Low momentum particle identification and its applications in CMS

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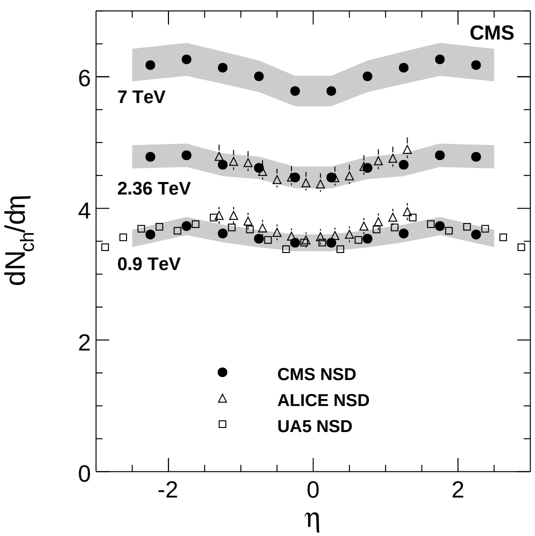
Outline

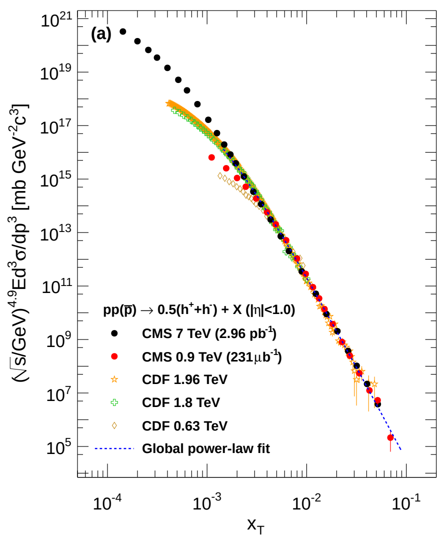
- Particle identification via "dE/dx"
  - Energy deposits in silicon
  - Estimation of energy loss rate
  - Determination of particle yields

- Identified charged hadrons from CMS
  - pp $\sqrt{s} = 0.9$, 2.76 and 7 TeV
  - Published in Eur Phys J C 72 (2012) 2164
  - All measured values are available in HepData at http://hepdata.cedar.ac.uk/view/ins1123117

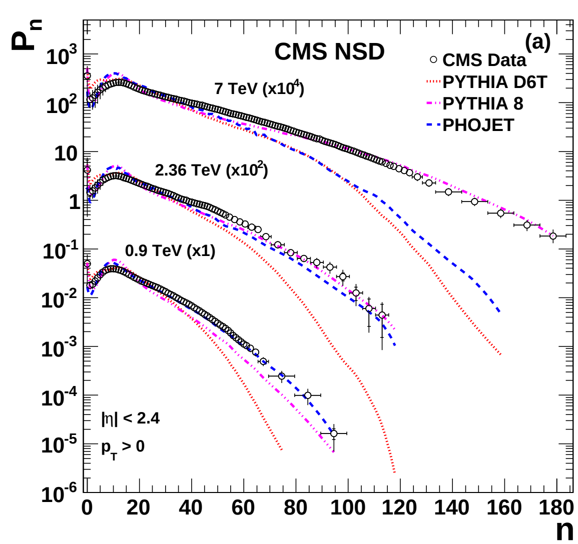
Previous CMS measurements



J. High Energy Phys. 02 (2010) 041

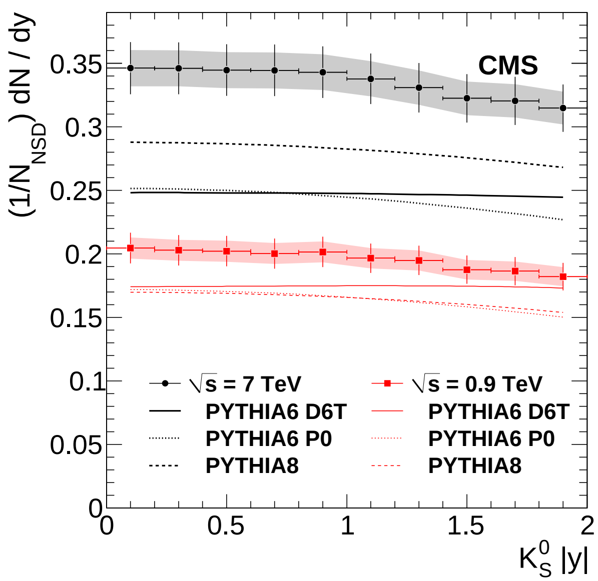


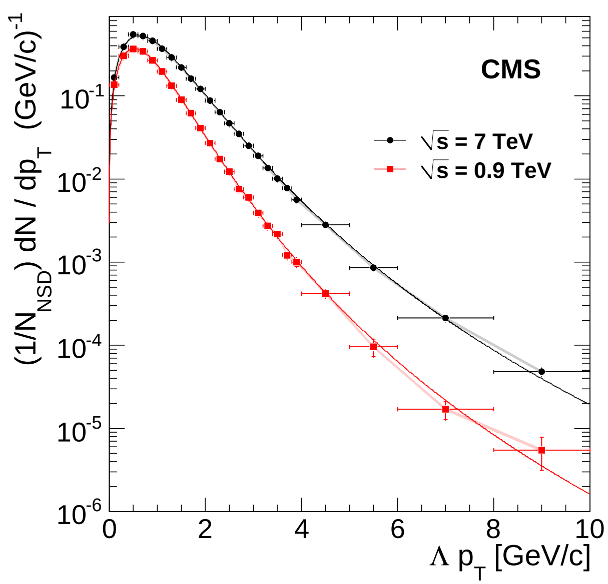
Phys. Rev. Lett. 105 (2010) 022002



J. High Energy Phys. 08 (2011) 086

J. High Energy Phys. 01 (2011) 079



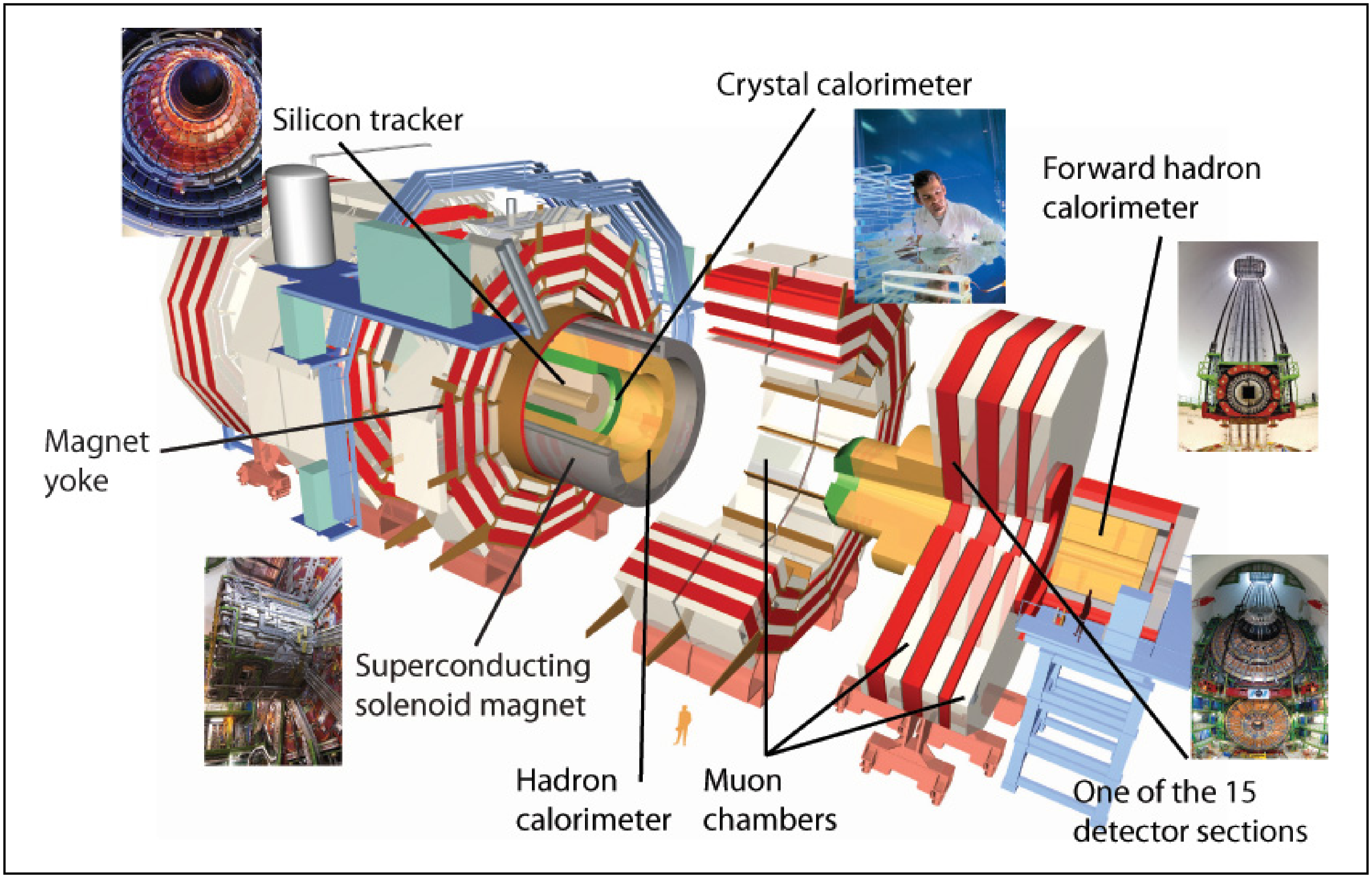


J. High Energy Phys. 05 (2011) 064

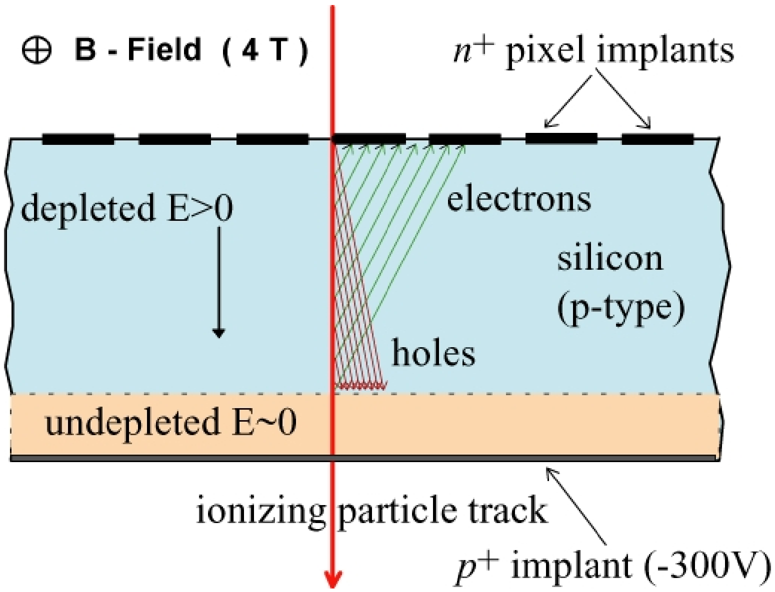
Motivation

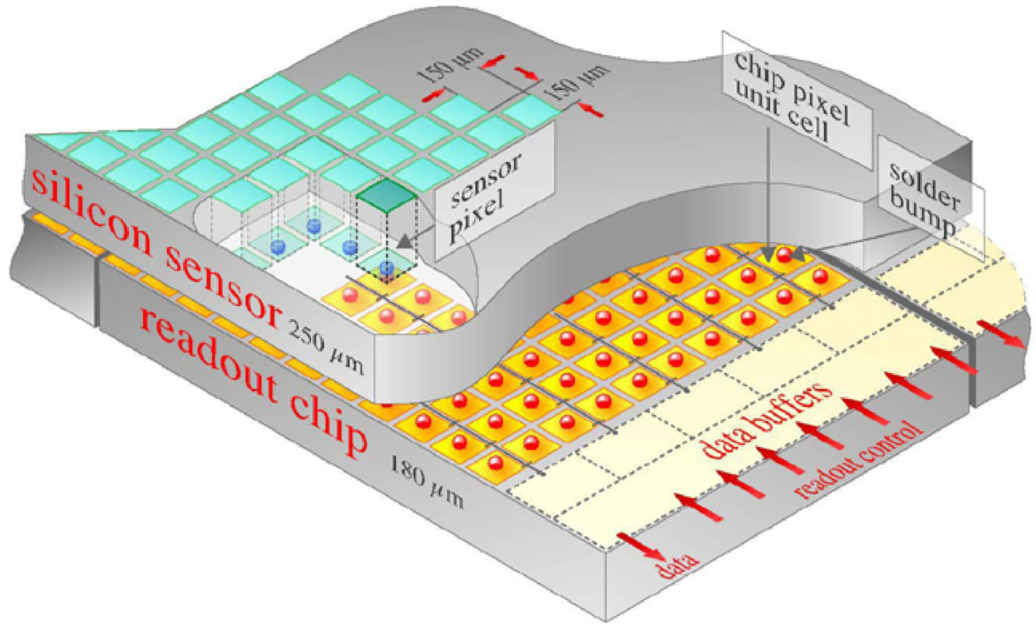
Can you identify or unfold charged hadrons?

