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

A) One (out of several) theoretical framework

B) Topologies of events in σ_{tot}

C) Direct measurement of σ_{inel}:

1) cosmic-ray experiments
2) collider experiments

D) The art of elastic scattering

E) Results: $\sigma_{Tot,}$ $\sigma_{SD,}$ σ_{DD}

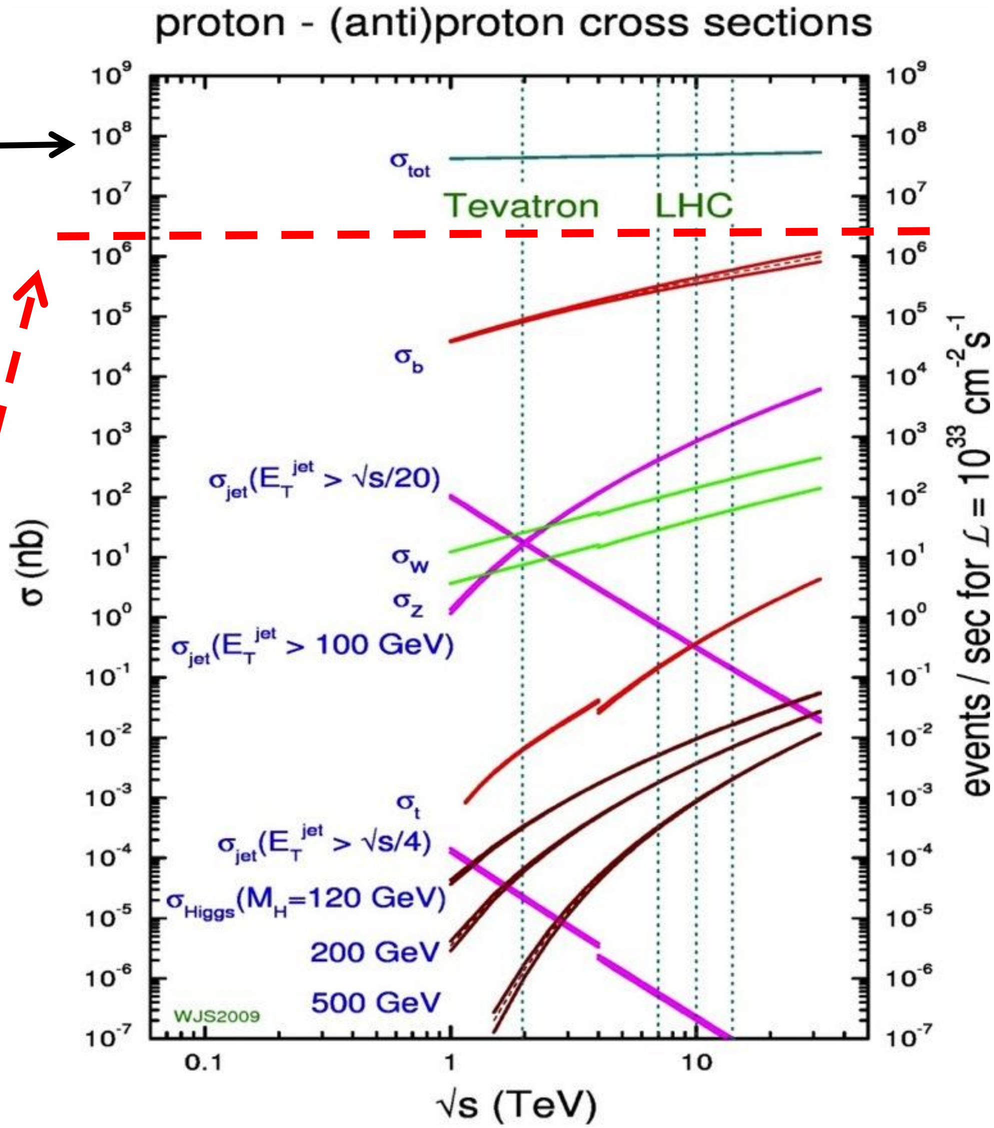
F) Implication of the new results

Let's set the scale…

The total cross section is dominated by soft processes.

100 mb

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

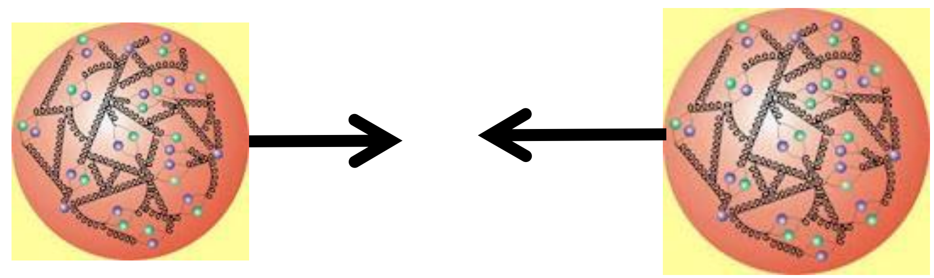


If $R_1 = R_2 = 10^{-13}$ cm (one fermi)

➔ $\sigma \sim 10^{-25}\ \mathrm{cm}^2 = 100$ mb

Scattering of composite particles

The cross section between composite particles has a much more complex dependence from the center-of-mass energy, and it's not calculable.



Let's consider a proton.

It contains:

-valence quarks

-sea quarks

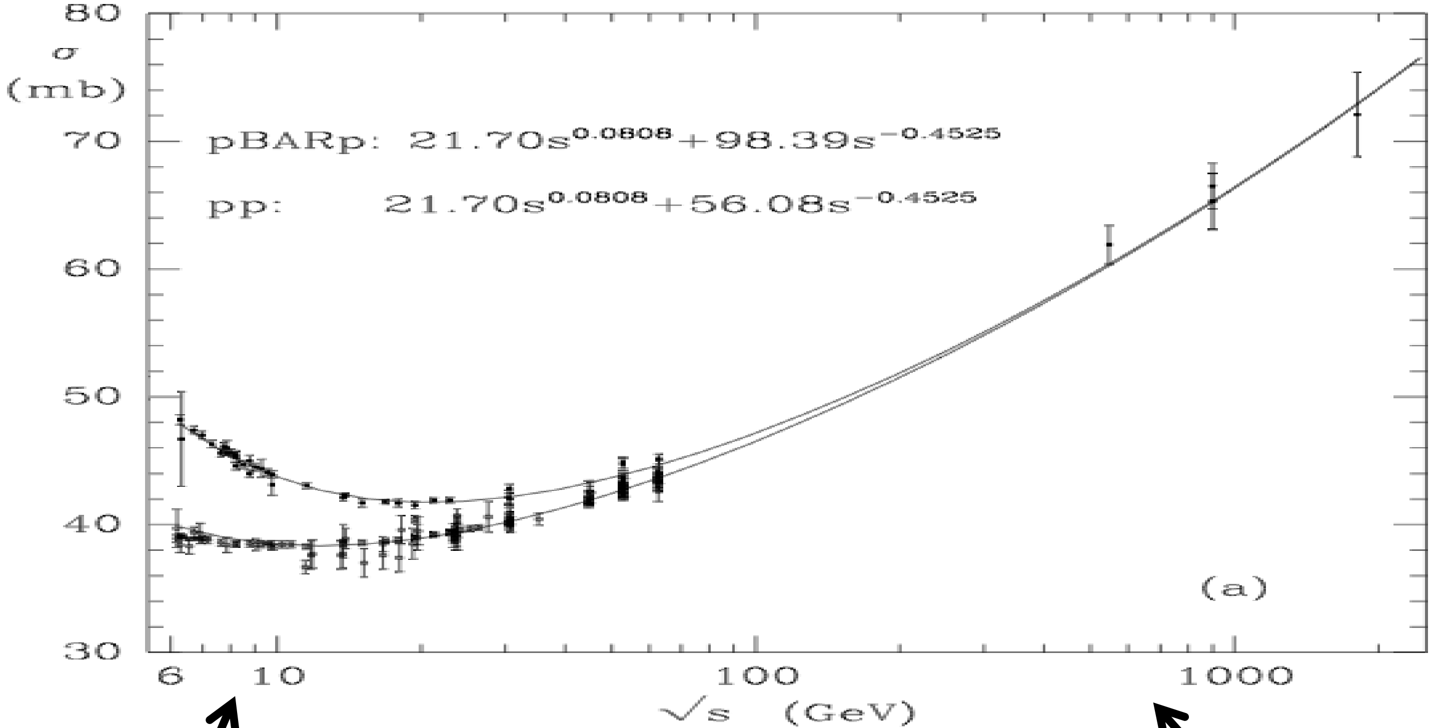
-gluons

These define the particle to be a proton

Mostly SU(3) color symmetric, common to protons and anti-protons (almost true..)

What part is controlling the total cross section?

pp vs pBARp cross section



At low energy σ is different: valence quarks need to be important here

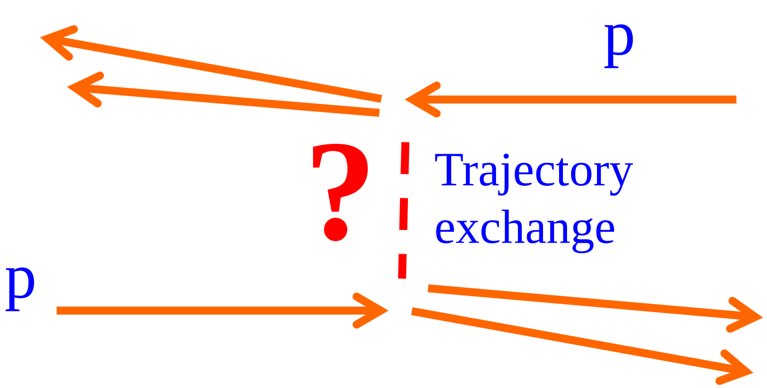
At high energy σ is the same: only sea quarks and gluons can contribute

Theoretical framework: Regge Theory

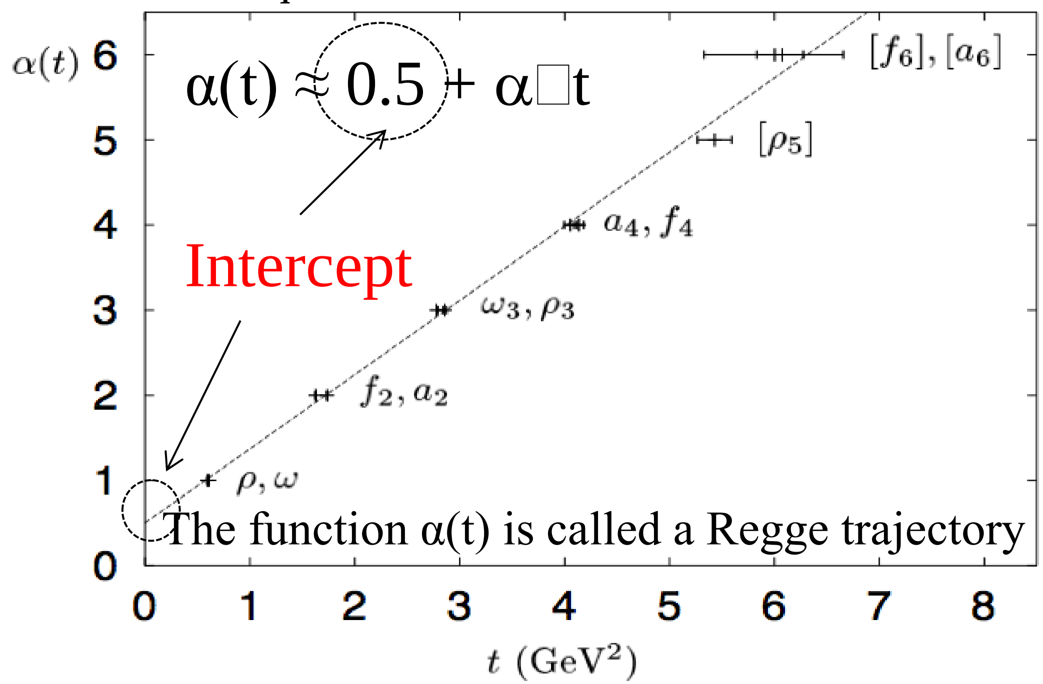
"Regge Theory", and derivations, is the language used to describe the total cross sections of hadron-hadron scattering.

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

1) Particles, when plotted in the mass (t) - spin plane, form lines, called trajectories.
2) You cannot exchange a single particle, you exchange all the particles on the trajectory.



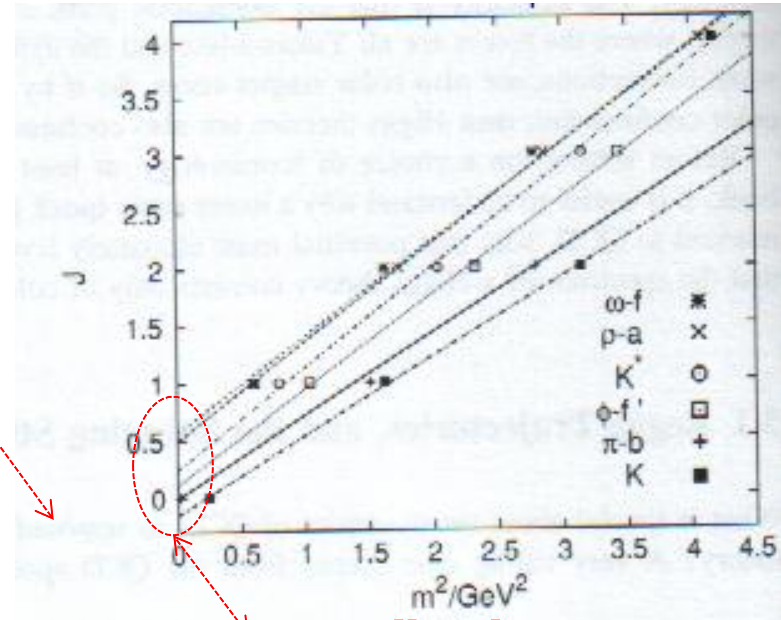
Plot of spins of families of particles against their squared masses:



Contribution of each trajectory to σ

All known particles lie on trajectories such as:

$$\alpha(t) \approx \alpha + \alpha\square t$$



Each trajectory contributes to σ according to:

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

α smaller than 1!!

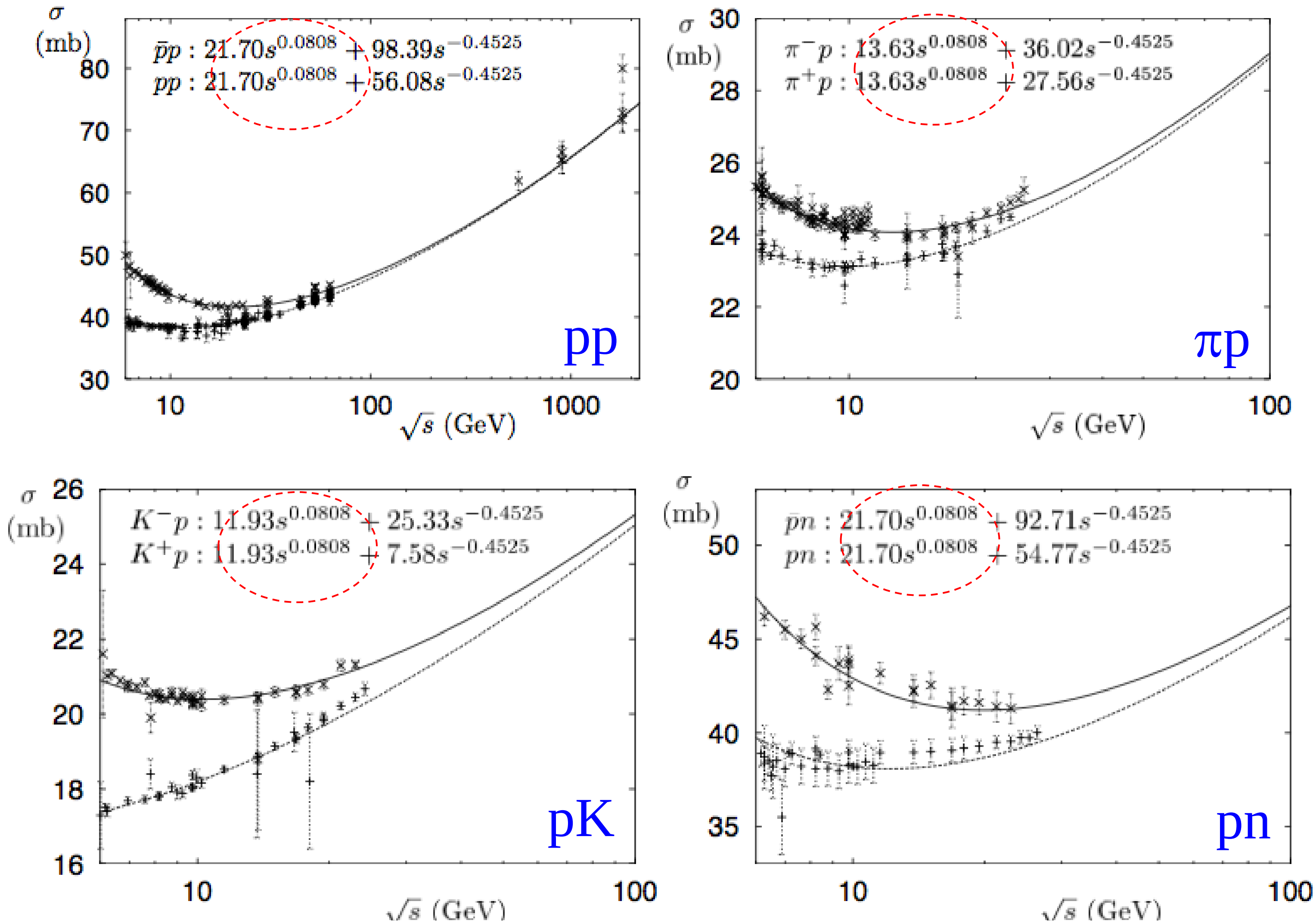
And therefore the prediction for the total cross section is:

$$\sigma_{TOT}(s) = s^{\alpha(0)-1} = s^{-1/2}$$

So, it should decrease with s.

