The odderon discovery by the D0 and TOTEM collaborations

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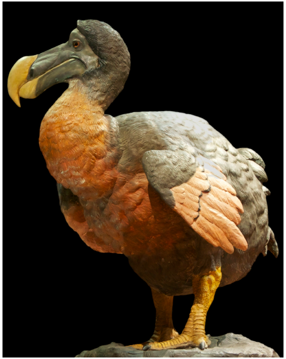
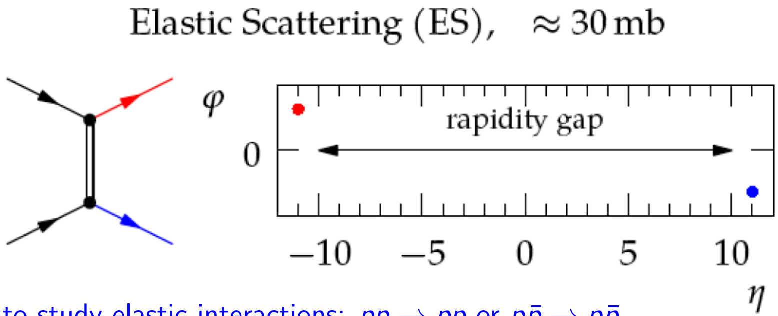


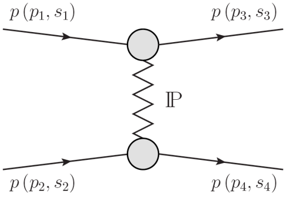
- Introduction to the Odderon
- D0 and TOTEM data
- Extrapolation of TOTEM data to Tevatron energies
- Comparison between D0 data and TOTEM extrapolated data

What do we want to study?



- We want to study elastic interactions: $pp \to pp$ or $p\bar{p} \to p\bar{p}$
- 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

The odderon in a nutshell

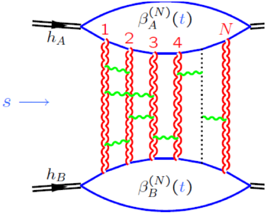


- Let us assume that elastic scattering can be due to exchange of colorless objects: Pomeron and Odderon
- Charge parity C: Charge conjugation changes the sign of all quantum charges
- Pomeron and Odderon correspond to positive and negative C parity: Pomeron is made of two gluons which leads to a $+1$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

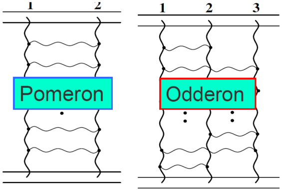
$$\begin{aligned} A_{pp} &= Even + Odd \\ A_{p\bar{p}} &= Even - Odd \end{aligned}$$

- 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

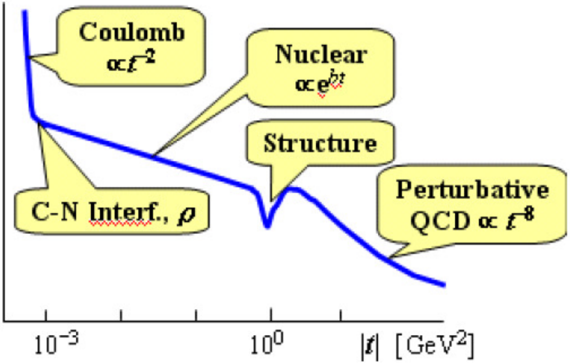


- Multi-gluon exchanges in hadron-hadron interactions in elastic *pp* interactions (Bartels-Kwiecinski-Praszalowicz)
- From B. Nicolescu: The Odderon is defined as a singularity in the complex plane, located at $J = 1$ when $t = 0$ and which contributes to the odd crossing amplitude



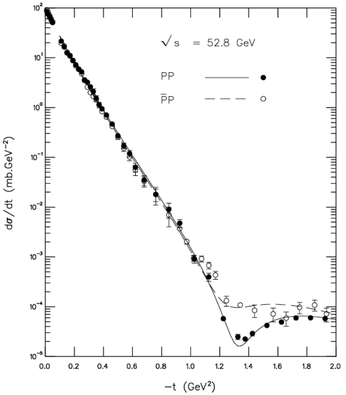
- Leads to contributions on 3,... gluon exchanges in terms of QCD for the perturbative odderon
- Colorless C-odd 3-gluon state (odderon) predicts differences in elastic $d\sigma/dt$ for pp and $p\bar{p}$ interactions since it corresponds to different amplitudes/ interferences

