Odderon signal from scaling in pp elastic cross-sections at the LHC

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In collaboration with Christophe Royon, Robi Peschanski and Bertrand Giraud.

Outline

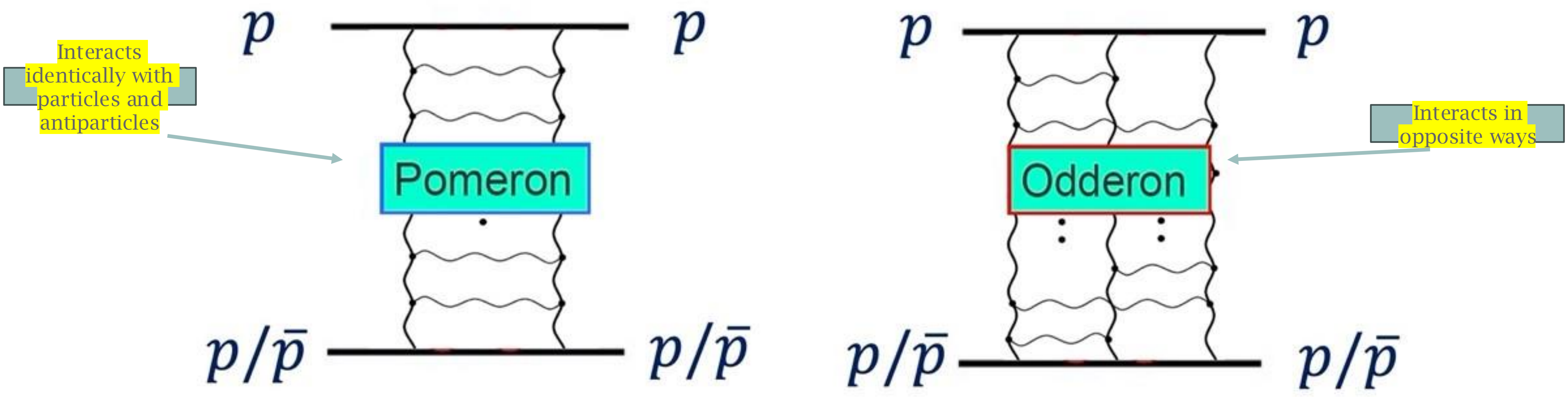
- Physics motivation
  - Elastic collisions in high energy physics
  - Odderon discovery
  - Theory characterization

From the scaling framework to the Odderon determination

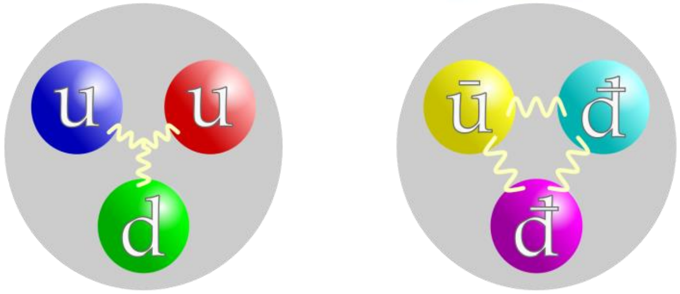
- Scaling law cross elastic scattering collision system
- Scaling amplitudes and pomeron signature
- Elastic proton-antiproton cross-section prediction
- Odderon exchange predictions
- Summary / Outlook

Physics motivation

How to explain the fact that protons can be intact? Quantum Chromodynamics (Diffractive Events)

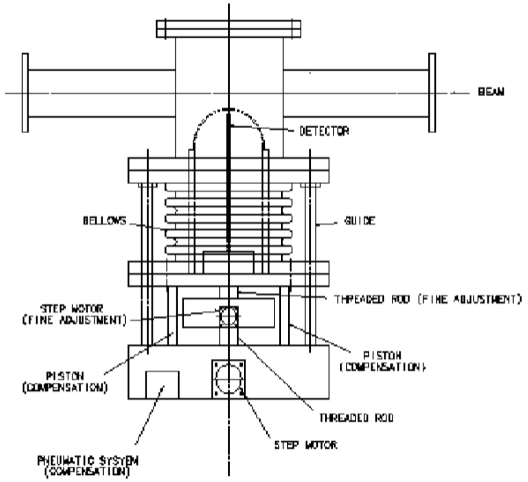


- Elastic scattering in high energy physics: proton-proton and proton-antiproton
- Colorless exchanges by Pomeron or Odderon
  - Pomeron exchange of two (or even number of) gluons
  - Odderon exchange of three (or odd number of) gluons

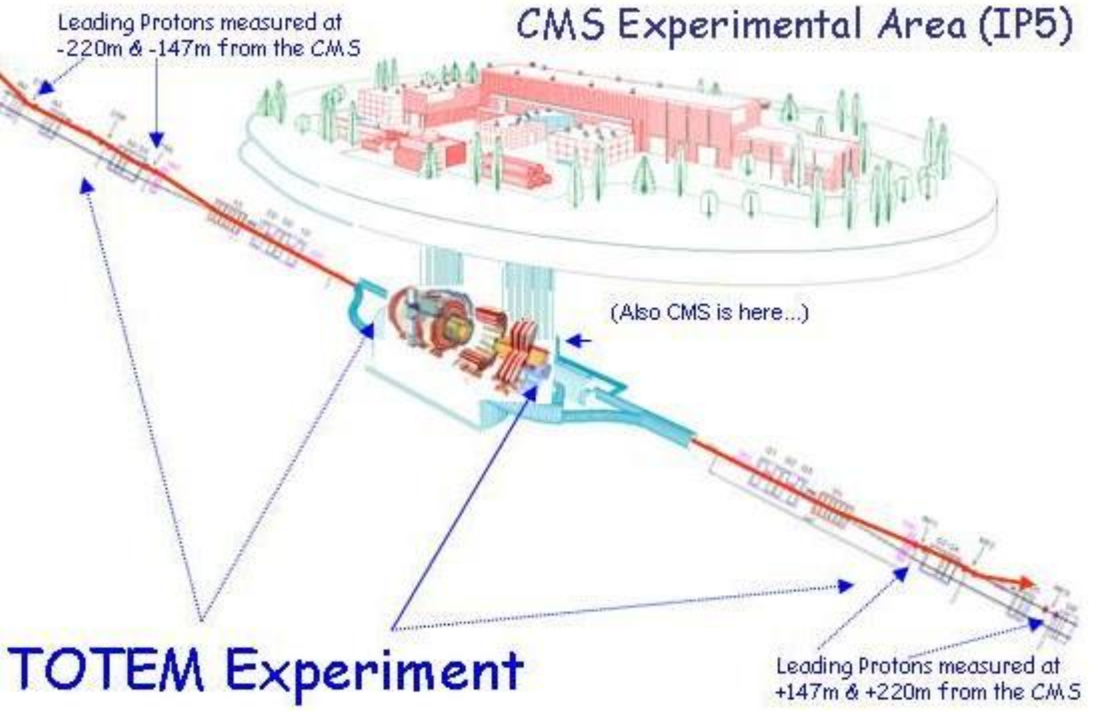


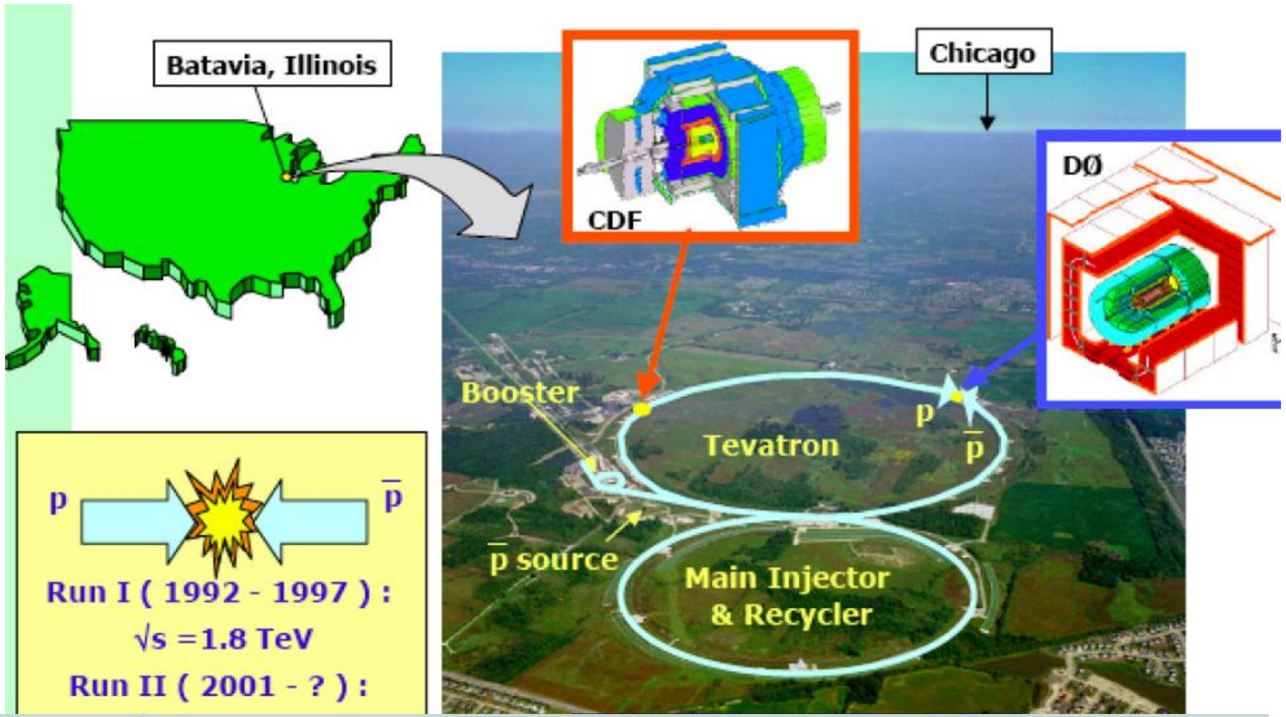
Physics motivation

Which tools and experiment we have?



