Minimum Bias, Underlying Event and Hadronic Event Shapes at LHC

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(on behalf of the ATLAS and CMS collaborations)

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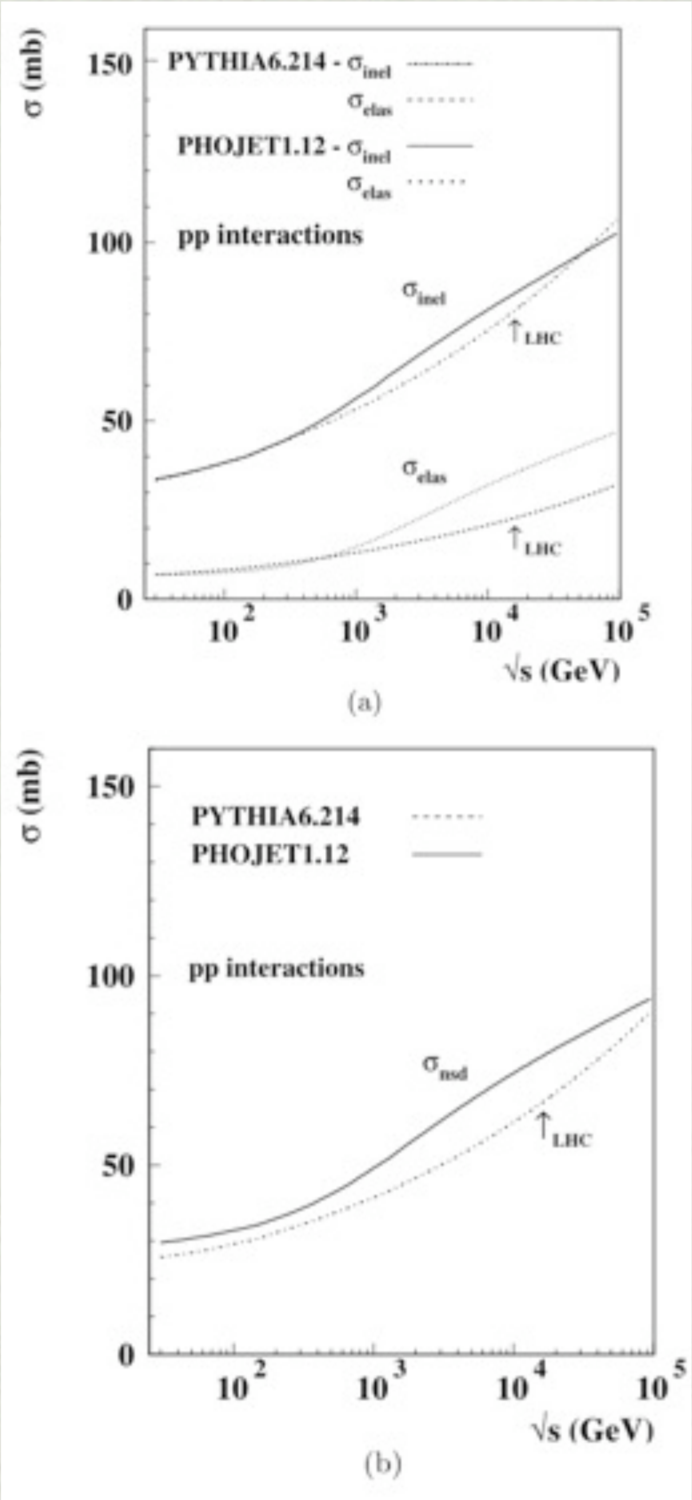
Outline

- Soft hadron interaction and its relevance for LHC.
- Uncertainties in the predictions of the soft hadron activity at LHC.
- ATLAS strategies for the minimum bias measurement.
- CMS strategies for the minimum bias measurement.
- Underlying event observables and their determination at ATLAS and CMS.
- Hadronic Event shapes as a tool for early QCD studies.
- Summary.

Introduction (1)

- The soft hadron interaction understanding will play an important role at LHC:
  - Minimum bias interactions:
    - *Experimental definition, which historically is associated to non single diffractive events.*
    - *σ_{NSD} (14 TeV) ~ 70 mb (~70% of the total cross section).*
    - *Pileup from Minimum bias: up to 25 MB interactions (at nominal luminosity) superimposed to the interesting event.*
  - Underlying event:
    - *Everything that is not the hard scattering in a single pp collision.*



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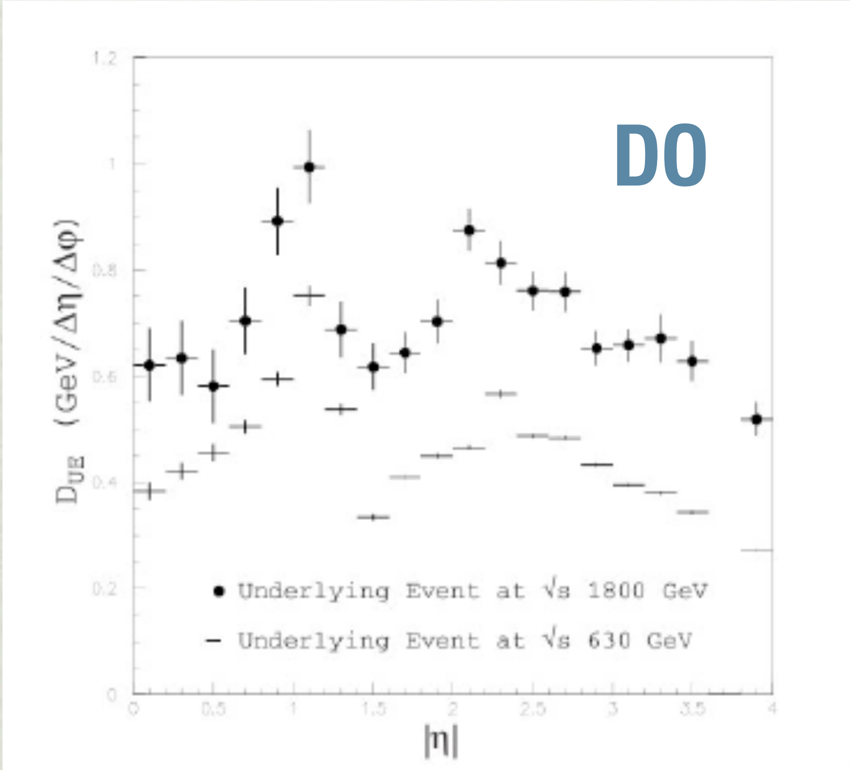
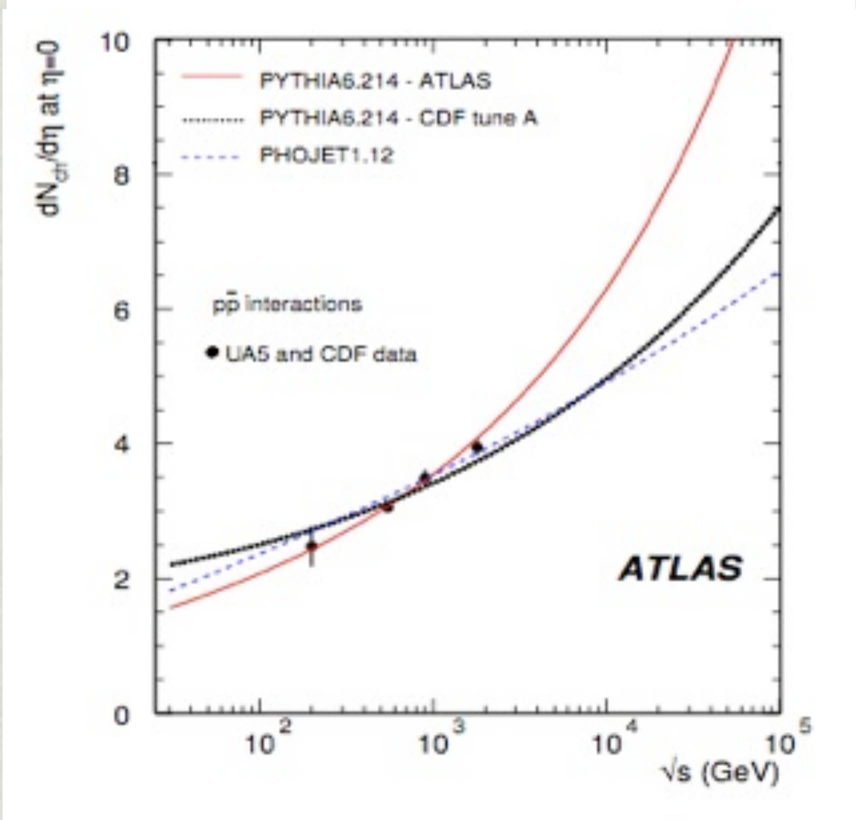
Introduction (2)

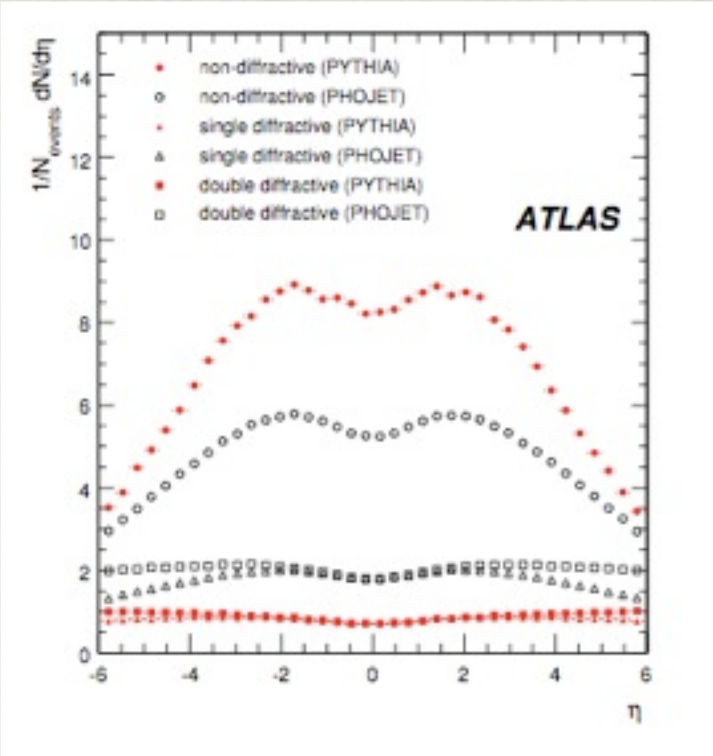
- A good understanding and modeling of the MB and UE is mandatory:
  - Detector occupancies, background.
  - Jet energy scale, E_T^{miss} scale, vertex finding, lepton isolation, jet veto (Higgs searches in VBF)...
  - Tevatron: UE corrections for the inclusive jet cross section: 25% at 50 GeV, 10% at 100 GeV.
  - Why so important to measure them at LHC:
    - *<u>Extrapolations are highly uncertain</u>*

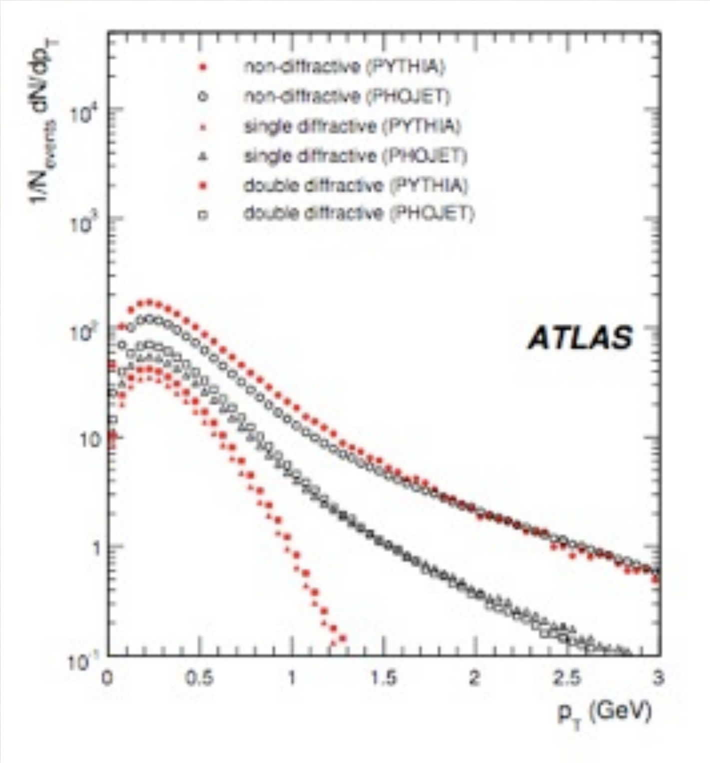




Minimum Bias

- Minimum bias determination: the observables are $dN_{ch}/d\eta$, dN_{ch}/dP_T :
  - Trigger bias must me minimized: detailed trigger strategies outlined by ATLAS and CMS.
  - Detector bias must be minimized: “nominal” tracking threshold (~500 MeV) must be reduced.
  - Effort in both the experiment to lower the tracking threshold with high efficiency (dedicated methods using directly hits and tracklets):
    - *Dedicated configurations of the tracking algorithms: threshold ~ 100-300 MeV.*

