Measurement of the inelastic proton-proton cross section at 13 TeV

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Introduction

- Measure the inelastic proton-proton cross section at $\sqrt{s}$ = 13 TeV, in the largest possible phase space that is experimentally accessible

- Extrapolate this measurement to the total inelastic phase space domain

$$\sigma_{tot}(s) = \sigma_{el}(s) + \sigma_{inel}(s).$$

$$\boxed{\sigma_{inel}(s) = \sigma_{sd}(s) + \sigma_{dd}(s) + \sigma_{cd}(s) + \sigma_{nd}(s).}$$

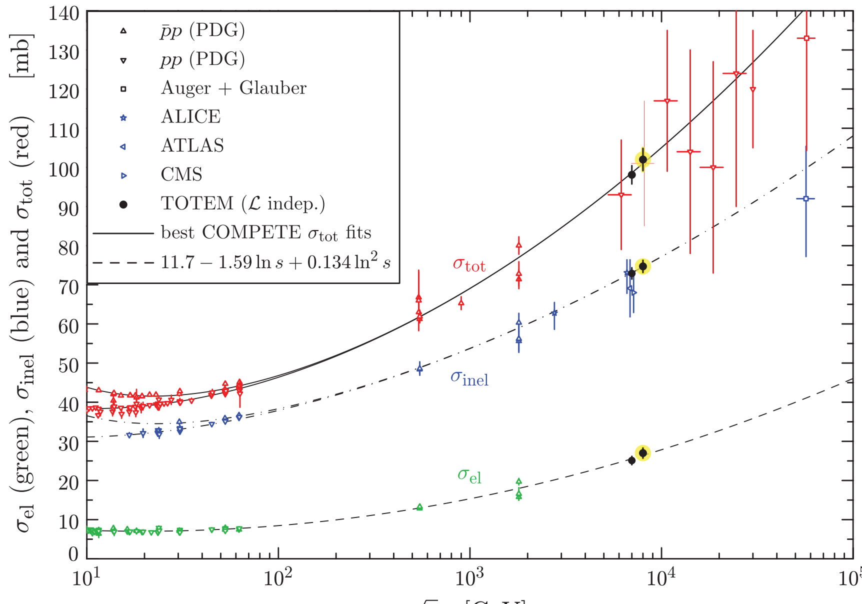
- Important basic QCD measurement
  ➔ Crucial to model pile-up

- Challenging to measure precisely
  ➔ requires good calibration of luminosity
  ➔ extrapolation leads to significant model dependences

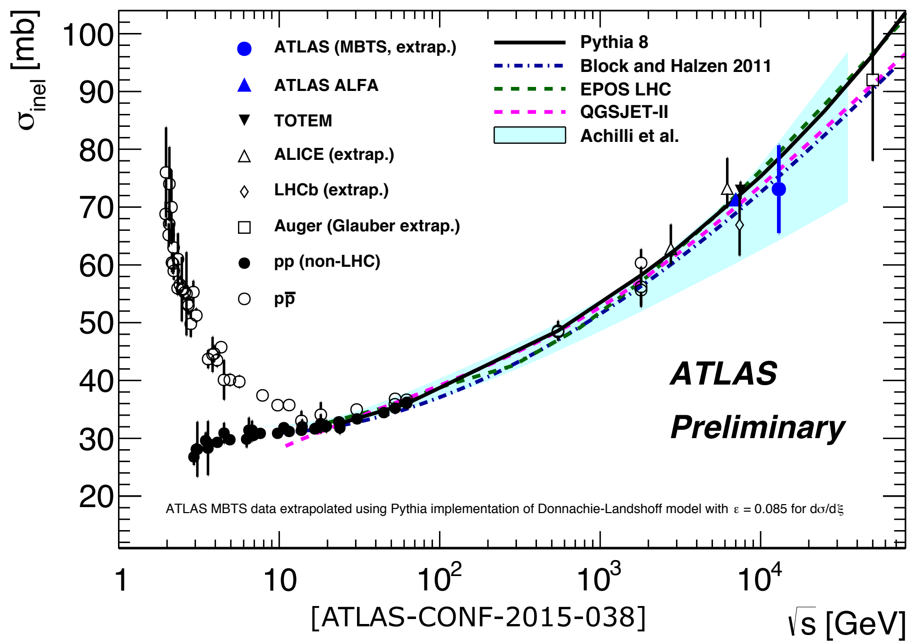
- Aim of CMS: measure inelastic cross section in two detector acceptances
  ➔ go more forward and gain information on relative increase
  ➔ reduce extrapolation uncertainty

