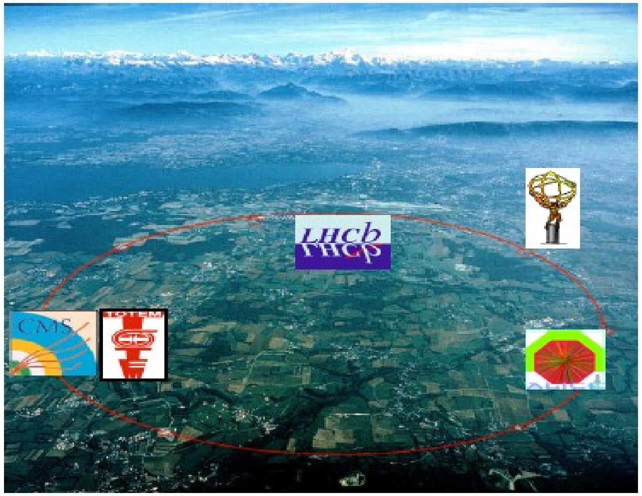
Lecture 2

Physics Program

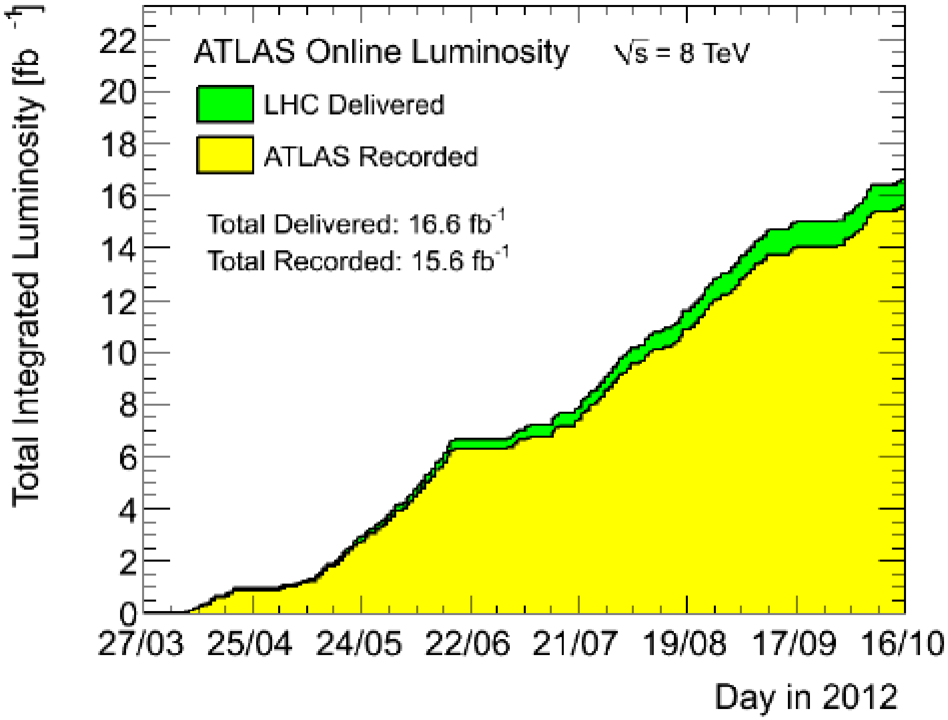
of the experiments at

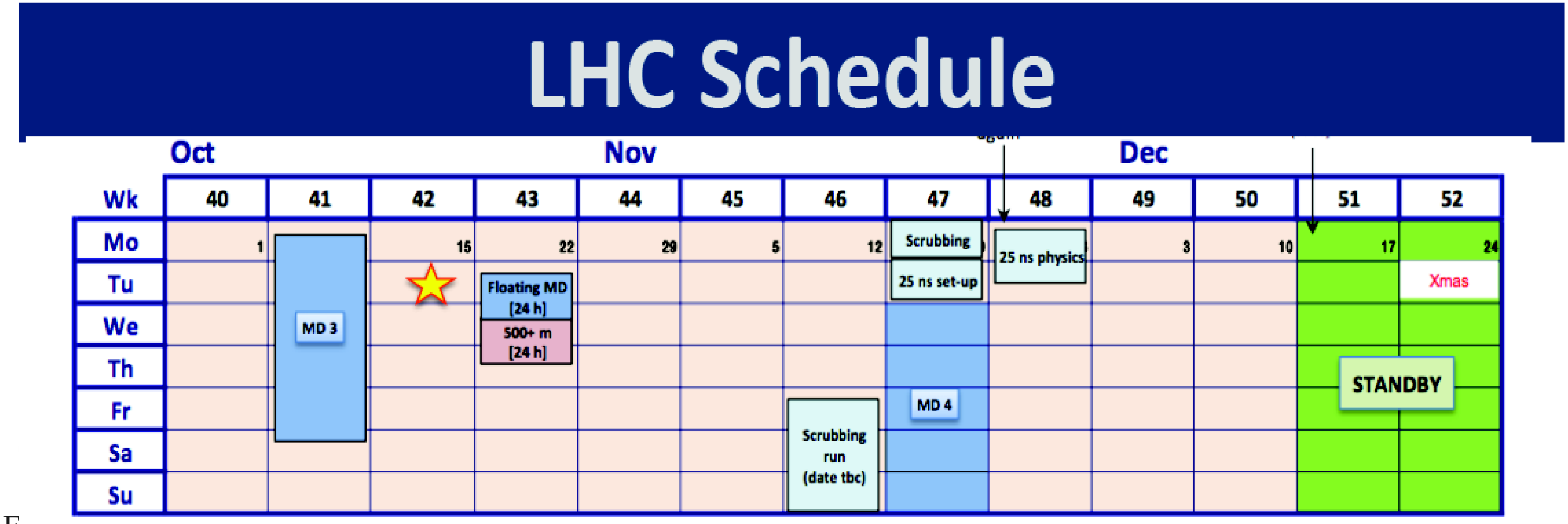
Large Hadron Collider

- **soft QCD**



News of last week





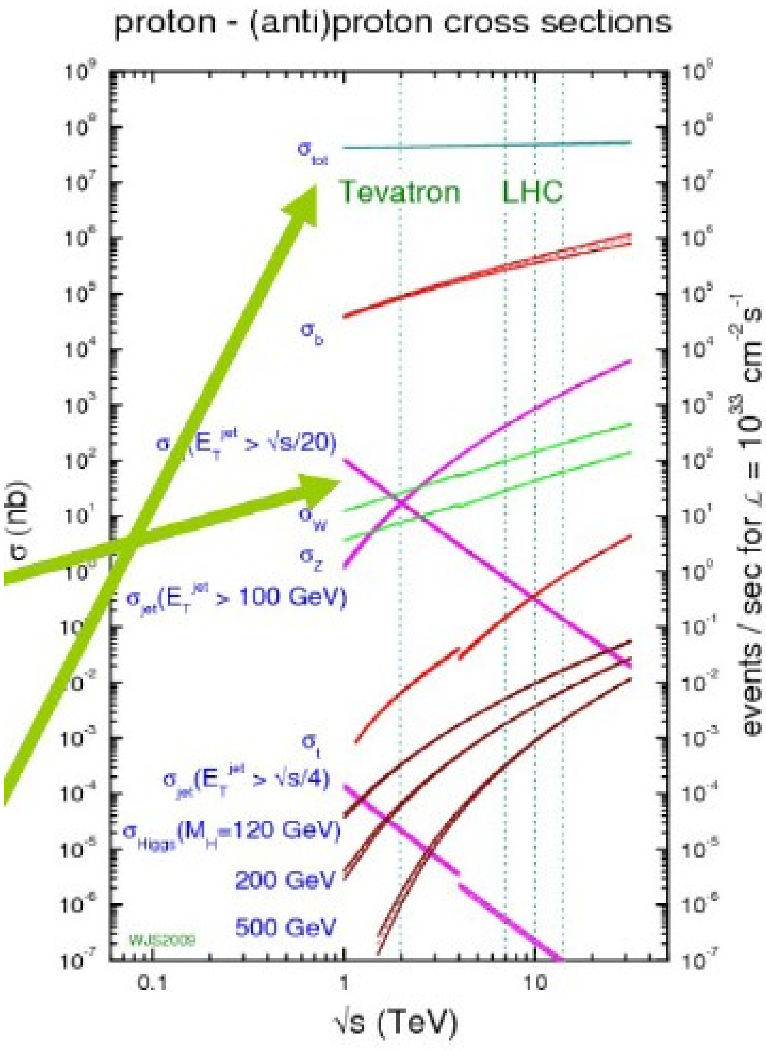
LHC Schedule

	Oct				Nov					Dec			
Wk	40	41	42	43	44	45	46	47	48	49	50	51	52
Mo	1	MD 3	15	22	29	5	12	Scrubbing	25 ns physics	3	10	17	24
Tu			★	Floating MD [24 h]				25 ns set-up					Xmas
We				500+ m [24 h]									
Th												STANDBY	
Fr							Scrubbing run (date tbc)	MD 4					
Sa													
Su													

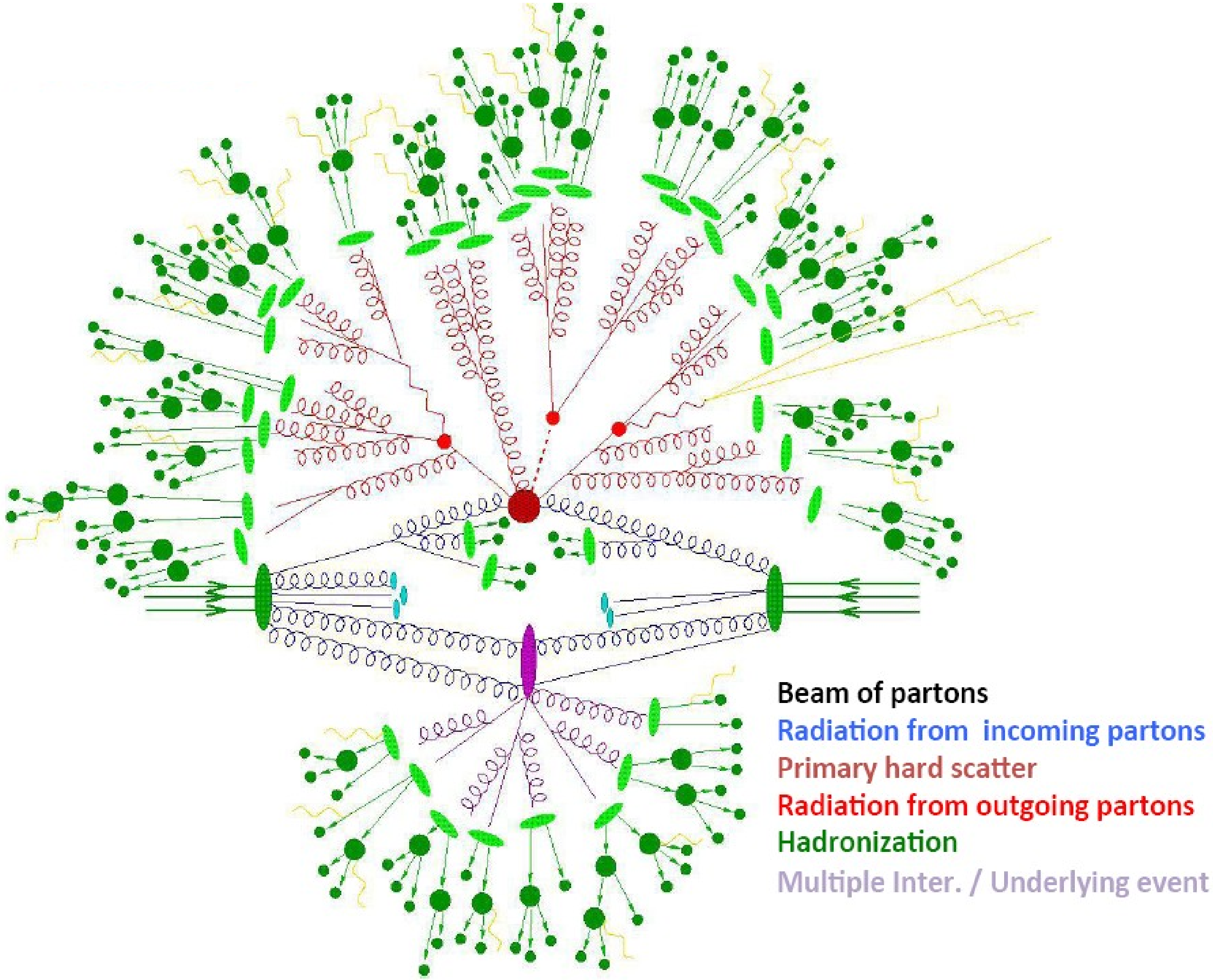
E

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 is very different for the two cases
- For **HARD** processes, e.g. W production, the rates and event properties can be predicted using perturbation theory
- For **SOFT** processes, eg. Total cross-section rates and properties predicted by non-perturbative models

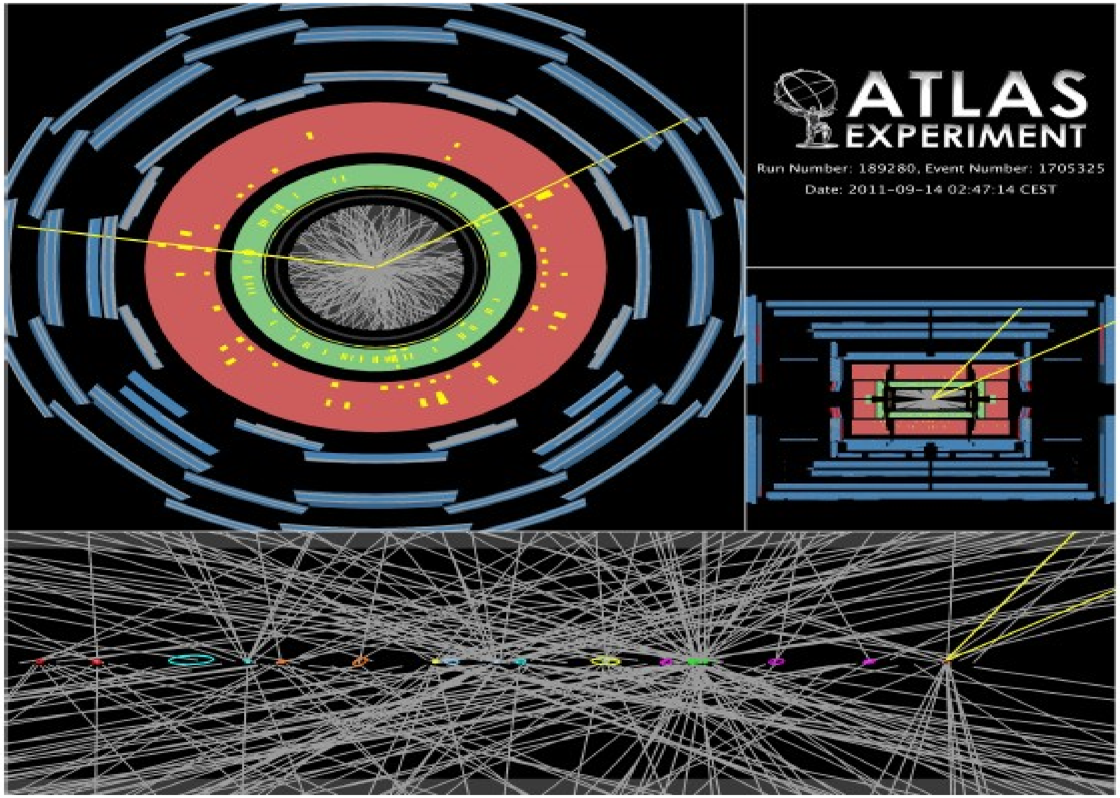


Typical pp collision



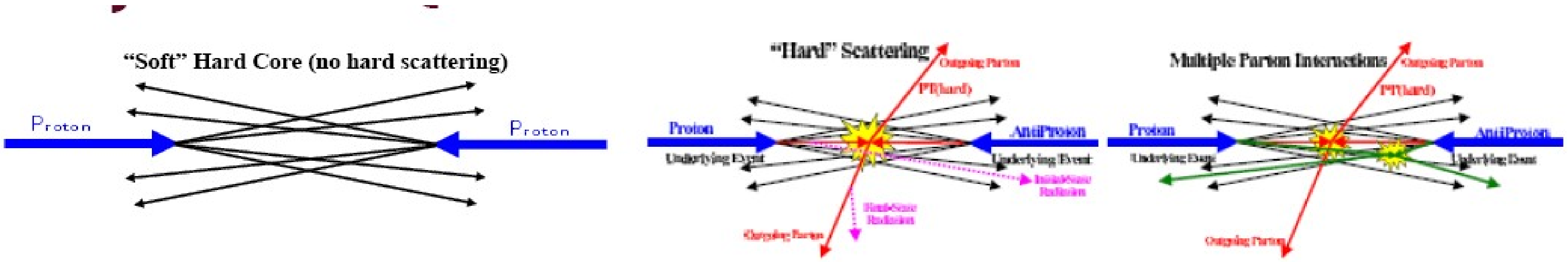
Why interest in soft QCD

- At almost every event triggered in ATLAS there will be soft (low p_T) QCD process underlying hard p_T physics



- Cannot be modelled from first principles (lagrangian),
- Has to be measured and then Monte Carlo will be tuned

Why “soft QCD” is interesting?

