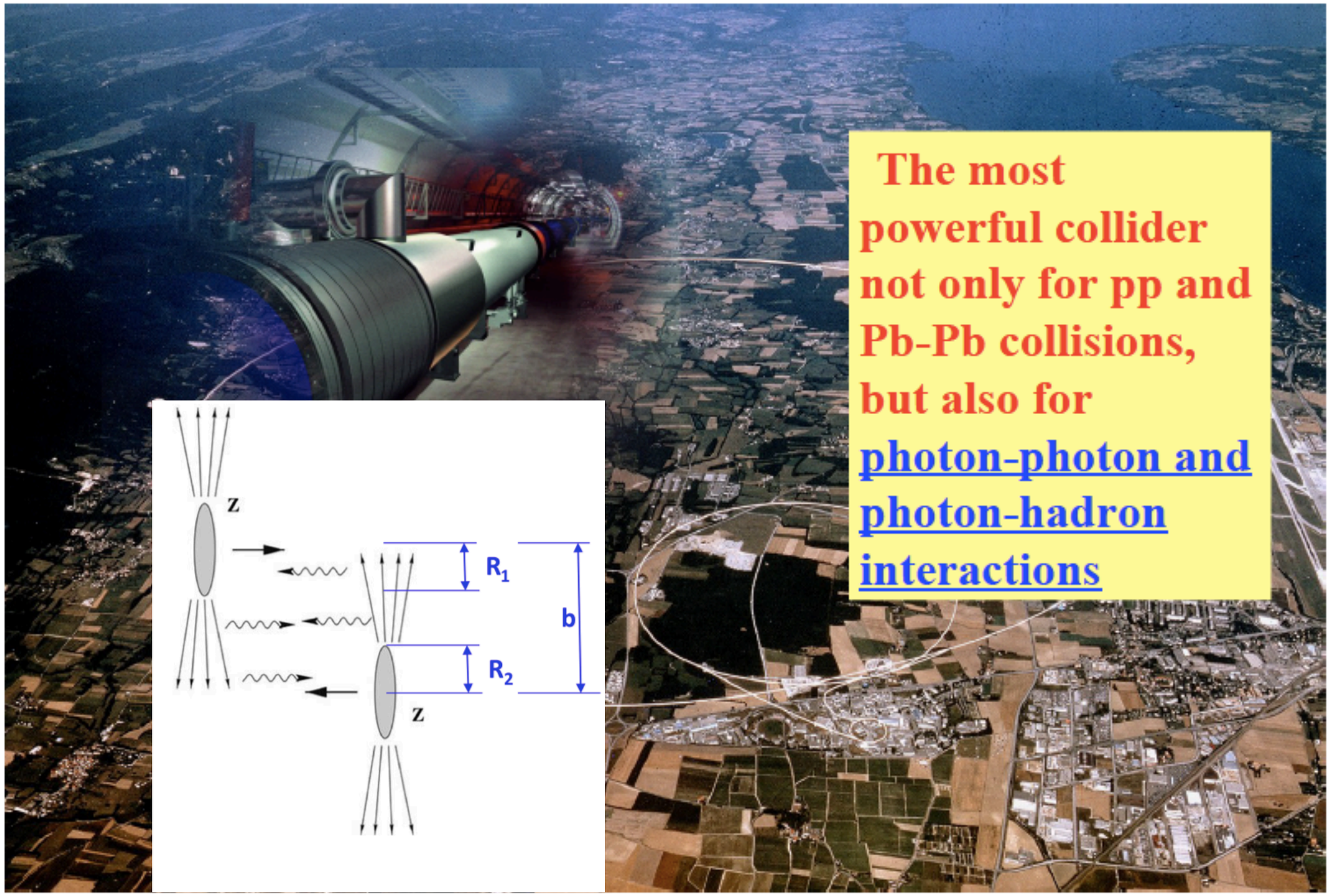
Ultra-peripheral heavy-ion collisions in CMS

Daniel Tapia Takaki
University of Kansas

8th Workshop of the APS Topical Group on Hadronic Physics
Denver, Colorado - April 10-12, 2019

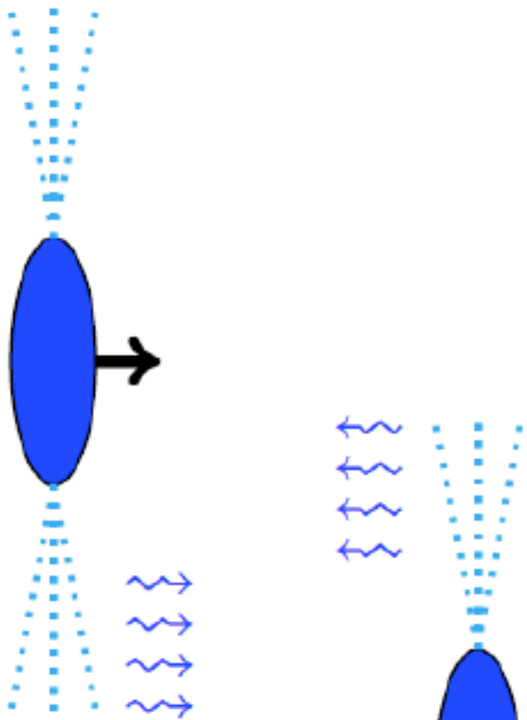
Photon-photon, photon-p, photon-A collider

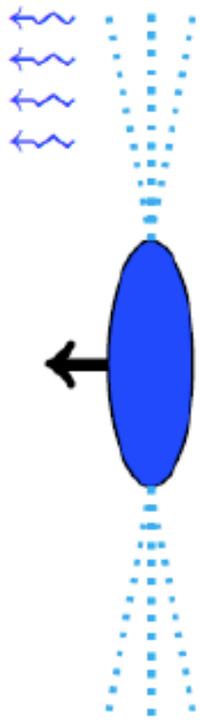


The most powerful collider not only for pp and Pb-Pb collisions, but also for photon-photon and photon-hadron interactions

See talk by P. Steinberg for introduction on UPCs

Ultra-peripheral collisions

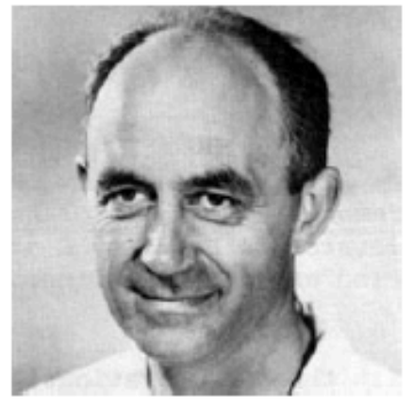




Nuovo Cim.,2:143-158,1925

http://arxiv.org/abs/hep-th/0205086

Therefore, we consider that when a charged particle passes near a point, it produces, at that point, a variable electric field. If we decompose this field, via a Fourier transform, into its harmonic components we find that it is equivalent to the electric field at the same point if it were struck by light with an appropriate continuous distribution of frequencies.



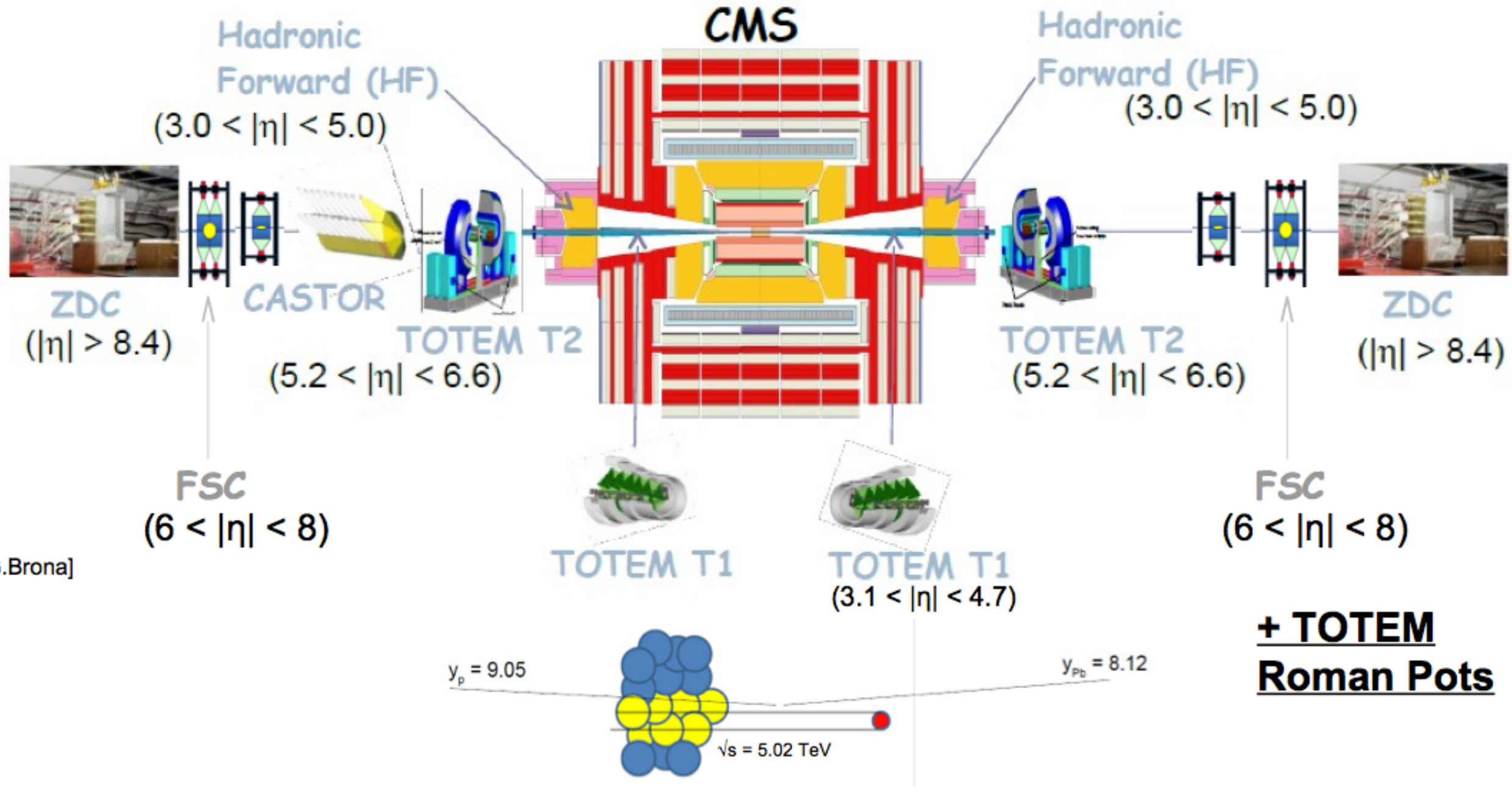
Enrico FERMI

The electromagnetic field surrounding these protons/ions can be treated as a beam of quasi real photons

High photon flux ~ Z^2
→ well described by the Weizsäcker-Williams approximation

Two ions (or protons) pass by each other with impact parameters b > 2R. **Hadronic interactions are strongly suppressed**

UPCs at CMS

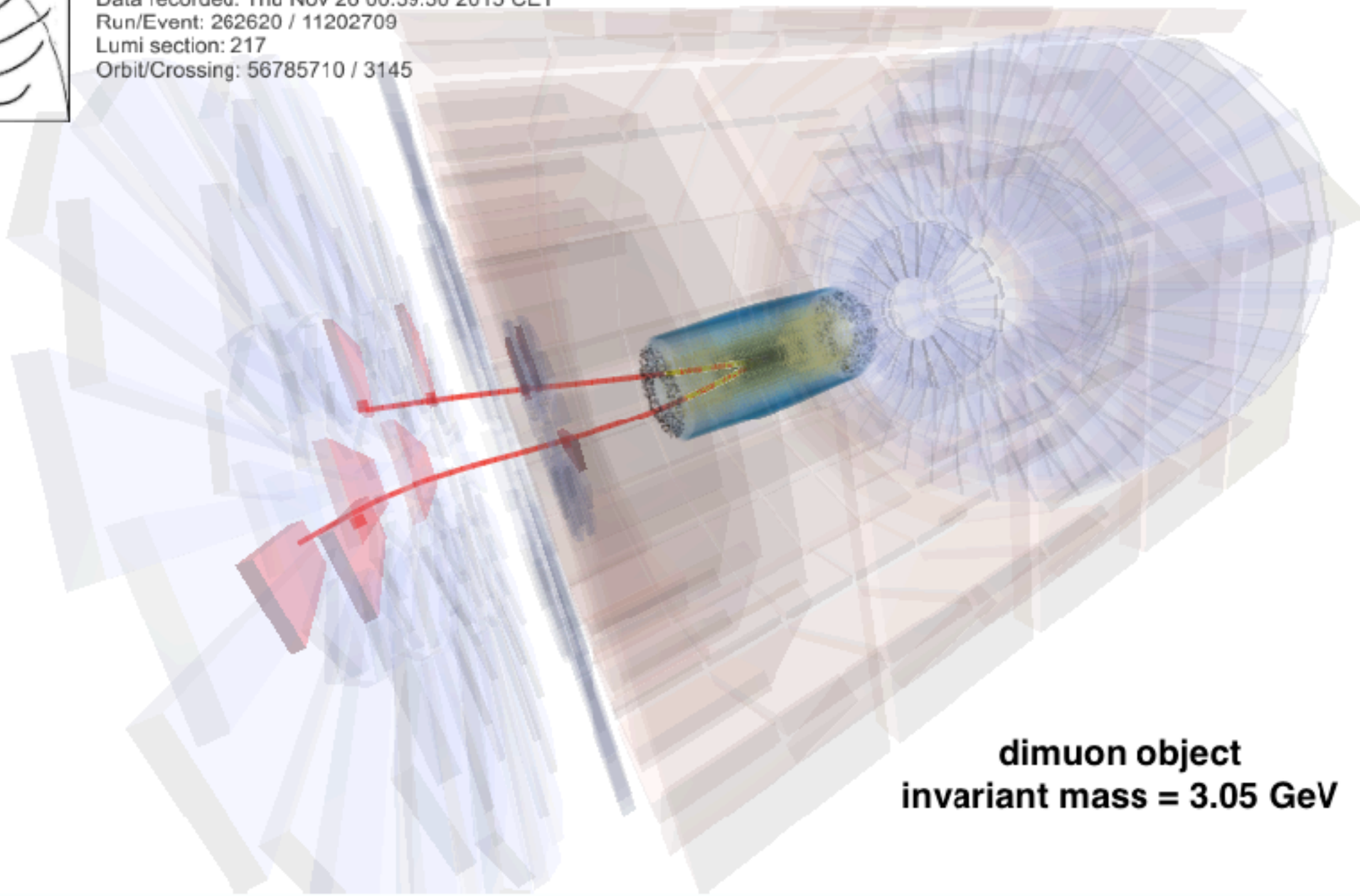


[G.Brona]

+ TOTEM Roman Pots

UPC Upsilon at CMS

CMS Experiment at LHC, CERN
Data recorded: Thu Nov 26 00:39:30 2015 CET
Run/Event: 262620 / 11202709
Lumi section: 217
Orbit/Crossing: 56785710 / 3145

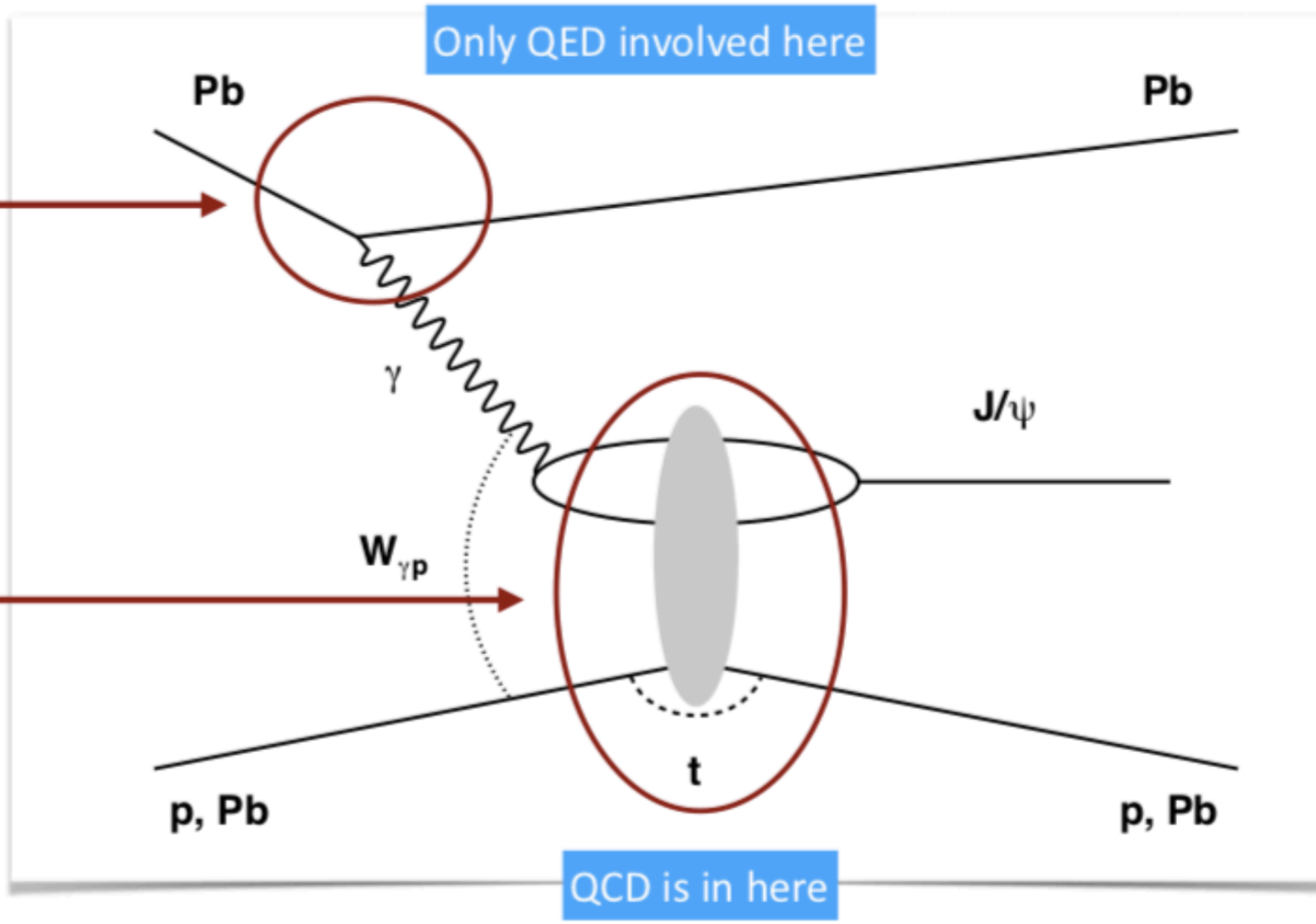


UPC Vector meson photoproduction in **Photon-p**

UPC VM photoproduction

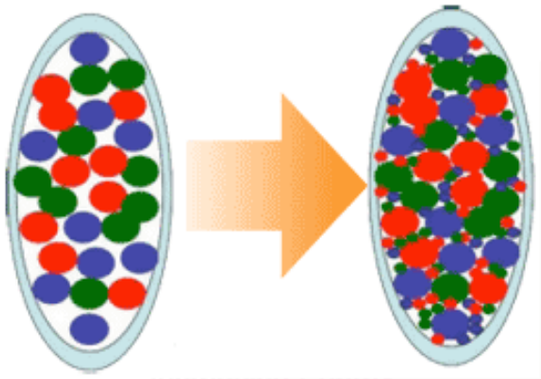
The process can be factorised in two parts:

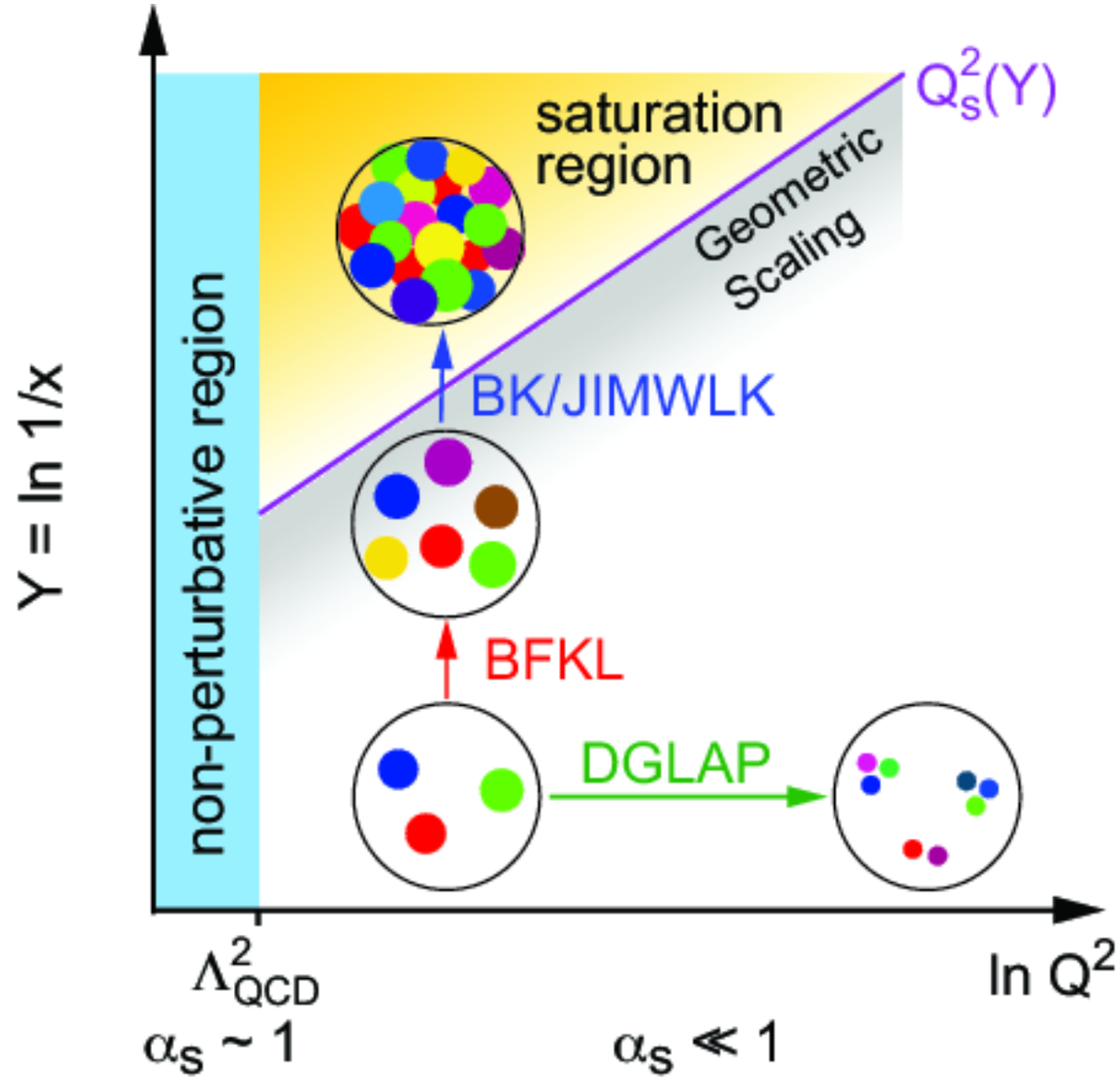
- Emission of the photon.
- Interaction of the photon with the target.



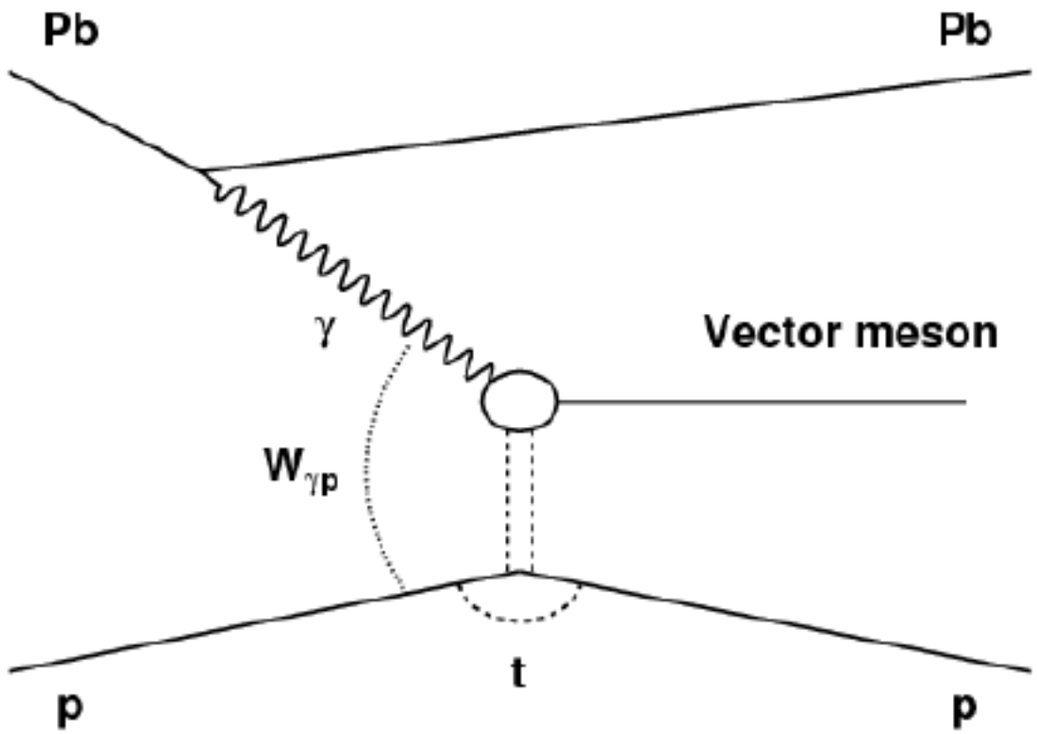
See talks by C. Bertulani and J. Seger for more on UPC VMs

Searching for gluon saturation





Exclusive VM photoproduction

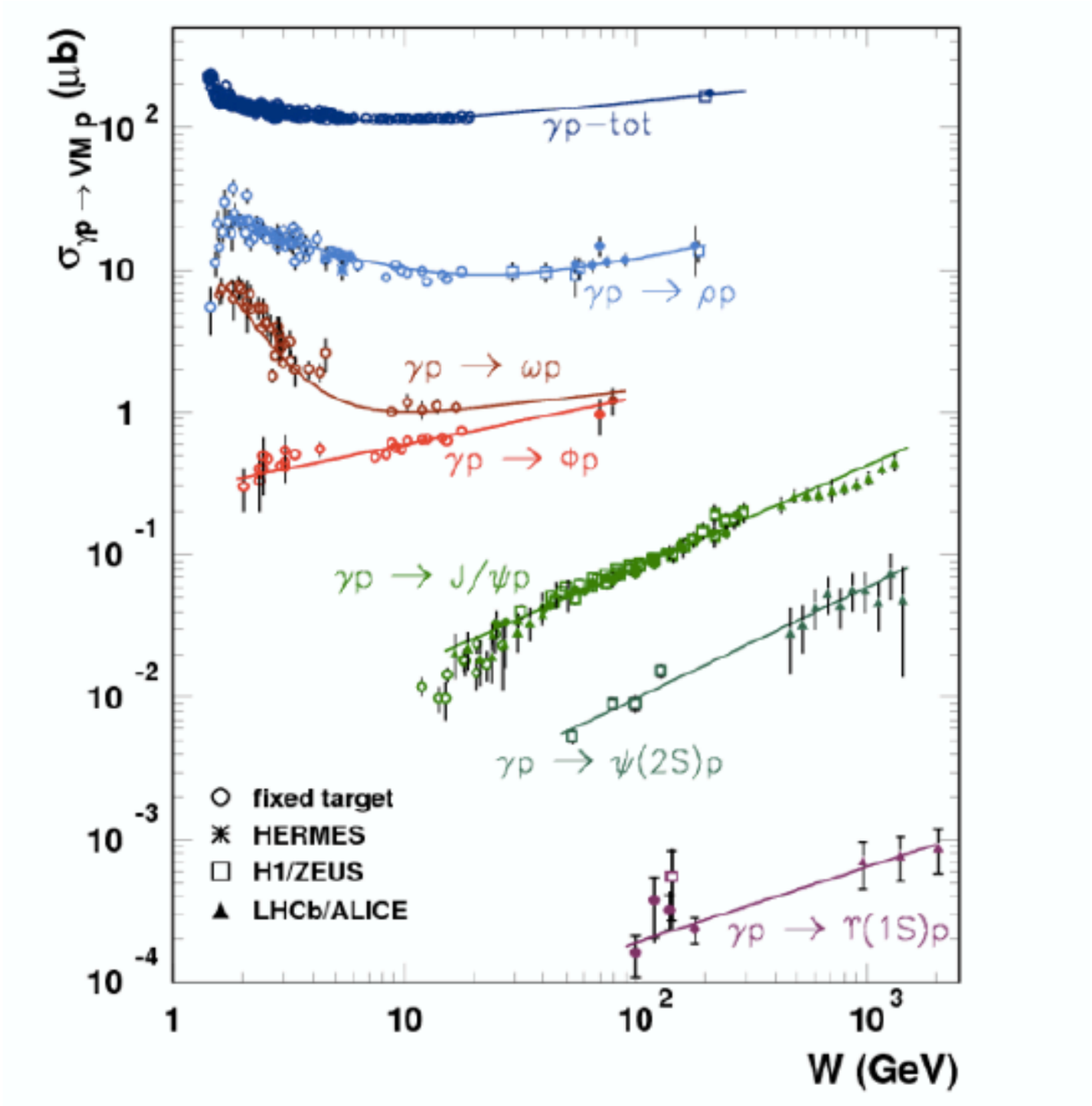


The energy dependance of the cross section

Suggested as a signature of gluon saturation

Exclusive VM photoproduction

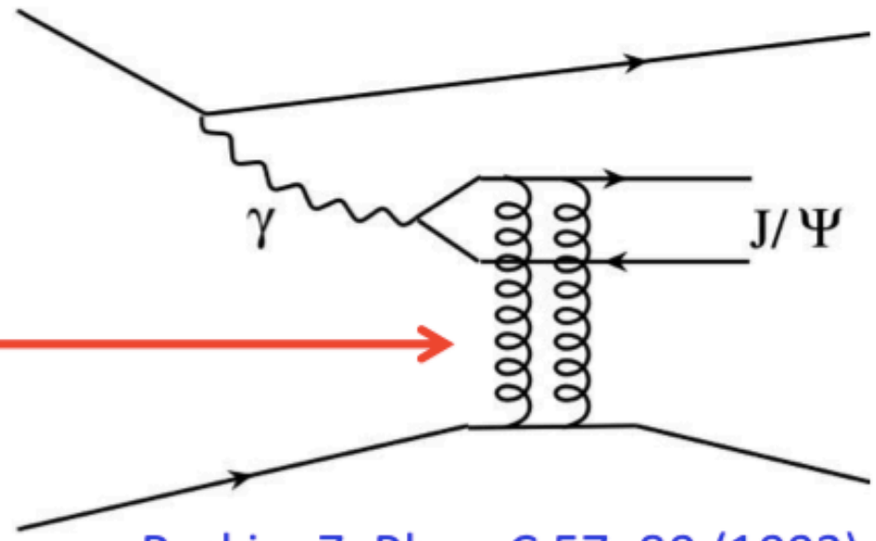
Eur. Phys. J. A52 (2016) no.6, 158



Exclusive VM photoproduction

- LO pQCD: exclusive J/ψ photoproduction cross section is proportional to the **square of the gluon density in the target**:

$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M_{J/\psi}^3\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{\rm em}Q^8}\left[xg_A(x,Q^2)\right]^2$$



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

- J/ψ mass serves as a hard scale:

$$Q^2 \sim \frac{M_{J/\psi}^2}{4} \sim 2.5\ \mathrm{GeV}^2$$

- Bjorken x ~ 10^{-2} – 10^{-5} accessible at LHC:

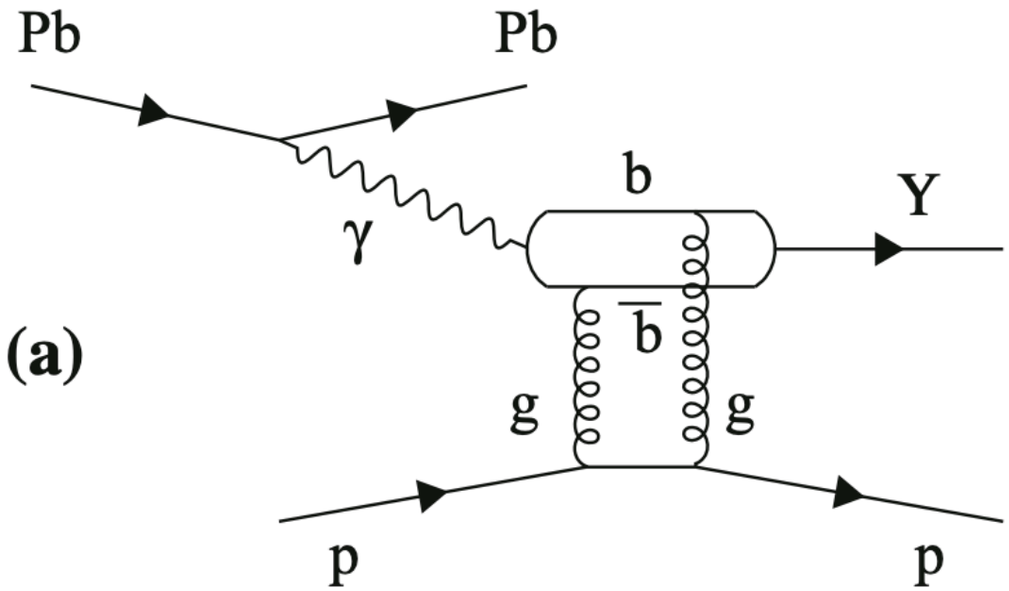
$$x = \frac{M_{J/\psi}^2}{W_{\gamma p}^2} = \frac{M_{J/\psi}}{2E_p}\exp(\pm y)$$

See ALICE talk by J. Seger

Exclusive Upsilon in γp

Eur. Phys. J. C 79 (2019) 277

Exclusive Upsilon photoproduction

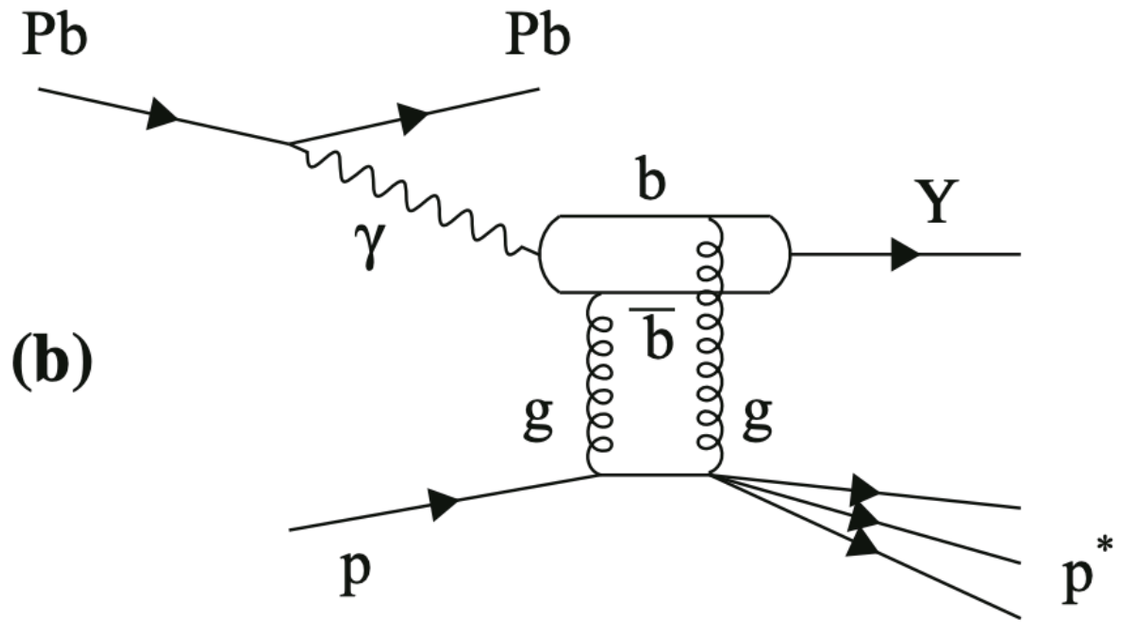


(a)

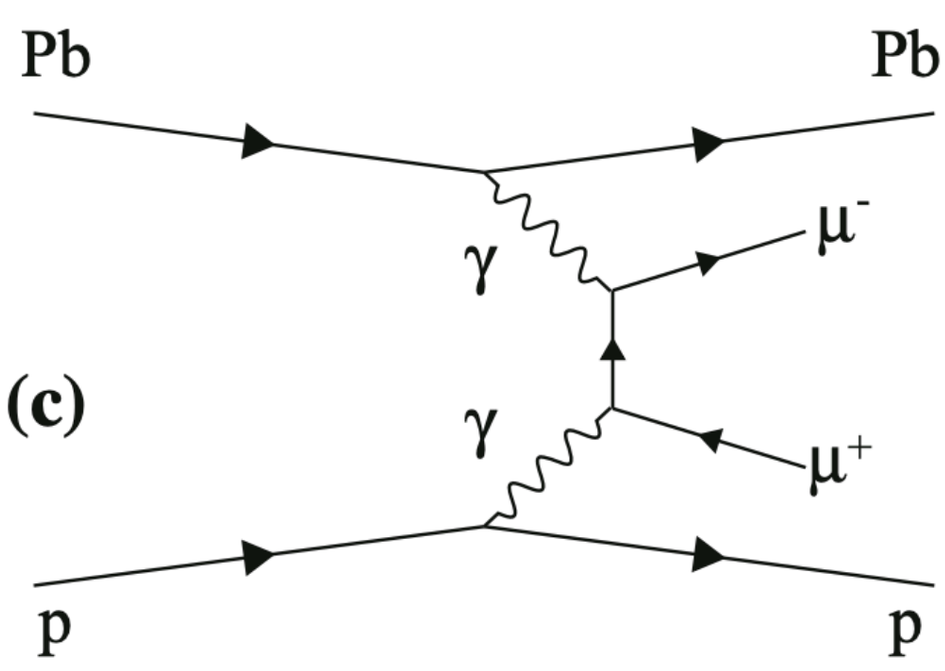
Exclusive Upsilon in γp

Eur. Phys. J. C 79 (2019) 277

Proton dissociation

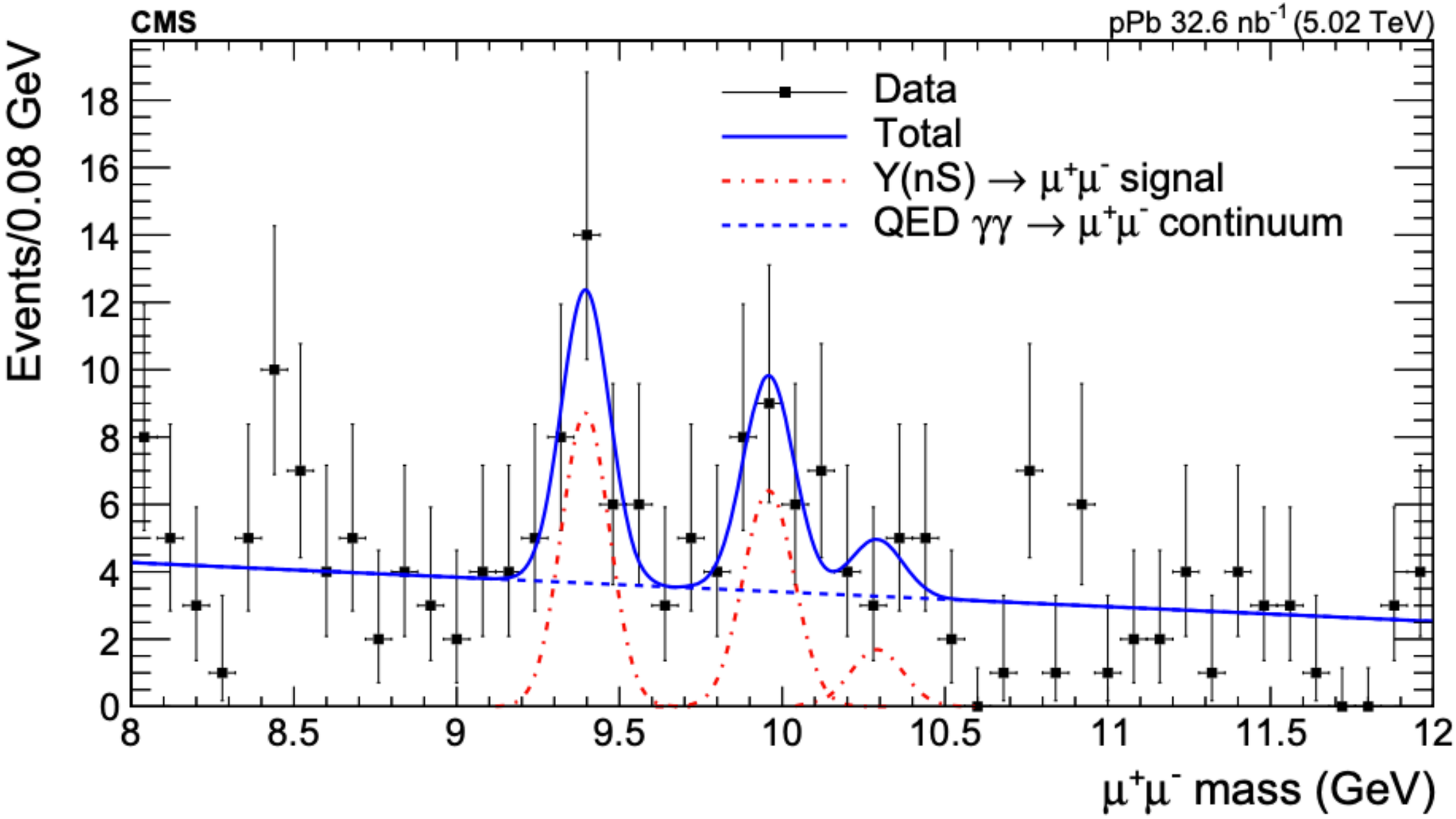


Two-photon process



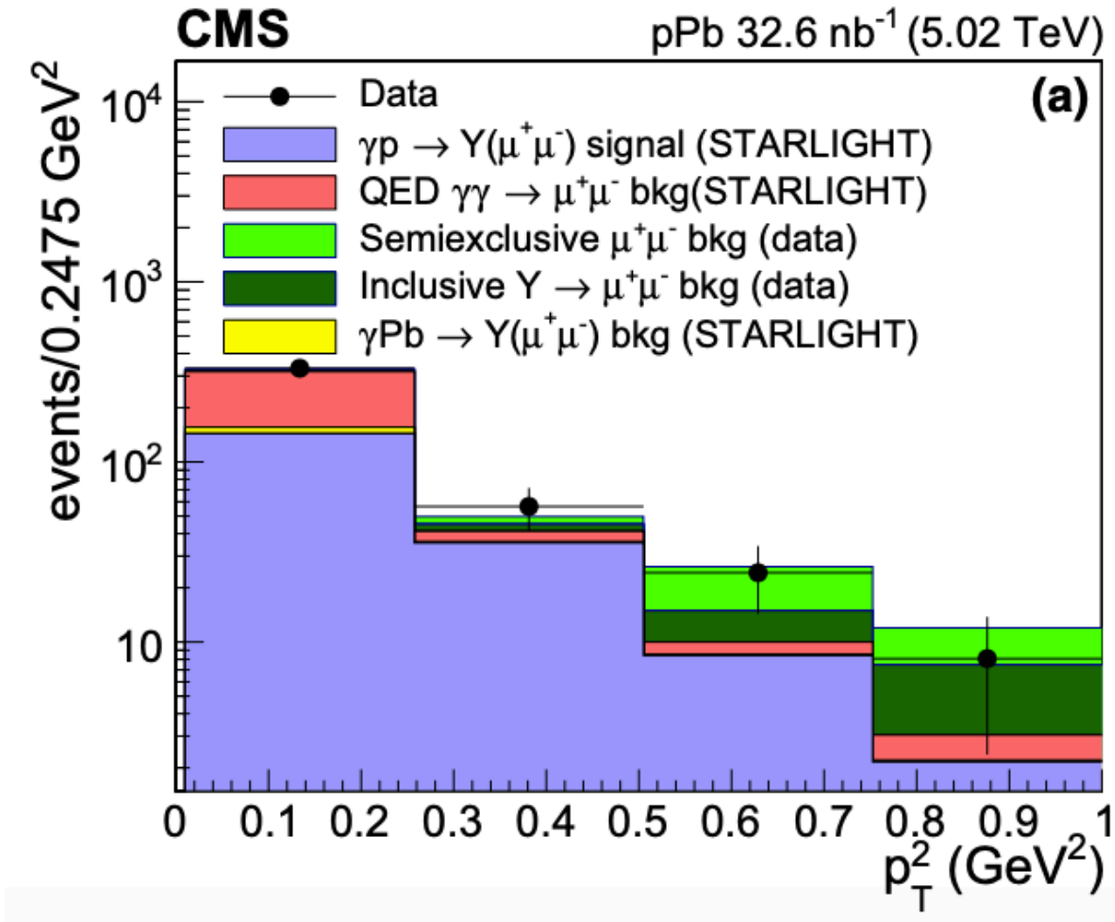
Exclusive Upsilon in γp

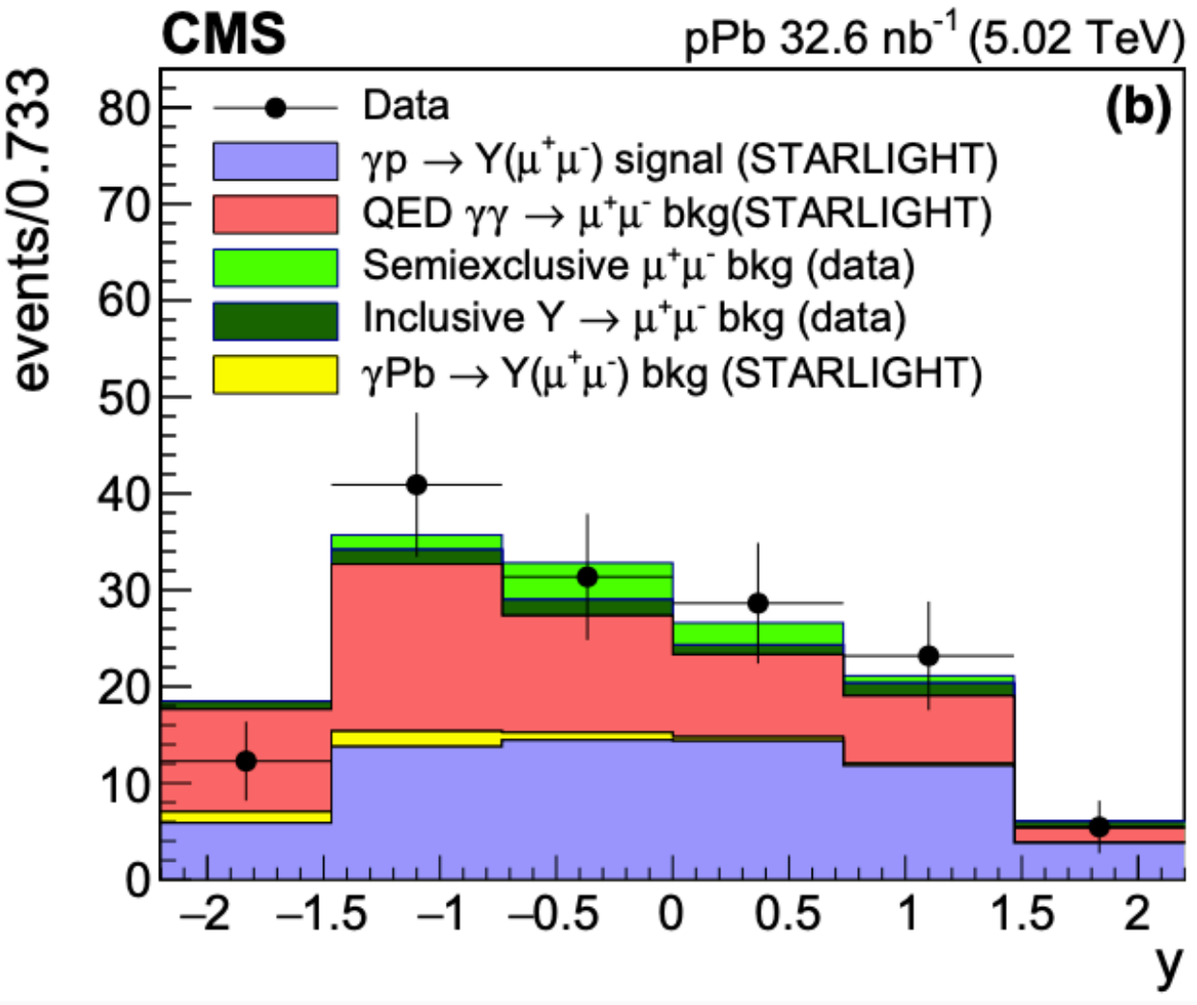
Eur. Phys. J. C 79 (2019) 277



Exclusive Upsilon in γp

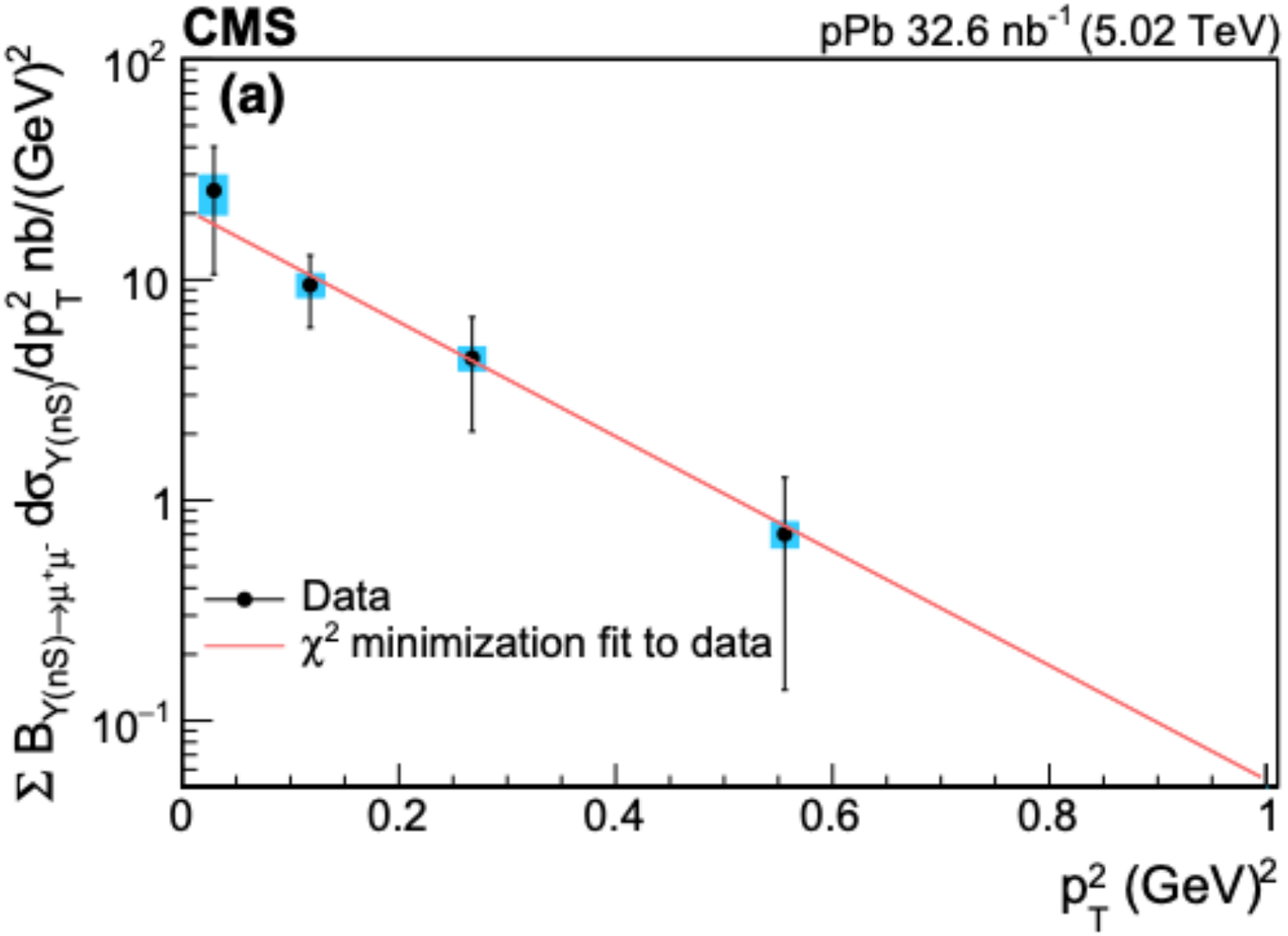
Eur. Phys. J. C 79 (2019) 277





Exclusive Upsilon in γp

Eur. Phys. J. C 79 (2019) 277



Exclusive Upsilon in γp

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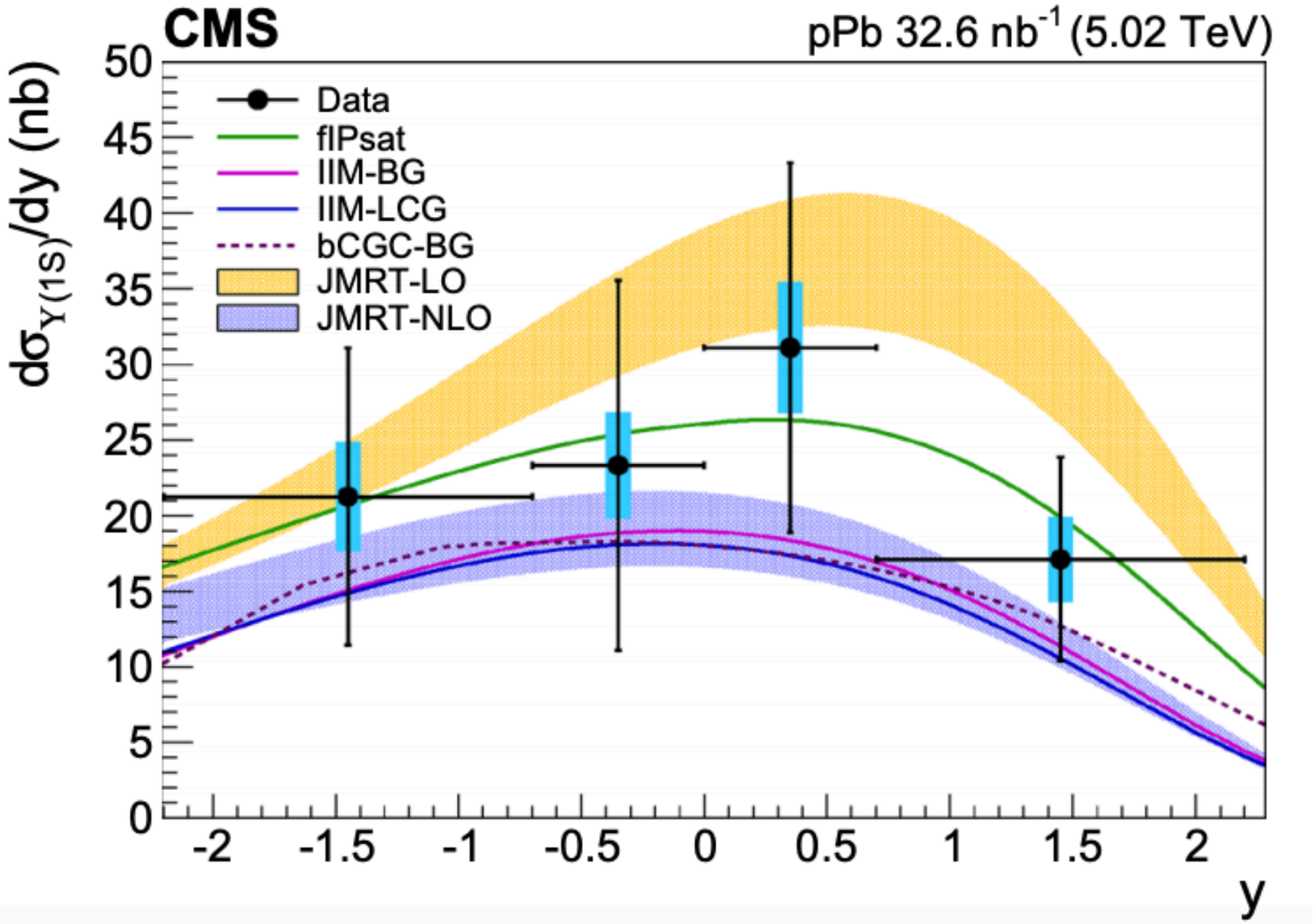

Exclusive Upsilon in γp

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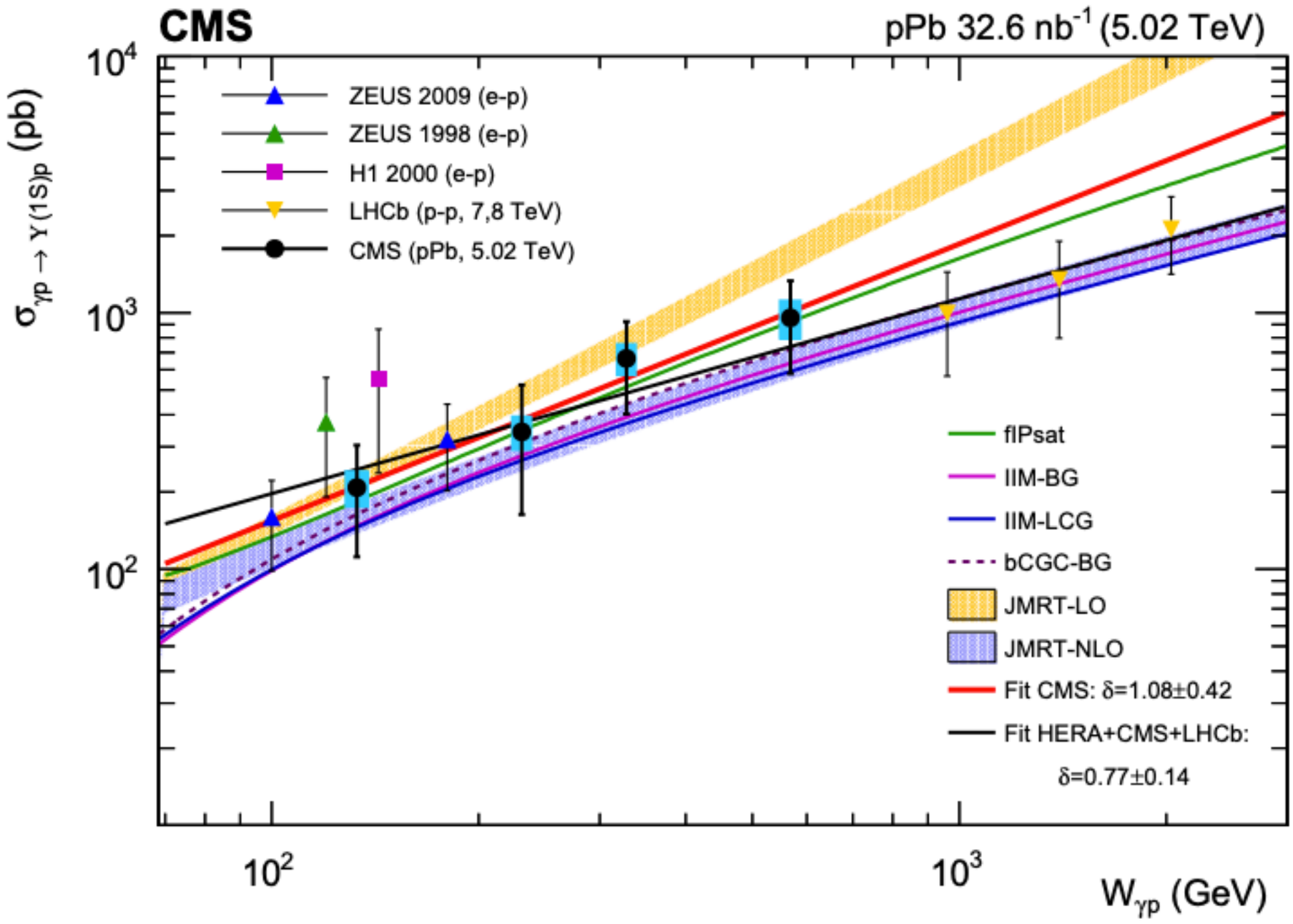
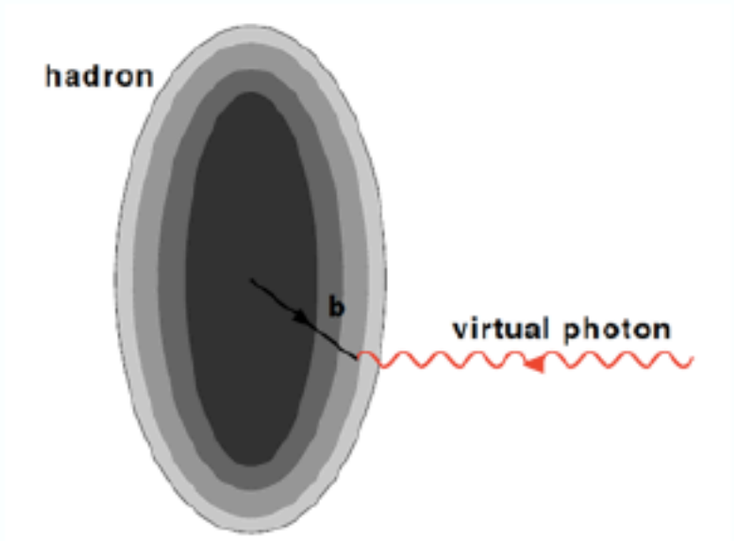


t-distribution

- t-differential measurements give a gluon tranverse mapping of the hadron/ nucleus.

