Physics Program

of the experiments at

Large Hadron Collider

Lecture 3

First physics measurements: soft QCD

Latest news!!!

As of today we have reached $1.35\ 10^{32}$ cm^{-2} sec^{-1}

- With 312 bunches, ~$1.1\ 10^{11}$ protons/bunch, β^*=3.5m
- This year's target is ~380 bunches ☞ $1.6\ 10^{32}$

Next year we could expect

- Up to a factor 3.5/2 from squeeze to β^*=2 m ☞ $2.8\ 10^{32}$
- A factor ~3 from 50 nsec from more bunches ☞ $8.4\ 10^{32}$
  - Assumes 50 nsec bunch separations
- Up to a factor $(1.3/1.1)^2$ from more bunch charge ☞ $1.2\ 10^{33}$
  - ~$1.3\ 10^{11}$ protons per bunch have been seen already
- Even stronger squeeze (β^*=1.5 m)? ☞ $1.6\ 10^{33}$
- Maybe even smaller emittances ? ☞ ?
- 4+4 TeV is being strongly pushed by the management
- 4.5+4.5 TeV seems too risky at the moment
  - Different cross sections, but effect on luminosity should be negligible

⇒ the message is: get ready for ~10^{33}

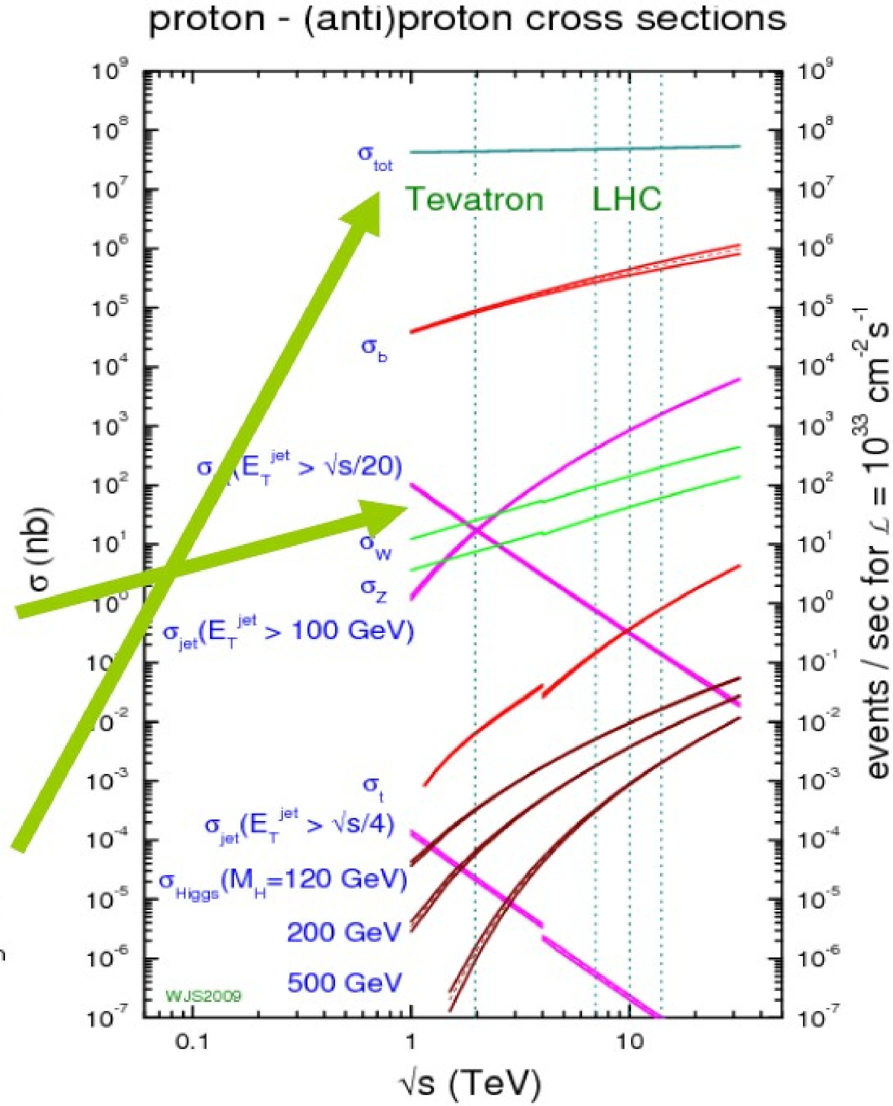
QCD

Scattering processes at high energy hadron colliders can be classified as either HARD or SOFT

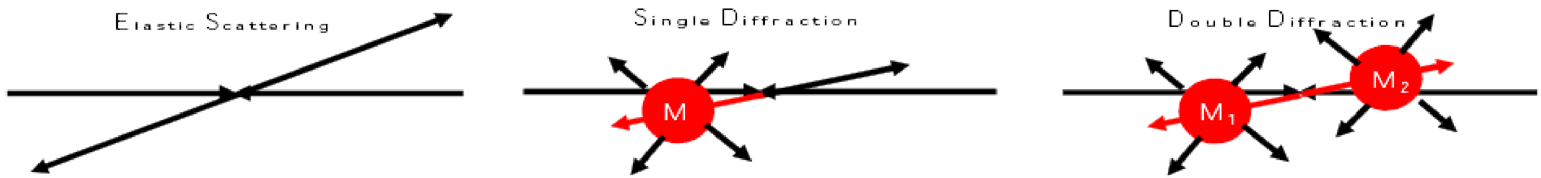
Quantum Chromodynamics (QCD) is the underlying theory for all such processes, but the approach (and the level of understanding) is very different for the two cases

For HARD processes, e.g. W or high-E_T jet production, the rates and event properties can be predicted with some precision using perturbation theory

For SOFT processes, e.g. the total cross section or diffractive processes, the rates and properties are dominated by non-perturbative QCD effects, which are much less well understood

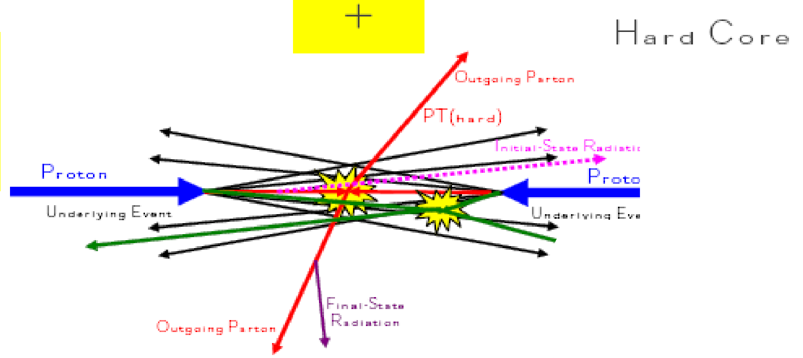


Total cross-section



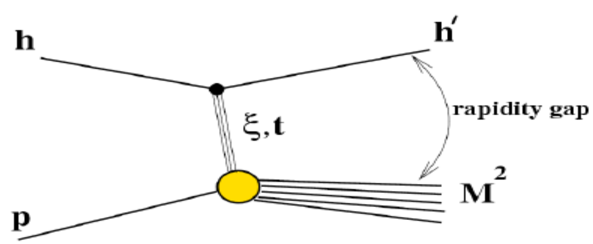
+

Rick Field's
Pictorial
Representation



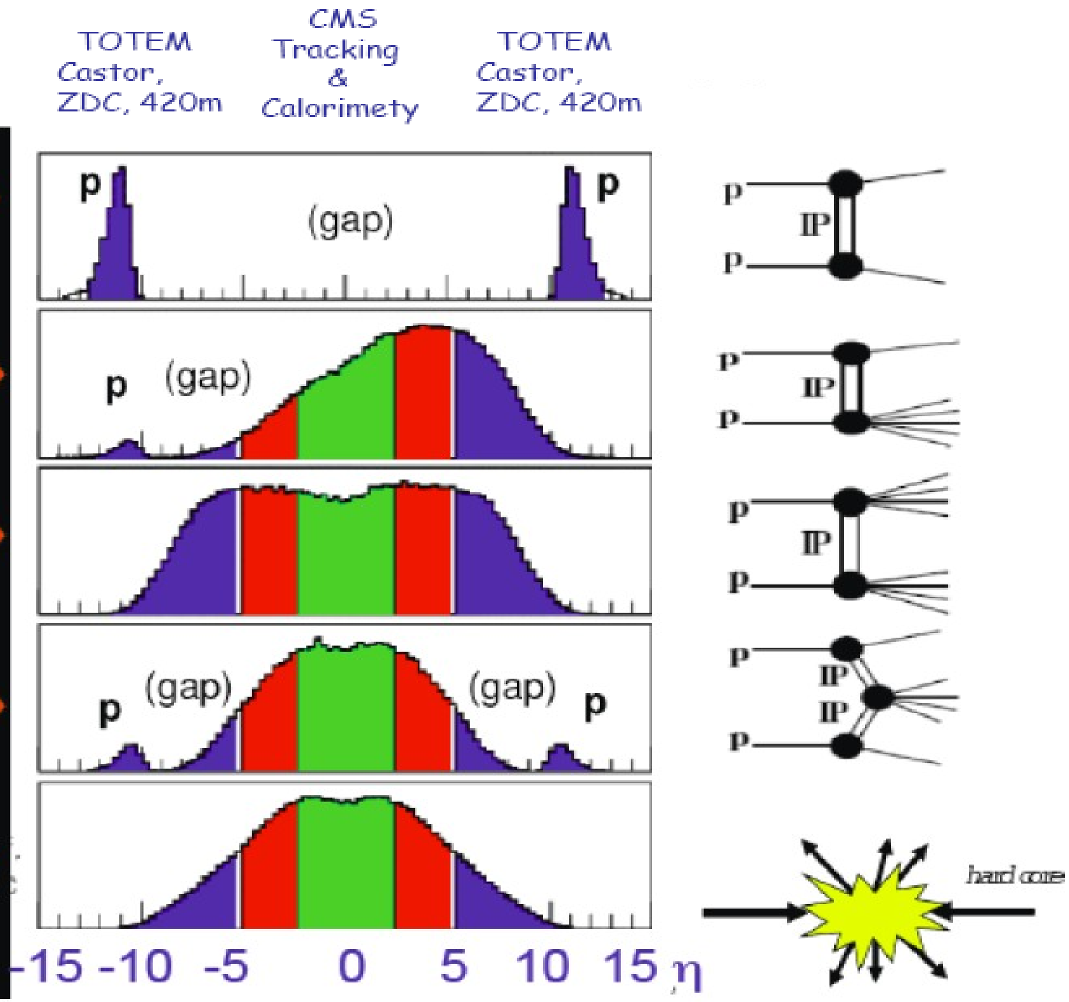
Elastic and diffractive processes
⇨ leading hadron emitted at small angle

The exchange ("pomeron") is colorless
⇨ large rapidity gap



Characteristic in pseudorapidity

- *Elastic (25% of σ_{tot})*
- *Single diffractive (10% of σ_{tot})*
- *Double diffractive (~1% if σ_{tot})*
- *Central diffractive DPE (~1% if σ_{tot})*
- *Inelastic (non diffractive) (60% of σ_{tot})*



Why “soft QCD” is interesting?

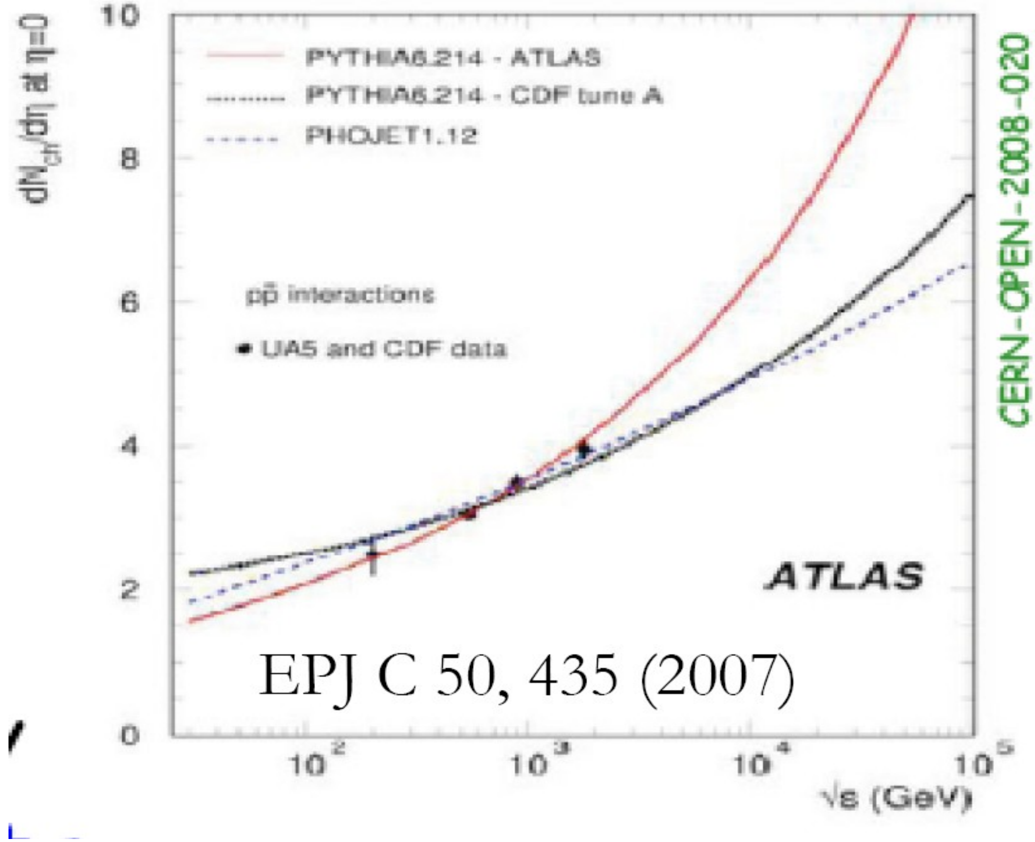
- It is non-perturbative physics and has an interesting phenomenology
  - Beam remnants
  - Multiple Parton Interactions
  - Color recombination

