Recent results on soft and hard diffraction at the LHC

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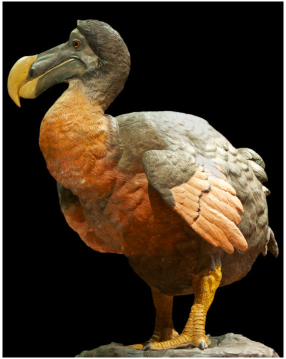
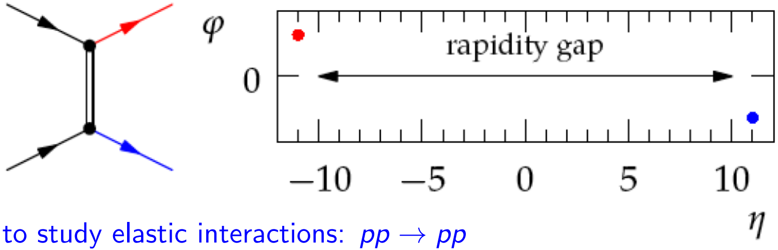


November 20-24 2023

- Soft diffraction: Total cross section and elastic interactions
- Odderon discovery
- Exclusive production of low mass pion pairs
- Hard diffraction: jet gap jets

Elastic scattering at the LHC

Elastic Scattering (ES), $\approx 30\,\mathrm{mb}$



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

Analysis methods in TOTEM: total cross section

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

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

$$L\sigma_{tot} = N_{el} + N_{inel}$$

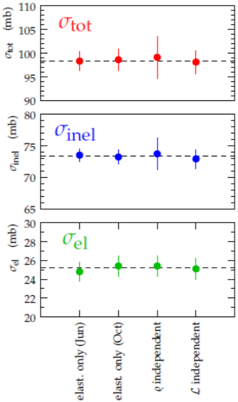
- Different methods to measure the total cross section
  - Lumi independent measurement

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

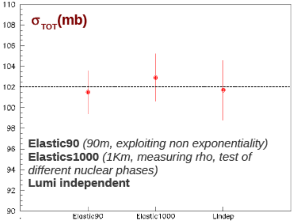
  - Lumi dependent measurement (elastic only)

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

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



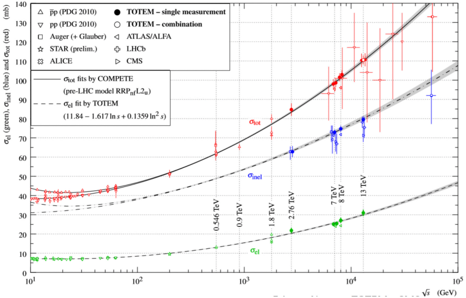
7 TeV, several methods
Same beam conditions

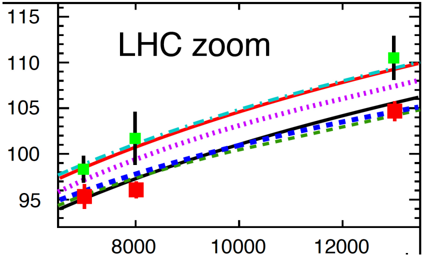


8 TeV, several methods
Different beam conditions

- 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

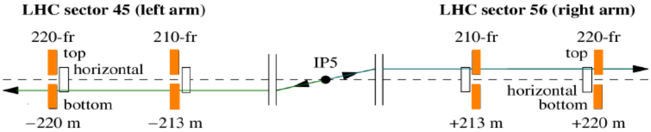
Elastic, inelastic, total cross section measurements (ATLAS/ALFA and TOTEM)

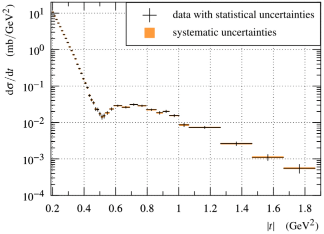


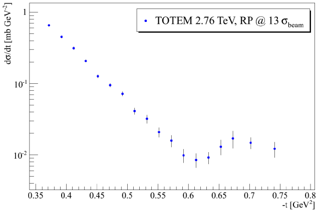


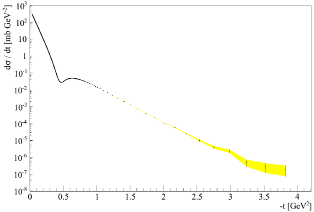
- High precision measurement of elastic, inelastic and total cross sections
- Measurements in agreement with cosmic-ray data (large error bars though)
- ATLAS $\sim 2\ \sigma$ lower than TOTEM at 8 and 13 TeV: differences due to luminosity measurements?

