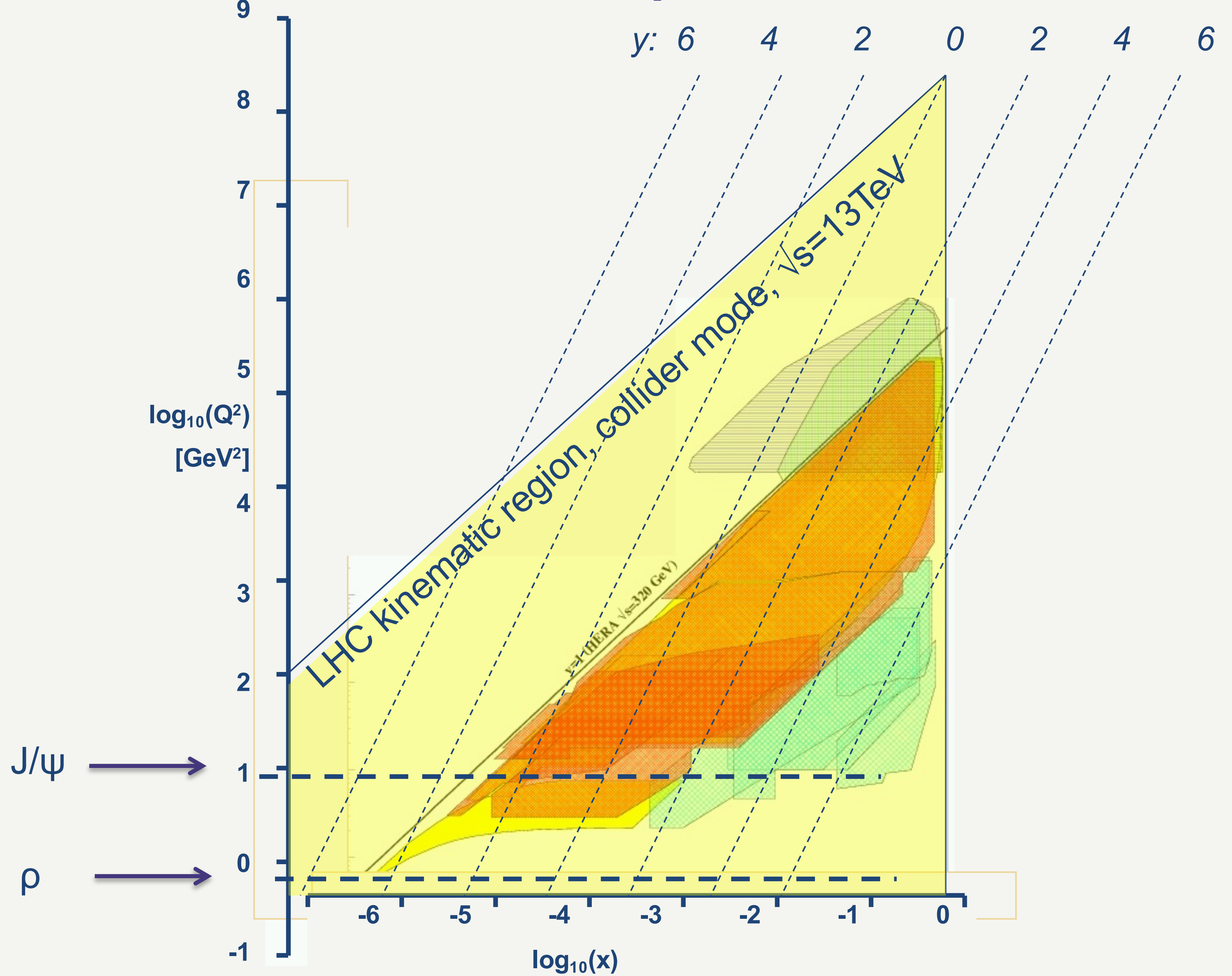
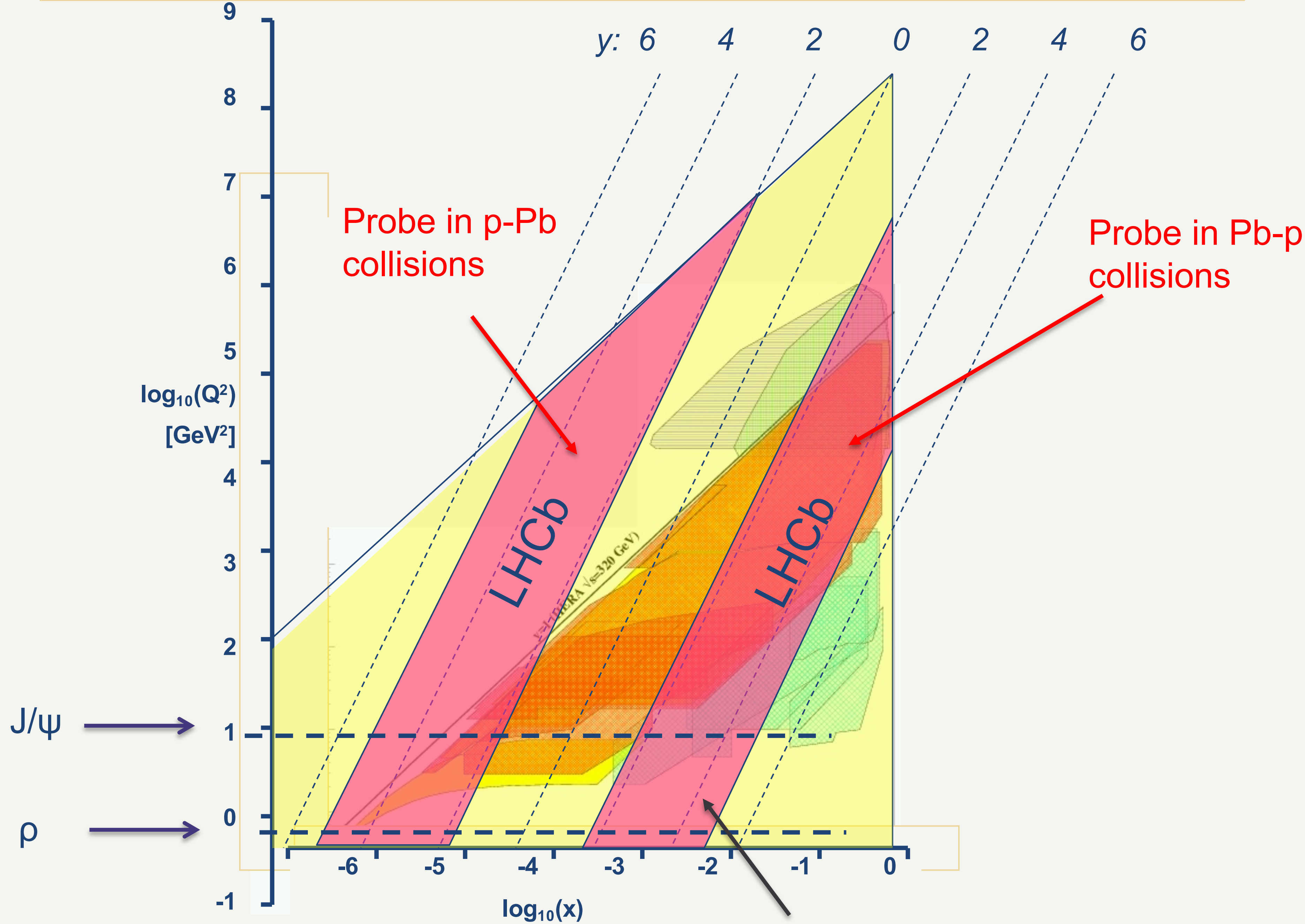
Low-x and forward physics

Ronan McNulty
DIS, Grenoble, April 8-12 2024

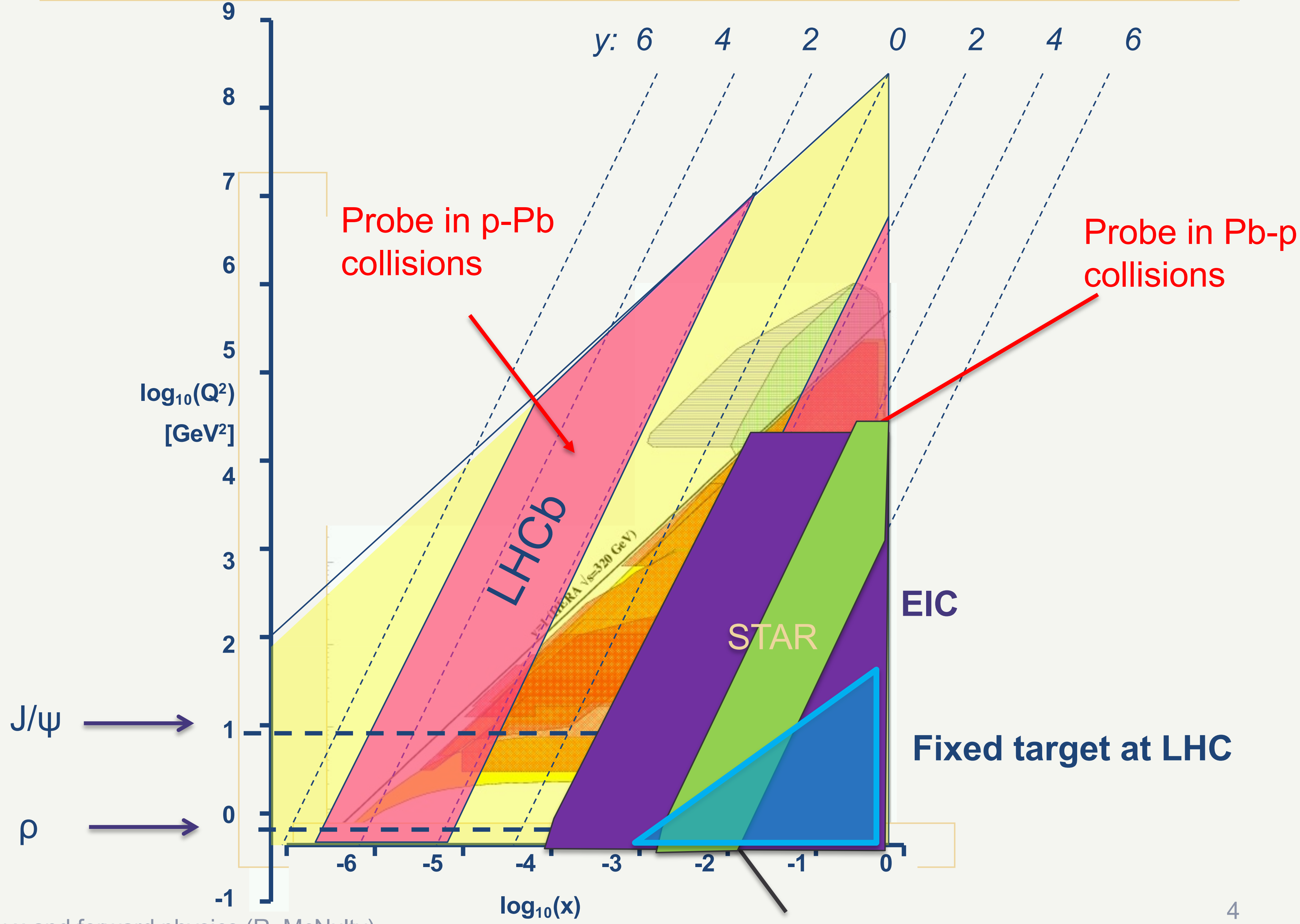
x-Q^2 values probed at LHC



Low-x & Forward physics



Low-x & Forward physics

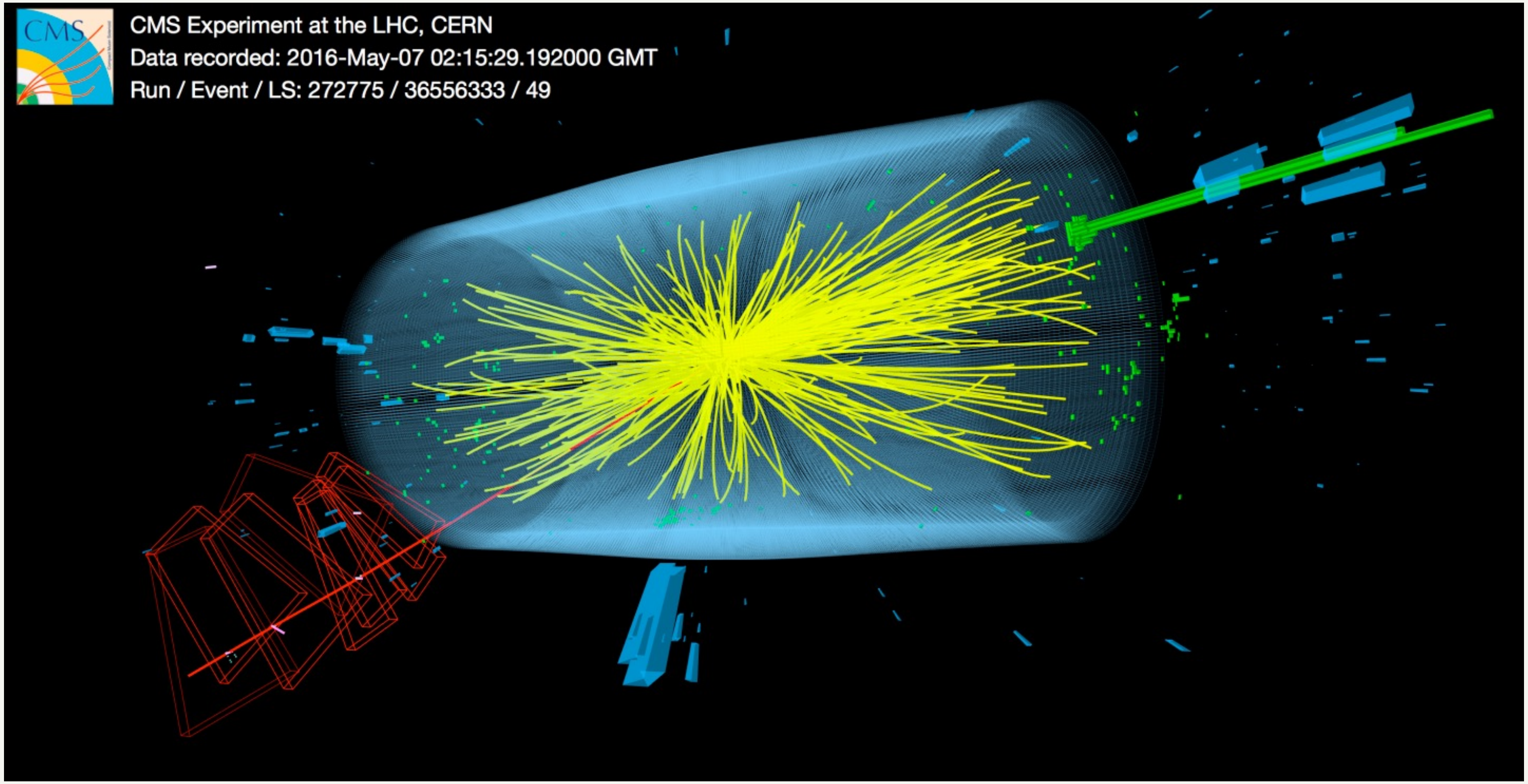


Motivation

- Much to understand about QCD
  - perturbative / non-perturbative regime
  - proton and nuclear structure (PDFs GPDs)
  - saturation
  - quark model bound states (ρ, ρ', f_0,$f_{2....}$)
  - beyond the naïve quark model (hybrids, tetraquarks, glueballs)
  - colourless propagators: pomerons and odderons

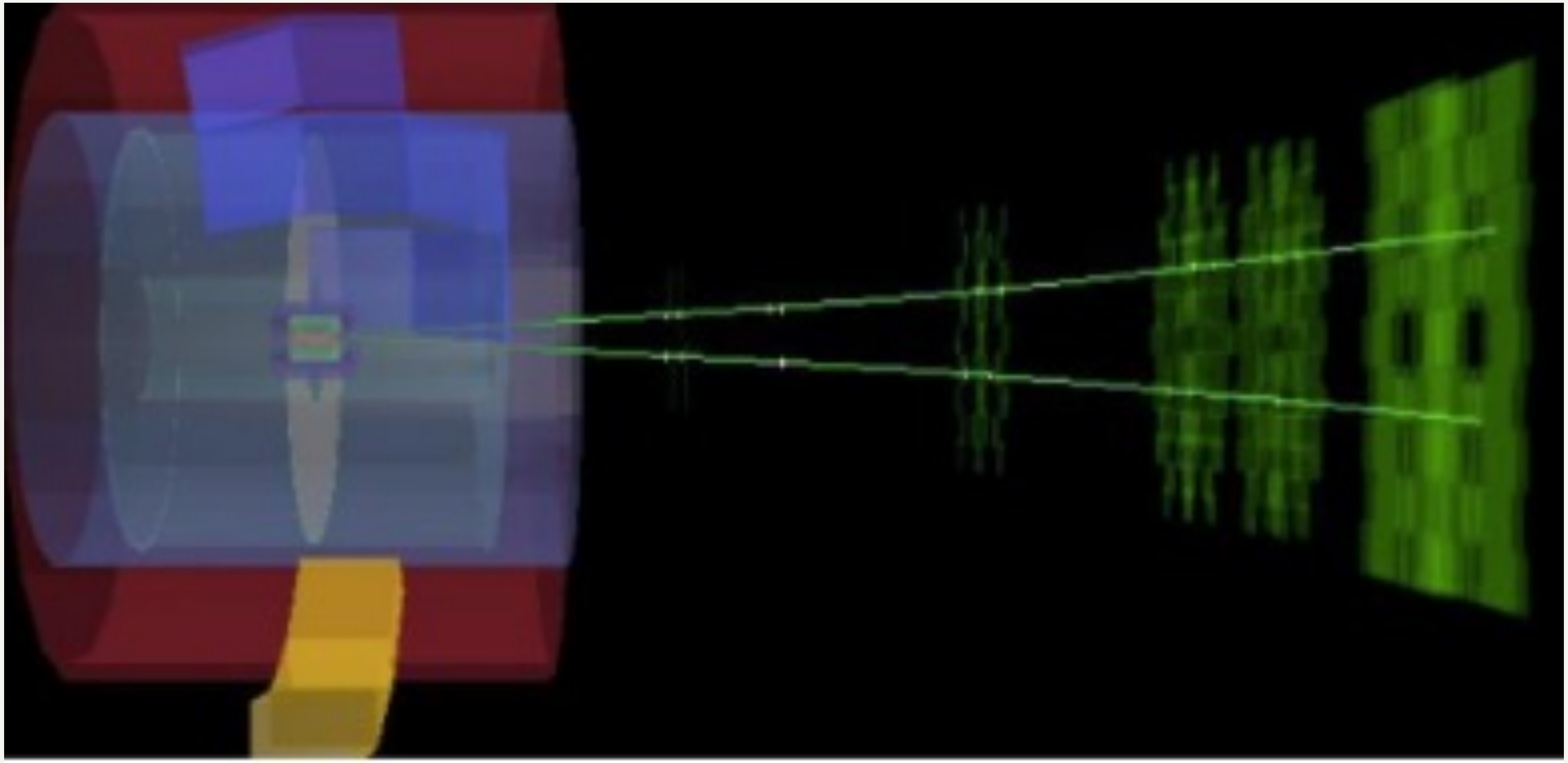
- Can be addressed in diffractive DIS.

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**.

