Inelastic cross section measurements at LHC

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on behalf of ATLAS and CMS Collaborations

Outline

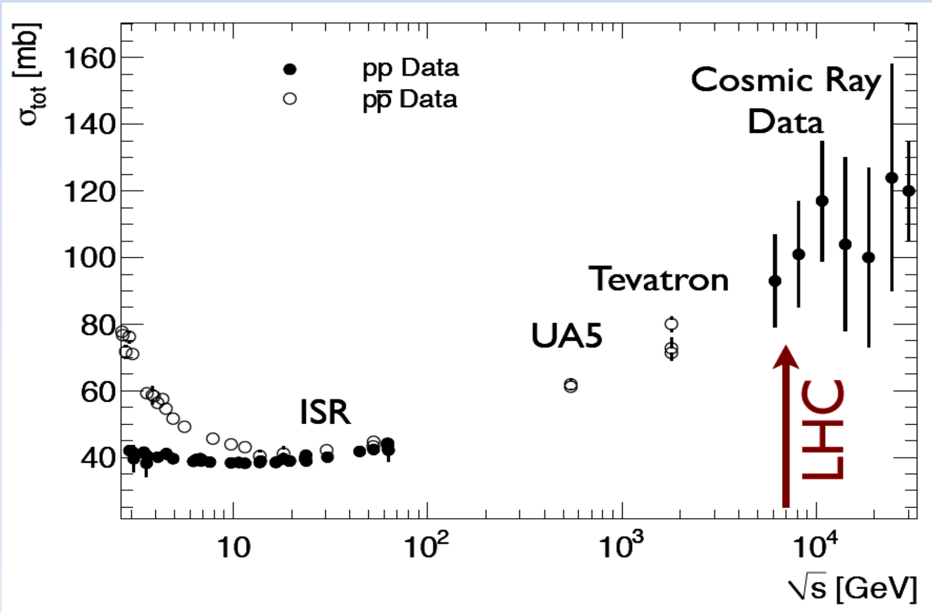
- *Motivations*
- *Short description of LHC and ATLAS/CMS detectors*
- *Introduction to LHC p-p interactions*
- *ATLAS Inelastic pp cross-section* Nature Comm. 2 (2011) 463
- *CMS Inelastic pp cross-section* *CMS-PAS-FWD-11*-001
- *Conclusions*

Motivation for the measurement

- Total proton-(anti)proton cross sections have been a fundamental quantity since the earliest days of particle physics
  - 20% elastic, 80% inelastic
  - diffractive contribution: σ_D / σ_{inel} ~ 0.2-0.3

- The dependence of the p-p interaction rate on the centre-of-mass collision energy √s cannot yet be calculated from first principle

- Common models manage to describe existing data using different methods:
  - Power Law (Donnachie & Landshoff)
  - Logarithmic (Block & Halzen)
  - Using aspects of QCD (Achilli et al.)



- For p-p σ_{inel} at √s=7 TeV there are no good prediction due to large extrapolation uncertainties

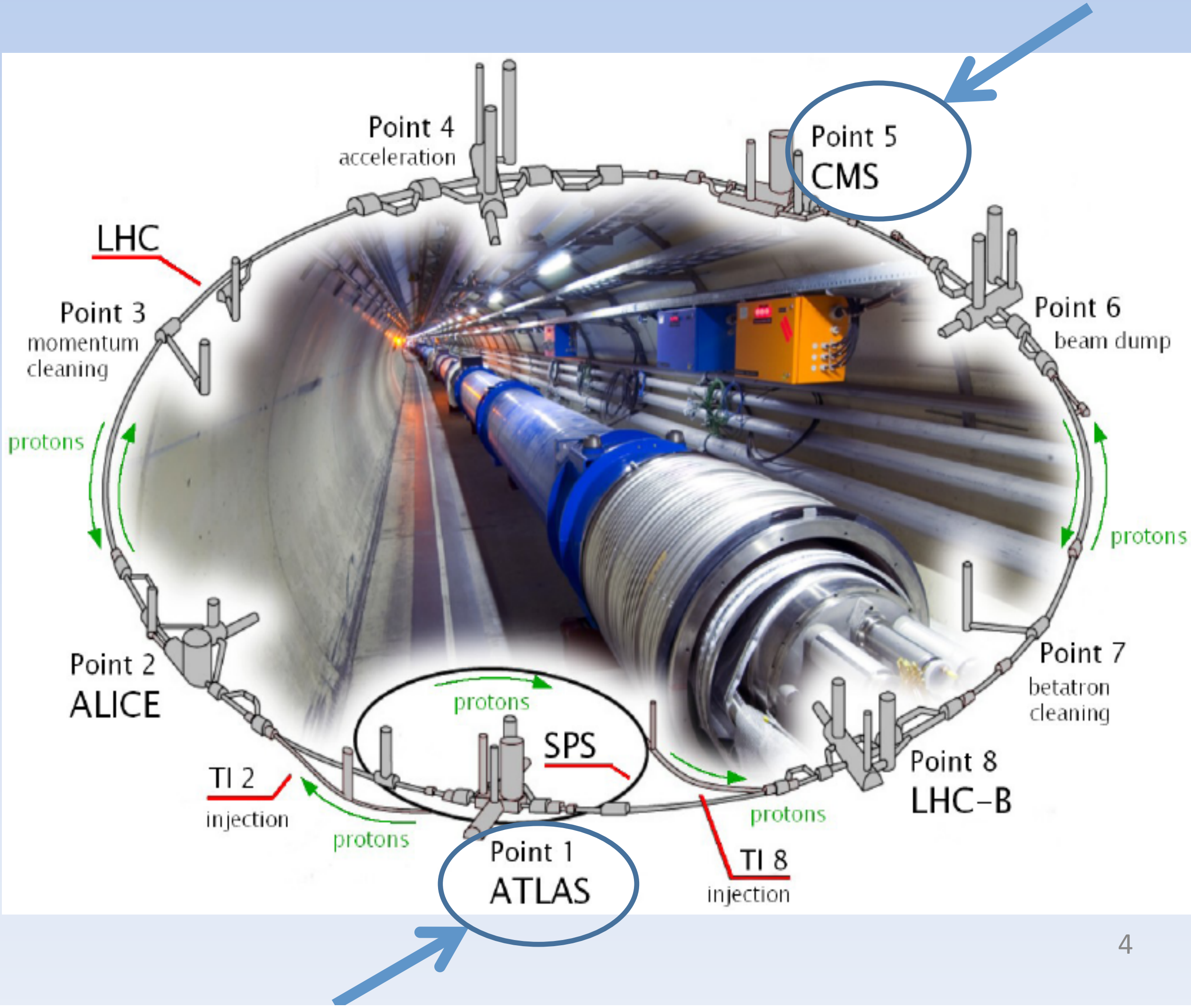
→What is the contribution that LHC experiments can offer?

LHC world

The **LHC** is a **proton-proton collider** running since March 2010 at **$\sqrt{s}$=7 TeV**

Up to November 2011

- Peak Luminosity:
  ~ $3.5 \cdot 10^{33}$ $cm^{-2}s^{-1}$
- # Colliding bunches:
  ~ 1300 for ATLAS/CMS
- Bunch spacing:
  50 ns (75 ns during 2010)
- Pile-up:
  ~ 11.6 average number of collisions/BC during 2011 (up to 24 collisions/BC)



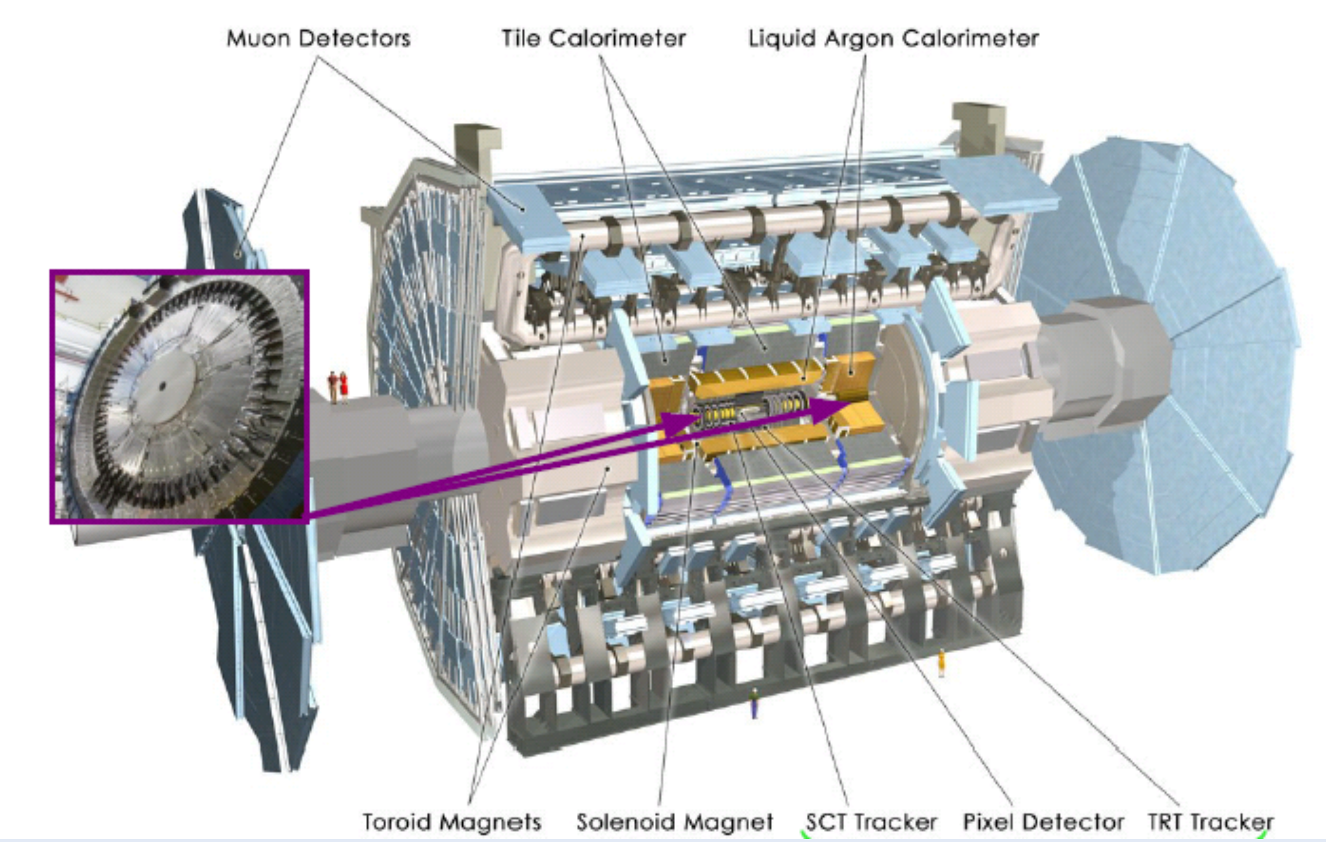
The ATLAS experiment

ATLAS: **A** **T**oroidal **L**HC **A**pparatu**S**

Three large super-conducting air-core toroidal magnets (2~6 T· m)

Minimum **B**ias **T**rigger **S**cintillators cover **$2.09 < | \eta | < 3.84$**
Modules in front of the end-cap calorimeters (z=± 3.5m);
2 rings in η for each side, divided in 8 sectors in ϕ.

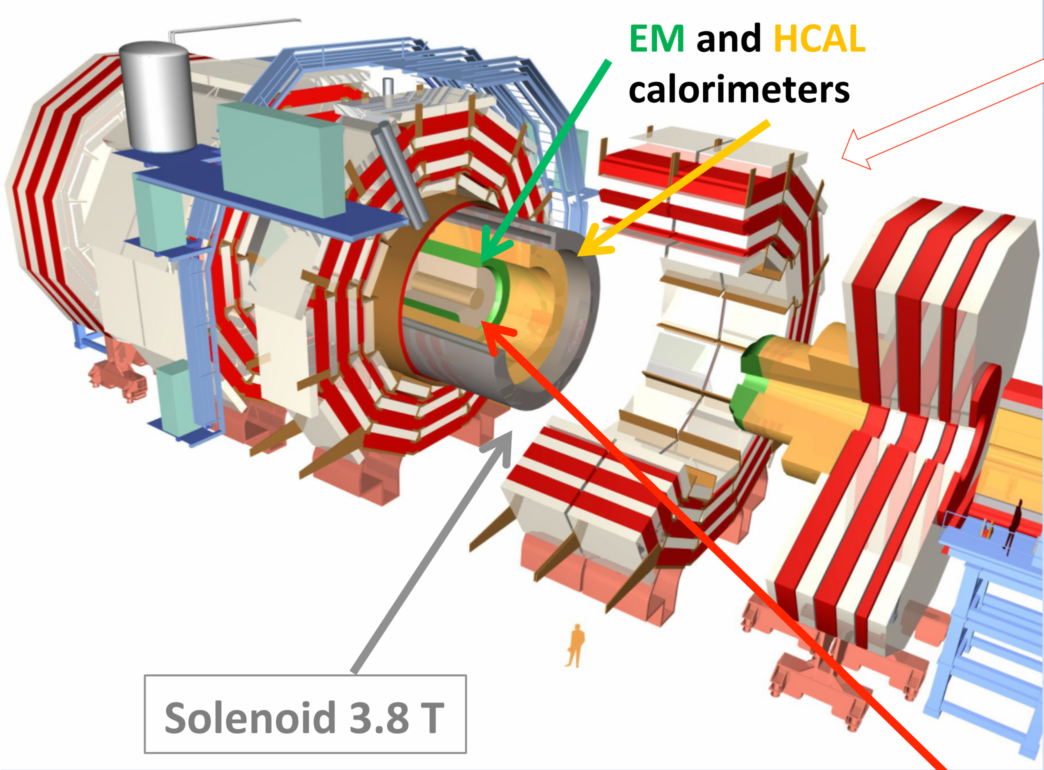
Total weight 7000 t
Overall diameter 25 m
Overall length 44 m



Inner **D**etector in 2 T axial magnetic field reconstructs charged particle "tracks" with **$|\eta| < 2.5$**