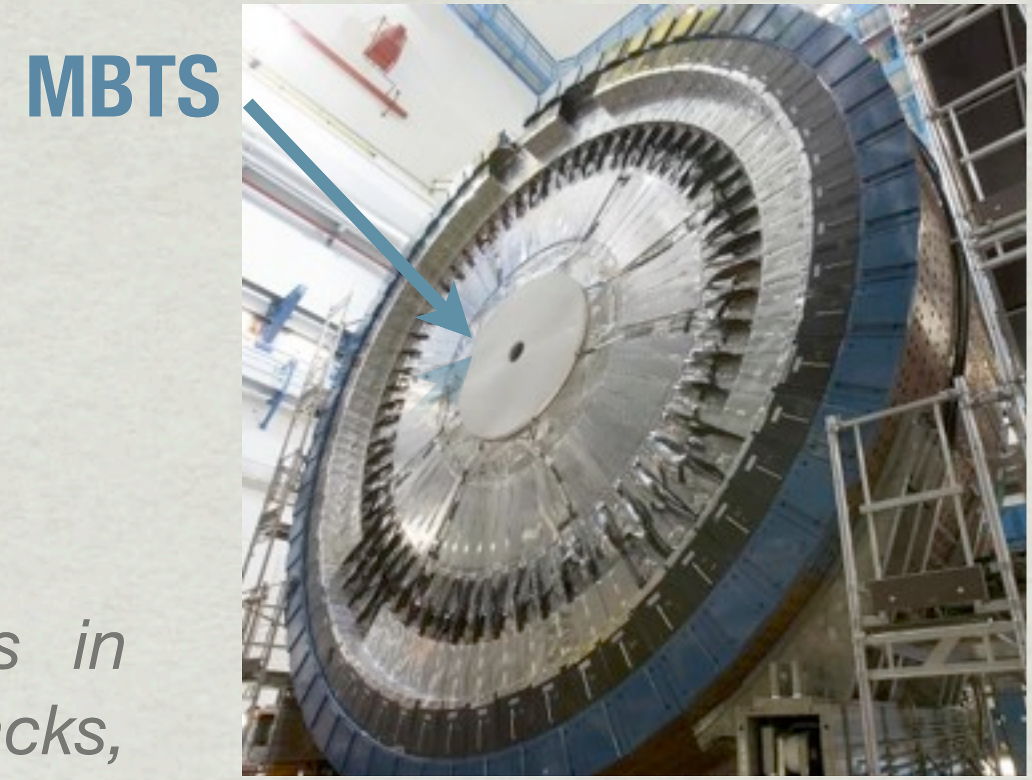


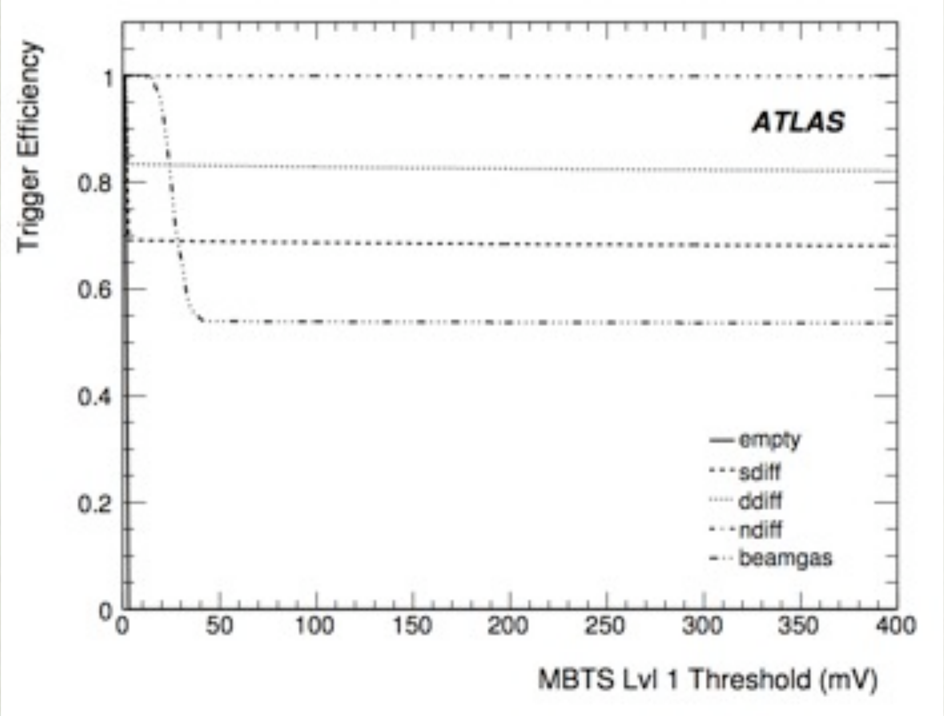


arXiv:0901.0512

Minimum bias - ATLAS

- Triggering on MB:
  - Collisions per BC << 1:
    - *L1: random trigger or MBTS.*
    - *L2/L3: number of space points in silicon detectors, number of tracks, loose track quality selection.*
  - Collisions per BC ~1:
    - *Random triggers.*
  - In case of non-random triggers, typically ND favored w.r.t. DD. Corrections needed to correctly measure NSD.





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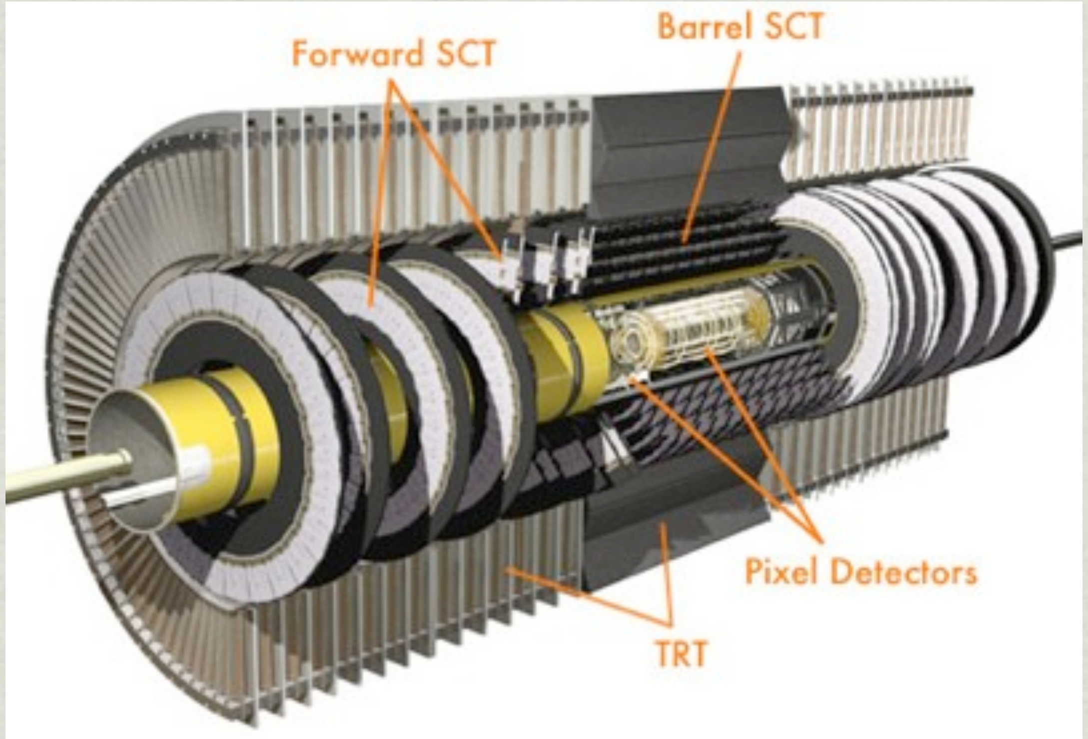
Event selection

- Events selected if there is at least 1 reconstructed vertex.
- Track selection (removing secondary tracks):
    - Accepting tracks with $P_T > 150$ MeV.
    - High number of silicon hits (1 in B-layer).
    - Track quality + association to vertex.

Cut	% Cut All	% Cut Primary tracks	% Cut Secondary tracks
b-layer hit	15.9	8.5	46.8
cov_{d0}	11.5	6.0	34.2
cov_{z0}	9.4	5.0	27.4
cov_{ϕ}	8.9	5.1	24.3
cov_{θ}	4.9	4.2	8.2
cov_{q/p_T}	6.4	4.3	14.9
Quality	15.9	8.5	46.8
Resolution	16.7	10.9	40.4
Q || R	24.6	15.6	62.1
Track-to-Vtx	30.7	16.9	87.8
$\eta \,\|\|\, p_T$	1.2	1.3	0.9
Total	38.6	24.6	96.5

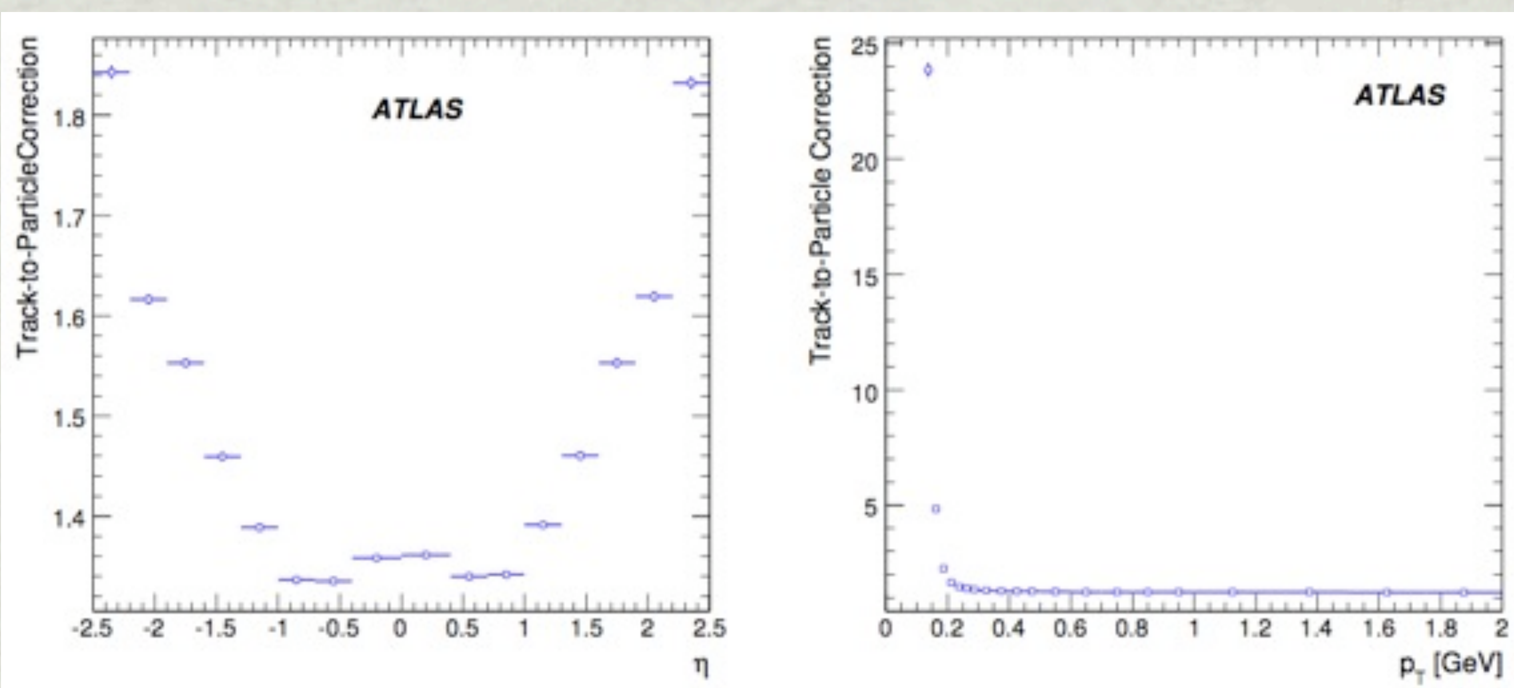


Corrections and results

- The measured distribution has to be corrected for:
  - Track selection efficiency ($C_{trk}(P_T,\eta,N_{vtx})$).
  - Vertex reconstruction efficiency.
  - Trigger biases.

$$
\begin{aligned}
P(\eta,v_z,p_T) &= \sum_{events}\sum_{tracks}\left(C_{trk}(\eta,v_z,p_T)\cdot C_{vtx}(\eta,v_z,p_T)\cdot C_{trig}(\eta,v_z,p_T)\right)\\
I(v_z,N) &= \sum_{events}\left(\tilde{C}_{vtx}(v_z,N)\cdot\tilde{C}_{trig}(v_z,N)\right).
\end{aligned}
$$

$$
\begin{aligned}
\left.\frac{dN_{ch}}{d\eta}\right|_{\eta=\eta'} &= \frac{\int_{V_1}^{V_2}\int P(\eta',v_z,p_T)\,dp_T\,dv_z}{\int_{V_1}^{V_2}\int I(v_z,N)\,dN\,dv_z},\\
\left.\frac{dN_{ch}}{dp_T}\right|_{p_T=p'_T} &= \frac{\int_{V_1}^{V_2}\int P(\eta,v_z,p'_T)\,d\eta\,dv_z}{\int_{V_1}^{V_2}\int I(v_z,N)\,dN\,dv_z}.
\end{aligned}
$$



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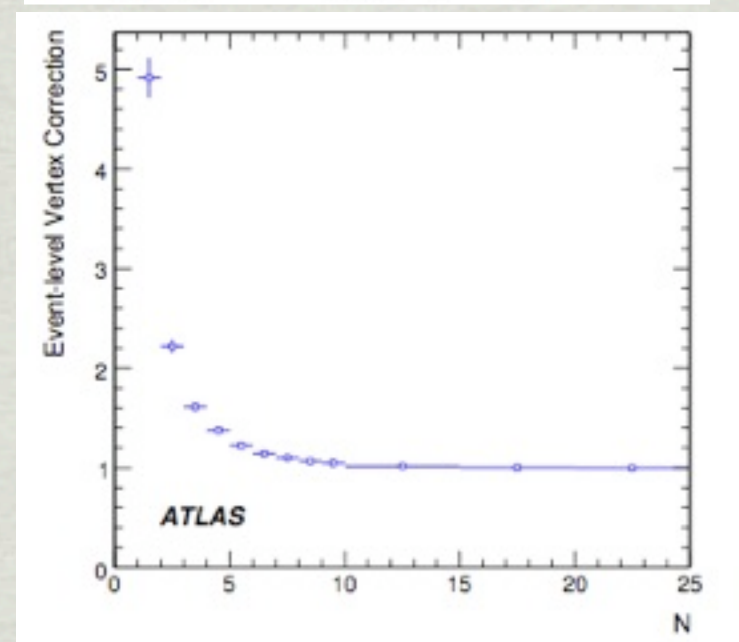
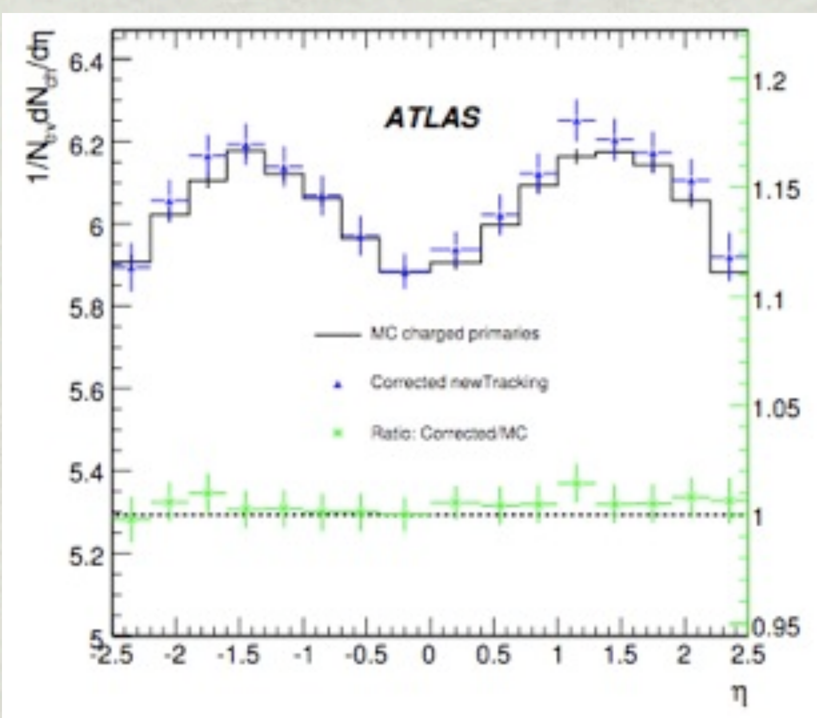


arXiv:0901.0512

Results

- The good agreement found between reco and generated distributions represents a consistency check of the method.
- Statistics used for the correction: ~few days of data taking.
- Used tracks with $P_T > 150$ MeV.

