Experimental aspects of Ultra-Peripheral Collisions (UPC) and future prospects

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Quarkonia as tools 2023

4/1- 14/1 Aussois, France

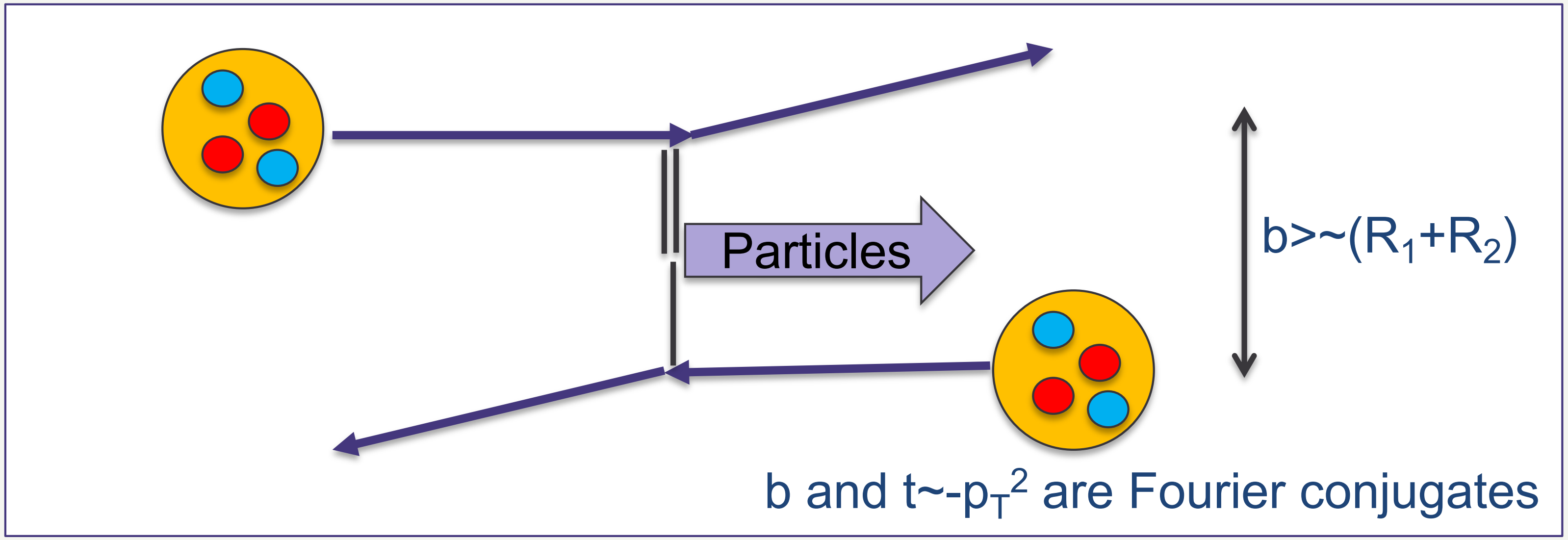
Overview

I will mainly concentrate on UPC in pp collisions. Charlotte will cover pA and AA.

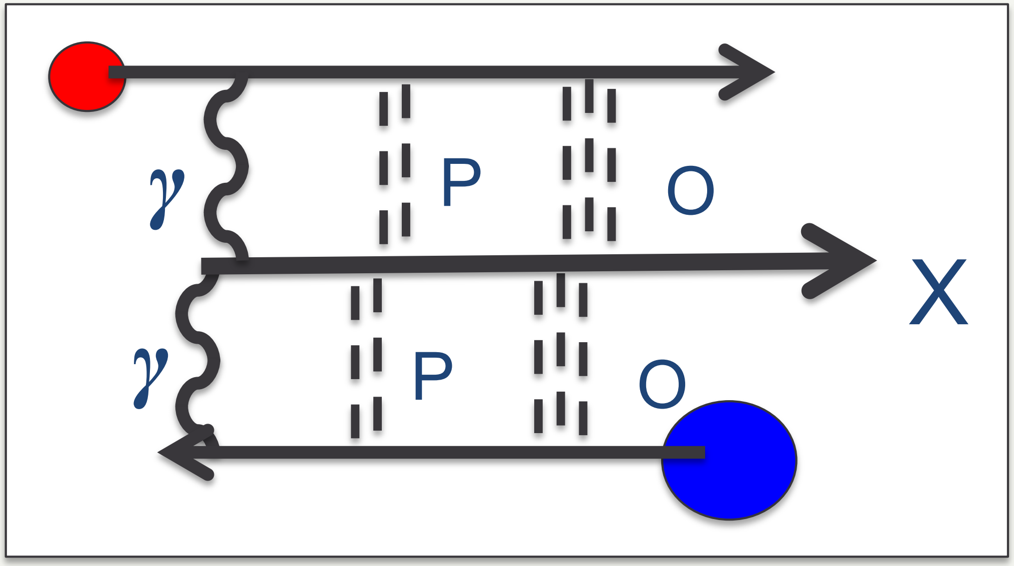
- The experimental environments
- gamma-gamma
- gamma-Pomeron
- Pomeron-Pomeron
- Odderon

Ultra-Peripheral Collisions

- Collisions in which projectiles remains intact
- (Only) colourless propagators
- Therefore large impact parameters (or else QCD will ensure coloured interactions and break-up.)



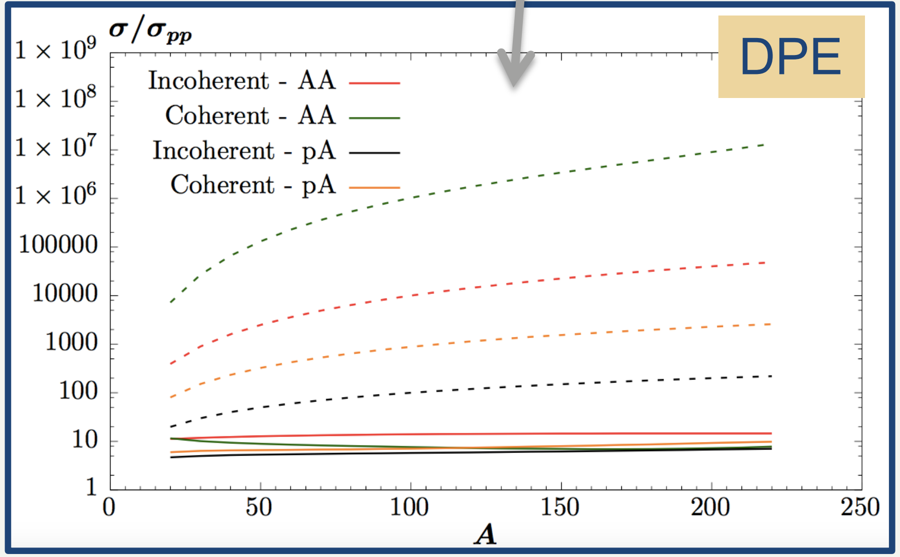
Propagators and final states

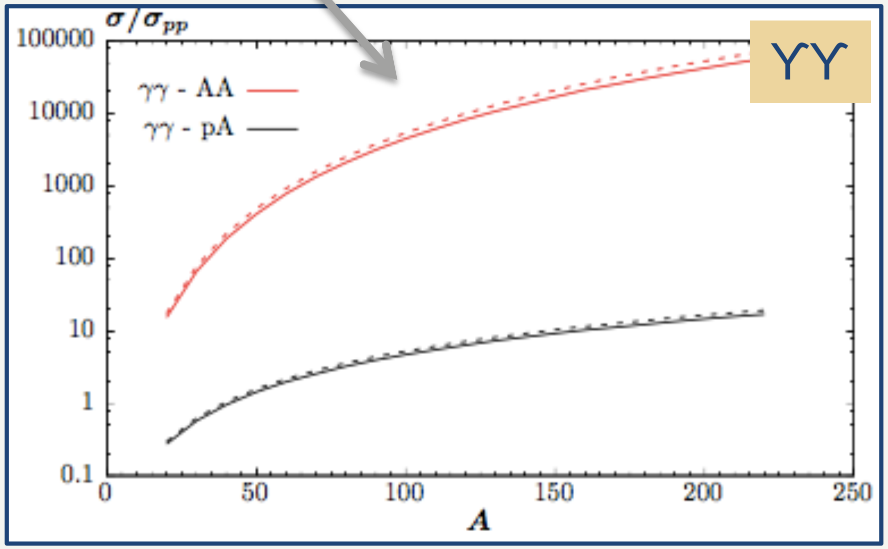


- Colourless propagators can be:
  - photons. $J^{PC}=1^{--}$.
  - 2 gluons (pomeron). $J^{PC} = 1^{--} + 1^{--} = 0^{++}$
  - 3 gluons (odderon). $J^{PC} = 1^{--} + 1^{--} + 1^{--} = 1^{--}$
  - ladder of correlated gluons
- Final states
  - nothing (but projectiles interact / scatter)
  - one particle with well-defined quantum numbers
  - multiple particle

Complementarity of collisions

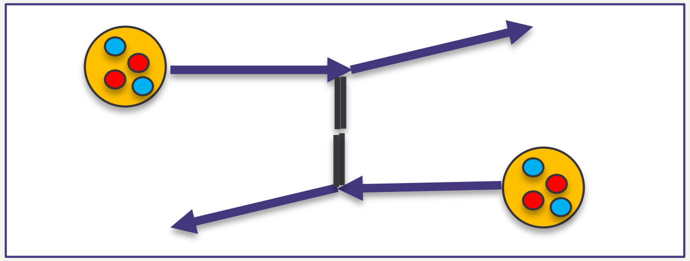
	DPE(PP)	γP	γγ	γO	OP
pp	~100μb	~100μb	~0.0001μb	?	?
pA	x $A^{1/3}$	x Z^2	x Z^2	x Z^2	x $A^{1/3}$
AA	x $A^{1/6}$	x AZ^2	x Z^4	x $A^{1/3}Z^2$	x $A^{1/6}$





Harland-Lang, Khoze, Ryskin, Eur.Phys.J. C79 (2019) no.1, 39

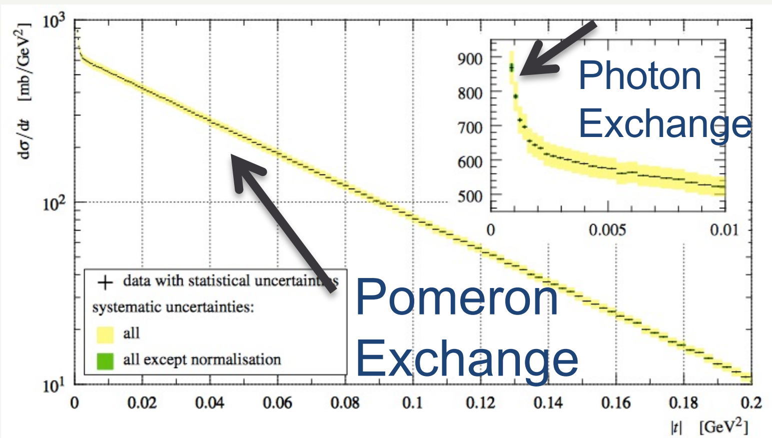
Elastic scattering

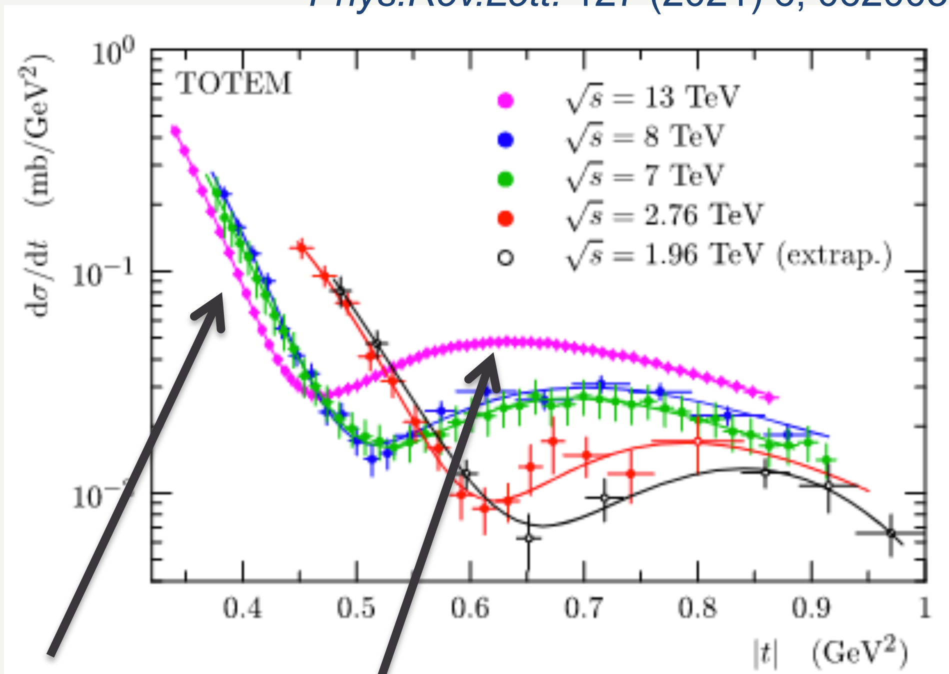


Totem and D0 collaborations
Phys.Rev.Lett. 127 (2021) 6, 062003

- Simplest experimental situation
- Complex theoretical.
  - All propagators play a role

