Experimental results on exclusive, diffractive and diffractive dissociative quarkonium production at the LHC

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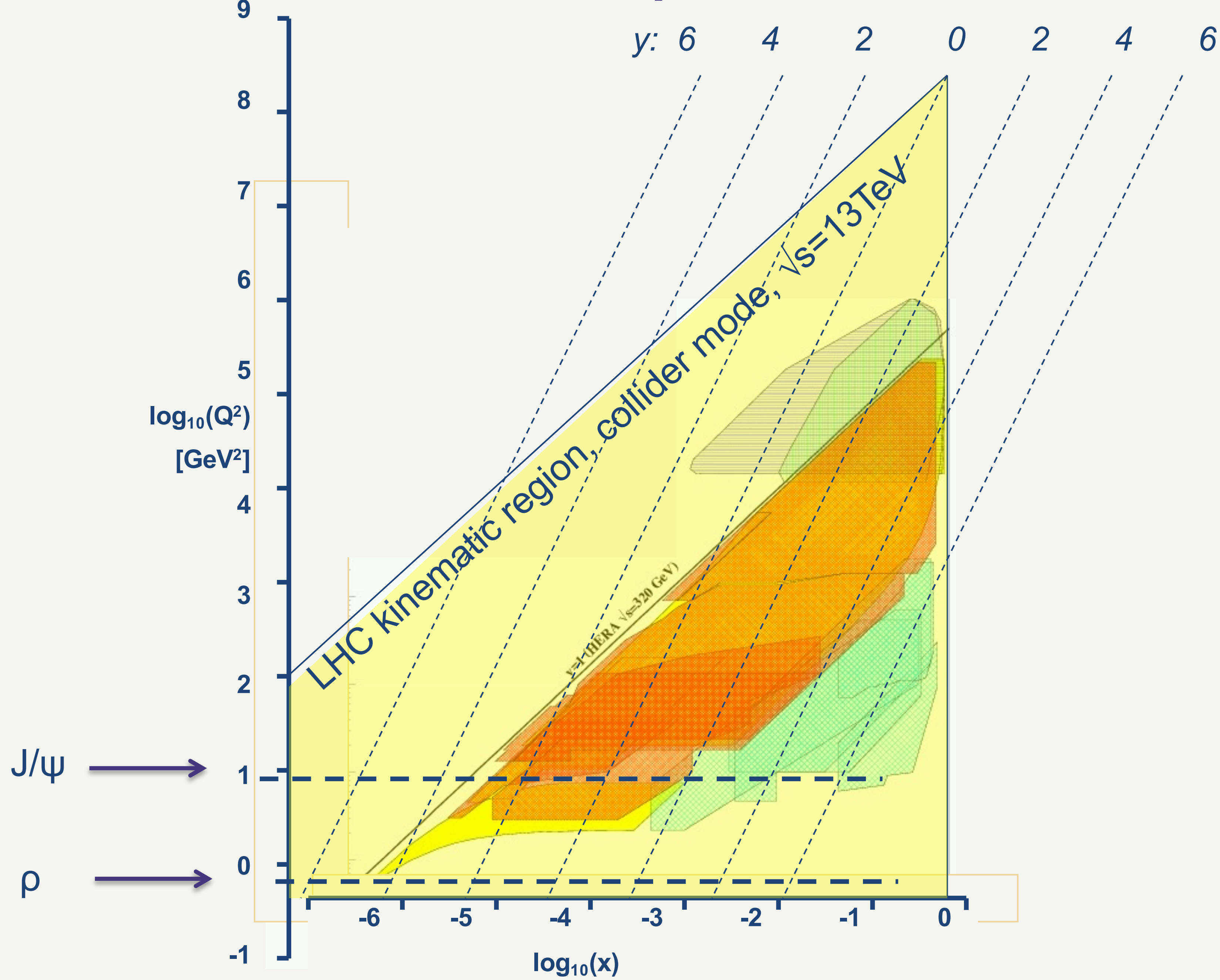
Synergies between LHC and EIC for quarkonium physics
EIC*, Trento, July 8-12 2024

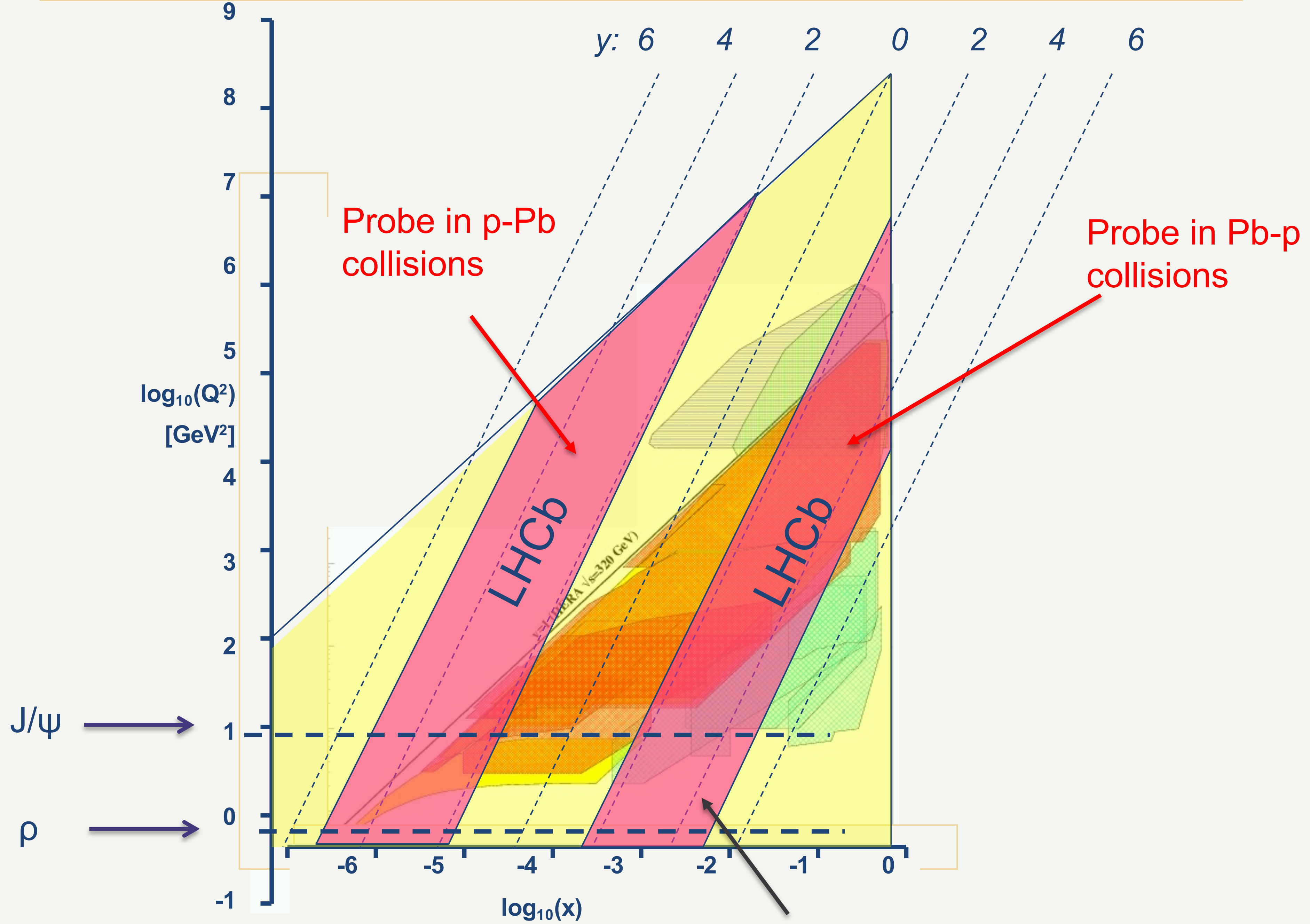
This workshop is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 824093.

x-Q² values probed at LHC



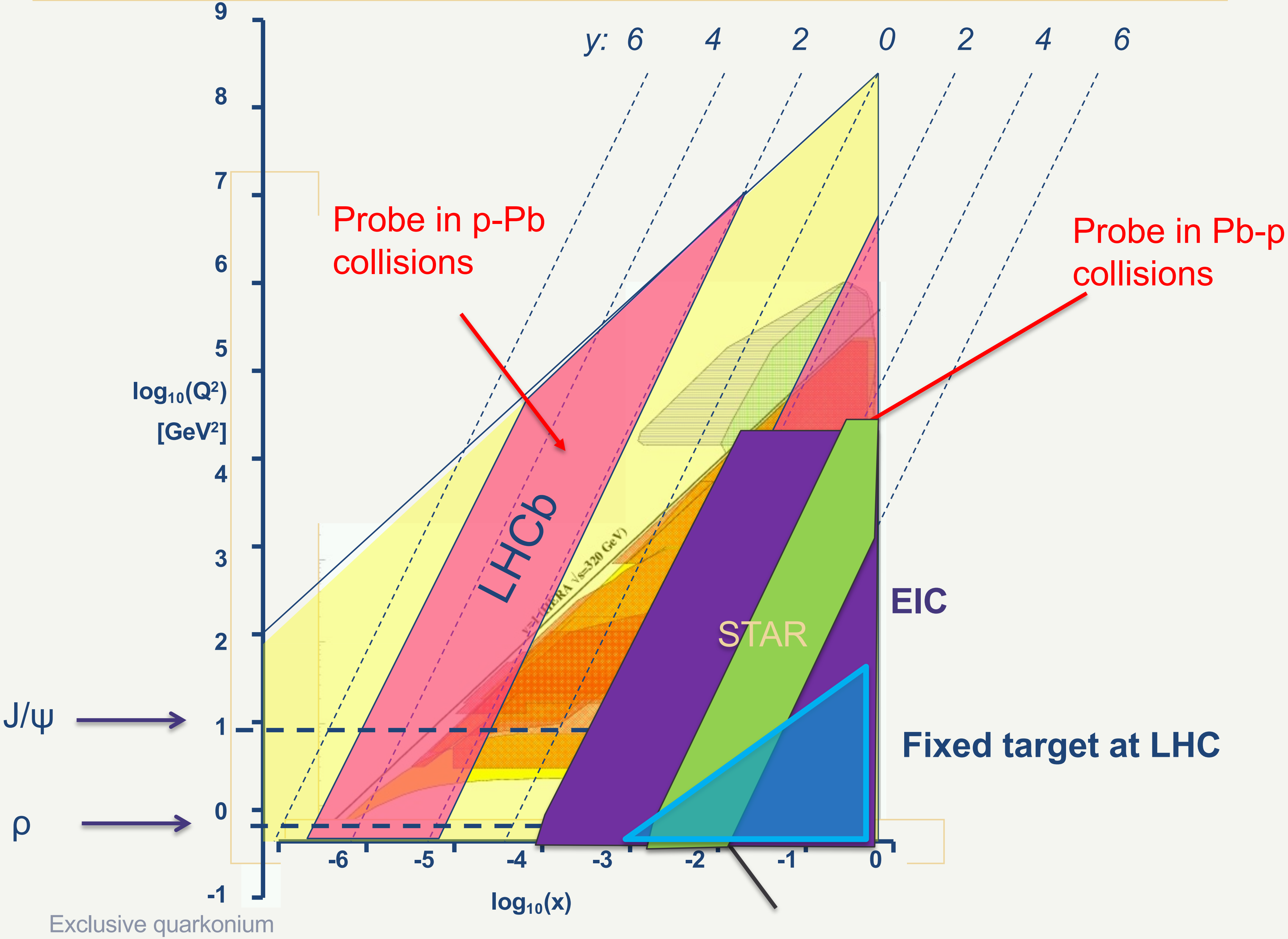
Exclusive quarkonium

Low-x & Forward physics



Exclusive quarkonium

Low-x & Forward physics

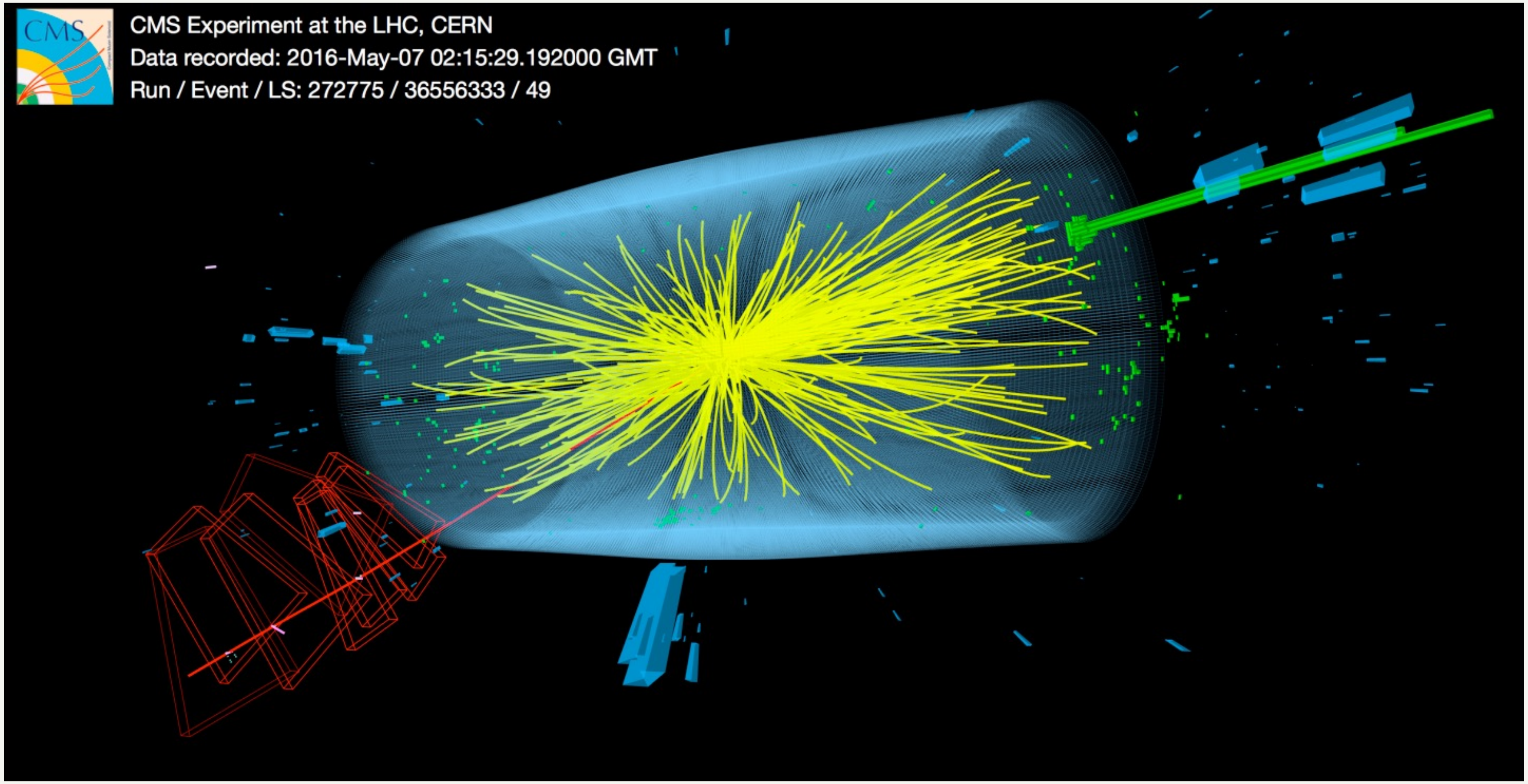


Motivation

- Much to understand about QCD
  - perturbative / non-perturbative regime
  - proton and nuclear structure (PDFs GPDs)
  - hot spots
  - saturation
  - quark model bound states (η_c, J/ψ, χ_c)
  - beyond the naïve quark model (hybrids, tetraquarks, glueballs)

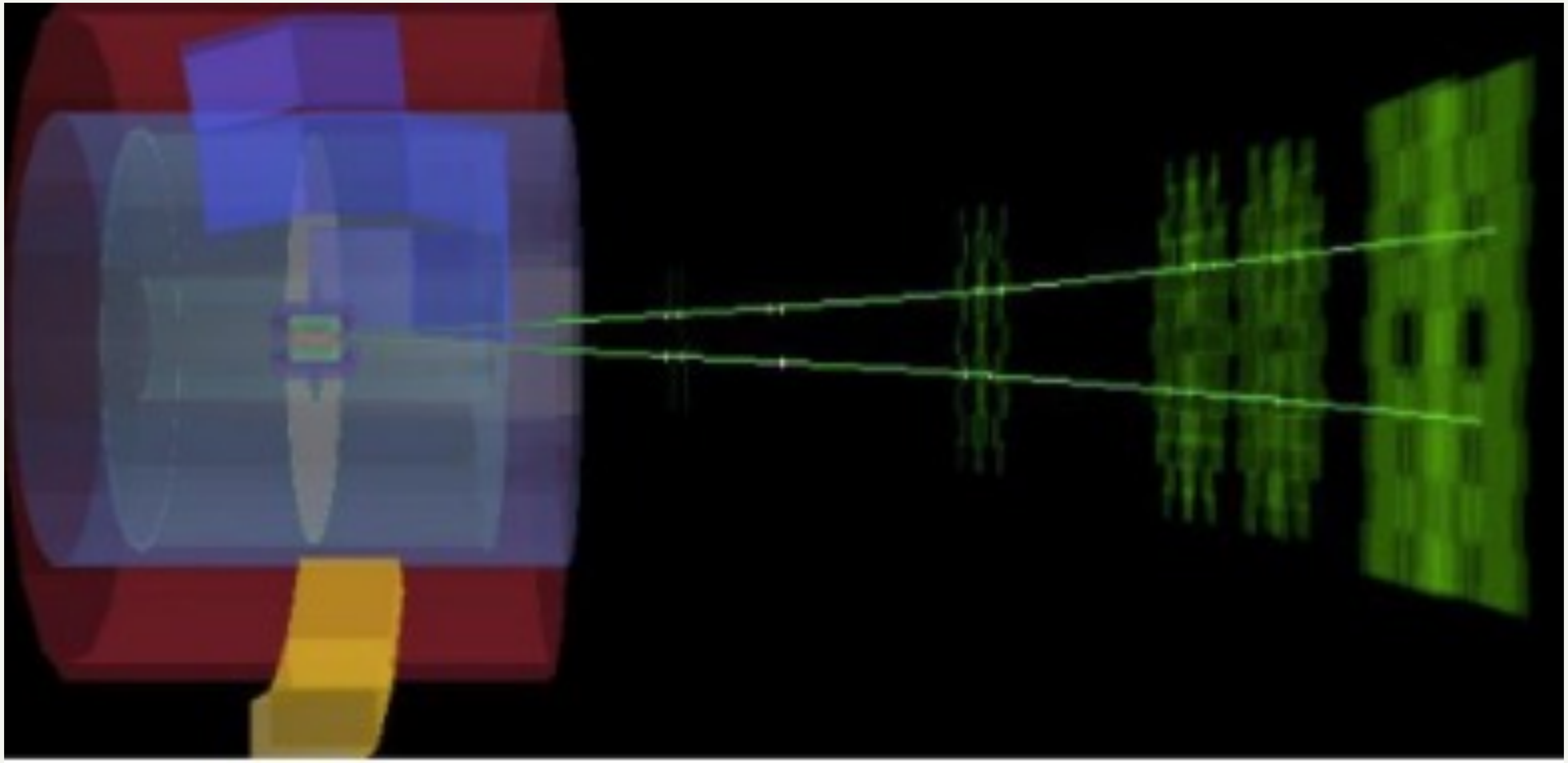
- Can be addressed in diffractive DIS.

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**.