- 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

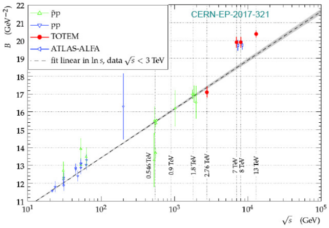


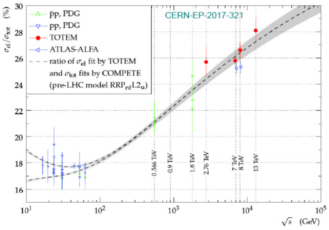


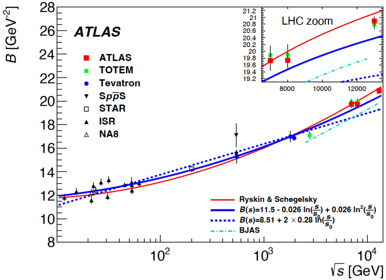




Implication of elastic cross section measurements: *B* slope at 13 TeV

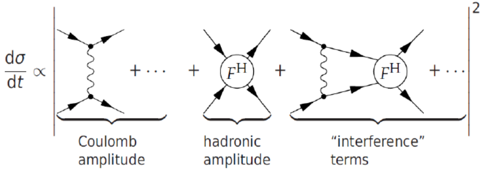






- B slope of $d\sigma/dt$: larger slope at 13 TeV
- Linear behavior (lns) compatible for $\sqrt{s} < 3$ TeV, incompatible at higher energy
- The increase of σ_{el}/σ_{tot} with energy is confirmed at LHC
- ATLAS Coll., Eur. Phys. J. C 83 (2023) 441

ρ measurement (TOTEM and ATLAS/ALFA)

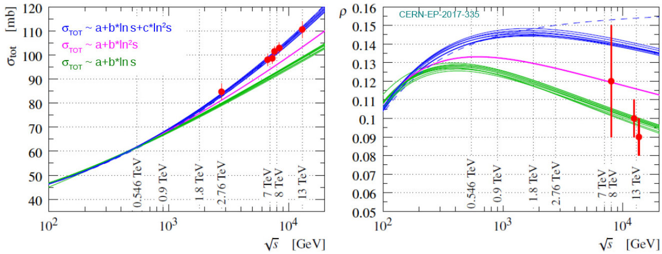


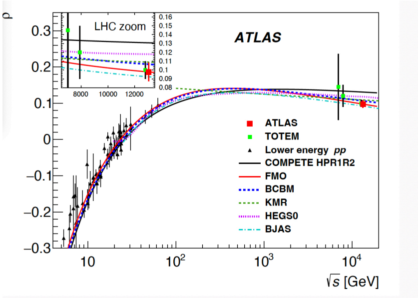
- Measure elastic scattering at very low t: Coulomb-Nuclear interference region

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

- 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

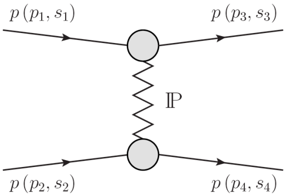
ρ measurement at 13 TeV (TOTEM and ATLAS/ALFA)





- ρ is the ratio of the imaginary and real part of the total cross section
- Using low $|t|$ data, measurement of ρ at 13 TeV: $\rho = 0.09 \pm 0.01$ (TOTEM, EPJC 79 (2019) 785)
- ATLAS: 0.098 ± 0.011 (EPJC 83 (2023) 441)
- ρ value at 13 TeV clearly below expectations (COMPETE fits as an example)
- Can be explained by the exchange of Odderon in addition to Pomeron

