Recent results on forward physics

DIS 2018
Kobe, Japan, 16-20 April, 2018

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Outline

"Forward Physics": The protons/nuclei continue in the forward direction, either in the ground state or "mildly" excited.

Particles may or may not be produced around mid-rapidity.

A personal selection of recent topics. Apologies to all whose results I do not cover.

- Elastic pp scattering.

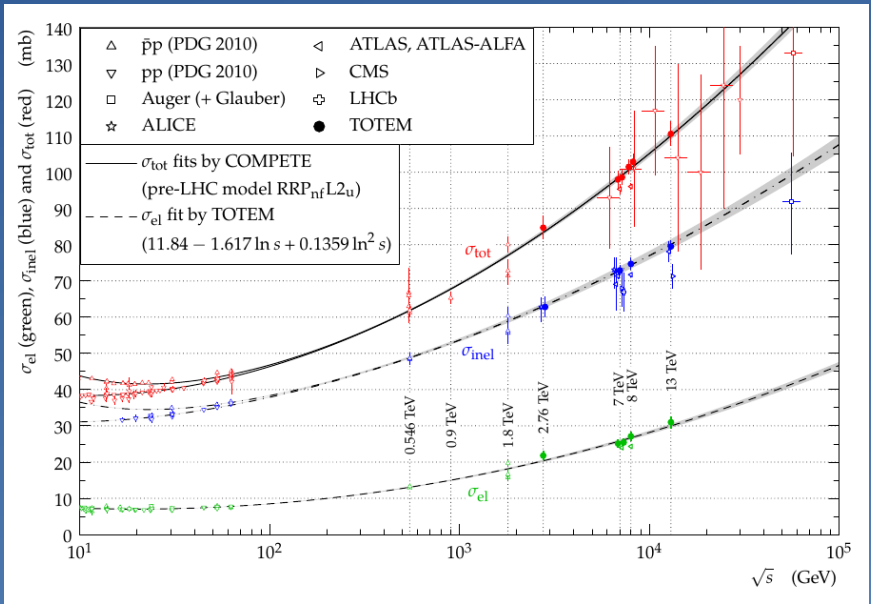
- Central exclusive (diffractive) production in pp.

- Ultra-Peripheral Collisions.

Elastic pp scattering

Elastic pp scattering and total cross section

Recent measurement by TOTEM Collaboration of σ_{tot}, $\sigma_{elastic}$ and $\sigma_{inelastic}$ at 13 TeV, ArXiv:1712.06153.



Totem arxiv:1712.06153

Measurement of $\sigma_{inelastic}$ also by CMS, for $M_X > 4.1$ GeV, $M_Y > 13$ GeV

$\sigma_{inelastic} = 68.6 \pm 0.5(syst.) \pm 1.6(lumi)$ mb

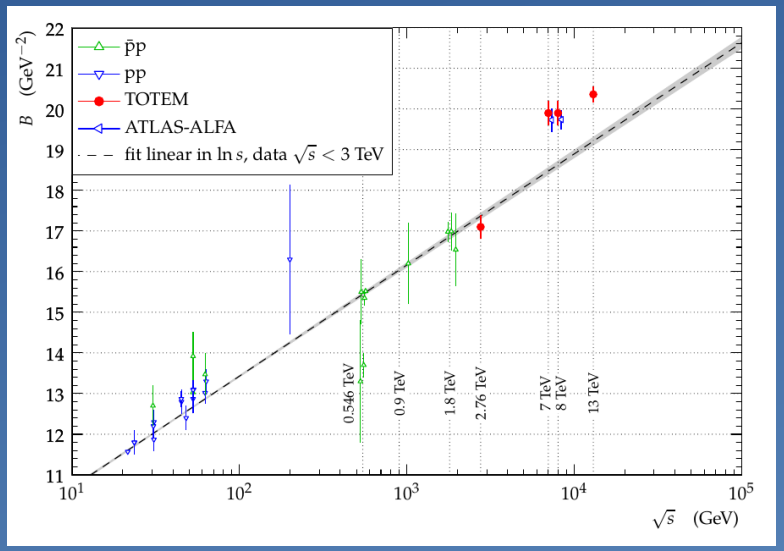
CMS arxiv:1802.02613

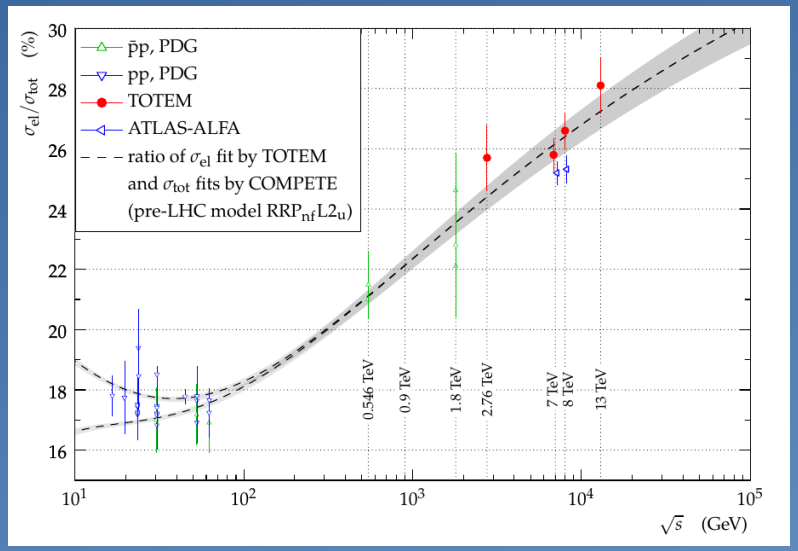
Elastic pp scattering and total cross section

Forward scattering amplitude described by exponential with slope B

$$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{-B|t|}$$

B increases with √s. ⇒ The proton grows with increasing energy.



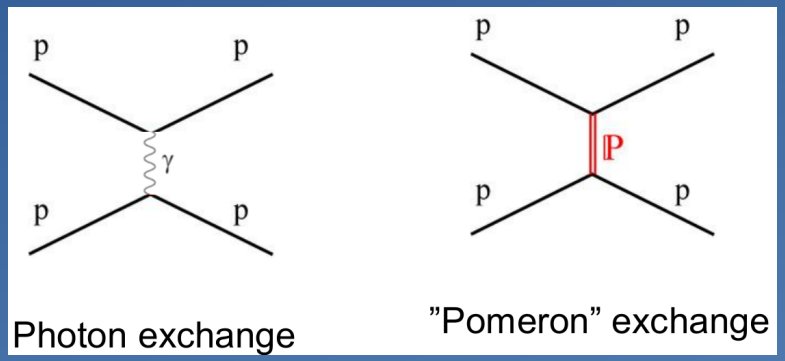


Totem arxiv:1712.06153

The ratio $\sigma_{elastic}/\sigma_{tot}$ increases with √s. ⇒ The proton becomes blacker ($\sigma_{elastic}/\sigma_{tot} \rightarrow 0.5$) with increasing energy.

Elastic pp scattering and total cross section

Totem has also measured ρ (ratio of real to imaginary part of the forward scattering amplitude).
This was done in the region where one has interference between Coulomb and strong scattering.

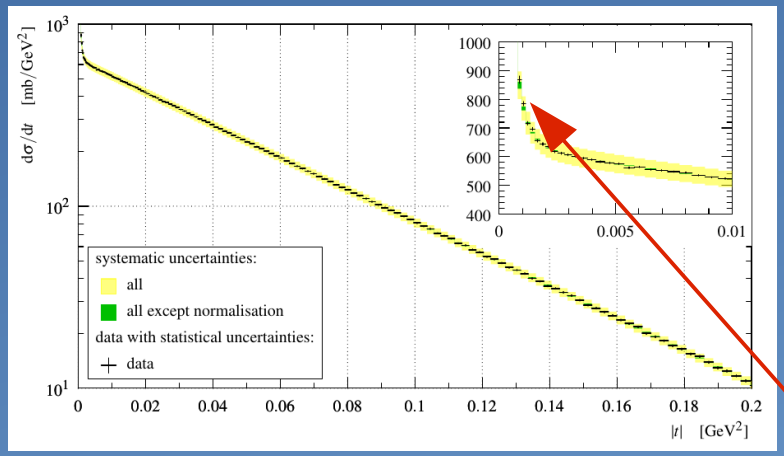


$$\frac{1}{\pi}\frac{d\sigma}{dt} = |f_C - f_S|$$

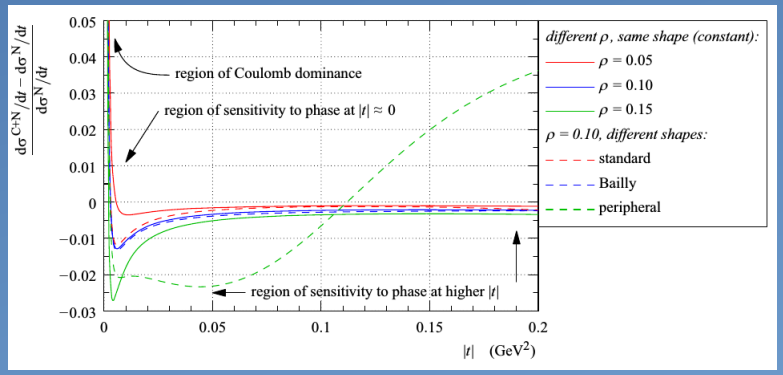
This leads to

$$\frac{1}{\pi}\frac{d\sigma}{dt} = K\left[\left(\frac{2\alpha}{t}\right)^2 G^4(t) - (\rho + \alpha\varphi)\frac{\alpha}{\pi}\sigma_T \frac{G^2(t)}{|t|} e^{bt/2} + \left(\frac{\sigma_T}{4\pi}\right)^2 (1+\rho^2) e^{bt}\right]$$

H. Bethe, Ann. Phys. (New York) 3 (1958) 190.



Maximum sensitivity for ρ when $f_C \approx f_S$.