  => All adding up to the colorless objects

- It is an essential ingredient for precision high pT physics
  - Causes an experimental bias: energy scale, isolation, efficiencies, fakes

Minimum bias at LHC

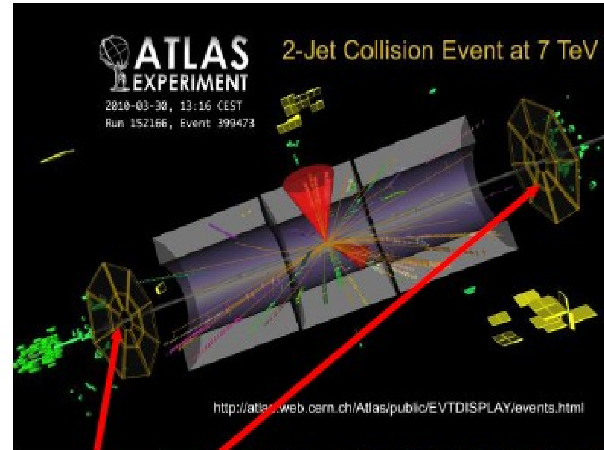
- Pre-LHC era



EPJ C 50, 435 (2007)

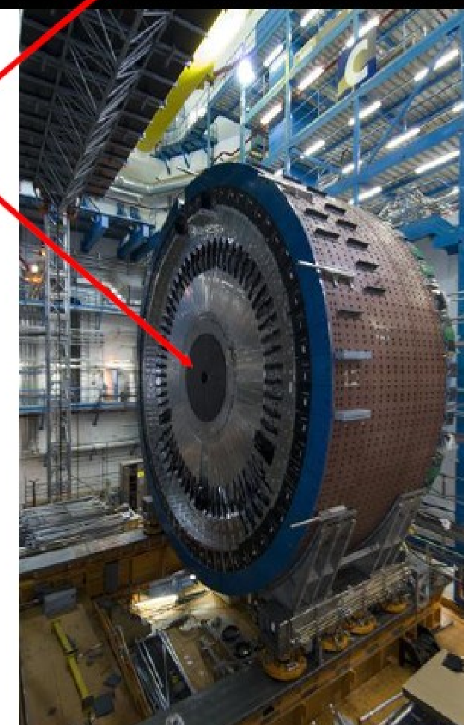
ATLAS

- Minimum bias events:
  - Require 1 MBTS counter to fire on either side
  - Require reconstructed primary vertex
  - At least N good quality tracks



Minimum Bias Trigger Scintillators (MBTS)

$2.09 < \eta < 3.84$



Minimum bias measurements

- charged particle reconstruction
    - various possibilities with different systematics
  - → hit counting
    - estimate charged particle density via number of hits (clusters) in pixel detector layer(s)
      - → pros: access to low p_T particles
      - → cons: determine secondary contribution from MC, no momentum measurement
  - → "tracklets"
    - correlate hits in two (three) detector layers to form track candidates
      - → pros: access to lower p_T particles
      - → cons: no momentum measurement
  - → tracks
    - reconstruct complete tracks
      - → pros: low fake rate, momentum measurement
      - → cons: challenge to access low p_T region
- vertexing: important tool to remove fakes and background
  - → and identify if several interactions per bunch crossing

ALICE publication

- First published results from LHC experiments

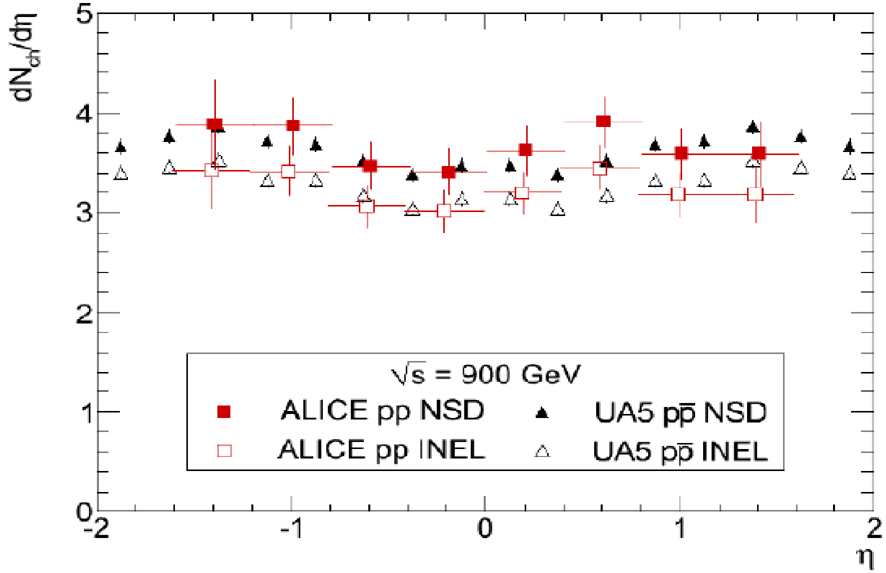
  arXiv:0911.5430v1 (28Nov 2009), EPJC 65 (2010) 111

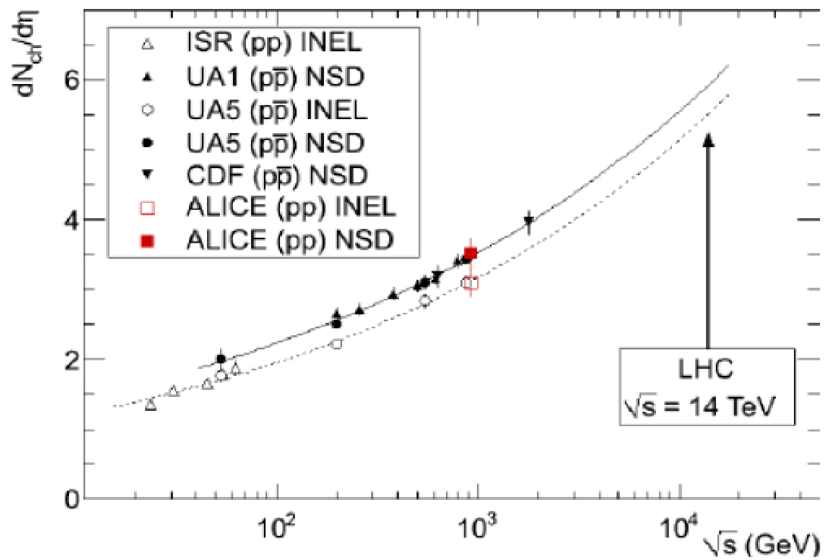
- Based on 284 recorded events, published pseudorapidity spectra of charge primary particles for inelastic interactions (INEL) and non-single diffractive (NSD) interactions.
- Results at 900 GeV and 2.36 TeV follow trend indicated by lower energy measurements: ISR, UA1, UA5, RHIC, Tevatron

ALICE publication

$dN_{ch}/d\eta$ @ 900 GeV

$|\eta| < 0.5$





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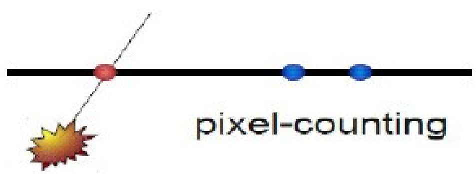
Details: no magnetic field, charged particles from counting number of tracklets, efficiencies from MC, confirms consistency with ppbar results (predicted diff 0.1-0.2%). Only statistical errors shown, systematic of 7.1 %(NSD), 7.2% (INEL), dominated by fraction and kinematics of diffractive processes

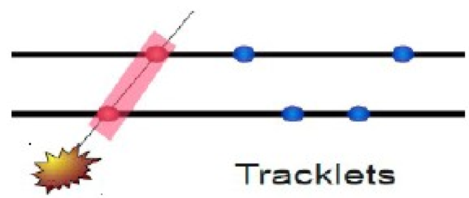
CMS publication

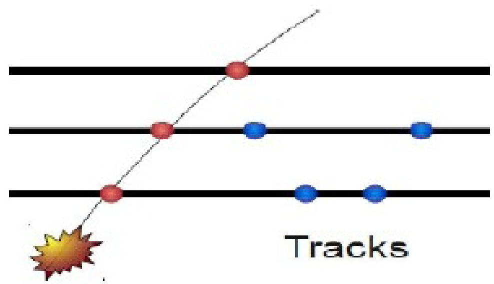
- First published ever results at 2.36 TeV
- Results at 900 GeV and 2.36 TeV follow trend indicated by lower energy measurements: ISR, UA1, UA5, RHIC, Tevatron

Three analysis techniques

- Event selection is aimed at selecting NonSingleDiffractive events with high efficiency (rejecting large fraction of SingleDiffractive)
- Efficiency: NSD ~86%, SD ~19%.







Pixel Counting

Clusters/layer

- Three dN/dη measurements

Largest acceptance

- Most Sensitive to backgrounds

Sensitivity: 30MeV/c

Tracklets

2 of 3 pixel layers

- Three dN/dη measurements
- Less sensitive to backgrounds

Sensitivity: 50MeV/c

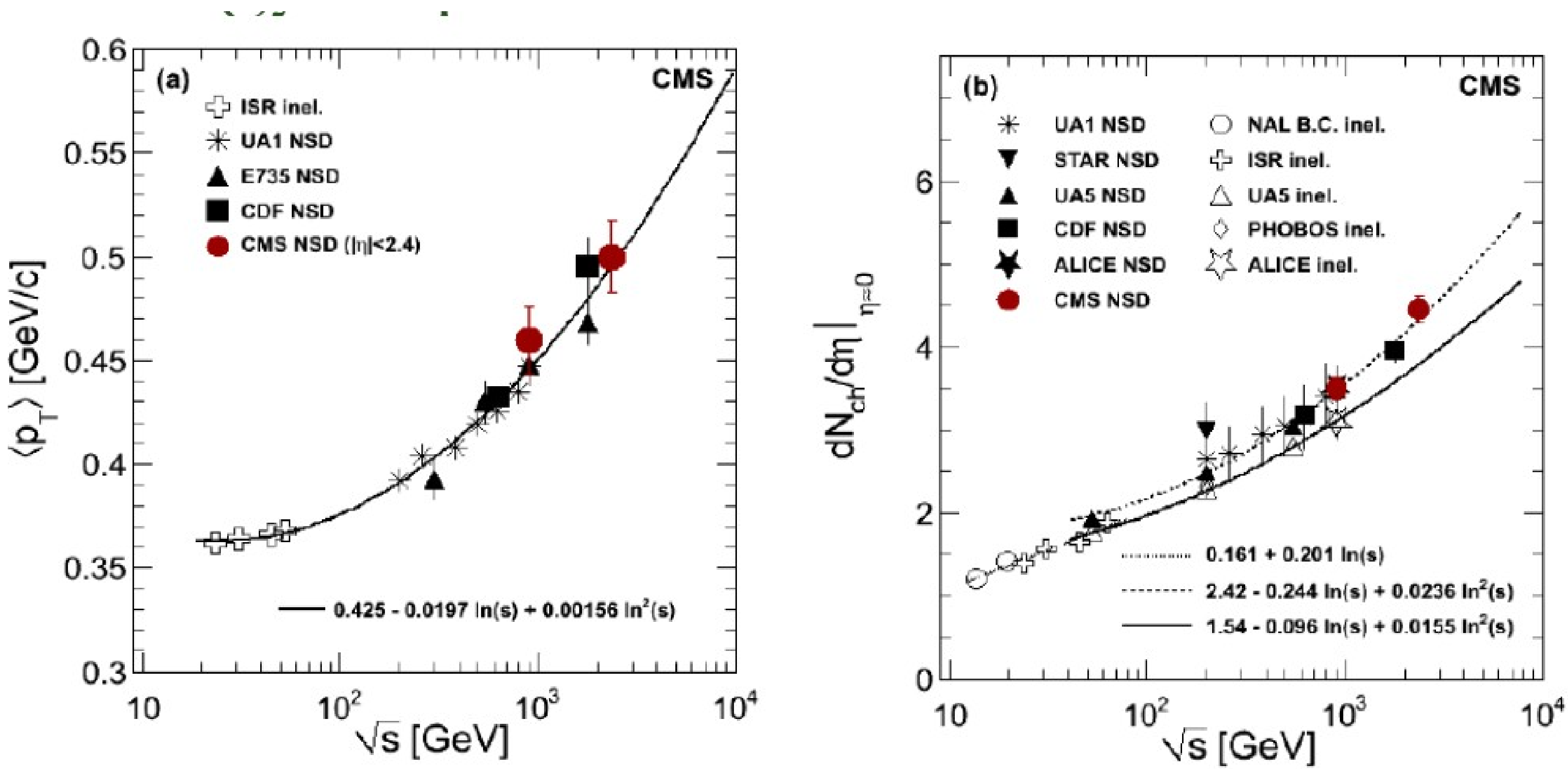
Tracks

dN/dη and dN/dpT

- Most robust against backgrounds

Sensitivity: 100MeV/c

Energy dependence



$dN/d\eta(@2.36\text{TeV}) / dN/d\eta(@0.9\text{TeV})$

$(28.4 \pm 1.4 \pm 2.6)\%$

Ratio @900GeV/@2.36TeV significantly larger than prediction from PYTHIA&PHOJET tunes used in the analysis 18.4% & 14.5%

