Proton-Proton Nuclear Elastic Scattering
Total Cross-Section
Forward Physics
@ LHC

S.Giani

Topics :

Elastic Scattering

Differential Cross-Section

Total Cross-Section

3g $J^{PC}=1^{--}$

Glueballs

PPS - Precision Proton Spectrometer

Forward Physics @ LHC

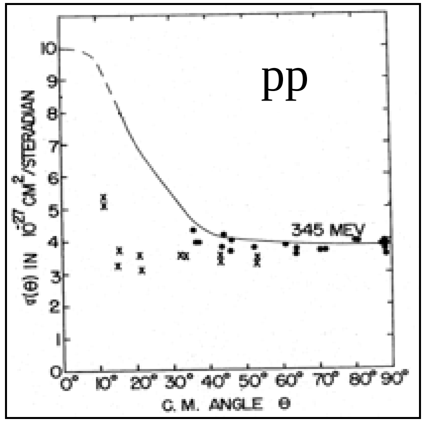
p-p and p-pbar nuclear elastic scattering cross-sections

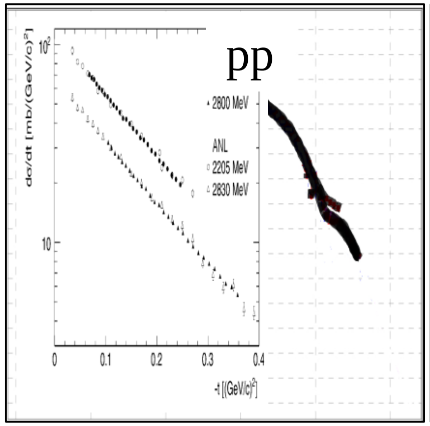
have always been theorized to be equal

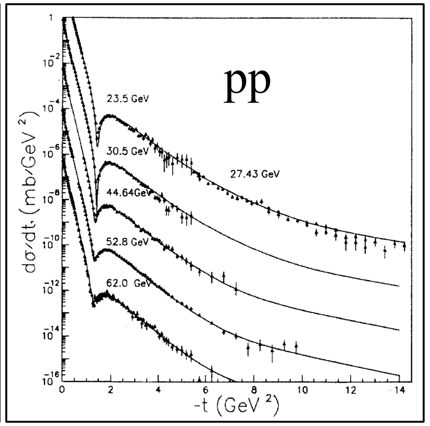
and

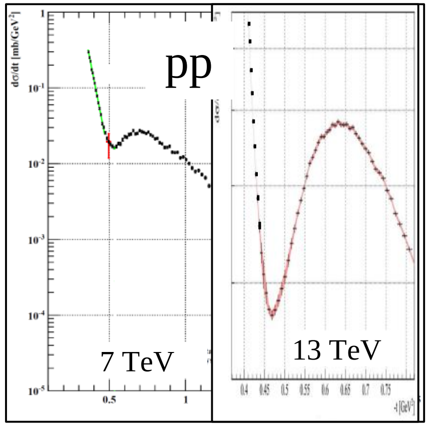
have always been observed to be different

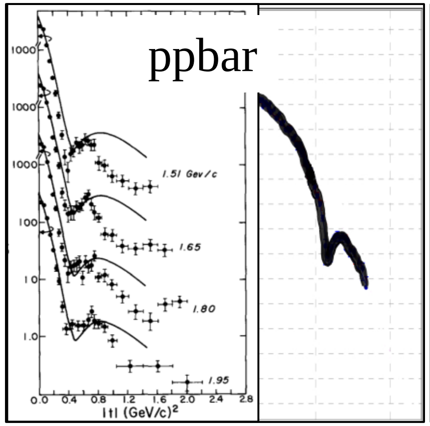
~ 100 MeV ~ 1-10 GeV ~ 50 GeV ~ 500 GeV ~ 2TeV ~ 10 TeV

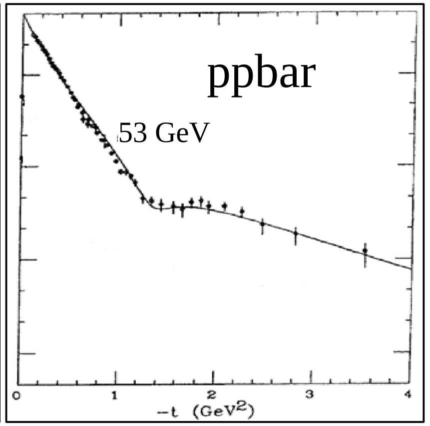


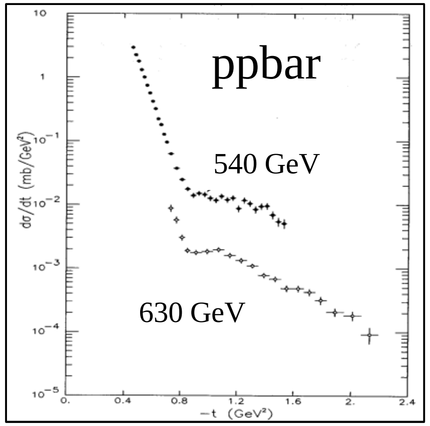


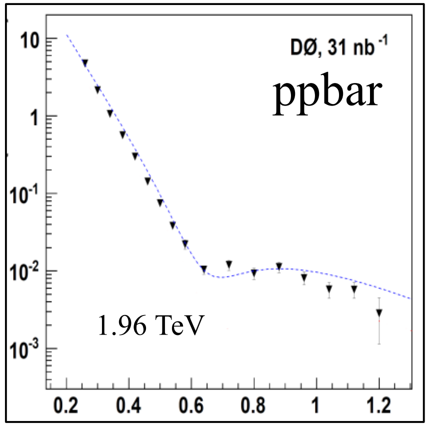




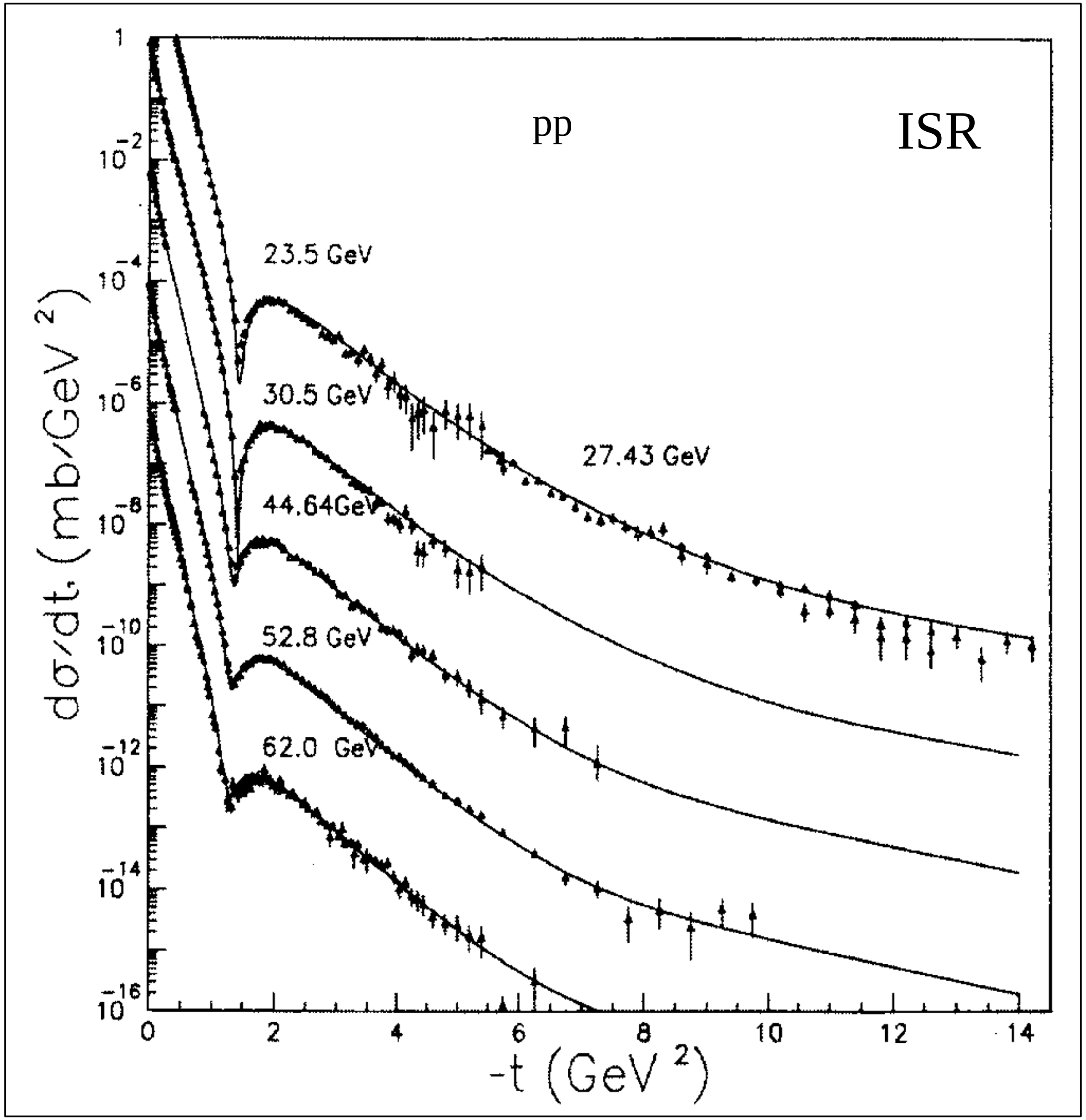


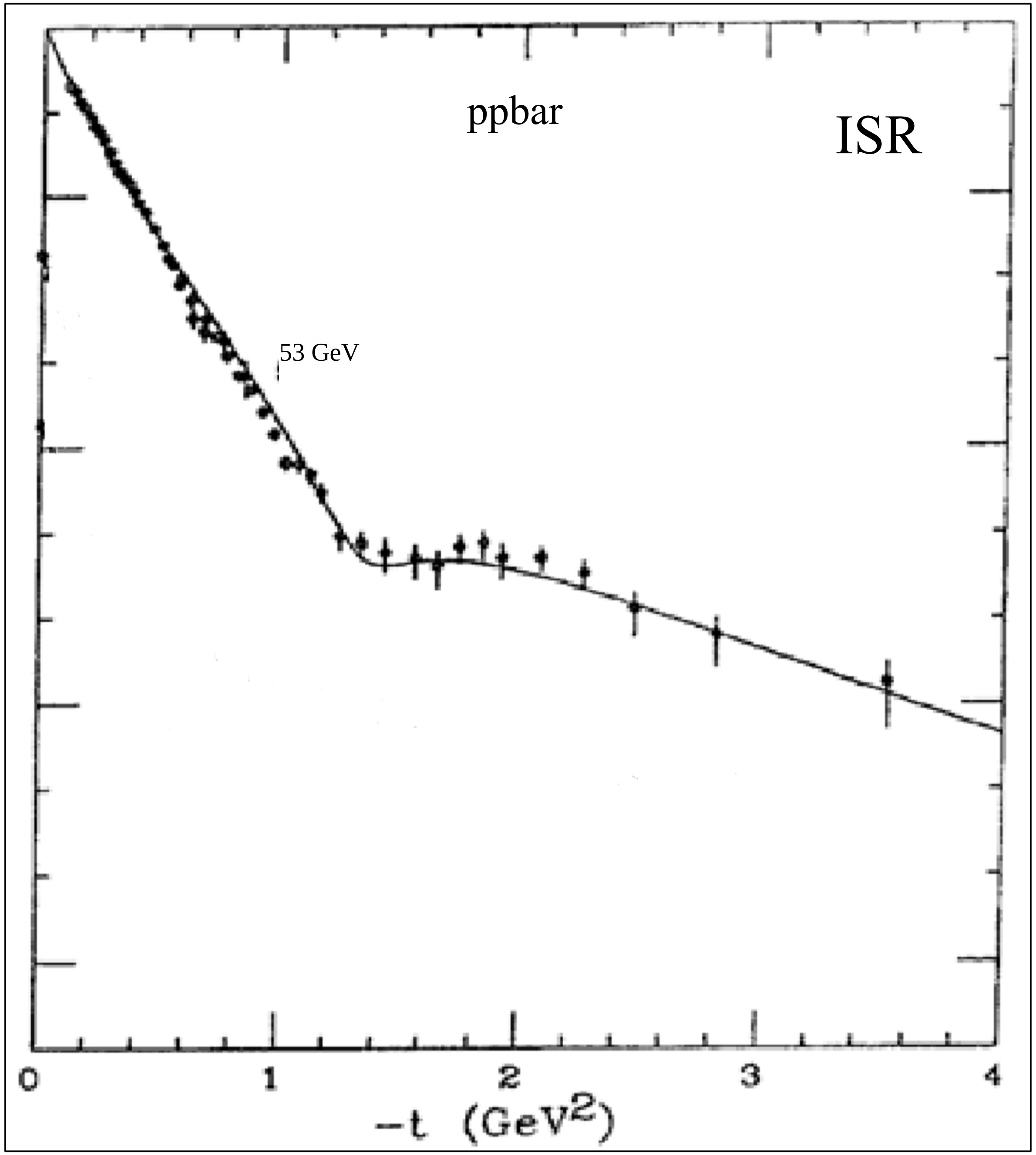






LBL ANL-BNL-… ISR SPS FNAL LHC


pp
ISR
23.5 GeV
30.5 GeV
27.43 GeV
44.64GeV
52.8 GeV
62.0 GeV
dσ/dt (mb/GeV 2)
-t (GeV 2)


ppbar
ISR
53 GeV
−t (GeV2)