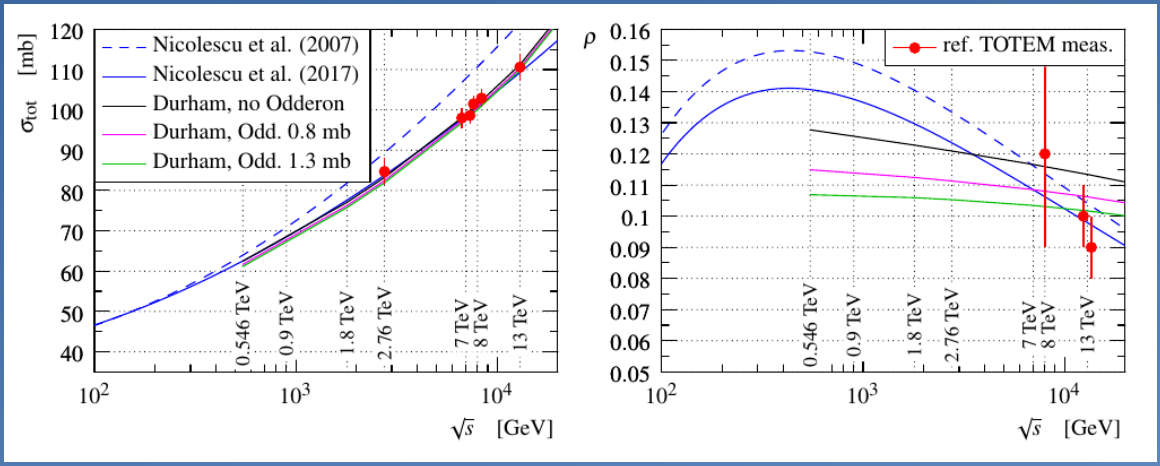


Coulomb dominates at very low $|t| < 10^{-3}$ GeV².

Elastic pp scattering and total cross section

Conclusion from Totem paper: Models fail to describe the combined σ_{tot} and ρ measurements.

A possible explanation might be a contribution from exchange of a $J^{PC} = 1^{--}$ state, corresponding to Odderon* or 3-gluon exchange.



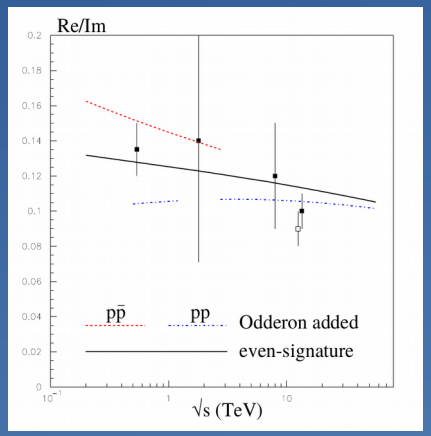
Totem CERN-EP-2017-335

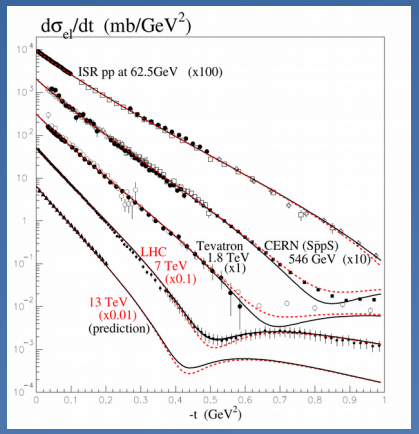
Presentation on this by E. Robutti on Wednesday.

*The Odderon was introduced in 1973 in the context of pp vs. $p\bar{p}$ scattering, L. Lukaszuk, B. Nicolescu, Lett. Nuovo Cim, 8 (1973) 405.

Elastic pp scattering and total cross section

Not clear to me how solid this conclusion is. The deviation from the Durham calculation with even signature exchange is just slightly above 1σ. The differential cross section in the dip region might provide more direct evidence.





V.A.Khoze, A.D.Martin, M.G.Ryskin, arXiv:1712.00325.

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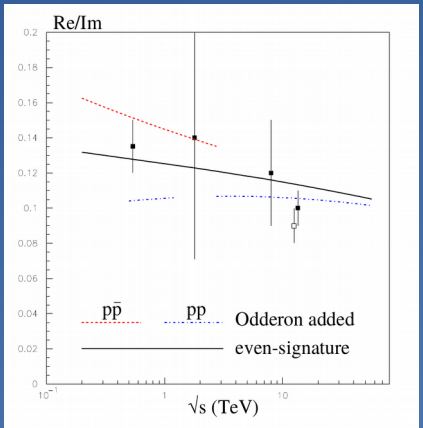

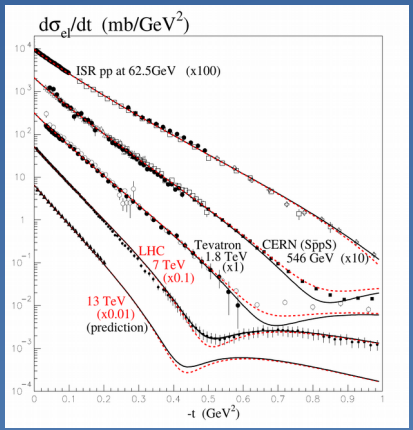

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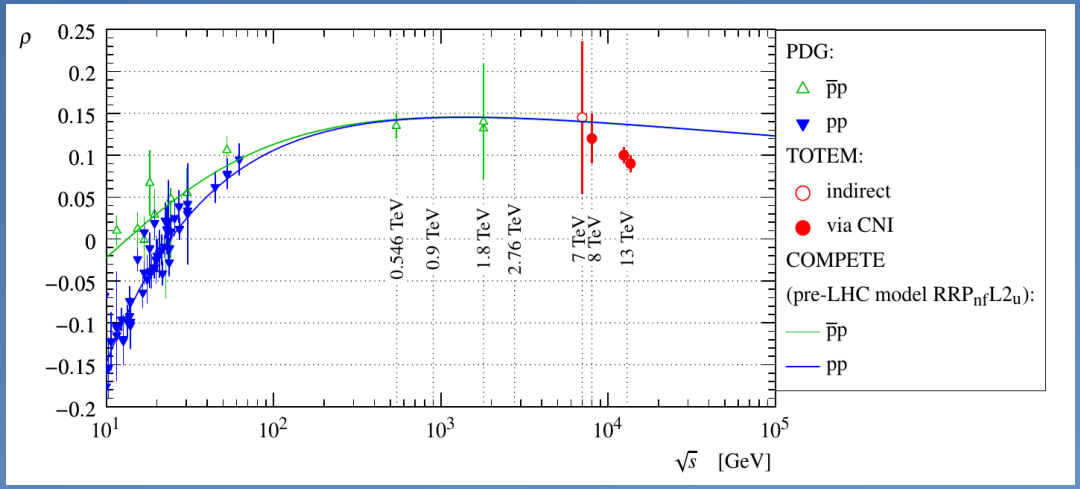


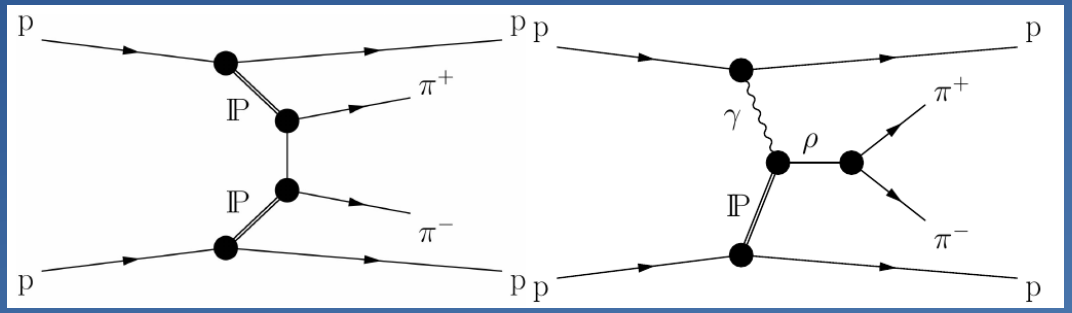
But value of ρ clearly below extrapolation from lower energies in a plot vs. √s.