ATLAS publication (March 2010) CERN-PH-EP-2010-004

- Measure charged particle multiplicity distributions from inelastic events
  - **Require $N_{ch} \geq 1$ ($|\eta| < 2.5$ & $p_T > 500$ MeV)**
  - **No removal of Single Diffractive component**
- Results only at 900 GeV, at 2.36 data taken without fully operational tracking (no stable beam conditions)
- Corrected reconstructed-track distributions back to hadron level for all detector effects.
  - **Measure trigger and vertex corrections from data.**
  - **Impressive work on the experimental technique for data-driven systematics (good investment for future)**

Analysis strategy

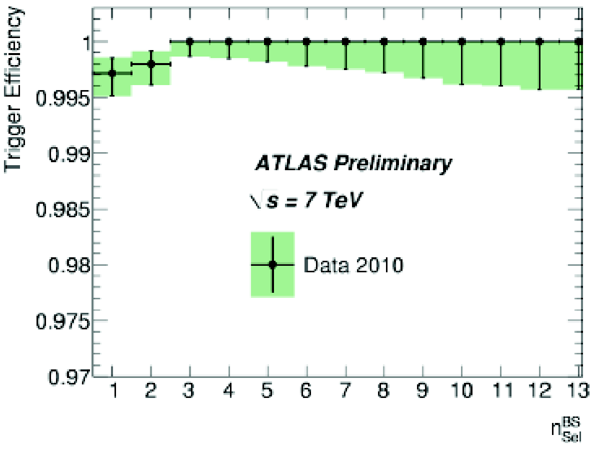
- Use charged particle multiplicity distributions to probe soft QCD:

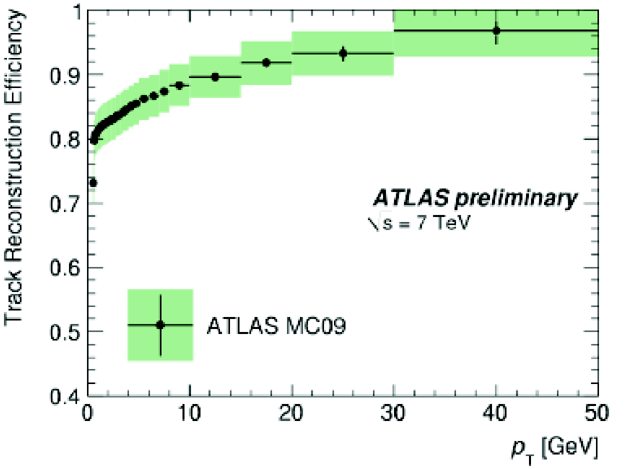
$$\frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}, \quad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{1}{2\pi p_{\mathrm{T}}} \cdot \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}, \quad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}n_{\mathrm{ch}}} \quad \text{and} \quad \langle p_{\mathrm{T}} \rangle \text{ v.s. } n_{\mathrm{ch}}$$

- Analysis components:
  - Trigger and event selection
  - Track reconstruction efficiency
  - Unfolding from track to hadron level (using MC)
  - Compare to Monte Carlo phenomenological models

Efficiency correction from Monte Carlo

- Trigger and vertex efficiencies derived from data
  - Trigger > 99.5% efficient (obtained from a control trigger)
- Tracking efficiency from Monte Carlo
  - various data ↔ Monte Carlo to set systematics
  - dominant systematics comes from knowledge of the material
- Unfold to the hadron level
  - complicated procedure





Track-to-particle correction

Correction for dN_{ch}/dη, dN_{ch}/dp_T distributions

- Apply efficiencies and other corrections as weights during analysis

Event-weight

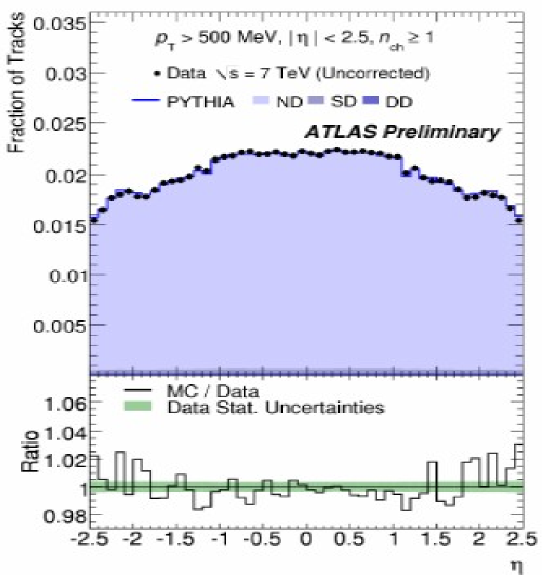
- Trigger- and vertex efficiency

$$w_{\text{ev}}(N_{\text{Sel}}^{\text{BS}}) = \frac{1}{\epsilon_{\text{trig}}(N_{\text{Sel}}^{\text{BS}})} \cdot \frac{1}{\epsilon_{\text{vtx}}(N_{\text{Sel}}^{\text{BS}})}$$

Track-weight

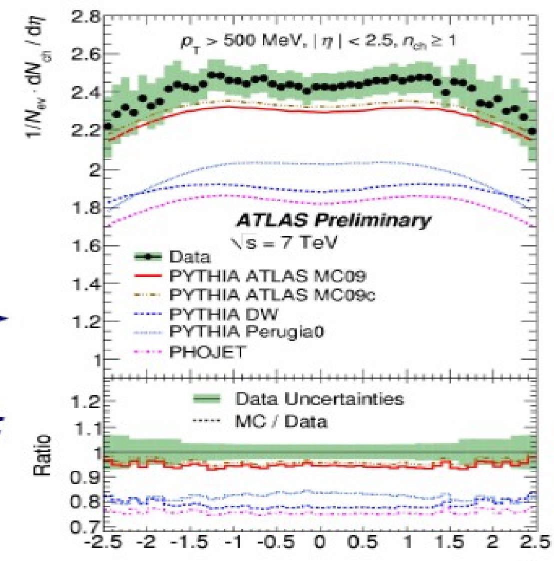
- Track efficiency
- Secondaries
- Out-of-phasespace

$$w_{\text{trk}}(p_{\text{T}}, \eta) = \frac{1}{\epsilon_{\text{bin}}(p_{\text{T}}, \eta)} \cdot (1 - f_{\text{sec}}(p_{\text{T}})) \cdot (1 - f_{\text{okr}}(p_{\text{T}}, \eta))$$



"Raw" distribution:
Measured track density

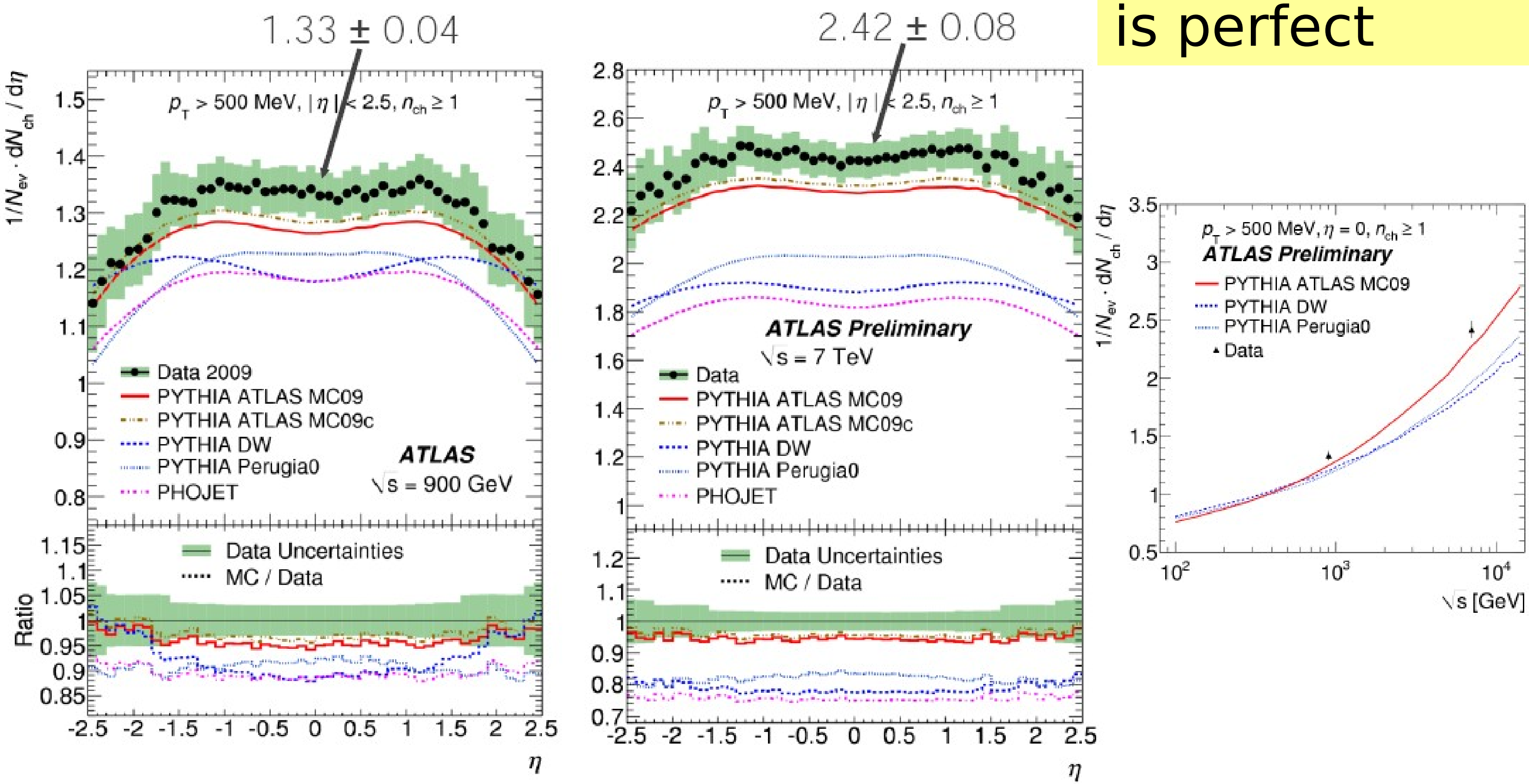
Final distribution:
Charged particle density