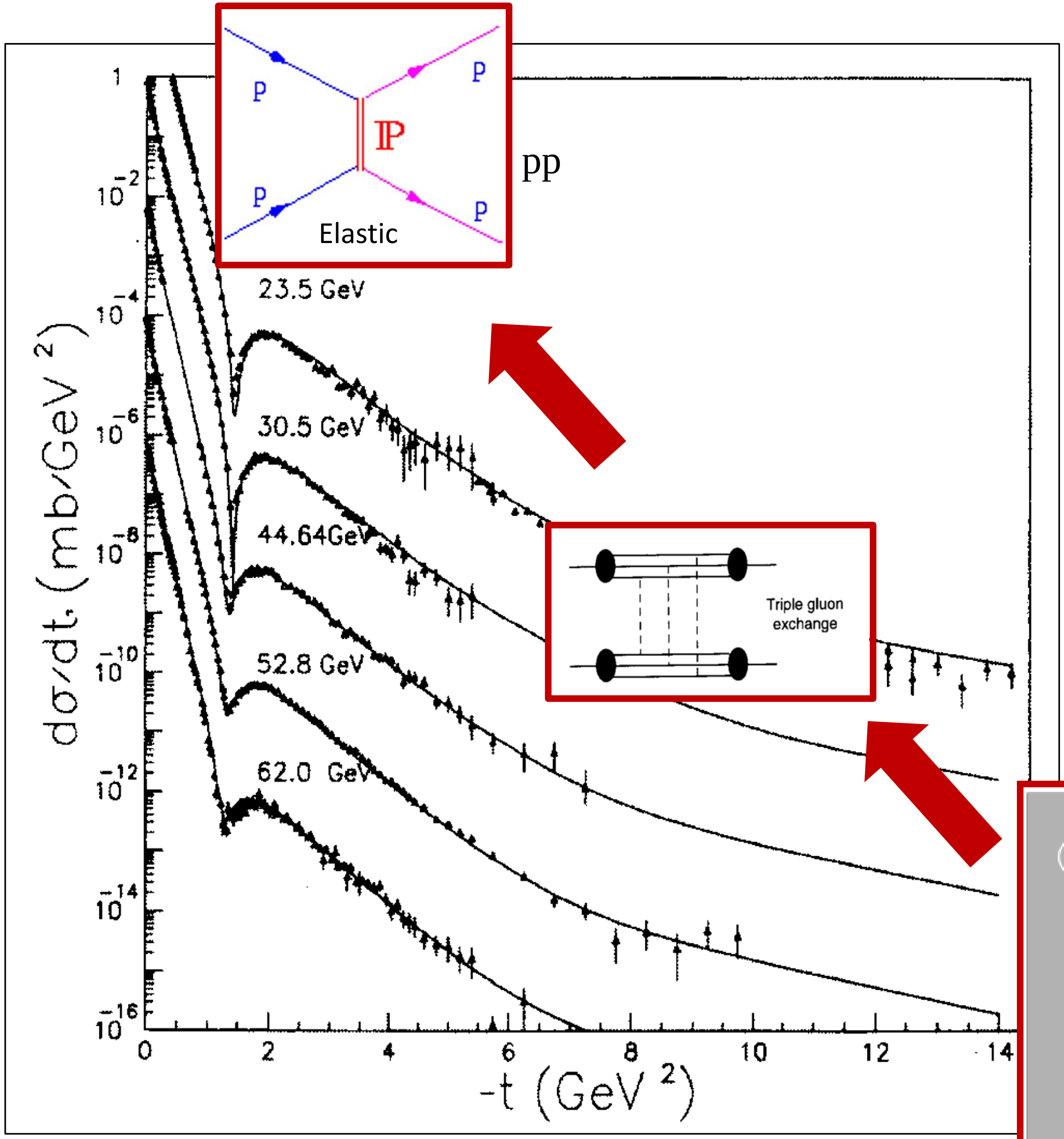
Given the [nuclear] elastic cross is sizeable (~1/4) wrt the total cross-section, any difference between pp and ppbar in the elastic cross-section implies non negligible potential differences in their total cross-section, with far-reaching theoretical consequences.

Why the pp and ppbar elastic cross-sections should have any difference ?

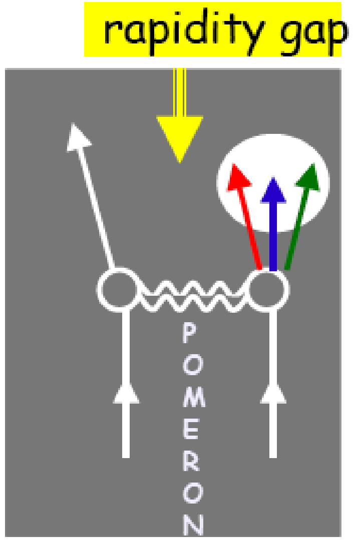
>>

Why the elastic cross-section is sizeable wrt the total cross-section ?

Pre-QCD theory of strong interaction would not anticipate the problems of 1st question.
Perturbative-QCD theory of strong interaction would not imply answer to 2nd question.

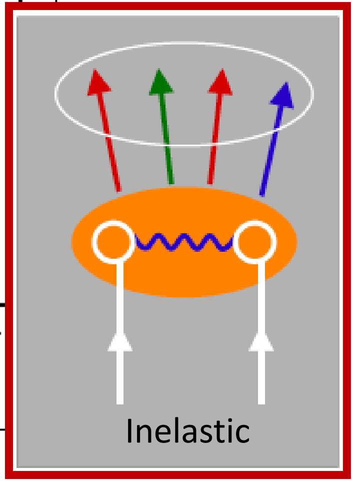


2nd question:



The strong interaction is so strong that it appeared to be the "strong nuclear force" (p-n) even when its charge (color) is compensated in 1st approximation.

The capability to mediate the strong interaction via color-neutral carriers is what allows both protons to remain intact, hence making the elastic scattering possible.



The capability to mediate the strong interaction via color-neutral carriers is what allows protons to interact soft (low-t, "long"-range), hence making the elastic scattering probable.

1st question:

Pomeron(s) as generic identifier of (partonic) color neutral interaction-carrier [Gribov].

For **$\sqrt{s}$ ~1s-10s-100s GeV** quark content of the Pomeron from relatively high to not negligible.
Working of Regge theory and Pomeron description of elastic interaction.

Virtual mesons t-channel exchange(s). *Interaction not mediated by total color charge ≠ 0 .*

Different quantum numbers:
- some invariant under p vs ppbar crossing (Pomeron)
- some not invariant under p vs ppbar crossing (ρ, ω)

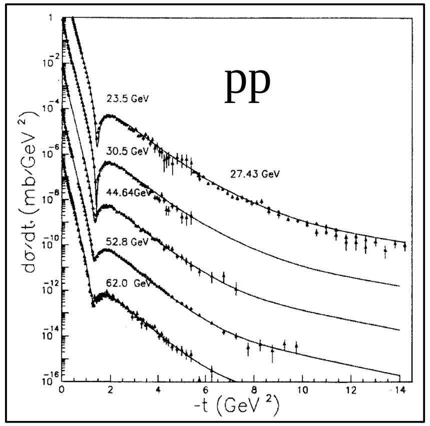
>> ***Therefore*** different behaviour of the pp vs ppbar elastic differential cross-section depending on the relative mesonic channels amplitudes at different energies. [ref. slide 3]

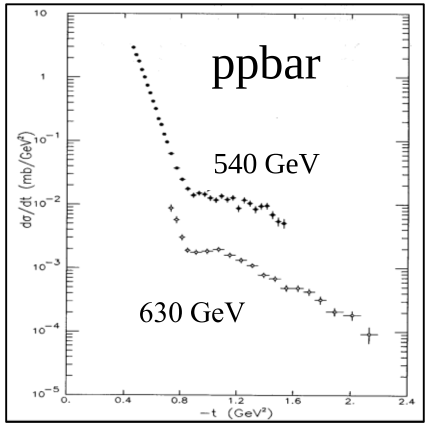
>> ***Therefore***, in particular, occurrence of diffractive dip different between pp and ppbar depending on wavelength of leading mesonic exchanges wrt protons size. [ref. slide 3]

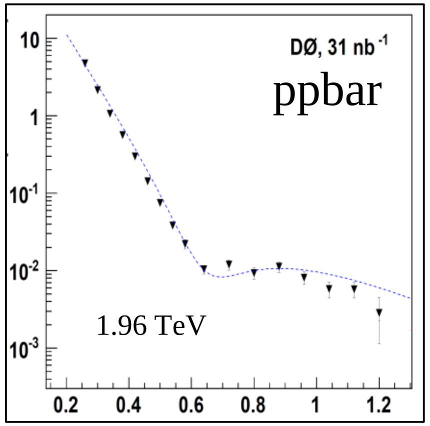
(1) Some theories do not give up equality of pp and ppbar elastic cross-section :

possibility that for increasing √s, the interaction being mediated only via Pomeron(s), the pp and ppbar elastic cross-section would tend to converge (in line with Pommeranchuk theorem);

assuming pp and ppbar to be the same, this possibility was supported by remark that pp dip at ISR (10-60 GeV) had decreasing depth with energy, at the SPS (500-600 GeV) just a shoulder / kink was observed, at the Tevatron (2 TeV) just a shoulder / kink was observed.