Measurement of elastic scattering at Tevatron and LHC



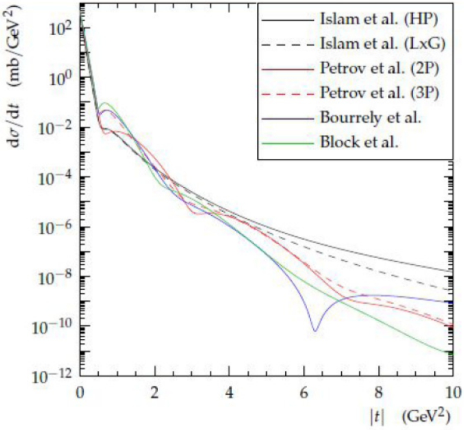
- Study of elastic $pp \to pp$ reaction: exchange of momentum between the two protons which remain intact
- Measure intact protons scattered close to the beam using Roman Pots installed both by D0 and TOTEM collaborations
- From counting the number of events as a function of $|t|$ (4-momentum transferred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

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



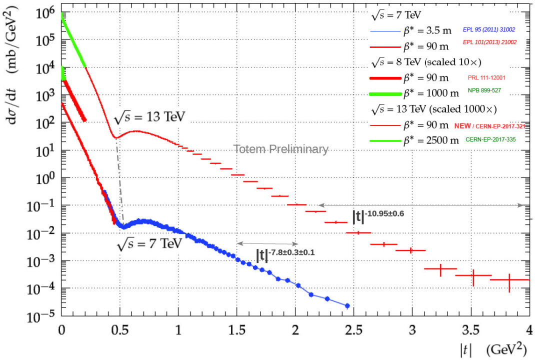
- The situation is not that simple: elastic scattering at low energies can be due to exchanges of additional particles to pomeron/odderon: ρ, ω, ϕ, reggeons...
- How to distinguish between all these exchanges? Not easy...
- At ISR energies, there was already some indication of a possible difference between 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 $\sqrt{s}$

What is the expected situation at the LHC?



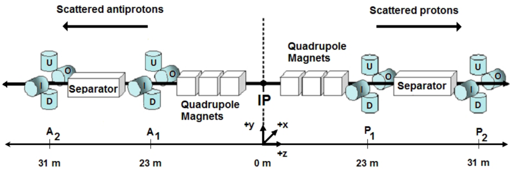
- Expected elastic $d\sigma/dt$ before LHC measurements
- Many different predictions including many possible contributions at high $|t|$, such as pomeron, reggeon, mesons (ω, ϕ) whereas other predictions mentioned that, at high energies, we should be more asymptotical and pomeron dominated
- Almost nobody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

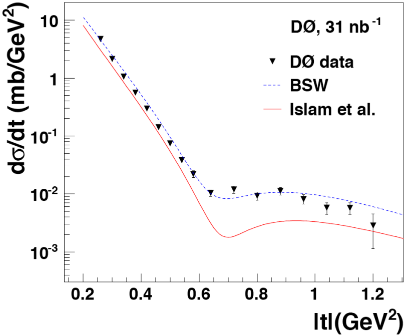
Are we in the asymptotic regime at the LHC?



- 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)

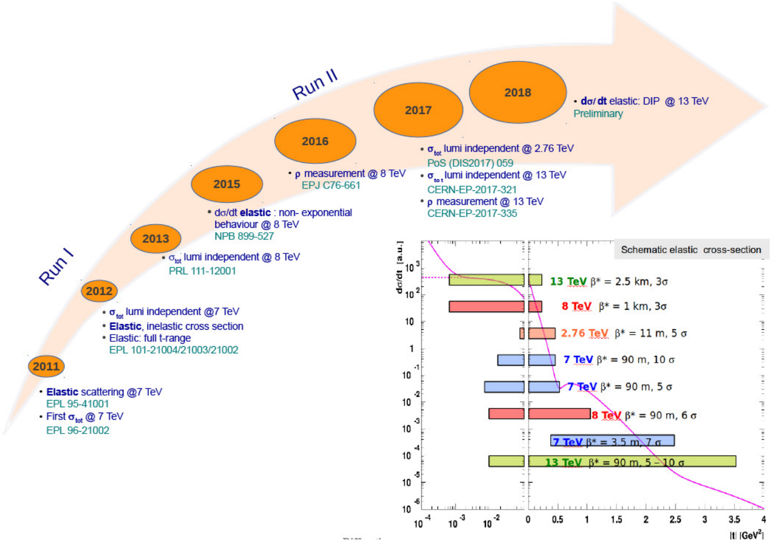
D0 elastic $p\bar{p}$ $d\sigma/dt$ cross section measurements



