

# Multiplicity dependence of the production of identified charged hadrons in pp and pPb collisions from CMS

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# Outline

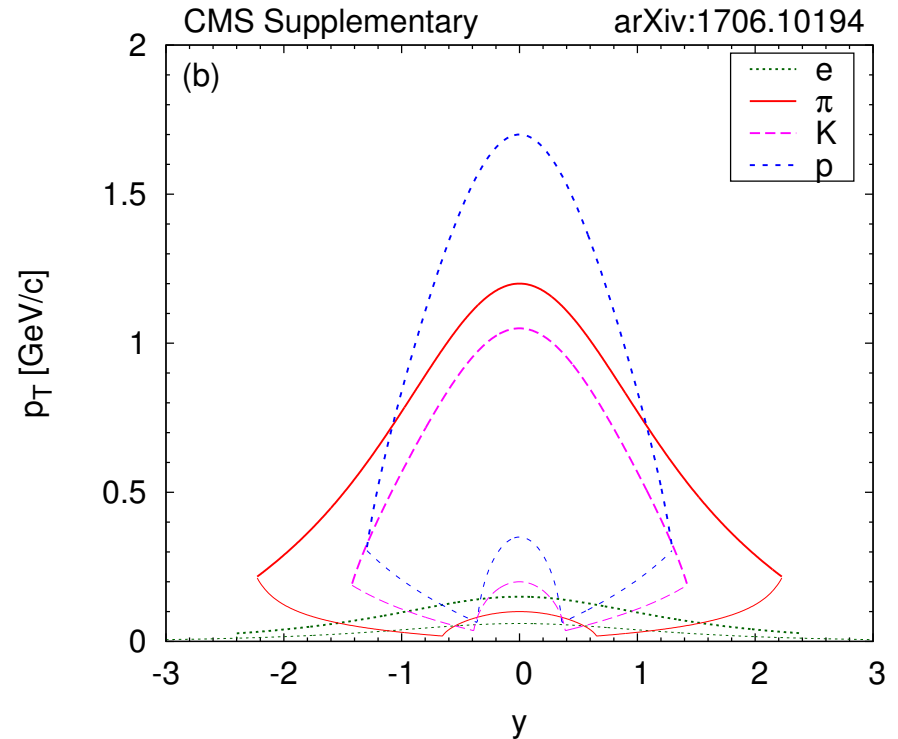
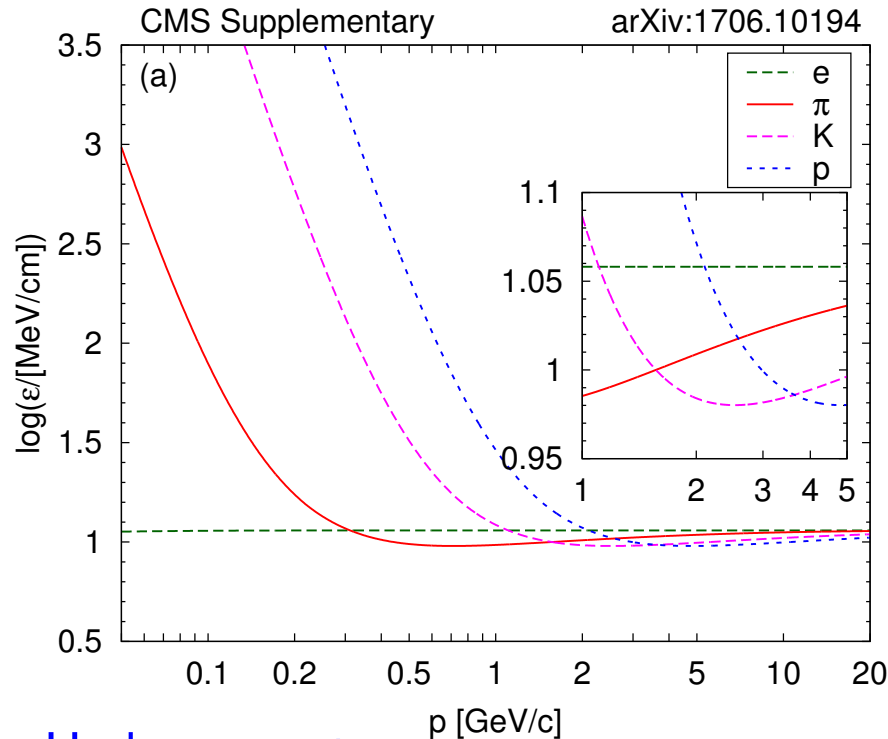
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- Charged  $\pi$ , K, and p in pp at  $\sqrt{s} = 13$  TeV
  - Results are public: arXiv:1706.10194 (hep-ex), submitted to Phys Rev D
  - Trigger, tracking, vertexing
  - Energy deposits and energy loss rate
  - Determination of particle yields
  - Corrections
  - Inclusive measurements
  - Multiplicity-dependent measurements
  - Comparisons to
    - \* pp,  $\sqrt{s} = 0.9, 2.76$ , and 7 TeV [EPJC 72 (2012) 2164]
    - \* pPb,  $\sqrt{s_{NN}} = 5.02$  TeV [EPJC 74 (2014) 2847]
    - \* peripheral PbPb [from ALICE]

With emphasis on particle spectra and ratios

# The scene



## • Hadron spectra

- Long history both in high energy particle and nuclear physics
- One of the simplest and most relevant physics quantities
- **Scaling properties** of particle production; predictions of models and generators
- Growing interest in **small systems with high multiplicity**
- PID:  $p < 1.20$  for  $\pi^\pm$ ,  $p < 1.05$  for  $K^\pm$ , and  $p < 1.70$  GeV/c for  $p/\bar{p}$

Accessible region is also limited by  $\eta$  acceptance of the tracker

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

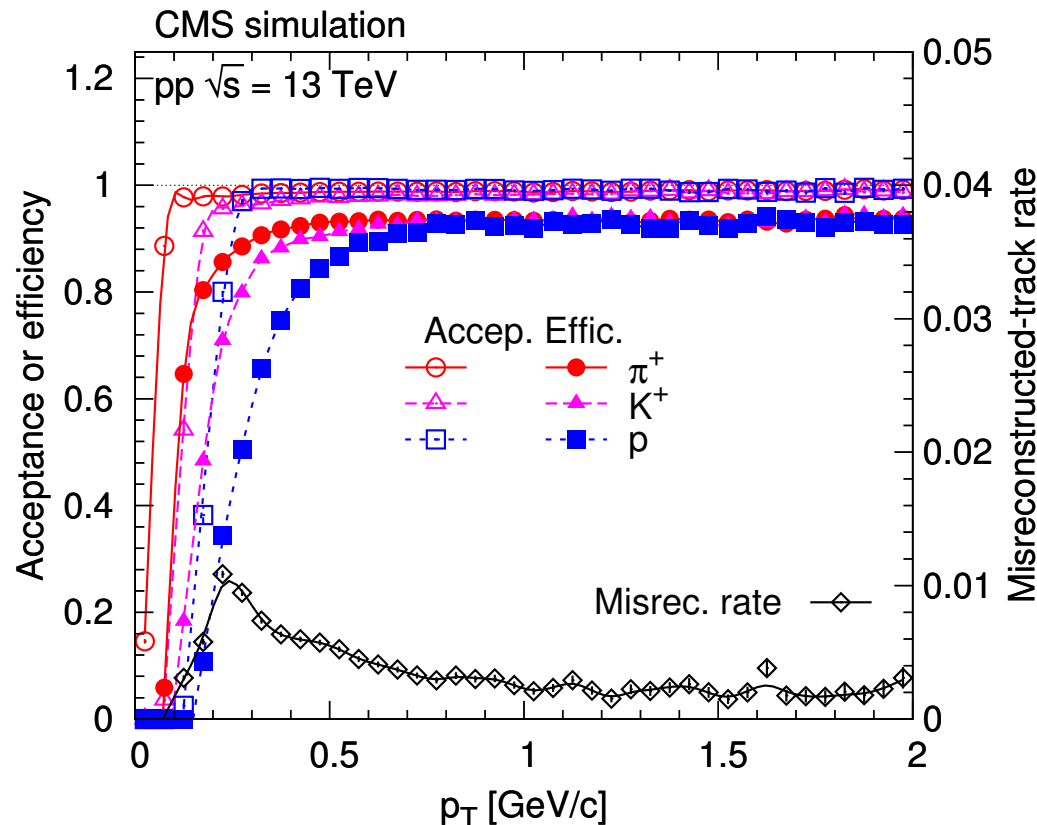
# Trigger, event definition

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- Data
  - Special low luminosity run, collected in July 2015
  - The average number of pp interactions in each bunch crossing was 1.0
  - About 7 million events; uncertainties are dominated by systematics
- Online and offline event selections
  - Coincidence of signals from both proton bunches present
  - At least one reconstructed interaction vertex
  - Beam-halo and beam-induced background events were rejected
- We corrected to the **inelastic selection**, closest to actual trigger
  - Fraction of inelastic pp collisions not resulting in a reconstructed interaction is about  $14\% \pm 3\%$ ; they are mostly diffractive ones with negligible central activity

Used MC event generators are Pythia6 Z2\*,  
Pythia8 CUETP8M1, and EPOS LHC

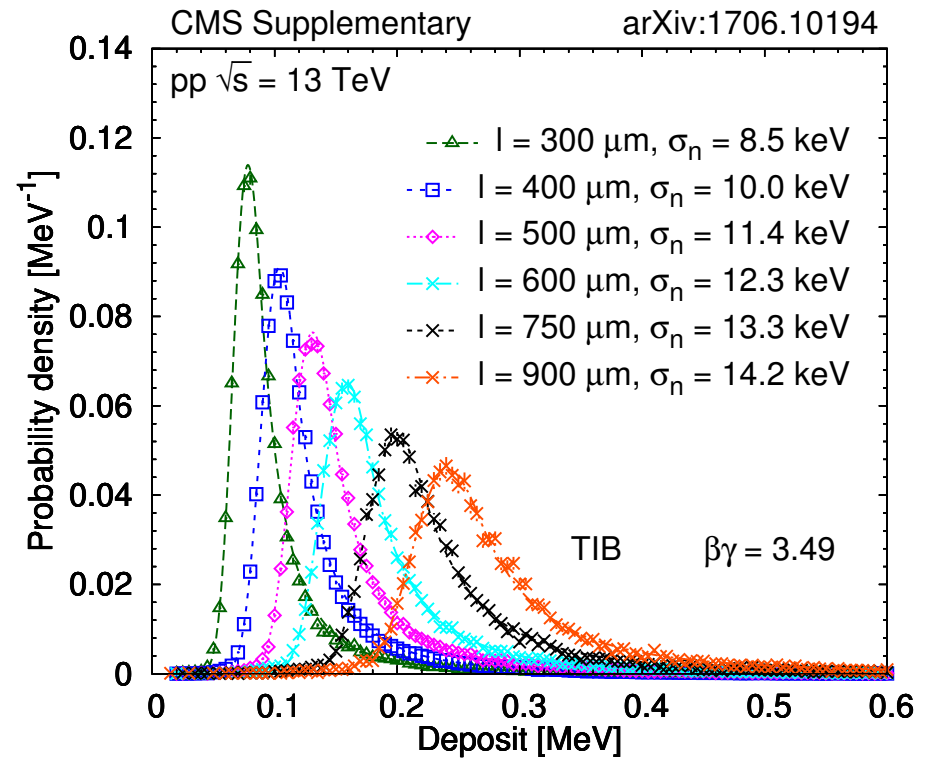
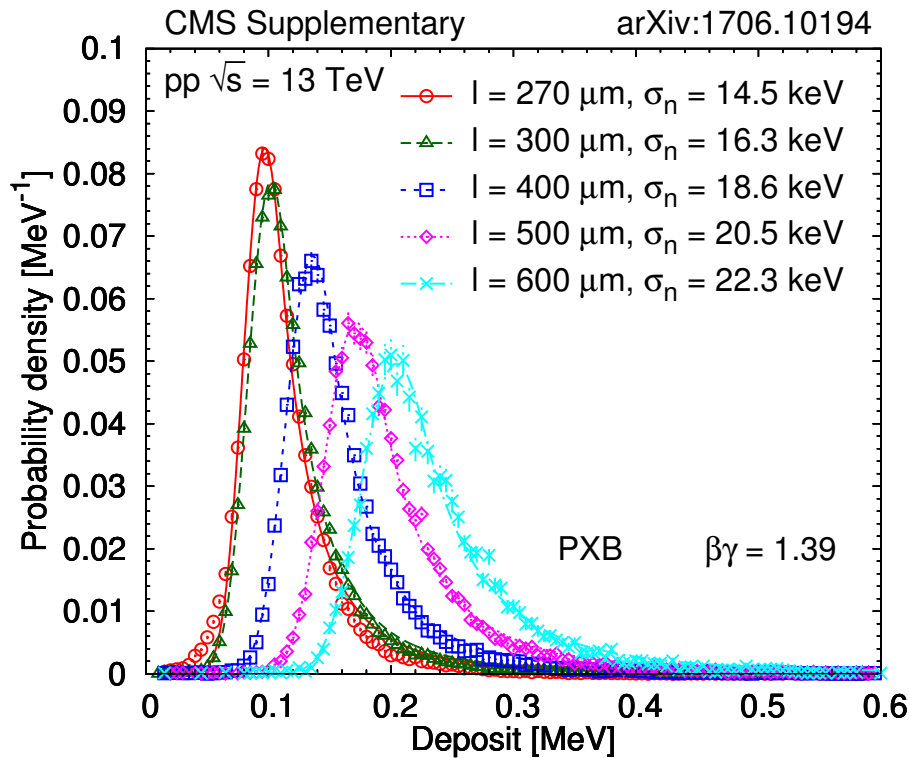
# Tracking performance



