Coherent production in UPC at the LHC

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University College Dublin

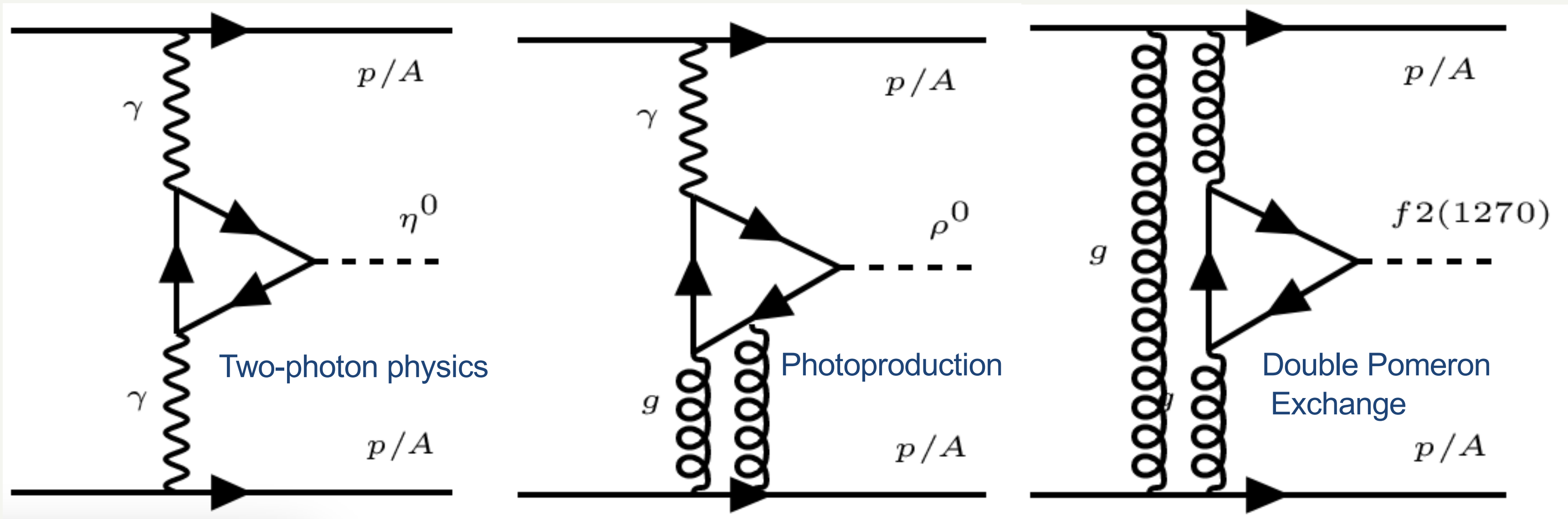
GDR/QCD workshop on coherence/incoherence in diffractive collisions at DIS and at hadron colliders

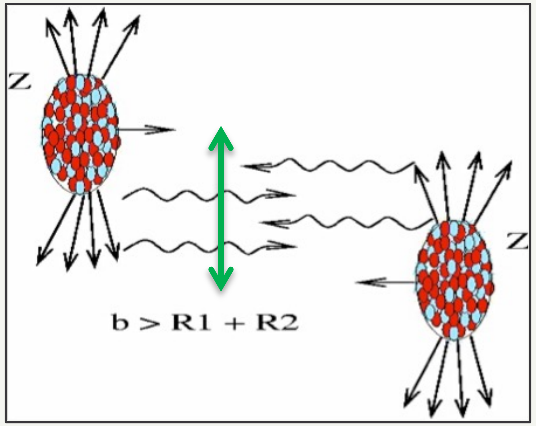
11/10- 12/10 IJCLab

Overview

- UPC at LHC
- The advantages of colliding pp, pPb, PbPb
- .... and pA in fixed target mode
- How we distinguish coherent / incoherent
- What has been measured.
- What we should measure.
- Summary

Colourless propagators

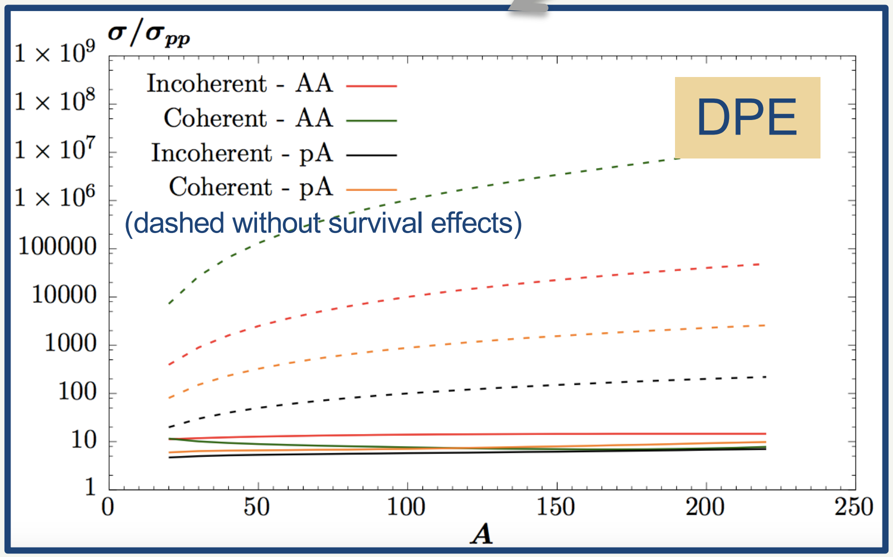


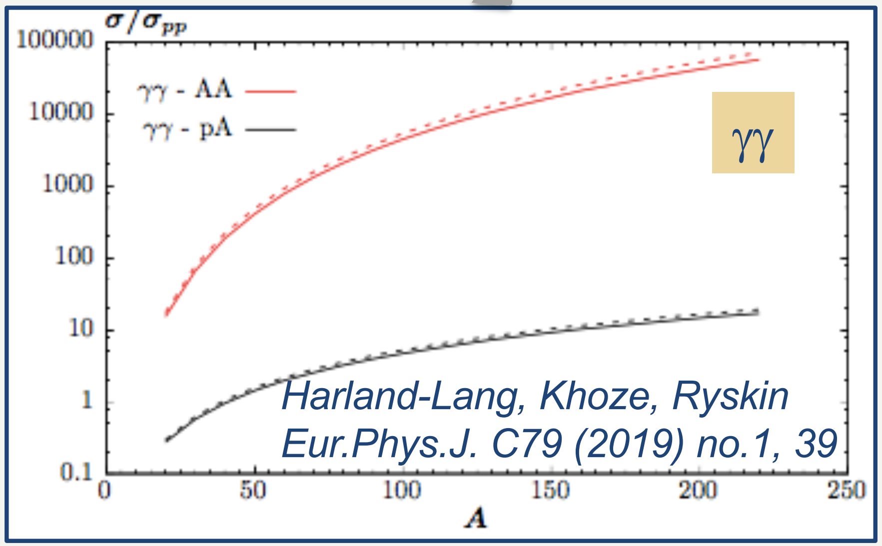


Generally, to ensure no (colourful) QCD interaction, $d > R_1 + R_2$ (1.5 - 6 fm).

Complementarity of collisions

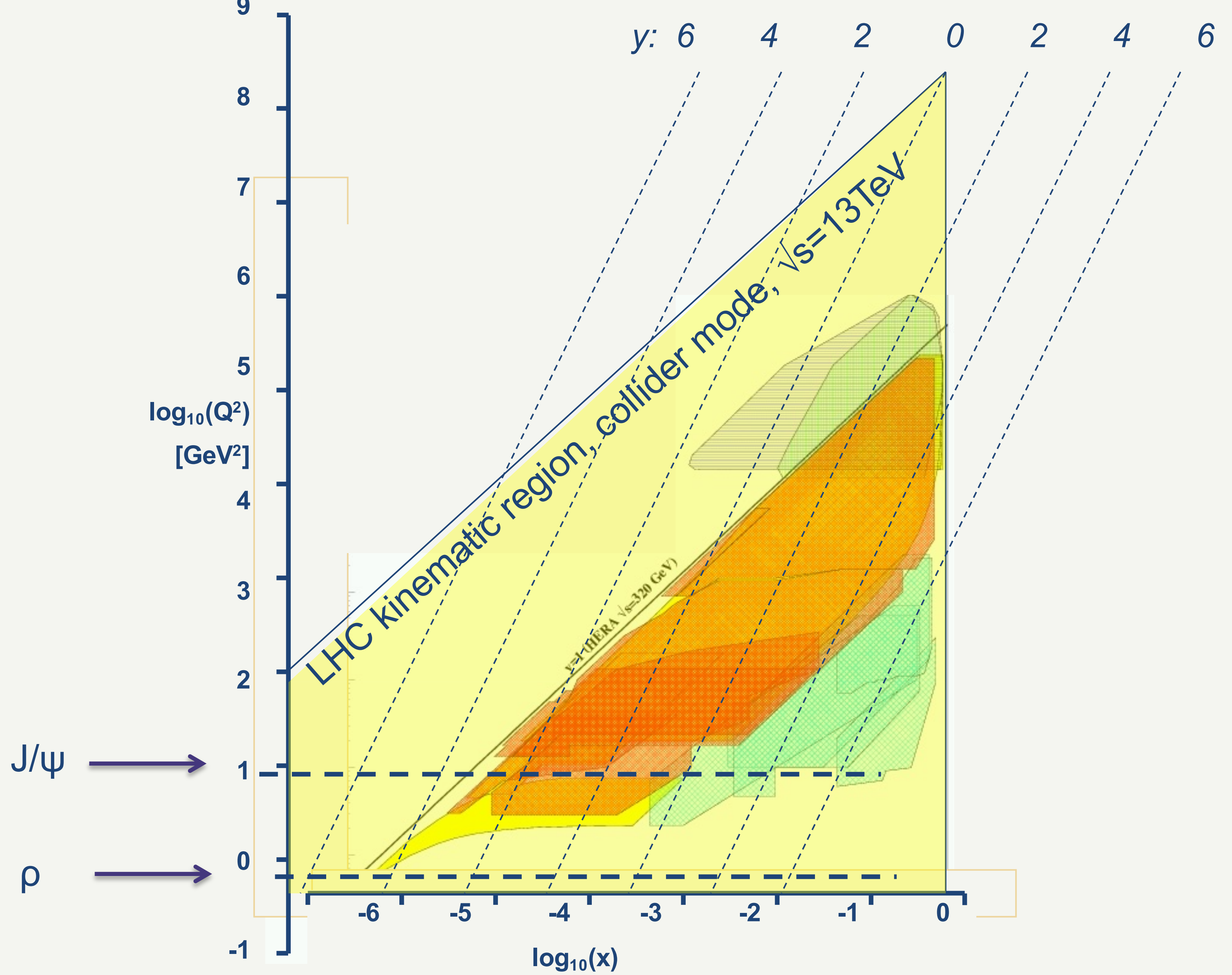
Coherent	DPE (PP)	γP	γγ
pp	~100μb	~100μb	~0.0001μb
pA	x $A^{1/3}$	x Z^2	x Z^2
AA	x $A^{1/6}$	x AZ^2	x Z^4



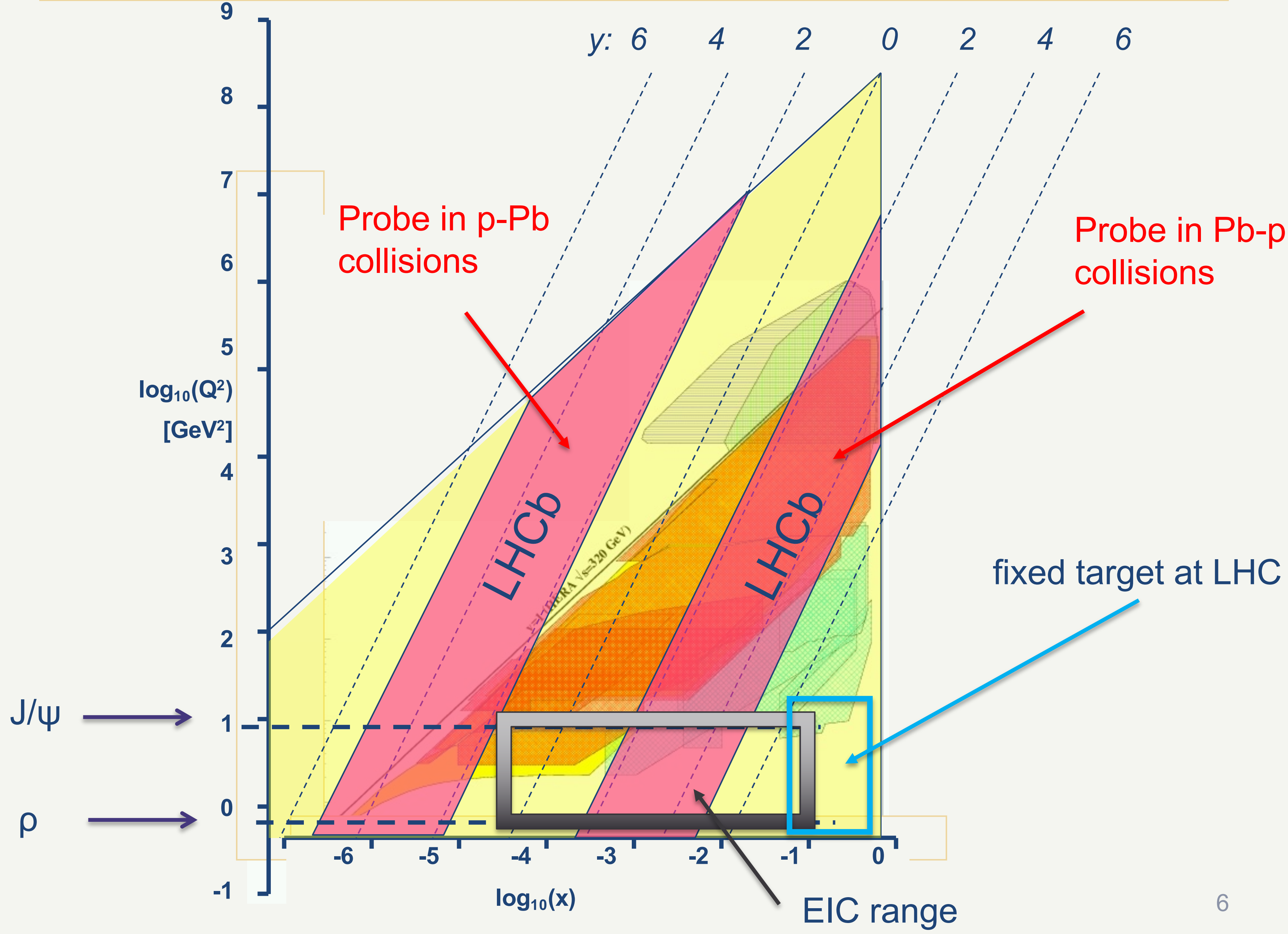


Harland-Lang, Khoze, Ryskin
Eur.Phys.J. C79 (2019) no.1, 39

x-Q² values probed at LHC



Complementarity of experiments/projectiles



Experimental design is important

- My signal is your background
- You can enhance your preferred physics by:
  - choice of beams
  - choice of signal
  - break-up of projectile
  - t-dependence

} coherent / incoherent

Coherent/Incoherent (theory)

- Definitions:
  - **Coherent** interaction with whole projectile and exclusive production of central state:
    A+B->A+C+B
  - **Incoherent** is A+B->A+C+B' with change of one or both projectiles

(sometimes excitations e,g, p->Δ->p+γ might be considered coherent
Most experiments have no chance of seeing this, even with proton tagging)

Coherent/Incoherent (exp)

- Definitions:
  - **Coherent** interaction where
    - no break-up is observed
    - pt distribution follows exp(bt) b large
      - Does this include nuclear excitation ?
      - Does this include coherent breakup
  - **Incoherent** is where:
    - break-up is observed
    - neutrons are observed
    - pt distribution follows exp(bt) b small
- The translation between the theory and (variable) experimental definitions requires clear definitions, and modelling of theory and detectors

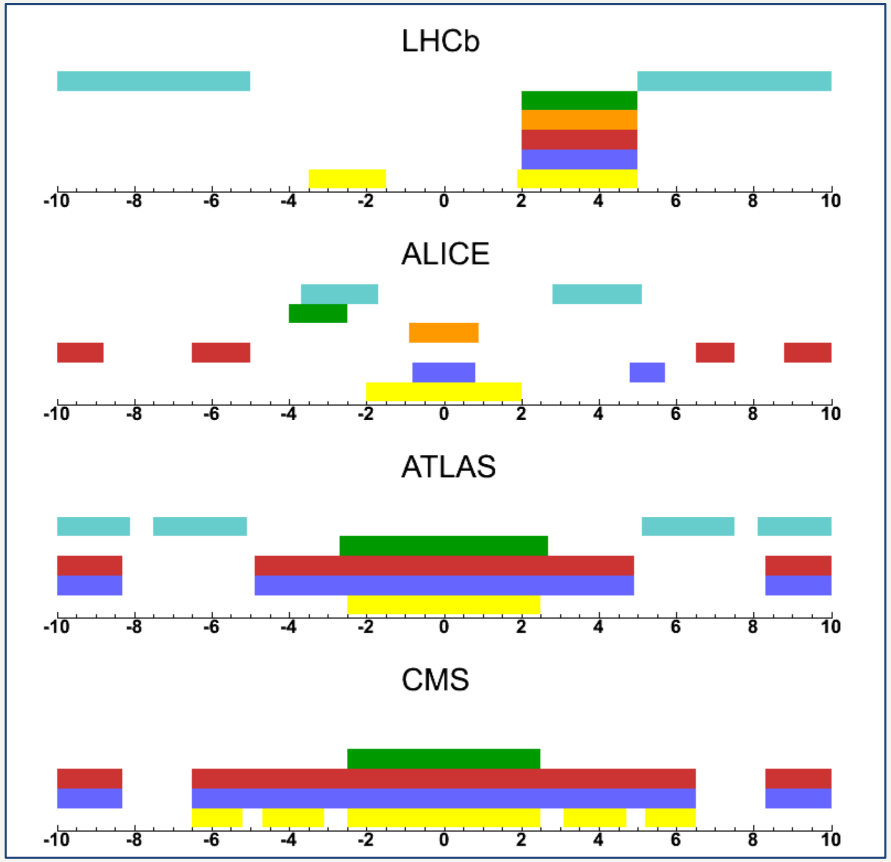
LHC and the detectors

- LHC collides pp, pPb and PbPb
- Also possible is **fixed target** mode of p or Pb on gas

ATLAS, CMS	High Lumi	High pT
ALICE, LHCb	Low Lumi	Low pT

- LHCb: full reconstruction $2<\eta<5$
- ATLAS, CMS, ALICE: $5<\eta<5$

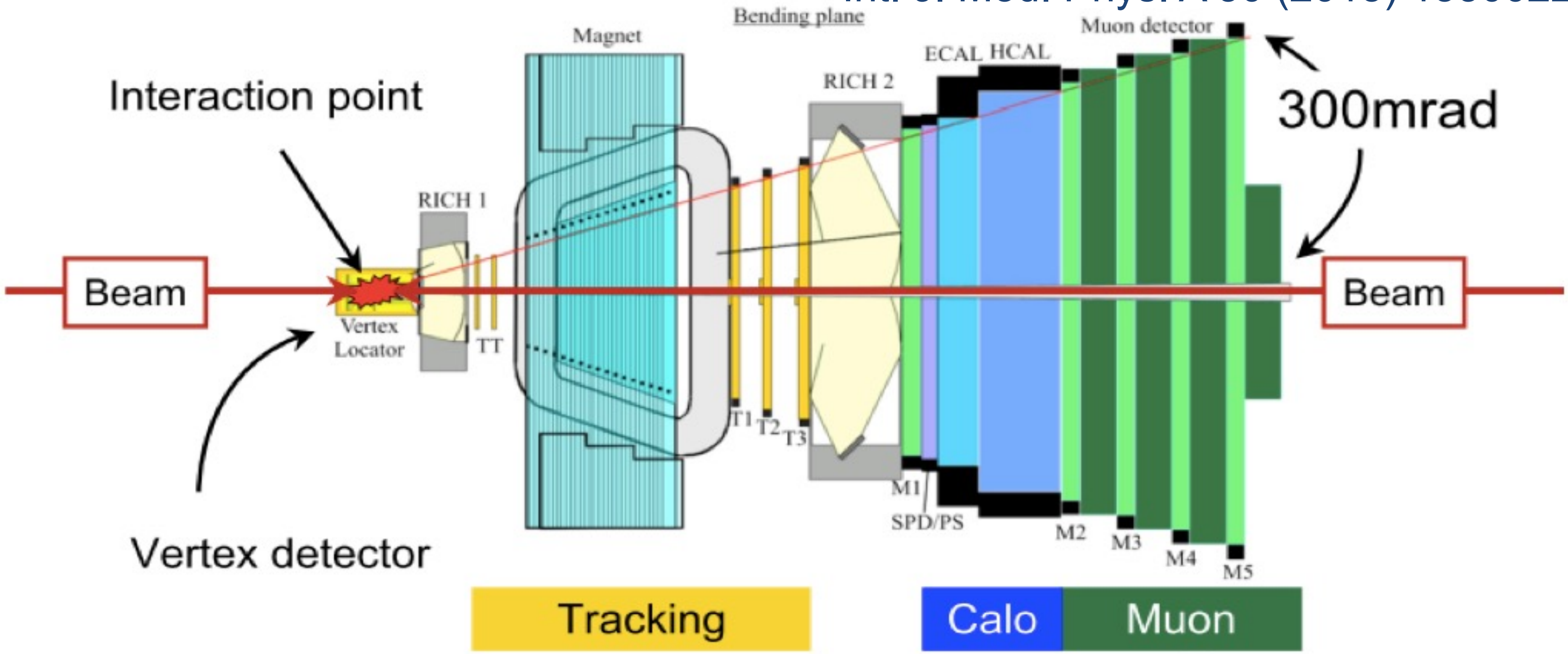
- All have vetos towards beam axis
- ATLAS, CMS, ALICE have ZDCs for neutrons
- ATLAS, CMS(+TOTEM) have roman pots close to beam (but generally do not detect recoil protons for low-mass objects)