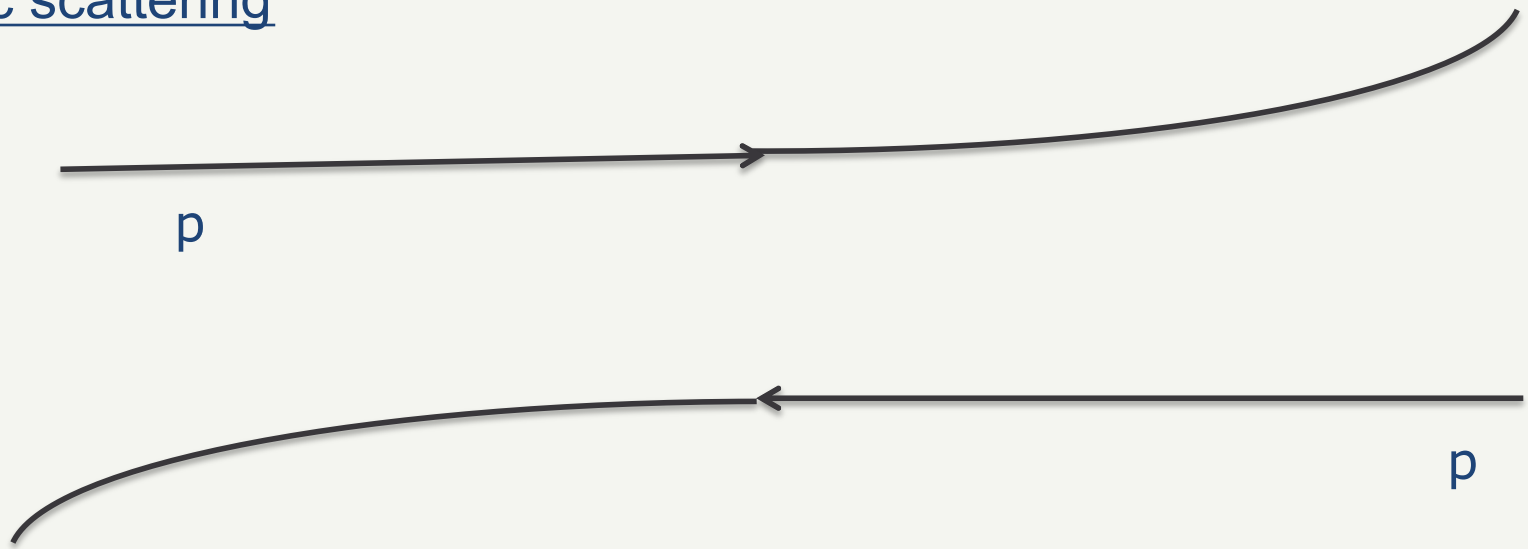
UPC J/ψ at forward rapidity in ALICE PbPb data



(from Evgeny Kryshen talk at INT workshop)

Physics of the Vacuum

Elastic scattering

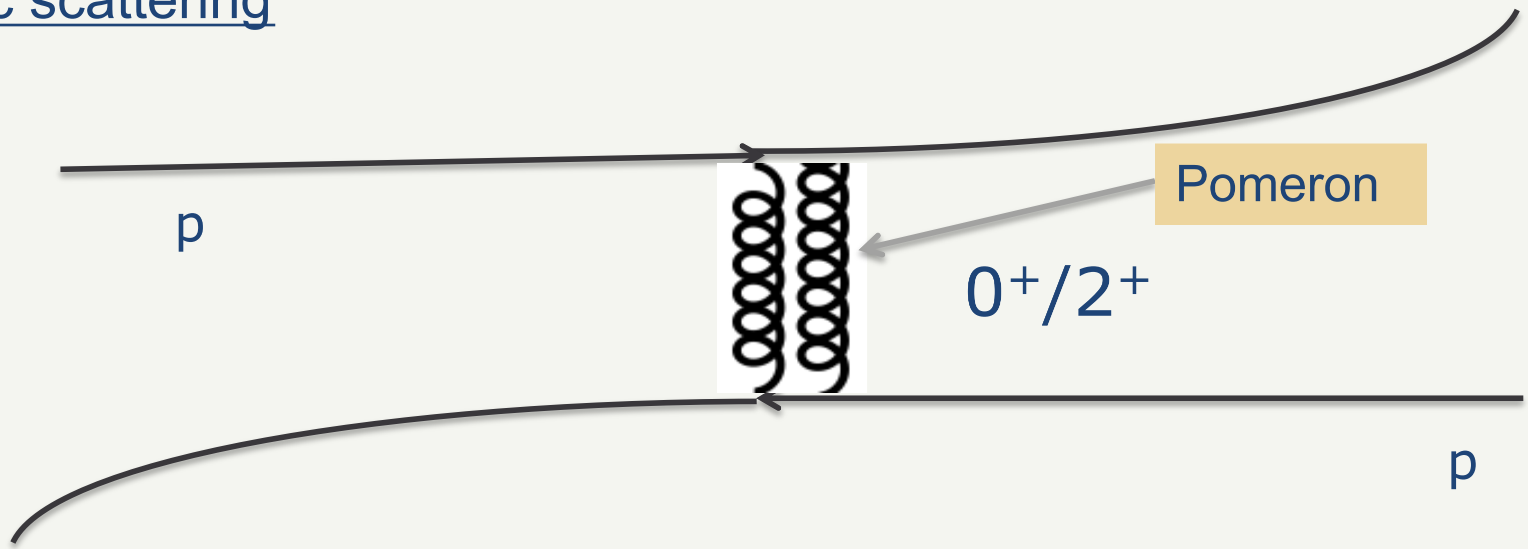


It's QCD – but not as we normally see it. It's colour-free

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

Physics of the Vacuum

Elastic scattering



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Physics of the Vacuum

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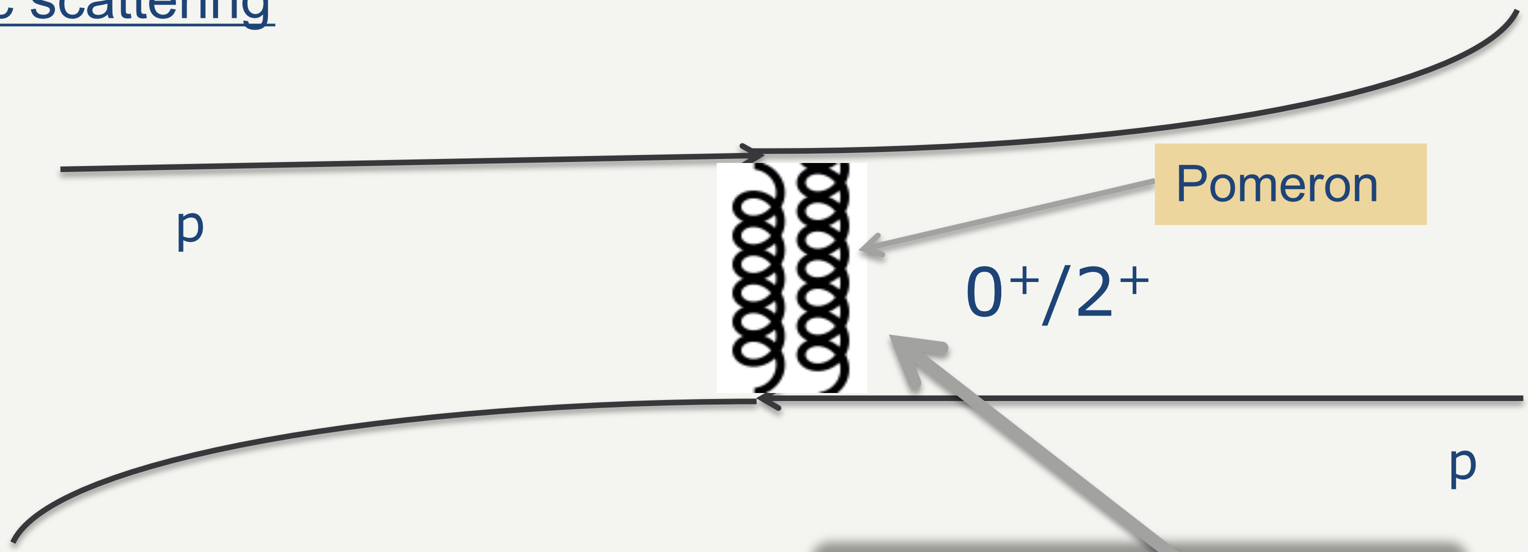
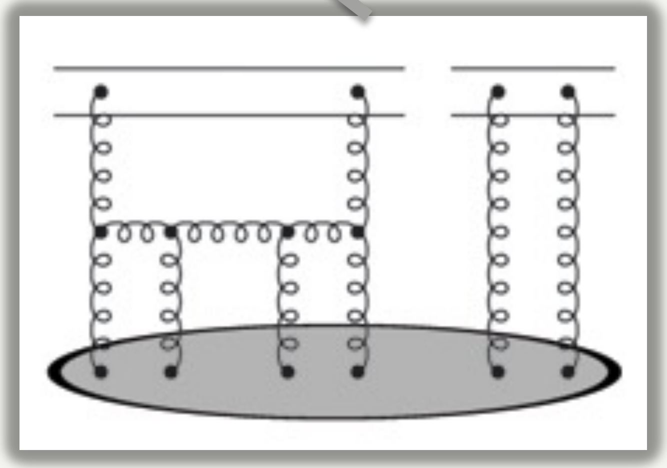


At high energy: $A(s,t)=s^{\alpha(t)}$
$\alpha_P(t)=\alpha_P(0)+\alpha' t$



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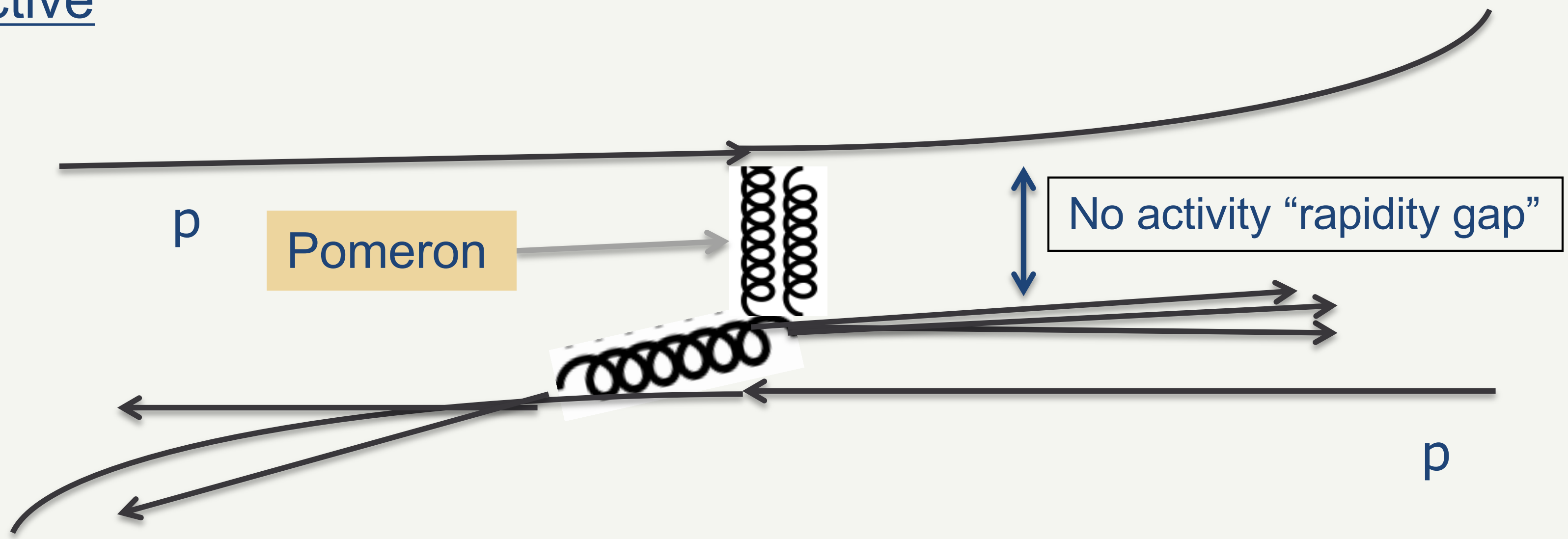
Physics of the Vacuum

Diffractive



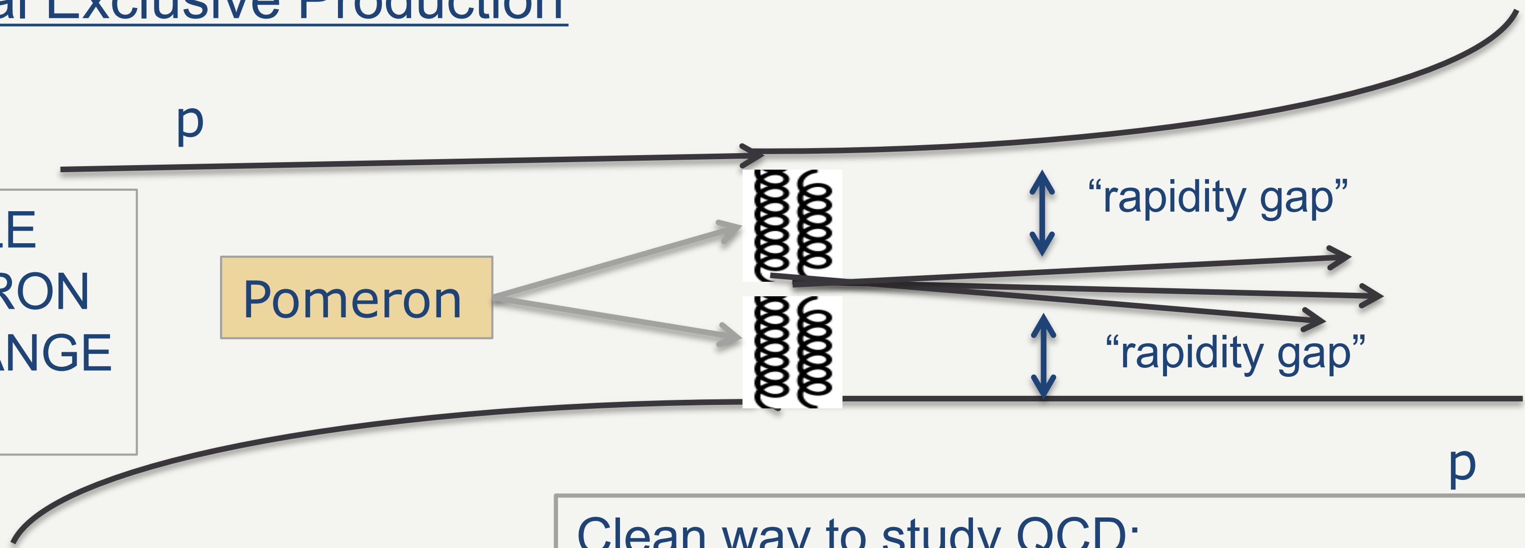
Experimental working definition of diffraction is presence of rapidity gap

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

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

$\sigma_{elastic}$ ≈ 40mb

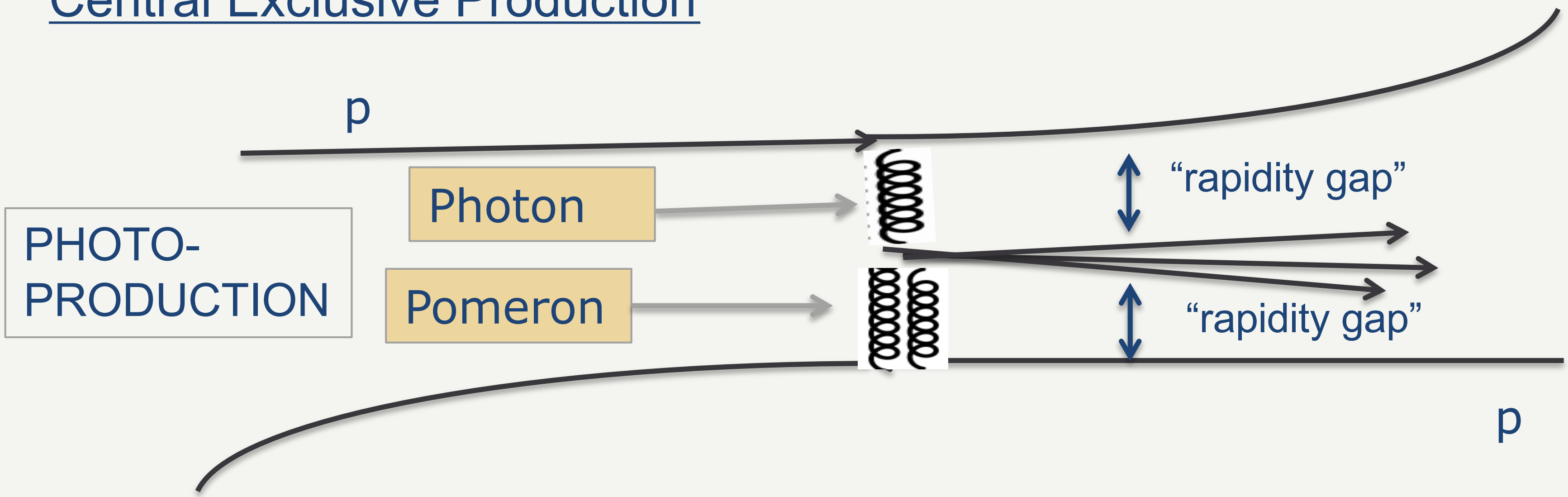
$\sigma_{diffractive}$ ≈ 10mb

$\sigma_{inelastic}$ ≈ 60mb

100 μb

Physics of the Vacuum

Central Exclusive Production



$\sigma_{elastic}$ ≈ 40mb

$\sigma_{diffractive}$ ≈ 10mb

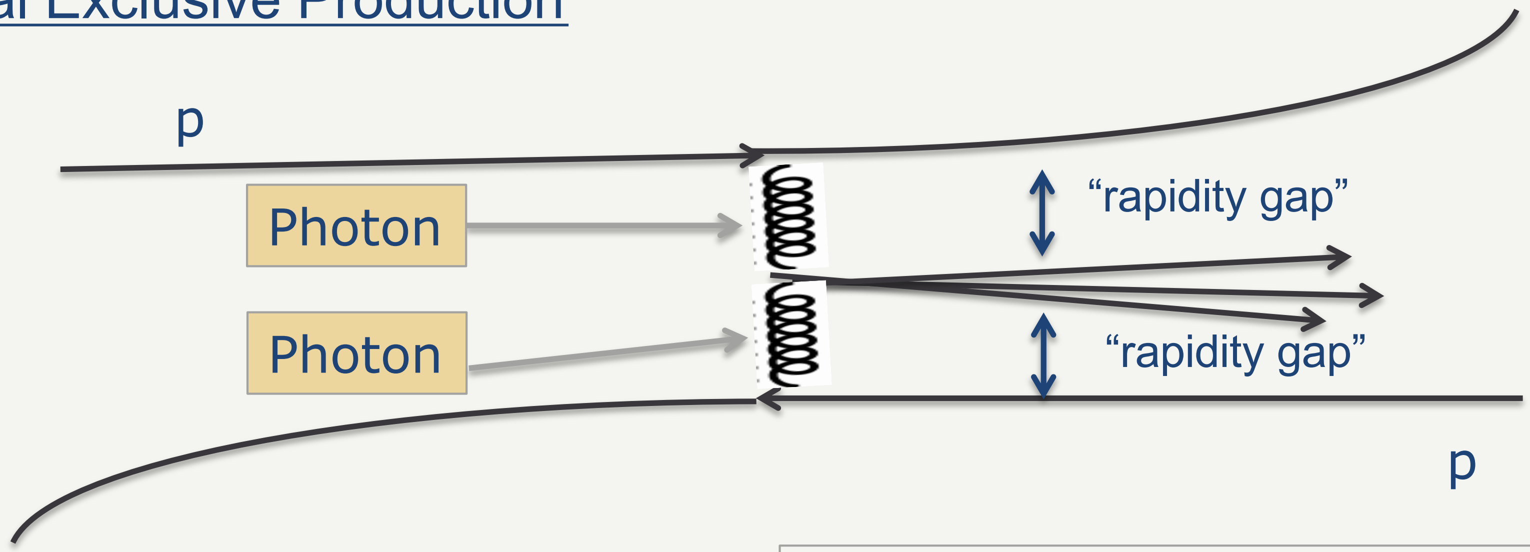
$\sigma_{inelastic}$ ≈ 60mb

100 μb

Physics of the Vacuum

Central Exclusive Production

QED



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

Detect as large a gap as possible...

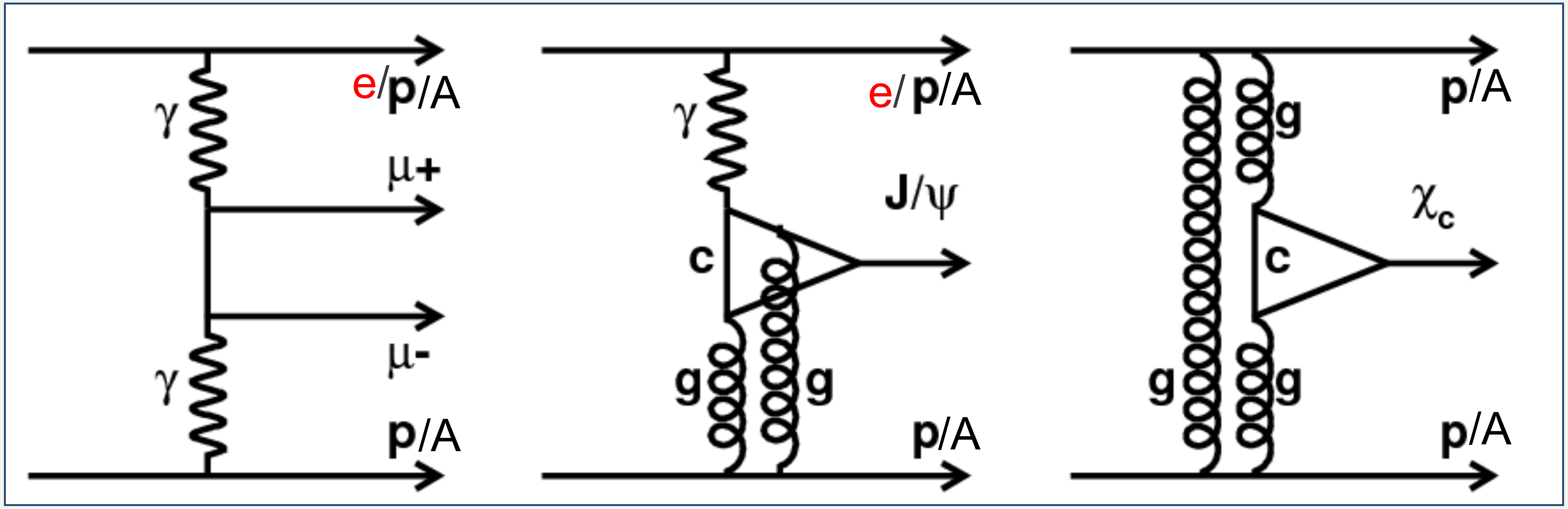
$\sigma_{elastic}$ ≈ 40mb

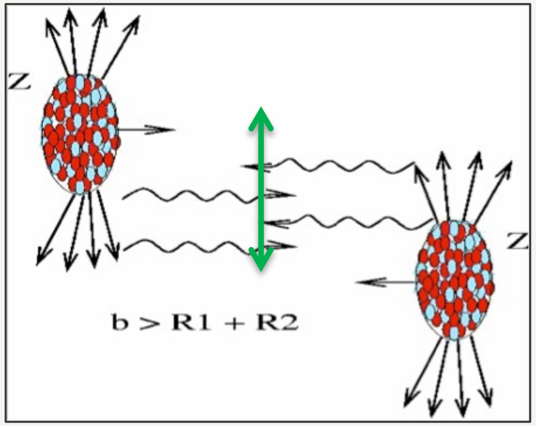
$\sigma_{diffractive}$ ≈ 10mb

$\sigma_{inelastic}$ ≈ 60mb

100 pb

Colourless propagators





Exclusive quarkonium

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

Large impact parameter ↔ Small p_T

<u>Electron-hadron collider:</u>
~70% of total cross-section is diffractive

$\gamma\mathcal{P}$ & $\mathcal{PP}$ measurements at LHC

- LHCb
  - J/ψ pp 7 TeV, *J.Phys.G* 41 (2014) 055002
  - J/ψ pp 13 TeV, *JHEP* 10 (2018) 167
  - J/ψ PbPb 5 TeV, *JHEP* 06 (2023) 146
  - Ψ pp 7 TeV, JHEP 09 (2015) 084
  - J/ψ J/ψ pp J.Phys.G 41 (2014) 11, 115002

- ALICE
  - ρ PbPb 5.02 TeV, *JHEP* 06 (2020) 035
  - J/ψ pPb 5.02 TeV, *Phys.Rev.Lett.* 113 (2014) 23, 232504, *Eur.Phys.J.C* 79 (2019) 5, 402
  - J/ψ PbPb 2.76 TeV, *Phys.Lett.B* 718 (2013) 1273-1283
  - J/ψ PbPb 5.02 TeV, *Phys.Lett.B* 798 (2019) 134926 , *Eur. Phys. J. C 81 (2021) 712, Phys.Lett.B* 817 (2021) 136280, *JHEP* 10 (2023) 119