- Tracking corrections
  - Acceptance, efficiency, fake tracks, unfolding  $p_T$  bias and resolution
- Non-primaries
  - Feed-down from  $K_S^0$  and  $\Lambda/\bar{\Lambda}$  via MCs (not measured yet); secondaries

Excellent tracking performance, for pions down to  $p_T = 0.1$  GeV/c

# Analytical energy loss parametrization – validation



The central quantity is the

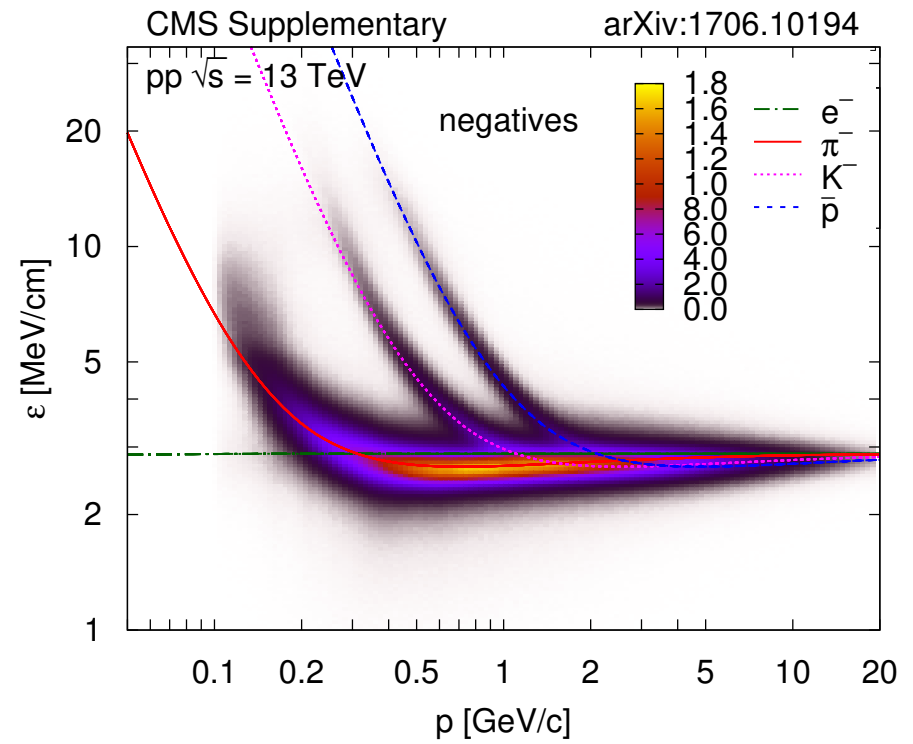
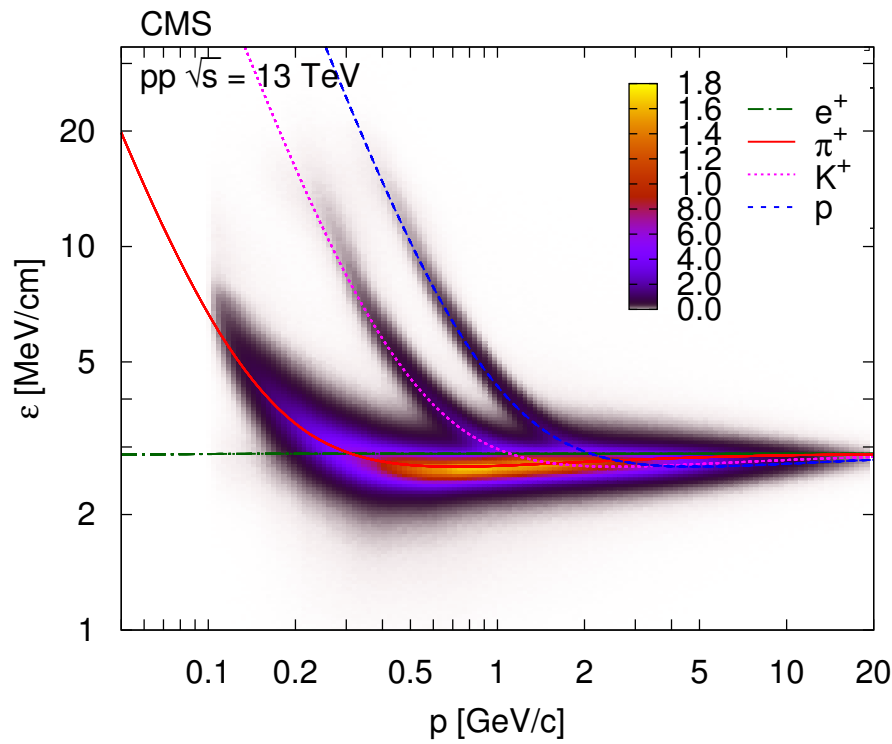
most probable energy loss rate  $\varepsilon$  along a reference length  $l_0$

Probability of an energy loss  $y$ , along a path length  $l$

$P(y|\varepsilon, l)$  has exponential and Gaussian parts

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

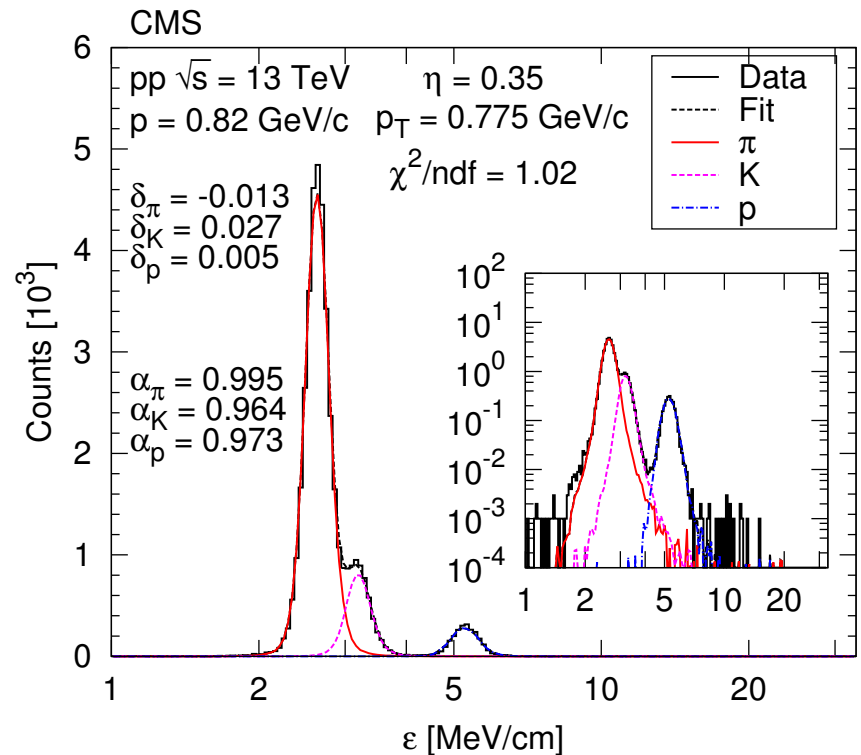
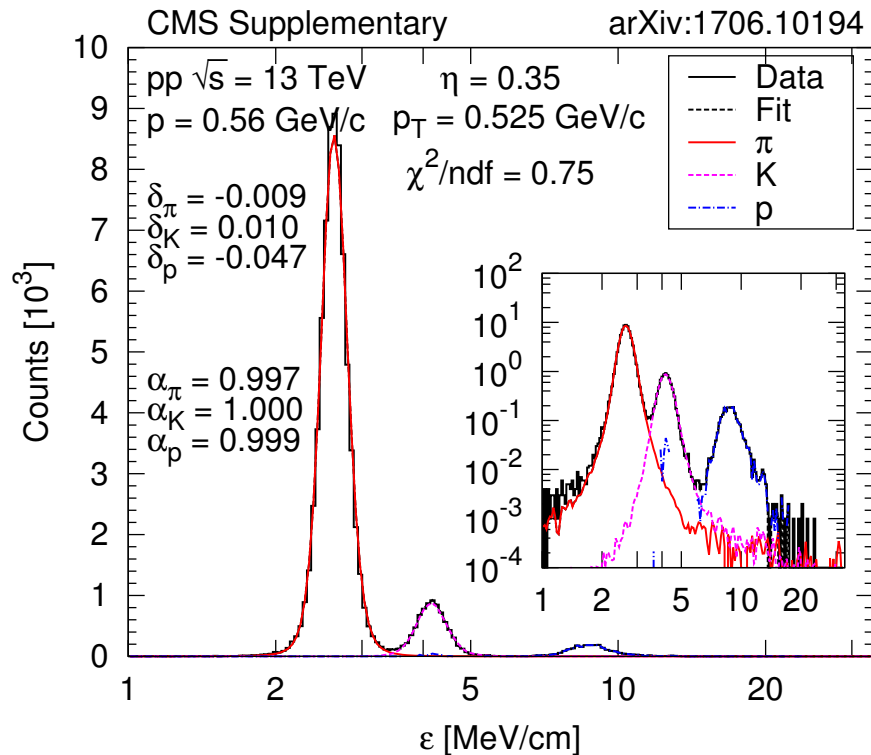
# Most probable energy loss rate $\varepsilon$



- Estimation of  $\varepsilon$ , for each track

- We have the properly corrected deposits  $y_i$  along the trajectory
- Minimize the joint energy-deposit  $\chi^2$  for a track
- False hit removal (energy deposit outliers)
- Estimate of  $\varepsilon$