Name	Level	Estimated Uncertainty
Track selection cuts	Analysis	2%
Mis-estimate of secondaries	Analysis	1.5%
Vertex reconstruction bias	Reconstruction	0.1%
Misalignment	Reconstruction	6%
Beam-gas and pileup	Offline Trigger	1%
Particle composition	Generation/Simulation	2%
Diffractive cross sections (NSD sample)	Generation	4%
Total		8%



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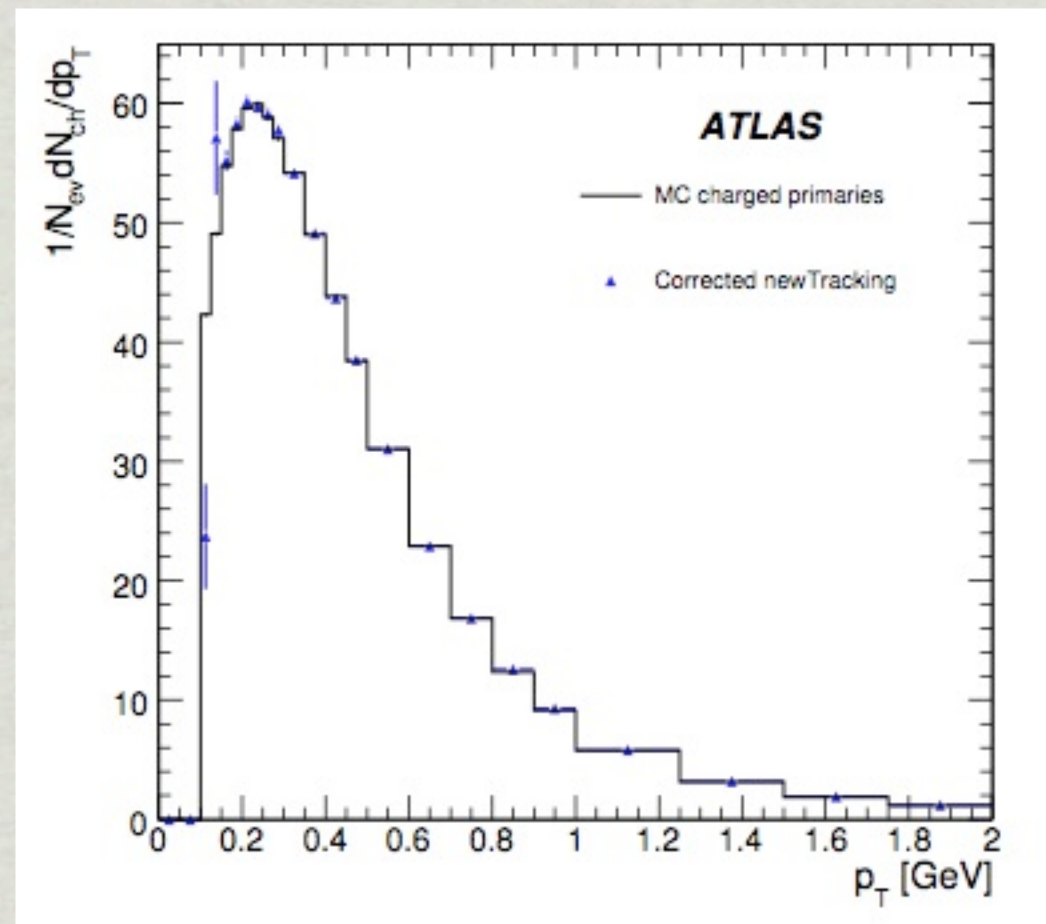

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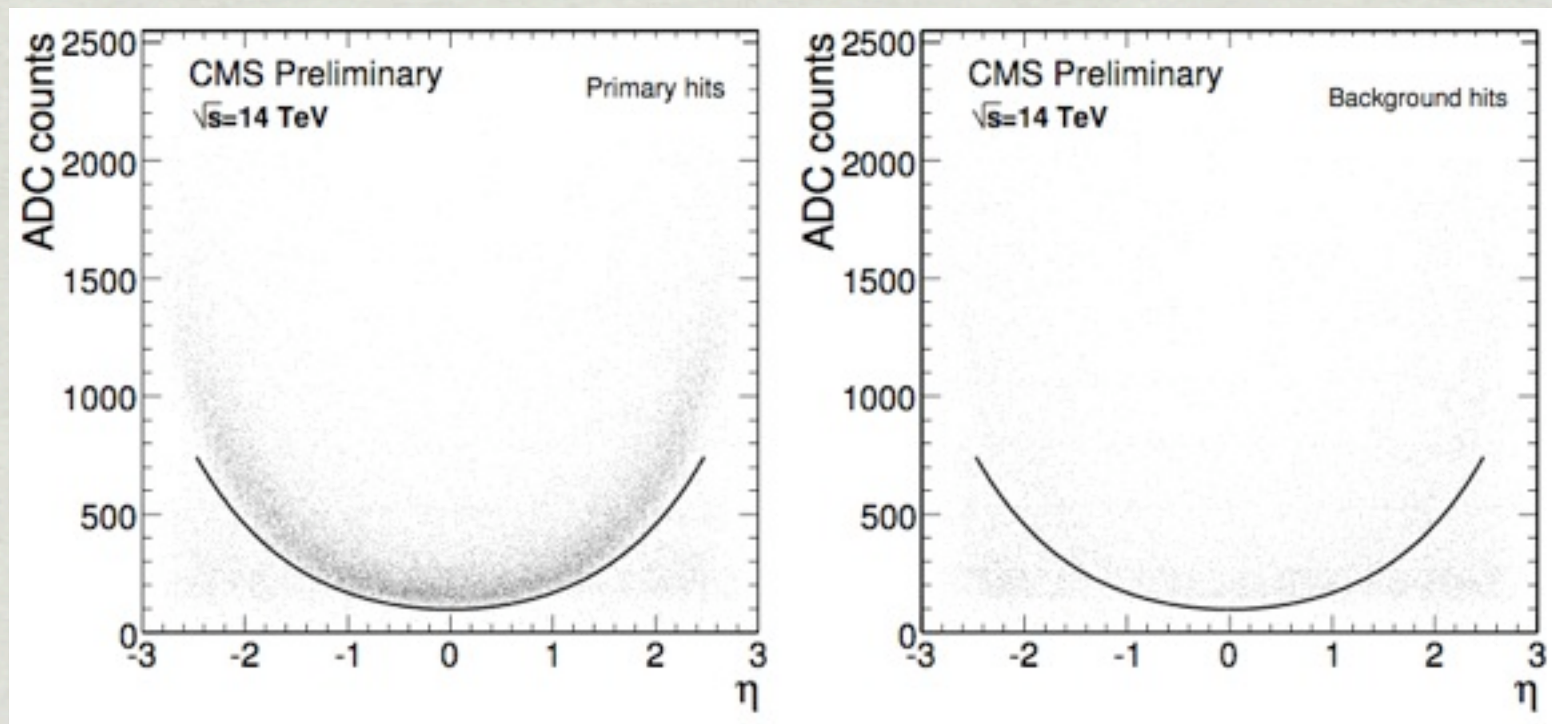
Minimum bias -CMS

- Trigger:
  - Collisions per BC << 1: number of towers in FCAL above threshold.
  - Collisions per BC ~ 1: random triggers.

CMS	Track ($\geq$ 1 track)	99%	69%	59%
	FCAL (1 tower on one side)	81%	15%	15%
	FCAL (1 tower on each side)	48%	1%	1%

- Analysis principle: counting hits in the pixel layers.
- Main background rejection: η dependence of the energy deposit in pixel hits.



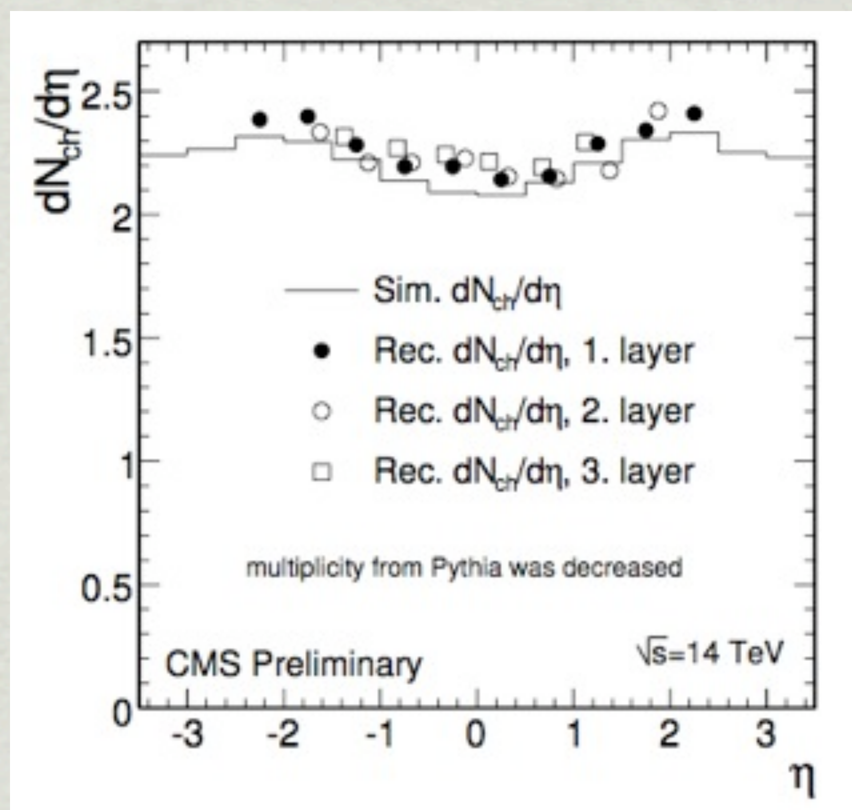
CMS PAS QCD-08-004

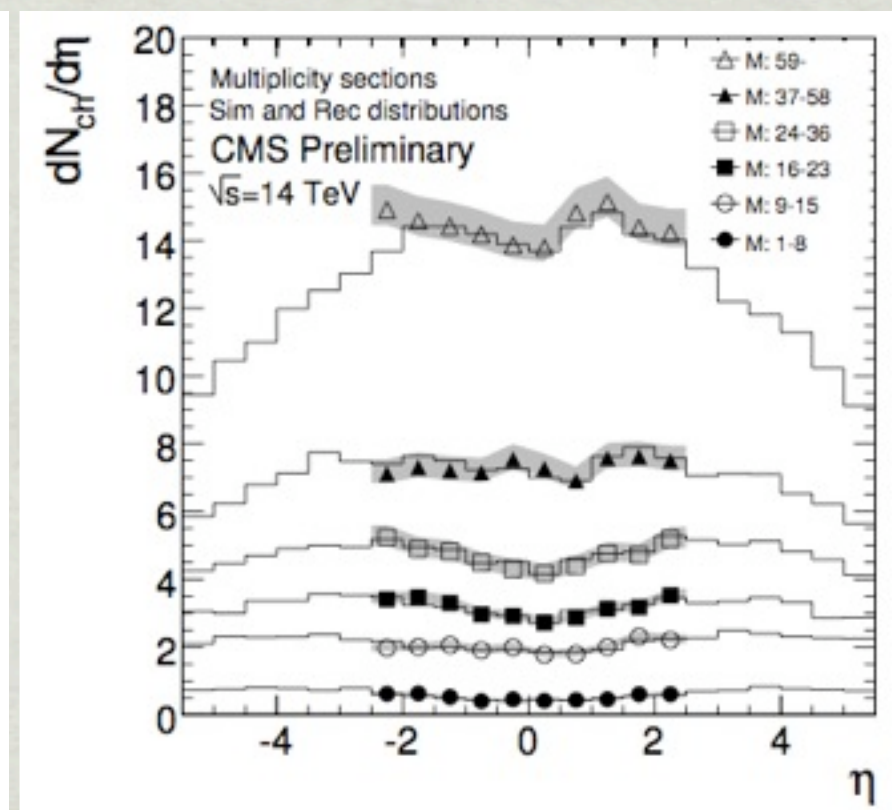
Minimum bias - CMS (2)

- The track distribution is computed from the hits distribution (HIT/track ratio, event selection corrections, corrections for loopers extracted from the MC).

- Main systematics arising from the vertex efficiency and bias and from the MC determined hit to track correction.

Robustness of the method tested computing the corrections and then applying them to an altered MC distribution. Stable results.