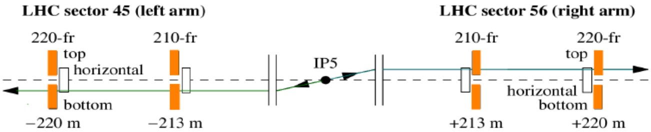


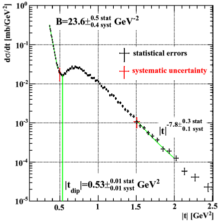
- D0 collected elastic $p\bar{p}$ data with intact p and $\bar{p}$ detected in the Forward Proton Detector with 31 nb^{-1} Phys. Rev. D 86 (2012) 012009
- Measurement of elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV for $0.26 < |t| < 1.2$ GeV^2

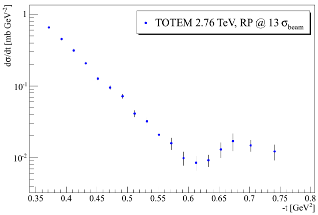
TOTEM cross section measurements

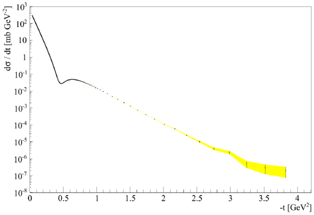


- Elastic $pp\ d\sigma/dt$ measurements: tag both intact protons in TOTEM Roman Pots 2.76, 7, 8 and 13 TeV
- Very precise measurements at 2.76, 7, 8 and 13 TeV: Eur. Phys. J. C 80 (2020) no.2, 91; EPL 95 (2011) no. 41004; Nucl. Phys. B 899 (2015) 527; Eur. Phys. J. C79 (2019) no.10, 861

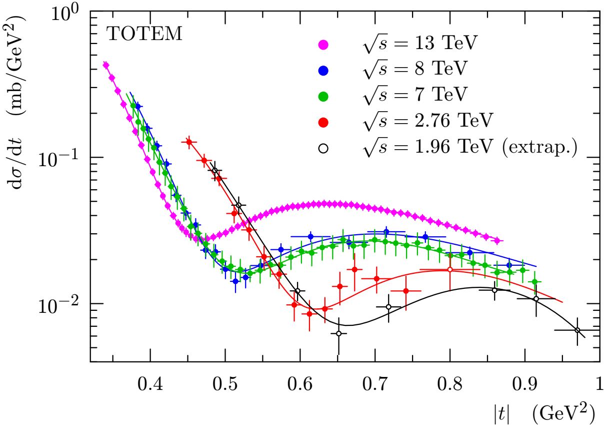






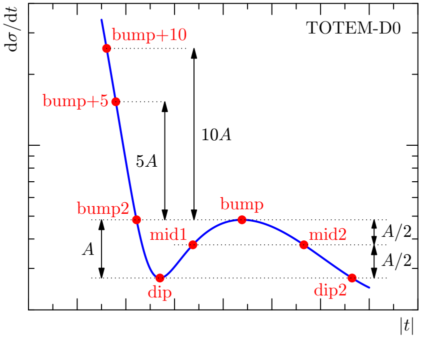


Strategy to compare pp and $p\bar{p}$ data sets



- 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

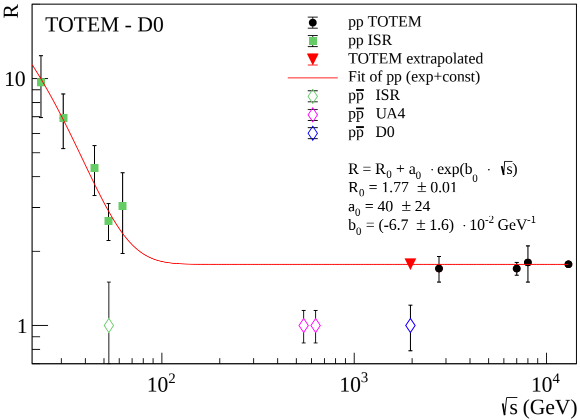
Reference points of elastic $d\sigma/dt$



