Recent results from TOTEM and the discovery of the odderon

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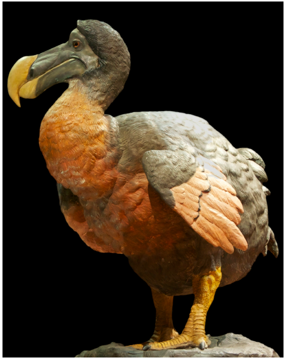
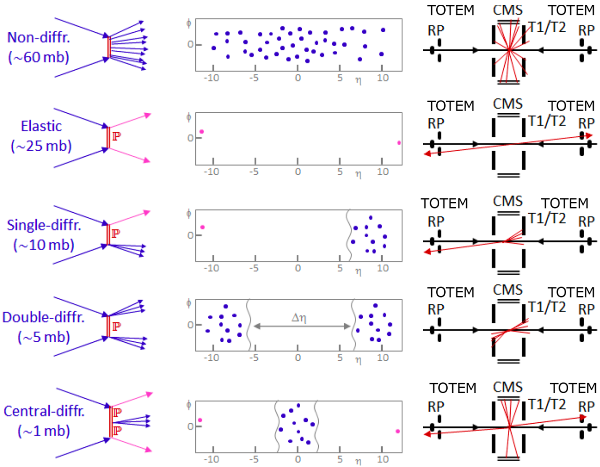


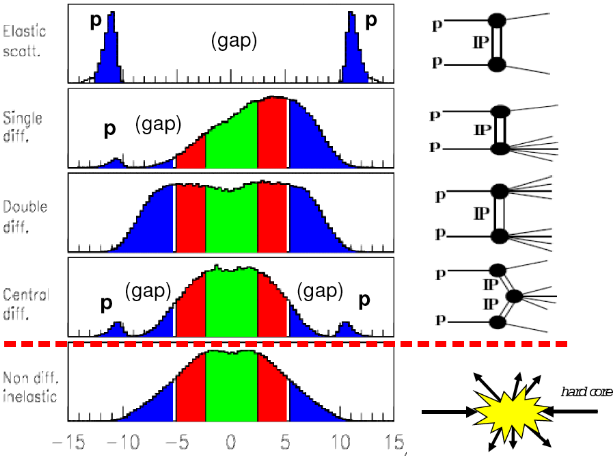
- Soft diffraction at the LHC
- Total cross section and elastic interactions
- Introduction to the Odderon
- D0 $p\bar{p}$ and TOTEM pp data
- The odderon discovery

What do we want to measure? Diffractive events!

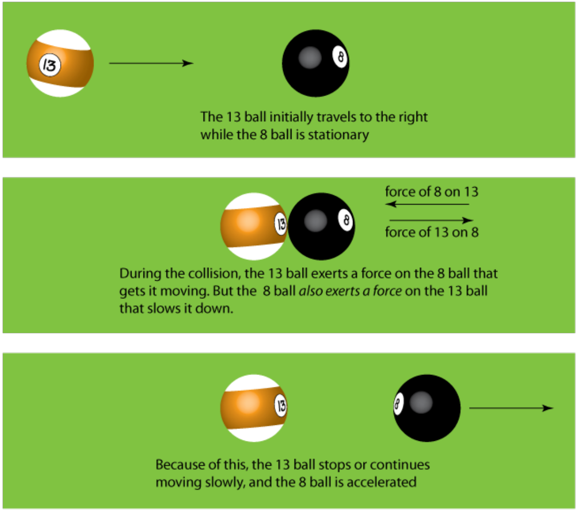


- Protons remain intact after interactions $pp \to pXp$ (central diffraction or double pomeron exchange) or $pp \to pXY$ (single diffraction)
- Non-diifractive interactions represent 60 *mb* out of 100 *mb* at LHC
- Intact protons can be detected using dedicated detectors
- Elastic interactions: $pp \to pp$

How do diffractive events look like in our detector?

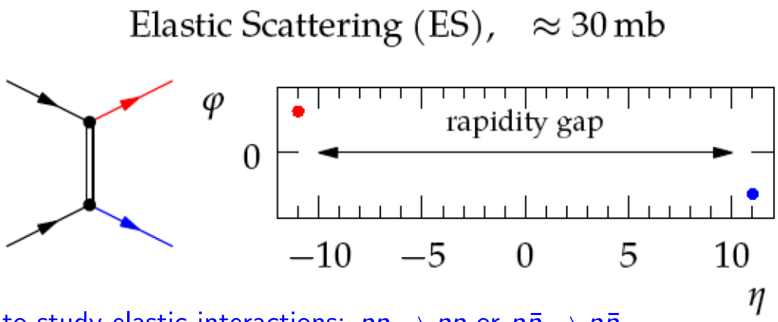


What is elastic scattering? The pool game...



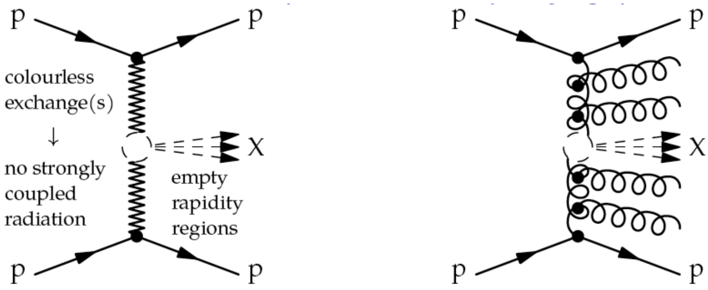
- We want to study "elastic" collisions between protons and proton-antiprotons
- In high energy physics: $pp \to pp$ and $p\bar{p} \to p\bar{p}$
- In these interactions, each proton/antiproton remains intact after interaction but are scattered at some angles and can lose/gain some momentum as in the pool game

What do we want to study?



