PROTON-PROTON CROSS-SECTION AT LHC ENERGIES: DATA - SIMULATION COMPARISON FOR THE STUDY OF RADIATION DAMAGE IN SILICON TRACKERS

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AGH

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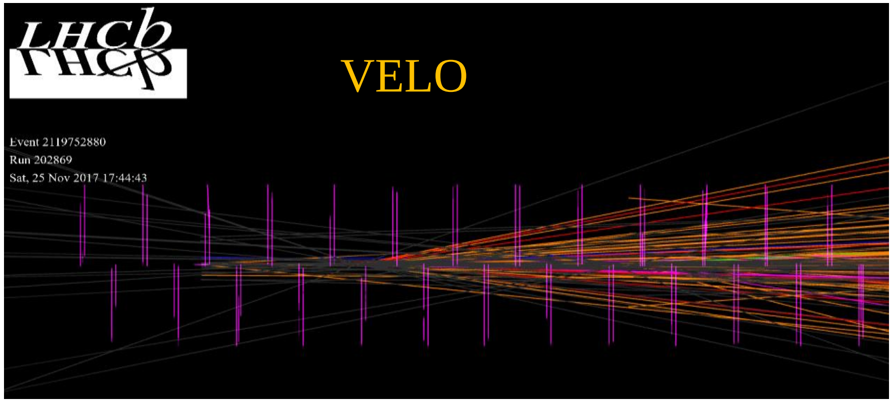
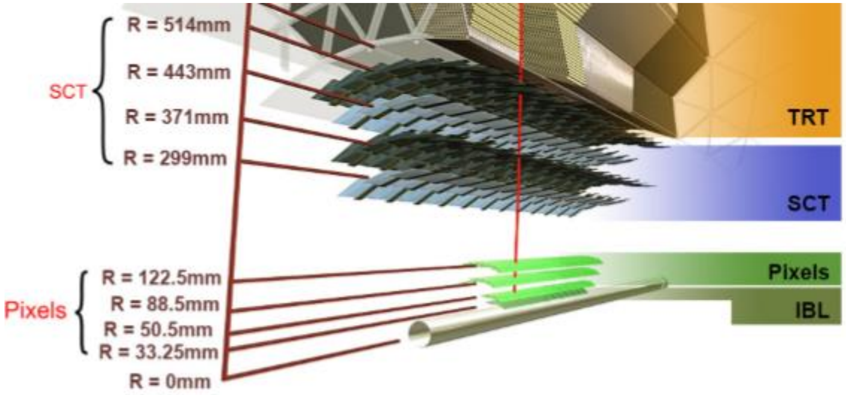
Outline

1. History of total and inelastic proton-proton cross-section measurements.
2. Prediction for high energy.
3. LHC measurements.
4. Radiation damage in silicon sensors.
5. Simulation of fluence

Motivation

- Value of the σ_{tot} determines the number of particles that pass through the detector.
- Silicon trackers are usually situated in the close proximity to the interaction point and are under influence of severe particle flux (VELO LHCb at 0.8 cm, ATLAS IBL at 3.5 cm, CMS 10 cm (?).





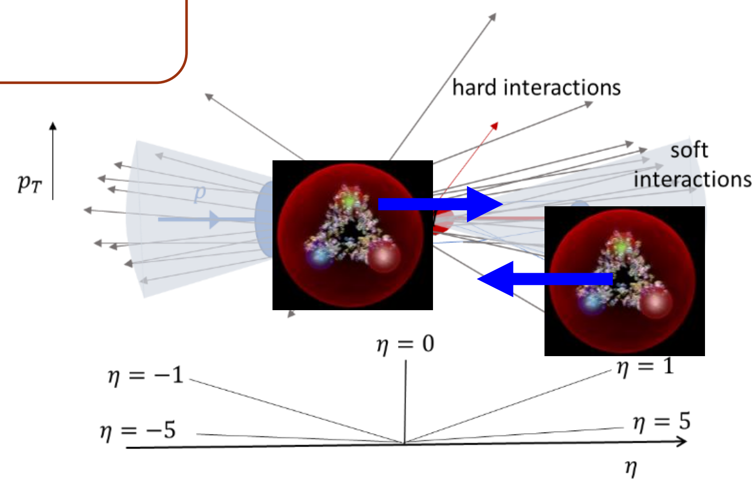
- Current technology of silicon sensors enables the operation at fluences up to 10^{16} n_{eq}/cm^2 .
- At the end of Run II LHCb and ATLAS silicon sensors were irradiated of the fluence that reached 10^{15} n_{eq}/cm^2 .
- During Run III (2021-2023) the amount of delivered data annually will reach value compared to the Run I and II together.
- Run IV (HL-LHC) the luminosity will be increased by one order of magnitude (3000 fb^{-1}) and new structures MUST be installed in the experiments.

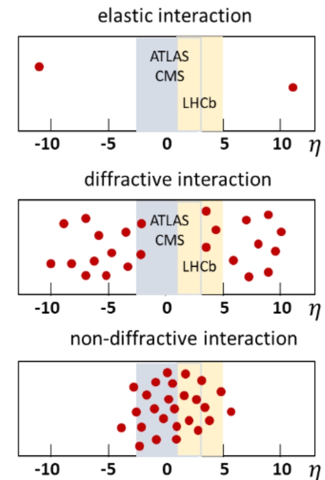
Methods for σ_{tot} measurement

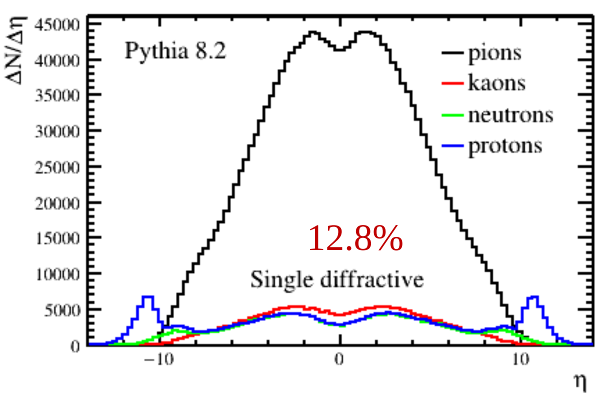
Cross-sections can not be calculated by quantum chromodynamics.

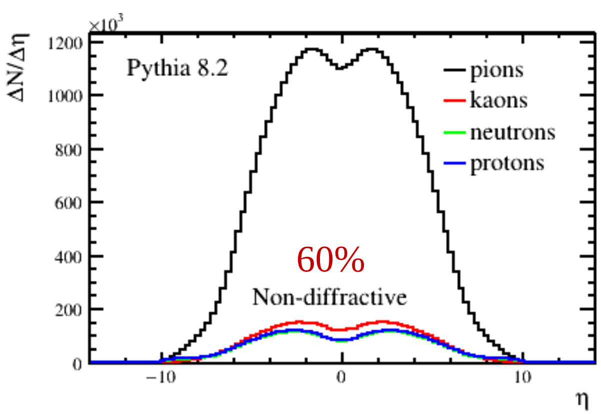
$$\sigma_{tot} = \underbrace{\sigma_{el}}_{\text{Method 1}} + \underbrace{\sigma_{inel}}_{\text{Method 2}} = \sigma_{el} + \sigma_{diff} + \sigma_{ND}$$

$$\eta = -ln\left(tg\,\frac{\theta}{2}\right)$$





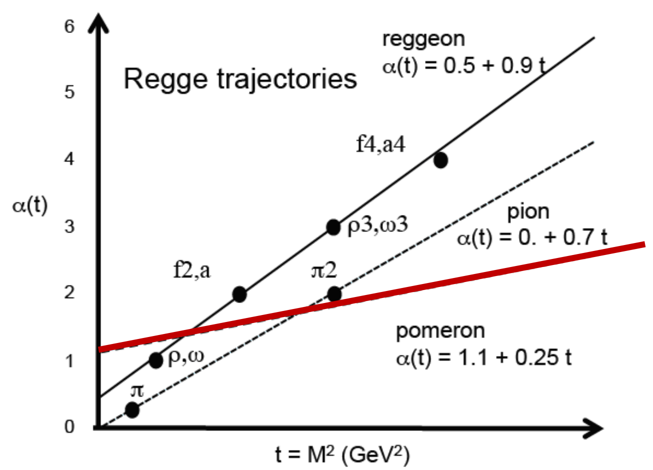




non diffractive ≅ min bias

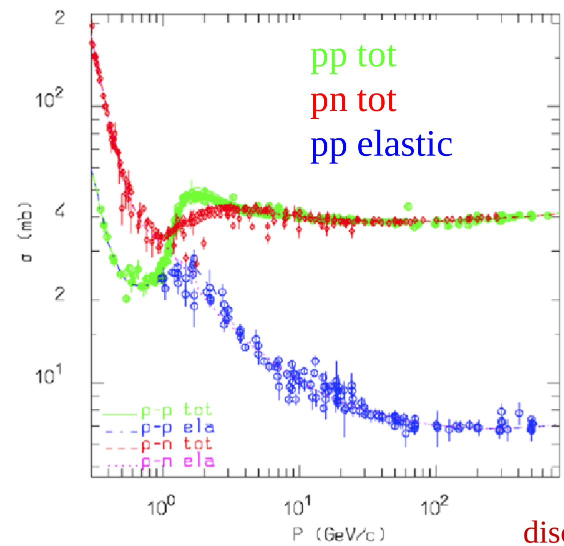
Total proton-proton cross-section - history

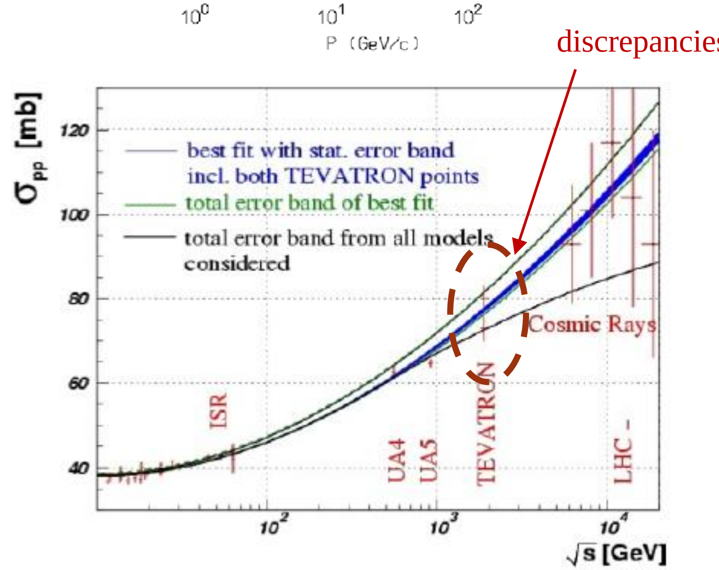
- σ_{tot} is not calculable in the framework of pQCD; Regge model is used in HEP generators to describe kinematic area where QCD cannot be applied
- Decrease of proton – proton cross-section at low energies is described by a model with exchange of known reggeons.



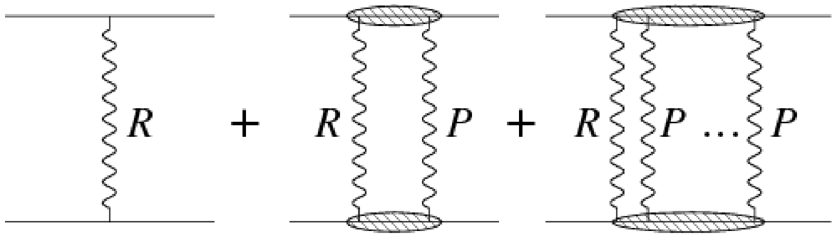
- 2011: experimentally observed increase of σ_{tot} is explained if $\alpha(t=0) > 1$, what can be achieved by adding the exchange of pomeron.

- 1973: soft interactions and Intersection Storage Rings (ISR)

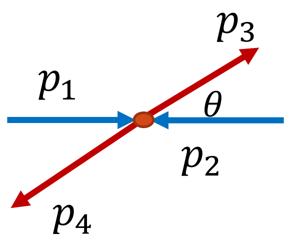




Total proton-proton cross-section – pre LHC era



- LHC era: with the increase of energy, the contributions of reggeons can be neglected, while multi-pomeron exchange describes multiparton scattering.
- Elastic scattering amplitude is parametrised by the sum of diagrams with R and P exchange.



