Total pp cross section measurements at 2, 7, 8 and 57 TeV

A) The evergreen Regge formalism

RFT and pQCD

B) Direct measurement of σ_{inel}:

1) cosmic-ray experiments

$\sigma_{p\text{-}air}$, σ_{pp} via Glauber models

2) collider experiments

σ_{inel} for specific final state

C) Measurements of diffraction: σ_{SD}, σ_{DD}

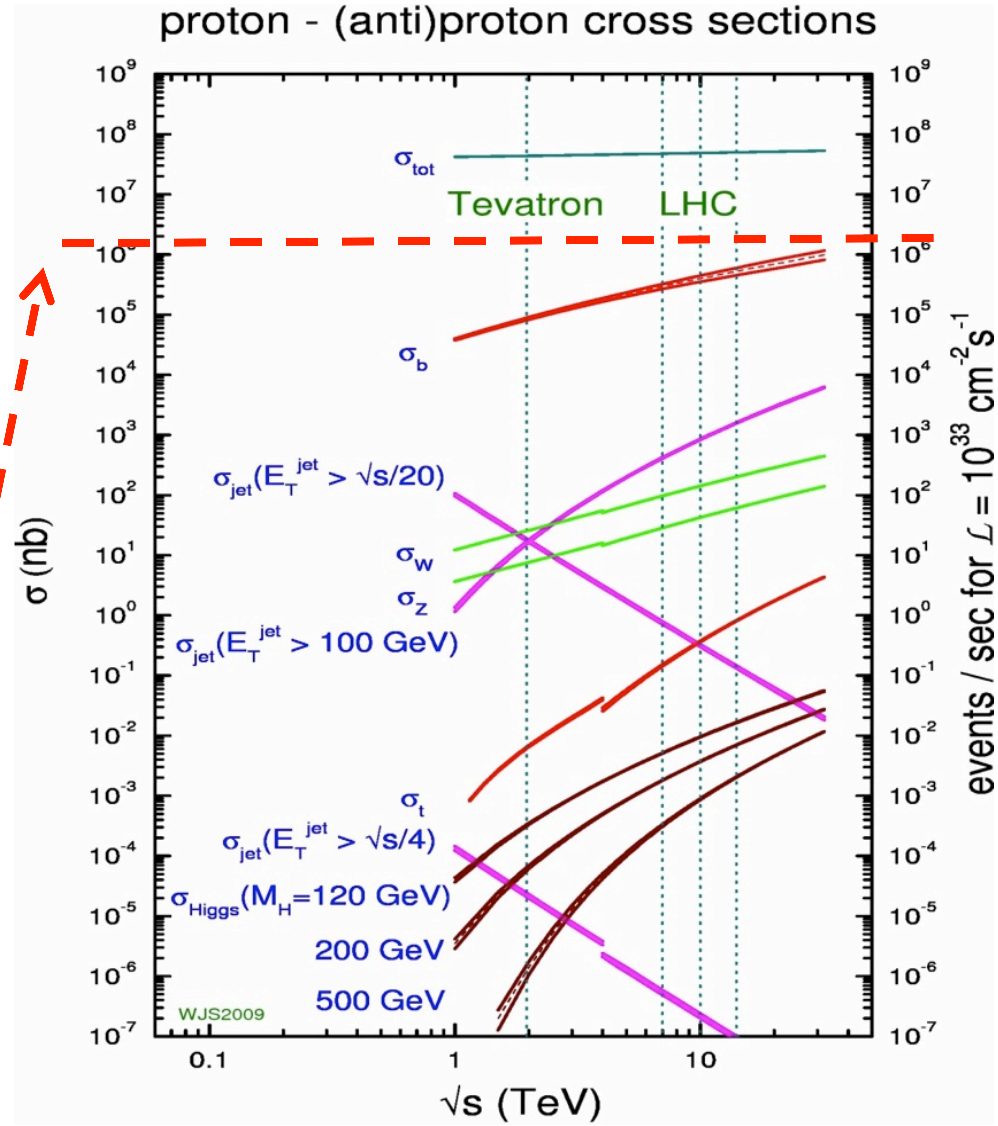
D) The art of elastic scattering:

1) σ_{el} and σ_{Tot} via the optical theorem

Let's set the scale…

The total cross section is dominated by soft processes.

If you were to eliminate every process below the first line (even the Higgs!) the value of the total cross section would be the same



What is driving this process?

The total cross section is traditionally described as a sum of 3 parts:

- Elastic: pp→ pp
- Diffraction: pp→ XY

  Where there is no color connection between the two outgoing systems
- Everything else: pp→ X

$$\sigma_{Tot} = \sigma_{elastic} + \sigma_{diffractive}(\sigma_{SD} + \sigma_{DD} + \ldots) + \sigma$$

The study of total cross section is intertwined with long range QCD, and as such, intrinsically not calculable.

Introducing extra assumptions, and using the available data points, lead to models with good predicting power.

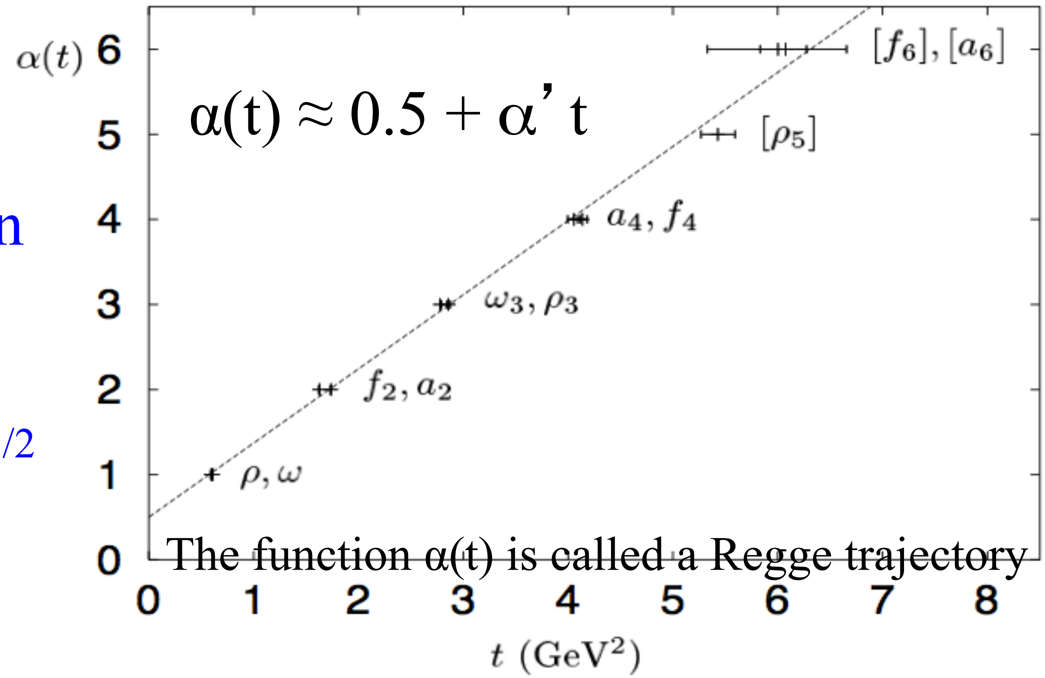
Regge Theory

"Regge Theory" , and derivations, is the language used to describe total cross sections,

The behavior of the total cross section depends on the sums of the exchanges of many particles.

The particles are grouped trajectories

Plot of spins of families of particles against their squared masses:



The function $\alpha(t)$ is called a Regge trajectory

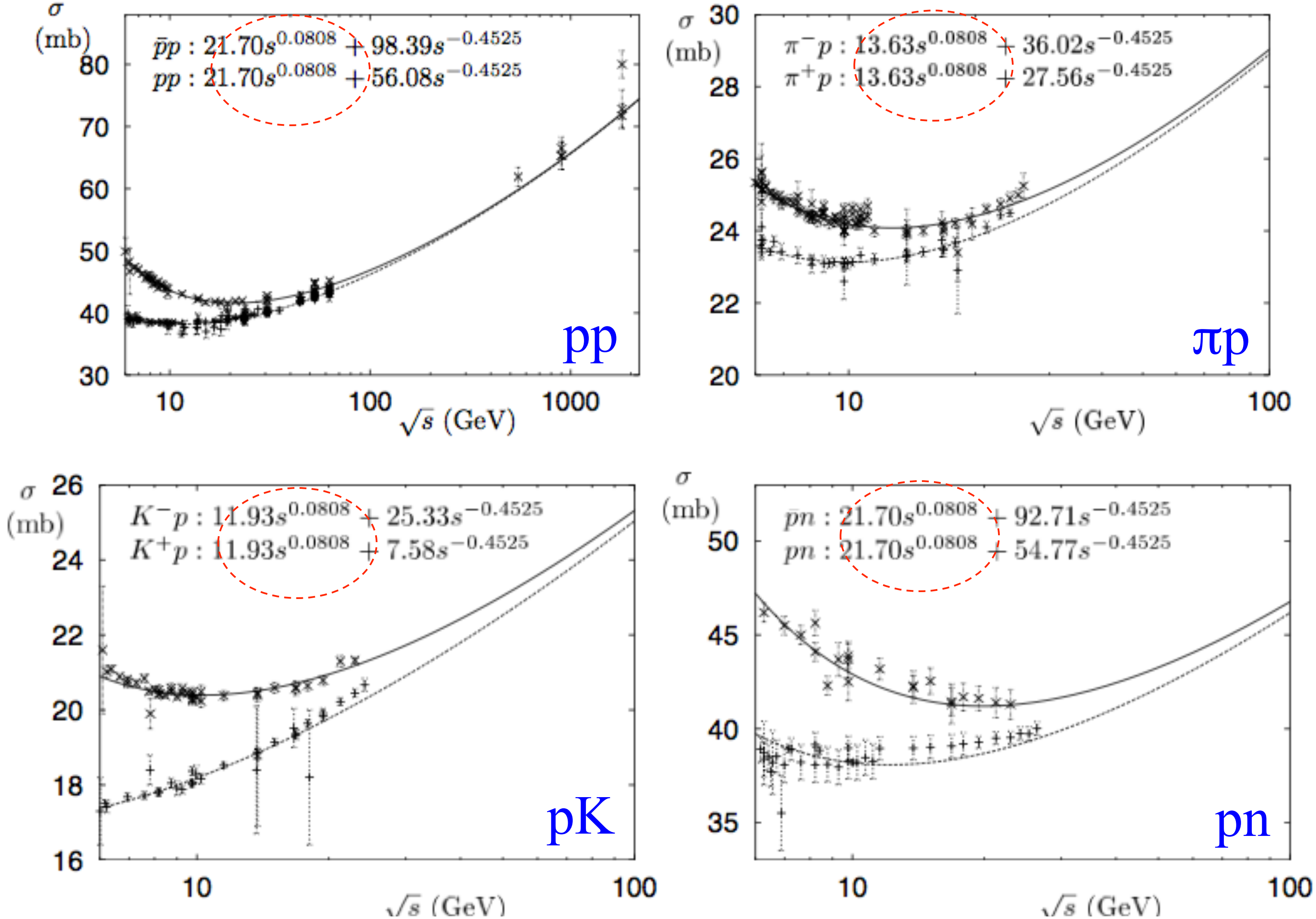
Each trajectory contributes a fixed power.

From the known particles, we obtain the following prediction:

$$\sigma_{TOT}(s) = \text{Im } A(s,t=0) = s^{\alpha(0)-1} = s^{-1/2}$$

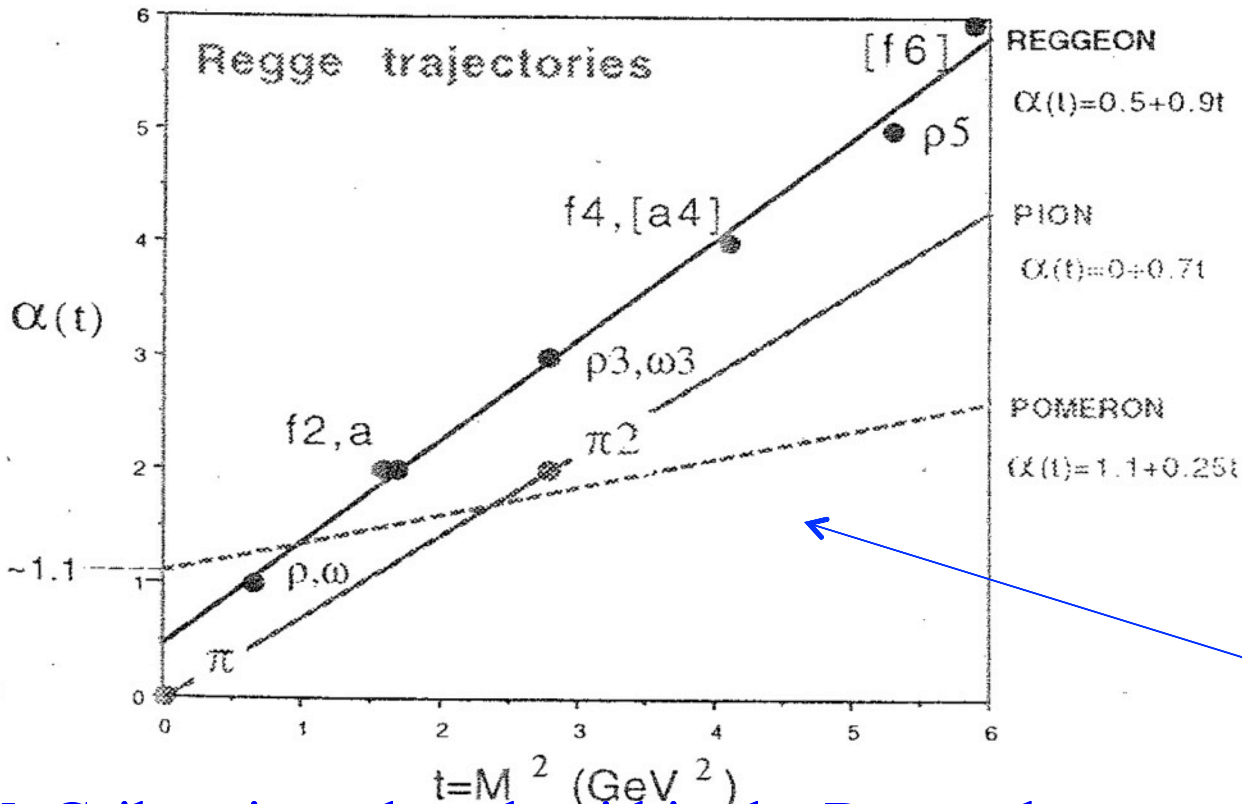
However…

Overview of hadronic cross sections



The cross section is raising at high energy: every process requires a trajectory with the same positive exponent: $s^{0.08}$ the pomeron trajectory