- We want to study elastic interactions: $pp \rightarrow pp$ or $p\bar{p} \rightarrow p\bar{p}$
- These are very clean events, where nothing is produced outside the two protons
- How to detect/measure these events? We need to detect the intact protons after interaction!
- Interactions explained by the exchange of a colorless object ($\geq$ 2 gluons, photon, etc...) between the two protons

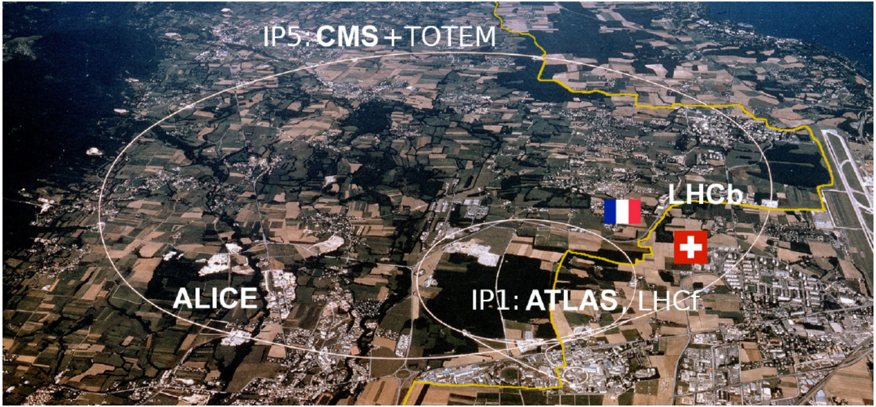
How to explain the fact that protons can be intact?



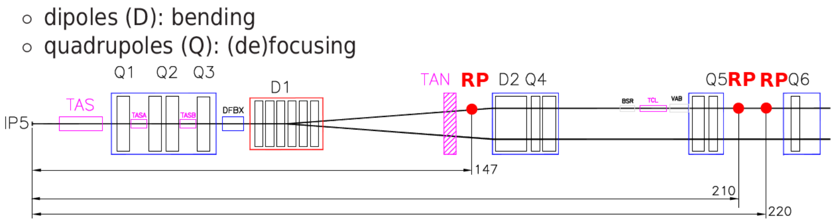
- Quarks/gluons radiate lots of gluons when one tries to separate them (confinement)
- Gluons exchange color, interact with other gluons in the proton and in that case protons are destroyed in the final state
- In order to explain how protons can remain intact: we need colorless exchanges, or at least 2 gluons to be exchanged

pp interactions: The Large Hadron Collider at CERN

- Large Hadron Collider at CERN: proton proton collider with 2.76, 7, 8 and 13 TeV center-of-mass energy
- Circonference: 27 km; Underground: 50-100 m

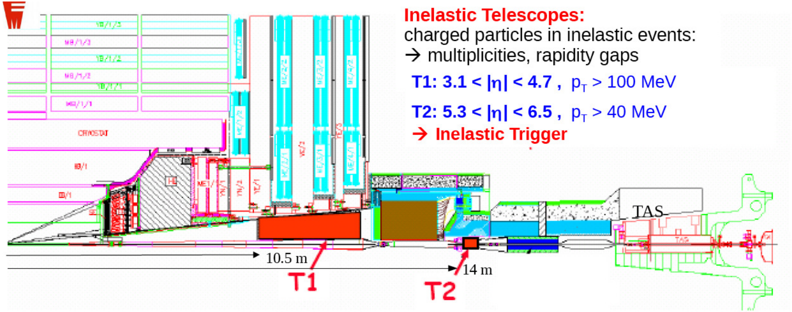


Proton detection



- But why are the protons/anti-protons not in the beam (which would prevent detection)?
- As we saw in the pool game, p or $\bar{p}$ are scattered at small angles and thus can be detected in the dedicated roman pot detectors
- NB: in non-elastic diffractive case with some particles produced in CMS $pp \to pXp$, p and $\bar{p}$ lose part of their energy and we use the LHC/Tevatron magnets as a spectrometer $p/\bar{p}$ at smaller v, so they have a smaller bending radius than the $p/\bar{p}$ from the beam

Forward coverage in CMS-TOTEM



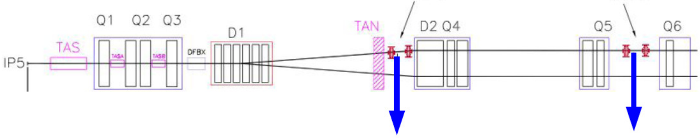
Inelastic Telescopes:
charged particles in inelastic events:
→ multiplicities, rapidity gaps

T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV

T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

→ Inelastic Trigger

Roman Pots: elastic & diffractive protons close to outgoing beams → **Proton Trigger**

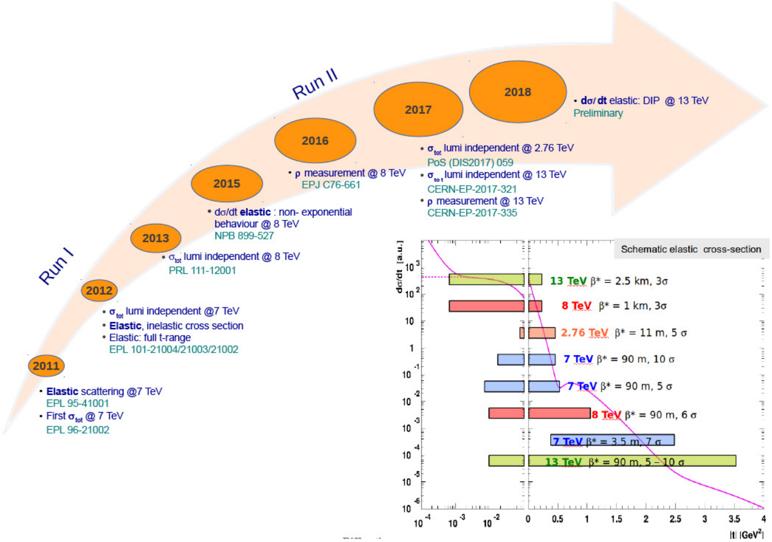


Roman Pot stations in the LHC tunnel
(before LS1)

RP (147 m)

RP (220m)

TOTEM cross section measurements



Analysis methods in TOTEM: total cross section

- N_{inel} measured using T_1 and T_2 telescopes, and N_{el} from the roman pots
- Known equations (Optical theorem) (ρ: ratio of real/Imaginary part of cross section)

$$L\sigma^2_{tot} = \frac{16\pi}{1+\rho^2}(dN_{el}/dt)_{t=0}$$
$$L\sigma_{tot} = N_{el} + N_{inel}$$