# Fits in $(\eta, p_T)$ bins

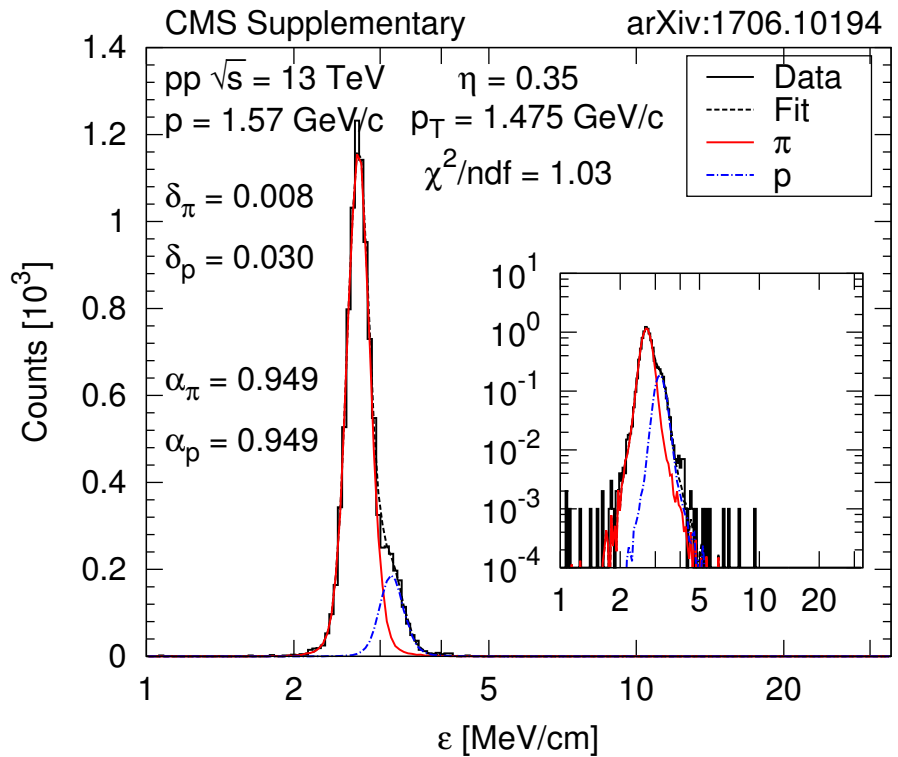
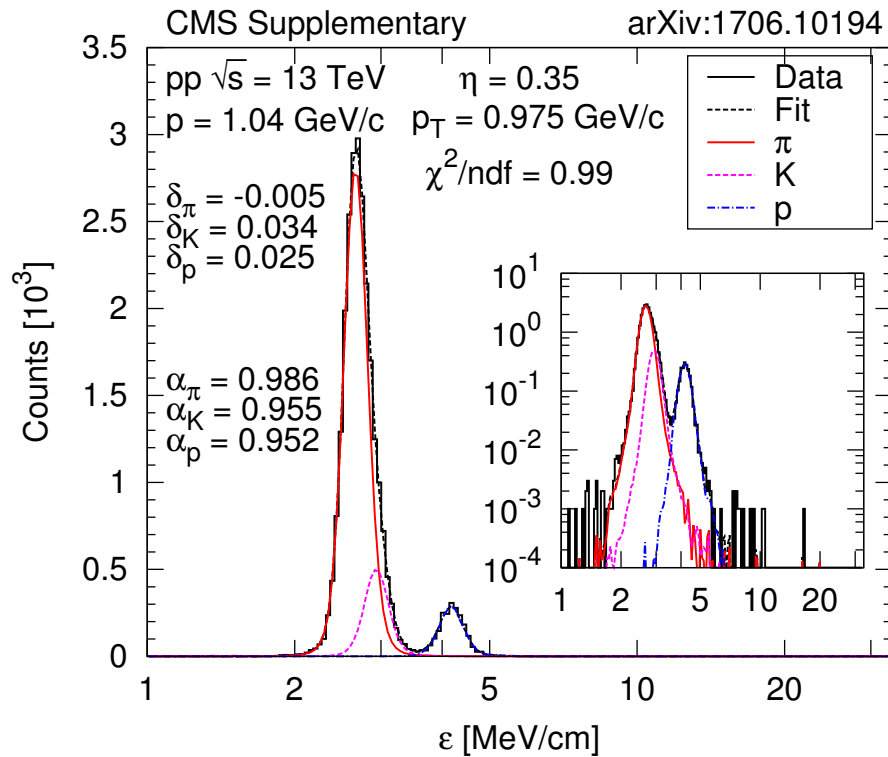


- Template fits

- They are not Gaussians: use tracks in data
- Keep all quantities, but regenerate energy deposits with the parametrization

High quality fits, good  $\chi^2/\text{ndf}$

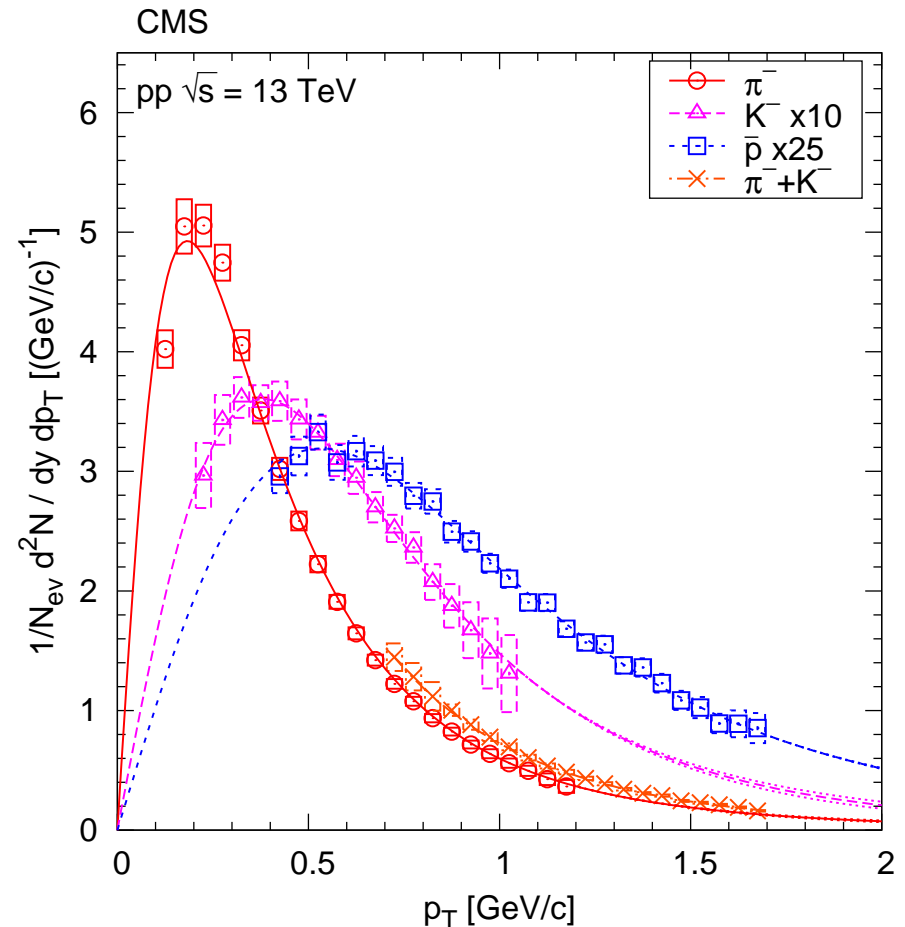
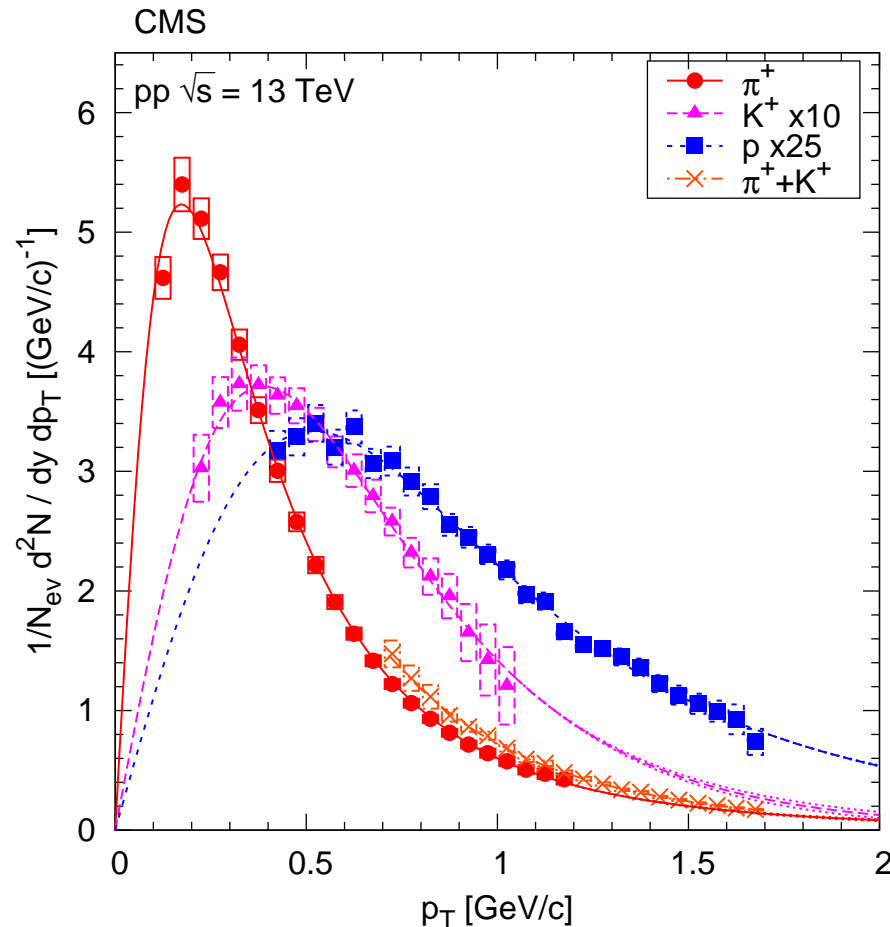
# Fits in $(\eta, p_T)$ bins



Total momentum range used for physics is limited by systematic uncertainty

We give results in  $|y| < 1$  (dictated by PID capabilities)

