Hadron Production at CMS in pp Collisions at $\sqrt{s}$ = 0.9, 2.4 and 7.0 TeV

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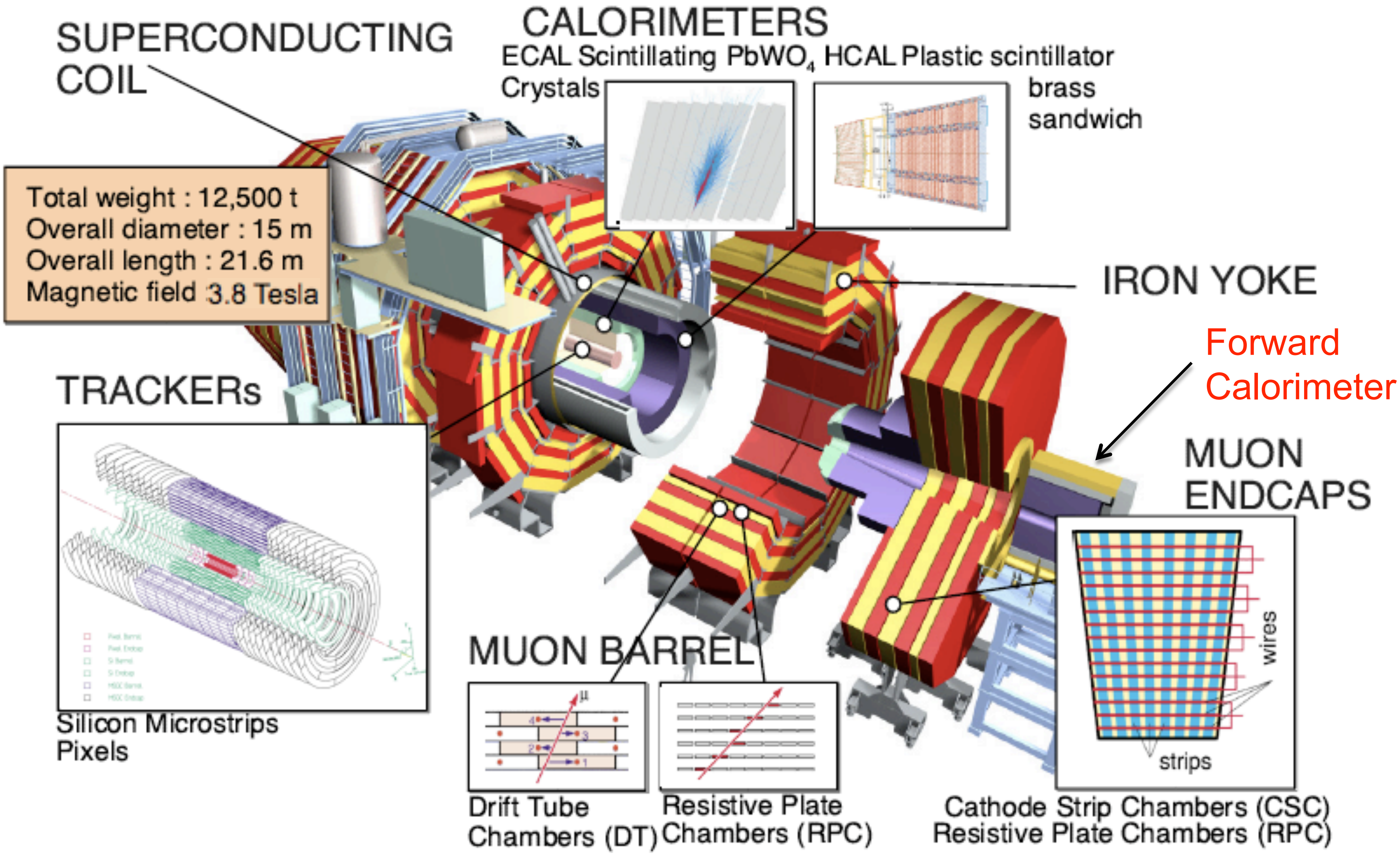
Motivation

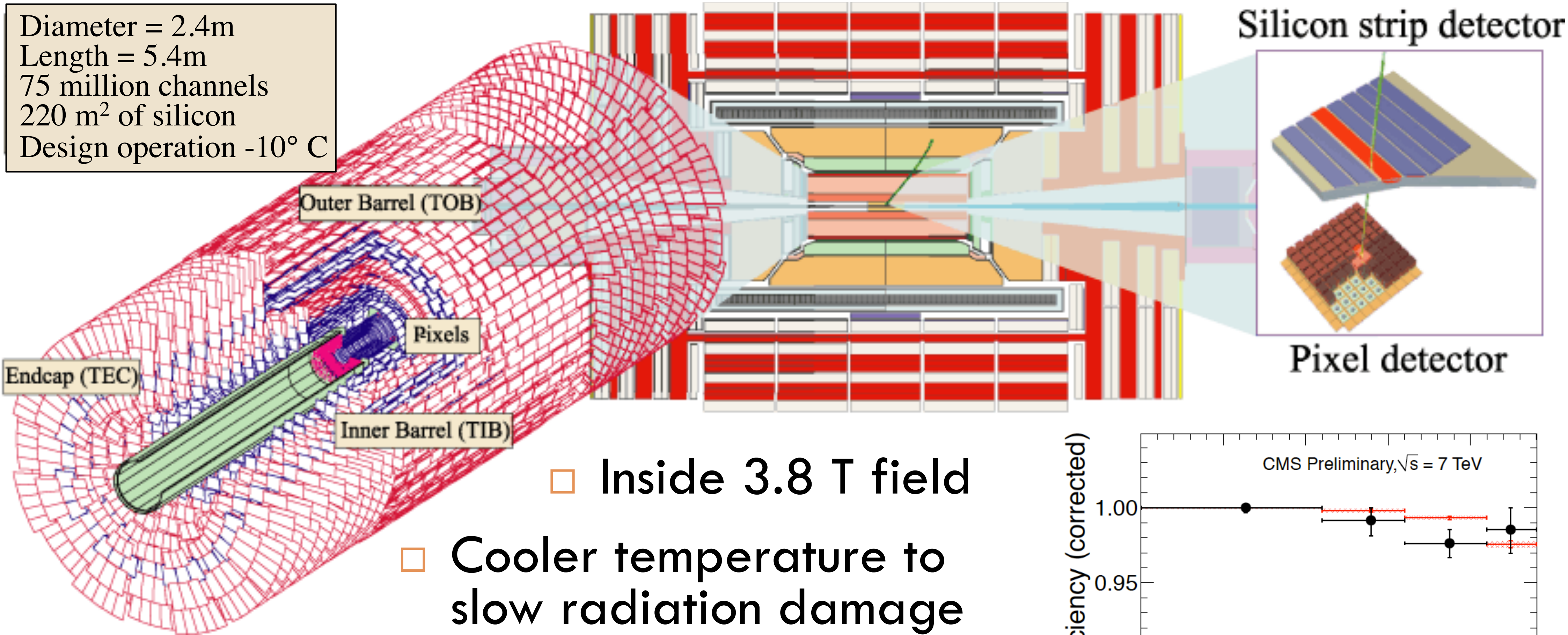
- Most LHC collisions are not hard interactions
  - Majority of particles produced with low transverse momentum
  - Particle production not always reliably calculable in QCD
- Soft hadron production is modeled phenomenologically
  - Experimental input is crucial for theoretical models
  - LHC opens up a new energy regime to test old models and develop new ones
- Must understand QCD processes well
  - Dominant backgrounds for many new physics searches
  - Provide reference for heavy ion results

The CMS detector

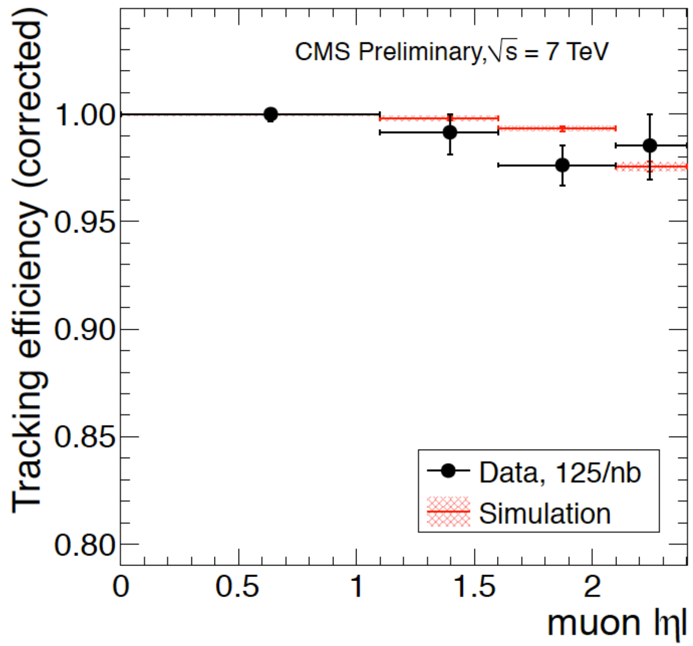


The CMS tracker

Diameter = 2.4m
Length = 5.4m
75 million channels
220 m^2 of silicon
Design operation -10° C

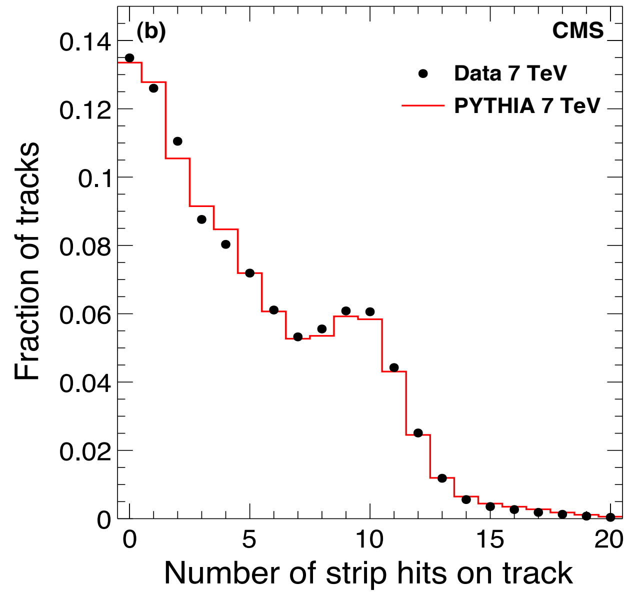


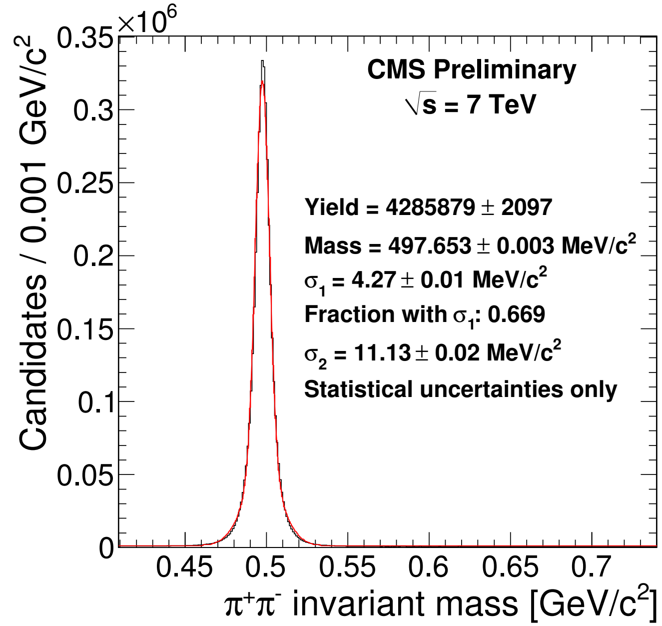
- Inside 3.8 T field
- Cooler temperature to slow radiation damage
- Coverage up to $|\eta| < 2.4$ with ≥3 pixel hits and ≥10 strip hits
- Efficiency >99% for central muons