Analysis techniques



CMS – tracker detectors

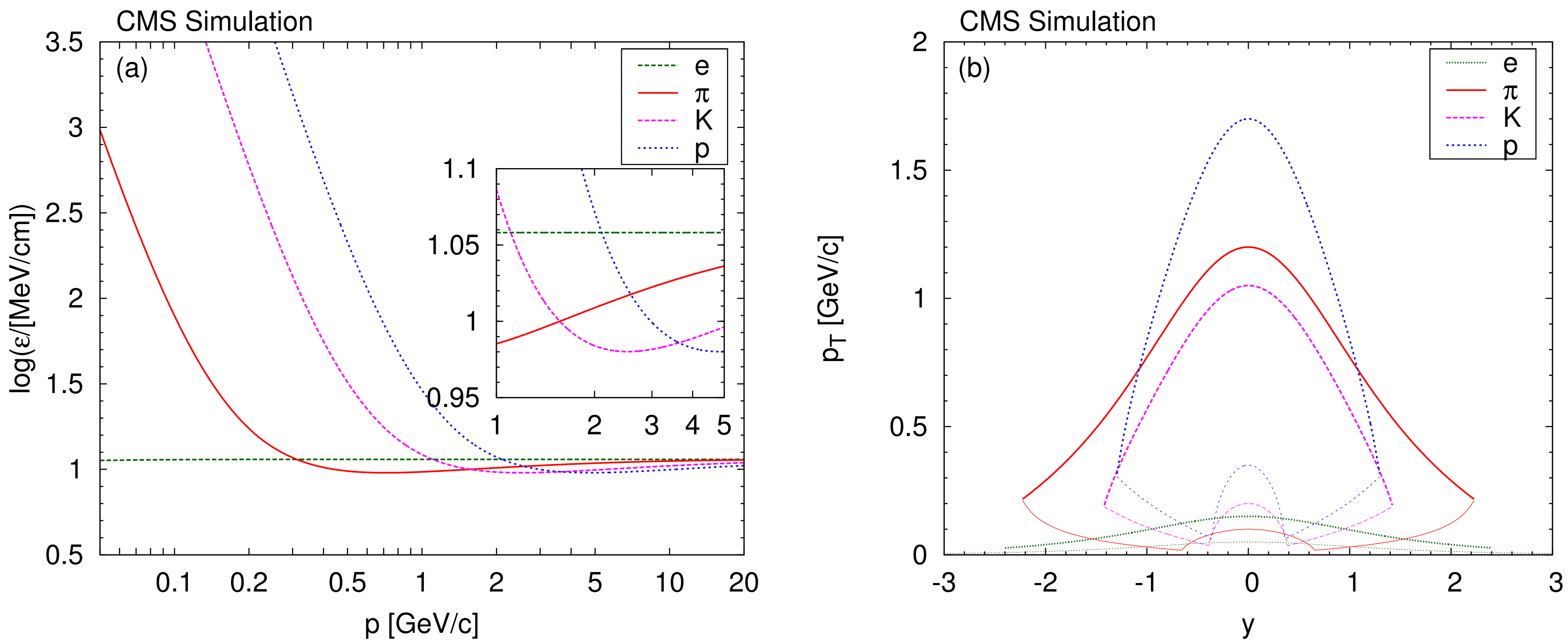




- Silicon tracker
  - Pixels: n-on-n; three barrels at 4.4, 7.3 and 10.2 cm radii, and two endcaps; 285 μm thickness; 1440 modules; 150 μm $\times$100 μm surface
  - Strips: p-in-n; some; double-sided 300 and 500 μm thickness 15 148 modules; varying width (80–150 μm); signal/noise 28–36

Clusters: groups of neighboring pixel and strips with energy deposit

The scene



- Silicon tracker
  - Need for particle identification or yield extraction
  - Only the low momentum range can be used
  - PID: $p < 1.20$ for $\pi^\pm$, $p < 1.05$ for $\mathrm{K}^\pm$, and $p < 1.70$ GeV/c for $\mathrm{p}/\overline{\mathrm{p}}$

Accessible region is also limited by η acceptance of the tracker

Final results are given for $|y| < 1$

Analytical energy loss parametization

- Most probable energy loss rate ε along a reference length l_0
  Most probable energy loss Δ:

$$\Delta(l) \approx \varepsilon l \left[1 + a \log(l/l_0)\right]$$

- Probability of a hits loss y, exponential and Gaussian parts

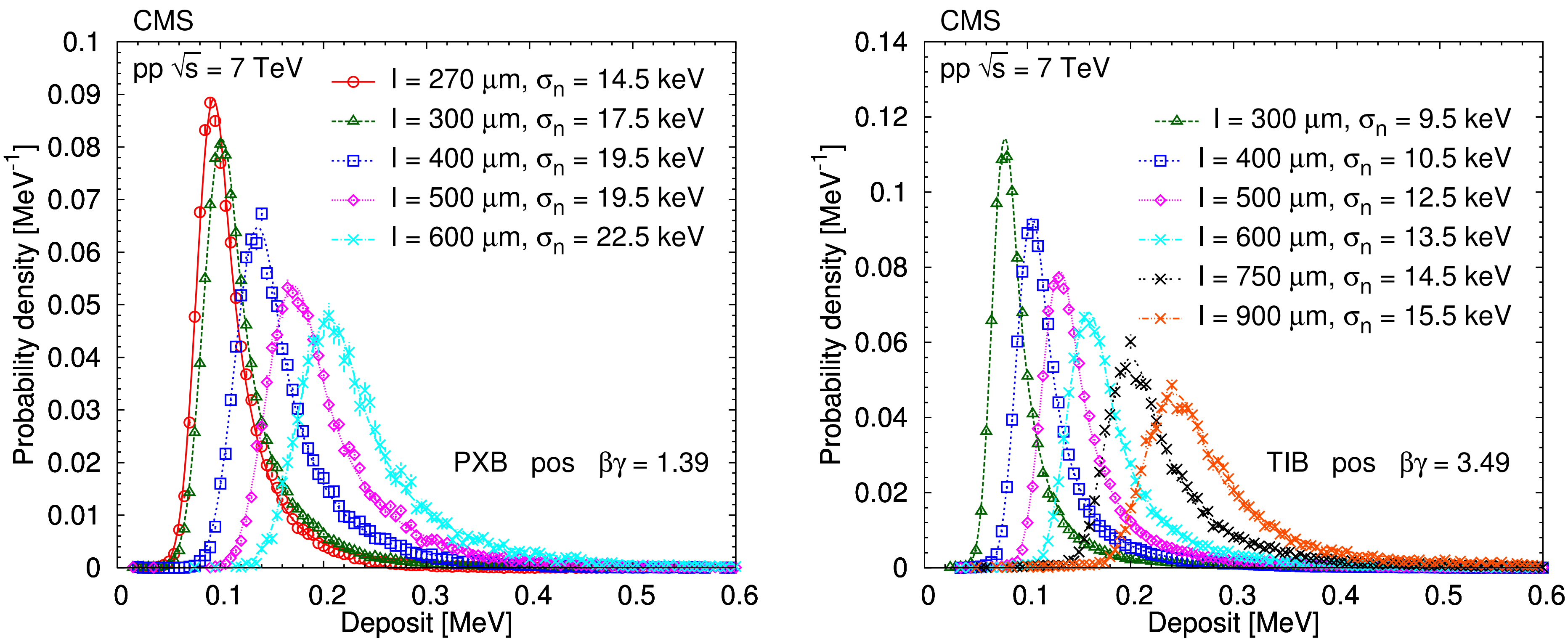
$$P(y|\varepsilon, l) \approx \frac{1}{\sigma_\Delta} \cdot \begin{cases} \exp\left[\frac{\nu(\Delta - y)}{\sigma_\Delta(y)} + \frac{\nu^2}{2}\right], & \text{if } \Delta < \Delta^* \\ \exp\left[-\frac{(\Delta - y)^2}{2\sigma_\Delta^2(y)}\right], & \text{if } \Delta \geq \Delta^*. \end{cases}$$

F. Siklér, "A parametrisation of the energy loss distributions of charged particles and its applications for silicon detectors", Nucl. Instrum. Meth. A 691 (2012) 16-29

- Why modelling?
  - Often very few hits, varying range (2–35); long-tailed energy loss distribution
  - Mixed detector types (pixels, strips, different thickness and path-lengths)
  - Plain truncated/power/weighted mean estimators are not enough
  - Model allows for precise **gain calibration** at the readout chip level
  - Model allows for correct **energy loss rate estimation** for tracks