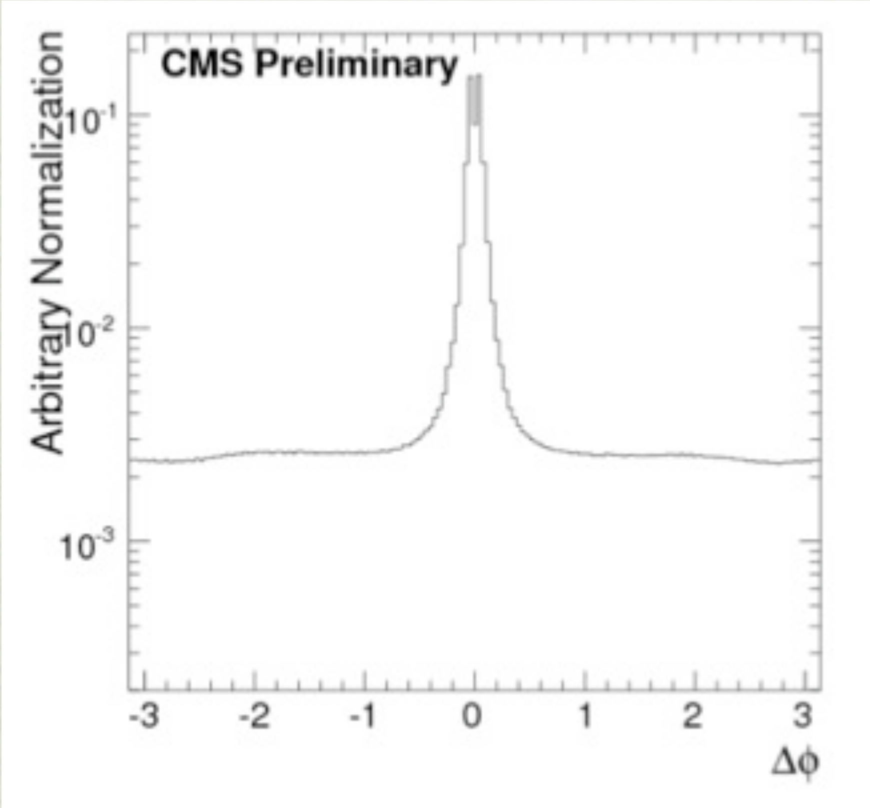


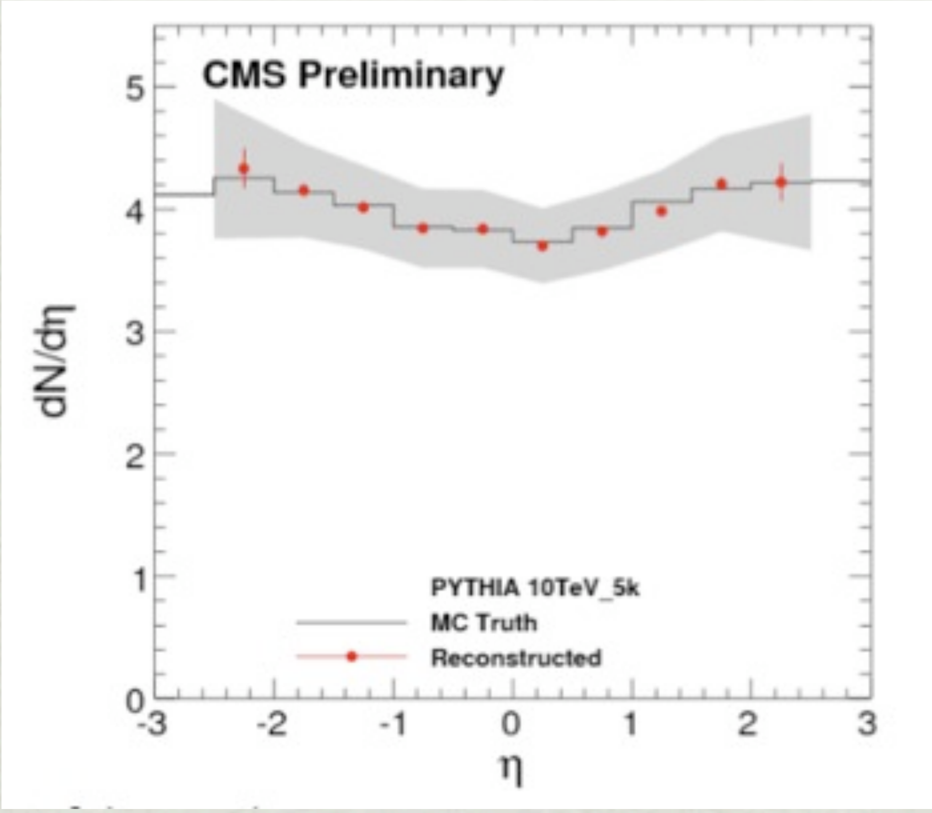


CMS PAS QCD-08-004

Minimum bias - CMS (3)

- Complementary approach: tracklets from two pixel layers:
  - Tracklets are reconstructed, the primary vertex is identified, then tracklets are rebuilt.
  - The background removal is data driven.
  - Correction take into account vertex corrections, events with no particles in the tracker, dead channels, tracklet to particle.
  - Main systematics: misalignment, vertex finding fakes.





Underlying event

- Measuring the underlying event important to tune the event generators:
  - Predictions from the current models/tuning uncertain at 14 TeV.
- Both ATLAS and CMS mainly follow the method a la CDF:
  - In a QCD event, divide the transverse plane in 3 regions, based on the direction of the leading track jet.
  - The transverse region is mostly sensitive to the UE.

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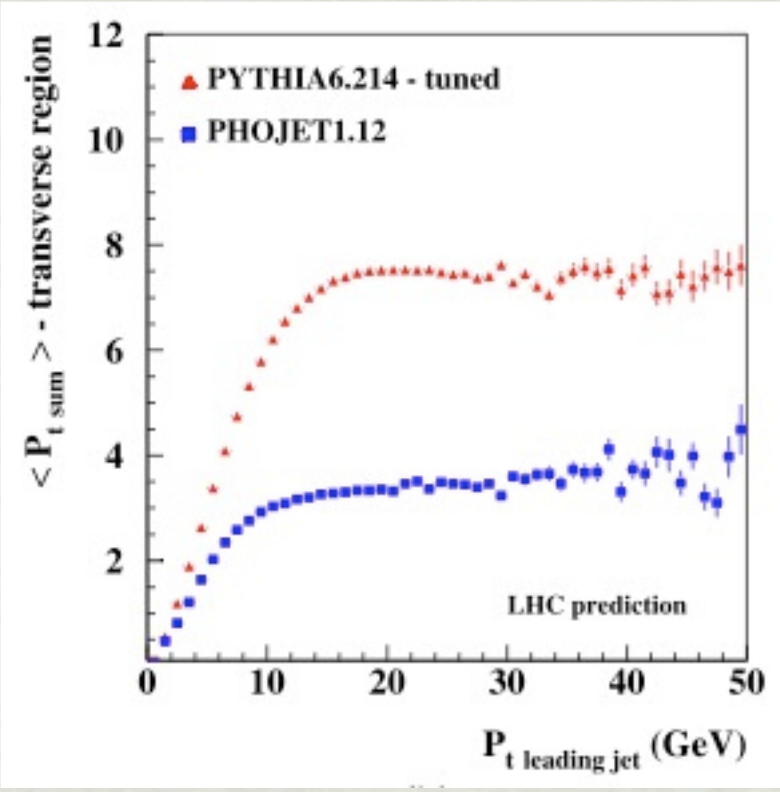
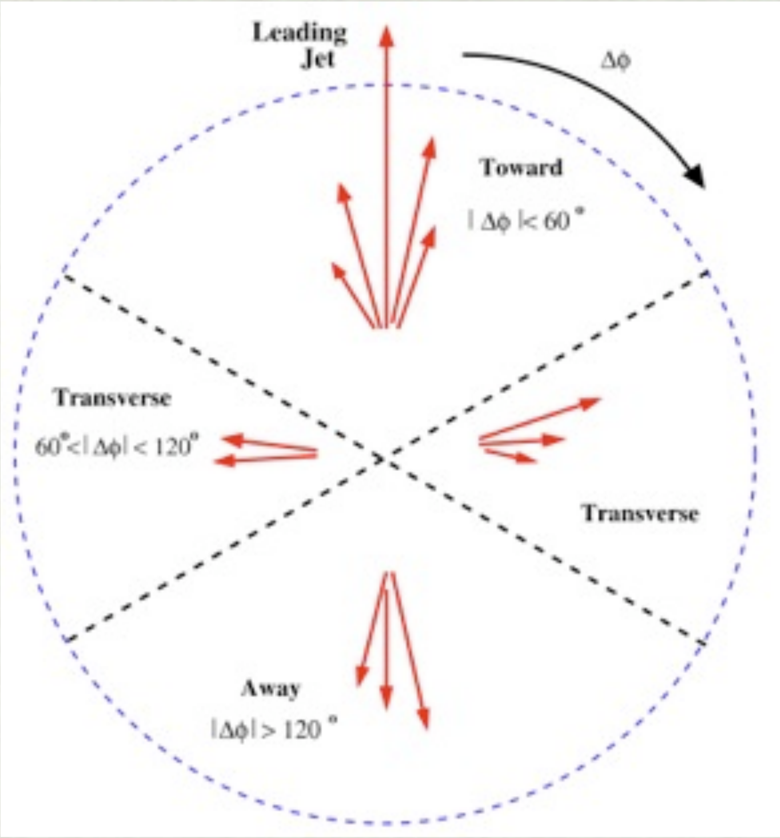
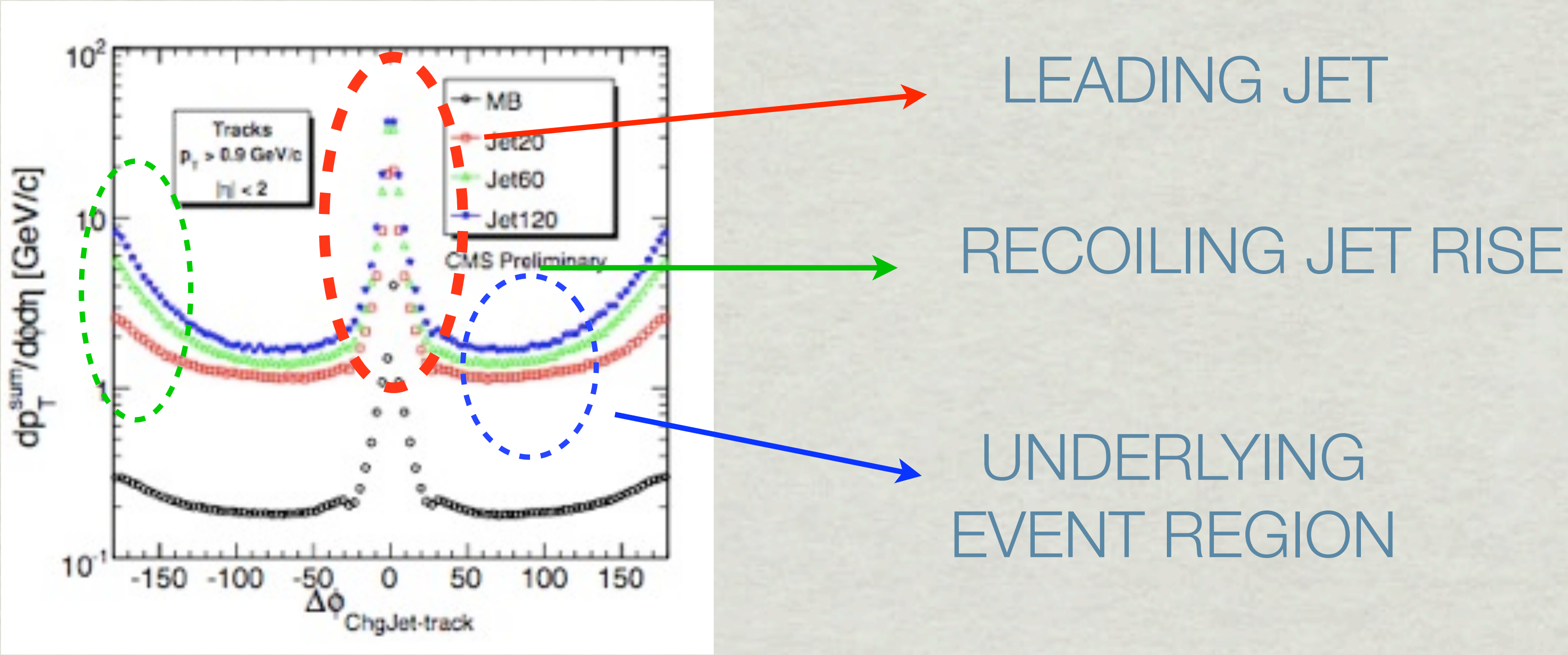