Outline of physics results

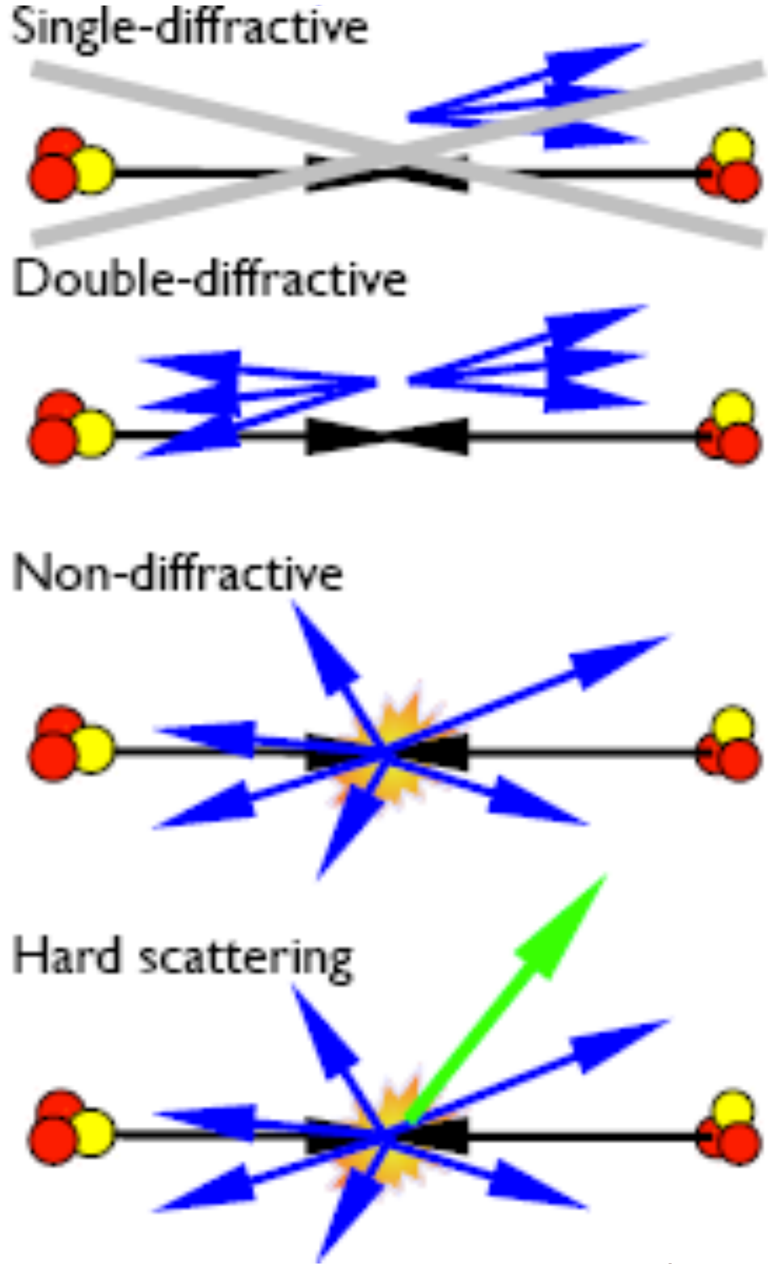
- Charged hadron production rate vs η and p_T and $\langle p_T \rangle$
  - JHEP 02:041, 2010 (at $\sqrt{s}$ = 0.9 and 2.36 TeV)
  - PRL 105:022002, 2010 (at $\sqrt{s}$ = 7.0 TeV)
- Charged hadron multiplicity at $\sqrt{s}$ = 0.9, 2.36, and 7.0 TeV
  - CMS-PAS-QCD-10-004 http://cdsweb.cern.ch/record/1279343?ln=en
- Strange particle production rates vs y and p_T and $\langle p_T \rangle$ at $\sqrt{s}$ = 0.9 and 7.0 TeV
  - CMS-PAS-QCD-10-007 http://cdsweb.cern.ch/record/1279344?ln=en





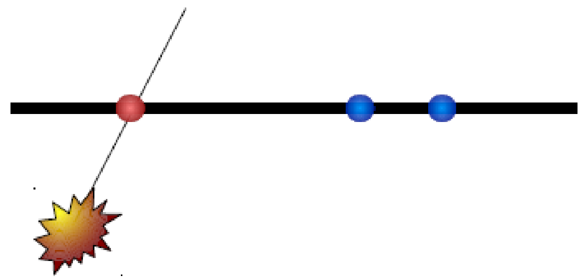
Trigger and event selection

- Results presented are normalized to non-single-diffractive events (NSD)
  - Trigger on signal in scintillation counters consistent with pp collision from coincident beams
  - Select events with
    - Forward calorimeter cluster with E ≥ 3 GeV on both sides (2.9<|η|<5.2)
    - Reconstructed primary vertex
  - Reject beam halo and beam background events
- Correct for trigger inefficiencies and SD contributions from MC simulation

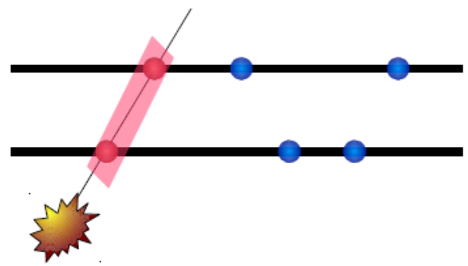


3 methods for finding charged tracks

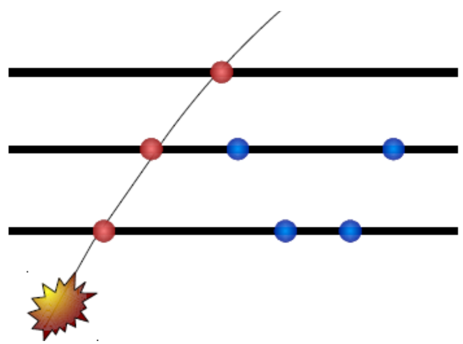
- Consistency of 3 different methods ensures robustness of results
  - Counting barrel pixel clusters
    - Efficient for $p_T \geq 30$ MeV/c
    - Insensitive to misalignment



  - Count 2-hit barrel pixel tracklets
    - Efficient for $p_T \geq 50$ MeV/c
    - Less sensitive to beam backgrounds



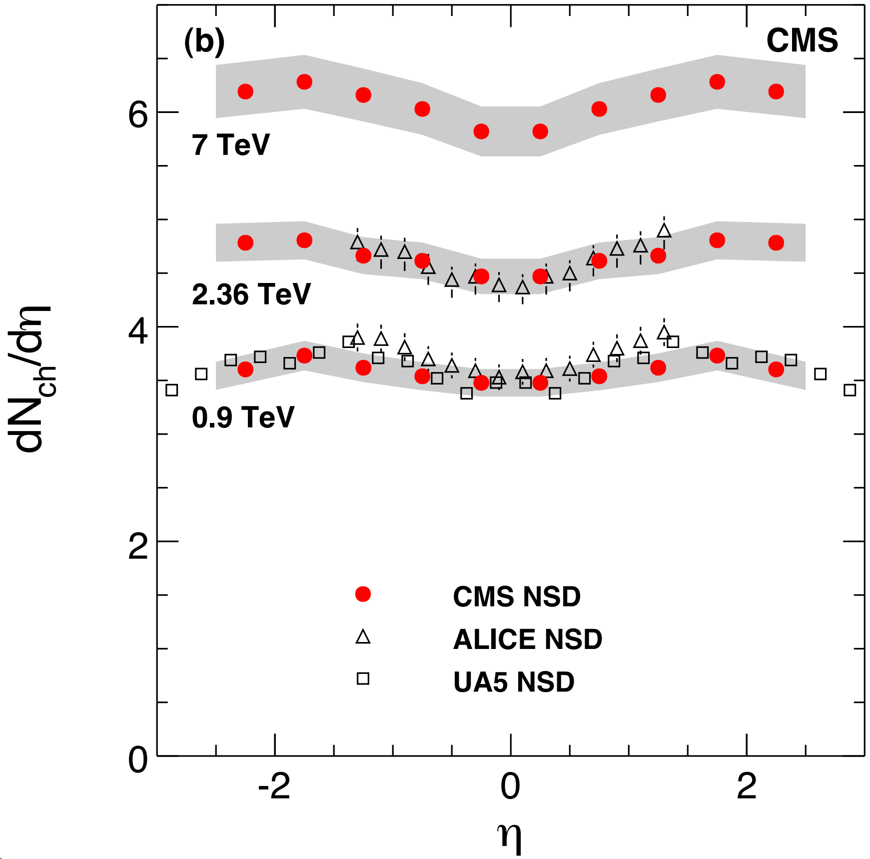
  - Full tracking (pixels + strips)
    - Efficient for $p_T \geq 100$ MeV/c
    - Also provides p_T measurement

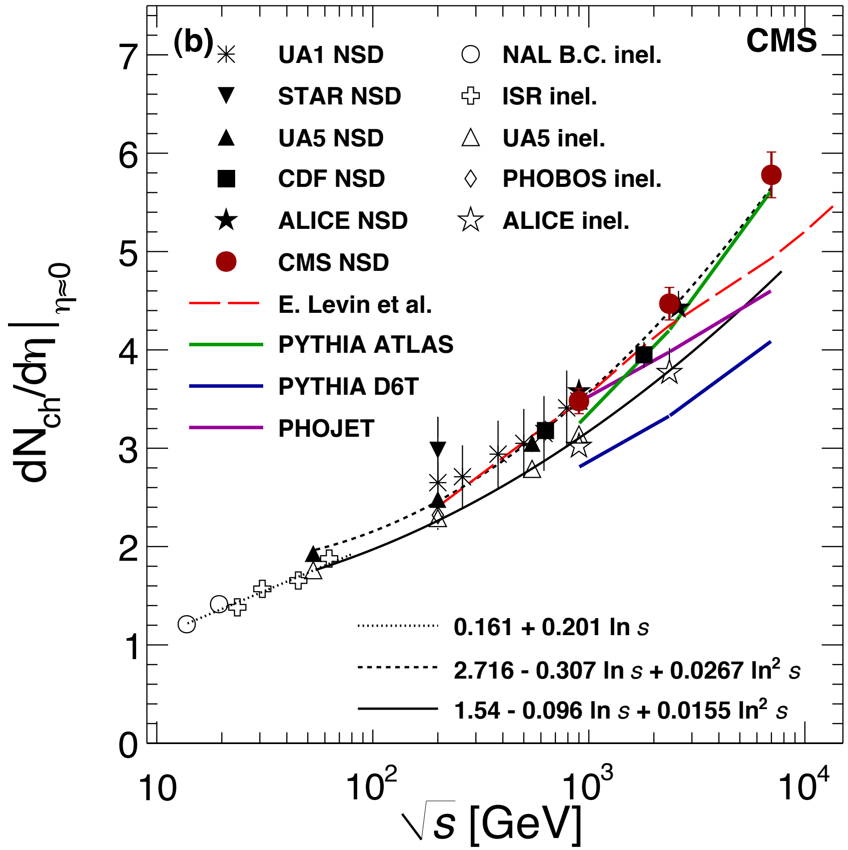


Results: charged hadron dN/dη

- Shapes similar at different energies
- Good agreement with other measurements
- Bands show systematic error (~5%)
  - Largest contribution from correction to NSD event selection