- Different methods to measure the total cross section
  - Lumi independent measurement

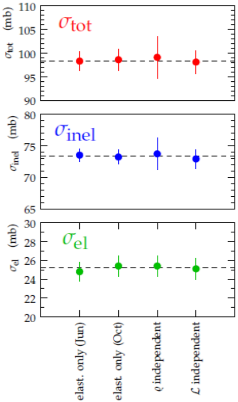
$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)}\frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

  - Lumi dependent measurement (elastic only)

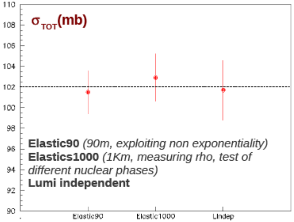
$$\sigma^2_{tot} = \frac{16\pi}{(1+\rho^2)}\frac{1}{L}(dN_{el}/dt)_{t=0}$$

  - ρ independent measurement $\sigma_{tot} = \sigma_{el} + \sigma_{inel}$

Elastic, Inelastic and Total cross section at 7, 8 and 13 TeV

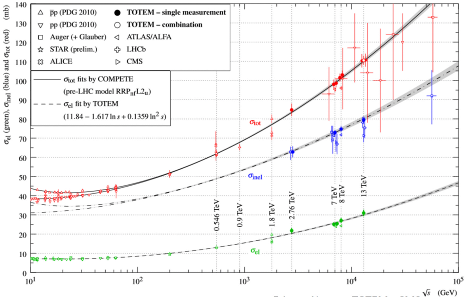


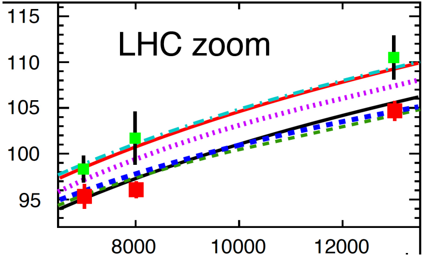
7 TeV, several methods
Same beam conditions



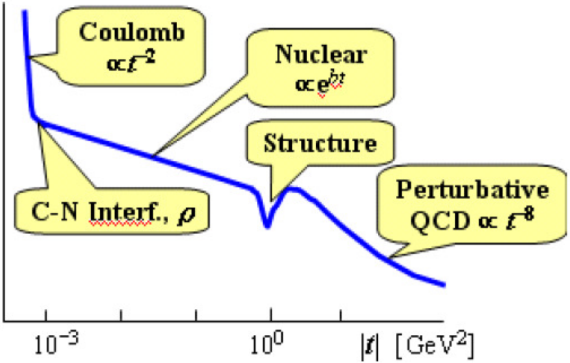
8 TeV, several methods
Different beam conditions

- Independent methods with different precision/systematics lead to similar results on elastic, inelastic and total cross sections
- In addition, at 13 TeV, total cross section using lumi independent method for $\beta^* = 90m$: $\sigma_{tot} = 110.6 \pm 3.4$mb, $\sigma_{el} = 31.0 \pm 1.7$mb, $\sigma_{inel} = 79.5 \pm 1.8$mb
- ρ measurement using $\beta^* = 2500m$ data



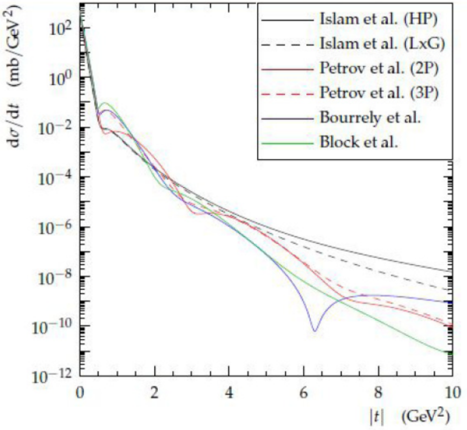


- High precision measurement of elastic, inelastic and total cross sections
- Measurements in agreement with cosmic-ray data (large error bars though)
- ATLAS $\sim 2\ \sigma$ lower than TOTEM at 8 and 13 TeV: differences due to luminosity measurements?



- Study of elastic $pp \to pp$ reaction: exchange of momentum between the two protons which remain intact
- Measure intact protons scattered close to the beam using Roman Pots installed both by D0 and TOTEM collaborations
- From counting the number of events as a function of $|t|$ (4-momentum transferred square at the proton vertex measured by tracking the protons), we get $d\sigma/dt$

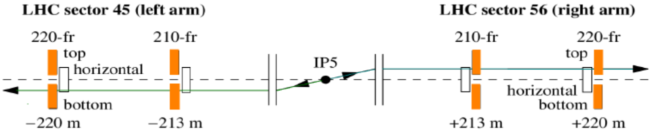
What is the expected situation at the LHC?

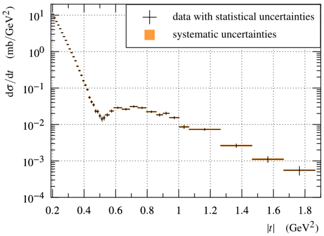


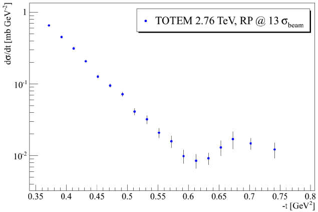
- Expected elastic $d\sigma/dt$ before LHC measurements
- Many different predictions including many possible contributions at high $|t|$, such as pomeron, reggeon, mesons (ω, ϕ) whereas other predictions mentioned that, at high energies, we should be more asymptotical and pomeron dominated
- Almost nobody thought about the odderon (except a few theorists such as Martynov, Nicolescu...)