However….

Overview of hadronic cross sections



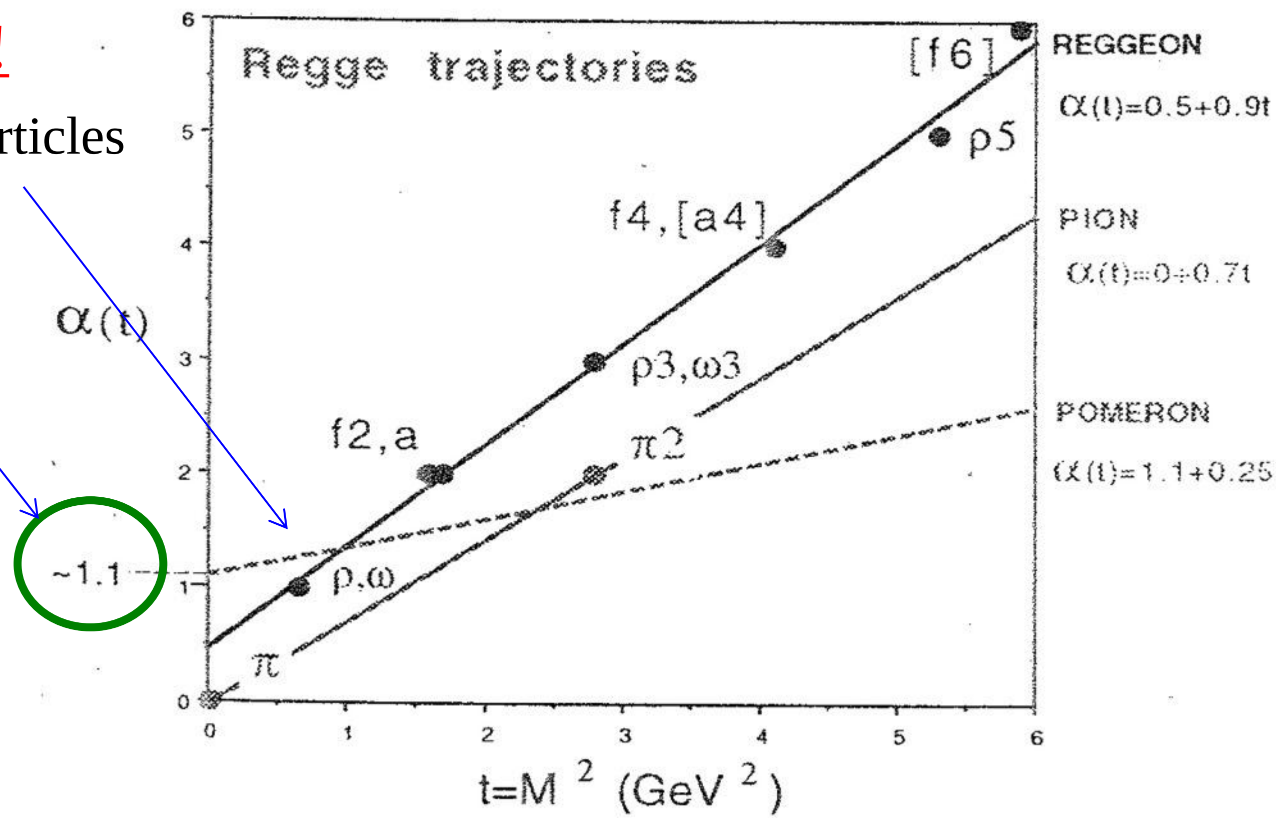
The cross section is raising at high energy: every process requires a trajectory with the same positive exponent: $s^{0.08}$…..something is clearly missing

The advent of the Pomeron

Intercept larger than one!

A trajectory without known particles

Intercept larger than one



V. Gribov introduced, within Regge theory, a vacuum pole (**Pomeron** with $\alpha(0) \sim 1.1$) in order to have a constant (or rising) total cross section.

The problem with the Pomeron trajectory

The exchanged particles (poles) on Reggeon an pion trajectories offer guidance on how to write the scattering amplitude A(s)

There is little spectroscopic guidance from the pomeron trajectory, as it has no particles.

Pomerons exchange contribute as:

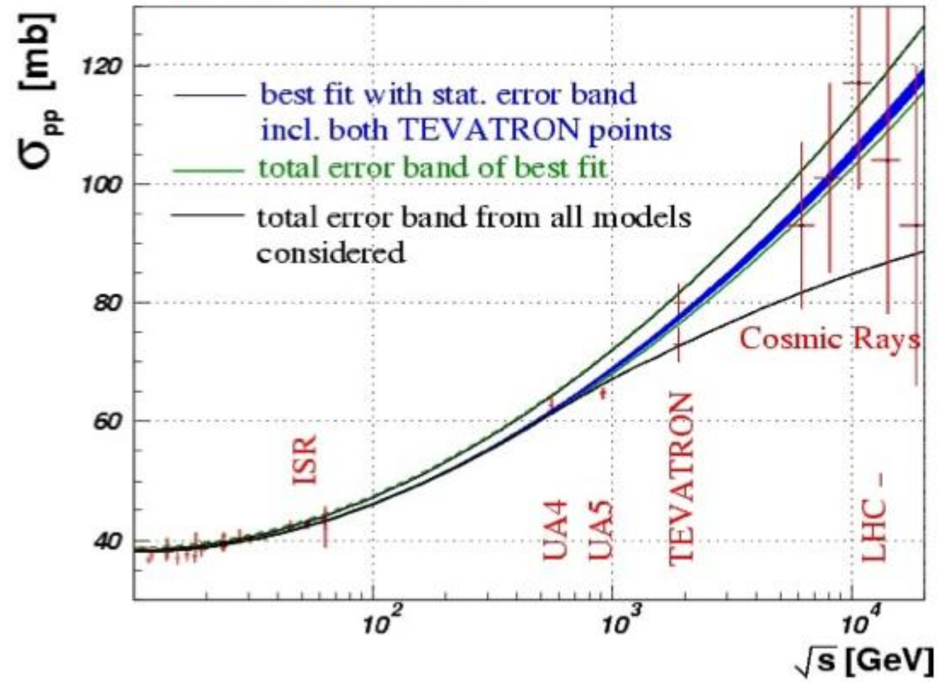
$\sigma_{TOT}(s) = \text{Im } A(s,t=0) \sim s^{\varepsilon}$ (simple pole)

$\sigma_{TOT}(s) = \text{Im } A(s,t=0) \sim \ln(s)$ (double pole)

$\sigma_{TOT}(s) = \text{Im } A(s,t=0) \sim \ln^2(s)$ (triple pole)

The COMPETE collaboration has scanned a large selection of models compared with all available experimental data points and has produced a comprehensive set of predictions.

COMPETE Collaboration:



COMPETE Collaboration fits all available hadronic data and predicts at LHC:

$$\sigma_{tot} = 111.5 \pm 1.2 \begin{array}{l} +4.1 \\ -2.1 \end{array} \text{ mb}$$

$\sigma_{tot}^{COMPETE}$ (7 TeV) = 98 ± 5 mb

$\sigma_{tot}^{COMPETE}$(8 TeV) = 101 ± 5 mb

Regge Theory: master formula pre-LHC

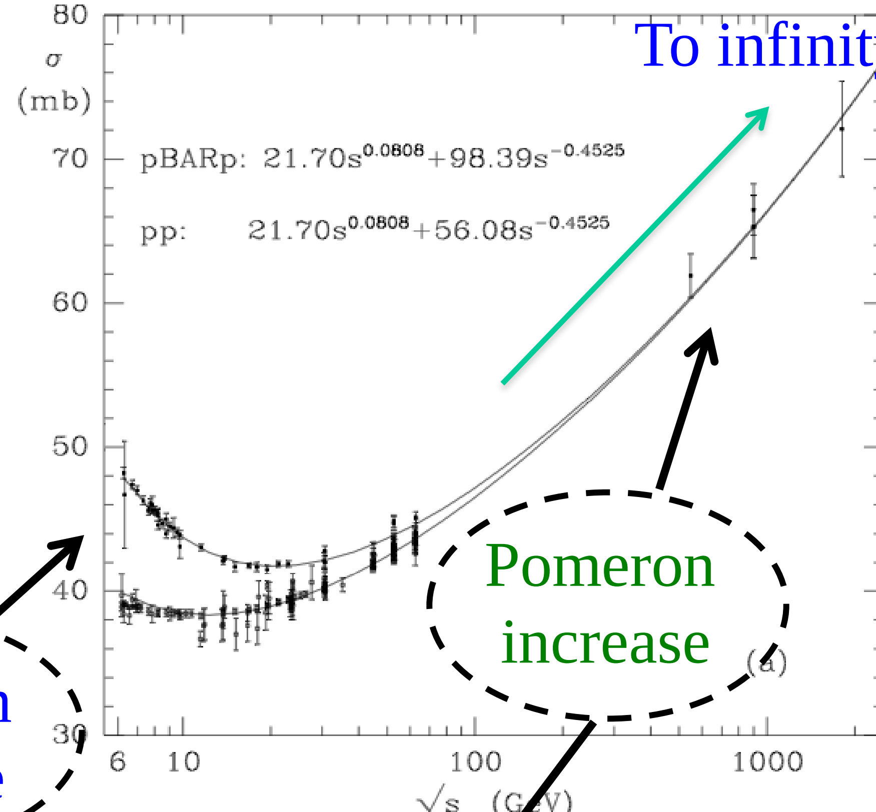
Three large families of parametrization:

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

$\sigma_{TOT}(s) = c + \alpha\, s^{-0.5} + \gamma \ln^2(s)$

(most favorite COMPETE prediction)

$\sigma_{TOT}(s) = c + \alpha\, s^{-0.5} + \beta \ln(s) + \gamma \ln^2(s)$



To infinity

Pomeron increase

Reggeon decrease

QCD: exchange of valence quark

QCD: exchange of sea quark and gluons, glueballs..

The Rise of the gluons

As measured at HERA, the gluon PDFs experience a very strong rise as the energy increases.

If the pomeron is related to “gluons”, it’s reasonable to assume a modification of the pomeron term:

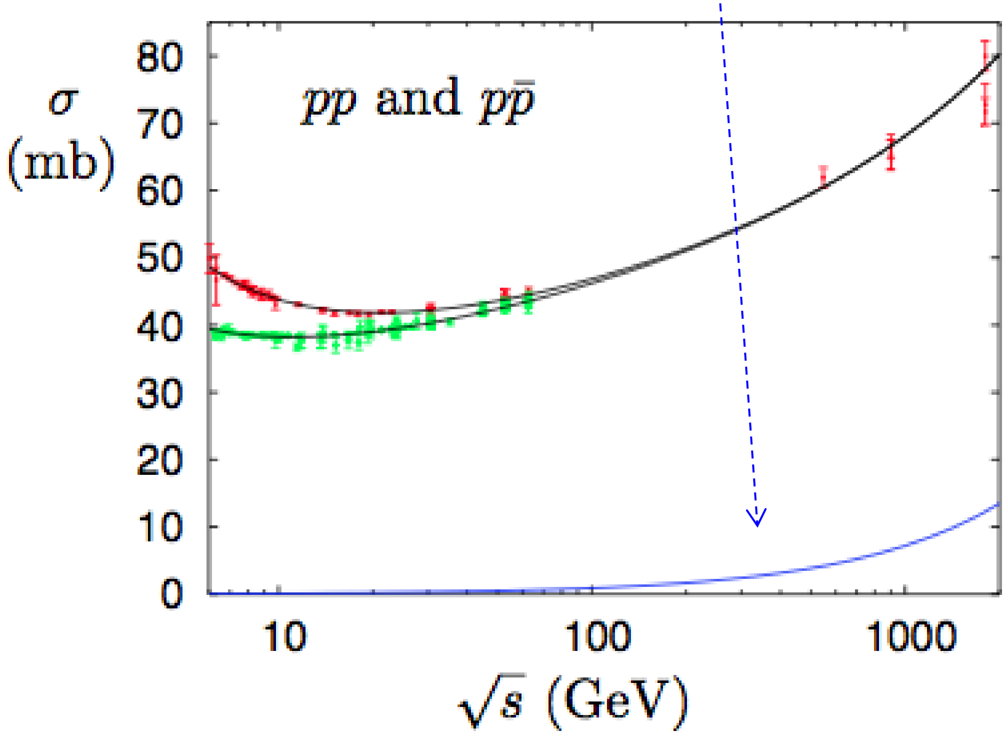
the cross section will start rising more rapidly at higher energy.

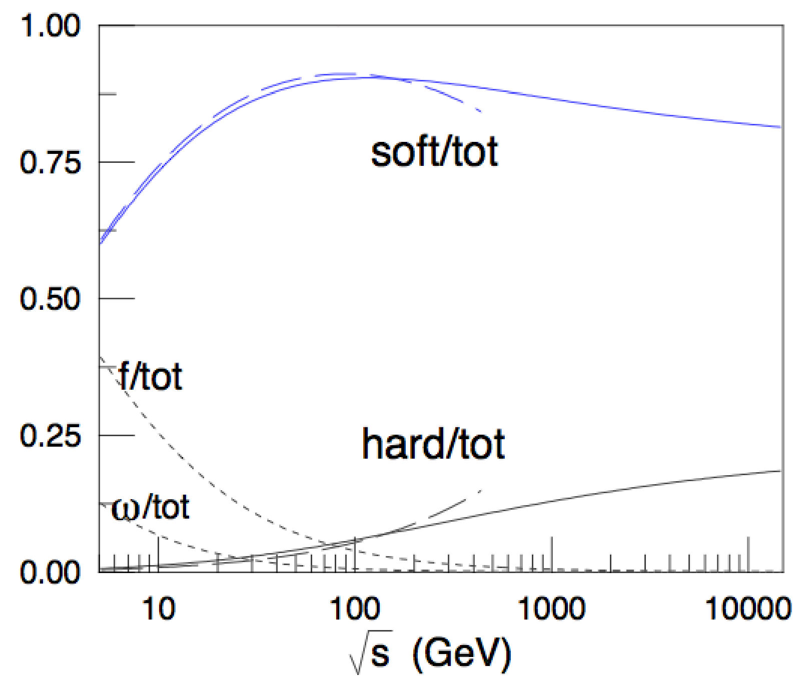
2-pomeron formula for higher energy

In a simple model (DL, Cudel et al.) an additional term called "hardPomeron" can be introduced in σ_{TOT} to account for this effect. It gives a steeper energy behavior:

$$\sigma_{TOT}(s) = \alpha\, s^{-0.5} + \beta\, s^{0.067} + \gamma\, s^{0.45}$$ (2 simple poles)

Hard pomeron contribution



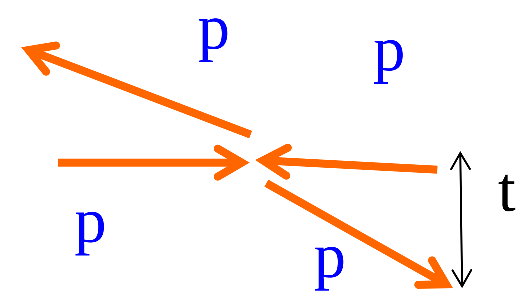


DL for LHC:
$\sigma_{TOT}(\sqrt{s} = 7) = 100$ +- 25 mb
$\sigma_{TOT}(\sqrt{s} = 14) = 125$ +- 25 mb

Total cross section and elastic scattering

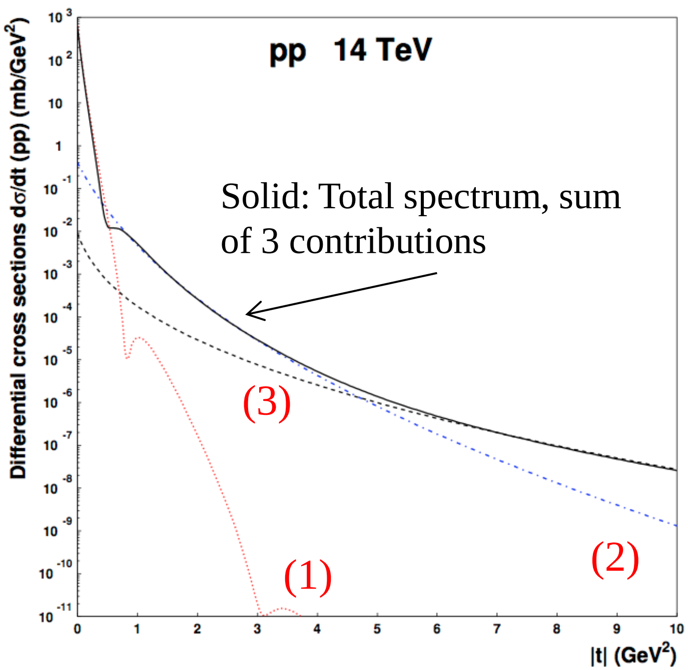
At small t, elastic scattering is governed by an exponential law.