- We use special detectors to detect intact protons/ anti-protons called Roman Pots
- TOTEM at the Large Hadron Collider and D0 at the Tevatron.
- TOTEM -> proton-proton and D0 -> proton-antiproton

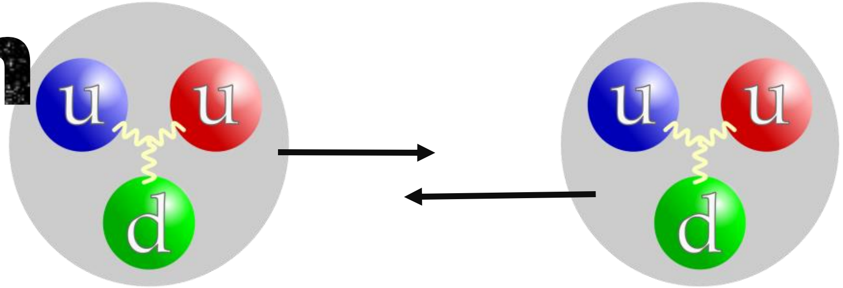




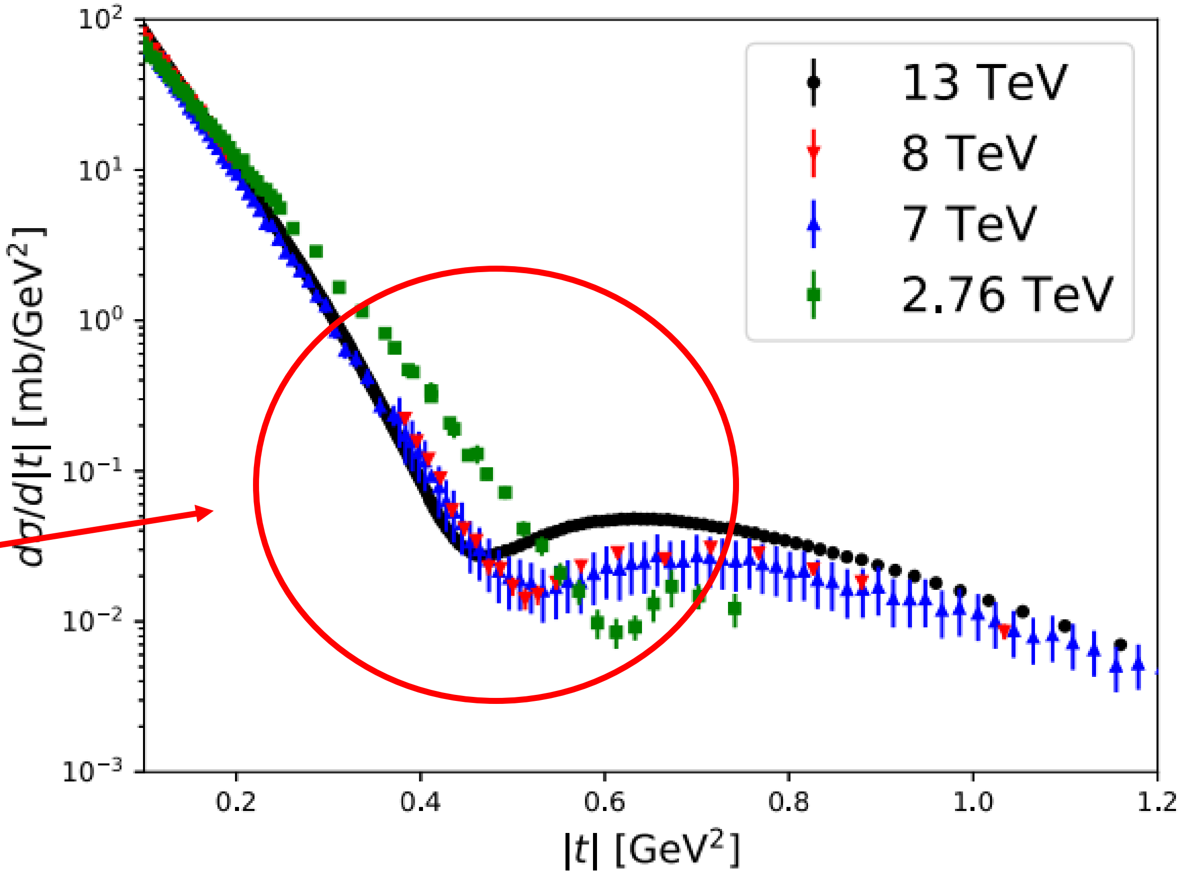
Physics motivation

How was the Odderon discovered?

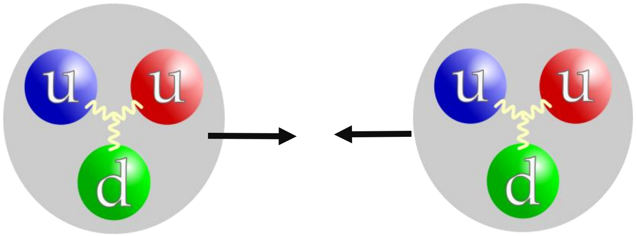
The ideal process is elastic scattering



- **Its so-called diffractive minimum. What is the diffractive minimum? *A particular dip***
- Elastic scattering distribution as a function of the variable transfer of momentum in the collision (|t|)
- A straightforward way to observe odderon comparison between colliding systems.
- For different center of mass energies, in the transfer momentum range of the dip-bump region
- Exhibit a pattern in which the data are shifted

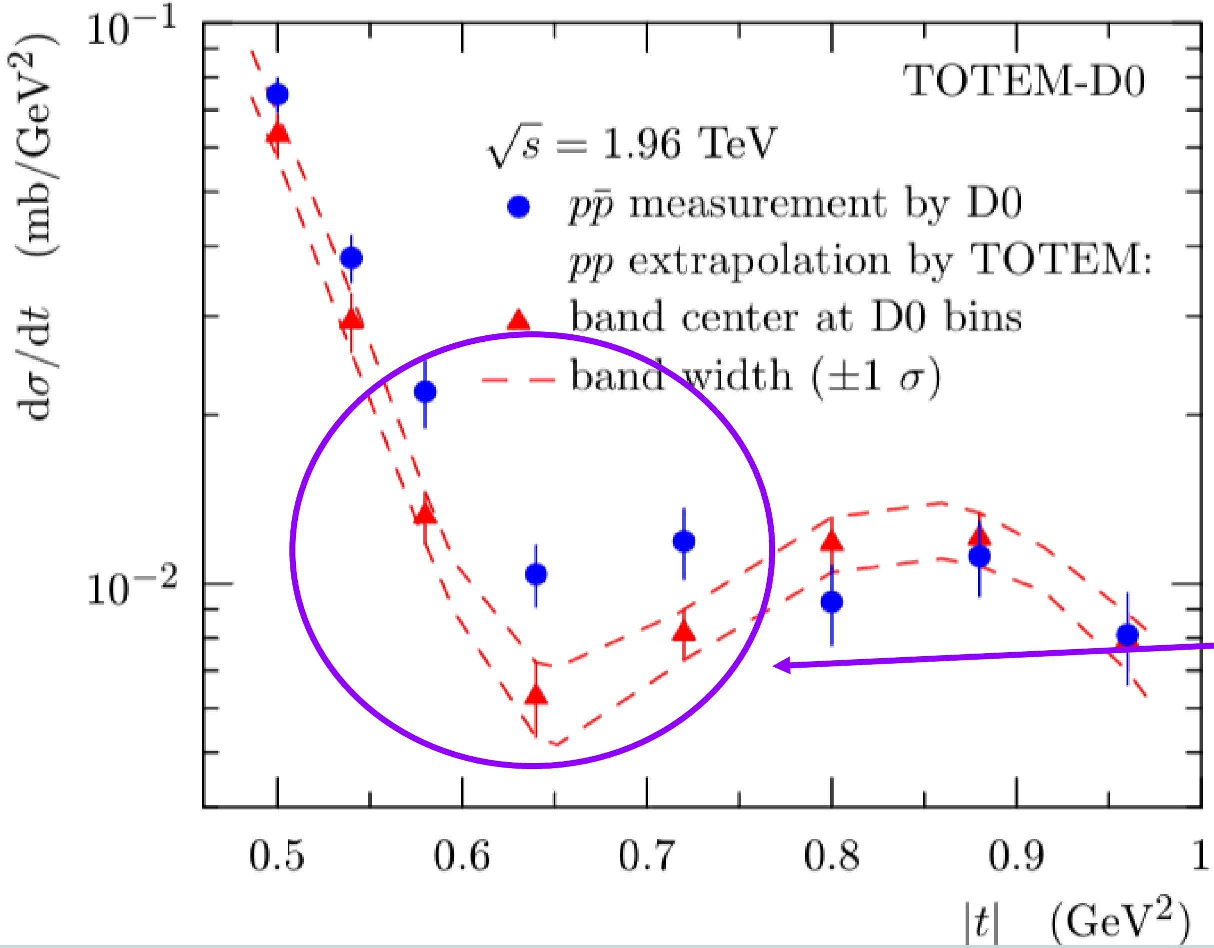


Physics motivation



How was the Odderon discovered?

Comparison proton-proton and antiproton-proton



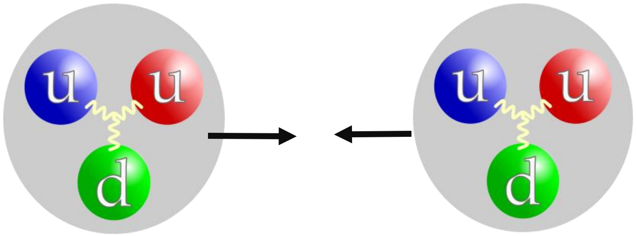
- In December 2020, the discovery of the Odderon was made public by the TOTEM experiment together with D0 experiment

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

- Difference can only be due to Odderon exchange.
- Odderon discovery!!!

