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: $\sigma_{Tot,}\ \sigma_{SD,}\ \sigma_{DD}$

F) Implication of the new results

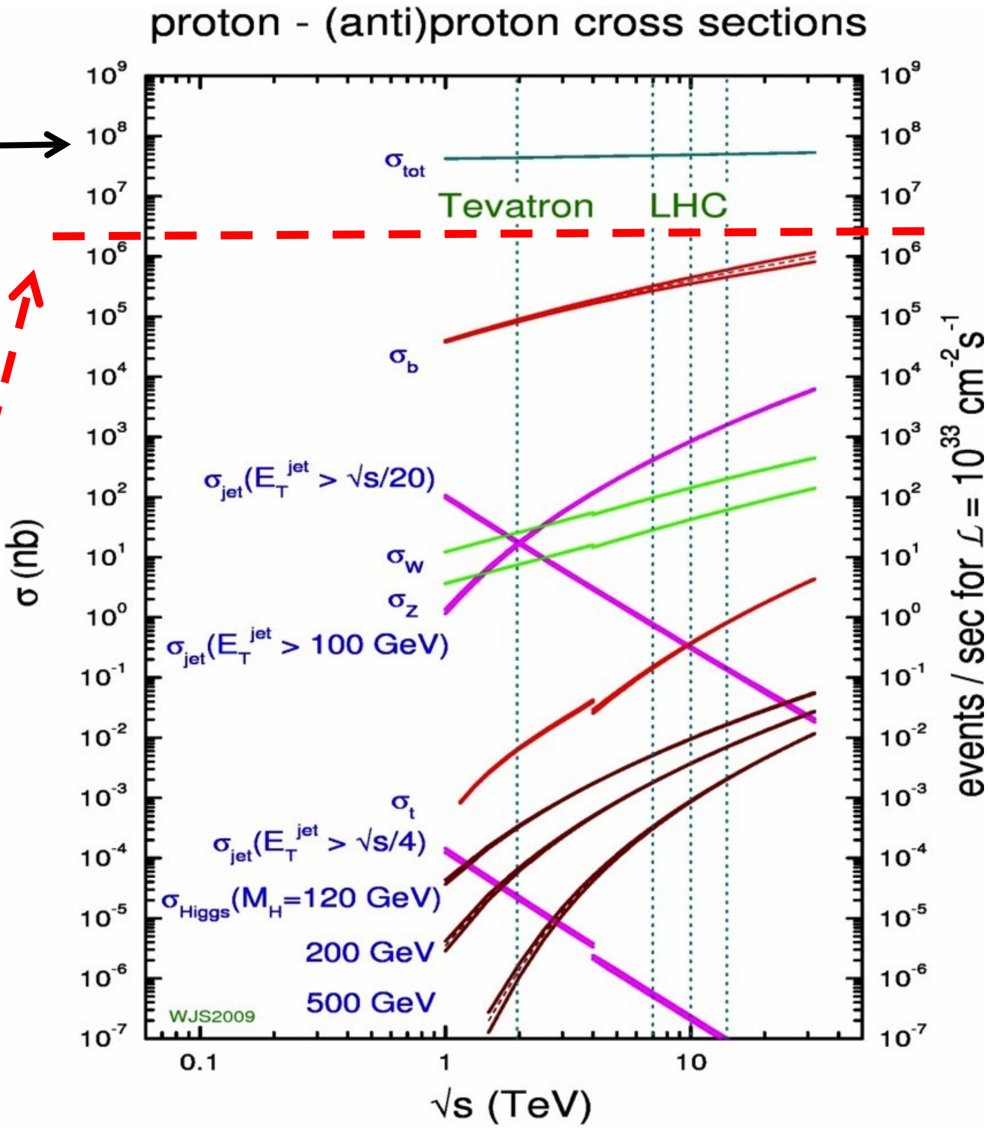
Let's set the scale…

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

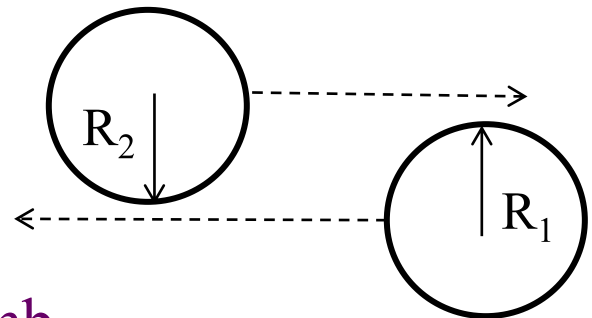
What does it means "100 mb"?



Units and billiard balls

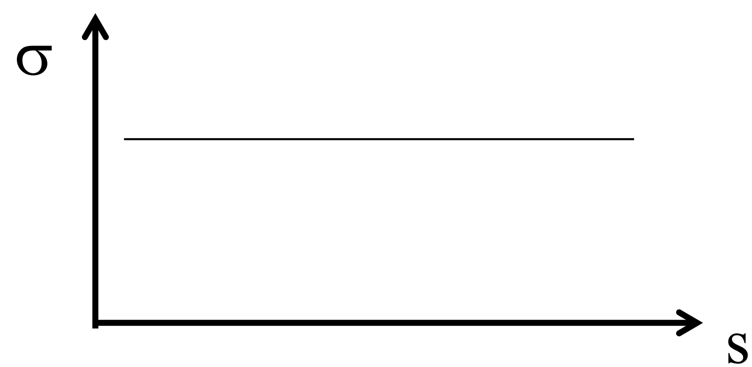
The cross section of 2 hard balls of radius R_1, R_2 is:

$$\sigma = \pi * (R_1+R_2)^2$$



If $R_1 = R_2 = 10^{-13}$ cm ➔ $\sigma \sim 10^{-25}$ cm^2 = 100 mb

Note: The cross section of two hard balls does not depend on the energy of the scattering process:



Cross section in particle physics

In particle physics, the total cross section is not simply related to the geometrical side of the participants.

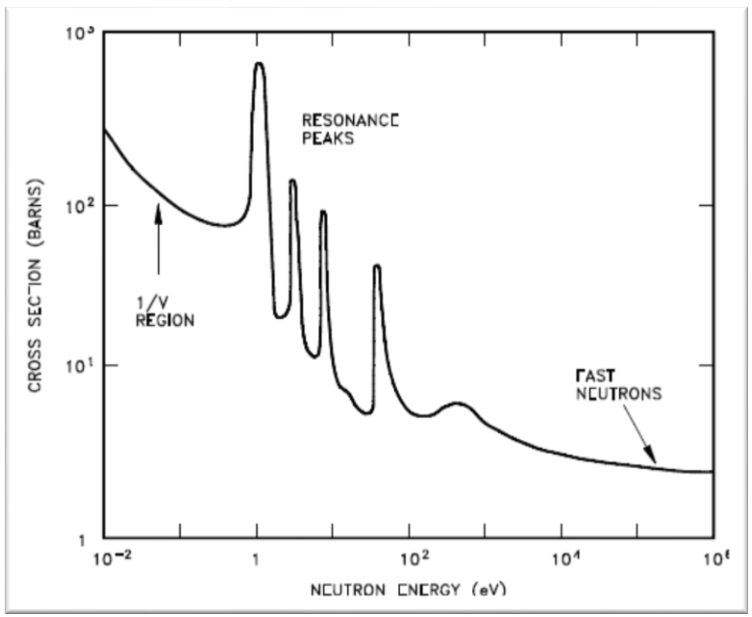
For example:

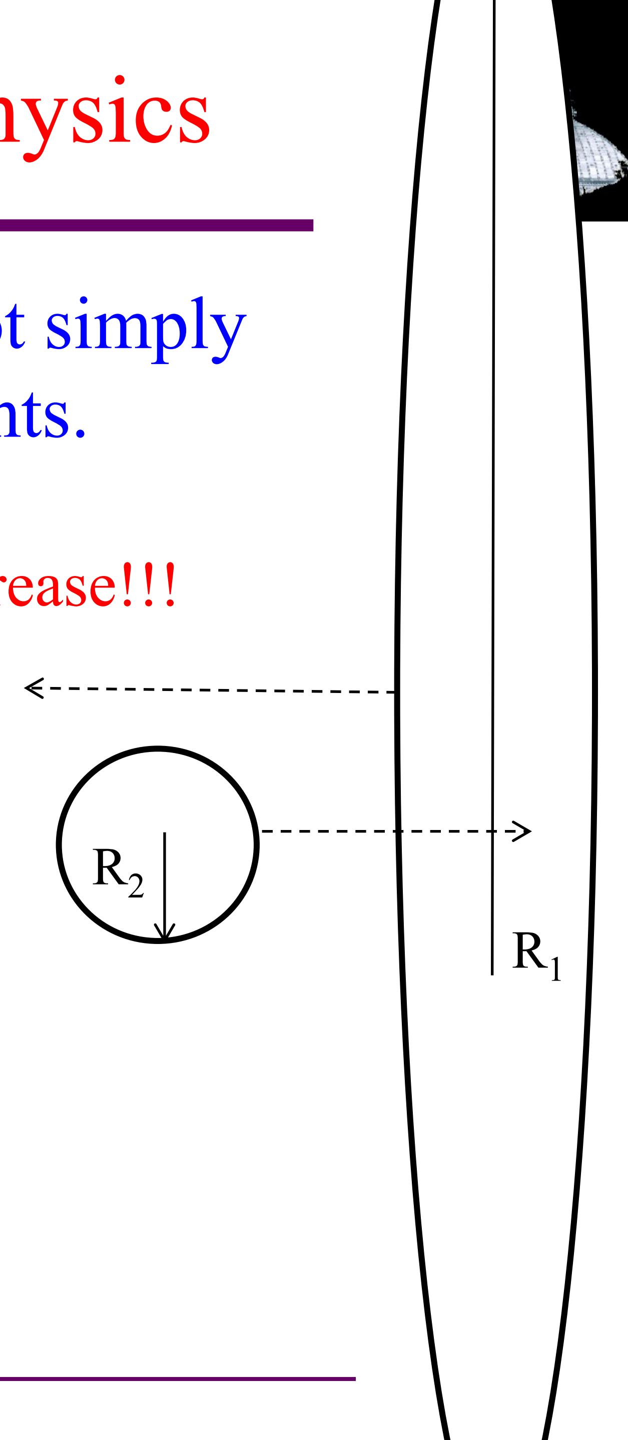
Boron's cross-sectional area ~ 0.1 barn

Boron neutron-capture reaction ~1,200 barns

} 10^4 increase!!!

It also depends on the energy:

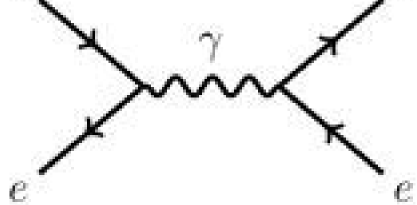


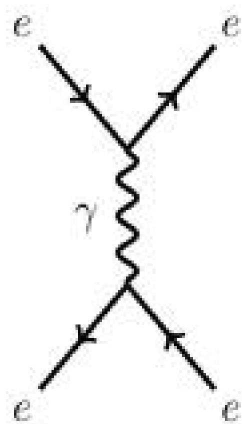


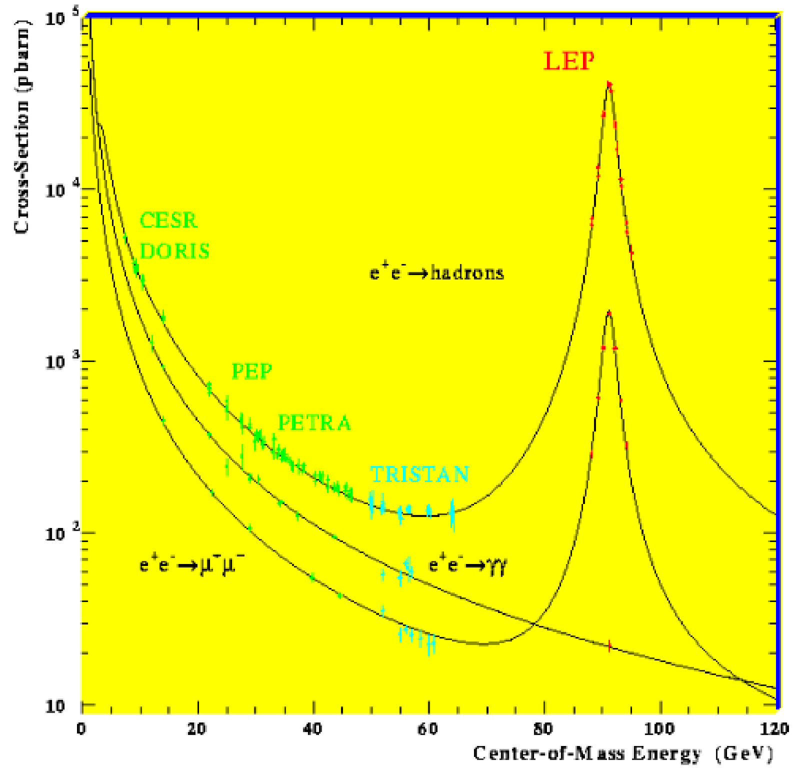
Scattering of elementary particles

The cross section of elementary particles, for example $e^+ e^-$, has a 1/s dependence, plus possible resonances.

$\sigma \approx 1/s$



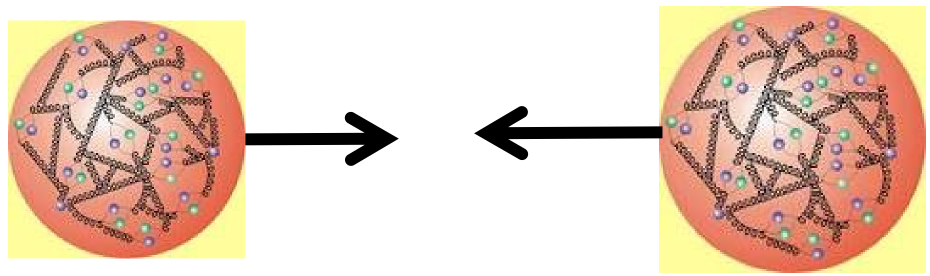




This dependence is due to the combination of the matrix element and the phase space, and it's calculable.