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

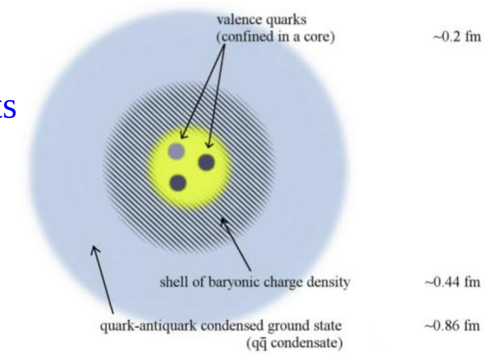


Elastic scattering probes the proton at a distance

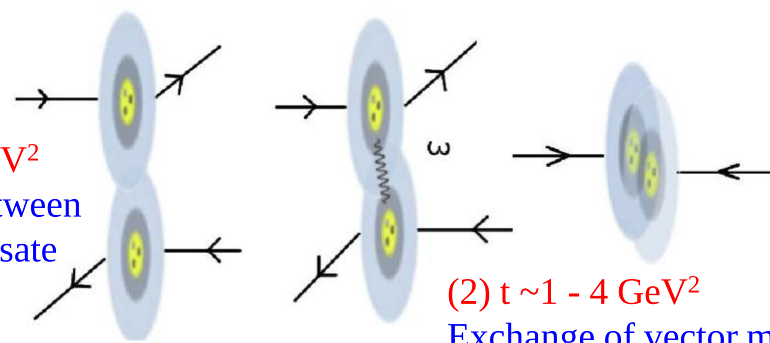
$b \sim 1/\sqrt{|t|}$



Different models predicts different t spectrum and contributions



The proton is made of different layers, each contributing differently to the cross section

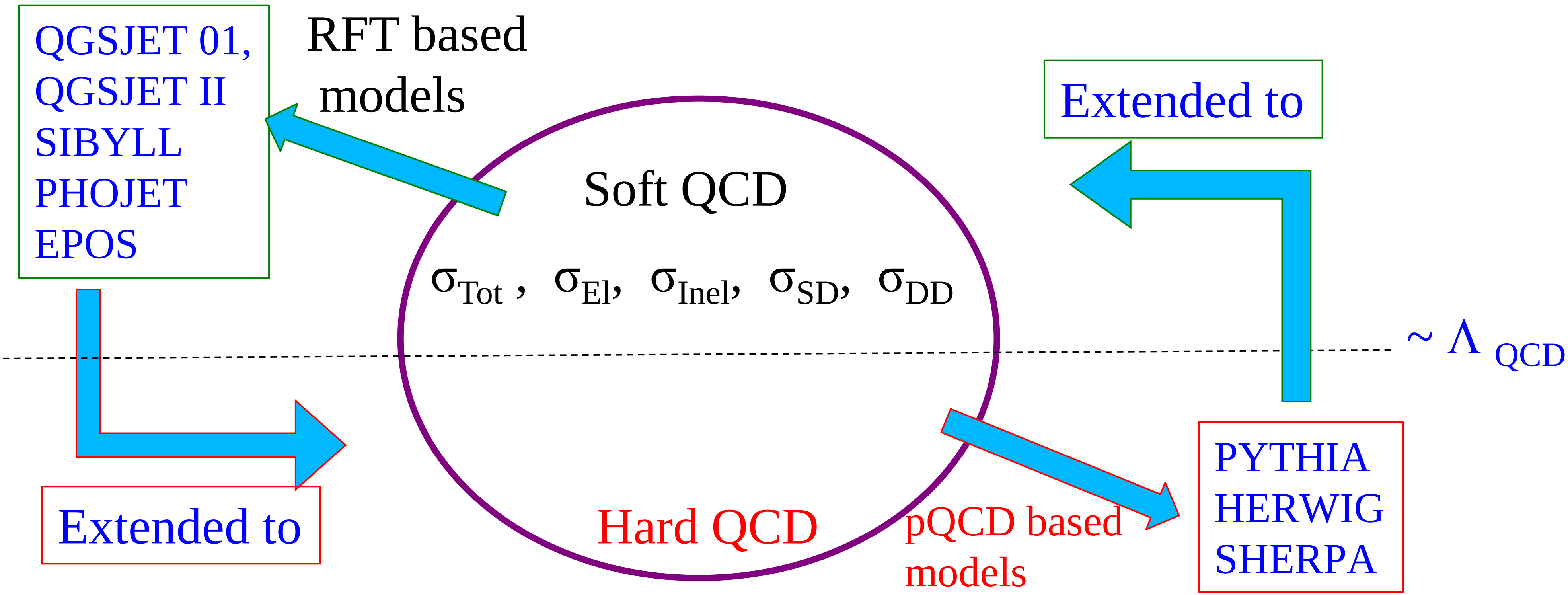


(1) $t < \sim 1$ GeV^2
Scattering between qqbar condensate $>\sim 0.4$ fm

(2) $t \sim 1 - 4$ GeV^2
Exchange of vector mesons

(3) $t > \sim 4$ GeV^2
Elastic scattering on valence quark ~ 0.2 fm

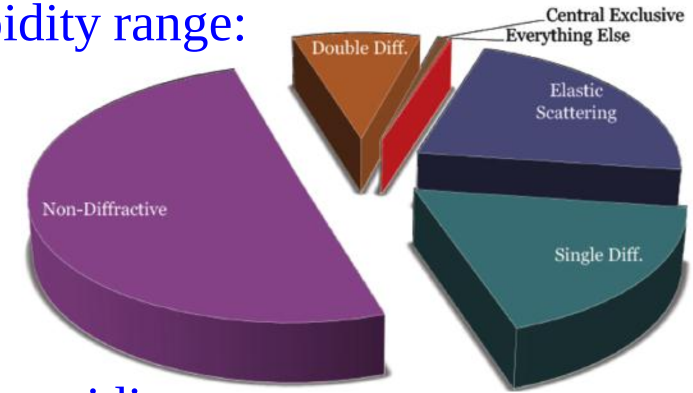
Monte Carlo models: RFT vs. pQCD



Topologies of events in σ_{tot}

TOTAL cross section means measuring everything…

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



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

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

➔ Very difficult, needs dedicated detectors near the beam

Diffractive: Single, Double, Central diffractions, gaps everywhere.

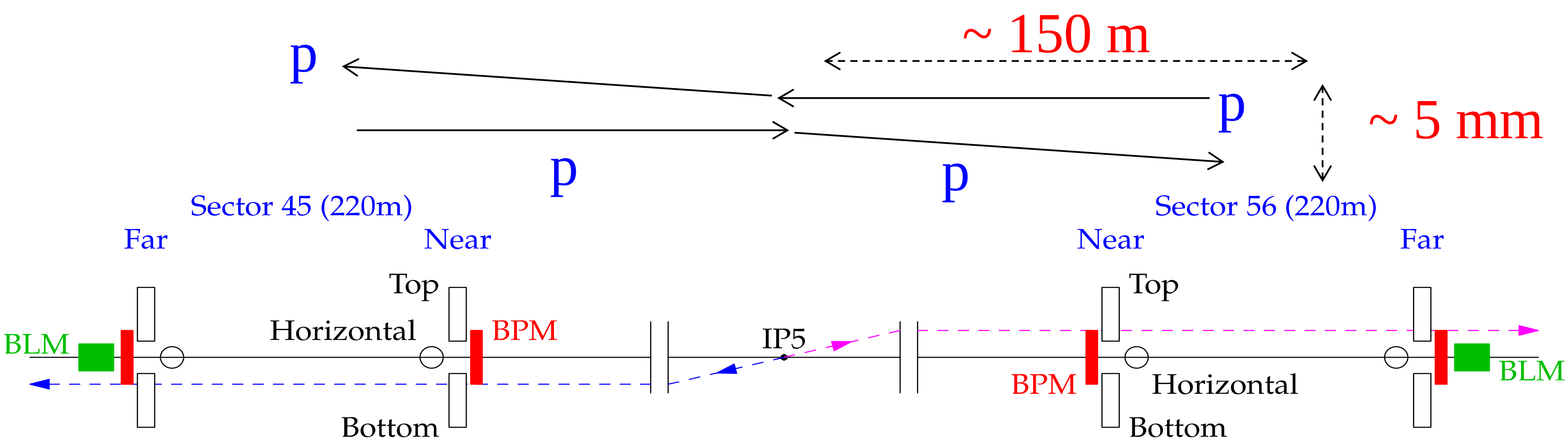
➔ Quite difficult, some events have very small mass, difficult to distinguish diffraction from standard QCD.

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

➔ Easy

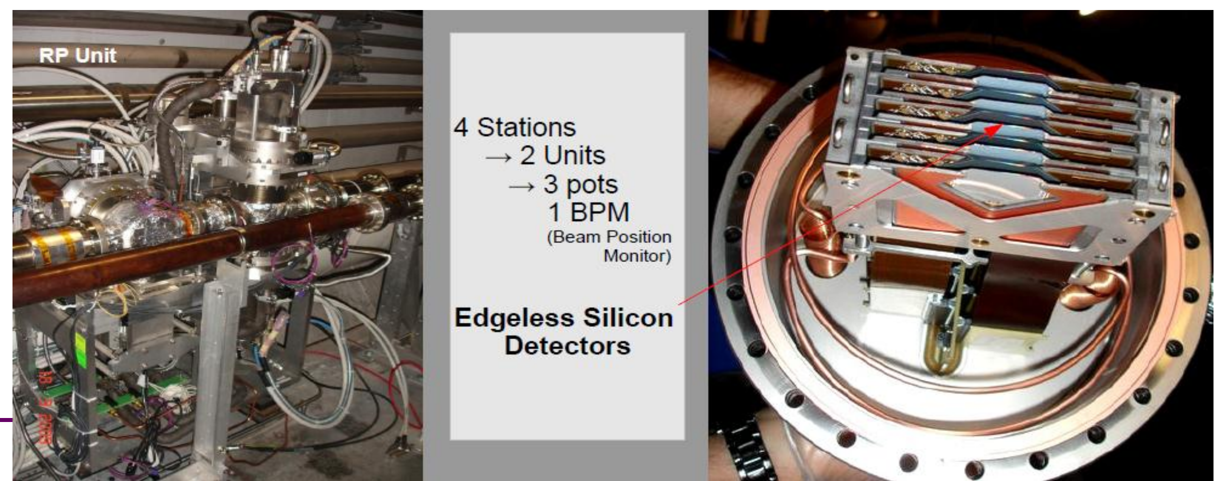
The very difficult part: elastic scattering

Need dedicated experiments able to detect scattered particles very closed to the beam line: pp ➔ pp



TOTEM @ LHC

Roman Pot and silicon detector

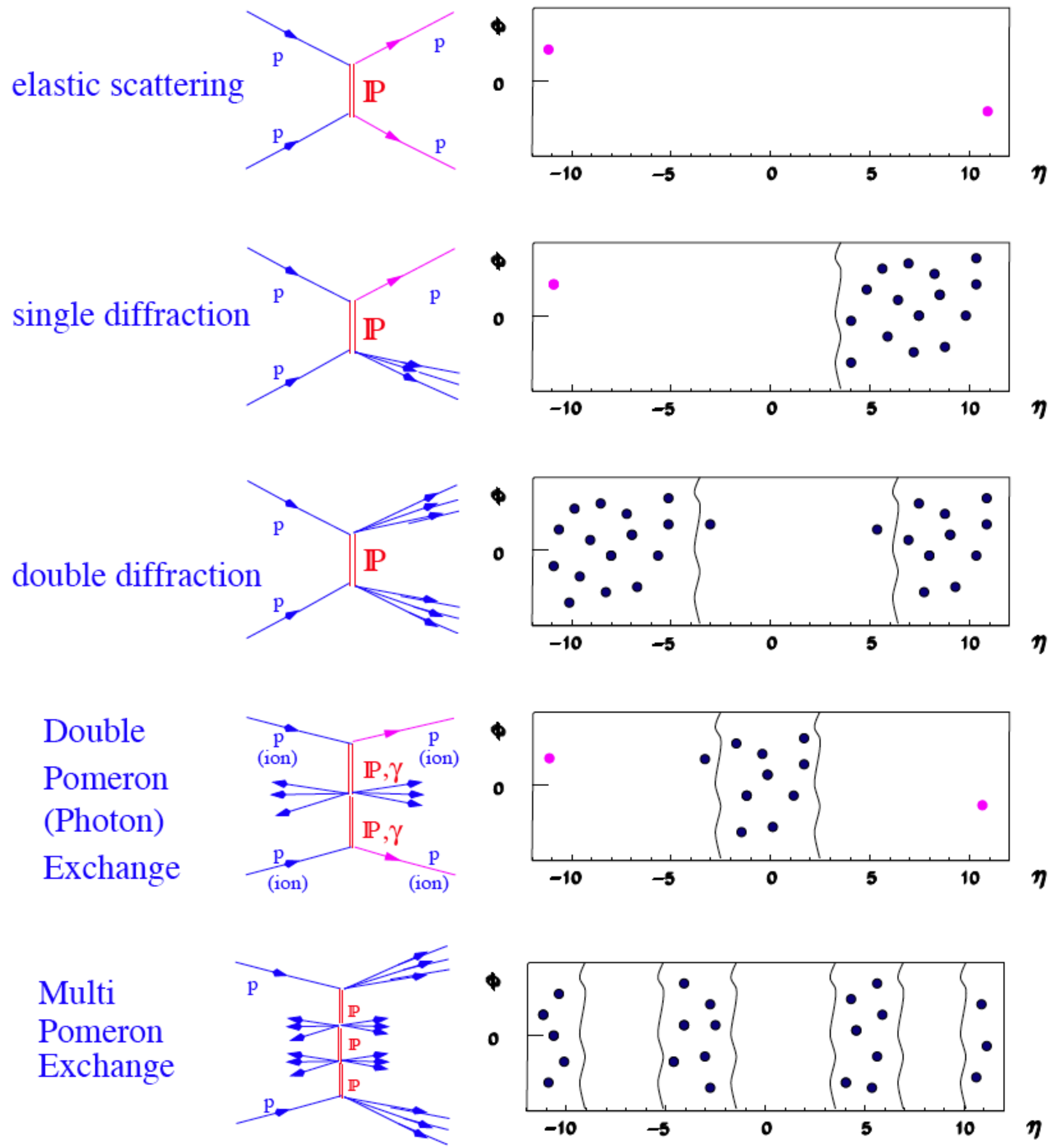


The difficult part: pomeron exchange

Pomeron exchange is a synonym of colour singlet exchange (diffraction)

