ELEMENTARY PARTICLE PHYSICS
Current Topics in Particle Physics
Laurea Magistrale in Fisica,
curriculum Fisica Nucleare e Subnucleare
Lecture 6

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November 4, 2018

Preliminaries

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Bibliography

- Bibliography
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  - F. Halzen and A. Martin, *Quarks and Leptons: An introductory course in Modern Particle Physics* , Wiley and Sons, USA(1984).

- Other basic bibliography:
  - A.Das and T.Ferbel, *Introduction to Nuclear Particle Physics* World Scientific,Singapore, 2^{nd} Edition(2009)(DF).
  - D. Griffiths, *Introduction to Elementary Particles* Wiley-VCH,Weinheim, 2^{nd} Edition(2008),(DG)
  - B.Povh *et al.*, *Particles and Nuclei* Springer Verlag, DE, 2^{nd} Edition(2004).(BP)
  - D.H. Perkins,*Introduction to High Energy Physics* Cambridge University Press, UK, 2^{nd} Edition(2000).
  - Y.Kirsh & Y. Ne'eman, *The Particle Hunters*

♠ Particle Detectors bibliography:

- William R. Leo *Techniques for Nuclear and Particle Physics Experiments*,
  Springer Verlag (1994)(LEO)
- C. Grupen, B. Shawartz *Particle Detectors*,
  Cambridge University Press (2008)(CS)
- *The Particle Detector Brief Book*,(BB)
  http://physics.web.cern.ch/Physics/ParticleDetector/Briefbook/

Specific bibliography is given in each lecture

Lecture Contents - 1 part

1. Introduction. Lep Legacy
2. Proton Structure
3. Hard interactions of quarks and gluons: Introduction to LHC Physics
4. Collider phenomenolgy
5. The machine LHC
6. Inelastic cros section pp
7. W and Z Physics at LHC
8. Top Physics: Inclusive and Differential cross section $t\bar{t}$ W, $t\bar{t}$ Z
9. Top Physics: quark top mass, single top production
10. Dark matter
    - Indirect searches
    - Direct searches

Specific Bibliography

♠ Bibliography of this Lecture

-

Contents

Soft proceses

- Measurements of *soft* processes (low p_T)

- soft-QCD affects high-$p_T$physics program at hadron colliders.
- Understand particle production in minimum-pias pp collisions.
- Test and improve phenominological models
- Tune parameters of model implementations in Montecarlo generators.
- Understand the underlying events
- Examples:
  - *Pile-up* $\approx 20 - 20$ pp interactions at same time, almost always soft-QCD processes
  - Multi-parton Interactions: An interesting parton-parton has many additional parton-parton interactions occurring in same proton-proton interaction, almost always soft-QCD processes.

Soft processes

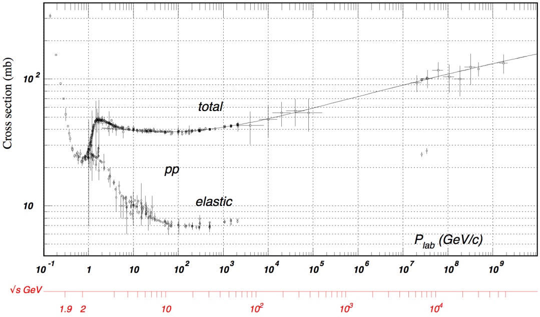


Figure :

⇑ LHC energies

$\sigma_{tot} \sim 100$ mbarn $\sim 10^{-25}\text{cm}^2$

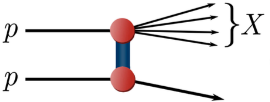
http://pdg.lbl.gov/2014/hadronic-xsections/rpp2014-pp_pbarp_plots.pdf

Total cross sections

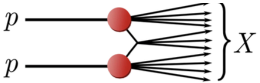
The total *pp* cross section is composed from different contributions:

$$\sigma_{\text{TOT}} = \underbrace{\sigma_{\text{EL}}}_{\text{elastic scattering}} + \underbrace{\sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}}_{\text{inelastic}}$$

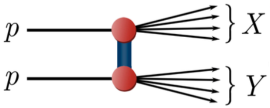
∼20% elastic 80% inelastic



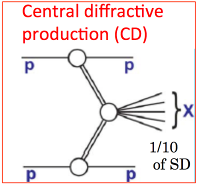
Single-Dissociation (SD)



Non-Diffractive (ND)
(color-exchange)



Double-Dissociation (DD)

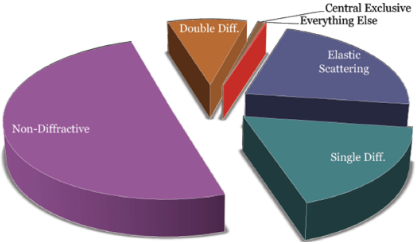


Total cross sections

The total pp cross section is composed from different contributions:

$$\sigma_{\text{TOT}} = \underbrace{\sigma_{\text{EL}}}_{\text{elastic scattering}} + \underbrace{\sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}}_{\text{inelastic}}$$

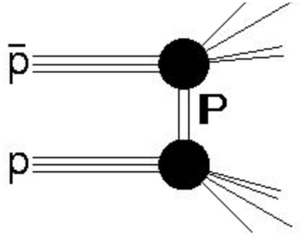
$\sim$20% elastic 80% inelastic



Theoretical Definition of Diffractive Physics

• Non-diffractive is dominant (70 -80%) ($\sim$ 70 mb)$\Longrightarrow$ interesting physics

