Odderon Observation: the comparison of pp and $p\bar{p}$ differential cross sections using D0 and TOTEM

D0 and TOTEM — speaker: Timothy G. Raben

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Saturation and Diffraction at the LHC and the EIC 2021

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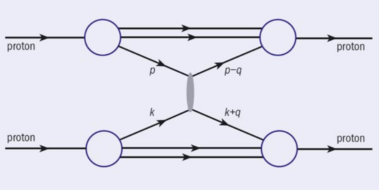
Where we are going

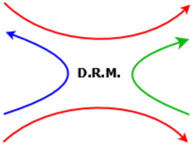
We know lots of very accurate things about fundamental physics with regards to weakly coupled electromagnetic and weak-force interactions. We know less about the strong-force interaction because it is often strongly coupled and/or confining.



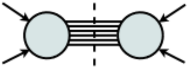
There is much we can learn from elastic scattering of (anti) protons in the near-forward limit: Odderon physics is one of these!

Why Odderon?

Before the wide spread adoption of QCD (1970's) as a fundamental theory of weakly coupled strong interactions physicists asked general questions about what scattering of hadrons should look like (e.g. S-matrix theory, dual resonance models, etc.).



Many results from this era and approaches accurately describe particle physics: optical theorem(s), cutkosky rules, etc.



One of these enduring approaches is known as (Tullio)*Regge Theory* which aims to describe scattering amplitudes by assuming physics is *unitary*, *Lorentz invariant*, parameterized by *analytic functions* of momenta, and then examines what happens in *high energy limits*.

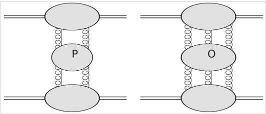
Let's do a *very brief* intro to some of the theoretical underpinning of Odderon physics. Much more detail to come afterward in talk by Leszek Motyka!

Odderon

With the reasonable assumptions of Regge Theory we find that in the Regge Limit, exchanges of a family of simple poles can be shown to dominate hadronic cross sections which leads to the classic Regge behavior,

$$A(s,t) = \oint \frac{2\ell+1}{2i\sin\pi\ell} \sum_{\eta=\pm1} \frac{\eta+e^{-i\pi\ell}}{2} a^{(\eta)}(\ell,t) P(\ell, 1+\tfrac{2s}{t}) \quad \xrightarrow[s\to\text{inf}]{s>>|t|} \quad A \sim \frac{\eta+e^{-i\pi\ell}}{2}\beta(t)s^{\alpha(t)} .$$

This dominant contribution is generally referred to as a Pomeron(Pomeranchuk) contribution. The Pomeron is a colorless, charge–parity(CP) even object. There is a partner family/trajectory that contributes with odd-signature (C–odd,P–odd). This contribution will be subleading to the Pomeron in most hadronic scattering: **this is an Odderon contribution.**



Cartoon of Pomeron (left) and Odderon (right) exchange.

Odderon (cont.)

Both Pomeron and Odderon can be described in pQCD.

[ZETF72,377-289(1977)] & [Nucl.Phys.B175,365–40(1980)] [Acta.Phys.Polon.B11,965(1980)] [PLB 94,413–416(1980)]

Takeaway: between Regge Theory and pQCD we know that there must* be Odderon physics!

Three good ideas to look for Odderon physics:

1 Look at the difference in $d\sigma/dt$ between pp (TOTEM) and $p\bar{p}$ in region where $|t| > 0$. (this work)

2 Look at the ratio $\rho = \text{Re}A/\text{Im}A$ in the forward $t = 0$ limit where A describes σ_{tot} via the optical theorem. [Eur.Phys.J.C76(2016): 661] [Eur.Phys.J.C79(2019)9,785]

3 Combine 1 & 2, the evidence from various t ranges. (this work)

There are other processes where Odderon physics could be present — e.g. electron–proton/positron collisions — but so far there is not suitable data.

So where is the odderon?

