New results on multiplicites and particle spectra

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3 December 2012

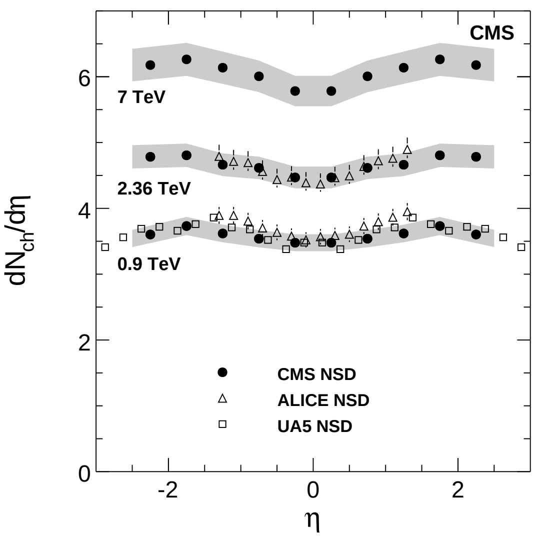
Outline

- Previous CMS measurements
  - Charged hadrons, K^0_S, $\Lambda/\overline{\Lambda}$, $\Xi^-/\overline{\Xi}^+$
- Showing this time: identified charged hadrons
  - Trigger, tracking, vertexing
  - Energy deposits and estimation of energy loss rate
  - Determination of particle yields
  - Corrections
  - Results
    - Inclusive measurements
    - Multiplicity-dependent measurements
  - Published in Eur Phys J C 72 (2012) 2164
  - All measured values are available in HepData at http://hepdata.cedar.ac.uk/view/ins1123117

pp $\sqrt{s} = 0.9$, 2.76 and 7 TeV

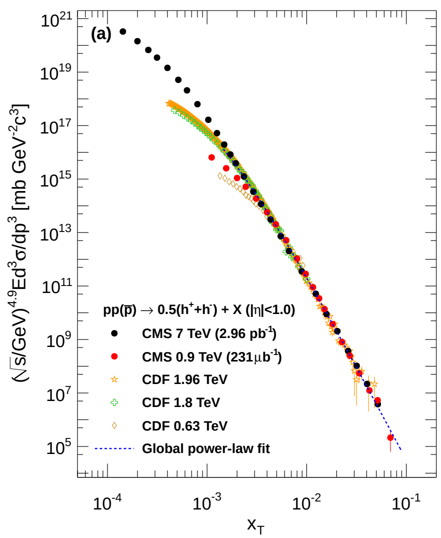
Analysis technique: energy deposits in silicon tracker, "dE/dx"

Previous CMS measurements

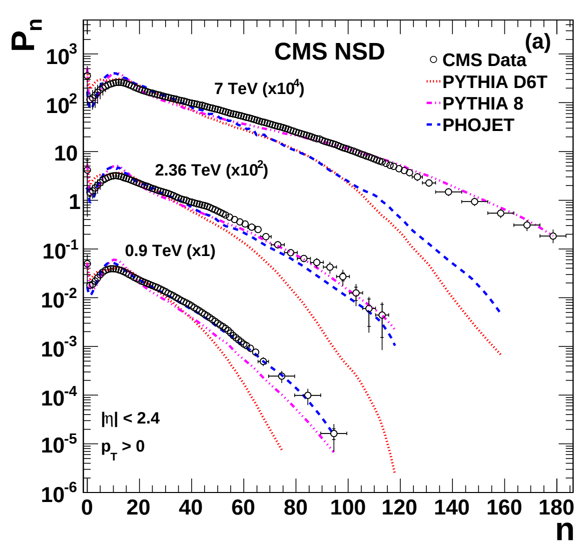


J. High Energy Phys. 02 (2010) 041

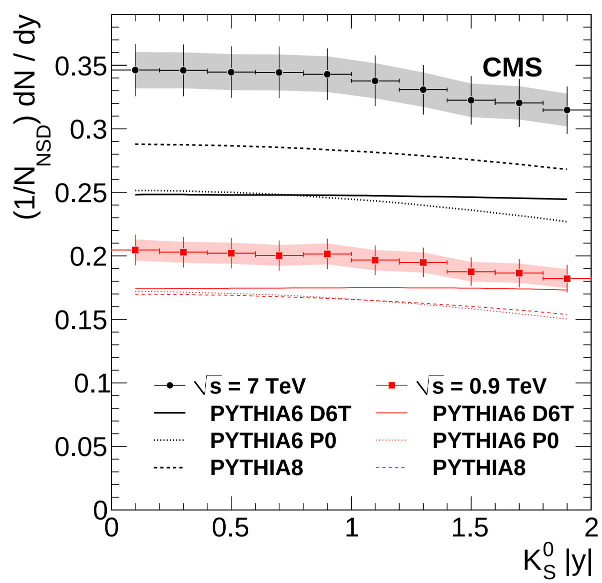
Phys. Rev. Lett. 105 (2010) 022002

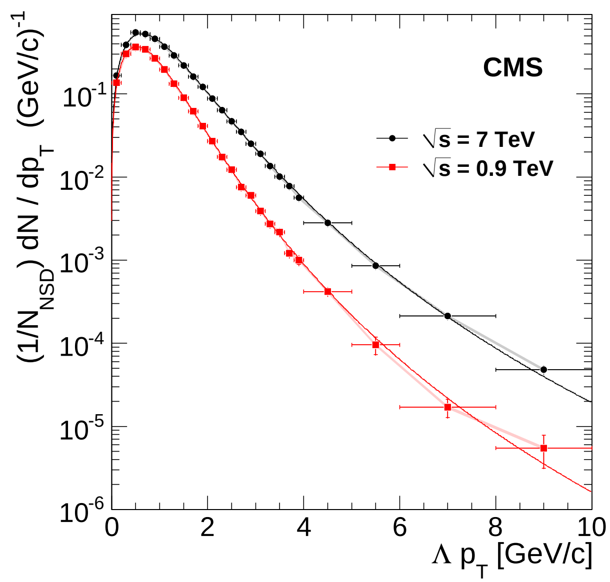


J. High Energy Phys. 08 (2011) 086



J. High Energy Phys. 01 (2011) 079



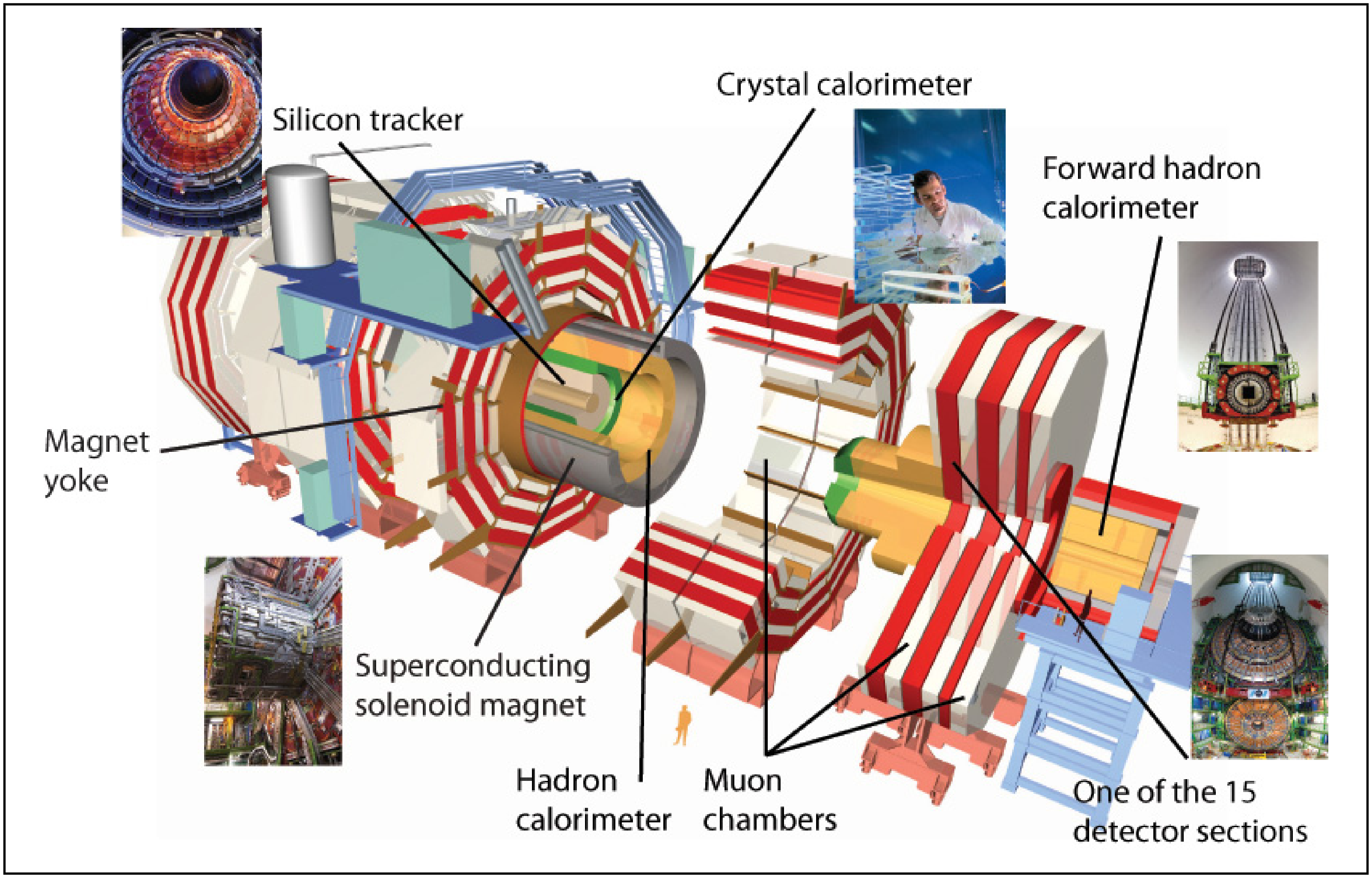


J. High Energy Phys. 05 (2011) 064

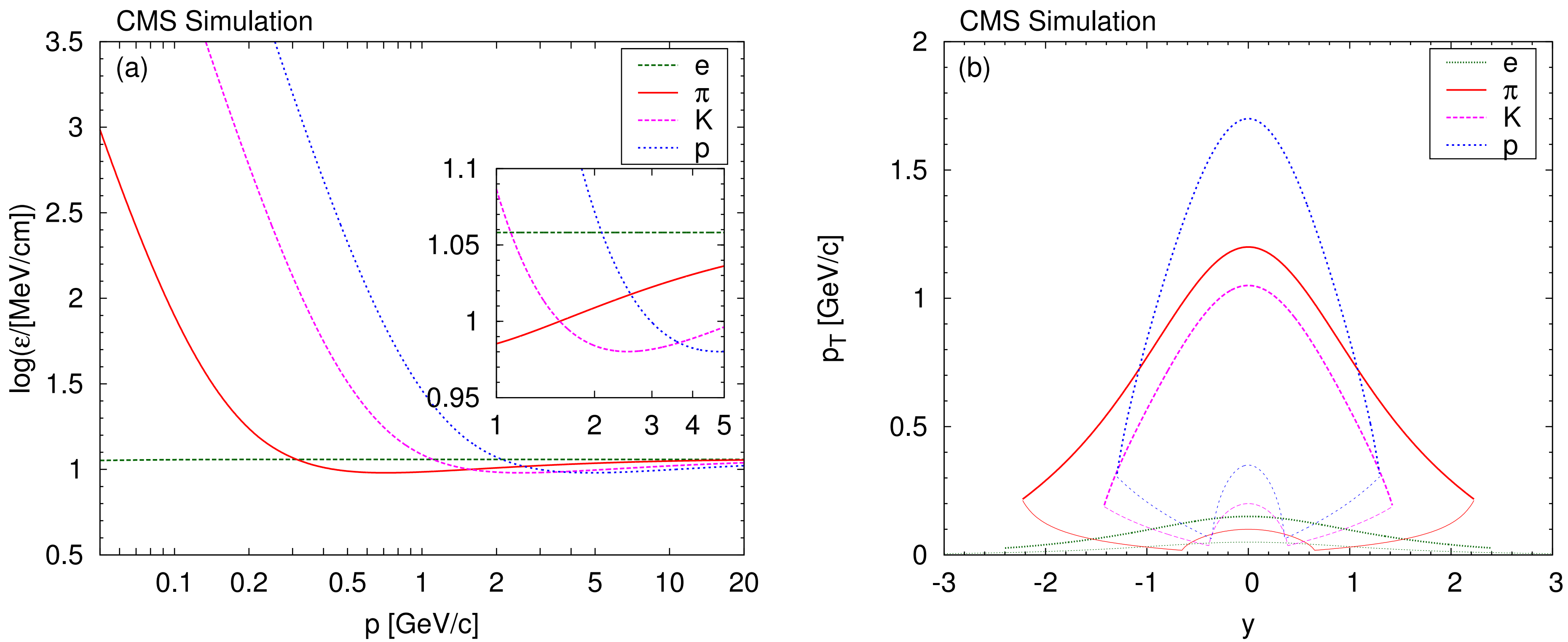
Spectra, $\langle p_T \rangle$, multiplicity: PhysicsResultsQCD#Hadrons

Can you identify or unfold charged hadrons?