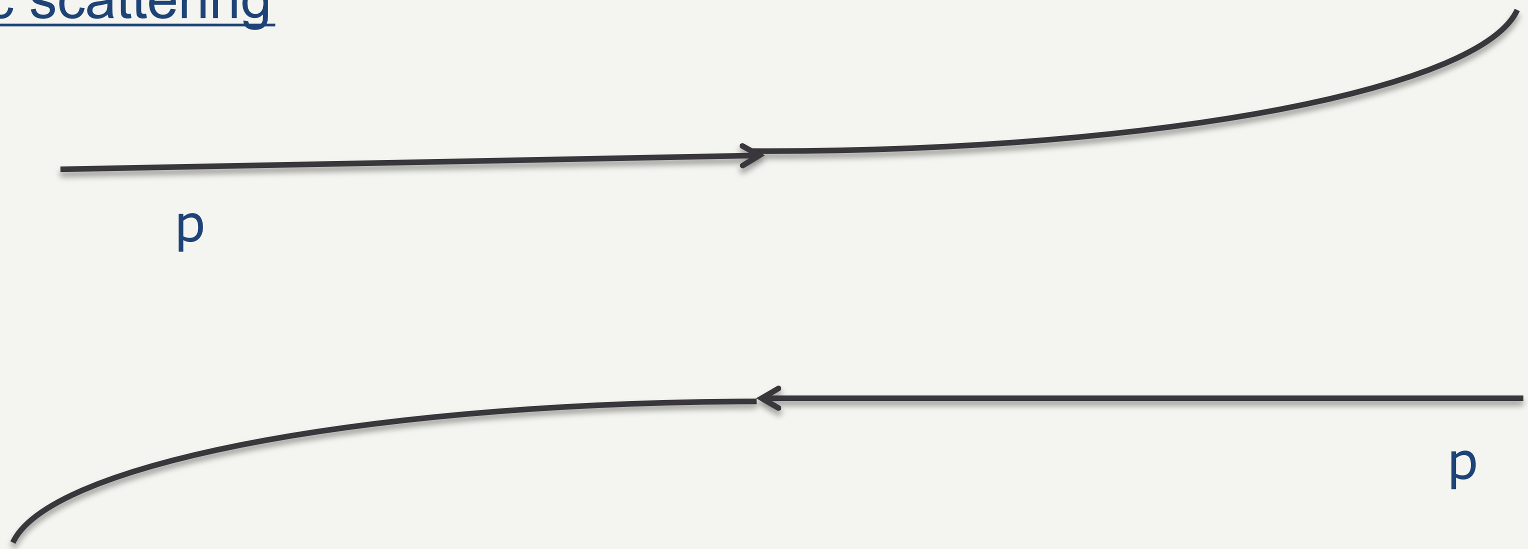
UPC J/ψ at forward rapidity in ALICE PbPb data



(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

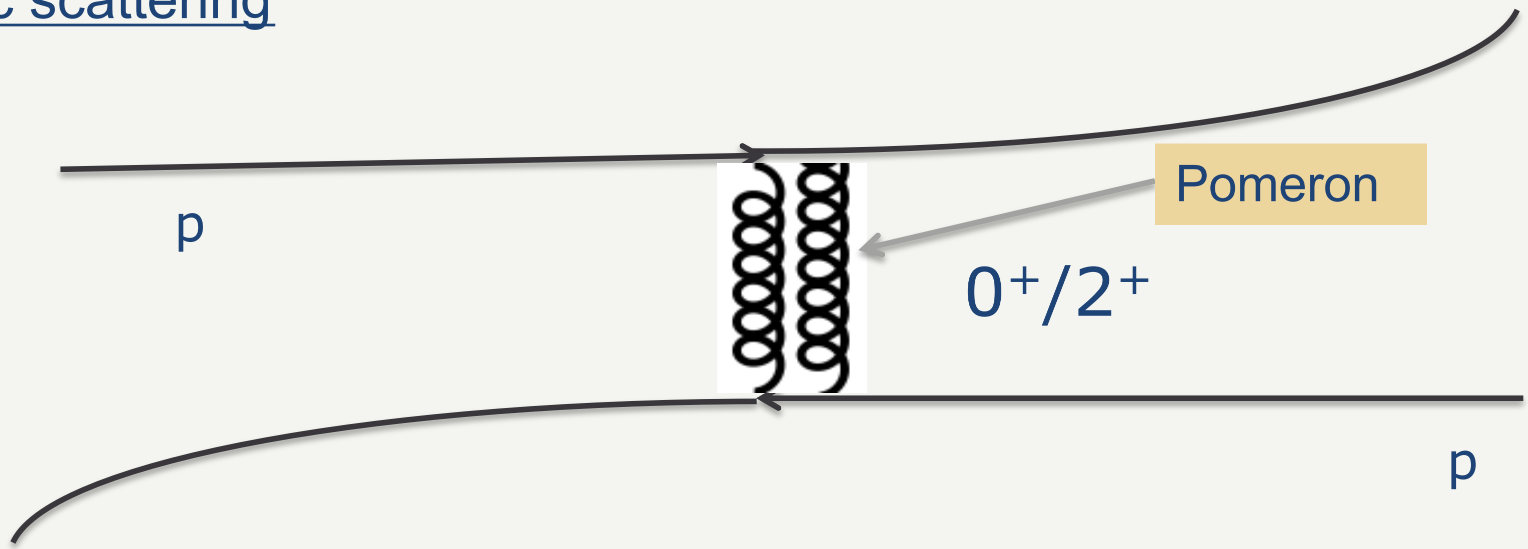
$\sigma_{elastic} \approx 40mb$ ⇦

$\sigma_{diffractive} \approx 10mb$

$\sigma_{inelastic} \approx 60mb$

Physics of the Vacuum

Elastic scattering

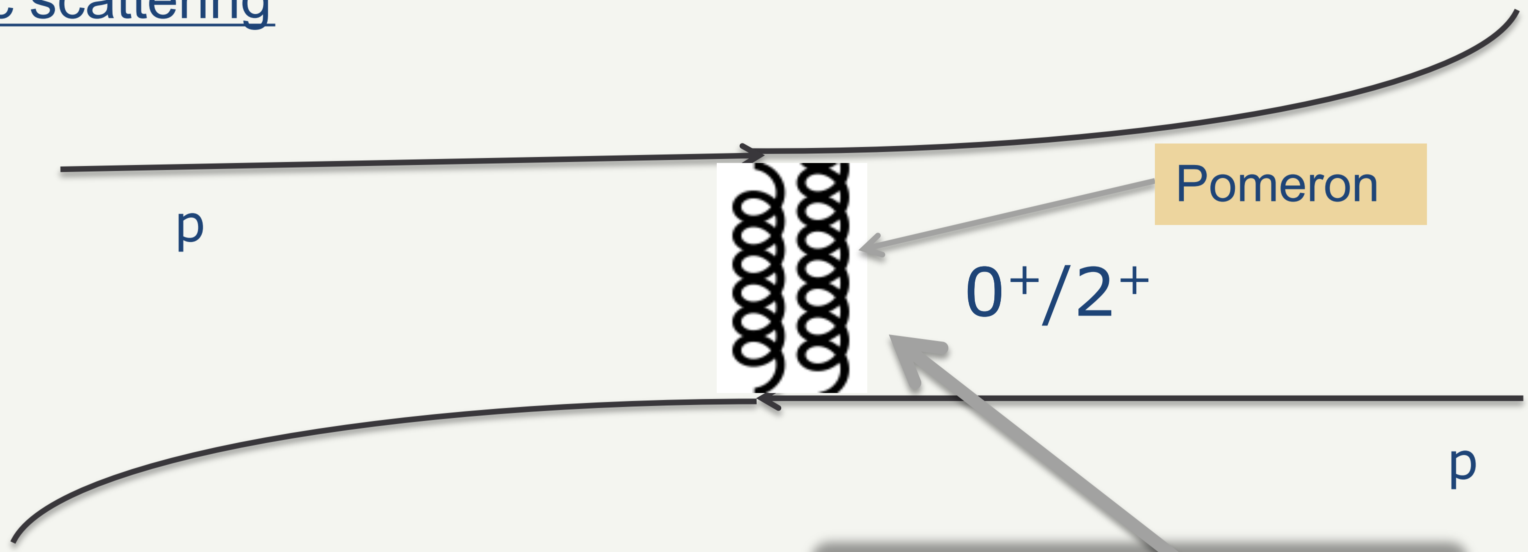


It's QCD – but not as we normally see it. It's colour-free

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

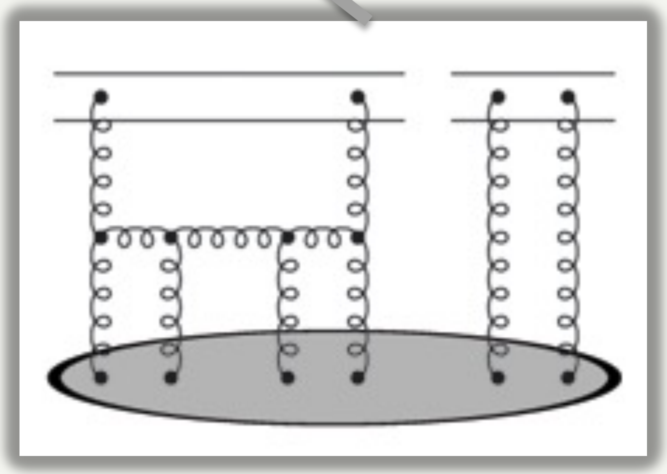
Physics of the Vacuum

Elastic scattering



At high energy: $A(s,t)=s^{\alpha(t)}$

$\alpha_P(t)=\alpha_P(0)+\alpha' t$



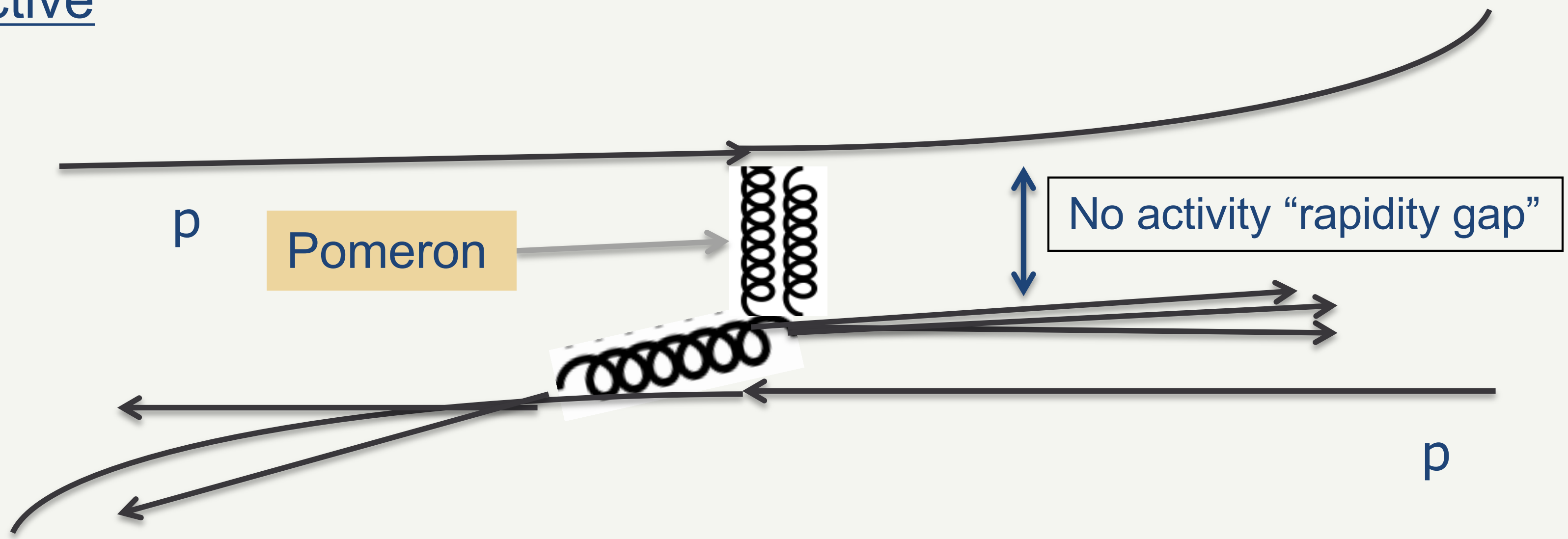
$\sigma_{elastic} \approx 40mb$ ⇦

$\sigma_{diffractive} \approx 10mb$

$\sigma_{inelastic} \approx 60mb$

Physics of the Vacuum

Diffractive

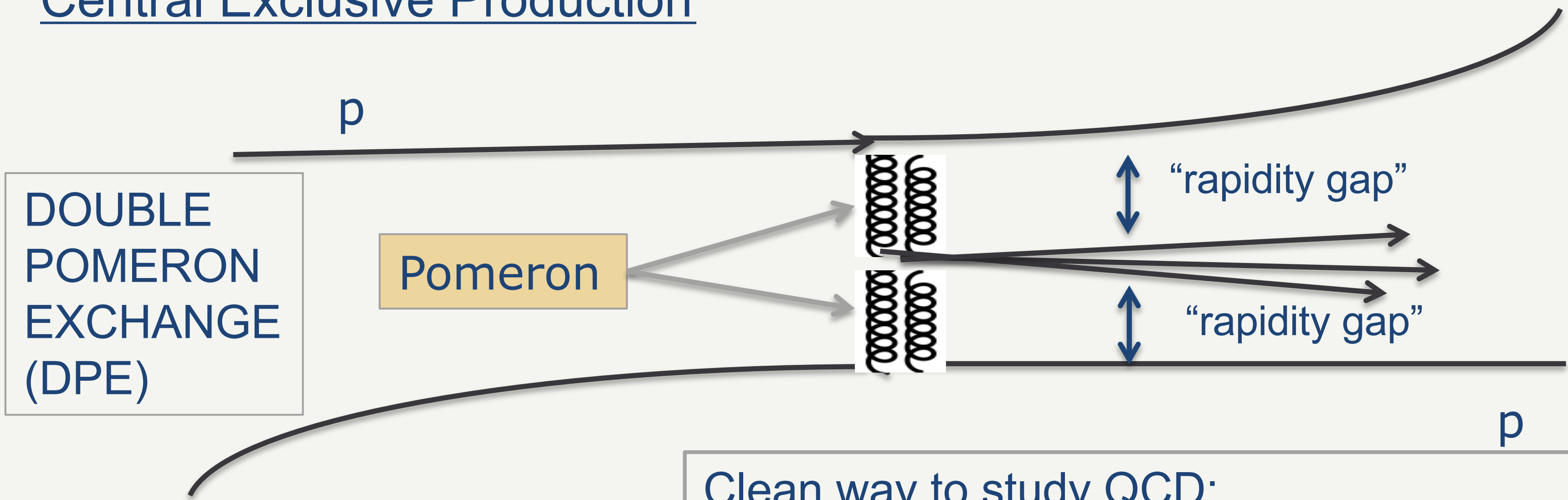


Experimental working definition of diffraction is presence of rapidity gap

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

Physics of the Vacuum

Central Exclusive Production



Clean way to study QCD:
- structure of projectiles
- nature of colour-free propagators
- structure of what is produced out of vacuum

$\sigma_{elastic} \approx 40mb$

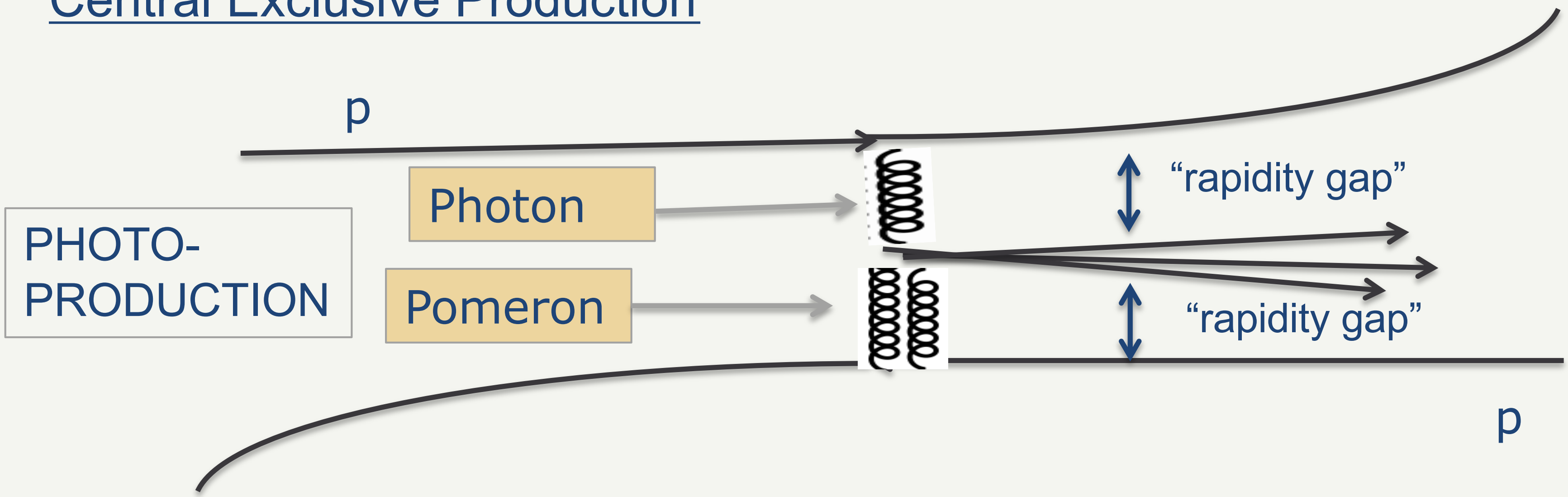
$\sigma_{diffractive} \approx 10mb$

$\sigma_{inelastic} \approx 60mb$

100 μb

Physics of the Vacuum

Central Exclusive Production



$\sigma_{elastic} \approx 40mb$

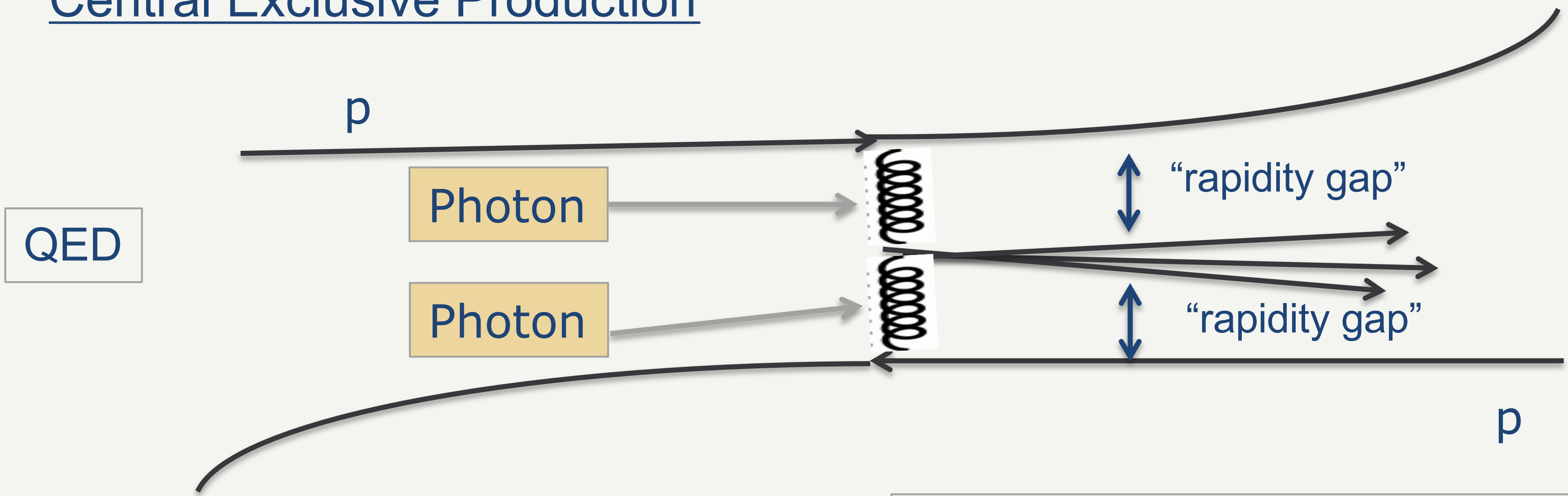
$\sigma_{diffractive} \approx 10mb$

$\sigma_{inelastic} \approx 60mb$

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...

