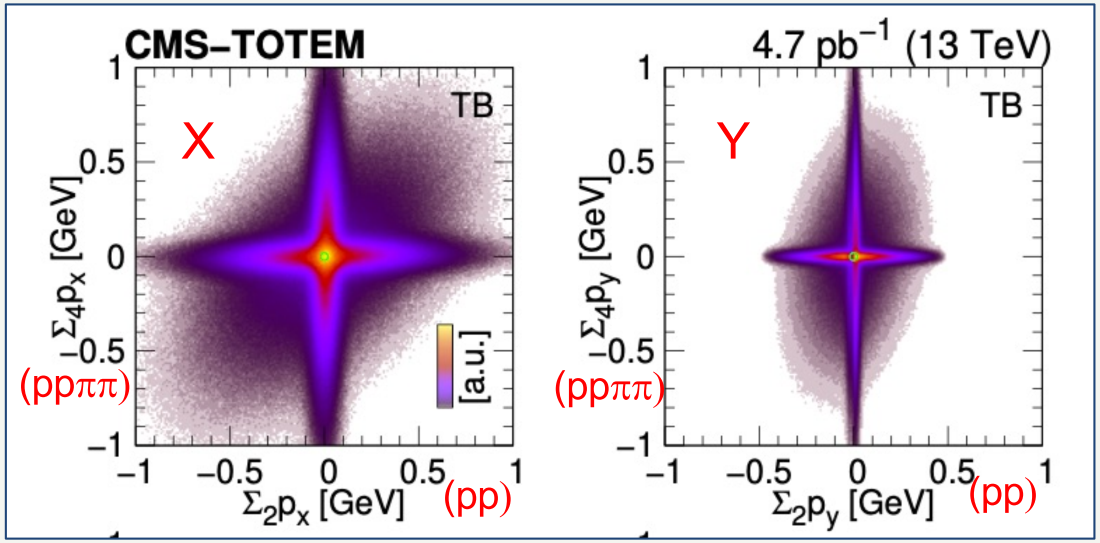
CMS-TOTEM: Simultaneous reconstruction of central system and protons



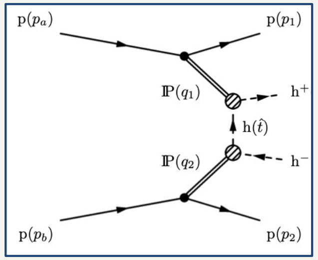
arXiv:2401.14494

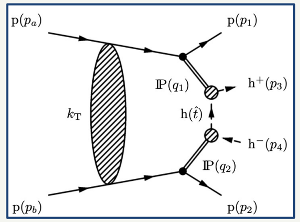


$$M^2 = (q_1^\mu + q_2^\mu)^2 = (p_1^\mu + p_2^\mu - p_3^\mu - p_4^\mu)^2$$



Precision determination of pomerons interactions





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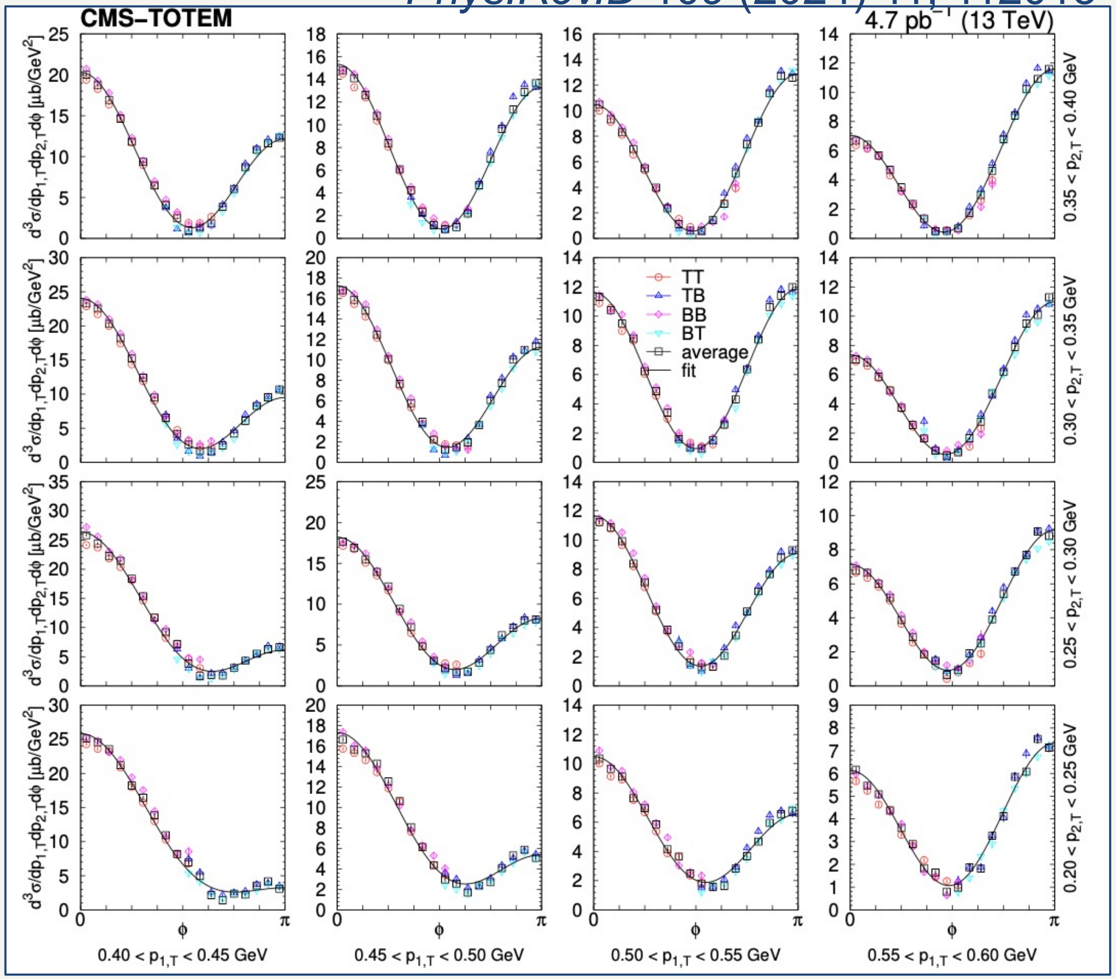
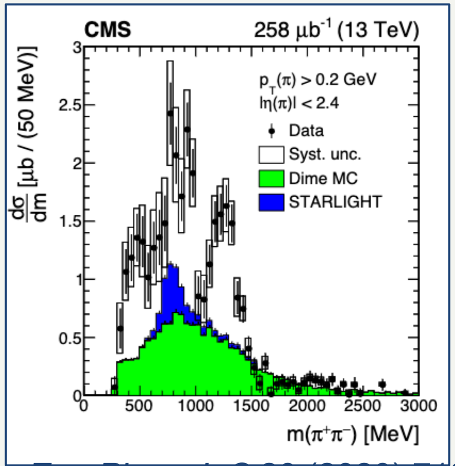


Shape distinctive of interference due to additional pomeron interactions

Measurements performed in non-resonant regions: (<0.7, >1.8 GeV).



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Eagerly await compelling spectroscopy of the complicated resonance region:
- photoproduced ρ, ω, ρ', ρ"
- DPE f0,f2, , glueball candidates