TOTEM: *Eur.Phys.J.* C79 (2019) 9,785

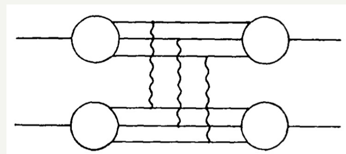




Single Pomeron

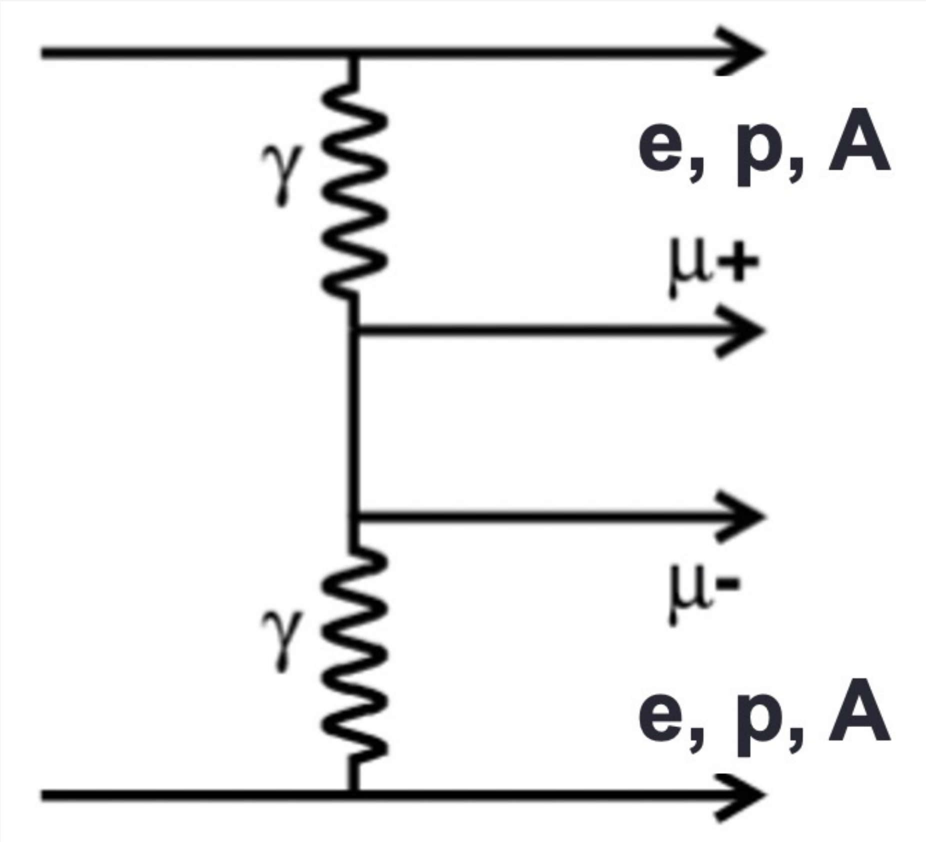
$$\frac{d\sigma}{dt} \sim e^{8t}$$

Triple gluon exchange



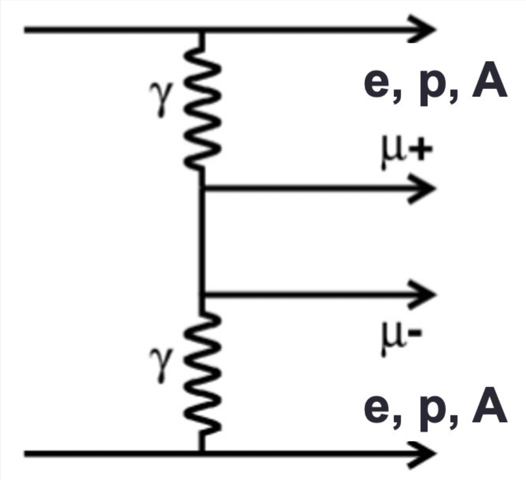
$$\frac{d\sigma}{dt} \sim \alpha_S^6 t^{-8}$$

γγ physics

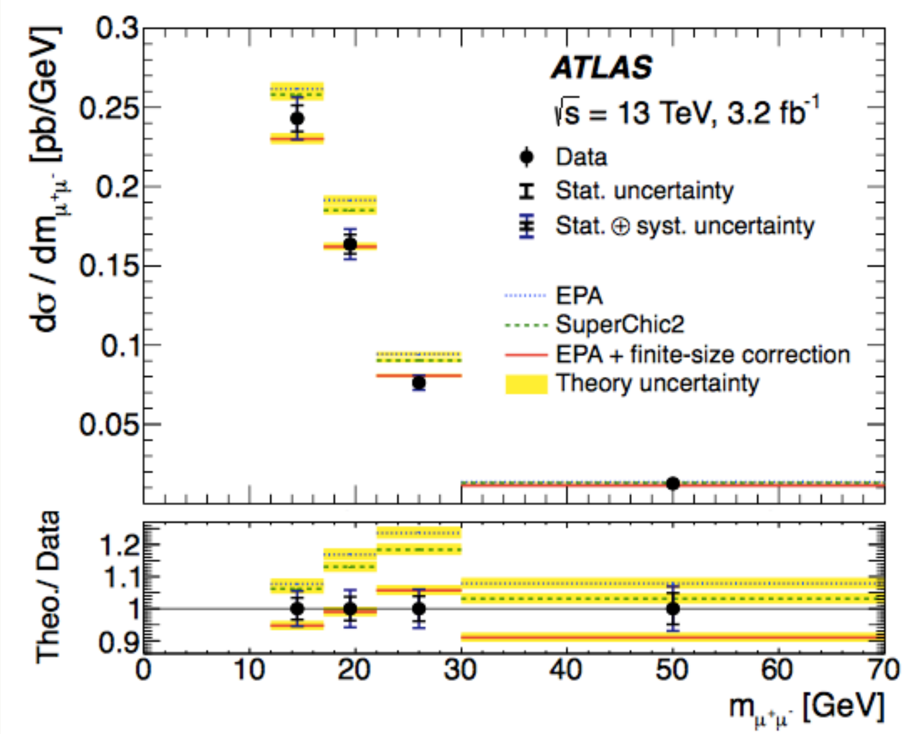


Photon propagators (QED)

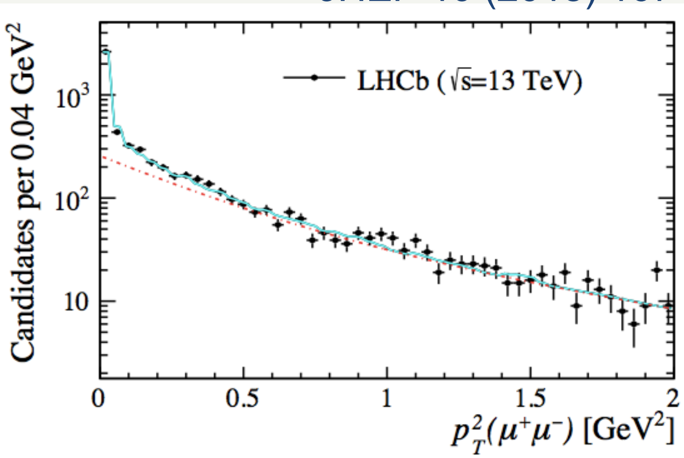
- $\gamma\gamma$ collisions are the only UPC at e^+e^- colliders.
- At LHC it's a unique QED process.
- Contaminated by additional interactions between projectiles



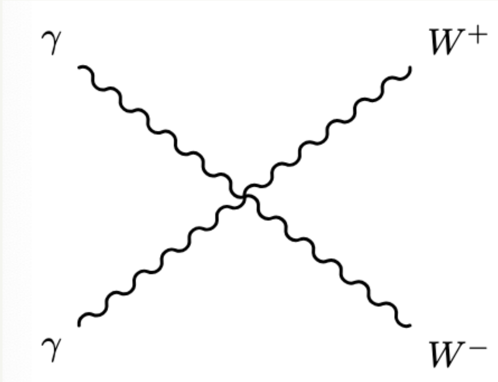
PLB 777 (2018) 303.



JHEP 10 (2018) 167

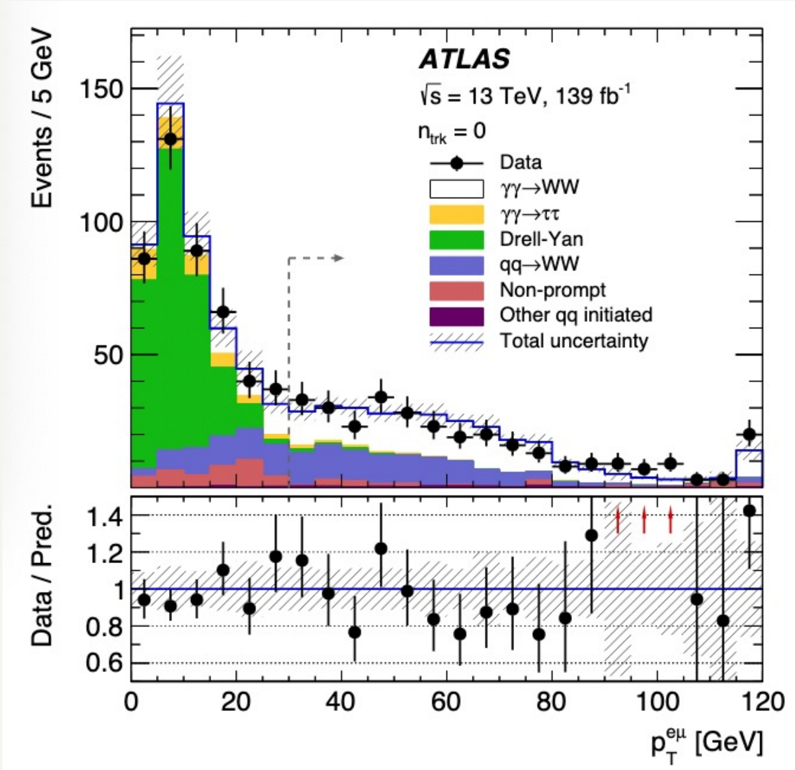


Photon propagators (QED)



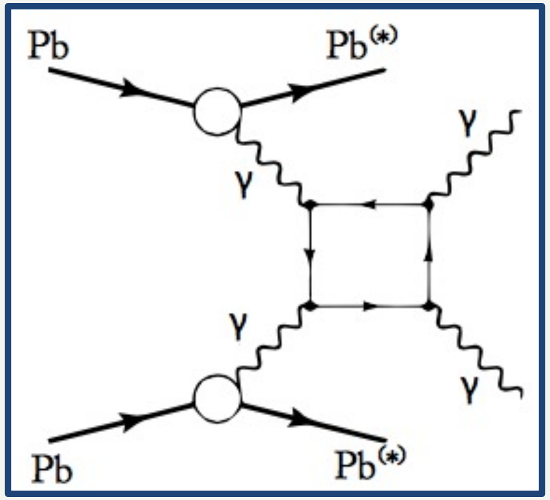
- Recently WW final state observed by ATLAS
- Sensitive to quartic gauge coupling.

PLB 816 (2021) 136190

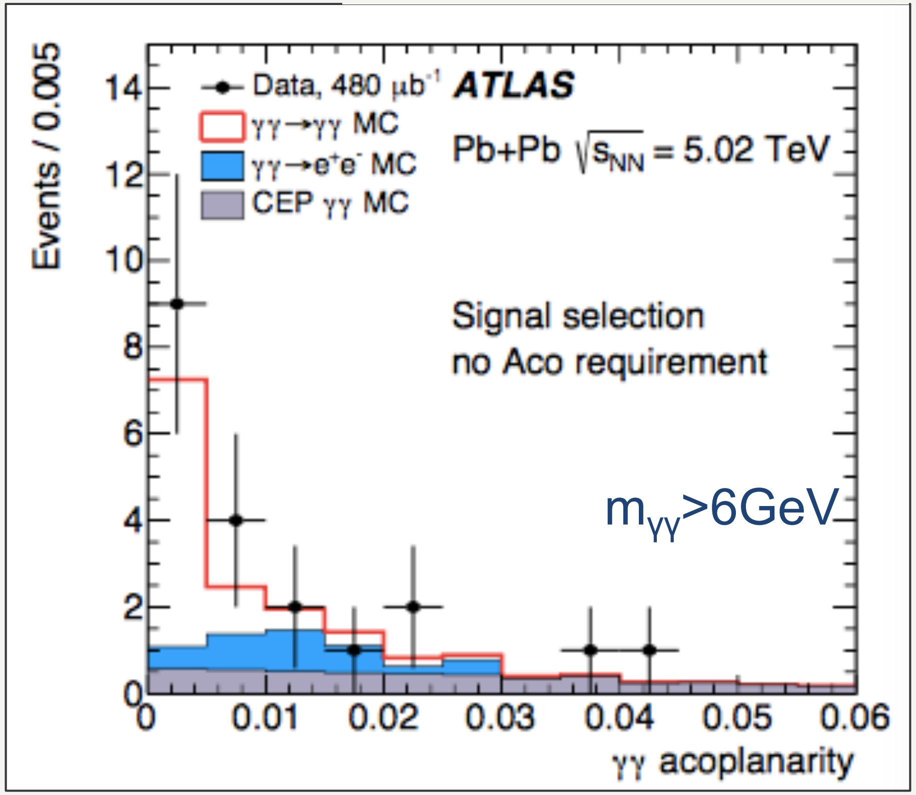


Light-by-light scattering

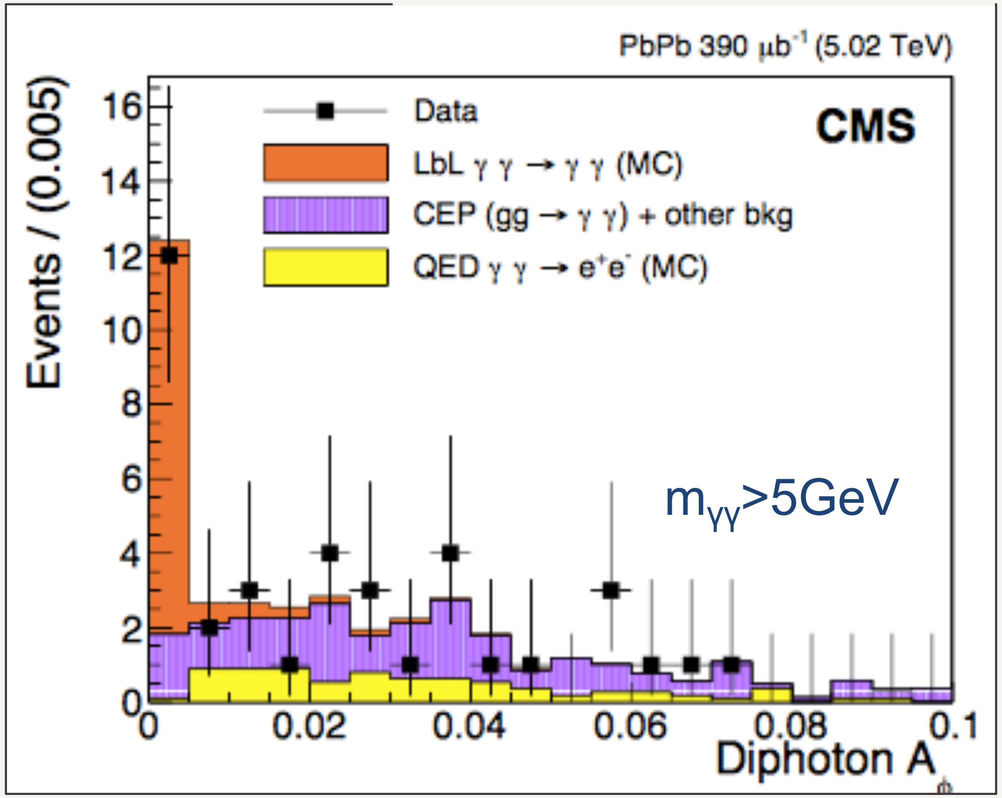
Forbidden in classical EM
Text-book illustration of QM