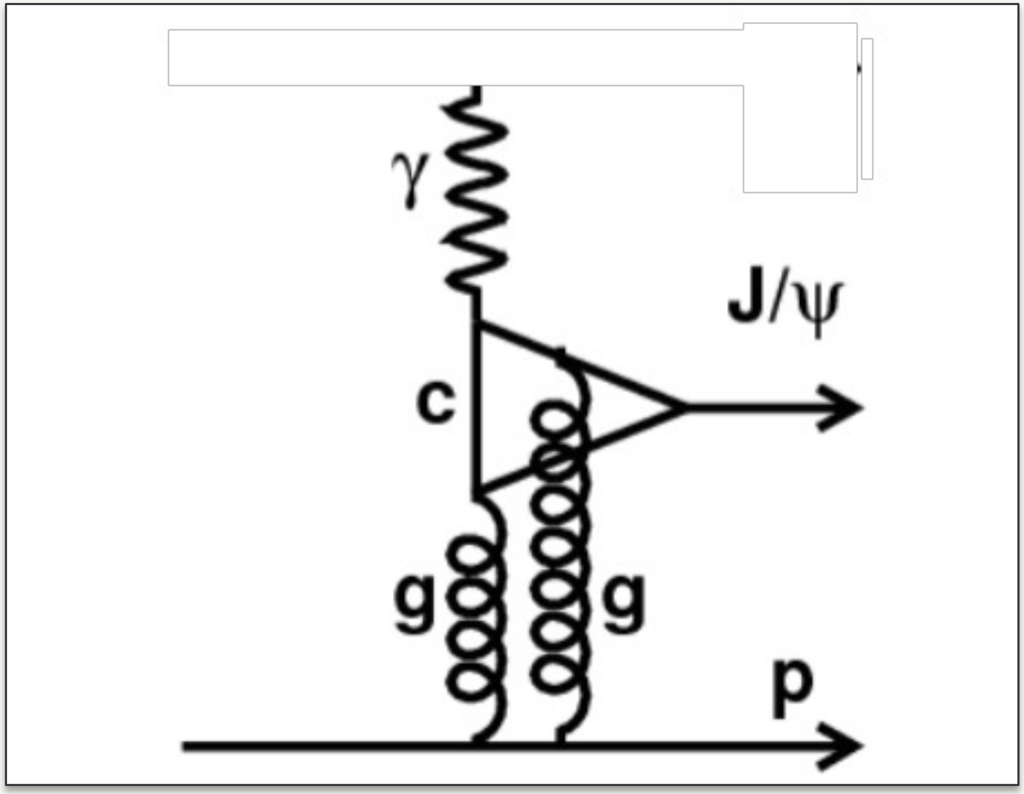
- CMS (+ TOTEM)
  - ρ pPb 5.02 TeV, *Eur.Phys.J.C* 79 (2019) 8, 702
  - J/ψ PbPb 2.76 TeV , *Phys.Lett.B* 772 (2017) 489-511
  - J/ψ PbPb 5.02 TeV, arXiv: 2303.16984
  - Ψ pPb 5.02 TeV Eur.Phys.J.C 79 (2019) 3, 277, Eur.Phys.J.C 82 (2022) 4, 343 (erratum)
  - $\pi\pi$ pp 5,02 and 13 TeV, *Eur.Phys.J.C* 80 (2020) 8, 718
  - Searches in pp 13TeV: *tt arXiv: 2310.11231,* new physics *2303.04596*

$\gamma\gamma$ measurements at LHC

- ATLAS
  - ee PbPb 5 TeV, *JHEP* 2306 (2023) 182
  - $\mu\mu$ pp 13 TeV, *Phys.Lett.B* 777 (2018) 303
  - $\mu\mu$ PbPb 5.02 TeV *Phys.Rev.C* 104 (2021) 024906
  - $\gamma\gamma$–>$\gamma\gamma$ *Nature Phys.* 13 (2017) 9, 852-858, *Phys.Rev.Lett.* 123 (2019) 5, 052001
  - $\gamma\gamma$–>$\gamma\gamma$ /*axions JEP* 11 (2021) 050 (erratum), *JHEP* 03 (2021) 243

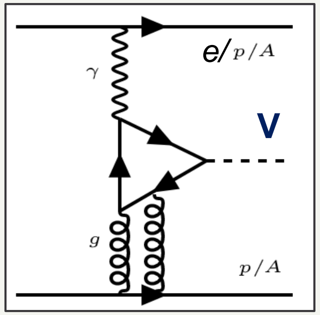
- CMS (+TOTEM)
  - $\mu\mu$ pp 7 TeV JHEP 01 (2012) 052
  - $\mu\mu$ PbPb 5.02 TeV *Phys.Rev.Lett.* 127 (2021) 12, 122001
  - $\gamma\gamma$–>$\gamma\gamma$/axions *Phys.Lett.B* 797 (2019) 134826
  - $\tau\tau$ *Phys.Rev.Lett.* 131 (2023) 151803
  - *WW JHEP* 08 (2016) 119, *JHEP* 07 (2023) 229

Photoproduction

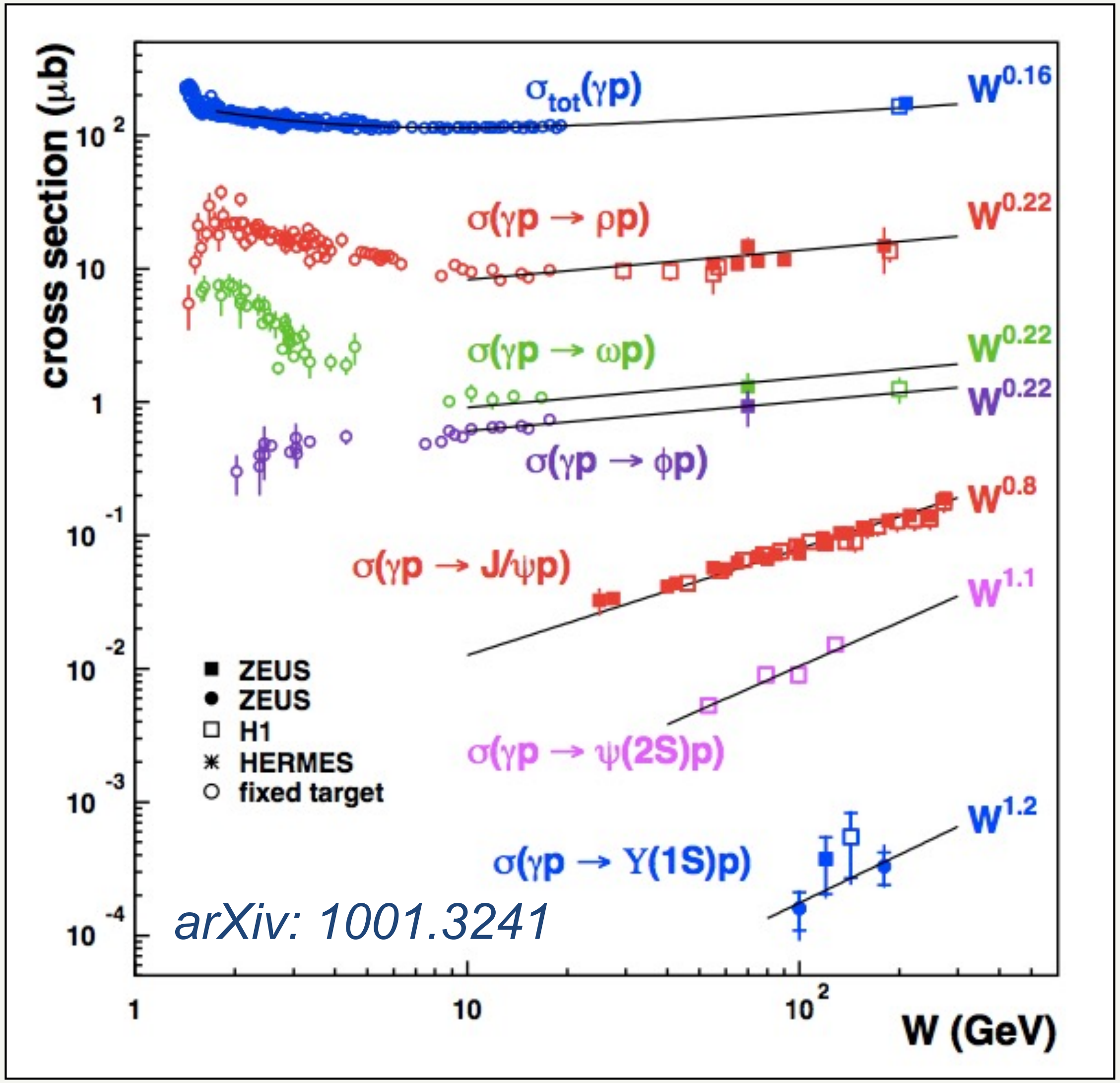


Unlike in inclusive J/ψ production, theory work really well in exclusive production.

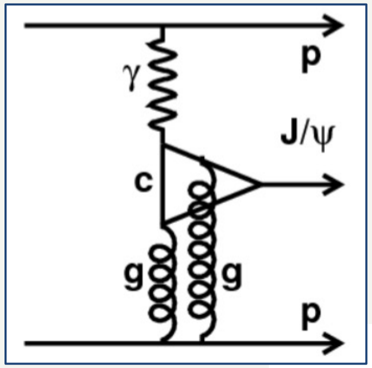
Photoproduction

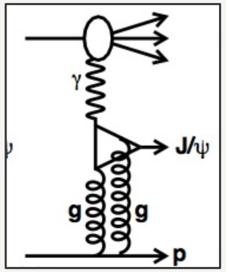


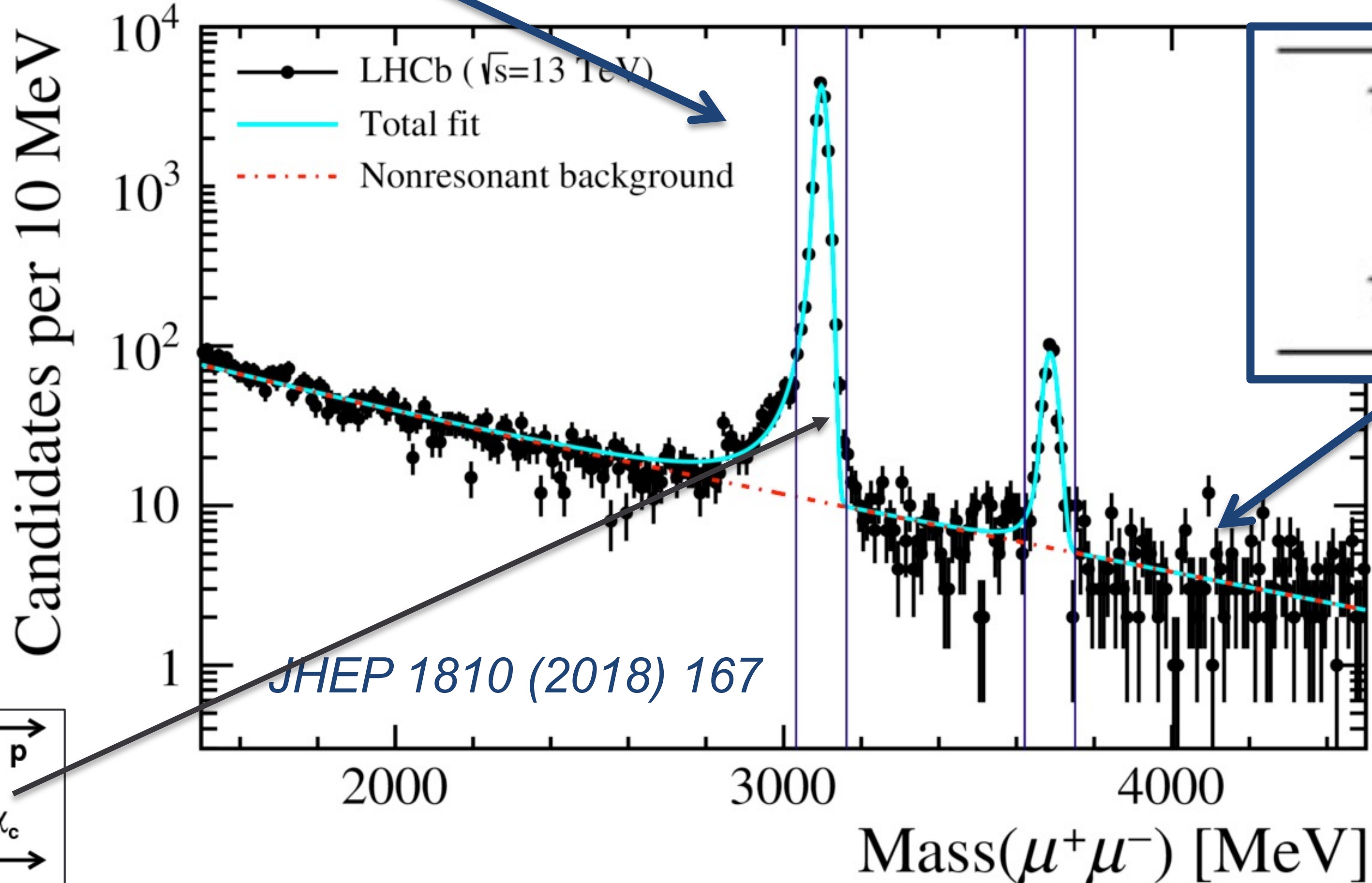
- Rise in σ related to Pomeron intercept
  - $\sigma \sim W^{\delta}$
  - $\delta=4(\alpha_P(t)-1)$
  - $\alpha_P(t)=\alpha_P(0)+\alpha' t$
- Compare slopes ρ,ω,ϕ to J/ψ,ψ',Υ
- Extract $g(x,Q^2)$



J/ψ and ψ(2s) in pp collisions







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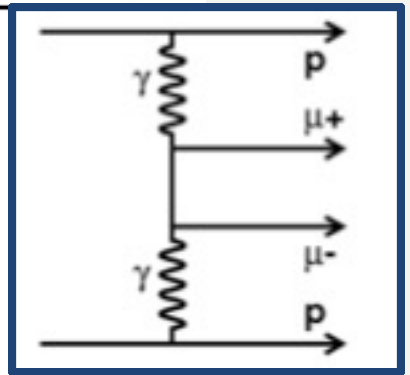
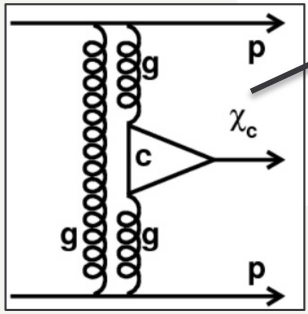


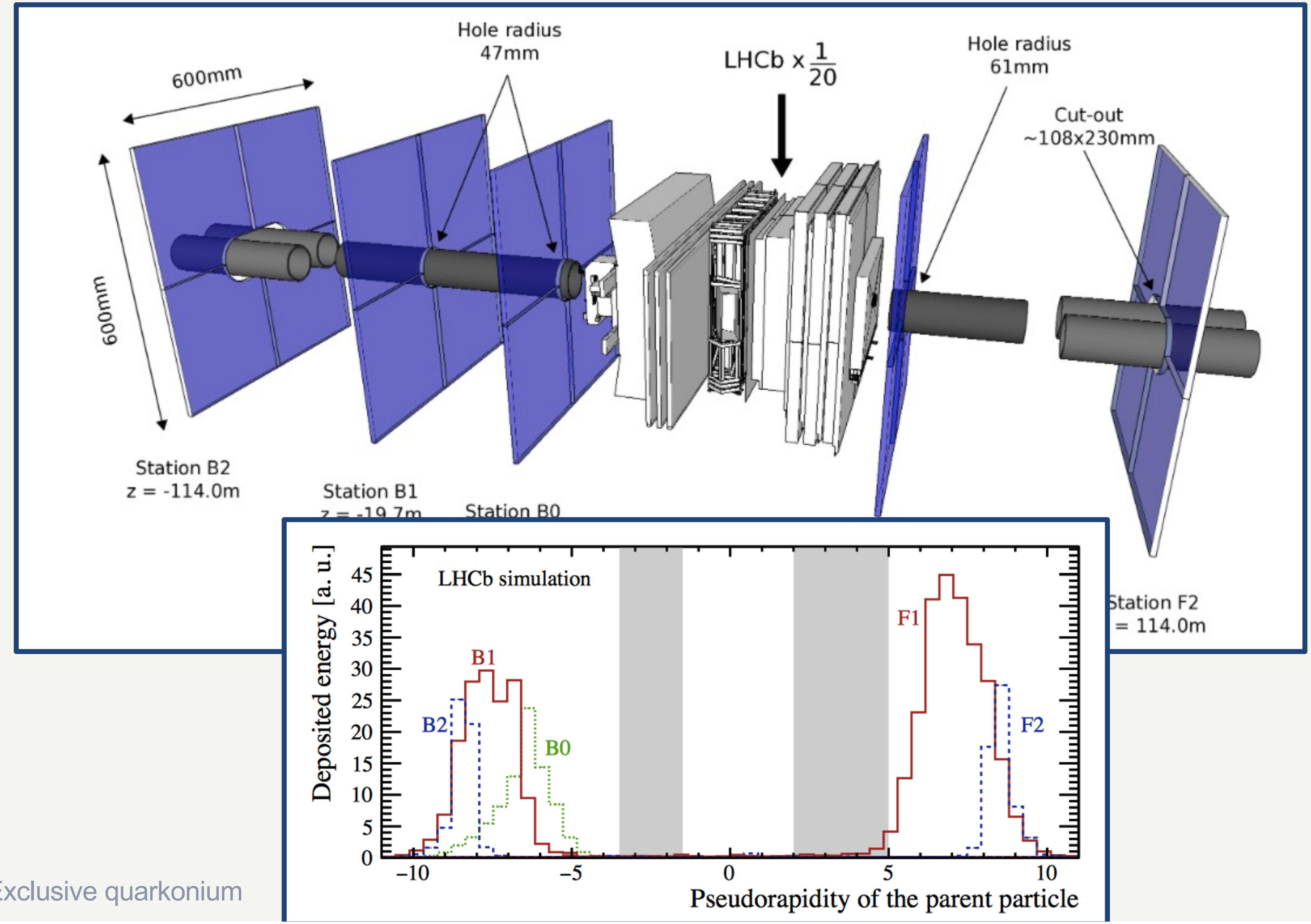
Feed-down

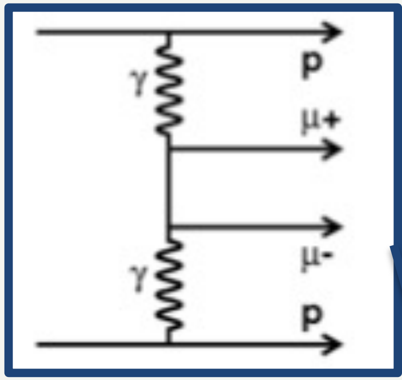


Exclusive quarkonium

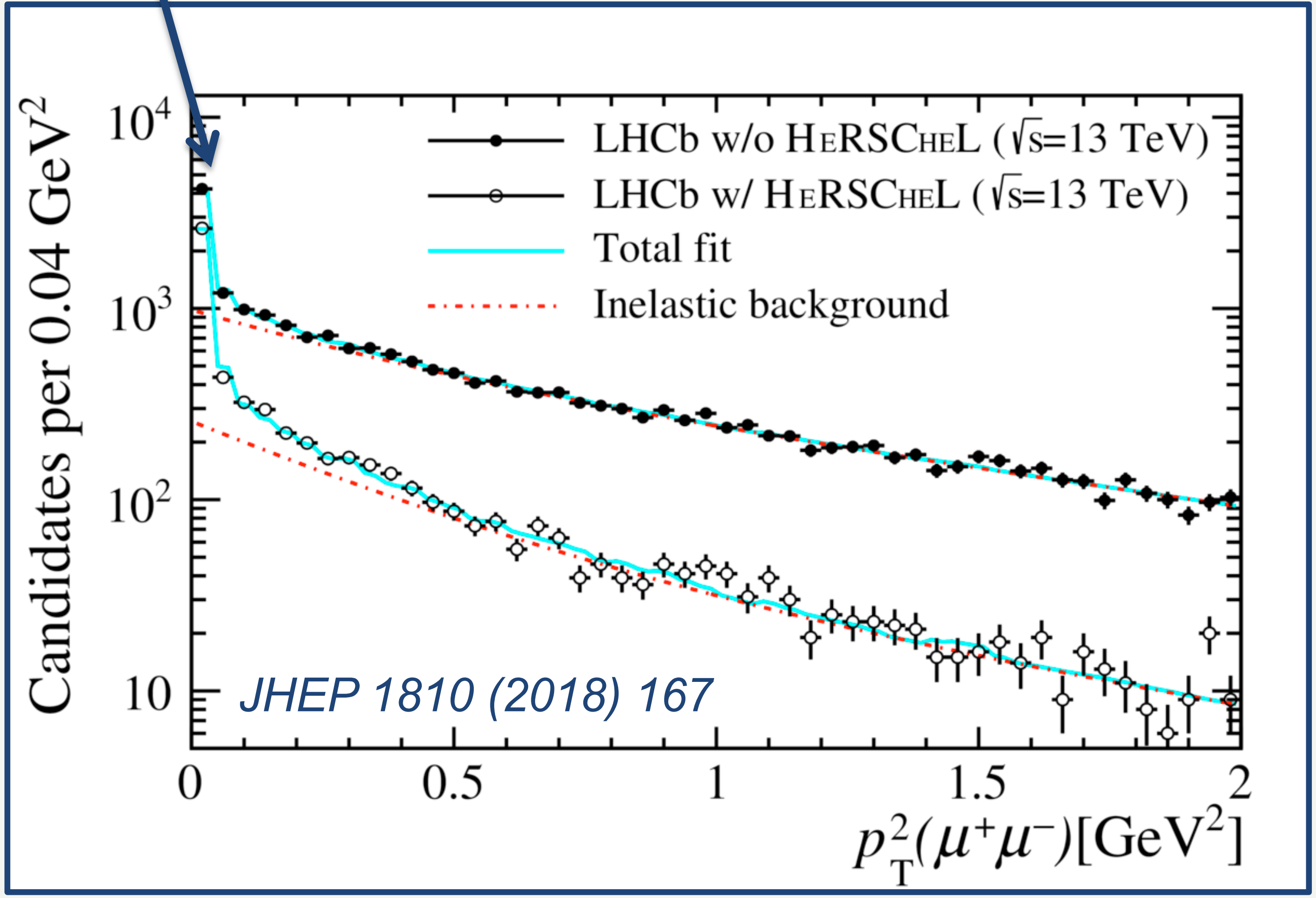
Two muons and nothing else in the LHCb detector