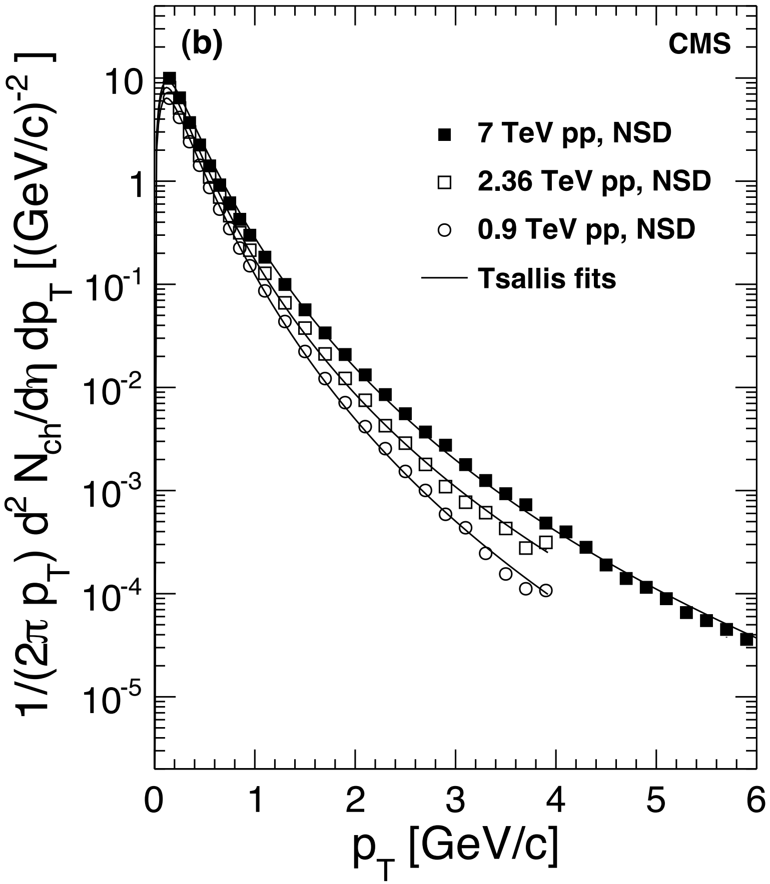
- Multiplicity at η ≈ 0 rises with √s (as expected)
- Rate of rise at 7 TeV exceeds most predictions

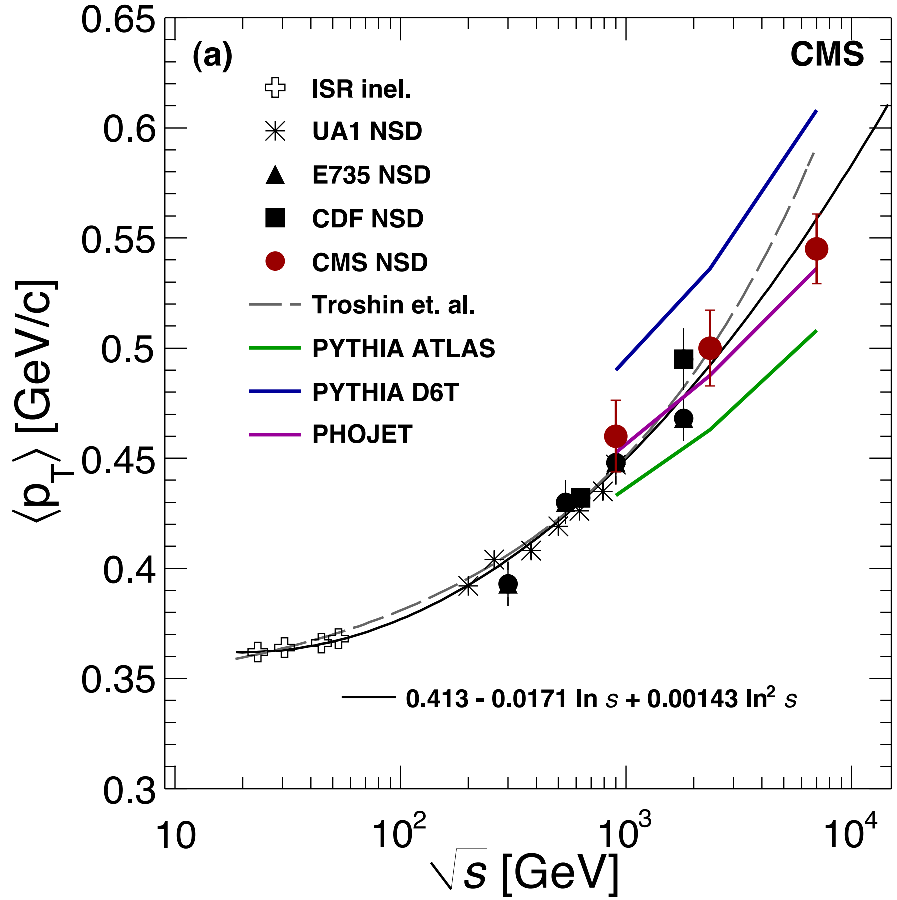




Results: charged hadron p_T

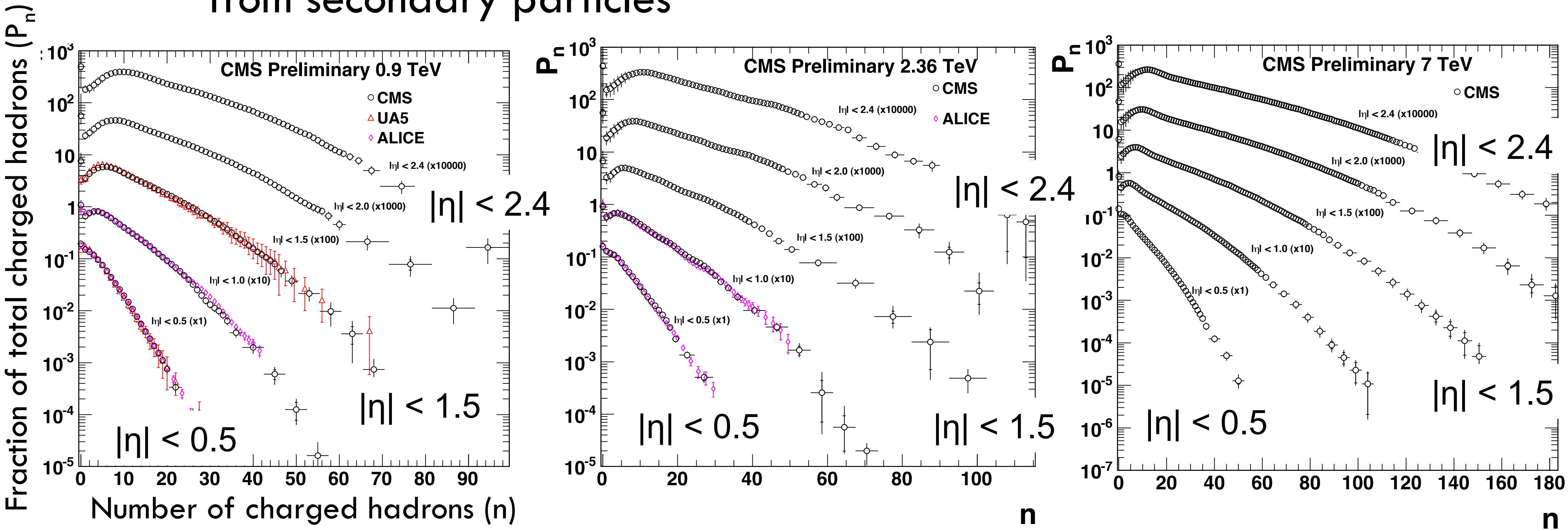
- Transverse momentum spectra and $\langle p_T \rangle$ measured for $|\eta| < 2.4$
  - Fit with Tsallis function: exponential at low p_T and power law tail
- Spectra grow in transverse momentum with higher $\sqrt{s}$
- Models bracket the observed increase





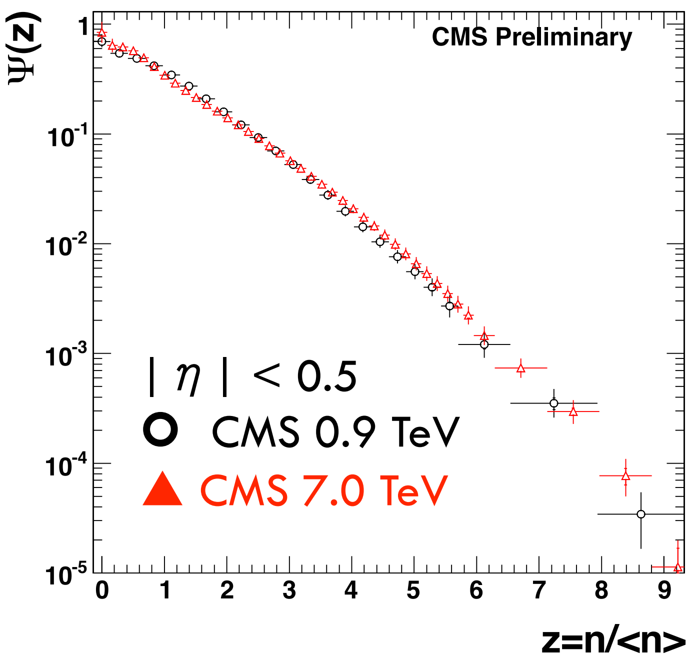
Measuring charged hadron multiplicity

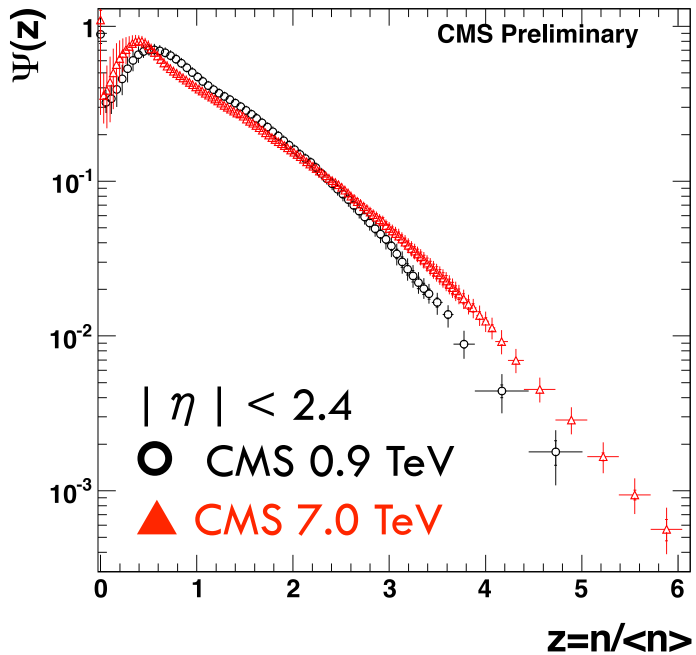
- Full tracking used to measure primary charged hadron multiplicity
- Use MC to correct for efficiency to select NSD events with a good primary vertex
- Obtain true multiplicity distribution from measured distribution with a Bayesian unfolding method
  - Corrects for track reconstruction efficiency, acceptance and tracks from secondary particles

