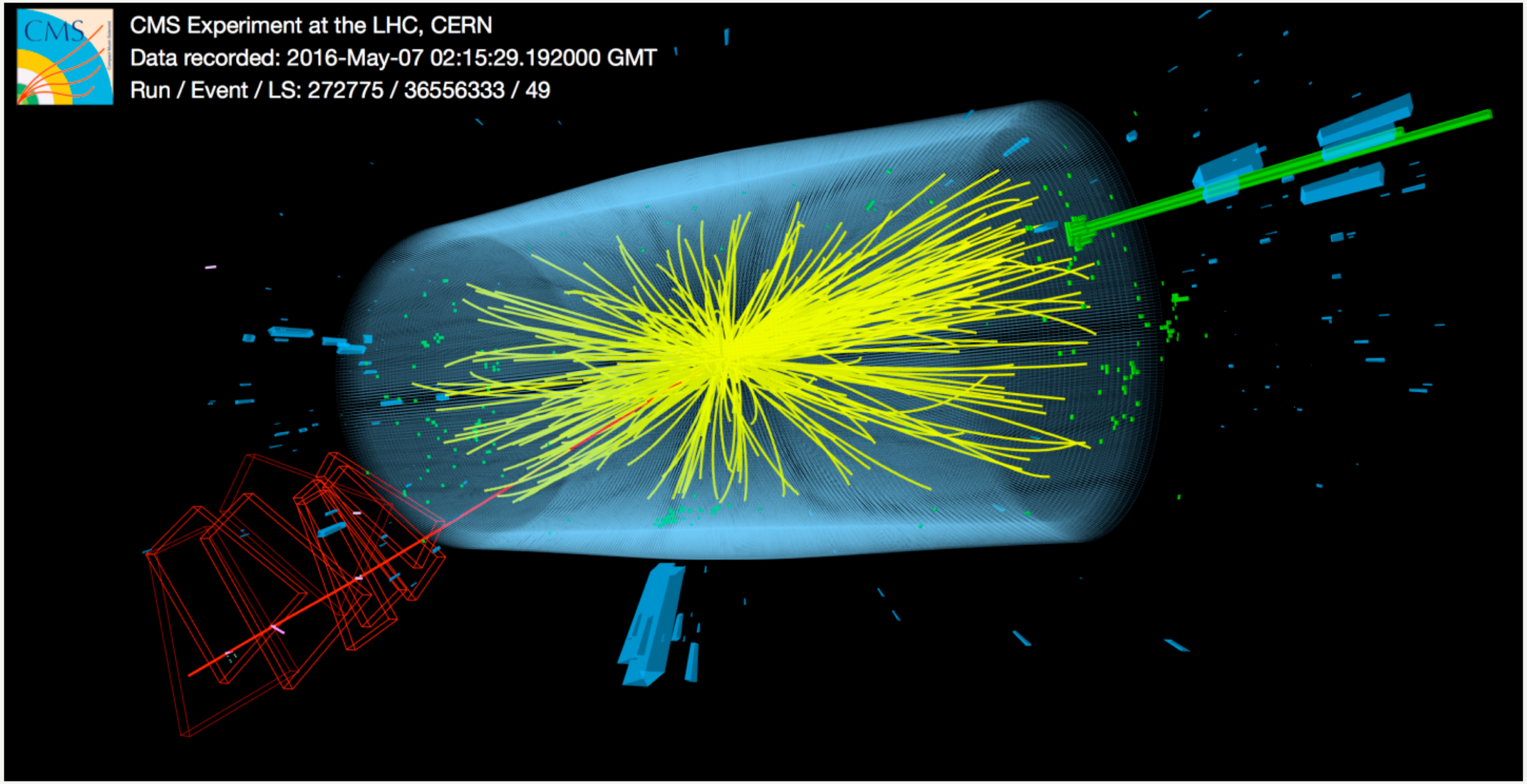
J/ψ in UPC at the LHC

Ronan McNulty
CFNS workshop, 9 Feb 2022

Overview

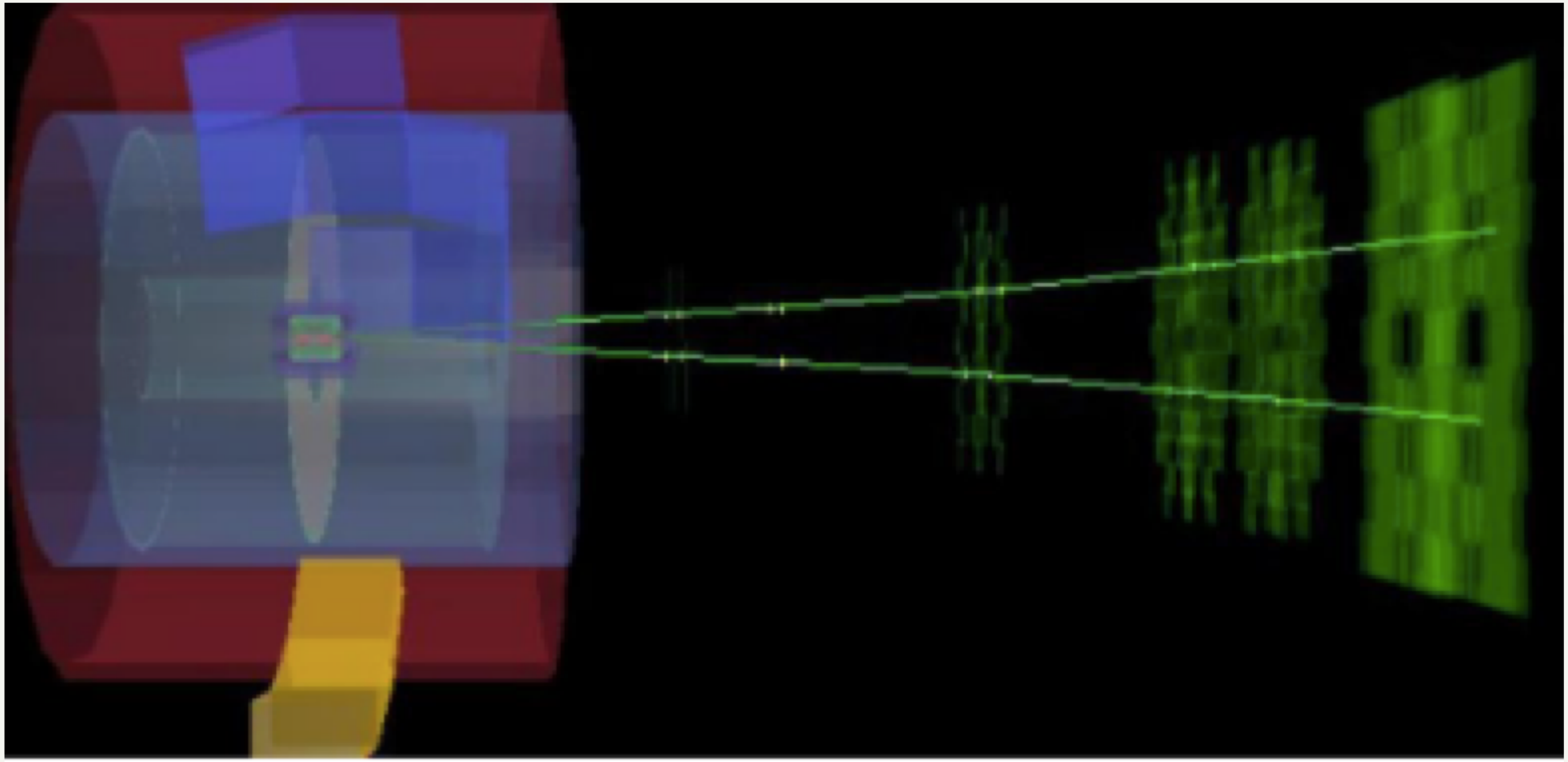
- Introduction
- Experimental Review
  - pp
  - pA
  - AA
- Impact
  - Photoproduction cross-section extraction
  - Comparison to e-p data
  - Gluon PDF
  - Nuclear suppression factors
  - Odderon
  - Hot spots

pp collision



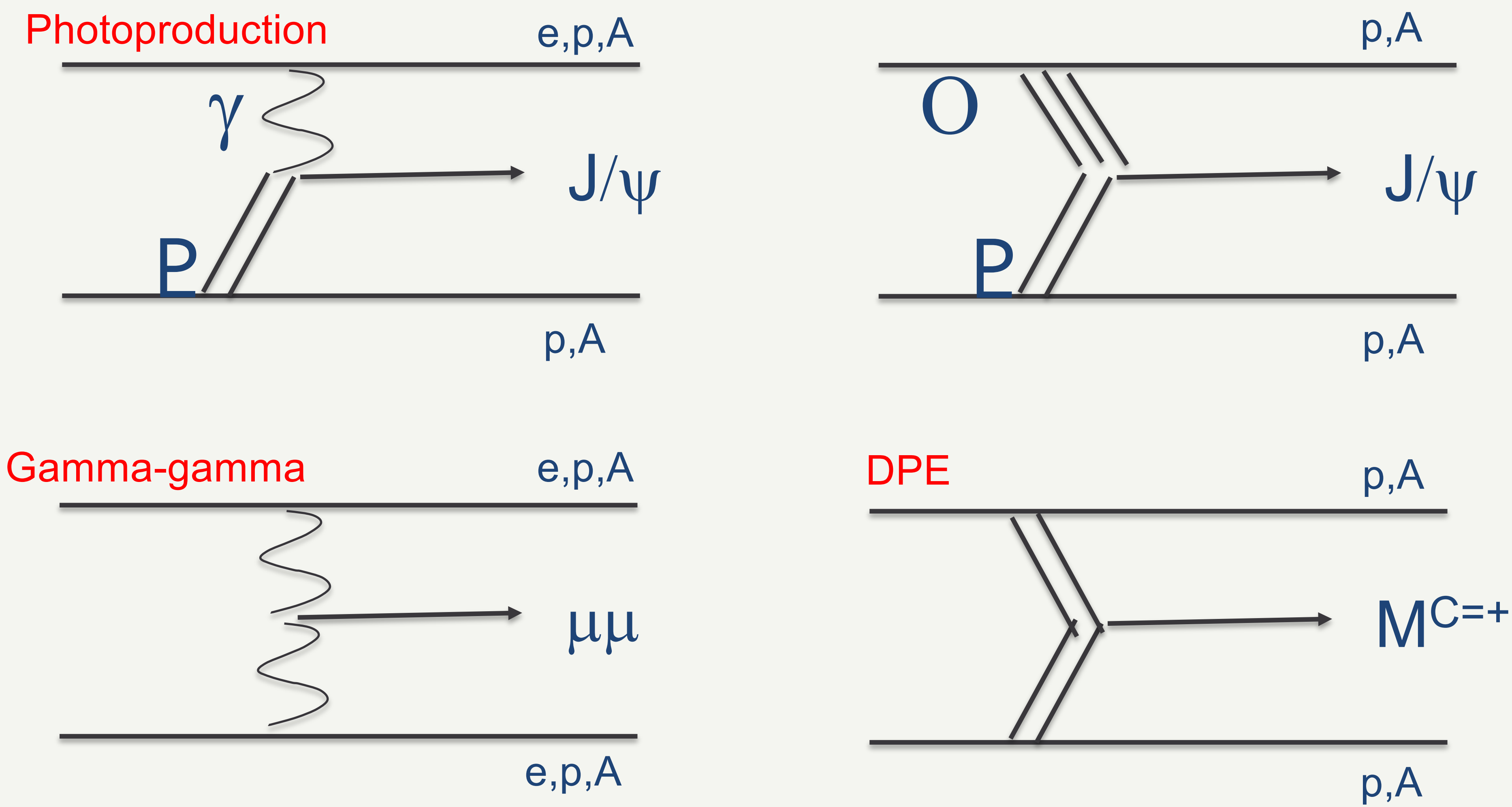
Most collisions at the LHC, pp, pA, AA have enormous multiplicities due to colour flow. However, when colourless propagators are involved, multiplicities are low and events have large **rapidity gaps**.

UPC J/ψ at forward rapidity in ALICE PbPb data



(from Evgeny Kryshen talk at INT workshop)

Central exclusive production (CEP)



Complementarity of colliders in investigating central exclusive production (CEP)

Measurements at LHC

- LHCb (pp, PbPb)
  - pp 7 TeV, *J.Phys.G* 41 (2014) 055002
  - pp 13 TeV, *JHEP* 10 (2018) 167
  - PbPb 5 TeV, *arXiv: 2107.03223 (2021)*

- ALICE (pPb, PbPb)
  - pPb 5.02 TeV, *Phys.Rev.Lett.* 113 (2014) 23, 232504
  - pPb 5.02 TeV, *Eur.Phys.J.C* 79 (2019) 5, 402
  - PbPb 2.76 TeV, *Phys.Lett.B* 718 (2013) 1273-1283
  - PbPb 5.02 TeV, *Eur. Phys. J. C 81 (2021) 712*

Usually J/ψ photoproduction is UPC

Probability of additional reaction is $1\text{-}\exp[-\sigma_{tot}(pN)T_A(b)]$

Gap survival probability

In pp: ~ 10-30% depending on rapidity
In pA : ~100% for $b<R_A + R_p$
In AA: ~100% for $b<2R_A$

pA and AA exclusive collisions are UPC.
pp are not necessarily UPC.