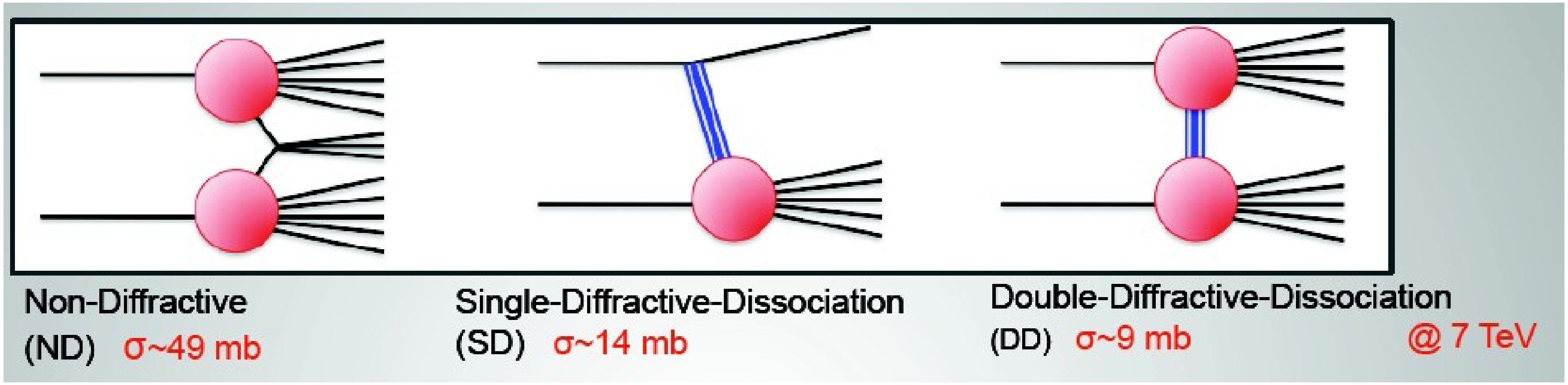


- It is non-perturbative physics and has an interesting phenomenology
  - Beam remnants
  - Multiple Parton Interactions
  - Color recombination

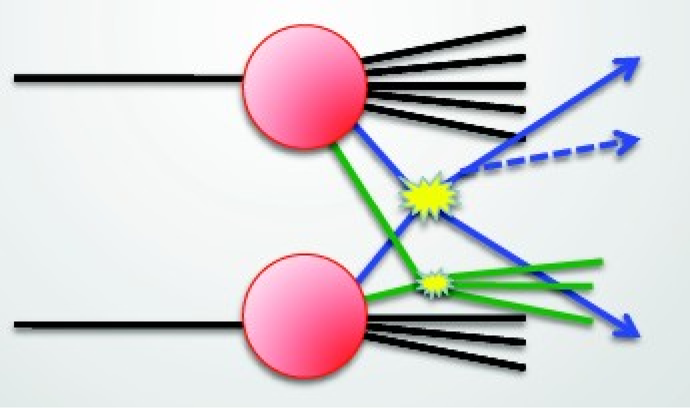
  => All adding up to the colorless objects

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

Dominant pp interactions



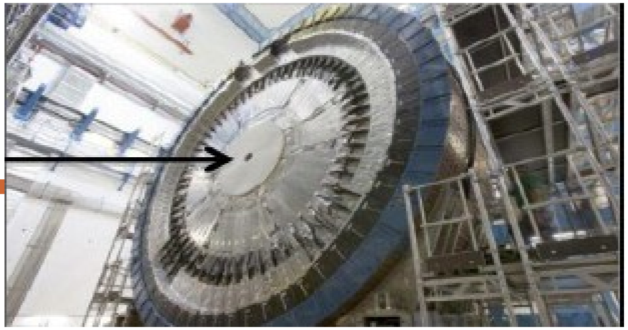
- Multi-parton interactions (**Underlying Event**)

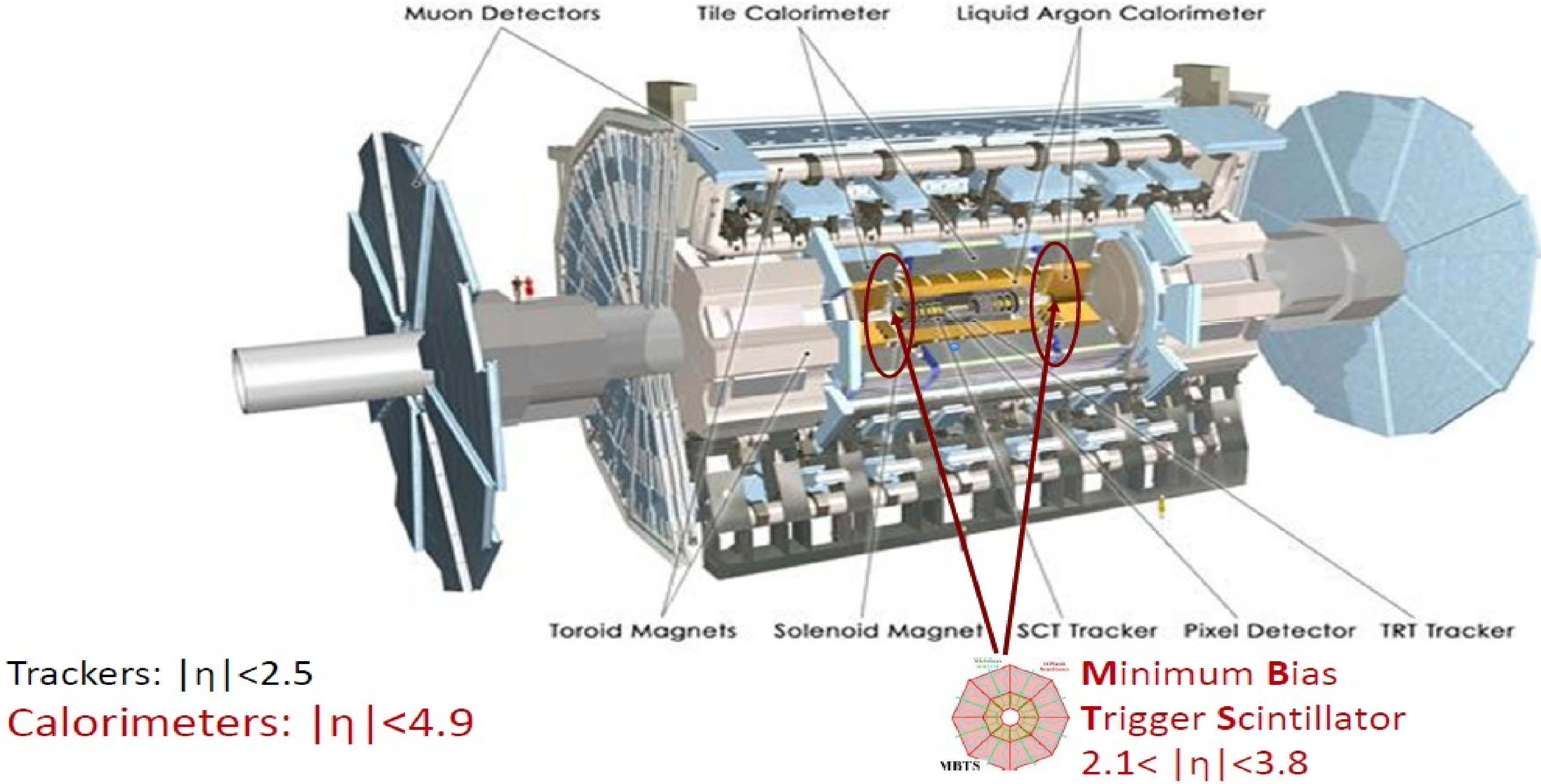


Inelastic cross-section

- Use only few runs: 7 TeV data (190 μb^{-1}) + 900 GeV data (7μb^{-1}) and 2.36TeV data (0.1μb^{-1})
  - We want to study **all** inelastic pp interactions
  - Instantaneous luminosity very low for these runs: on average ~0.007 interactions per bunch crossing → **99.3% of crossings are empty**.
  - Need to **"trigger"** on inelastic interactions: **Minimum Bias Scintillator Trigger (MBTS)**
    - ➔ sensitive to any charged particle $2.09<|\eta| < 3.84$
    - ➔ 16 counters on each side of ATLAS
- Correct for detector inefficiencies and resolution, eg. present **spectrum of charge particles** not tracks
- **No extrapolation** to regions not seen by ATLAS

MBTS trigger





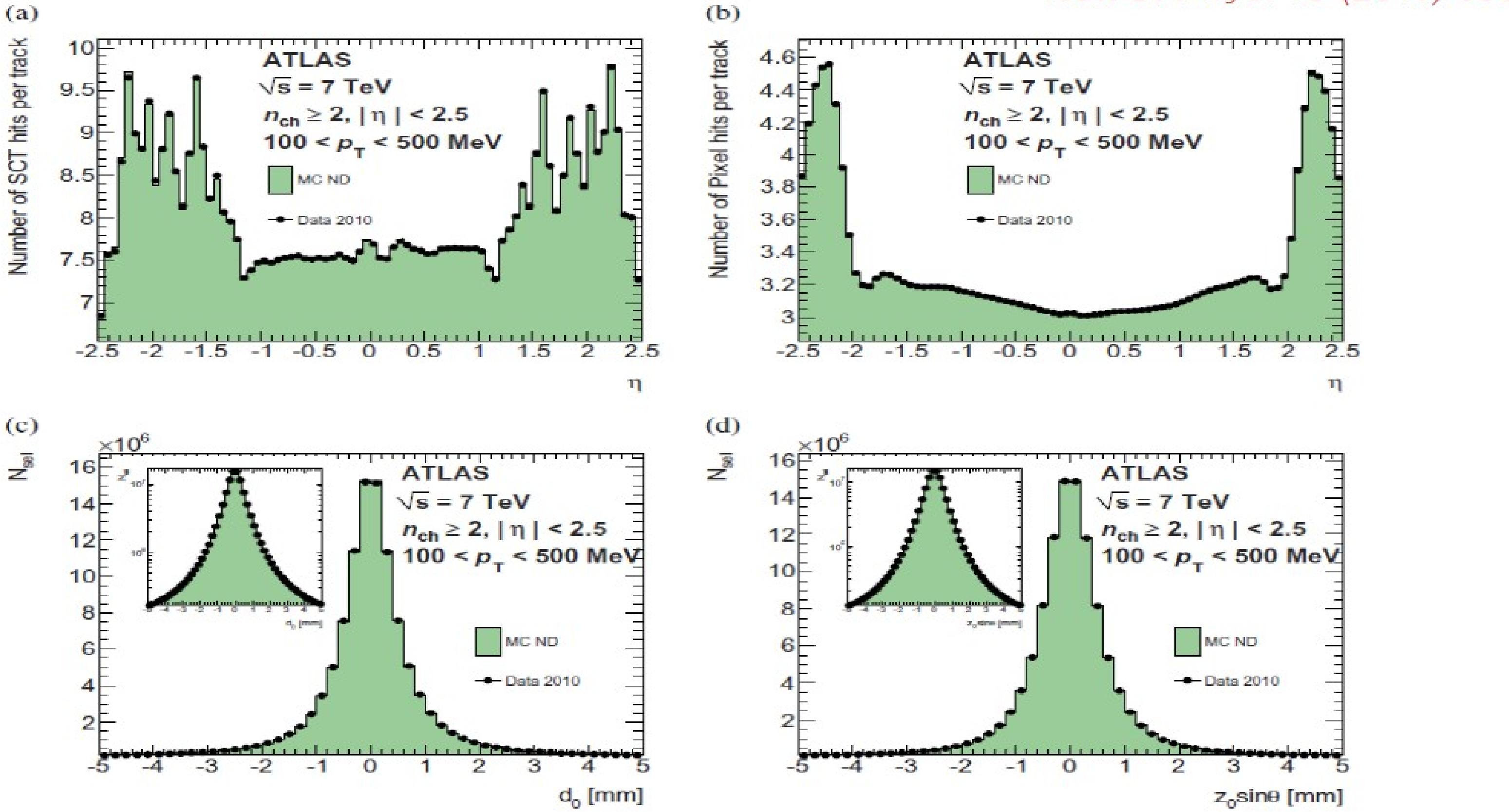
Trackers: |η|<2.5

Calorimeters: |η|<4.9

Minimum **B**ias **T**rigger **S**cintillator 2.1< |η|<3.8

How well understood detector?

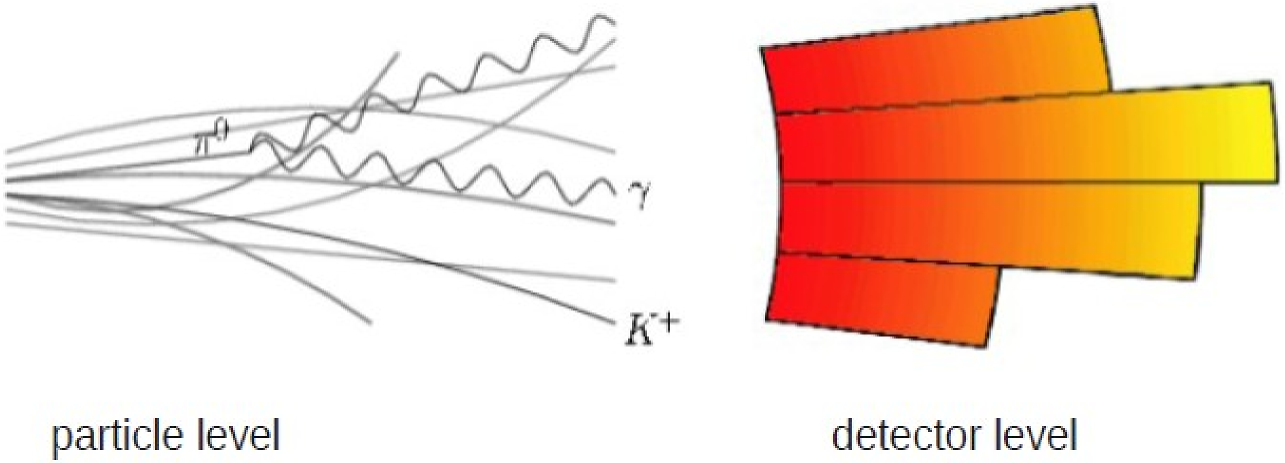
New J. Phys. 13 (2011) 053033



- Excellent agreement between data and MC: Pixel and Silicon hits per track

Unfolding to particle level

- Bayesian iterative unfolding used to correct tracks and clusters back to particle level.
  - Use mapping of truth particles on reconstructed objects (use Monte Carlo)



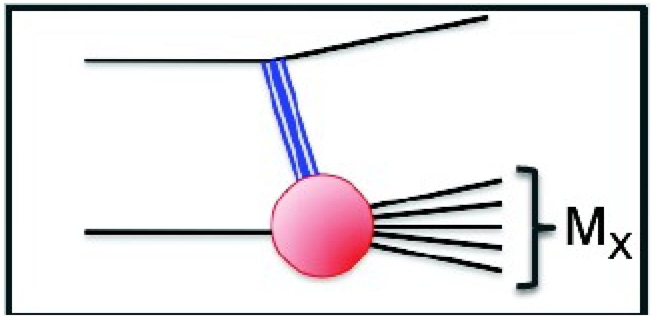
Total inelastic pp cross-section

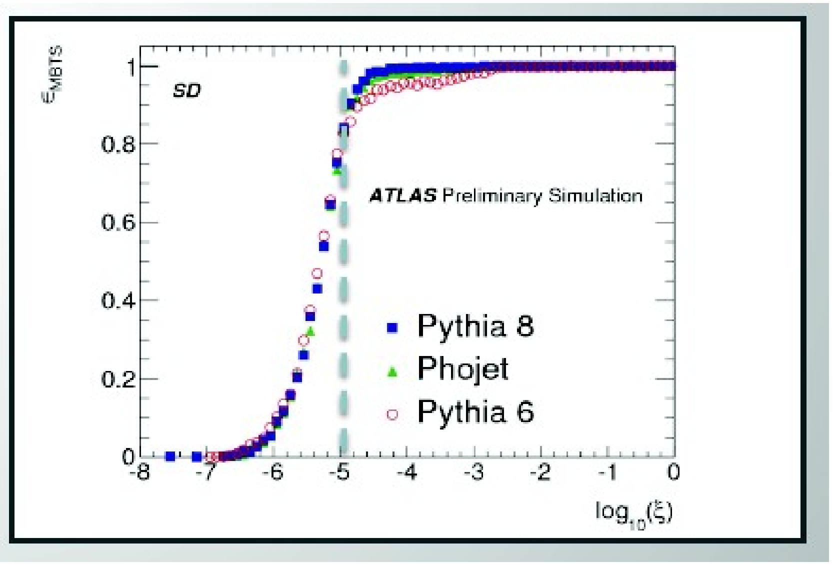
- ATLAS made measurement with new and simple method (publ. in Nature Commun.)
  - Count inelastic collisions: $N^{evts} - N^{bck}$
  - Correct for efficiencies: ε
  - Normalise with luminosity

$$\sigma_{inel} = \frac{N^{evts} - N^{bck}}{\varepsilon \times \mathcal{L}}$$

$\xi = M^2_X/s$

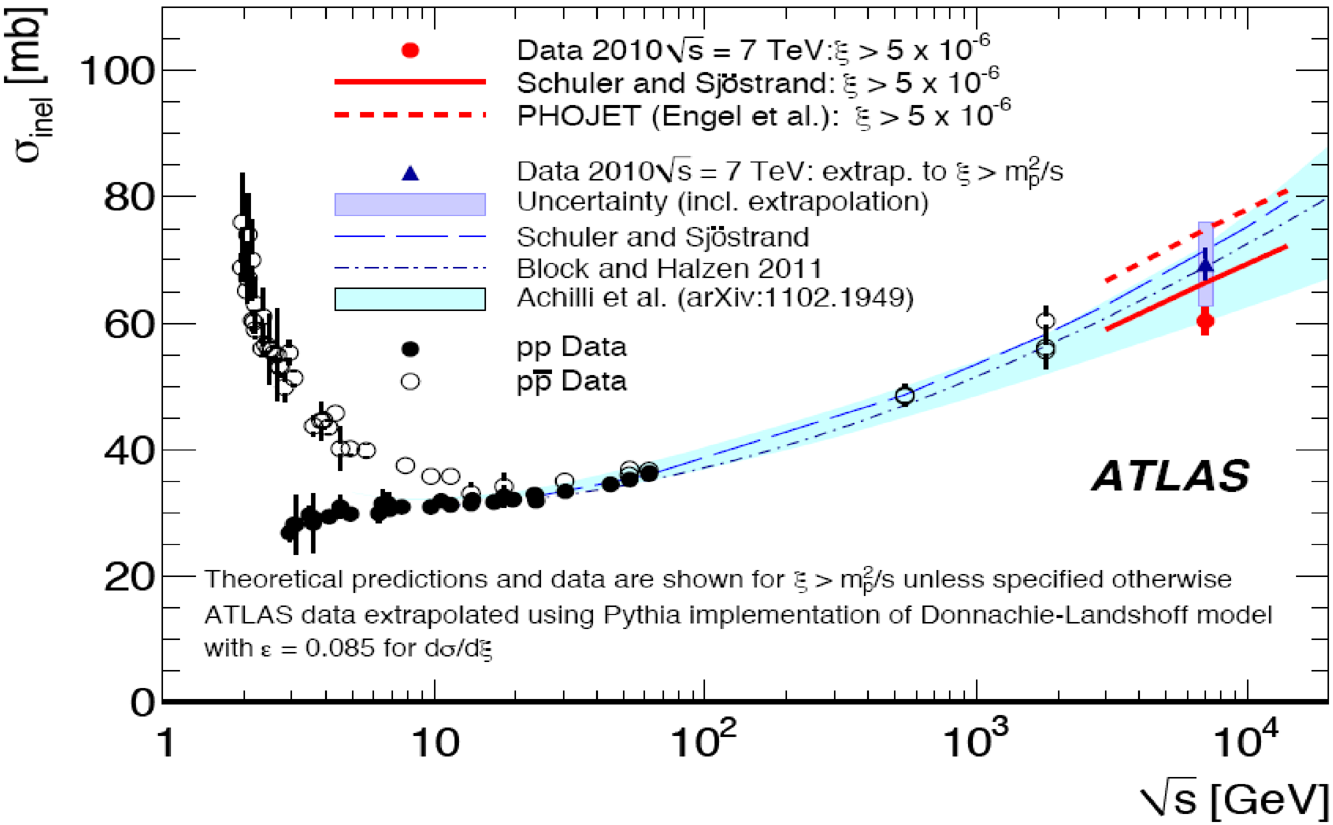
Restrict measurement to $\xi > 5\times10^{-6}$ ($M_X > 16$ GeV)