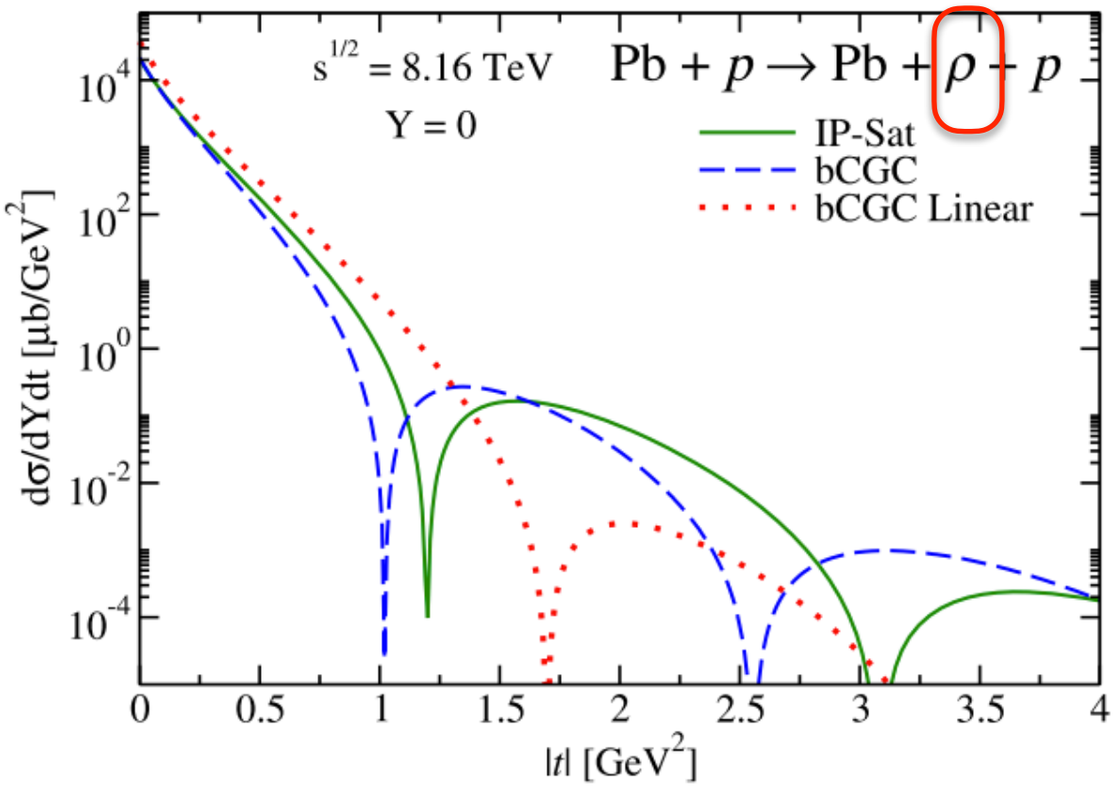


The study of the t-distribution
discussed in documents of the U.S.-based EIC and LHeC

Appearance and location of diffractive dips: signature of gluon saturation

t-distribution
Exclusive VM in γp

V. Goncalves, et al.
Phys. Lett. B791 (2019) 299-304



Location of the Diffractive dips:
Different for IP-Sat and bCGC

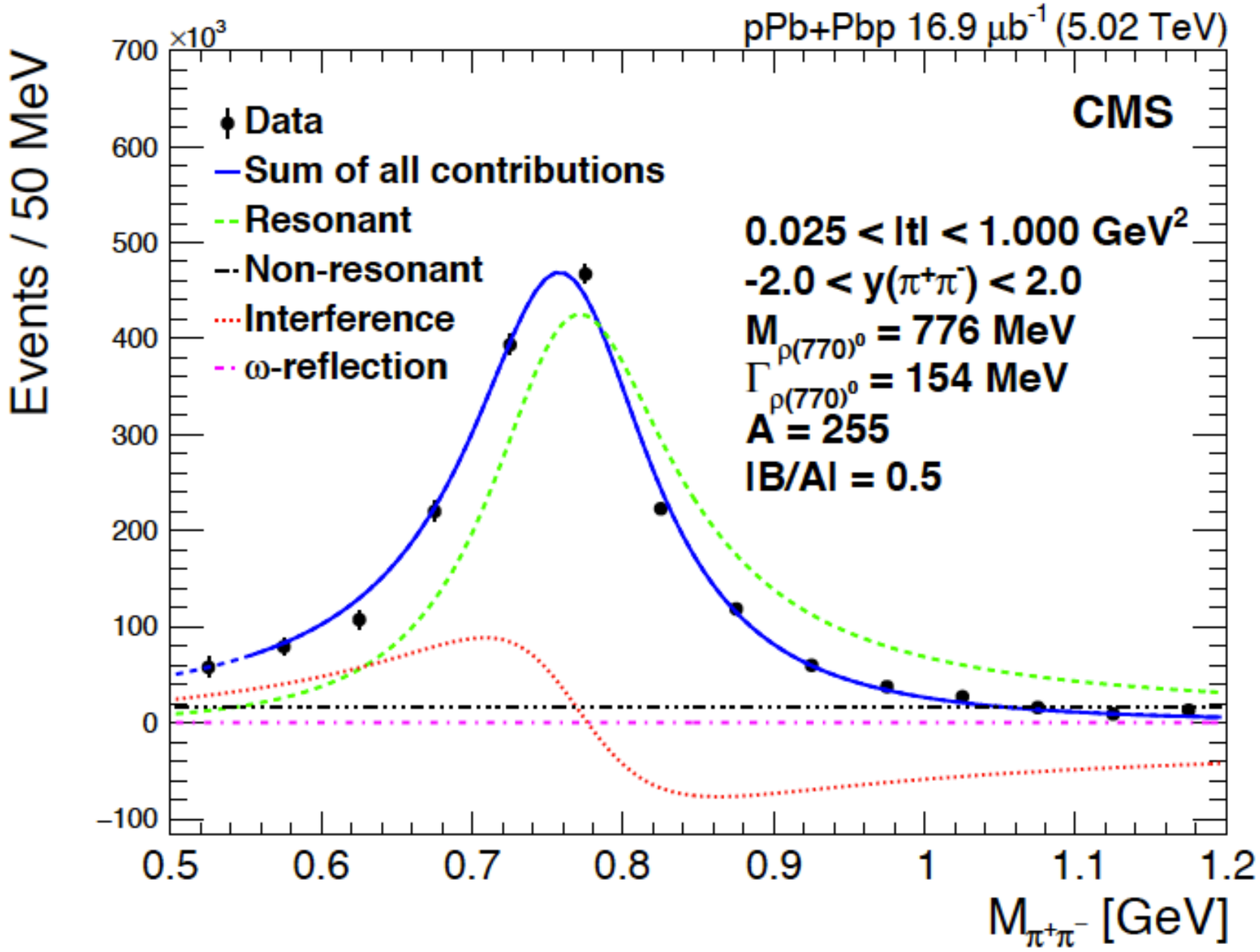
Energy dependence of the
t-distribution: onset of gluon saturation

Signature of gluon saturation

Study of ρ^0 is very promising since diffractive dips expected at lower t values

Exclusive ρ^0 in γp

arXiv:1902.01339
Submitted to EPJ C



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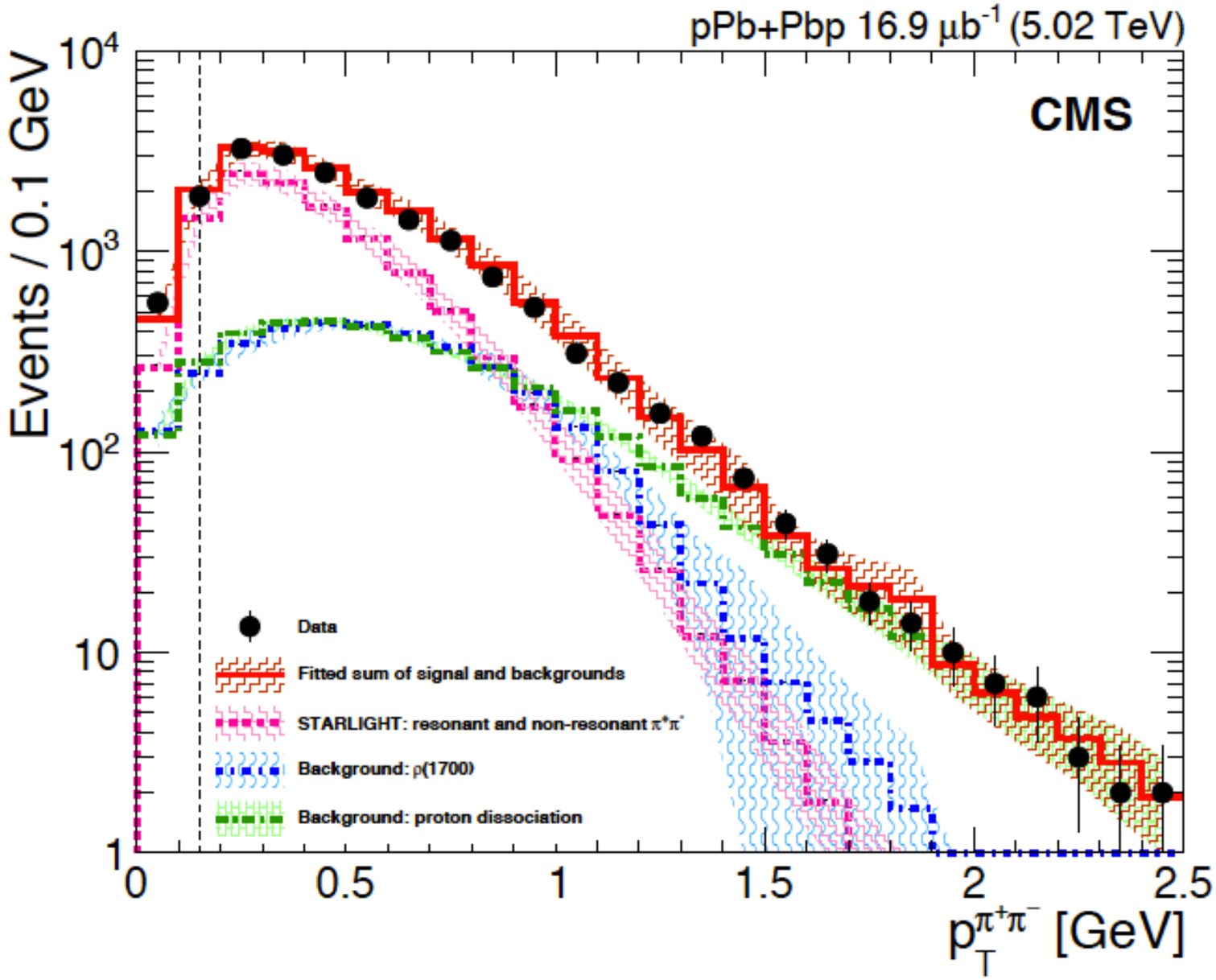

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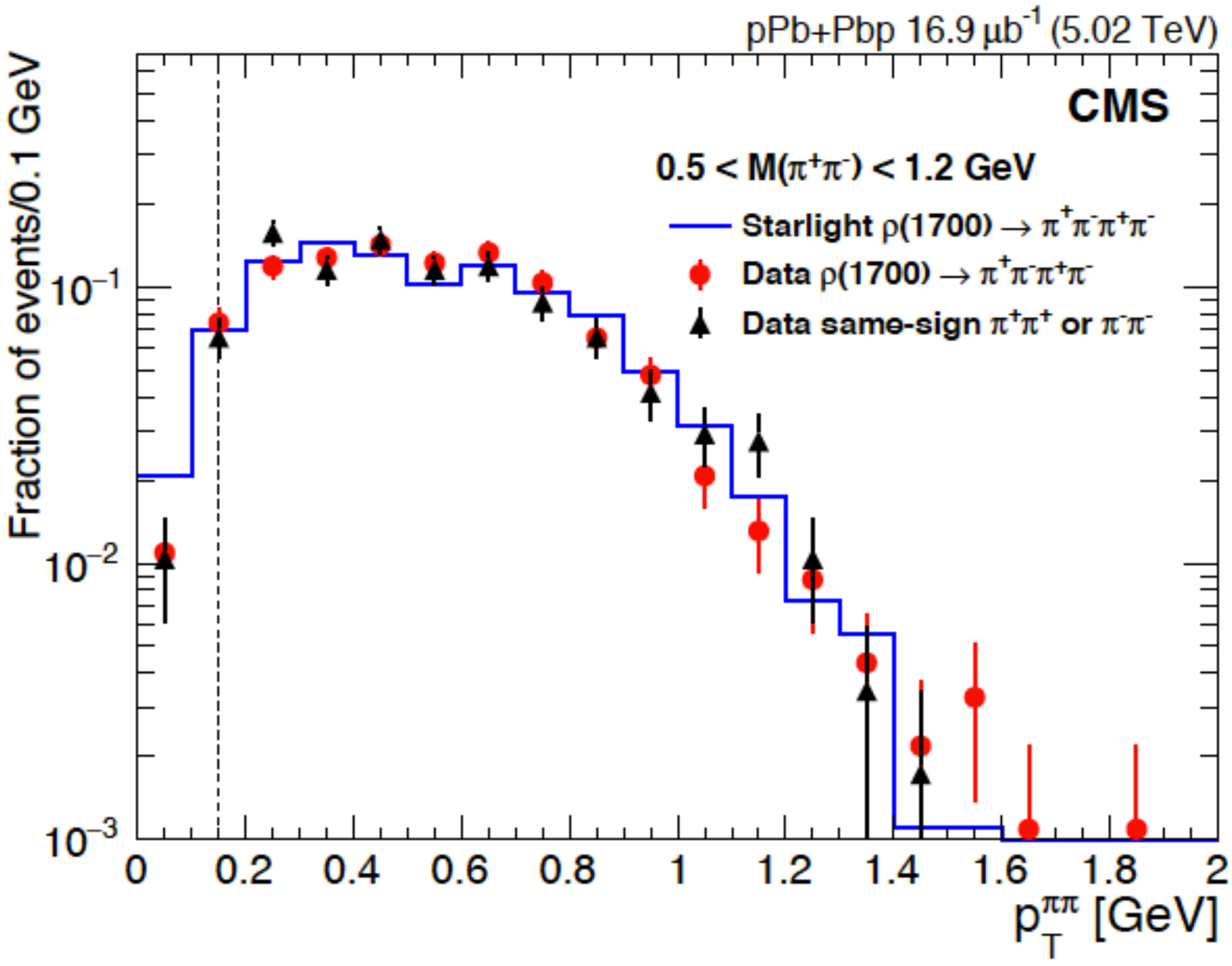

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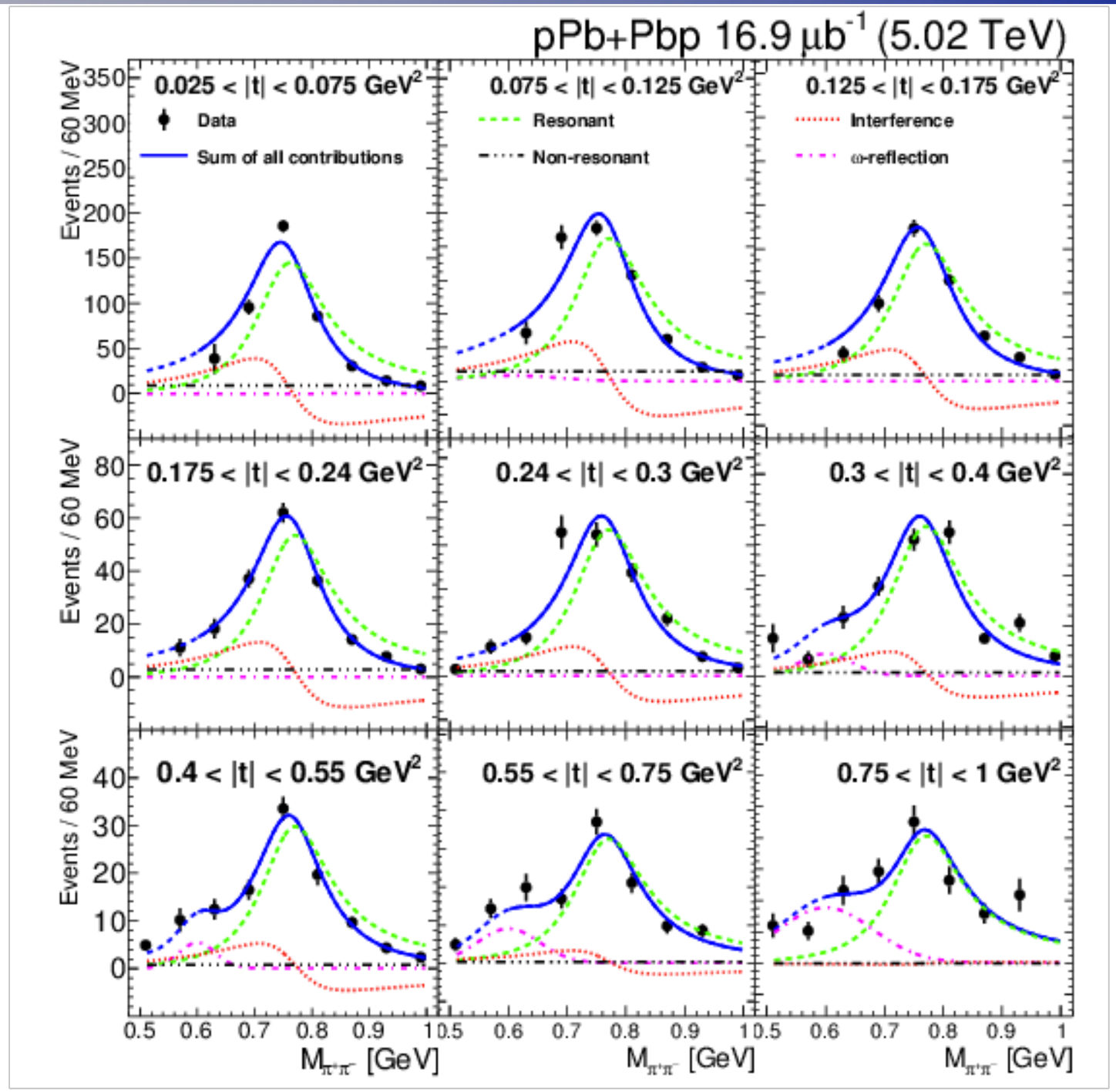

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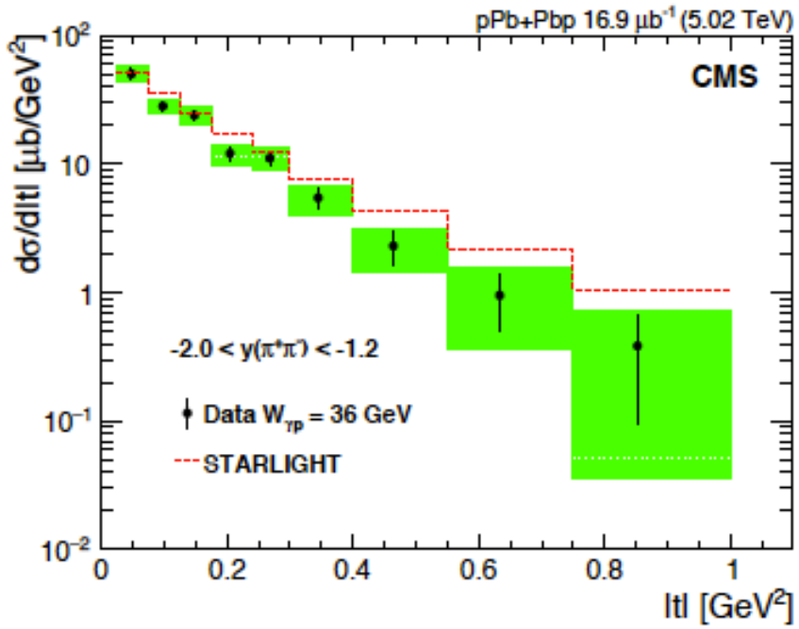

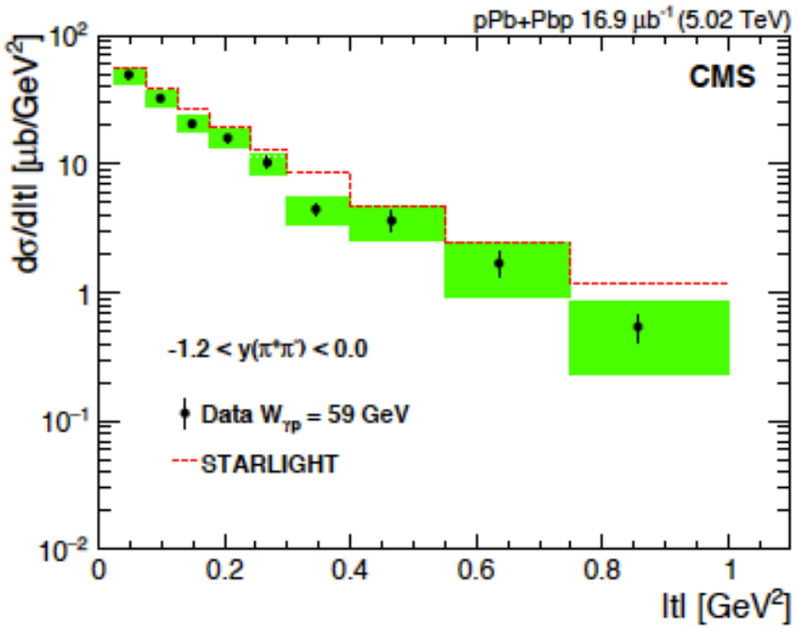

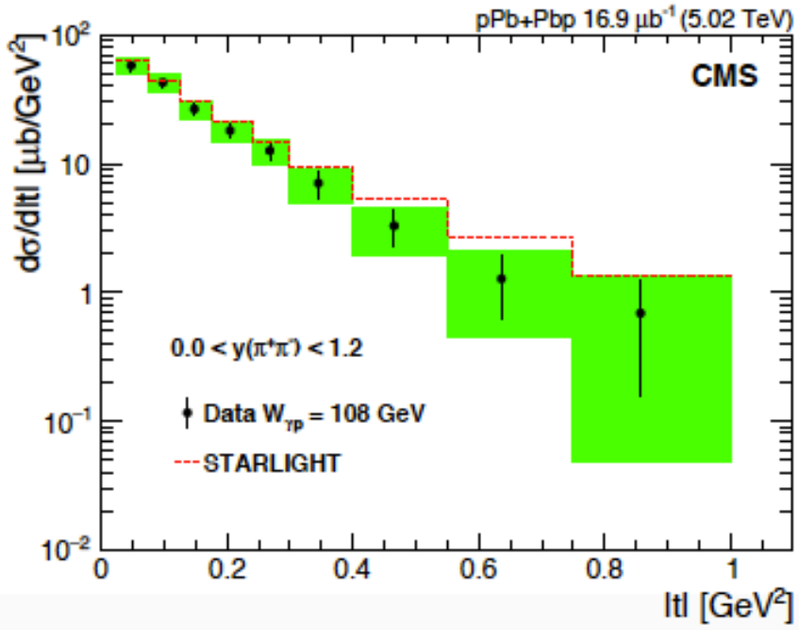

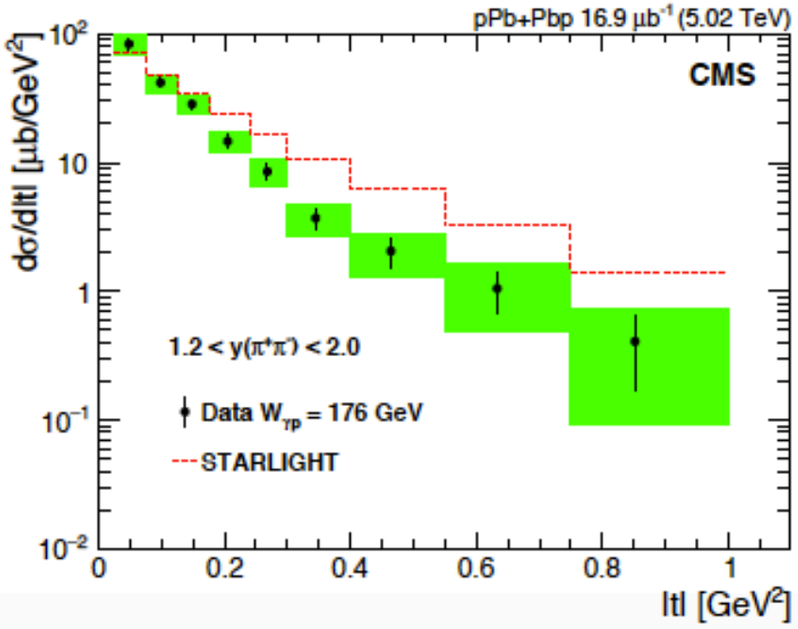

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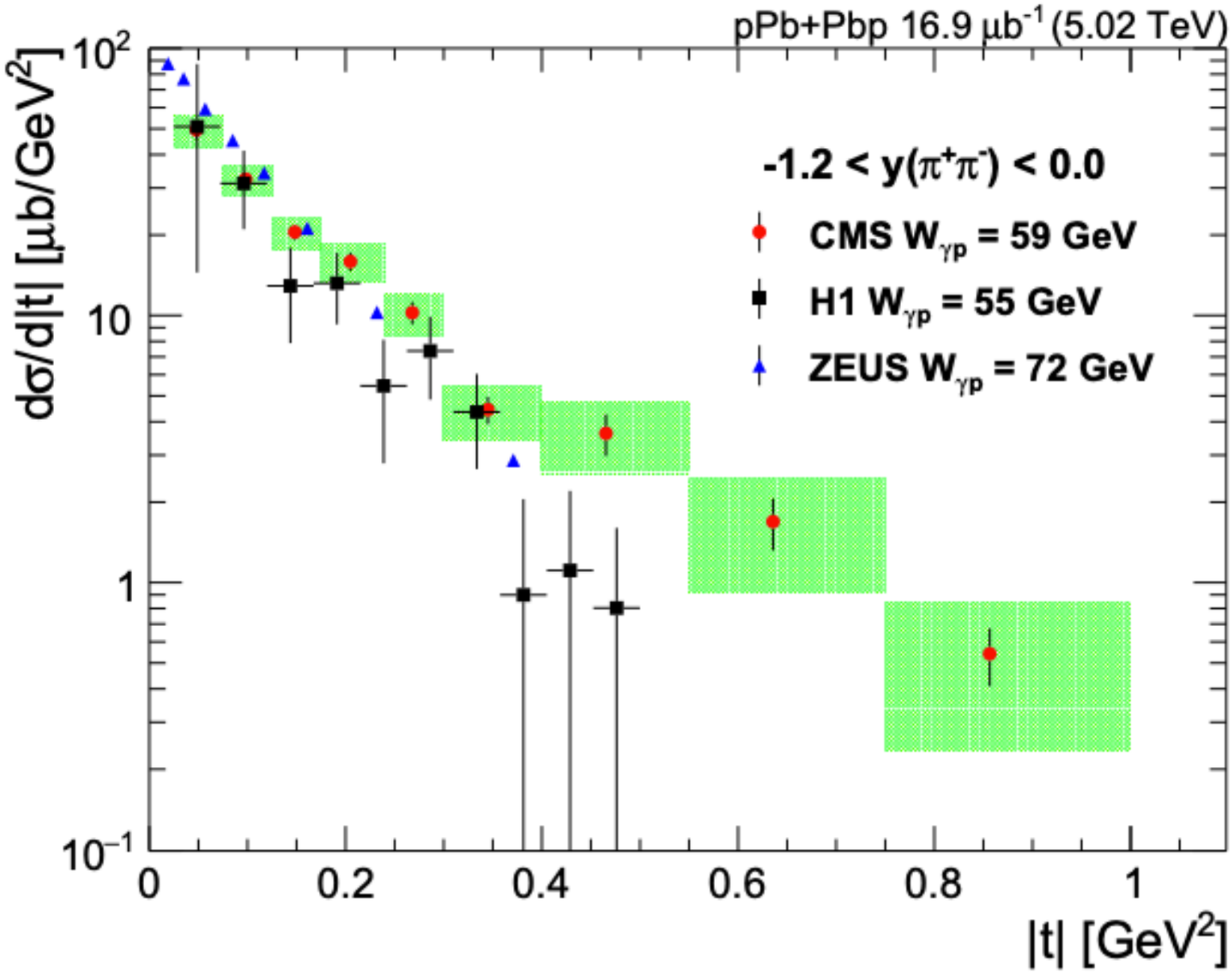