The advent of the Pomeron



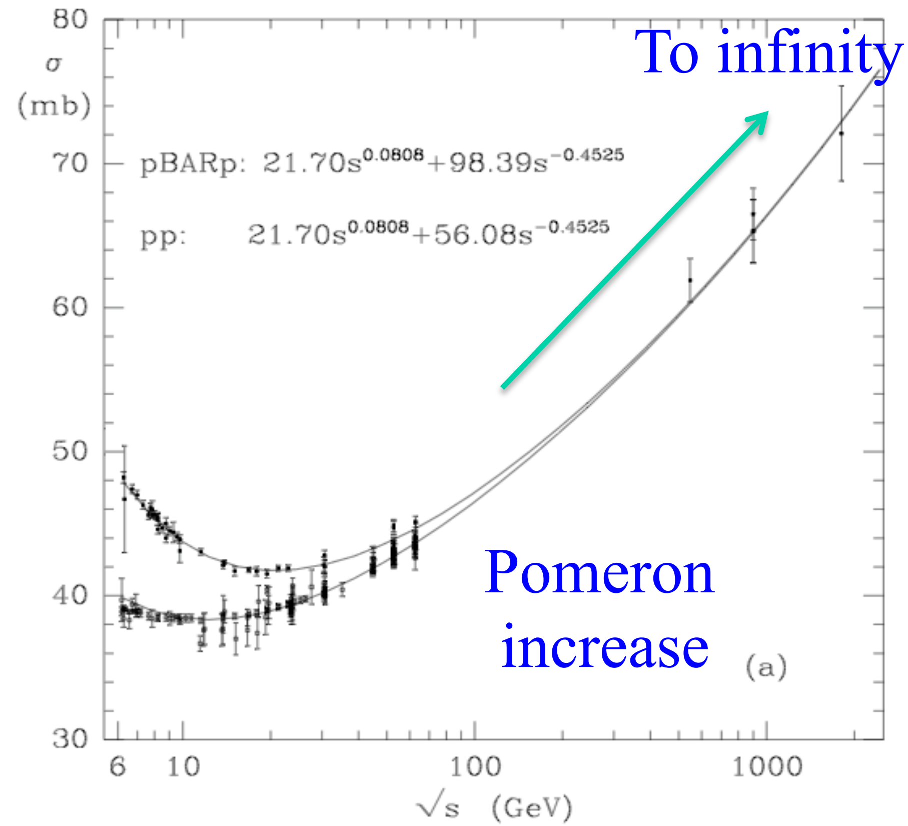
A trajectory without known particles

V. Gribov introduced, within the Regge theory, a vacuum pole (**Pomeron** with $\alpha(0) \sim 1.$) in order to have a constant (or rising) total cross section.

Regge Theory: master formula pre LHC

$$\sigma_{TOT}(s) = \alpha\, s^{0.08} + \beta\, s^{-0.5}$$

Reggeon decrease



Problem: it violates unitarity. Froissart-Martin bound, $\sigma_{TOT}(s) < \pi/m^2_{\pi} \log^2(s)$

However it's not a big deal for LHC: $\sigma_{TOT} < 4.3$ barns

Pumplin bound: $\sigma_{El}(s) < ½\, \sigma_{TOT}(s)$

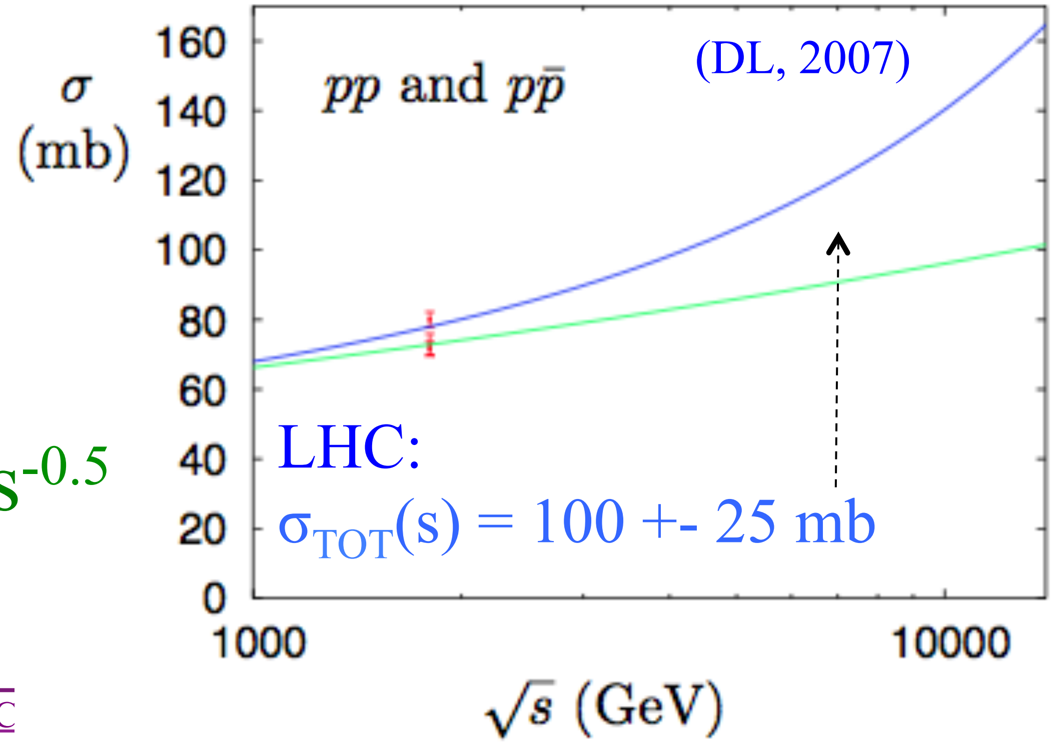
Regge Theory: master formula for higher energy

At energy at or above Tevatron, particle density functions (PDF) become very steep, and the cross section rises more quickly.

Donnachie and Landshoff introduced in σ_{TOT} an additional term to account for this effect called “hardPomeron”, with a steeper energy behavior:

Steeper increase with energy

$$\sigma_{TOT}(s) = \alpha\, s^{0.08} + \gamma\, s^{0.4} + \beta\, s^{-0.5}$$



Reggeon Field Theory Models

This simple-minded Regge Theory becomes a "real" theory in RFT (Gribov et al) .

RFT explains soft QCD physics using the exchange of trajectories, together with principles such as unitarity and analyticity of the scattering amplitude. In this framework, it can make predictions of cross section values.

RFT can also explain hard QCD physics (handled by the DGLAP equation in other frameworks) with the introduction of hard pomeron diagrams. The mathematics becomes daunting..

Perturbative QDC Models

The basic block of hadronic Monte Carlo models is the

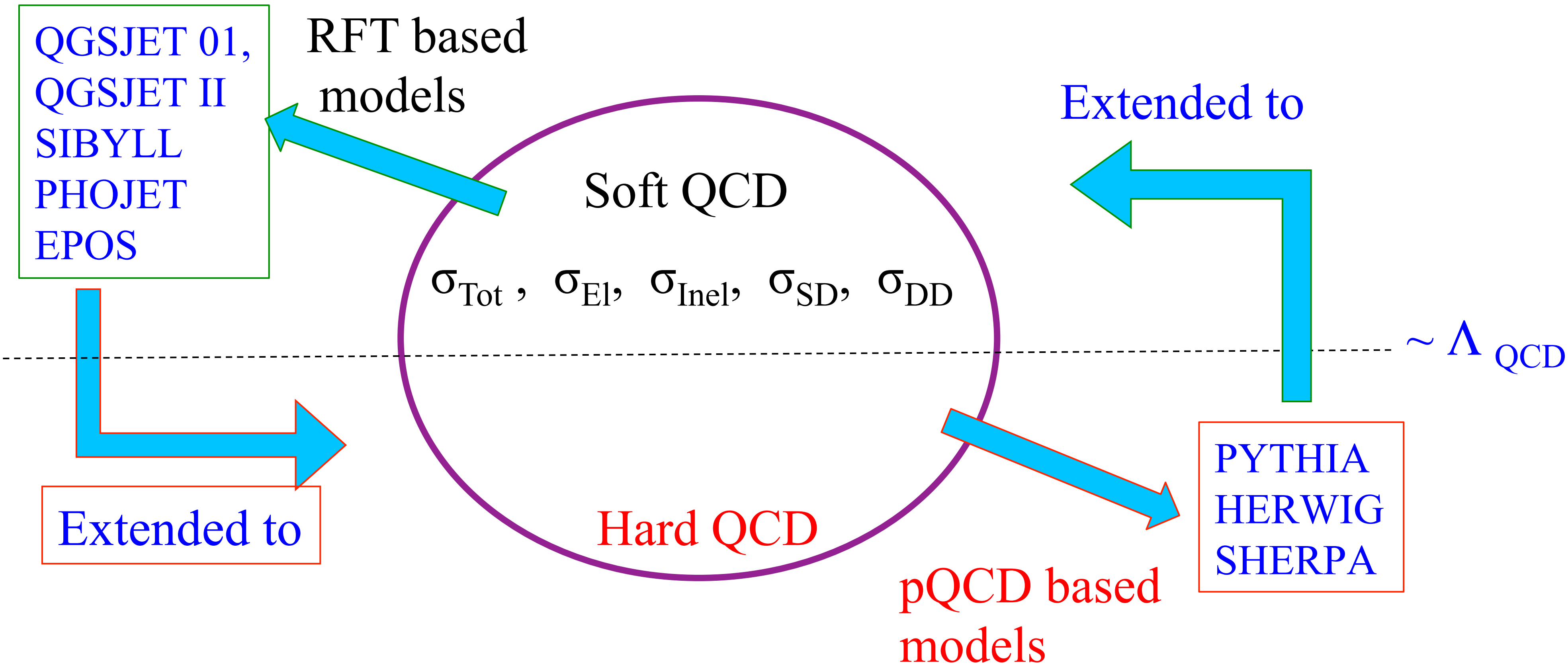
2➔2 pQCD matrix element

together with

ISR +FSR + PDF.

Soft QCD, diffraction and total cross sections are added by hand, using a chosen parameterization. They are not the main focus of these models.

Monte Carlo models: RFT vs. pQCD



Measuring the total cross section

TOTAL cross section means measuring everything…

We need to measure every kind of events, in the full rapidity range:

Elastic: two-particle final state, very low p_t, at very high rapidity.

➔ Very difficult, needs dedicated detectors near the beam

Diffractive: gaps everywhere.

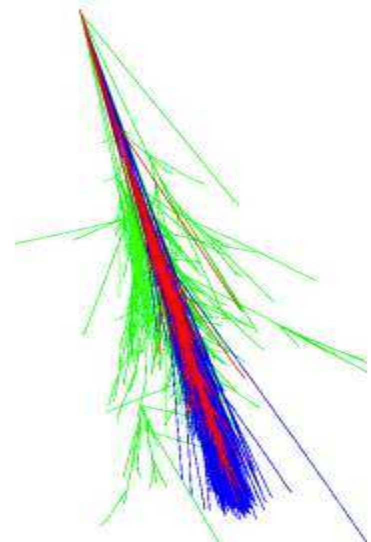
➔ Quite difficult, some events have very small mass, difficult to distinguish diffraction from standard QCD.

Everything else: jets, multi-particles, Higgs….

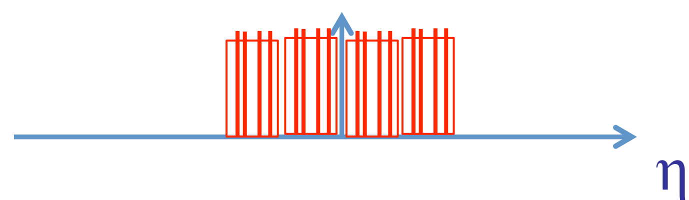
➔ Easy

Direct measurement of σ_{TOT}: cosmic-ray and collider experiments

In cosmic-ray experiments (AUGER just completed its analysis), the shower is seen from below. Using models, the value of σ_{inel} (p-air) is inferred, and then using a technique based on the Glauber method, σ_{inel} (pp) is evaluated.

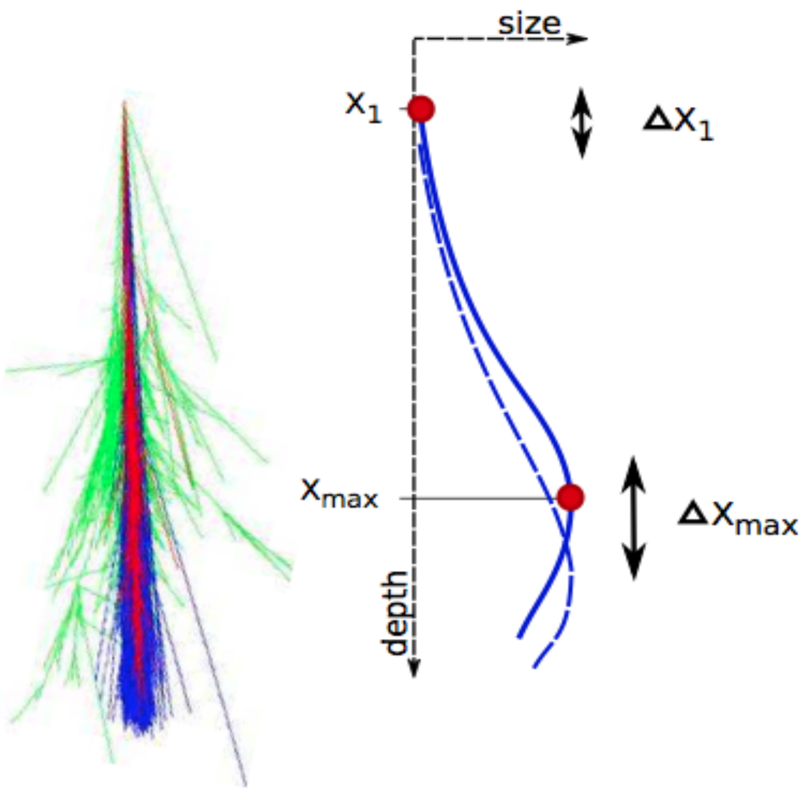


In collider experiments (currently ALICE, ATLAS, CMS, and TOTEM @ LHC), the detector covers a part of the possible rapidity space. The measurement is performed in that range, and then it might be extrapolated to $\sigma_{inel.}$



Cosmic-ray experiments: the method to measure σ_{inel}

- The path before interaction, X_1, is a function of the p-air cross section.
- The experiments measure the position of the maximum of the shower, Xmax
- Use MC models to related X_{max} to X_1, and then σ (p-air)



$$\frac{dp}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\text{RMS}(X_1) = \lambda_{int}$$