The LHCb detector

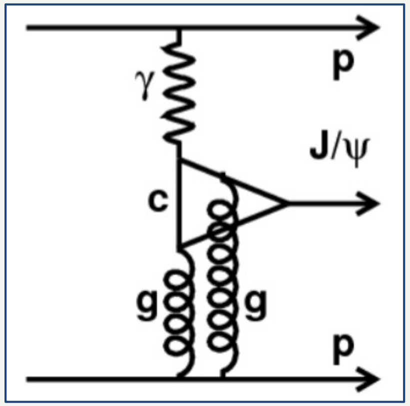




Forward tagging suppresses dissociation



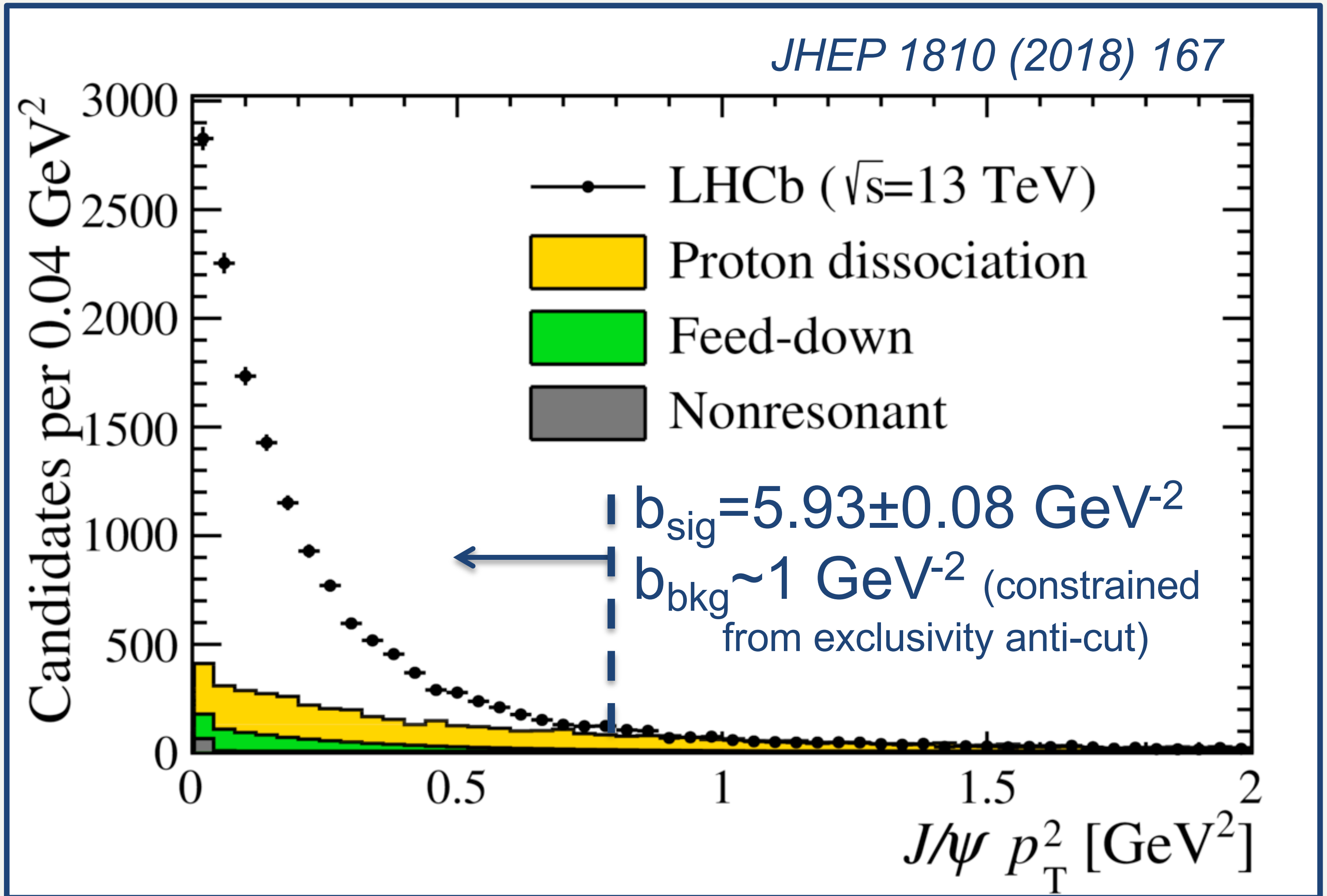
Note for later: this is p_T~50 MeV



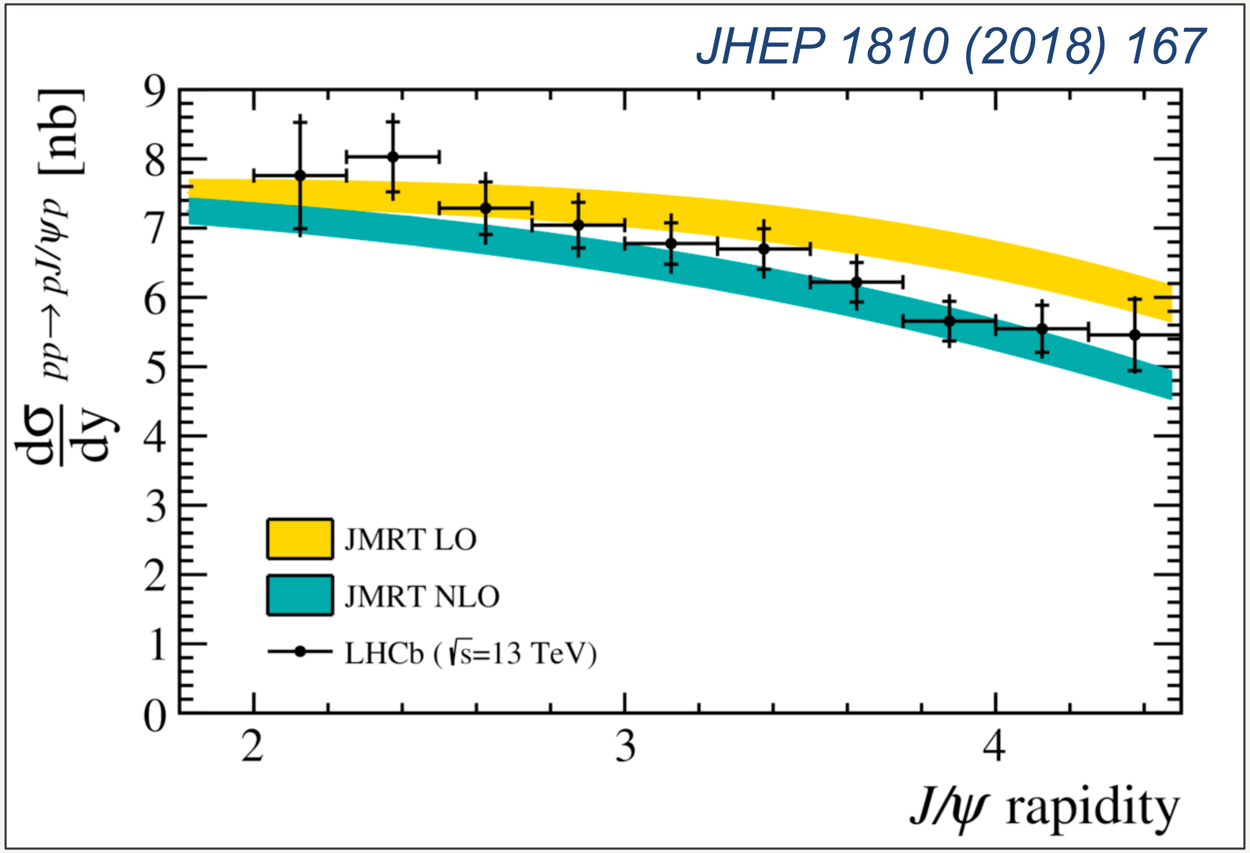
Separating elastic and dissociative J/ψ

Assume Signal and Background

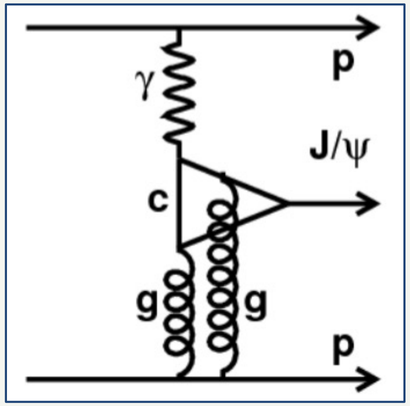
$$\frac{d\sigma}{dt} \sim e^{bt}$$



Differential cross-section pp→pJ/ψp



Implications: GPDs and PDF

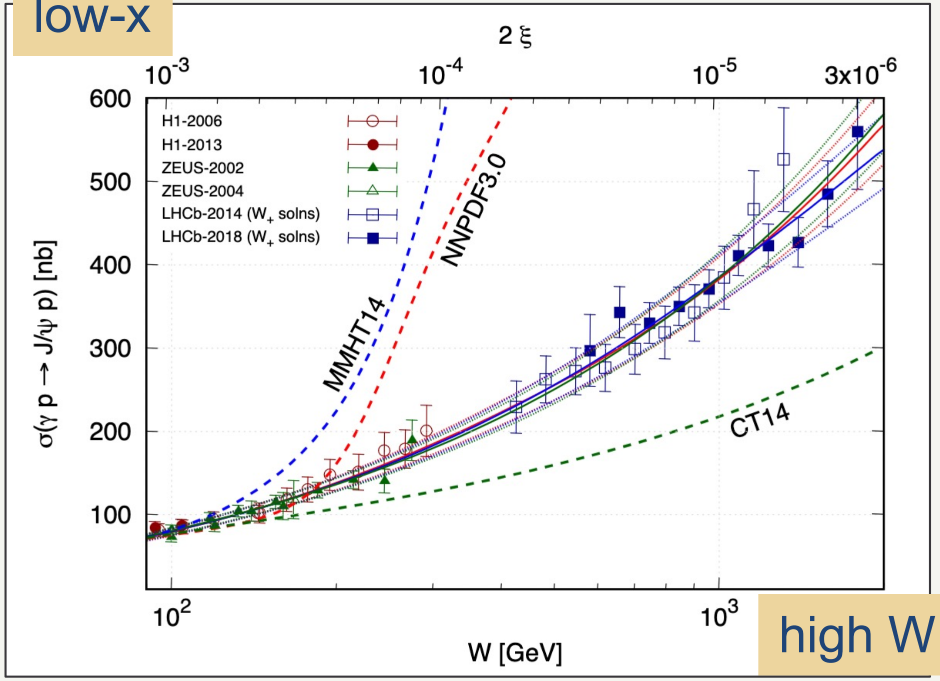


Ryskin, Z. Phys. C 57 (1993) 89

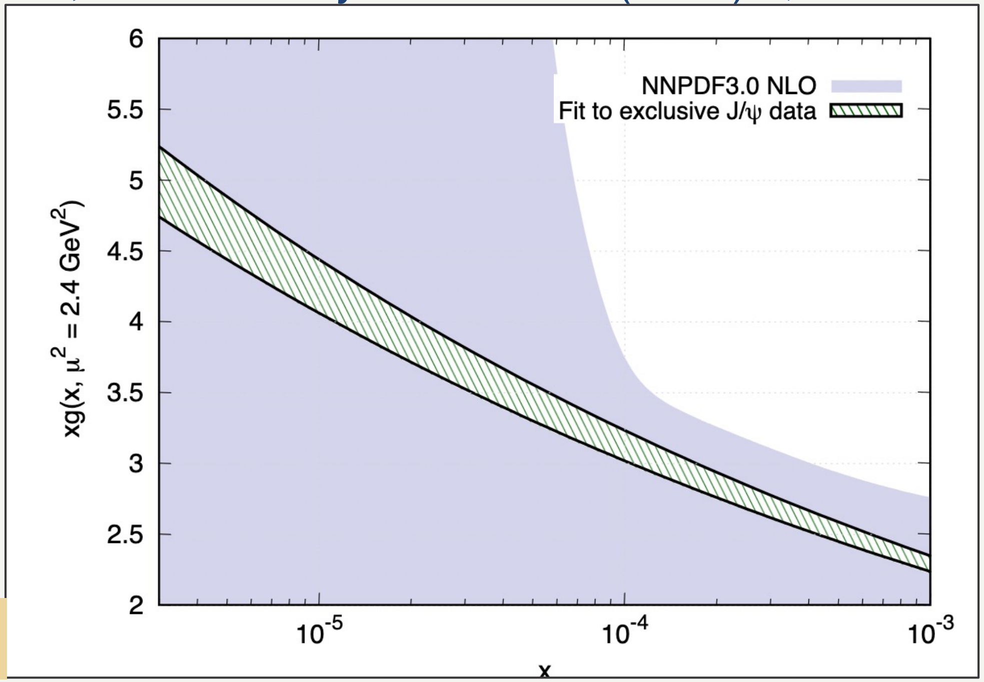
$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\, p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$

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

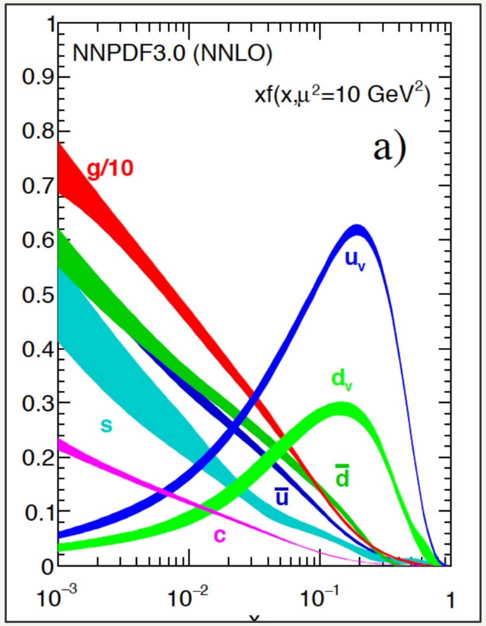
$$H_q(X,\xi) = \int_{-1}^{1} dx' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{ds}{y(s)\sqrt{1-y(s)x'}}\right]\frac{d}{dx'}\left(\frac{q(x')}{|x'|}\right),$$

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

where the transform kernel,

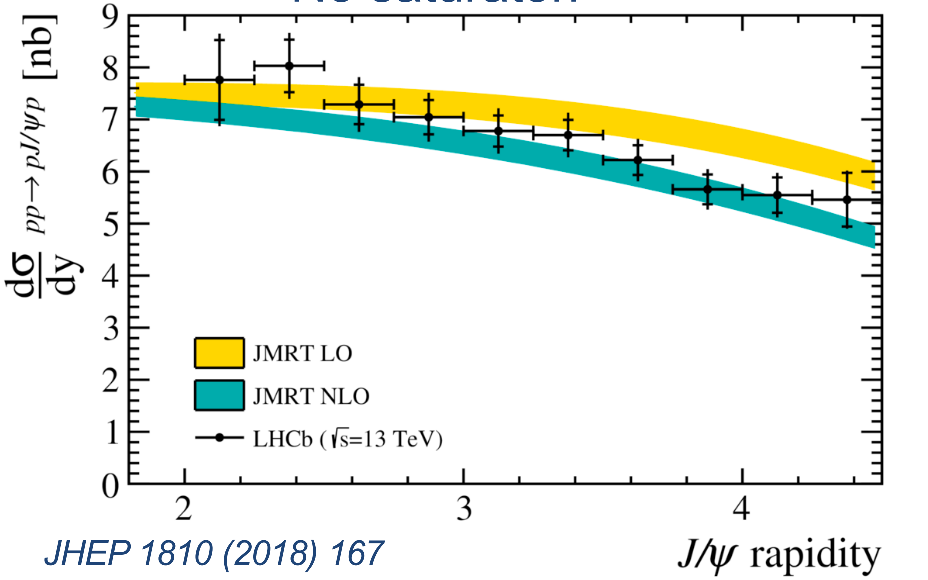
$$y(s) = \frac{4s(1-s)}{(X+\xi(1-2s))}.$$

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



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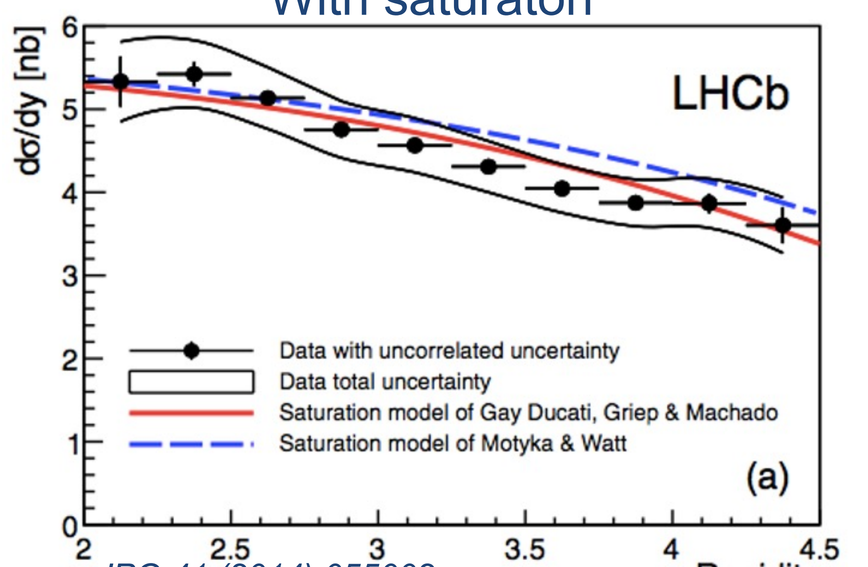
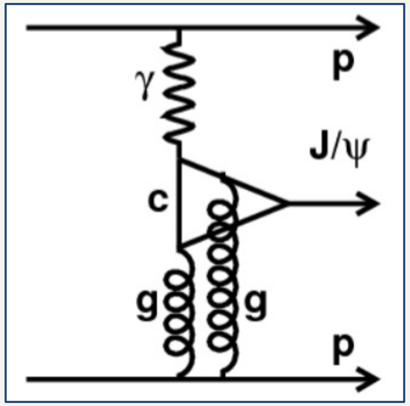
With saturaton



JPG 41 (2014) 055002

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

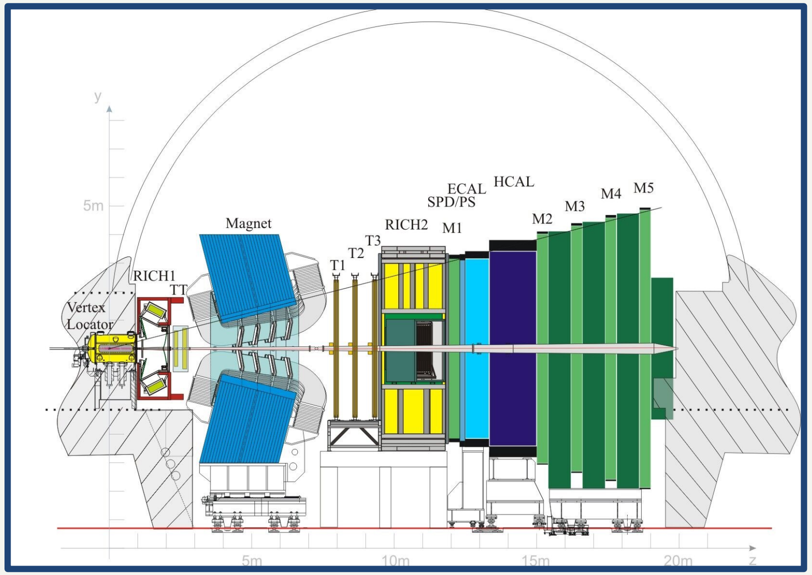


Which proton produced the photon?

pomeron

Photon

Softer photon.
Harder pomeron
Low W.