The odderon in a nutshell

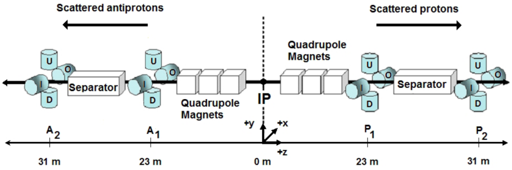


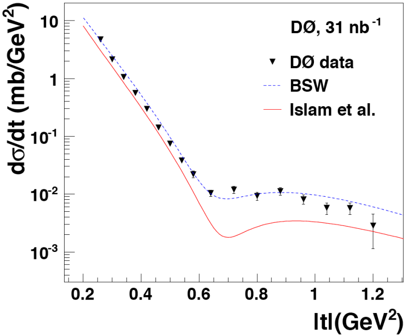
- Let us assume that elastic scattering can be due to exchange of colorless objects: Pomeron and Odderon
- Charge parity C: Charge conjugation changes the sign of all quantum charges
- Pomeron and Odderon correspond to positive and negative C parity: Pomeron is made of two gluons which leads to a $+1$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

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

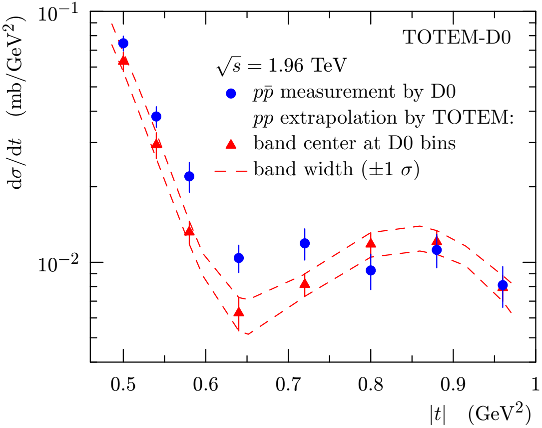




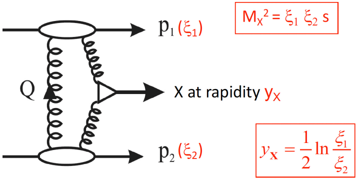
- D0 collected elastic $p\bar{p}$ data with intact p and $\bar{p}$ detected in the Forward Proton Detector with 31 nb^{-1} Phys. Rev. D 86 (2012) 012009
- Measurement of elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV for $0.26 < |t| < 1.2$ GeV^2

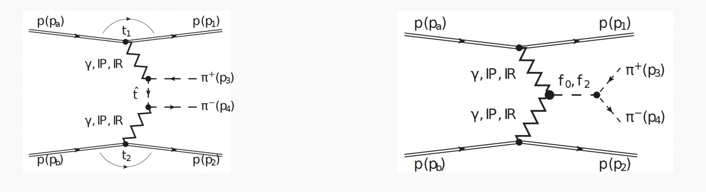
Predictions at $\sqrt{s} = 1.96$ TeV

- Reference points at 1.96 TeV (extrapolating TOTEM data) and 1σ uncertainty band
- Comparison with D0 data: 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 independent evidence of the odderon using ρ and total cross section measurements at low t: combined significance ranges from **5.3 to 5.7σ depending on the model**
- TOTEM and D0: PRL 127 (2021) 062003

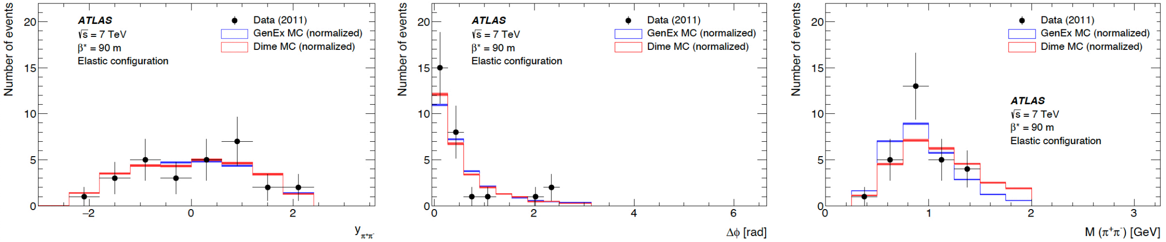


Central exclusive production



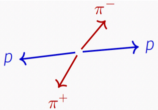


- Measurement of central exclusive production of pair of particles
- Measure both intact protons in TOTEM or in ATLAS-ALFA and pions in ATLAS/CMS
- Background can be controlled by matching the proton and CMS/ATLAS measurements: $M_{pp} = M_{central}$, $y_{pp} = y_{central}$



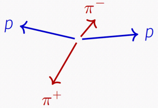
– elastic *pp* configuration

$$\sigma = 4.8 \pm 1.0(\text{stat})^{+0.3}_{-0.2}(\text{syst}) \pm 0.1(\text{lumi}) \pm 0.1(\text{model})\ \mu\text{b}$$