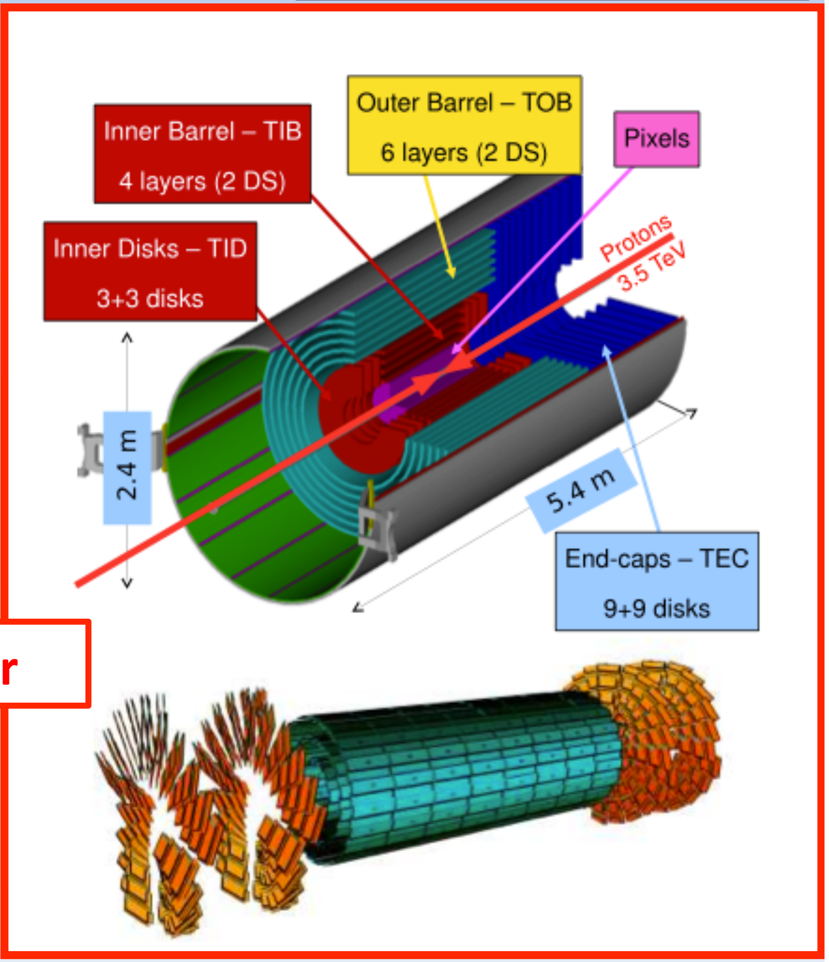
Electro-**M**agnetic (**H**adronic) **Cal**orimeters measure energy of particles with **$|\eta| < 3.2$ (4.9)**

CMS: **C**ompact **M**uon **S**olenoid



Muon detectors
Magnet Yoke

Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m



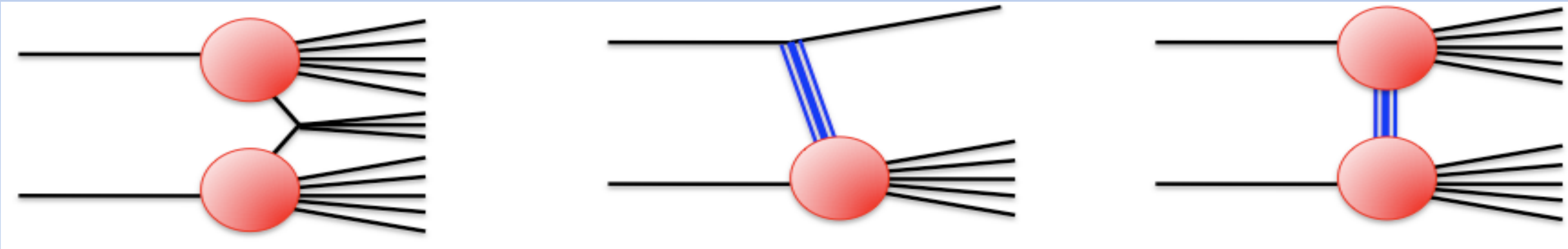
Inner Tracker

CMS η coverage:
Tracker (Pixel + Strip)| η | < 2.4
Calorimeters (EM+HCAL) **| η | < 3.0**
HF Calorimeter **3 < | η | < 5**
Muon Detectors **|η| < 2.4**

Dominant p-p interactions at LHC

Inelastic p-p collisions are the result of a combination of non-diffractive and diffractive events:

$$\sigma_{\text{total-inelastic}} = \sigma_{\text{ND-inelastic}} + \sigma_{SD} + \sigma_{DD}$$



Non-Diffractive (**ND**) Single-Diffractive-Dissociation (**SD**) Double-Diffractive Dissociation(**DD**)

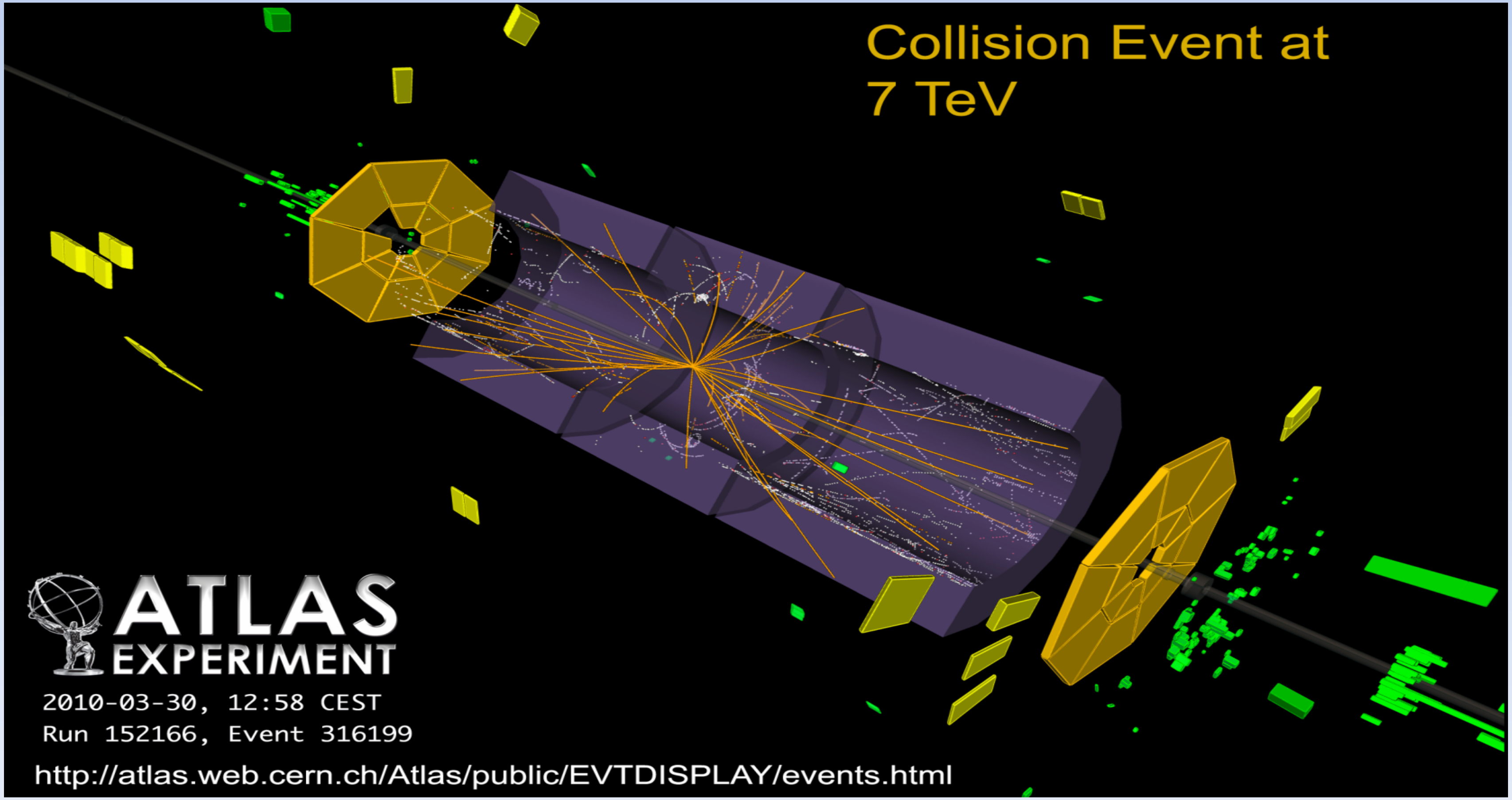
Pythia@7TeV σ~49 mb σ~14 mb σ~9 mb

These soft-QCD processes are needed in Monte Carlo Event Generators

✓ To model pileup (up to ~20 extra pp interactions per bunch crossing)

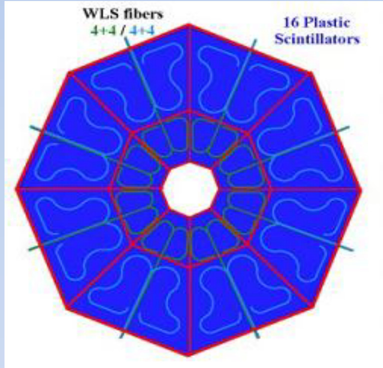
✓ To model the soft processes occurring in the same pp interaction as an "interesting" event

Measurement of the Inelastic Proton-Proton Cross-Section at √s=7 TeV with the ATLAS Detector



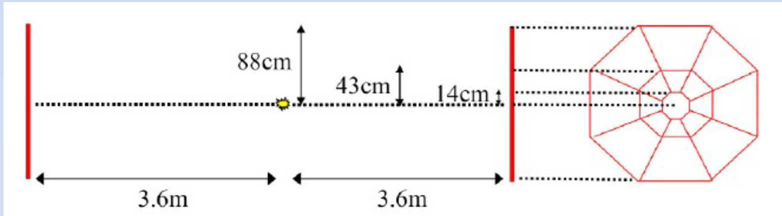
ATLAS Inelastic cross section: preamble on detector acceptance

- Direct measurement of σ_{inel} using **M**inimum **B**ias trigger



- Blind to events with all the particles at $|\ \eta\ | > 3.84$, (mostly diffractive events)

- $\xi = M^2_X/s$, where M^2_X is calculated for the most spread set of hadrons

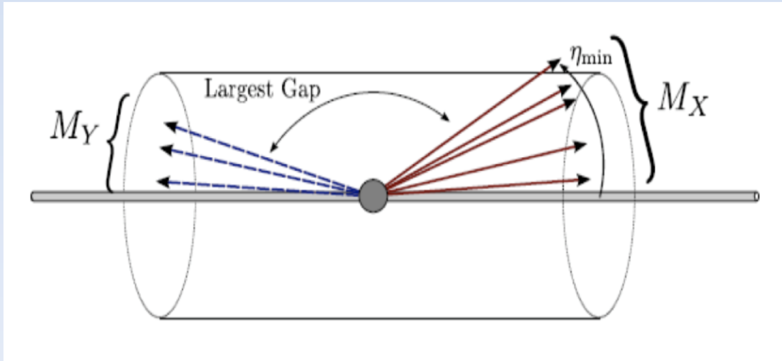


- ξ relates to rapidity gap size inside the detector acceptance:

$$\boldsymbol{\eta_{Min} \propto \log(1/\xi)}$$

$$\boldsymbol{\xi > 5\text{x}10^{-6}}$$

(M_X>15.7 GeV for $\sqrt{s}$=7 TeV)



ATLAS Inelastic cross section: definition of fiducial cross section

At least two MBTS hits

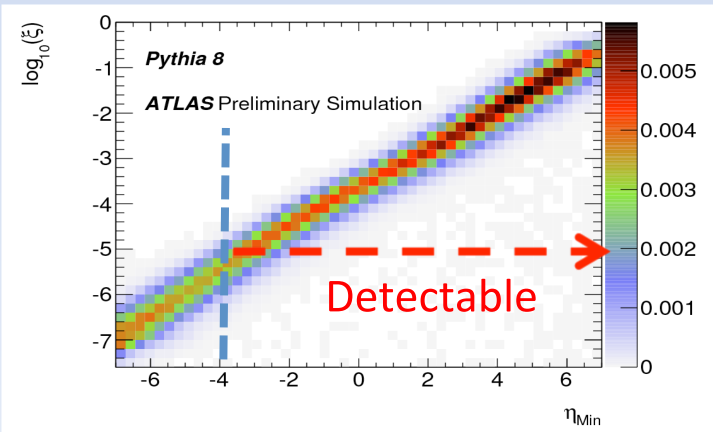
Background and trigger efficiency measured in Data

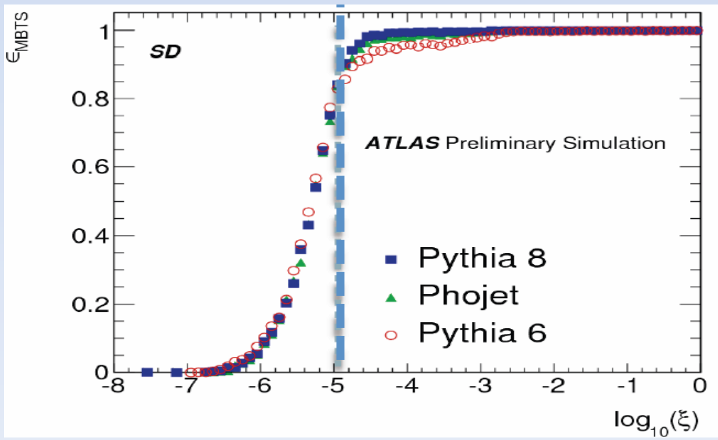
$$\sigma(\xi > 5 \times 10^{-6}) = \frac{(N - N_{BG})}{\epsilon_{trig} \times \int L dt} \times \frac{1 - f_{\xi < 5 \times 10^{-6}}}{\epsilon_{sel}}$$

Limit measurement to detector acceptance
($M_X > 15.7$ GeV)

From Beam Scan Calibration

Correction factors taken from MC, detector response tuned to Data





ATLAS Inelastic cross section: event selection and background

- *Trigger requirements*: at least one hit in the MBTS counters
  very efficient w.r.t. to the offline selection: $\boldsymbol{\varepsilon_{trig}}$**=99.98%**

- *Offline selection*: ≥ 2 MBTS hits, counter's charge > 0.15 pC (noise ~ 0.02 pC)

Inclusive sample - for the actual cross section measurement*:*
- ≥2 counters above threshold in the whole detector
  → **1.2 M events** at 7 TeV in a single run (~20 μb^{-1})

Single-sided sample - to be able to constrain the diffractive contribution*:*
- ≥ 2 counters above threshold on one side, none on the opposing side
  → **120 K events** at 7 TeV in a single run (~20 μb^{-1})

Background estimation coming from *direct beam interactions* with gas in the beam-pipe, beam-pipe itself and material upstream the detector (single proton bunch) and from *"afterglow"*, like slowly decaying beam remnants (timing distribution) **≤ 0.4%**

