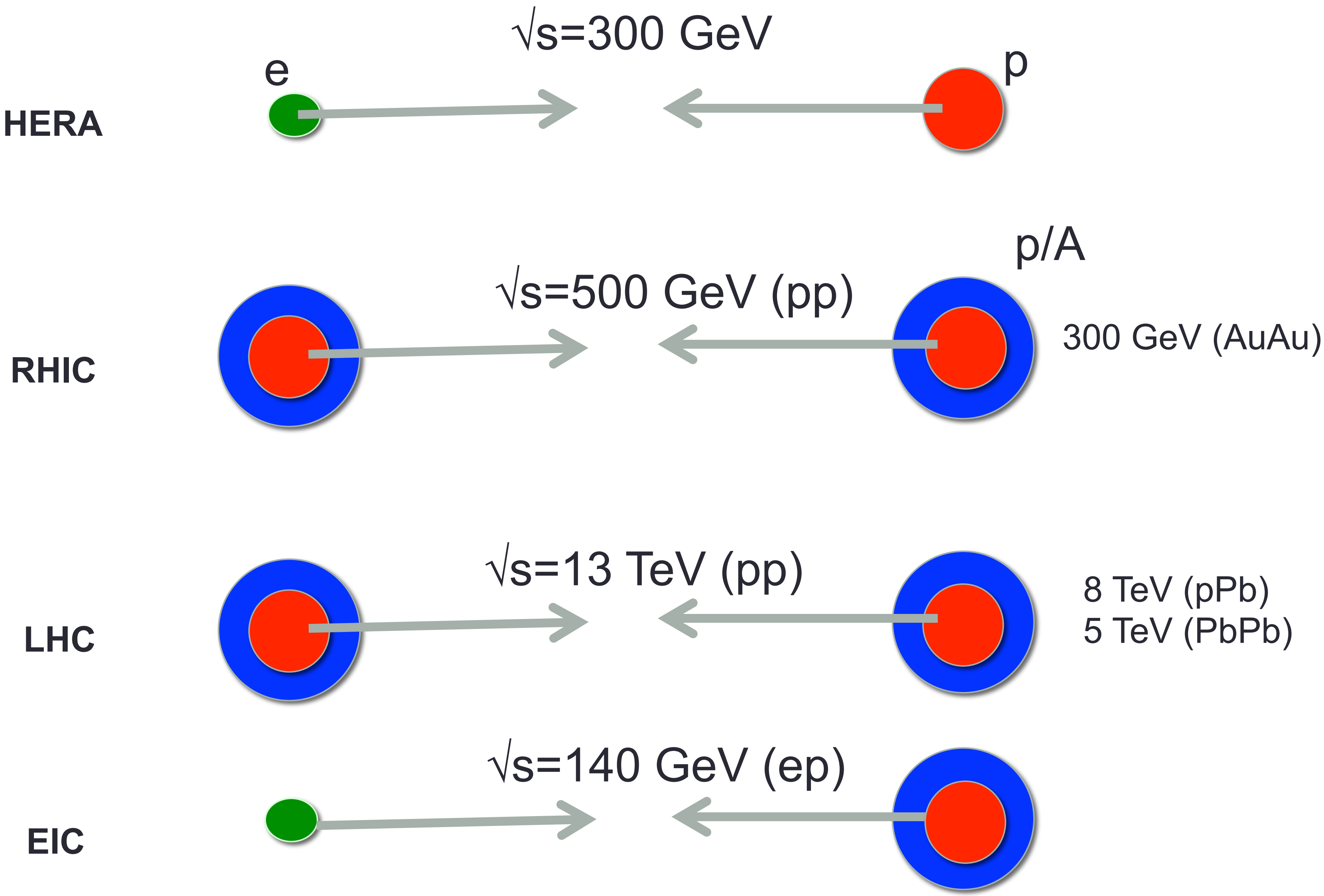
ULTRA-PERIPHERAL COLLISIONS: FROM HERA, RHIC & LHC TO EIC

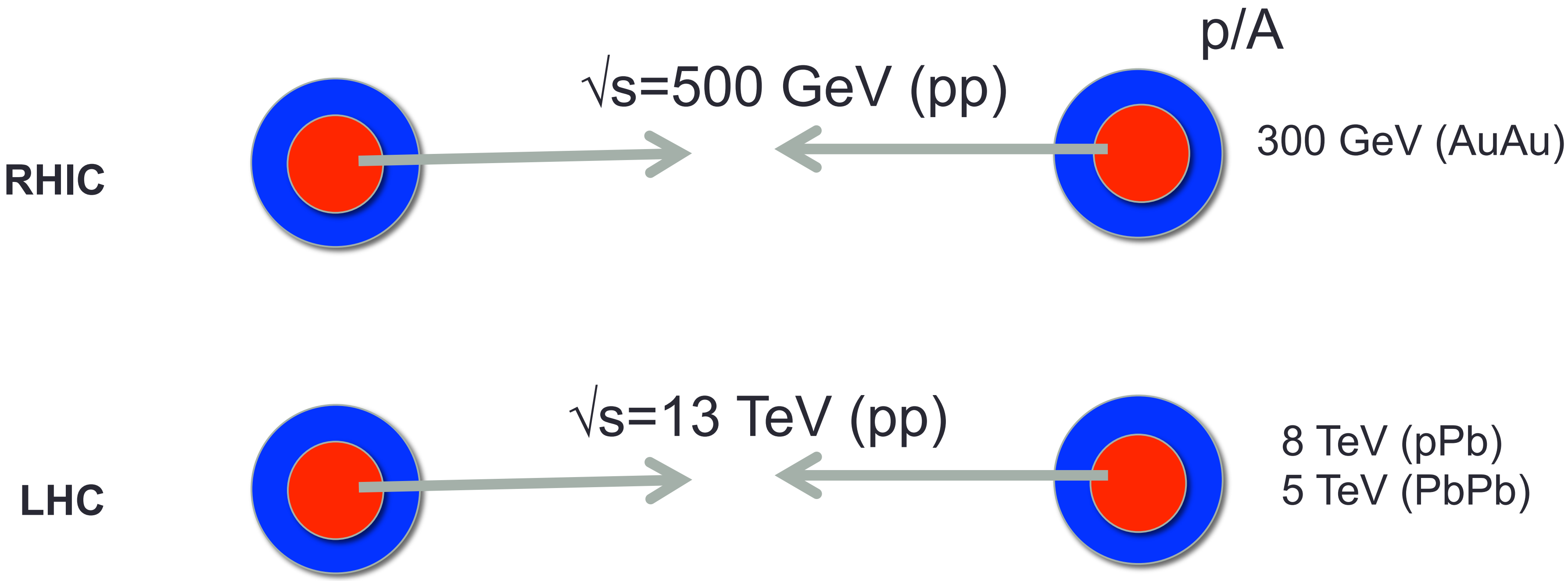
Ronan McNulty

EIC Workshop, Paris, 21-25 July 2019.

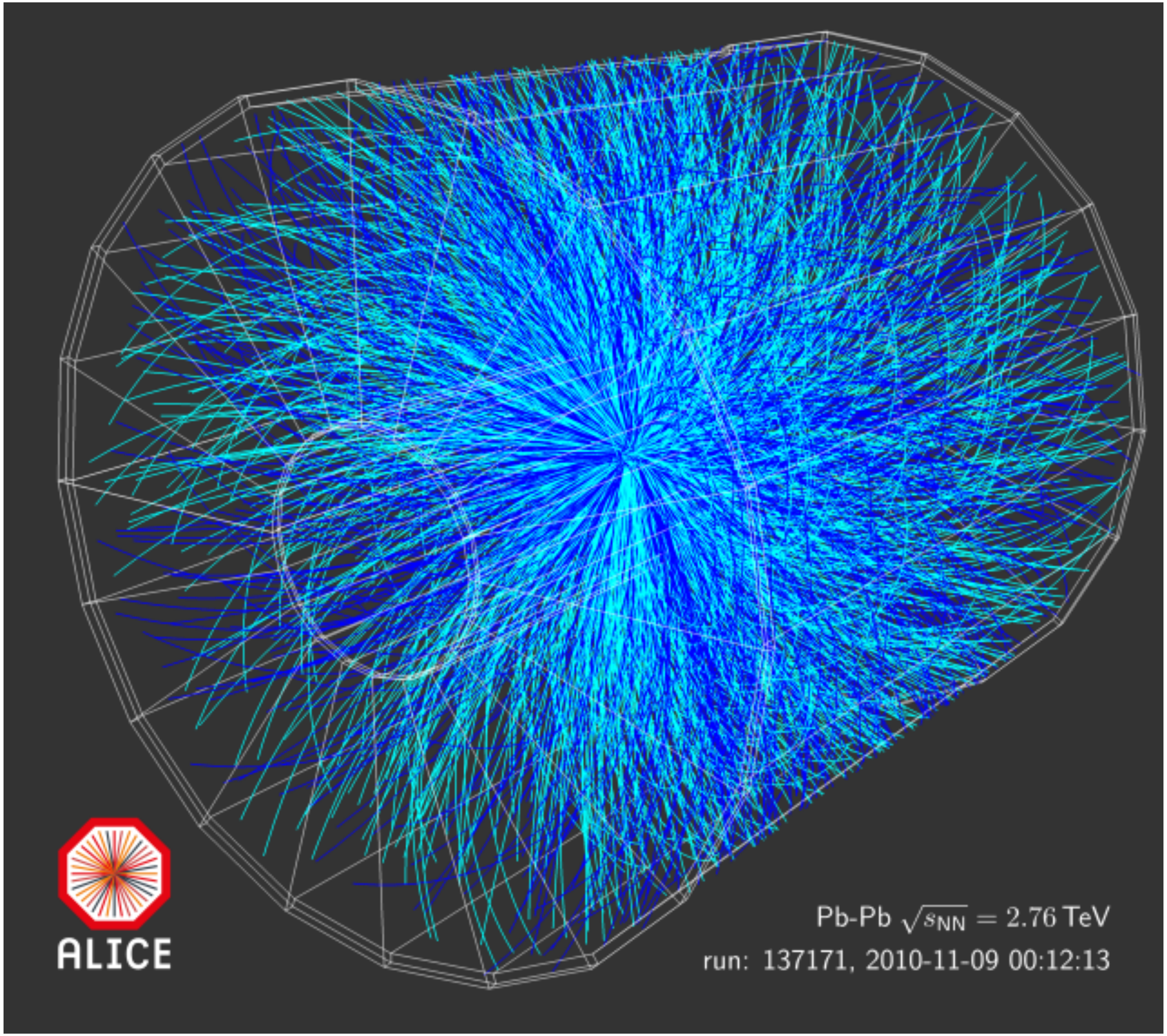
Overview

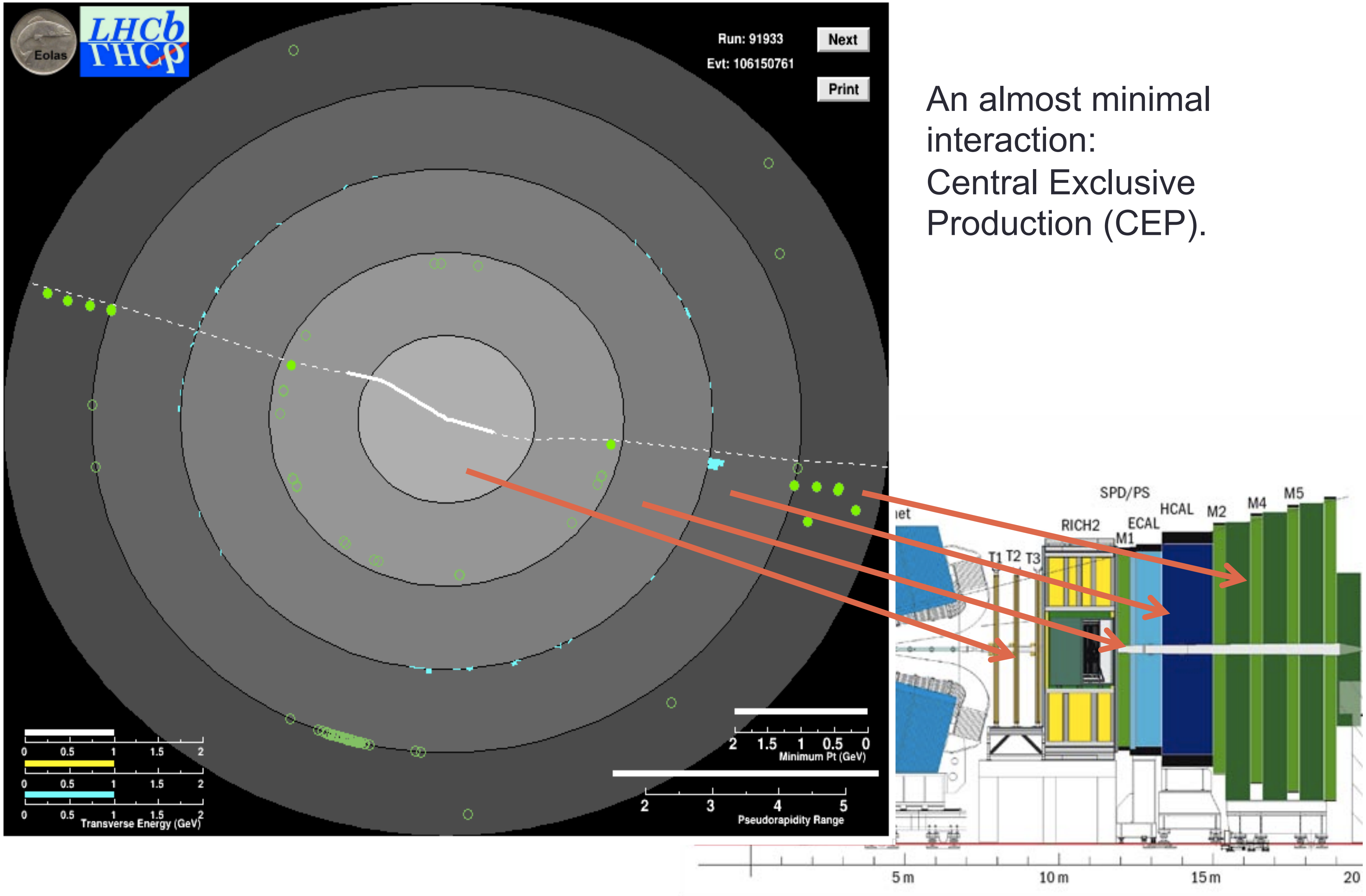
- Introduction to Ultra-peripheral Collisions
- QCD: the present
  - Soft to hard physics
  - The Pomeron
  - Parton density functions
- QCD: the future ?
  - The odderon
  - Beyond the quark model
  - Saturation


HERA
e
√s=300 GeV
p
RHIC
p/A
√s=500 GeV (pp)
300 GeV (AuAu)
LHC
√s=13 TeV (pp)
8 TeV (pPb)
5 TeV (PbPb)
EIC
√s=140 GeV (ep)

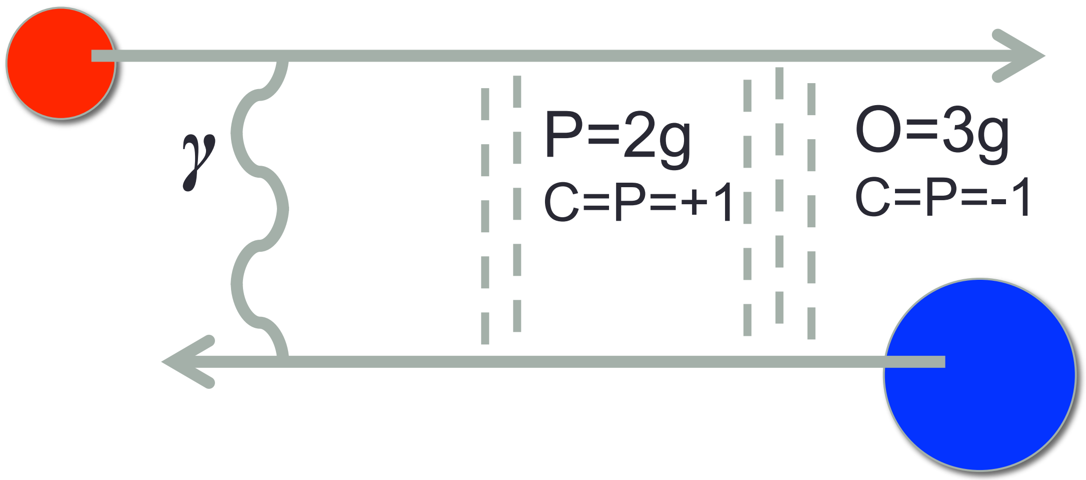

p/A
√s=500 GeV (pp)
RHIC
300 GeV (AuAu)
√s=13 TeV (pp)
LHC
8 TeV (pPb)
5 TeV (PbPb)

ALICE-PHO-GEN-2015-004-2





An almost minimal interaction:
Central Exclusive Production (CEP).

