CMS results on inelastic and diffractive cross sections

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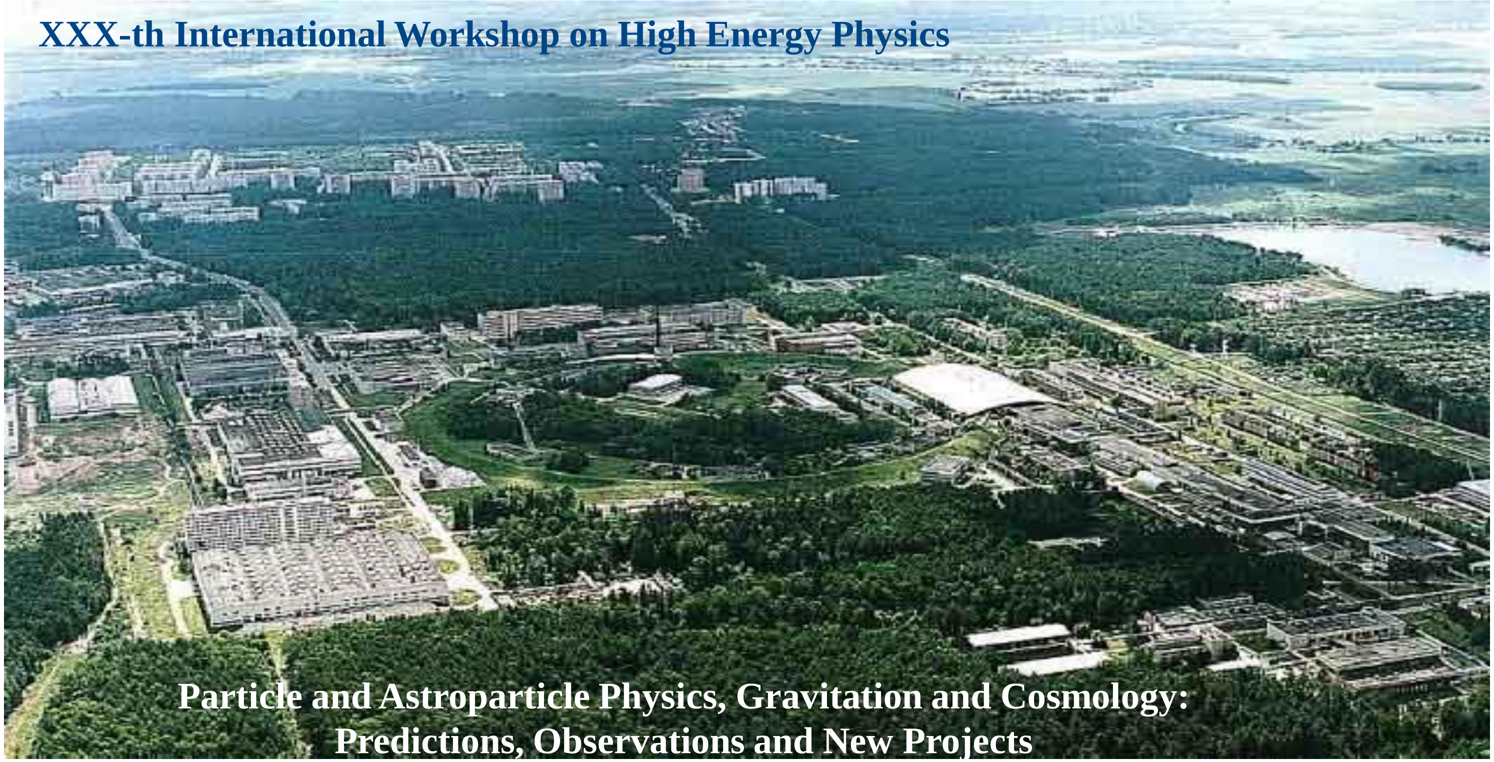


IHEP, Protvino, Russia 23-27 June, 2014

Structure of *Forward and Small-x QCD group* in CMS

Diffractive & exclusive production

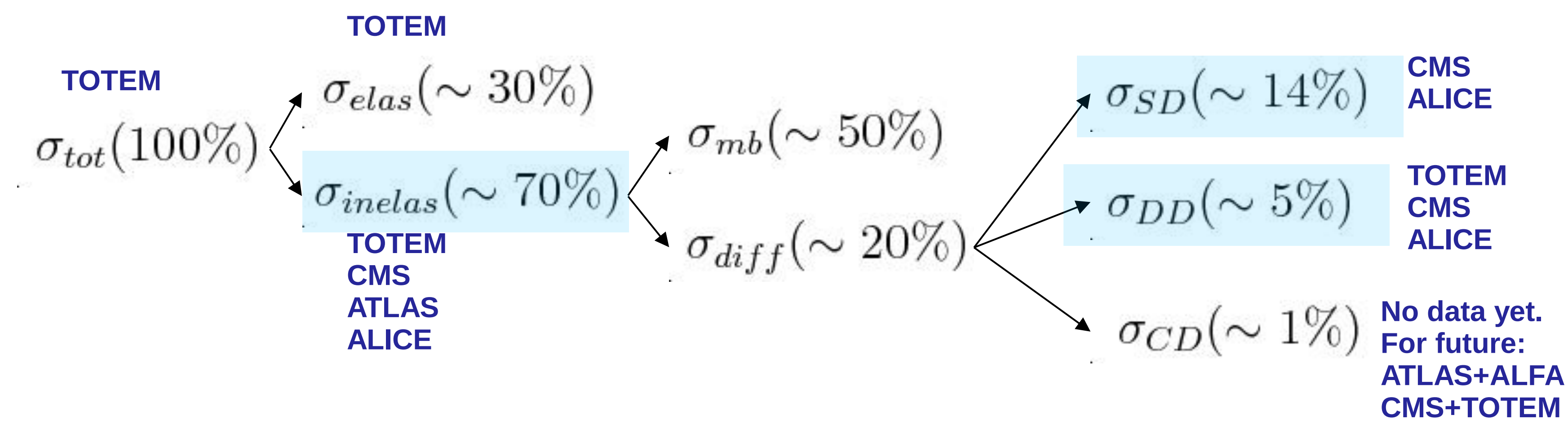
8 PAS

Forward jets & small-x QCD physics studies

12 PAS

Multi-Parton Interactions (MPI), Underlying Event (UE) & soft QCD studies

22 PAS



Inelastic pp cross section at √s = 7 TeV

1st method: event counting with HF as a single-sided trigger

Measurement of the inelastic pp cross section at √s = 7 TeV
CMS PAS QCD-11-002

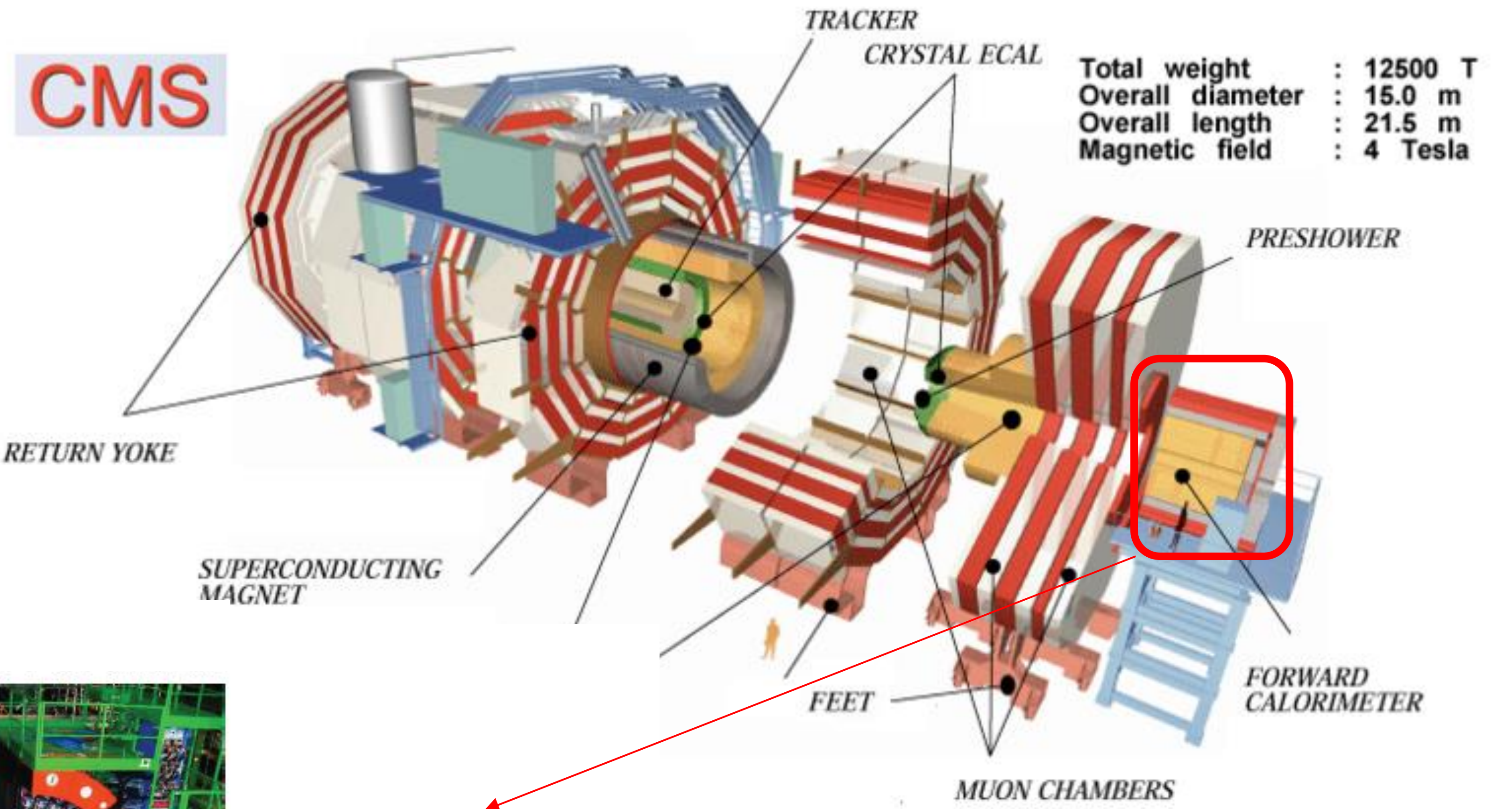
2nd method: pile-up counting

Measurement of the inelastic pp cross section at √s = 7 TeV with the CMS detector
CMS PAS FWD-11-001

Single and Double Diffractive cross sections at √s = 7 TeV

Measurement of pp diffraction dissociation cross sections at √s = 7 TeV at the LHC
CMS PAS FSQ-12-005