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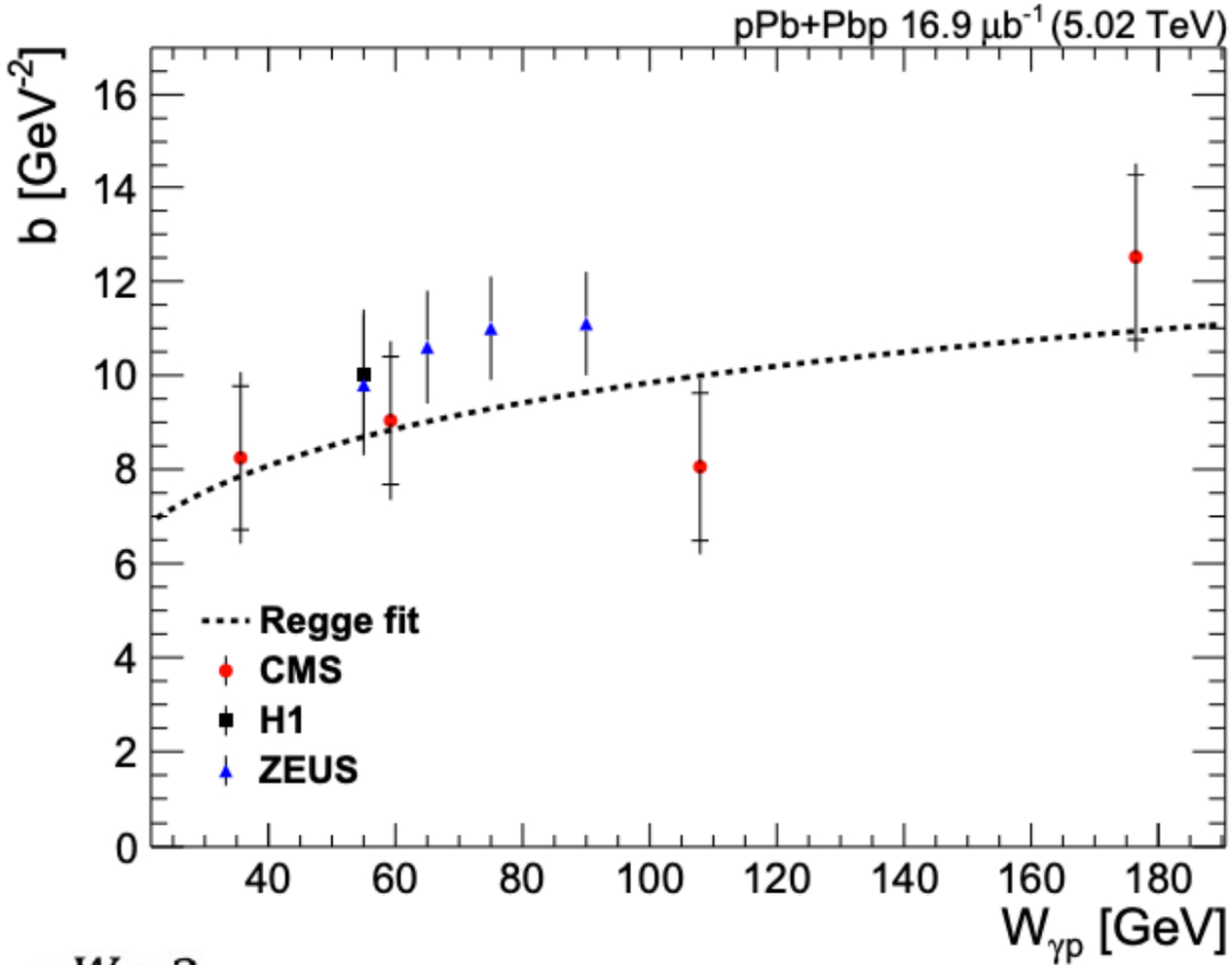


Regge fit $b = b_0 + 2\,\alpha' \ln(\frac{W}{W_0})^2$

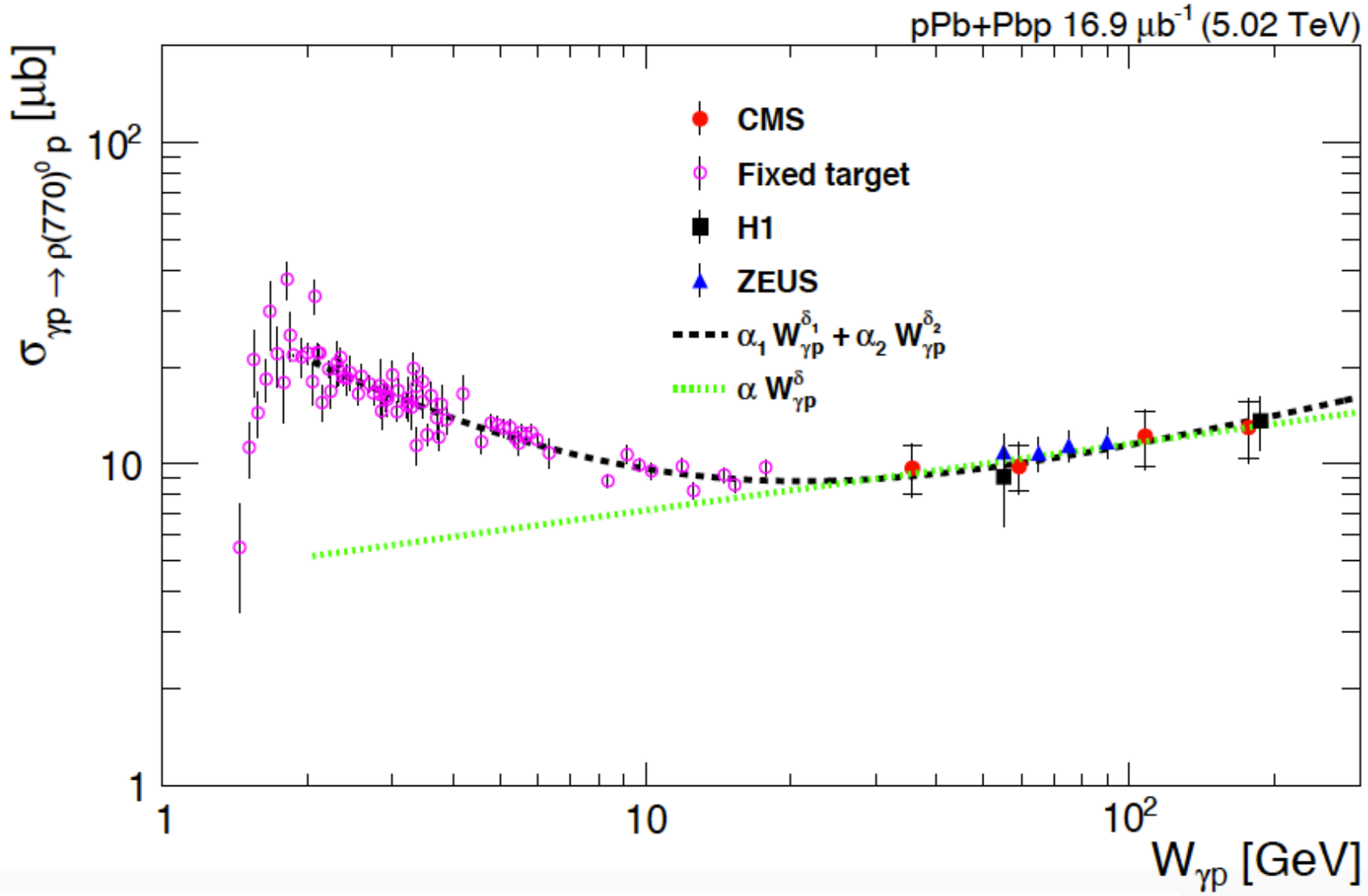
Pomeron trajectory extracted using the CMS data only:

$\alpha' = 0.48 \pm 0.33(stat.) \pm 0.12(syst.)$

Consistent with the ZEUS value ($0.23 \pm 0.15(stat.) \pm 0.10(syst.)$) and Regge expectations.

Exclusive ρ^0 in γp

arXiv:1902.01339
Submitted to EPJ C

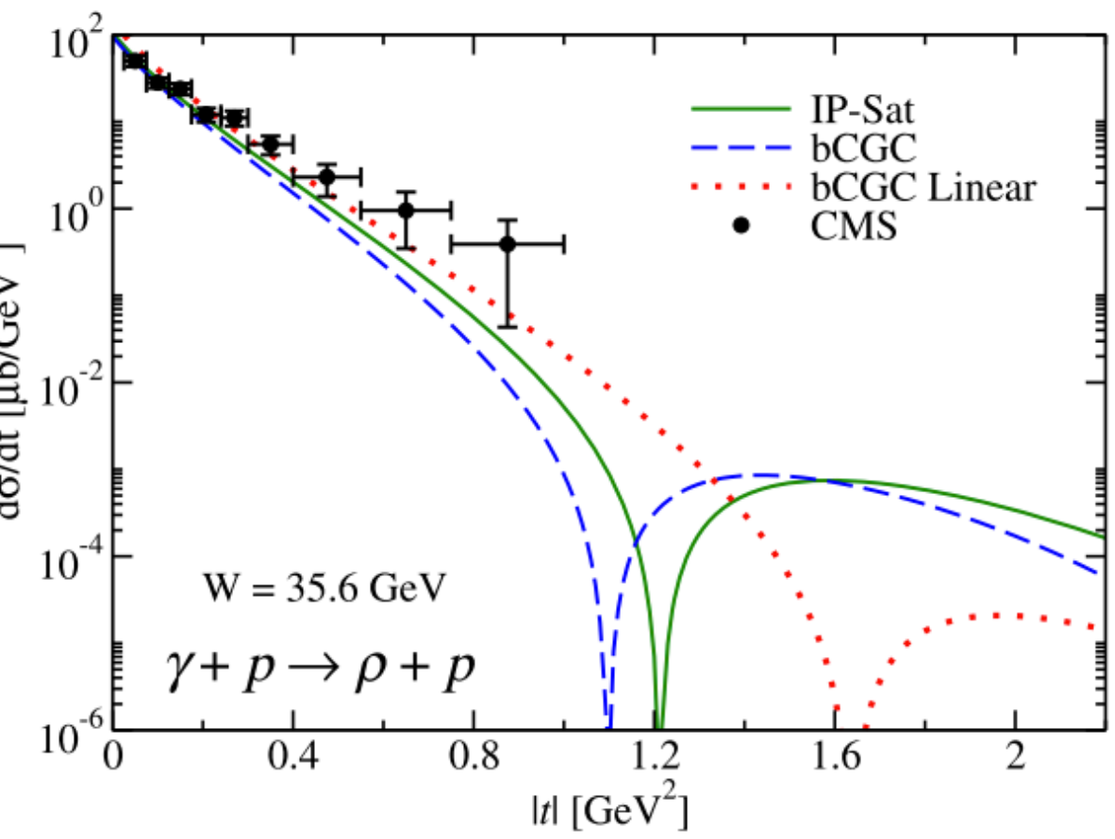


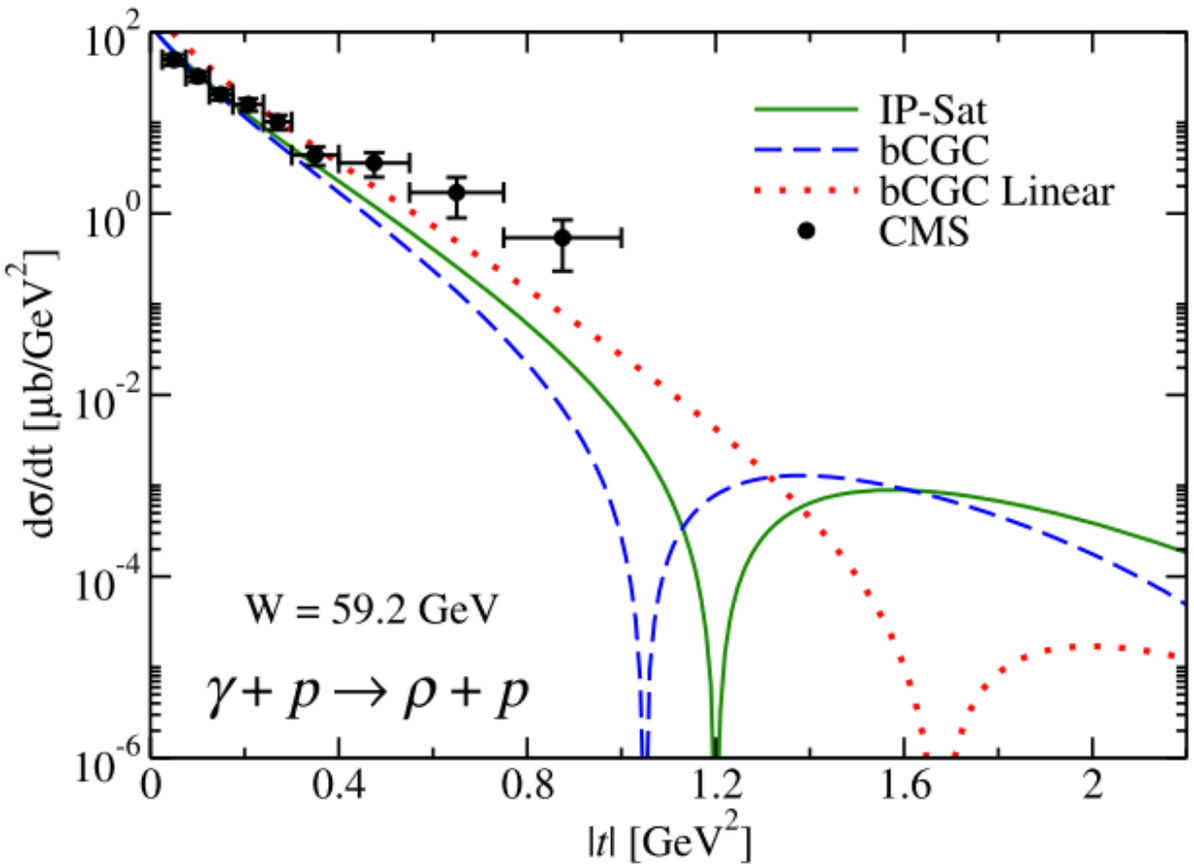
Good agreement with the HERA data and theoretical models

$$\delta = 0.23 \pm 0.14(\text{stat}) \pm 0.04(\text{syst})$$

Exclusive ρ^0 in γp

V. Goncalves, et al.
Phys. Lett. B791 (2019) 299-304





Exclusive ρ^0 in γp

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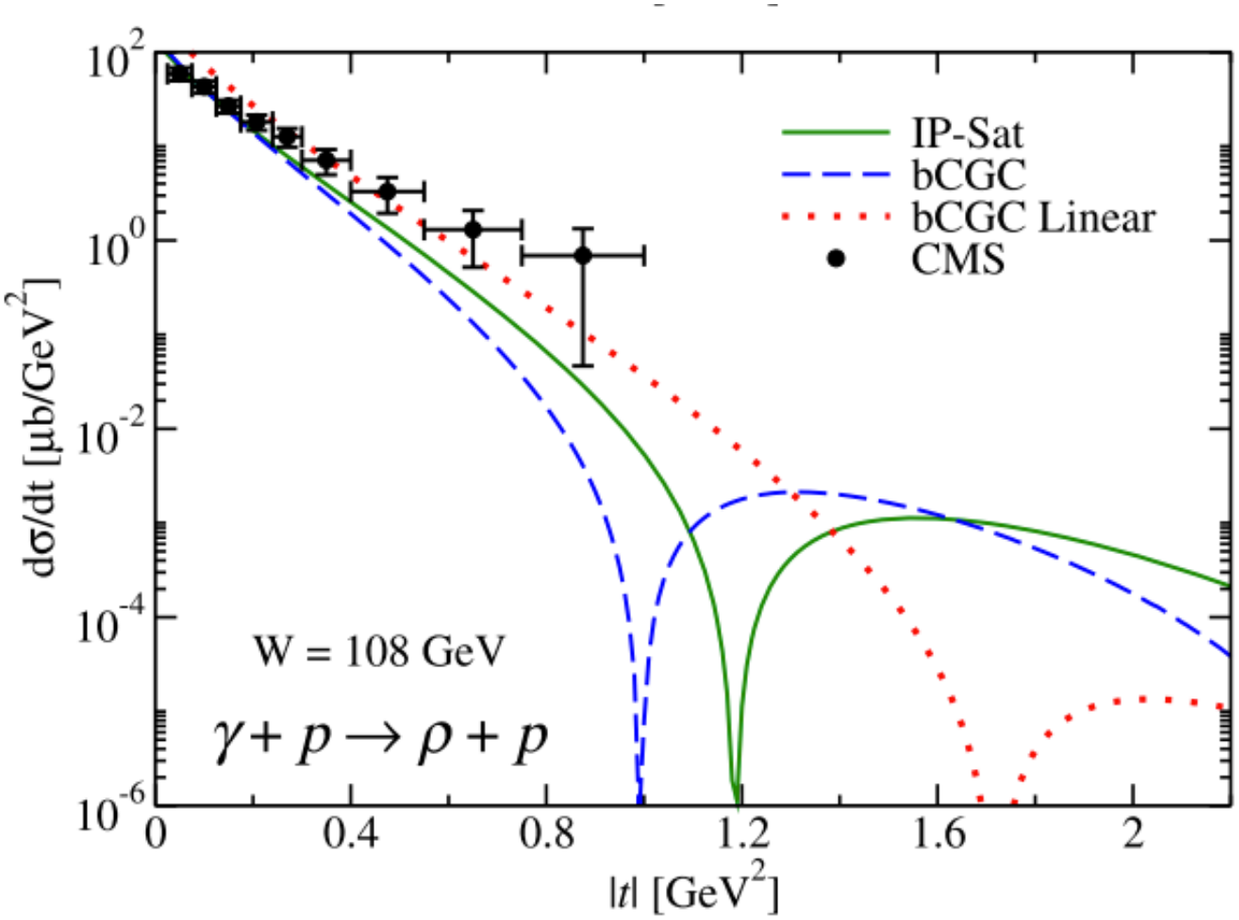
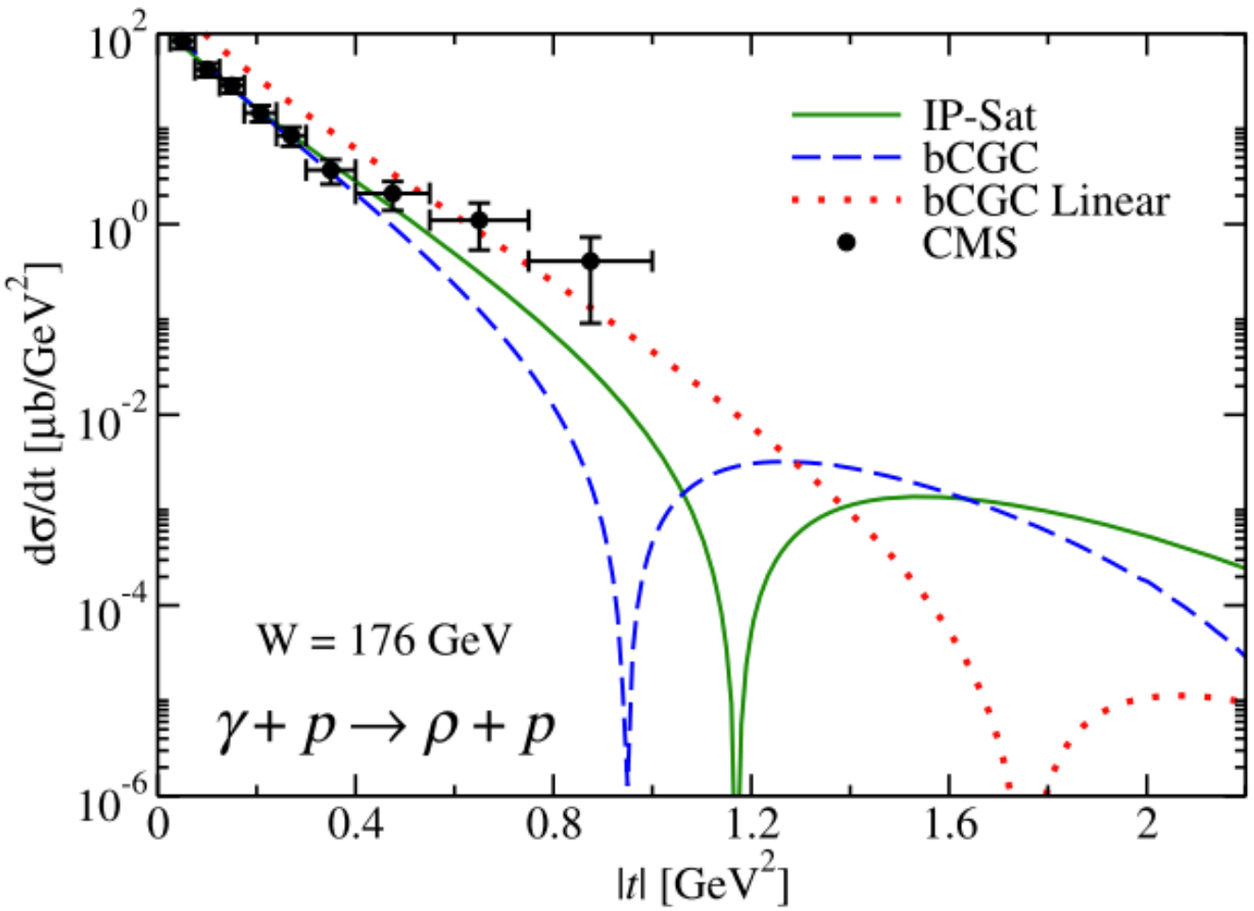
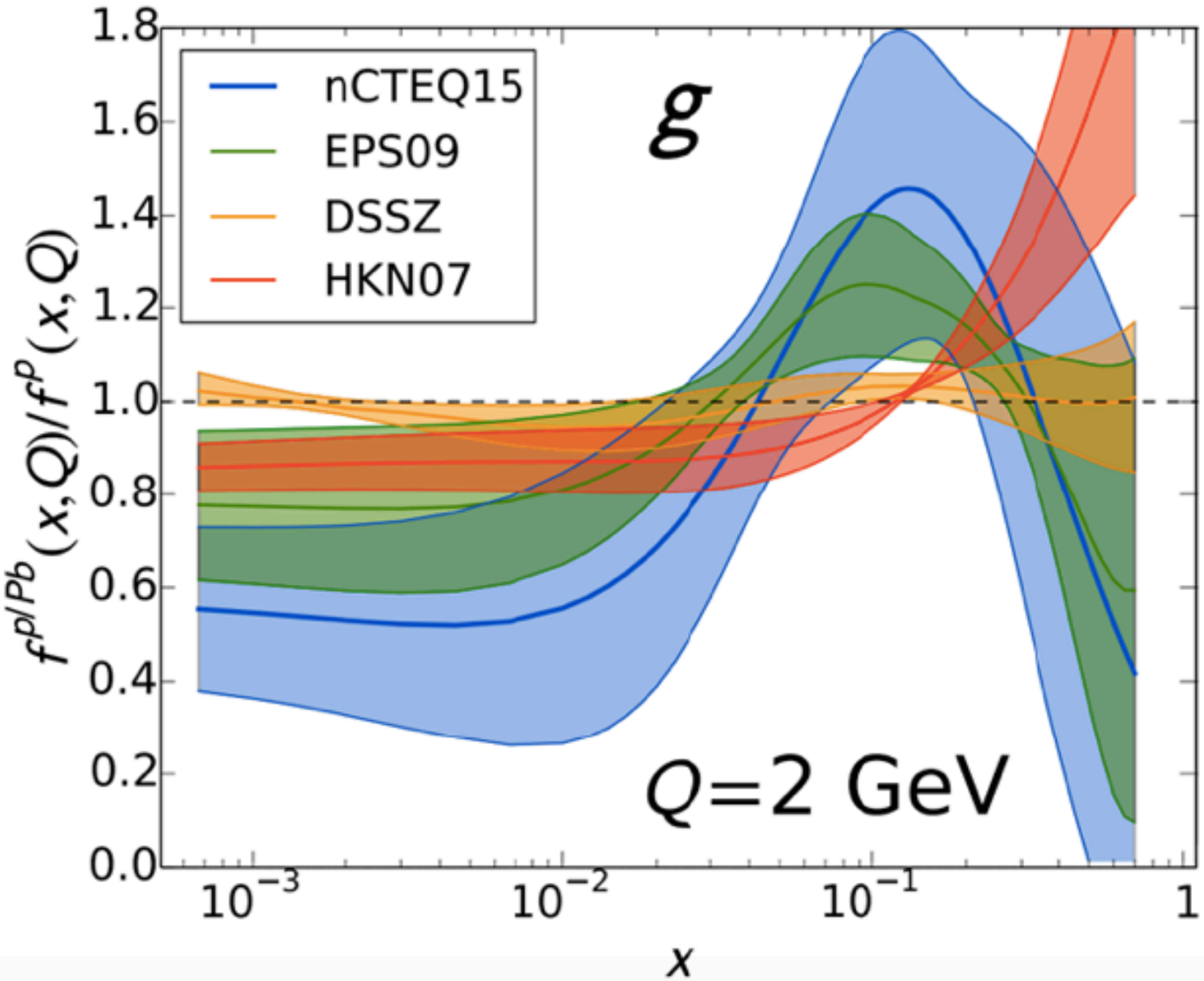
High energy points !