$s = (p_1 + p_2)^2$

$t = (p_1 - p_3)^2$

- Using optical theorem: $\sigma_{tot}(s) \approx s^{\alpha(0)-1}$,

$$\frac{d\sigma_{el}}{dt} \approx s^{2(\alpha(0)-1)} e^{-B|t|}$$

where $\alpha(0)$ is an intercept of a Regge trajectory: $\alpha(t) = \alpha(0) + \alpha' t$; $t = (p_1 - p_2)^2$;

- σ_{tot} can be parametrised as (before LHC, HERA and Tevatron data):

$$\sigma(s) \sim \ln^2(s)$$

$$\sigma(s) = c_1 + c_R\ s^{-0.5} + c_{sP}\ s^{0.067} + c_{hP}\ s^{0.45}$$

many parameters; we need data!!!

Cross-section measurements

- Measurement of the inelastic pp cross-section at a centre-of-mass energy of √s= 7 TeV, The LHCb collaboration, Aaij, R., Adeva, B. et al. J. High Energ. Phys. (2015) 2015: 129. https://doi.org/10.1007/JHEP02(2015)129
- Measurement of the inelastic *pp* cross-section at a centre-of-mass energy of 13 TeV, The LHCb collaboration, Aaij, R., Adeva, B. et al. J. High Energ. Phys. (2018) 2018: 100. https://doi.org/10.1007/JHEP06(2018)100
- Measurement of the total cross section from elastic scattering in pp collisions at √s=7 TeV with the ATLAS detector - ATLAS Collaboration (Aad, Georges et al.) Nucl.Phys. B889 (2014) 486-548 arXiv:1408.5778 [hep-ex] CERN-PH-EP-2014-177
- Measurement of the total cross section from elastic scattering in pp collisions at √s=8 TeV with the ATLAS detector - ATLAS Collaboration (Aaboud, Morad et al.) Phys.Lett. B761 (2016) 158-178 arXiv:1607.06605 [hep-ex] CERN-EP-2016-158
- Measurement of the Inelastic Proton-Proton Cross Section at √s=13 TeV with the ATLAS Detector at the LHC, Phys. Rev. Lett. 117, 182002 (2016), 10.1103/PhysRevLett.117.182002
- First measurement of elastic, inelastic and total cross-section at s√=13 TeV by TOTEM and overview of cross-section data at LHC energies - TOTEM Collaboration (Antchev, G. et al.) Eur.Phys.J. C79 (2019) no.2, 103 arXiv:1712.06153 [hep-ex] CERN-EP-2017-321, CERN-EP-2017-321-V2
- Luminosity-Independent Measurement of the Proton-Proton Total Cross Section at √s=8 TeV - TOTEM Collaboration (Antchev, G. et al.) Phys.Rev.Lett. 111 (2013) no.1, 012001 TOTEM-2012-005, CERN-PH-EP-2012-354
- Measurement of the inelastic proton-proton cross section at √s= 13 TeV, the CMS collaboration, Sirunyan, A.M., Tumasyan, A. et al. J. High Energ. Phys. (2018) 2018: 161

Total proton-proton cross-section derived from elastic

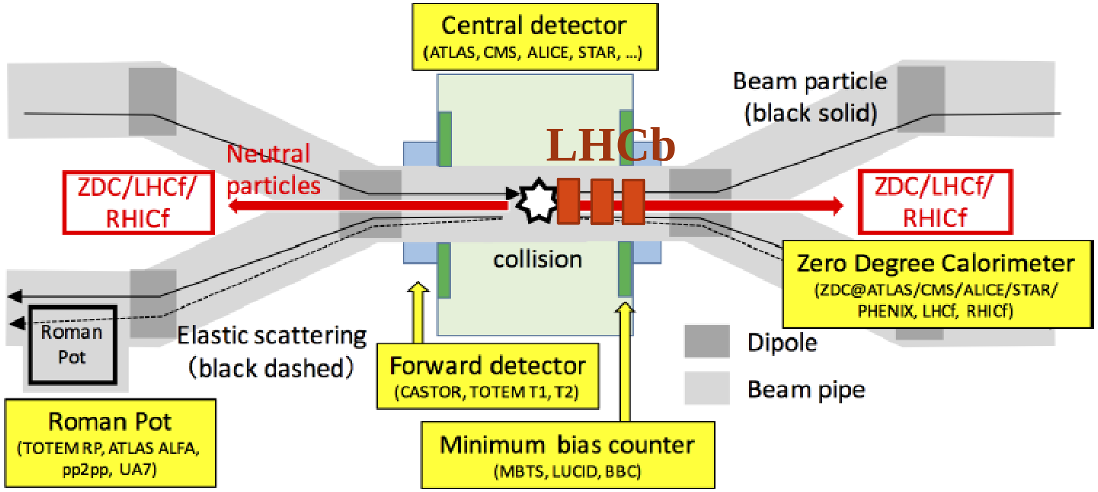
- Direct σ_{tot} measurement is non-trival due to limited acceptance.
- 1973: Intersecrion Storage Rings (ISR) – via elastic cross-section measurement and the use of optical theorem: $\sigma_{tot} = 4\pi\, Im[f_{el}(t=0)]$
- Rise of σ_{tot} with $\sqrt{s}$ was predicted
- Lumi dependent method:

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

- Lumi independent method:

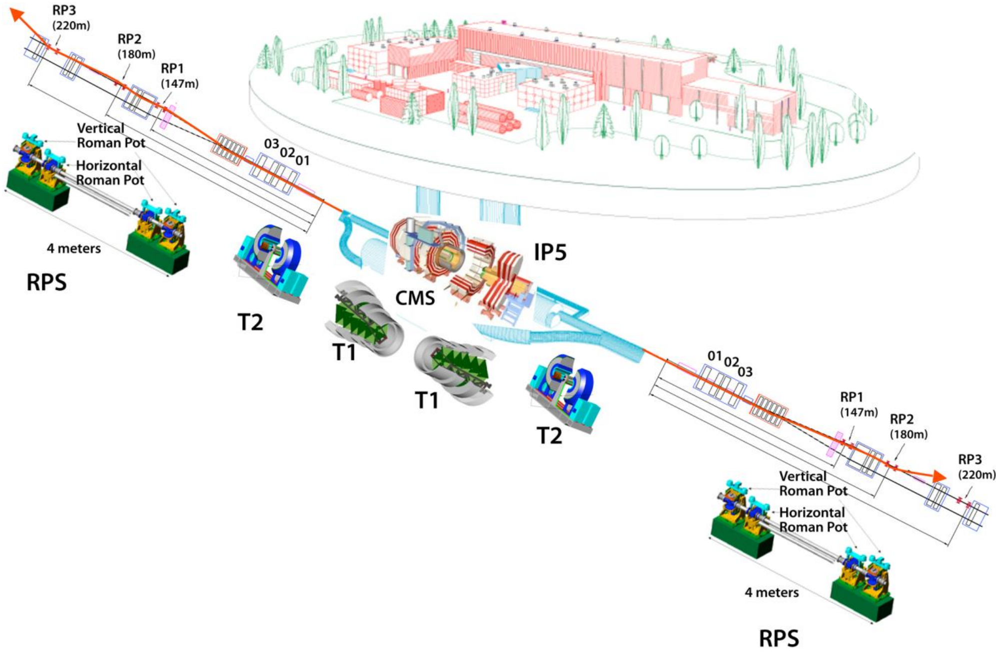
$$\sigma_{tot} = \frac{16\pi}{1+\varrho^2}\frac{1}{N_{tot}}\left(\frac{dN_{el}}{dt}\right)_{t=0}$$

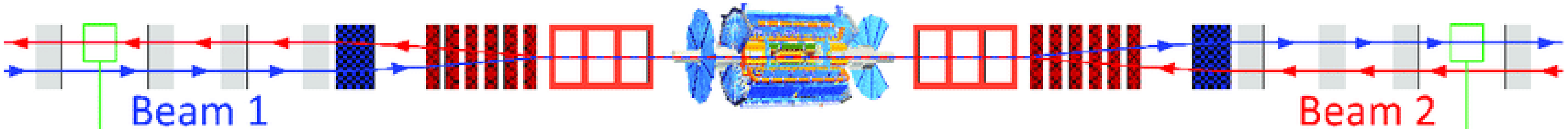
$$\rho = \frac{Re\, f(0)}{Im\, f(0)} \simeq 0.009$$



Elastic proton-proton cross-section

- To measure $\left(\frac{dN_{el}}{dt}\right)_{t=0}$ we need to collect particles at very small angles.
- LHC: special runs and two experiments: TOTEM (0.5 km around CMS) and ALFA (at ATLAS)

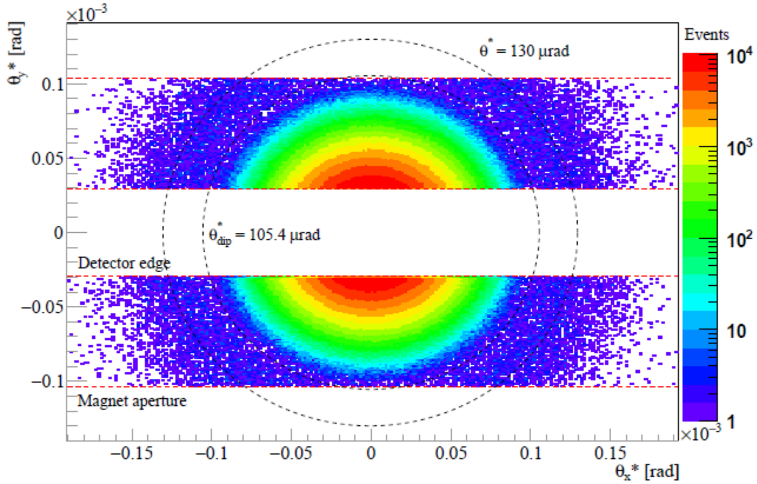




Elastic proton-proton cross-section

TOTEM experiment (LHC, ~0.5 km around CMS):

- elastic pp scattering, $\frac{d\sigma_{el}}{dt}(t)$,
- diffractive (single, double, central) (with CMS),
- total cross-section.



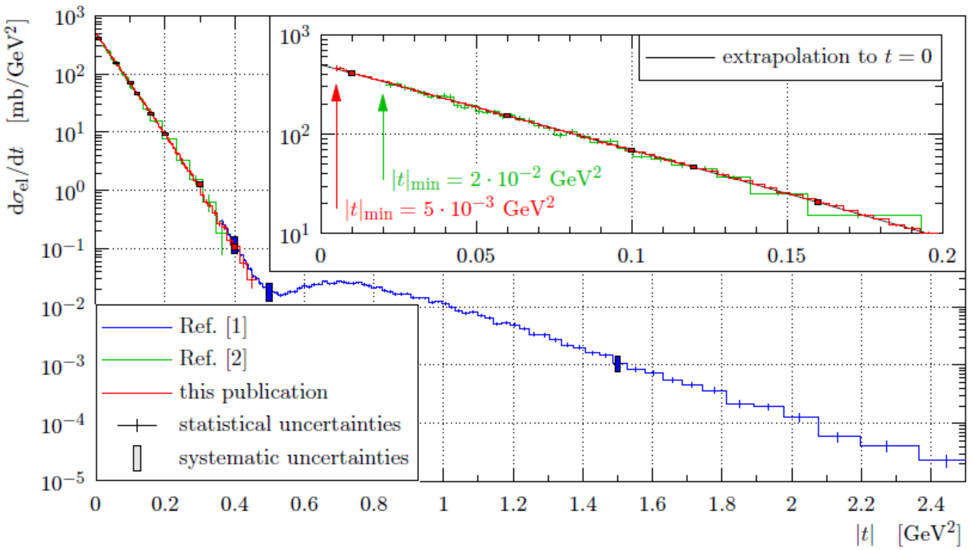
Elastic x-section can be measured up to
$0.36 < |t| < 2.5$ GeV^2 with very small azimutal angles θ:

$$t = (p_1 - p_2)^2 = 4p^2 \sin^2\frac{\theta}{2} \simeq -(p\theta)^2$$

Special LHC runs enables $|t| < 0.01$ GeV^2

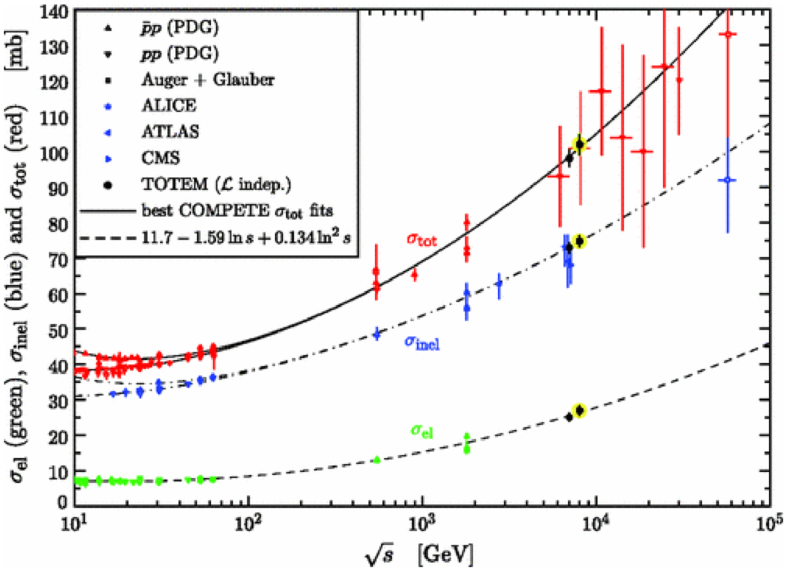
$$\frac{d\sigma_{el}}{dt} = \frac{d\sigma_{el}}{dt}(\mathrm{t}=0)\, \mathrm{e}^{-\mathrm{B}|\mathrm{t}|}$$

$$\sigma_{tot}^2 \sim \frac{d\sigma_{el}}{dt}(\mathrm{t}=0)$$

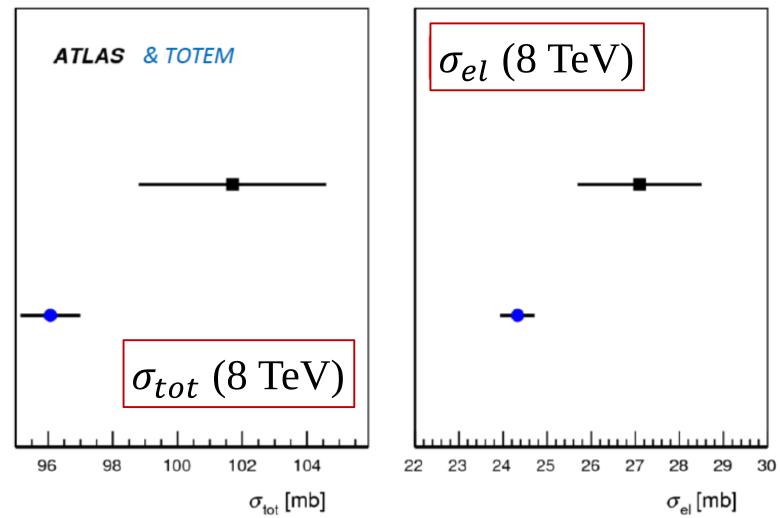


Inlastic pp cross-section in Run I

- $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$



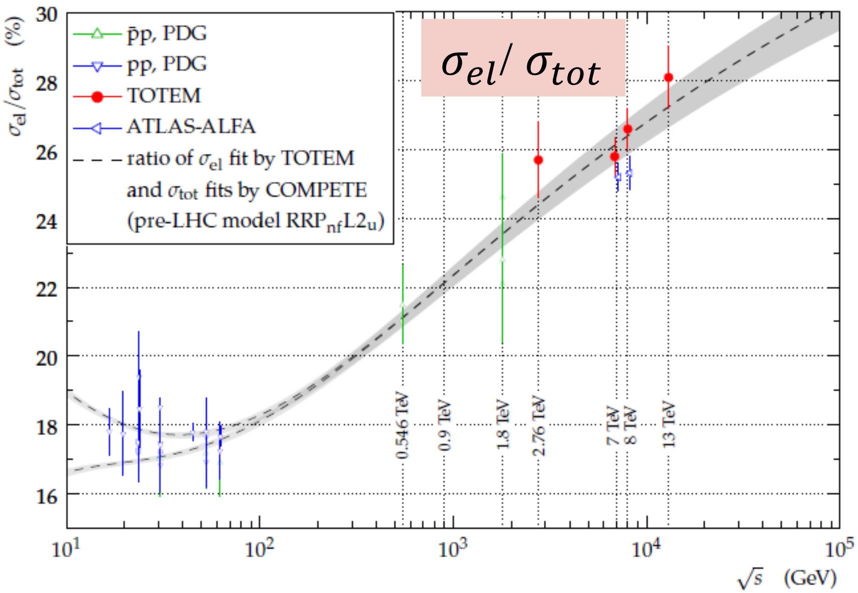
ATLAS=ALFA

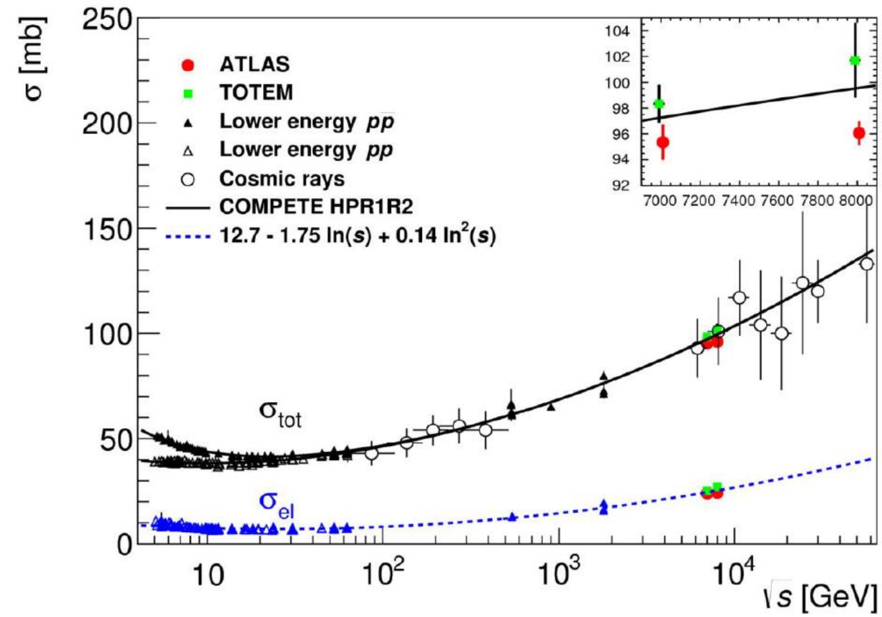


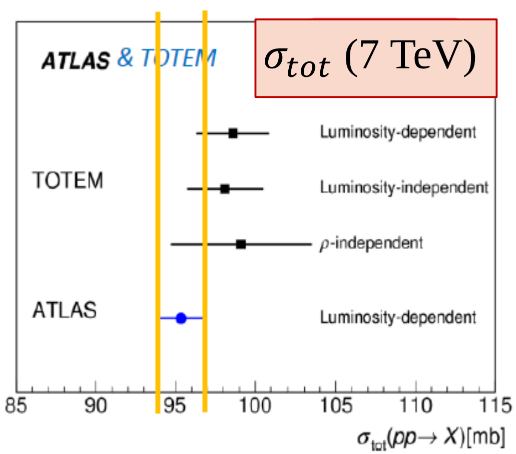
$\sqrt{s}$ = 8 TeV σ_{tot}= 96.07 ± 0.18 (exp) ± 0.85 (lumi) ± 0.31 (extrap.) mb

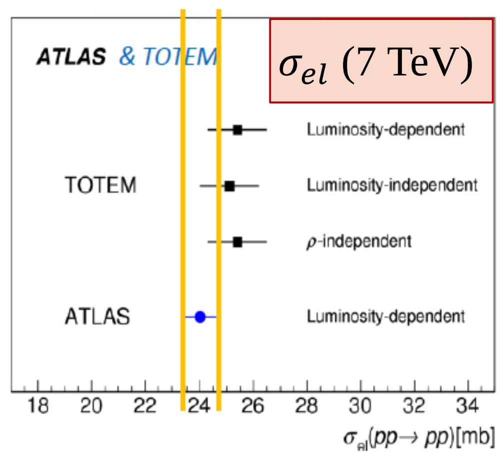
$\sqrt{s}$ = 8 TeV σ_{inel}= 71.78-74.7 mb

Elastic 2 total cross-section









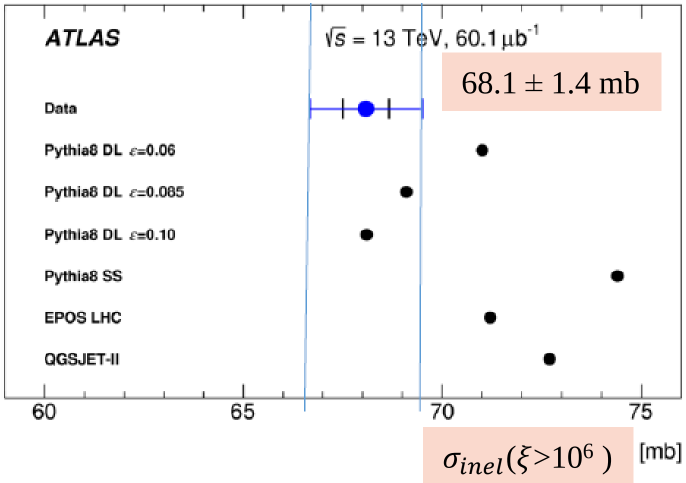
$$\sigma_{tot}^2 \sim \frac{d\sigma_{el}}{dt}(\mathrm{t}=0)$$

$$\sigma_{inel} = \sigma_{tot} - \sigma_{el}$$

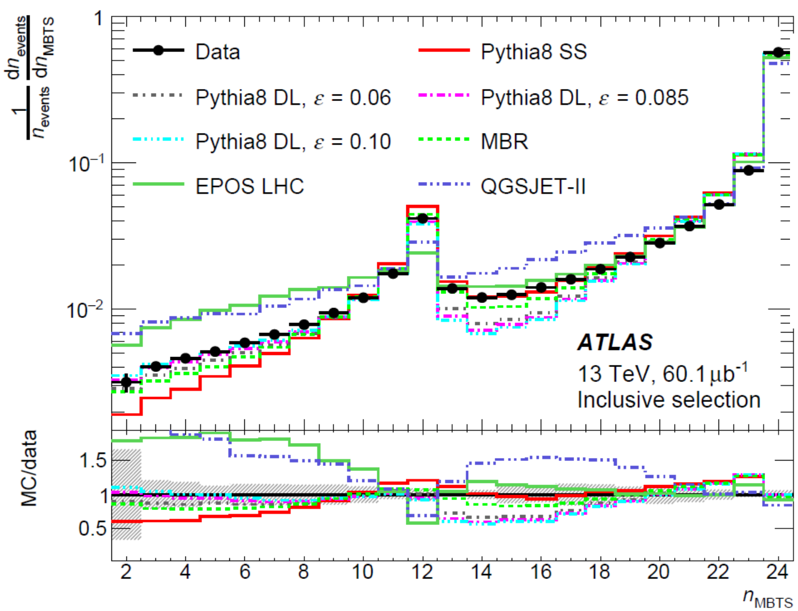
$\sqrt{s}$ = 7 TeV σ_{inel}= 66.9-73.7 mb

Inelastic pp cross-section in Run II (ATLAS)

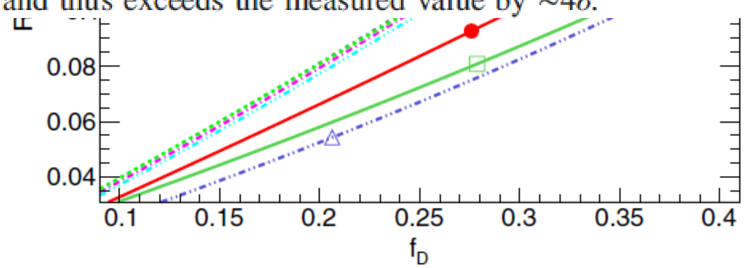
- The measurement of the inelastic yield is based on the counting of hits in the Minimum Bias Trigger Scintillator in $2.07 < \eta < 3.86$ (diffractive and inclusive ND events with $M_X > 13$ GeV).
- Cross-section is calculated in fiducial volume of $\xi = M_X^2 > 10^{-6}$ and extrapolated to full phase space with the help of models of ineleastic interactions.
- Ratio $f_D(MC) = (\sigma_{SD} + \sigma_{DD})/\sigma_{inel}$ varied and compared with data for usage in simulation.