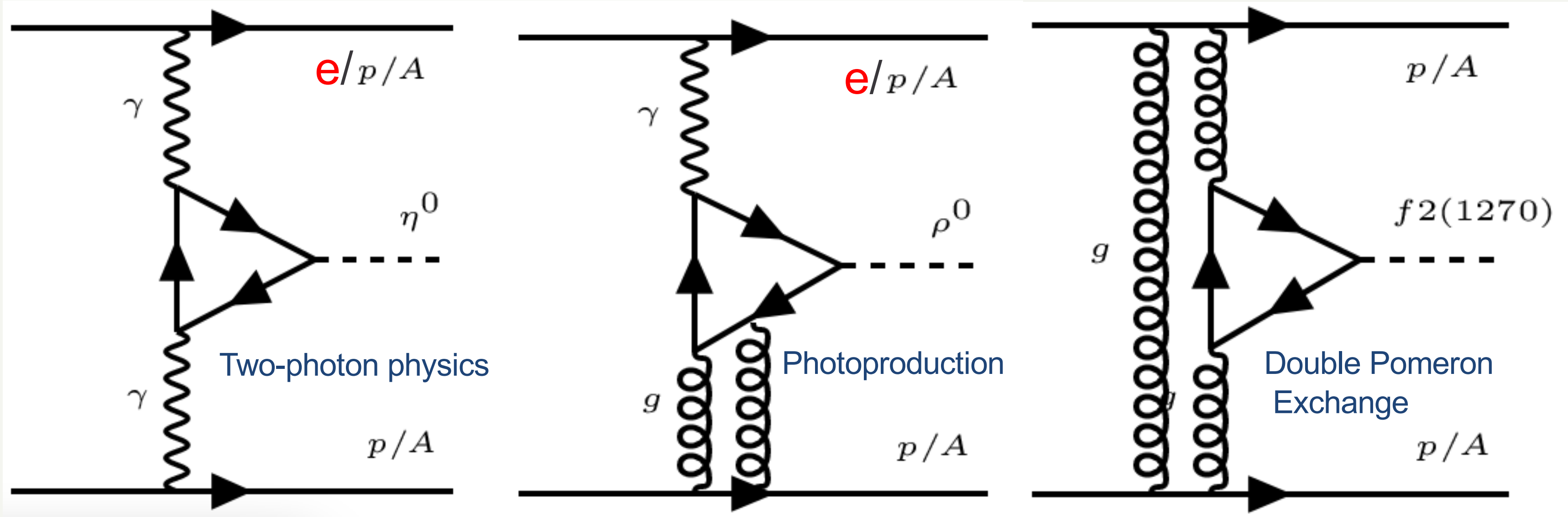
$\sigma_{elastic}$ ≈ 40mb

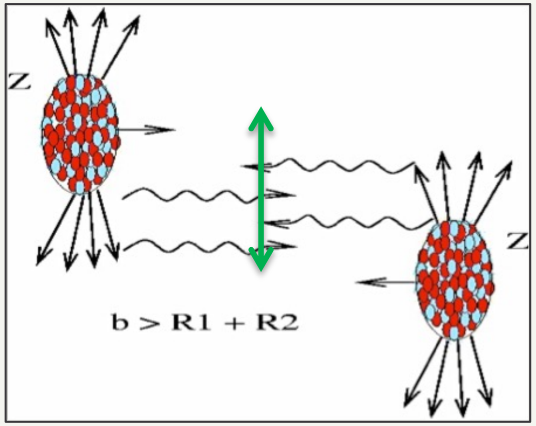
$\sigma_{diffractive}$ ≈ 10mb

$\sigma_{inelastic}$ ≈ 60mb

100 pb

Colourless propagators



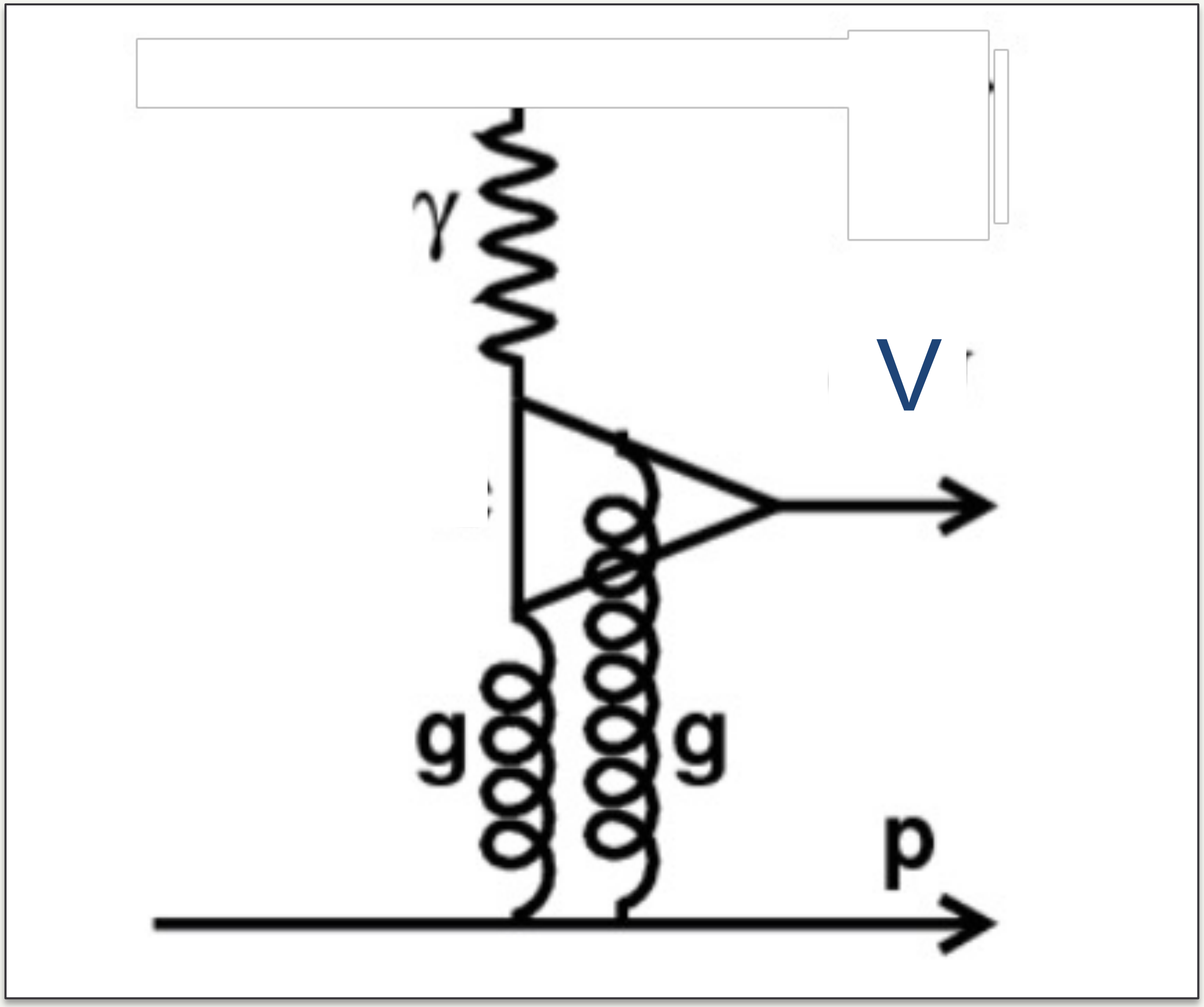


Hadron colliders:
Generally, to ensure no (colourful) QCD interaction, $d > R_1 + R_2$ (1.5 - 6 fm).

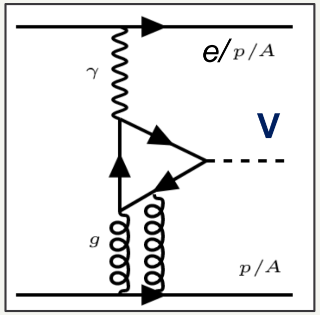
Large impact parameter ↔ Small p_T

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

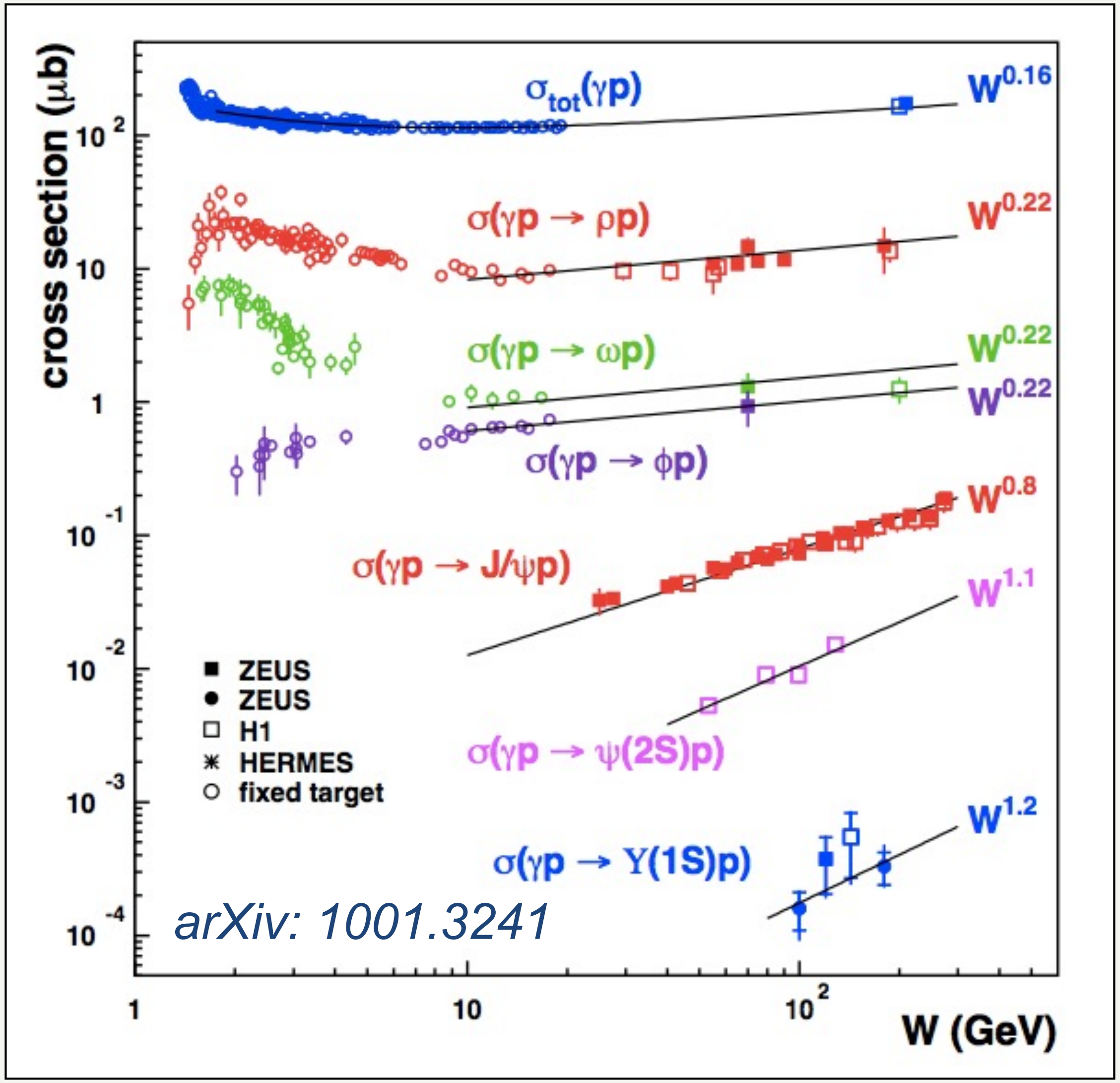
Photoproduction

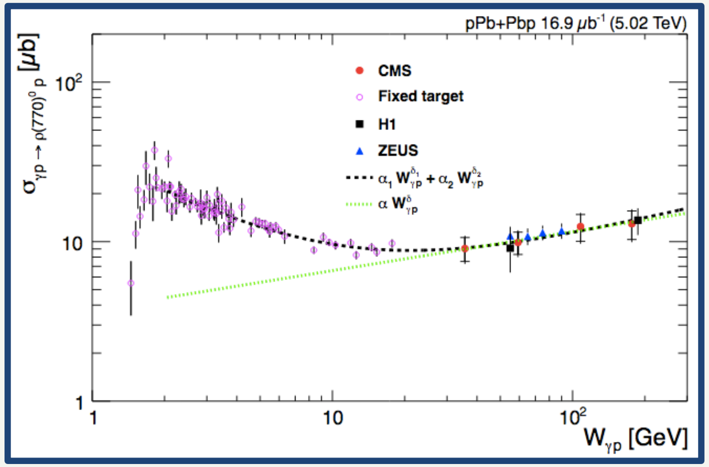


Photoproduction



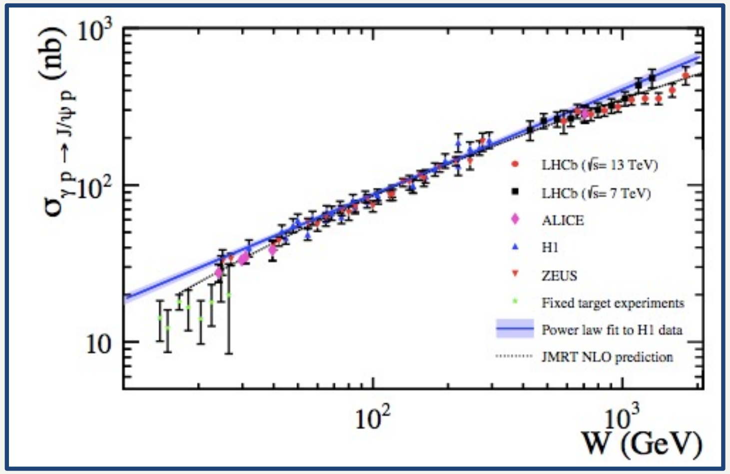
- Rise in σ related to Pomeron intercept
  - $\sigma \sim W^{\delta}$
  - $\delta = 4(\alpha_P(t) - 1)$
  - $\alpha_P(t) = \alpha_P(0) + \alpha' t$
- Compare slopes ρ,ω,ϕ to J/ψ,ψ',Υ
- Extract $g(x,Q^2)$



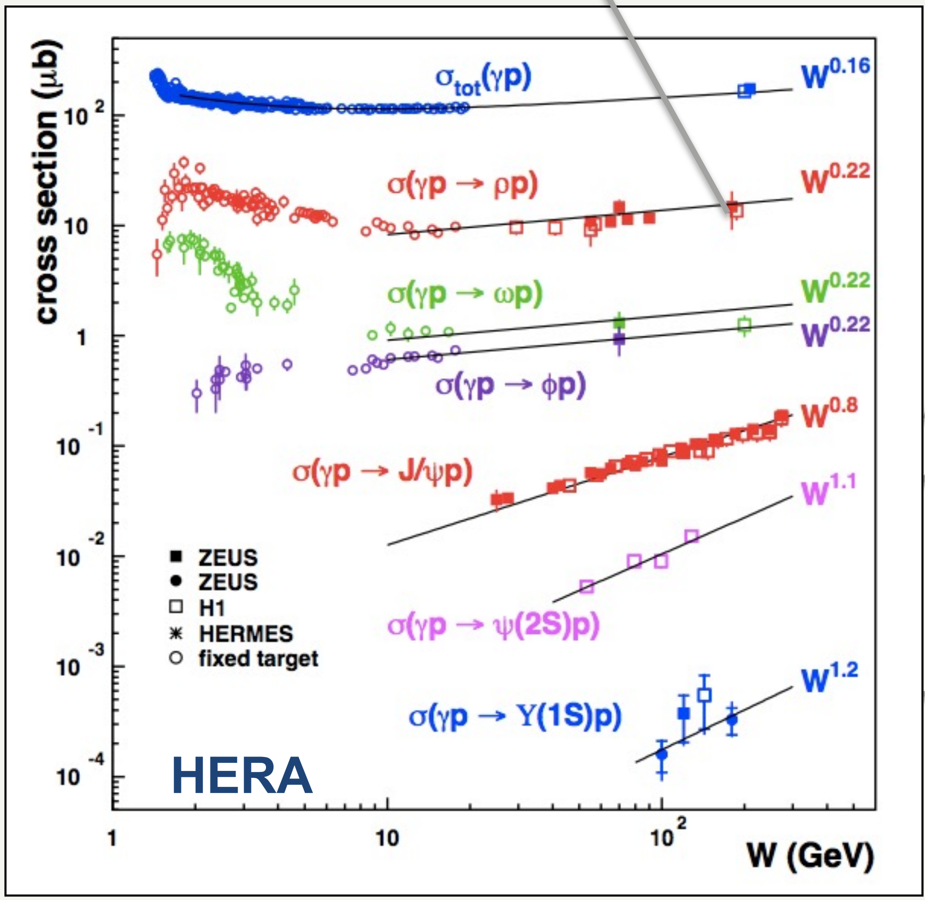


CMS (pPb) ALICE (XeXe, PbPb)

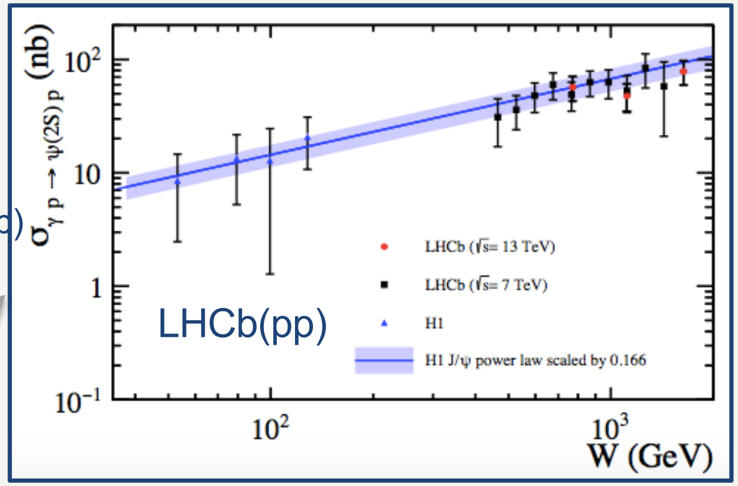
ALICE (pPb, PbPb)
LHCb (pp, PbPb)



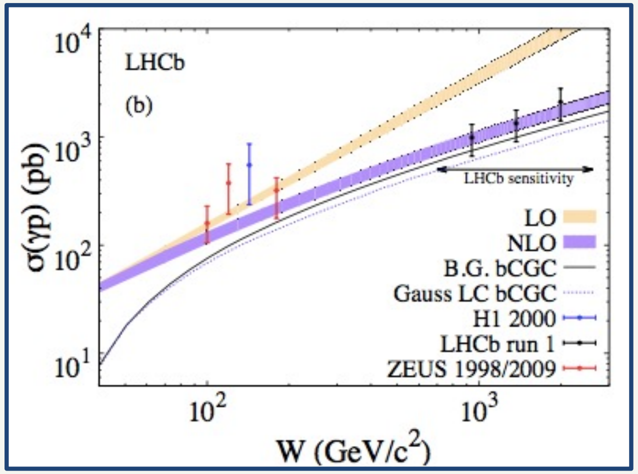
Central region
$W_{LHC} \sim W_{HERA}$
Forward
$W_{LHC} >> W_{HERA}$



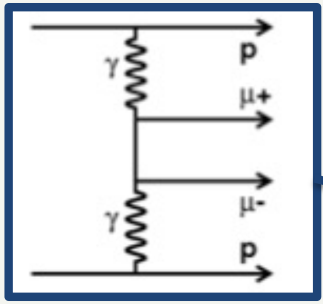
LHCb
(pp, PbPb)



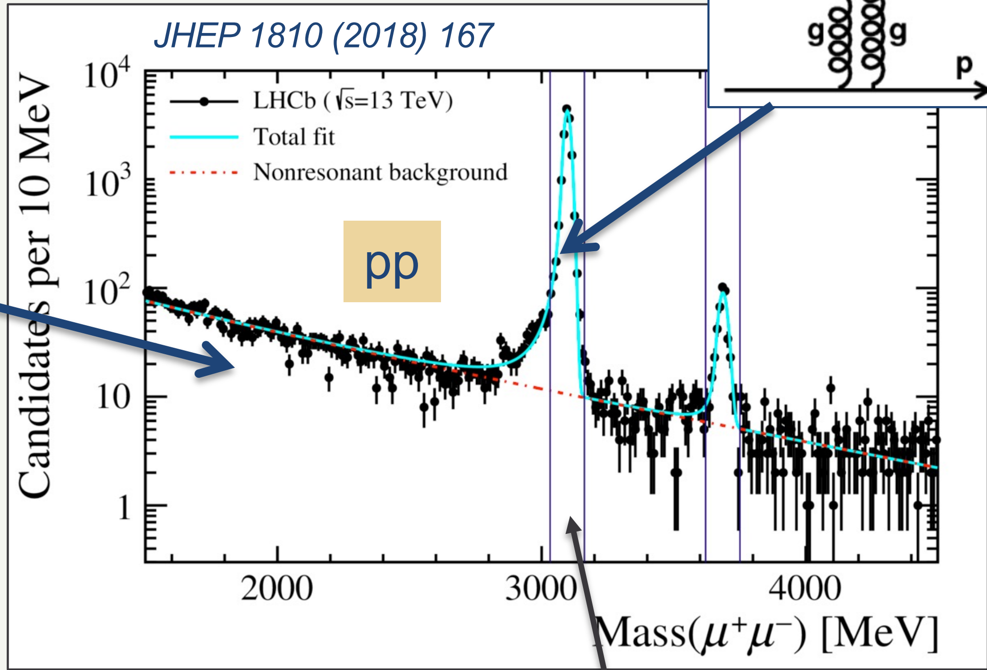
LHCb (pp)
CMS (pPb)

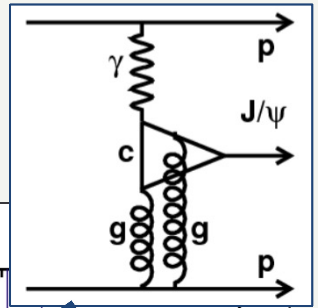


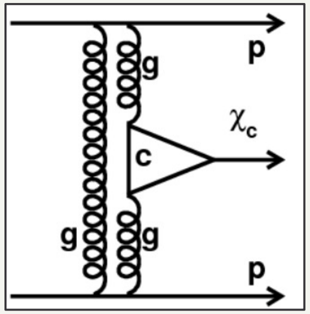
Dimuons in p(Pb)p(Pb) collisions



$\gamma\gamma$ events continue to detection threshold at ~ 600 MeV (enhanced in PbPb)