In most single processes, in the Regge limit, the Pomeron is the dominant contribution. Regge limits often involve non-perturbative physics. One of the best ways to look for Odderon effects is to compare particle– particle to particle–anti-particle. Put it all together: **i.e. it's hard!**

How to do pheno: a *VERY* brief and incomplete list of theoretical references

There are various Odderon states/solutions

[PRL 82,1092(1999)] [PLB 477,886178–186(2000)] [PLB 679,288-292(2009)]

Many Regge-models which have contributions that are Pomeron-like, Odderon-like, and general Reggeon-like.

[PRL 54,2656(1985)] [PLB 238,406–412(1990)] [PLB 784,192-198(2018)] [EPJ C79,237(2019)]

There are stochastic vacuum, Monte-Carlo, and stringy/holographic non-perturbative models.

[PLB 205,339–344(1988)] [JHEP 063(2009)] [JHEP 104(2015)] [PRD 94,034019(2016)]

Highlights from previous analyses (not exhaustive)

- Pomeron+Odderon model of elastic diff. cross section "dip" [Nucl.Phys. B231(1984)189]
- **Comparison of pp and $p\bar{p}$ at $\sqrt{s} = 53 GeV$** [Nucl.Phys. B150 (1979)221] [PRL 54(1985)2180] [Nucl.Phys. B262(1985)689] **$\sim 3\sigma$ evidence, but low energy (could be mesons/Reggeons)**
- Exhaustive model comparison to ISR data [EPJ C24(2002):561-571]
- Phillips-Barger model analysis of LHC and Tevatron datasets [EPJ C79(2019):237]
- Using model-independent Levy expansion for ISR, S$p\bar{p}$S, and LHC datasets leading to $> 6\sigma$. [EPJ C79(2019)] [EPJ C81(2021):180]
- And talks later today by Evgenij Martynov, Yoshitaka Hatta, and Dmitri Melnikov— and Chung-I Tan tomorrow!

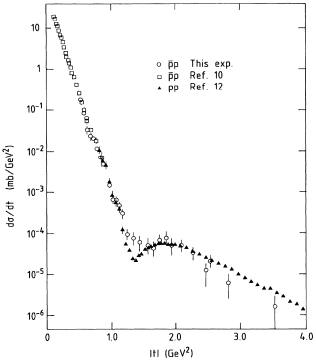
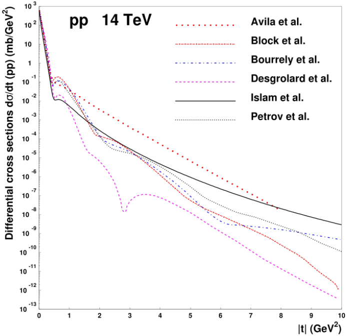
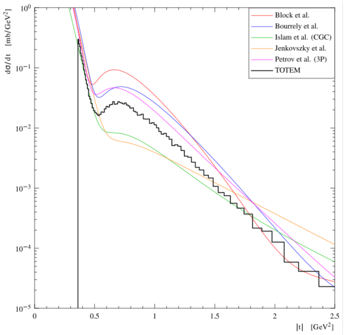


FIG. 2. Elastic differential $\bar{p}p$ cross section at $\sqrt{s} = 53$ GeV. Only t-dependent errors are shown. The systematic scale error is estimated at $\pm 30\%$. Included are the low-t data from our previous experiment (Ref. 10) and the pp data of Ref. 12.

[PRL 54(1985)2180]

$\sqrt{s} > 1\text{TeV}$ preview

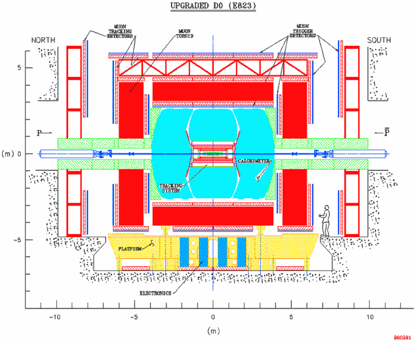




[EDS 07(2007),267-272] [EPL,95(2011) 41001]