- Impact of generators?



The PYTHIA8 DL model predicts values of 71.0 mb, 69.1 mb, and 68.1 mb for $\varepsilon = 0.06$, 0.085, and 0.10, respectively, all of which are compatible with the measurement. The PYTHIA8 MBR model predicts 70.1 mb, also in agreement with the measurement. The EPOS LHC (71.2 mb) and QGSJET-II (72.7 mb) predictions exceed the data by 2–3σ. The PYTHIA8 SS model predicts 74.4 mb, and thus exceeds the measured value by $\sim 4\sigma$.



Inelastic pp cross-section in Run II (ATLAS)

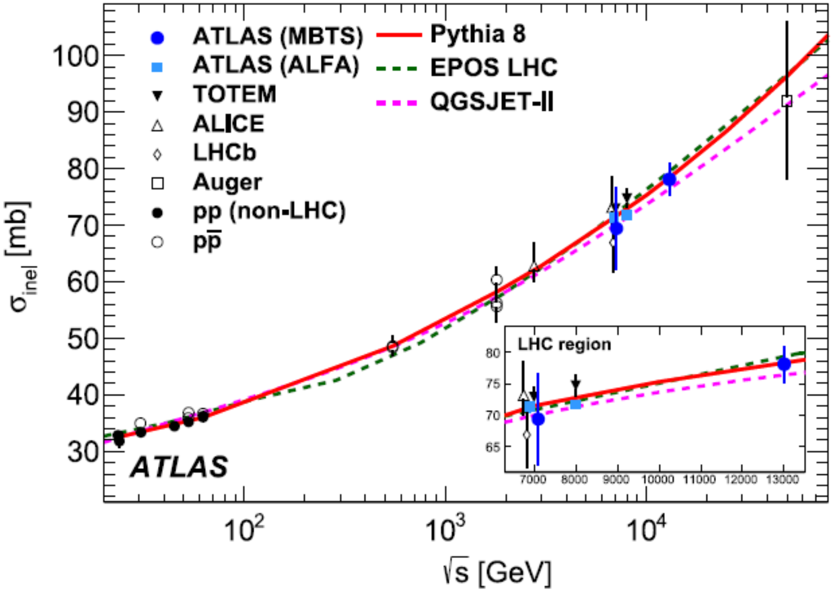
- Cross-section is calculated in fiducial volume of $\xi = M_X^2 > 10^{-6}$ and extrapolated to full phase space with the help of models.

$$\sigma_{\rm inel} = \sigma_{\rm inel}^{\rm fid} + \boxed{\sigma^{7\ \rm TeV}(\xi < 5\times10^{-6})} \times \frac{\sigma^{\rm MC}(\xi < 10^{-6})}{\sigma^{7\ \rm TeV,MC}(\xi < 5\times10^{-6})}$$

$$\sigma^{7\ \rm TeV}(\xi < 5\times10^{-6}) = \sigma_{\rm inel}^{7\ \rm TeV} - \sigma^{7\ \rm TeV}(\xi > 5\times10^{-6}) = 9.9 \pm 2.4\ \rm mb$$

diffrence between σ_{inel}(7 TeV, ALFA) and σ_{inel} at 7 TeV with MBTS

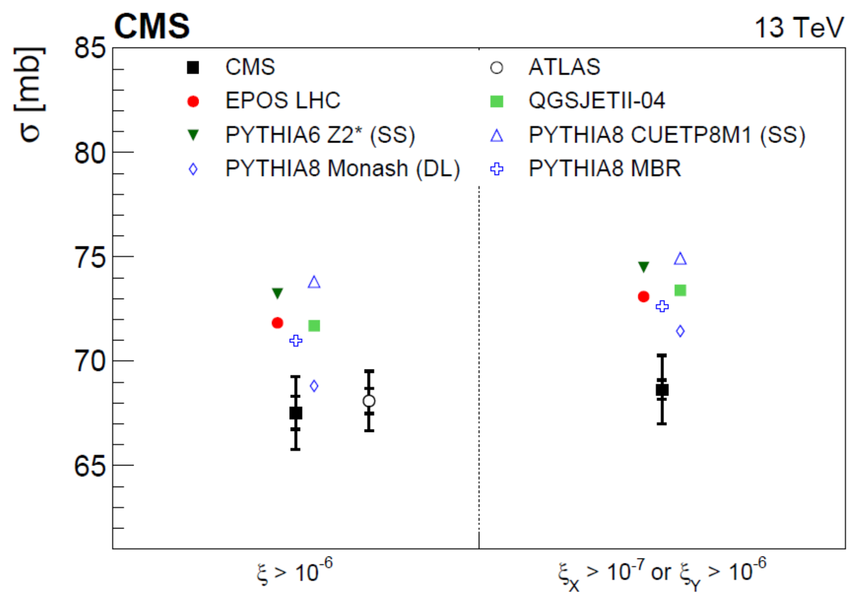
- This procedure makes the measuremet less sensitive to models.



$\sqrt{s}$ = 13 TeV σ_{inel}= 78.1 ± 0.6 (exp) ± 1.3 (lumi) ± 2.5 (extrap.) mb

Inelastic pp cross-section in Run I - II (CMS)

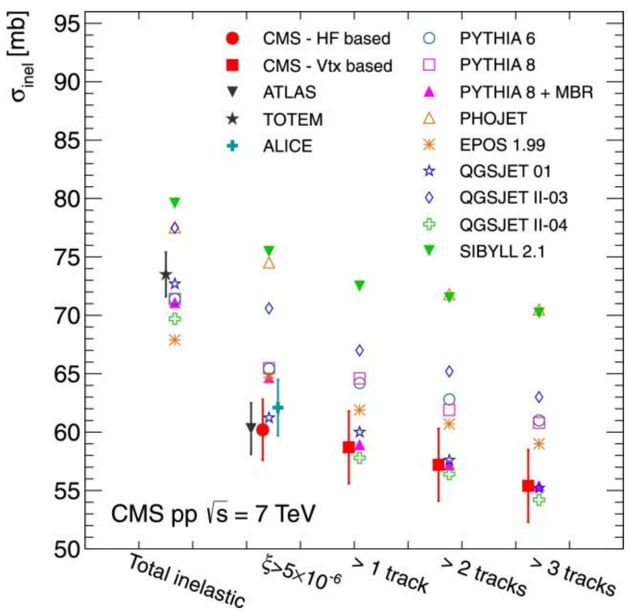
- Data collected with the CMS forward calorimeters HF and CASTOR $-6.6 < \eta < -3$ and $3.0 < \eta < 5.2.$
- Sensitivity to a large part of the total inelastic cross section, including diffractive events with dissociated protons



$\sqrt{s} = 13\ \text{TeV} \quad \sigma_{tot} = 68.6 \pm 0.5\ (\text{syst}) \pm 1.6\ (\text{lumi})\ \text{mb}$

$\xi_X > 10^{-7}\ or\ \xi_Y > 10^{-6}$

Physics Letters B Vol 722, Issues 1–3, 2013, P 5-27



measured cross section is significantly lower than predicted by models for hadronic scattering and ATLAS

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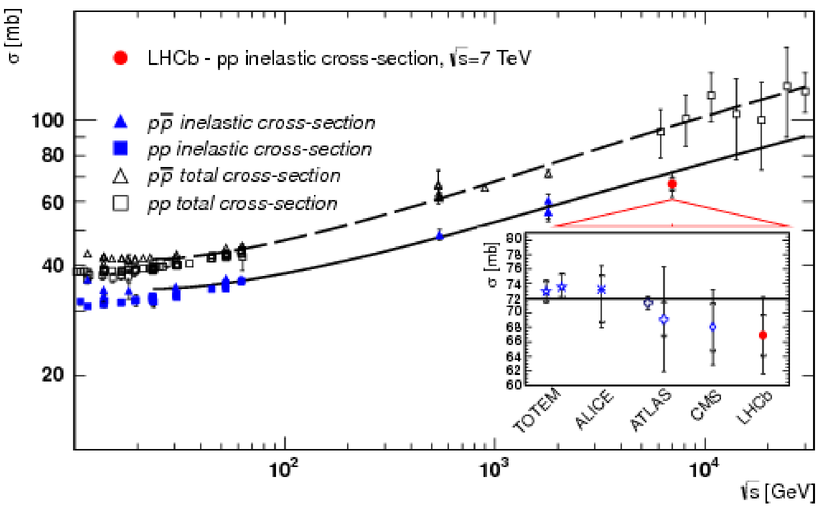
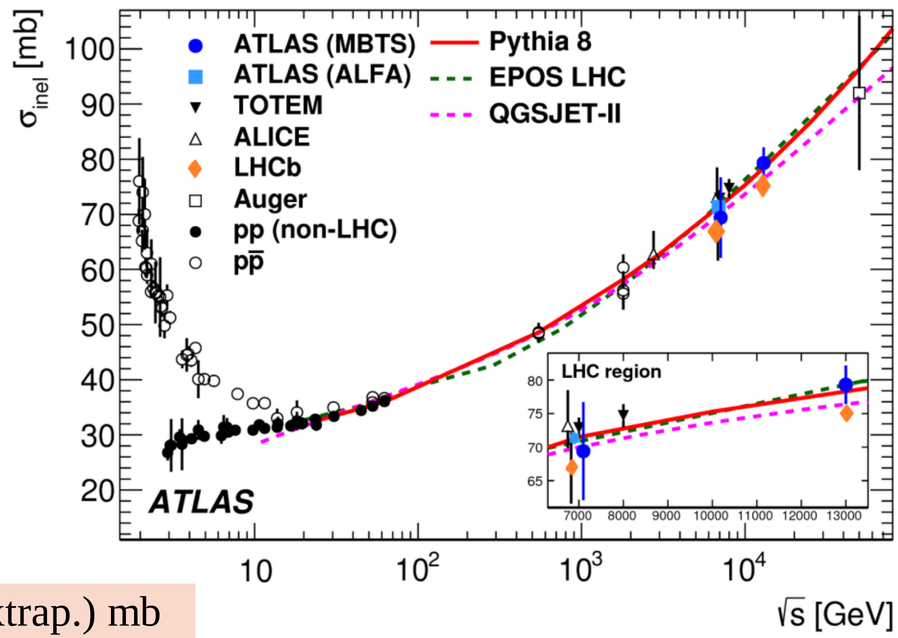
- Selection of events with at least one prompt long-lived particle with $p_t > 0.2$ GeV in $2.0 < \eta < 4.5$.
- Simulation: Pythia 6 and EvtGen,
- Measurement of $\sigma_{inel}^{acc} = \frac{N^{acc}}{\mathcal{L}}$; $N^{acc} = \frac{N_{vis}}{\varepsilon}$; $\mathcal{E}$ from MC;
- Extrapolation to full phase space is done with Pythia 8 and different tunings (model dependent), using fraction of SD, DD, ND events.



