Overview of QCD results from CMS

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Zimányi 2010 Winter School, Budapest, Hungary
2 December 2010

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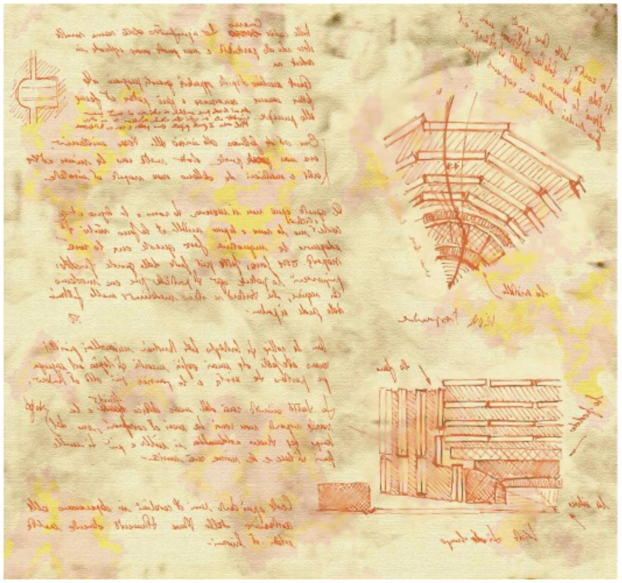
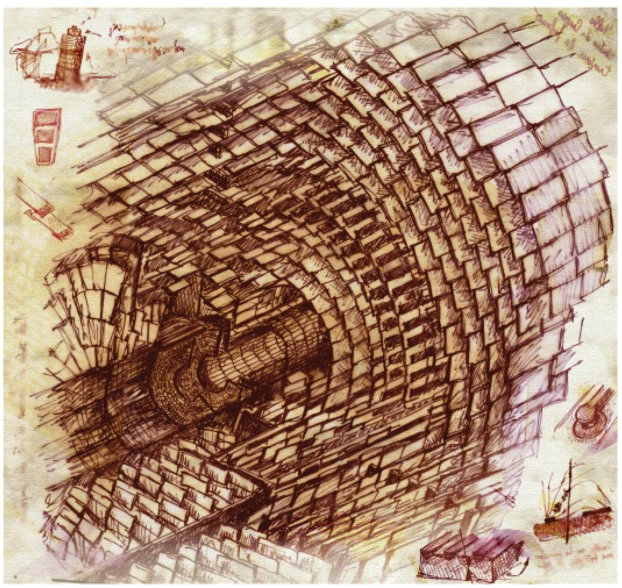
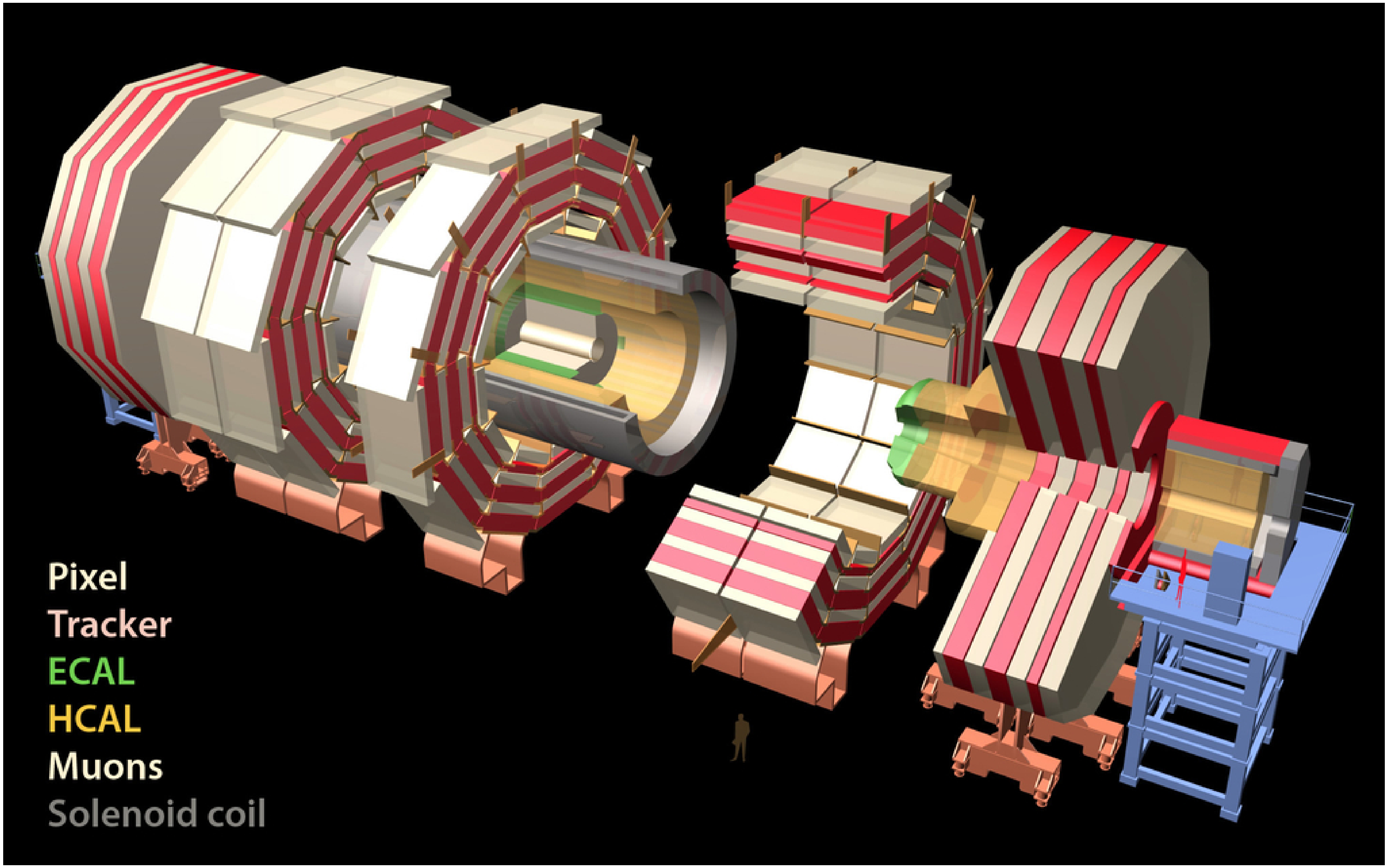




- The CMS detector
- Performance results
  - Tracking and vertexing
  - Jets
  - Missing E_T
  - Electrons and photons
  - Particle flow
- Physics results (pp, QCD, a selection)
  - Hadron spectra (vs η and p_T) charged; strange
  - Event-by-event multiplicity
  - Hadron correlations angular; Bose-Einstein
  - Underlying event
  - Jet spectra

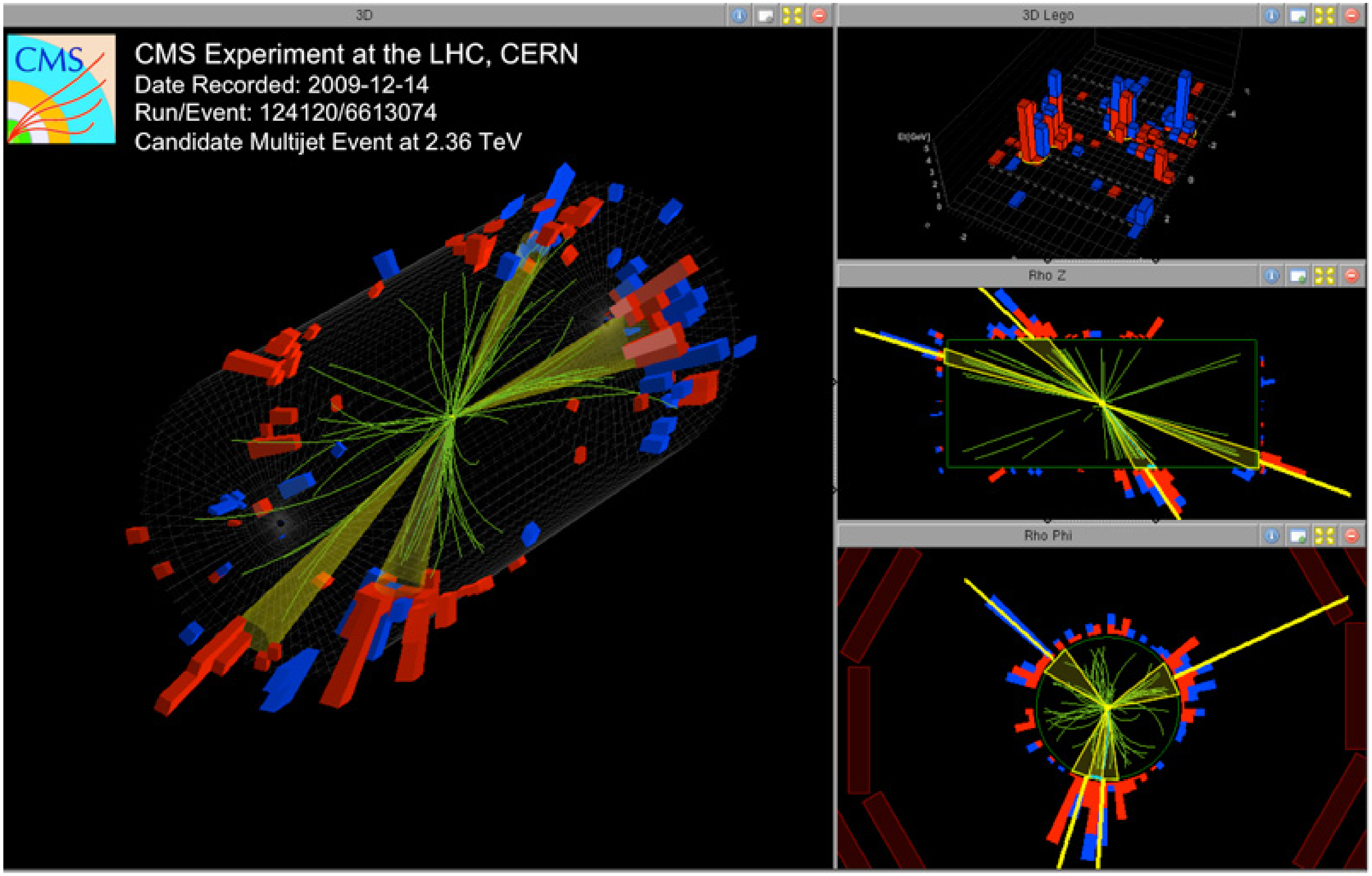
The CMS detector



Silicon tracker (pixels+strips) Lead tungstate crystal ECAL

Hermetic ($|\eta| < 5.2$) HCAL Muon system (RPC, DT, CSC) 3.8 T field

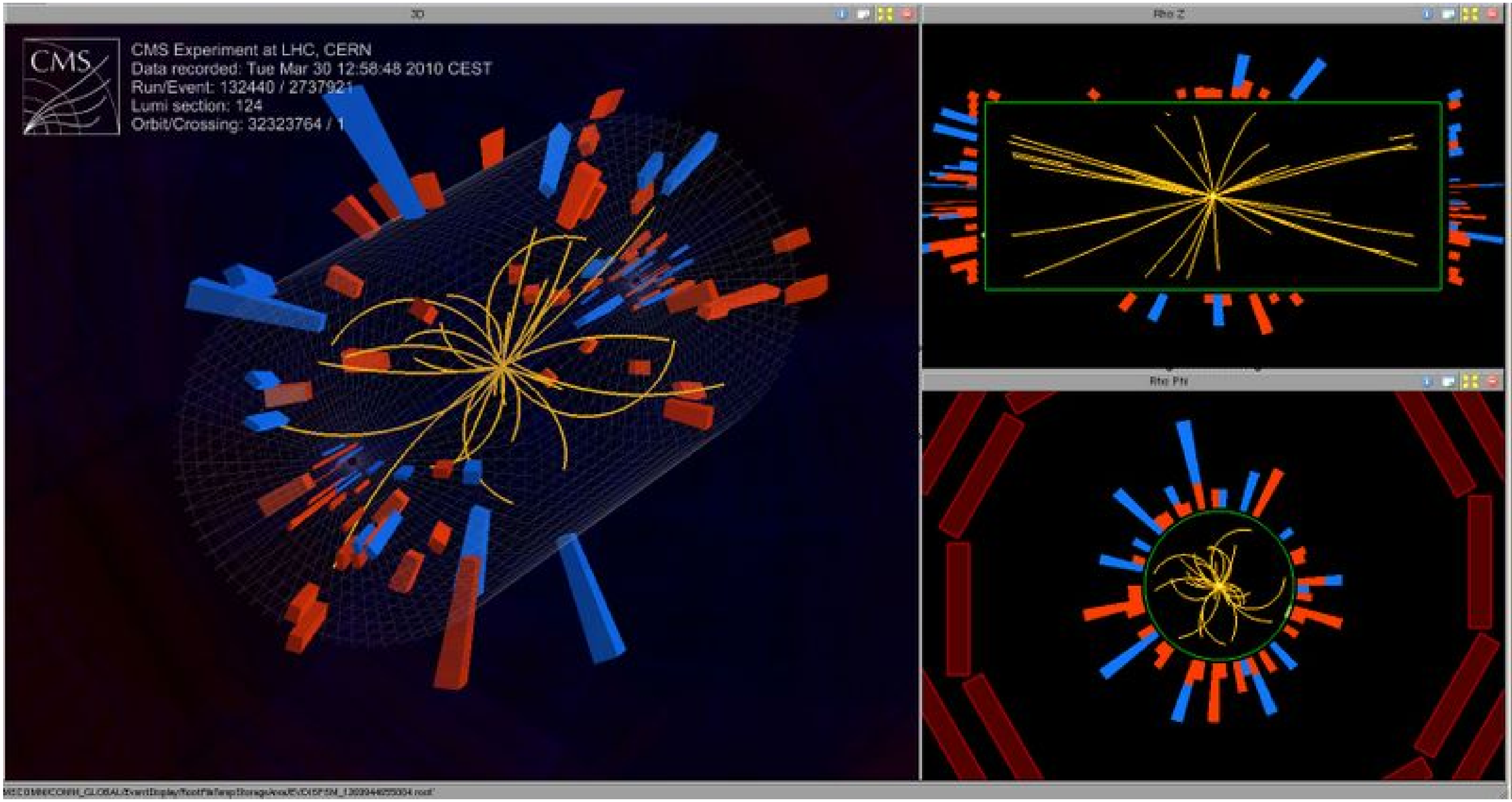
The detector at work



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

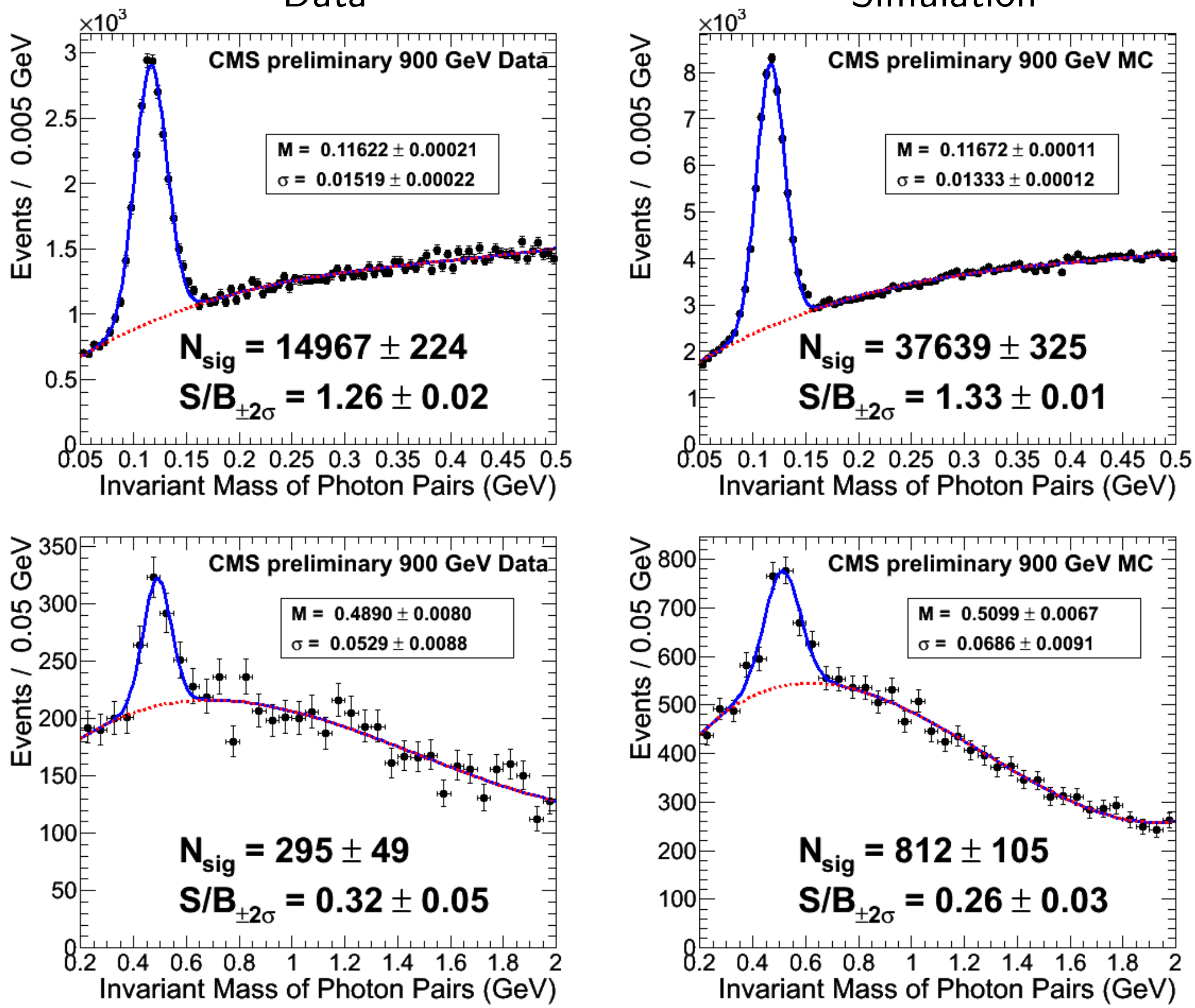
2010: $\sqrt{s} = 7$ TeV

42.5 pb^{-1} recorded this year at CMS

Performance results within some months

Neutrals decaying to $\gamma\gamma$

Data Simulation



$\pi^0 \to \gamma\gamma$

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

$\eta \to \gamma\gamma$

Corrected,

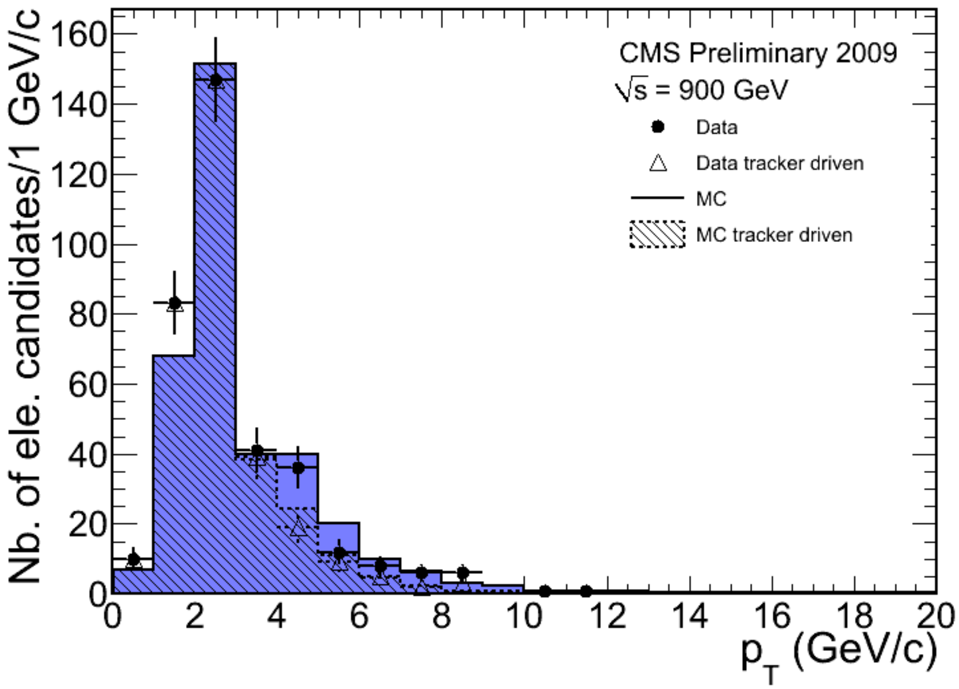
good agreement:

peak position and S/B

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

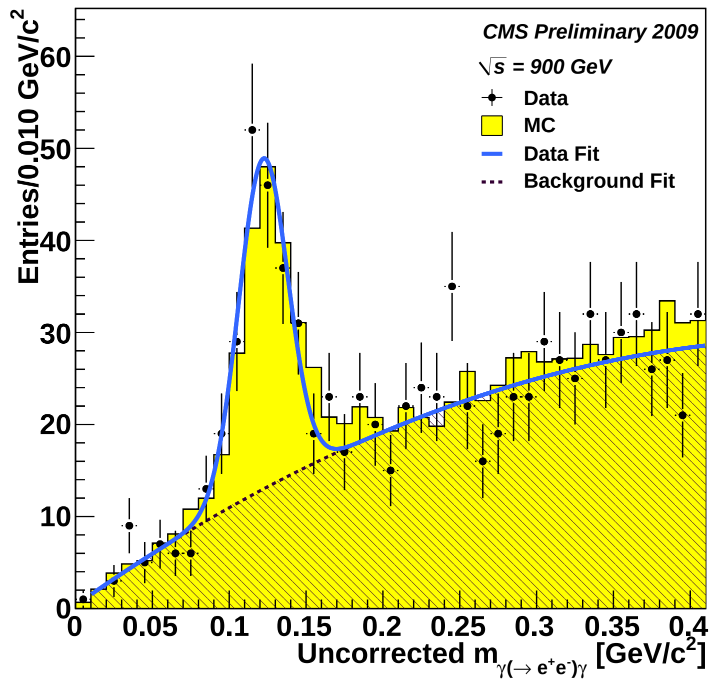
Electrons and conversions

Electrons



p_T distribution of electron candidates
Tracker or ECAL driven

π^0 with conversion

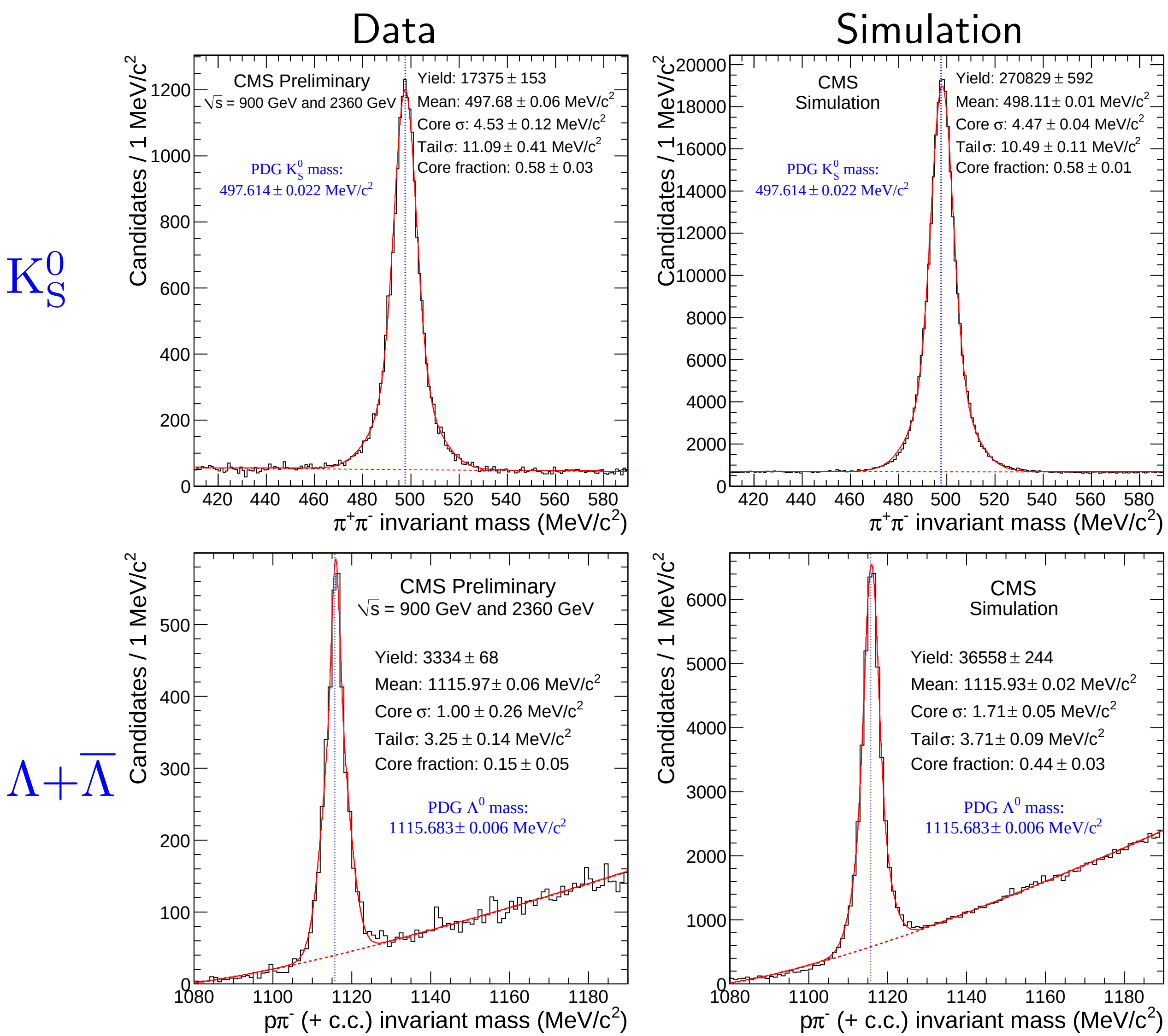


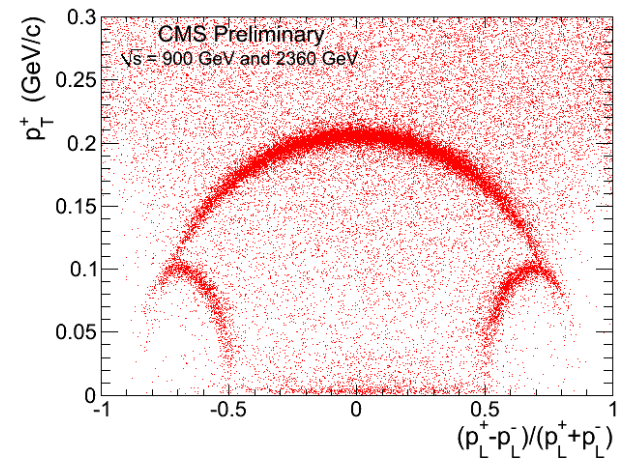
CMS-PAS-EGM-10-001

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

Good agreement between data and MC

Tracking – long lived resonances



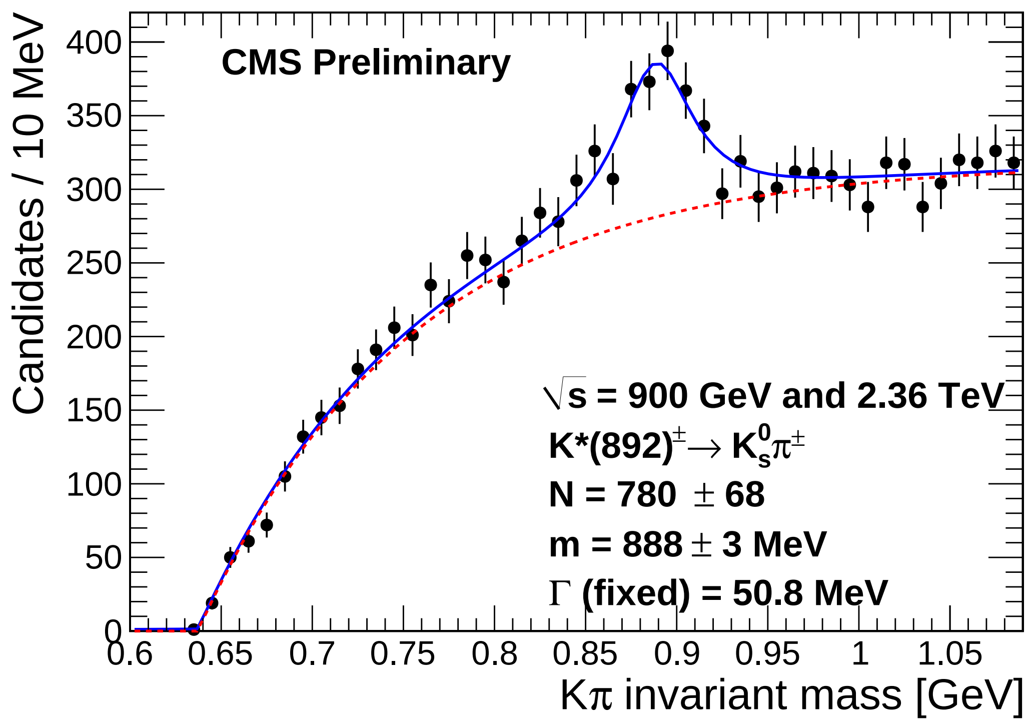


CMS-PAS-TRK-10-001

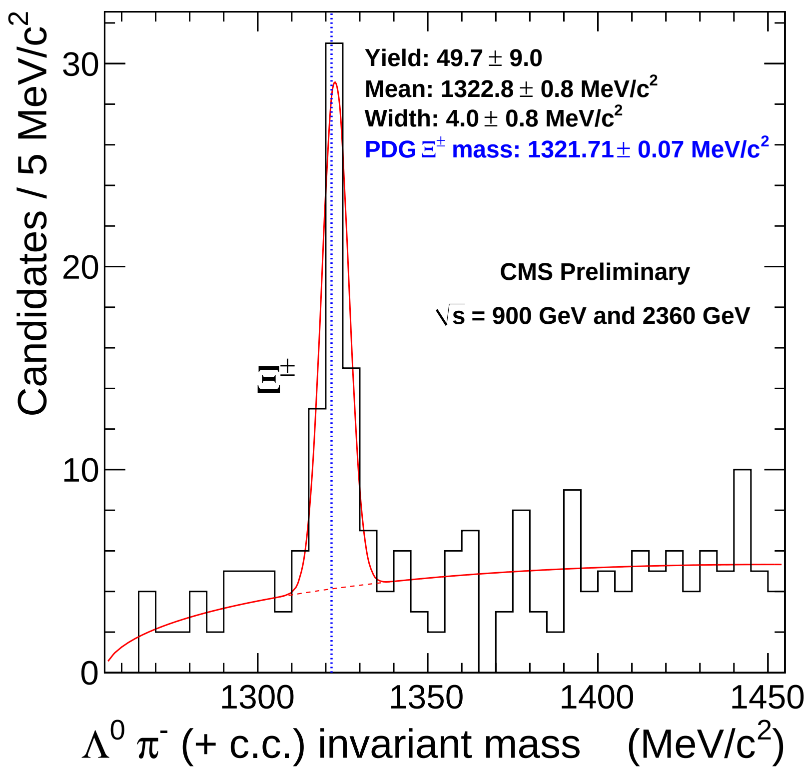
Peak shape and S/B agrees beautifully: per mille precision in momentum

Tracking – on-vertex resonances

$K^*(892)$



$\Xi^- + \overline{\Xi}^+$



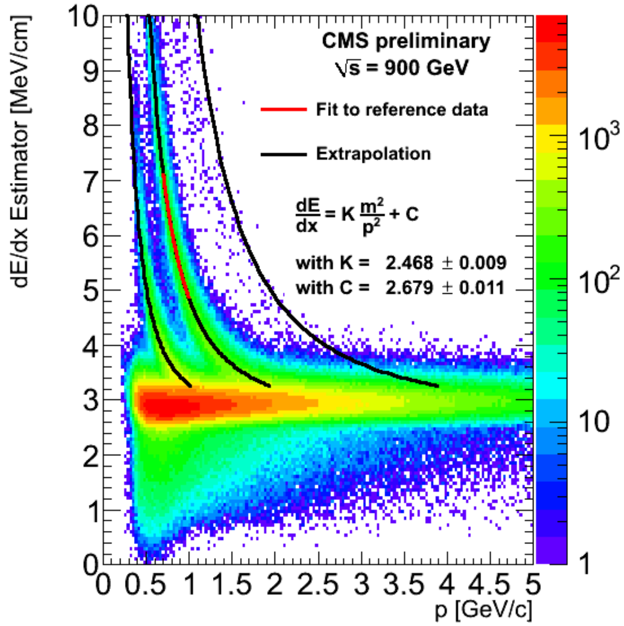
CMS-PAS-TRK-10-001

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

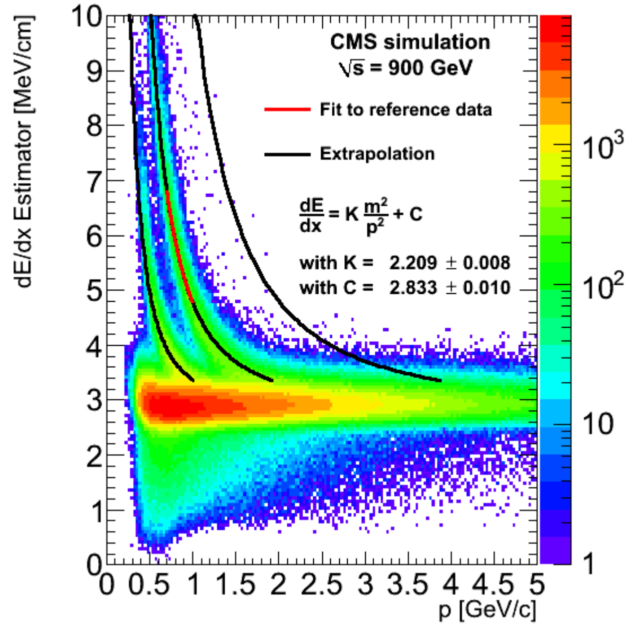
Mass peaks: excellent agreement with PDG