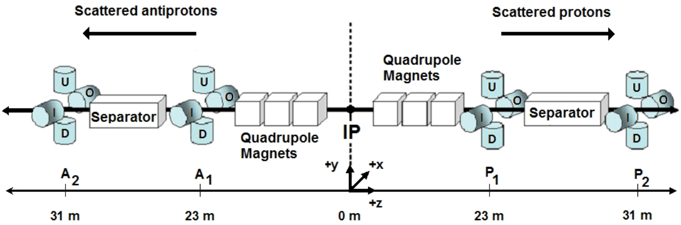
Meson and Reggeon contributions would be reflected in structure (shape) of $d\sigma/dt$ (left). However, we see smooth differential cross-sections (right, 7 TeV): dominated by Pomeron/Odderon. Wealth of measurements at different $\sqrt{s}$: 1.96 TeV (Tevatron), 2.76 TeV, 7 TeV, 8 TeV, 13 TeV (LHC)

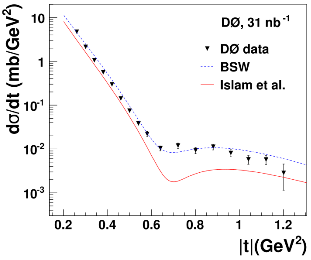
D0 at the Tevatron



D0 collected elastic $p\bar{p}$ data with intact p and $\bar{p}$ detected in the Forward Proton Detectors with 31 nb^{-1}. [PRD 86(2012)012009] (Near)forward scattering requires special (near)forward detectors (e.g. Roman pots).

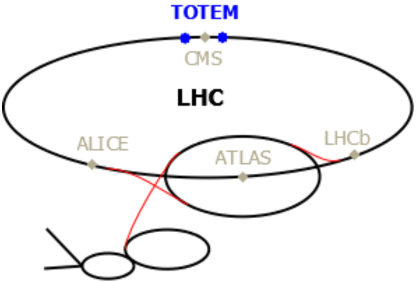
$p\bar{p}$ at D0

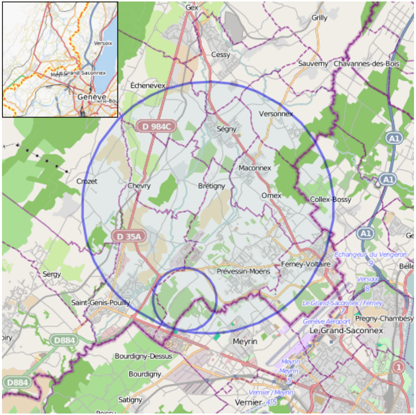




- D0 detector [Nucl.Instr.Meth. Phys.Res. A565,463(2006)] involves a Central Tracking System and Forward Proton Detectors.
- Forward Proton Detectors use quadrupole spectrometers (23 and 31 meters from interaction point) and Roman pots
- $\sim$ 20 million events collected with special set of triggers used for elastic ($\sim$ 10% of data collected), single diffractive, and double diffractive events.

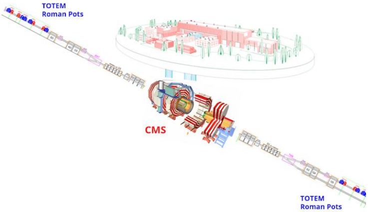
TOTEM





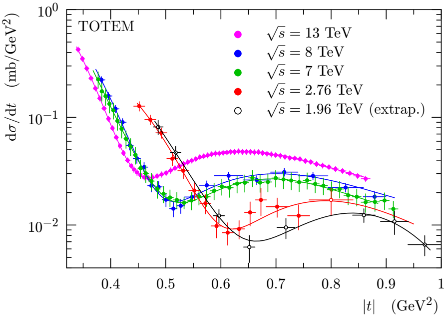
Precise measurements at 2.76, 7, 8, and 13 TeV [EPJ C90(2020)2,91][EPL 95(2011)41004][Nucl.Phys.B899(2015)527][EPJ C79(2019)10,861] includes measurements of elastic pp cross-section $d\sigma/dt$.