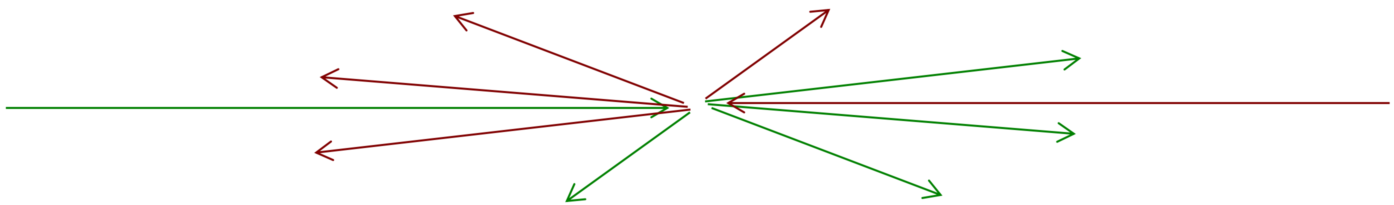
Many different topologies to measure

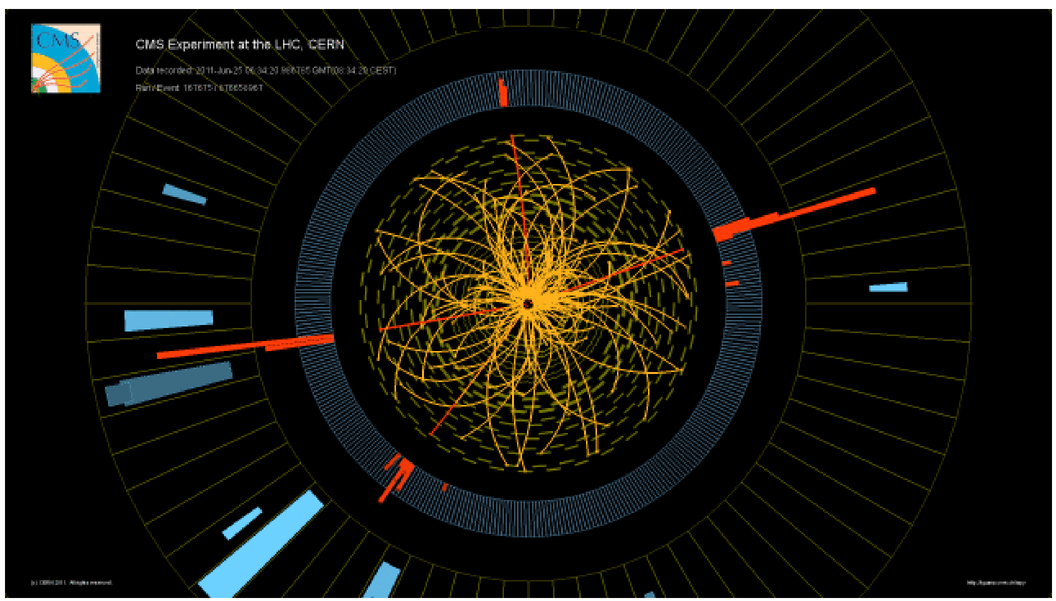
Importance of very low mass events



The easy part: everything else

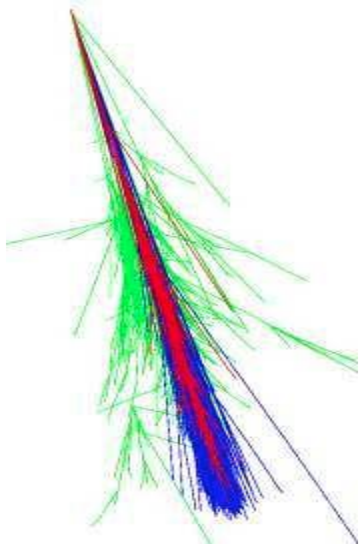
The non-diffractive inelastic events are usually not difficult to detect:



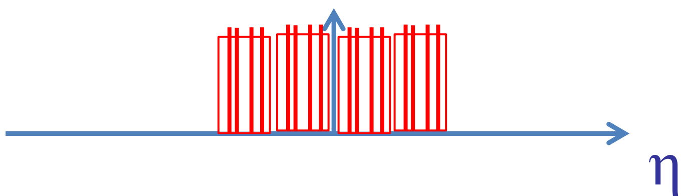


Direct measurement of parts of σ_{TOT}: cosmic-ray and collider experiments

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.

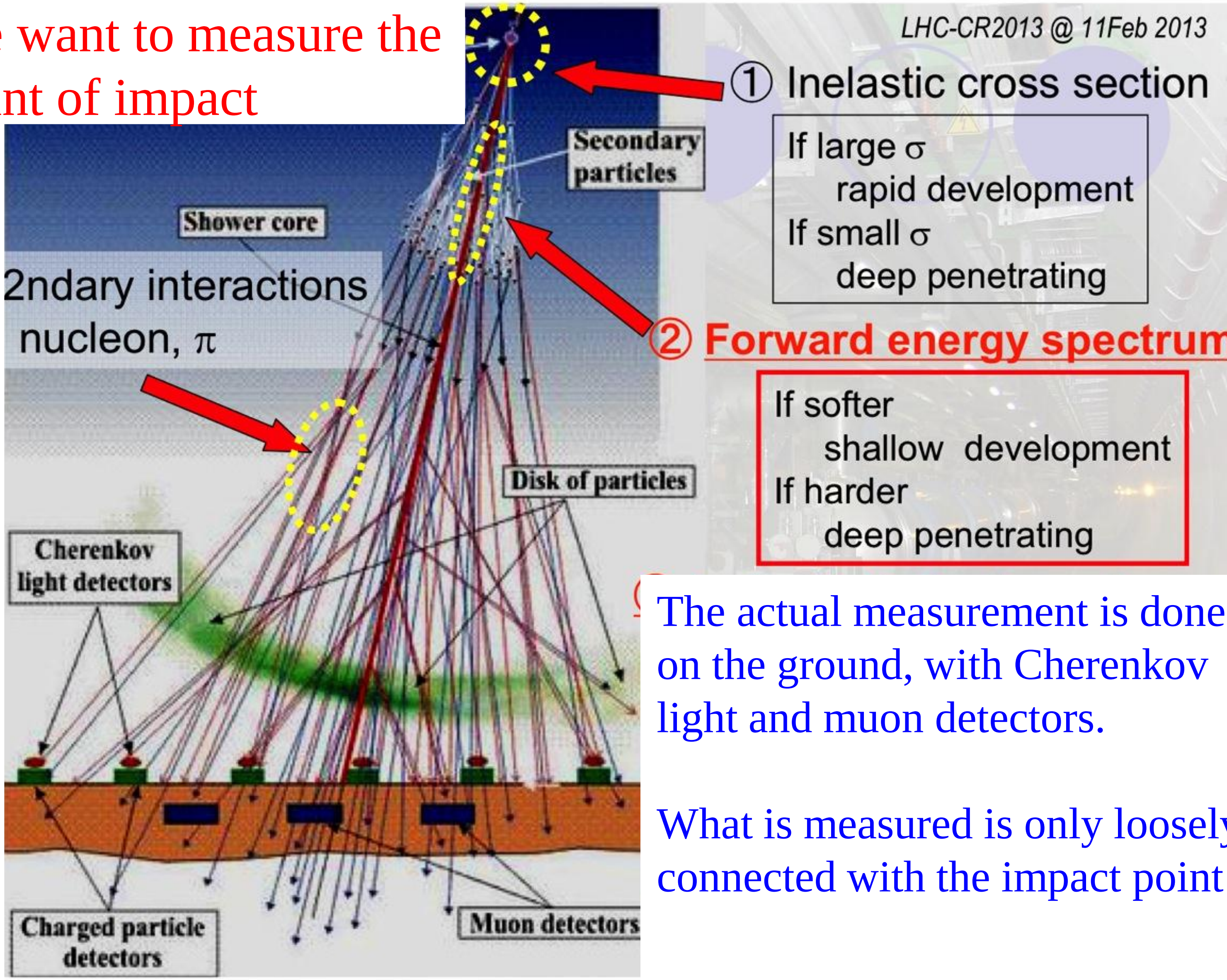


In collider experiments (currently ALICE, ATLAS, CMS, and TOTEM @ LHC), the detector covers a part of the possible rapidity space. The measurement is performed in that range, and then it might be extrapolated to $\sigma_{inel.}$



Cosmic-ray shower

We want to measure the point of impact

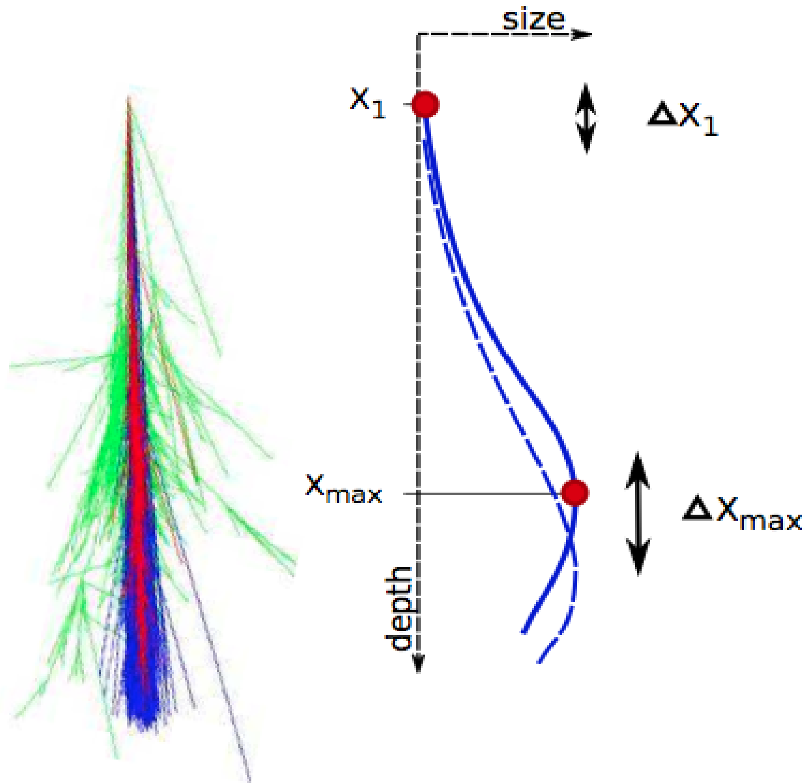


The actual measurement is done on the ground, with Cherenkov light and muon detectors.

What is measured is only loosely connected with the impact point

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)



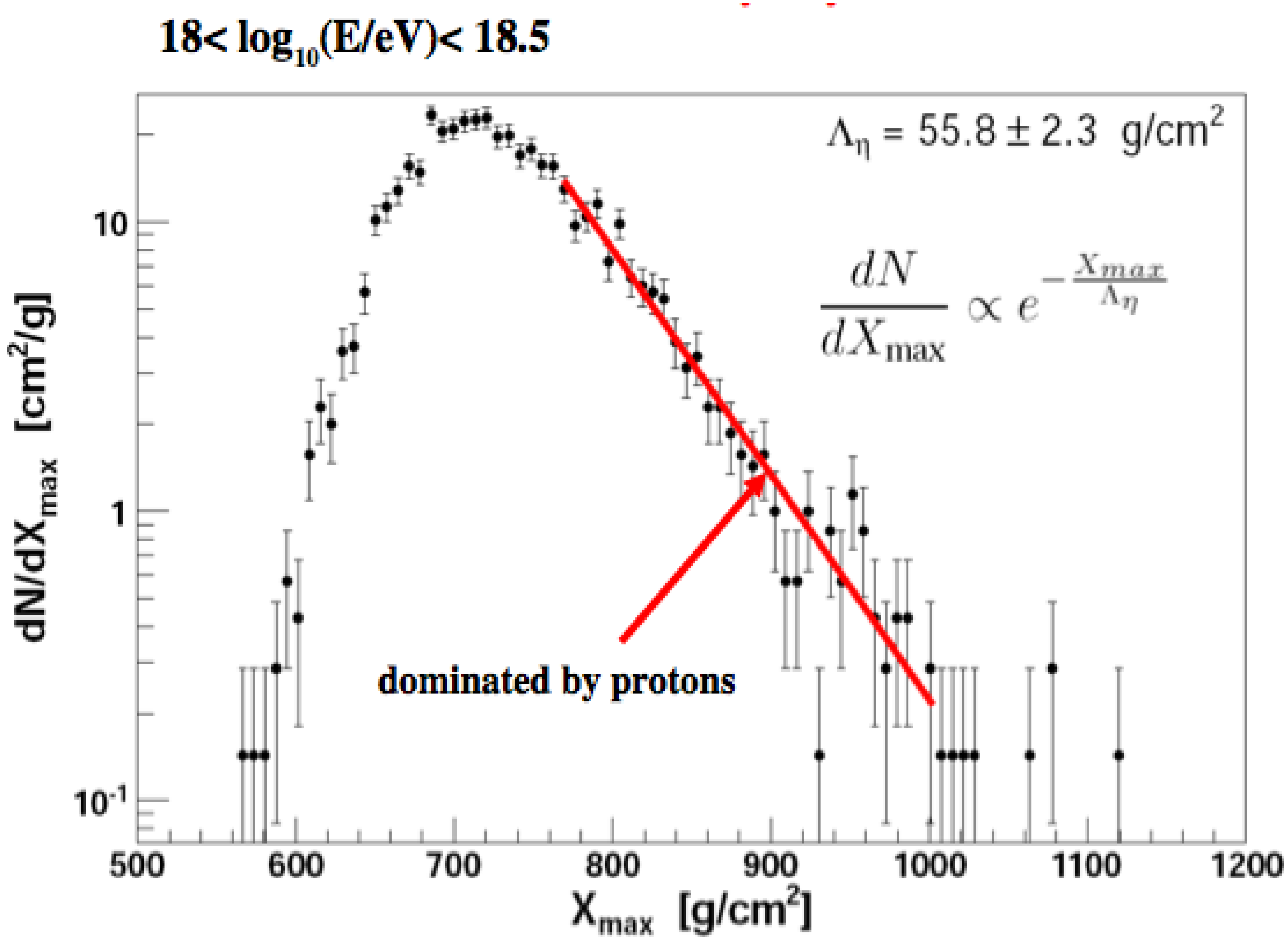
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

Difficulties:

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

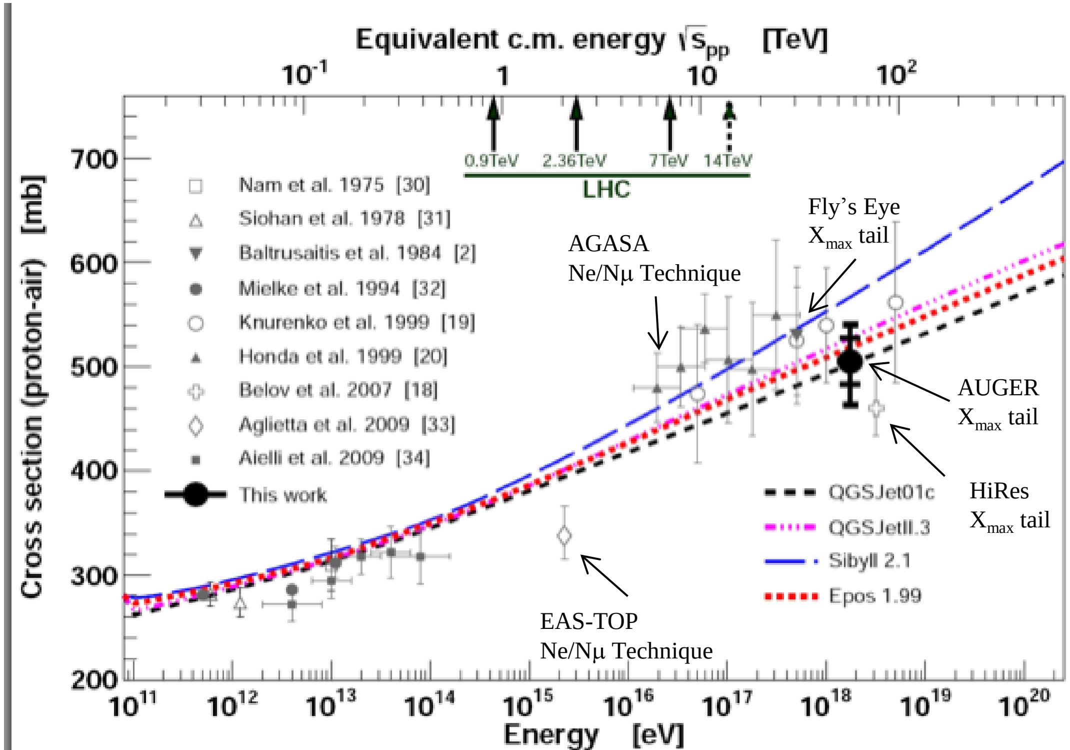
Auger: the measurement

The position of the air shower maximum, at fixed energy, 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 $\quad \sqrt{s} = 57$ TeV $\pm\ 0.3_{\text{stat}} \pm\ 6_{\text{sys}}$