Cross-sections in pp, pA, AA

For pp collisions:

$$\underbrace{\sigma = 2}_{\text{Either p can be target}} \int d^2p_\perp \int_0^\infty dk \underbrace{\left(\frac{dn}{dk}\right)_p}_{\text{Photon flux}} \sigma(\gamma^* p \to J/\psi + p)$$

For AA collisions:

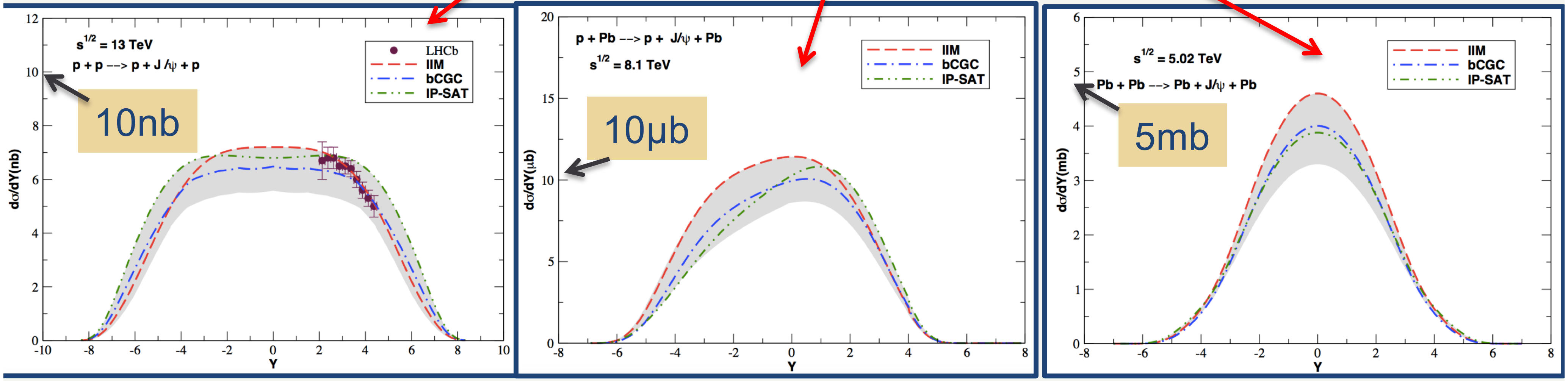
$$\sigma = 2 \int d^2p_\perp \int_0^\infty dk \underbrace{\left(\frac{dn}{dk}\right)_A}_{\text{Flux from ion (x } Z^2\text{)}} \underbrace{\sigma(\gamma^* A \to J/\psi + A)}_{\text{Factor (x A)}}$$

For pA collisions:

$$\begin{aligned}\sigma \;&= \int d^2p_\perp \int_0^\infty dk \overbrace{\left(\frac{dn}{dk}\right)_A}^{\text{x } Z^2} \sigma(\gamma^* p \to J/\psi + p) \\ &+ \int d^2p_\perp \int_0^\infty dk \left(\frac{dn}{dk}\right)_p \underbrace{\sigma(\gamma^* A \to J/\psi + A)}_{\text{x A}}\end{aligned}$$

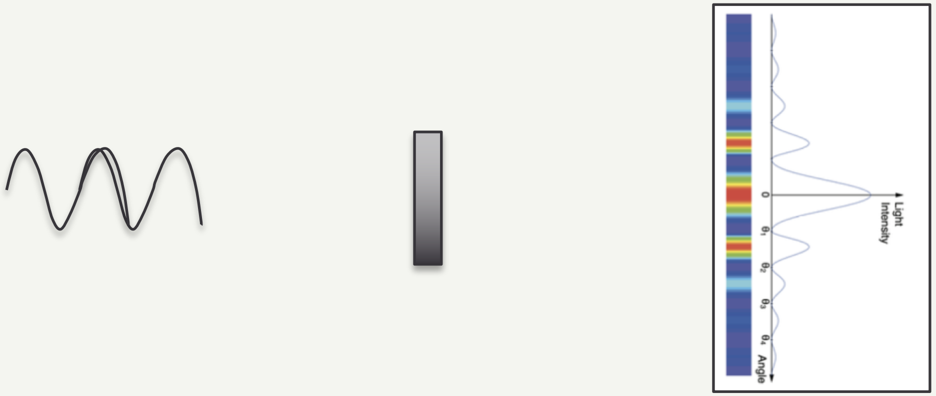
Complementarity of collisions

Coherent	DPE (PP)	γP	γγ
pp	~100μb	~100μb	~0.0001μb
pA	x $A^{1/3}$	x Z^2	x Z^2
AA	x $A^{1/6}$	x AZ^2	x Z^4

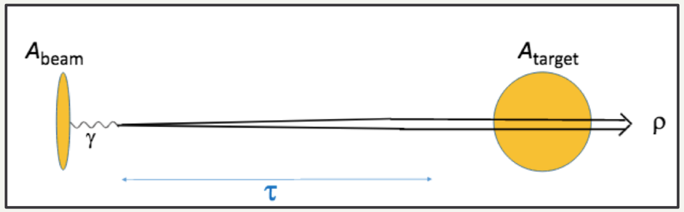


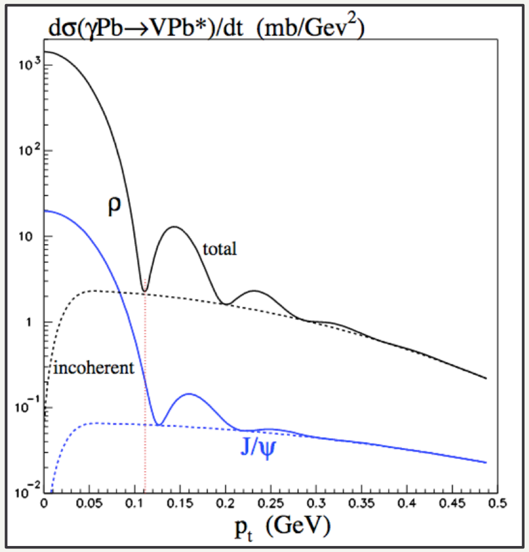
Goncalves et al. Phys.Rev.D 96 (2017) 9, 094027

Transverse momentum



Optical diffraction:
minima occur at $\theta = 1/kR$





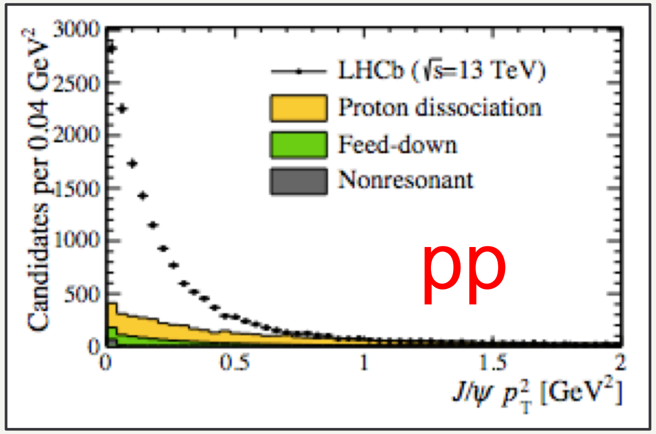
In black-disk limit, first minimum in AA collisions at $p_T \sim 1/R_A$

$$\frac{d\sigma_{\rho A}}{dp_t^2} = \frac{|A_{\rho A}(p_t)|^2}{16\pi s^2},$$

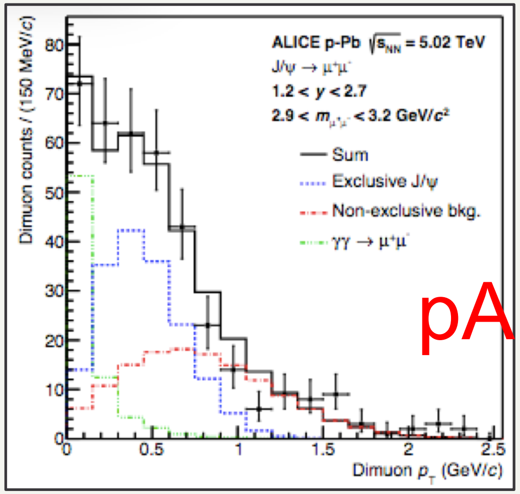
$$A_{\rho A}(p_t) = 2s \int d^2b \, e^{ib\cdot p_t} \, A_{\rho A}(b)$$

Transverse momentum

JHEP 10 (2018) 167

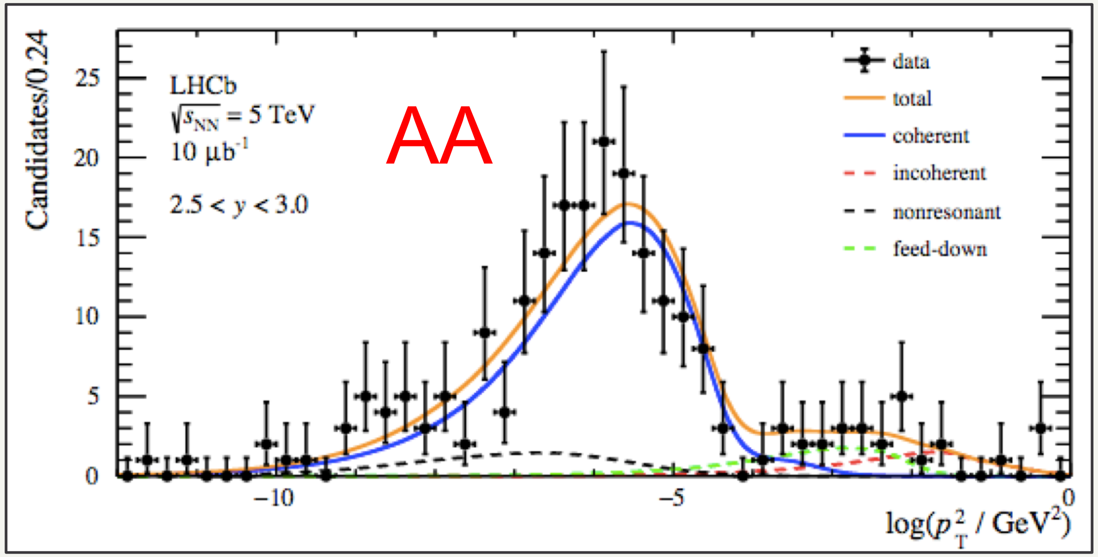


Eur.Phys.J.C 79 (2019) 5, 402



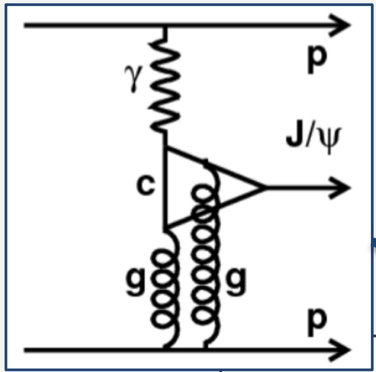
$<p_T>$ in pp and pA is ~0.5 GeV = $1/R_p$