Totem CERN-EP-2017-335

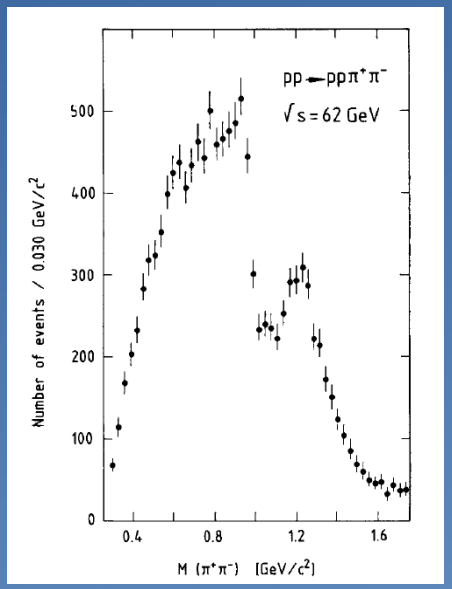
Central Exclusive Production

Central exclusive production in pp

Central exclusive production: p+p → p+p+X



For X = hadrons ($\pi^+\pi^-$), Pomeron+Pomeron expected to dominate with a contribution from photoproduction of Vector Mesons (ρ).



Studied for a long time.

Low mass region characterized by

-Continuum contribution.

-Resonance contribution from $f_2(1270)$.

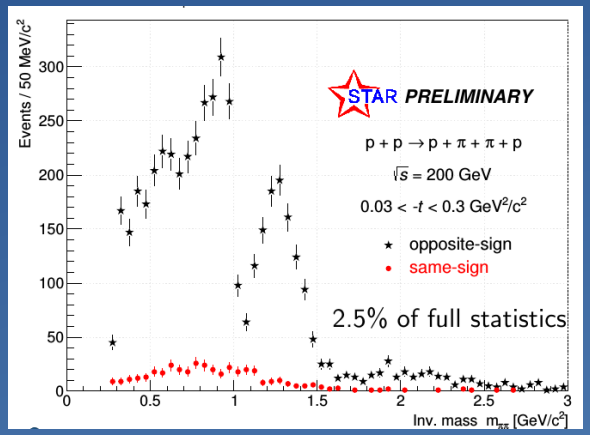
-Resonance contribution from $f_0(980)$, "peak" distorted by interference between resonance and continuum.

-Contribution from photoproduced ρ.

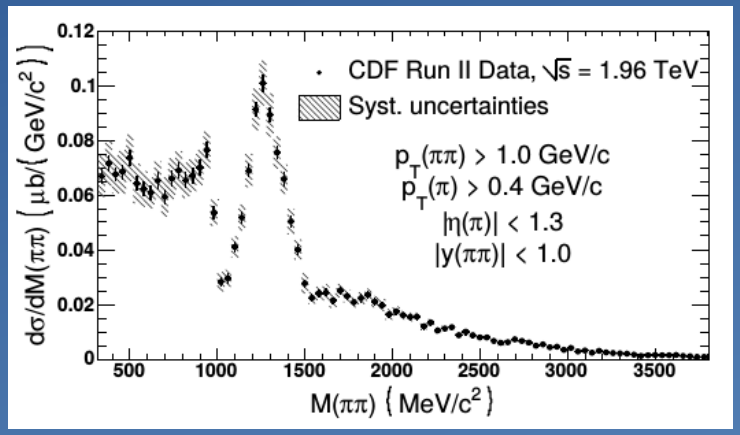
A. Breakstone et al., Z. Phys. C 32 (1986) 185

Central, exclusive production in pp

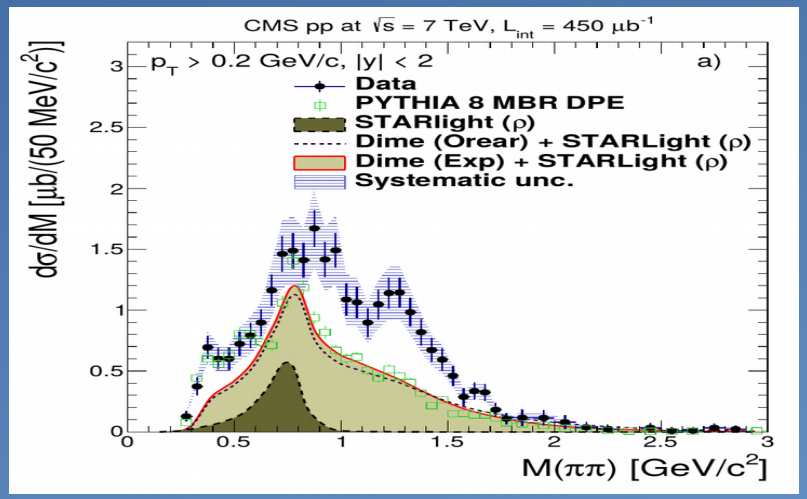
- Appears to be a universal, energy independent observation.
- Similar features observed at RHIC, Tevatron, LHC.



STAR, R. Sikora, Diffraction 2016.



CDF, Phys. Rev. D 91 (2015) 091101.



CMS, arXiv:1706.08310

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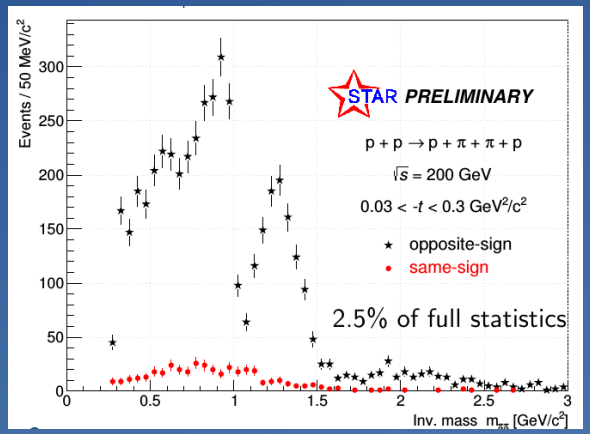
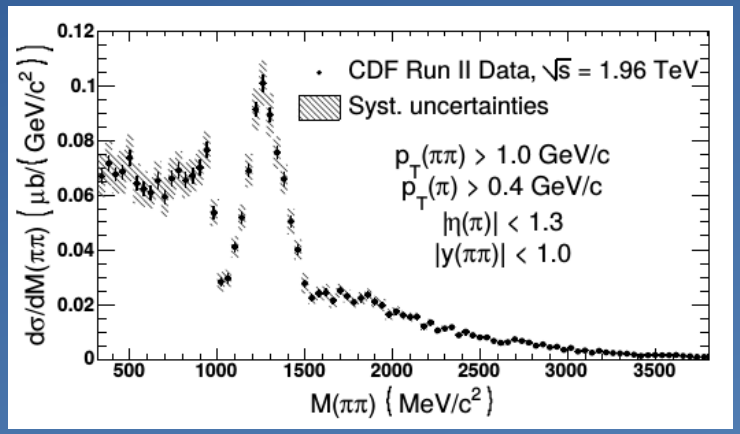
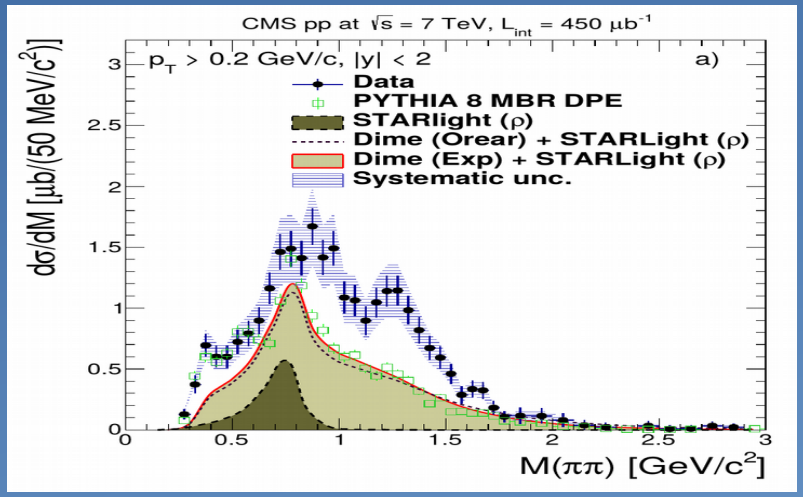


STAR, R. Sikora, Diffraction 2016.



CDF, Phys. Rev. D 91 (2015) 091101.



CMS, arXiv:1706.08310

- But what can one learn from it?

Central exclusive production in pp

There are not too many theoretical predictions around.

One recent, however, is P. Lebiedowicz, O. Nachtmann, A. Szczurek, Phys. Rev. D 93 (2016) 054015.