• No unique definition of diffraction processes



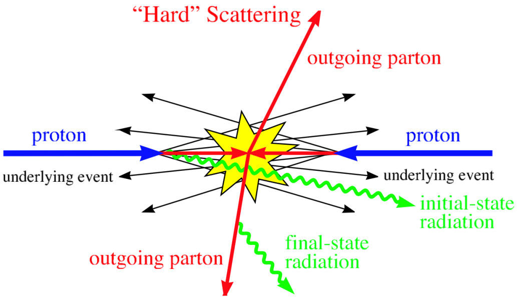
1. Interactions mediated by t-channel exchange of object (ladder of gluons)
2. Interactions where the beam particles emerge intact or dissociated into low mass states.

Diffractive physics not completely described by QCD.

Phenomenological approaches based on QCD + different models implemented in MC simulations $\Longrightarrow$ **importance to compare models to data.**

• First physics at the LHC was dominated by large cross section of inelastic hadronic interactions .

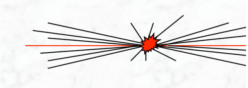
•Measurements necessary to constrain phenomenological models of soft-hadronic interactions and to predict properties at higher centre-of-mass energies(underlying event, pile-up of minimum bias at high luminosity.)



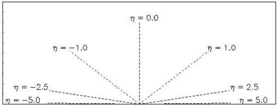
Inelastic low $p_T pp$ collission

Most interactions are due to interactions at large distance between incoming protons.
small momentum transfer, particles in the final state have large longitudinal, but small transverse momentum

$< p_T > \approx 600$ MeV. of charged particles in the final state



$$\frac{dN}{d\eta} \approx 7$$

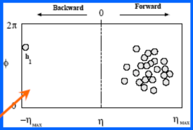


- about 7 charged particles per unit of pseudorapidity in the central region of the detector
- uniformly distributed in ϕ
- These events are usually referred to as minimum bias events.

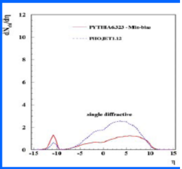
Components of soft *pp* collisions

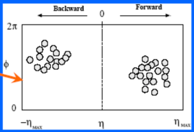
pp collisions at √s = 14TeV	PYTHIA6.323	PHOJET1.12
σ_{tot}	101.5 mb	119.1 mb
σ_{elas}	22.2 mb	34.5mb
$2^*\sigma_{SD}$	14.4mb	11.0mb
σ_{DD}	10.3mb	4.1mb
σ_{ND}	54.7mb	69.5mb

Minimum bias
Made up of
combination of
non-diffractive
and diffractive

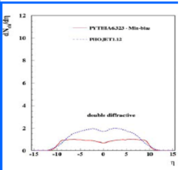


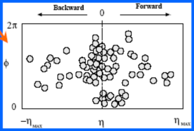
Single diffractive SD



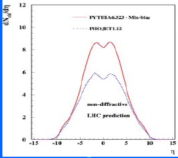


Double diffractive DD





Non-diffractive ND



Pomeron exchange is synonymous of colour singlet exchange(diffraction). **Many different topology to measure**

Importance of very low mass events.

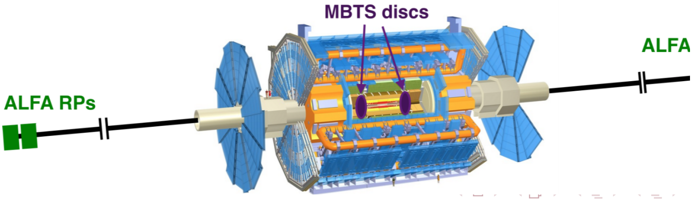
Example of measurements of σ_{pp}

MBTS(inelastic)

- Measure $\sigma_{\text{pp}}^{\text{inel}}$ in fiducial region.
- Extrapolate to total $\sigma_{\text{pp}}^{\text{inel}}$ using pp model.

ALFA(elastic)

- Measure elastic event rates in fiducial region
- Correct for acceptance and resolution, obtain $\frac{d\sigma_{\text{pp}}^{\text{el}}}{dt}$
- Fit to a model, integrate to get $\sigma_{\text{pp}}^{\text{el}}$
- Use optical theorem to infer σ_{pp} and $\sigma_{\text{pp}}^{\text{inel}}$



- Polystyrene scintillator discs placed on both sides of the interaction point.
- Each disk has 12 counters (8 inner, 4 outer).
- Acceptance $2.07 < |\eta| < 3.86$. Completely replaced between 7 TeV and 13 TeV measurements.
- $\sim 99\%$ efficient to charged particles.ATLAS calorimeter and inner detector also used.