Tracking – particle identification

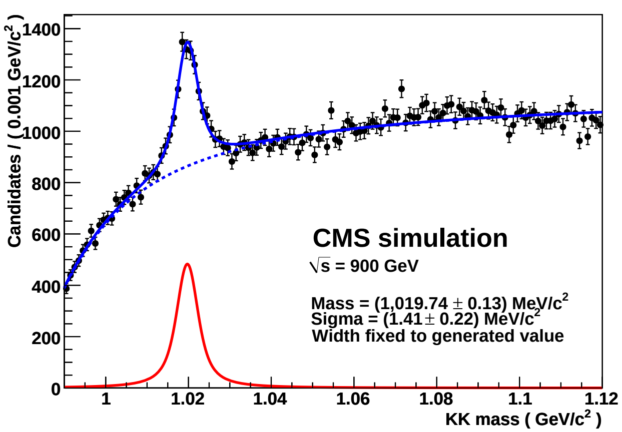
Data

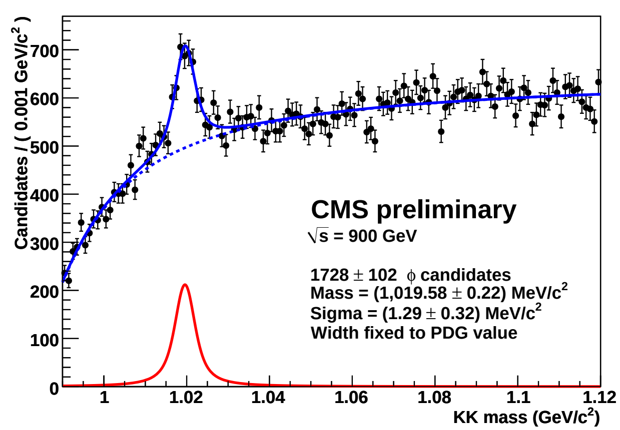


Simulation



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



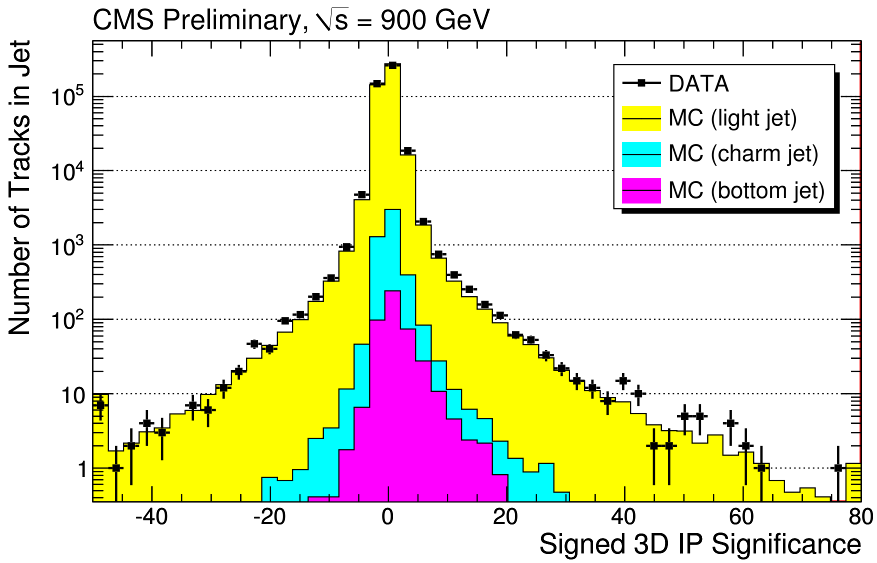


Reconstruction of
$\phi(1020) \to K^+K^-$
with help of dE/dx

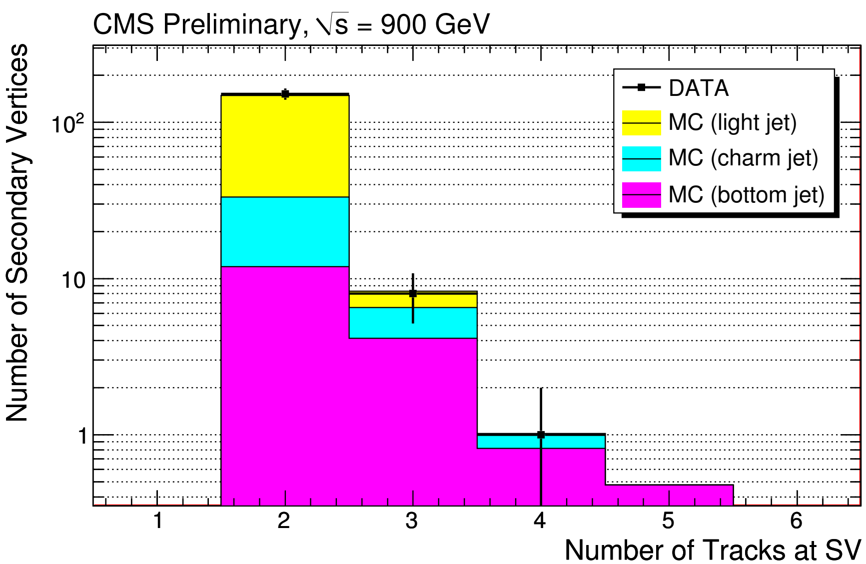
CMS-PAS-TRK-10-001

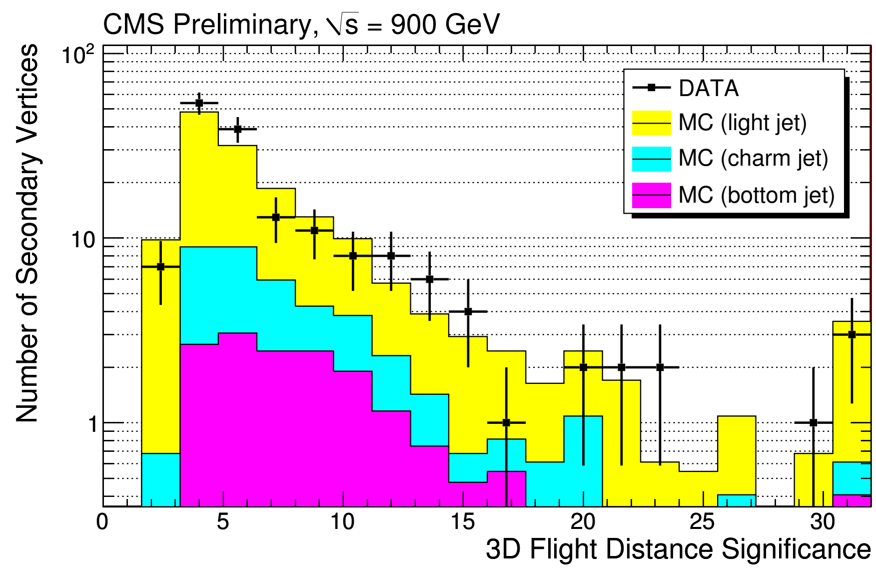
Particle identification at low momentum

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

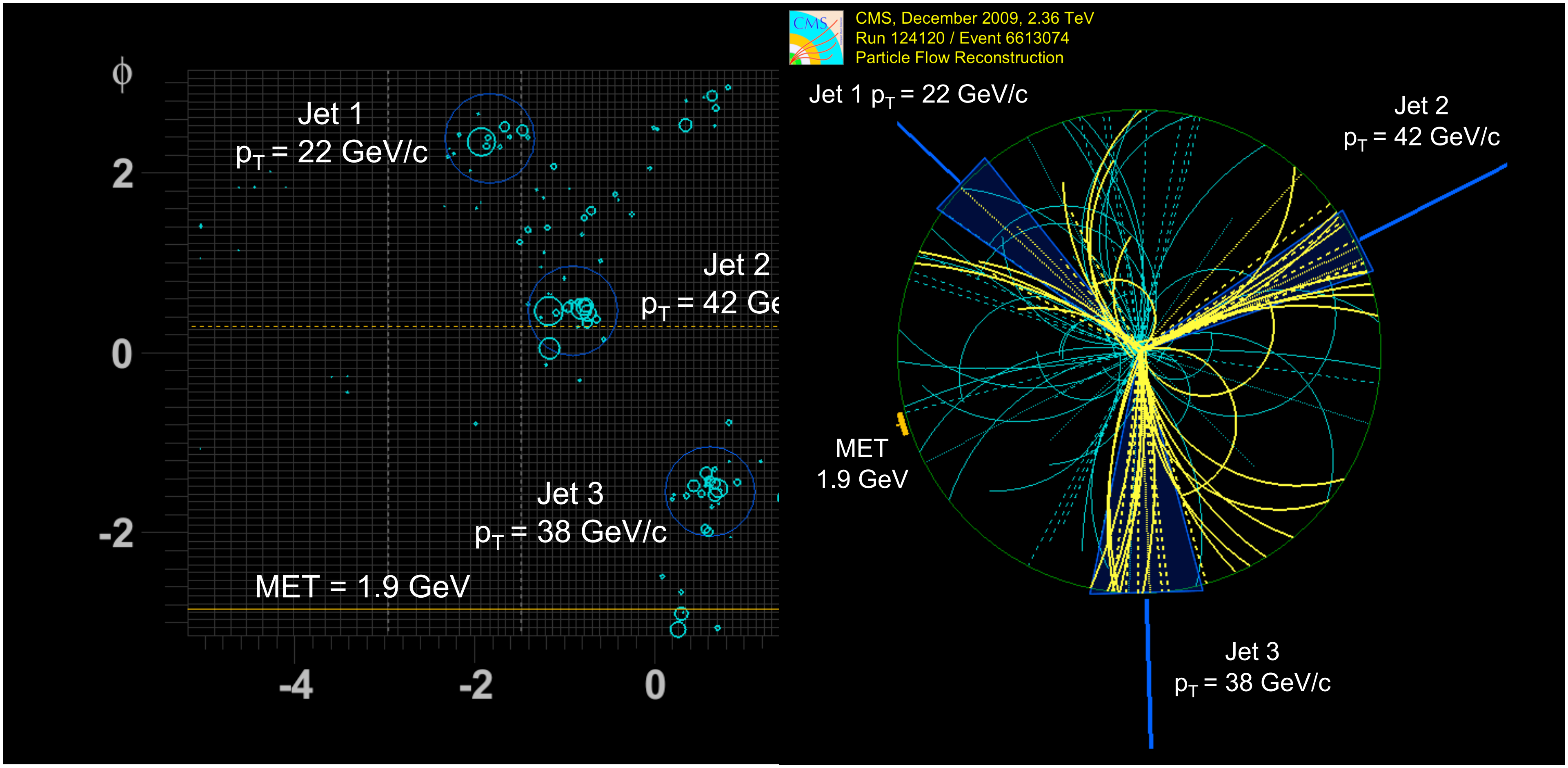




CMS-PAS-TRK-10-001

Basic b-tagging related variables are well described

Particle flow

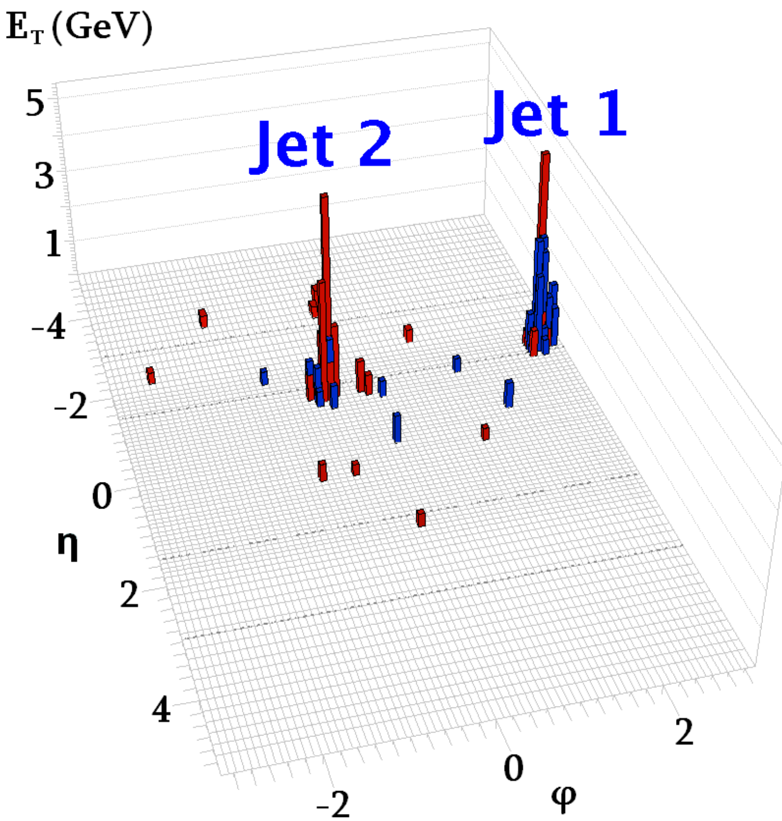


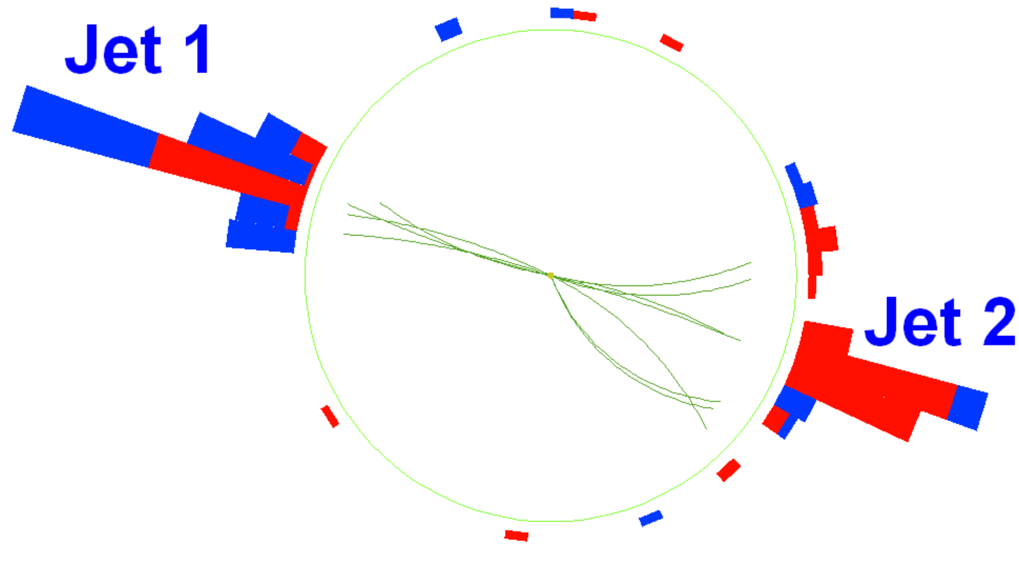
CMS-PAS-PFT-10-001

A particle-flow reconstructed event at 2.36 TeV

Circles – particle p_T Thinner circles – jets with $p_T > 20$ GeV/c

Jets



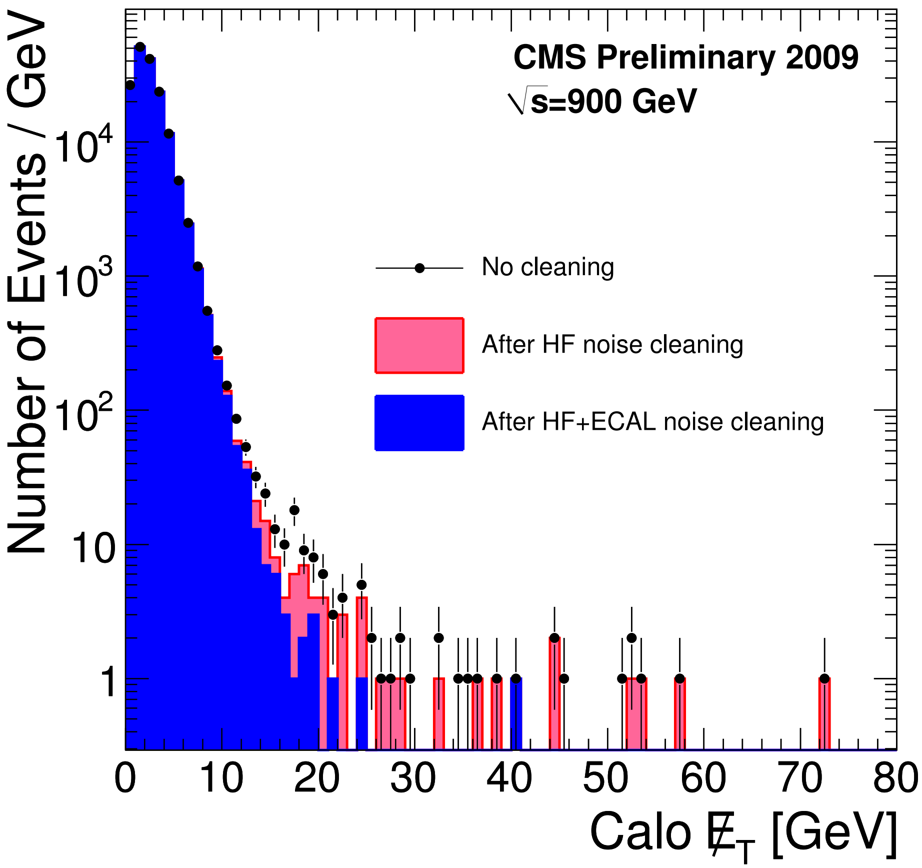


CMS-PAS-JME-10-001

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

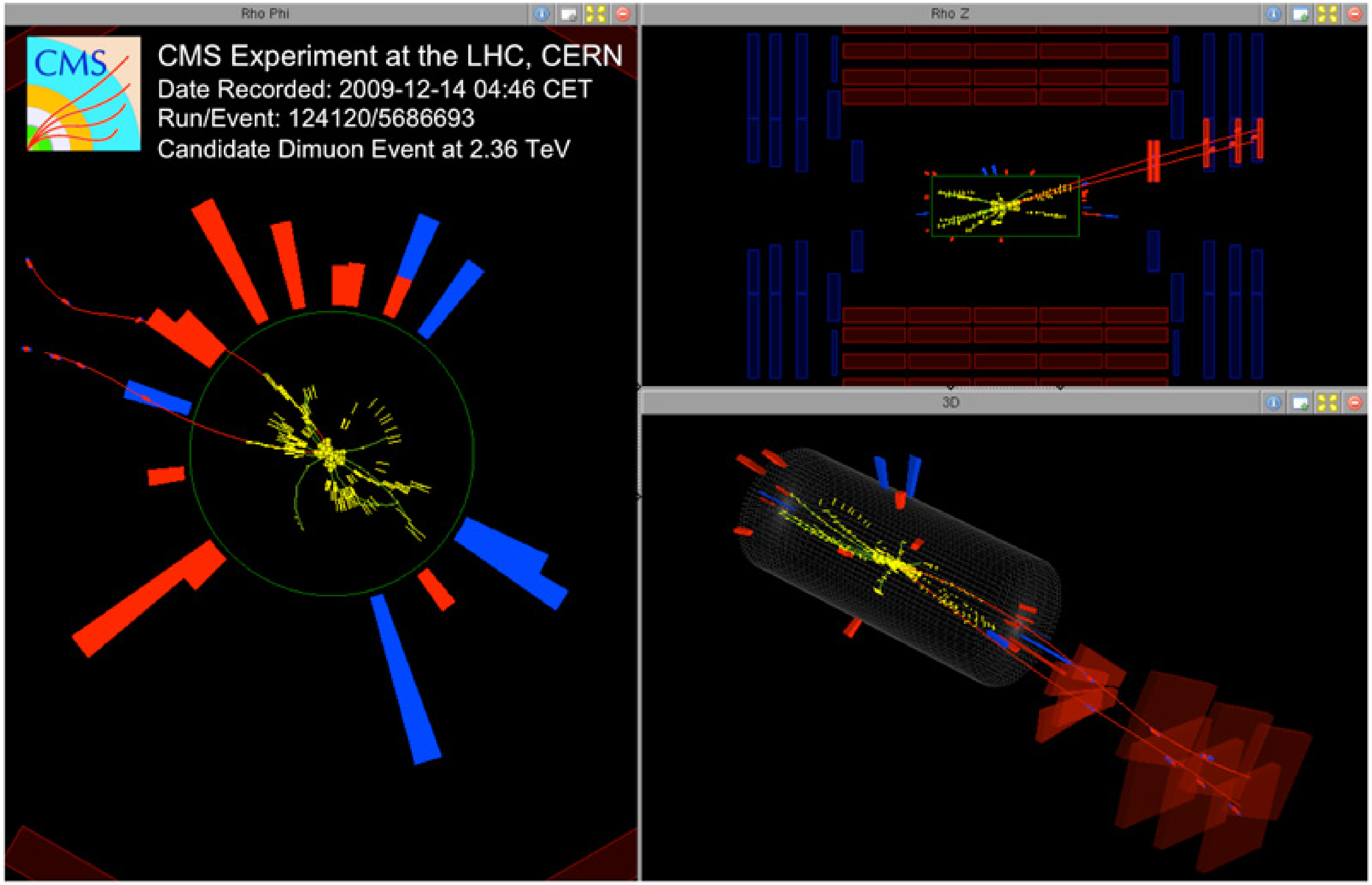


- Corrections
  - Robust missing E_T measurement over the full data-taking period
  - Anomalous noise in HCAL
    - hybrid photo diodes
    - photo-multiplier window hits
  - Anomalous noise in ECAL
    - single crystals, "spikes"
  - Beam-halo muons

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

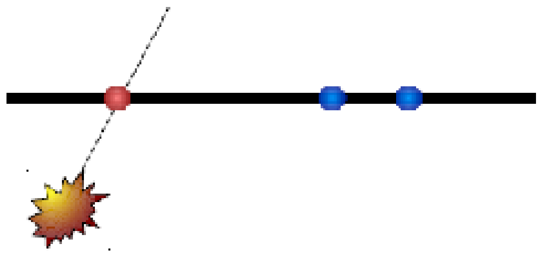
Topic	CMS PAS	arXiv	Publication
Spectra of charged hadrons	QCD-09-010	1002.0621	JHEP **02** (2010) 041
	QCD-10-006	1005.3299	PRL **105** (2010) 022002
	QCD-10-008		
Spectra of strange hadrons	QCD-10-007		
Event-by-event multiplicity	QCD-10-004	1011.5531	JHEP, submitted
Bose-Einstein correlations	QCD-10-003	1005.3294	PRL **105** (2010) 032001
Angular correlations	QCD-10-002		
Long-range near-side angular	QCD-10-002	1009.4122	JHEP **09** (2010) 091
Underlying event	QCD-10-001	1006.2083	EPJC, accepted
	QCD-10-010		
	QCD-10-005		
Jet spectra	QCD-10-011		

PAS = Physics Analysis Summary, they are all public at CERN Document Server

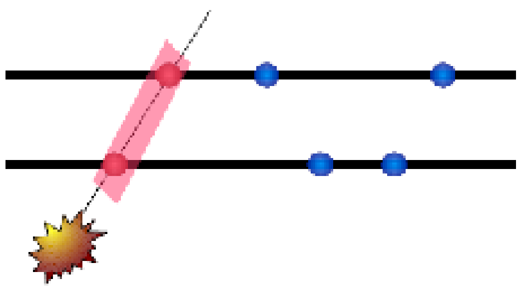
Blank fields indicate a paper in preparation

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

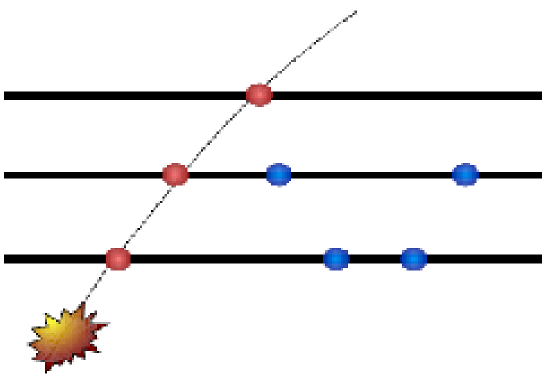
Spectra of charged hadrons – methods



- Pixel hit counting (1 hit)
  - Using the primary vertex, calculate η for each cluster
  - Immune to detector mis-alignment, simplest
  - $p_T > 30$ MeV/c, $|\eta| < 2$



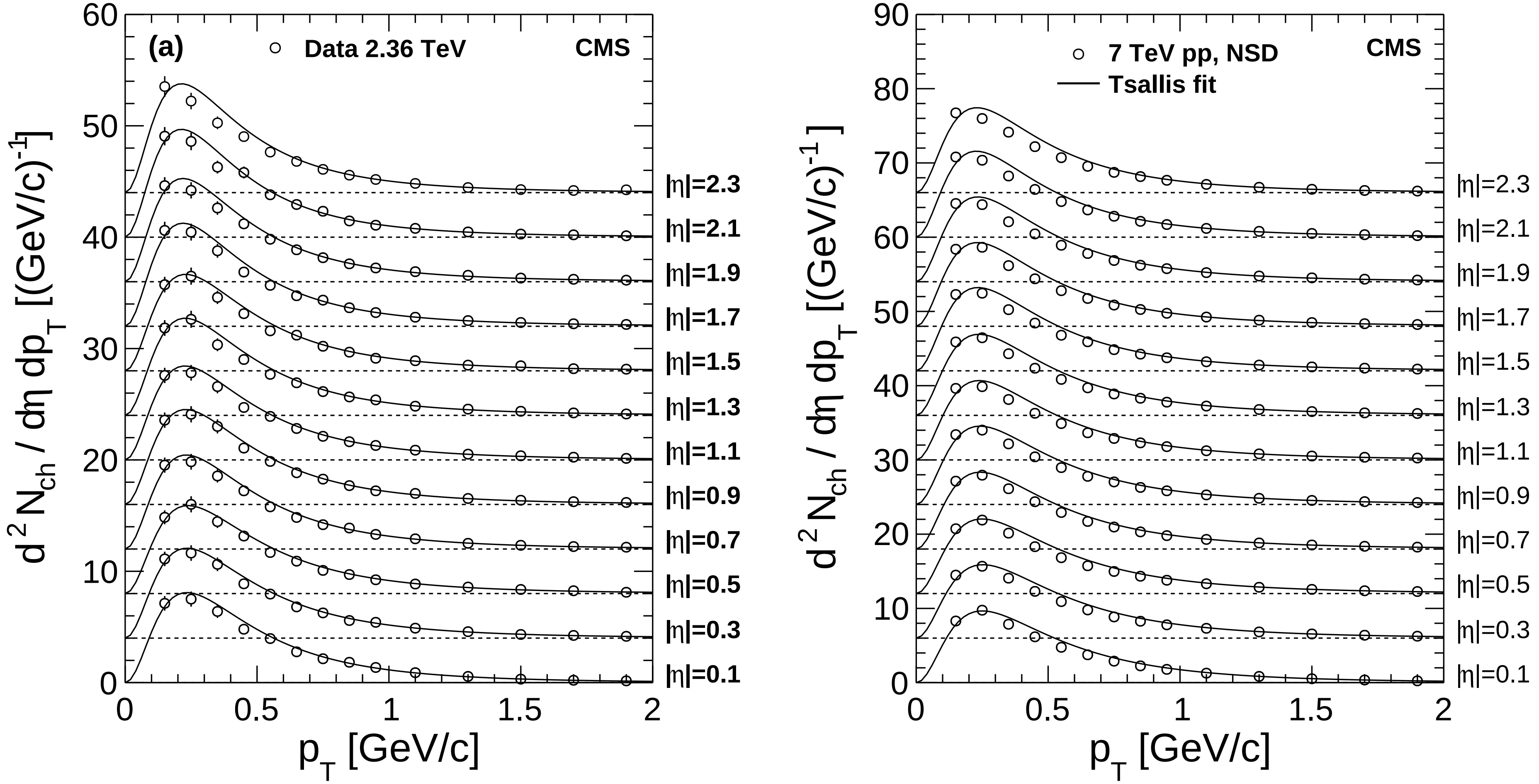
- Tracklets (2 hits)
  - Form hit pairs, calculate η
  - Data-driven background subtraction
  - $p_T > 50$ MeV/c, $|\eta| < 2$



- Full tracks
  - Use all pixel and strip hits, provide η and p_T
  - Sensitive, most complex
  - $p_T > 100$ MeV/c, $|\eta| < 2.4$