Nature Physics 13 (2017) 852

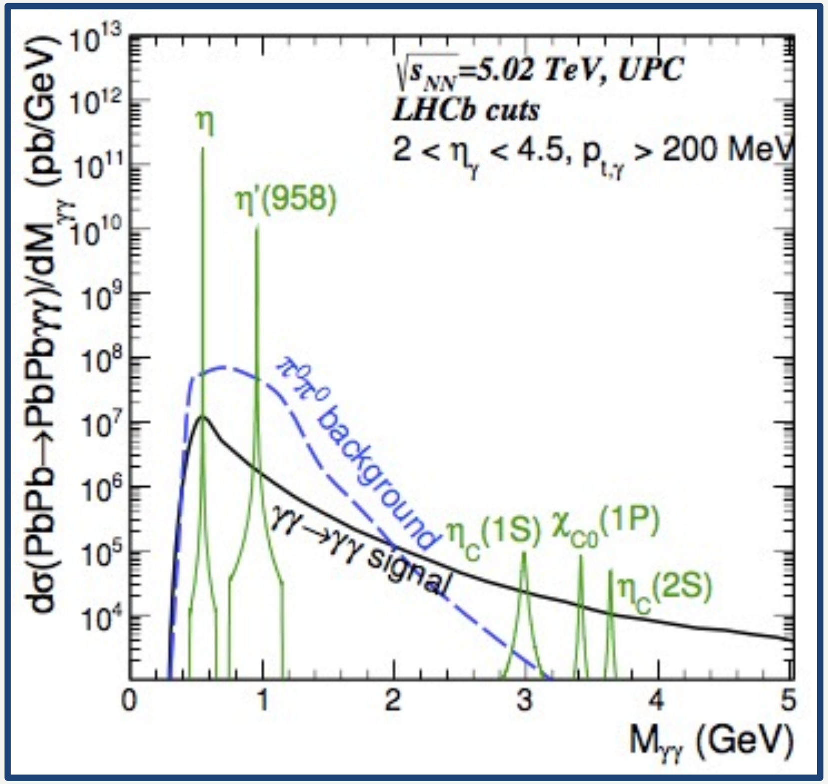


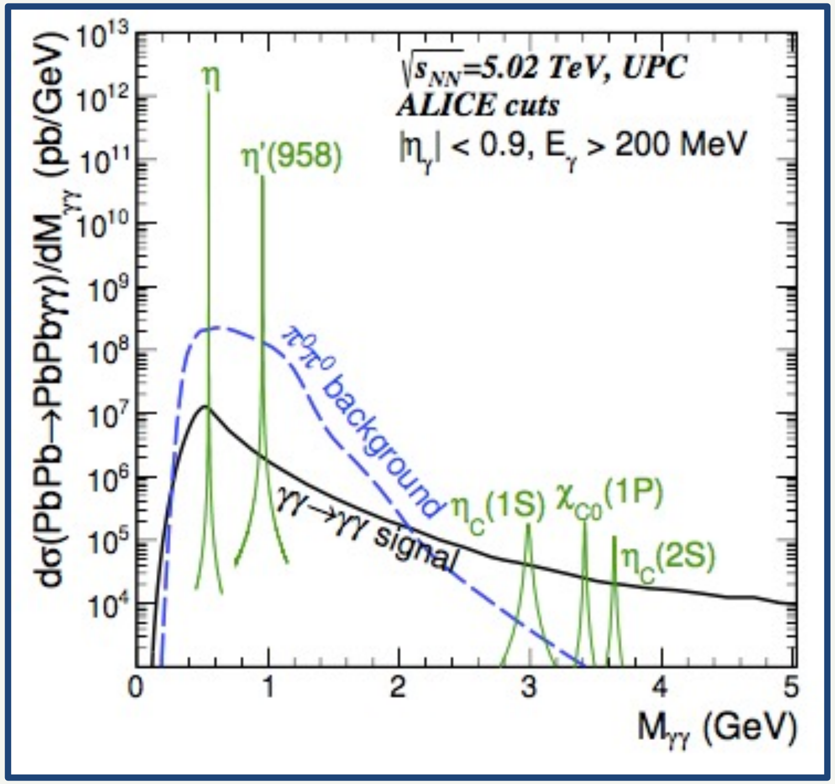
Phys.Lett.B 797 (2019) 134826



Light-by-light scattering

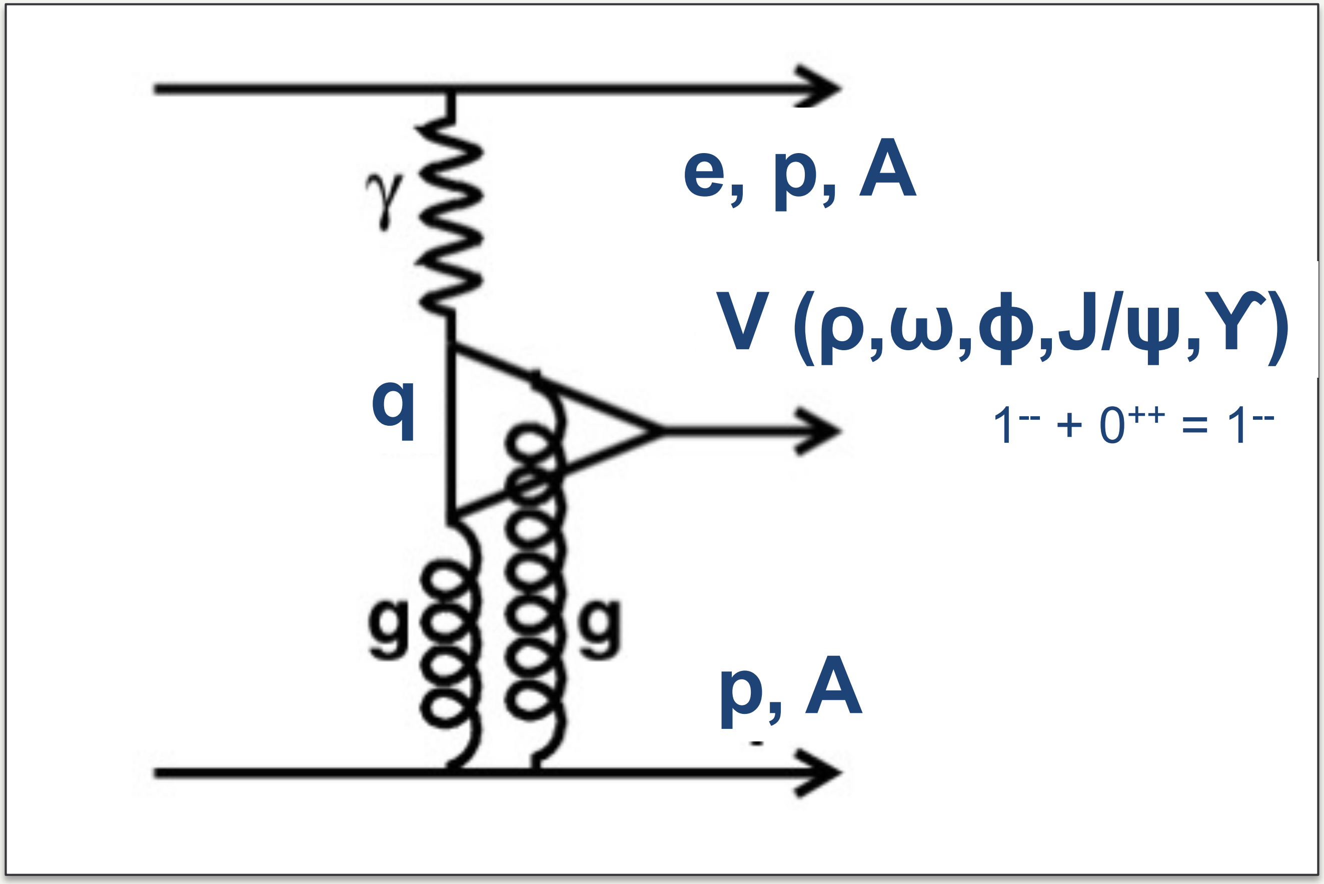
Klusek-Gawenda, McNulty, Schicker, Szczurek, Phys.Rev. D99 (2019) no.9, 093013





LHCb and ALICE have potential to observe this at low mass.
Also important in searches for new particle decaying to photons
(e.g. dark matter candidates)

C-odd mesons



Also odderon-pomeron fusion in hadron-hadron collisions is possible

(J/ψ as tool for odderon discovery)

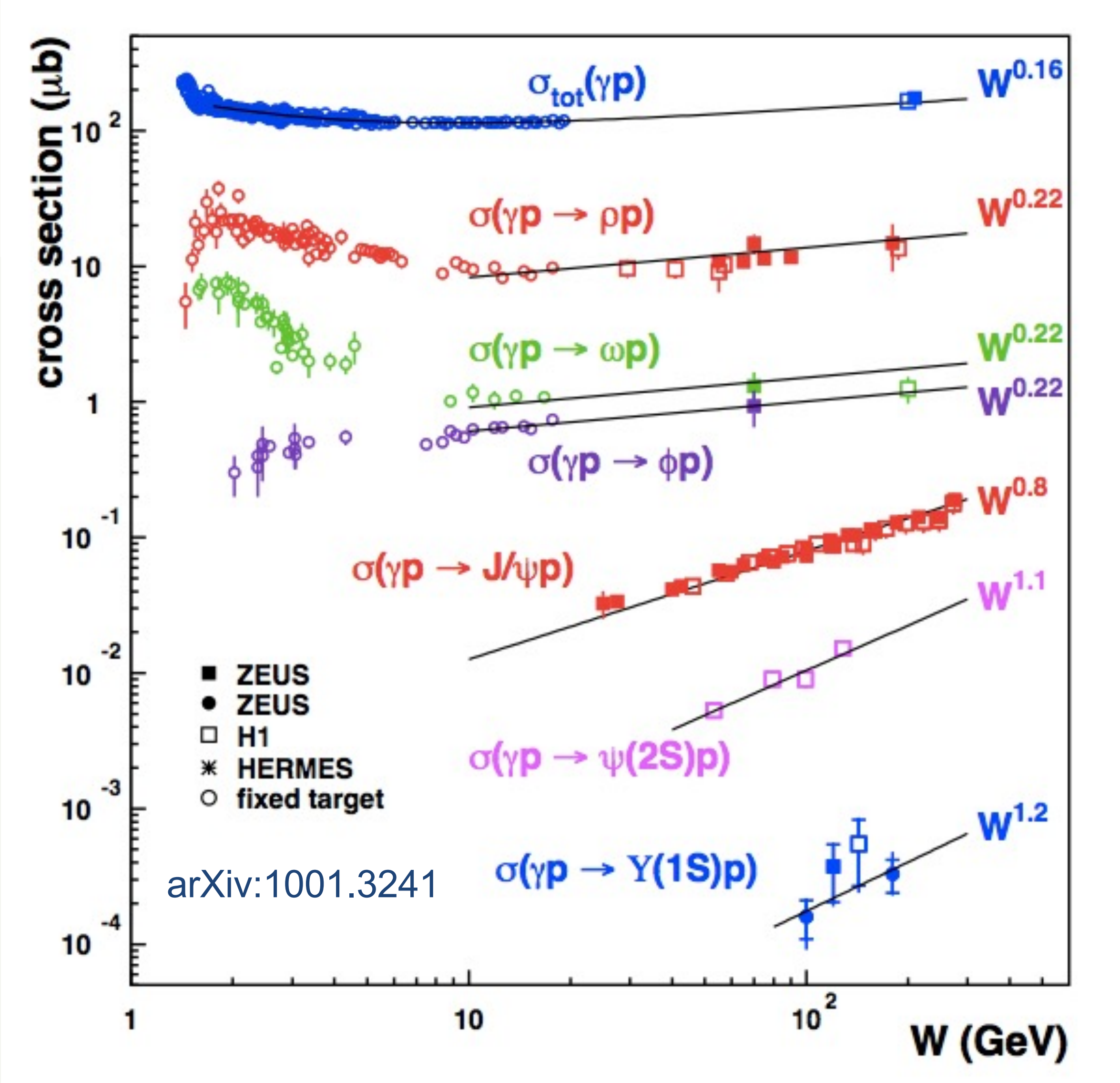
Vector mesons

Physics of the Vacuum: soft and hard QCD

Pomeron trajectory:

$$\alpha(t) = \alpha_0 + \alpha' t$$

The structure of the proton and nucleus



L.O. prediction
in perturbative regime

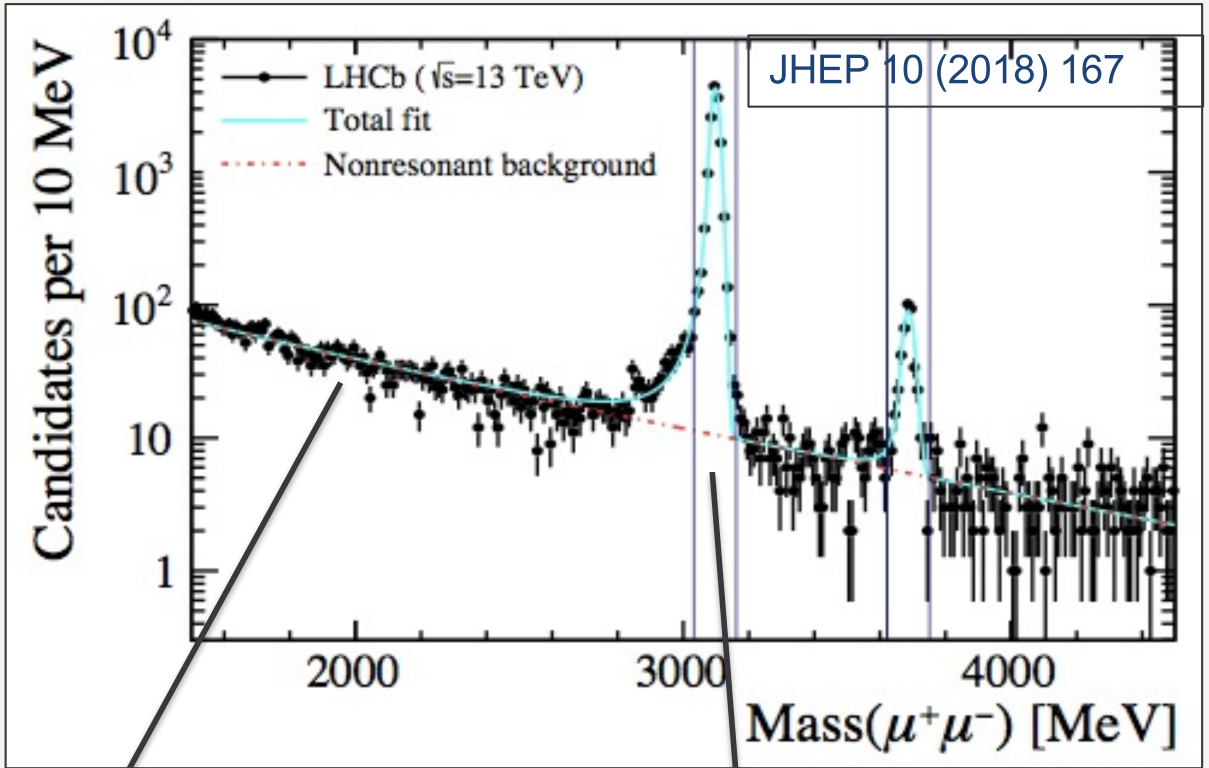
$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\, p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} x g(x, \bar{Q}^2)\right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right)$$

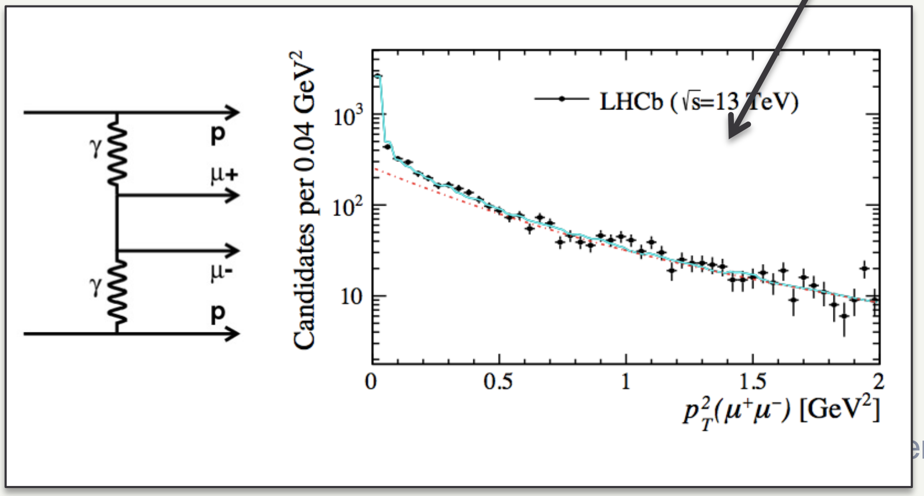
J/Ψ photoproduction

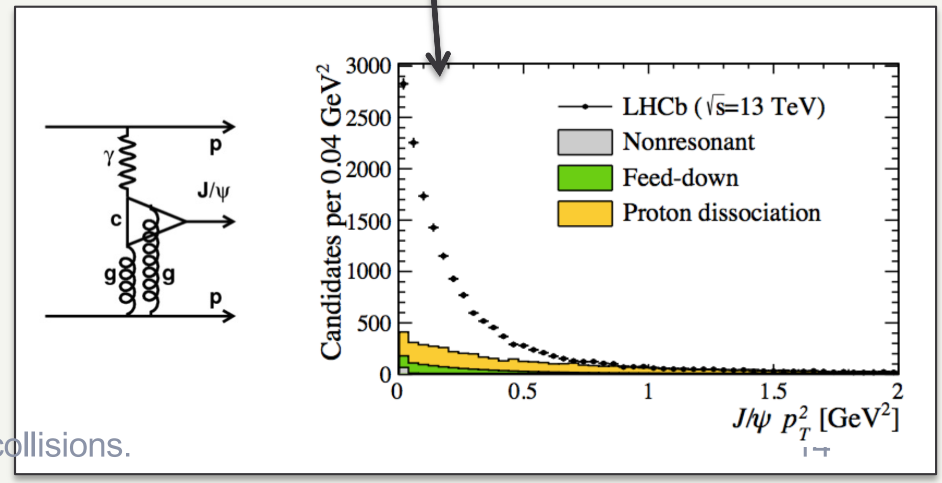
pp collisions
(Charlotte will deal with pA and AA)

Perturbative region

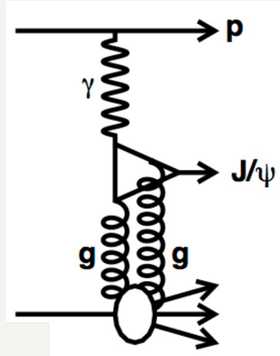
$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\, p)\Big|_{t=0} = \frac{\Gamma_{ee} M^3_{J/\psi}\pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4}\, xg(x,\bar{Q}^2)\right]^2\left(1+\frac{Q^2}{M^2_{J/\psi}}\right)$$



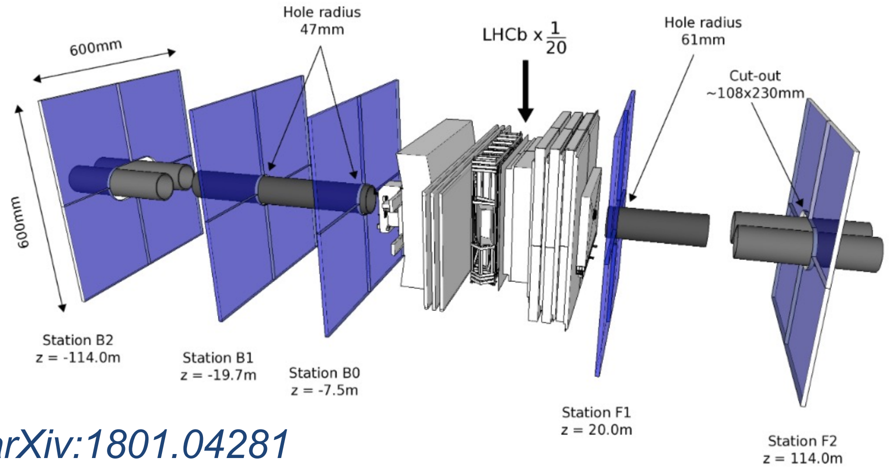




Suppressing proton-dissociation

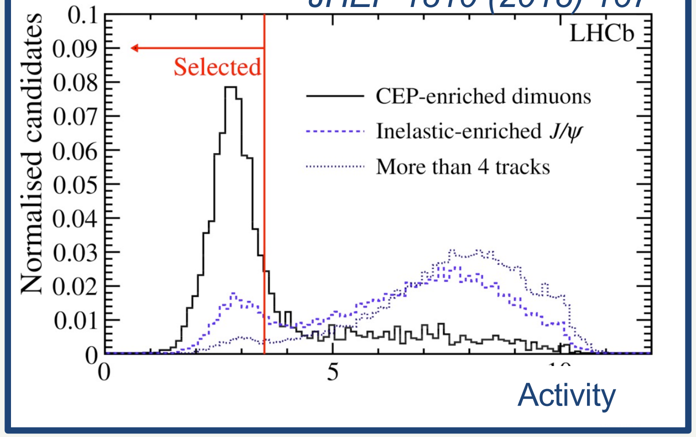


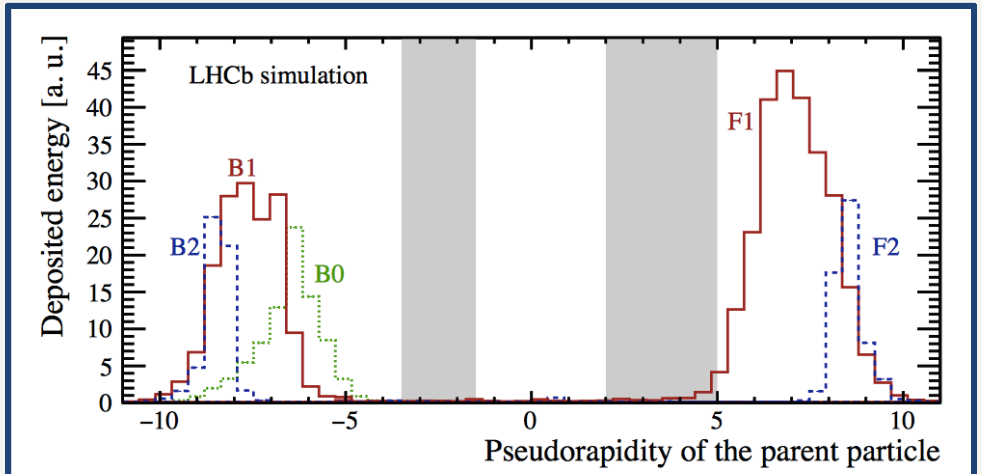
Two handles: (1) forward activity (2) greater p_T^2

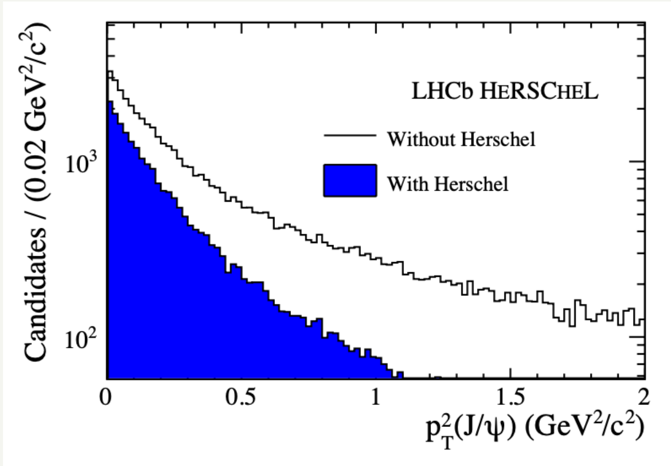


arXiv:1801.04281

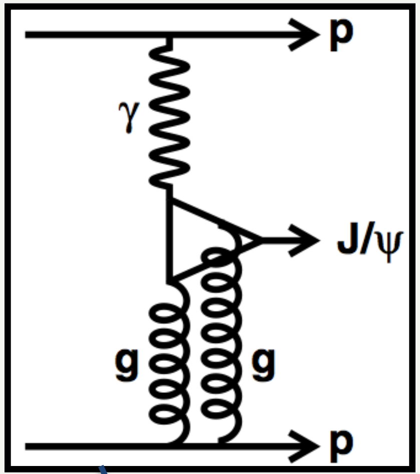
JHEP 1810 (2018) 167



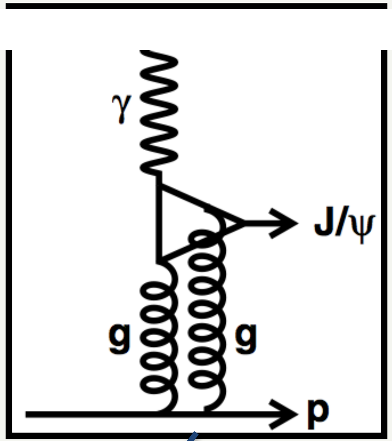




Convert to photo-production cross-section



LHCb measures



HERA measured

Photon Flux

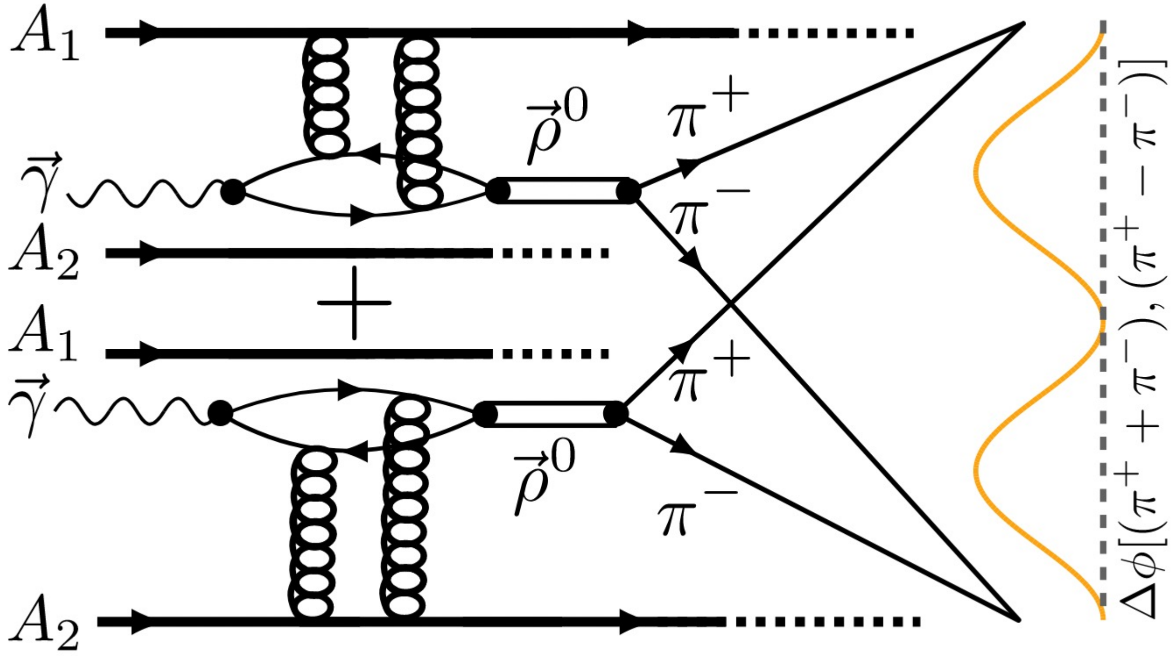
$$\left.\frac{d\sigma}{dy}\right|_{pp\to pJ/\psi p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to J/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi p}(W_-)$$