The article with the discovery was published in *Physical Review Letters* (August 2021)

Physics motivation

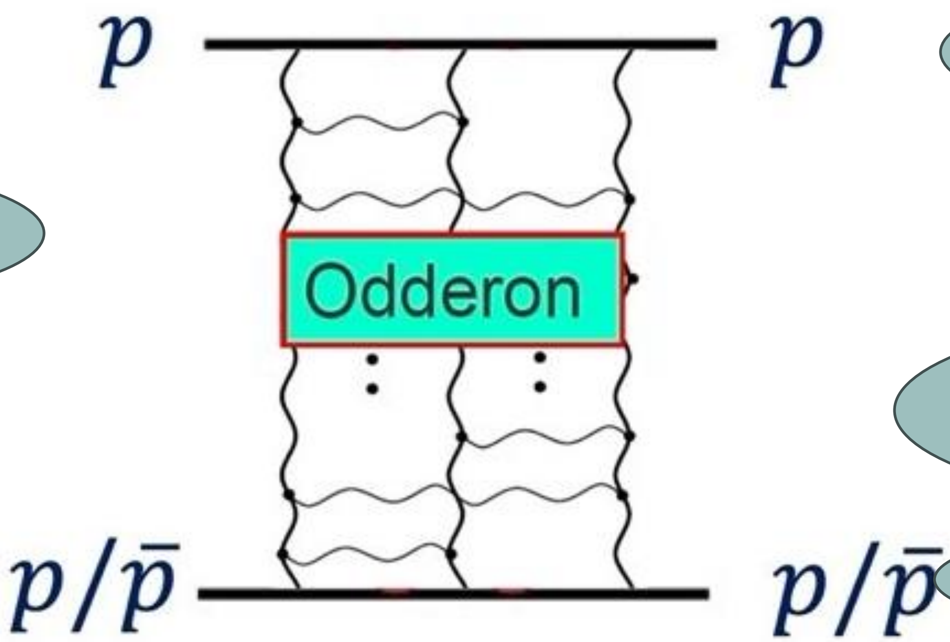


Experimentally found nor theoretically grounded

Theory frameworks

- Spin-dependent form-factor
- Holographic approaches
- Bound-state
- Perturbative evolution

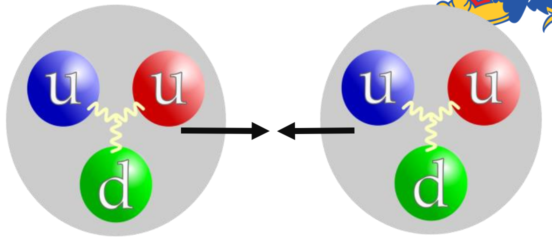
Colorless compound of an odd number of gluons

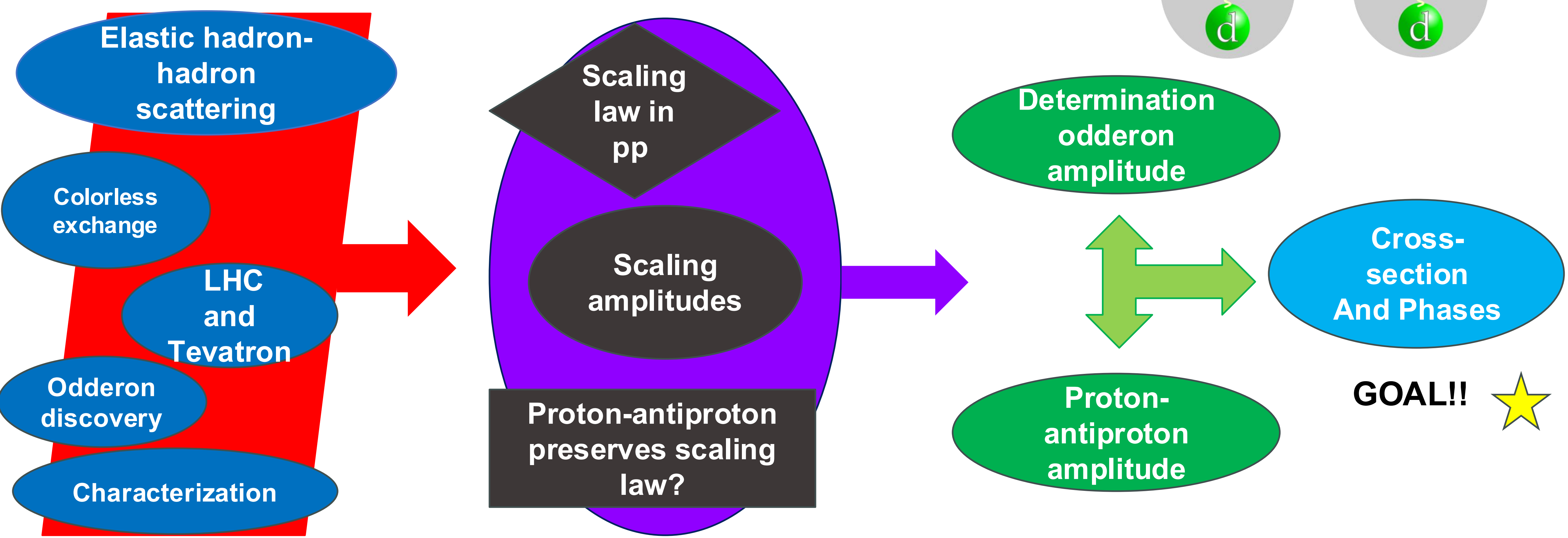


Phenomenology

- Regge-based spin 3 oddball
- Reggized-exchange models
- Froissaron-Maximal-Odderon parametrisation
- Flat Odderon

From the scaling framework to the Odderon determination





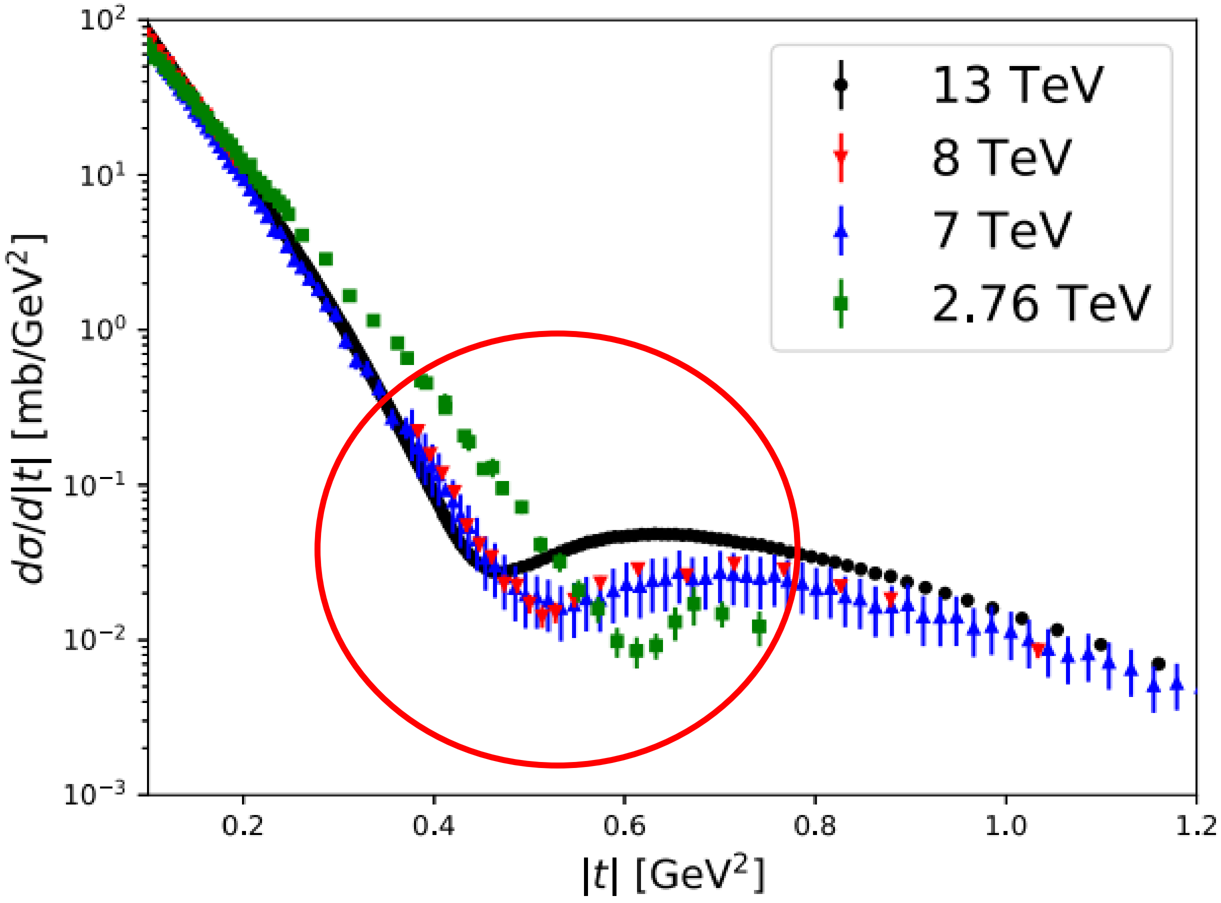
Scaling behavior of elastic cross-section

- **A scaling law defined across all the energies measured by TOTEM at the LHC**
- Baldenegro, C. Royon and A. M. Stasto, “Scaling properties of elastic proton-proton scattering at LHC energies,” Phys. Lett. B 830 (2022)
- Adopting scaling definitions for the transfer momentum and cross-section

$$t^{**} = \left(\frac{s}{1\,\mathrm{TeV}^2}\right)^{0.065} \left(\frac{|t|}{1\,\mathrm{GeV}^2}\right)^{0.72}$$

$$\left(\frac{d\sigma}{dt}\right)_{\mathrm{scaled}} = \left(\frac{s}{1\,\mathrm{TeV}^2}\right)^{-\alpha} \frac{d\sigma}{d|t|}$$

- Where the scaling exponent α = 0.305



Source: Phys. Lett. B 830

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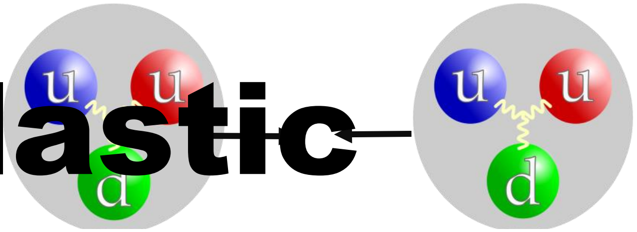