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

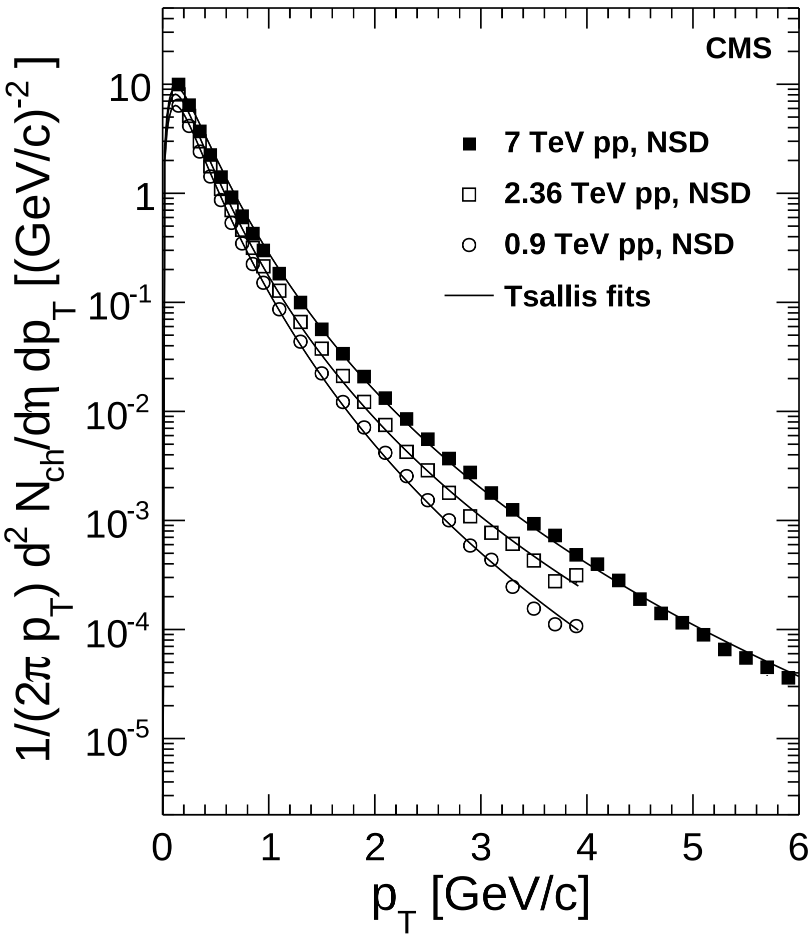
Spectra of charged hadrons – spectra

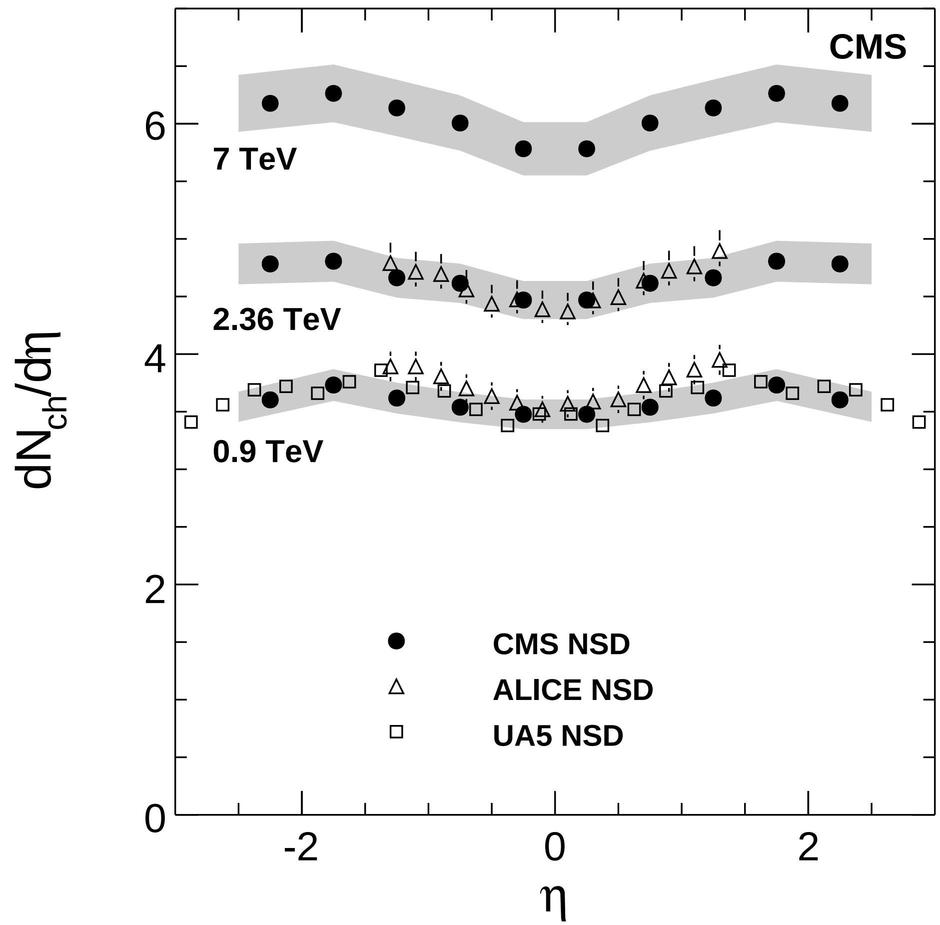


Full tracks, agglomerative vertex finder, negligible pile-up

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

Spectra of charged hadrons – spectra



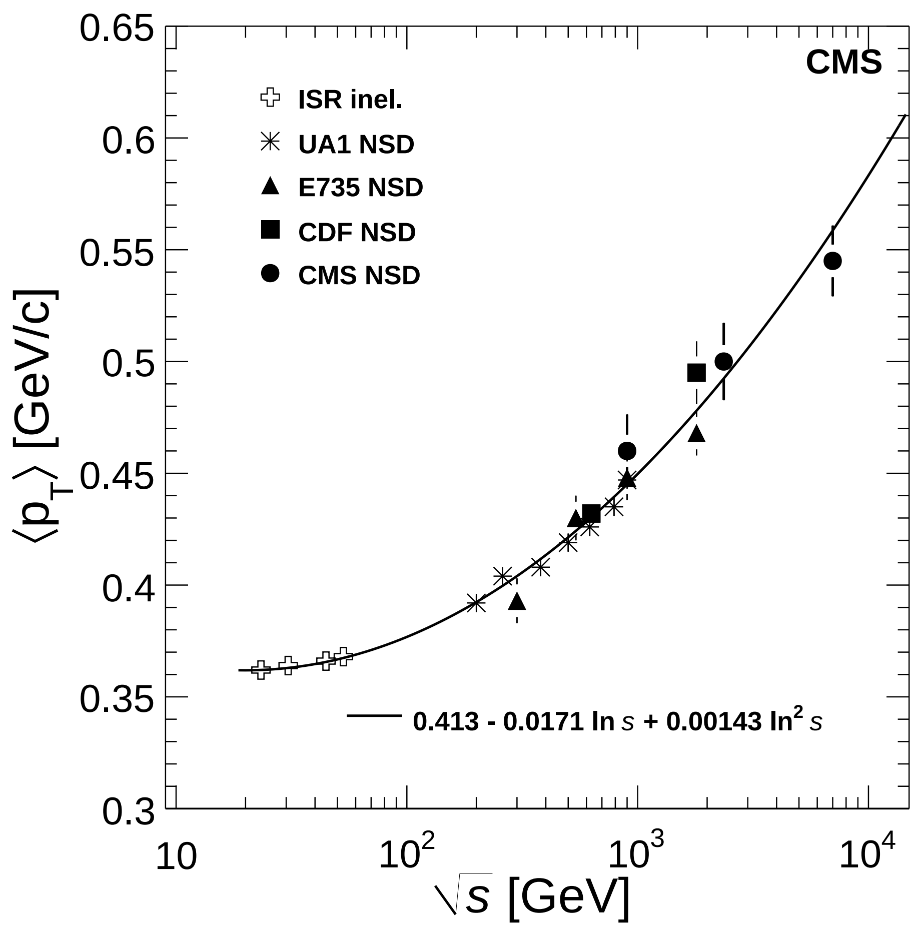


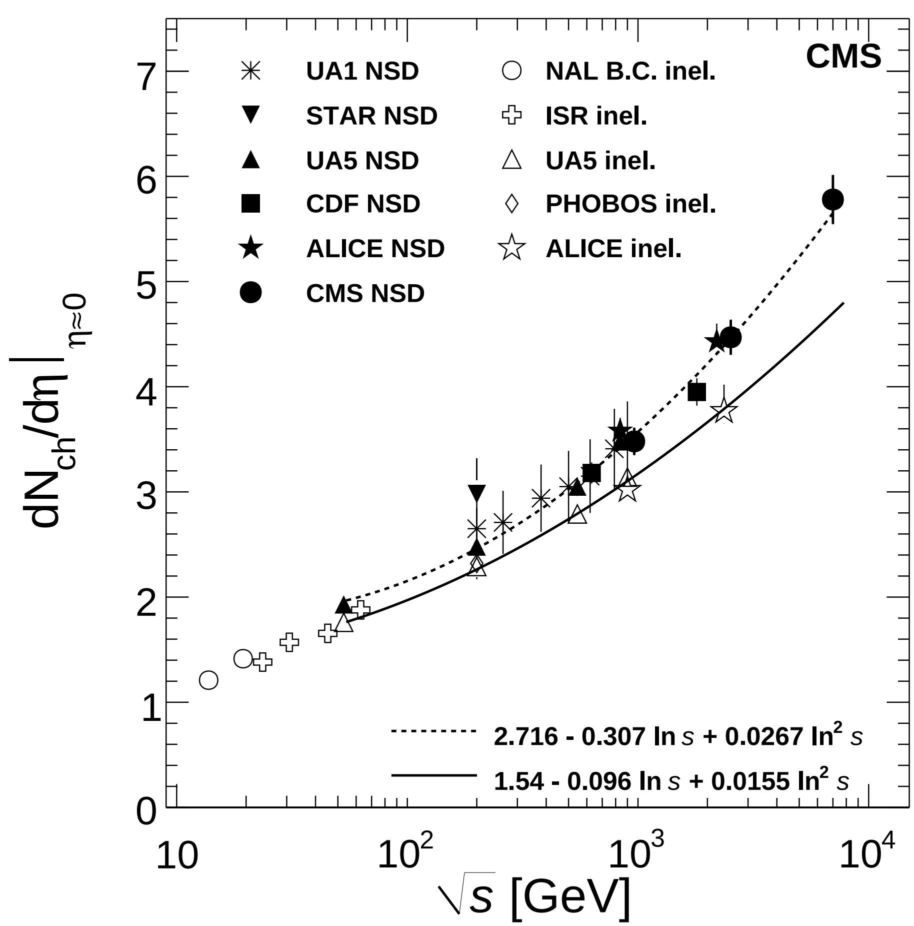
For $dN/d\eta$ combination of three methods

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

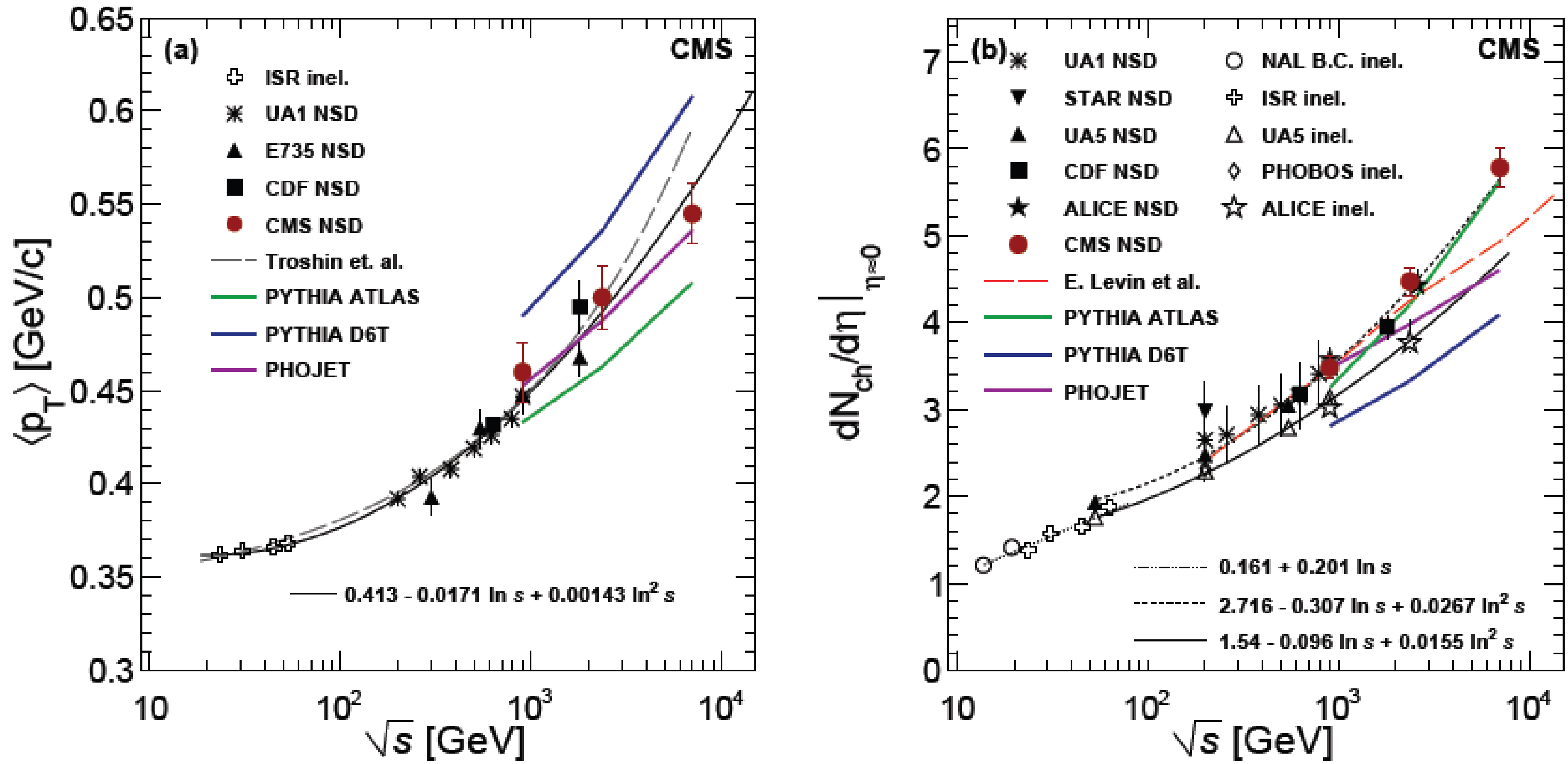




Higher $\langle p_T \rangle$, accelerated increase of $dN_{ch}/d\eta$ density

Input for theory

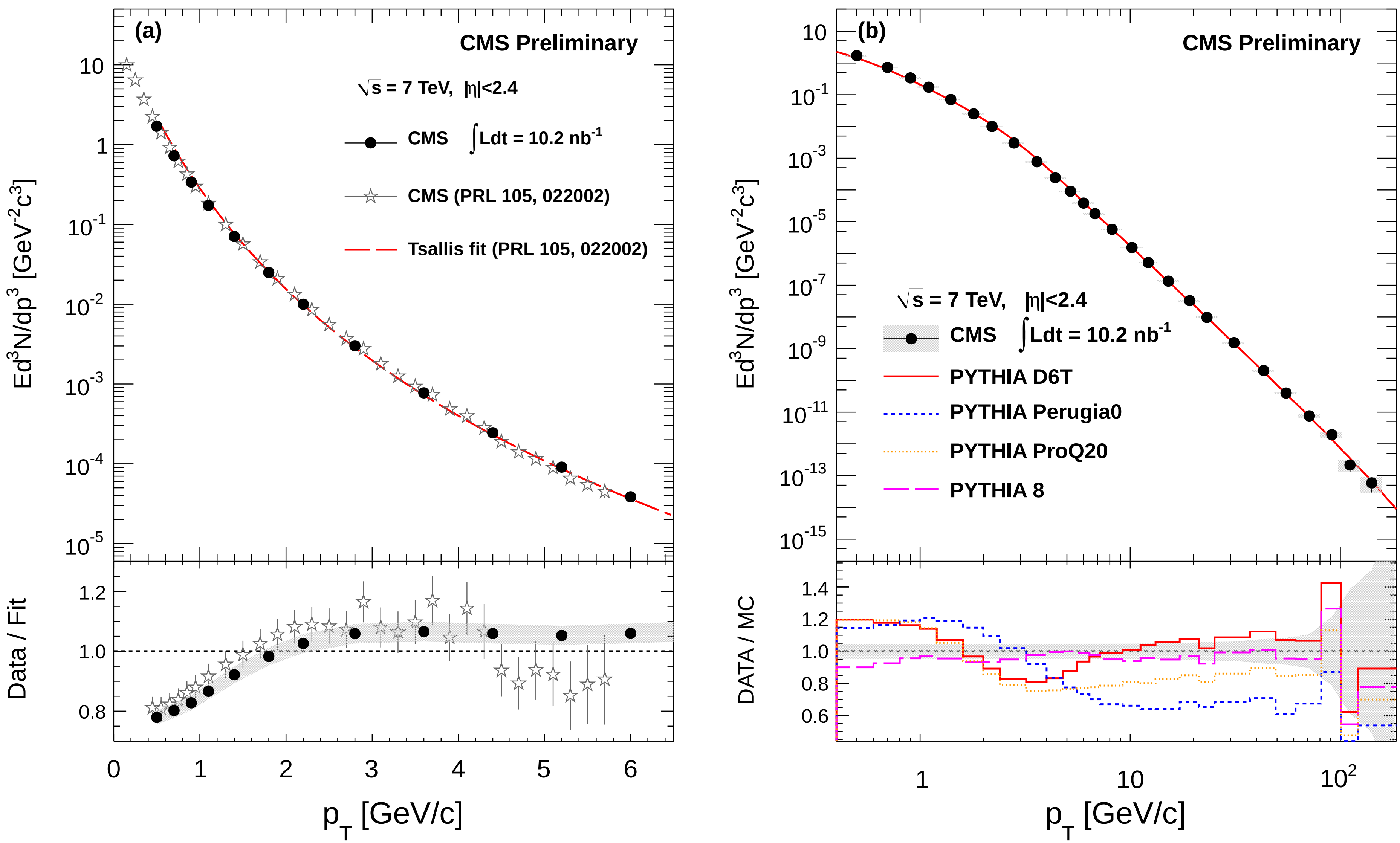
Spectra of charged hadrons – models?



Phojet describes $\langle p_T \rangle$ well

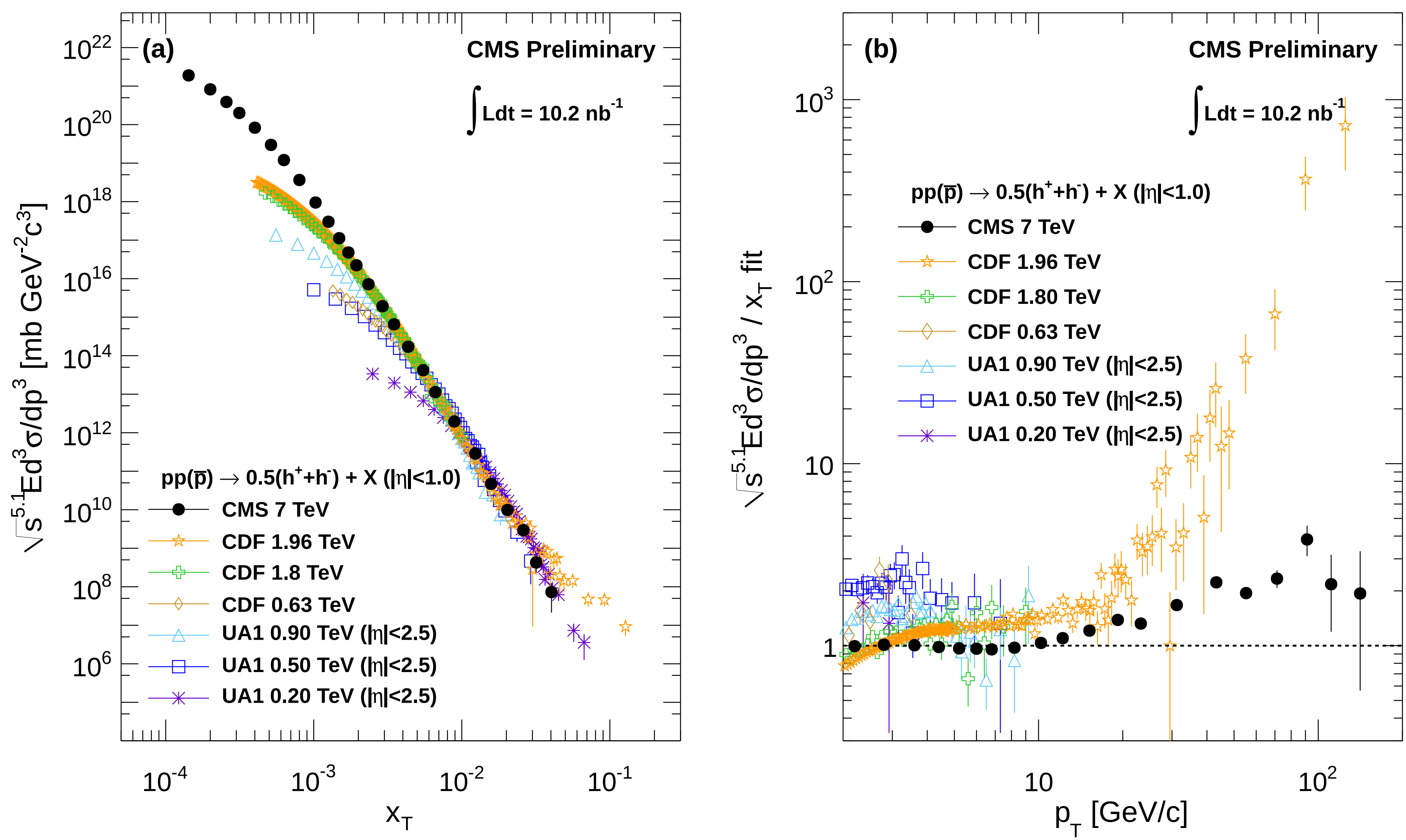
Most tunes underestimate $dN/d\eta$ at 7 TeV

Spectra of charged hadrons – high p_T



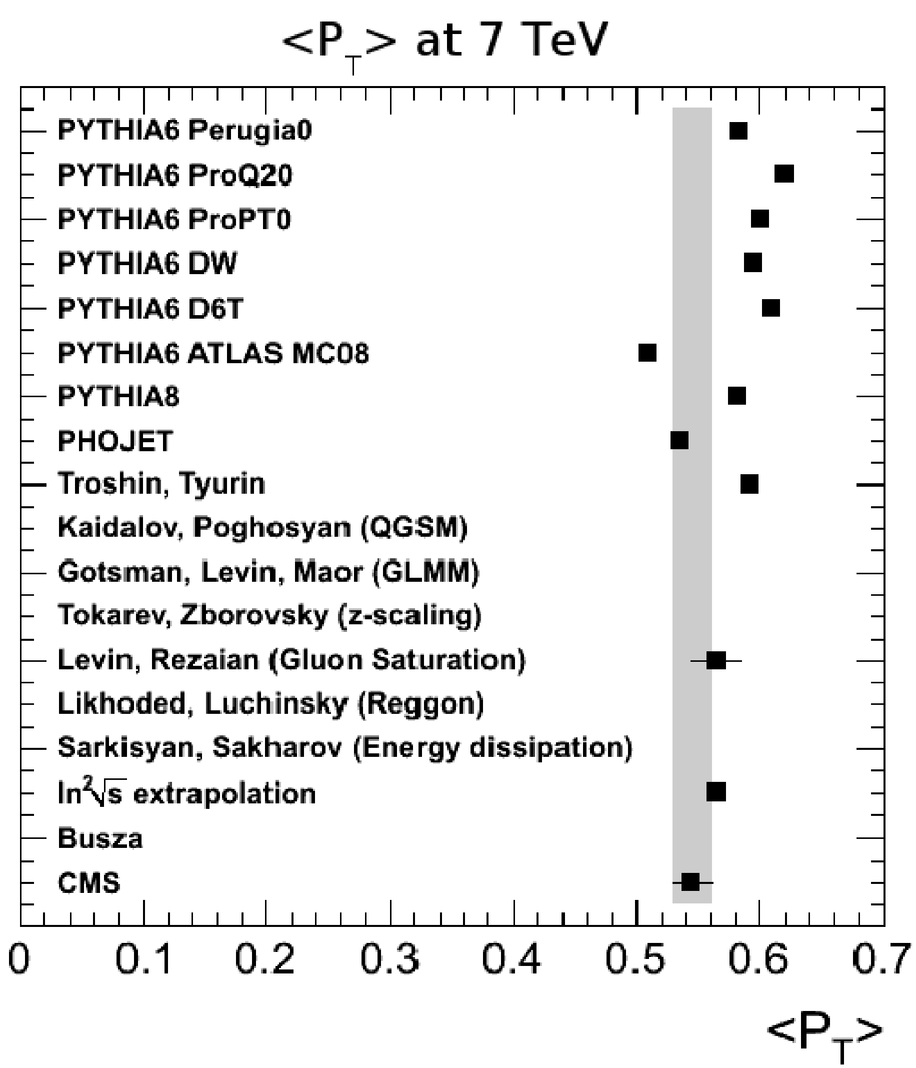
Jet triggers used to extend reach, nice match with first results

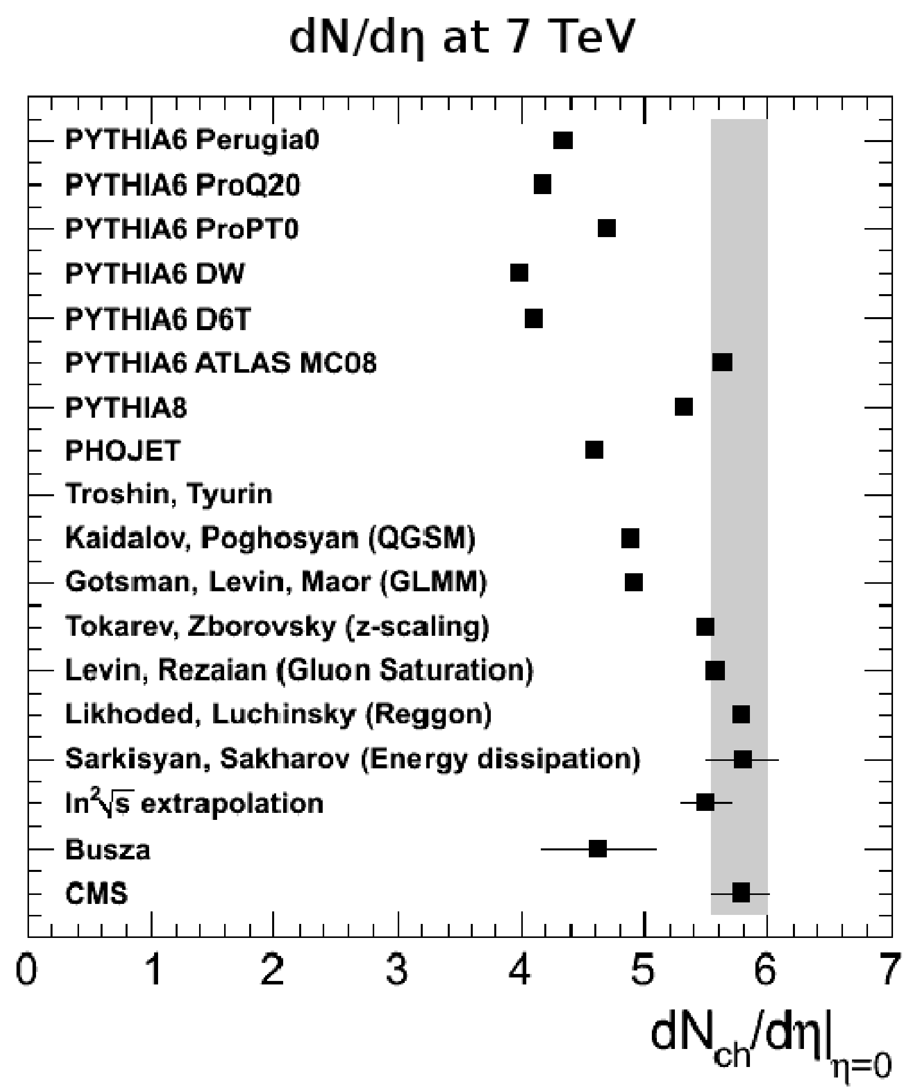
Spectra of charged hadrons – high p_T



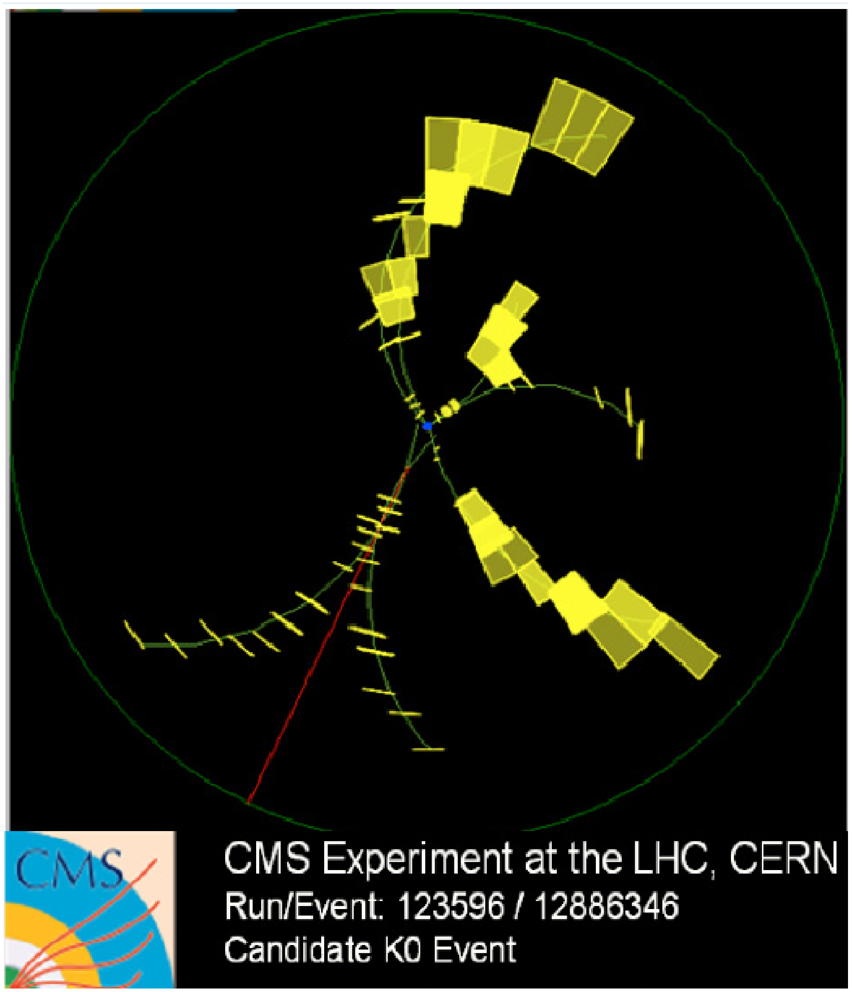
Power-law trend, flattening and high p_T is not seen

Spectra of charged hadrons – models?