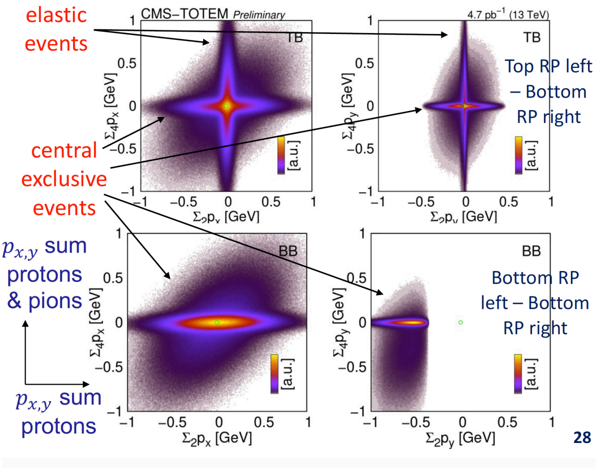


– anti-elastic *pp* configuration

$$\sigma = 9 \pm 6(\text{stat}) \pm 1(\text{syst}) \pm 1(\text{lumi}) \pm 1(\text{model})\ \mu\text{b}$$



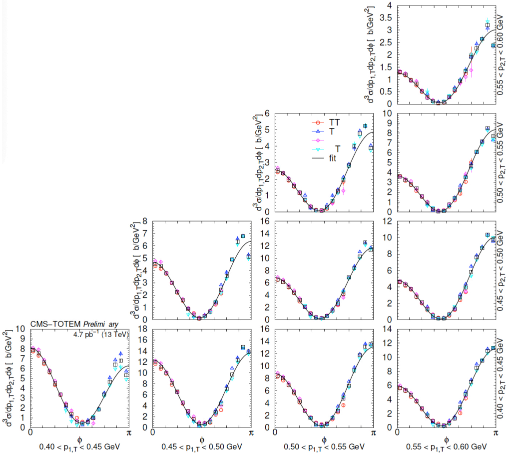
Non-resonant exclusive dipion production (CMS/TOTEM)



CMS-PAS-SMP-21-004 ; TOTEM-NOTE-2023-001

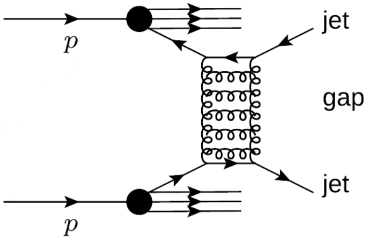
- Non-resonant exclusive di-pion production: Very clean events, 2 pions measured in CMS and 2 protons in TOTEM
- $pp \to p\pi\pi p$
- Sum of proton transverse momentum ($p_{X,Y}^{TOTEM}$) versus sum of charged particles in tracker ($p_{X,Y}^{CMS}$)
- Allows to select very pure sample
- Require diproton and dipion p_x and p_y to match ($\Sigma_4 p_x \sim 0$ and $\Sigma_4 p_y \sim 0$)
- Main background: elastic with inelastic pileup

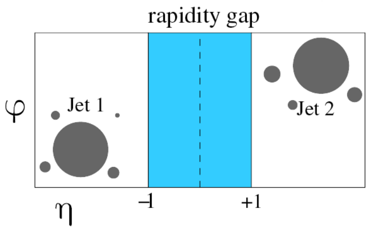
Non-resonant exclusive dipion production (CMS/TOTEM)



- Variables studied: $m_{\pi^+\pi^-}$, proton p_T and ϕ (2-proton azimuthal angle difference)
- Focus on non-resonant region: $0.35 < m_{\pi\pi} < 0.65$ GeV
- First observation of parabolic minimum in ϕ
- Study nucleon-pomeron and meson-pomeron couplings in different models with different form factors
- Two channel model favored
- Remarkable agreement with DIME model