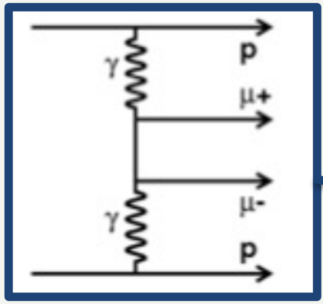




Feed-down (not present in pA)

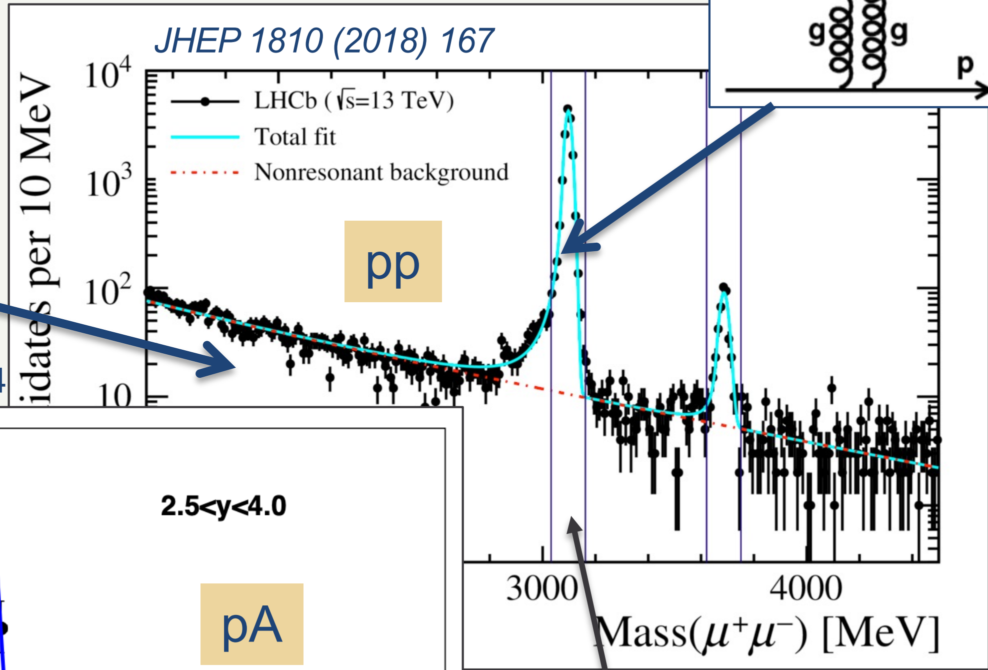
$$\chi_c \longrightarrow J/\psi + \gamma$$

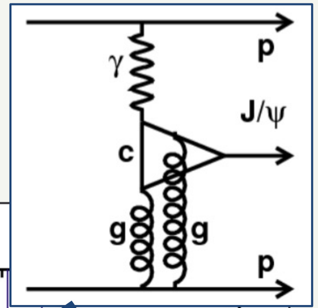
Dimuons in p(Pb)p(Pb) collisions



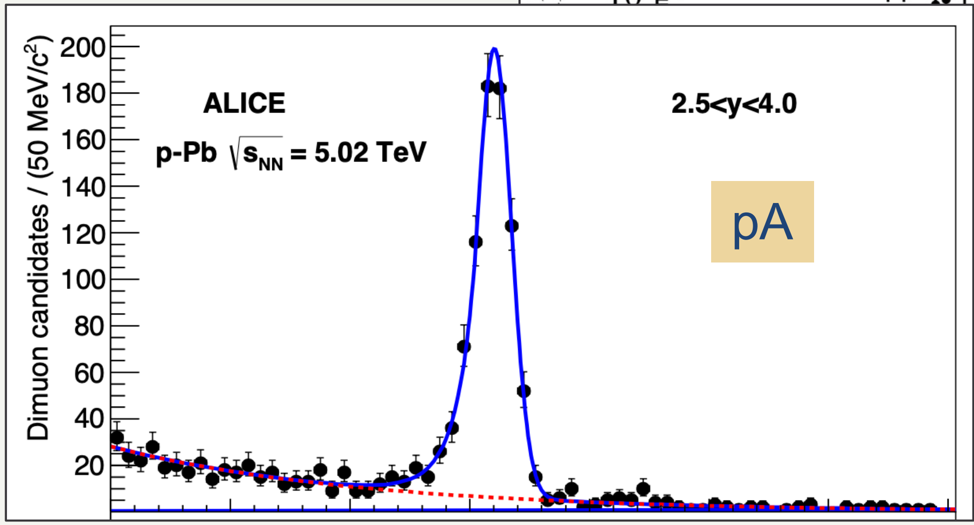
$\gamma\gamma$ events continue to detection threshold at ~ 600 MeV (enhanced in PbPb)

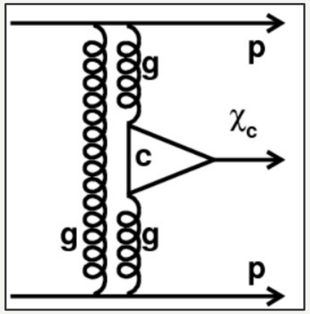
JHEP 1810 (2018) 167





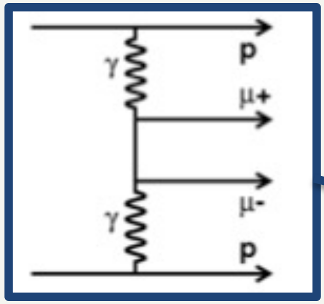
Phys.Rev.Lett. 113 (2014) 23, 232504



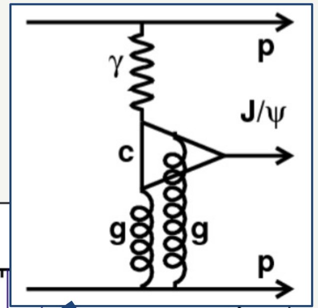


Feed-down (not present in pA)

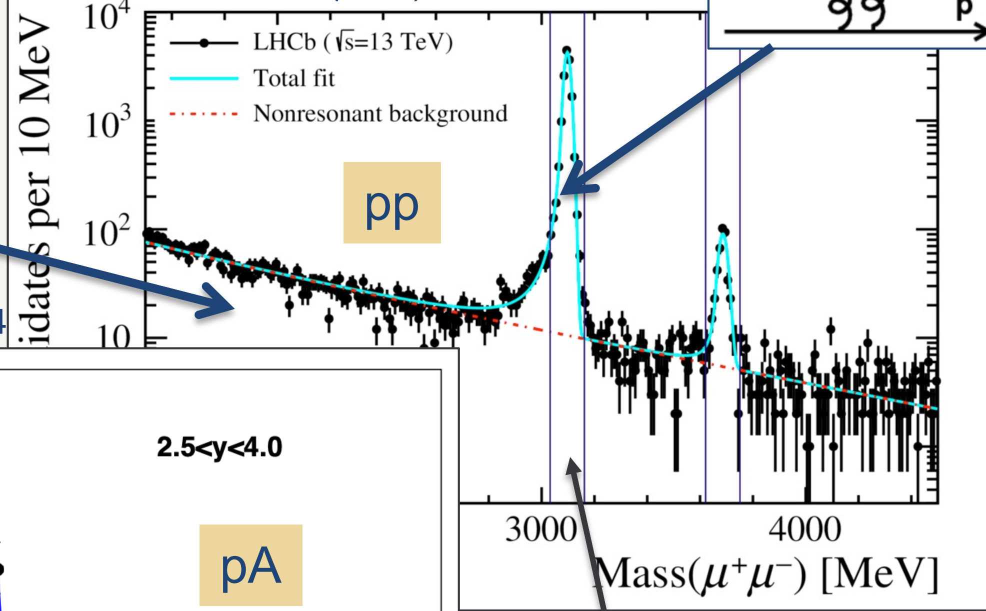
Dimuons in p(Pb)p(Pb) collisions



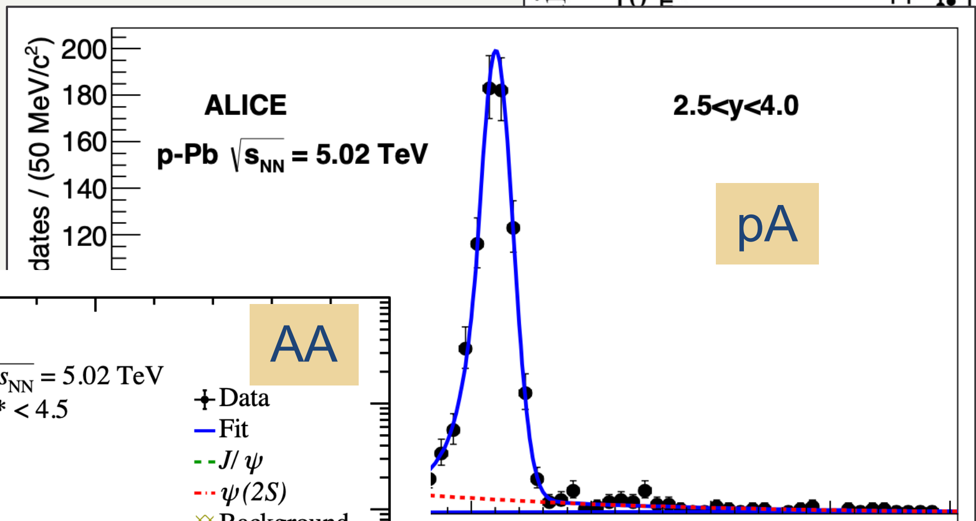
$\gamma\gamma$ events continue to detection threshold at ~ 600 MeV (enhanced in PbPb)



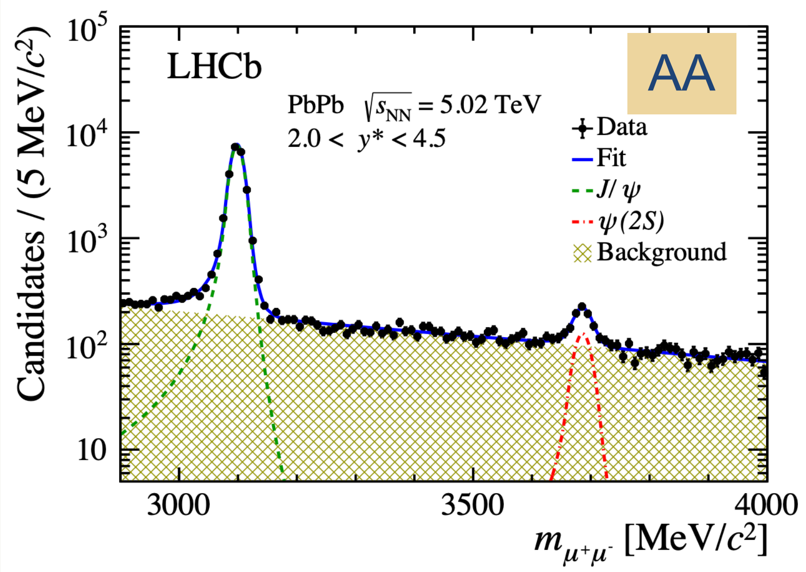
JHEP 1810 (2018) 167

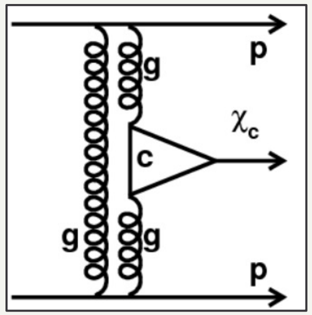


Phys.Rev.Lett. 113 (2014) 23, 232504



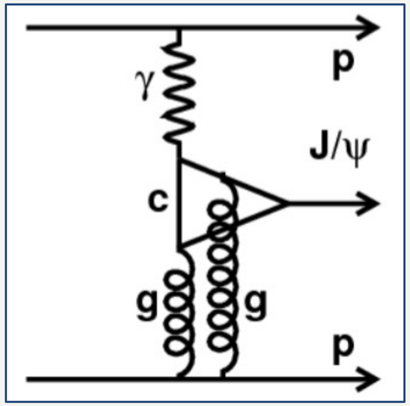
JHEP 06 (2023) 146





Feed-down (not present in pA)

Implications: GPDs and PDF

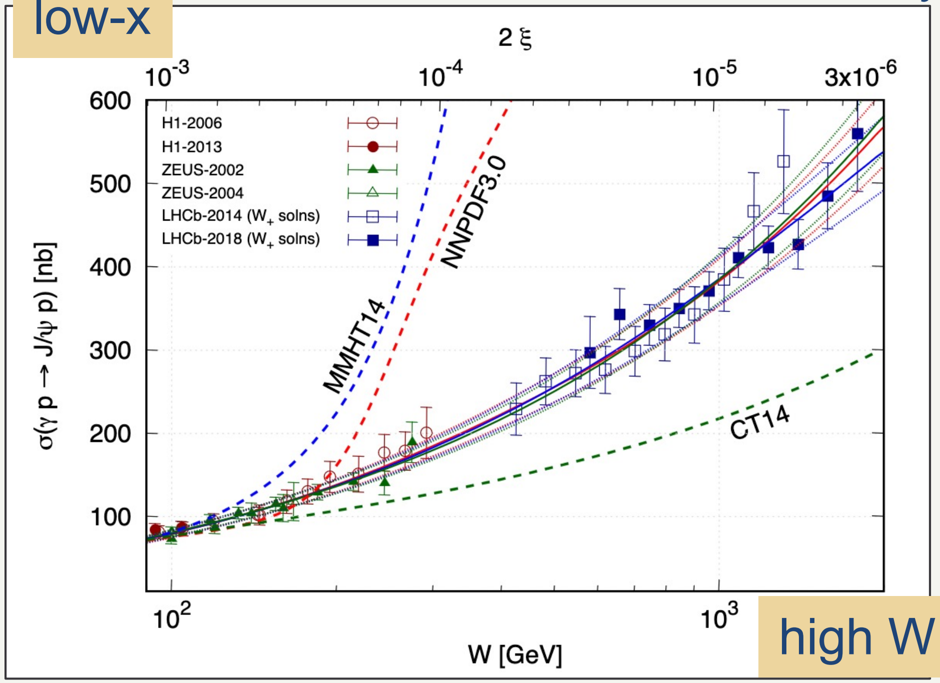


Ryskin, Z. Phys. C 57 (1993) 89

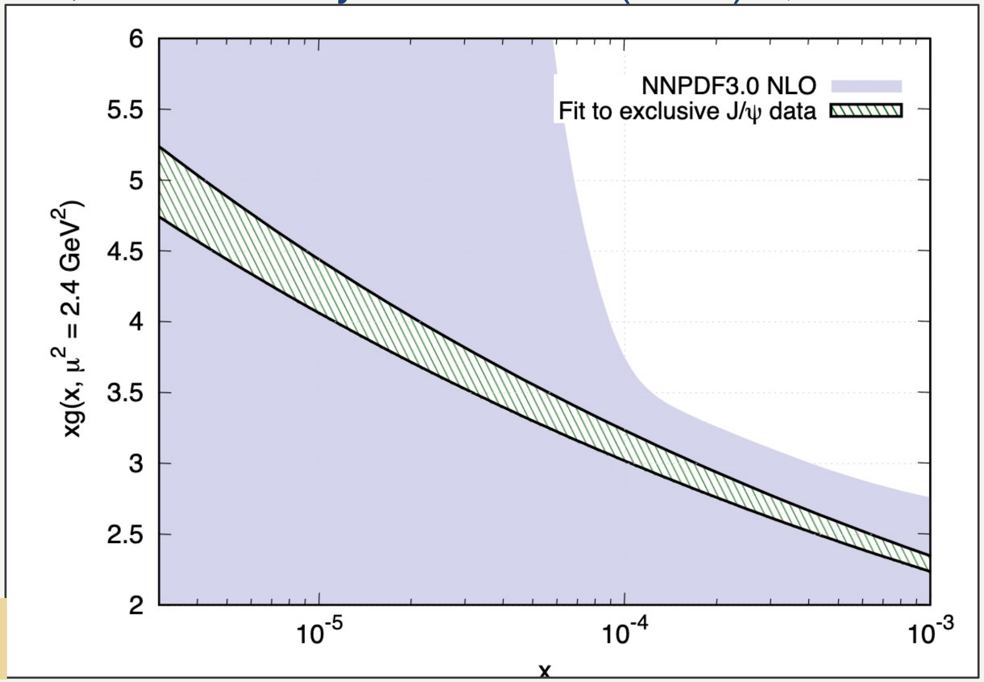
$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\, p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4}\, xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$

Flett, Martin, Ryskin, Teubner. Phys.Rev.D 102 (2020) 114021
Flett, Jones, Martin, Ryskin, Teubner. Phys.Rev.D 101 (2020) 9, 094011

low-x



high W



makes use of Shuvaev transform to relate GPDs and PDFs

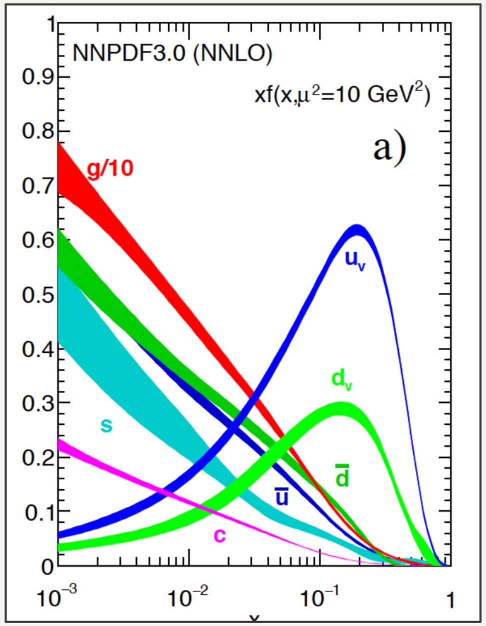
$$H_q(X,\xi) = \int_{-1}^{1} dx' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{ds}{y(s)\sqrt{1-y(s)x'}}\right] \frac{d}{dx'}\left(\frac{q(x')}{|x'|}\right),$$

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

where the transform kernel,

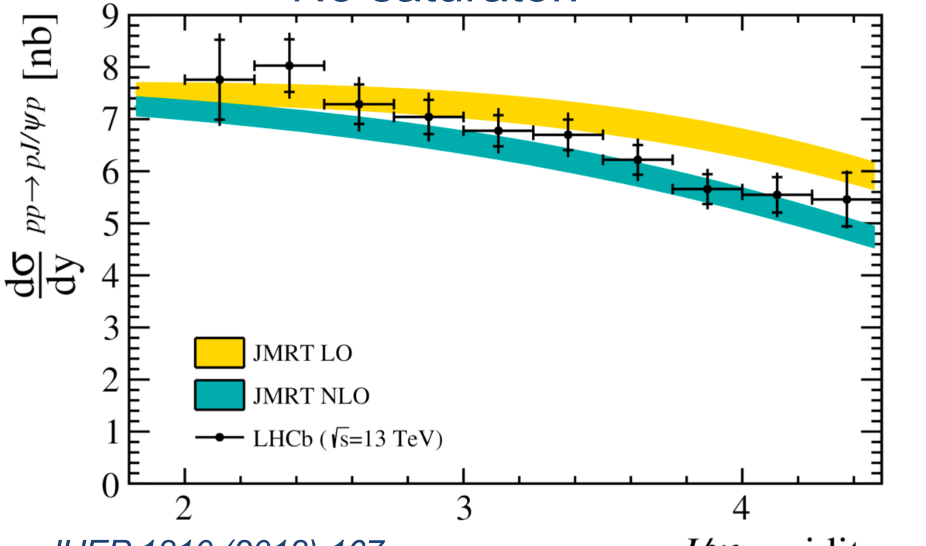
$$y(s) = \frac{4s(1-s)}{(X+\xi(1-2s))}.$$

Implications: Saturation



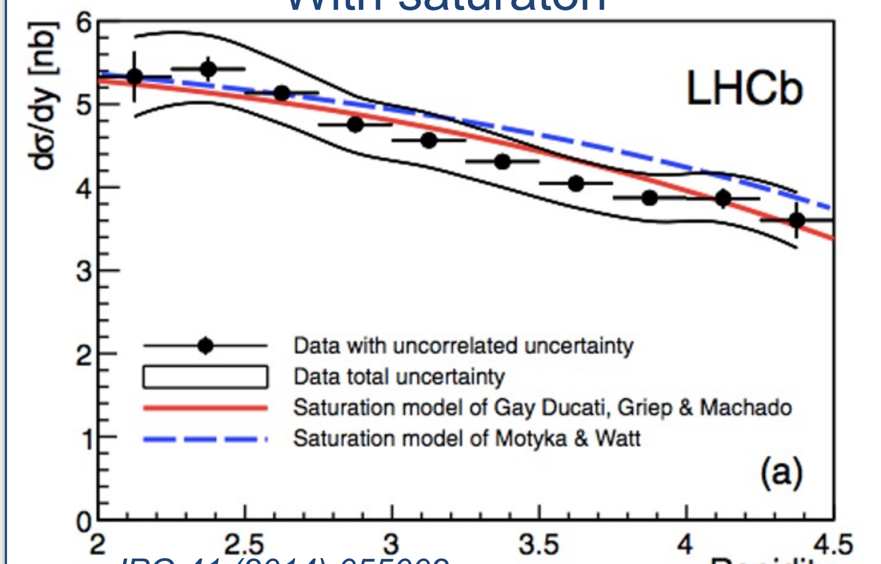
Saturation effects become visible at low-x.
Onset of saturation expected to scale with nucleon density ~ $A^{1/3}$ so
may be easier to see in nuclear collisions

No saturaton



JHEP 1810 (2018) 167

With saturaton



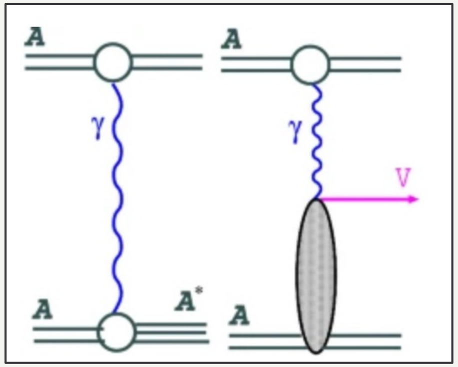
JPG 41 (2014) 055002

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

Looking for saturation in nuclear collisions

<u>**Coherent**</u> interaction: all nucleons behave as one.