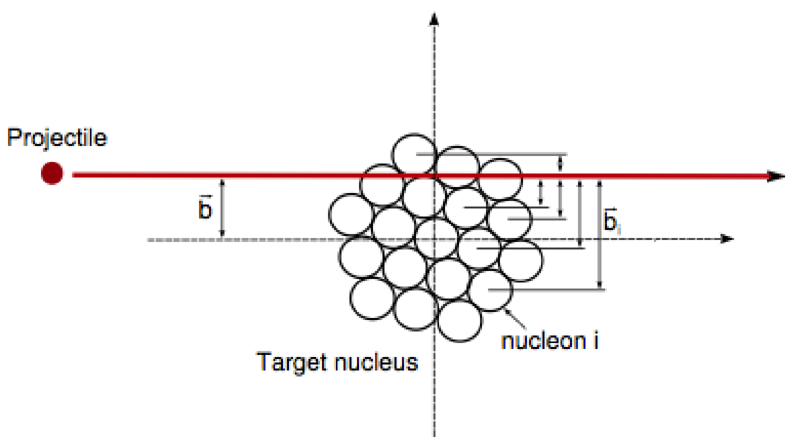
$$\boxed{\sigma_{\text{p-air}} = (505 \pm 22_{\text{stat}}\ (^{+28}_{-36})_{\text{syst}})\ \text{mb}}$$

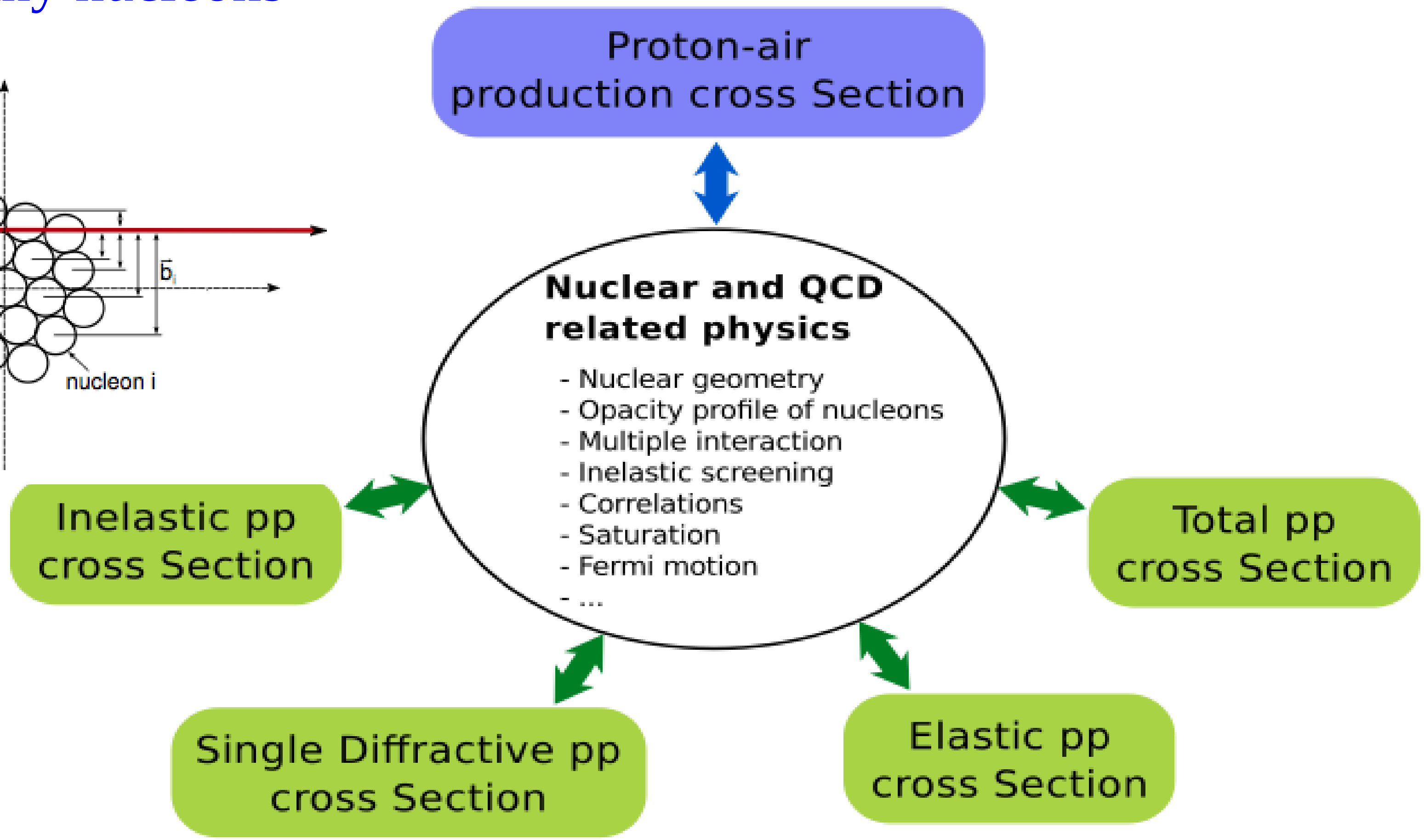
Additional Uncertainties due to diverse contaminations:

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

The Glauber model

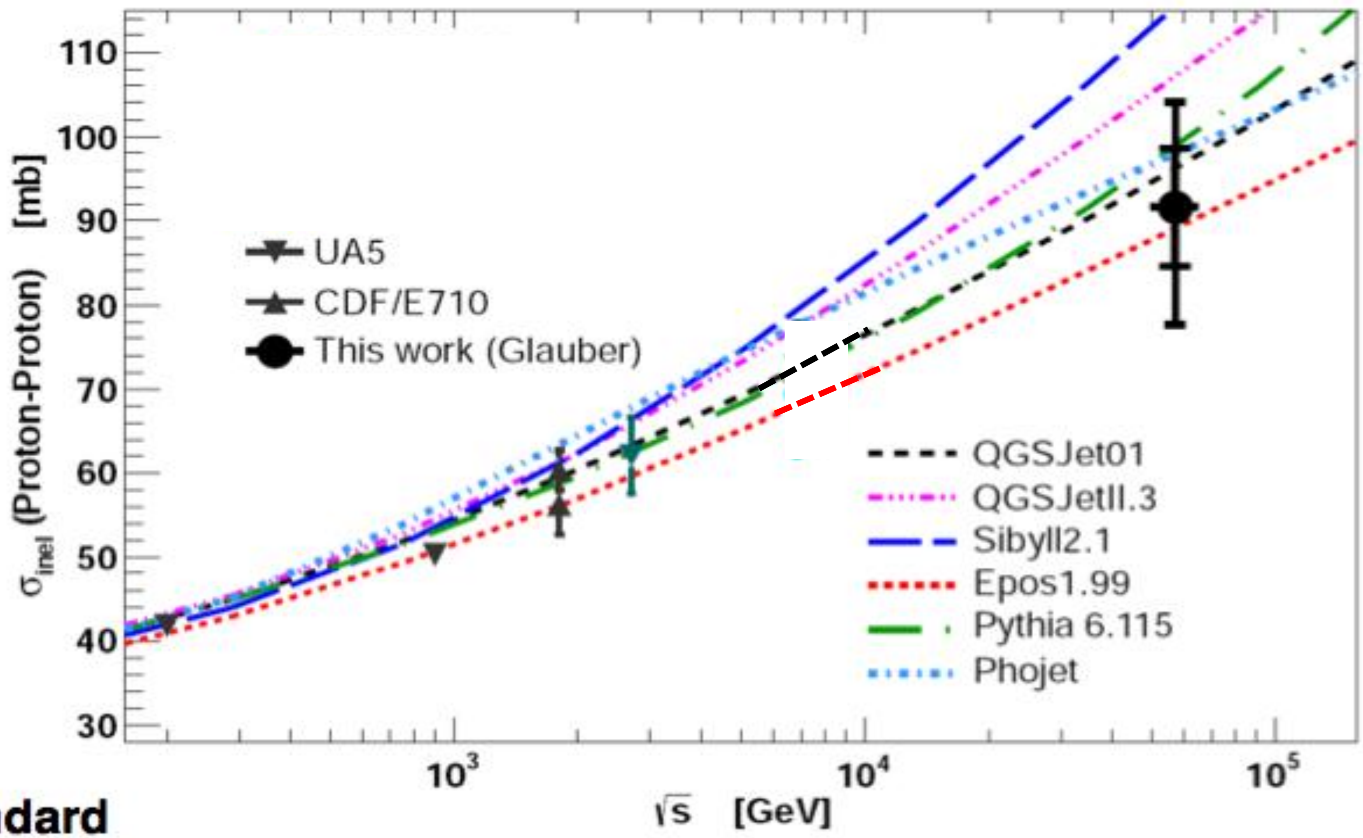
The p-air cross section is interpreted as the convolution of effects due to many nucleons





Auger: pp cross section

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

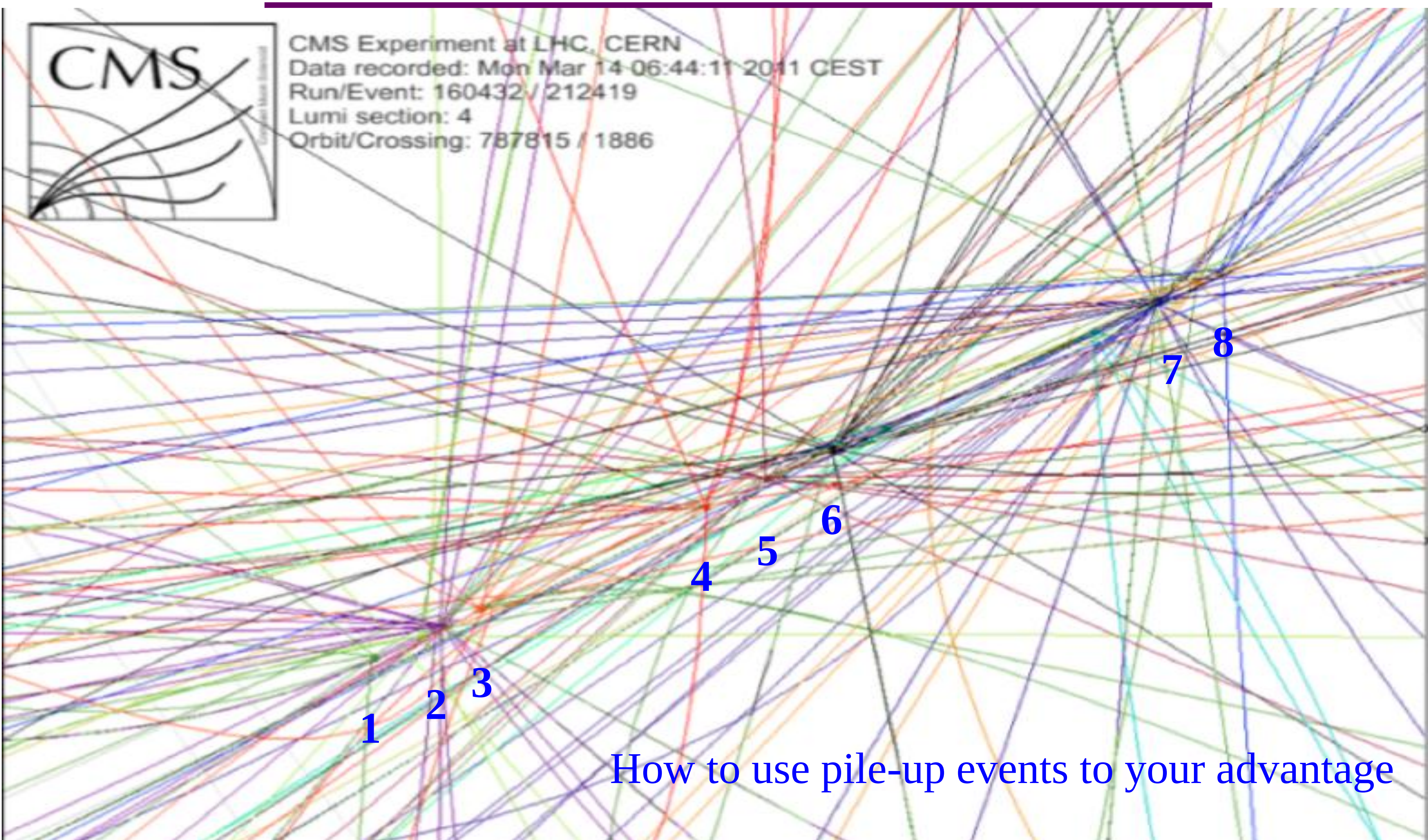


Using standard Glauber formalism

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

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

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



How to use pile-up events to your advantage

Pileup Analysis Technique

The probability of having n_{pileup} depends only on the *visible* $\sigma(pp)$ cross section:

$$P(n) = \frac{(L \cdot \sigma)^n}{n!} e^{-L \cdot \sigma}$$

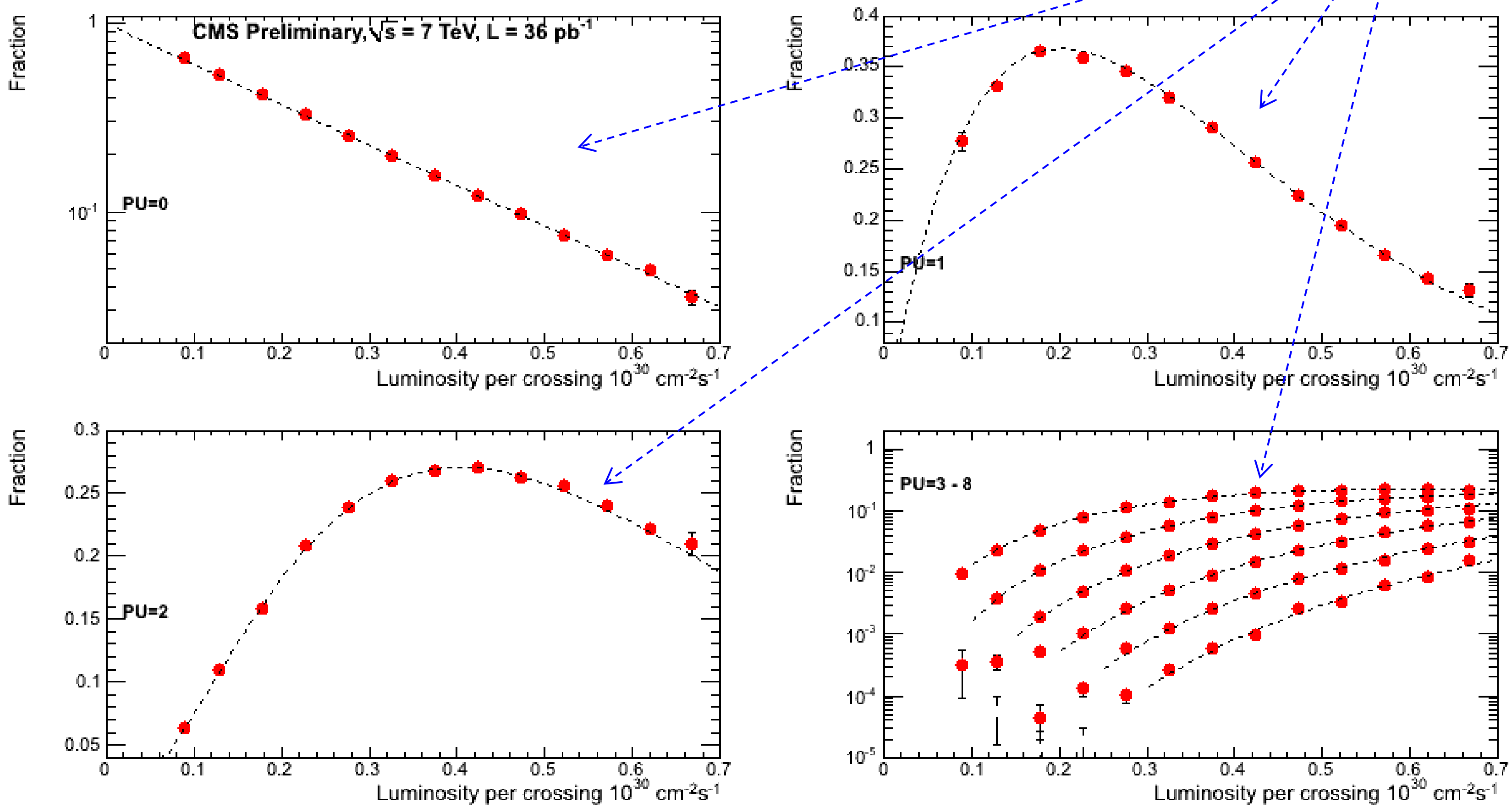
If we count the number of pile-up events as a function of luminosity L, we can measure $\sigma_{vis}(pp)$.