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 quark

-sea quark

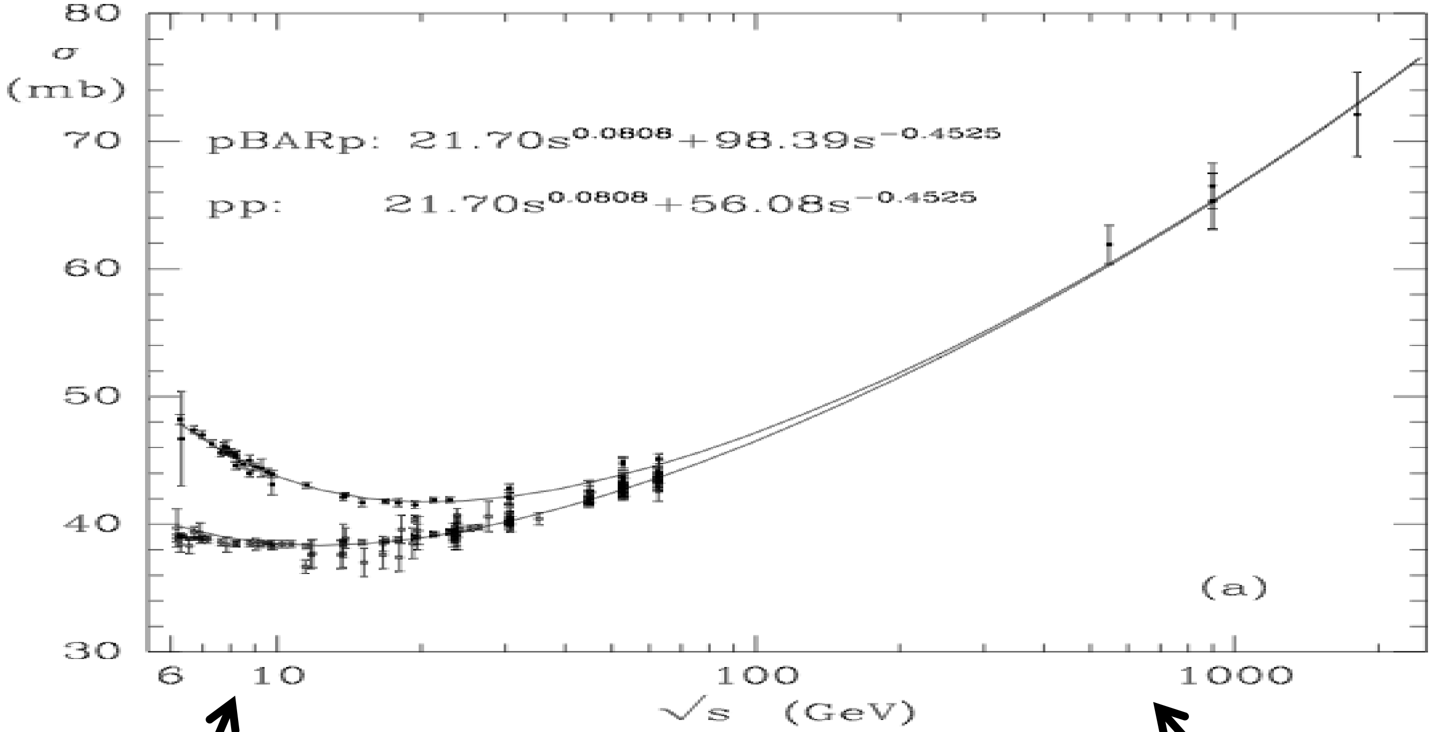
-gluons

This defines 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

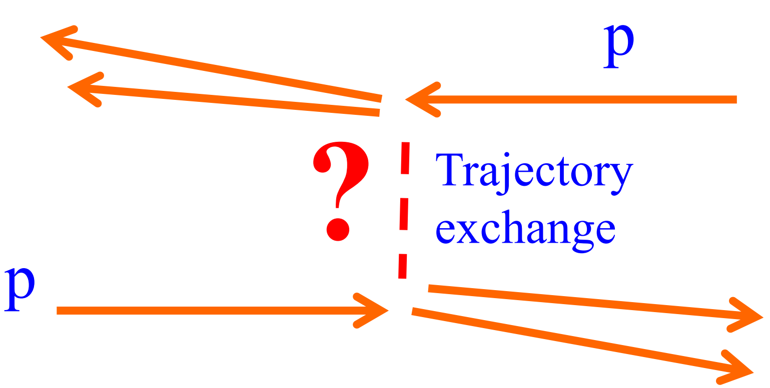
At high energy σ is the same: only sea quarks and gluons can contribute

Theoretical framework: Regge Theory

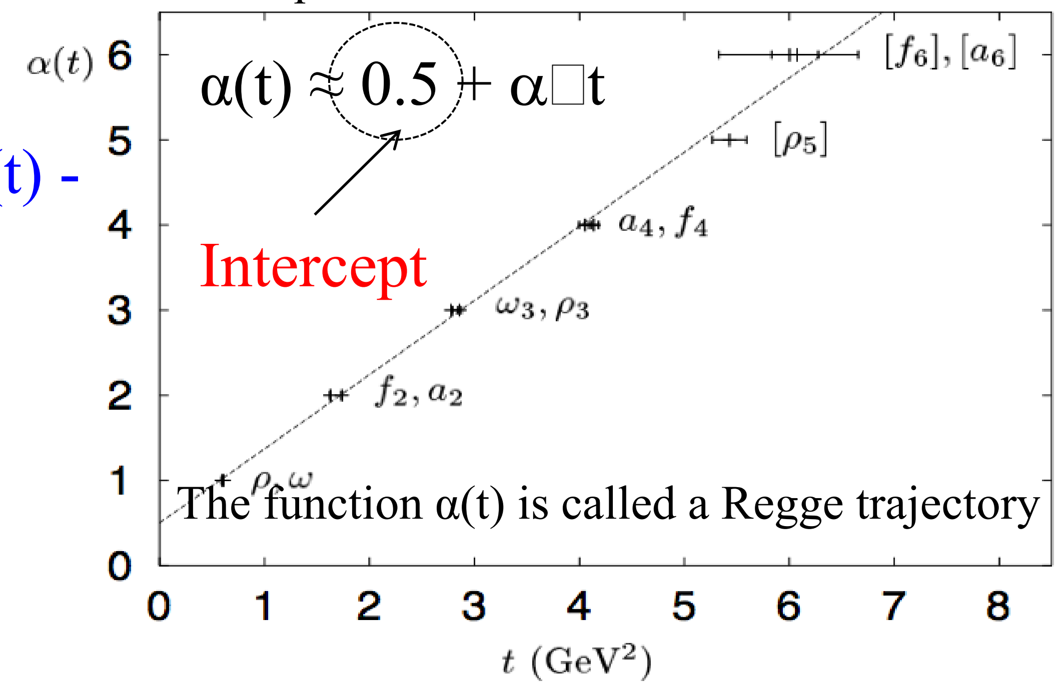
"Regge Theory", and derivations, is the language used to describe the total cross sections of hadron-hadron scattering.

The behavior of the total cross section depends on the sum of exchanges of groups of many particles, called trajectories

The particles are grouped into trajectories, with a given slope and intercept when plotted in the mass (t) - spin plane



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



Contribution of each trajectory to σ

Each trajectory contributes to σ according to this expression:

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

All known particles lie on trajectories such as: $\alpha(t) \approx 0.5 + \alpha' t$

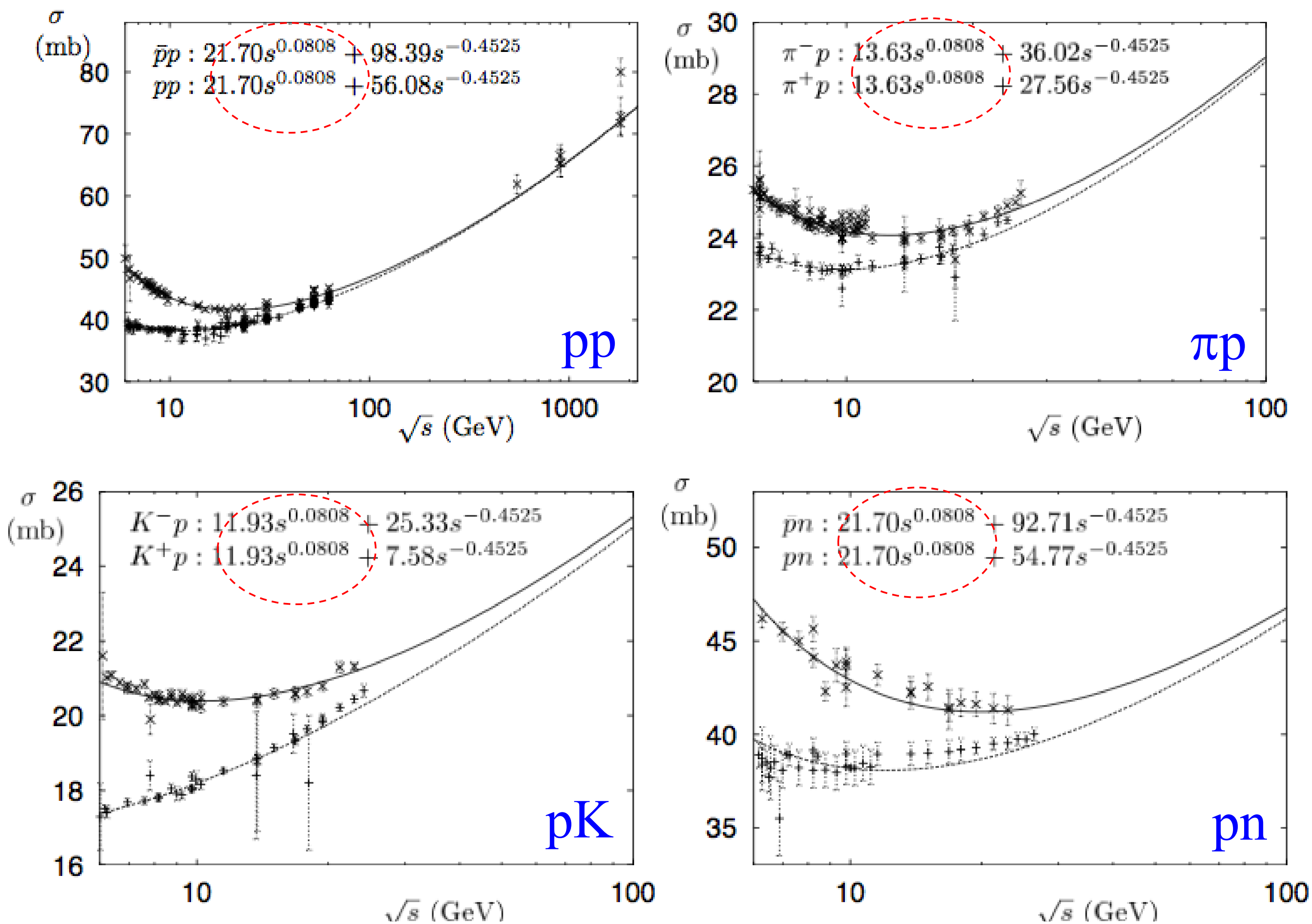
And therefore the prediction for the total cross section is:

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

So, it should decrease with s.

However….

Overview of hadronic cross sections



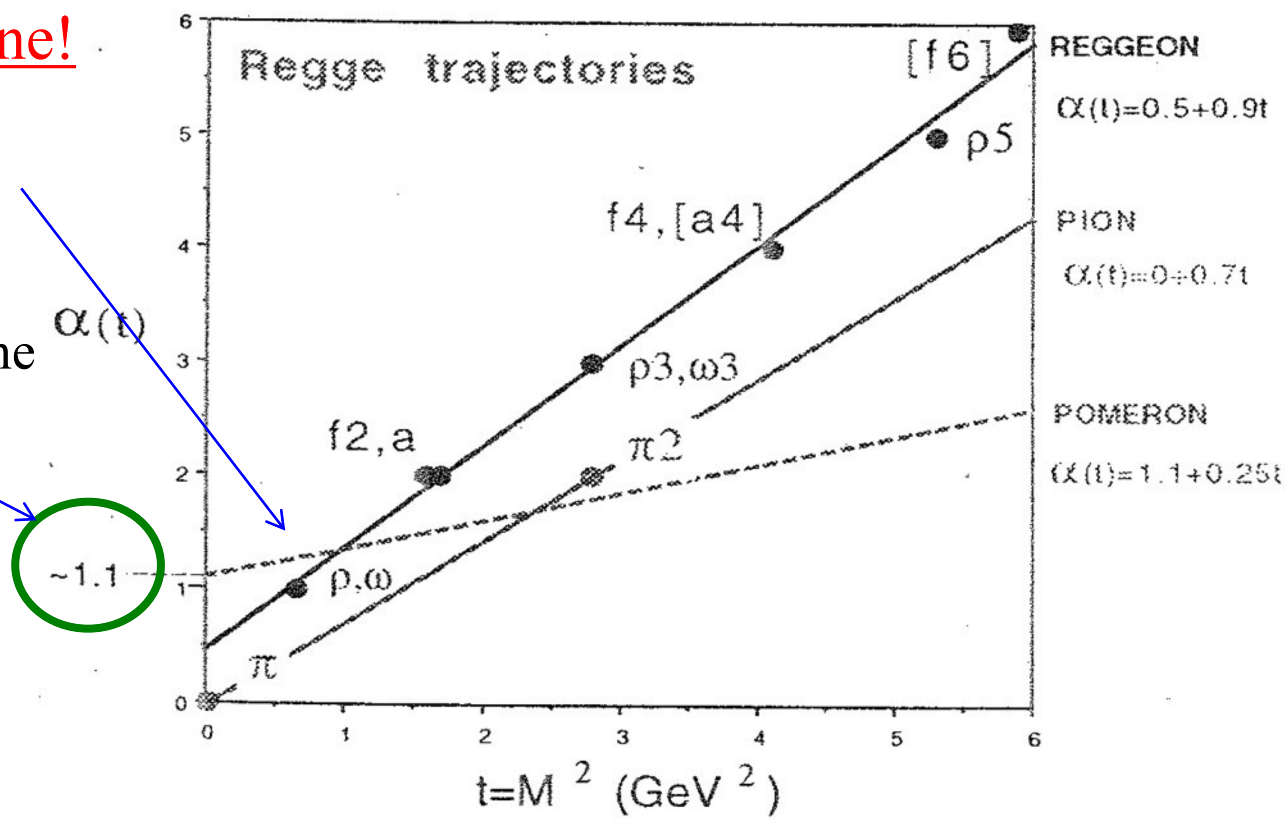
The cross section is raising at high energy: every process requires a trajectory with the same positive exponent: $s^{0.08}$…..something is clearly missing

The advent of the Pomeron

Intercept larger than one!

A trajectory without known particles

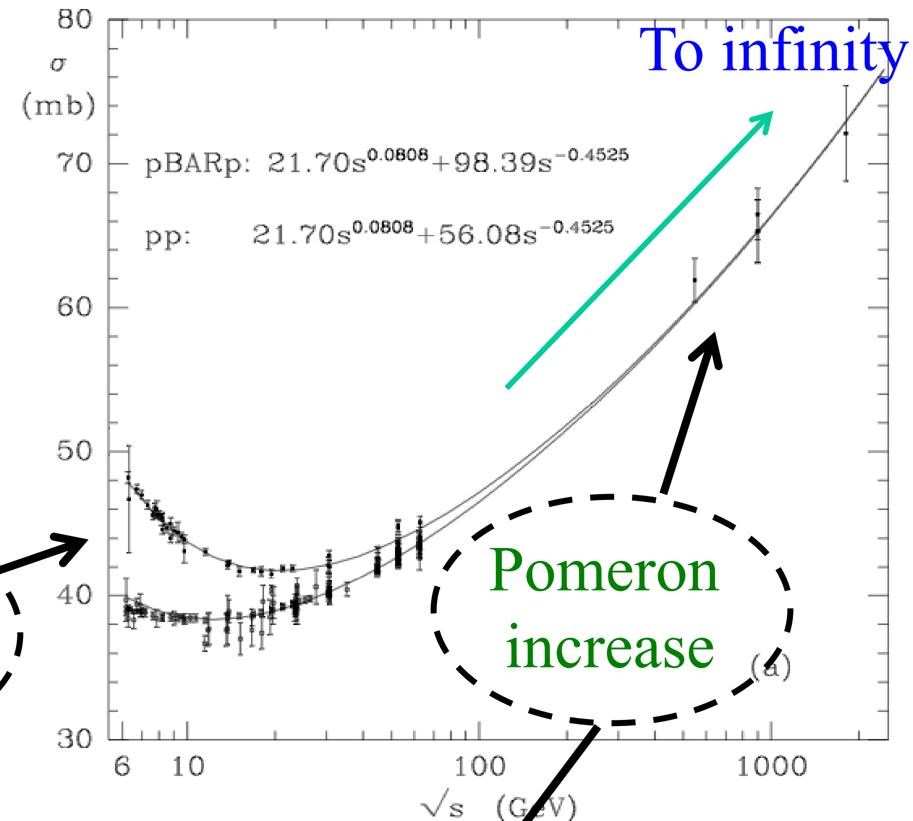
Intercept larger than one



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.