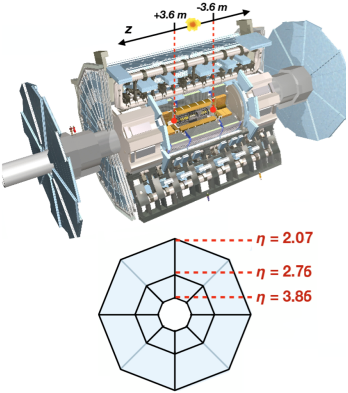
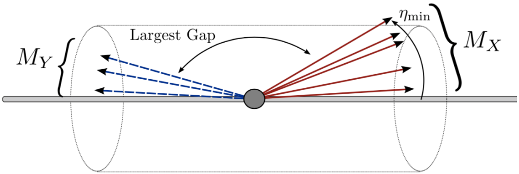
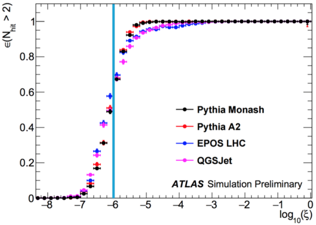


Figure : MBTS

MBTS: Detector Acceptance



- M_X, M_Y : invariant masses of the dissociated protons
- M_X largest of the two
- $\tilde{\xi} = M_X^2/s$ s closely correlated with the largest η of a dissociated system
- $|\eta| < 3.86 \rightarrow \tilde{\xi} > 1 \times 10^6$ $(M_X > 13$ GeV$)$



Measurements

Recorded events have at least 1 hit in the MBTS.

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

- N = Number of events with $n_{\mathrm{mbts}} \geq 2$
- N_{BG} background estimated with unpaired bunches
- ϵ_{trig} trigger efficiency measured in data wrt offline selection
- $\mathcal{L}$ integrated luminosity
- ϵ_{sel} offline selection efficiency for events $f_{\tilde{\xi}<10^{-6}}$, from MC
- $f_{\tilde{\xi}<10^{-6}}$ Migration from outside fiducial region, from MC.

The efficiency and migration corrections are correlated, they are combined in a single correction factor, $C_{MC} \sim 1$.The measured cross section in fiducial volume is extrapolated to total σ_{inel}, using $\sqrt{\mathrm{s}}$= 7TeV data to minimize the model dependence.

Cross section measurements: Inelastic

Inelastic cross section[1]

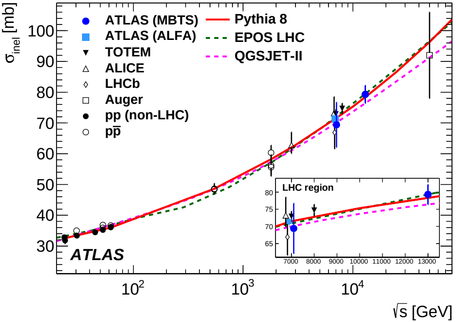


Figure : The inelastic proton-proton cross section versus $\sqrt{s}$.

$$\sigma_{\text{inel}}(13\text{ TeV}) = 78.1 \pm 0.6(exp) \pm 1.3(lum) \pm 2.6(extrap)nb$$

[1] Measurement of the Inelastic Proton-Proton Cross Section at $\sqrt{s}$=13 TeV with the ATLAS Detector at the LHC, PRL 117,182002 (2016), arXiv:1606.02625

Elastic cross section measurements: ALFA

- The ALFA detector (Absolute Luminosity For ATLAS) is designed to measure **small-angle proton scattering**.
- Two tracking stations are placed on each side of the central ATLAS detector at distances of 238 m and 241 m from the interaction point.
- The tracking detectors are housed in so-called Roman Pots (RPs) which can be moved close to the circulating proton beams.
- Combined with special beam optics this allows the detection of protons at scattering angles down to 10 μrad.

Elastic cross section measurements: ALFA

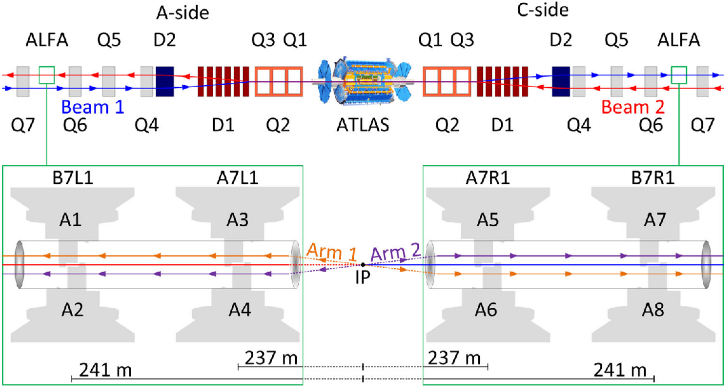


Figure : A sketch of the experimental set-up, not to scale, showing the positions of the ALFA Roman Pot stations in the outgoing LHC beams, and the quadrupole (Q1–Q6) and dipole (D1–D2) magnets situated between the interaction point and ALFA. The ALFA detectors are numbered A1–A8.

ALFA: Detector

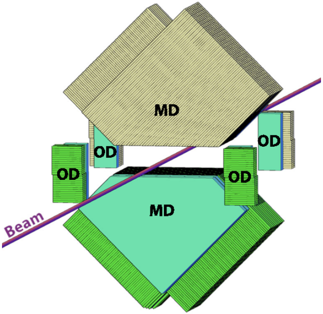


Figure : ALFA tracking detectors. The Overlap Detectors (OD) are attacched on either side of each MD (Main Detectors),The orientation of the scintillating fibres is indicated by dashed lines. The plain objects visible in front of the lower MD and ODs are the trigger counters.

- Small-angle proton scattering: $|\eta| > 8.5$, scattering angles down to 10 μrad.
- Main Detectors (MDs): arrays of scintillating fibers in criss-cross pattern at 45 deg.
- Overlap Detectors (ODs): allow for precise position calibration of MDs.
- ALFA mechanically moved in closer to the beam.
- One trigger plate in front or behind each MD.