Maximum likelihood estimation (MLE), use energy-deposit χ^2

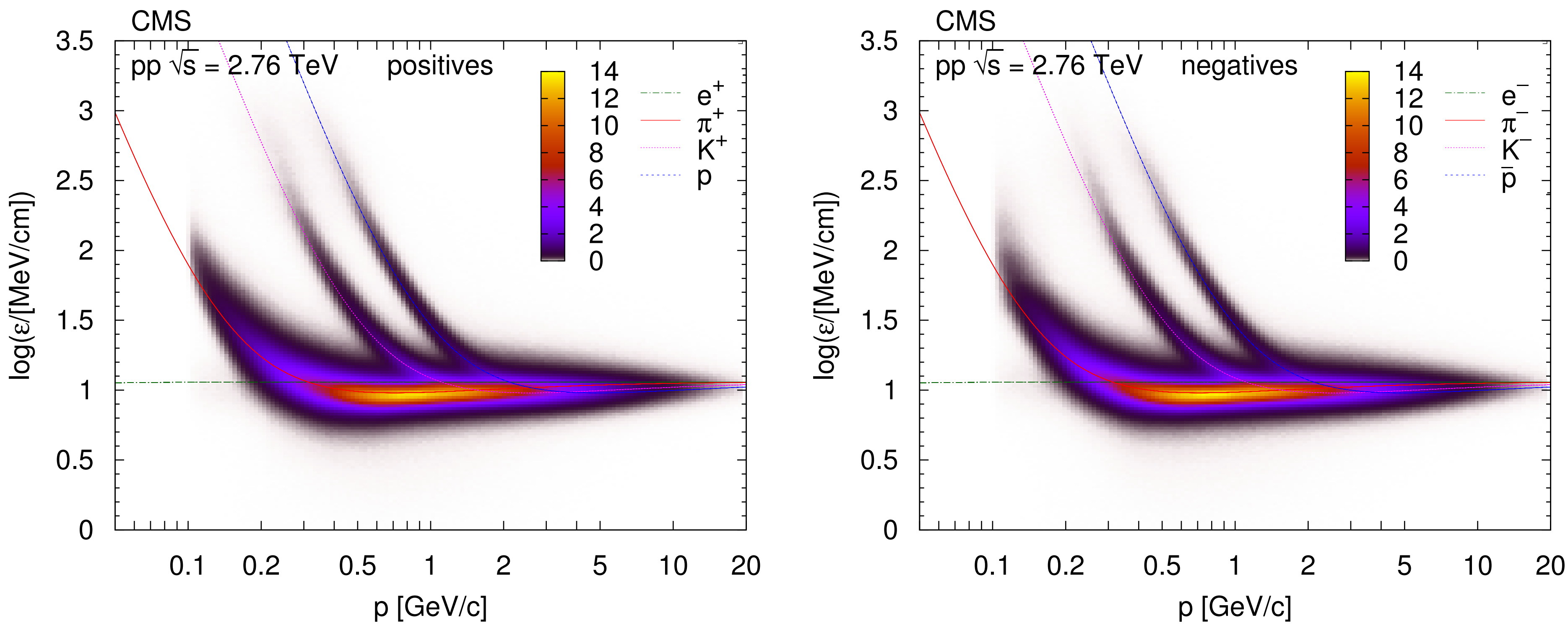
Model validation



Usually a very good match, success of the analytical parametrization

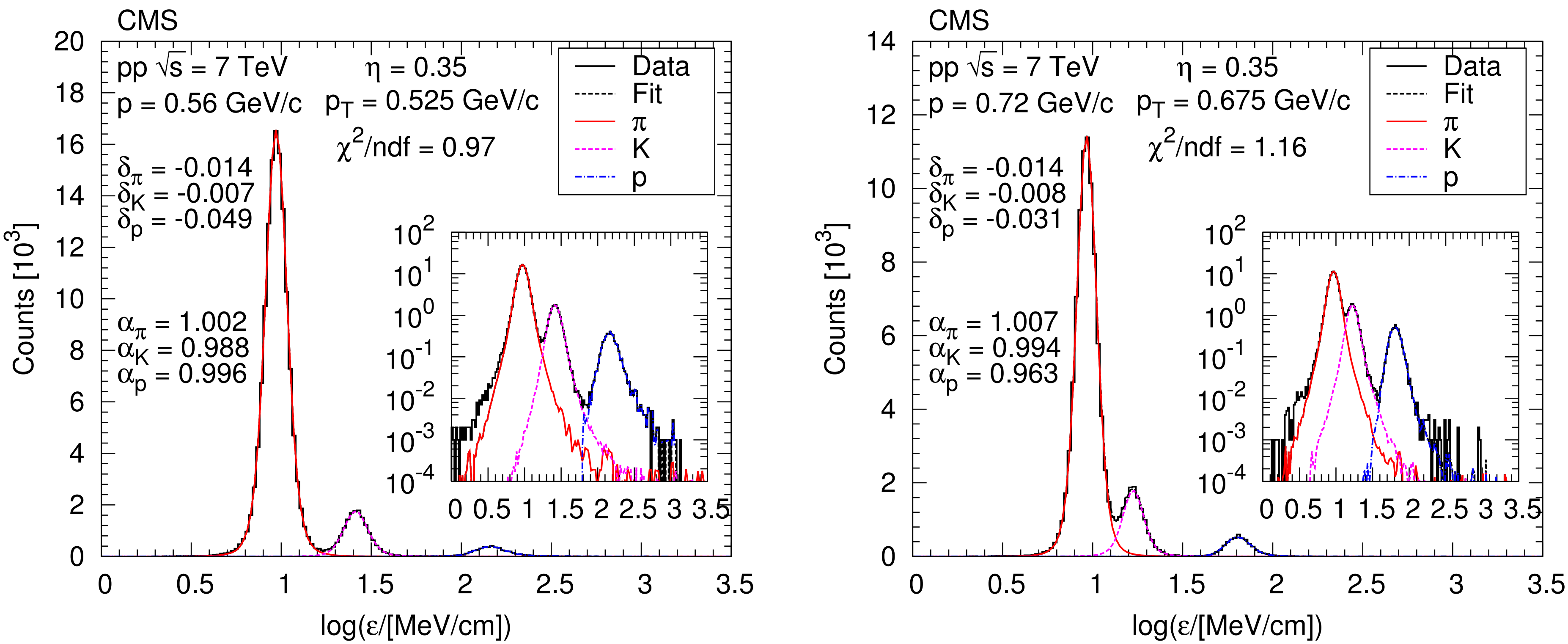
We allow for an affine transformation: scale factor + shift
Hit-level residuals

Most probable energy loss rate ε



- Estimation of $\log \varepsilon$, for each track
  - We have the properly corrected deposits y_i along the trajectory
  - Minimize the joint energy-deposit χ^2 for a track
  - False hit removal (energy deposit outliers)
  - We get the estimate of $\log \varepsilon$

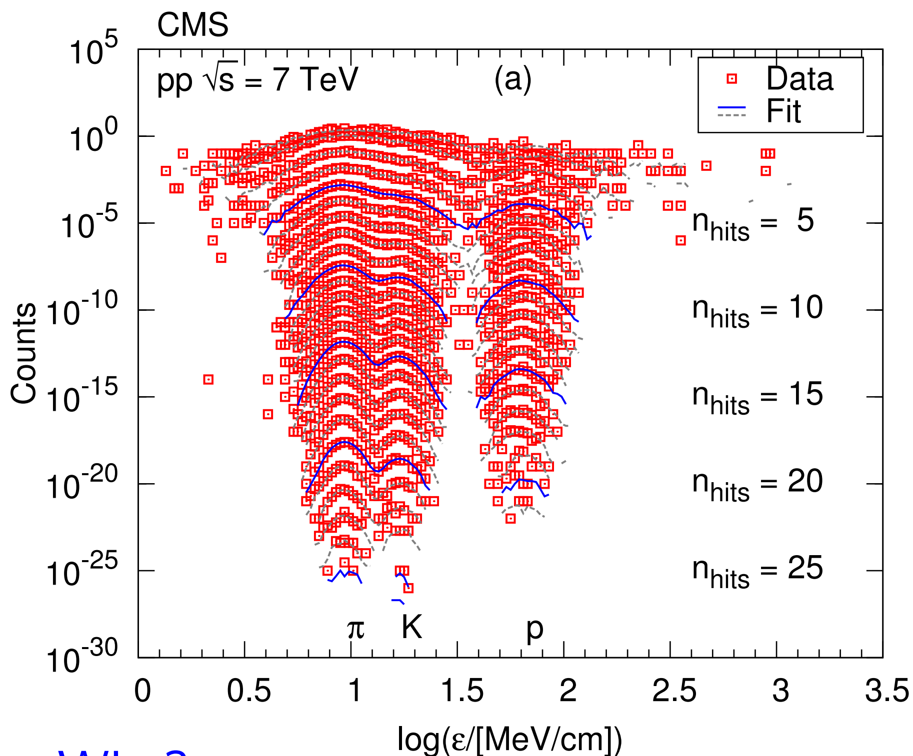
Fitting $\log \varepsilon$ distributions

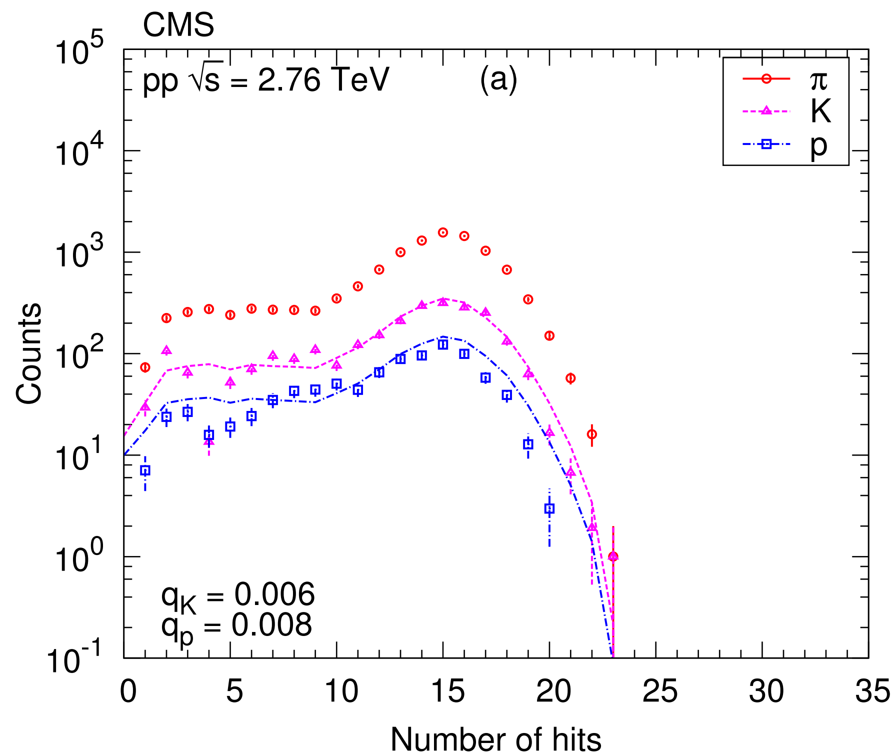


- Template fits
  - Use tracks in data
  - Keep all quantities, but regenerate each energy deposit according to the parametrization
  - Free parameters: track-level corrections (scale factors, shifts), particle yields

Need for additional information to better constrain fits at higher momentum

Fits in number-of-hits slices

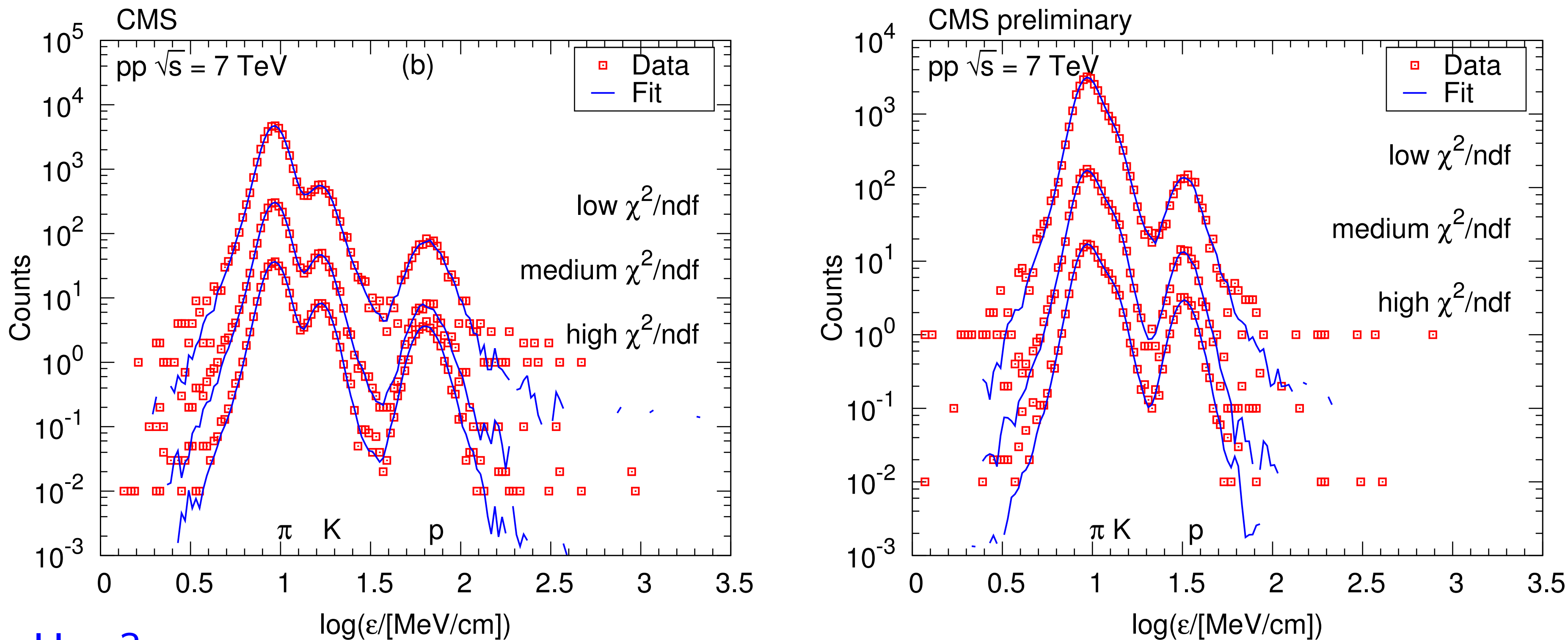




- Why?
  - Higher n_{hits} curves contain important information
  - Also: The pions usually have a higher average number of hits on track, less hits for kaons, and even less for protons
  - The n_{hits} distribution of particle species differs in an (η, p_T) bin, they are even related $g_k = r\left[(1-q)^k f_k + (1-q)^k q \sum_{n=k+1}^{\infty} f_n\right]$, where q is the additional loss q wrt pions, r is the ratio of abundances $(= g/f)$