# Results – $p_T$ spectra



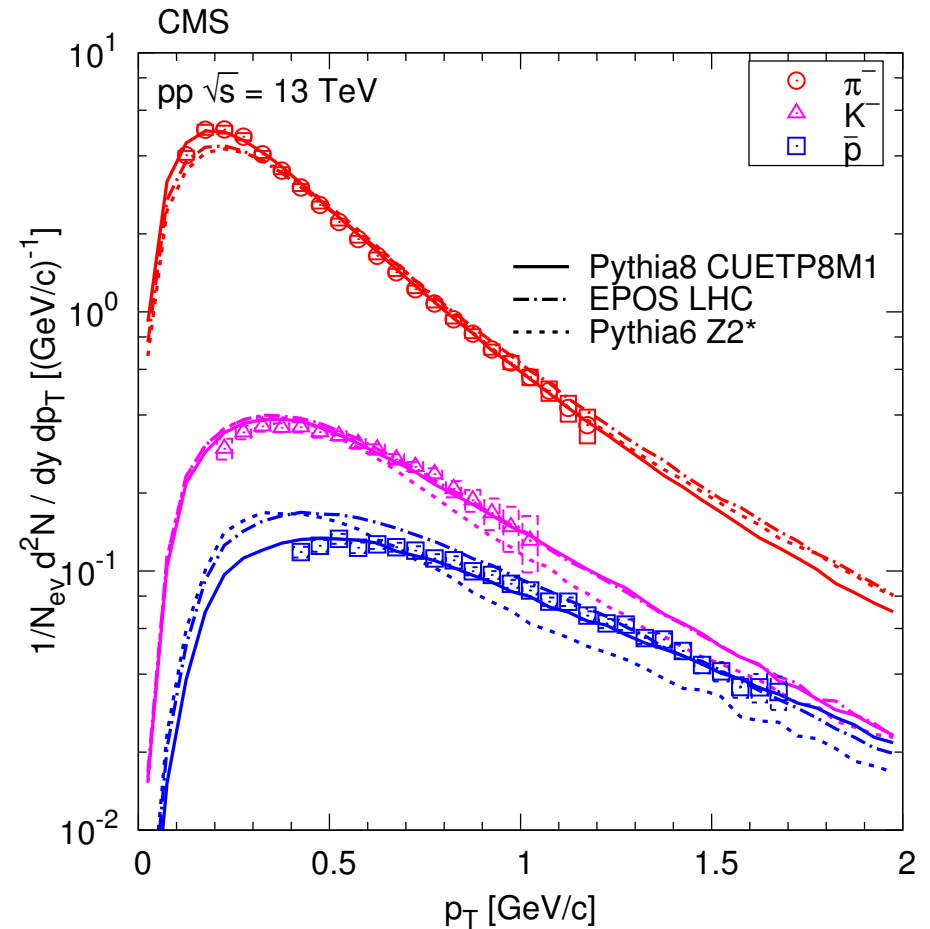
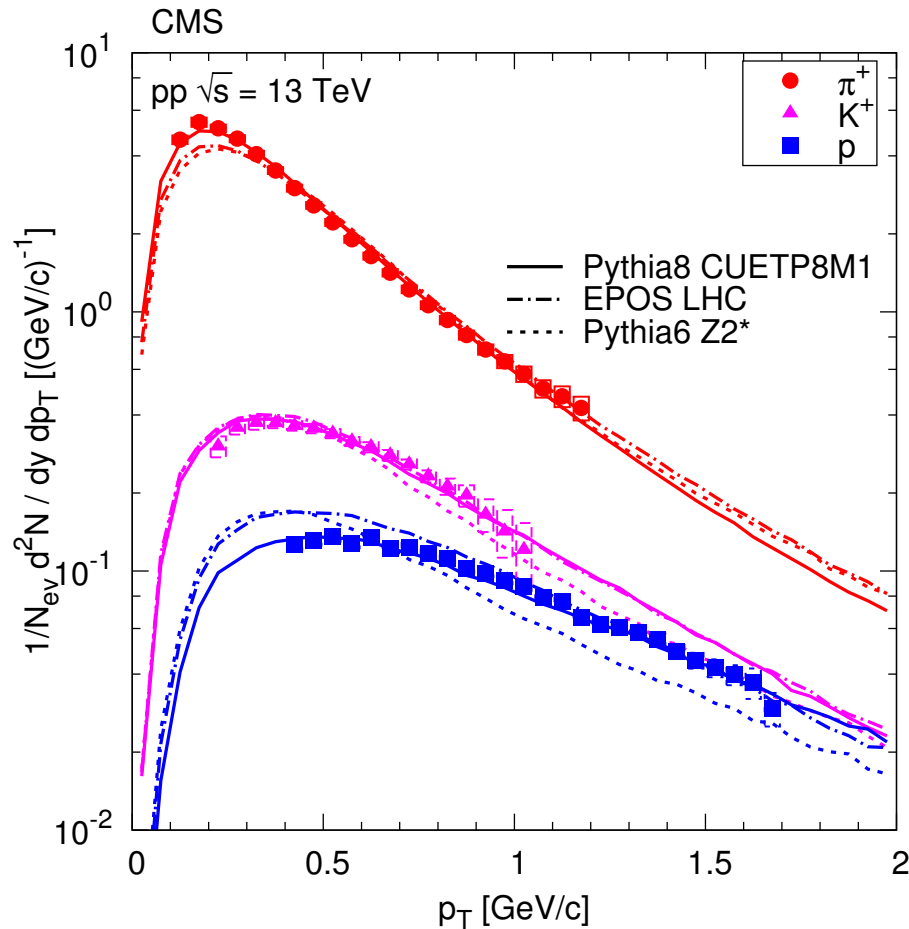
Statistical (error bars) and systematic uncertainties (boxes)

The fully correlated normalization uncertainty (not shown) is 3–4%

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

The fits are of good quality

# Results – $p_T$ spectra

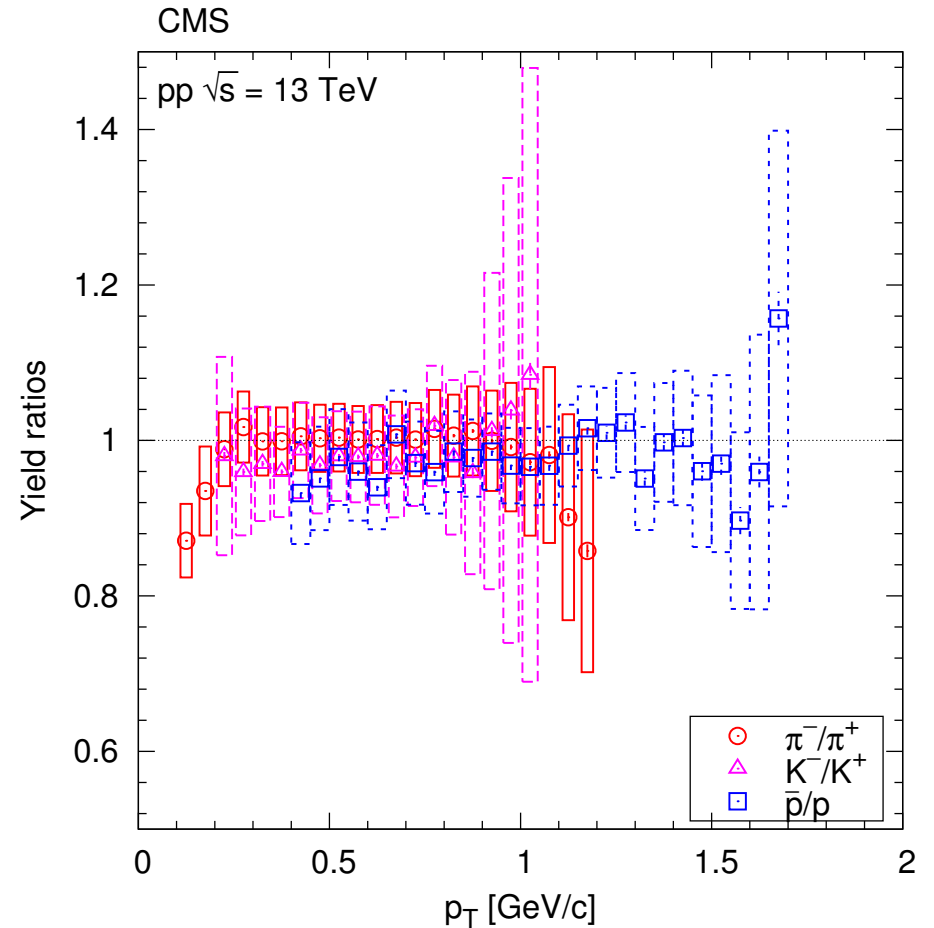
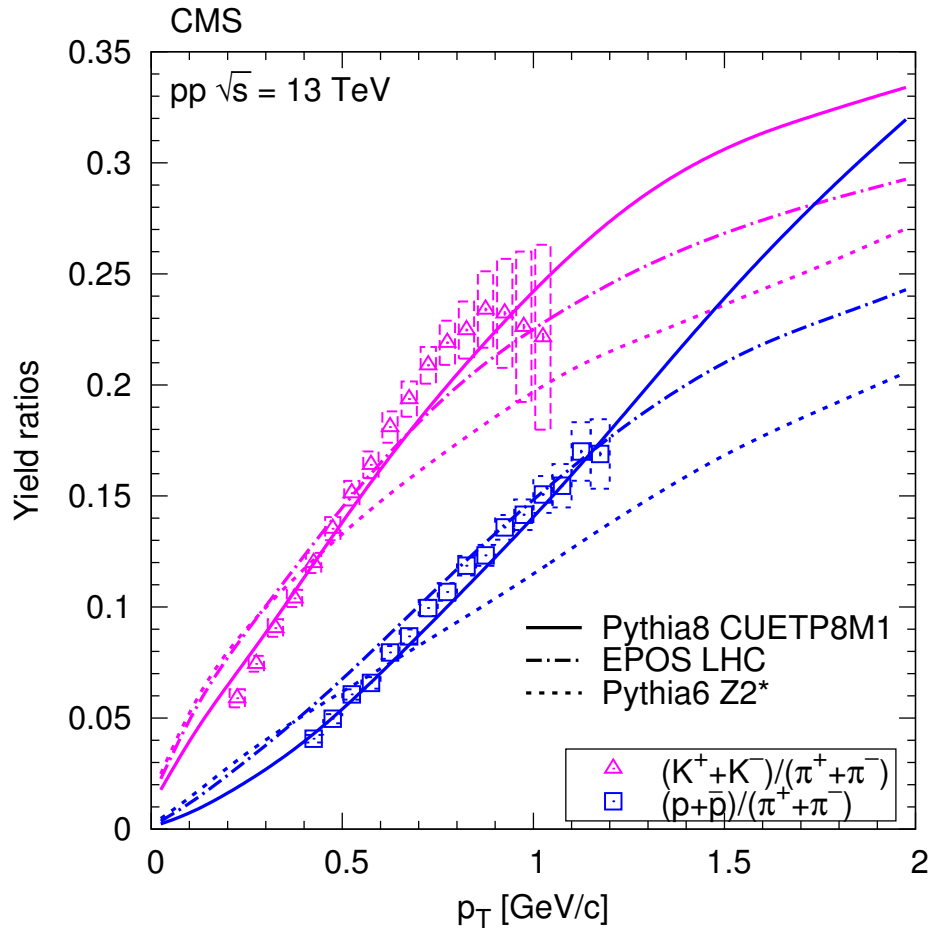


Logarithmic vertical scale

Reasonable job from generators

Pythia8 CUETP8M1 is the best (thanks to tuning at 7 TeV)

# Results – ratios vs $p_T$



- $p_T$  dependence

- $K/\pi$  ratios are **well approximated** by Pythia8 and EPOS LHC
- Ratios of oppositely charged particles are compatible with 1, indep of  $p_T$

# Track multiplicity classes

- How?

- take the measured  $d^2N/d\eta dp_T$  values
- use adjusted MC corrections (take PID ratios from data)
- correct for low  $p_T$  part ( $p_T < 0.1$  GeV/c), assuming a linear startup with  $p_T$
- no Tsallis fits are needed here