Gap Survival

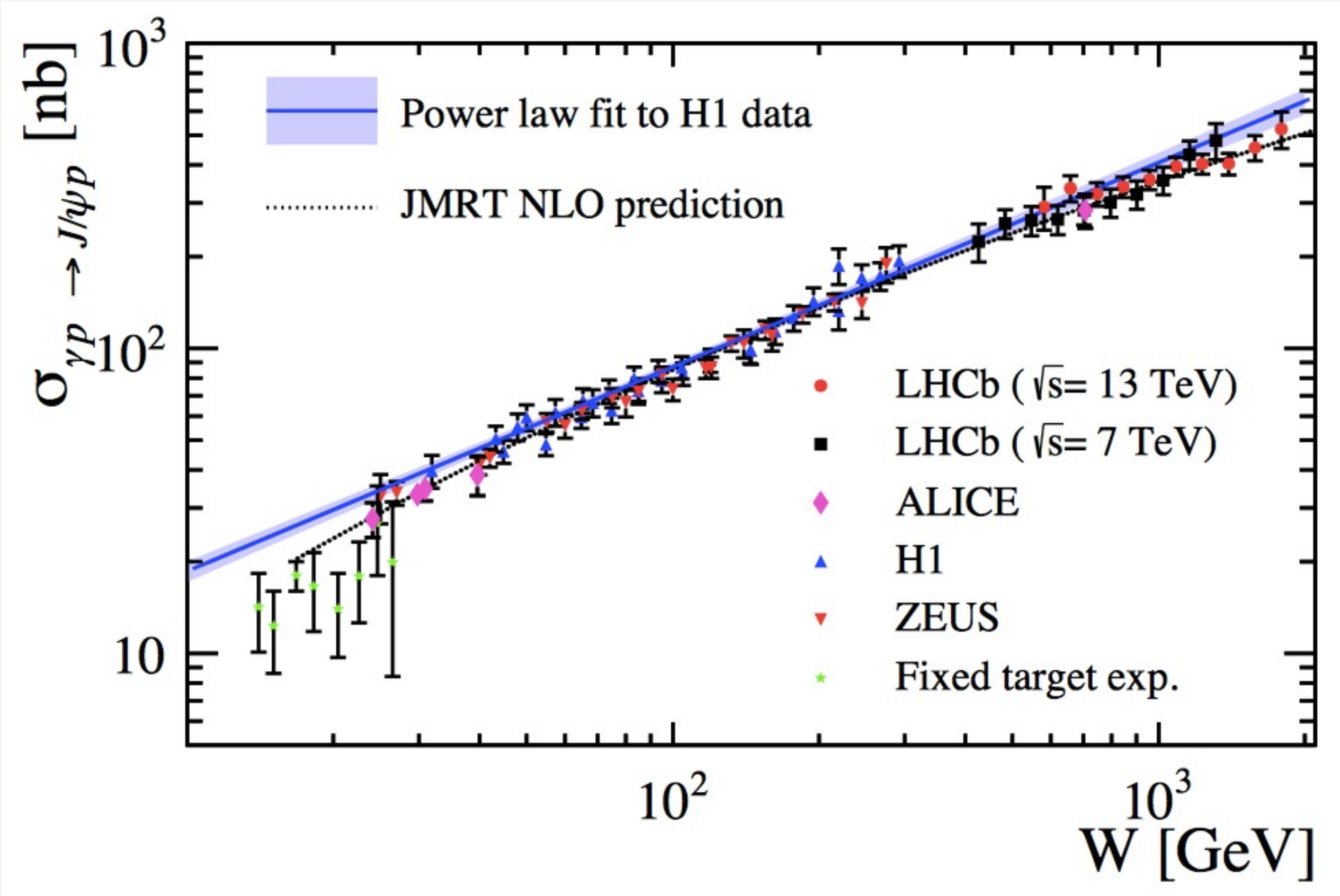
HERA measured power-law: $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\,\mathrm{GeV})^{0.67}\,\mathrm{nb}$

Check out: arXiv:2204.01625

Quantum Entanglement Enabled Nuclear Tomography



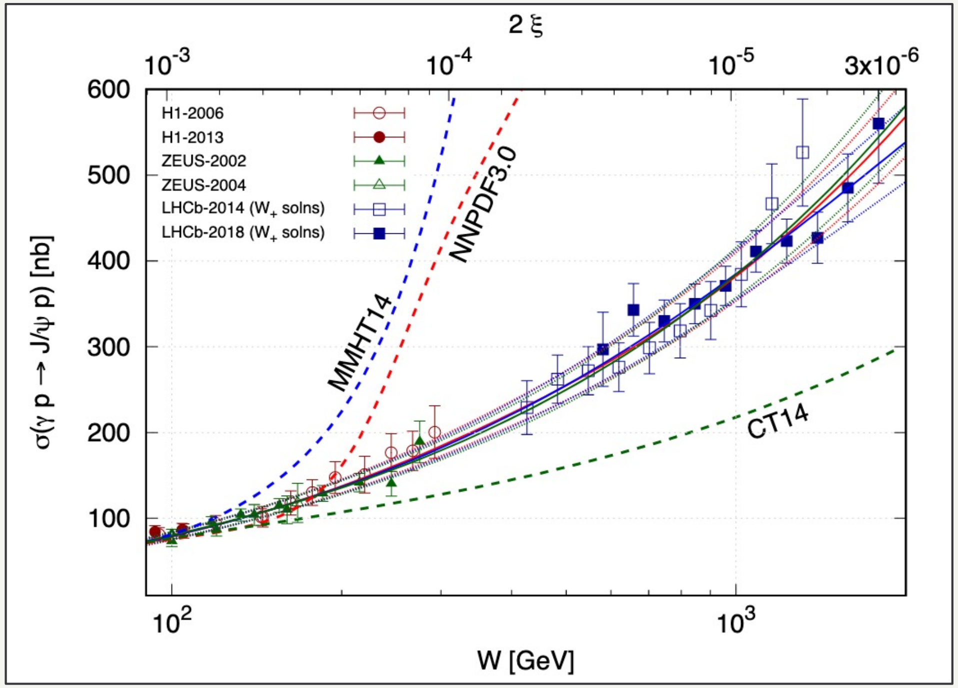
J/Ψ photoproduction

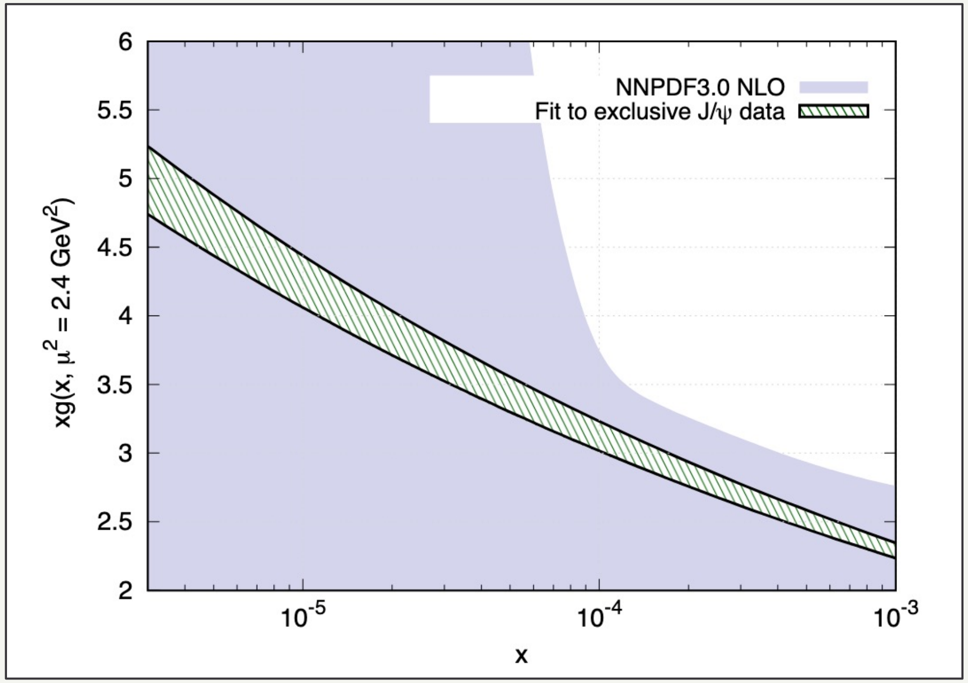


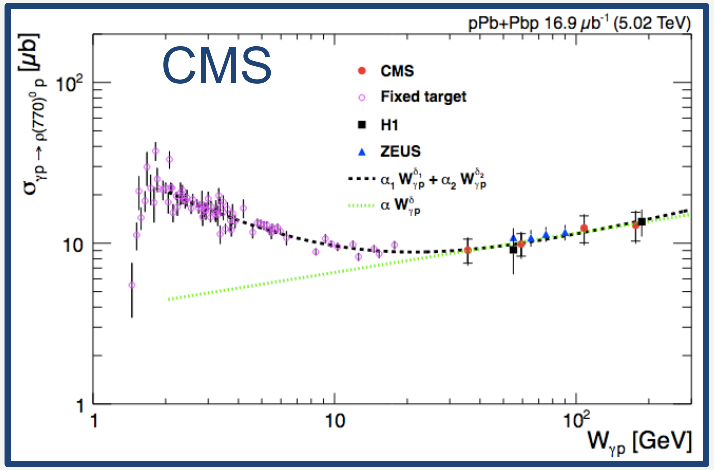
$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M^3_{J/\psi}\pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4}xg(x,\bar{Q}^2)\right]^2\left(1+\frac{Q^2}{M^2_{J/\psi}}\right)$$

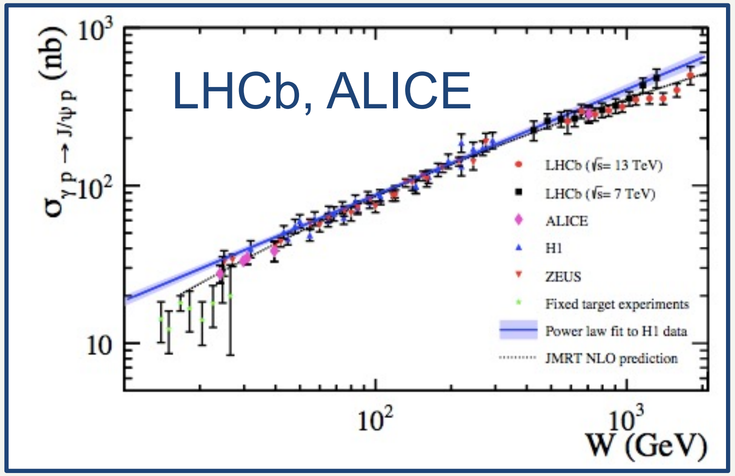
Gluon PDF extraction

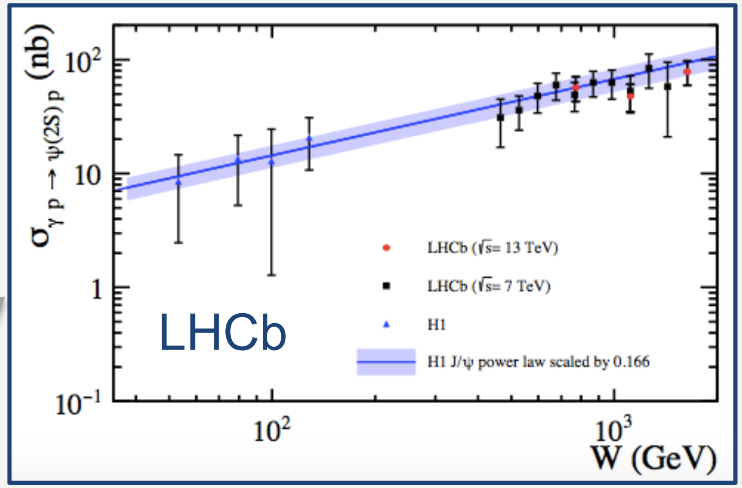
Flett, Jones, Martin, Ryskin, Teubner, Phys.Rev.D 106 (2022) 7, 074021