Tracking
ECAL
HCAL
Hadron PID
Muon
Counters

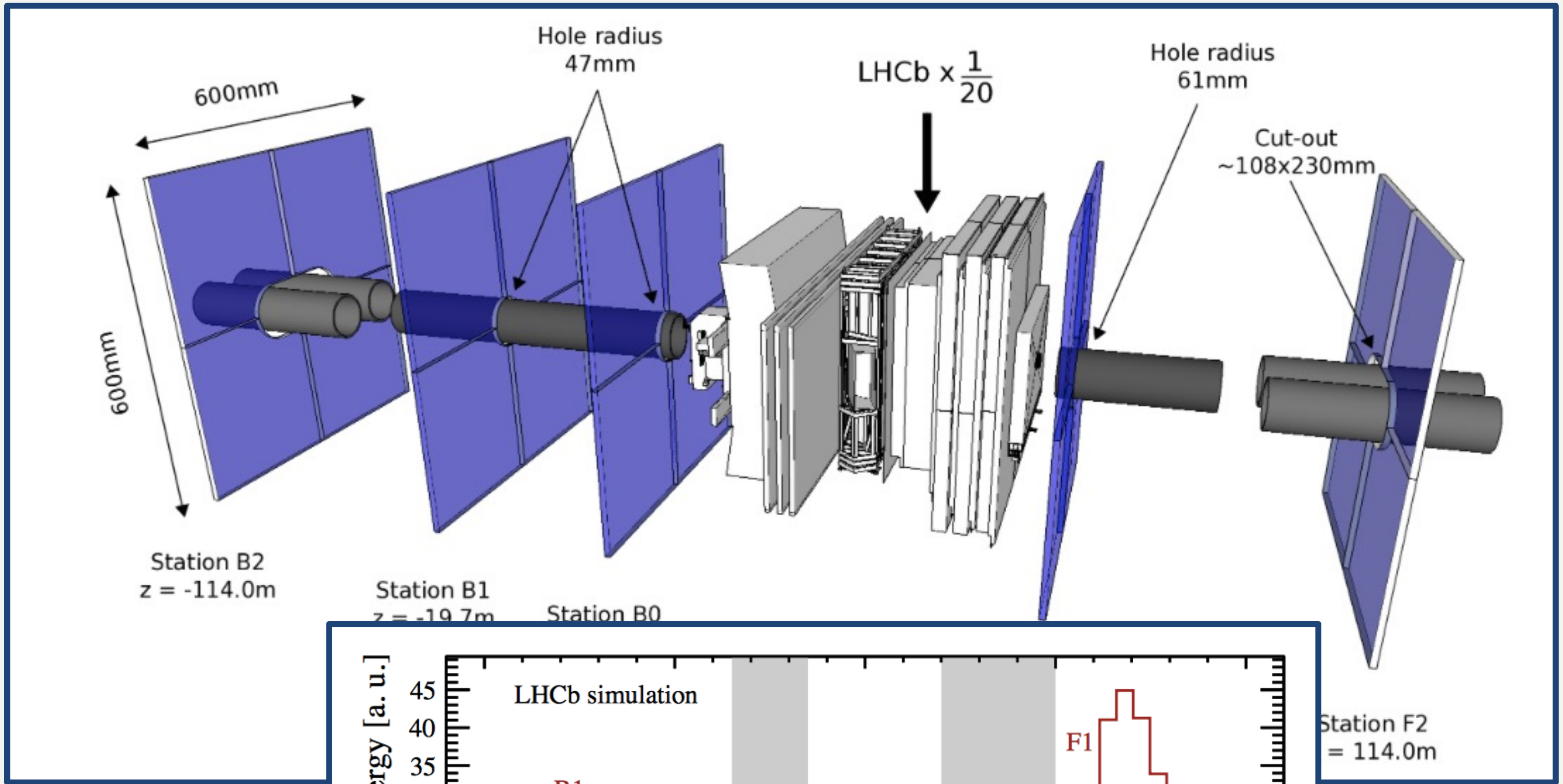
The LHCb detector

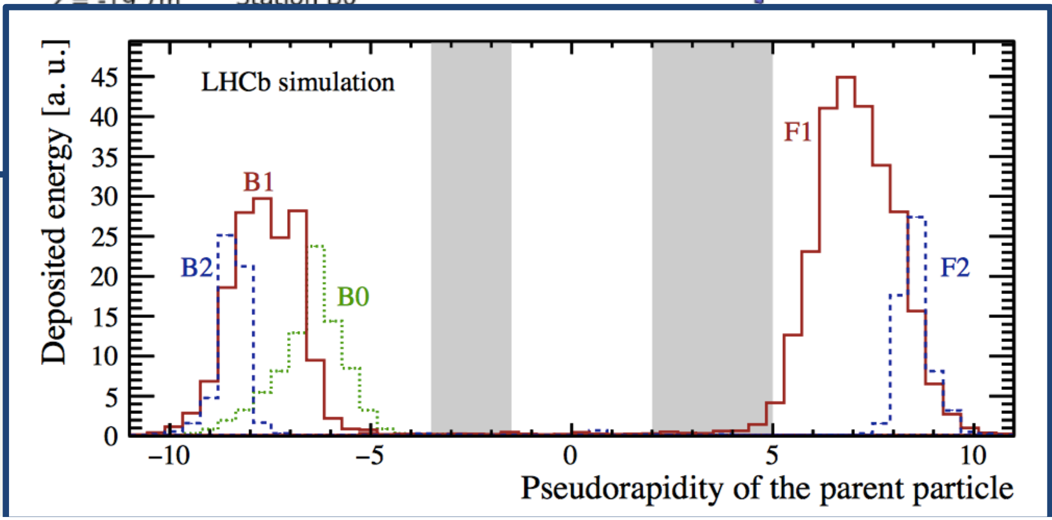
Int. J. Mod. Phys. A 30 (2015) 1530022



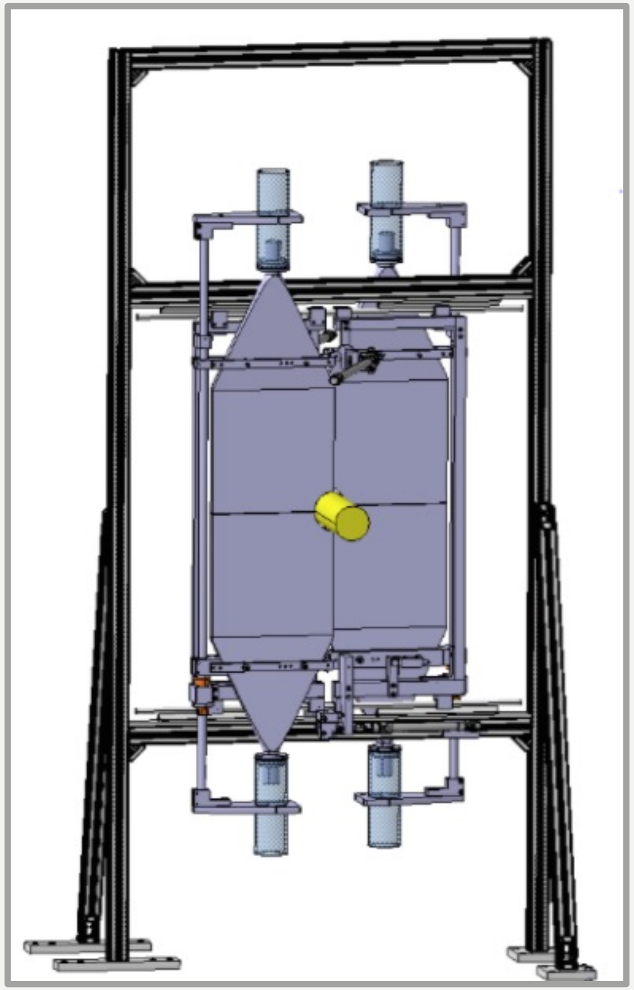
Fully instrumented: $2 < \eta < 5$
Veto region (Run 2): $-10<\eta<-5$, $5<\eta<10$

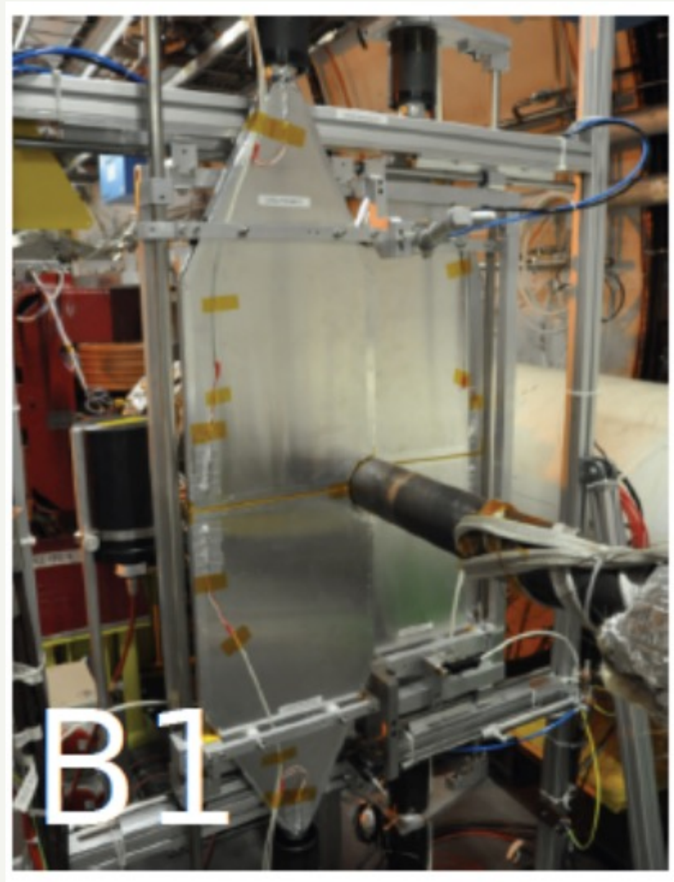
The LHCb detector





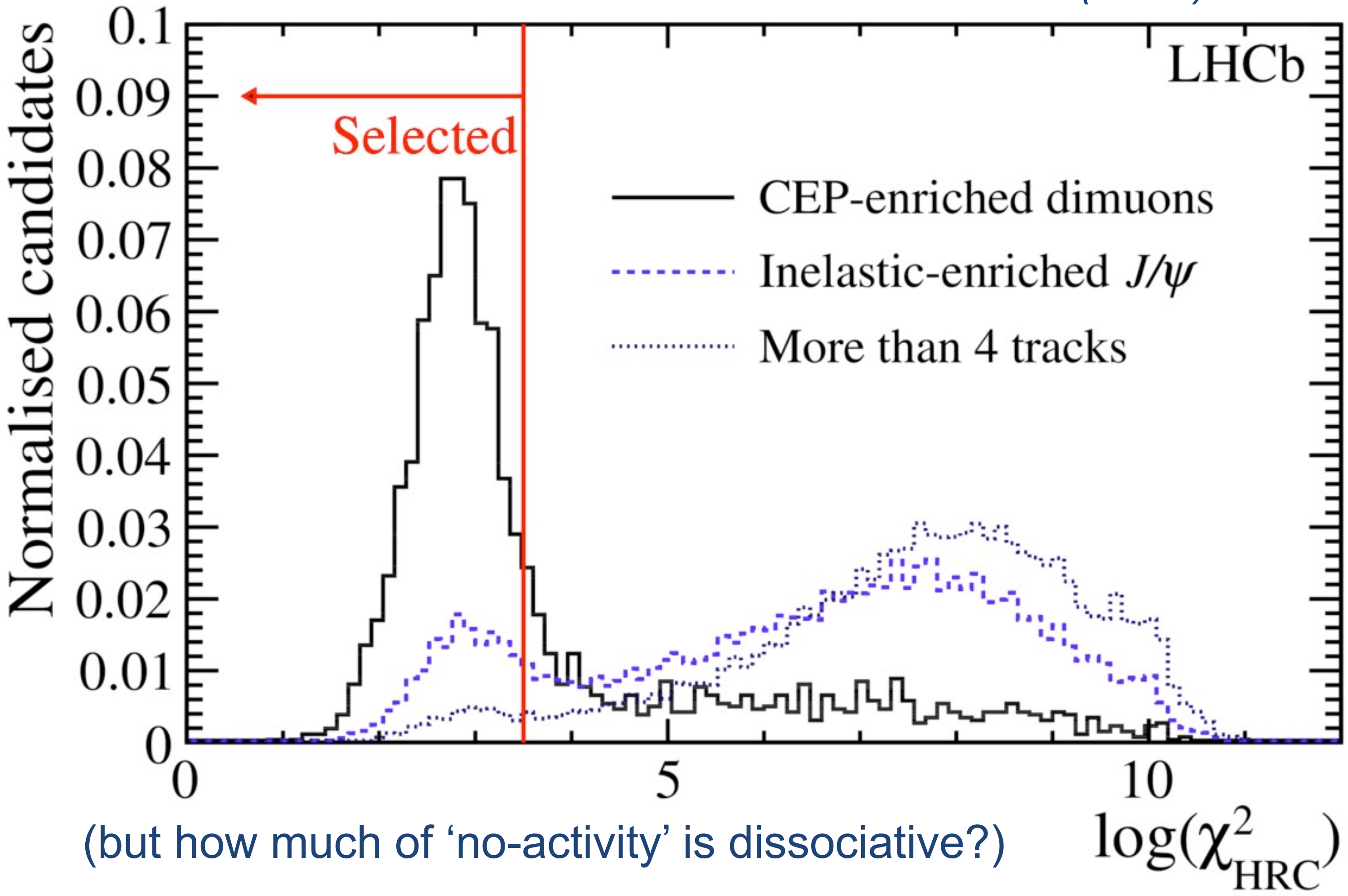
The LHCb detector





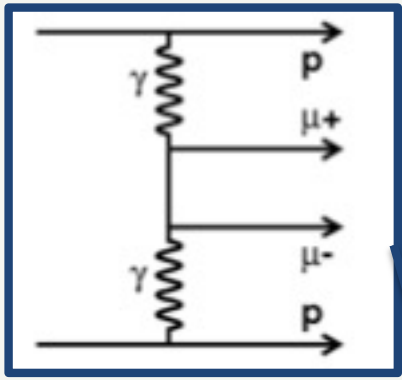
Discrimination power of Herschel

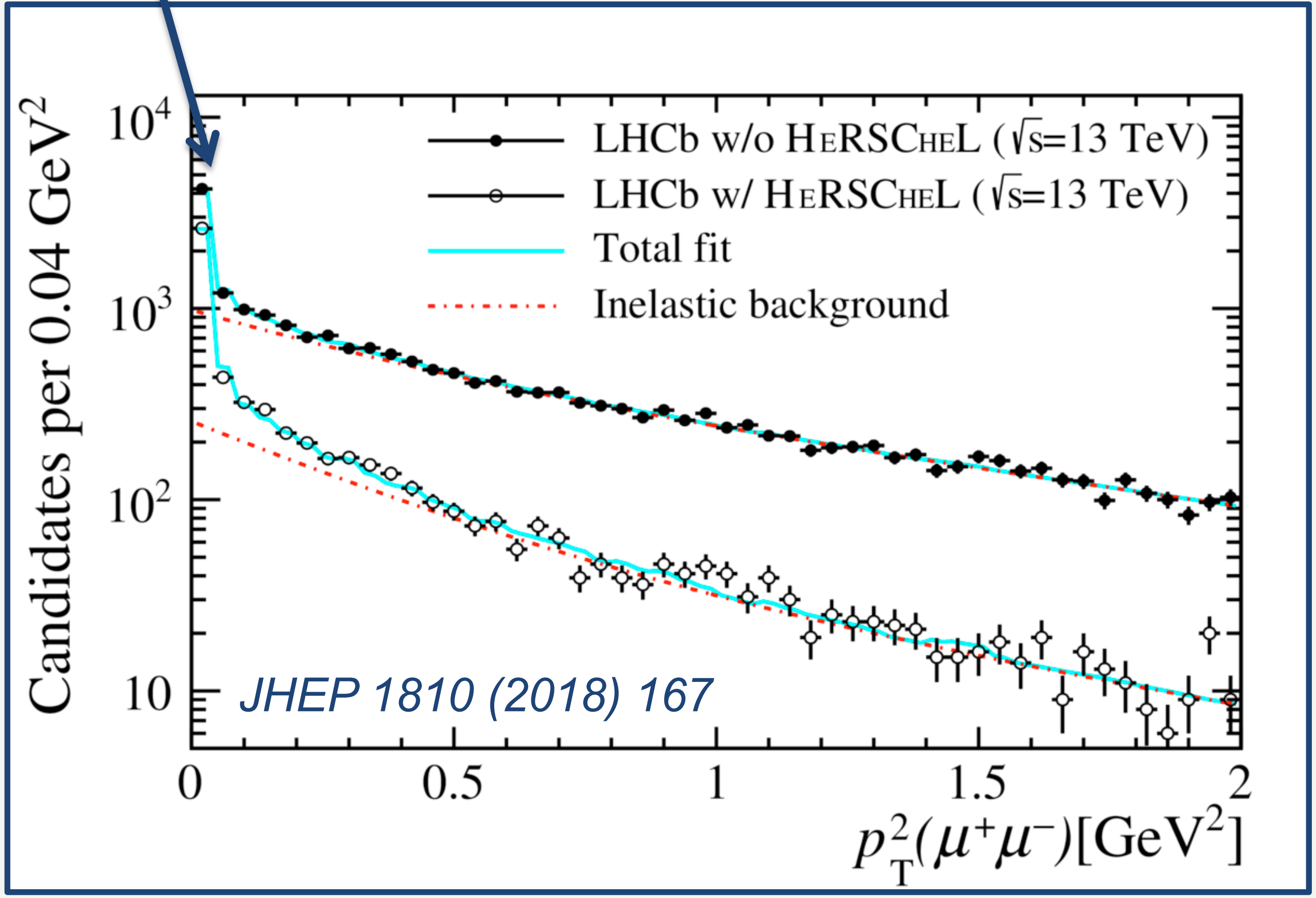
JHEP 1810 (2018) 167



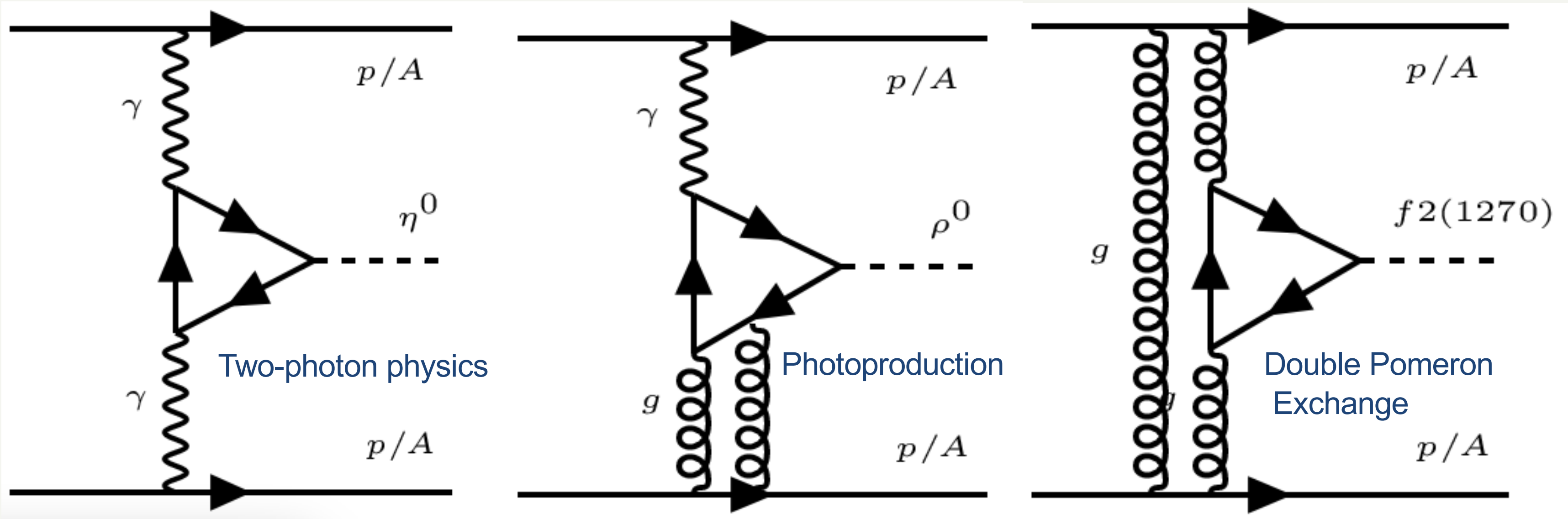
(but how much of 'no-activity' is dissociative?)