Analysis techniques



The scene



- Hadron spectra
  - Long history in high energy particle, nuclear and cosmic ray physics
  - One of the simplest and most relevant physics quantities
  - Scaling properties of particle production; predictions of models and generators
  - PID: $p < 1.20$ for $\pi^{\pm}$, $p < 1.05$ for $\mathrm{K}^{\pm}$, and $p < 1.70$ GeV/c for $\mathrm{p}/\overline{\mathrm{p}}$

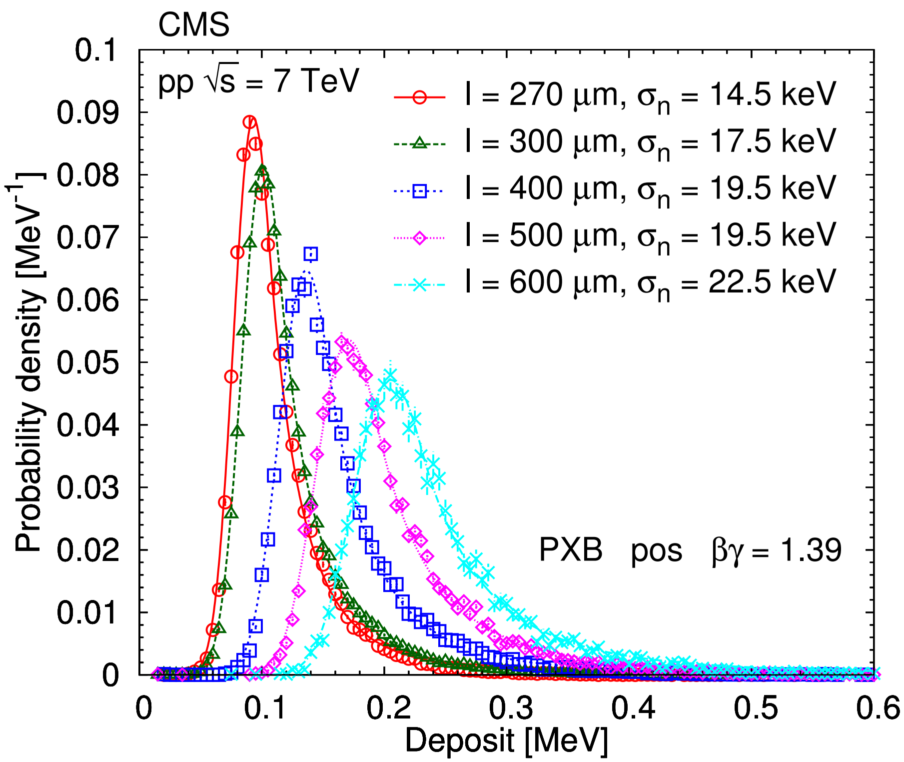
Accessible region is also limited by η acceptance of the tracker

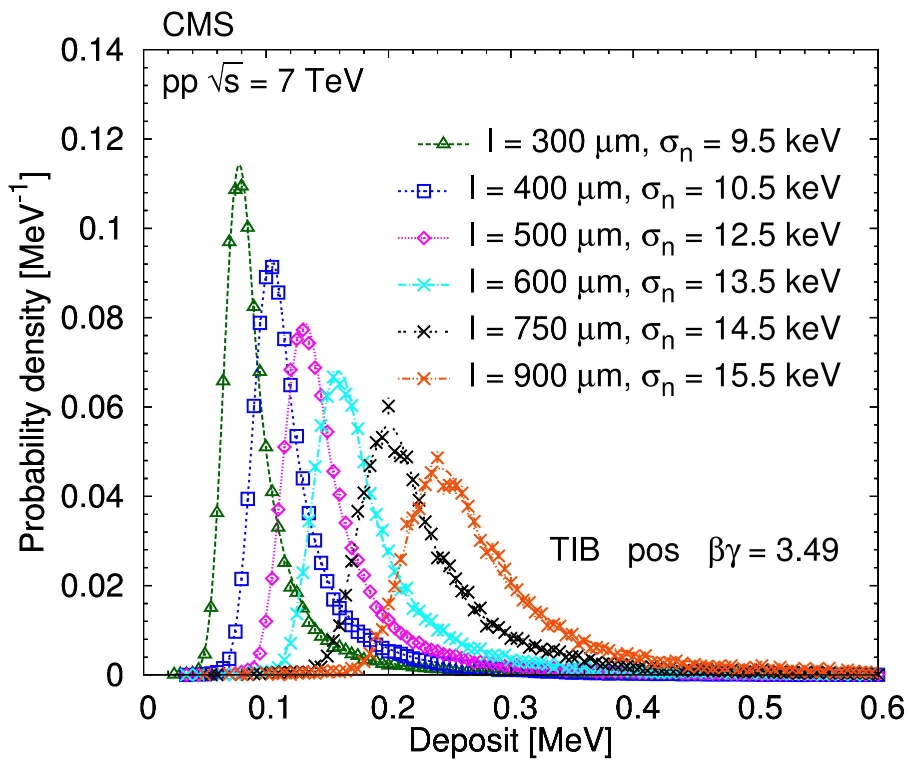
Final results are given for $|y| < 1$

Trigger, tracking, vertexing

- Online and offline triggers
  - Presence of both beams
  - Coincidence of at least one forward calorimeter (HF) tower with more than 3 GeV energy on each side
- Results are corrected to a double-sided selection (DS)
  - At least one particle with E $>$ 3 GeV on both sides ($-5 < \eta < -3$ and $3 < \eta < 5$), at generator level
  - Overall efficiency: 66-72% (0.9 TeV), 70-76% (2.76 TeV) and 73-78% (7 TeV).
  - About 90% of the selected events are ND, while the rest is DD or SD
- Minimum bias tracking
  - Low p_T and low fake rate tracking
  - At least three (two) hits to form a track
- Agglomerative vertexing
  - Takes z coordinate of tracks at the point of closest approach to the beam
  - Performs an agglomerative clustering by adding tracks to form groups
  - Stopping condition: keep both the number of merged and split vertices low

Analytical energy loss parametrization – validation





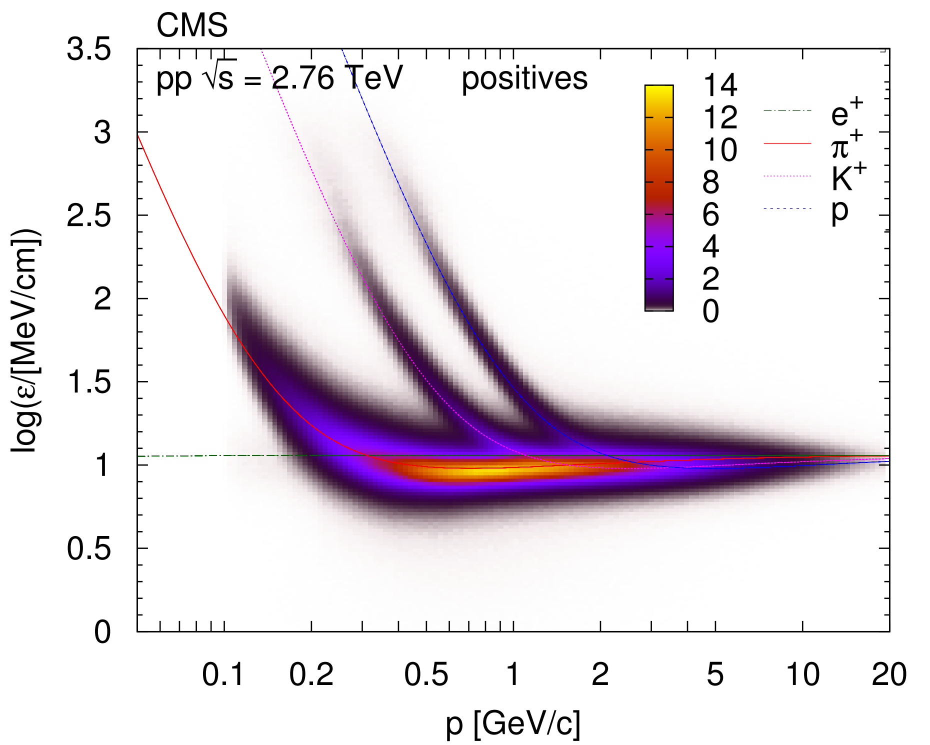
The central quantity is the

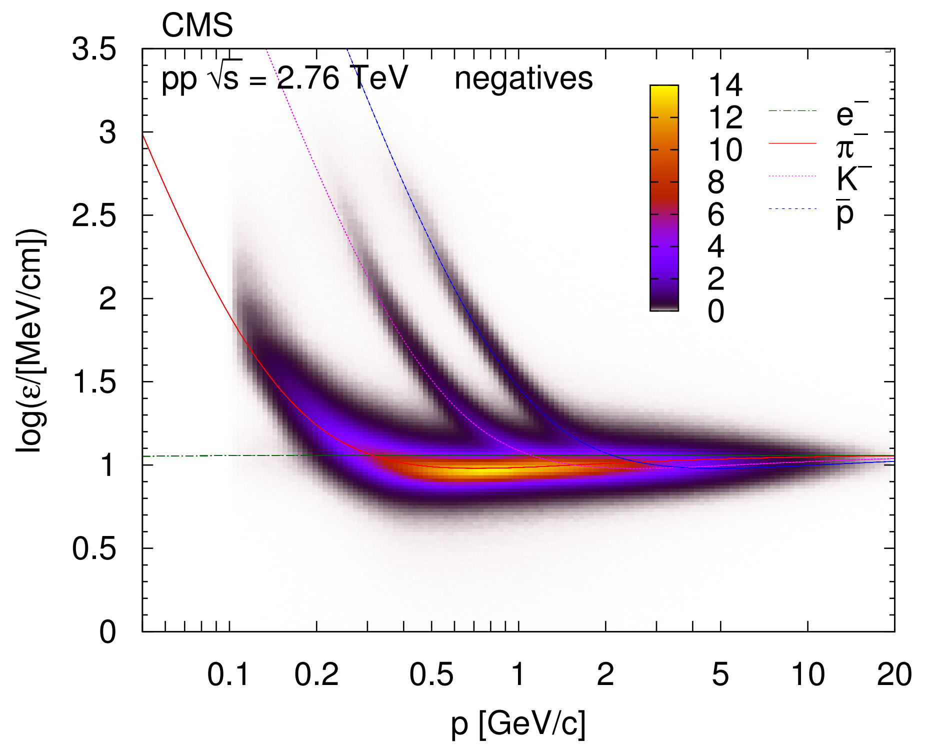
most probable energy loss rate ε along a reference length l_0

Probability of an energy loss y, along a path length l
$P(y|\varepsilon, l)$ has exponential and Gaussian parts (see backup)

Analytical model with few (4) pameters; a very good match

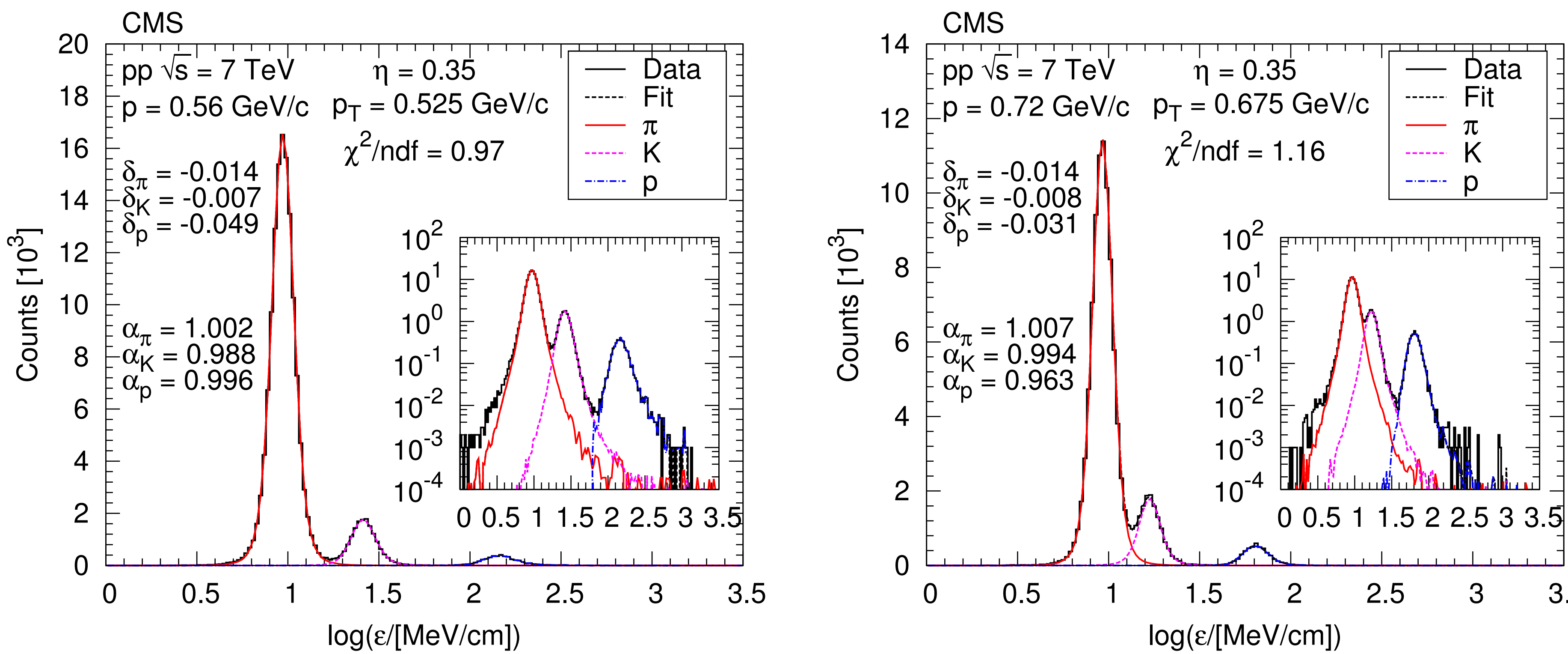
Most probable energy loss rate ε





- 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 $\log \varepsilon$

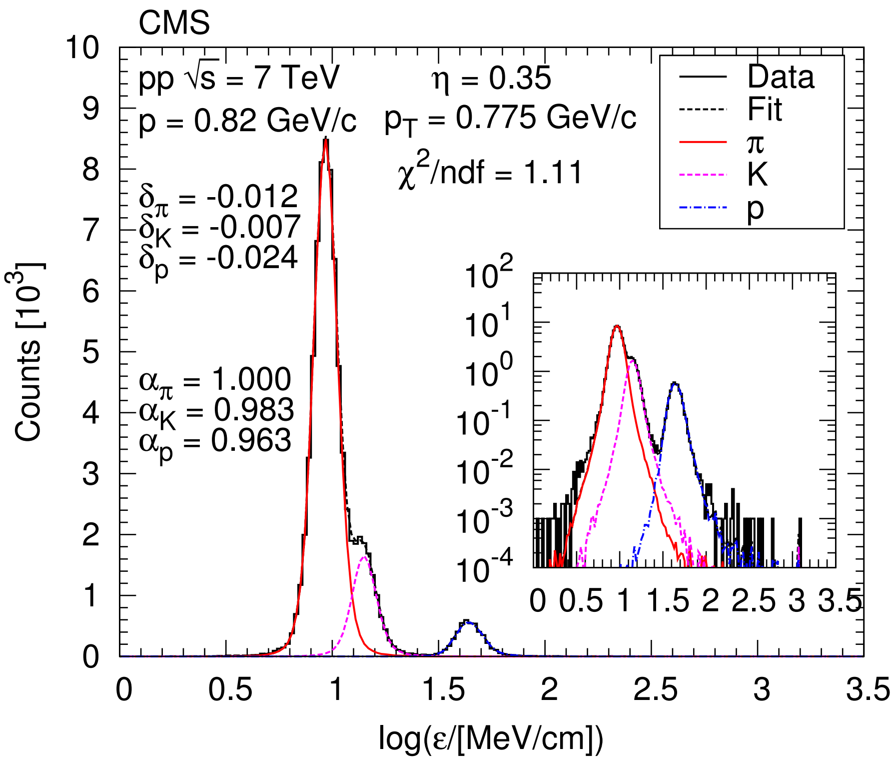
Fitting $\log \varepsilon$ distributions

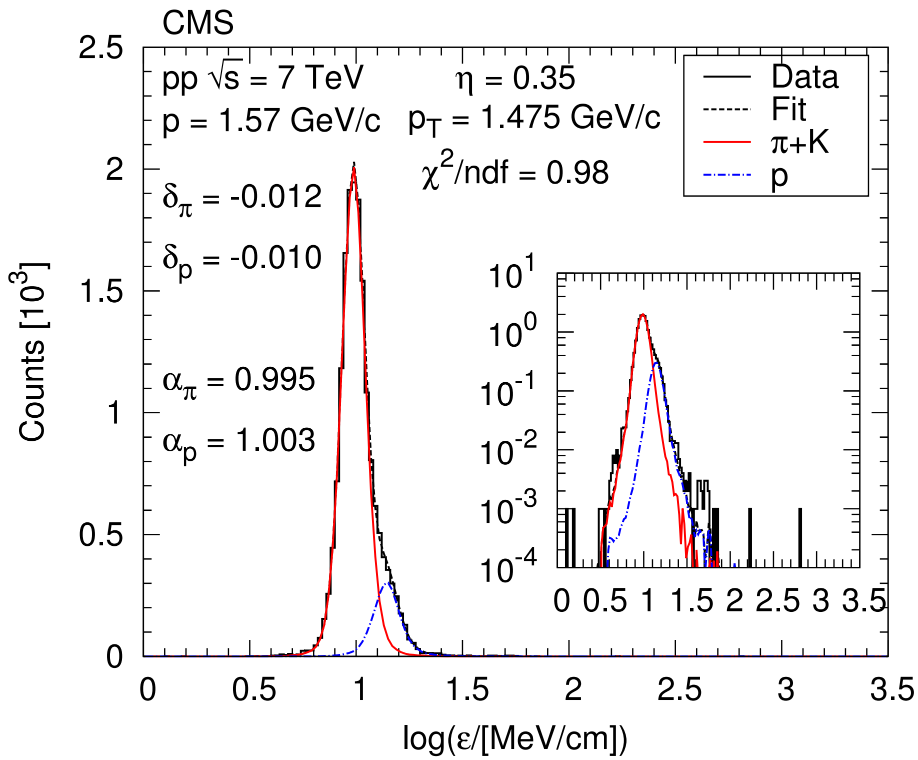


- Template fits
  - Use tracks in data
  - Keep all quantities, but regenerate each energy deposit according to the parametrization
  - Free parameters: track-level corrections (scale factors, shifts), particle yields

