

Measurements of hadron production at CMS

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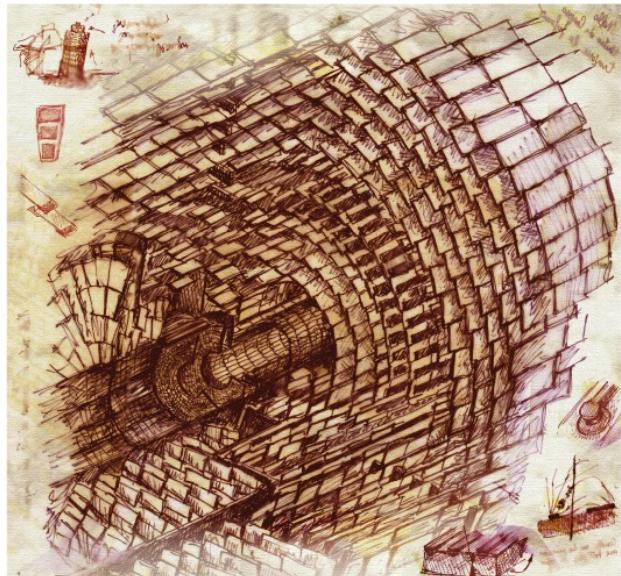
on behalf of the CMS Collaboration



HCBM 2010, Budapest, Hungary
17 August 2010



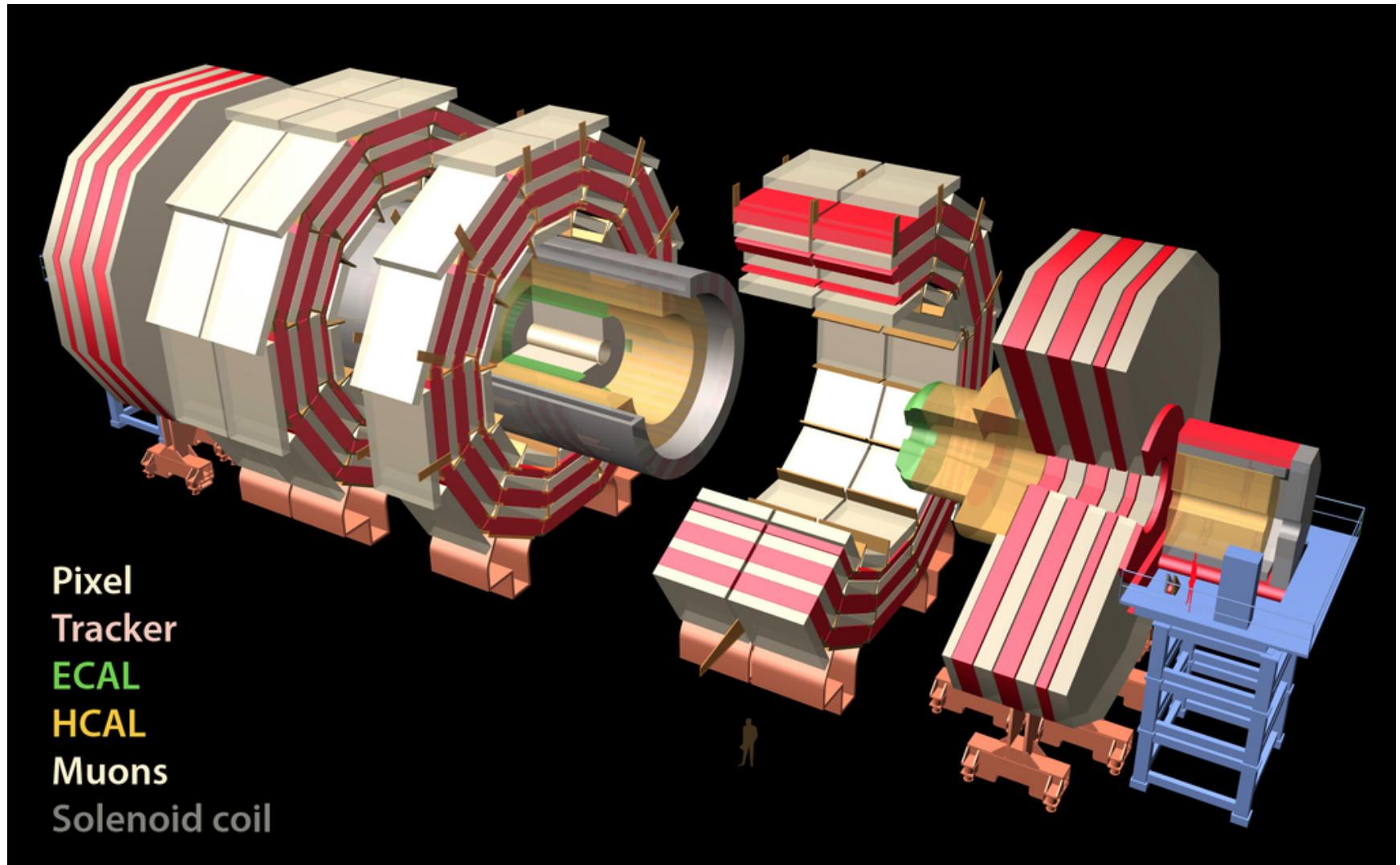
Contents



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 - Particle flow
- Physics results (pp, QCD)
 - Hadron spectra (vs η and p_T)
charged; strange
 - Event-by-event multiplicity
 - Hadron correlations
angular; Bose-Einstein
 - Underlying event
 - Jet spectra



The CMS detector



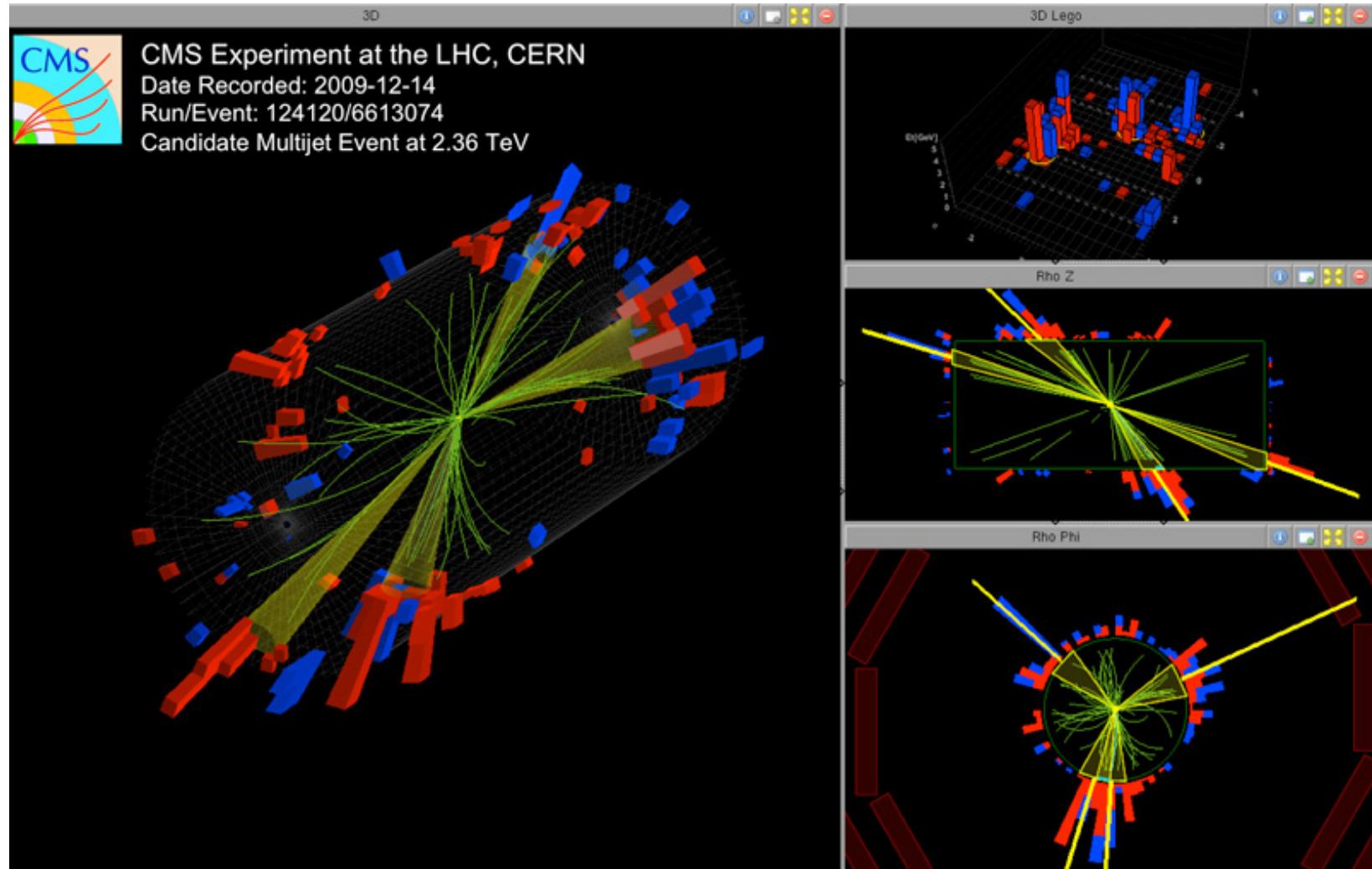
Silicon tracker (pixels+strips)
Hermetic ($|\eta| < 5.2$) HCAL

Lead tungstate crystal ECAL
Muon system (RPC, DT, CSC)

3.8 T field



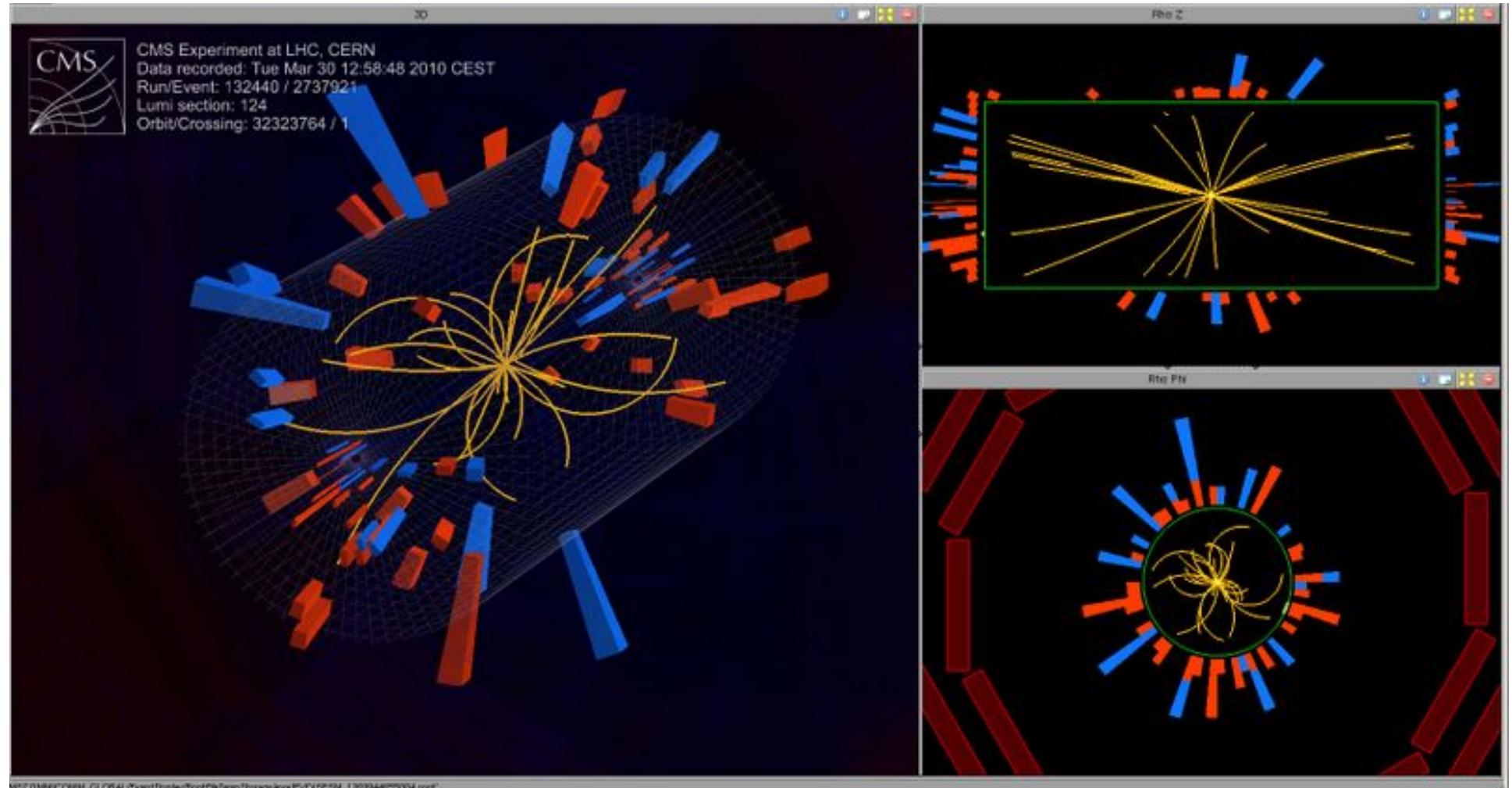
The detector at work



Tracks, calorimeter towers and jet candidates at 2.36 TeV
2009: $\sqrt{s} = 0.9$ and 2.36 TeV



First 7 TeV collisions



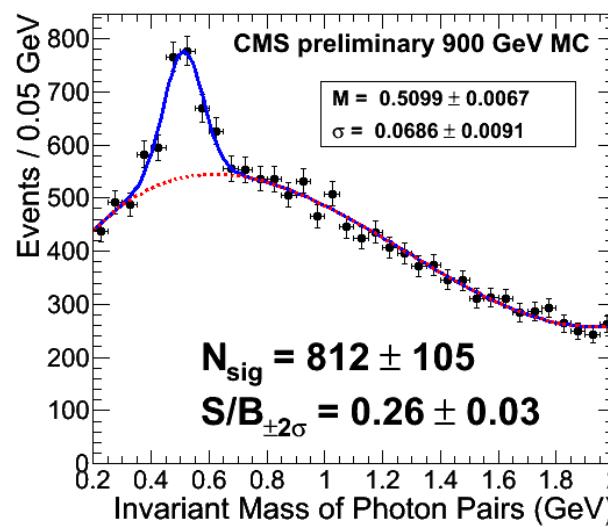
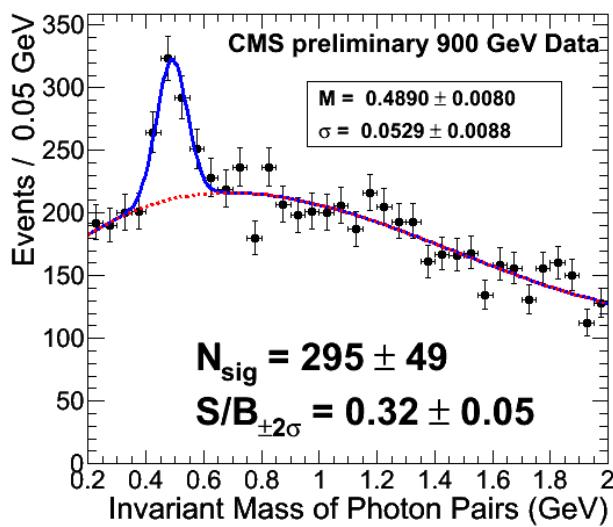
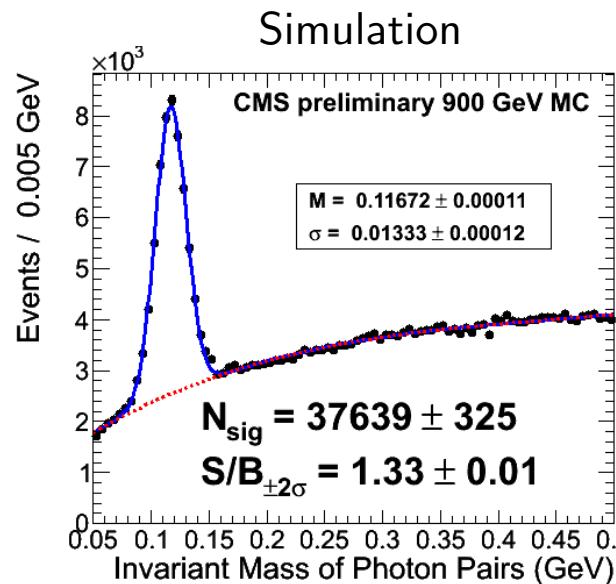
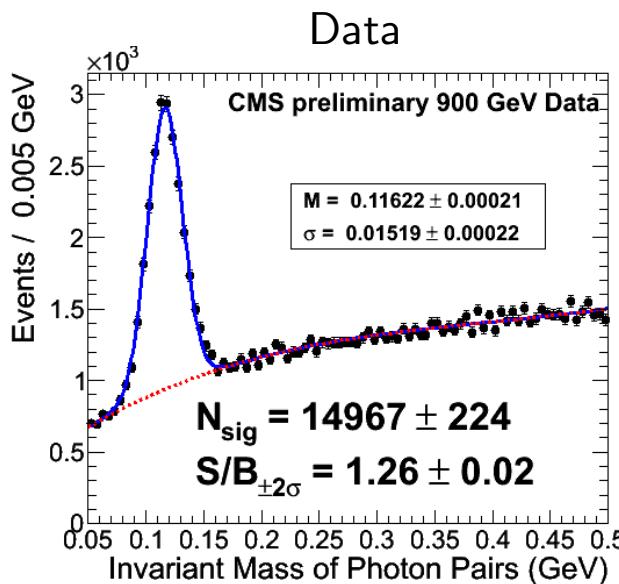
A minimum bias pp event at CMS
2010: $\sqrt{s} = 7 \text{ TeV}$

About to 1 pb⁻¹ recorded so far

Performance results



Neutrals decaying to $\gamma\gamma$



$\pi^0 \rightarrow \gamma\gamma$

No corrections
(for shower containment,
thresholds, energy loss)

$\eta \rightarrow \gamma\gamma$

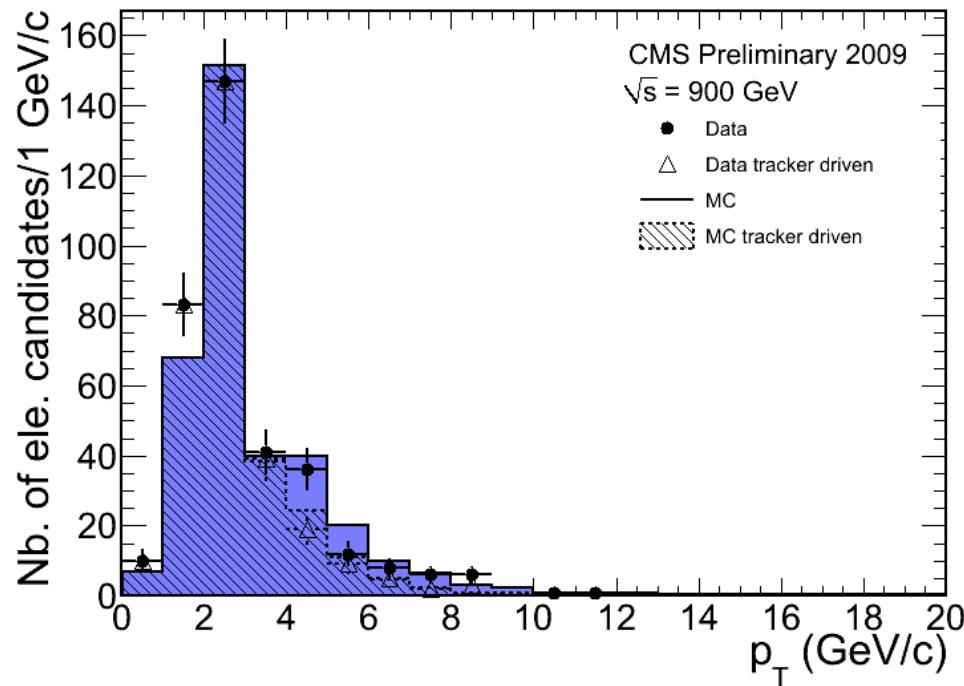
Corrected,
good agreement:
peak position and S/B

ECAL photons: energy scales now in data and MC agree within 2%



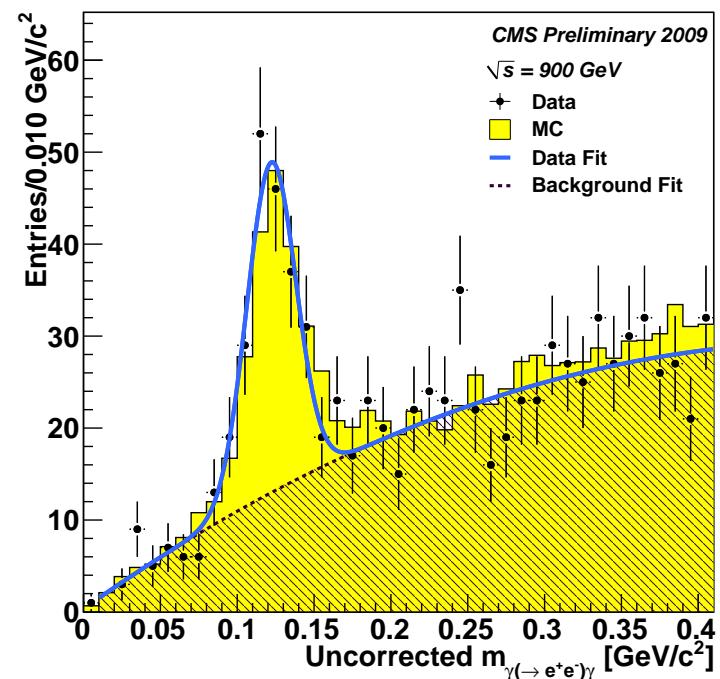
Electrons and conversions

Electrons



p_T distribution of electron candidates
Tracker or ECAL driven

π^0 with conversion



CMS-PAS-EGM-10-001

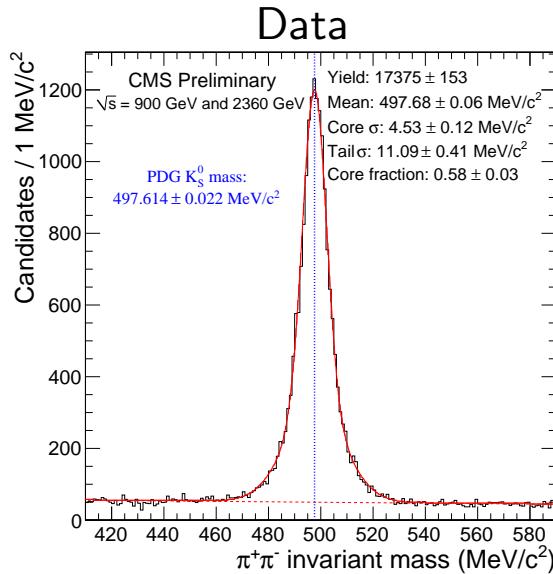
Observation of $\pi^0 \rightarrow \gamma\gamma$
One leg reco'd from conversion