1st method:
event counting with HF as a single-sided trigger



Hadron Forward calorimeter
$2.9<|\eta|<5.2$
@11.2 m from IP
quartz fiber & steel absorber
0.175x0.174 η/φ-segmentation

- low pile-up runs with λ from 1% to 12%

- HF as a single sided trigger:
  either HF has at least one hit above 5 GeV (4 GeV) total energy

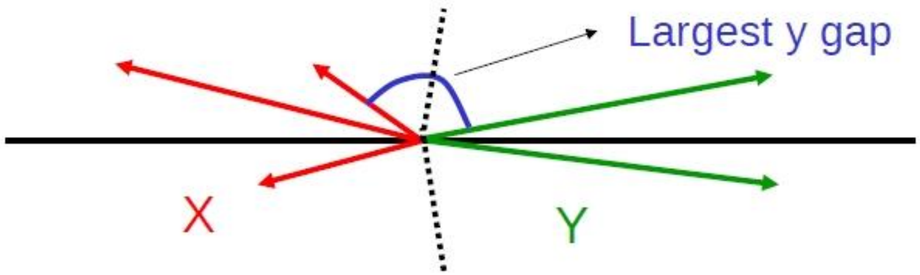
- 3 data samples with different triggers
  "coincidence trigger" = zero-bias trigger -> 2 colliding proton bunches
  "single-bunch" = BPTX exclusive OR(XOR) trigger -> single proton bunch
  "random"

are used to subtract background from inelastic events

Trigger Name	No. of Triggers	4 GeV	5 GeV
Coincidence trigger	9244011	239782	191654
Single-bunch trigger	1097292	8883	3291
Random trigger	27759	254	89

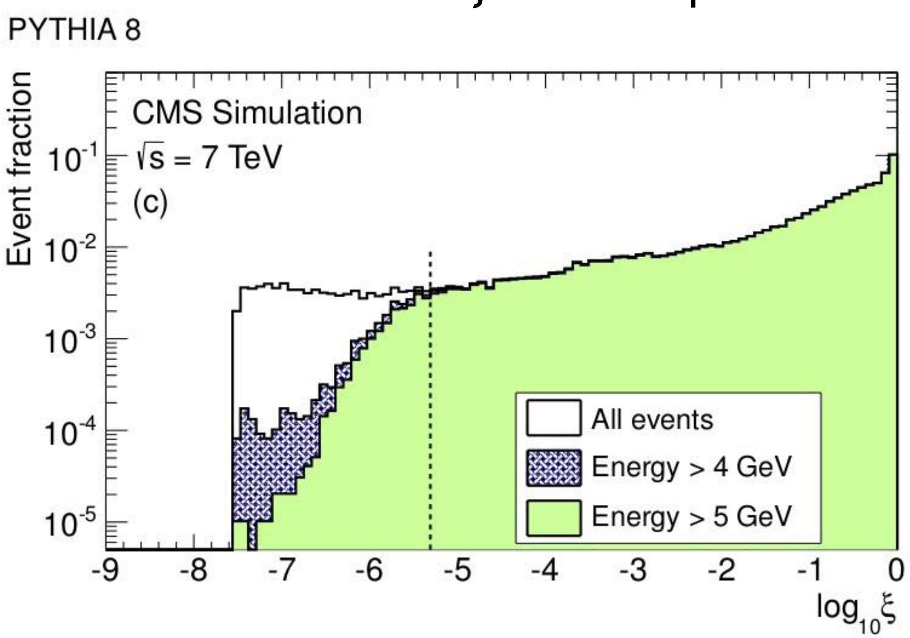
Over 9.2 million events were processed in the dataset with low pile-up data 2010y., corresponding to an integrated effective luminosity of 2.78 μb^{-1}.

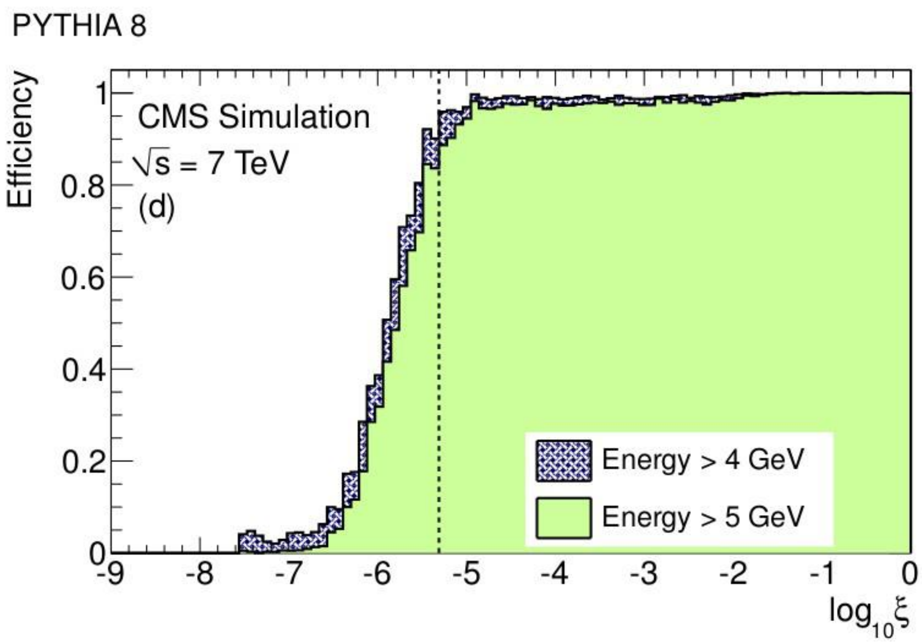
$\xi = M_x^2 / s$, where $M_x > M_y$ the invariant mass of the system



- In case of single diffractive events, ξ is the fractional momentum loss of the scattered proton

- Events with small ξ can escape detection

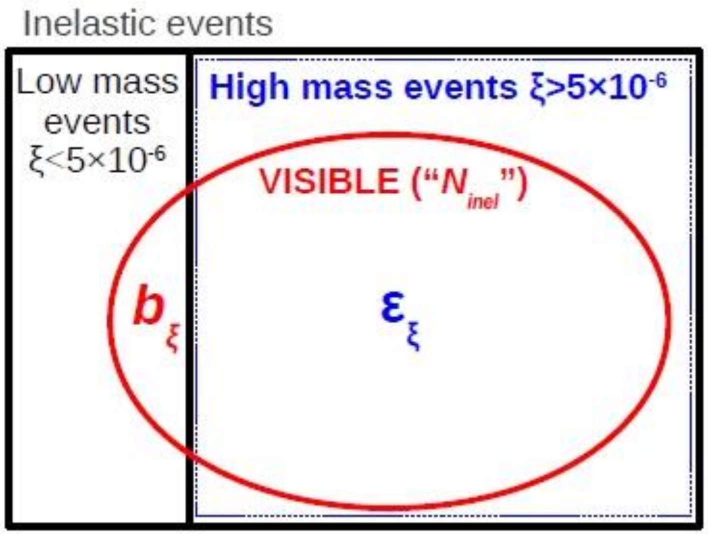




For $\xi > 5\times10^{-6}$ ($M_x > 15.7$ GeV), CMS has more than ~98% efficiency of detection

Inelastic cross section: definition

$$\sigma_{\rm inel}(\xi > 5\times 10^{-6}) = \frac{N_{\rm inel}(1-b_\xi)(1+f_{\rm pu})}{\epsilon_\xi \int L\,{\rm d}t}$$



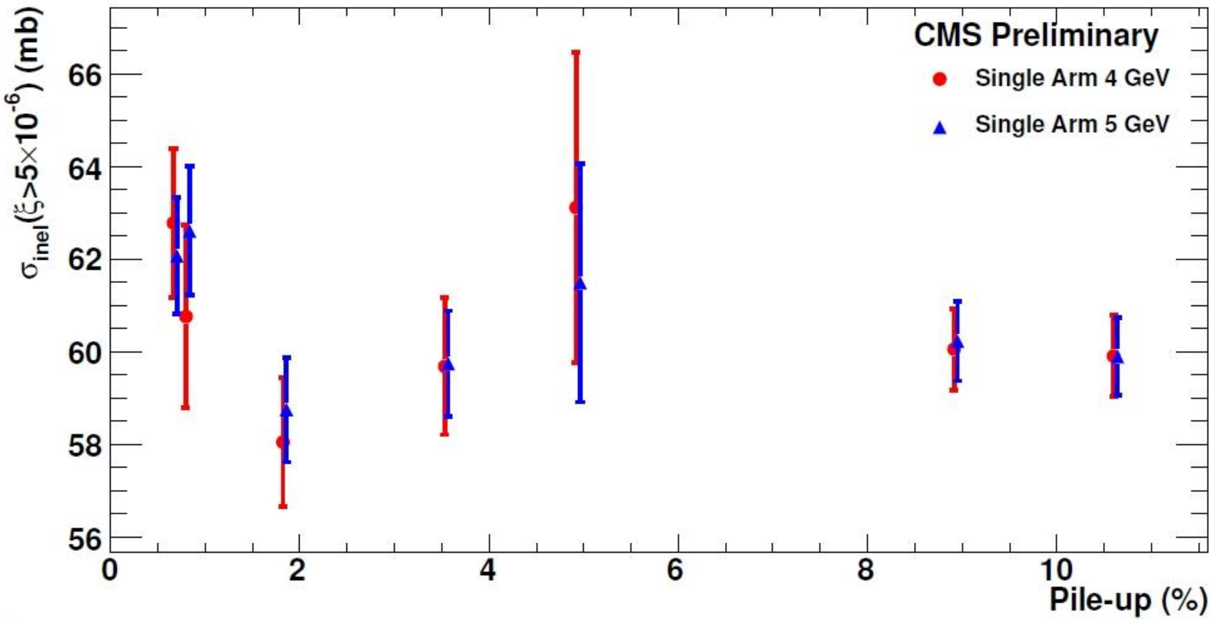
- b_ξ is the fraction of low mass events, which are visible as high mass events;
- ϵ_ξ is the efficiency of detection of high mass events;
- $f_{\rm pu}$ is the pile-up correction factor because more than one collision is also counted as one;

$$f_{\rm pu} = \frac{\Sigma_{i=2}^{\infty} P(i,\lambda)}{\Sigma_{i=1}^{\infty} P(i,\lambda)} = \frac{1-(1+\lambda)e^{-\lambda}}{1-e^{-\lambda}} \sim \frac{\lambda}{2} - \frac{\lambda^2}{12} + \mathcal{O}(\lambda^3)$$

- λ is the average pile-up number, which is calculated from data directly
- $\int L\,{\rm d}t$ is the integrated luminosity based on the Van der Meer scans. The uncertainty of the luminosity is 4%, which is dominating systematic uncertainty of this analysis.
- $N_{\rm inel}$ is the number of visible inelastic events after background subtraction

$$N_{\rm inel} = \frac{N^{\rm ZB} - N_{\rm noise}}{1 - N^{\rm SB}_{\rm noise} / N^{\rm SB}_{\rm triggers}}$$