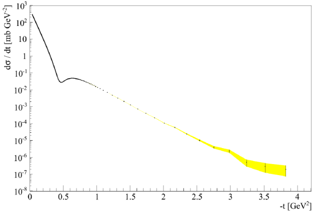
TOTEM elastic $pp\ d\sigma/dt$ cross section measurements

- Elastic $pp\ d\sigma/dt$ measurements: tag both intact protons in TOTEM Roman Pots 2.76, 7, 8 and 13 TeV
- Very precise measurements at 2.76, 7, 8 and 13 TeV: Eur. Phys. J. C 80 (2020) no.2, 91; EPL 95 (2011) no. 41004; Nucl. Phys. B 899 (2015) 527; Eur. Phys. J. C79 (2019) no.10, 861

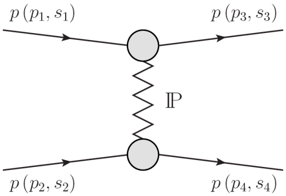








The odderon in a nutshell

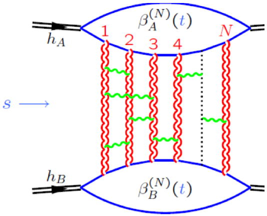


- Let us assume that elastic scattering can be due to exchange of colorless objects: Pomeron and Odderon
- Charge parity C: Charge conjugation changes the sign of all quantum charges
- Pomeron and Odderon correspond to positive and negative C parity: Pomeron is made of two gluons which leads to a $+1$ parity whereas the odderon is made of 3 gluons corresponding to a -1 parity
- Scattering amplitudes can be written as:

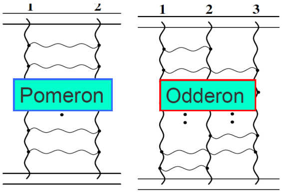
$$A_{pp} = Even + Odd$$
$$A_{p\bar{p}} = Even - Odd$$

- From the equations above, it is clear that observing a difference between pp and $p\bar{p}$ interactions would be a clear way to observe the odderon

What is the odderon? The QCD picture

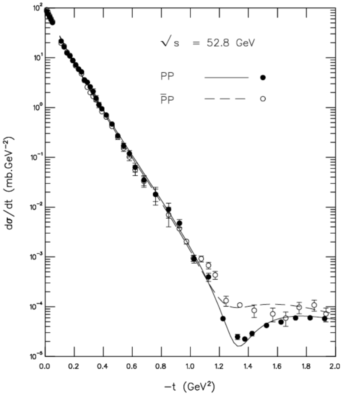


- Multi-gluon exchanges in hadron-hadron interactions in elastic *pp* interactions (Bartels-Kwiecinski-Praszalowicz)
- From B. Nicolescu: The Odderon is defined as a singularity in the complex plane, located at $J = 1$ when $t = 0$ and which contributes to the odd crossing amplitude



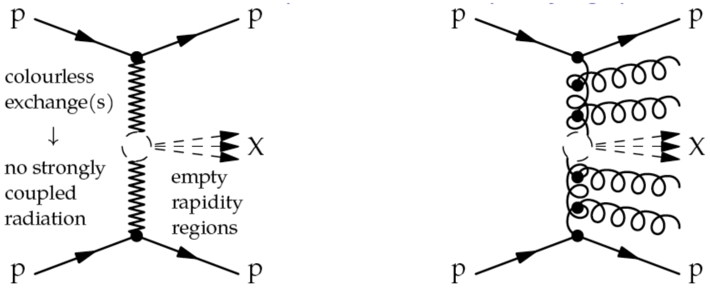
- Leads to contributions on 3,... gluon exchanges in terms of QCD for the perturbative odderon
- Colorless C-odd 3-gluon state (odderon) predicts differences in elastic $d\sigma/dt$ for pp and $p\bar{p}$ interactions since it corresponds to different amplitudes/ interferences

Why has the odderon not been observed yet? Why is it so elusive?



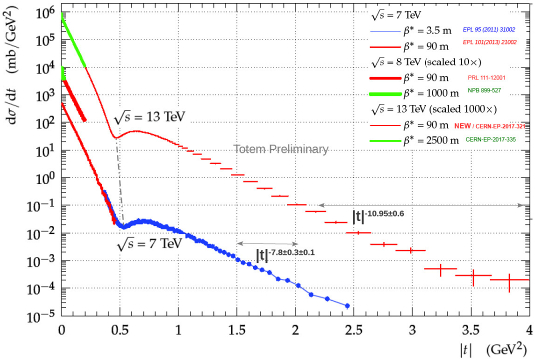
- The situation is not that simple: elastic scattering at low energies can be due to exchanges of additional particles to pomeron/odderon: ρ, ω, ϕ, reggeons...
- How to distinguish between all these exchanges? Not easy...
- At ISR energies, there was already some indication of a possible difference between pp and $p\bar{p}$ interactions, differences of about 3σ between pp and $p\bar{p}$ interactions but this was not considered to be a clean proof of the odderon because of these additional reggeon, meson exchanges at low $\sqrt{s}$

How to explain the fact that protons can be intact?



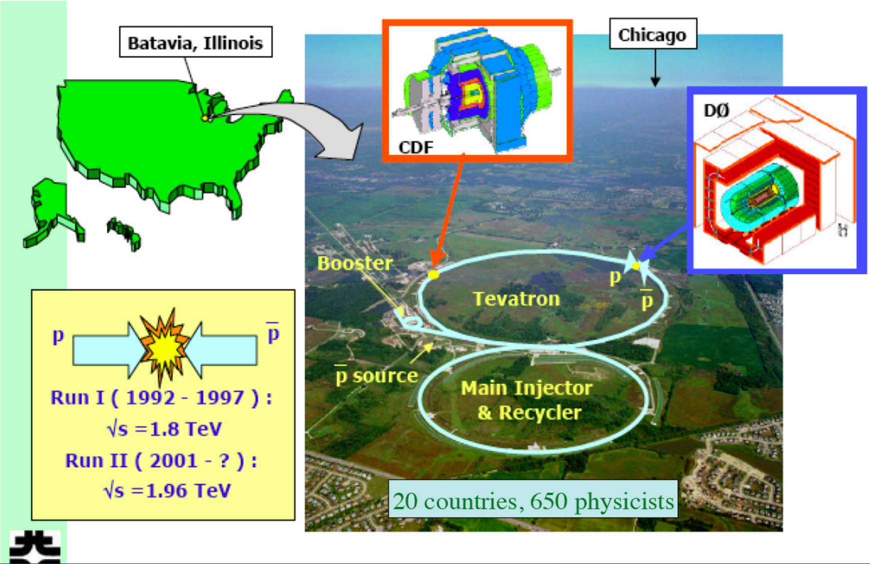
- We mentioned that we can have exchanges of pomeron/odderon
- Unfortunately, at low energies, situation is much more complicated: meson, reggeon exchanges are possible in addition and there can be interferences

Are we in the asymptotic regime at the LHC?