Good agreement between data and MC

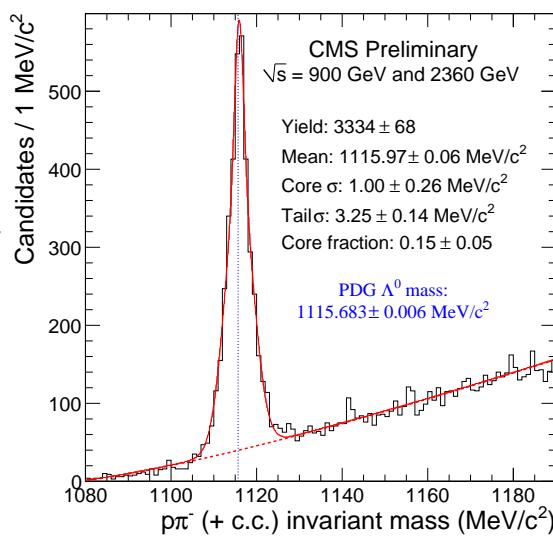


Tracking – long lived resonances

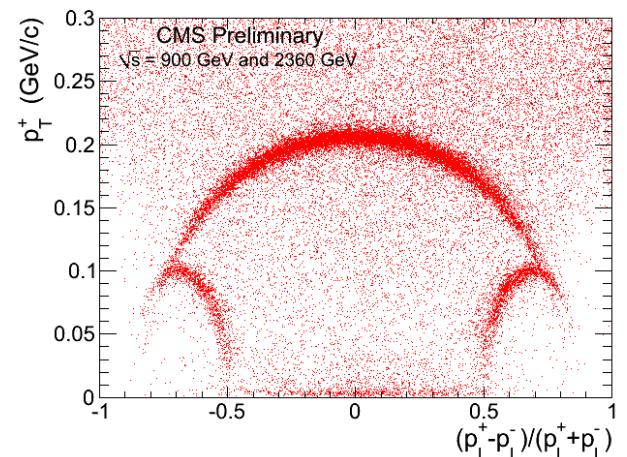
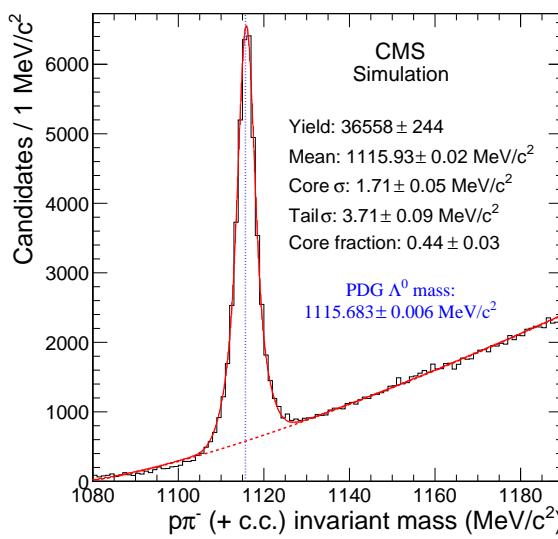
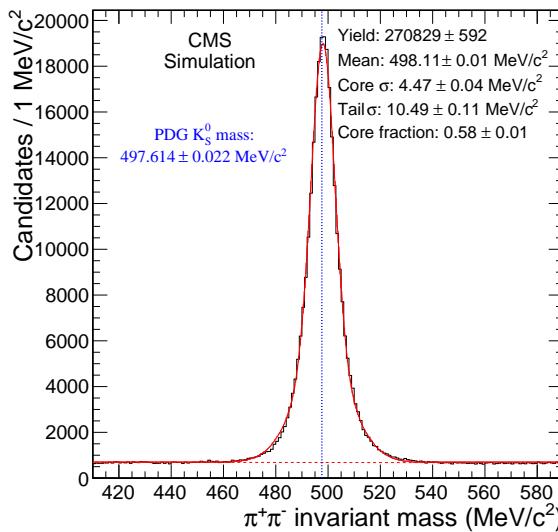
K_S^0



$\Lambda + \bar{\Lambda}$



Simulation

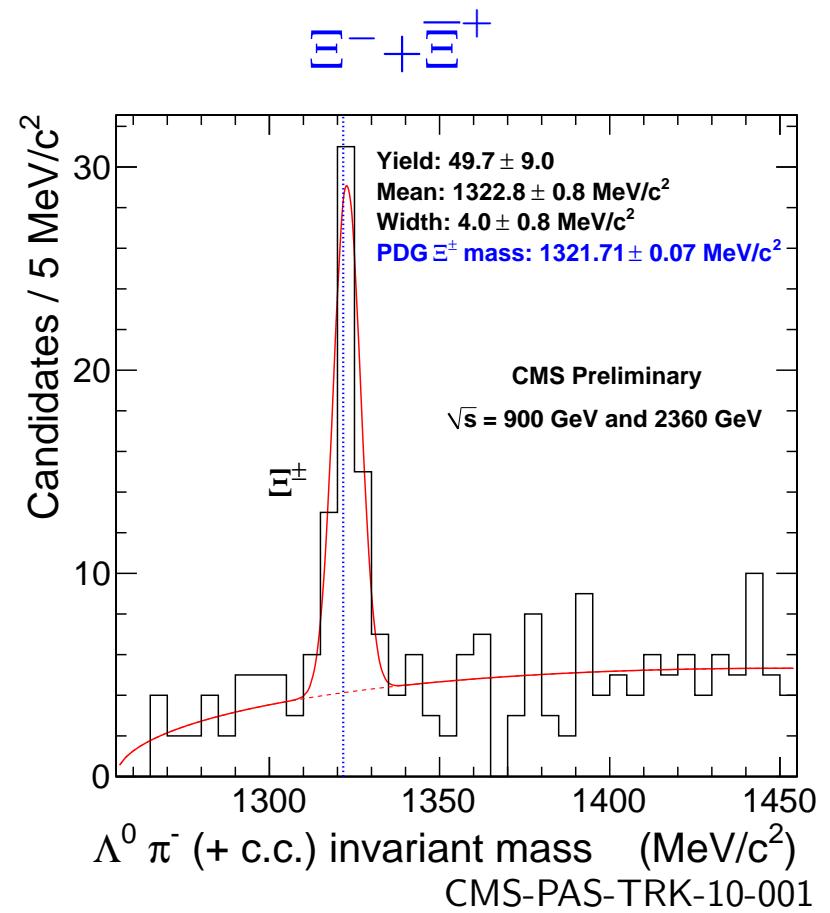
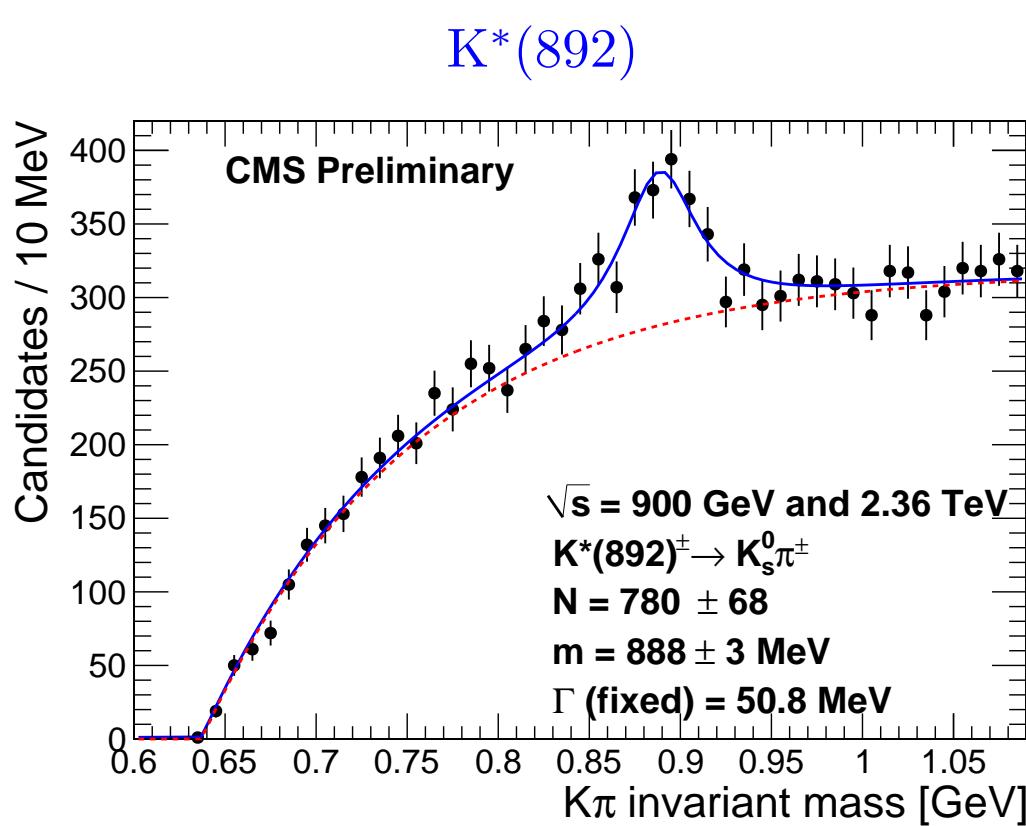


CMS-PAS-TRK-10-001

Peak shape and S/B agrees beautifully: per mille precision in momentum



Tracking – on-vertex resonances

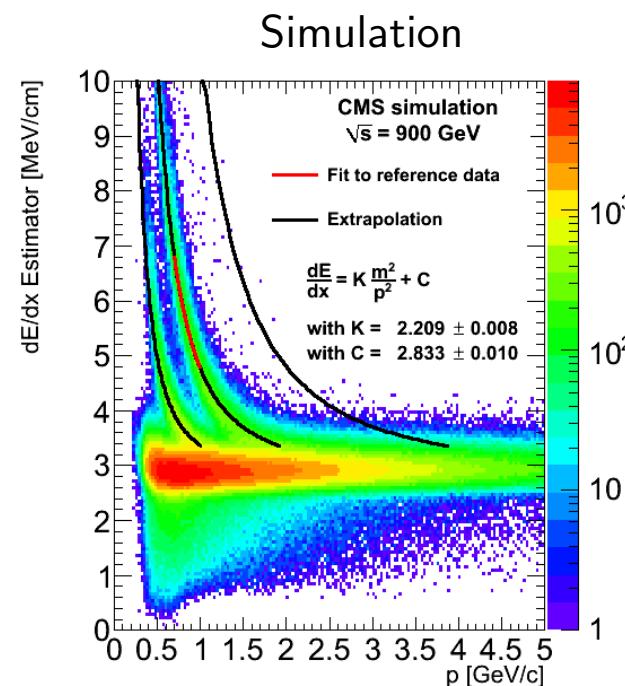
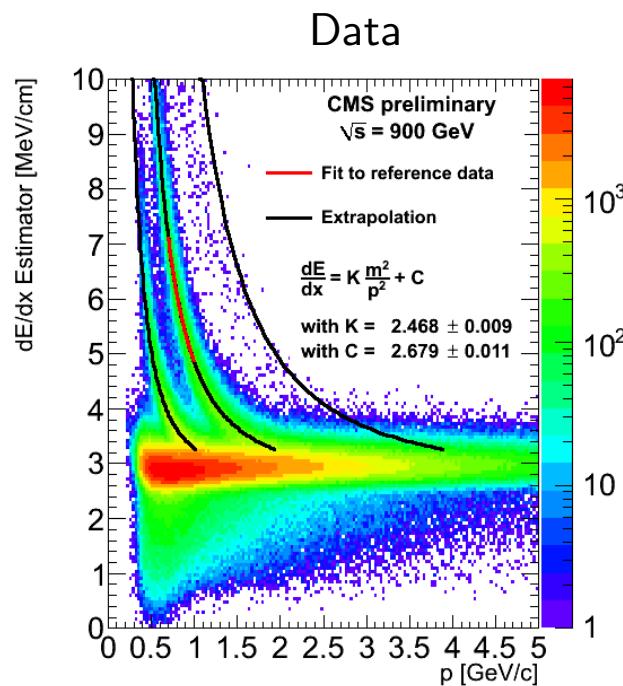


One step further: cascade decays with three charged hadrons in the final state

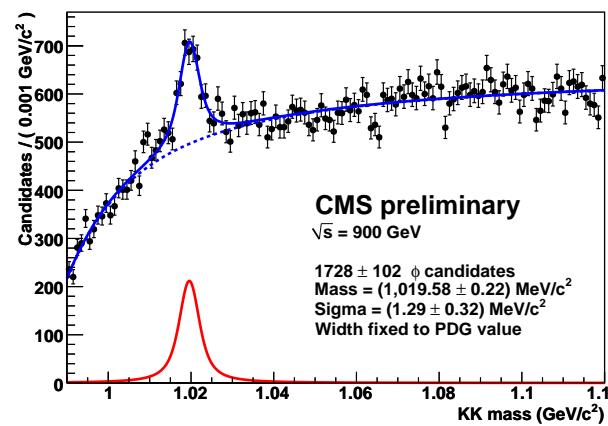
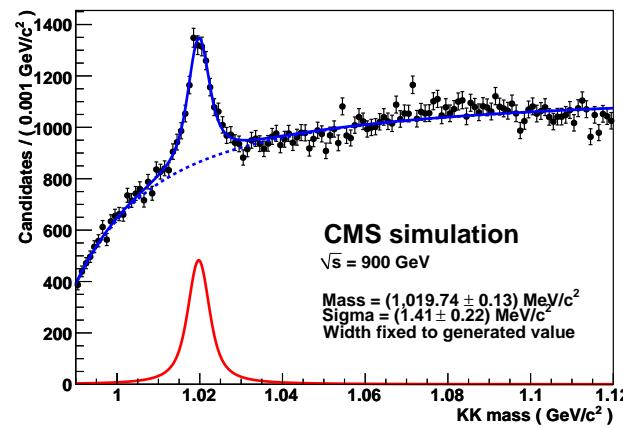
Mass peaks: excellent agreement with PDG



Tracking – particle identification



Energy loss
in the silicon layers
(power mean)
vs momentum

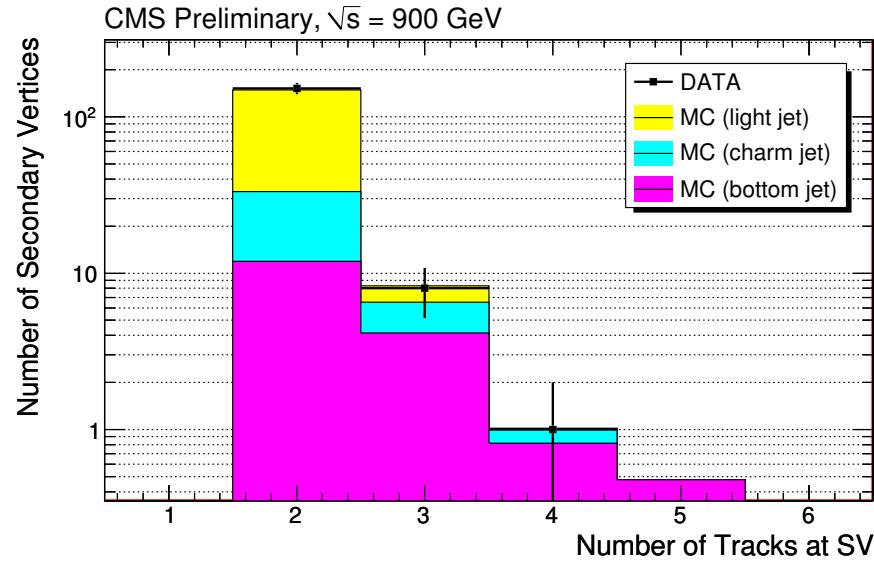
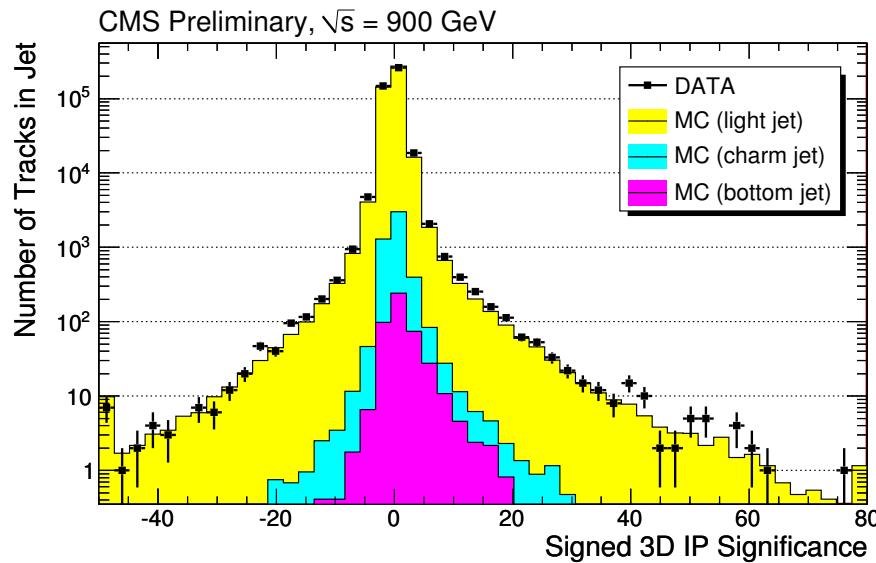


Reconstruction of
 $\phi(1020) \rightarrow K^+K^-$
with help of dE/dx

Particle identification at low momentum

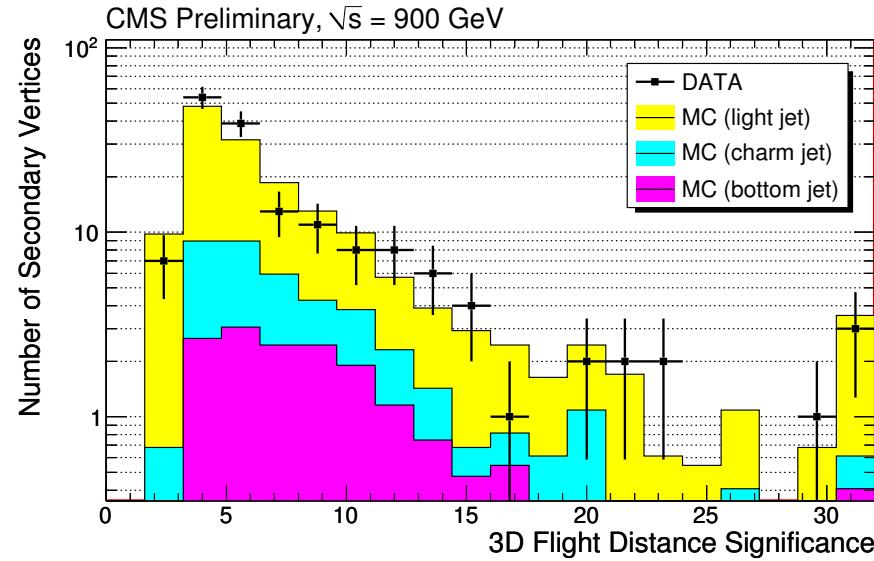
CMS-PAS-TRK-10-001

Vertexing – b-tagging



- Variables

- Impact parameter significance
tracks with at least 7 hits,
associated to a jet,
impact given wrt the primary vertex
- Number of tracks at seco vertex
- Decay length significance