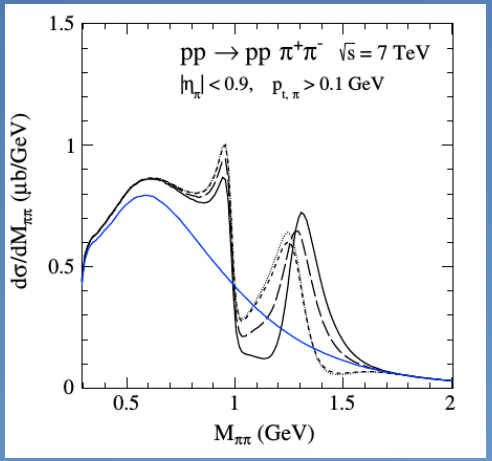
- Calculate cross section for continuum and resonance production from fusion of two tensor Pomerons.

- Reproduce the prominent features of the exclusive M_{inv} spectrum.

- Identify 7 (so far unknown) Pomeron-Pomeron-f2 couplings based on an effective field theory approach.

- Comparison with data will constrain these couplings.

More model predictions would be desirable to understand the underlying physics.

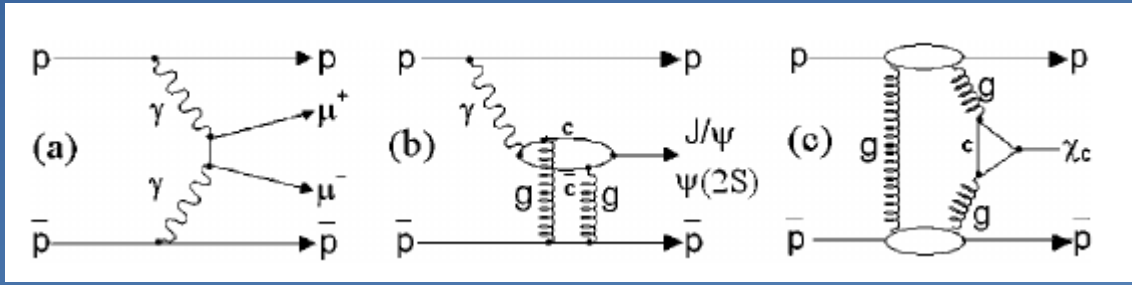


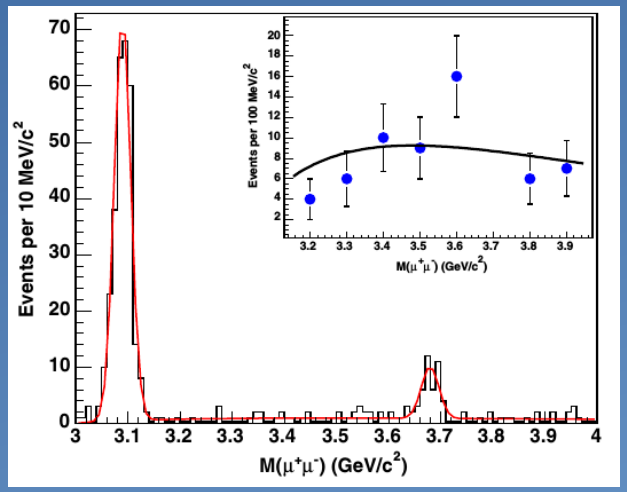
PRD 93 (2016) 054015

Central exclusive production in pp

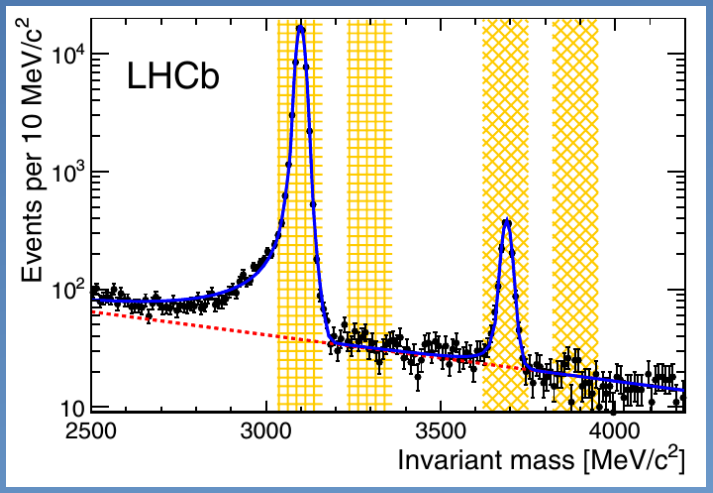
Central, exclusive production: p+p → p+p+X, with X = dilepton pair.

Dominant contribution from
γ+Pomeron → Vector Meson → l^+l^- and
$\gamma+\gamma$ → l^+l^-.





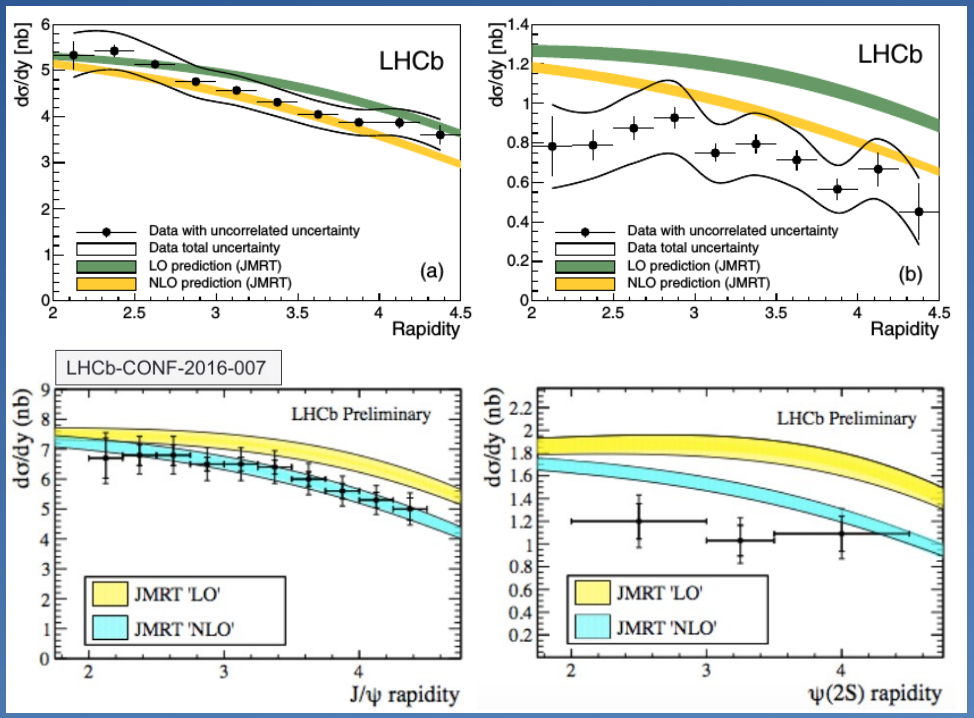
CDF, Phys. Rev. Lett. 102 (2009) 242001.



LHCb, J. Phys. G 41 (2014) 055002.

Central exclusive production in pp

LHCb has measured dσ/dy for exclusive J/ψ and ψ(2S) photoproduction.



LHCb, J. Phys. G 41 (2014) 055002.

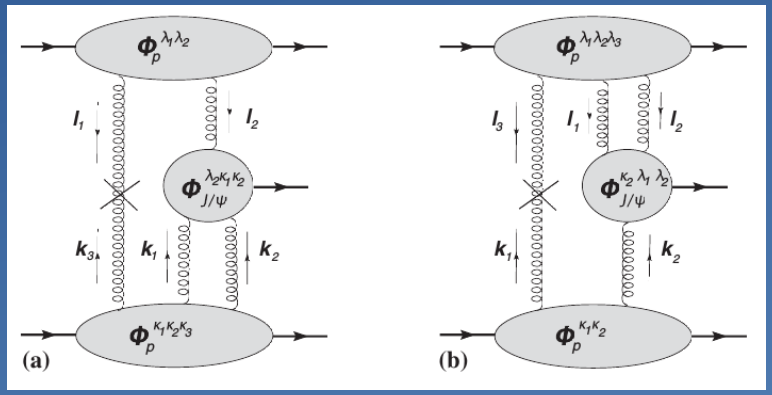
Cross section is a convolution of the photon spectrum with the photonuclear cross section.

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

From dσ/dy one can thus extract σ(γ+p → V+p), but the two-fold ambiguity in photon energy makes this difficult, more on this in the UPC section.

Central exclusive production in pp

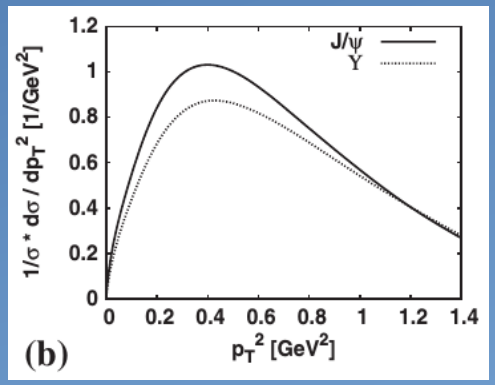
Exclusive vector meson production (through Odderon+Pomeron fusion) is an alternative channel to search for the Odderon: A. Bzdak, L. Motyka, L. Szymanowski, J.R. Cudell, Phys Rev. D 75 (2007) 094023.