State of the art

- Overview of existing results:



[PRL 111, 012001 (2013)]



[ATLAS-CONF-2015-038]

At 7 TeV, measurements of ALICE, ATLAS, CMS, LHCb available:
σ_{inel} ranges from 66.9 to 72.7 mb,
with total uncertainties up until ±7.3 mb

13 TeV preliminary ATLAS result:
σ_{inel} = 73.1 ± 0.9 (exp.) ± 6.6 (lum.) ± 3.8 (ext.) mb

Most precise measurements from TOTEM (with optical theorem)
7 TeV: σ_{inel} = 73.5 ± 1.9 mb
8 TeV: σ_{inel} = 74.7 ± 1.7 mb

Analysis strategy

- Count events with an energy deposit above threshold

Number of events above threshold

Data driven correction for noise and pile-up

$$\sigma = \frac{N_{\text{int}}(1 - b_\xi)}{\epsilon_\xi \int \mathcal{L}\, dt},$$

Correction to particle level (efficiency ε and contamination b) from Monte Carlo simulations

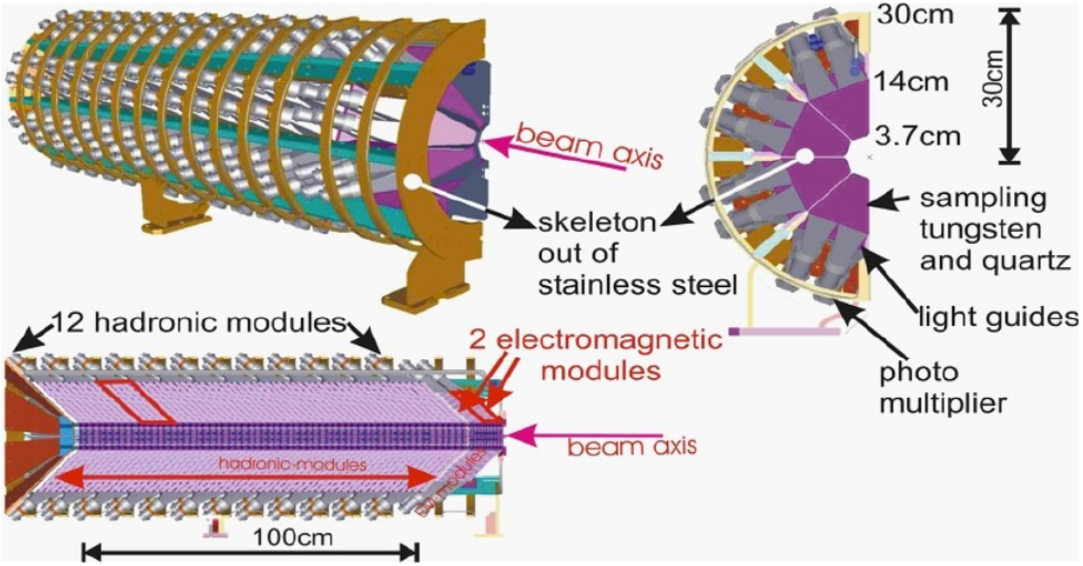
Integrated luminosity

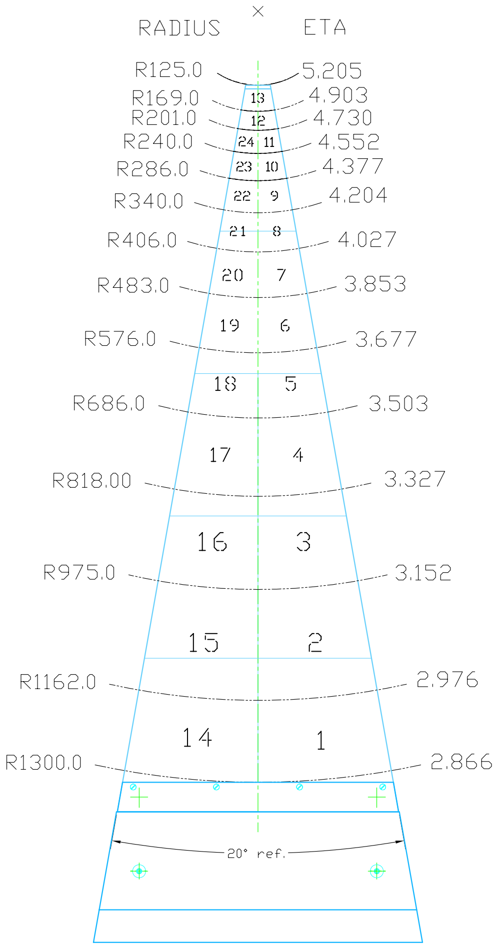
- Extrapolate to total inelastic phase space domain
  ➔ purely model driven…