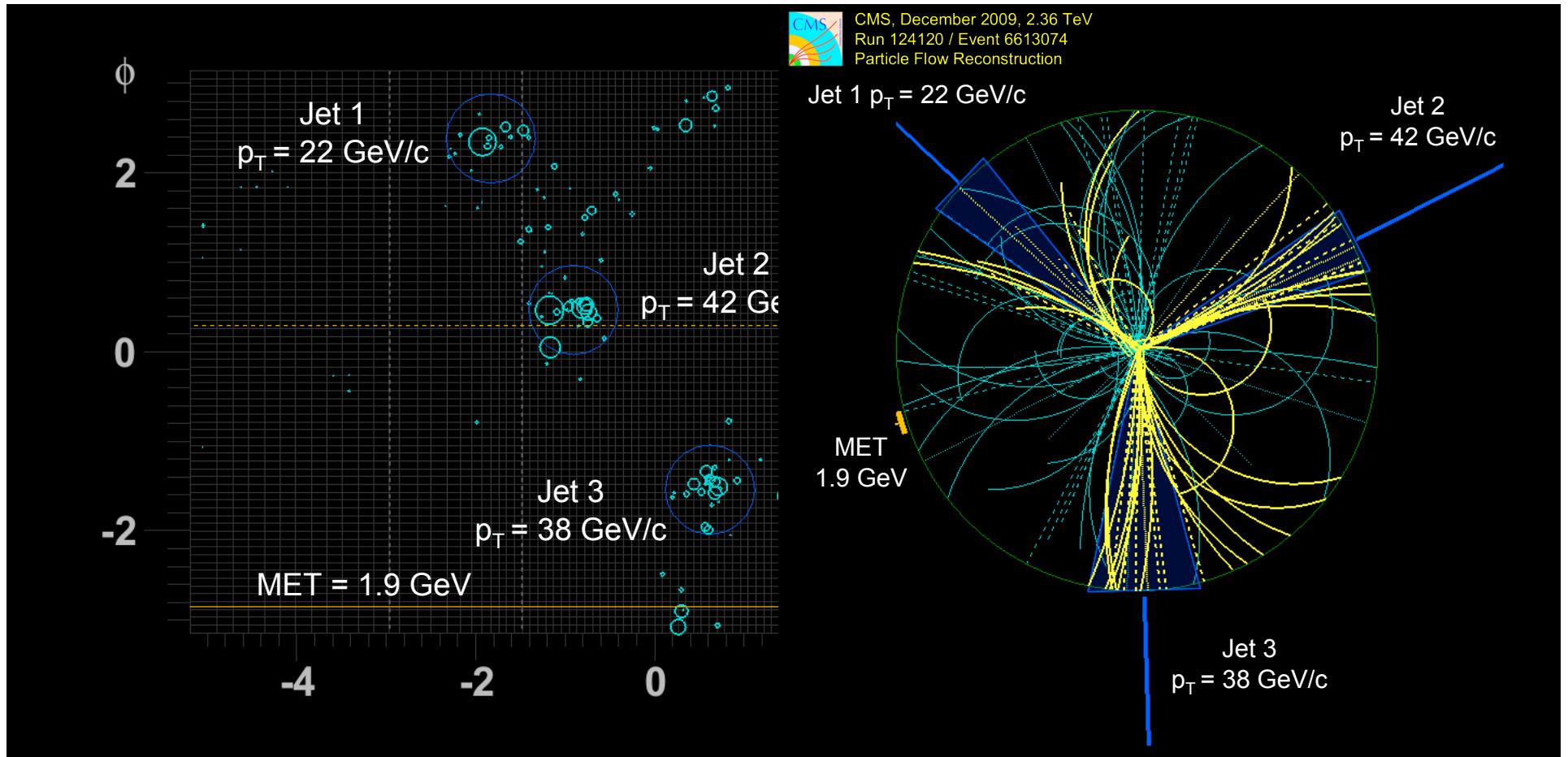


Basic b-tagging related variables are well described

CMS-PAS-TRK-10-001



Particle flow



CMS-PAS-PFT-10-001

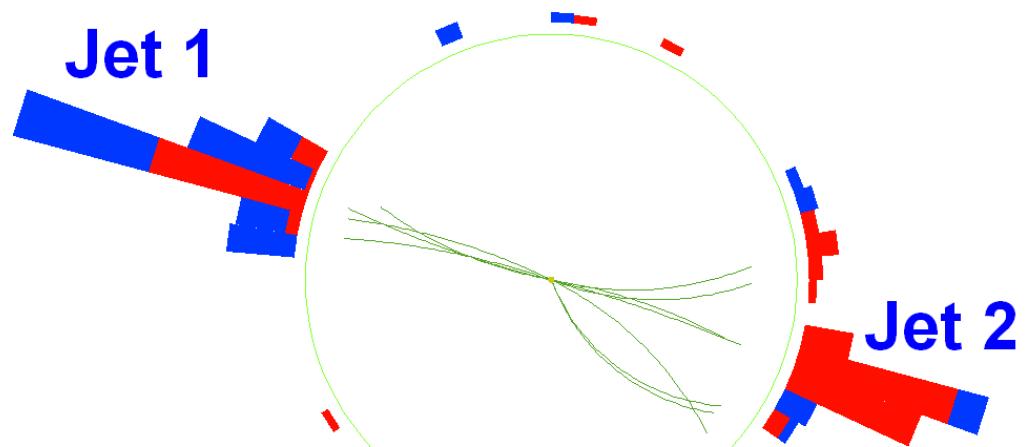
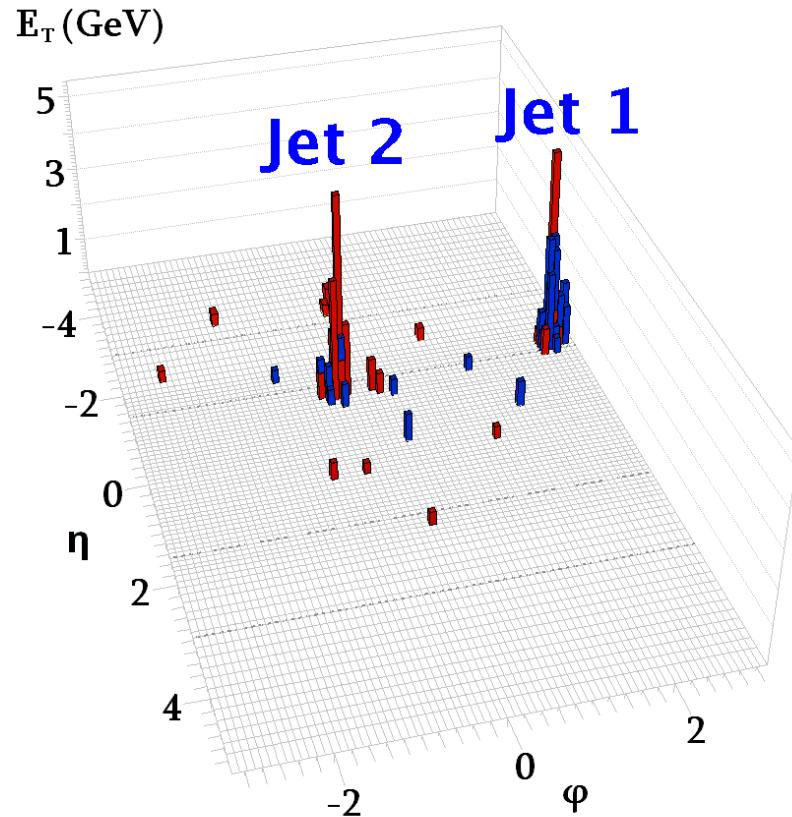
A particle-flow reconstructed event at 2.36 TeV

Circles – particle p_T

Thinner circles – jets with $p_T > 20 \text{ GeV}/c$



Jets



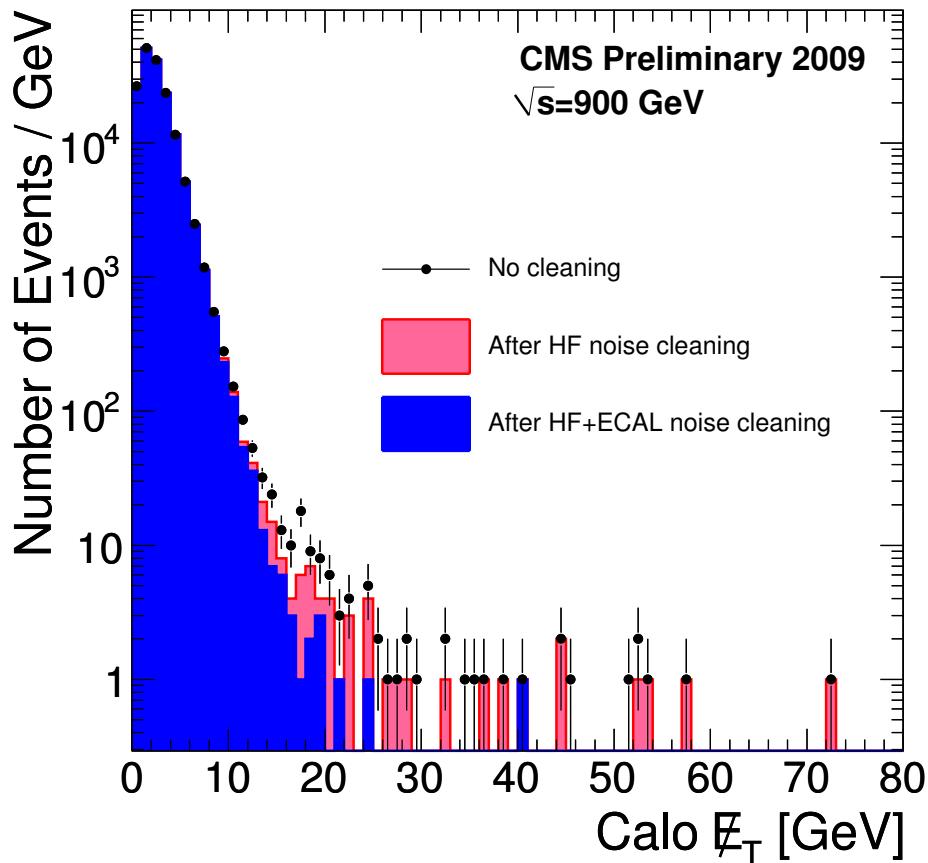
CMS-PAS-JME-10-001

Tracks with $p_T > 1$ GeV/c and calorimeter towers with $E_T > 0.3$ GeV
Jet transverse momenta are measured to be 39-45 GeV and 31-37 GeV

Dijet candidate event at $\sqrt{s} = 0.9$ TeV



Missing E_T



- Corrections

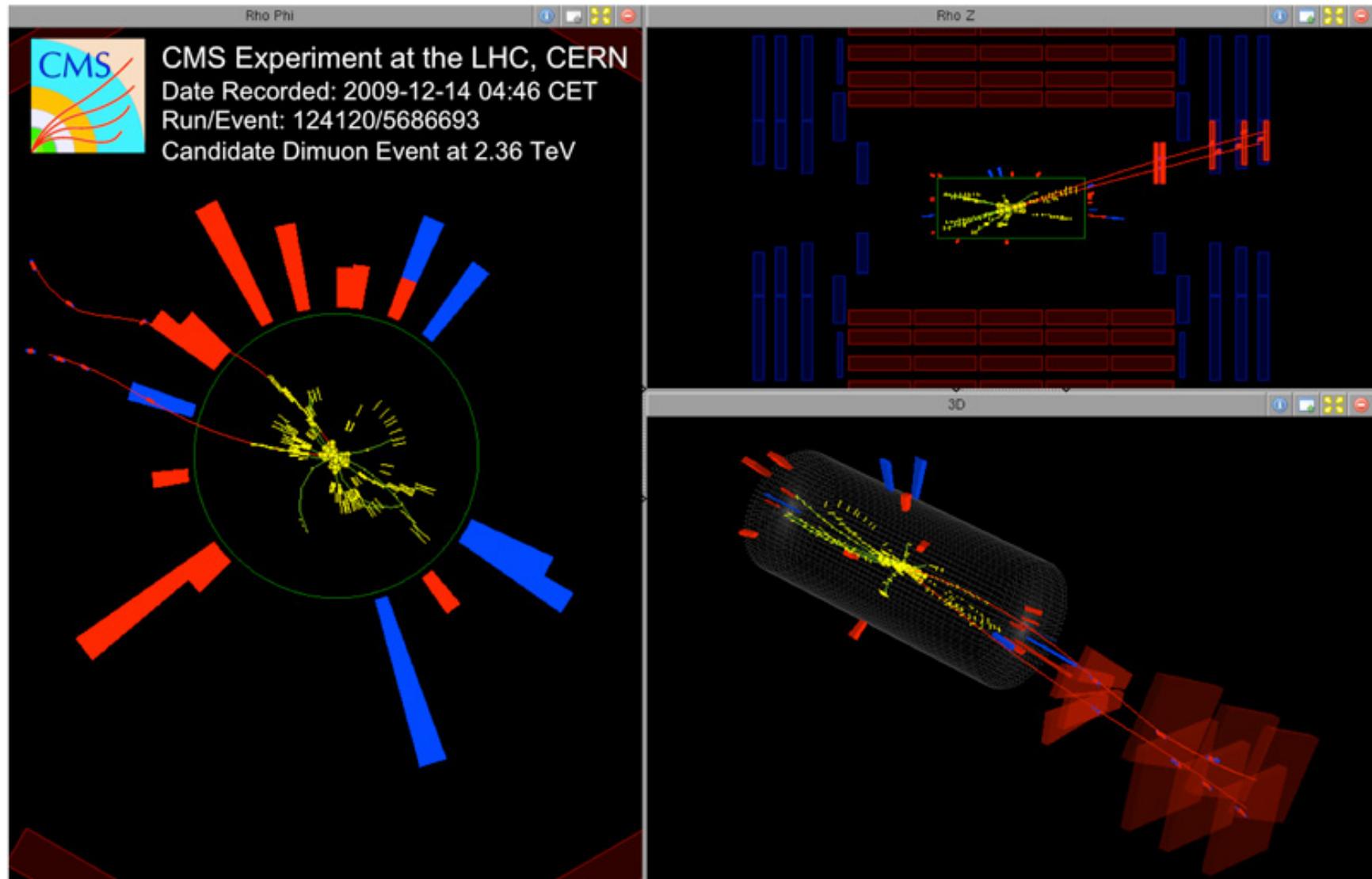
- Robust missing E_T measurement over the full data-taking period
- Anomalous noise in HCAL
 - * hybrid photo diodes
 - * photo-multiplier window hits
- Anomalous noise in ECAL
 - * single crystals, "spikes"
- Beam-halo muons

CMS-PAS-JME-10-002

Very efficient cleaning procedure: reduction of the E_T tail



Muons



Muon pair at $\sqrt{s} = 2.36$ TeV

Physics results



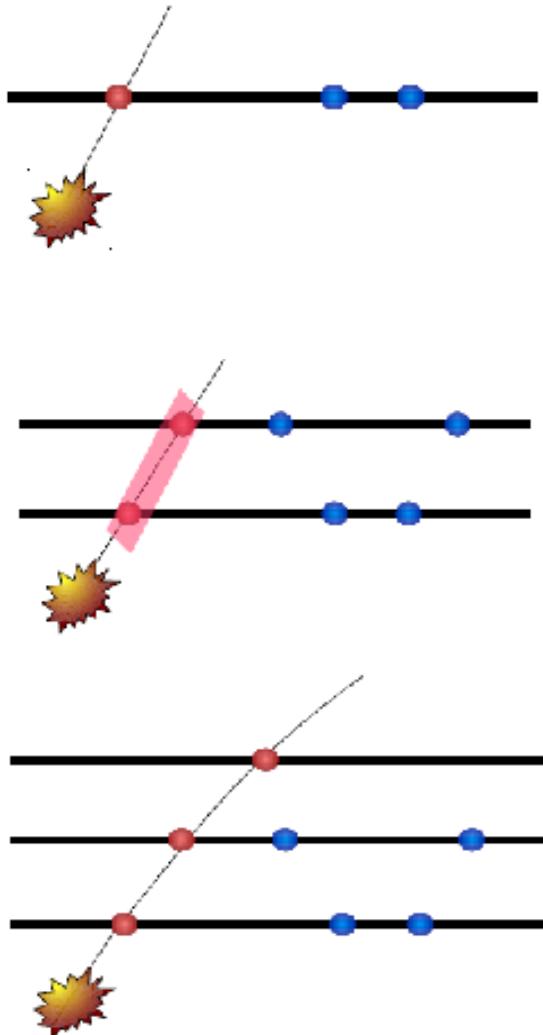
References

Topic	CMS PAS	arXiv	Publication
Spectra of charged hadrons	QCD-09-010	1002.0621	JHEP 02 (2010) 041
	QCD-10-006	1005.3299	PRL 105 (2010) 022002
Spectra of strange hadrons	QCD-10-007		
Event-by-event multiplicity	QCD-10-004		
Bose-Einstein correlations	QCD-10-003	1005.3294	PRL 105 (2010) 032001
Angular correlations	QCD-10-002		
Underlying event	QCD-10-001	1006.2083	Submitted to EPJC
	QCD-10-010		
	QCD-10-005		
Jet spectra	QCD-10-011		

PAS = Physics Analysis Summary, they are all public at CERN Document Server
Blank fields indicate a paper in preparation

Data points are also published, txt file at journal site and at Durham

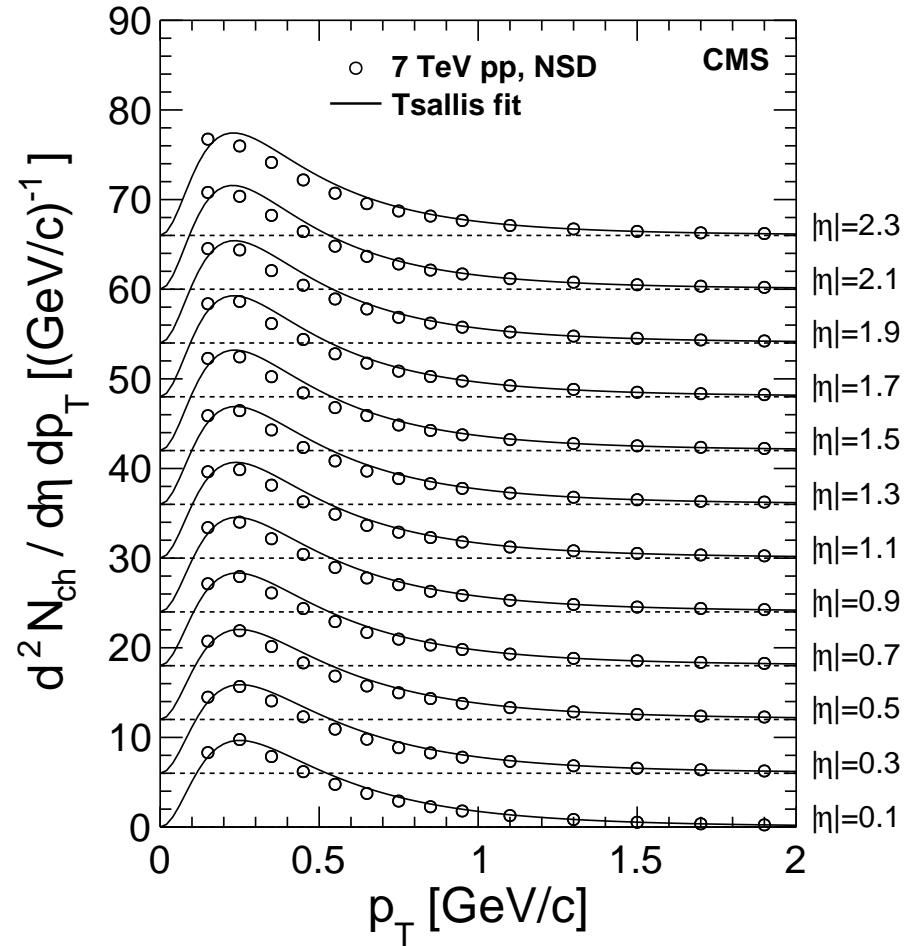
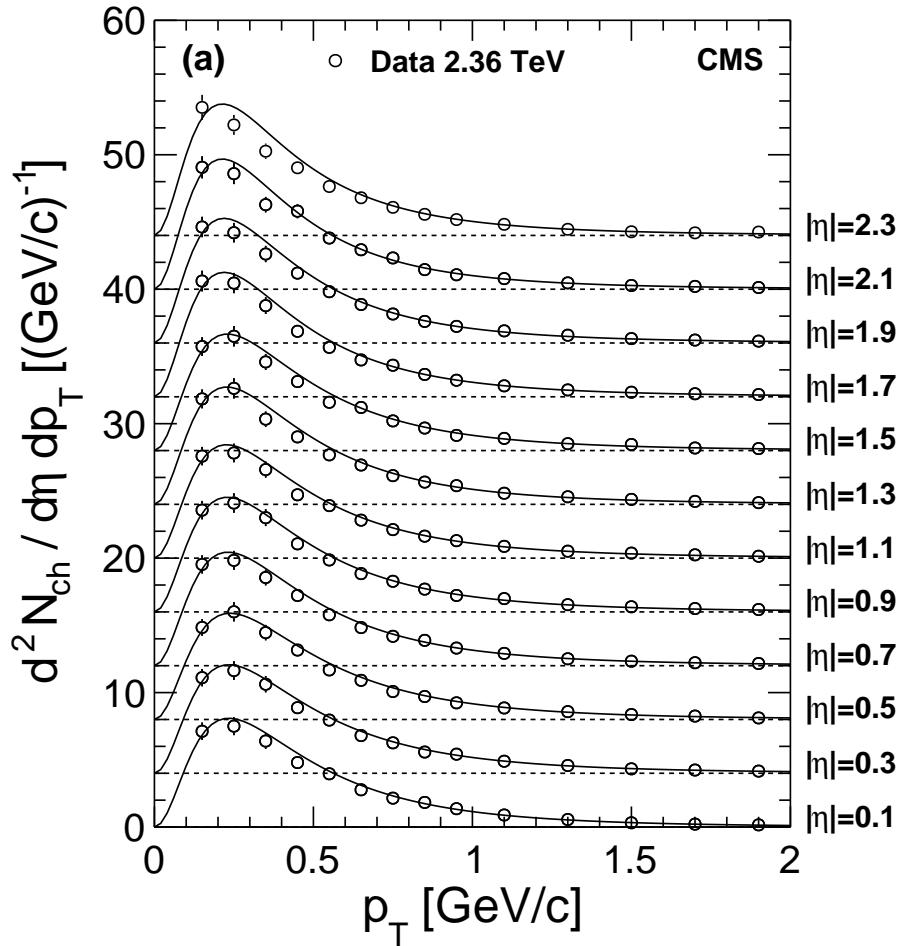
Spectra of charged hadrons – methods



- Pixel hit counting (1 hit)
 - Using the primary vertex, calculate η for each cluster
 - Immune to detector mis-alignment, simplest
 - $p_T > 30 \text{ MeV}/c$, $|\eta| < 2$
- Tracklets (2 hits)
 - Form hit pairs, calculate η
 - Data-driven background subtraction
 - $p_T > 50 \text{ MeV}/c$, $|\eta| < 2$
- Full tracks
 - Use all pixel and strip hits, provide η and p_T
 - Sensitive, most complex
 - $p_T > 100 \text{ MeV}/c$, $|\eta| < 2.4$