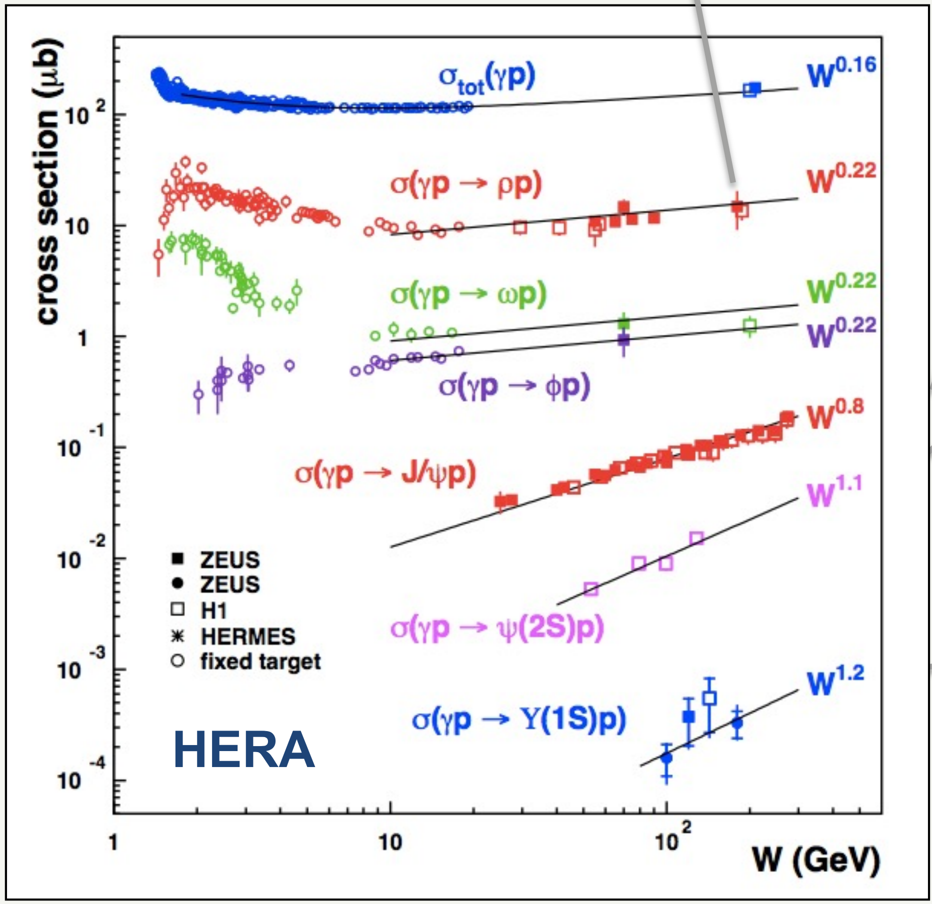


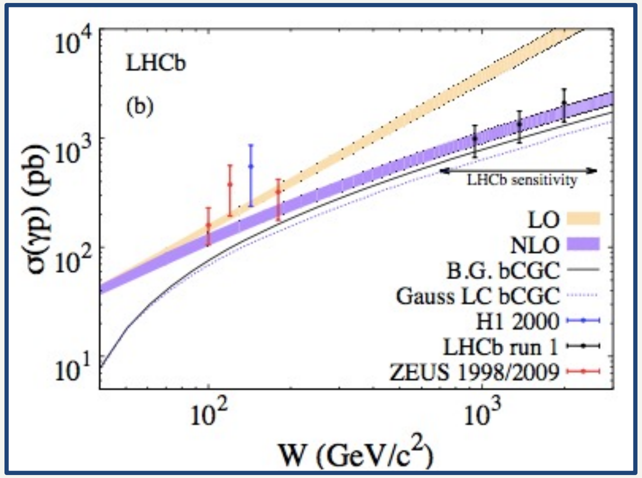



CMS
pPb+Pbp 16.9 μb⁻¹ (5.02 TeV)
CMS
Fixed target
H1
ZEUS
W_γp [GeV]

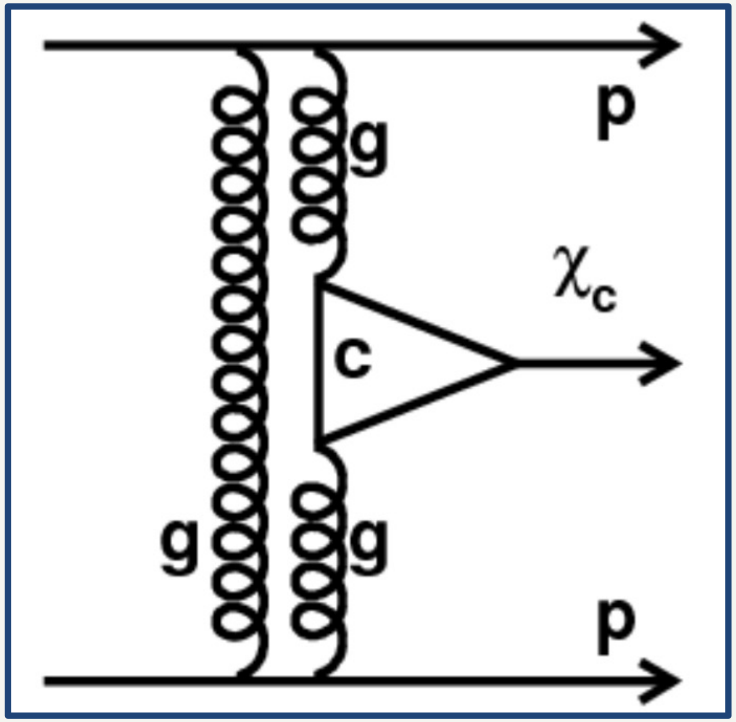

LHCb, ALICE
LHCb (√s= 13 TeV)
LHCb (√s= 7 TeV)
ALICE
H1
ZEUS
Fixed target experiments
Power law fit to H1 data
JMRT NLO prediction
W (GeV)


LHCb
LHCb (√s= 13 TeV)
LHCb (√s= 7 TeV)
H1
H1 J/ψ power law scaled by 0.166
W (GeV)


cross section (μb)
HERA
σtot(γp)
σ(γp → ρp)
σ(γp → ωp)
σ(γp → φp)
σ(γp → J/ψp)
σ(γp → ψ(2S)p)
σ(γp → Υ(1S)p)
W0.16
W0.22
W0.22
W0.22
W0.8
W1.1
W1.2
ZEUS
ZEUS
H1
HERMES
fixed target
W (GeV)


LHCb
(b)
σ(γp) (pb)
LHCb sensitivity
LO
NLO
B.G. bCGC
Gauss LC bCGC
H1 2000
LHCb run 1
ZEUS 1998/2009
W (GeV/c²)

Double Pomeron Exchange

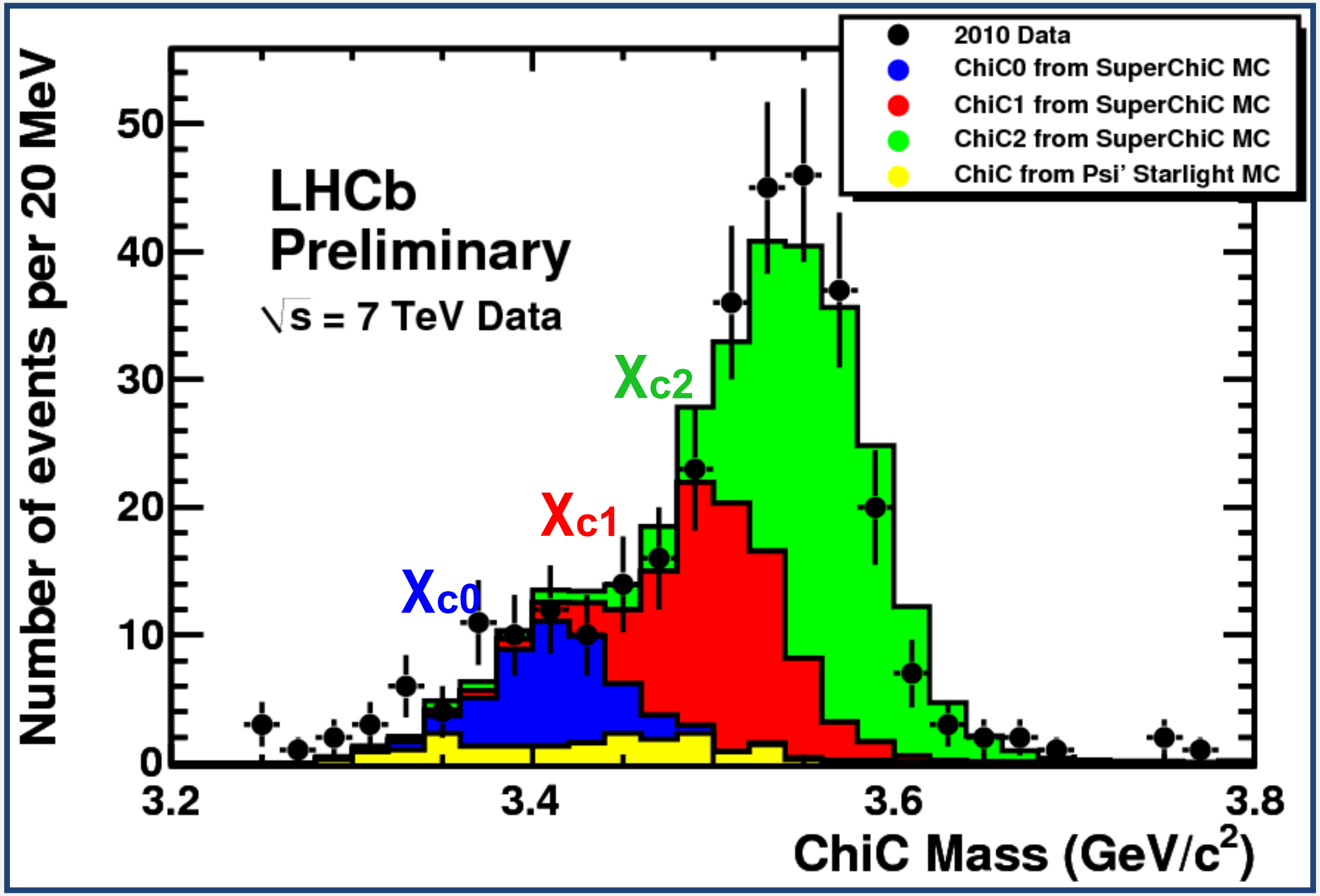


$0^{++} + 0^{++} = 0^{++}, 1^{++}, 2^{++}$
(gluons in Pomeron have transverse momentum)

Many different final states accessible.
Concentrate here on single and double charmonium.

Double Pomeron Exchange

LHCb-CONF-2011-022



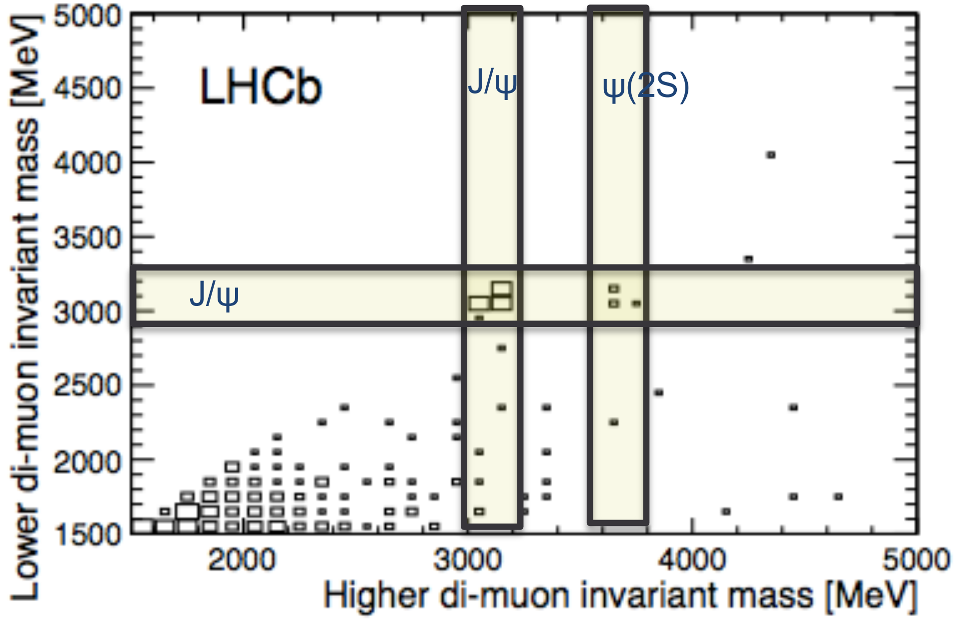
Can only be produced in DPE

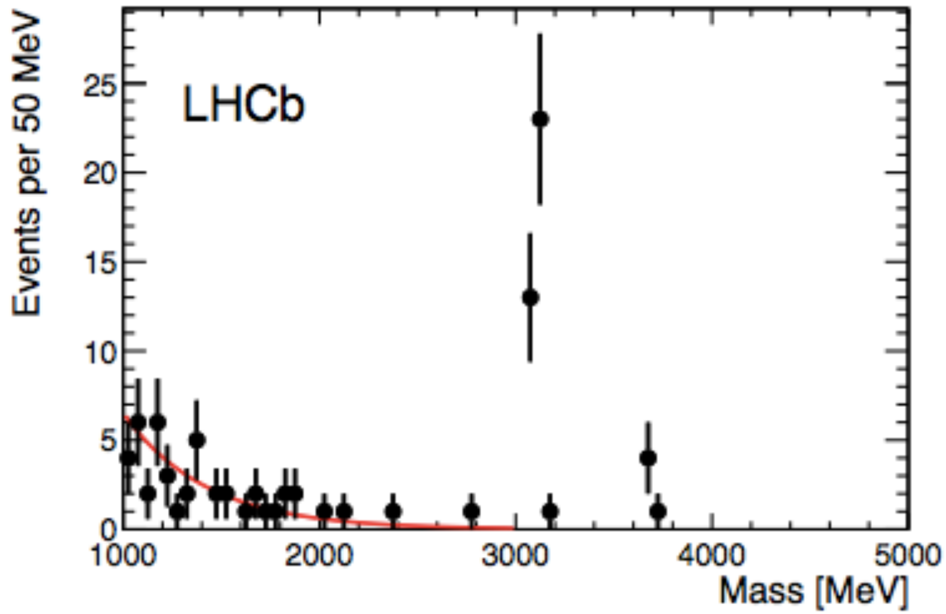
Difficult to separate peaks: work ongoing with photon conversions