At midrapidity $d\sigma(y=0)/dy$ (calculations done for 14 TeV)

	γp Starlight*	Odderon+Pomeron (Bzdack et al.)
J/ψ	7.5 nb	0.3 – 4 nb
$\Upsilon(1S)$	24 pb	1.7 – 21 pb

Upper range for J/ψ may already be excluded.
The p_T distributions will be different as well.

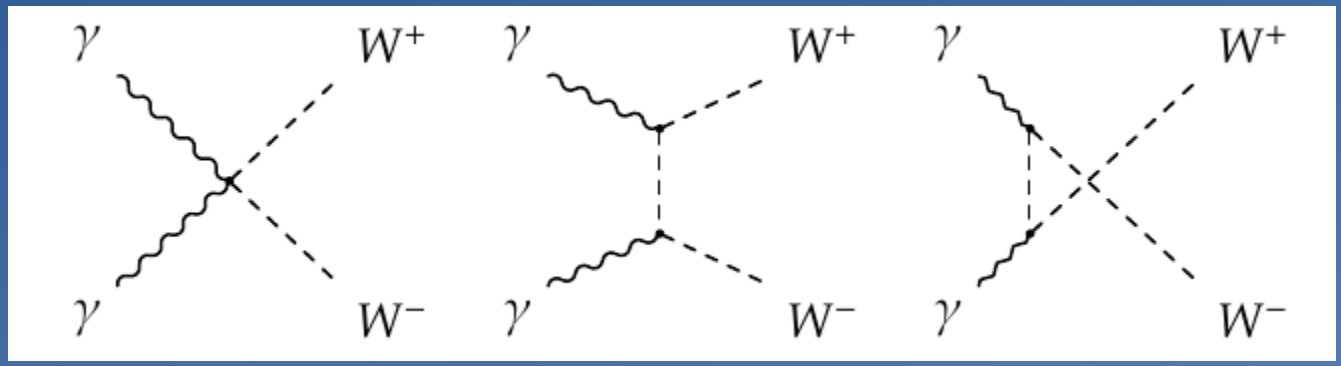


* S.R. Klein, J. Nystrand Phys. Rev. Lett. 92 (2004) 142003.

Central exclusive production in pp

Two-photon production of W^+W^- pairs.

LO diagrams for $\gamma\gamma \rightarrow WW$



Involves triple γWW and quartic γγWW couplings.

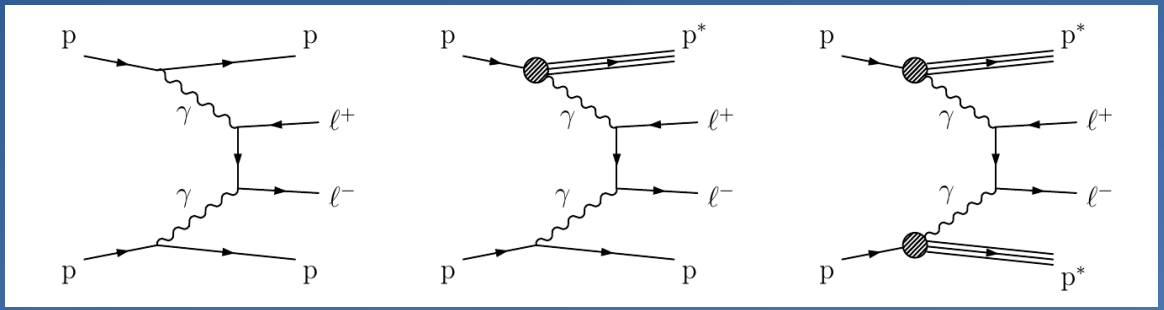
Has been observed by Atlas (3.0σ significance) and CMS (3.4σ significance).
Atlas: Phys. Rev. D 94 (2016) 032011; CMS: JHEP 08 (2016) 119.

Yield consistent with Standard Model expectations.

Sets the best limit so far on any anomalous quartic γγWW coupling.

Central exclusive production in pp

Central exclusive production typically include events where the protons remain intact or dissociate.



Calculations are usually done for the elastic case only.

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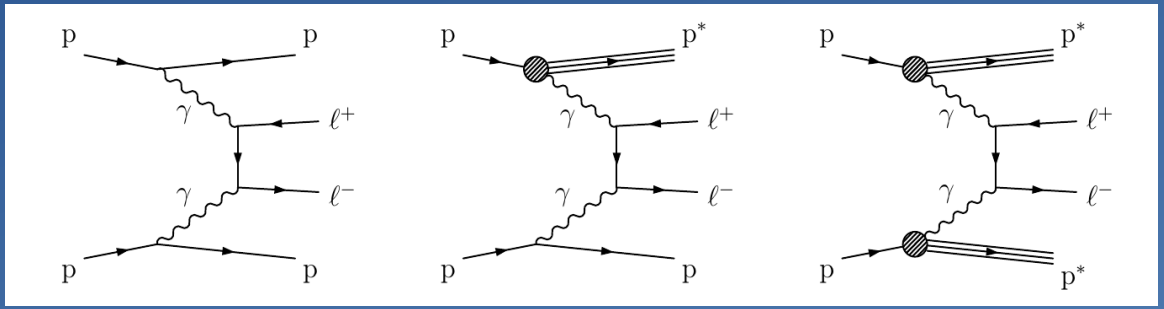


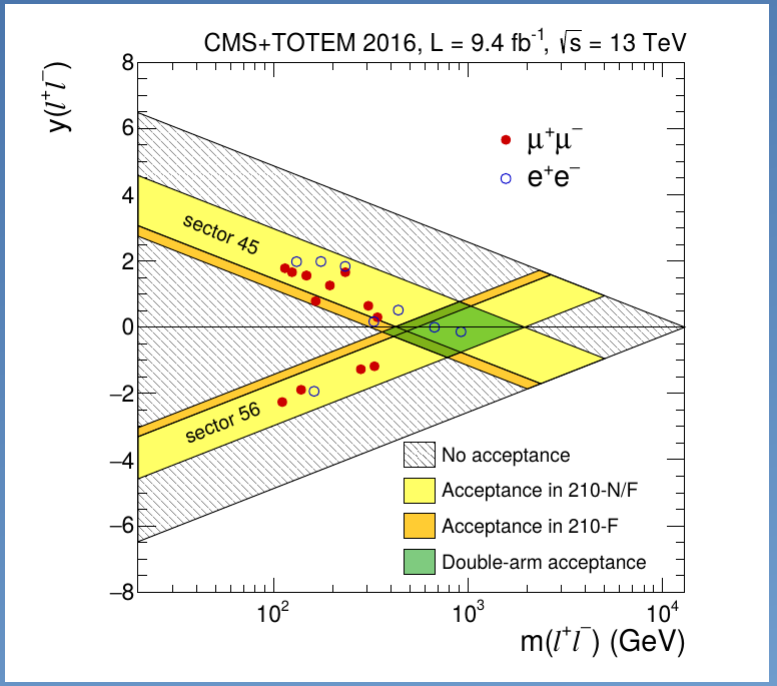
Calculations are usually done for the elastic case only.

Recent measurement by the CMS+Totem collaboration: dilepton pair production with one proton tagged, arXiv:1803.04496.

- Results for $M_{inv}(l^+l^-) > 110$ GeV in good agreement with expectations.

- Tagging both protons would require $M_{inv}(l^+l^-) > 400$ GeV.

- Should help resolve theoretical uncertainties related to proton dissociation.

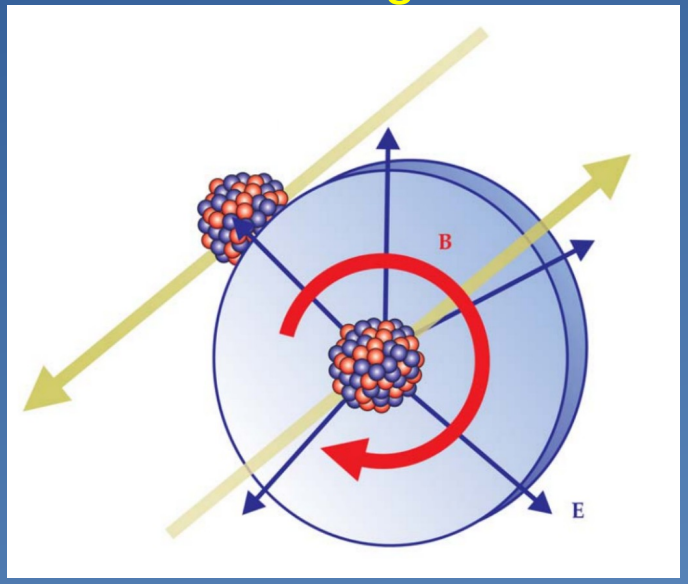


Ultra-Peripheral Collisions

What are Ultra-Peripheral Collisions?