HF and CASTOR calorimeters

- HF:
  - 18 iron φ wedges, long+short quartz fibres
  - at both sides of CMS: HF- and HF+
  - used acceptance: **$3.152 < |\eta| < 5.205$**
  - Energy scale known to ±10%

- CASTOR:
  - 16 φ sectors, 14 z-modules, tungsten/quartz plates
  - only minus side of CMS, acceptance: **$-6.6 < \eta < -5.2$**
  - Energy scale: ±15%, alignment: ±2 mm





Data and event selection

- Low pile-up (5 % - 50 %) $\sqrt{s}$ = 13 TeV data samples from LHC RunII taken in 2015 at B = 0 T and 3.8 T during several run periods
- CMS data acquisition was triggered by the presence of both beams in the interaction point (ZeroBias)
- Events selected offline in **two** different detector acceptances:

At least one HF tower above a threshold of 5 GeV (**HF OR**)	At least one HF or CASTOR tower above a threshold of 5 GeV (**HF OR CASTOR**)

- Selected number of inelastic events is corrected for the contribution of noise:

$$N_{cor} = N_{ZB}[(F_{ZB} - F_{EB}) + F_{EB}(F_{ZB} - F_{EB})]$$

N_{ZB} = number of ZeroBias triggered events; F_{ZB} = fraction of ZeroBias triggered events above threshold
F_{EB} = fraction of no-beam triggered events above threshold; N_{cor} = corrected number of events

- Resulting purities ($N_{cor}/(N_{ZB} \times F_{ZB})$) of 98.5 – 99.3 %

Data driven pile-up correction

- The observed number of proton-proton collisions per bunch crossing (n) follows a Poisson distribution, P(n, λ), with the average value λ

- Probability to have no interaction in a ZeroBias sample:

$$P(0,\lambda) = 1 - r, \qquad r = \frac{N_{\mathrm{cor}}}{N_{\mathrm{ZB}}}$$

- Determine mean number of inelastic collisions per bunch crossing:

$$P(0,\lambda) = \exp(-\lambda), \qquad \Rightarrow \lambda = -\ln(1-r)$$

- Derive pile-up correction factor:

$$f_{\mathrm{pu}} = \frac{\sum_{n=0}^{\infty} n P(n,\lambda)}{\sum_{n=1}^{\infty} P(n,\lambda)} = \frac{\lambda}{1-P(0,\lambda)},$$

- This correction is applied per colliding bunch
- The total reconstructed number of interactions, corrected for the contributions of noise and pileup, is then given by:

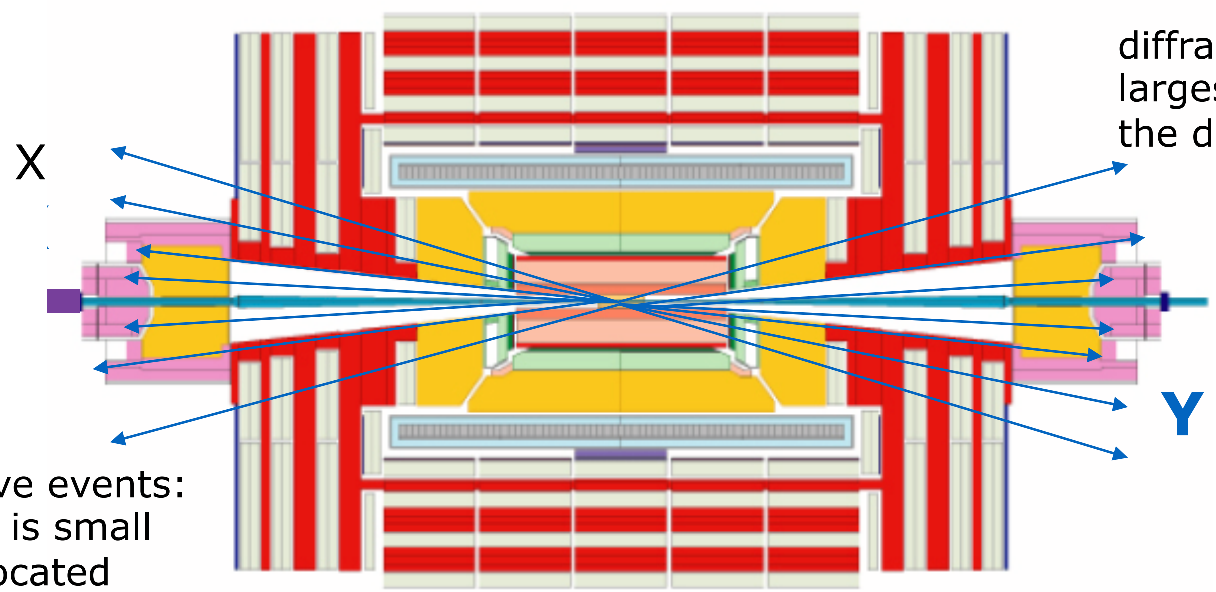
$$N_{\mathrm{int}} = \sum_{\mathrm{bunches}} N_{\mathrm{cor}}^{\mathrm{b}} \times f_{\mathrm{pu}}^{\mathrm{b}}.$$

Correction to particle level

- Definition of visible phase space domain:
  - split final state into systems X (negative side) and Y (positive side) separated by the largest rapidity gap
  - calculate invariant masses M_X and M_Y, and use:

$$\xi_{\mathrm{X}} = \frac{M_{\mathrm{X}}^2}{s}, \qquad \xi_{\mathrm{Y}} = \frac{M_{\mathrm{Y}}^2}{s}, \qquad \xi = \max(\xi_{\mathrm{X}}, \xi_{\mathrm{Y}})$$

- Event inside detector acceptance if ξ_X or ξ_Y large enough
  ➔ go as forward as possible to tag lowest diffractive dissociation masses



diffractive events:
largest gap separates the dissociation systems

Non-diffractive events:
- largest gap is small
- randomly located

Correction to particle level

- Definition of visible phase space domain:
  - split final state into systems X (negative side) and Y (positive side) separated by the largest rapidity gap
  - calculate invariant masses M_X and M_Y, and use:

$$\xi_{\mathrm{X}} = \frac{M_{\mathrm{X}}^2}{s}, \qquad \xi_{\mathrm{Y}} = \frac{M_{\mathrm{Y}}^2}{s}, \qquad \xi = \max(\xi_{\mathrm{X}}, \xi_{\mathrm{Y}})$$

- Acceptance limits are obtained from a dedicated study using fully simulated events from various Monte Carlo event generators

- Relation between stable-particle level phase space definition and detector-level offline selection is quantified by efficiency and contamination factors.

  - Efficiency (ε_ξ) = fraction of selected stable-particle level events that pass offline detector-level selection
  - Contamination (b_ξ) = fraction of offline detector-level selected events that are not part of the considered stable-particle level phase space domain

- Optimal acceptances:
  HF OR ➔ $\xi > 10^{-6}$
  HF OR CASTOR ➔ $\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6}$ ➔ $M_X > 4.1$ GeV or $M_Y > 13$ GeV

Systematic uncertainties

- Model dependence of correction factors (efficiency, purity)
- HF and CASTOR energy scale uncertainties
  ➔ change HF (CASTOR) response in simulation by ±10% (±15%)
- CASTOR alignment: vary measured position within uncertainty in simulation
- Run-to-run variation

	$\sigma(\xi > 10^{-6})$ (mb)	$\sigma(\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6})$ (mb)
Model dependence	0.66	0.38
HF energy scale uncertainty	0.34	0.13
CASTOR energy scale uncertainty	-	0.04
CASTOR alignment	-	0.03
Run-to-run variation	0.15	0.14
Total	0.76	0.44
Luminosity	1.78	1.96