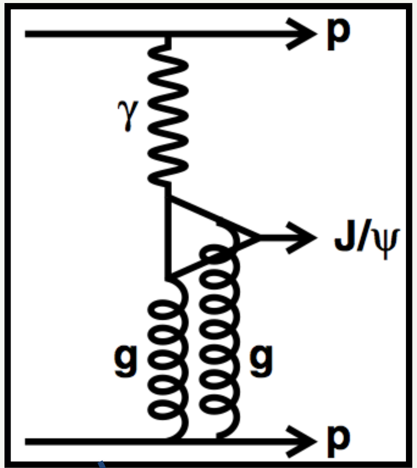


pomeron

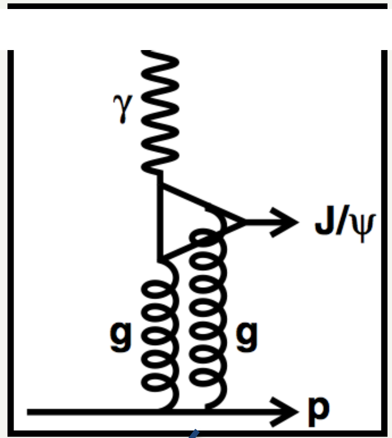
Photon

Harder photon,
Softer pomeron
High W

Convert to photo-production cross-section



LHCb measures



HERA measured

Photon Flux

$$\left.\frac{d\sigma}{dy}\right._{pp\to pJ/\psi\, p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to J/\psi\, p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi\, p}(W_-)$$

Gap Survival

HERA measured power-law: $\sigma_{\gamma p\to J/\psi\, p}(W) = 81(W/90\,\mathrm{GeV})^{0.67}\,\mathrm{nb}$

Photoproduction cross-section

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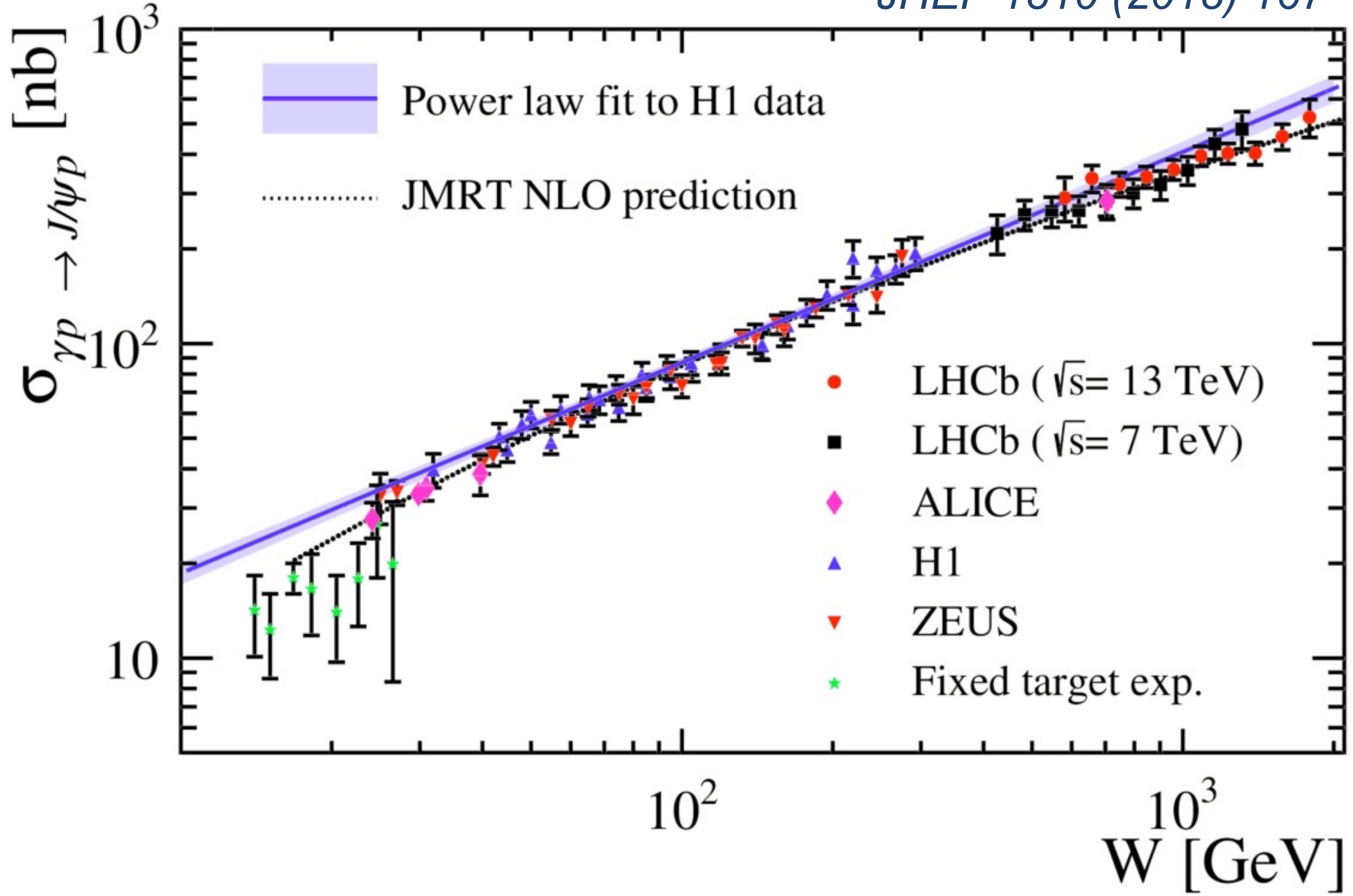
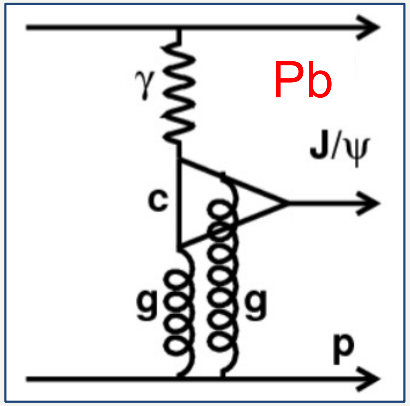
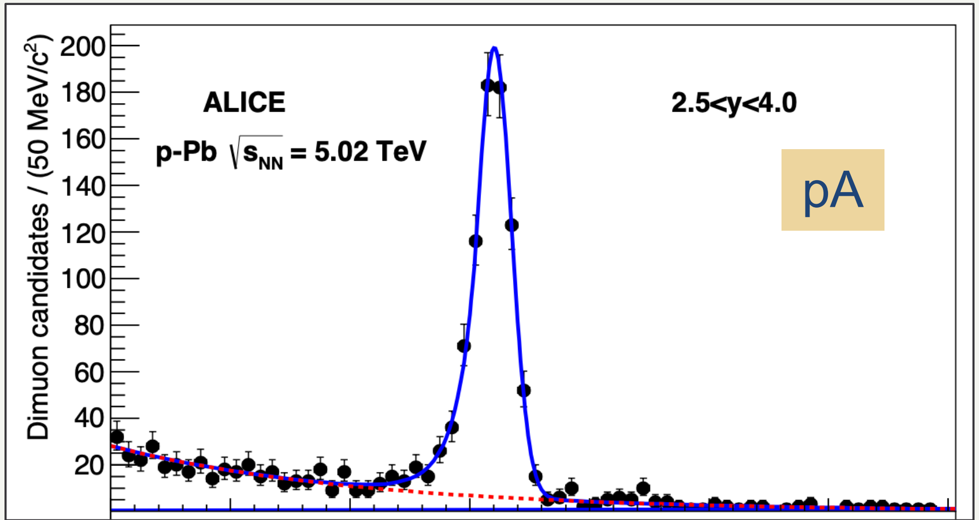


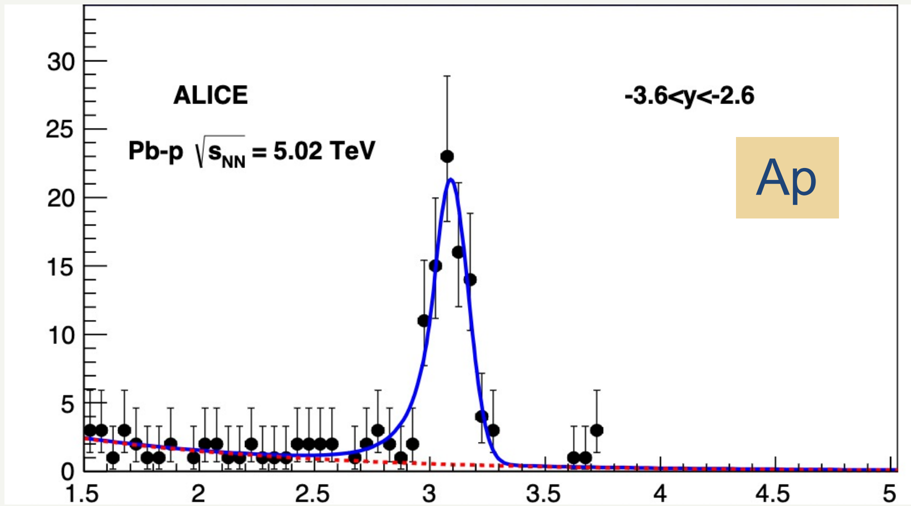


Which projectile produced the photon?

pomeron → ← Photon — pPb collisions

Photon → ← pomeron — Pbp collisions

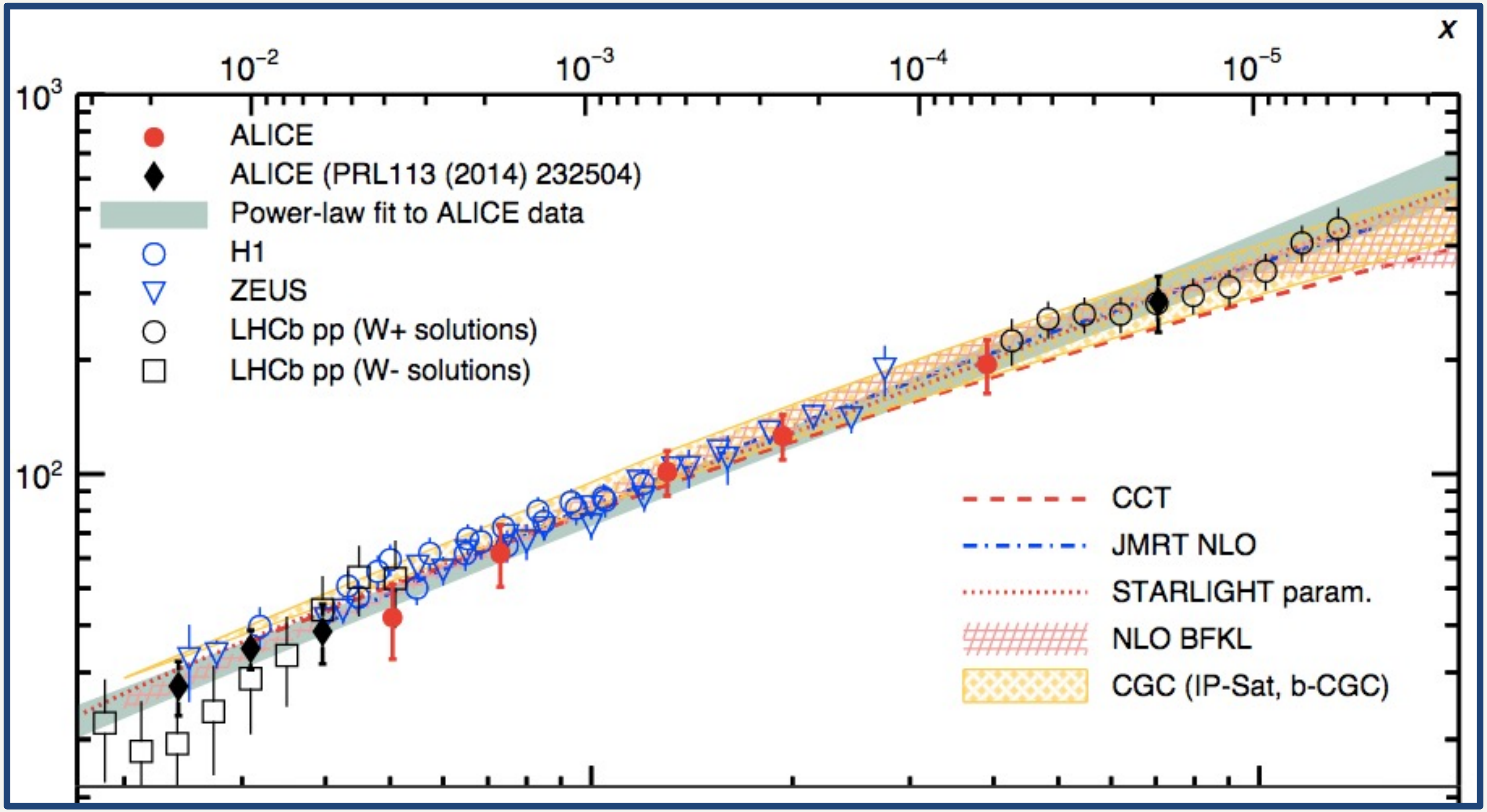


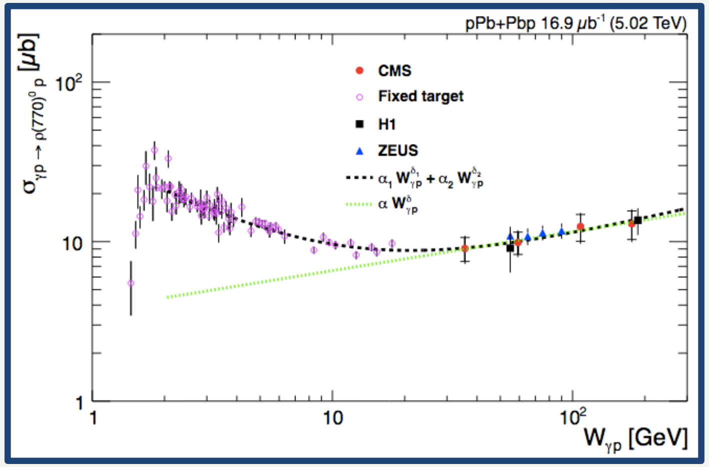


Exclusive quarkonium *Phys.Rev.Lett.* 113 (2014) 23, 232504

J/ψ production in pPb and Pbp

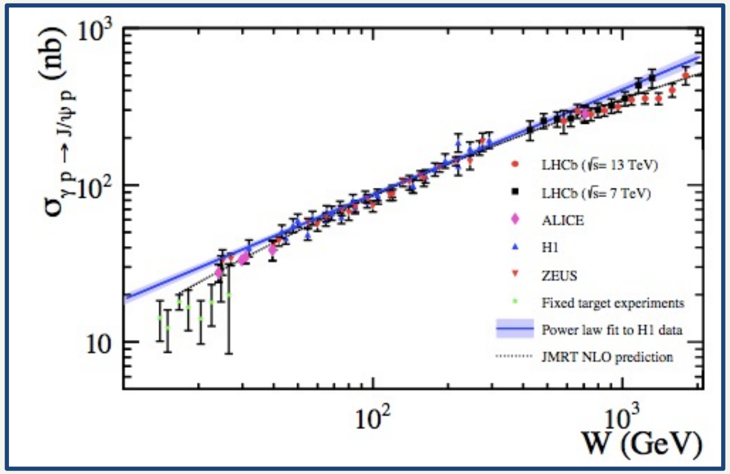
Eur.Phys.J. C79 (2019) no.5, 402





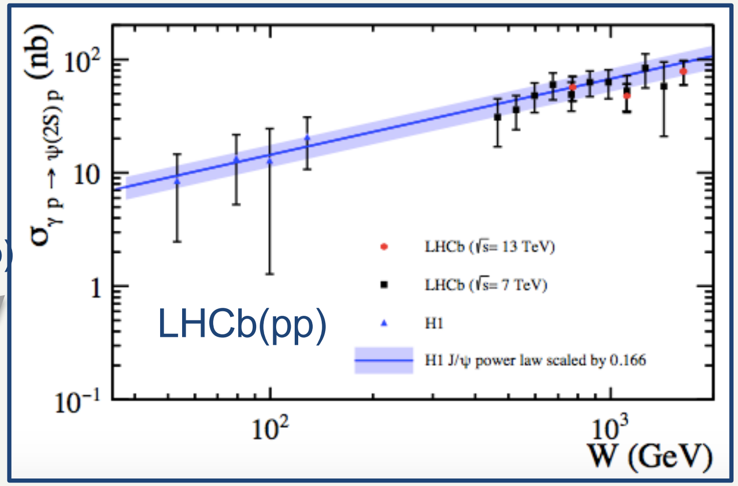
CMS (pPb) ALICE (XeXe, PbPb)

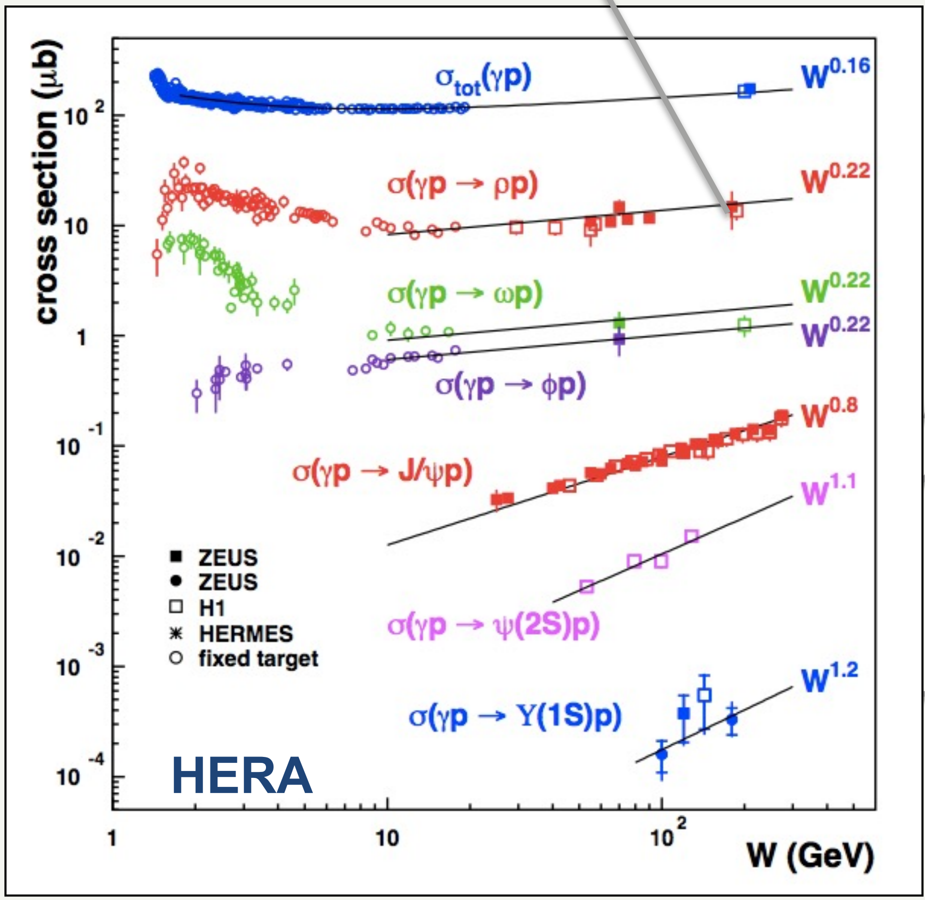
ALICE (pPb, PbPb)
LHCb (pp, PbPb)



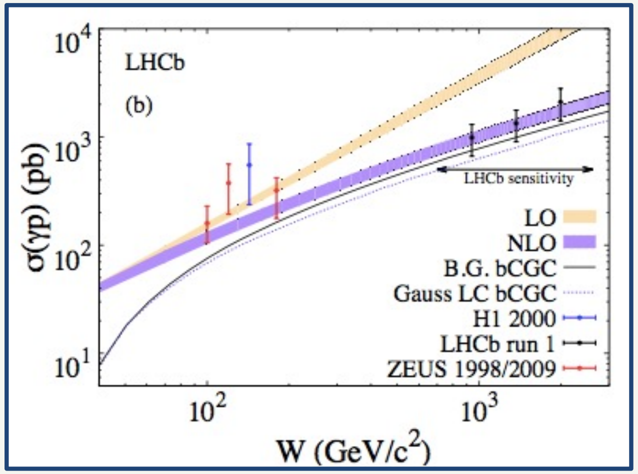
Central region
$W_{LHC} \sim W_{HERA}$
Forward
$W_{LHC} >> W_{HERA}$

LHCb
(pp, PbPb)

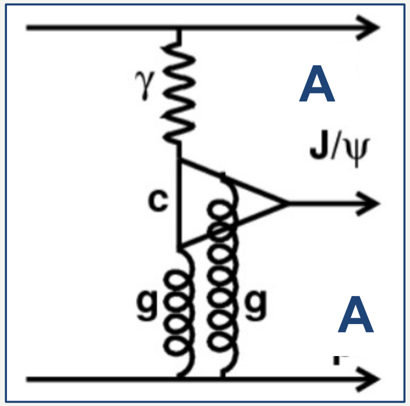




LHCb (pp)
CMS (pPb)

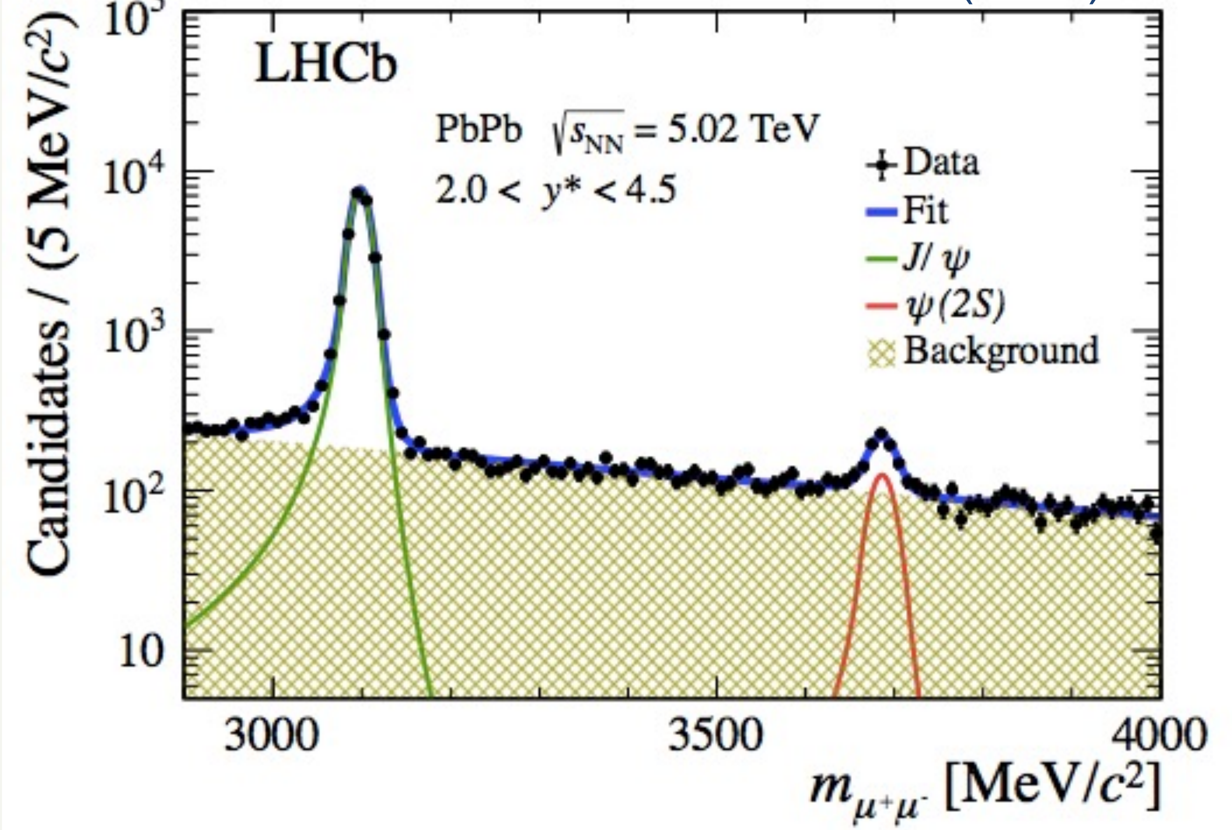


Exclusive quarkonium



Photoproduction in PbPb

JHEP 06 (2023) 146



$\sigma_{\gamma A}$ in PbPb is sensitive to **nuclear PDFs** and possibly saturation.