Inelastic cross section: result at $\xi > 5\times10^{-6}$



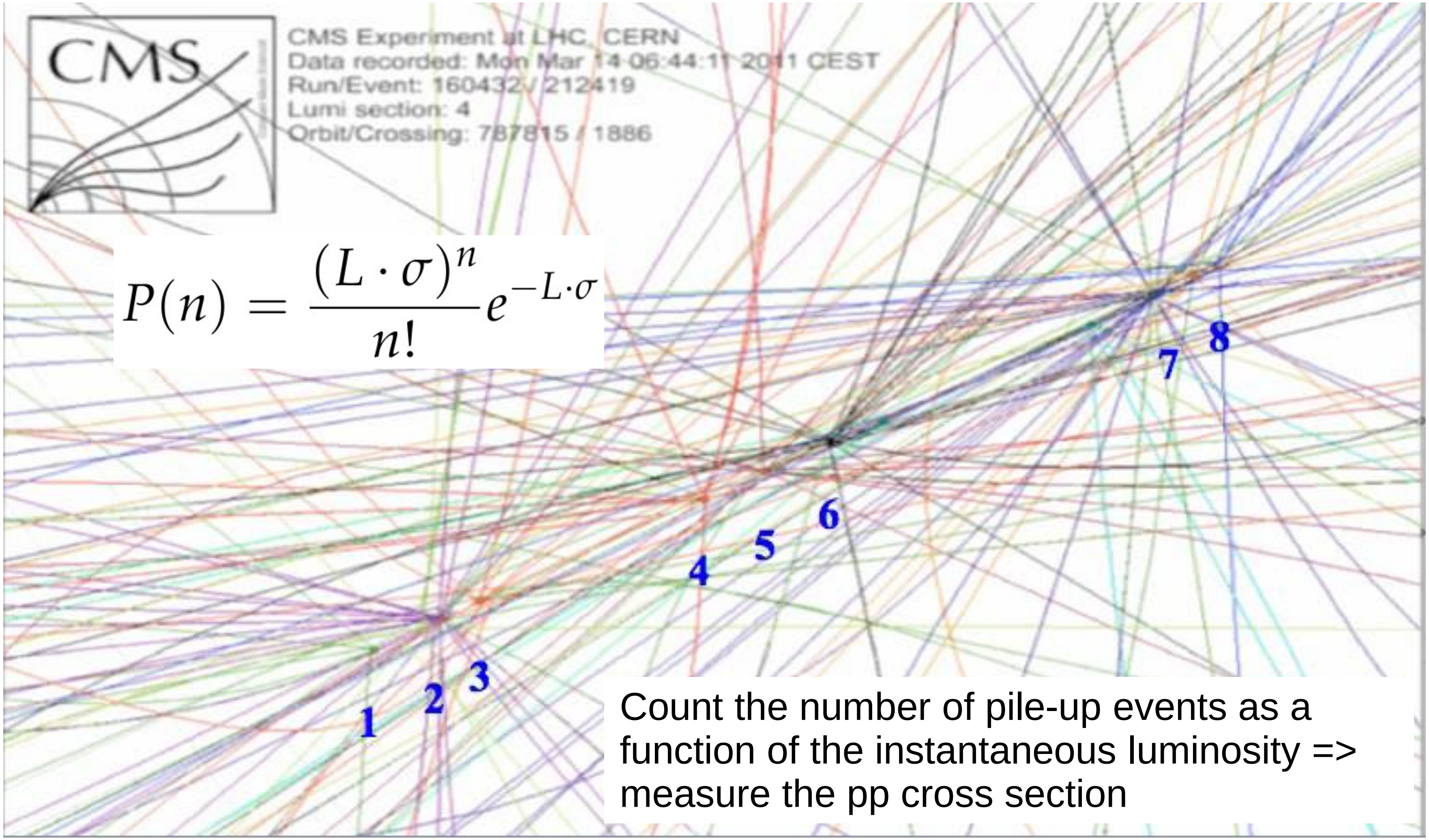
average σ value obtained under various (low) pile-up conditions for the 5 GeV threshold

$\chi^2/\text{ndof} = 1.2$

$$\sigma_{\text{inel}}(\xi > 5\times10^{-6}) = [60.2 \pm 0.2\,(\text{stat.}) \pm 1.1\,(\text{syst.}) \pm 2.4\,(\text{lum.})]\ \text{mb}$$

Systematic uncertainty of $\sigma_{\text{inel}}(\xi > 5\times10^{-6})$	
HF energy threshold	0.19%
Tower exclusion	0.41%
Run-by-run variations	1.3%
Selection efficiency	1.0%
Fraction of events below the ξ threshold	0.50%
Total	1.8% (±1.1 mb)
Overall scale (luminosity) uncertainty	4%

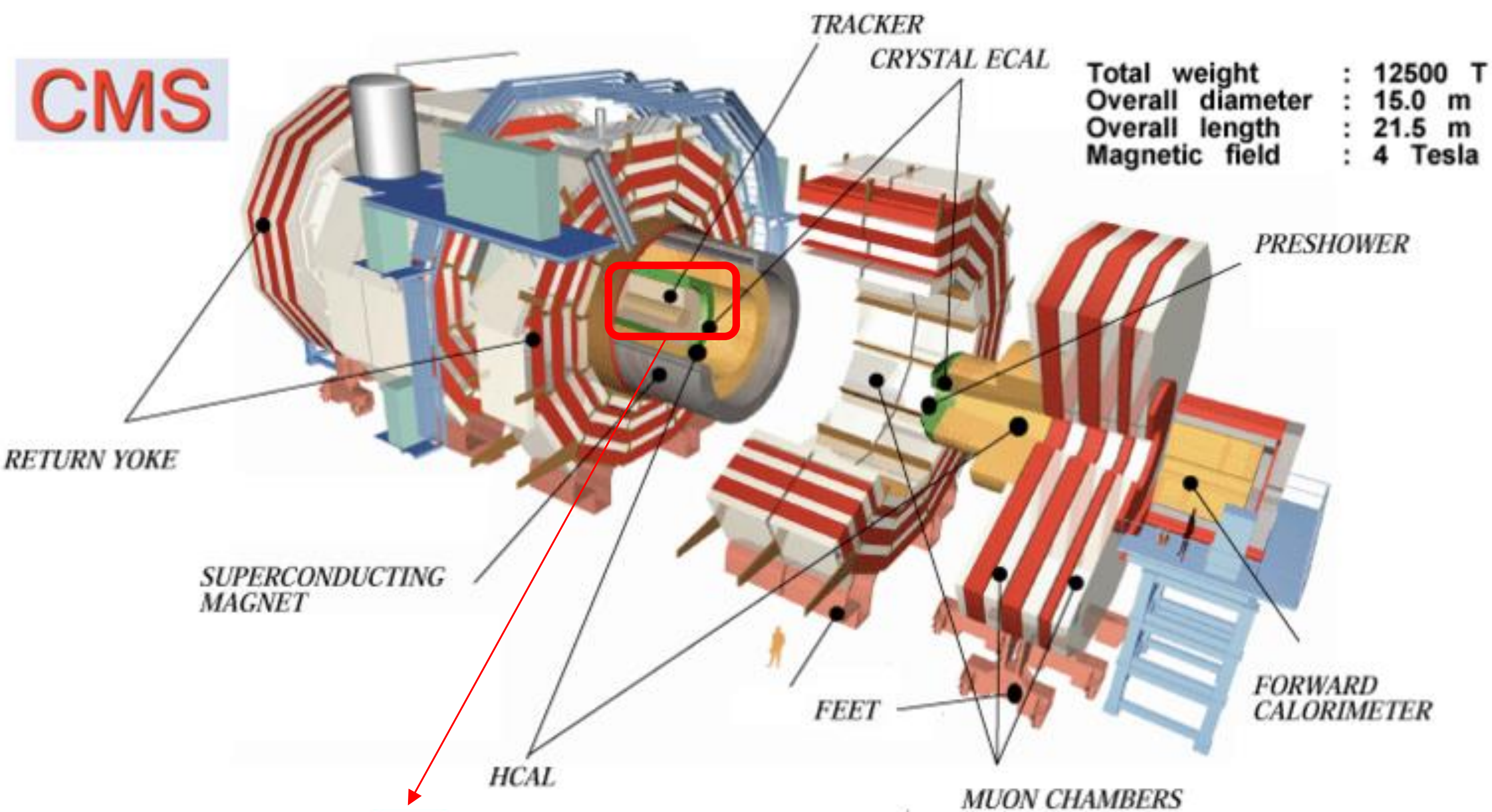
2nd method:
Pile-up counting method

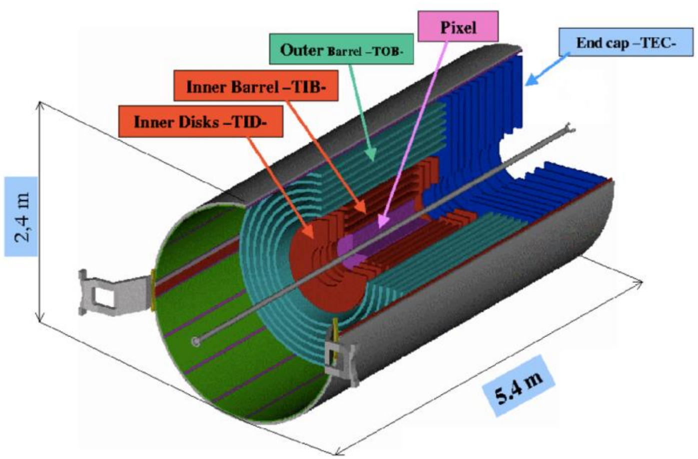


$$P(n) = \frac{(L \cdot \sigma)^n}{n!} e^{-L \cdot \sigma}$$

Count the number of pile-up events as a function of the instantaneous luminosity => measure the pp cross section

Key instrument: Tracker





Tracker: $|\eta| < 2.4$, pT > 100 MeV

- 2 different data samples are collected with CMS triggers ($3x10^6$ inclusive di-electrons and $1.5x10^6$ single muons)

- count the number of primary verticies in each bunch crossing, which is considered as a pile-up value in the first approximation

- for events with pile-up from 0 to 8 the distributions is plotted in 13 equal luminosity bins ($0.05x10^{30} < L < 0.7x10^{30}$ cm^{-2} s^{-1})

- a bin-by-bin correction method is applied to calculate corrected factors for each luminosity bin

- corrected 9 distributions on lumi for different pile-up are fitted with Poisson curve to get 9 estimations of inelastic cross sections