Dimuon continuum



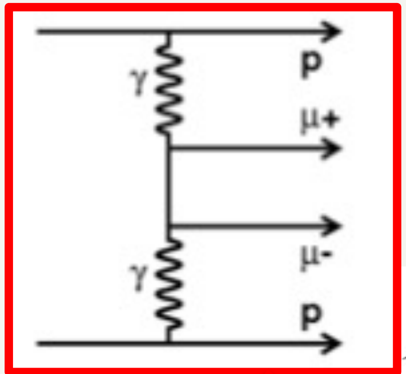


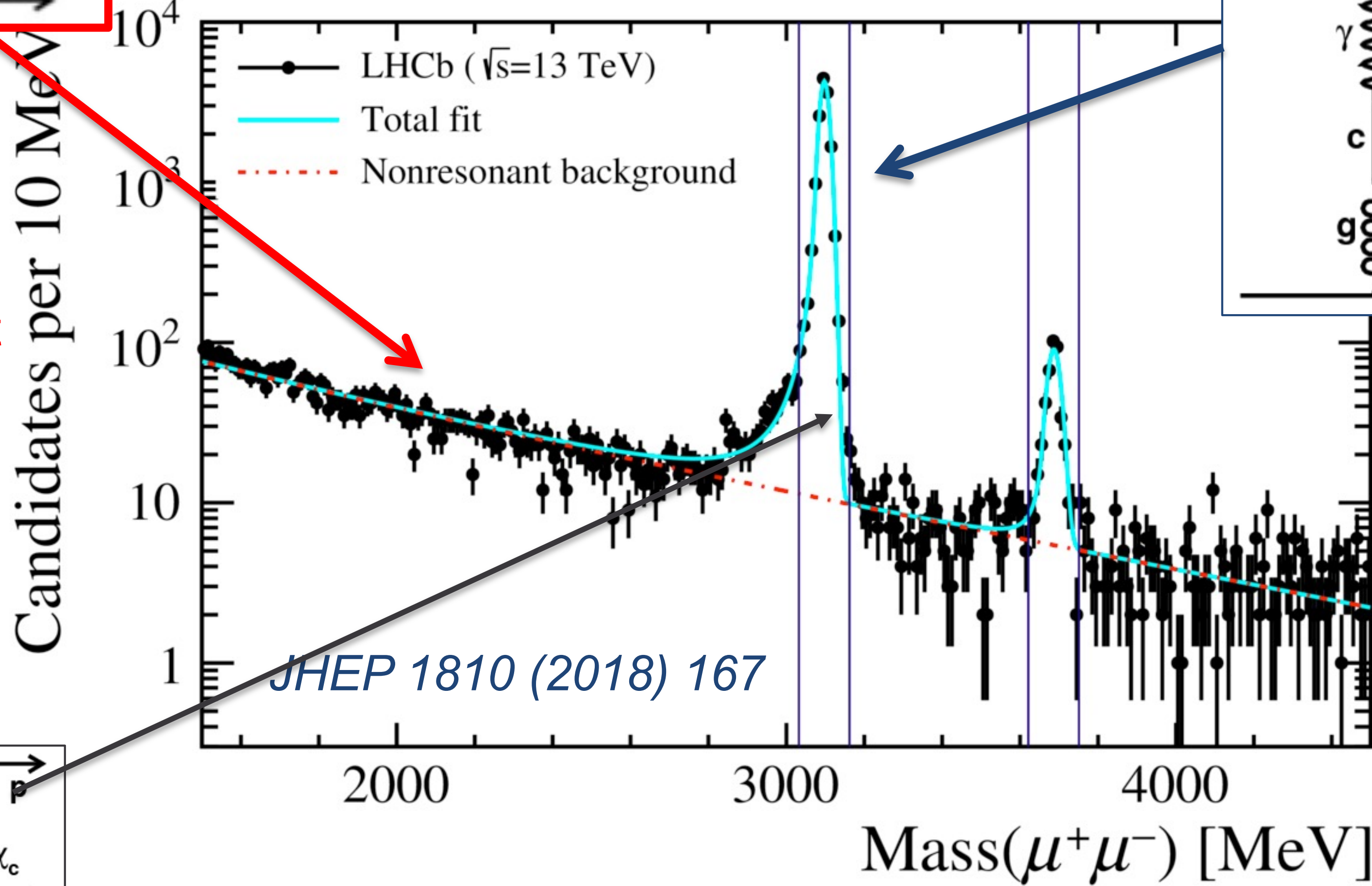
UPC physics

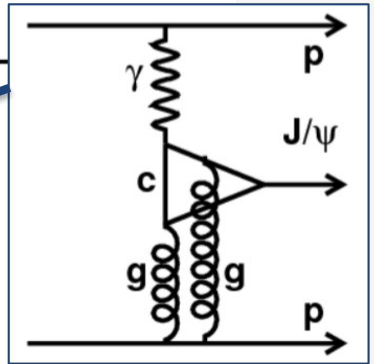


p / A
γ
η0
Two-photon physics
γ
p / A
p / A
γ
ρ0
Photoproduction
g
p / A
p / A
f2(1270)
g
Double Pomeron Exchange
p / A

Dimuons in pp collisions



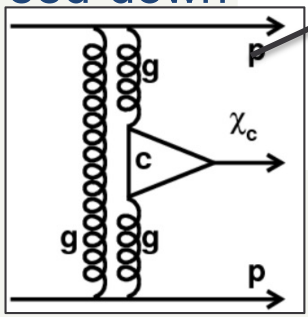




γγ events continue to detection threshold at ~ 600 MeV

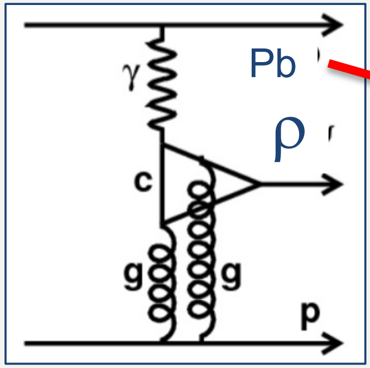
(electrons down to ~200MeV)

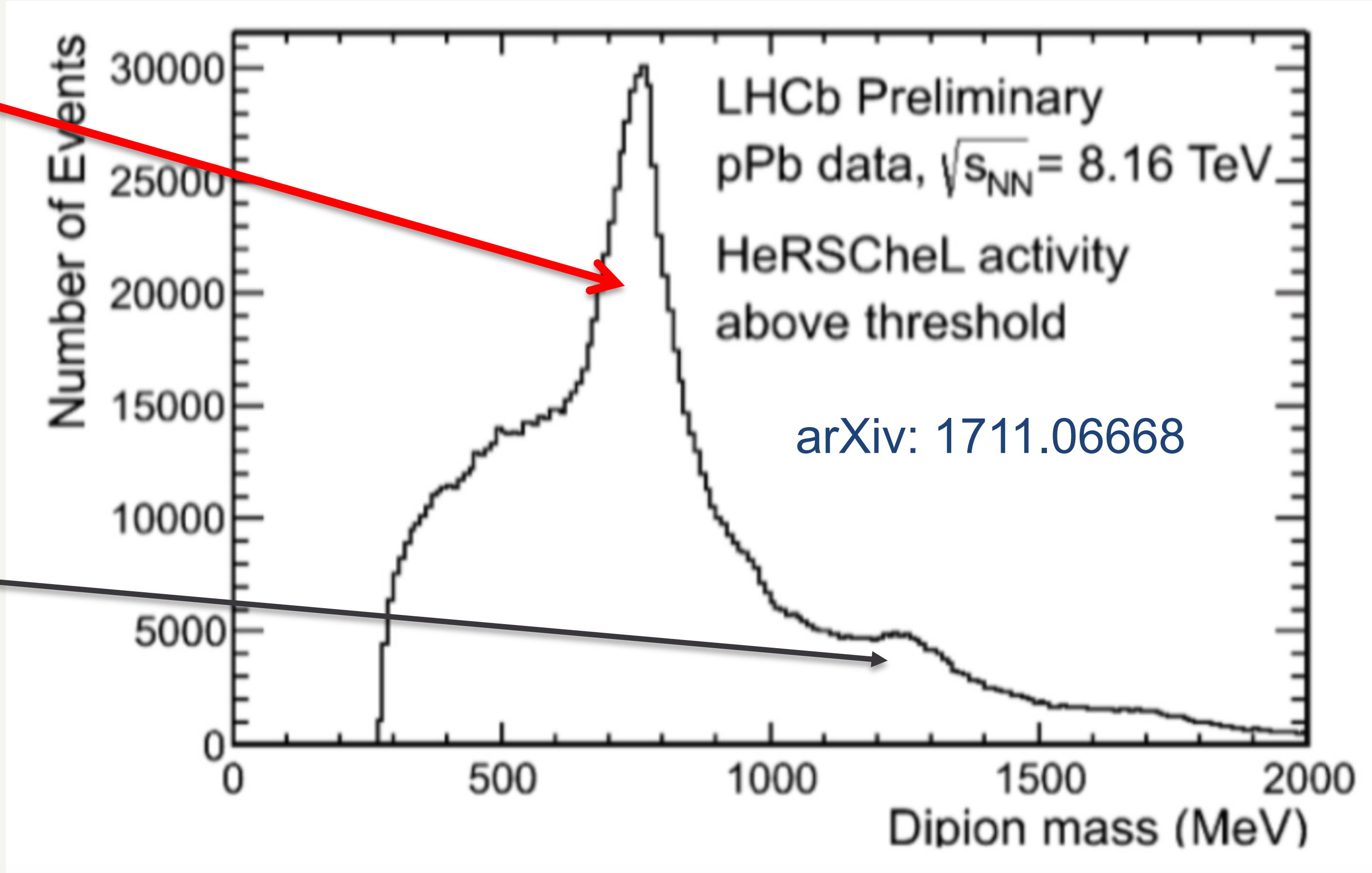
Feed-down

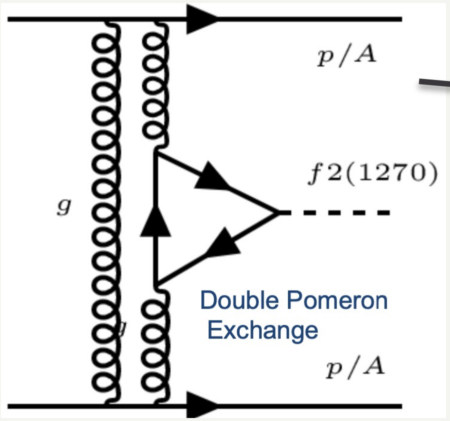


Two muons and nothing else in the LHCb detector

Dipions in pPb collisions



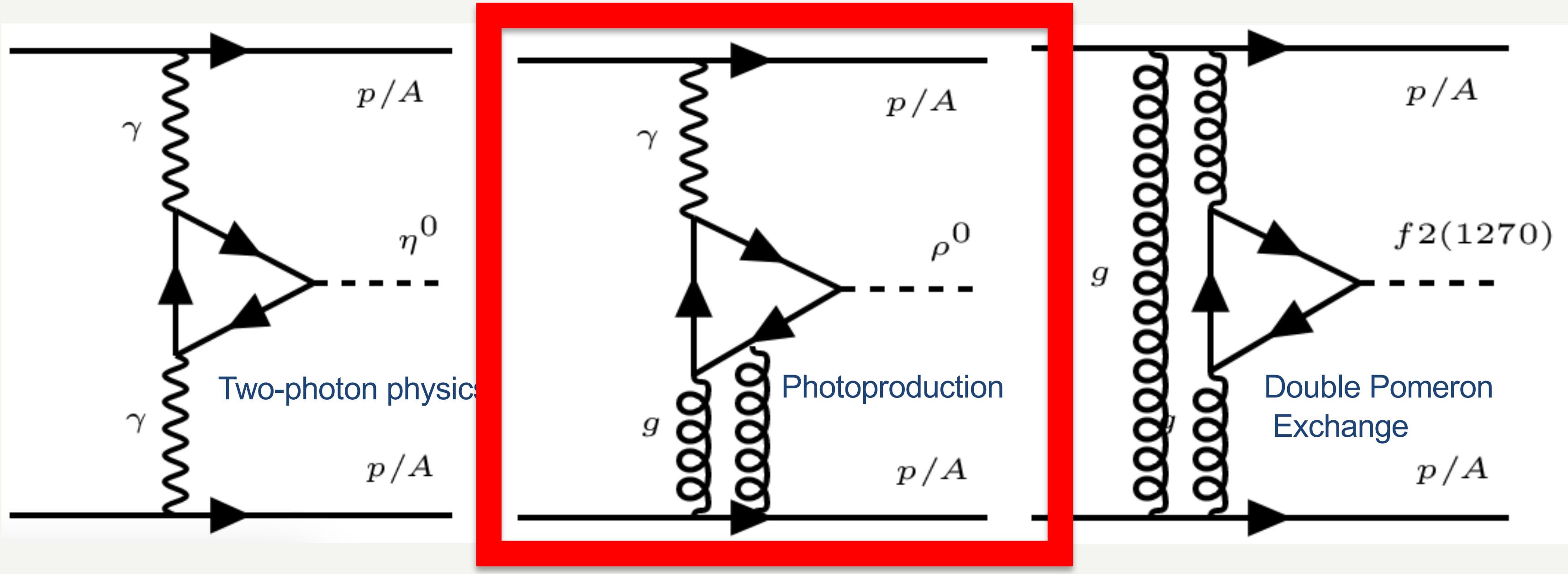




DPE and photoproduction via Reggeons

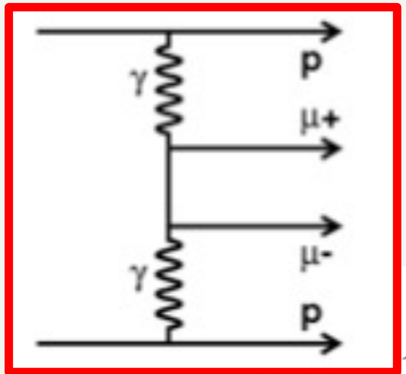
Two pions and nothing else in the LHCb detector

UPC physics



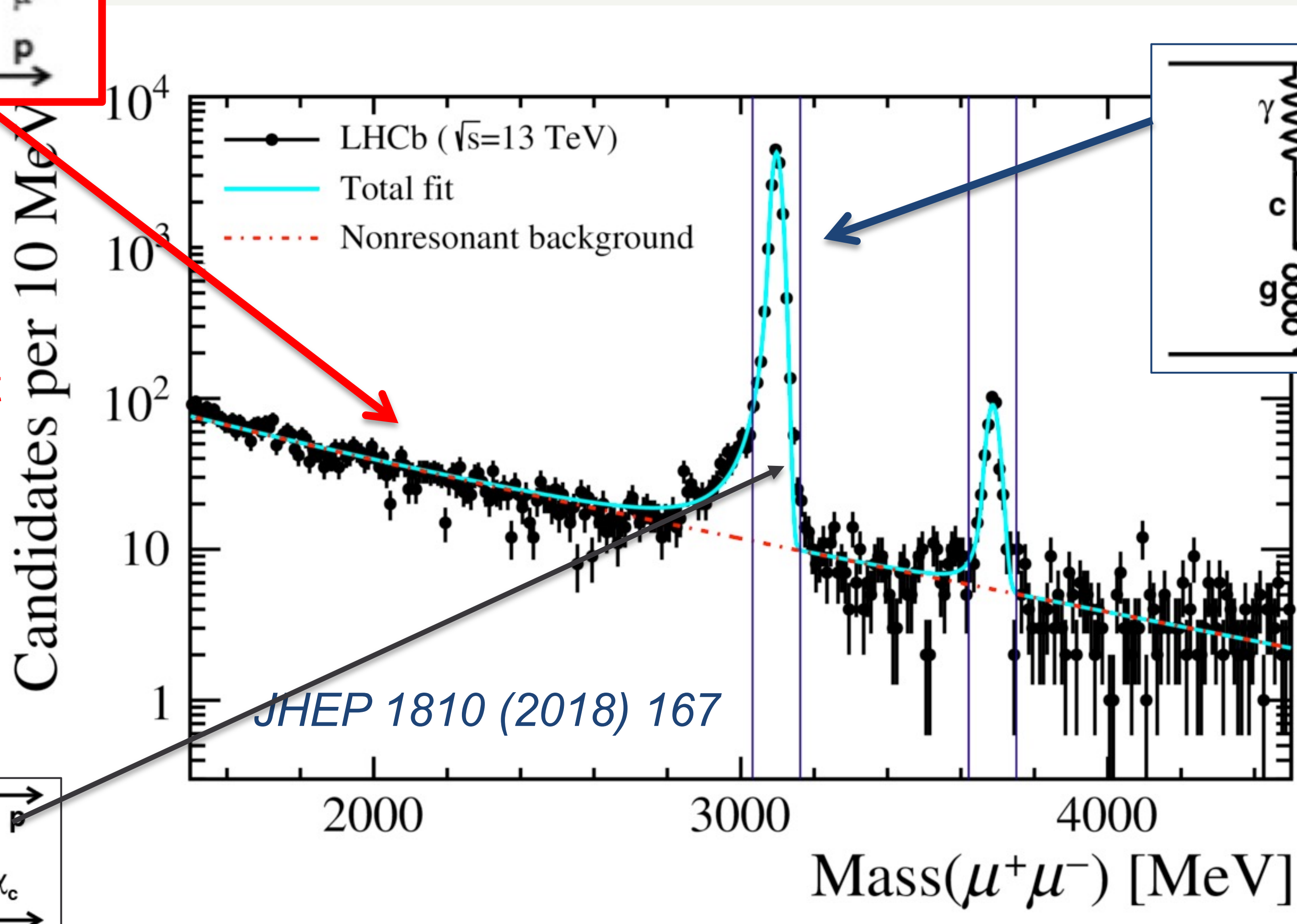
p/A
γ
η^0
Two-photon physics
γ
p/A
p/A
γ
ρ^0
Photoproduction
g
p/A
p/A
g
$f2(1270)$
Double Pomeron Exchange
p/A

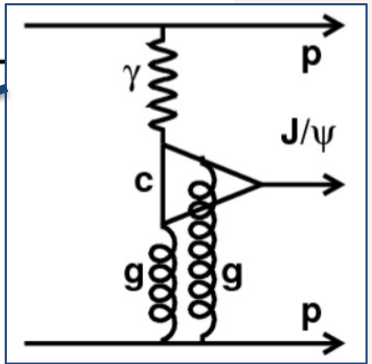
Photoproduction of J/ψ in pp collisions



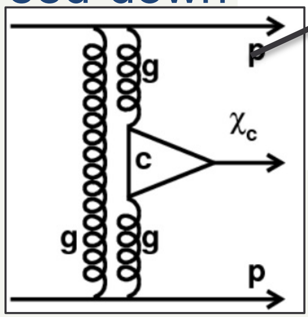
γγ events continue to detection threshold at ~ 600 MeV

(electrons down to ~200MeV)

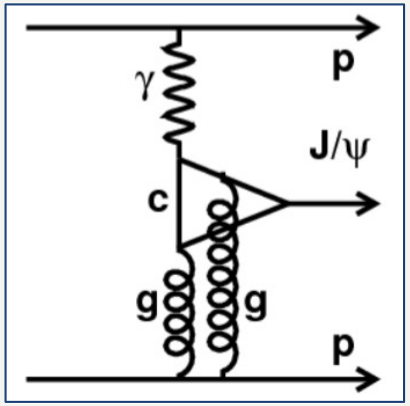




Feed-down



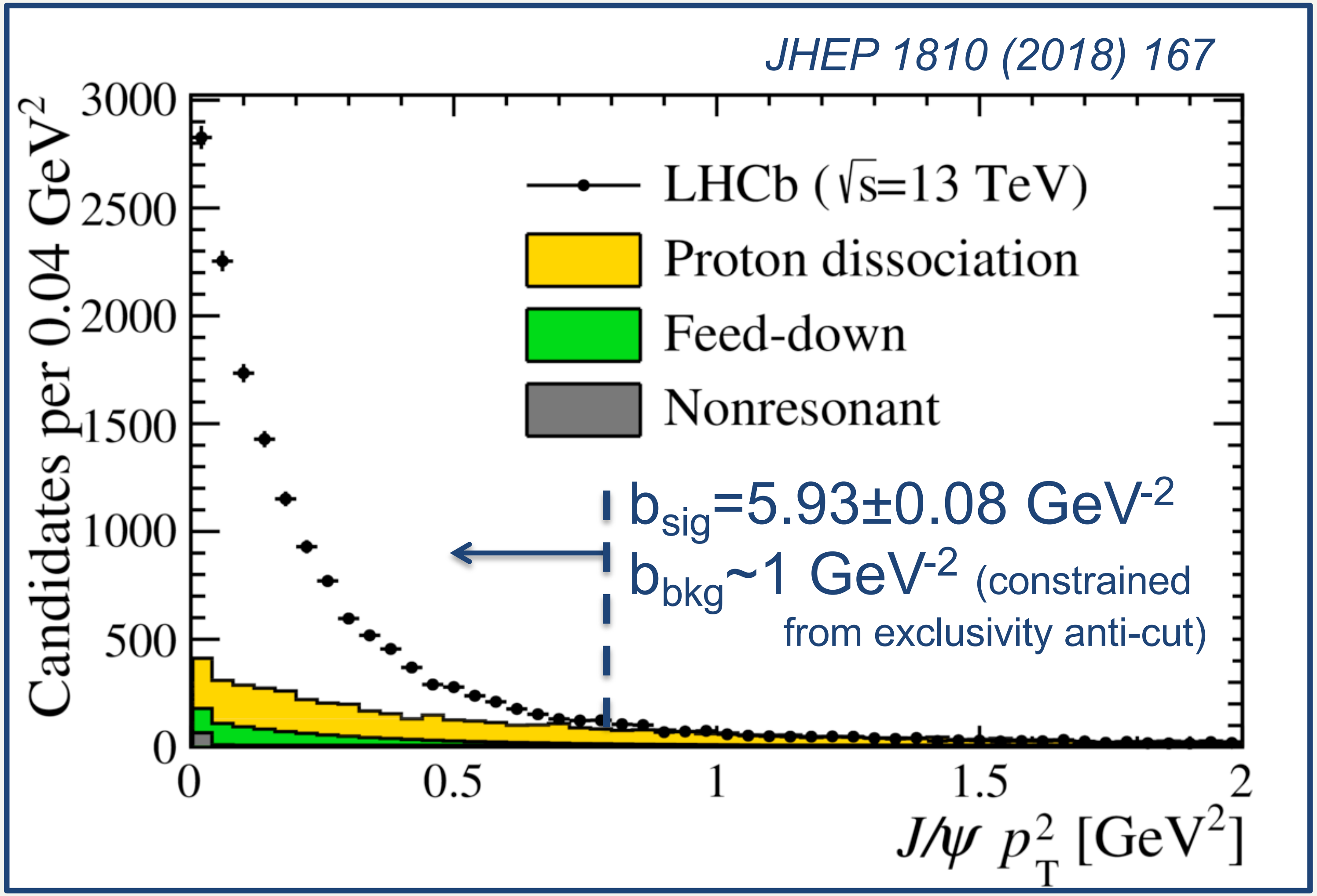
Two muons and nothing else in the LHCb detector