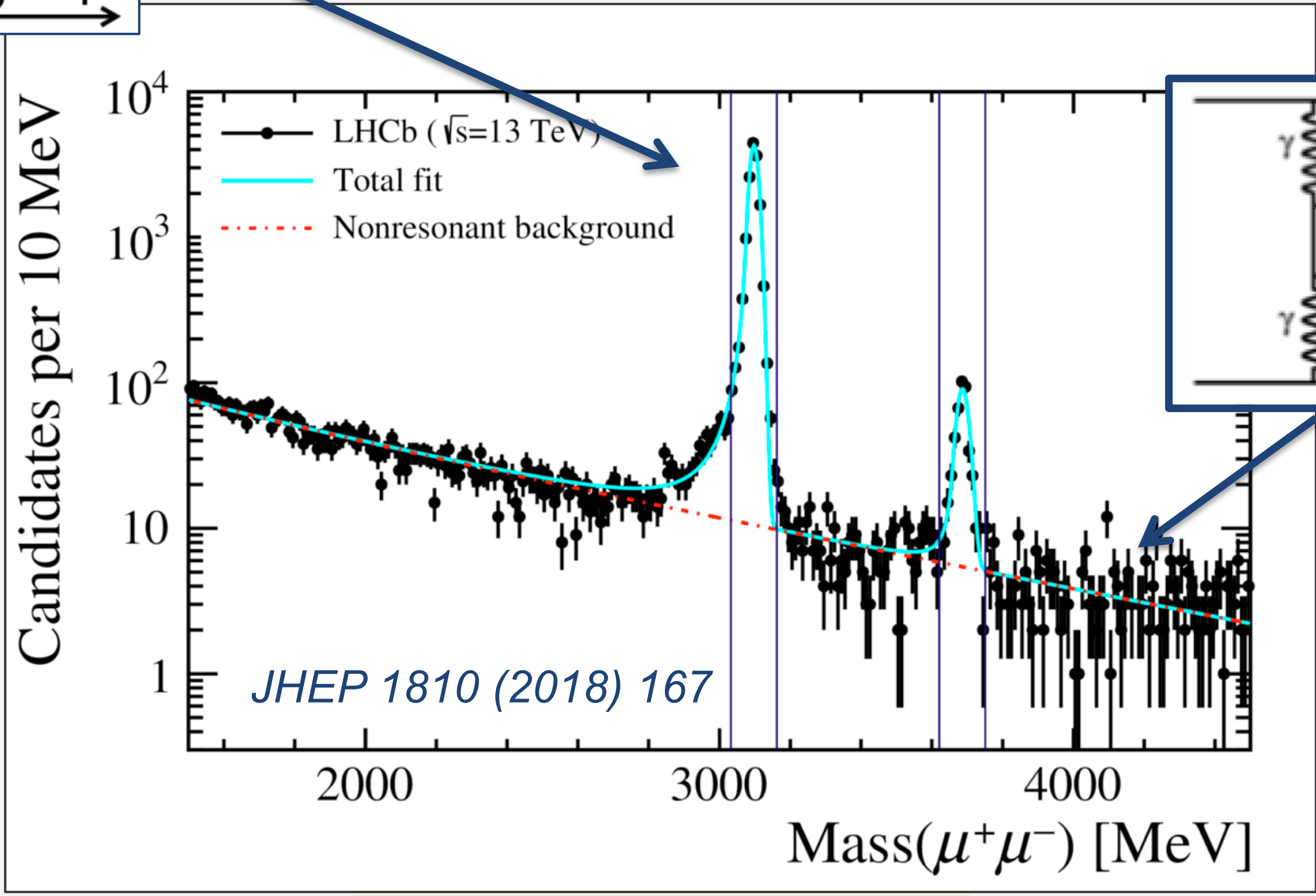
arXiv: 2107.03223 (2021)

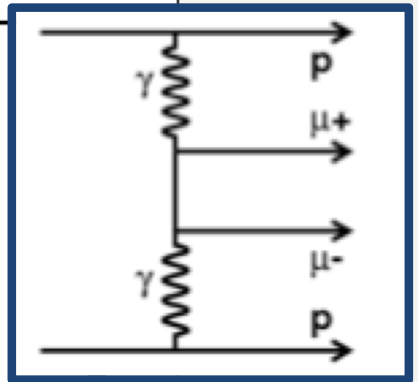


$<p_T>$ in AA. ~0.05 GeV ~ $1/R_A$

J/ψ production in pp







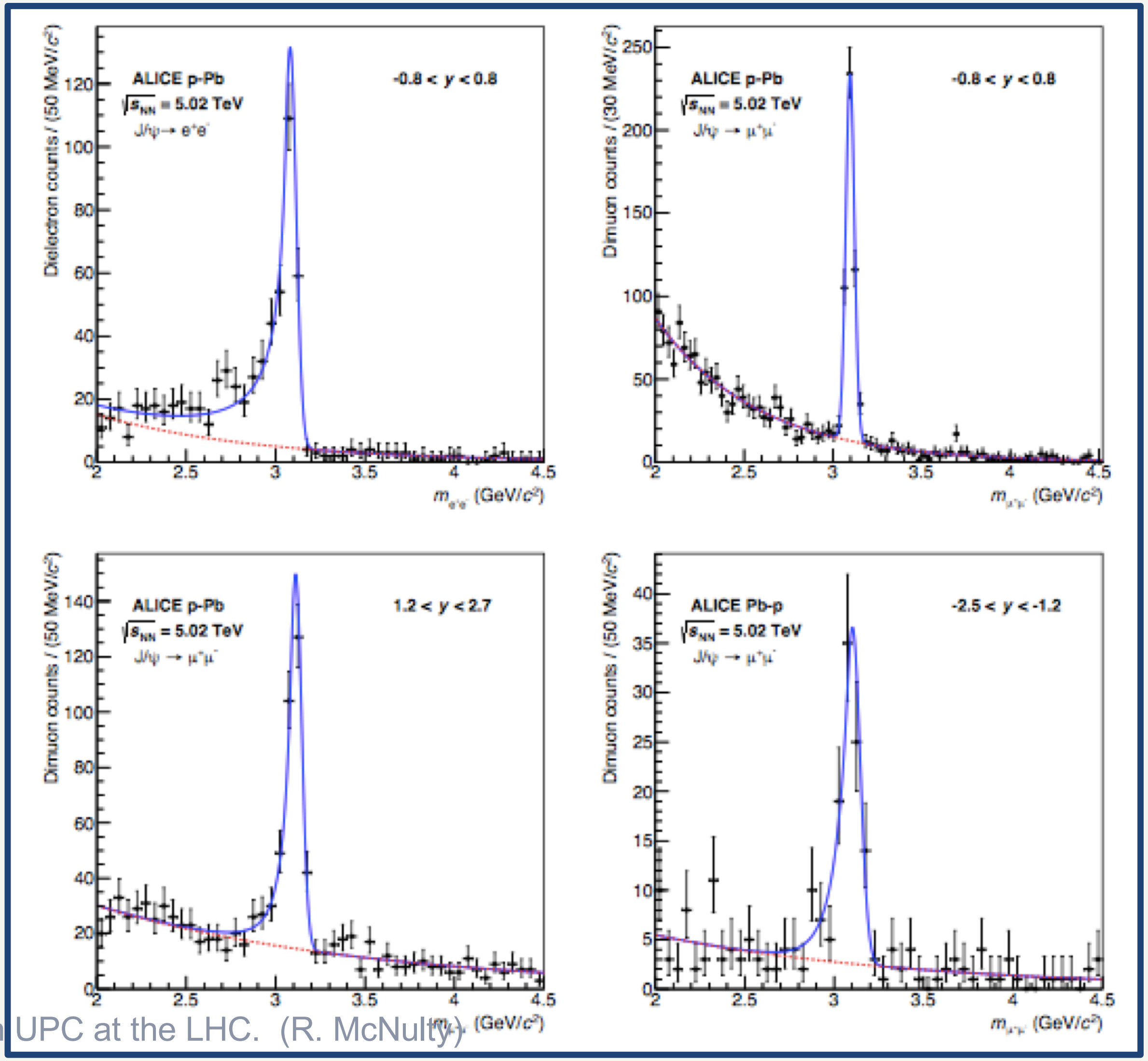
Two muons and nothing else

J/ψ production in pPb and Pbp

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

Relative amount of continuum γγ->μμ is greater in pA collisions.

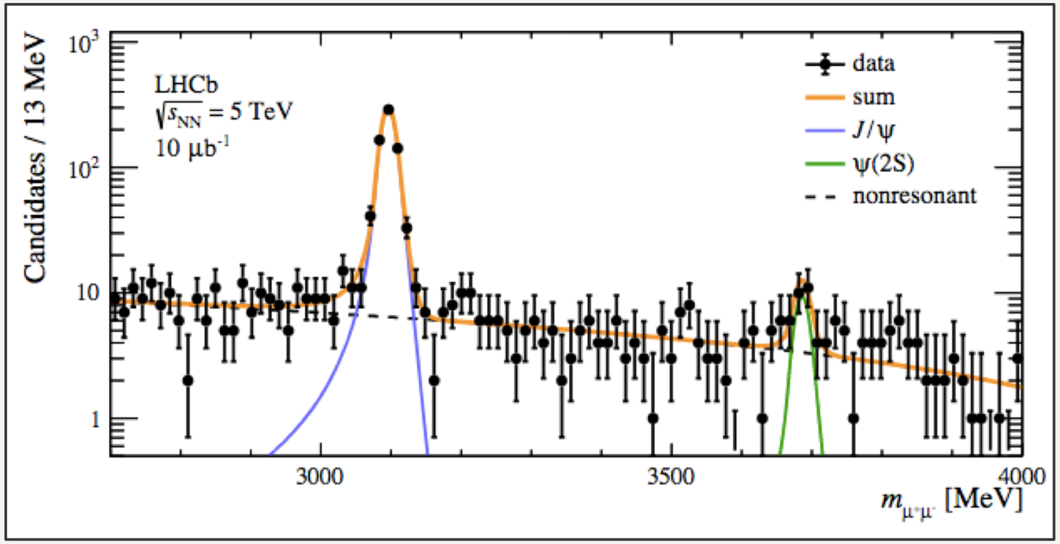
However, no J/ψ feed-down from DPE charmonium production.



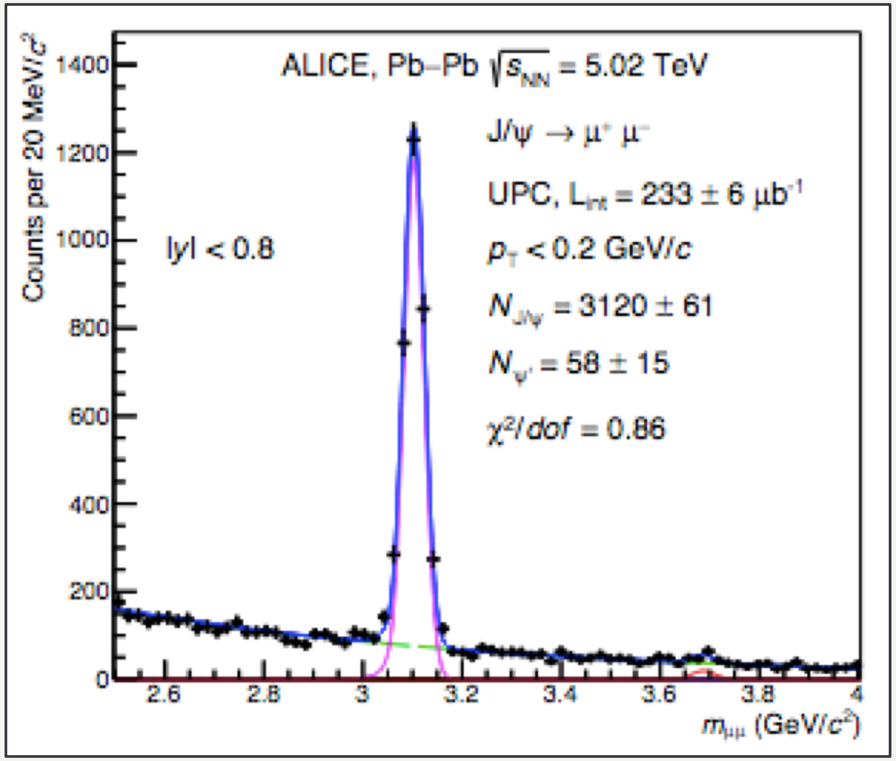
J/ψ production in PbPb

Relative amount of continuum
$\gamma\gamma \to \mu\mu$ even greater.

Again, no J/ψ feed-down from
DPE charmonium production.



arXiv:2107.03223



Eur. Phys. J. C 81 (2021) 712

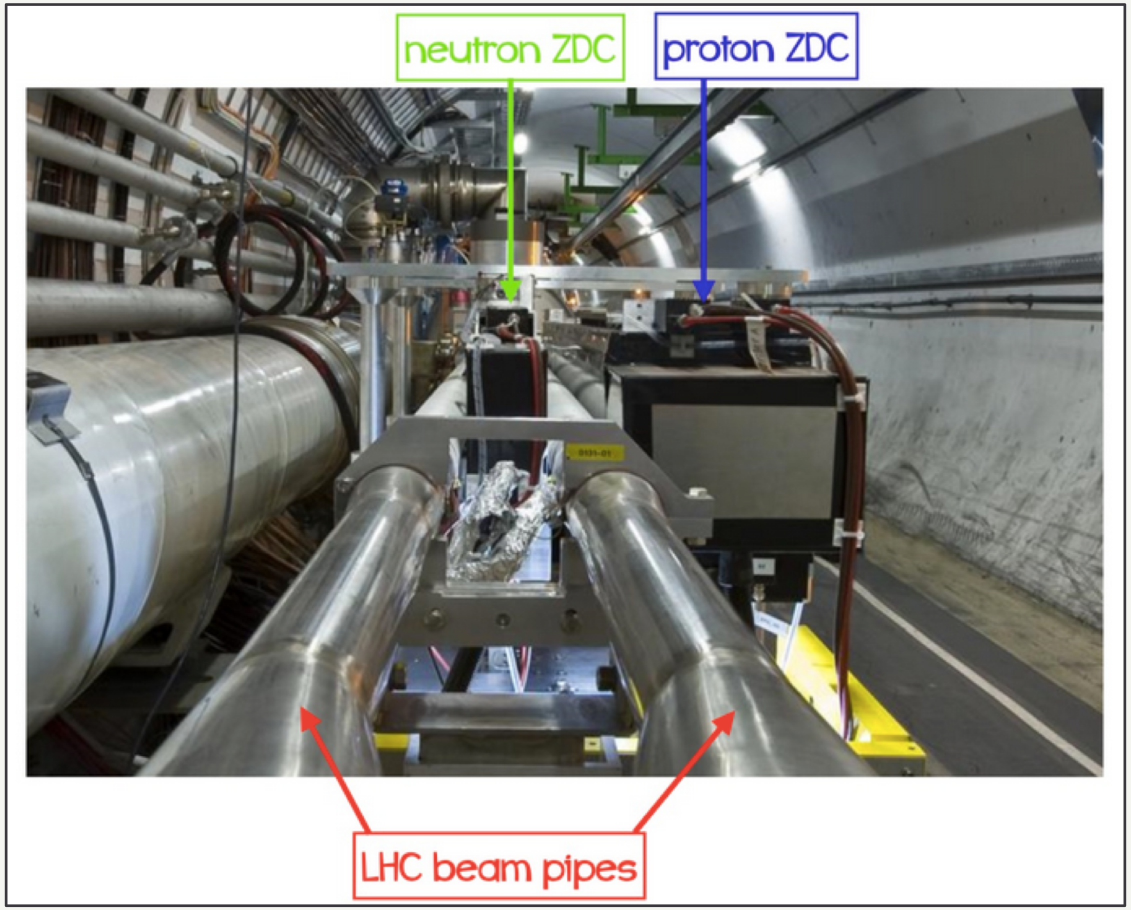
Non-exclusive background

How do you know an event is truly exclusive?