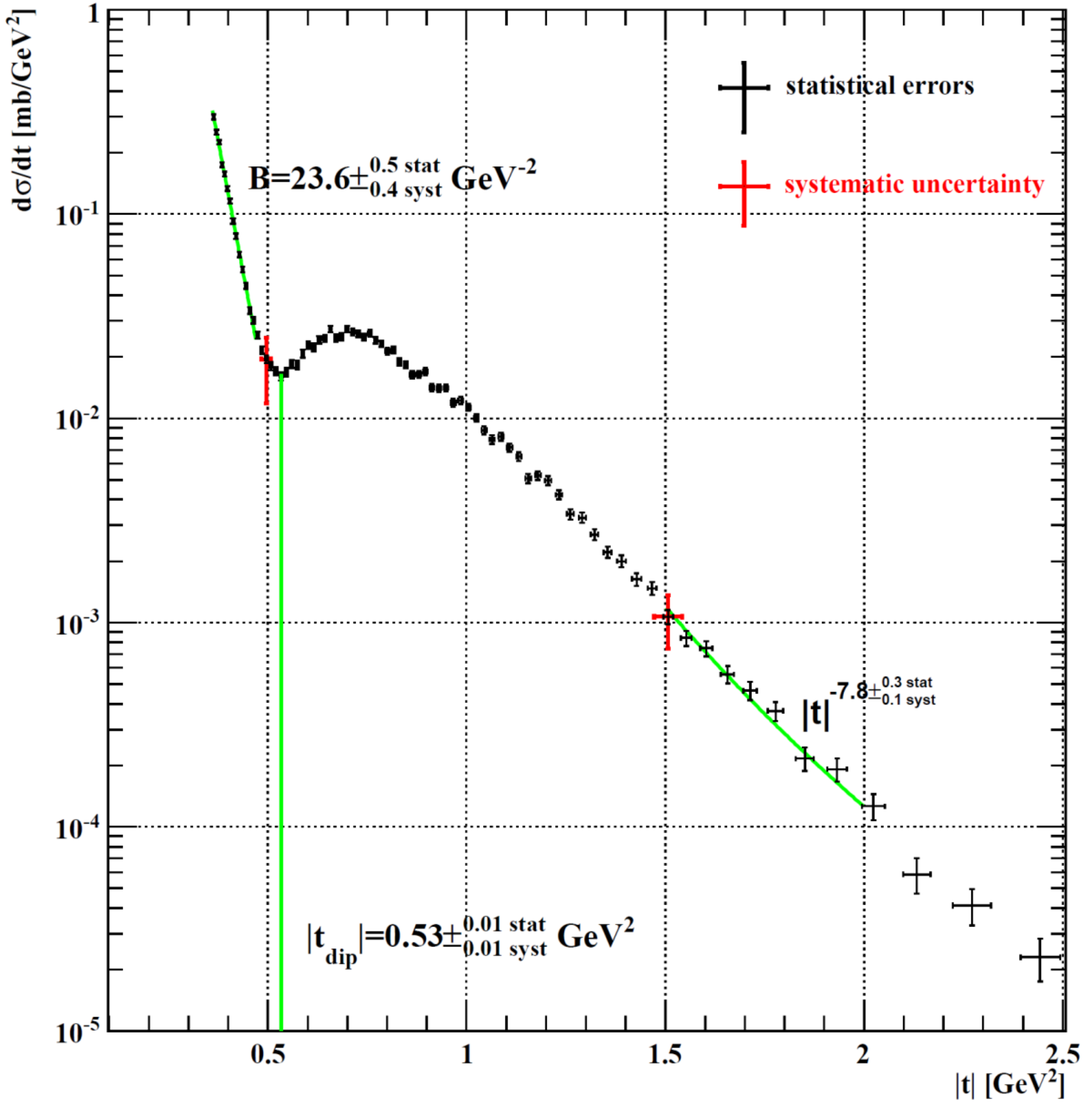


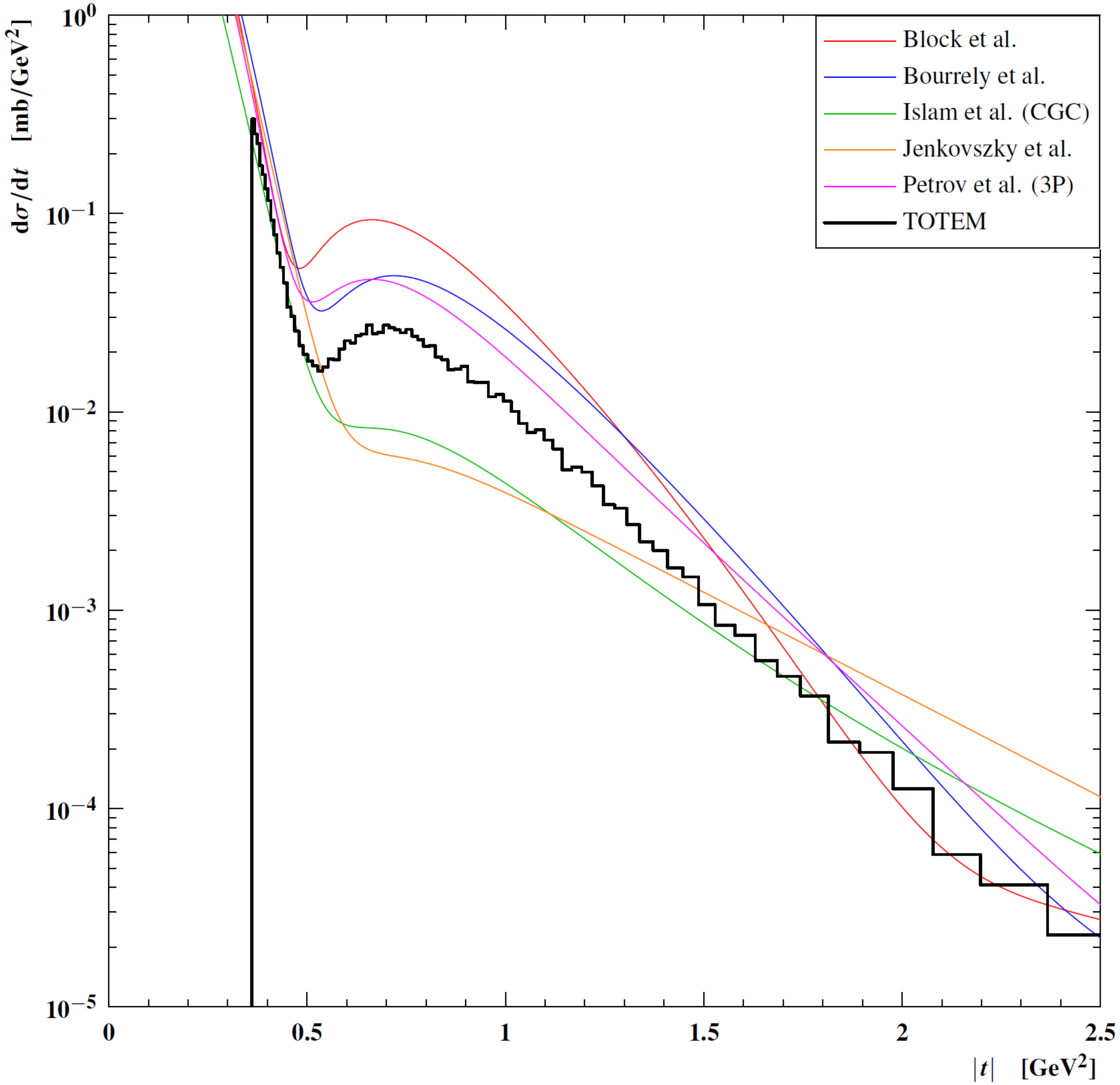
LHC

?

Prediction: no dip in pp at the LHC…

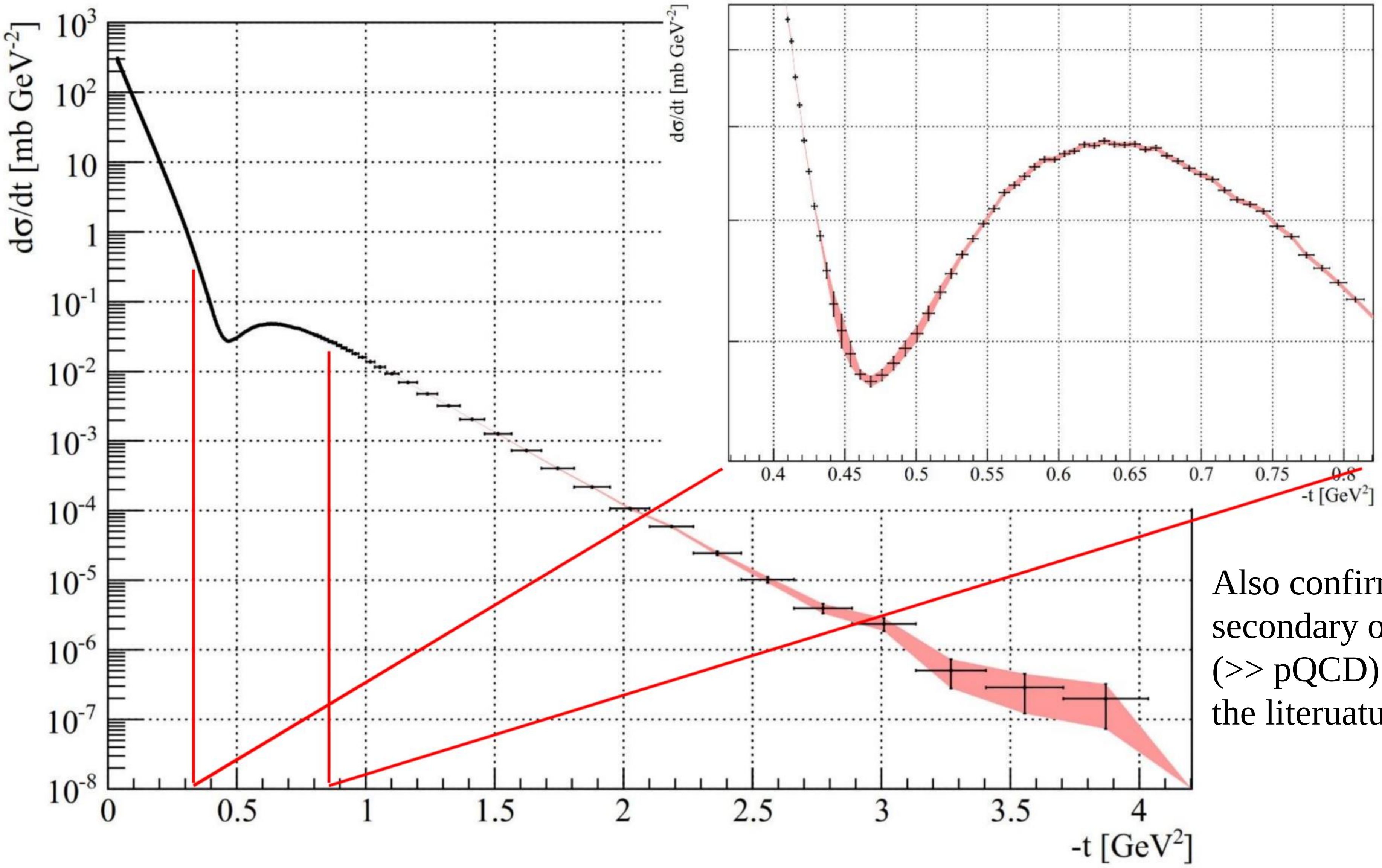
LHC 7 TeV : TOTEM results





The dip in pp is confirmed 40y after the ISR at energy two orders of magnitude larger.

LHC 13 TeV : TOTEM results



Outstanding statistical & systematic precison

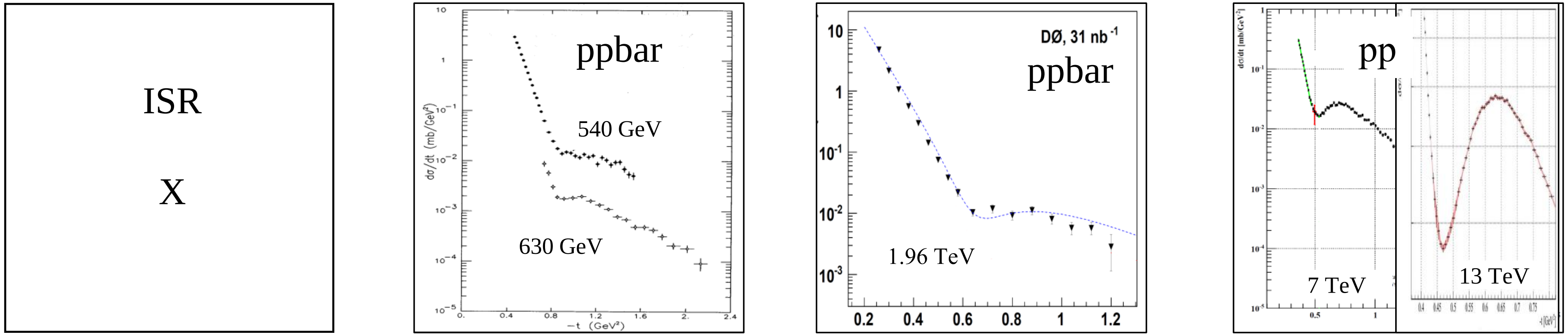
Also confirmed ISR result of no secondary oscillations at large-t (>> pQCD) ruling out 90% of the literuature.