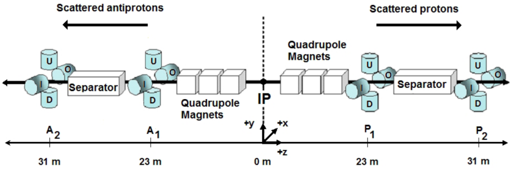


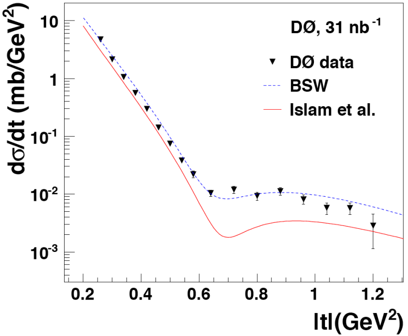
- Contrary to what some models expected before LHC, the elastic cross section is smooth: we do not see reggeons, mesons...!
- Effects of reggeon, meson exchanges are negligible at LHC energies: we can concentrate on pomeron/odderon studies!
- We can directly look for the existence of the odderon by comparing pp and $p\bar{p}$ elastic cross sections at very high energies: 1.96 TeV (Tevatron), 2.76, 7, 8, 13 (LHC)

$p\bar{p}$ interactions: the Tevatron



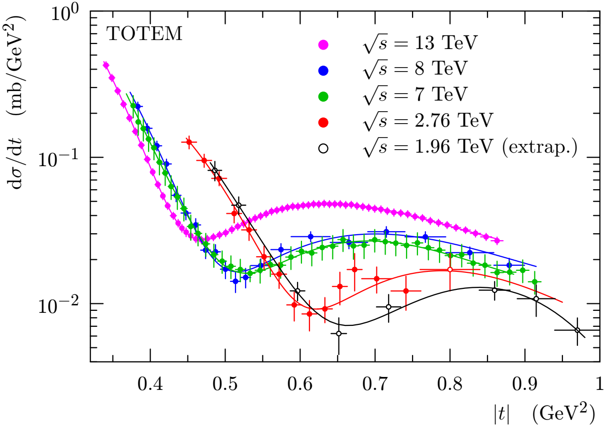
D0 elastic $p\bar{p}$ $d\sigma/dt$ cross section measurements





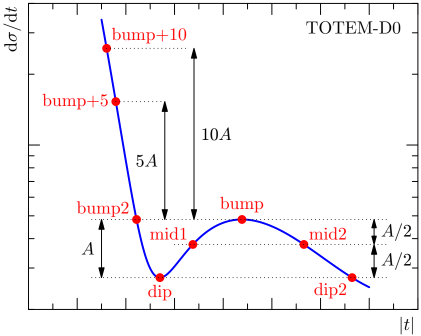
- D0 collected elastic $p\bar{p}$ data with intact p and $\bar{p}$ detected in the Forward Proton Detector with 31 nb^{-1} Phys. Rev. D 86 (2012) 012009
- Measurement of elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV for $0.26 < |t| < 1.2$ GeV^2

Strategy to compare pp and $p\bar{p}$ data sets



- In order to identify differences between pp and $p\bar{p}$ elastic $d\sigma/dt$ data, we need to compare TOTEM measurements at 2.76, 7, 8, 13 TeV and D0 measurements at 1.96 TeV
- All TOTEM $d\sigma/dt$ measurements show the same features, namely the presence of a dip and a bump in data, whereas D0 data do not show this feature

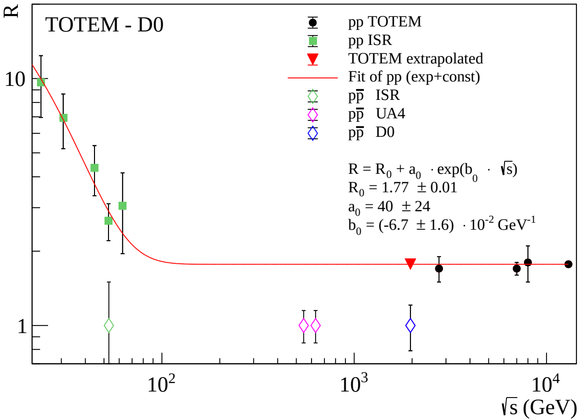
Reference points of elastic $d\sigma/dt$



- Define 8 characteristic points of elastic *pp* $d\sigma/dt$ cross sections (dip, bump...) that are feature of elastic *pp* interactions

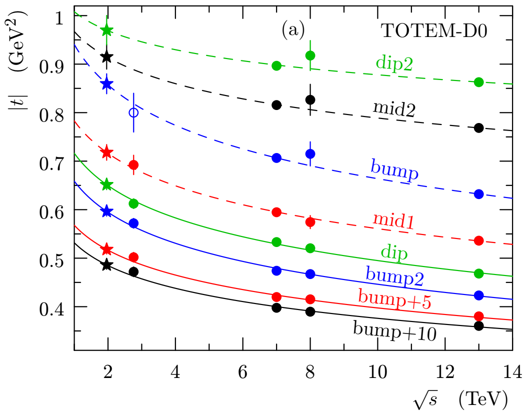
- Determine how the values of $|t|$ and $d\sigma/dt$ of characteristic points vary as a function of $\sqrt{s}$ in order to predict their values at 1.96 TeV
- We use data points closest to those characteristic points (avoiding model-dependent fits)
- Data bins are merged in case there are two adjacent dip or bump points of about equal value
- This gives a distribution of t and $d\sigma/dt$ values as a function of $\sqrt{s}$ for all characteristic points