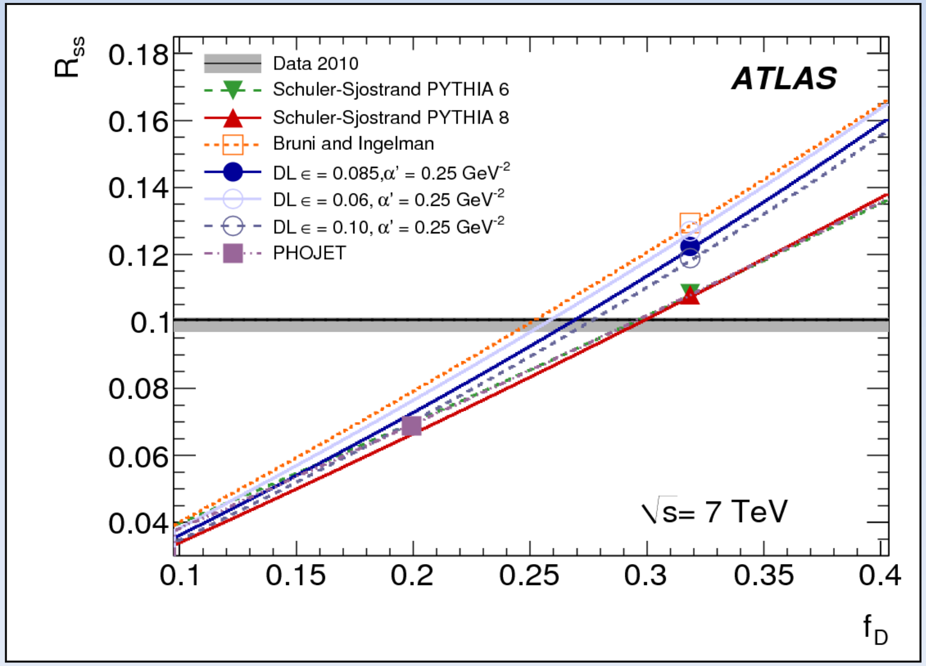
ATLAS Inelastic cross section: relative diffractive contribution

- Measure the ratio of the single-sided to inclusive event sample $\mathbf{R_{ss}}$
- Compare with predictions (from several models) of $\mathbf{R_{ss}}$ as a function of an assumed value of $\mathbf{f_D}$ (fractional contribution of diffractive events to the inelastic cross-section)

$$R_{ss}(f_D) = \frac{N_{SS}}{N_{inc}} = \frac{A^D_{SS} f_D + A^{ND}_{SS}(1-f_D)}{A^D_{inc} f_D + A^{ND}_{inc}(1-f_D)}$$

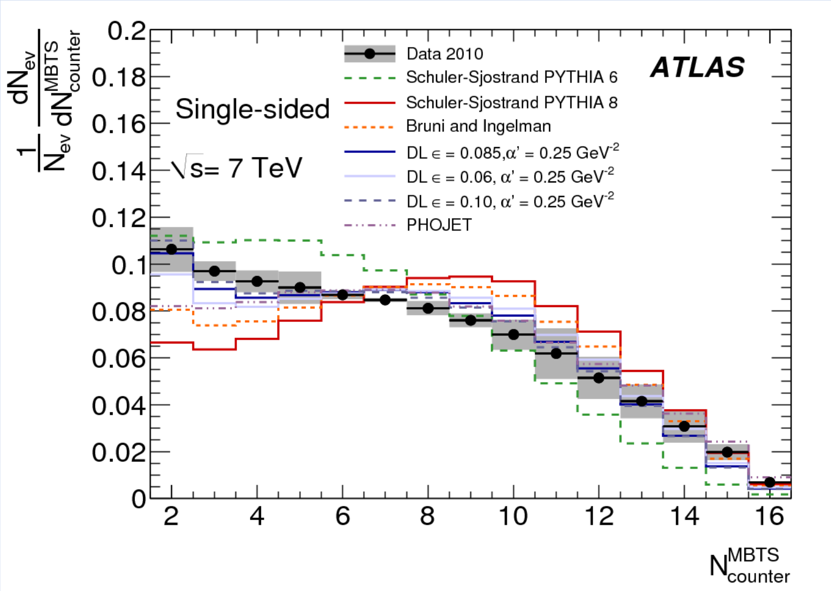
$\mathbf{R_{ss}}$ = [10.02 ± 0.03(stat.)i+0.1−0.4(sys.)]%

- Default $\mathbf{f_D}$ = **32.2%** for all models but Phojet (20.2%)
- Constrain $\mathbf{f_D}$ such that it reproduces the measured $\mathbf{R_{ss}}$
  → $\mathbf{f_D = 26.9^{+2.5}_{-1.0}}$ **%** (from Donanchie & Landshoff)
- Systematic uncertainties: propagated from $\mathbf{R_{ss}}$, by variating the ratio SD/DD



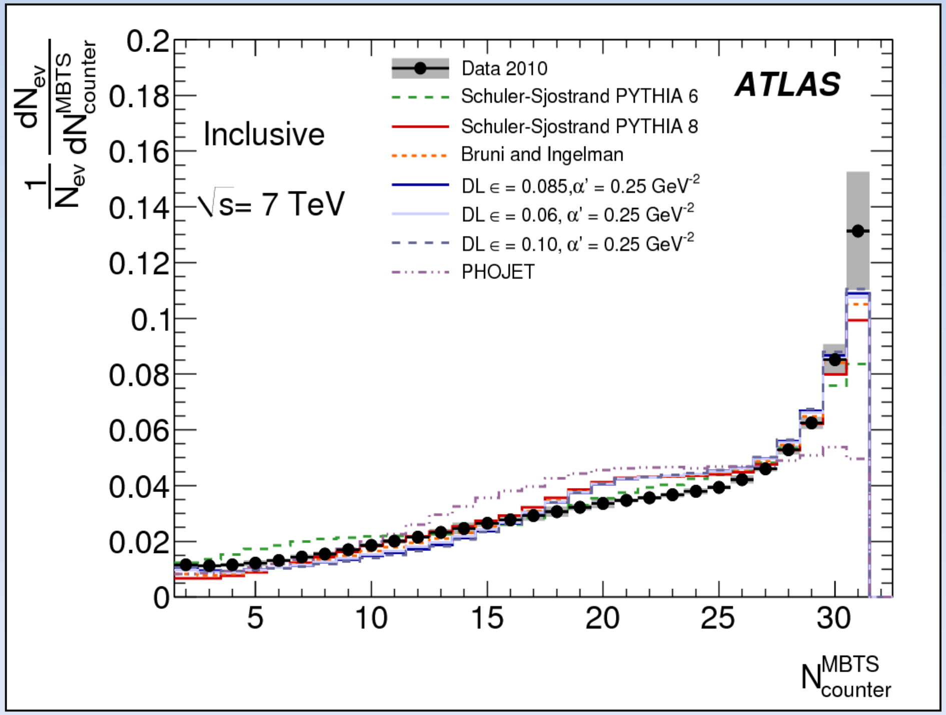
ATLAS Inelastic cross section: efficiency determination

- ε_{sel} **= fraction of event in the kinematic range (ξ > 5x10^{-6}) that pass the selection**
- **Single-sided** sample choose as **benchmark for the MC**
- Data best described by Donnachie & Landshoff (DL) model (ε = 0.085, α' = 0.25 GeV^{-2})
  ↪ **Taken as the default model** for the efficiency estimate
- MBTS hit multiplicity distribution in the data compared with MC expectations for several MC models using the fitted f_D values.
  → ε_{sel} **= 98.77%**
- Very low migration into the fiducial region: f(ξ < 5 × 10^{-6}) = 0.96 %
- Spread among models considered: < 0.5%



ATLAS Inelastic cross section: efficiency determination

- MBTS hit multiplicity distribution in the inclusive sample compared with MC expectations for several MC models using the fitted f_D values : for low multiplicities, data is within the various predictions.



Systematic uncertainty due to:

- Fragmentation difference between Pythia6 and Pythia8: 0.4%

- ξ dependence: maximum deviation of default model $DL|_{\varepsilon=0.085,\ \alpha'=0.25\ GeV-2}$ from the other DL models: 0.4%

MBTS detector response and the amount of material in front of the MBTS detector lead to systematic uncertainties on data

ATLAS Inelastic cross section: cross section and uncertainties

Calculate fiducial cross-section using:

ε_{sel} = 98.77%
ε_{trig} = 99.98%
$f_{\xi<5x10^{-6}}$ = 0.96%

0.4% correction factor

Lumi =20.25 μb^{-1}

$\sigma(\xi > 5 \times 10^{-6})$ [mb]	
ATLAS Data 2010	$60.33 \pm 2.10(\text{exp.})$
Schuler and Sjöstrand	**(Pythia6/8)** 66.4
PHOJET	74.2
Ryskin *et al.*	51.8 – 56.2

- Statistical uncertainty negligible (±0.05 mb) ➔0.08%
- Luminosity is the dominant sys. uncertainty
  - Measured using dedicated Van der Meer scans
  - Limited by bunch current measurement
- Very efficient and well understood trigger
- Detector response in general well modeled (~2%), differences corrected for in the MC
- Conservative estimate of beam backgrounds

Source	Uncertainty (%)
Trigger Efficiency	0.1
MBTS Response	0.1
Beam Background	0.4
f_D	0.3
MC Multiplicity	0.4
ξ-Distribution	0.4
Material	0.2
Luminosity	3.4
Total	3.5

ATLAS Inelastic cross section: extrapolation to total inelastic

- Comparison with analytic theoretical calculations or other measurements

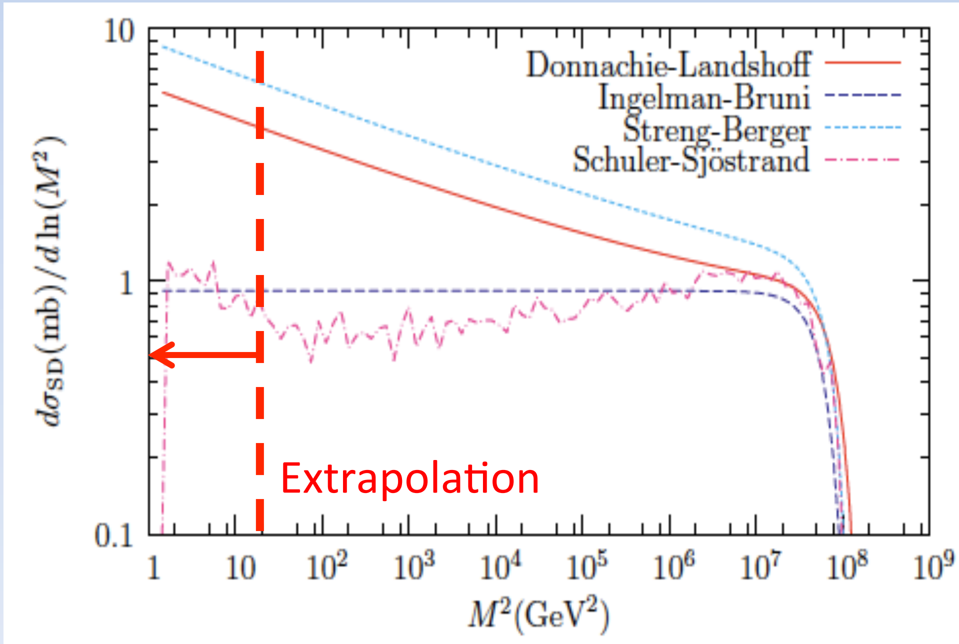
- <u>Fraction of events in the selected fiducial region depends on the ξ evolution of the cross section</u>

Extrapolation via using DL (default)

- 87.3 % of the total cross section within the kinematic acceptance

- Other models go from 79% (Ryskin *et al.*) to 96% (PHOJET)

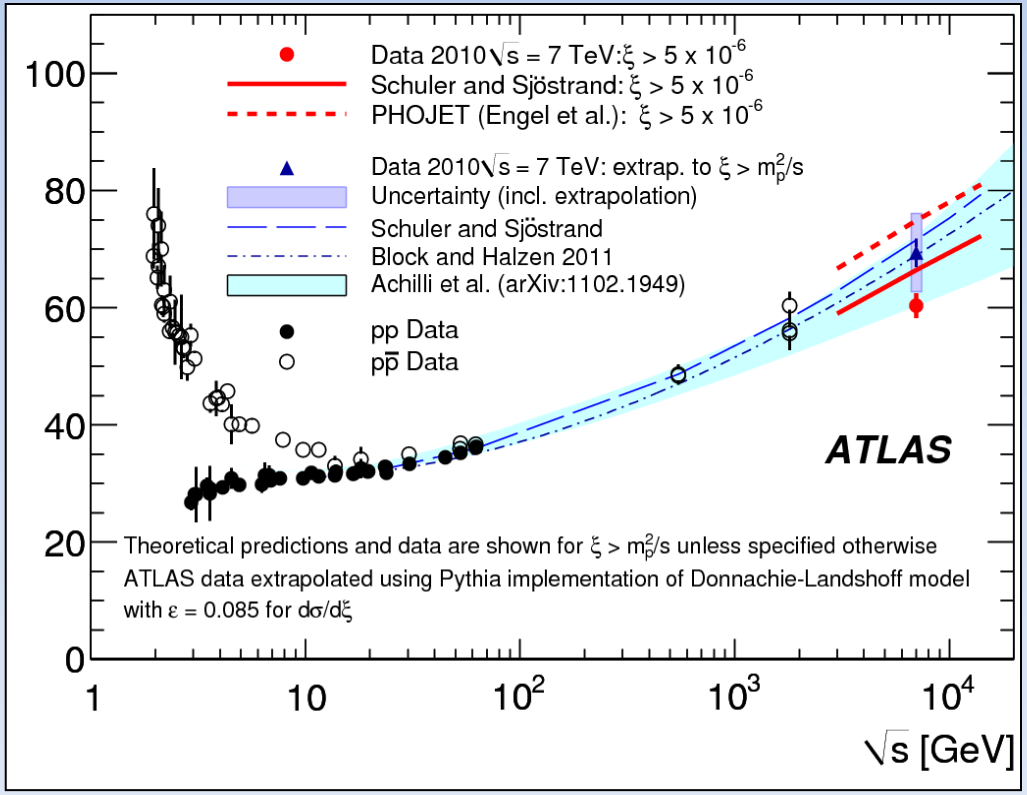
- **+/-10%** as extrapolation uncertainty