Need for additional information: number-of-hit and track-fit χ^2/ndf slices (see backup)

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 $\frac{1}{N_{\text{ev}}} \frac{d^2 N}{dy dp_T}$

Systematic uncertainties

Source	*Uncertainty of the source* [%]	*Propagated yield uncertainty* [%]		
Fully correlated, overall				
Correction on event selection	3.0 (1.0)	3.0(1.0)		
Pile-up correction (merged and split vertices)	0.3			
Mostly uncorrelated, fix relative magnitude				
Pixel hit efficiency	0.3	0.3		
Misalignment, different scenarios	0.1			
Mostly uncorrelated, (y, p_T) dependent, varying magnitude		π	K	p
Acceptance of the tracker	1–6	1	1	1
Efficiency of the reconstruction	2–5	2	2	2
Multiple track reconstruction	50% of the corr.	–	–	–
Fake track rate	50% of the corr.	<0.5	<0.5	0.5
Correction for secondary particles	20% of the corr.	<0.5	–	2
Fitting $\log \varepsilon$ distributions	1–10	1	2	1

Representative particle specific numbers are shown at $p_T = 0.6$ GeV/c

Consistent propagation of uncertainties
(mapping, fits, unfolding, integration)

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

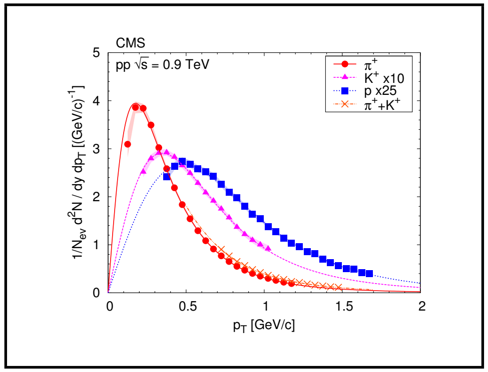
n – exponent, T – inverse slope parameter, m – particle mass

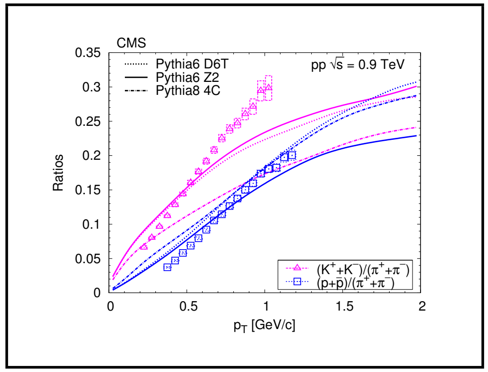
$\langle p_T \rangle$ is calculable with Monte Carlo integration

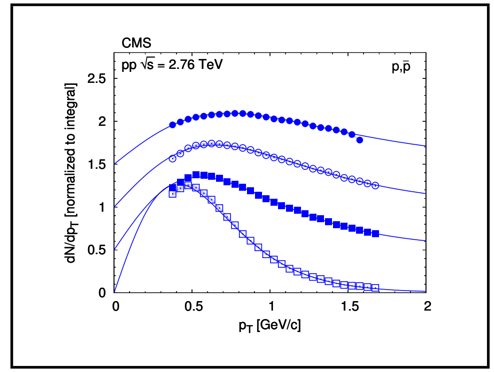
Combined π+K fits with $\chi^2_\pi + \chi^2_{\pi+\mathrm{K}} + 4 \cdot \chi^2_\mathrm{K}$

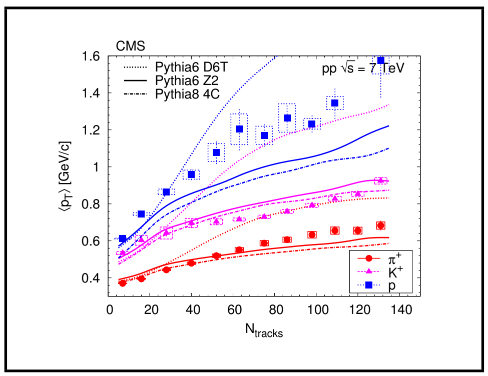
Regions where only the sum is accessible constrain both π and K yields

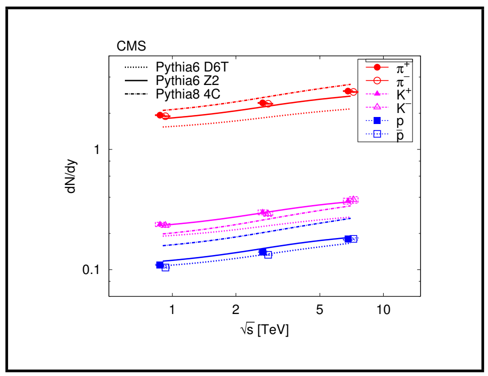
Physics results

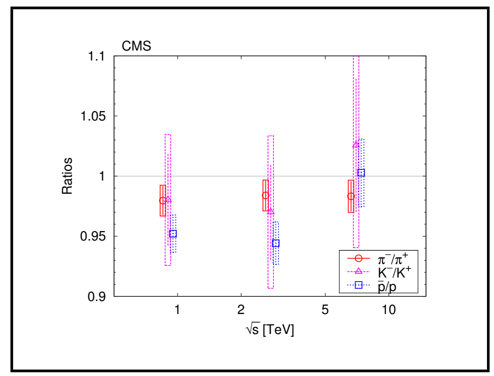




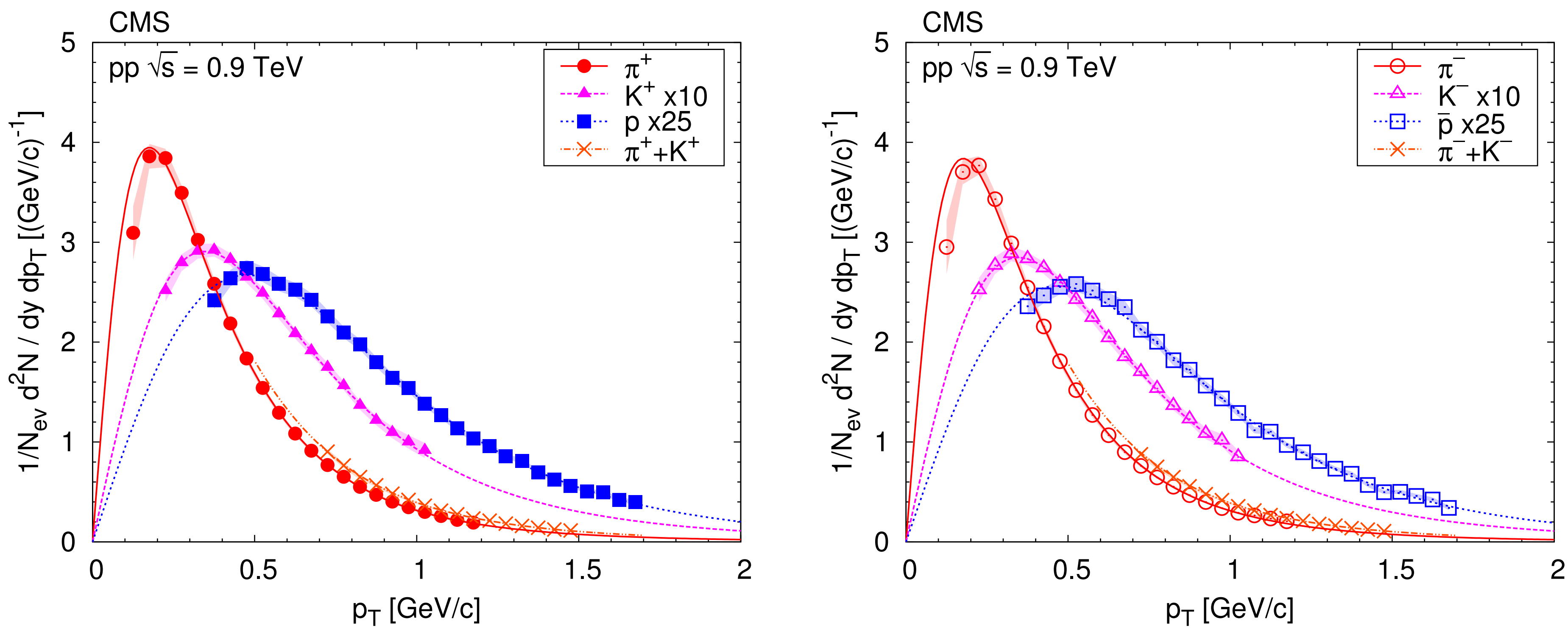








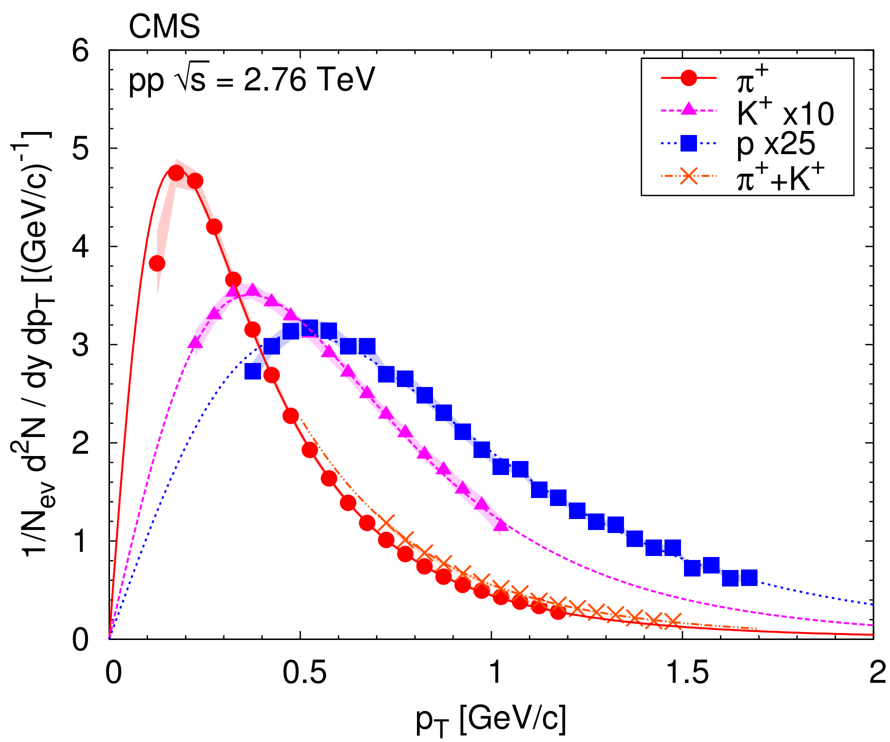
Results – p_T spectra

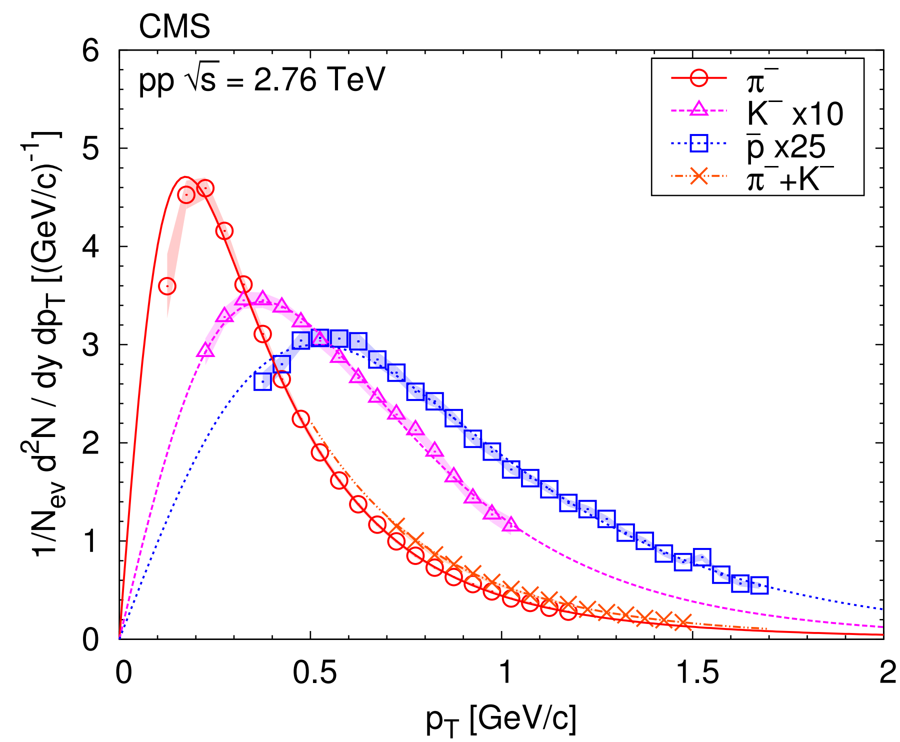


Error bars indicate the uncorrelated statistical,
while bands show the uncorrelated systematic uncertainties