Differential fits in n_{hits}

Fits in track-fit χ^2/ndf slices

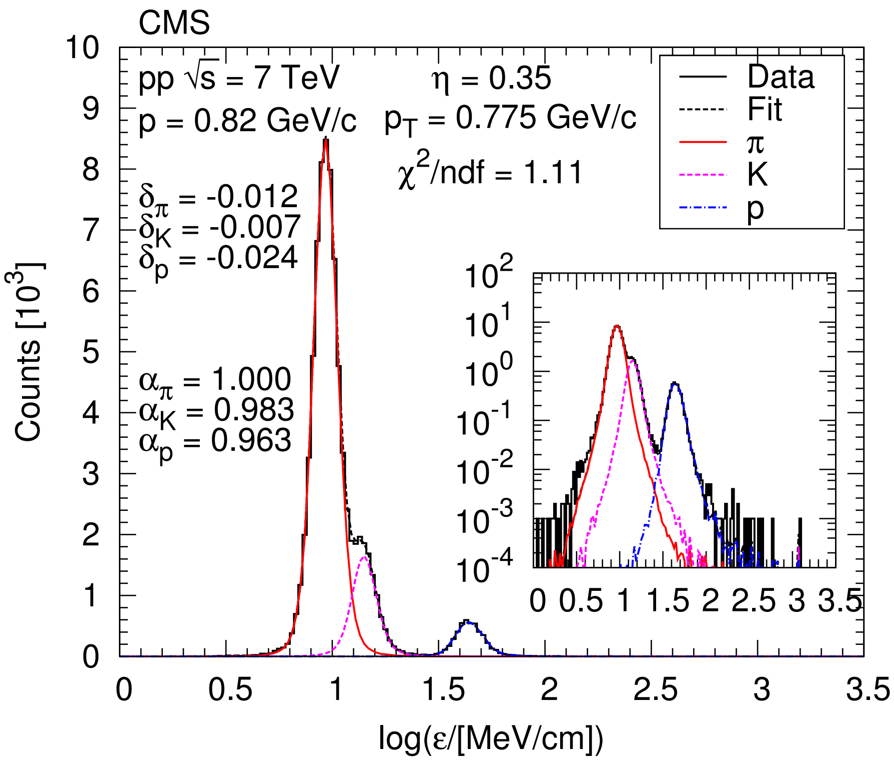


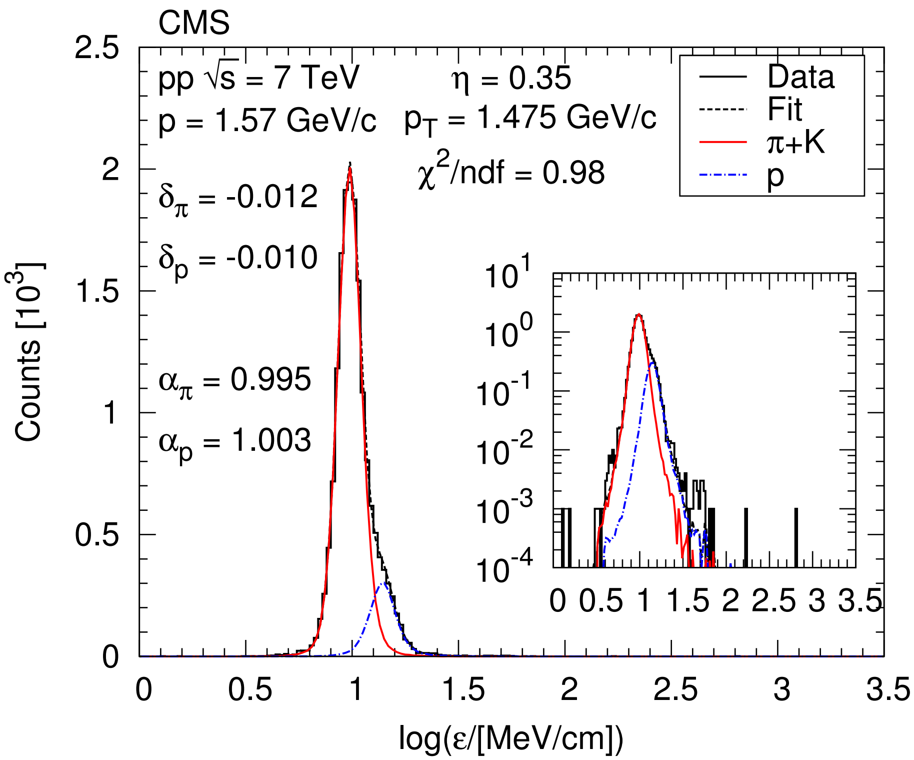
- How?
  - The global track-fit χ^2/ndf is obtained with pion mass m_0 assumption using the known physics of multiple scattering and energy loss
  - For pions $x = \sqrt{\chi^2/n}$ is Gaussian with mean 1, and $\sigma \approx 1/\sqrt{2\text{n}}$
  - For other particles with mass m this is scaled up by $\beta(m_0)/\beta(m)$
  - Define three classes (low = enh pion, medium = enh kaon, high = enh proton)

F. Sikler, "Particle identification with a track fit χ^2",
Nucl. Instrum. Meth. A 620 (2010) 477-483

Differential fits in χ^2/ndf

Fits in (η, p_T) bins





Total momentum range used for physics is limited by systematics

- Corrections
  - Acceptance, tracking efficiency, multiple reco and fate rate, secondaries
  - Unfold p_T spectra in η slices
  - Transform values from (η, p_T) to (y, p_T) map

Final results are $\frac{1}{N_{\text{ev}}} \frac{d^2N}{dy\,dp_T}$

Tsallis-Pareto-type distributions

By now a well known functional form, success at RHIC – LHC:

$$\frac{d^2N}{dy dp_T} = \frac{dN}{dy} \cdot C \cdot p_T \left[1 + \frac{(m_T - m)}{nT}\right]^{-n}$$

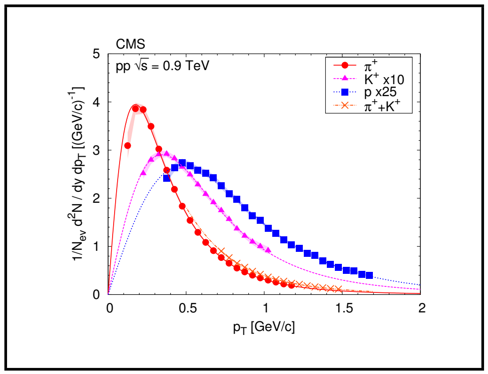
where

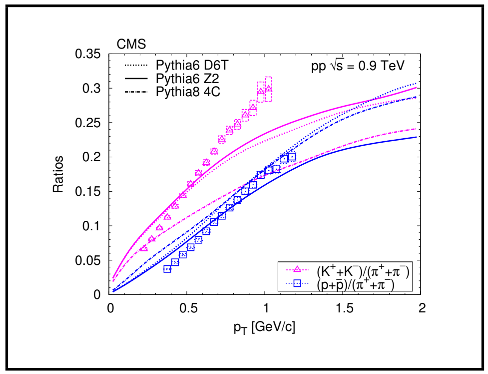
$$C = \frac{(n-1)(n-2)}{nT[nT + (n-2)m]}, \qquad m_T = \sqrt{m^2 + p_T^2}.$$

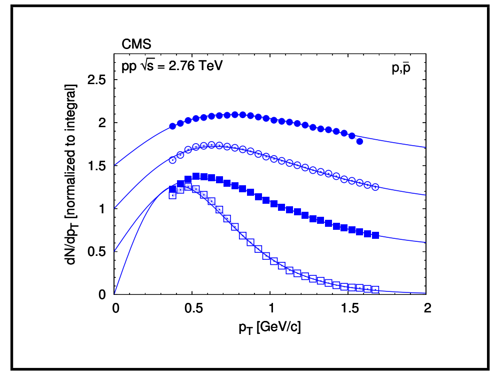
With roots in non-extensive statistics; a Lévy function
n – exponent, T – inverse slope parameter, m – particle mass
$\langle p_T \rangle$ is calculable with Monte Carlo integration

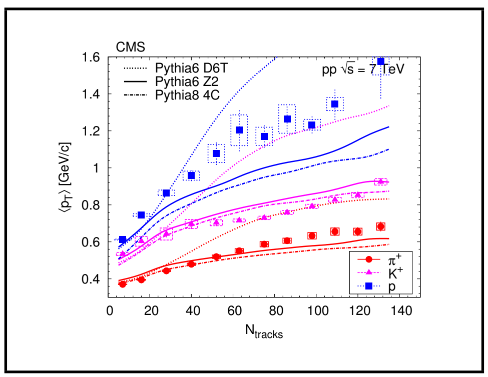
Regions where only the sum is accessible constrain both π and K yields