- average value of inelastic cross section is calculated

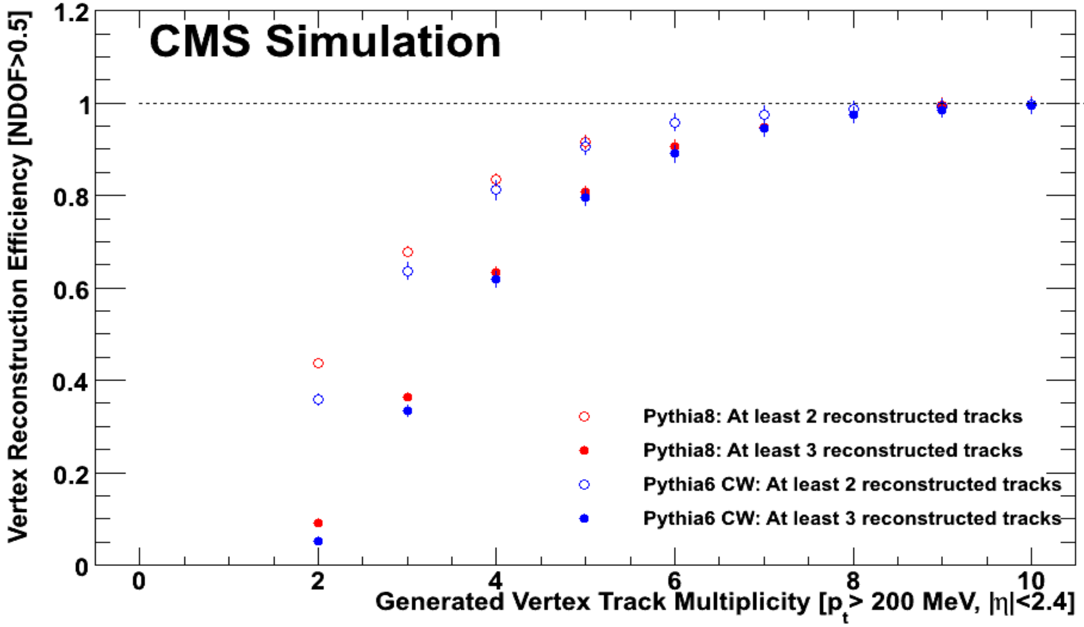
The analysis was made for 4 samples of events

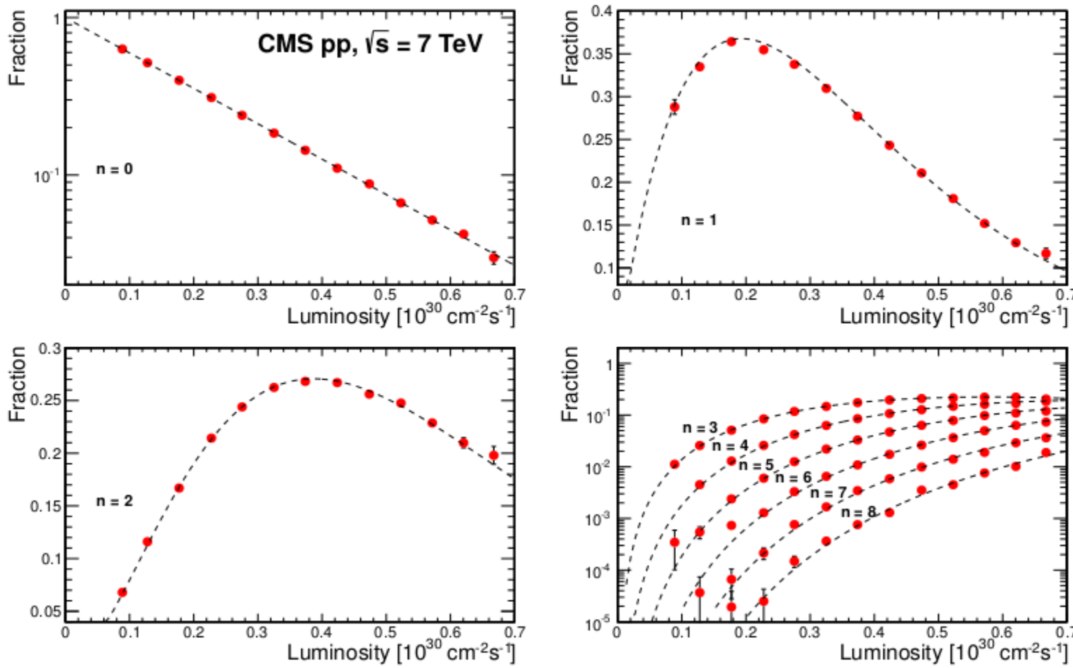
1. events with at least 2 charged particles, each with pt > 200 MeV and $|\eta|<2.4$
2. events with at least 3 charged particles, each with pt > 200 MeV and $|\eta|<2.4$
3. events with at least 4 charged particles, each with pt > 200 MeV and $|\eta|<2.4$
4. events with at least 3 particles, each with pt > 200 MeV and $|\eta|<2.4$

- each track should have at least 2 pixel hits and 5 strip hits
- each vertex should pass an overall quality cut, NDOF > 0.5 $NDOF = 2 * \Sigma_{tracks}(weights) - 3$
- overlapping vertices are merged
- real pile-up vertices should aligned along the beam pipe (d<0.094 +/- 0.06 cm)
- secondary vertices, from decay of long lived particles, are deleted
- fake vertices, generated by vertexing reco algorithm, are deleted

Efficiency of vertex reconstruction is 40% for 2 tracks, reaching 100% for 10 tracks

Overall integrated efficiency is around 96%

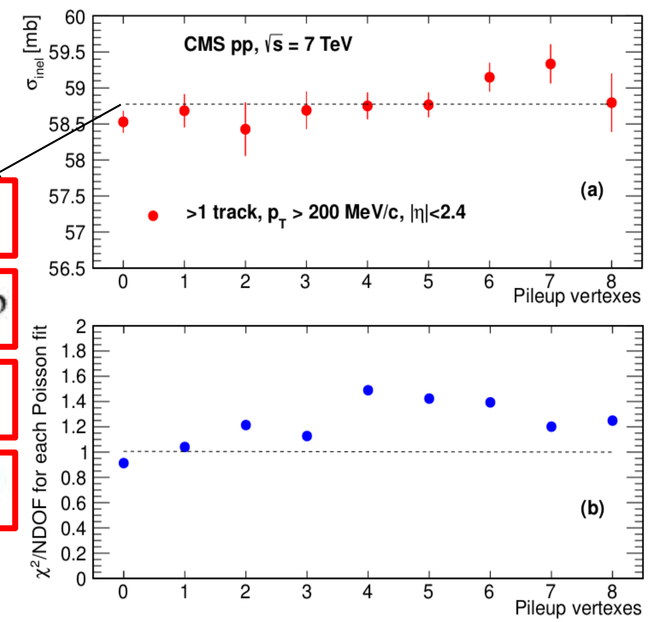




Corrected event distributions is fitted with a Poisson function. It provides 9 estimations of cross section, for each pile-up number.

Lastly 9 values are fitted together to obtain the final result

The same procedure was performed for each of 4 different hadron level samples of event



Ntr>1, pt>200MeV, |η|<2.4 $\sigma = 58.7 \pm 2.0\ (\mathrm{Syst}) \pm 2.4\ (\mathrm{Lum})$ mb

Ntr>2, pt>200MeV, |η|<2.4 $\sigma = 57.2 \pm 2.0\ (\mathrm{Syst}) \pm 2.4\ (\mathrm{Lum})$ mb

Ntr>3, pt>200MeV, |η|<2.4 $\sigma = 59.7 \pm 2.0\ (\mathrm{Syst}) \pm 2.4\ (\mathrm{Lum})$ mb

Np>2, pt>200MeV, |η|<2.4 $\sigma = 55.4 \pm 2.0\ (\mathrm{Syst}) \pm 2.4\ (\mathrm{Lum})$ mb

Extrapolation of the cross sections measured at some kinematical limits to the total inelastic cross sections can be made by model dependent method only.

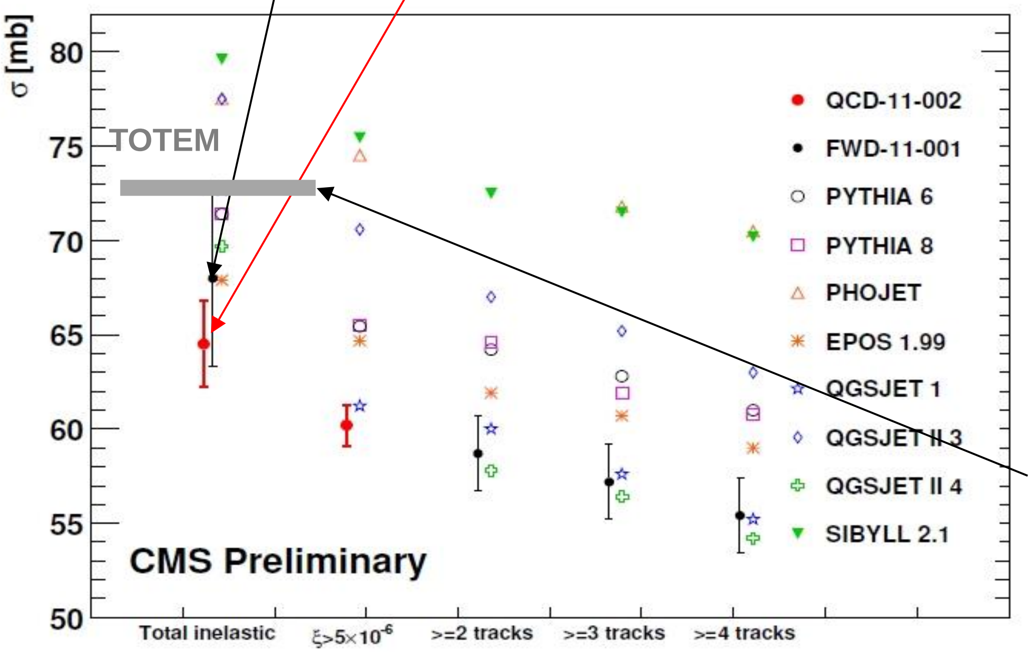
Extrapolation factors are calculated using different MC models:
PYTHIA 6, PYTHIA 8, PHOJET, EPOS, SYBILL, QGSJET I, QGSJET II

Pile-up counting method gives:

$$\sigma_{\text{inel}} = 64.5 \pm 0.2(\text{stat.}) \pm 1.1(\text{syst.}) \pm 2.6(\text{lumi.}) \pm 1.5(\text{extr.})\ \text{mb.}$$

Event counting method with single sided trigger gives:

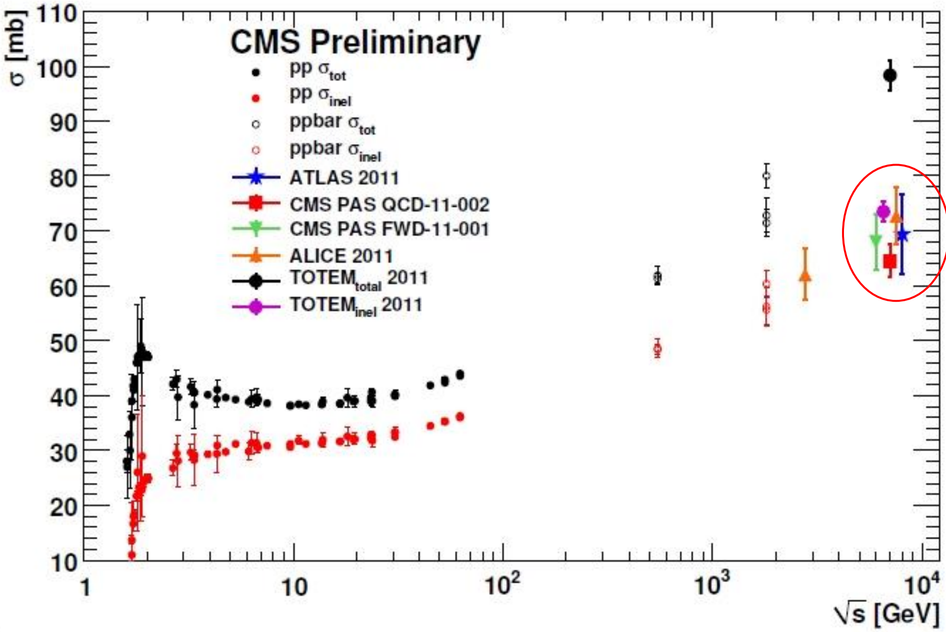
$$\sigma_{inel}(pp) = 68 \pm\ 2.0\ (\text{Syst}) \pm\ 2.4\ (\text{Lum})\ \pm\ 4(\text{Ext.})\ \text{mb}$$

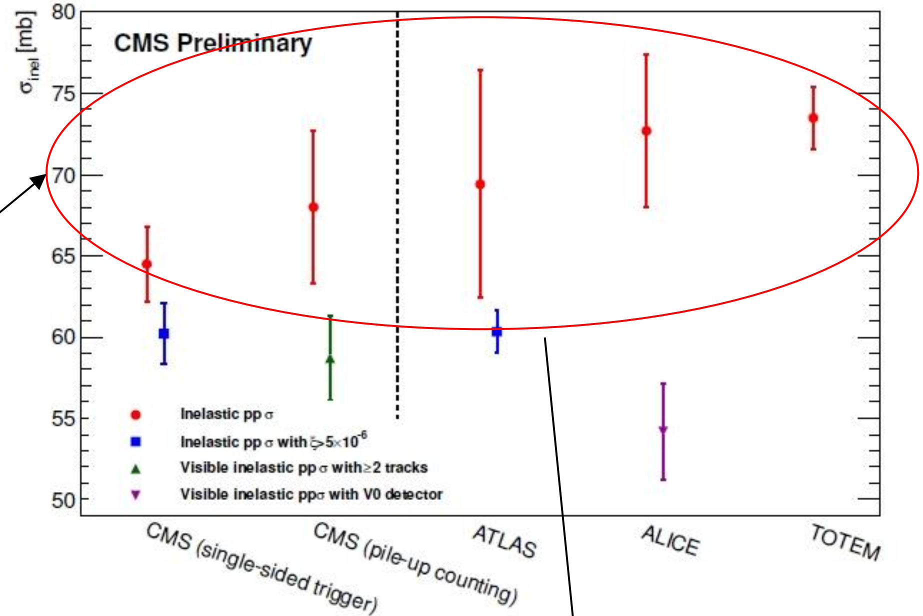


Extrapolated cross sections is about 5% larger than visible ones.

All models show a similar trend for the measured cross sections, but there are substantial differences in the absolute values for many models.

Measurements made by TOTEM shows that invisible part of the inelastic events is underestimated by a wide range of MC models.





	$\sigma_{inel}(\xi > 5 \times 10^{-6})$	$\sigma_{inel}(\geq 2$ tracks$)$	σ_{inel}
CMS present analysis	$60.2 \pm 0.2(\text{stat.}) \pm 1.1(\text{syst.})$		$64.5 \pm 3.0(\text{exp.}) \pm 1.5(\text{extr.})$
ATLAS	$60.3 \pm 0.05(\text{stat.}) \pm 0.5(\text{syst.})$		$69.4 \pm 2.4(\text{exp.}) \pm 6.9(\text{extr.})$
CMS pile-up counting		$58.7 \pm 2.0(\text{syst.})$	$68 \pm 3(\text{exp.}) \pm 4(\text{extr.})$

$$\sigma_{INEL} = 73.2^{+2.0}_{-4.6}(model) \pm 2.6(lumi) \text{ mb}$$

ALICE

$$\sigma_{inel} = 73.5^{+2.4}_{-1.9} \text{ mb}$$

TOTEM

Within the large uncertainties of extrapolation and luminosity, we can say that CMS result is in agreement with ATLAS, ALICE and TOTEM.

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Comparison of the inelastic cross sections at $\sqrt{s}$ = 7 TeV with theory

"Visible" cross section, $\sigma(\xi > 5 \cdot 10^{-6})$(mb)	
CMS	60.2±2.6(exp.)
ATLAS	60.3±2.1(exp.)
ALICE	62.1±2.4(exp.)
PYTHIA	66.4
Phojet	74.2
Ryskin et al.	56.2 - 51.8

Within the large uncertainties of measurements and extrapolations, results of all LHC experiments are in agreement with models predicted inelastic cross section at $\sqrt{s}$ = 7 TeV from 60 to 75 mb.

Extrapolated cross section, $\sigma(\xi > m_p^2/s)$(mb)	
CMS	64.5±3.2(exp.&extr.)
ATLAS	69.1±7.3(exp.&extr.)
ALICE	73.2±5.3(exp.&extr.)
TOTEM	73.5±2.4(exp.)
PYTHIA	71.5
Phojet	77.3
Petrov-Prokudin	70.3±2.1
Ryskin et al.	67.1- 65.2
Bourrely-Soffer-Wu	68.4±1.1
Gotsman et al.	68
Achilli et al.	60 - 75

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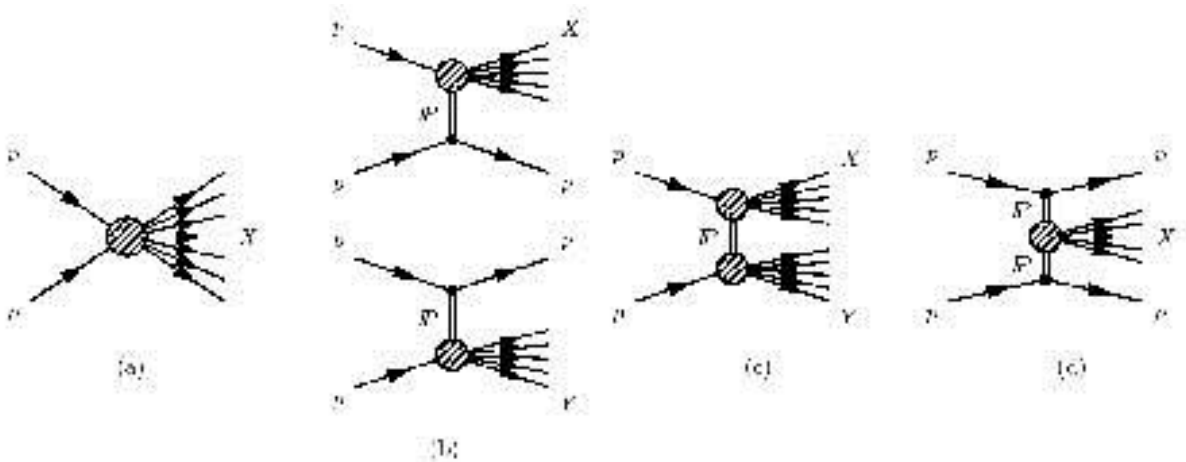
Black Disc limit: $\sigma_{inel}/\sigma_{tot} = 0.5$

LHC: $\sigma_{inel}/\sigma_{tot} \approx 0.7$

Single and Double Diffractive cross sections at √s = 7 TeV



Non-diffractive events ND

Single Diffraction SD

Double Diffraction DD

Central Diffraction CD

~35% of σ total

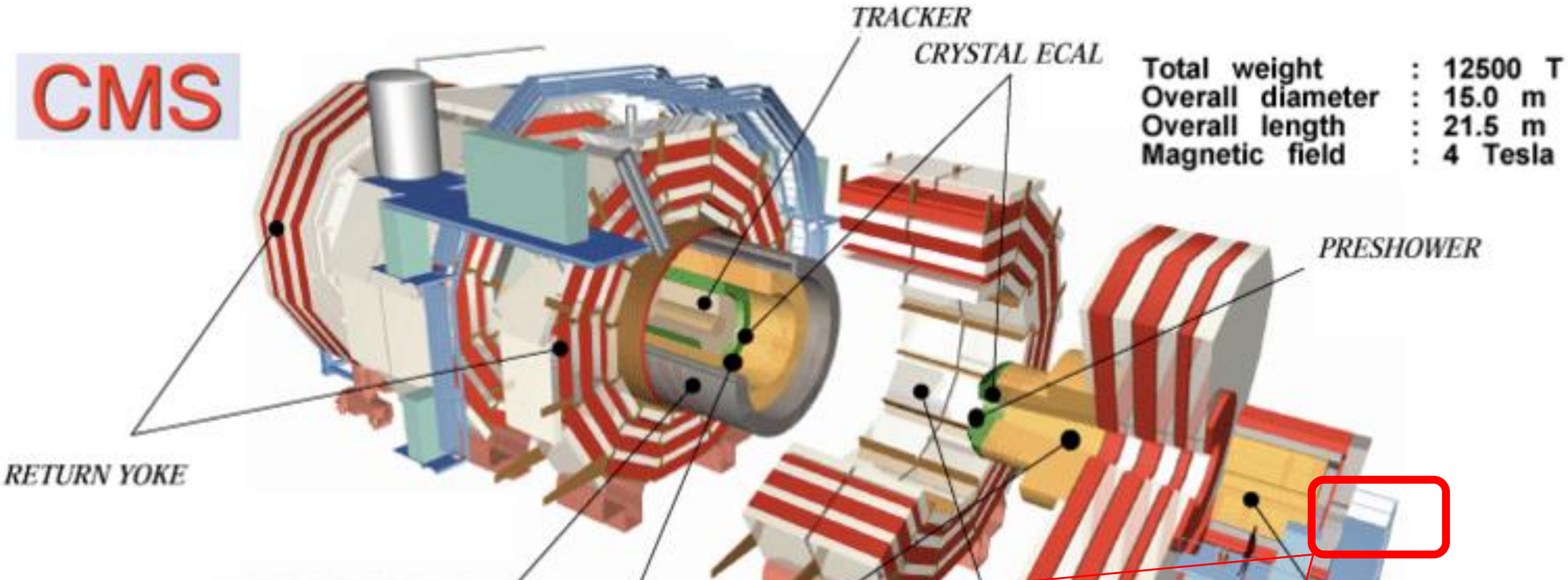
exponential suppression of rapidity gaps