The fully correlated normalization uncertainty (not shown) is around 3.0%

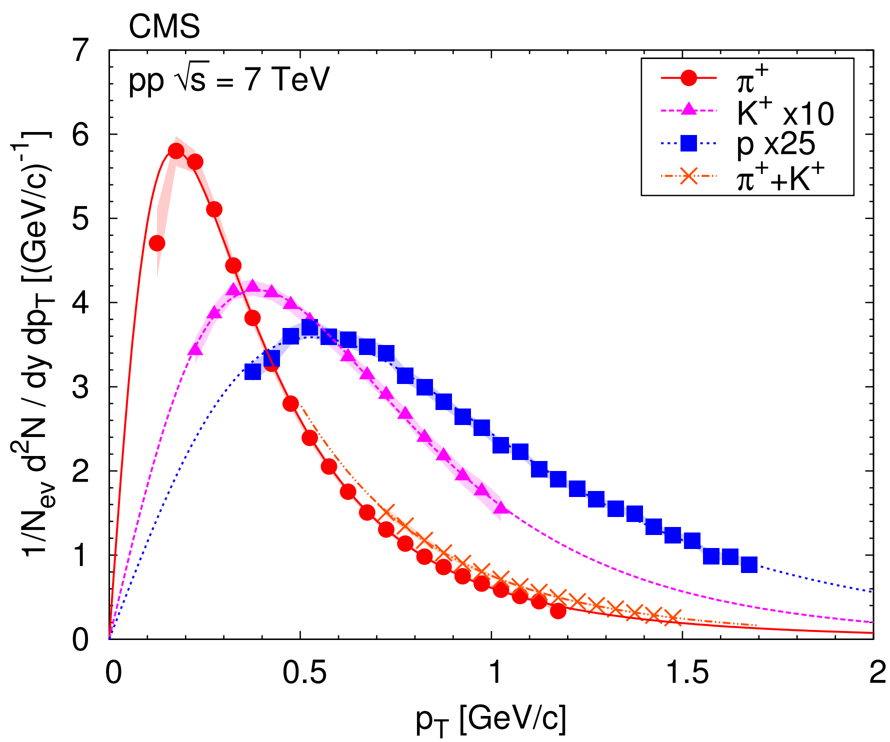
Results – p_T spectra

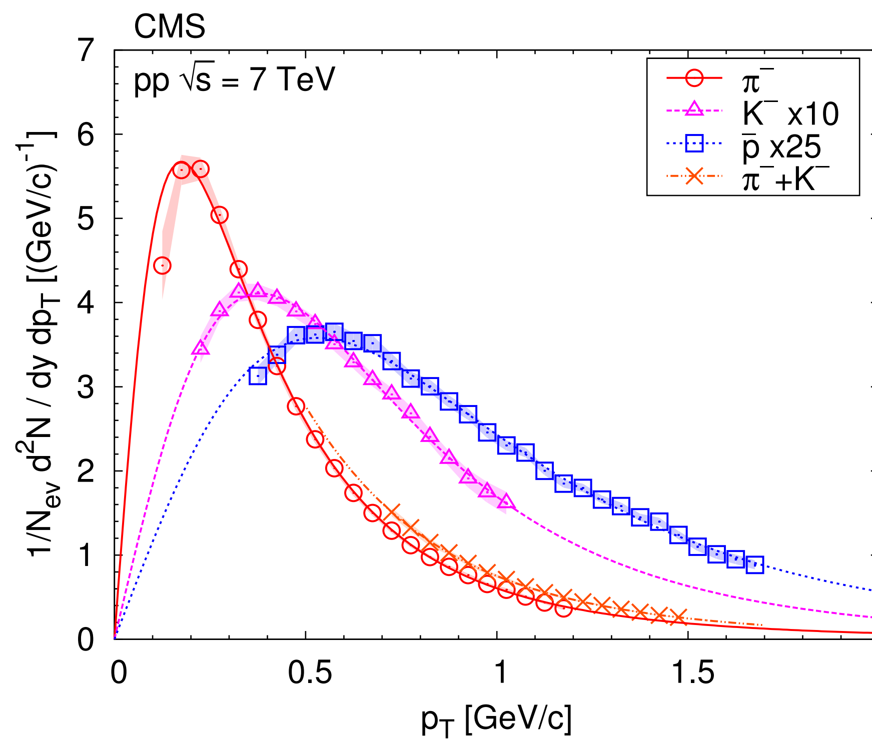




The fits are usually of good quality

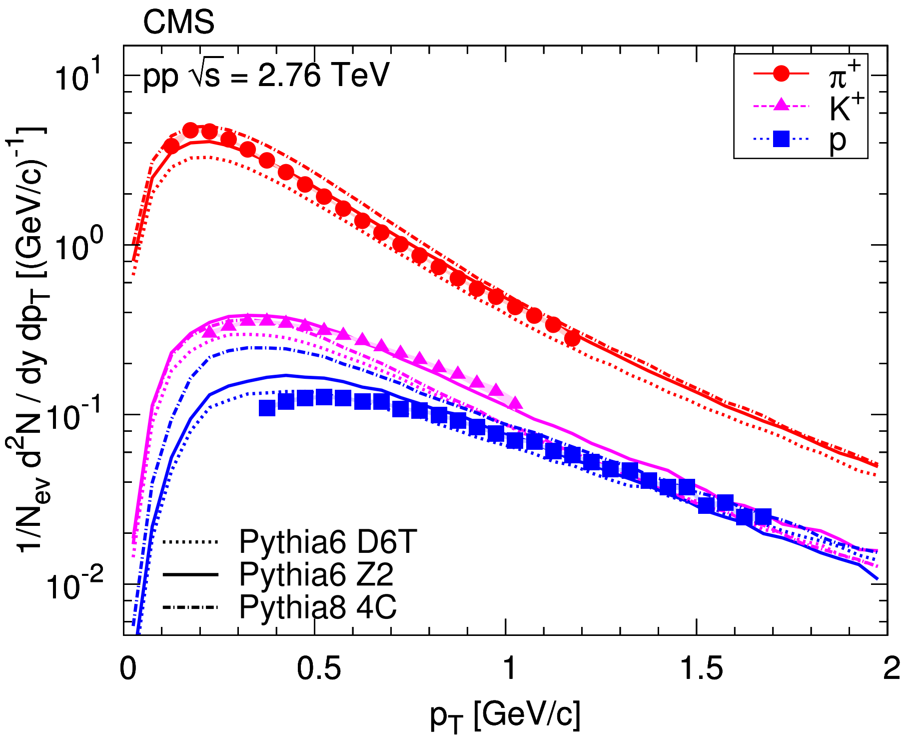
Results – p_T spectra

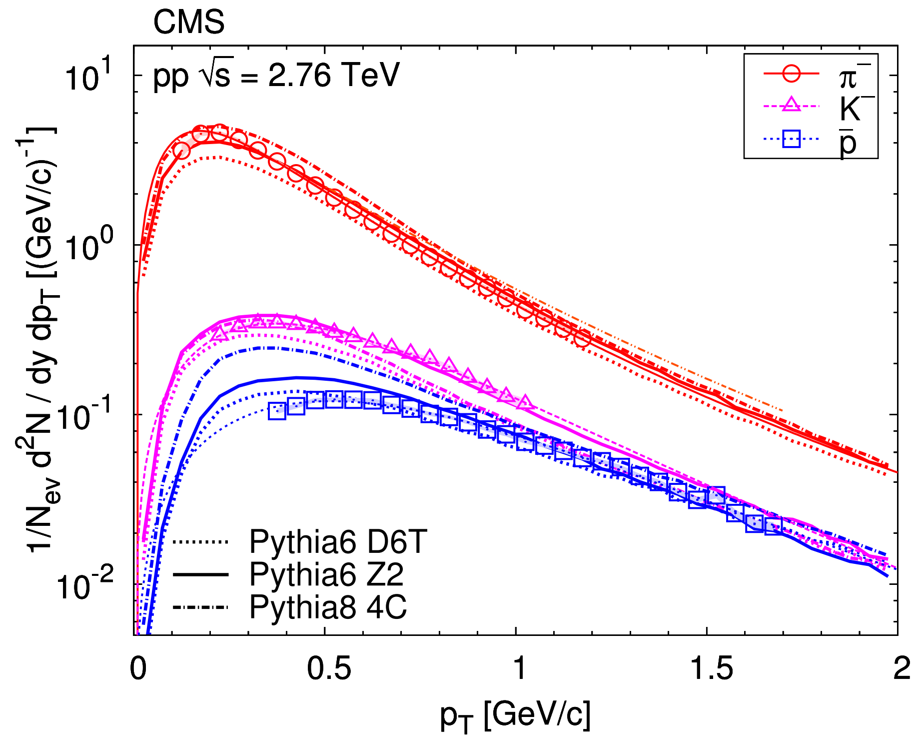




With χ^2/ndf values in the range 0.6-1.5 for pions, 0.6-2.1 for kaons, and 0.4-1.1 for protons

Results – p_T spectra

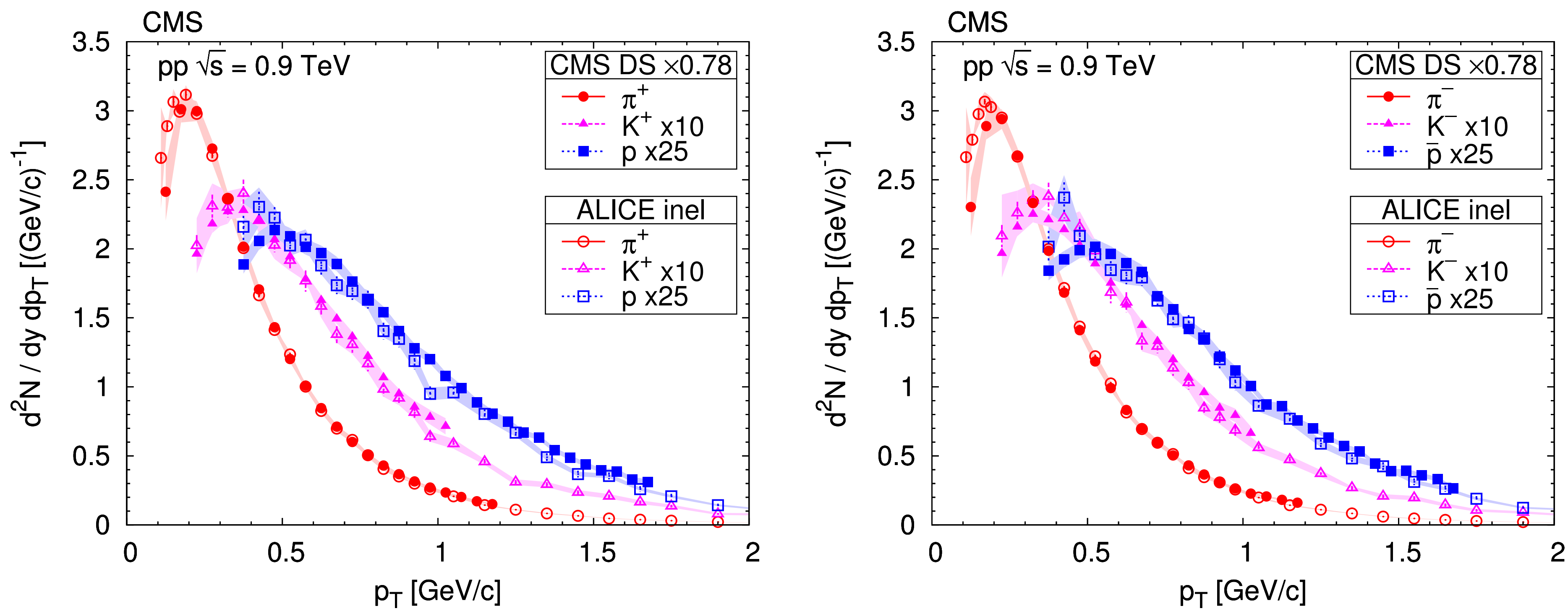




Logarithmic scale, comparison to models

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

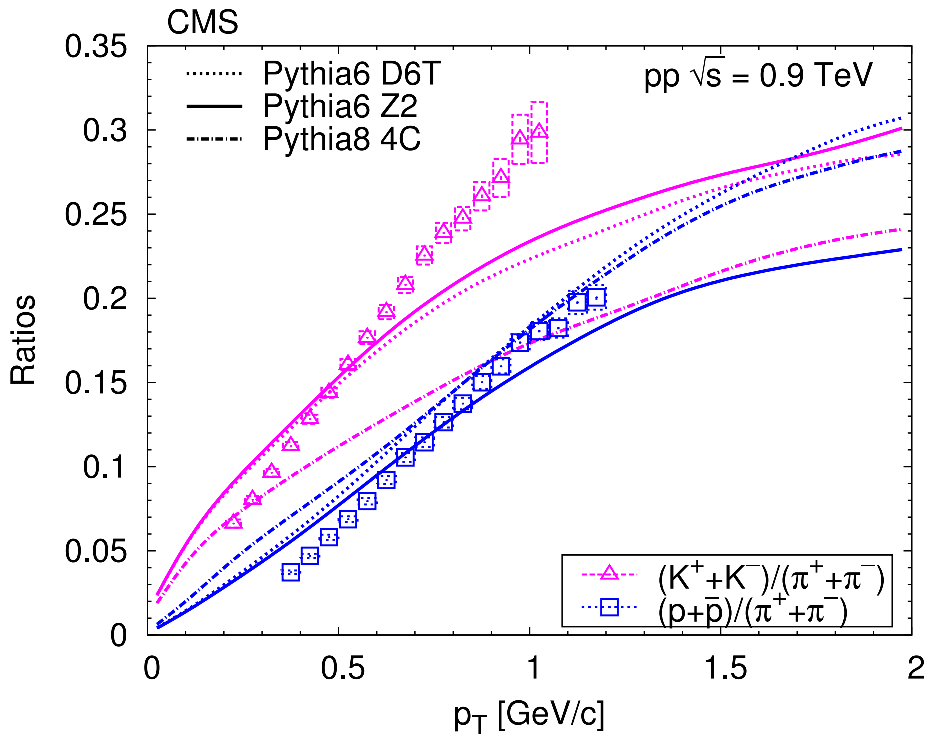


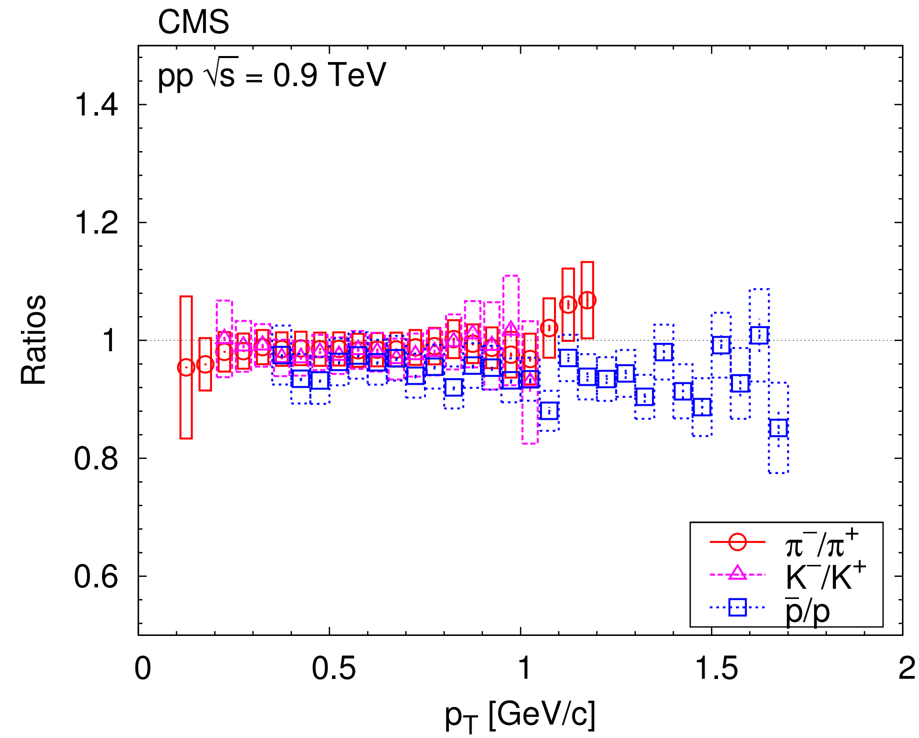
ALICE Collaboration, "Production of pions, kaons and protons in pp collisions at sqrt(s)= 900 GeV with ALICE at the LHC"
Eur.Phys.J. **C71** (2011) 1655