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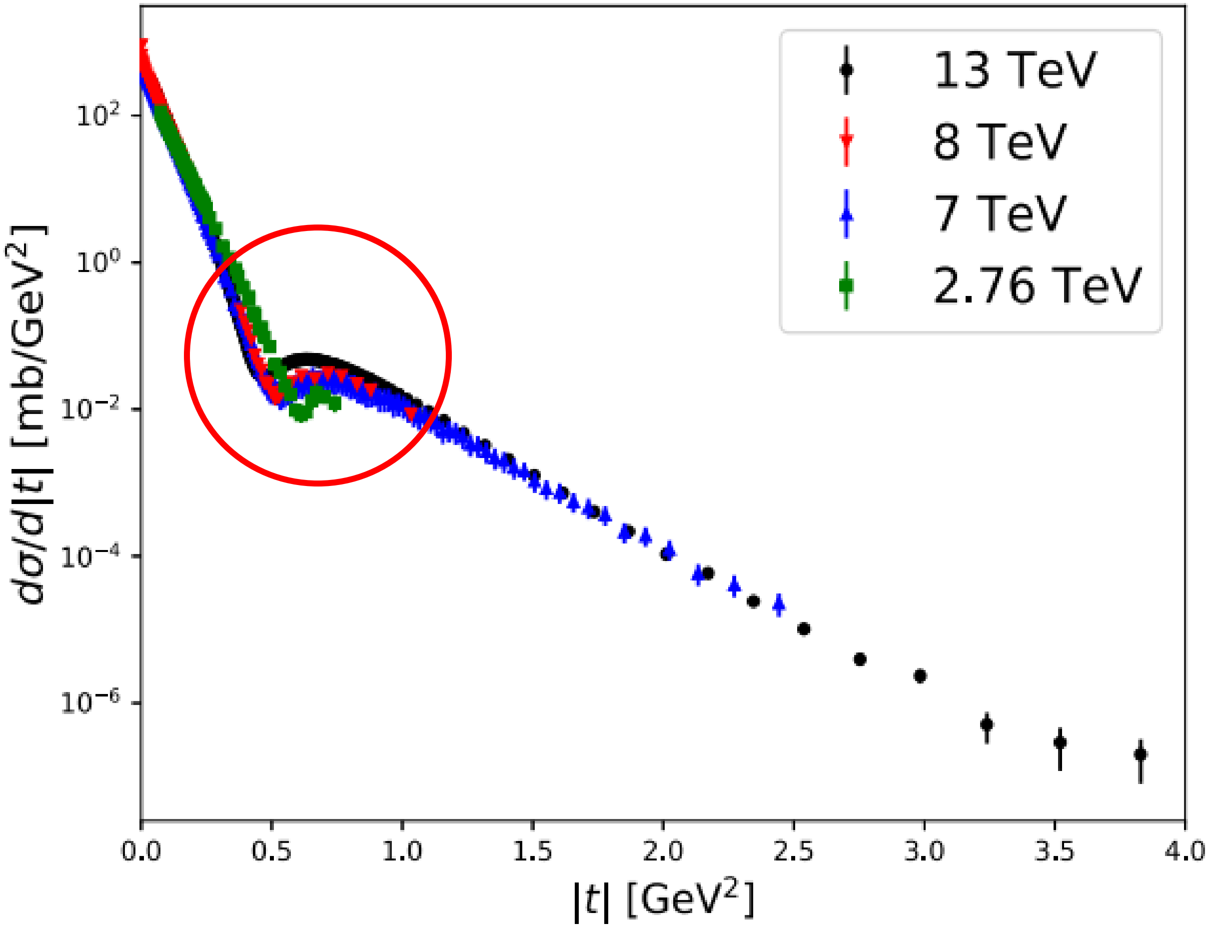

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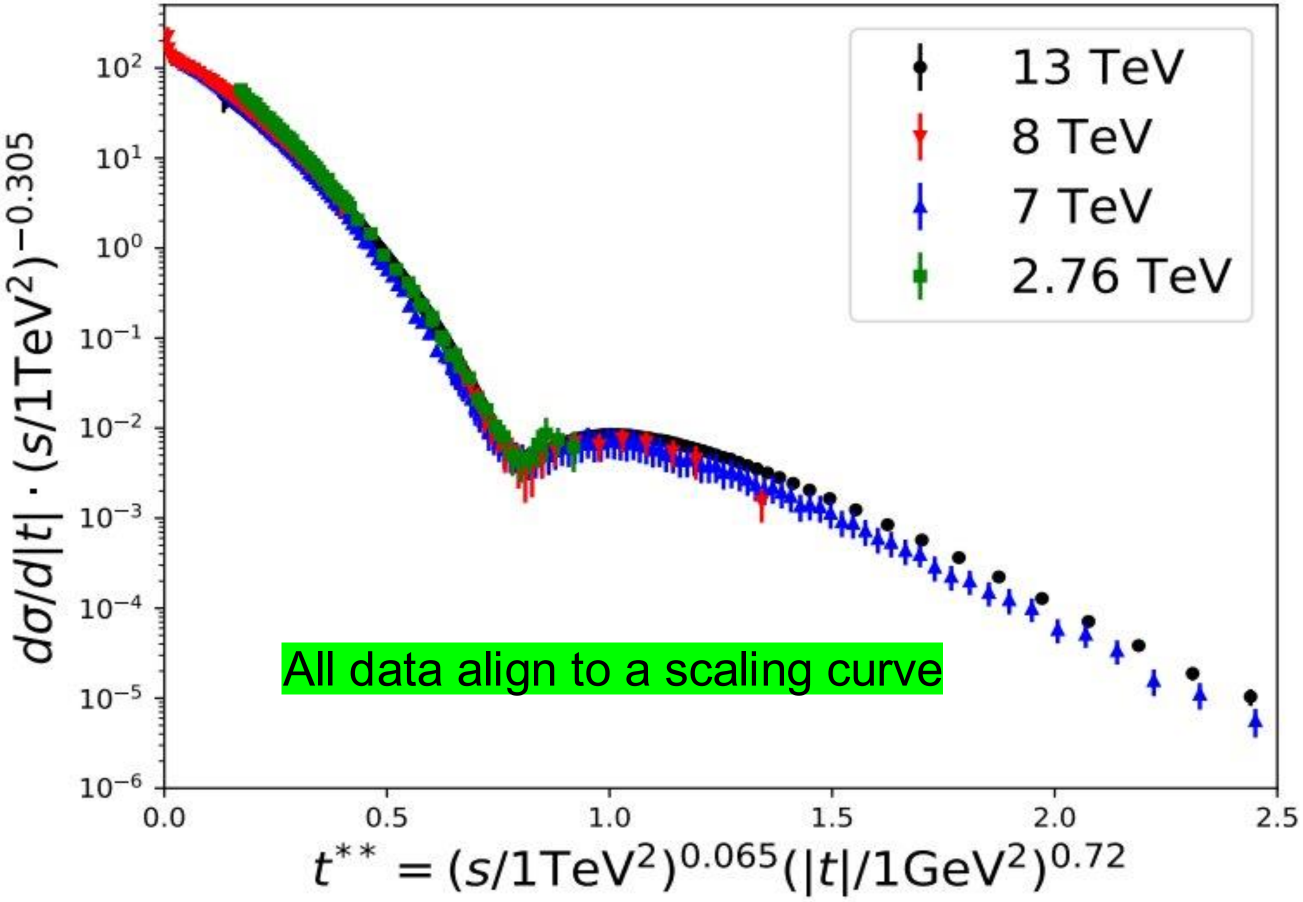

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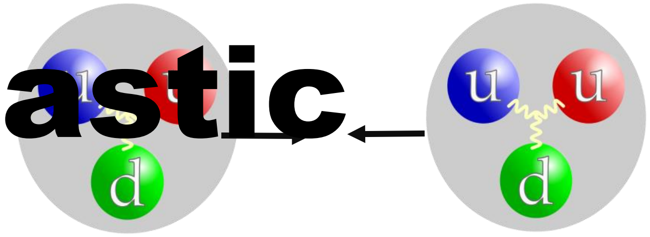
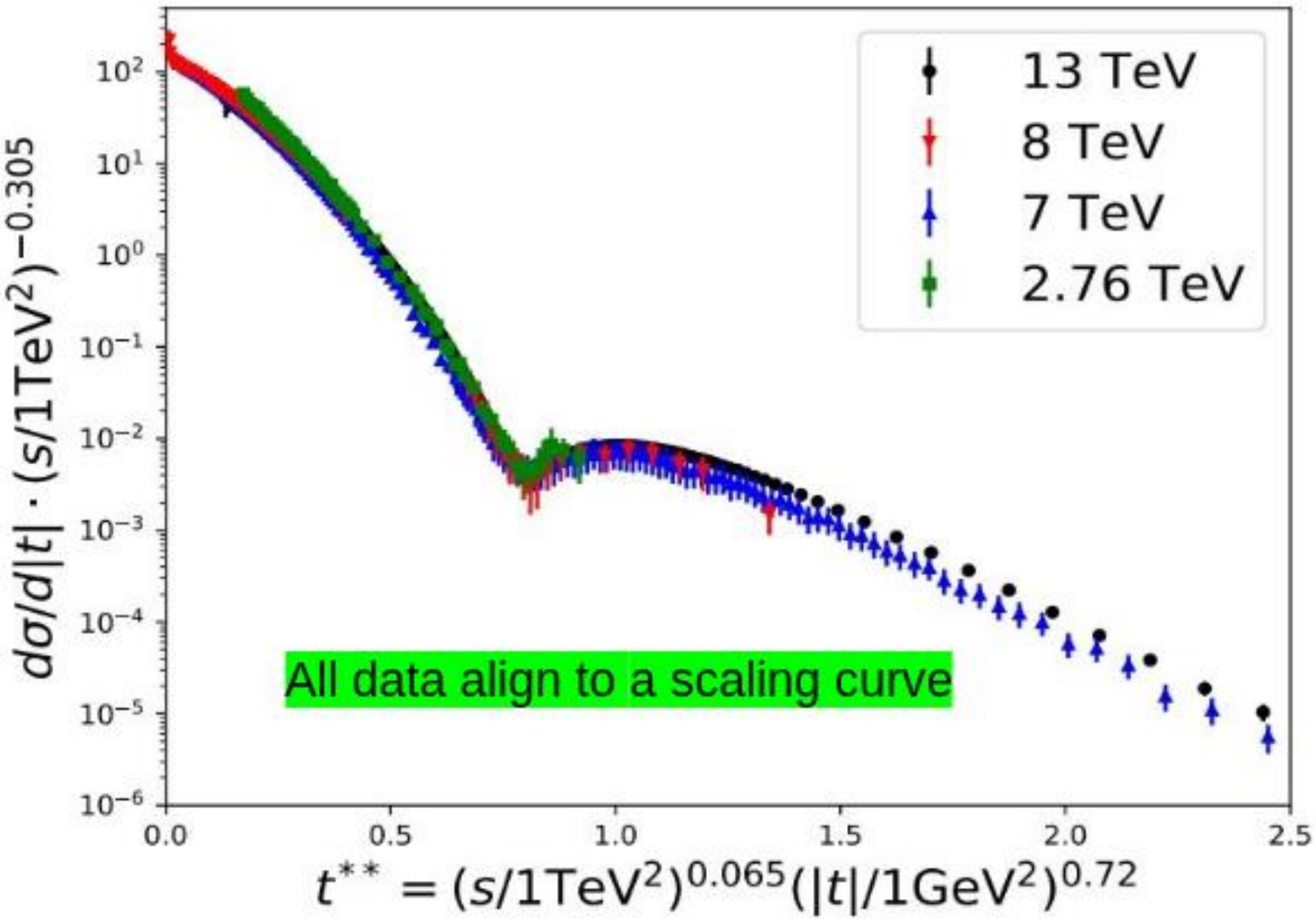
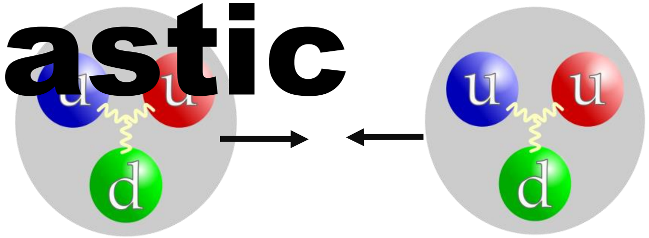
Scaling behavior of elastic cross-section