η spectra and particle multiplicity

$1/N_{ev}\ dN_{ch}/d\eta$: 900 GeV and 7 TeV

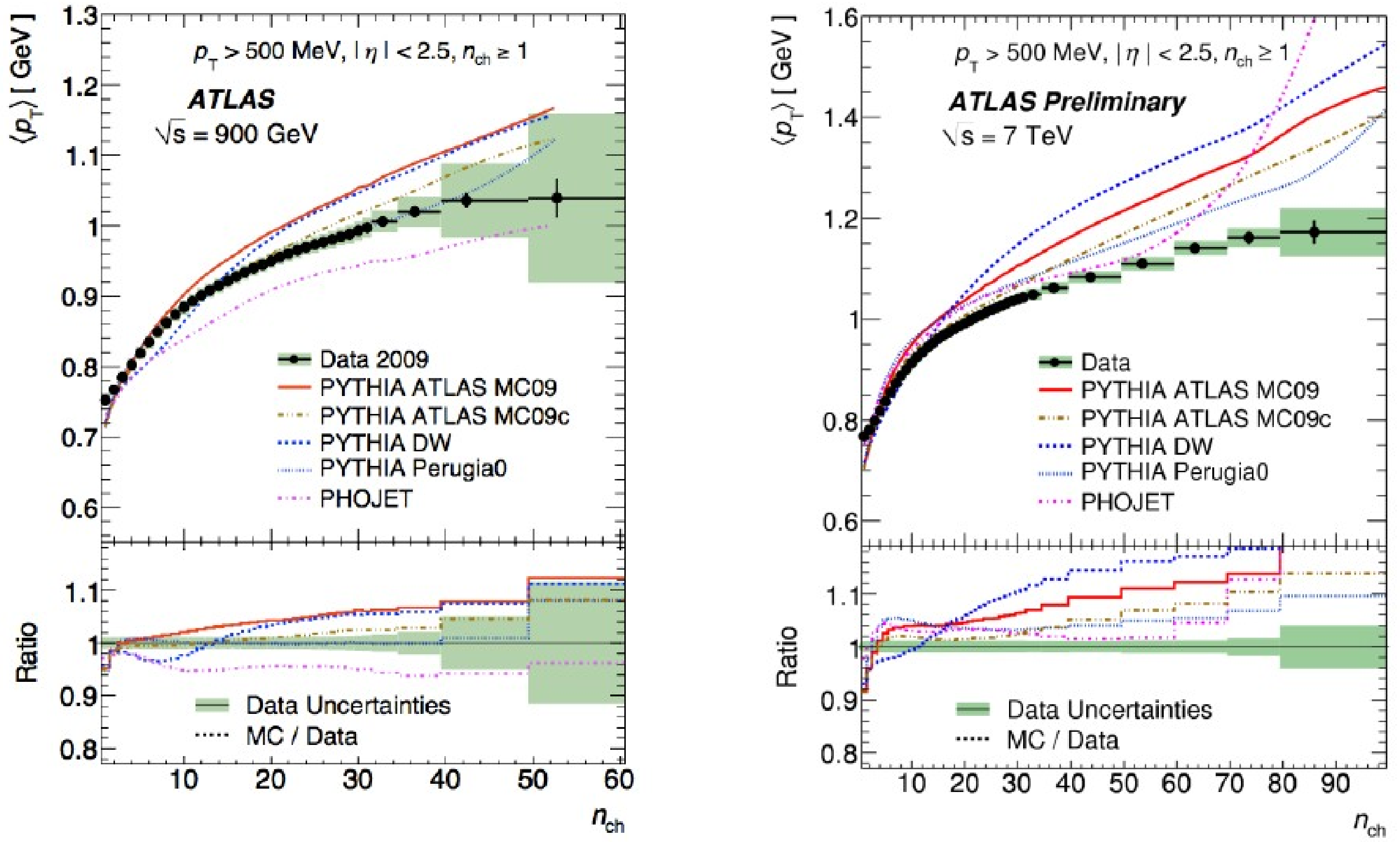
No Monte Carlo is perfect



p_T spectra

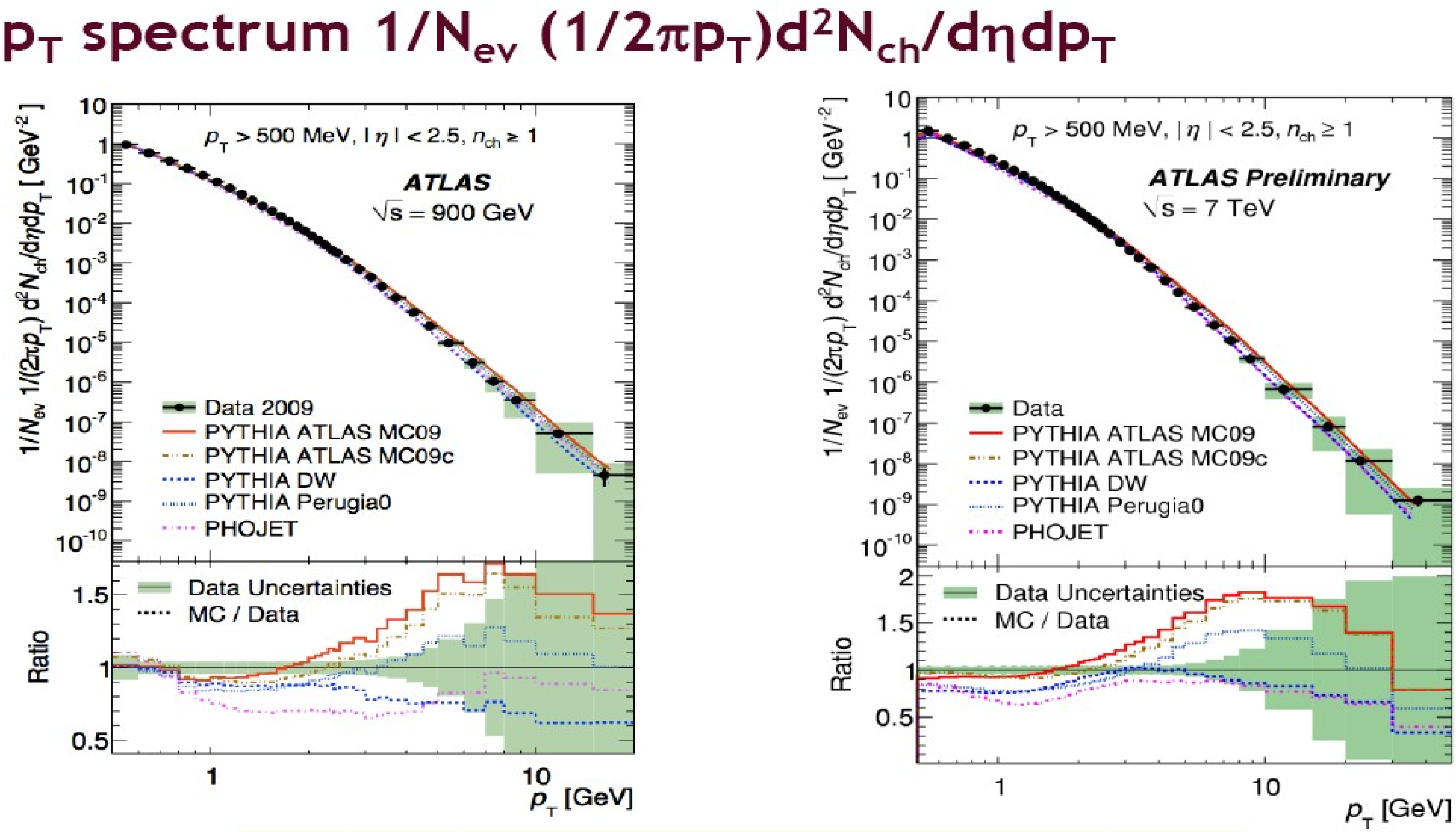
All disagree with data for high charged particle multiplicity

$<P_t>$ vs n_{ch}: 900 GeV and 7TeV

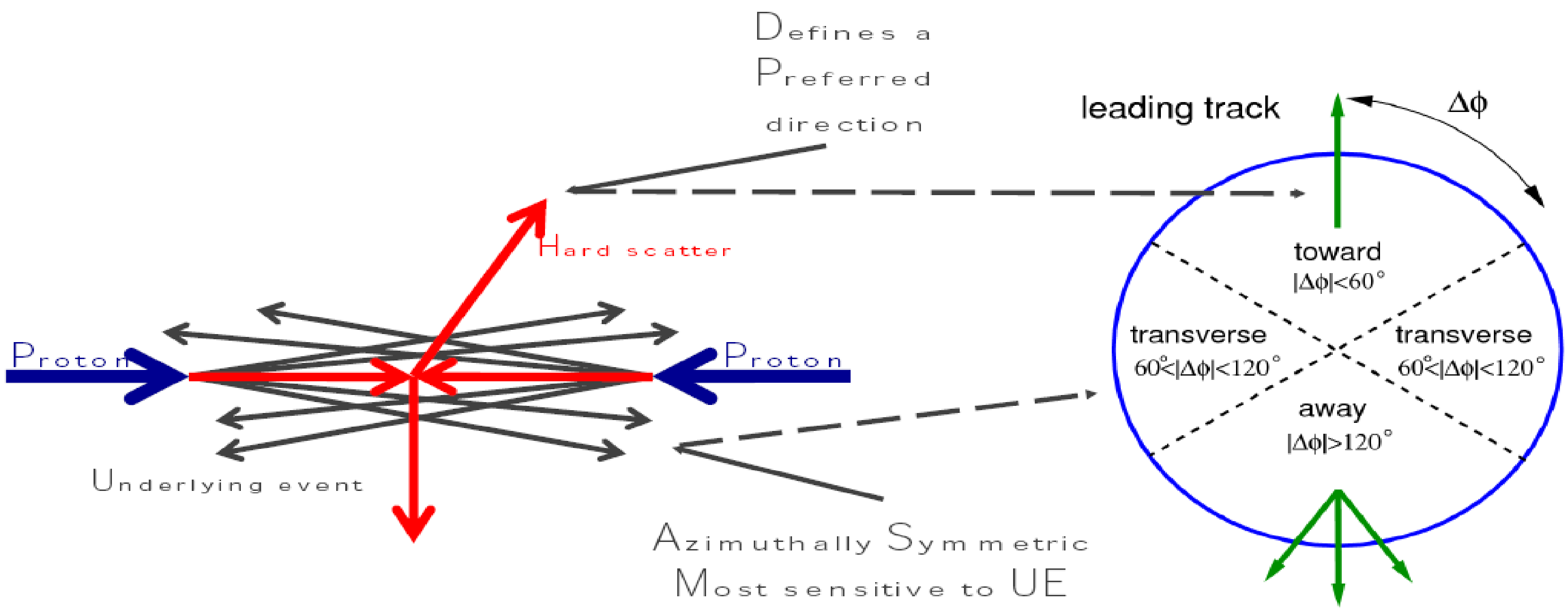


p_T spectra

Significant disagreement for p_T> 2 GeV, the hard part for soft model



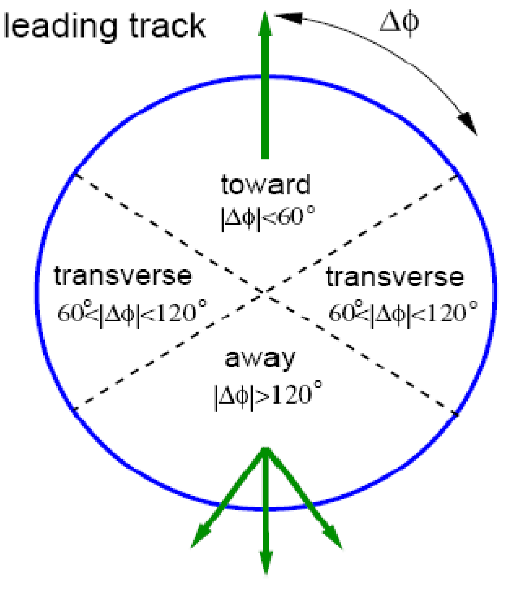
Underlying event



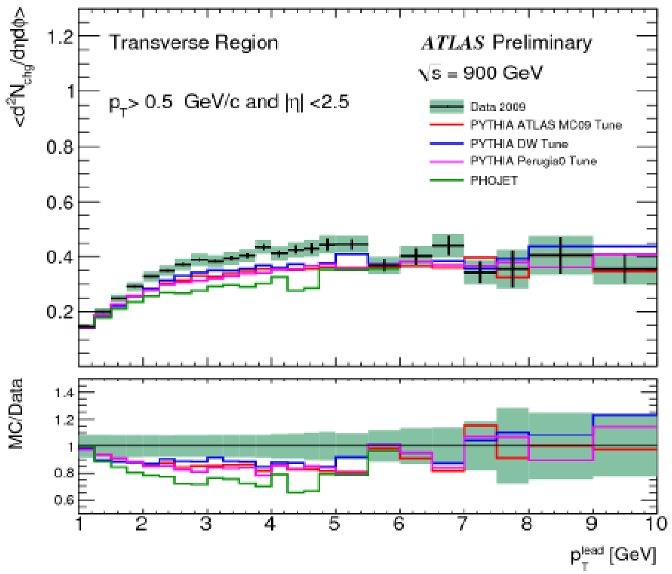
- UE = "everything" - "hard scatter" = beam-beam remnants, MPI, ISR
- Study: charged particle density, transverse momentum, average p_T. Transverse region considered most sensitive to UE

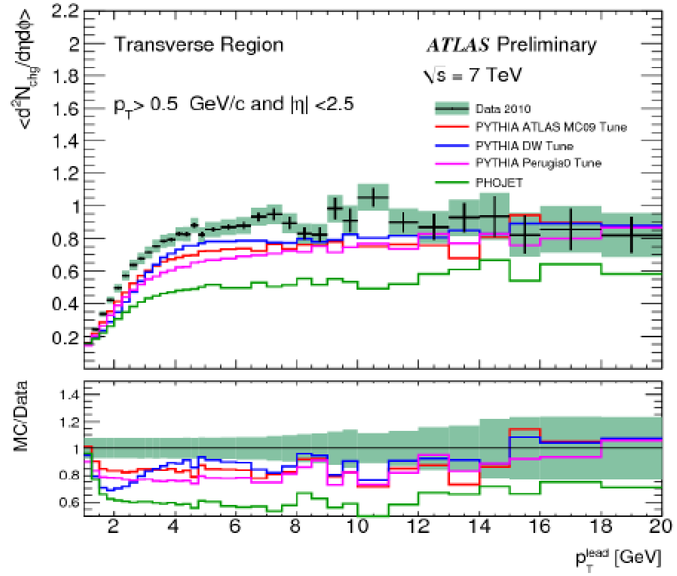
Underlying event

- **How to measure the UE?**
  - Separate off hard scattering region
  - Assume Di-jet structure
  - Region transverse in φ to Jets is filled mostly by UE
- **Leading track method**
  - Use leading track to define directions
  - Usually contained in leading jet
  - Low p_T: leading track-jet often has leading track as only constituent
  - Can already be used with small statistics => early data



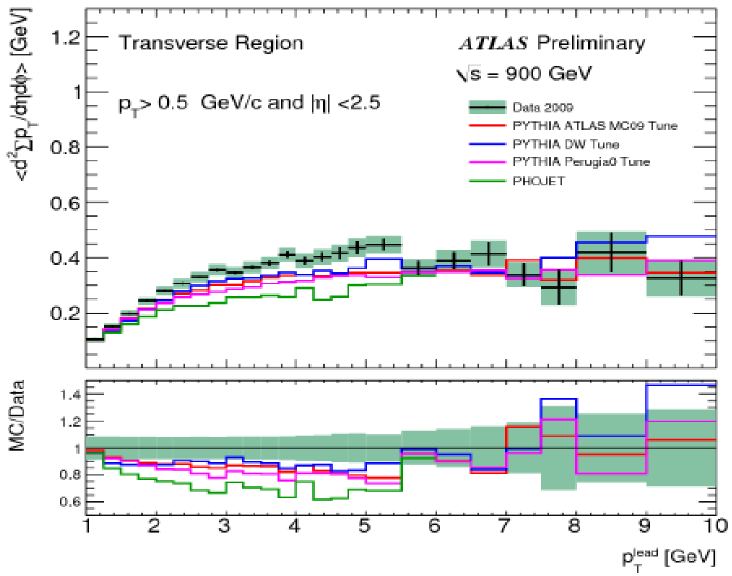
Transverse region particle density

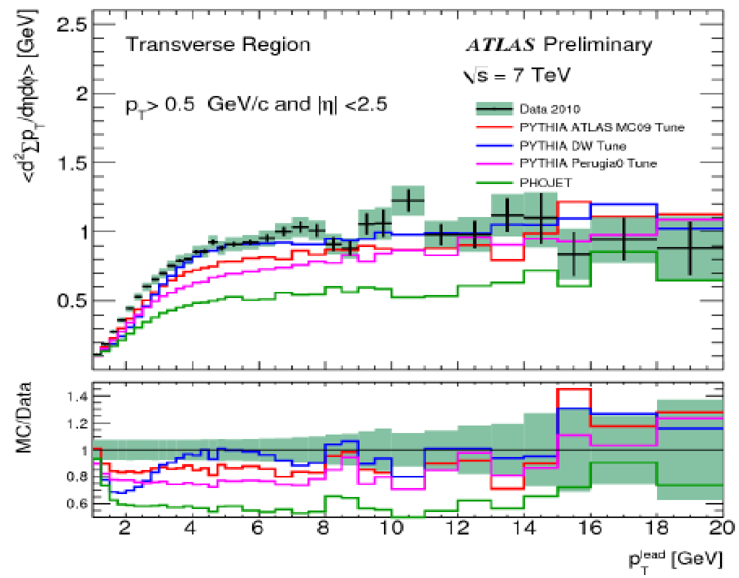




- All tunes underestimate particle density by 10%-15% in the plateau region
- There is factor of ~2 increase in activities between 900 GeV and 7 TeV
- In the plateau region the measured density corrsponds to ~ 2.5 per unit η at 900 GeV and 5 particle at 7 TeV