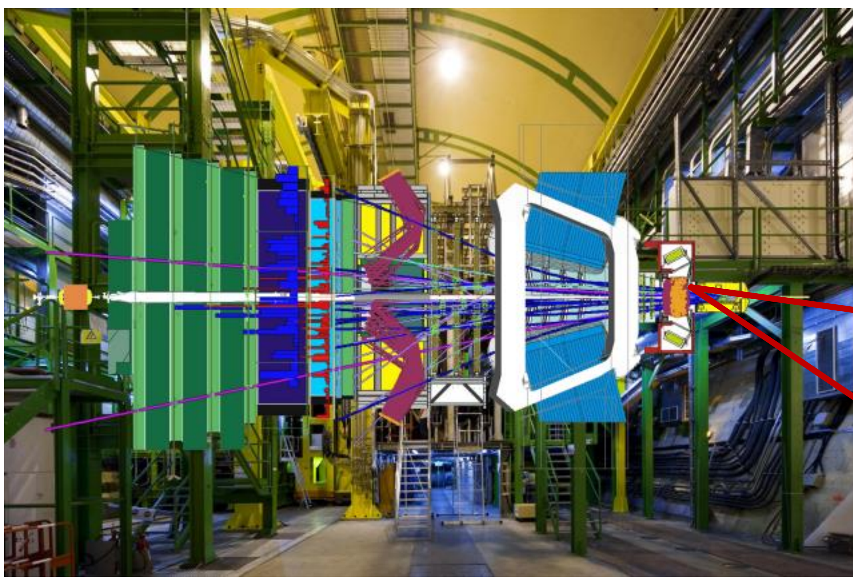


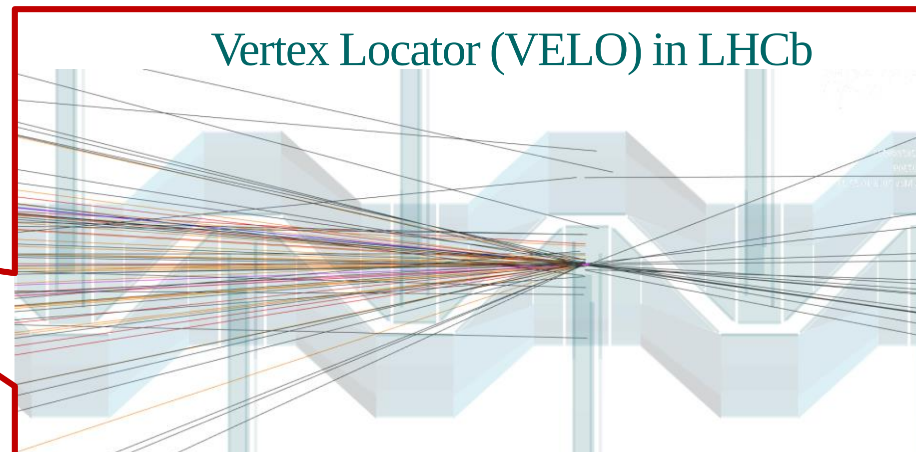
$\sqrt{s} = 7$ TeV $\sigma_{inel} = 68.7 \pm 2.1$ (exp) ± 4.5 (extrap.) mb

$\sqrt{s} = 13$ TeV $\sigma_{inel} = 75.4 \pm 3.0$ (exp) ± 4.5 (extrap.) mb

Differences in σ_{in} – should RD bother at all?

- For the radiation damage studies (monitoring, predictions and comparison with RD models) we need to know fluence in standardised units, called neutron equivalence fluence n_{eq}.
- We need to know much more than the σ_{tot}:
  - how many pp interactions occurred in 1 fb^{-1},
  - how many particles were produced (multiplicity),
  - type of particles (protons, neutrons, pions, kaons),
  - energy spectrum,
  - angular distribution.
- Determination of n_{eq} depends very strongly on σ_{in} and physics model used in generators.

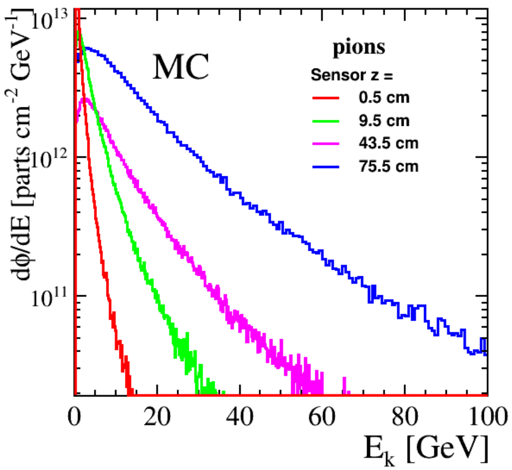




Neutron equivalence fluence

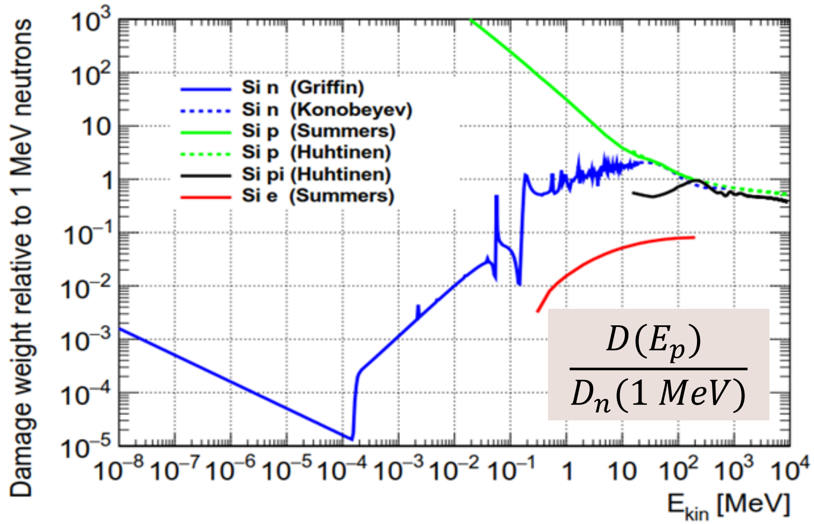
- The particle flux is converted into neutron equivalence units with an experimentally established hardness factor:

$\phi(E_p)$



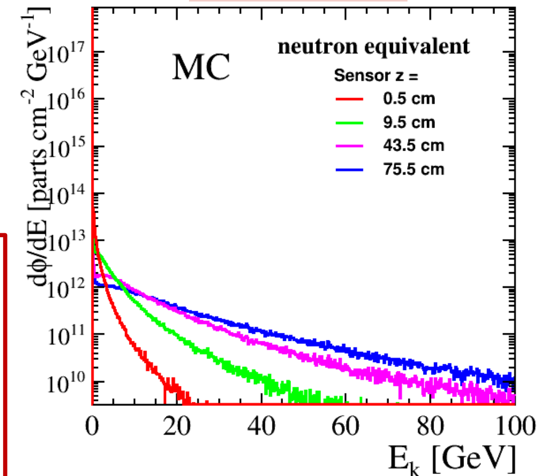
$$\phi_{eq} = \kappa \int \phi(E_p)\, dE_p$$

$$k = \frac{1}{D_n(1\ MeV)} \frac{\int_{Emin}^{Emax} dE_p \phi(E_p)\ D(E_p)}{\int_{Emin}^{Emax} dE_p \phi(E_p)}$$

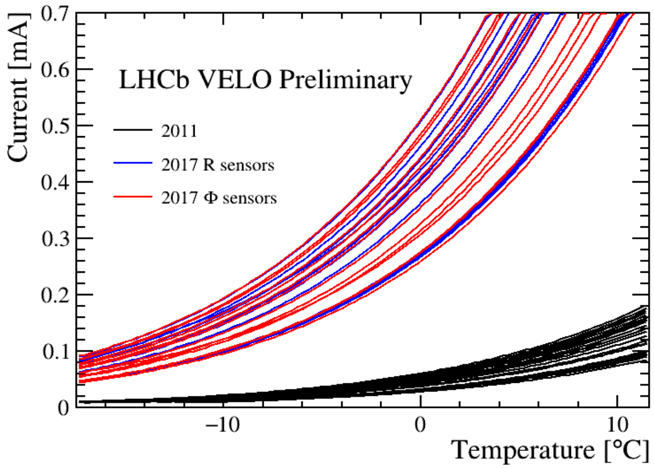


$$\frac{D(E_p)}{D_n(1\ MeV)}$$

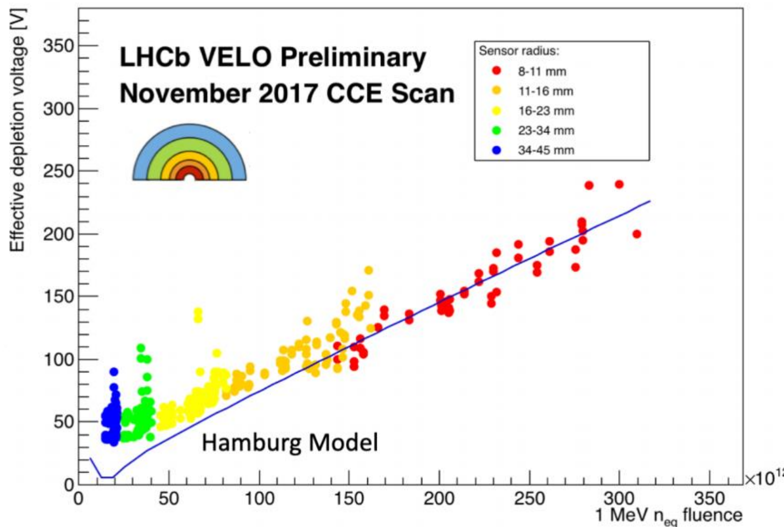
$\phi_{eq}(E_p)$



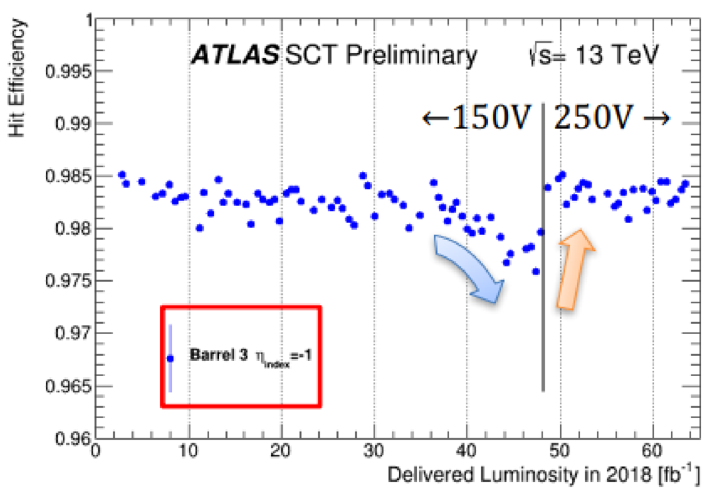
Increase of leakage current: $\Delta I = \alpha \, V_{ol} \, \phi_{eq}$



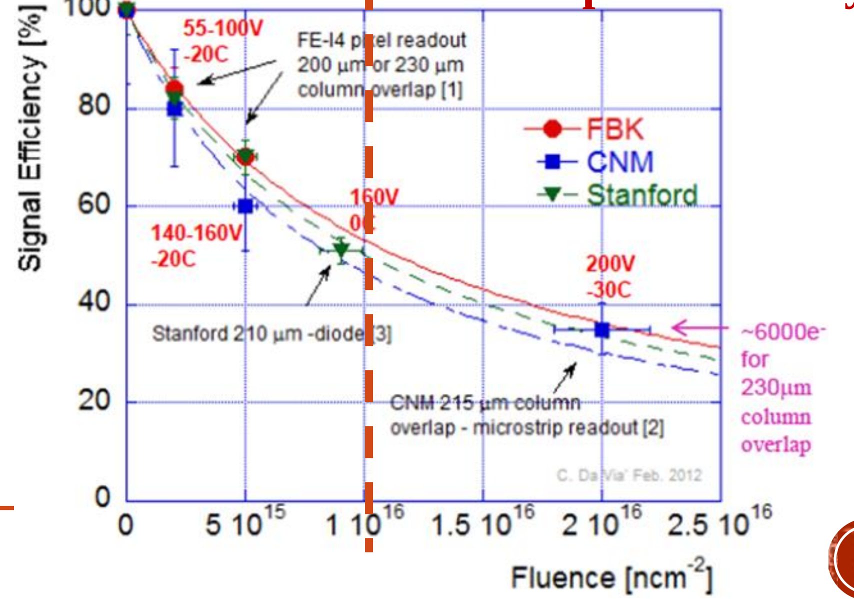
Change of depletion voltage



Decrease of efficiency



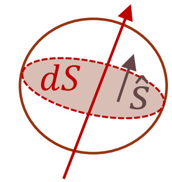
50% drop in efficiency



Fluence definition

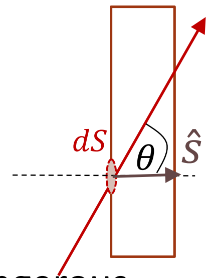
1. Fluence – number of particles dN traversing the sphere of cross section dS:

$$\phi = \frac{dN}{dS}$$



When counting particles hitting siliconsensors one should consider $cos\theta$:

$$\phi = \frac{dN}{dS_{\parallel}} = \frac{dN}{dS\ \ cos\theta}$$



Geant 4

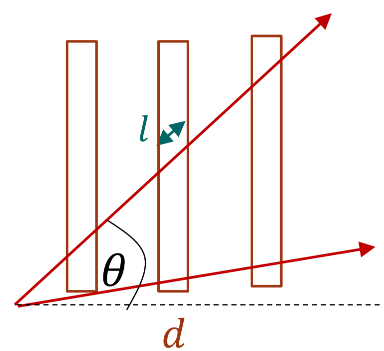
+ Pythia

That makes the particles crossing at large angle the most dangerous.