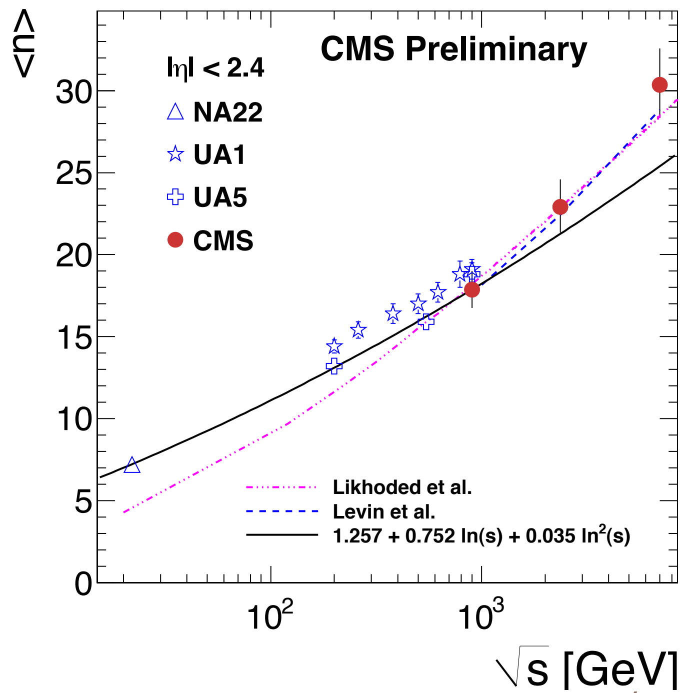


Results: charged hadron multiplicity

- KNO scaling: $\Psi(z) = \langle n \rangle P_n$ shown to be independent of $\sqrt{s}$ for scale invariant particle production
  - True for $|\eta| < 0.5$, violated for $|\eta| < 2.4$
- Large tail at high n also reflected in steep rise in $\langle n \rangle$ with $\sqrt{s}$

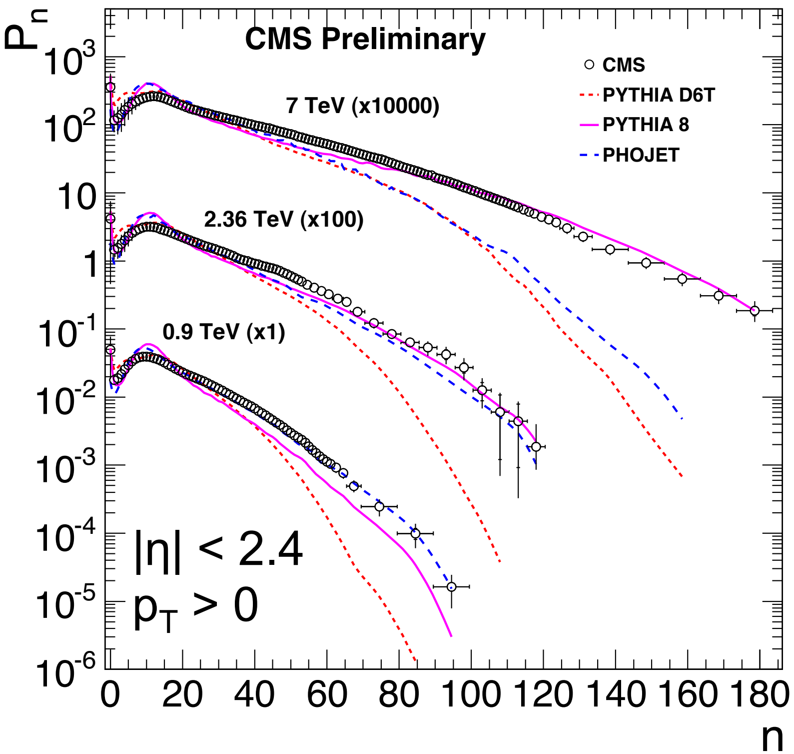


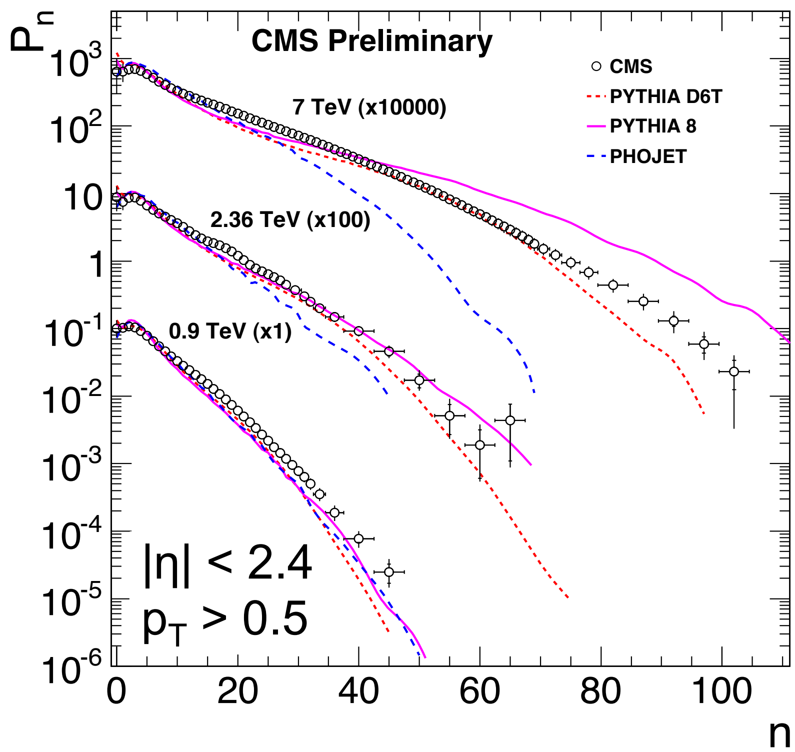




Multiplicity Data-MC comparison

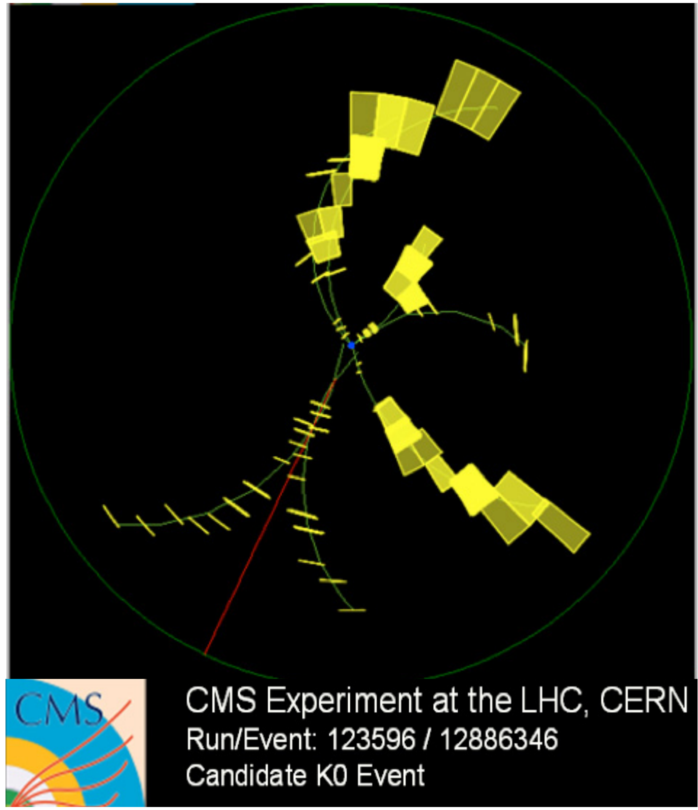
- Different models for simulation have varying degrees of success—no model gets everything right at 7 TeV
- Pythia 8 models total multiplicity well, but predicts too many high p_T particles at large multiplicities

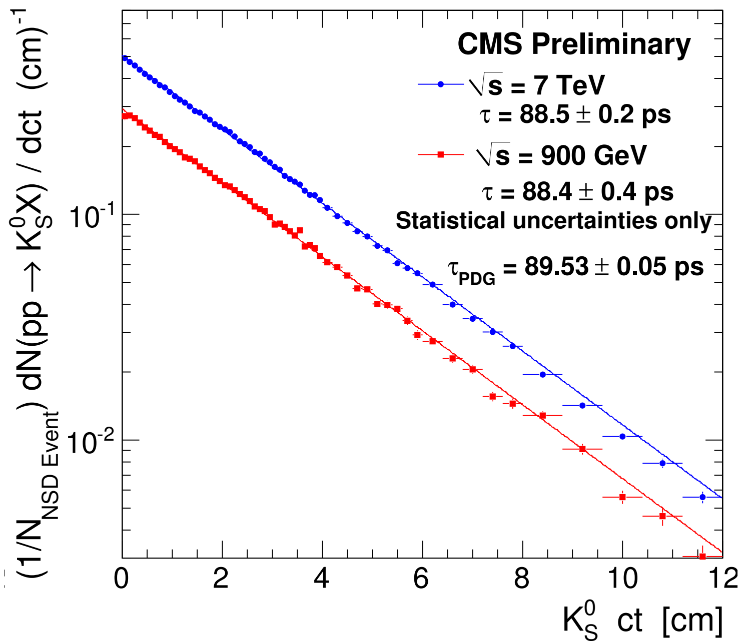




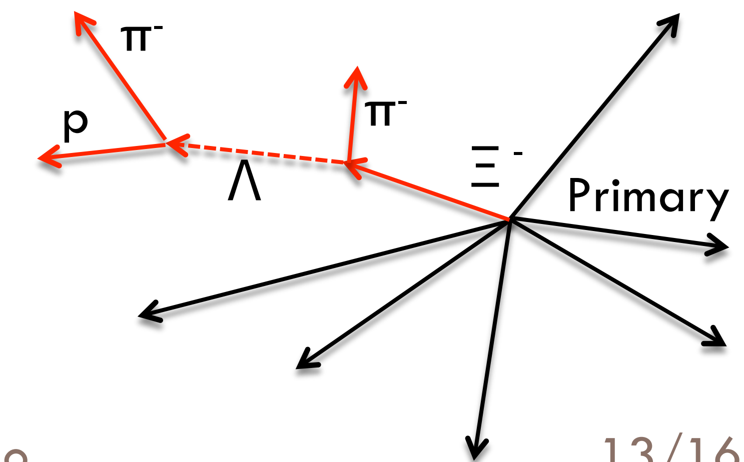
Strange particle reconstruction

- K_S^0 and Λ (+ c.c.) reconstructed in decays to $\pi^-\pi^+$ and π^-p
- Ξ^- (+ c.c.) reconstructed in decays to $\Lambda\pi^-$
- Long-lived particles identified by displaced vertices ($c\tau$ = 2.7-7.9 cm)
- All results shown for |y| < 2.0