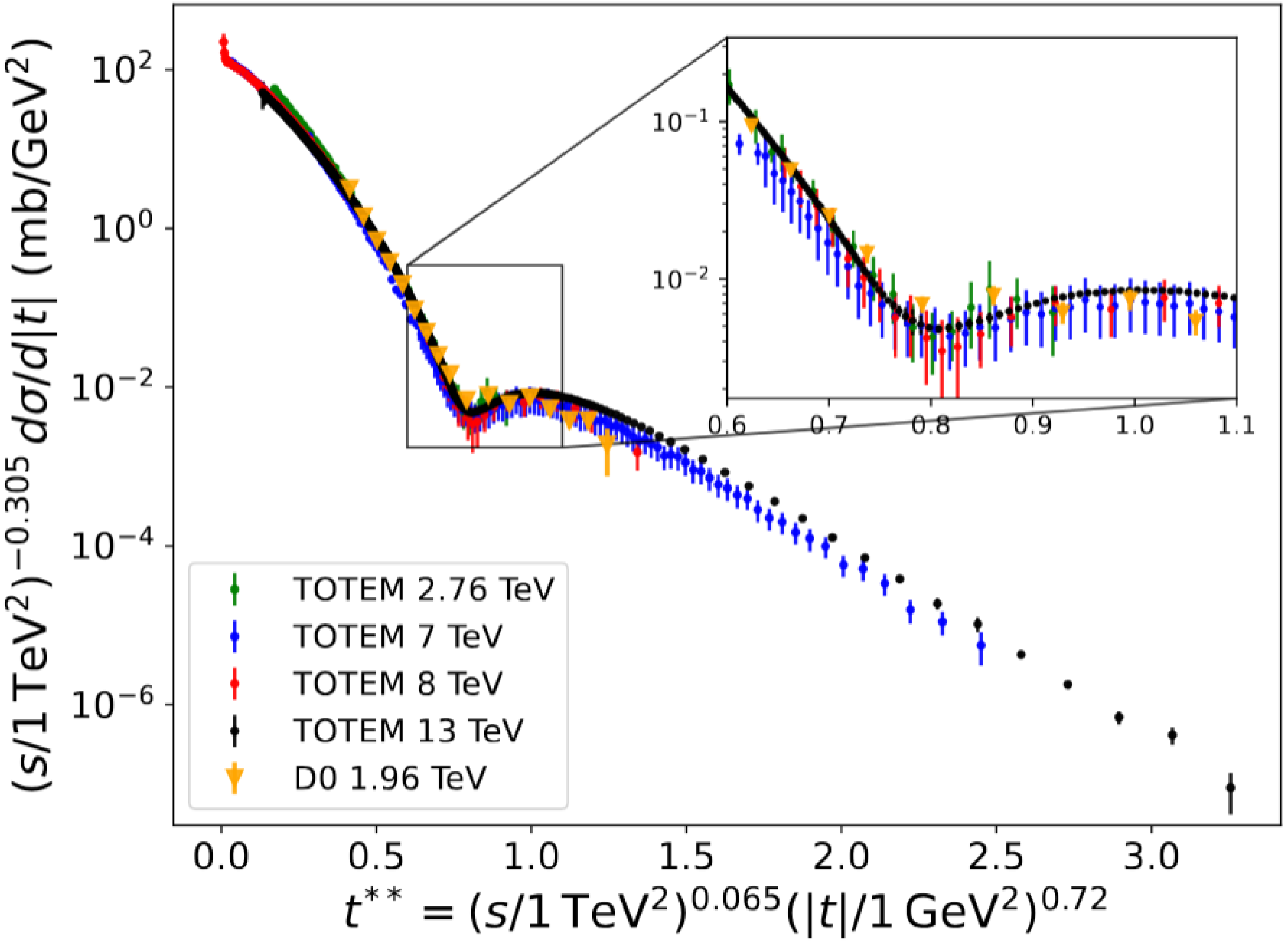


- Can we use the same scaling law to proton-antiproton collision?

Scaling behavior of elastic cross-section



First step : Same scaling



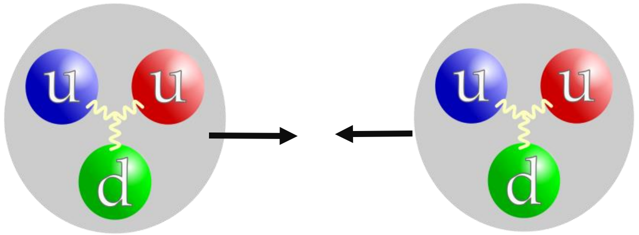
- Can we use the same scaling to proton-antiproton collision?

YES !!!

- Direct comparison between proton-antiproton data and pp results within same kinematic scaling plane.
- Flat behavior for the scaled elastic proton-antiproton remains.
- It gives some preliminary signal of a possible negative signature component.

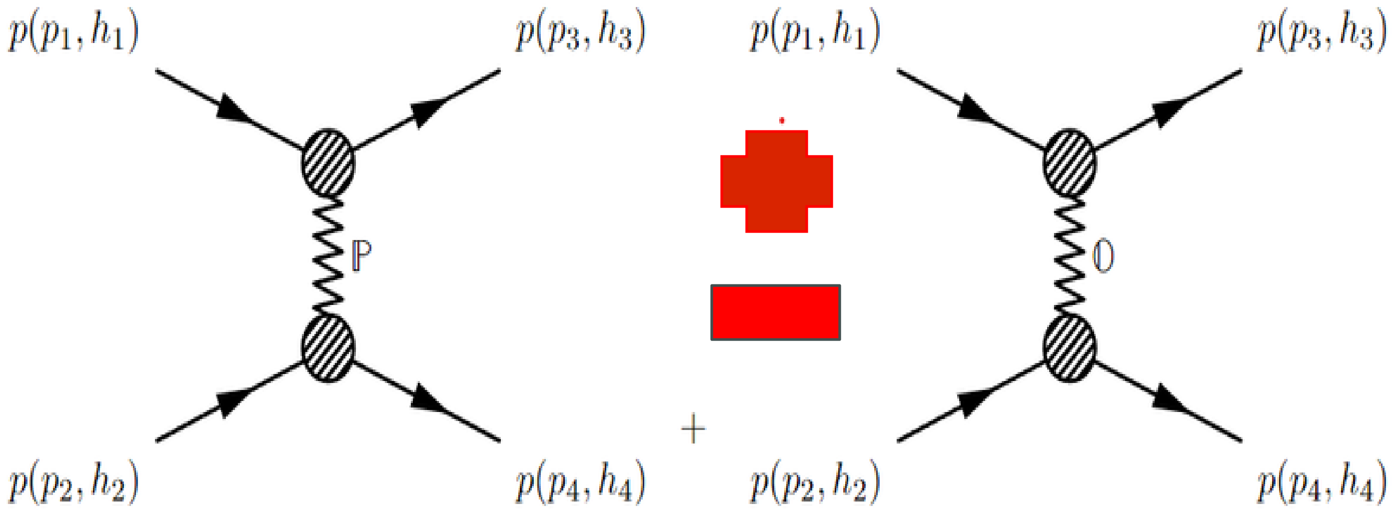
$$A_{pp} = Even + Odd$$
$$A_{p\bar{p}} = Even - Odd$$

Scaling amplitudes



- Let consider the pp differential cross-section

$$\frac{d\sigma}{dt}(s,t) = |\mathcal{A}(s,t)|^2 \; ,$$



- Defining a pp scaling amplitude

$$\mathcal{A}(s,t) = i\left(\mathcal{A}_1(s,t) + \mathcal{A}_2(s,t)\right) e^{i\theta}$$

- pp amplitude -> FIT 1

$$\mathcal{A}_1(s,t) = N_1(s)\; e^{-B_1(s)|t|}$$

$$\mathcal{A}_2(s,t) = N_2(s)\; e^{-B_2(s)|t| + i\phi}$$

$$N_{1,2}(s) = N_{1,2}^0 \left(\frac{s}{\mathrm{TeV}^2}\right)^{\alpha/2}$$

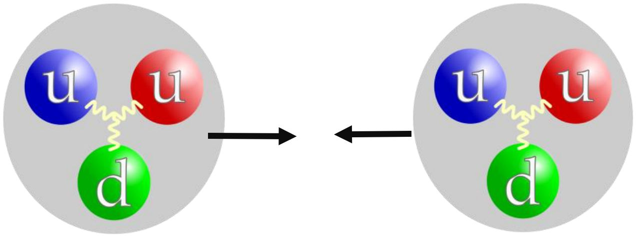
$$B_{1,2}(s) = B_{1,2}^0 \left(\frac{s}{\mathrm{TeV}^2}\right)^{\gamma/2}$$