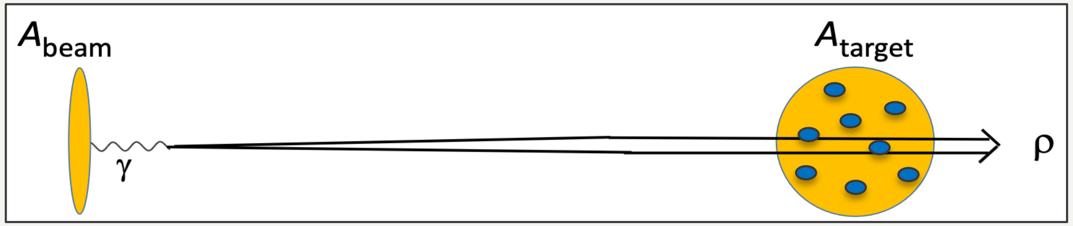
- b ~ 2R=13.2 fm so p_T~15 MeV
- nucleus remains intact*.



*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'?



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

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

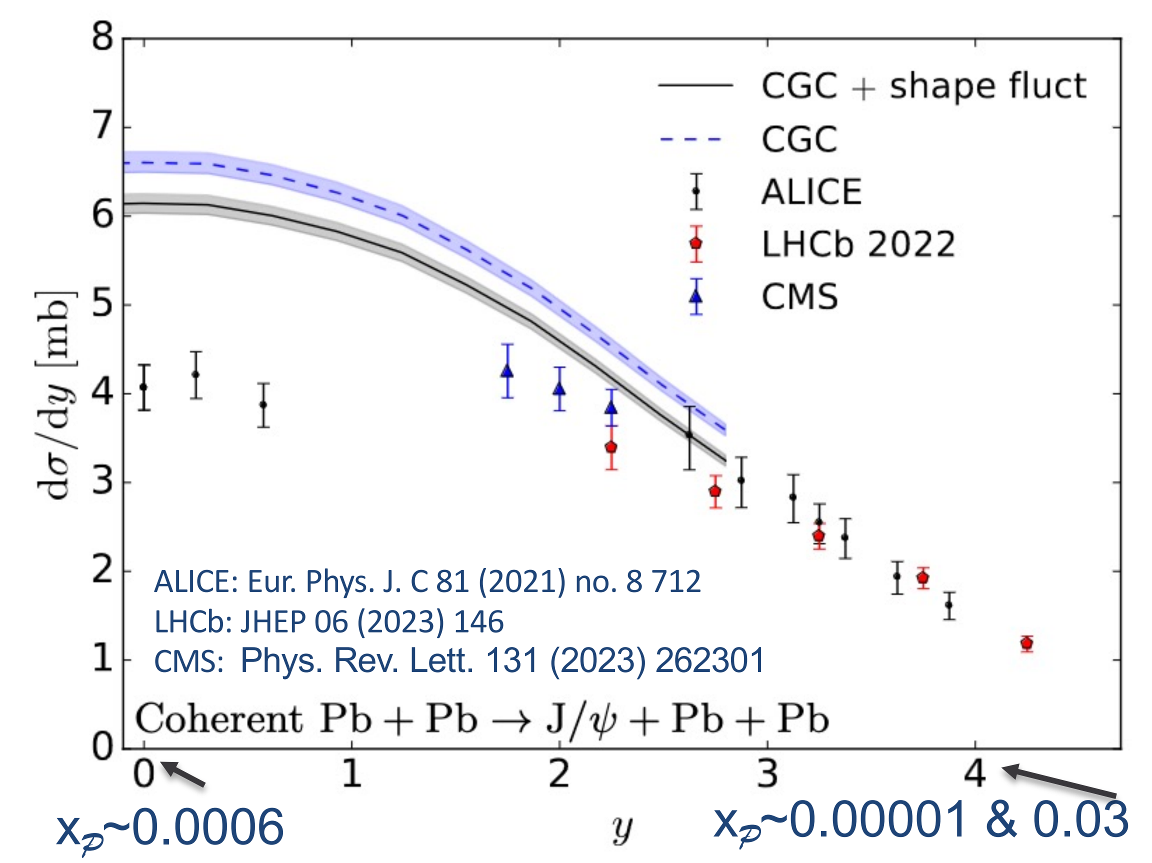
Glauber eikonal approx.

<u>**Incoherent**</u> 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.

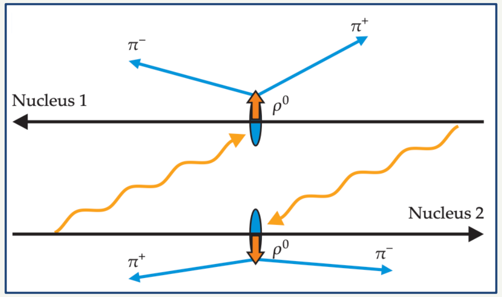
Coherent J/ψ in PbPb

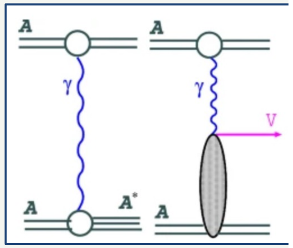
See WG2 talk by Heikki Mäntysaaryi



H. Mäntysaari, F. Salazar, B. Schenke: arXiv: 2312.04194

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



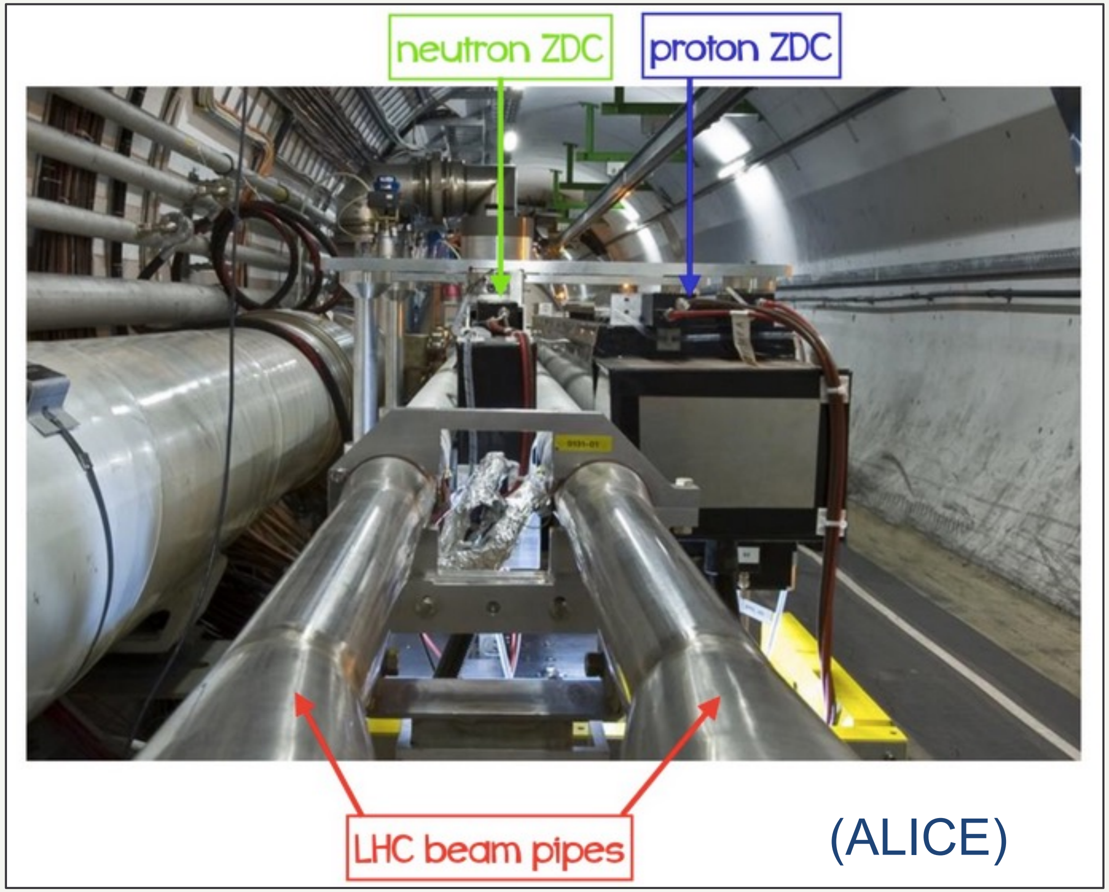


S. Klein, J. Nystrand, Physics Today 70, (2017) 40.

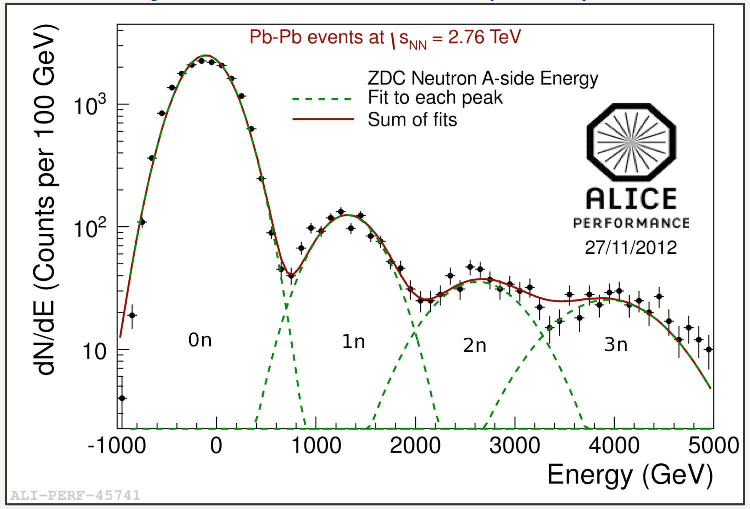
However, away from y=0, there is a two-fold ambiguity in the photon emitter and two-fold ambiguity in the value of W.

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

ZDC calorimeters installed in CMS, ALICE, STAR



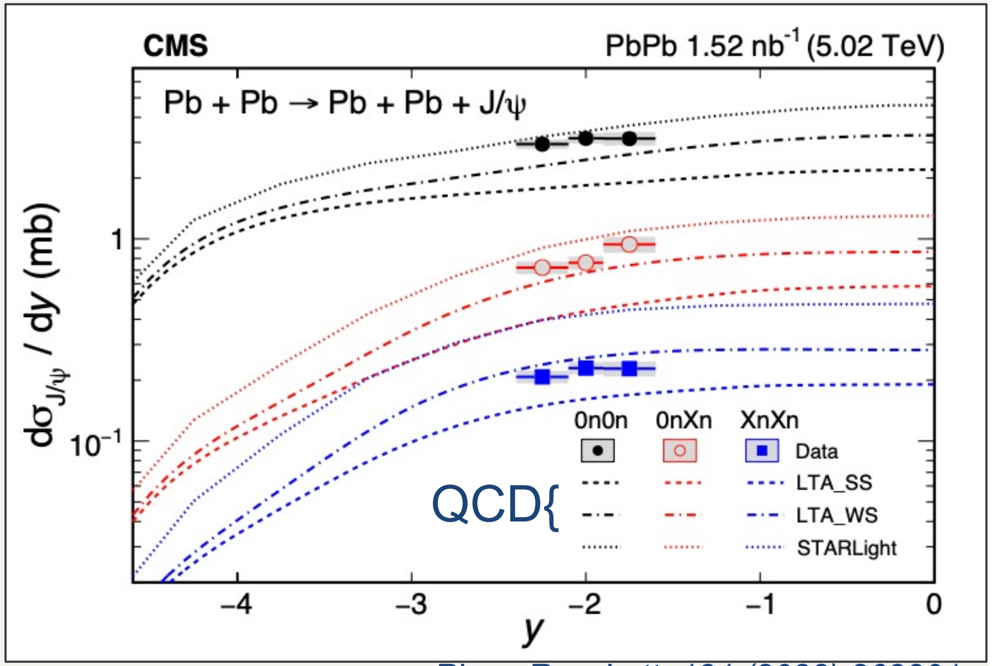
J. Phys.: Conf. Ser. 455 (2013) 012010



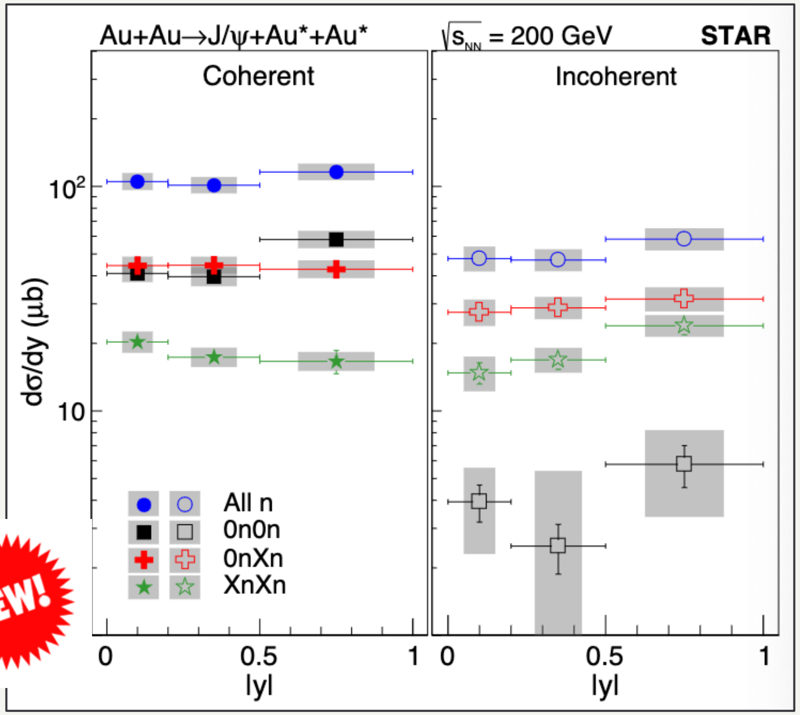
Detection of neutrons when ion breaks up allows identification of Electromagnetic Dissociation (EMD)

Resolving the two-fold ambiguity in PbPb

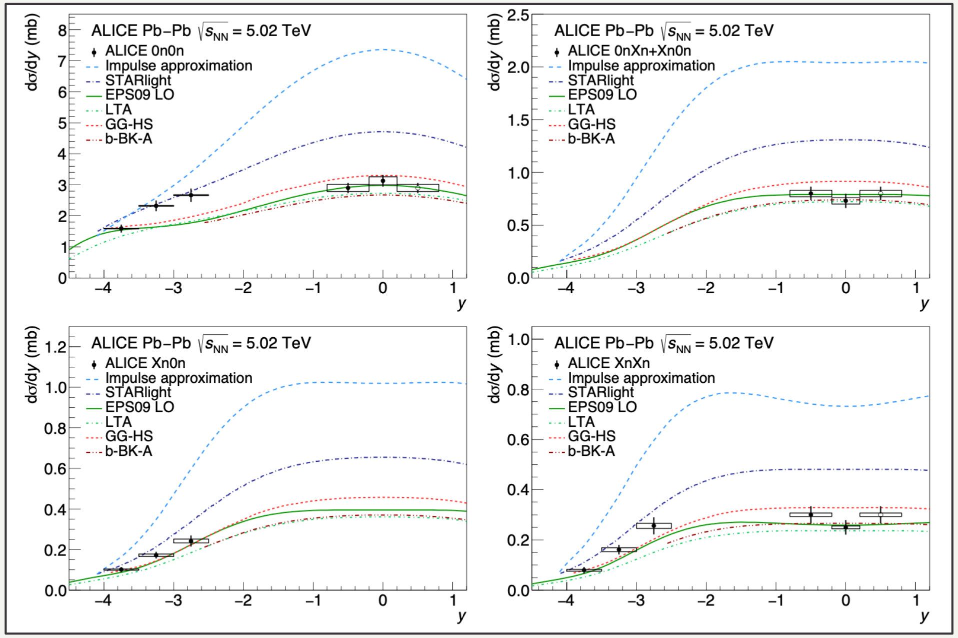
EMD is more likely at small impact parameters.
So fluxes for 0n and (X>=1)n different.