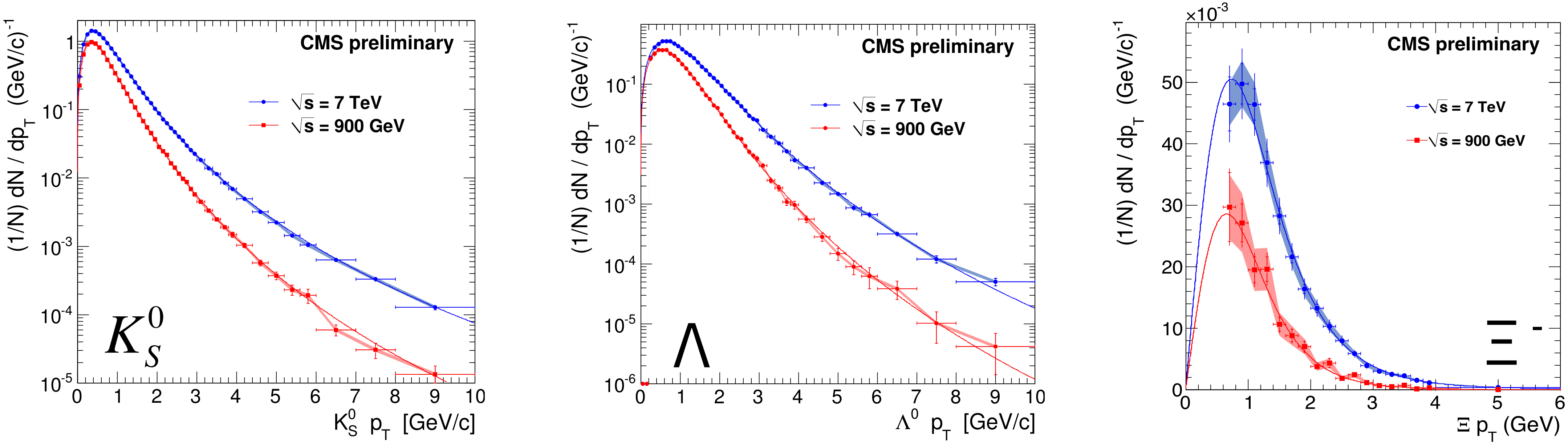


- Validate understanding of reconstruction efficiency by finding correct lifetime in data



Results: strange particle dN/dp_T

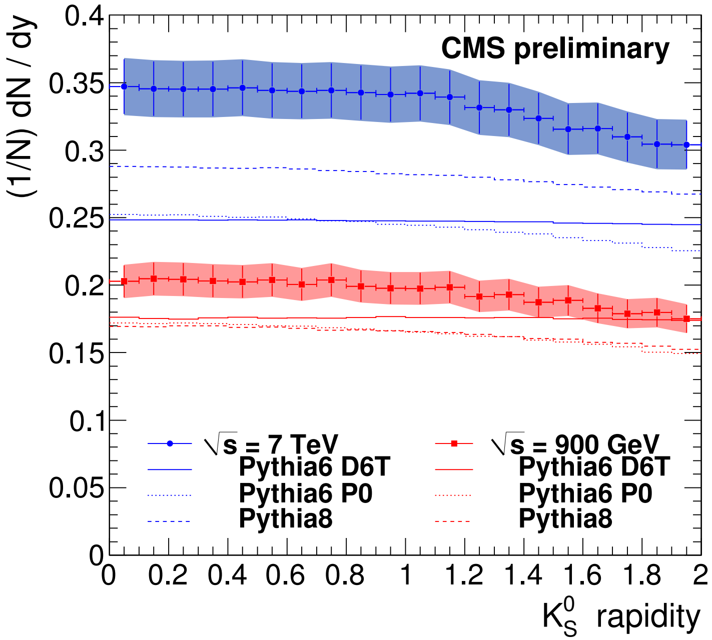
- Fit for yields and correct for efficiency in bins of p_T
  - Reweight MC to account for discrepancy in $K_S^0 / \Lambda / \Xi^-$ kinematic distributions between data and MC

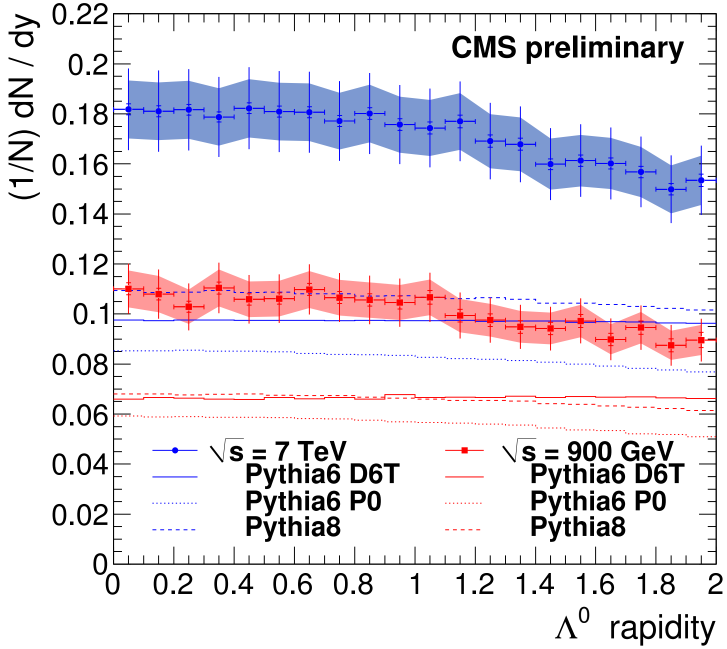


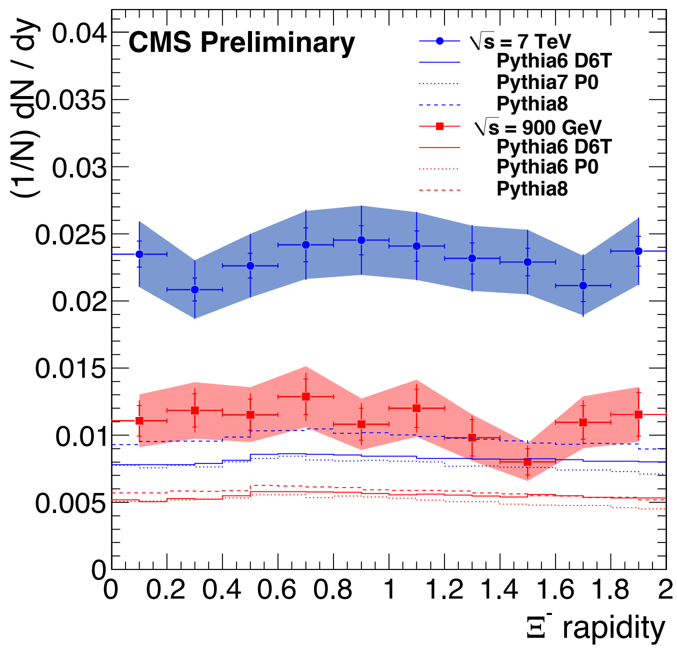
$< p_T >$ (GeV/c)	$\sqrt{s} = 900$ GeV		$\sqrt{s} = 7$ TeV	
Particle	data	Pythia6 D6T MC	data	Pythia6 D6T MC
K_S^0	$0.657 \pm 0.002 \pm 0.038$	0.577	$0.789 \pm 0.001 \pm 0.046$	0.750
Λ^0	$0.849 \pm 0.004 \pm 0.076$	0.752	$1.054 \pm 0.003 \pm 0.094$	1.062
Ξ^-	$1.01 \pm 0.03 \pm 0.10$	0.763	$1.22 \pm 0.01 \pm 0.12$	1.162

Results: strange particle dN/dy

- Results vs rapidity compared to Pythia predictions







Particle	$\frac{\frac{dN}{dy}\|_{y=0}(\mathrm{MCD6T})}{\frac{dN}{dy}\|_{y=0}(\mathrm{Data})}$ 900 GeV	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^-	$0.48 \pm 0.05 \pm 0.09$	$0.33 \pm 0.02 \pm 0.05$

- Significantly more strangeness in data than MC
  - Discrepancy grows with increasing mass, strangeness and $\sqrt{s}$
  - Factor of 3 for Ξ^- at $\sqrt{s}$ = 7 TeV!

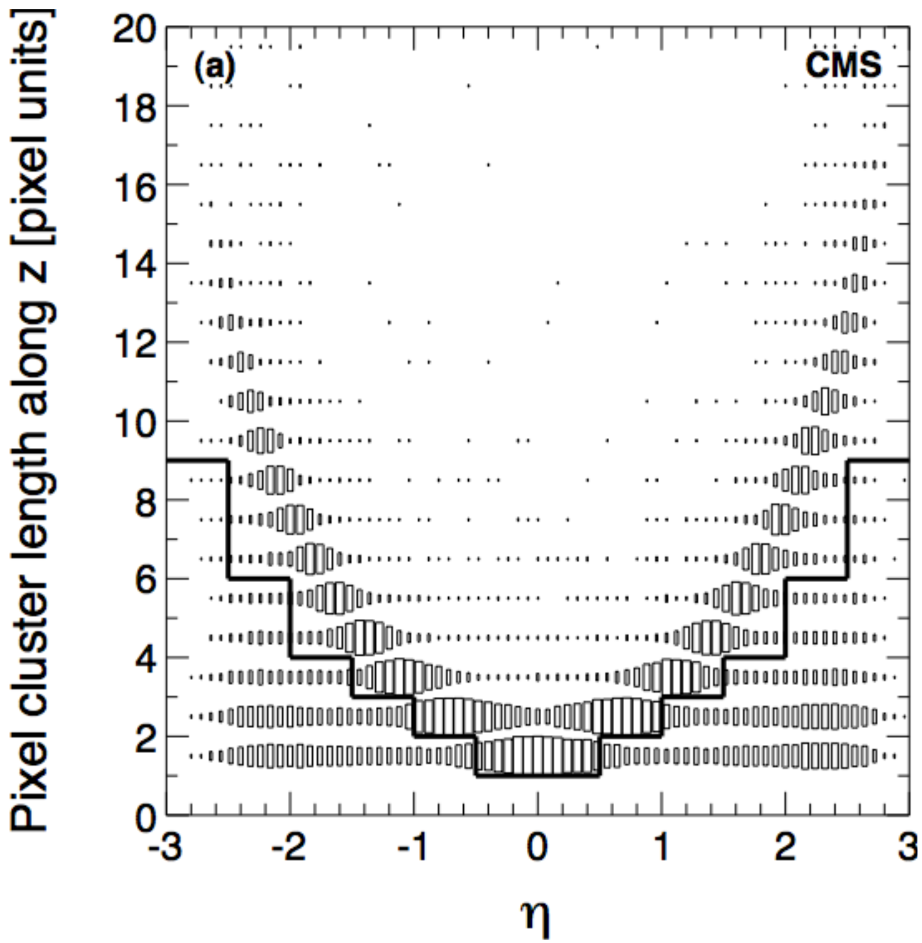
Conclusions

- CMS is operating well, and taking full advantage of the luminosity delivered by the LHC
  - Proton collisions at $\sqrt{s} = 7$ TeV represent a large jump in energy with lots of new terrain to explore
- Hadron production studies have already provided surprises
  - Charged hadron multiplicity distribution scaling law is violated
  - Strange particle production is greatly enhanced compared to Pythia predictions
- We're deepening our understanding of QCD in a new energy regime, and providing the foundation for more surprises yet to come…