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

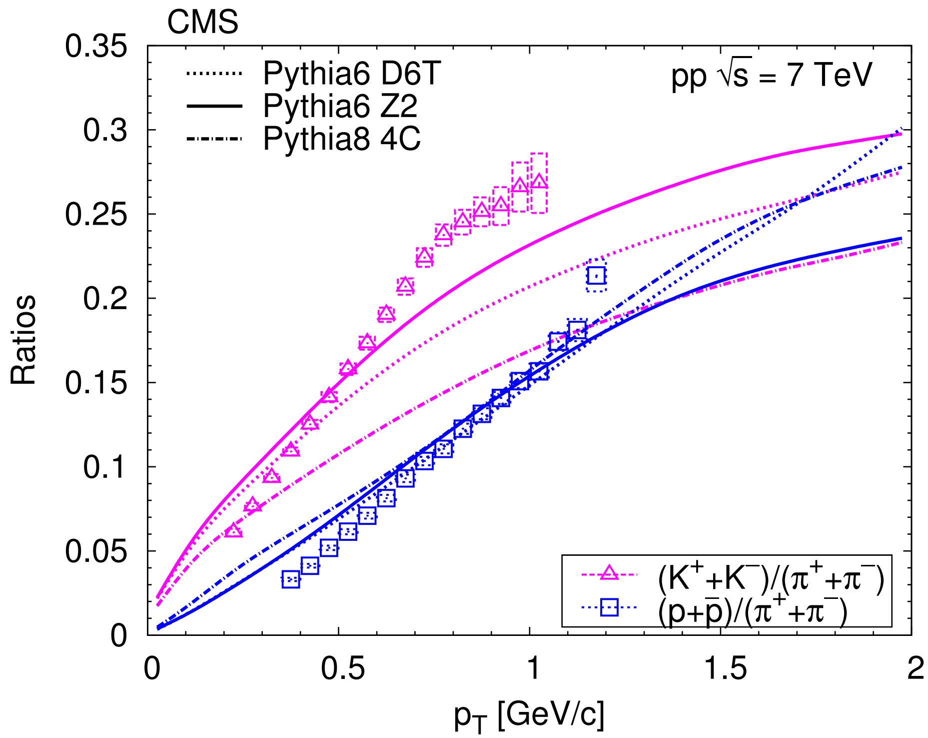
Results – ratios of p_T spectra

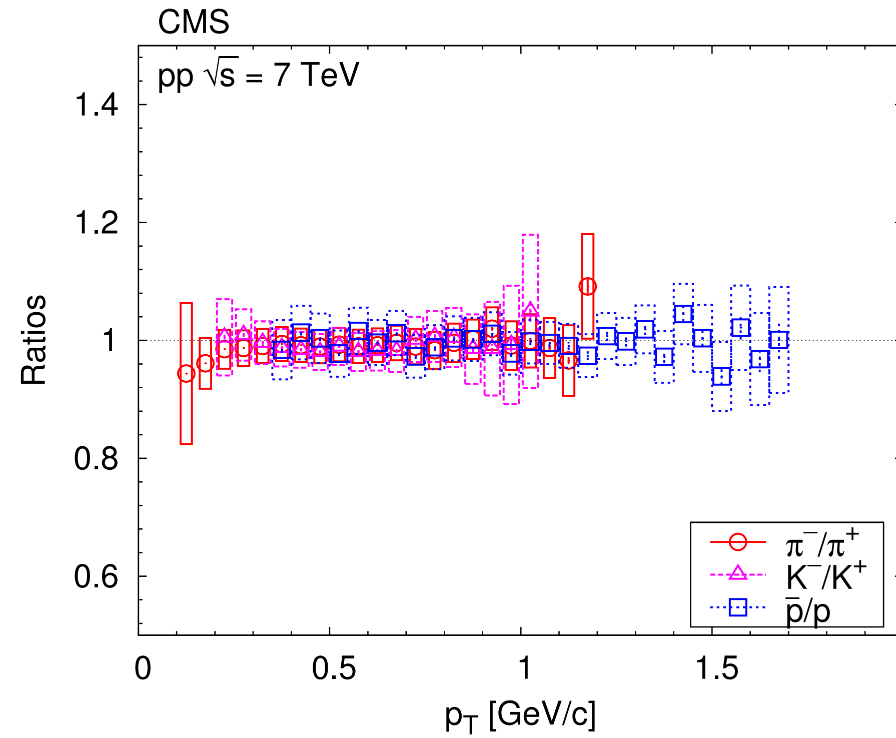




- p_T dependence
  - p/π ratios are are well described by all tunes
  - There are substantial deviations in case of K/π ratios
  - Ratios of opposite charged pions are around 1
  - Ratios of kaons are compatible with 1, independent of p_T

Results – ratios of p_T spectra





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  - Ratios of opposite charged pions are around 1
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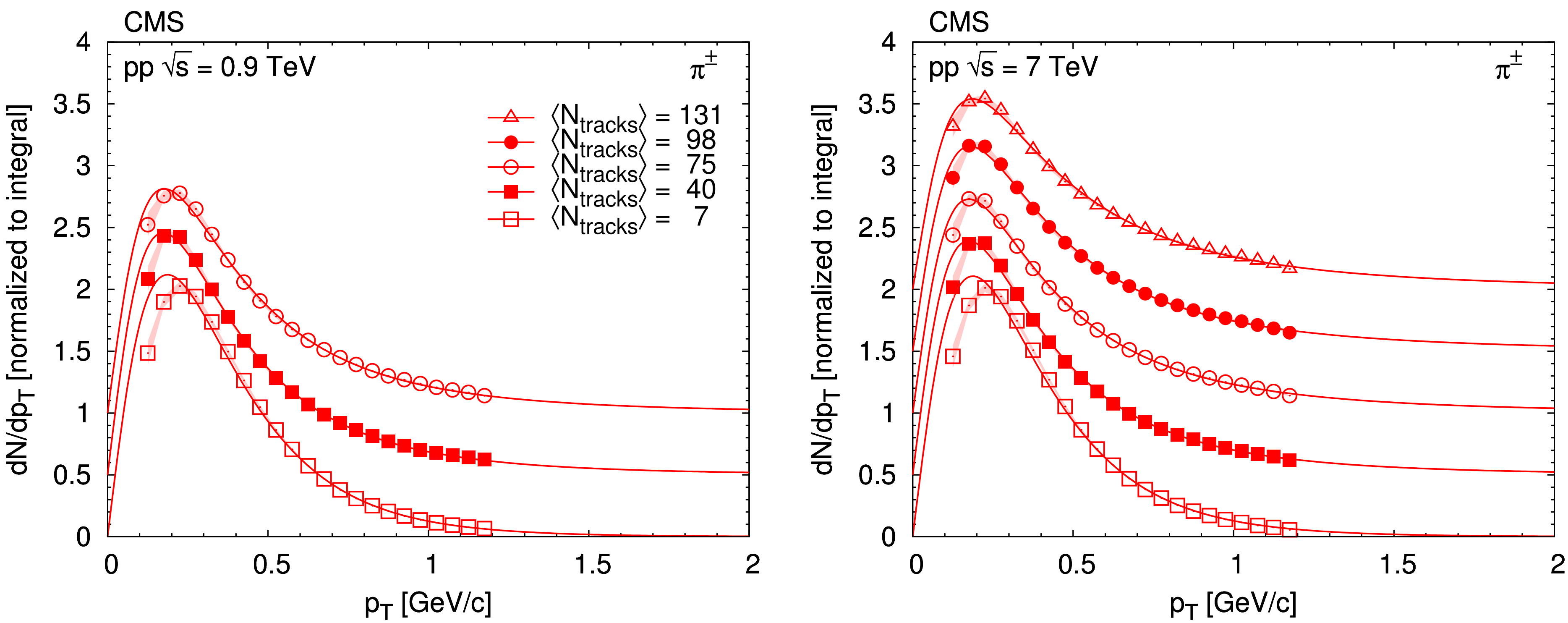
While the $\overline{\mathrm{p}}/\mathrm{p}$ ratios are also flat, they show an increase with increasing $\sqrt{s}$

Results – multiplicity dependence – pions

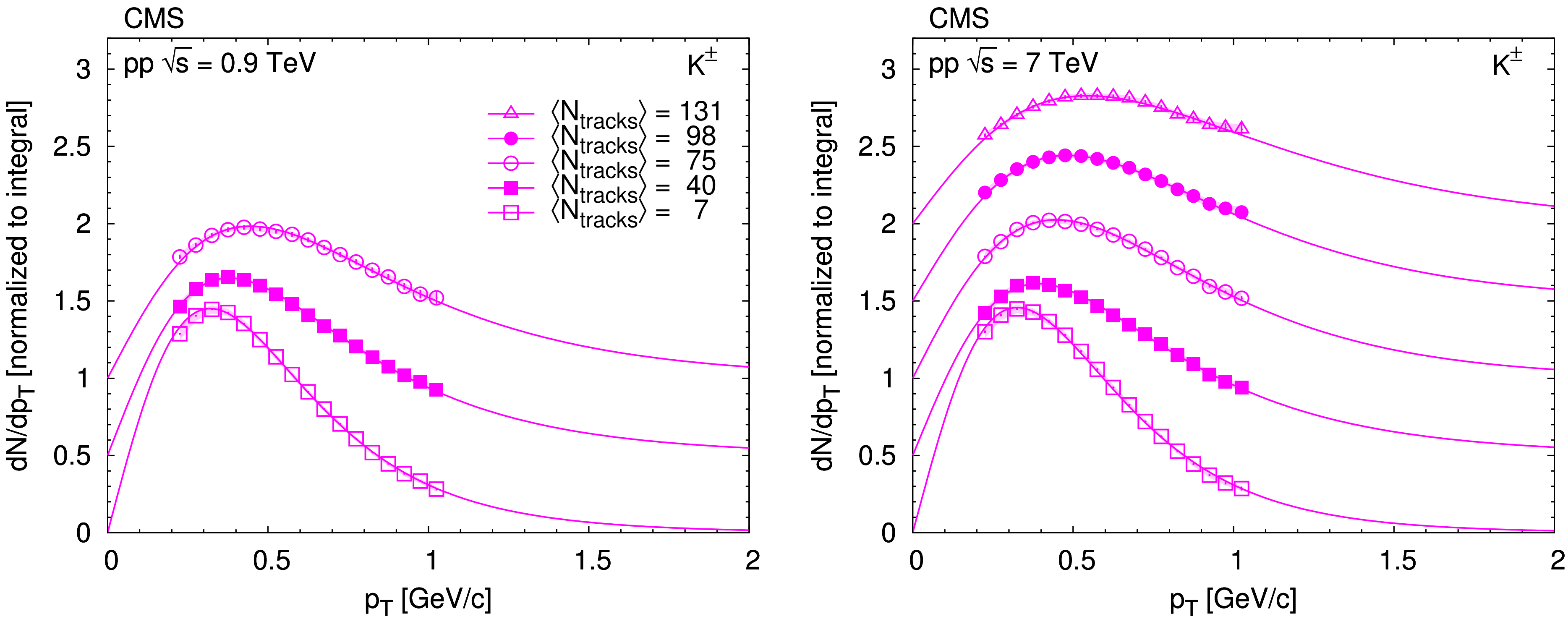


Multiplicity classes: relate measured N_{rec} to true $\langle N_{\text{tracks}} \rangle$ in $|\eta| < 2.4$

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

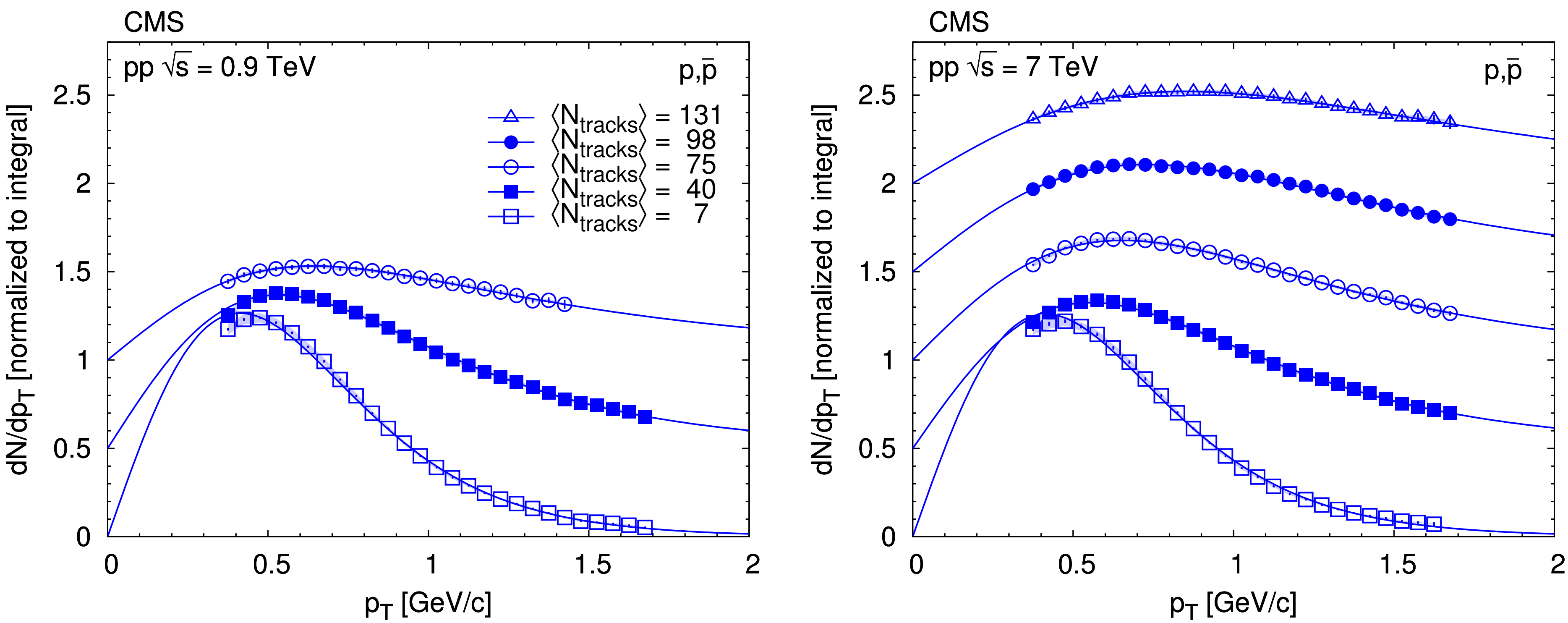
Unchanged shapes

Results – multiplicity dependence – kaons



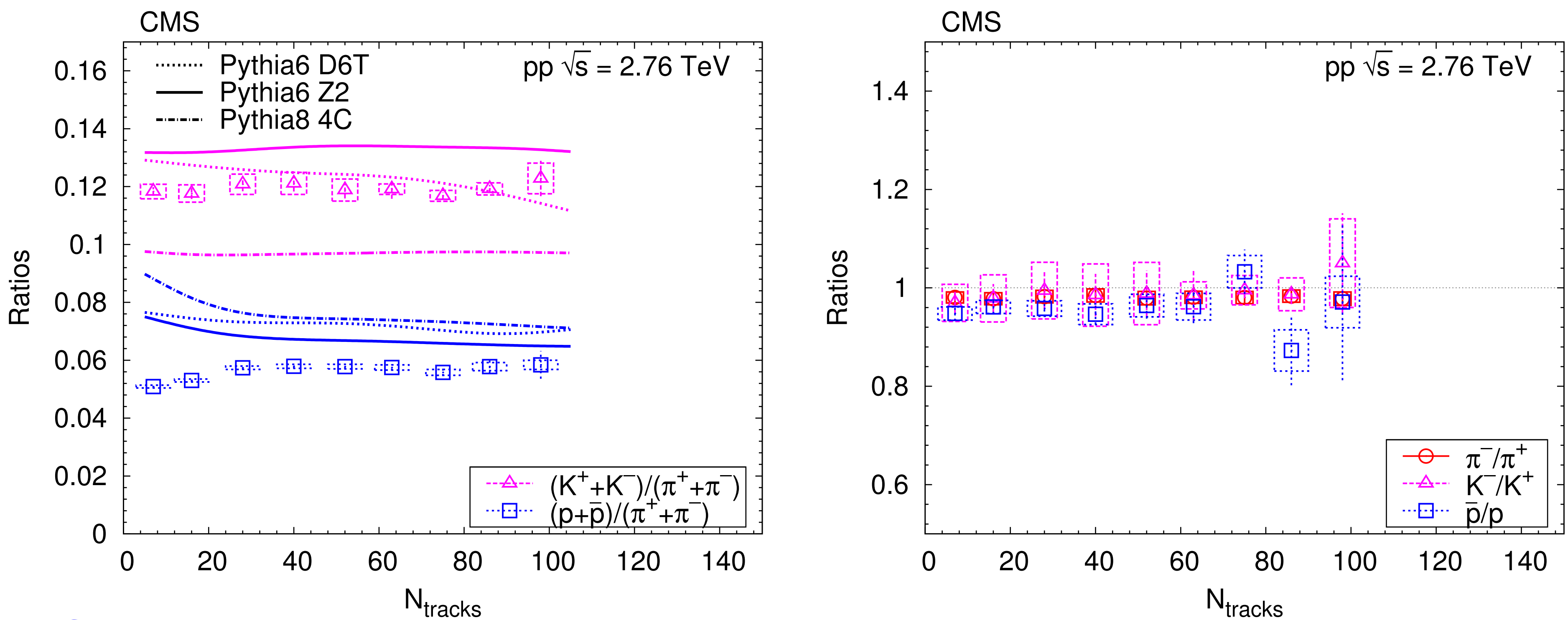
Harder spectral shape with increasing multiplicity