- The classes

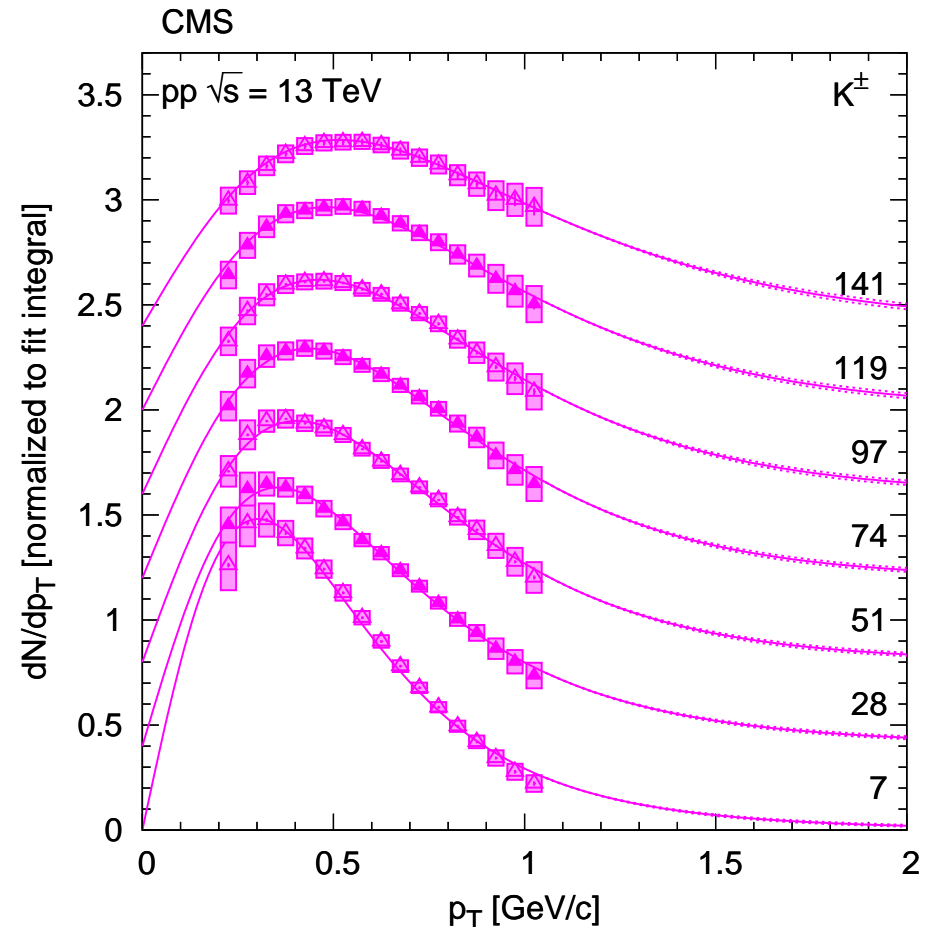
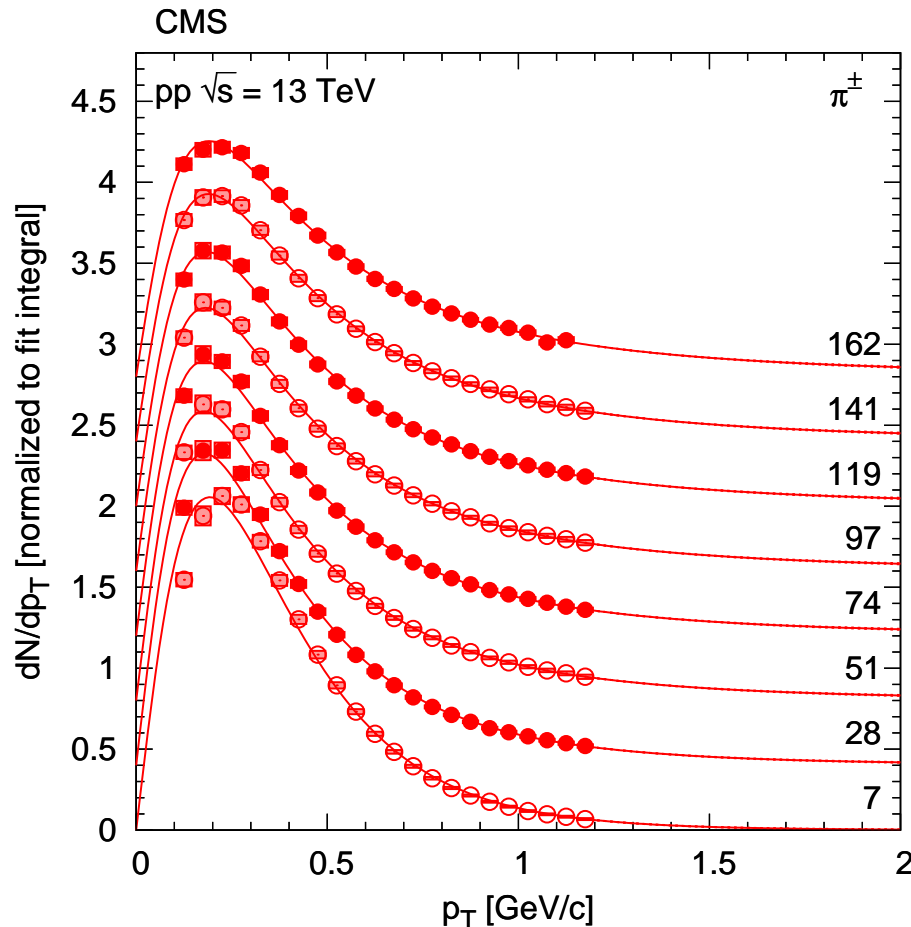
	“peripheral”										“central”							
$N_{\text{rec}}$	0–9	10–19	20–29	30–39	40–49	50–59	60–69	70–79	80–89	90–99	100–109	110–119	120–129	130–139	140–149	150–159	160–169	170–179
$\langle N_{\text{tracks}} \rangle$	7	16	28	40	51	63	74	85	97	108	119	130	141	151	162	172	183	187

Collect data in  $N_{\text{rec}}$ , and plot the results in (theoretical)  $\langle N_{\text{tracks}} \rangle$  bins

We give the corresponding fully corrected  $N_{\text{tracks}}$  values in  $|\eta| < 2.4$

$N_{\text{tracks}}$  – Poor man’s centrality measure

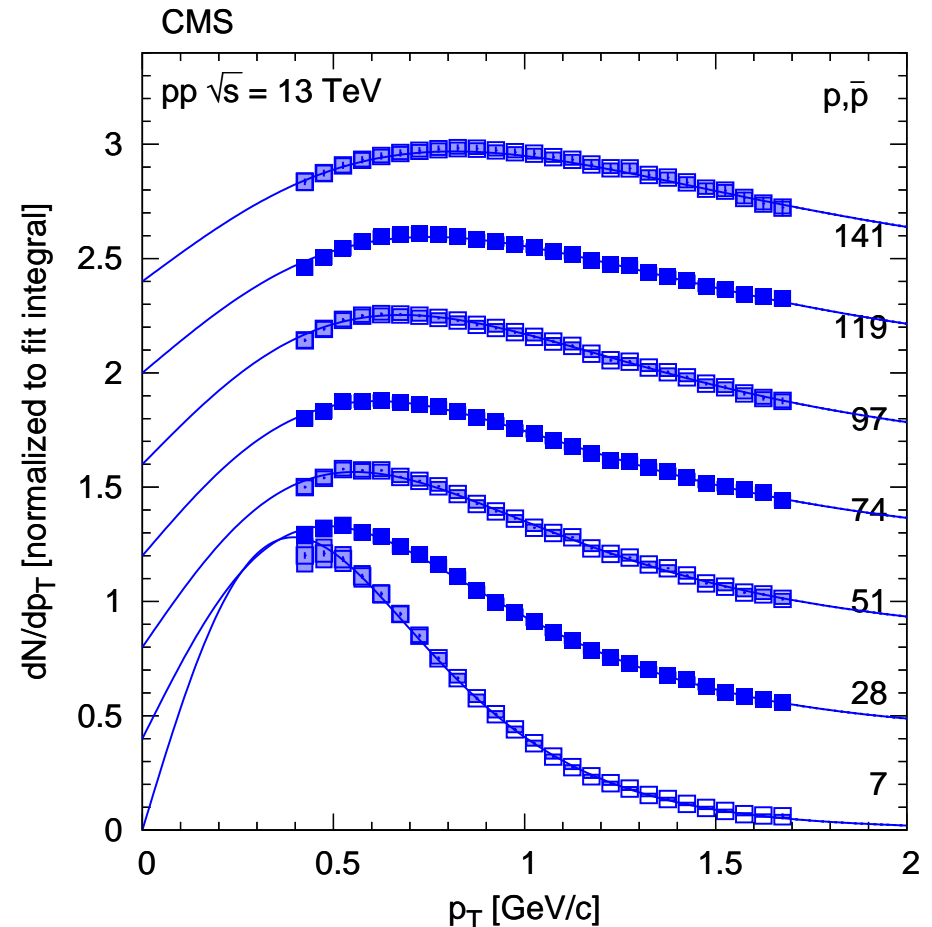
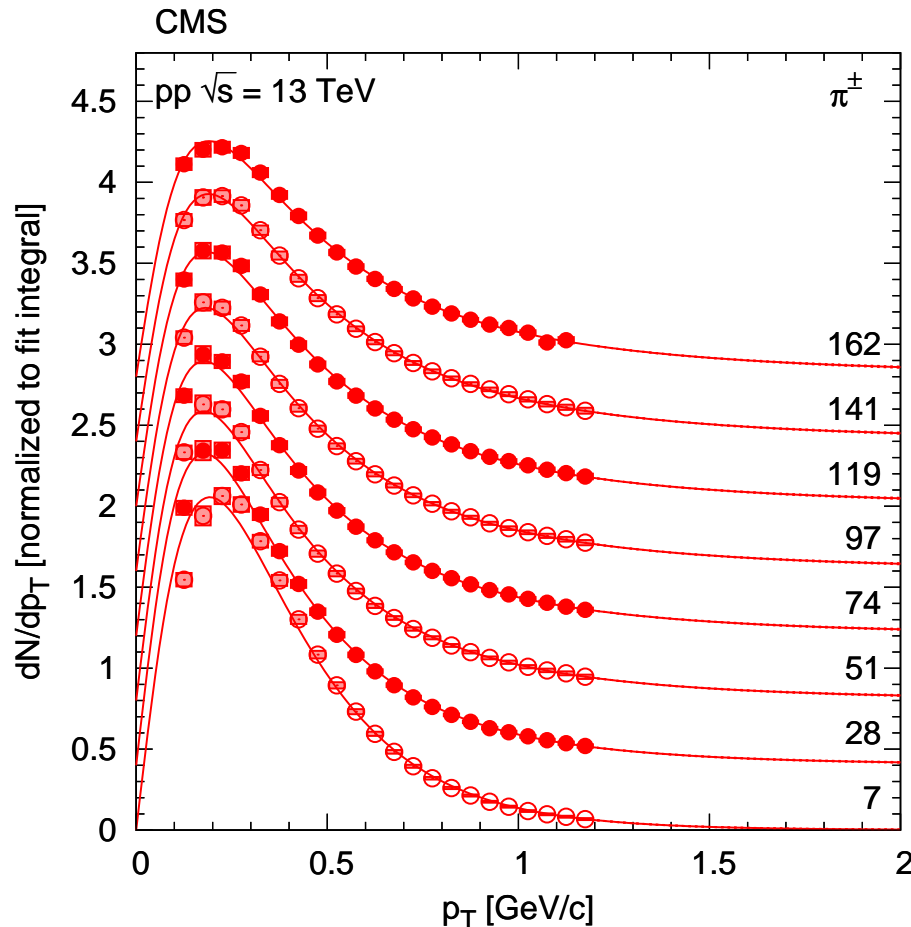
# Results – multiplicity dependence



The values with increasing multiplicity are successively shifted by 0.1 units along the vertical axis

Unchanged (pion) vs changed shapes (kaons)

