Investigating the soft and hard limits of the transverse momentum spectra in pp collisions

24th Zimányi School

Winter Workshop On Heavy Ion Physics

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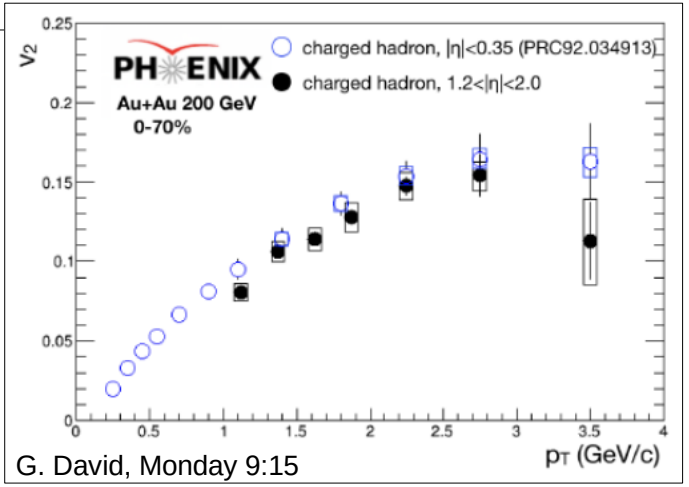
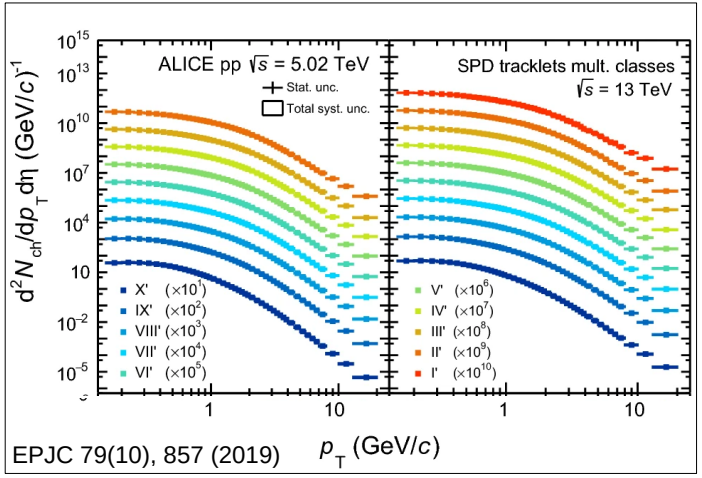
arXiv:2403.07512

Soft-hard limit - motivation

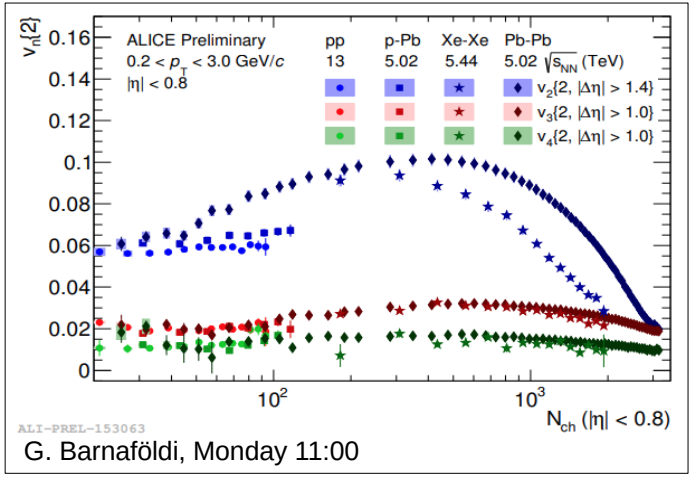
- p_T spectra and their multiplicity dependence: key tools for extracting parameters to be compared with theoretical models
- High multiplicity events and question of collectivity in small systems
- Cutoff parameters in Monte Carlo calculations
- Soft physics



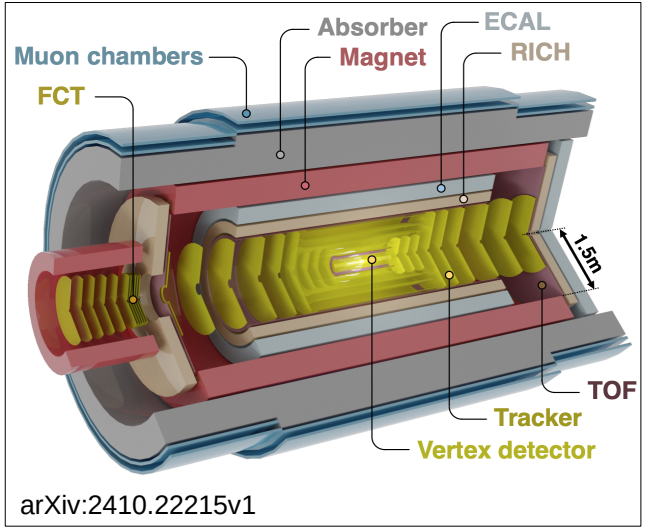
G. David, Monday 9:15



EPJC 79(10), 857 (2019)



G. Barnaföldi, Monday 11:00



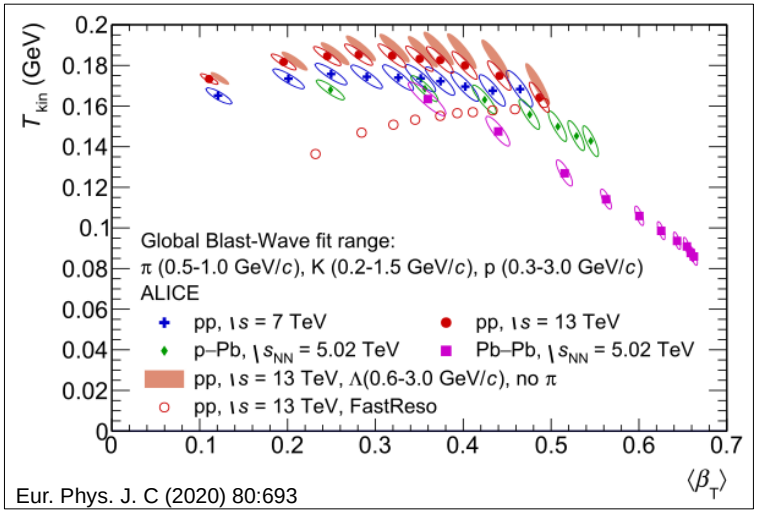
arXiv:2410.22215v1

Collective flow in every system

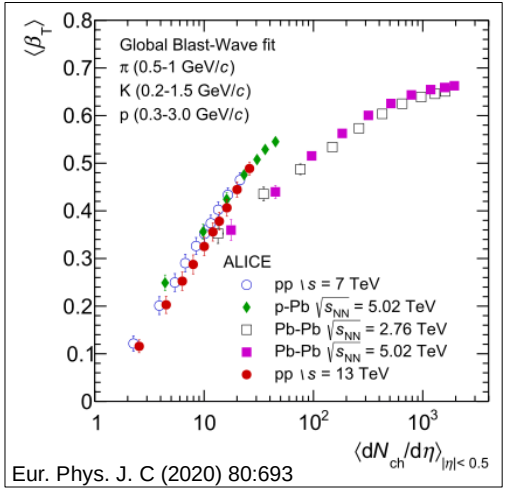
- High quality, multiplicity dependent (PID) data for various collision systems
- Traditional Blast-wave fits (Phys. Rev. C, 48 (1993), pp. 2462-2475):

$$\frac{dN}{p_T\ dp_T} \propto \int_0^R r\ dr\ m_T\ I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

where $\rho = \tanh^{-1}(\beta_T)$



Eur. Phys. J. C (2020) 80:693



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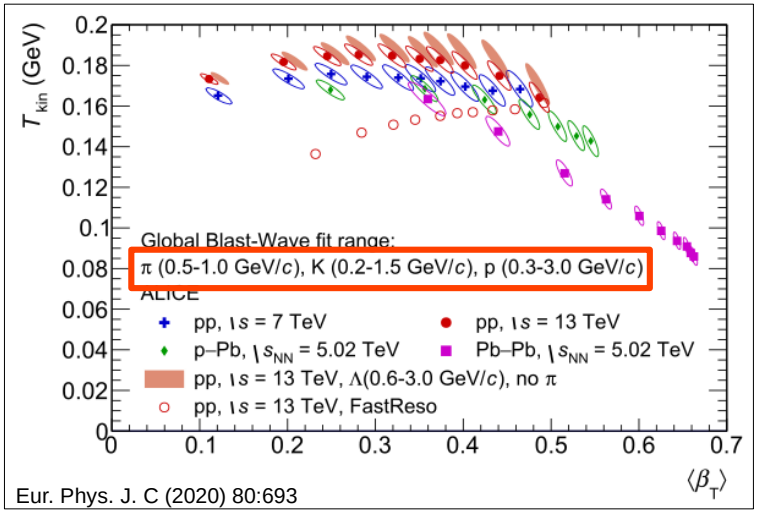

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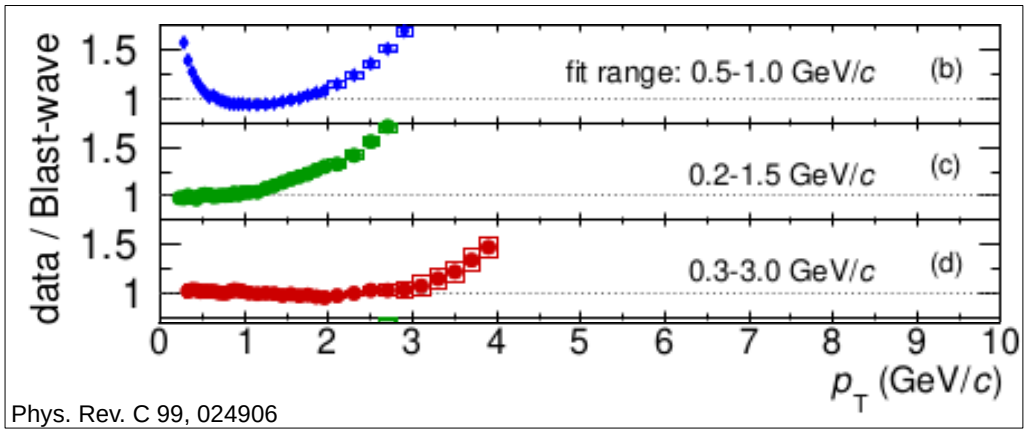
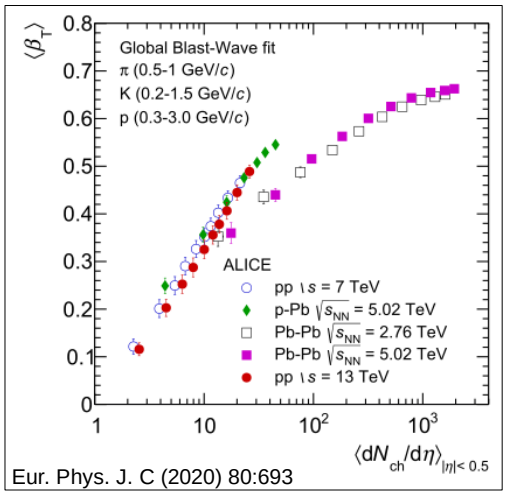
Issues:



Phys. Rev. C 99, 024906



Eur. Phys. J. C (2020) 80:693

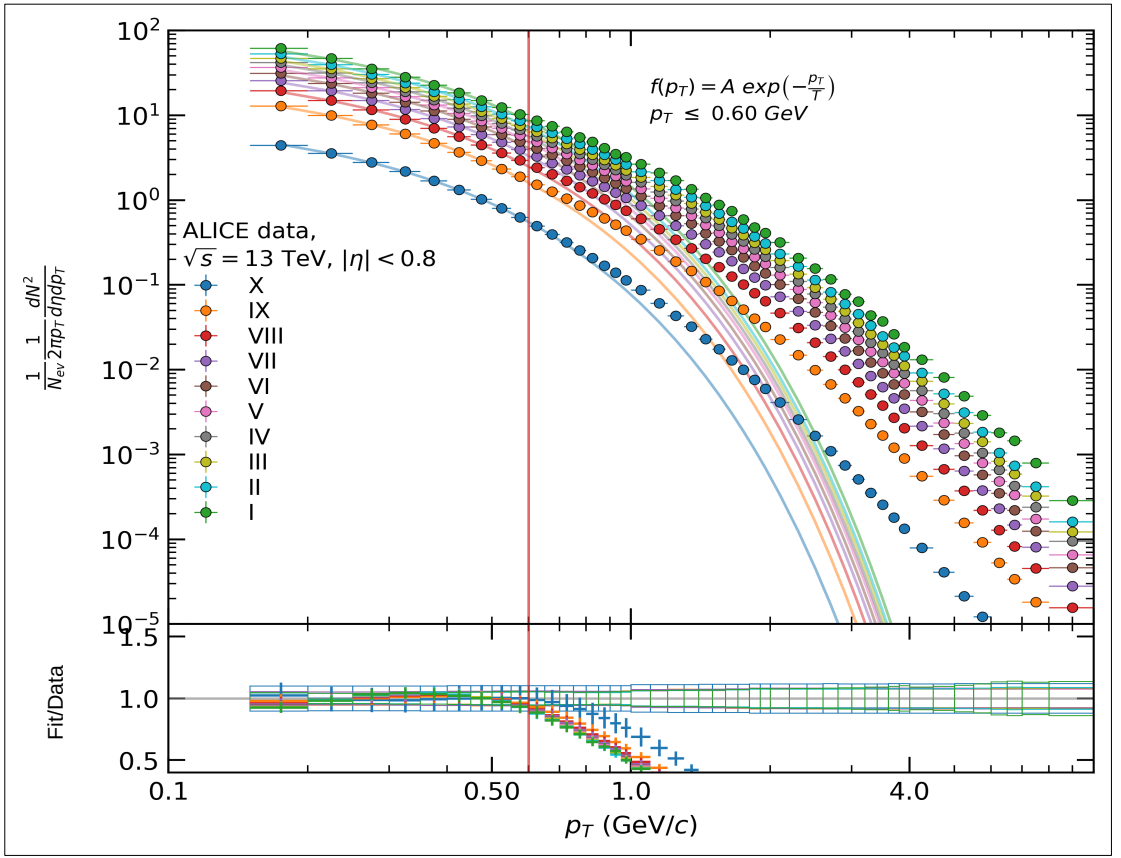
Systematic study of fit ranges

- Systems:
  - 5.02 TeV, 13 TeV (pp→ ch)
- p_T ranges:
  - 0.15 GeV ≤ p_T ≤ **p_0**
  - **p_0** in [0.4, 3.0], dp_T = 0.05
- Fit functions:
  - Most simple Boltzmann

$$f(p_T) = A \exp\left(-\frac{p_T}{T}\right)$$

  - Most simple Tsallis

$$f(p_T) = A\left(1 + p_T \frac{q-1}{T}\right)^{-\frac{q}{q-1}}$$



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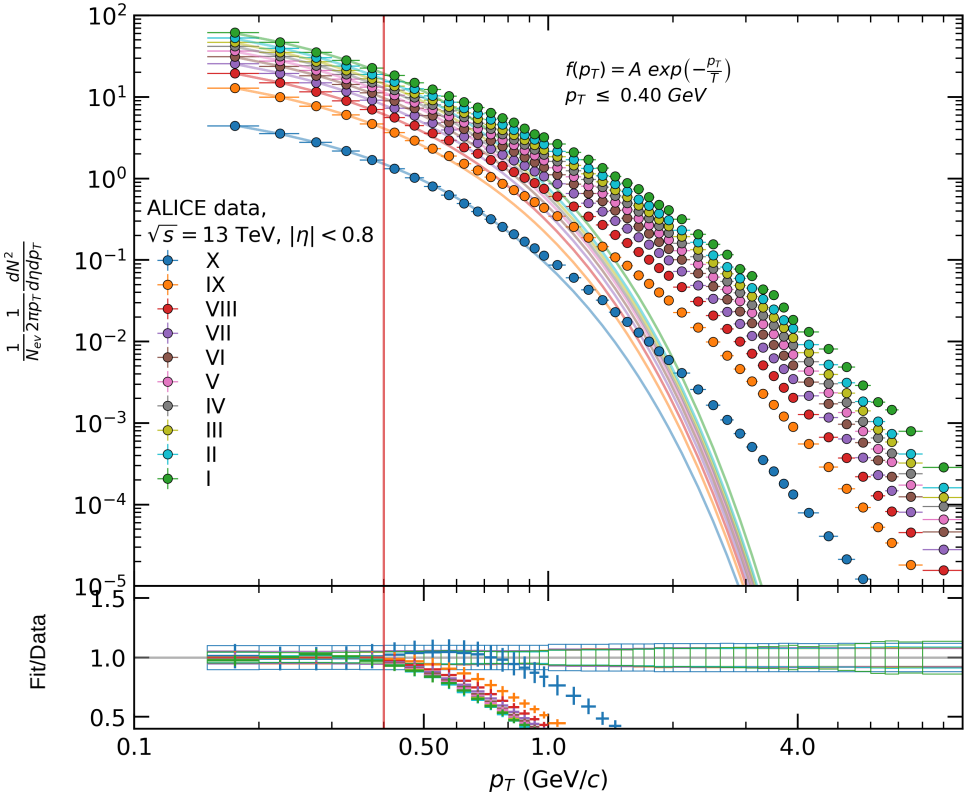

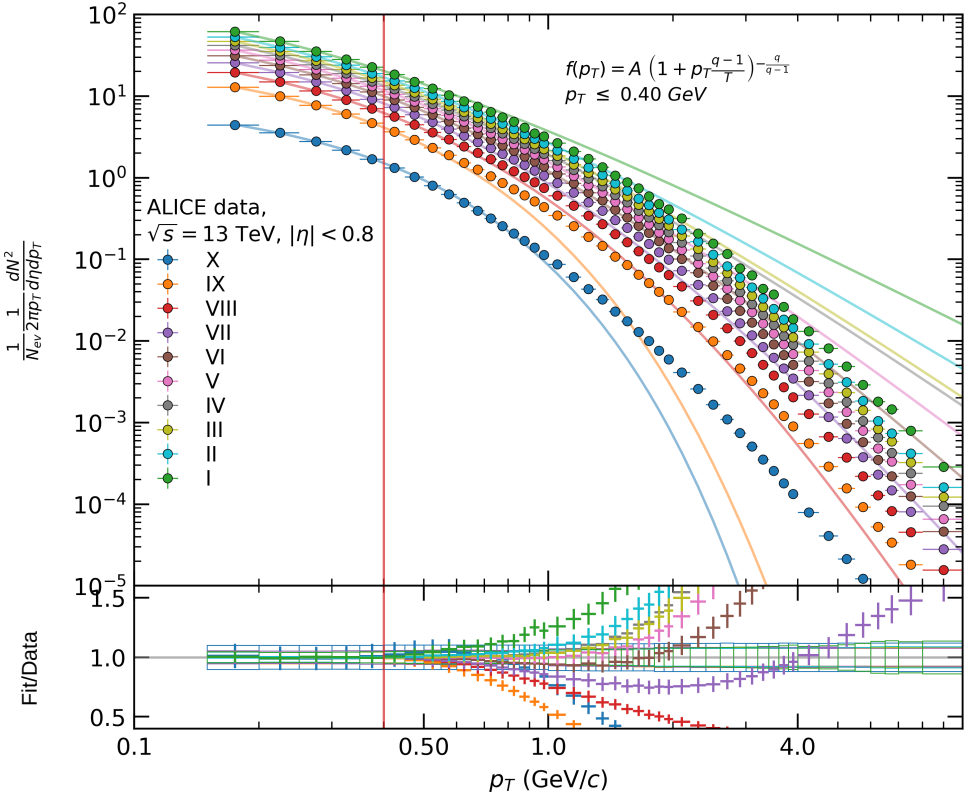

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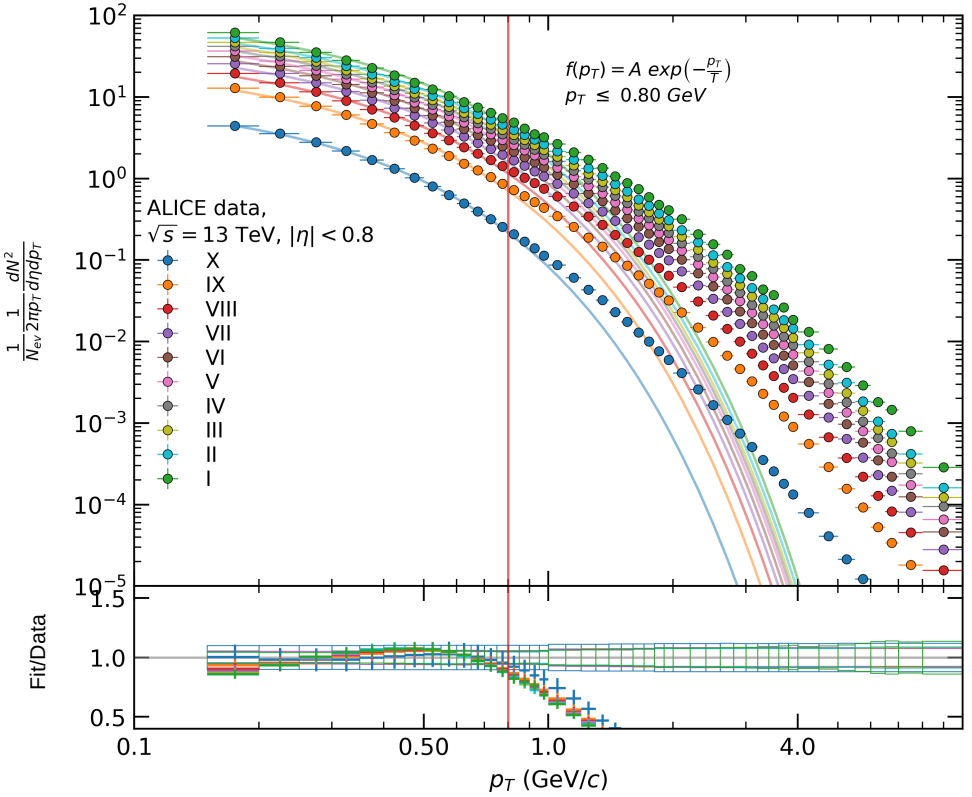