Extra slides

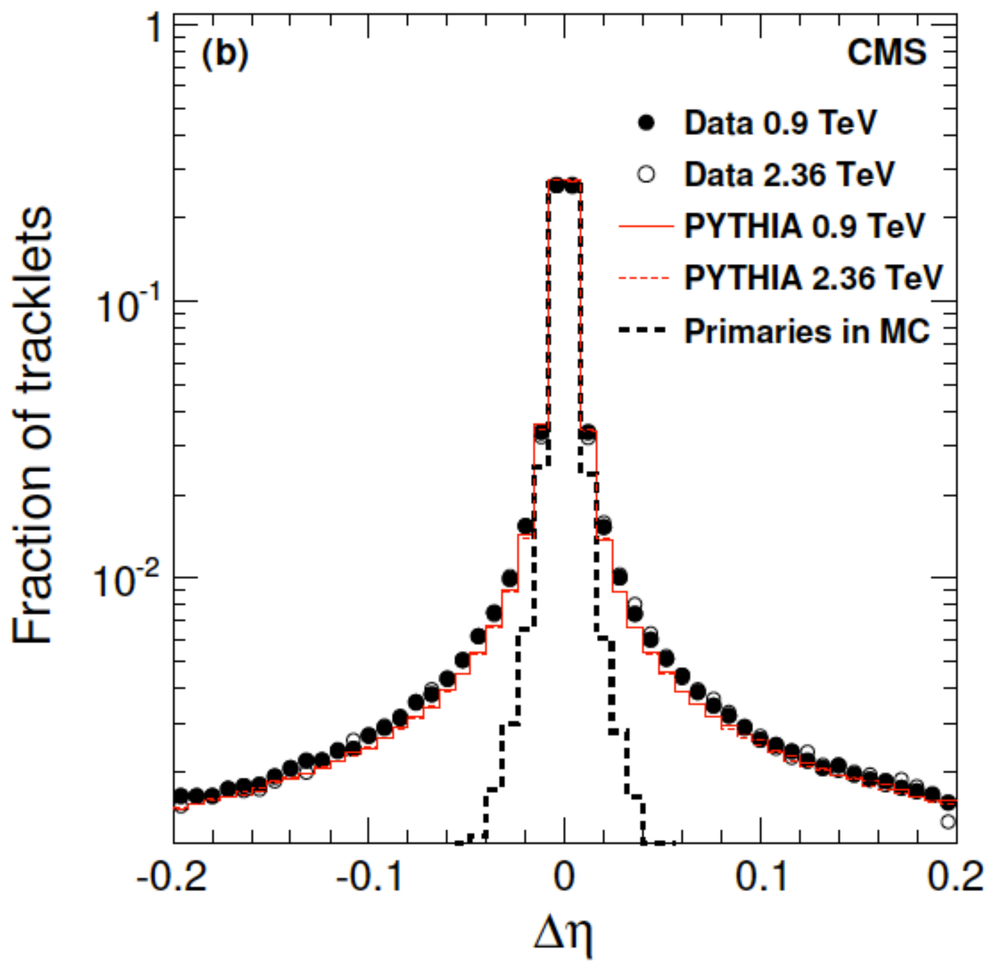
Cluster counting method

- Cluster length should be a function of pitch and track angle
  - Reject too-short clusters inconsistent with originating at the primary (loopers, secondaries etc.)
- Correct measured rates for remaining non-primary tracks
- Independent results obtained for all three pixel barrel layers



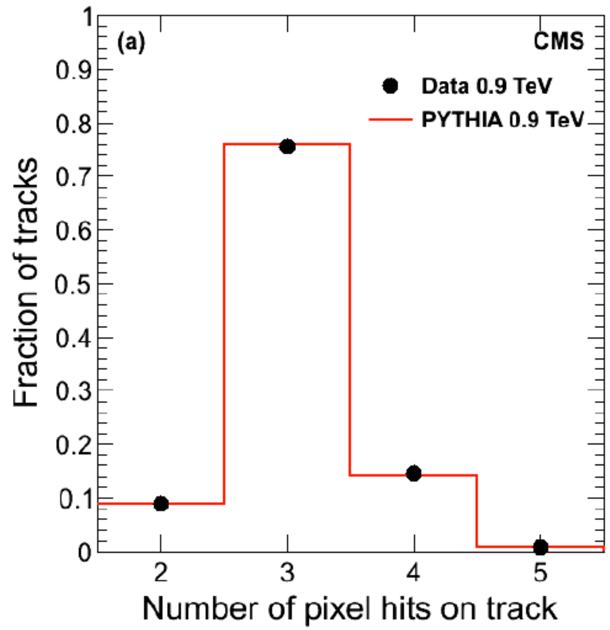
Tracklet method

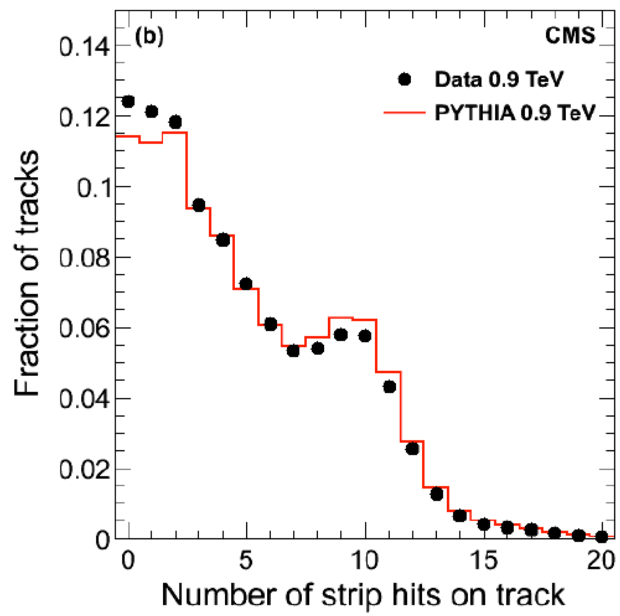
- Use all three independent combinations of pixel barrel layer pairs
- Compute $\Delta\eta$ and $\Delta\phi$ for each pair
  - η and ϕ defined at the angles between the primary vertex and one of the tracklet hits
  - $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ between the two tracklet hits
- Use sidebands in $\Delta\phi$ to subtract combinatorial backgrounds
- Correct for efficiency, weak decays, and secondaries with MC



Tracking method

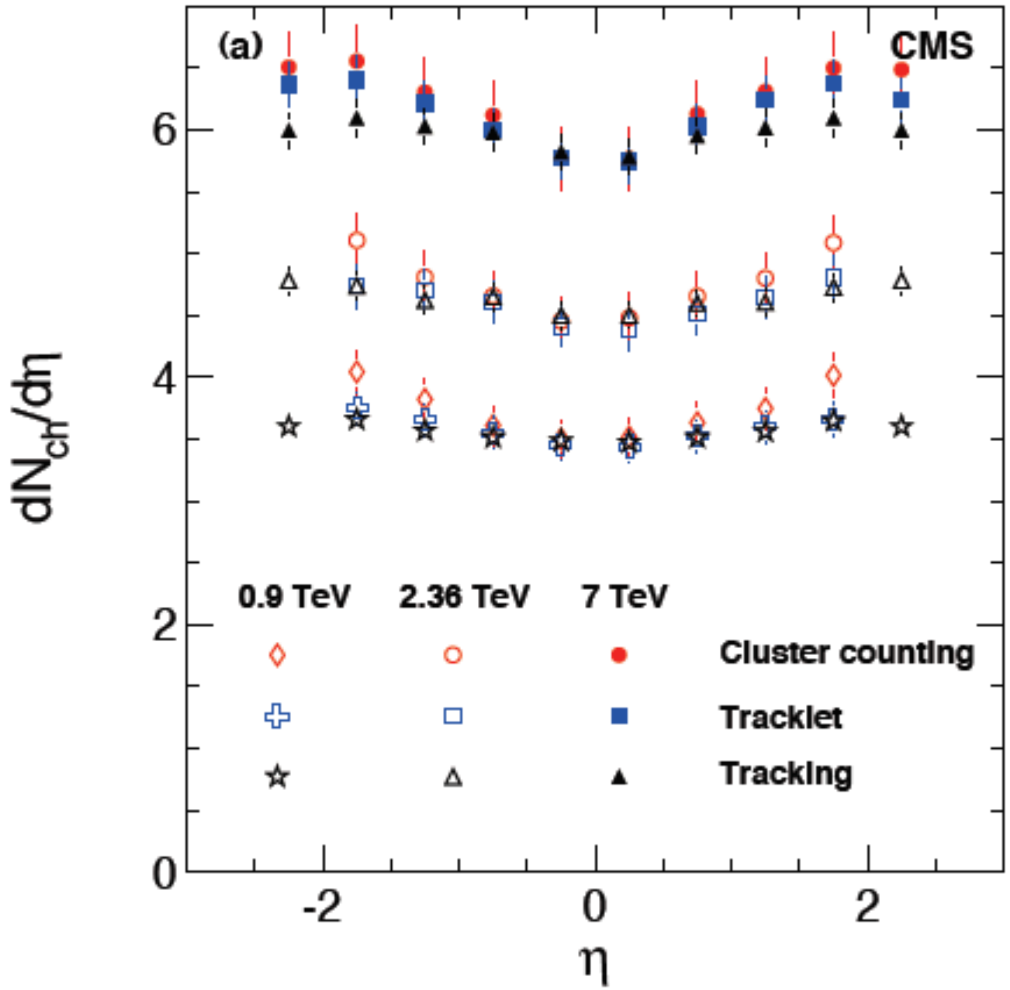
- Use iterative step approach to track building
- Require compatibility with beam spot and primary vertex
  - Sensitive to beamspot position and alignment
- Track cleaning based on cluster shape helps keep fake rate low
- Good agreement between data and MC in number of hits on track