For an accurate measurement we need a large luminosity interval.

Probability of *n* extra vertices depends upon σ

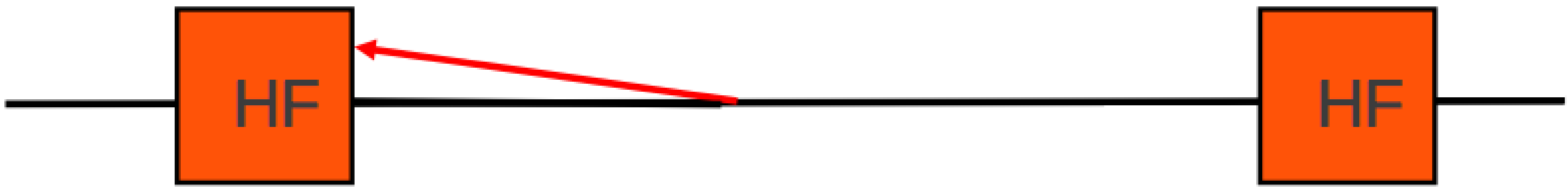
$$P(n_{vertexes}) = \frac{(Ls)^{n_{vertexes}} e^{-(Ls)}}{n_{vertexes}!}$$

Fit to σ



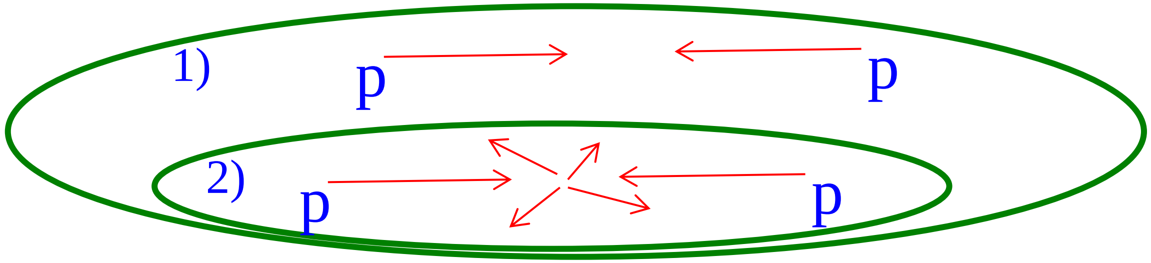
Collider experiments: measure σ_{inel} by counting number of events

The total inelastic proton-proton cross section is obtained by measuring the number of times opposite beams of protons hit each other and leave some energy in the most Hadronic Forward calorimeter (HF)



$E_{HF} > 5$ GeV is converted, using MC correction, into $M_x > 15$ GeV ($M^2_x/s = \xi > 5 * 10^{-6}$)

Hadronic Forward Activity: analysis technique



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.

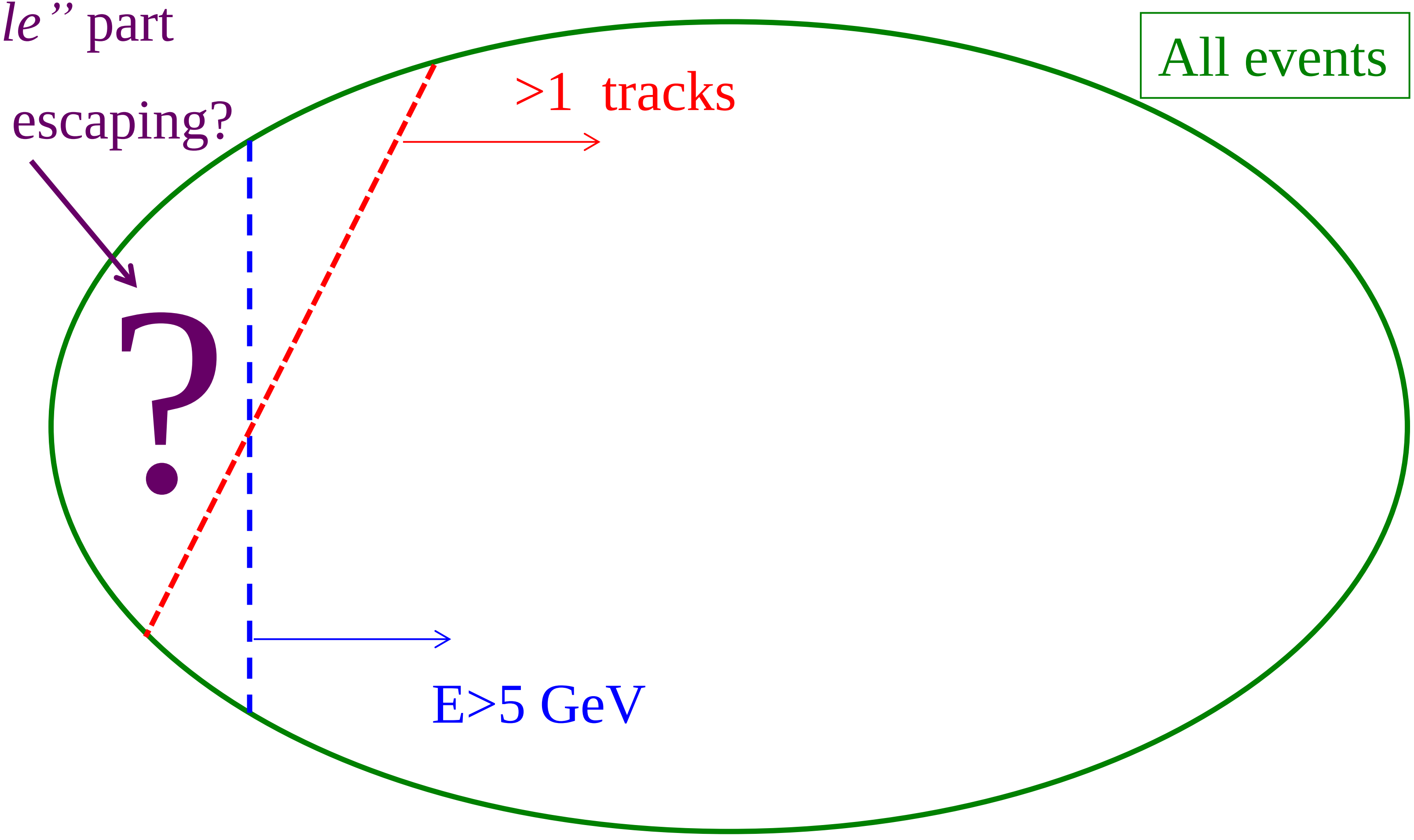
$$\sigma_{Inel} = \frac{N_{Event} F_{pu}}{\varepsilon \int L\,dt}$$

This method works only at low luminosity

Coverage of pileup and HF measurements

Very small masses,
"invisible" part

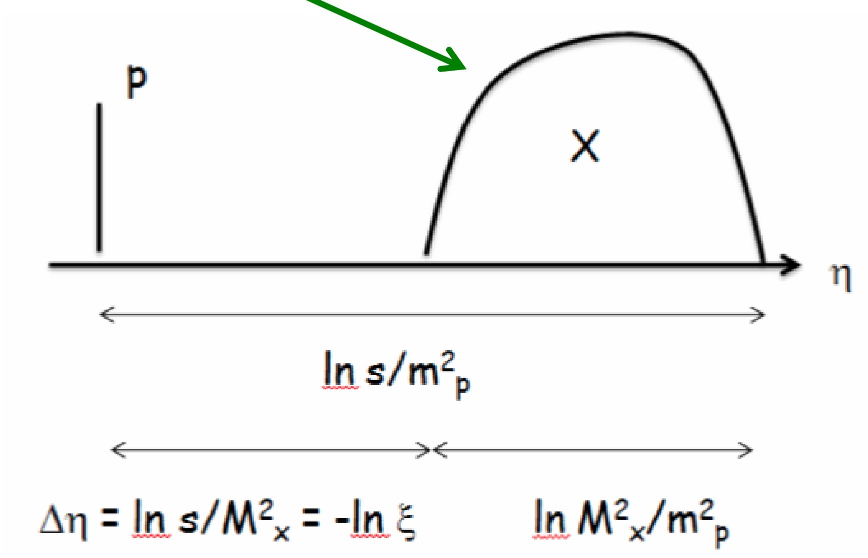
What is escaping?



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	

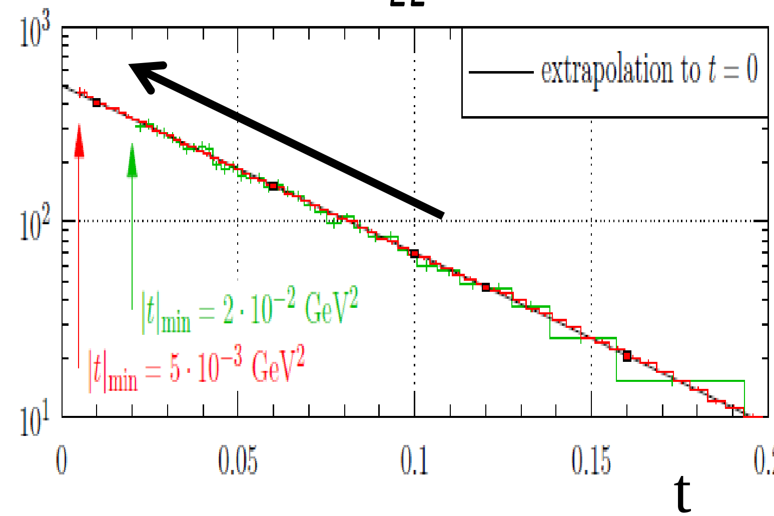
Escape

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

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

Optical theorem: elastic scattering at 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: $$\rho = 0.14^{+0.01}_{-0.08}$$

$\rho = Ref_{el}|_{t=0} / Imf_{el}|_{t=0}$

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

Results

Three basic type of results:

1) Elastic scattering

1) Comparison of the total value of the cross section between data and parameterizations as a function of the center-of-mass energy

2) Comparison of the value of parts of the cross section (elastic, diffractive, soft) with hadronic models (for example MCs) of pp interactions.

TOTEM: pp cross section at LHC @ 7 TeV

Elastic cross section:

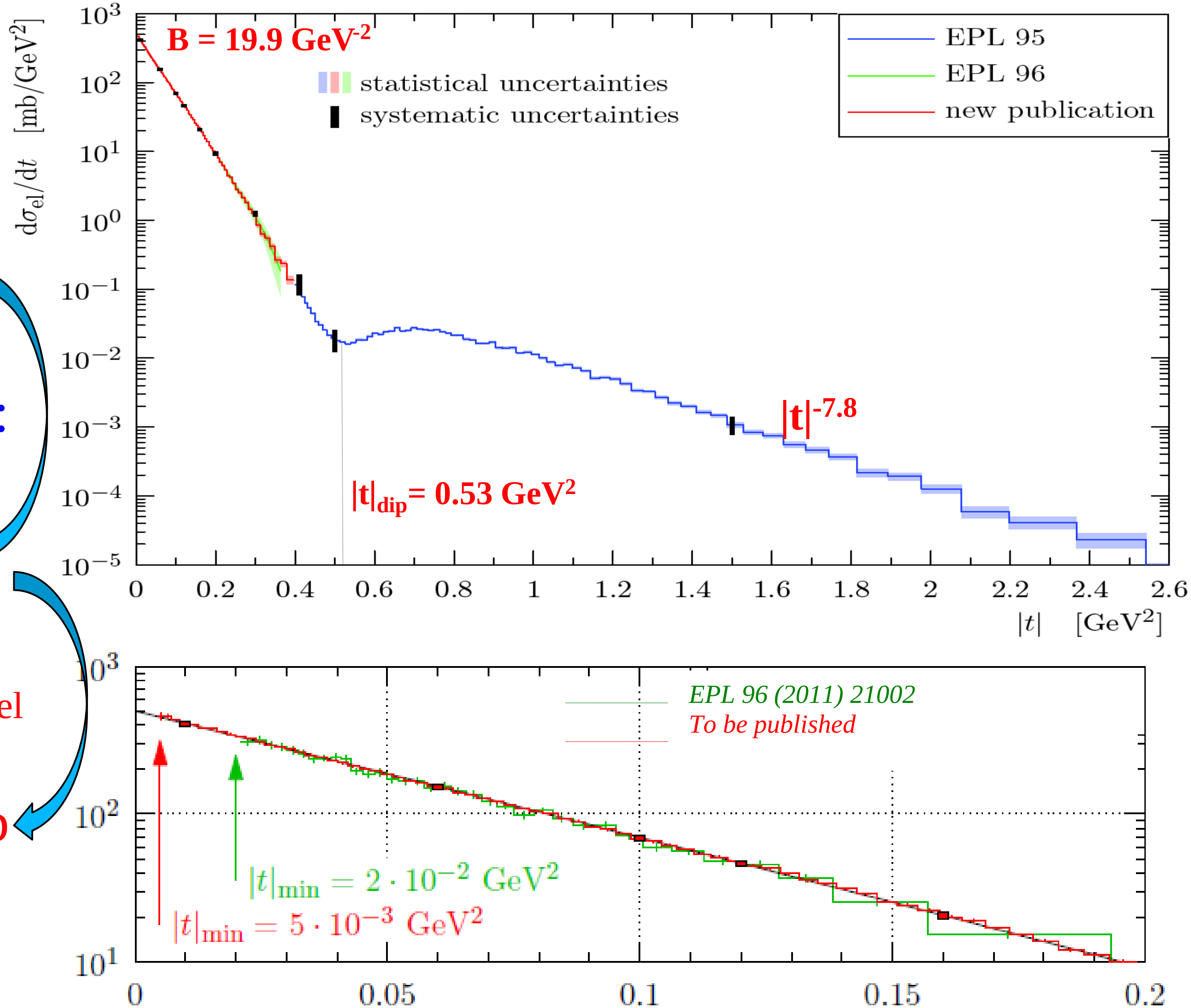
$\sigma_{el} = 25.4 \pm 1.1$ mb

Using the optical theorem:

$\sigma_{TOT} = 98.6$ mb $\pm$ 2.2 mb

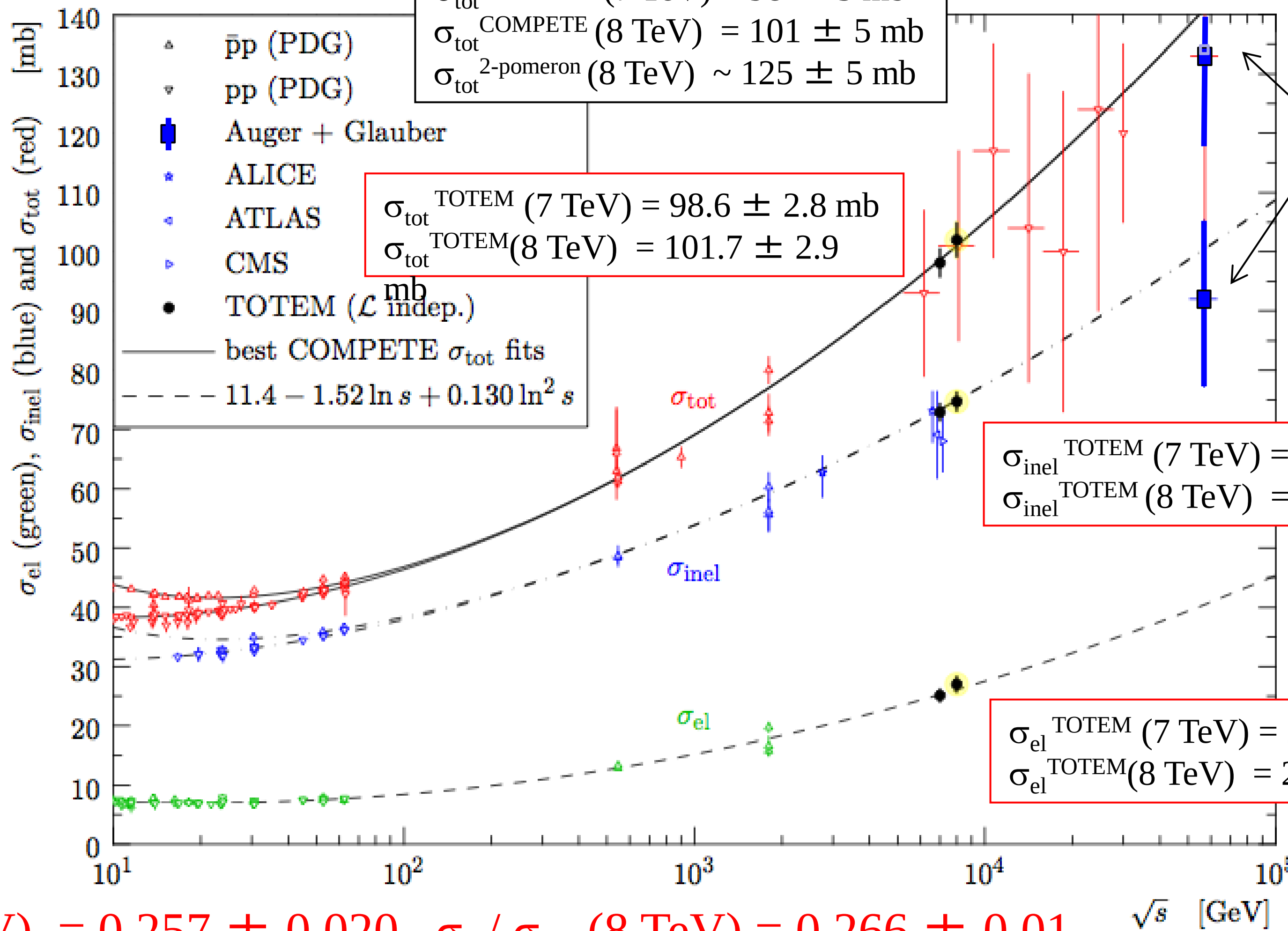
And then: $\sigma_{inel} = \sigma_{TOT} - \sigma_{el}$