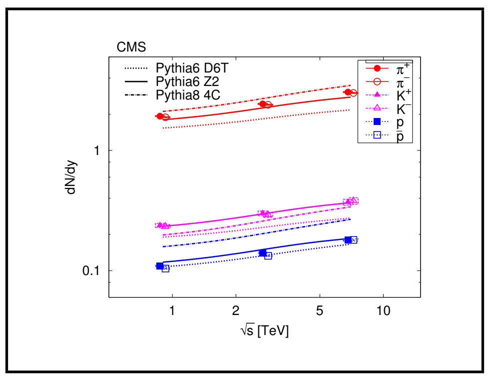
Physics results

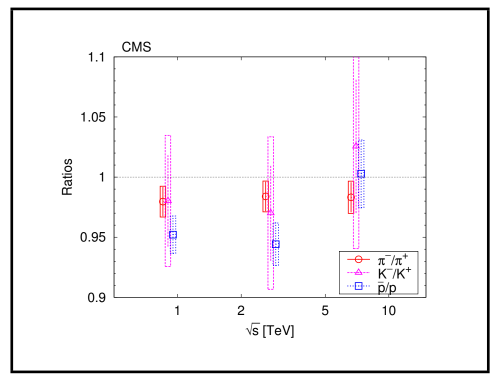




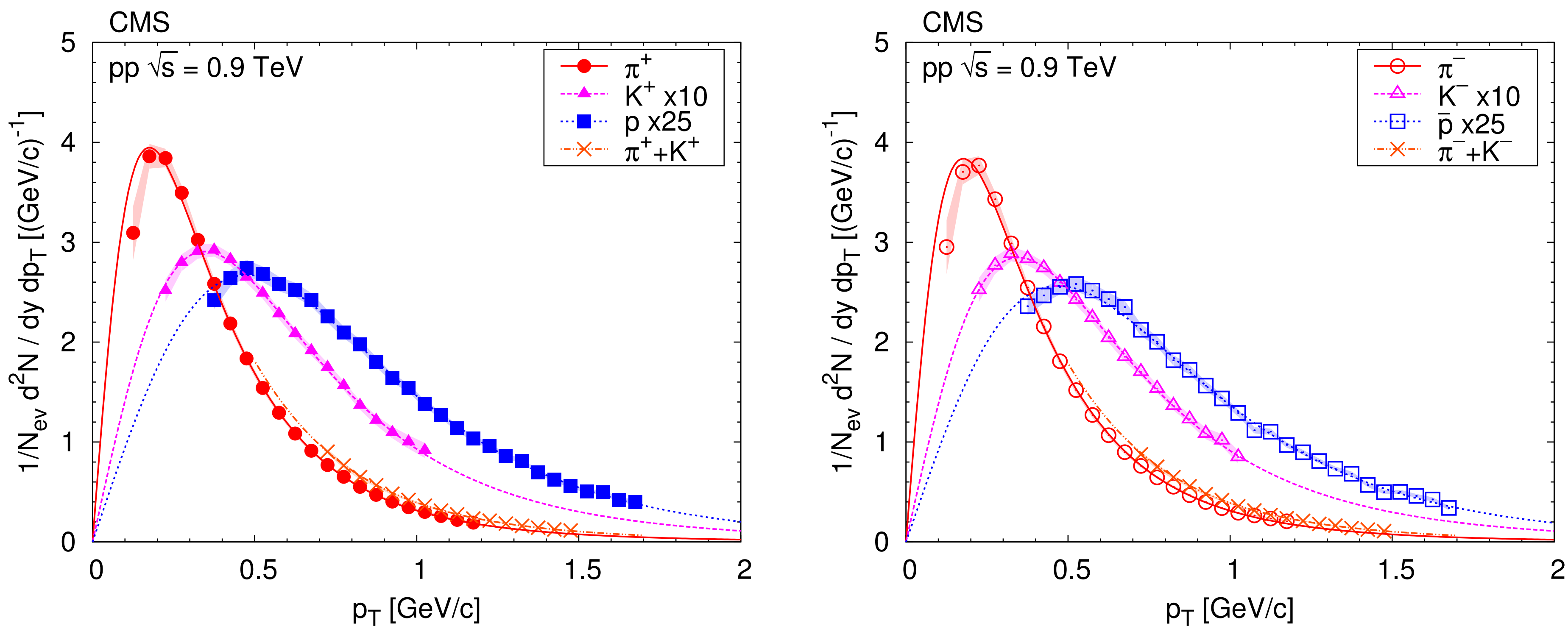






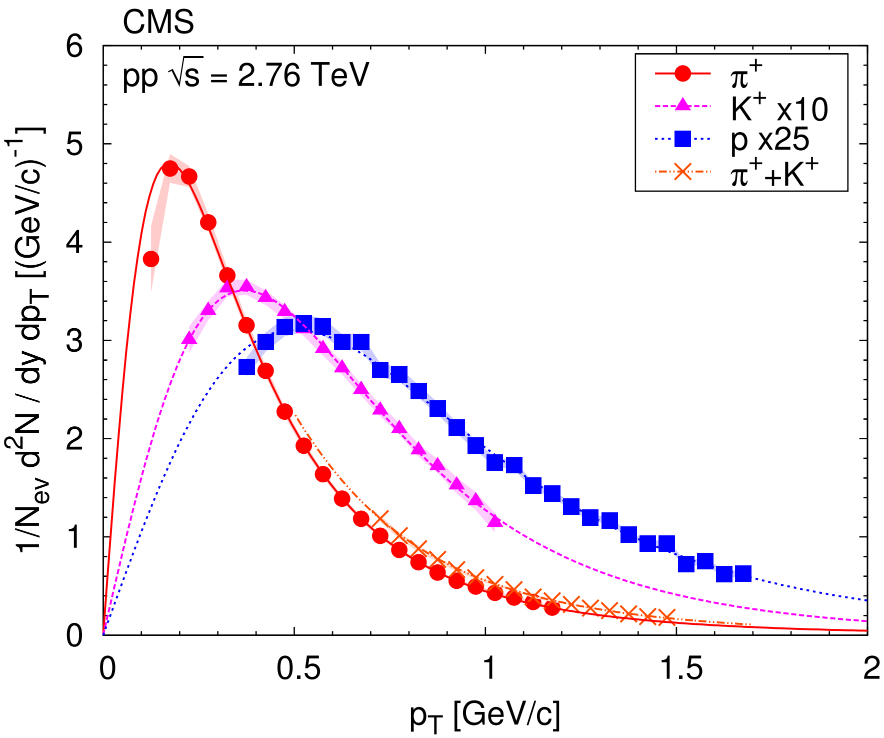


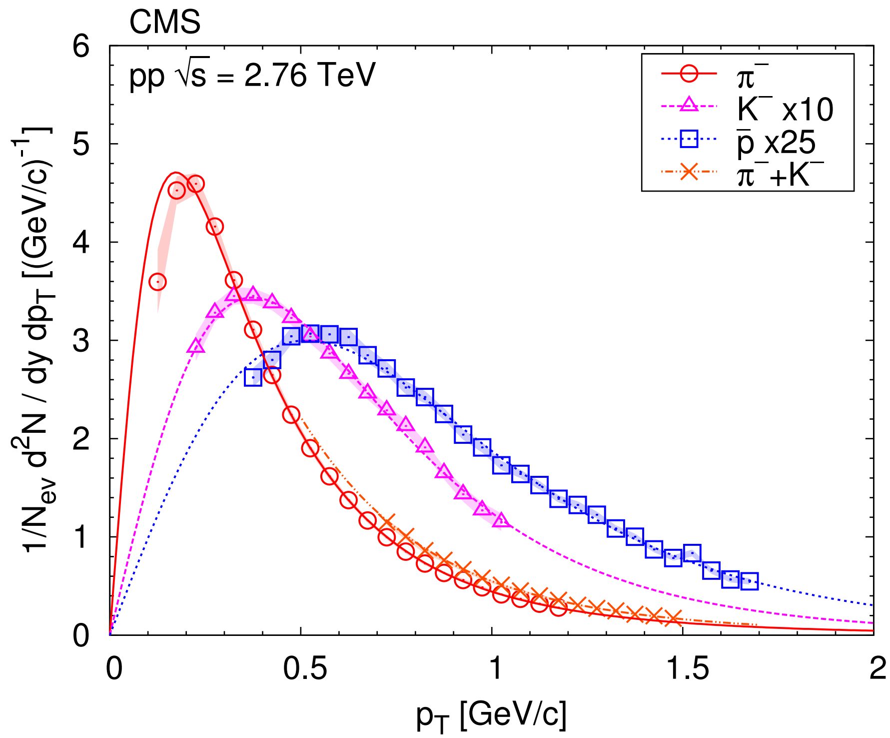
Results – p_T spectra



Results are corrected to a double-sided selection (DS):
at least one particle with E $>$ 3 GeV on both sides
$(-5 < \eta < -3$ and $3 < \eta < 5)$

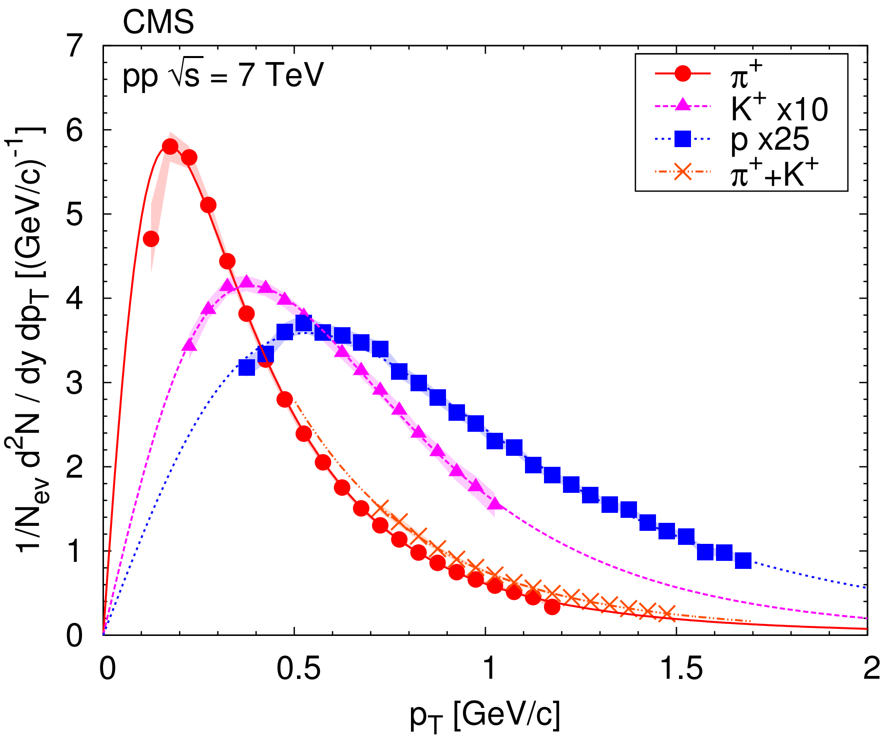
Results – p_T spectra

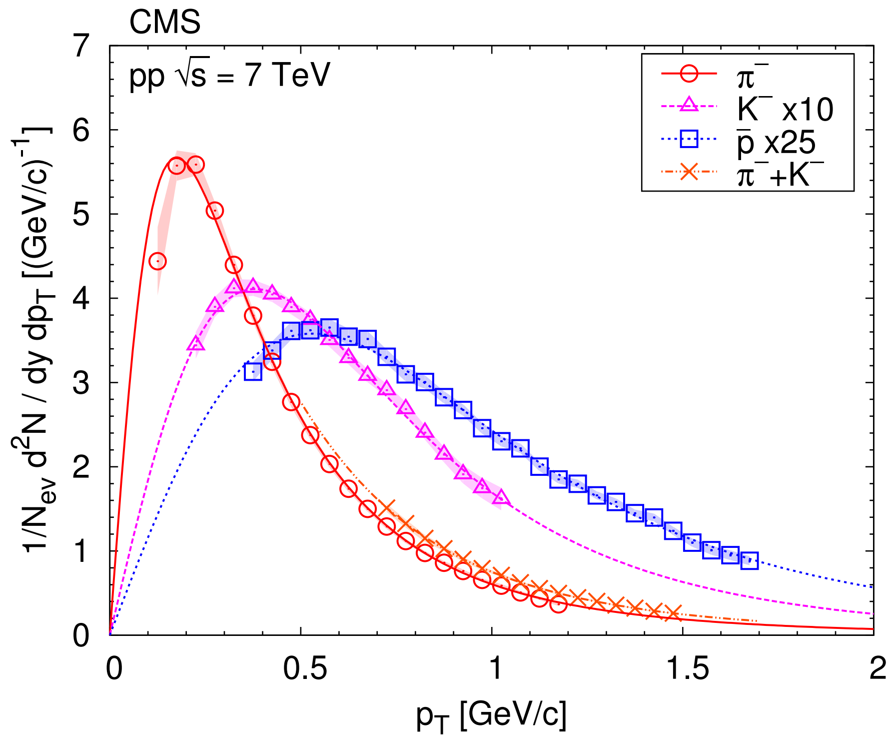




The fits are usually of good quality

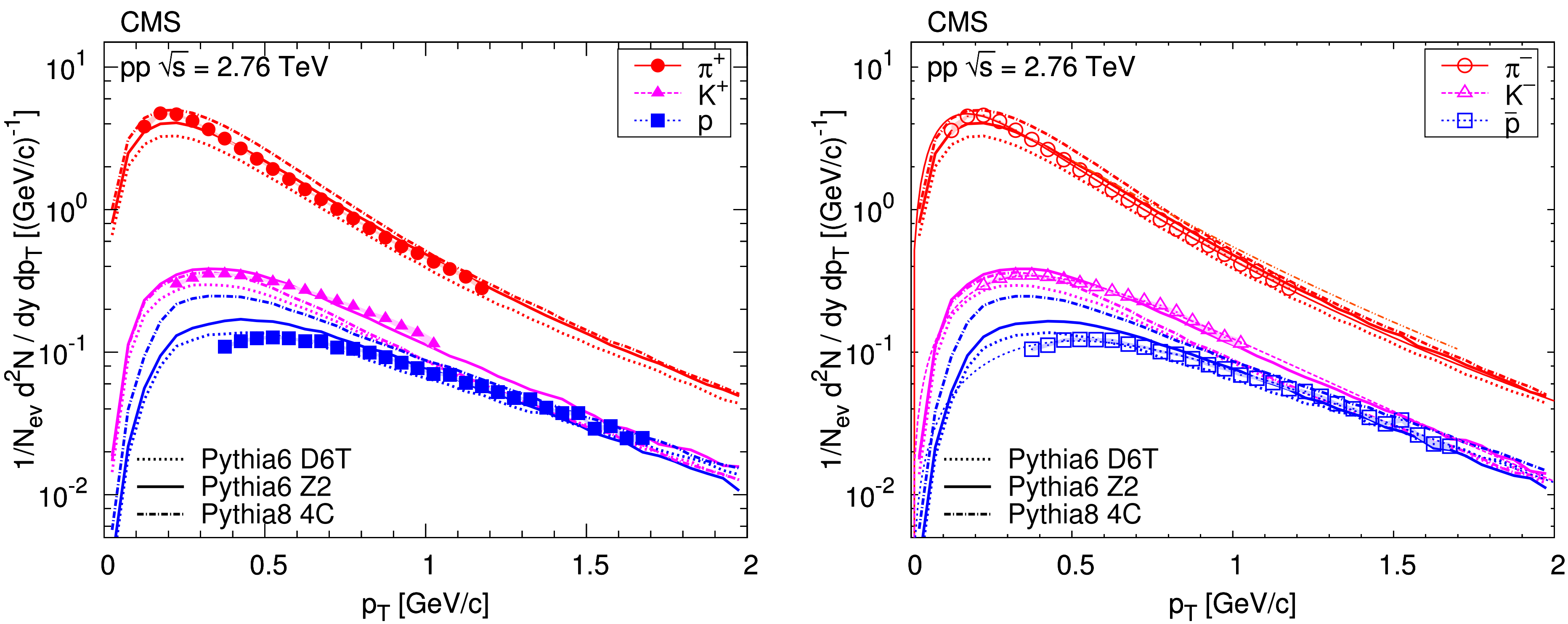
Results – p_T spectra





With χ^2/ndf values in the range 0.6-1.5 for pions, 0.6-2.1 for kaons, and 0.4-1.1 for protons

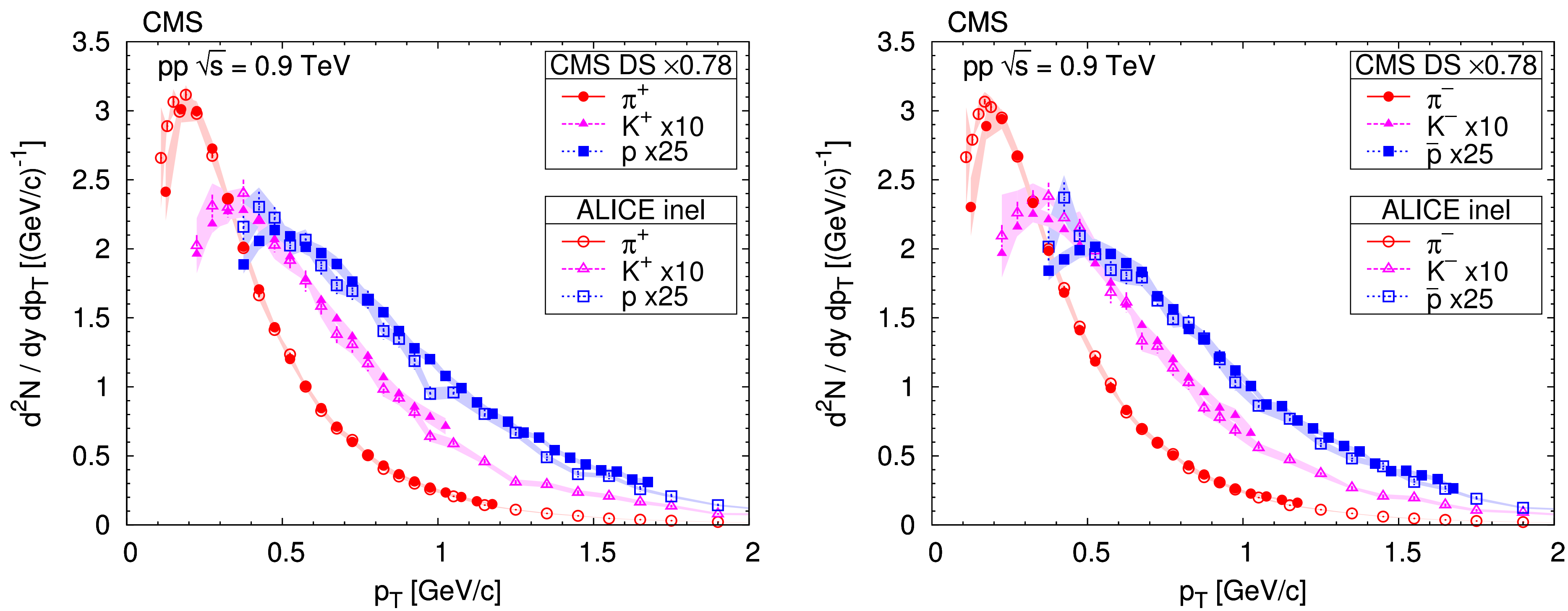
Results – p_T spectra



Logarithmic scale, comparison to models

Pythia6 D6T and Pythia8 4C tend to systematically under/overshoot the spectra
Pythia6 Z2 is generally closer to the measurements (except for low-p_T protons)