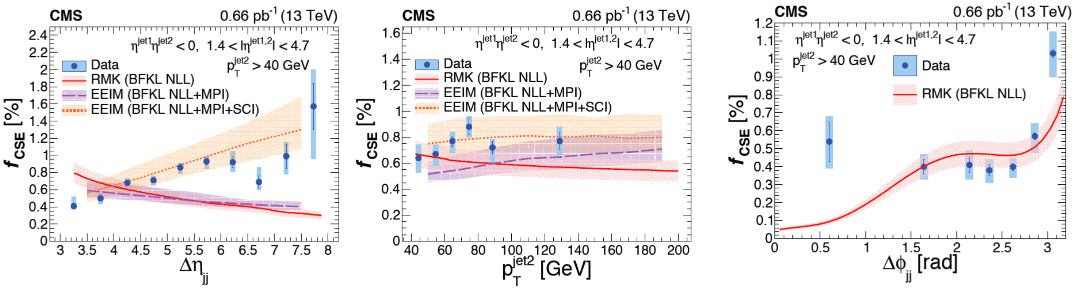
Mueller Tang: Gap between jets at the Tevatron and the LHC





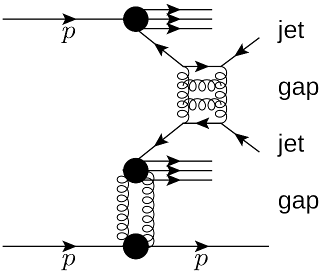
- Looking for a gap between two jets: Region in rapidity devoid of any particle production, energy in detector
- Exchange of a BFKL Pomeron between the two jets: two-gluon exchange in order to neutralize color flow
- Method to test BFKL resummation: Implementation of BFKL NLL formalism in HERWIG/PYTHIA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

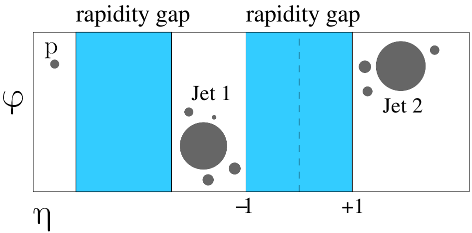
LHC: Measurement of jet gap jet fraction (CMS)



- 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): Sensitivity to ISR

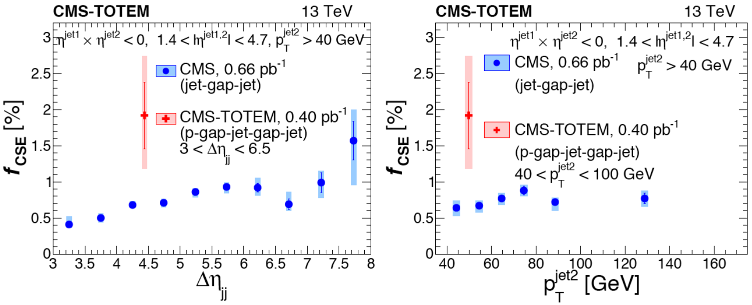
Another kind of events: Jet gap jet events in diffraction (CMS/TOTEM)





- 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)

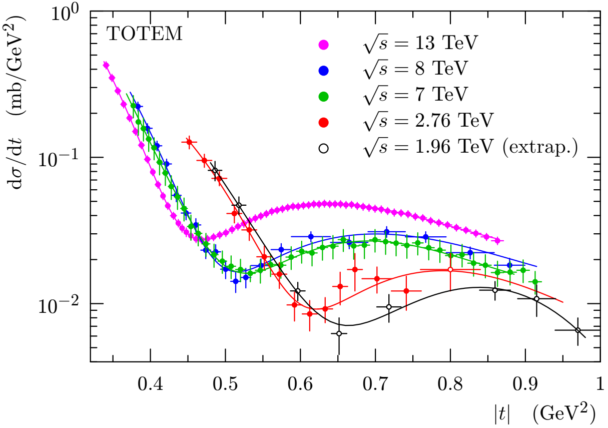


- First observation: 11 events observed with a gap between jets and at least one proton tagged with ~ 0.7 pb^{-1}
- Leads to very clean events for jet gap jets since MPI are suppressed and might be the "ideal" way to probe BFKL
- Would benefit from more stats $>$10 pb^{-1} needed, 100 for DPE