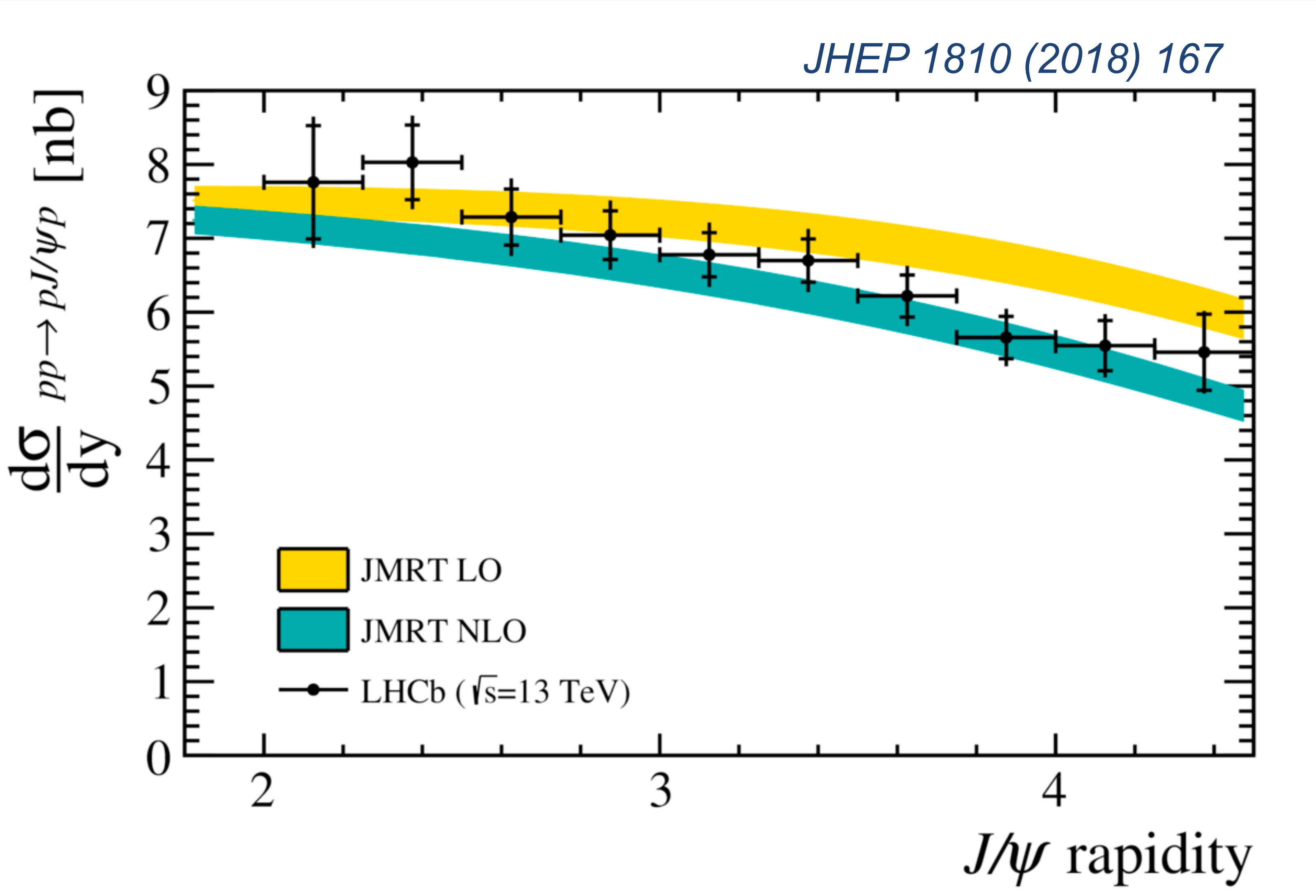
Purity for CEP of J/ψ

Assume Signal and Background

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

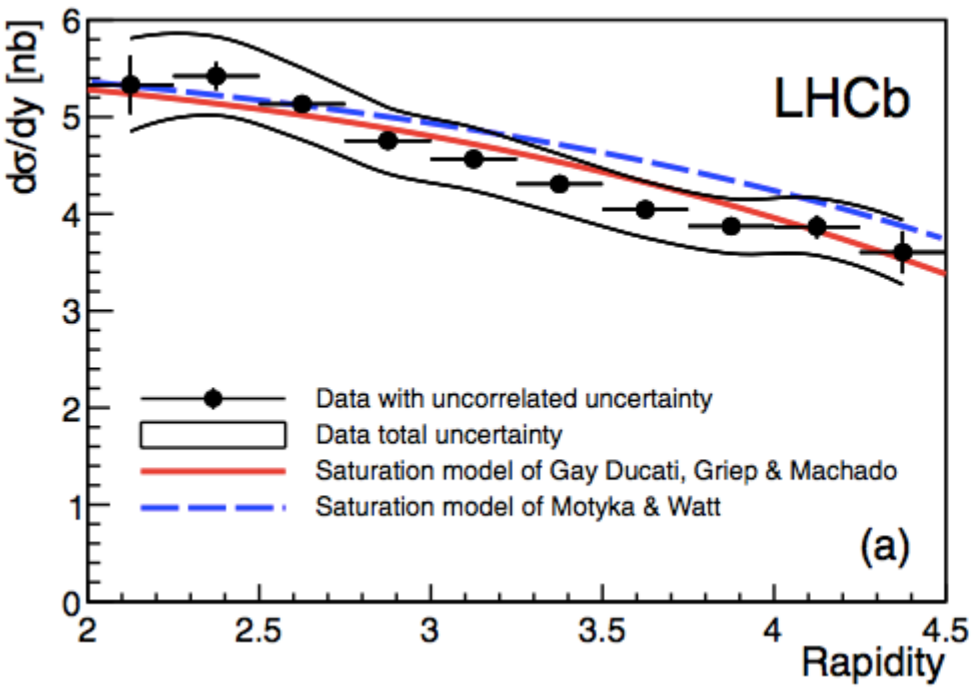


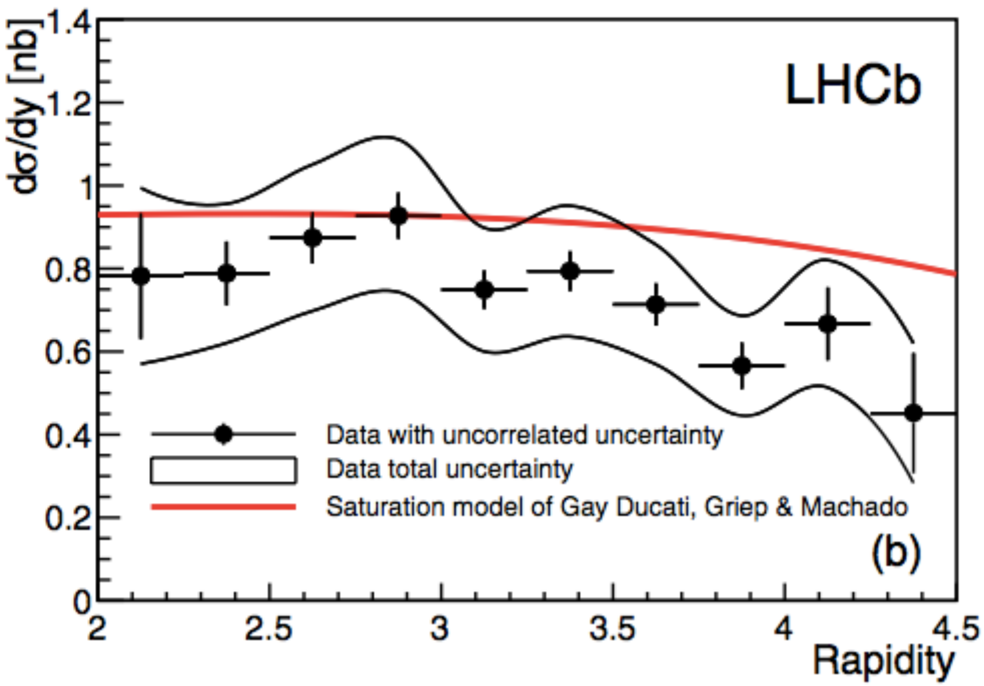
Differential cross-section pp→pJ/ψp



Implications: Saturation?

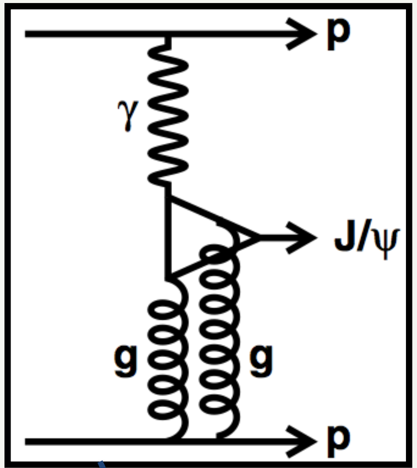
JPG 41 (2014) 055002



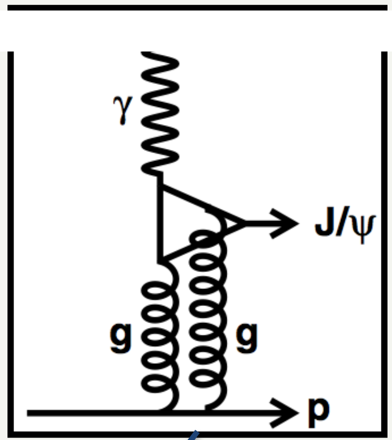


LO doesn't fit data
NLO does
Various saturation models do

Convert to photo-production cross-section



LHCb measures



HERA measured

Photon Flux

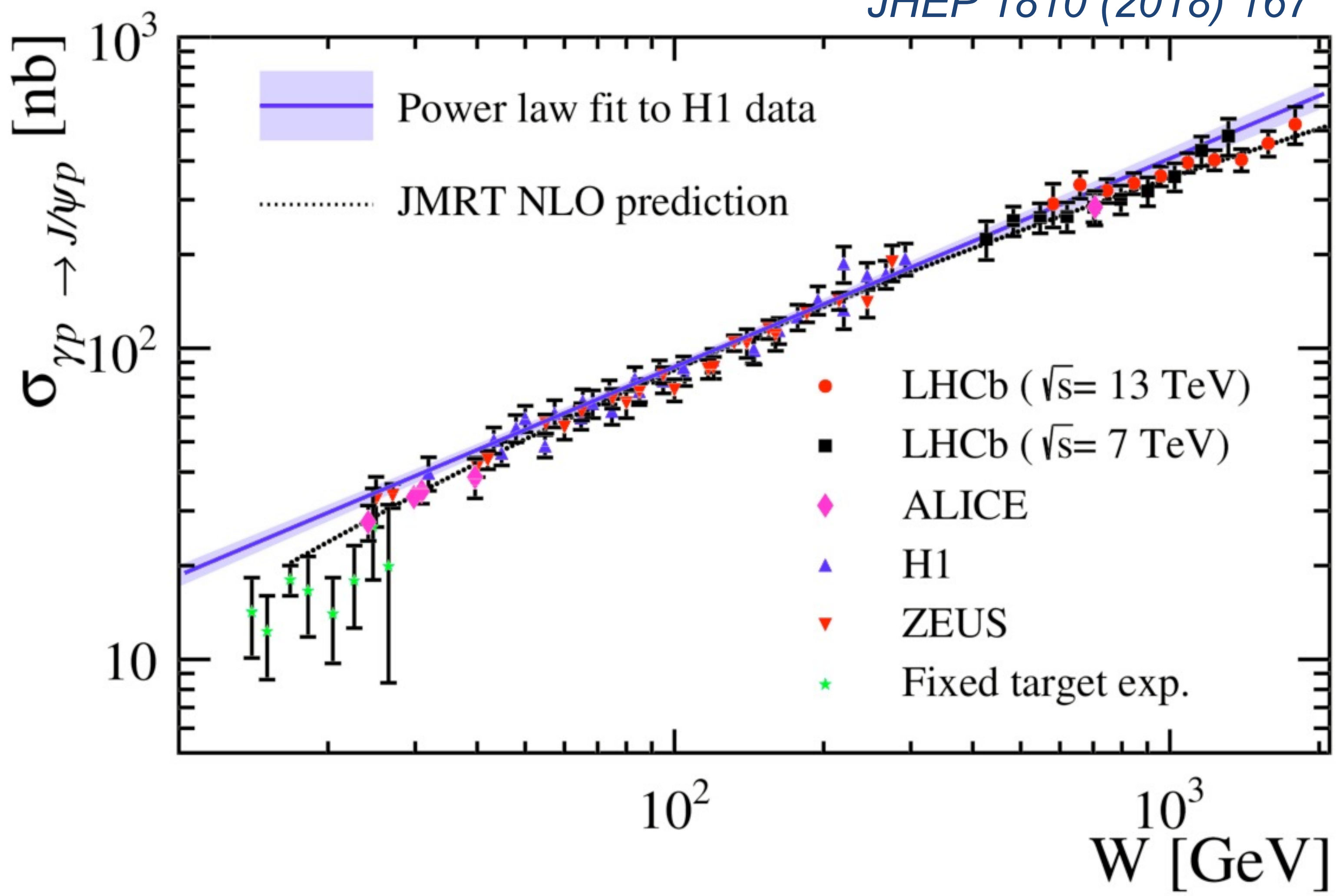
$$\frac{d\sigma}{dy}_{pp\to pJ/\psi p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to J/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi p}(W_-)$$

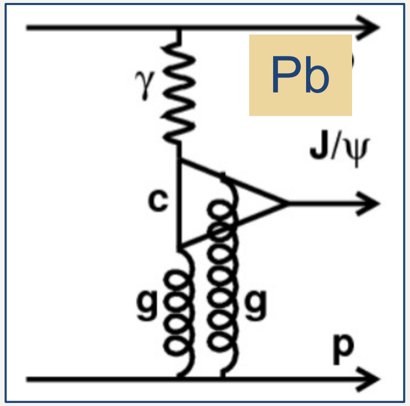
Gap Survival

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

Photoproduction cross-section

JHEP 1810 (2018) 167

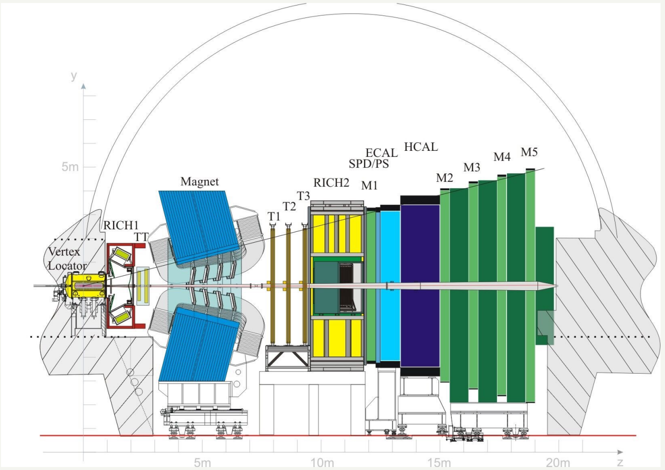




Which projectile produced the photon?

pomeron → ← Photon

pPb collisions

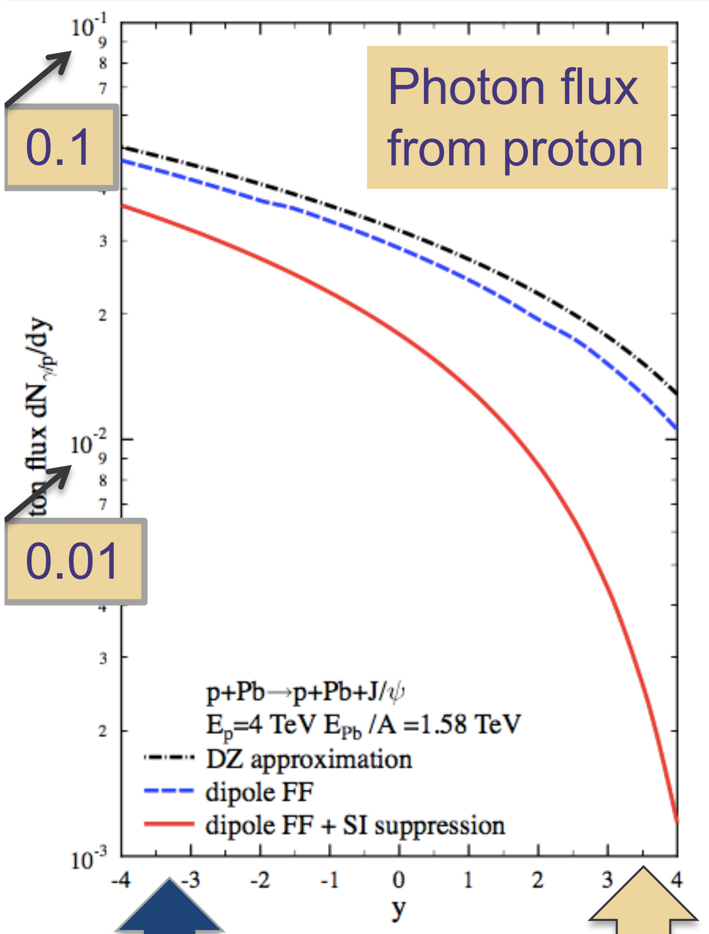


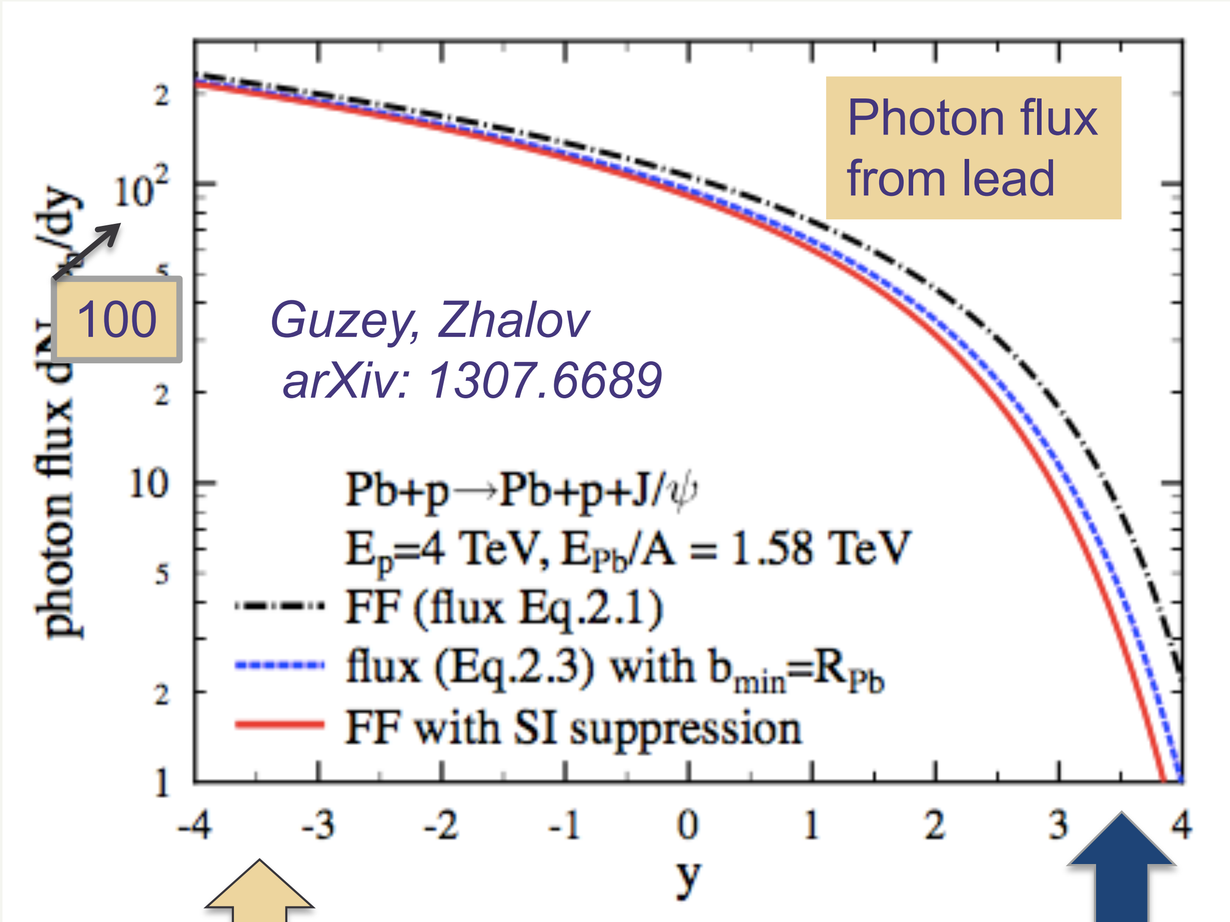
Photon → ← pomeron

Pbp collisions

Which projectile produced the photon?