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

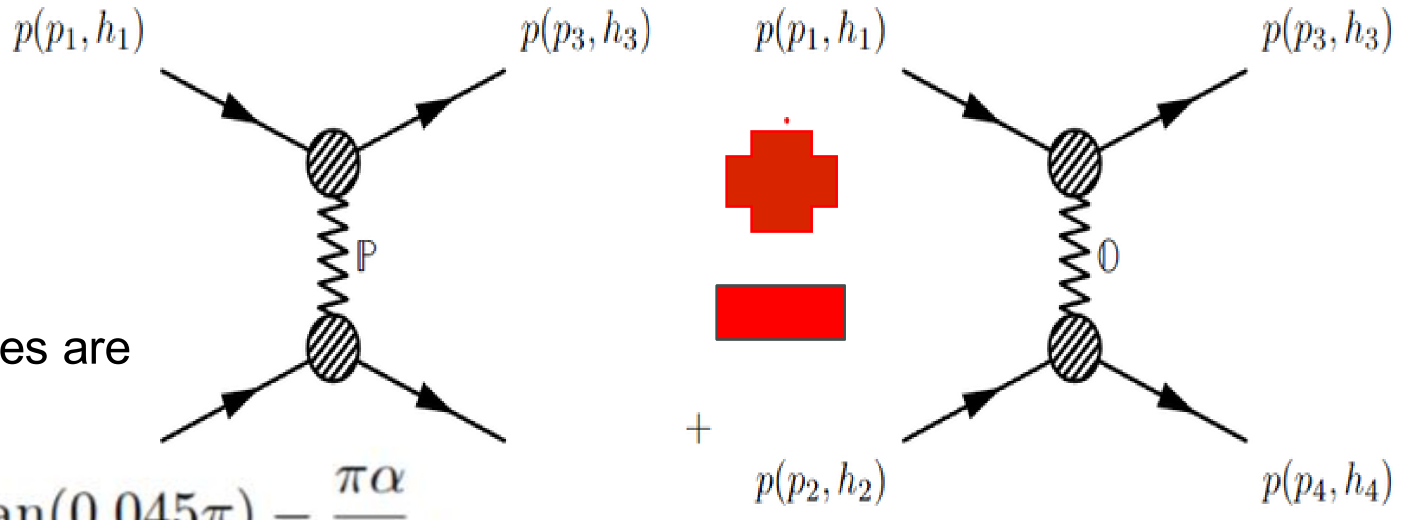
free parameters: $N_1^0, N_2^0, B_1^0, B_2^0, \phi$

- Where $\theta = 0.09$ rad

Scaling amplitudes



- Let consider the Pomeron contribution only



$$\mathcal{A}_+(s,t) = i\left(N_1^+(s)e^{-B_1^+(s)|t|} + N_2^+(s)e^{-B_2^+(s)|t|}e^{i\phi_\tau}\right)e^{i\theta_\tau}$$

within the general analyticity of the S-matrix phases are constructed strictly using the parameters of

$$s \Rightarrow e^{-i\pi/2}s$$

"energy to phase relation"

$$\theta_\tau = B_1^+|t|s^{0.09}\tan(0.045\pi) - \frac{\pi\alpha}{4},$$

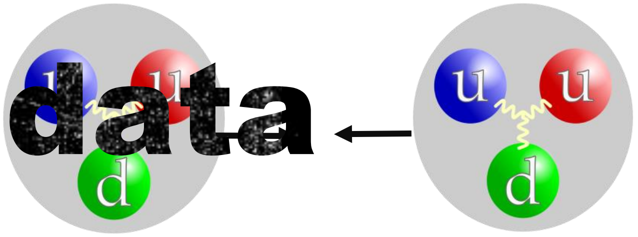
$$\phi_\tau = \phi^+ + \left(B_2^+ - B_1^+\right)|t|s^{0.09}\tan(0.045\pi)$$

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

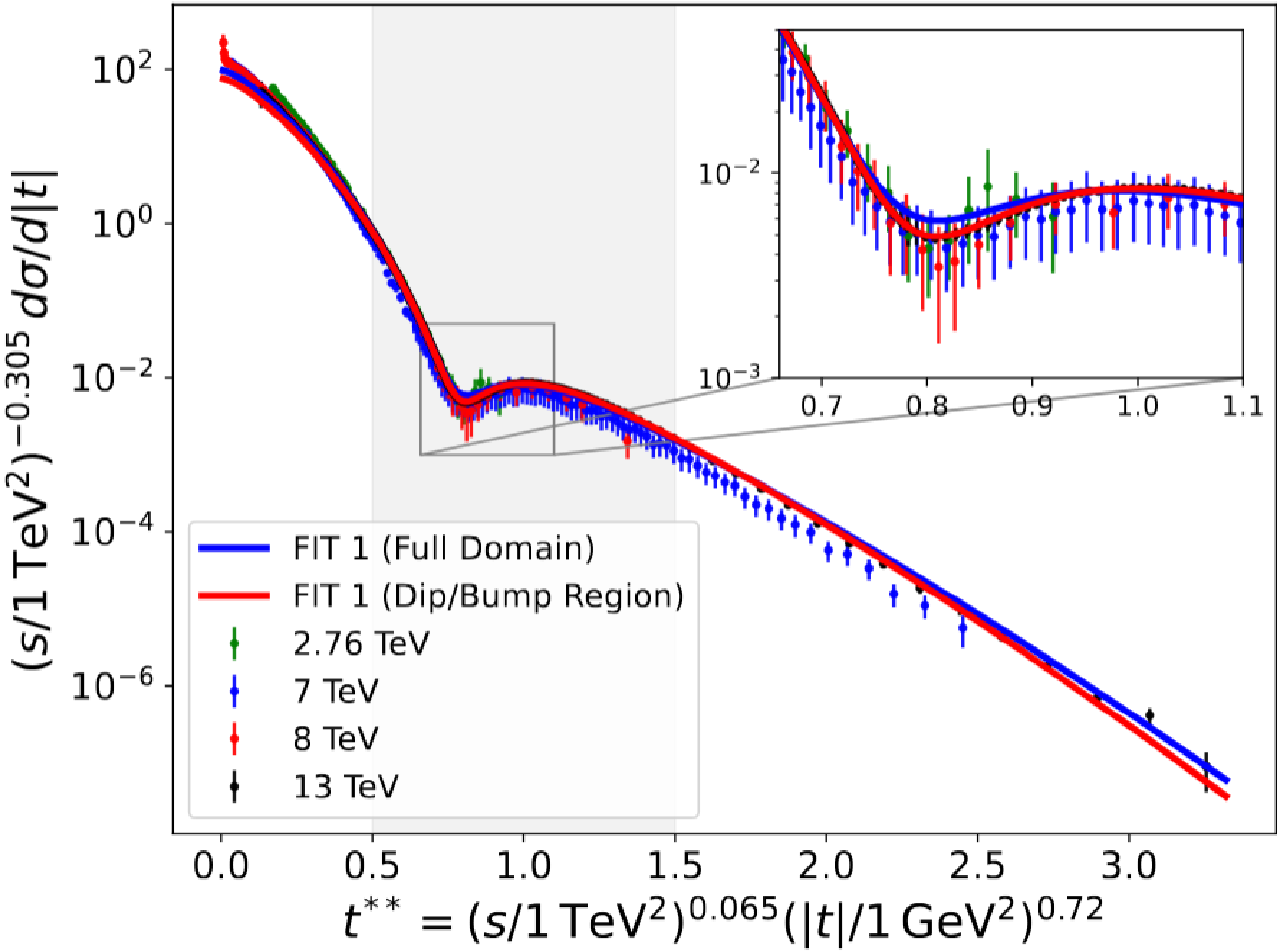
$$\frac{d\sigma_+}{d|t|} = [N_1^+(s)]^2e^{-2B_1(s)|t|} + [N_2^+(s)]^2e^{-2B_2(s)|t|} + 2N_1^+(s)N_2^+(s)e^{-B_2^+(s)+B_2^+(s)]|t|}\cos\phi_\tau$$

- Pomeron amplitude -> FIT 2

Fits to TOTEM elastic data



Second step : Comparison FIT1 and FIT2



- Study discrepancies shown by fits of pp cross-sections in TOTEM using the positive signature scaling amplitude