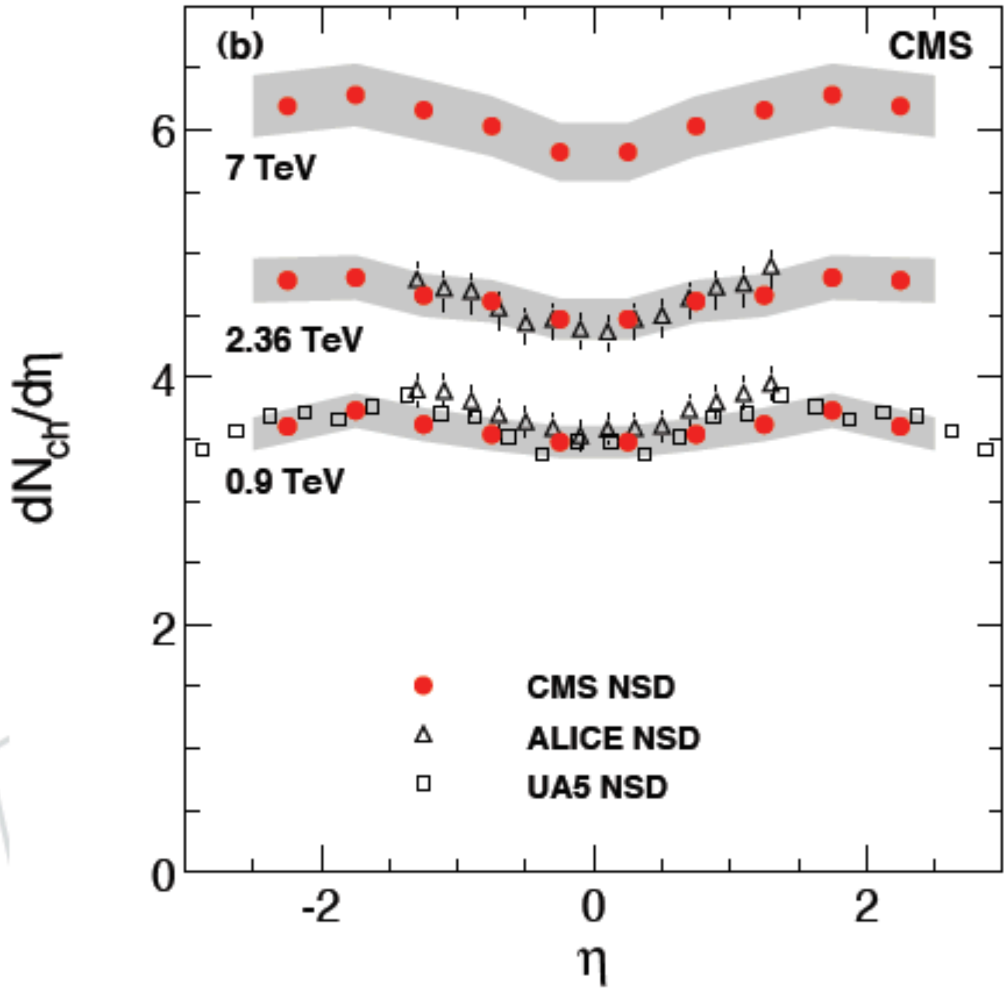




Comparison of dN/dη results

- Three methods produce consistent results
  - Average used a final CMS result





Tsallis function

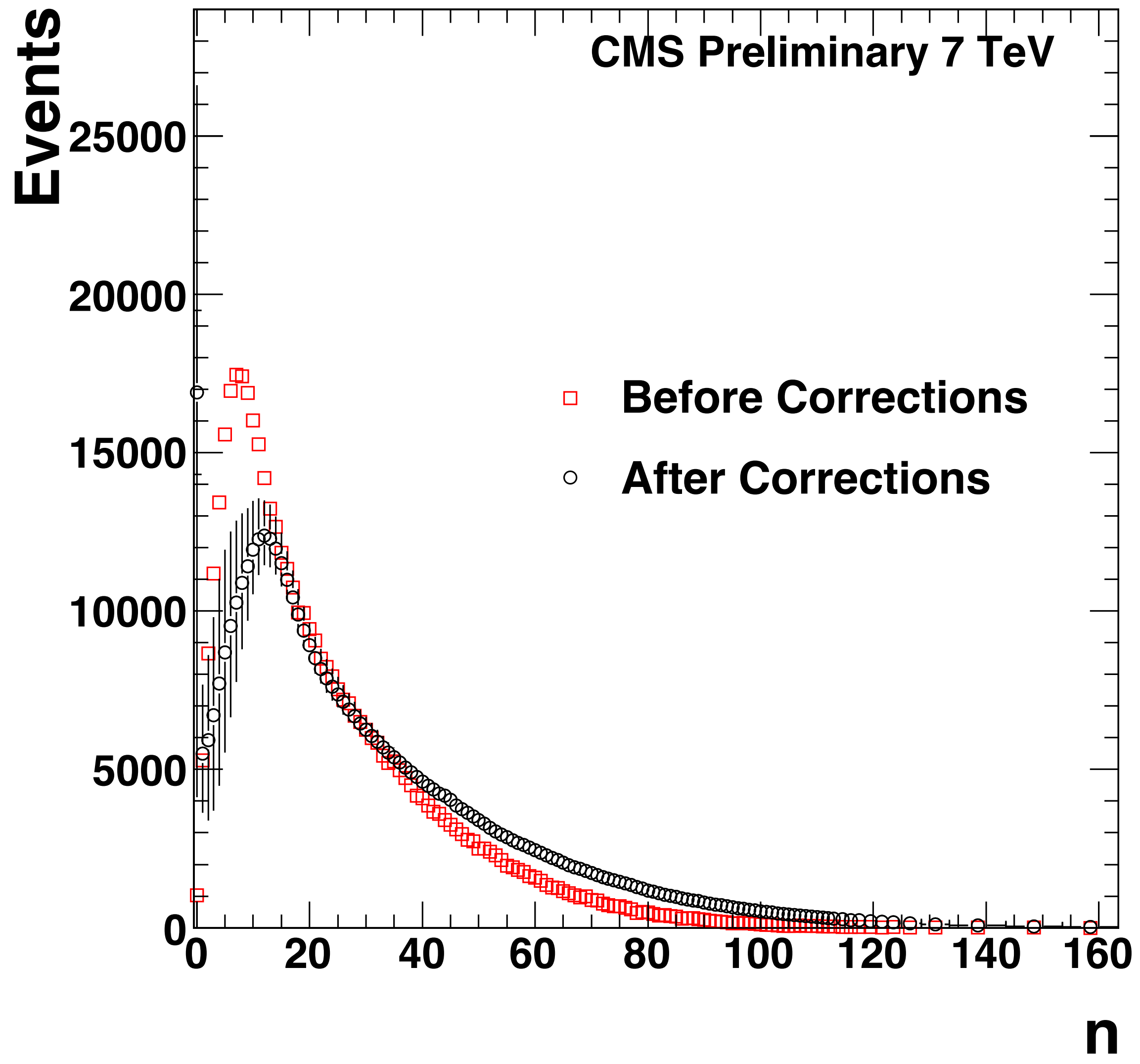
- Tsallis function:

$$(1/N)dN/dp_T = Cp_T\left[1+\frac{\sqrt{p_T^2+m^2}-m}{nT}\right]^{-n}$$

- m = particle mass, n and T are shape parameters and C is a normalization parameter
- C. Tsallis, “Possible generalization of Boltzmann-Gibbs statistics”, *J. Stat. Phys.* **52** (1988) 479. doi:10.1007/BF01016429.

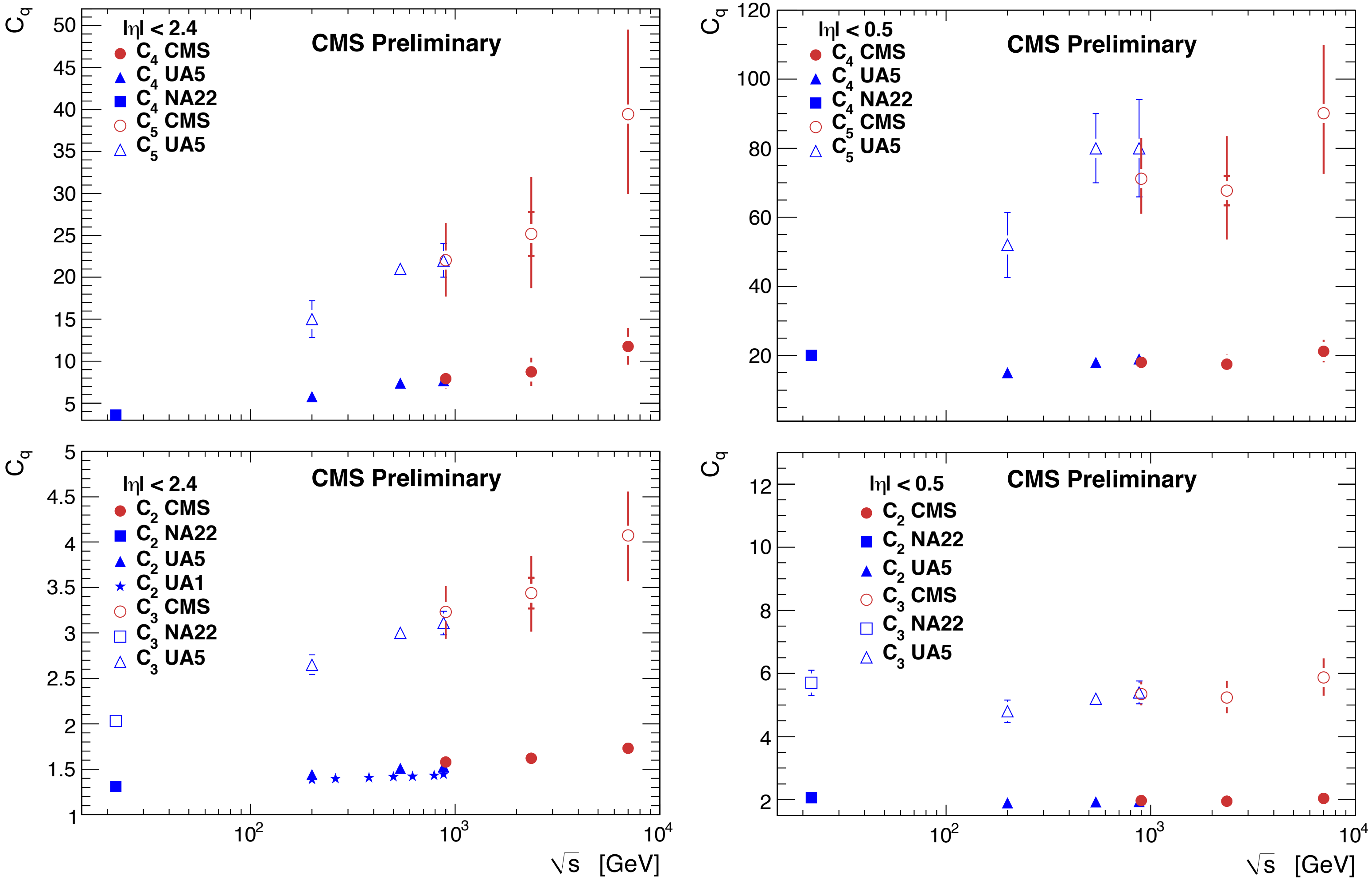
Track multiplicity unfolding

- Corrections are a significant effect
- Uncertainties obtained from full covariance matrix calculated with a resampling technique



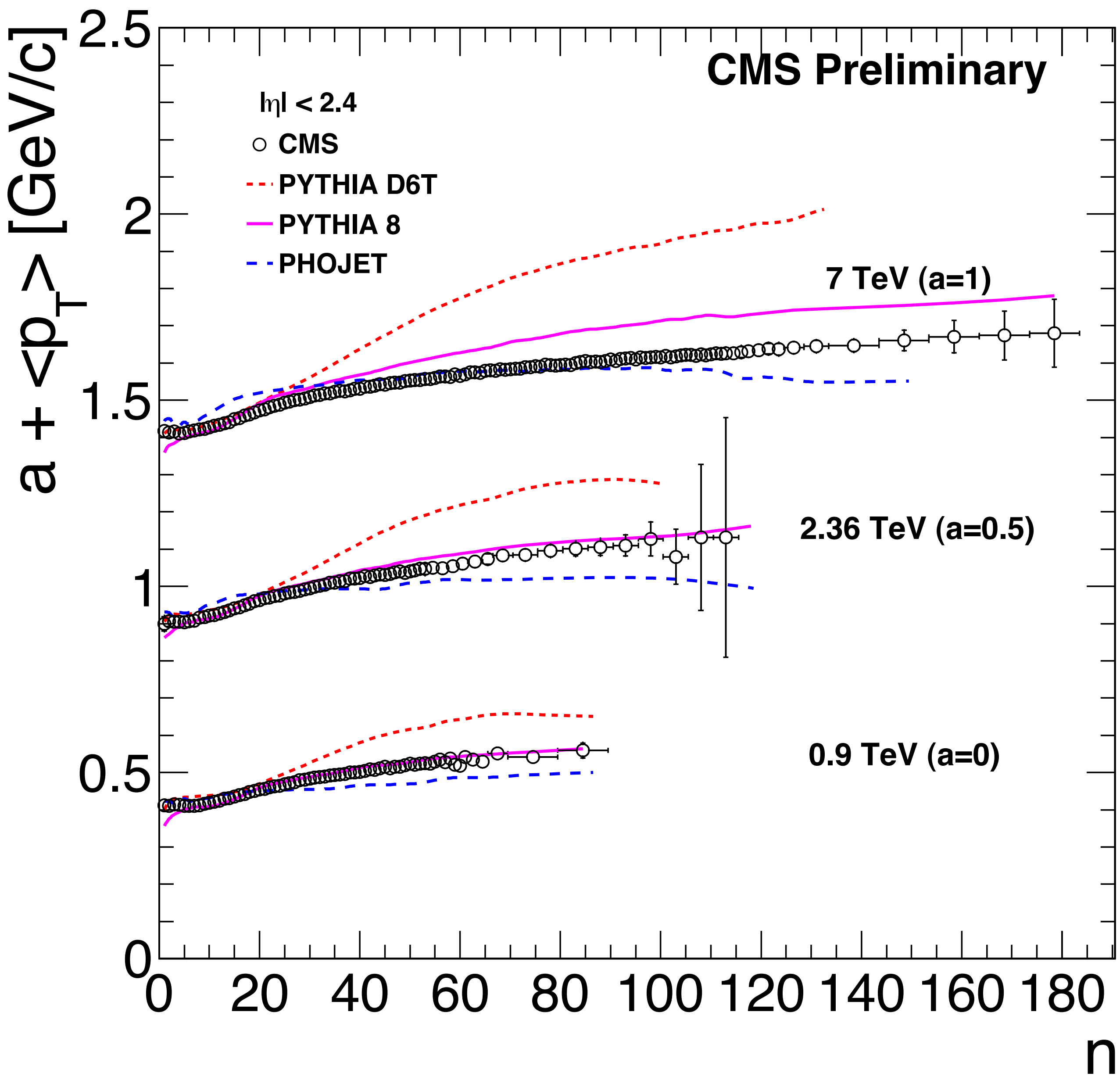
Moments of track multiplicity

- Normalized moments of charged hadron multiplicity
  - Flat distributions for |η| < 0.5, as predicted by GNO scaling
  - Rising distributions for |η| < 2.4 in violation of GNO scaling