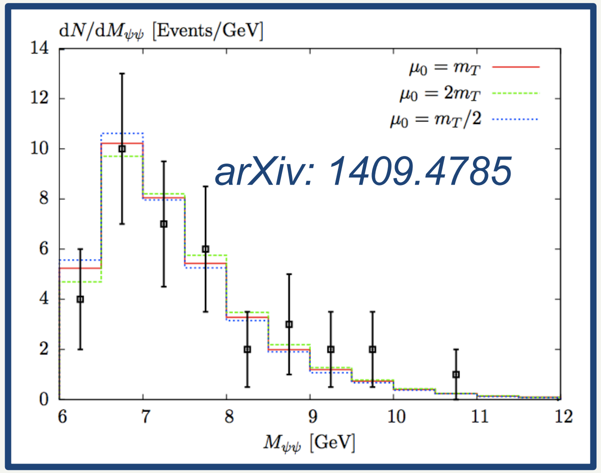
J/ψJ/ψ: search for exotica

JPG 41 (2014) 115002

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



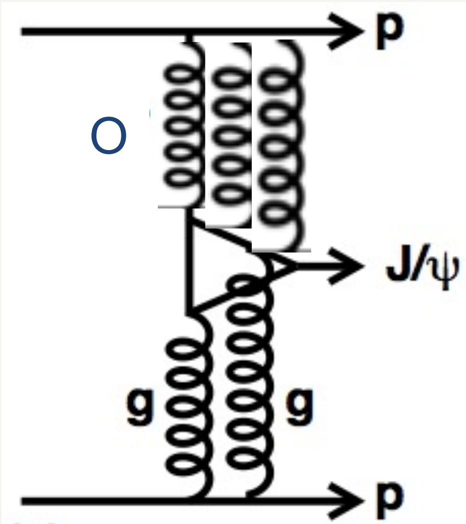




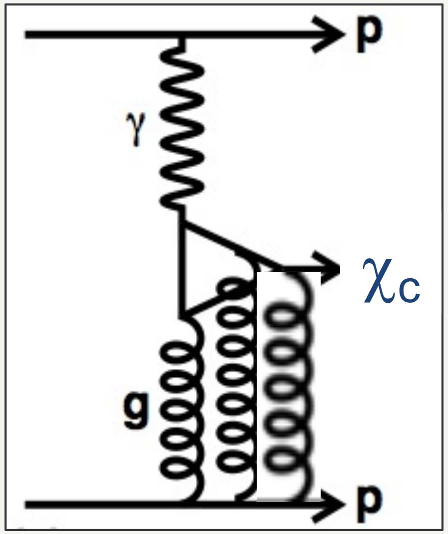
LHCb estimate exclusive cross-section. **24+-9 pb**
Harland-Lang, Khoze, Ryskin: **2-7 pb**

Shape agrees with model.
Continuum only – nothing exotic ☹

Quarkonia as tools:
Searching for the odderon



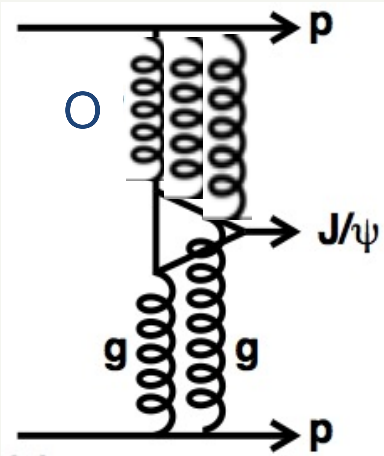
C-odd
meson

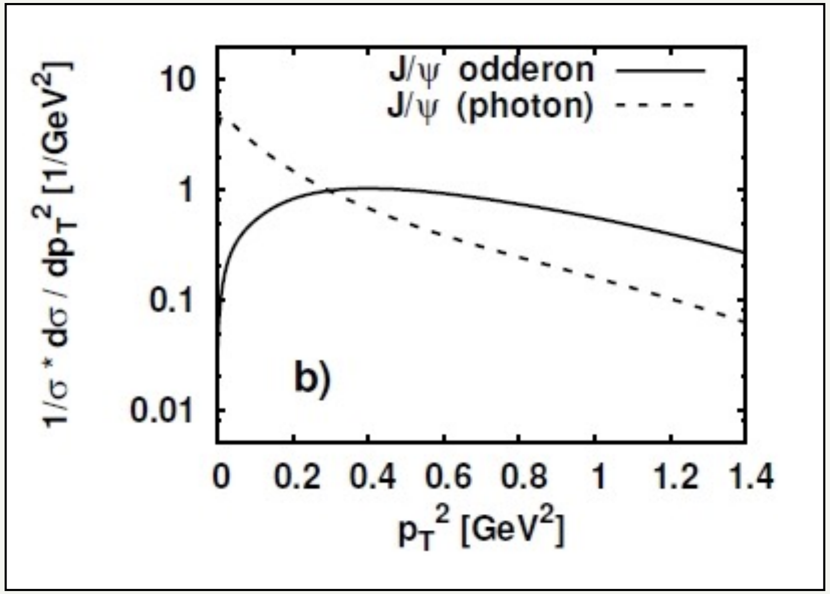


C-even
meson

Method 1: High p_T CEP of J/ψ and Υ.

Replace 1^- g with 1^- O





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

$d\sigma^{corr}/dy$	J/ψ		Υ	
	odderon	photon	odderon	photon
Tevatron	0.3–1.3–5 nb	0.8–5–9 nb	0.7–4–15 pb	0.8–5–9 pb
LHC	0.3–0.9–4 nb	2.4–15–27 nb	1.7–5–21 pb	5–31–55 pb

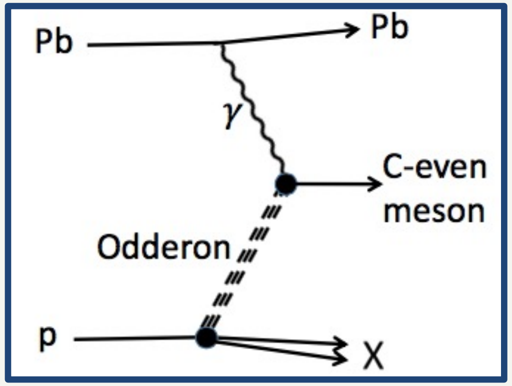
Odderon contribution might be 1-10% at LHC and would dominate at high p_T

….. but experimentally this is difficult to see

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

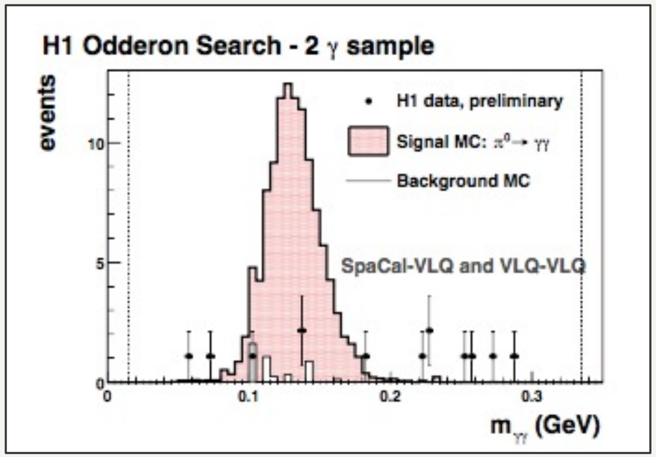
Method 2: Photoproduction of C+

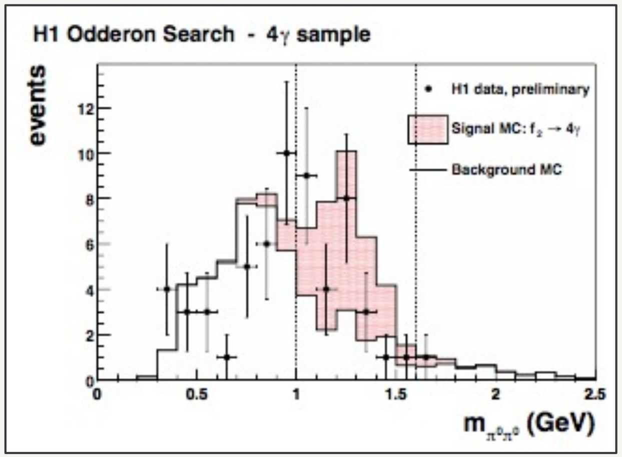
Search in CEP photoproduction where quantum numbers inconsistent with pomeron

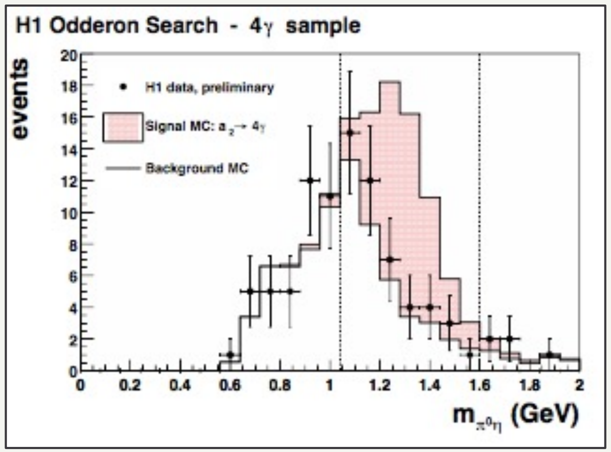


Czyzewski, Kwiecinski, Motyka, PLB398 (1997) 400.
Berger, Donnachie, Dosch, Kilian, Nachtmann, EPJ C9 (1999) 491.
Ryskin EPJ C2 (1998) 339.
Kilian & Nachtmann, EPJ C5 (1998) 317.
Harland-Lang, Khoze, Martin, Ryskin PRD 99 (2019) 3, 034011

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







Direct observation at LHC?

Harland-Lang, Khoze, Martin, Ryskin PRD 99 (2019) 3, 034011

$d\sigma/dy|_{y=0}$ for Pbp collisions

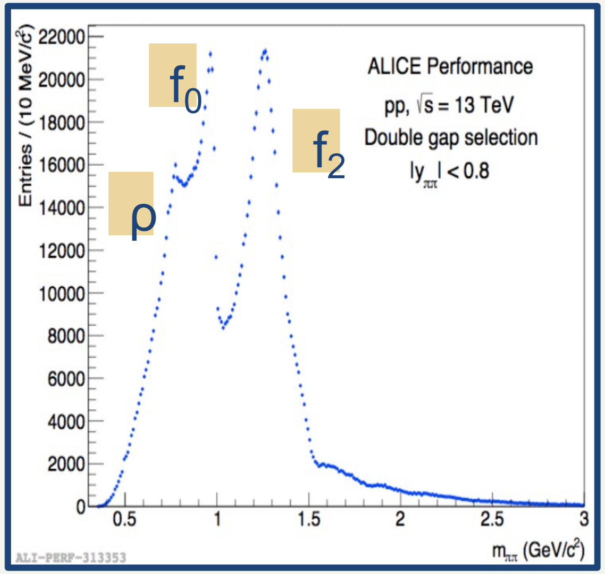
C-even meson (M)	Odderon Signal		Backgrounds		
	Upper Limit	QCD Prediction	$\gamma\gamma$	Pomeron-Pomeron	$V \to M + \gamma$
π^0	7.4	0.1 - 1	0.044	–	30
$f_2(1270)$	3	0.05 - 0.5	0.020	3 - 4.5	0.02
$\eta(548)$	3.4	0.05 - 0.5	0.042	negligible	3
η_c	–	$(0.1 - 0.5) \cdot 10^{-3}$	0.0025	$\sim 10^{-5}$	0.012

Note: Background processes are always much bigger

Which modes can provide significant signal?
How can you be sure any excess is due to odderon?