- Luminosity:
  The Pixel Cluster Counting method is used and the absolute luminosity scale calibration is derived from an analysis of Van der Meer Scans performed in August 2015
  ➔ known to 2.7% uncertainty for B = 3.8 T runs [CMS-PAS-LUM-15-001]
  ➔ known to 2.9% uncertainty for B = 0 T runs

Measured inelastic cross sections at 13 TeV

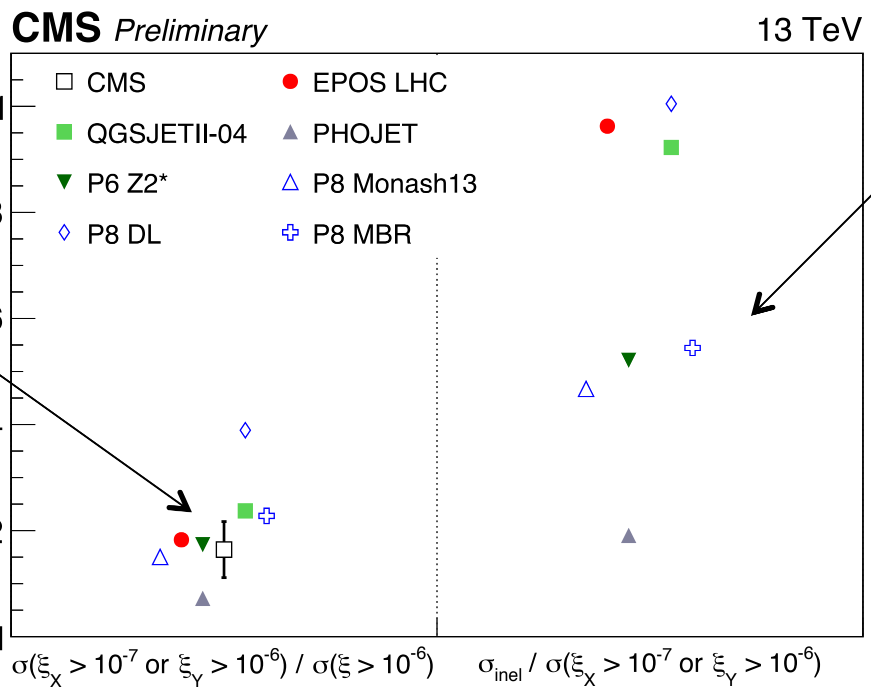
- Fully corrected cross section HF OR:

$$\boxed{\sigma(\xi > 10^{-6}) = 65.8 \pm 0.8\ (\text{exp.}) \pm 1.8\ (\text{lum.})\ \text{mb}}$$

- Fully corrected cross section HF OR CASTOR:

$$\boxed{\sigma(\xi_X > 10^{-7} \text{ or } \xi_Y > 10^{-6}) = 66.9 \pm 0.4\ (\text{exp.}) \pm 2.0\ (\text{lum.})\ \text{mb}}$$

Most models describe the increase from $\xi > 10^{-6}$ to $\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6}$ observed in data reasonably well