UPC Vector meson in **Photon-Pb**

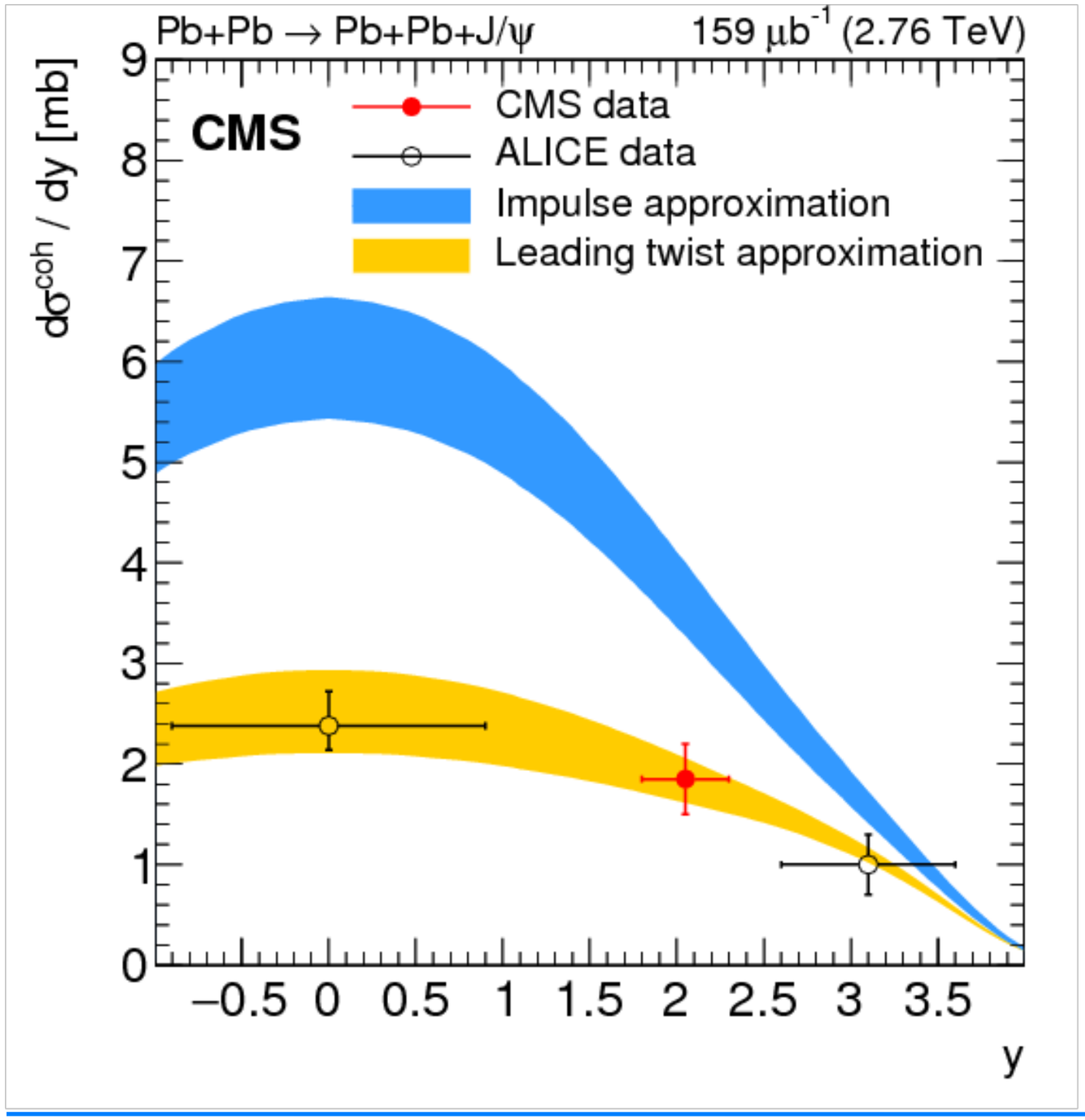
Nuclear gluon density



UPC studies provide the best information the community will get for the next 10 years before, the EIC turns on

See talk by B. Cole on nPDF determination using Inclusive UPC Dijets in PbPb

Coherent J/ψ



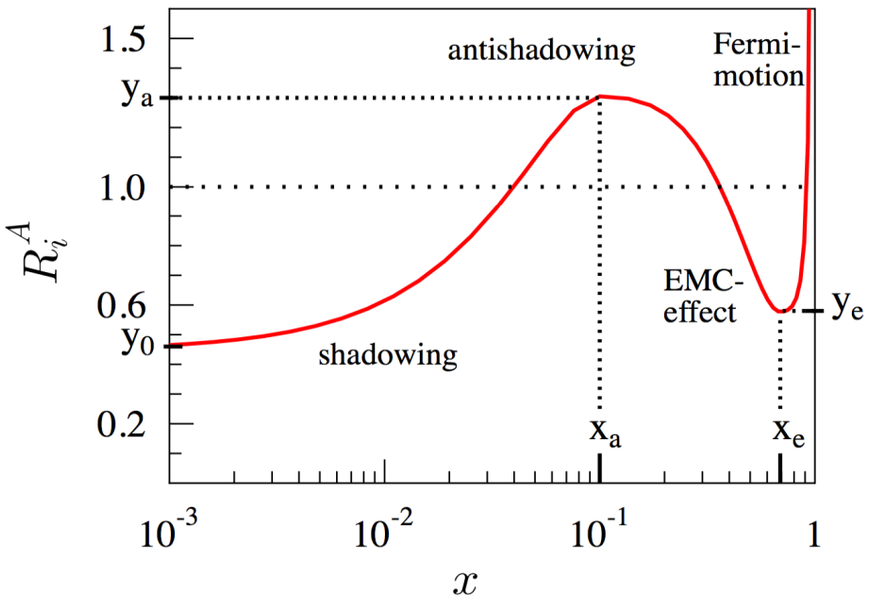
Phys. Lett. B772 (2017) 489-511

Model independent. Parametrization of exclusive J/Ψ data in gamma-proton

i.e. No nuclear effects

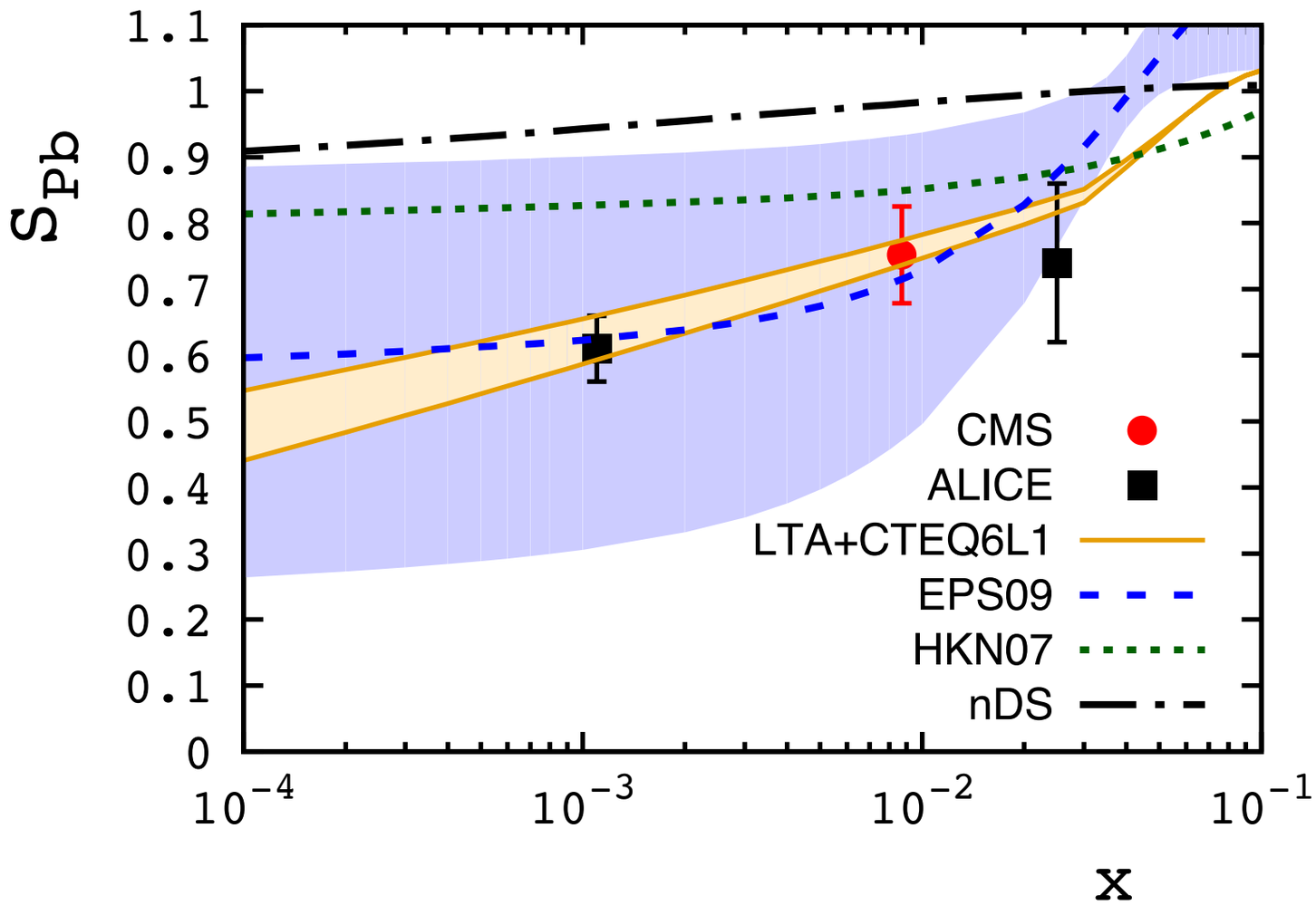
Experimental evidence of nuclear gluon shadowing

Nuclear effects at **Low x**



Coherent J/ψ photoproduction off Pb nuclei

By V. Guzey, et. al using Phys. Lett. B726 (2013) 290–295 and latest ALICE and CMS results



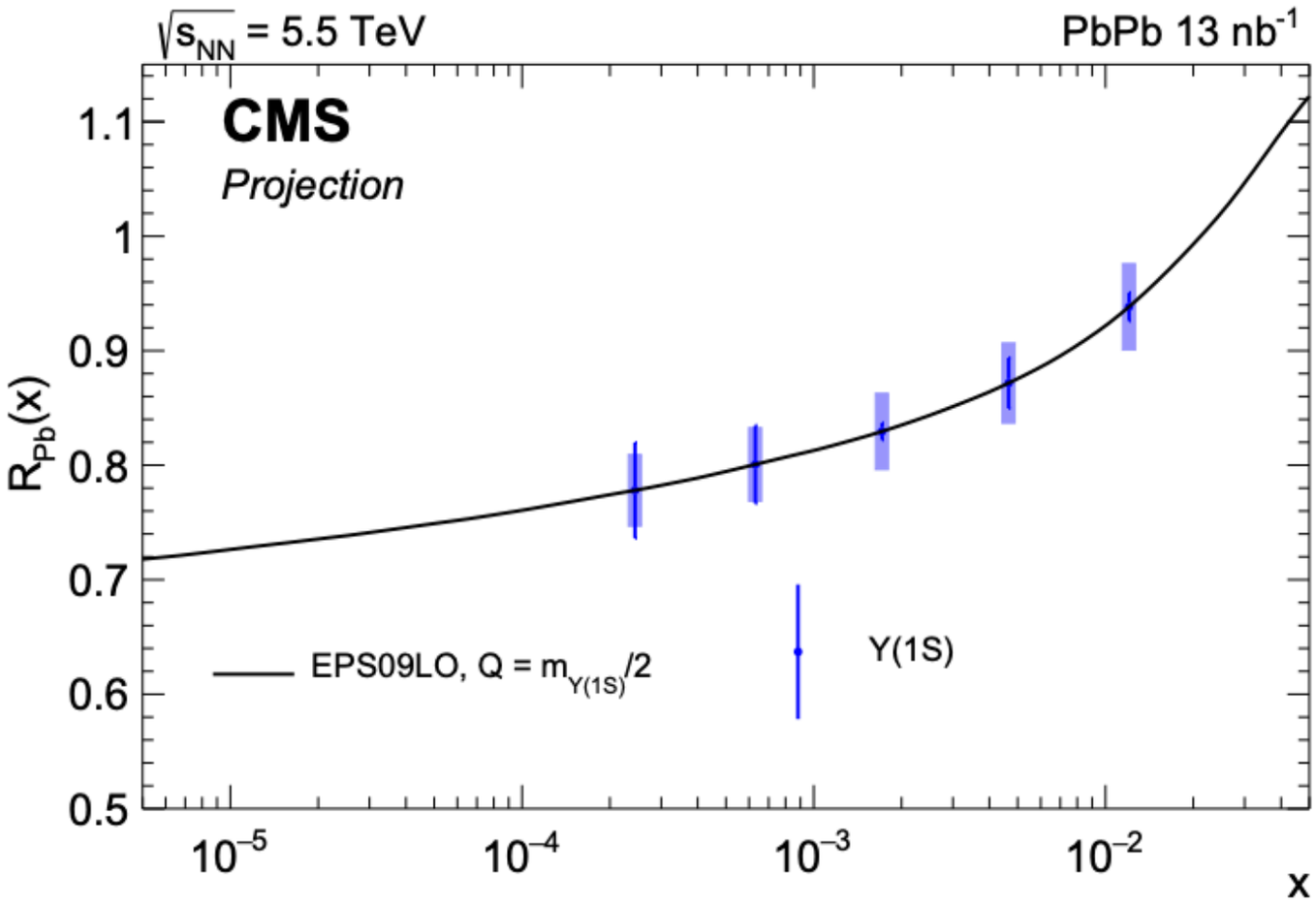
See Janet Seger's talk for ALICE Run 2 results

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

LHC Run 3 projections

CMS-PAS-FTR-18-027
&
CERN-LPCC-2018-07
arXiv:1812.06772

$$R_{\mathrm{Pb}}(x) = \left(\frac{\sigma_{\gamma\mathrm{Pb}}(x)}{\sigma_{\mathrm{IA}}(x)}\right)^{1/2}, \qquad \text{where} \qquad x = \frac{m_V}{\sqrt{s_{\mathrm{NN}}}}\exp(-y).$$



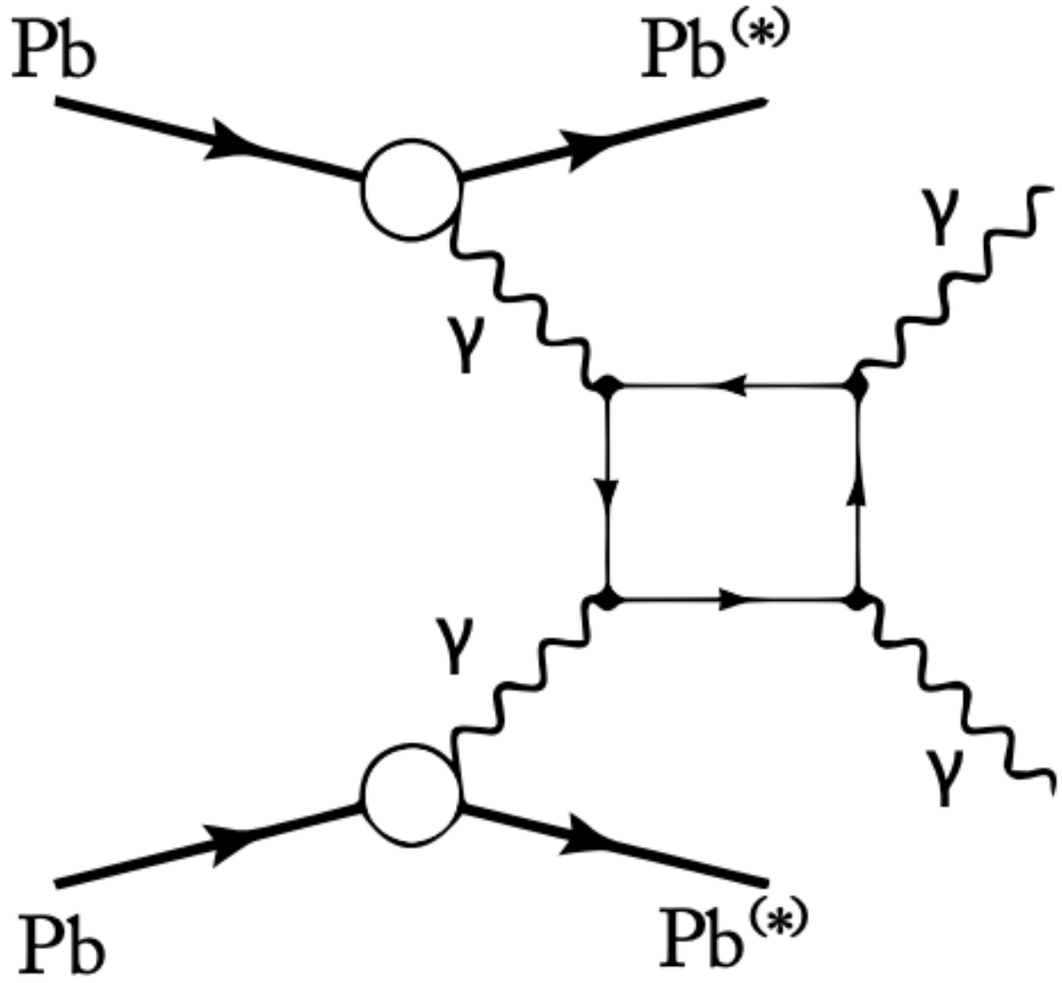
Similar studies will be done for *UPC J/ψ in γPb*

For this analysis, ***crucial to study neutron dependence using ZDCs***
Needed to determine the photon emitter uncertainty - intrinsic to symmetric systems (AA)

Light-by-light scattering

Light-by-light scattering

arXiv:1810.04602
Submitted to PLB



See talk by P. Steinberg
for ATLAS results on LbyL scattering

Light-by-light scattering

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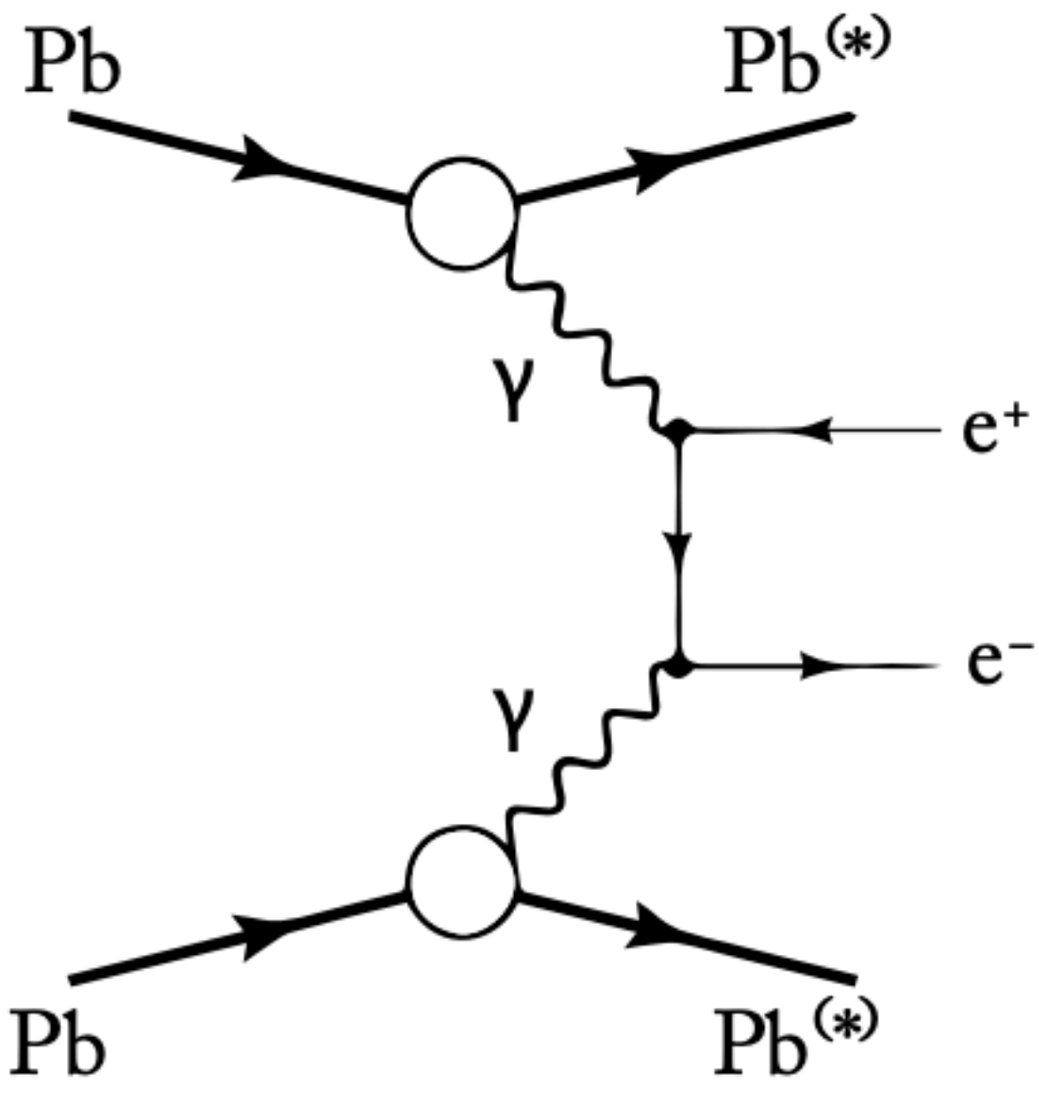

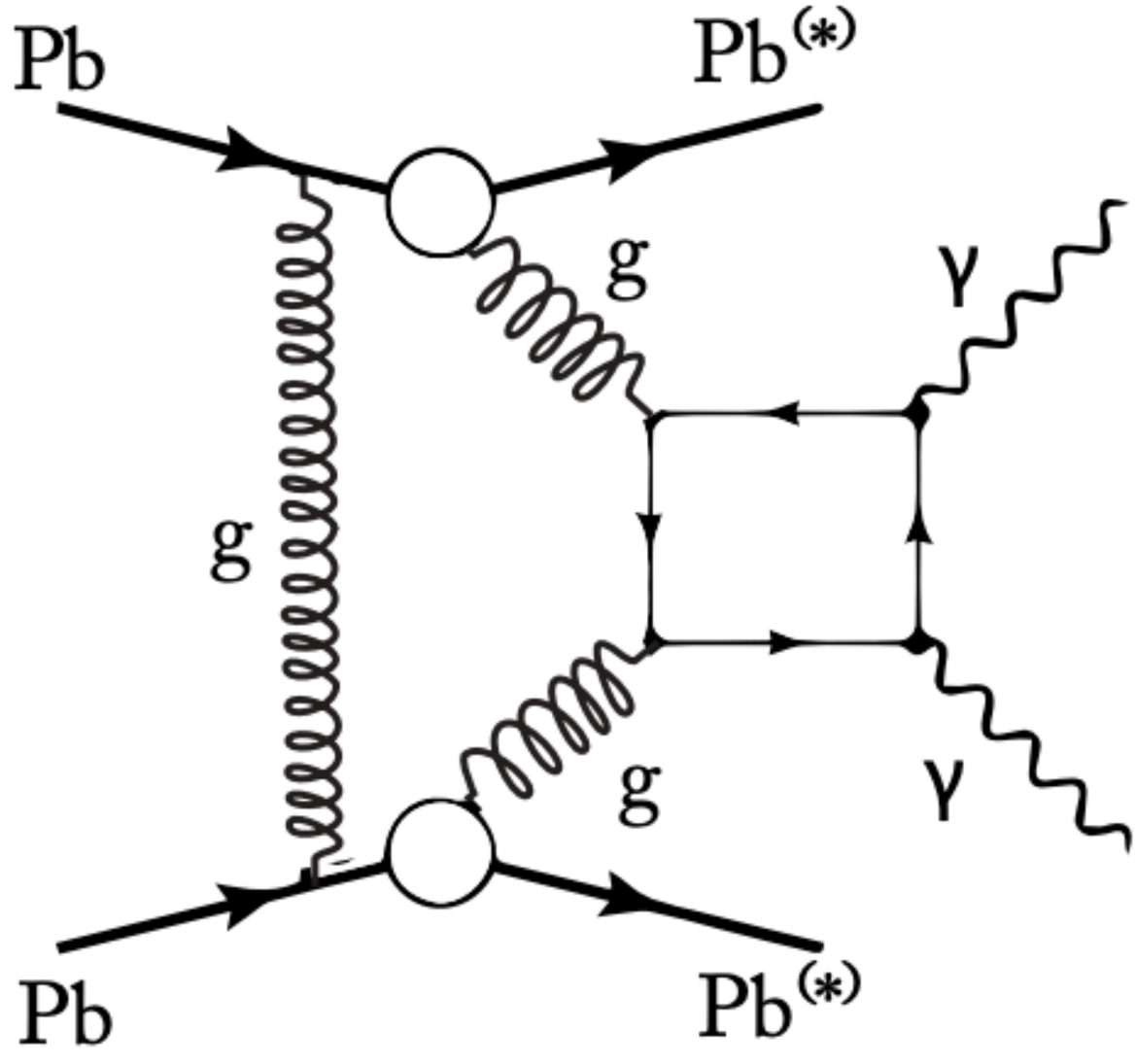

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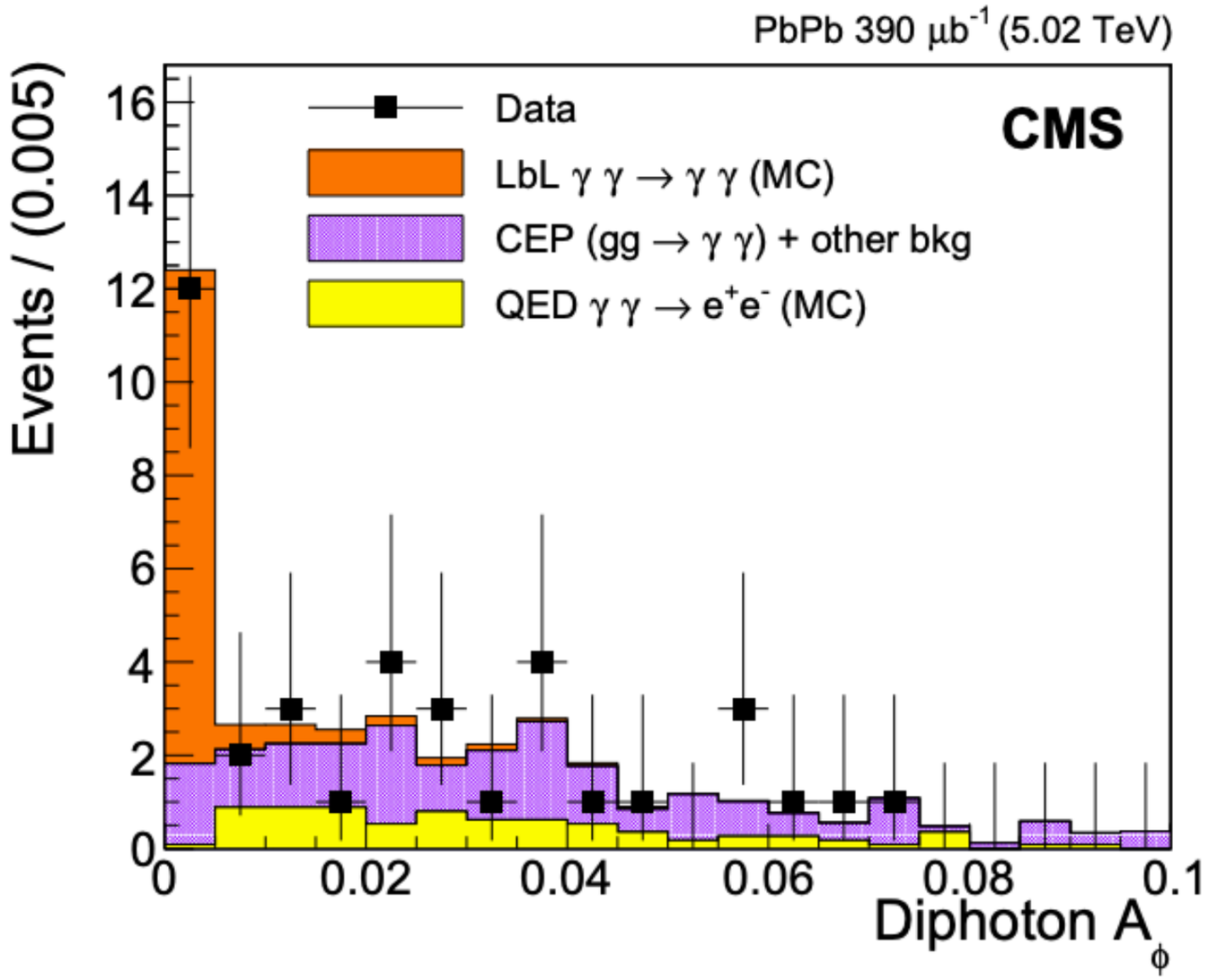