Two-sided calorimeter trigger; correct to non-single-diffractive (NSD) events

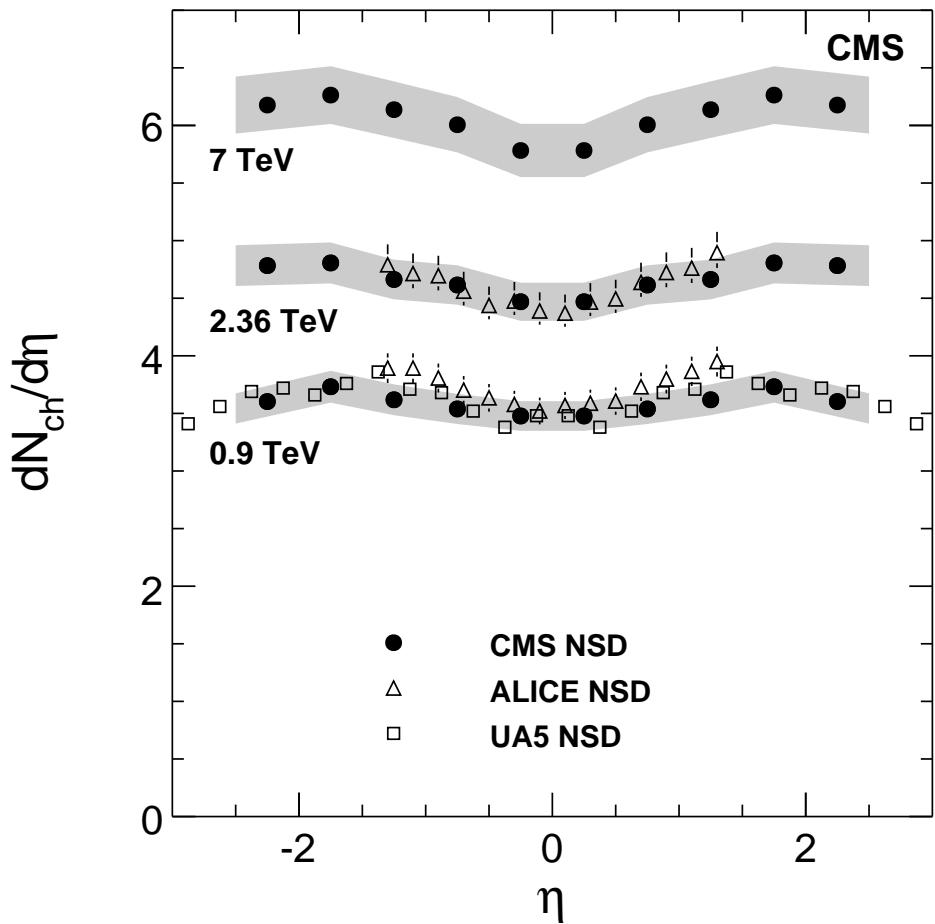
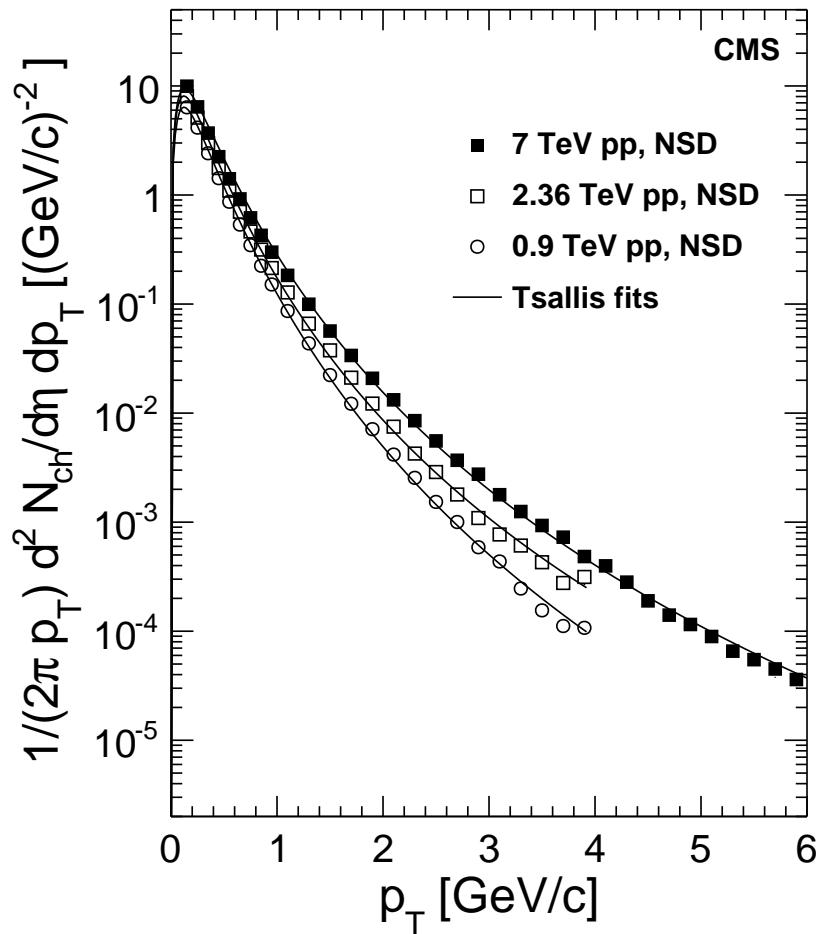
Spectra of charged hadrons – spectra



Full tracks, agglomerative vertex finder, negligible pile-up

Tsallis fits: combination of low- p_T exponential and high- p_T power law

Spectra of charged hadrons – spectra



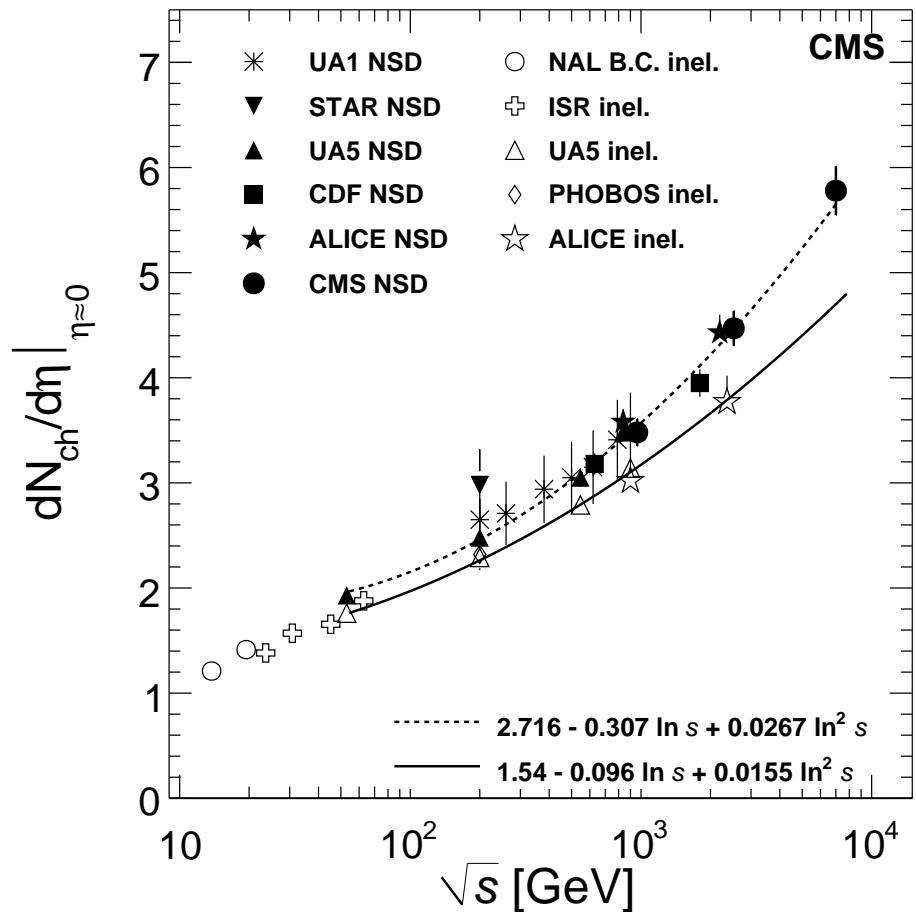
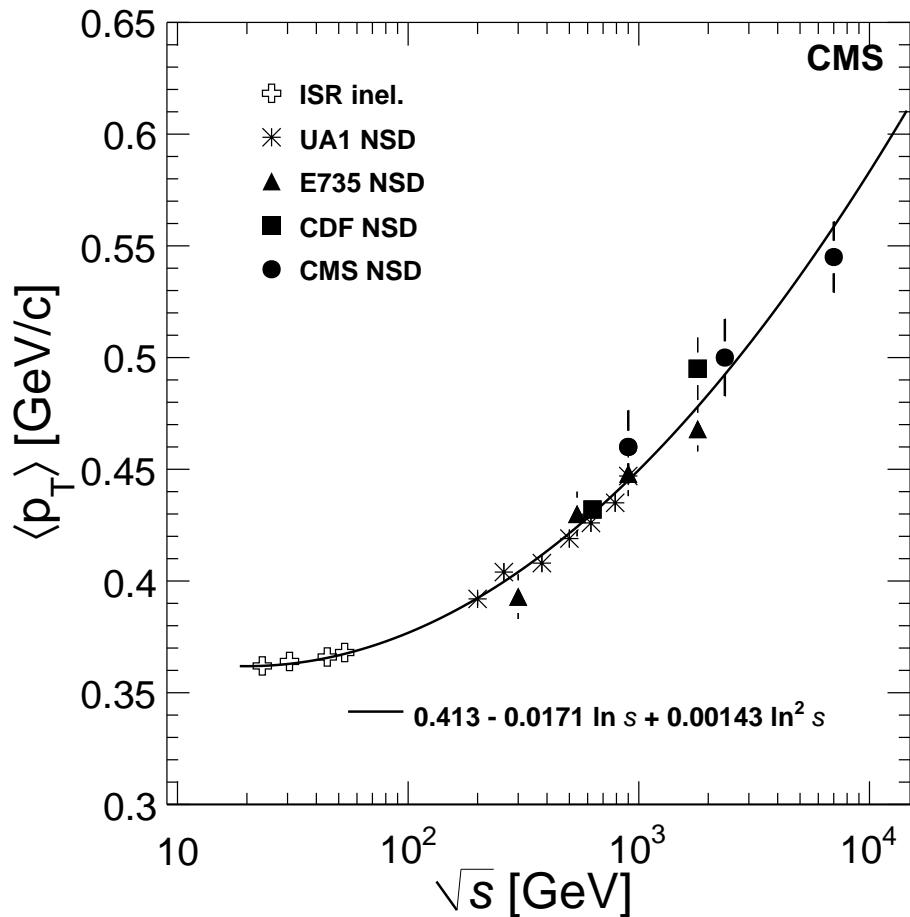
For $dN/d\eta$ combination of three methods

Full tracks; tracklets with bckg subtraction; hit counting with corr's

First published momentum distribution, first 2.36 TeV results

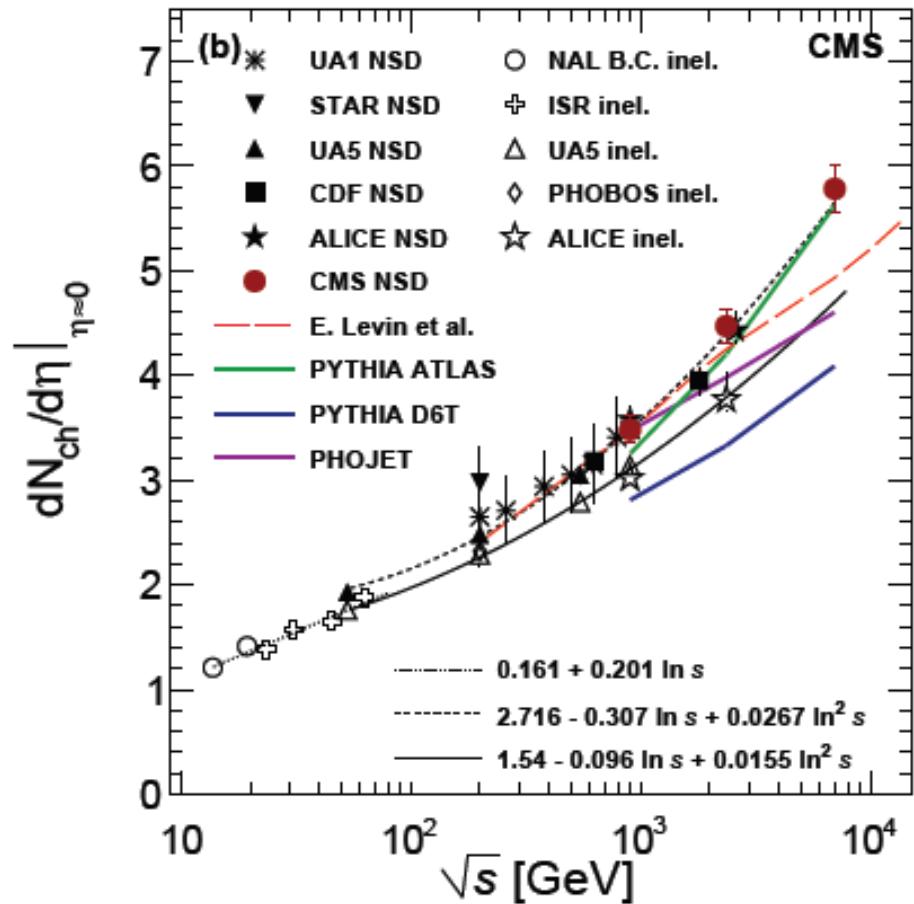
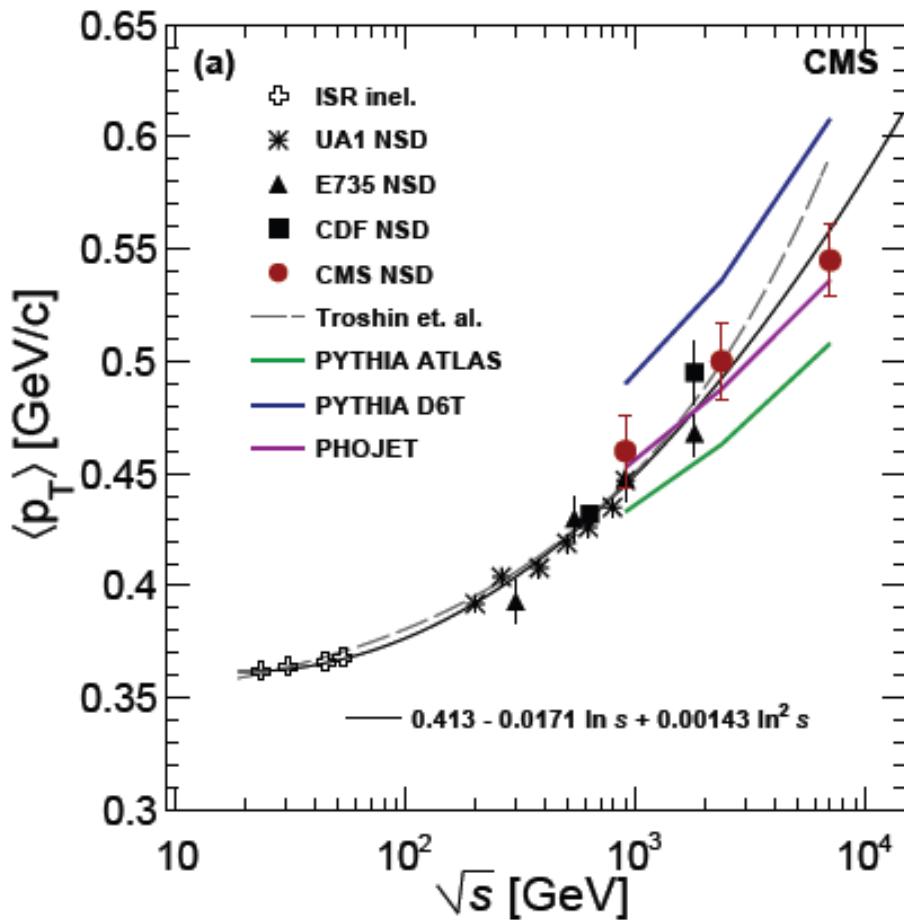


Spectra of charged hadrons – \sqrt{s} dependence



Higher $\langle p_T \rangle$, accelerated increase of $dN_{ch}/d\eta$ density
Input for theory

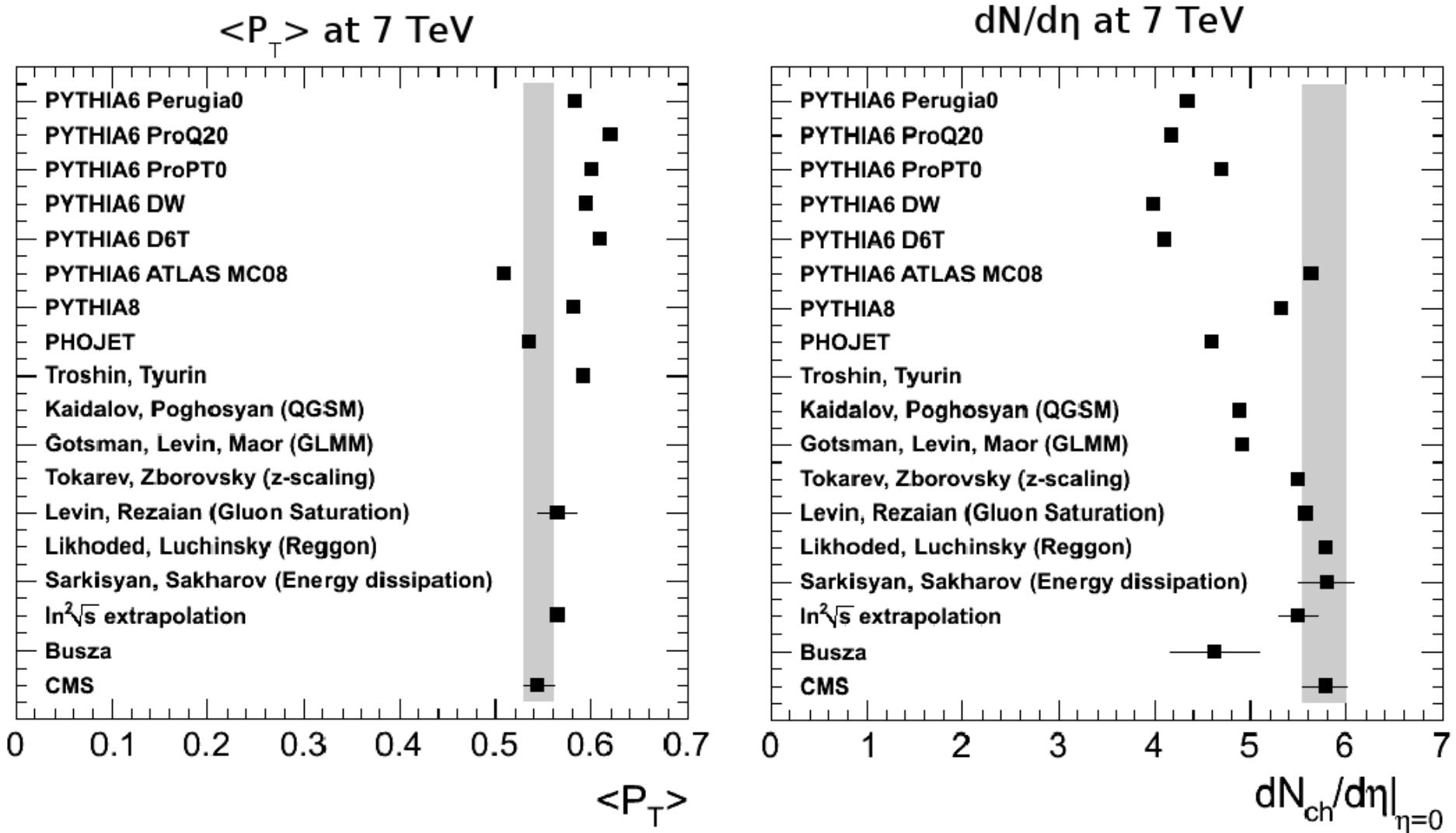
Spectra of charged hadrons – models?



Phojet describes $\langle p_T \rangle$ well

Most tunes underestimate $dN/d\eta$ at 7 TeV

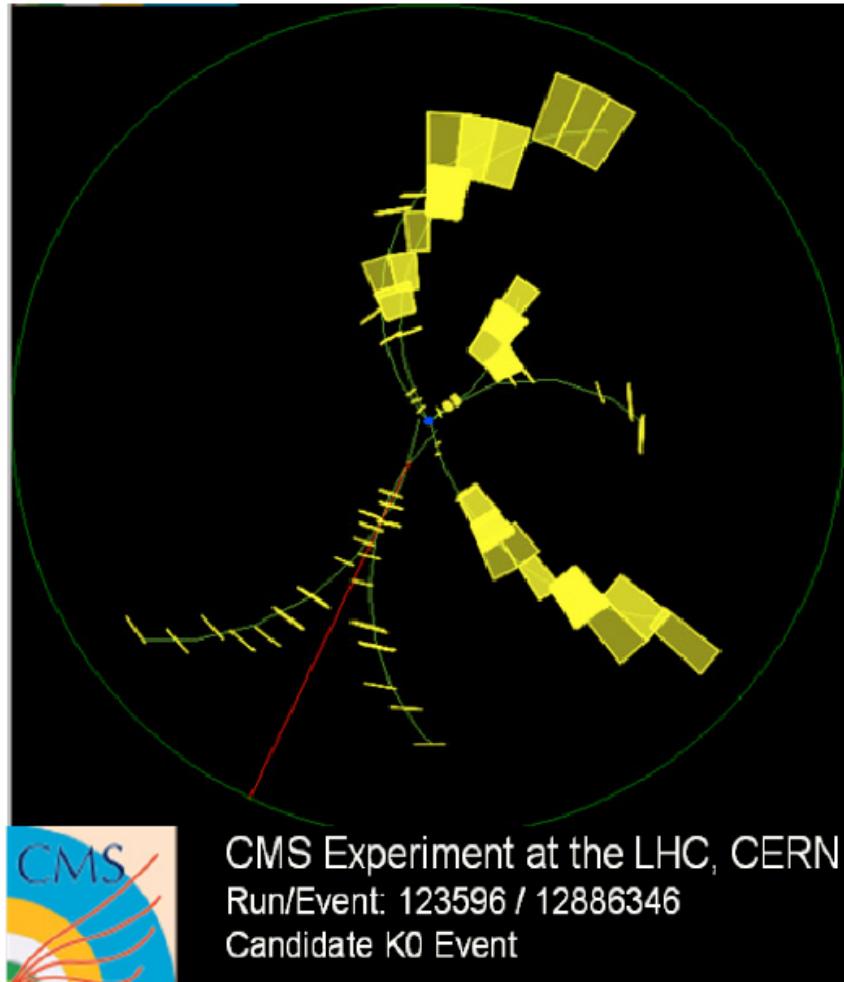
Spectra of charged hadrons – models?