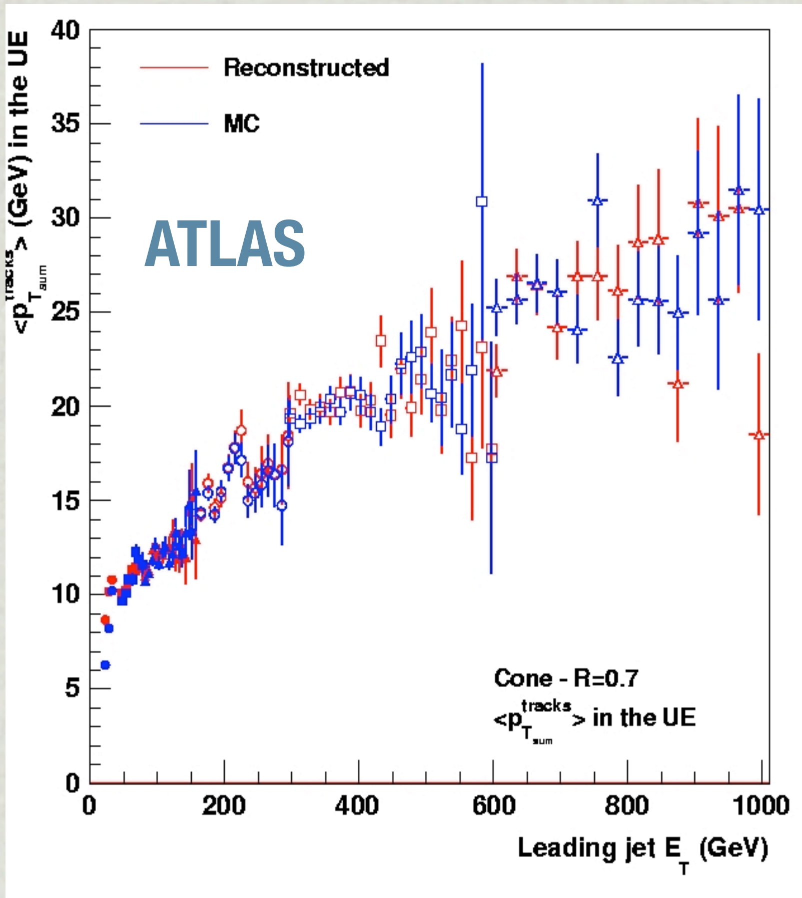


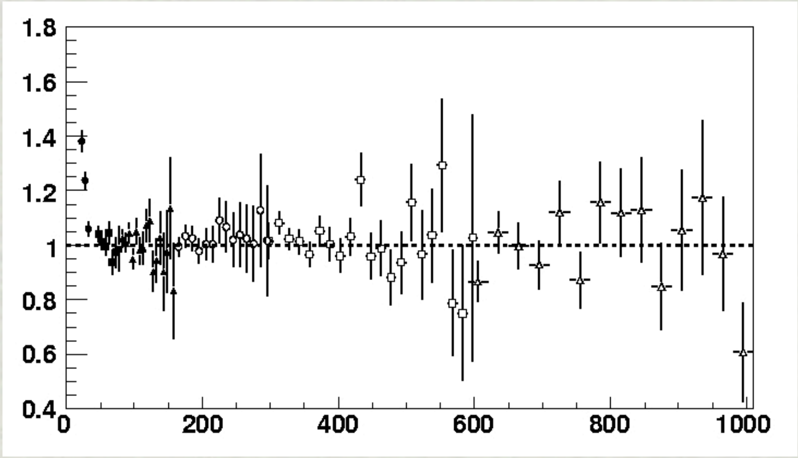
CMS PAS QCD07003



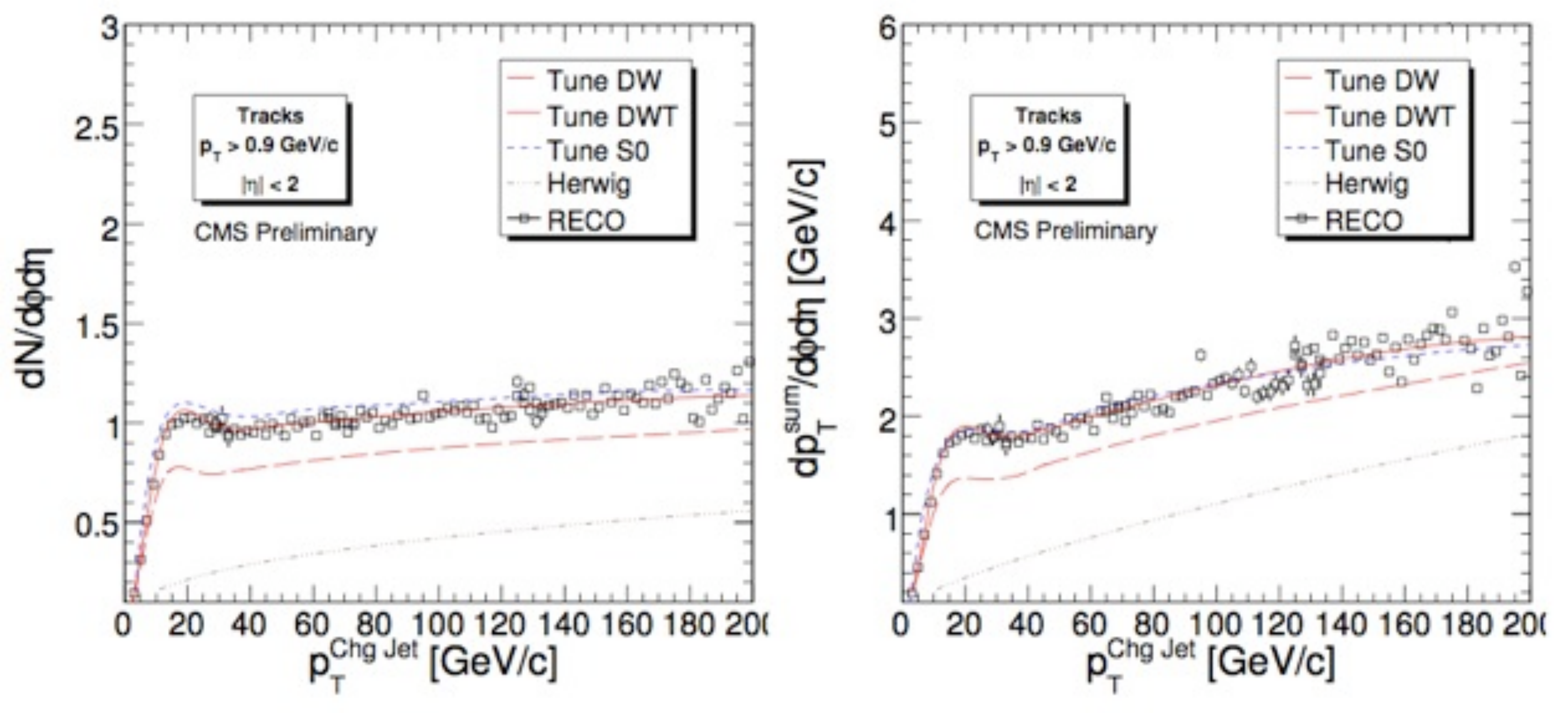
UE Measurements

- Typically measure the density of tracks and P_T in the transverse region.
- The reconstructed quantities well reproduce the input MC.
- Sensitivity to the input model is achieved.





CMS PAS QCD07003



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Hadronic Event Shapes

- Defined in terms of the 4-momenta of the particles in the final state.
- Infrared safe, computed with NLL. Normalization to SumEt makes them relatively insensitive to energy scale variations. Investigated as a “first data” tool for MC tuning.
- Concentrating on:

- Global transverse thrust: it is 1 for 2->2 processes, 1/2 for spheric events.

$$T_{\perp,g} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$

- Global thrust minor:

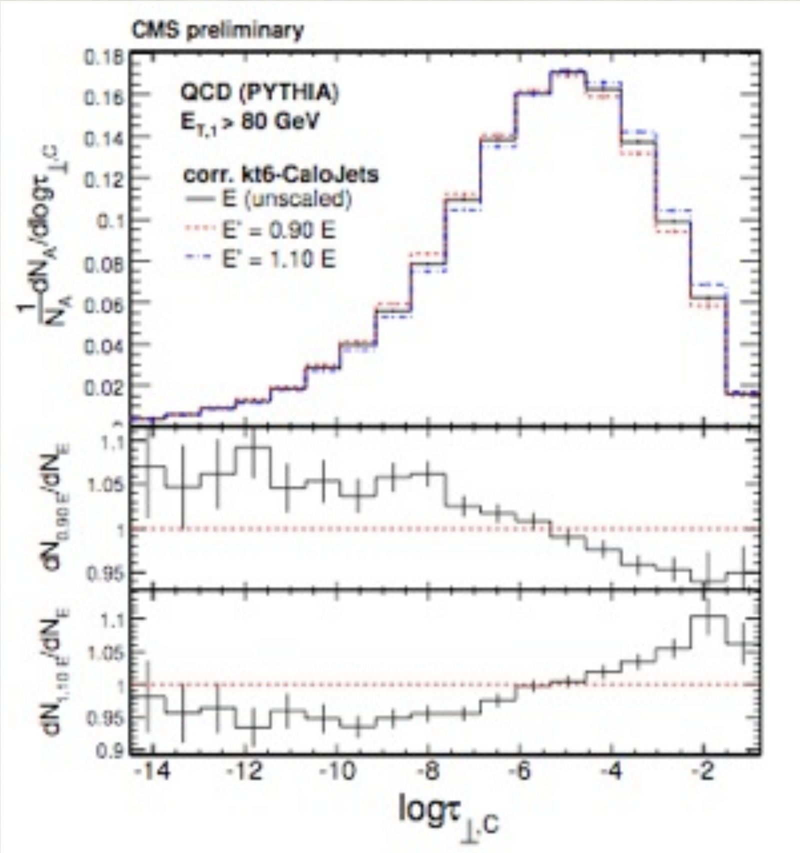
$$T_{m,g} \equiv \frac{\sum_i |p_{x,i}|}{\sum_i p_{\perp,i}} = \frac{\sum_i |(\vec{p} \times \vec{n}_B) \times \vec{n}_T|}{\sum_i p_{\perp,i}}.$$

  - n_b is the normalized beam axis.

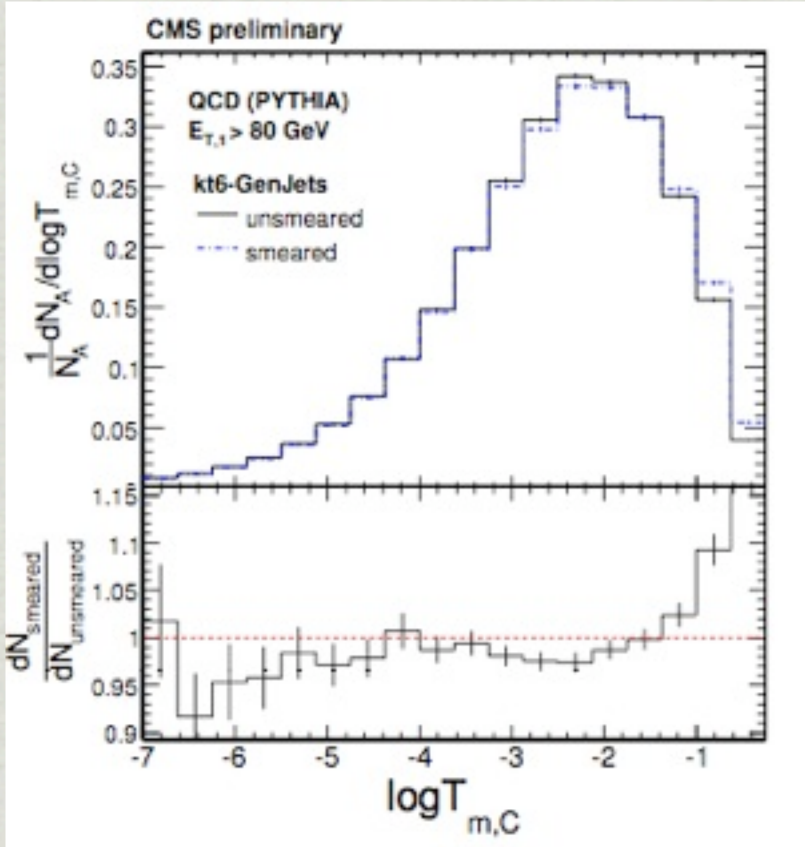
Hadronic Event Shapes (2)

- Sensitivity to the jet energy scale checked varying +- 10% the JES in fullsim. Maximum deviation found 5%.
    - Mostly due to the threshold effect behaving differently for changes JES.

CMS PAS QCD-08-003



CMS PAS QCD-08-003

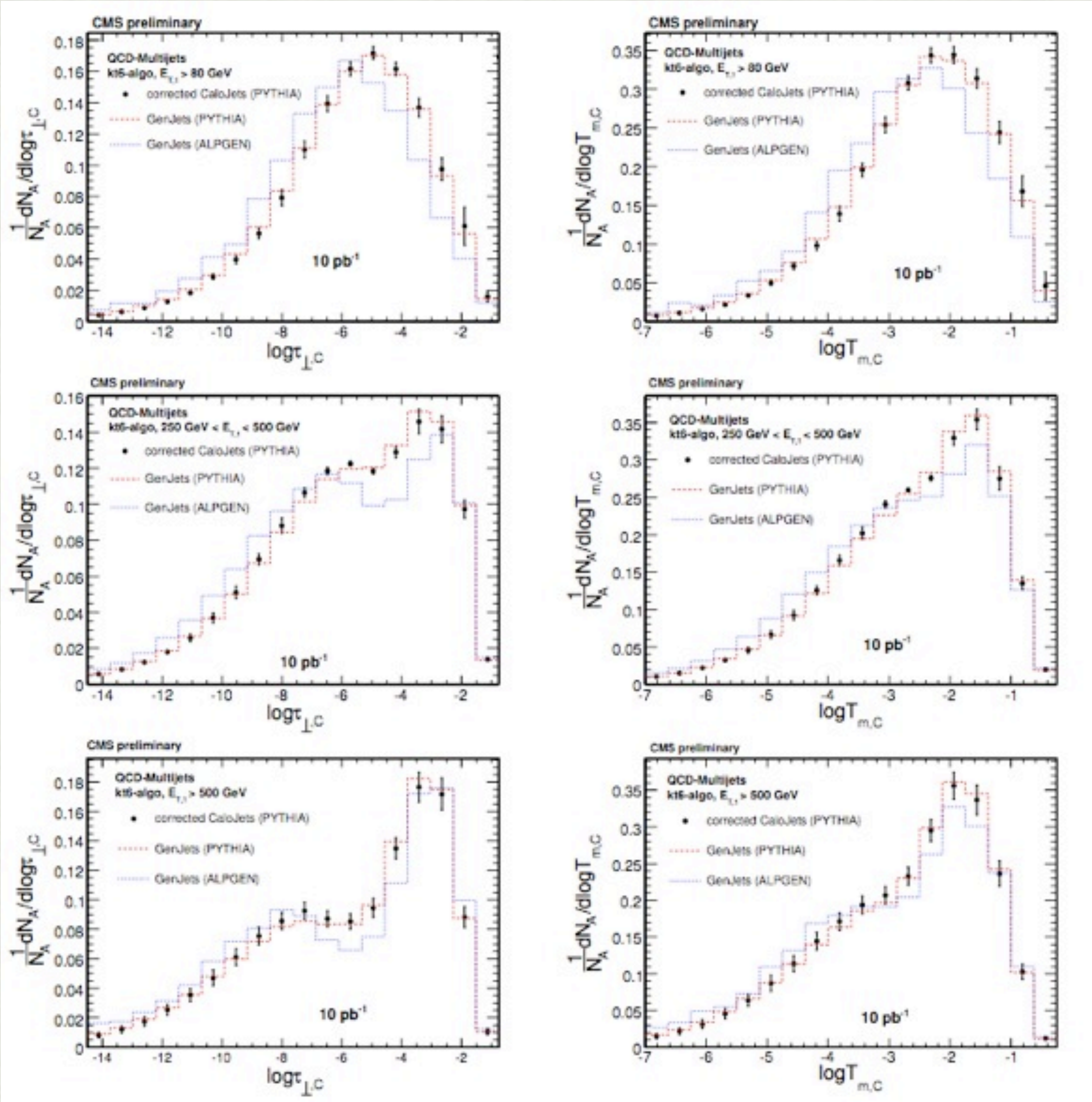


- Resolution effects studied smearing the particle level jets.
- Maximum deviation observed: 5% (except high thrust minor).
    - Region sensitive to threshold effects.

Hadronic Event Shapes (2)

CMS PAS QCD-08-003

- Full simulation events in three jet E_T bins (10 pb^{-1}).
- The event generator used as input is Pythia.
- Reconstructed thrusts compared against the Pythia and Alpgen prediction.
- Hadronic event shapes can disentangle between the two.