ALFA: Measurement strategy

1. The data were recorded with special beam optics characterized by a β^* of 90 m.
2. Measure $\frac{d\sigma^{el_{pp}}}{dt}$ (el = elastic scatt.) $t = (p\theta^*)^2$
   - p: scattered proton momentum $\simeq$ beam momentum.
   - θ^*: scattering angle
3. All particles scattered at the same angle are focused at the same position at the detector, independent of their production vertex position. This focusing is only achieved in the vertical plane.
4. Calculate acceptance vs. t in simulation, used to unfold total $\frac{d\sigma^{el_{pp}}}{dt}$
5. Fit $\frac{d\sigma^{el_{pp}}}{dt}$ to extract σ_t^{tot}
6. Use optical theorem to extract $\sigma^{el_{pp}}$ and $\sigma^{inel_{pp}}$

Few remarks on optical theorem

Traditionally, the total cross section at hadron colliders has been measured via elastic scattering using the optical theorem. The optical theorem states:

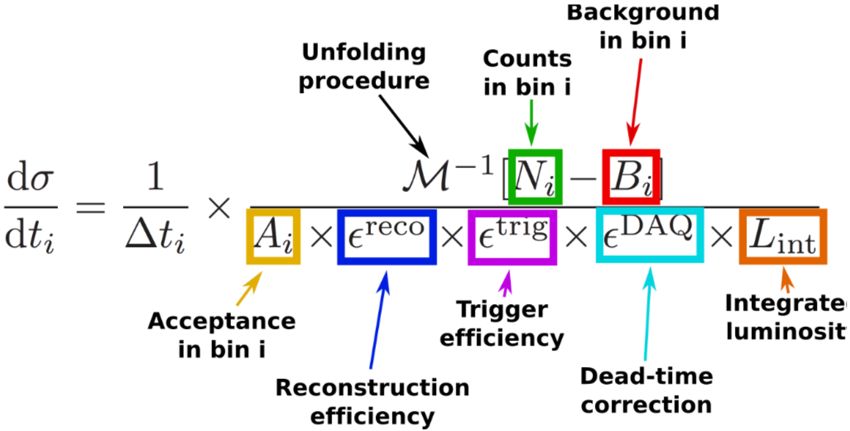
$$\sigma_{\text{tot}} \propto \text{Im}\Big[f_{\text{el}}(t \to 0)\Big]$$

$f_{\text{el}}(t \to 0)$ is the elastic-scattering amplitude extrapolated to the forward direction, i.e. at $|t| \to 0$, t being the four-momentum transfer. a measurement of elastic scattering in the very forward direction gives information on the total cross section.An independent measurement of the luminosity is required, [2] to normalize the cross section. From an extrapolation of the differential cross section to $|t| \to 0$ gives the total cross section :

$$\sigma_{\text{tot}} \;=\; \frac{16\pi(\hbar c)^2}{1 \;+\; \rho^2} \cdot \frac{\text{d}\sigma^{\text{el}_{\text{pp}}}}{\text{dt}}\Big|_{t=0}$$

t is four momentum transfer, ρ represents a small correction arising from the ratio of the real to imaginary part of the elastic-scattering amplitude in the forward direction and is taken from theory.

[2] *e.g.*Luminosity is determined from LHC beam parameters using van der Meer scans.


Background
in bin i
Unfolding
procedure
Counts
in bin i
$$\frac{d\sigma}{dt_i} = \frac{1}{\Delta t_i} \times \frac{\mathcal{M}^{-1}[N_i - B_i]}{A_i \times \epsilon^{reco} \times \epsilon^{trig} \times \epsilon^{DAQ} \times L_{int}}$$
Acceptance
in bin i
Reconstruction
efficiency
Trigger
efficiency
Dead-time
correction
Integrate
luminosit

ALFA: Acceptance & Unfolding

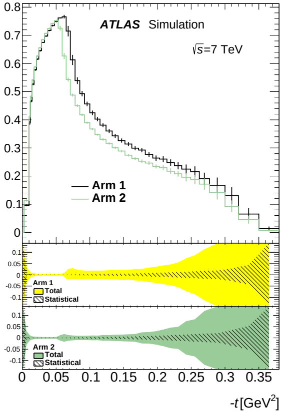


Figure : The acceptance as a function of the true value of t for each arm.

- Simulation used to calculate acceptance unfolding matrix $\mathcal{M}$ for each arm.
- An unfolding procedure *undoes* bin migration due to resolution effects.

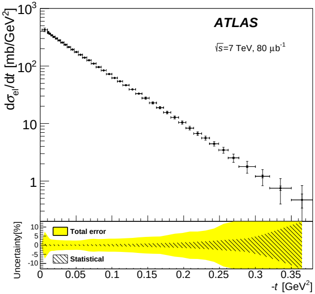


Figure : Unfolding .

ALFA: Fit to Theory

- **Fit theoretical prediction**
- Fit within range where deviations from exponential behavior are small.
- Fit for σ_{tot} and **nuclear slope parameter B**,. describing the exponential t-dependence of the nuclear amplitude at small t-values. In a simple geometrical model of elastic scattering, B is related to the size of the proton and thus its energy dependence is strongly correlated with that of σ_{tot}.