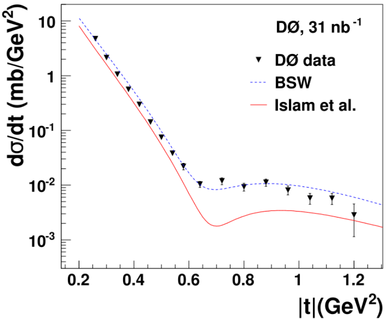
pp at TOTEM

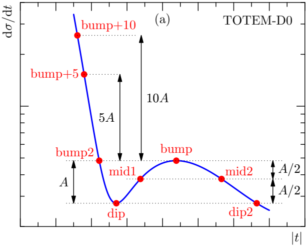


TOTEM roman pots are located roughly 200m on either side of IP5. These detectors are part of a moveable beam-pipe that can get less than a millimeter from the beamline. (full detailed description in [INST 3(2008) S08007][Int.J.Mod.Phys. A28(2013)1330046])

As an example, in the 2.76 TeV run, [EPJ C90(2020)2,91], integrated luminosity of 0.4nb^{-1} was gathered with more than 7 million elastic event candidates tagged.

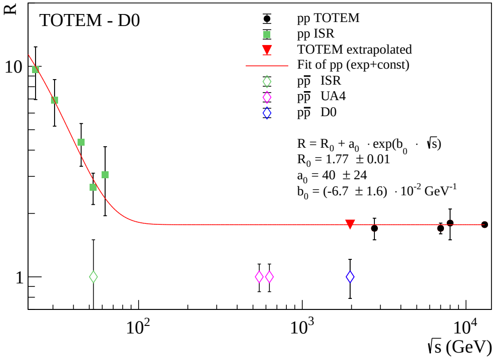






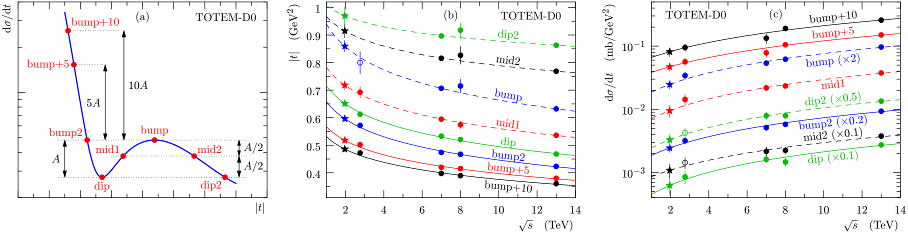
- Need to compare TOTEM (pp) data at 2.76, 7, 8, 13 TeV to D0 ($p\bar{p}$) data at 1.96 TeV
- All TOTEM measurements show same general features—smooth with dip and bump region–whereas D0 appears naively more flattened.
- Let's characterize general features of TOTEM cross-section measurements, extrapolate to 1.96 TeV and compare.

Classic bump–over–dip ratio: R



- R defined as the bump–over–dip $d\sigma/dt$ ratio. Measured at ISR, Tevatron, LHC.
- For elastic pp collisions, R decays up to $\sqrt{s} \sim 100$ GeV then flattens out.
- D0 finds $R_{p\bar{p}} = 1.00 \pm 0.21$ given no dip–bump behavior observed within uncertainties.
- **Assuming this flat behavior $\rightarrow > 3\sigma$ difference between pp and $p\bar{p}$**

Characteristic points



Procedure: (1) Define 8 characteristic points of elastic pp $d\sigma/dt$ cross–sections. (2) Determine how the values of $|t|$ and $d\sigma/dt$ of each characteristic point varies as a function of $\sqrt{s}$. Use data points closest to characteristic points, and data bins are merged in cases where there are two adjacent dip or bump points of roughly equal value (3) This gives distributions as a function of $\sqrt{s}$ that can be extrapolated to 1.96 TeV (4) Adjust for common $|t|$ values. (5) Compare!

Extrapolation

For the analysis the following parameterization was used.

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

- For simplicity, this same form was used for all 8 characteristic points (this is an assumption, but not strictly necessary).
- The extrapolation is done within less than 1 order of magnitude and involves at most 4 points (i.e. data from $\sqrt{s} = 2.76$, 7, 8, and 13 TeV).
- Alternate parameterizations, e.g. $|t| = e(s)^f$, were also tried and lead to results that are compatible within 1σ.
- Fitting characteristic points leads to very good χ^2/dof (better than 1 for most fits) and characteristic points and then be extrapolated down to D0 energy.