$E_T\gamma > 2$ GeV
$|\eta| < 2.4$

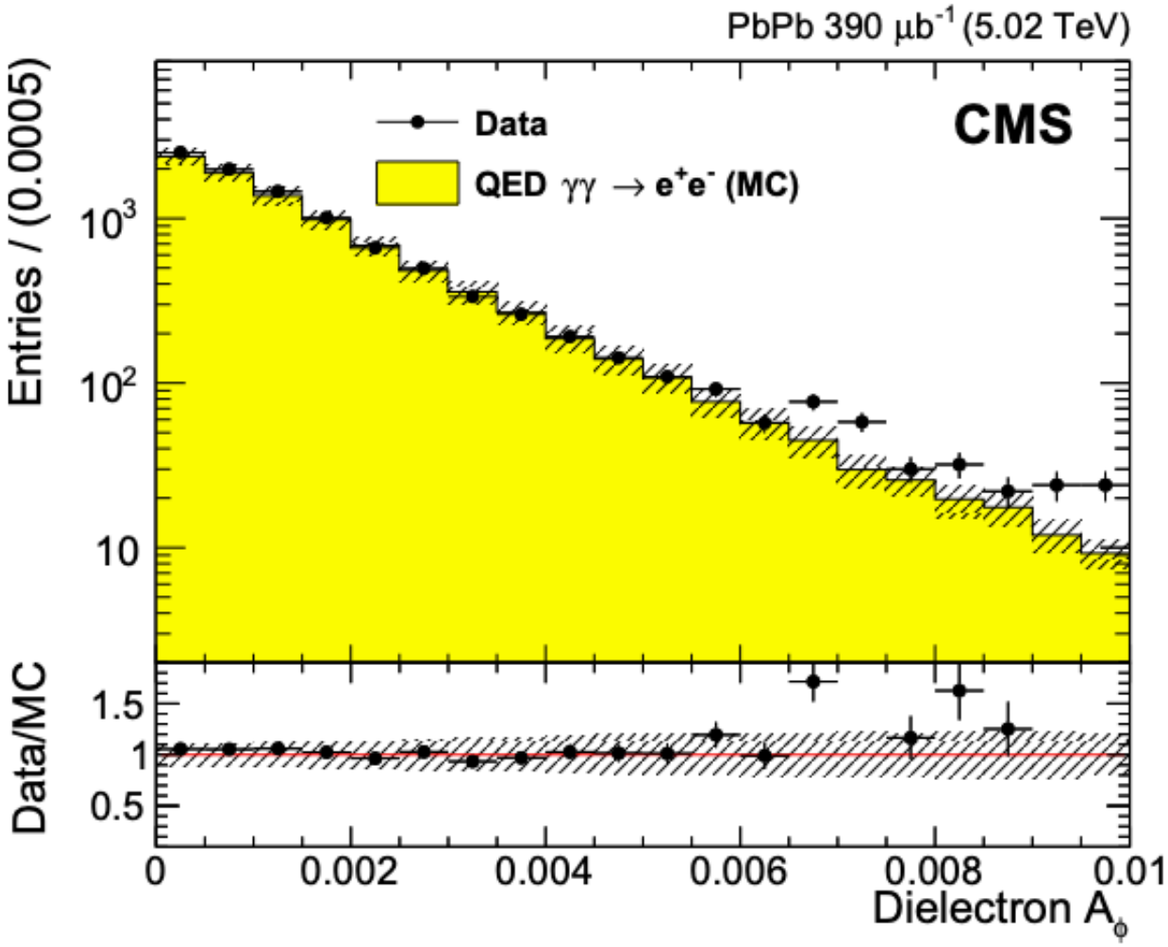
$M\gamma\gamma > 5$ GeV,

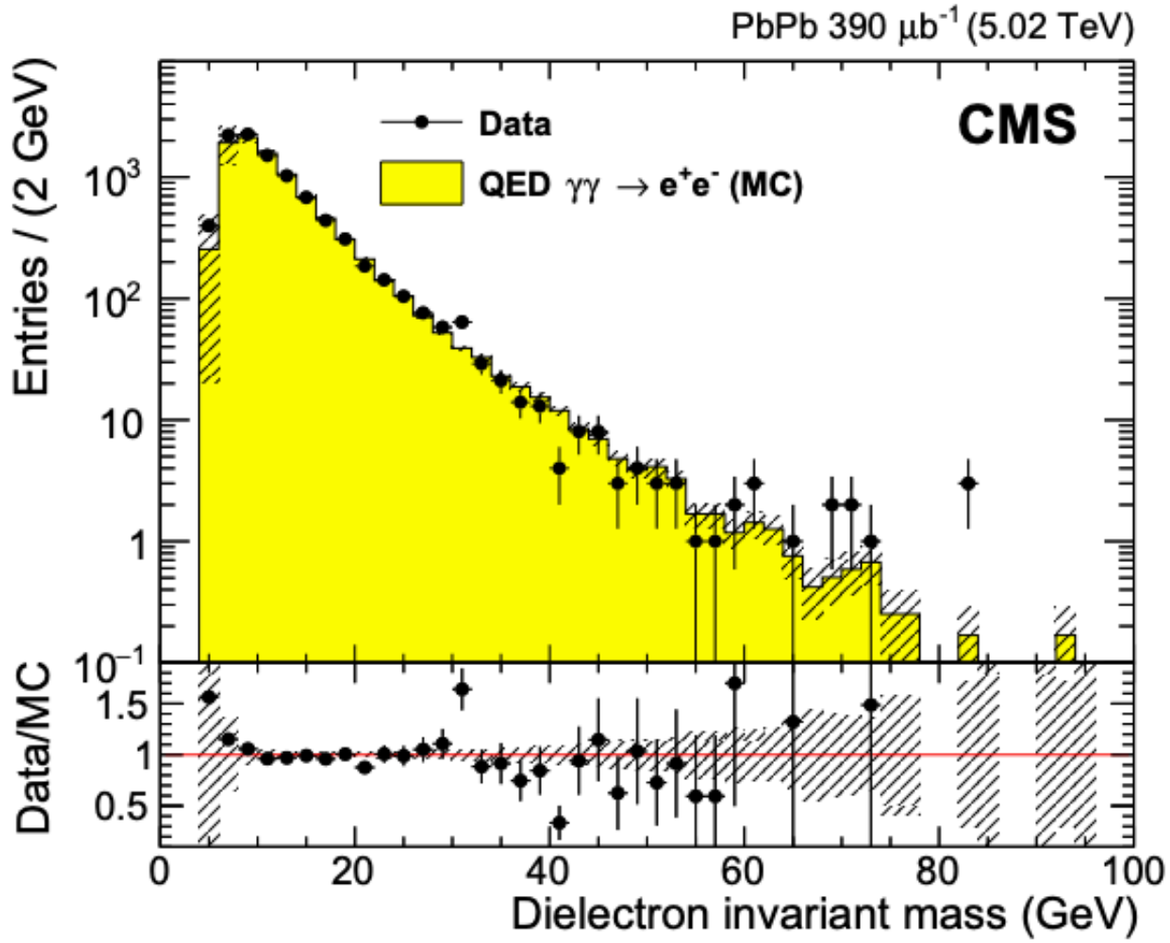
$p_T(\gamma) < 1$ GeV

Acoplanarity
$A_\phi < 0.01$

Light-by-light scattering

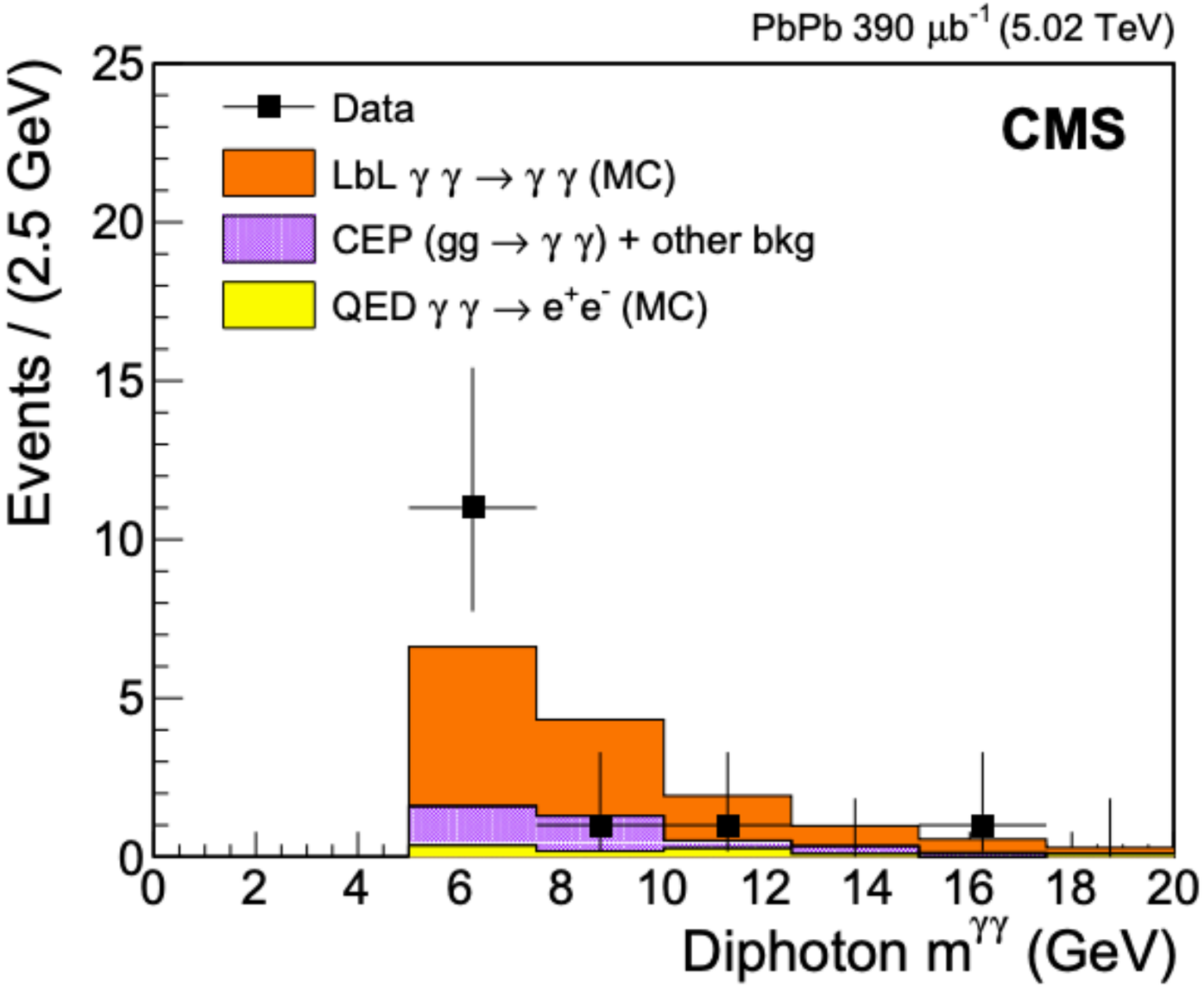
arXiv:1810.04602
Submitted to PLB





Light-by-light scattering

arXiv:1810.04602
Submitted to PLB



Evidence for light-by-light scattering

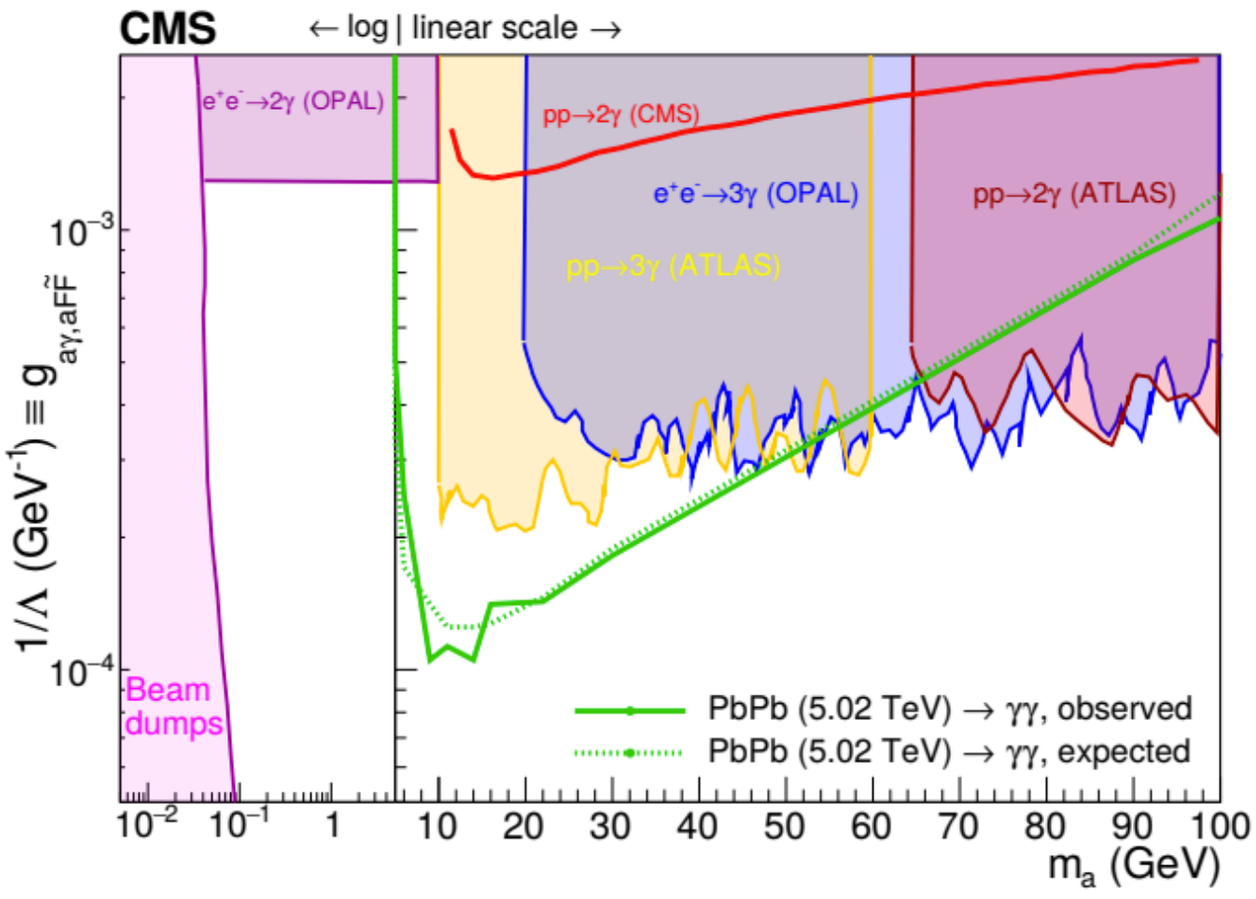
4.1 (4.4)σ observed (expected)

14 LbyL events observed - consistent with the SM prediction

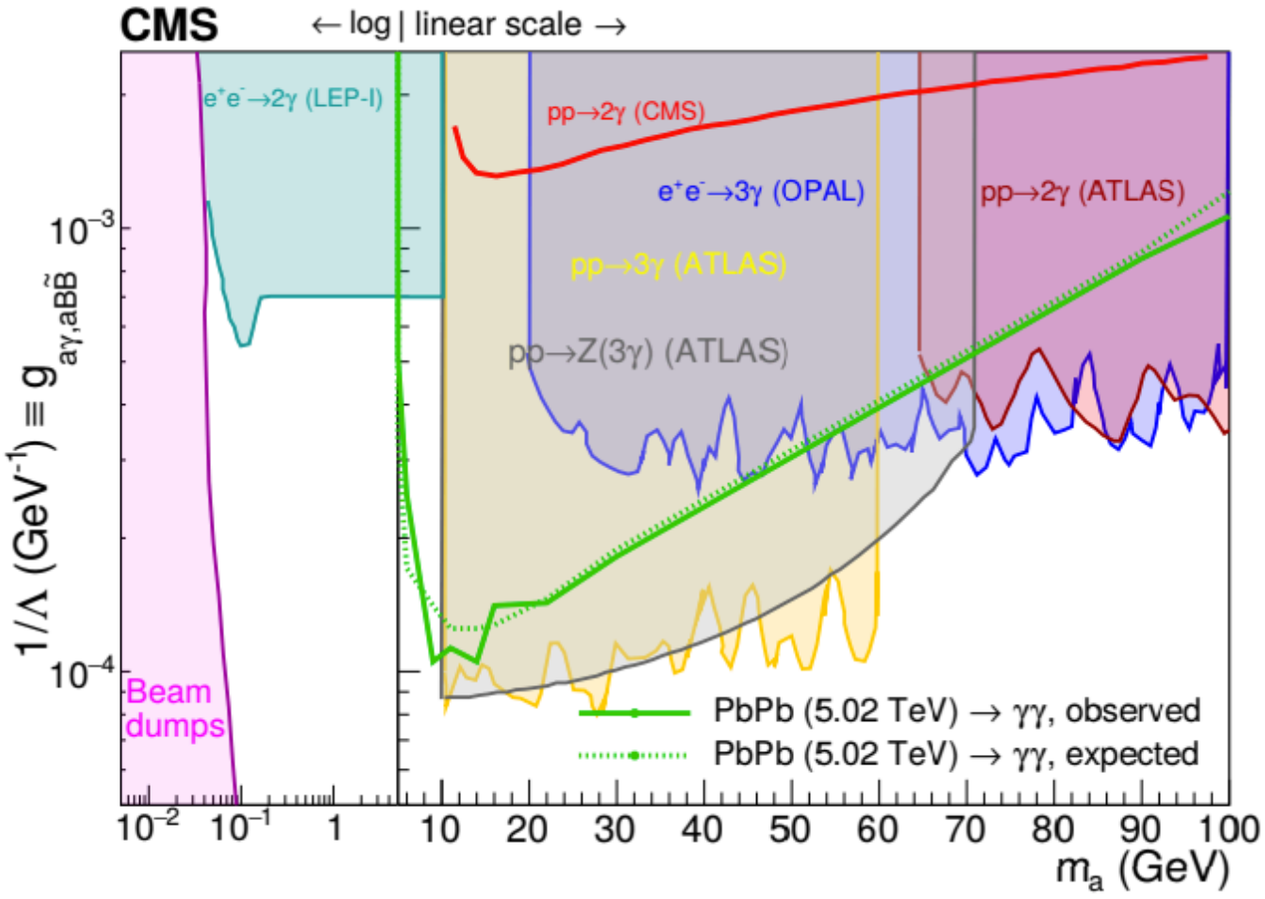
Axion-Like Particle Limits (ALP)
Light-by-light scattering

arXiv:1810.04602
Submitted to PLB

ALP coupling to photons only



ALP coupling to photons or hypercharge



No significant excess observed

Summary

UPC studies at LHC- *covering an unexplored energy regime & synergies with the EIC.* **At CMS studying a wide variety of physics topics in UPCs** *relevant to the hadronic/nuclear physics community today*

Results in UPC VMs by CMS (and ALICE), *studying UPC J/ψ in γPb already found evidence of nuclear gluon shadowing at low-x and* Q^2
Energy dependent studies of the t-distribution of UPC ρ^0 *in γp promising for determining the onset of gluon saturation*

Evidence of light-by-light scattering. *Competitive exclusion limits on axion-like particles. Novel searches for dark matter/exotica candidates*

Lots of UPC triggered data collected by CMS in Nov/Dec 2018 (4 - 10 times more statistics. Unique setup at LHC with both CASTOR and ZDC detectors)

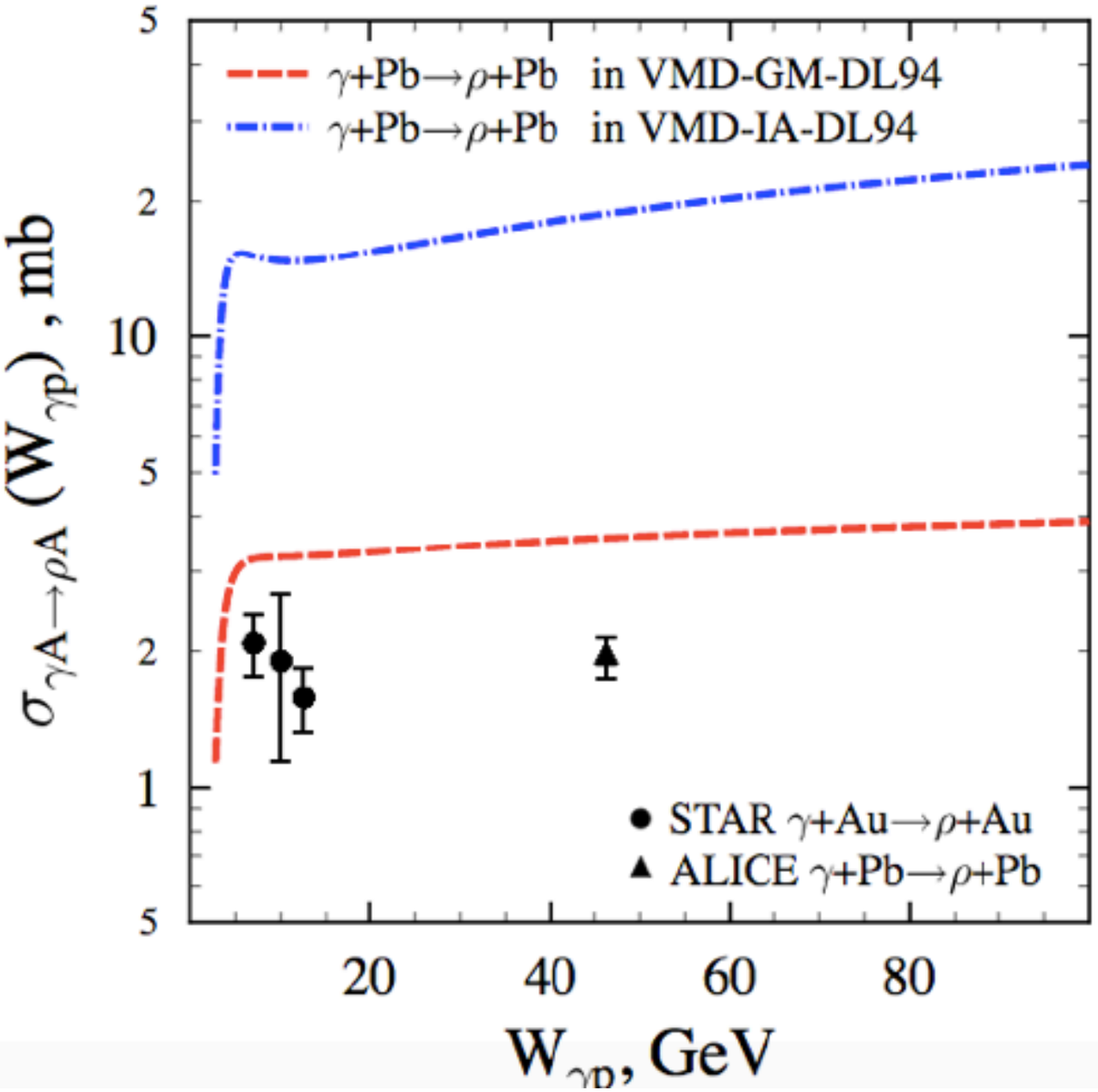
Other interesting UPC studies also ongoing!

Additional slides

Coherent ρ^0

ALICE
JHEP 1509 (2015) 095

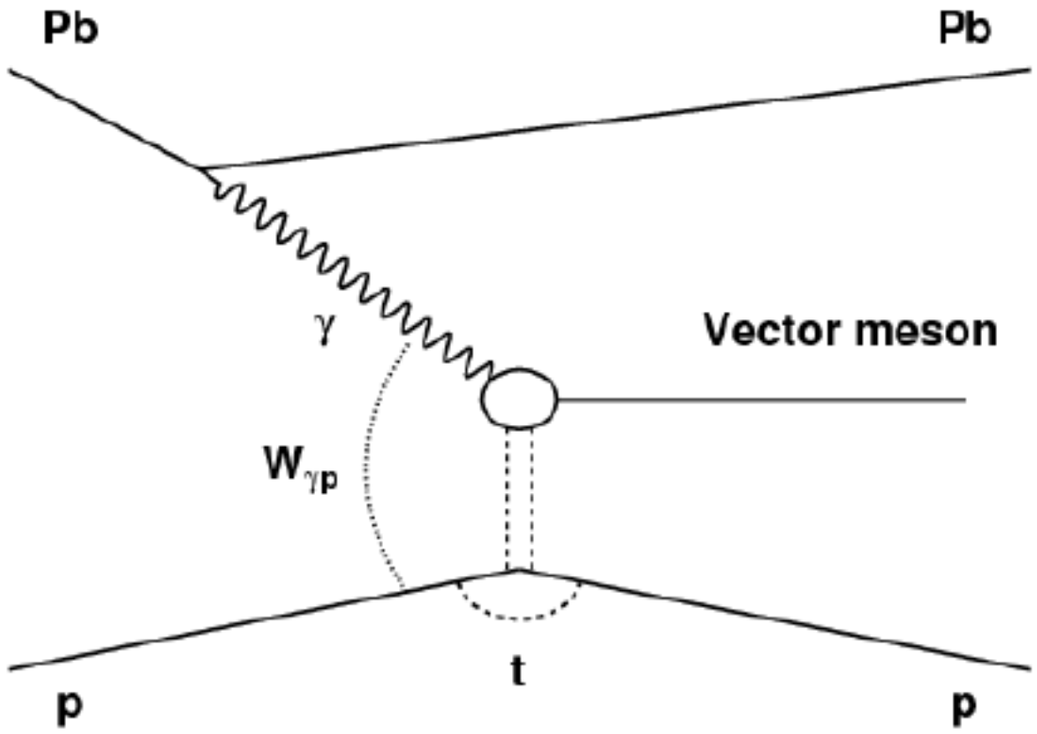
L. Frankfurt et al.
Phys.Lett. B752 (2016) 51-58

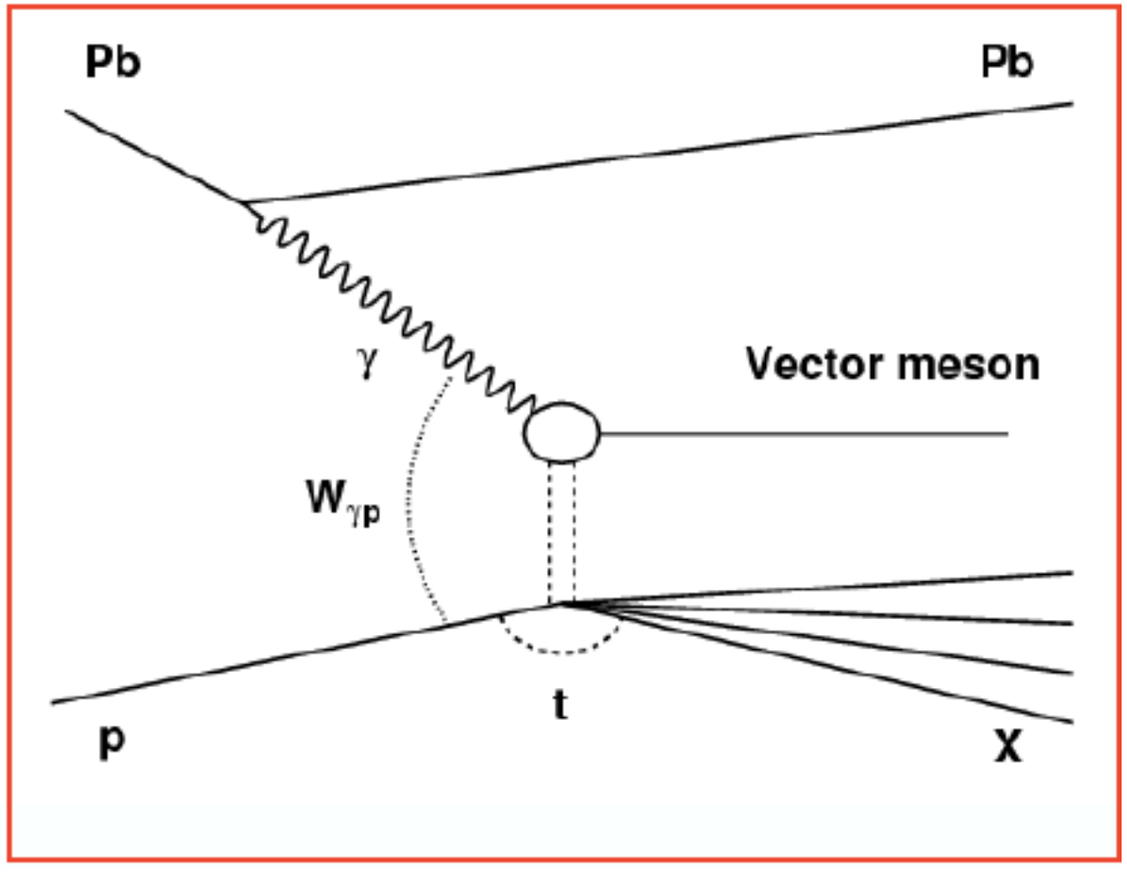


Both ALICE and STAR find measured cross section ~40% lower than predicted by Glauber, ….although works fine at fixed-target experiments

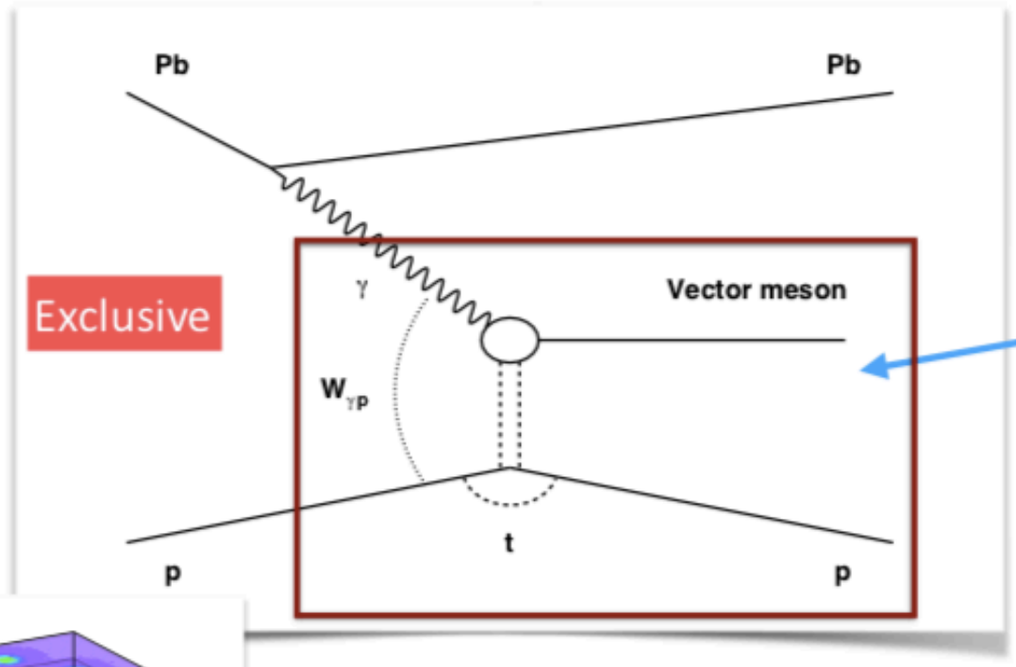
Nuclei does not behave like individual nucleons?