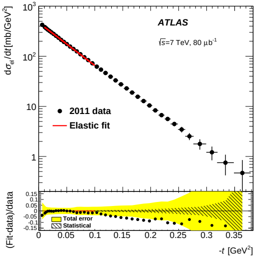


Figure : The fit of the theoretical prediction to the differential elastic cross section.The red line indicates the fit range; the fit result is extrapolated in the lower plot outside the fit range.

ALFA: Uncertainties

- The fit to theory counts 24 nuisance parameters:
  - Luminosity,
  - Beam energy,
  - Beam optics,
  - Reconstruction efficiency,
  - Acceptance & unfolding corrections,
  - ....
- The dominant uncertainty is on the integrated luminosity at 2.3%.

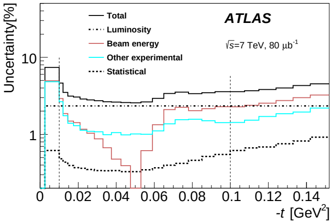


Figure : Uncertainties $\sqrt{s}$= 7TeV.

How these variation of uncertainties are reflected on cross section?

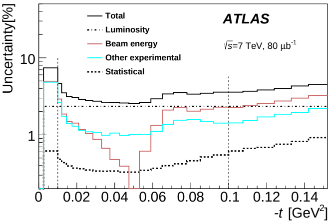


Figure : Uncertainties

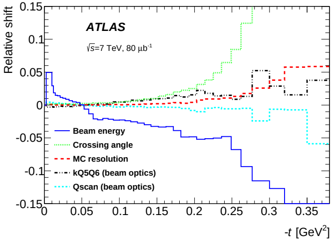
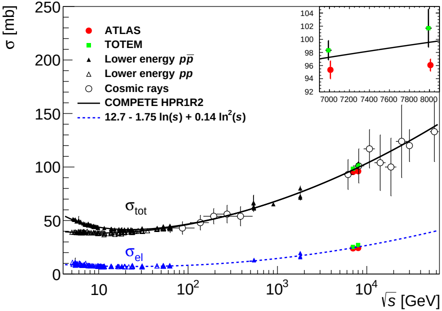


Figure : Cross $\sqrt{s}$= 7 TeV.

Same results at $\sqrt{s}$= 8 TeV

Cross section measurements:elastic

Elastic cross section[3]



$$\sigma_{TOT}(pp \to X)(7\ \text{TeV}) = 95.35 \pm 0.38(stat) \pm 1.25(exp) \pm 0.37(extr)\text{mb}$$
$$\sigma_{TOT}(pp \to X)(8\ \text{TeV}) = 96.07 \pm 0.18(stat) \pm 0.85(exp) \pm 0.31(extr)\text{mb}$$

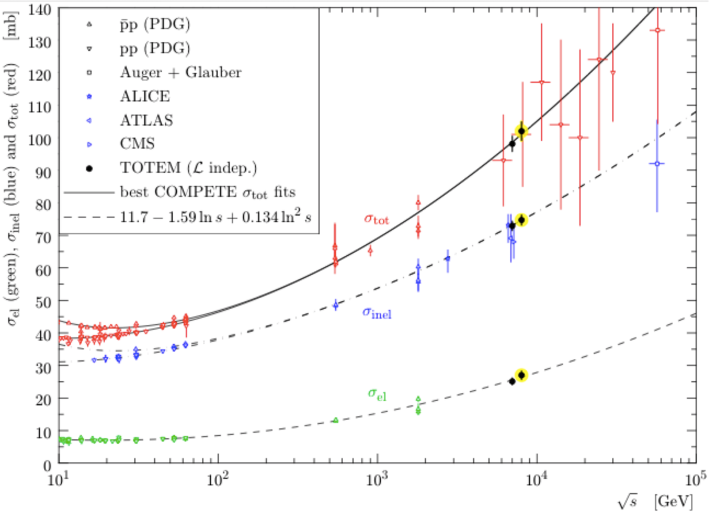
[3] Measurement of the total cross section from elastic scattering in pp collisions at $\sqrt{s}$=8 TeV with the ATLAS detector arXiv:1607.06605, Phys. Lett. B (2016) 158, arXiv:1607.06605

Measurements from an experimentalist point of view

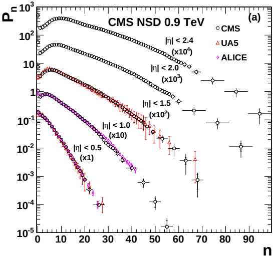
TOTAL cross section means measuring everything.. It is necessary measure any kind events in full rapidity range.

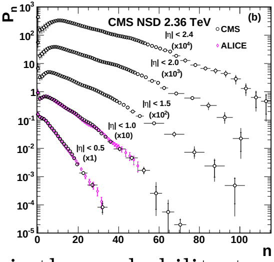
- Elastic two-particle final state, very low p_{T}, at very high rapidity
  $\Longrightarrow$ Very difficult needs dedicated detectors near the beam.
- Diffractive (Single, Double, Central diffractions), gaps everywhere,
  $\Longrightarrow$ Quite difficult , some events have very small mass,
- Everyrhing else : jets multiparticles;Higgs
  $\Longrightarrow$ Easy