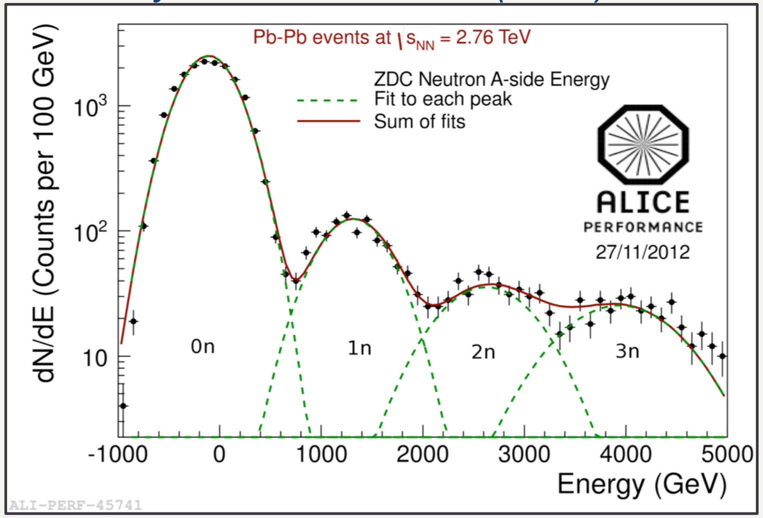
- Increase coverage, especially in (far) forward region
- Find different characteristic of background (e.g. p_T)

ZDC calorimeters in ALICE

(used for pPb analysis)

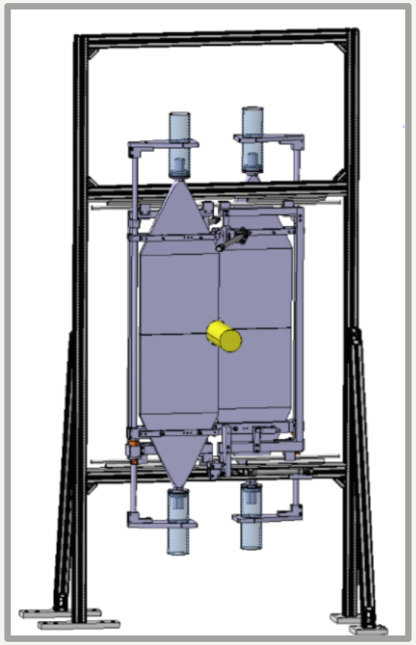


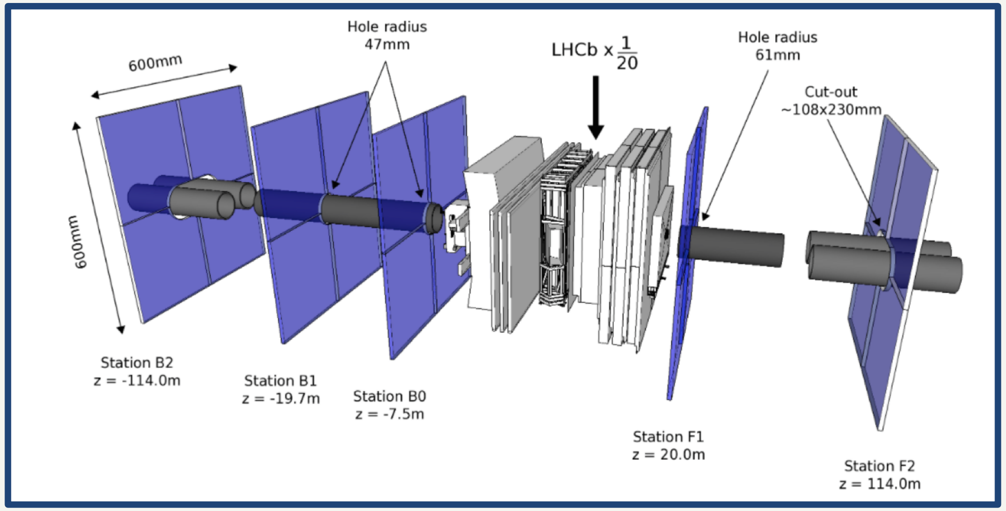
J. Phys.: Conf. Ser. 455 (2013) 012010



Detection of neutrons when ion breaks up allows template characterisation of incoherent events

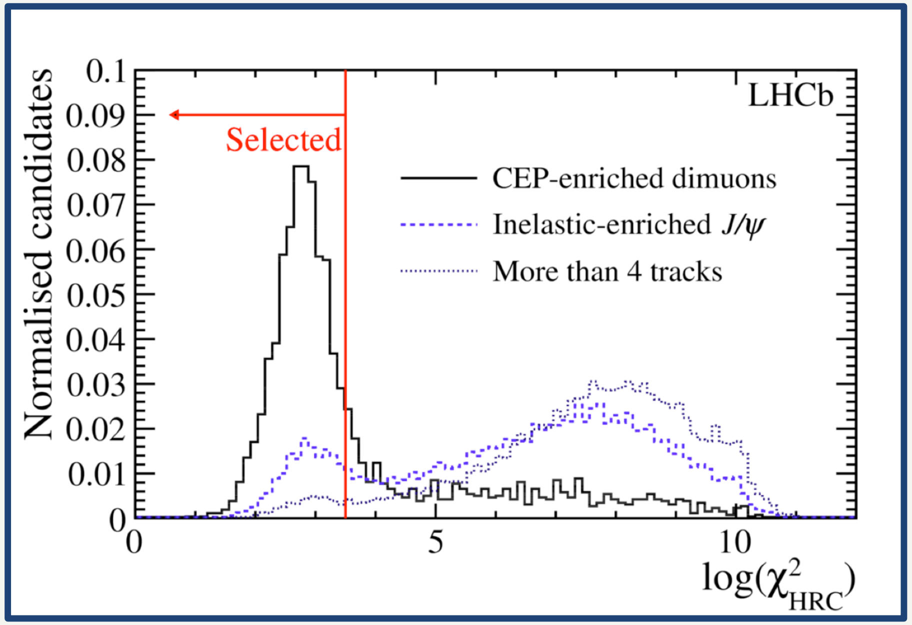
Forward scintillators in LHCb





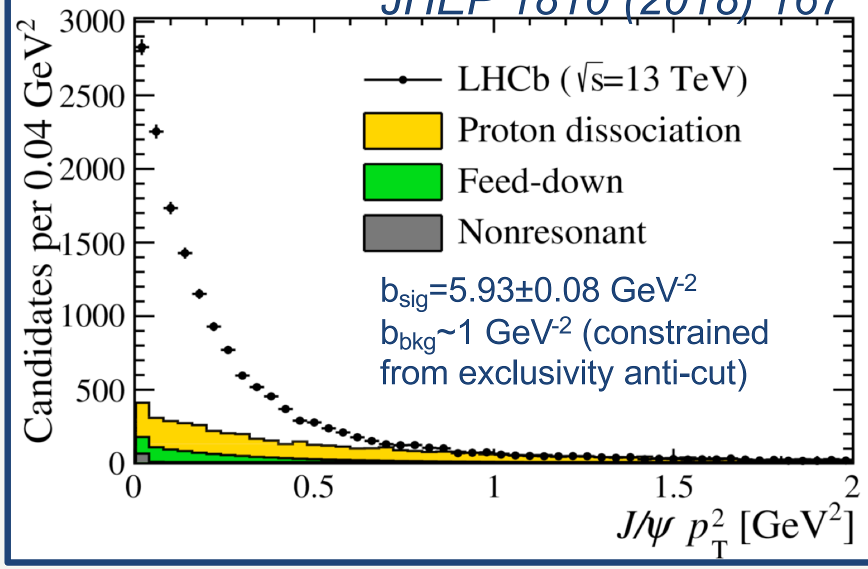
LHCb fully instrumented: $2 < \eta < 5$
Veto region (Run 2): $-10<\eta<-5$, $5<\eta<10$

JHEP 1810 (2018) 167



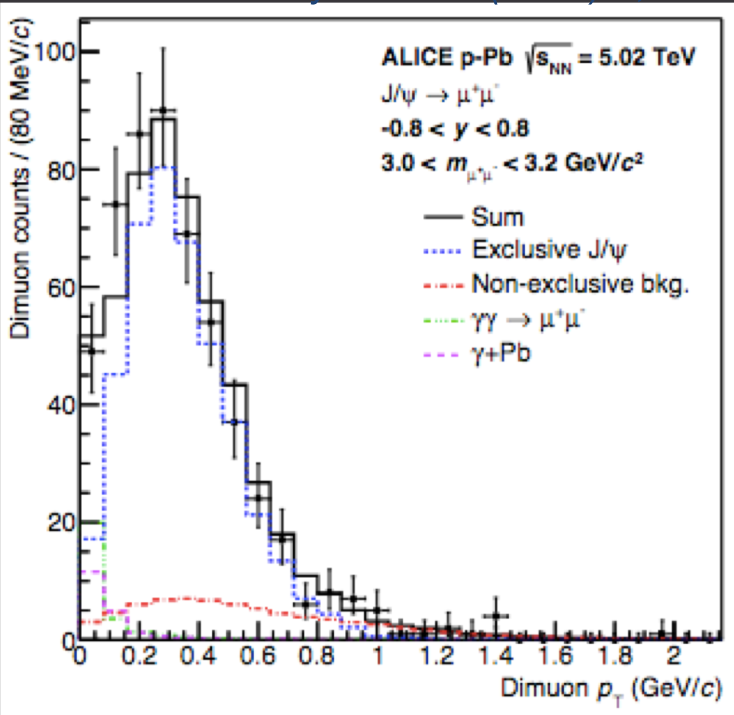
The CEP signal is known
The background is process dependent

Estimating proton-dissociation in pp and Ap



b_{sig}=5.93±0.08 GeV^{-2}
b_{bkg}~1 GeV^{-2} (constrained from exclusivity anti-cut)

Eur.Phys.J.C 79 (2019) 5, 402



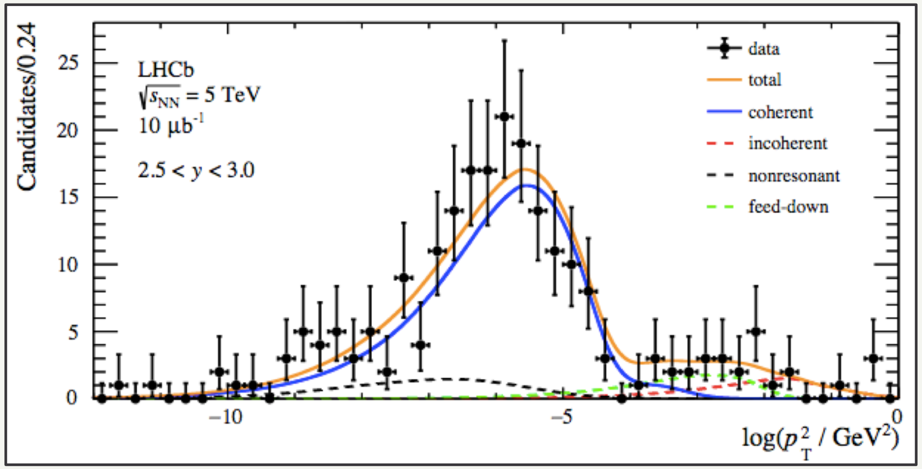
$$\frac{d\sigma}{dt} \sim \exp(bt) = \exp(-bp_T^2)$$