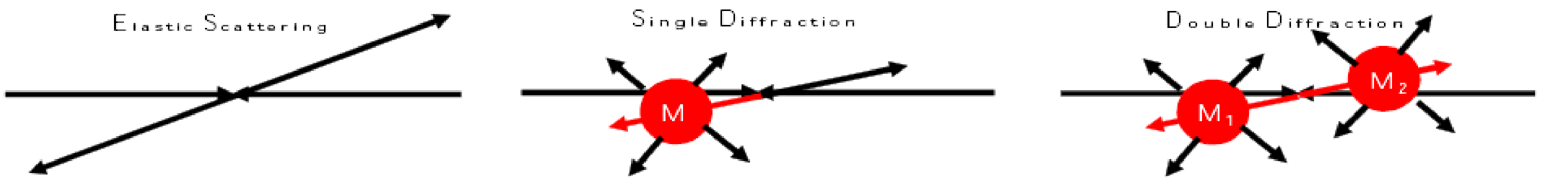


Total inelastic pp cross-section

$$\sigma(\xi > 5\cdot 10^{-6}) = 60.3 \pm 0.05\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{sys.}) \pm 2.1\,(\mathrm{lumi})\ \mathrm{mb}$$
$$\sigma_{inel} = 69.1 \pm 2.4\,(\mathrm{exp.}) \pm 6.9\,(\mathrm{extr.})\ \mathrm{mb}$$

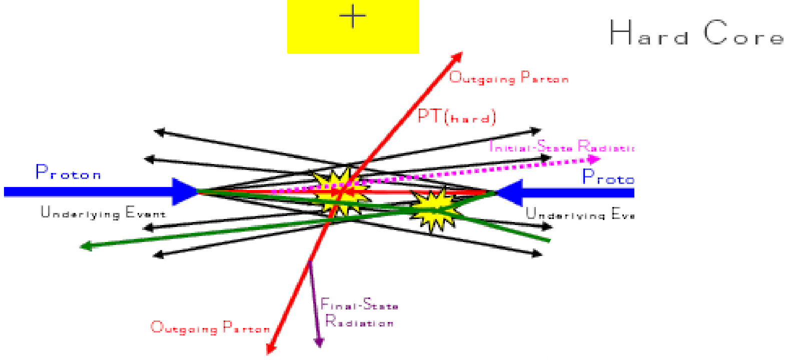


Total cross-section



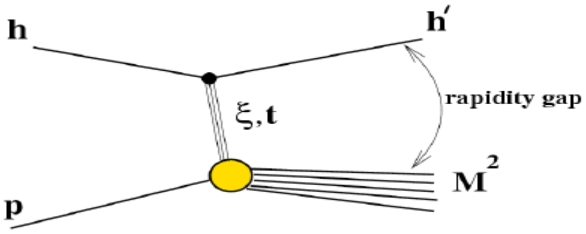
+

Rick Field's
Pictorial
Representation



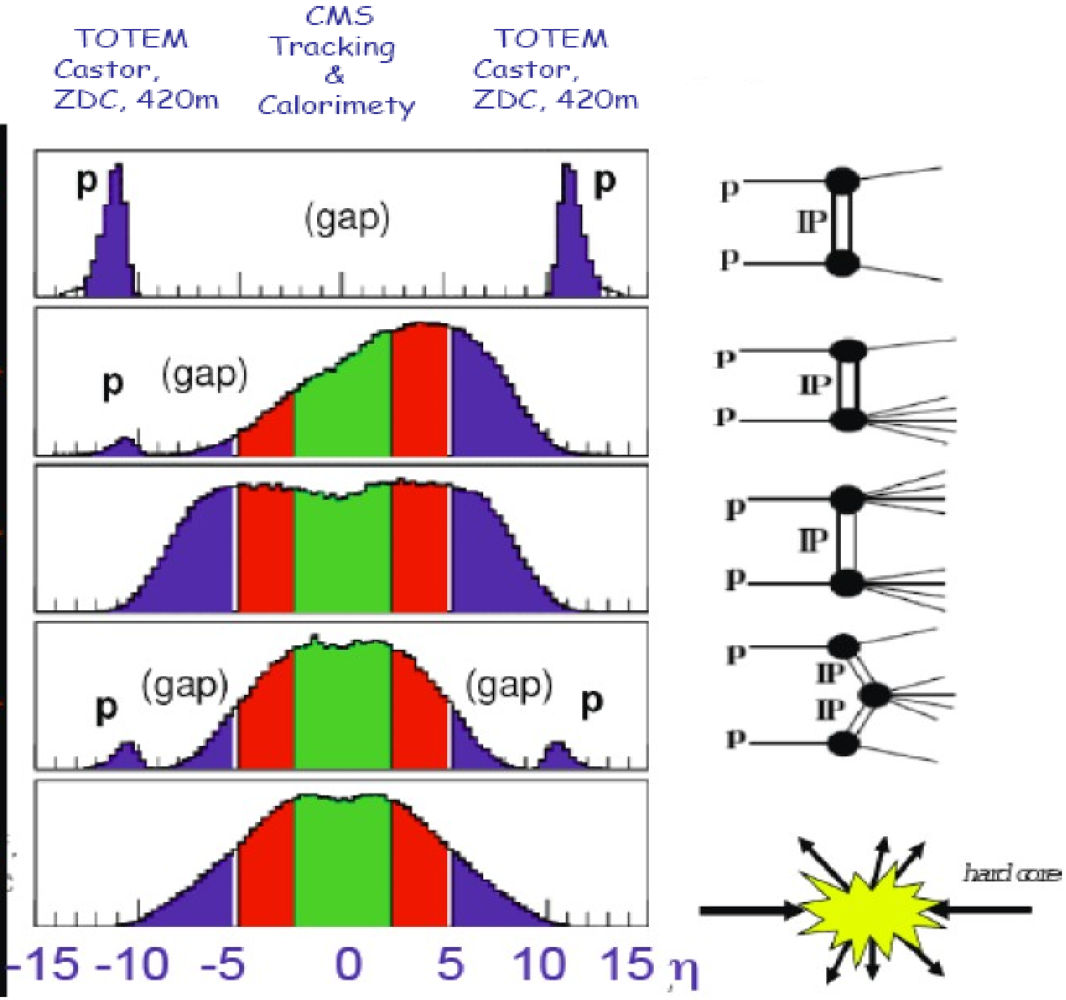
Elastic and diffractive processes
⇨ leading hadron emitted at small angle

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



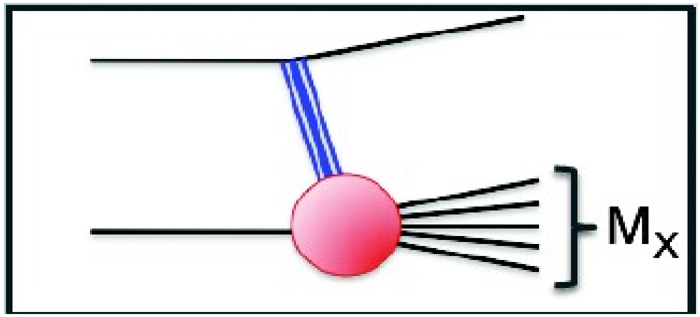
Characteristic in pseudorapidity

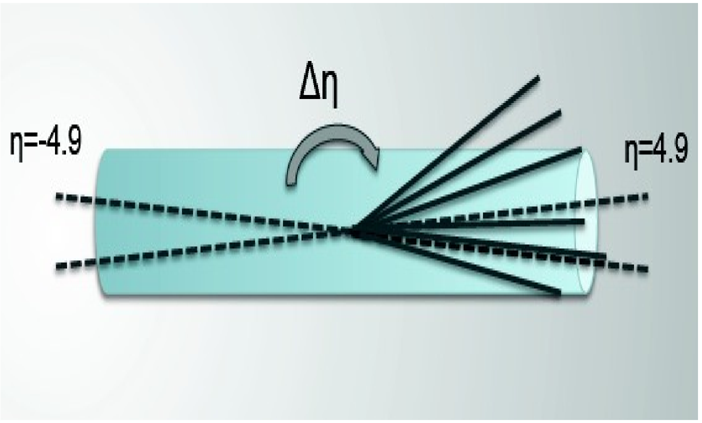
- *Elastic*
  (25% of σ_{tot})
- *Single diffractive*
  (10% of σ_{tot})
- *Double diffractive*
  (~1% if σ_{tot})
- *Central diffractive*
  DPE (~1% if σ_{tot})
- *Inelastic*
  (non diffractive)
  (60% of σ_{tot})



Gap cross-section

- Diffractive events tend to have large “rapidity gaps”
- Measure σ vs Δη (large Δη dominated by diffraction)

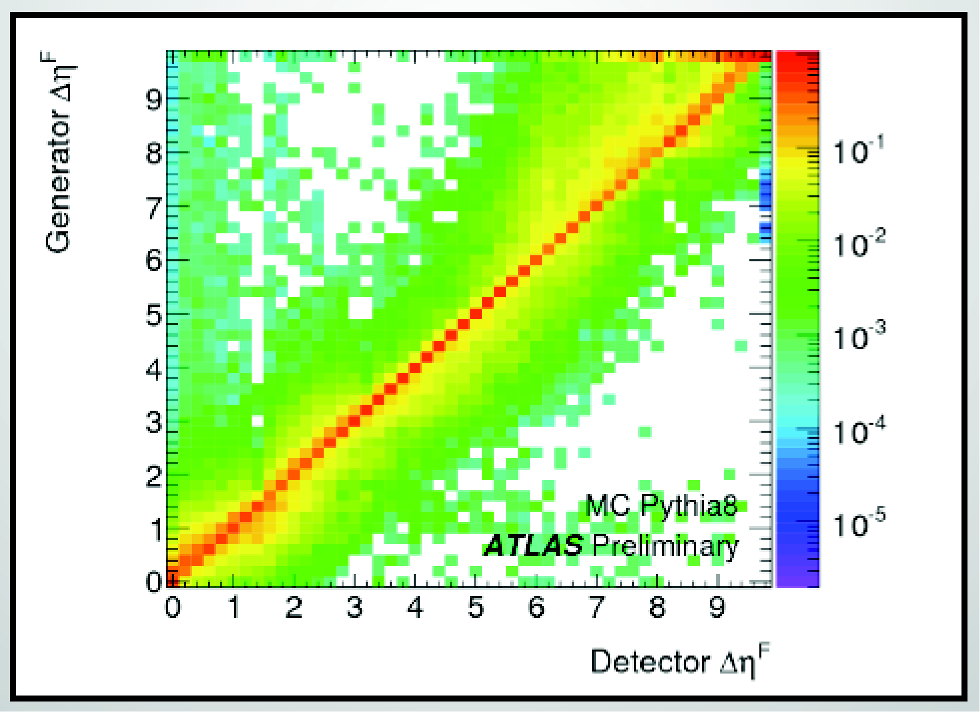




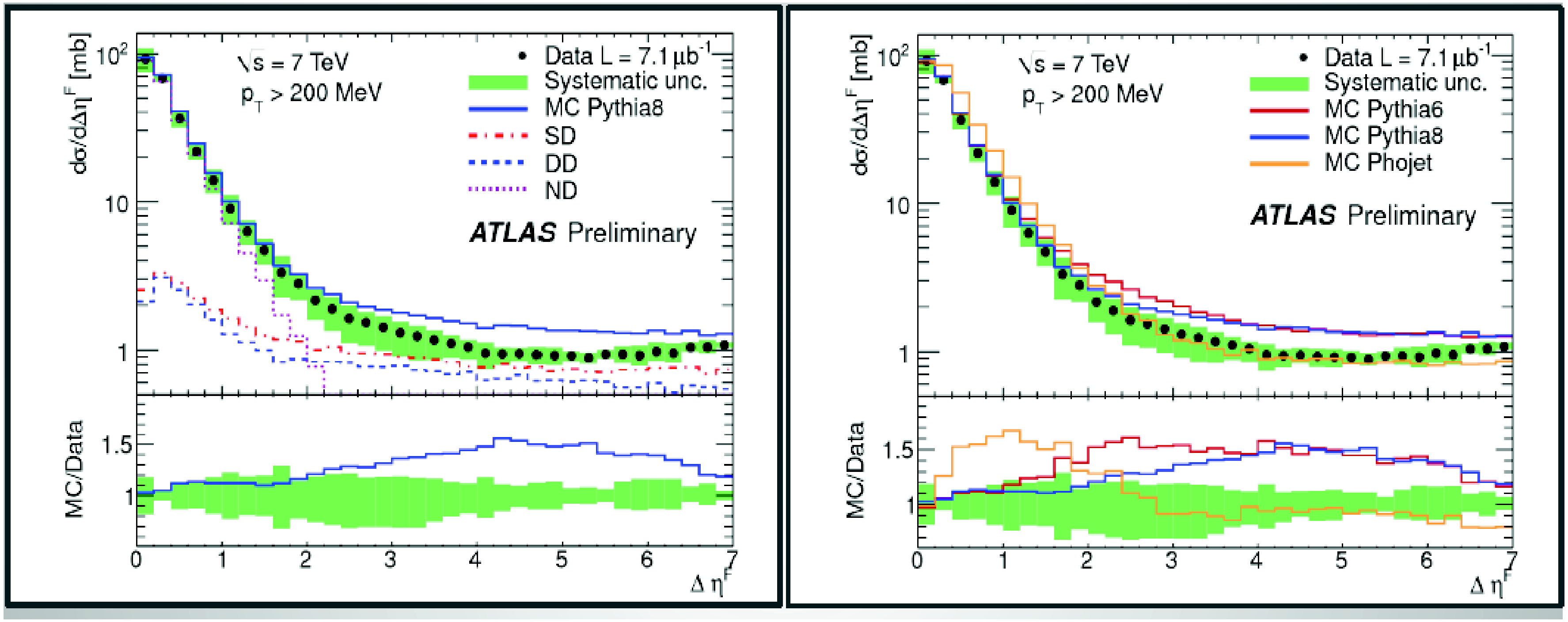
- Detector split into h rings (0.2 wide)
- Ring (detector) is empty if:
  - No calorimeter cells above threshold |η| < 4.9
  - No Inner Detector tracks |η| <2.5 with p_T>200 MeV
- Ring (Monte Carlo) is empty
  - No particles with p_T>200 MeV

Gap cross-section

- Unfolding matrix



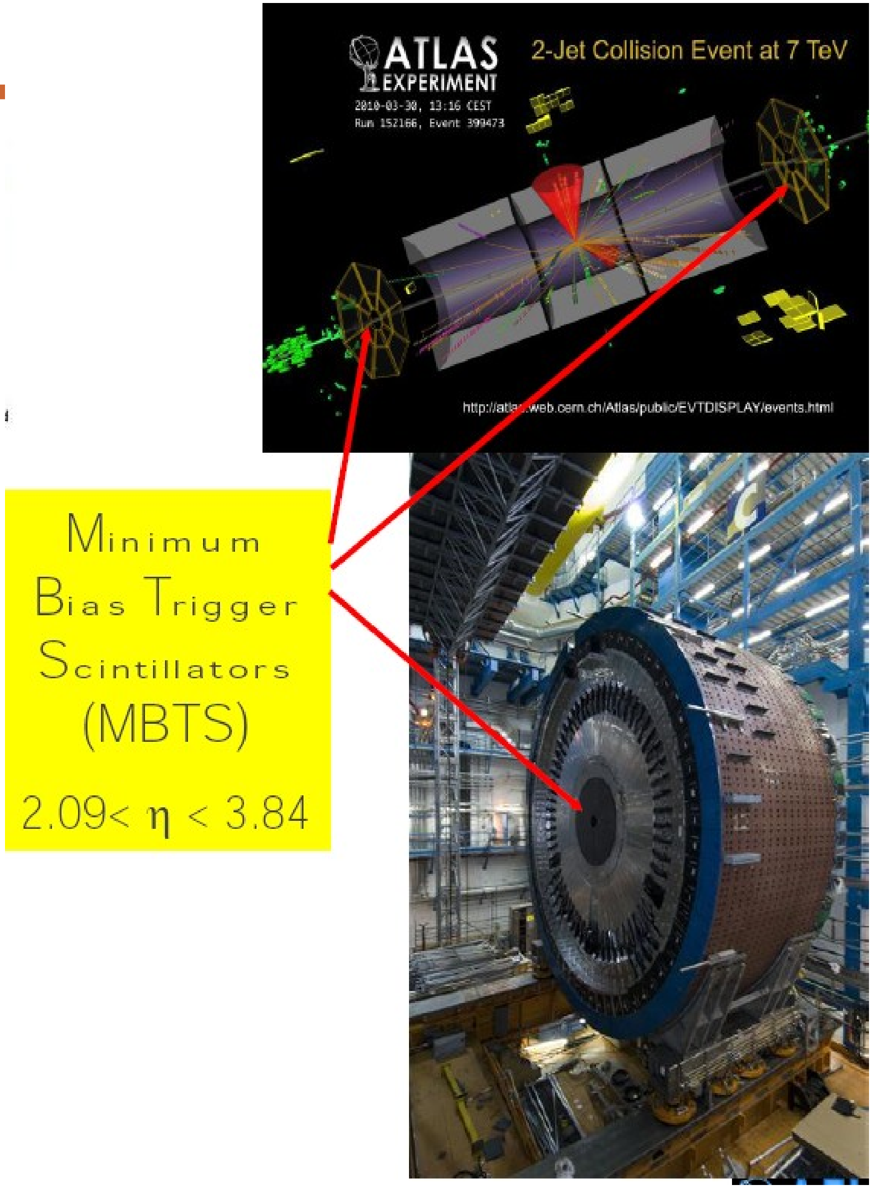
Gap cross-section



- Dominant systematic uncertainties
  - MC model dependence of corrections
  - Calorimeter energy-scale

Minimum bias

- Minimum bias events: minimum possible requirements that ensure an inelastic collision occurred
  - Require 1 MBTS counter to fire on either side
  - Require reconstructed primary vertex
  - At least N good quality tracks