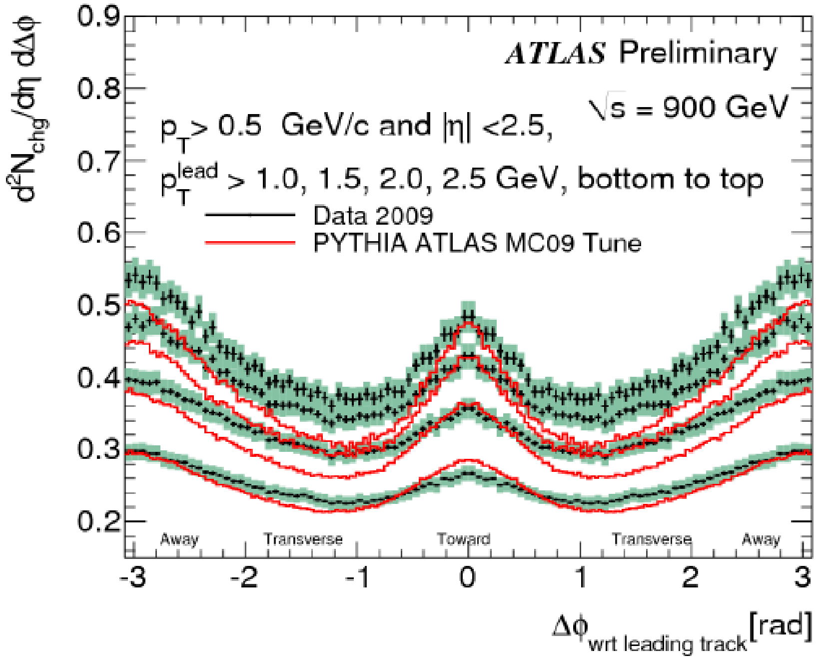
Transverse region <Σp_T> density

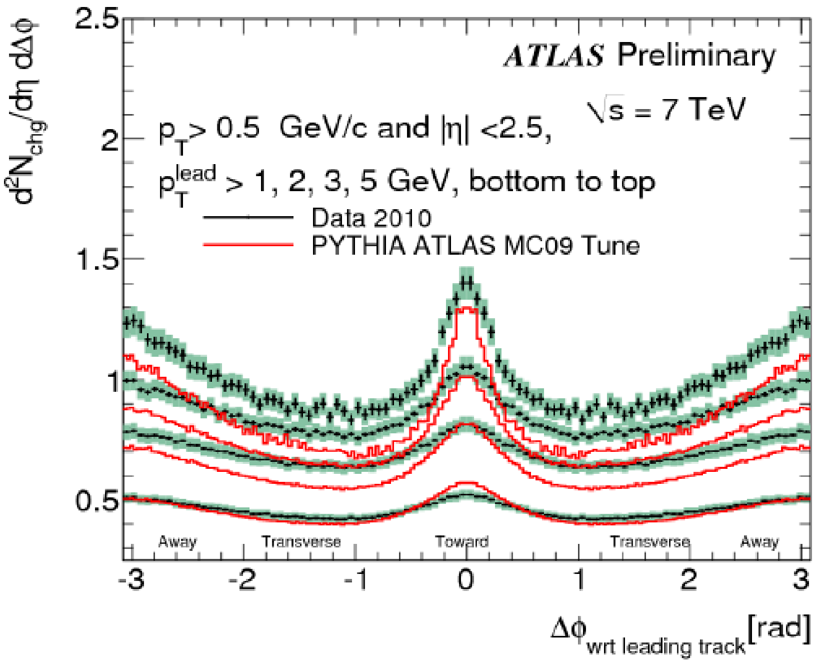




- Similar conclusions:
  - there is factor of ~2 increase in activities between 900 GeV and 7 TeV
  - all tunes underestimate the scalar sum pT in the transverse region

Particle Density Angular Correlation

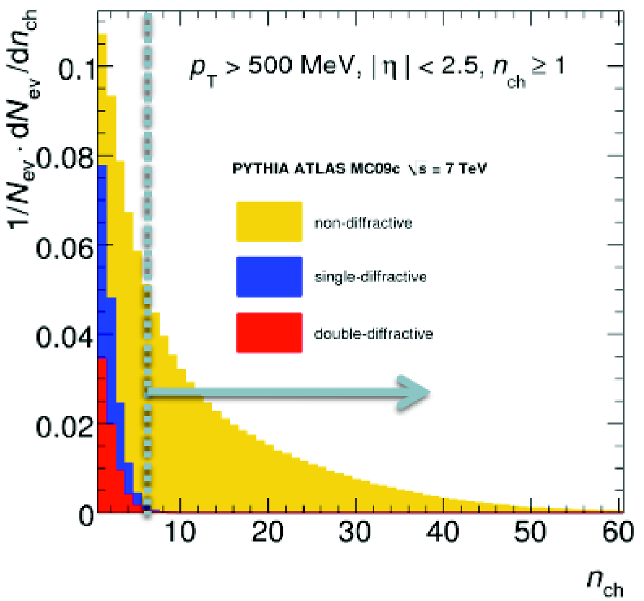




- Define the event orientation by the azimuthal angle on the track with the highest pT.
- MC tunes only reproduce the general features, disagreement in rates both in the transverse region (UE) and in the away region (MPI/Hard Core)

Minimum bias distributions

- Charged particle distributions:
  - multiplicity, p_T, η, mean p_T vs multiplicity



- Define a *diffraction suppressed* sample for MC tuning : $n_{ch} \geq 6$ {$p_T > 500$ MeV, $|\eta| < 2.5$}

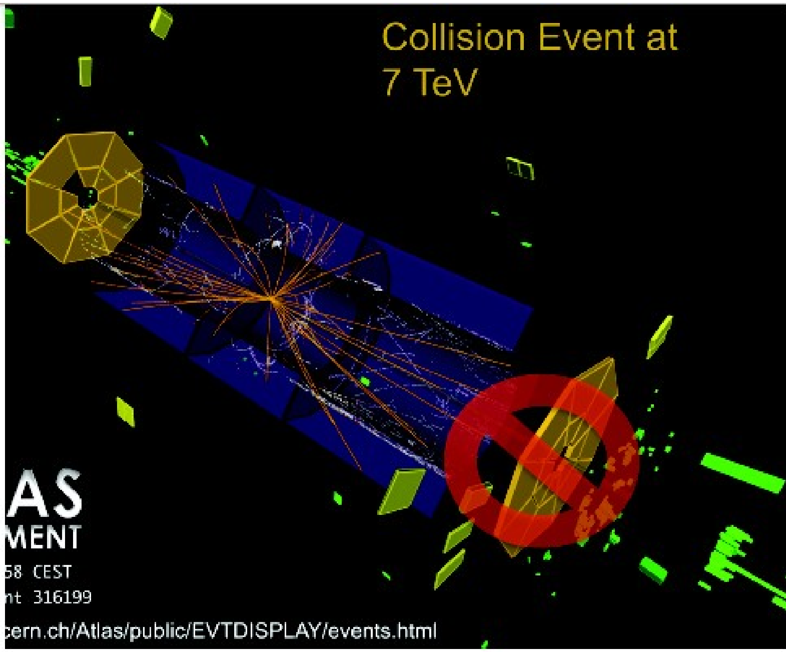
√s	lumi.	N_{ev}
0.9 TeV	9 μb^{-1}	157,896
7 TeV	6.8 μb^{-1}	231,665

- Define a *diffraction enhanced* sample :
  - $n_{ch} \geq 1$ {$p_T > 500$ MeV, $|\eta| < 2.5$}
  - veto activity in *one* forward scintillator disk

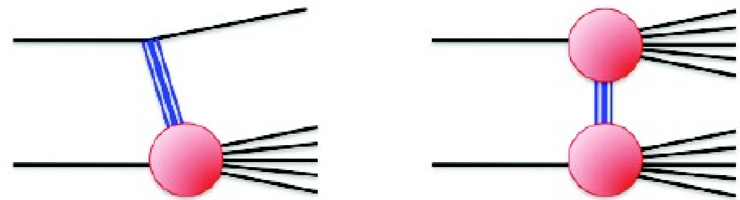
√s	lumi.	N_{ev}
7 TeV	23 μb^{-1}	52,801

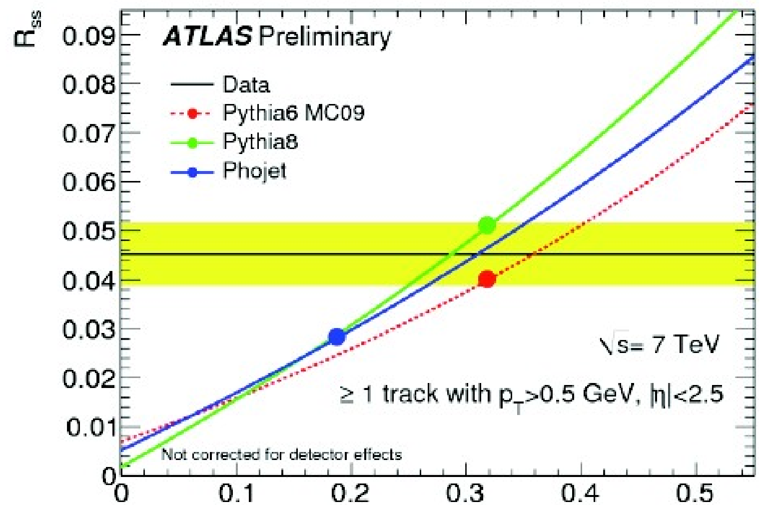
Diffraction enhanced samples

(no detector correction yet, compared to full sim)



veto activity in one forward scintillator disk
$\{2.09 < \eta < 3.84 \ \text{ OR } -2.09 > \eta > -3.84\}$





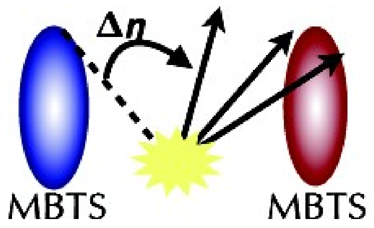
$n_{trk} \geq 1 \ \{p_T > 500 \text{ MeV}, |\eta| < 2.5\}$

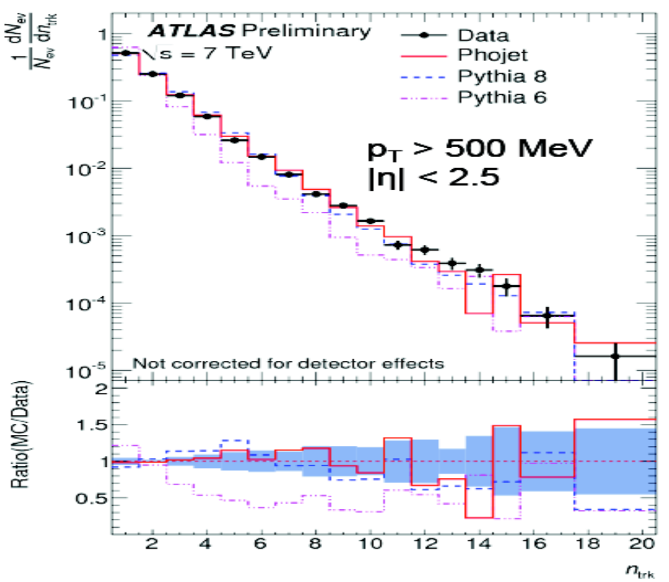
$$R = \frac{\#\ \text{single-sided}}{\#\ \text{single-sided} + \#\ \text{double-sided}}$$

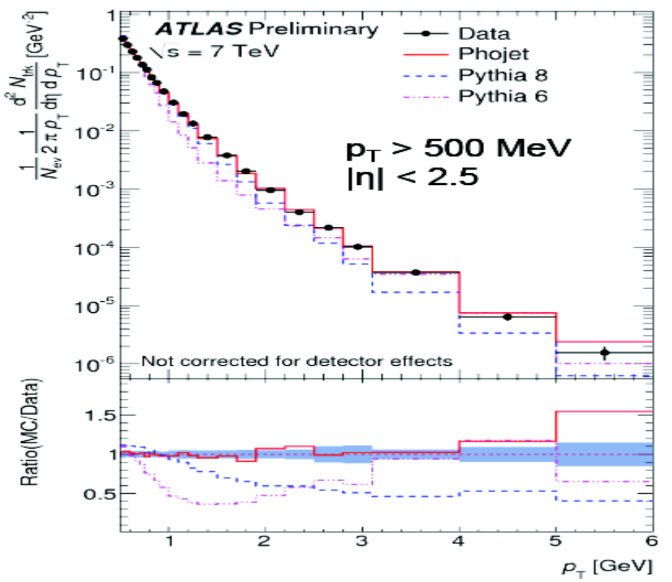
sensitive to relative diffractive cross-section → $\sigma_{diff} / \sigma_{inel}$