Conclusion

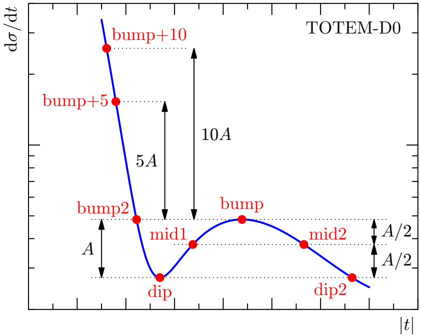
- Total and elastic cross sections measured by the TOTEM/ATLAS-ALFA collaborations: non-exponential behavior of $d\sigma/dt$, discrepancy of $\sim 2\sigma$ between both collaborations
- pp and $p\bar{p}$ cross sections differ with a significance of 3.4σ in a model-independent way and thus provides evidence for the odderon (D0-TOTEM)
- When combined with ρ and total cross section results at 13 TeV, the significance 5.3 to 5.7σ
- Measurements of exclusive dipions by ATLAS and CMS-TOTEM: MC tuning
- Jet gap jet measurements (test of BFKL) and first observation of jet gap jets in diffraction

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

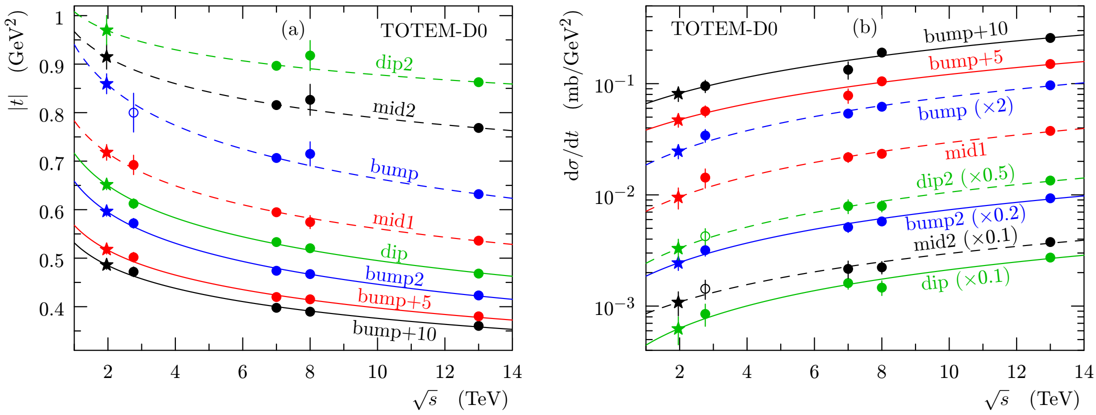
Reference points of elastic $d\sigma/dt$



- 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

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



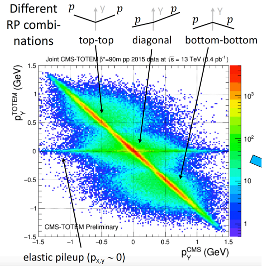
$$|t| = a \log(\sqrt{s}[\mathrm{TeV}]) + b \qquad (d\sigma/dt) = c\sqrt{s}\ [\mathrm{TeV}] + d$$

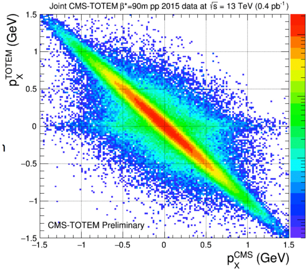
Non-resonant exclusive dipion production (CMS/TOTEM)