- 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$\pm$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 $\sqrt{s} = 100 GeV$)

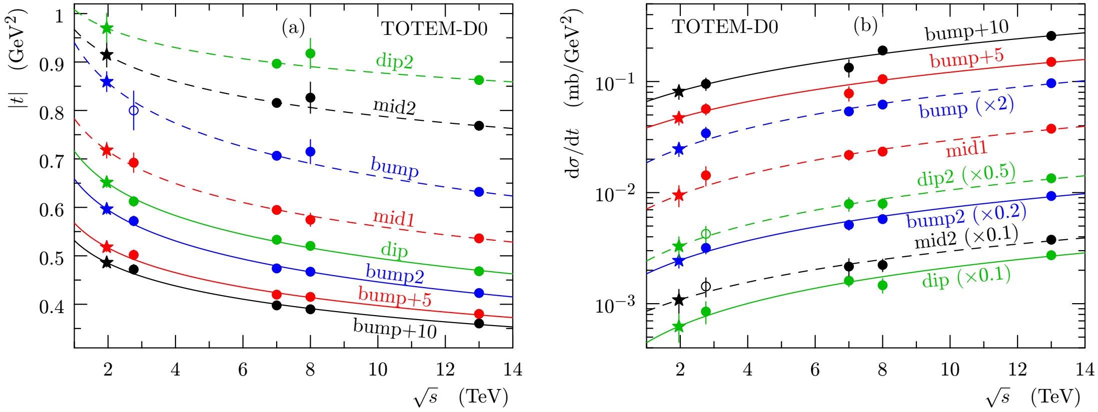
Fits of t and $d\sigma/dt$ values for reference points

- Fit of all reference points using the following formulae:

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

- The same form is used for the 8 reference points (this is an assumption and works to describe all characteristic points): this simple form is chosen since we fit at most 4 points, corresponding to $\sqrt{s} = 2.76$, 7, 8 and 13 TeV
- We also tried alternate parametrizations such as $|t| = e(s)^f$ leading to compatible results well within 1σ
- Leads to very good χ^2 per dof, better than 1 for most of the fits
- Extrapolating the fits leads to predictions for $|t|$ and $d\sigma/dt$ at 1.96 TeV for each characteristic point

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

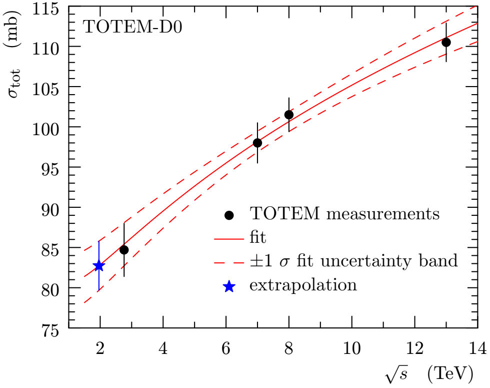


$$|t| = a\log(\sqrt{s}[\mathrm{TeV}]) + b \qquad (d\sigma/dt) = c\sqrt{s}\ [\mathrm{TeV}] + d$$

Fits of TOTEM extrapolated characteristic points at 1.96 TeV

- The last step is to predict the *pp* elastic cross sections at the same *t* values as measured by D0 in order to make a direct comparison
- Fit the reference points extrapolated to 1.96 TeV from TOTEM measurements using a double exponential fit ($\chi^2 = 0.63$ per dof): $h(t) = a_1 e^{-b_1|t|^2 - c_1|t|} + d_1 e^{-f_1|t|^3 - g_1|t|^2 - h_1|t|}$
  - This function is chosen for fitting purposes only
  - Low-*t* diffractive cone (1st function) and asymmetric structure of bump/dip (2nd function)
  - The two exponential terms cross around the dip, one rapidly falling and becoming negligible in the high *t*-range where the other term rises above the dip
- Systematic uncertainties evaluated from an ensemble of MC experiments in which the cross section values of the eight characteristic points are varied within their Gaussian uncertainties. Fits without a dip and bump position matching the extrapolated values within their uncertainties are rejected, and slope and intercept constraints are used to discard unphysical fits
- Such formula leads also to a good description of TOTEM data in the dip/bump region at 2.76, 7, 8 and 13 TeV