The dip in pp does not vanish with √s . ***Intrinsic difference pp vs ppbar ?***

(2) Some theories do not give up equality of pp and ppbar elastic cross-section :

possibility that for increasing √s, the interaction being mediated only via Pomeron(s), even-under-crossing, gluon-dominated, the pp and ppbar elastic cross-section would tend to converge (in line with Pommeranchuk theorem); ISR data not to be considered as different mechanism;

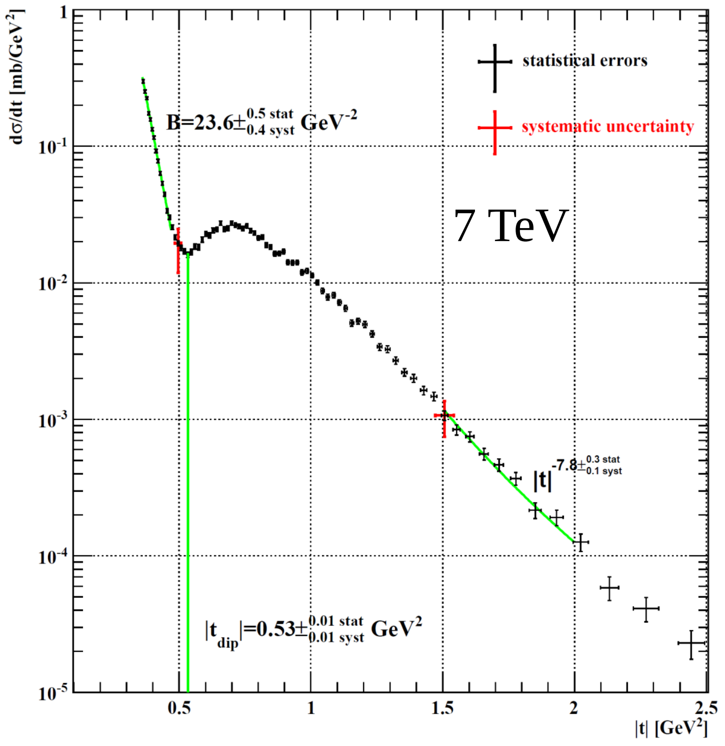
assuming pp and ppbar to be the same, this possibility was supported by remark that shoulder in ppbar at SPS (500-600 GeV) and at the Tevatron (2 TeV) can become deeper with energy and could evolve monothonically into the the observed pp dip at LHC (7-13 TeV), deeper with √s .

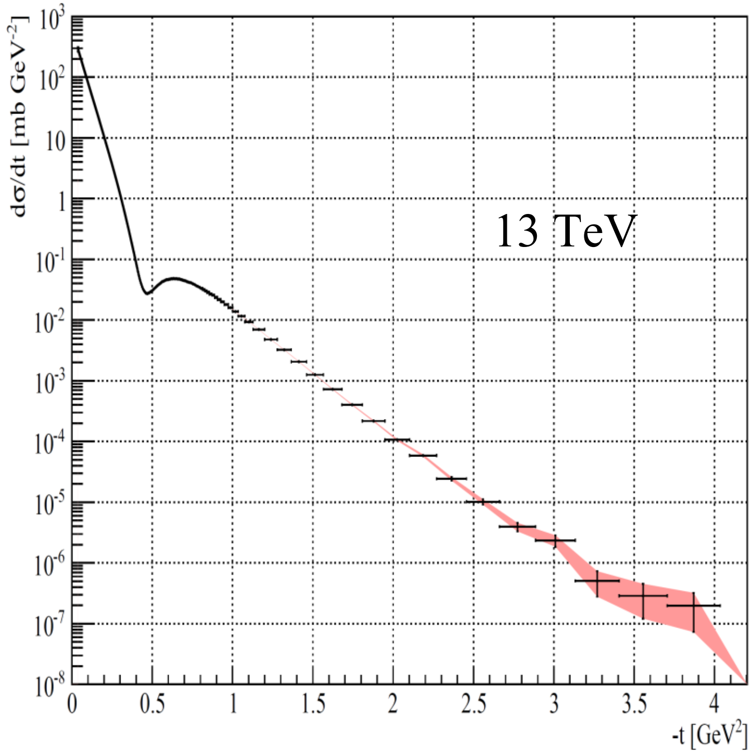


Prediction: no dip in pp would be observed at Tevatron, dip in ppbar would be observed at LHC…

Experimental constraints :

Ad-hoc peculiar tuning of amplitudes required to go from smooth variation between SPS 0.5 TeV and Tevatron 2 TeV, to the LHC pronounced effect at 7 TeV and then smooth variation again between 7-13 TeV; in fact TOTEM data show just 6% increase of dip depth in such √s range:

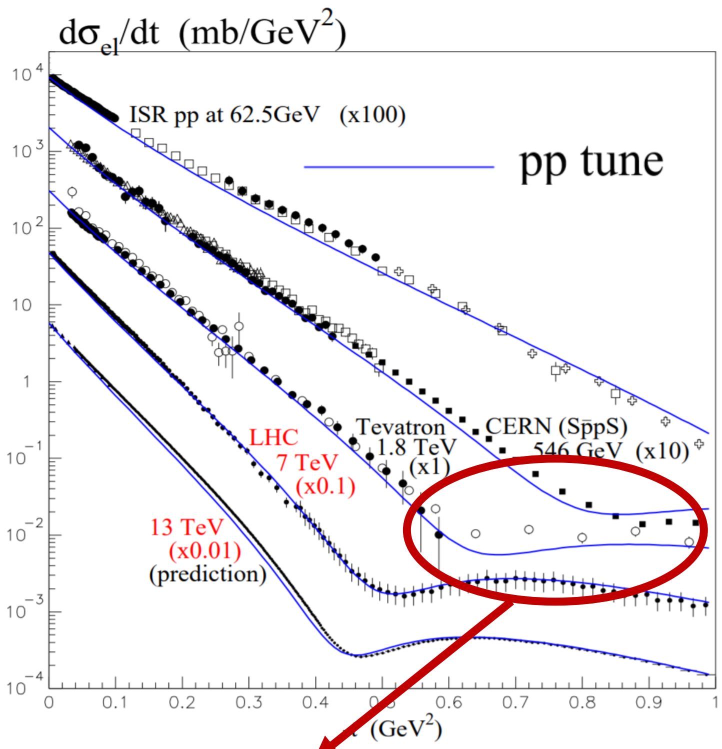




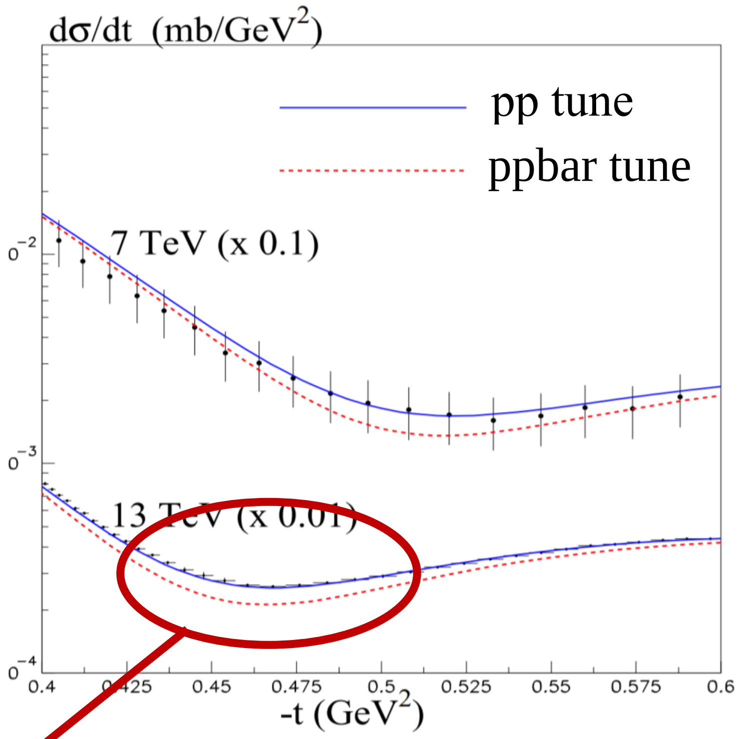
TOTEM data at 2.76 TeV may definitively rule out the theoretical assumption, or prove it.

Experimental constraints :

Moreover such Pomeron(s)-only or Pomeron(s)-dominated tuning [Durham] fail to describe simultaneously the D0 ppbar data and the TOTEM pp data:



ppbar not OK



pp not OK

Also not OK low-t TOTEM data & total cross-section. ***Intrinsic difference pp vs ppbar ?***

Odderon

If evidence of intrinsic difference pp vs ppbar for the elastic cross-section at TeV scale
>>
existence of odd-under-crossing t-channel amplitude(s).

In 1973 Nicolescu-Lukaszuk introduced the Odderon as a general mathematical concept in the framework of extended Regge theory as odd-under-crossing counter-part of the Pomeron.

Consistent pattern of predictions including growth rate of total cross-section, deviation of elastic slope from pure exponential, ρ (real to imaginary ratio of nuclear elastic amplitude at $t=0$) evolution at LHC energies, difference in dip region between pp and ppbar, no secondary oscillation at large-t.

In the ‘80s developed in pQCD (as necessary prediction of QCD) including evolution equations [Lipatov, Vacca, Bartels]

QCD

At TeV scale √s nuclear elastic interaction purely dominated by gluons exchange.

Why elastic cross-section still exist ?

Self-interaction

Gluons as force carriers interact between themselves making color-neutral compounds.

Natural extension of Pomeron from diffraction: 2 (or even) interacting gluons ($J^{PC} = 0^{++}, 2^{++}$)
Dominating amplitude (low-t, medium-t), even-under-crossing, pp vs ppbar invariant.
Gluons >> even faster probability increase for soft, long-range interaction, hence for low-t.

QCD gauge theory with color tensor : 3 (or odd) interacting gluons can be color-neutral.

Odderon as compound of 3 gluons exchanged in t-channel elastic scattering. [Lipatov]

Diffractive dip

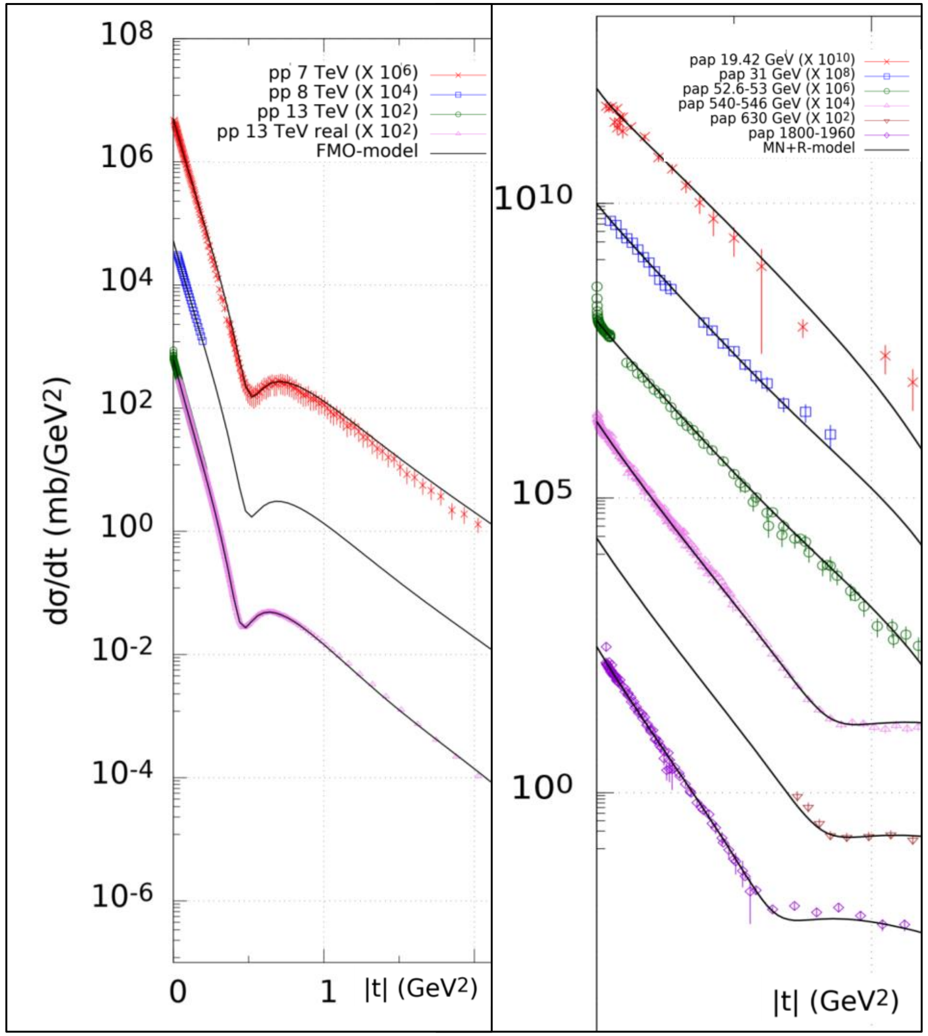
At TeV scale √s nuclear elastic interaction purely dominated by gluons exchange.
At TeV scale pp and ppbar elastic differential cross-section should have shown the same features.