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



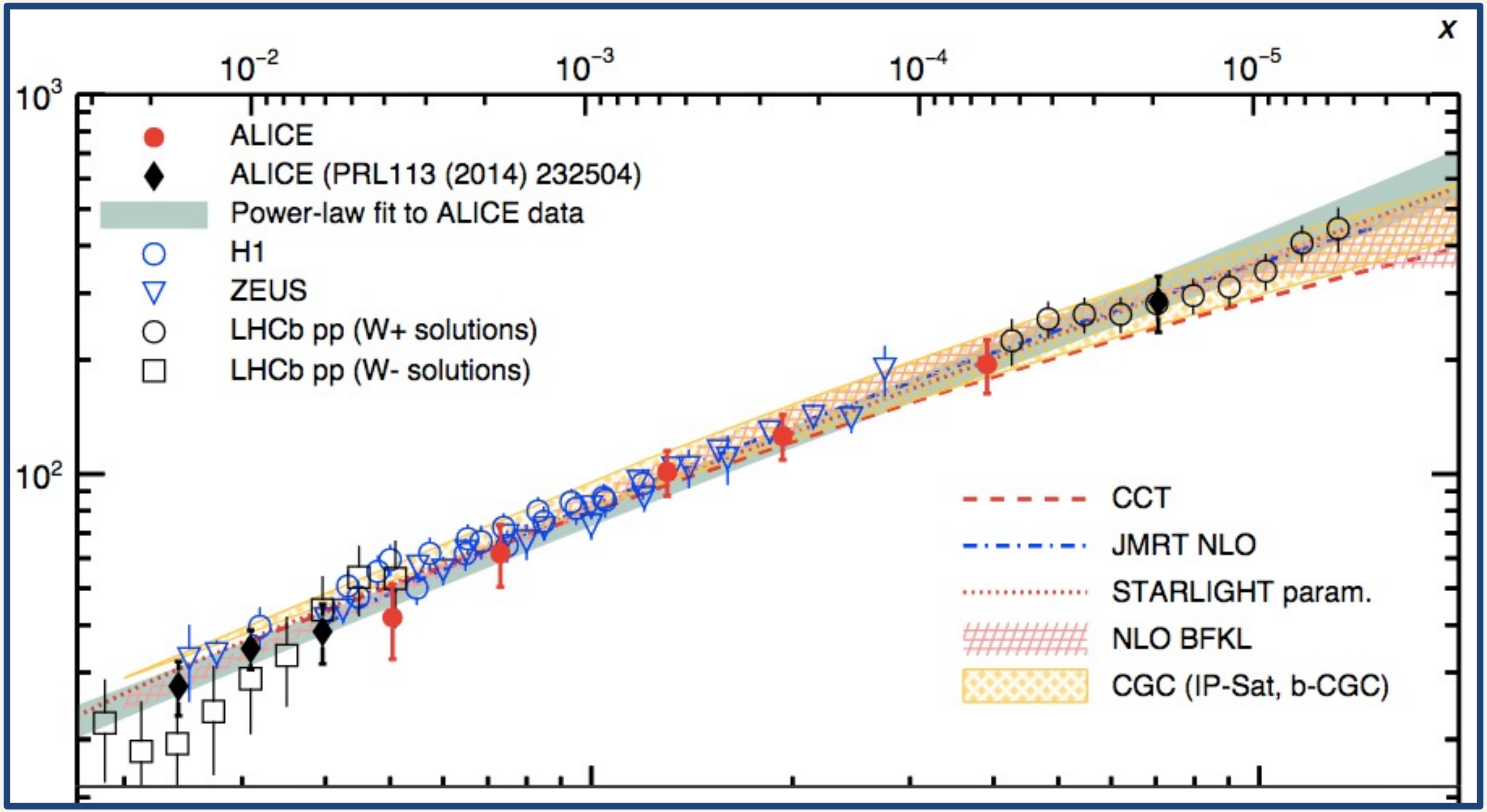


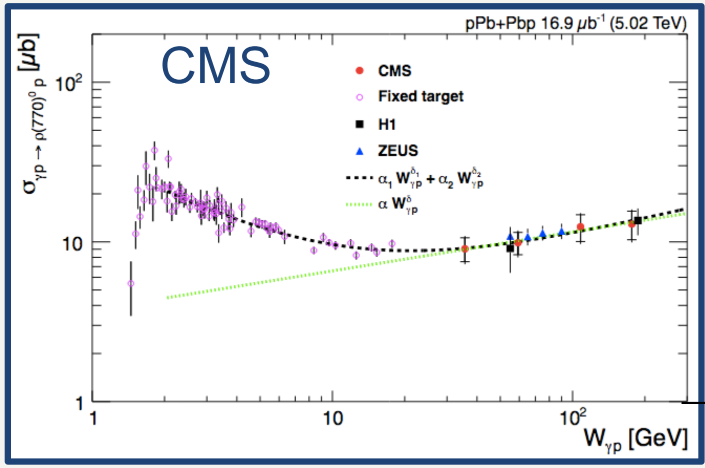
For LHCb, In pPb collisions, photon comes from lead

For Pbp collisions, ~1% comes from p

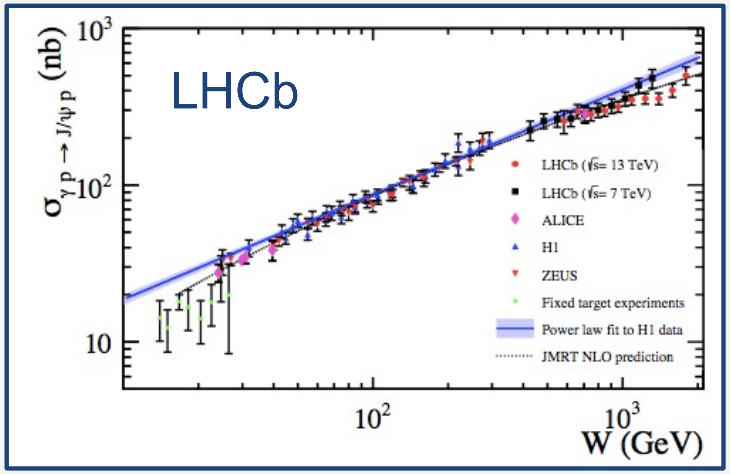
J/ψ production in pPb and Pbp

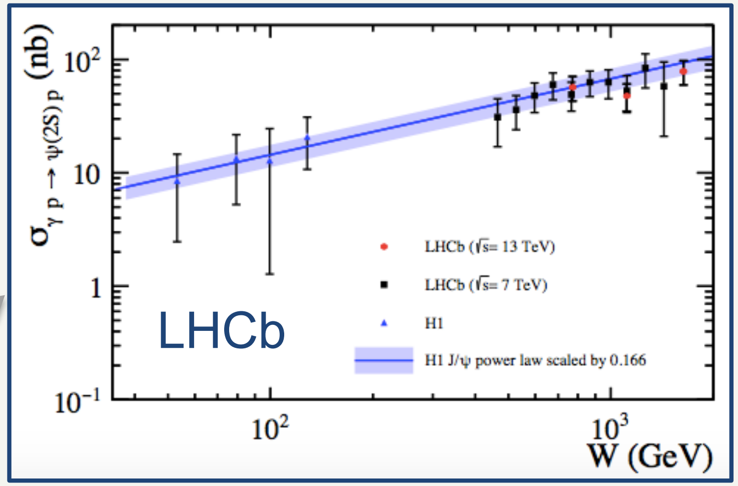
Eur.Phys.J. C79 (2019) no.5, 402

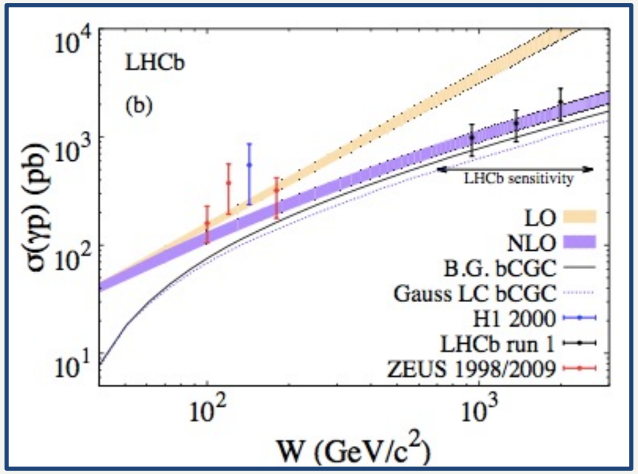


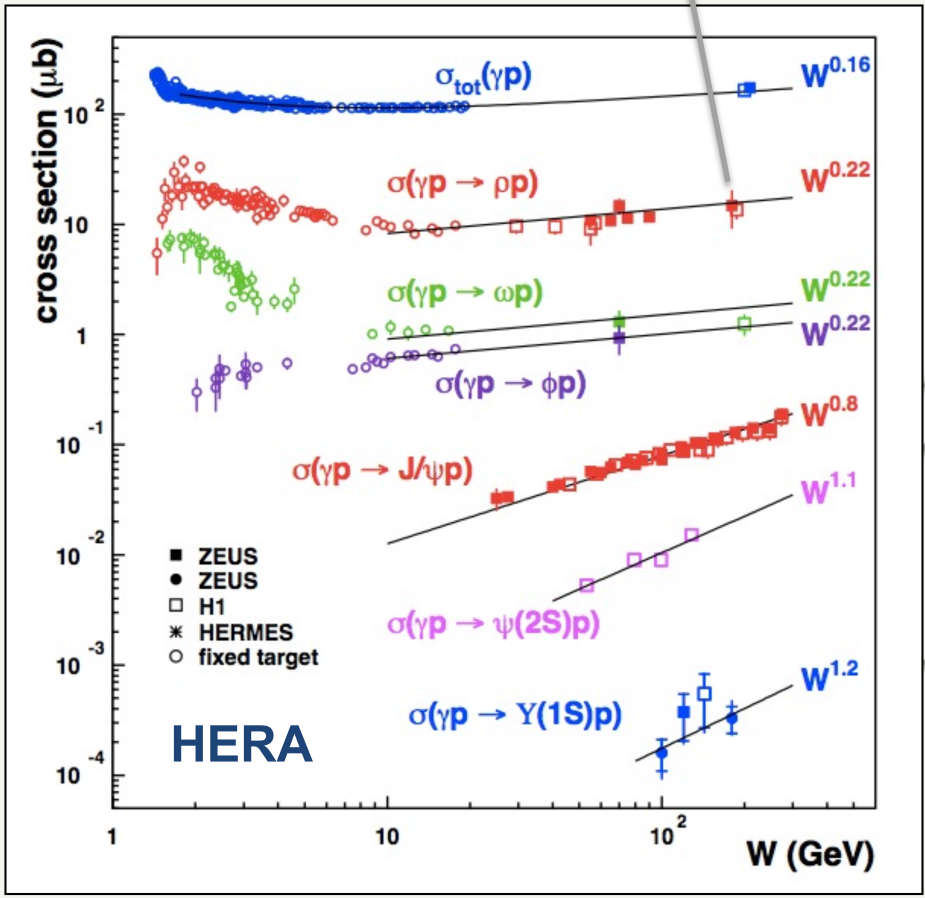


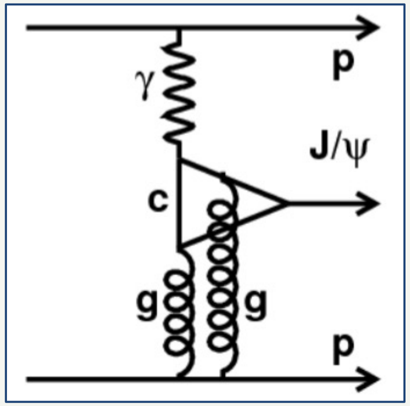
LHCb points here









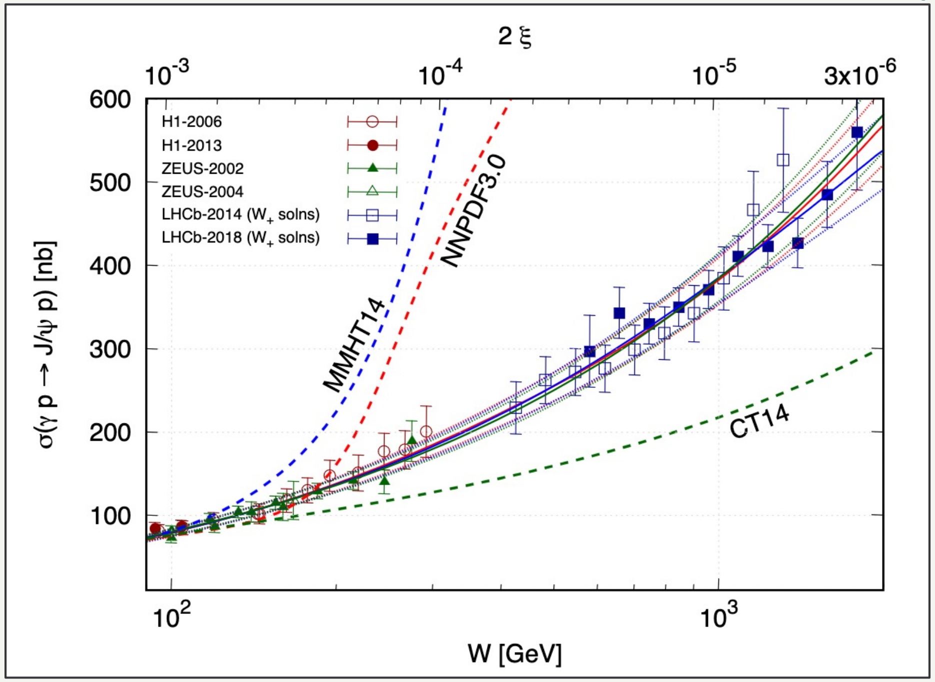


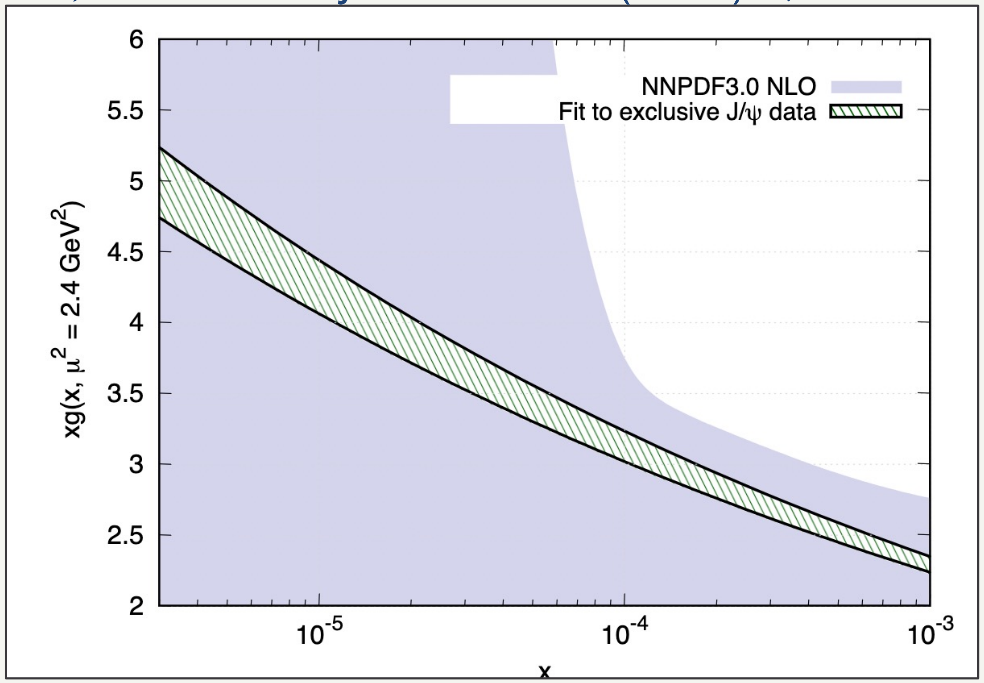
Implications: gluon PDF

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

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

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





makes use of Shuvaev transform to relate GPDs and PDFs

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

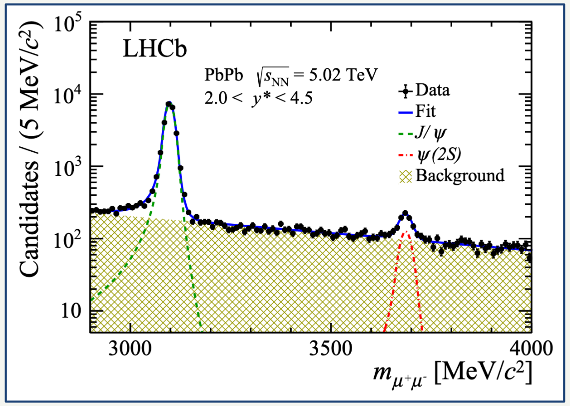
$$H_g(X,\xi) = \int_{-1}^{1} dx' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{ds\,(X+\xi(1-2s))}{y(s)\sqrt{1-y(s)x'}}\right]\frac{d}{dx'}\left(\frac{g(x')}{|x'|}\right),$$

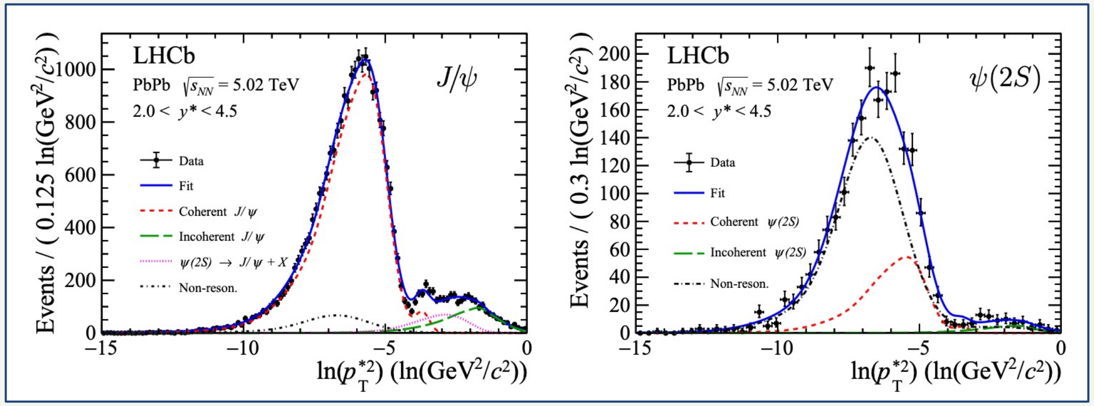
where the transform kernel,

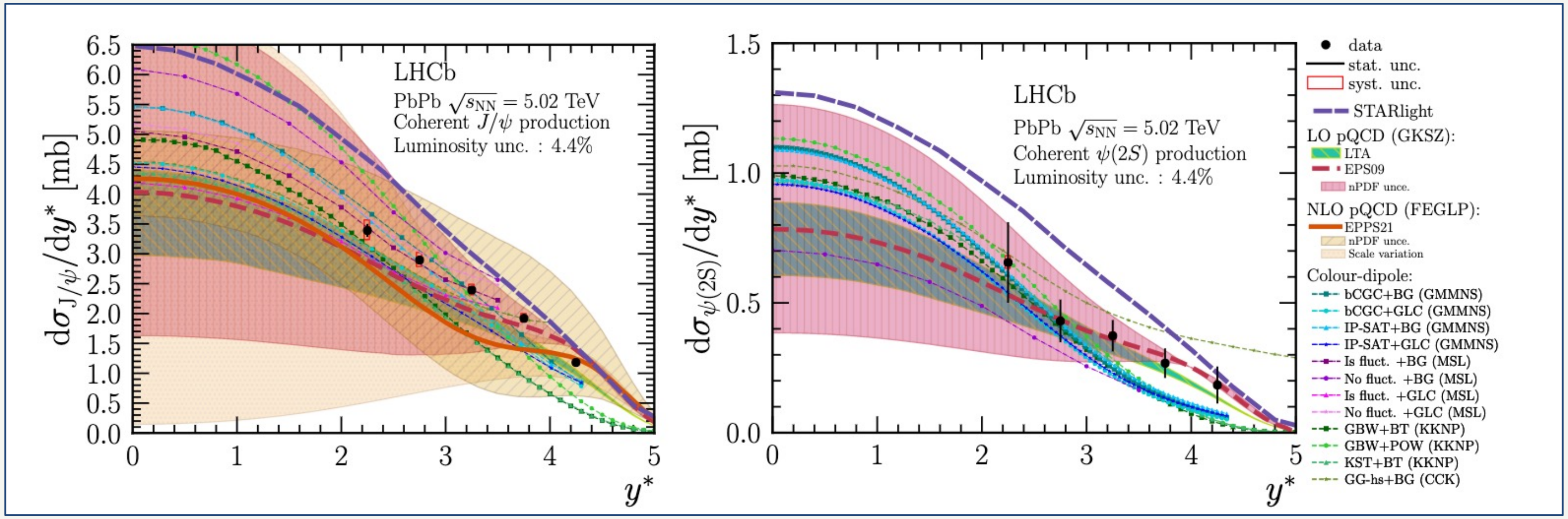
$$y(s) = \frac{4s(1-s)}{(X+\xi(1-2s))}.$$