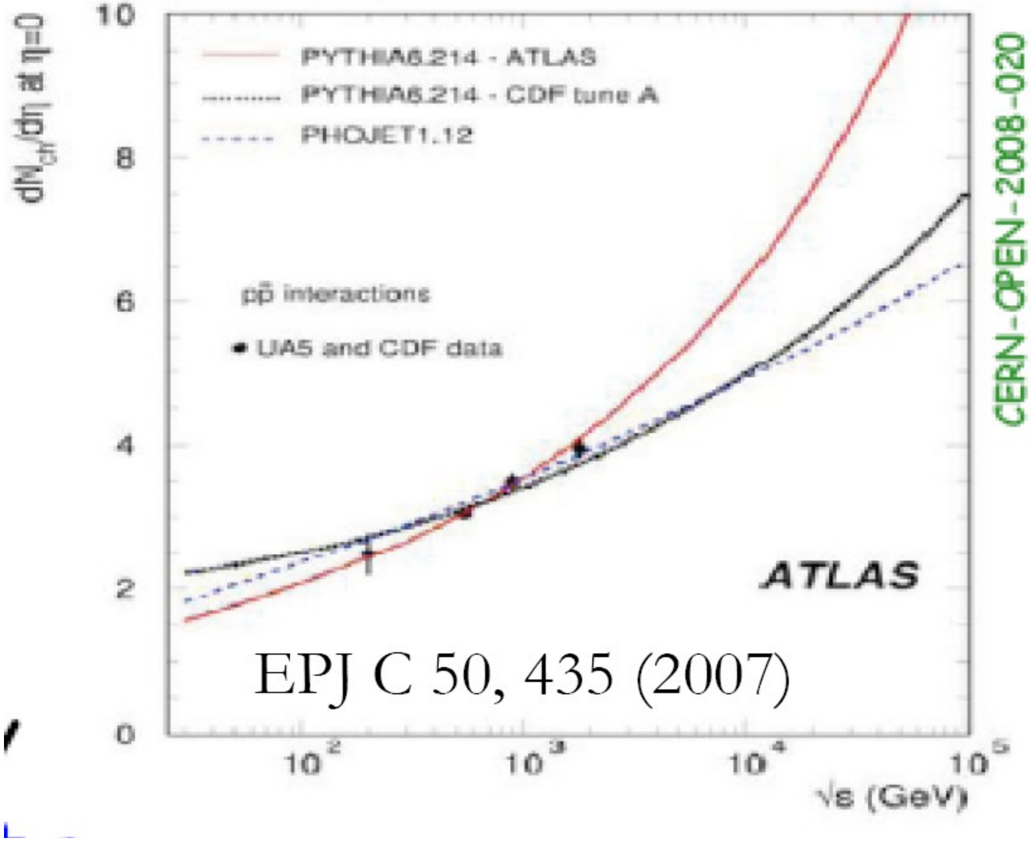


Minimum Bias Trigger Scintillators (MBTS)

$2.09 < \eta < 3.84$

Minimum bias at LHC

- Pre-LHC era

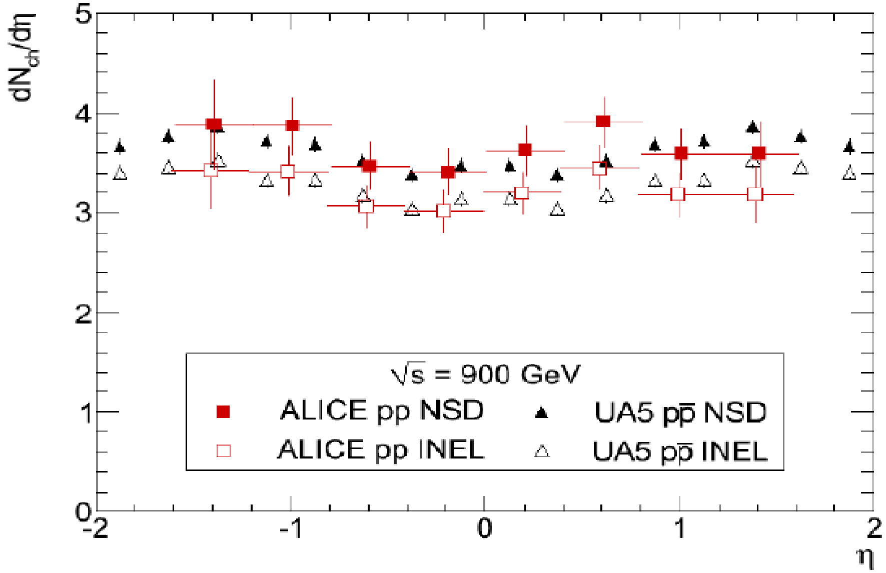


EPJ C 50, 435 (2007)

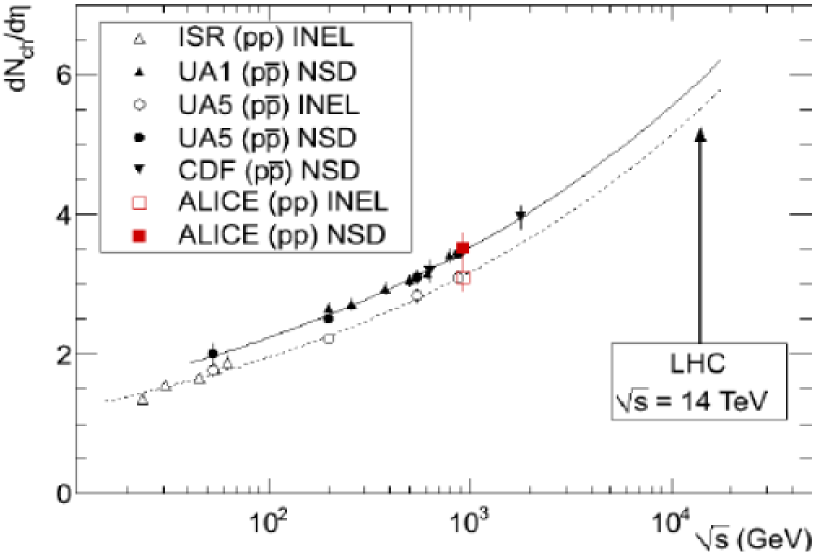
CERN-OPEN-2008-020

ALICE publication

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



$|\eta| < 0.5$

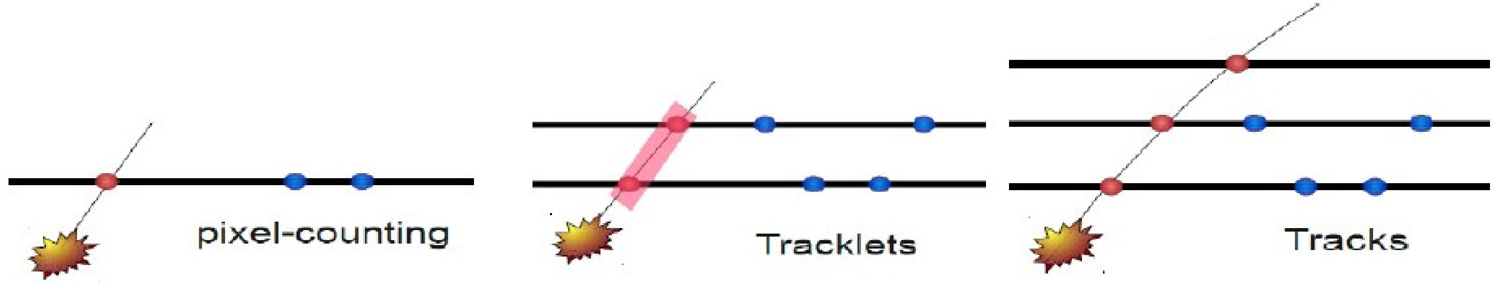


European Physical Journal C: Volume 65, Issue 1 (2010), Page 111

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

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

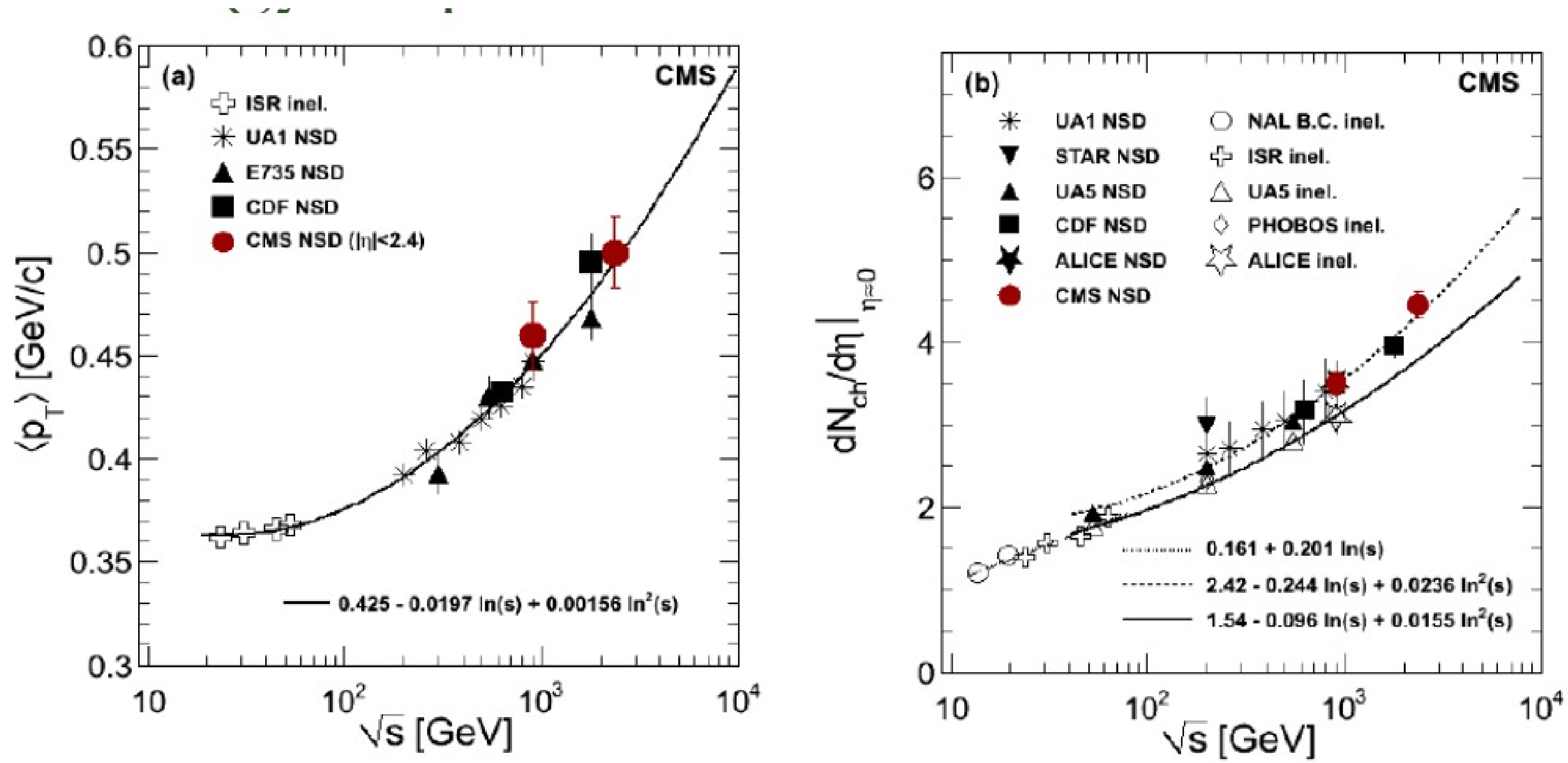
Tracks

dN/dη and dN/dpT

  - Most robust against backgrounds

Sensitivity: 100MeV/c

Energy dependence



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

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

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

Atlas analysis strategy

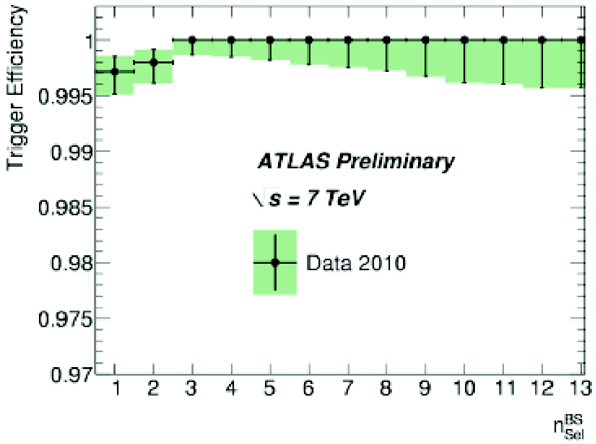
- Use charged particle multiplicity distributions to probe soft QCD:

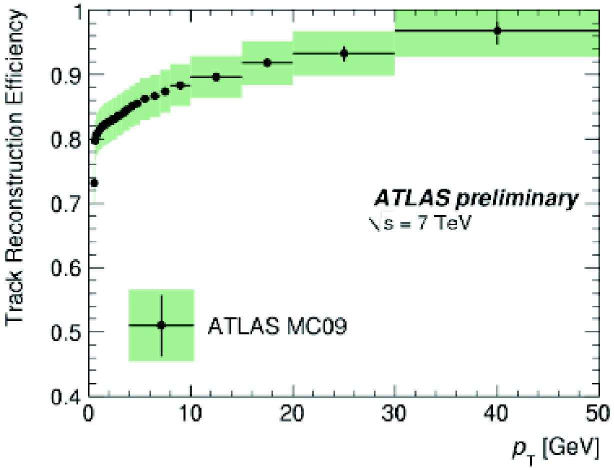
$$\frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}, \quad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{1}{2\pi p_{\mathrm{T}}} \cdot \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}\eta\,\mathrm{d}p_{\mathrm{T}}}, \quad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}n_{\mathrm{ch}}}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