Result up to very high p_T will be public in these days, compare to CDF

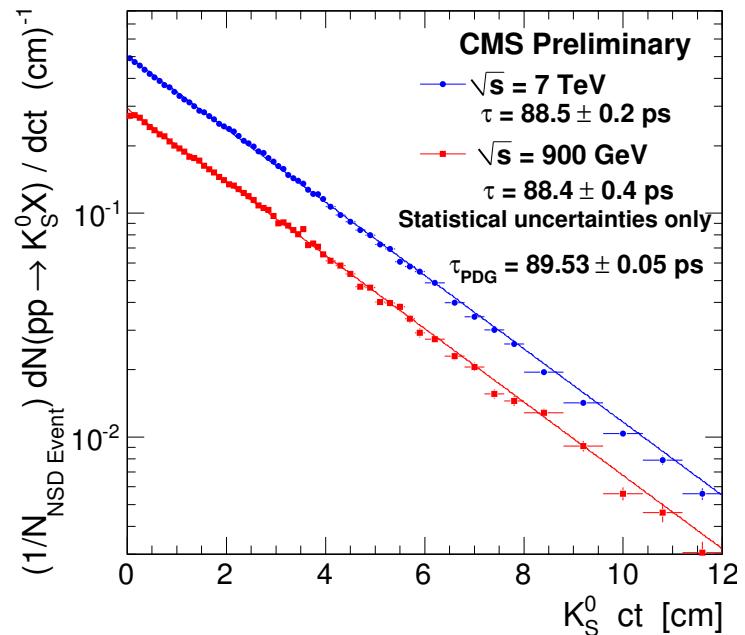


Spectra of strange hadrons



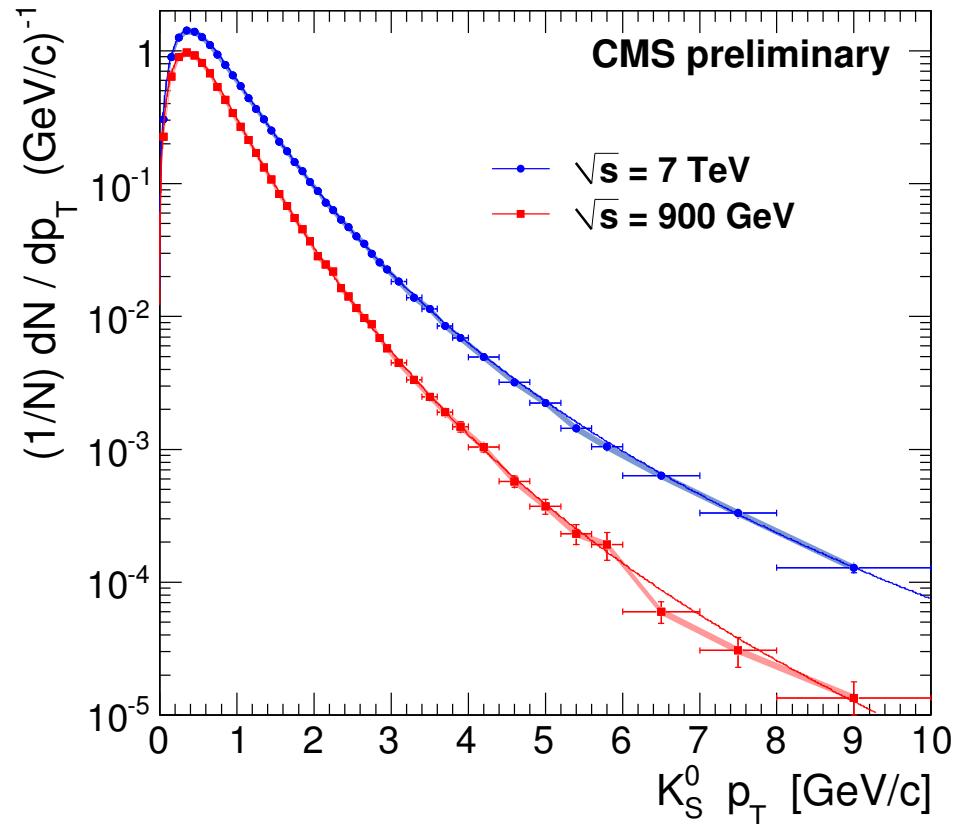
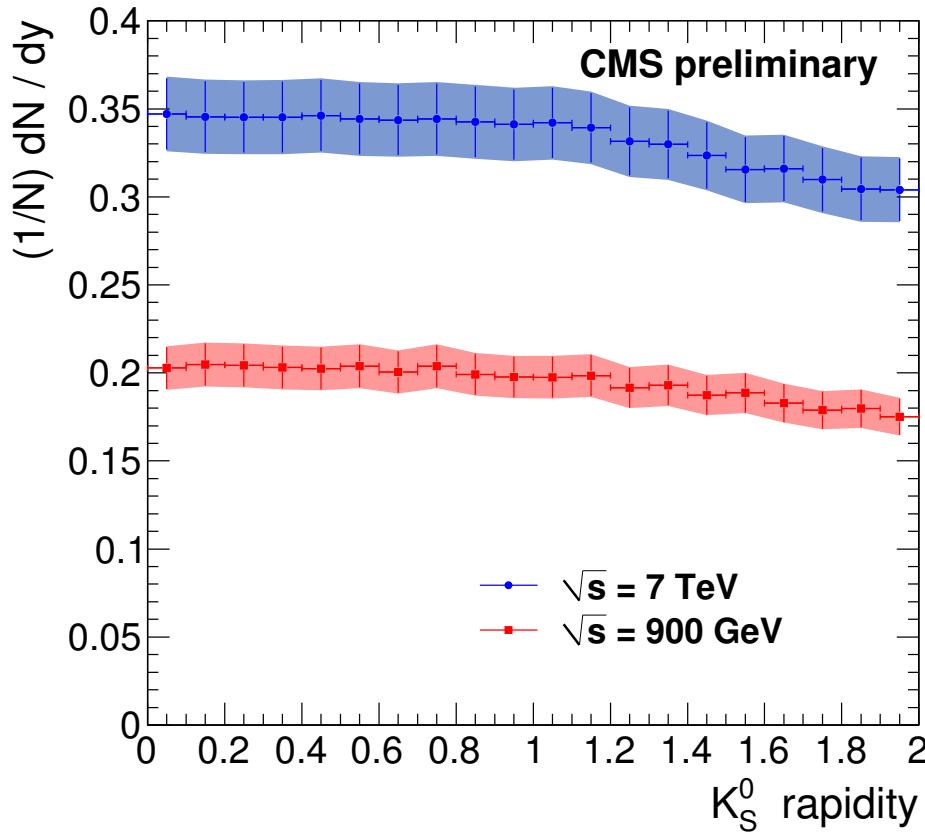
- Analysis

- Reconstruction with decay topology
 $K_S^0 \rightarrow \pi^+ \pi^-$, $\Lambda \rightarrow p \pi^-$, $\bar{\Lambda} \rightarrow \bar{p} \pi^+$,
 $\Xi^- \rightarrow \Lambda \pi^-$, $\Xi^+ \rightarrow \bar{\Lambda} \pi^+$
- All results for $|y| < 2.0$
- Reconstruction efficiencies are validated by lifetime measurements





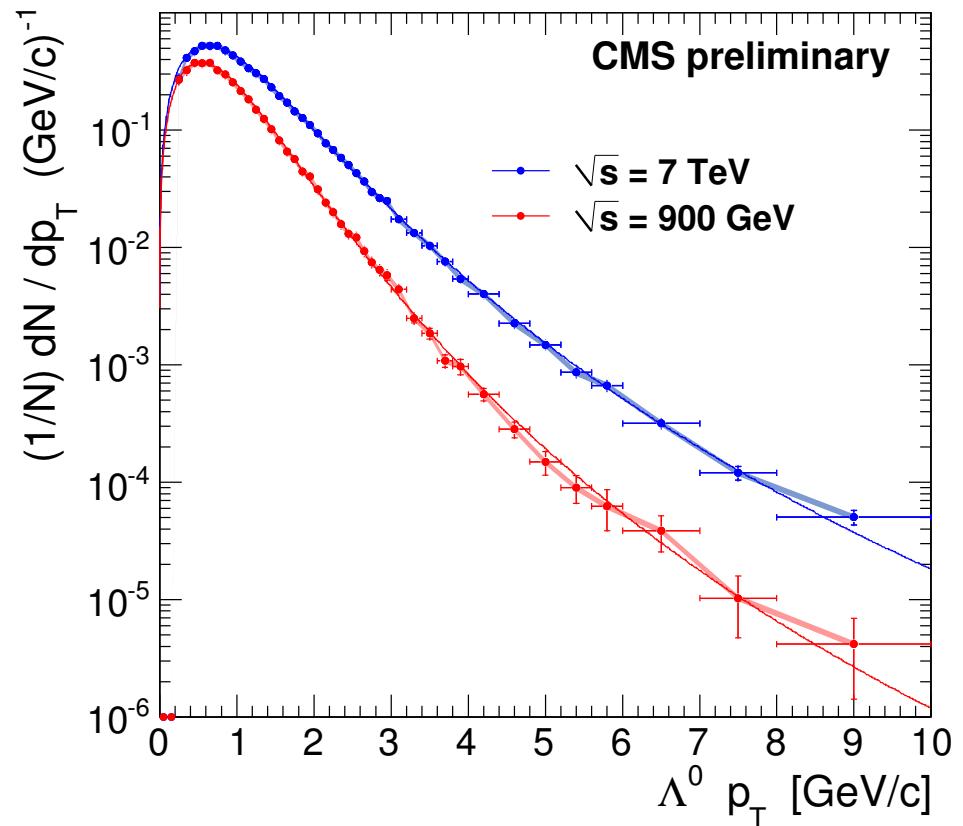
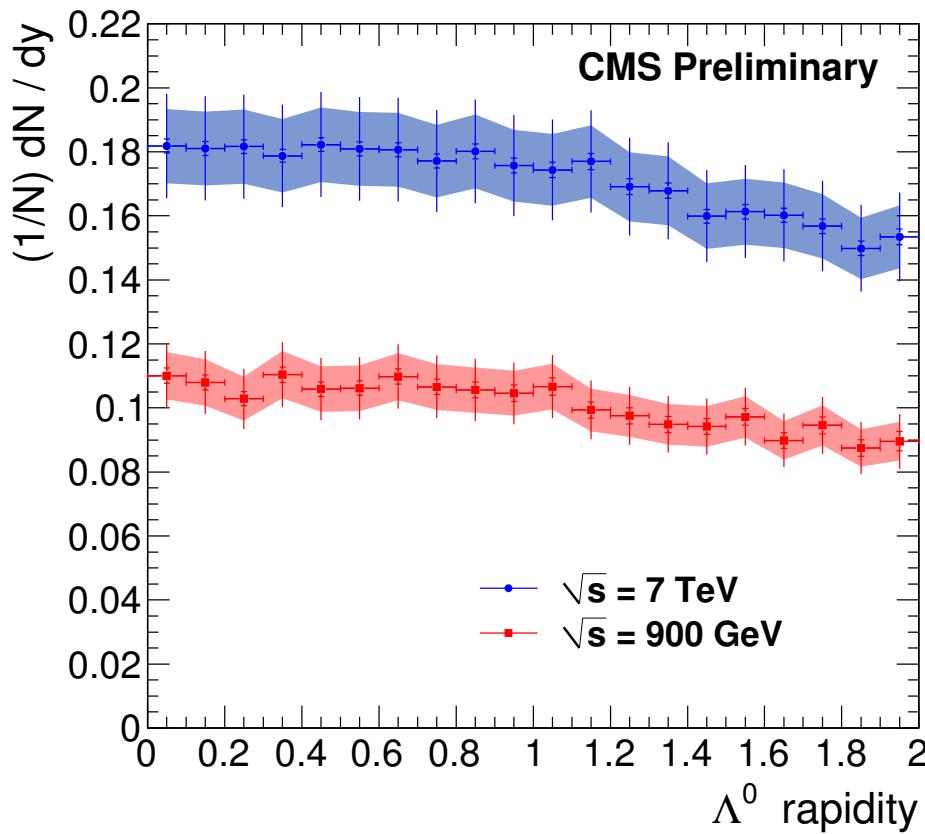
Spectra of strange hadrons – K_S^0



Two methods for cross-check
Fit in (y, p_T) bins or separately in y and p_T with re-weighted MC



Spectra of strange hadrons – Λ + $\bar{\Lambda}$

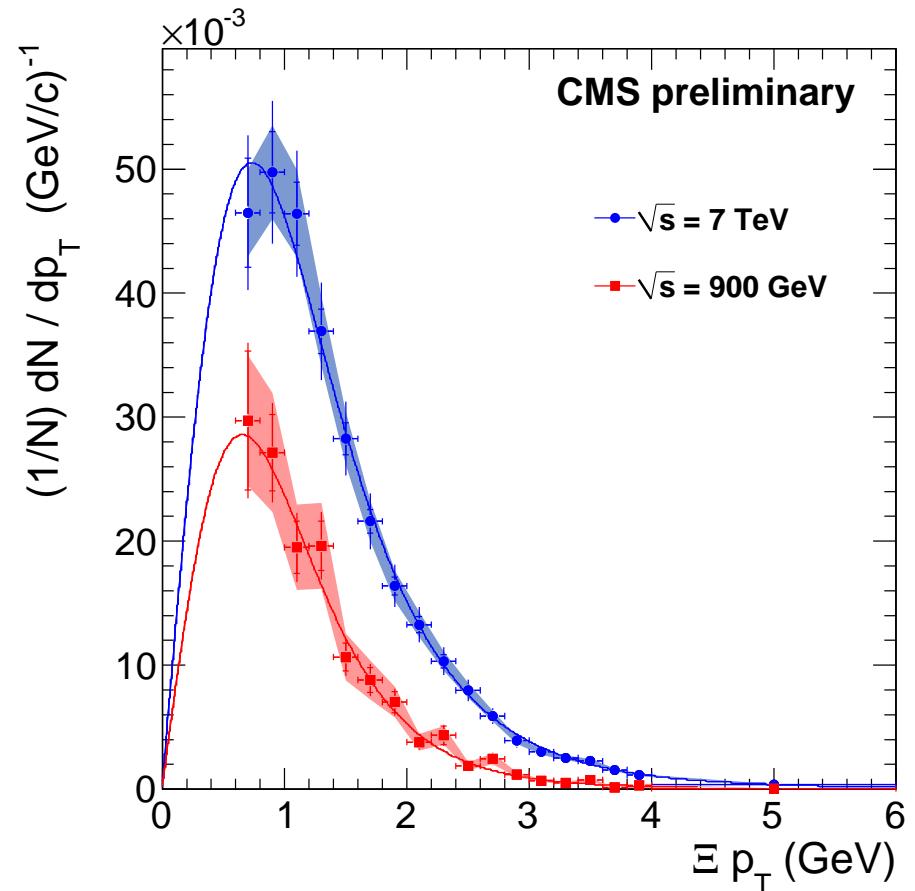
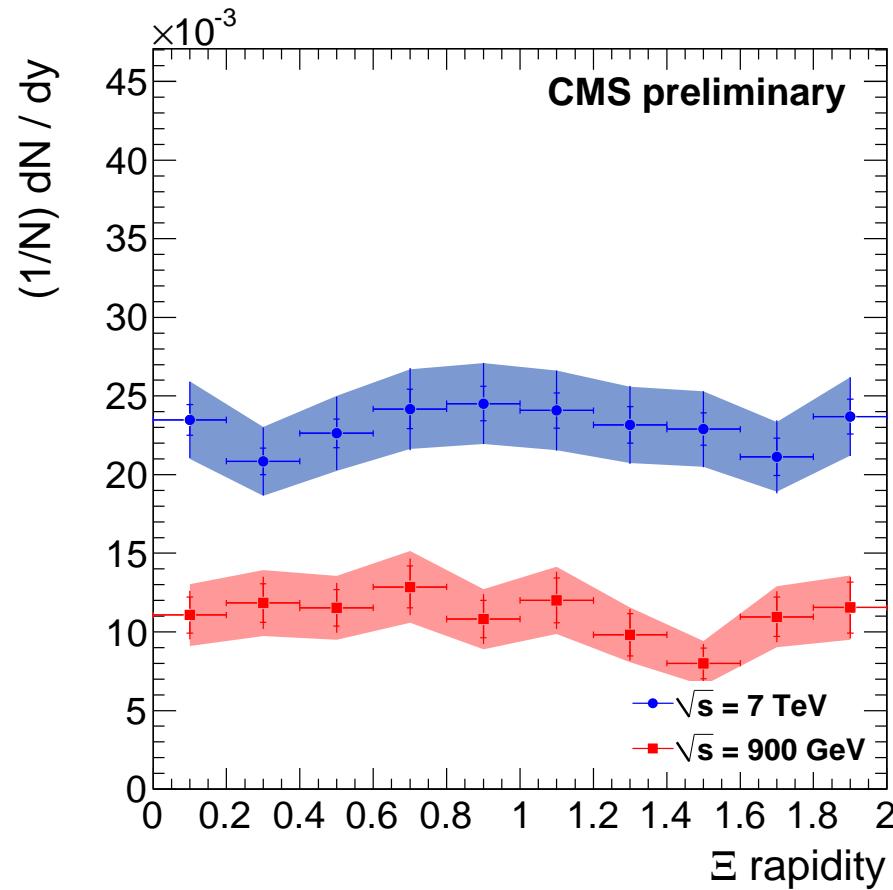


Very good fits with a Tsallis-function

$$\frac{1}{N} \frac{dN}{dp_T} \propto p_T \left[1 + \frac{\sqrt{p_T^2 + m^2} - m}{nT} \right]^{-n}$$



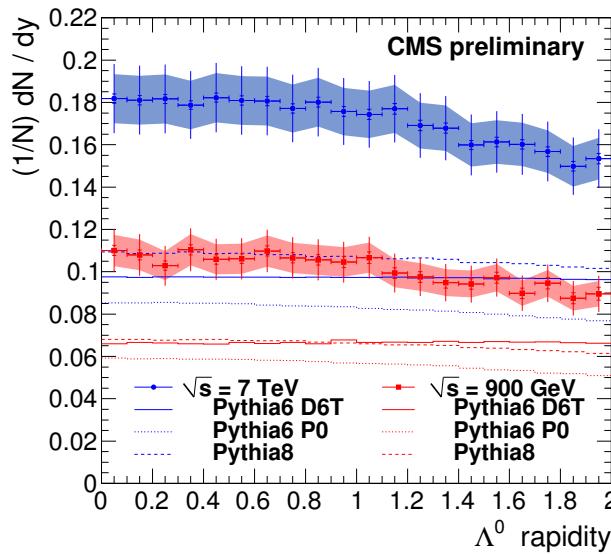
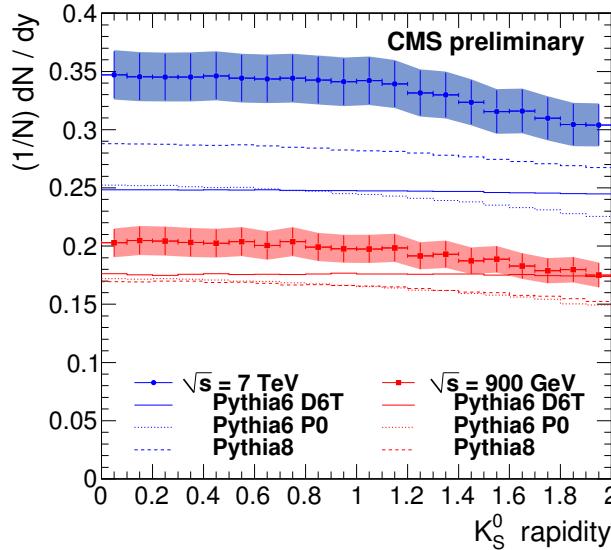
Spectra of strange hadrons – Ξ^- + Ξ^+



Reasonable precision for Ξ , a challenge



Spectra of strange hadrons – models?



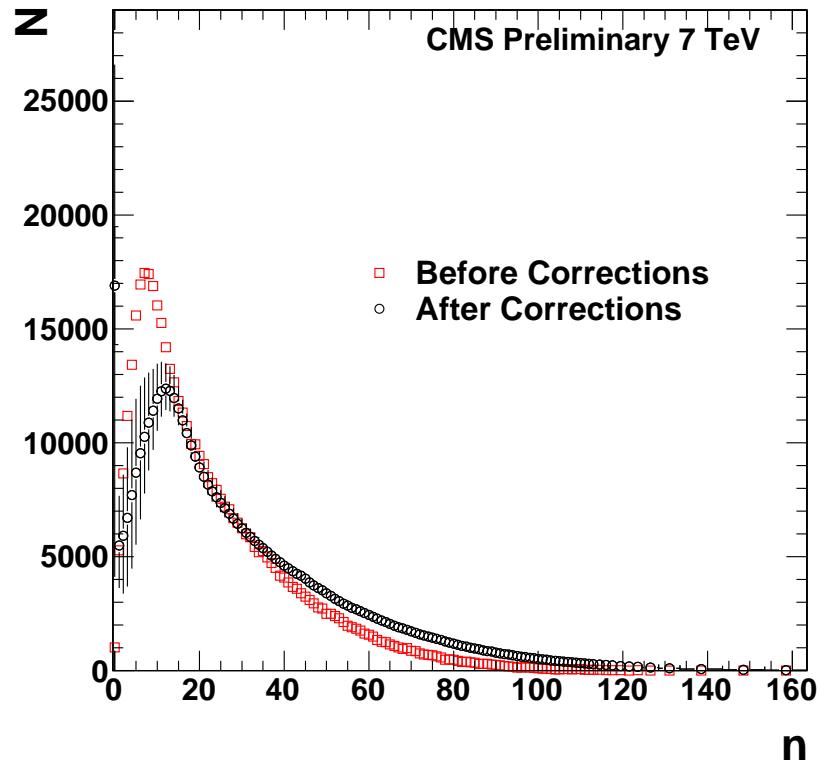
Particle	$\frac{dN}{dy} _{y=0}(\text{PYTHIA D6T})$	
	0.9 TeV	7 TeV
K_S^0	$0.87 \pm 0.01 \pm 0.07$	$0.72 \pm 0.01 \pm 0.06$
Λ^0	$0.60 \pm 0.01 \pm 0.07$	$0.54 \pm 0.01 \pm 0.06$
Ξ^-	$0.48 \pm 0.05 \pm 0.09$	$0.33 \pm 0.02 \pm 0.05$

- Strangeness

- Significantly more strangeness is seen in data than in MC
- Factor 3 for Ξ at 7 TeV
- Discrepancy grows with increasing mass and \sqrt{s}
- $\langle p_T \rangle$ is much better described