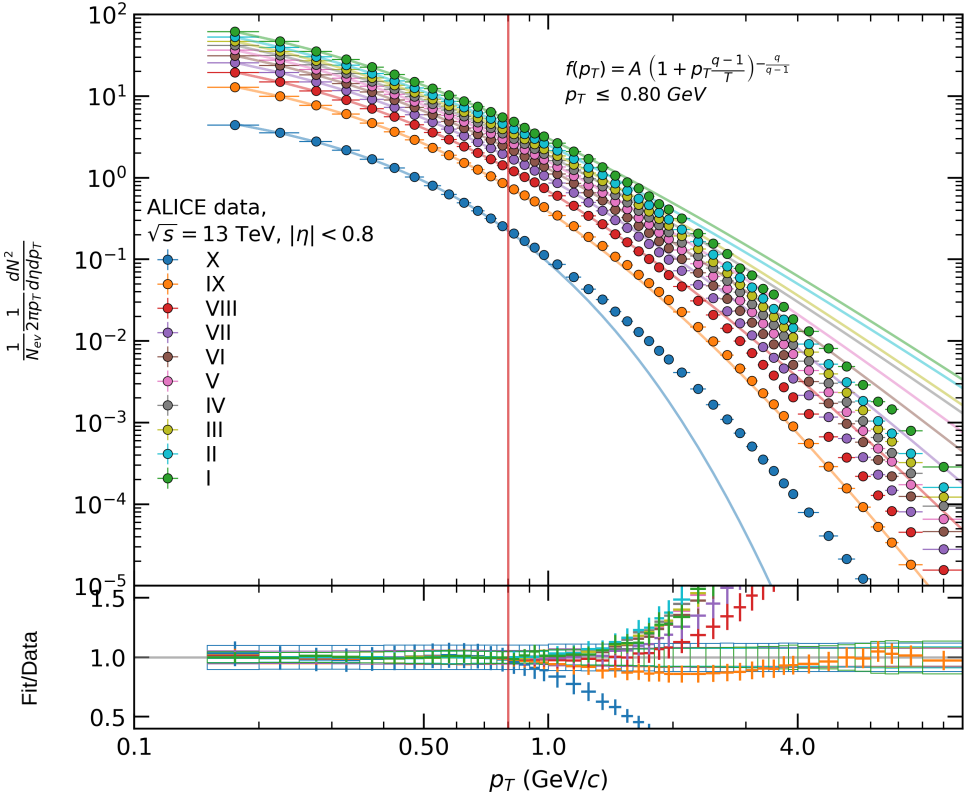

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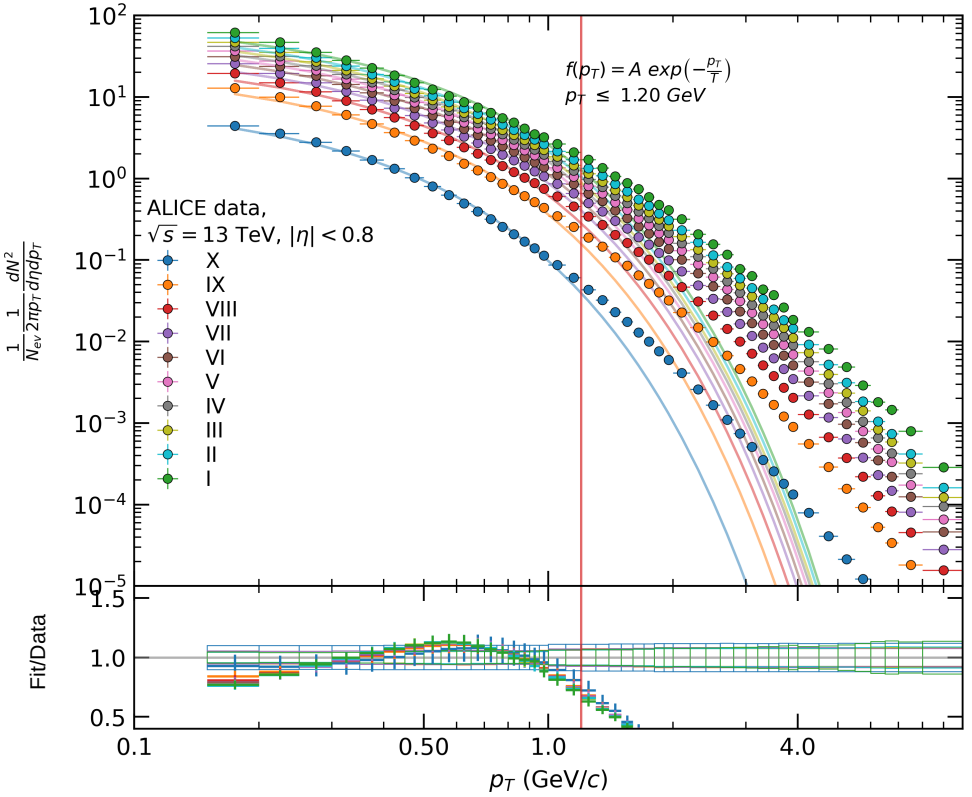

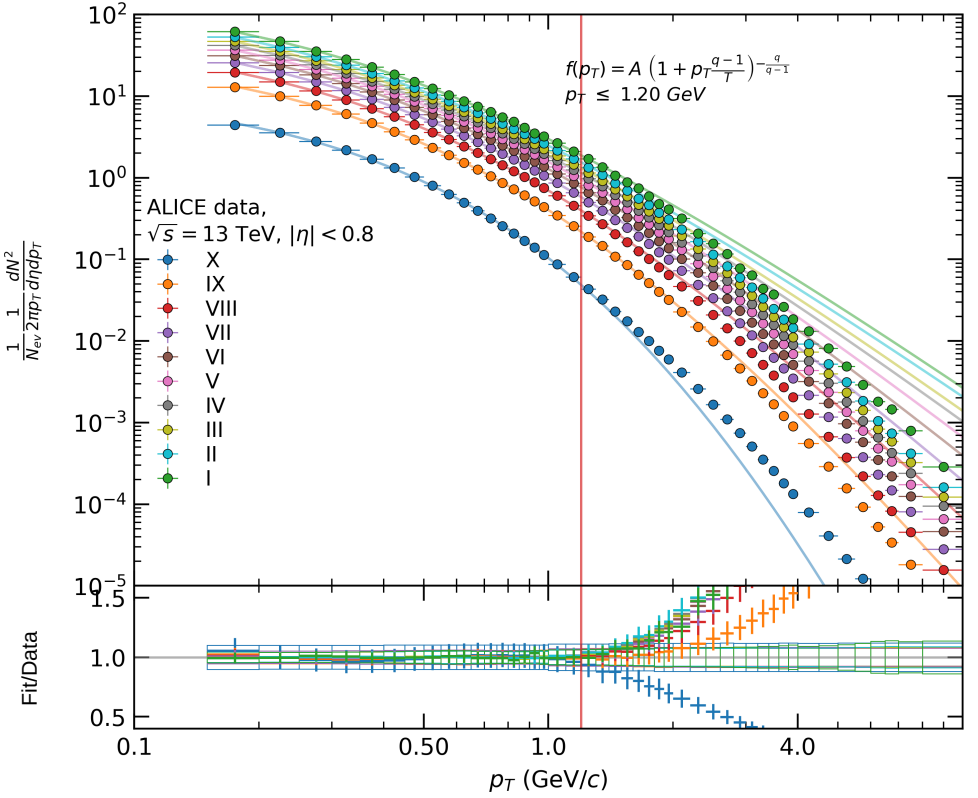

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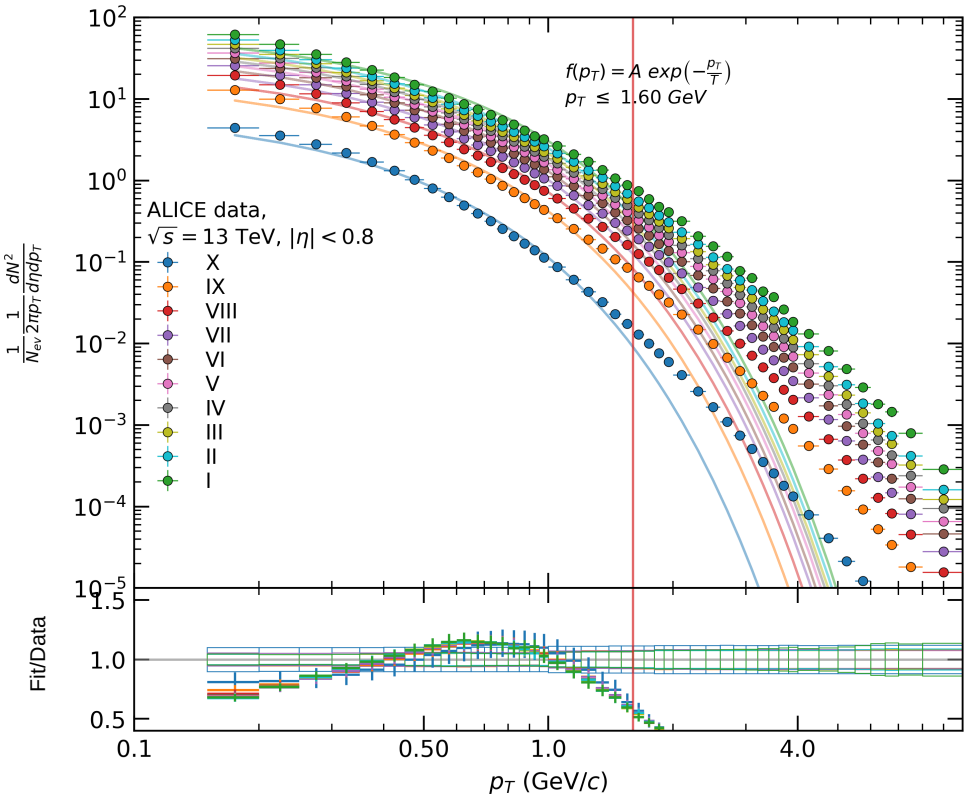

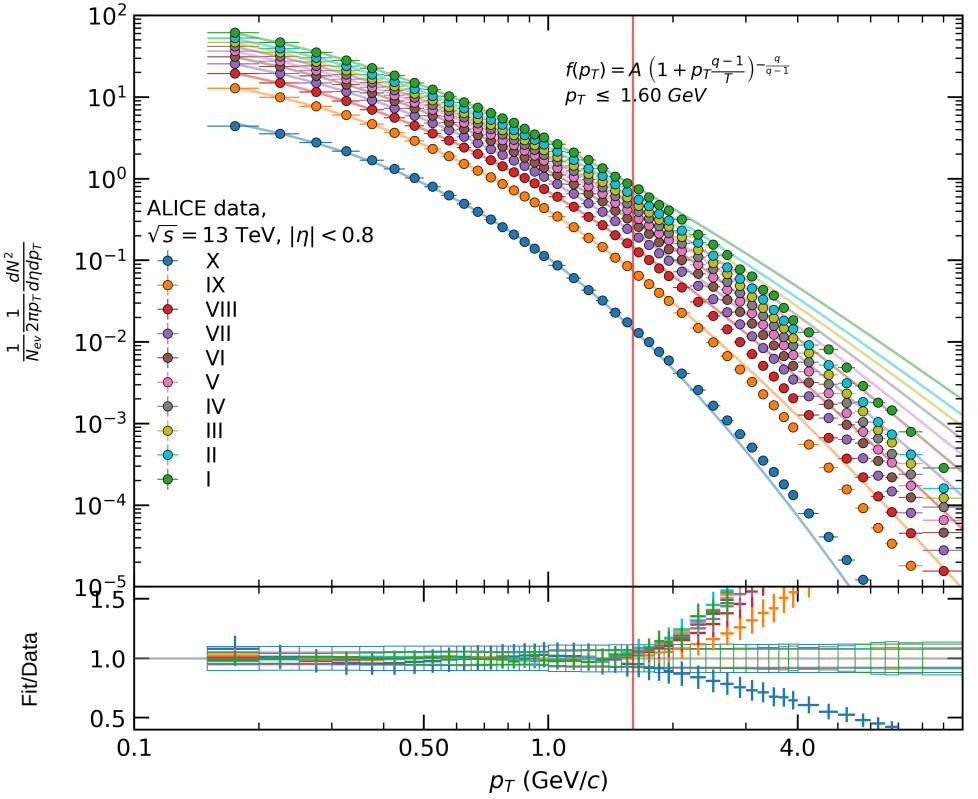

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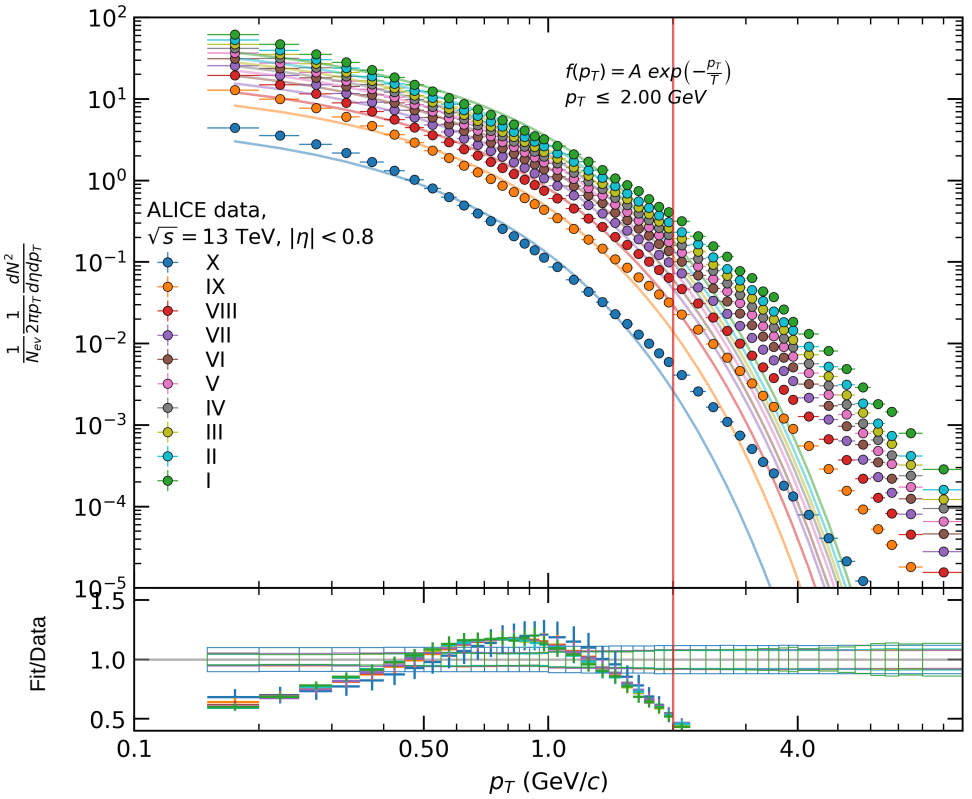