Results – comparison to ALICE at 0.9 TeV

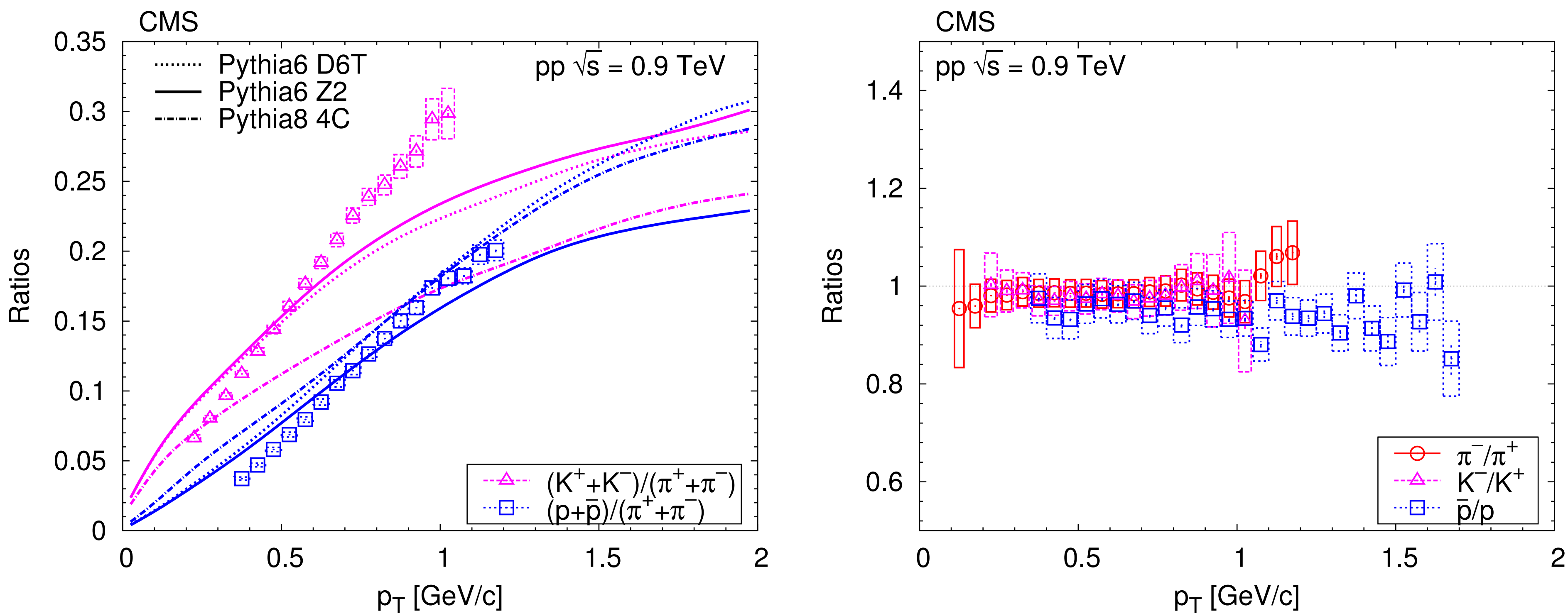


ALICE Collaboration, "Production of pions, kaons and protons in pp collisions at sqrt(s)= 900 GeV with ALICE at the LHC"
Eur.Phys.J. **C71** (2011) 1655

Nice agreement; ALICE gives numbers corrected to inel

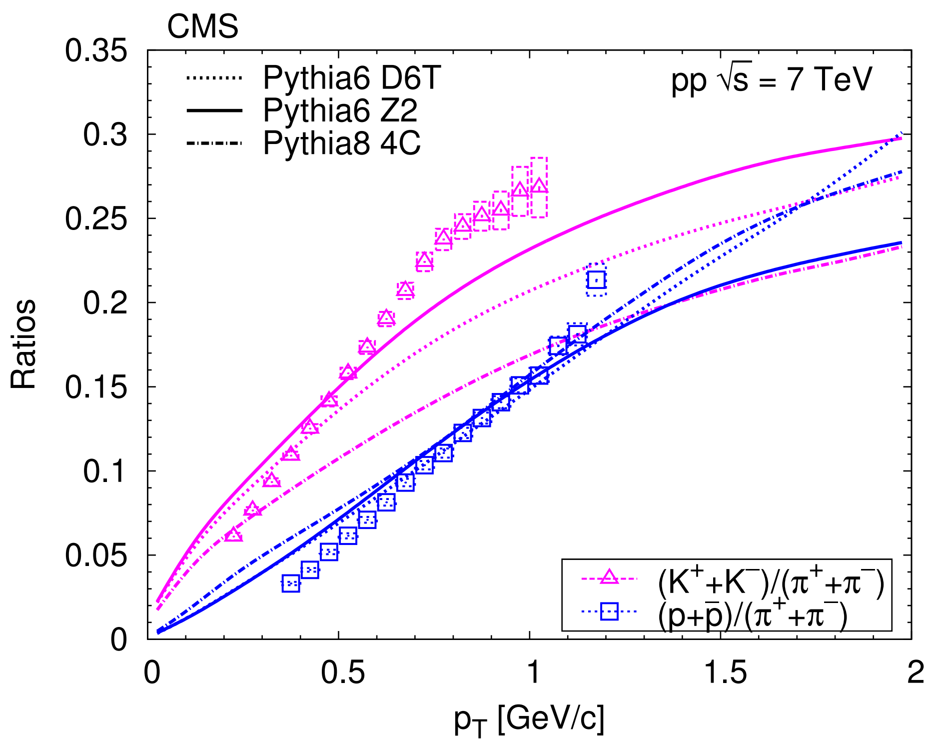
A scale factor of 0.78 was needed for CMS data, about that is expected from models

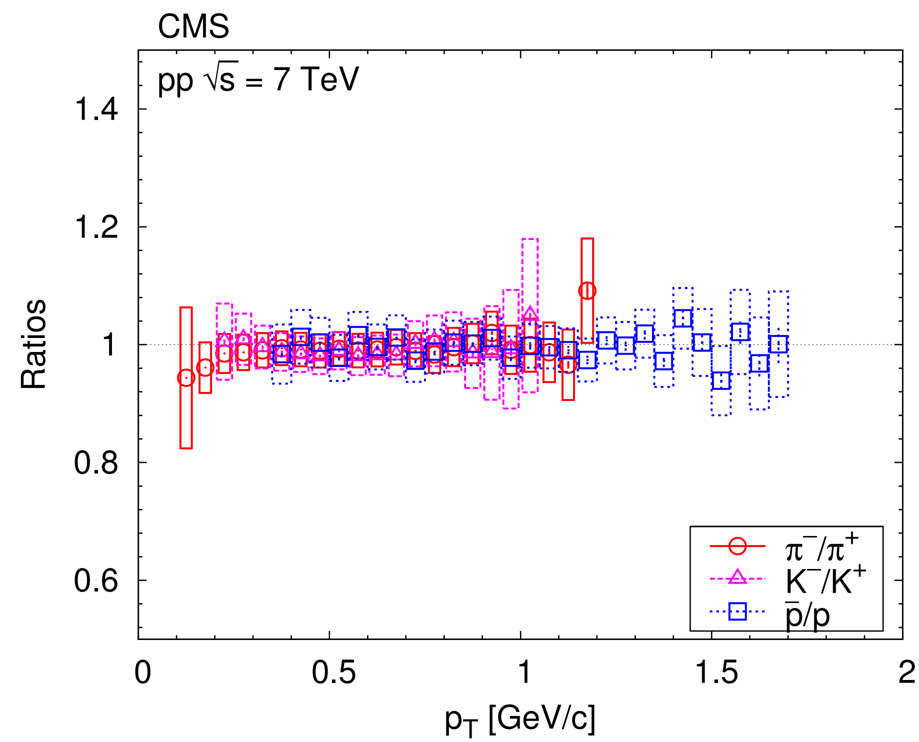
Results – ratios of p_T spectra



- p_T dependence
  - p/π ratios are are well described by all tunes
  - There are substantial deviations in case of K/π ratios
  - Ratios of opposite charged pions are around 1
  - Ratios of kaons are compatible with 1, independent of p_T

Results – ratios of p_T spectra





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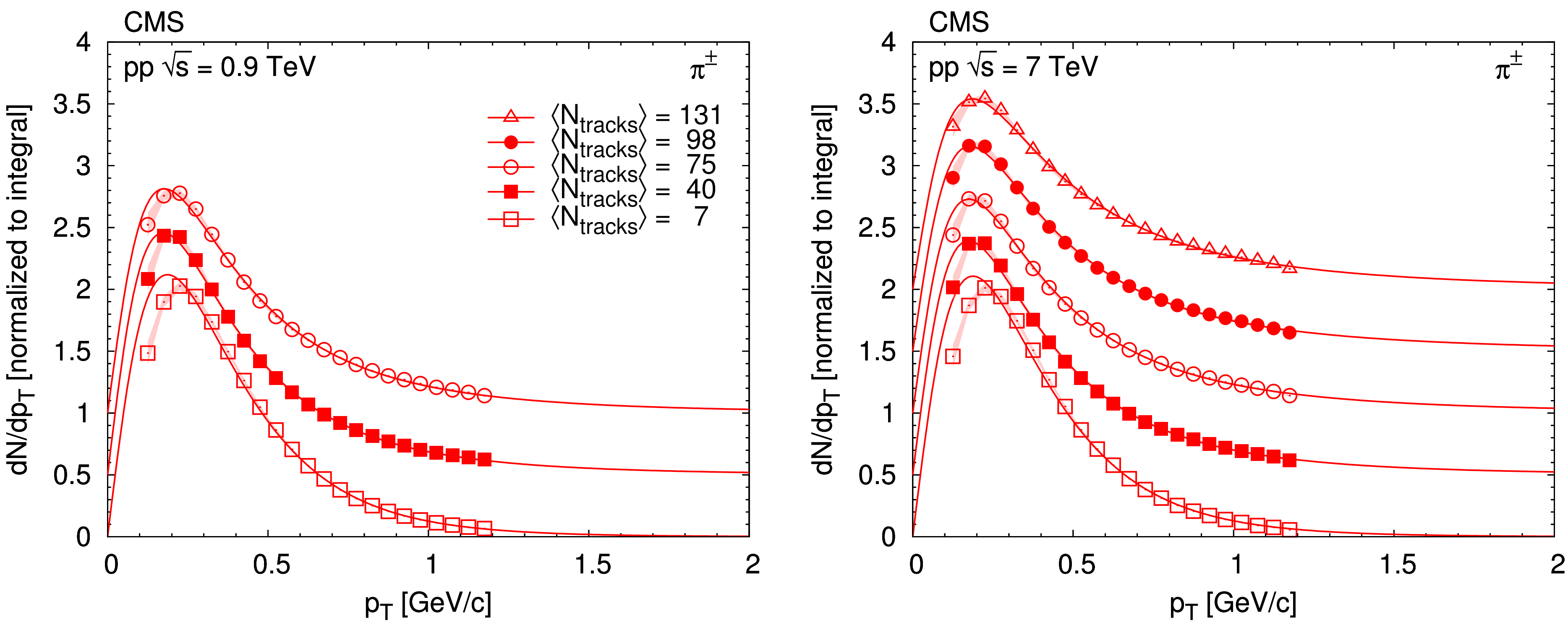
While the $\overline{\mathrm{p}}/\mathrm{p}$ ratios are also flat, they show an increase with increasing $\sqrt{s}$

Results – multiplicity dependence – pions

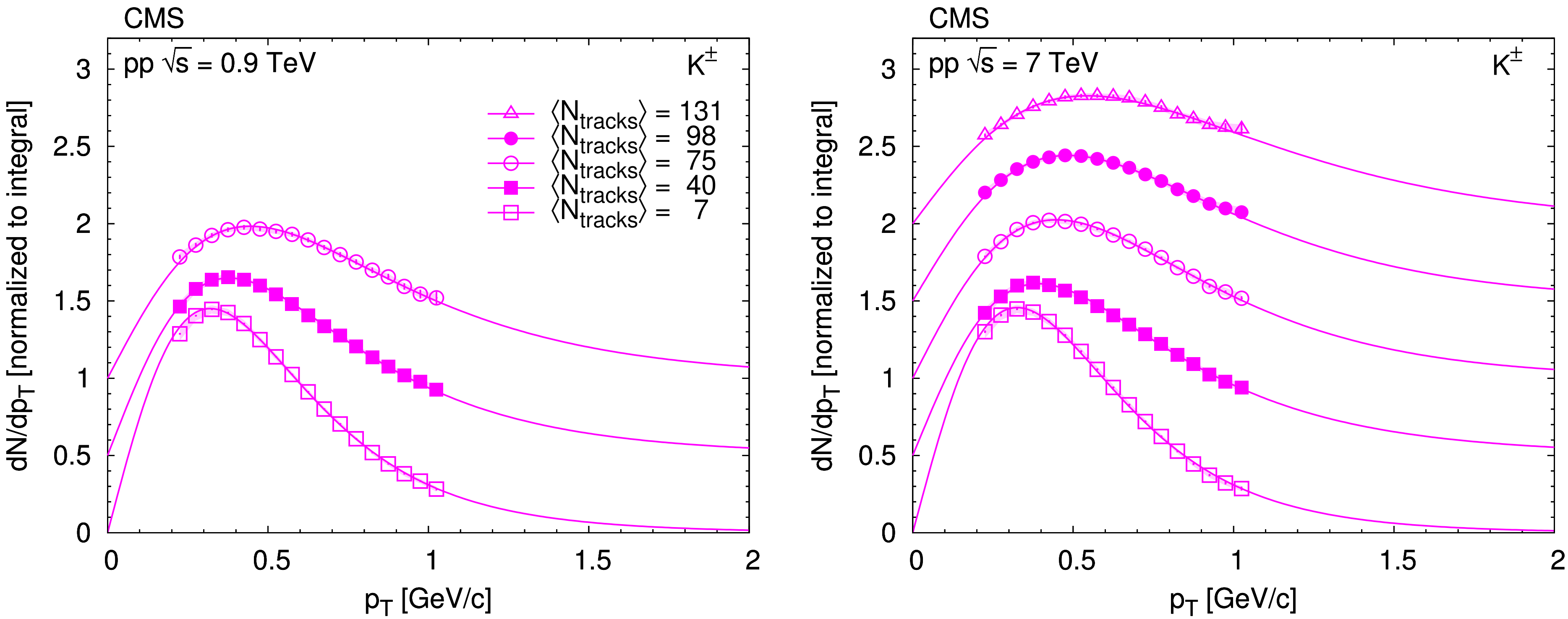


Multiplicity classes: relate measured N_{rec} to true $\langle N_{\text{tracks}} \rangle$ in $|\eta| < 2.4$