2. We can take the track length - fluence is then defined as the tracklength density:

$$\phi = \frac{\sum l}{V} = \frac{\sum d/cos\theta}{V}$$

what is equivalent to the definition above.



FLUKA

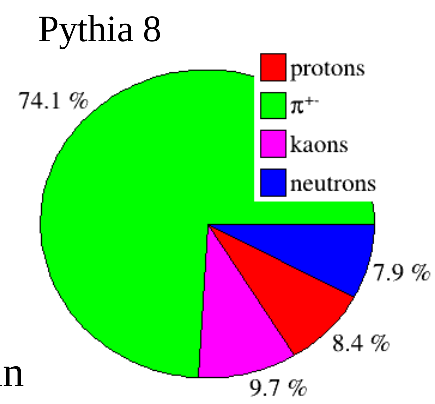
+ DPMJET3

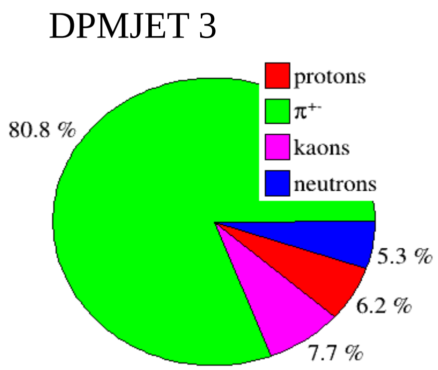
Motivation:

1. Differences between simulation of fluence with Pythia8/Geant4 and Fluka/DPMJET3 were reported.
   a) Discrepancies among generators in event multiplicities at LHC energy.
   b) Each experiment generates the minimum bias MC with different cuts.
2. Tools:
   a) Pythia 8: stand-alone generator (without LHCb framework but with „standard” LHC settings).
   b) DPMJET3: embedded in FLUKA, latest version. This is PHOJET generator for proton-proton collisions with Run II LHC tuning.

N_{had}	Pythia 8	DPMJET 3
pions	98	59
(a)protons	11.1	4.5
(a)neutrons	10.5	3.9
kaons	12.8	5.6
Total hadrons	**132.5**	**73**

~25% more particles is produced in Pythia 8.2 than in DPMJET 3 (first study)





DPMJET:
- originally DTUJET (1992) for soft hadronic interaction,
- σ_{tot} via Dual Parton Model and optical theorem,
- MPI and hard processes obtained with „hard-pomeron",
- DPMJET 3 is tuned to the LHC results and embedded in Fluka,
- diffractive processes are the integral part of the model,
- no parameters can be set by the user.

Pythia:
- successor of fortran Pythia 6 (v4.8 in 1987),
- written to describe MPI with pQCD,
- constantly tuned,
- diffractive processes are a separate part simulated with a special models, v8 contains hard diffraction,
- many parameters to chose from during simulation.

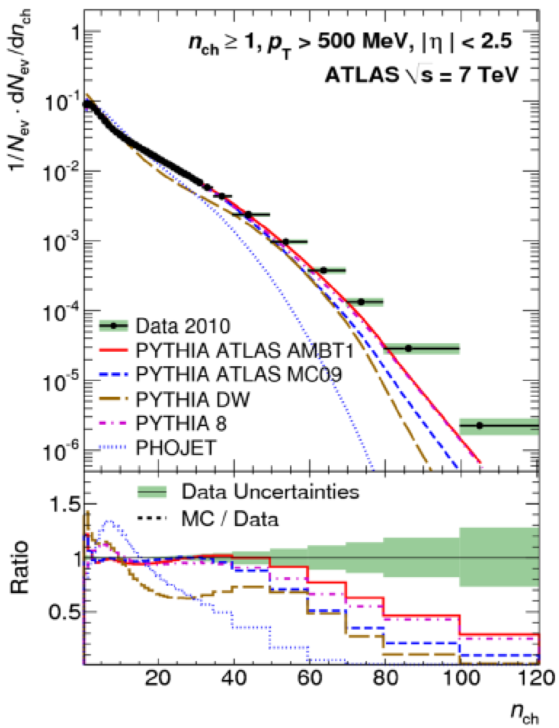
DPMJET 3 tunes low- p_T processes into hard scale.

Pythia uses pQCD to describe low- p_T processes.

It may influence:

- multiplicity of events
- particle transverse momentum distribution.

Both models were revised and retuned after Run I LHC data and once more after results from $\sqrt{s}$=13 TeV.



Quite a lot of MC tunings are available:

Monte Carlo Models

Parton Shower

Pythia8 4C	(Author) MB+UE tune with CTEQ6L1
Pythia8 Monash	(Author) MB+UE tune with NNPDF2.3LO
Pythia8 CUETP8S1	(CMS) UE tune based on 4C
Pythia8 CUETP8M1	(CMS) UE tune based on Monash
Pythia8 A2	(ATLAS) Minbias/Central ET flow tune based on 4C
Pythia A3	(ATLAS) Minbias/inelastic cross-section
Herwig++ UE-EE-5C	(Author) UE tune with energy scaling using CTEQ6L1

Cosmic Ray/Air Shower

Epos LHC	Based on Gribov's Pomeron exchange/collective flow approach, use LHC and fixed target experiment data to describe hadron and nuclear collisions.
QGSJET-II	
Sibyll	

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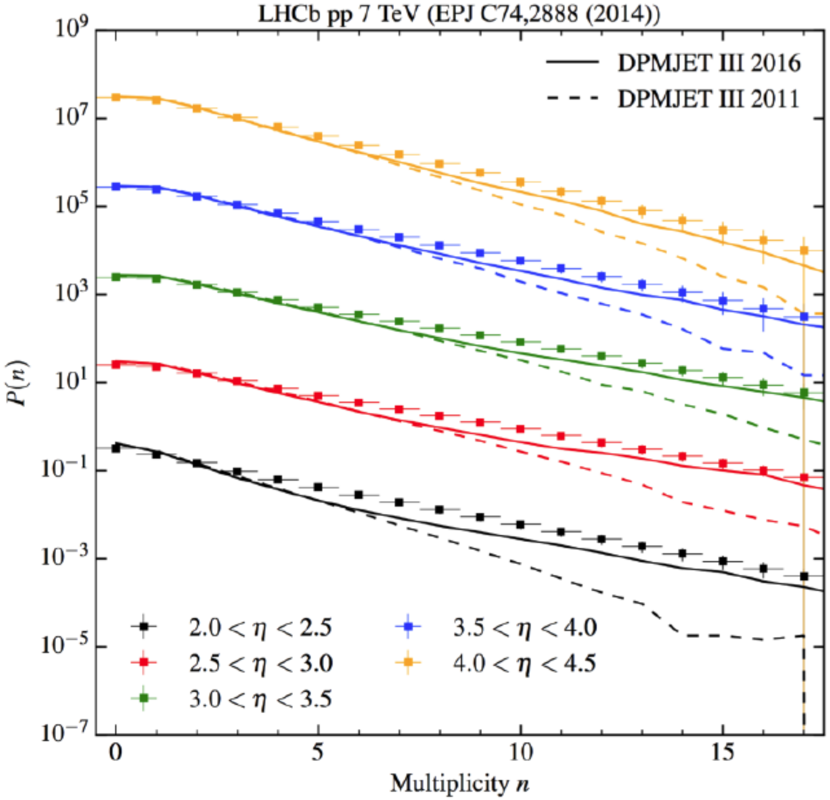
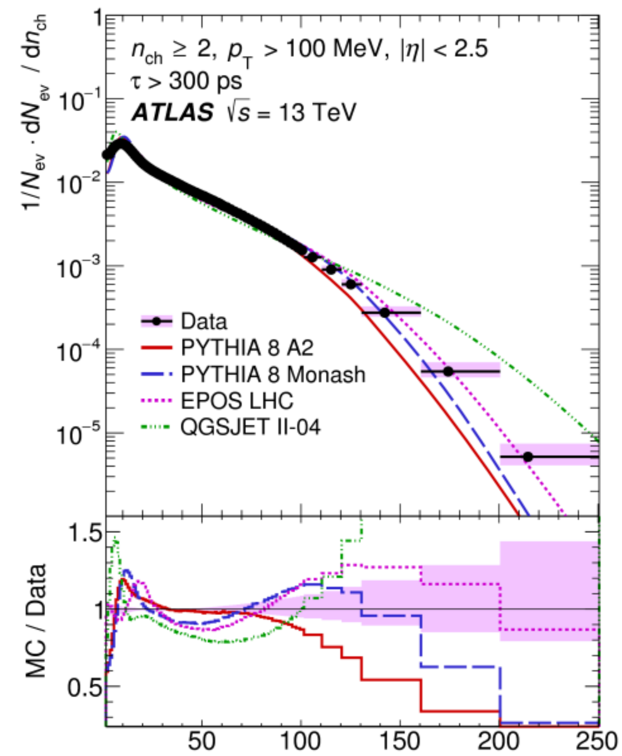
Deepak Kar RD50 Workshop 2019

Comparison of models for fluence simulation

None of these models describe min bias events correctly in wide range of n_{ch} and p_T.





arXiv:1606.01133

Pythia cross-section

- Perturbative hard scattering cross-section of point-like partons:

$$\sigma = \sum_{i,j,k} \int dx_1\, dx_2\, d\hat{t}\, \hat{\sigma}_{ij}^{k} \times f_i^1(x_1, Q^2) f_j^2(x_2, Q^2)$$

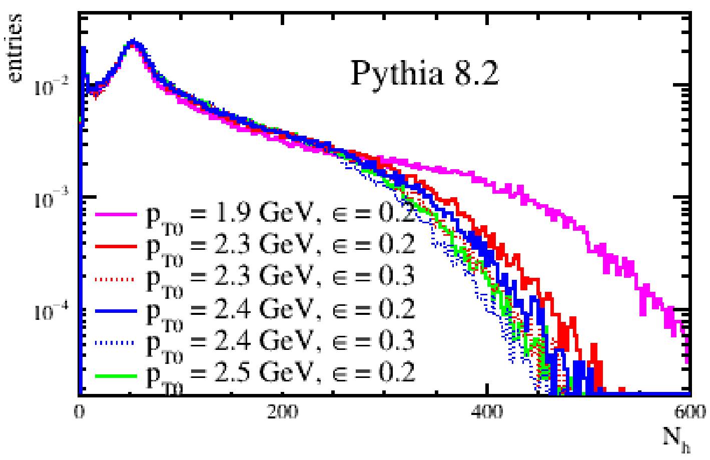
- $\hat{\sigma}_{ij}^{k}$ is the QCD hard-scattering cross-section for the *k*th process between parton flavour i and j, with a momentum transfer $\hat{t}$.

$$\sigma(p_{Tmin}) = \int_{p_{Tmin}}^{s/4} d\hat{p}_T^2 \frac{d\hat{\sigma}}{d\hat{p}_T^2}$$

- $\hat{\sigma}_{ij}^{k}$ is dominated by t-channel gluon exchange, is divergent at low-momentum transfers like $1/t^2 \sim 1/\hat{p}_T^4$.
- The main parameter introduced to regularize the divergency when $p_T \to 0$ in Pythia is p_{T0}:

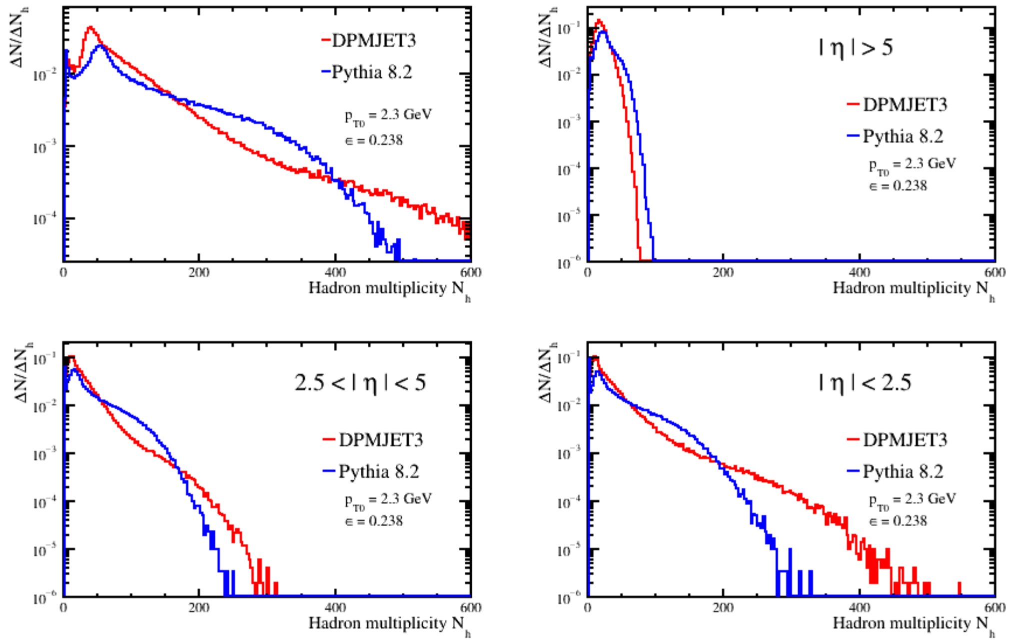
$$1/\hat{p}_T^4 \to 1/(\hat{p}_T^2 + \hat{p}_{T0}^2)^2$$