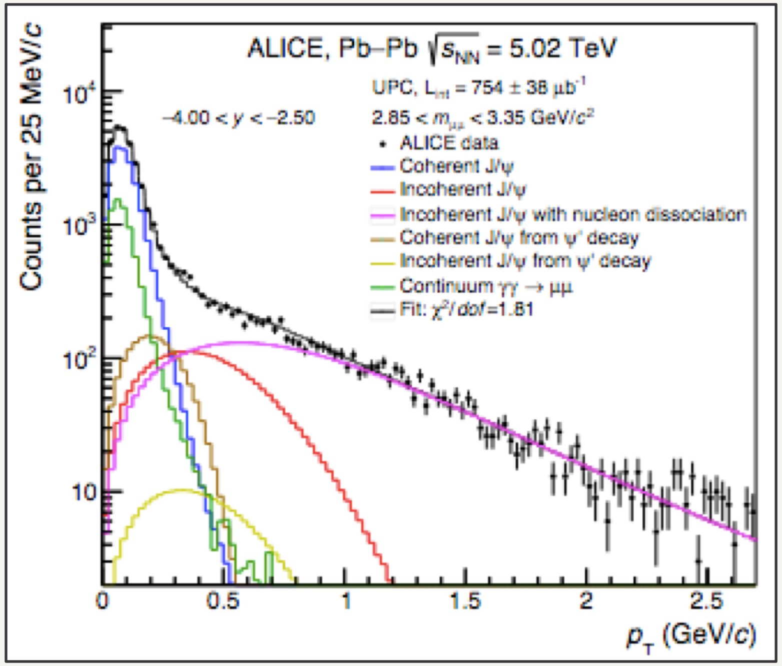
Estimating incoherent production in AA

It is much easier to detect the break-up of the larger ion….

Eur. Phys. J. C 81 (2021) 712

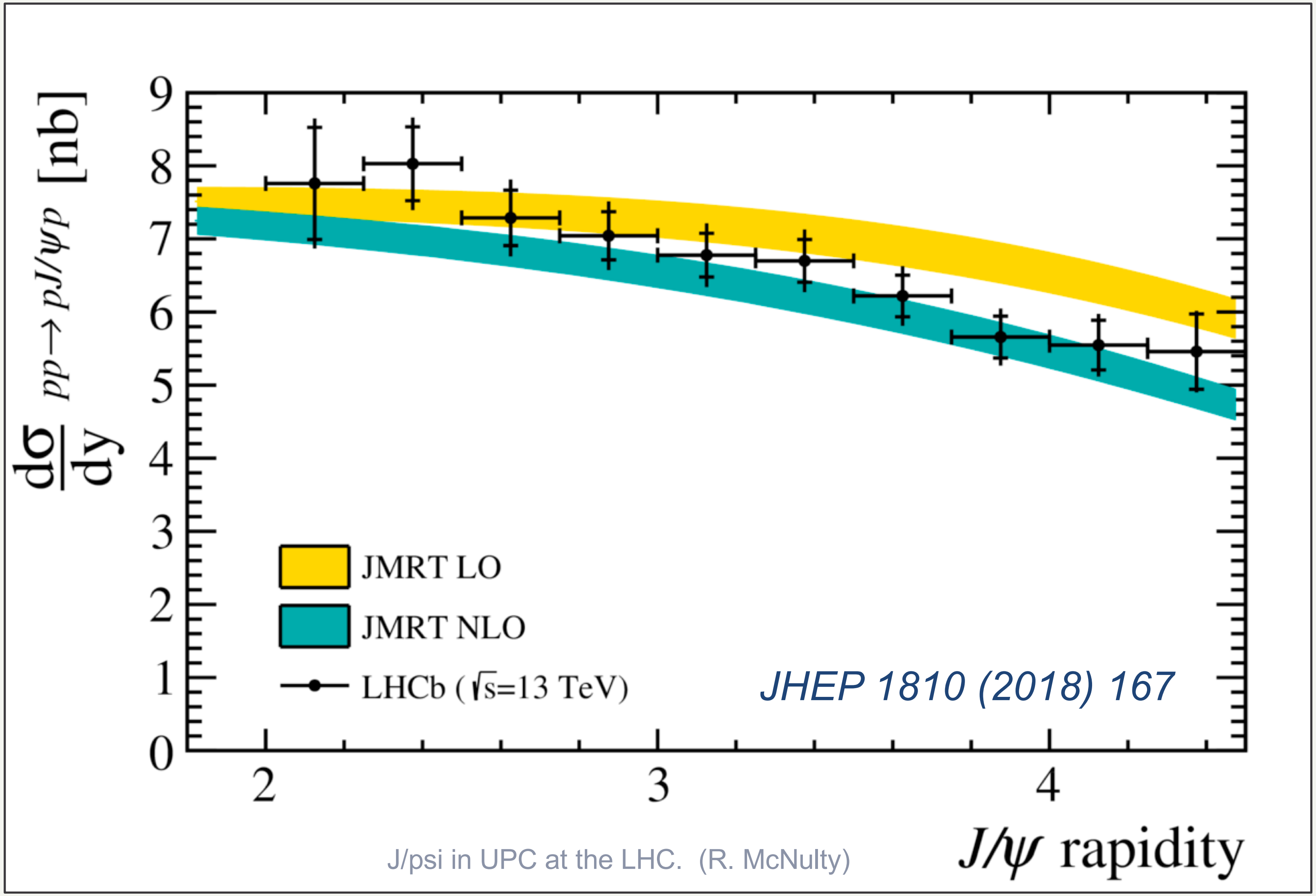
arXiv: 2107.03223 (2021)



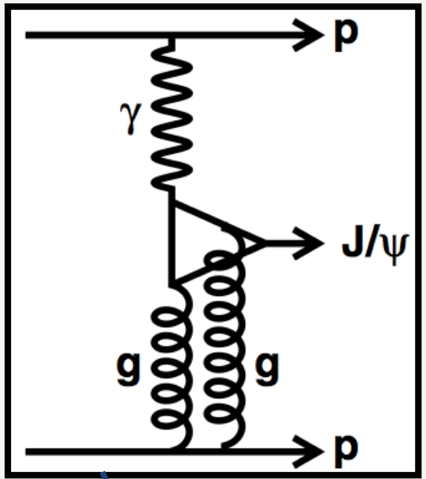


$$\frac{dN}{dp_T} \sim p_T \left(1 + \frac{b_{pd}}{n_{pd}} p_T^2\right)^{-n_{pd}}$$

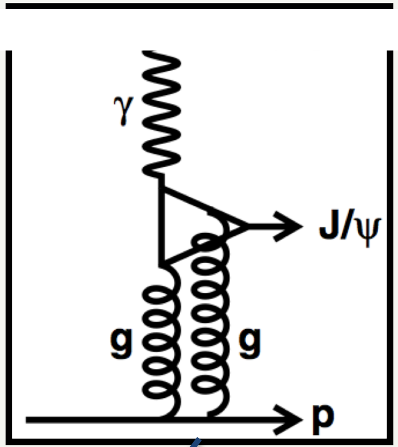
Differential cross-section pp→pJ/ψp



Convert to photo-production cross-section



LHCb measures



HERA measured

Photon Flux

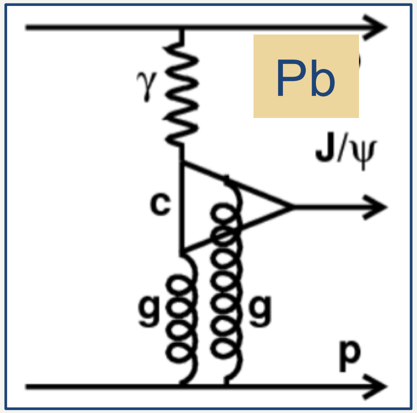
$$\frac{d\sigma}{dy}_{pp\to pJ/\psi p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to J/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi p}(W_-)$$

Gap Survival

W+ term contributes about 2/3
Take W- from HERA measurement

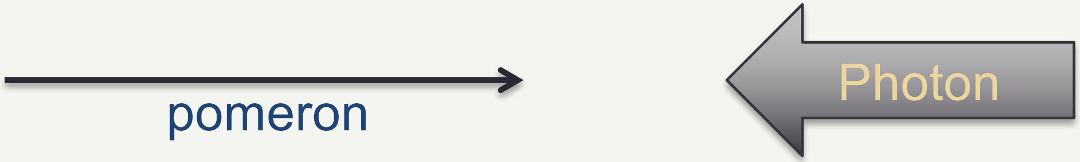
HERA measured power-law: $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\,\mathrm{GeV})^{0.67}\,\mathrm{nb}$

Ambiguity is much removed in pPb collisions



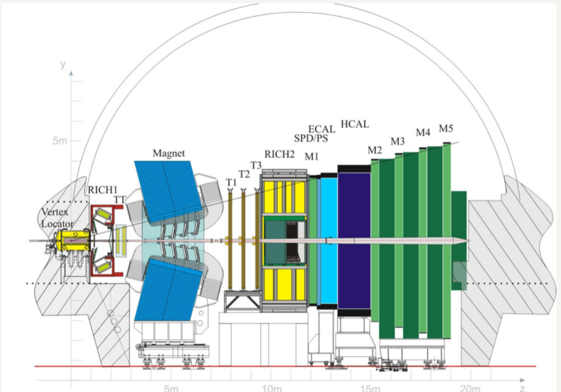
Which projectile produced the photon?

Assuming the photon always comes from Pb……



pPb collisions

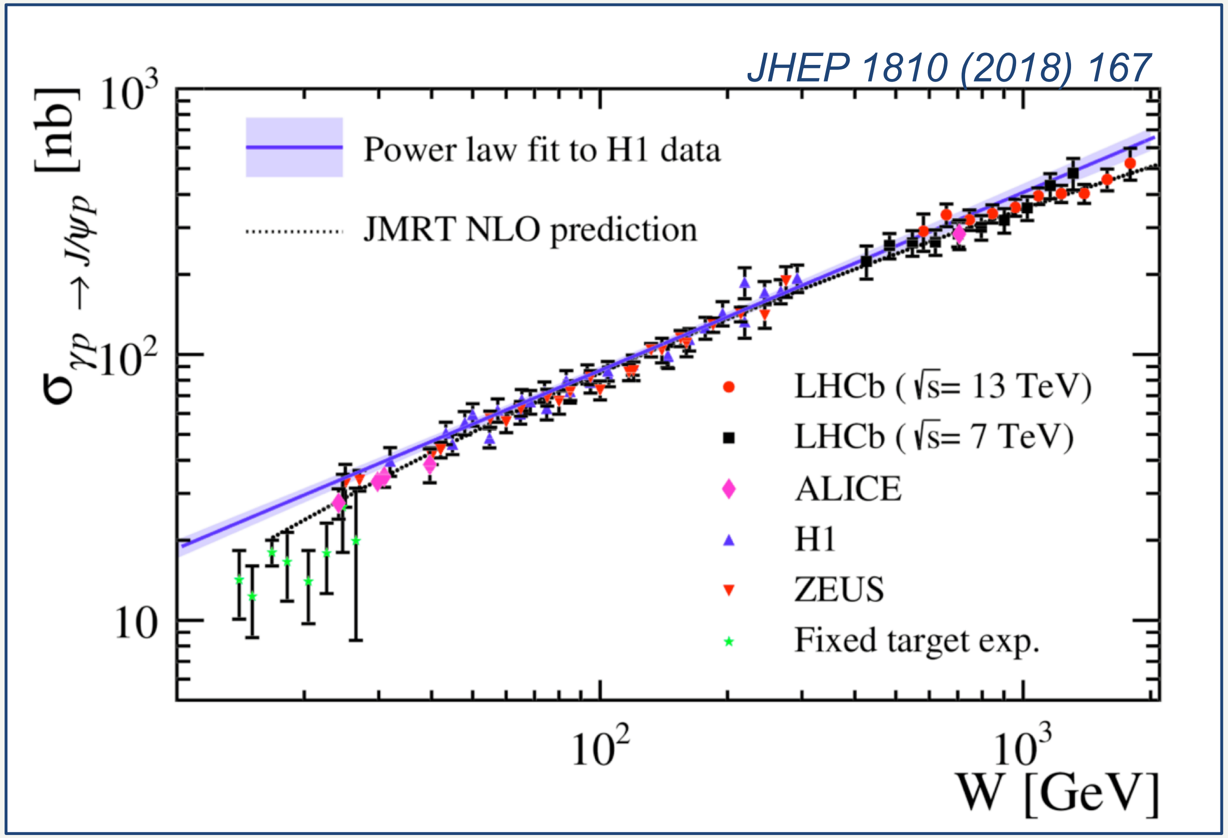
(low W – Hera region)