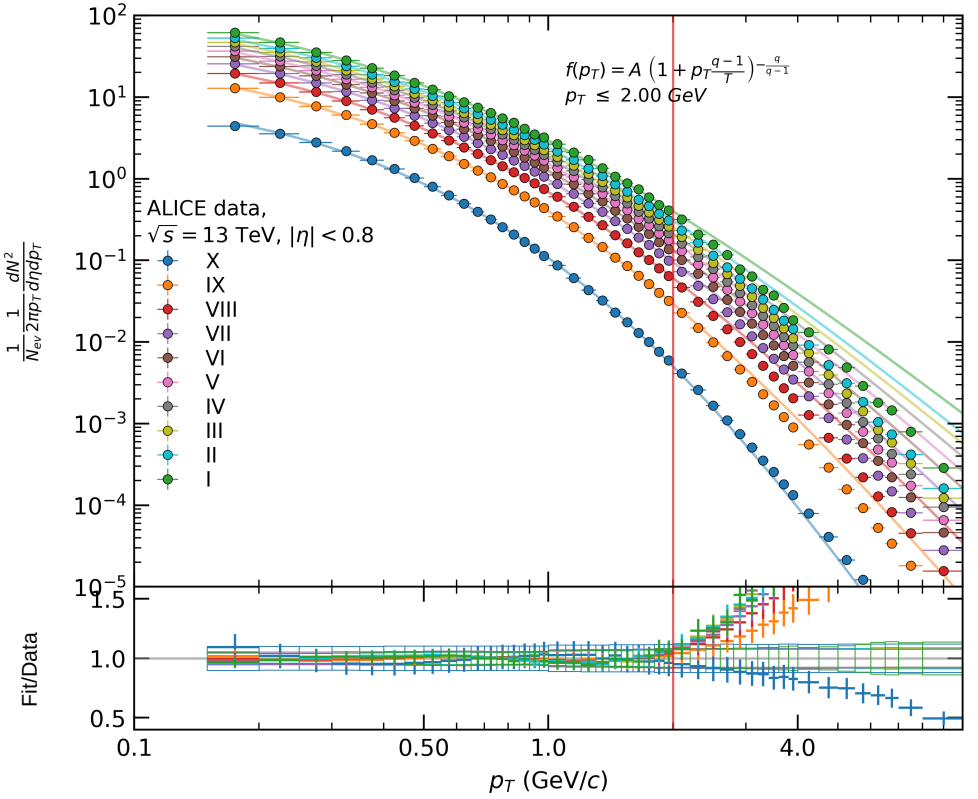

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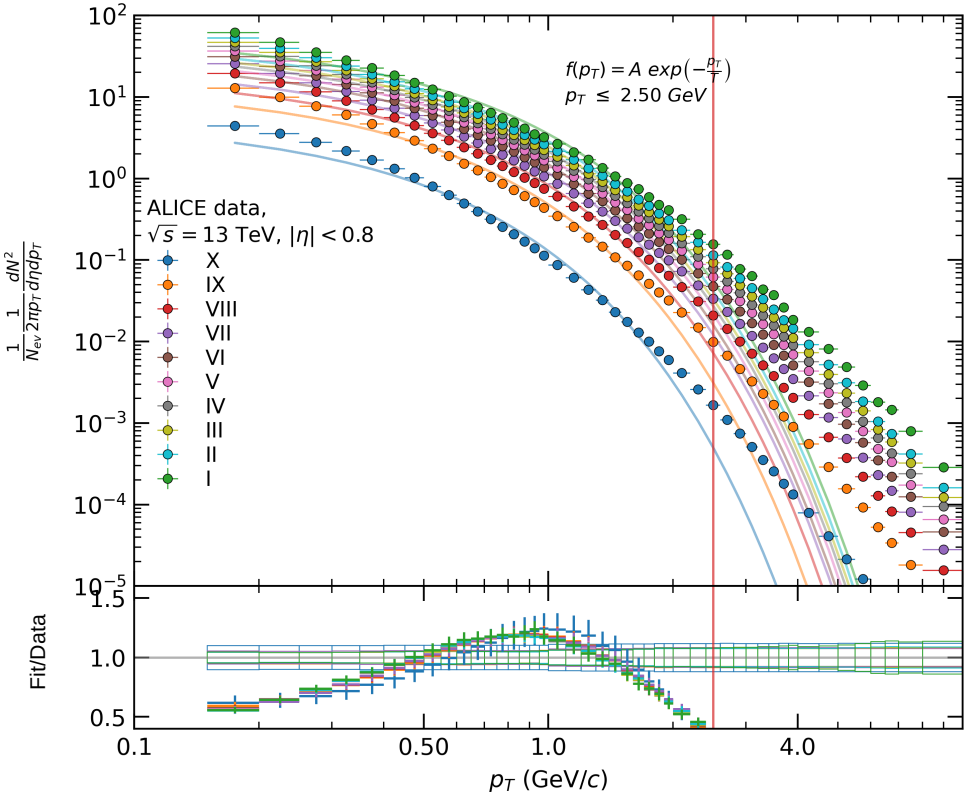

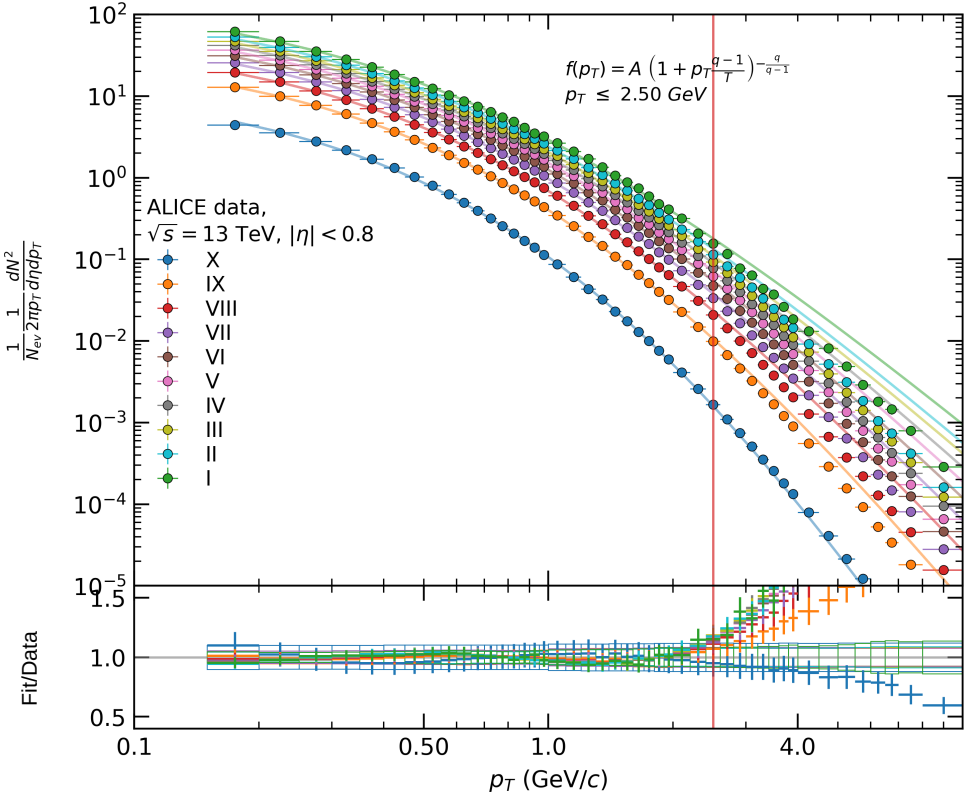

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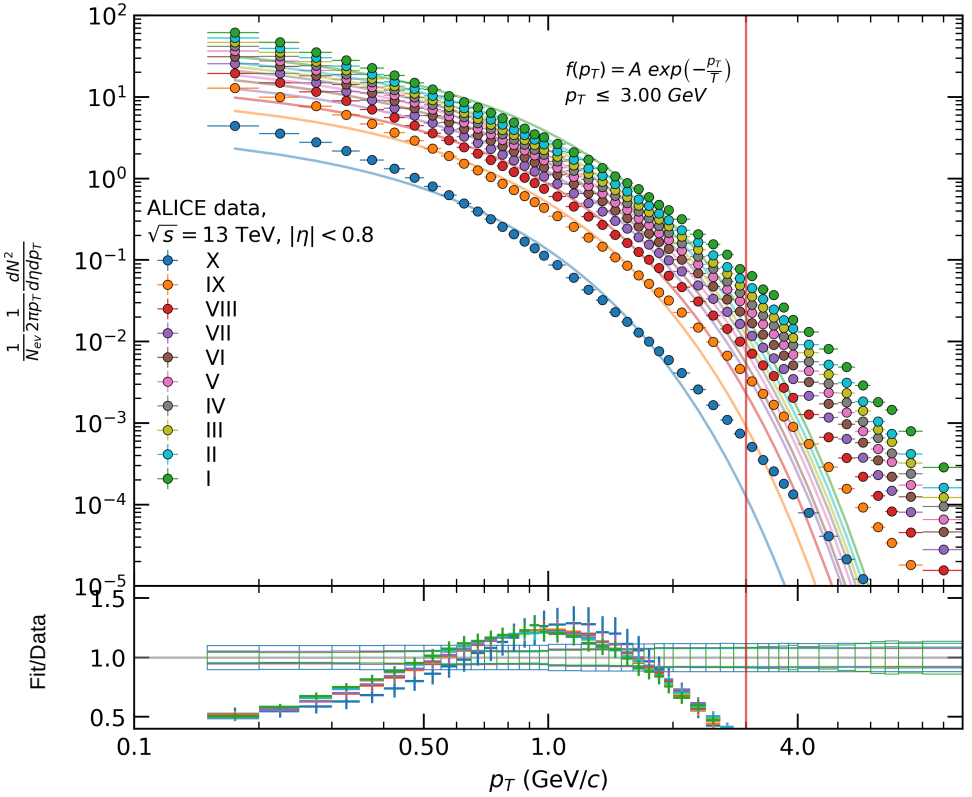