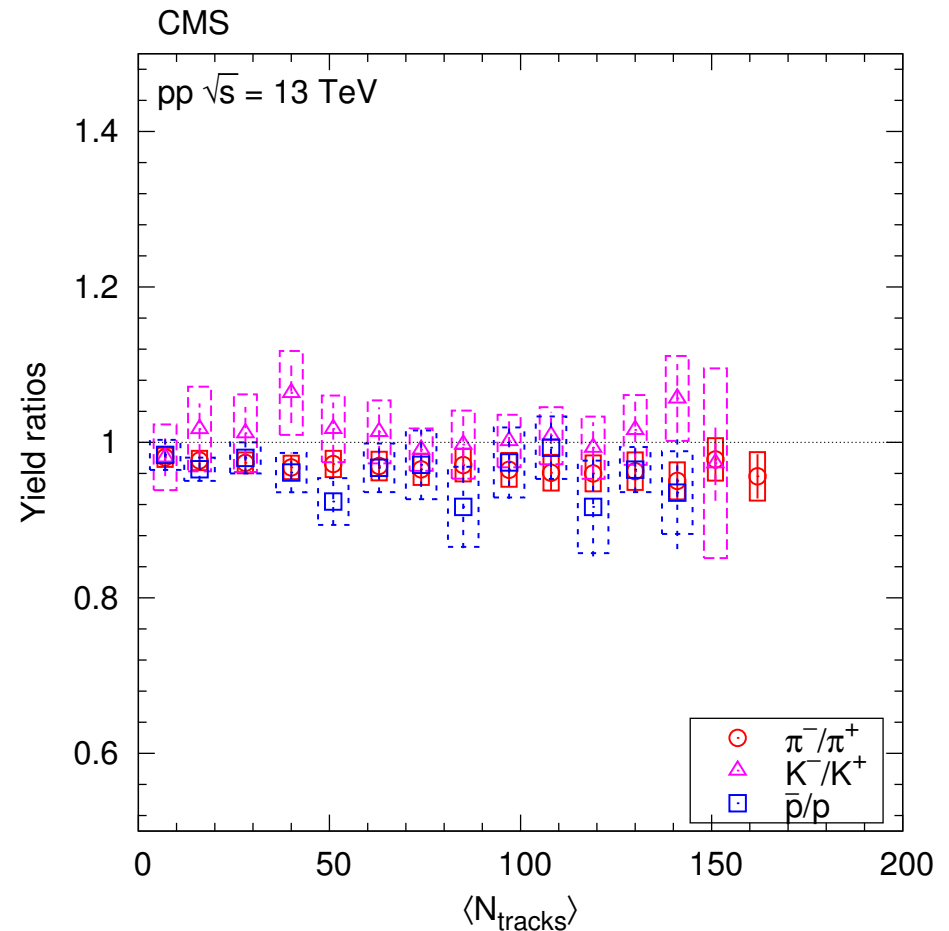
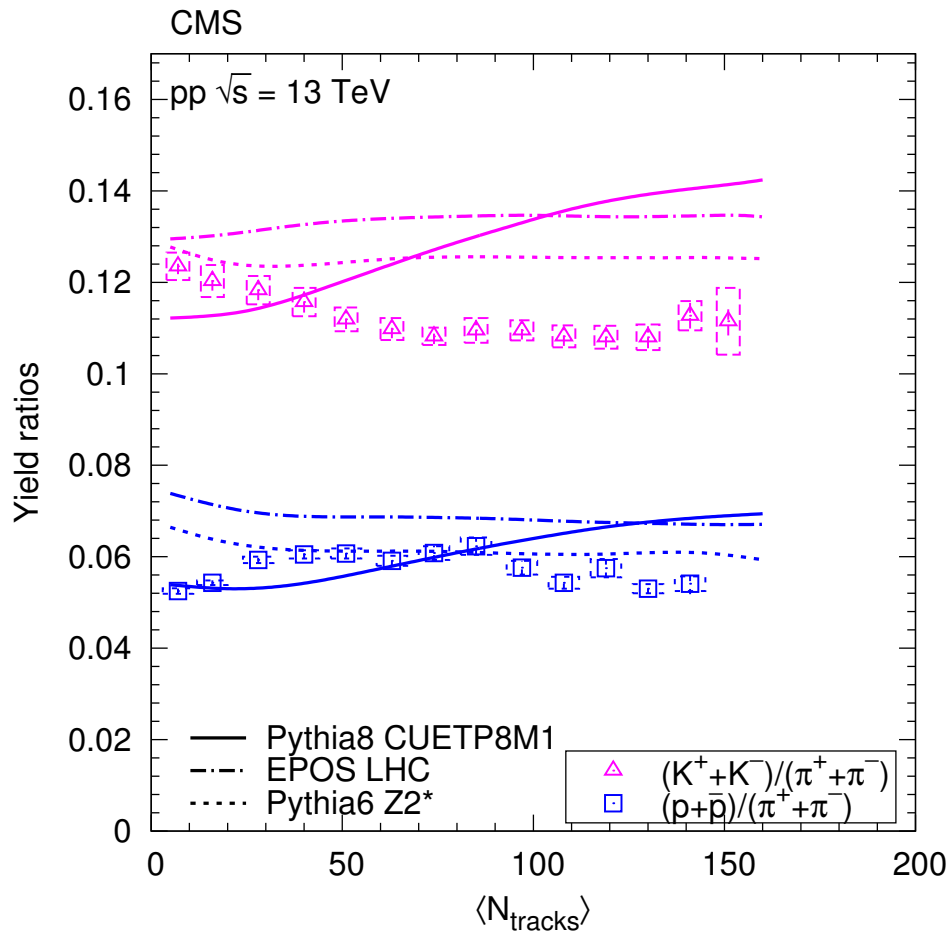
# Results – multiplicity dependence



The values with increasing multiplicity are successively shifted by 0.1 units along the vertical axis

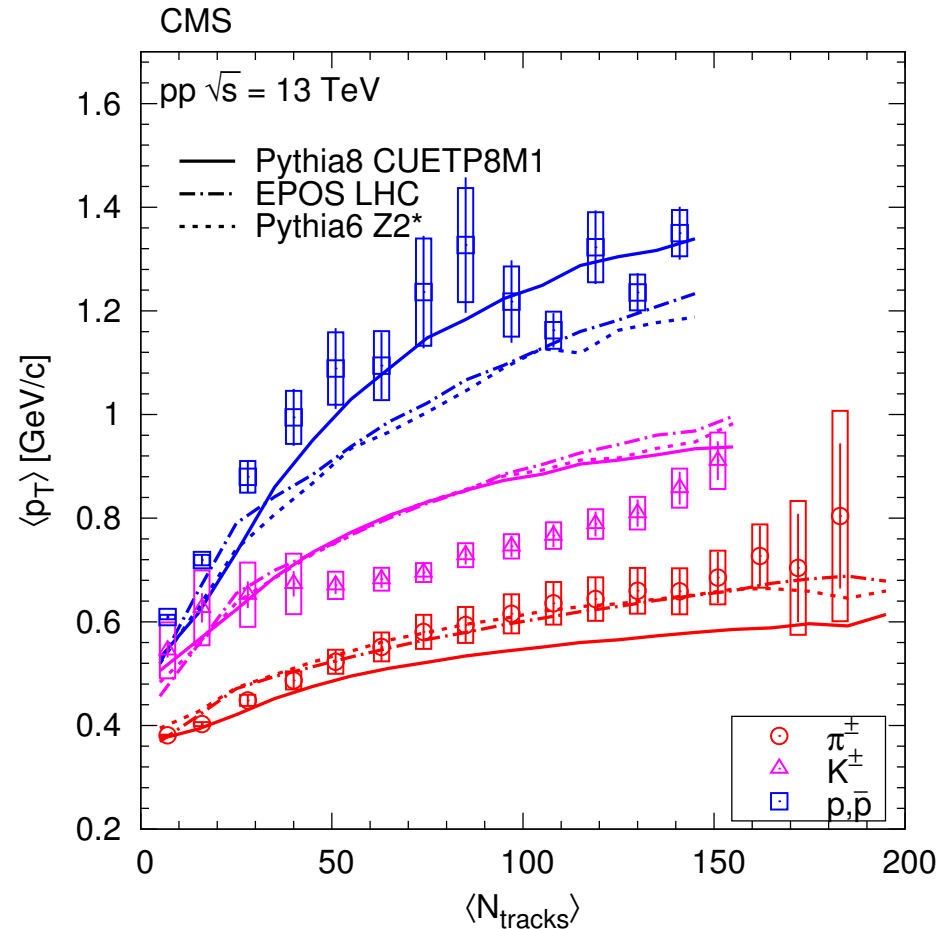
**Strong change** for protons

# Results – ratios – multiplicity dependence



- Cross ratios
  - $K/\pi$  and  $p/\pi$  ratios are flat
- Opposite charge ratios
  - The ratios are close to 1, no dependence on  $\langle N_{\text{tracks}} \rangle$

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



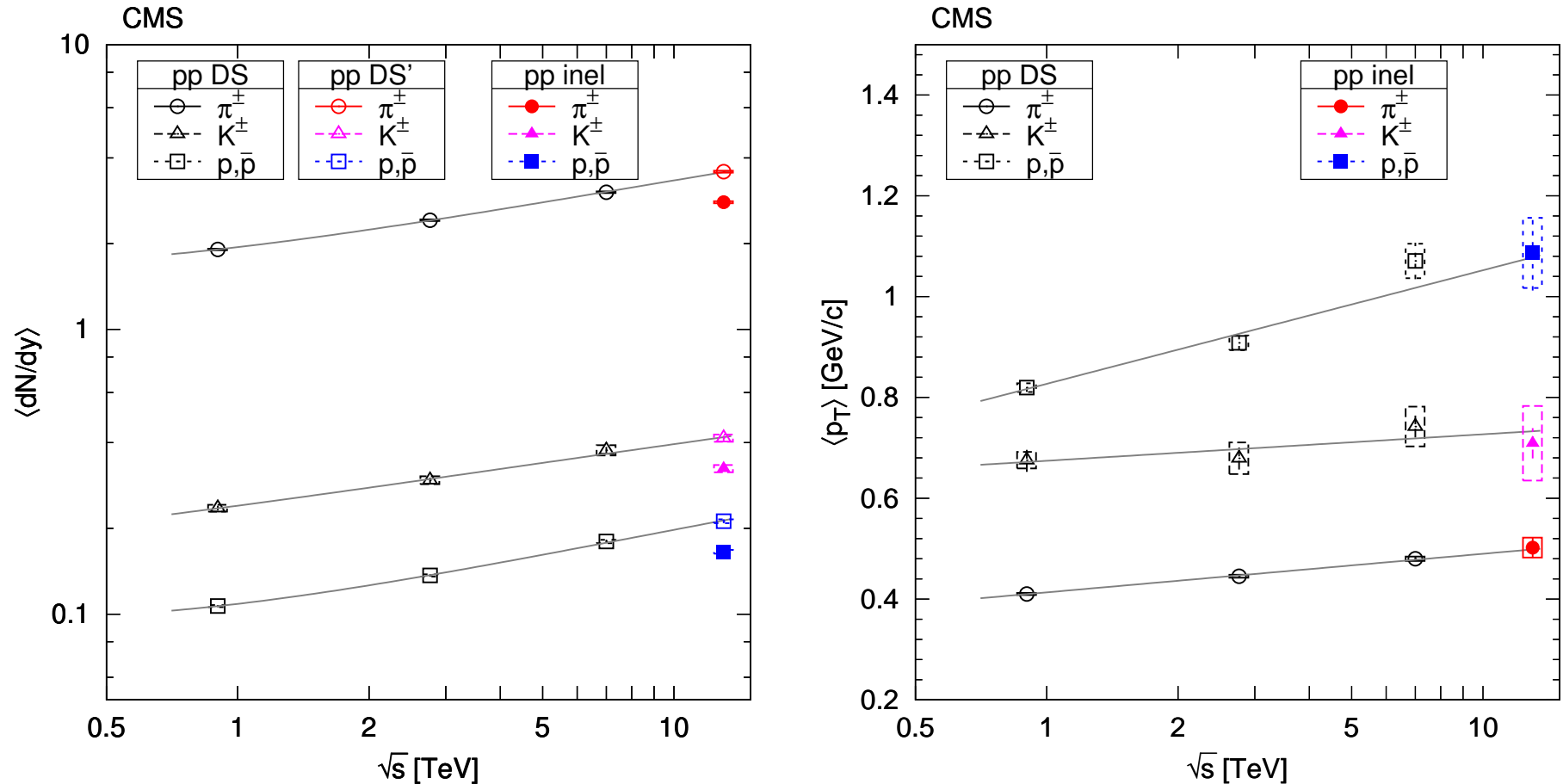
Calculated using MC technique followed by numerical integration