- „Tuninng" Pythia means „changing p_{T0}" (and a few further parameters) to describe better the data.
- Pythia 6 used lower values of p_{T0} and generated events with too high multiplicity



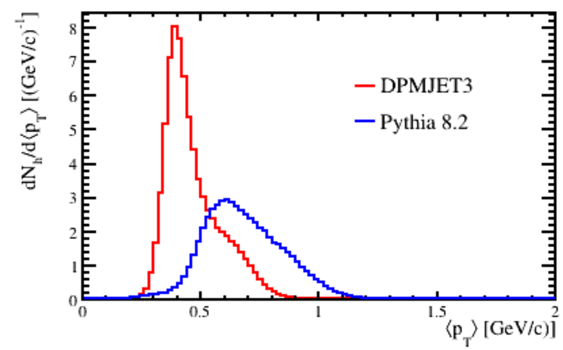
Comparison of models for fluence simulation

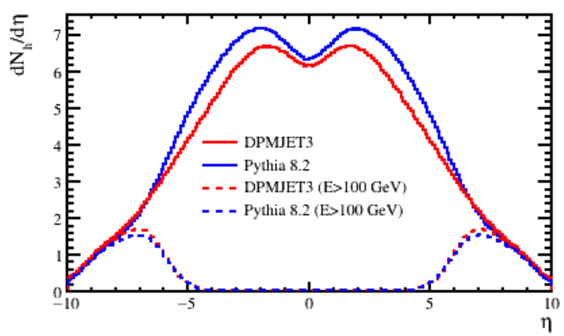
Both generators were revised and tuned to LHC $\sqrt{s}$ =13 TeV data.

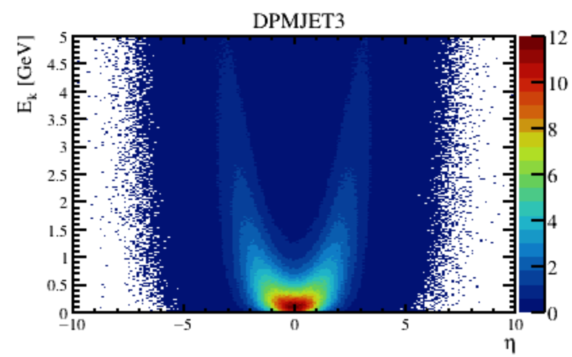


Differences:

- number of generated particles (long tail in multiplicity in DPMJET3).
- mean transverse momentum is lower in case of DPMJET3

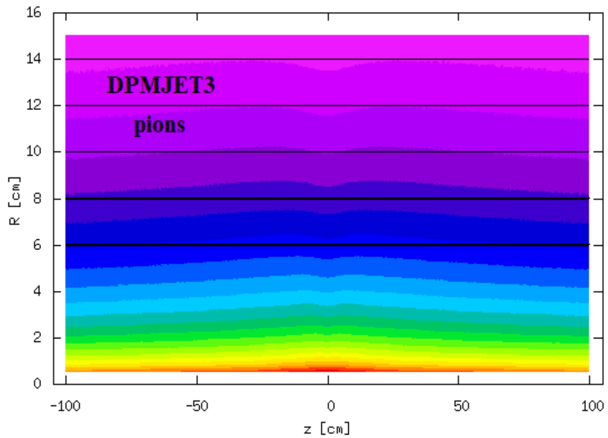


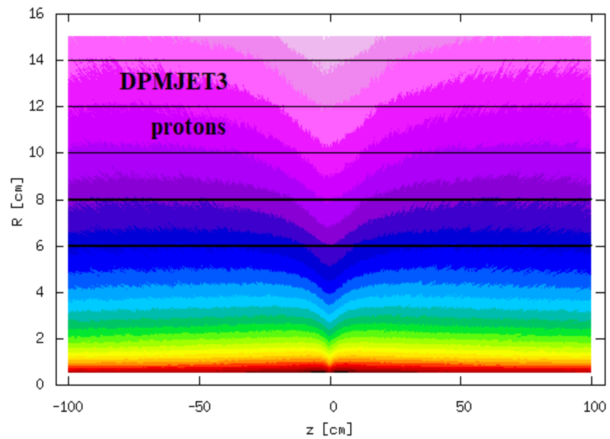


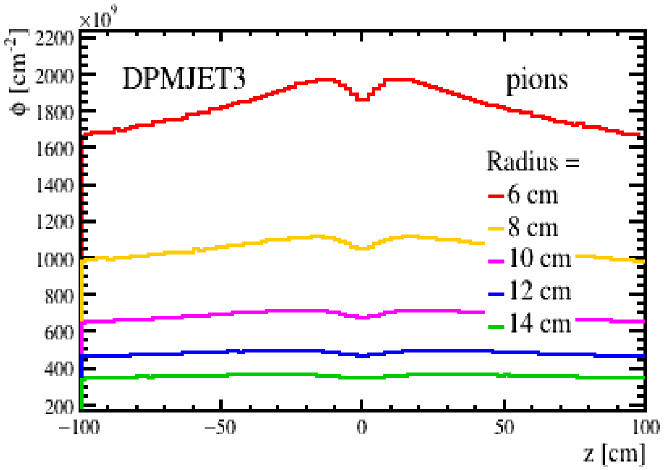


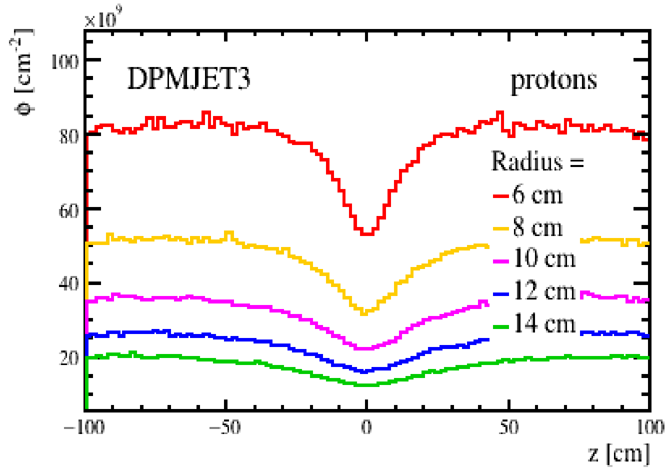
Particle fluence simulation

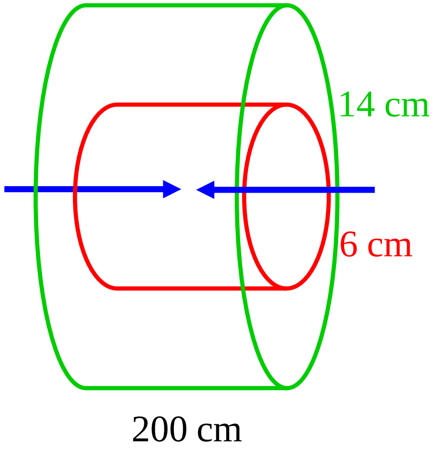
- Simulation of proton-proton collision with Fluka and two generators: DPMJET3 and Pythia 8.2.
- Silicon barrel layers with radius from 6 to 14 cm.
- Fluence ϕ calculated for $1fb^{-1}$ as track-length density.





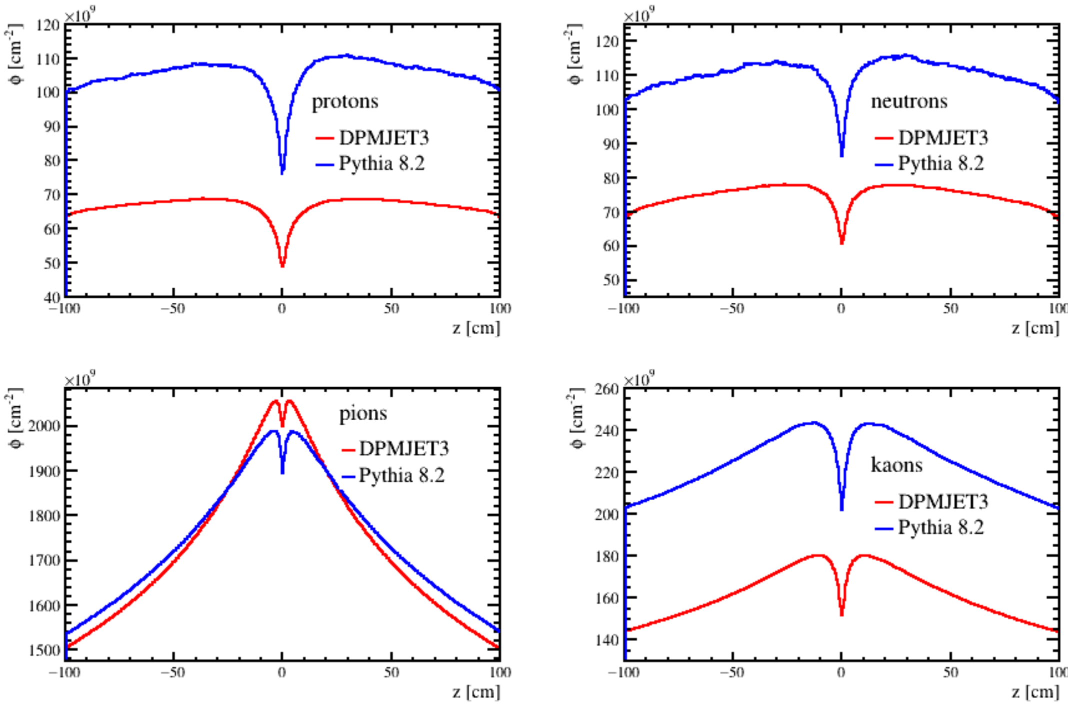




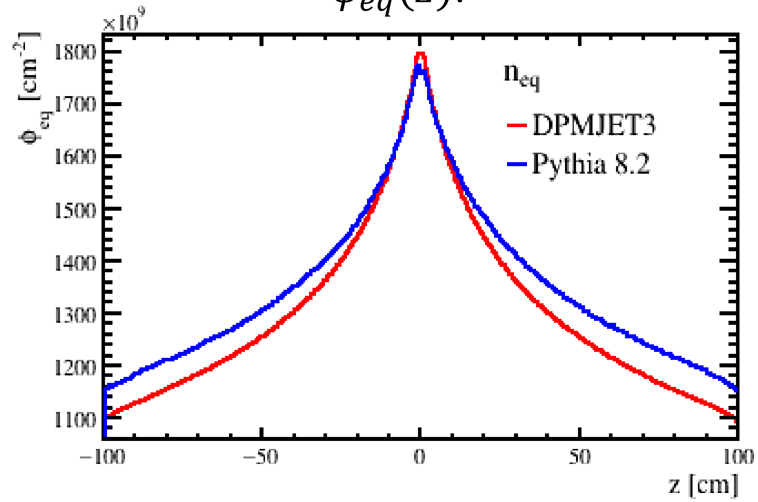


n_{eq} and particle fluence comparison

- Simulation of proton-proton collision with Fluka and two generators: DPMJET3 and Pythia 8.2.
- Particle fluence:



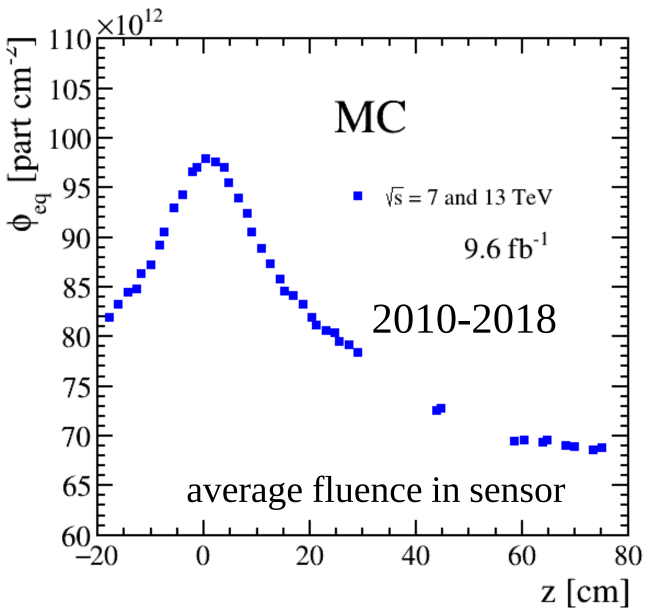
$\phi_{eq}(z)$:



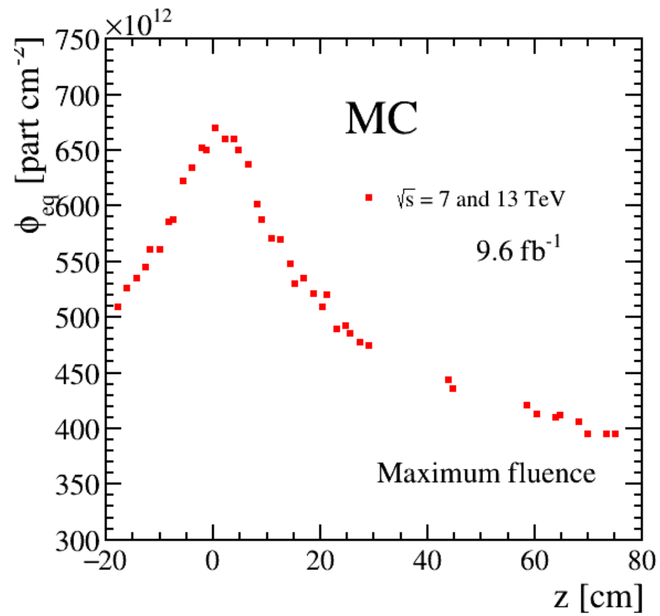
Main contribution to ϕ_{eq} comes from pions (80%).
The overall number of particles is lower in DPMJET3, but the number of pions is similar.
Therefore ϕ_{eq} is the same in places close to the Interaction Point.

- VELO LHCb was situated 8 mm from IP.
- The radiation field was strong and non-uniform

$\sqrt{s}$	7 TeV	13 TeV
Delivered Lumi $[fb^{-1}]$	3.46	6.15
$\sigma_{pp}\ [mb]$	71	78
$N_{pp}\ /1fb^{-1}$	71×10^{12}	78×10^{12}



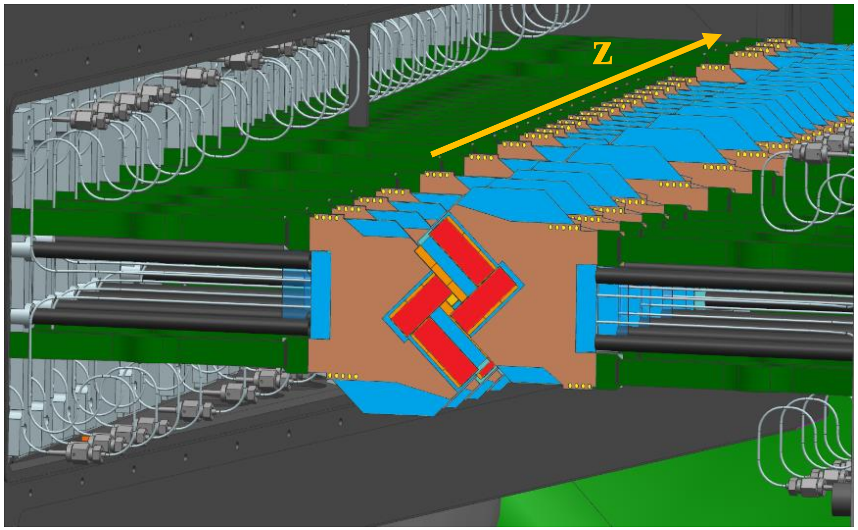
$$\phi_{avg} = 0.98 \times 10^{14}\ \mathrm{n_{eq}/cm^2}$$

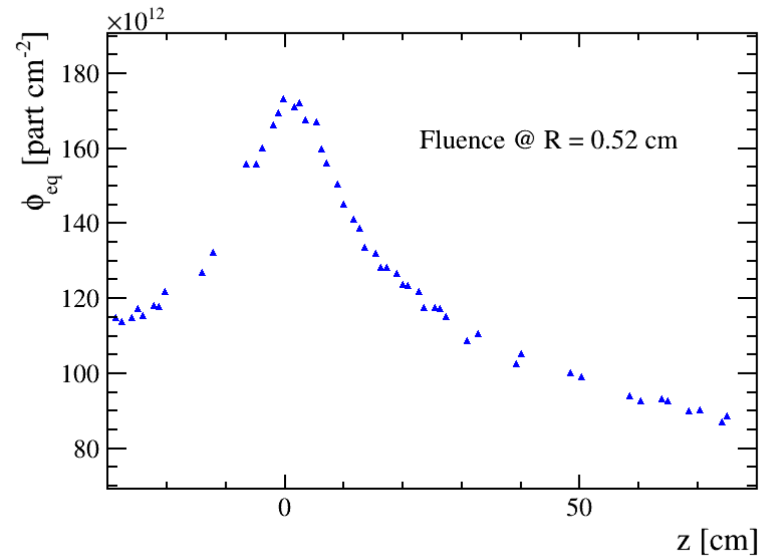


$$\boxed{\phi_{max} = 6.5 \times 10^{14}\ \mathrm{n_{eq}/cm^2}}$$

Fluence simulation for LHCb VELO in Run III

- Pixel VELO LHCb (Upgraded) will be situated 5 mm from IP.



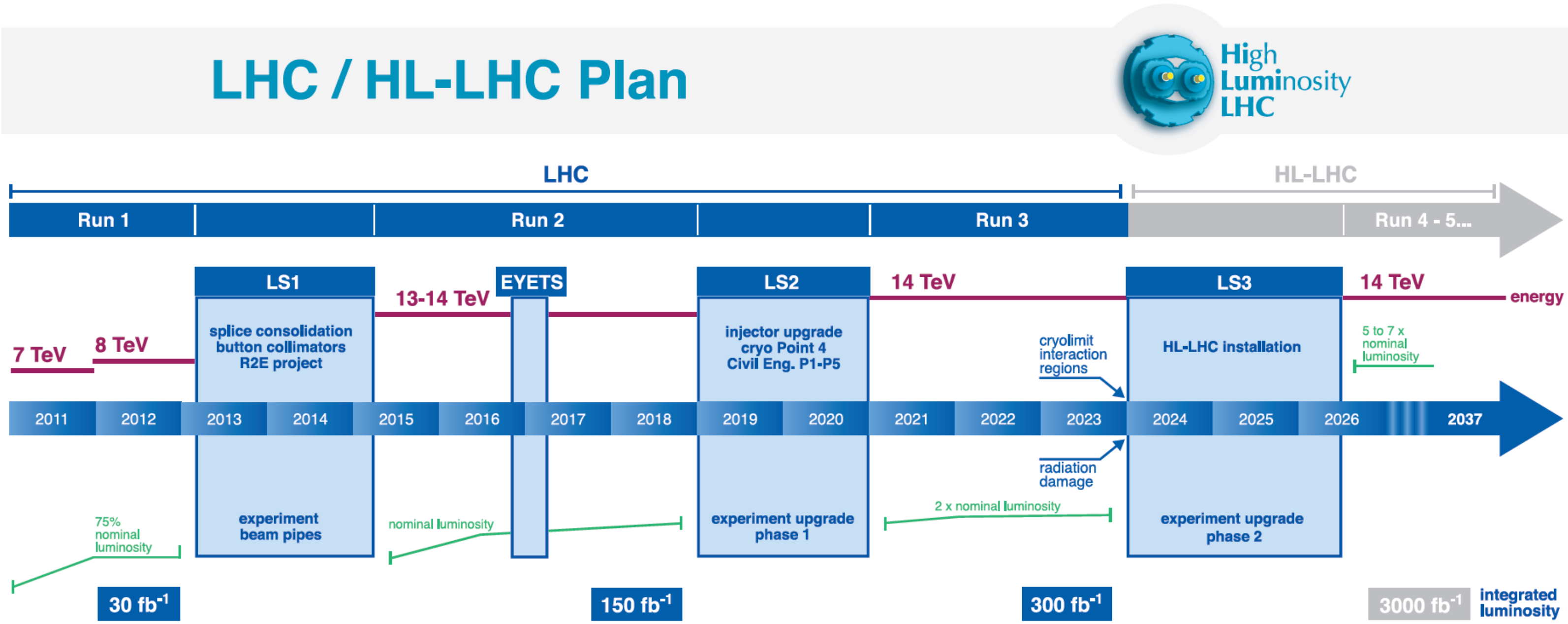


- The maximum fluence in the inner tip of one of the most irradiated sensor: $\phi_{max} = 1.72 \times 10^{14}$ n_{eq}/cm^2 for 1 fb^{-1}
- For the 50 fb^{-1} in Run III:

$$\boxed{\phi_{max,\,50fb} = 0.86 \times 10^{16}\ n_{eq}/cm^2}$$

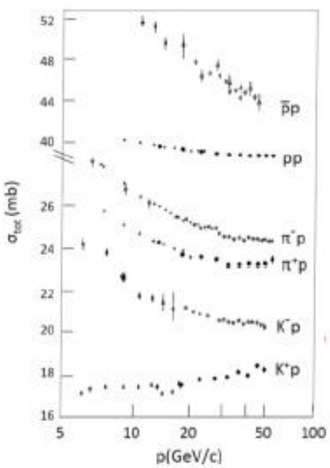
Conclusions

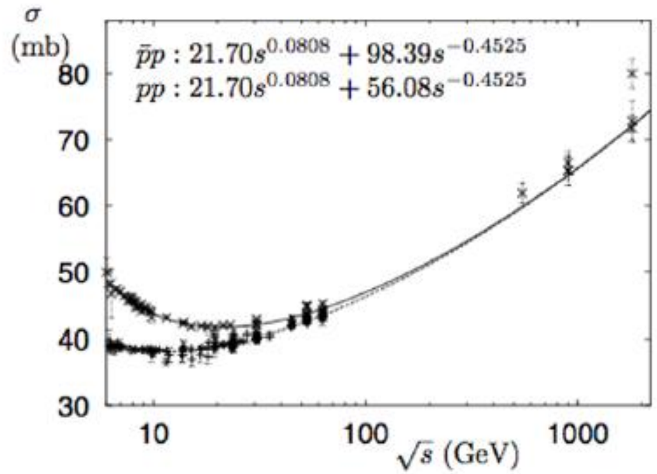
- The measurement of the inelastic proton-proton cross-section are crucial for the prediction of the radiation damage in silicon sensors for LHC Run III and IV.
- Physics model used in generators need to be tuned to the current experimental results.
- It seems that fluence predictions overestimate the real value.
- But if not – the inner part of VELO Pixel sensors close to the IP will reach the limit of optimal performance.



Thank you!

- Total proton-proton cross-section σ_{tot} before LHC
- 1973: Intersection Storage Rings (ISR)





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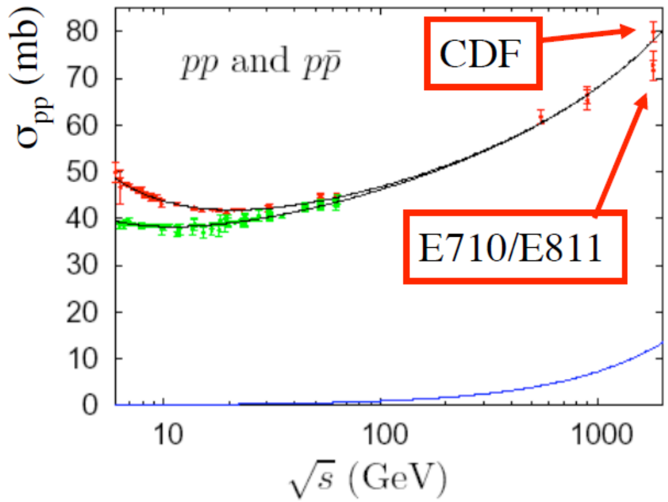

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