Phys. Rev. Lett. 131 (2023) 262301



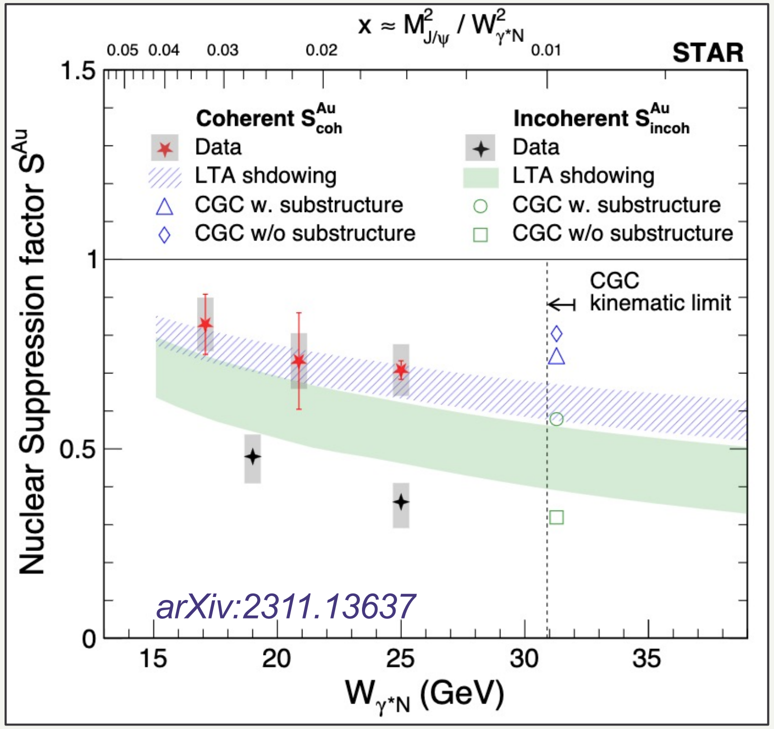
arXiv: 2311.13632

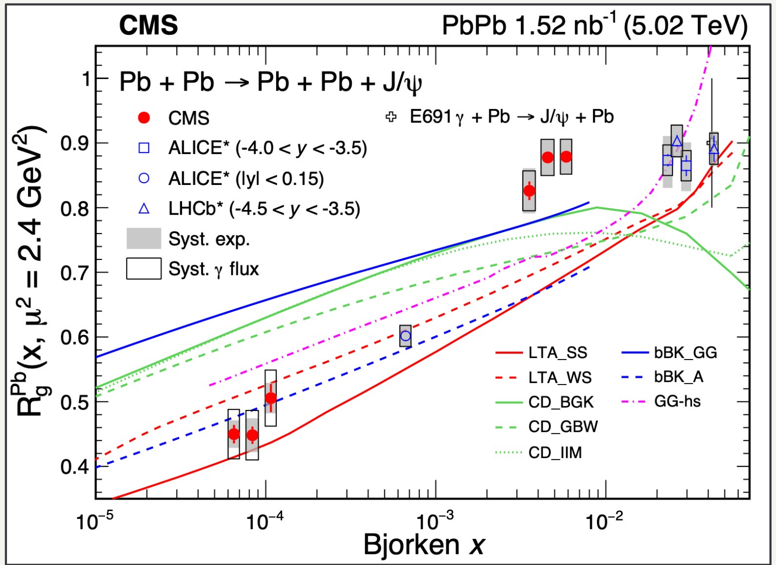


JHEP 10 (2023) 119

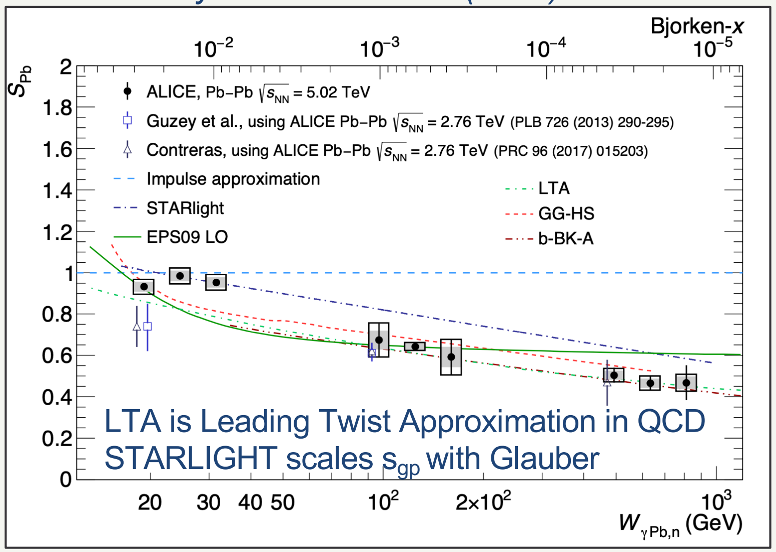
See WG2 talks Afnan Shatat, Guillermo Contreras

Re-expressed in terms of nuclear suppression factors





Phys. Rev. Lett. 131 (2023) 262301



JHEP 10 (2023) 119

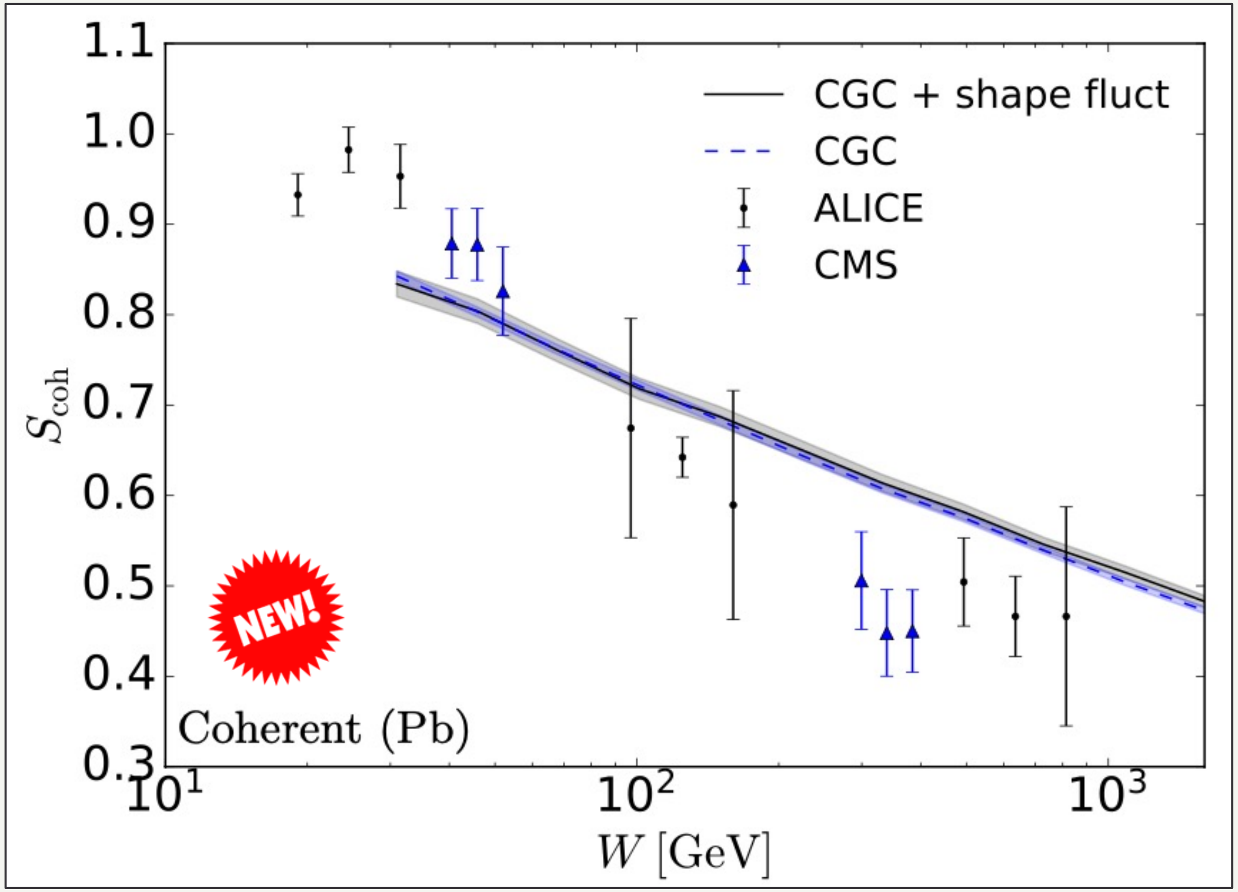
$$S_{\rm coh} = \sqrt{\frac{\sigma^{\gamma A}}{\sigma^{\rm IA}}}$$

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....

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



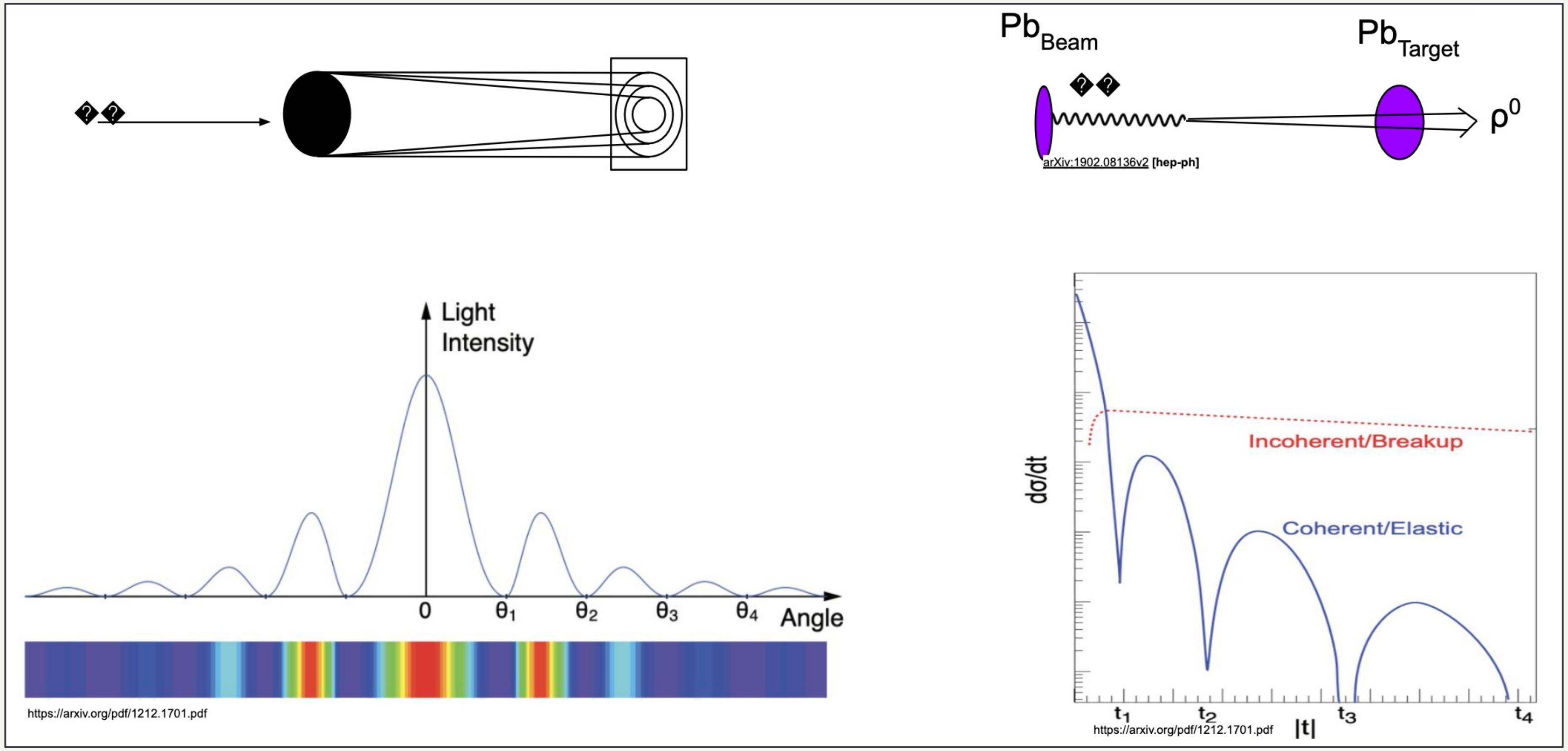
H. Mäntysaari, F. Salazar, B. Schenke: arXiv: 2312.04194

See WG2 talk by Heikki Mäntysaaryi

Transverse momentum distribution

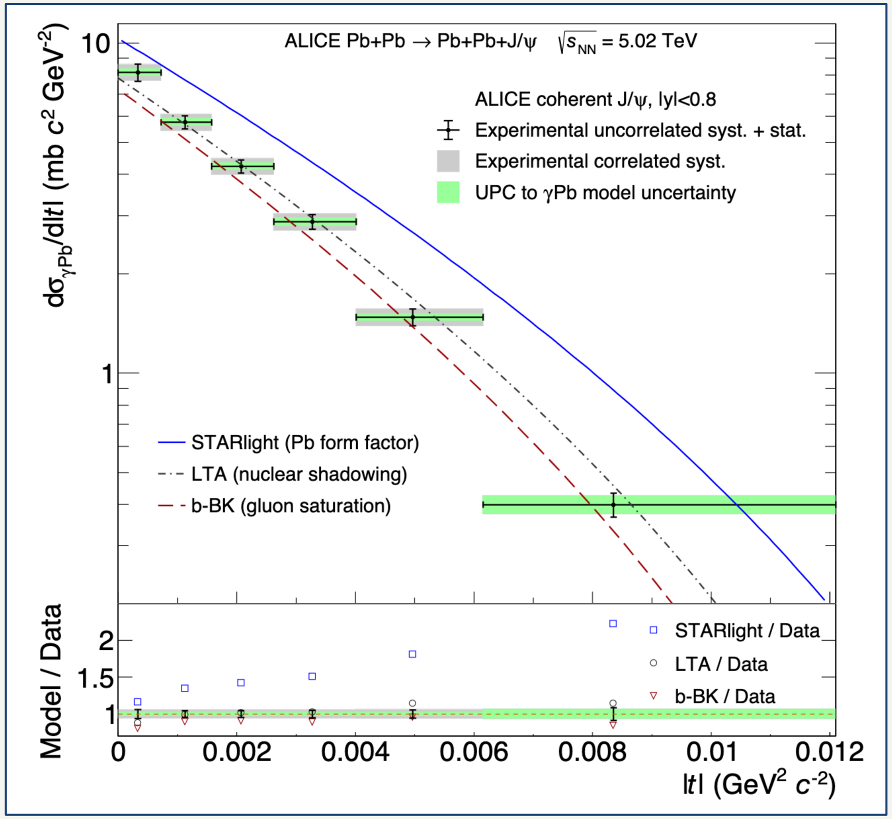
$d\sigma/dt \sim \exp(-bt)$ with $b \sim 6$ GeV^{-2} in pp collisions and ~ 400 GeV^{-2} in PbPb. (F.T. of ip)

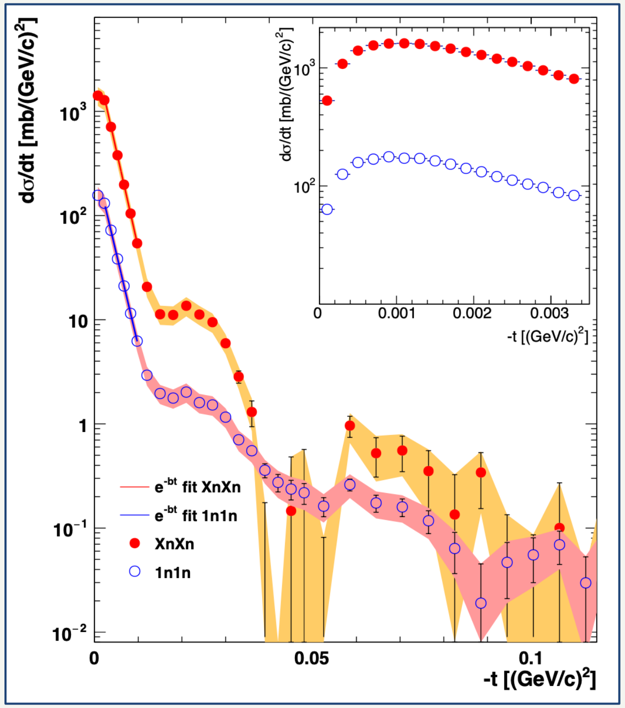
$\langle p_T \rangle$ in pp and pA is ~0.5 GeV = $1/R_p$
$\langle p_T \rangle$ in AA. ~0.05 GeV ~ $1/R_A$



First measurements in UPC

ρ

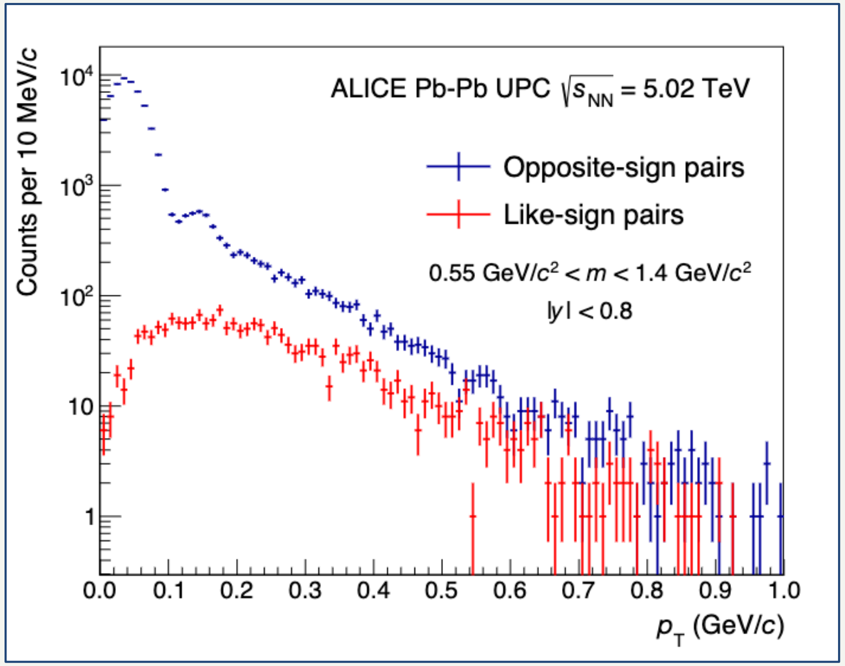




Phys.Rev. C96 (2017) 054904

Phys.Lett.B 817 (2021) 136280

see WG2 talk by David Grund



JHEP 06 (2020) 035

Incoherent scatters also interesting

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

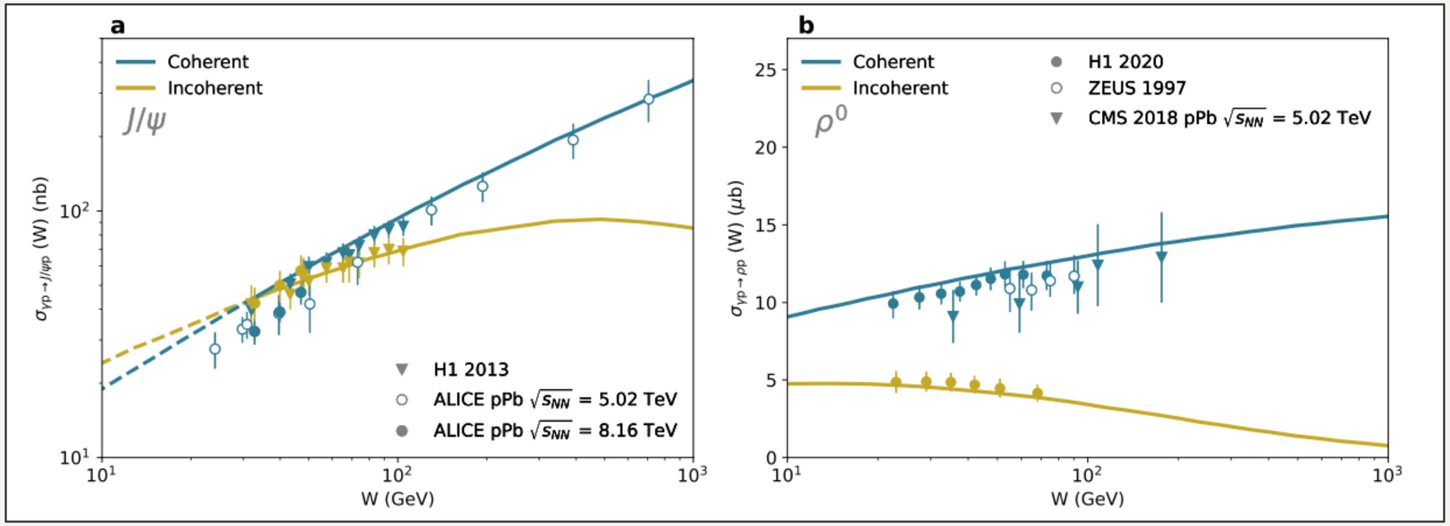
$$\frac{\mathrm{d}\sigma^{\gamma^* p \to J/\Psi p}}{\mathrm{d}t} = \frac{1}{16\pi} \left| \langle A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \rangle \right|^2$$

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

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

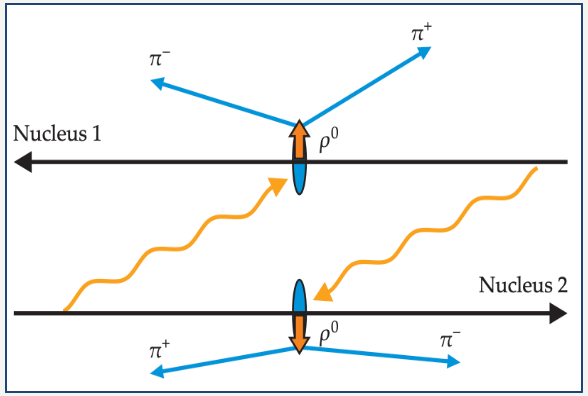
- Original model based on gluonic fluctuations around three hot-spots (valence quarks)
- Hot-spot evolution model (see WG2 talk by Tobias Toll)
- Energy-dependent hot-spots (J. Cepila, J. G. Contreras, J. D. Tapia Takaki Phys. Lett. B766 (2017) 186–191)
- The onset of saturation? (J. Cepilaa, J. G. Contrerasa, M. Matasa, A. Ridzikova, arXiv:2313.11320)

NEW!

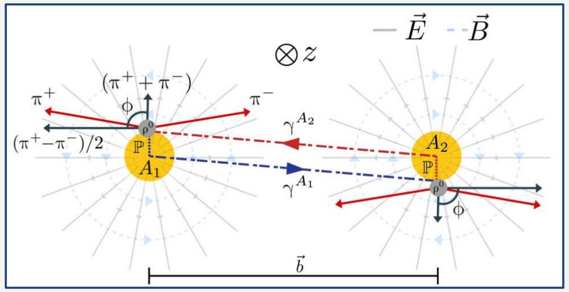


see WG2 talk by Alexandra Ridzikova

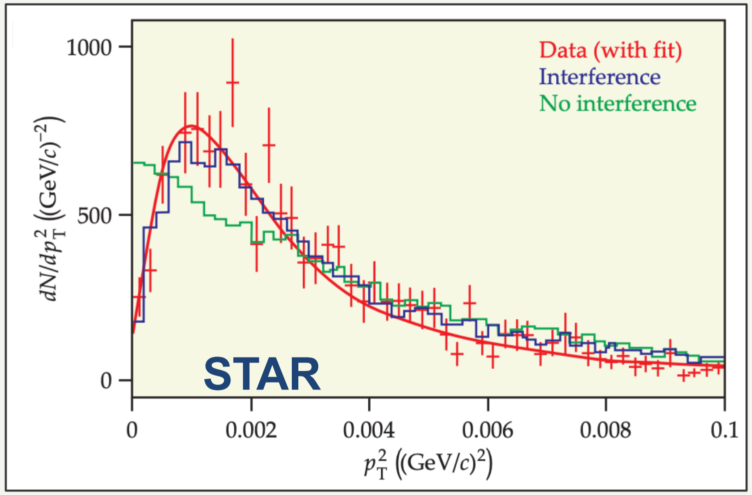
The two-fold photon ambiguity...