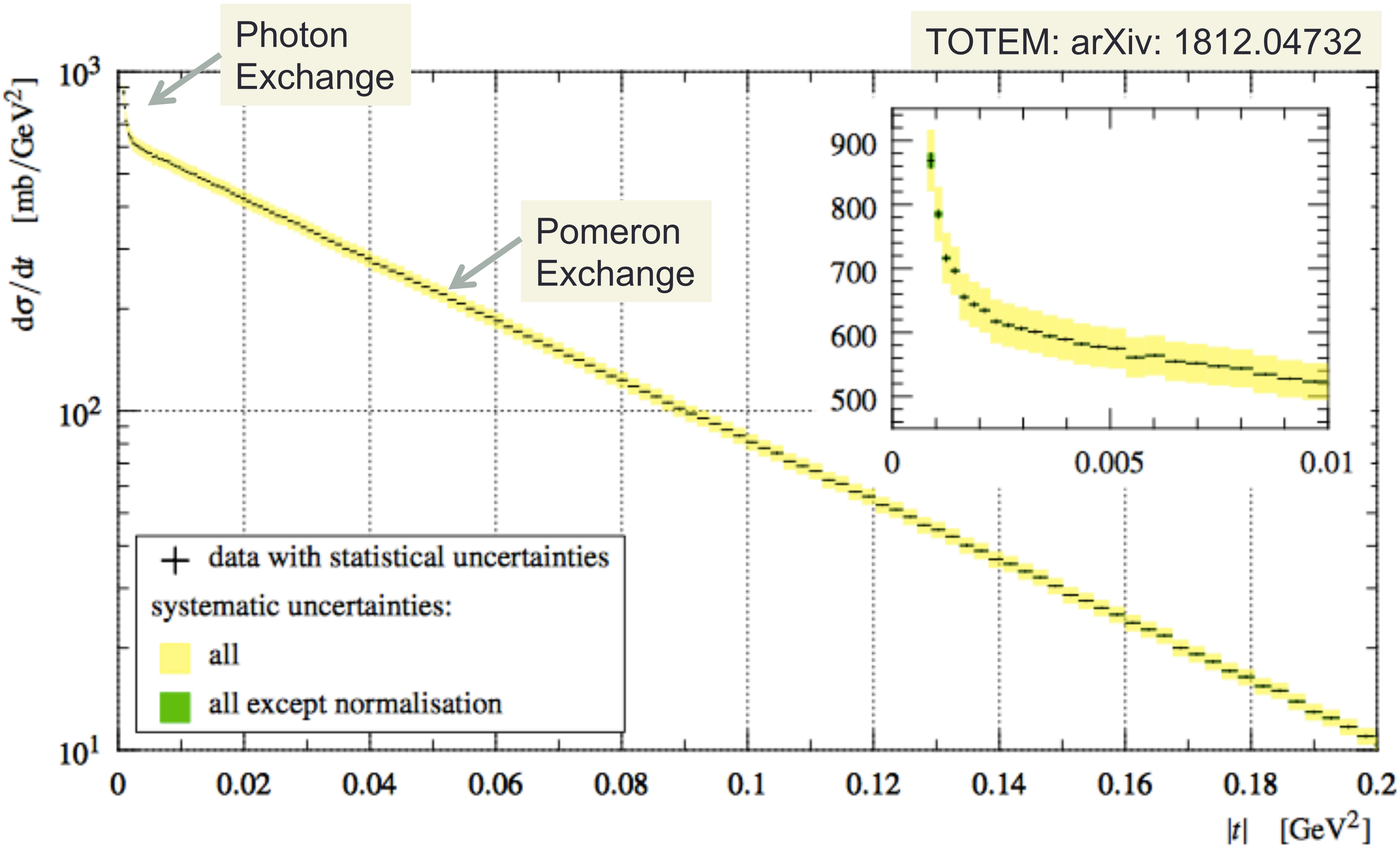


Elastic scattering

$d\sigma/dt \sim \exp(-bt)$

$b \sim R^2$

$p_T \sim \sqrt{t} \sim 30$ MeV (QED)
$p_T \sim \sqrt{t} \sim 300$ MeV (QCD) pp-collisions
$p_T \sim \sqrt{t} \sim 100$ MeV (QCD) AA-collisions



$$\sigma^{pp}_{tot} = 110.6 \pm 3\text{mb}, \qquad \rho^{pp} = 0.098 \pm 0.01$$

PLB 778 (2018) 414.

Did TOTEM experiment discover the Odderon?

Evgenij Martynov[a], Basarab Nicolescu[b]

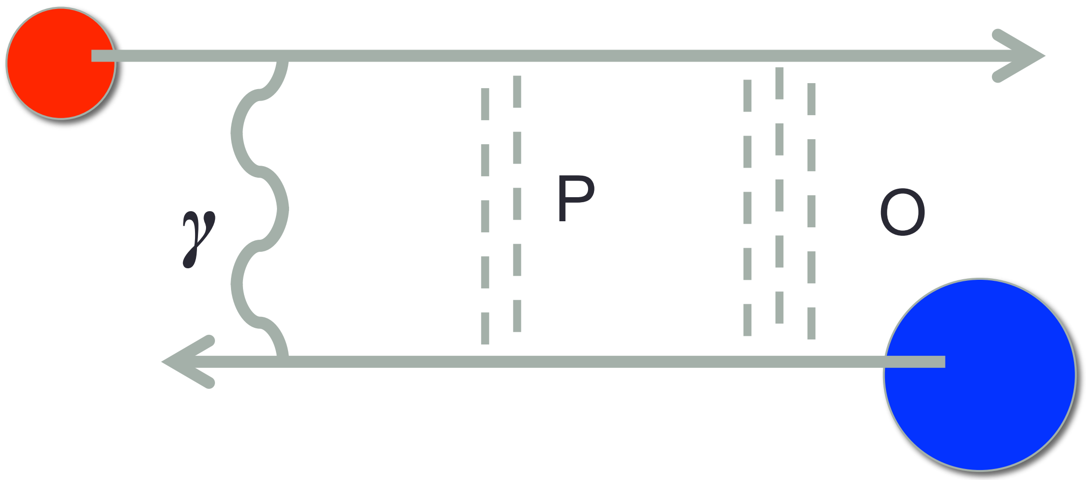
arXiv:1901.05863

TOTEM data and the real part of the hadron elastic amplitude at 13 TeV

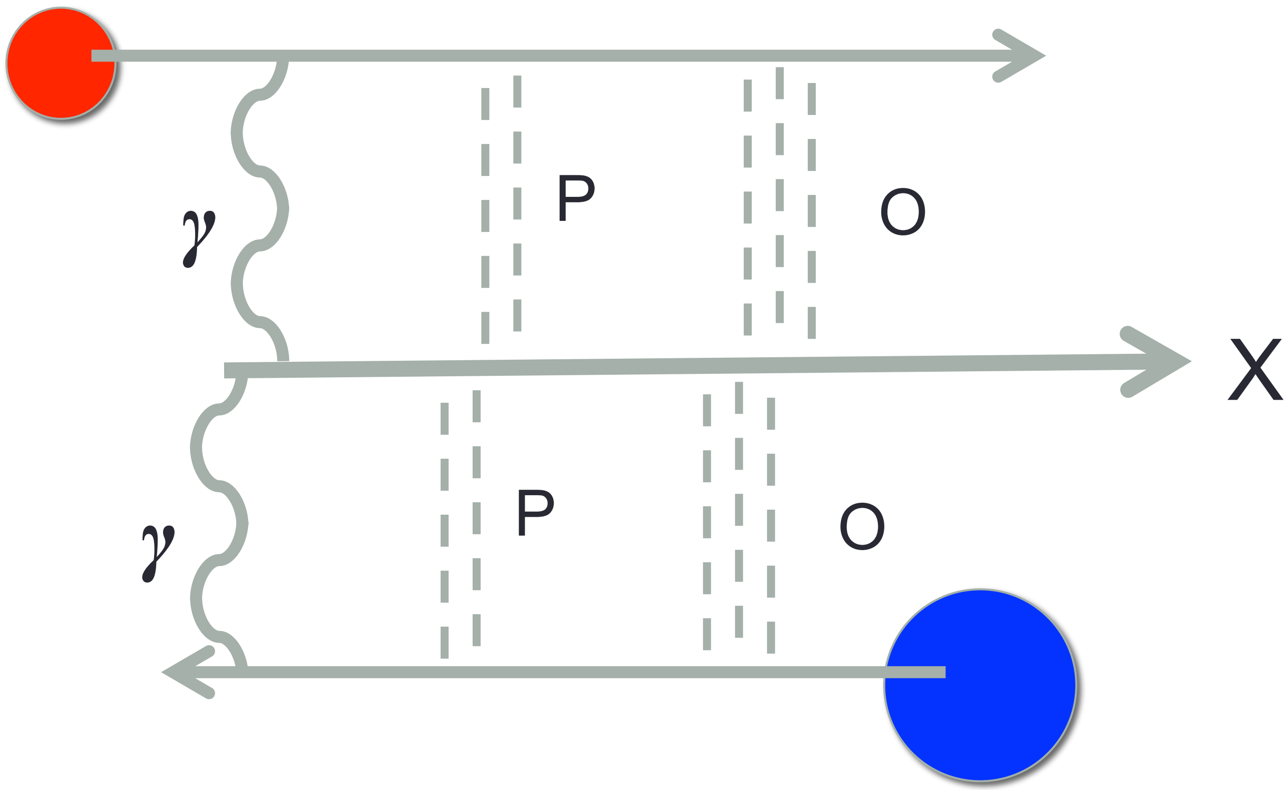
J.R. Cudell & O. V. Selyugin

Abstract

We analyse the 13 TeV TOTEM data on elastic proton-proton scattering through a thorough statistical analysis, and obtain that $\rho = 0.096 \pm 0.006$ and $\sigma_{tot} = (107.5 \pm 1.5)$ mb. Theoretical errors could lower the cross section by about 2 mb and increase ρ by about 0.002. We also show that these results do not imply the existence of an odderon at $t = 0$.



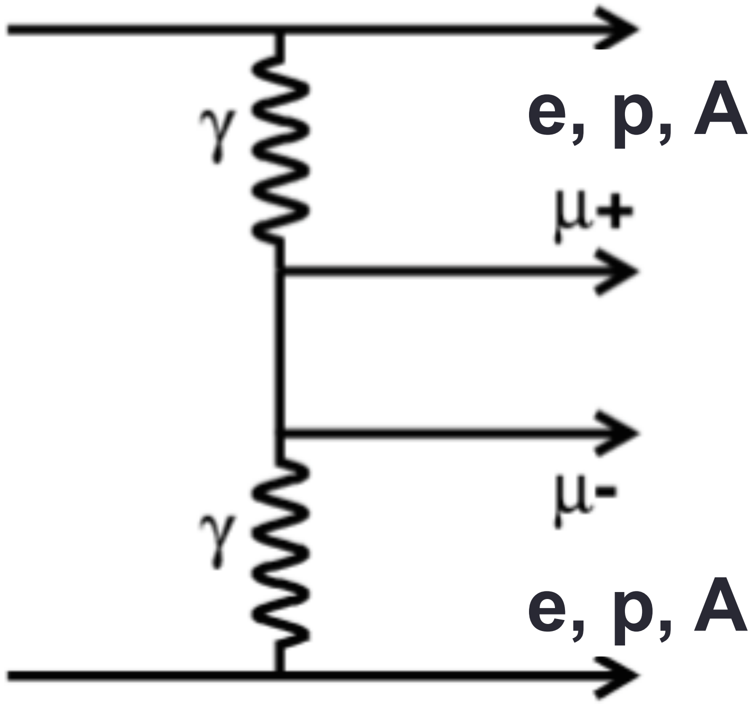
(Elastic Scattering)



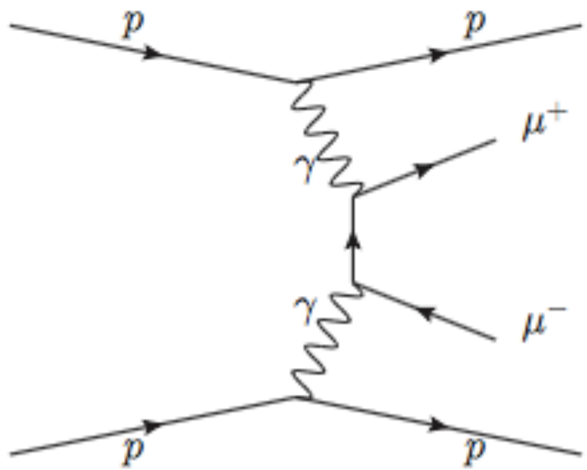
Central Exclusive Production (CEP)

Di-photon fusion (QED)

A enhanced by Z^2

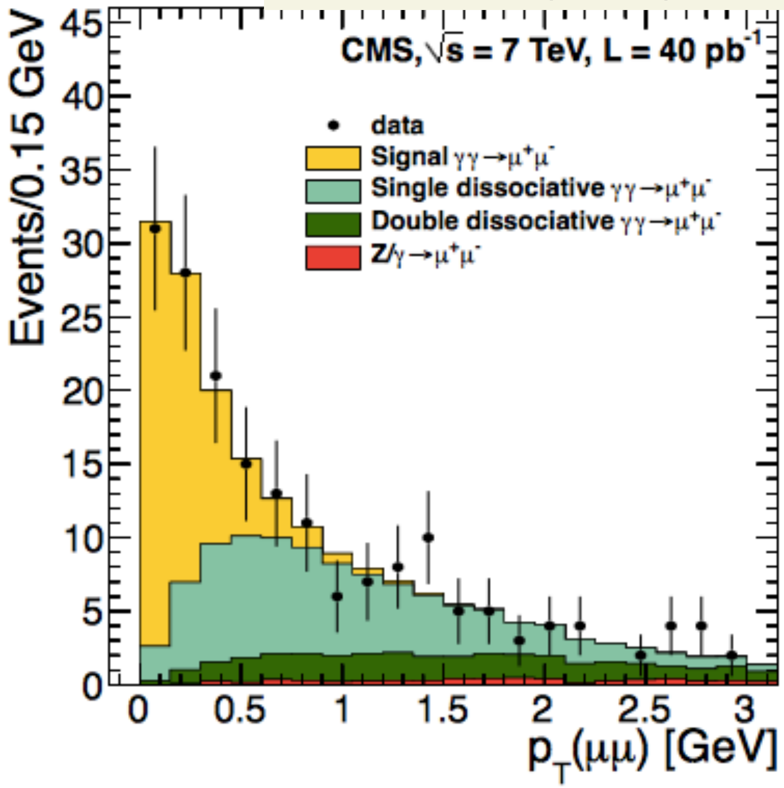


Di-photon fusion (QED)

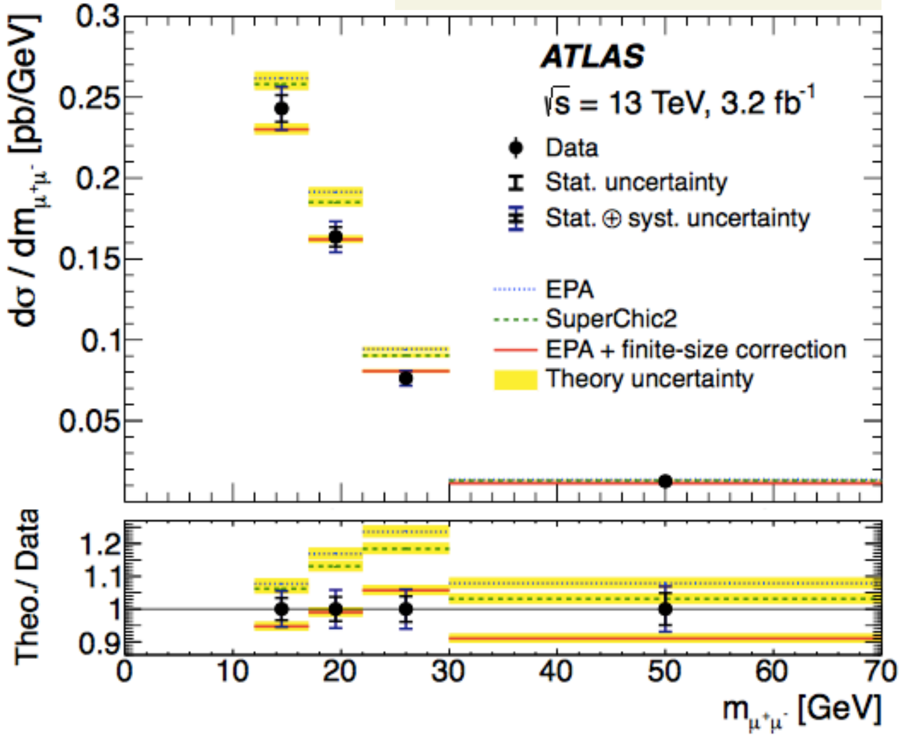


QED CEP process precisely predicted.
Data sensitive to re-scattering corrections

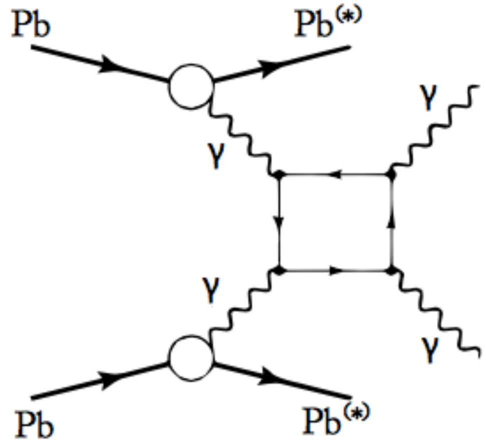
JHEP 1201 (2012) 052



PLB 777 (2018) 303.