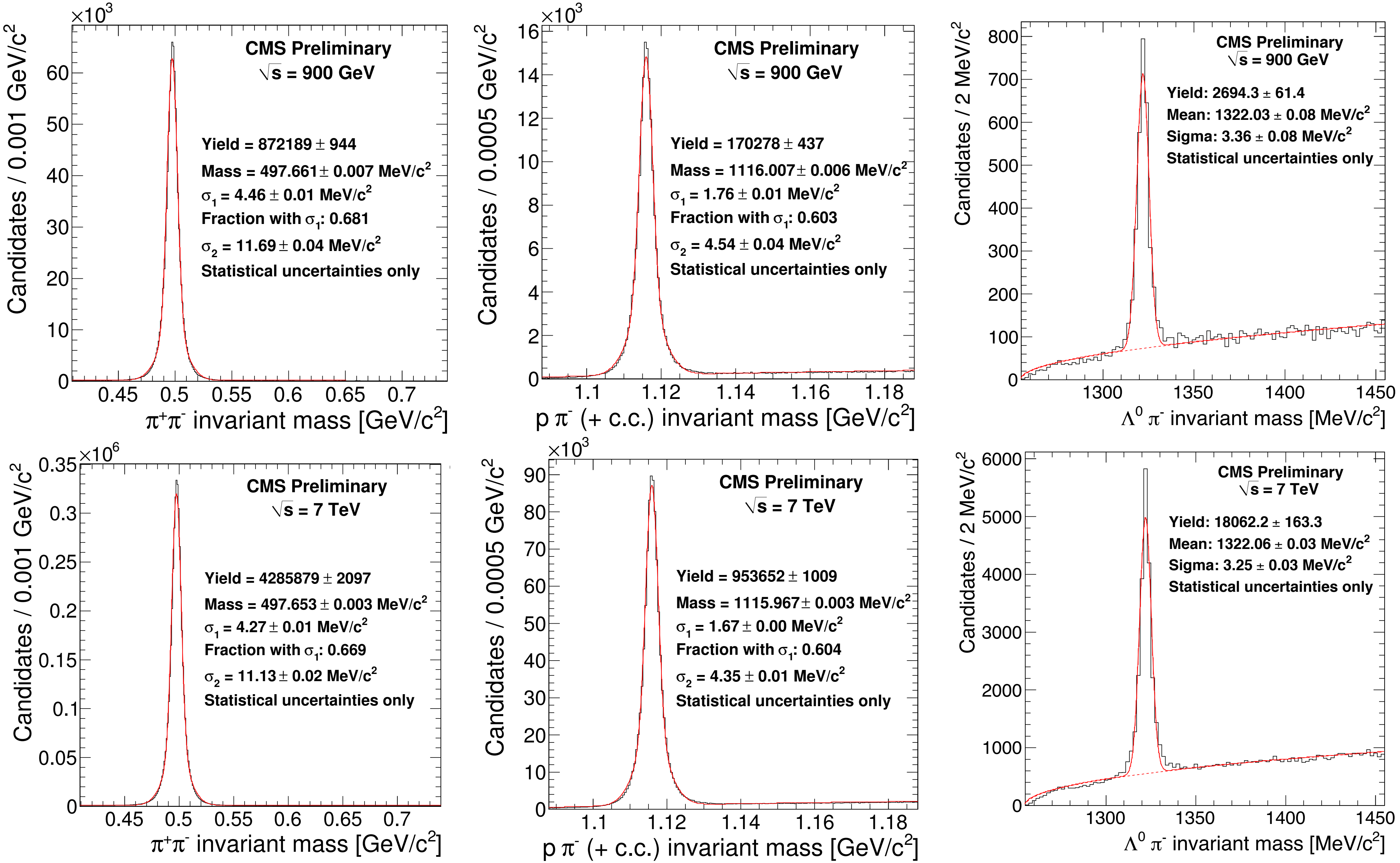


$\langle p_T \rangle$ with predictions

- PYTHIA $\langle p_T \rangle$ rises too fast for events with many tracks
- Modeled better by PHOJET

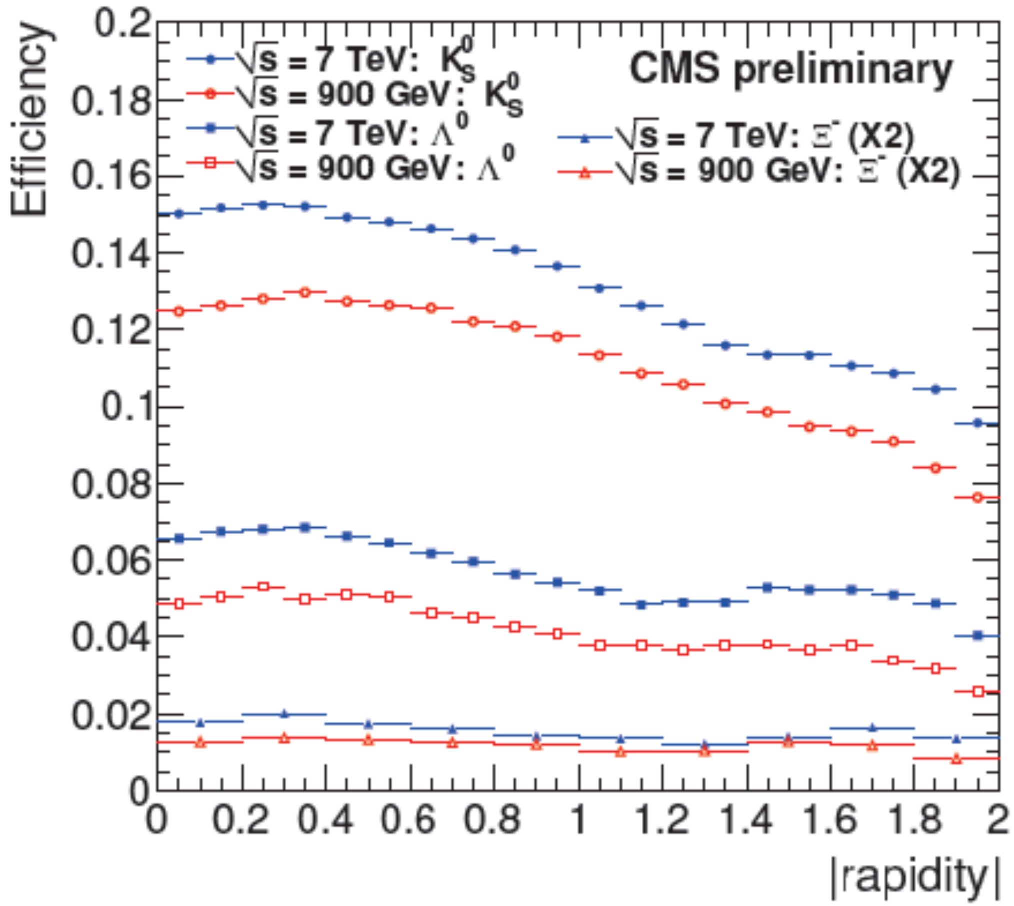


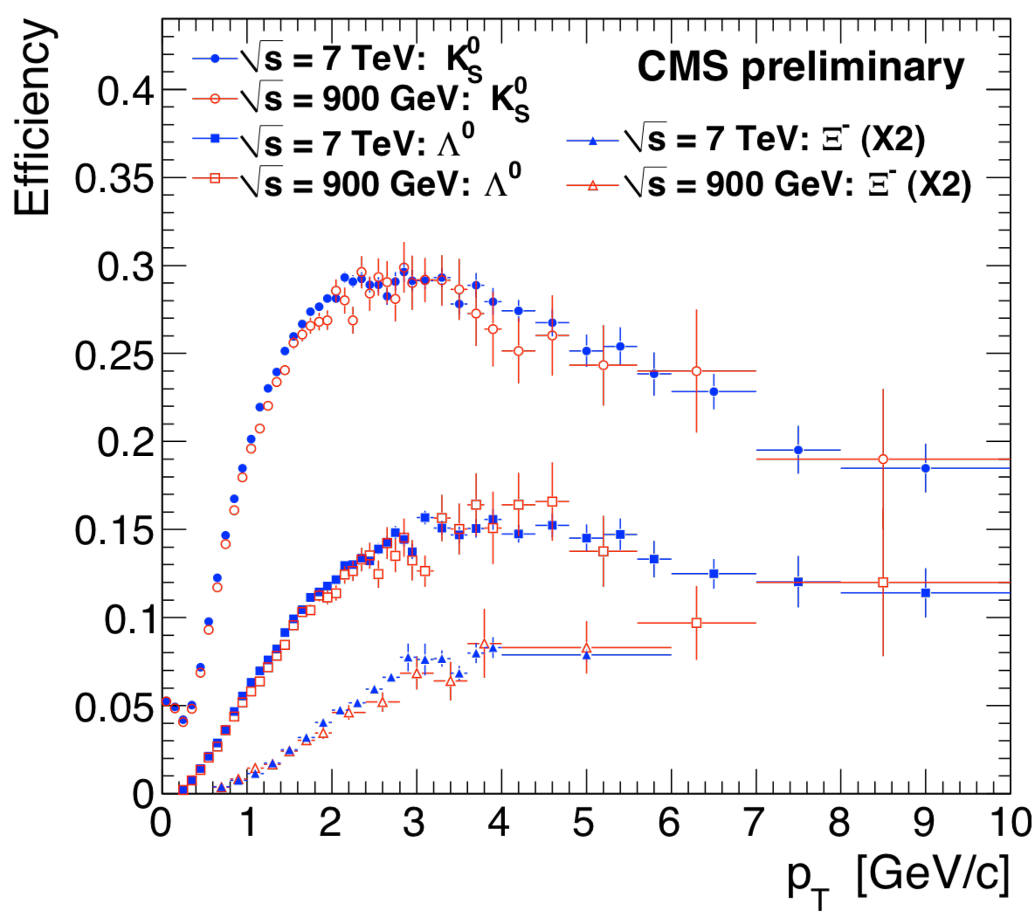
Strange particle mass plots



Strange particle efficiencies

- Reconstruction efficiency of K_S^0, Λ and Ξ^-
  - Including branching fractions, trigger, acceptance, and reconstruction efficiencies





Strange particle ⟨p$_T$⟩ scaling

- ⟨p$_T$⟩ as a function of √s for K_S^0, Λ and Ξ$^-$ compared to charged hadrons