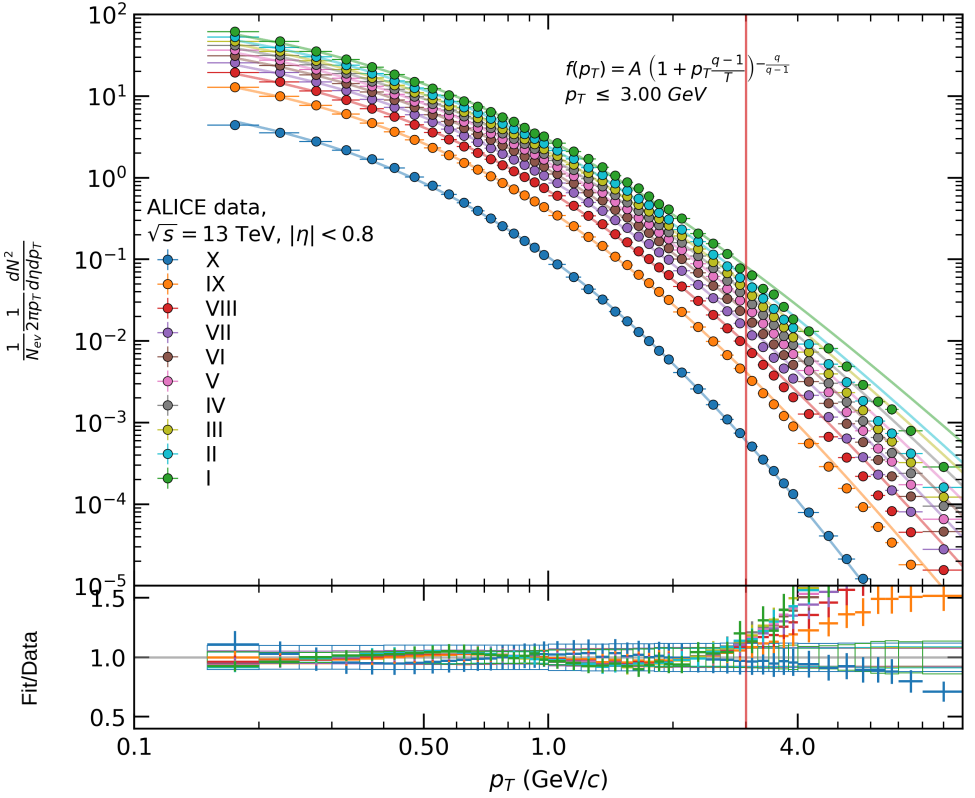

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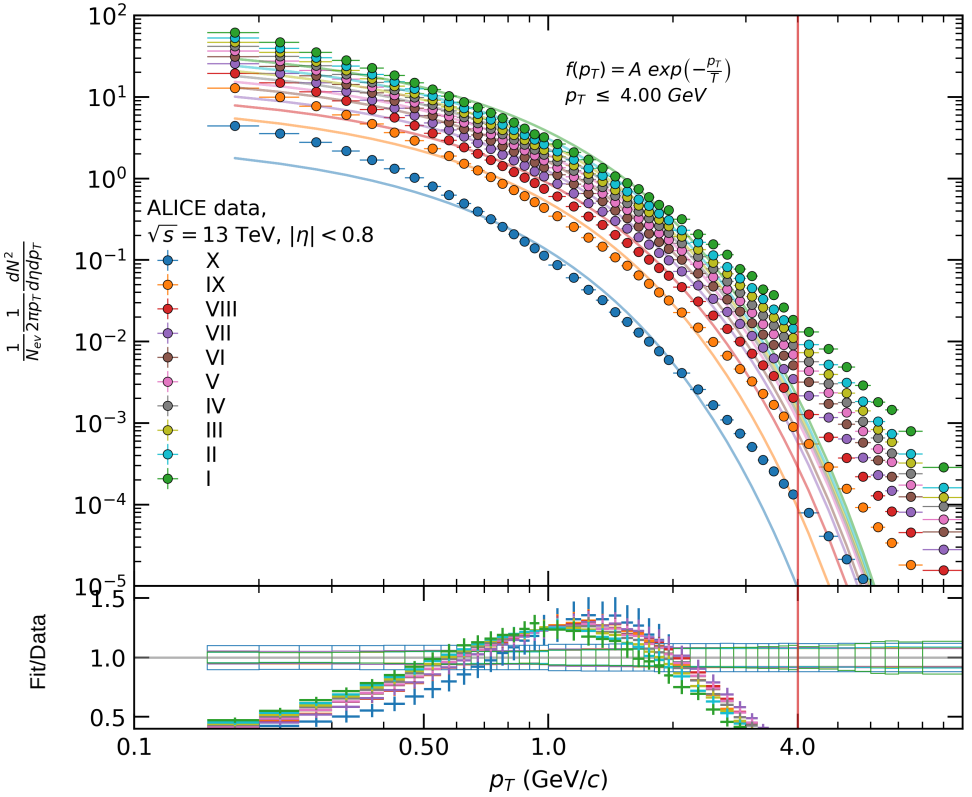

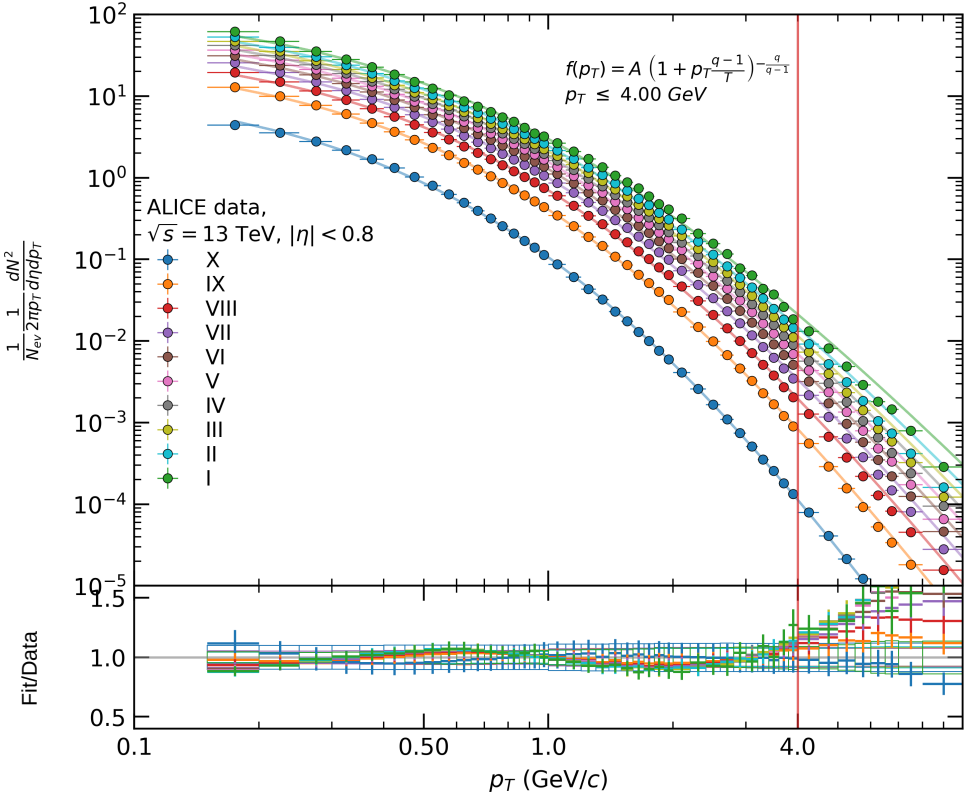

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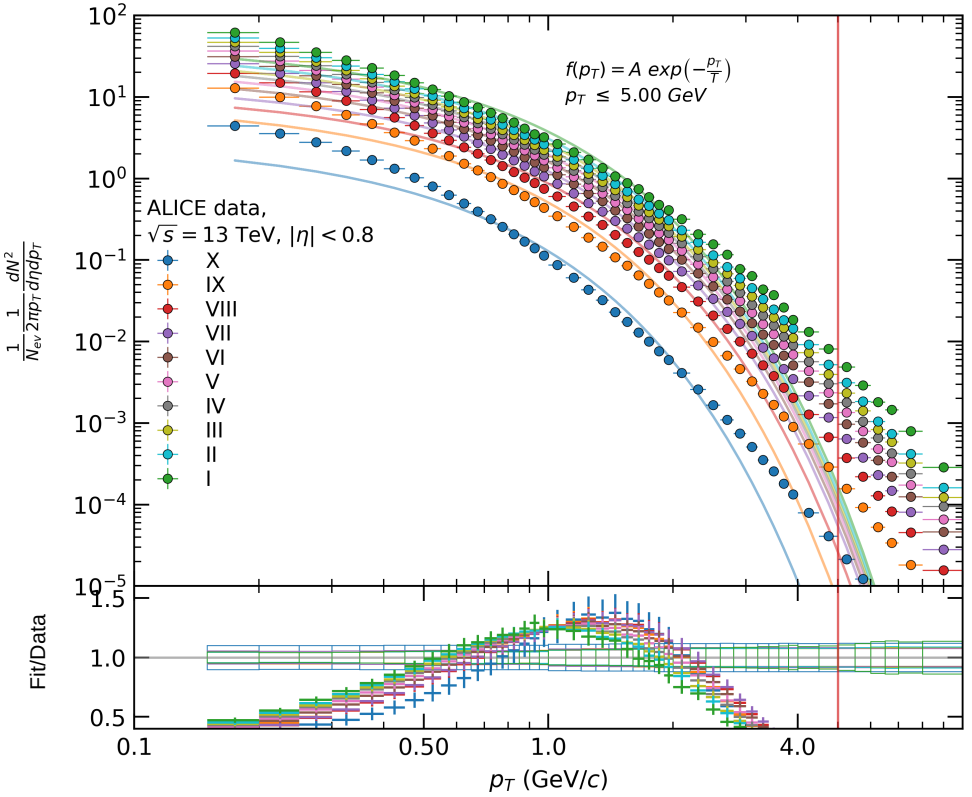