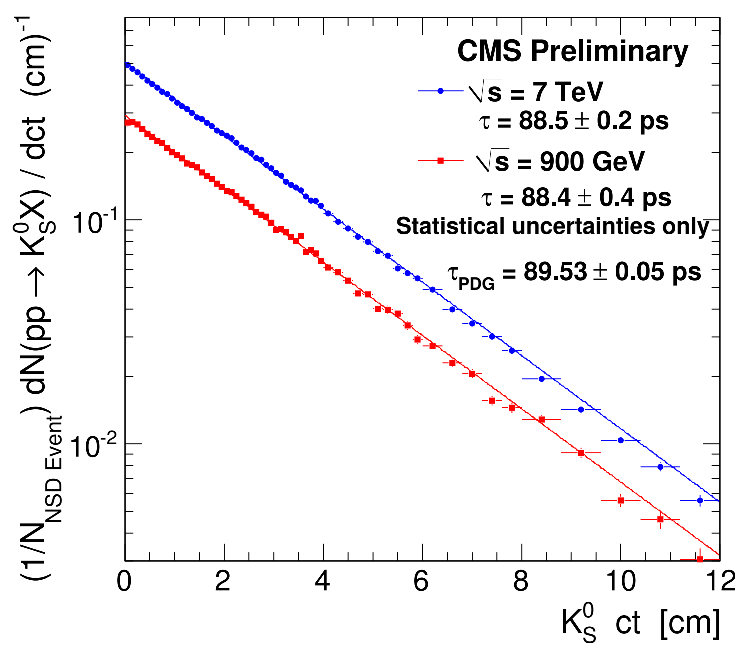




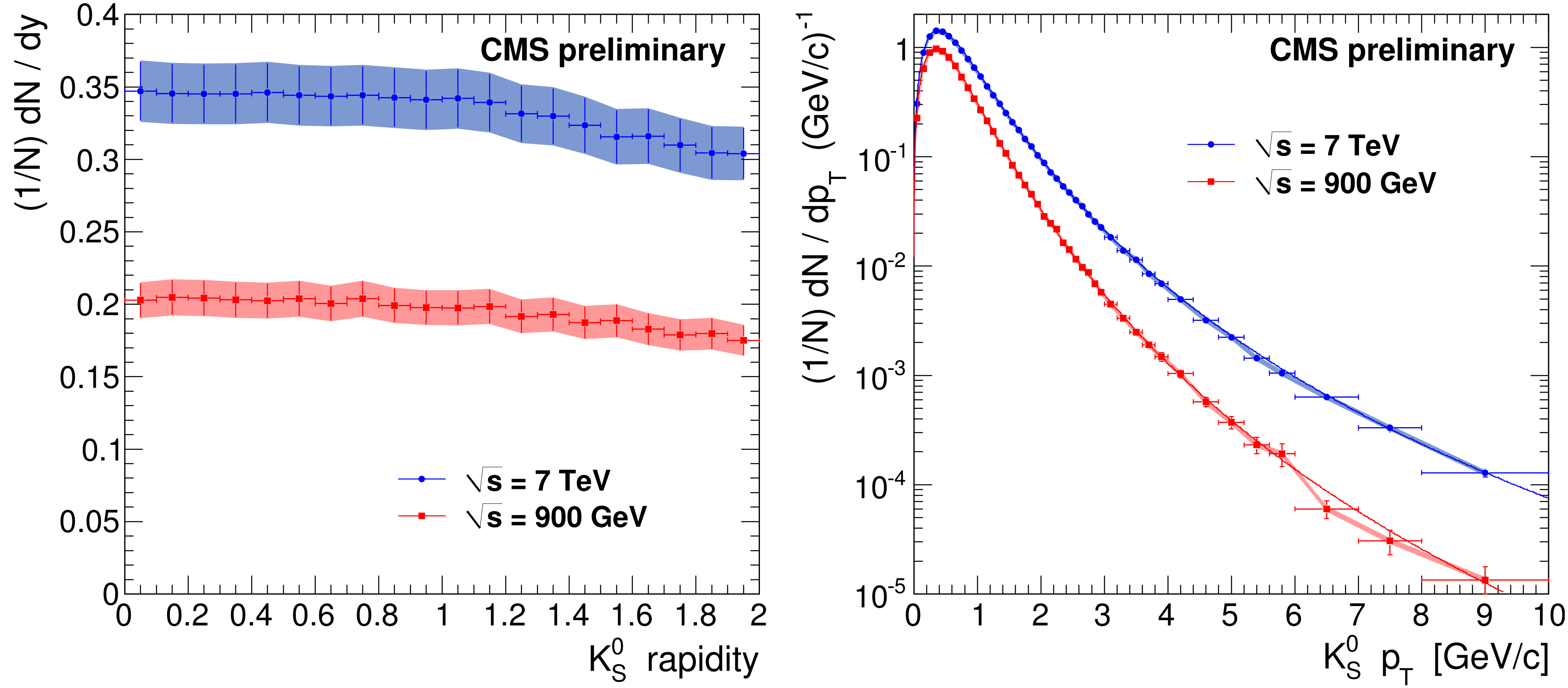
Spectra of strange hadrons



- Analysis
  - Reconstruction with decay topology $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, $\overline{\Lambda} \to \overline{p}\pi^+$, $\Xi^- \to \Lambda\pi^-$, $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$
  - All results for $|y| < 2.0$
  - Reconstruction efficiencies are validated by lifetime measurements



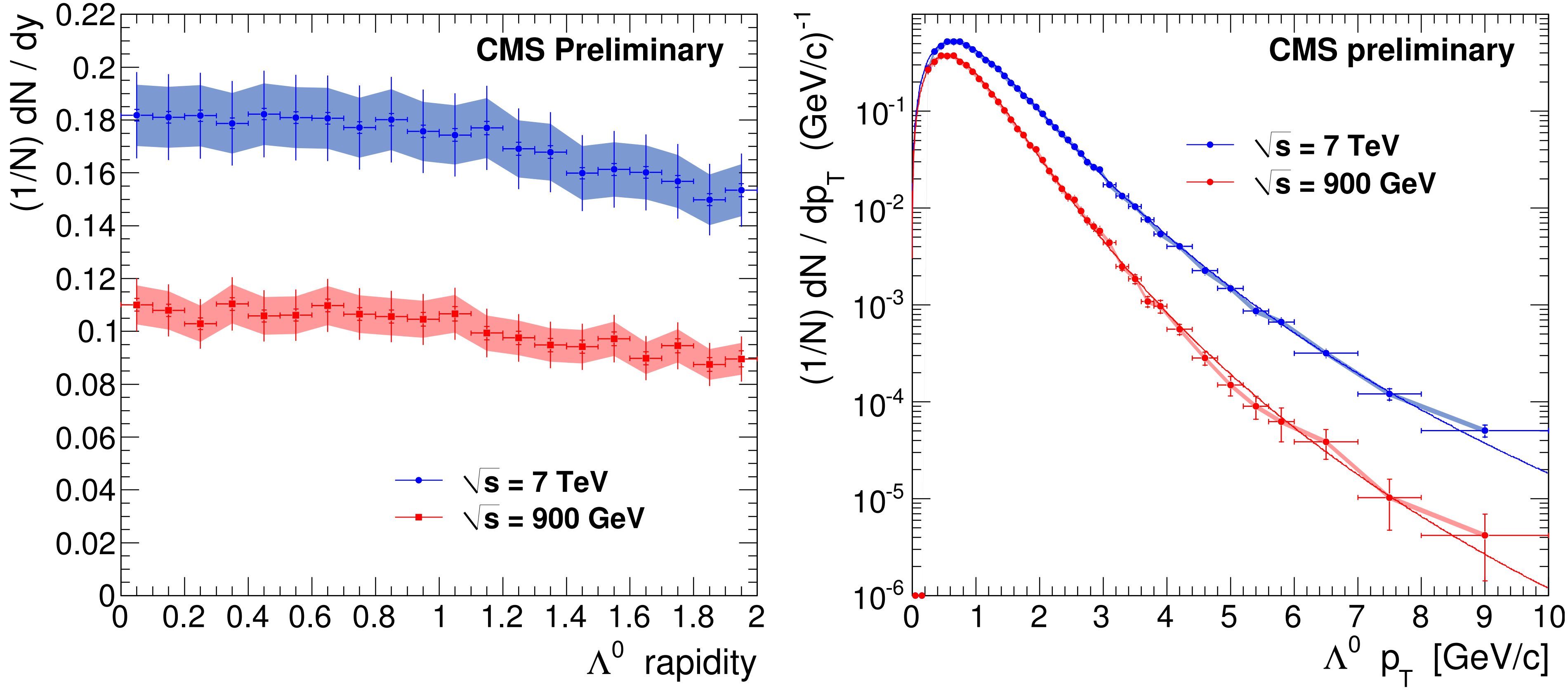
Spectra of strange hadrons – K^0_S



Two methods for cross-check

Fit in (y, p_T) bins or separately in y and p_T with re-weighted MC

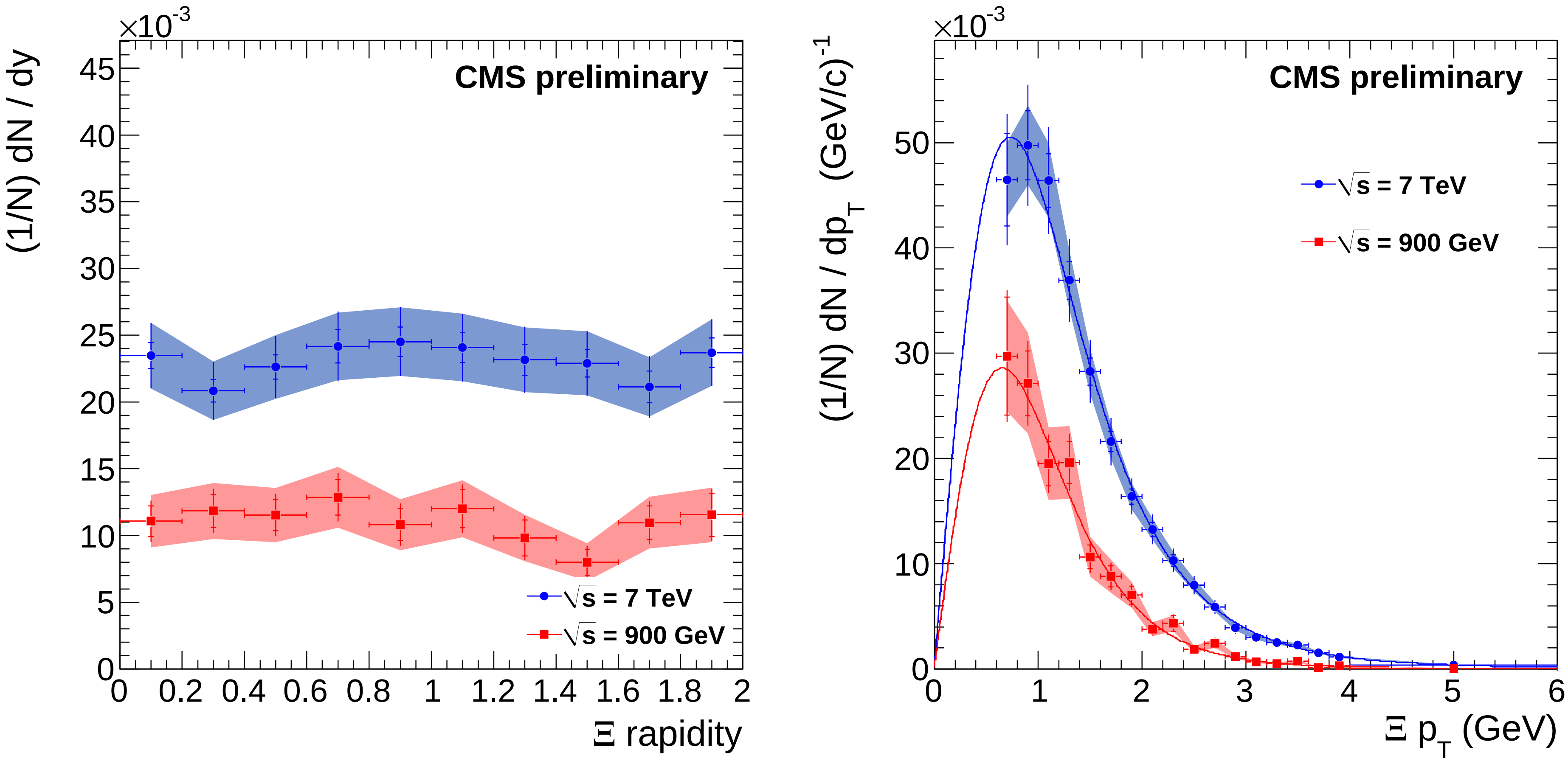
Spectra of strange hadrons – $\Lambda + \overline{\Lambda}$



Very good fits with a Tsallis-function

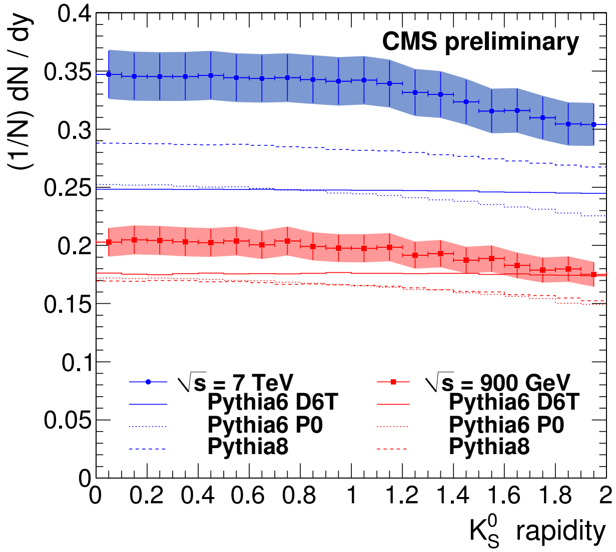
$$\frac{1}{N}\frac{dN}{dp_T} \propto p_T \left[1 + \frac{\sqrt{p_T^2+m^2}-m}{nT}\right]^{-n}$$

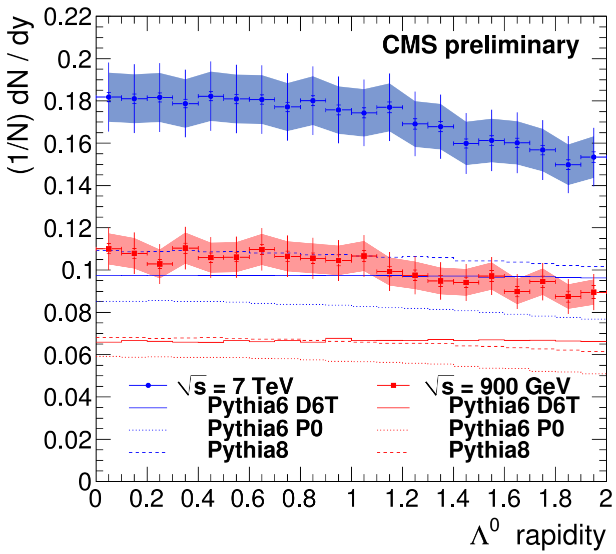
Spectra of strange hadrons – $\Xi^- + \overline{\Xi}^+$



Reasonable precision for Ξ, a challenge

Spectra of strange hadrons – models?

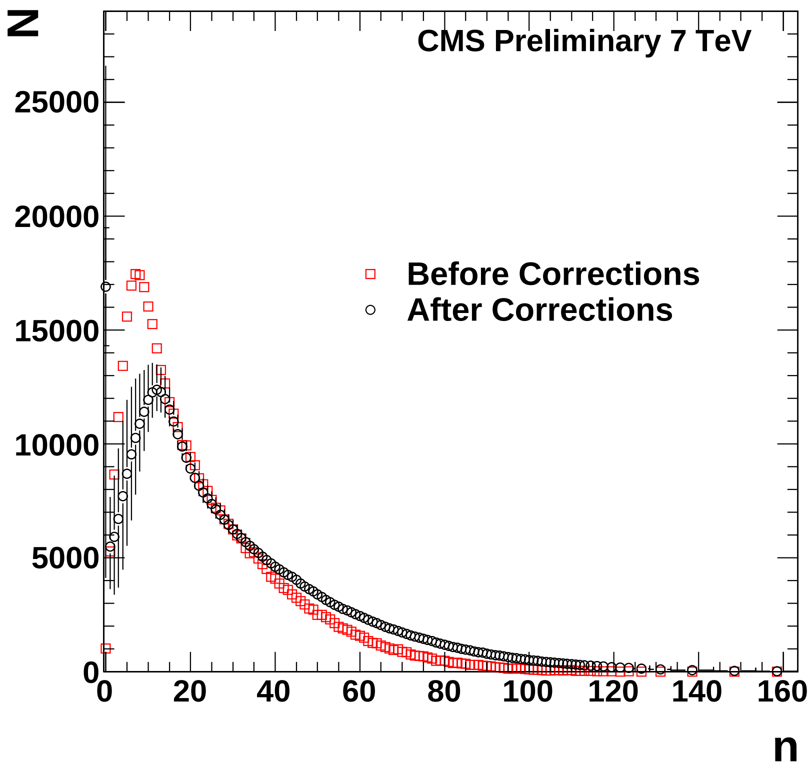




Particle	$\frac{\frac{dN}{dy}\|_{y=0}(\text{PYTHIA D6T})}{\frac{dN}{dy}\|_{y=0}(\text{Data})}$ 0.9 TeV	7 TeV
K^0_S	$0.87 \pm 0.01 \pm 0.07$	$0.72 \pm 0.01 \pm 0.06$
Λ^0	$0.60 \pm 0.01 \pm 0.07$	$0.54 \pm 0.01 \pm 0.06$
Ξ^-	$0.48 \pm 0.05 \pm 0.09$	$0.33 \pm 0.02 \pm 0.05$