Collisions between nuclei and protons with impact parameters larger than the sum of the radii.

Strong interactions suppressed. Interactions instead mediated by the electromagnetic field.



The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

Two-photon and photonuclear/photon-proton interactions can be studied at unprecedented energies in UPC at the LHC.

It's a matter of definition, by I would call the γp and $\gamma\gamma$ interactions in pp collisions in the previous section UPC.

Recent review of UPC: S.R. Klein, J. Nystrand, Physics Today 70 (2017) 40, October issue.

UPC vs. e+e- and ep collisions

Traditionally, photon-induced interactions studied with lepton beams.

$\gamma\gamma$ at LEP, Belle, ...

γp at HERA, fixed target experiments.

Hadronic collisions: γ-energy << beam energy.
Coherence requirement ==> max. γ-energy limited by Form Factor.

Max. E$\gamma \sim \gamma$/R R – radius of nucleus/proton

At LHC	pp	pPb	PbPb
Max $W_{\gamma\gamma}$	2 TeV	240 GeV	150 GeV
Max $W_{\gamma p}$	5 TeV	1.4 TeV	900 GeV

Exclusive processes: A+A → A+A+X
$\gamma\gamma \rightarrow$ X
γA → X+A

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Two-photon production of lepton pairs at the LHC

Leading order QED calculation. The Breit-Wheeler cross section (1934)

$$\sigma_{\gamma\gamma} = \frac{4\pi\alpha^2}{W^2}\left[\left(2+\frac{8M^2}{W^2}-\frac{16M^4}{W^4}\right)\ln\frac{W+\sqrt{W^2-4M^2}}{2M} - \sqrt{1-\frac{4M^2}{W^2}}\left(1+\frac{4M^2}{W^2}\right)\right]. \quad (10)$$

is convoluted with the photon spectra from the two nuclei:

$$\sigma(A + A \rightarrow A + A + X) = \int dk_1 dk_2 \frac{n(k_1)}{k_1}\frac{n(k_2)}{k_2}\sigma[\gamma\gamma \rightarrow X(W)],$$

The $n(k_1)$ and $n(k_2)$ are the Weizsäcker-Williams photon fluxes from the two nuclei.

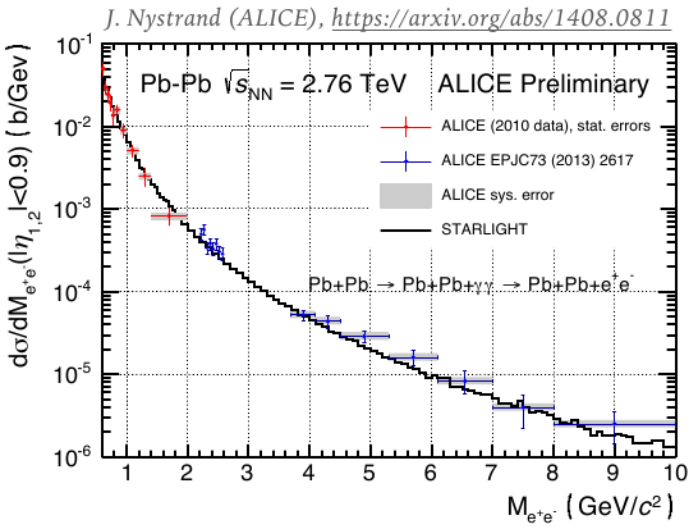
Implemented in the STARLIGHT Monte Carlo (A.J. Baltz, Y. Gorbunov, S.R. Klein, J. Nystrand, Phys. Rev. C 80 (2009) 044902).

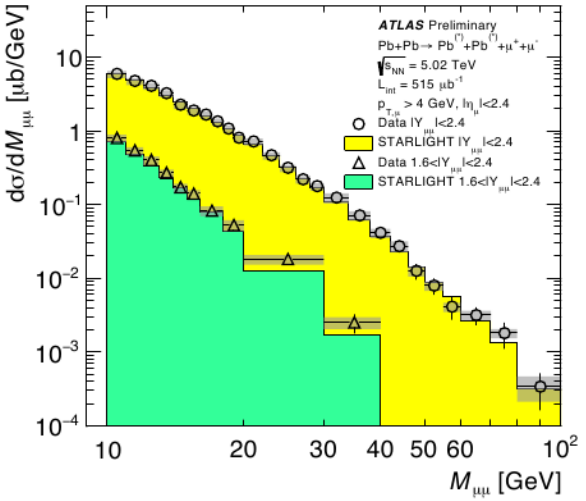
Two-photon production of lepton pairs at the LHC

Measurements by ALICE ($0.5 < M_{inv} < 10$ GeV/c^2) and ATLAS ($10 < M_{inv} < 100$ GeV/c^2) in good agreement with expectations.

ALICE & ATLAS RESULTS

ATLAS-CONF-2016-025

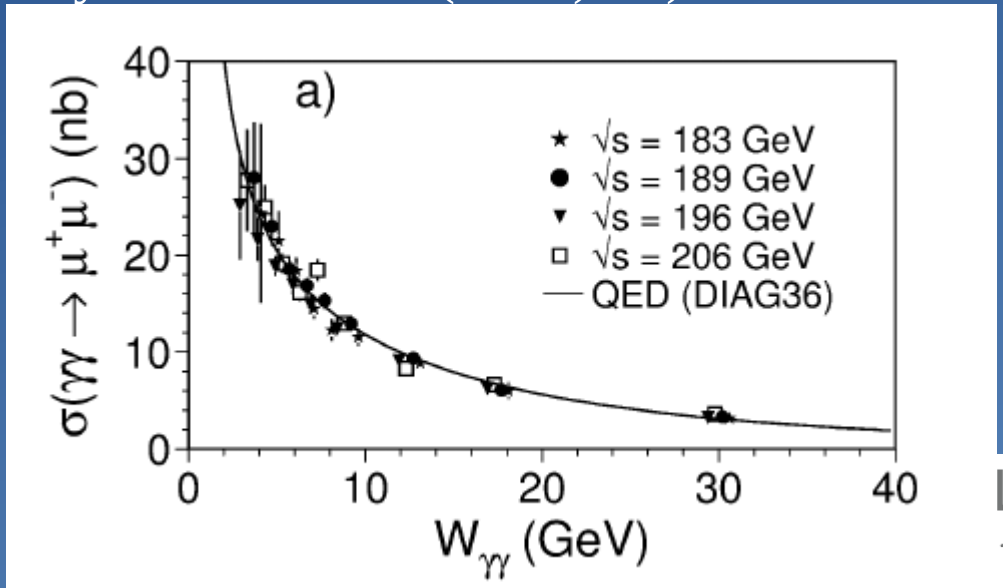




The relatively simple calculation in STARLIGHT thus reproduces the measurements over nearly 9 orders of magnitude in cross section and more than two orders of magnitude in M_{inv}!

Two-photon production of lepton pairs at the LHC

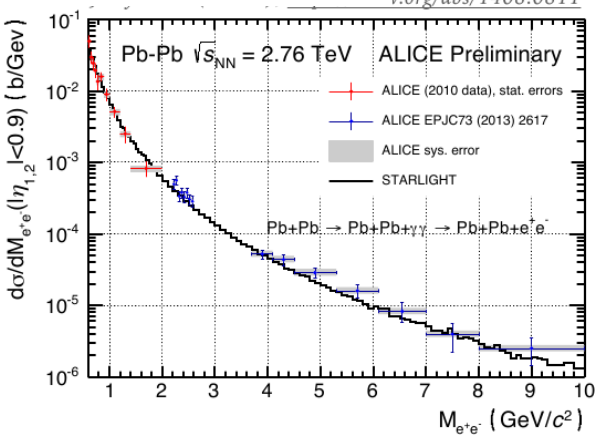
A clear extension of the dynamical range compared with the corresponding measurement in e^+e^- collisions (L3 Experiment at LEP, Phys. Lett. B 585 (2004) 53).

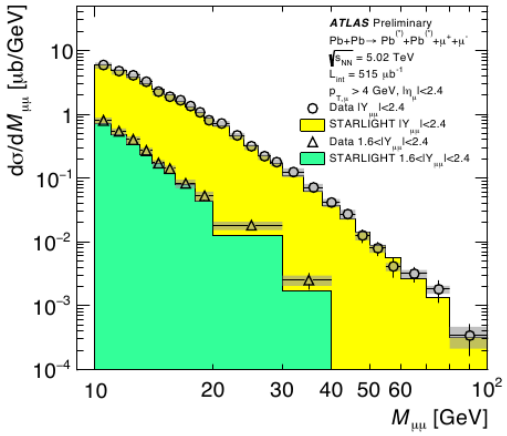


The photon fluxes in UPC are under control!