N_{rec}	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100-109	110-119
$\langle N_{\text{tracks}} \rangle$	7	16	28	40	52	63	75	86	98	109	120	131

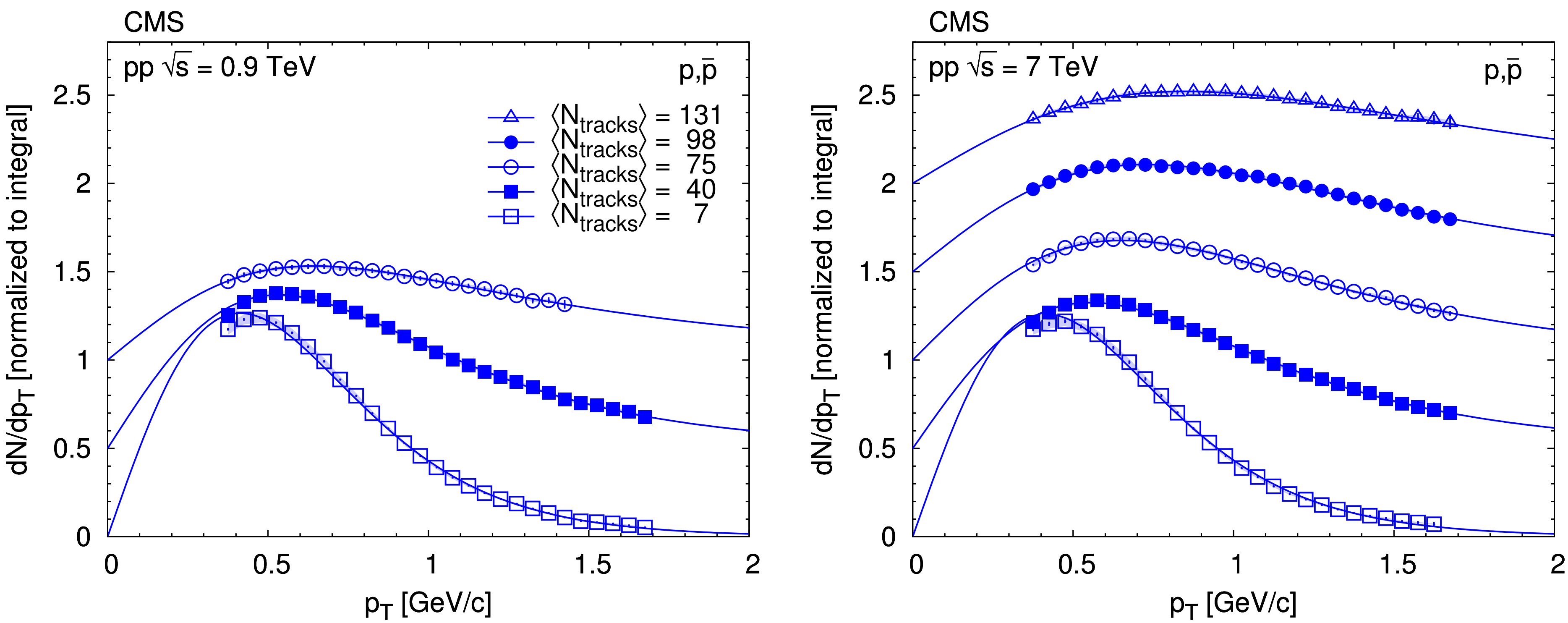
Unchanged shapes

Results – multiplicity dependence – kaons



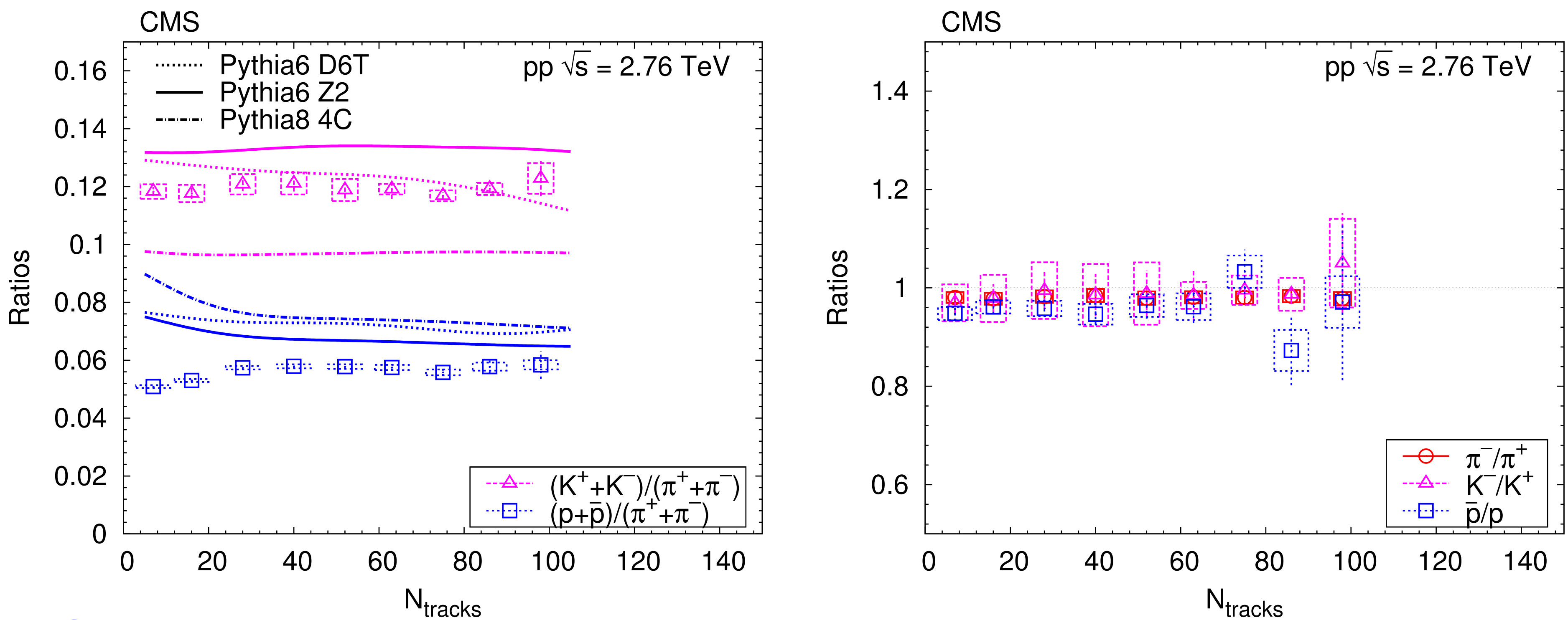
Harder spectral shape with increasing multiplicity

Results – multiplicity dependence – protons



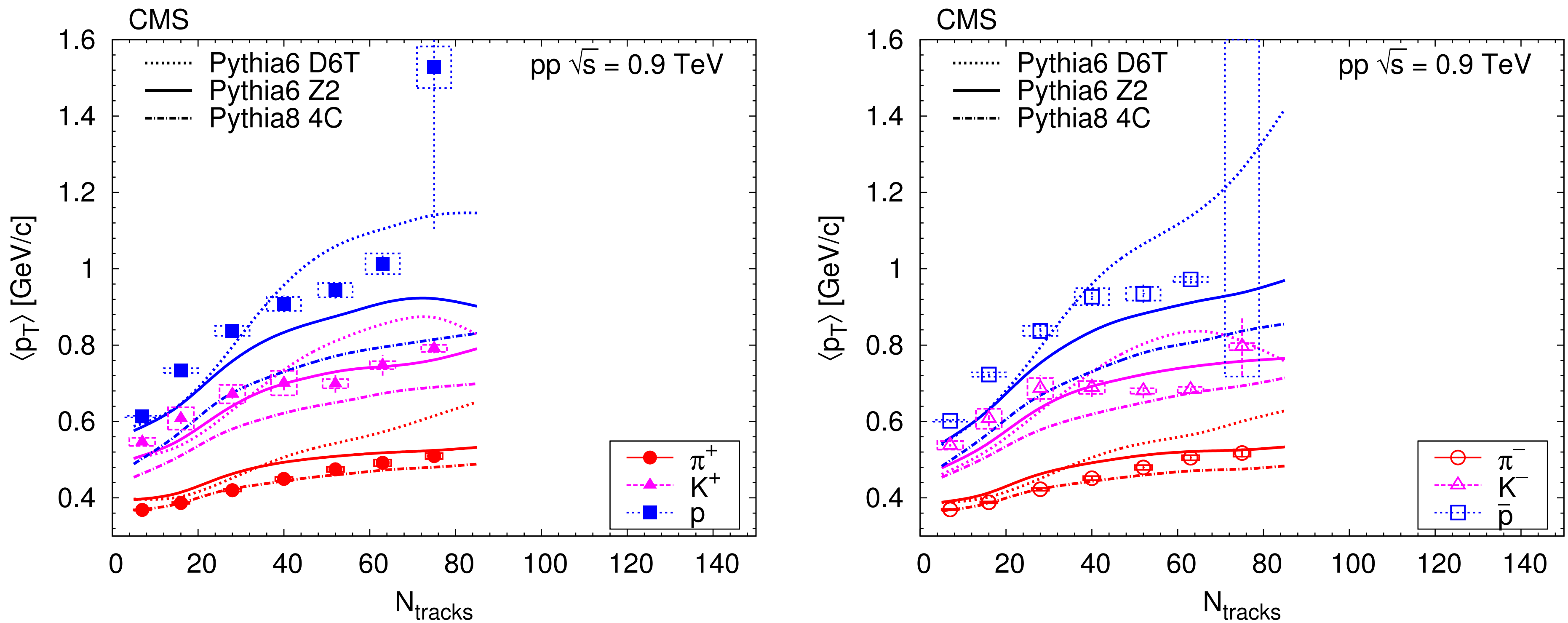
Harder spectral shape with increasing multiplicity

Results – ratios – multiplicity dependence



- Cross ratios
  - K/π and p/π ratios are flat, reasonably described by Pythia D6T and Z2
  - Pythia8 4C is off, especially for K/π
- Opposite charge ratios
  - The ratio π^-/π^+ is around 0.98, due to the initial charge asymmetry
  - The ratio of kaons is compatible with 1
  - While the $\overline{\mathrm{p}}/\mathrm{p}$ ratios are also flat, they show an increase with increasing $\sqrt{s}$