Common t values

The extrapolated characteristic points are *not* at the same values of $|t|$ as the D0 measurement. To adjust, the extrapolated 1.96 TeV characteristic points are fit ($\chi^2/dof = 0.63$) with a double exponential:

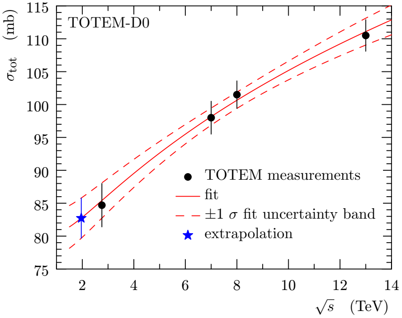
$$h(t) = a_1 \text{Exp}\left[-b_1|t|^2 - c_1|t|\right] + d_1 \text{Exp}\left[-f_1|t|^3 - g_1|t|^2 - h_1|t|\right]$$

- chosen for fitting purposes only and to be as simple as possible
- 1st term: low-t diffractive cone. 2nd term: asymmetric structure of dip–and-bump.
- In dip–and–bump region on exponential begins to rapidly fall off (i.e. become negligible) and then in the high-t range the other term becomes dominant.
- Same formula leads to good description of the TOTEM 2.76, 7, 8, and 13 TeV measurements.

Systematic uncertainties are 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. Slope and intercept constraints are also used to discard unphysical fits.

Relative normalization between D0 and TOTEM–extrapolated

There is a difference in normalization between D0 and TOTEM. At the optical point (OP) $d\sigma/dt(t=0)$, cross–sections are expected to be equal if there are only C-even exchanges (null hypothesis). We require that the pp and $p\bar{p}$ OP cross sections are the same while keeping the slopes of the cross sections un-modified.



- Use TOTEM measurements of σ_{tot} also at 2.76, 7, 8, 13 TeV.
- Similar extrapolation as before: $\sigma_{tot} = a_2 \log^2 \sqrt{s}[\text{TeV}] + b_2$.
- Again, other parameterizations tested.
- **Extrapolation:** $\sigma_{tot}^{pp} = 82.7 \pm 3.1$ **mb at 1.96 TeV**

Relative norm. (cont.)

Use σ_{tot} to adjust extrapolated 1.96 TeV TOTEM data to D0 measurement.

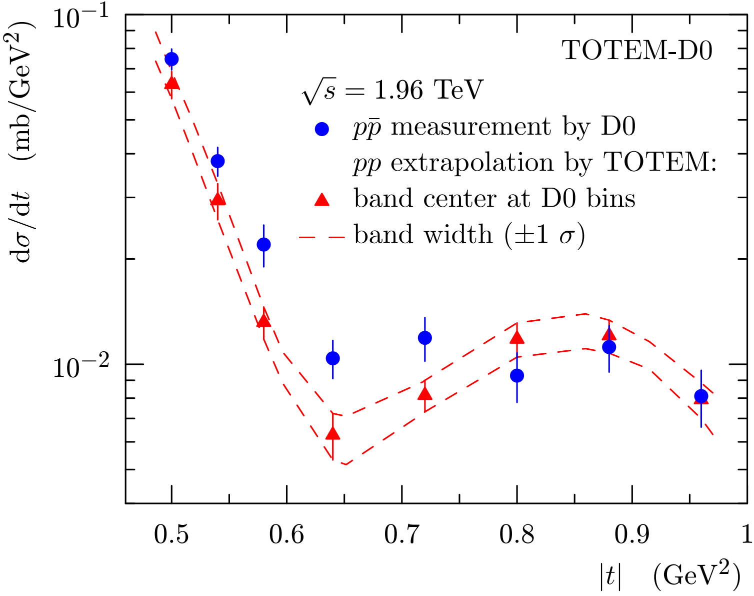
$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left(\frac{d\sigma}{dt}\right)_{t=0}$$