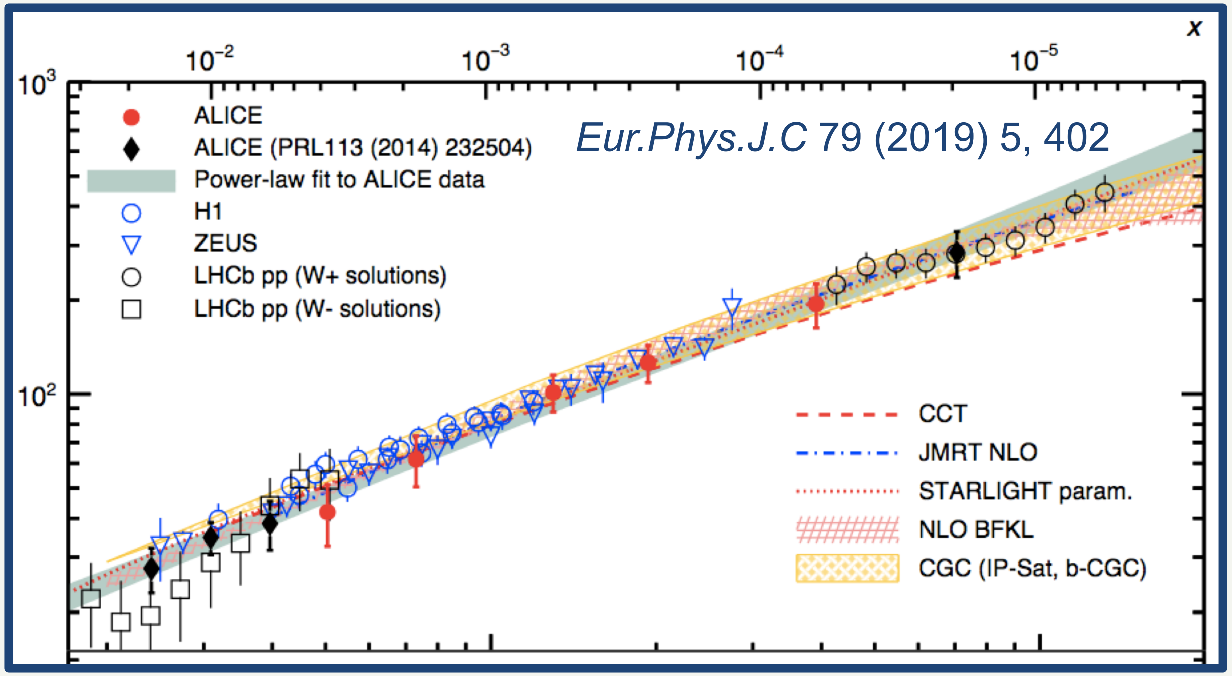


Pbp collisions

(high W
up to 2 TeV or x=2E-6)

Photoproduction cross-section



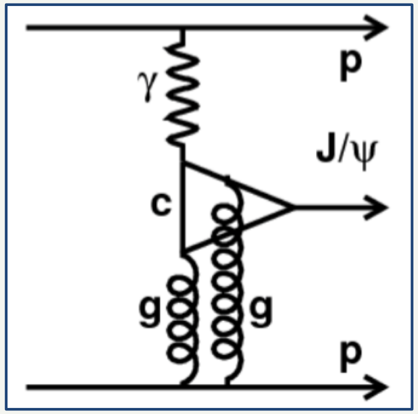


Consistency across experiments and projectiles:
ep, pp, Pbp

Linear power-law not sufficient

Consistent with NLO predictions (and with models that include saturation)

Gluon parton density function



In principle, this should be a clean probe of the gluon PDF.

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

M. Ryskin, Z. Phys. C 57 (1993) 89–92

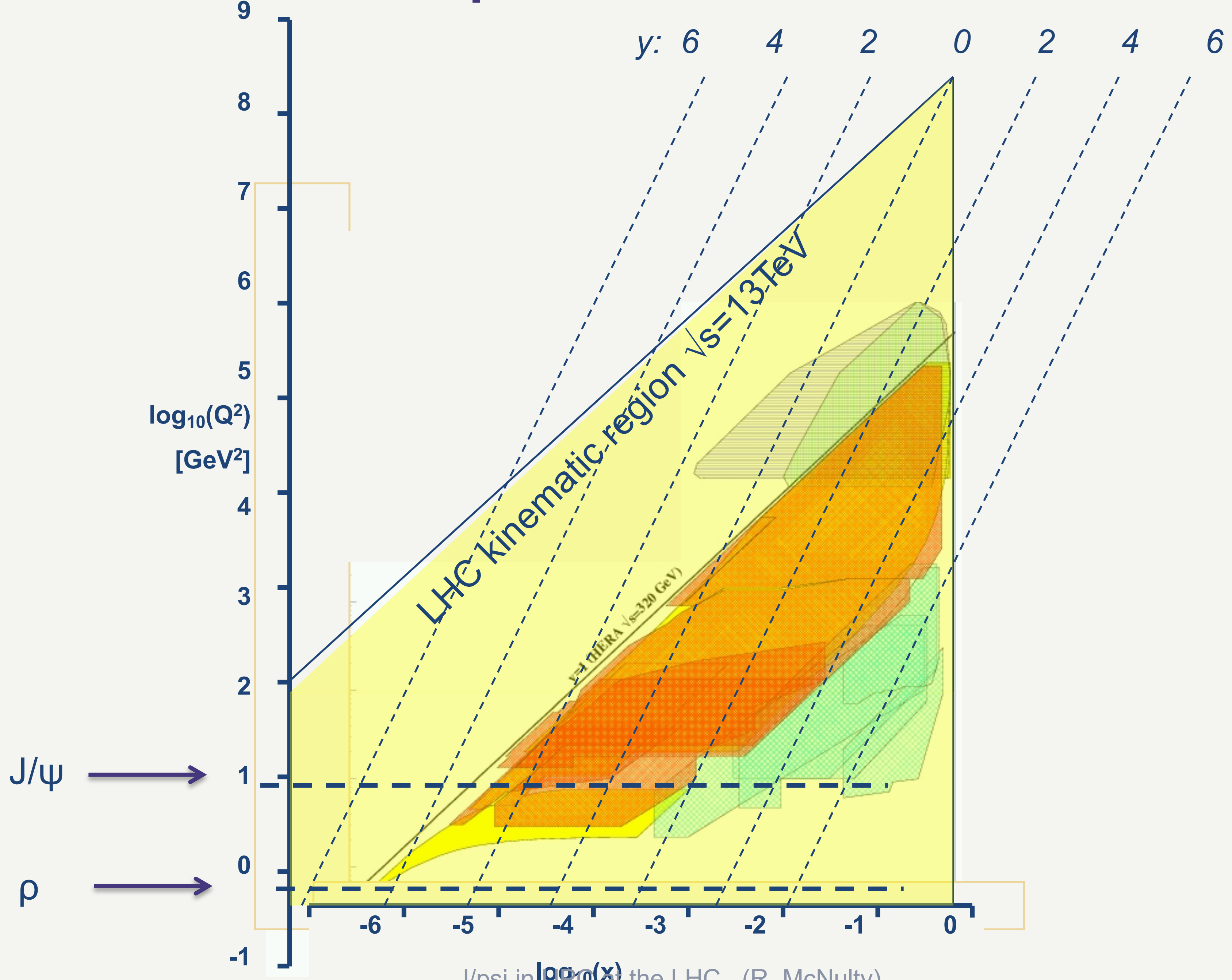
Large programme of work to make predictions at NLO and to tame strong scale dependencies.

S.P. Jones et al., J.Phys.G 44 (2017) 3, 03LT01

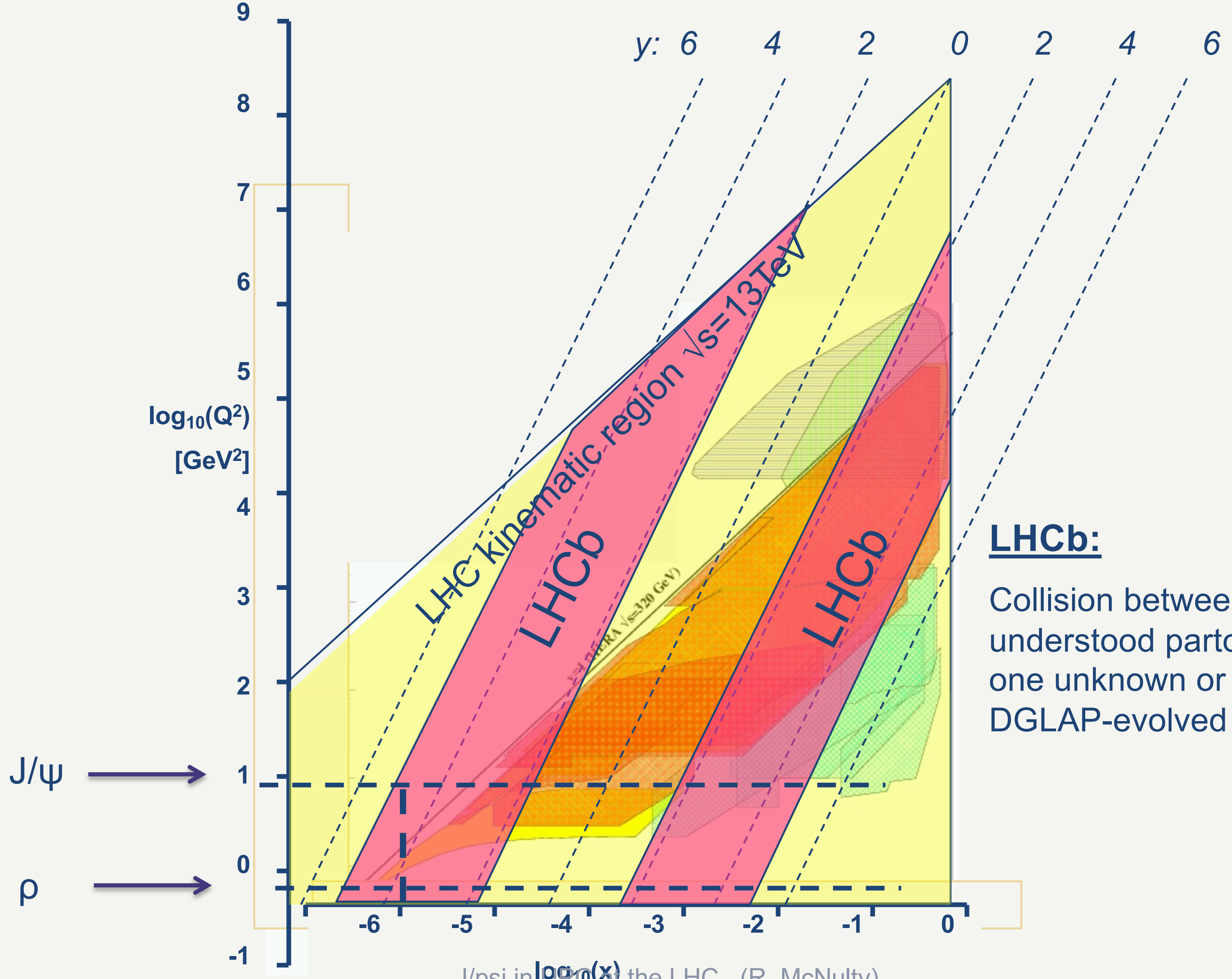
C. Flett et al., Phys.Rev.D 101 (2020) 9, 094011

C. Flett et al., Phys.Rev.D 102 (2020) 114021

x-values probed at LHC



x-values probed at LHC

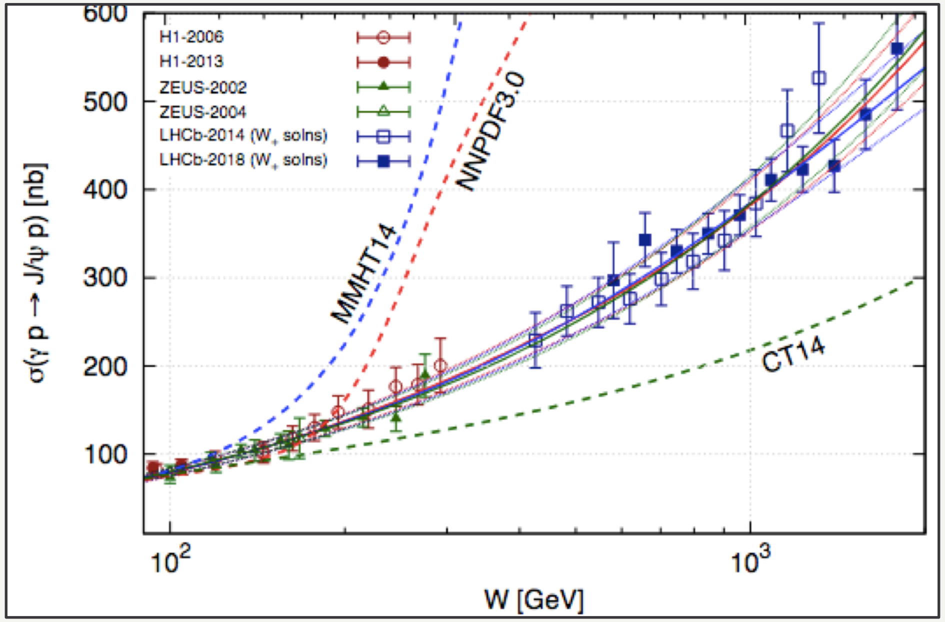


LHCb:

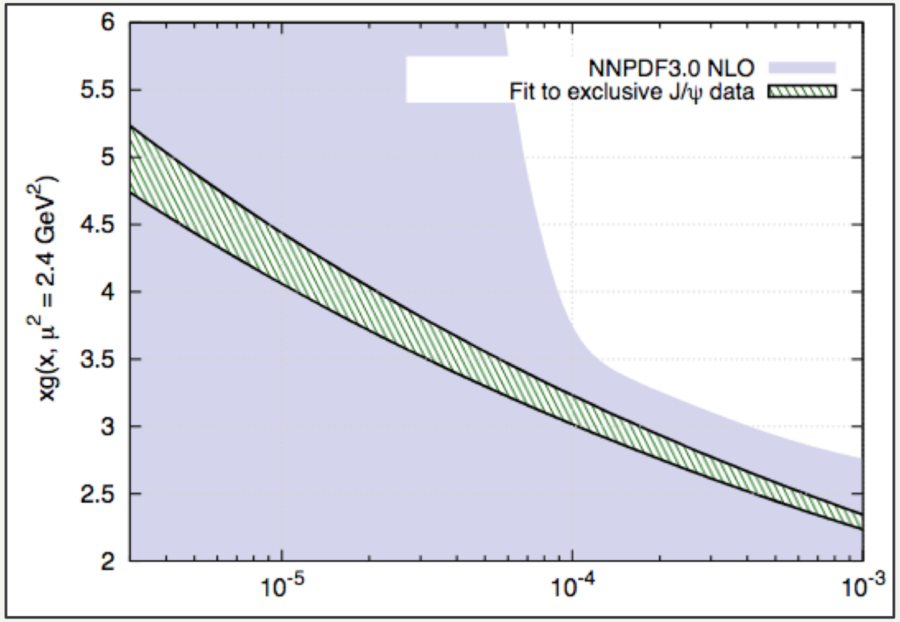
Collision between one well understood parton and one unknown or large DGLAP-evolved parton.

Gluon parton density function

Central values of three global PDF fitting groups

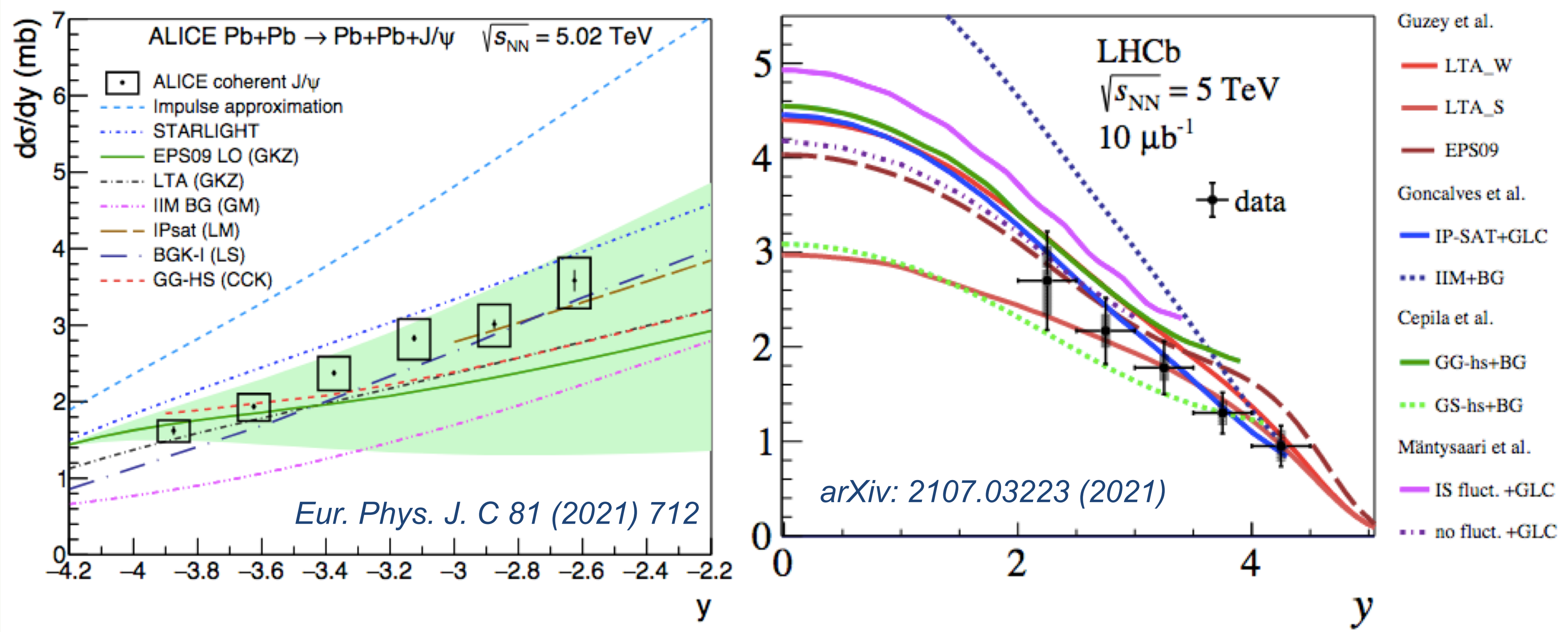


Improvement in the gluon PDF with J/ψ data

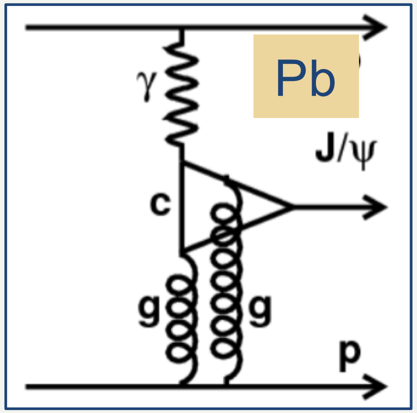


C. Flett et al., Phys.Rev.D 102 (2020) 114021

Nuclear cross-sections



Agreement within systematic uncertainties (luminosity: 13% LHCb, 5% Alice)
Allows critical comparison with theoretical models.



Which projectile produced the photon?

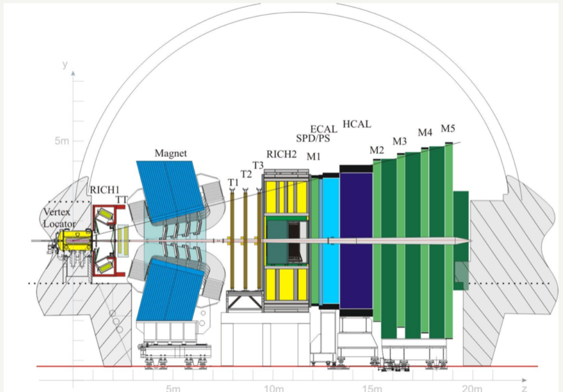
Assuming the photon always comes from Pb……

pomeron

Photon

pPb collisions

(low W – Hera region)



Photon

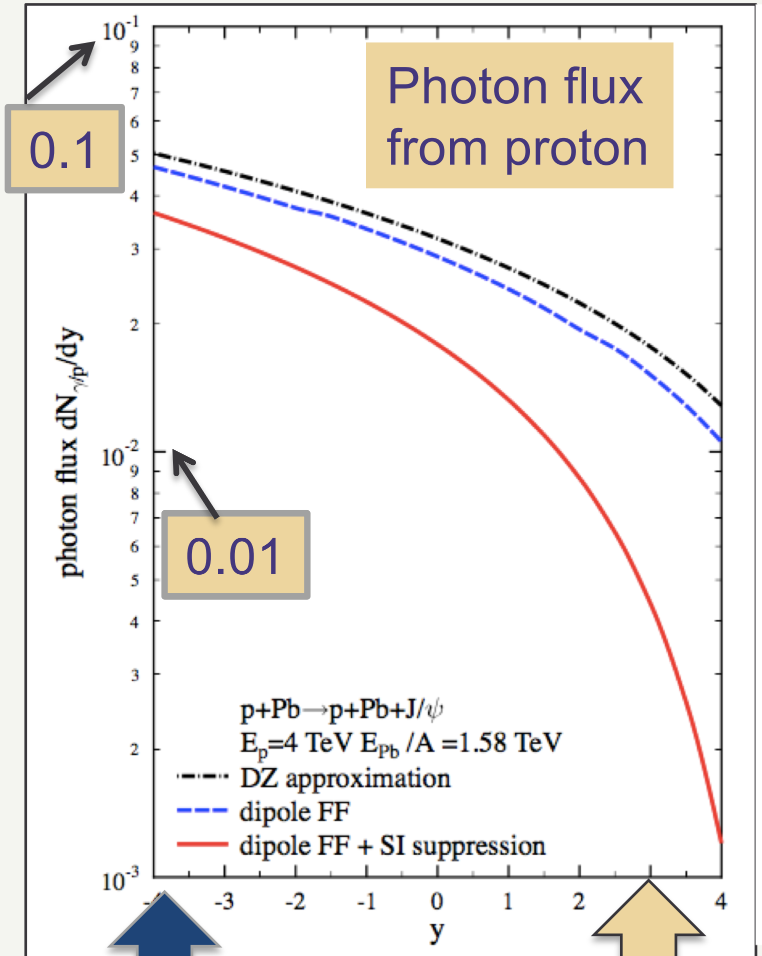
pomeron

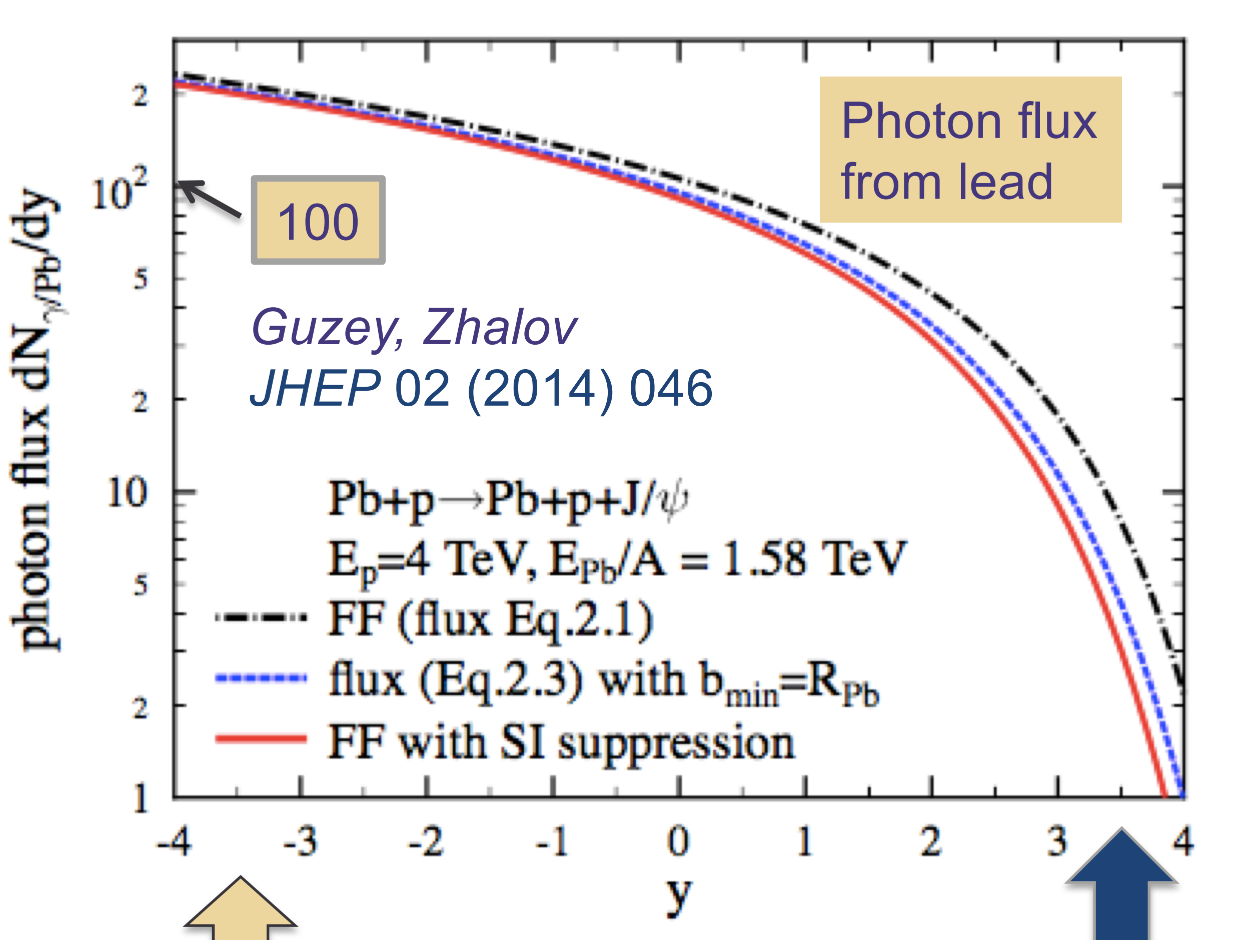
Pbp collisions

(high W
up to 2 TeV or x=2E-6)

Which projectile produced the photon?