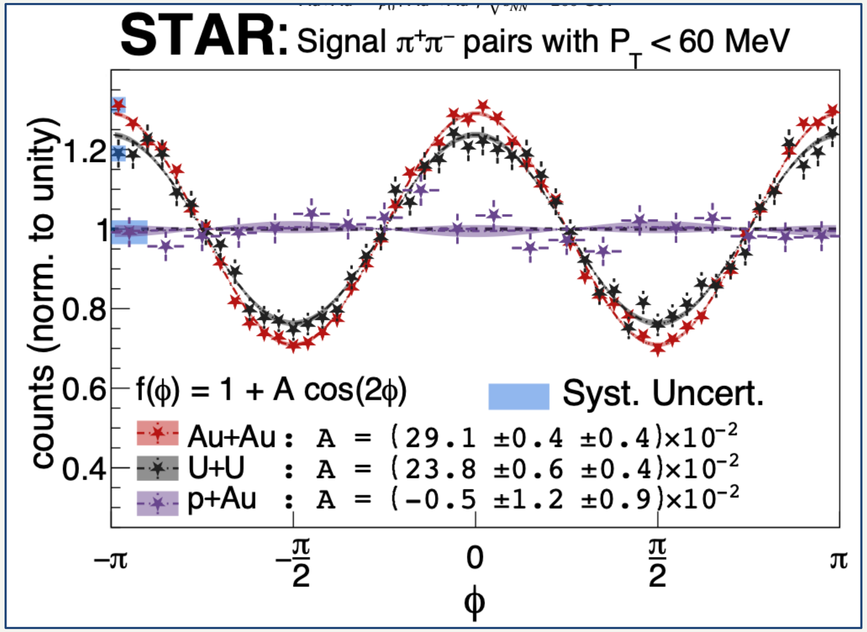
S. Klein, J. Nystrand,
Physics Today 70, (2017) 40.

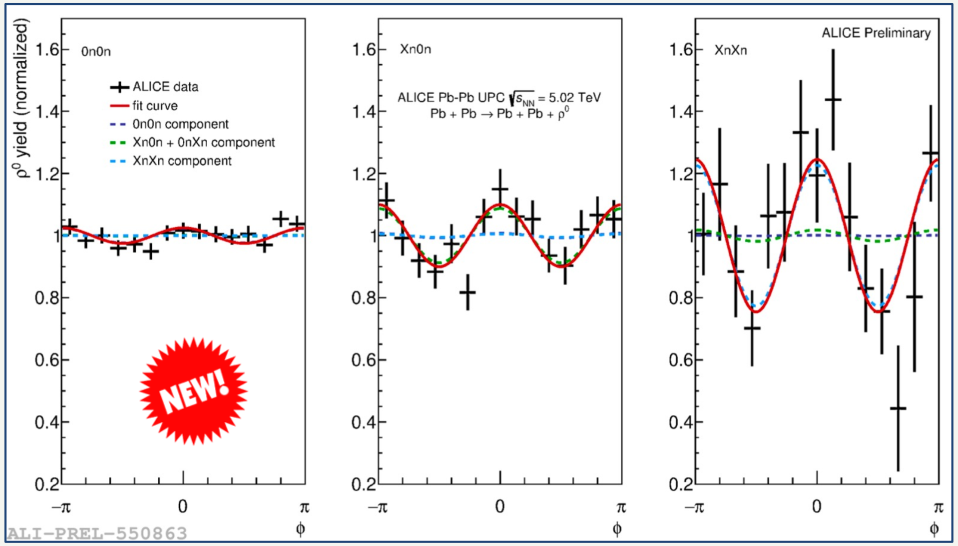


Sci.Adv. 9 (2023) eabq3903



Phys. Rev. Lett. 102, 112301 (2009)

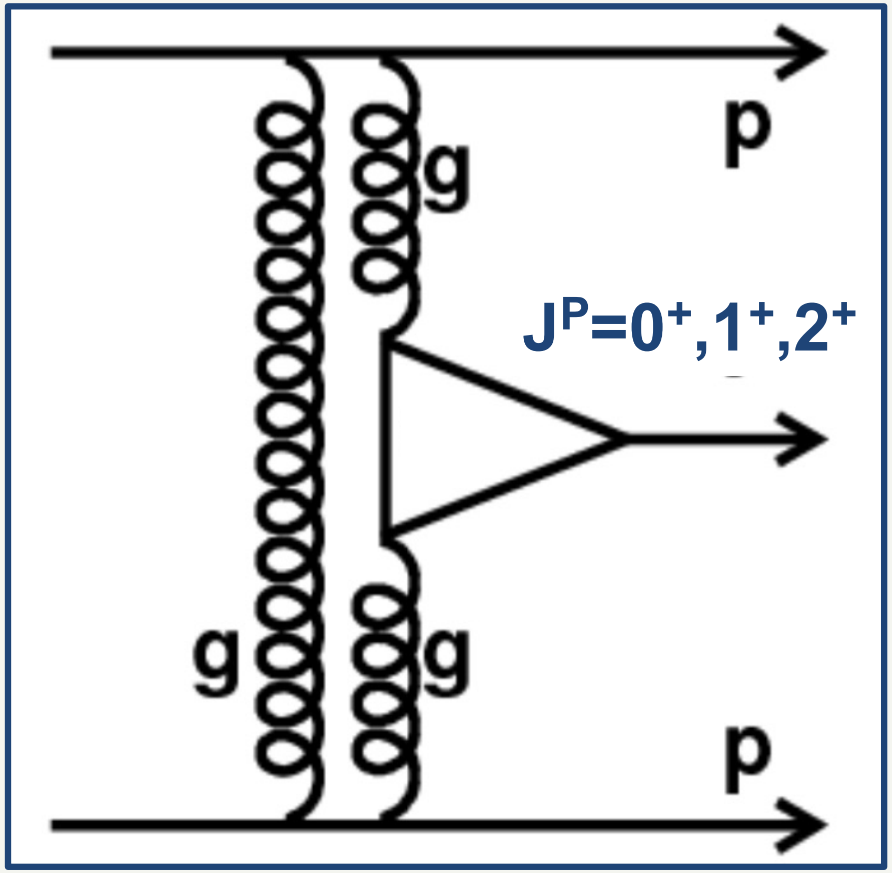




Sci.Adv. 9 (2023) eabq3903

see Andrea Riffero talk WG2.

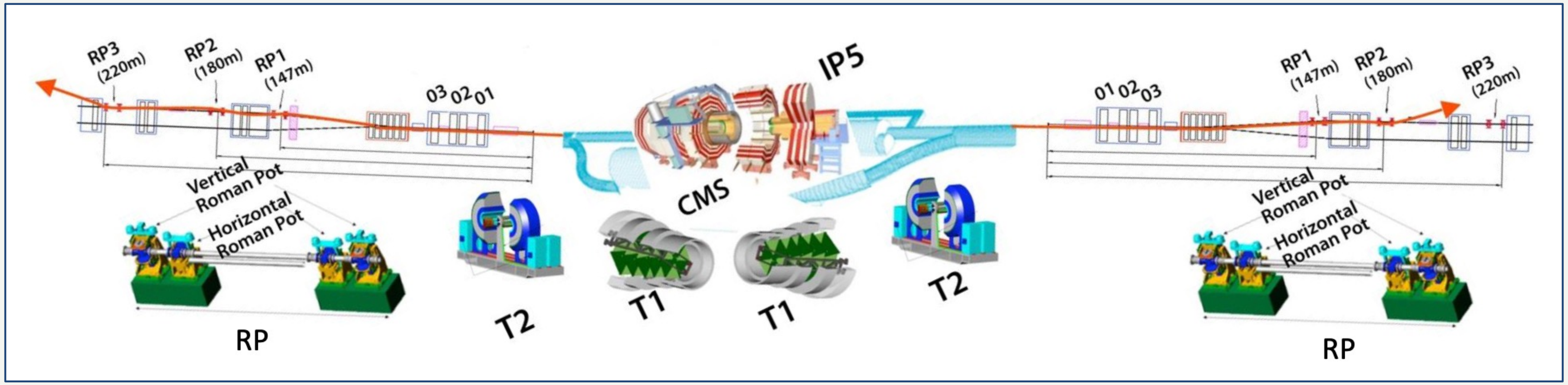
Double Pomeron Exchange



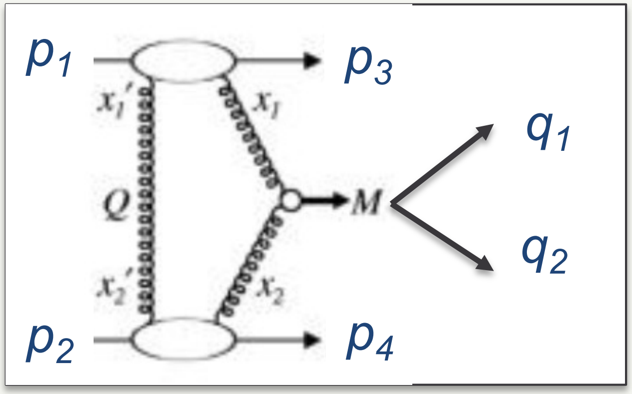
Understanding colourless strong interactions is fundamental

Also simple environment for spectroscopy, in particular, glueballs

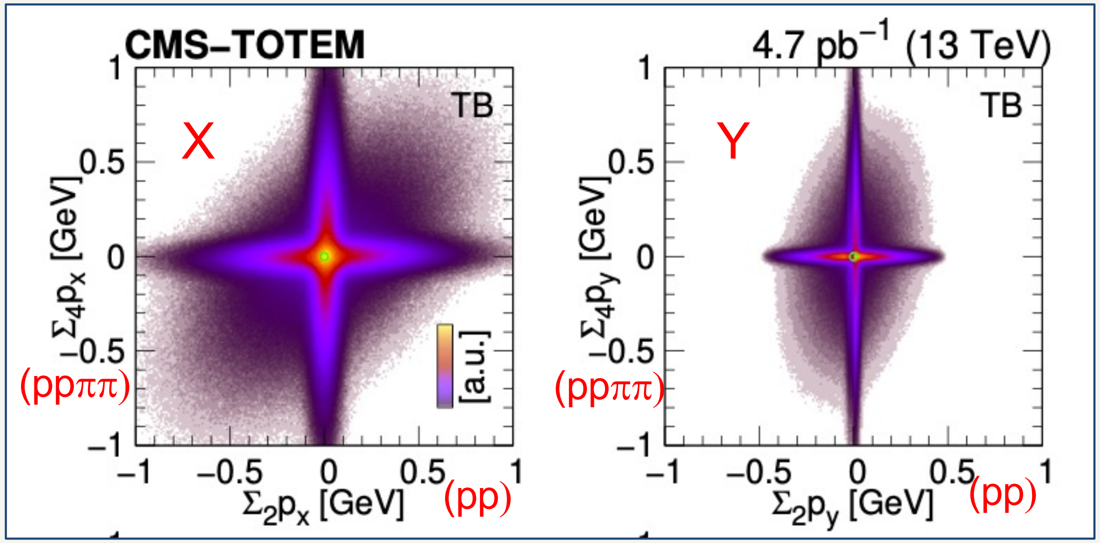
CMS-TOTEM: Simultaneous reconstruction of central system and protons



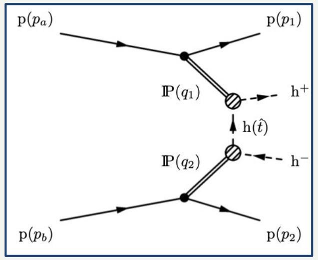
arXiv:2401.14494

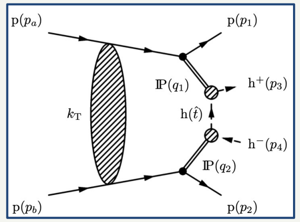


$$M^2 = (q_1^\mu + q_2^\mu)^2 = (p_1^\mu + p_2^\mu - p_3^\mu - p_4^\mu)^2$$

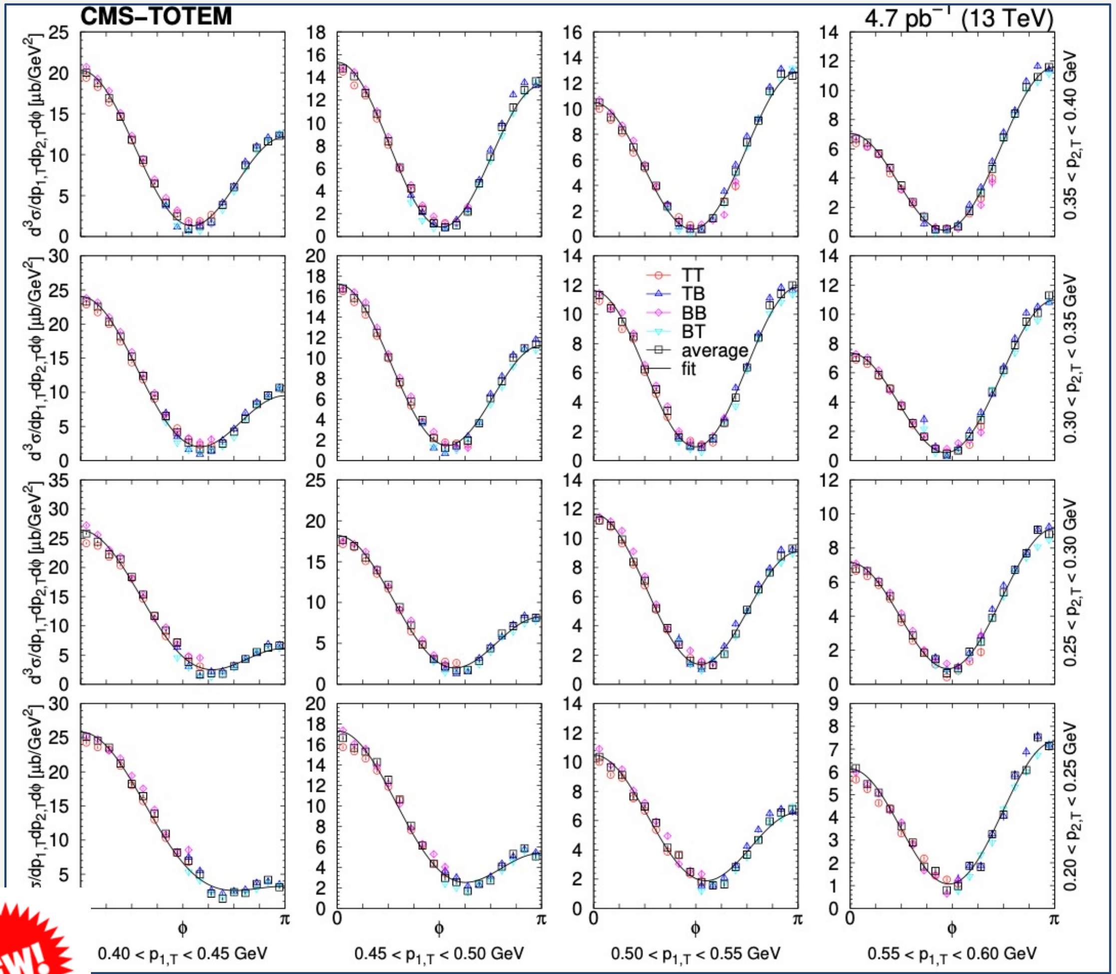


Precision determination of pomerons interactions



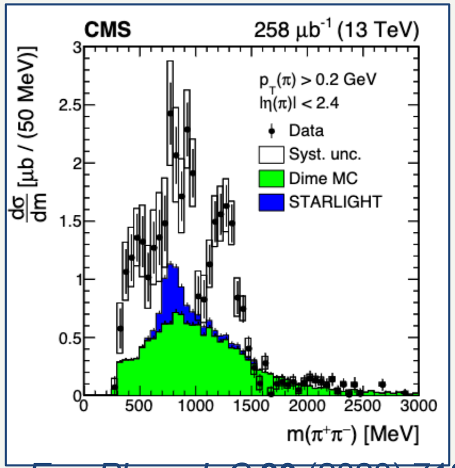


arXiv:2401.14494



Shape distinctive of interference due to additional pomeron interactions

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



Eur. Phys. J. C **80** (2020) 718

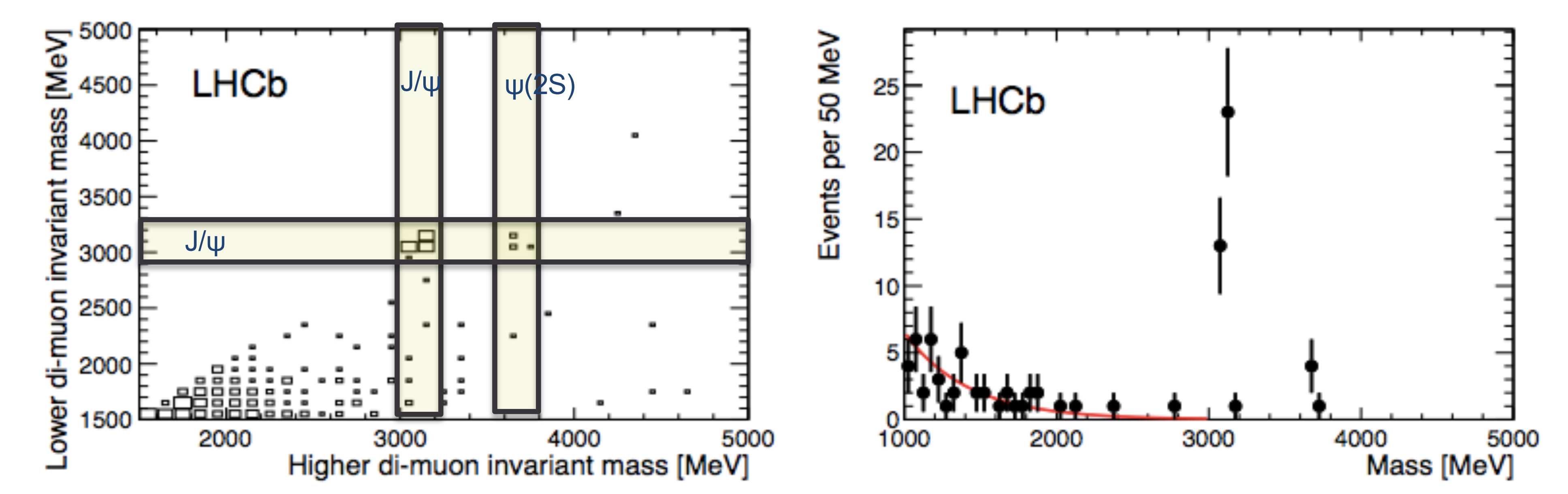
Eagerly await compelling spectroscopy of the complicated resonance region:
- photoproduced ρ, ω, ρ', ρ''
- DPE f0,f2, , glueball candidates

see Michael Pitt talk WG2.