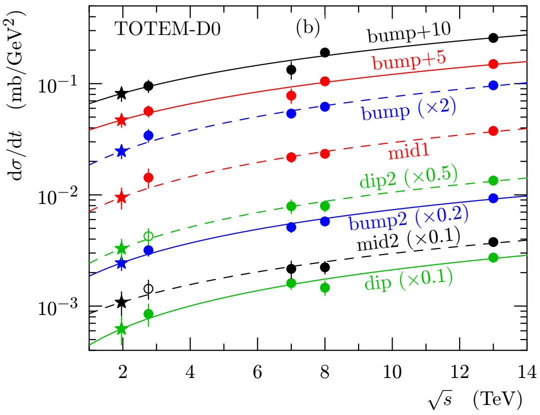
Bump over dip ratio



- Bump over dip ratio measured for *pp* interactions at ISR and LHC energies
- Bump over dip ratio in *pp* elastic collisions: decreasing as a function of $\sqrt{s}$ up to $\sim$ 100 GeV and flat above
- D0 $p\bar{p}$ shows a ratio of 1.00 ± 0.21 given the fact that no bump/dip is observed in $p\bar{p}$ data within uncertainties: **more than 3σ difference between *pp* and $p\bar{p}$ elastic data** (assuming flat behavior above $\sqrt{s} = 100 GeV$)

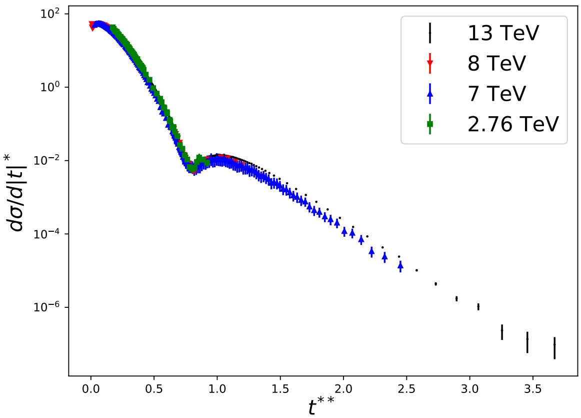
Variation of t and $d\sigma/dt$ values for reference points





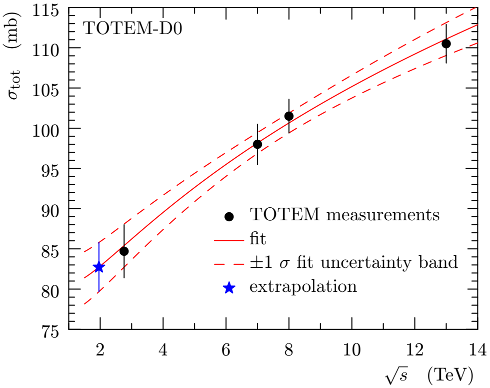
$$|t| = a\log(\sqrt{s}[\mathrm{TeV}]) + b \qquad (d\sigma/dt) = c\sqrt{s}\ [\mathrm{TeV}] + d$$

One aside: why all characteristic points vary in the same way?



- The fact that all characteristic points (both t and $d\sigma/dt$) vary in the same way in the dip/bump region as a function of $\sqrt{s}$ is not by chance
- if we display $d\sigma/dt^*$ as a function of t^{**}, we clearly observe scaling ($t^* = |t|(s/|t|)^A$ inspired by saturation models and $t^{**} = s^{0.065}|t|^{1-A}$ with $A = 0.28$, A value obtained by fitting all TOTEM $d\sigma/dt$ elastic data (599 data points) using the Quality Factor method)

Relative normalization between D0 measurement and extrapolated TOTEM data: total *pp* cross section at 1.96 TeV



- Differences in normalization taken into account by adjusting TOTEM and D0 data sets to have the same cross sections at the optical point $d\sigma/dt(t=0)$ (NB: OP cross sections expected to be equal if there are only C-even exchanges)
- Predict the *pp* total cross section from extrapolated fit to TOTEM data (χ^2 =0.27)

$$\sigma_{tot} = a_2 \log^2 \sqrt{s}[\mathrm{TeV}] + b_2$$

Other parametrizations lead to same results

- Leads to estimate of *pp* σ_{tot} =**82.7 ± 3.1 mb at 1.96 TeV**

Relative normalization between D0 measurement and extrapolated TOTEM data: Rescaling TOTEM data

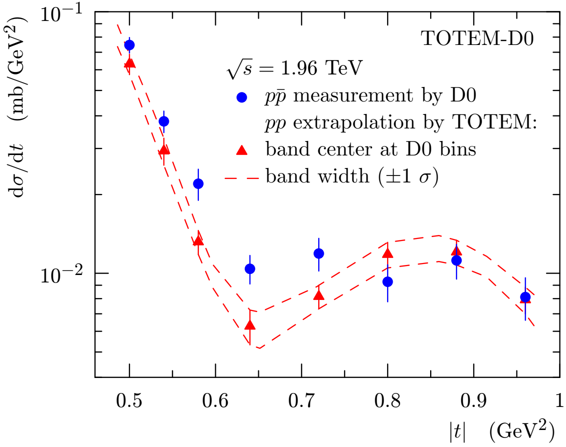
- Adjust 1.96 TeV $d\sigma/dt(t=0)$ from extrapolated TOTEM data to D0 measurement
- From TOTEM pp σ_{tot}, obtain $d\sigma/dt(t=0)$:

$$\sigma^2_{tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left(\frac{d\sigma}{dt}\right)_{t=0}$$

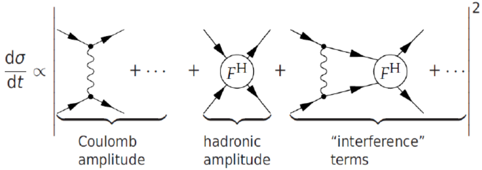
- Assuming $\rho = 0.145$, the ratio of the imaginary and the real part of the elastic amplitude, as taken from COMPETE extrapolation
- This leads to a TOTEM $d\sigma/dt(t=0)$ at the OP of 357.1 ± 26.4 mb/GeV^2
- D0 measured the optical point of $d\sigma/dt$ at small t: 341 ± 48 mb/GeV^2
- TOTEM data rescaled by 0.954 ± 0.071
- NB: We do not claim that we performed a measurement of $d\sigma/dt$ at the OP at $t=0$ (it would require additional measurements closer to $t=0$), but we use the two extrapolations simply in order to obtain a common and somewhat arbitrary normalization point