- 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

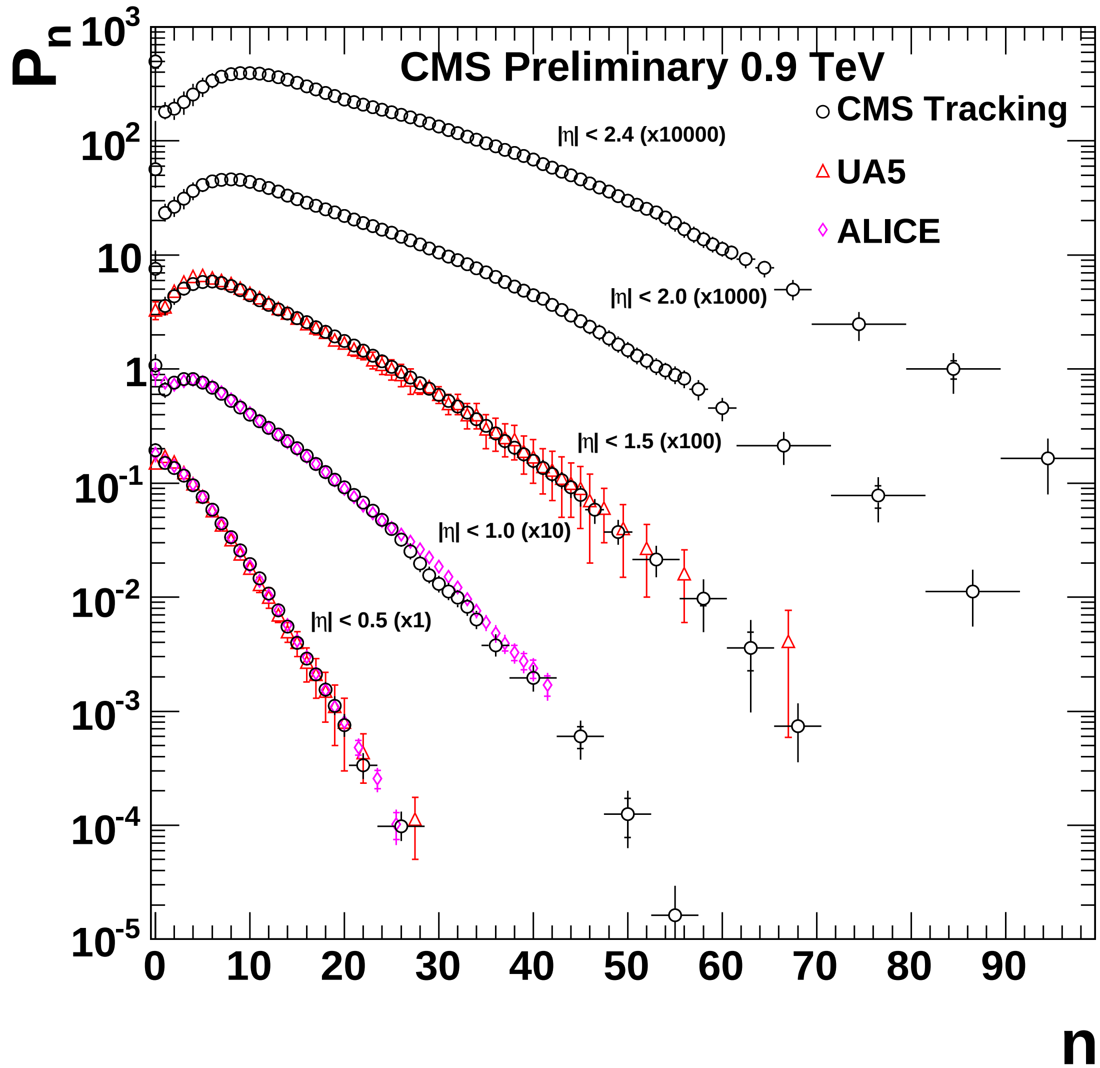
Event-by-event multiplicity



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

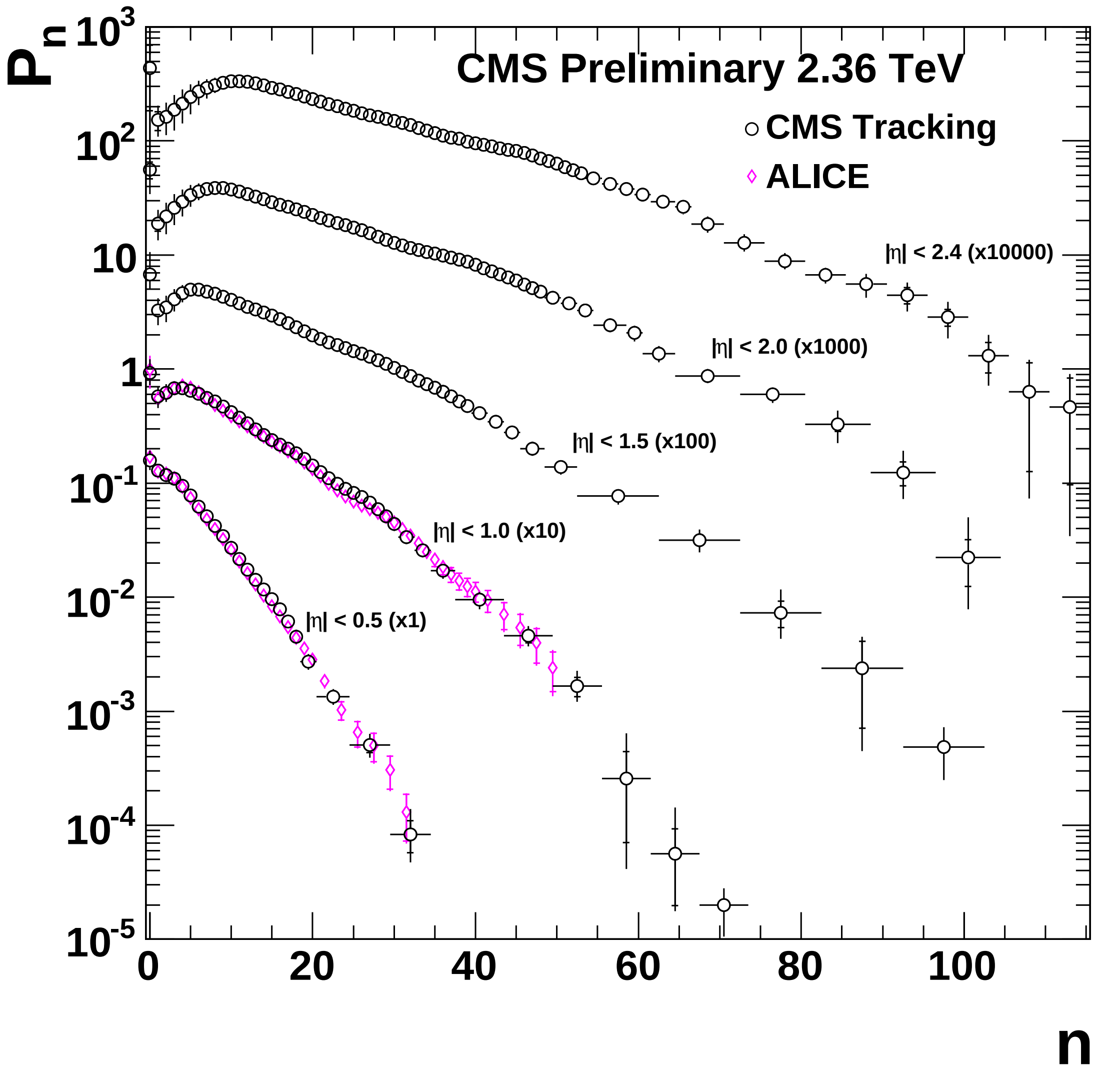
- Analysis
  - Events used: 132 k (0.9 TeV); 12 k (2.36 TeV); 442 k (7 TeV)
  - Full tracks, corrected to NSD events
  - True distribution is obtained from measured, after Bayesian unfolding

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



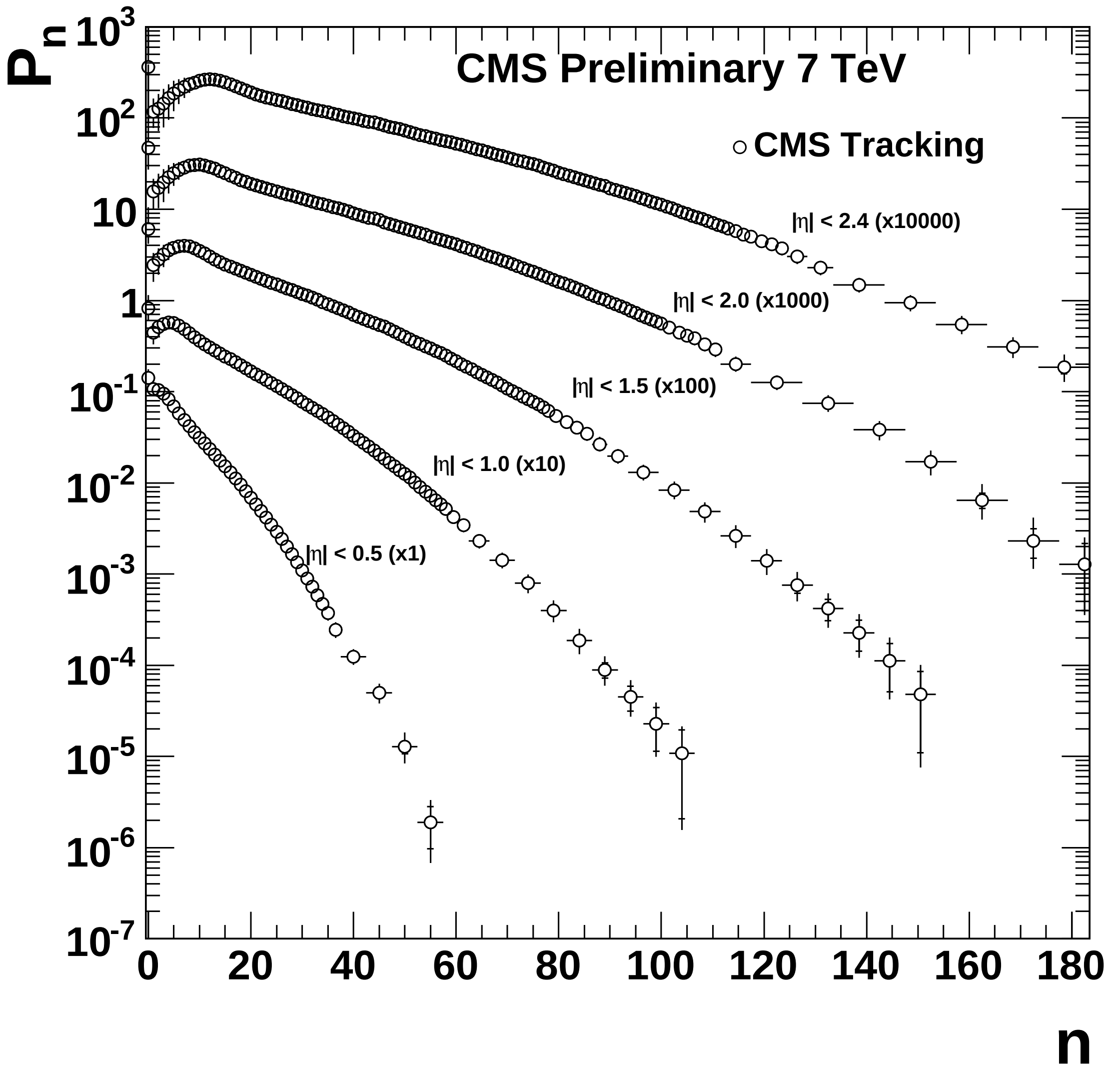
Nice match with UA5 and ALICE

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



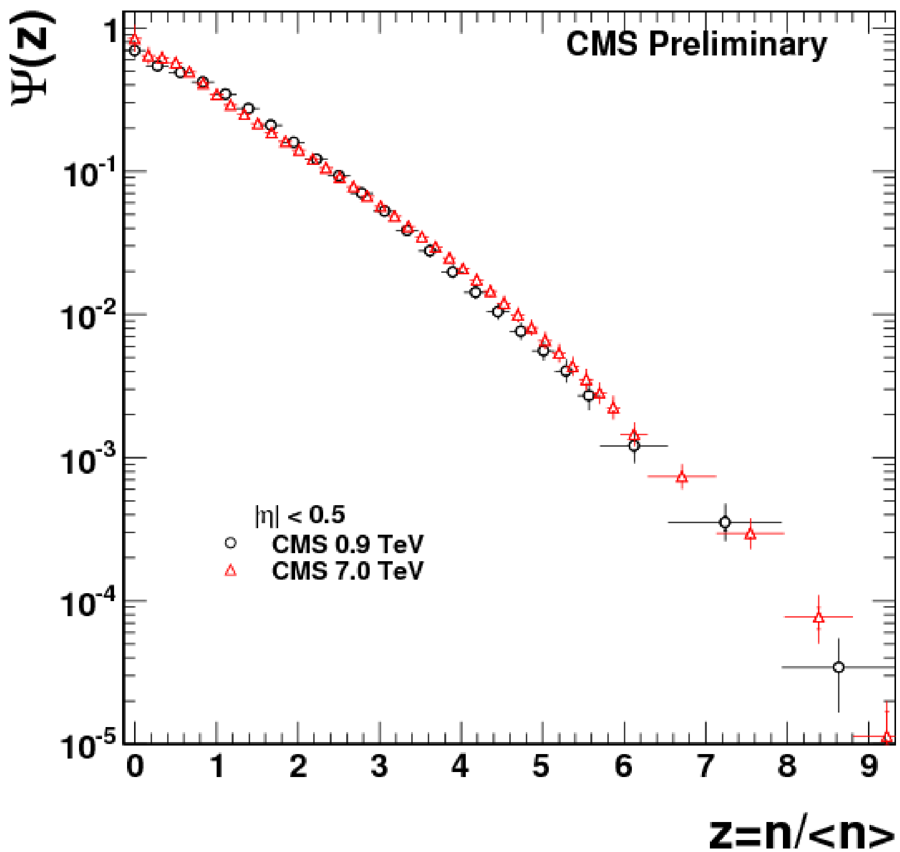
Nice match with ALICE

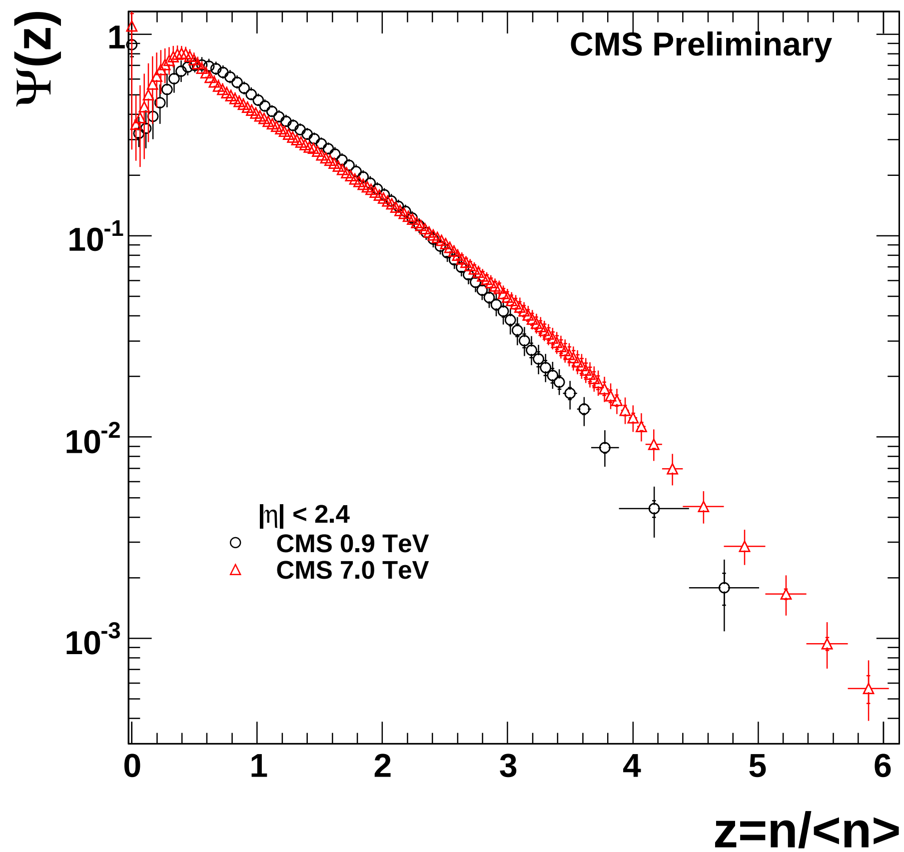
Event-by-event multiplicity – η bins – 7 TeV



Smooth distributions, no "waves" are seen

Event-by-event multiplicity – scaling?

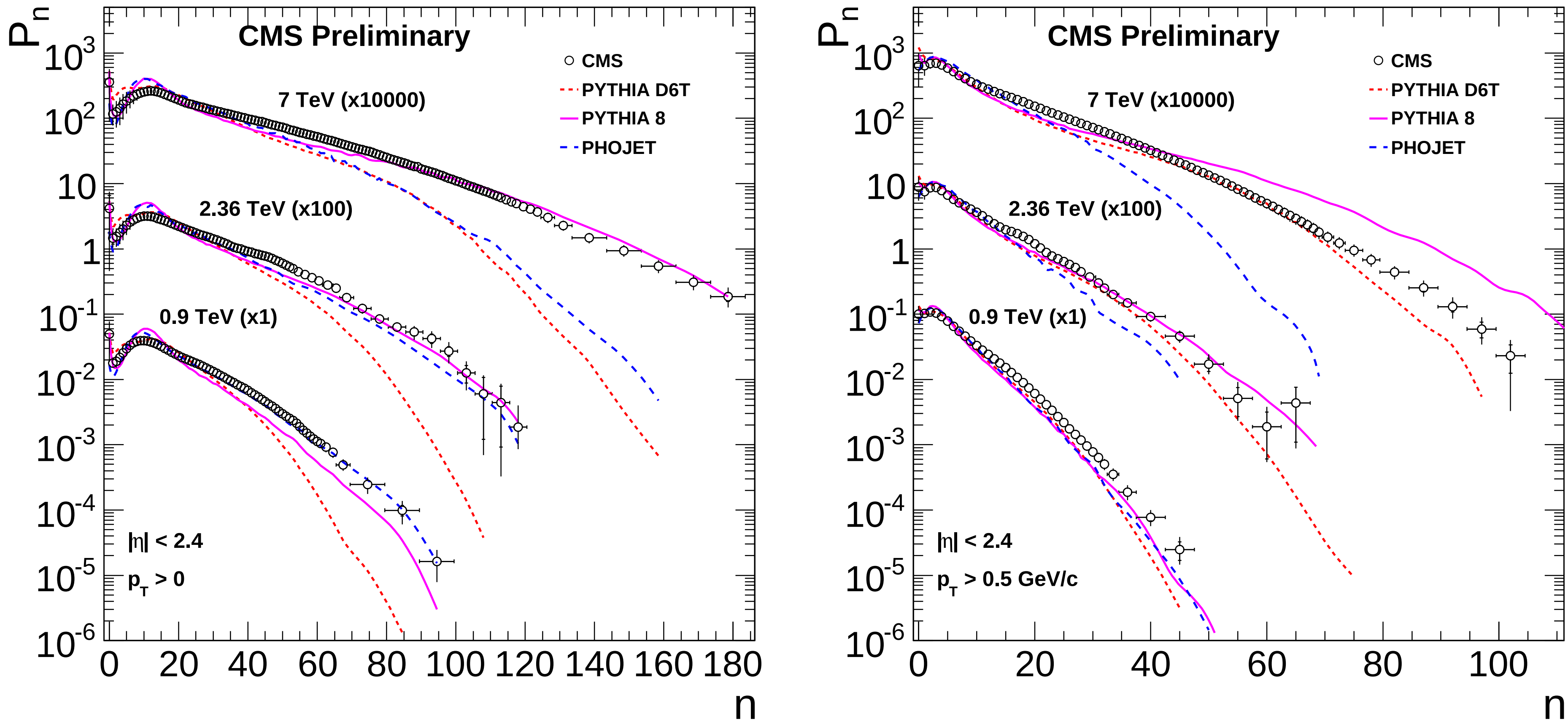




- KNO scaling
  - $\Psi(z) = \langle n \rangle P_n$ was shown to be independent of $\sqrt{s}$
  - True for $|\eta| < 0.4$, but it is violated for $|\eta| < 2.4$

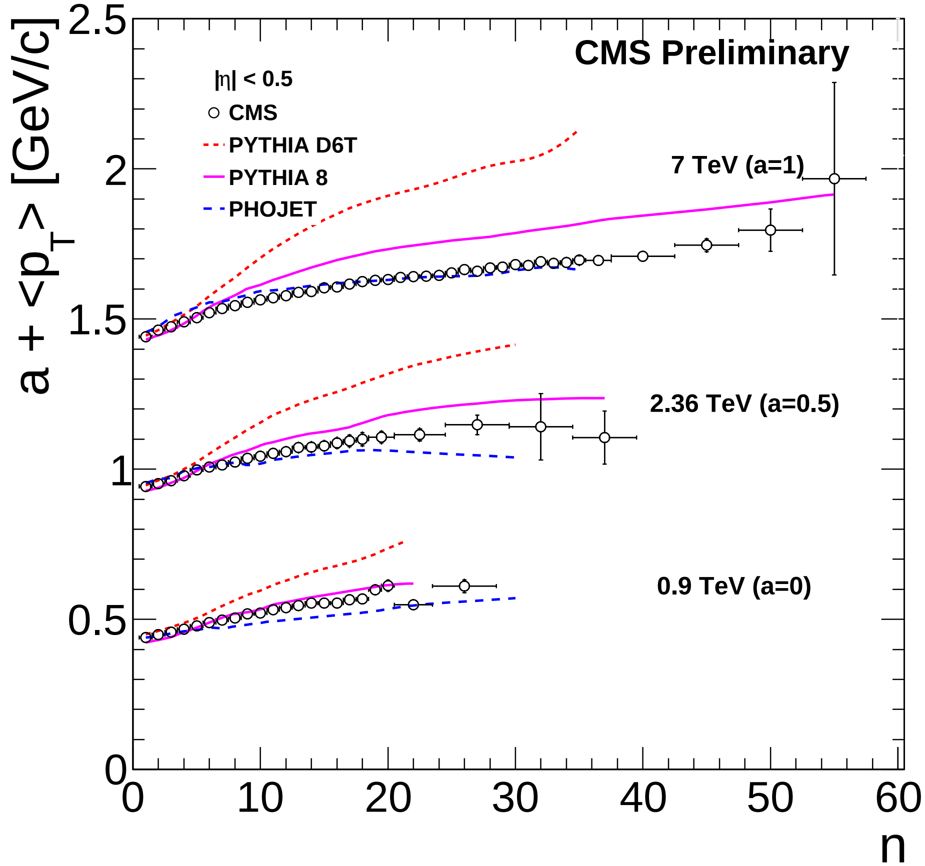
Large tail at high n is also seen in the steep rise of $\langle n \rangle$

Event-by-event multiplicity – models?