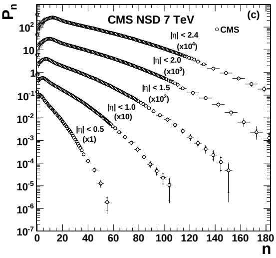
State-of-art



p̄p (PDG)
pp (PDG)
Auger + Glauber
ALICE
ATLAS
CMS
TOTEM ($\mathcal{L}$ indep.)
best COMPETE σ_{tot} fits
$11.7 - 1.59 \ln s + 0.134 \ln^2 s$
σ_{tot}
σ_{inel}
σ_{el}
σ_{el} (green), σ_{inel} (blue) and σ_{tot} (red) [mb]
$\sqrt{s}$ [GeV]



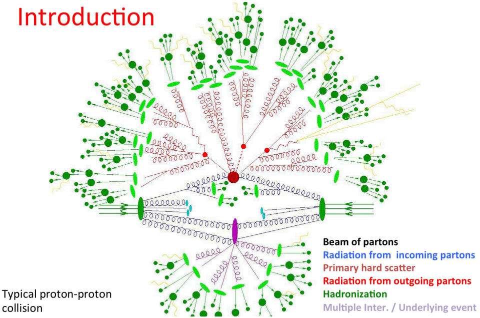




P_n, is the probability to produce n charged hadrons in an event

- The fully corrected multiplicity spectrum in $|\eta|$=0.5, 1.0, 1.5, 2.0 and 2.4 at $\sqrt{s}$= 0.9, 2.36, and 7.0 TeV, compared with other measurements.

CMS Collaboration *Charged particle multiplicities in pp interactions at $\sqrt{s}$= 0.9, 2.36, and 7 TeV* , CMS PAS QCD-10-004 , J. High Energy Phys. 01 (2011) 079.

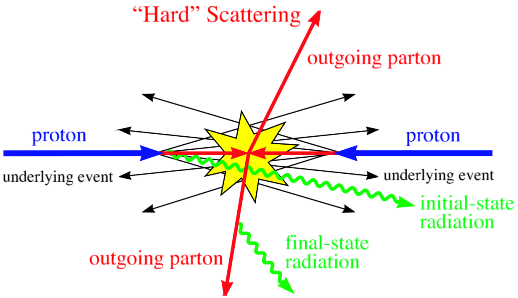


These effects (radiation, spectator interaction,(physics) detector noise,pile-up(detector) ..) are often formally suppressed for inclusive cross sections. In practice, their significance can be enhanced by:

- experimental acceptance
- cuts to suppress backgrounds
- their impact on detector calibration
- the need to measure more exclusive quantities

Contents

Underlying event



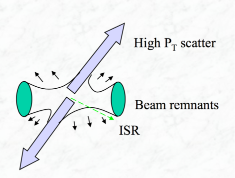
- Proton remnants(in many case coloured) interact.
- The underlying event consists of low p_{T} objects superimposed to the hard scattering products.

Underlying event

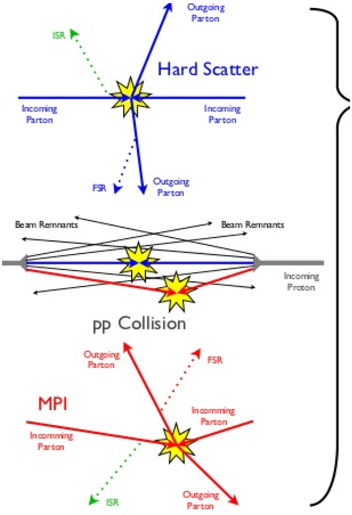
Underlying event : For a single proton-proton (pp) collision, the Under- lying Event (UE) is defined to be any hadronic activity not associated with the jets or leptons produced in the hard scattering process.

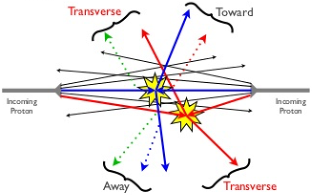
In practice, because color fields connect all the strongly interacting partons in the proton proton event, no unambiguous assignment of particles to the hard scattering partons or UE is possible.

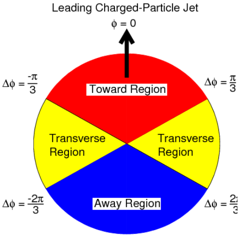
Instead, distributions that are sensitive to UE modeling are constructed from the tracks that are far from the direction of the products of the hard scatter. This direction is approximated by the direction of the highest- p_{T}(leading) object in the event.



Underlying event:regions



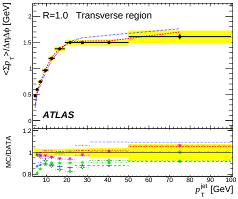




Underlying event

- Studying underlying event is crucial for understanding high p_{T} SM events at LHC
- Ingredient for many analysis. They affect: jet reconstructions and lepton isolation, jet tagging...
- Look in transverse and away region, where are little affected by the high p_{T} objects: N_{ch}, the number of tracks , $<p_{\mathrm{T}}>$ the average p_{T} of the tracks in the region $(\sum p_{\mathrm{T}}/\mathrm{N}_{ch})$.
- Reasonably described by models, after a lot of tuning.