QCD: 3-gluons color-neutral compound less probability than 2-gluons Pomeron.
Regge-like theory: Pomeron amplitude imaginary-dominated, Odderon amplitude real-dominated.

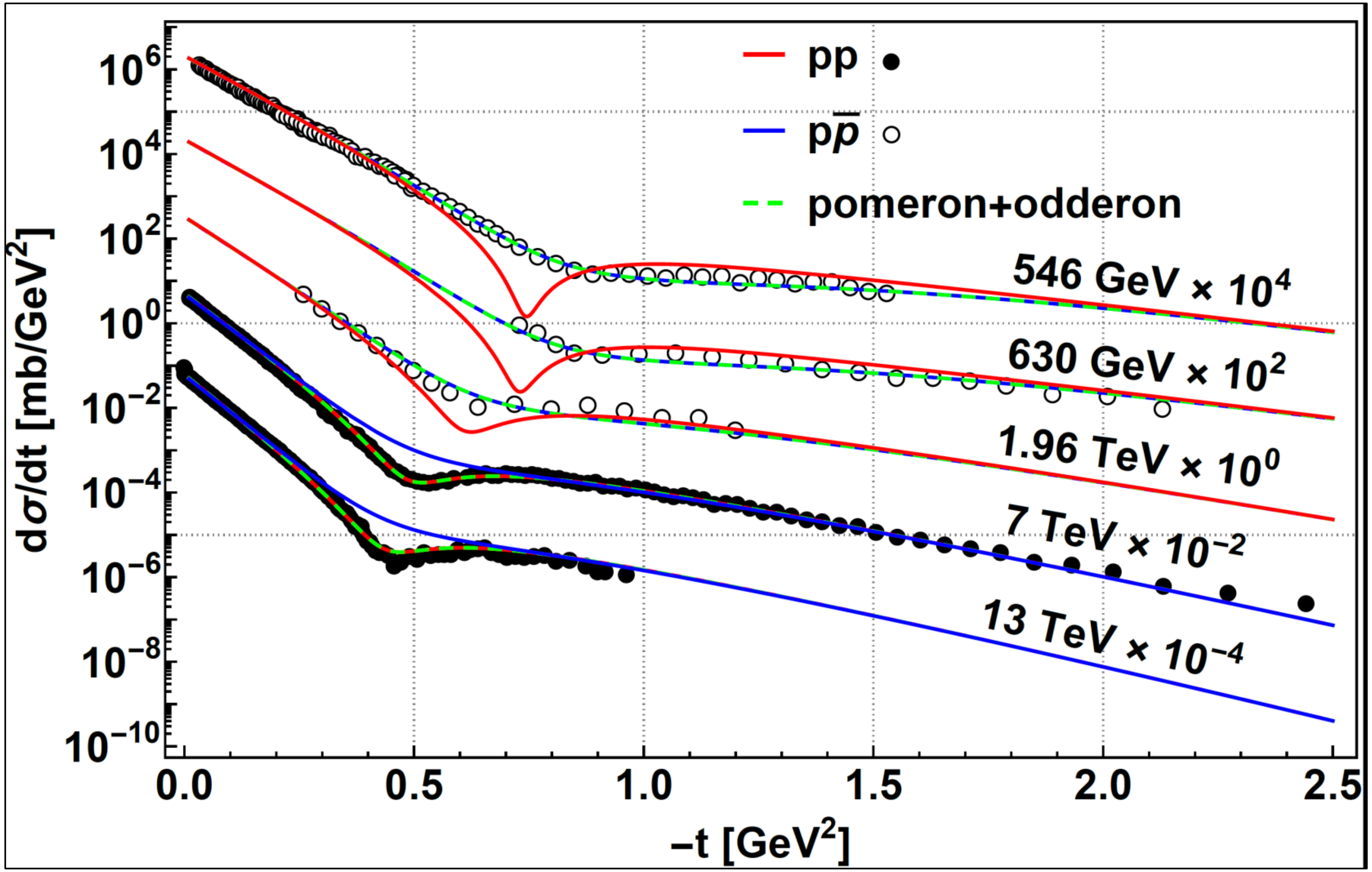
At the diffractive dip, the even-under-crossing 2-gluons (~imaginary, Pomeron) suppressed.
At the diffractive dip, the odd-under-crossing 3-gluons (~real, Odderon) effect may be observed.
[Similar situation in Coulomb-Nuclear interference for t→0 (TOTEM preprints Dec2017)].

The inconsistency of the D0 ppbar 2 TeV data and the TOTEM pp 7-13 TeVdata in the dip region are the experimental pillars of the physics described here.

Theoretical models with Pomeron+Odderon



[Nicolescu, Martynov - preliminary]



[Jenkowszky, Csorgo - preliminary]

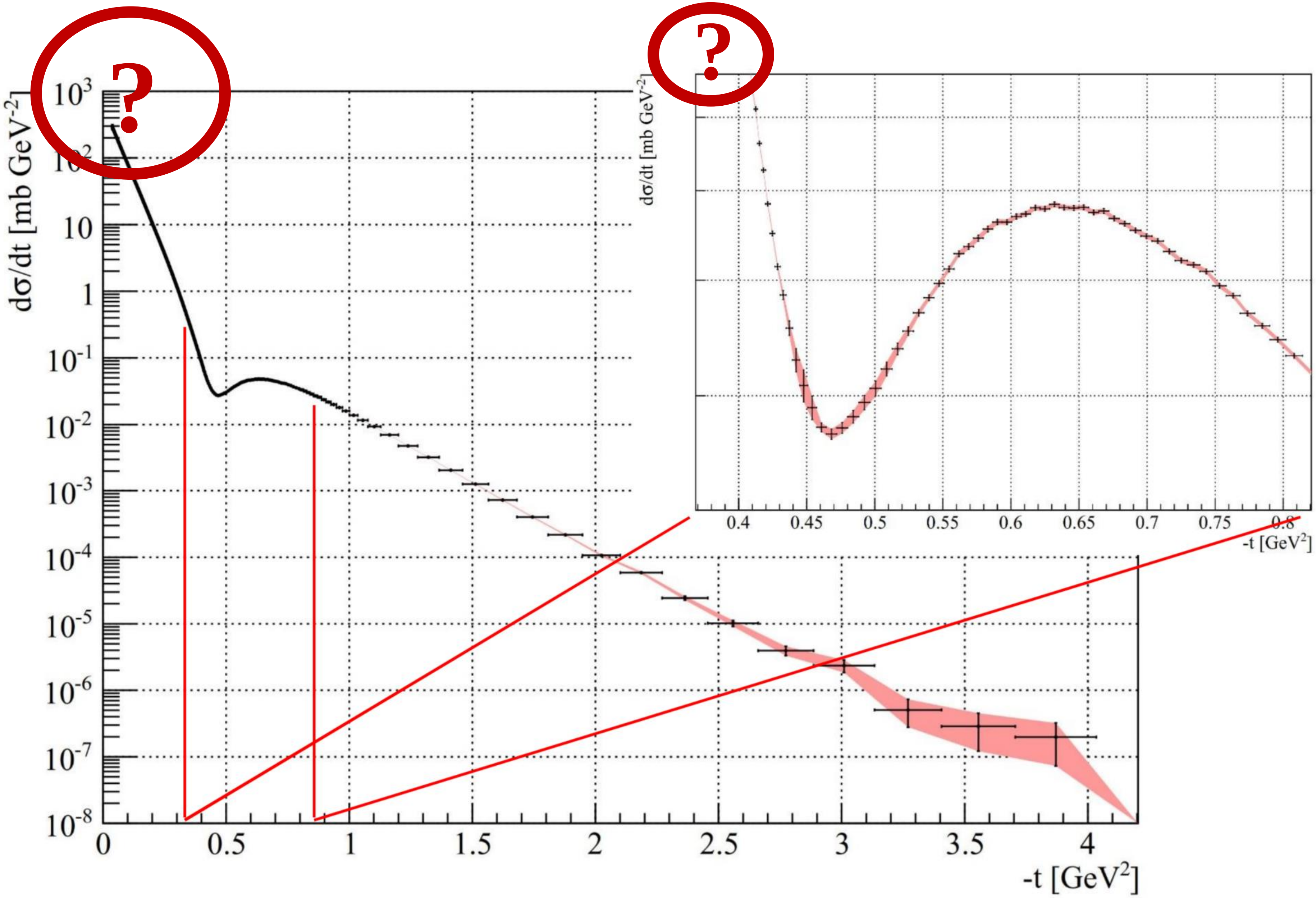
Consistent description of both pp and ppbar data including gluon-dominated regime.

Far-reaching theoretical implications :

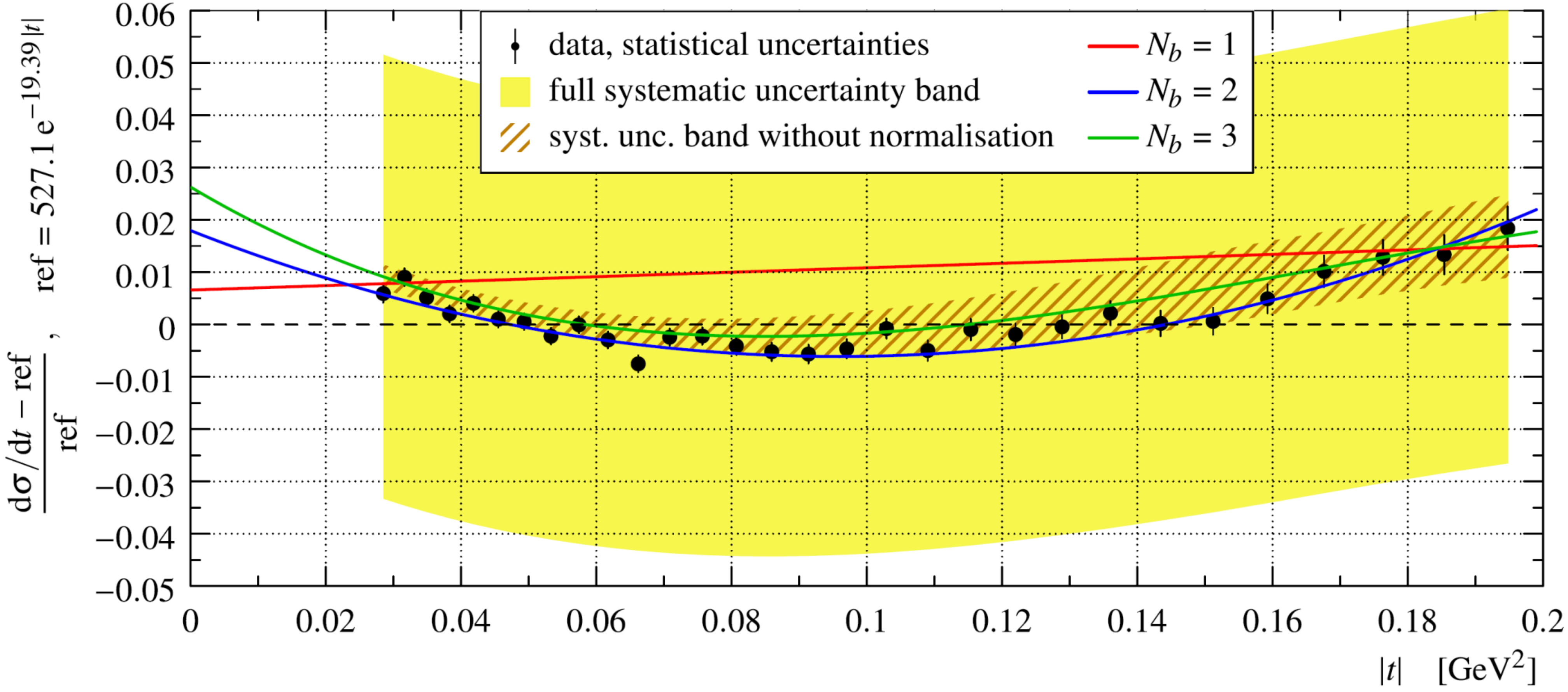
Generalization of Pommeranchuk theorem $\sigma_{pp} / \sigma_{\bar{p}p} \rightarrow 1$ as $\sqrt{s} \rightarrow \infty$