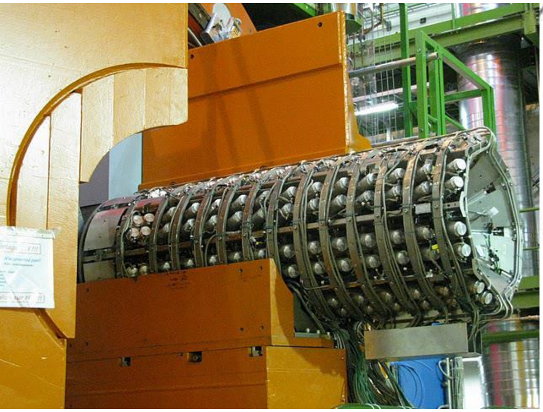
~25% of σ total

Exchange of color singlets: Reggeons, Pomeron

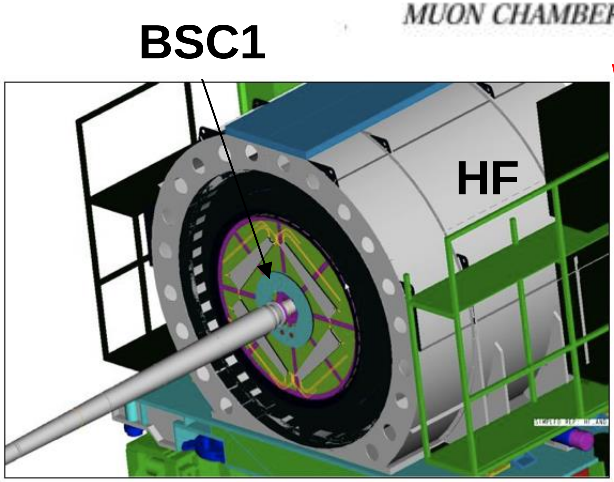
Large Rapidity Gaps

Forward instrumentation: CASTOR and BSC





CASTOR
-6.6<η<-5.2 (one side only)
@14.4 m from IP
Quartz fiber/plates & tungsten absorber
16 φ-sectors and 14 z-modules



Beam Scintilator Counters
@ 10.86 m (BSC1) and
14.4 m (BSC2) from IP
BSC1**: 3.2<|η|<4.7**

Events selection

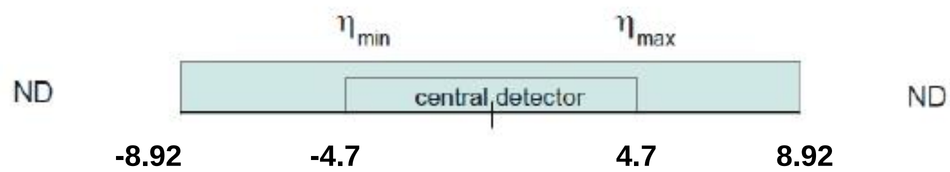
- Low pile up 2010 data, 16.2 μb^{-1}, at $\sqrt{s}$ = 7 TeV
- Inclusive selection
  online:
  signal in both BPTX & activity in either of the BSC (Minimum Bias trigger)
  offline:
  at least 10 reconstructed tracks (with high quality at least 25%)
  beam-halo events are rejected
  events with noise in HCAL are rejected
- Diffractive selection
  at least 2 particle candidates in the BSC acceptance ($3.23<|\eta|<4.65$)
  Large Rapidity Gaps (LRG) tagging based on particle candidates in $|\eta| < 4.7$
  SD and DD contributions separated with CASTOR tag

MC simulations

- Acceptance & background:
  PYTHIA8-MBR (Minimum Bias Rockfeller model) with
  Pomeron intercept $\alpha(0) = 1.08$ and additional scaling of DD downwards by 15%

-Systematic uncertainties:
  PYTHIA8-4C (Schuler & Sjostrand model from PYTHIA6) with SD and DD
  scaling downwards by 10 and 12%

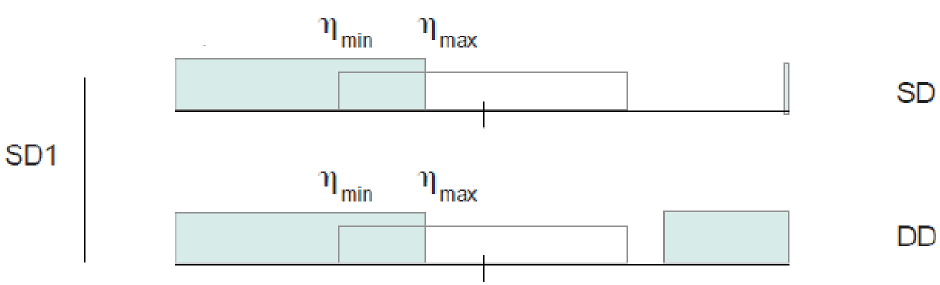
Non-diffractive inelastic events

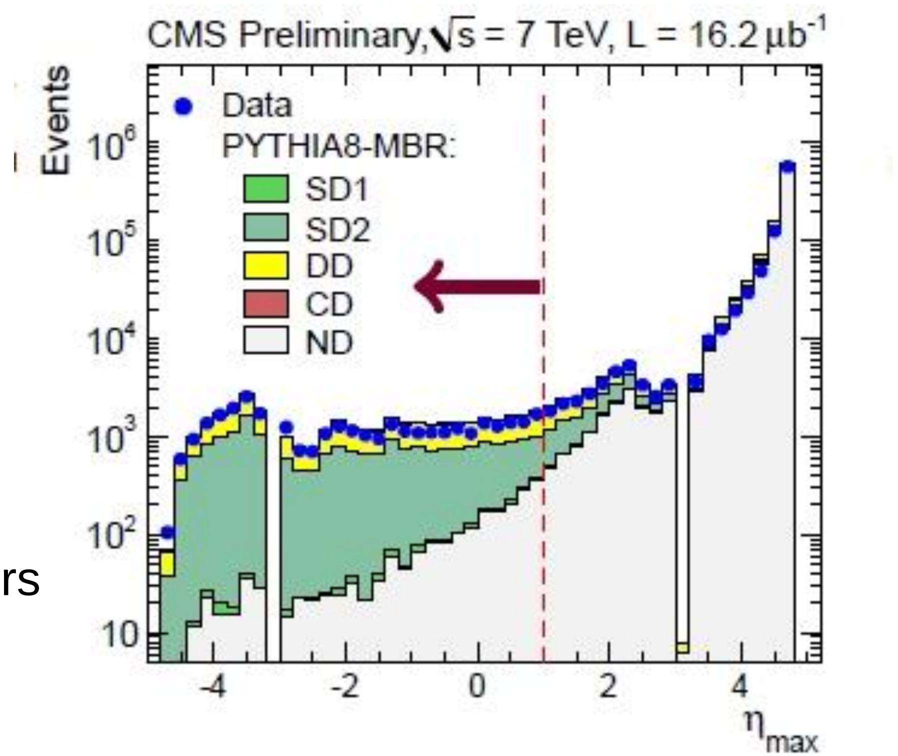


at $\sqrt{s} = 7$ TeV, $|\eta| \lesssim \ln(\sqrt{s}/m_p) = 8.92$

CMS central part: $|\eta|<4.7$

SD1: LRG on the positive side

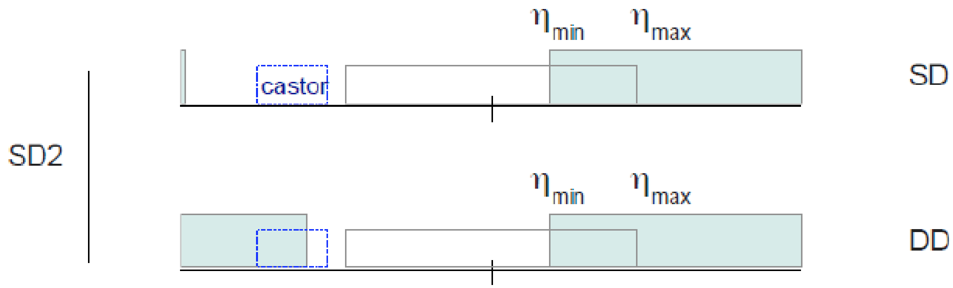




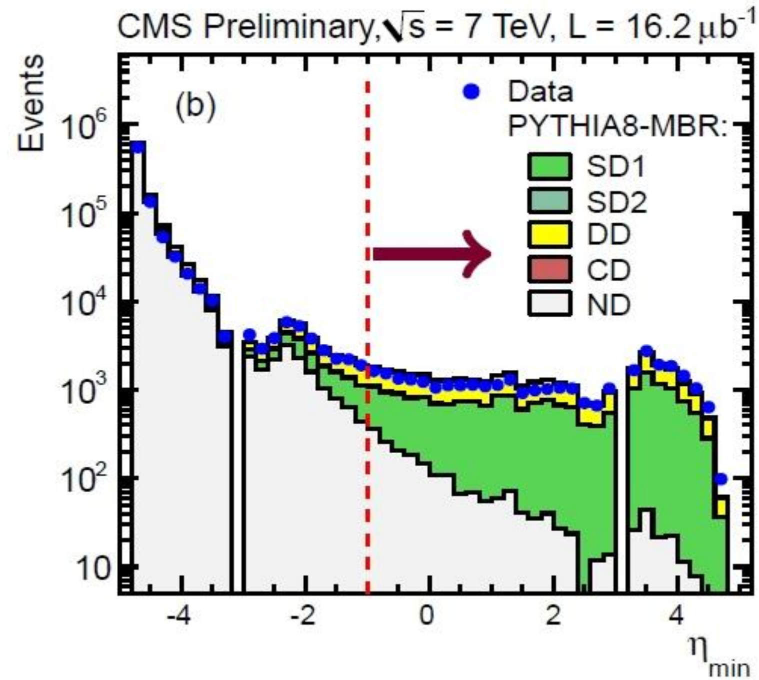
Selection: $\eta_{max} < 1$

- SD1 dominated by SD and DD events
- only central part CMS, no forward detectors
- low mass DD escapes detection
- used as control sample in the analysis