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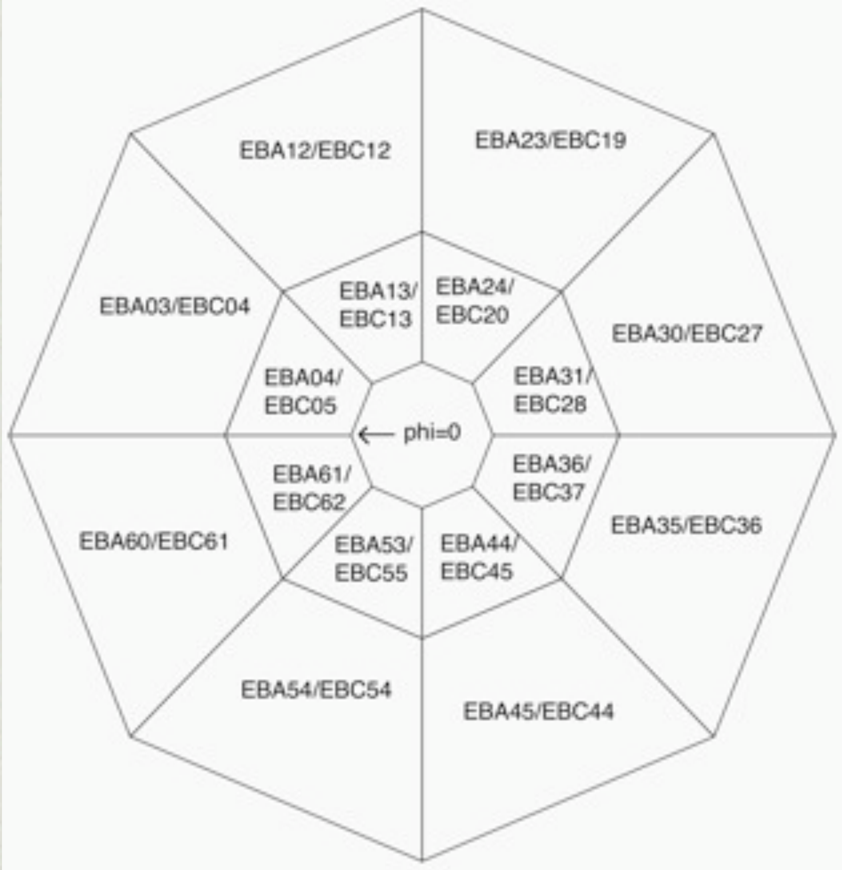
Summary

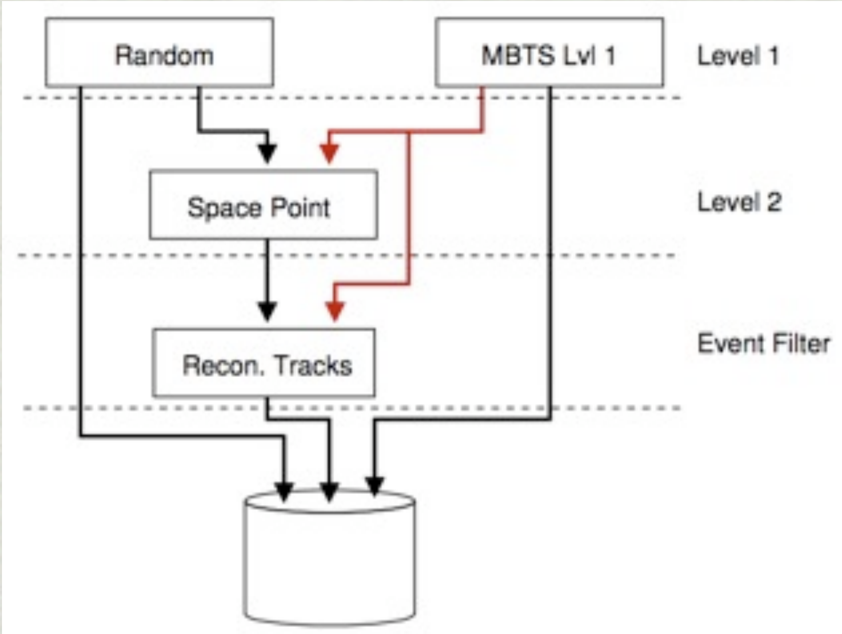
- The extrapolation at the LHC energies of the predictions for the minimum bias and underlying event track multiplicity and momenta are highly uncertain.
  - A direct measurement is mandatory.
- Both ATLAS and CMS have a detailed strategy for the trigger and measurement of the MB.
  - Results on simulation indicate that the developed strategies are effective.
- Underlying event studies show that both ATLAS and CMS can efficiently face the challenge of event generator parameter tuning.
- Hadronic Event shapes: a promising tool for early QCD studies.

Backup

MBTS

- Scintillators placed above the LAr endcap cryostat, covering $2.12 < |\eta| < 3.85$.
- The signal is read out through the hadronic Tile Calorimeters with HAMAMATSU photomultipliers
- They can be used as a L1 signal or in the HLT in association with ID HITS/tracks
- Expected to die with increasing luminosity. They will be removed from the trigger chain, that will then be based on random triggers

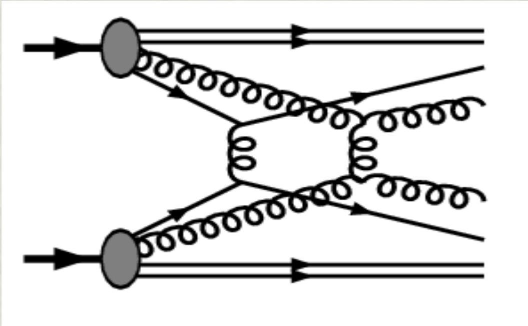


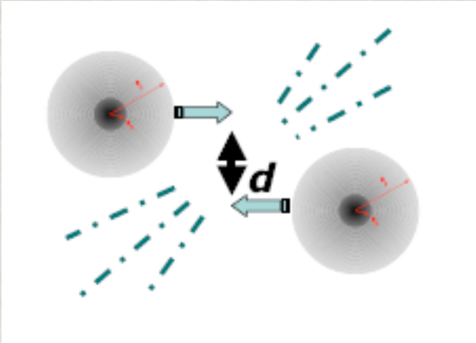


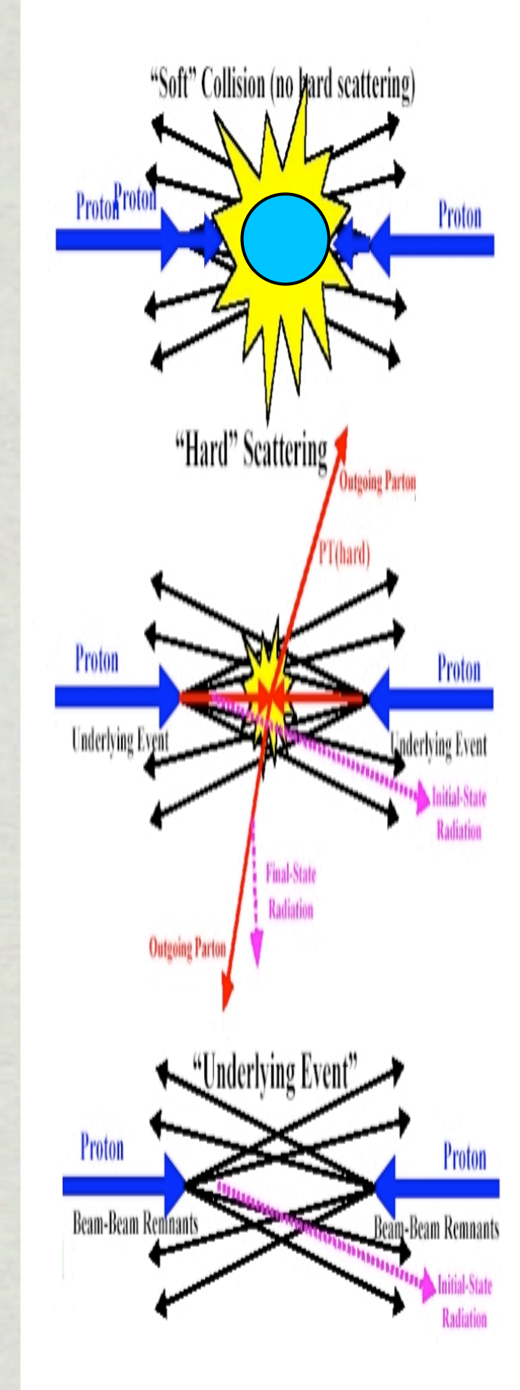
Underlying Event

$$\sigma_{\text{int}} = \int_{p_T(\min)}^{s/4} \frac{d\sigma}{dp_t^2}\, dp_t^2$$

- Everything which is not hard interaction
- In PYTHIA, the main ingredient is the multiple parton-parton interaction:
  - Total perturbative cross section greater than total cross section interpreted as multiple interaction
  - $\langle N_{int} \rangle = \sigma_{\text{parton-parton}} / \sigma_{\text{proton-proton}}$
  - In the simplest model, P_{Tmin} determines the multiplicty of the particles produced.

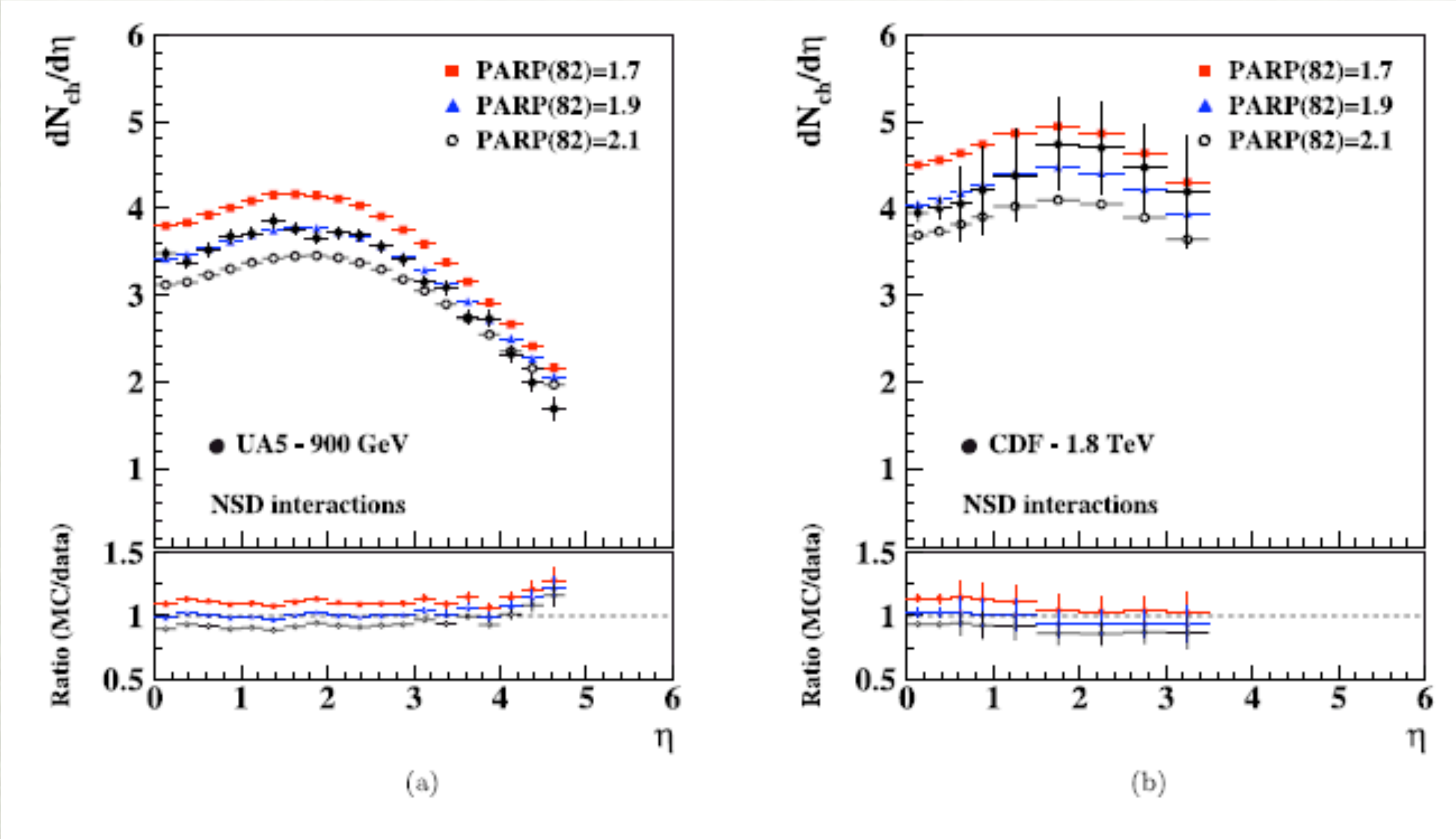






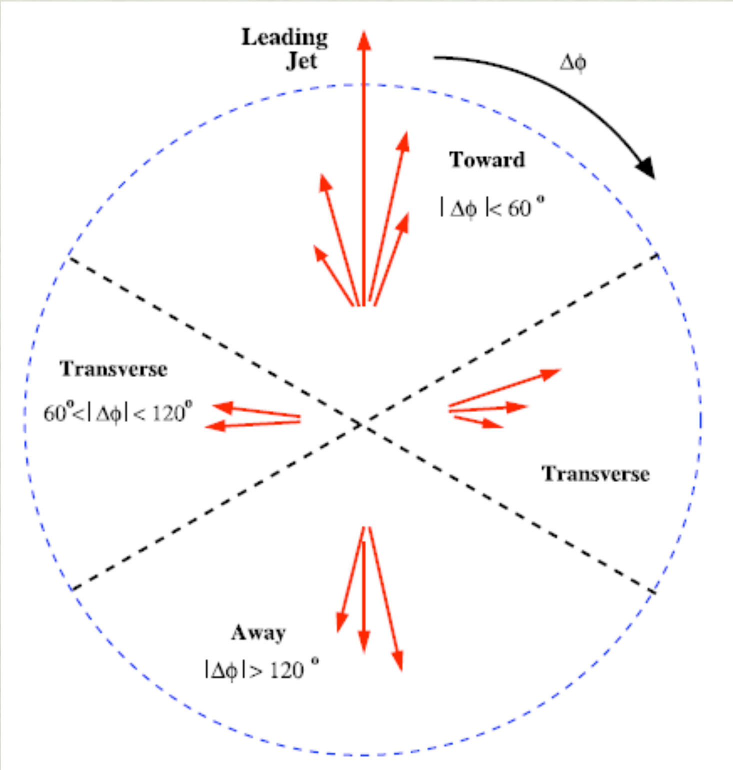
Example of tuning

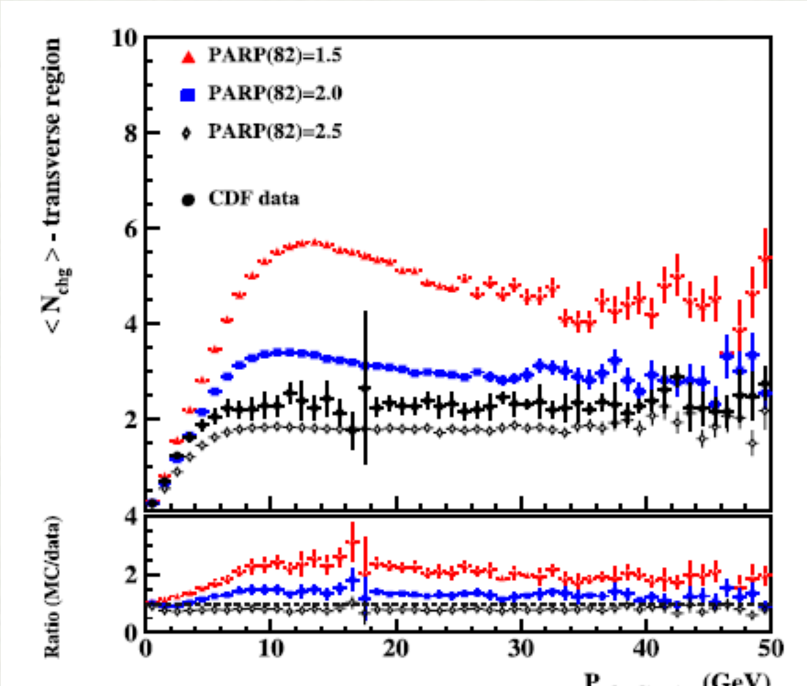
- dN/dη and dP$_T$/dη are sensitive to the modeling of the multiple interaction
- They are both, for example , sensitive to the P$_{Tmin}$