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)

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

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

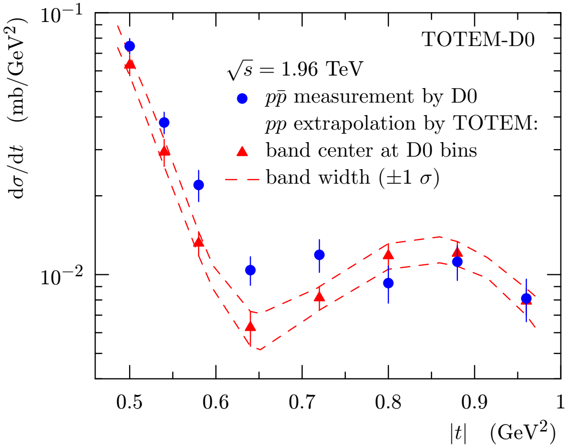
- Adjust 1.96 TeV $d\sigma/dt(t=0)$ from extrapolated TOTEM data to D0 measurement
- From TOTEM pp σ_{tot}, obtain $d\sigma/dt(t=0)$:

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

- 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



Comparison between D0 measurement and extrapolated TOTEM data

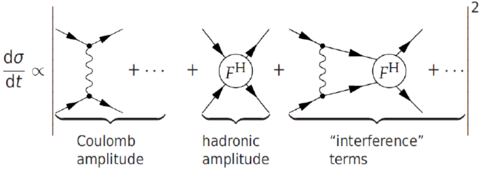
- χ^2 test to examine the probability for the D0 and TOTEM $d\sigma/dt$ to agree

$$\chi^2 = \Sigma_{i,j}[(T_i - D_i)C_{ij}^{-1}(T_j - D_j)] + \frac{(A - A_0)^2}{\sigma_A^2} + \frac{(B - B_0)^2}{\sigma_B^2}$$

where T_j and D_j are the j^{th} $d\sigma/dt$ values for TOTEM and D0, C_{ij} the covariance matrix, A (B) the nuisance parameters for scale (slope) with A_0 (B_0) their nominal values

- Slopes constrained to their measured values (pp to $p\bar{p}$ integrated elastic cross section ratio (dominated by the exp part) becomes 1 in the limit $\sqrt{s} \to \infty$ which means similar slopes at small $|t|$ as observed in data)
- Test using the difference of the integrated cross section in the examined $|t|$-range with its fully correlated uncertainty, and the experimental and extrapolated points with their covariance matrices
- Given the constraints on the OP normalization and logarithmic slopes of the elastic cross sections, the χ^2 test with six degrees of freedom yields the p**-value of 0.00061, corresponding to a significance of 3.4σ**

Combination with additional TOTEM measurement: ρ measurement

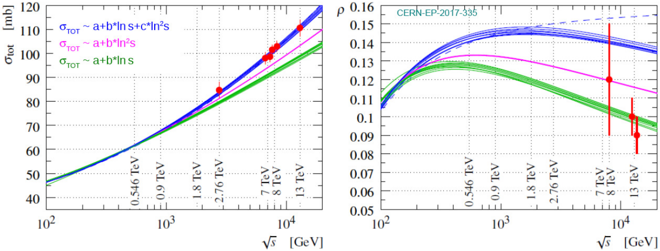


- Measure elastic scattering at very low t: Coulomb-Nuclear interference region

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

- 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 previous measurement by TOTEM: ρ and σ_{tot} measurements as an indication for odderon



- ρ is the ratio of the real to imaginary part of the elastic amplitude at $t = 0$
- 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)

Conclusion

- 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
- R **ratio of bump/dip shows a difference of more than 3**σ between D0 (R=1.0±0.21), and TOTEM (assuming flat behavior above $\sqrt{s} = 100$ GeV)
- Fits of 8 "characteristic" points of elastic pp $d\sigma/dt$ data such as dip, bump, etc as a function of $\sqrt{s}$ in order to predict pp data at 1.96 TeV
- pp **and** $p\bar{p}$ **cross sections differ with a significance of 3.4**σ **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 5.7**σ **and thus constitutes the first experimental observation of the odderon: Major discovery at CERN/Tevatron**