SD2: LRG on the negative side

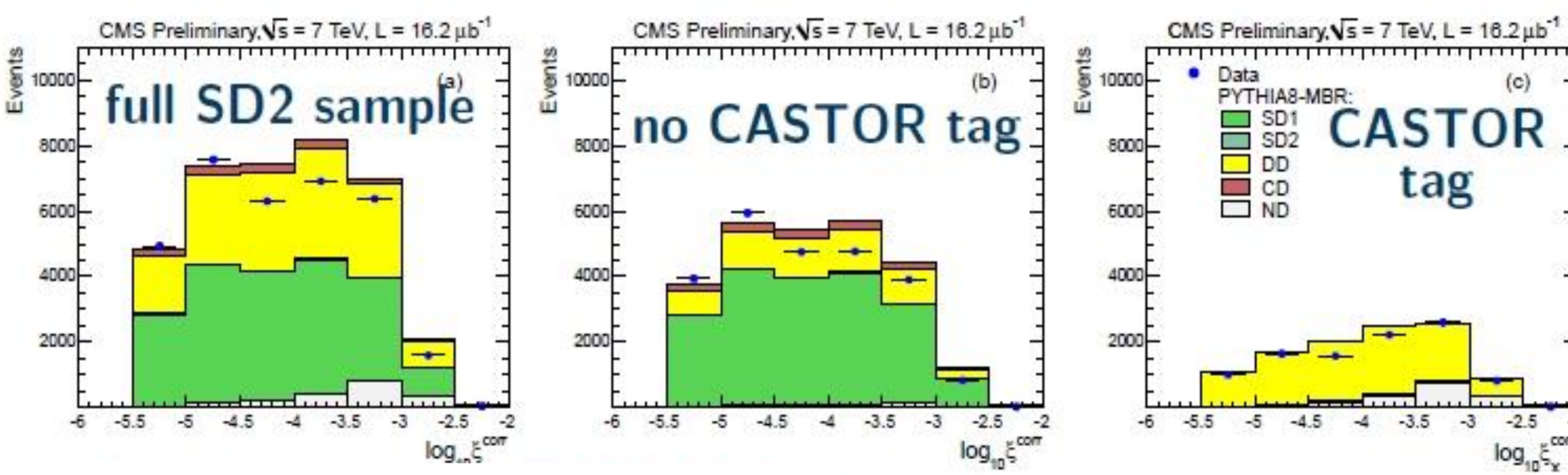


Selection: $\eta_{min} > -1$

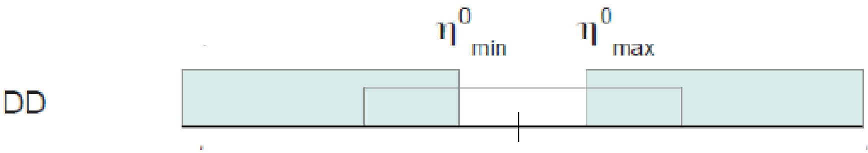


- SD2 dominated by SD and DD events
- CASTOR used to tag low mass DD at $-6.6<\eta<-5.2$ with mass $3.2<M<12$ GeV
- used to measure SD and DD cross sections as function of ξ

$$\xi = \frac{M_X^2}{s}$$



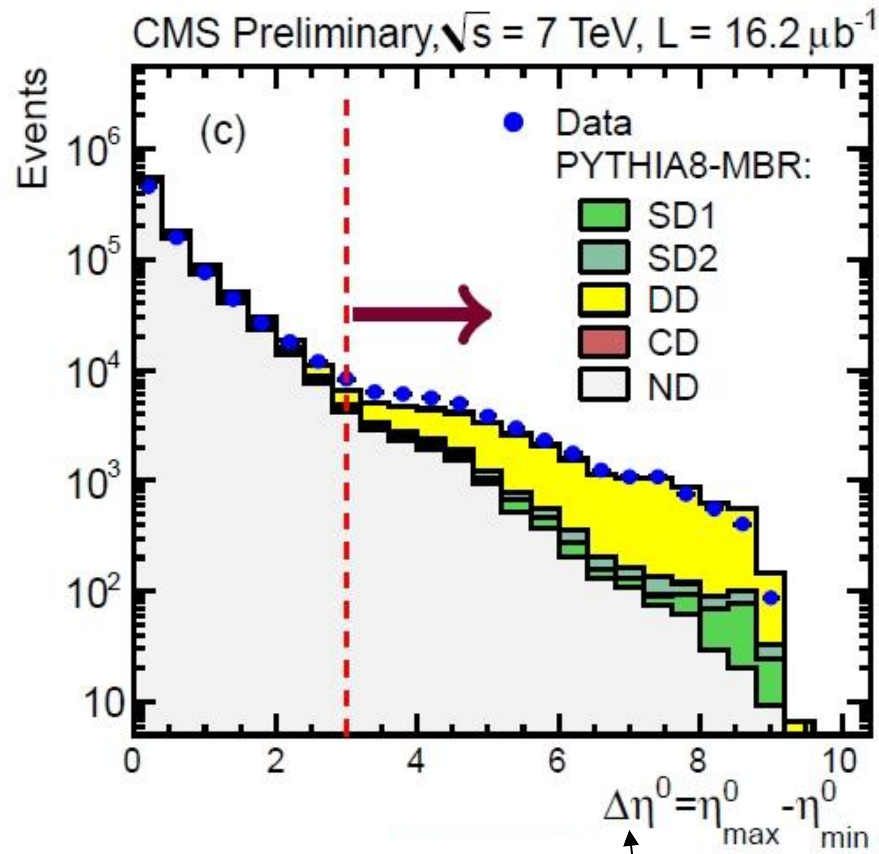
DD: central LRG



- DD sample has a big fraction of DD events

- used to measure DD cross section as function of $\Delta\eta = -\ln\xi$

$$\xi = M_X^2 \cdot M_Y^2 / (s \cdot m_p^2),$$

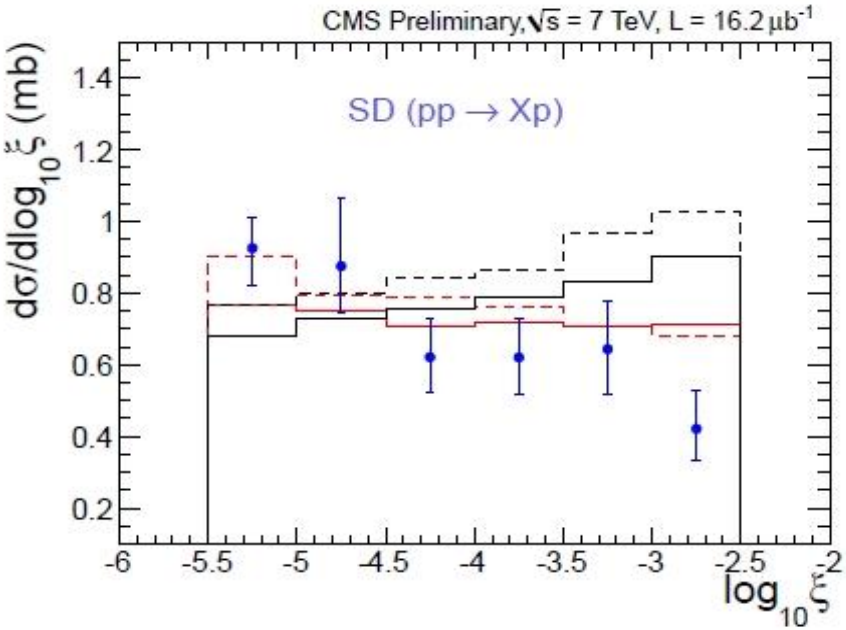


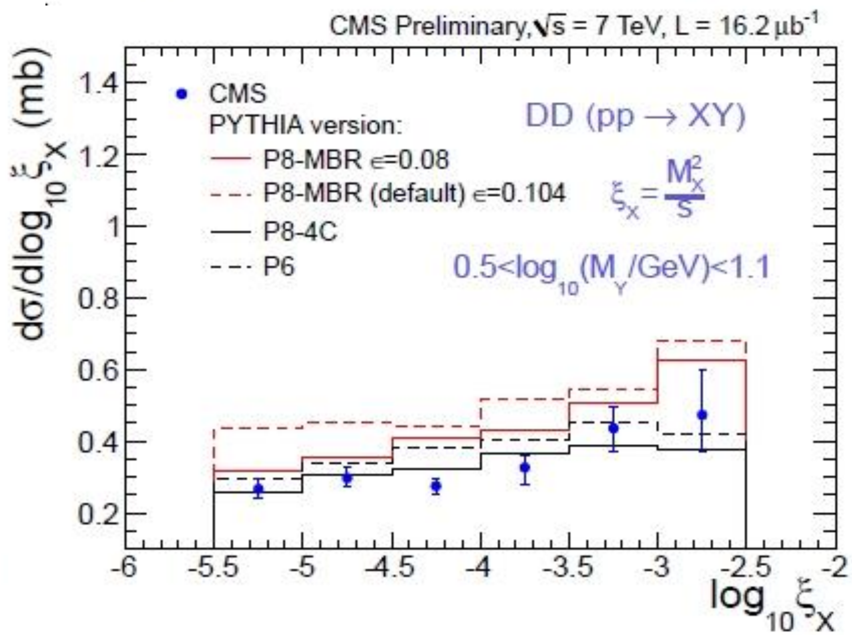
Selection: $\Delta\eta^0 > 3$

SD and DD cross sections from SD2 sample

$$\frac{d\sigma^{SD}}{d\log_{10}\xi} = \frac{N^{data}_{noCASTOR} - (N_{DD}+N_{CD}+N_{ND})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta \log_{10}\xi)_{bin}}$$

$$\frac{d\sigma^{DD}}{d\log_{10}\xi_X} = \frac{N^{data}_{CASTOR} - (N_{ND}+N_{SD}+N_{CD})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta \log_{10}\xi_X)_{bin}}$$