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

**None of the MCs reproduces well** the multiplicity dependences for all species

All generators **overestimate** the measured values **for kaons**

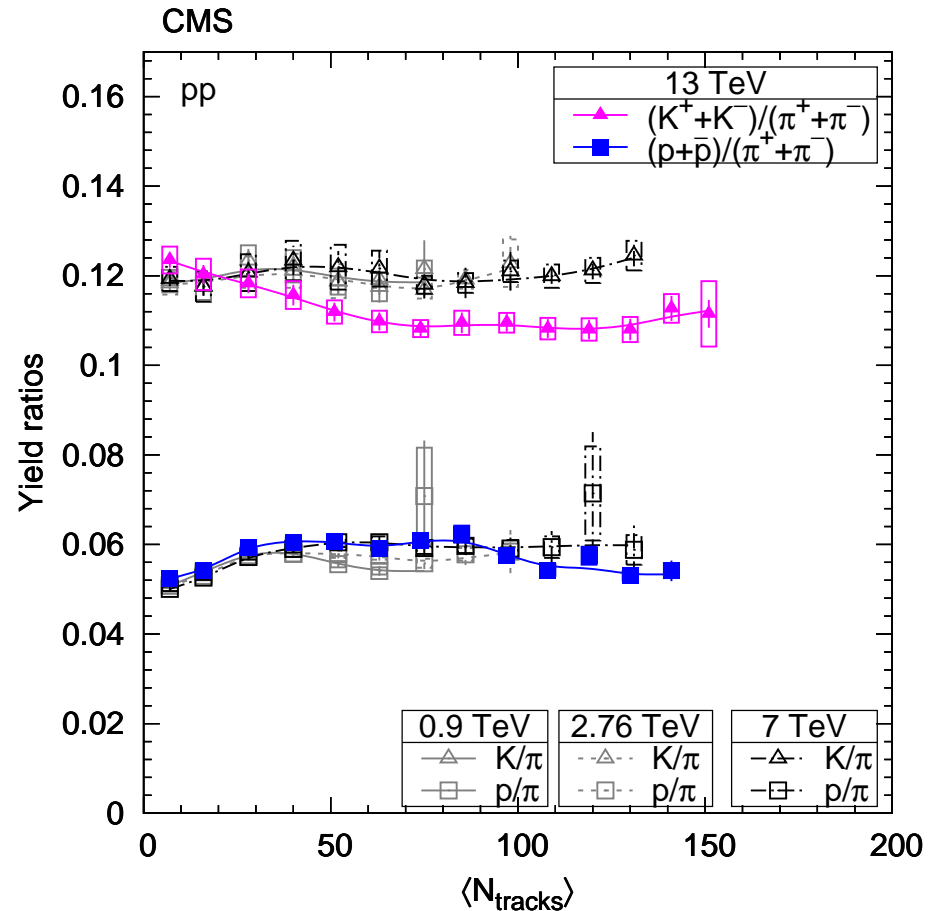
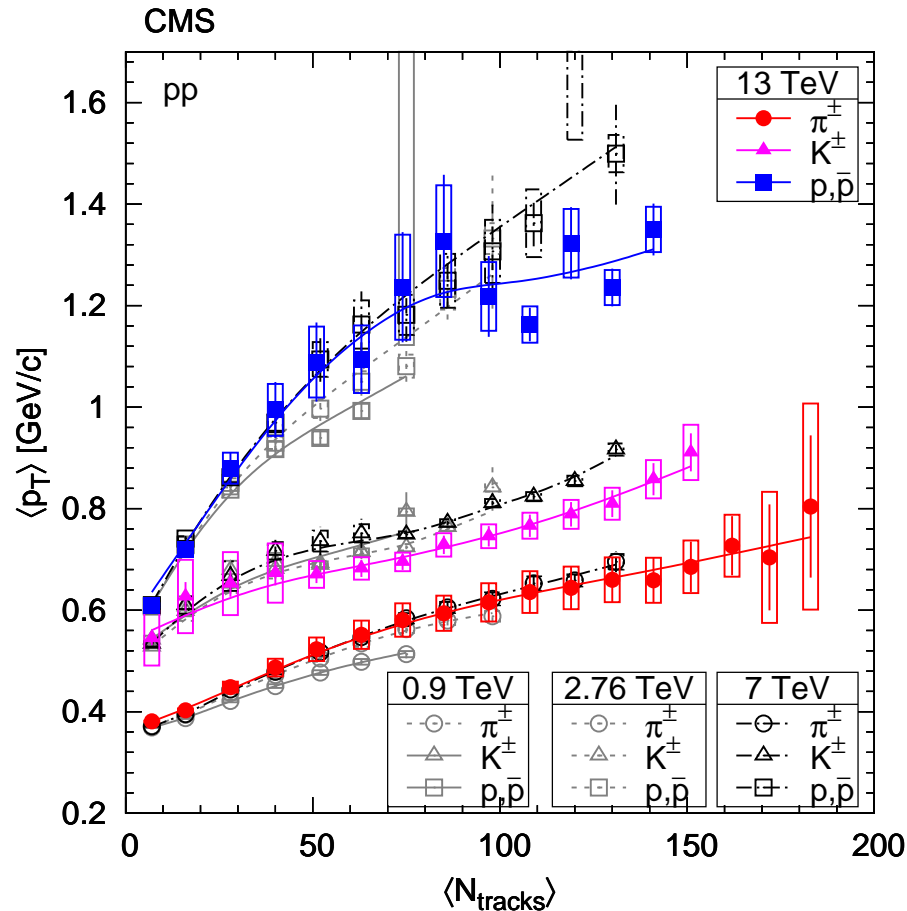
# Comparisons – $\sqrt{s}$ dependence – pp



Comparing to previous CMS measurements with double sided (DS) selection

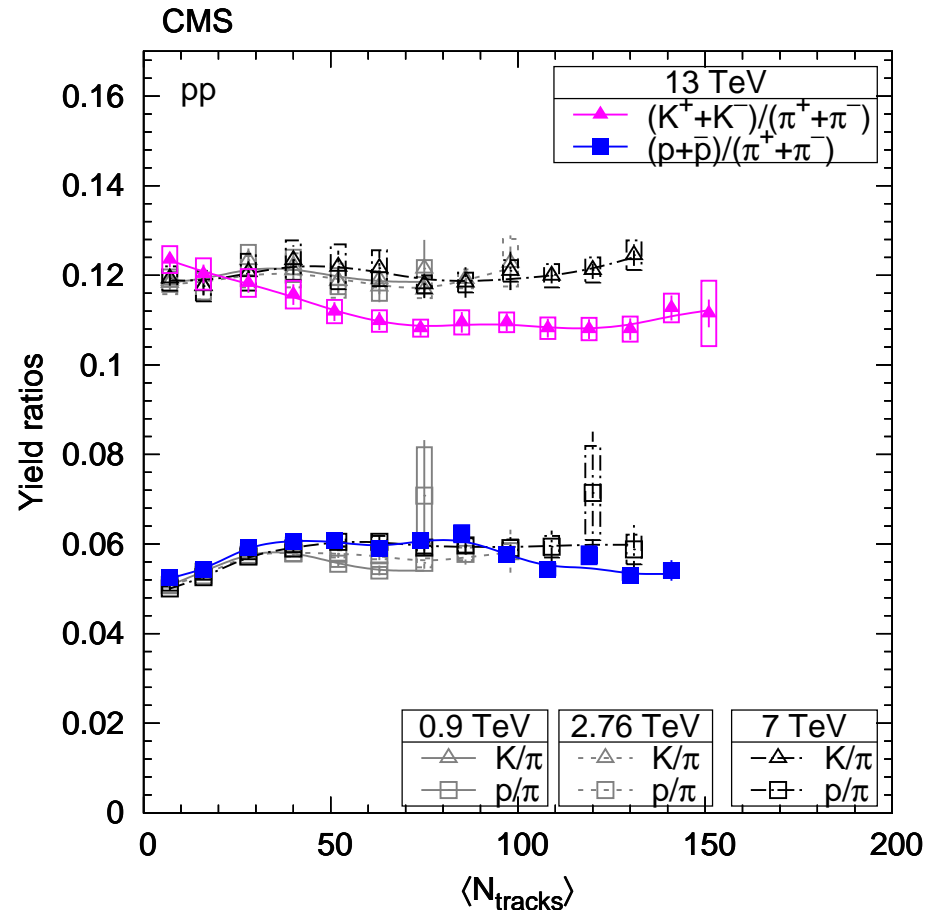
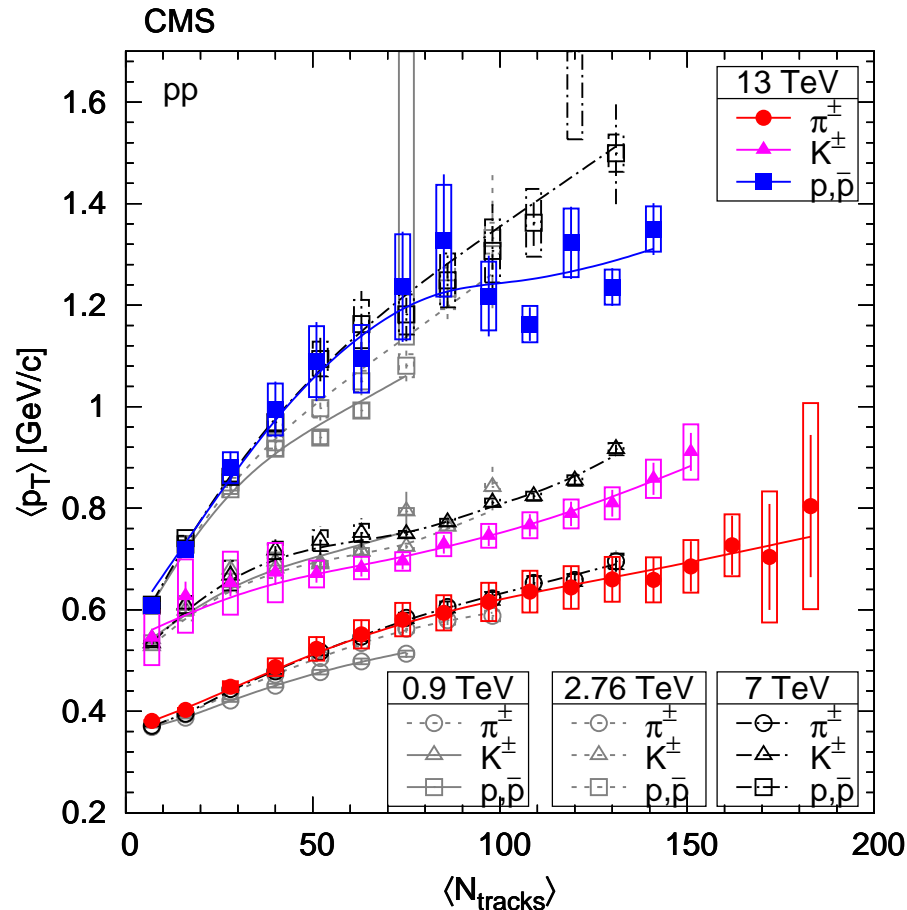
The curves show parabolic ( $dN/dy$ ) or linear ( $\langle p_T \rangle$ ) fits in  $\ln s$

# Comparisons – $\sqrt{s}$ dependence – physics message



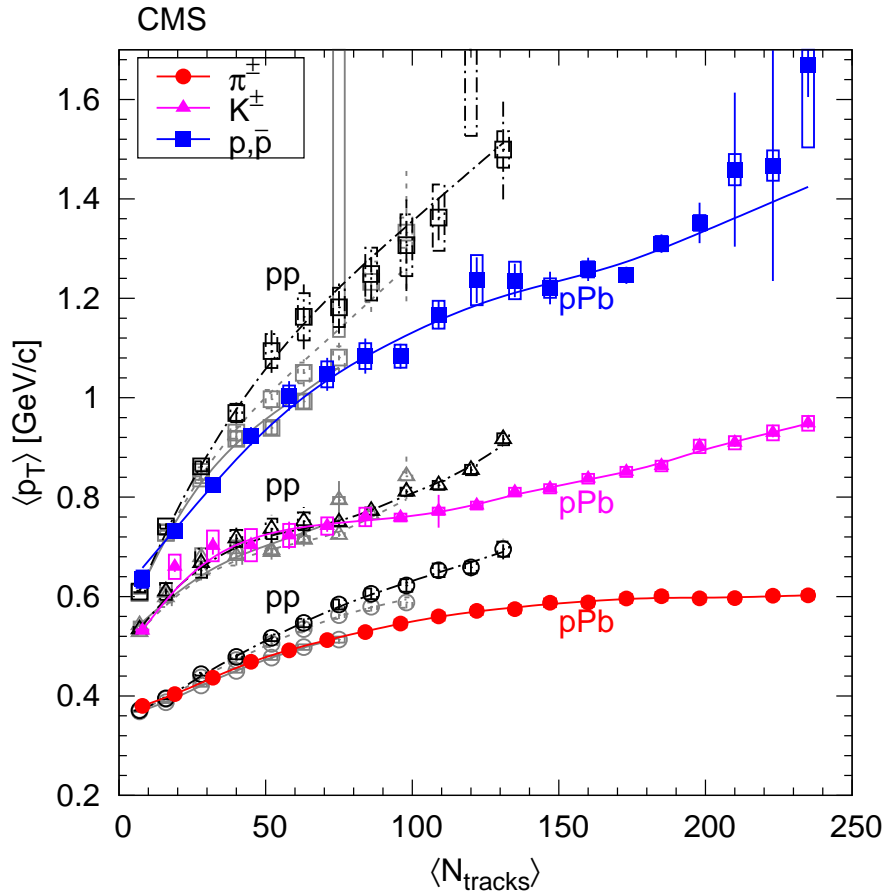
- Both  $\langle p_T \rangle$  and yield ratios show **very similar dependences** on the **particle multiplicity**, independently of  $\sqrt{s}$
- The  $\sqrt{s}$ -evolution provides information on the “**saturation scale**” ( $Q_{\text{sat}}$ ) of the **gluons in the proton** [d’Enterria, Pierog JHEP 08 (2016) 170]