Using COMPETE [PRL 89(2002)201801]extrapolation, we assume $\rho = 0.145$. (ρ being the ratio of imaginary to real part of the elastic amplitude). This leads to

$$\left.\frac{d\sigma}{dt}\right|_{t=0}^{TOTEM-ext} = 357.1 \pm 26.4\,\frac{\text{mb}}{\text{GeV}^2} \quad \text{vs.} \quad \left.\frac{d\sigma}{dt}\right|_{t=0}^{D0} = 341 \pm 48\,\frac{\text{mb}}{\text{GeV}^2}$$

Leading to a rescaling of the TOTEM data by 0.945 ± 0.071.
(Note: this is not a new independent measurement of the differential cross–section at the OP point. Instead, a common and somewhat arbitrary normalization point is needed and we took what appeared to be the simplest approach using the extrapolations.)

Comparison Plot



Comprehensive comparison of $d\sigma/dt$

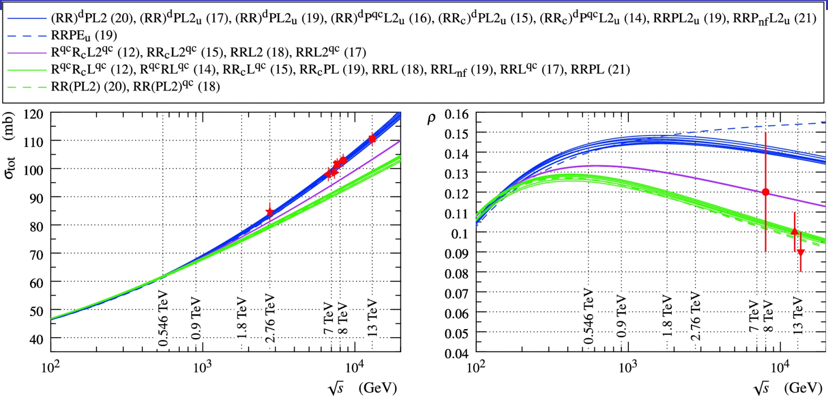
We can use a χ^2 test to examine the probability that the D0 and TOTEM differential cross–sections agree:

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

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

- Slopes are constrained to their measured values (Cornille–Martin theorem $\rightarrow$ similar slopes at small $|t|$.)
- 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 a p-value of 0.00061, corresponding to a significance of 3.4σ. (result cross–checked with a Kolmogorov-Smirnov test)

Previous measurements by TOTEM: ρ and σ_{tot}



Previously reported TOTEM measurement of $\rho = \text{Re}A/\text{Im}A|_{t=0}$, and σ_{tot} [EPJ C79(2019)785]. Use of low $|t|$—$|t| \lesssim 0.05$ GeV—in a region complementary to new result.

Exhaustive tests of models *without a crossing odd contribution* from COMPETE were unable to simultaneously describe σ_{tot} and ρ.

Combine results

The previous ρ and σ_{tot} results of TOTEM use separate low $|t|$ data in a different kinematic region. Depending on the COMPETE model used, the previous TOTEM result indicated 3.4 to 4.6σ discrepancy between models with and without a crossing odd contribution.

- Results are combined with the Stouffer method.
- From previous results on ρ and σ_{tot}, models without Odderon contribution were selected.
- **Total combination with new results leads to $5.3\sigma < \chi^2 < 5.7\sigma$.**

Where analyses can go next:

- Detailed optical point and slope analyses
- Future colliders could give us information at higher $|t|$ where Odderon may dominate
- Purely perturbative comparison.
- Model based analyses and distinguish between various odderons within models.

Conclusions

- Presented a detailed description of pp elastic differential cross–sections at 2.76, 7, 8, and 13 TeV from TOTEM.
- Extrapolated these results down to 1.96 TeV to compare with D0 measurement of $p\bar{p}$ elastic differential cross–section.
- Without C-odd colorless gluonic object, pp and $p\bar{p}$ differential cross–sections differ with 3.4σ significance.
- **Combining with previous ρ and σ_{tot} measurements of TOTEM and comparison with COMPETE models leads to improved 5.3 to 5.7σ evidence: observation of Odderon physics.**

As always, if you are new to Odderon physics, an excellent entryway into the subject is through the well sourced review [arXiv:hep-ph/0306137v2]