Diffraction enhanced samples

(no detector correction yet, compared to full sim)



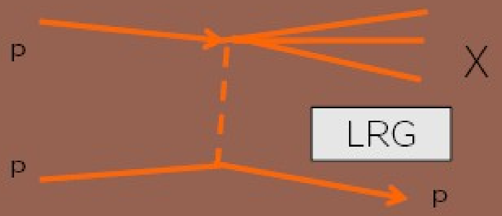




- Excellent agreement with PHOJET

Strategy for Single Diffraction Detection at CMS

Single diffraction (SD)



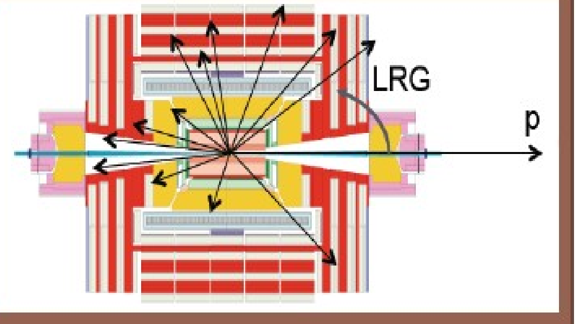
$\xi = M_X^2 / s$

$\sigma \approx 1 / \xi$

$\Delta y \approx -\ln \xi$

$\xi \approx \Sigma_i (E_i \pm p_{z,i}) / \sqrt{s}$

No measurement of the proton → rely on Large Rapidity Gaps



LOOK FOR A SD PEAK @ low $\xi \approx \Sigma_i (E_i \pm p_{z,i}) / \sqrt{s}$

Sum runs over all the Calo Towers:

$p_{z,I} = E_i \cos \vartheta_i$

Hadron Forward:

- @11.2m from interaction point
- rapidity coverage: $3 < |\eta| < 5$
- Steel absorbers/ quartz fibers (Long +short fibers)
- 0.175x0.175 η/φ segmentation

CONFIRM SD PEAK @ low $E_{HF\pm}$, $N_{HF\pm}$

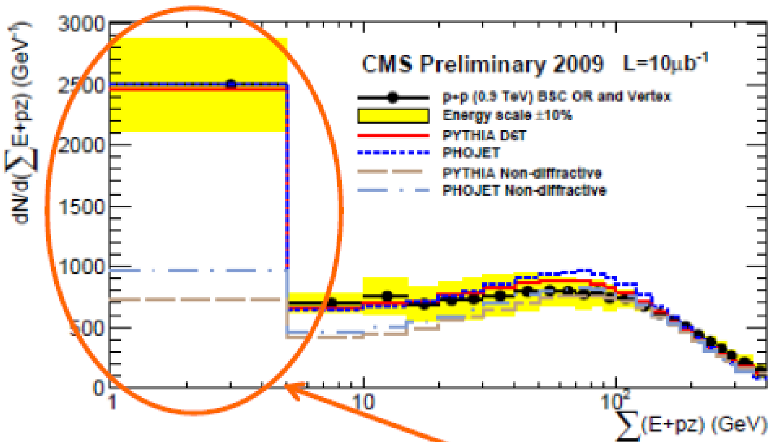
$E_{HF\pm}$ = energy deposition in HF±

$N_{HF\pm}$ = multiplicity of towers above threshold in HF±

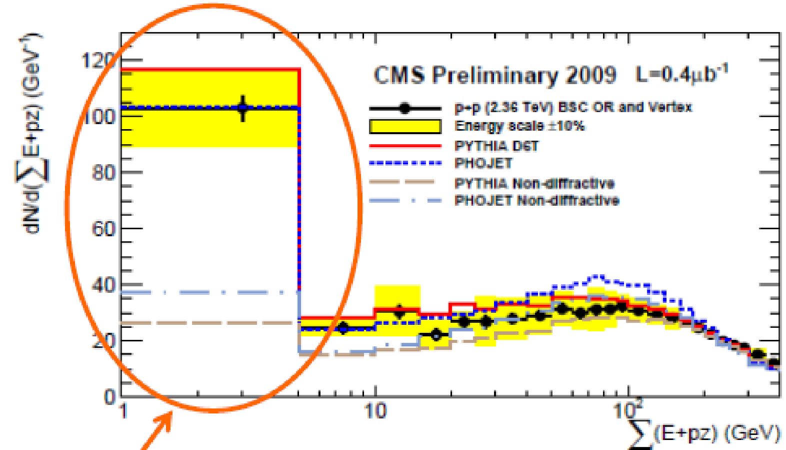
Observation of Single Diffraction at CMS

(Results at 7 TeV to become public in the near future)

900 GeV (10 μb^{-1})



2360 GeV (0.4 μb^{-1})



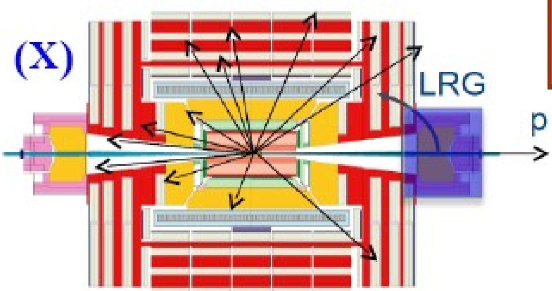
Systematic uncertainty dominated by energy scale

Acceptance for SD ~ 20%
For NSD ~80% (PYTHIA)

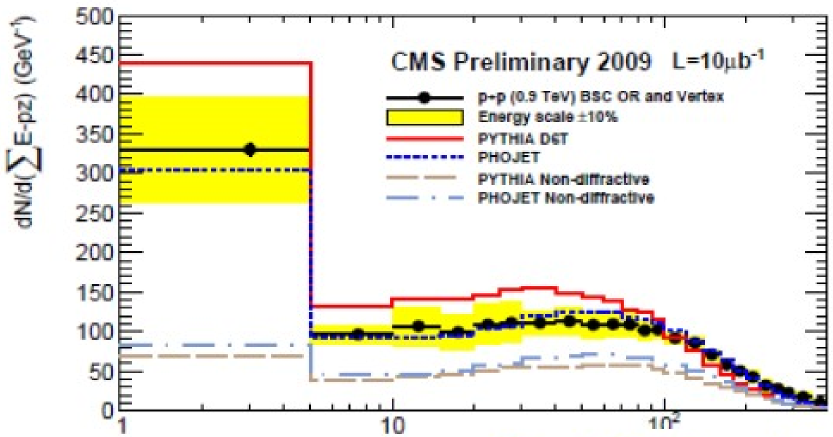
SD seen in Σ E+pz distribution due to cross section peaking at small values of ξ

Enriched SD Sample → E(HF+) < 8 GeV

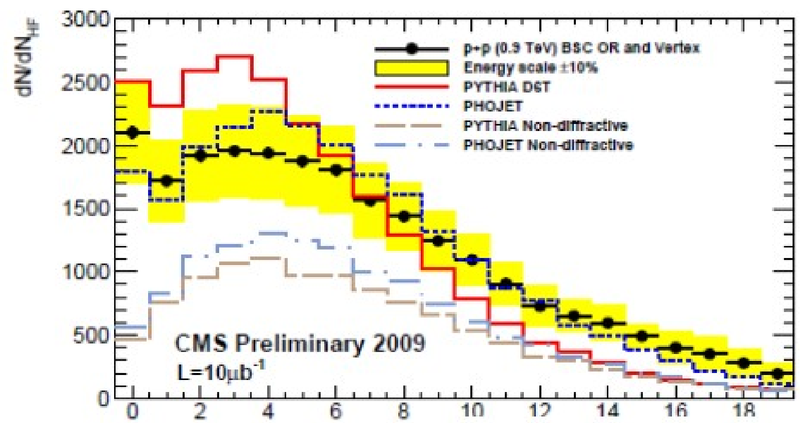
Requirement of low Activity in one side of CMS



SD component of the data
LRG in z+ direction
Concentrating on the fragmenting object
(X) boosted in z- direction

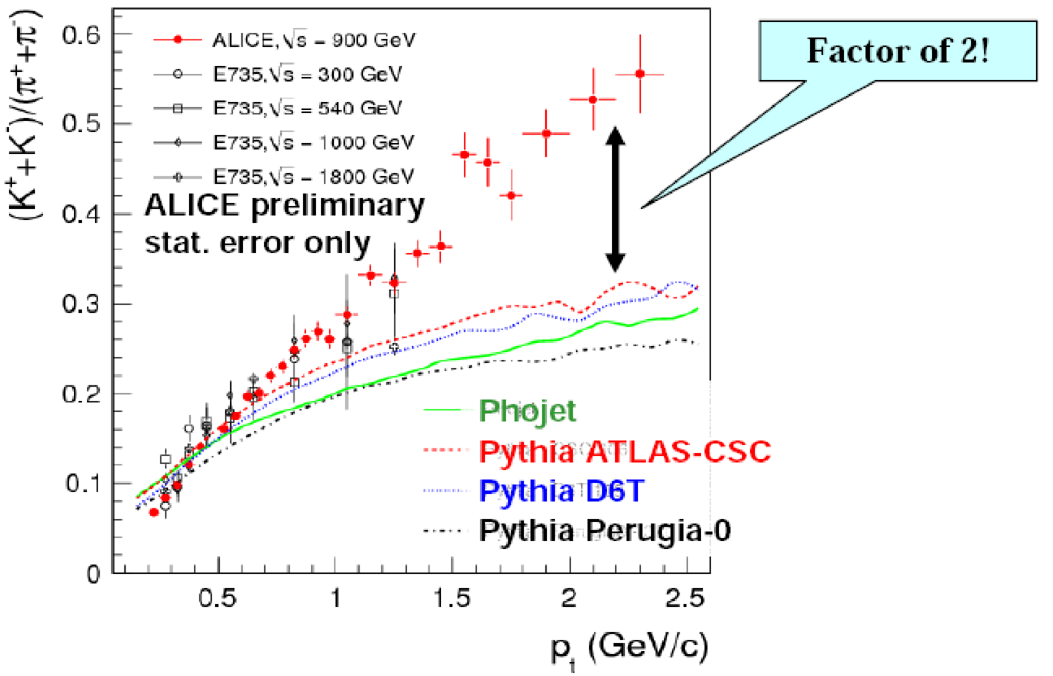


$\xi = \Sigma_i (E_i \pm p_{z,i})$



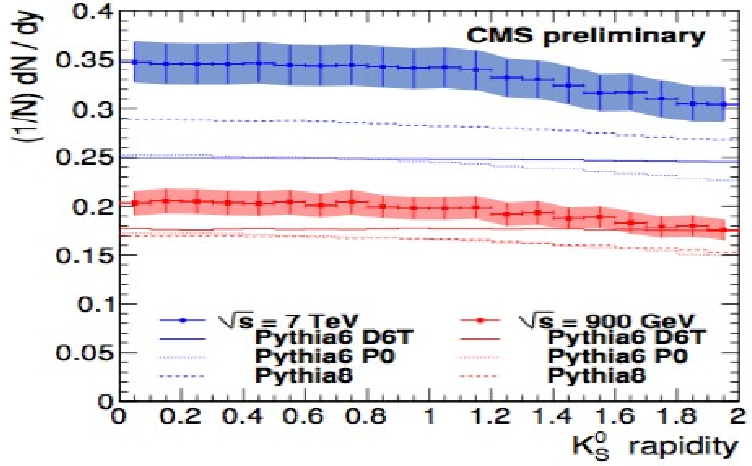
HF- Multiplicity

Strange particle production

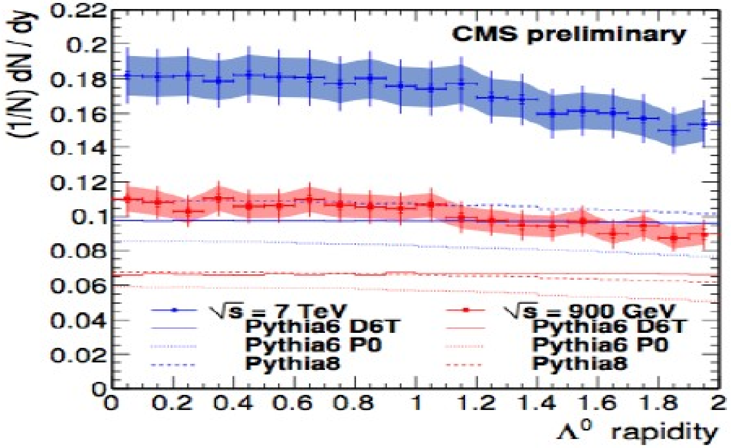


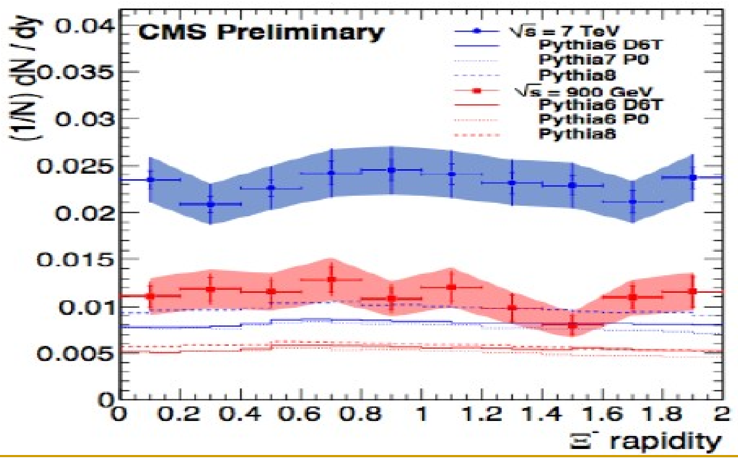
- A lot more strange mesons at large p_T than predicted by models
- K/π ratio fairly independent of the centre-of-mass energy