Predictions at $\sqrt{s} = 1.96$ TeV

- Reference points at 1.96 TeV (extrapolating TOTEM data) and 1σ uncertainty band
- Comparison with D0 data



Additional measurement in TOTEM: ρ

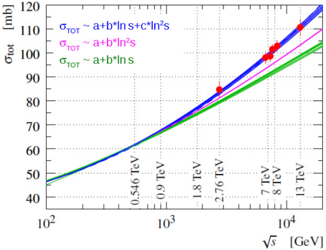


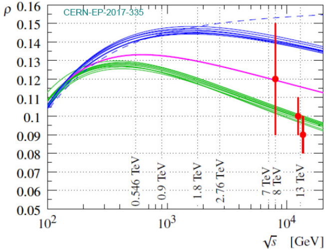
- Measure elastic scattering at very low t: Coulomb-Nuclear interference region

$$\frac{d\sigma}{dt} \sim |A^C + A^N(1 - \alpha G(t))|^2$$

- The differential cross section is sensitive to the phase of the nuclear amplitude
- In the CNI region, both the modulus and the phase of the nuclear amplitude can be used to determine $\rho = \frac{Re(A^N(0))}{Im(A^N(0))}$ where the modulus is constrained by the measurement in the hadronic region and the phase by the t dependence

A reminder: ρ and σ_{tot} measurements as an indication for odderon

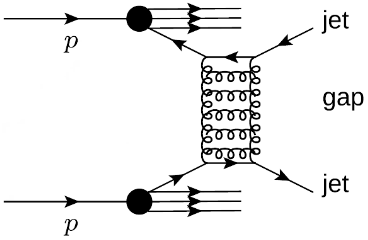


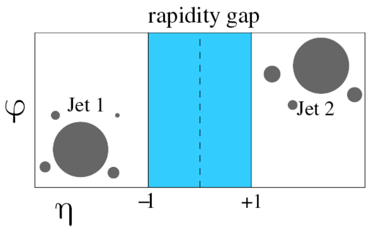


- Using low $|t|$ data in the Coulomb-nuclear interference region, measurement of ρ at 13 TeV: $\rho = 0.09 \pm 0.01$ (EPJC 79 (2019) 785)
- Combination of the measured ρ and σ_{tot} values not compatible with any set of models without odderon exchange (COMPETE predictions above as an example)
- This result can be explained by the exchange of the Odderon in addition to the Pomeron

Comparison between D0 measurement and extrapolated TOTEM data

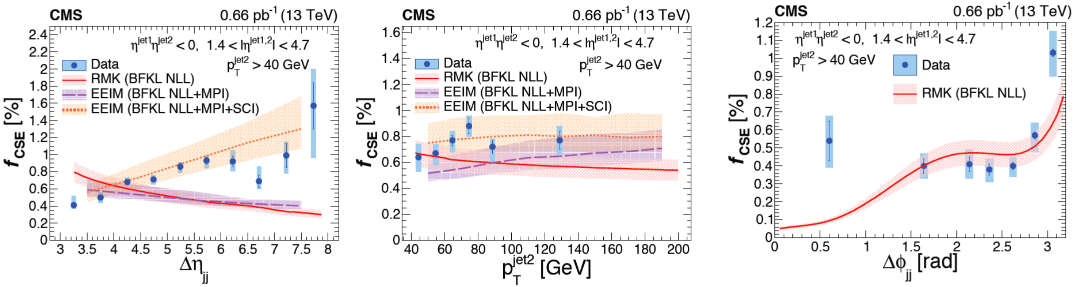
- Combination with the independent evidence of the odderon found by the TOTEM Collaboration using ρ and total cross section measurements at low t in a completely different kinematical domain
- For the models included in COMPETE, the TOTEM ρ measurement at 13 TeV provided a 3.4 to 4.6σ significance, to be combined with the D0/TOTEM result
- The combined significance ranges from **5.3 to 5.7σ depending on the model**
- Models without colorless C-odd gluonic compound are excluded including the Durham model and different sets of COMPETE models (blue, magenta and green bands on the previous slide)





- Looking for a gap between two jets: Region in rapidity devoid of any particle production, energy in detector
- Exchange of a BFKL Pomeron between the two jets: two-gluon exchange in order to neutralize color flow
- Method to test BFKL resummation: Implementation of BFKL NLL formalism in HERWIG/PYTHIA Monte Carlo

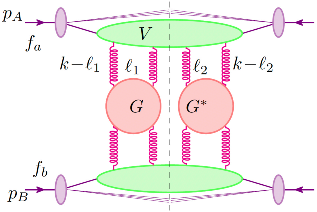
LHC: Measurement of jet gap jet fraction (CMS)



- Measurement of fraction of jet gap jet events as a function of jet $\Delta\eta$, p_T, $\Delta\Phi$ (Phys.Rev.D 104 (2021) 032009)
- Comparison with NLL BFKL (with LO impact factors) as implemented in PYTHIA, and soft color interaction based models (Ingelman et al.)
- Disagreement between BFKL and measurements ($\Delta\eta$ dependence): What is going on?

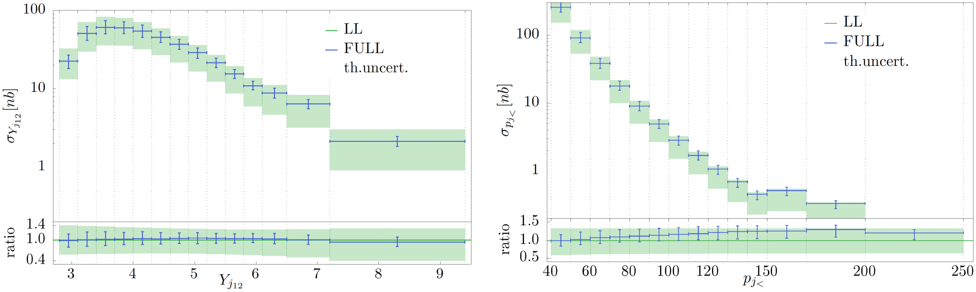
Jet gap jet: Full NLO BFKL calculation including NLO impact factor

- Combine NLL kernel with NLO impact factors (Hentschinski, Madrigal, Murdaca, Sabio Vera 2014)