ATLAS Inelastic cross section: results

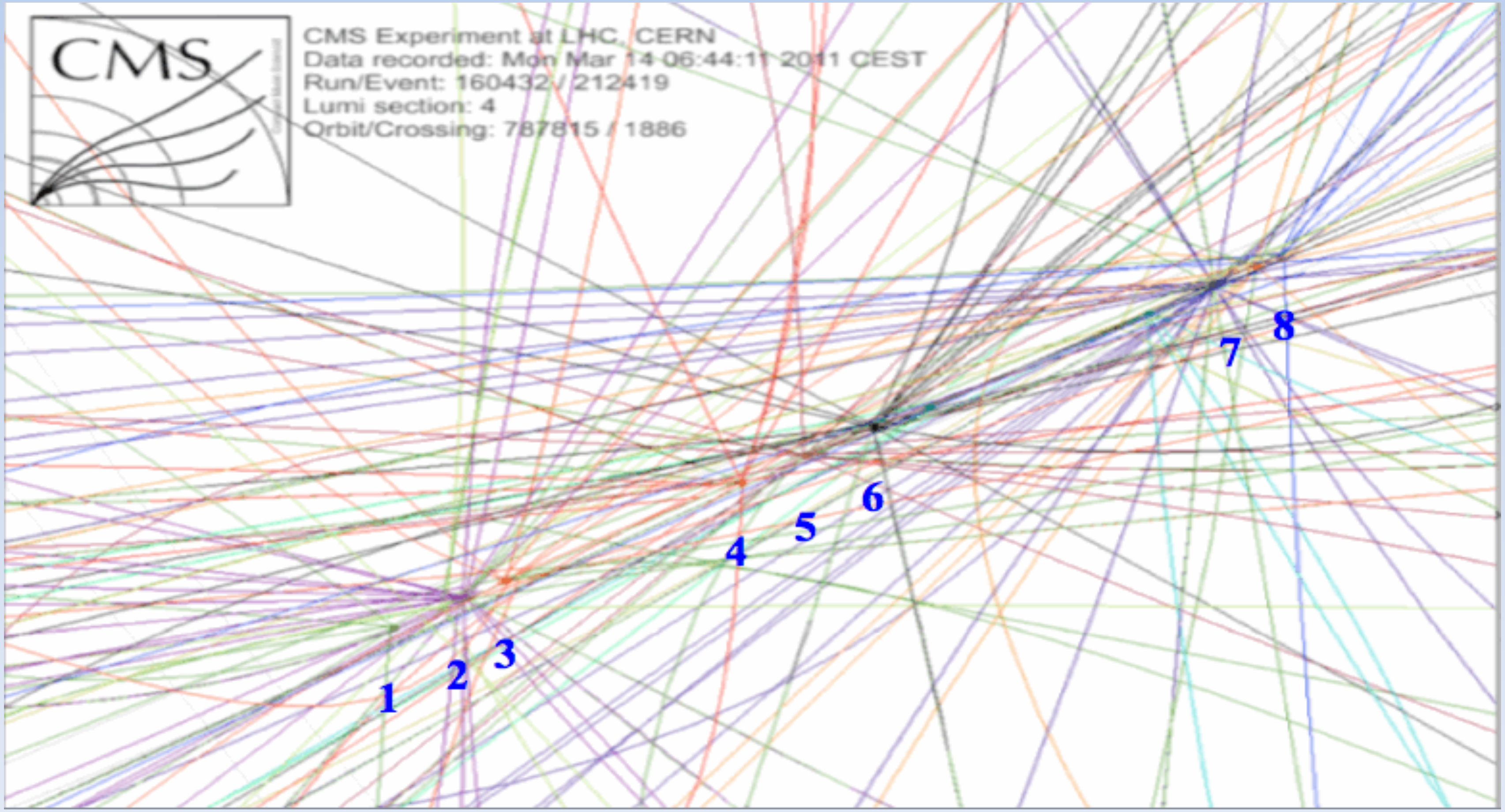
Extrapolated down to $\xi = m^2_p/s$ using Pythia

$\sigma(\xi > m_p^2/s)$ [mb]	
ATLAS Data 2010	$69.4 \pm 2.4(\text{exp.}) \pm 6.9(\text{extr.})$
Schuler and Sjöstrand	71.5
PHOJET	77.3
Block and Halzen	69
Ryskin *et al.*	65.2 – 67.1
Gotsman *et al.*	68
Achilli *et al.*	60 – 75



- Data (ξ **> 5x10^{-6}**) significantly lower than MC predictions from both S&S and PHOJET
- Uncertainty dominated by absolute luminosity calibration
- Extrapolated value agrees with models (power law, logarithmic rise,..) within uncertainties dominated by uncertainty on the ξ–dependence of σ

<u>Measurement of the inelastic *pp* cross section at √s = 7 TeV with the CMS detector</u>



CMS Inelastic cross section: preamble

- New method based on the assumption that the number of inelastic p-p interactions in a given bunch crossing (# pile-up events) follows the Poisson probability distribution:

$$P(n_{Pileup}) = \frac{(L^*\sigma)^{n\_pileup} * e^{-(L^*\sigma)}}{n_{pileup}!}$$

- $\mathbf{n_{Pileup}}$ depends on the total σ(pp) cross section and on the luminosity L , where $L=L_{bx}$ (luminosity per bunch crossing), known with a precision of ± 4%
  →cross-checked using the number of triggers in each bunch (L* σ = Nevents)

- Pile up events are recorded by a high efficient and stable trigger (double ee, $p_T > 10$ GeV); important that trigger efficiency does not depend on $\mathbf{n_{Pileup}}$

- <u>The goal of the analysis is to count the number of primary vertexes ($\mathbf{n_{Pileup}}$) as a function of luminosity ($\mathbf{L_{bx}}$) to extract **σ**</u>

CMS Inelastic cross section: analysis procedure

1. Acquire the bunch crossing (BC) using a primary event:

   the BC is recorded because of a firing trigger.

   Primary event used “only“ to record the BC producing an unbiased sample

2. Count the number of pile-up (PU) events:

   for any BC count the number of vertices in the event.

3. Correct the number of visible vertices for various effects:

   vertex merging, vertex splitting, real secondary vertices…

4. Fit the probability of having *n = 0,….8 pile-up events as a function of luminosity:*

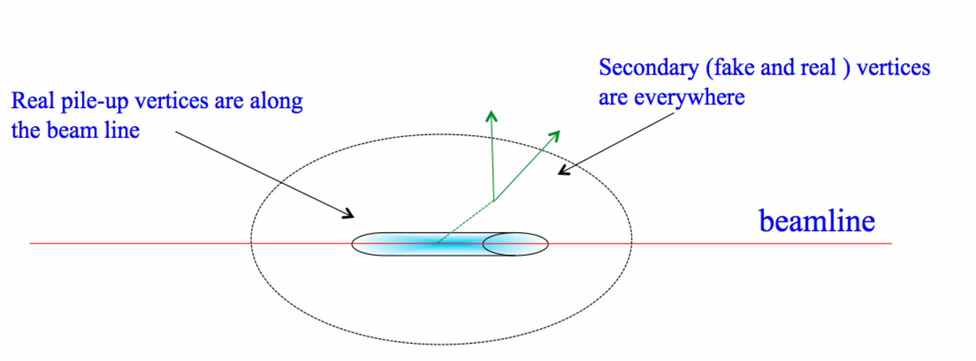
   using a Poisson fit for each bin → 9 values of $\sigma(pp)_n$

5. Fit the 9 values together:

   from $\sigma(pp)_n$ we *obtain* ***σ(pp)***

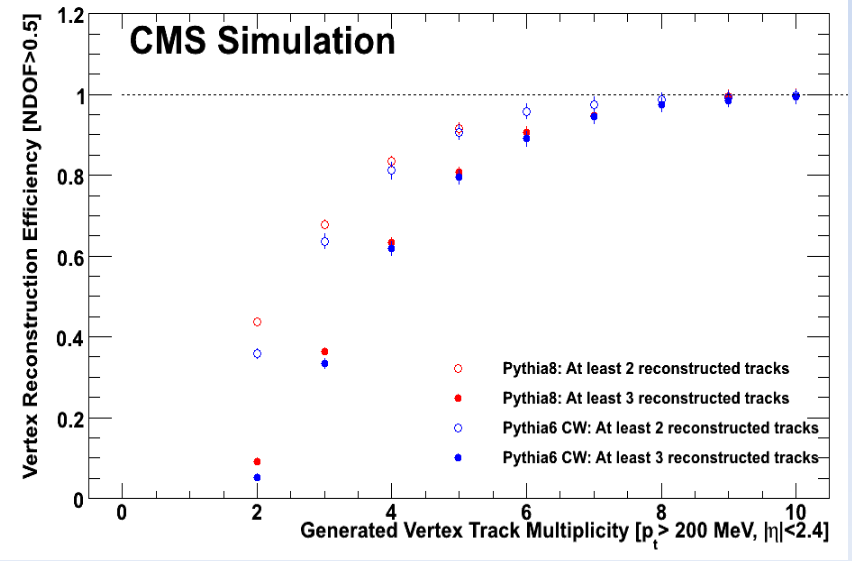
CMS Inelastic cross section: vertex requirement and efficiency

- Track requirements : (≥ 2 pixel hits) && (≥5 strip hits)
- Vertex requirements : (≥2 tracks) && (p_T>200 MeV) && (|η|<2.4)
- Vertex quality cut : NDOF>0.5



Fake vertices contamination (~ 1.5 10^{-3}):

- real secondary vtxs (long lived particles)
- fake secondary vtxs (vtx alg. splitting a single vtx)



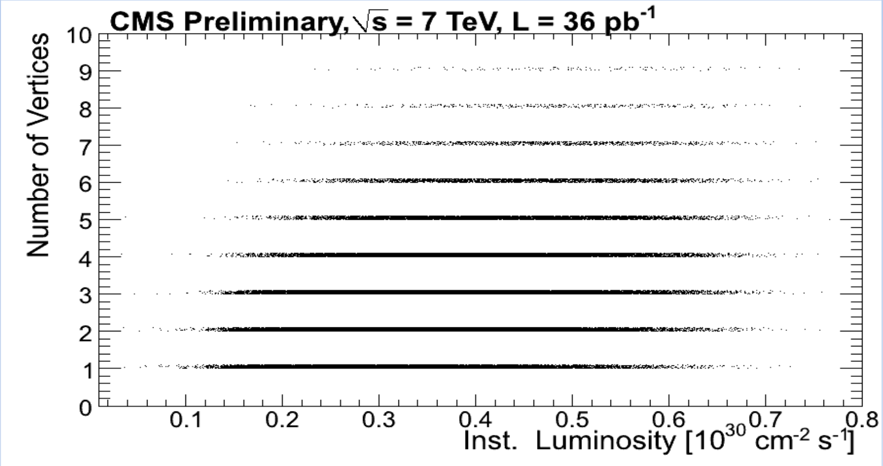
- Tracker GEANT simulation used to compute the vertex reconstruction efficiency
- Algorithm reconstructs vertices separated by ≥ 0.06 mm. The "blind distance" is largely independent of the number of tracks in the vertexes

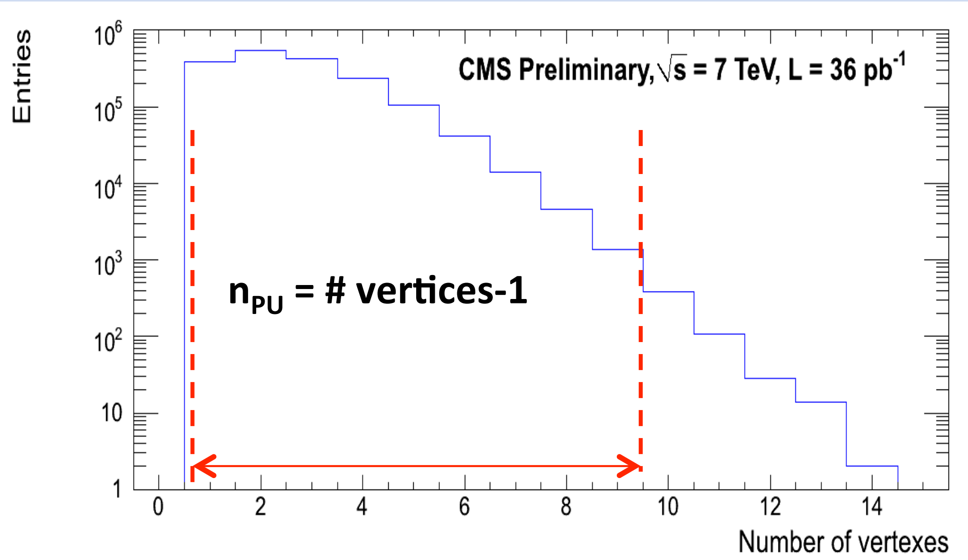
→ <u>Need to correct PU distribution for the missing fraction of events at low multiplicity and for vertex merging effect</u>

CMS Inelastic cross section: count the number of PU events

- LHC has reached a peak luminosity of $2*10^{32}$ cm^{-2} s^{-1} for this 2010 analysis

- However, the important parameter is the **luminosity per bunch crossing**
  → an accurate measurement needs a large luminosity interval: 0.05 ÷ 0.7 $\cdot 10^{30} cm^{-2} s^{-1}$





Data divided into 13 luminosity bins

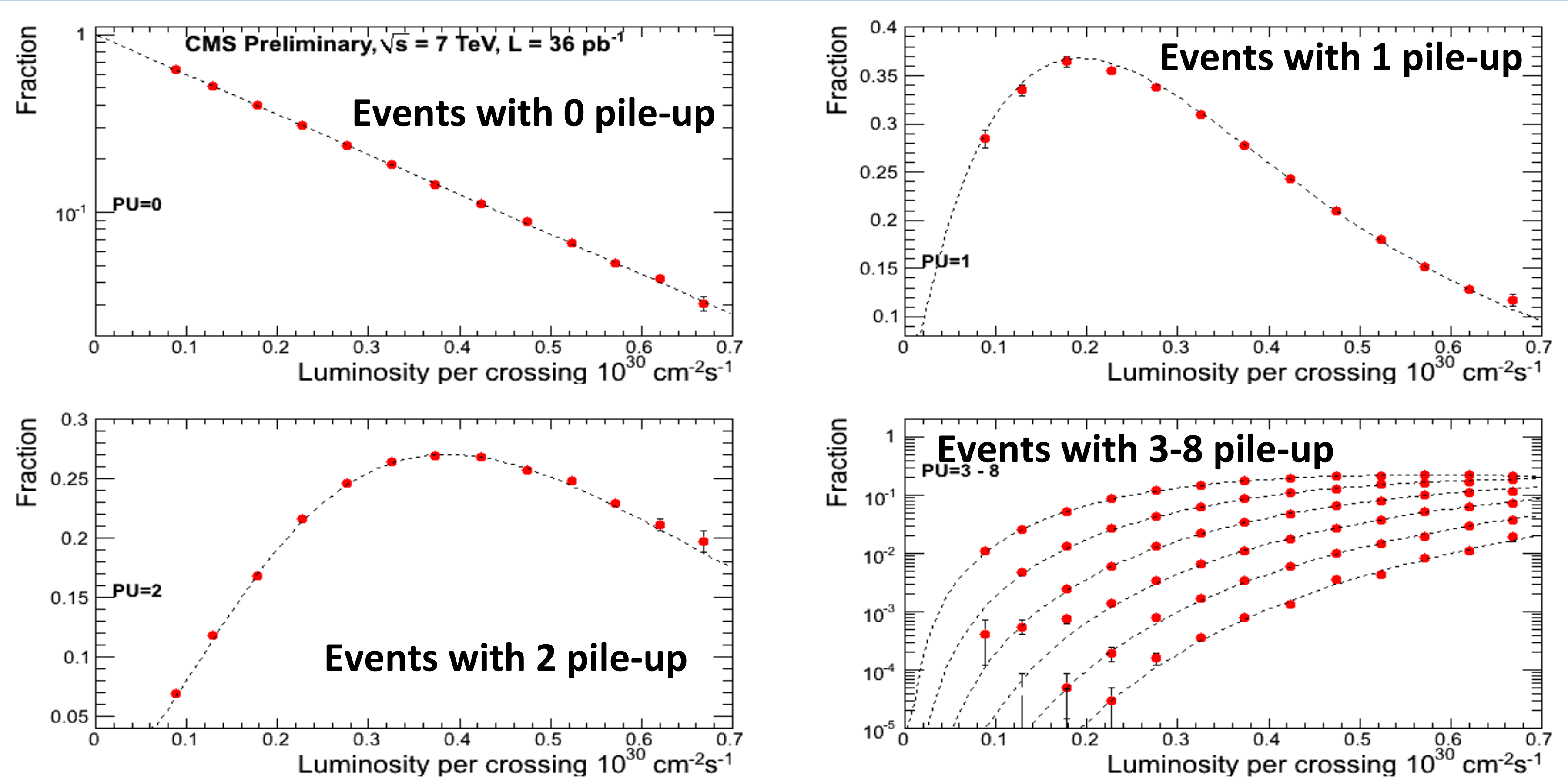
In each luminosity bin the number of vertices is computed