- p_{T}



- number charged particles

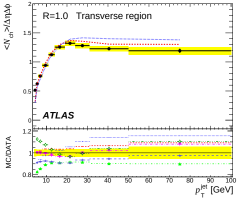
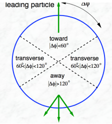
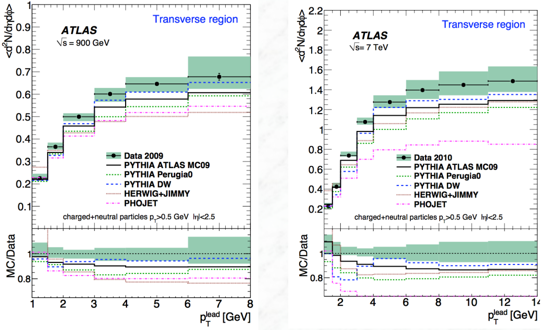


Figure : from ATLAS Coll. Phys. Rev. D 86 (2012) 072004

Underlying event





Number of particles (charged and neutrals) increase in the transverse region (plateau) by about a factor of two by going from 0.9 TeV to 7 TeV collisions

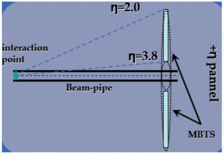
Contents

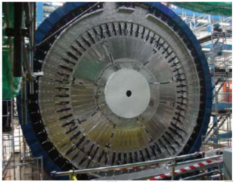
Minimum bias

- **Minimum bias** is an experimental definition,defined by experimental trigger selection and analysis, to select events with minimum possible requirements that ensure an inelastic collision occurred
- Minimum bias are NON head-on collisions with only low p_{T} object,there is a small momentum transfer
- Relation to physics:

$$\sigma_{\text{measured}} = f_{\text{SD}}\sigma_{\text{SD}} + f_{\text{DD}}\sigma_{\text{DD}} + f_{\text{nd}-\text{inelastiic}}\sigma_{\text{nd}_{\text{i}}\text{nelastic}}$$

where f_i are the efficiencies for different physics processes determined by the trigger





Minimum bias

- $< p_T > \approx$ 600 MeV. of charged particles in the final state
- $$\frac{\mathrm{d}N}{\mathrm{d}\eta} \approx 7$$
- The exact definition depends from detector and analysis
- Measurements of kinematics (multiplicity, p_T, η spectra..) of charged particles in minimum bias events using central tracking detector
- MonteCarlo parameters tuned on these distribution

Minimum bias

• The exact definition of Minimum Bias depends from detector and analysis: *e.g.* in ATLAS[4]

Most inclusive

- ≥ 2 good tracks
- $p_{\mathrm{T}} > 100$ MeV, $\eta \leq 2.5$

Lower diffraction contribution

- ≥ 6 good tracks
- $p_{\mathrm{T}} > 5\ 00$ MeV, $\eta \leq 2.5$

A recent paper: Charged-particle distributions in $\sqrt{\mathrm{s}}$=13 TeV pp interactions measured with the ATLAS detector at the LHC Physics Letters B (2016), Vol. 758, pp. 67-88 (and reference therein)

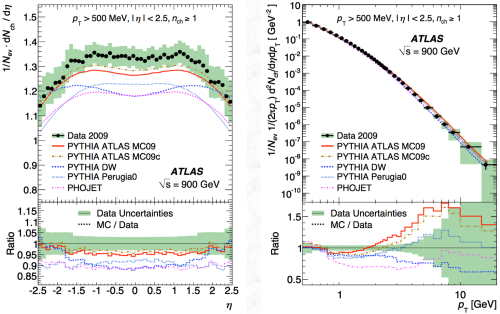
[4] for more than these two: arXiv:1012.5104v2

Charged particle density vs η p_T

N_{ch} number of primary charged particles normalized to the number of selected events N_{ev}