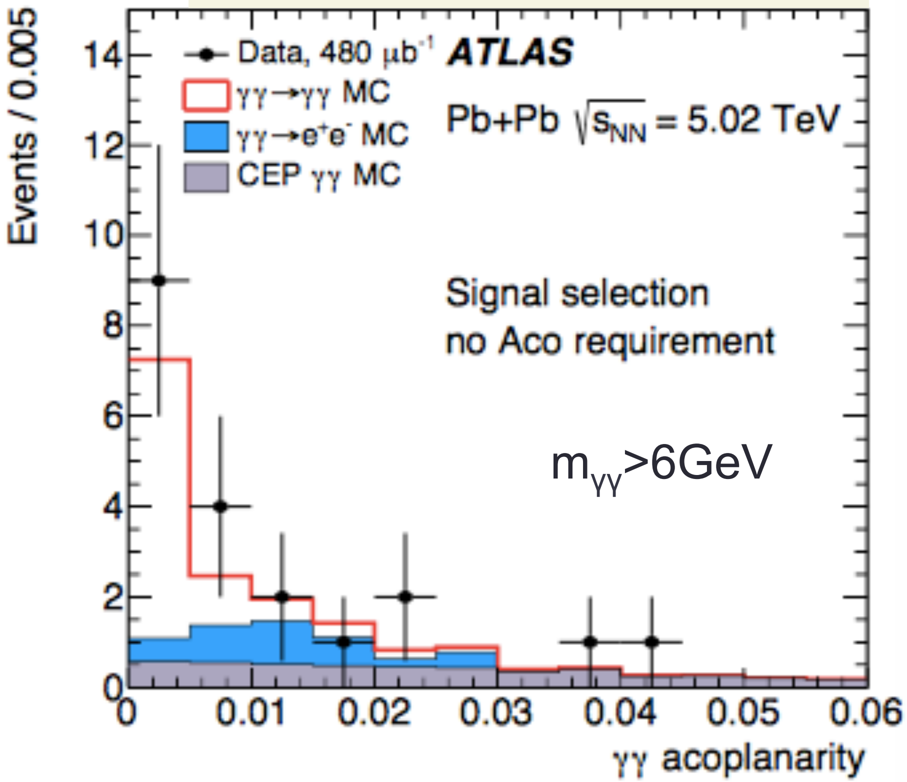


Di-photon fusion (QED)

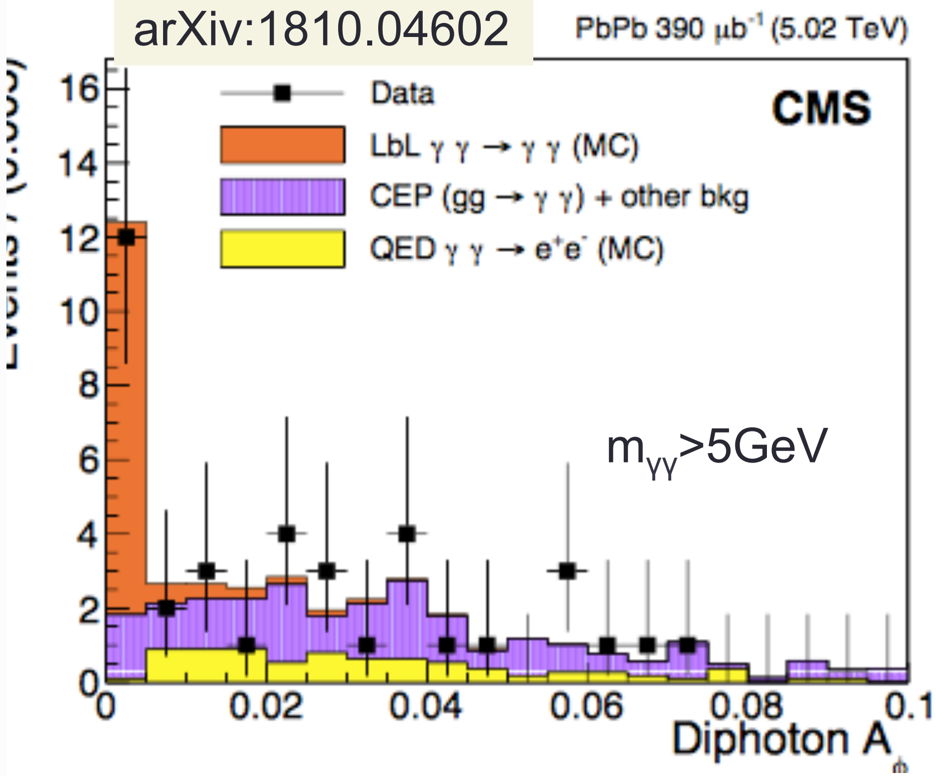


Light-by-light scattering
Forbidden in classical EM
Text-book illustration of QM

Nature Physics 13 (2017) 852

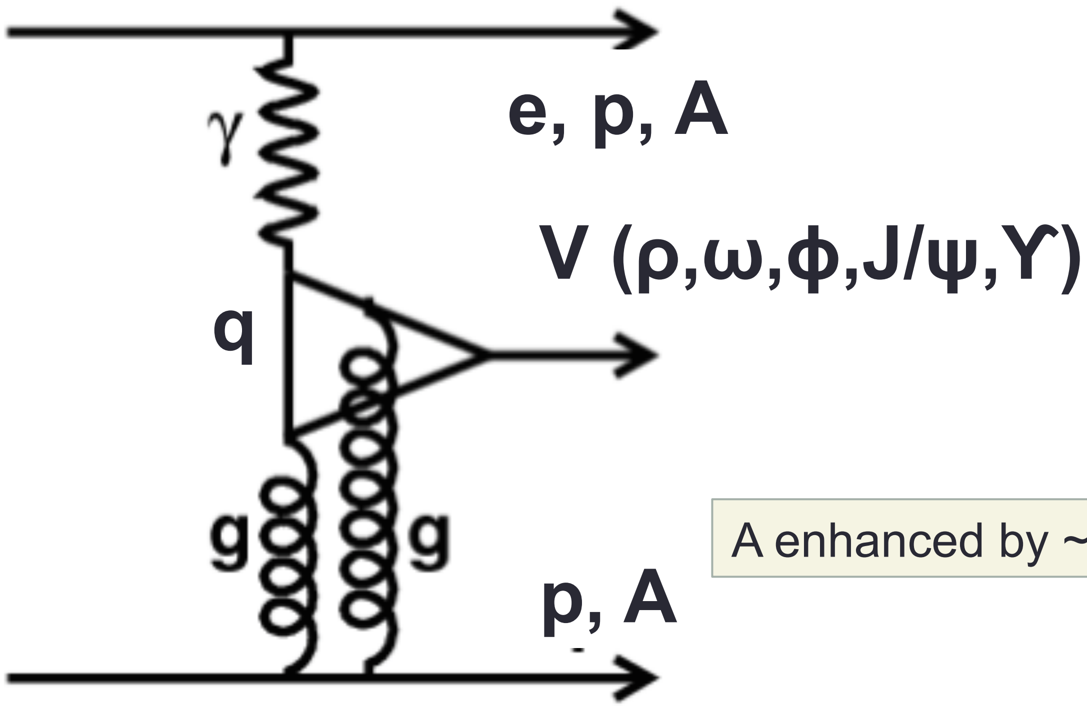


arXiv:1810.04602



C-odd mesons

A enhanced by Z^2



A enhanced by $\sim A^{1.5}$

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

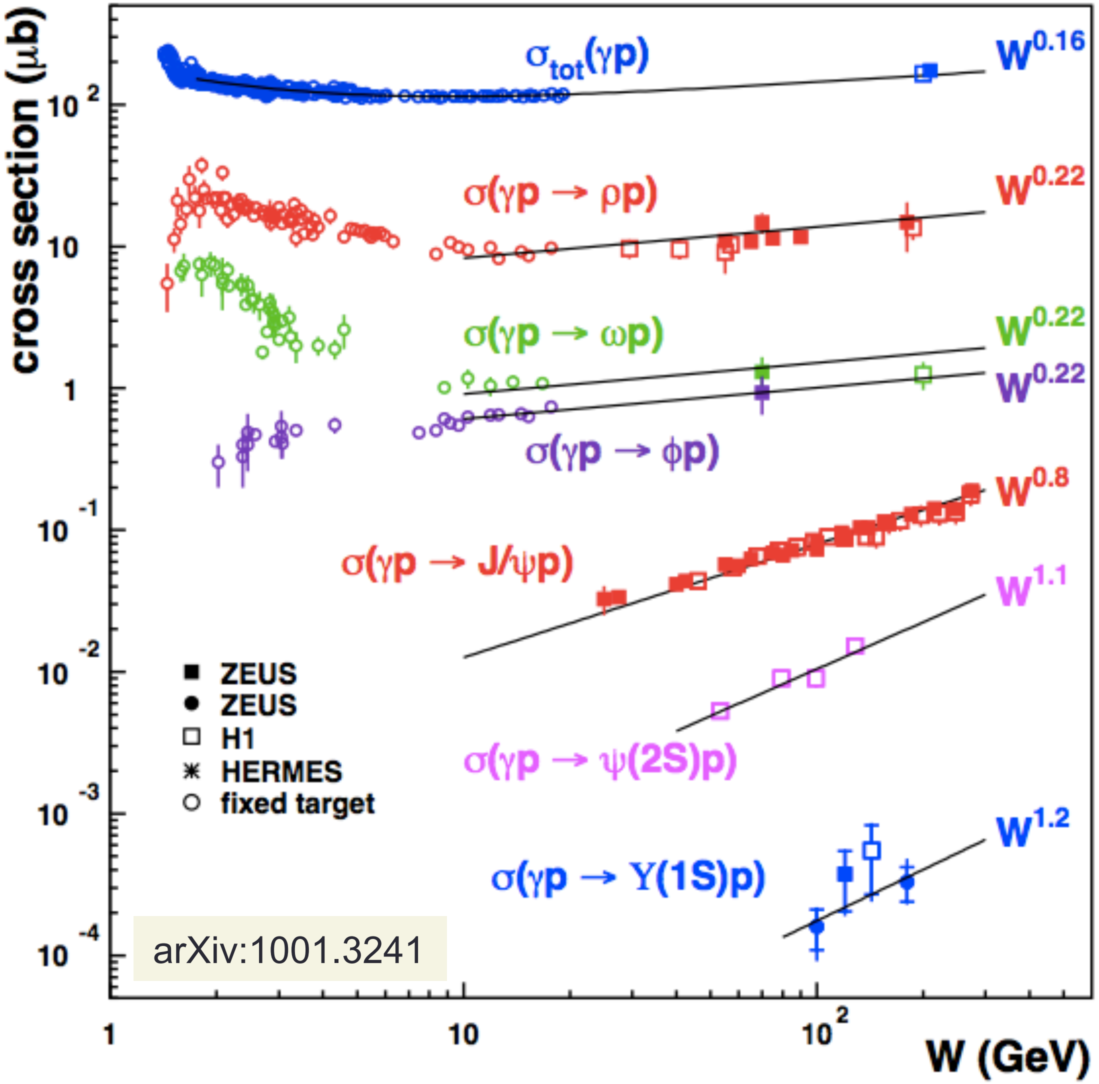
Vector mesons

Physics of the Vacuum: soft and hard QCD

Pomeron trajectory:

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

The structure of the proton and nucleus

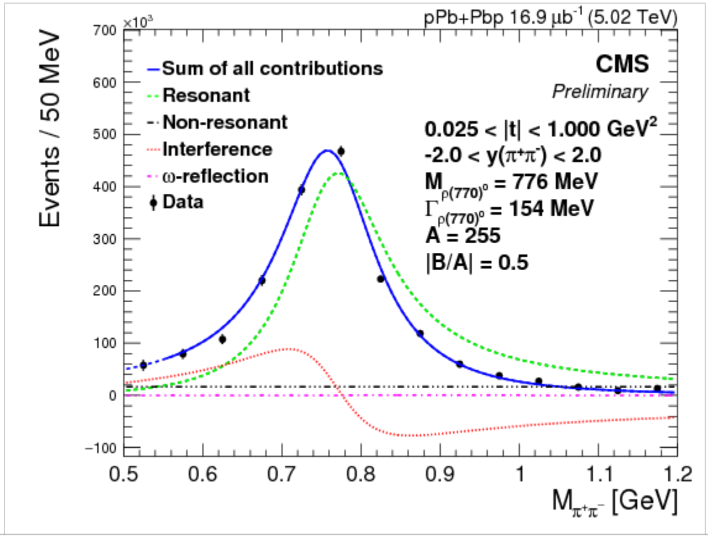


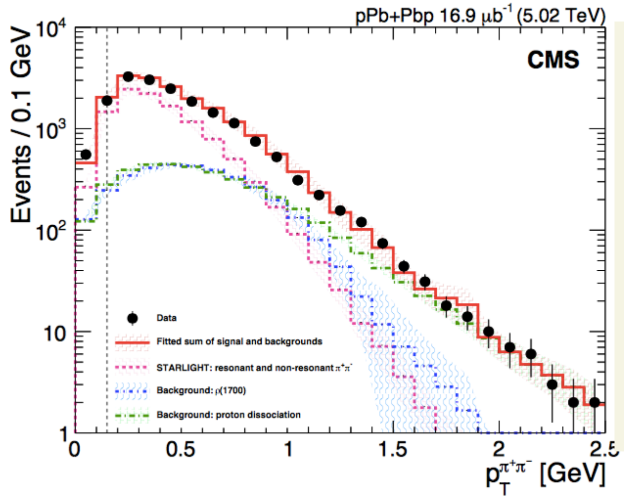
L.O. prediction in perturbative regime

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

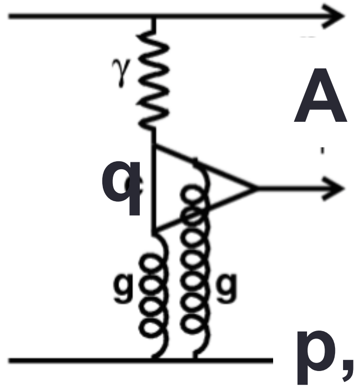
ρ photoproduction

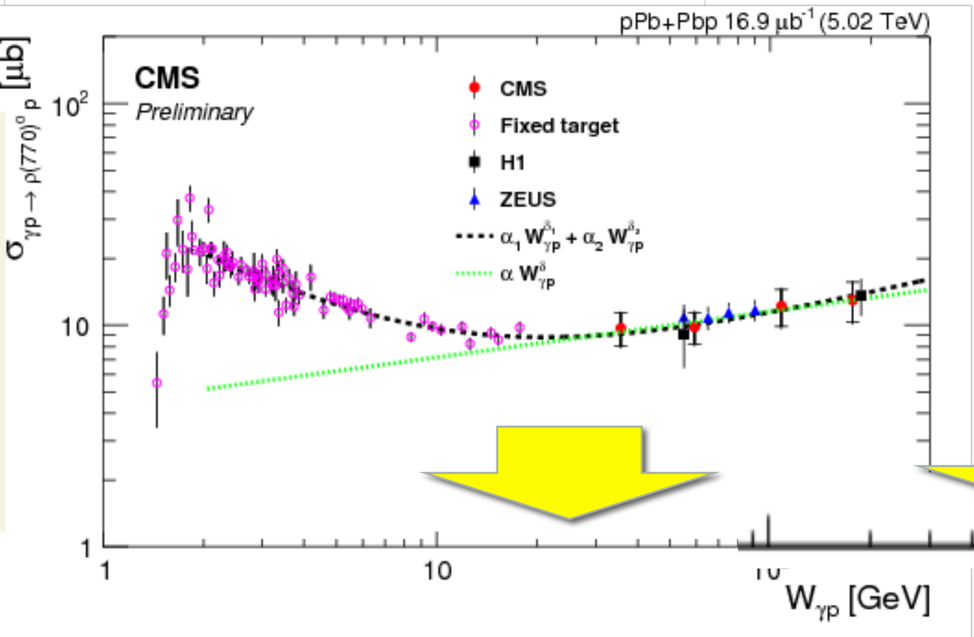
pPb collisions at 5.02 and 8.16 TeV



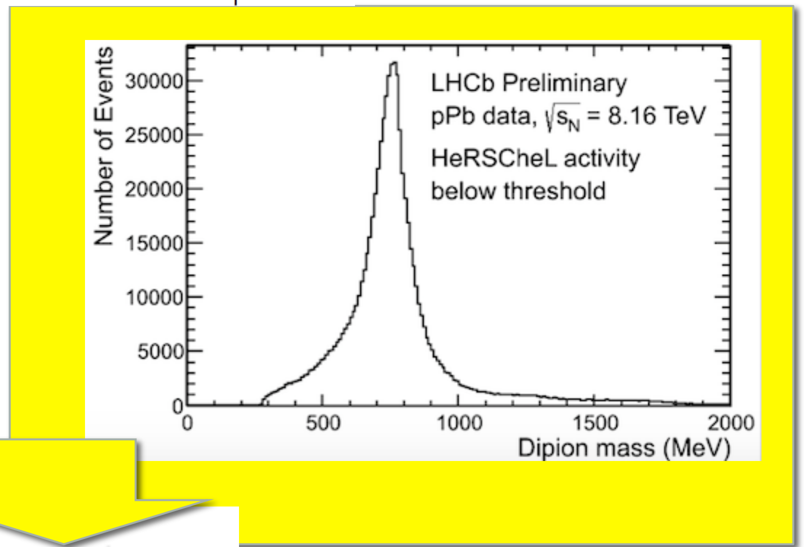


arXiv:1902.01339



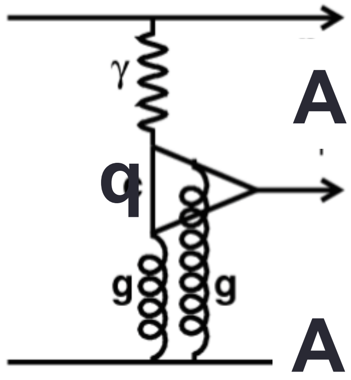


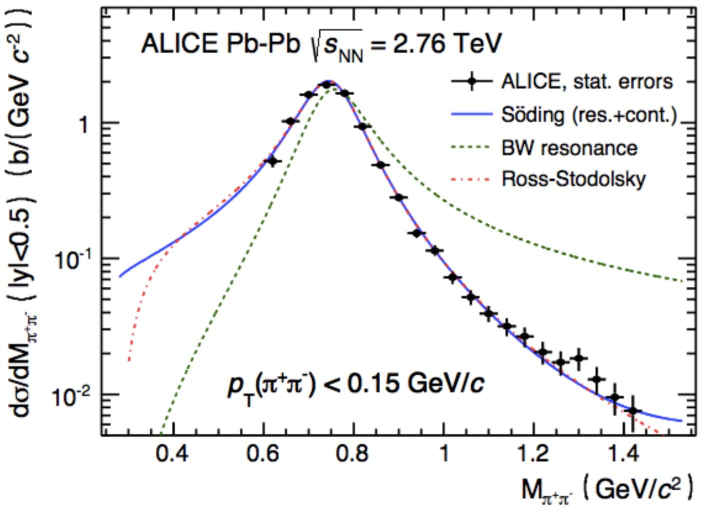
arXiv:1902.01339



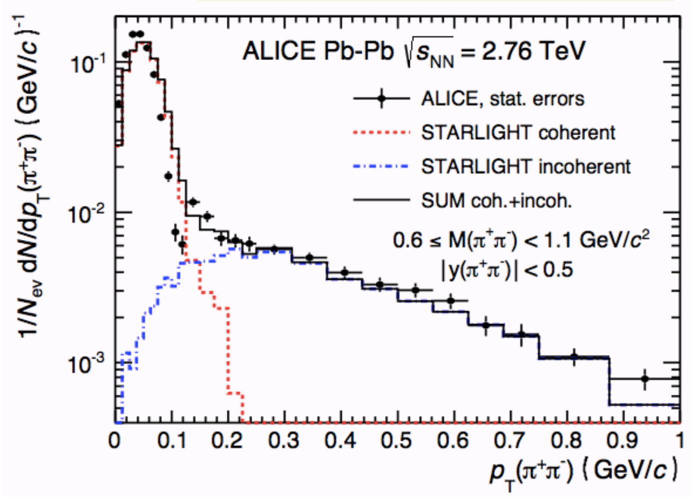
ρ photoproduction

AA collisions



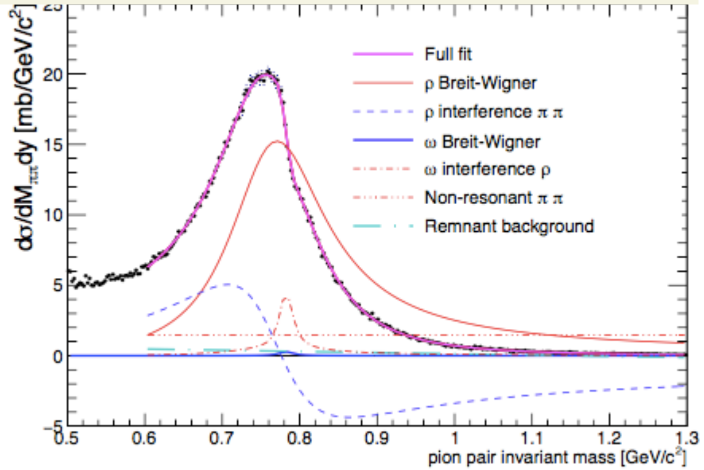


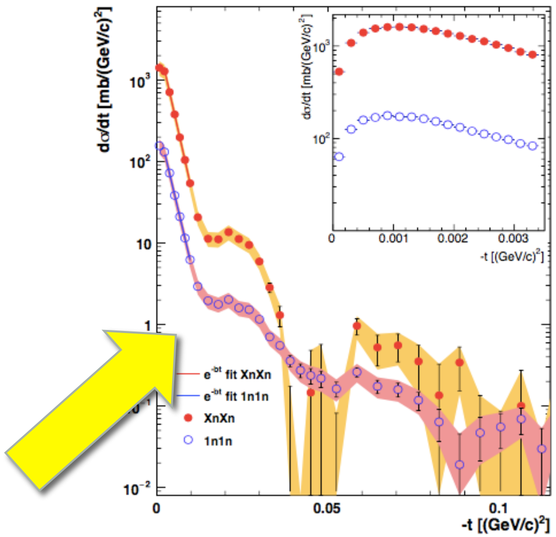
JHEP 1509 (2015) 095



ALICE@LHC
PbPb 2.76 TeV

Phys.Rev. C96 (2017) no.5, 054904





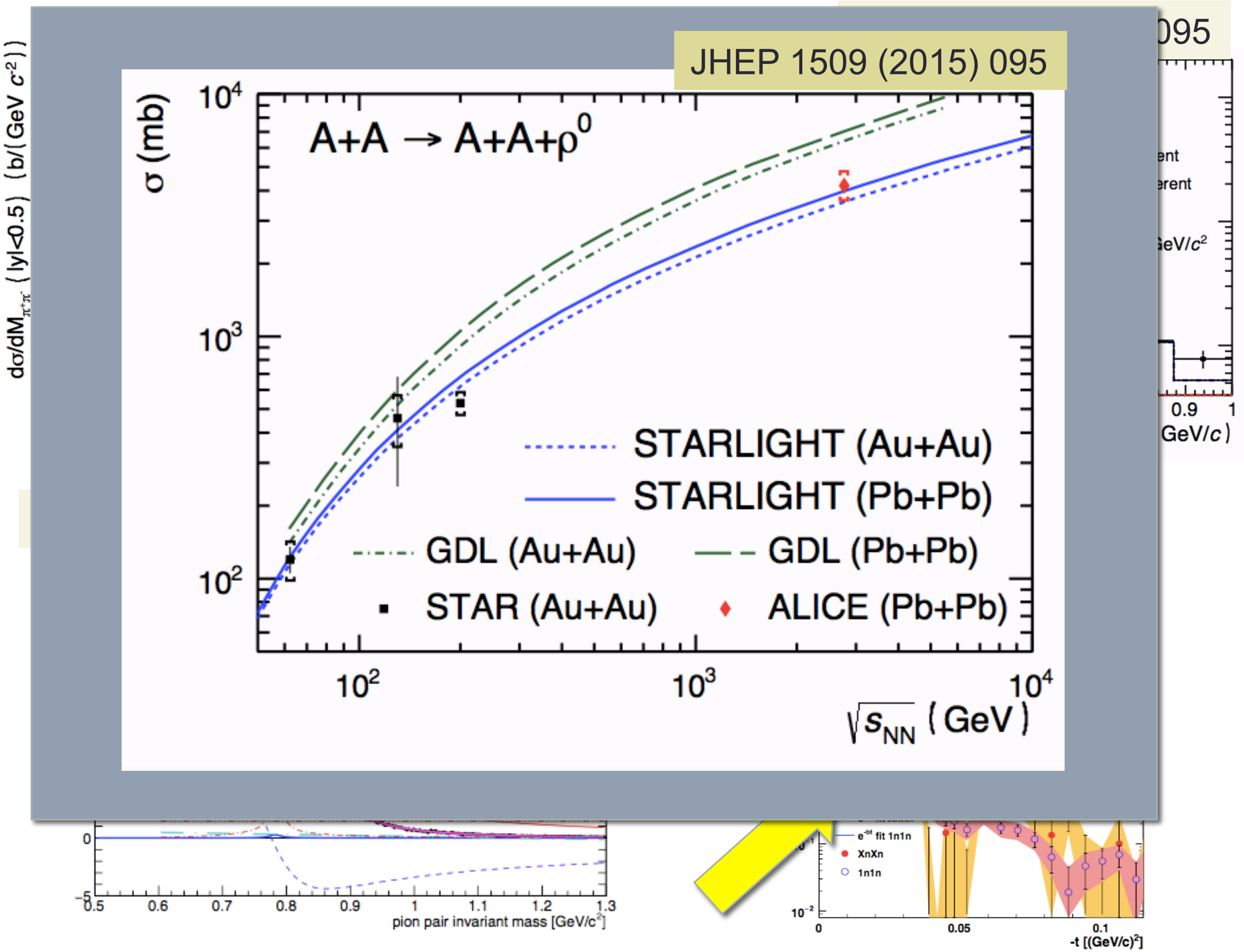
STAR@RHIC
AuAu 200 GeV

ρ photoproduction

AA collisions

ALICE@LHC
PbPb 2.76 TeV

STAR@RHIC
AuAu 200 GeV



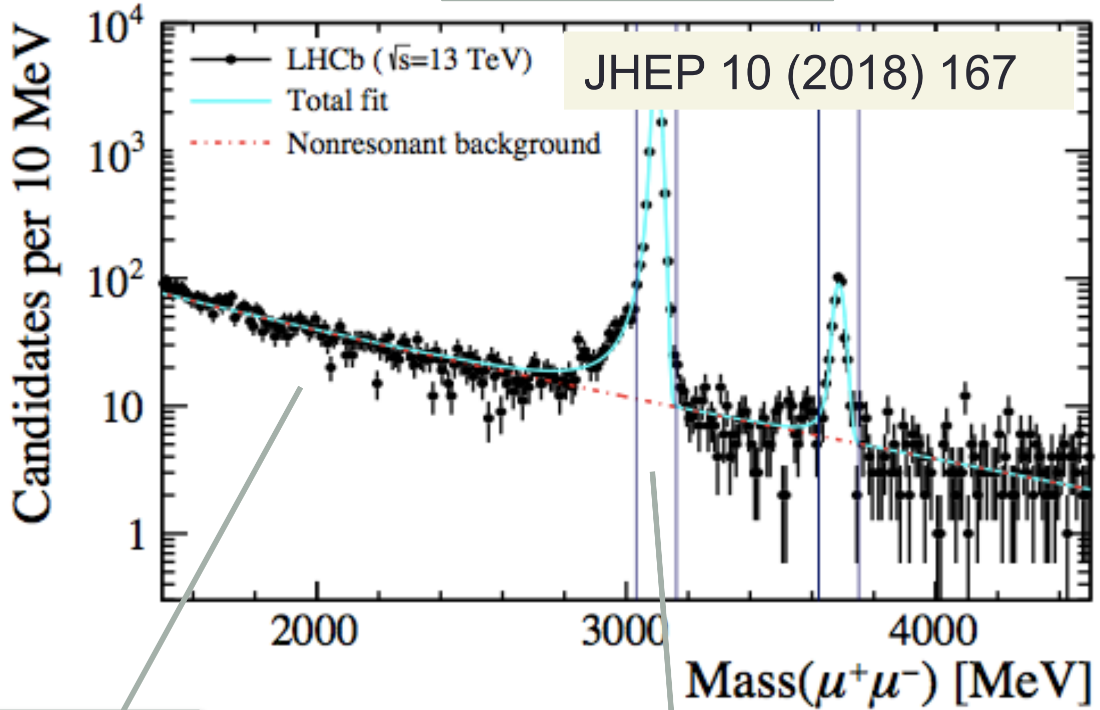
J/Ψ photoproduction

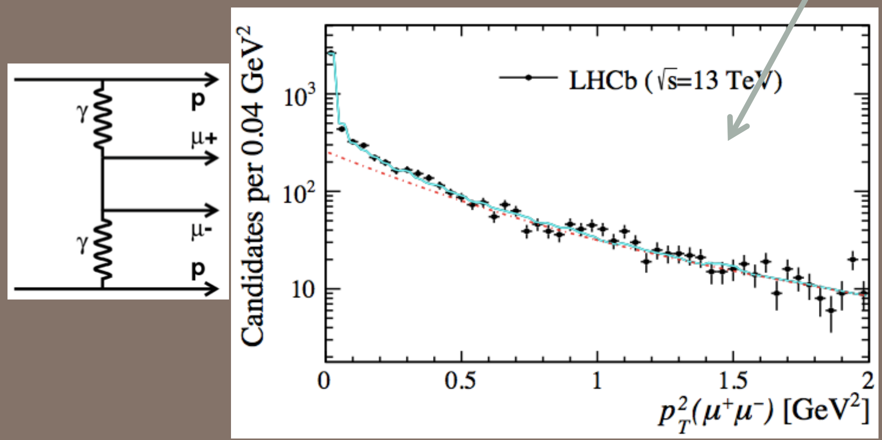
pp collisions

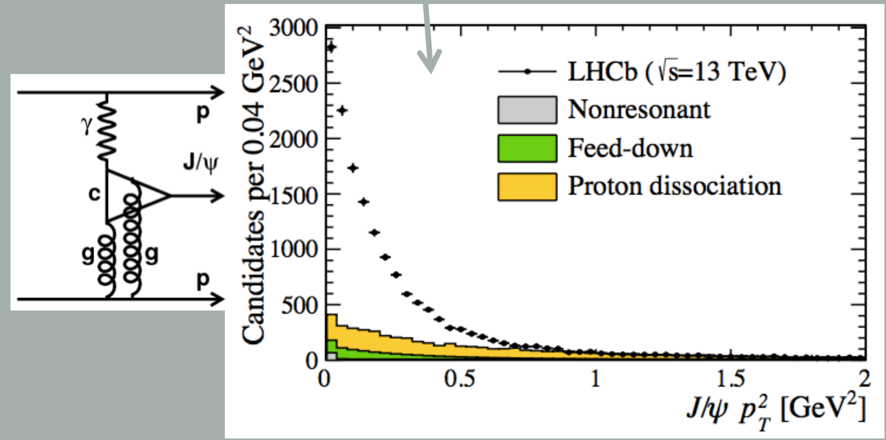
Perturbative region

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

JHEP 10 (2018) 167