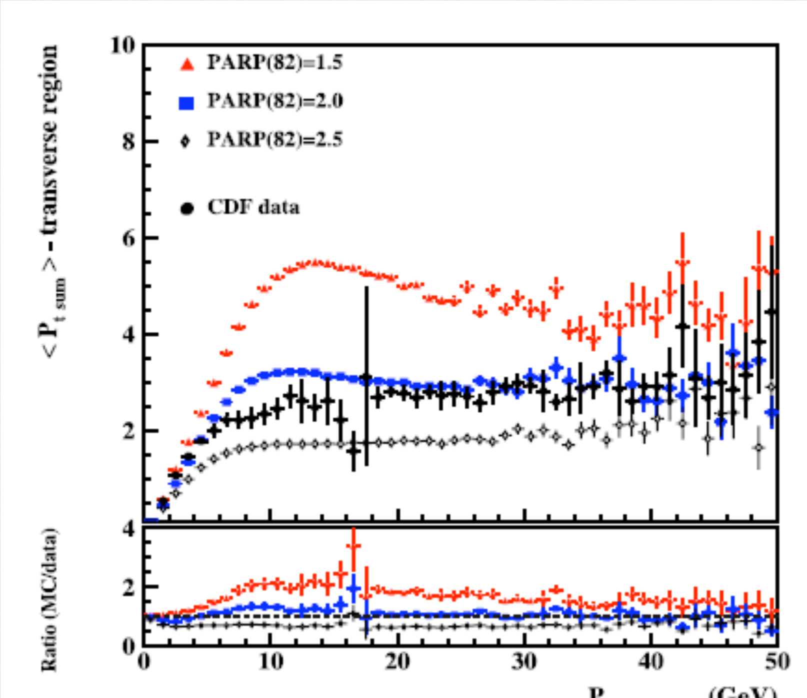
Example of tuning - UE

- CDF analysis (Phys.Rev. D 65 (2002) 072005)
- The leading charged jet defines three regions in the transverse plane
- dN/dη and dP_T/dη are measured as a function of $P_{T\ (leading)}$





(a)



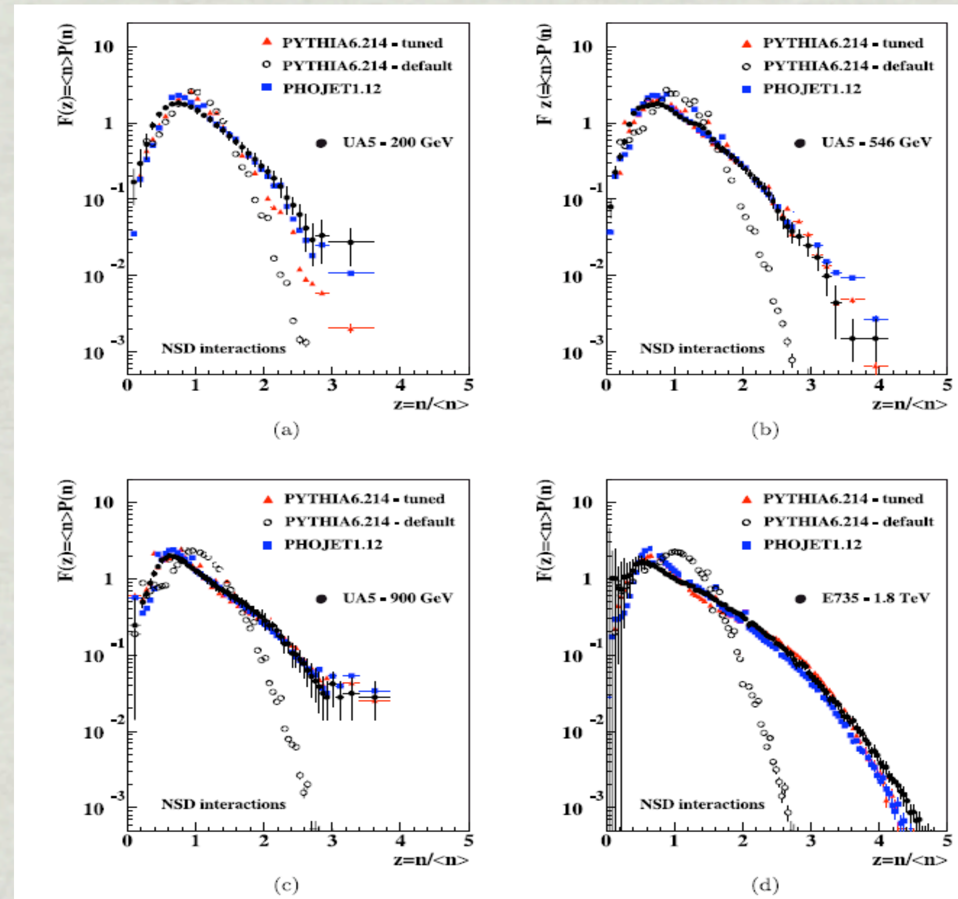
(b)

TRACKS WITH P_T > 0.5 GEV, |ETA| < 1

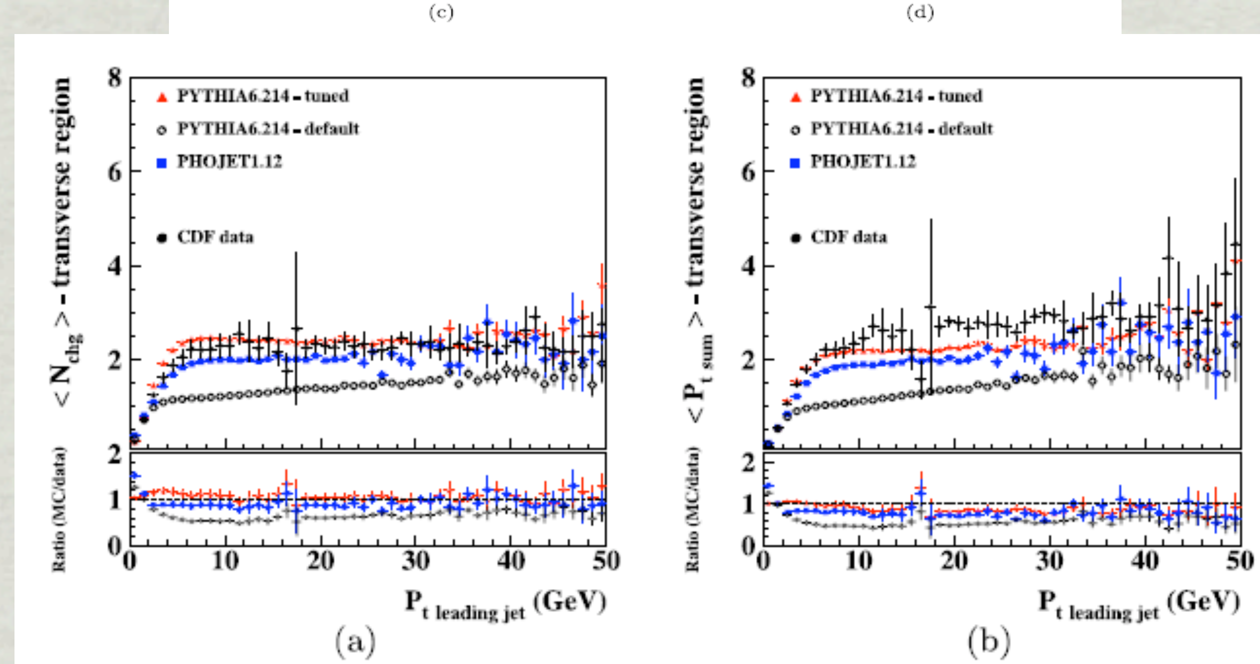
- ATLAS tuning: tuning of the minbias done using the KNO variables (Nucl. Phys. B40 (1972) 317)

$$F(z) = \langle n \rangle P_n = \langle n \rangle \frac{\sigma_n}{\sum_n \sigma_n}$$

$$z = \frac{n}{\langle n \rangle}$$



PYTHIA6.214 – tuned	
ISUB: 11,12,13,28,53, 68,94,95,96	QCD $2 \to 2$ partonic scattering +non-diffractive+ double diffractive
MSTP(51) = 7	CTEQ5L – selected p.d.f. (default)
MSTP(81) = 1	multiple interactions (default)
MSTP(82) = 4	complex scenario +double Gaussian matter distribution
PARP(82) = 1.8	$p_{t_{min}}$ parameter
PARP(84) = 0.5	core radius: 50% of the hadronic radius
PARP(89) = 1.0	energy scale (TeV) used to calculate $p_{t_{min}}$ (default)
PARP(90) = 0.16	power of the energy dependence of $p_{t_{min}}$ (default)



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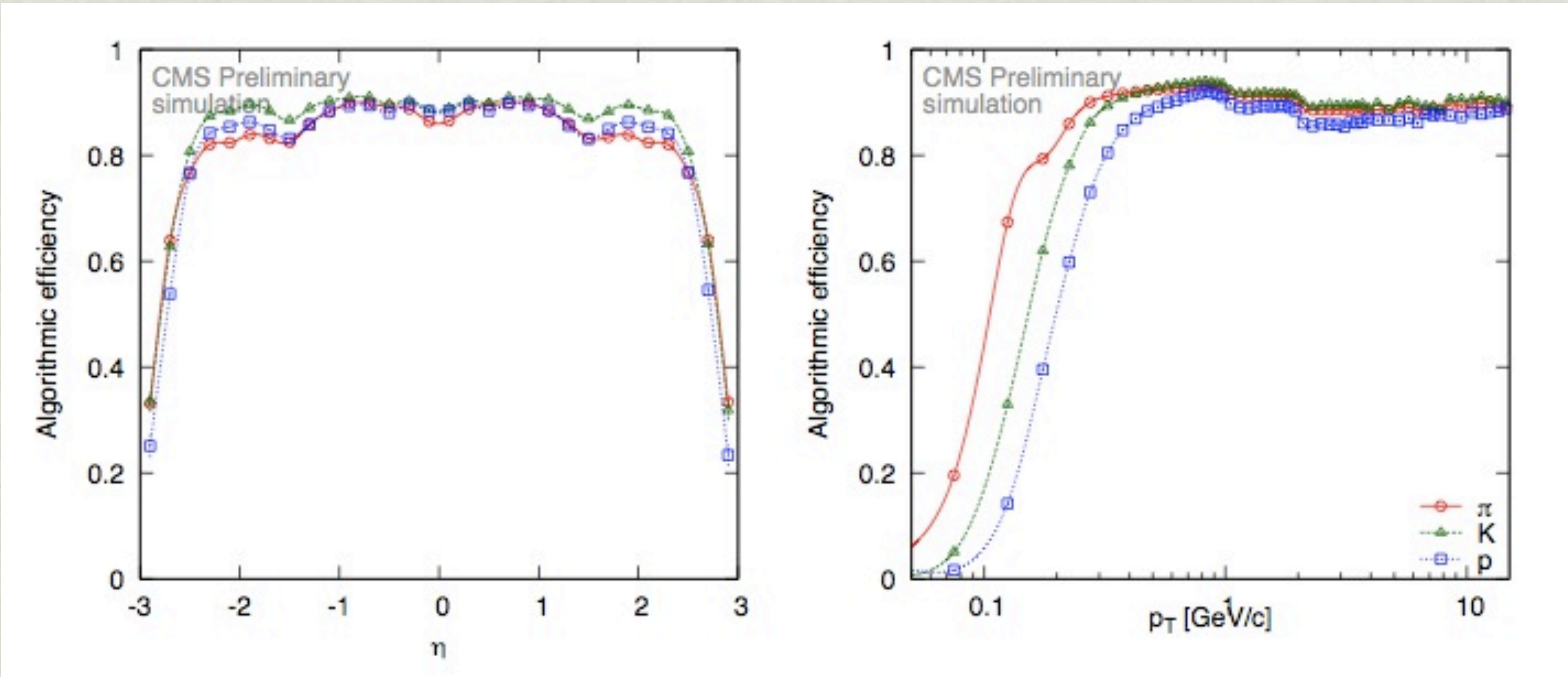
ATLAS ID and tracking

- ATLAS ID: 7 layers of silicon plus transition radiation tracker:
  - Pixel detector up to $|\eta| < 2.5$, 50.5 mm < r < 149.6 mm
  - Silicon microstrip system (SCT) detector up to $|\eta| < 2.5$, 299 mm < r < 1066 mm
  - Transition Radiation Tracker up to $|\eta| < 2.5$, 644 mm < r < 1000 mm.
  - Magnetic field B=2 T
- Tracking threshold ~ 500 MeV for tracks traversing the whole ID.
- It can be lowered to ~100 MeV requiring hits only in the silicon tracker (with dedicated tracking algorithms)

CMS low P_T tracking

- Requiring proto-tracks with three hits + vertex requirement allows the tracking to be efficient from few hundreds of GeV (depending on the particle type)
- References: F. Sikl, CMS note, AN 2006/100 (2006)



Minimum bias - CMS (2)

- The track distribution is computed from the hits distribution (HIT/track ratio computed from MC)