Go forward

Photoproduction of C+ meson

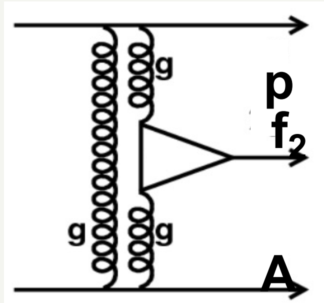


arXiv:1912.00611

- To enhance the photon flux consider heavy ion collisions
  - Proton-ion (pA)
  - Ion-ion (AA*)
- Compared to pp collisions:
  - SIGNAL: For Pb, photon flux is ~Z^2=6700 greater and strongly peaked to backward rapidities
  - Pomeron-pomeron BKG: cross-section is factor 2-5 greater than for protons
  - γγ BKG: Z^2 enhanced in pA. Z^4 in AA! (Z^2 in AA*)

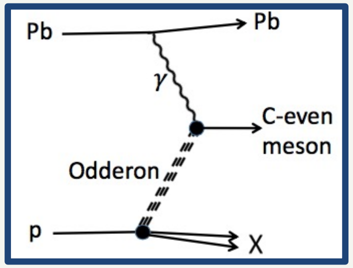
Key idea

C+ mesons dominantly produced by Double Pomeron Exchange: roughly flat with rapidity



SIGNAL PROCESS:

C+ production by photoproduction is peaked towards low rapidities due to energy dependence of photon flux



Ap -> A + f_2 + p
AA* -> A + f_2 + A*

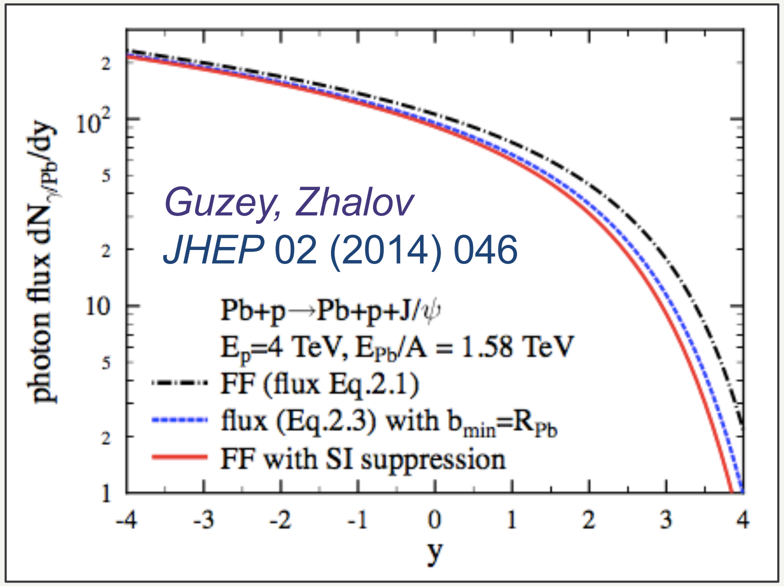
$$\frac{d\sigma_{\rm Odd}}{dy} = \frac{dN}{dy}\sigma_{\rm Odd}(\gamma D \to f_2 D)$$

γp -> f_2 + p

γA-> f_2 + A*

$x=M_V e^{-y}$

$$\frac{d^3 N_\gamma}{dx d^2 b_\gamma} = \frac{Z^2 \alpha^{\rm QED}}{x \pi^2 b_\gamma^2} (x m_n b_\gamma)^2 \; K_1^2 (x m_n b_\gamma)$$



$b>R_A+R_p$ for pA
$b>2R_A$ for AA

Results for p-Pb collisions

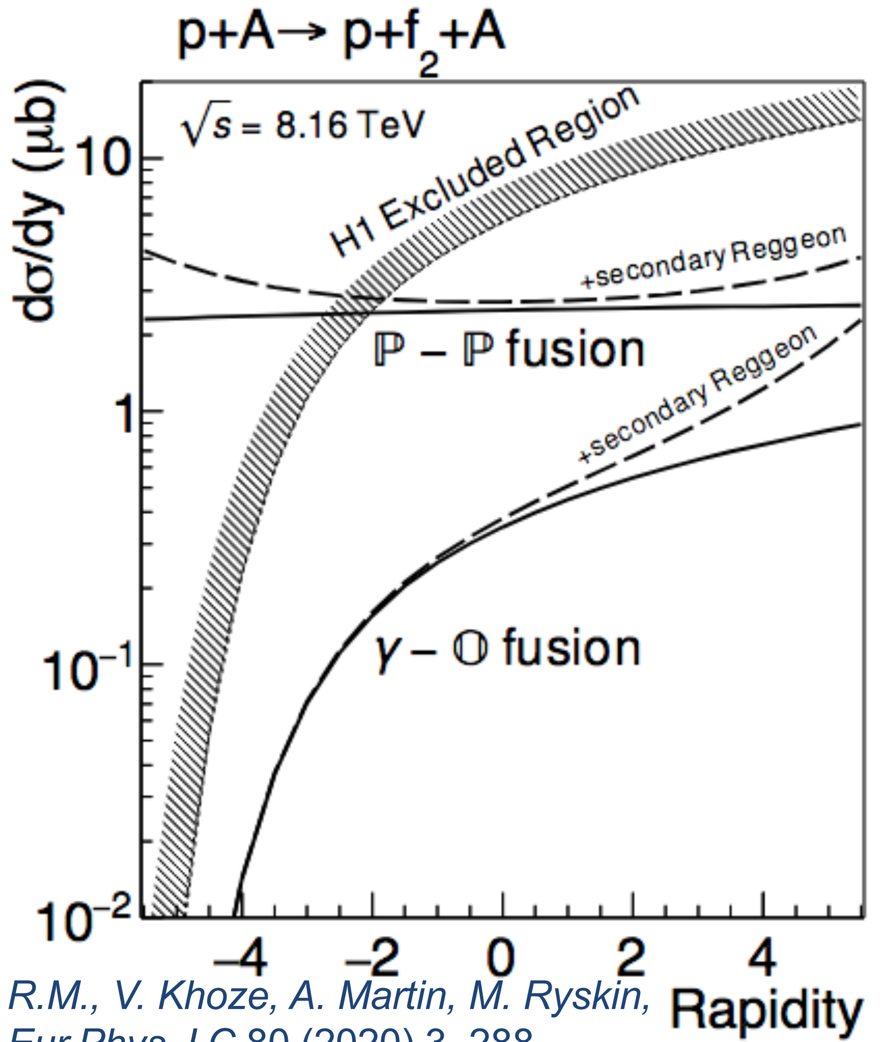
Pomeron-Pomeron production is flat and scaled to p-p results
(CMS arXiv:1706.08310)

Gamma-Odderon is forward peaked. Value unknown. Assume nominal 1nb photoproduction cross-section.

The excluded region comes from preliminary H1 result
(Acta Phys. Polon. B33, 3499 (2002))

Greater sensitivity than previous result.

An excess of events would be seen, but only in the forward region
i.e. for LHCb in pA and not Ap.
Distinctive signature



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

Results for (incoherent) AA* collisions

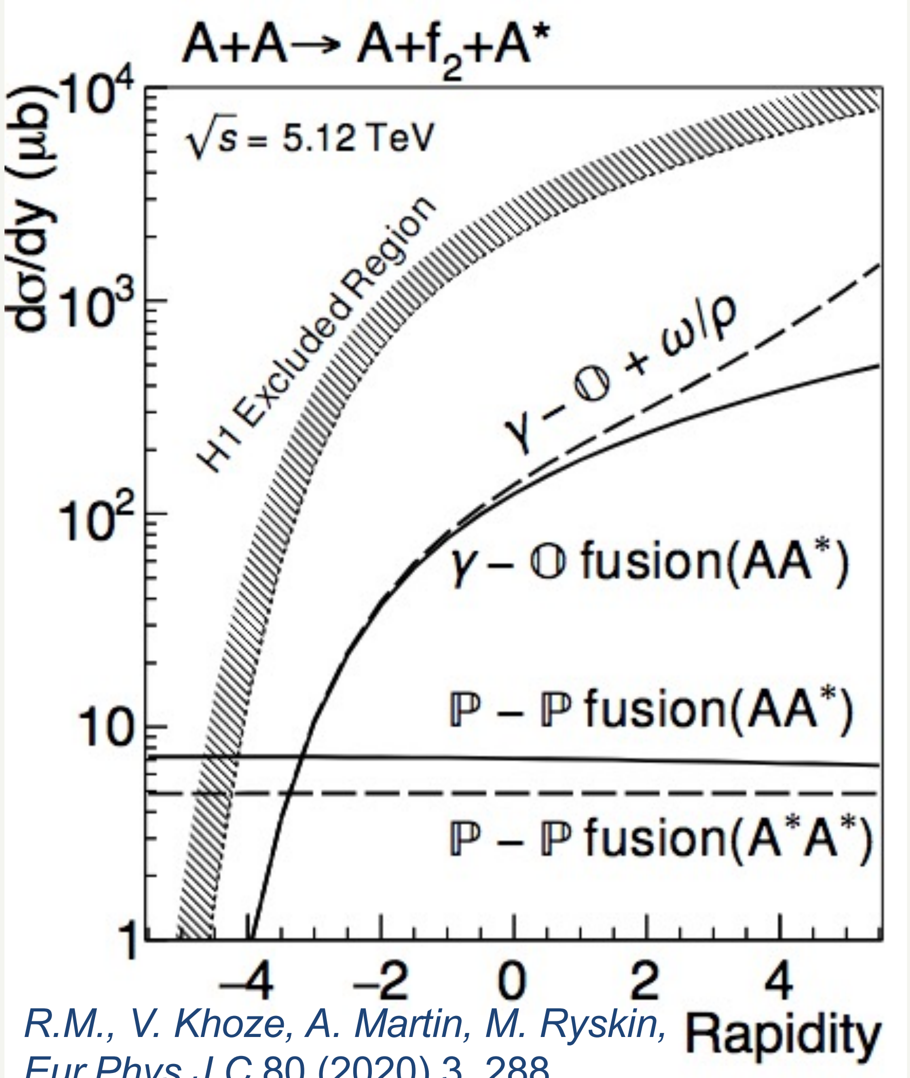
Pomeron-Pomeron production is flat and scaled to p-p results

Gamma-Odderon is forward peaked but **one needs to know which ion emitted the photon.** Detecting break-up allows us do this.

1nb photoproduction cross-section assumed again.

Cross-section is ~ factor 100 greater than in pA. However, luminosity at LHC for AA is ~ factor 100 lower.

Relative background is much lower than in pA collisions.

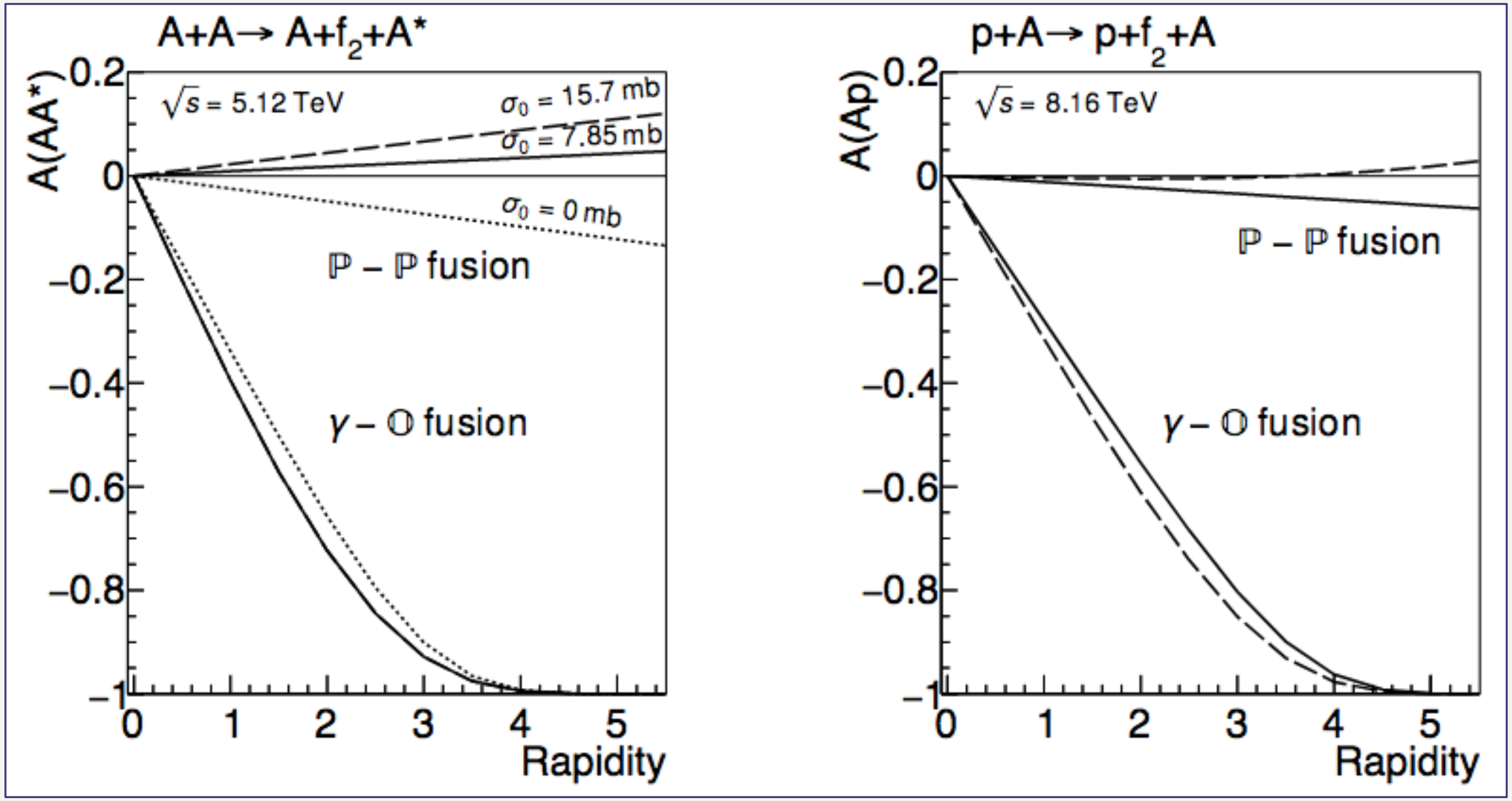


R.M., V. Khoze, A. Martin, M. Ryskin, Eur.Phys.J.C 80 (2020) 3, 288

Asymmetry

$$A(Ap) = \frac{\sigma(pA) - \sigma(Ap)}{\sigma(pA) + \sigma(Ap)}$$

$$A(AA^*) = \frac{\sigma(A^*A) - \sigma(AA^*)}{\sigma(A^*A) + \sigma(AA^*)}$$



Asymmetry in pA/Ap would be most clearly seen in forward/backward detectors.
Note: LHC has runs where they swap the direction of the projectiles

Asymmetry in AA requires you 'tag' the photon emitter: the ion that doesn't break

Conclusions

- UPC provide a wealth of information on the production of one or two mesons with well defined quantum numbers.
- Suitable combinations of pp, pA, AA collisions and observables of isolation and pT are powerful tools.
- Quarkonia allow perturbative predictions
  - testing QCD
  - constraining PDFs
  - searching for exotica