$\sigma_{inel} = 73.1$ mb $\pm$ 1.3 mb



σ_{tot}, σ_{inel}, and σ_{el}

$\sigma_{tot}^{COMPETE}$ (7 TeV) = 98 ± 5 mb
$\sigma_{tot}^{COMPETE}$ (8 TeV) = 101 ± 5 mb
$\sigma_{tot}^{2\text{-pomeron}}$ (8 TeV) ~ 125 ± 5 mb



σ_{tot}^{TOTEM} (7 TeV) = 98.6 ± 2.8 mb
σ_{tot}^{TOTEM}(8 TeV) = 101.7 ± 2.9 mb

133 ± 29 mb

Auger

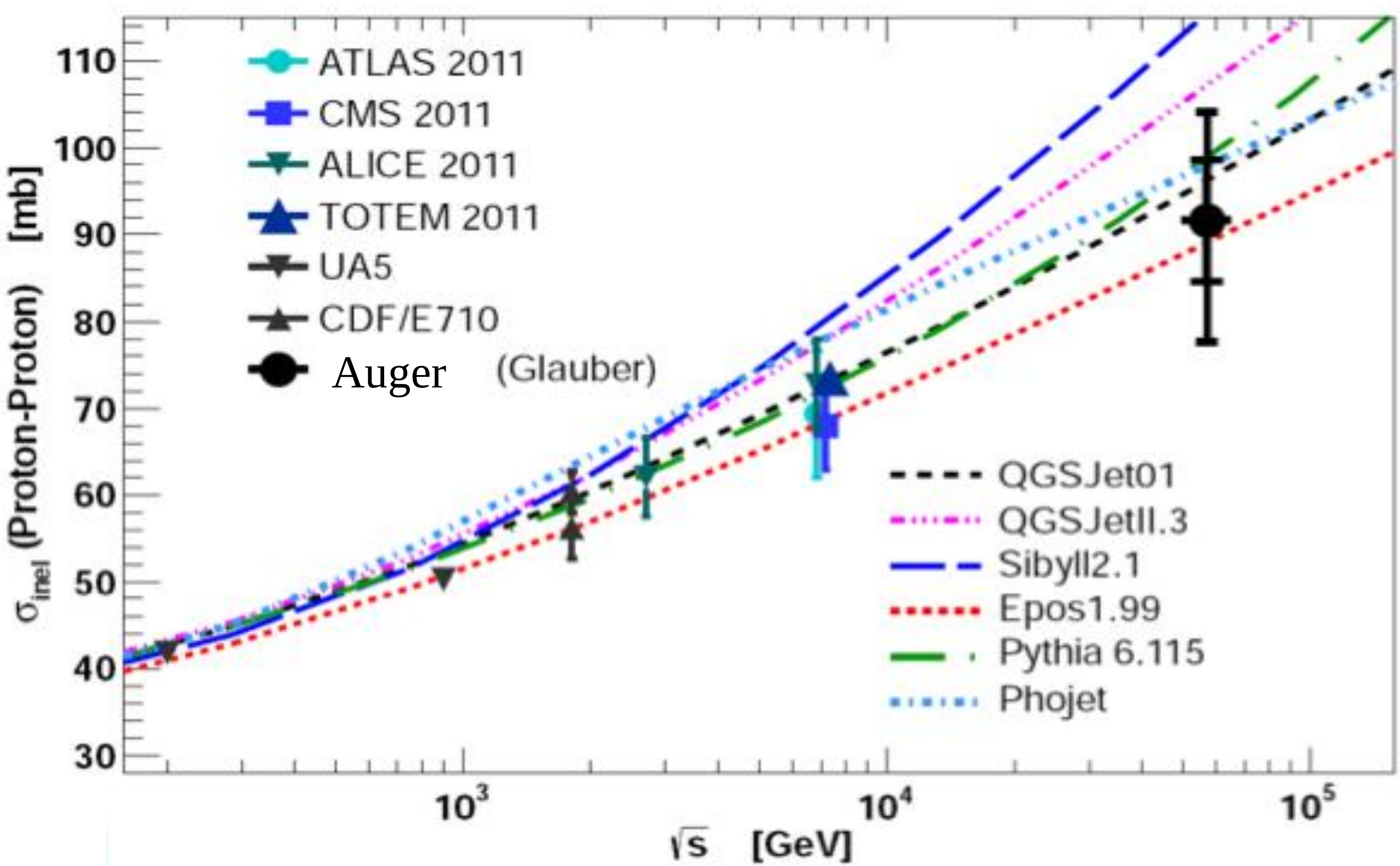
92 ± 14 mb

σ_{inel}^{TOTEM} (7 TeV) = 73.1 ± 1.3 mb
σ_{inel}^{TOTEM} (8 TeV) = 74.7 ± 1.7 mb

σ_{el}^{TOTEM} (7 TeV) = 25.4 ± 1.1 mb
σ_{el}^{TOTEM}(8 TeV) = 27.1 ± 1.4 mb

σ_{el}/σ_{tot} (7 TeV) = 0.257 ± 0.020 σ_{el}/σ_{tot} (8 TeV) = 0.266 ± 0.01
$\sigma_{el}/\sigma_{inel}$ (7 TeV) = 0.354 ± 0.026 $\sigma_{el}/\sigma_{inel}$ (8 TeV) = 0.362 ± 0.011

Compilation of inelastic pp cross section

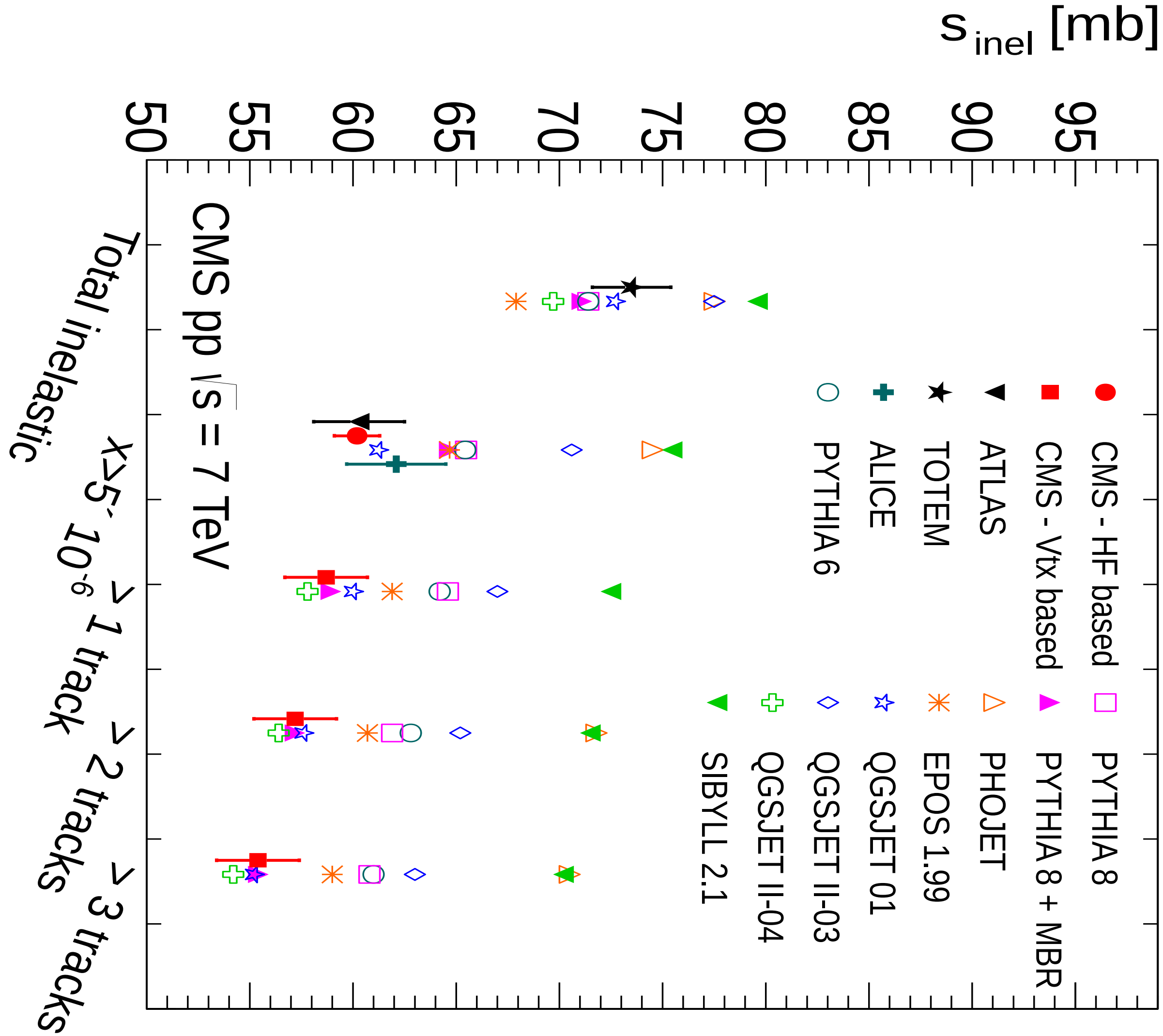


σ_{inel} for specific final states

LHC experiments have 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 specific final states and σ_{Tot}



Summary and outlook - I

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)
- σ_{Tot}(8 TeV) , σ_{El}(8 TeV) , σ_{Ine}(8 TeV)
- B slope and dip position of elastic scattering at 7 TeV
- σ_{Tot}(57 TeV) , σ_{Inel}(57 TeV)
- $\sigma_{Mx>15}$ (7 TeV) , $\sigma_{>1trk}$(7 TeV) , σ_{2trk}(7 TeV), σ_{3trk}(7 TeV)

Summary and outlook - II

The value of the total cross section σ_{tot}^{TOTEM} (8 TeV) = 101.7 ± 2.9 mb

is well reproduced by the preferred COMPETE fits, $\sigma_{tot}^{COMPETE}$ (8 TeV) = 101 ± 5 mb (~ $\ln^2(s)$) while the 2-pomeron prediction, $\sigma_{tot}^{2\text{-pomeron}}$ (8 TeV) ~ 125 ± 5 mb, is disfavored.

Commonly used MCs such as PYTHIA do not reproduce correctly the "sub-components" of the total cross section.

LHC data at 7 & 8 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: the extrapolation between LHC @ 14 GeV and AUGER is the same as Tevatron → LHC.

Please invite me back in 3 years, 14 TeV in 2015!!

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
7. COMPETE collaboration (and reference in the linked page): http://hermes.ihep.su:8001/compas/kuyanov/OK/eng/intro.html
8. Many articles from the "13th Int. Conf. on Elastic and Diffractive Scattering CERN", http://indico.cern.ch/conferenceOtherViews.py?confId=41547&view=standard&showDate=all&showSession=all&detailLevel=contribution

EXTRA

Experimental reach of t and β*

Beam angular spread:

$$\sigma(\theta) \sim \sqrt{(1/\beta^*)}$$

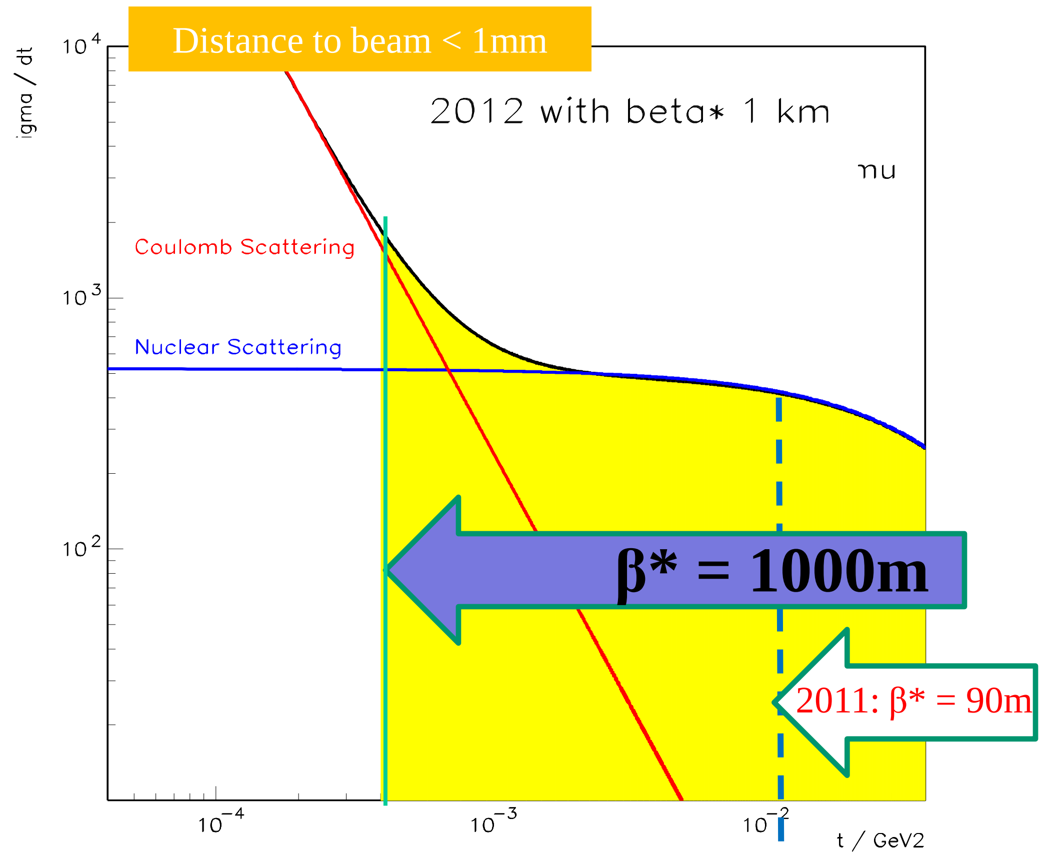
Low t requires very small angular spread ➔ very large β*

October 24-25, 2012:

β*: 11 → 90 → 500 → 1000m

de-squeeze in 45 minutes

2012: β* = 1000m



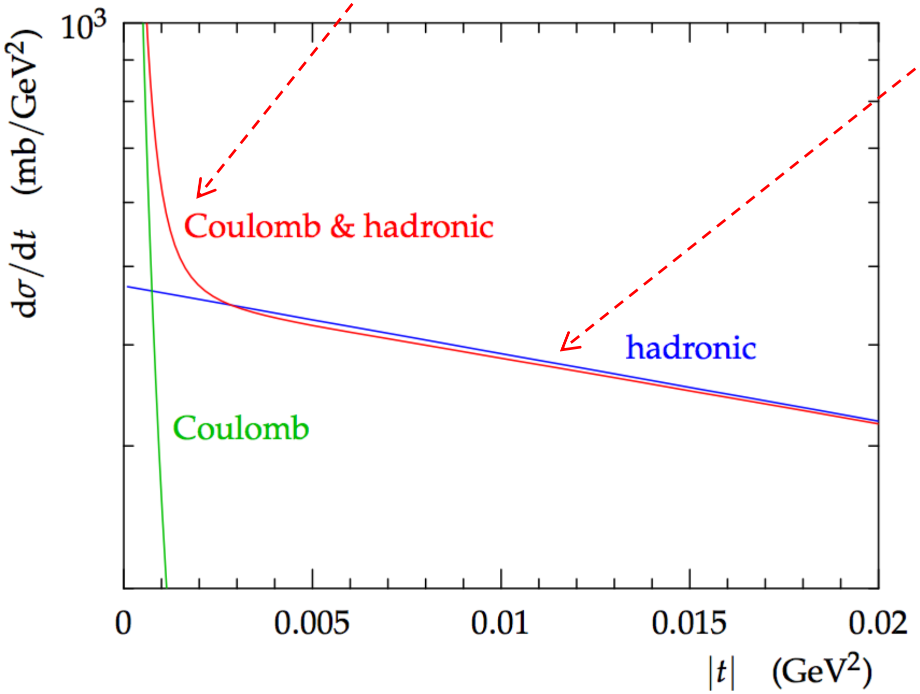
The Coulomb peak at t = 0

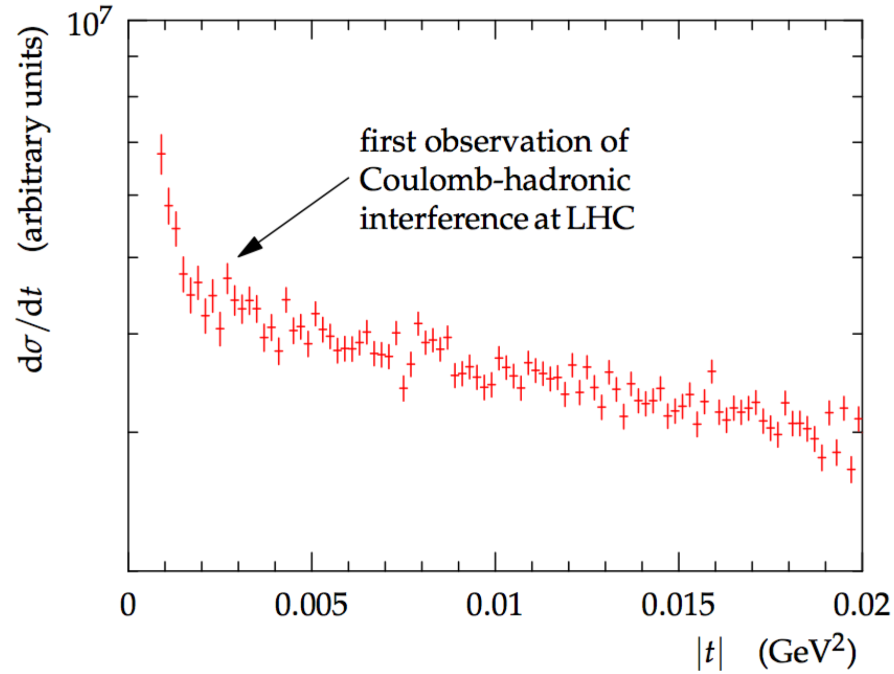
The t slope changes as a function of t value.

We need to measure this part

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

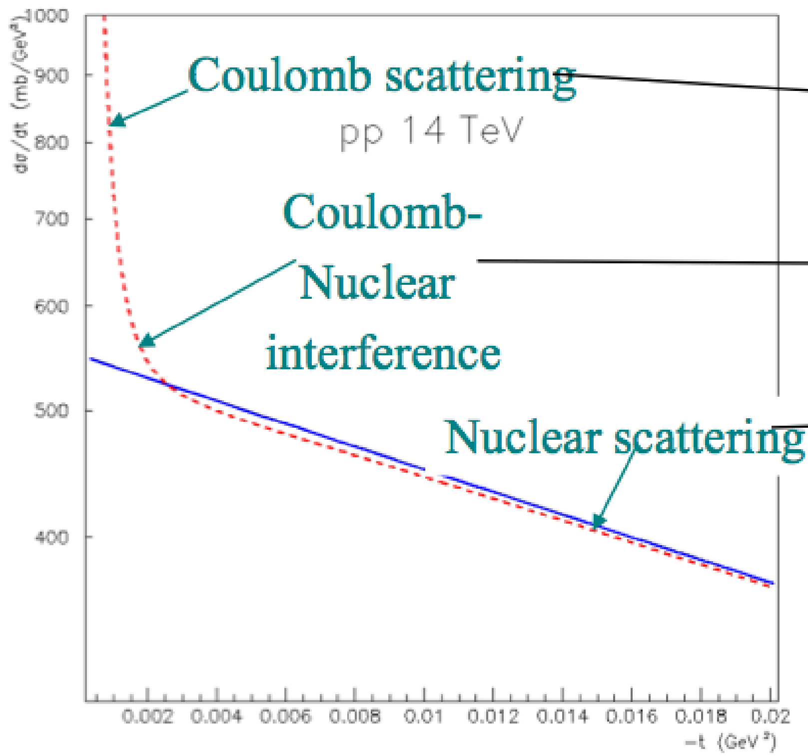
Do no use: Coulomb part





Measurement of ρ by studying the Coulomb – Nuclear interference region down to **$|t| \sim 6 \times 10^{-4}$ GeV^2**

Measuring ρ using the Coulomb part



$$\frac{d\sigma}{dt} =$$

$$\frac{4\pi\alpha^2(\ c)^2 G^4(t)}{|t|^2} +$$

$$\frac{\alpha(\rho - \alpha\phi)\sigma_{tot} G^2(t)}{|t|} e^{-B|t|/2} +$$

$$\frac{\sigma_{tot}^{\ 2}(1+\rho^2)}{16\pi(\ c)^2} e^{-B'|t|}$$

a = fine structure constant

ϕ = relative Coulomb-nuclear phase

G(t) = nucleon em form factor = $(1 + |t|/0.71)^{-2}$

ρ = Re/Im f(p←p)

Measure the exponential slope B in the t-range 0.002 - 0.2 GeV^2

From Marco Bozzo

Experimental coverage of rapidity

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

ALICE covers $-3.7 < \eta < 5.1$

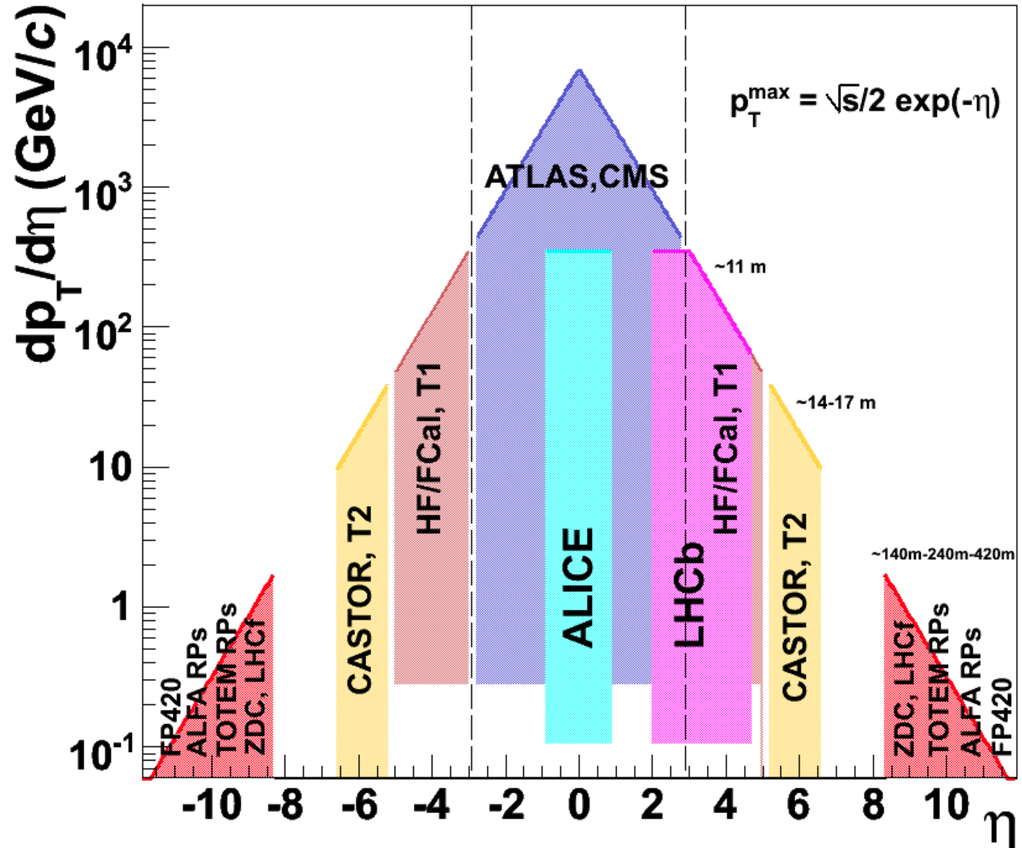
TOTEM has two detectors:
T1: $3.1 < |\eta| < 4.7$, T2: $5.3 < |\eta| < 6.5$,
$\xi > 2 * 10^{-7}$ (Mx ~ 3.4 GeV)

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

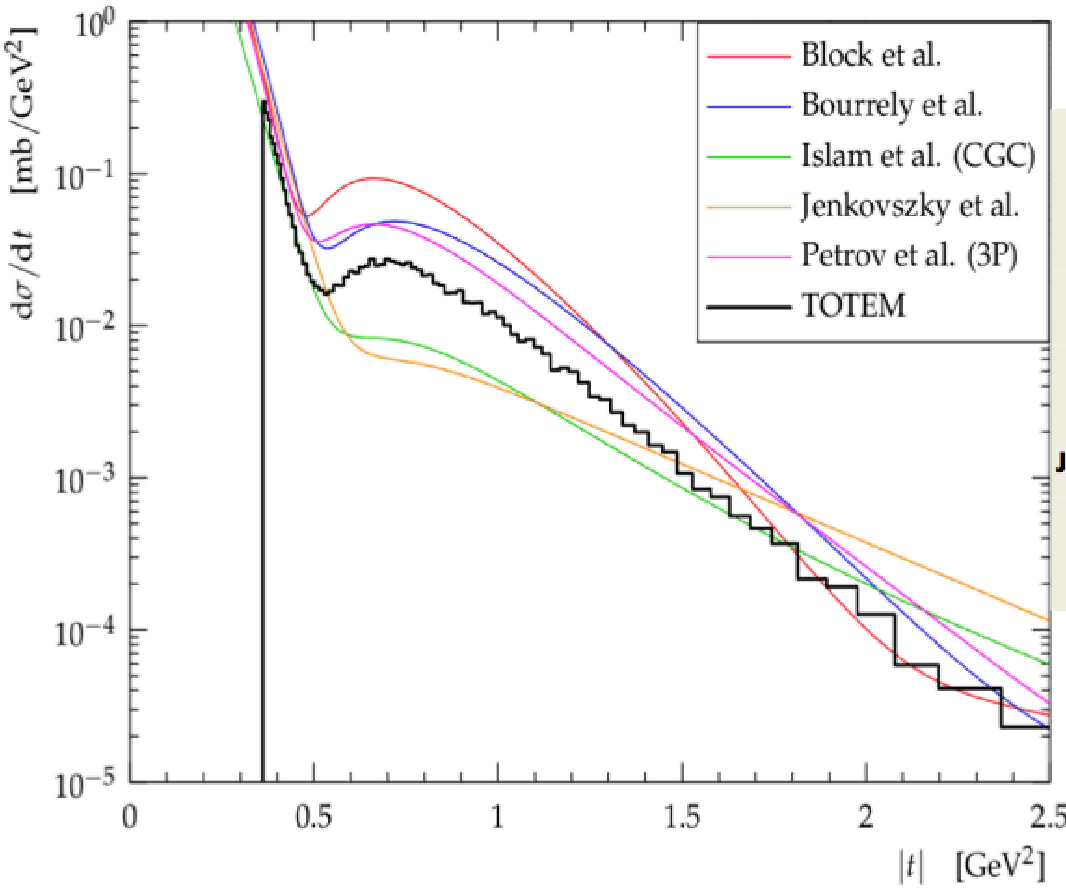
Solutions:

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

LHC detectors coverage



TOTEM: t-distribution of pp elastic scattering at @ 7 TeV



	B (t=-0.4 GeV²)	t_{DIP}	t^{-x} [1.5–2 GeV²]
Block	25.3	0.48	10.4
Bourrely	22.0	0.54	8.4
Islam	20.2	0.60	5.0
Jenkovsky	20.1	0.72	4.2
Petrov	23.3	0.51	7.0
TOTEM	23.6 ± 0.3	0.53 ± 0.01	7.8 ± 0.3

The t-distribution measured by TOTEM was not predicted by any of the dynamical models of the proton

Predictions for 14 TeV (pre-LHC)

J. R. Cudell:

The measurement of the total cross section at the LHC will tell us a lot about the analytic structure of the amplitude, as there is a variety of predictions that span the region from 90 to 230 mb:

- $\sigma_{tot} > 200$ mb: the only unitarisation scheme able to accommodate such a large number is the U matrix. It basically predicts the same inelastic cross section as more standard schemes, but the elastic cross section is much larger, and accounts for the difference.

- 120 mb $< \sigma_{tot} <$ 160 mb: this would be a clear signal for a two-pomeron model, and would also tell us about the unitarisation scheme.

- $\sigma_{tot} \approx 110$ mb: this is the standard prediction not only of the COMPETE fits, but also of many models based on a simple eikonal and only one pomeron pole.

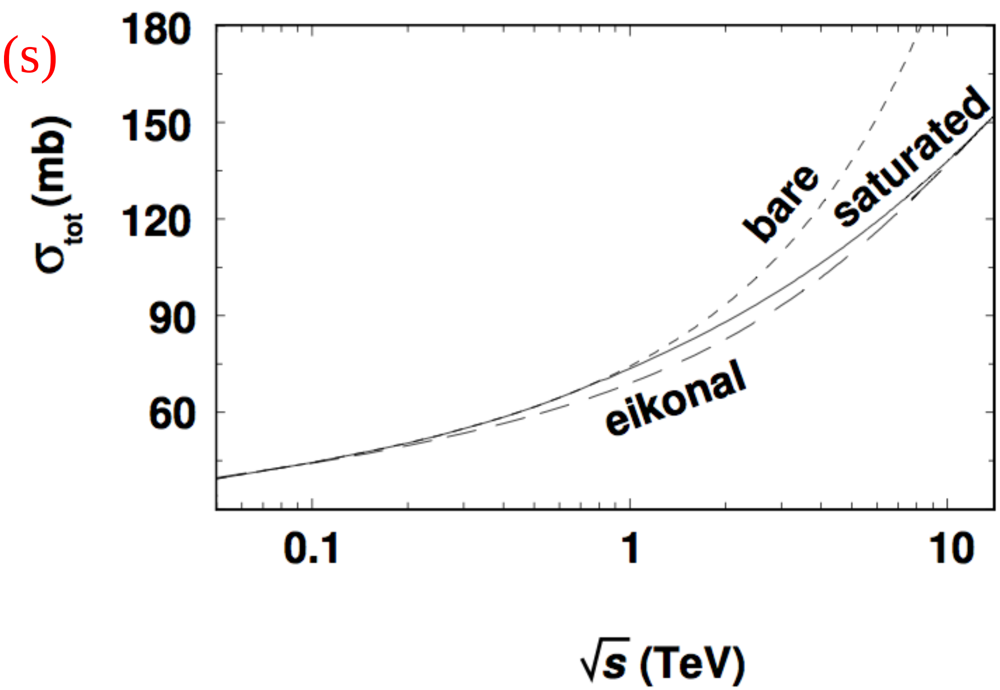
- $\sigma_{tot} < 100$ mb: this would indicate either the validity of double-pole parametrisations, or that of unitarisation schemes in which multiple-pomeron vertices are important.

Cross Section Bounds

Problem: the infinite rise of the cross section violates unitarity. The predictions have incorporated various processes and unitarity constrains that tame the rise of the value of the cross section.

This process is called "unitarization"

Two-pomeron model without and with simple unitarization models



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

$\sigma_{El}(s) \sim s^{2\varepsilon}$

$\sigma_{Tot}(s) \sim s^{\varepsilon}$

At high energy: $s^{2\varepsilon} > s^{\varepsilon}$

TOTEM: Shrinkage and $\sigma_{el} / \sigma_{tot}$ @ 7 TeV

The shrinkage of the forward peak continues, the proton becomes larger and larger.

The elastic component is becoming more important with energy