Dissociative/Incoherent production





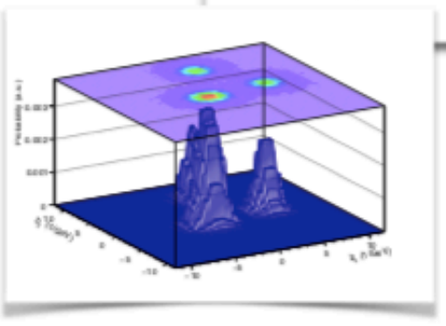
Exclusive and dissociative production



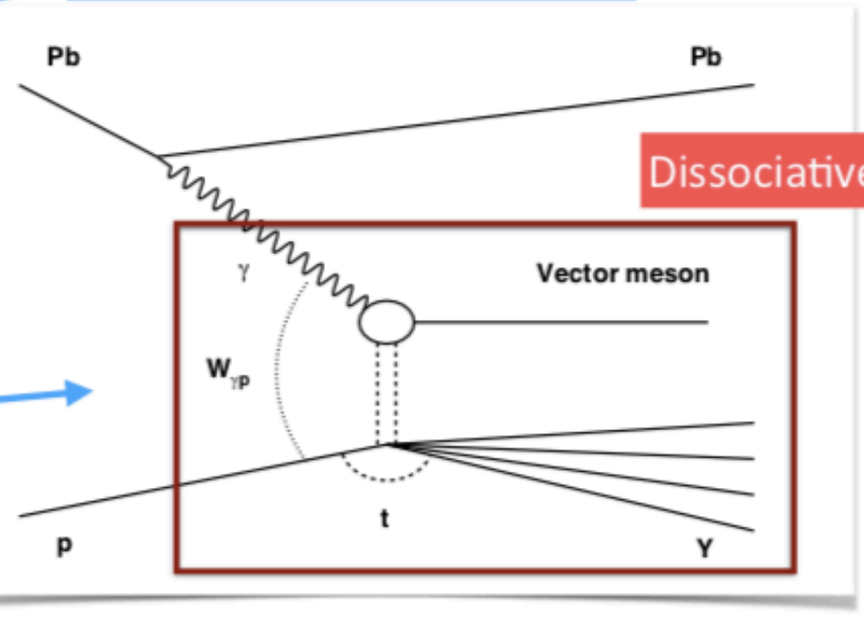
Exclusive

$$\frac{d\sigma(\gamma p \to \mathrm{J}/\psi p)}{dt} = \frac{R_g^2}{16\pi}\left|\left\langle A(x,Q^2,\vec{\Delta})\right\rangle\right|^2$$

Average over configurations



Variance over configurations



Dissociative

$$\frac{d\sigma(\gamma p \to \mathrm{J}/\psi Y)}{dt} = \frac{R_g^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})\right\rangle\right|^2\right)$$

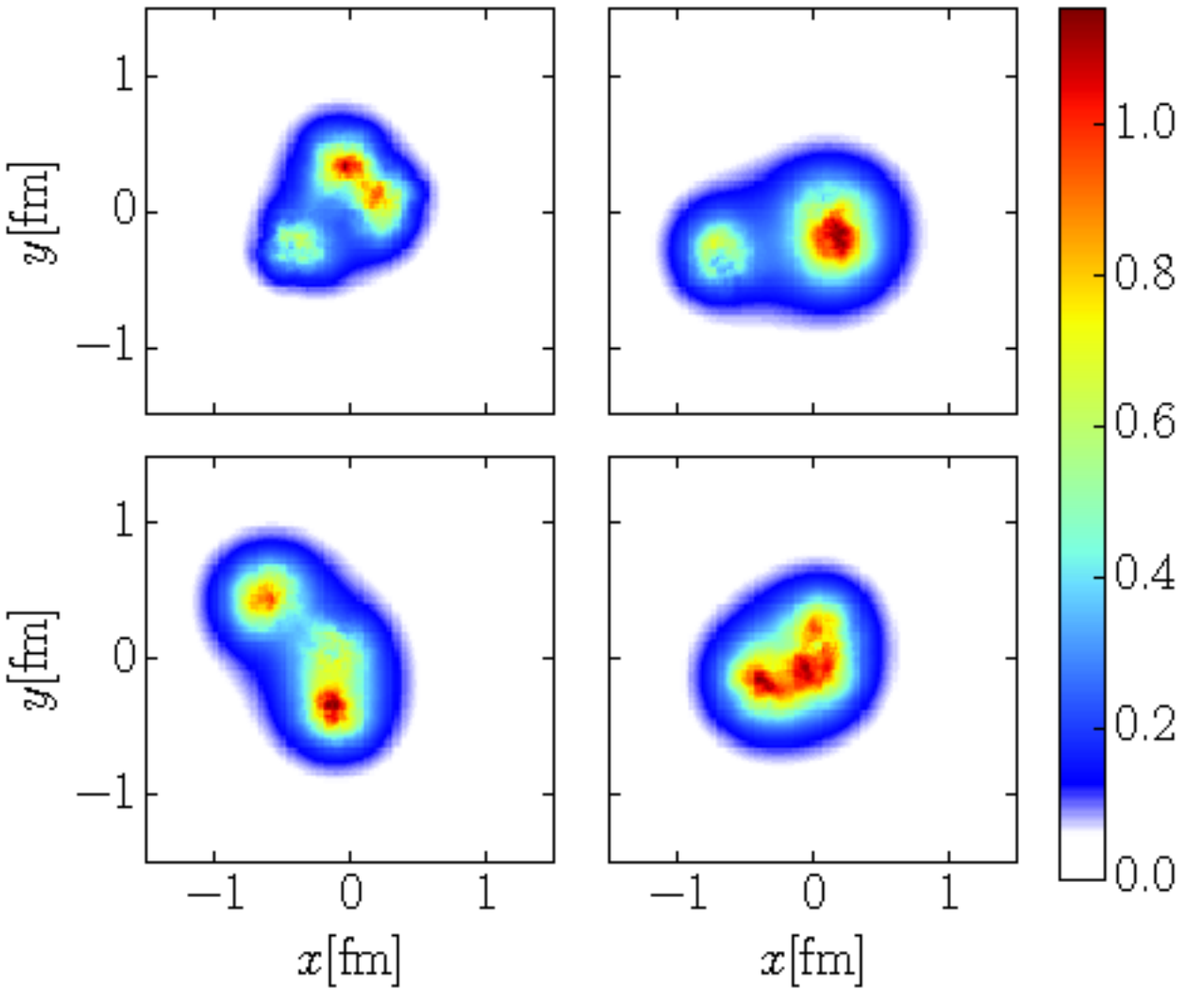
Good,Walker , PR 120 (1960) 1857

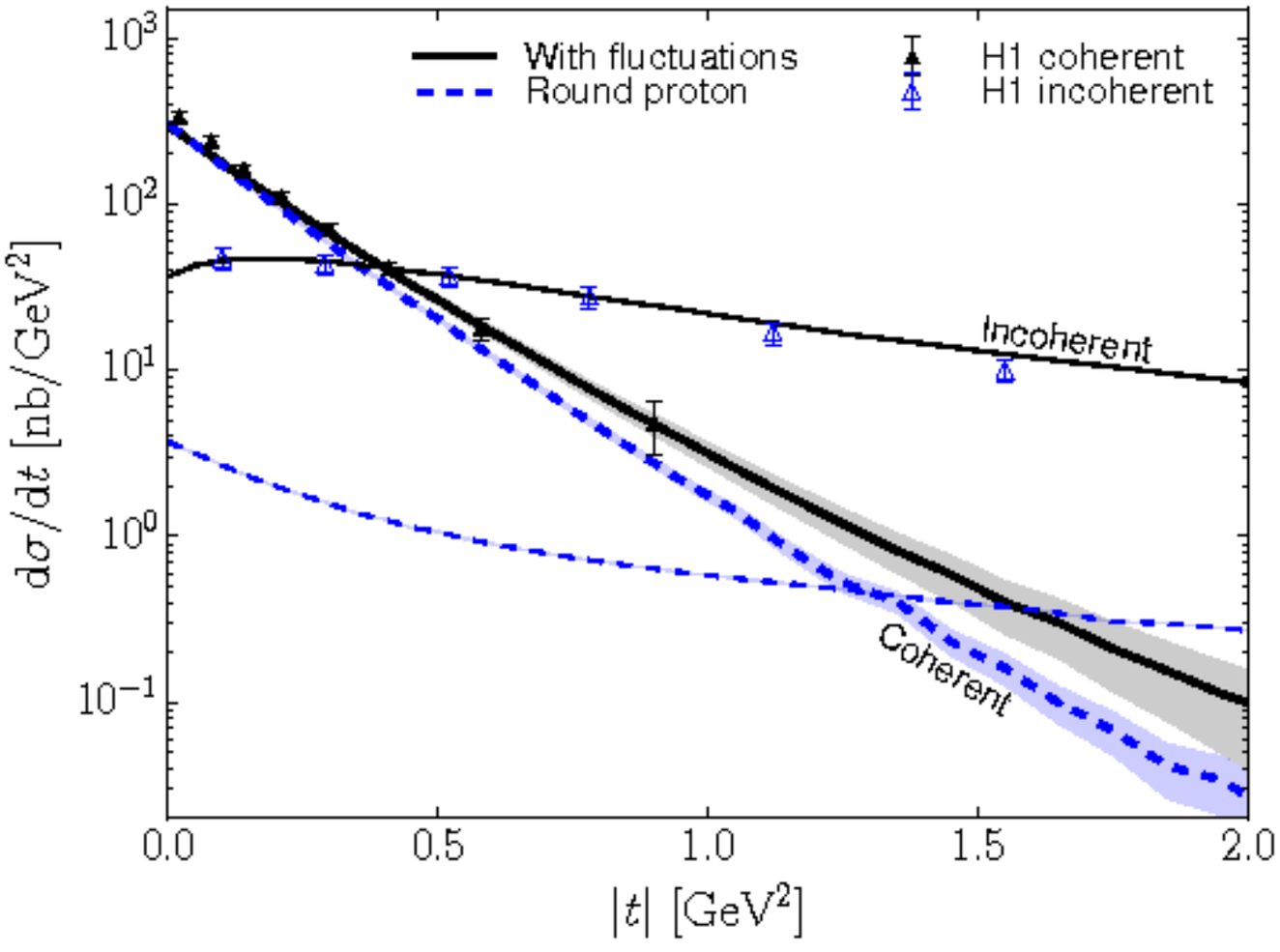
Miettinen, Pumplin, PRD18 (1978) 1696

Mantysaari, Schenke, PRL 117 (2016) 052301

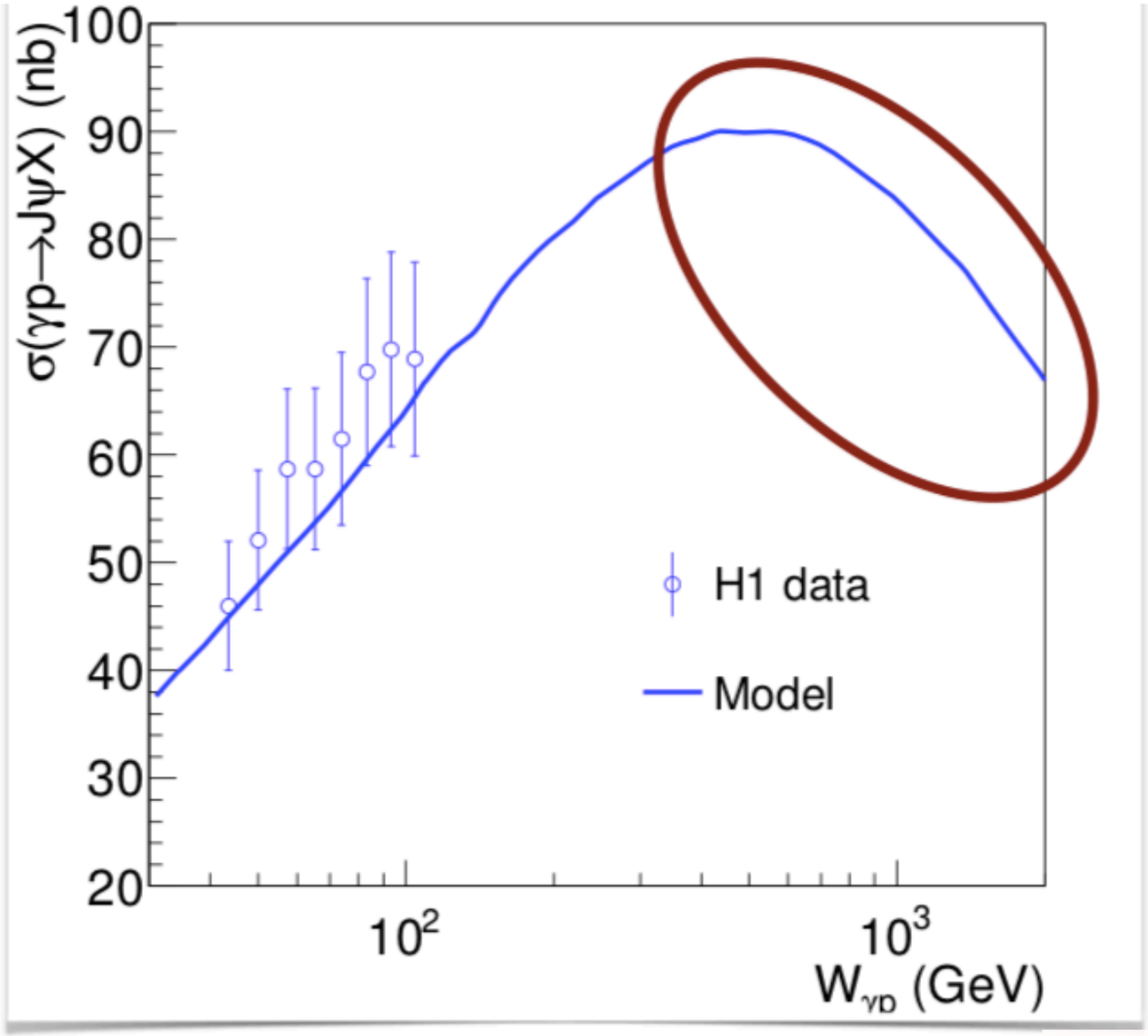
t-dependance

H. Mäntysaari





Energy dependance of the t-distribution for dissociative production



Phys. Lett. B766 (2017) 186-191

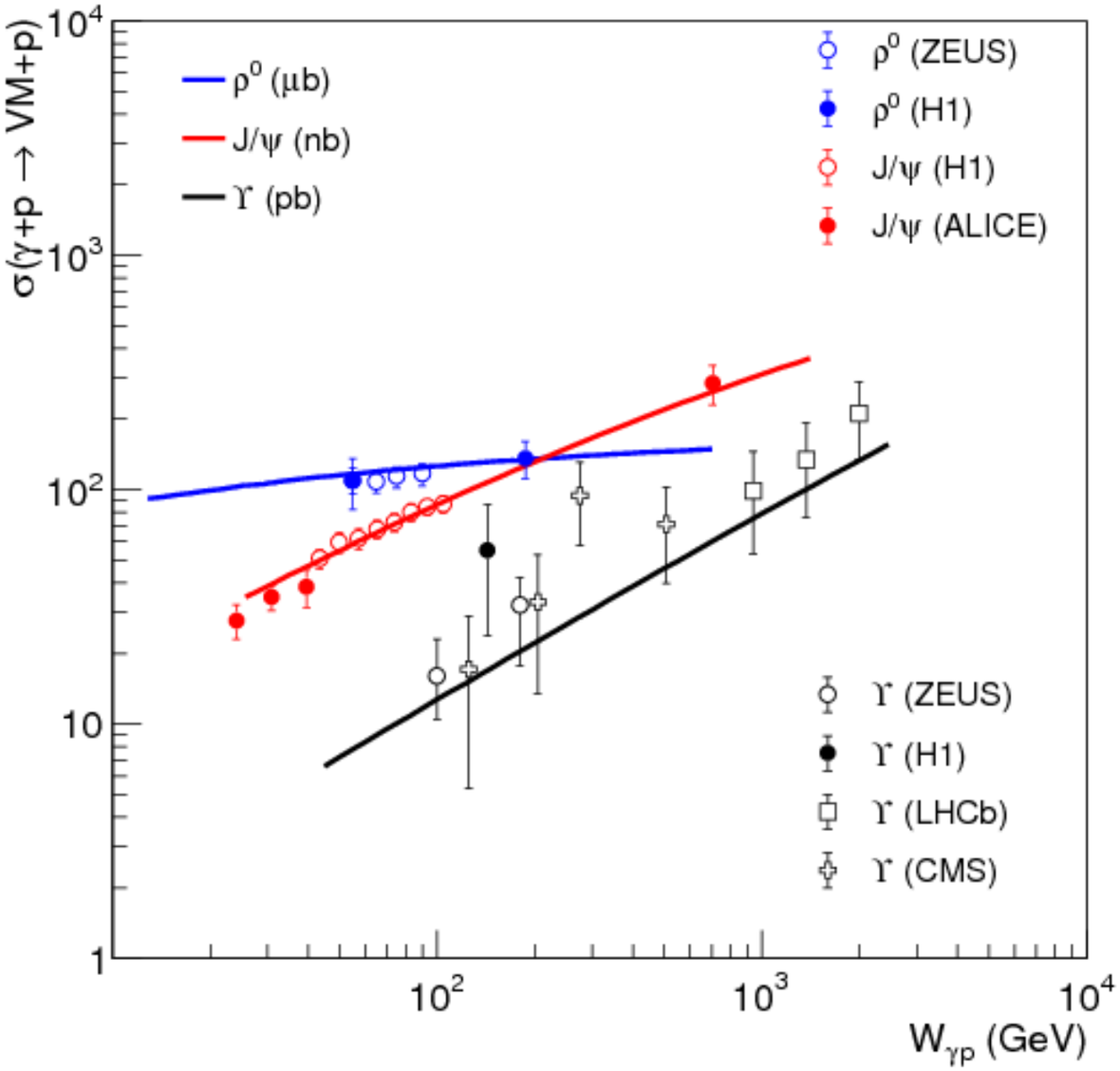
- The model predicts an **striking signature** for saturation:
  - As the number of hot spot grows, the hot spots fill up the proton.
  - When saturation is reached, all configurations are very similar and the variance over configurations tends to zero.

At the LHC we can measure J/ψ production accompanied by proton dissociation in this energy range!

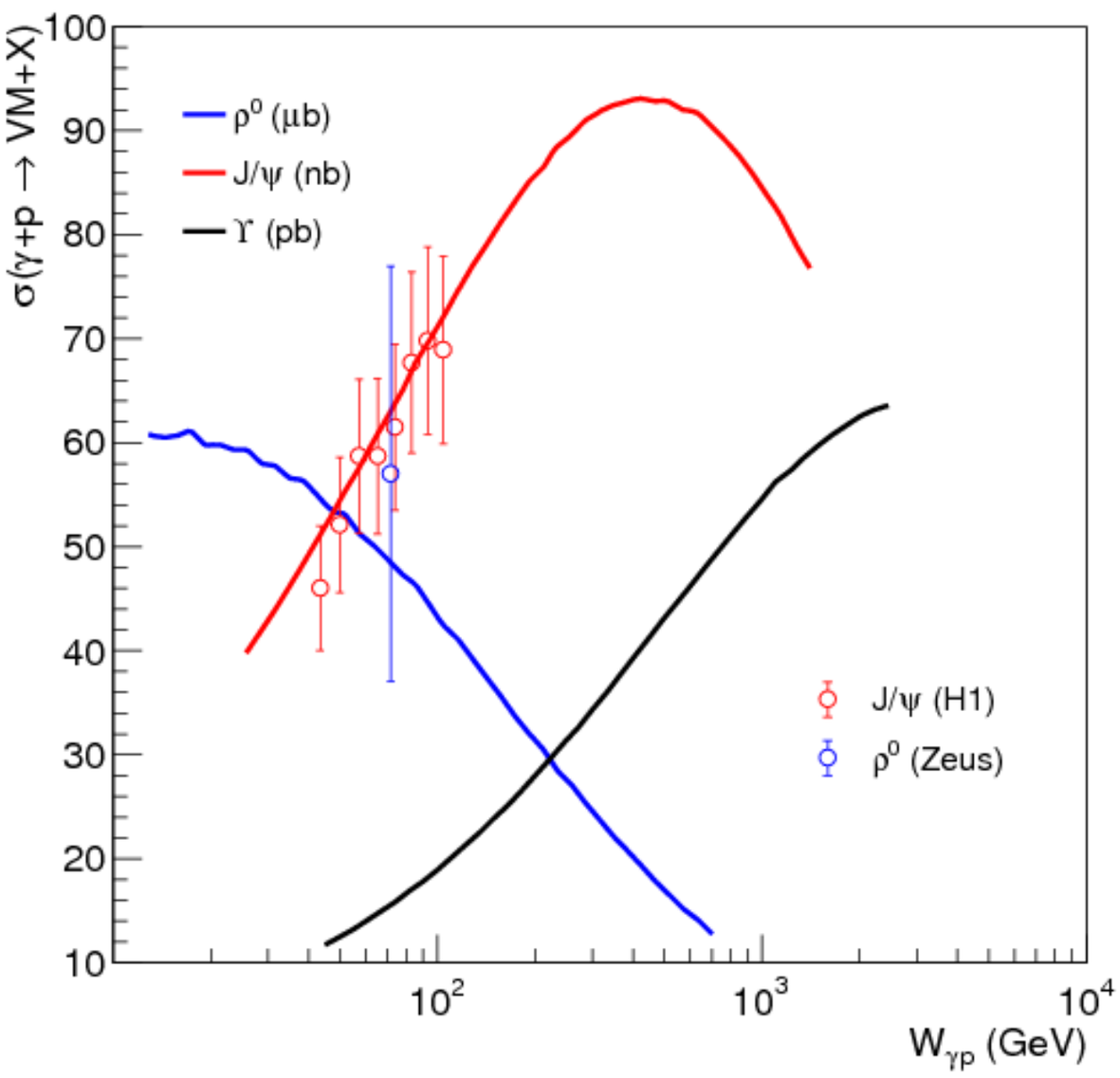
Mass dependance and energy dependance

Nucl. Phys. B934 (2018) 330-340

Exclusive



Dissociative



Neutron dependance and photon direction determination

Total cross section

Low W: x~ 10-2 **High W:** x~ 10-4

$$\frac{d\sigma_{\mathrm{PbPb}}(y)}{dy} = N_{\gamma/\mathrm{Pb}}(y, M)\sigma_{\gamma\mathrm{Pb}}(y) + N_{\gamma/\mathrm{Pb}}(-y, M)\sigma_{\gamma\mathrm{Pb}}(-y)$$

Neutron dependence

$$d\sigma(\mathrm{total})/dy = d\sigma(\mathrm{0n0n})/dy + 2d\sigma(\mathrm{0nXn})/dy + d\sigma(\mathrm{XnXn})/dy$$

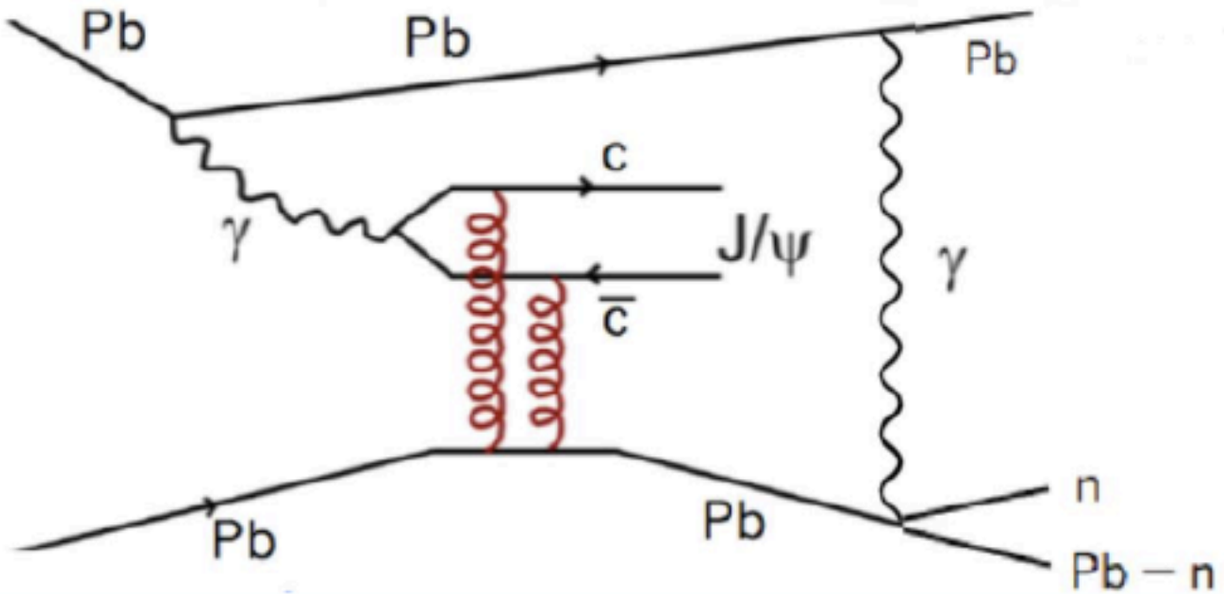
Vector meson is accompanied by at least one neutron on one side of the interaction point and no neutron activity on the other side