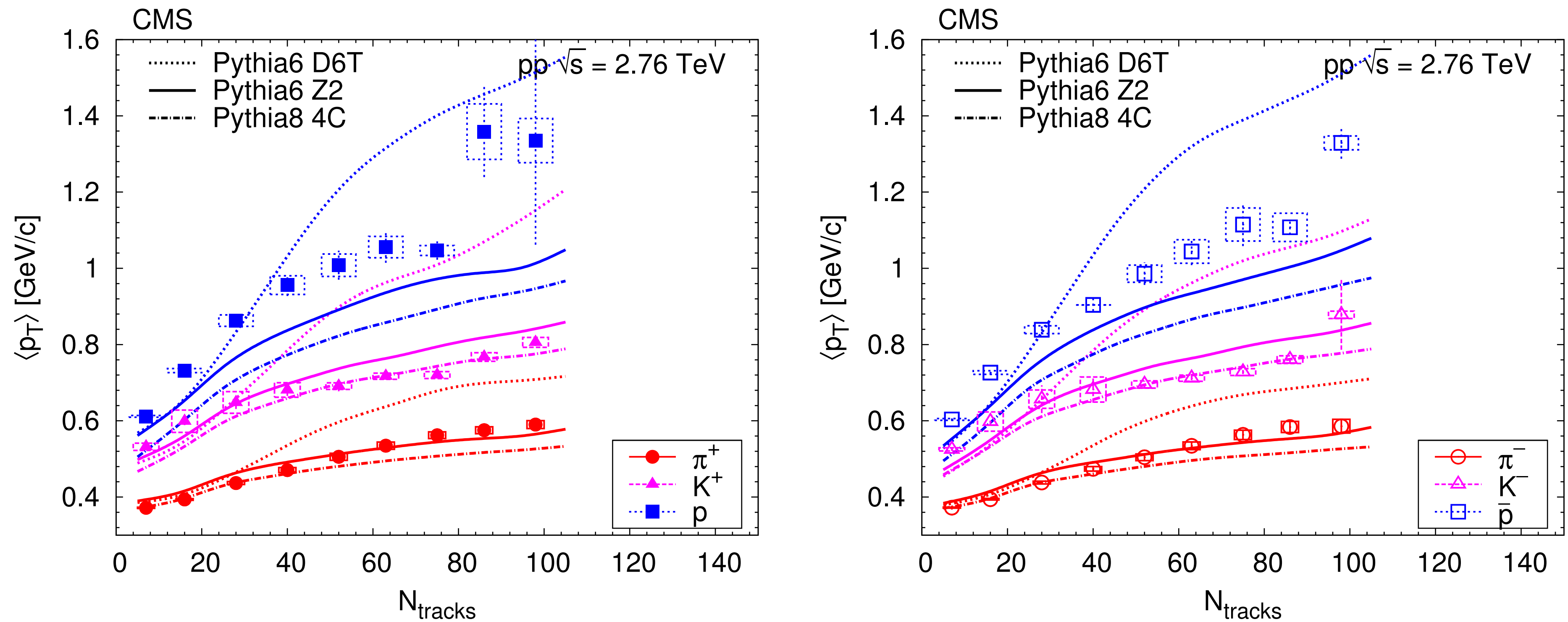
Results – $\langle p_T \rangle$ – multiplicity dependence



Calculated using MC technique followed by numerical integrations

Errorbars will show the combined $\sqrt{\mathrm{stat}^2 + \mathrm{syst}^2}$ errors, boxes give systematic only

Results – $\langle p_T \rangle$ – multiplicity dependence



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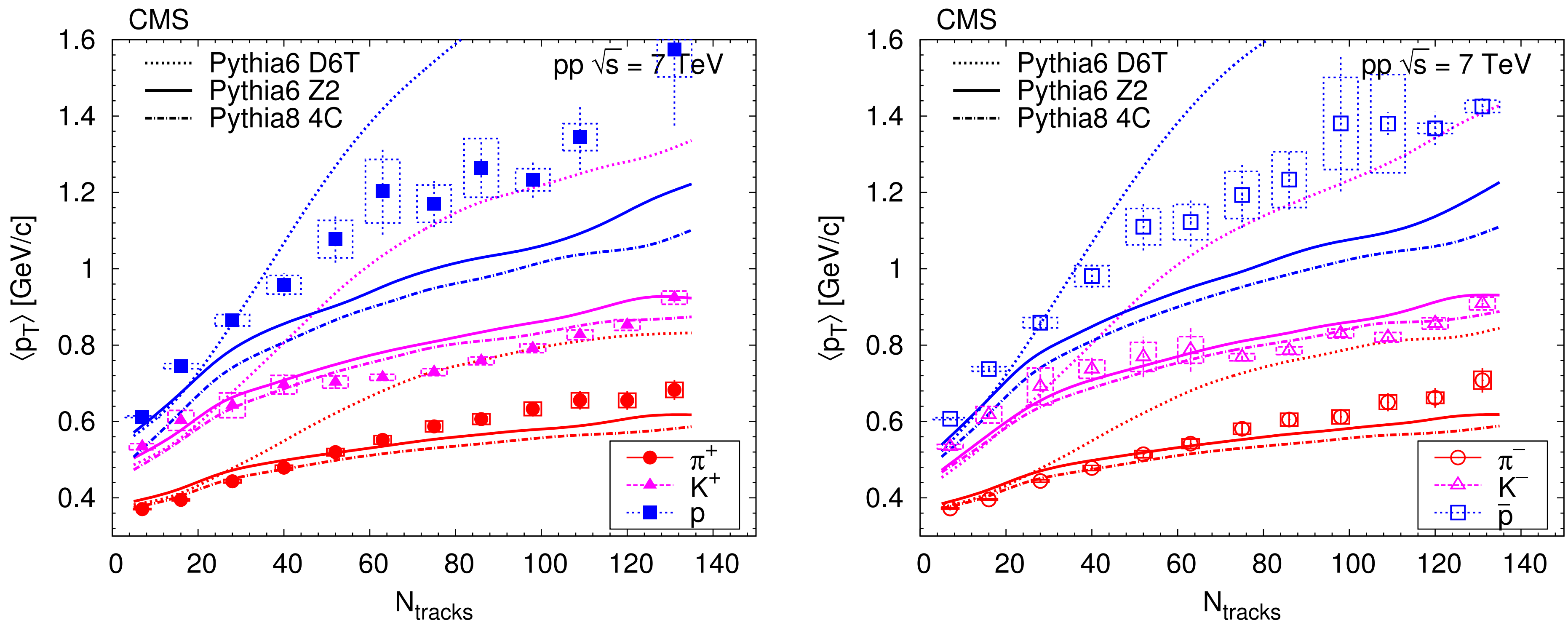
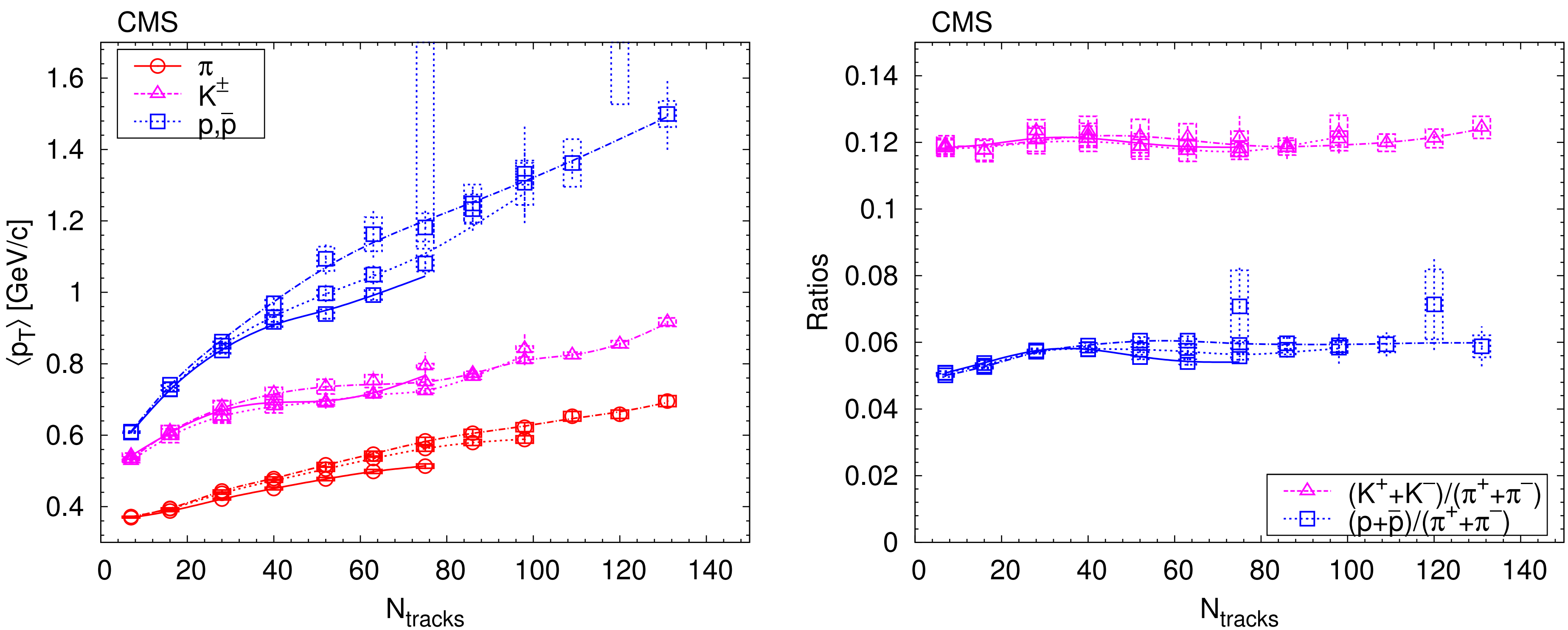
Results – $\langle p_T \rangle$ – multiplicity dependence



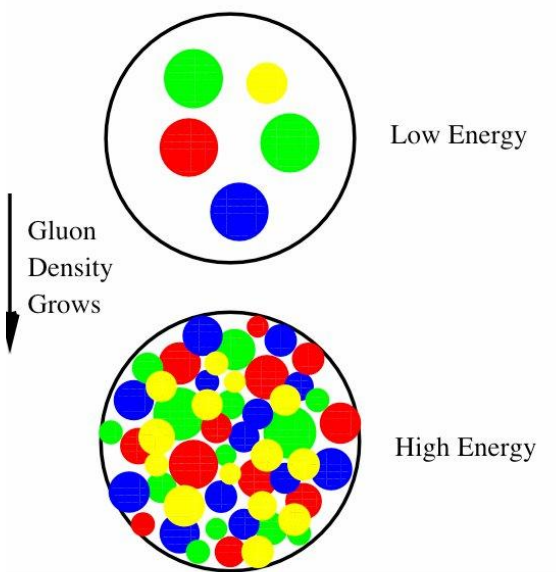
- Observations
  - Distributions are remarkably similar, in practice independent of $\sqrt{s}$ and multiplicity
  - Pions and kaons are well described by Pythia6 Z2 and Pythia8 4C
  - Pythia6 D6T usually predicts too high values at higher multiplicities
  - Protons behave differently and none of the tunes give acceptable description

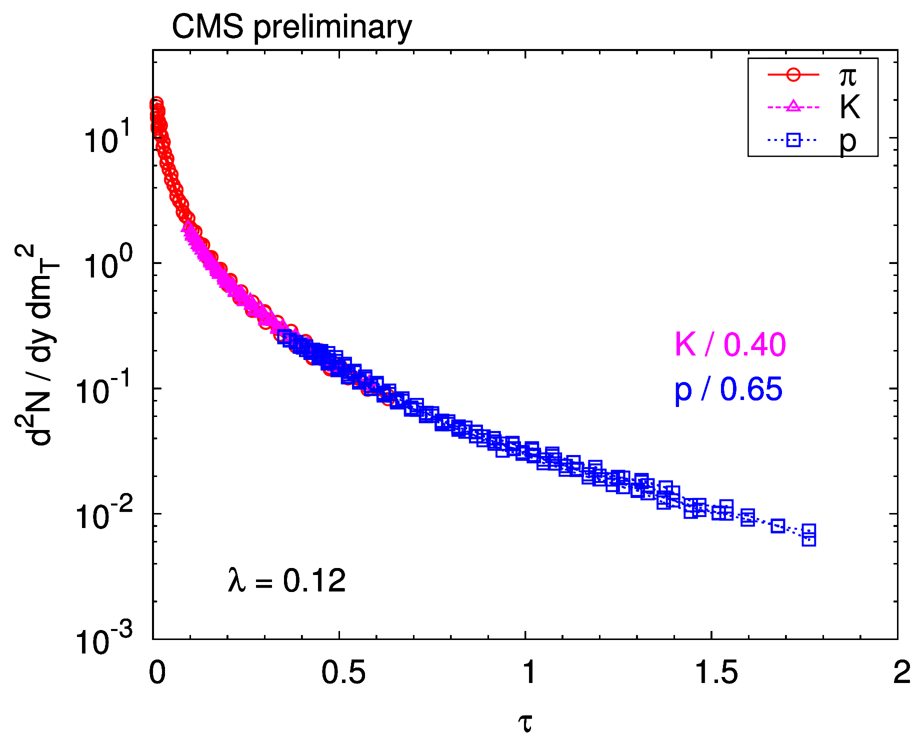
Results – universal multiplicity-dependence



Multiplicity-dependences are very similar for the three collision energies
Energy independence? Universal dependence of $\langle p_T \rangle$ and yield-ratios?

Other ideas – scaling





FS

$$Q_{\text{sat}} = Q_0(p_T/\sqrt{s})^{-\lambda/2} \qquad \tau = m_{\text{T}}^{2+\lambda}/(Q_0^2\sqrt{s}^{\lambda})$$

With $\lambda = 0.12$ for pions, kaons, andprotons; for all $\sqrt{s}$

Gluon saturation – geometrical scaling

M. Praszalowicz et al

Summary

- Energy loss parametrization
  - Few parameters, good precision
  - Can be used for several tasks (gain calibration, energy loss rate estimation)

- Application in CMS – particle spectra
  - Particle production at LHC energies is **correlated with event multiplicity** rather than with the center-of-mass energy of the collision
  - At TeV energies, the characteristics of particle production are constrained by the amount of **initial parton energy** that is available in any given collision

Thank you for your attention!