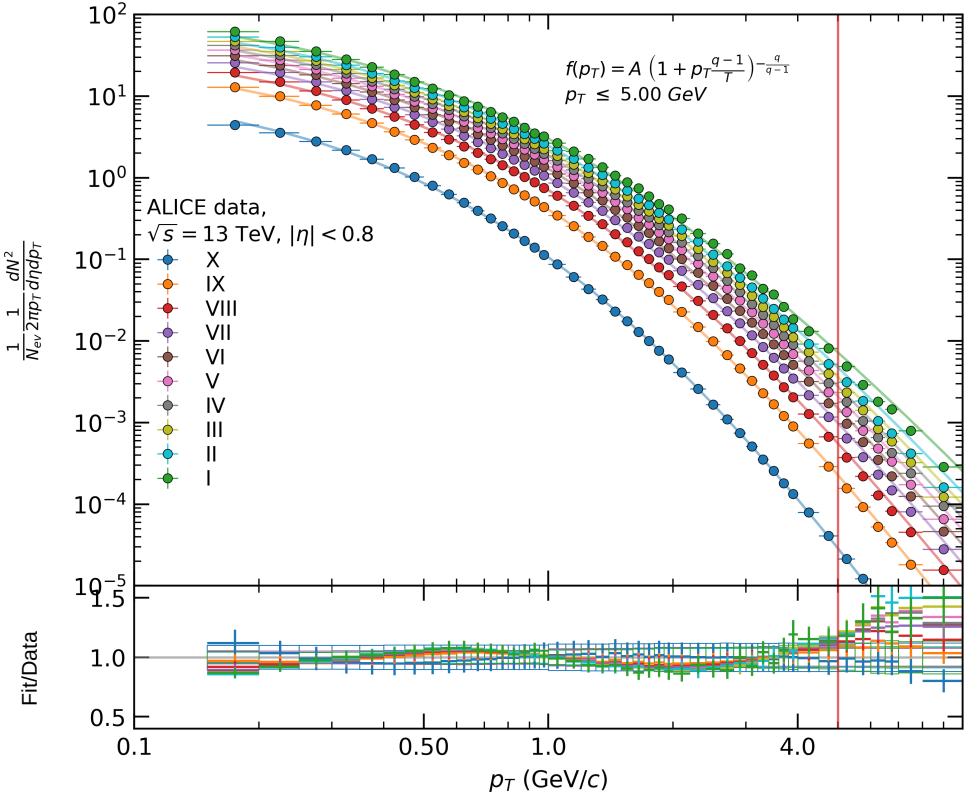

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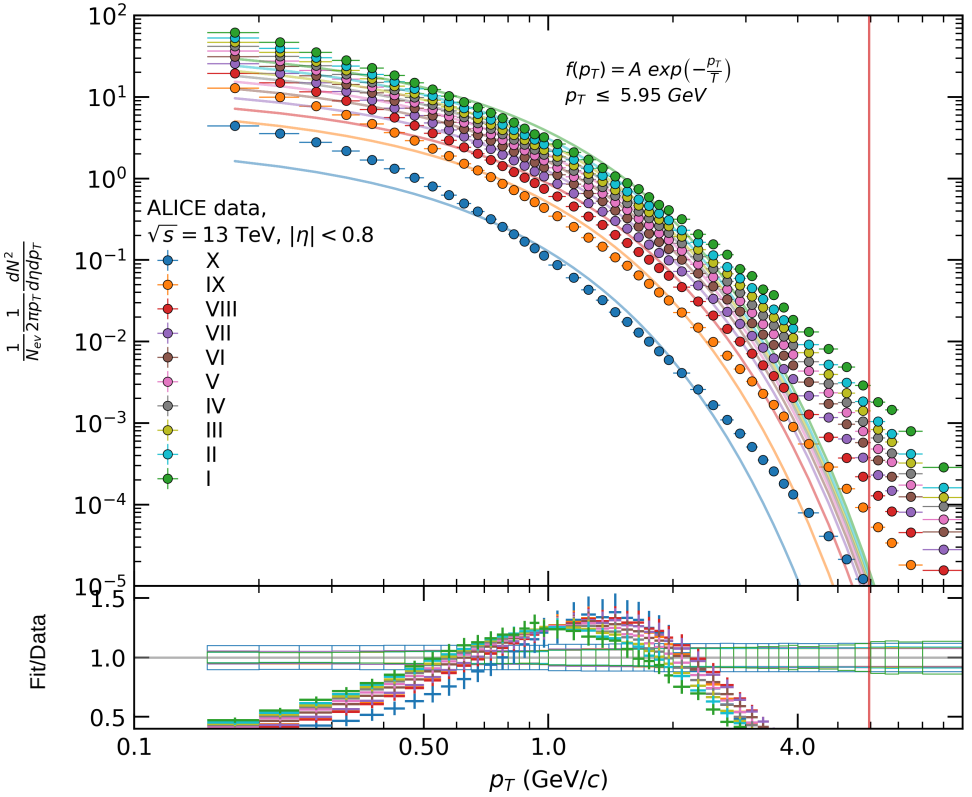
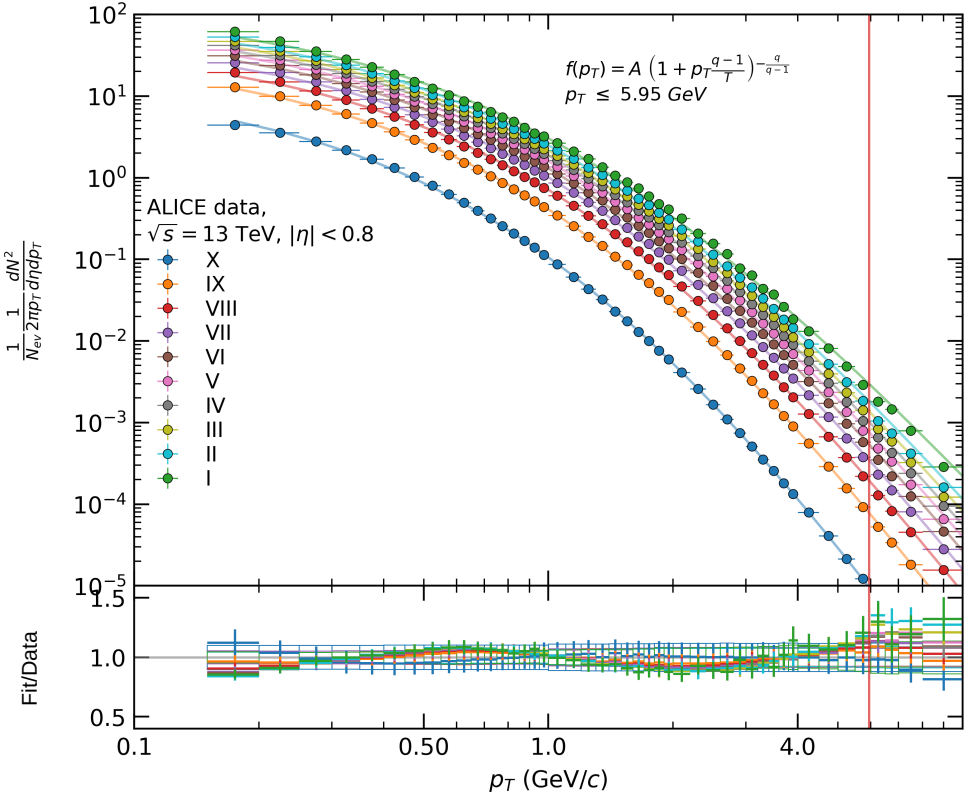
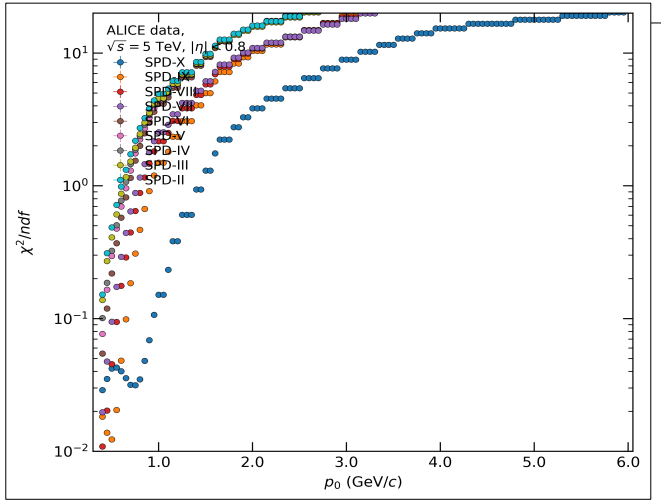
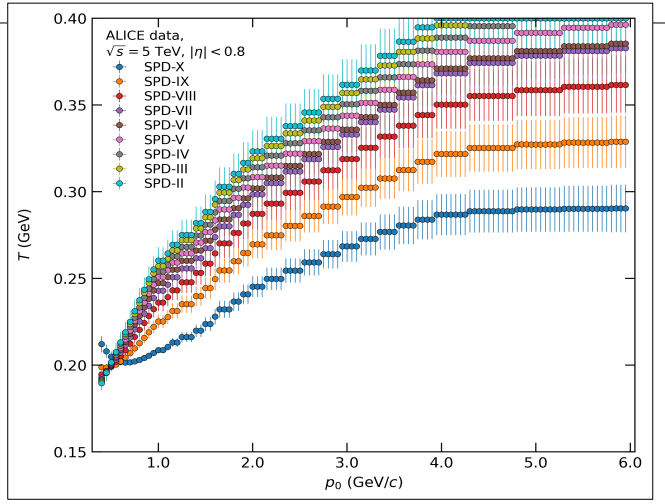


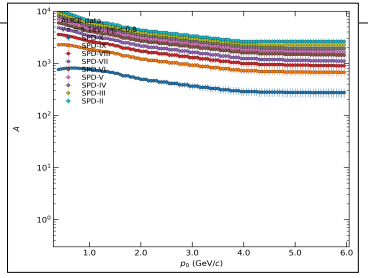


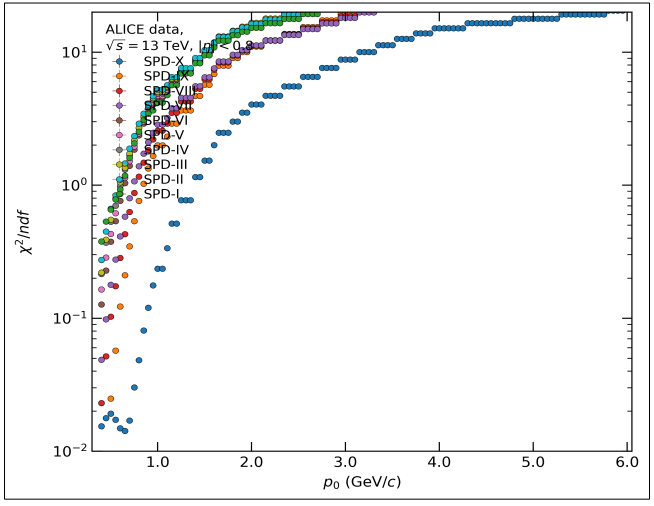
What are the fit parameters?