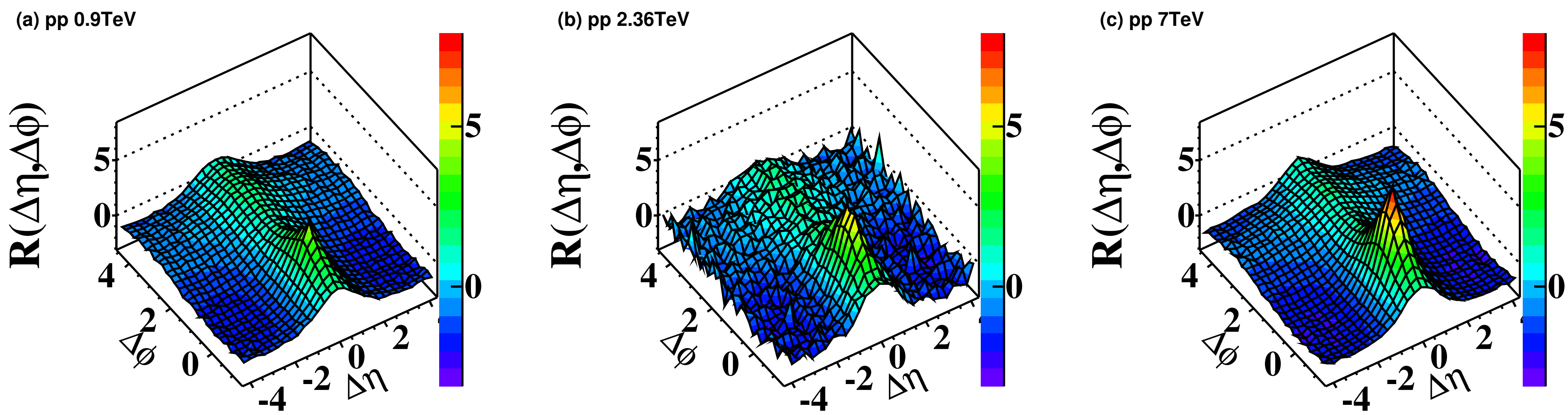
- Models
  - With varying success, no model gets everything right at 7 TeV
  - Pythia8 matches the total multiplicity,
    but predicts too many high p_T particles at large η

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



Difficult to match data with MC at all energies

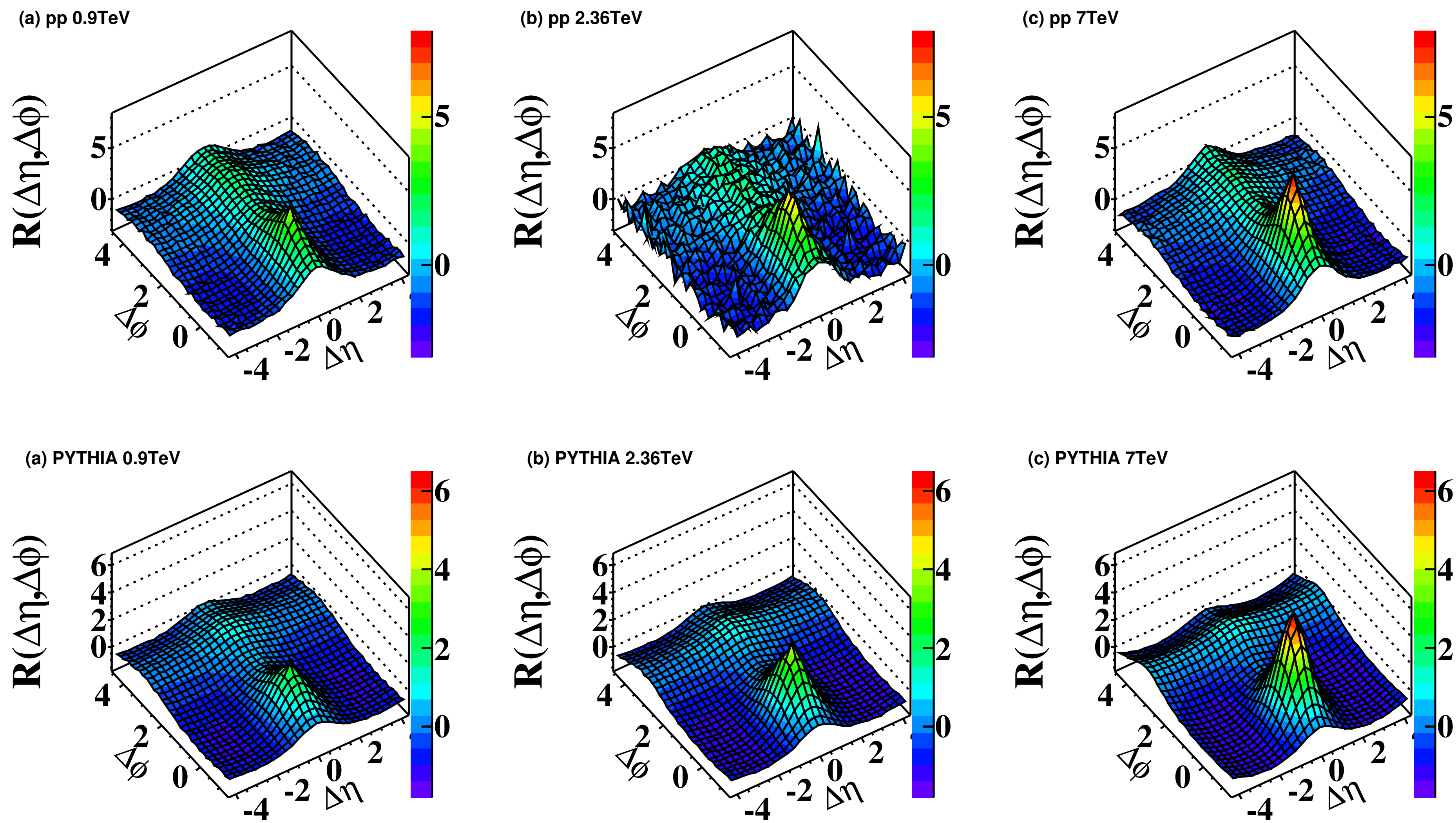
Hadron correlations – angular – data



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

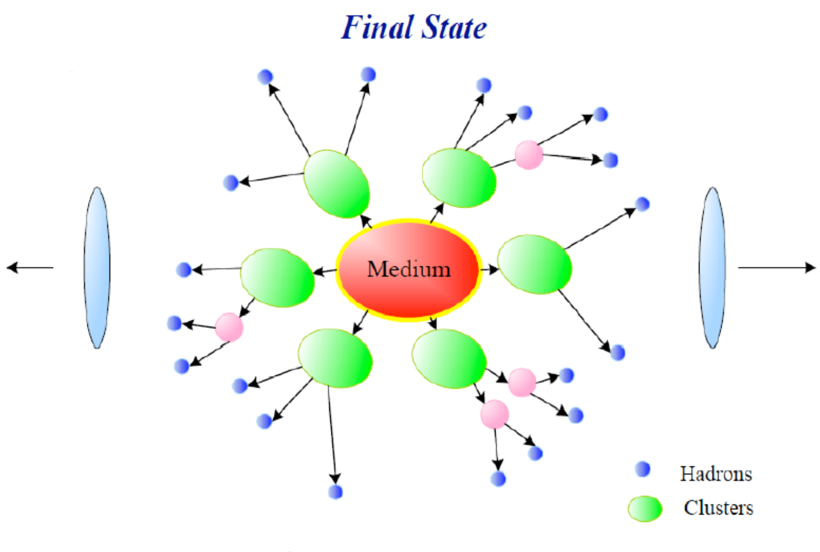
Gaussian in $\Delta\eta$, broader at large $\Delta\phi$

Hadron correlations – angular – models?



MC is qualitatively similar to data

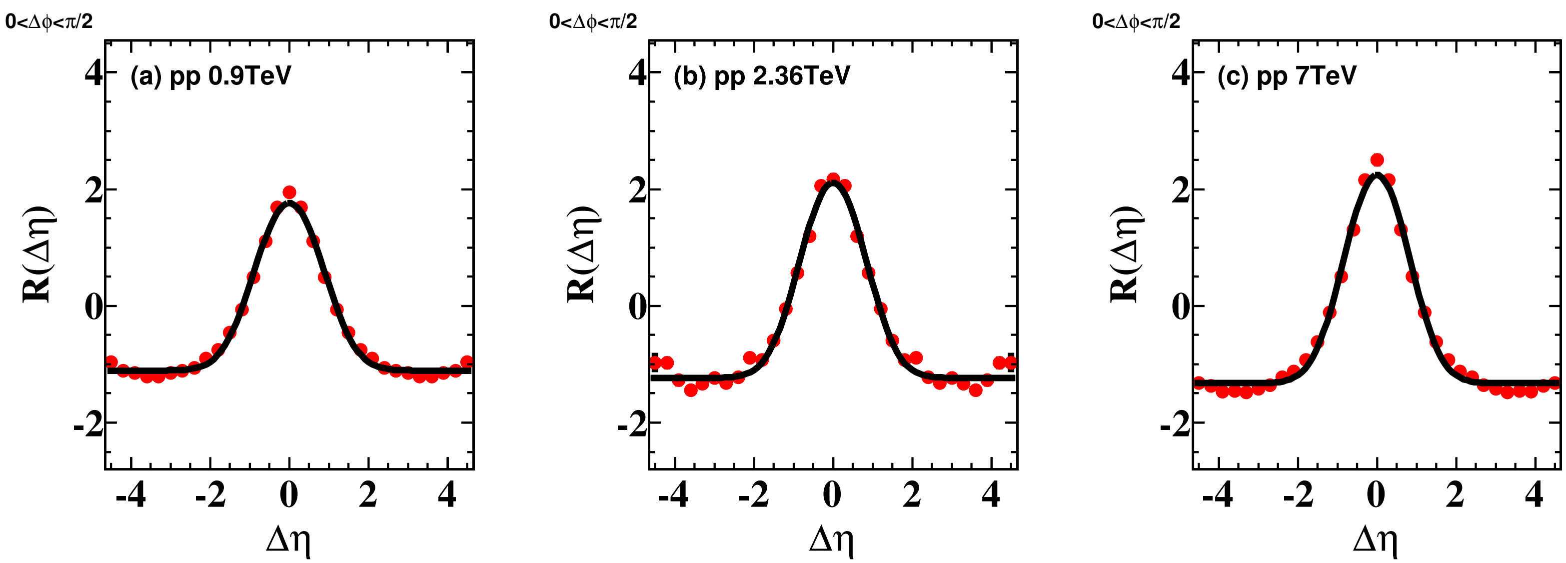
Hadron correlations – angular – a simple model



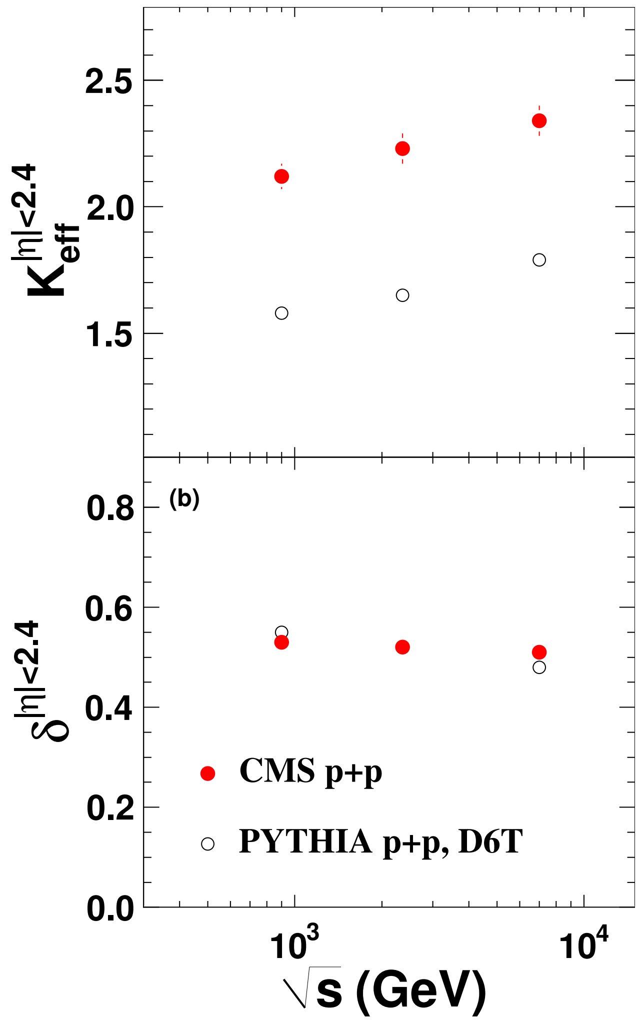
- Independent cluster model
  - Clusters are produced independently
  - They decay isotropically into hadrons
  - Only two parameters:
    cluster size K_{eff}, cluster width δ

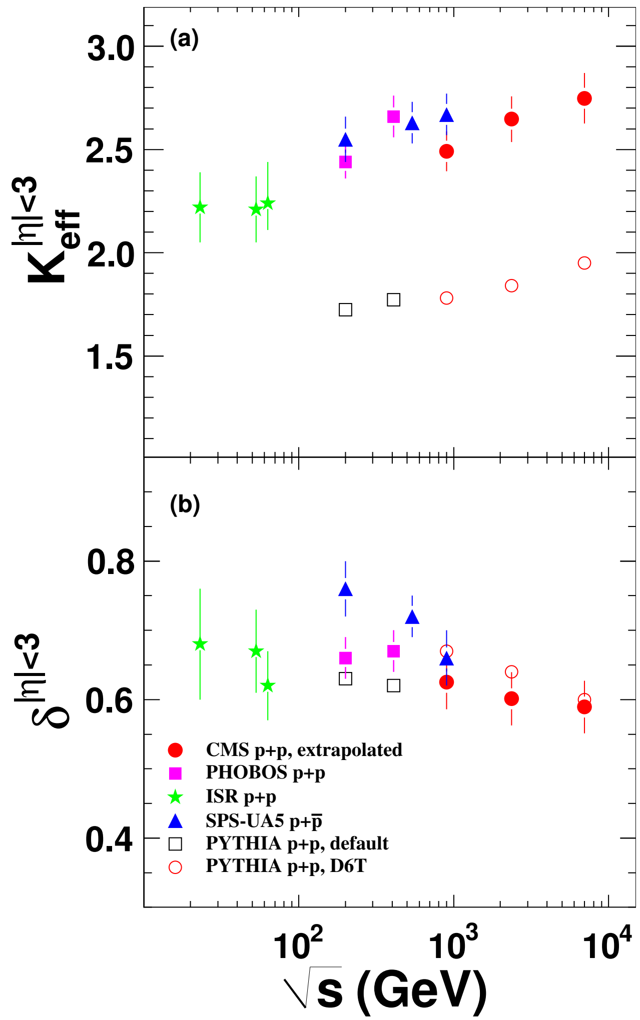
$$R(\Delta\eta) = (K_{eff} - 1)\left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1\right]$$

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



Hadron correlations – angular – $\sqrt{s}$ dependence

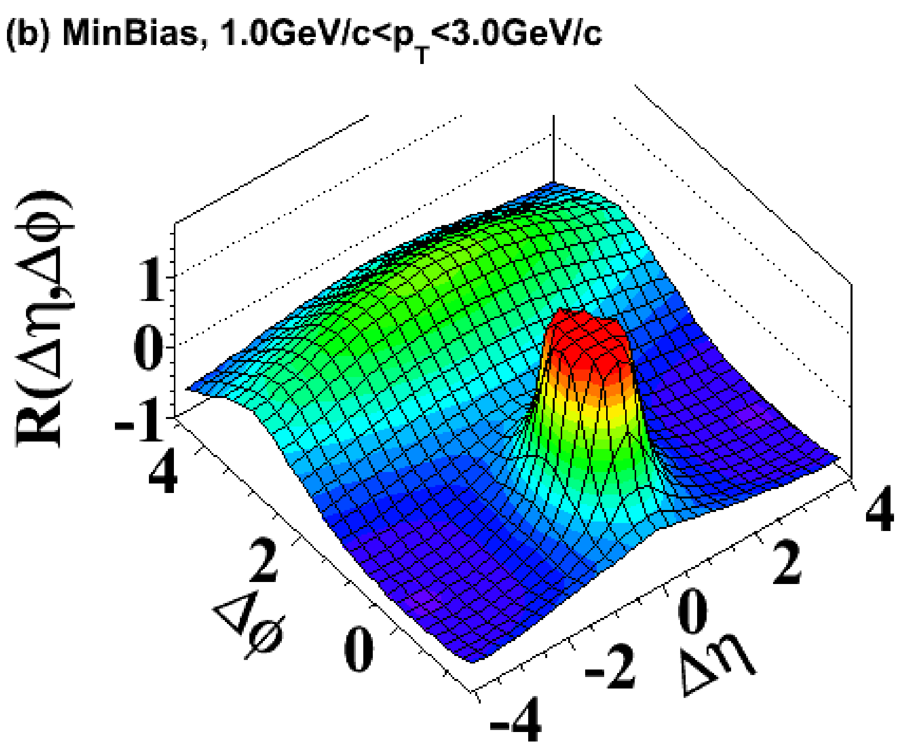


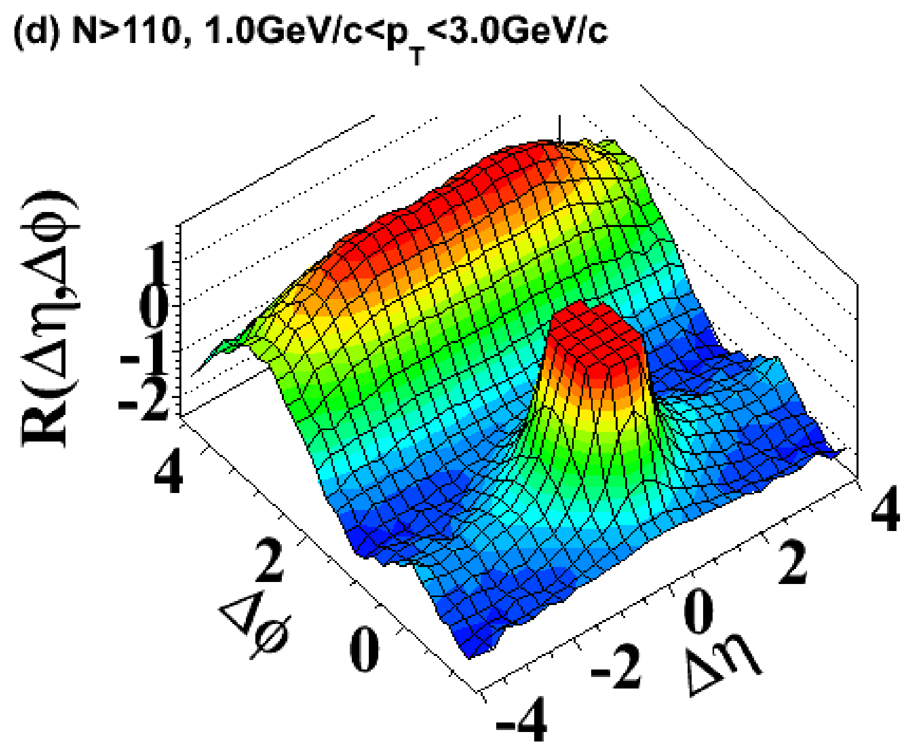


Results extrapolated to $p_T = 0$, compared to others

Pythia shows correct trend but smaller cluster size

Hadron correlations – multiplicity dependence





Pronounced new structure at large $\delta\eta$ at $\delta\phi \approx 0$

Effect is maximal in the $1 < p_T < 3$ GeV/c range

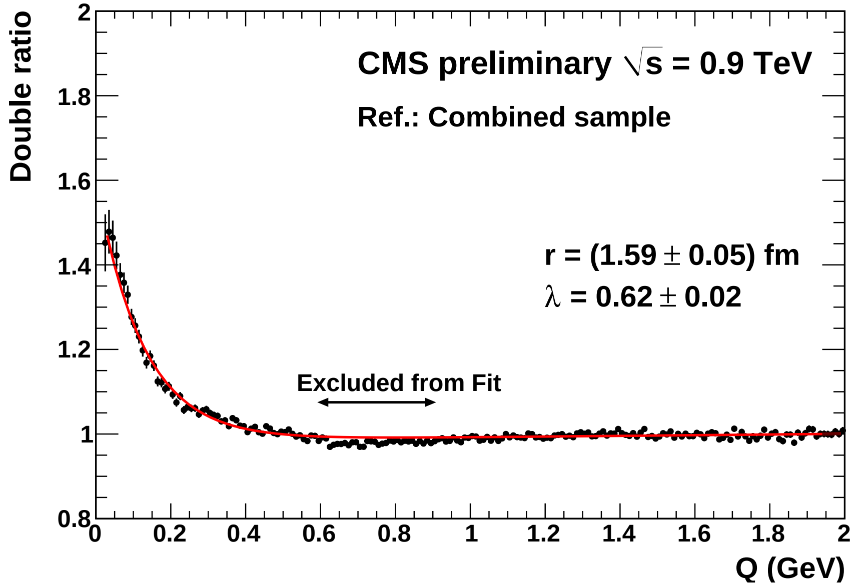
Hadron correlations – Bose-Einstein

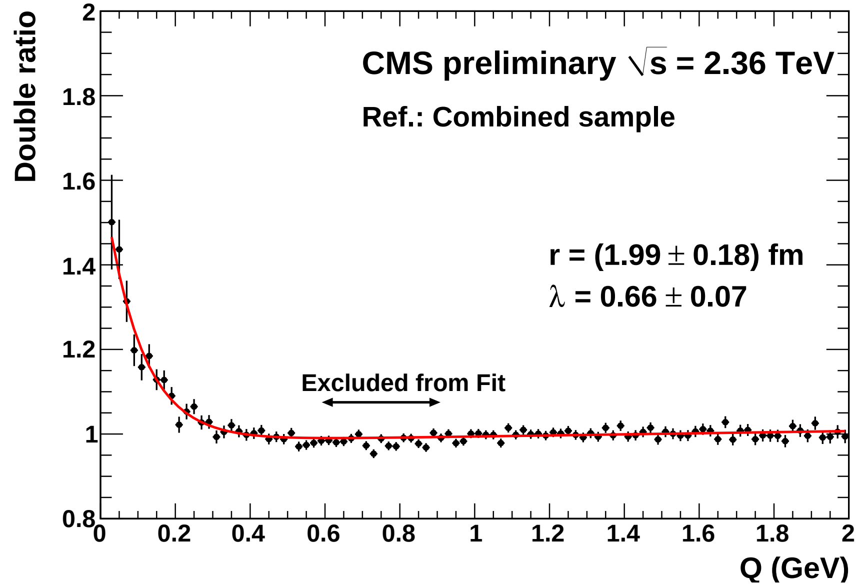
- Analysis
  - Correlation between identical bosons
  - The size of the correlated emission region can be inferred
  - What to measure? Difference of four-vectors, $Q = \sqrt{-(p_1 - p_2)^2}$
  - Parametrization
    $R(Q) = C\,[1 + \lambda\Omega(Qr)]\,(1 + \delta Q)$
    effective radius r, strength 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