Results – multiplicity dependence – protons



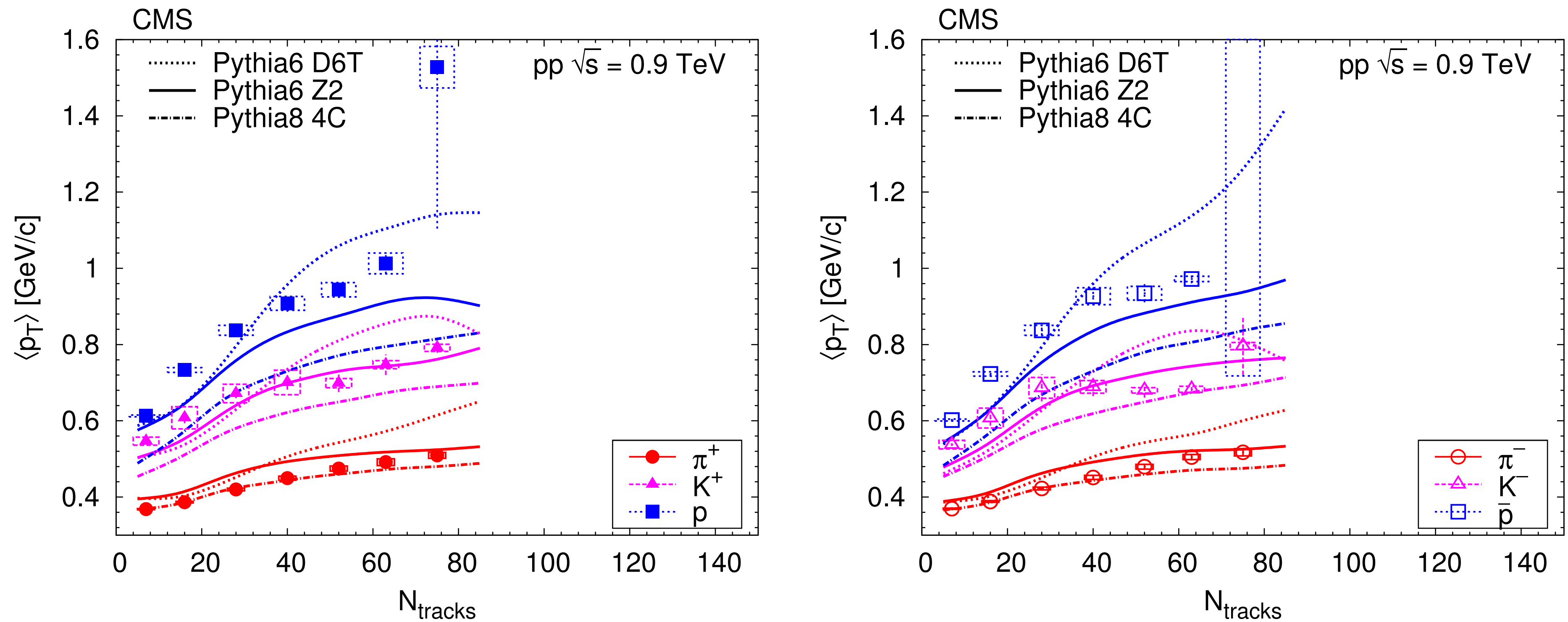
Harder spectral shape with increasing multiplicity

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 $\sqrt{s}$

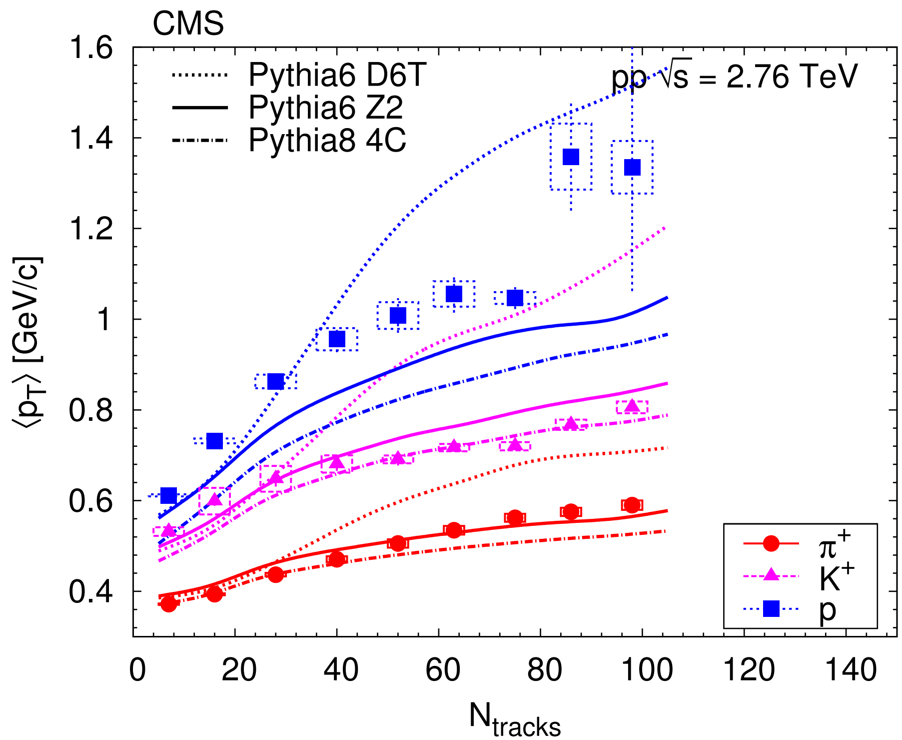
Results – $\langle p_T \rangle$ – multiplicity dependence

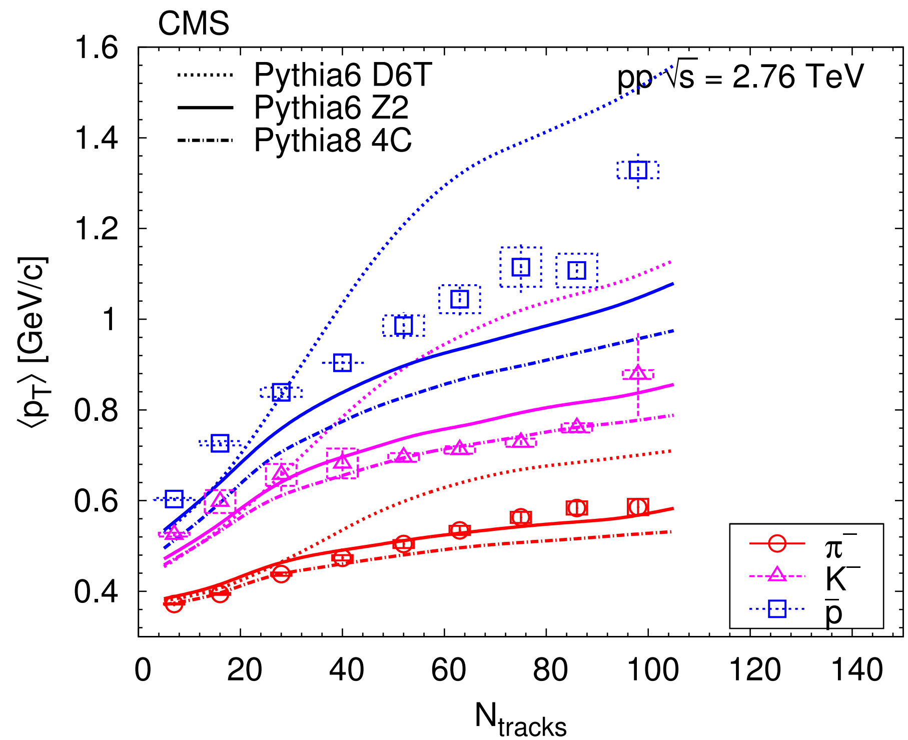


Calculated using MC technique followed by numerical integrations

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

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





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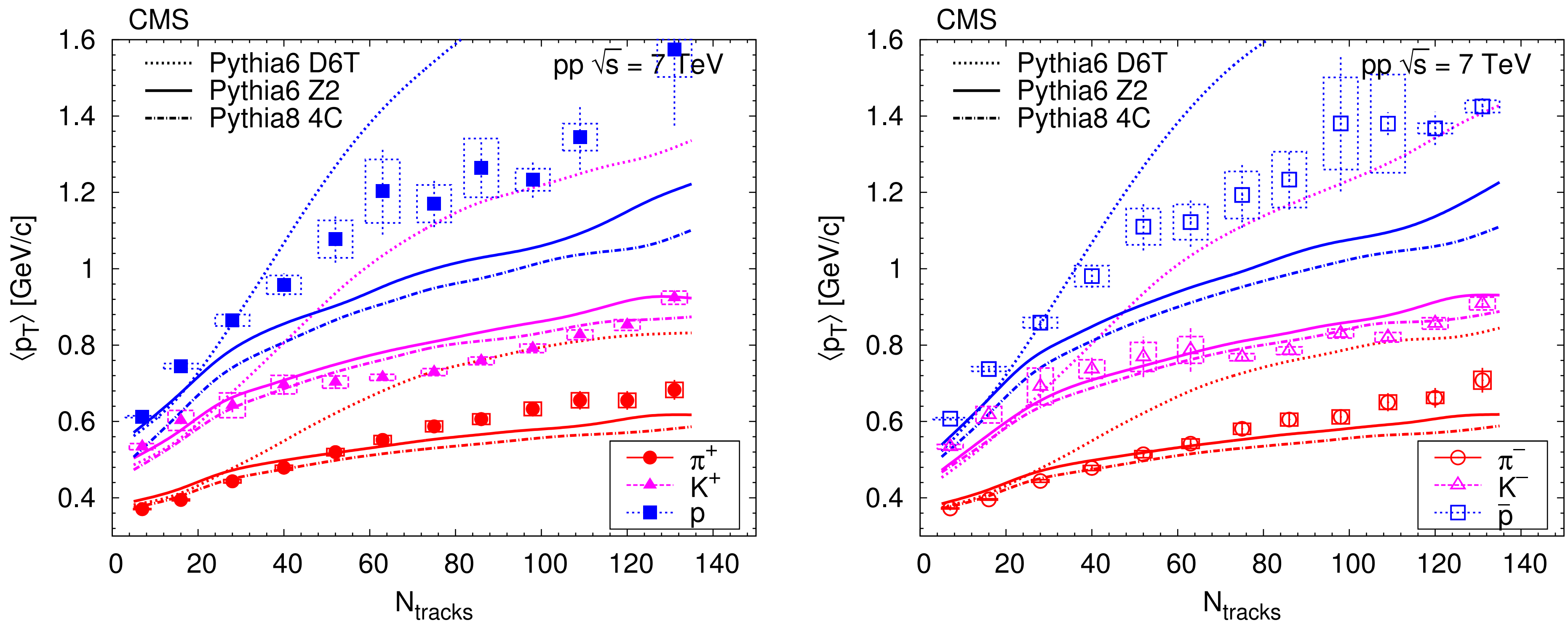
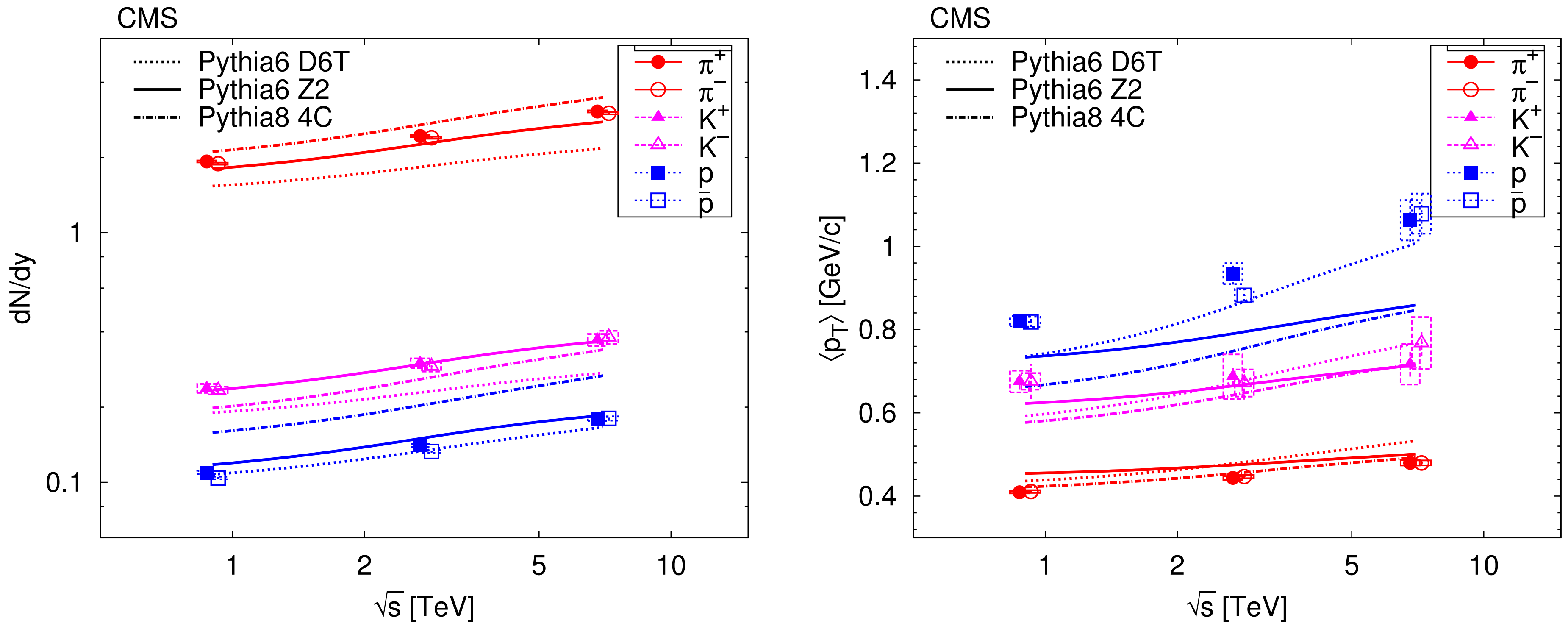
Results – $\langle p_T \rangle$ – multiplicity dependence