LTS

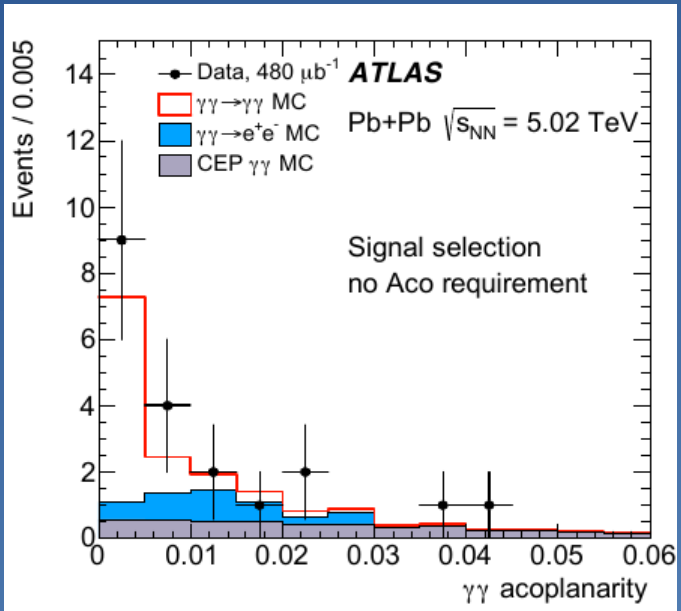
v.org/abs/1408.0811

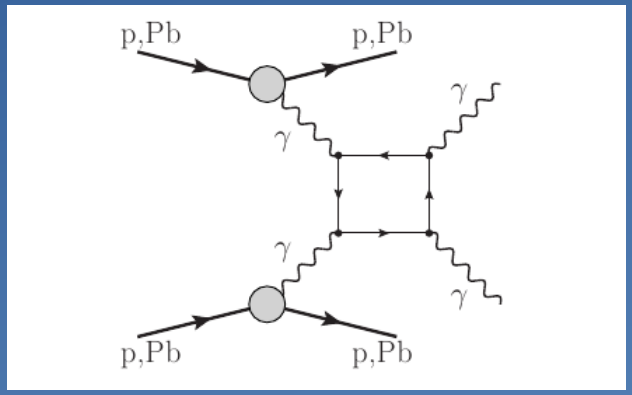




Light-by-light scattering at the LHC

Recent observation by ATLAS Experiment of $\gamma\gamma \rightarrow \gamma\gamma$ (Nature Phys. 13 (2017) 852) with 4.4σ significance.





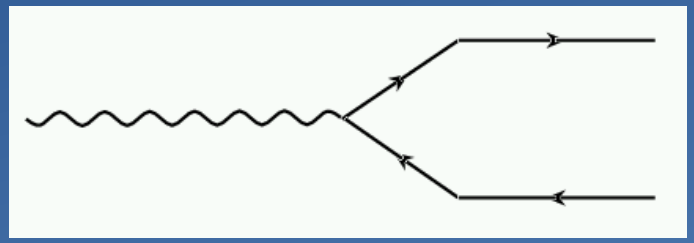
Calculations for this process: D. d'Enterria, G.G. da Silveira, Phys. Rev. Lett. 111 (2013) 080405, Erratum ibid. 116 (2016) 129901; M. Klusek-Gawenda, P. Lebiedowicz, A. Szczurek, Phys. Rev. C 93 (2016) 044907.

Measured yield: 13 events.
Expected yield (Standard Model): 9.9 events (signal 7.3, bkg 2.6).

Small yield, but the result has already been used to set new limits on the Born-Infeld extension of the Standard Model (J.Ellis, N.E. Mavromatos, T. You, Phys. Rev. Lett. 118 (2017) 261802).

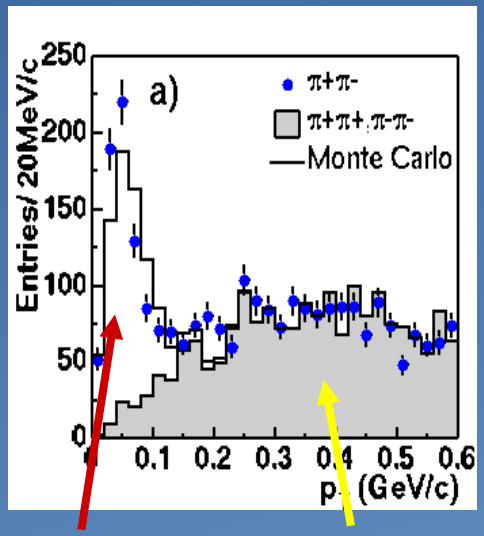
Photonuclear/photon-proton interactions at the LHC

Vector Meson Dominance: γ+A → A+V.



Lightest VM: ρ^0.

First UPC result from RHIC: Exclusive ρ^0-production, Au+Au→Au+Au+ρ^0 (STAR Collaboration PRL 89(2002)272302).



Signal+background, unlike-sign pairs

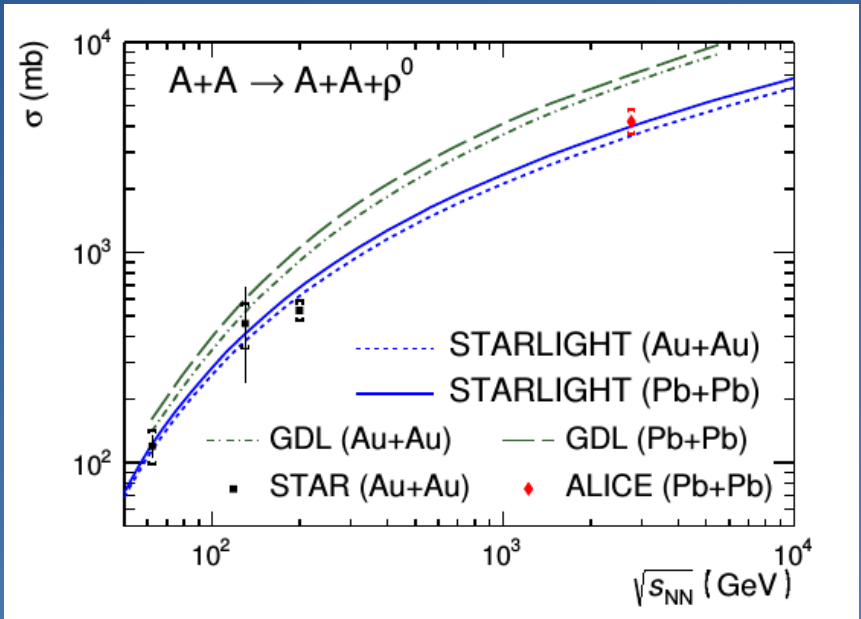
background, like-sign pairs

Experimenta signal: ”Two charged particles in an otherwise empty detector”.

Clear signal for coherent production seen in p_T distribution.

Photonuclear/photon-proton interactions at the LHC

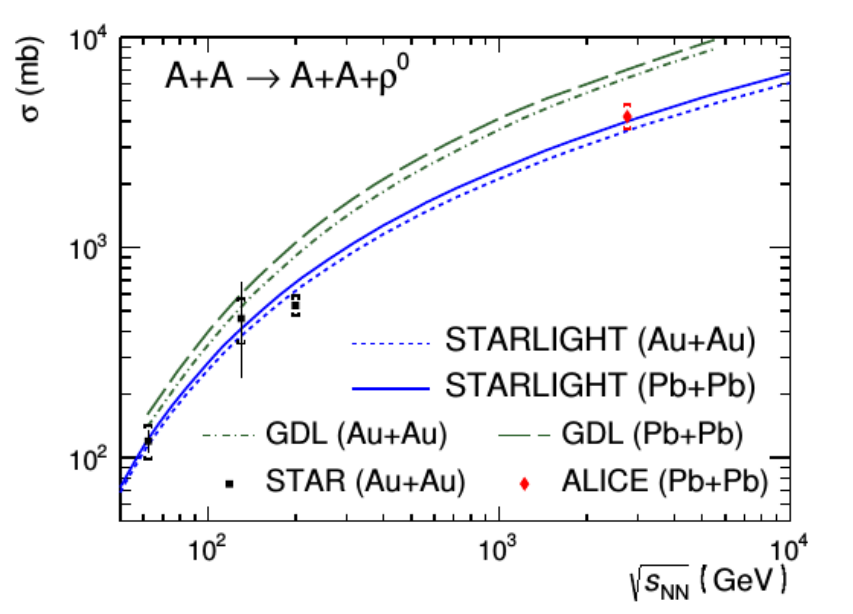
Cross section for coherent and exclusive ρ^0 production comparable to the total hadronic cross section at the LHC.



Transverse momentum, p_T (ρ^0) < 0.15 GeV/c.