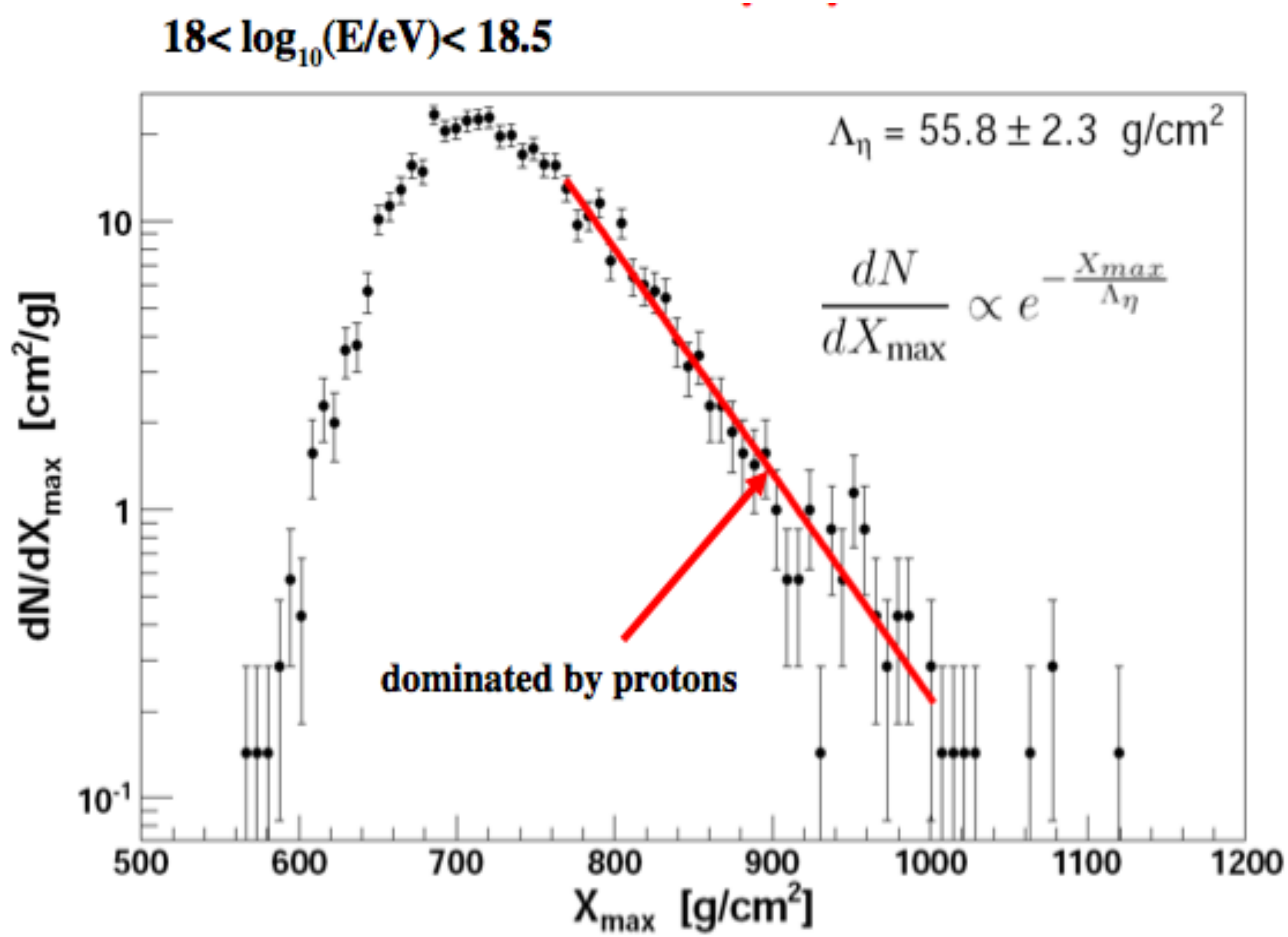
$$\sigma_{int} = \frac{<m_{air}>}{\lambda_{int}}$$

Difficulties:

- mass composition
- fluctuations in shower development
  RMS(X_1) ~ RMS($X_{max} - X_1$)
  ⇒ model needed for correction

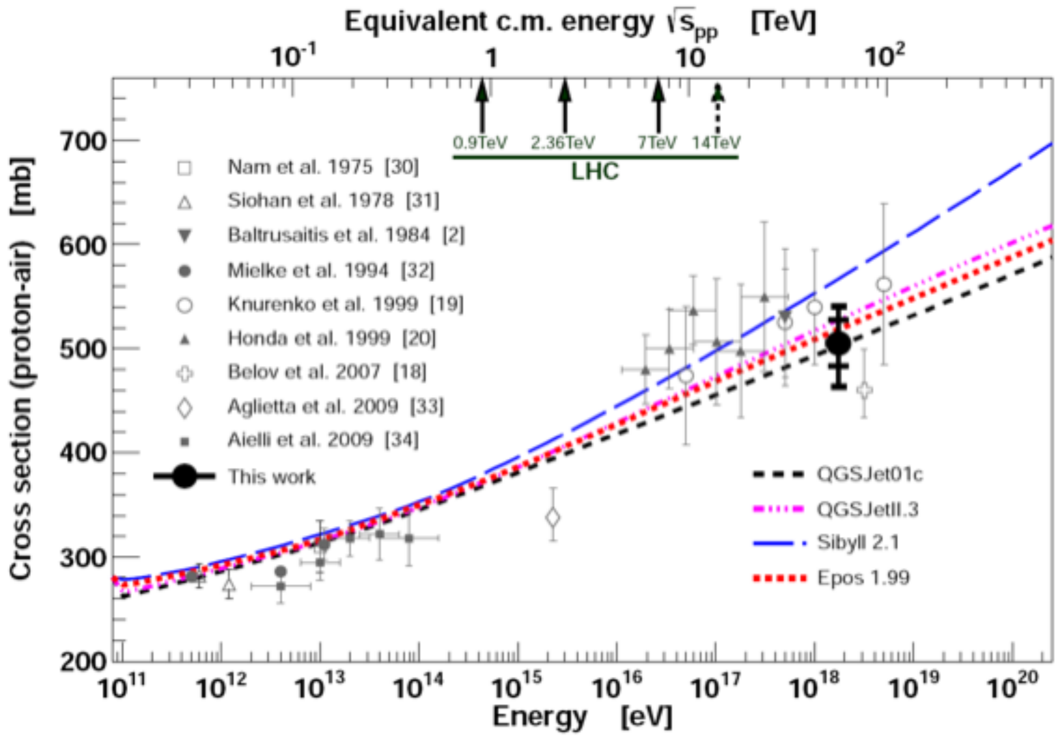
Auger: the measurement

The position of the air shower maximum, X_{max}, is sensitive to the cross section



The Pierre Auger Collaboration, Phys. Rev. Lett. 109, 062002 (2012)

Auger: p-air cross section



Energy well above the LHC measurements

Systematic Uncertainties

- **hadr. Models up to 19 mb**
- **energy scale 7 mb**
- **Λ_η systematics 15 mb**
- **conversion of Λ_η 7 mb**

$< E > \sim 1.7$ EeV $\sqrt{s} = 57$ TeV $\pm\ 0.3_{stat} \pm\ 6_{sys}$

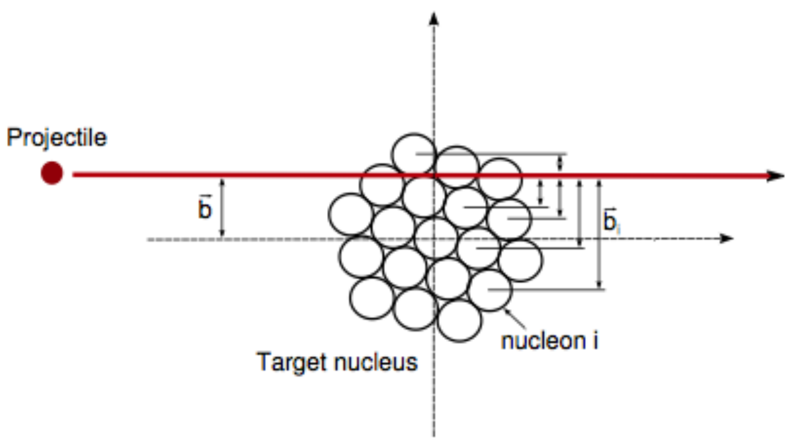
$$\sigma_{\text{p-air}} = (505 \pm 22_{\text{stat}}\ (^{+28}_{-36})_{\text{syst}})\ \text{mb}$$

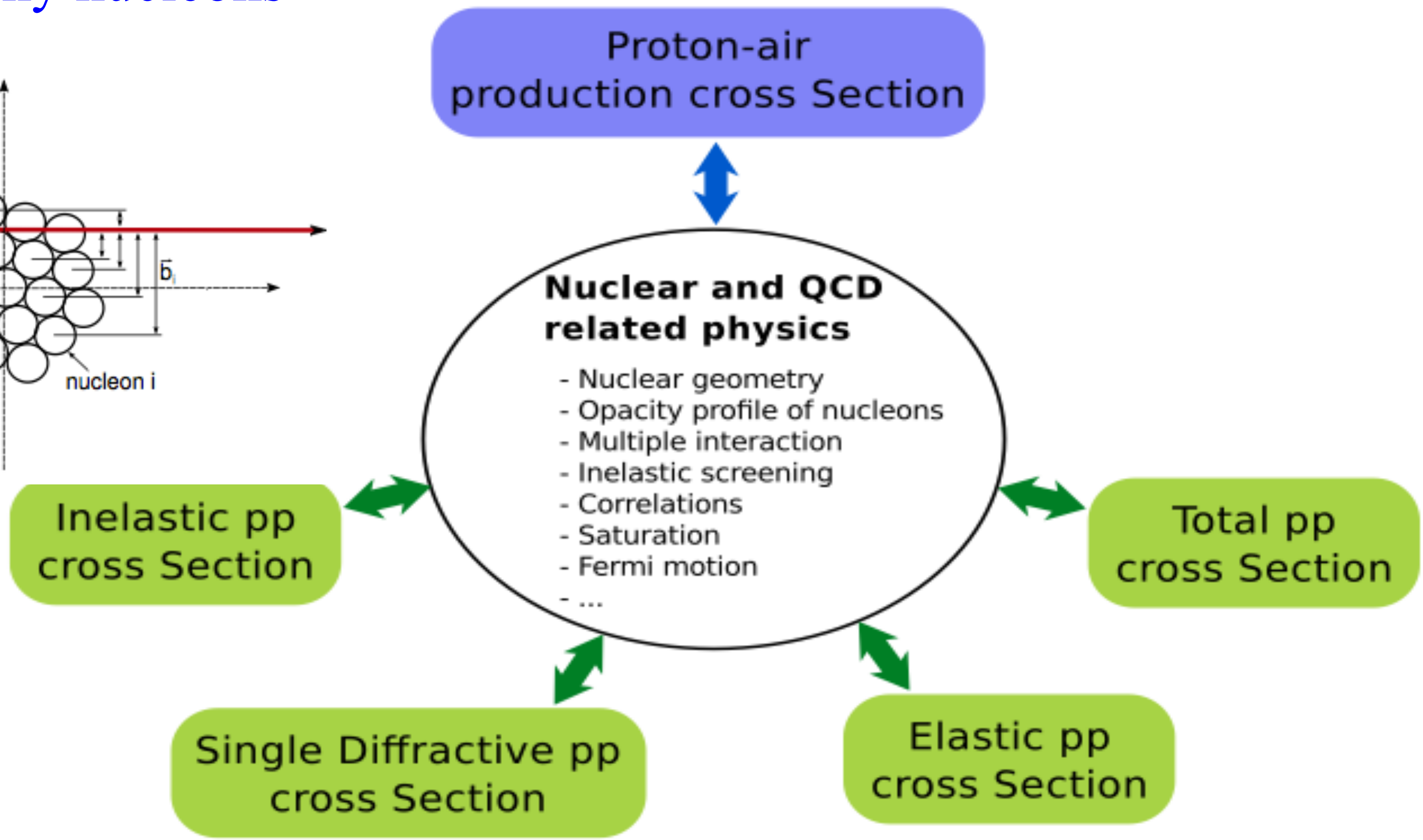
Additional Uncertainties due to diverse contaminations:

- photon fraction 0.5% +10 mb
- helium fraction 10% -12 mb
- **helium fraction 25% -30 mb**

The Glauber model

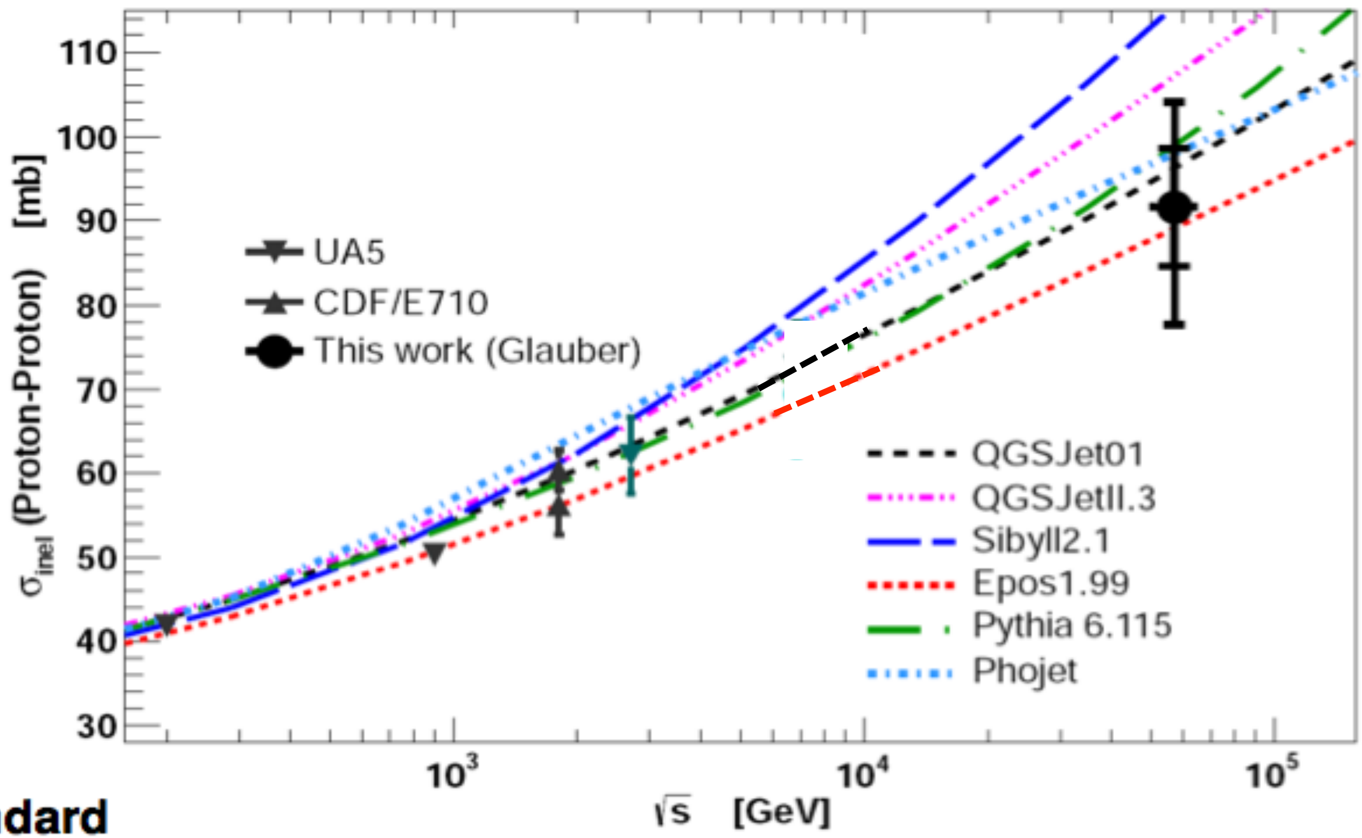
The p-air cross section is interpreted as the convolution of effects due to many nucleons