Existence of vector glueball $J^{PC} = 1^{--}$

Differential cross-section for t → 0



First evidence @ LHC of since long predicted deviation from pure exponential of elastic slope

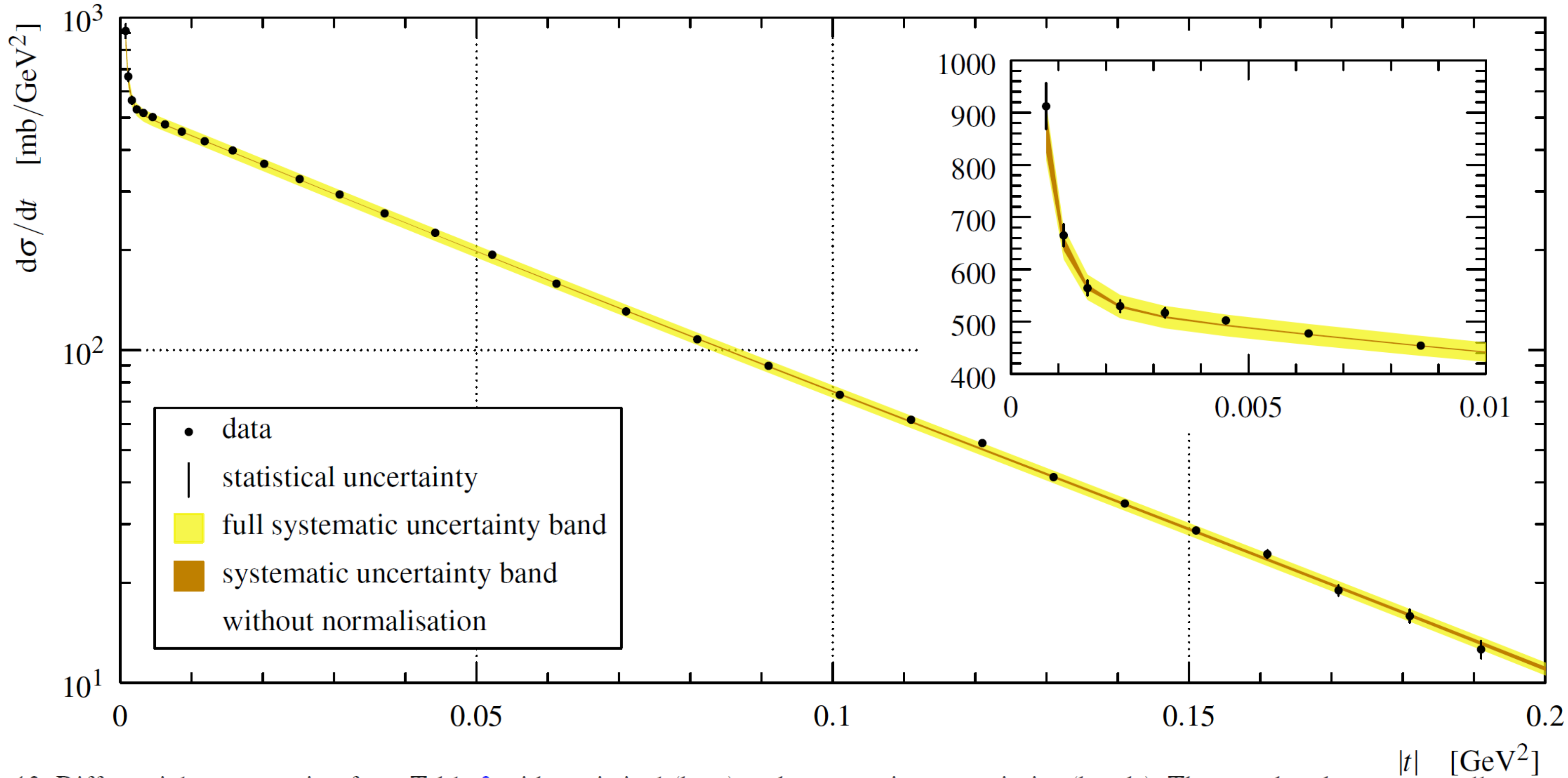


Experimental confirmation that multiple channels contribute to low-t elastic scattering

Observationof consistent effect at 7 TeV, 8 TeV, 13 TeV

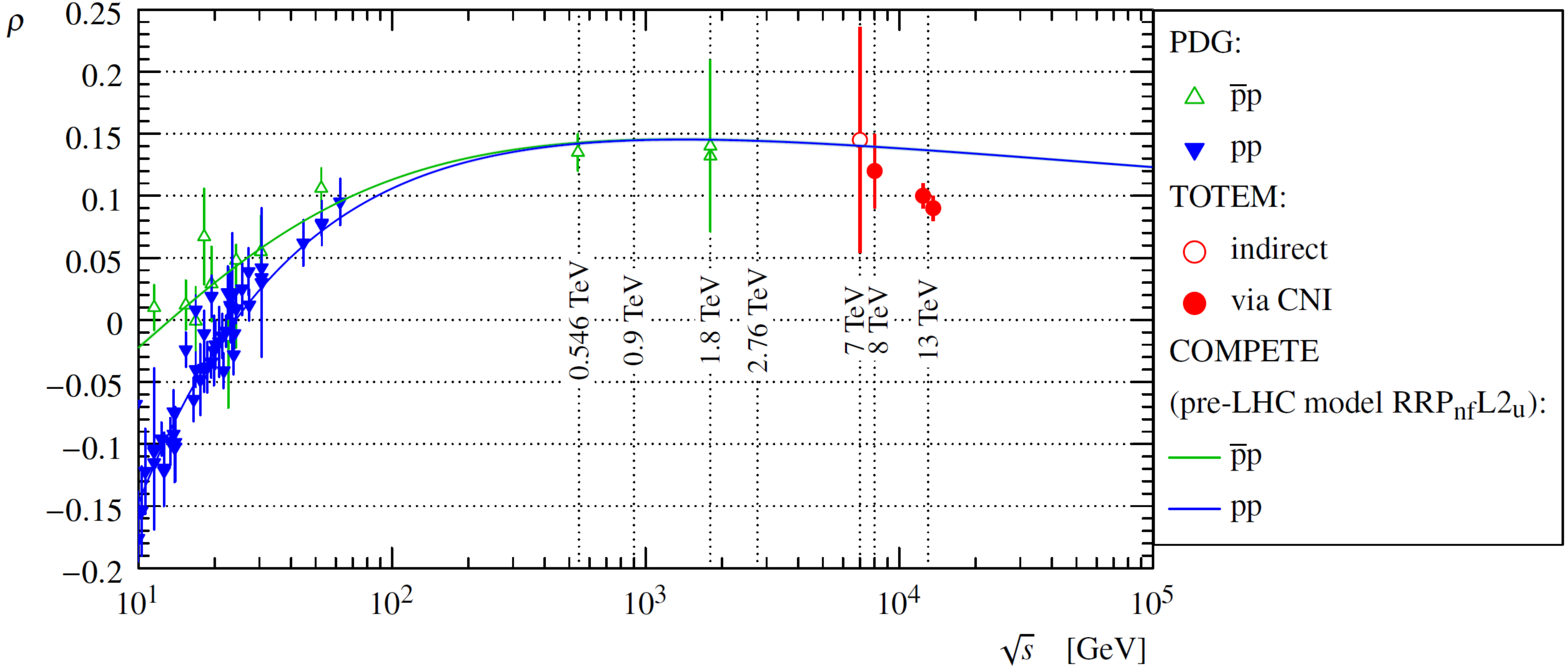
Coulomb-Nuclear Interference

Test of theoretical assumptions on shape of nuclear amplitude at $t \to 0$
Test of theoretical modelling of the phase: central vs peripheral in impact parameter space
Determination of rho: real to imaginary ratio of nuclear amplitude at $t = 0$

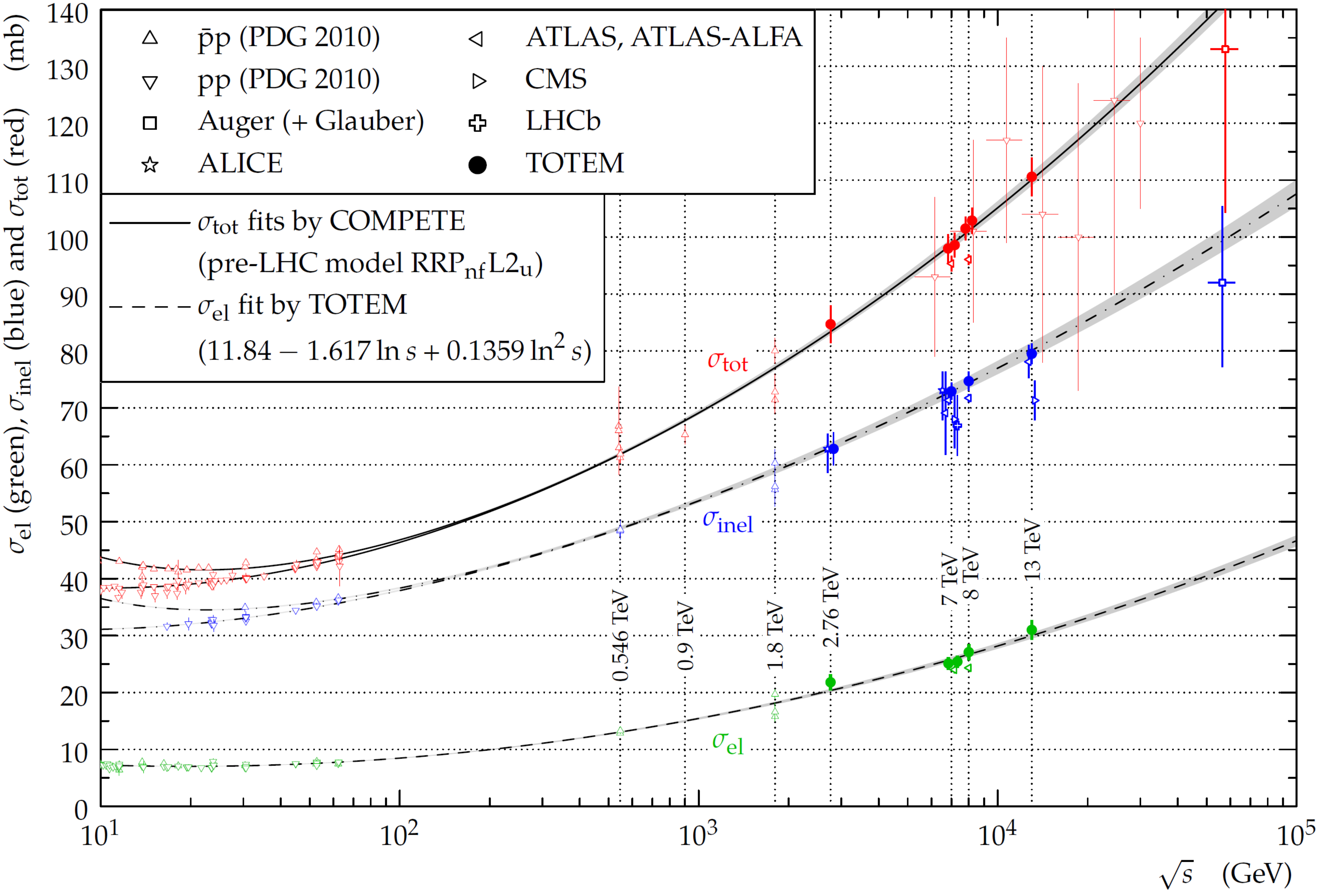


ρ as a function of √s

Orthogonal evidence of Odderon effect (t=0)
or
First evidence of slowing growth rate of total cross-section beyond LHC (dispersion relation)



pp elastic, inelastic, total cross-section @ LHC



TOTEM measurements:
luminosity-independent or
rho-independent or
OpticalTheorem-independent or
w/o Coulomb-Nuclear interference or
w/o modelling of low-t nuclear amplitude