Analyzed events with 0-8 PU events

Ratio Data/MC very flat up to 8 pile-up events

CMS Inelastic cross section: corrected distributions

Using the correction functions, we unfold the measured vertex distributions to obtain the correct distributions to fit with a Poisson function:



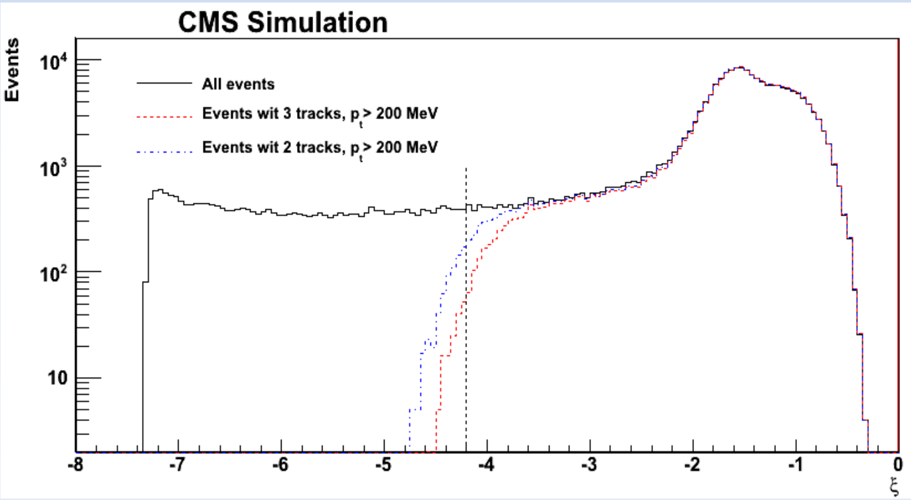
CMS Inelastic cross section: fitted cross sections

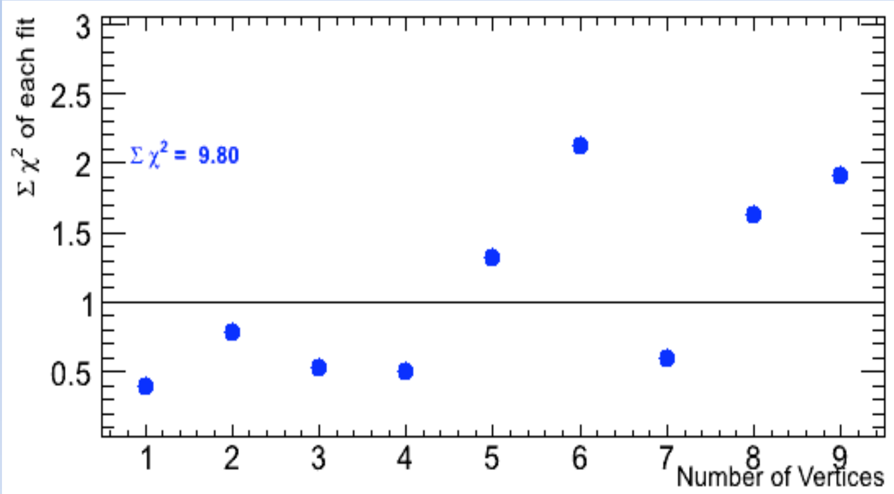
From the fit to each distribution → $\sigma(pp)_n$ with n=1,..9 being the number of vertices. A fit to these 9 values gives the final value:

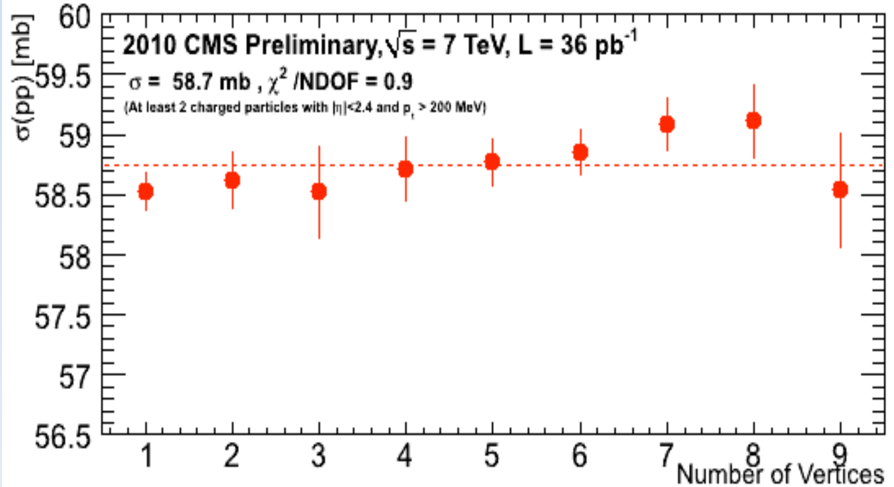
σ(pp) = 58.7 mb

(2 charged particles, p_T>200 MeV, |η|< 2.4)

ξ ($\xi = M^2_X/s$) interval: > 6 *10^{-5}







CMS Inelastic cross section: main systematic checks

Variation of the luminosity values:

CMS luminosity value known with a precision of 4% → $\Delta\sigma$ = 2.4 mb

Modification of some analysis parameters:

- Different set of primary events (single mu/double el) → $\Delta\sigma$ = 0.9 mb
- Change the Poisson fit limit by $0.05 \cdot 10^{30}$ → $\Delta\sigma$ = 0.2 mb
- Change the minimum distance between vertices from 0.1 cm to 0.06 and 0.2 cm → $\Delta\sigma$= 0.3 mb
- Change the vertex quality requirement (NDOF 0.1 – 2) → $\Delta\sigma$= 0.3 mb
  Vertex Transverse position cut (0.05-0.08 cm) → $\Delta\sigma$= 0.3 mb
  Number of minimum tracks at reconstruction → $\Delta\sigma$ = 0.1 mb

$\Delta\sigma$ = 1.4 mb

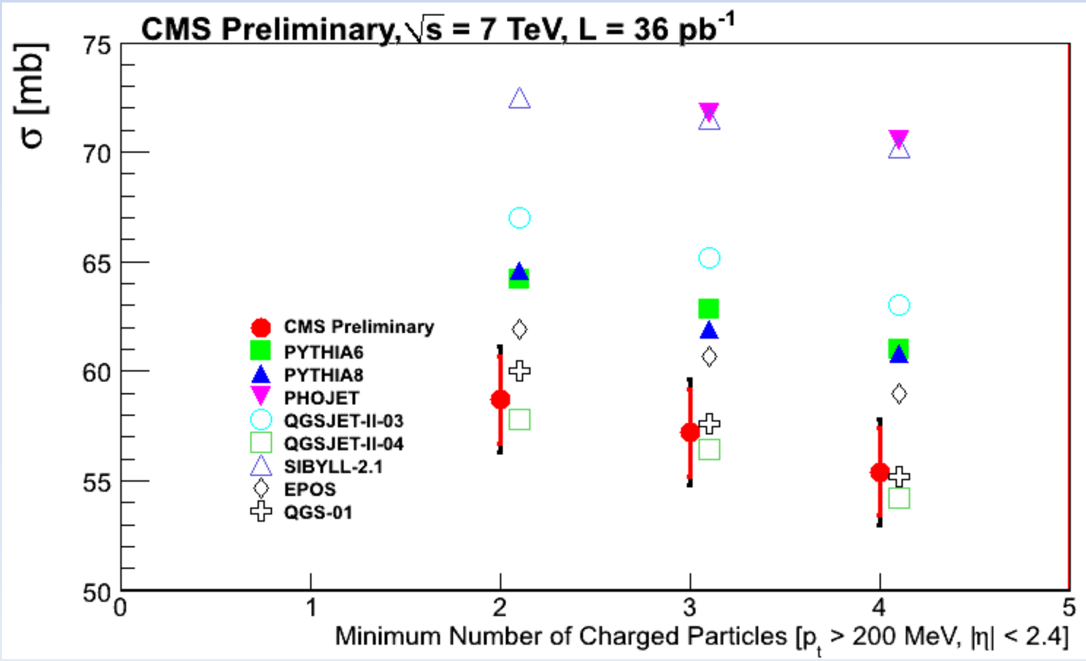
Use the analytic method

Use the analytic method instead of a MC → $\Delta\sigma$ = 1.4 mb

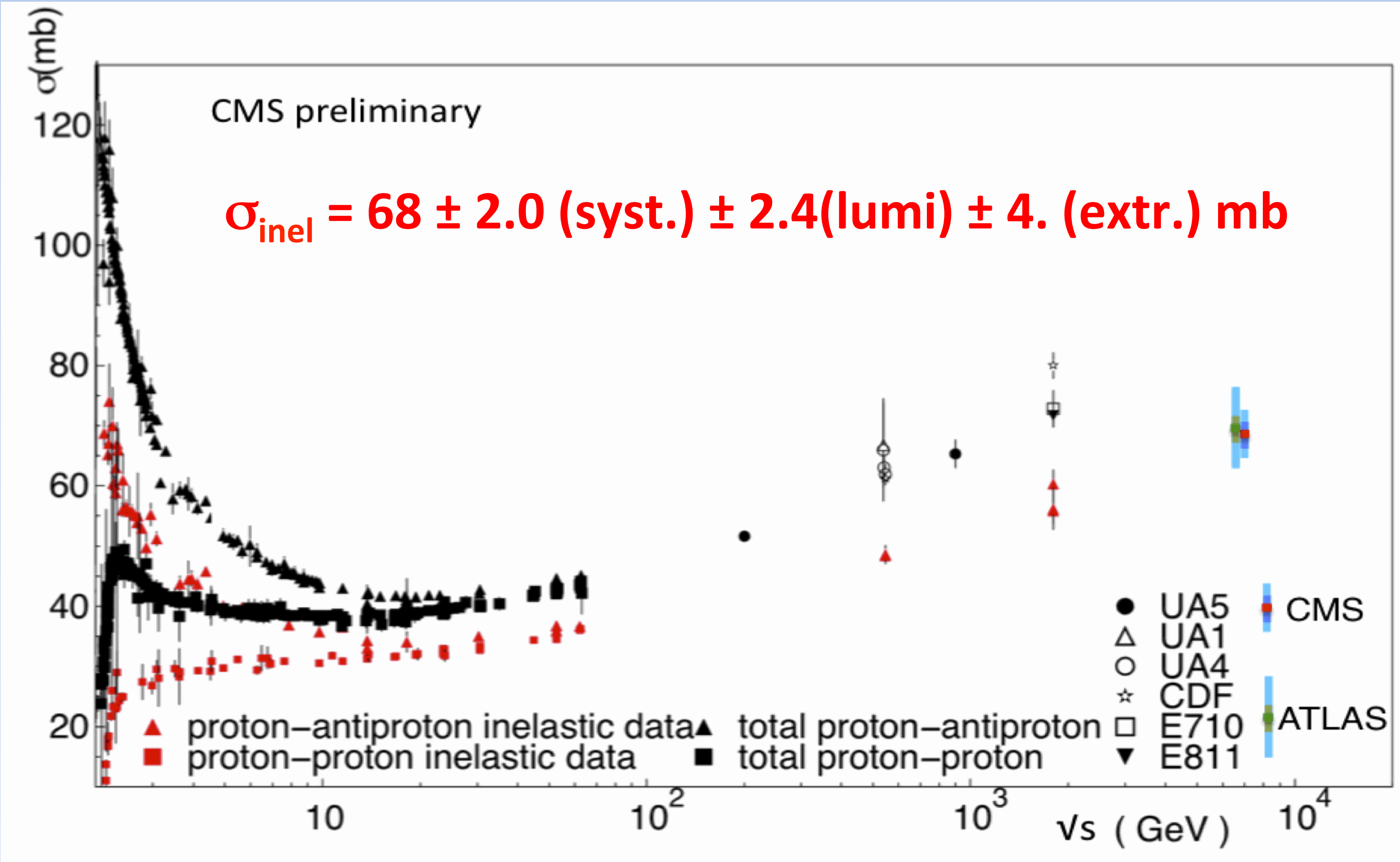
σ(pp) = 58.7 ± 2.0 (Syst) ± 2.4 (Lumi) mb

CMS Inelastic cross section: MC models and extrapolation

- Comparison between the CMS results and several Monte Carlo models
- CMS Systematic uncertainties (inner red error bars) and luminosity uncertainty (outer black bars)
- Monte Carlo predictions with a common uncertainty of ~1 mb
- Except PHOJET and SIBYLL (overestimating), QGSJET (too high), the other models agree (±2 σ) →used for extrapolation!