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

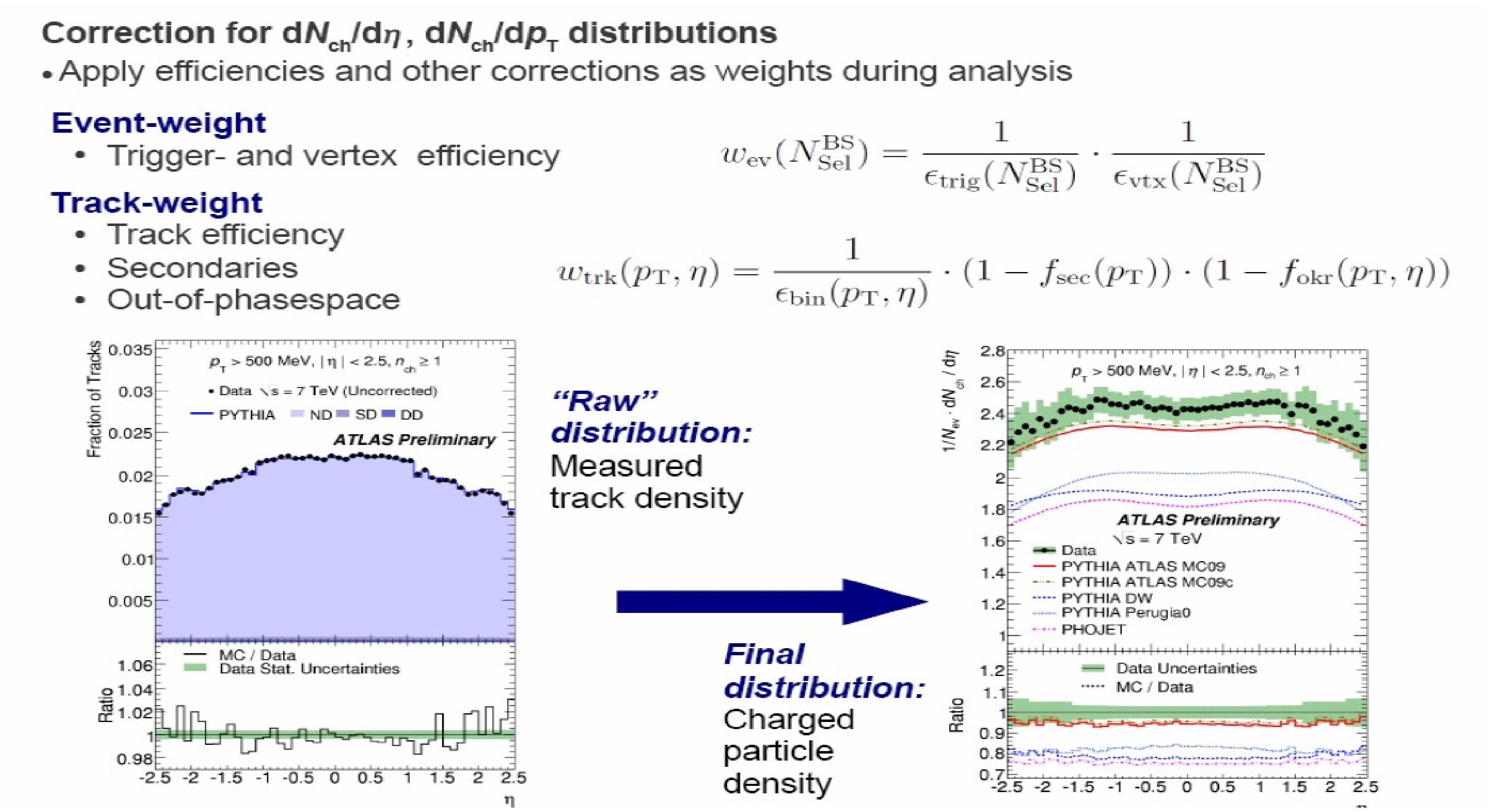
Efficiency correction from Monte Carlo

- 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

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

Track-weight

- Track efficiency
- Secondaries
- Out-of-phasespace

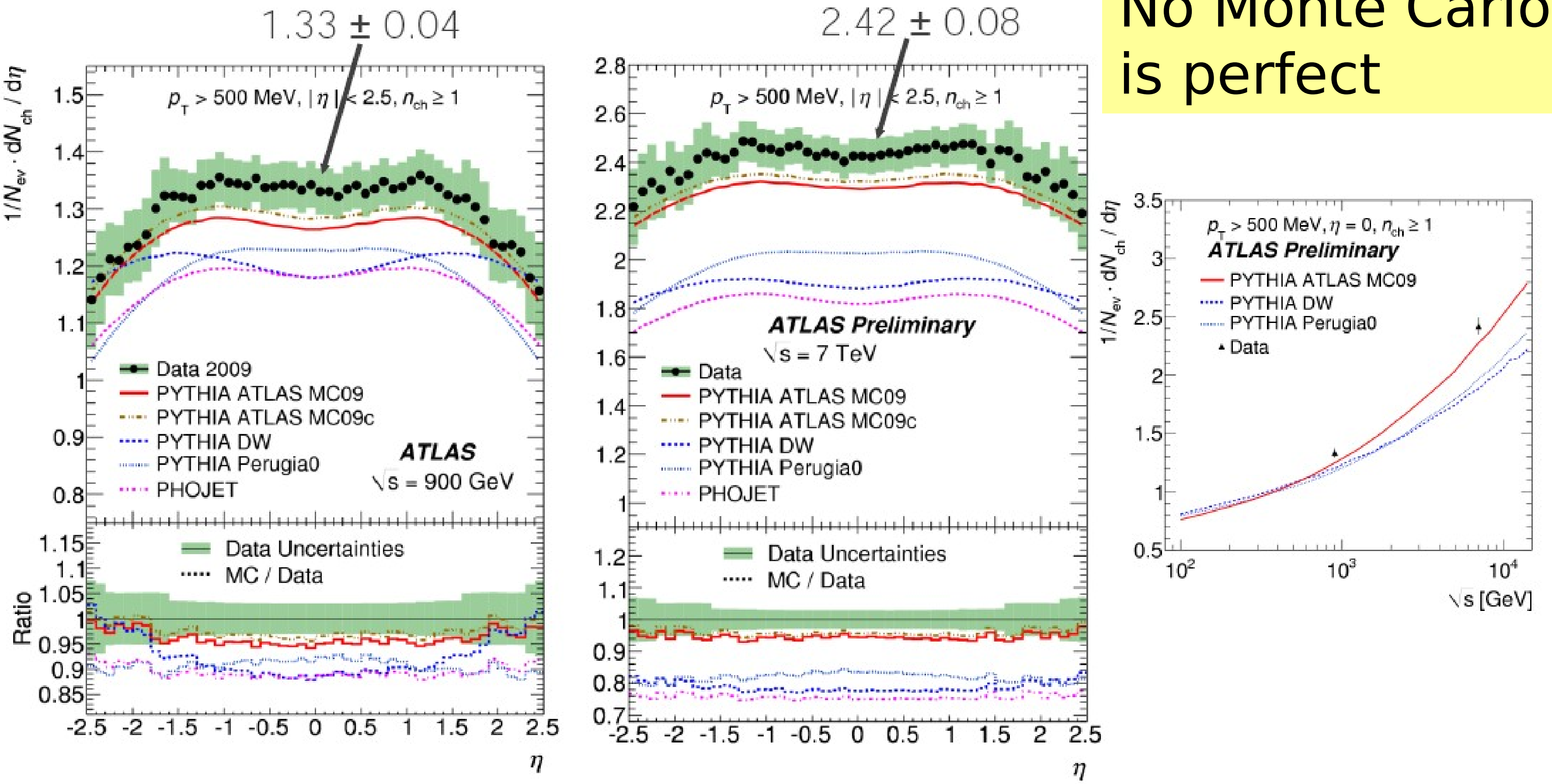
$$w_{\rm trk}(p_{\rm T},\eta) = \frac{1}{\epsilon_{\rm bin}(p_{\rm T},\eta)}\cdot(1-f_{\rm sec}(p_{\rm T}))\cdot(1-f_{\rm okr}(p_{\rm T},\eta))$$

"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

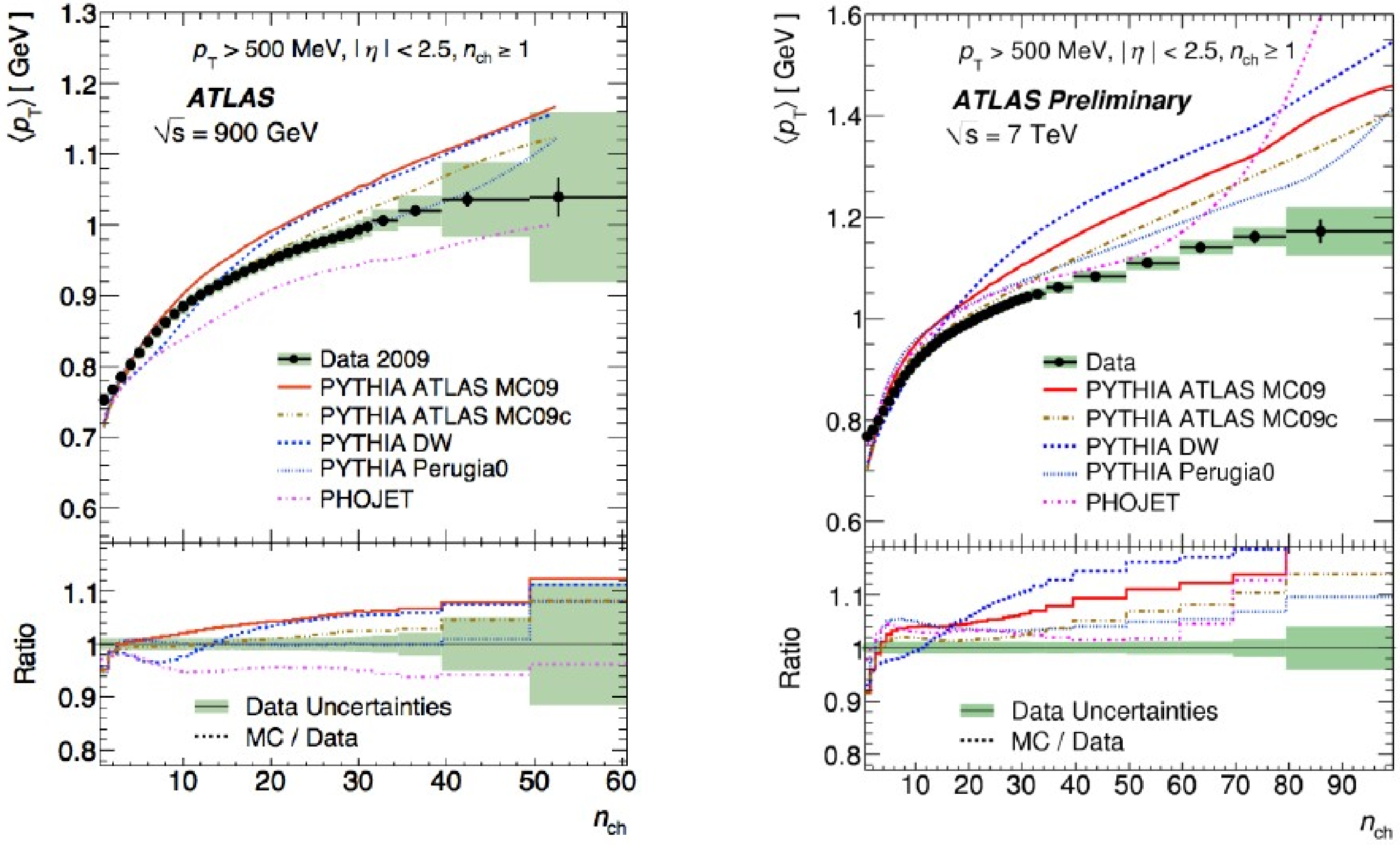


No Monte Carlo is perfect

p_T spectra

All disagree with data for high charged particle multiplicity

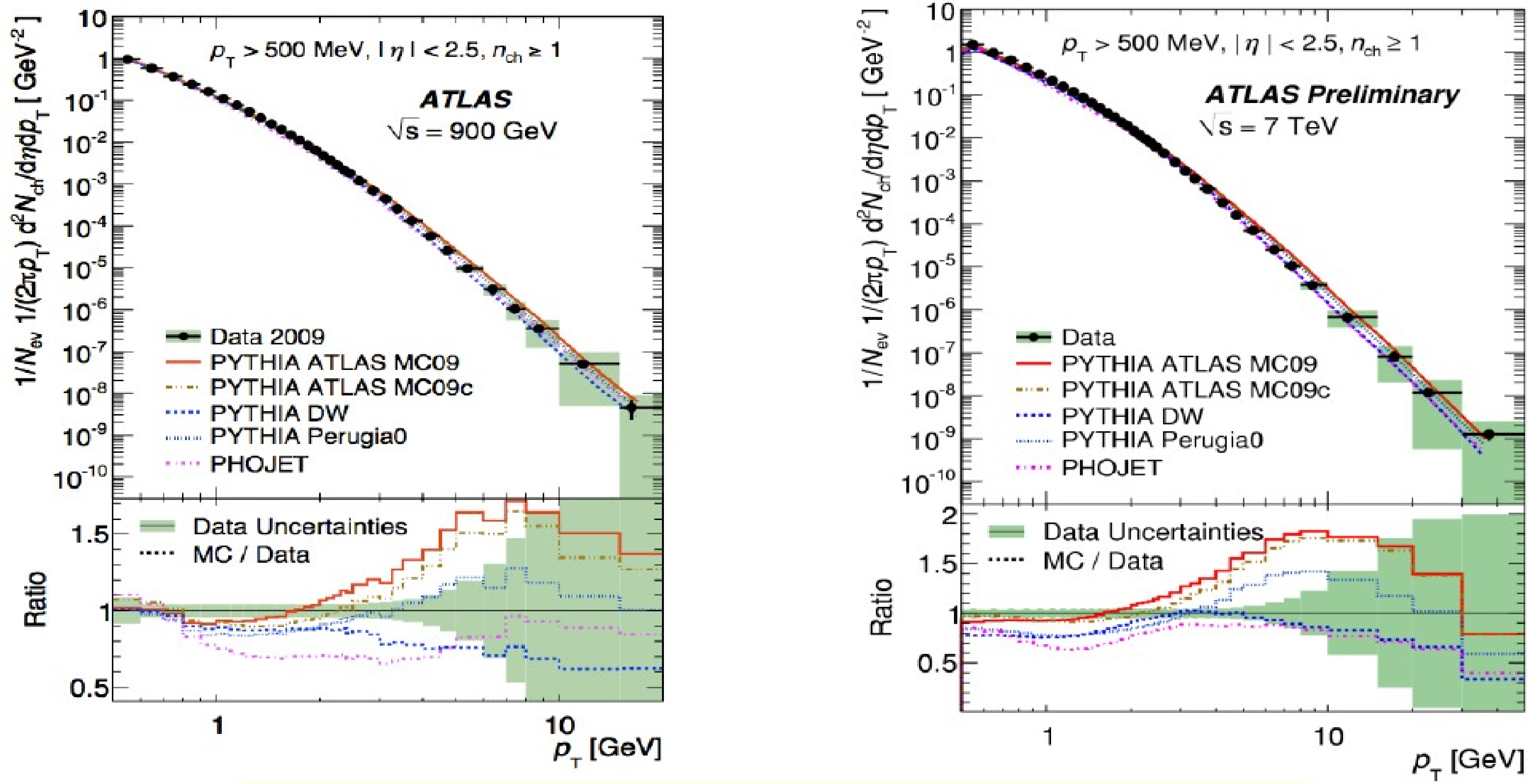
$\langle P_t \rangle$ vs n_{ch}: 900 GeV and 7TeV



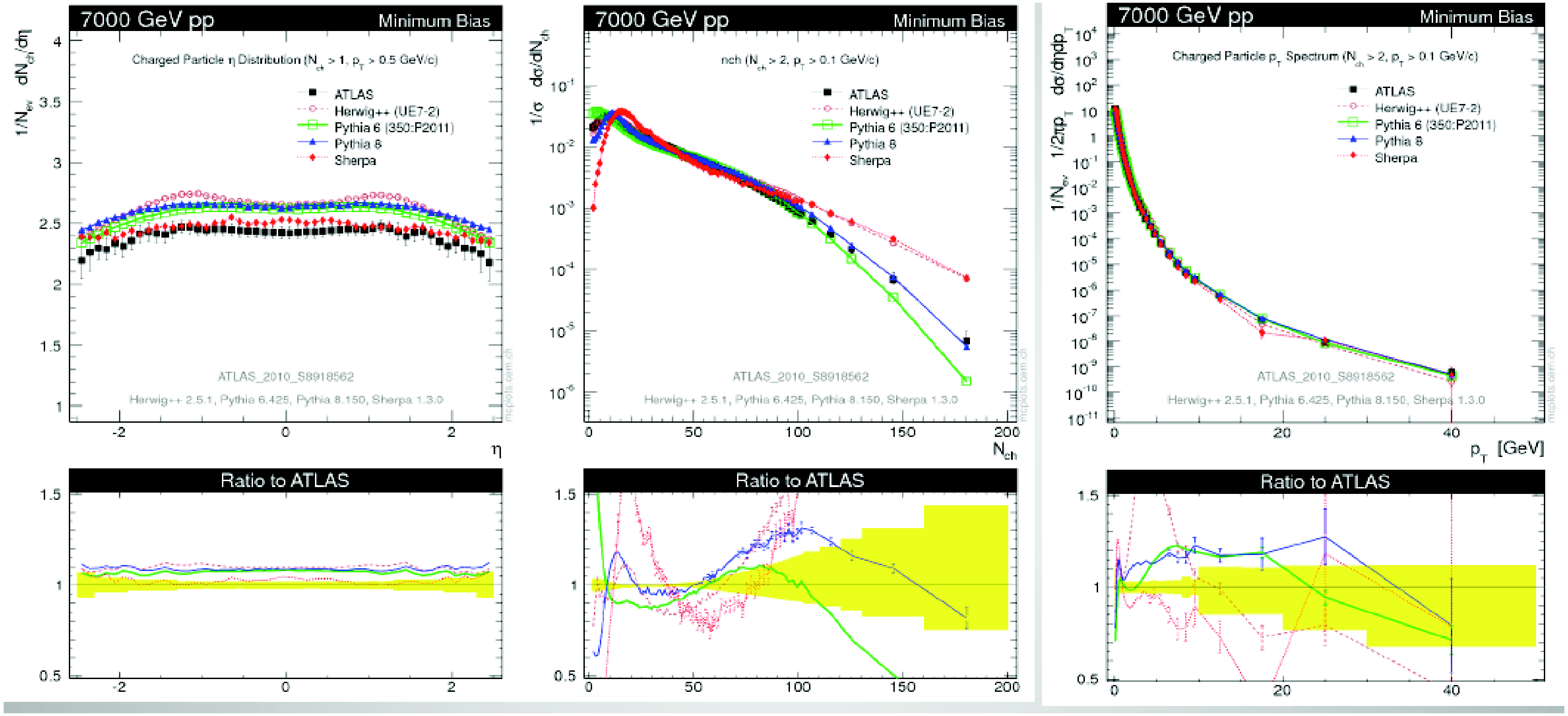
p_T spectra

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

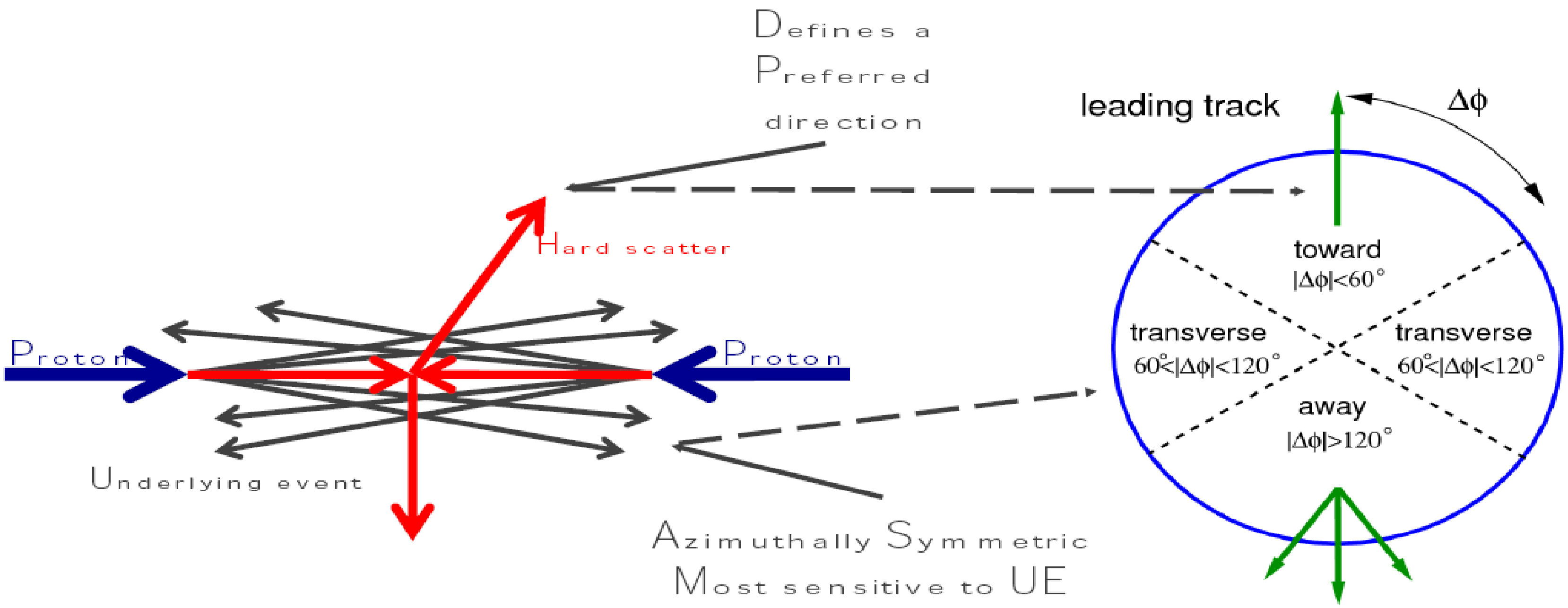
p_T spectrum $1/N_{ev}\,(1/2\pi p_T)\,d^2N_{ch}/d\eta dp_T$