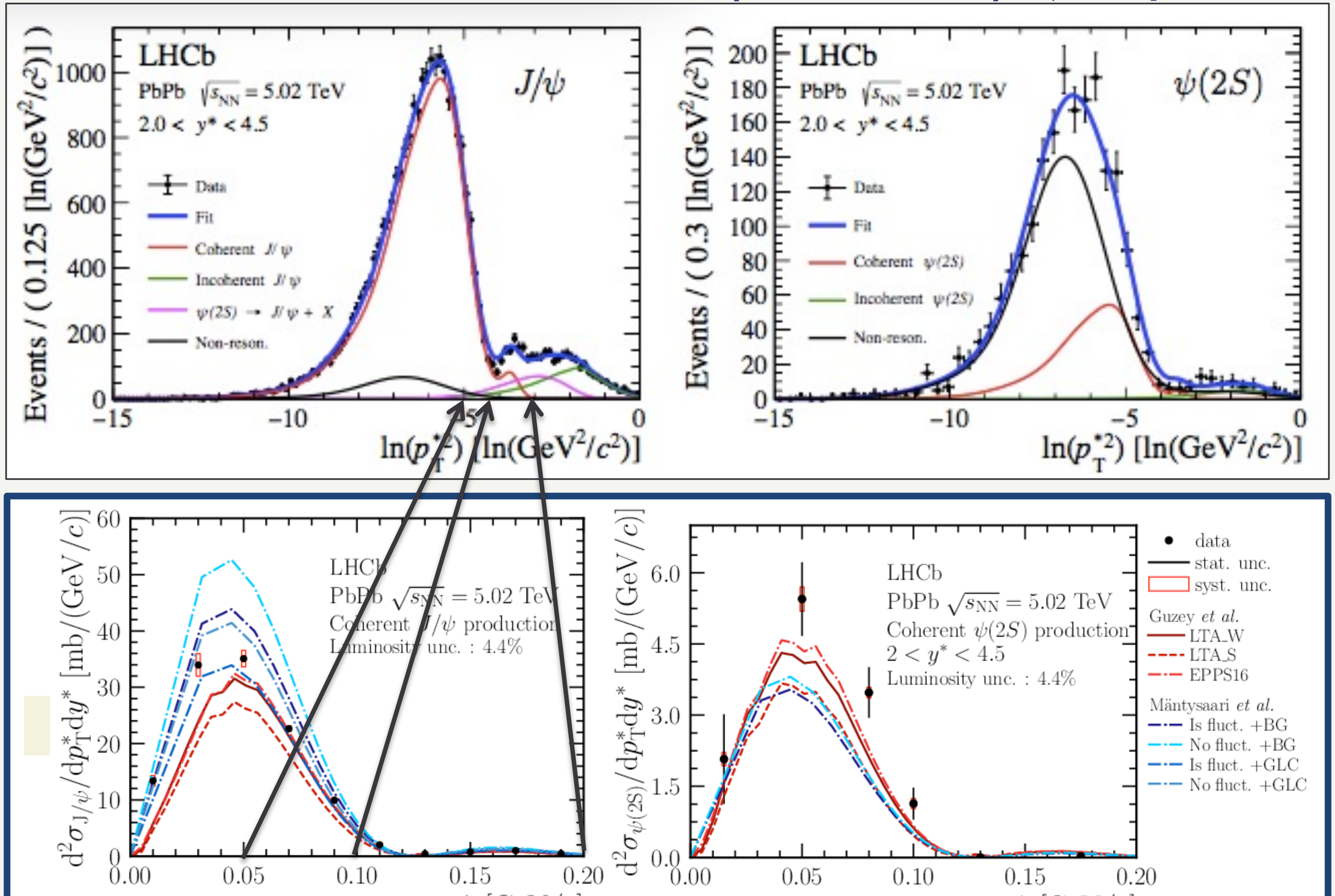
Source	Relative uncertainty [%]	
	$\sigma^{coh}_{J/\psi}$	$\sigma^{coh}_{\psi(2S)}$
Tracking efficiency	0.5–2.0	0.5–2.0
PID efficiency	0.9–1.6	0.9–1.6
Trigger efficiency	2.7–3.7	2.1–2.5
HeRSChel efficiency	1.4	1.4
Background estimation	1.2	1.2
Signal shape	0.04	0.04
Momentum resolution	0.9–34	1.3–27
Branching fraction	0.6	2.1
Luminosity	4.4	4.4

Continuum background is order of magnitude larger than in proton-proton (but still small for J/ψ, though not for ψ’).
Note, there is almost no feed-down background.

Separating elastic and dissociative J/ψ and ψ(2s)

log(pT)

linear



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Cross-sections

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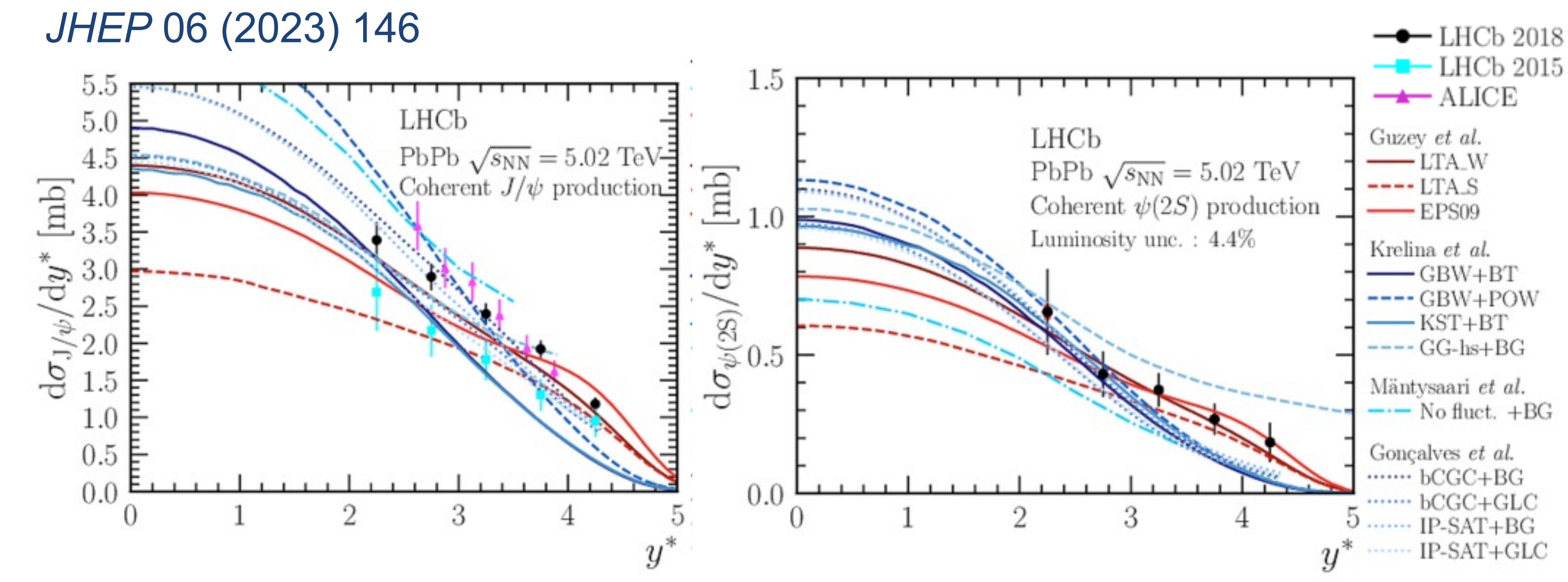
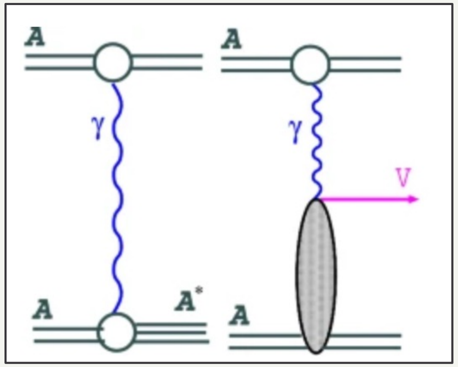


Sensitive to details of the models:
QCD / CGC / dipole / meson wave fn.

$$\sigma^{coh}_{J/\psi} = 5.965 \pm 0.059 \pm 0.232 \pm 0.262 \text{ mb}$$
$$\sigma^{coh}_{\psi(2S)} = 0.923 \pm 0.086 \pm 0.028 \pm 0.040 \text{ mb}$$

$2.0 < y^* < 4.5$

Looking for saturation in nuclear collisions

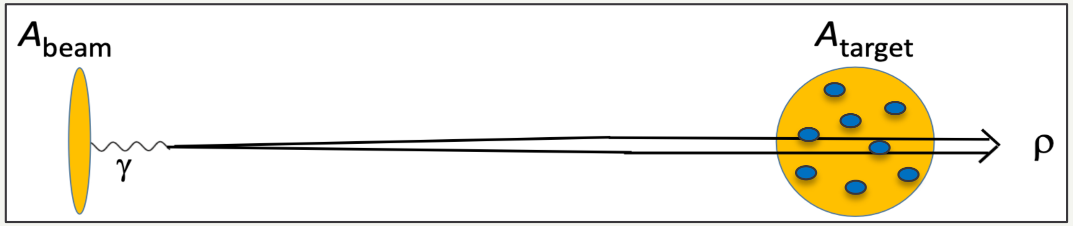


*additional EMD can excite or break nucleus

Coherent interaction: all nucleons behave as one.
- b ~ 2R=13.2 fm so p_T~15 MeV
- nucleus remains intact*.

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'?



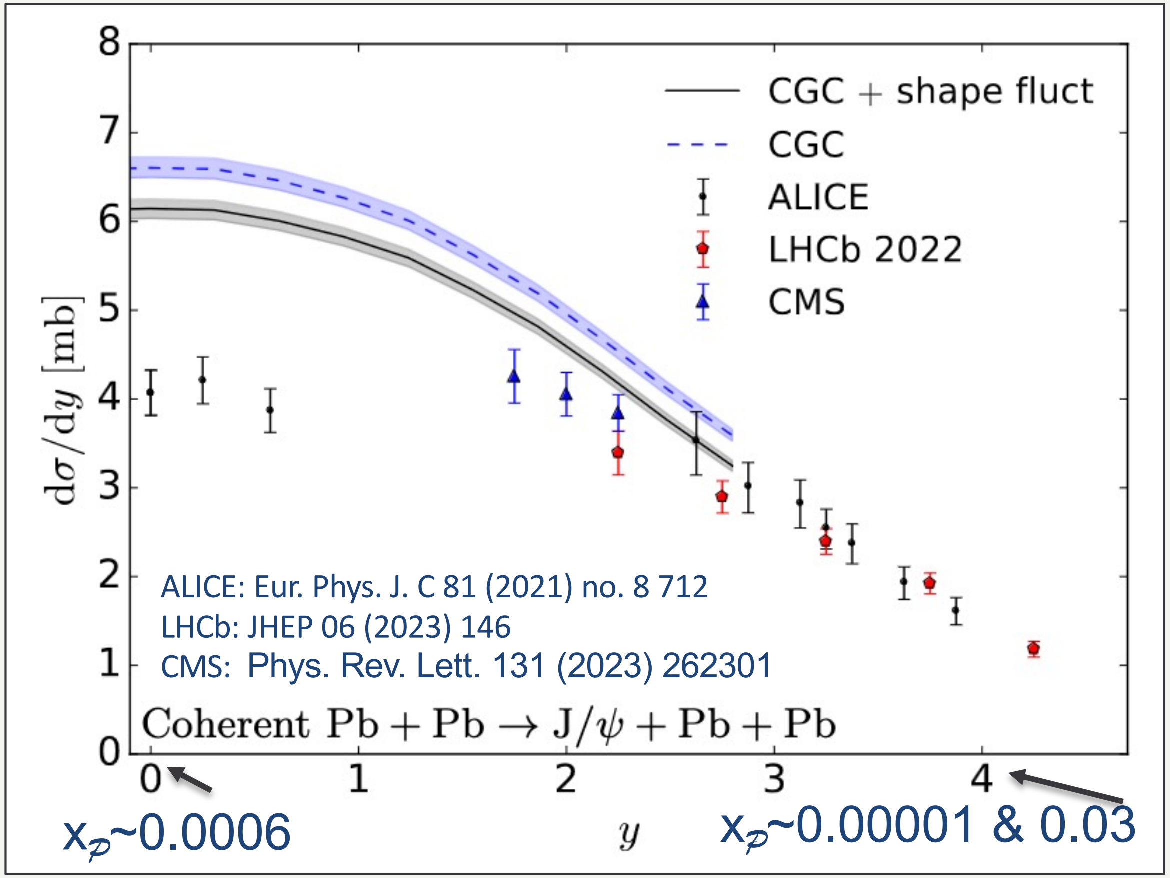
$$\mathcal{A}_{\rho n}(b) = i(1 - e^{-\Omega(b)/2})$$

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

Glauber eikonal approx.

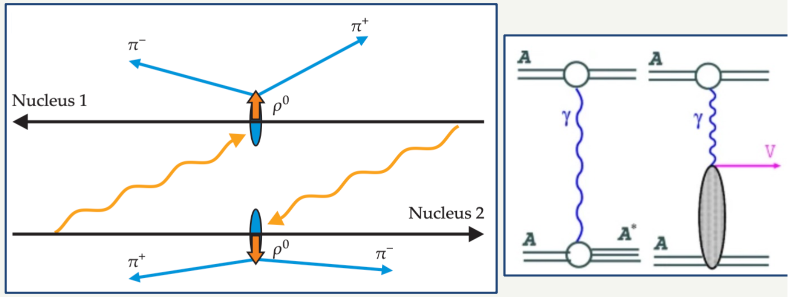
Incoherent interaction with nucleon or parton
- p_T distribution follows exp(bt) b smaller than for coherent
- break-up is observed
- sensitive to smaller structures – saturation gives deviations from isotropy.

Coherent J/ψ in PbPb



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

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

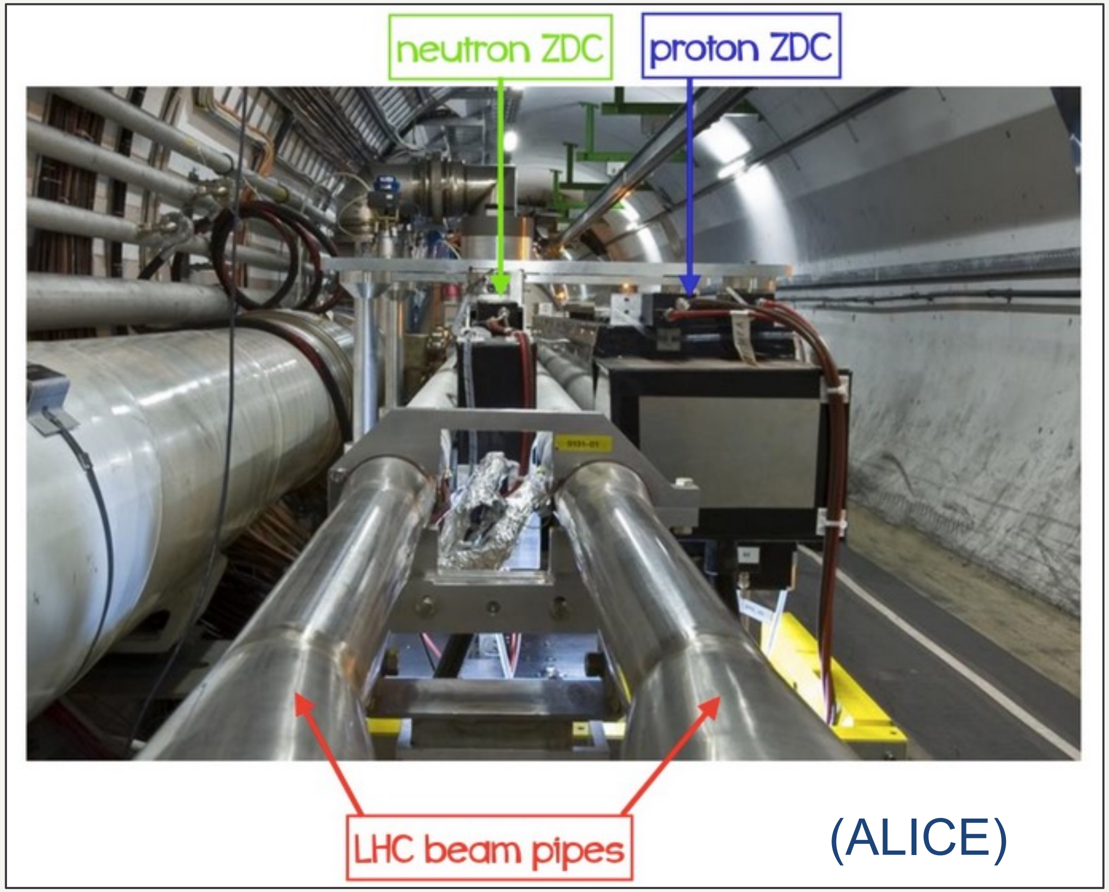


S. Klein, J. Nystrand, Physics Today 70, (2017) 40.

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

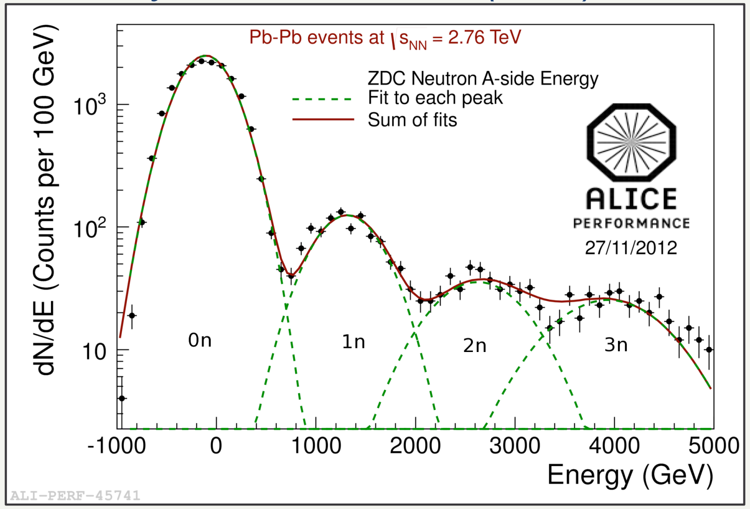
$$\frac{d\sigma_{PbPb\to PbJ/\psi Pb}}{dy} = \left(k\frac{dN_\gamma}{dk}\right)^{+}\sigma_{\gamma Pb\to J/\psi Pb}(W^{+}) + \left(k\frac{dN_\gamma}{dk}\right)^{-}\sigma_{\gamma Pb\to J/\psi Pb}(W^{-})$$

ZDC calorimeters installed in CMS, ALICE, STAR



(ALICE)

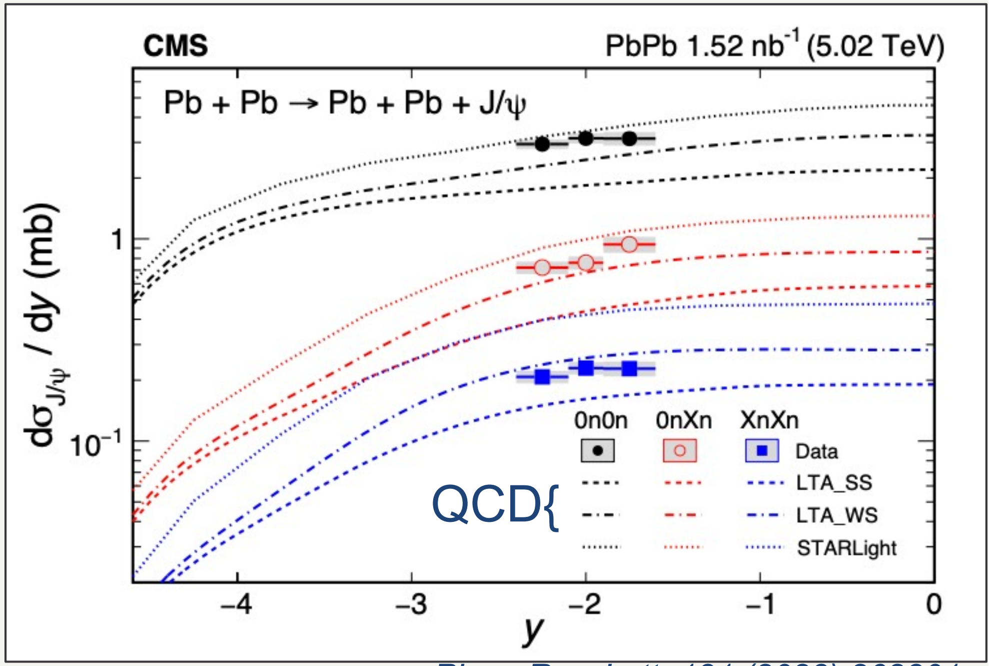
J. Phys.: Conf. Ser. 455 (2013) 012010



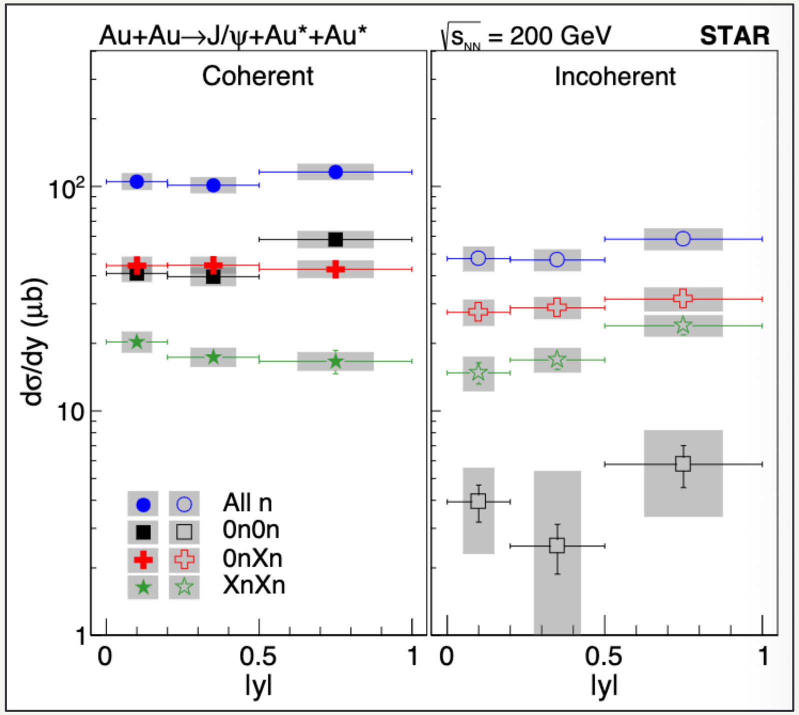
Detection of neutrons when ion breaks up allows identification of Electromagnetic Dissociation (EMD)

Resolving the two-fold ambiguity in PbPb

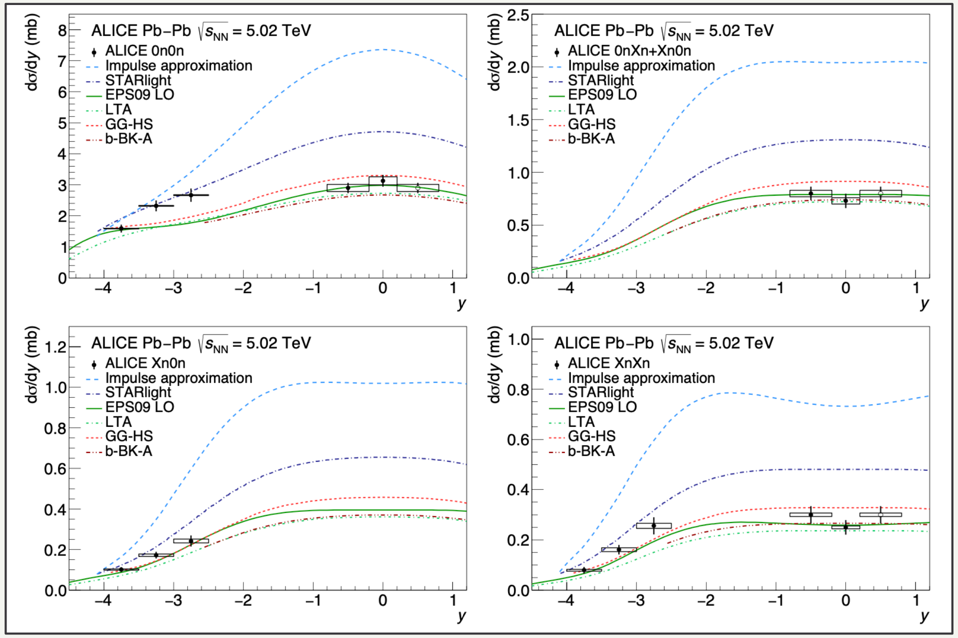
EMD is more likely at small impact parameters.
So fluxes for 0n and (X>=1)n different.