CMS Inelastic cross section: results



ATLAS and CMS comparison between them

CMS σ **(**ξ **> 6x10^{-5}) =** 58.7 ± 2.0 (sys) ± 2.4 (lum) mb

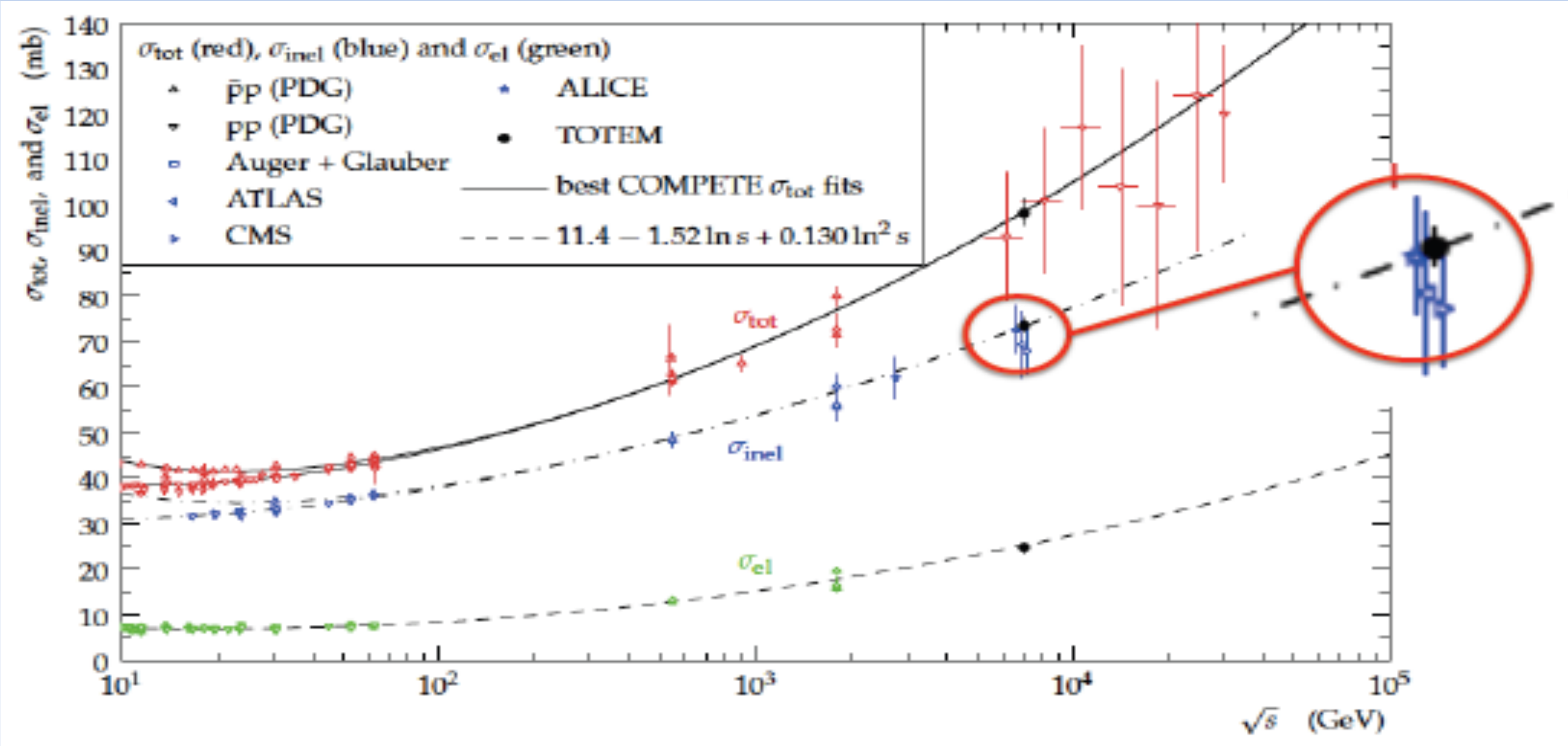
ATLAS σ (ξ **> 5x10^{-6}**) **=** 60.3 ± 0.5 (sys.) ± 2.1 (lum) mb

CMS σ_{inel} **= 68.0 ± 2.0 (sys.) ± 2.4(lum) ± 4. (extr.) mb**

ATLAS σ_{inel} **= 69.1 ± 2.4 (exp.) ± 6.9 (extr.) mb**

Total and Inelastic p-p cross section at LHC

✓ ATLAS and CMS central values lower than TOTEM after extrapolation into region of very low ξ (extrapolation error is dominant)



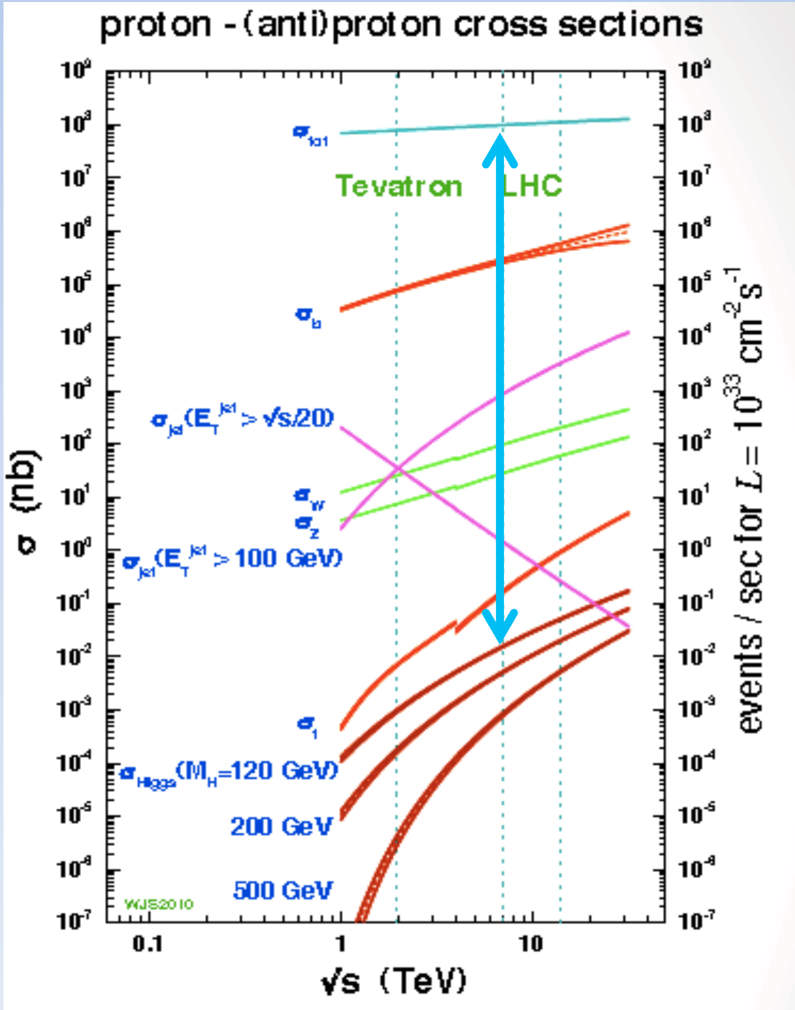
Conclusions

- ATLAS and CMS have performed precise (3.5-5%) measurements of the fiducial inelastic proton-proton cross section for LHC at √s 7 TeV
- Both measurements are dominated by the absolute luminosity calibration (3.5-4%)
- ATLAS results are significantly below predictions by PHOJET and *Schuler & Sjöstrand* (Pythia); CMS finds a similar discrepancy for PHOJET but a smaller discrepancy with Pythia respect to ATLAS
- ATLAS and CMS total inelastic cross section both suffer from uncertainties on the ξ-dependence that imply a large extrapolation error.
- The results are consistent with predictions from Pythia (power law dependence on √s), from *Block & Halzen* (logarithmic dependence) and from other theoretical calculation (Ryskin *et al*., Achilli *et al.*)

Back up

Dominant p-p interactions at LHC

- The pp inelastic cross-section is much larger than that for “new” particle production
  → only 1/10^9 interactions would produce a Higgs
- p-p dominated by soft QCD (low-p_T transfer):
  - Initial and final state radiations
  - Colour recombination
  - Multiple Parton Interactions (MPI)
  - Underlying events…
- Soft QCD processes are unavoidable background for jet cross sections, missing energy, isolation…
  → impact on resolutions for E^T_{miss}, jet reconstruction, lepton ID,…
- Soft QCD can not be predicted using p-QCD
  → phenomenological models are needed and Monte Carlo tunes can be tested looking for agreement with data for various observables.

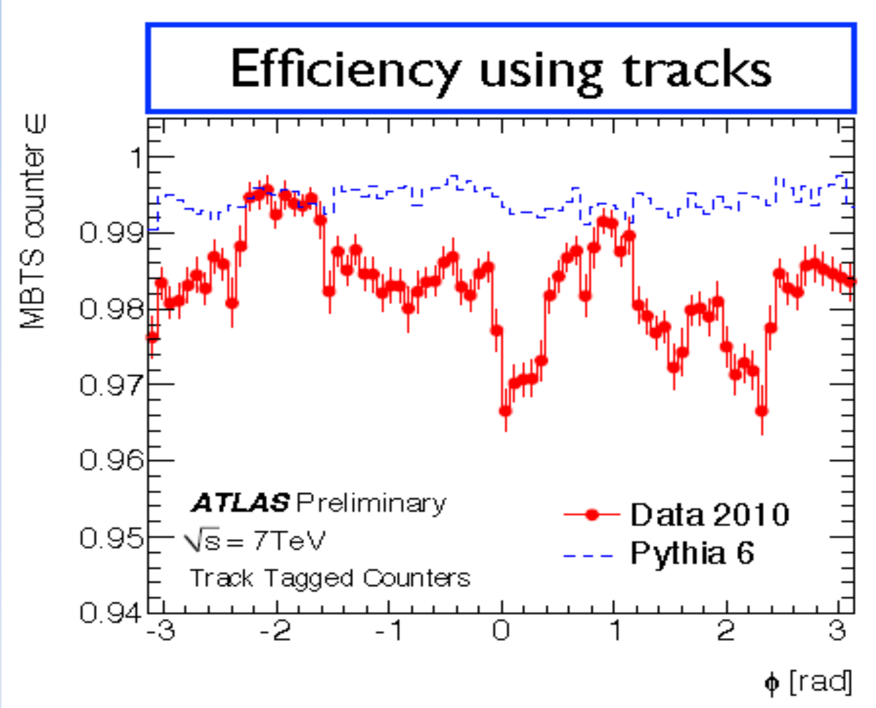


ATLAS Inelastic cross section: MBTS response

MBTS hit multiplicities dependent on efficiencies of single scintillators and material budget

Efficiencies measured data driven:

- Using extrapolated tracks with pT > 200 MeV
- Calorimeter signals behind the MBTS detectors
- Efficiency overestimated in the MC, by ~1%



Impact of material estimated using MC with different amount of dead material, in combination with data

ATLAS Inelastic cross section: background evaluation

Backgrounds from direct beam interactions with:

- residual gas in the beam-pipe or the beam-pipe itself
- material upstream from the detector

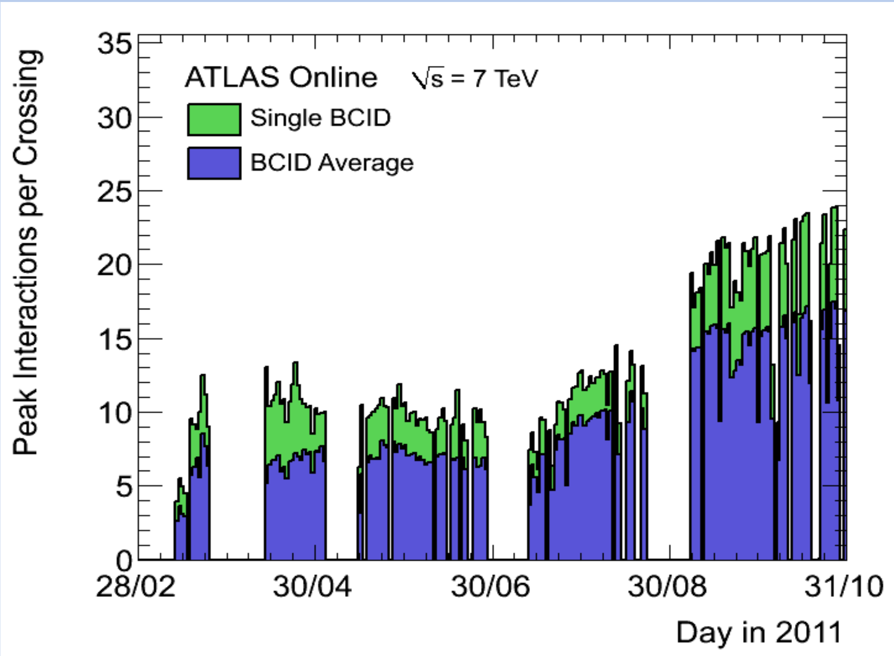
→estimate by using bunch crossings with only a single proton bunch

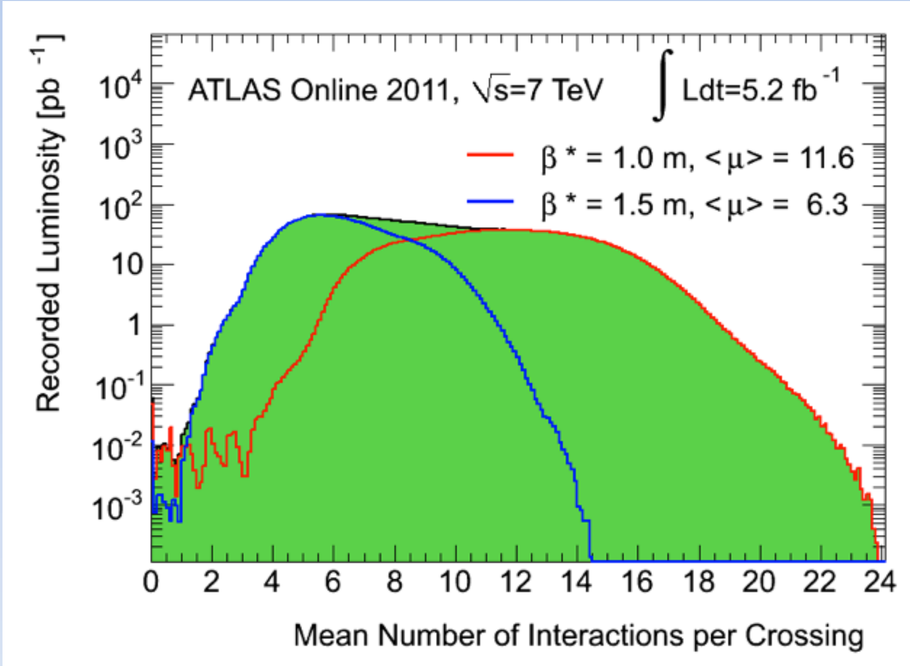
  – Inclusive selection: 0.1%
  – Single-sided: 0.3%