Regge Theory: master formula pre LHC

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



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:

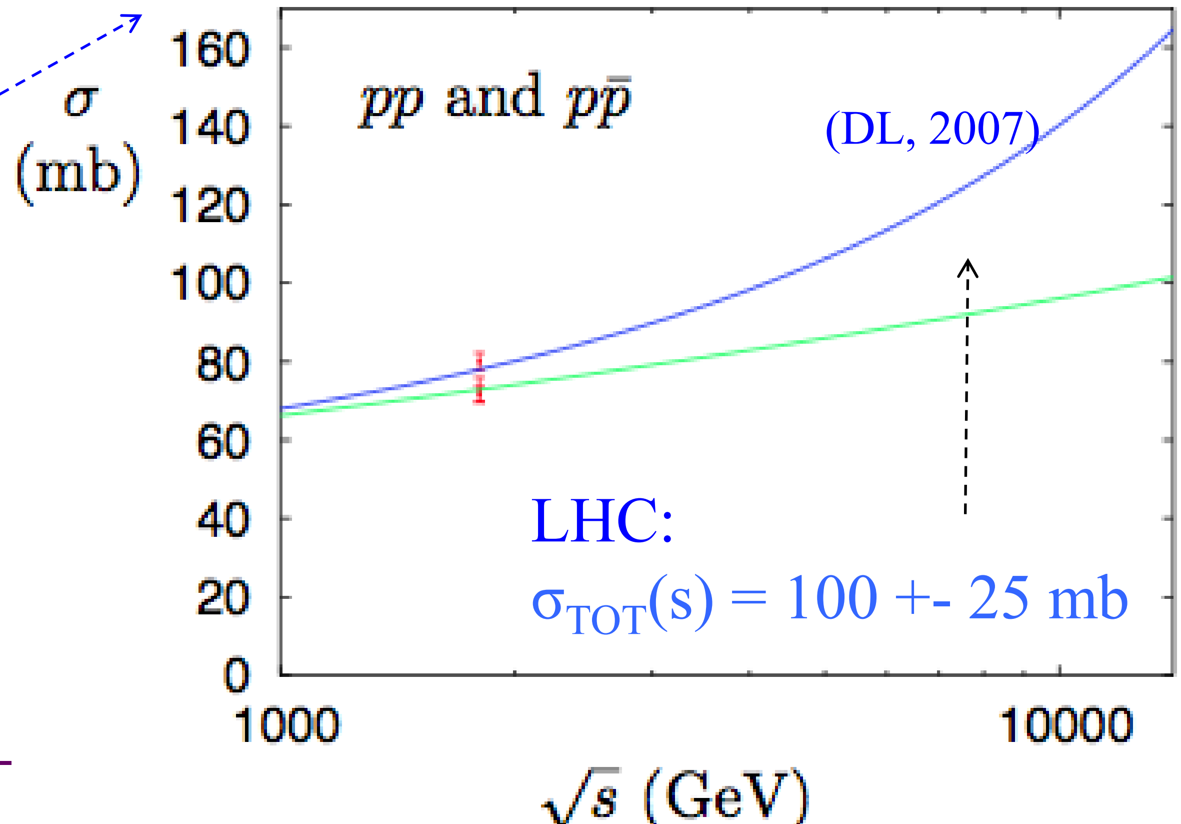
The cross section will start rising more rapidly at higher energy.

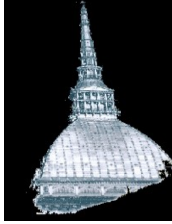
Regge Theory: master formula for higher energy

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

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

Steeper increase with energy





Cross section Bounds

Problem: some relationships violates unitarity.

Froissart-Martin bound: $\sigma_{TOT}(s) < \pi/m^2_{\pi}\log^2(s)$

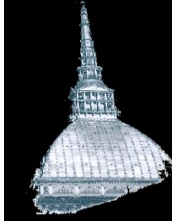
However it's not a big deal for LHC: $\sigma_{TOT} < 4.3$ barns

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

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

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

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 become daunting..

The opposite approach: perturbative QDC models

The basic block of hadronic Monte Carlo models (for example PYTHIA) is the

2➔2 pQCD matrix element

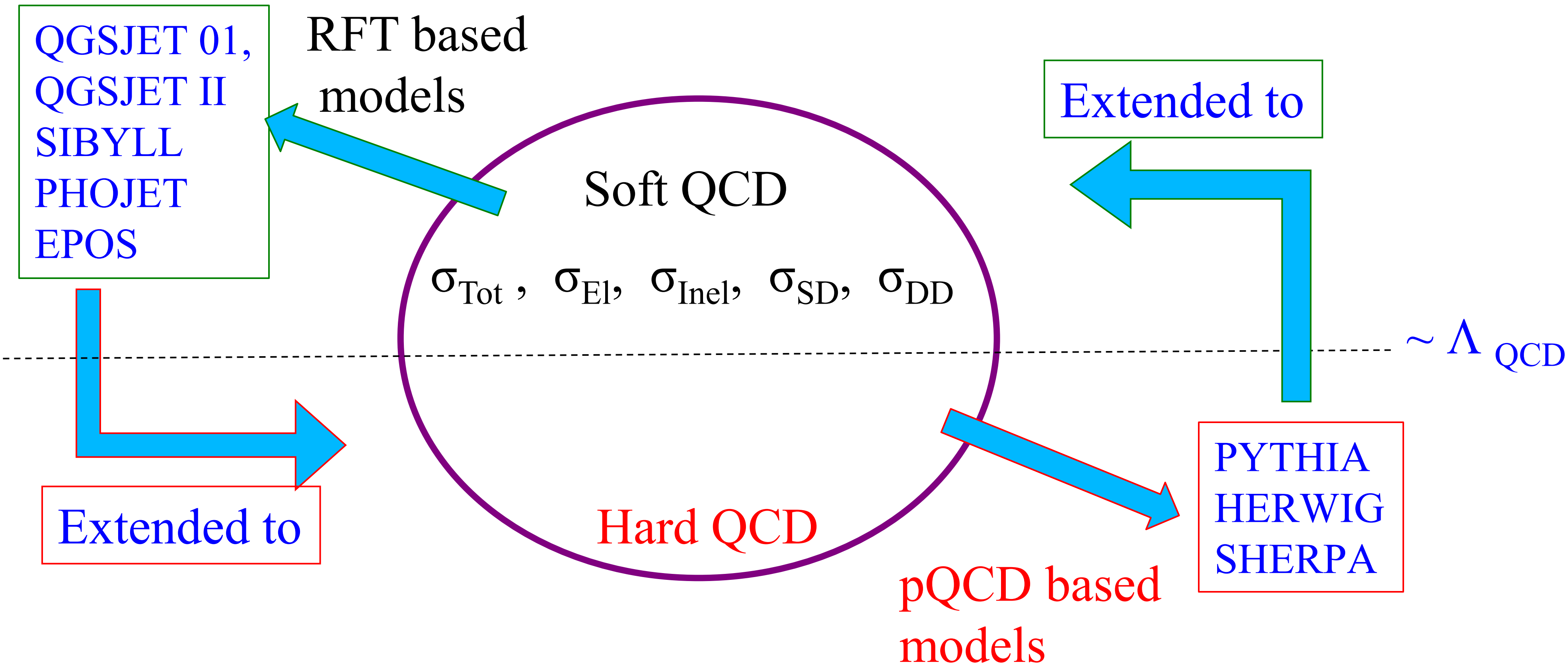
together with

ISR +FSR + PDF.

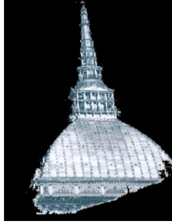
Soft QCD, diffraction and total cross sections are added by hand, using a chosen parameterization. They are not the main focus of these models.

Typical examples of parametrizations are the “Ingelman & Schlein” model or the “Rockefeller” model.

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: gaps everywhere.

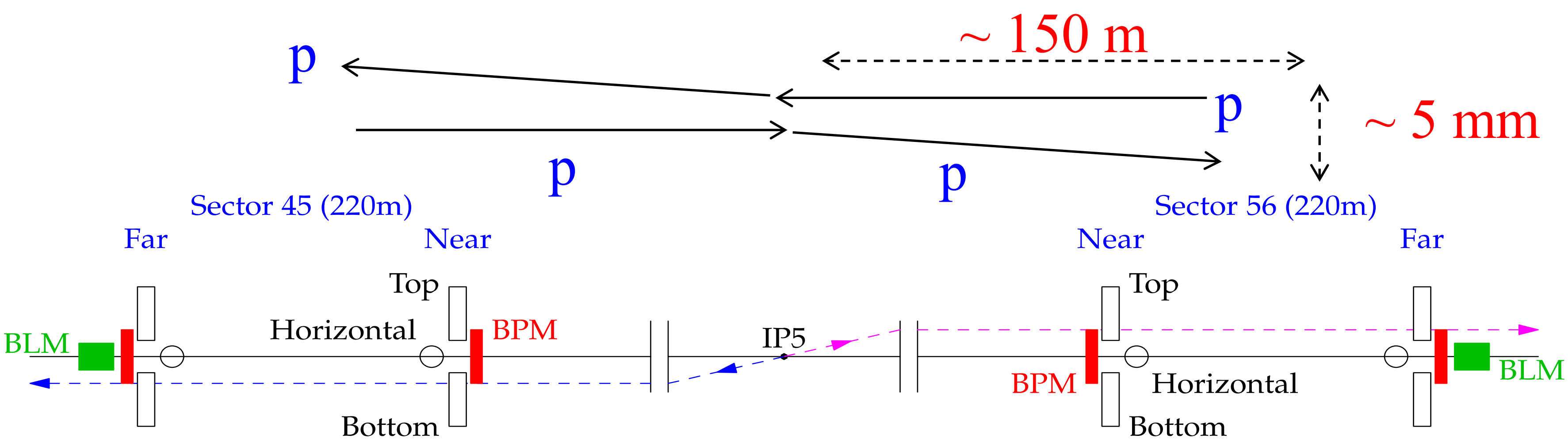
➔ Quite difficult, some events have very small mass, difficult to distinguish diffraction from standard QCD.

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

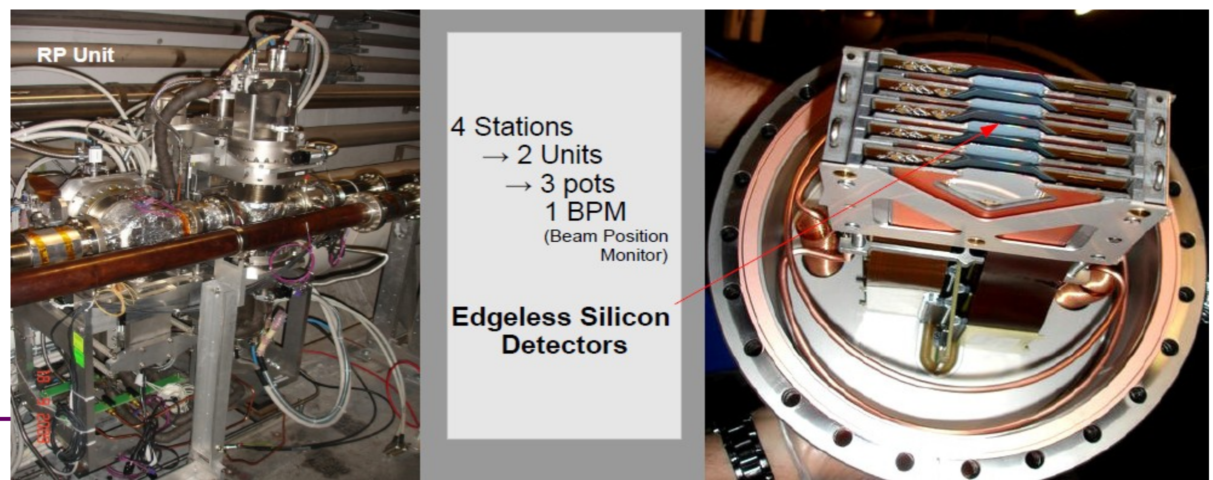
➔ Easy

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

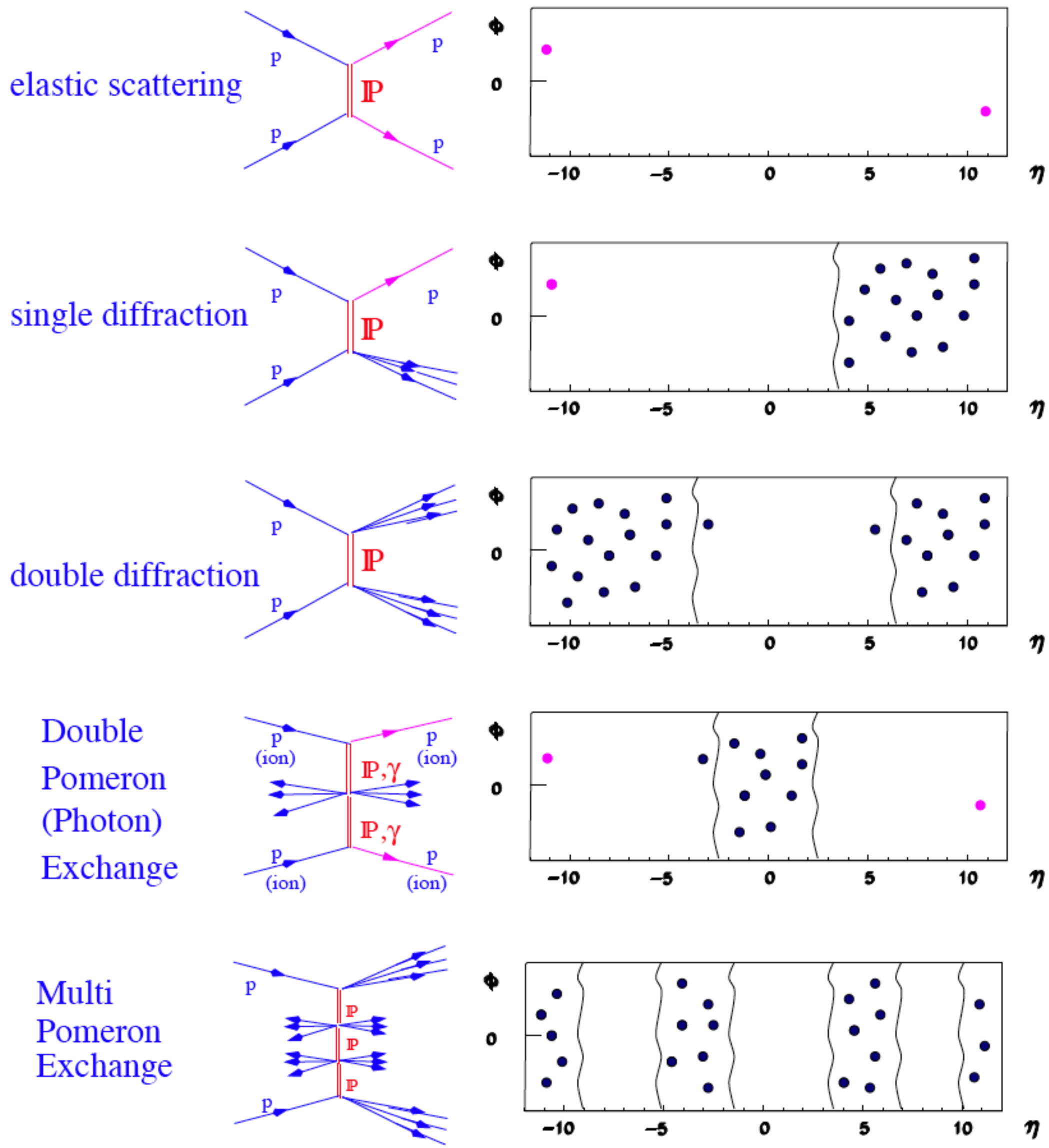


The difficult part: pomeron exchange

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

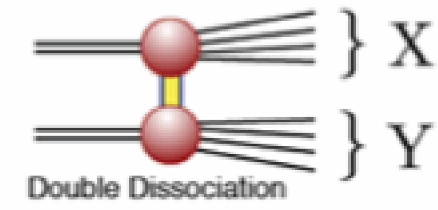
Many different topologies to measure

Importance of very low mass events



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 $\xi_{x,y} > 10^{-6}$, $\Delta\eta_{DD} > 3$

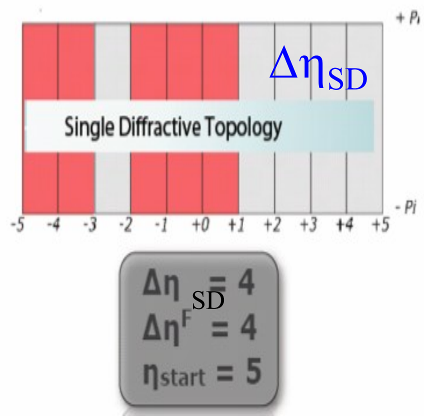
SD-like events are events with $\xi_x > 10^{-6}$ and $\xi_y < 10^{-6}$, $\Delta\eta_{SD} > 4$