Strange particle production

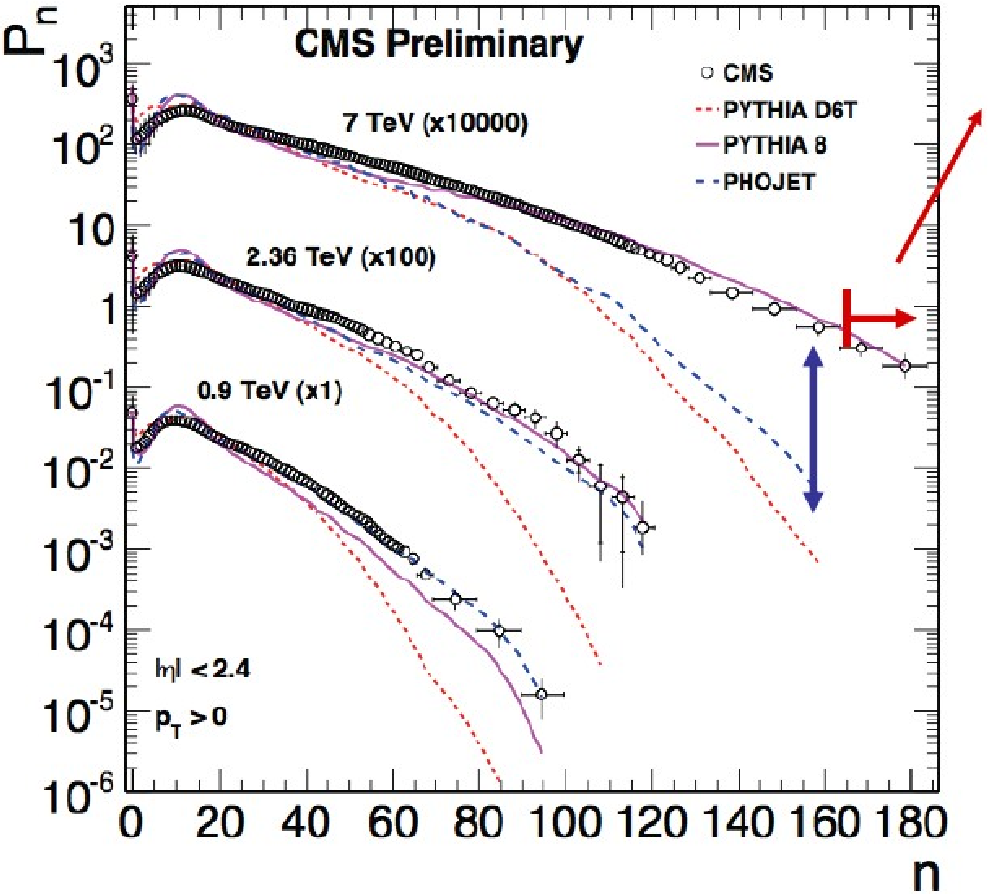


- All generators underestimate the amount of **Strange Particles** produces at both 0.9 and 7TeV



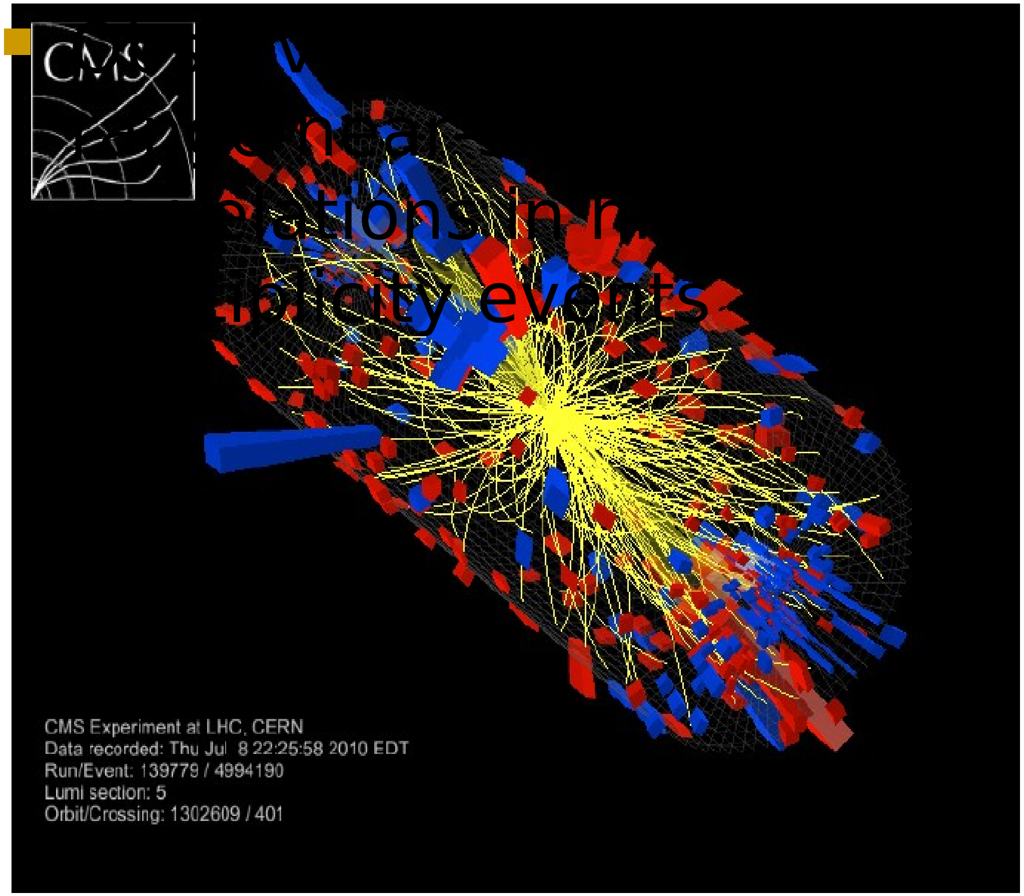


High multiplicity events



- Tails of the distributions where several MC generators underestimate the data (except Pythia)
- Trying to find unexpected (non in MC) effects in this regime)
- Highest multiplicities in pp begins to approach those in ion collisions; can learn about similarities or differences

CMS observation

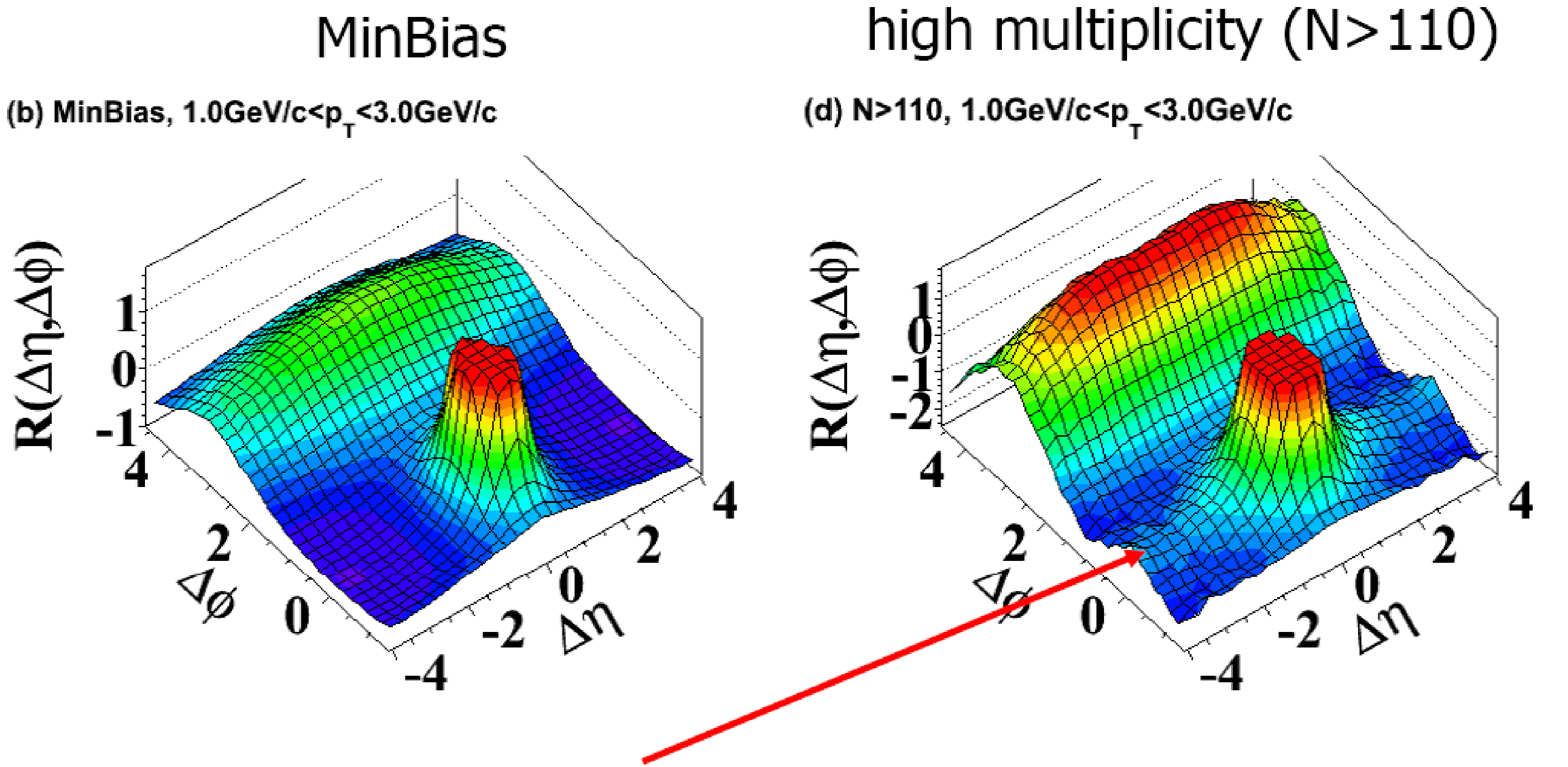


268 reconstructed particles in the tracker in a single pp collision:
the highest multiplicity event in ~70 billion inelastic events sampled (1/pb)

- Observed long-range near-side correlations in high multiplicity events

CMS Collab., arXiv:1009:4122, accepted by JHEP

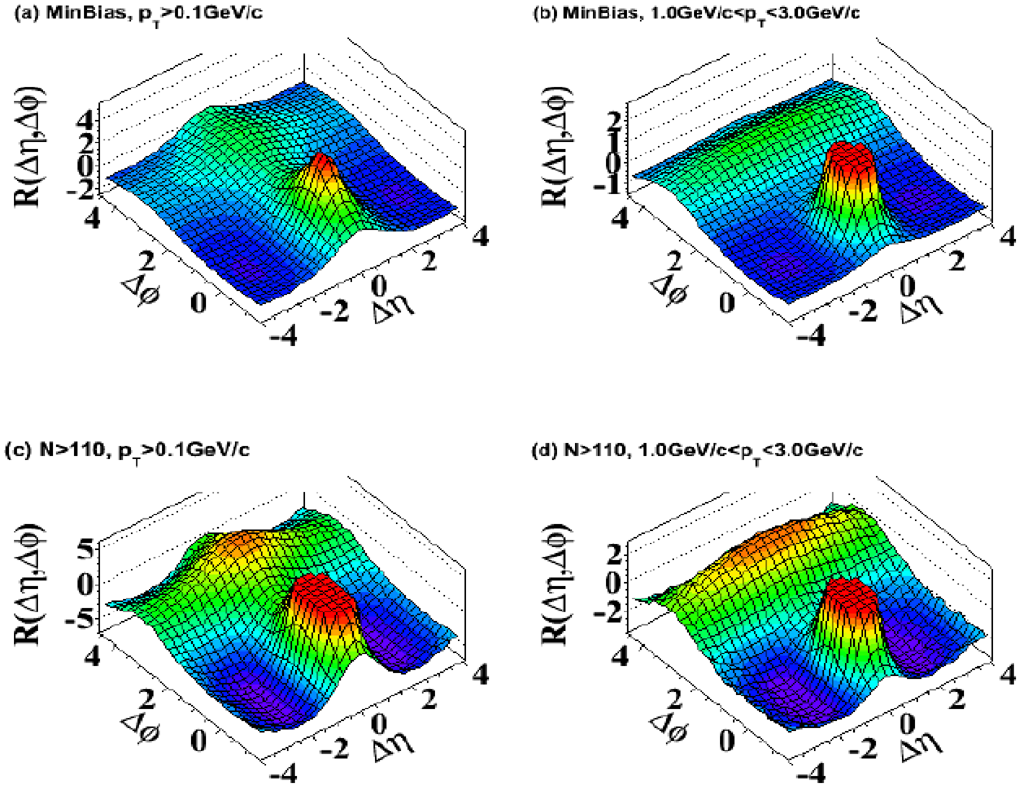
High multiplicity events



Pronounced new structure at large $\delta\eta$, around $\delta\phi \sim 0$!

CMS Collab., arXiv:1009:4122, accepted by JHEP.