See poster by Krisztián Krajczár

Event-by-event multiplicity



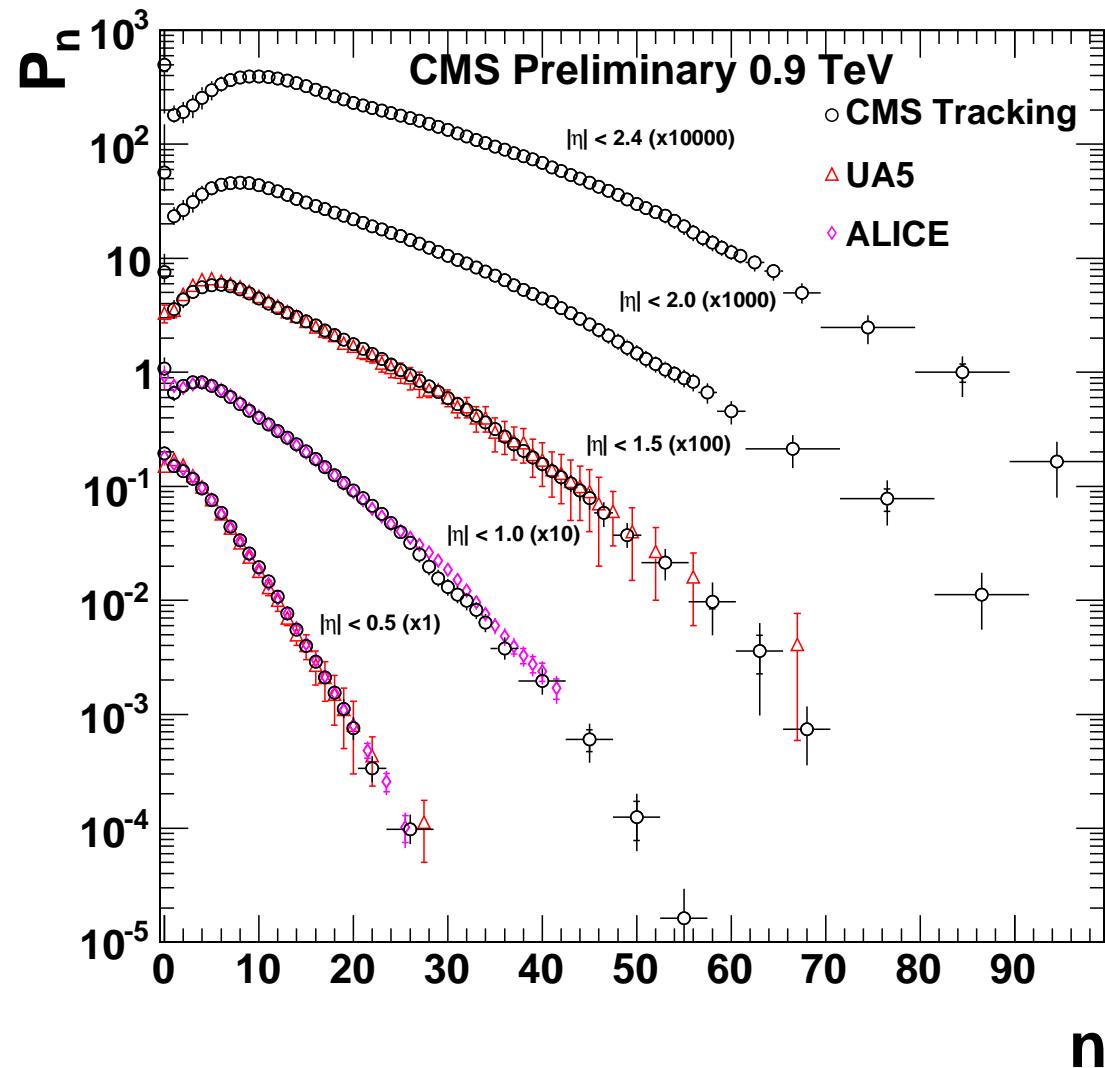
Source	tracking uncertainty (%)
Tracking efficiency	2.0
Acceptance uncertainty	1.0
Pixel hit efficiency	0.3
Pixel cluster splitting	0.2
Correction of secondaries	1.0
Misalignment	0.1
Beam halo	0.1
Multiple track counting	0.1
Fake track rate	0.5
p_T extrapolation	1.0
Total	2.5

- Analysis

- Events used: 132 k (0.9 TeV); 12 k (2.36 TeV); 442 k (7 TeV)
- Full tracks, corrected to NSD events
- True distribution is obtained from measured, after Bayesian unfolding



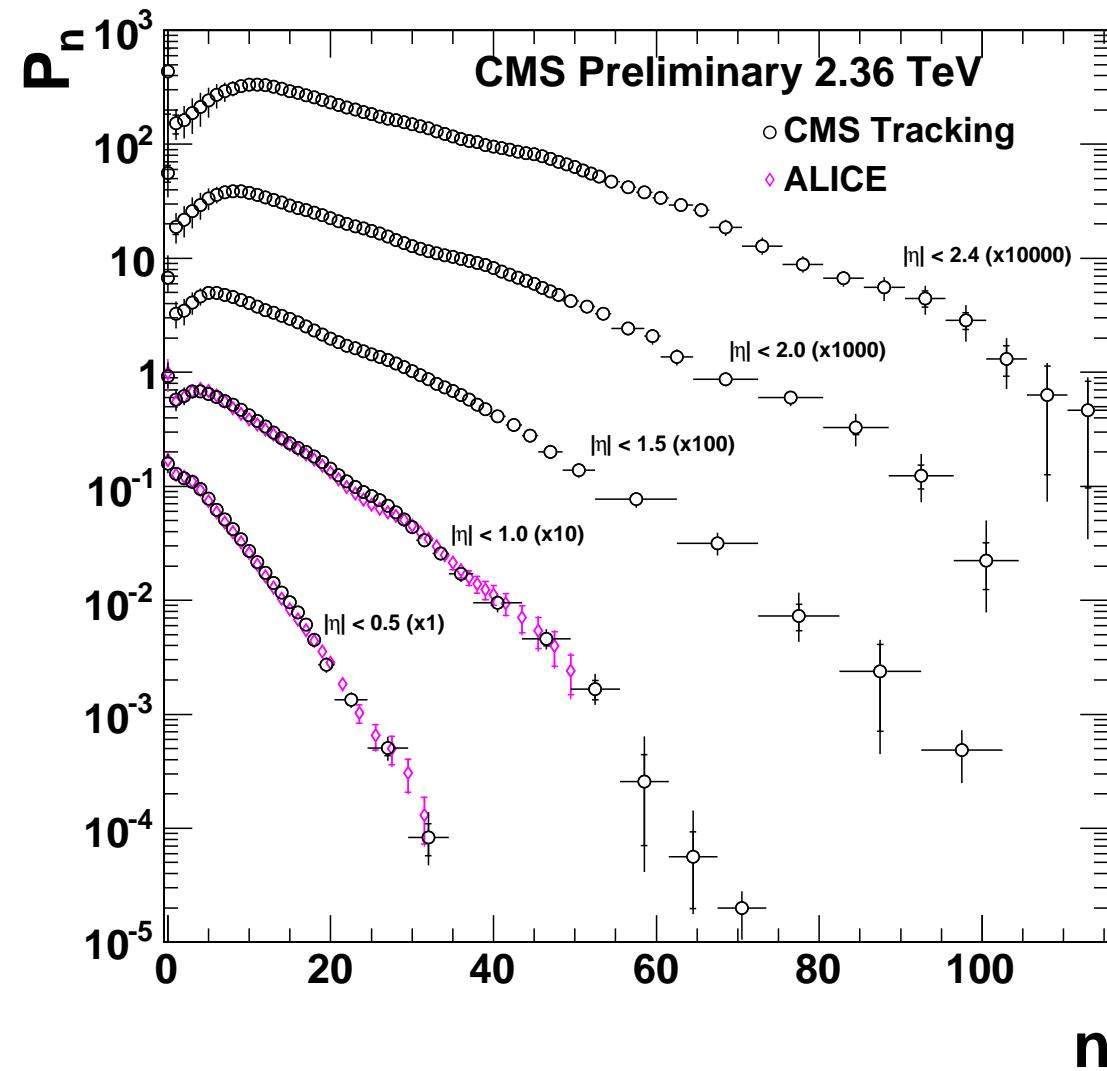
Event-by-event multiplicity – η bins – 0.9 TeV



Nice match with UA5 and ALICE



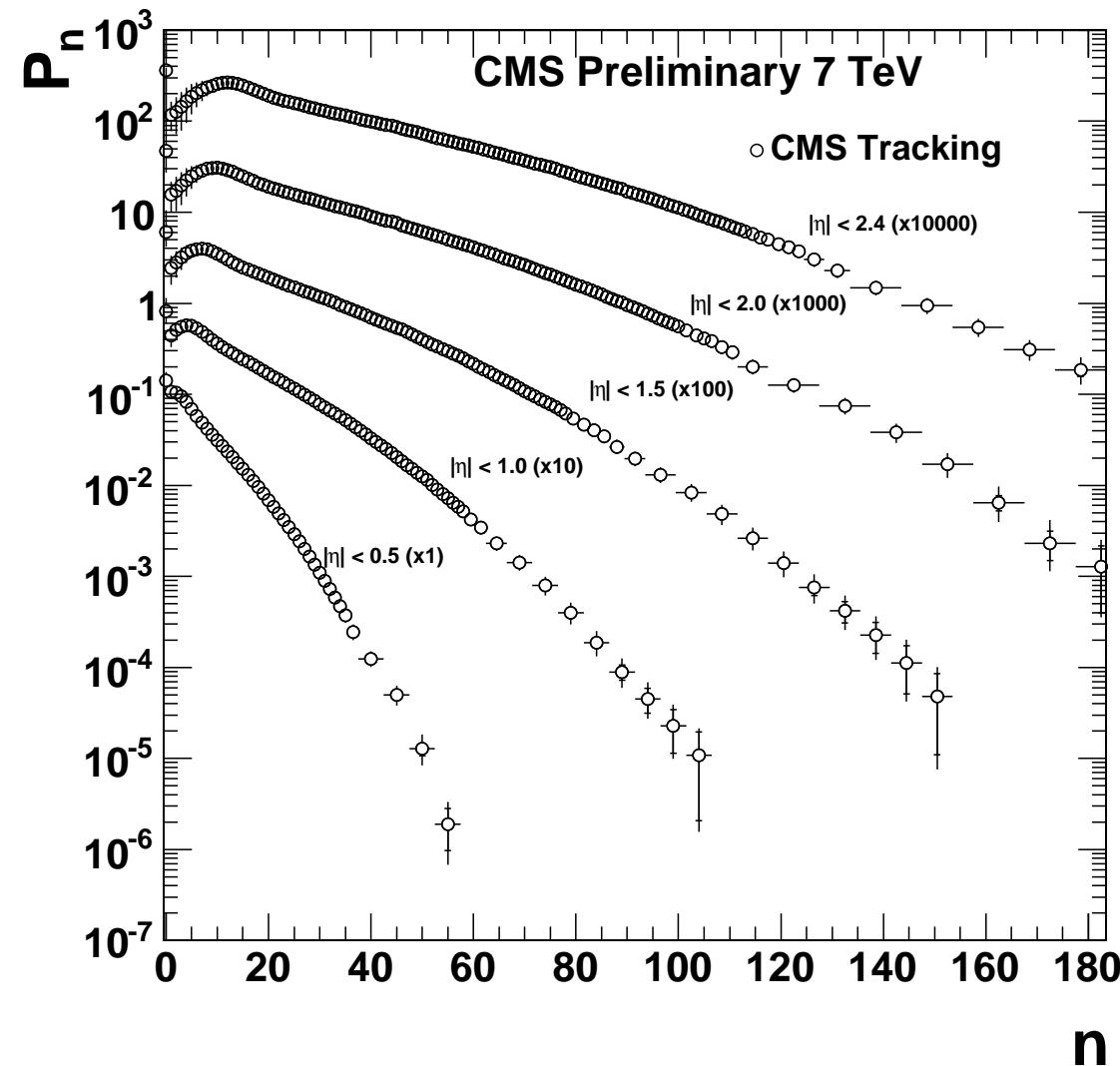
Event-by-event multiplicity – η bins – 2.36 TeV



Nice match with ALICE

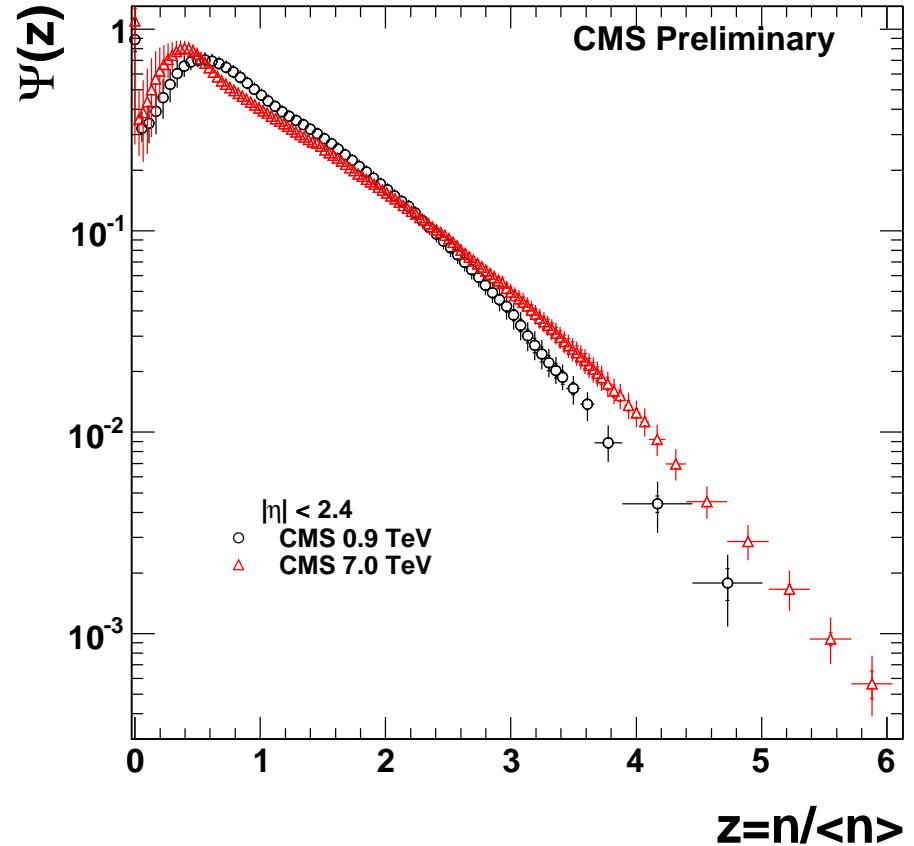
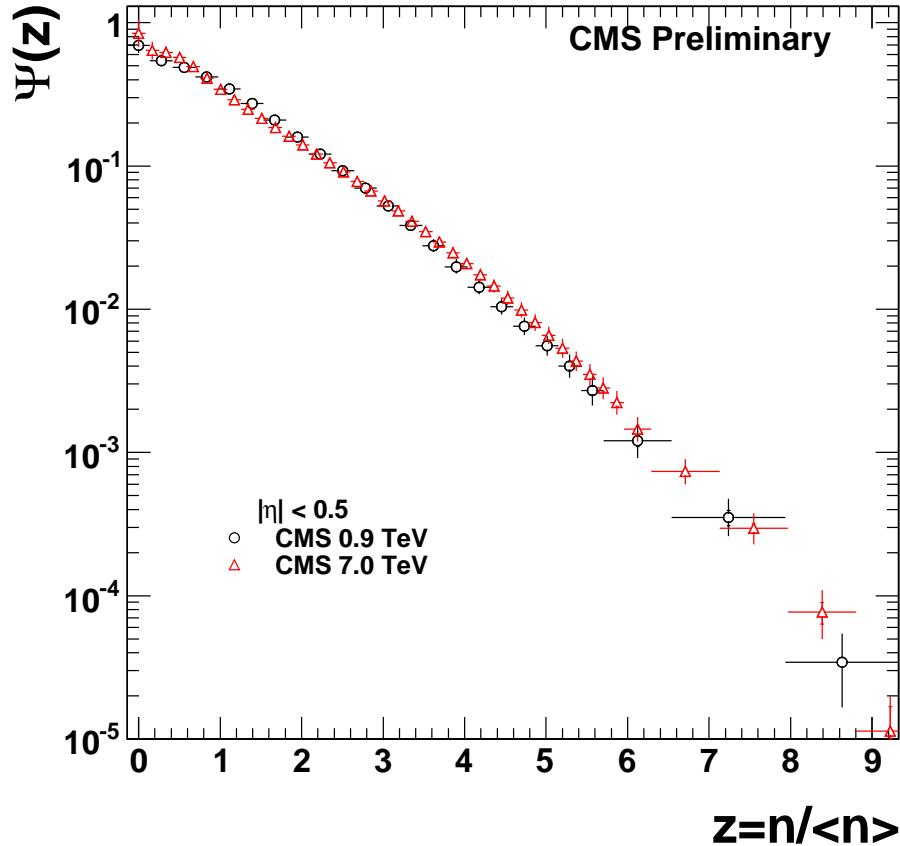


Event-by-event multiplicity – η bins – 7 TeV



Smooth distributions, no "waves" are seen

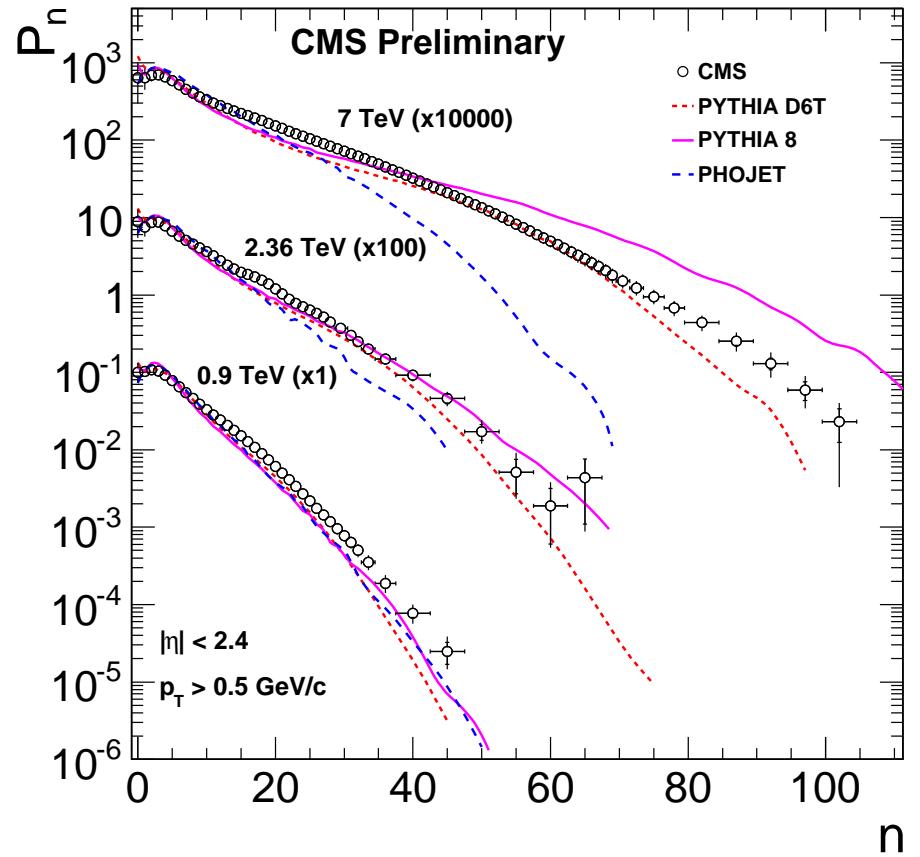
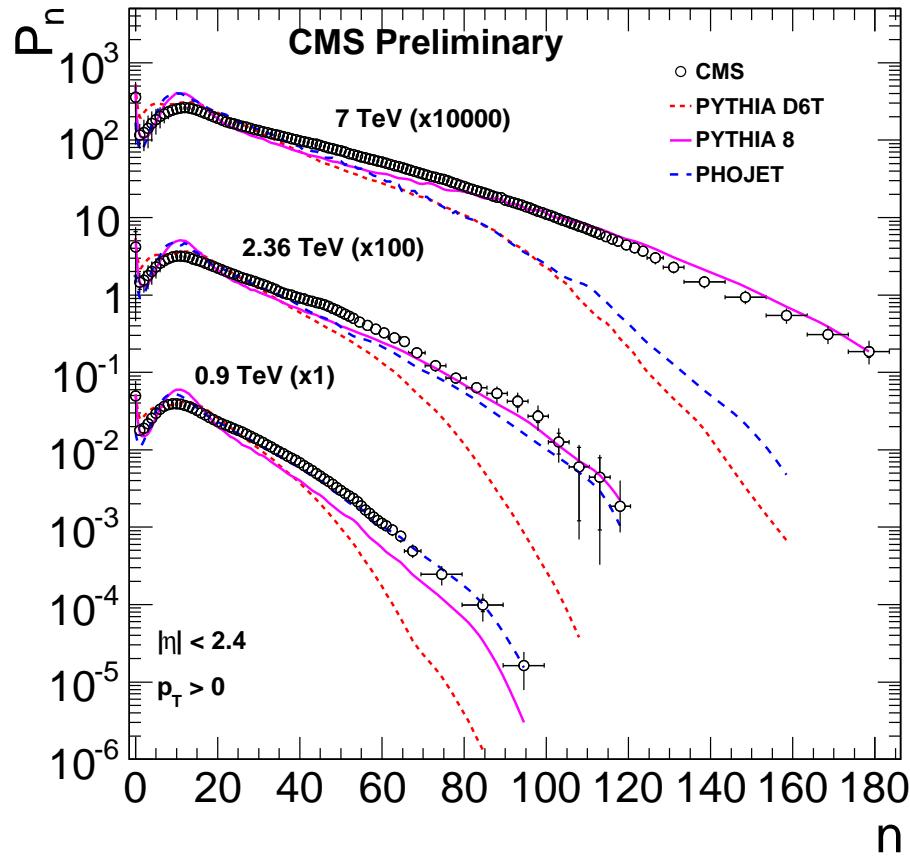
Event-by-event multiplicity – scaling?



- KNO scaling
 - $\Psi(z) = \langle n \rangle P_n$ was shown to be independent of \sqrt{s}
 - True for $|\eta| < 0.4$, but it is violated for $|\eta| < 2.4$

Large tail at high n is also seen in the steep rise of $\langle n \rangle$

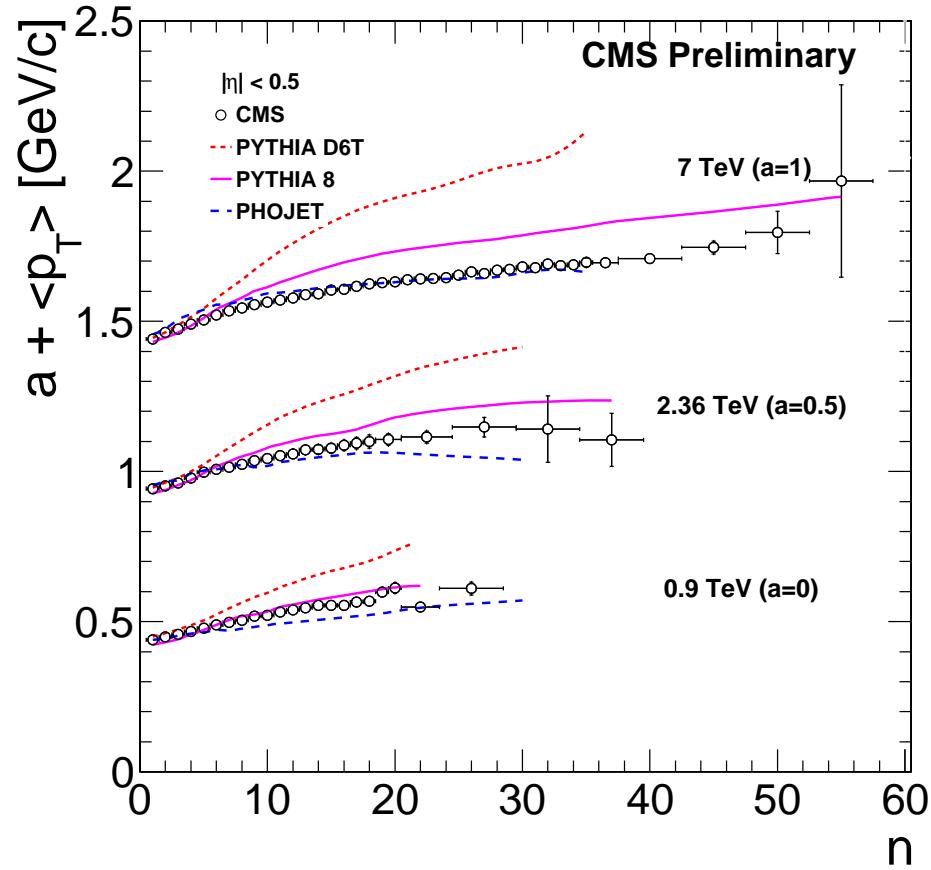
Event-by-event multiplicity – models?