# Comparisons – $\sqrt{s}$ dependence – physics message

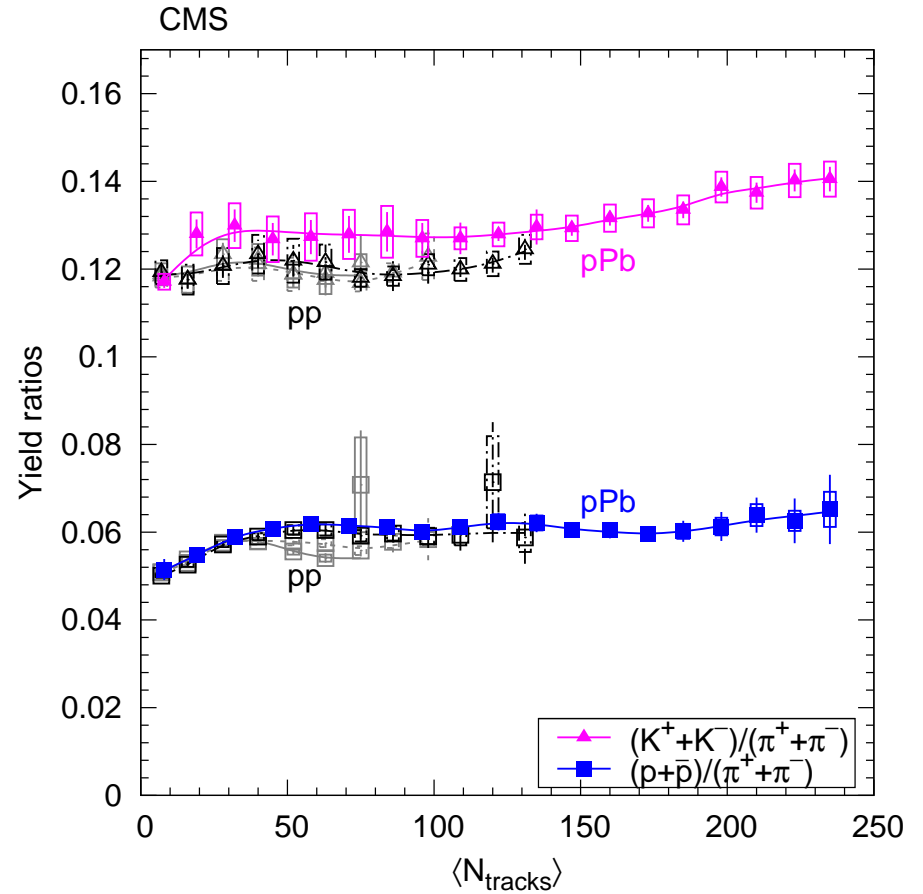


- Minijet-based models such as Pythia have an energy-dependent **infrared  $p_T$  cutoff** that mimics the power-law evolution of  $Q_{sat}$  characteristic of **gluon saturation models** [McLerran et al, Nucl Phys A 916 (2013) 210]
- Saturation models **consistently connect  $Q_{sat}$  to the impact parameter** of the hadronic **collision**, giving a natural dependence of  $\langle p_T \rangle$  on the multiplicity

# Comparisons – $\sqrt{s}$ dependence – pp vs pPb

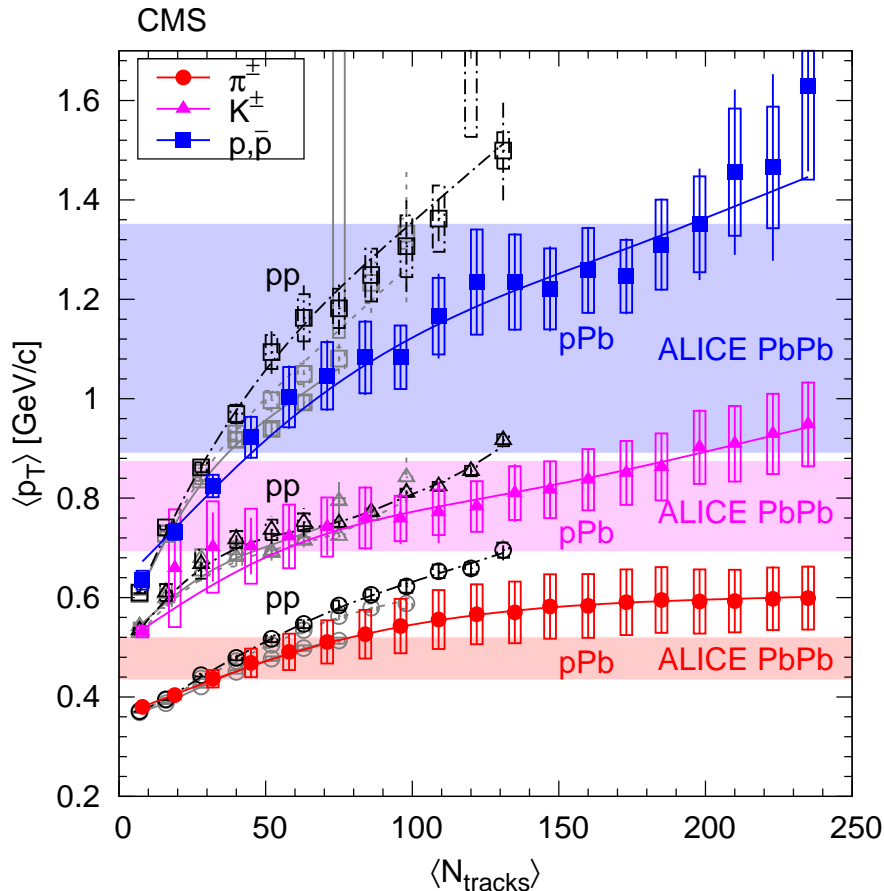


pp (0.9, 2.76, 7 TeV), pPb (5.02 TeV)

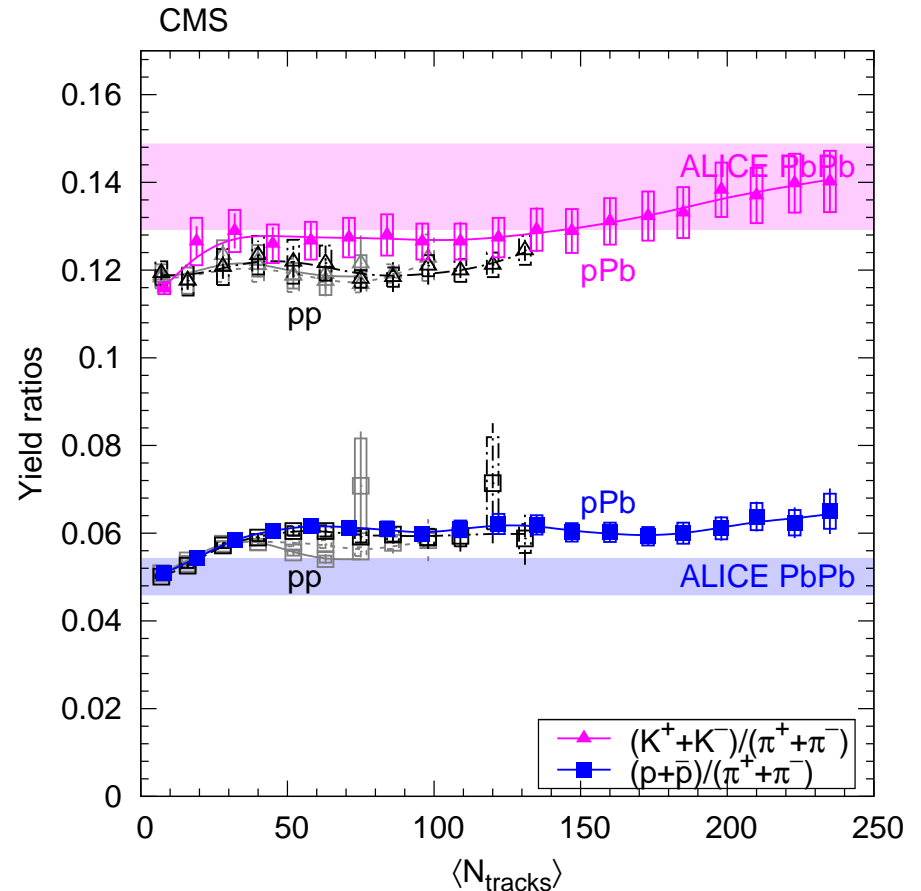


- For low track multiplicity ( $N_{\text{tracks}} \lesssim 40$ ), **pPb behaves very similarly to pp**; mostly peripheral pPb collisions are present with a few proton-nucleon collisions
- By asking for more produced particles those collisions are chosen, where the projectile proton collided with the thick disk of the lead nucleus

# Comparisons – $\sqrt{s}$ dependence – pp vs pPb vs PbPb



pp (0.9, 2.76, 7 TeV), pPb (5.02 TeV), PbPb (2.76 TeV, periph to central bands)



- **Highest multiplicity** pPb interactions yield higher  $\langle p_T \rangle$  than in central PbPb collisions (Phys Rev C 88 (2013) 044910), or reach those values in case of pp
- Even the most central PbPb collisions contain a mix of soft and hard
- In case of pp or pPb specifically **the most violent interactions** are selected

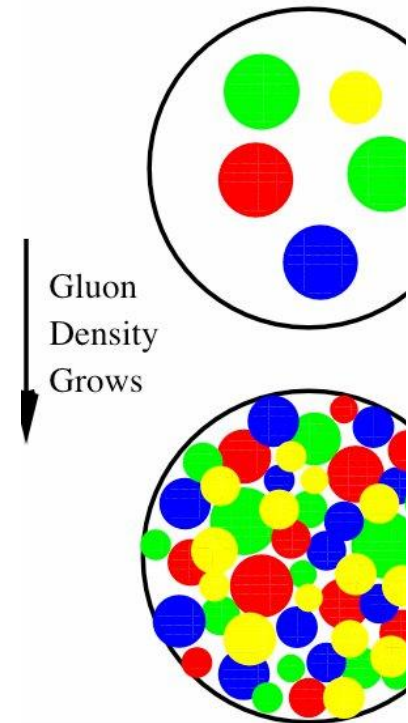
# Summary

- Results

- Measured inelastic spectra of identified charged hadrons in pp  $\sqrt{s} = 13$  TeV; as a function of track multiplicity

- Conclusions

- Particle production at LHC energies is strongly **correlated with event multiplicity in both pp and pPb**, rather than with the center-of-mass energy of the collision or with the masses of the colliding nuclei
- Common underlying physics mechanism: the characteristics of particle production are **constrained by** the amount of **initial parton energy** that is available in any given collision
- Success of **gluon saturation models** with  $Q_{\text{sat}}$ ; as well as minijet-based models **with energy-dependent cutoff**



Thank you for your attention!

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# Backup

# Systematic uncertainties

Source	Uncertainty of the source [%]	Propagated yield uncertainty [%]		
Fully correlated, normalization				
Correction for event selection	3.0 (1.0)	}	3–4 (5–9)	
Pileup correction (merged and split vertices)	0.3			
High- $p_T$ extrapolation	1–3 (4–8)			
Mostly uncorrelated				
Pixel hit efficiency	0.3	}	0.3	
Misalignment, different scenarios	0.1			
Mostly uncorrelated, $(y, p_T)$ -dependent		$\pi$	K	p
Acceptance of the tracker	1–6	1	1	1
Efficiency of the reconstruction	3–6	3	3	3
Multiple-track reconstruction	50% of the corr.	–	–	–
Misreconstructed-track rate	50% of the corr.	0.1	0.1	0.1
Correction for secondary particles	25% of the corr.	0.2	–	2
Fit of the $\varepsilon$ distributions	1–10	1	2	1

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