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

TOTEM 2017-001

CERN-PH-EP-2017-231
January 25, 2018

First measurement of elastic, inelastic and total cross-section at $\sqrt{s} = 13$ TeV by TOTEM and overview of cross-section data at LHC energies

The TOTEM Collaboration

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

TOTEM-2017-002
16 December 2017

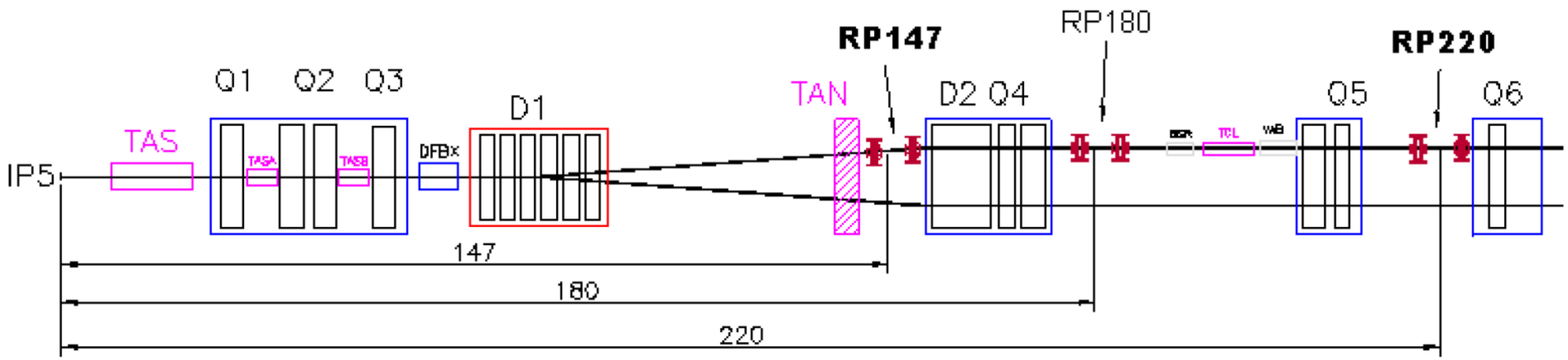
CERN-EP-2017-335
19 December 2017

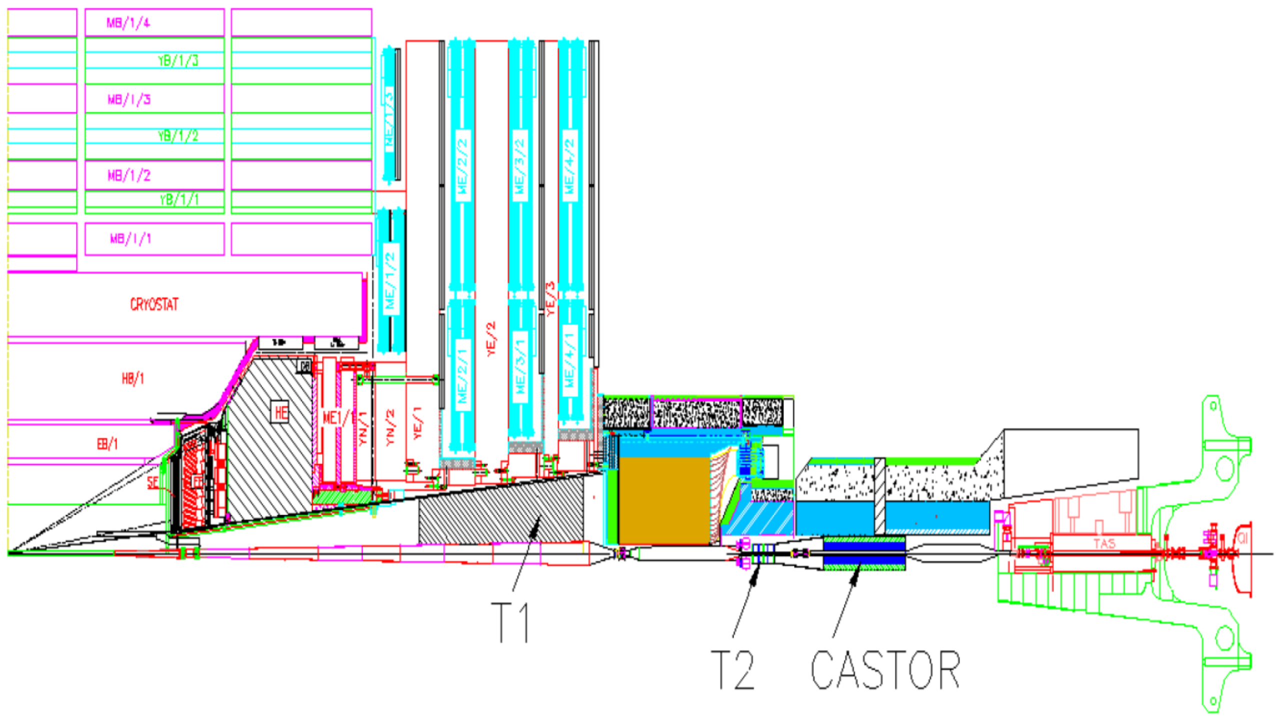
First determination of the ρ parameter at $\sqrt{s} = 13$ TeV – probing the existence of a colourless three-gluon bound state

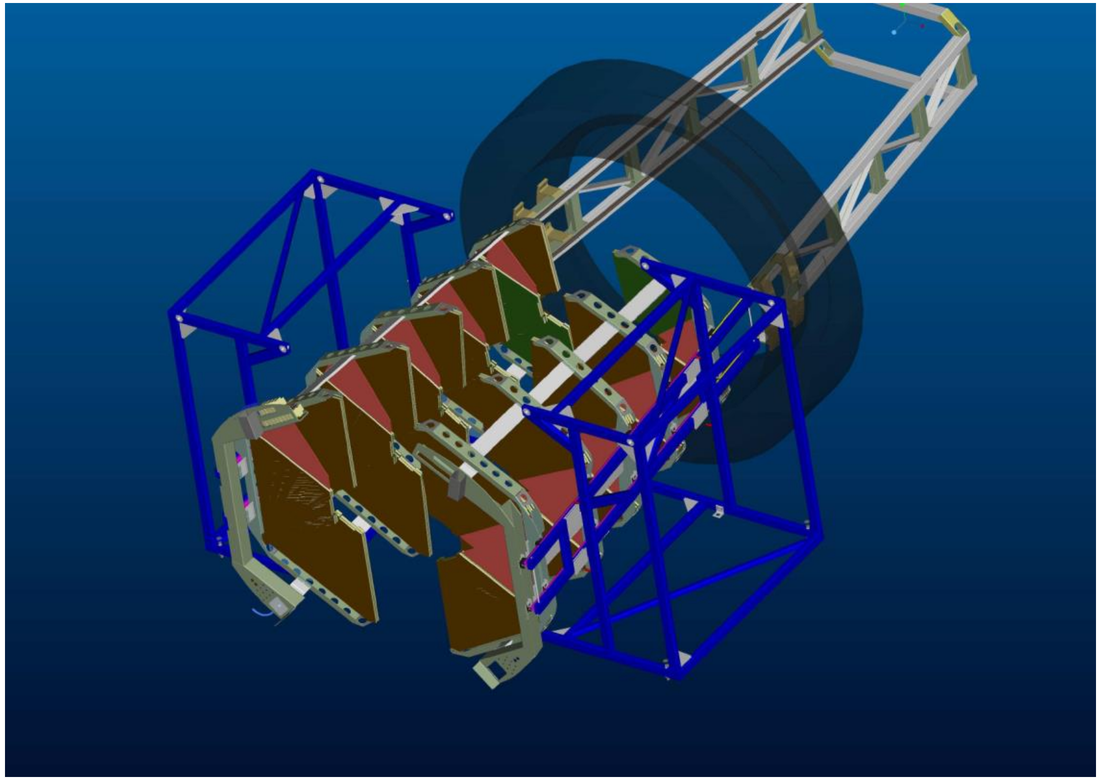
The TOTEM Collaboration

TOTEM detectors: RPs, T1, T2

T1[Genoa] instrumental for inelastic cross-section, forward diffractive, total cross-section





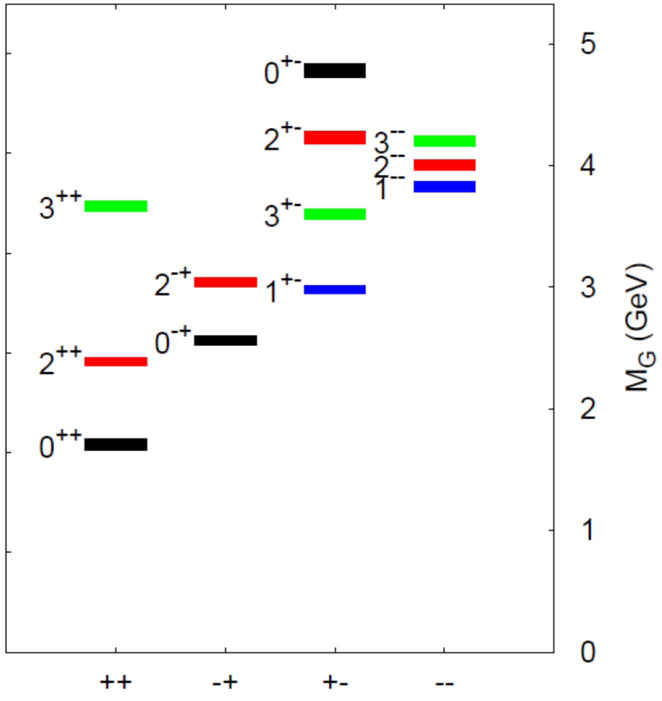


Combined CMS-TOTEM low-luminosity physics spectroscopy, glueball searches

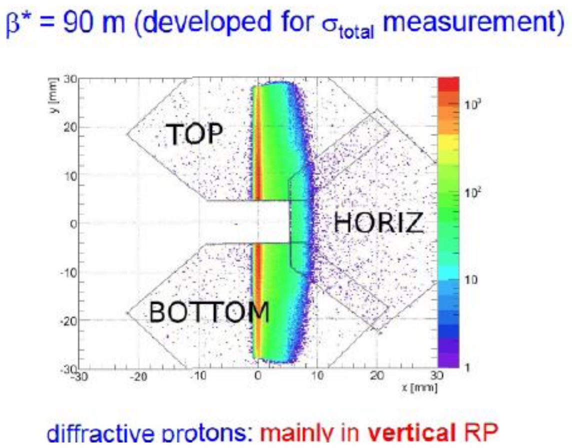
3 Experimental advantage of CMS+TOTEM detectors

The experimental advantages of CMS+TOTEM in the glueball search with respect to past experiments can be summarized in the following points:

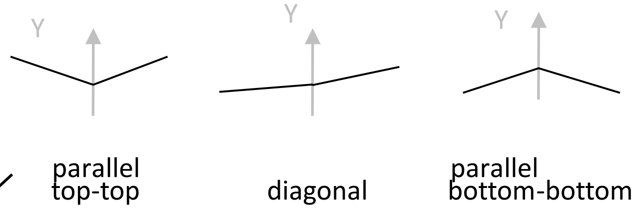
- LHC gives $\sqrt{s}$ such that central masses $M = \sqrt{s\xi_1\xi_2} \sim$ 1–10 GeV are produced diffractively at unprecedently low values of the proton longitudinal momentum loss fractions, $\xi_{1,2} \sim 10^{-3}$–10^{-4}, ensuring pure gluonic exchange conditions.
- TOTEM can measure both protons emerging from CD interactions.
- TOTEM and CMS together can select exclusive events by requiring that the total transverse momentum (protons+charged tracks) be compatible with zero.
- The very forward T2 detector, which records 95% of the total inelastic cross section, acts as a unique veto-detector that helps to select pure exclusive events already at the trigger level.
- CMS can reconstruct 4 charged particles in the tracker with invariant mass resolution of 20–30 MeV (given sufficient statistics, even the neighboring resonances can be discriminated directly in the distributions, without model- and multi-parameter-dependent partial-wave analysis).