- ≥ 1 good tracks
- $p_T > 500$ MeV, $\eta \leq 2.5$

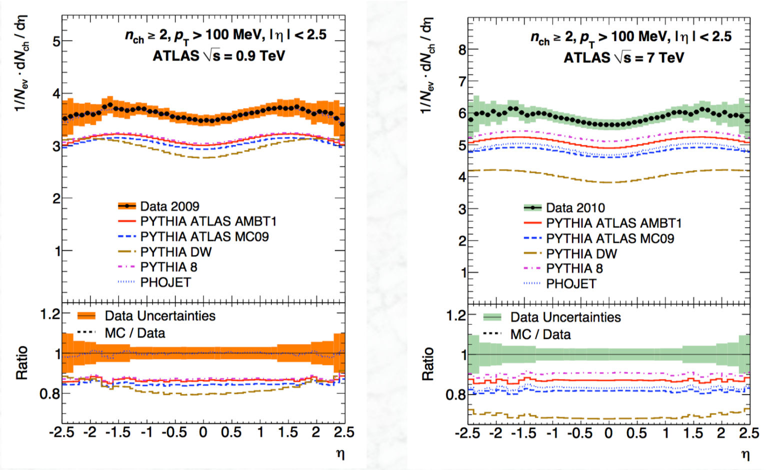
March 2010 900 GeV



Various Monte Carlo failed to describe the data

Charged particle density vs η p_T

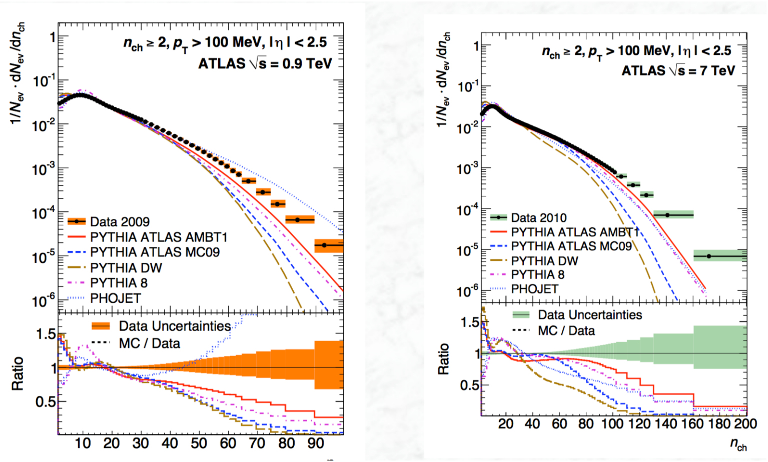
900 GeV and 7 TeV data



Various Monte Carlo failed to describe the data at both collider energies

Multiplcity distributions of charged particles

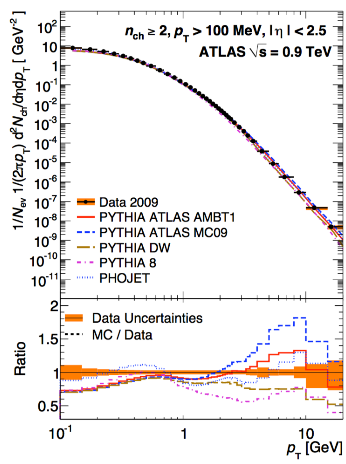
900 GeV and 7 TeV data

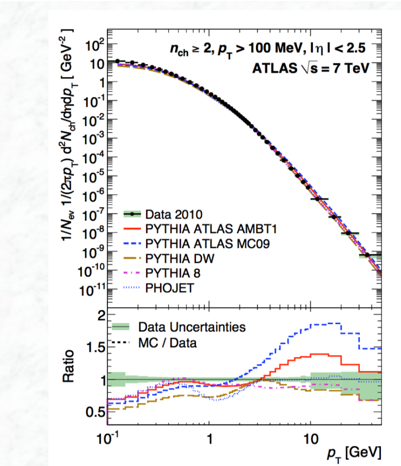


Various Monte Carlo failed to describe high multeplicity events

Multiplcity distributions of charged particles

900 GeV and 7 TeV data





Monte Carlo models failed to describe p_T spectrum

Multiplcity distributions of charged particles

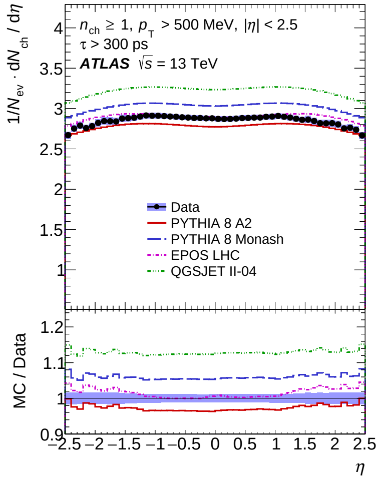


Figure : Primary-charged-particle multiplicities vs η

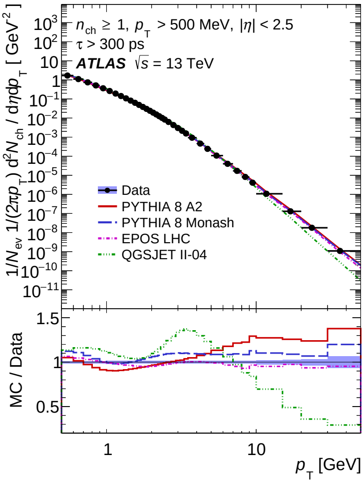


Figure : Primary-charged-particle multiplicities vs p_T

Multiplcity distributions of charged particles

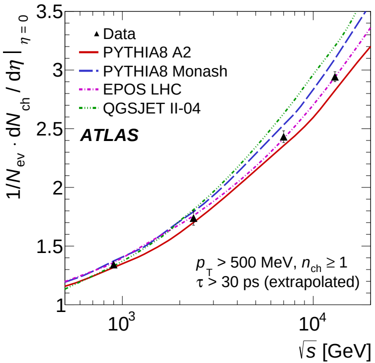


Figure : The average primary-charged-particle multiplicity in pp interactions per unit of pseudorapidity, η, for $|\eta| < 0.2$ as a function of the centre-of-mass energy

- Rise of particle density in data stronger than extrapolations from lower energies and model.
- Careful tuning effort. Marginal impact on high p_T physics.
- 13 TeV data : Monte Carlo models and statistics improved the description, but not finished..

Hadron Collider Dictionary

- The **hard scatter** is an initial scattering at high q^2 between partons (gluons, quarks, antiquarks).
- The **underlying event**is the interactions of what is left of the protons after parton scattering.
- **Initial and final state radiation**(ISR and FSR) are high energy gluon emissions from scattering partons.
- **Fragmentation** is the process of producing final state particles from parton produced in the hard scattering.

Hadron Collider Dictionary

- A hadronic **jet** is a collimated con of particles associated with a final state parton, produced in the hard scattering.
- **Transverse** quantities are measured transverse beam direction.
- An event with high **high transverse momentum**(p_{T}) jets or isolated leptons, is a signature for production of high mass particles (**W,Z,H,t**)
- An event with **missing transverse energy** (E_T) is a signature for neutrinos, or other particles.
- A **minimum bias** event has no missing energy, and no high mass final states particles (**W,Z,H,b,t**). At LHC are treated as background.