J/ψ production in PbPb

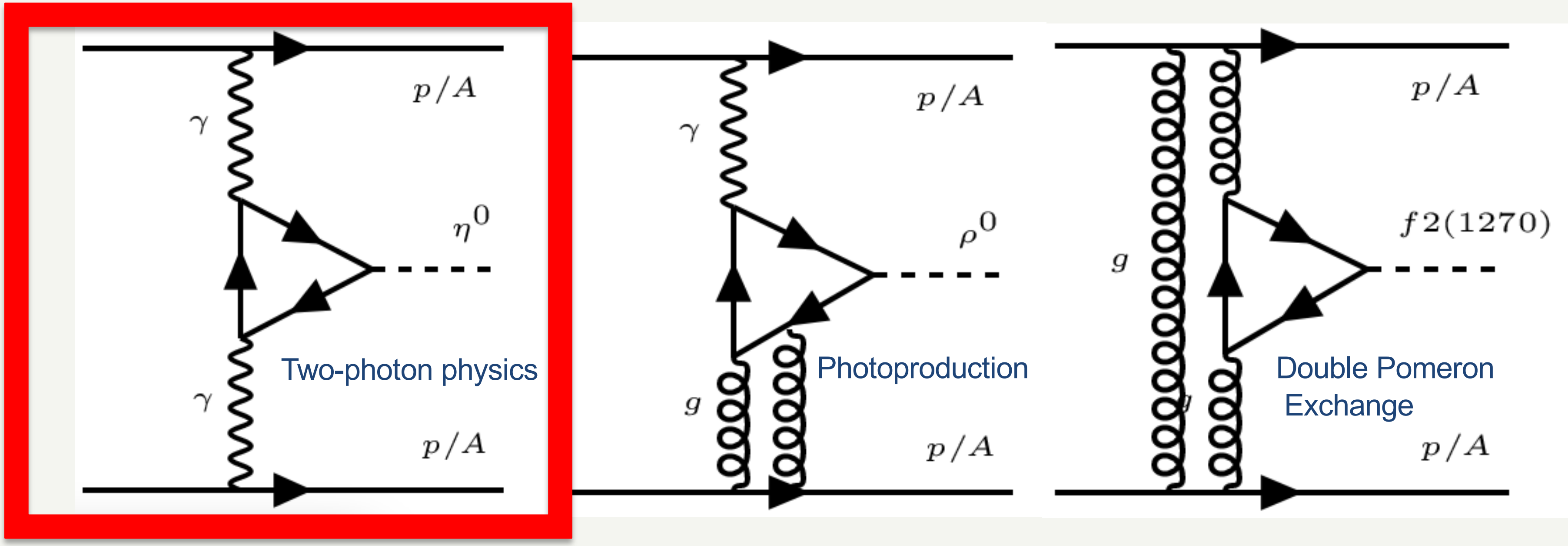
JHEP 06 (2023) 146







UPC physics



p/A
γ
η0
Two-photon physics
γ
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Photoproduction
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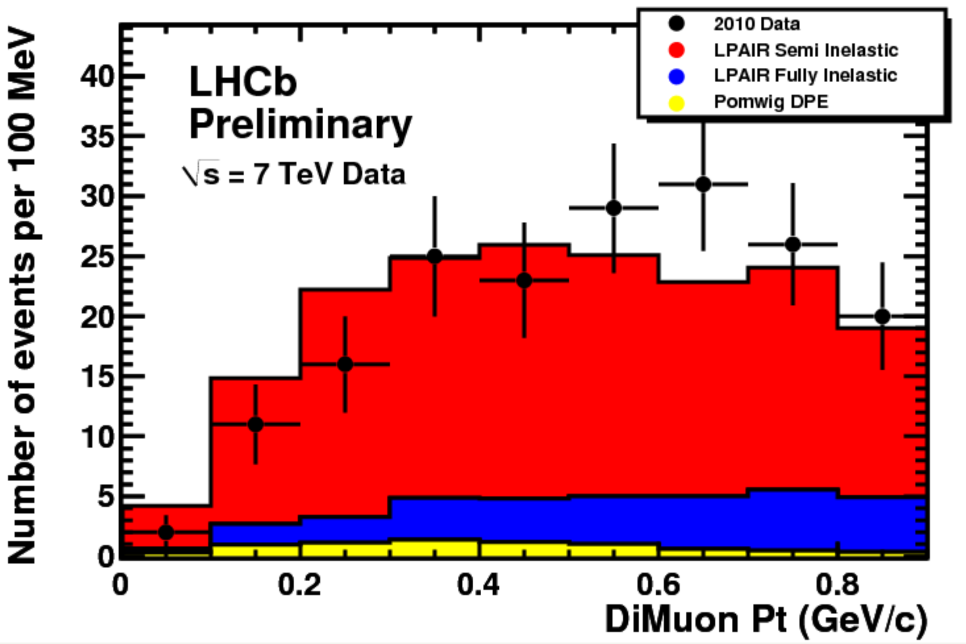
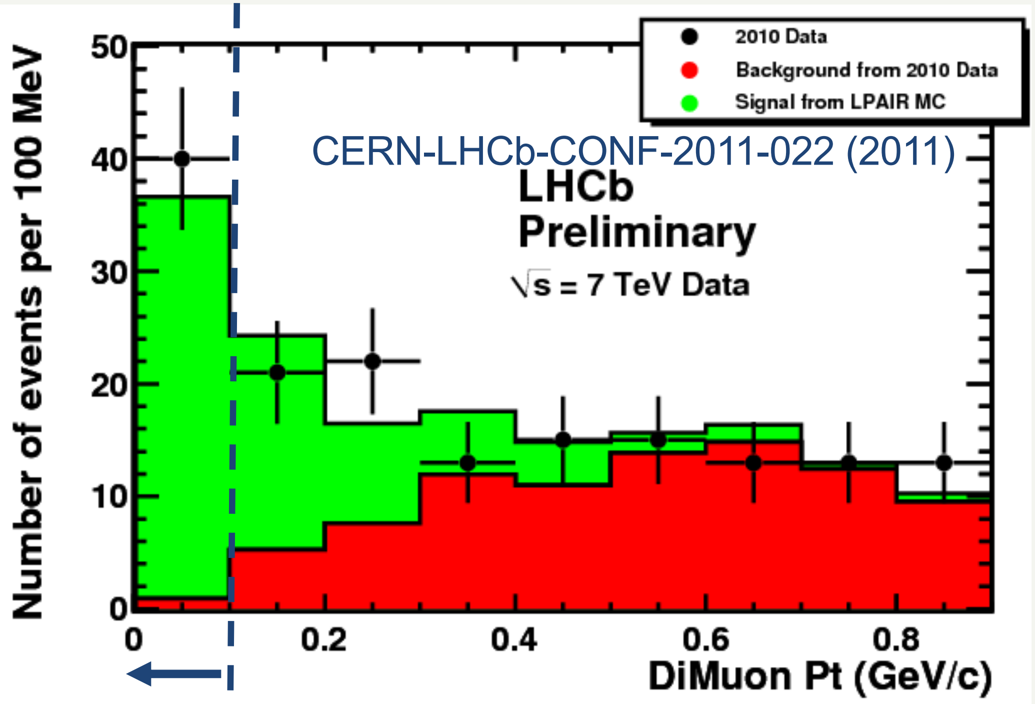
g
f2(1270)
Double Pomeron Exchange
p/A

$\gamma\gamma \rightarrow \mu\mu$ ($m_{\mu\mu}$>2.5 GeV)





Shape for inelastic events

Note: this time we have simulation that predicts the shape for the three contributions.

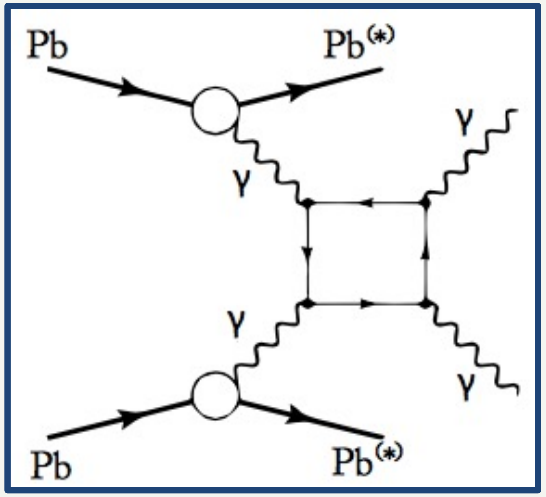
Fit to signal events

Background shape from data
Signal shape from simulation.

Measured cross-section pμμp: 67 +- 19 pb

LPAIR (J. Vermaseren) 42 pb

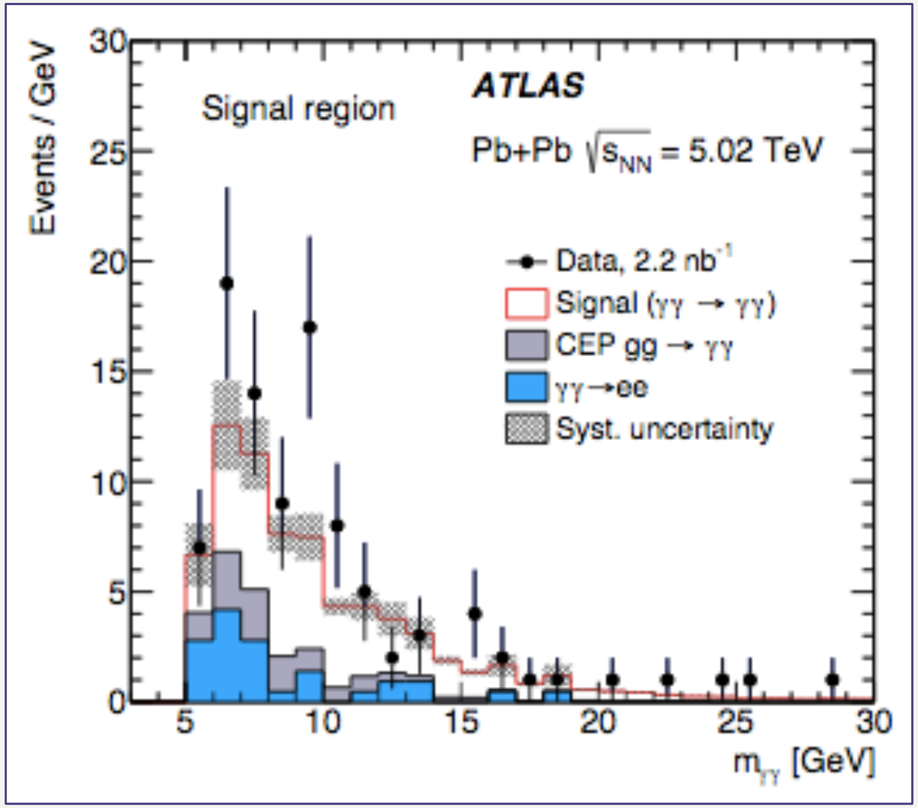
Light-by-light scattering



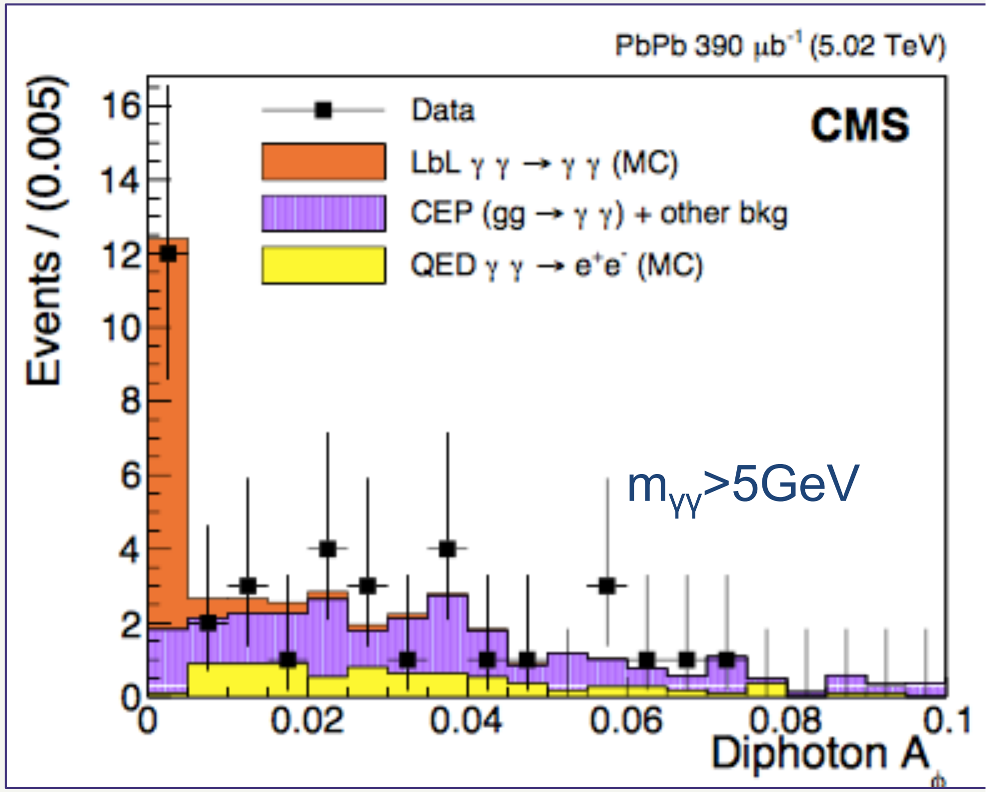
Forbidden in classical EM
Text-book illustration of QM

ATLAS collab., Nature Physics 13 (2017) 852

ATLAS collab., arXiv: 2008.05355

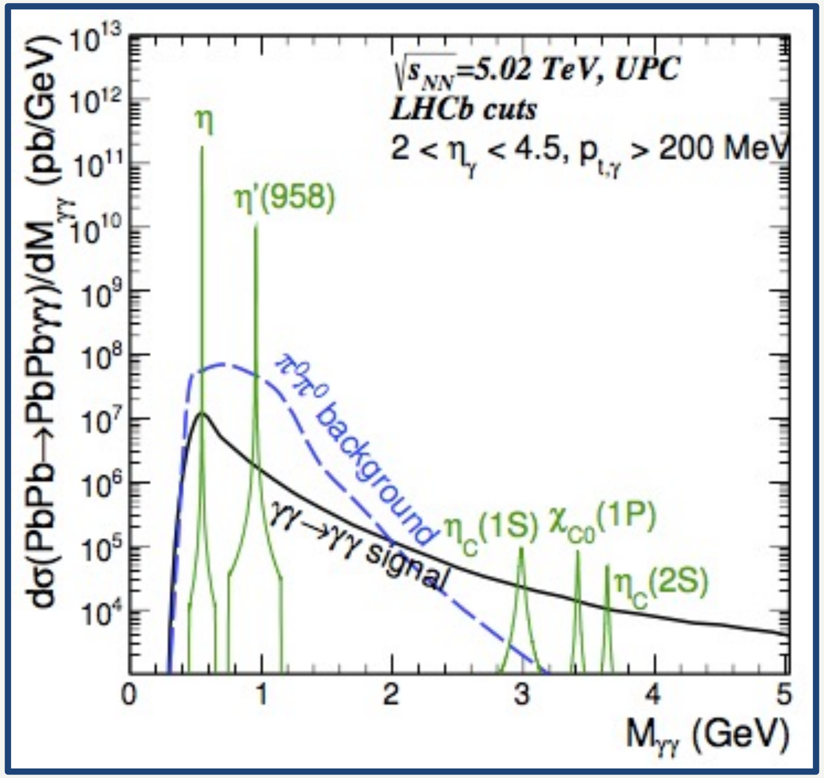


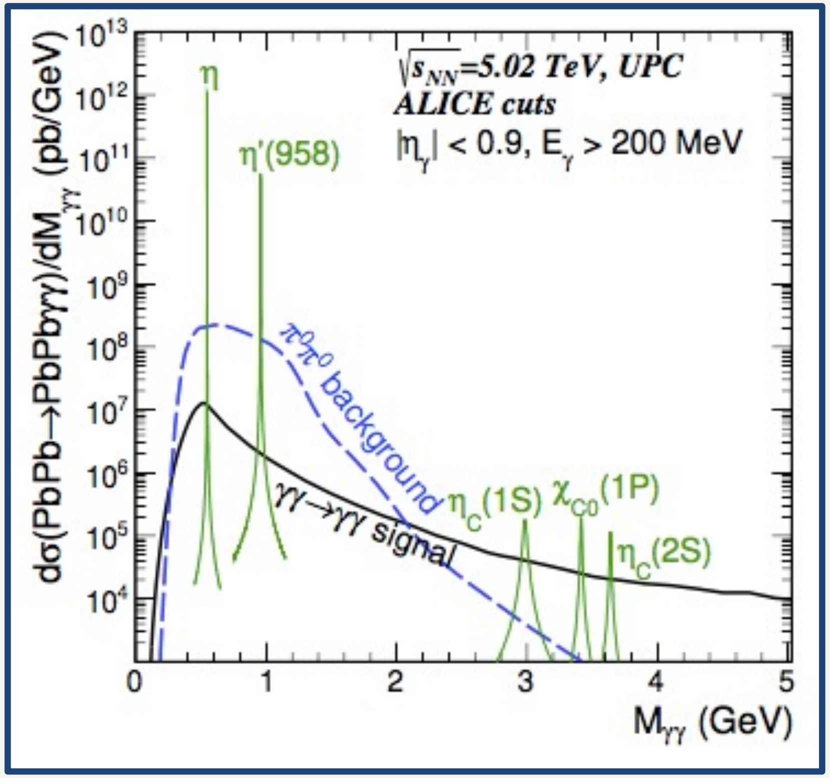
CMS. collab., Phys.Lett.B 797 (2019) 134826



Light-by-light scattering

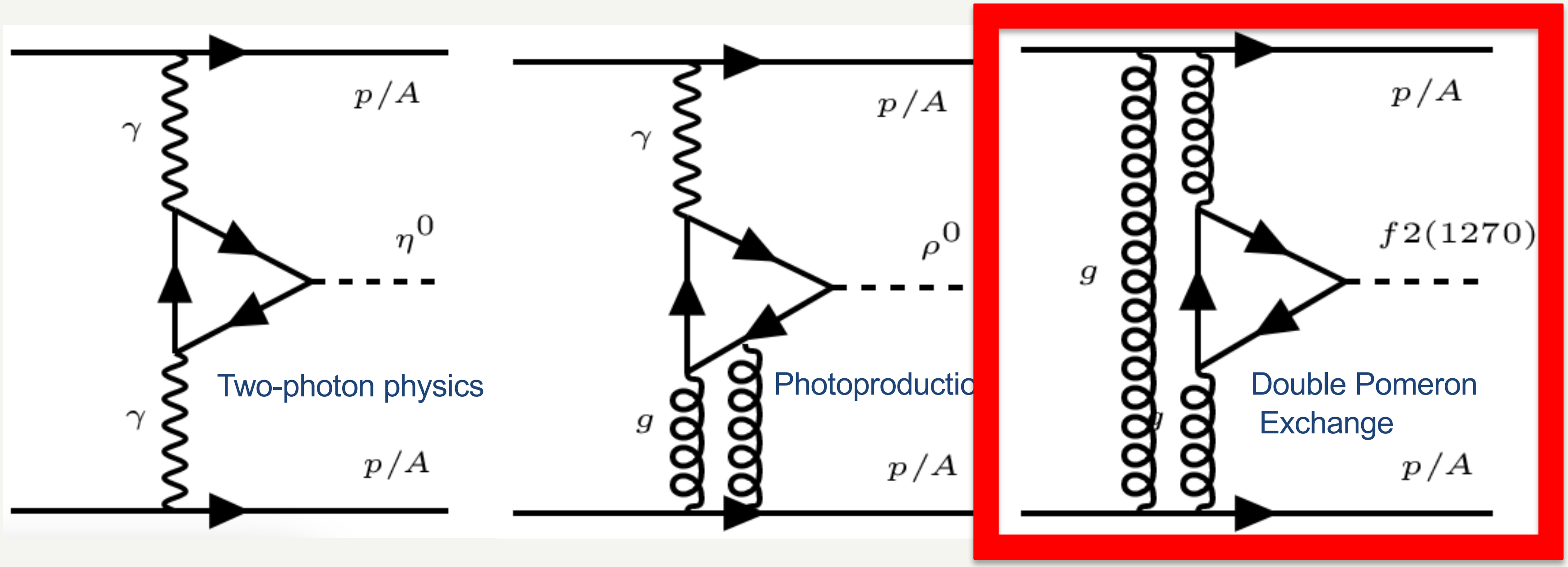
M. Klusek-Gawenda, R. McNulty, R. Schicker, A. Szczurek, Phys.Rev. D99 (2019) no.9, 093013





LHCb and ALICE have potential to observe this at low mass.
Important in searches for new particle decaying to photons
Also: Standard candles for η and f_2 production. Are these of interest?