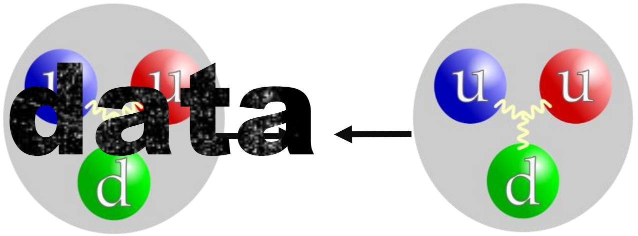
- pp amplitude -> FIT 1

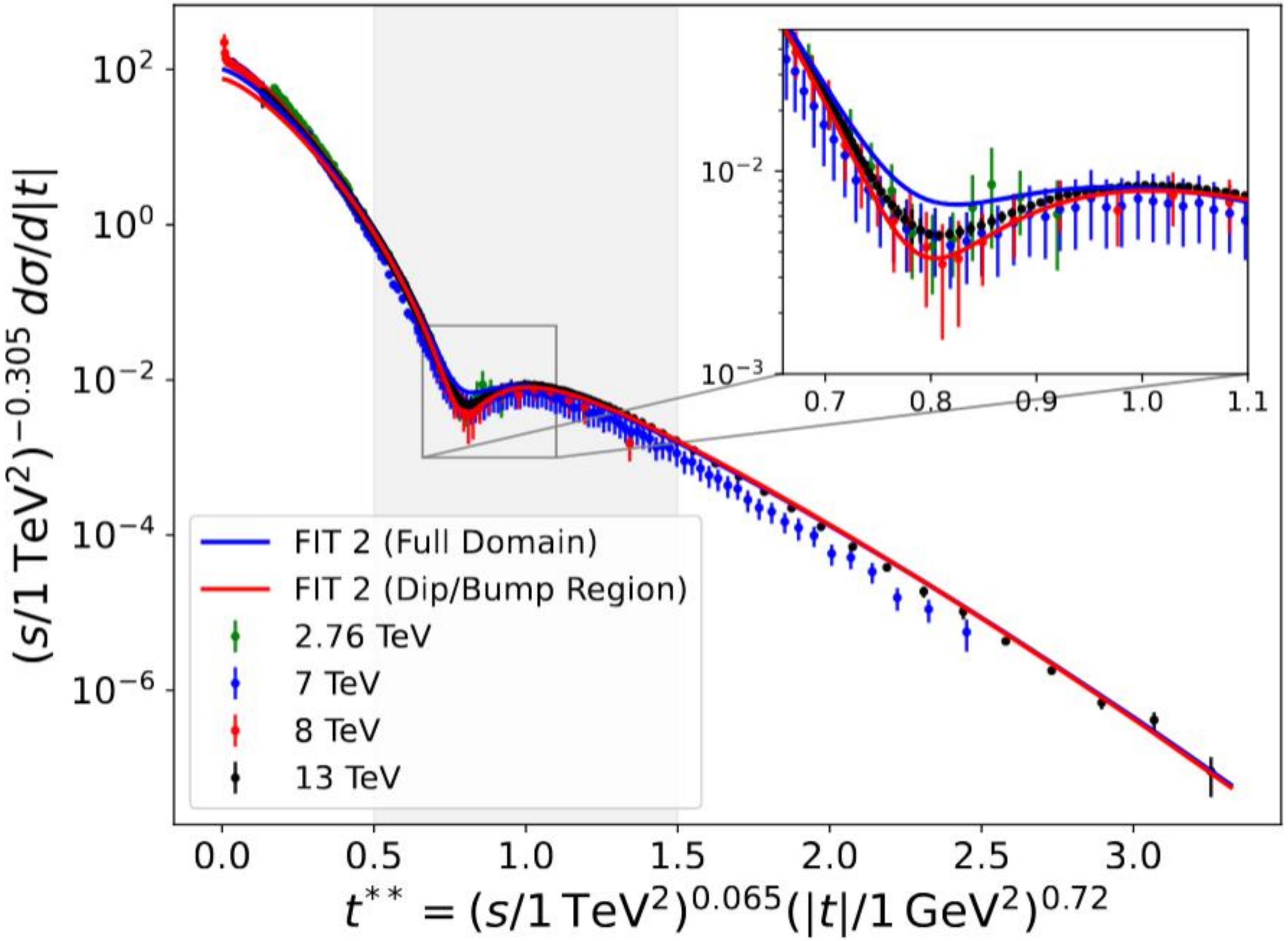
$$\frac{d\sigma}{d|t|} = [N_1(s)]^2 e^{-2B_1(s)|t|} + [N_2(s)]^2 e^{-2B_2(s)|t|}$$
$$+2N_1(s)N_2(s)e^{-[B_1(s)+B_2(s)]|t|}\cos\phi$$

- Dip/Bump region -> Good description at the region where D0 range is present
- Full domain -> Fair description of data

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

Fits to TOTEM elastic data ←





- Study discrepancies shown by fits of pp cross-sections in TOTEM using pomeron signature scaling amplitude

- Pomeron amplitude -> FIT 2

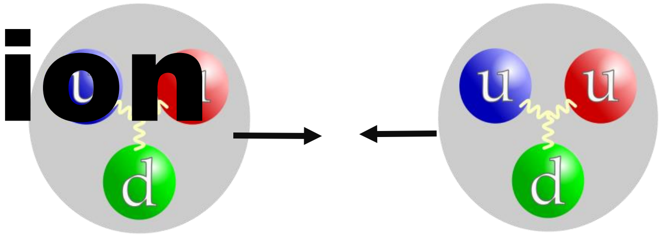
$$\frac{d\sigma_+}{d|t|} = [N_1^+(s)]^2 e^{-2B_1(s)|t|} + [N_2^+(s)]^2 e^{-2B_2(s)|t|} + 2N_1^+(s)N_2^+(s)e^{-B_2^+(s)+B_2^+(s)]|t|}\cos\phi_\tau$$

- Dip/Bump region and Full domain -> Bad description of elastic pp data.

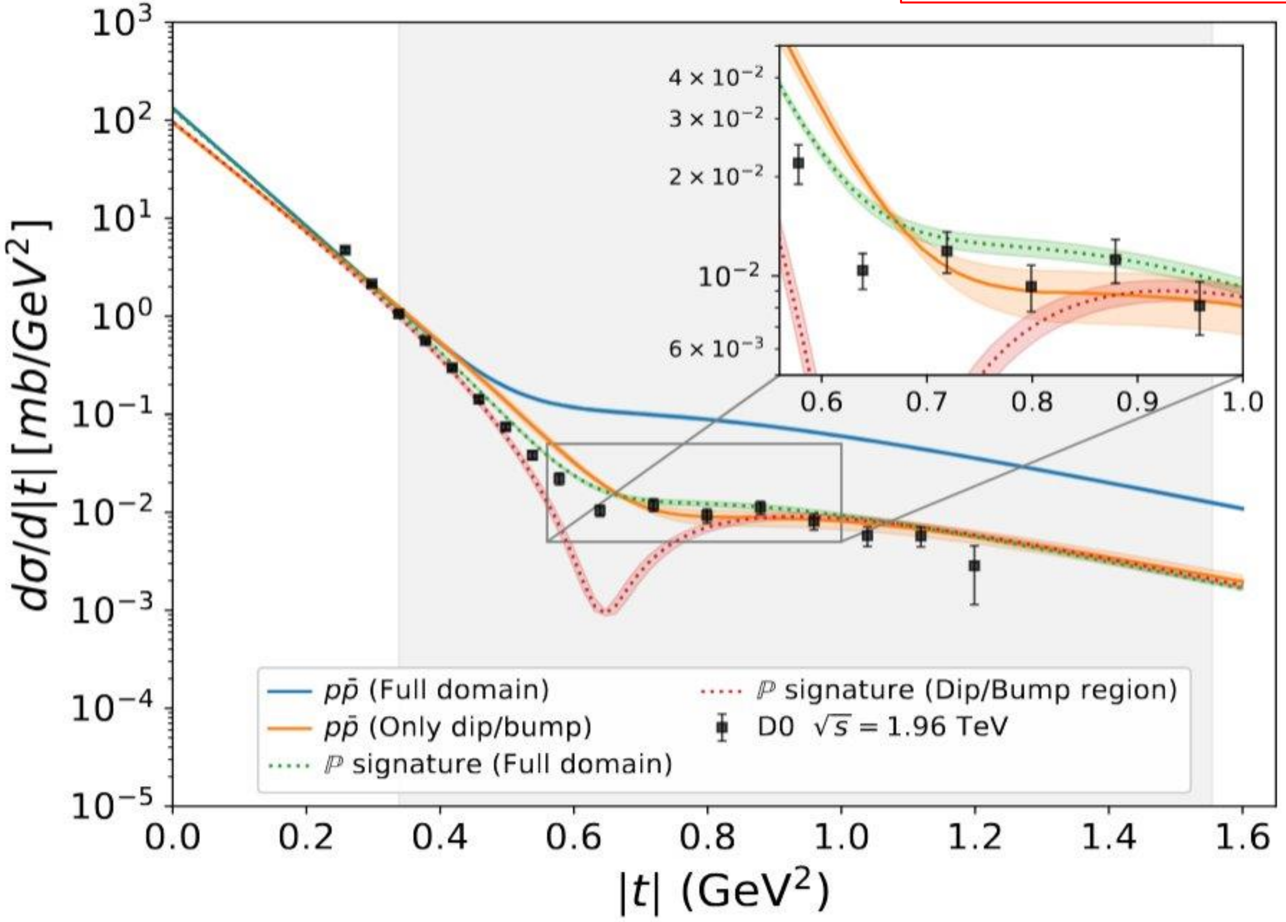
- It signals the existence of an Odderon contribution

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

Cross-Section Prediction



Third step : Confront proton-antiproton predictions with D0 data $\boxed{\mathcal{A}^{p\bar{p}} = 2\mathcal{A}_{+} - \mathcal{A}}$ - Proton-Antiproton (pp̄) amplitude ->



$$
\begin{aligned}
\mathcal{A}^{p\bar{p}}(s,t) \; = \; & i\left[2N_1^{+}(s)e^{-B_1^{+}(s)|t|}e^{i\theta_\tau}\right. \\
& \left. - N_1(s)e^{-B_1(s)|t|}e^{i\theta}\right] \\
& + i\left[2N_2^{+}(s)e^{-B_2^{+}(s)|t|}e^{i(\theta_\tau+\phi_\tau)}\right. \\
& \left. - N_2(s)e^{-B_2(s)|t|}e^{i(\theta+\phi)}\right]
\end{aligned}
$$

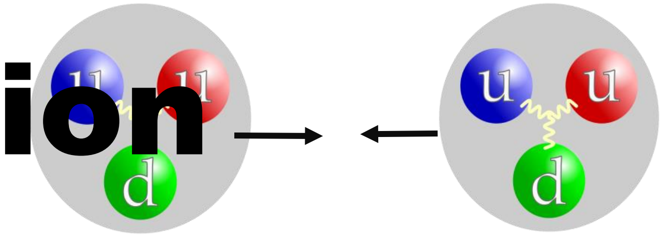
Two options:

1. Dip/Bump region (orange)-> Good agreement with data
2. Full domain (blue)-> The amplitude act as a positive signature amplitude, no need for an odderon signature!!!