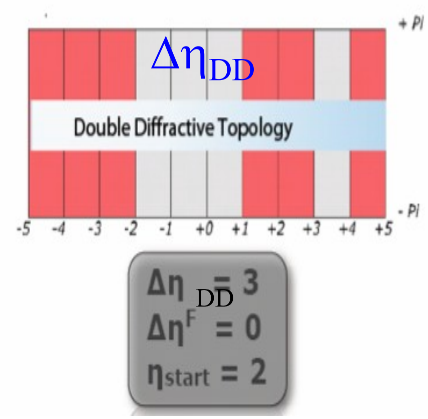
ATLAS measures the fraction of SD events, and the total fraction of events with gaps consistent with SD and DD topologies

ALICE:

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

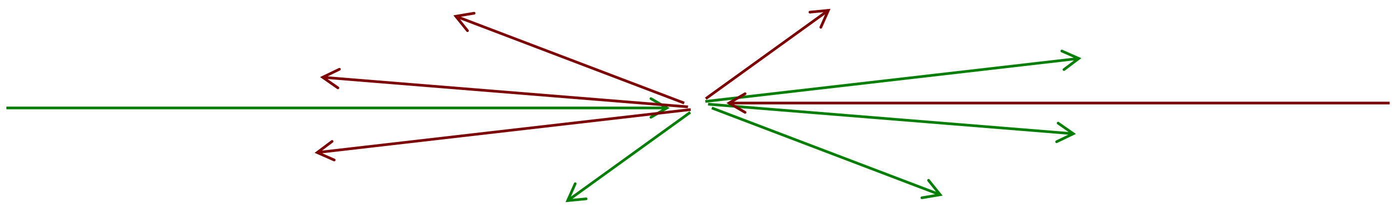
DD events are not SD, $\Delta\eta > 3$

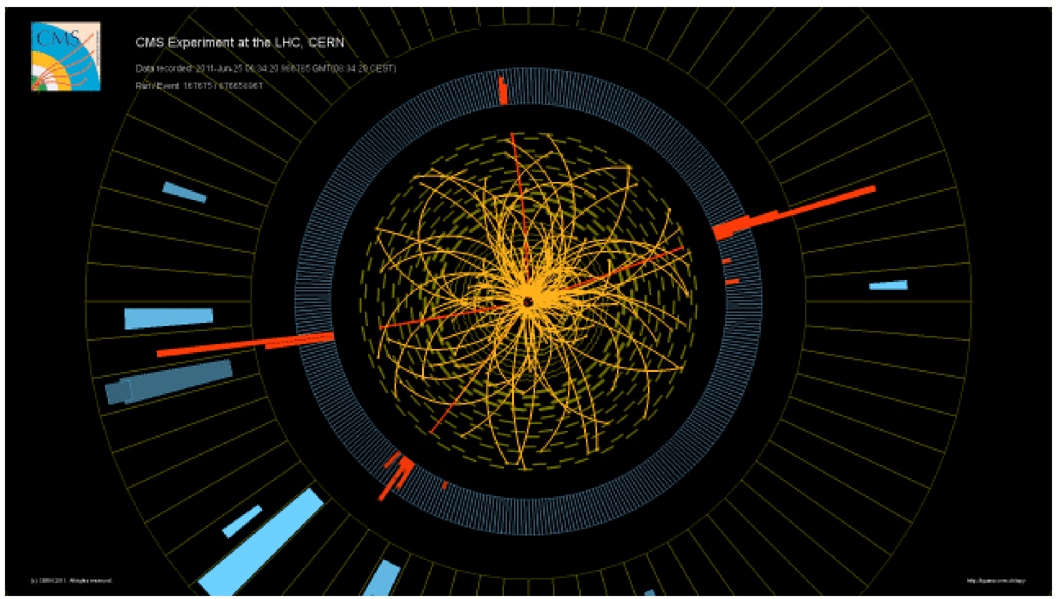




The easy part: everything else

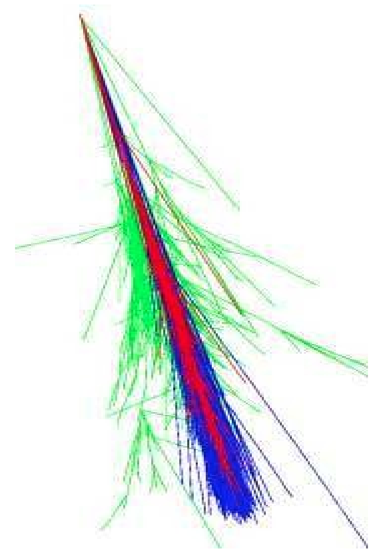
The non-diffractive inelastic events are usually not difficult to detect:



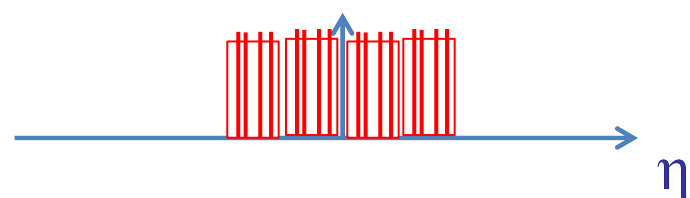


Direct measurement of parts of σ_{TOT}: cosmic-ray and collider experiments

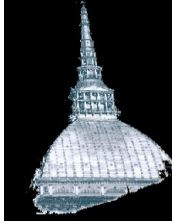
In cosmic-ray experiments (AUGER just completed its analysis), the shower is seen from below. Using models, the value of σ_{inel} (p-air) is inferred, and then using a technique based on the Glauber method, σ_{inel} (pp) is evaluated.



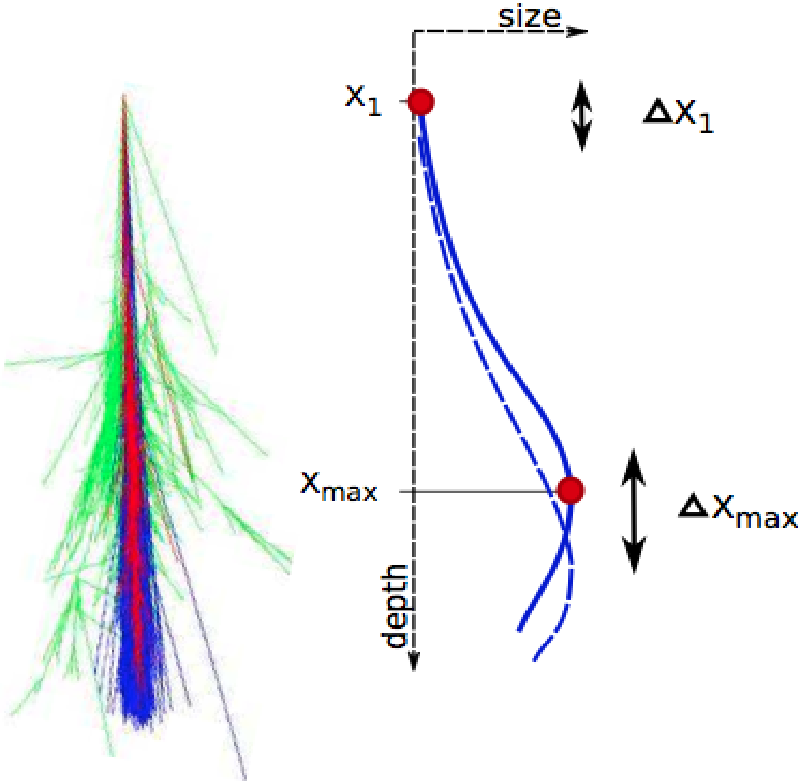
In collider experiments (currently ALICE, ATLAS, CMS, and TOTEM @ LHC), the detector covers a part of the possible rapidity space. The measurement is performed in that range, and then it might be extrapolated to $\sigma_{inel.}$



Cosmic-ray 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)



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

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

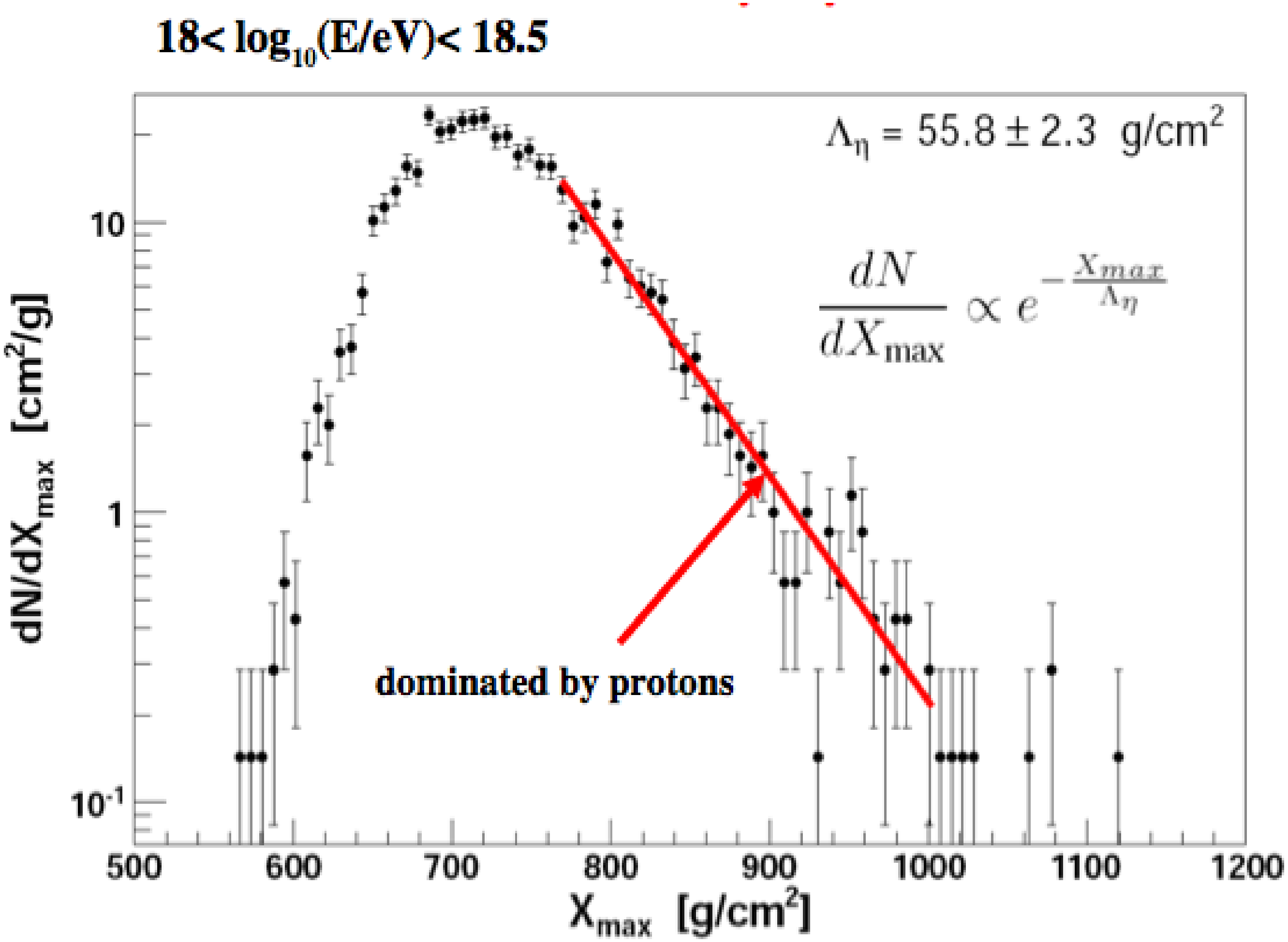
$$\sigma_{int} = \frac{<m_{air}>}{\lambda_{int}}$$

Difficulties:

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

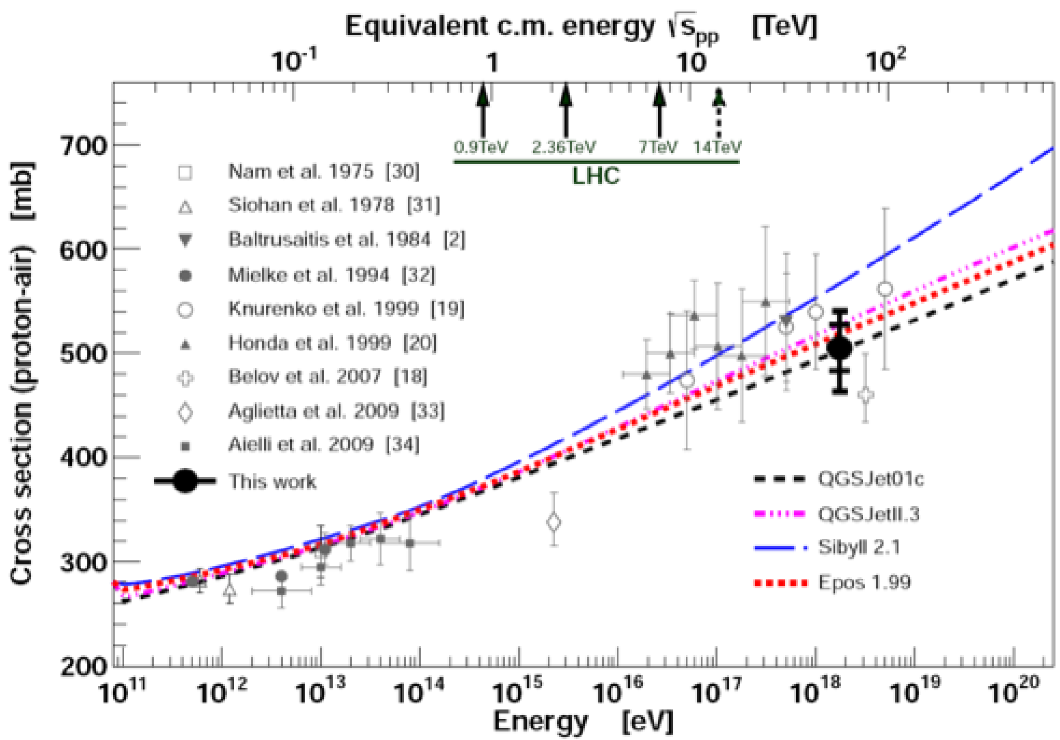
Auger: the measurement

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

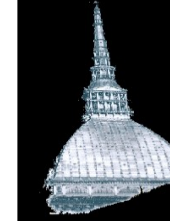
- **hadr. Models up to 19 mb**
- **energy scale 7 mb**
- **Λ_η systematics 15 mb**
- **conversion of Λ_η 7 mb**