Phys. Rev. Lett. 131 (2023) 262301

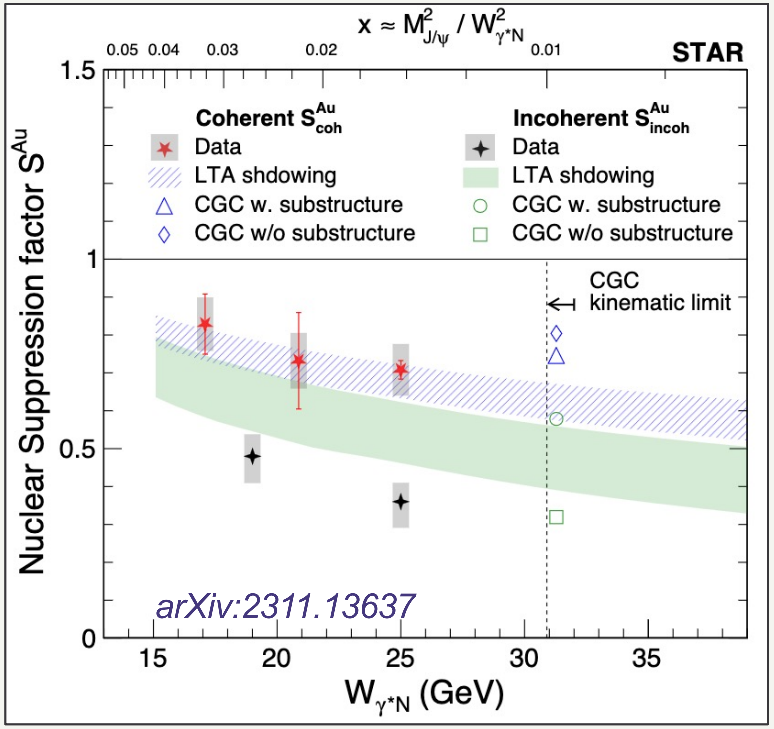


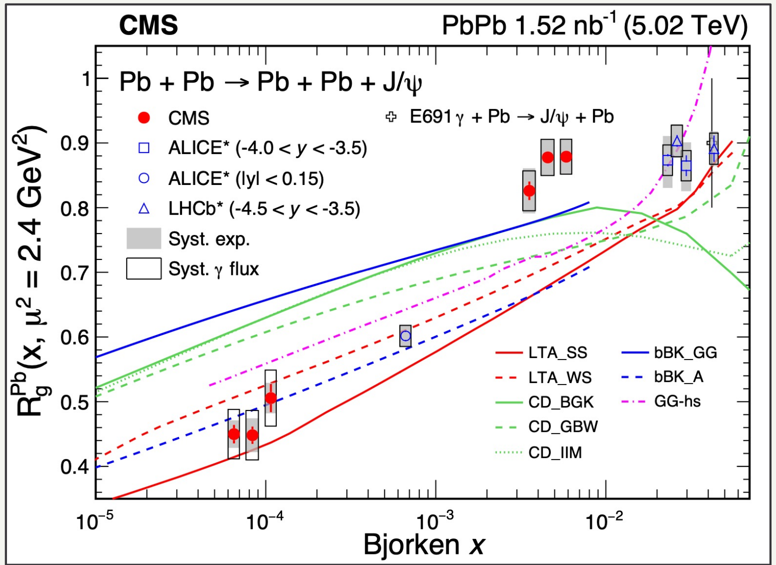
arXiv: 2311.13632



JHEP 10 (2023) 119

Re-expressed in terms of nuclear suppression factors



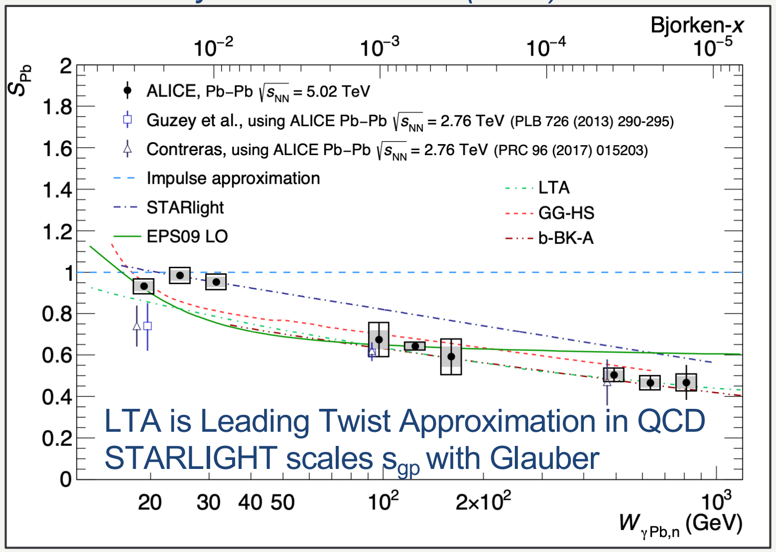


Phys. Rev. Lett. 131 (2023) 262301

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

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

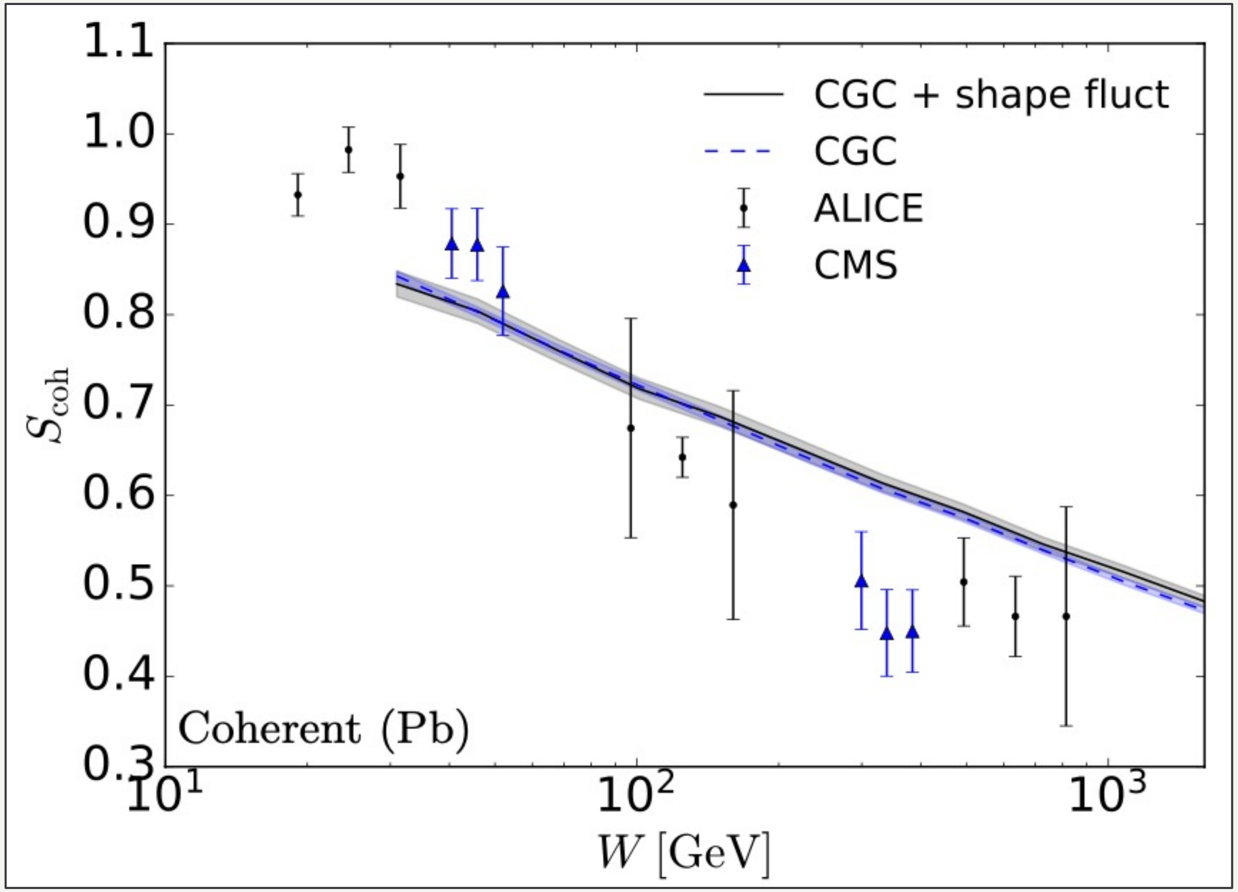
None of the models does a perfect job.
QCD/Starlight not too bad.
Models with saturation also reasonable



JHEP 10 (2023) 119

The case for saturation....

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

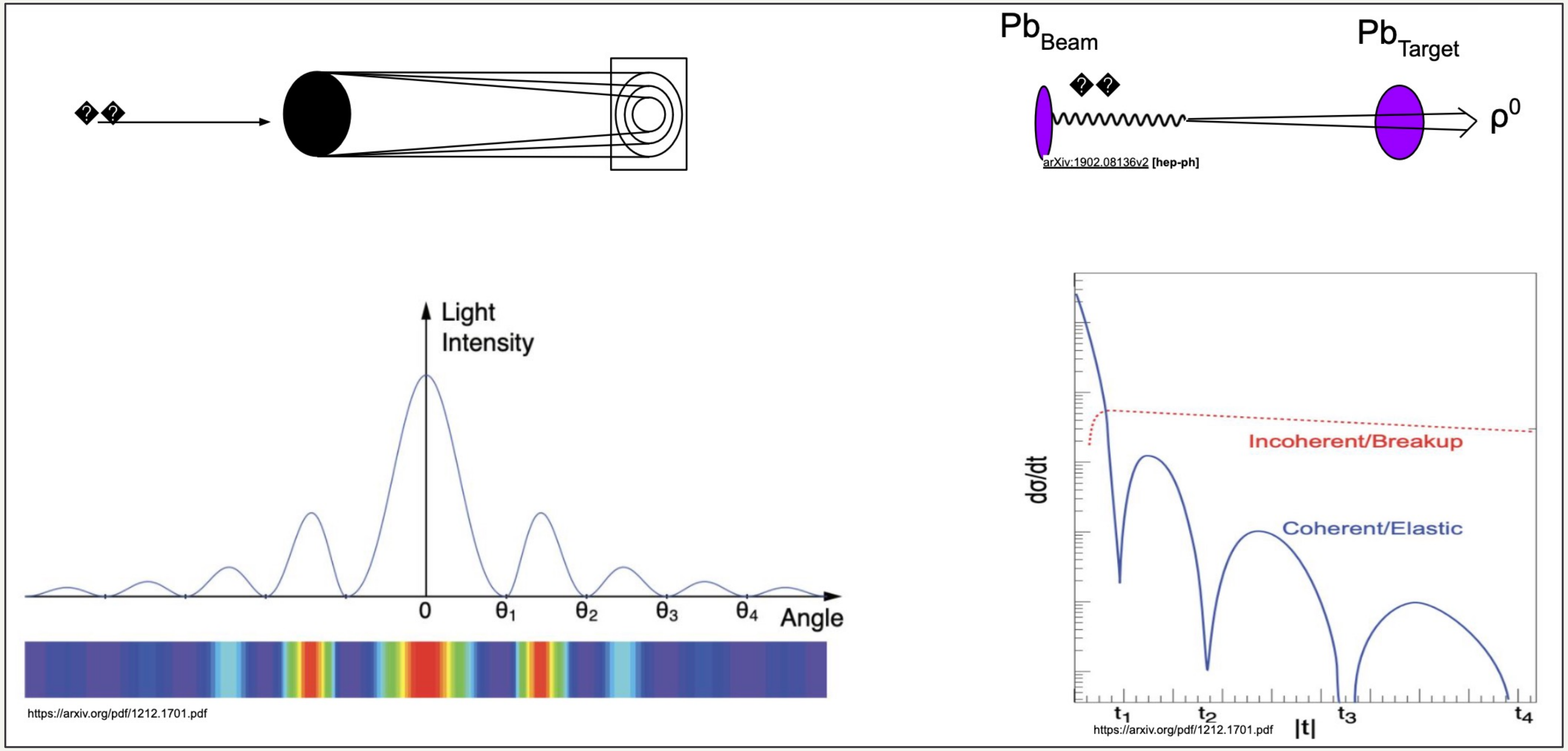


H. Mäntysaari, F. Salazar, B. Schenke: arXiv: 2312.04194

Transverse momentum distribution

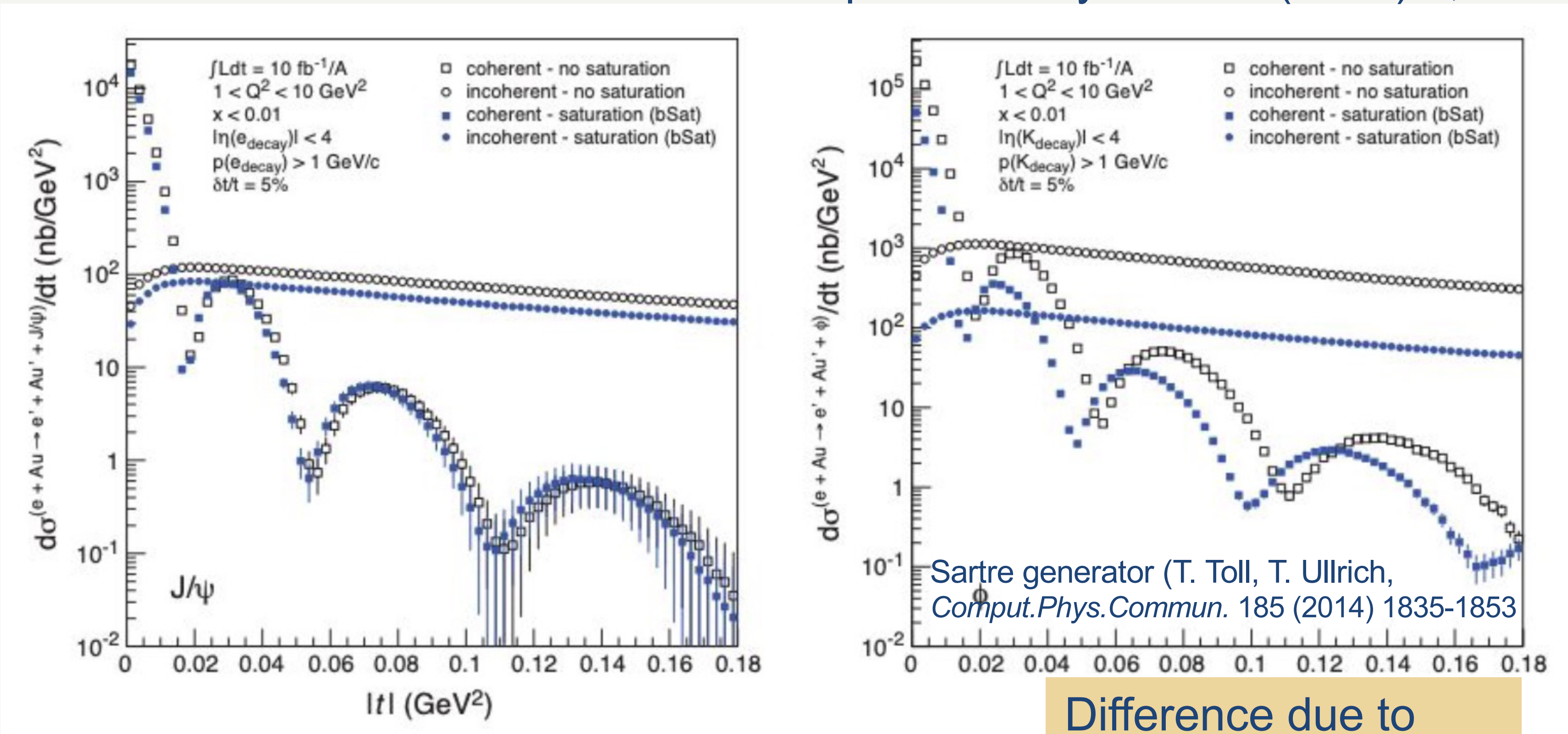
$d\sigma/dt \sim \exp(-bt)$ with $b \sim 6$ GeV^{-2} in pp collisions and ~ 400 GeV^{-2} in PbPb. (F.T. of ip)

$<p_T>$ in pp and pA is ~0.5 GeV = $1/R_p$
$<p_T>$ in AA. ~0.05 GeV ~ $1/R_A$



Sensitivity to saturation?

EIC White Paper: Eur.Phys.J.A 52 (2016) 9, 268



Sartre generator (T. Toll, T. Ullrich, *Comput.Phys.Commun.* 185 (2014) 1835-1853

The dip positions depend on the nuclear structure and the interaction probability.
In principle sensitive to hot-spots or saturation.

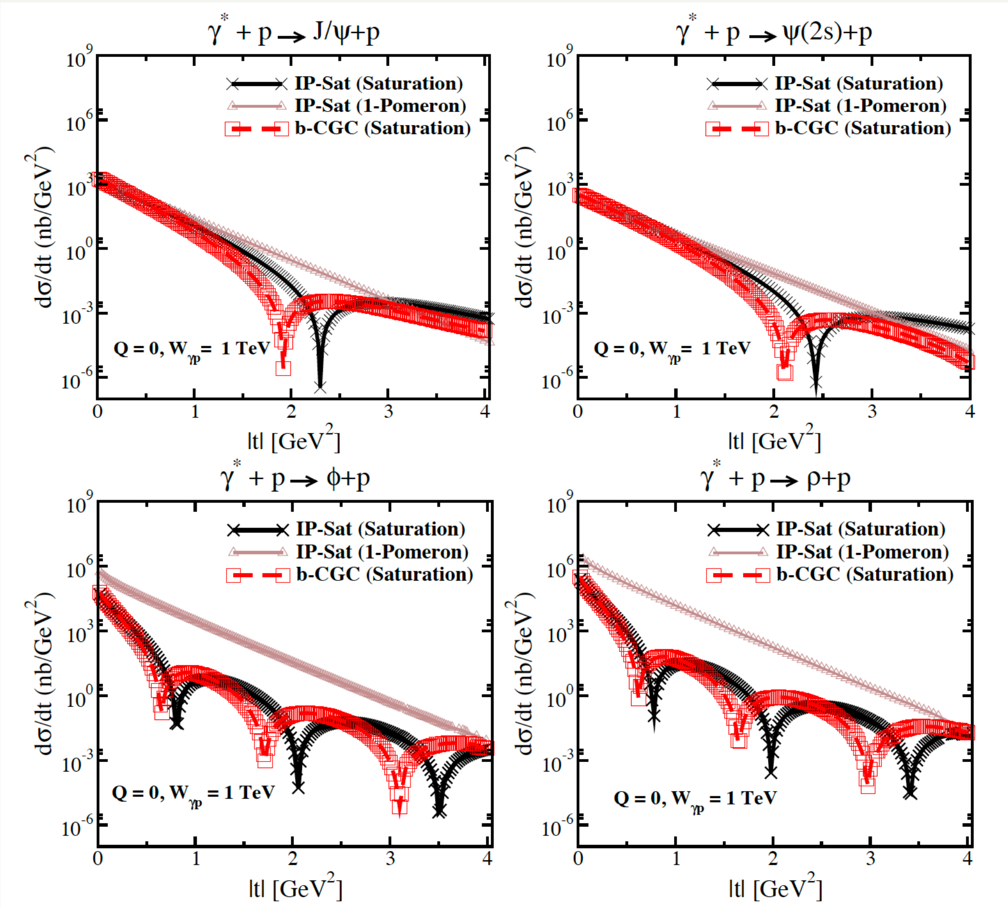
Difference due to saturation or to Glauber calculation?

$$A_{\rho A}(b) = i\theta(R_A - b)$$

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

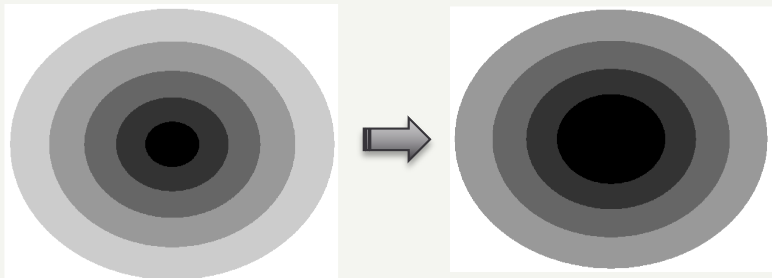
Scattering on the proton

N. Armesto & A. Rezaeien
Phys.Rev.D 90 (2014) 5, 054003



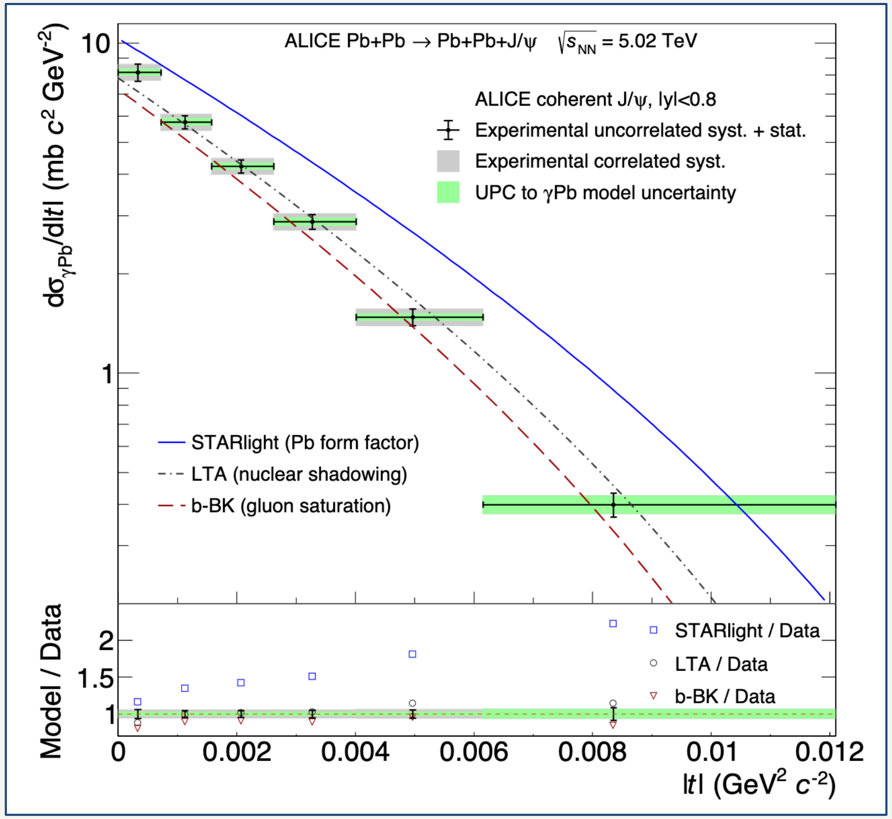
Experimentally tricky as incoherent reactions dominate at high-t