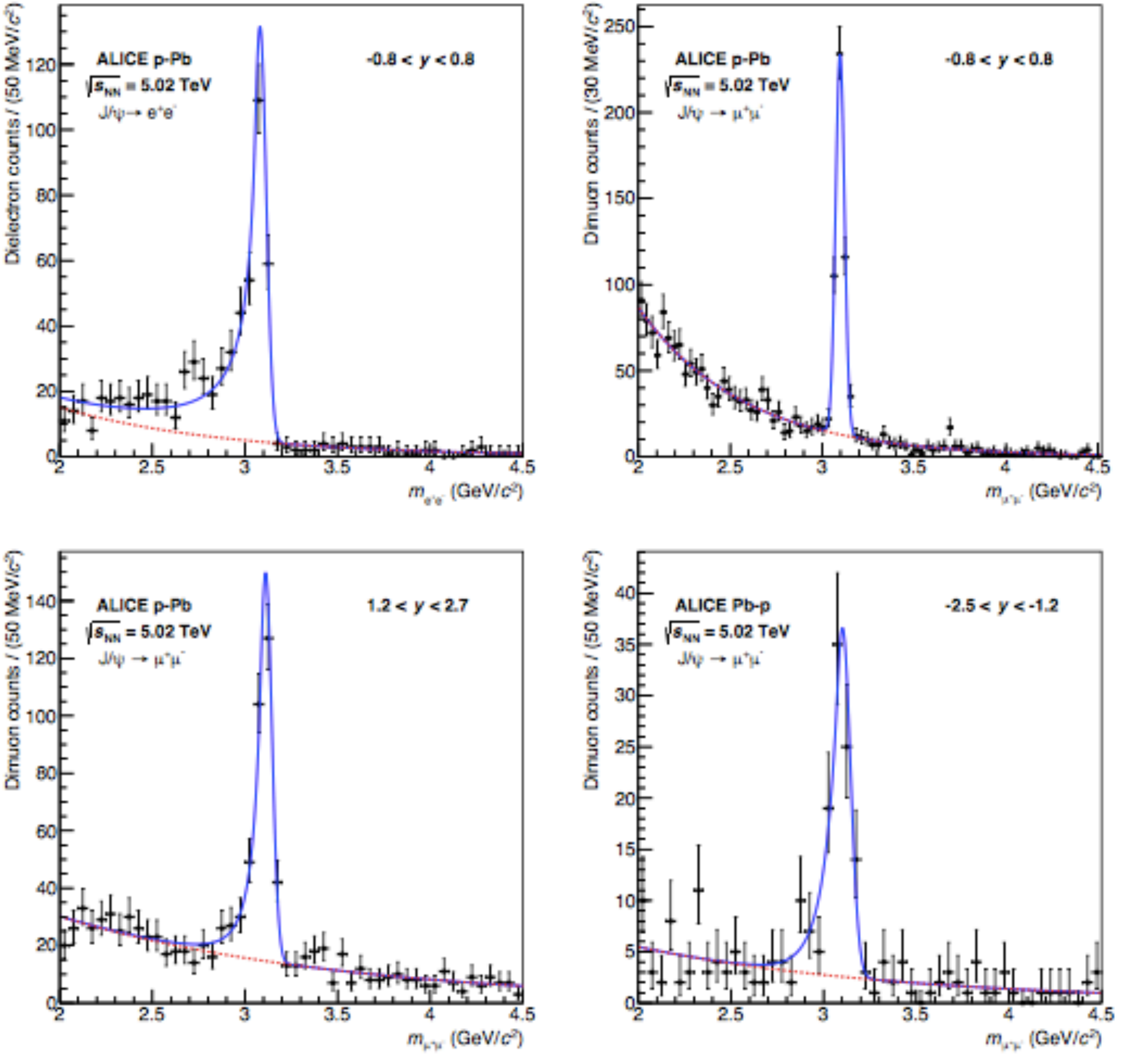




J/Ψ photoproduction

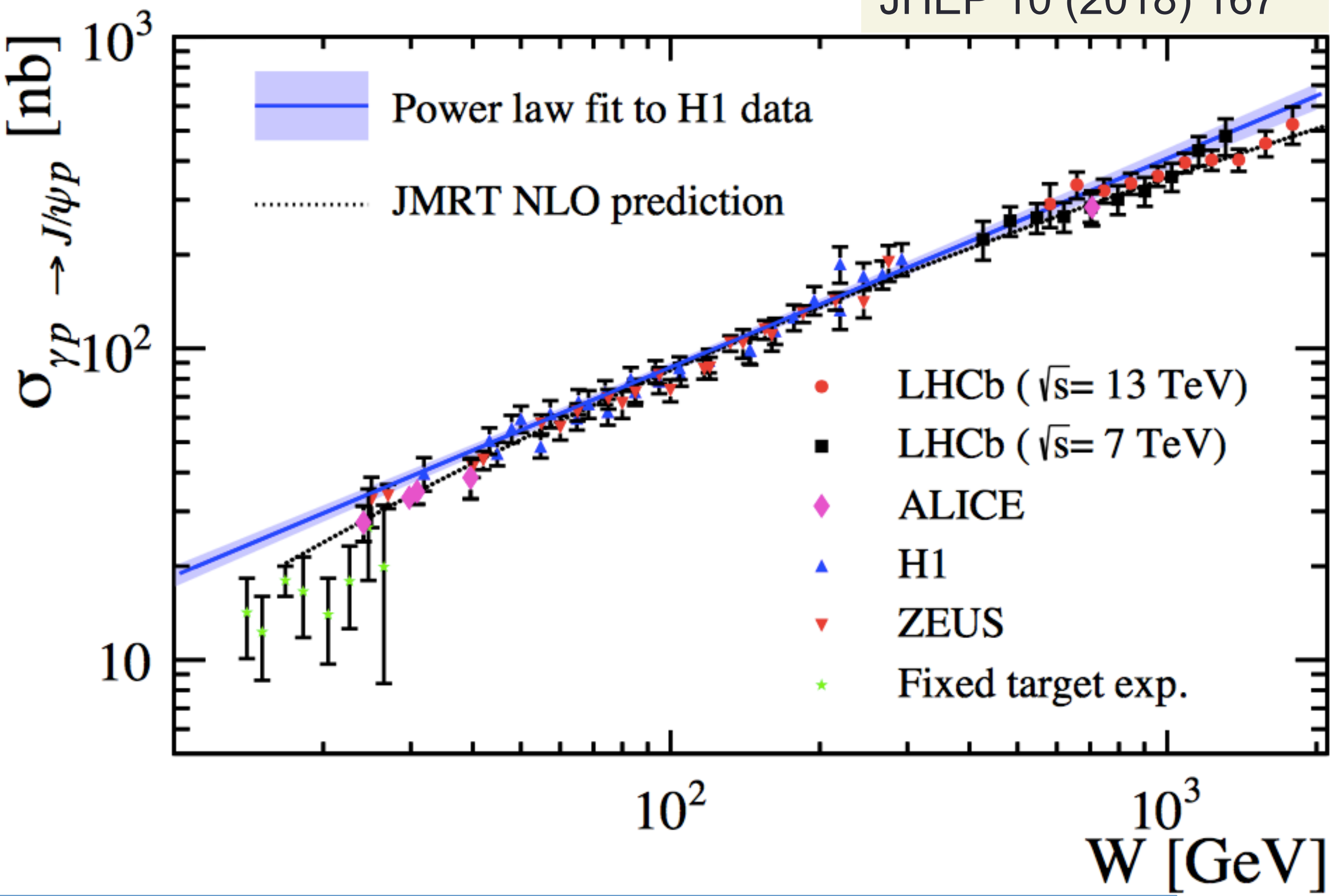
pPb collisions

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



J/Ψ photoproduction

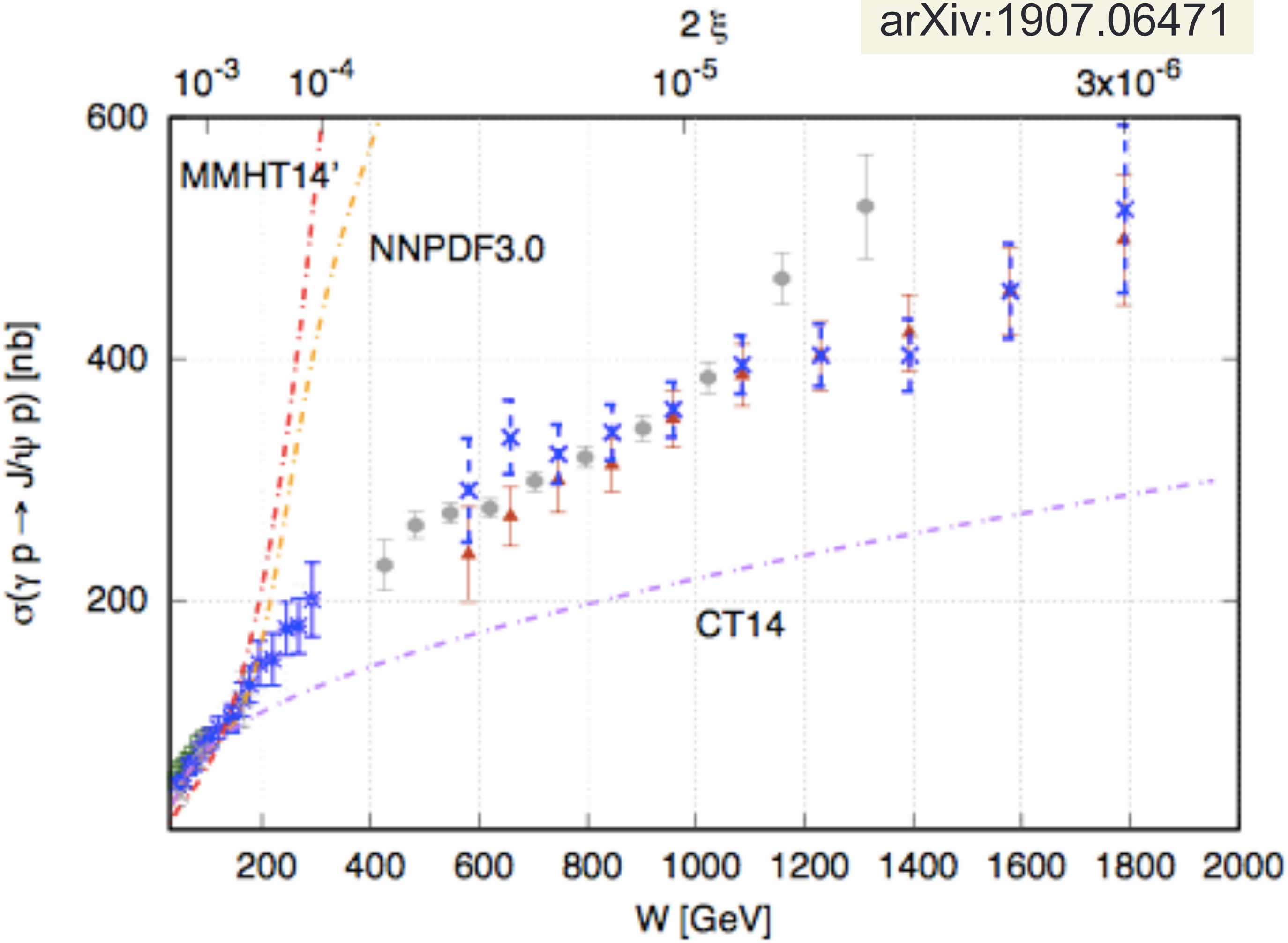
JHEP 10 (2018) 167



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

Gluon PDF extraction

arXiv:1907.06471

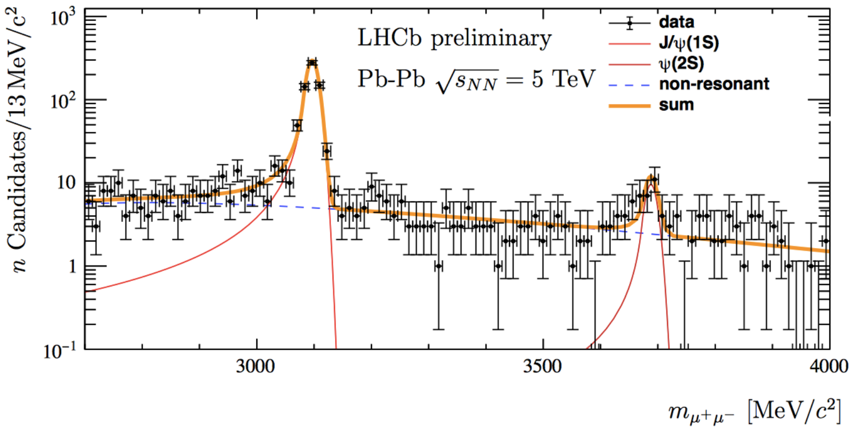


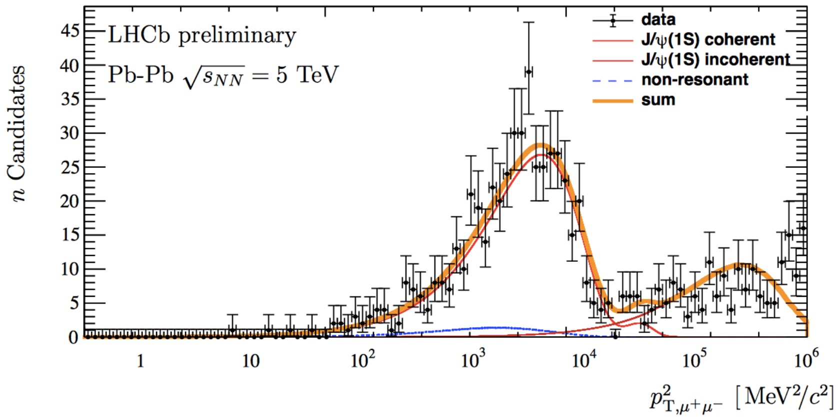
Flett, Jones, Martin, Ryskin, Teubner.

J/Ψ photoproduction

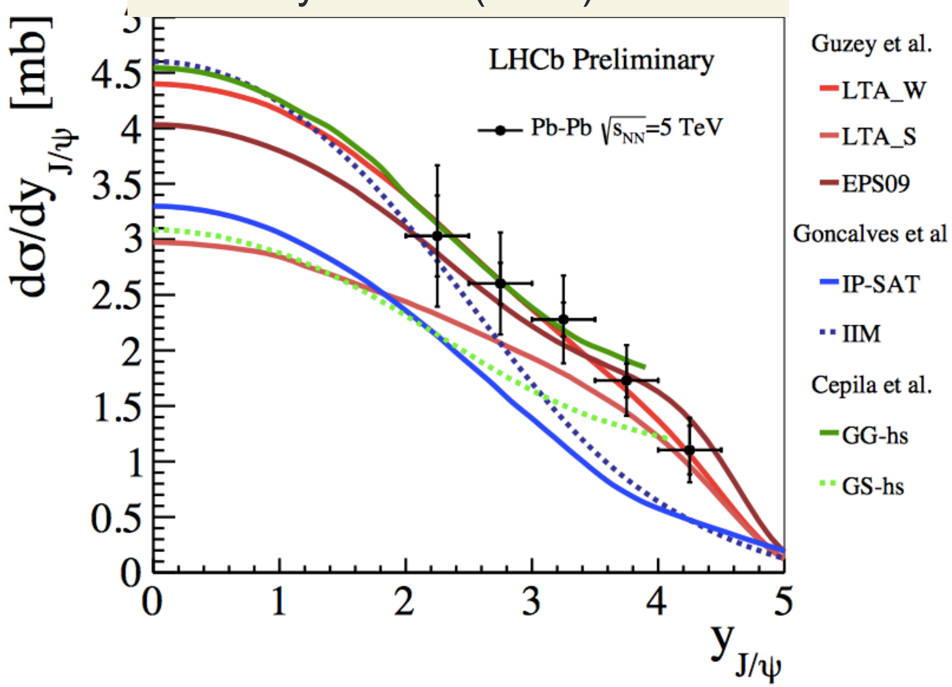
PbPb collisions

- In similar way $\sigma_{\gamma A}$ gives **nuclear PDFs** (or shadowing)
- LHCb measurement of J/ψ CEP in Lead-lead collisions





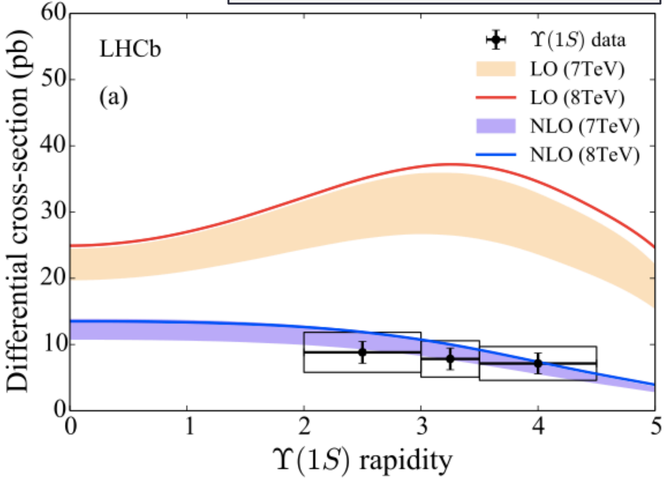
Nucl.Phys. A982 (2019) 247-250



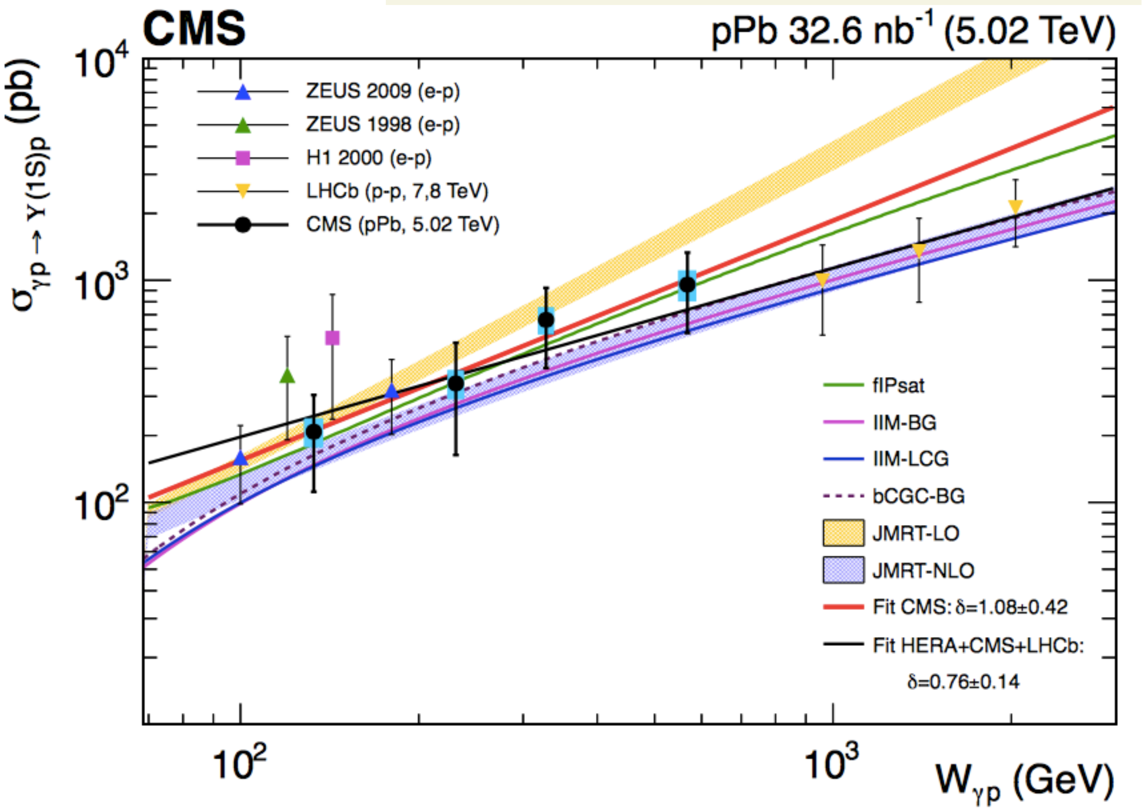
Upsilon photoproduction

Measurement by LHCb in pp and CMS in pPb

JHEP 1509 (2015) 084



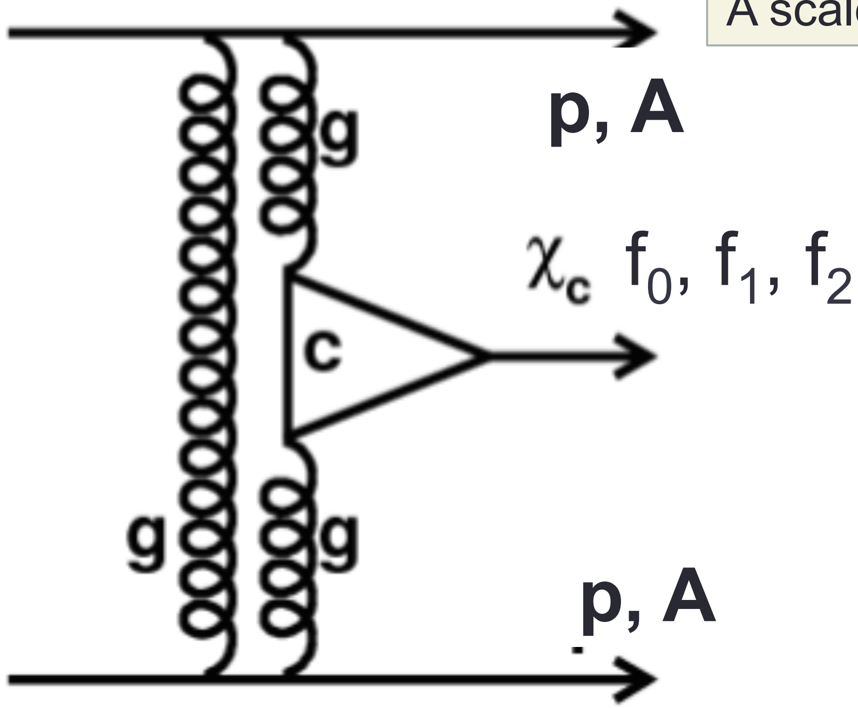
Eur.Phys.J. C79 (2019) no.3, 277



C-even mesons

(Eur.Phys.J. C74 (2014) 2848)

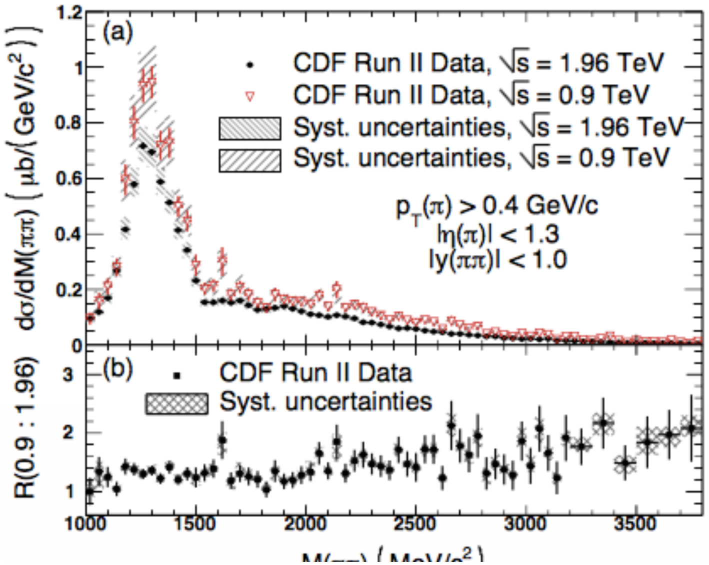
A scaled by $0.04A^{1/6}$



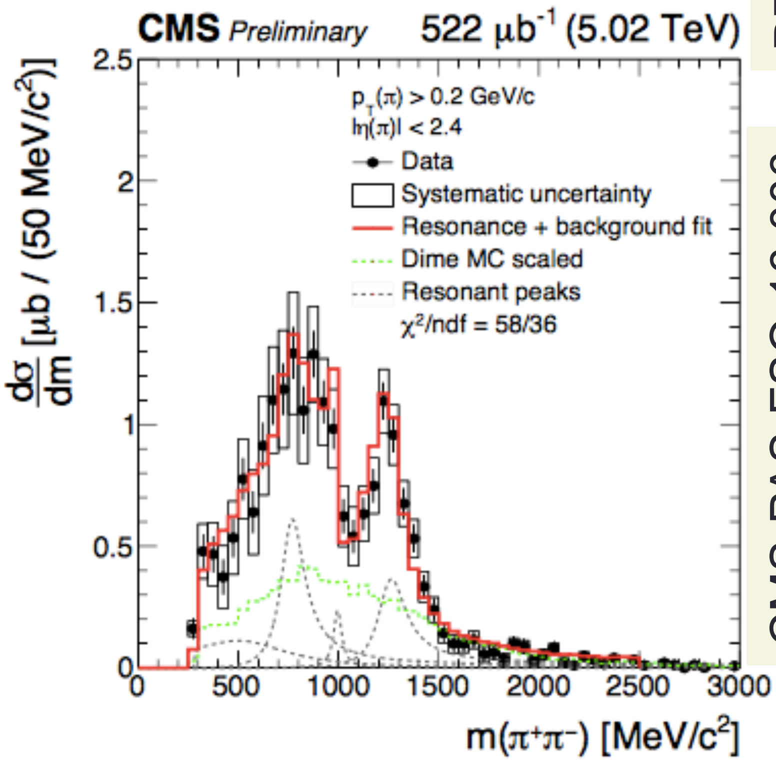
Important for EIC

(Photon-odderon fusion is also possible – if odderon exists)