Example of comparison

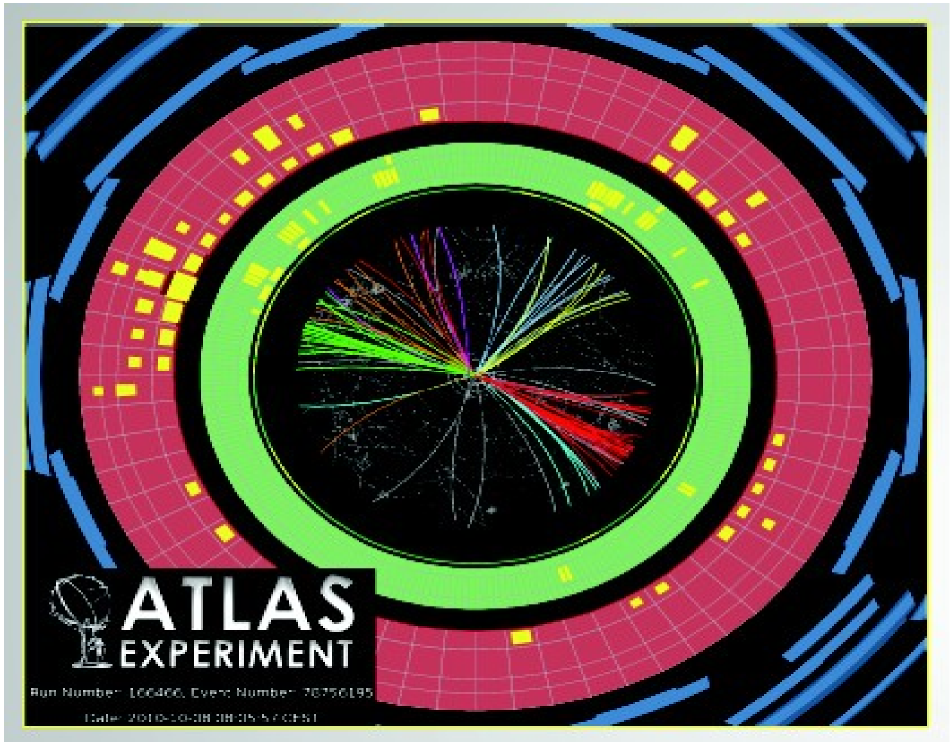


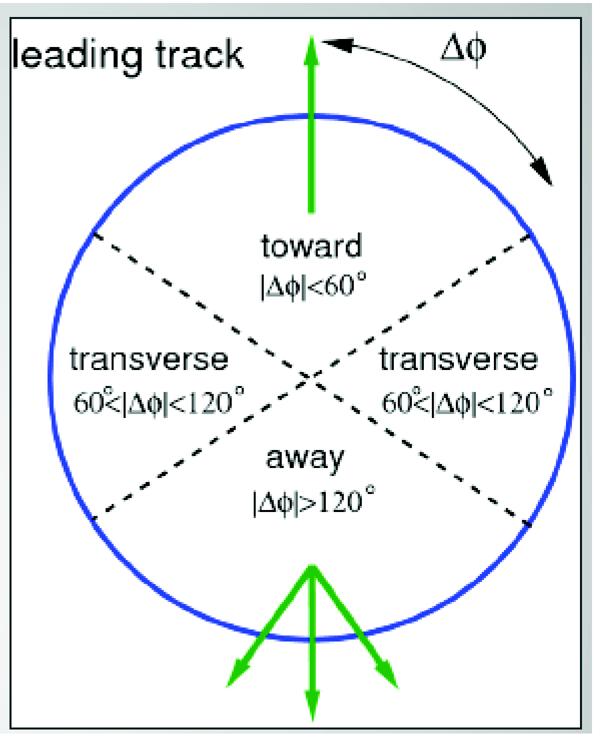
Underlying event



- 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

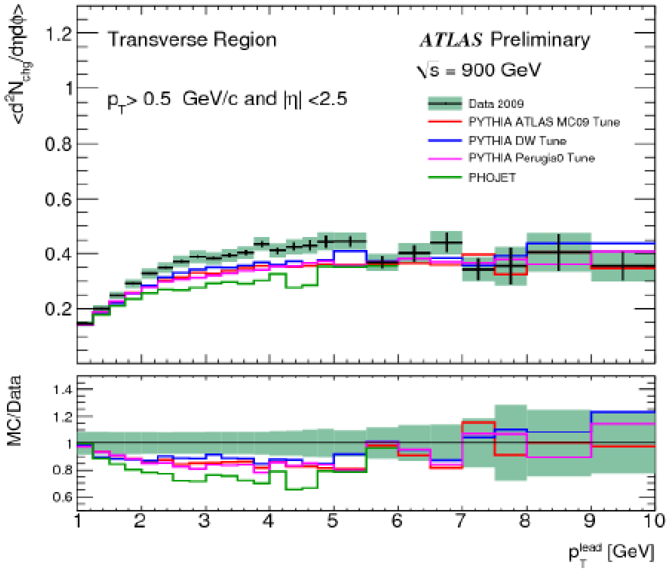
“Underlying event”

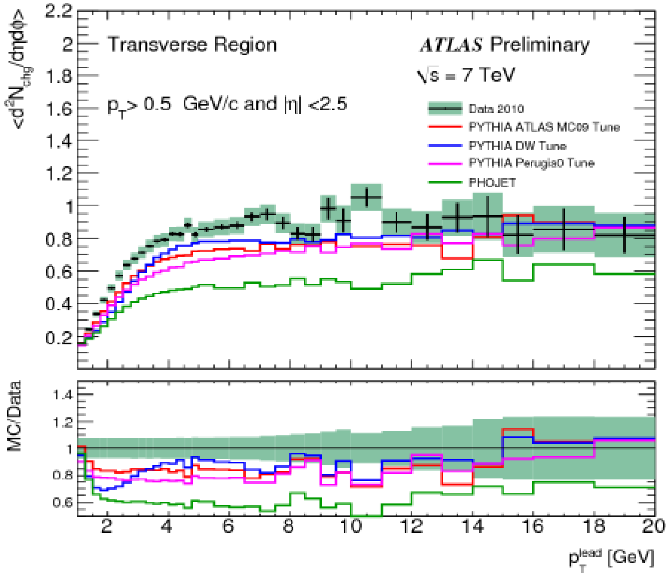




- Define the direction of “hard scatter” as the highest p_T particle
- Study the activity (#of particles) in the region “transverse” to the hard scatter.

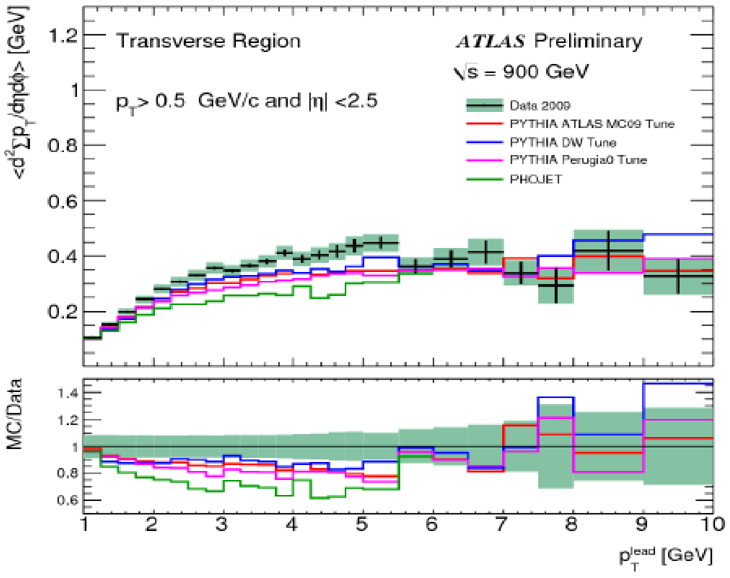
Transverse region particle density

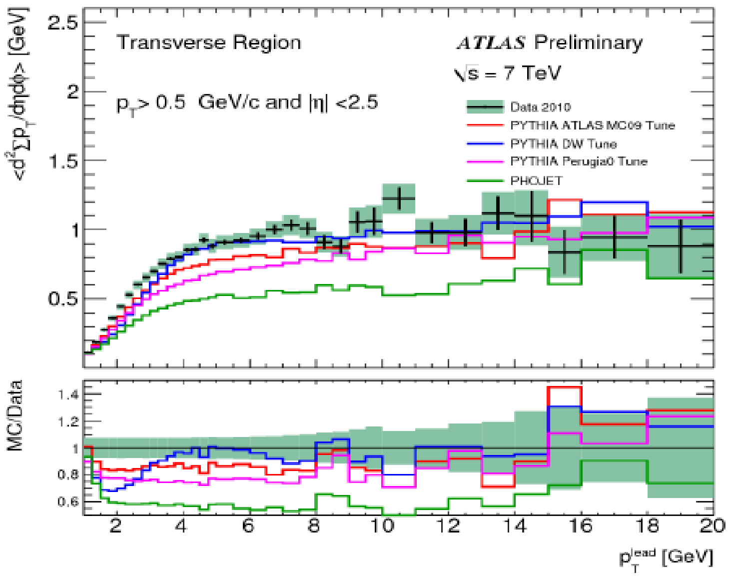




- All tunes underestimate particle density by 10%-15% in the plateau region
- There is factor of ~2 increase in activities between 900 GeV and 7 TeV
- In the plateau region the measured density corrsponds to ~ 2.5 per unit η at 900 GeV and 5 particle at 7 TeV

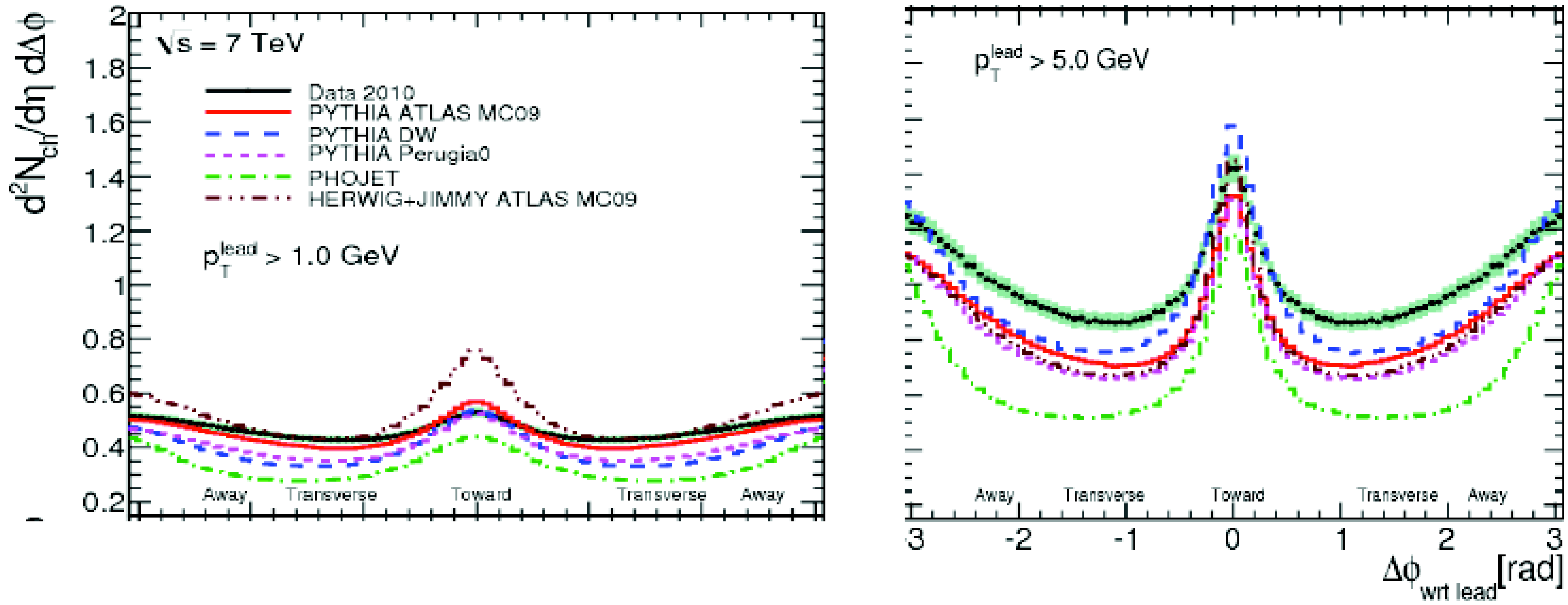
Transverse region <Σp_T> density





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

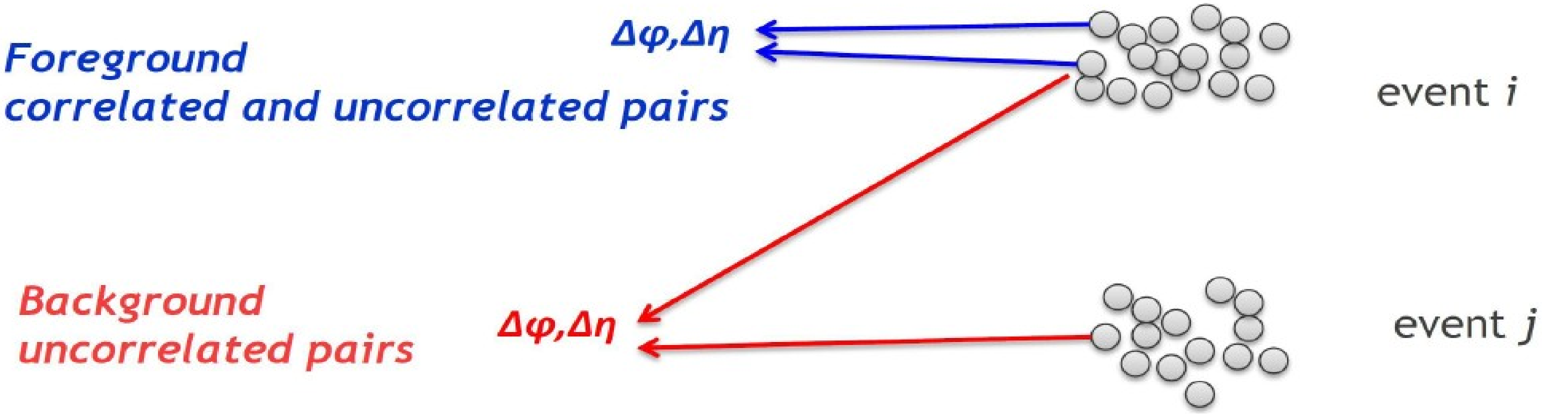
Particle Density Angular Correlation



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

Two-particle correlations

$$R(\Delta\eta, \Delta\phi) = \frac{\langle (N_{ch} - 1)\, F(N_{ch}, \Delta\eta, \Delta\phi) \rangle_{ch}}{B(\Delta\eta, \Delta\phi)} - \langle N_{ch} - 1 \rangle_{ch}$$



- Multiplicity-independent 2-particle correlations over the multiplicity averaged background.

Two-particle correlations

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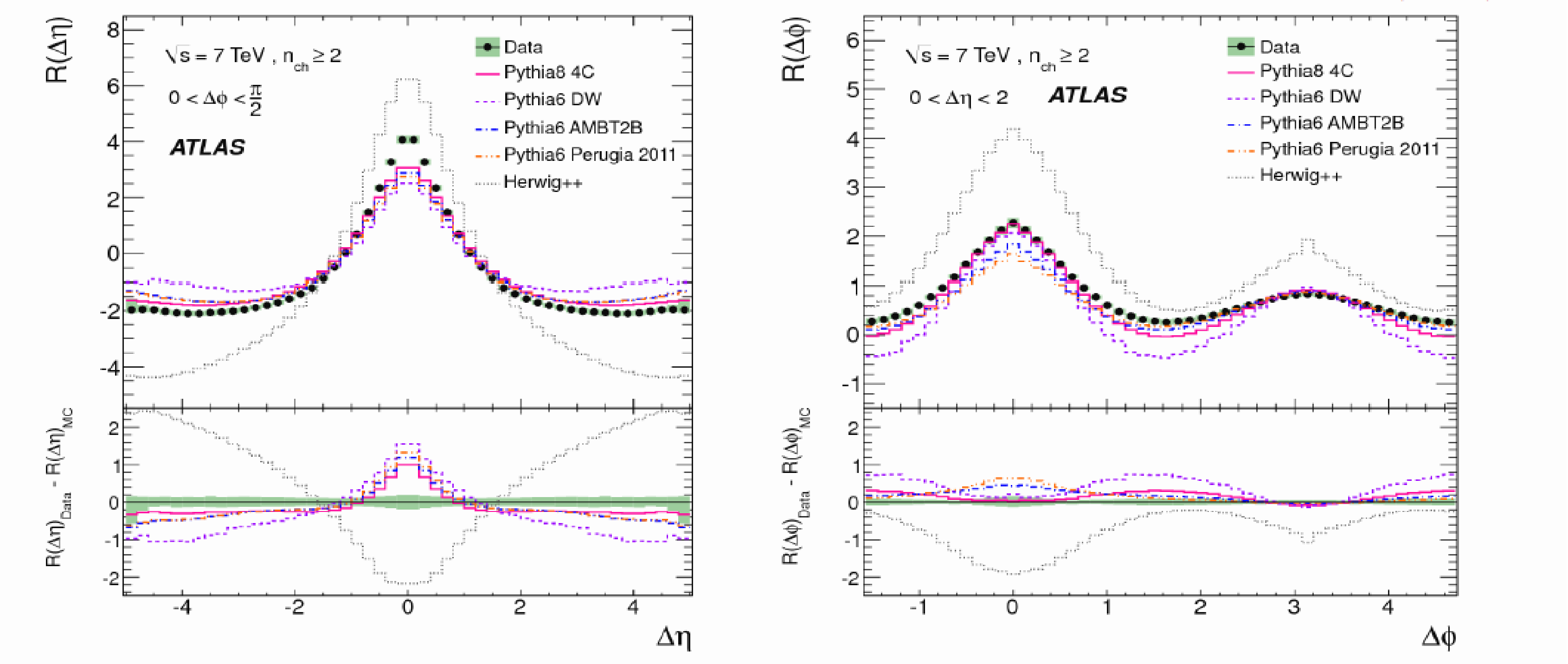
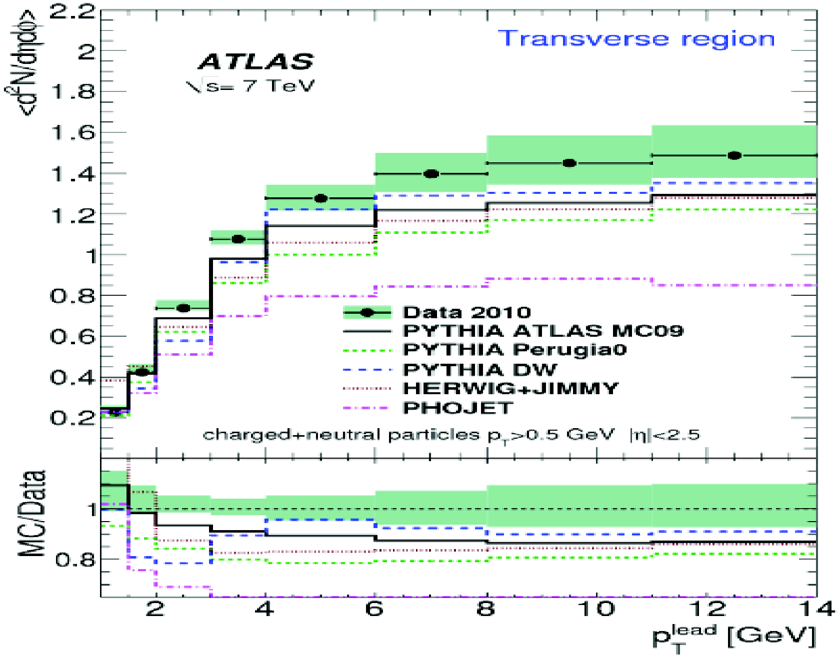


- Data demonstrate existence of 2-particle angular correlations of different types.
- MC reproduces general features but not the strength