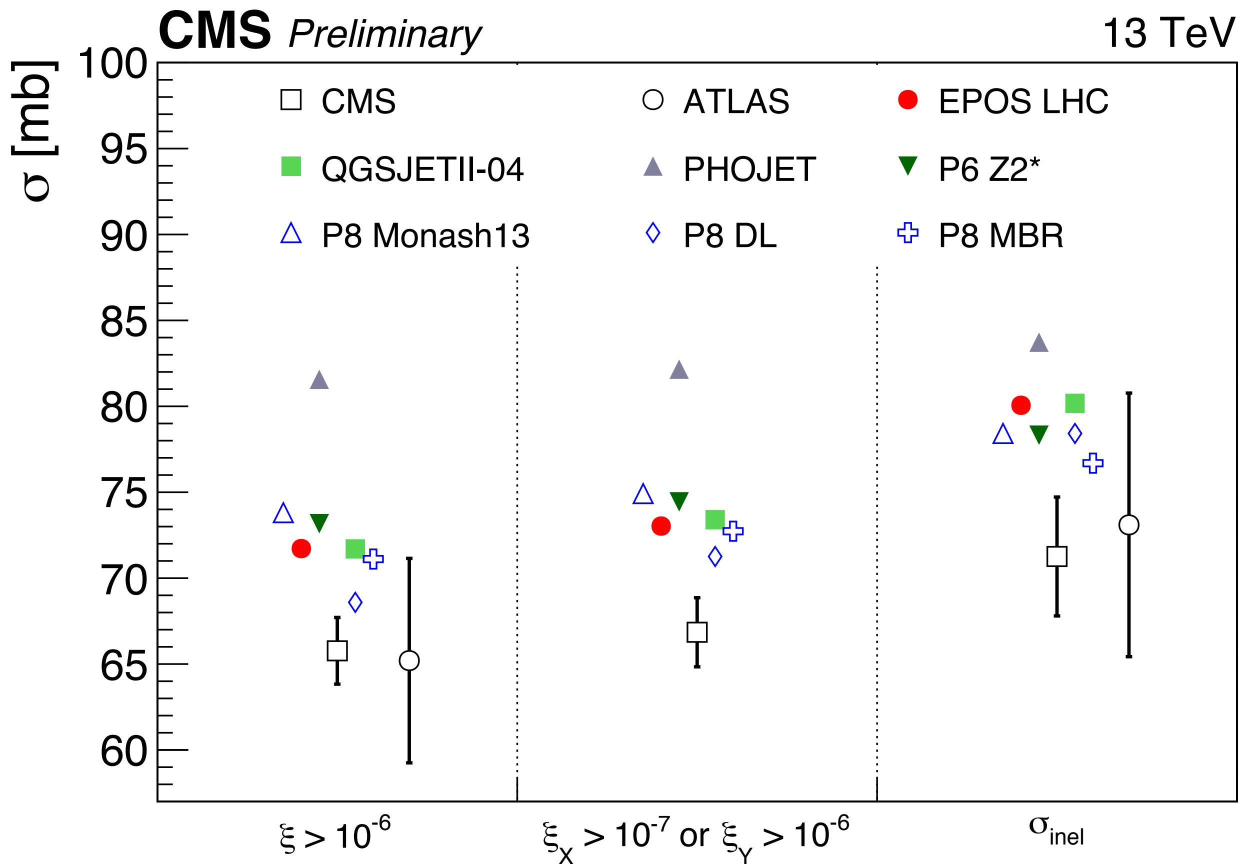
Use model-dependent extrapolation factors to go to full inelastic phase space

Take average factor, uncertainty: (max - min)/2

Model	Extrapolation factor
EPOS LHC	1.096
QGSJETII	1.092
PHOJET	1.019
PYTHIA6 Z2*	1.052
PYTHIA8 Monash	1.047
PYTHIA8 DL	1.101
PYTHIA8 MBR	1.054
Average	1.066

Extrapolation to full phase space domain

- Result: $\boxed{\sigma_{inel} = 71.3 \pm 0.5\ (\text{exp.}) \pm 2.1\ (\text{lum.}) \pm 2.7\ (\text{ext.})\ \text{mb}}$



Preliminary ATLAS result:
$\sigma(\xi > 10^{-6}) = 65.2 \pm 0.8$ (exp.) ± 5.9 (lum.) mb
$\sigma_{inel} = 73.1 \pm 0.9$ (exp.) ± 6.6 (lum.) ± 3.8 (ext.) mb
[ATLAS-CONF-2015-038]

Summary

- CMS has measured the inelastic proton-proton cross section at $\sqrt{s}$ = 13 TeV in two acceptances: $\xi > 10^{-6}$ (HF OR) and $\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6}$ (HF OR CASTOR)

  $\sigma(\xi > 10^{-6}) = 65.8 \pm 0.8\ (\text{exp.}) \pm 1.8\ (\text{lum.})$ mb

  $\sigma(\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6}) = 66.9 \pm 0.4\ (\text{exp.}) \pm 2.0\ (\text{lum.})$ mb

- And extrapolated this to the total inelastic phase space domain:

  $\sigma_{inel} = 71.3 \pm 0.5\ (\text{exp.}) \pm 2.1\ (\text{lum.}) \pm 2.7\ (\text{ext.})$ mb

- The absolute values can not be described by Monte Carlo event generators

- But most models describe the relative increase from $\xi_X>10^{-6}$ or $\xi_Y>10^{-6}$ to $\xi_X>10^{-7}$ or $\xi_Y>10^{-6}$ rather well

- Results public in CMS-PAS-FSQ-15-005: http://cds.cern.ch/record/2145896