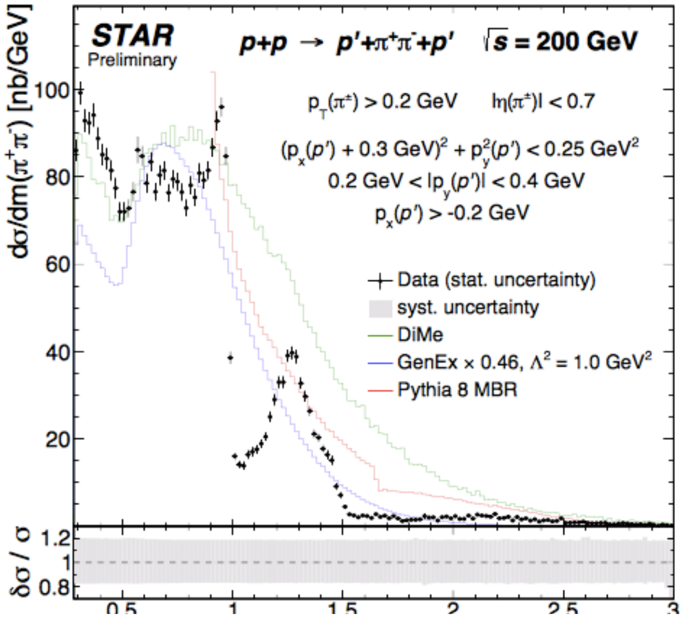
ππ/KK DPE production

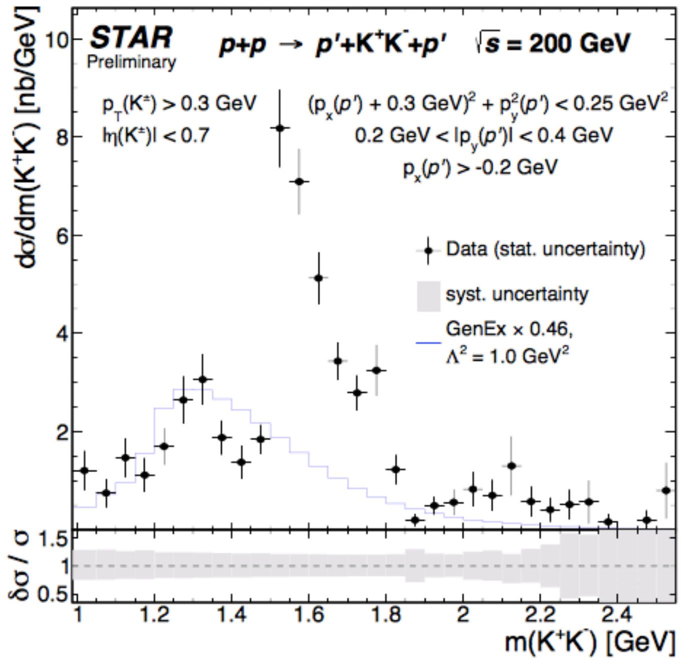


PRD91 (2015) no.9, 091101



CMS-PAS-FSQ-16-006





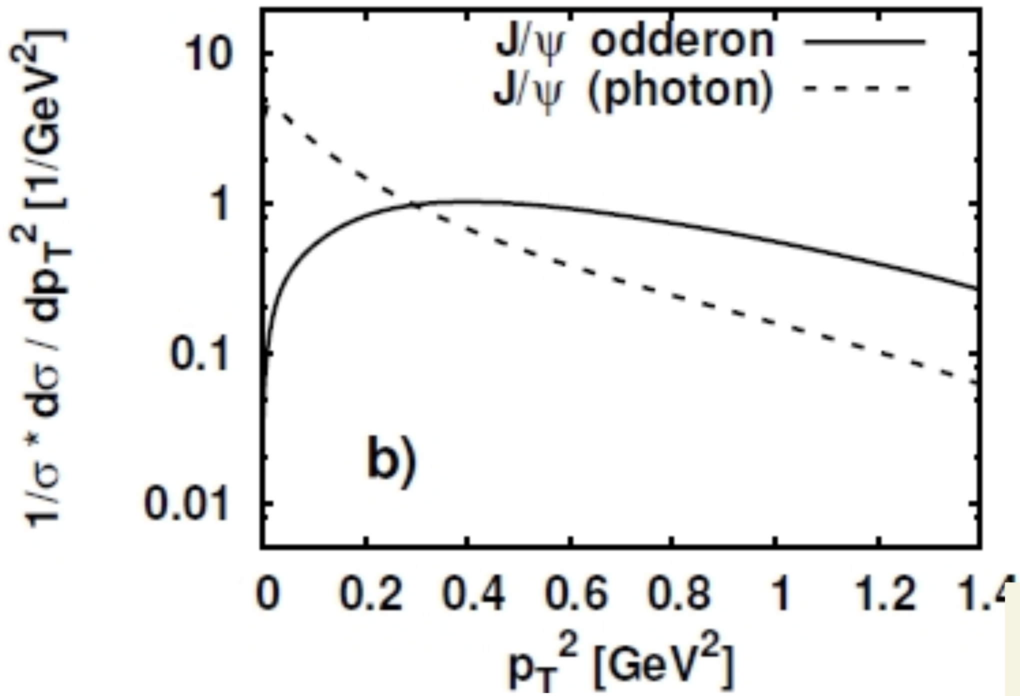
arXiv:1811.03315

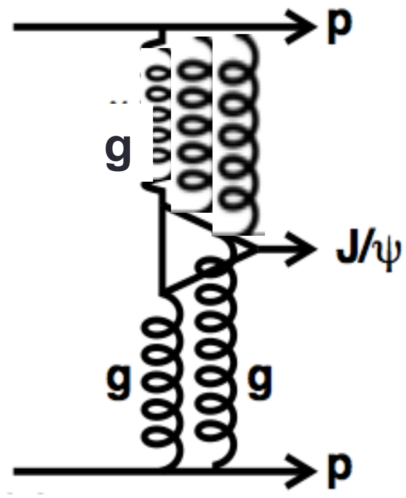
QCD: Open questions and opportunities

- Odderon
- Extensions to the quark model
  - Tetraquarks
  - Hybrids
  - Glueballs
- Saturation

“Take nothing on its looks; take everything on evidence. There's no better rule.”
Charles Dickens, Great Expectations.

The odderon (1)





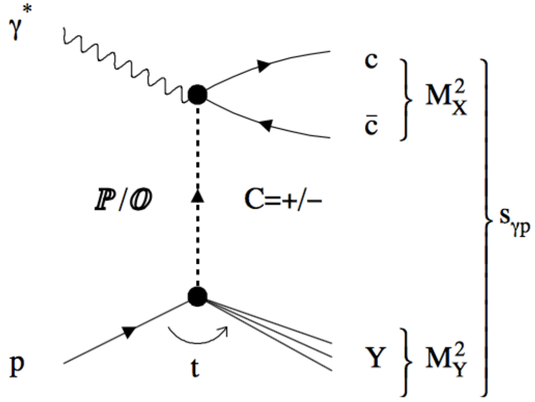
Bzdak, Motyka, Szymanowski, Cudell
PRD 75 (2007) 094023

$d\sigma^{corr}/dy$	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

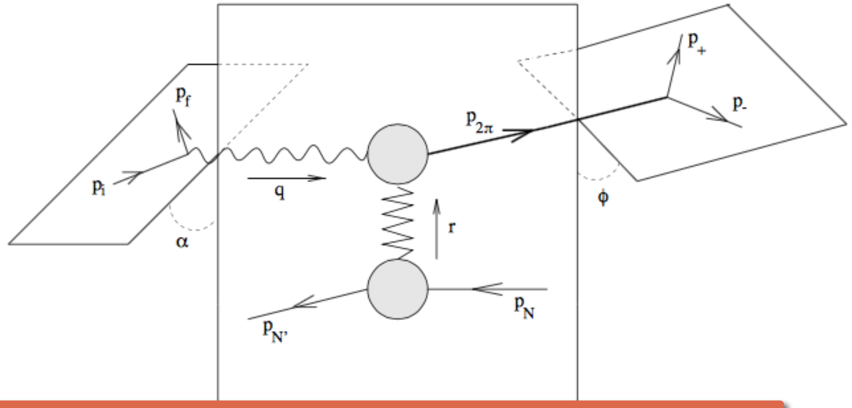
Requires understanding p_T^2 spectrum for proton dissociation (or rejection of it)

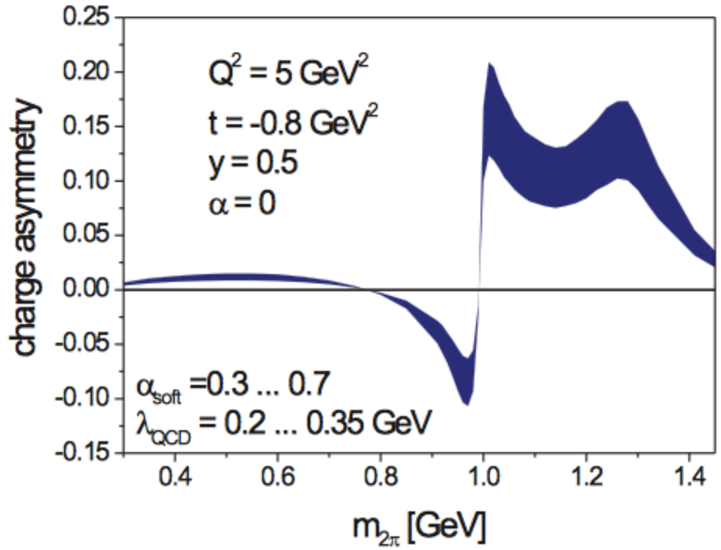
The odderon (2)

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



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

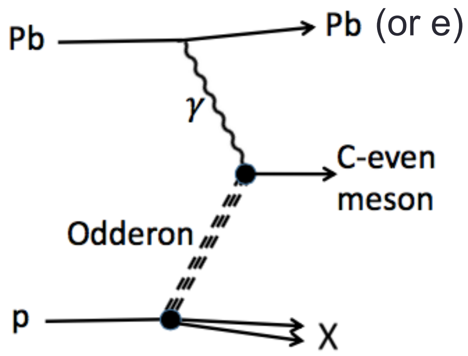




EIC message: Detect outgoing proton

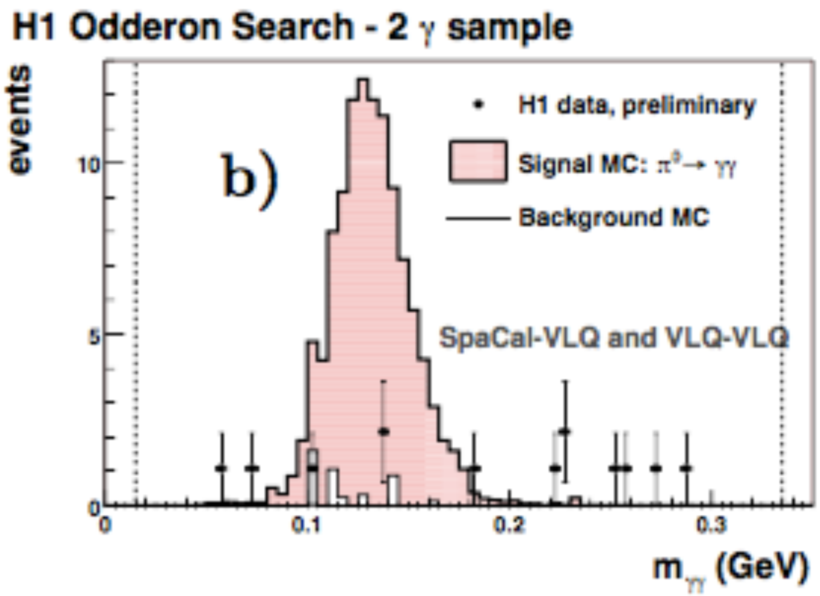
The odderon (3)

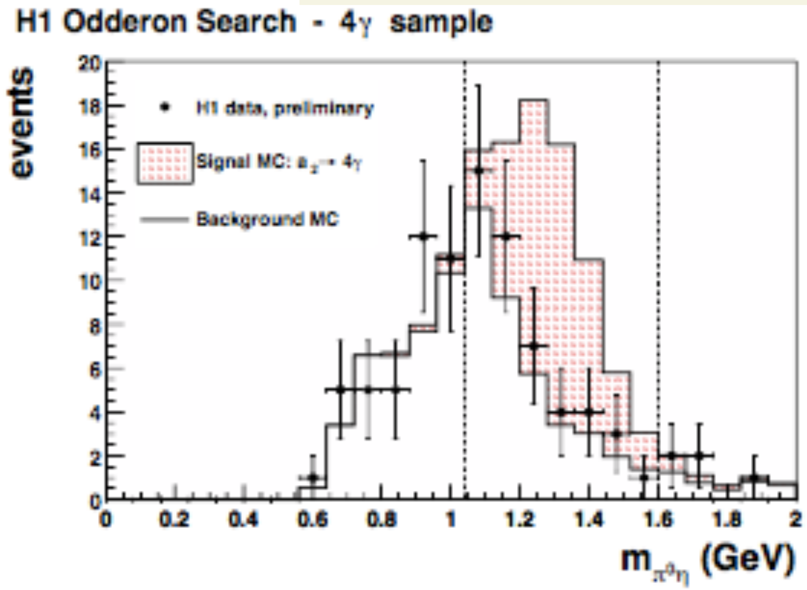
$\gamma p \to \eta p$, $\gamma p \to \pi^0 p$, $\gamma p \to f_2 p$, $\gamma\gamma \to \pi^0\pi^0$



Czyzewski et al., PLB398 (1997) 400.
Berger et al., EPJ C9 (1999) 491.
M.G. Ryskin EPJ C2 (1998) 339.
Kilian & Nachtmann, EPJ C5 (1998) 317.
Harland-Lang et al. arXiv:1811.12705

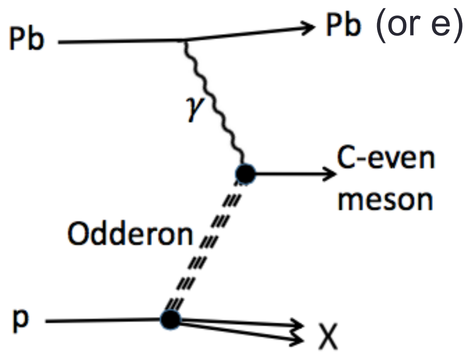
arXiv:hep-ex/0112012





The odderon (4)

$\gamma p \to \eta p$, $\gamma p \to \pi^0 p$, $\gamma p \to f_2 p$, $\gamma\gamma \to \pi^0\pi^0$



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M.G. Ryskin EPJ C2 (1998) 339.
Kilian & Nachtmann, EPJ C5 (1998) 317.
Harland-Lang et al. arXiv:1811.12705

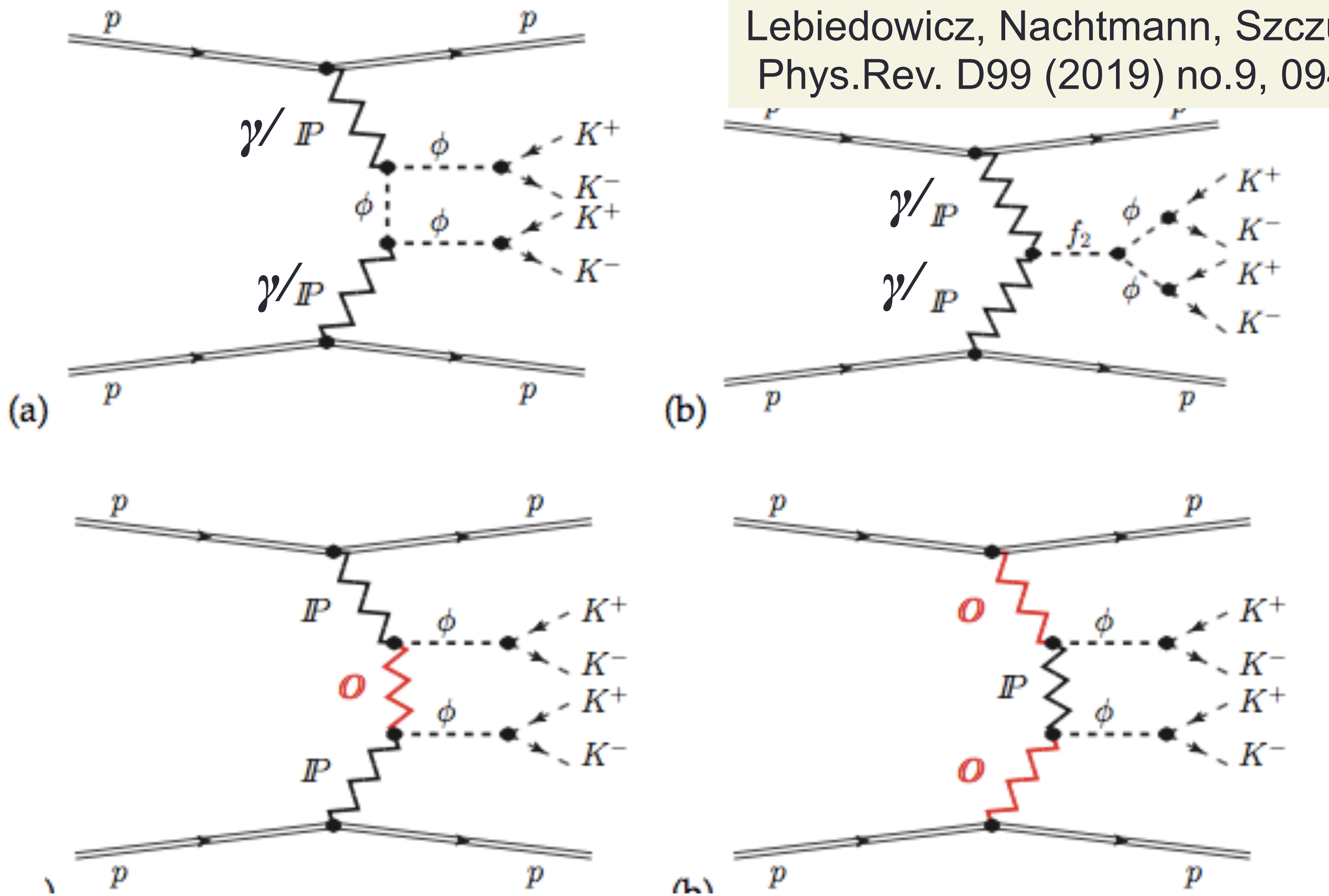
$d\sigma/dy|_{y=0}$ for Pbp collisions (arXiv:1811.12705)