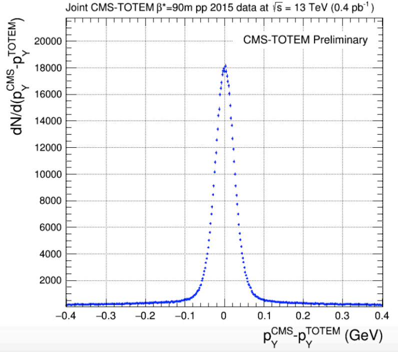
Parameter	Exponential	Orear-type	Power-law	DIME 1 / 2
empirical model				
a_{ore} [GeV]	—	0.735 ± 0.015	—	
$b_{exp/ore/pow}$ [$GeV^{-2 \text{ or } -1}$]	1.084 ± 0.004	1.782 ± 0.014	1.356 ± 0.001	
$B_{\mathbb{P}}$ [GeV^{-2}]	3.757 ± 0.033	3.934 ± 0.027	4.159 ± 0.019	
χ^2/dof	9470/5796	10059/5795	11409/5796	
one-channel model				
σ_0 [mb]	34.99 ± 0.79	27.98 ± 0.40	26.87 ± 0.30	
$\alpha_P - 1$	0.129 ± 0.002	0.127 ± 0.001	0.134 ± 0.001	
α'_P [GeV^{-2}]	0.084 ± 0.005	0.034 ± 0.002	0.037 ± 0.002	
a_{ore} [GeV]	—	0.578 ± 0.022	—	
$b_{exp/ore/pow}$ [$GeV^{-2 \text{ or } -1}$]	0.820 ± 0.011	1.385 ± 0.015	1.222 ± 0.004	
$B_{\mathbb{P}}$ [GeV^{-2}]	2.745 ± 0.046	4.271 ± 0.021	4.072 ± 0.017	
χ^2/dof	7356/5793	7448/5792	8339/5793	
two-channel model				
σ_0 [mb]	20.97 ± 0.48	22.89 ± 0.17	23.02 ± 0.23	23 / 33
$\alpha_P - 1$	0.136 ± 0.001	0.129 ± 0.001	0.131 ± 0.001	0.13 / 0.115
α'_P [GeV^{-2}]	0.078 ± 0.001	0.075 ± 0.001	0.071 ± 0.001	0.08 / 0.11
a_{ore} [GeV]	—	0.718 ± 0.012	—	
$b_{exp/ore/pow}$ [$GeV^{-2 \text{ or } -1}$]	0.917 ± 0.007	1.517 ± 0.008	0.931 ± 0.002	0.45
$\Delta\|a\|^2$	0.070 ± 0.026	-0.058 ± 0.009	0.042 ± 0.011	−0.04 / −0.25
$\Delta\gamma$	0.052 ± 0.042	0.131 ± 0.018	0.273 ± 0.023	0.55 / 0.4
b_1 [GeV^2]	8.438 ± 0.108	8.951 ± 0.041	8.877 ± 0.040	8.5 / 8.0
c_1 [GeV^2]	0.298 ± 0.012	0.278 ± 0.004	0.266 ± 0.006	0.18 / 0.18
d_1	0.472 ± 0.007	0.465 ± 0.002	0.465 ± 0.003	0.45 / 0.63
b_2 [GeV^2]	4.982 ± 0.133	4.222 ± 0.052	4.780 ± 0.060	4.5 / 6.0
c_2 [GeV^2]	0.542 ± 0.015	0.522 ± 0.006	0.615 ± 0.006	0.58 / 0.58
d_2	0.453 ± 0.009	0.452 ± 0.003	0.431 ± 0.004	0.45 / 0.47
χ^2/dof	5741/5786	6415/5785	7879/5786	

- Two channel model favored
- Remarkable agreement with DIME model

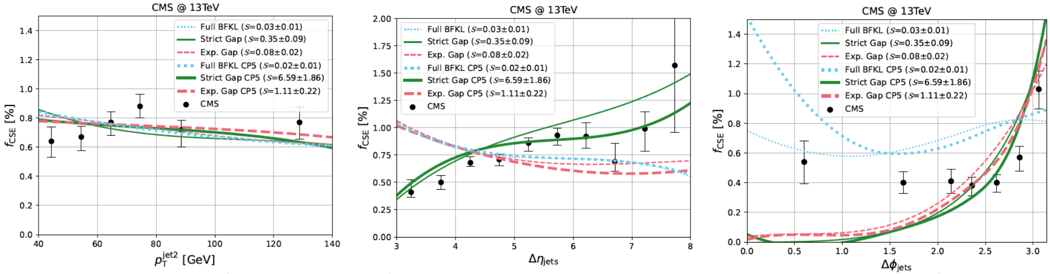
Central exclusive production (CMS/TOTEM)





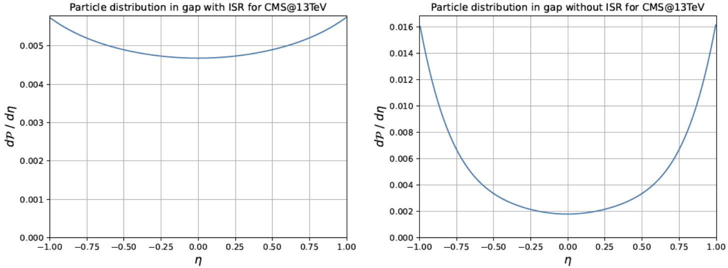


- $pp \to p\pi\pi p$
- Sum of proton transverse momentum ($p_{X,Y}^{TOTEM}$) versus sum of charged particles in tracker ($p_{X,Y}^{CMS}$)
- Allows to select very pure sample



- 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); CMS data: Phys.Rev.D 104 (2021) 032009
- 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)