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

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

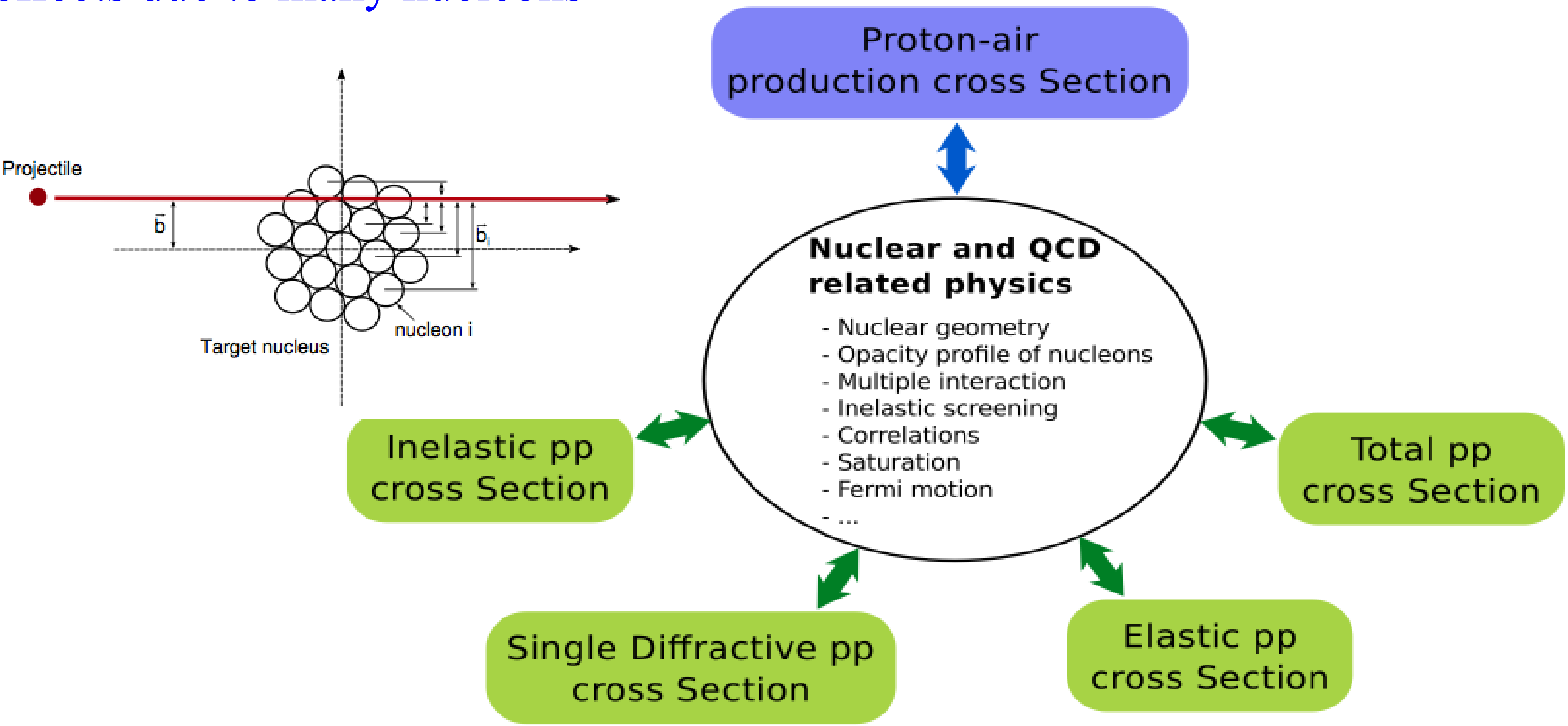
Additional Uncertainties due to diverse contaminations:

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



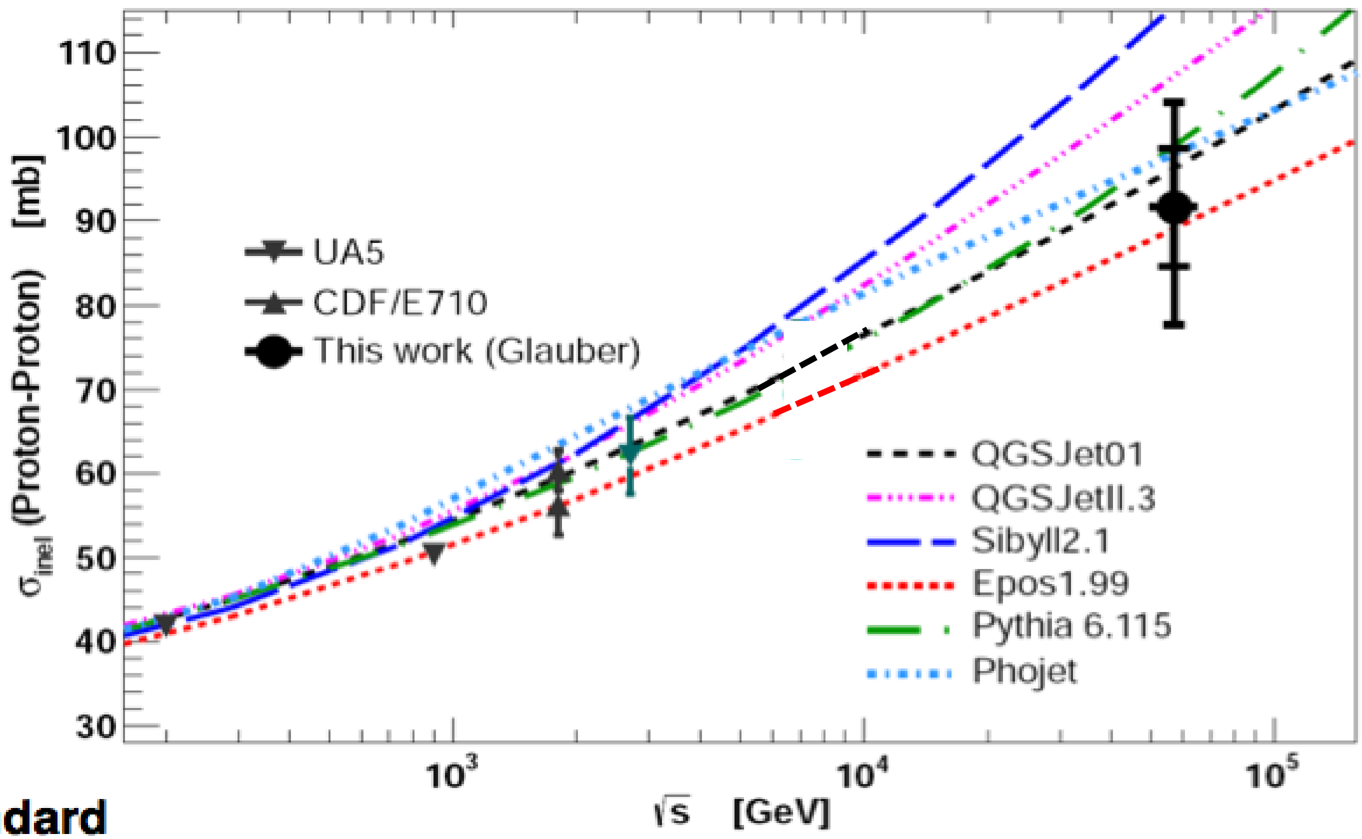
The Glauber model

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)

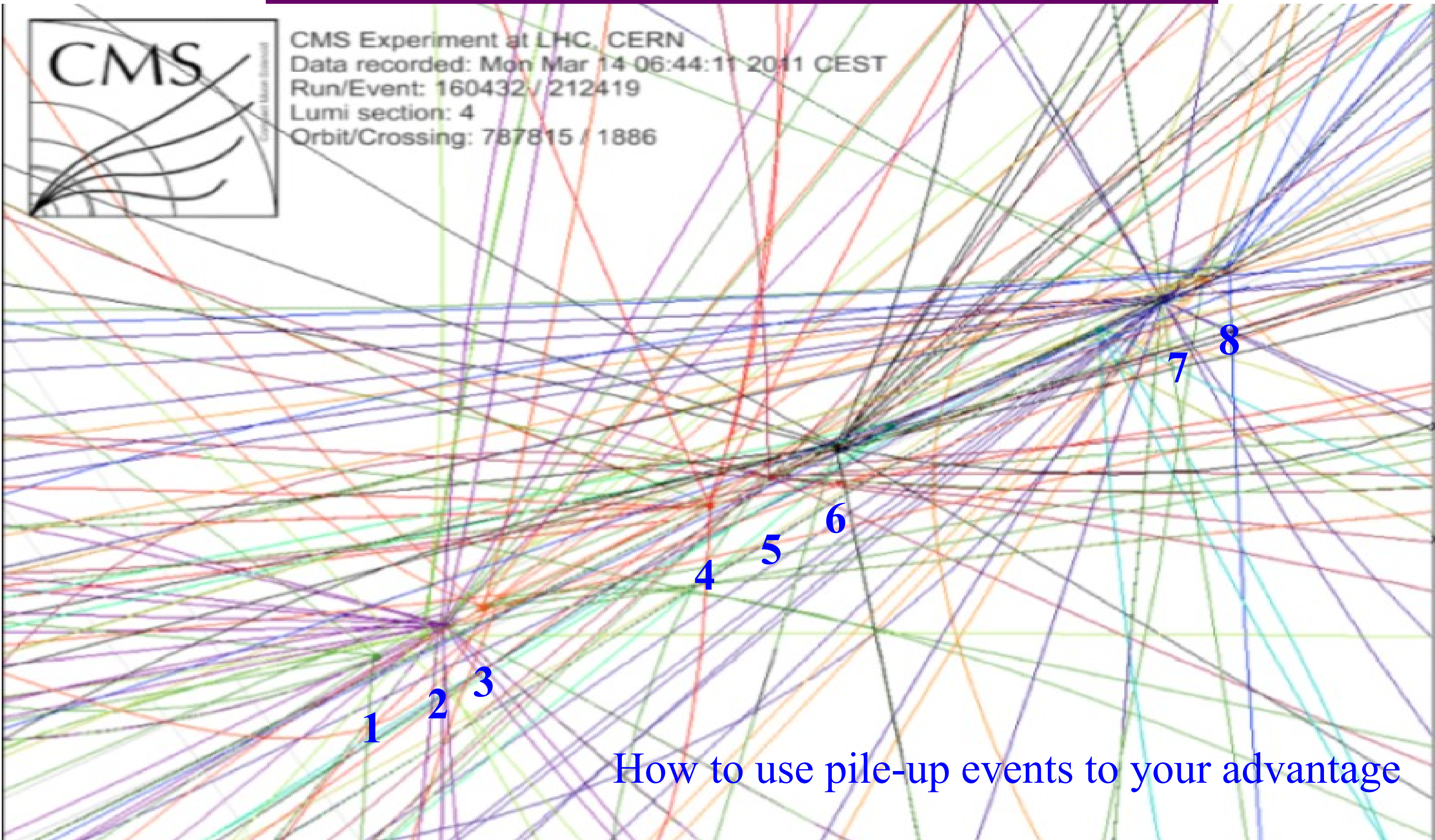


Using standard Glauber formalism

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

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

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* σ(*pp*) cross section:

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

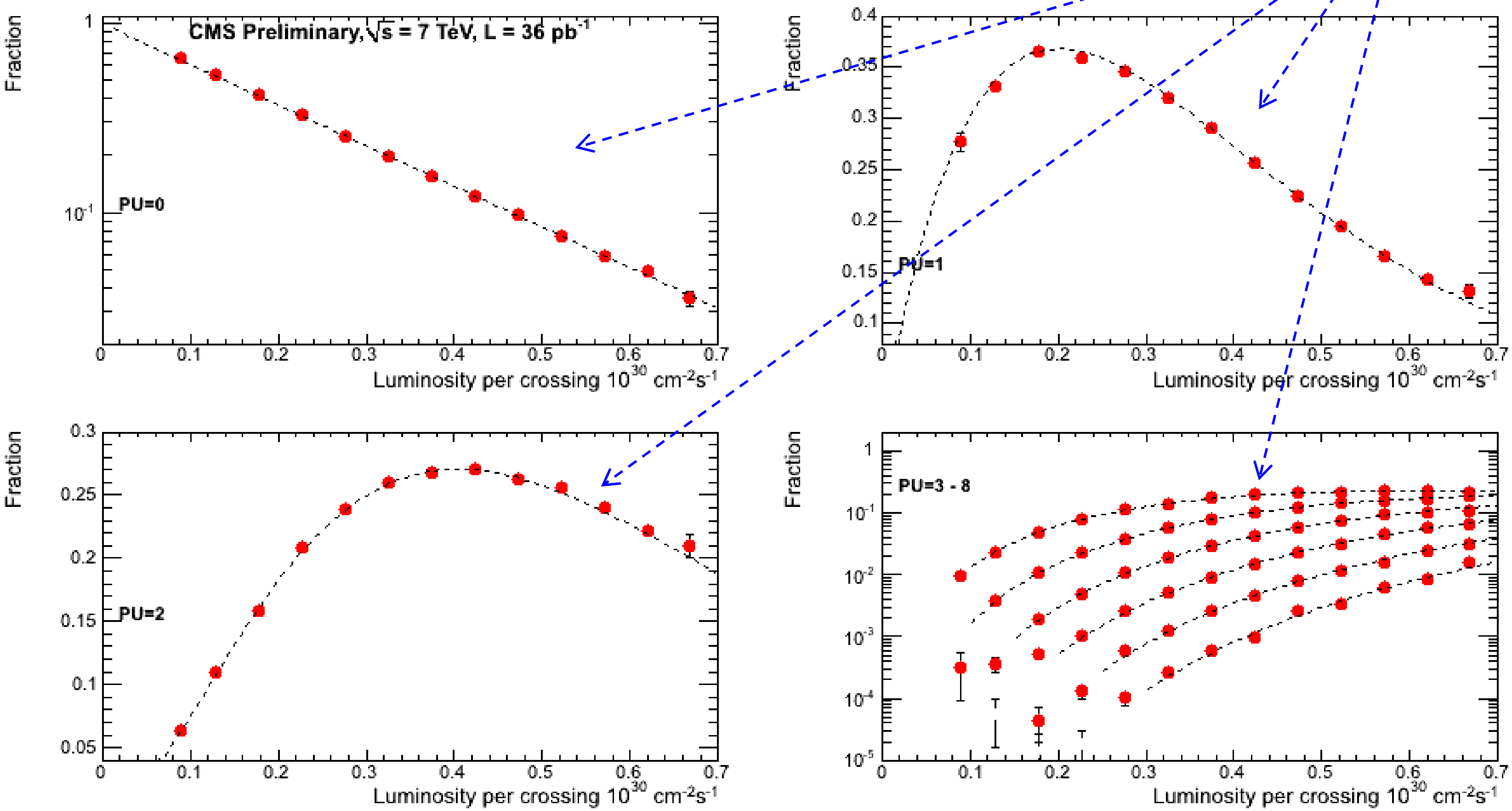
If we count the number of pile-up events as a function of single bunch luminosity, we can measure σ_{vis}(*pp*).

For an accurate measurement we need a large luminosity interval.

Probability of *n* extra vertices depends upon σ

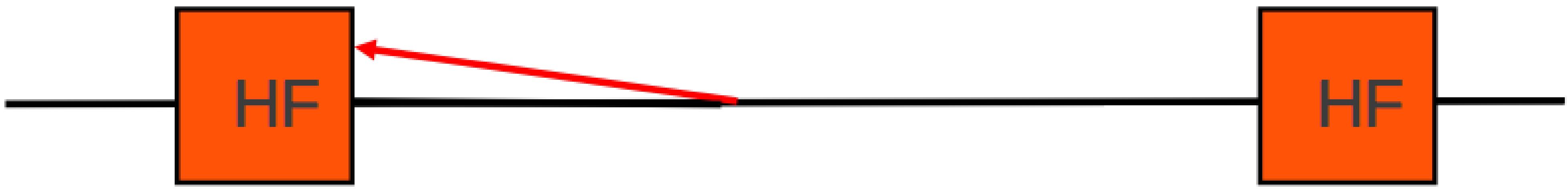
$$P(n_{vertexes}) = \frac{(L\sigma)^{n_{vertexes}} e^{-(L\sigma)}}{n_{vertexes}!}$$

Fit to σ



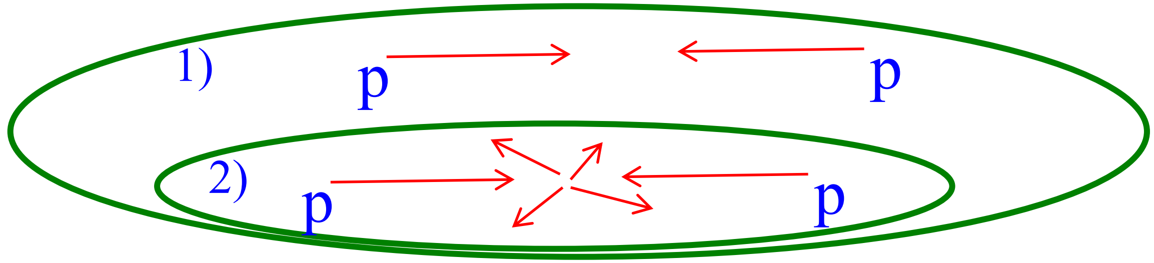
Collider experiments: measure σ_{inel} by counting number of events

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.