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

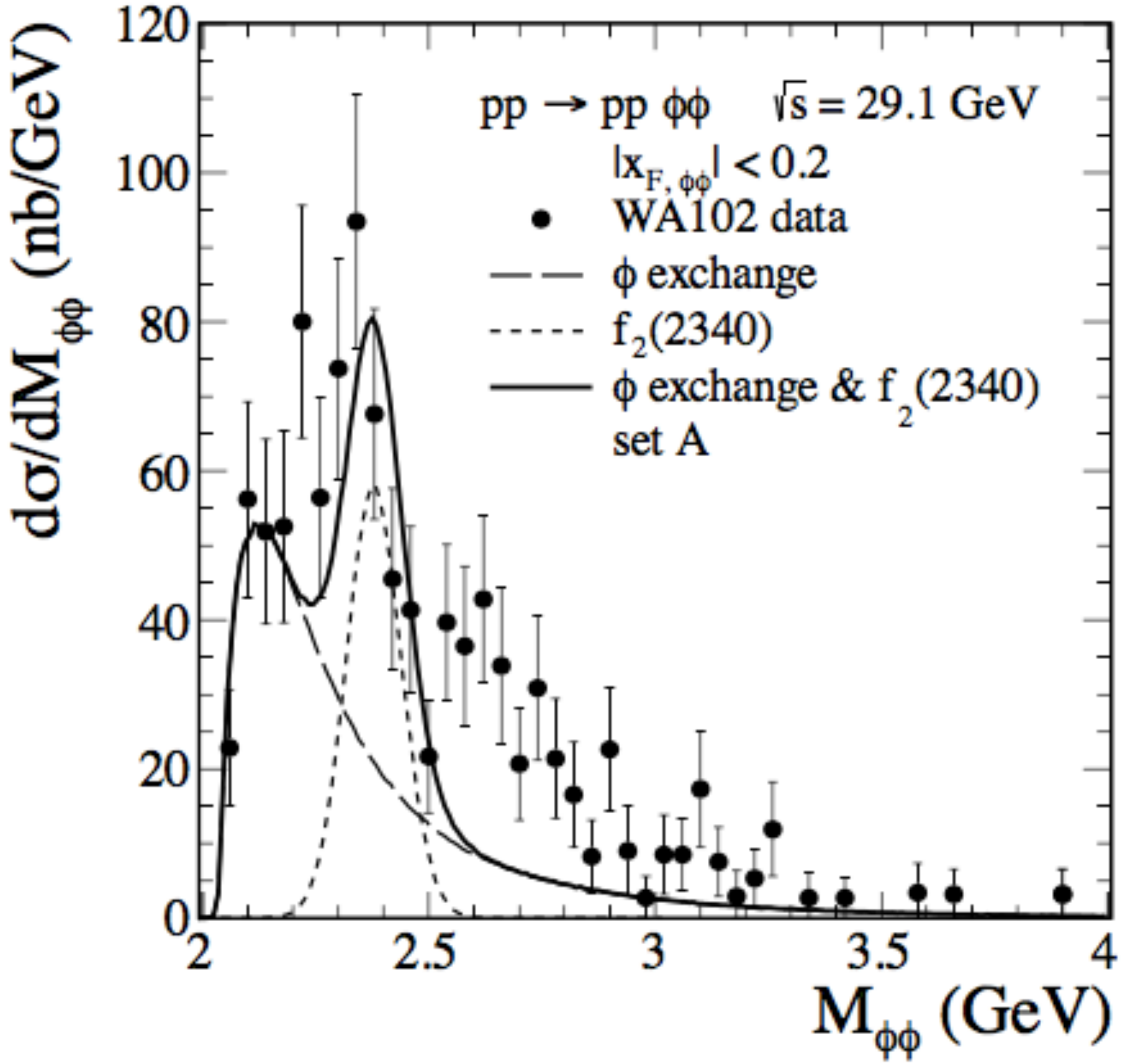
EIC message: Perfect use-case.
High luminosity required.

Tetraquarks, hybrids, glueballs (1)

Lebiedowicz, Nachtmann, Szczurek
Phys.Rev. D99 (2019) no.9, 094034



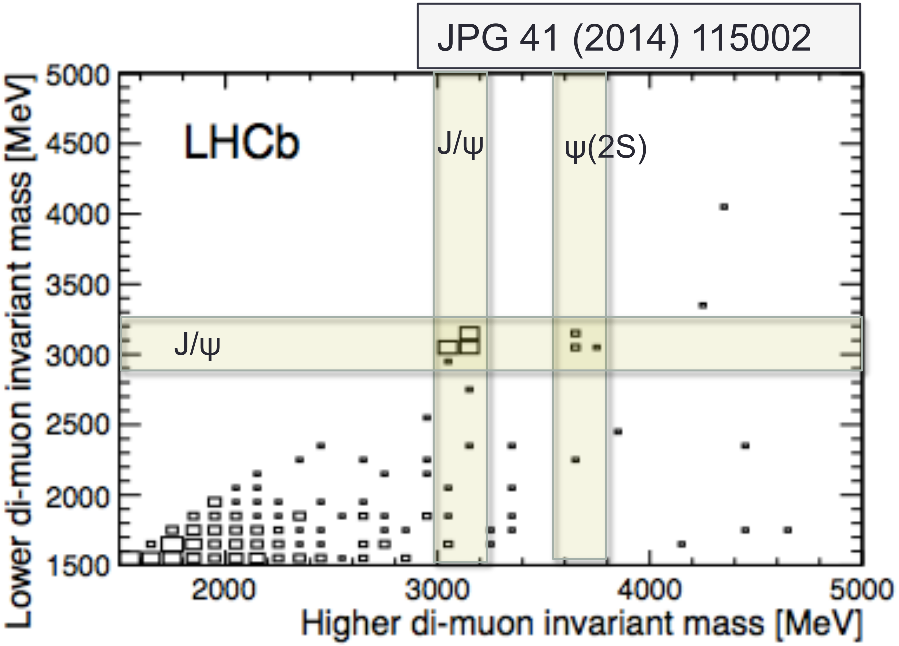
Tetraquarks, hybrids, glueballs (2)

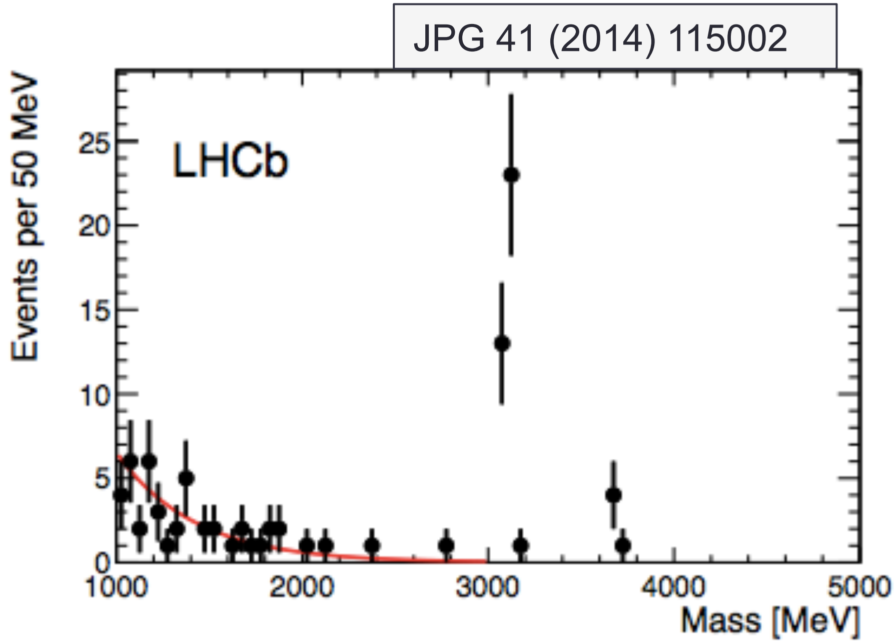


WA102 data
PLB432 (1998) 436,

Model from
Phys.Rev. D99 (2019) no.9, 094034

Tetraquarks, hybrids, glueballs (3)



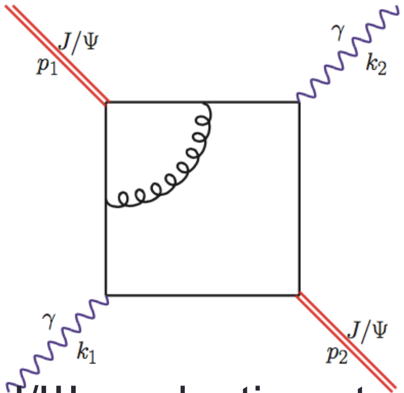


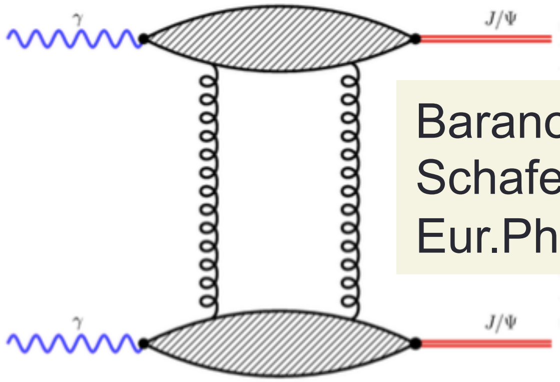
Dimuon spectrum having required other two muons have J/ψ mass

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

Tetraquarks, hybrids, glueballs (4)

Double J/Ψ production studied in γγ collisions

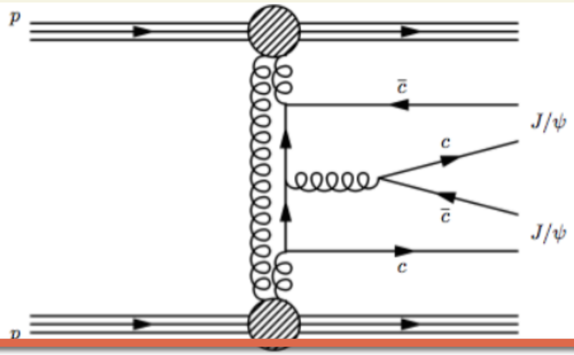


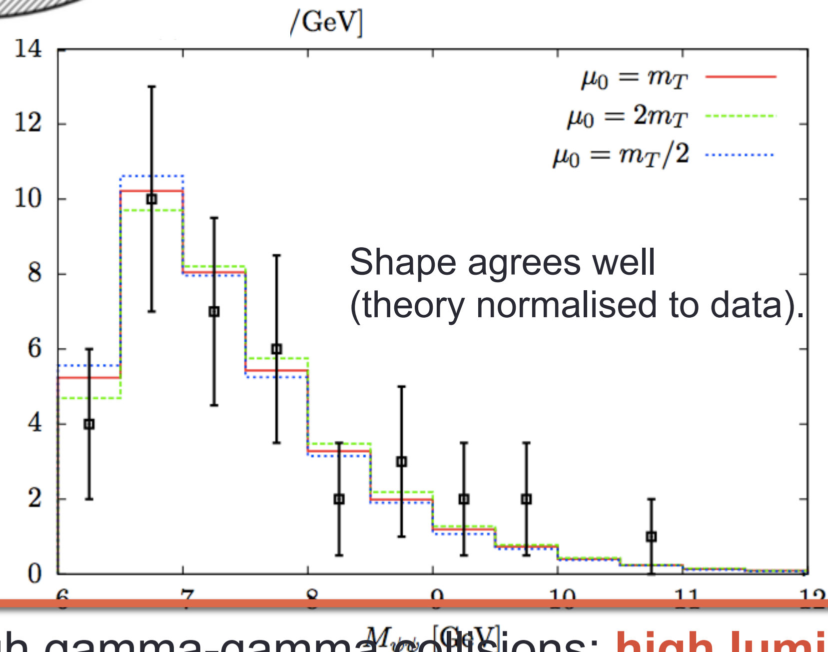


Baranov, Cisek, Klusek-Gawenda, Schafer, Szczurek.
Eur.Phys.J. C73 (2013) no.2, 2335

Double J/Ψ production studied in hadron collisions

Harland-Lang, Khoze, Ryskin,
J.Phys. G42 (2015) no.5, 055001

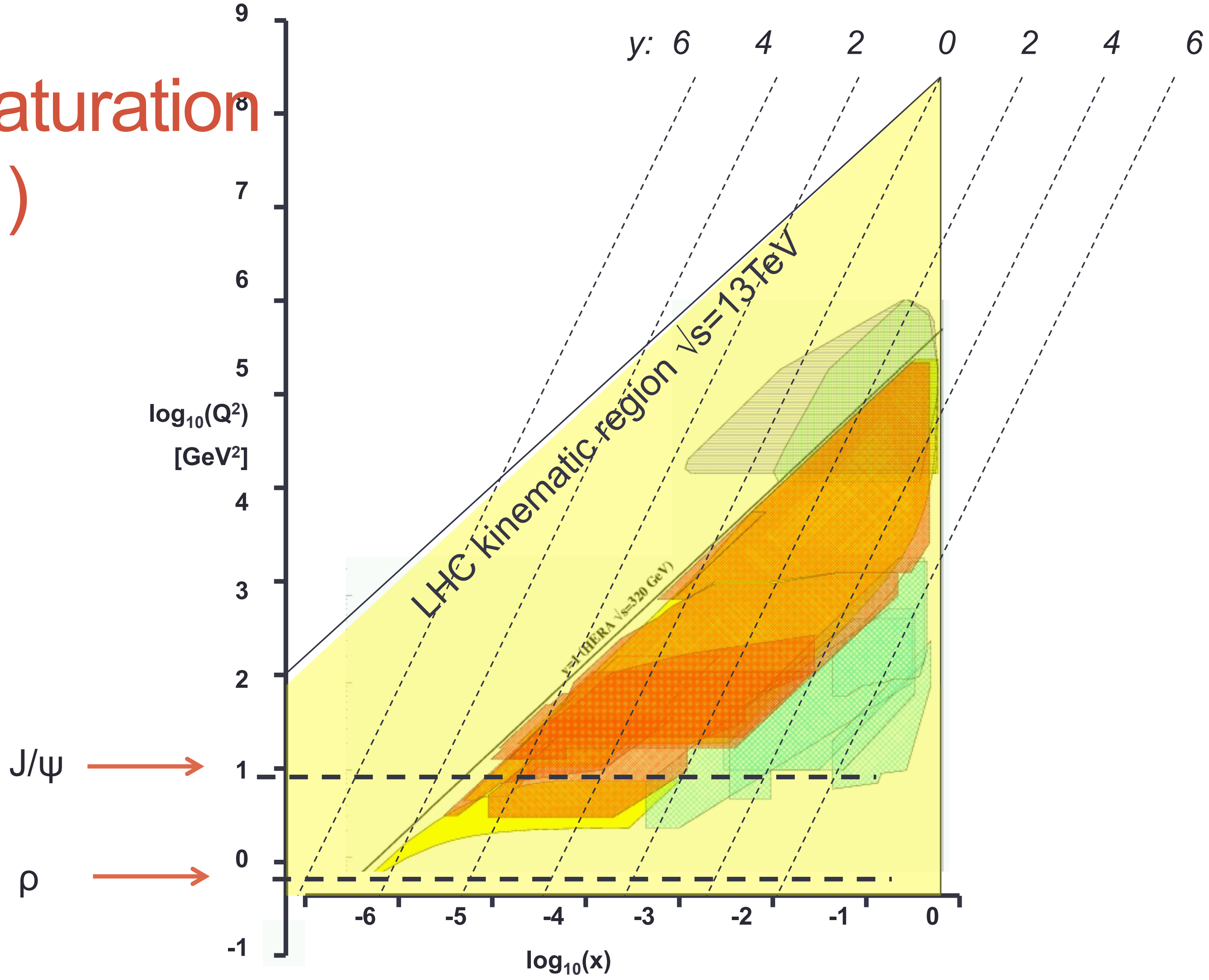




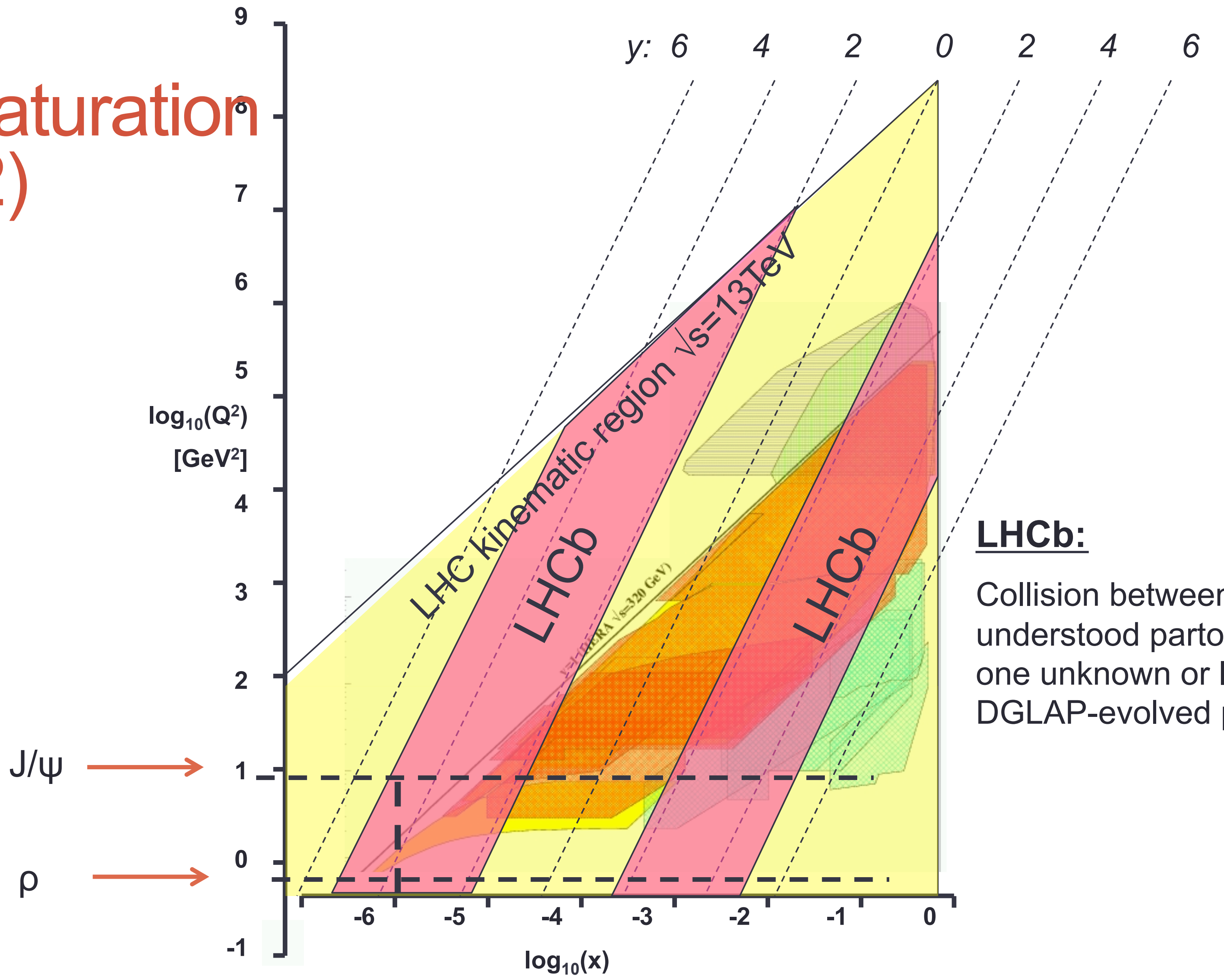
Shape agrees well
(theory normalised to data).