Additional background from ‘afterglow‘, like slowly decaying beam remnants

→can be estimated from timing distributions: < 0.4%

ATLAS Pile-up 2011

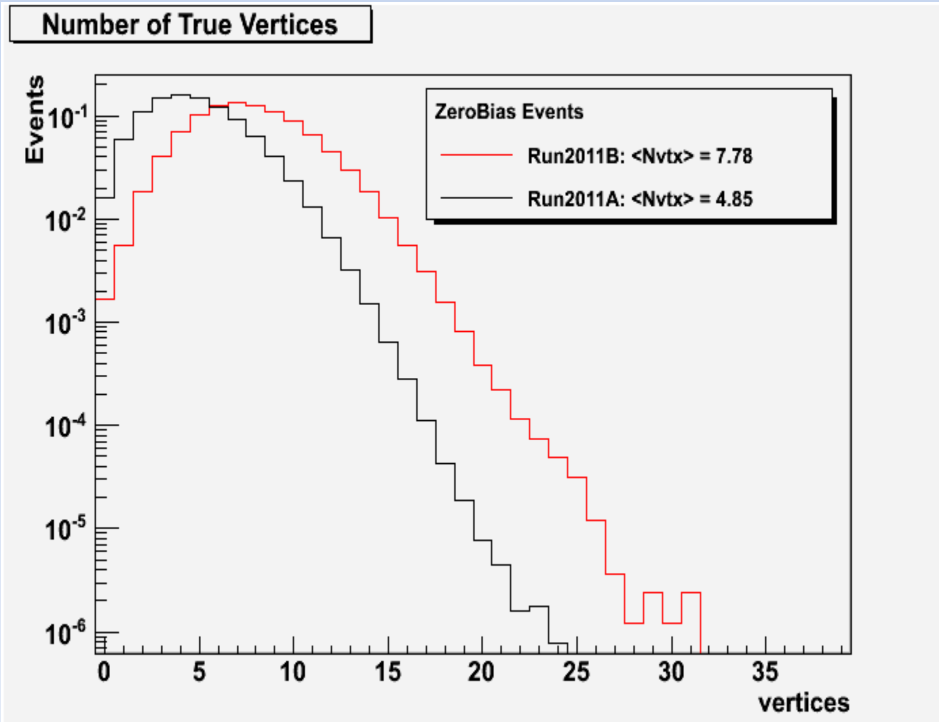




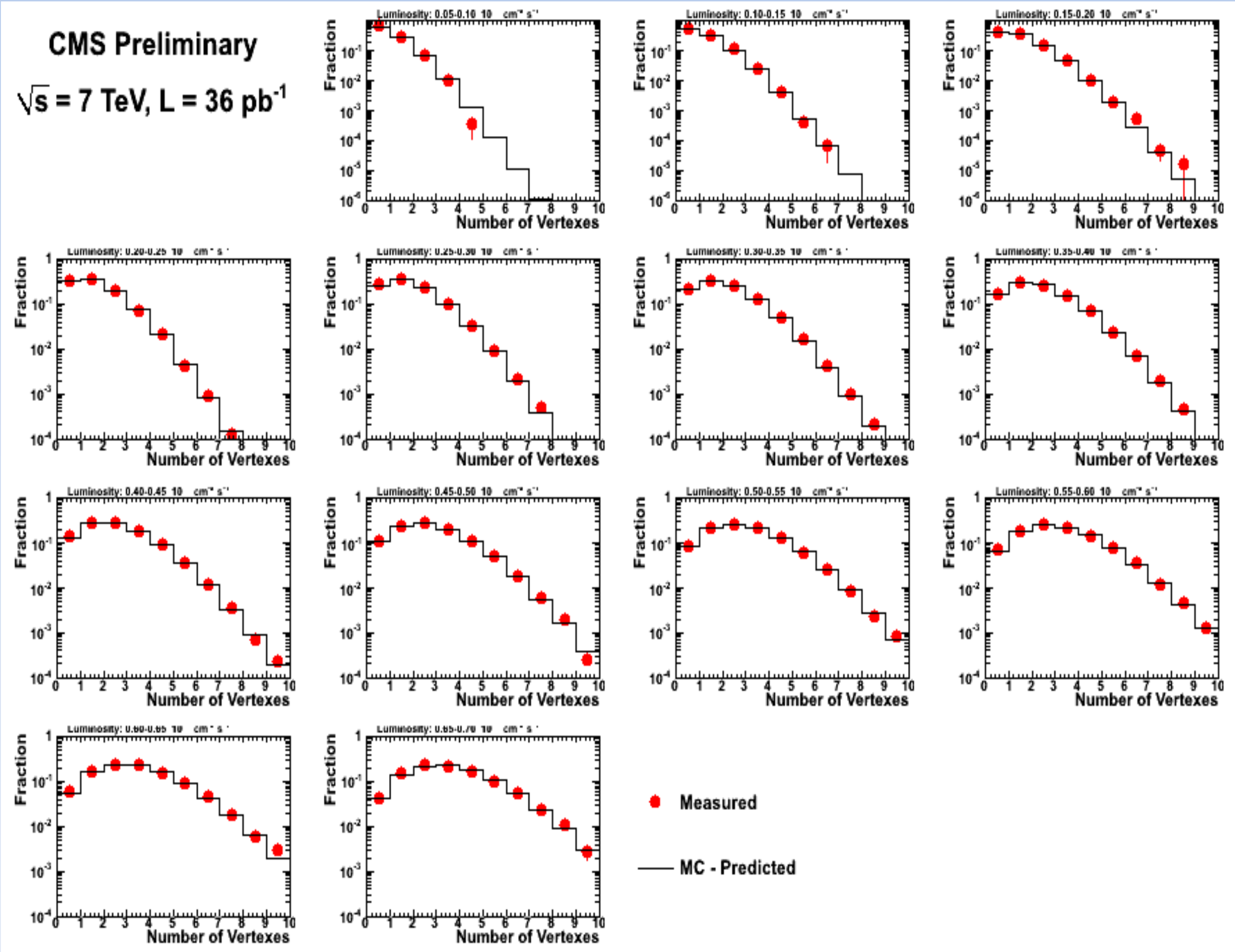
CMS Pile-up 2011

The number of reconstructed vertices after the August Technical Stop increased by factor 1.5 (β^*=1.5m → 1m)

Fills start with ~15 pile-up interactions.



CMS Inelastic cross section: correct the number of vertices



Vertex merging and secondary vertices

Vertex merging:

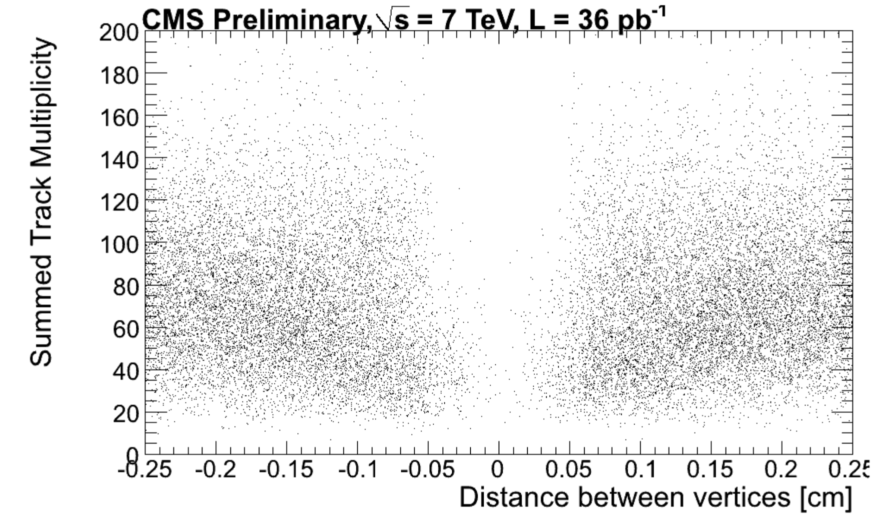
When two vertexes overlap they are merged into a single one.
This blind distance is ~ 0.06 cm

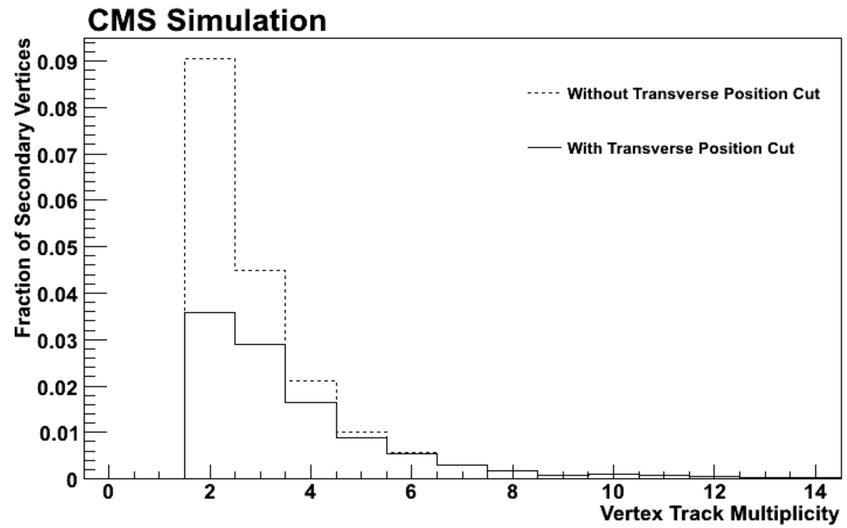
Secondary vertices:

1.Fakes from the reconstruction program
2.Real non prompt decay

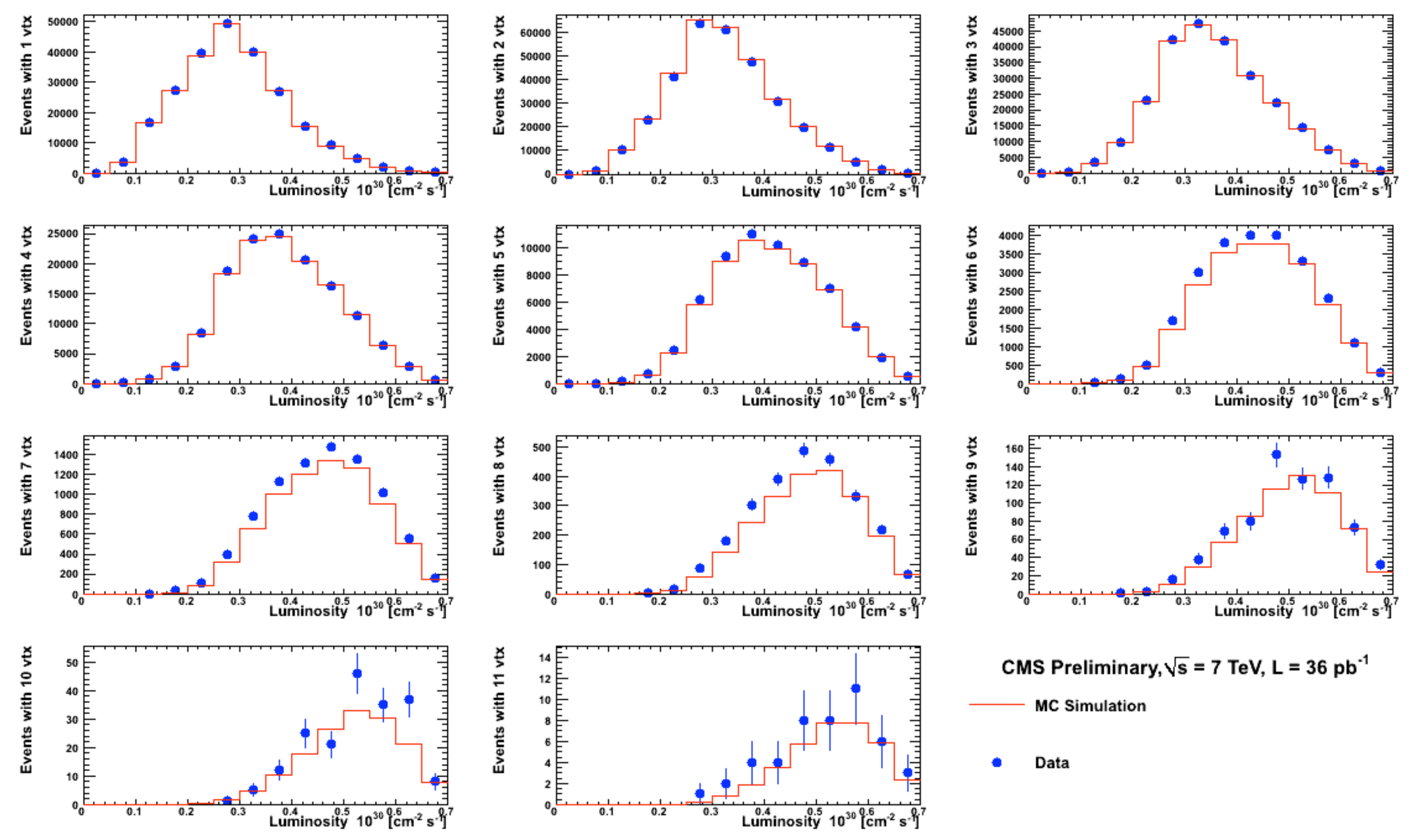
Both reduced by the request on the transverse position