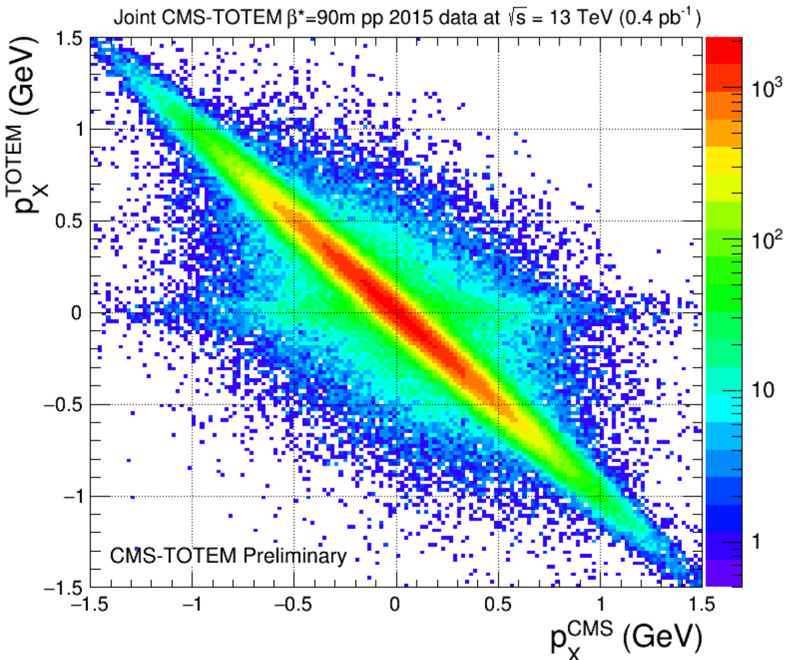
Combined CMS-TOTEM low-luminosity physics spectroscopy, glueball searches

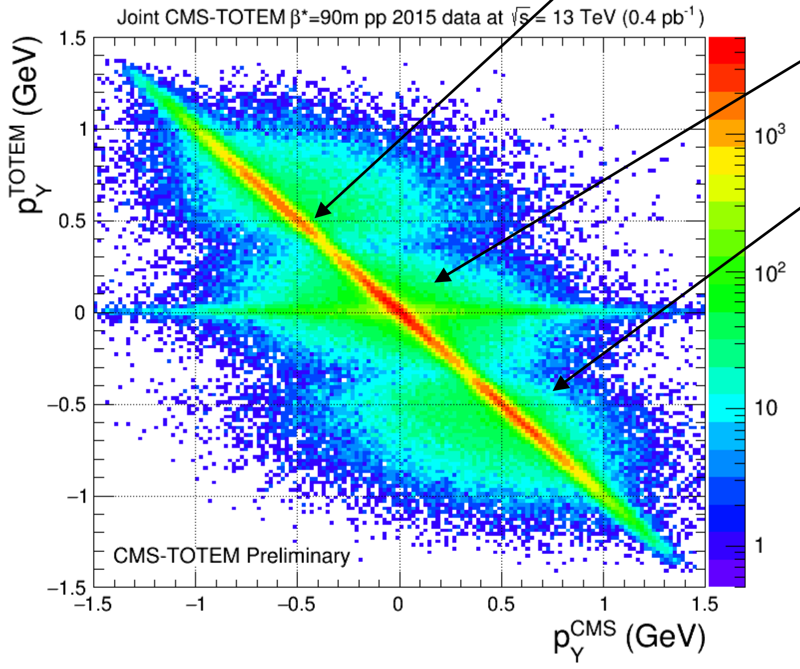


Different proton configurations



Exclusivity condition: $p_{x,y}^{CMS} = p_{x,y}^{TOTEM}$





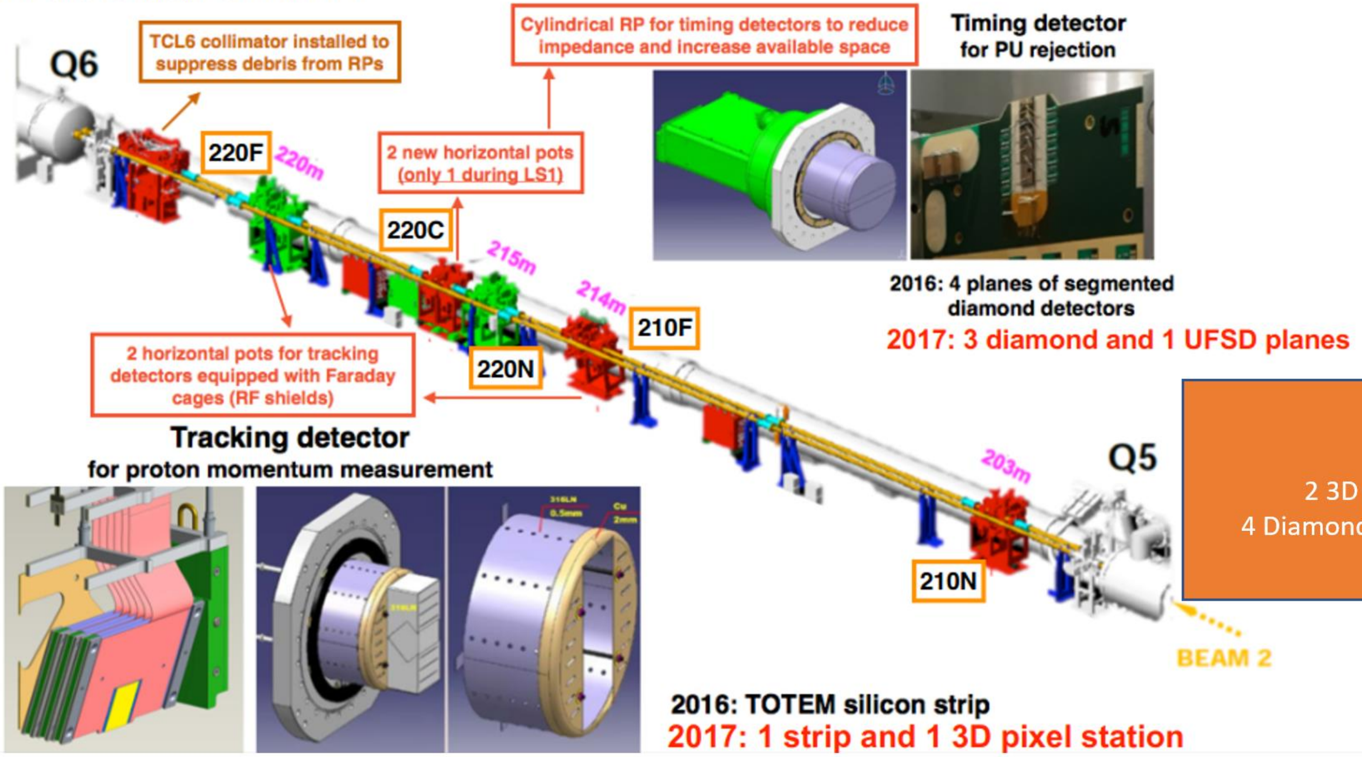
Combined central-forward high-luminosity physics

Challenge: pile-up

Solution: CT-PPS [Precision Proton Spectrometer] :

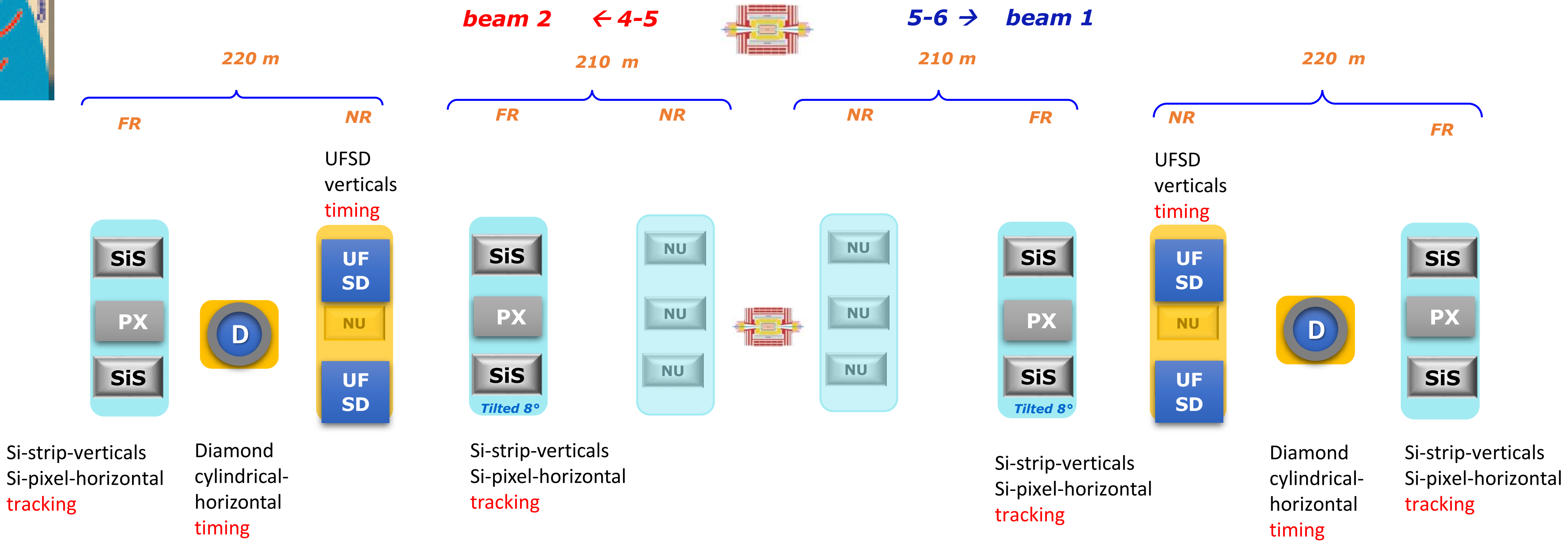
tracking 3D Si pixels detectors [Genoa] & **timing** diamond and ufsd detectors

- The **CMS-TOTEM Precision Proton Spectrometer** (CT-PPS) allows the measurement of **protons in the very forward regions** on both sides of CMS in **standard LHC running conditions**, taking advantage of the machine magnets to bend the protons.
- **Tracking and timing detectors** are installed in Roman pots between 205 and 220 m from the CMS/TOTEM IP.



2018:
2 3D pixel stations
4 Diamond planes (2 double)

PPS RP & Detector layout 2018



Luminosity integrated 2016 : 14 fb-1

Luminosity integrated 2017 : 40 fb-1

Luminosity integrated 2018 (until now) : > 20 fb-1

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS-PPS-17-001
TOTEM 2018-001

CERN-EP-2018-014
2018/03/14

Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV with the CMS–TOTEM precision proton spectrometer

The CMS and TOTEM Collaborations*

Abstract

The process pp $\rightarrow$ p$\ell^+\ell^-$p$^{(*)}$, with $\ell^+\ell^-$ a muon or an electron pair produced at midrapidity with mass larger than 110 GeV, has been observed for the first time at the LHC in pp collisions at $\sqrt{s}$ = 13 TeV. One of the two scattered protons is measured in the CMS–TOTEM precision proton spectrometer (CT–PPS), which operated for the first time in 2016. The second proton either remains intact or is excited and then dissociates into a low-mass state p*, which is undetected. The measurement is based on an integrated luminosity of 9.4 fb^{-1} collected during standard, high-luminosity LHC operation. A total of 12 $\mu^+\mu^-$ and 8 e$^+$e$^-$ pairs with $m(\ell^+\ell^-) > 110$ GeV, and matching forward proton kinematics, are observed, with expected backgrounds of 1.49 $\pm$ 0.07 (stat) $\pm$ 0.53 (syst) and 2.36 $\pm$ 0.09 (stat) $\pm$ 0.47 (syst), respectively. This corresponds to an excess of more than five standard deviations over the expected background. The present result constitutes the first observation of proton-tagged $\gamma\gamma$ collisions at the electroweak scale. This measurement also demonstrates that CT–PPS performs according to the design specifications.

Submitted to the Journal of High Energy Physics

Ready for BSM physics,
anomalous couplings,
missing energy,
…