Auger: pp cross section

The Pierre Auger Collaboration, Phys. Rev. Lett. 109, 062002 (2012)



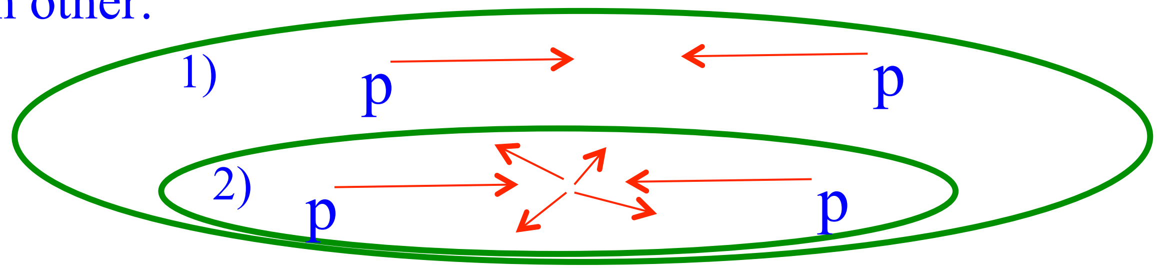
Using standard Glauber formalism

$$\sigma_{pp}^{inel} = [92 \pm 7(\mathrm{stat})\ ^{+9}_{-11}(\mathrm{sys}) \pm 7(\mathrm{Glauber})]\ \mathrm{mb}$$

$$\sigma_{pp}^{tot} = [133 \pm 13(\mathrm{stat})\ ^{+17}_{-20}(\mathrm{sys}) \pm 16(\mathrm{Glauber})]\ \mathrm{mb}$$

Collider experiments: measure σ_{inel} by counting number of events

The total inelastic proton-proton cross section is obtained by measuring the number of times opposite beams of protons hit each other:



1) Count the number of times (i.e. the luminosity, $\int L\,dt$) in which there could have been scattering, for example using beam monitors that signal the presence of both beams.
2) Measure the number of times there was a scattering, for example measuring a minimum energy deposition in the detector
3) Correct for detection efficiency ε
4) Correct for the possibility of having more than one scattering (pileup) Fpu.

$$\sigma_{Inel} = \frac{N_{Event} F_{pu}}{\varepsilon \int L\,dt}$$

This method works only at low luminosity

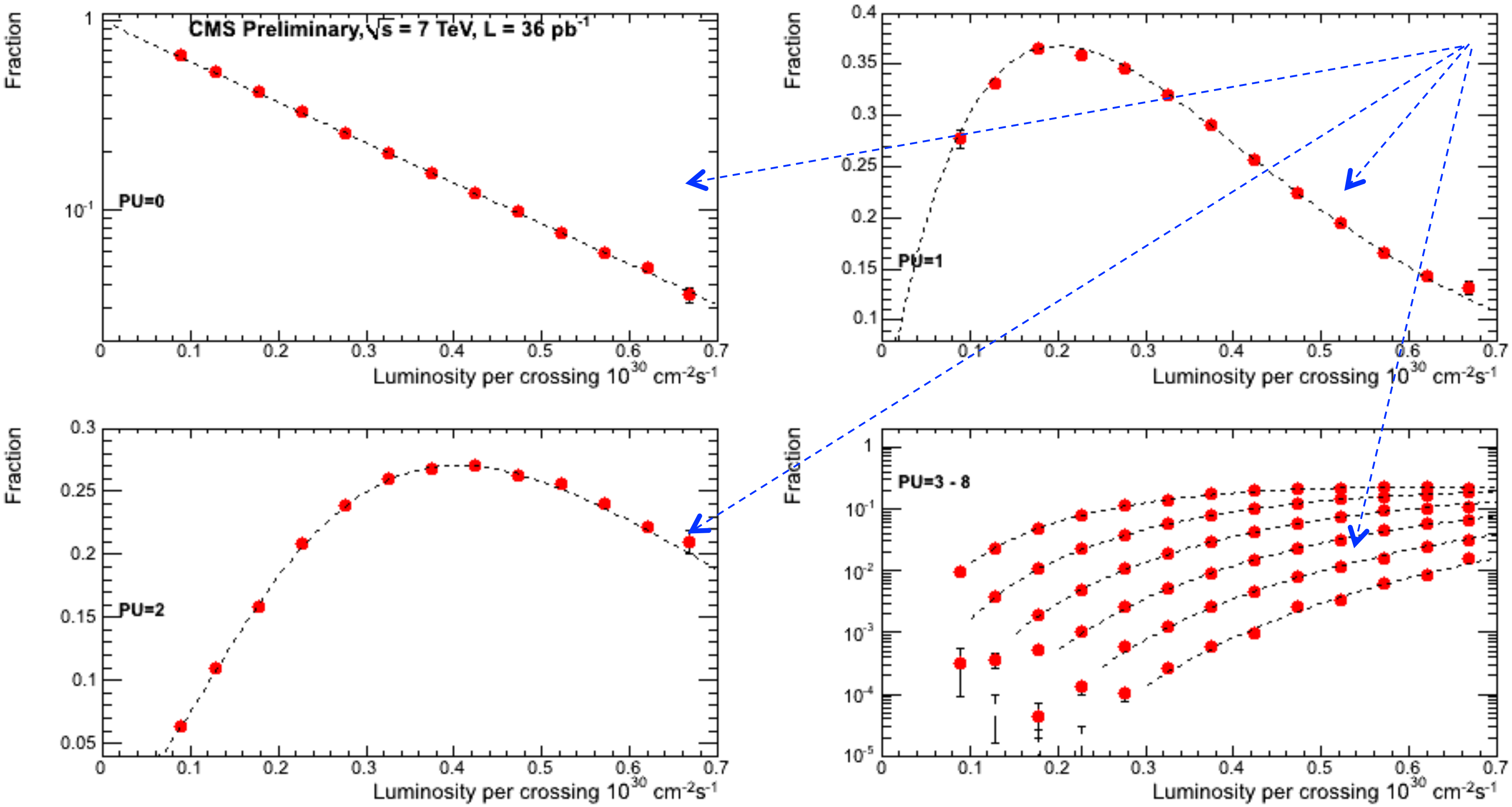
Collider experiments: measure σ_{inel} by counting number of vertexes

The probability of having $n_{vertexes}$ in a single bunch crossing follows Poisson statistics and it depends only on σ and luminosity.

$$P(n_{vertexes}) = \frac{(L\sigma)^{n_{vertexes}} e^{-(L\sigma)}}{n_{vertexes}!}$$

Medium luminosity method

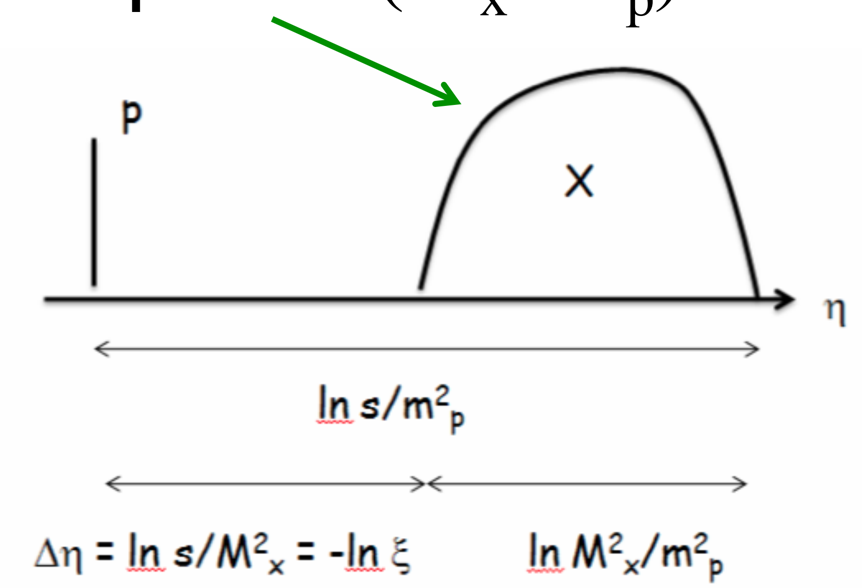
Fit to σ



Rapidity coverage and low mass states

The difficult part of the measurement is the detection of low mass states (M_x). A given mass M_x covers an interval of rapidity:

$$\Delta\eta = -\ln(M_x^2/m_p)$$



M_x [GeV]	$\Delta\eta$	$\xi = M_x^2/s$
3	2.2	$2\ 10^{-7}$
10	4.6	$2\ 10^{-6}$
20	6	$8\ 10^{-6}$
40	7.4	$3\ 10^{-5}$
100	9.2	$2\ 10^{-4}$
200	10.6	$8\ 10^{-4}$
7000	17.7	

$\xi = M_x^2/s$ characterizes the reach of a given measurement.

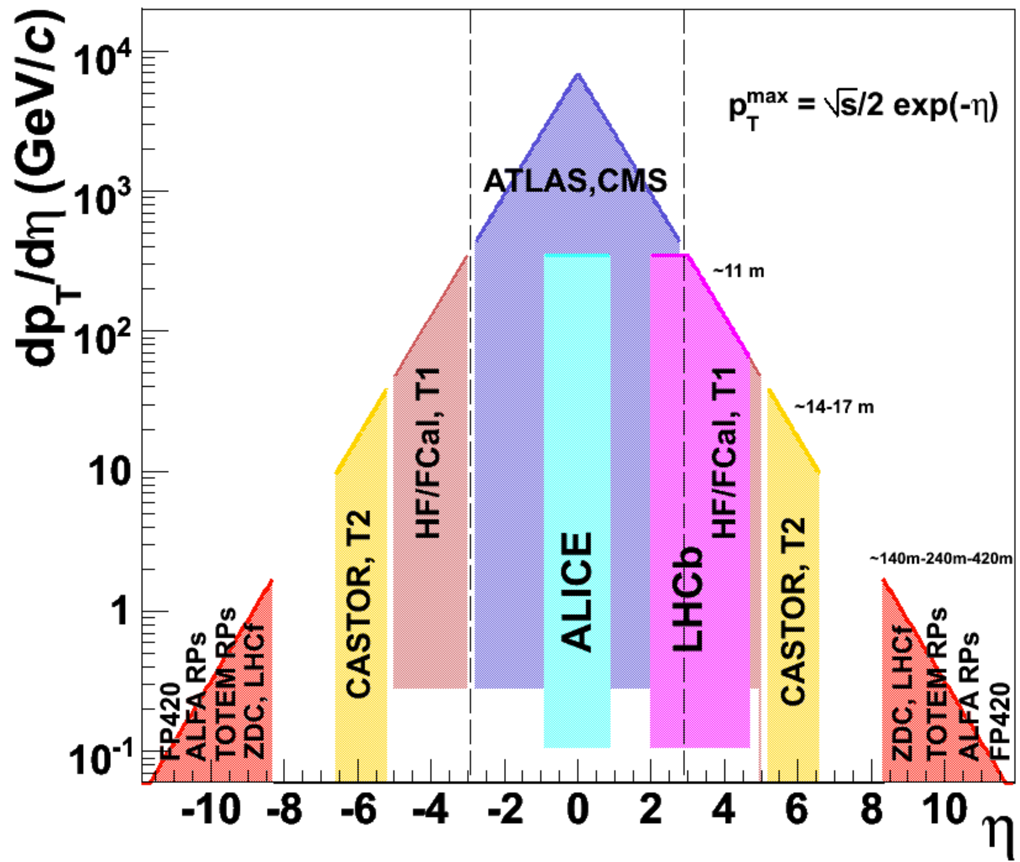
Experimental coverage of rapidity

ATLAS and CMS measure up to $\eta = +- 5$, which means they can reach values as low as $\xi > 5 * 10^{-6}$ (Mx ~ 17 GeV)

ALICE covers $-3.7 < \eta < 5.1$

TOTEM has two detectors:
T1: $3.1 < |\eta| < 4.7$, T2: $5.3 < |\eta| < 6.5$,
$\xi > 2 * 10^{-7}$ (Mx ~ 3.4 GeV)

LHC detectors coverage



Main problem:
from σ_{inel}^{vis} to the total value σ_{inel}

Solutions:

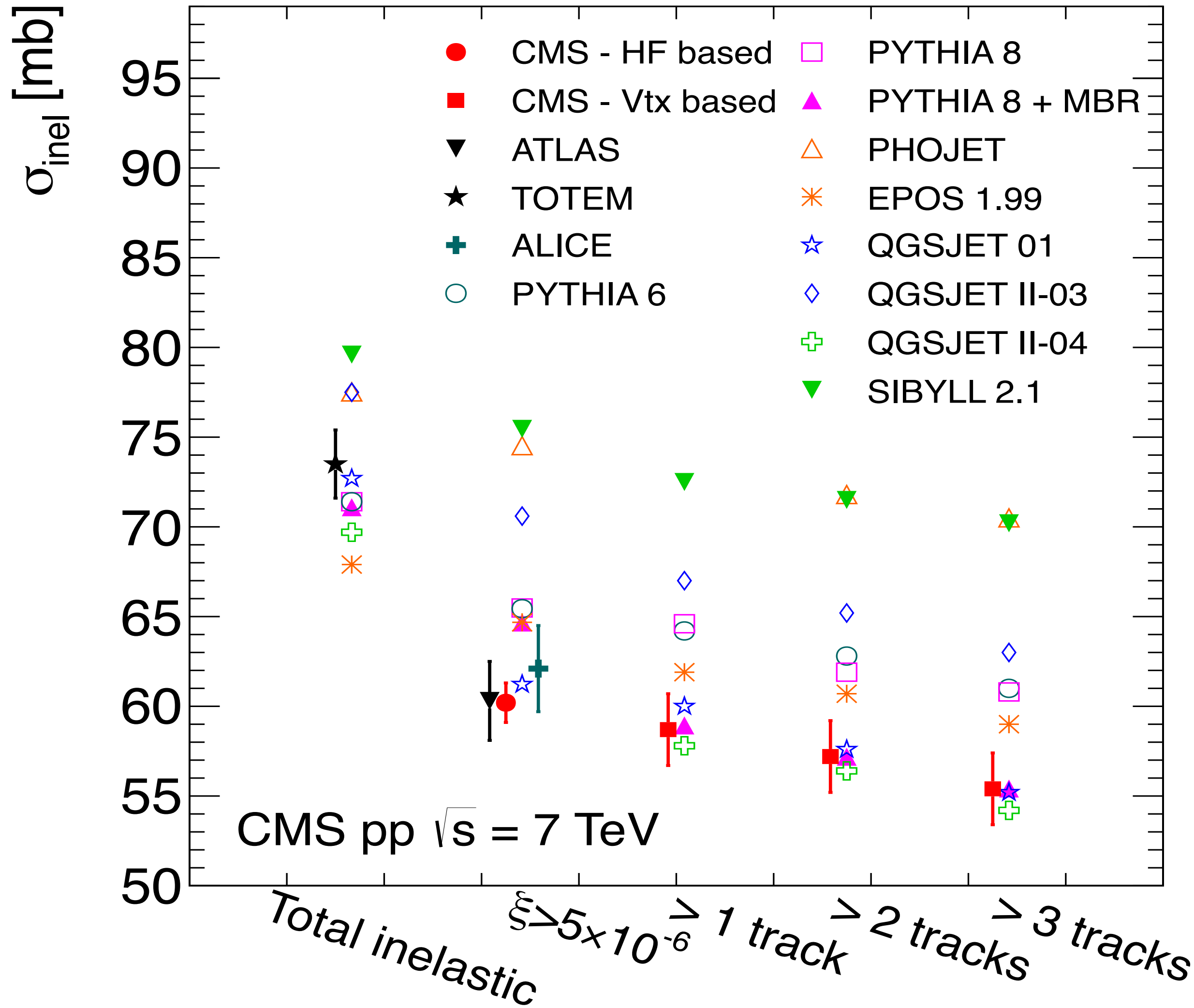
1) Don't do it
2) Put large error bars

σ_{inel} for specific final states

LHC experiments have also measured the cross section for specific final states.

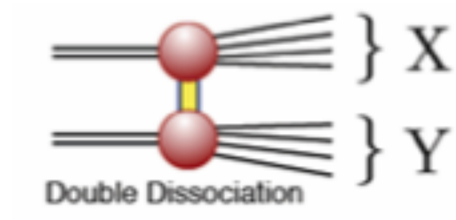
These results are really useful to distinguish the importance of the various processes that are making up σ_{tot}

Very few models predict concurrently the correct values of σ for the specific final states and σ_{Tot}



Experimental definition of diffraction

Experiments use "detector level" definition of diffraction. "Diffraction" is normally tagged by the presence of a gap ($\Delta\eta$ >2 – 3 units) in particles production



ATLAS:

DD-like events are events with both $\xi_{x,y} > 10^{-6}$, $\Delta\eta_{DD} > 3$

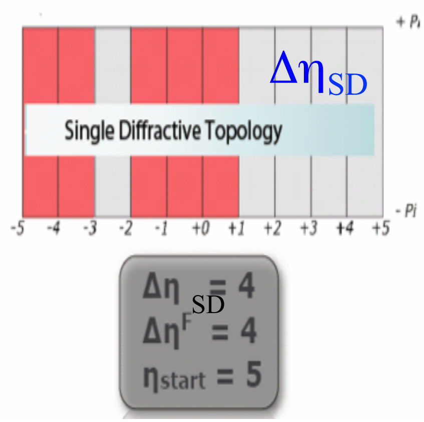
SD-like events are events with $\xi_x > 10^{-6}$ and $\xi_y < 10^{-6}$, $\Delta\eta_{SD} > 4$

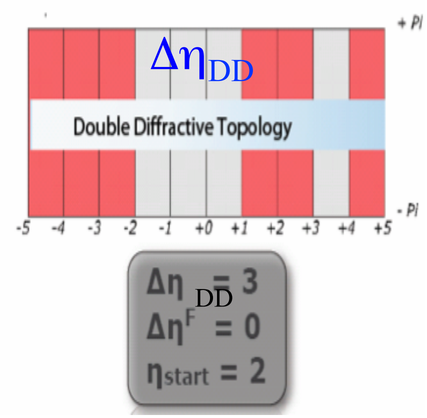
ATLAS measures the fraction of SD events, and the total fraction of events with gaps consistent with SD and DD topologies

ALICE:

SD events are events with $M_x < 200$ GeV/c^2

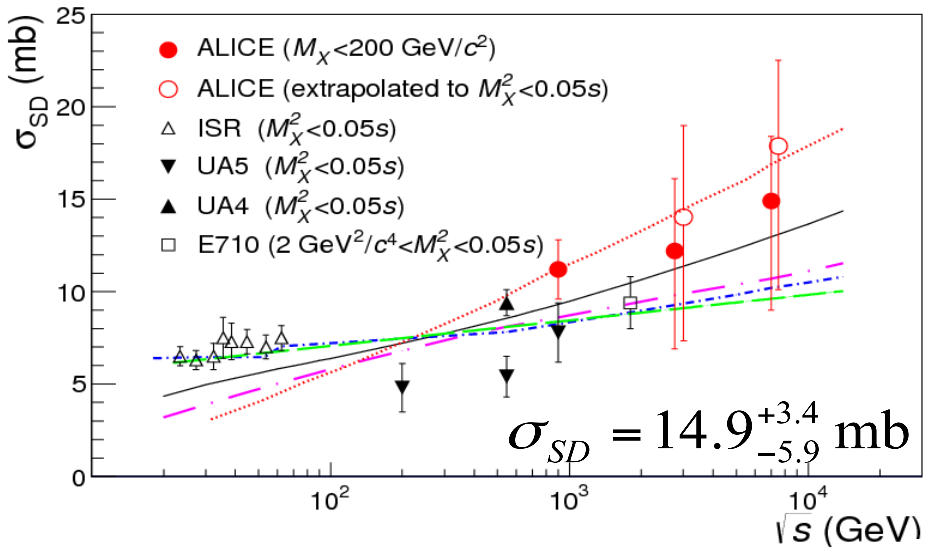
DD events are not SD, $\Delta\eta > 3$

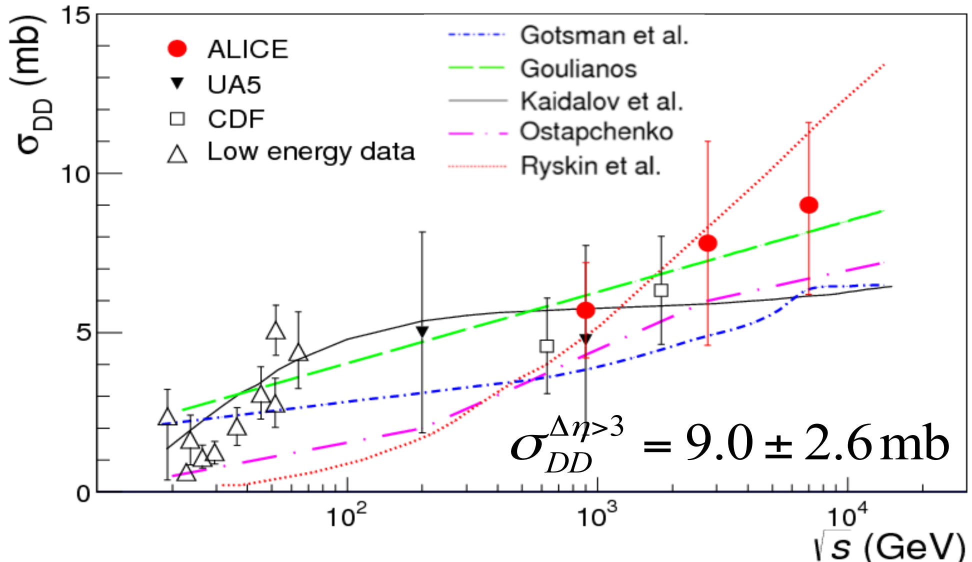




σ_{Inel} for specific processes: σ_{SD}, σ_{DD}

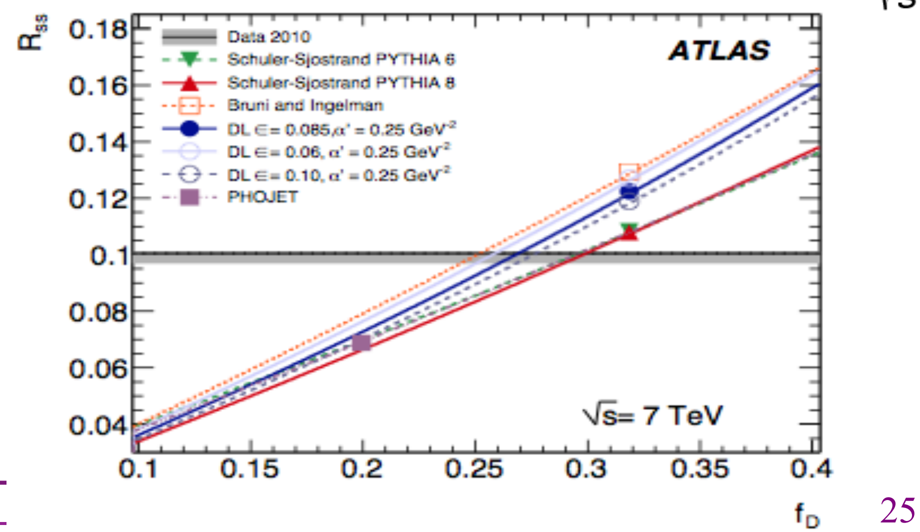
ALICE measured single (SD) and double diffractive (DD) cross-sections





ATLAS: $\sigma_{GAP}/\sigma_{Inel} \sim 0.1$

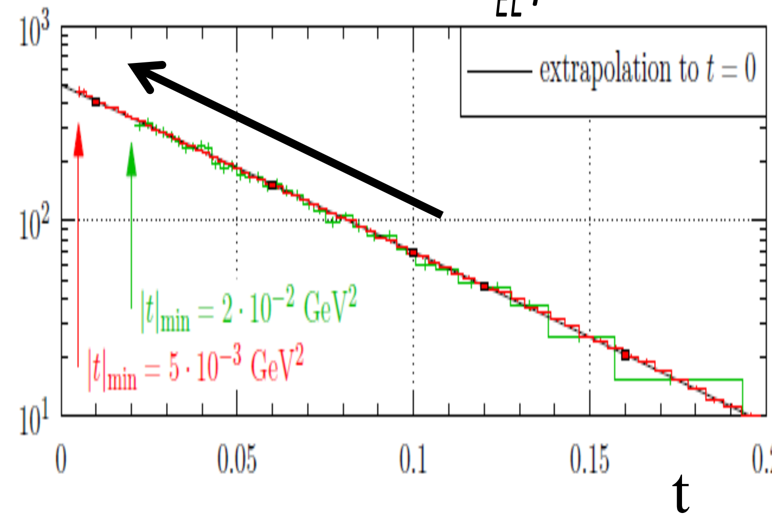
$f_D = (\sigma_{SD} + \sigma_{DD} + \sigma_{CD})/\sigma_{Inel} \sim 0.3$



A different way: σ_{TOT} measured via optical theorem

Optical theorem: elastic scattering at $p_t=0$ → σ_{TOT}

$d\sigma_{EL}/dt = Ae^{-B|t|}$



Optical Theorem: $$\sigma_{TOT}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$$

Using luminosity from CMS: $$\frac{d\sigma_{EL}}{dt} = \frac{1}{L} \cdot \frac{dN_{EL}}{dt}$$

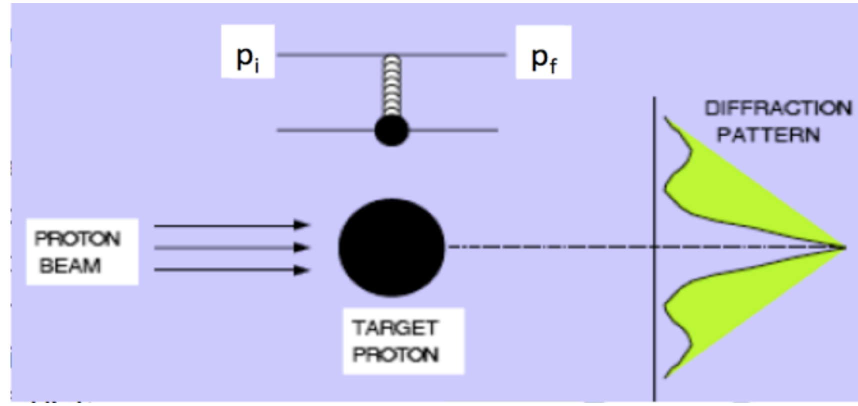
ρ from COMPETE fit: $$\rho = 0.14^{+0.01}_{-0.08}$$

$\rho = Re\,\mathrm{fel}|_{t=0} / Im\,\mathrm{fel}|_{t=0}$

$$\sigma_{TOT} = \sqrt{19.20\,\mathrm{mb\,GeV}^2 \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}}$$