Neutron dependance and photon direction determination

Total cross section

Low W: x~ 10-2 **High W:** x~ 10-4

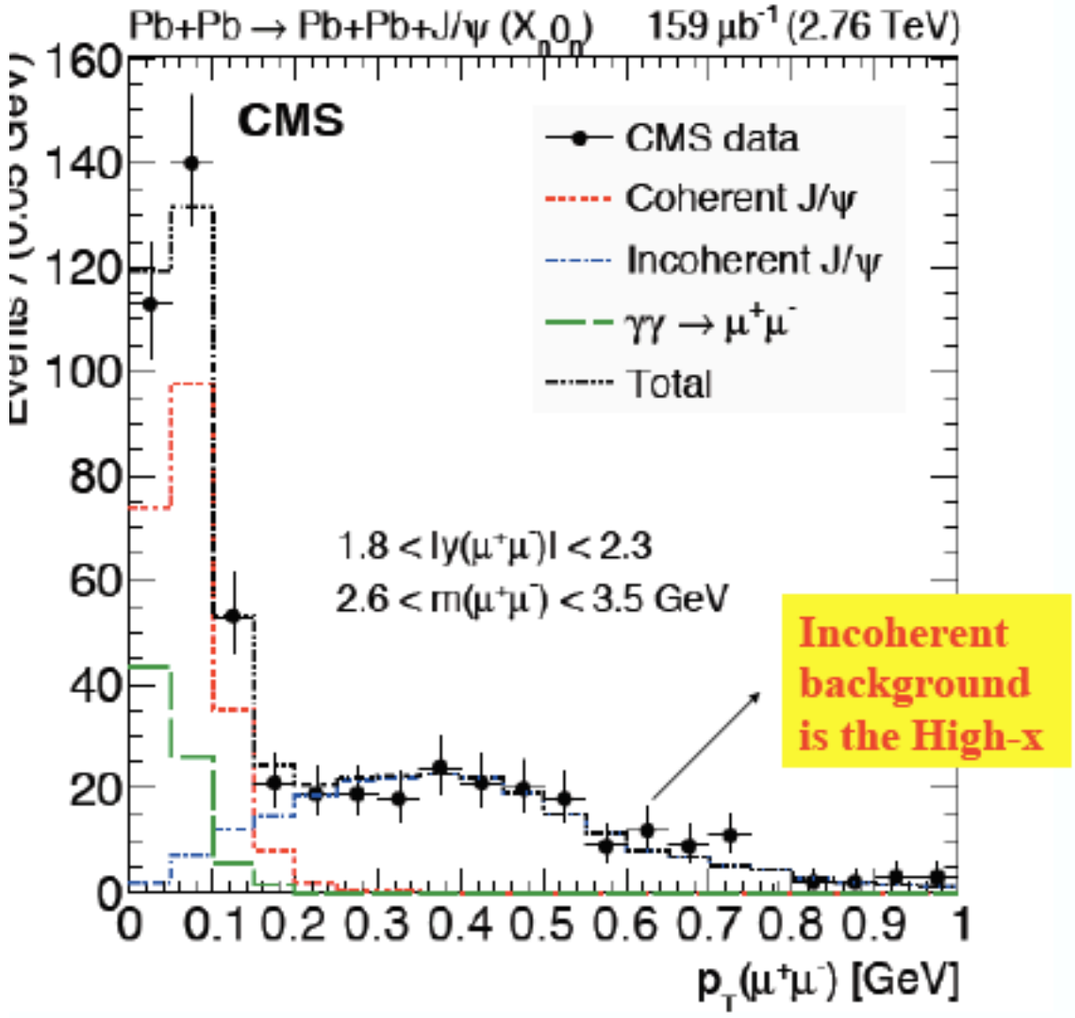
$$\frac{d\sigma_{\mathrm{PbPb}}(y)}{dy} = N_{\gamma/\mathrm{Pb}}(y, M)\sigma_{\gamma\mathrm{Pb}}(y) + N_{\gamma/\mathrm{Pb}}(-y, M)\sigma_{\gamma\mathrm{Pb}}(-y)$$



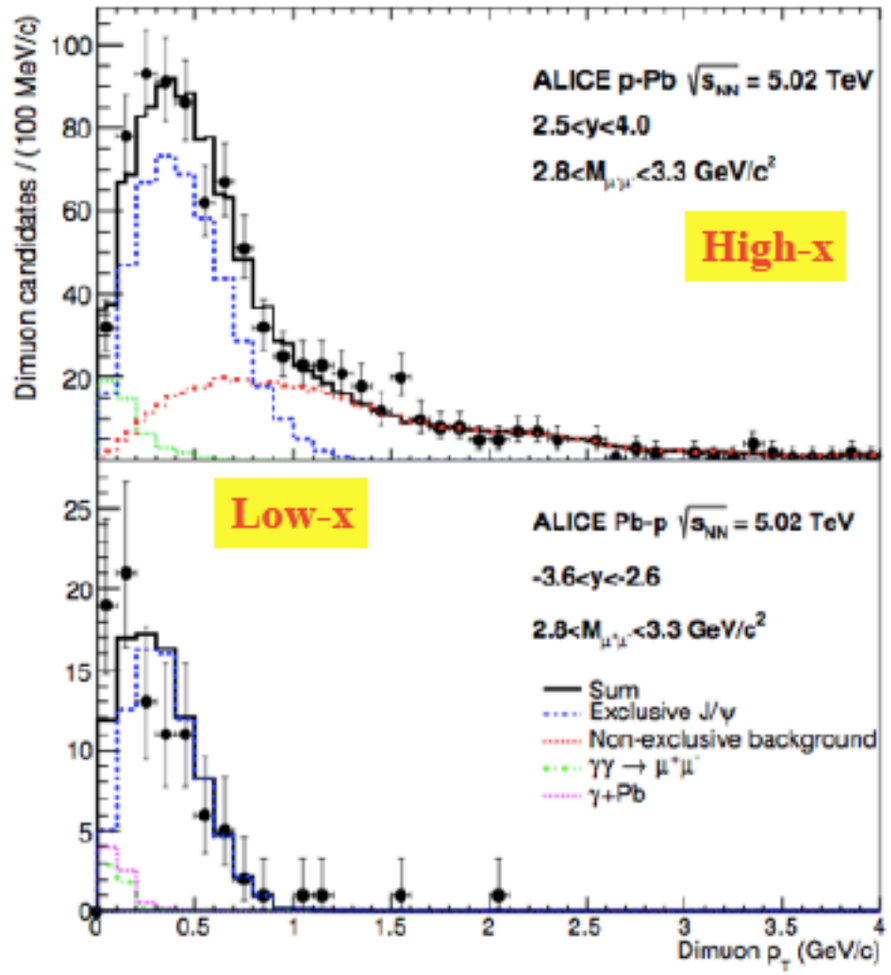
Incoherent production is expected to be more sensitive to the photon direction (energy dependence). Here 0nXn and Xn0n will unfold the two x-values

Neutron dependance and photon direction determination

γ+Pb interactions



γ+p interactions



Incoherent J/ψ background (Xn0n): ***Events are in the High-x region. At Low-x incoherent background is heavy suppressed***

In qualitative agreement with ALICE Collaboration. Phys. Rev. Lett. 113 (2014) 23, 232504 (see also J. Cepina et al. Phys. Lett. B766 (2017) 186-191)

Exclusive VM photo production

Caveats:

- J/ψ photoproduction probes generalized gluon distributions (two gluons have different x values):
  - Connected with collinear PDFs via Shuvaev transform: PRD 60 (1999) 014015
- Scale uncertainty ($\mu^2 \sim 2.4\text{-}3\ \text{GeV}^2$ is a reasonable choice)
- Large NLO contributions

ρ^0 photo-production

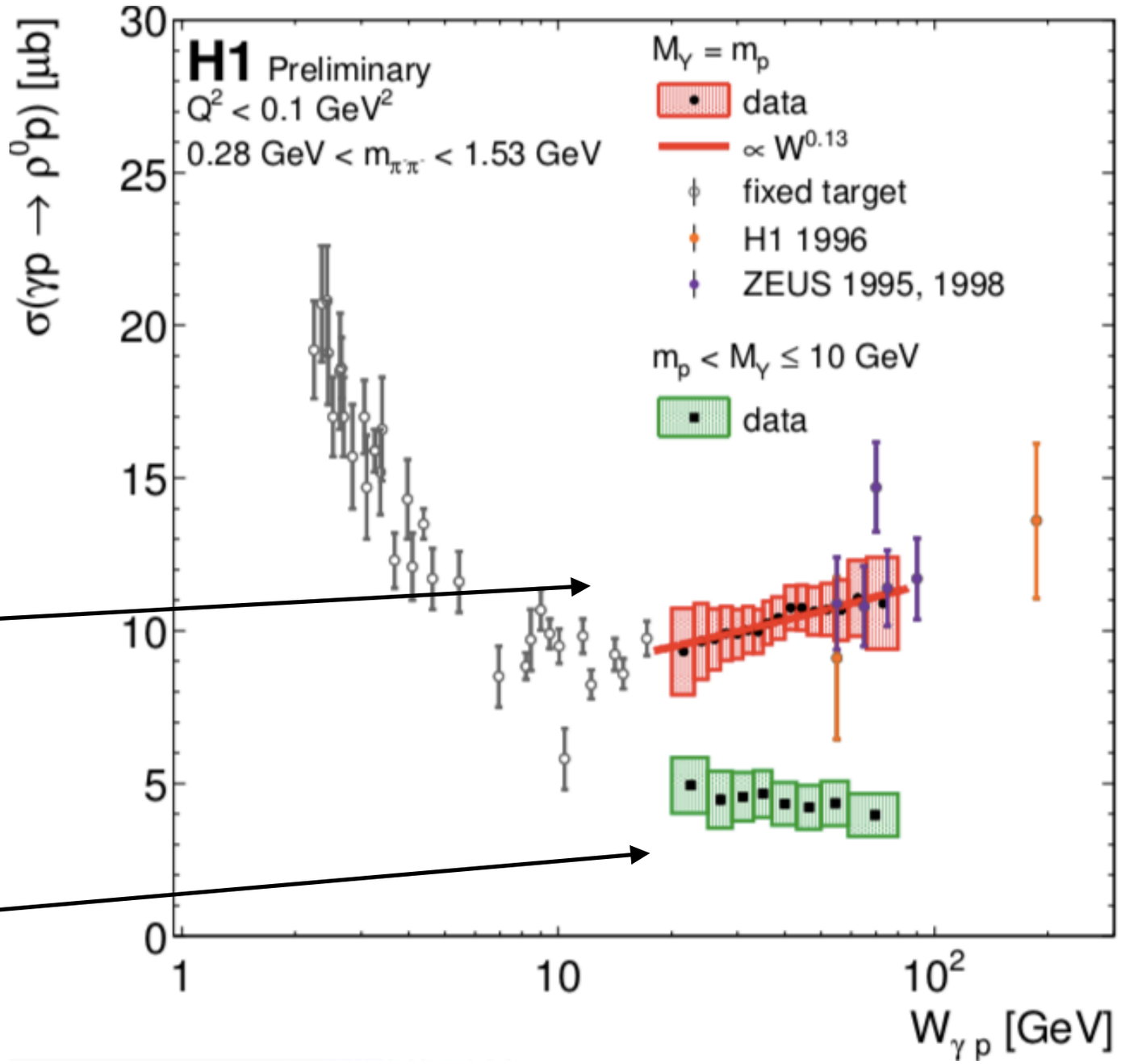
New H1 preliminary results

Arthur Bolz

ICHEP 2018

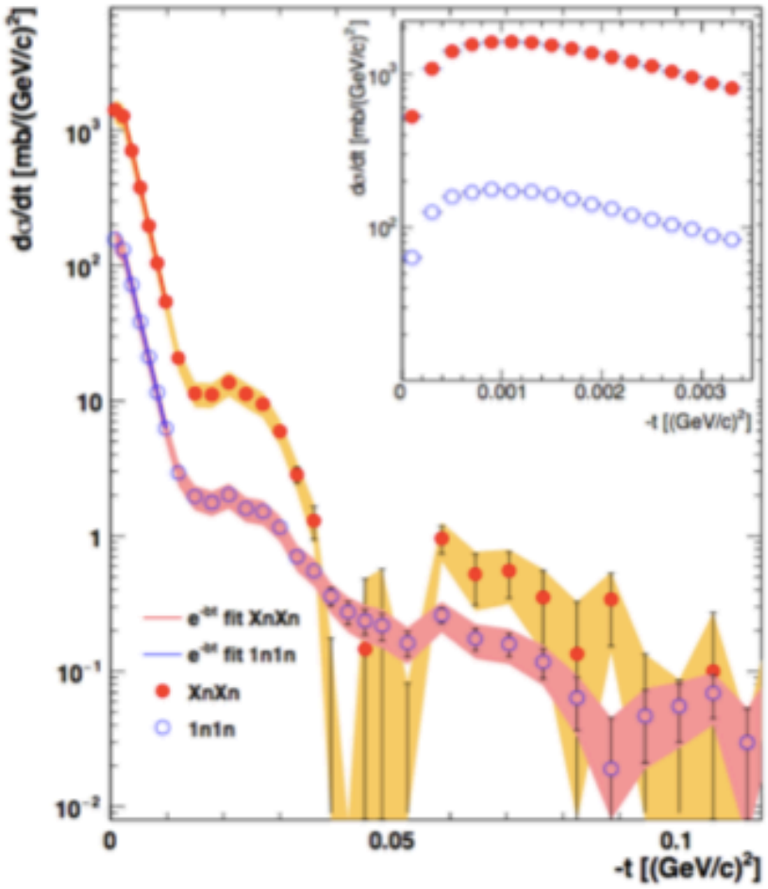
Exclusive

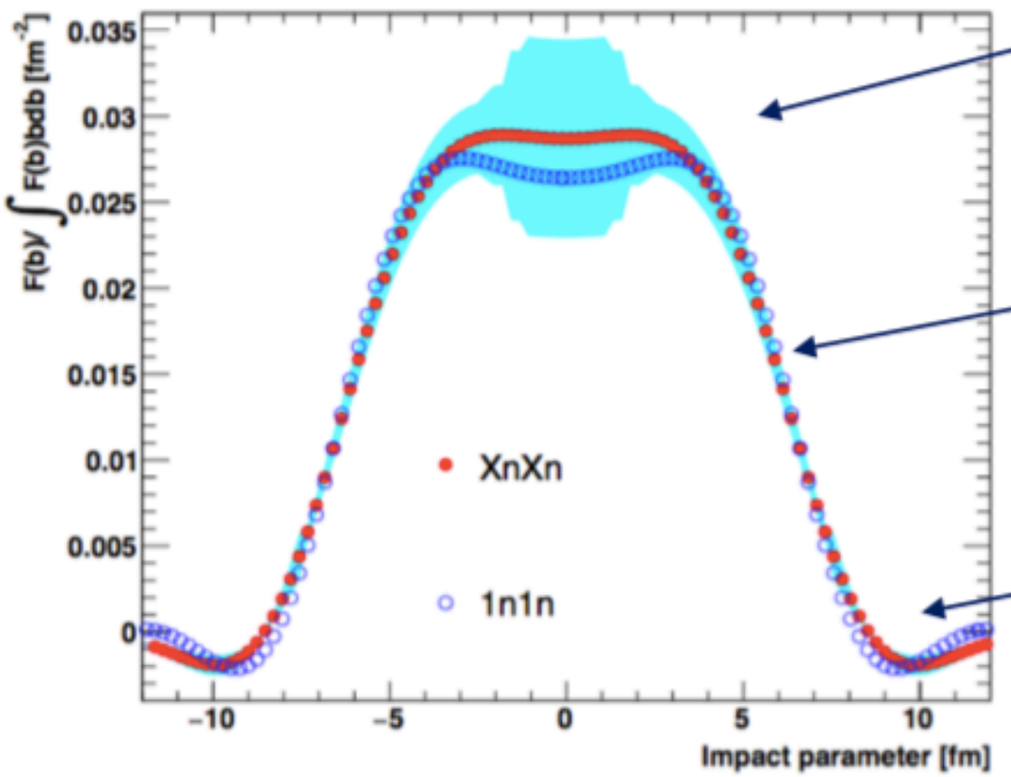
Dissociative



STAR results for ρ^0

S. Klein
DIS 2018





Large variation with t_{max} Windowing?

Sharp edges

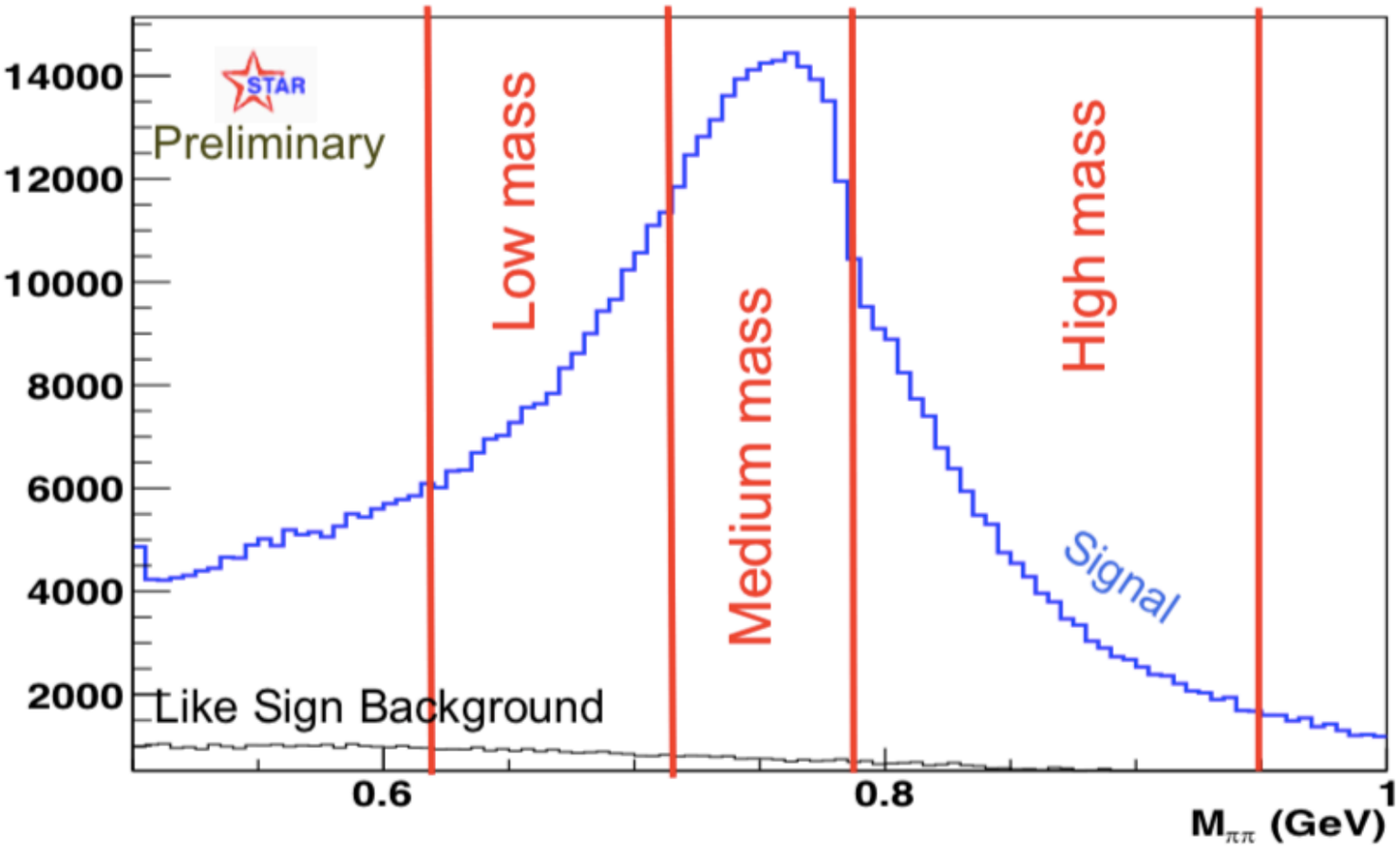
Negative due to destructive interference

STAR, Phys. Rev. **C96**, 054904 (2017)

Sensitive to the distribution of nuclear interaction sites within the nucleus

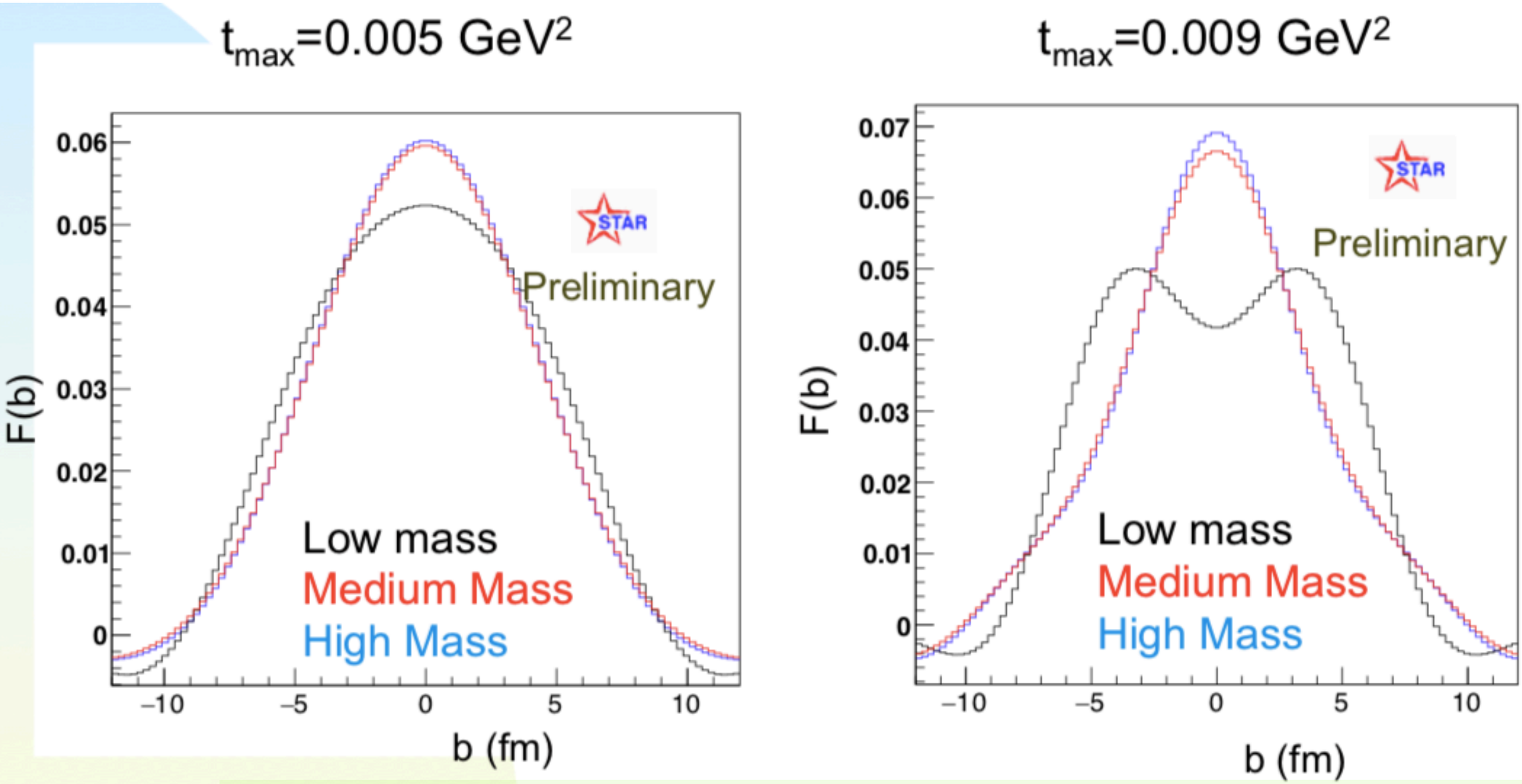
STAR preliminary results for ρ^0

S. Klein
DIS 2018



STAR preliminary results for ρ^0

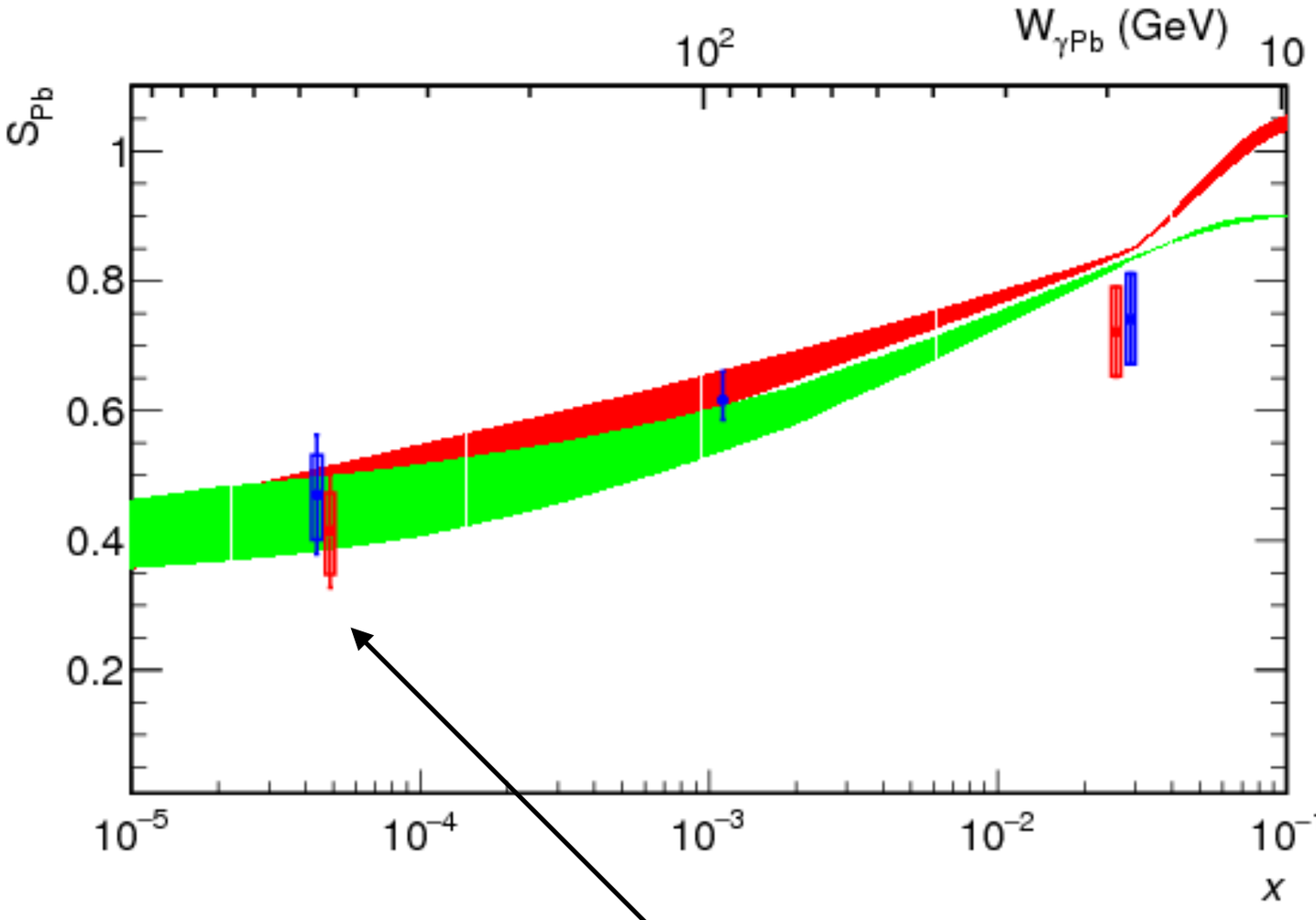
S. Klein
DIS 2018

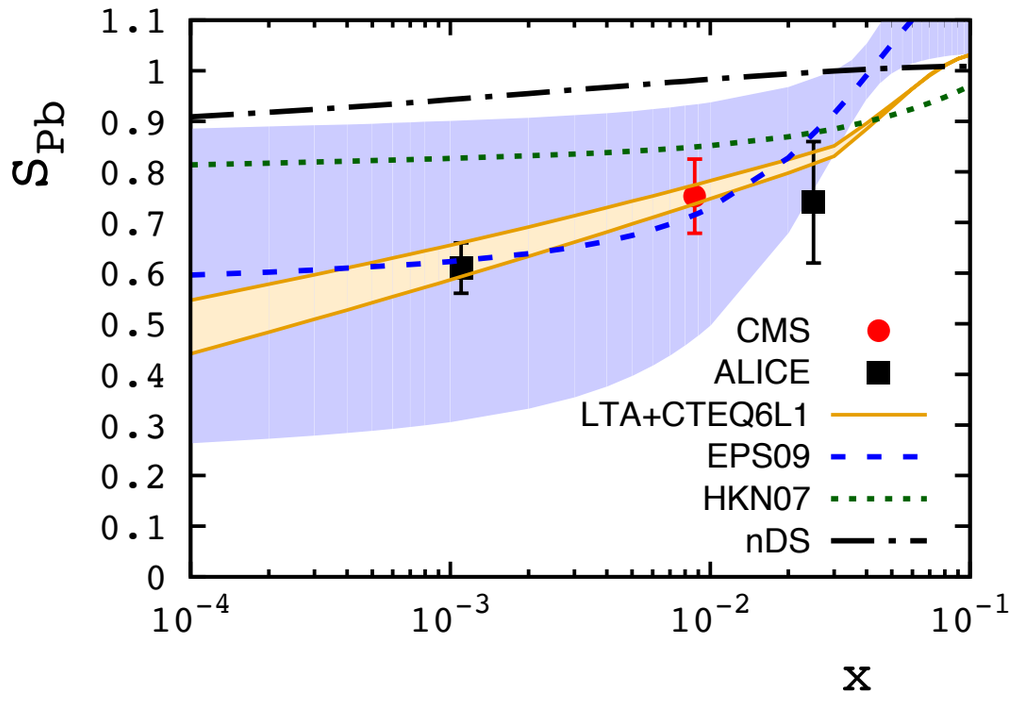


low-mass distribution is always wider than the others

Photon induced processes at b<2R

Phys.Rev. C96 (2017) no.1, 015203





From the low pT J/ψ in hadronic collisions

Thanks to different photon flux