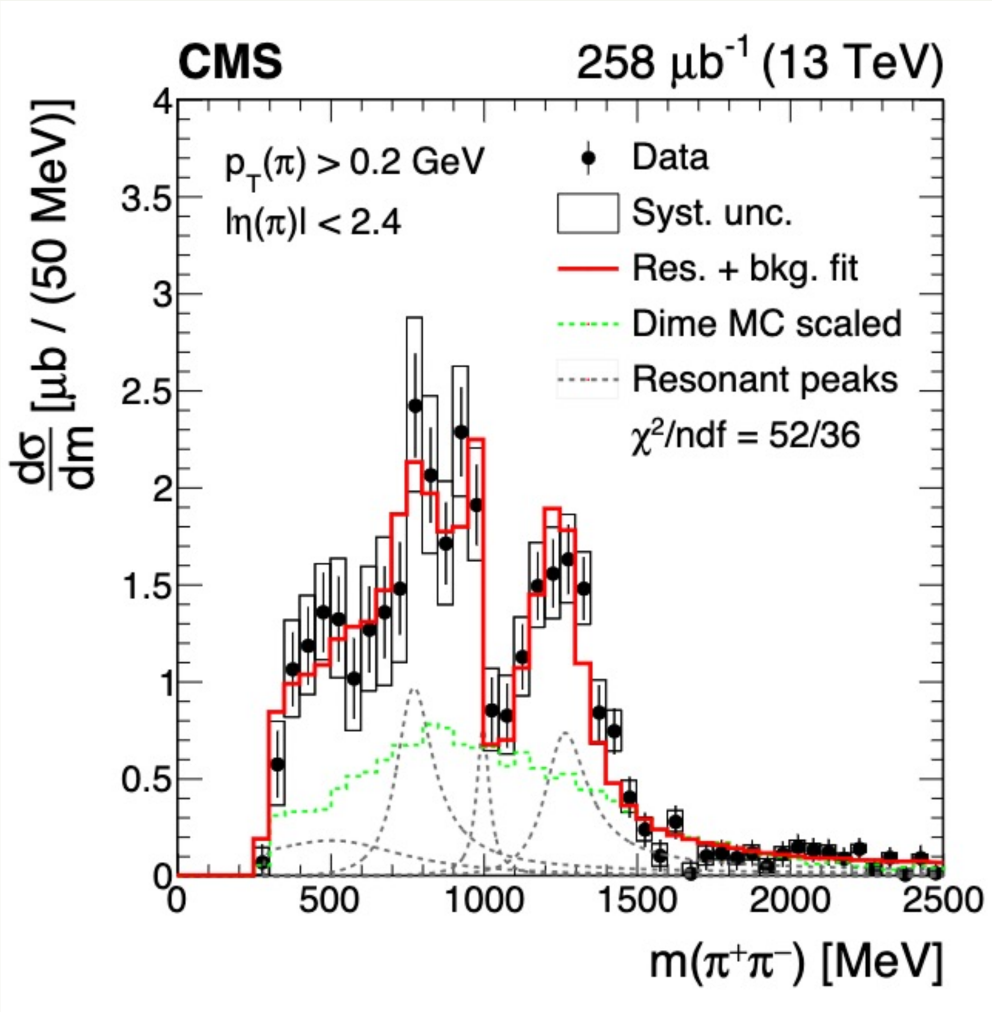
UPC physics

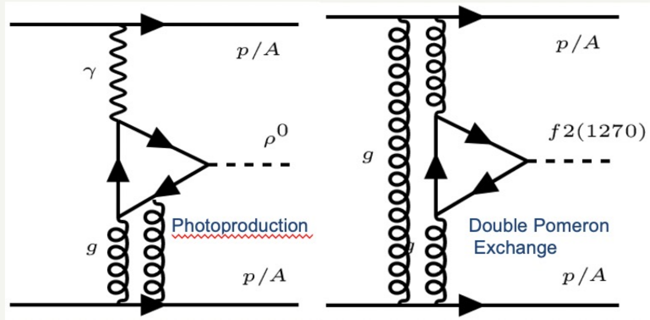


p/A
γ
η^0
Two-photon physics
γ
p/A
p/A
γ
ρ^0
Photoproductio
g
p/A
p/A
g
$f2(1270)$
Double Pomeron Exchange
p/A

Double pomeron exchange

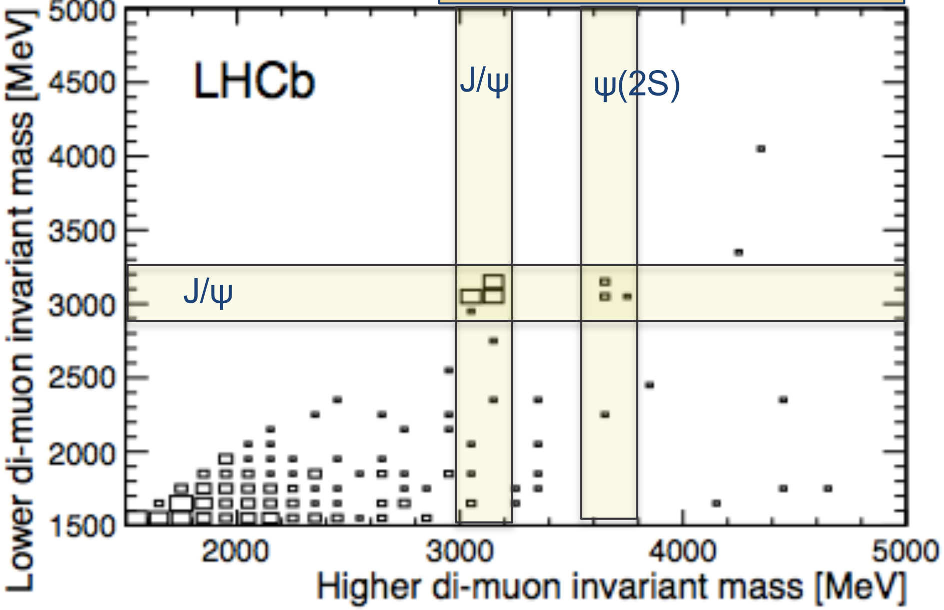
CMS, *Eur.Phys.J.C* 80 (2020) 8, 718



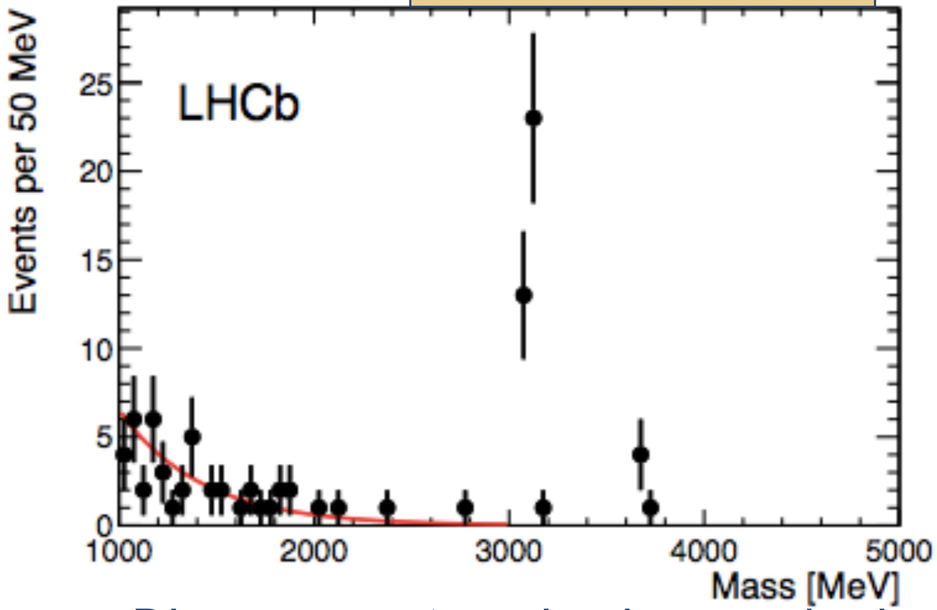


Tetraquarks, hybrids, glueballs

JPG 41 (2014) 115002



JPG 41 (2014) 115002



Dimuon spectrum having required other two muons have J/ψ mass

Selection requirement:
Require precisely 4 tracks, at least three identified as muons

Physics Letters B

Volume 831, 10 August 2022, 137199

Lack of evidence for an odderon at small t

A. Donnachie [a], P.V. Landshoff [b]

Springer Link

Regular Article - Theoretical Physics | Open Access | Published: 19 September 2022

The ReBB model and its $H(x)$ scaling version at 8 TeV: Odderon exchange is a certainty

I. Szanyi & T. Csörgő

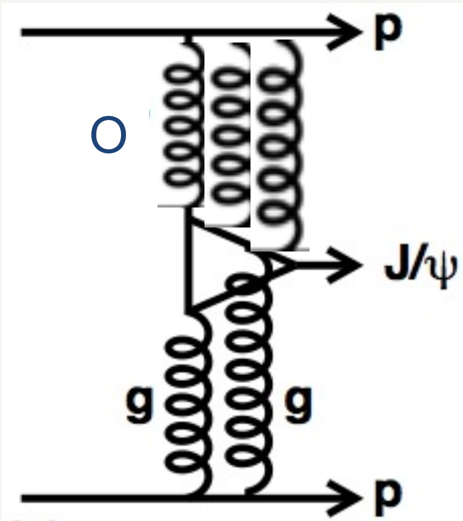
The European Physical Journal C **82**, Article number: 827 (2022) | Cite this article

arXiv:2202.03724

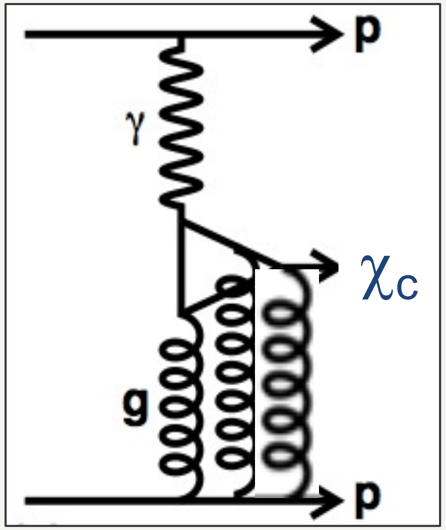
Odderon observation: explanations and answers to questions/objections regarding the PRL publication

Kenneth Österberg on behalf of the D0 and TOTEM collaborations

Odderon search in central production

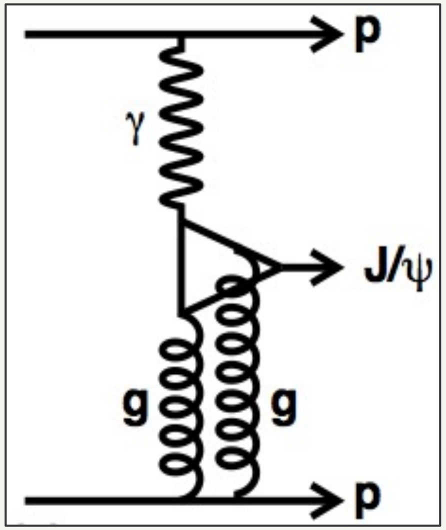


C-odd meson



C-even meson

Method 1: High p_T CEP of vector mesons.

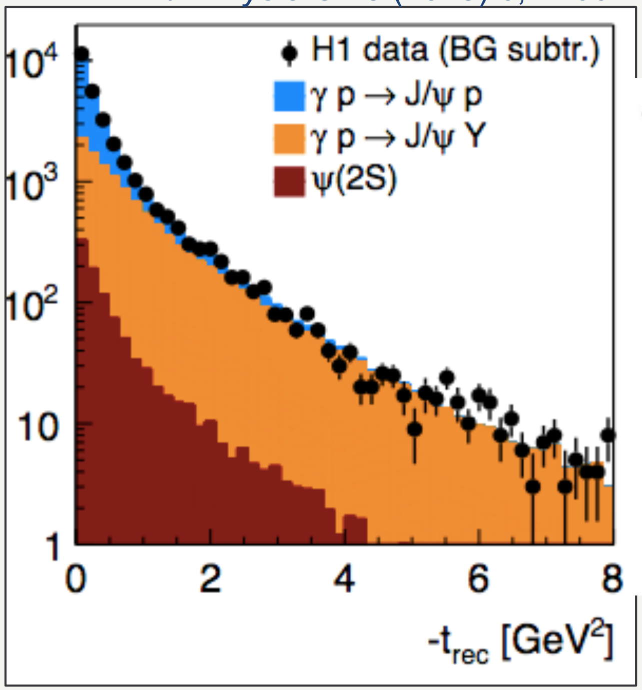


Photoproduction of J/ψ has been measured at HERA (γ from e), Tevatron and LHC (γ from p or A)

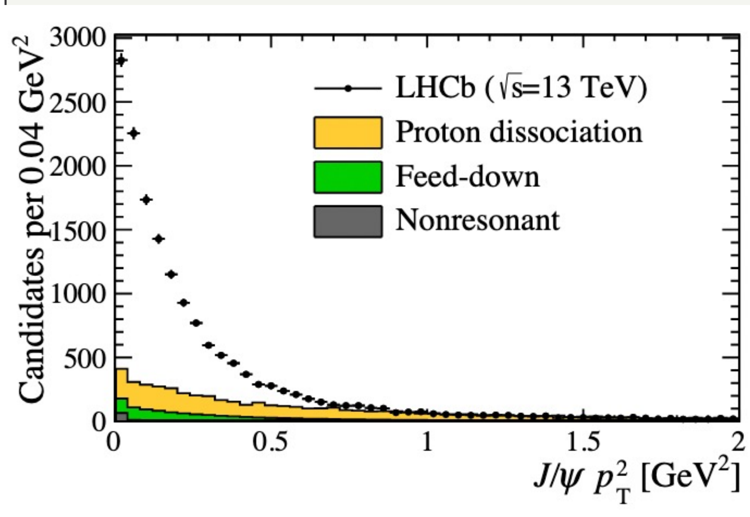
In Regge theory the momentum transfer through the Pomeron is usually modelled and the experimental data broadly supports this

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

Eur.Phys.J.C 73 (2013) 6, 2466



LHCb collaboration JHEP 10 (2018) 167

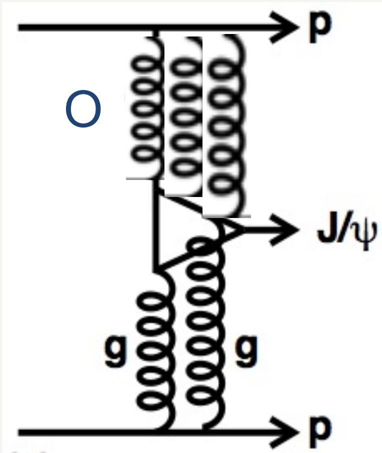


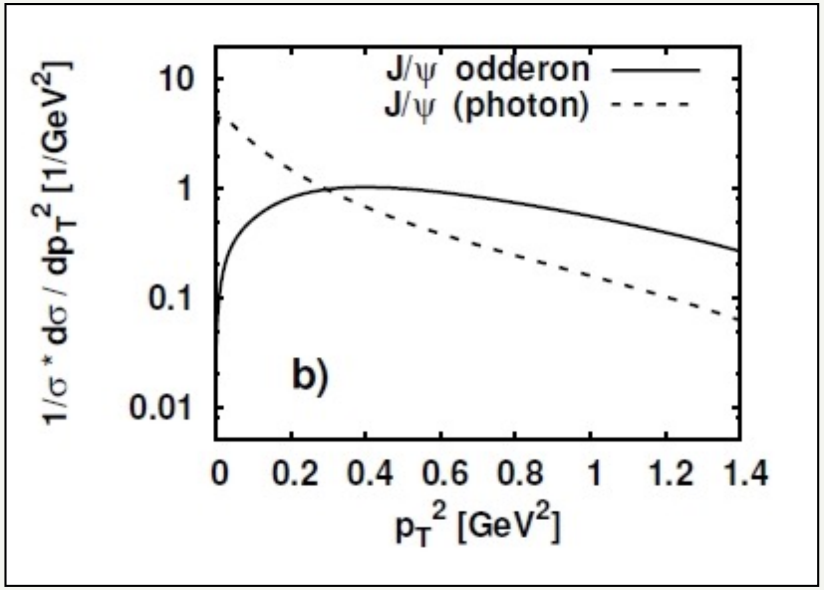
Note:

1. H1 required power-law to fit high p_T tail
2. Backgrounds dominate at high p_T

Method 1: High p_T CEP of vector mesons.

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

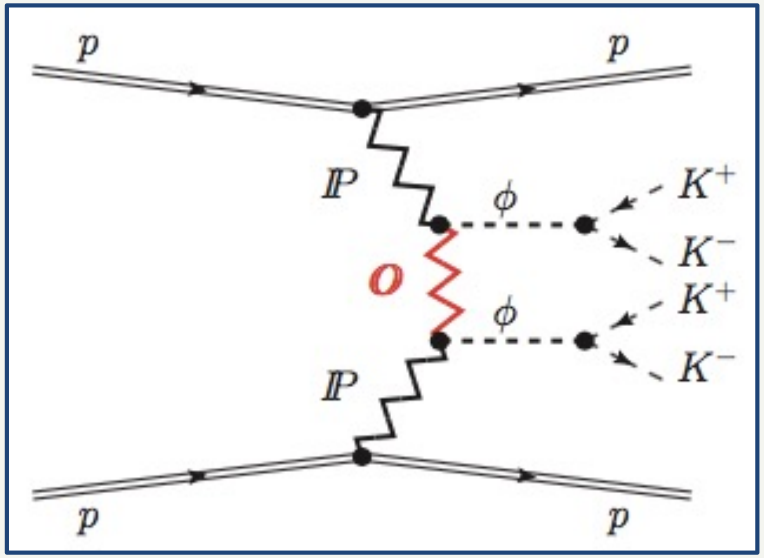
Odderon contribution might be 1-10% at LHC and would dominate at high p_T

….. but experimentally this is difficult to see

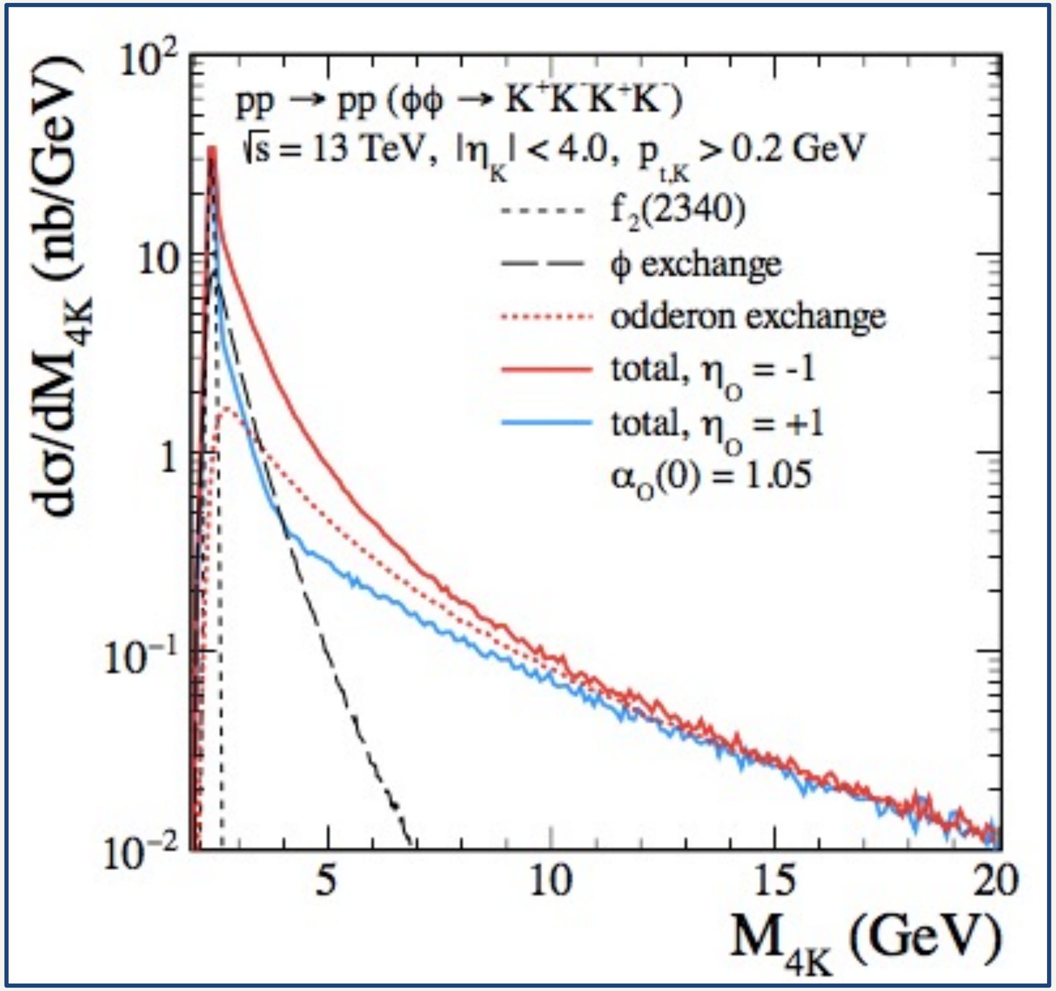
Angular distribution of muons due to polarisation may also differ (R. Schnicker)

Method 2: High mass CEP of VM pairs

Visible in high mass tail of ϕϕ ?



An intriguing aspect of ϕϕ is that is may have a contribution from odderon, visible at high mass.