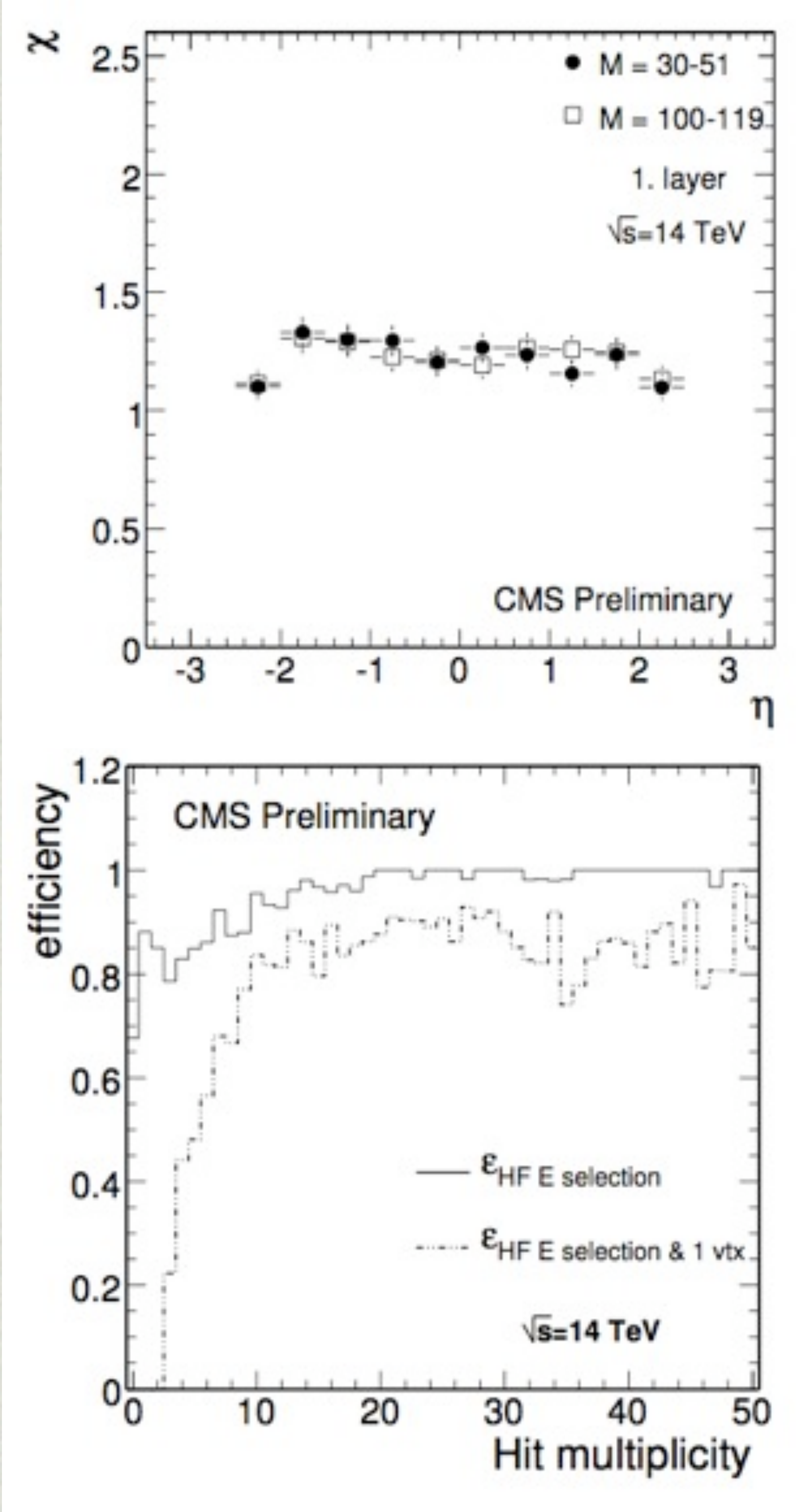
$$\chi(\eta, M) = \frac{H^{MC}(\eta, M)}{T^{MC}(\eta, M)}.$$

$$\frac{dN_{ch}}{d\eta}(\eta, M) = \frac{1}{\chi(\eta, M)} \frac{H(\eta, M)}{E_{sel}(M)}$$

- Event selection efficiency computed with MC, track distribution corrected for that

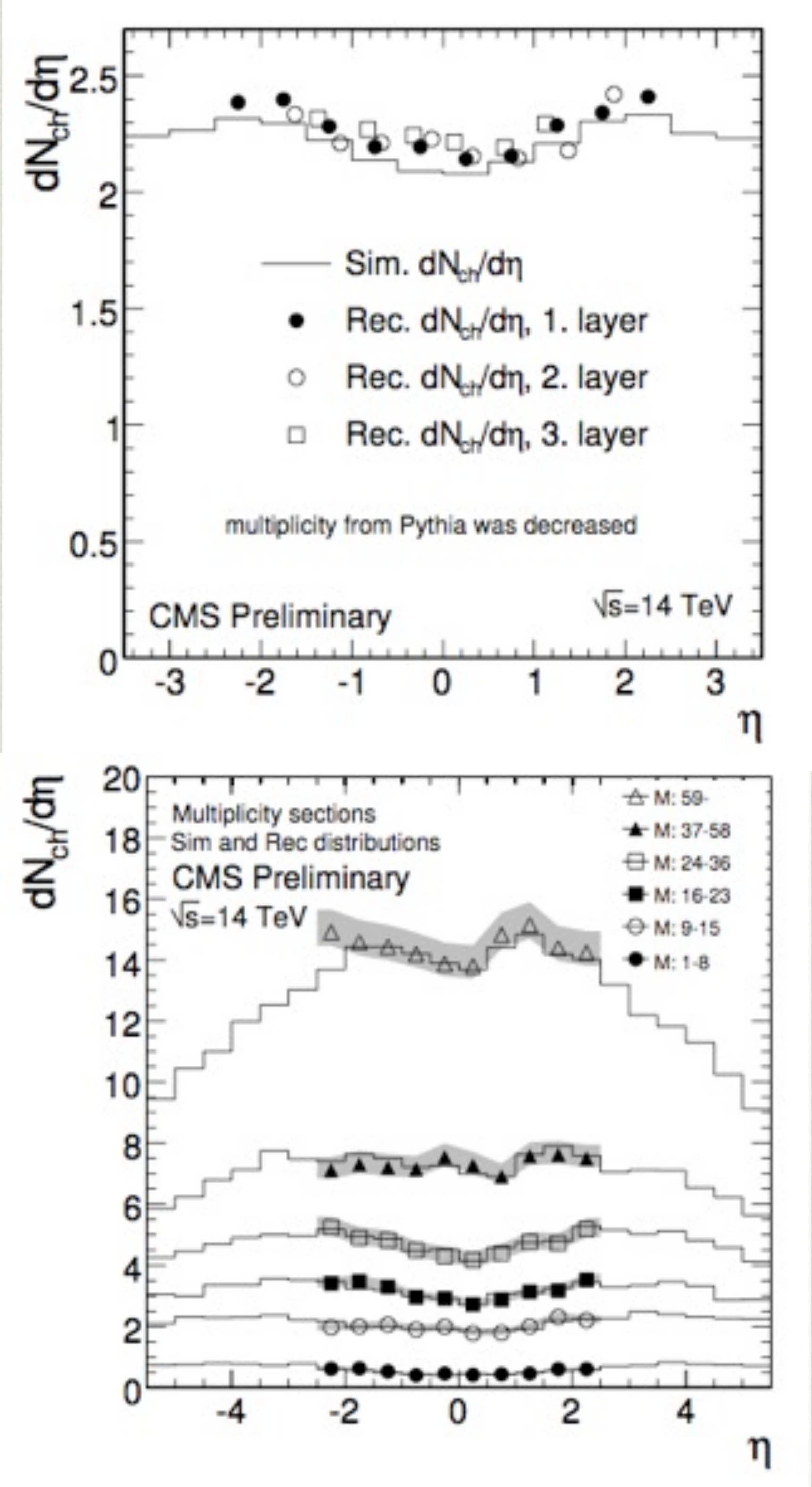
$$\frac{dN_{ch}}{d\eta} = \frac{\sum_M E_{sel}(M) \frac{1}{\epsilon(M)} \frac{dN_{ch}}{d\eta}(M)}{\sum_M E_{sel}(M) \frac{1}{\epsilon(M)}}$$

- Correction for loopers estimated extrapolating (with MC) from the number of hits failing the acceptance cut.



CMS PAS QCD-08-004

Results

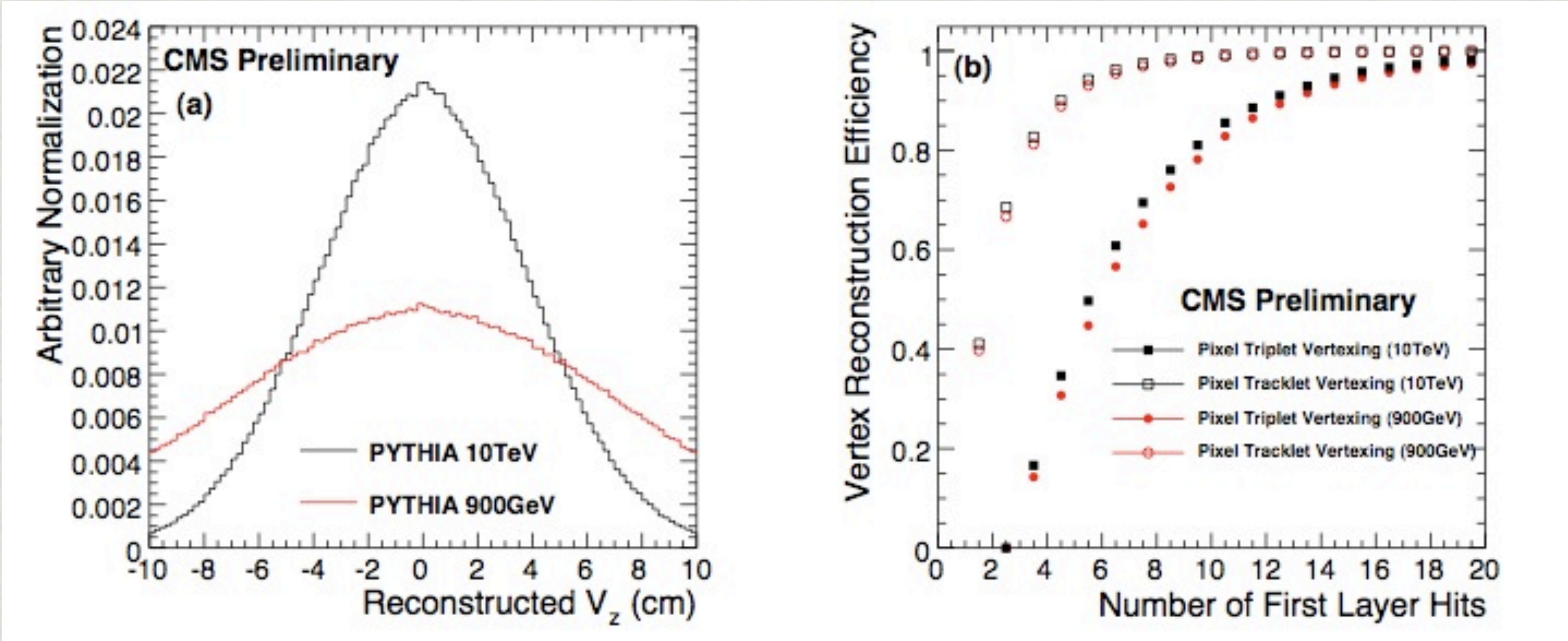


CMS PAS QCD-08-004

- Main systematics arising from the vertex efficiency and bias and from the MC determined hit to track correction.
- Robustness of the method tested computing the corrections and then applying them to an altered MC distribution. Stable results.

Tracklets method

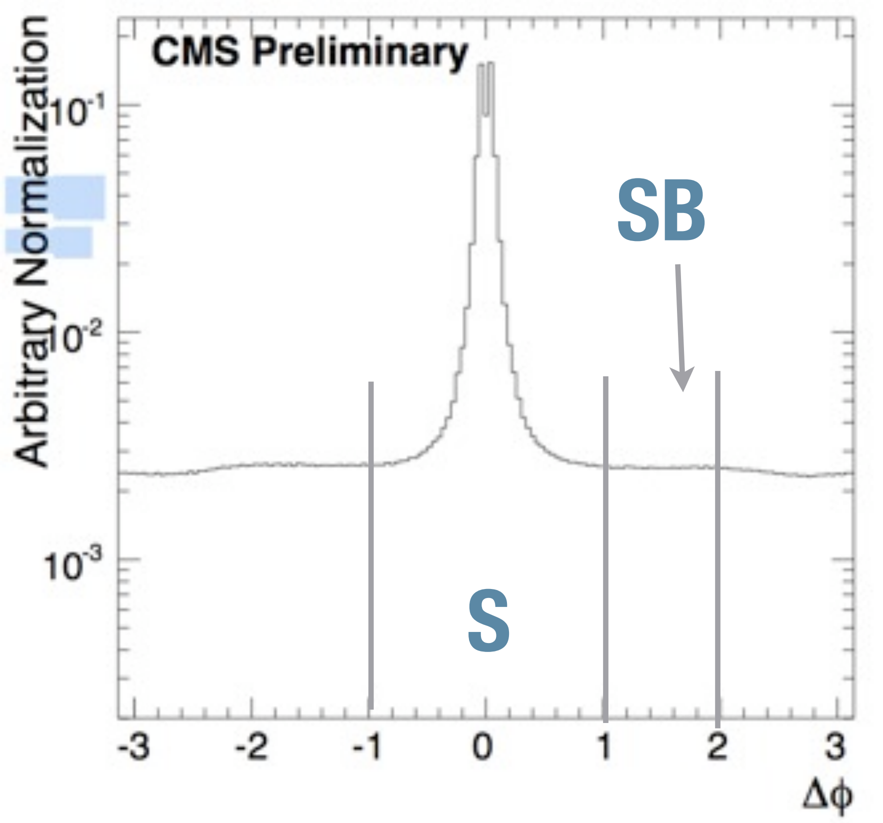
- Take hits in the first pixel layer of the CMS ID. Loop on the second layer hits:
  - Associate hits if $\Delta\varphi < \Delta\varphi_{cut}$
- Estimate the vertex position from each doublets of hits. Merge vertex candidates if $\Delta z < \Delta z_{cut}$
- Define the primary vertex as the one with more vertex candidates merged.
- Typical fake rate 1-5%



Tracklets method (2)

- Hits pseudorapidity computed with respect to primary vertex
- Background subtraction using sidebands in the Δφ distribution ($\beta = N_{SB}/N_S$)
- MC correction to go back to the tracks:

$$\alpha(M,\eta,V_z) = \frac{N^{Truth}_{Hadron}(M,\eta,V_z)}{(1-\beta(M,\eta,V_z))N^{raw,MC}_{Tracklet}(M,\eta,V_z)}.$$



- Final track distribution computed as follows:

$$\frac{dN_{ch}}{d\eta}(\eta)|_{selected} = \frac{1}{N_{selected}(\eta)\delta\eta} \sum_{(M,V_z)} \alpha(M,\eta,V_z)(1-\beta(M,\eta,V_z))N^{raw}_{Tracklet}(M,\eta,V_z)$$

- ζ: correction for selection efficiency (MC based)

$$\xi(\eta) = \frac{dN/d\eta(\eta)}{dN/d\eta(\eta)|_{selected}}$$

$$\frac{dN_{ch}}{d\eta}(\eta) = \xi(\eta)\frac{dN_{ch}}{d\eta}(\eta)|_{selected}$$

Tracklets method (3)

- Study of the systematics:
  - Dominating systematics: Correction on event selection and pixel hit reconstruction efficiency
  - Total uncertainty ~10%

Source	Related correction factor	900GeV (%)	10TeV (%)
Statistical error of α	α	1.0	1.0
Monte Carlo efficiency correction	α	0.5-2.0	0.5-2.5
Pixel hit reconstruction algorithm	α	0.1	0.1
Pixel hit reconstruction efficiency	α	5.0	5.5
Pixel hit splitting	α	1.5-3.5	1.0-2.0
Acceptance uncertainty	α	0.0-10.0	0.0-10.0
Background subtraction	β	0.5-1.5	0.5-2.0
Misalignment	α, β	1.0	2.0
Random hits from beam halo and loopers	α, β	0.1-1.5	0.1-1.0
GEANT Simulation	α, β	2.0	2.0
Effect of event pile-up	α, β	1.0	1.0
Correction on event selection	ξ	5.0	5.0
Total		7.5-13.5	8.5-13.5