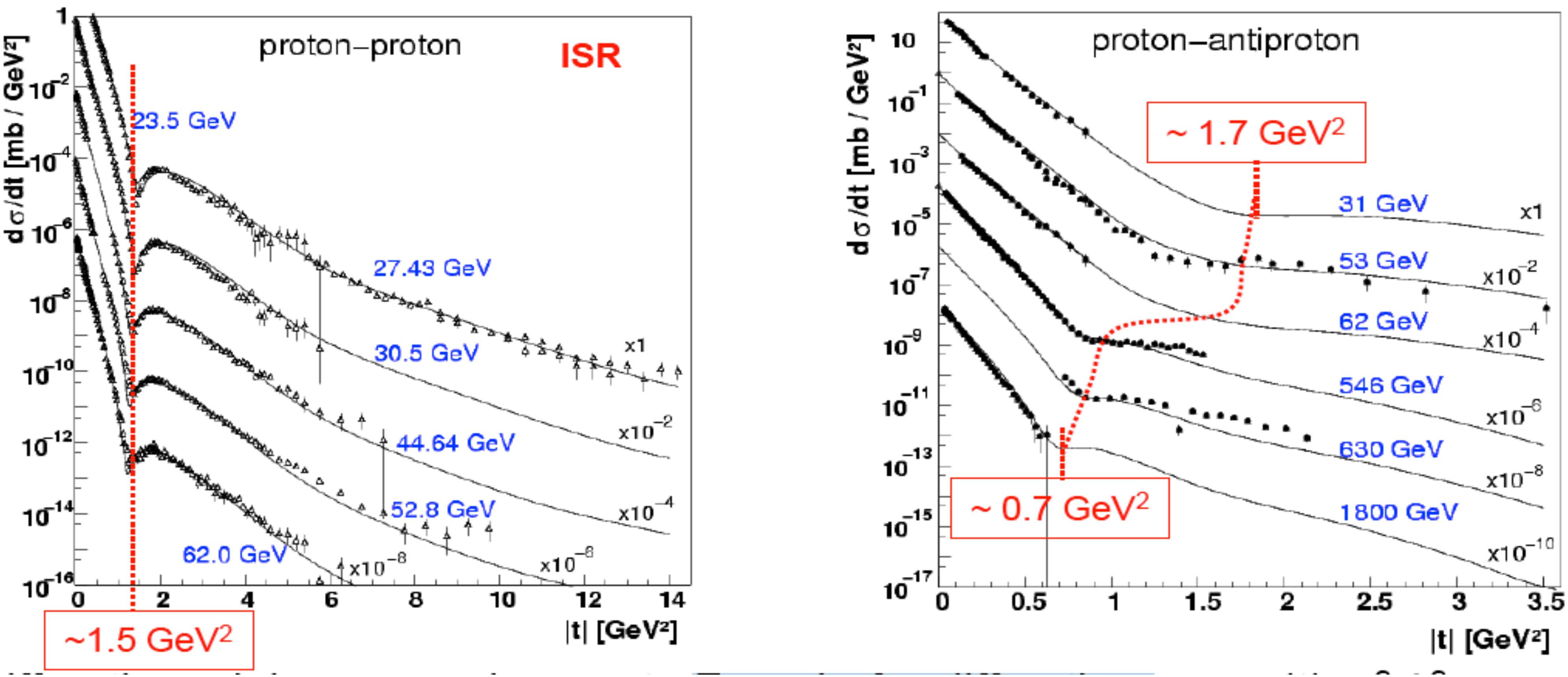
The art of elastic scattering: theory and detection

$$\frac{d\sigma_{EL}}{dt} = Ae^{-B|t|}$$



- At small t, elastic scattering is governed by an exponential law
- Shrinkage of the forward peak: exponential slope B at low |t| increases with √s, it gets steeper at higher energies.
- Dip moves to lower |t| as $1/\sigma_{tot}$
- At large t, data are energy independent: $d\sigma/dt = 0.09\ t^{-8}$

Elastic Scattering data



Shrinkage of forward peak: steeper, and dip moves to lower energy

TOTEM: pp cross section at LHC

Elastic cross section:

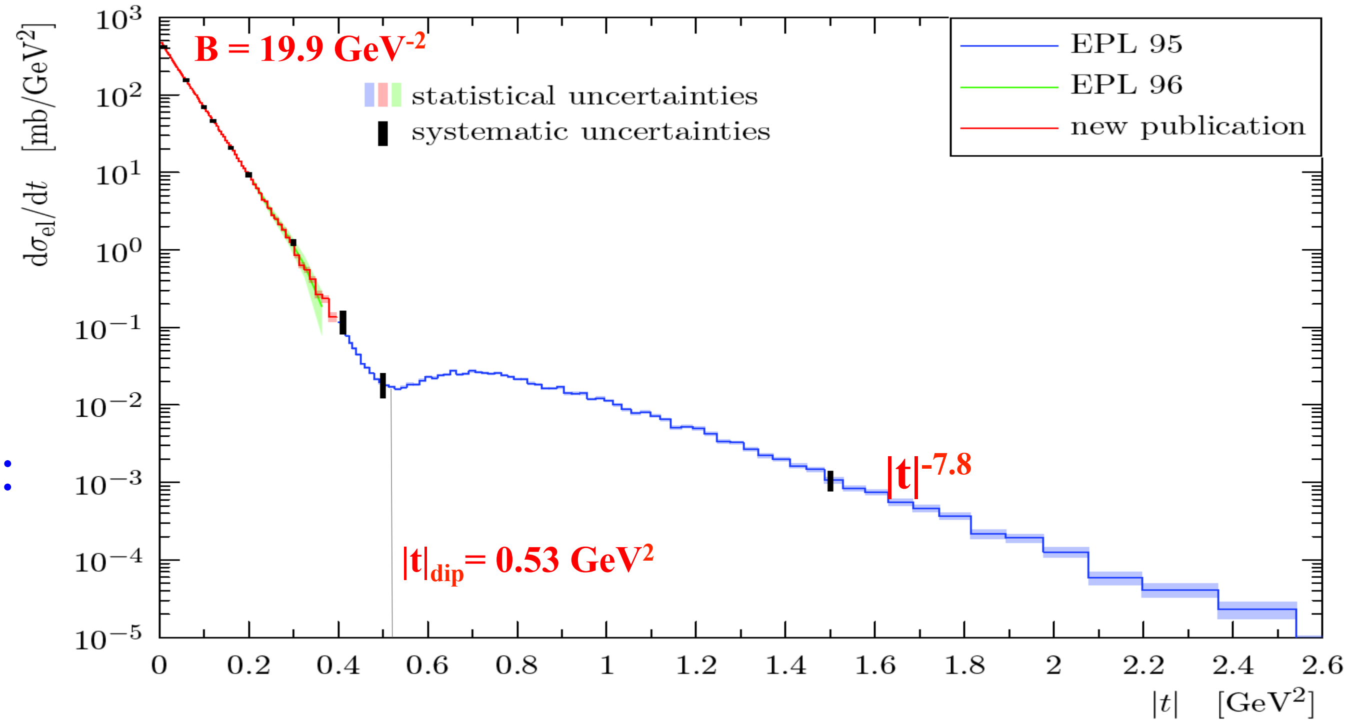
$\sigma_{el=}$ 25.4±1.1 mb

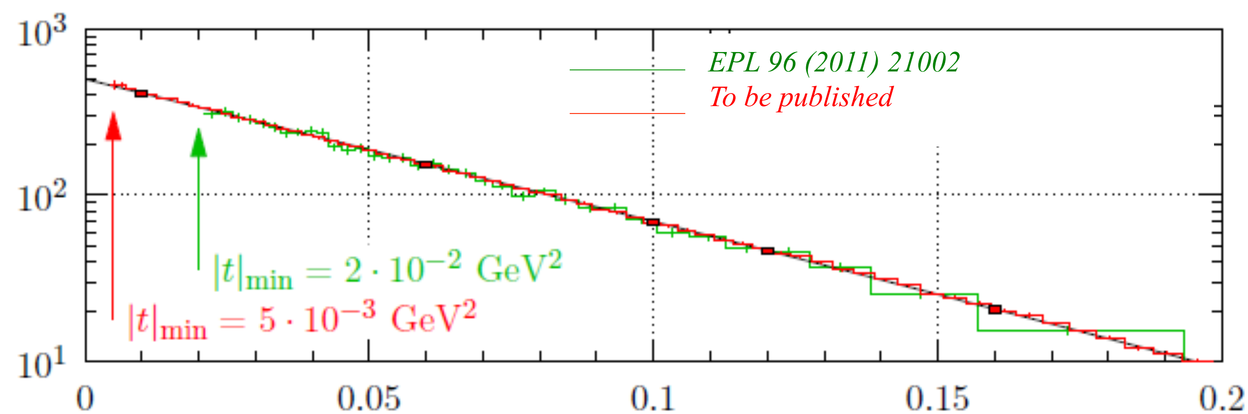
Using the optical theorem:

σ_{TOT} = 98.6 mb ± 2.2 mb

And then: $\sigma_{inel} = \sigma_{TOT} - \sigma_{el}$

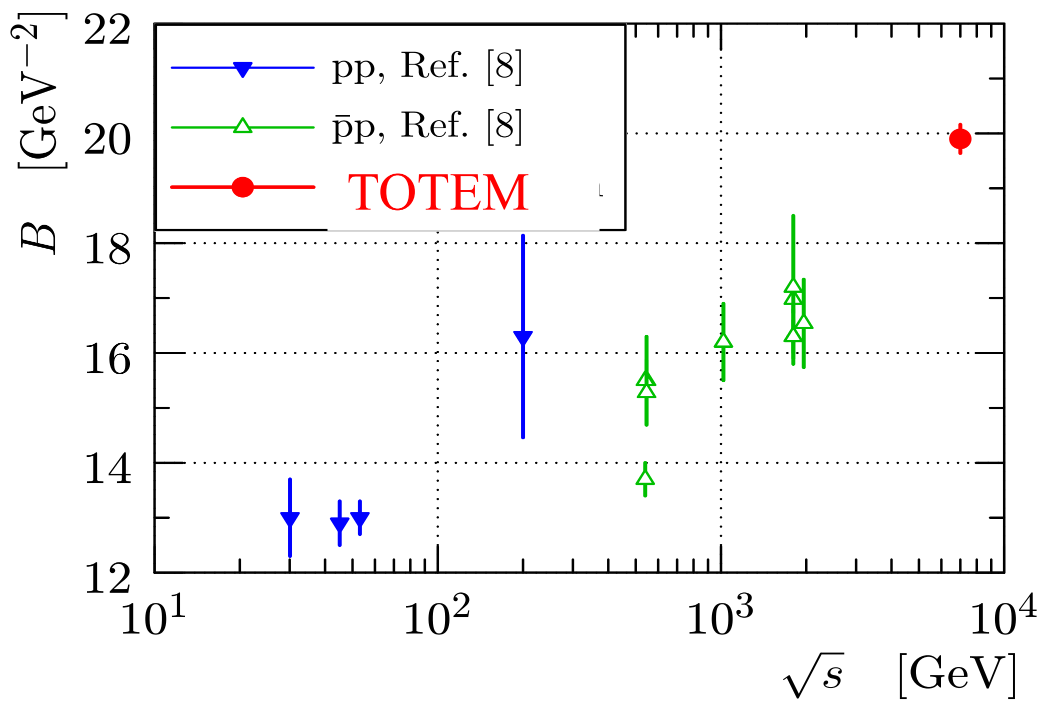
σ_{inel} = 73.1 mb ± 1.3 mb



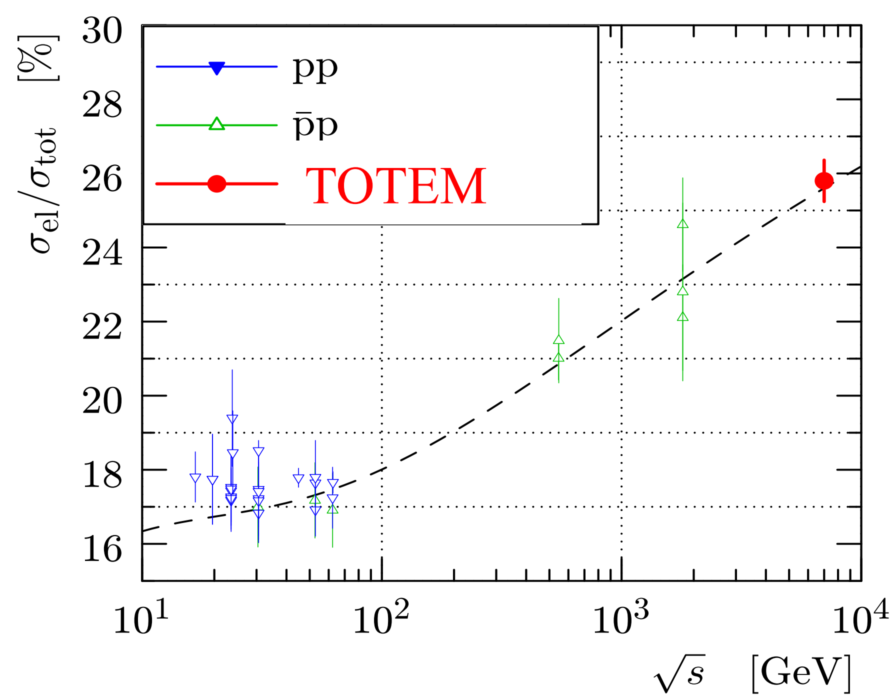


TOTEM: Shrinkage and $\sigma_{el} / \sigma_{tot}$

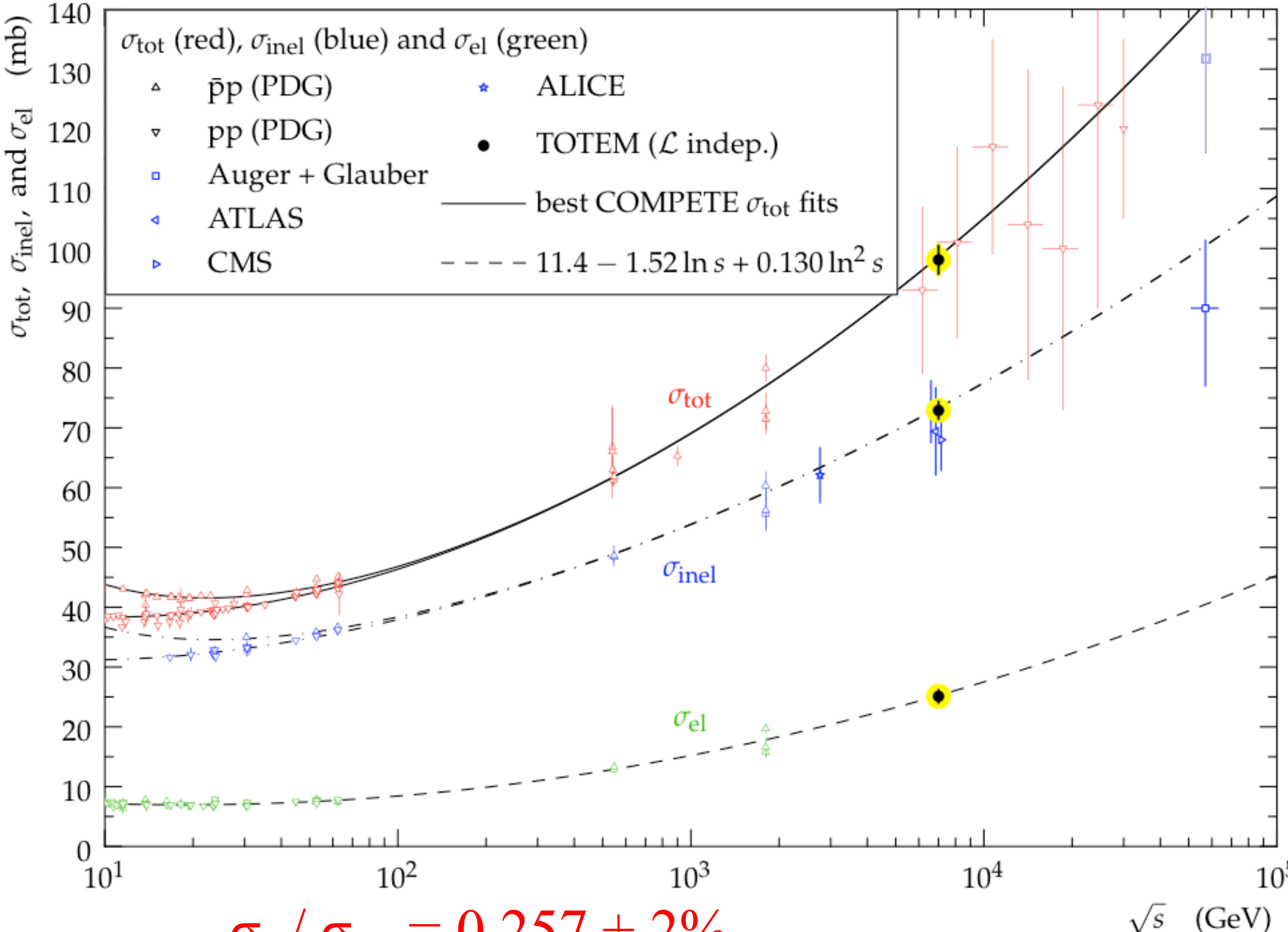
The shrinkage of the forward peak continues…