At y~0, photon comes from lead (Z^2 enhancement)

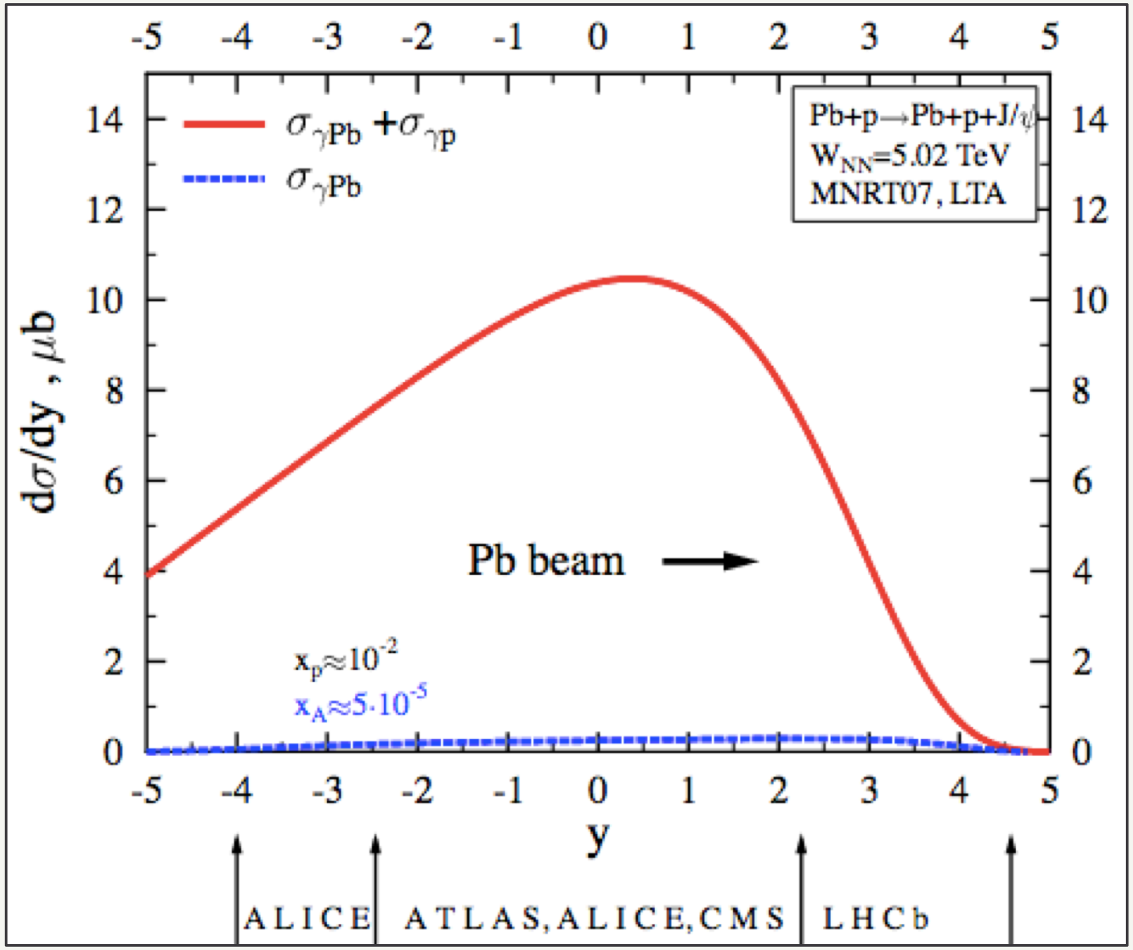




For LHCb, In pPb collisions, photon comes from lead

For Pbp collisions, ~1% comes from p

γp->J/ψp and γA->J/ψA

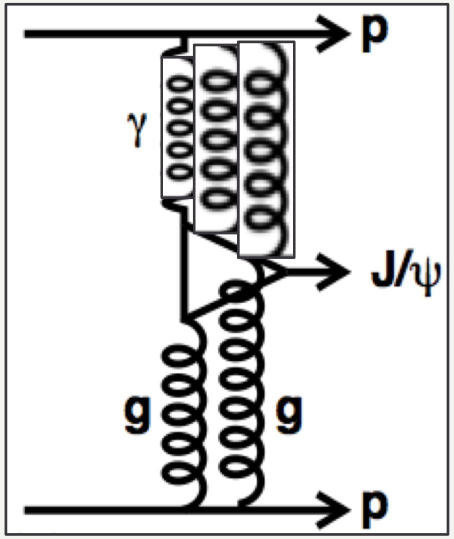


Possibility to measure
γ p->J/ψ p and
γ A->J/ψ A
simultaneously thus getting a direct measurement of the nuclear suppression factor

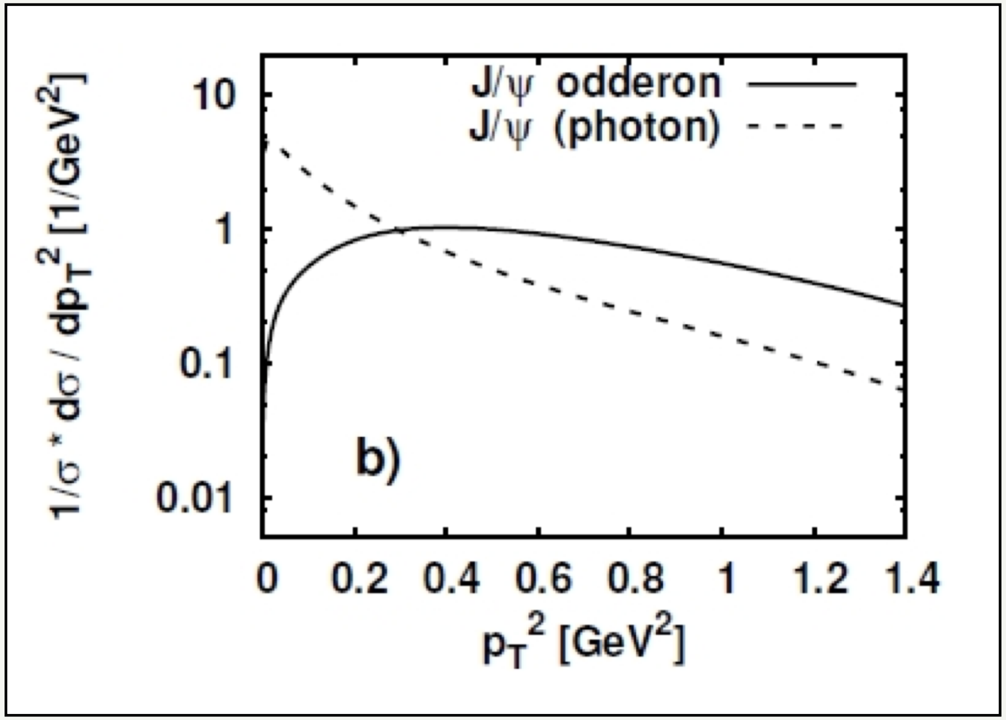
Guzey, Zhalov
JHEP 02 (2014) 046

Odderon

Visible in heavy V.M. at high p_T^2?



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



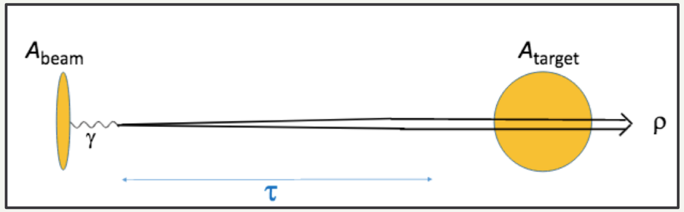
Bzdak, Motyka, Szymanowski, Cudell
PRD 75 (2007) 094023

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

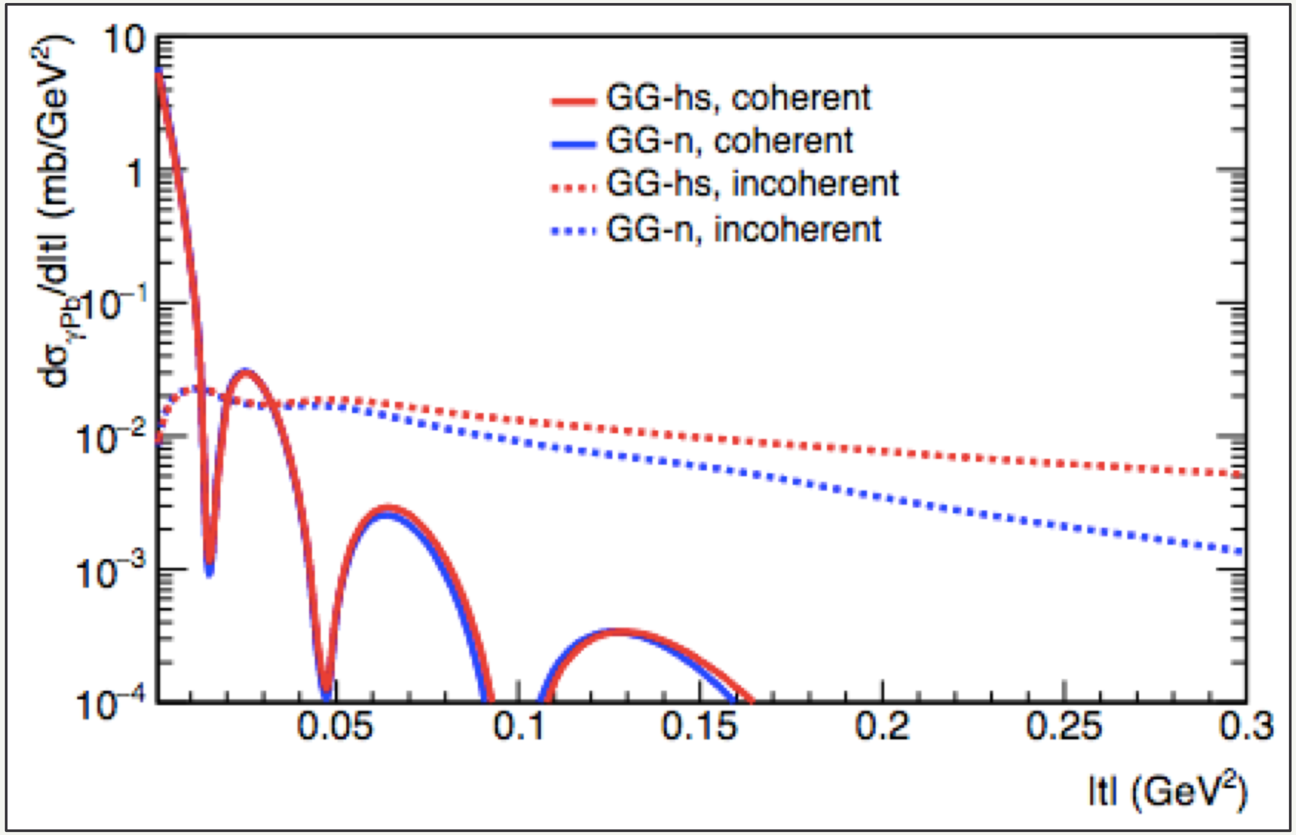
$d\sigma^{corr}/dy$	J/ψ	
	odderon	photon
Tevatron	0.3–1.3–5 nb	0.8–5–9 nb
LHC	0.3–0.9–4 nb	2.4–15–27 nb

Given incoherent backgrounds it is likely difficult to attribute a tail to odderon but the comparison of spectra in e-p, pA, AA to pp may be sufficient.

Hot spots in the nucleus



J. Cepila et al., Phys.Rev.C 97 (2018) 2, 024901
Mäntysaari, Schenke, Phys.Rev.Lett. 117 (2016) 5, 052301
Mäntysaari, Schenke, Phys.Lett.B 772 (2017) 832.



Conclusions

- J/ψ mesons have been measured in UPC of pp, pPb, PbPb at the LHC
- The photoproduction cross-sections on p and on A have been derived
- Very good agreement with HERA e-p data
- Sensitivity to low-x PDFs, saturation, odderon, hot-spots and nuclear suppression factors.