EIC message: Produce such states through gamma-gamma collisions: **high lumi.**

Saturation (1)



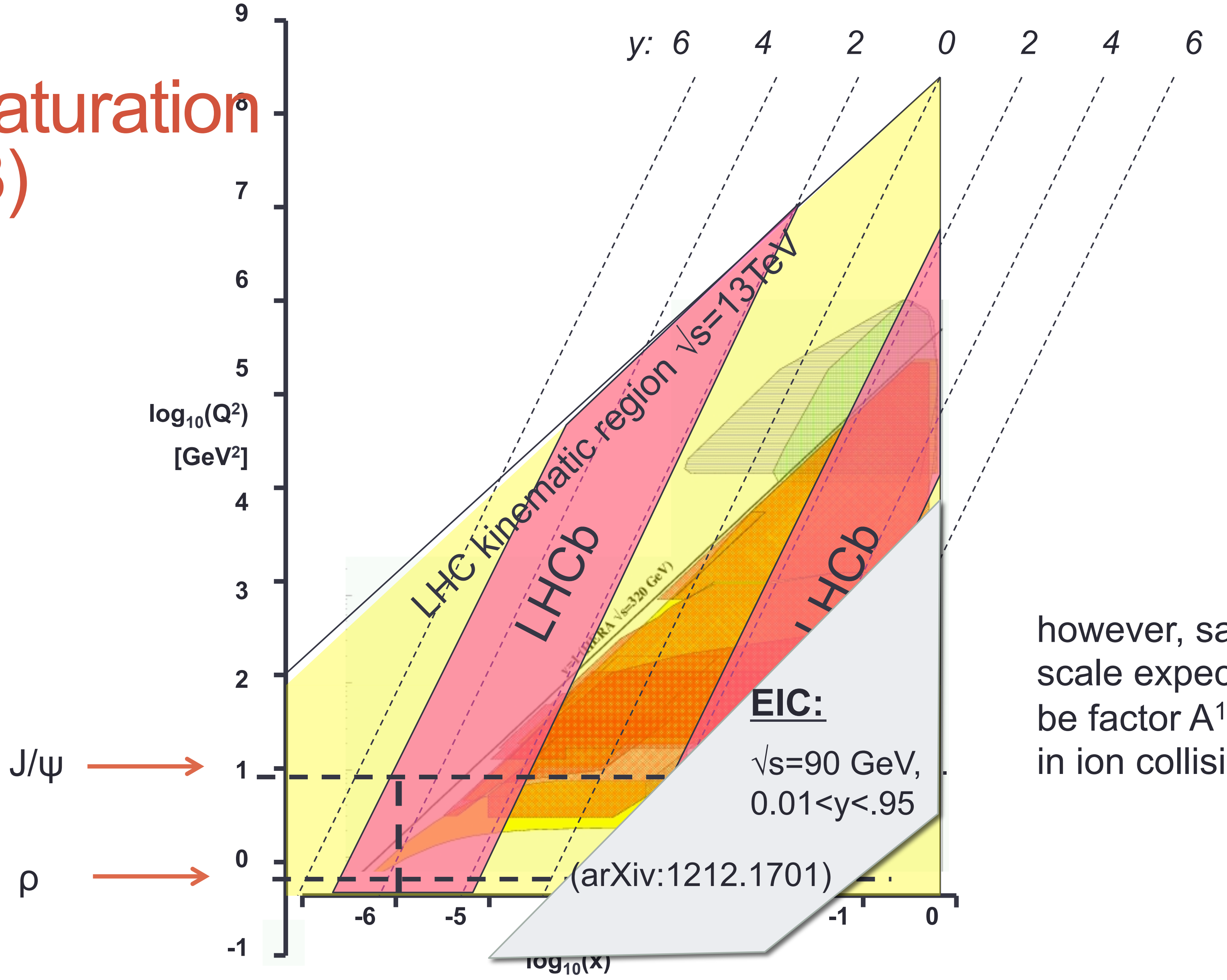
Saturation (2)



LHCb:

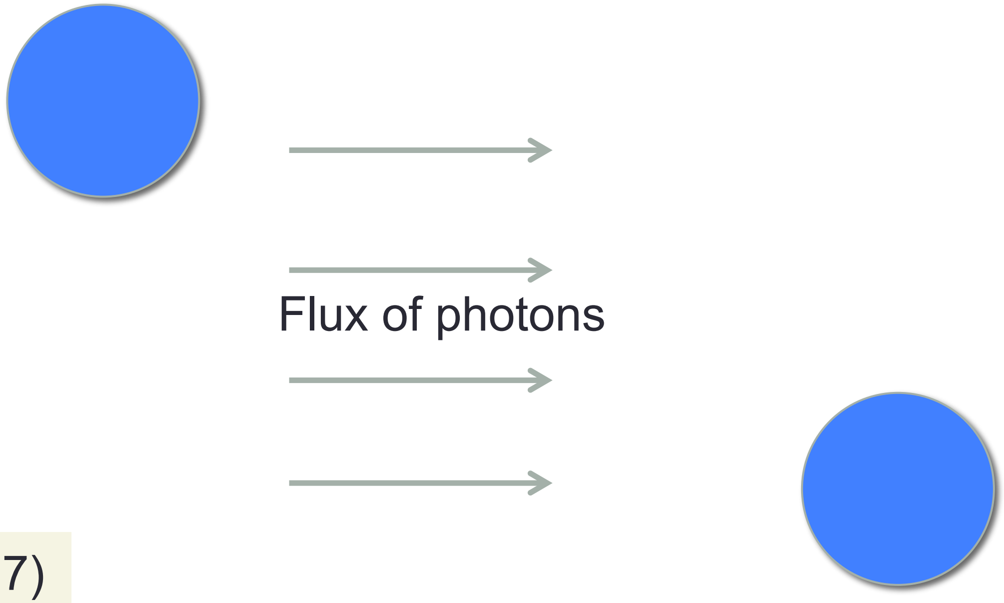
Collision between one well understood parton and one unknown or large DGLAP-evolved parton.

Saturation (3)

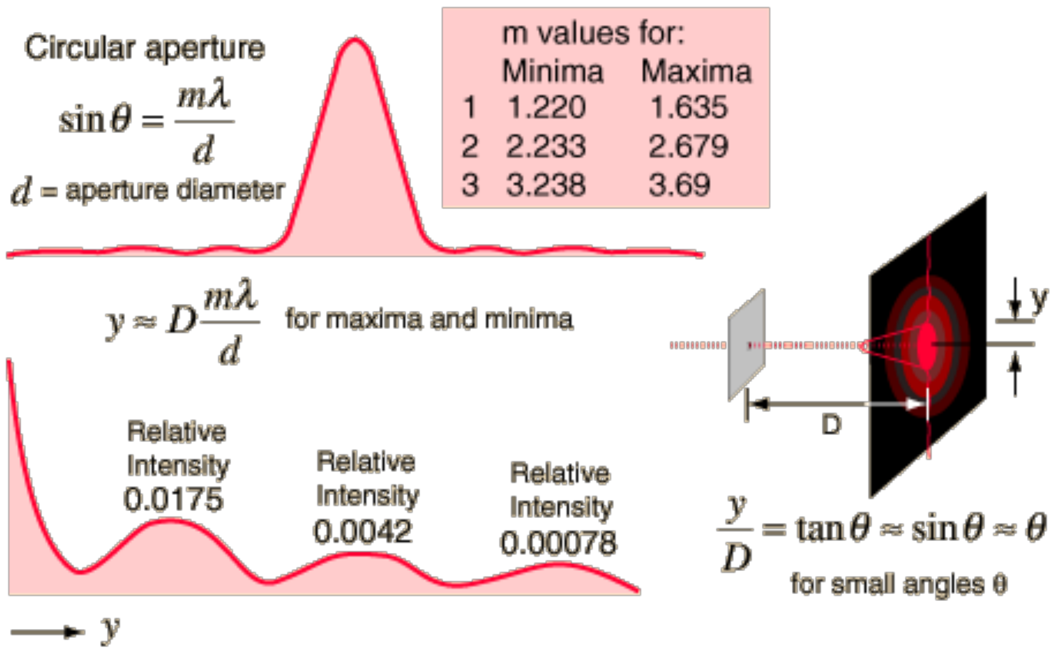


however, saturation scale expected to be factor $A^{1/3}$ larger in ion collisions

Optical diffraction



HyperPhysics (©C.R. Nave, 2017)



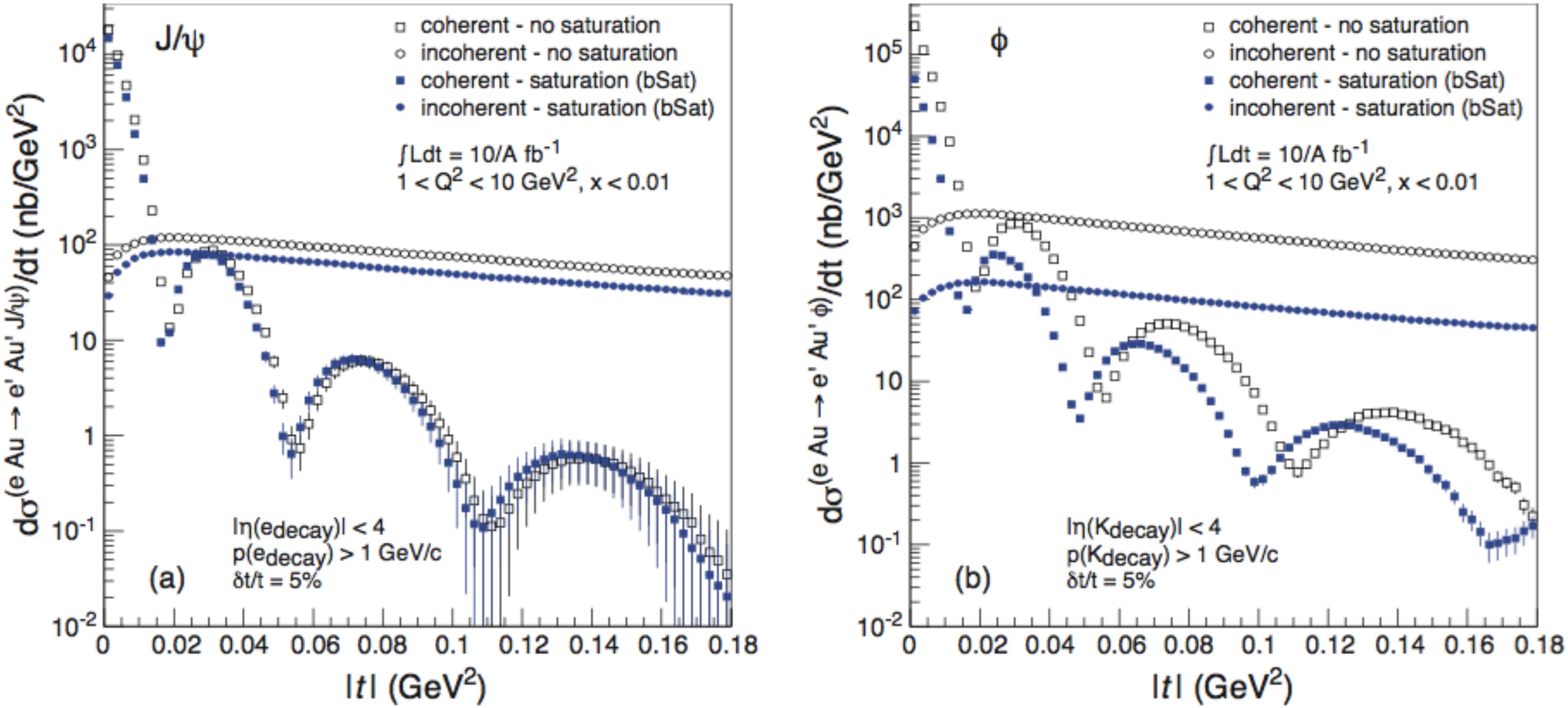
m values for:	Minima	Maxima
1	1.220	1.635
2	2.233	2.679
3	3.238	3.69

Scatter off an object of size 7.1fm
DeBroglie wavelngth 14.2 fm
Momentum =87 MeV

Shape of peak depends on nuclear form factor

Saturation (4)

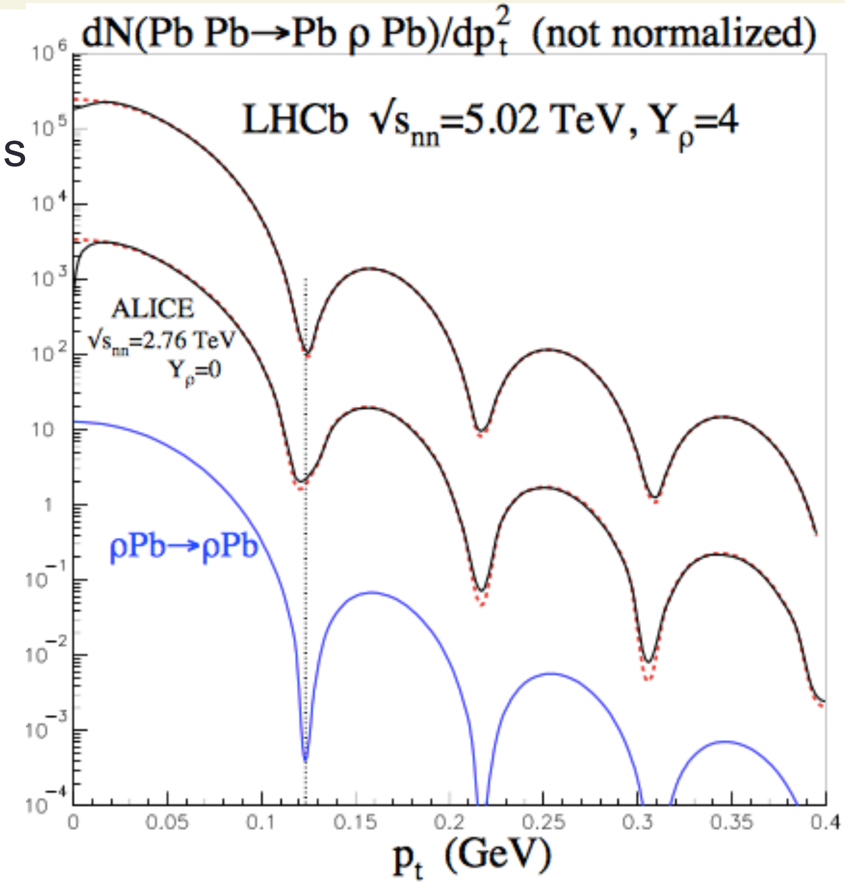
Toll, Ulrich, Phys.Rev. C87 (2013) no.2, 024913



Once again, the ‘smoking gun’ is in the non-perturbative plot.....
Can we separate ‘saturation’ from soft QCD or nuclear effects?

Saturation (5)

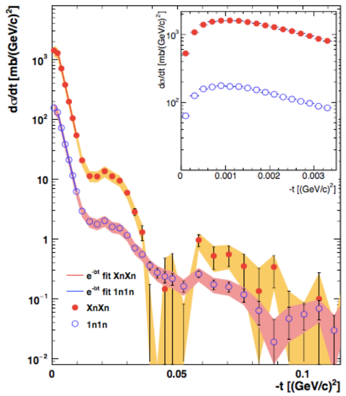
Khoze, Martin, Ryskin, JPG46 (2019) no.8, 085002



Recent prediction for ρ dips in Pb-Pb collisions at LHC (no saturation).

What do saturation predictions look like?

1st (and 2nd?) already seen by STAR



Can be measured at LHC if incoherent backgrounds suppressed.

EIC message (slightly provocative): The forward region of the LHC accesses much lower-x than EIC. If saturation is not found in LHC data, it is unlikely to be found in EIC e-p data.

On the other hand, eA data will have much higher luminosity, less backgrounds than in AA or pA LHC data, and $A^{1/3}$ enhancement.

Summary

- Ultra-peripheral collisions are an excellent place to study QCD, both for a precise understanding of the structure of matter and searches for more exotic phenomena.