- Models
 - With varying success, no model gets everything right at 7 TeV
 - Pythia8 matches the total multiplicity,
but predicts too many high p_T particles at large η

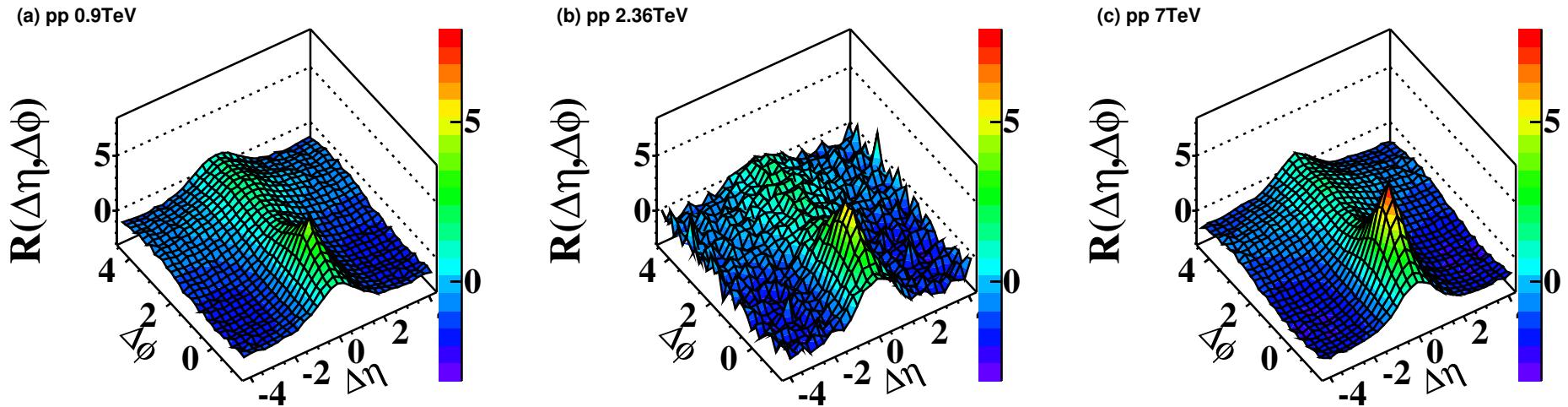


Event-by-event multiplicity – $\langle p_T \rangle$



Difficult to match data with MC at all energies

Hadron correlations – angular – data



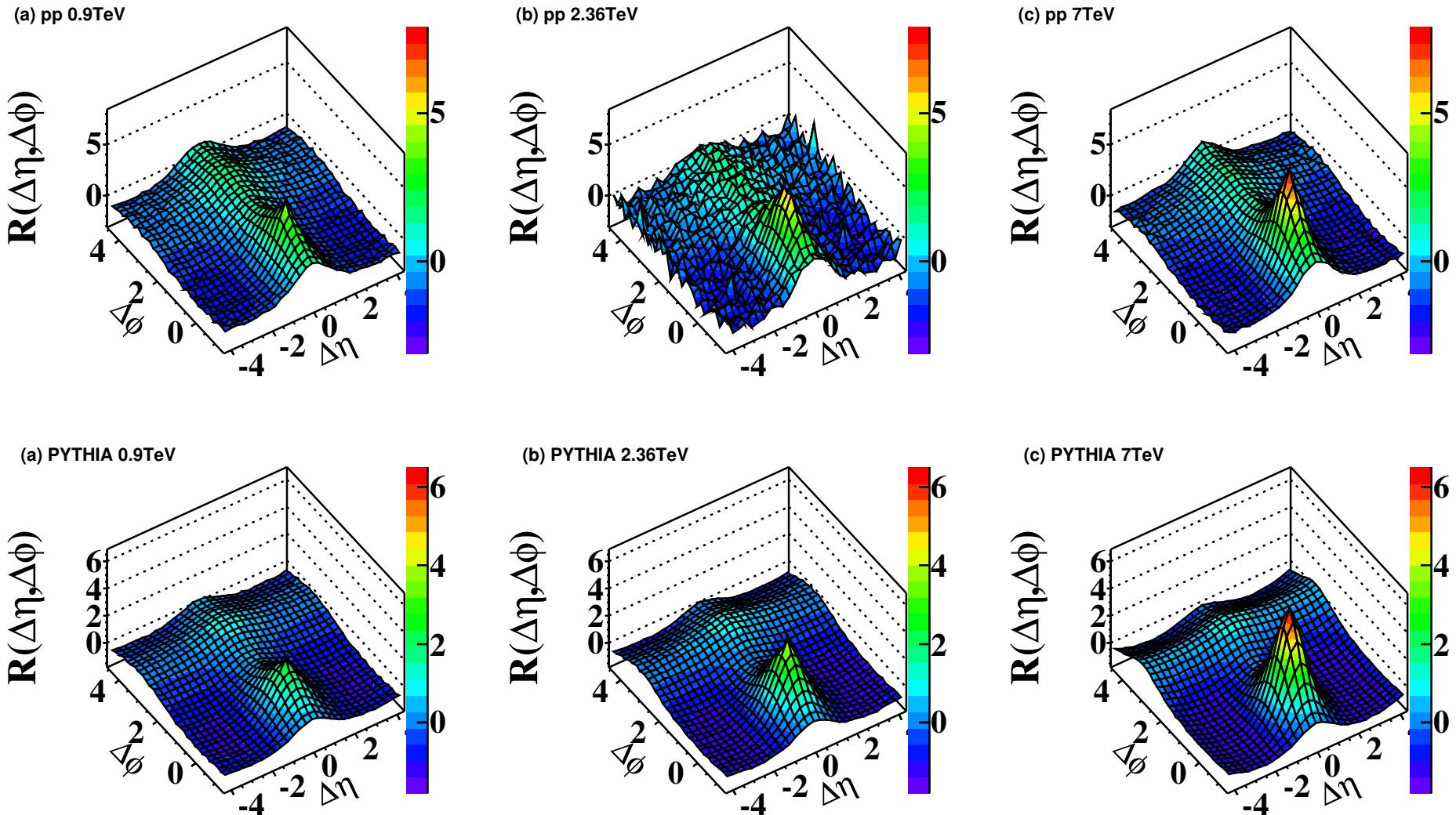
- Analysis

- Particles tend to be produced correlated, in clusters
- Extensive studies exist at lower energies
- Count the number of track pairs in $(\Delta\eta, \Delta\phi)$ bins
signal and background (mixed events with similar z_{vtx} and multiplicity N)
- Look at the ratio

$$R(\Delta\eta, \Delta\phi) = \left\langle (N - 1) \left(\frac{S_N(\Delta\eta, \Delta\phi)}{B_N(\Delta\eta, \Delta\phi)} - 1 \right) \right\rangle_N$$

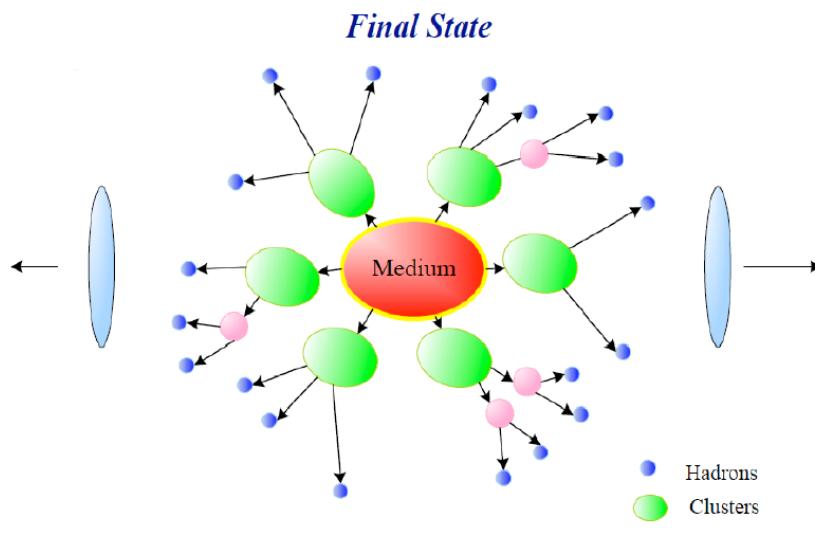
Gaussian in $\Delta\eta$, broader at large $\Delta\phi$

Hadron correlations – angular – models?



MC is qualitatively similar to data

Hadron correlations – angular – a simple model



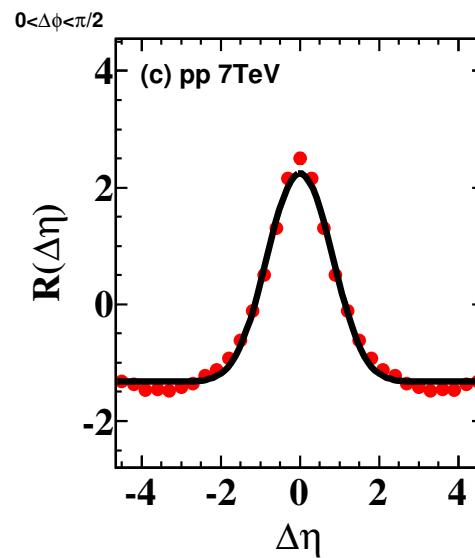
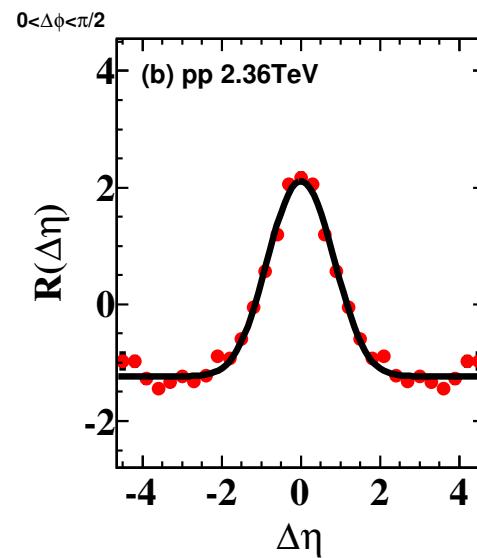
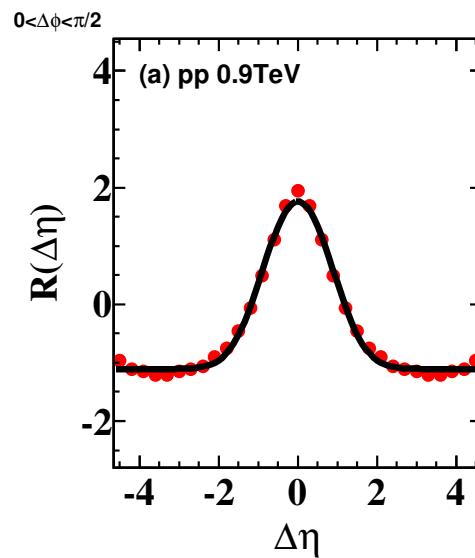
- Independent cluster model

- Clusters are produced independently
- They decay isotropically into hadrons
- Only two parameters:

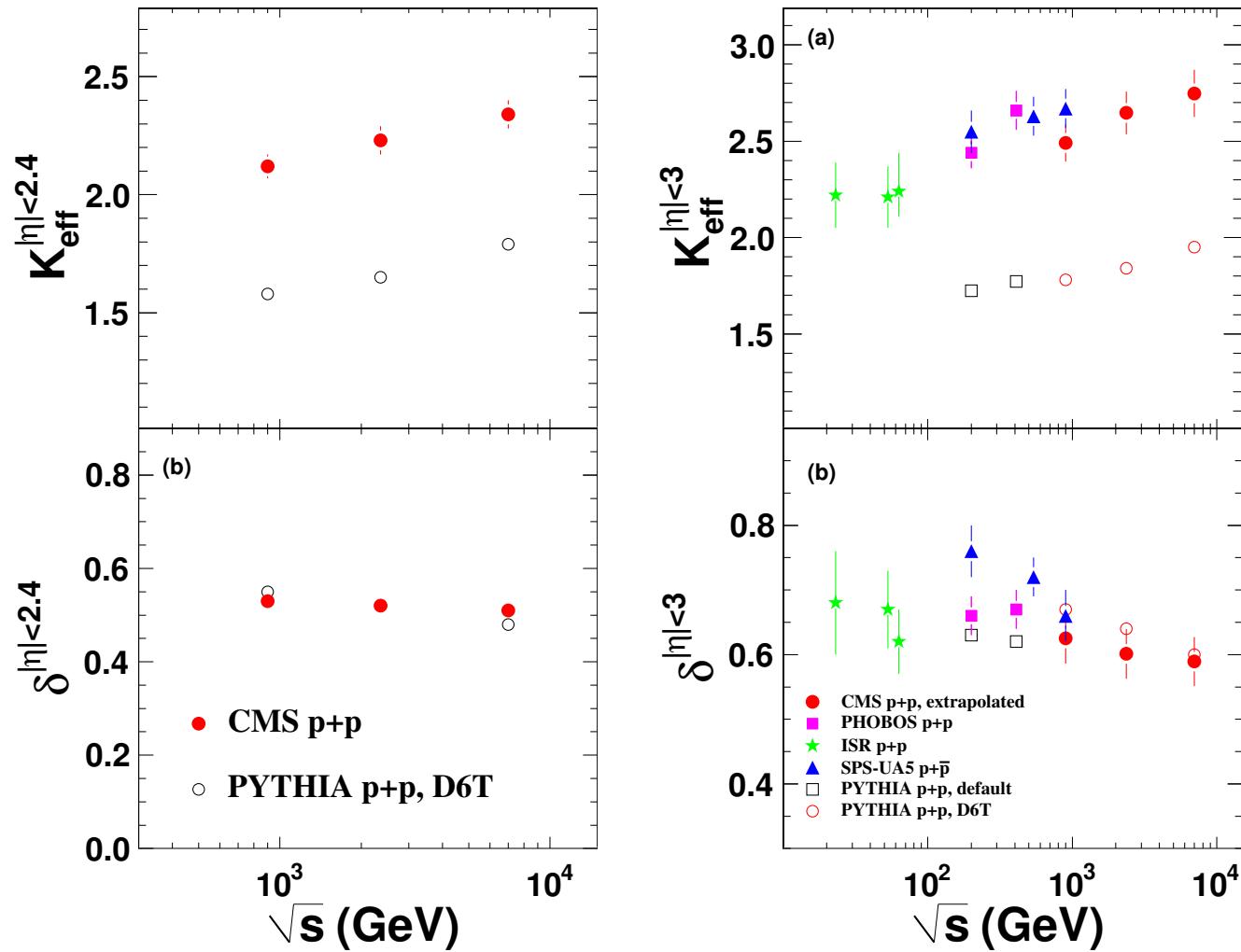
cluster size K_{eff} , cluster width δ

$$R(\Delta\eta) = (K_{eff} - 1) \left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1 \right]$$

$$\Gamma(\Delta\eta) \propto \exp \left[-\frac{(\Delta\eta)^2}{4\delta^2} \right]$$



Hadron correlations – angular – \sqrt{s} dependence



Results extrapolated to $p_T = 0$, compared to others
 Pythia shows correct trend but smaller cluster size



Hadron correlations – Bose-Einstein

- Analysis

- Correlation between identical bosons
- The size of the correlated emission region can be inferred
- What to measure? Difference of four-vectors, $Q = \sqrt{-(p_1 - p_2)^2}$
- Parametrization

$$R(Q) = C [1 + \lambda \Omega(Qr)] (1 + \delta Q)$$

effective radius r , strength λ , long range correlation δ

$\Omega(Qr)$ is the Fourier transform of the emission region

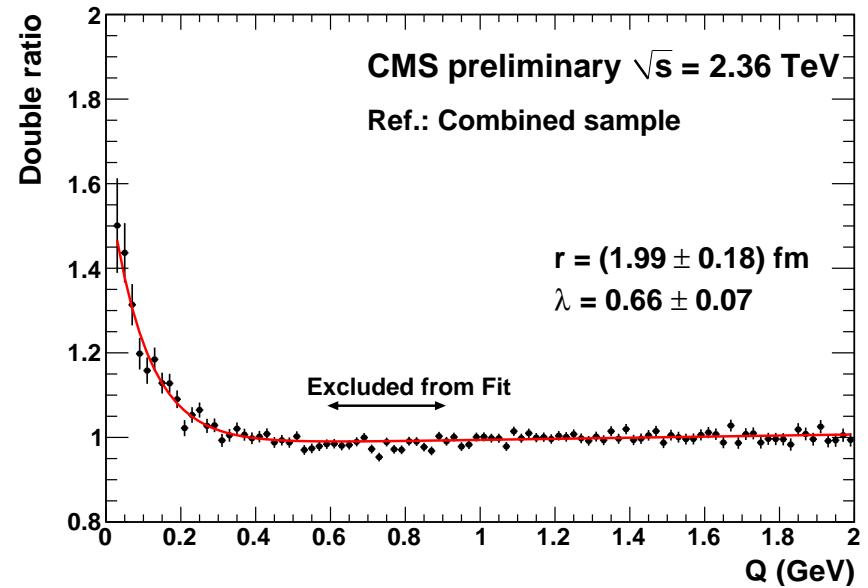
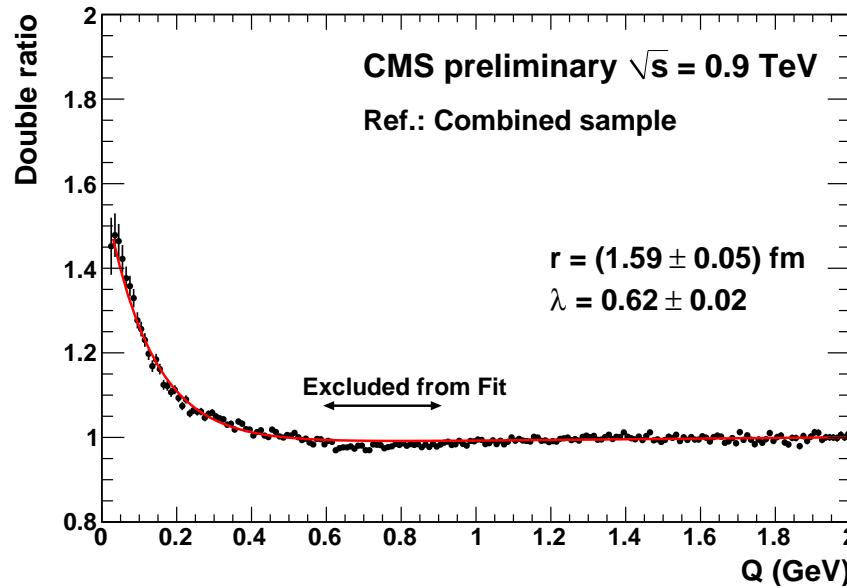
- Uncorrelated background distributions?