Presence of dips not necessarily evidence for saturation but non-linear models change dip position with W as you approach black-disk limit

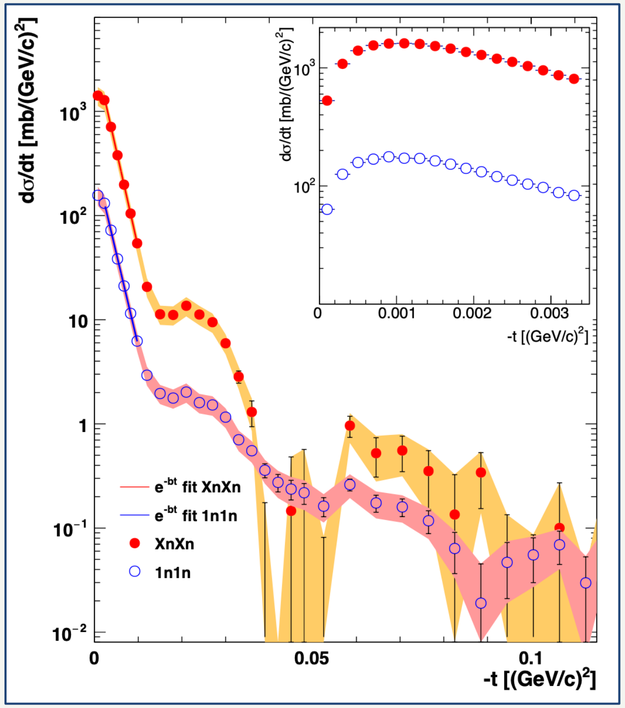


First measurements in UPC on lead

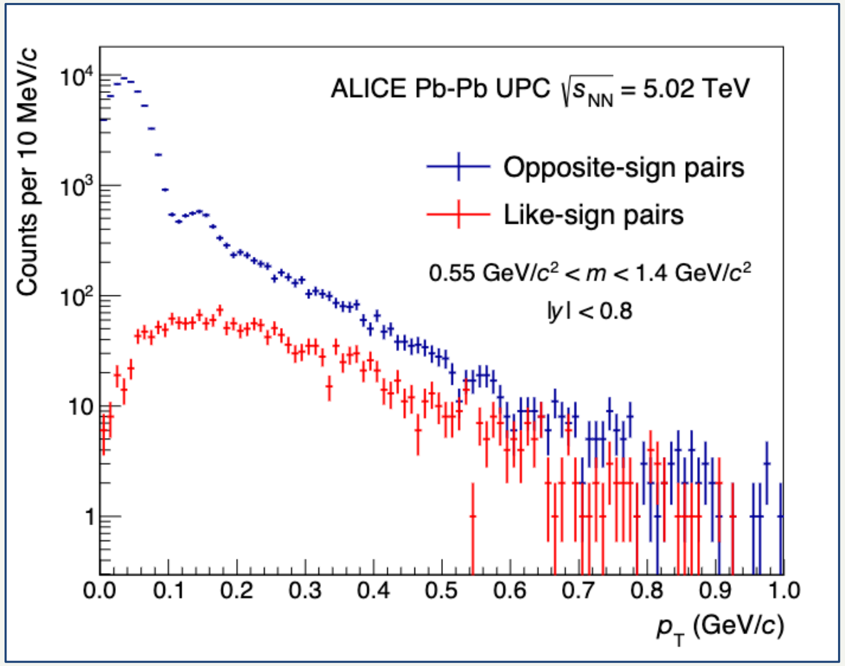
ρ



Phys.Lett.B 817 (2021) 136280



Phys.Rev. C96 (2017) 054904



JHEP 06 (2020) 035

Incoherent scatters also interesting

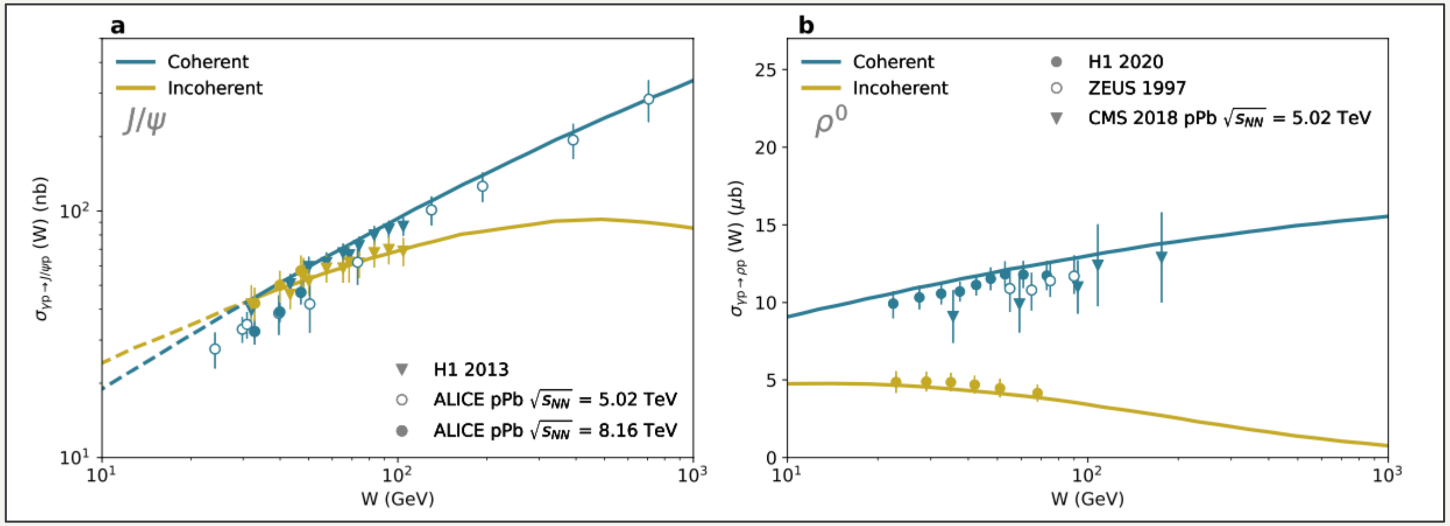
Intact target: sensitive to **average** colour
Breakup: sensitive to fluctuations (**rms**)

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

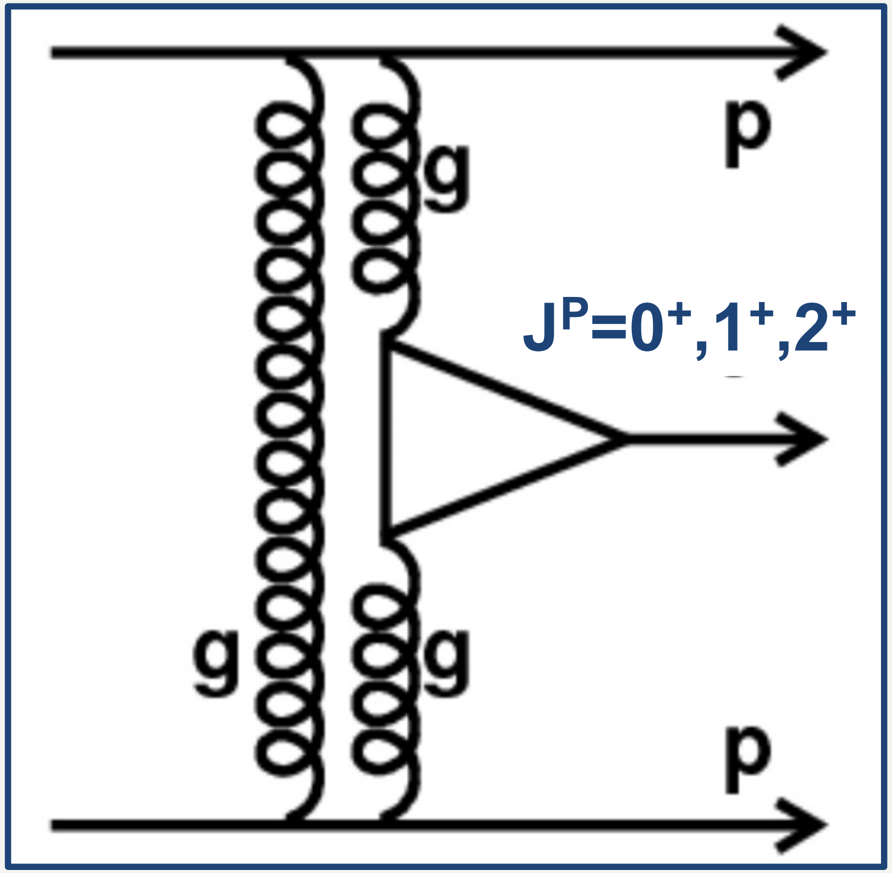
$$\frac{d\sigma^{\gamma^* N \to J/\Psi N^*}}{dt} = \frac{1}{16\pi} \left(\left\langle \left| A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \right|^2 - \left| \langle A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \rangle \right|^2 \right\rangle \right)$$

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)



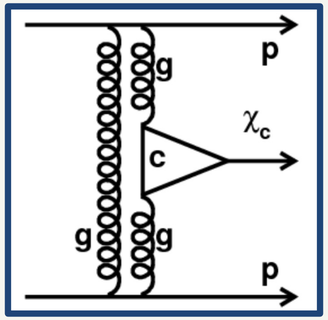
Double Pomeron Exchange

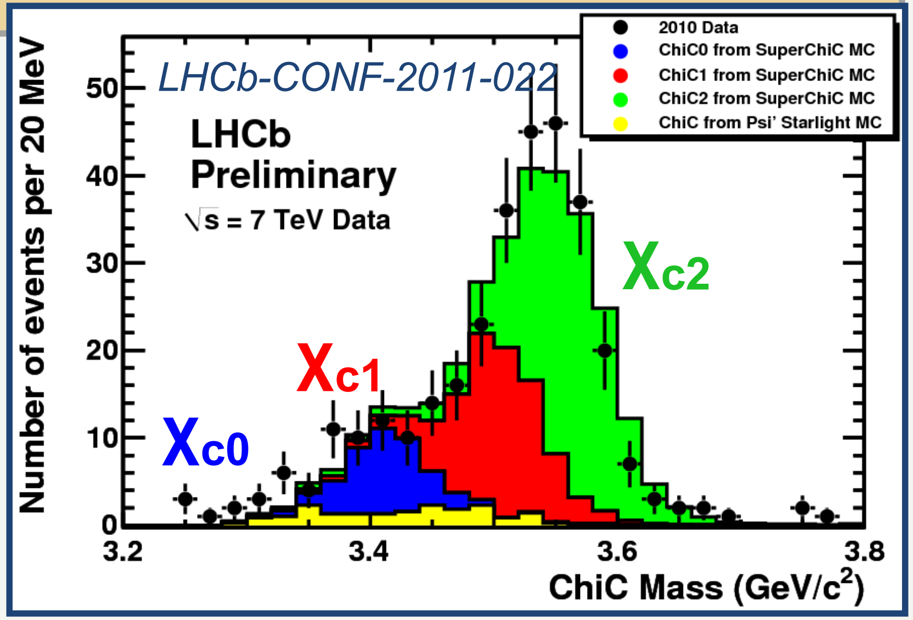


Understanding colourless strong interactions is fundamental

Also simple environment for spectroscopy, in particular, glueballs

Double Pomeron Exchange

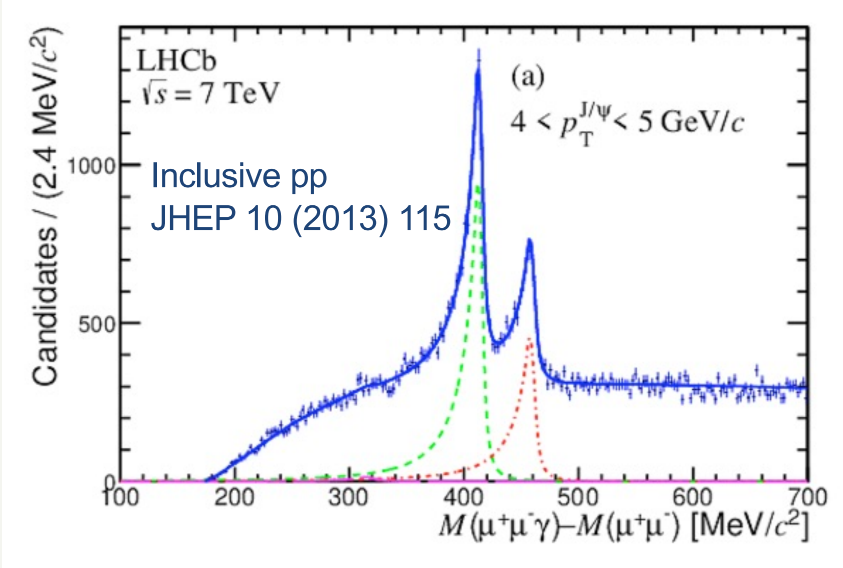




Preliminary. √s=7 TeV

$$\sigma_{\chi_{c0}\to J/\psi\gamma\to\mu^+\mu^-\gamma}(2<\eta_{\mu+},\eta_{\mu-},\eta_\gamma<4.5) = 9.3 \pm 2.2 \pm 3.5 \pm 1.8 \text{ pb}$$
$$\sigma_{\chi_{c1}\to J/\psi\gamma\to\mu^+\mu^-\gamma}(2<\eta_{\mu+},\eta_{\mu-},\eta_\gamma<4.5) = 16.4 \pm 5.3 \pm 5.8 \pm 3.2 \text{ pb}$$
$$\sigma_{\chi_{c2}\to J/\psi\gamma\to\mu^+\mu^-\gamma}(2<\eta_{\mu+},\eta_{\mu-},\eta_\gamma<4.5) = 28.0 \pm 5.4 \pm 9.7 \pm 5.4 \text{ pb}$$

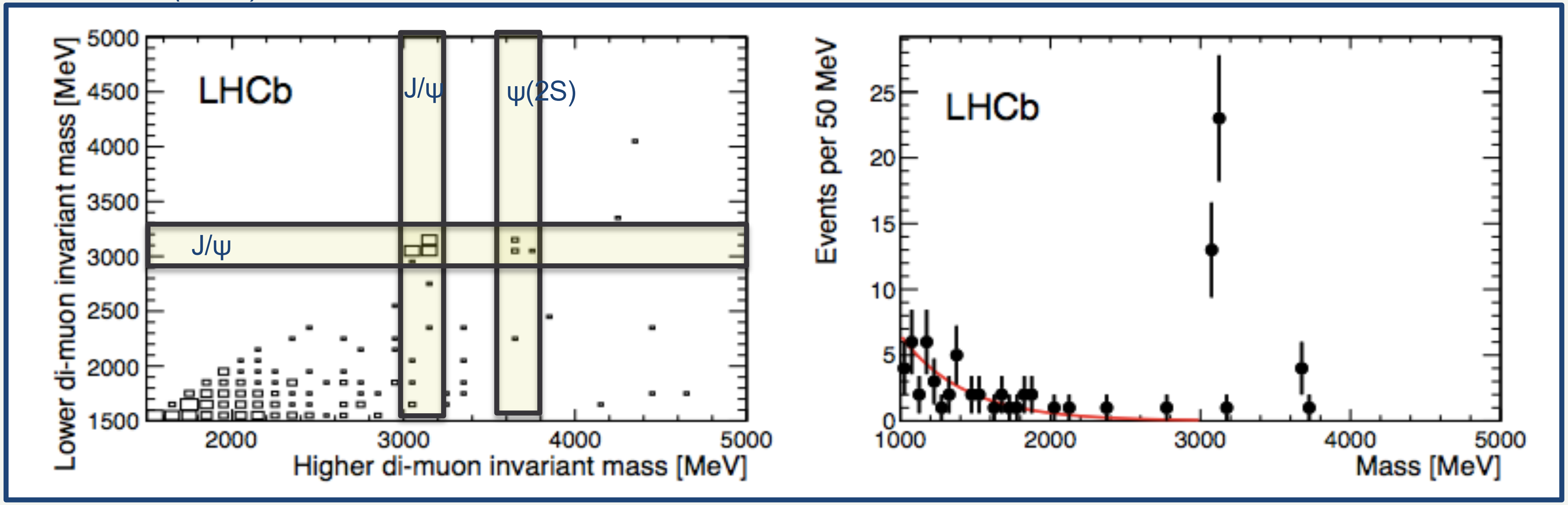
Difficult to separate peaks. Would be much improved using photon conversions.



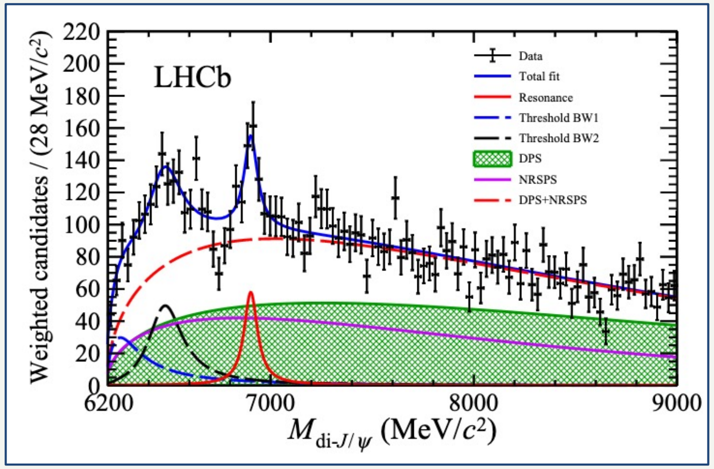
J/ψJ/ψ: search for exotica

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

JPG 41 (2014) 115002



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

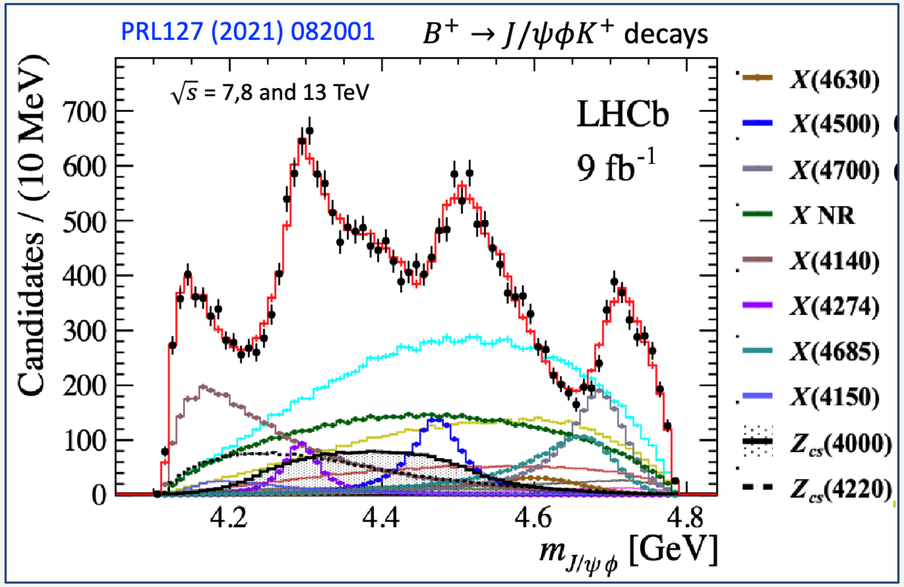


Exclusive quarkonium

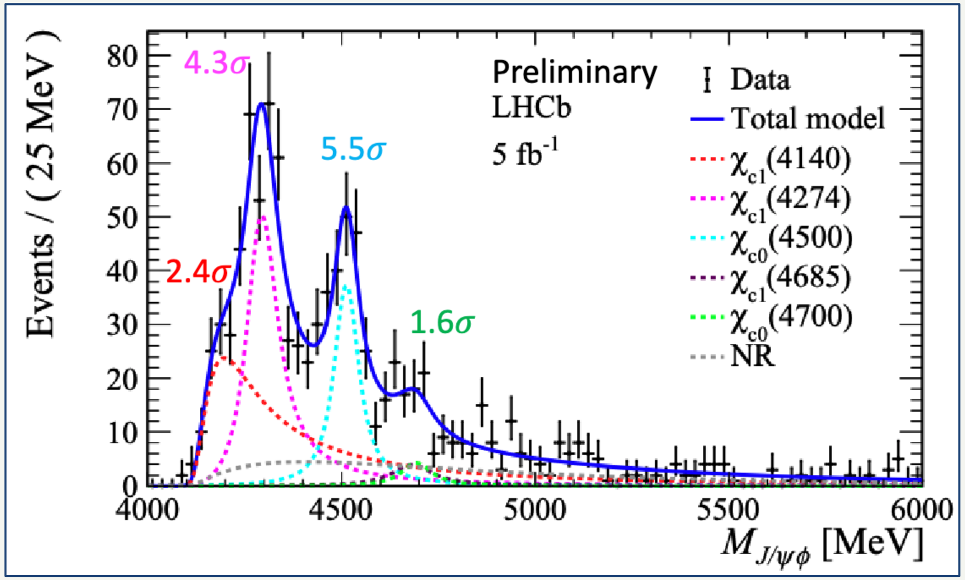
Today from inclusive measurements we know there is significant structure and tetraquark candidates

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.

Summary

- Quarkonia exclusive prodution
  - Photo-produced quarkonia are well described
  - Need to measure χ_c states
  - Pairs of quarkonia and vector mesons probe exotics
- Quarkonia as a tool
  - Proton and nuclear structure
  - Saturation