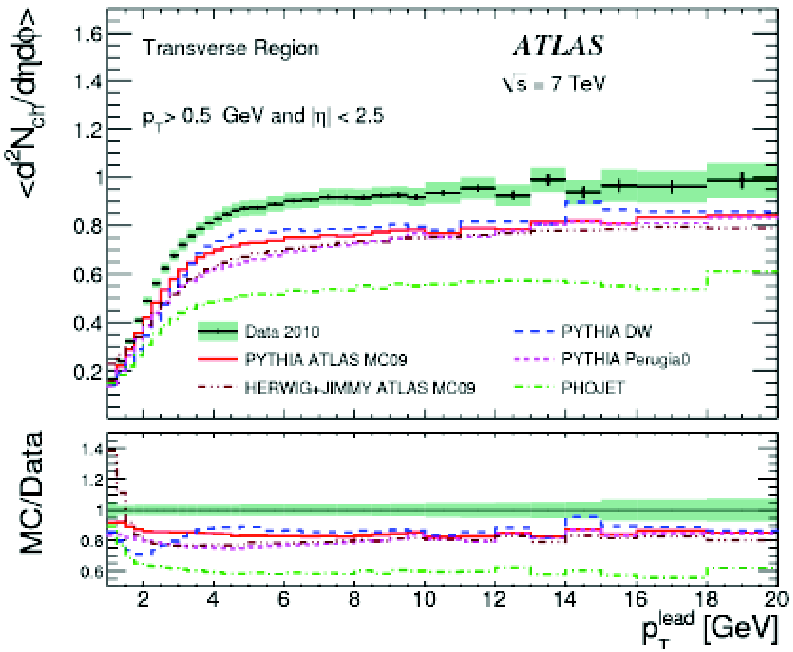
UE results with calorimeter

- Count calorimeter clusters instead of tracks, sensitive also to neutral particles

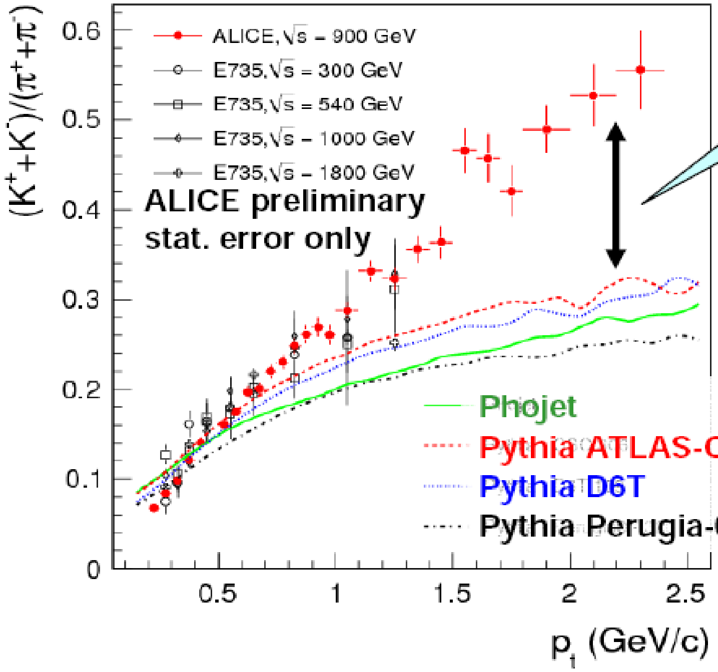
Calorimetric clusters count



Charged particles count



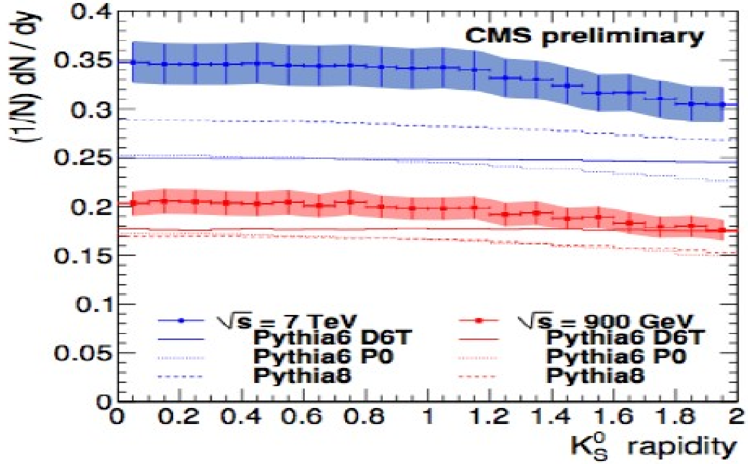
Strange particle production



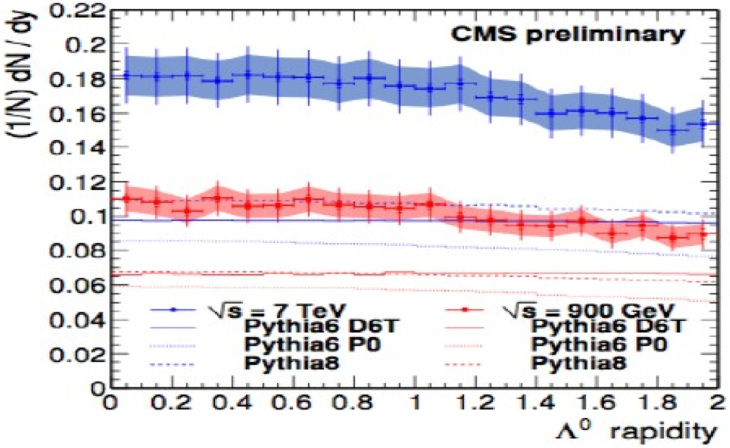
Factor of 2!

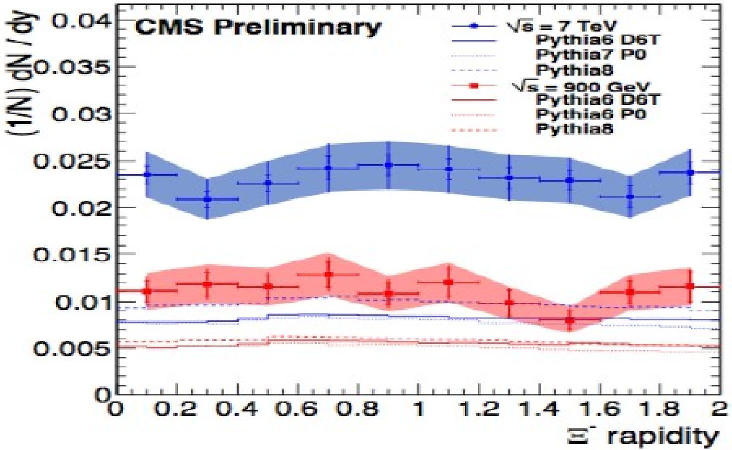
- A lot more strange mesons at large p_T than predicted by models
- K/π ratio fairly independent of the centre-of-mass energy

Strange particle production

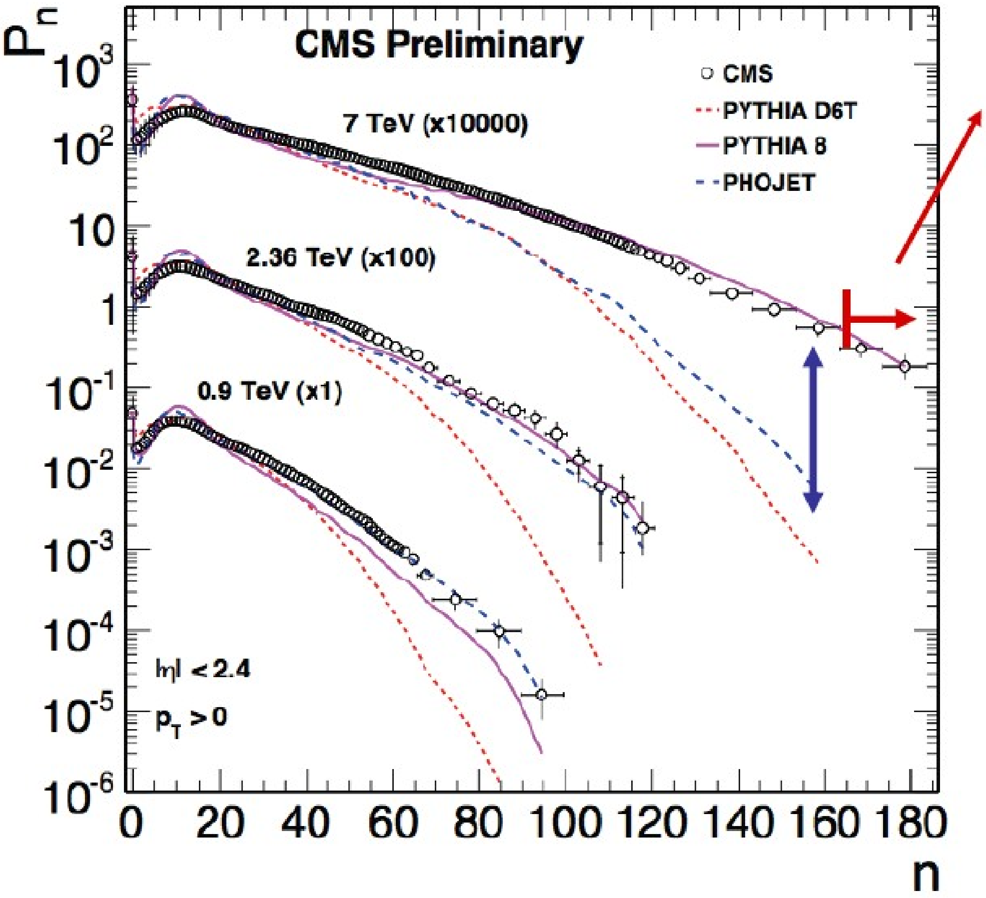


- All generators underestimate the amount of Strange Particles produces at both 0.9 and 7TeV



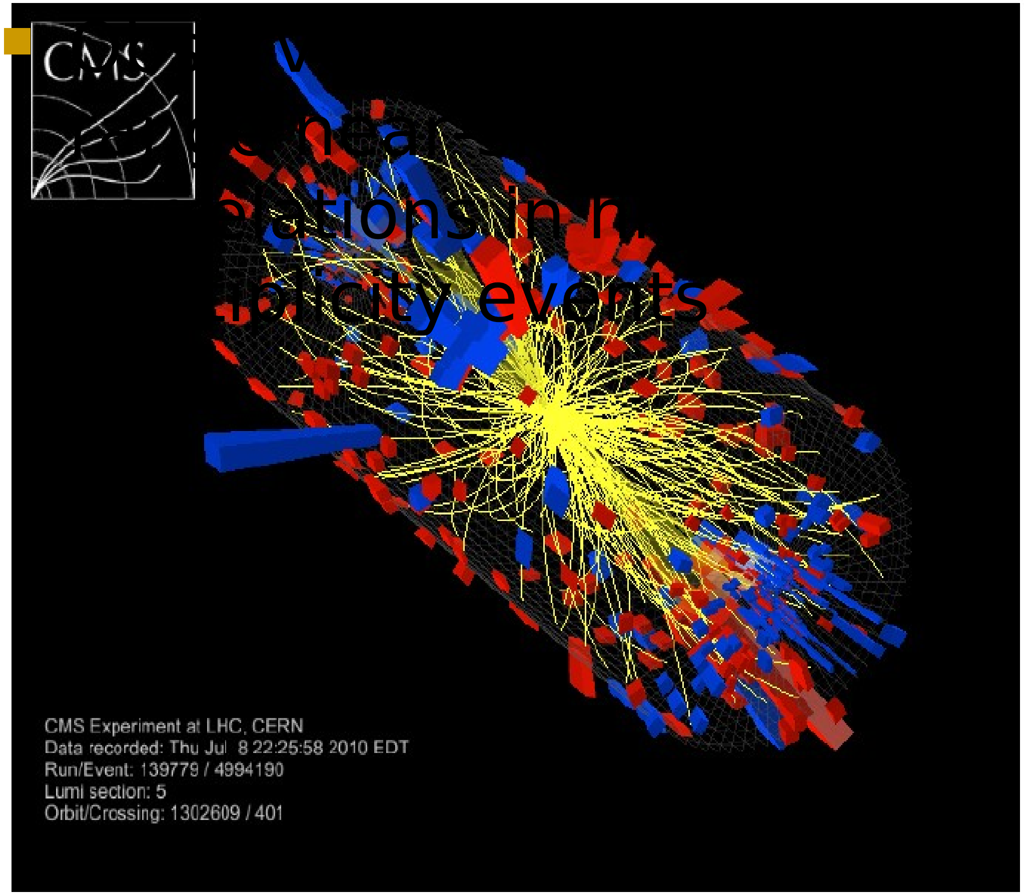


High multiplicity events



- 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)

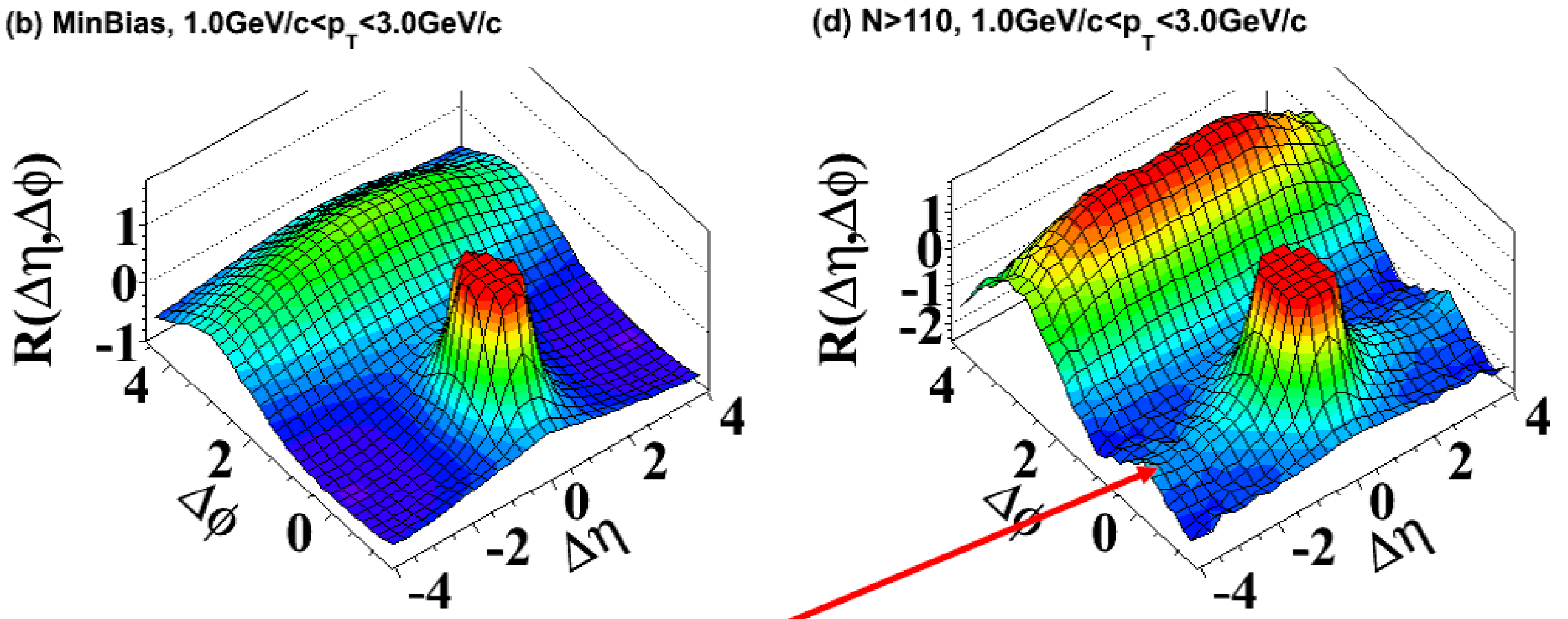
- Observed long-range near-side correlations in high multiplicity events

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

High multiplicity events

MinBias

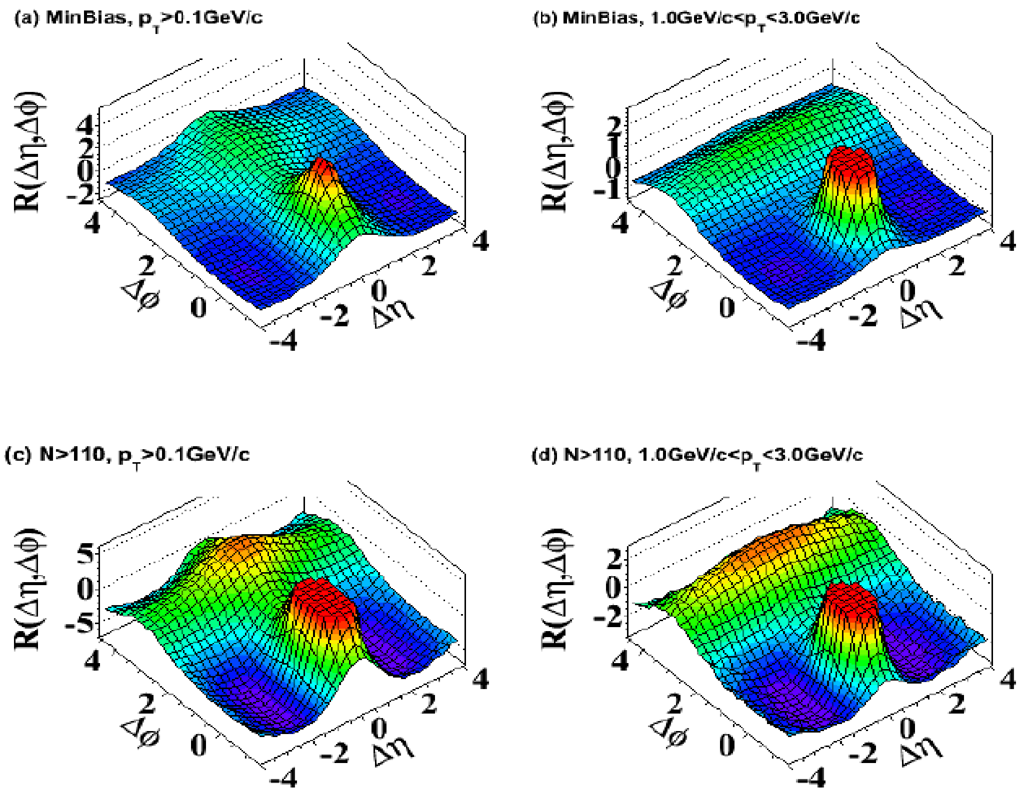
high multiplicity (N>110)