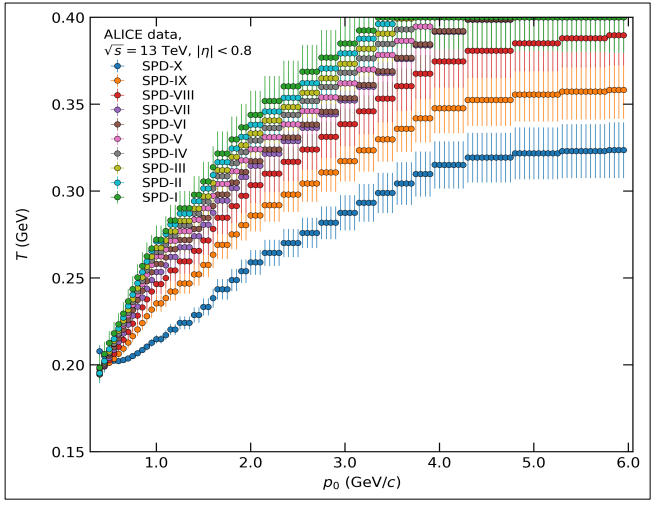
Results - Boltzmann

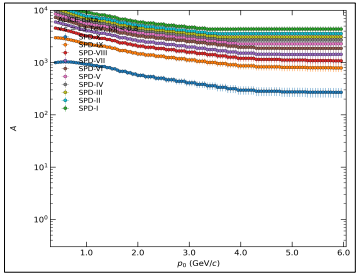




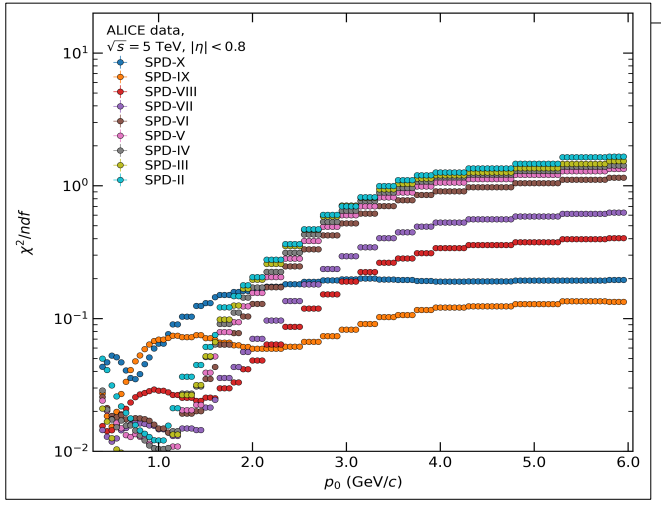


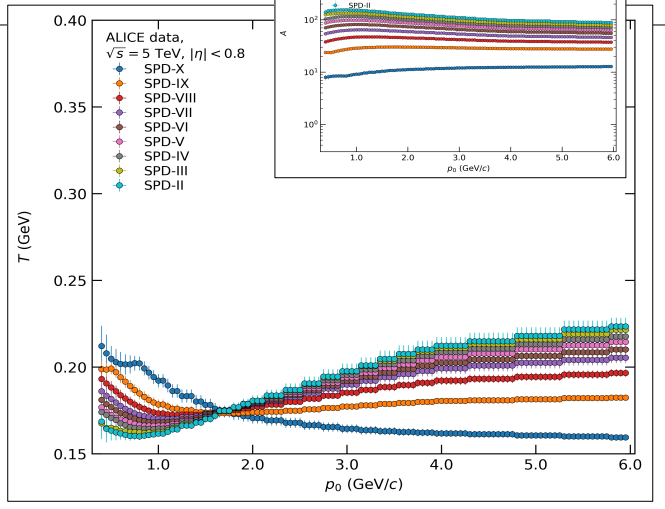


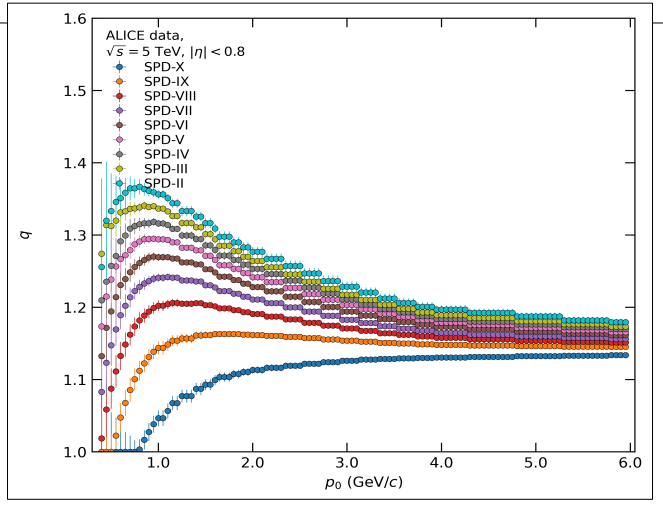


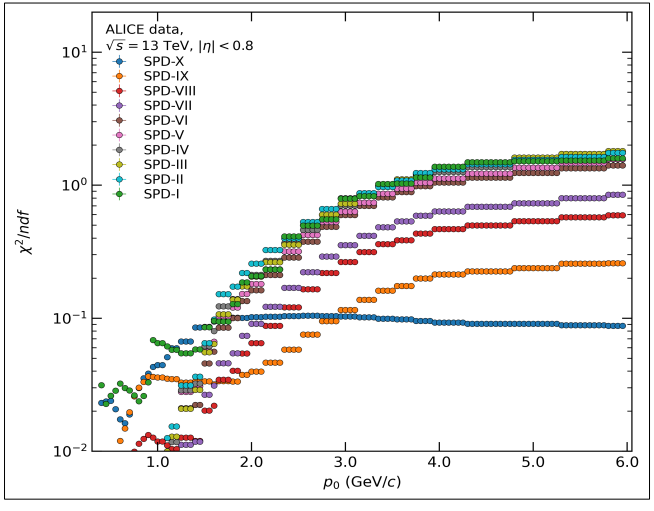


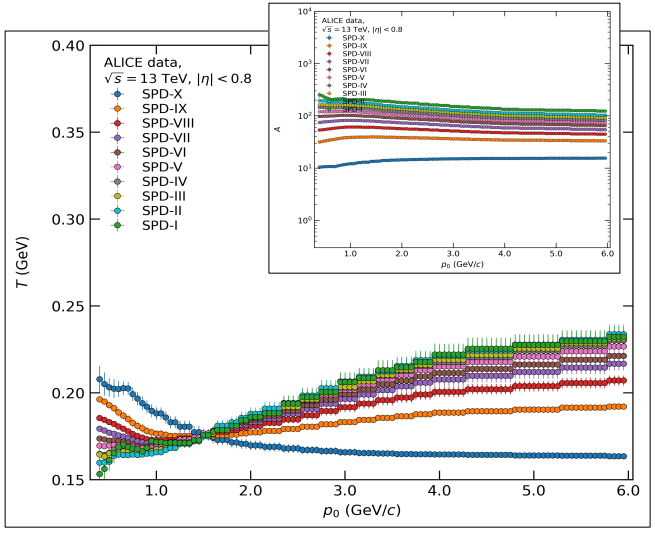
Results - Tsallis

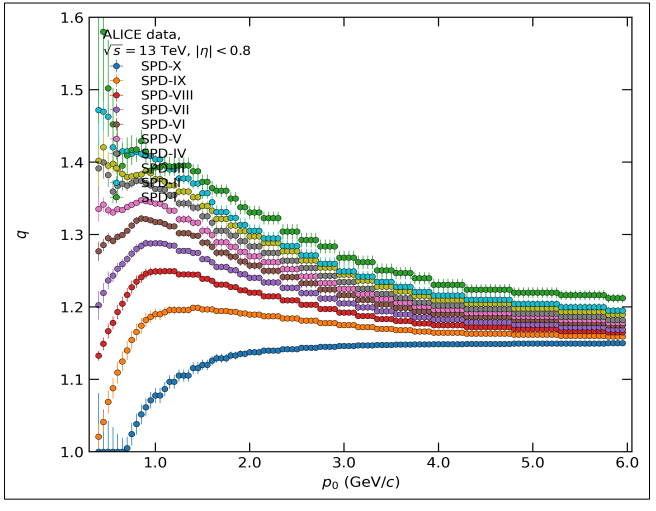












Results - Tsallis

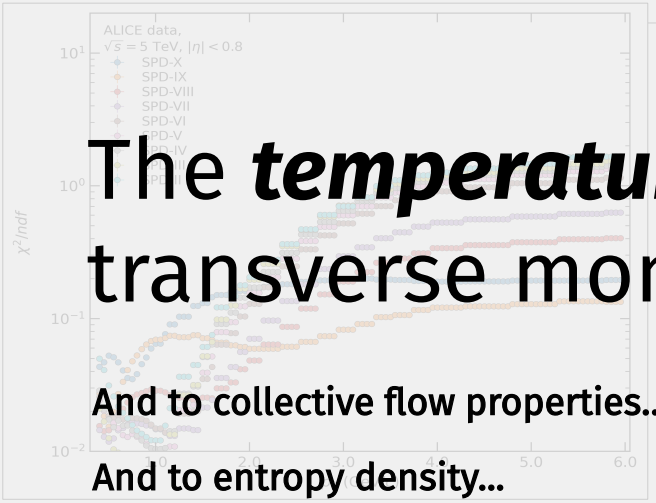
The ***temperature*** is related to the mean transverse momentum...

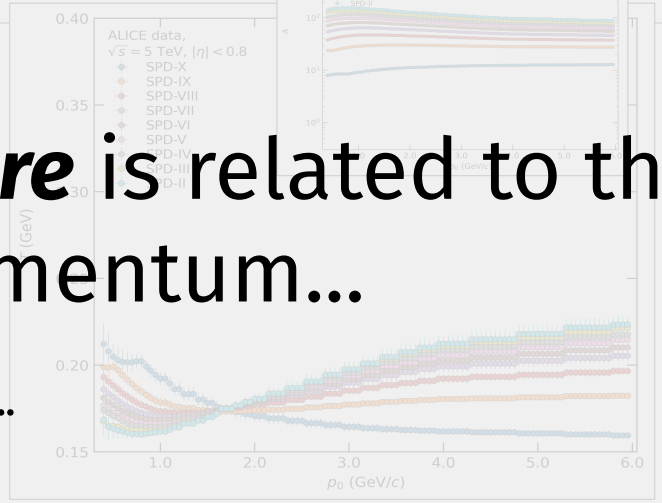
And to collective flow properties...

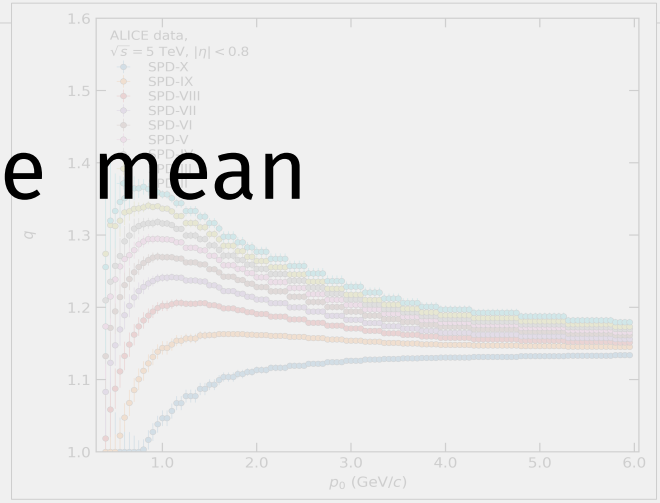
And to entropy density...

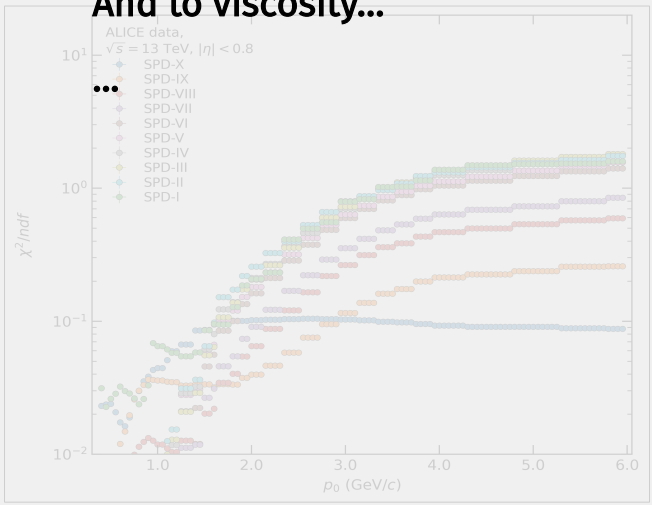
And to viscosity...

...



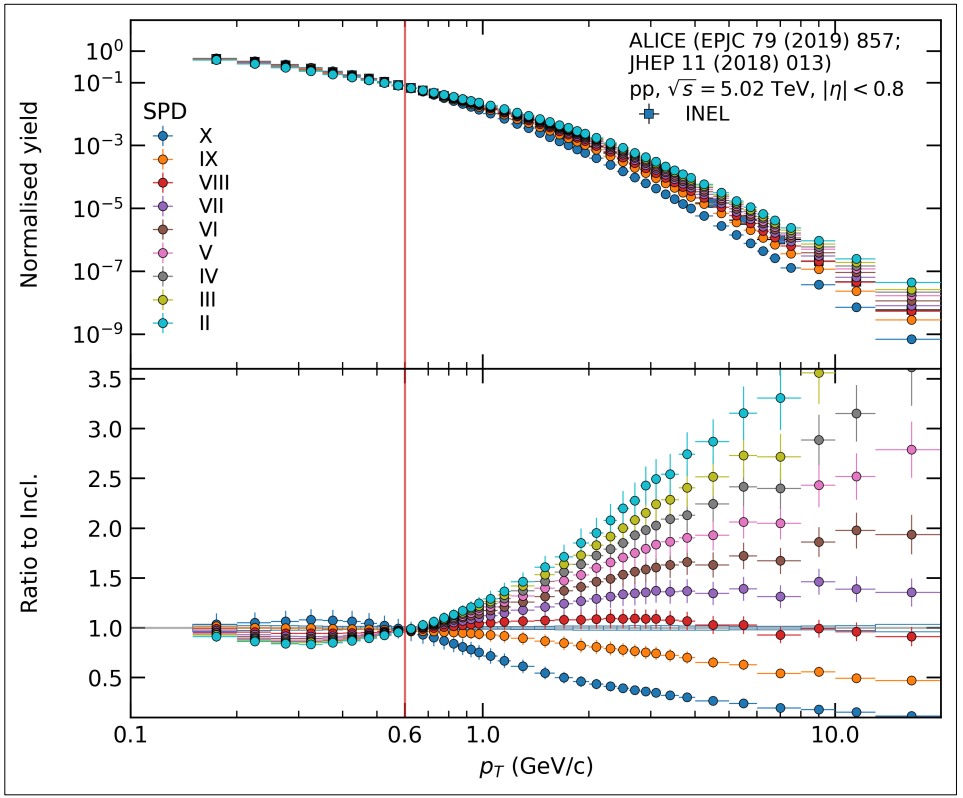


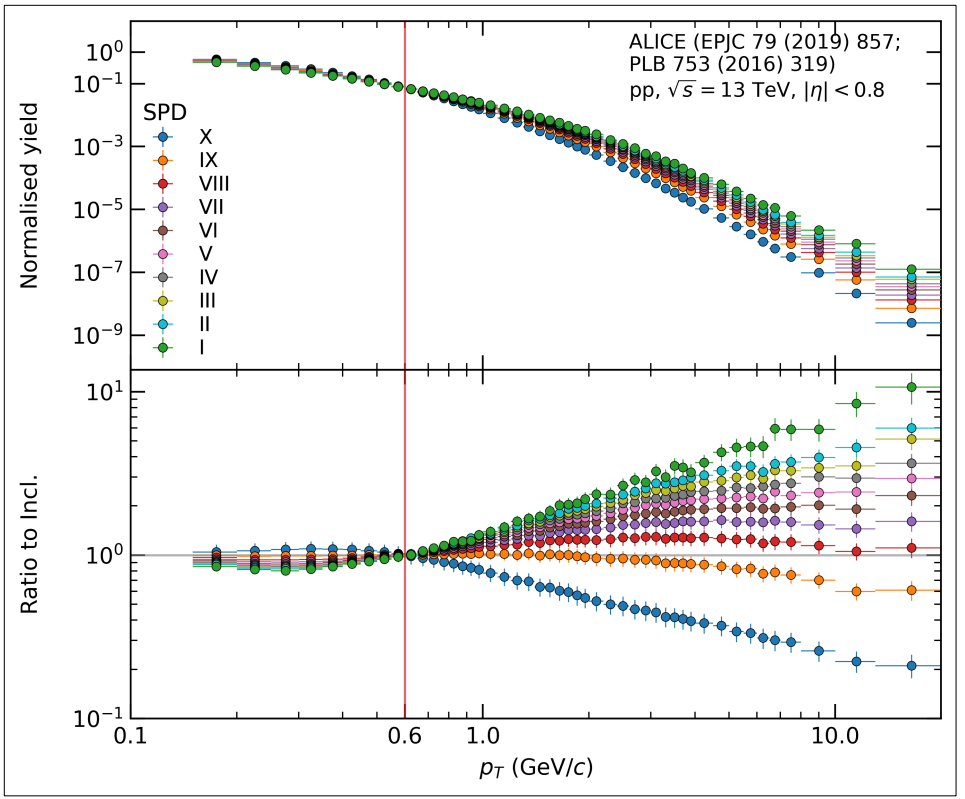




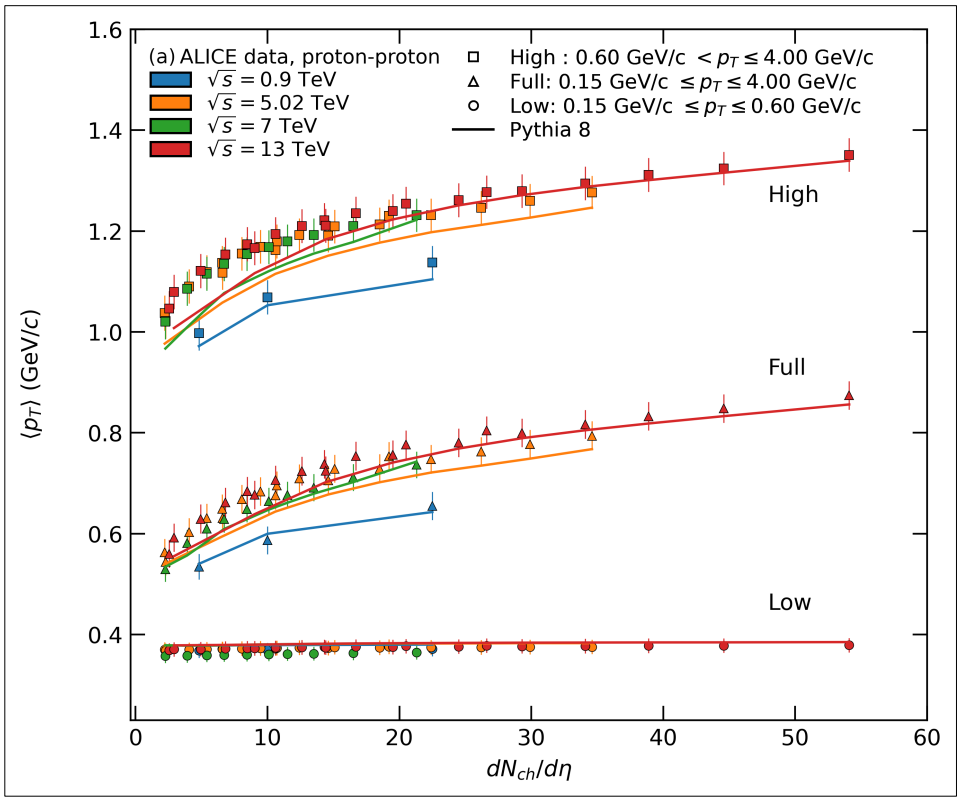
Normalized yields and event multiplicity