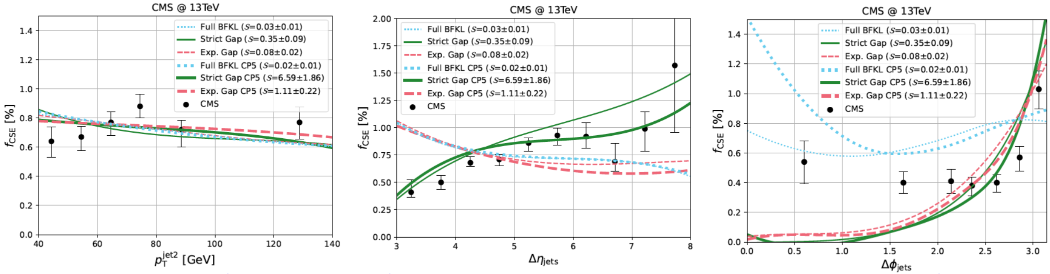
- Gluon Green functions in red
- Impact factors in green
- Will lead to an improved parametrisation to be implemented in HERWIG/PYTHIA
- D. Colferai, F. Deganutti, T. Raben, C. Royon, JHEP 06 (2023) 091

Effect of NLO impact factor on jet gap jet cross section: final results



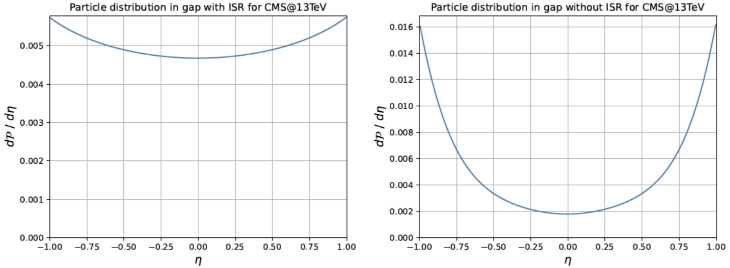
- Higher cross section by 20% at high p_T and small effect on the y dependence
- Total uncertainties are much smaller at NLO: 15-20%

Jet gap jet measurements at the LHC (CMS@13 TeV)



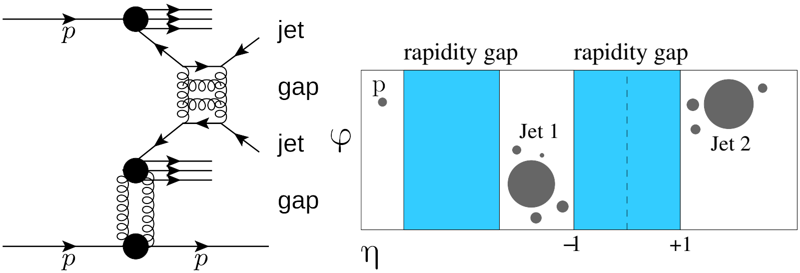
- Implementation of BFKL NLL formalism in Pythia and compute jet gap jet fraction
- Dijet cross section computed using POWHEG and PYTHIA8
- Three definitions of gap: theory (pure BFKL), experimental (no charged particle above 200 MeV in the gap $-1 < \eta < 1$) and strict gap (no particle above 1 MeV in the gap region) (C. Baldenegro, P. Gonzalez Duran, M. Klasen, C. Royon, J. Salomon, JHEP 08 (2022) 250)
- Two different CMS tunes: CP1 without MPI, CP5 with MPI

Charged particle distribution



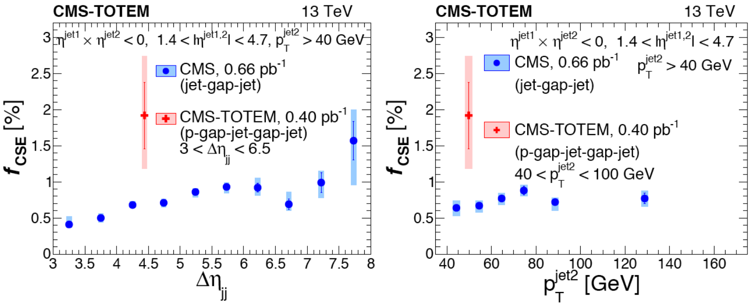
- Disitribution of charged particles from PYTHIA in the gap region $-1 < \eta < 1$ with ISR ON (left) and OFF (right)
- Particles emitted at large angle with $p_T > 200$ MeV from initial state radiation have large influence on the gap presence or not, and this on the gap definition (experimental or strict)

Jet gap jet events in diffraction (CMS/TOTEM)



- Jet gap jet events: powerful test of BFKL resummation C. Marquet, C. Royon, M. Trzebinski, R. Zlebcík, Phys. Rev. D 87 (2013) 3, 034010
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events were observed for the 1st time by CMS!** (Phys.Rev.D 104 (2021) 032009)

First observation of jet gap jet events in diffraction (CMS/TOTEM)



- First observation: 11 events observed with a gap between jets and at least one proton tagged with ~ 0.7 pb^{-1}
- Leads to very clean events for jet gap jets since MPI are suppressed and might be the "ideal" way to probe BFKL
- Would benefit from more stats $>$10 pb^{-1} needed, 100 for DPE

Conclusion

- Total and elastic cross sections measured by the TOTEM collaboration at 2.76, 7, 8 and 13 TeV: non-exponential behavior of $d\sigma/dt$
- Detailed comparison between $p\bar{p}$ (1.96 TeV from D0) and pp (2.76, 7, 8, 13 TeV from TOTEM) elastic $d\sigma/dt$ data - FERMILAB-PUB-20-568-E; CERN-EP-2020-236, accepted in PRL
- **pp and $p\bar{p}$ cross sections differ with a significance of 3.4σ in a model-independent way and thus provides evidence that the Colorless C-odd gluonic compound i.e. the odderon is needed to explain elastic scattering at high energies**
- **When combined with the ρ and total cross section result at 13 TeV, the significance is in the range 5.3 to 5.7σ and thus constitutes the first experimental observation of the odderon: Major discovery at CERN/Tevatron**
- New scaling observed in elastic $d\sigma/dt$ data: Proton as a black disk at low b?
- Jet gep jet events at the LHC

We need to look everywhere! For instance using intact protons...