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

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

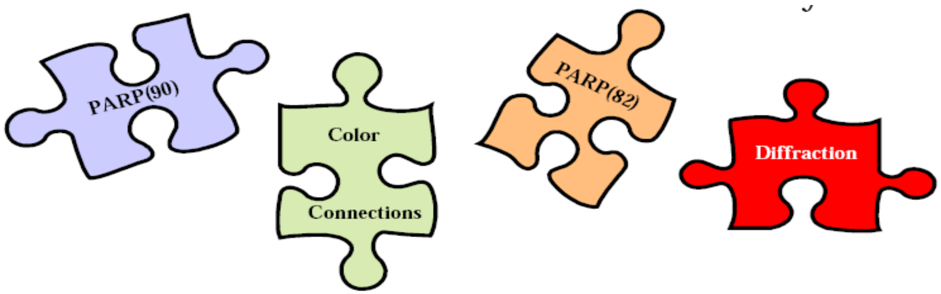
Correlations for PYTHIA



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

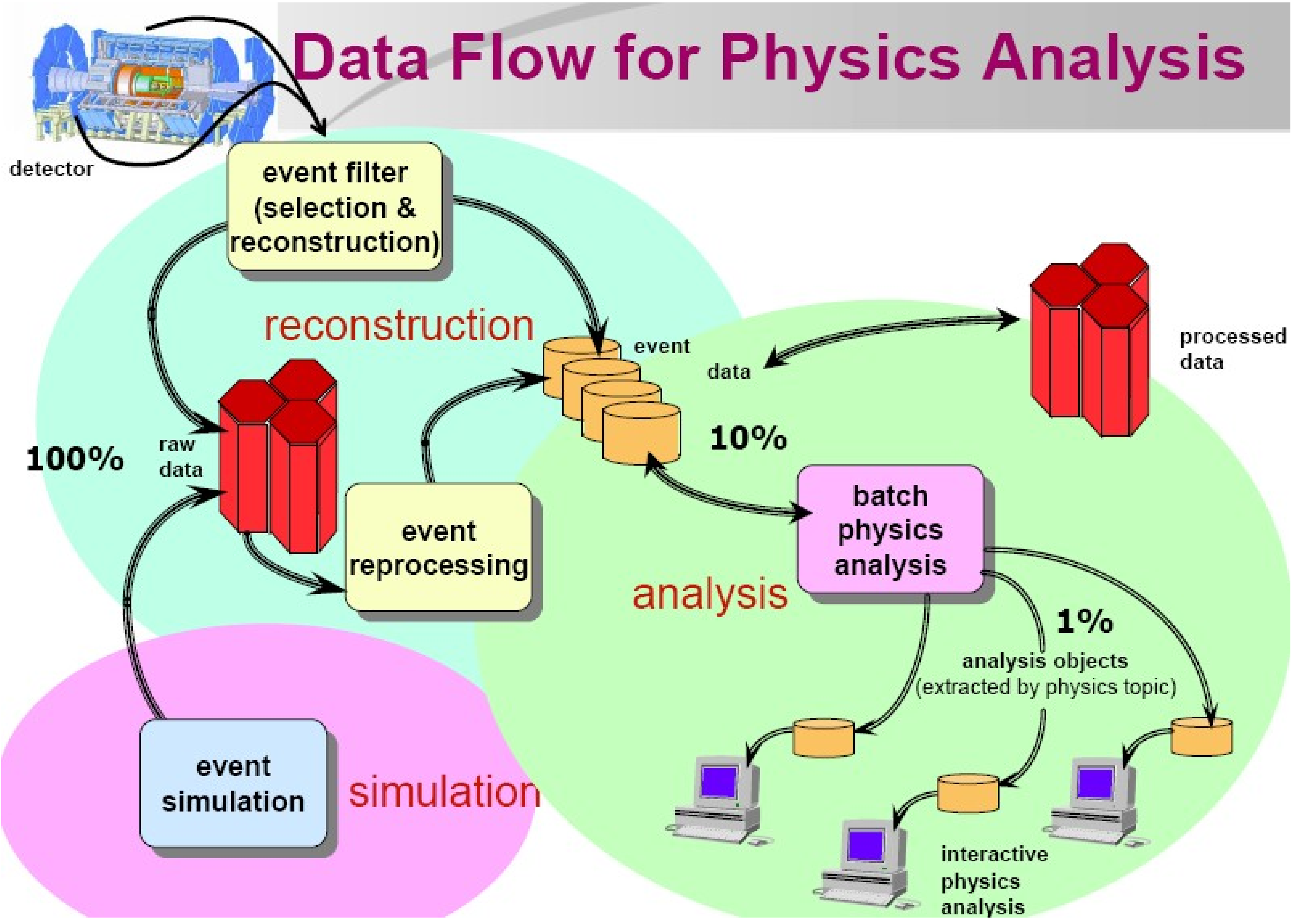
→ Same for Herwig++, madgraph, PYTHIA6

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

Data Flow for Physics Analysis



detector

event filter (selection & reconstruction)

reconstruction

100%

raw data

event reprocessing

event data

10%

processed data

batch physics analysis

analysis

1%

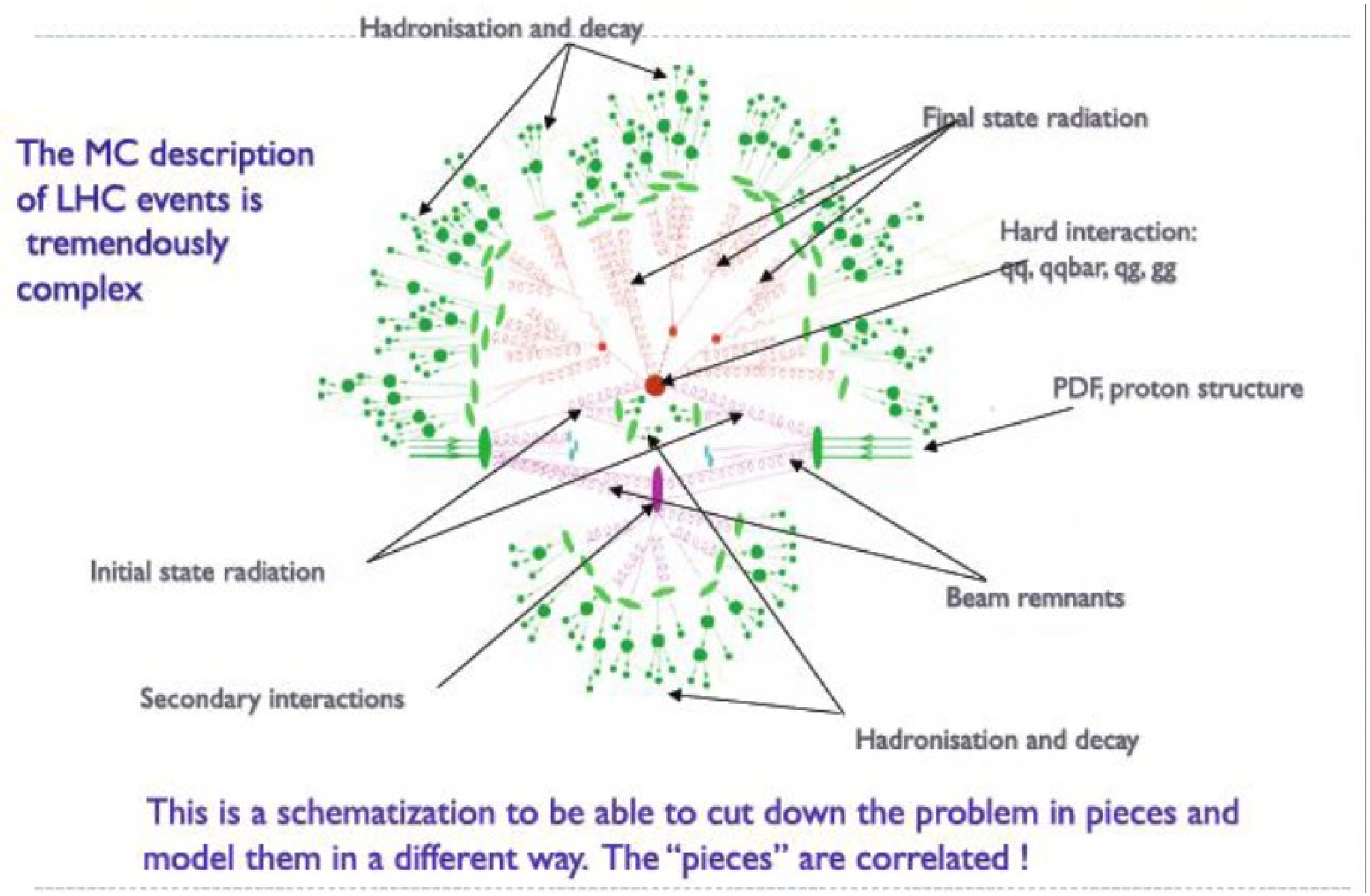
analysis objects
(extracted by physics topic)

event simulation

simulation

interactive physics analysis

MC tunes: hadronic event



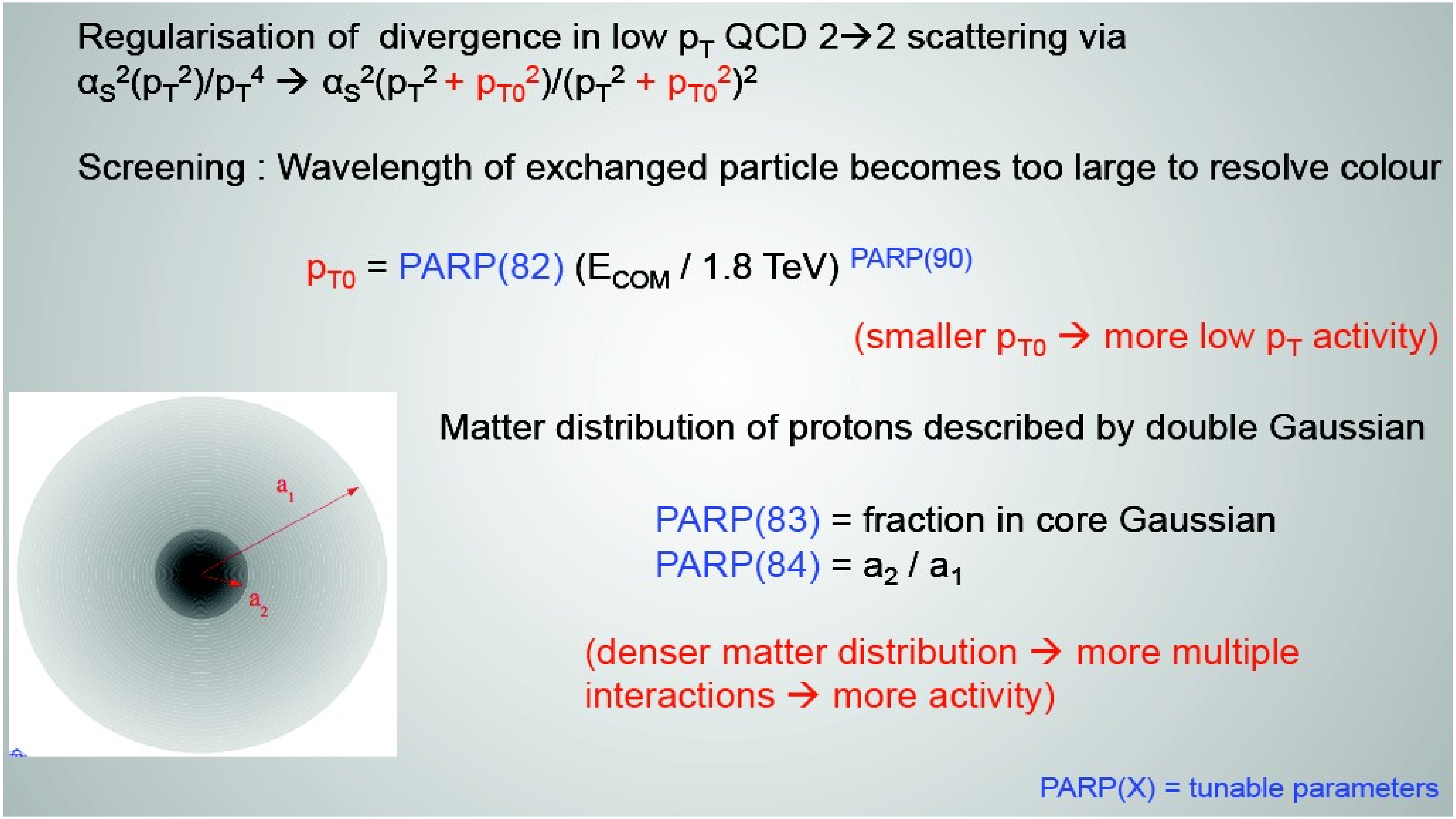
The MC description of LHC events is tremendously complex

This is a schematization to be able to cut down the problem in pieces and model them in a different way. The "pieces" are correlated !

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

Example of MC tunning



Regularisation of divergence in low p_T QCD 2→2 scattering via
$\alpha_S^2(p_T^2)/p_T^4 \rightarrow \alpha_S^2(p_T^2 + p_{T0}^2)/(p_T^2 + p_{T0}^2)^2$

Screening : Wavelength of exchanged particle becomes too large to resolve colour

$$p_{T0} = \text{PARP(82)}\,(E_{COM} / 1.8\ \text{TeV})^{\text{PARP(90)}}$$

(smaller p_{T0} → more low p_T activity)

Matter distribution of protons described by double Gaussian

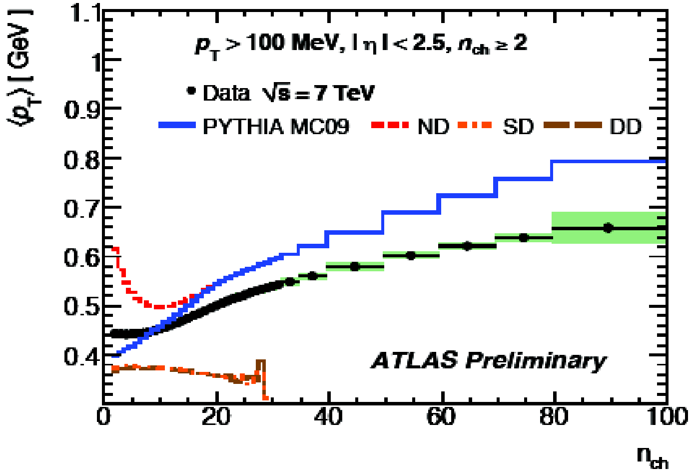
PARP(83) = fraction in core Gaussian
PARP(84) = a_2 / a_1

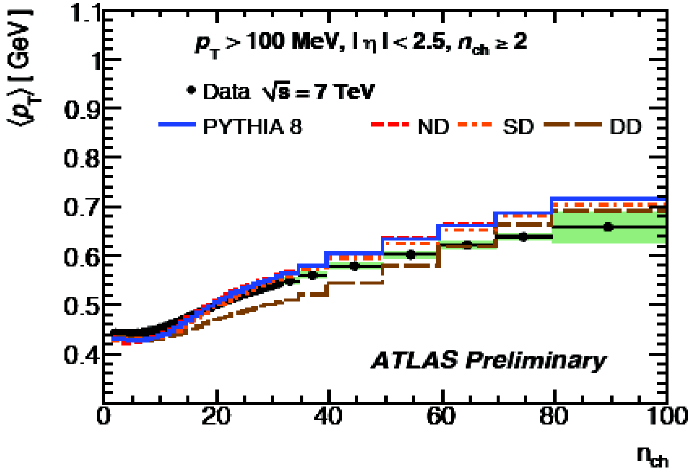
(denser matter distribution → more multiple interactions → more activity)

PARP(X) = tunable parameters

Diffraction: how important for MC tunings

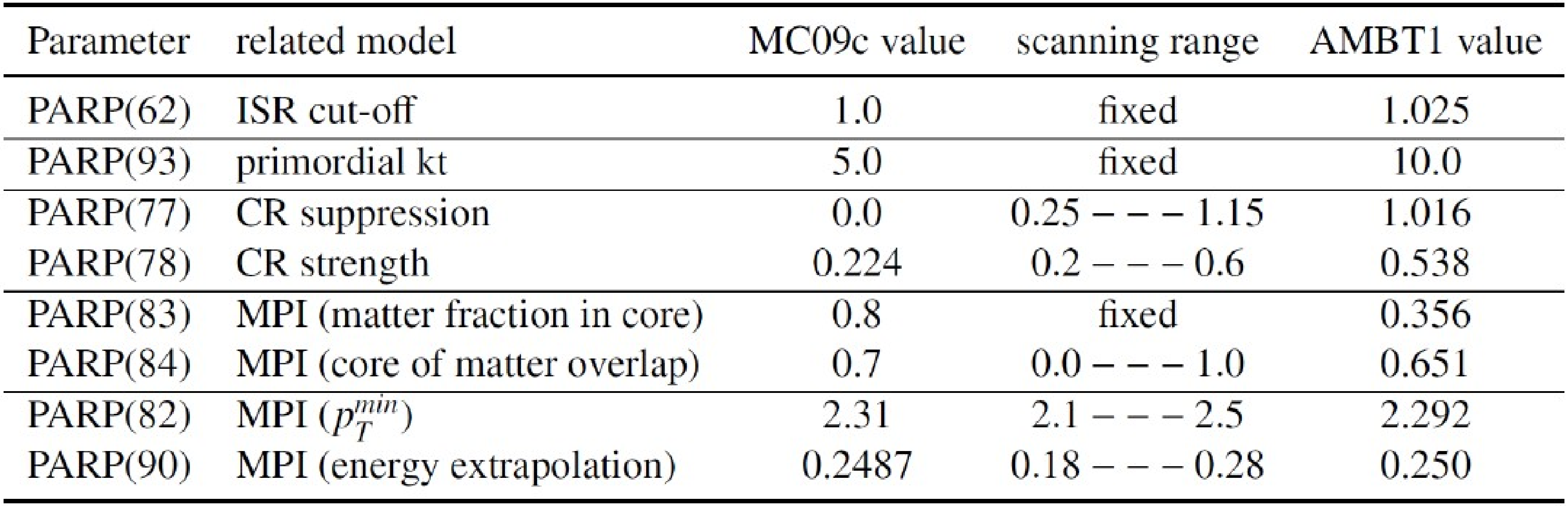
- The low p_T low N_{ch} region is problematic
  - Diffractive component important
- Case PYTHIA 6:
  - Diffractive component soft and low multiplicity
- Case PYTHIA 8:
  - At low N_{ch}, $<p_T>$ similar for SD,DD & ND





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

- 24.10 – hard QCD
- 7.11 - W, Z bosons: inclus. cross-sections, W/Z+jets
- 14.11 – W, Z bosons:precise measurements
- 21.11 – Top: xsection, mass
- 28.11 – Dibosons and anomalous couplings
- 5.12, 12.12 **- Higgs**
- 19.12 – **SUSY**
- 9.1 – other searches for New Physics
- 16.1 - B-physics programme
- 23.1 – heavy ion programme