The elastic component is becoming more important with energy



σ_{tot}, σ_{inel}, and σ_{el}



$\sigma_{el}/\sigma_{tot} = 0.257 \pm 2\%$

$\sigma_{el}/\sigma_{inel} = 0.354 \pm 2.6\%$

Summary and outlook

The study of the total cross section and its components is very active.

A large set of new results have been presented in the last year:

σ_{Tot}(7 TeV) , σ_{El}(7 TeV) , σ_{Ine}(7 TeV) , σ_{SD}(7 TeV) , σ_{DD}(7 TeV)

B slope and dip position of elastic scattering at 7 TeV

σ_{Tot}(57 TeV) , σ_{Inel}(57 TeV)

LHC data at 7 TeV, together with cosmic-ray results, are becoming more and more precise, and they are constraining the available models.

A very interesting contact is happening: measurements at LHC detectors are used to constrain cosmic-ray models, as finally collider energies are high enough

Extra

Reference

1. Several talks from the TOTEM home page: http://totem.web.cern.ch/Totem/conferences/conf_tab2012.html
2. Donnachie & Landshoff: http://arxiv.org/abs/0709.0395v1
3. AUGER: http://lanl.arxiv.org/abs/1208.1520v2
4. ALICE results, ISVHECRI 2012, Berlin, August 2012
5. D'Enteria et al, Constraints from the first LHC data on hadronic event generators for ultra-high energy cosmic-ray physics
6. ATLAS http://arxiv.org/abs/1104.0326v1

RFT vs pQCD

The measurements are compared to several models.

1) Models developed to simulate high pt events: PYTHIA, HERWIG, and SHERPA. These models make precise predictions for calculable, high pt, processes, but they don't address soft physics with the same precision.
2) Cosmic-ray interaction models such as QGSJET 01, QGSJET II and SIBYLL. They contain sophisticated models of soft particle production and of relation total, elastic and inelastic cross sections to particle production.
3) Mixed models, such as PHOJET – DPMJET and EPOS propose a fix set of parameters, and should be able to fit collider and cosmic-ray results.

A very interesting contact is happening: measurements at LHC detectors are used to constrain cosmic-ray models, as finally collider energies are high enough

Pomerone exchange - Diffractive scattering

The mathematics to study pomeron exchange is quite complicated and it's similar to that used in optics.

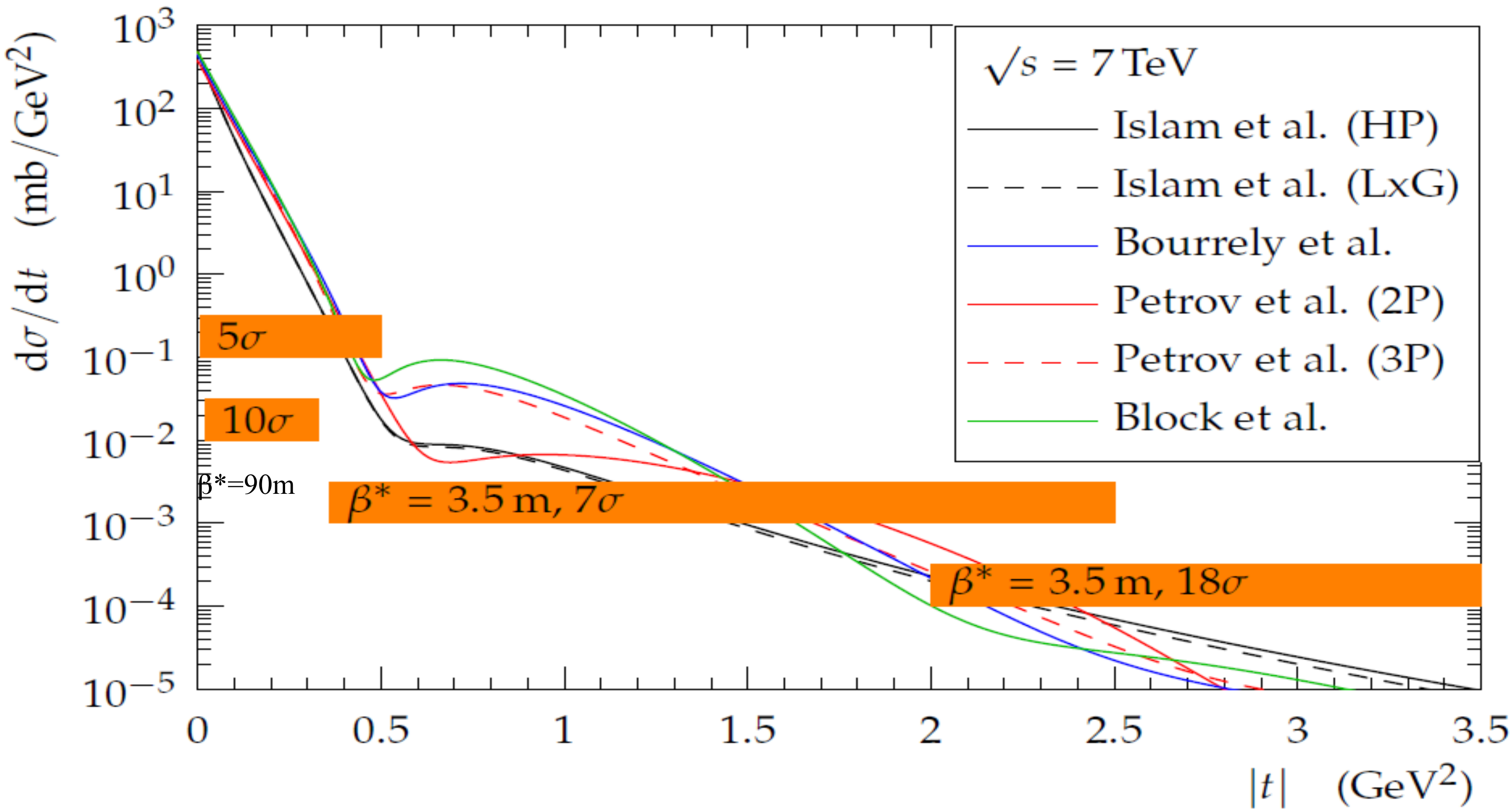
It leads to prediction of elastic scattering differential cross sections with an optic-like diffractive patters.

Pomeron exchange (colour singlet exchange) leads to the formation of large gap in rapidity distribution of final state particles, as the gap width is not suppressed as a function of the gap size:

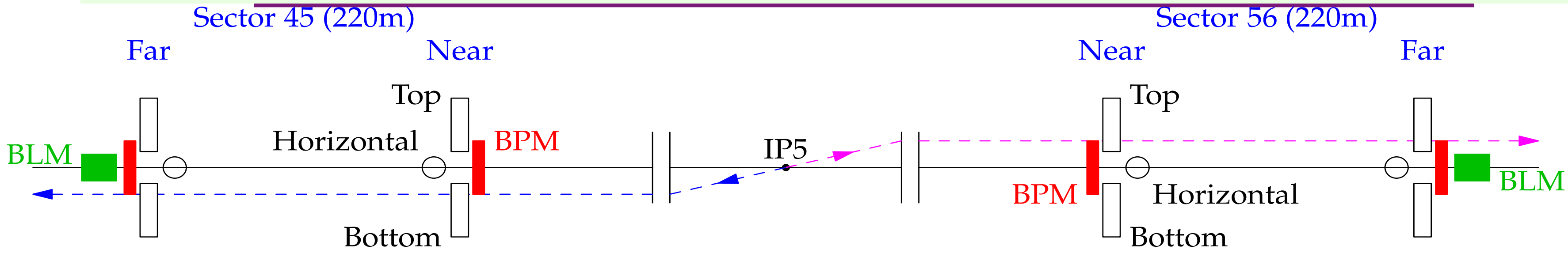
$$\Delta \eta \sim e^{(1.-\alpha(0))}$$

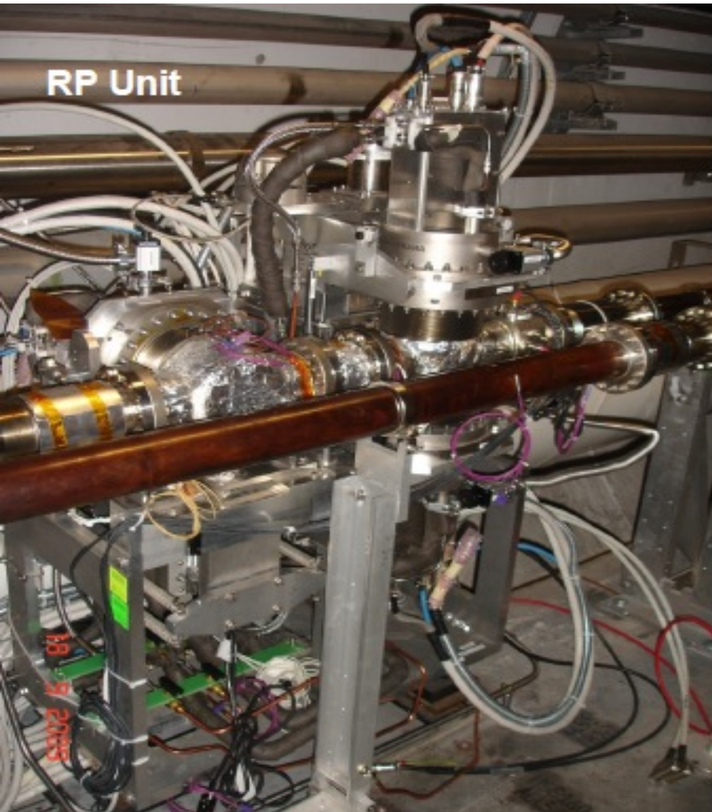
The LHC march toward t = 0

Low values of t are reached by changing the LHC parameters β*



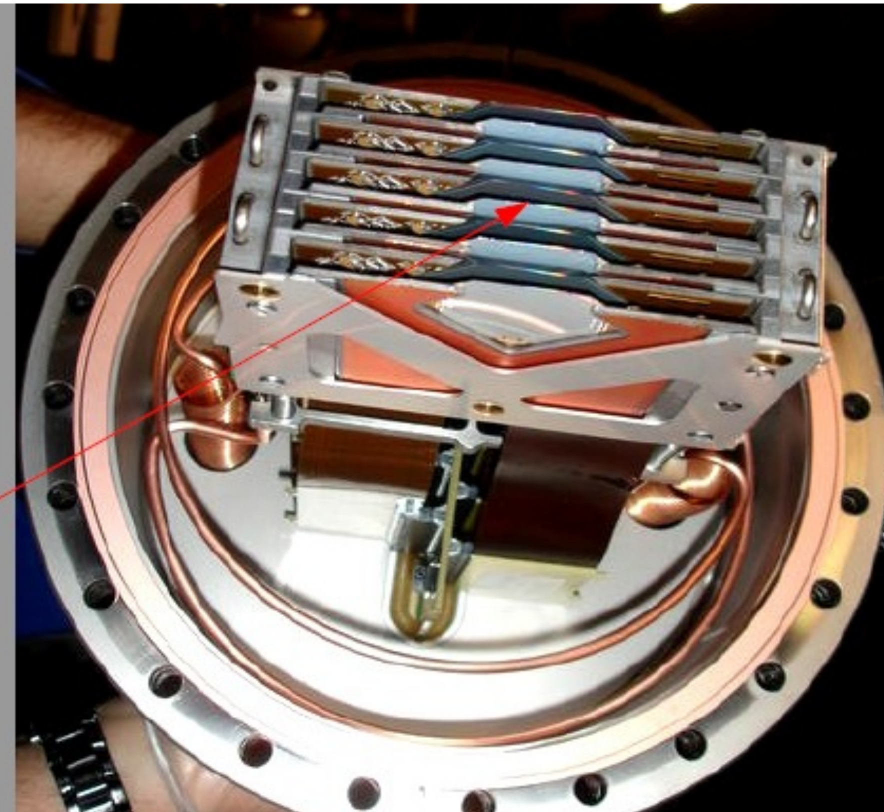
The TOTEM Roman Pot System at 220 m





4 Stations
→ 2 Units
→ 3 pots
1 BPM
(Beam Position Monitor)

Edgeless Silicon Detectors



A short summary..

Total cross section raises with energy.

This behavior is parameterized using "Regge Theory", with 3 trajectories: softPomeron, hardPomeron, and Reggeon:

$$\sigma_{TOT}(s) = \alpha\, s^{0.08} + \gamma\, s^{0.4} + \beta\, s^{-0.5}$$

The total cross section is understood as a sum of components:

Elastic + diffractive + everything else.