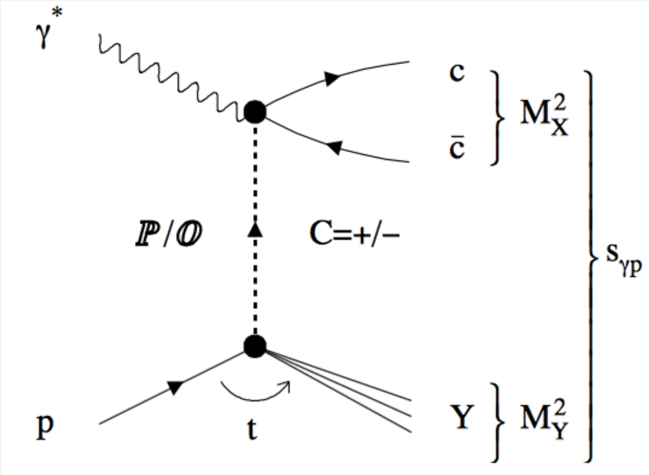


P. Lebiedowicz,O. Nachtmann,, A.Szczurek
PRD 101 (2020) 9, 094012

Method 3: Interference C+/C-

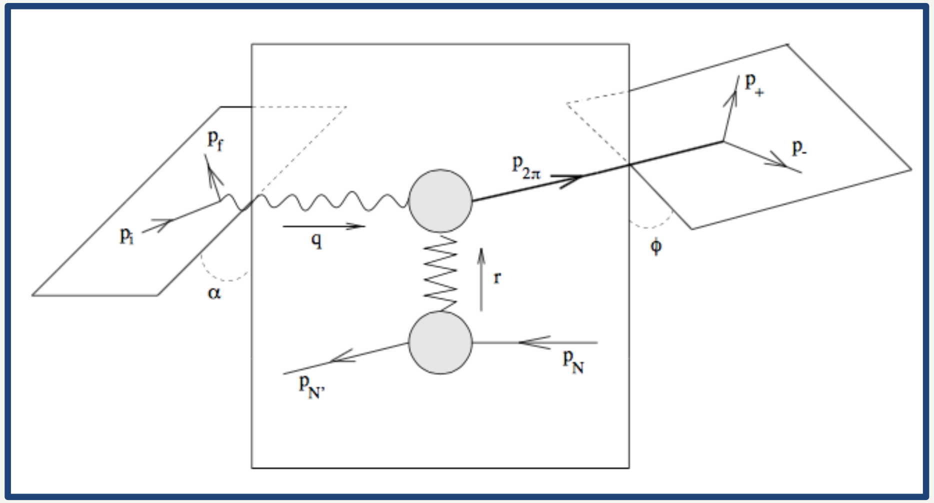
Interference of photoproduction processes

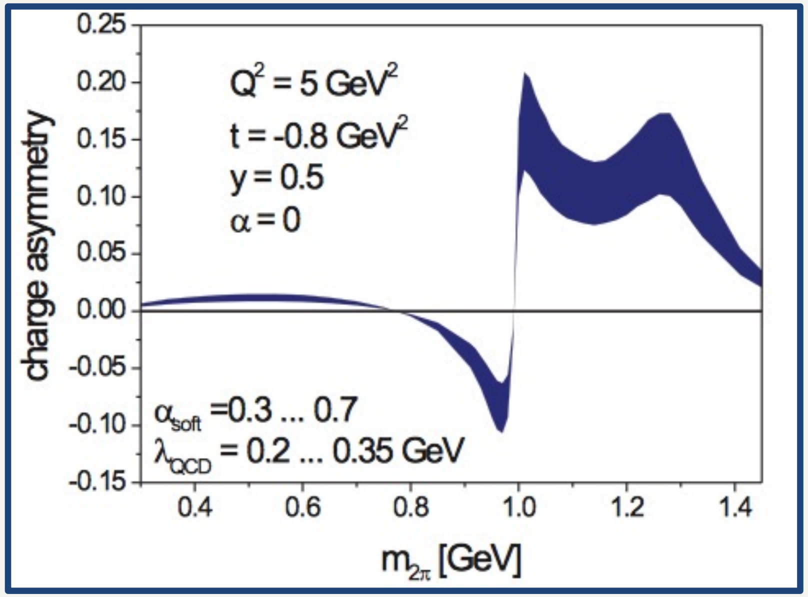
Brodsky, Rathsman, Merino, PLB461 (1998) 114.
Hagler, Pire, Szymanowski, Teryaev, EPJ26 (2002) 261.
Ginzburg, Ivanov, Nikolaev, EPJdirect 1 (2003) 1.
Bolz, Ewerz, Maniatis, Nachtmann, Sauter, Schoening, JHEP 1501 (2015) 151.



$$A(Q^2,t,m_{2\pi}^2,y,\alpha)=\frac{\sum_{\lambda=+,-}\int\cos\theta\,d\sigma(s,Q^2,t,m_{2\pi}^2,y,\alpha,\theta,\lambda)}{\sum_{\lambda=+,-}\int d\sigma(s,Q^2,t,m_{2\pi}^2,y,\alpha,\theta,\lambda)}=\frac{\int d\cos\theta\cos\theta\ N_{charge}}{\int d\cos\theta\ D}$$

N.B. linear with amplitude

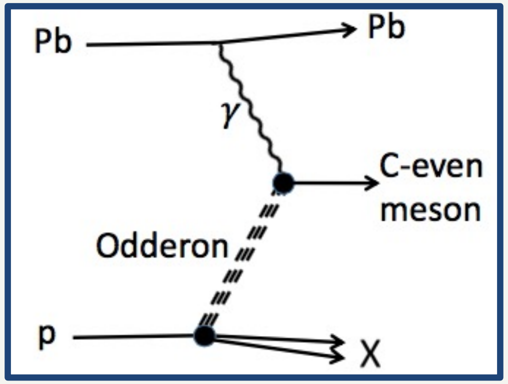




Need to tag outgoing proton to define production plane?

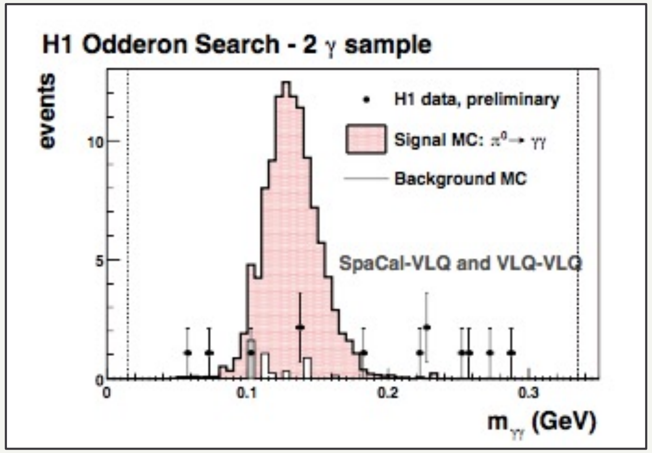
Method 4: Photoproduction of C+

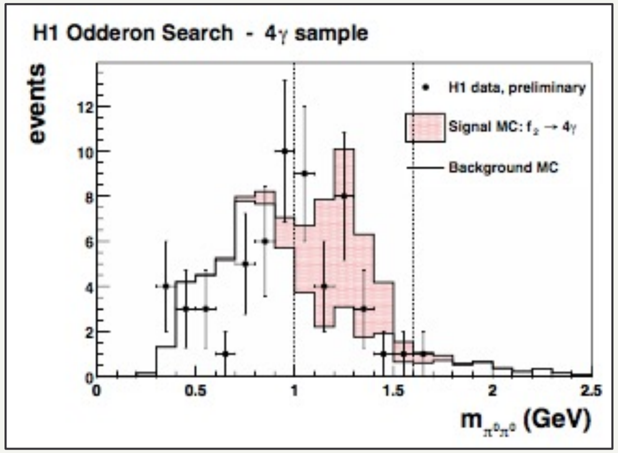
Search in CEP photoproduction where quantum numbers inconsistent with pomeron

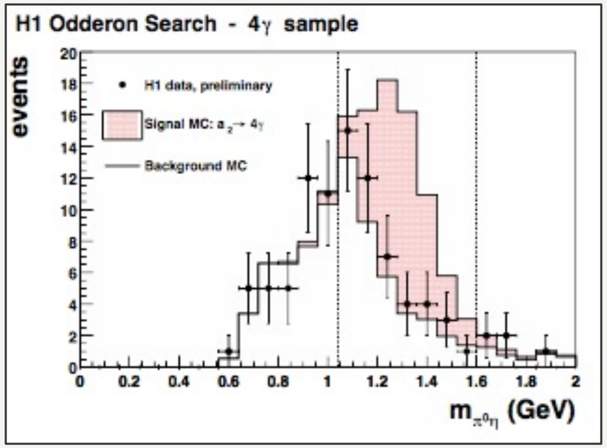


Czyzewski, Kwiecinski, Motyka, PLB398 (1997) 400.
Berger, Donnachie, Dosch, Kilian, Nachtmann, EPJ C9 (1999) 491.
Ryskin EPJ C2 (1998) 339.
Kilian & Nachtmann, EPJ C5 (1998) 317.
Harland-Lang, Khoze, Martin, Ryskin PRD 99 (2019) 3, 034011

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

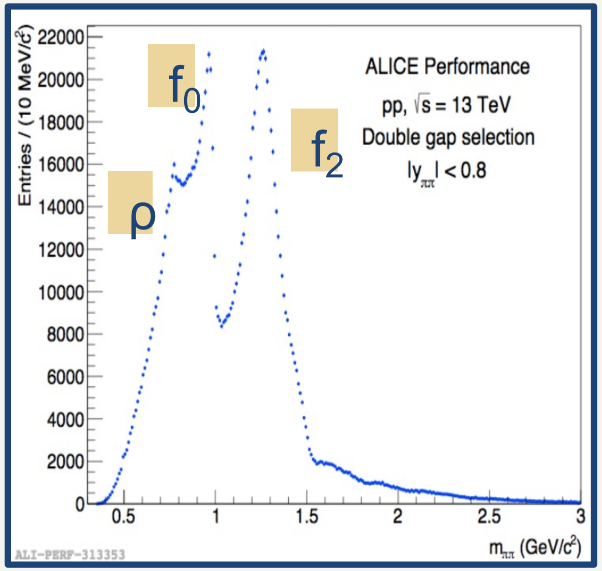
Note: Background processes are always much bigger

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

Go forward

Photoproduction of C+ meson

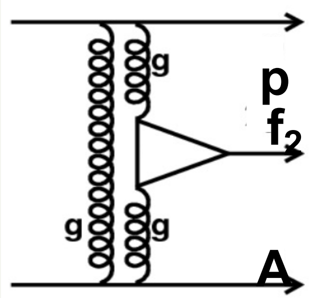
- To enhance the photon flux consider heavy ion collisions
  - Proton-ion (pA)
  - Ion-ion (AA*)
- Compared to pp collisions:
  - SIGNAL: For Pb, photon flux is ~Z^2=6700 greater and strongly peaked to backward rapidities
  - Pomeron-pomeron BKG: cross-section is factor 2-5 greater than for protons
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



arXiv:1912.00611

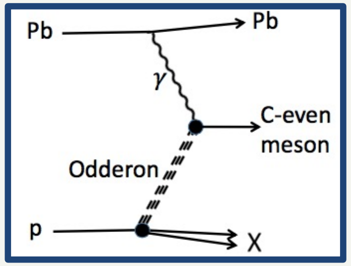
Key idea

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



SIGNAL PROCESS:

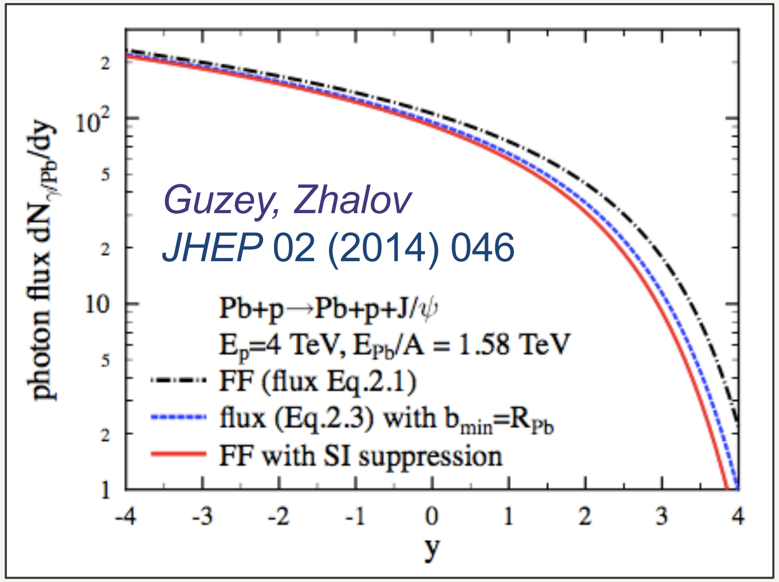
C+ production by photoproduction is peaked towards low rapidities due to energy dependence of photon flux



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*



Guzey, Zhalov
JHEP 02 (2014) 046

$x=M_V e^{-y}$

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

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

Results for p-Pb collisions

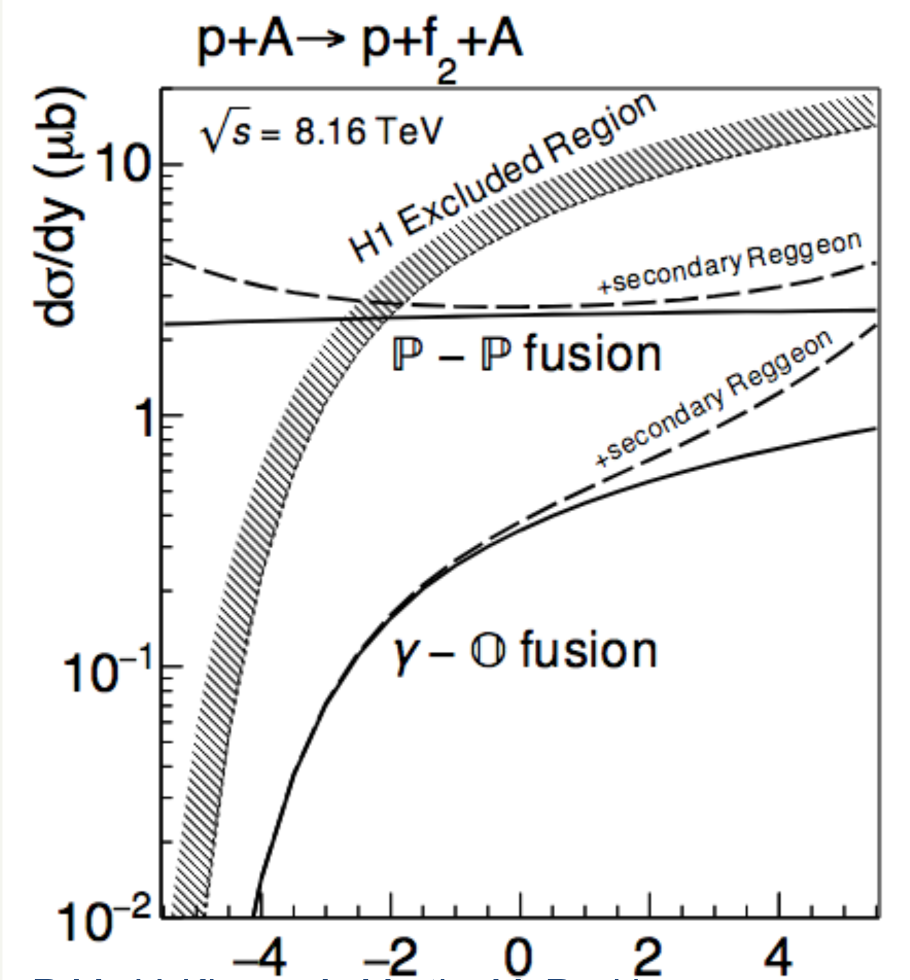
Pomeron-Pomeron production is flat and scaled to p-p results
(CMS arXiv:1706.08310)

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

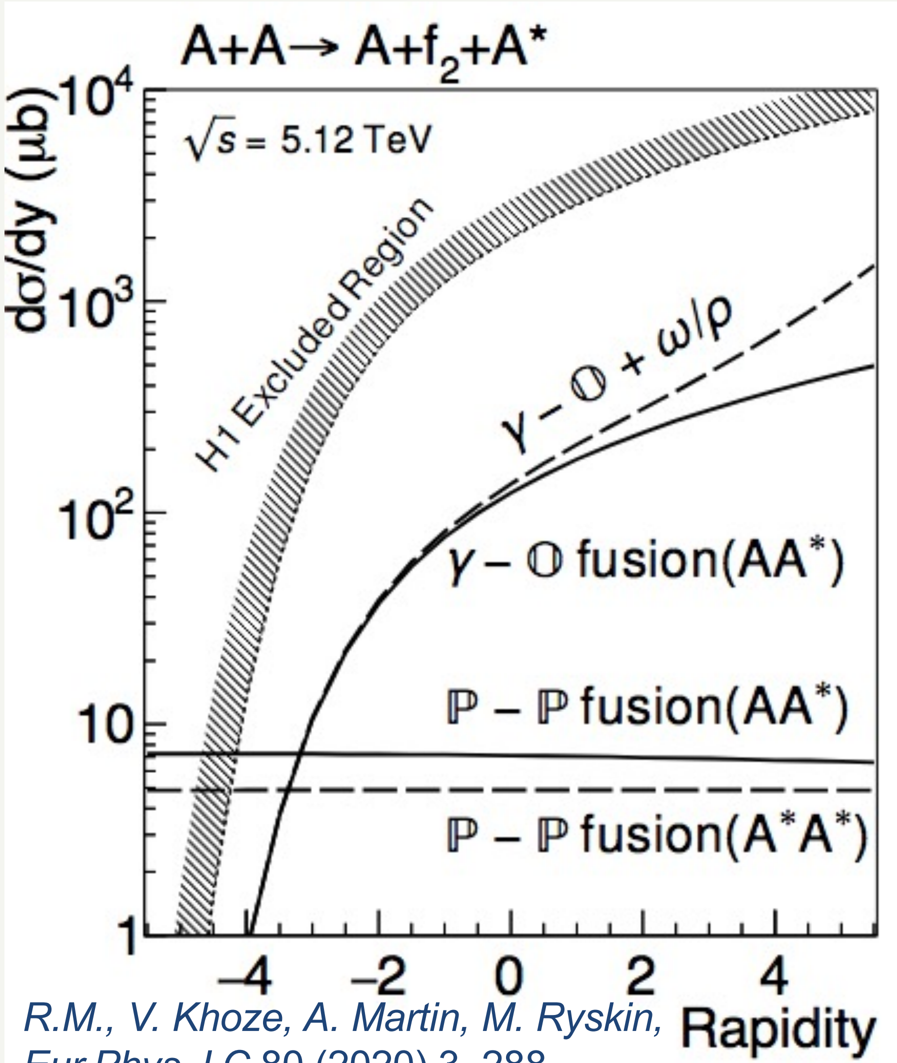
Pomeron-Pomeron production is flat and scaled to p-p results

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.

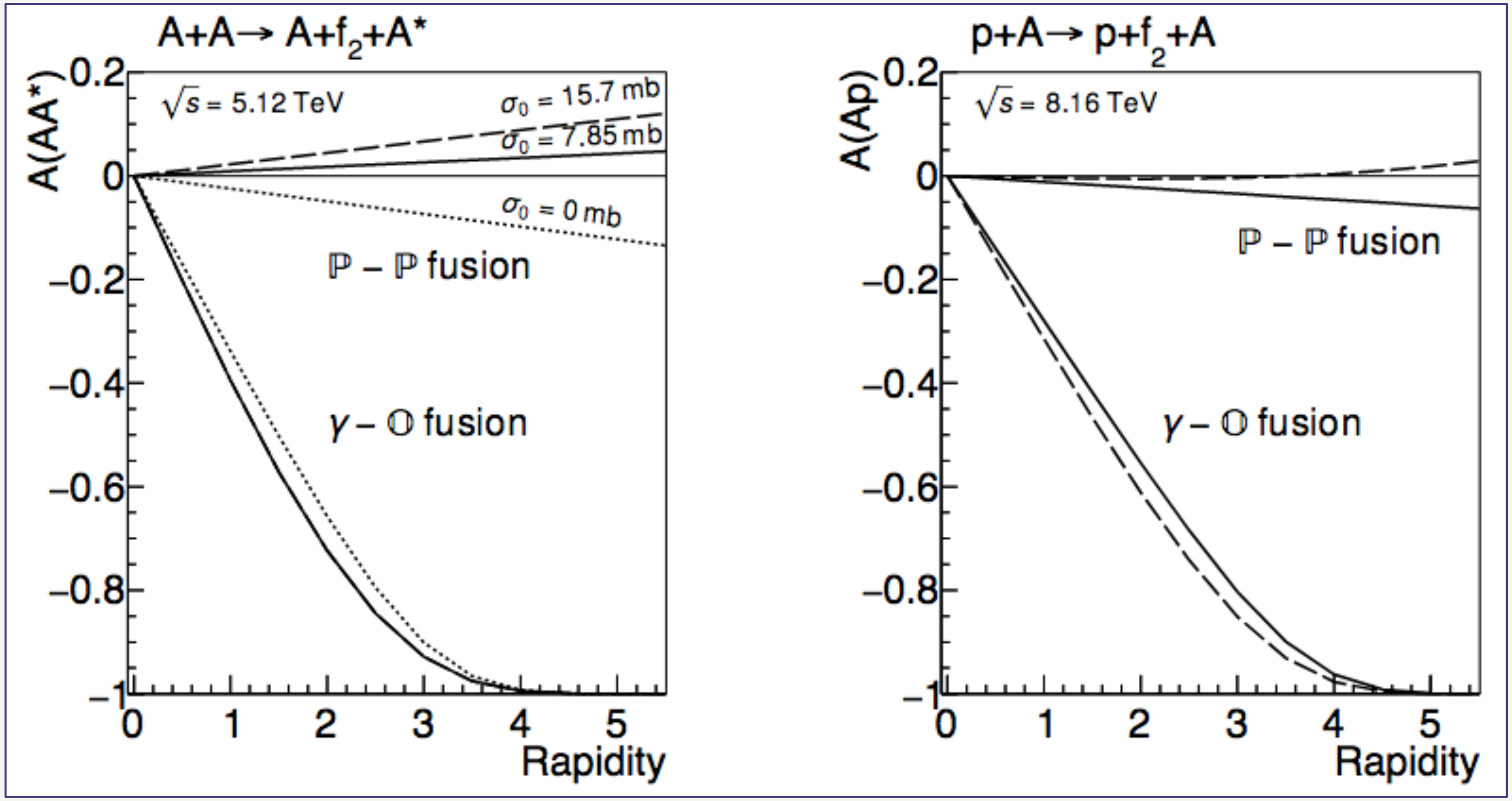


R.M., V. Khoze, A. Martin, M. Ryskin, Eur.Phys.J.C 80 (2020) 3, 288

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

- Rich physics
  - QCD v Regge Theory and transition from perturbative to non-perturbative regimes
  - PDF extraction
  - nuclear suppression
  - meson spectroscopy
  - exotica: tetraquarks, glueballs
  - saturation
  - dark photon searches
  - odderon searches
- Separation of different processes requires better understanding of break-up process.