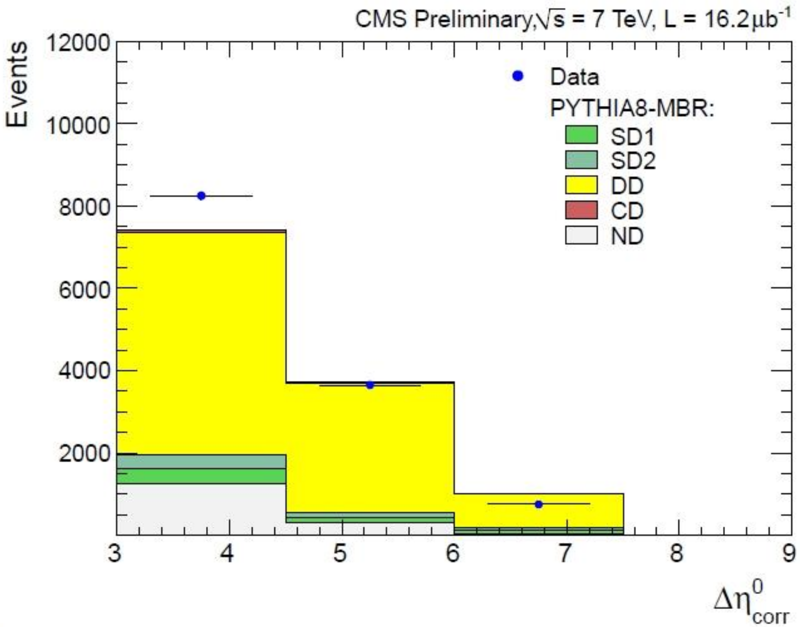
SD cross sections integrated over $-5.5 < \log\xi < -2.5$ ($12.4 < M_X(\mathrm{GeV}) < 393.6$) and multiplying by 2

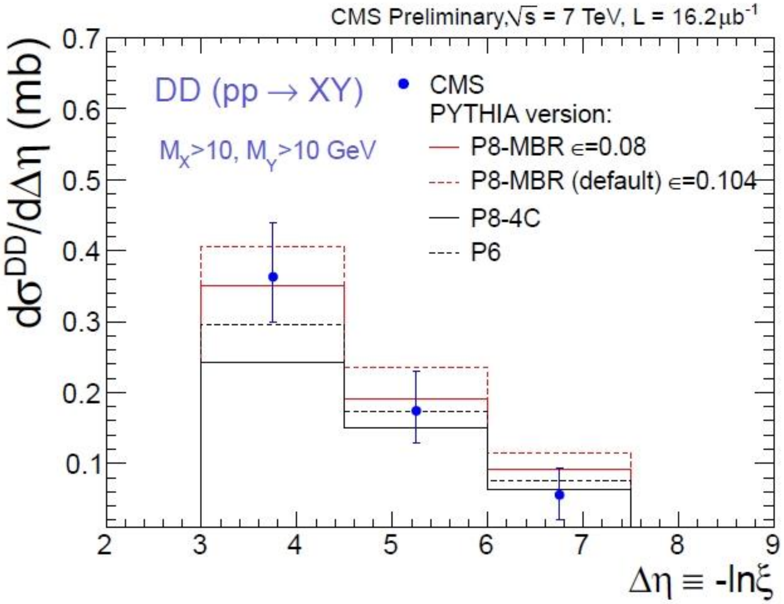
$$4.27 \pm 0.04(\mathrm{stat.})^{+0.65}_{-0.58}(\mathrm{syst.})\ \mathrm{mb}$$

- MBR model presented for 2 values of the Pomeron intercept $\alpha_{IP}(0) = 1.08$ & 1.104
  both values can describe well the SD cross section measurement
  DD cross section is better described with a smaller intercept value

- Schuler & Sjostrand model implemented in PYTHIA8-4C and PYTHIA6
  can describe the DD cross section
  but can not describe the falling behavior of SD

DD cross sections from DD sample



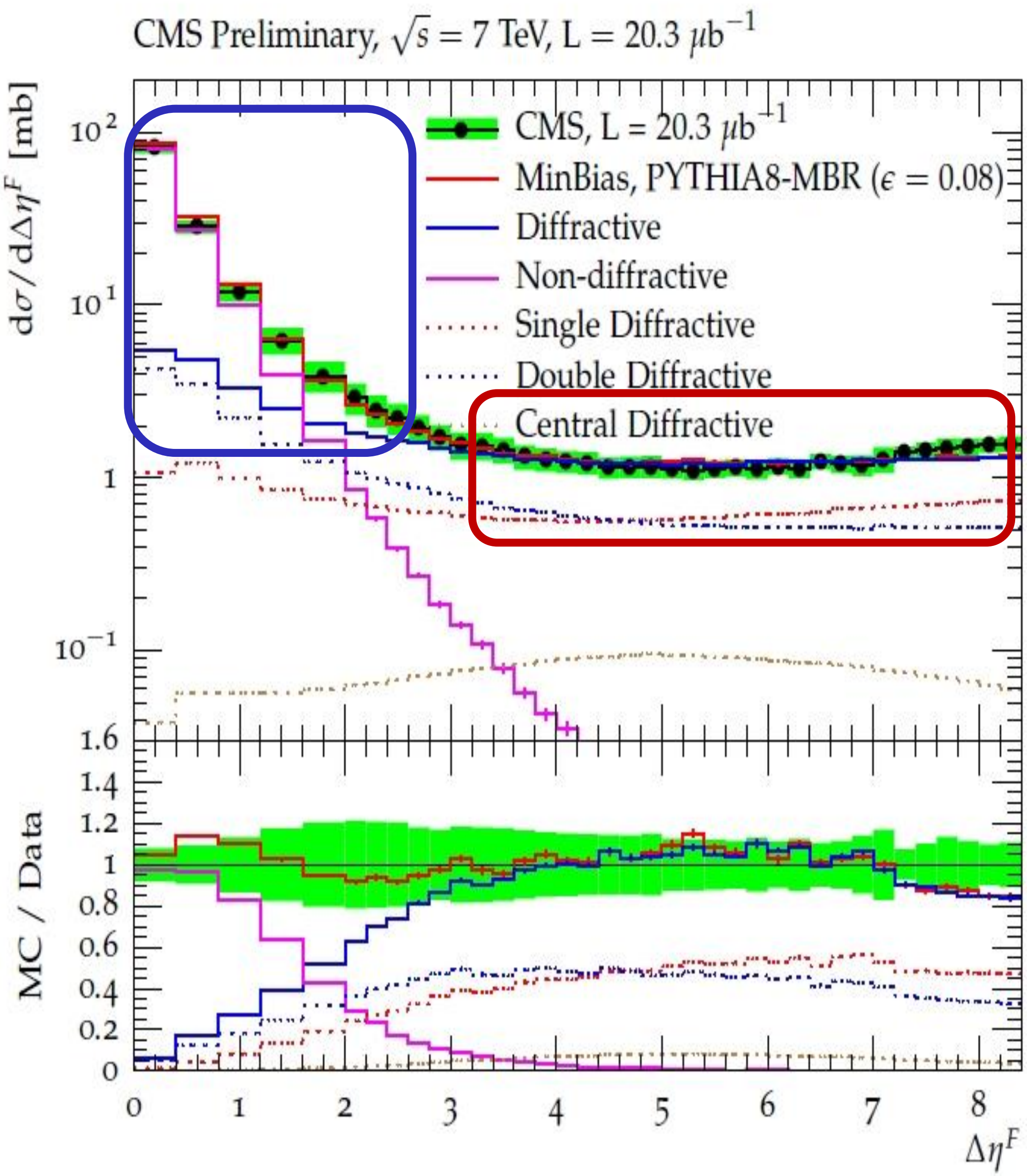


$$\frac{d\sigma^{DD}}{d\Delta\eta} = \frac{N^{data} - (N_{ND} + N_{SD} + N_{CD})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta\eta)_{bin}},$$

DD cross section integrated over $\Delta\eta>3$, $M_X>10$ GeV, $M_Y>10$ GeV :

$$\sigma^{DD} = 0.93 \pm 0.01(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})\ \text{mb}$$

PYTHIA8-MBR (with 2 intercepts), PYTHIA8-4C and PYTHIA6 predictions are in uncertainties of measured cross section



- FRG – gap between the edge of the detector (|η|=4.7) and the nearest particle

$$\Delta\eta^F = Max(4.7 - \eta_{min}, 4.7 + \eta_{min})$$

- the same sample of inelastic events
- no separation of ND, SD, DD
- no LRG

at low Δη:
exponentially decreasing of ND contribution is dominant

at high Δη:

- diffractive plateau at 1 mb/unit of frg
- slow increasing of diffractive cross sections due to α(0) > 1
- high sensitivity to diffractive models: PYTHIA8-MBR with soft Pomeron α(0) = 1.08 gives the best description of data

Other measurements of diffraction at LHC

ALICE

$\sqrt{s}$ (TeV)	σ_{SD} (mb)	σ_{DD} (mb)
0.9	$11.2^{+1.6}_{-2.1}$	5.6 ± 2.0
2.76	$12.2^{+3.9}_{-5.3}$	7.8 ± 3.2
7	$14.9^{+3.4}_{-5.9}$	9.0 ± 2.6

ALICE presented model-depending results on the total SD and DD cross sections at 3 LHC energies.

SD: Mx<200 GeV
DD: $\Delta\eta$>3

PYTHIA6 with some tuning used to extract from data ratio of diffractive events to the inelastic ones

TOTEM

$$\sigma_{DD} = (116 \pm 25)\ \mu\text{b}$$

$$4.7 < |\eta|_{min} < 6.5$$

DD at 7 TeV:
First measurement of DD in so forward region. It is around 3% of DD cross section.

CMS

$$\sigma^{SD} = 4.27 \pm 0.04(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})\text{mb}$$

$$\sigma^{DD} = 0.93 \pm 0.01(\text{stat.})^{+0.65}_{-0.58}(\text{syst.})\text{mb}$$

SD at 7 TeV:
- integrated σ at 12.4<Mx<393.6GeV
- $d\sigma/d(\log\xi)$ at -5.5 < $\log\xi$ < -2.5

DD at 7 TeV:
- integrated σ over
  $\Delta\eta$>3, Mx>10 GeV, My>10 GeV
- $d\sigma/d(\log\xi)$ at -5.5 < $\log\xi$ < -2.5 for
  12.4<Mx<393.6 GeV, 3.2<My<12.6 GeV

CMS measurements in pp collisions at $\sqrt{s} = 7$ TeV

Model independent inelastic cross section at $\xi > 5 \cdot 10^{-6}$
60.2±2.6(exp.) mb

Model dependent (extrapolated) inelastic cross section at $\xi > m_p^2/s$
64.5±3.2(exp.&extr.) mb

Cross section of Single Diffraction at $-5.5 < \log\xi < -2.5$
4.27±0.65(exp.) mb

Cross section of Double Diffraction at $\Delta\eta > 3$ & $M_x > 10$ GeV & $M_y > 10$ GeV
0.93±0.26(exp.) mb

Conclusion

CMS (alongside other LHC Collaborations) gives a valuable information on inelastic and diffractive processes in new energy regions.

Experimental results rule out some models while some survive.

Further measurements are mandatory.
In particular of the differential cross-sections of diffractive processes as function of missing masses and transferred momenta.

Up to now we have no concrete predictions from QCD to verify the latter in diffractive processes.