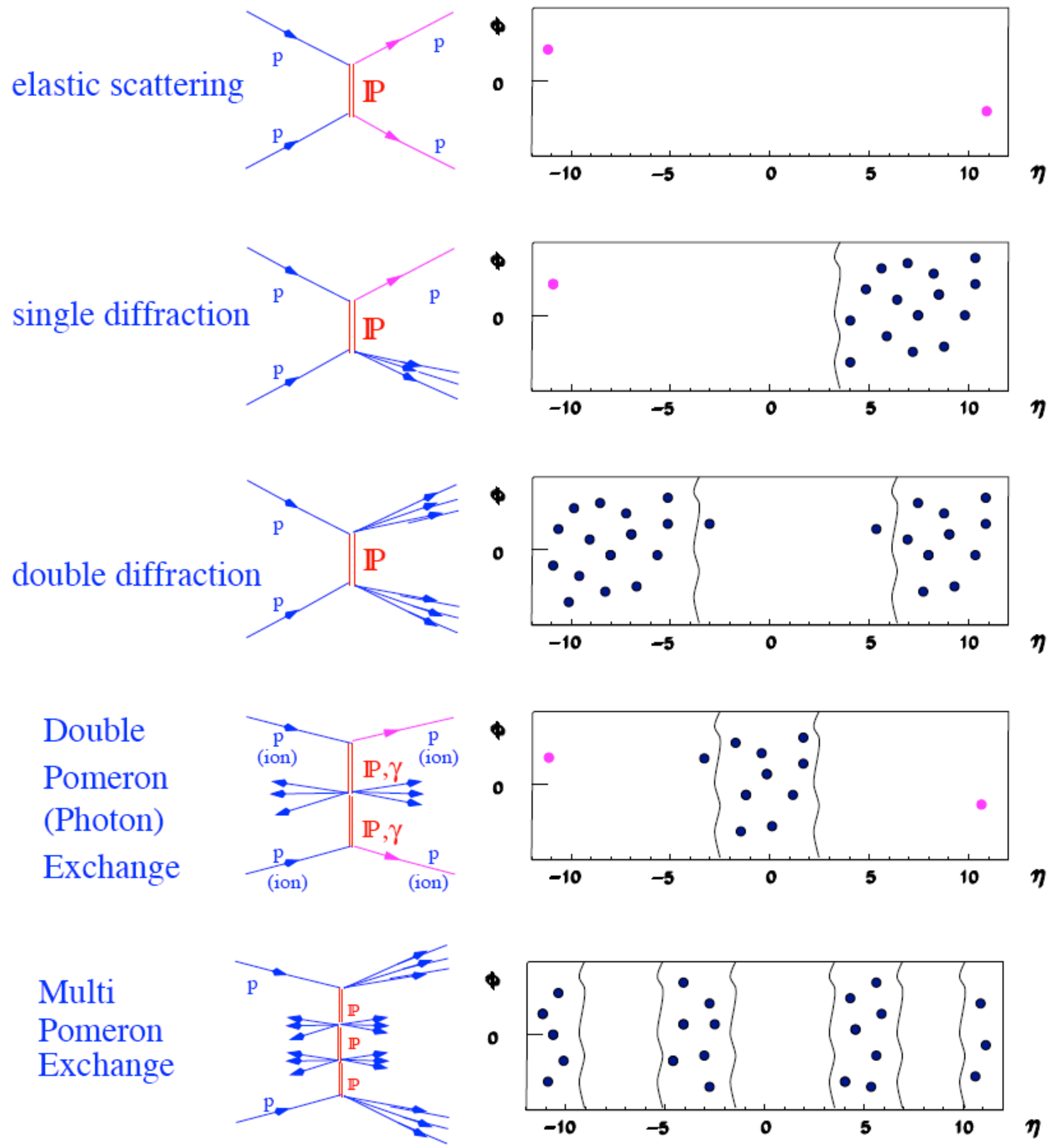
The "RFT" and the "pQCD" models will help in understanding what is going on..

The difficult part: pomeron exchange

Pomeron exchange is a synonym of colour singlet exchange

Importance of diffractive component

➔ Very low mass



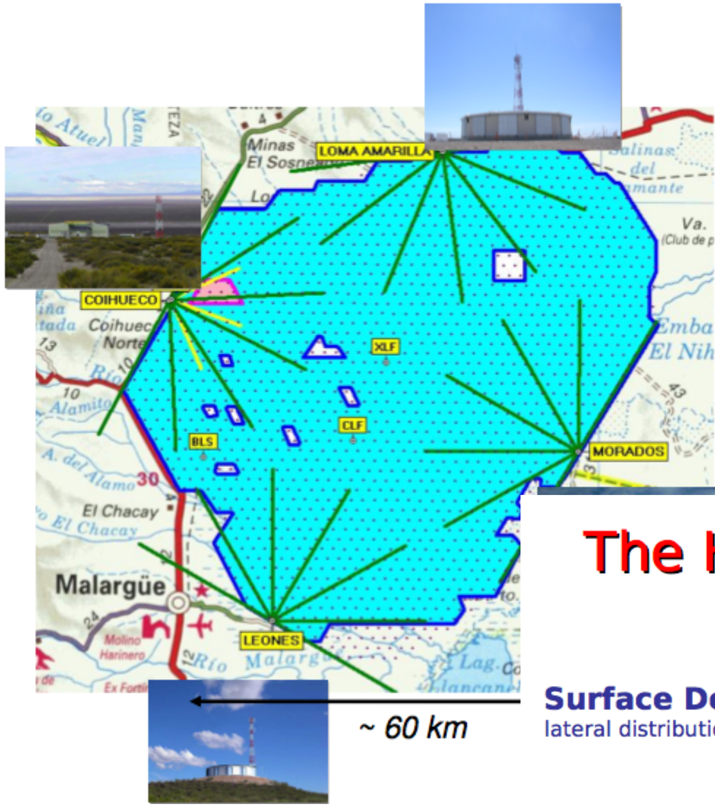
The Pierre Auger Observatory

- ***Surface detector***
an array of 1660 Cherenkov stations on a 1.5 km hexagonal grid (~ 3000 km²)

- ***Fluorescence detector***
4+1 buildings overlooking the array (24+3 telescopes)

Low energy extensions

AMIGA: dense array plus muon detectors
HEAT: three further high elevation FD telescopes



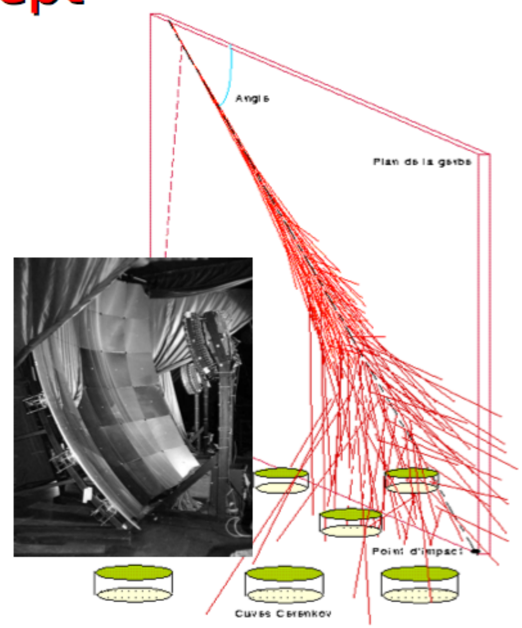
The Hybrid Concept

Surface Detector Array
lateral distribution, 100% duty cycle

Air Fluorescence Detectors
Longitudinal profile, calorimetric energy measurement, ~15% duty cycle

accurate energy and direction measurement

mass composition studies in a complementary way



Extrapolation at t = 0

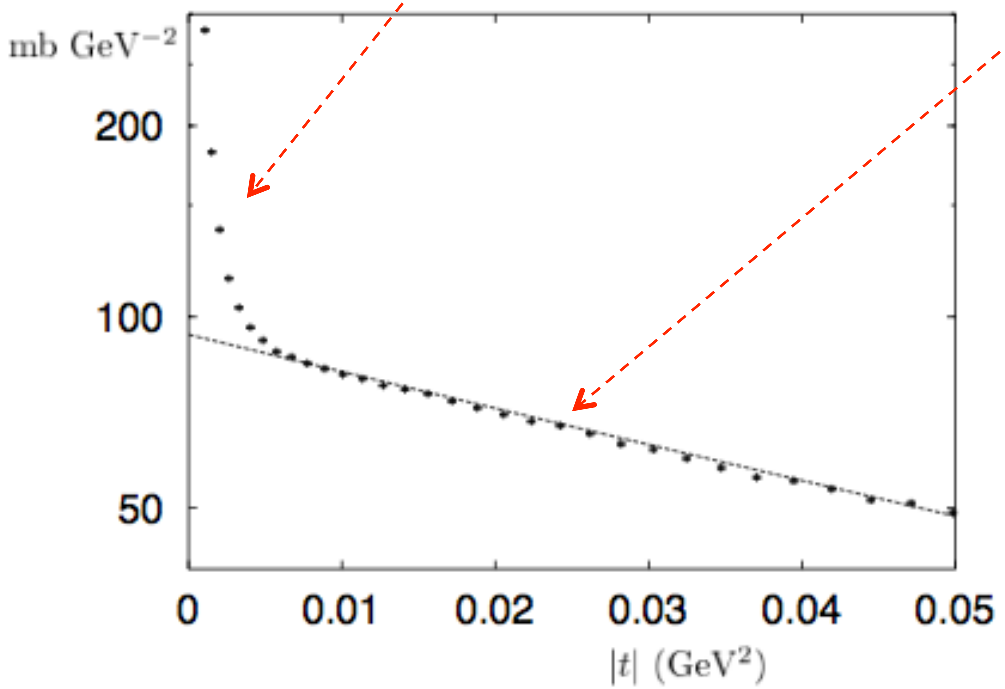
The t slope changes as a function of t value.

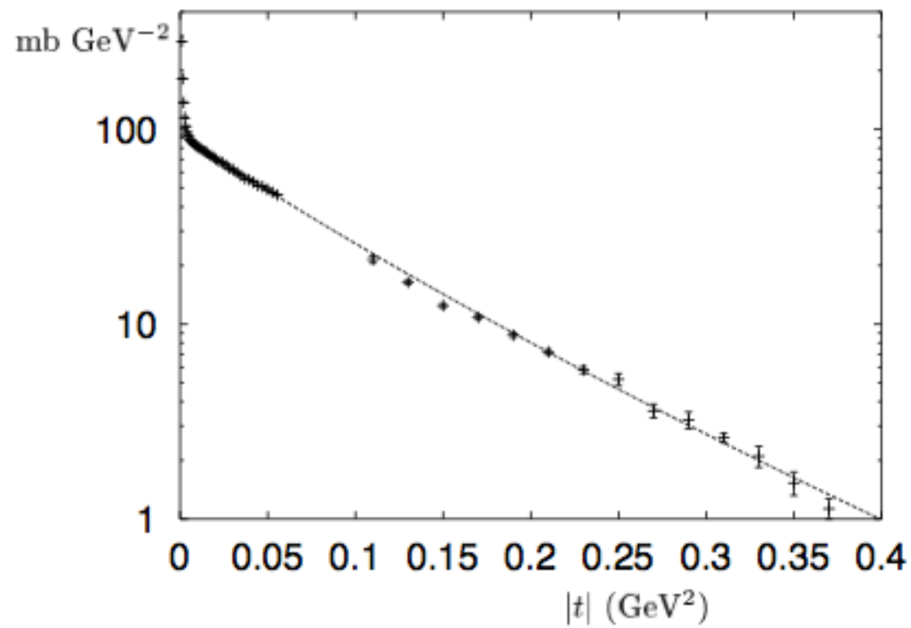
Let's consider the data at √(s) = 53 GeV.

Do no use: Coulomb part

We need to measure this part

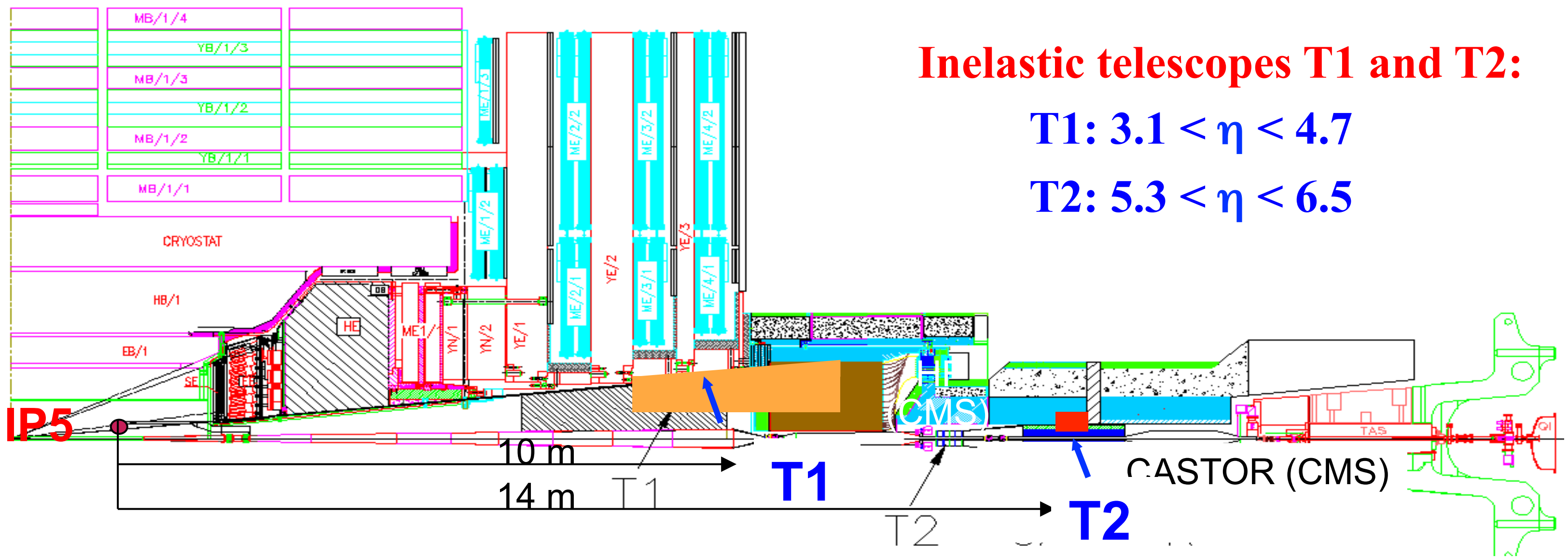
$$\sigma^2_{tot} = \frac{16\pi}{(1+\rho^2)}\frac{1}{\mathcal{L}}\left(\frac{dN_{el}}{dt}\right)_{t=0}$$





TOTEM at LHC

CMS



Inelastic telescopes T1 and T2:

T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$

24 Roman Pots in the LHC tunnel on both sides of IP5

measure elastic & diffractive protons close to outgoing beam