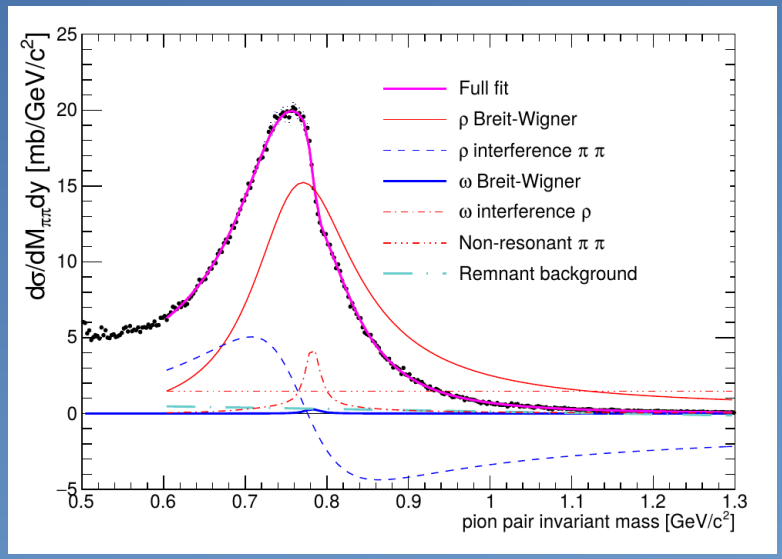
Photonuclear/photon-proton interactions at the LHC

Cross section for coherent and exclusive ρ^0 production comparable to the total hadronic cross section at the LHC.



Transverse momentum, p_T (ρ^0) < 0.15 GeV/c.

Recent update on ρ^0 photoproduction from STAR, Phys. Rev. C 96 (2017) 054904. Statistics of $\approx 4 \cdot 10^5$ ρ^0s. Diffractive peaks and ρ - ω interference visible.



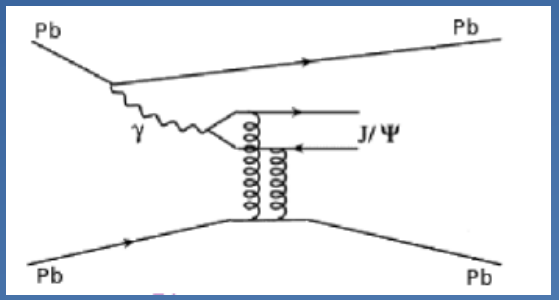
See talk by S.R. Klein Wednesday.

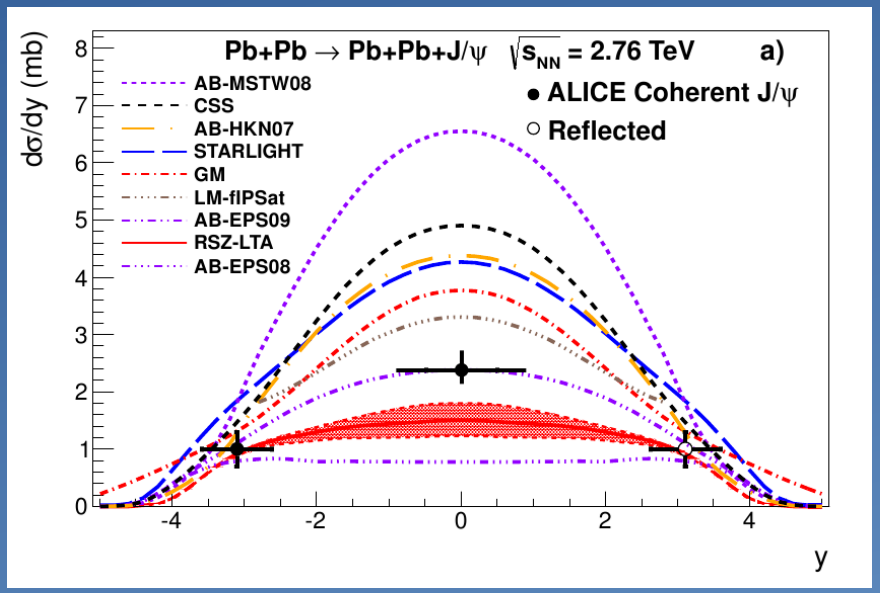
Photonuclear/photon-proton interactions at the LHC

Exclusive heavy vector meson production dominated by 2-gluon exchange.

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, \frac{M_V^2}{4})]^2$$

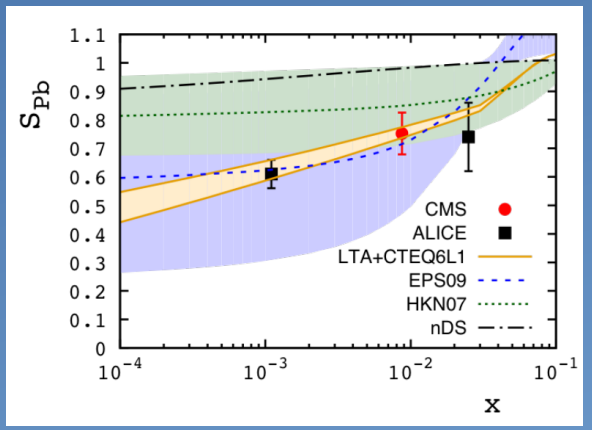
Ryskin 1993





ALICE Collaboration, Phys. Lett. B 718 (2013) 1273; EPJ C 73 (2013) 2617.

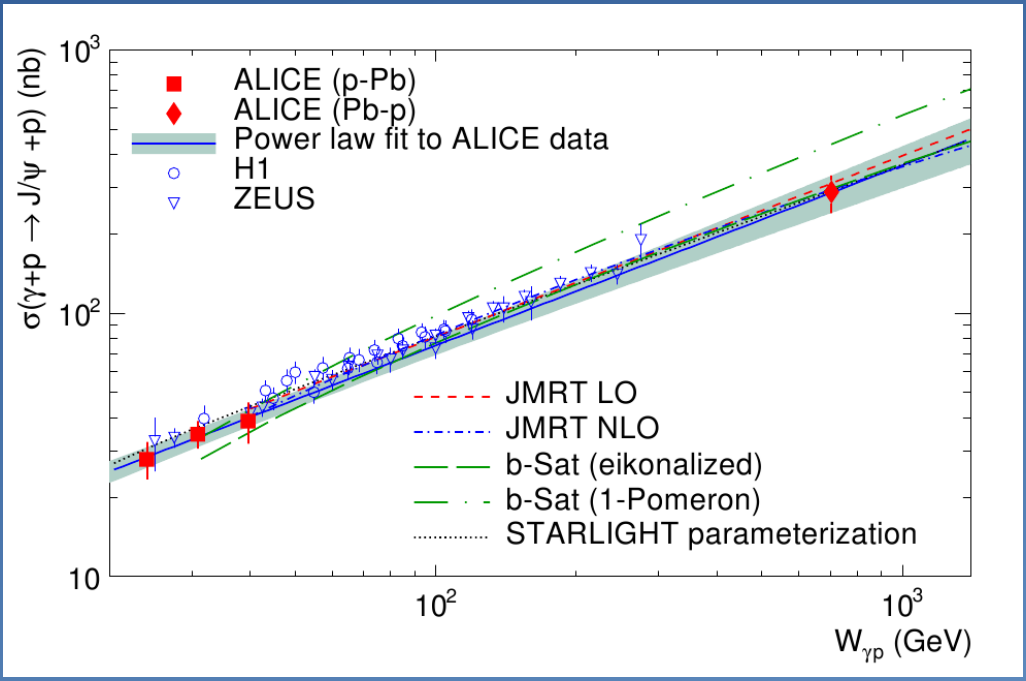
Has been used to constrain nuclear gluon shadowing at Bjorken x ≈ 10^{-2} – 10^{-3}.



V. Guzey, E. Kryshen, M.Strikman, M. Zhalov, JHEP 1310 (2013) 207; V. Guzey priv. comm.

Photoproduction in p+Pb Collisions at the LHC

Dominated by γp interactions, where the Pb-ion emits the photon (95% of cases). Advantage compared with p-p.
Exclusive VM production (γ+p → V+p) at unprecedented energies.
Studied by ALICE (Phys. Rev. Lett. 113(2014)232504).



There will be new results on this in the talk by J.G. Contreras on Wednesday.

Also studied by LHCb in pp collisions (see previous section), but the two-fold ambiguity in photon energy in a symmetric system makes the extraction of $W_{\gamma p}$ difficult.

Summary

- Has the Odderon been found 45 years after it was proposed?

- I think more data, e.g. in the dip region of $d\sigma/dt$, and improved model calculations are needed to confirm this.

- Central production of $\pi^+\pi^-$ pairs shows energy independent features from ISR ($\sqrt{s}$ = 62 GeV) to LHC ($\sqrt{s}$ = 7 TeV).

- More quantitative models would be desirable to understand the underlying physics.

- Ultra-Peripheral Collisions are the energy frontier for electromagnetic interactions and a natural step towards the EIC.

- Exclusive J/ψ production in Pb+Pb collisions indicate moderate gluon shadowing in the $x \approx 10^{-2} - 10^{-3}$ region.

- Energy range for exclusive J/ψ production on proton targets greatly extended thanks to UPC. Power law shows no sign of saturation.