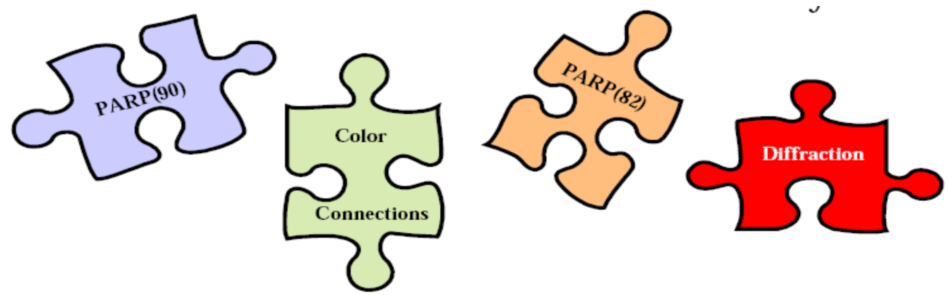
Correlations for PYTHIA



No $\delta\phi \sim 0$ structure at large $\delta\eta$

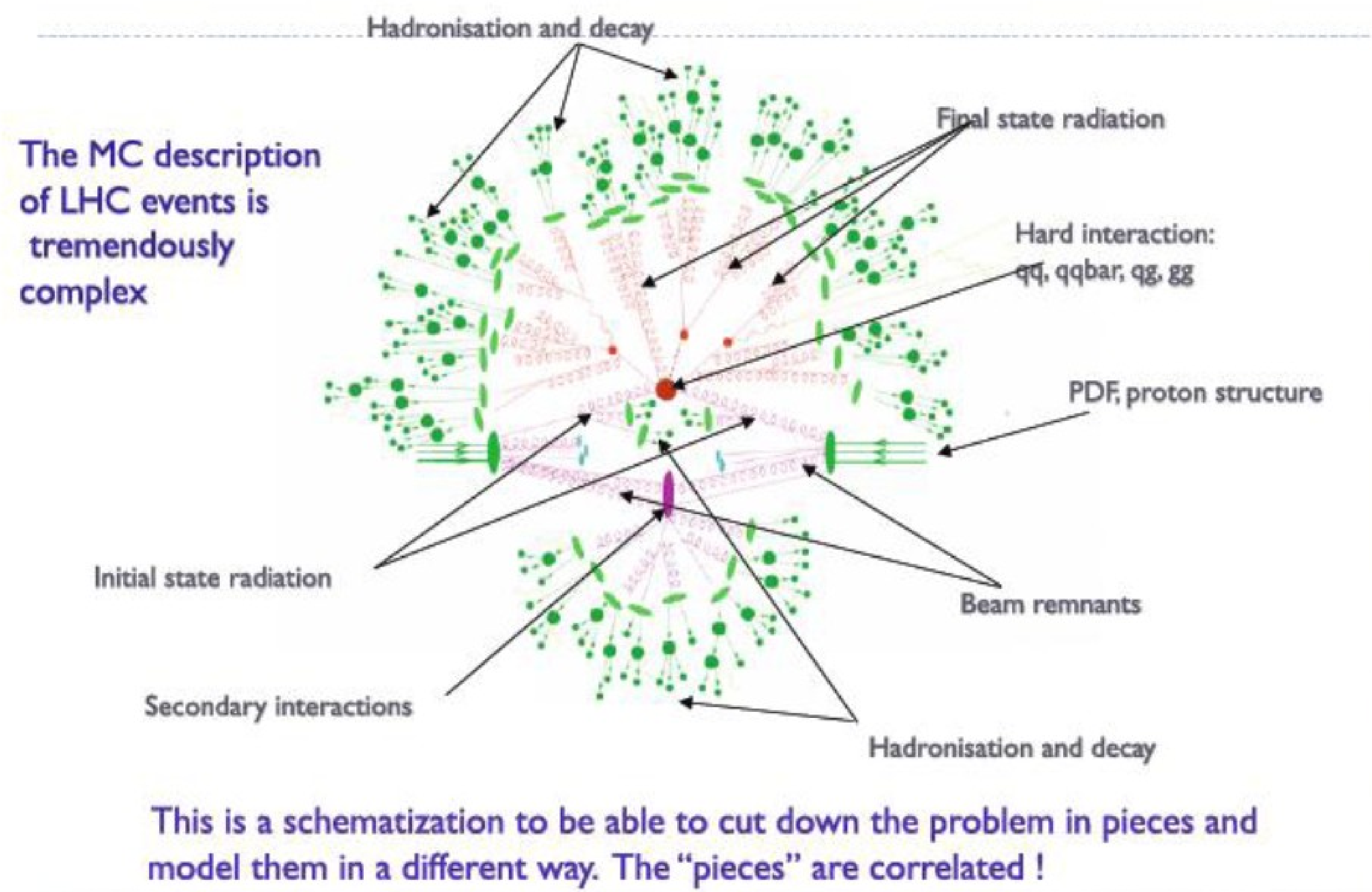
$\rightarrow$ Same for Herwig++, madgraph, PYTHIA6

MC tunes



- There are more soft particles than expected
- We need better understanding and modeling of diffraction
  - Diffraction enhanced minbias sample (not yet detector corrected) favours 30% (PYTHIA) relative diffractive cross-sections and hard (PHOJET) particle spectra
- Seems to be more “min-bias” high multiplicity soft events than expected
- The models do not produce enough strange particles

MC tunes: hadronic event

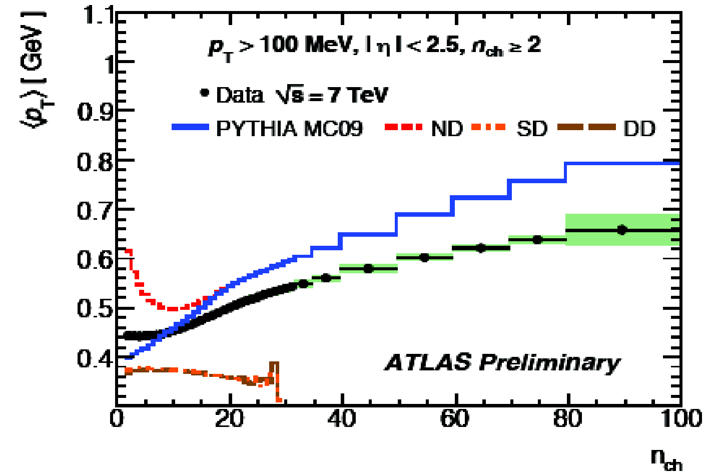


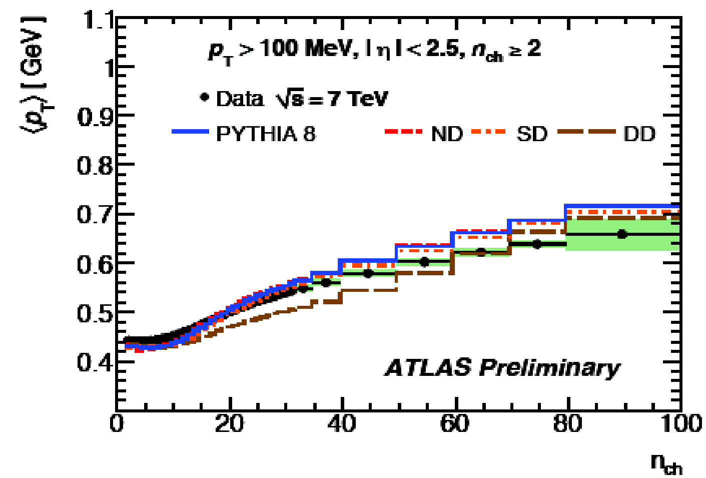
Tuning phenomenological models

- Number of relatively free parameters which must be tweaked if generator is to describe experimental data;
- Profilation of parameters, between O(10-30) of importance for collider physics simulations. Few examples: kinematic distribution of transverse momentum (p_T) in hadron fragmentation, barion/meson ratios, strangeness and $\{\eta,\eta'\}$ suppression, distribution of orbital angular momentum, etc. etc.
- Nowdays tunings became an „industry”:
  - **Rivet** – system for comparing generastor tuning with experimental data
  - **Professor** – system for parametrising generators behaviour in bins of parameter vectors

Diffraction: how important for MC tunings

- The low p_T low N_{ch} region is problematic
  - Diffractive component important
- Case PYTHIA 6:
  - Diffractive component soft and low multiplicity
- Case PYTHIA 8:
  - At low N_{ch}, $<p_T>$ similar for SD,DD & ND



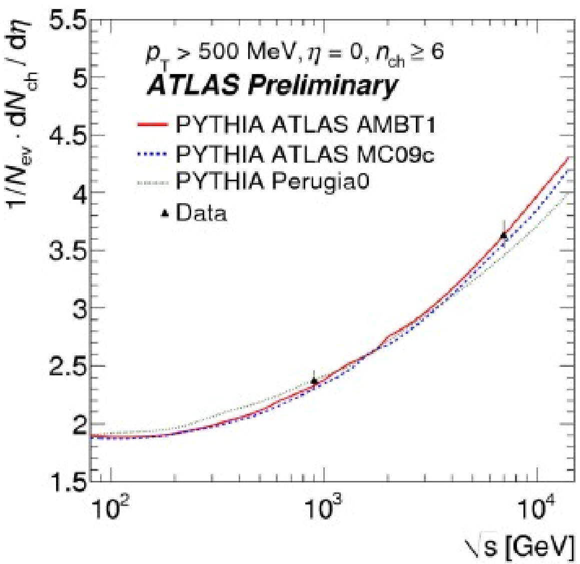


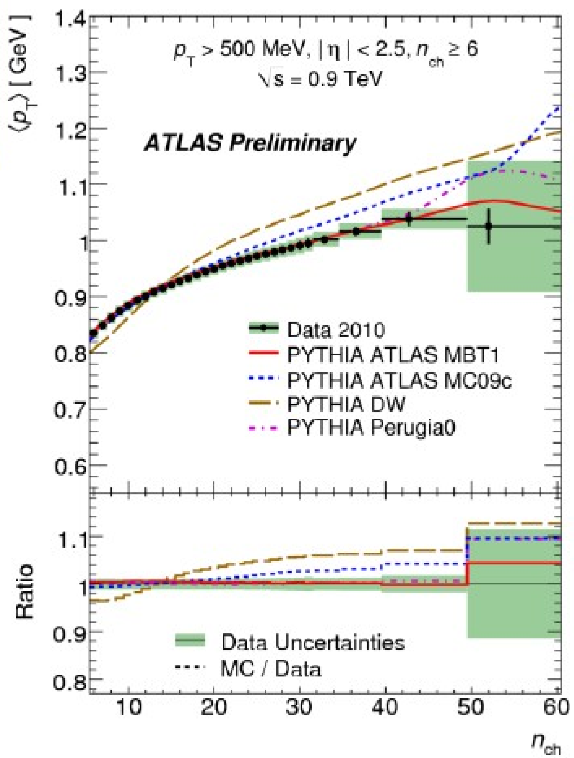
PYTHIA tune to ATLAS minbias and UE data: significant improvement vs pre-LHC era

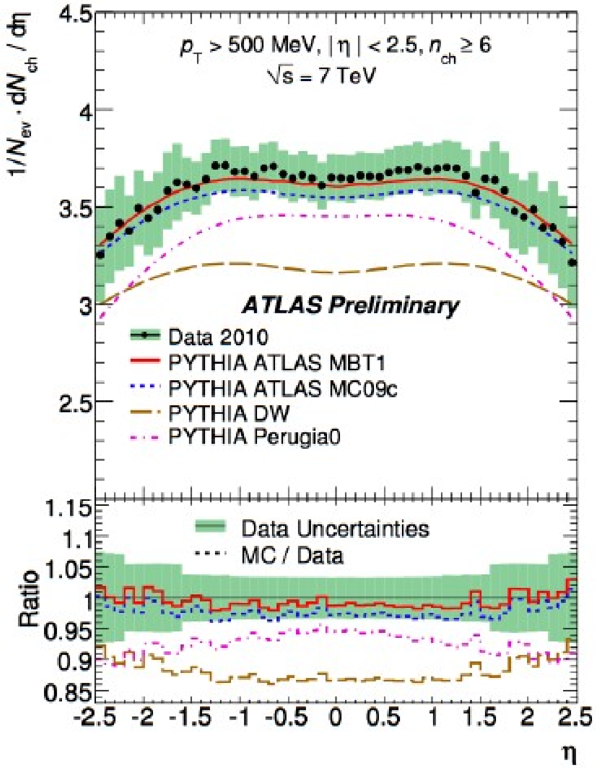
Input to Tune:

- ATLAS UE data and charged particle densities at 0.9 and 7 TeV
- CDF Run I & Run II: min bias, UE, Z P_t
- D0 Run II dijet angular correlations

Tune to reduced phase space (n_{ch} ≥6) to insure no contribution from SD







Parameters tunnings

- ATLAS new tune:

Parameter	related model	MC09c value	scanning range	AMBT1 value
PARP(62)	ISR cut-off	1.0	fixed	1.025
PARP(93)	primordial kt	5.0	fixed	10.0
PARP(77)	CR suppression	0.0	0.25 − − − 1.15	1.016
PARP(78)	CR strength	0.224	0.2 − − − 0.6	0.538
PARP(83)	MPI (matter fraction in core)	0.8	fixed	0.356
PARP(84)	MPI (core of matter overlap)	0.7	0.0 − − − 1.0	0.651
PARP(82)	MPI (p_T^{min})	2.31	2.1 − − − 2.5	2.292
PARP(90)	MPI (energy extrapolation)	0.2487	0.18 − − − 0.28	0.250

Next topics

- 27.10 – hard QCD
- 3.11 - W,Z bosons:
  - cross-sections (incl. differential), W/Z+jets
  - asymmetry
- 10.11 - W,Z bosons:
  - precise measurements
- 17.11 – Top: xsection, mass
- 24.11 – Hot topics: new exclusion limits
- 1.12, 8.12, 15.12 – Higgs