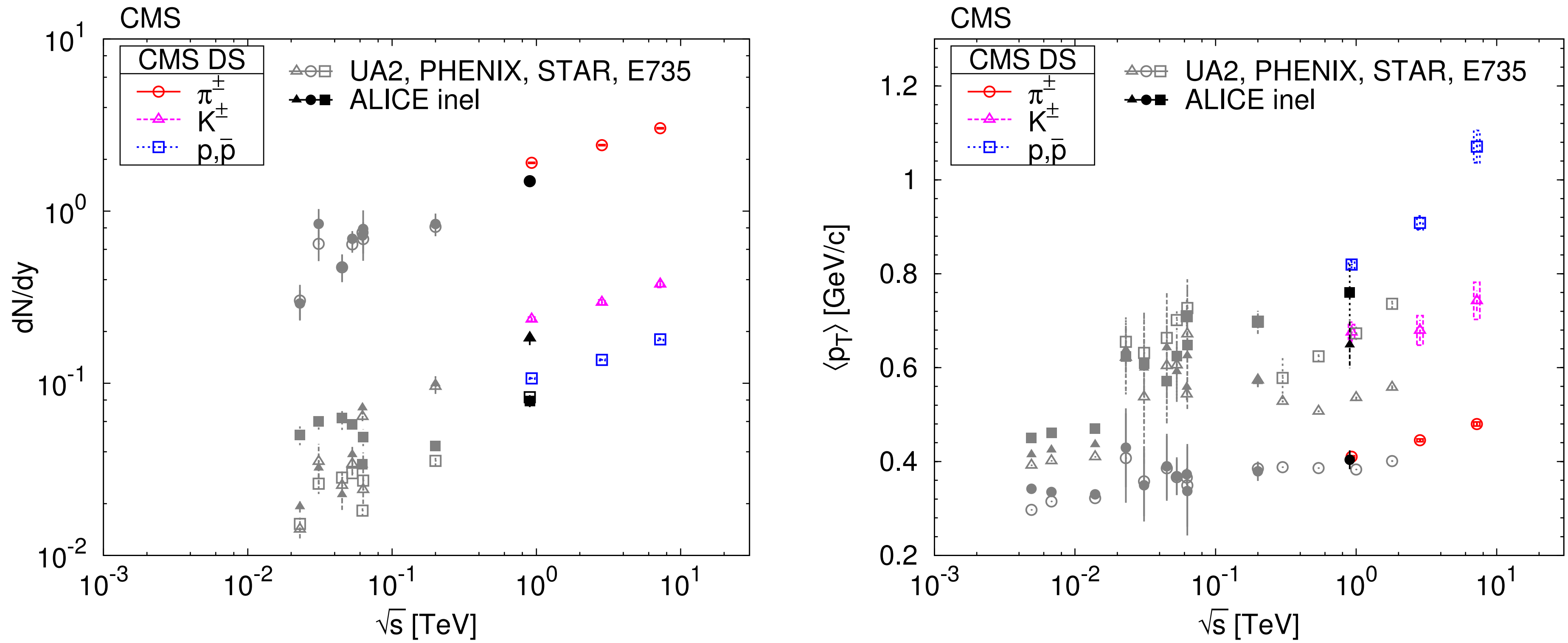
- Observations
  - Distributions are remarkably similar, in practice independent of $\sqrt{s}$ and multiplicity
  - Pions and kaons are well described by Pythia6 Z2 and Pythia8 4C
  - Pythia6 D6T usually predicts too high values at higher multiplicities
  - Protons behave differently and none of the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

Results – $\sqrt{s}$ dependence of dN/dy and $\langle p_T \rangle$



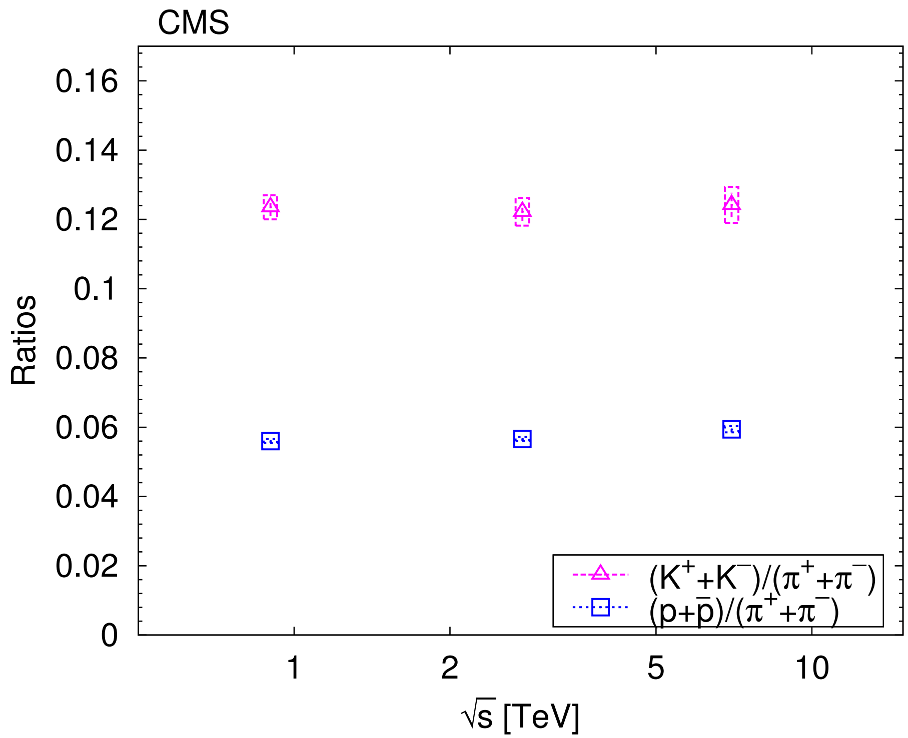
- dN/dy
  - Pythia6 Z2 tune gives a good description, although it overpredicts protons
  - Pythia8 4C is also far away for protons
- $\langle p_T \rangle$
  - For pions it is nicely matched by Pythia8 4C
  - Kaons are best described by Pythia6 Z2
  - Protons are missed by all tunes, maybe Pythia6 D6T being the closest

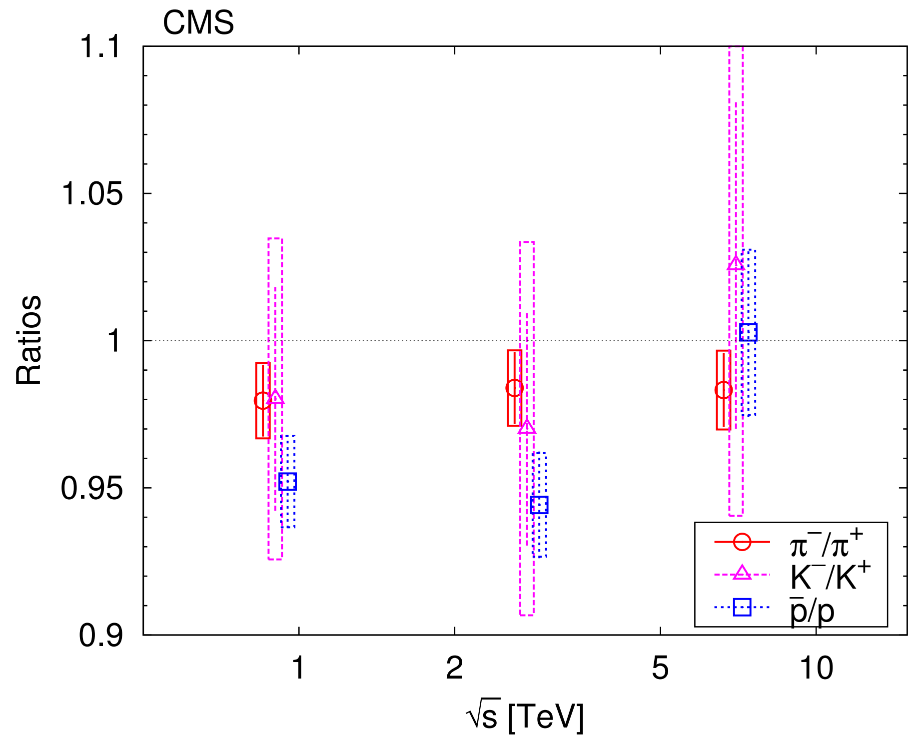
Results – $\sqrt{s}$ dependence – comparisons



$\sqrt{s}$ evolution, consistent with power-law increase

Results – $\sqrt{s}$ dependence of yield-ratios

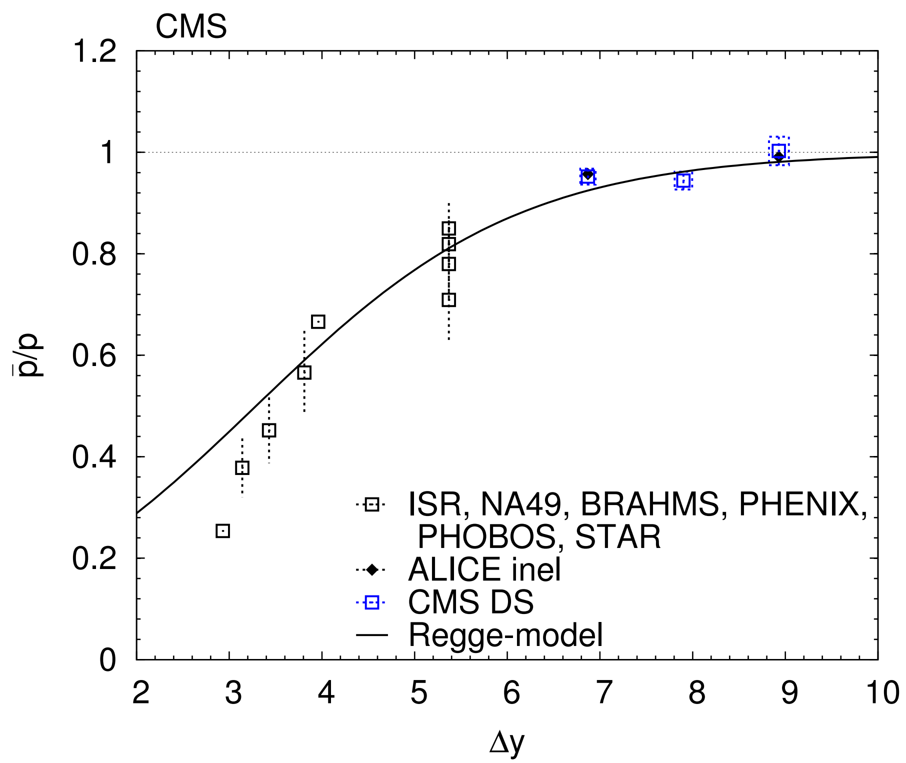




- Cross ratios
  - K/π and p/π are flat with values 0.13 and 0.06-0.07

- Opposite charge ratios
  - Flat, around 0.97-0.98 for pions; compatible with 1 for kaons
  - In case of protons there is an increase

Results – $\sqrt{s}$ dependence – comparisons of $\bar{\mathrm{p}}/\mathrm{p}$ ratio

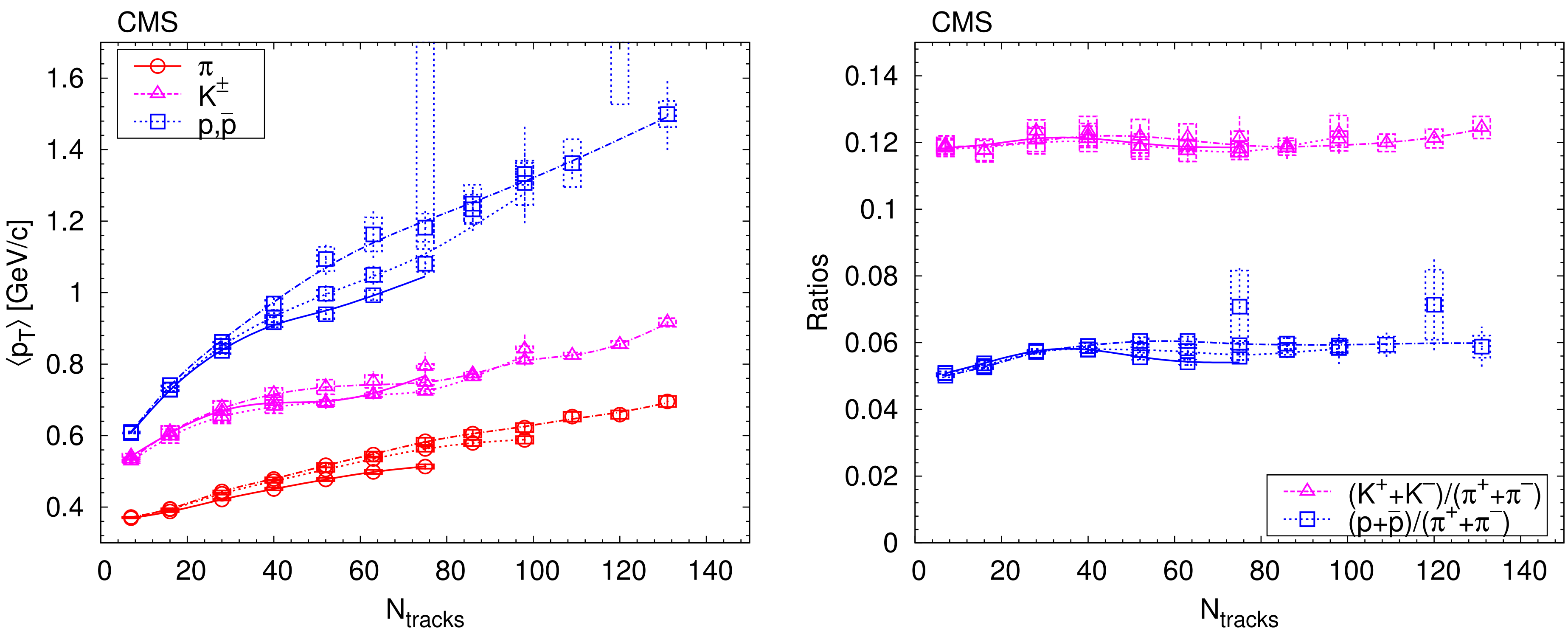


ALICE Collaboration, "Midrapidity antiproton-to-proton ratio in pp collisions at $\sqrt{s} =$ 0.9 and 7 TeV measured by the ALICE experiment" Phys.Rev.Lett. **105** (2010) 072002

$\bar{\mathrm{p}}/\mathrm{p}$ as a function of the rapidity loss $\Delta y = y_{\text{beam}} - y_{\text{baryon}}$
Measurements from ISR, NA49, BRAHMS, PHENIX, PHOBOS and STAR + ALICE

Curve: Regge model, Pomeron exchange, baryon transport by string-junction
$(\bar{\mathrm{p}}/\mathrm{p})^{-1} = 1 + C\exp[(\alpha_J - \alpha_P)\Delta y]$ with $C = 10$, $\alpha_P = 1.2$ and $\alpha_J = 0.5$

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?