- Charged hadrons: universal crossing for all LHC energies → hint for soft limit?
- Soft vs. mixed (soft+hard) regions





Normalized yields and event multiplicity



$\langle p_T \rangle$:

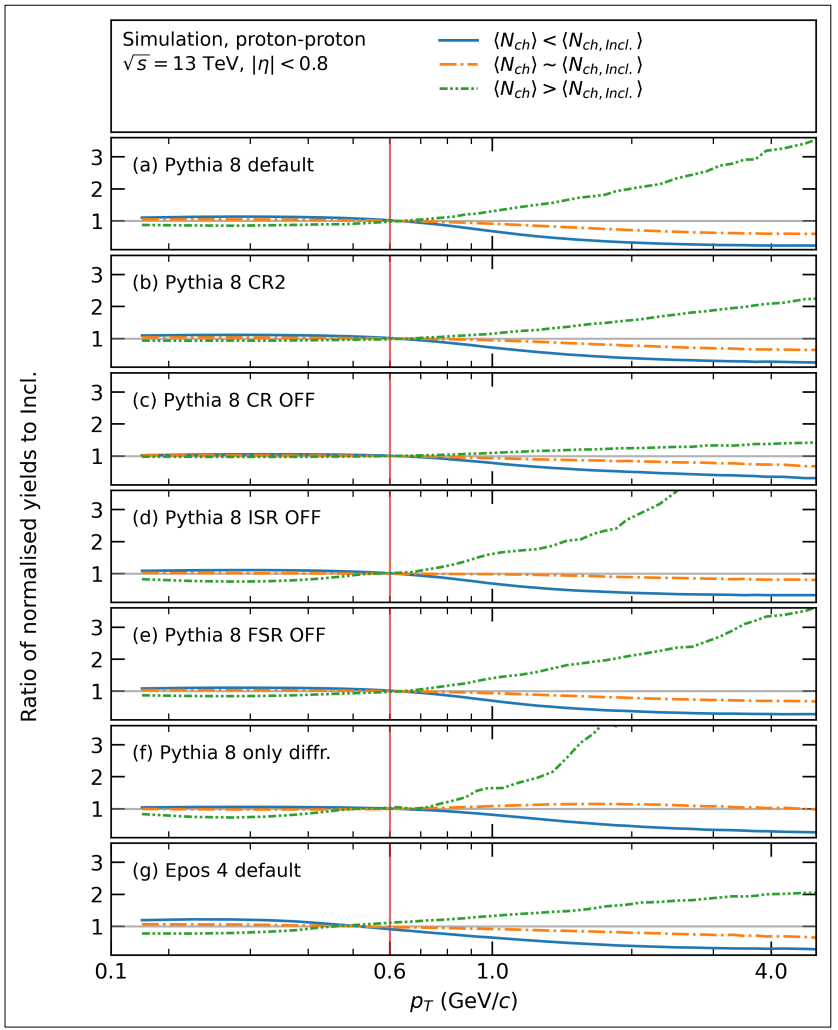
- highly sensitive to the selected p_T range
- not sensitive within the soft (low-p_T) region

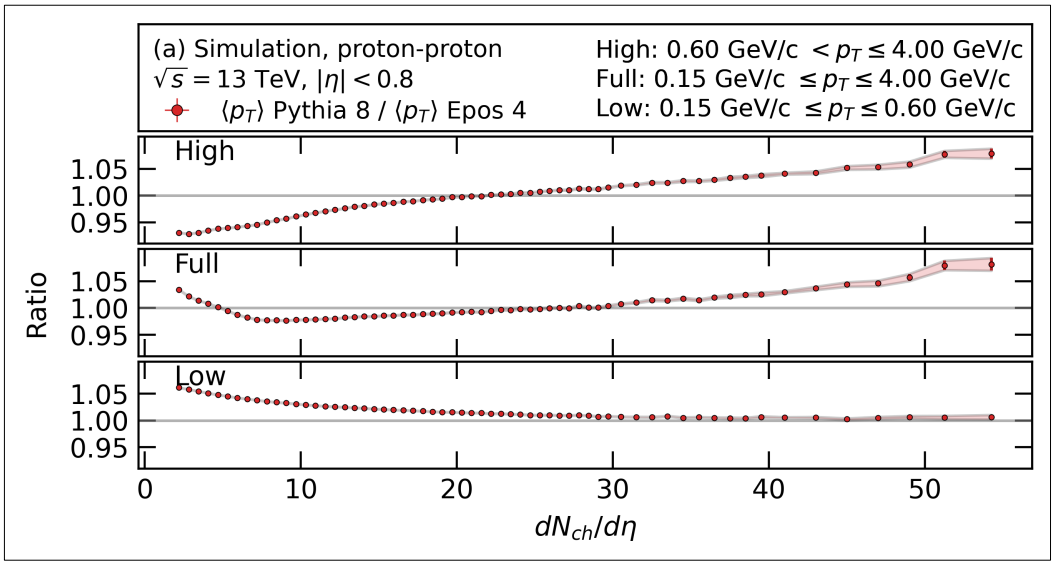
- p_T < 0.6 GeV/c: predominantly associated with soft processes
- p_T > 0.6 GeV/c: a mixture of soft and hard ones

- consistent with the hypothesis of centre-of-mass energy invariance within the low-p_T part of the spectra → a phenomenon observed by the CDF collaboration in pp collisions at √s = 630 GeV and 1.8 TeV [1]

[1] Phys. Rev. D 65, 072005 (2002)

Normalized yields and event multiplicity - MC





Universal crossing point:

- Observed at MC calculations
- Pythia 8: perturbative QCD and string fragmentation
- Epos 4: incorporates collective effects and hydrodynamic considerations
  - Minor dependence on tunes
- Similar $\langle p_T \rangle$ trends for Pythia 8 and Epos 4

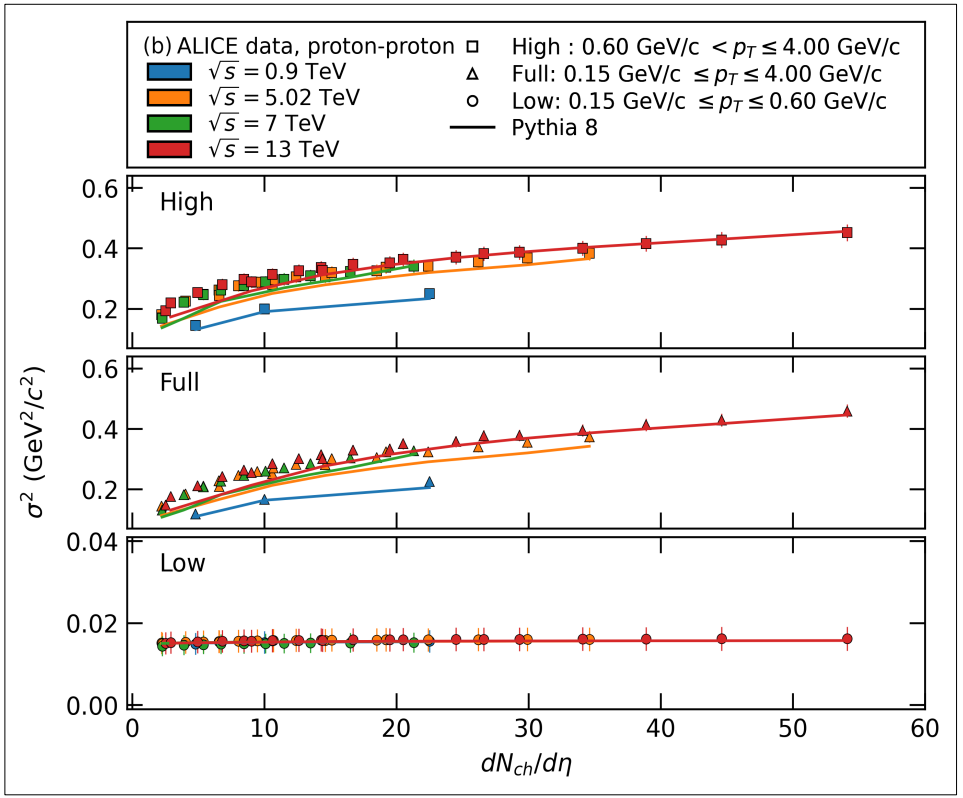
Summary

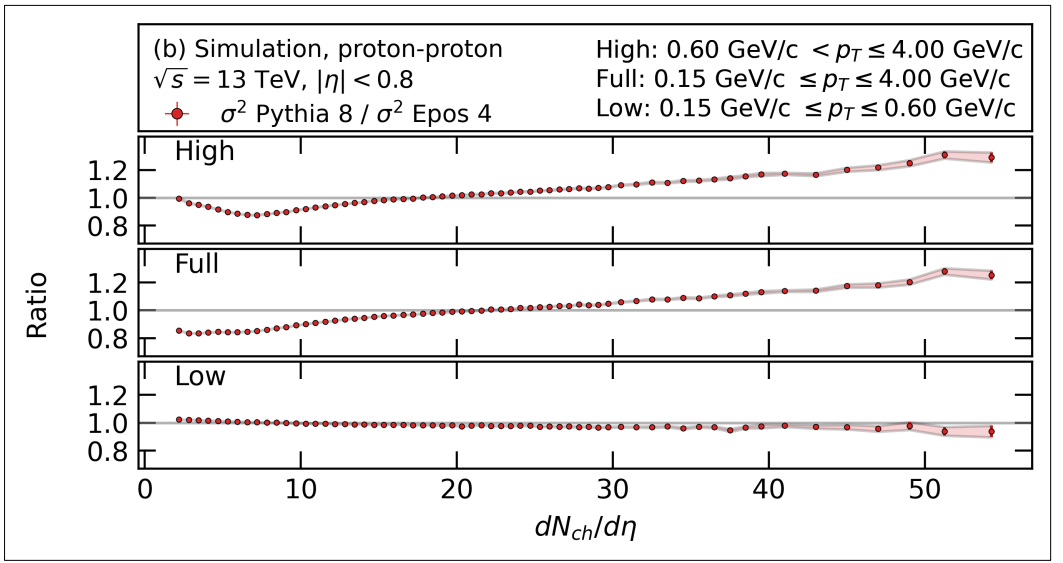
- Charged hadron transverse momentum distributions at LHC energies with various multiplicity classes
- The mean of the distributions can be **ill defined** (not to mention the extrapolations)
- The extracted physical quantities may **depend strongly** on the applied definitions
- The soft/hard limit is controversial and question of interpretation
- **Studies in the low p_T region demands greater scrutiny to avoid potentially misleading conclusions (especially regarding collective effects in small systems)**

Thank you for your attention!

The research was supported by OTKA K135515, 2021-4.1.2-NEMZ_KI-2024-00031, 2021-4.1.2-NEMZ_KI-2024-00033, the **Wigner Scientific Computating Laboratory** (former Wigner GPU Laboratory).

Variance


(b) ALICE data, proton-proton
$\sqrt{s} = 0.9$ TeV
$\sqrt{s} = 5.02$ TeV
$\sqrt{s} = 7$ TeV
$\sqrt{s} = 13$ TeV
High : 0.60 GeV/c $< p_T \leq$ 4.00 GeV/c
Full: 0.15 GeV/c $\leq p_T \leq$ 4.00 GeV/c
Low: 0.15 GeV/c $\leq p_T \leq$ 0.60 GeV/c
Pythia 8
High
Full
Low
σ^2 (GeV^2/c^2)
$dN_{ch}/d\eta$


(b) Simulation, proton-proton
$\sqrt{s} = 13$ TeV, $|\eta| < 0.8$
σ^2 Pythia 8 / σ^2 Epos 4
High: 0.60 GeV/c $< p_T \leq$ 4.00 GeV/c
Full: 0.15 GeV/c $\leq p_T \leq$ 4.00 GeV/c
Low: 0.15 GeV/c $\leq p_T \leq$ 0.60 GeV/c
High
Full
Low
Ratio
$dN_{ch}/d\eta$