Most evident at low track multiplicity





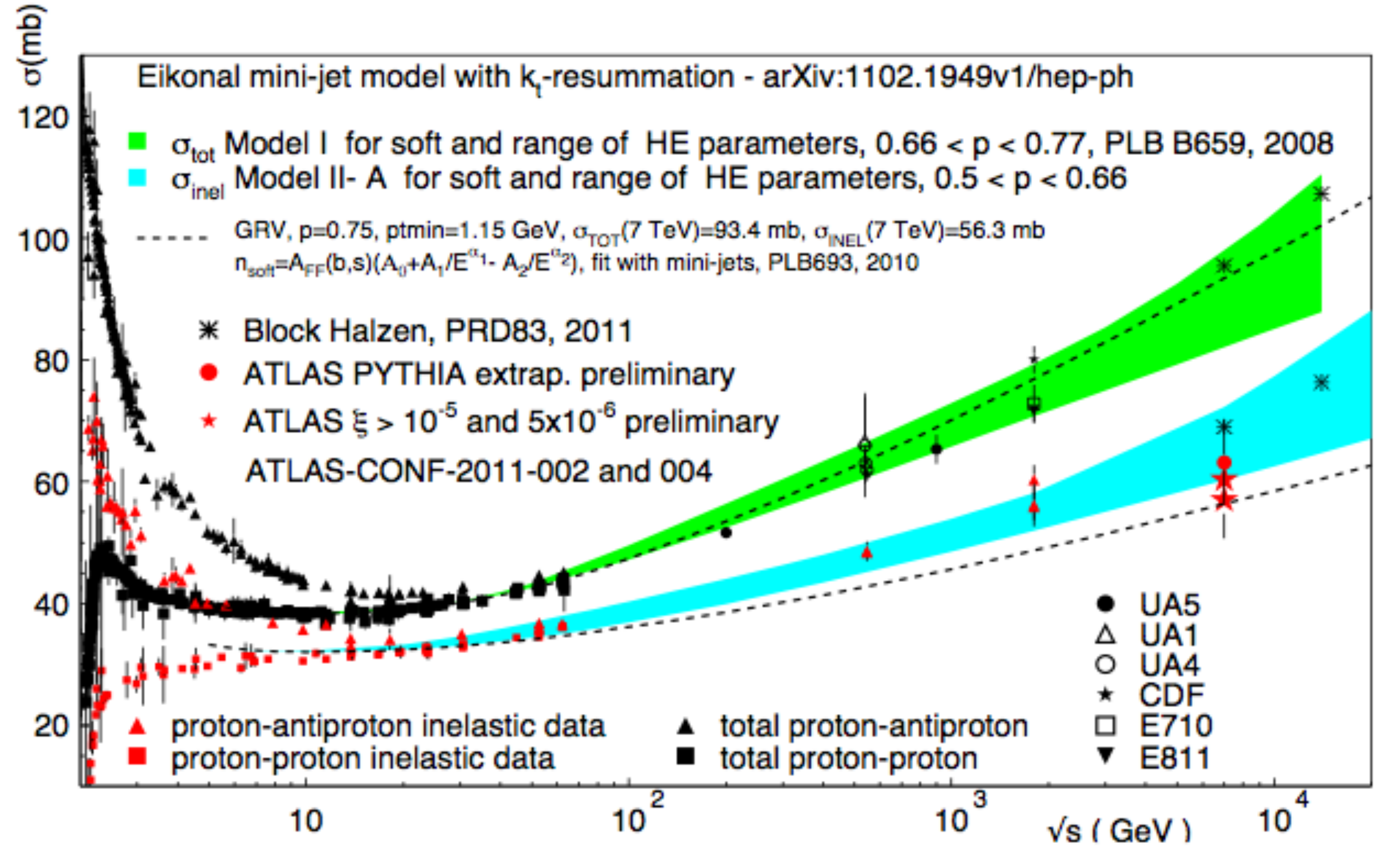
Vertex Multiplicity Correction



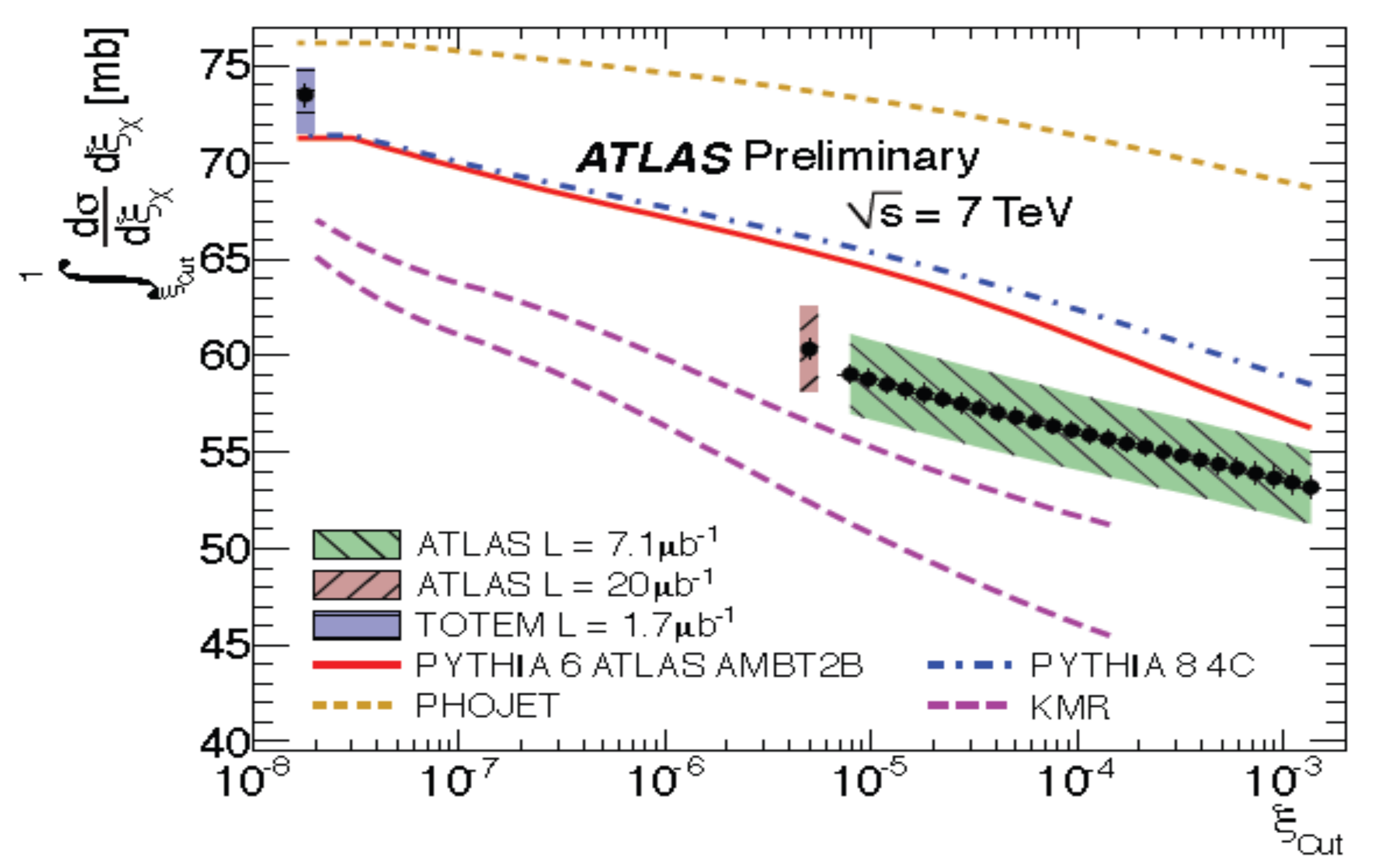
CMS Inelastic cross section: additional measurements

Using the same technique, 4 different cross sections have been measured:

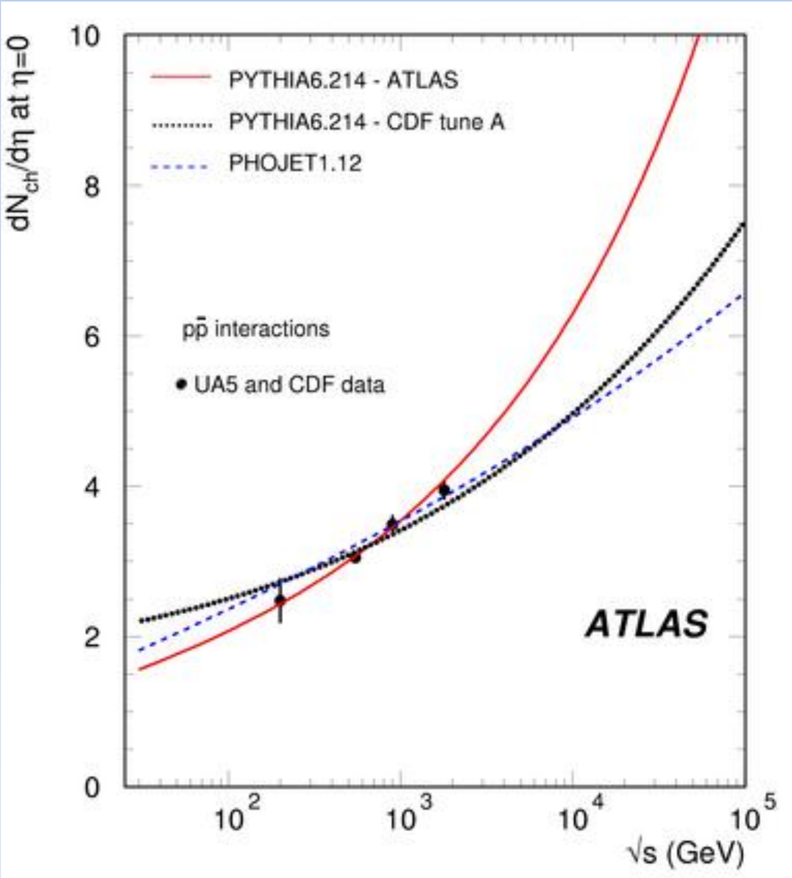
- 2 charged particles with p_T>200 MeV in $|\eta|$< 2.4
  σ (pp) = 58.7 ± 2.0 (Syst) ± 2.4 (Lum) mb
- 3 charged particles with p_T>200 MeV in $|\eta|$< 2.4
  σ (pp) = 57.2 ± 2.0 (Syst) ± 2.4 (Lum) mb
- 4 charged particles with p_T>200 MeV in $|\eta|$< 2.4
  σ (pp) = 55.4 ± 2.0 (Syst) ± 2.4 (Lum) mb
- 3 particles with p_T>200 MeV in $|\eta|$< 2.4
  σ (pp) = 59.7 ± 2.0 (Syst) ± 2.4 (Lum) mb



σ(mb)
Eikonal mini-jet model with k_t-resummation - arXiv:1102.1949v1/hep-ph
σ_tot Model I for soft and range of HE parameters, 0.66 < p < 0.77, PLB B659, 2008
σ_inel Model II- A for soft and range of HE parameters, 0.5 < p < 0.66
GRV, p=0.75, ptmin=1.15 GeV, σ_TOT(7 TeV)=93.4 mb, σ_INEL(7 TeV)=56.3 mb
Block Halzen, PRD83, 2011
ATLAS PYTHIA extrap. preliminary
ATLAS ξ > 10^-5 and 5x10^-6 preliminary
ATLAS-CONF-2011-002 and 004
UA5
UA1
UA4
CDF
E710
E811
proton-antiproton inelastic data
proton-proton inelastic data
total proton-antiproton
total proton-proton
√s (GeV)


ATLAS Preliminary
√s = 7 TeV
ATLAS L = 7.1μb-1
ATLAS L = 20μb-1
TOTEM L = 1.7μb-1
PYTHIA 6 ATLAS AMBT2B
PYTHIA 8 4C
PHOJET
KMR
75
70
65
60
55
50
45
40
10-8
10-7
10-6
10-5
10-4
10-3
ξCut
[mb]

Minimum Bias Events (from CSC book)

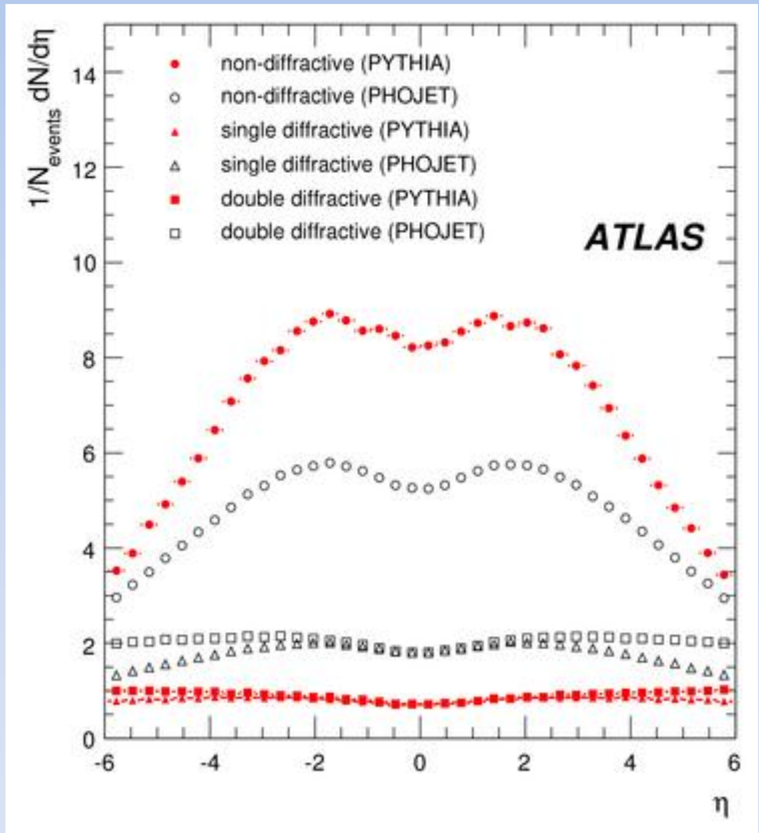


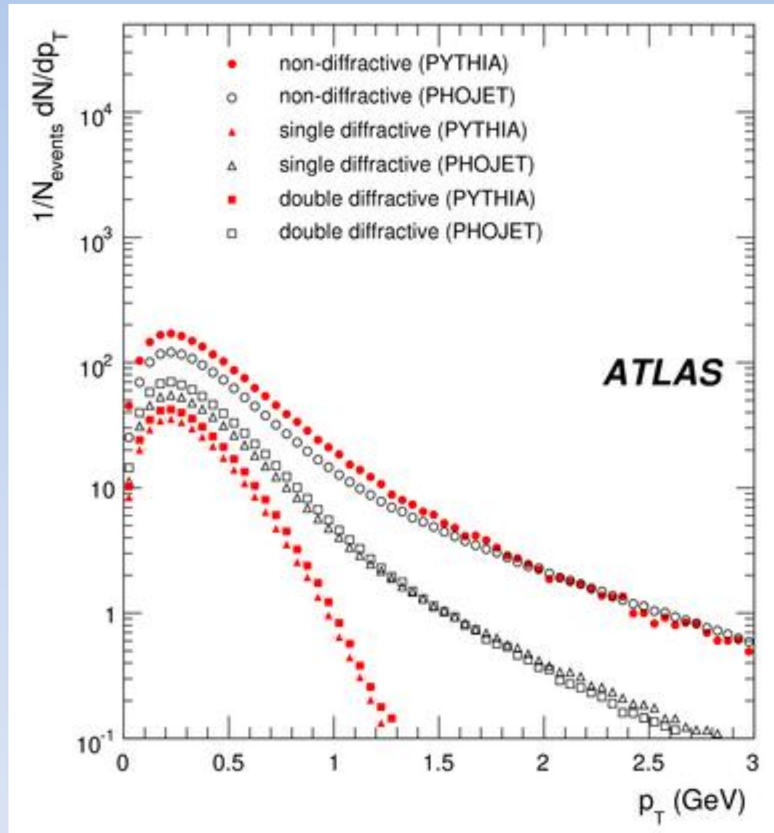
Central charged particle density for non-single diffractive inelastic events as a function of energy.

The lines show predictions from PYTHIA using the ATLAS tune and CDF tune-A, and from PHOJET.

The data points are from UA5 and CDF p-(anti)p data.

Minimum Bias Events (from CSC book)





Pseudorapidity (a) and transverse momentum distribution (b) of stable charged particles from simulated 14TeV pp inelastic collisions generated using PYTHIA and PHOJET event generators.