Summary

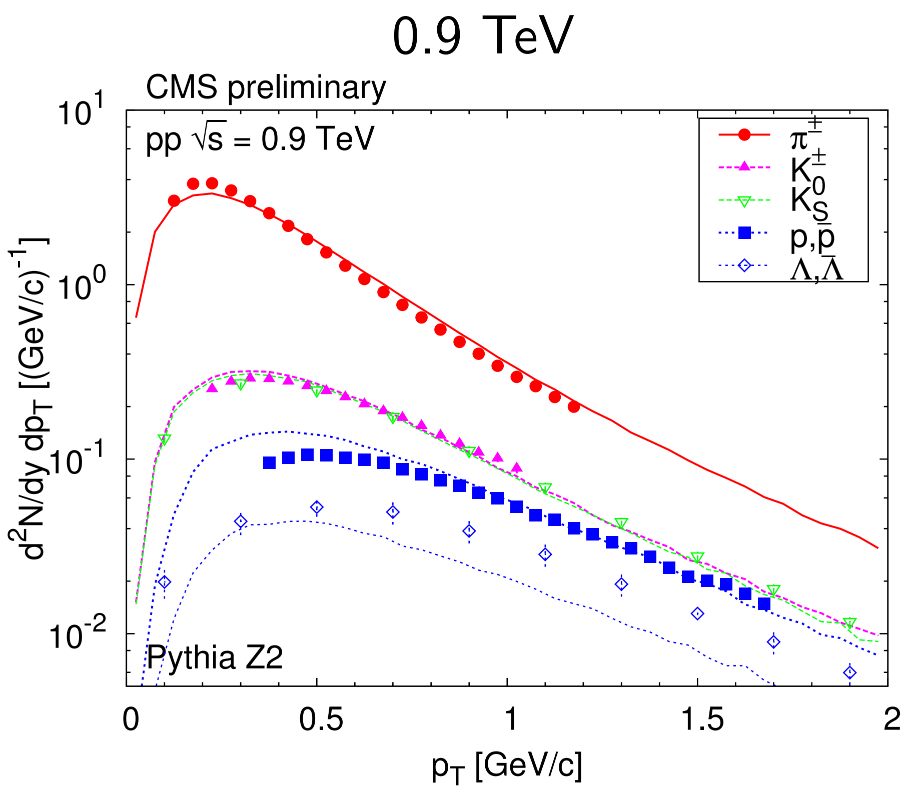
- Results
  - Measured spectra of identified charged hadrons with a double-sided trigger via energy deposits in the pixel and strip tracker at $\sqrt{s} = 0.9$, 2.76 and 7 TeV as a function of track multiplicity

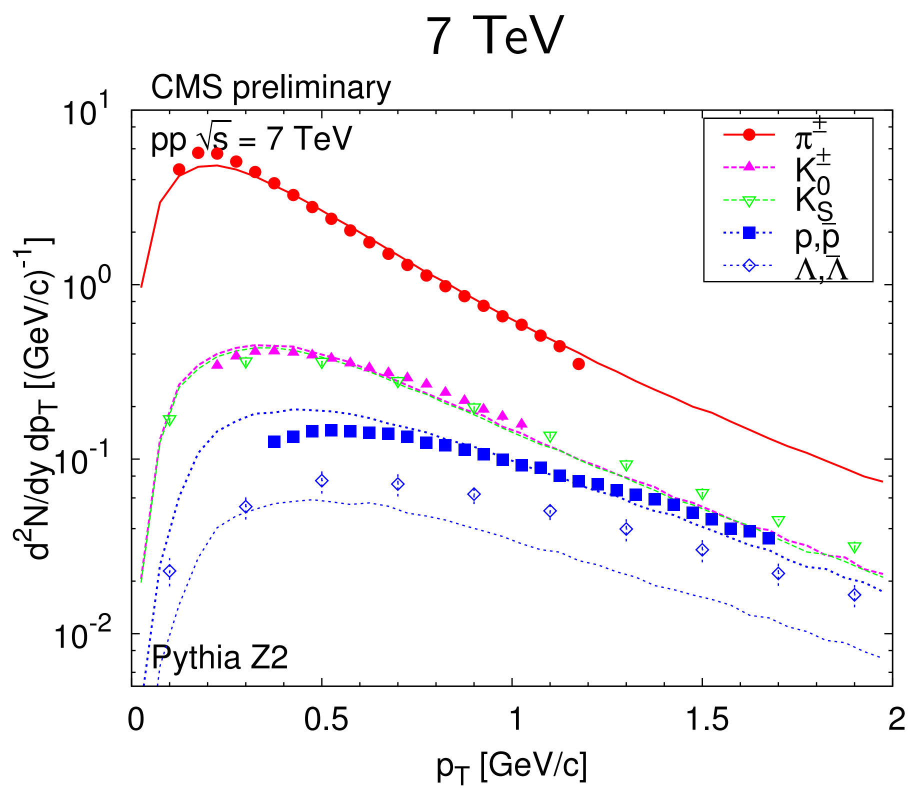
- Conclusions
  - Particle production at LHC energies is strongly **correlated with event multiplicity** rather than with the center-of-mass energy of the collision
  - Common underlying physics mechanism:
  - At TeV energies, the characteristics of particle production are constrained by the amount of **initial parton energy** that is available in any given collision

Thank you for your attention!

Backup

Summary – CMS identified hadrons





$\pi^{\pm}$, $K^{\pm}$, K^0_S, p, $\bar{p}$, Λ, $\bar{\Lambda}$

Comparisons to Pythia Z2

Analytical energy loss parametrization

- 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 energy deposit y, exponential and Gaussian parts

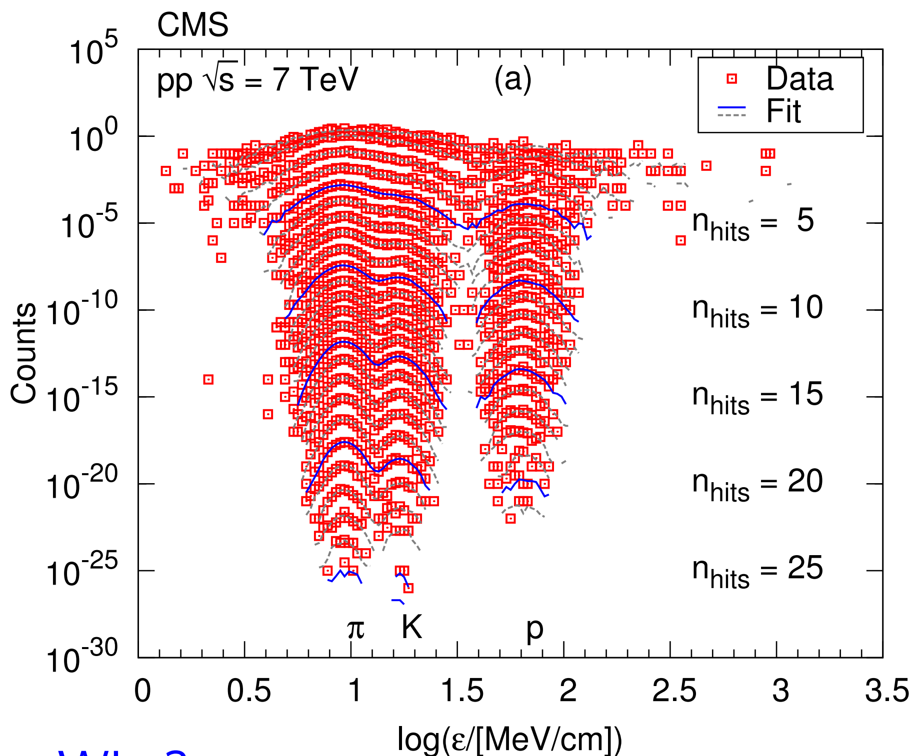
$$P(y|\varepsilon, l) \approx \frac{1}{\sigma_\Delta} \cdot \begin{cases} \exp\left[\frac{\nu(\Delta - y)}{\sigma_\Delta(y)} + \frac{\nu^2}{2}\right], & \text{if } \Delta < \Delta^* \\ \exp\left[-\frac{(\Delta - y)^2}{2\sigma_\Delta^2(y)}\right], & \text{if } \Delta \geq \Delta^*. \end{cases}$$

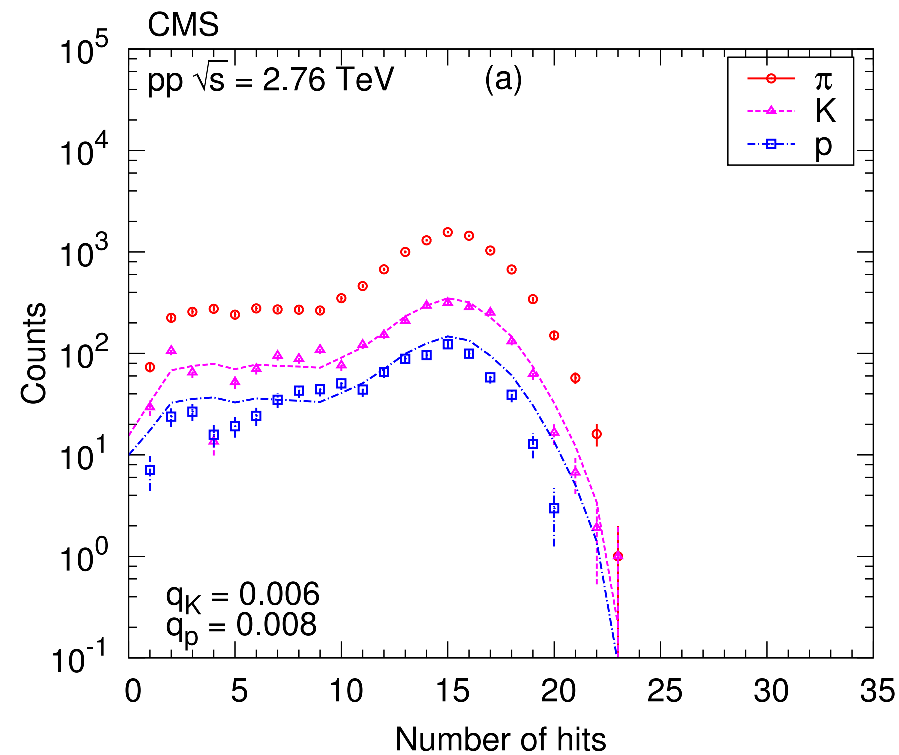
F. Sikler, "A parametrisation of the energy loss distributions of charged particles and its applications for silicon detectors", Nucl. Instrum. Meth. A 691 (2012) 16-29

- 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

Fits in number-of-hits slices

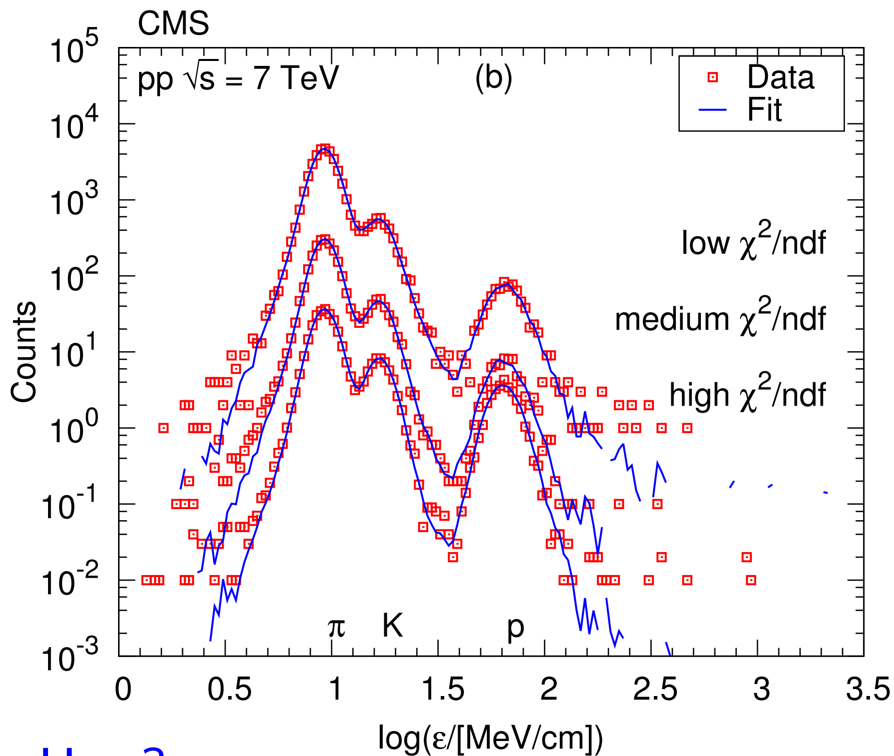


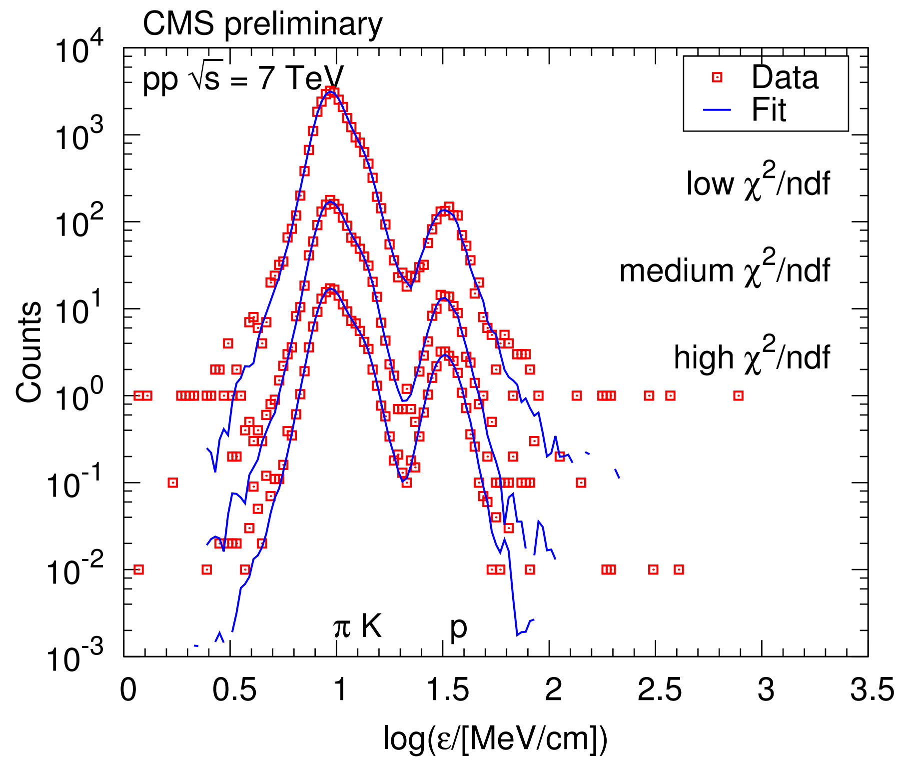


- Why?
  - Higher n_{hits} curves contain important information
  - Also: The pions usually have a higher average number of hits on track, less hits for kaons, and even less for protons
  - The n_{hits} distribution of particle species differs in an (η, p_T) bin, they are even related $g_k = r\left[(1-q)^k f_k + (1-q)^k q \sum_{n=k+1}^{\infty} f_n\right]$, 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 $\sigma \approx 1/\sqrt{2n}$
  - 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