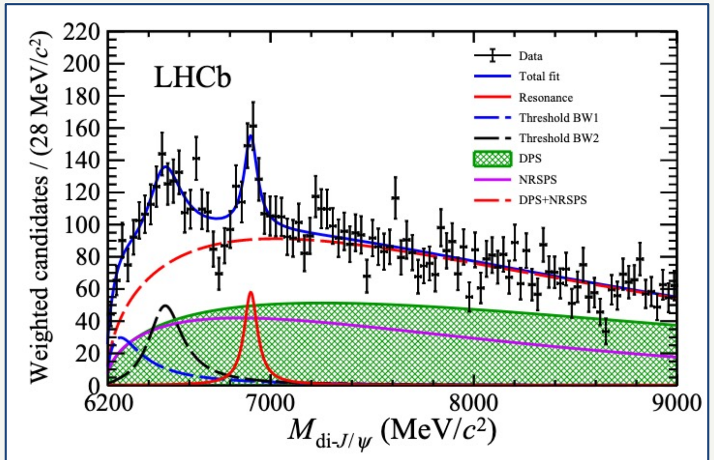
J/ψJ/ψ: search for exotica

$$
\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst})\,\text{pb},\\
\sigma^{J/\psi\,\psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\,\text{pb},\\
\sigma^{\psi(2S)\psi(2S)} &< 237\,\text{pb},\\
\sigma^{\chi_{c0}\chi_{c0}} &< 69\,\text{nb},\\
\sigma^{\chi_{c1}\chi_{c1}} &< 45\,\text{pb},\\
\sigma^{\chi_{c2}\chi_{c2}} &< 141\,\text{pb},
\end{aligned}
$$

JPG 41 (2014) 115002



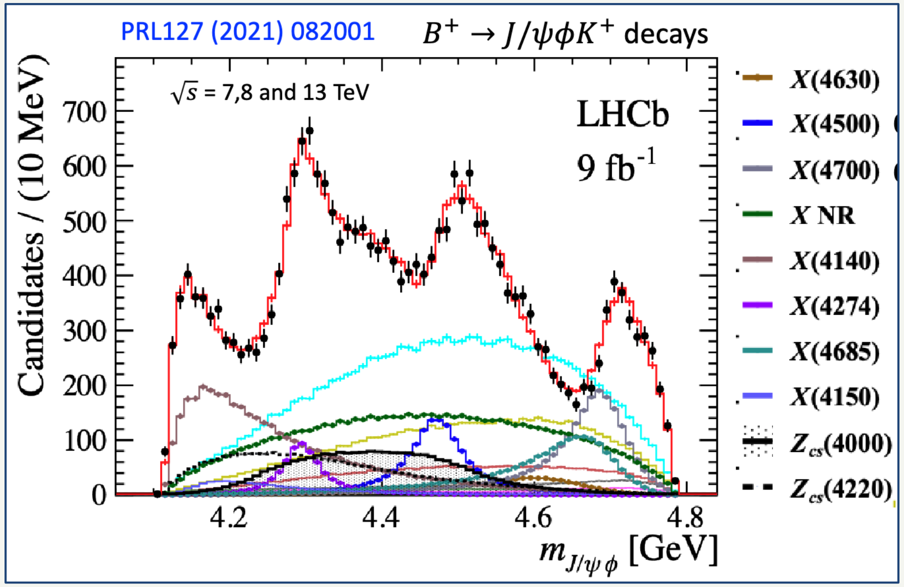
Sci.Bull. 65 (2020) 23, 1983-1993



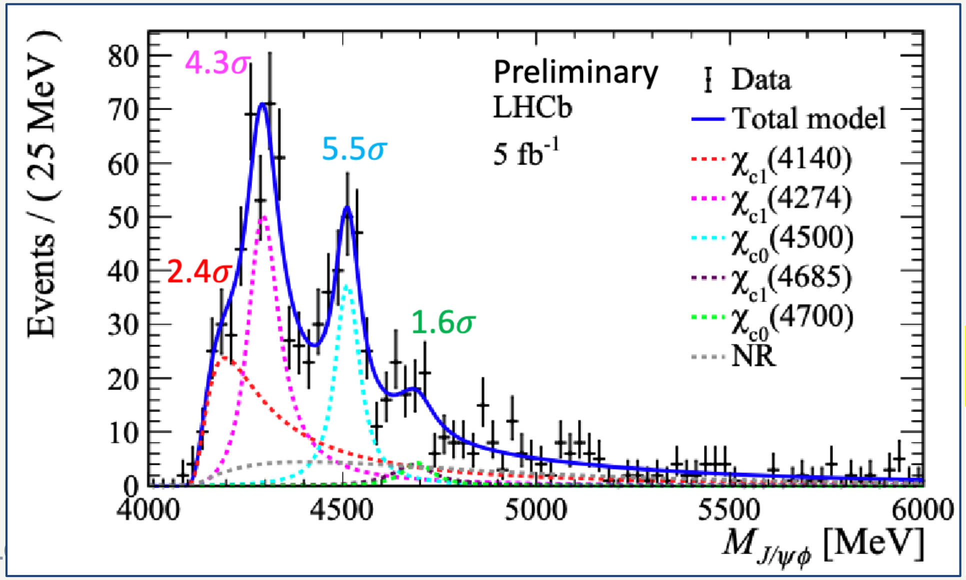
Today from inclusive measurements we know there is significant structure and tetraquark candidates

Diffractive measurements are cleaner and help identify quantum numbers

J/ψ+φ: search for exotica



Structure seen in Inclusive production of J/ψ+φ .

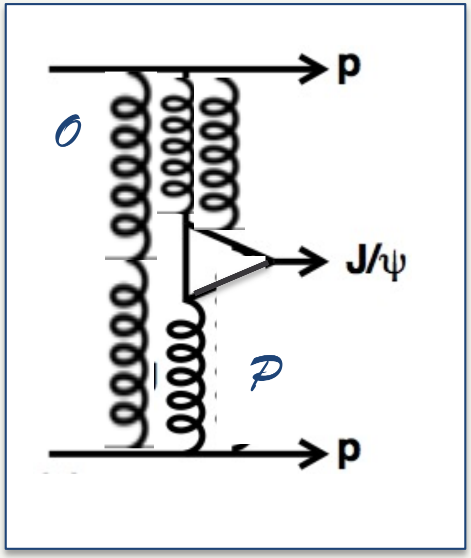


Similar and much cleaner structure now seen exclusively.

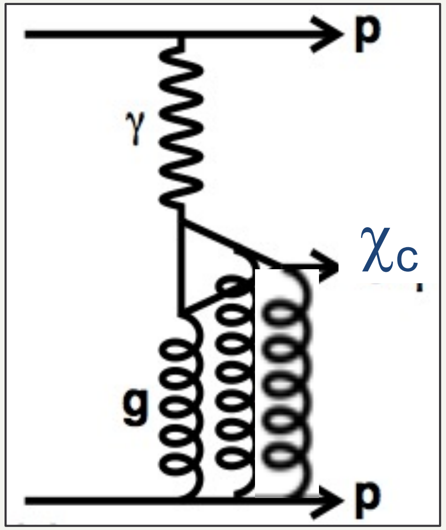
see Cesar da Silva talk WG2.

NEW!

Odderon search: partner of pomeron



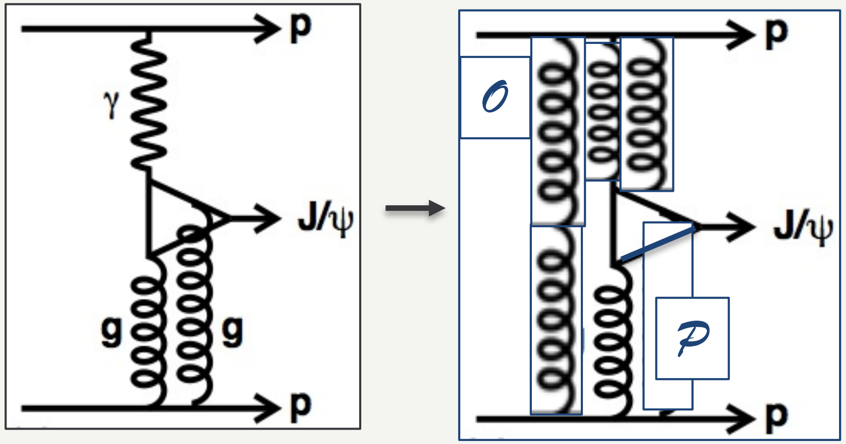
C-odd
meson

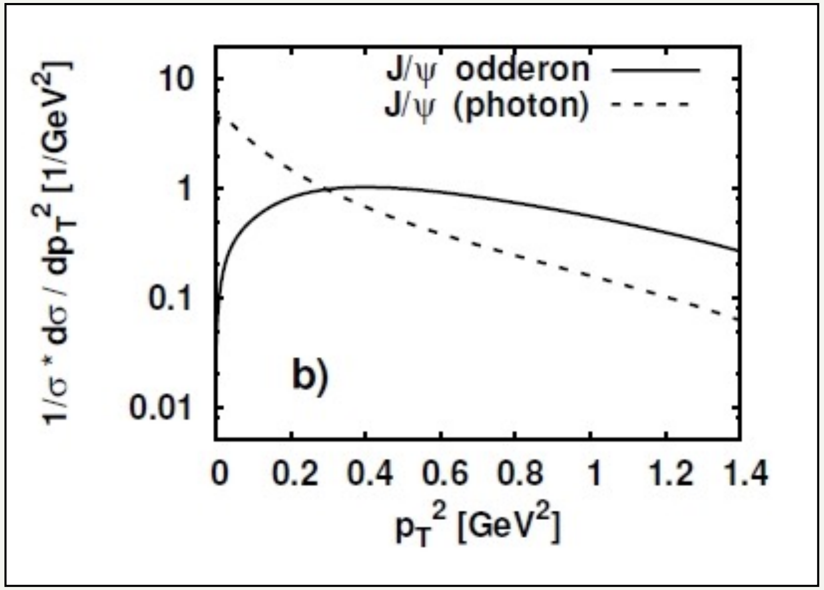


C-even
meson

Method 1: High p_T exclusive C- production

Replace γ with $\mathcal{O}$





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

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

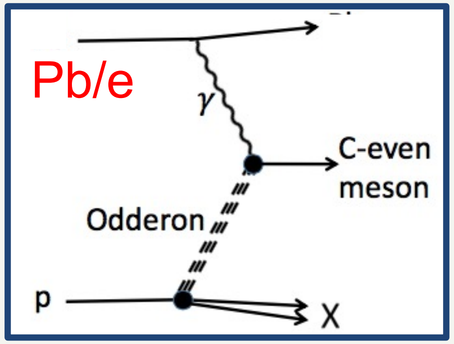
Photoproduction: b~6 GeV^{-2}
Proton dissociation b~1 GeV^{-2}
Odderon b small

$d\sigma^{corr}/dy$	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

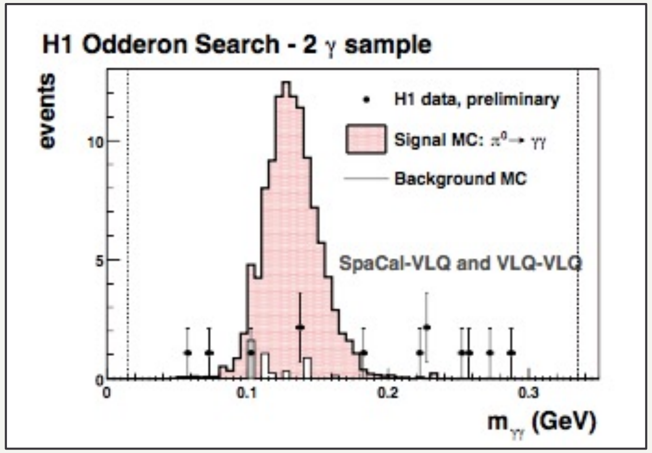
Angular distribution of muons due to polarisation may also differ (R. Schnicker)

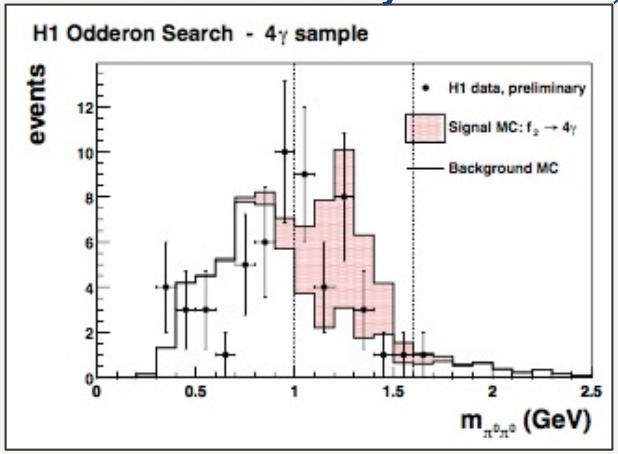
Method 2: Photoproduction of C+

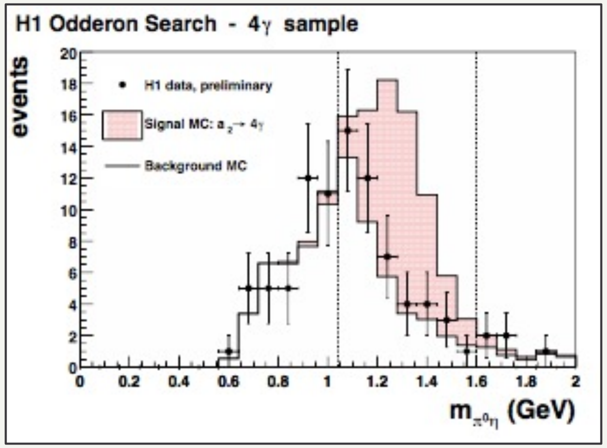


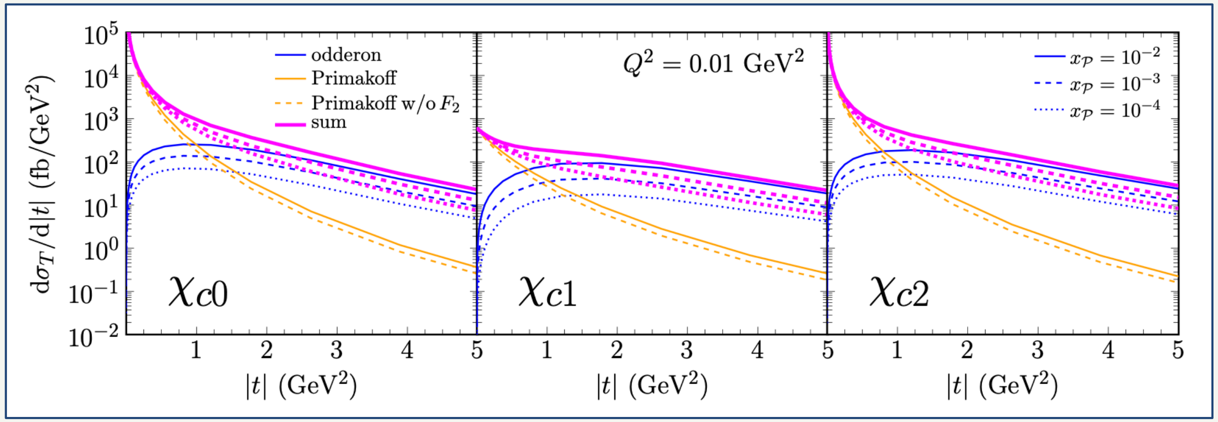
Czyzewski, Kwiecinski, Motyka, PLB398 (1997) 400.
Berger, Donnachie, Dosch, Kilian, Nachtmann, EPJ C9 (1999) 491.
Ryskin EPJ C2 (1998) 339.
Kilian & Nachtmann, EPJ C5 (1998) 317.
Harland-Lang, Khoze, Martin, Ryskin PRD 99 (2019) 3, 034011

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





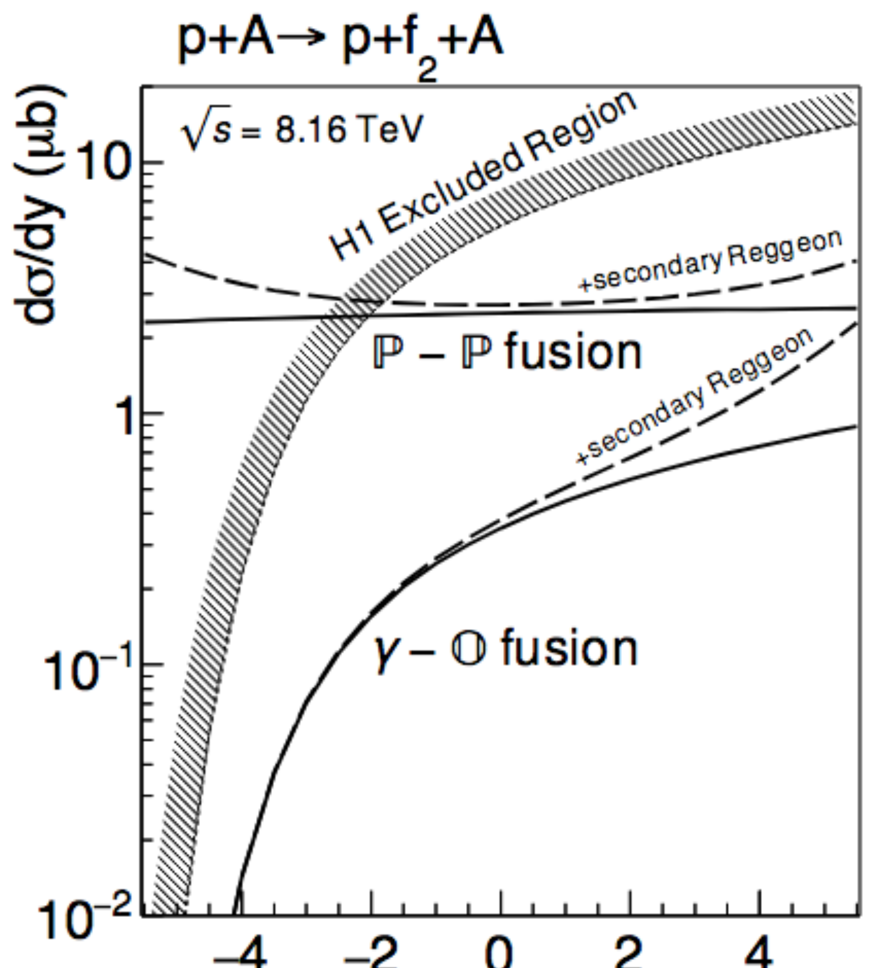




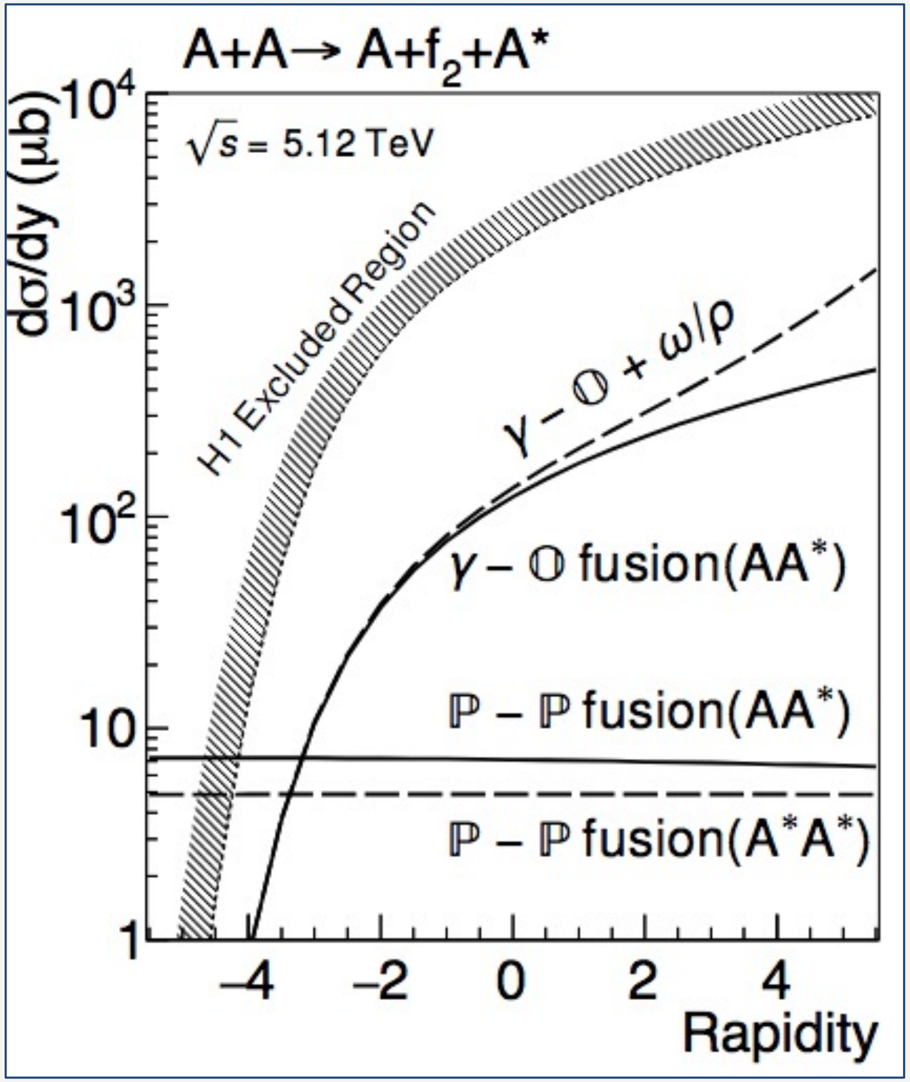
arXiv: 2402.19134

Talk by Sanjin Benić in WG2

Might be seen forward in p-Pb / PbPb



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



Summary

- Much to understand about QCD
  - perturbative / non-perturbative regime
  - proton and nuclear structure (PDFs GPDs)
  - saturation
  - quark model bound states (ρ, ρ’, f_0,$f_{2....}$)
  - beyond the naïve quark model (hybrids, tetraquarks, glueballs)
  - colourless propagators: pomerons and odderons

- Can be addressed in diffractive processes.