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

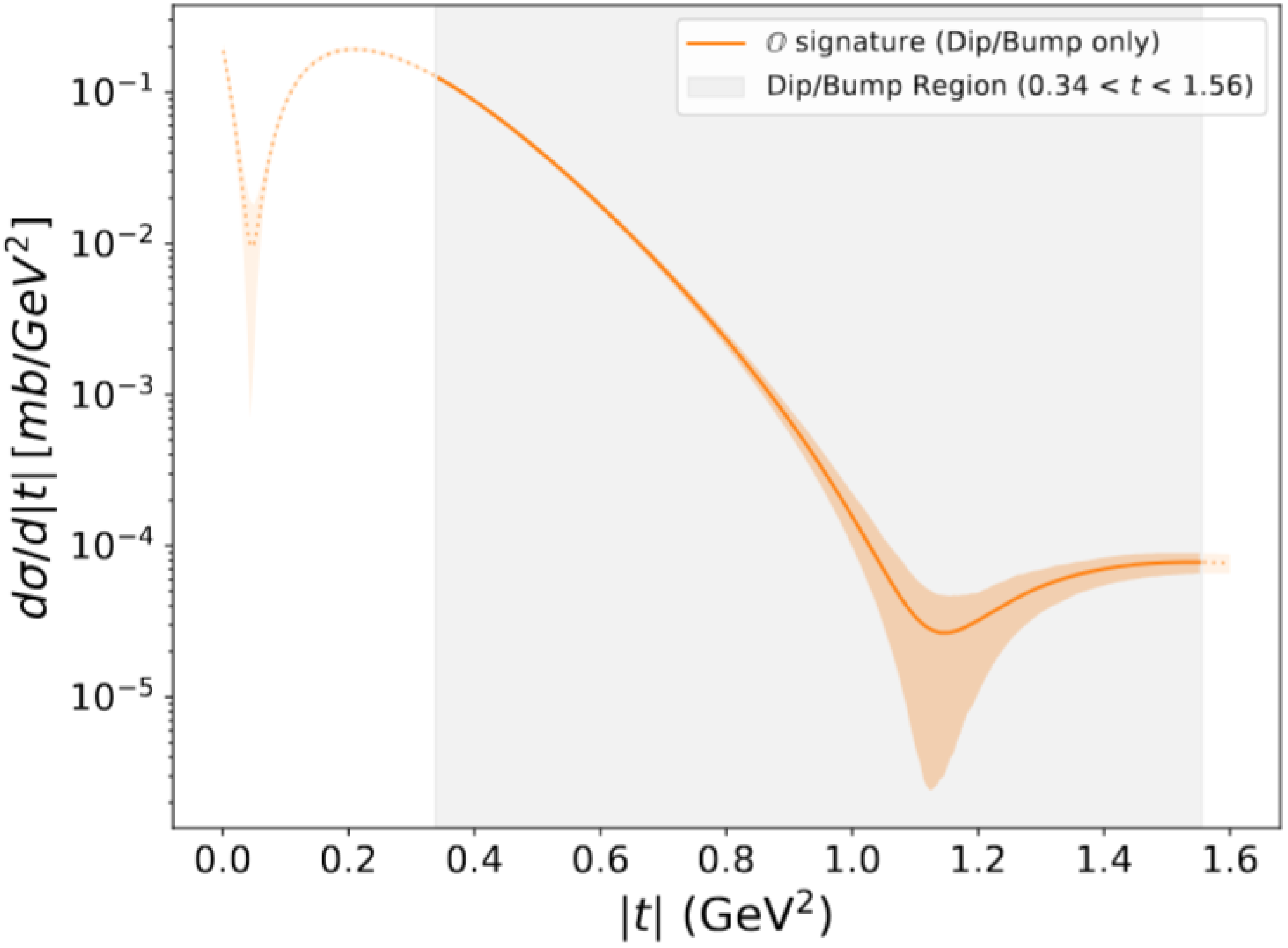
! Direct attention to 1)

Cross-Section Prediction



Odderon determination

$$\boxed{\mathcal{A}_- = \mathcal{A} - \mathcal{A}_+}$$



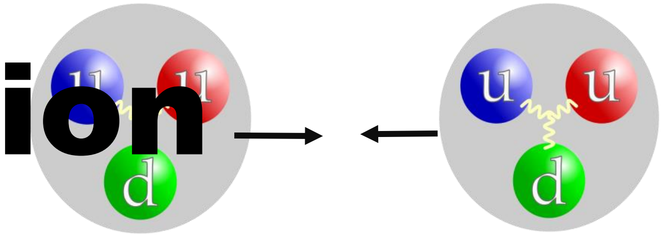
- Odderon amplitude ->

$$\begin{aligned}\mathcal{A}_-(s,t) \;=\; & i\left[N_1(s)e^{-B_1(s)|t|}e^{i\theta} - N_1^+(s)e^{-B_1^+(s)|t|}e^{i\theta_\tau}\right] \\ & + i\left[N_2(s)e^{-B_2(s)|t|}e^{i(\theta+\phi)} - N_2^+(s)e^{-B_2^+(s)|t|}e^{i(\theta_\tau+\phi_\tau)}\right]\end{aligned}$$

Isolate the negative-signature (Odderon)!!!

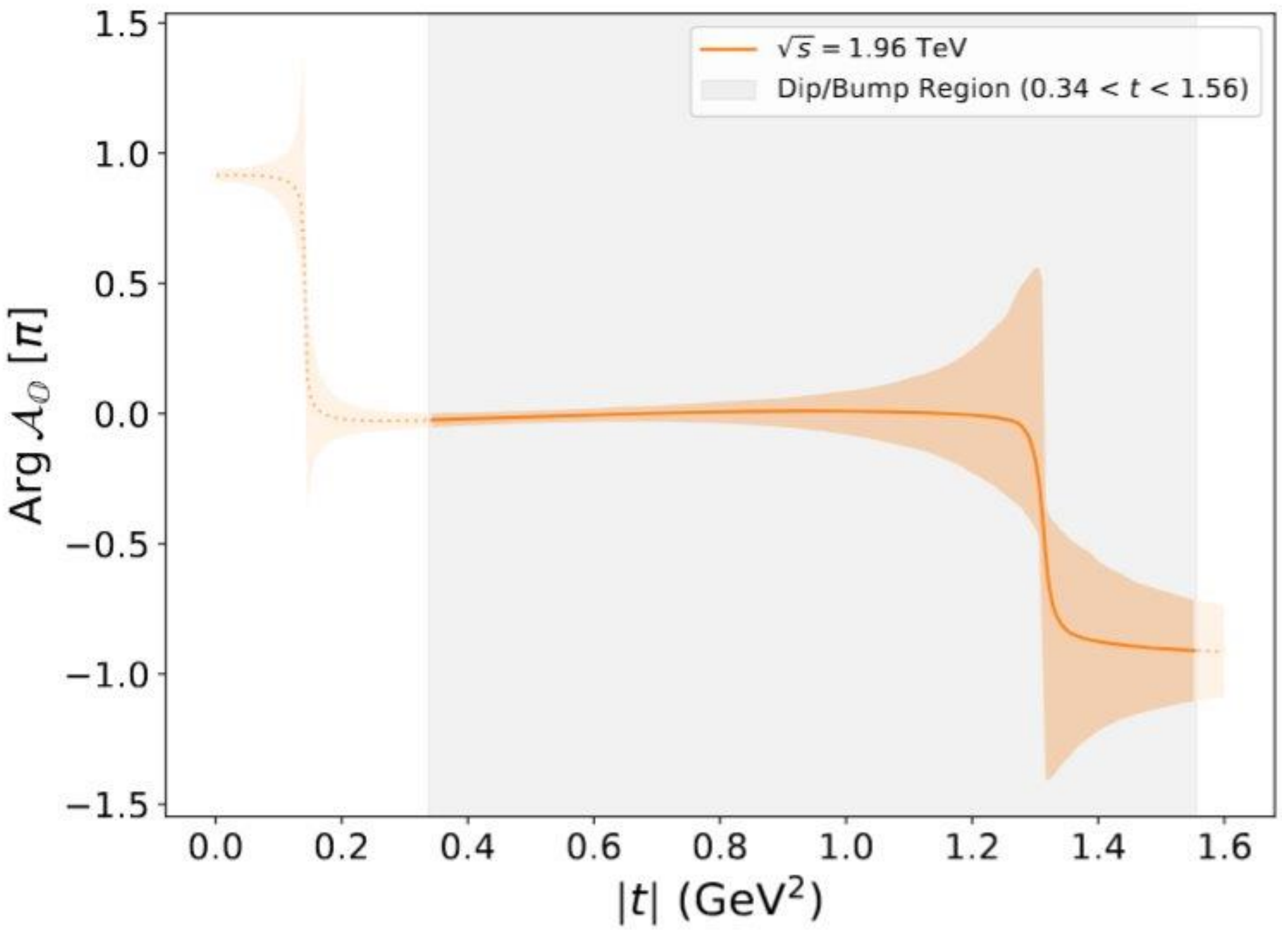
1. Prediction of a nonzero differential cross-section
   - In the dip and bump region
   - 0.4 < |t| < 1.1

Cross-Section Prediction



Odderon determination

$$\boxed{\mathcal{A}_- = \mathcal{A} - \mathcal{A}_+}$$



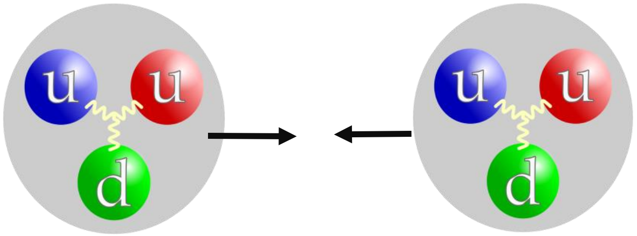
- Odderon amplitude ->

$$\begin{aligned} \mathcal{A}_-(s,t) &= i\Big[N_1(s)e^{-B_1(s)|t|}e^{i\theta} \\ &\quad - N_1^+(s)e^{-B_1^+(s)|t|}e^{i\theta_\tau}\Big] \\ &\quad + i\Big[N_2(s)e^{-B_2(s)|t|}e^{i(\theta+\phi)} \\ &\quad - N_2^+(s)e^{-B_2^+(s)|t|}e^{i(\theta_\tau+\phi_\tau)}\Big] \end{aligned}$$

Isolate the negative-signature (Odderon)!!!

1. Prediction of a nonzero differential cross-section
   - In the dip and bump region
   - $0.4 < |t| < 1.1$
2. An exponentially decreasing modulus in $|t|$ with zero phase

Summary / Outlook



- Tevatron $p\bar{p}$ data follow the same scaling law as LHC pp data → single unified framework to search for the Odderon.
- Two competing $p\bar{p}$ predictions were tested: (i) From the dip/bump-only fit in pp data, (ii) A_{pp} treated as an effective positive-signature amplitude over the full range. Option (ii) is excluded, fails to satisfy the S-matrix energy-phase relation; Discovery of the Odderon exchange.
- Extracted Odderon amplitude: exponentially falling modulus in |t|, phase ≈ 0
- Model-independent extraction (modulus + phase) enables direct comparison/selection among existing phenomenological Odderon models.

In collaboration with Christophe Royon, Robi Peschanski and Bertrand Giraud soon to appear publish