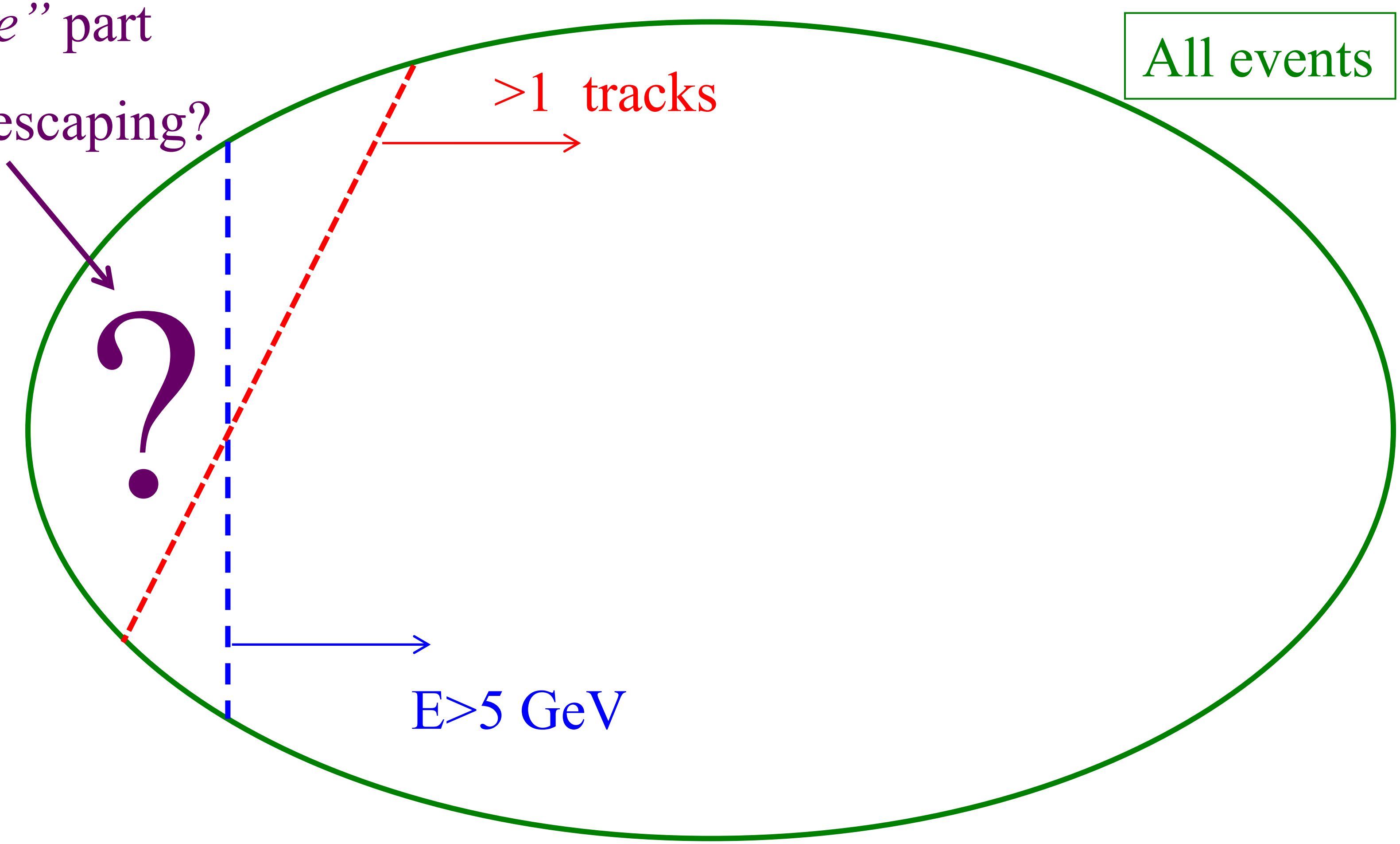
$$\sigma_{Inel} = \frac{N_{Event} F_{pu}}{\varepsilon \int L\,dt}$$

This method works only at low luminosity

Coverage of pileup and HF measurements

Very small masses,
"invisible" part

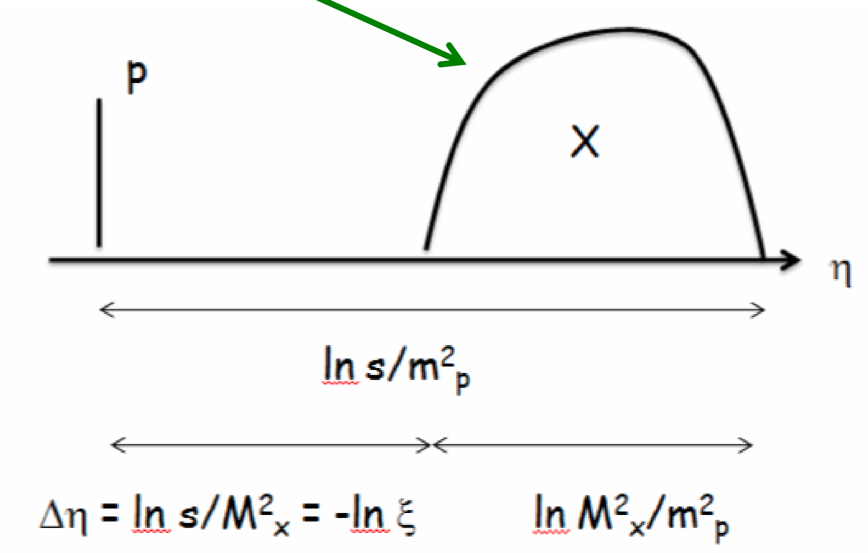
What is escaping?



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.

Experimental coverage of rapidity

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

ALICE covers $-3.7 < \eta < 5.1$

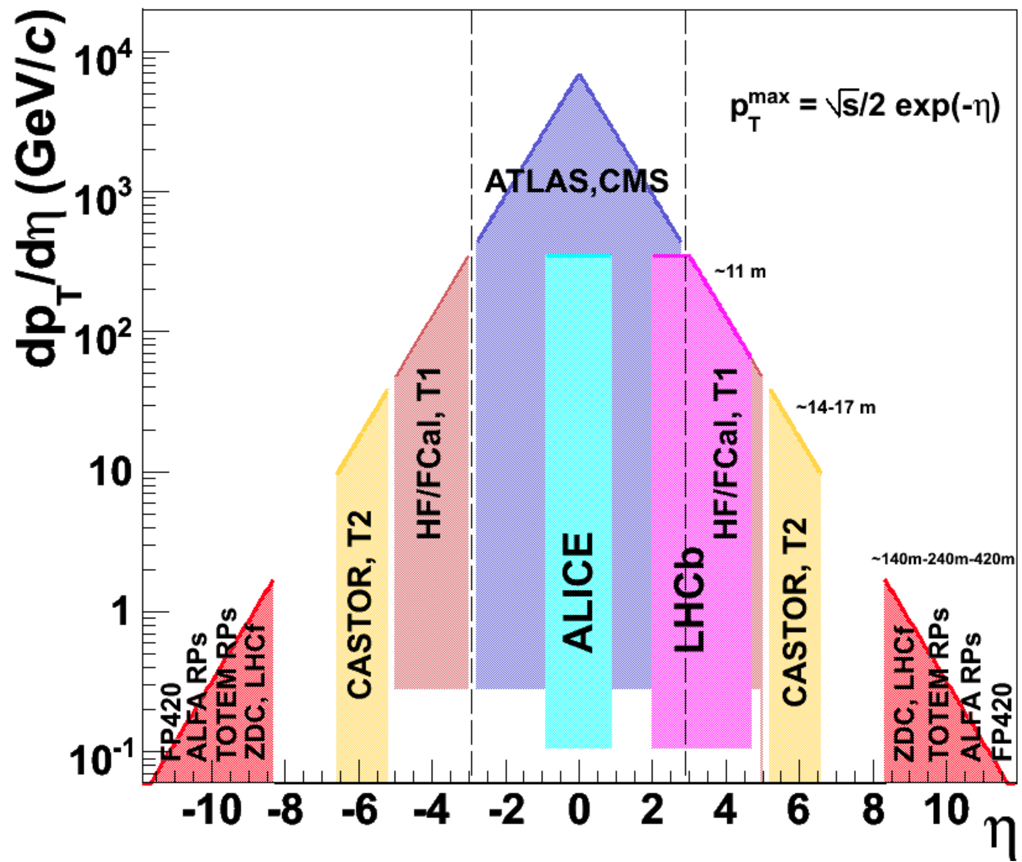
TOTEM has two detectors:
T1: $3.1 < |\eta| < 4.7$, T2: $5.3 < |\eta| < 6.5$,
$\xi > 2 * 10^{-7}$ (Mx ~ 3.4 GeV)

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

Solutions:

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

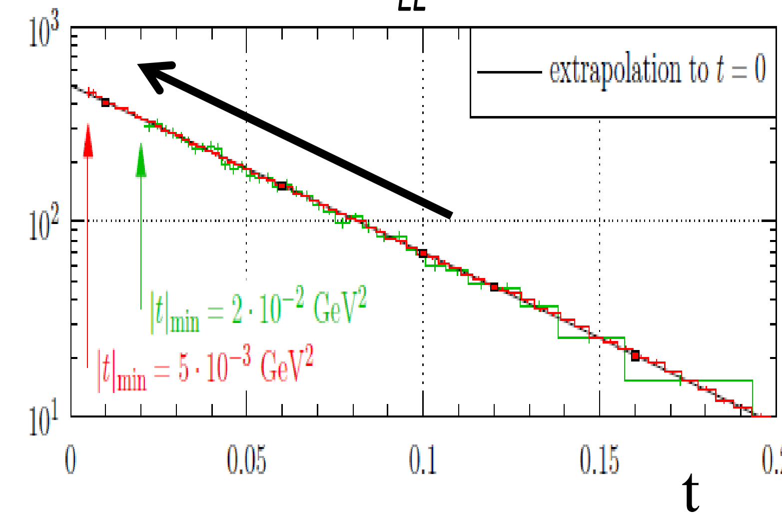
LHC detectors coverage



A different way: 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: $$\frac{d\sigma_{EL}}{dt} = \frac{1}{L} \cdot \frac{dN_{EL}}{dt}$$

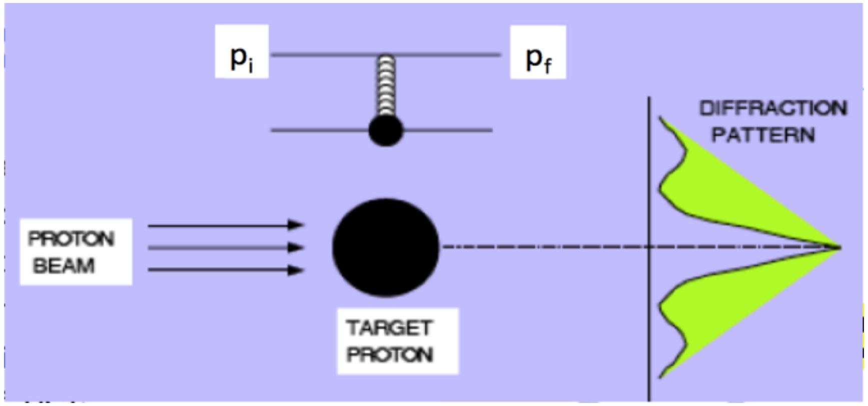
ρ from COMPETE fit: $$\rho = 0.14^{+0.01}_{-0.08}$$

$$\rho = Re f_{el}|_{t=0} / Im f_{el}|_{t=0}$$

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

The art of elastic scattering: theory and detection

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



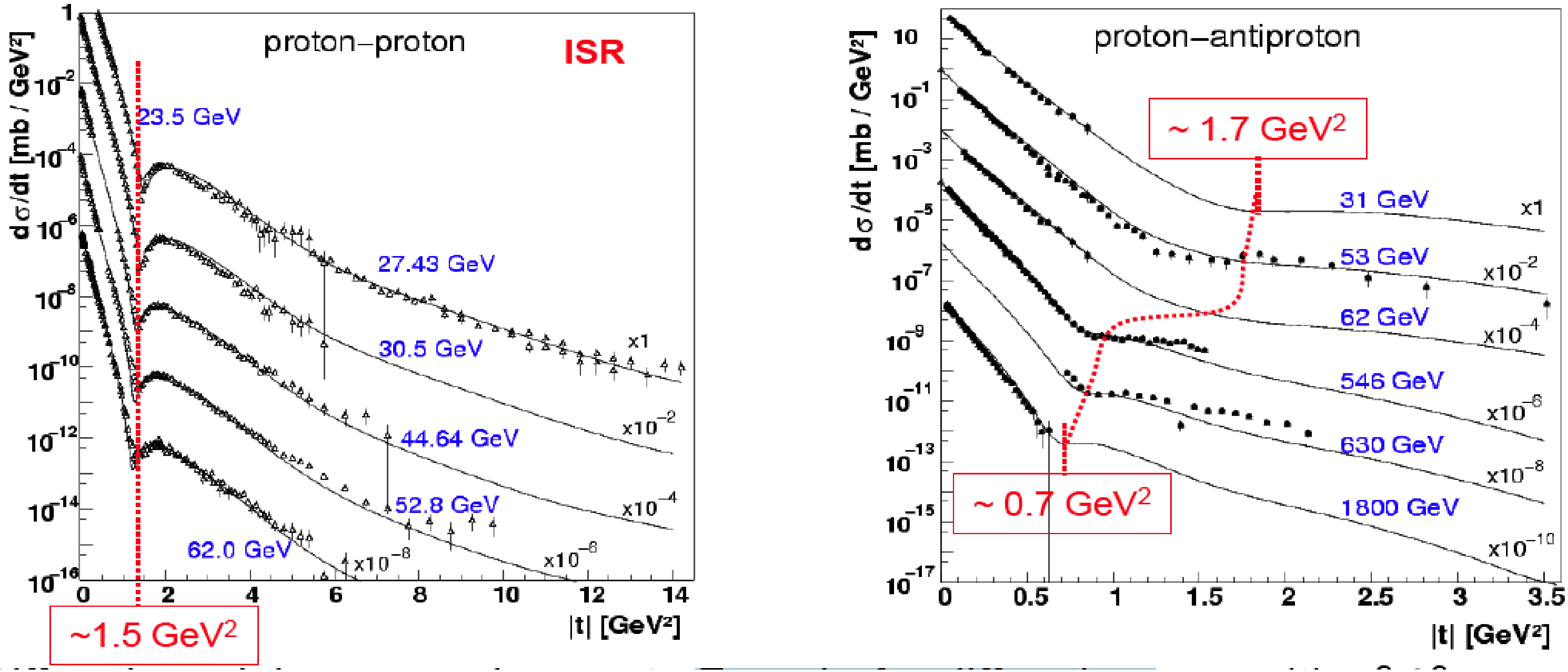
-At small t, elastic scattering is governed by an exponential law