- pairs from same event
 - opposite charge; opposite charge with one track \mathbf{p} inverted; same charge with \mathbf{p} inverted; same charge with \mathbf{p} rotated in the transverse plane
- pairs from different events
 - random; similar $dN/d\eta$; similar total invariant mass of charged particles

Combined reference sample was used



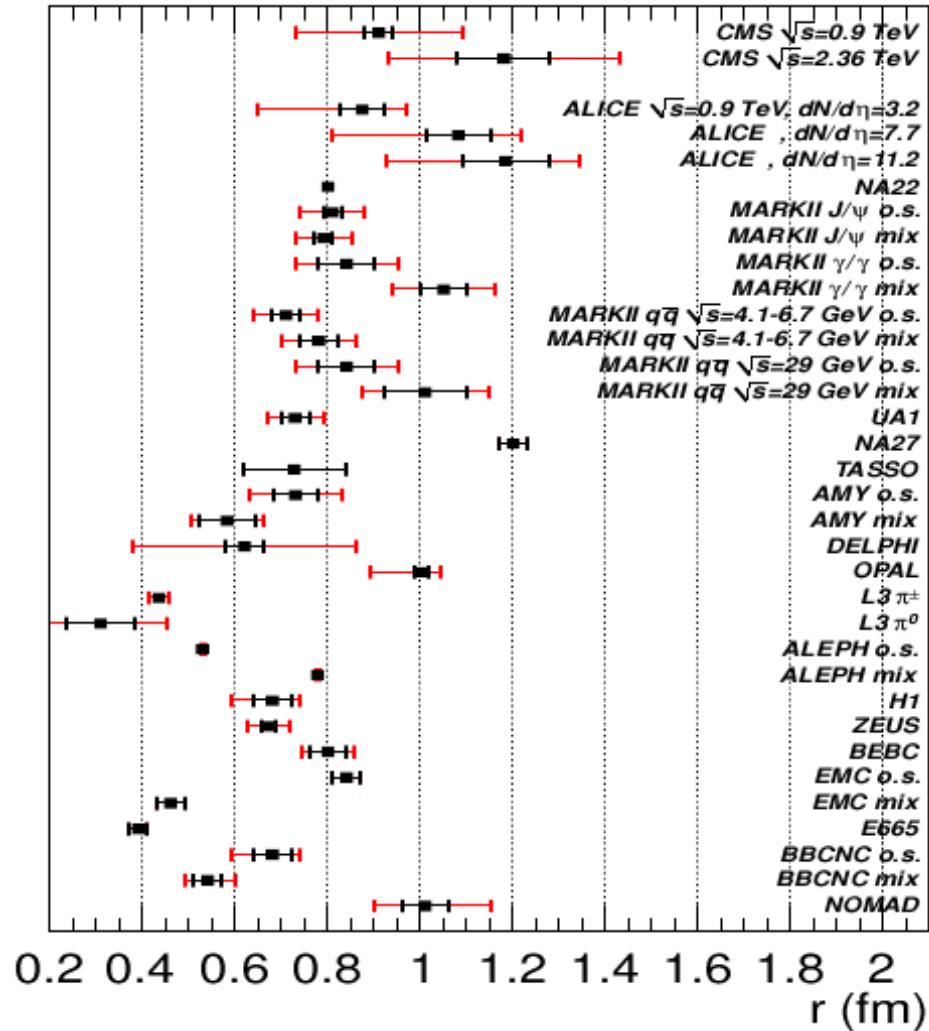
Hadron correlations – Bose-Einstein



Ratio of signal and uncorrelated background distributions
Combined reference sample is used

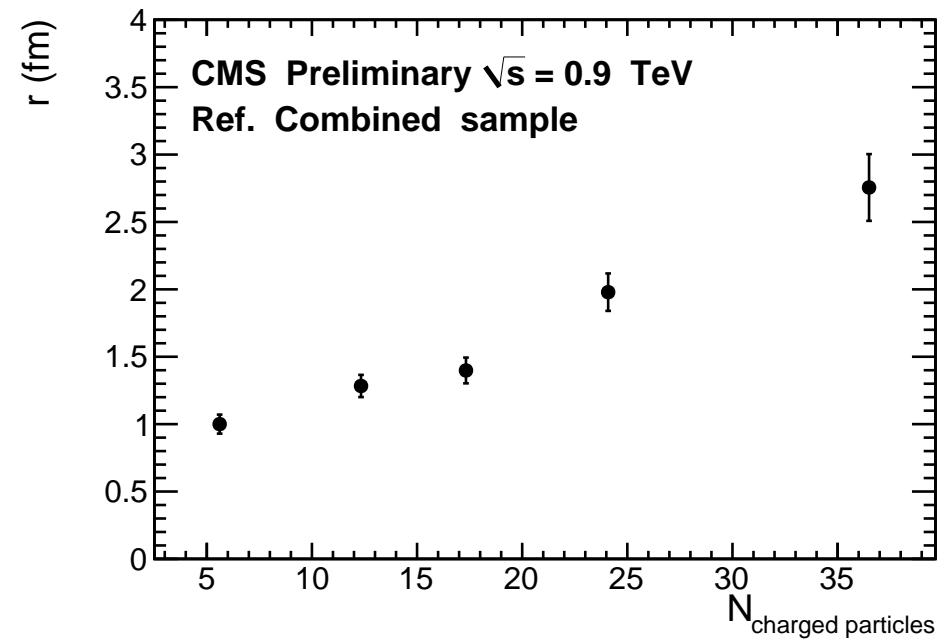
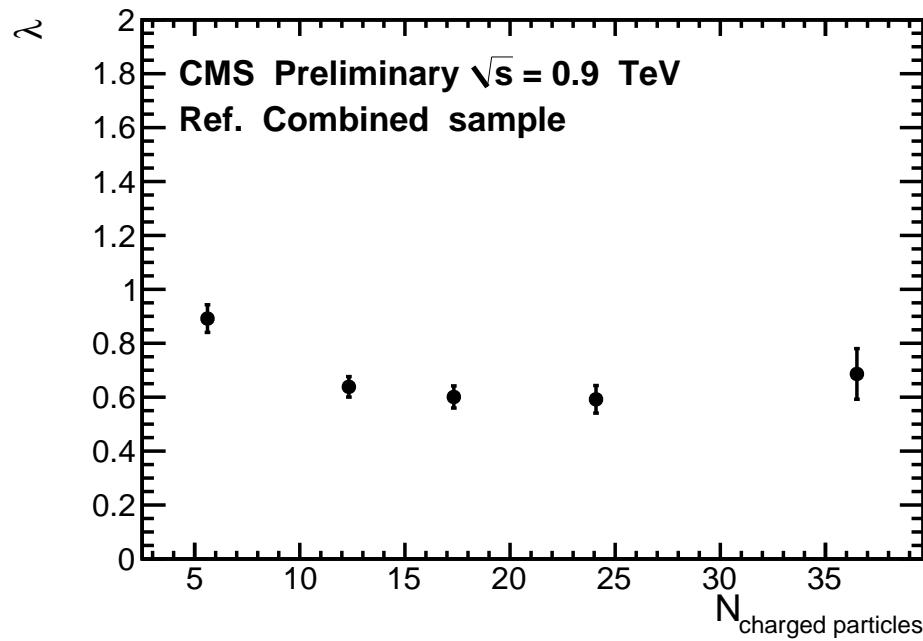
Exponential function is favored, $\Omega(Qr) = e^{-Qr}$

Hadron correlations – Bose-Einstein – others



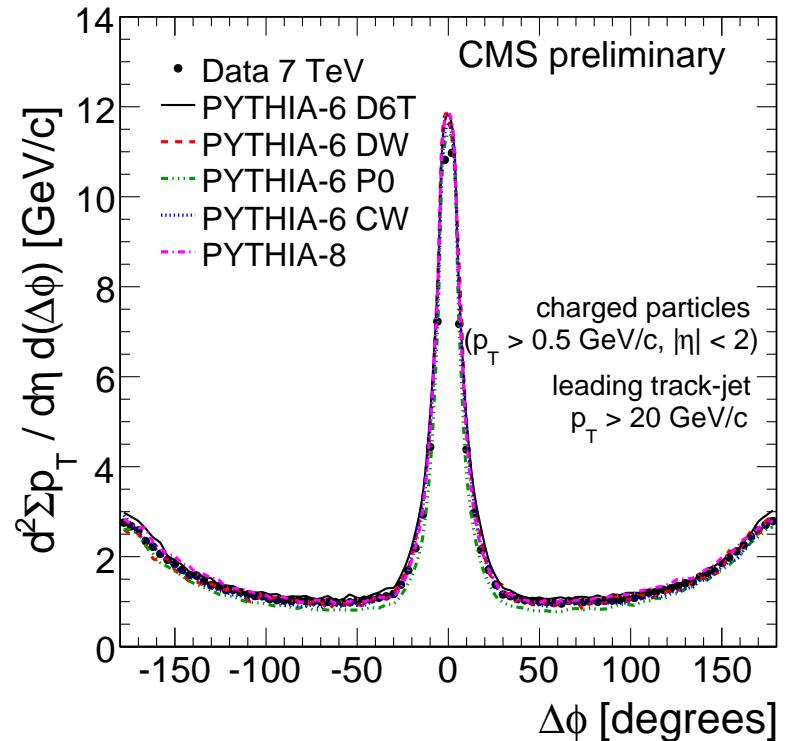
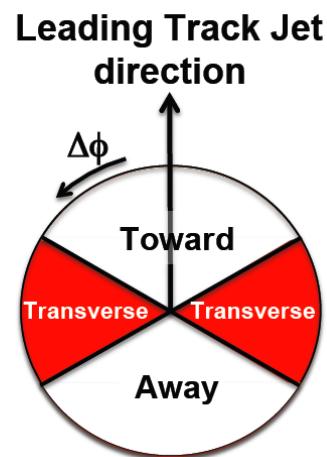
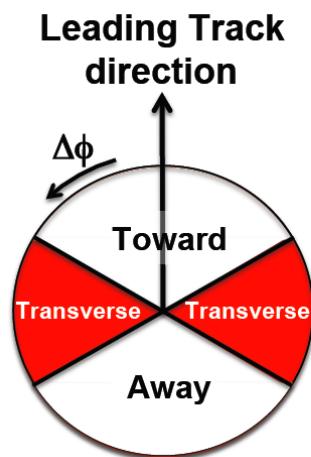
CMS values scaled by $1/\sqrt{\pi}$ to match first moment

Hadron correlations – Bose-Einstein



Radius clearly depends on charged particle multiplicity in the event
7 TeV result is also public soon

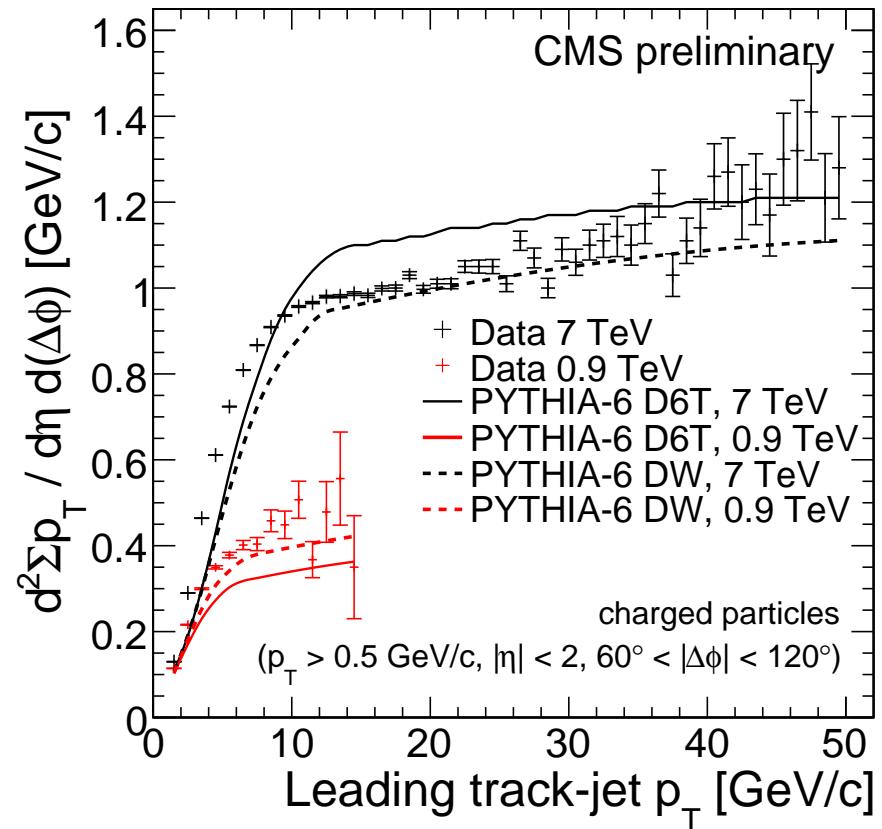
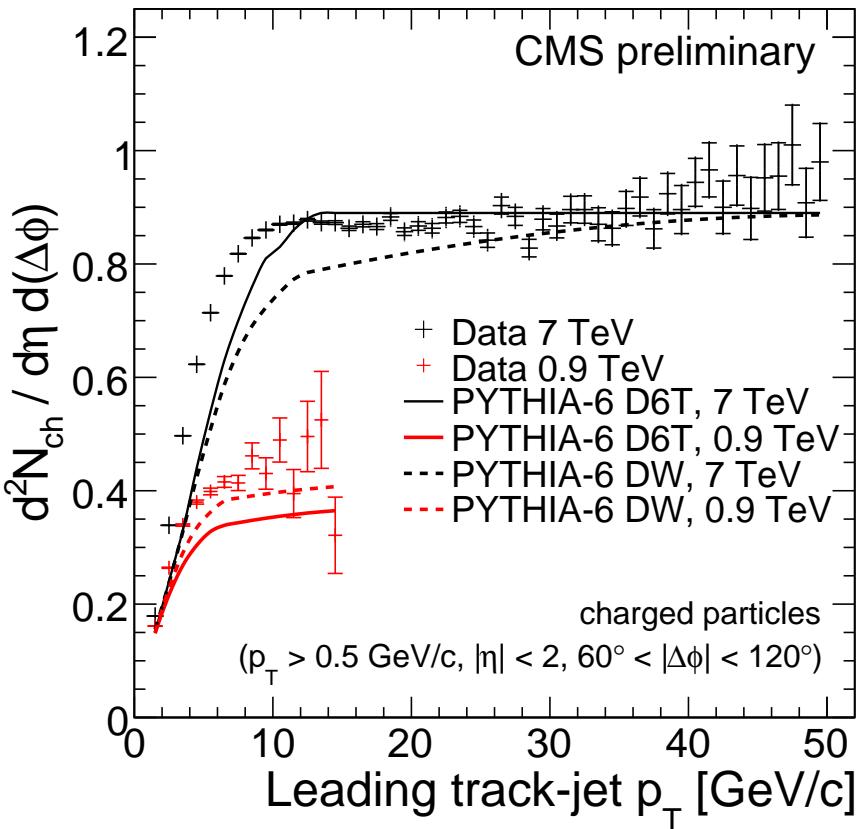
Underlying event



Look at particle production wrt to a high energy object (track or jet),
mostly in transverse direction

Important field for MC tuning, understanding of the interaction process
Sensitive to new effects, e.g. multi-parton interactions

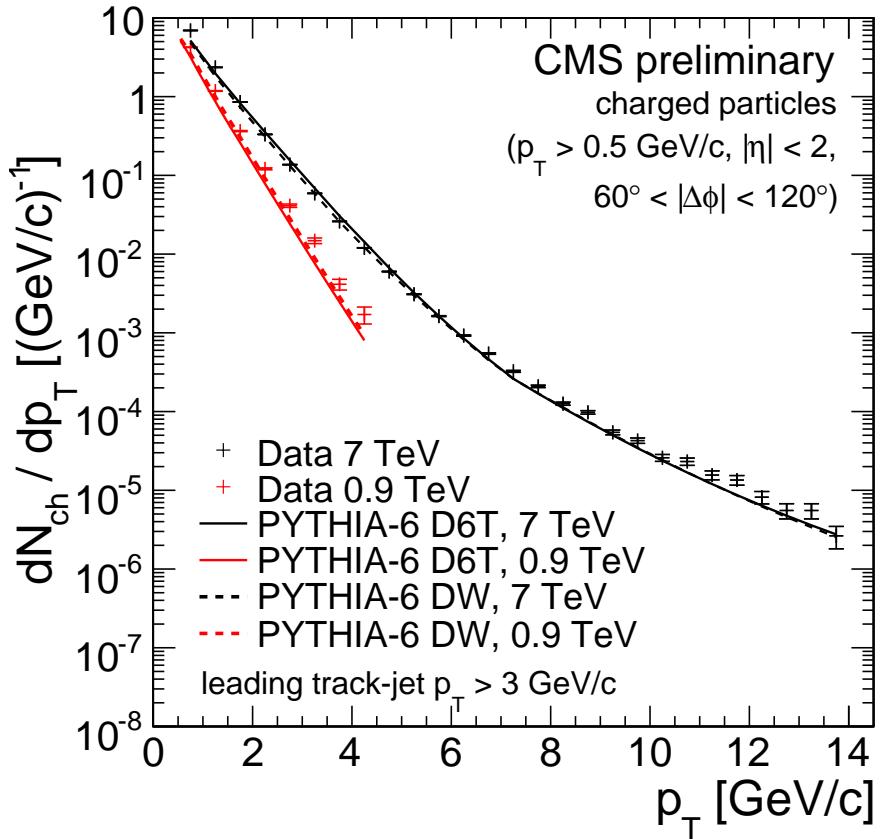
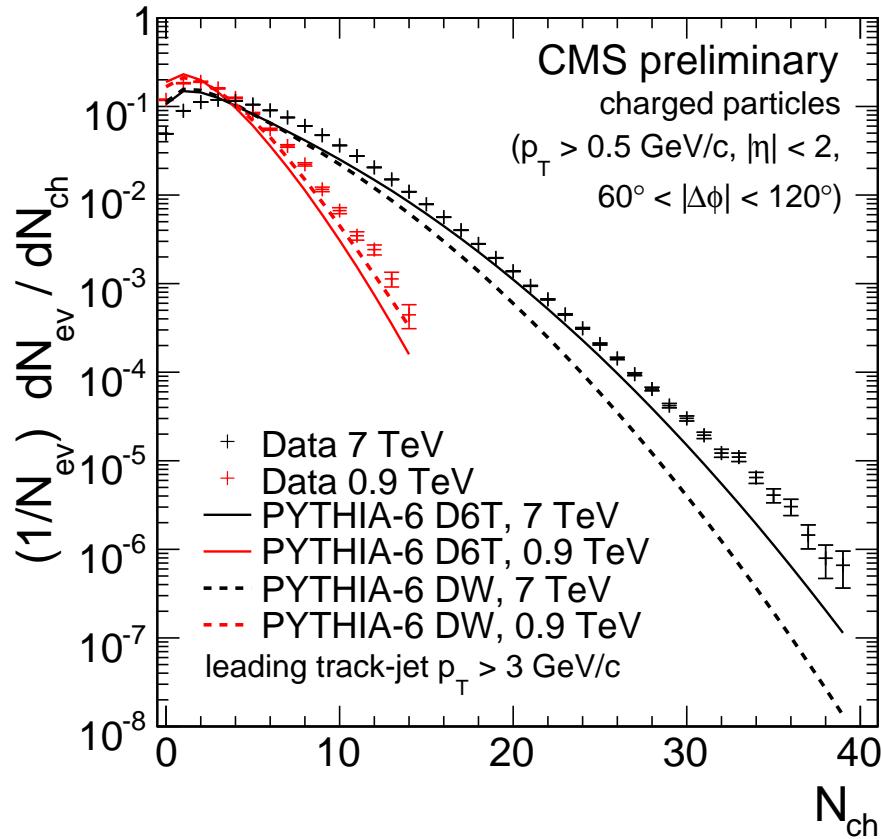
Underlying event



Uncorrected data, comparison to models
 Particle densities, sum of p_T in the transverse region

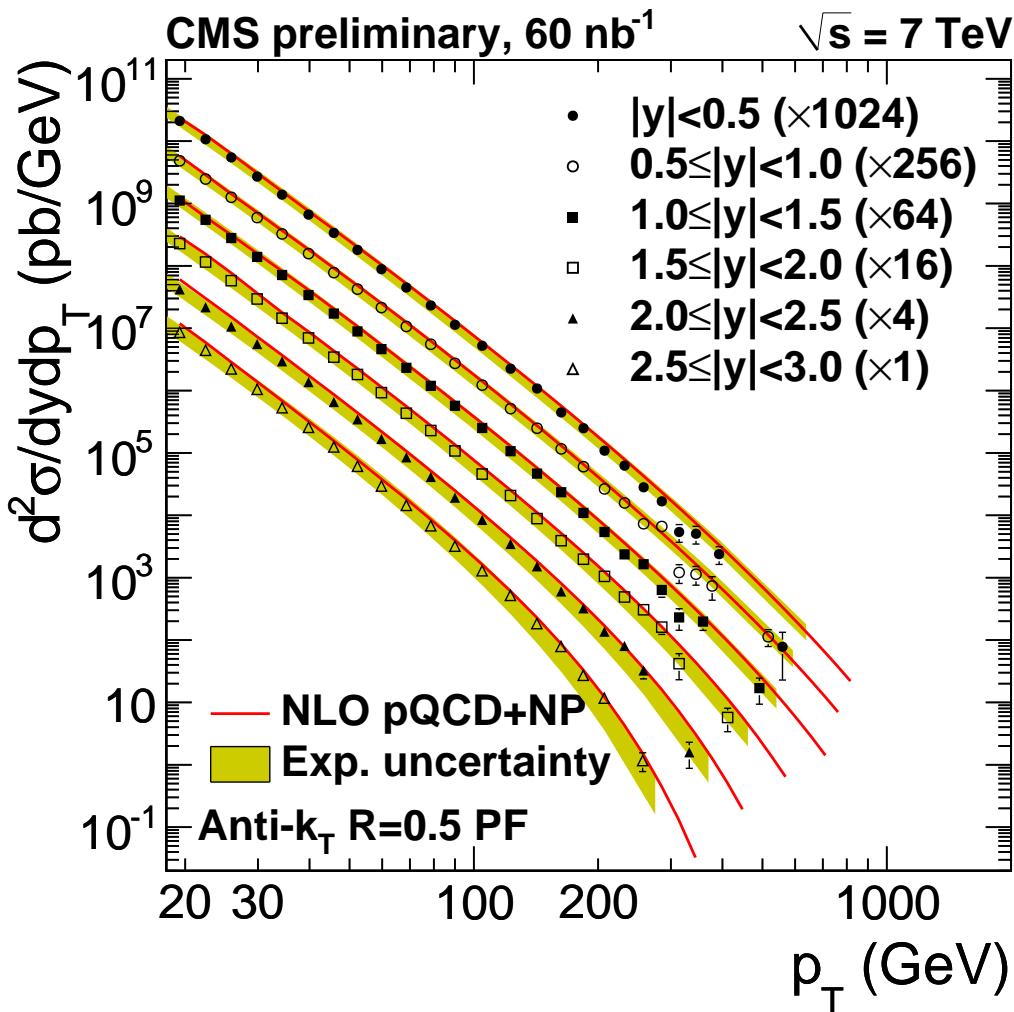


Underlying event



Uncorrected data, comparison to models
New Pythia tunes based on these and previous data

Jet spectra



- **Analysis**

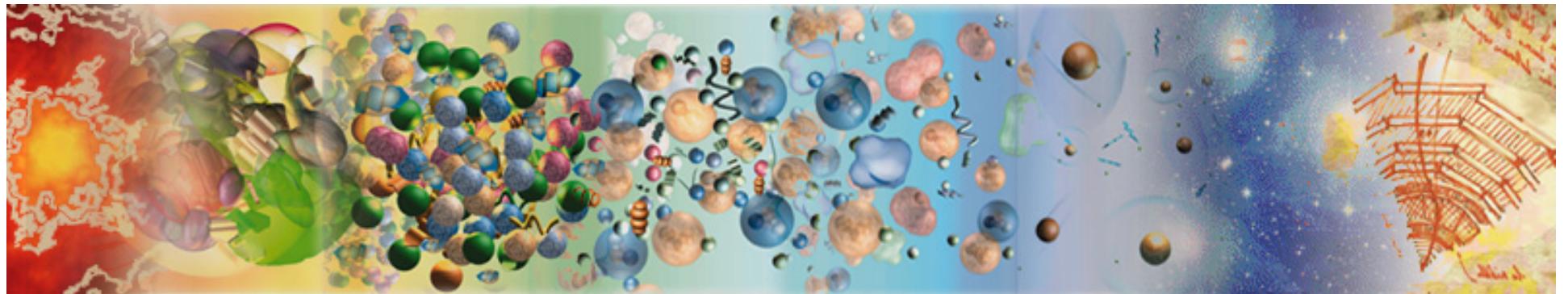
- Three reconstruction methods: calorimeter, jet+tracks, particle flow
- Inclusive jet spectra are in good agreement with NLO theory
- Extending below 50 GeV thanks to novel reco algo
- Extending up to $|y| < 3.0$
- Low p_T reach limited from theory side by non-perturbative corrections

Past Tevatron published (0.7 fb⁻¹) record



Summary

- Performance
 - The detector is well commissioned
 - Excellent performance seen
 - Results at all energies
- Physics
 - Physics analyses and publications at 0.9, 2.36 TeV and 7 TeV
 - Heavy-ion run at the end of the year



Starting the long march towards 1 fb^{-1} and possible discoveries