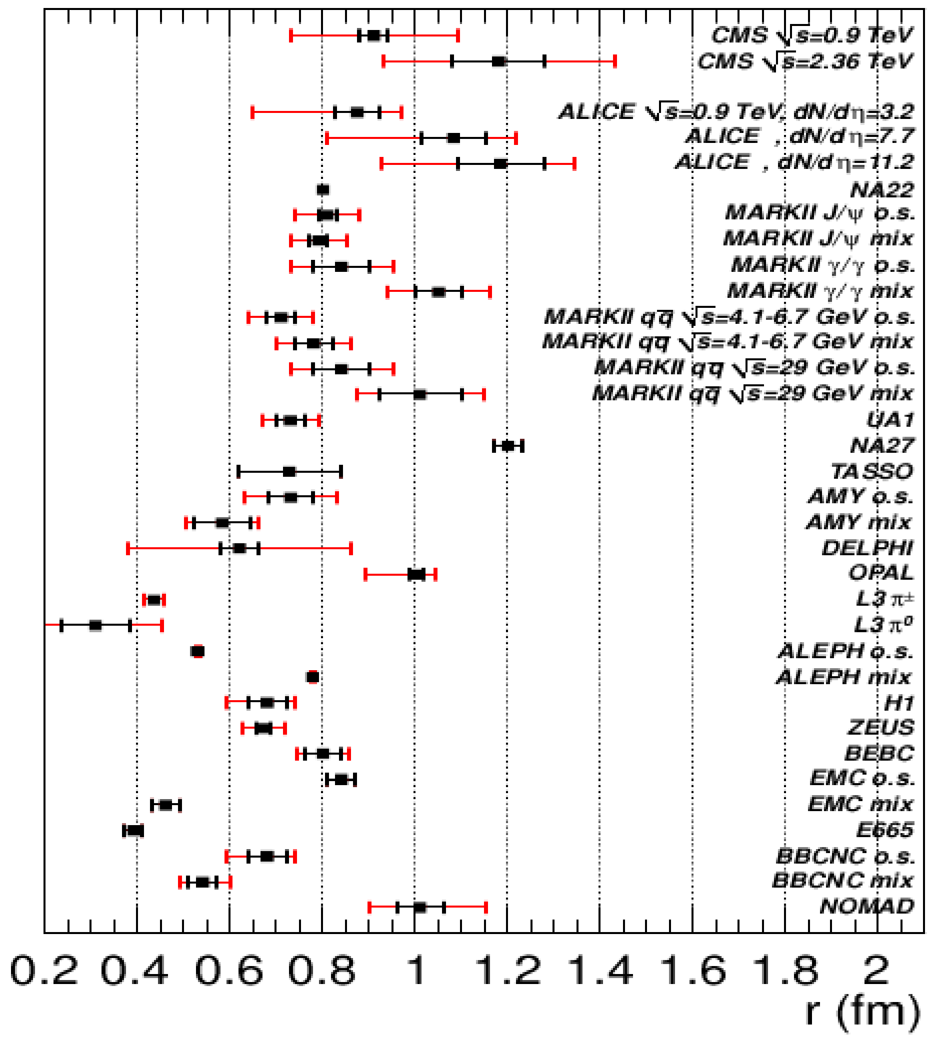




Ratio of signal and uncorrelated background distributions
Combined reference sample is used

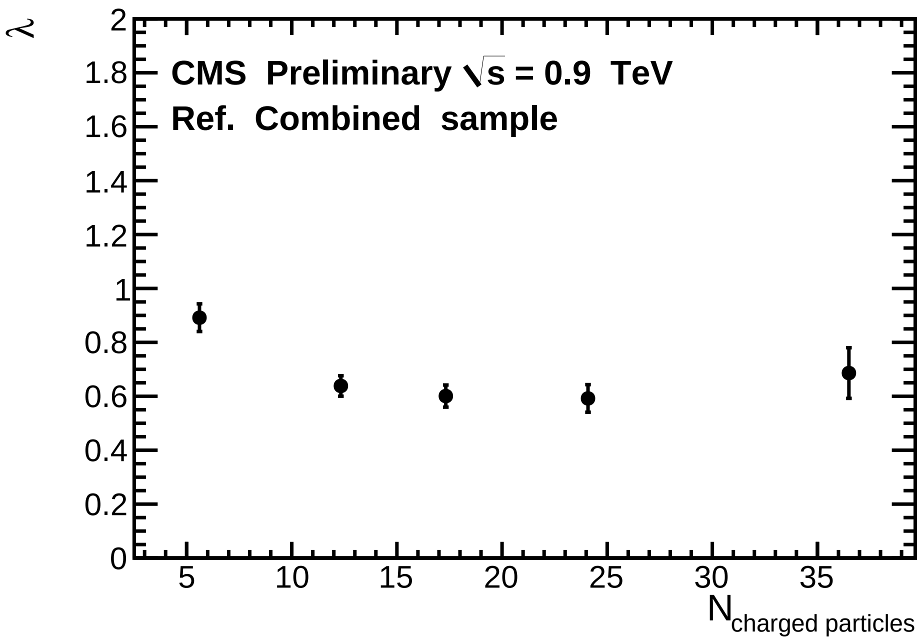
Exponential function is favored, $\Omega(Qr) = e^{-Qr}$

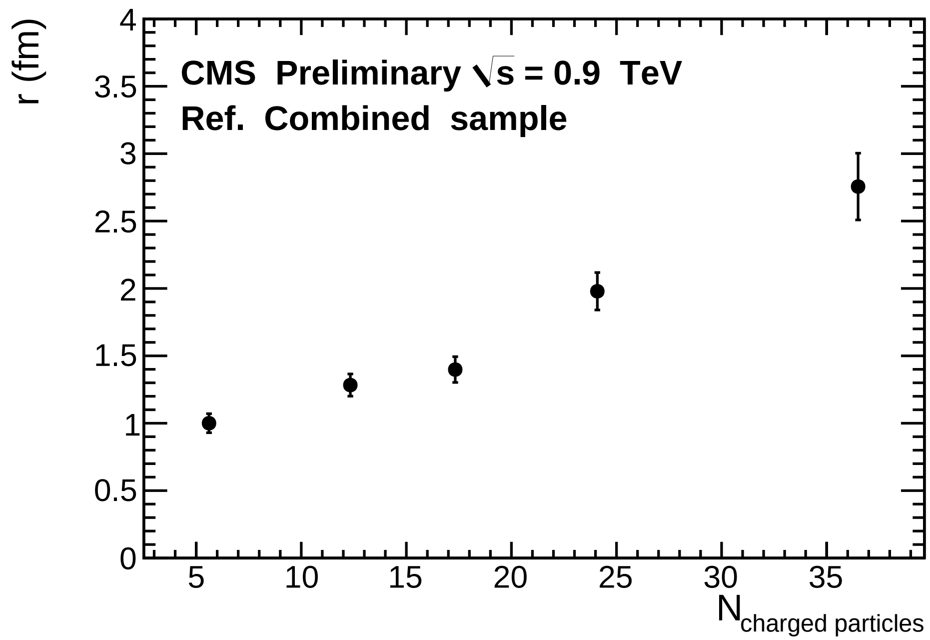
Hadron correlations – Bose-Einstein – others



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

Hadron correlations – Bose-Einstein

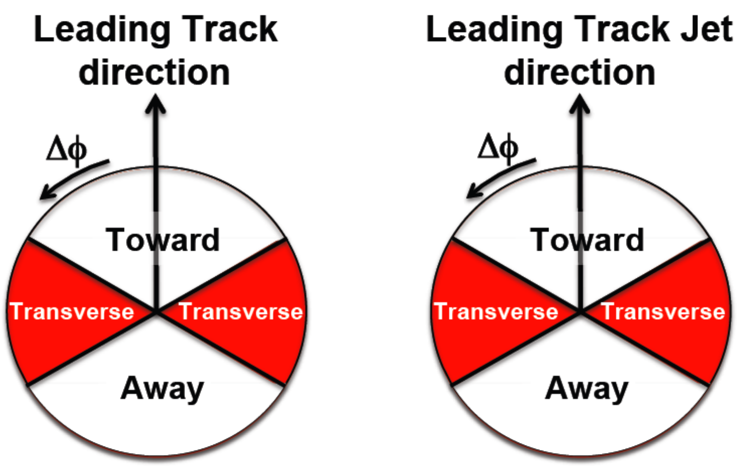


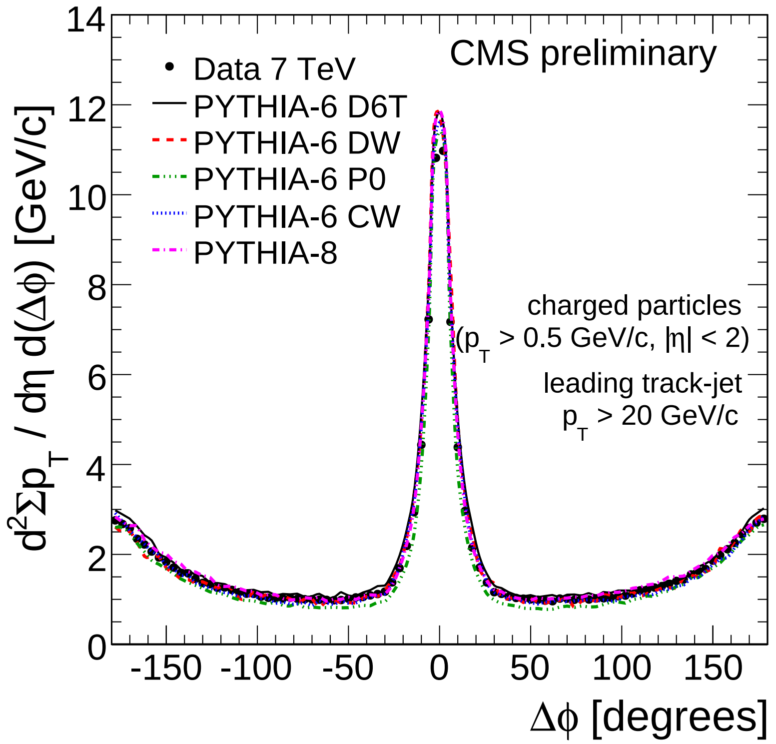


Radius clearly depends on charged particle multiplicity in the event

7 TeV result is also public soon

Underlying event

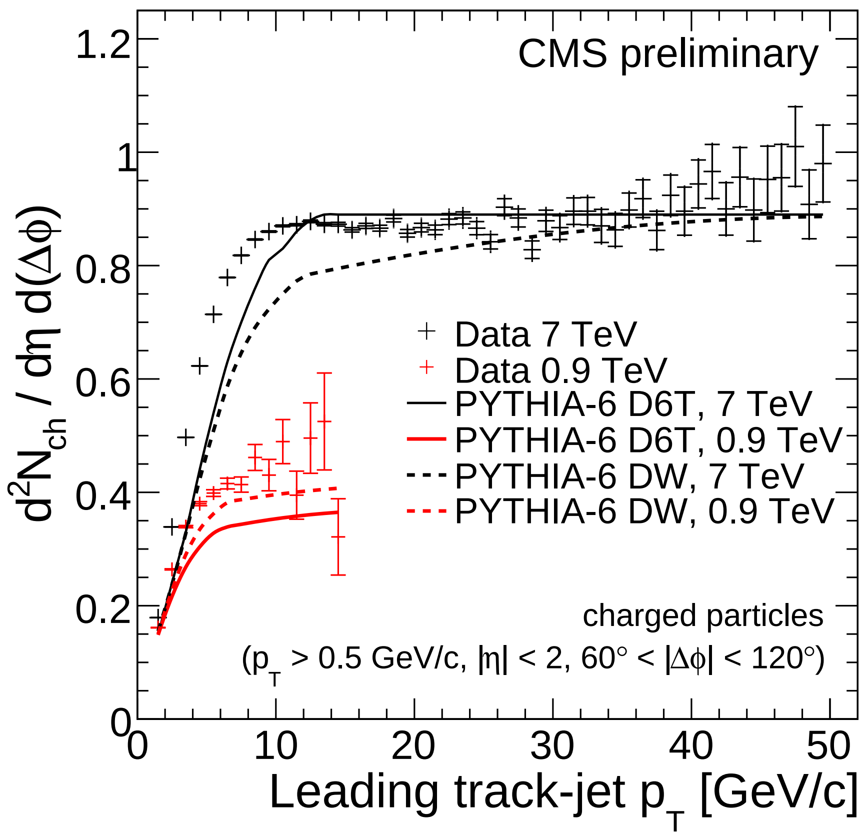


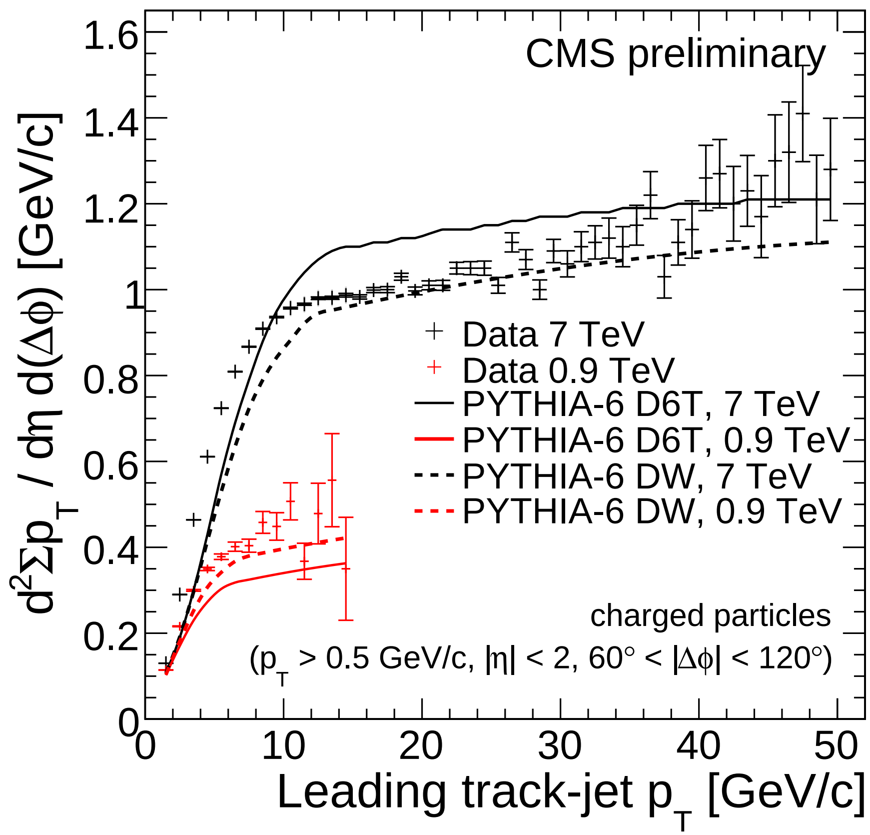


Look at particle production wrt to a high energy object (track or jet), mostly in transverse direction

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

Underlying event

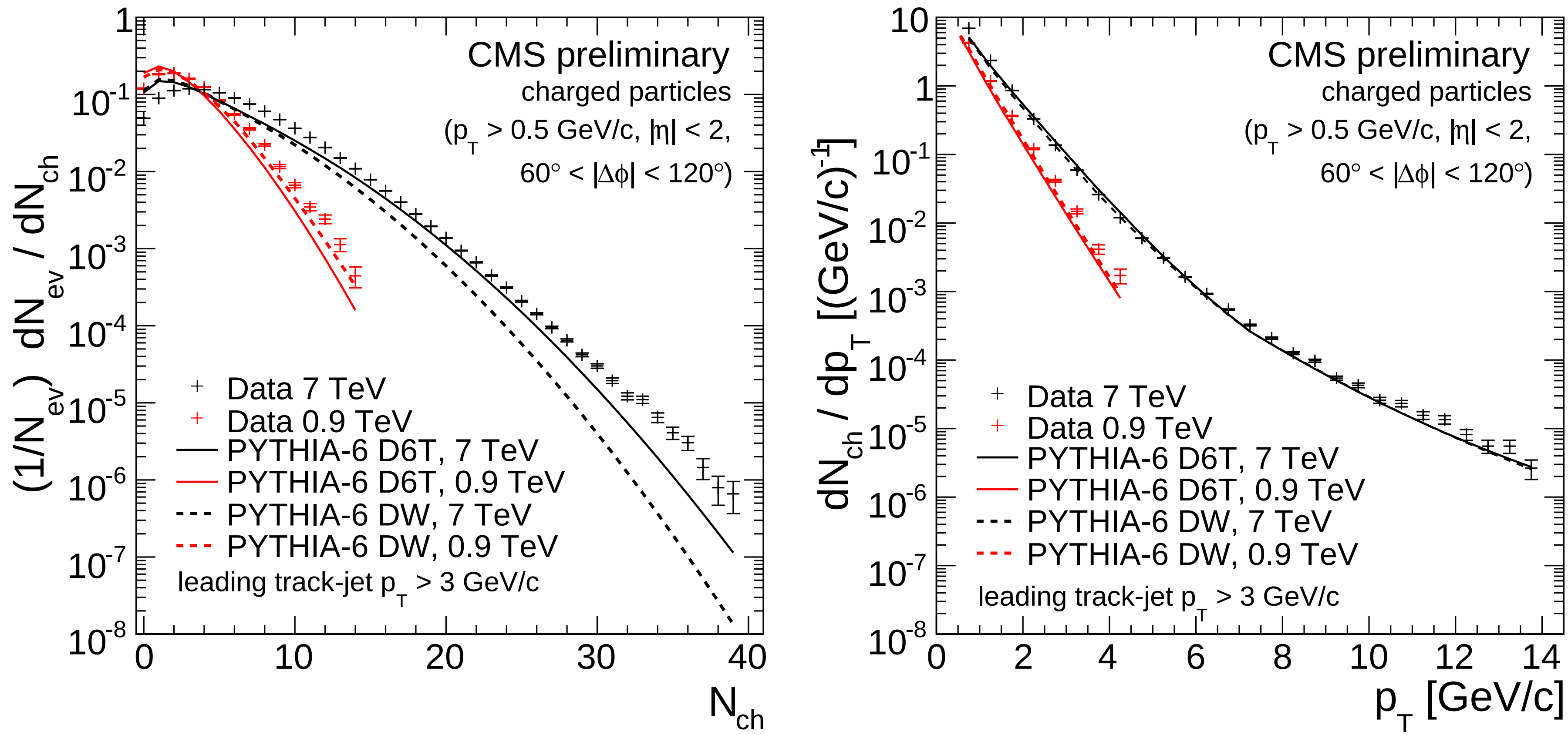




Uncorrected data, comparison to models

Particle densities, sum of p_T in the transverse region

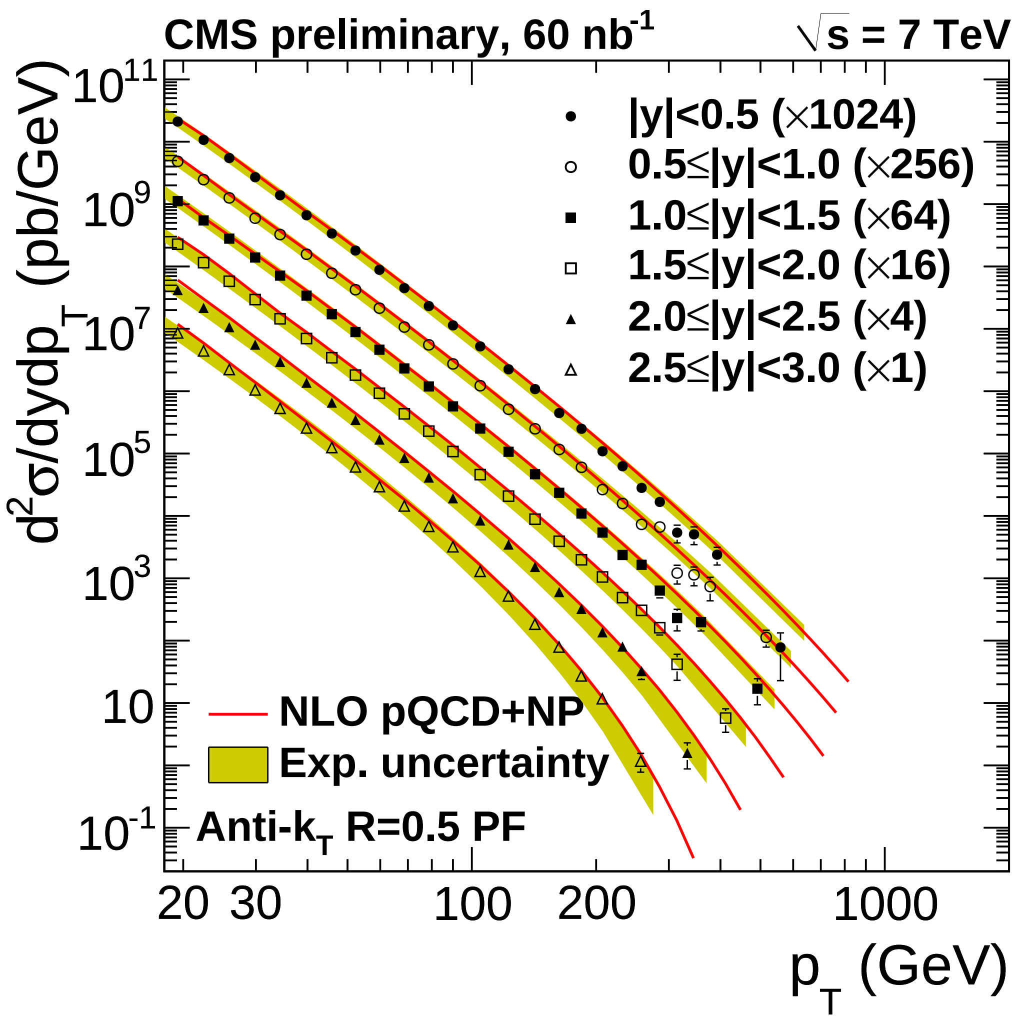
Underlying event



Uncorrected data, comparison to models

New Pythia tunes based on these and previous data

Jet spectra

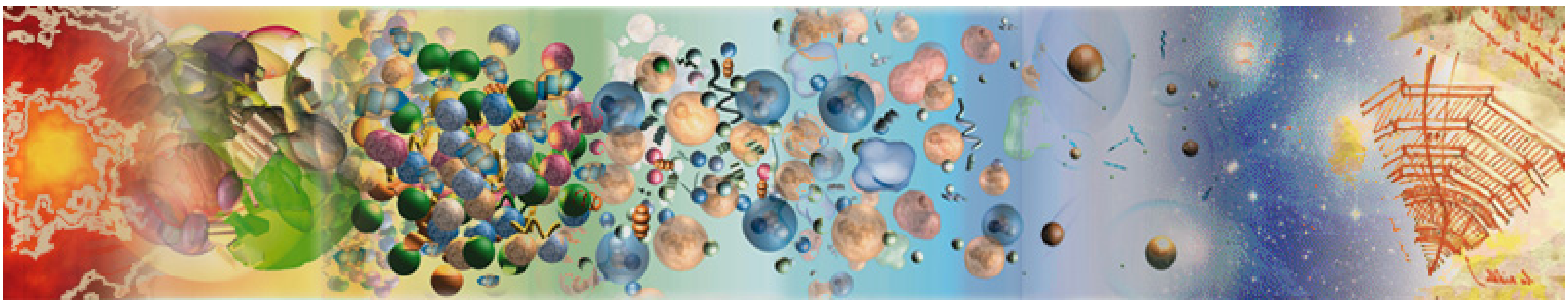


- Analysis
  - Three reconstruction methods: calorimeter, jet+tracks, particle flow
  - Inclusive jet spectra are in good agreement with NLO theory
  - Extending below 50 GeV thanks to novel reco algo
  - Extending up to $|y| < 3.0$
  - Low p_T reach limited from theory side by non-perturbative corrections

Past Tevatron published (0.7 fb^{-1}) record

Summary

- Performance
  - The detector works excellently
- Physics
  - Physics analyses and publications at 0.9, 2.36 TeV and 7 TeV, more to come
  - Already some surprises ⇐ Monday talk
  - Ongoing heavy-ion run ⇒ next talk
  - Move to 8 TeV next year, continuous running with short stops



Starting the long march, towards possible discoveries?

We could be there in two years