-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

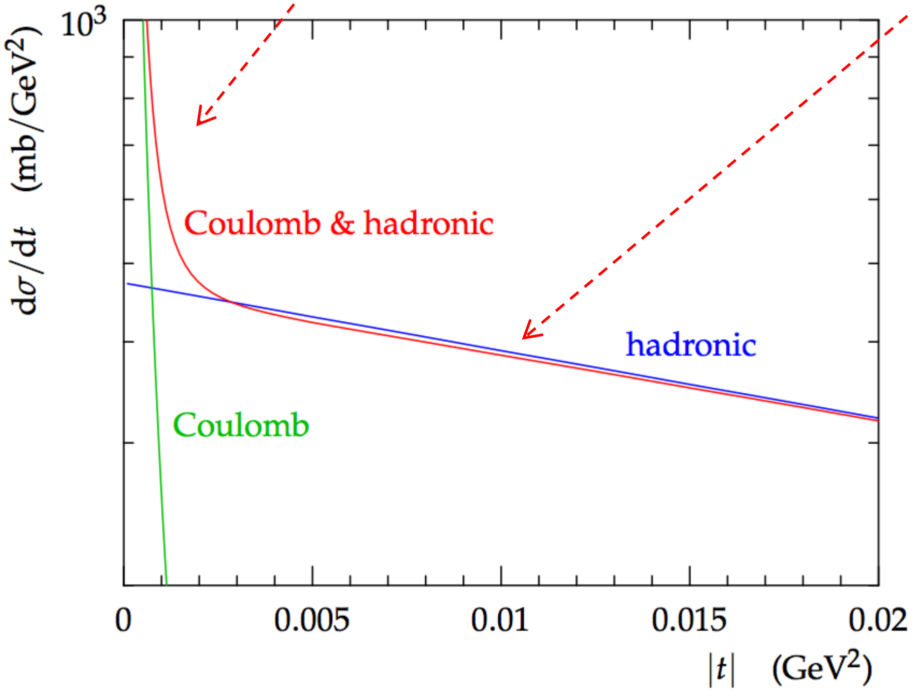
The Coulomb peak at t = 0

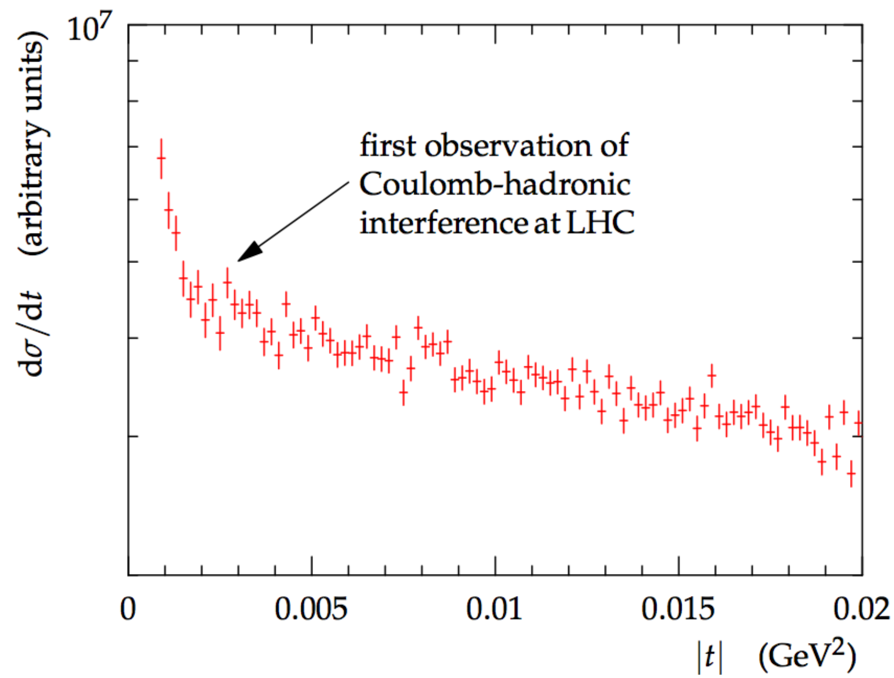
The t slope changes as a function of t value.

We need to measure this part

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

Do no use: Coulomb part





Results

Two basic type of results:

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

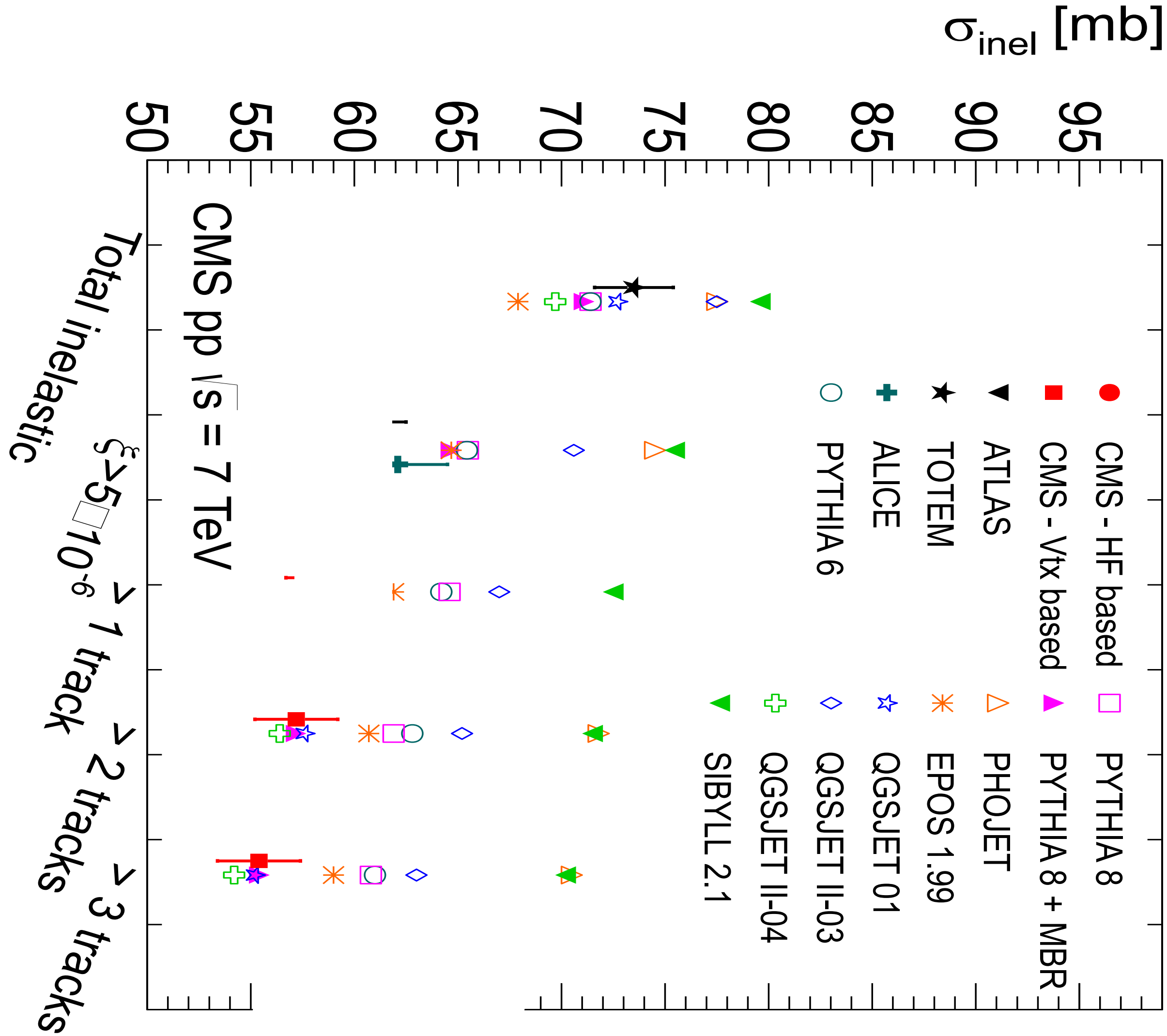
1) Comparison of the total value of the cross section between data and parameterizations as a function of the center-of-mass energy

σ_{inel} for specific final states

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

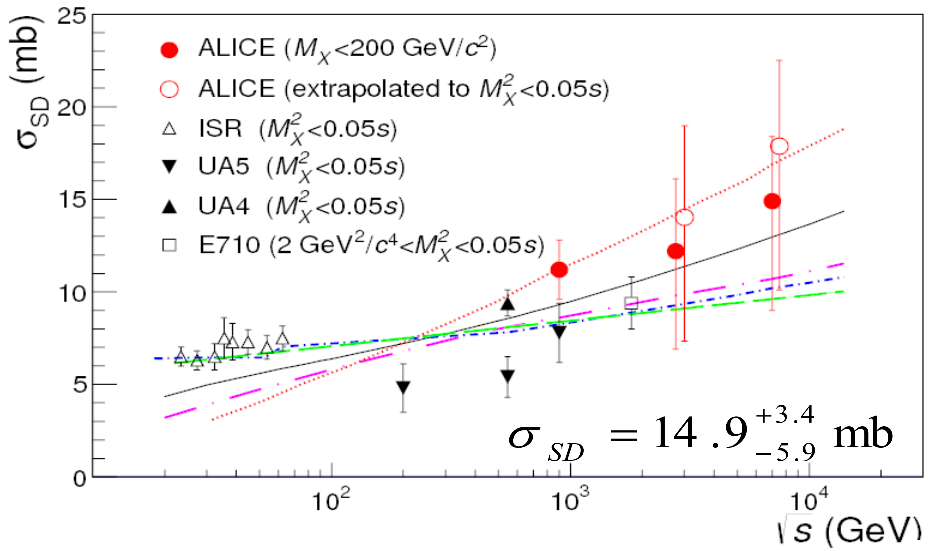
These results are really useful to distinguish the importance of the various processes that are making up σ_{tot}

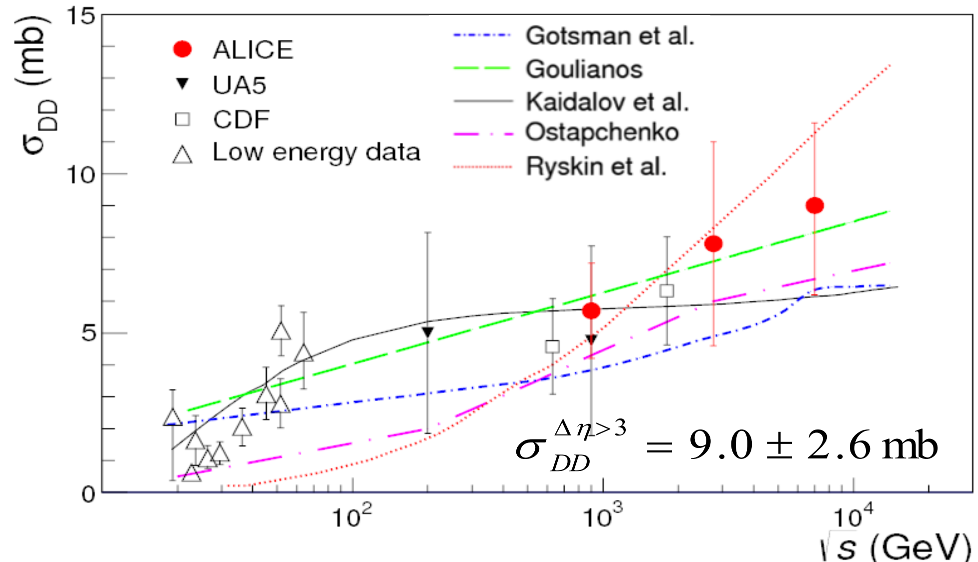
Very few models predict concurrently the correct values of σ for specific final states and σ_{Tot}



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

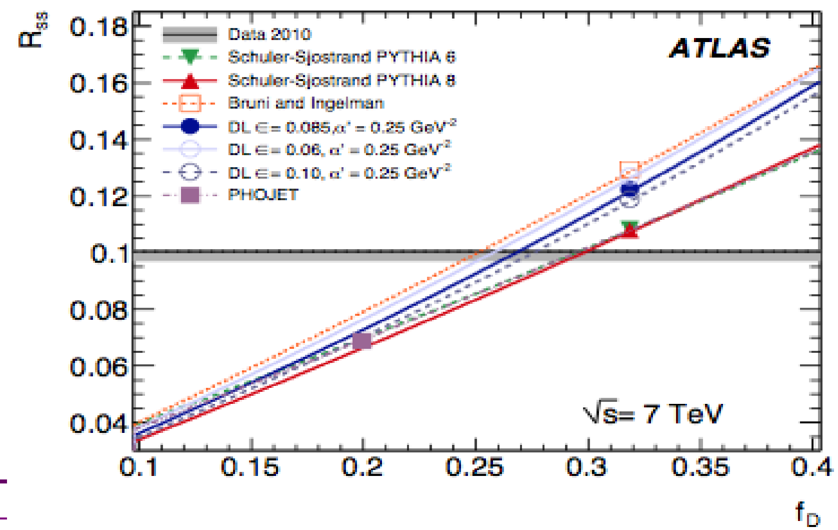
ALICE measured single (SD) and double diffractive (DD) cross-sections





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

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



TOTEM: pp cross section at LHC

Elastic cross section:

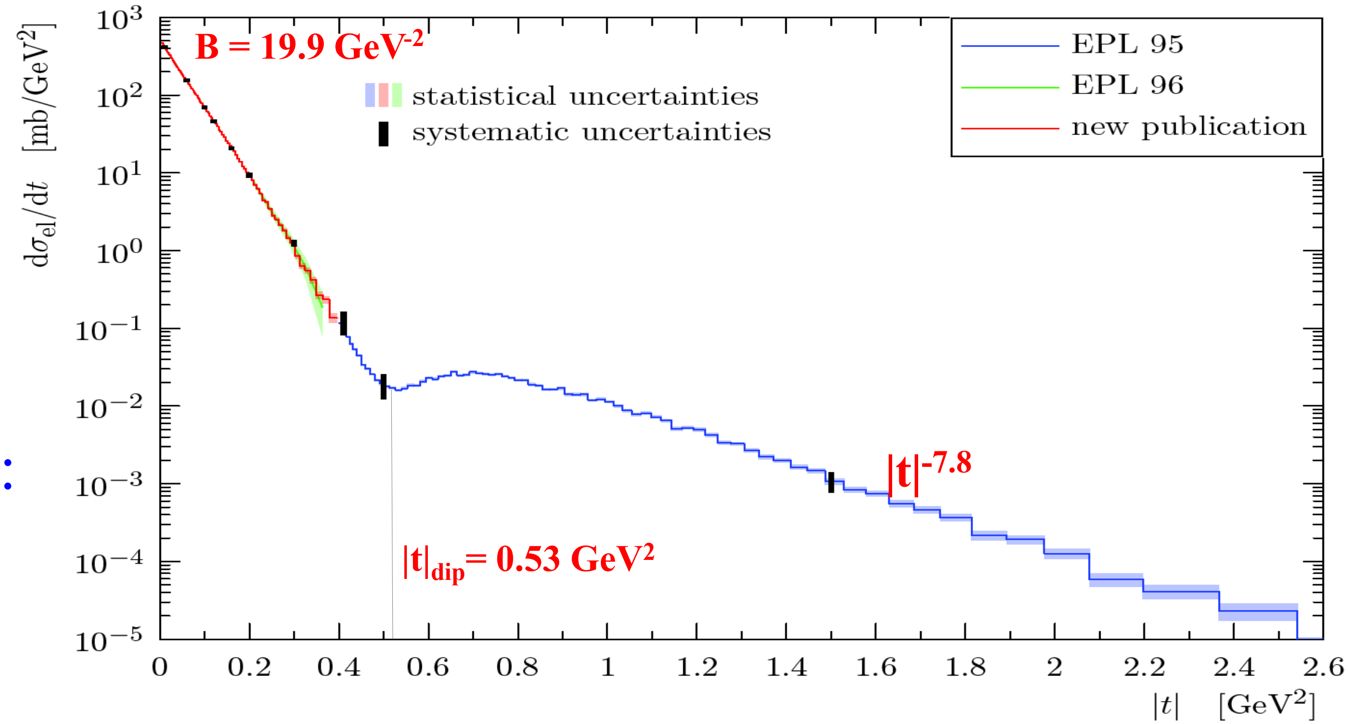
$\sigma_{el=}$ 25.4±1.1 mb

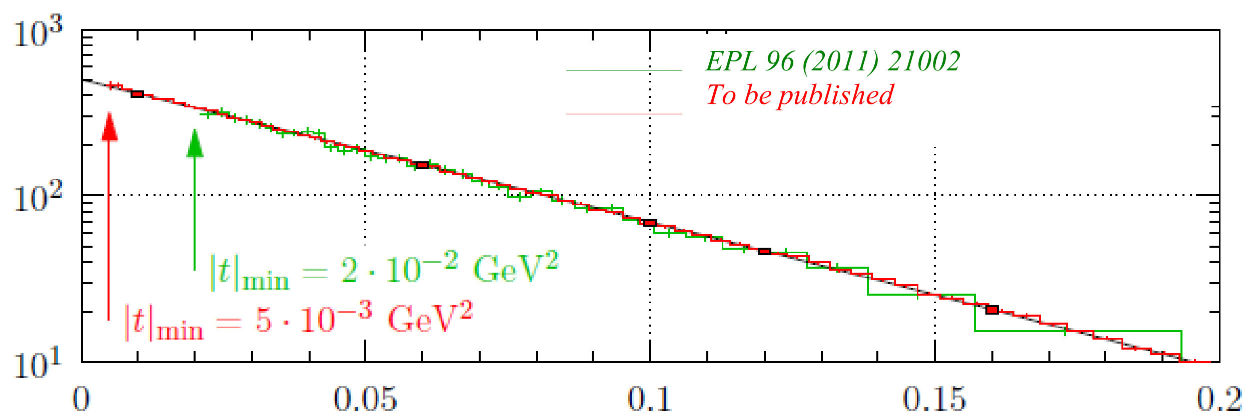
Using the optical theorem:

σ_{TOT} = 98.6 mb ± 2.2 mb

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

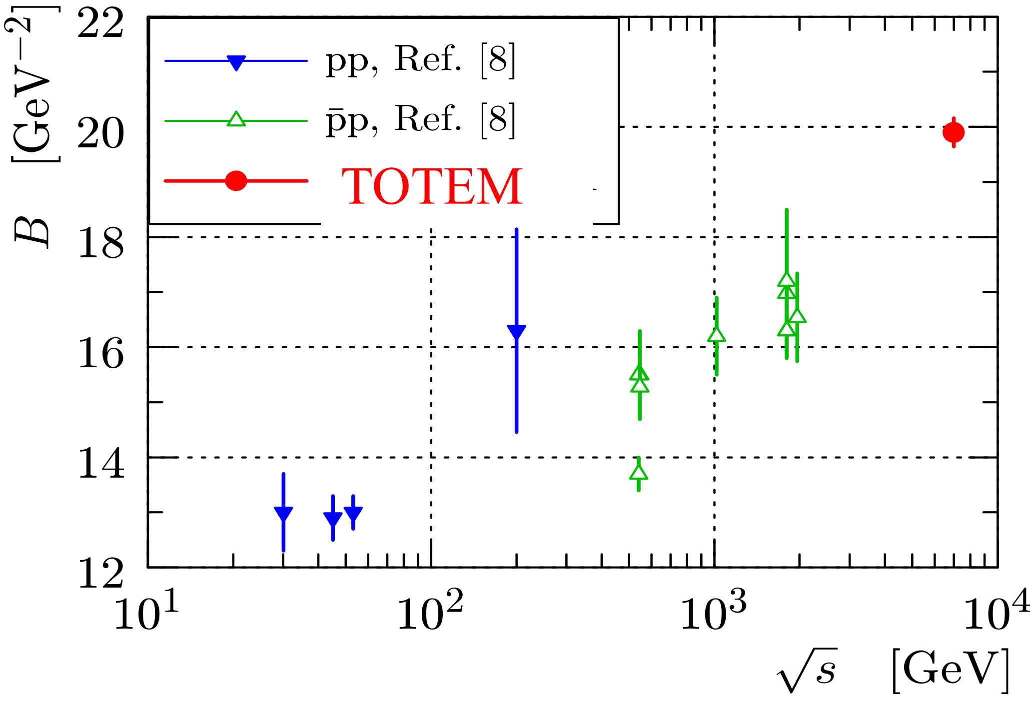
σ_{inel} = 73.1 mb ± 1.3 mb



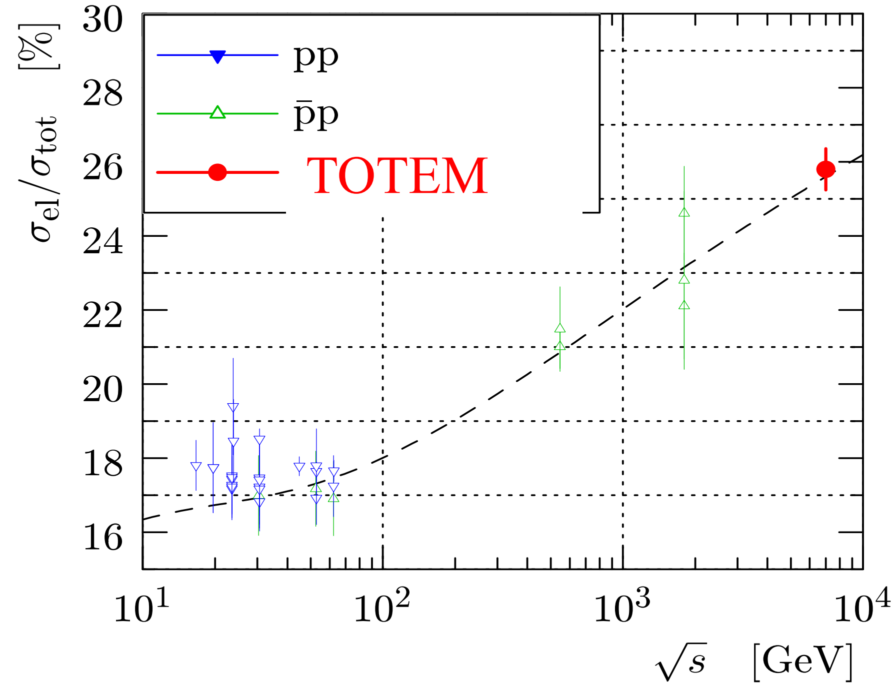


TOTEM: Shrinkage and σ_{el} / σ_{tot}

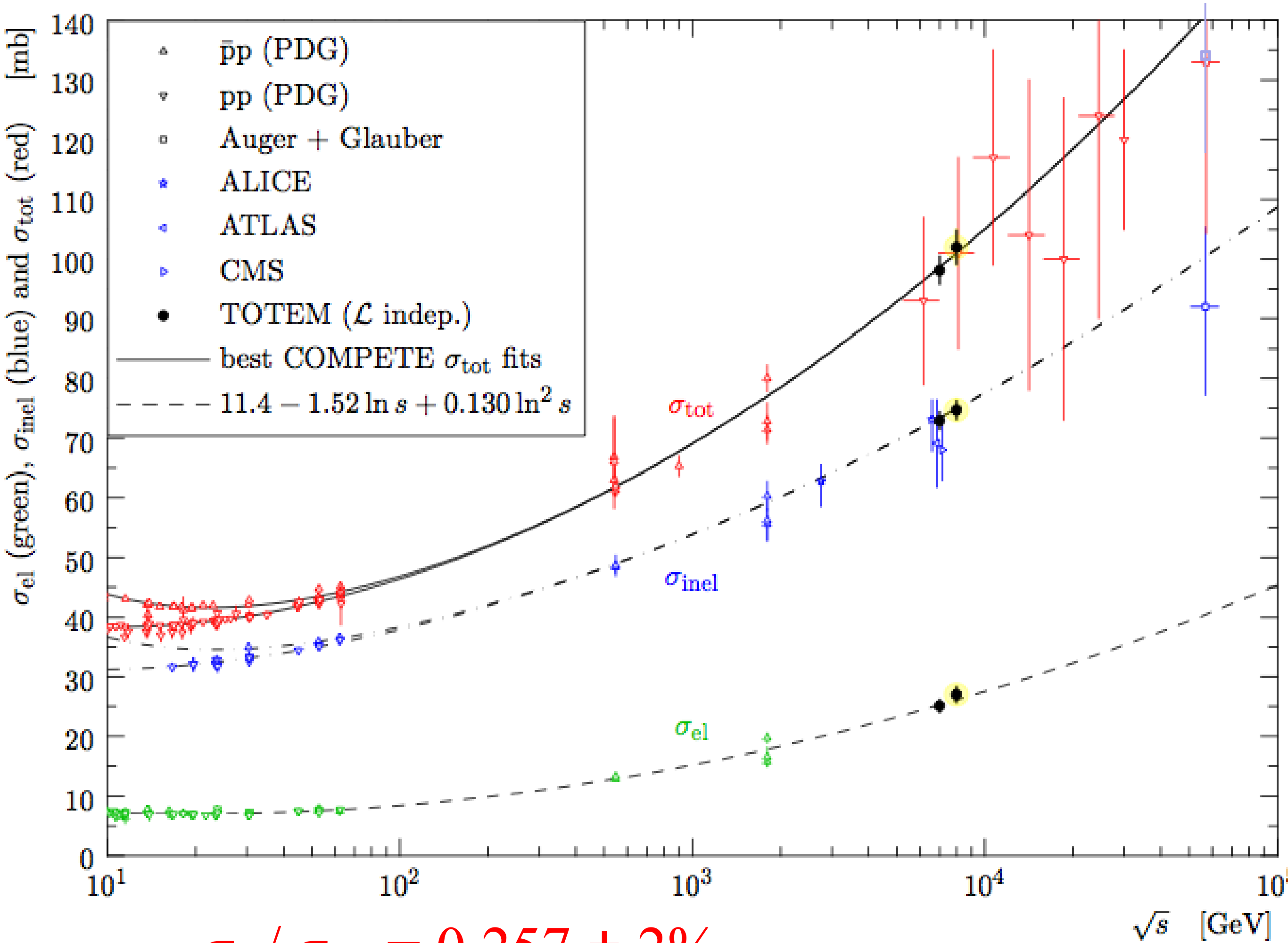
The shrinkage of the forward peak continues…



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 - 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)

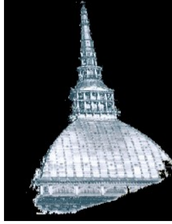
Summary and outlook - II

LHC data at 7 & 8 TeV, together with cosmic-ray results, are becoming more and more precise, and they are constraining the available models.

The cross section values are important to determine the parameters used in hadronization, multi-particle production, multiplicity studies…

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.

This talk will be updated 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

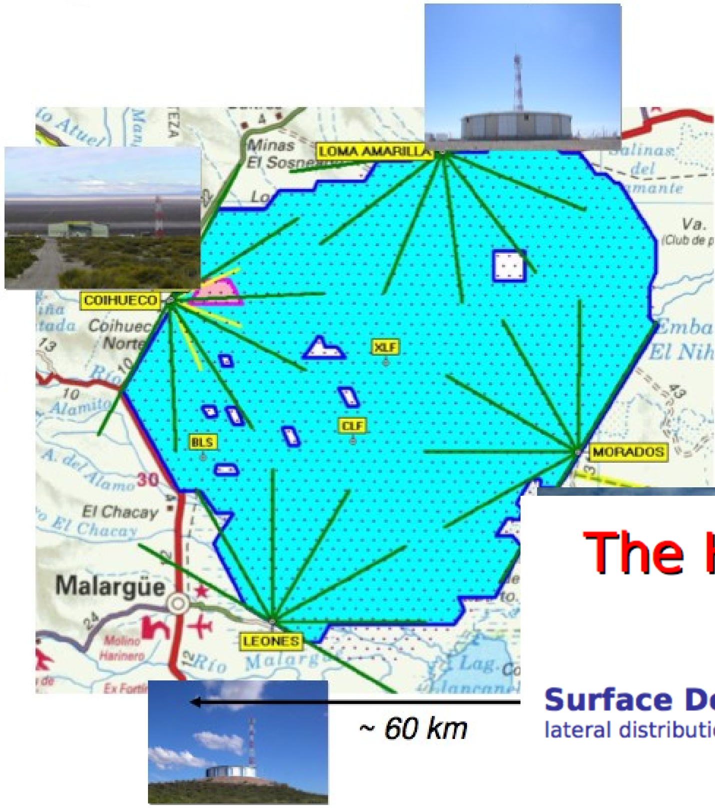
The Pierre Auger Observatory

- ***Surface detector***
  an array of 1660 Cherenkov stations on a 1.5 km hexagonal grid (~ 3000 km^2)

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

Low energy extensions

<u>AMIGA</u>: dense array plus muon detectors
<u>HEAT</u>: three further high elevation FD telescopes



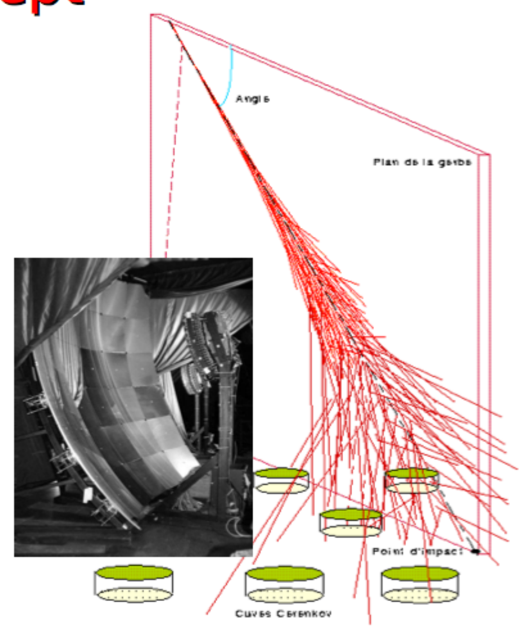
The Hybrid Concept

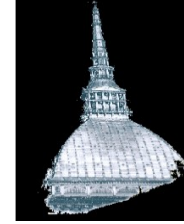
Surface Detector Array
lateral distribution, 100% duty cycle

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

accurate energy and direction measurement

mass composition studies in a complementary way





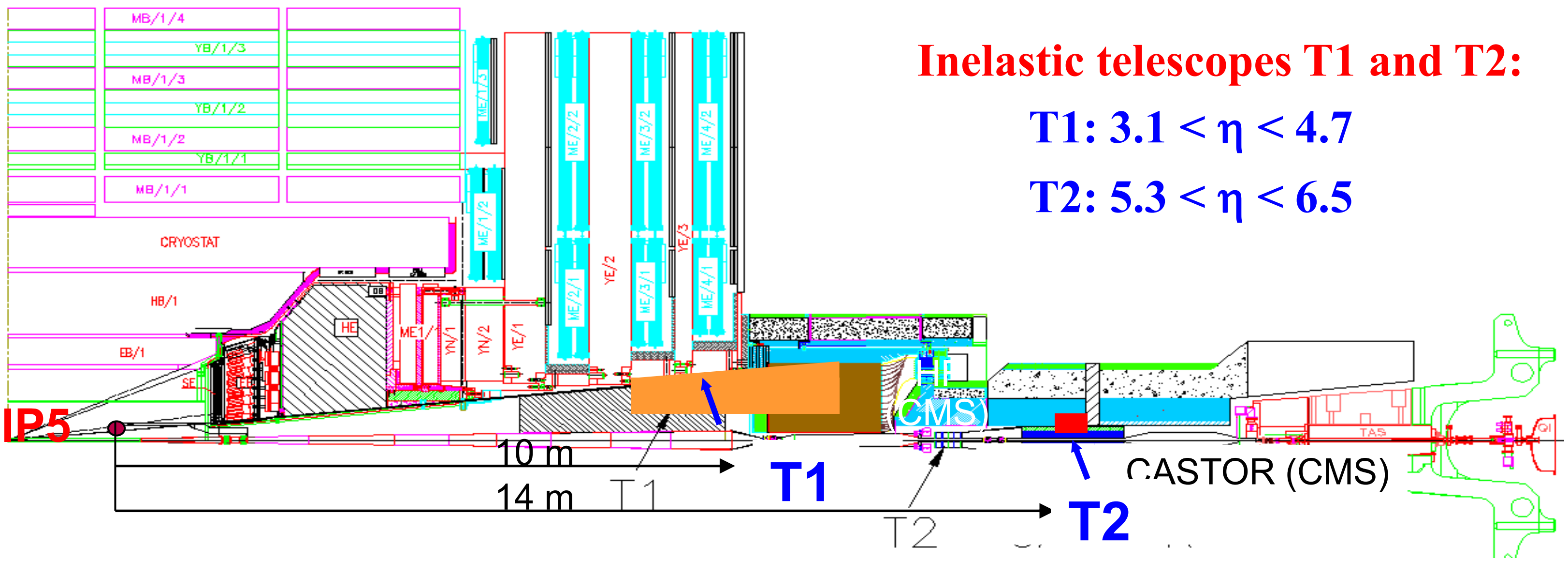
TOTEM at LHC

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