XIX Mexican Workshop on Particles and Fields

October 2025

Description of the softened hadron production at the LHC energies

Authors:
Diana Rosales Herrera*, J. Ricardo Alvarado García, Arturo Fernández Téllez, Eleazar Cuautle Flores, Jhony Eredi Ramírez Cancino
*diana.rosales.herrera@cern.ch

This presentation is based on:

Eur. Phys. J. C (2025) 85:760
https://doi.org/10.1140/epjc/s10052-025-14469-3

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Scaling laws for softened hadron production at LHC energies

D. Rosales Herrera[1], **J. R. Alvarado García**[1], **A. Fernández Téllez**[1], **E. Cuautle**[2], **J. E. Ramírez**[3,a]

[1] Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Apartado Postal 165, 72000 Puebla, Puebla, Mexico
[2] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70-543, 04510 Ciudad de México, Mexico
[3] Centro de Agroecología, Instituto de Ciencias, Benemérita Universidad Autónoma de Puebla, Apartado Postal 165, 72000 Puebla, Puebla, Mexico

Received: 3 March 2025 / Accepted: 25 June 2025

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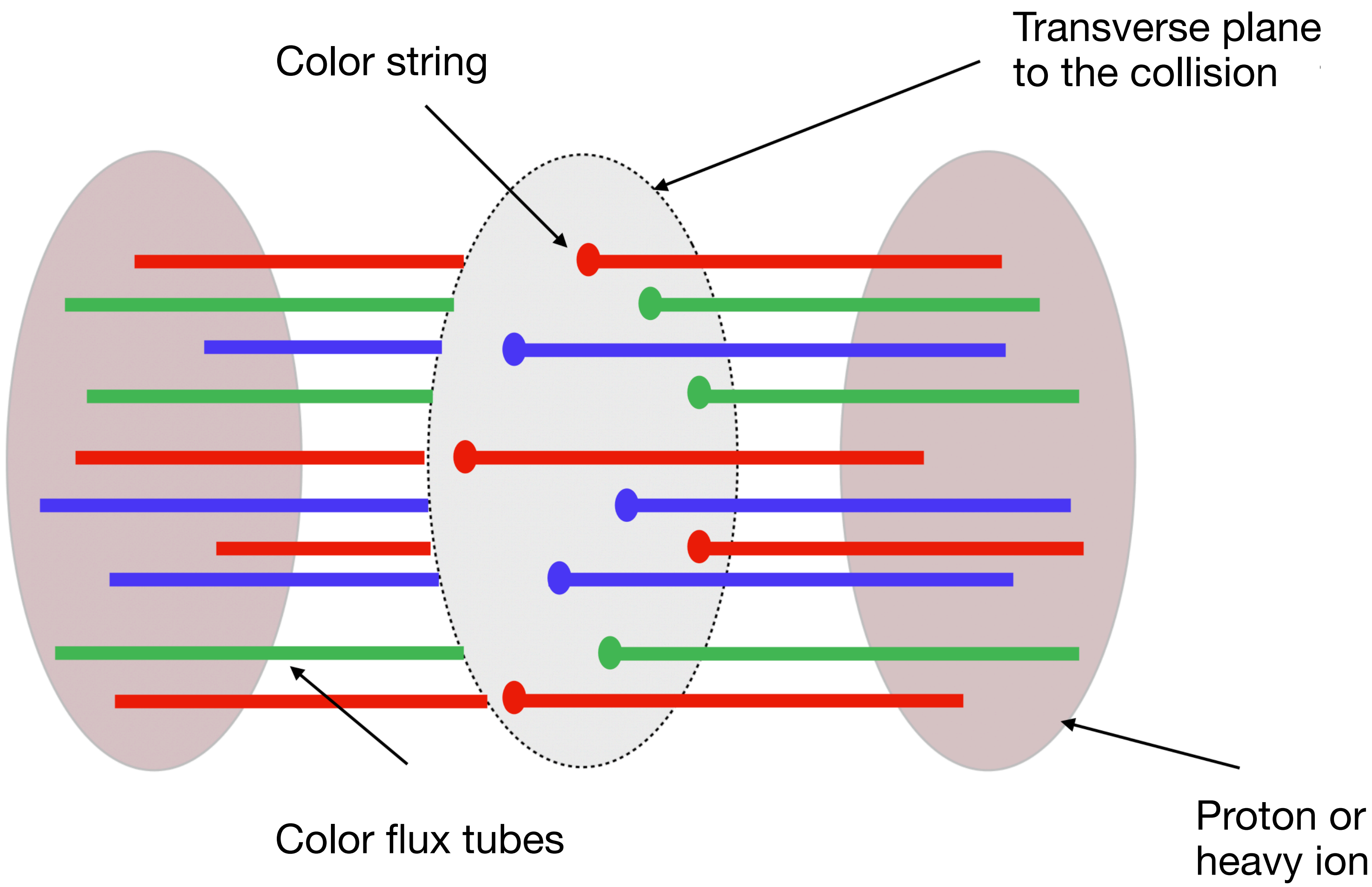
Particle production from Schwinger mechanism



$$\frac{dN}{dp_T^2} \sim \int_0^\infty \exp\left(-\frac{\pi p_T^2}{x^2}\right) P(x)dx$$

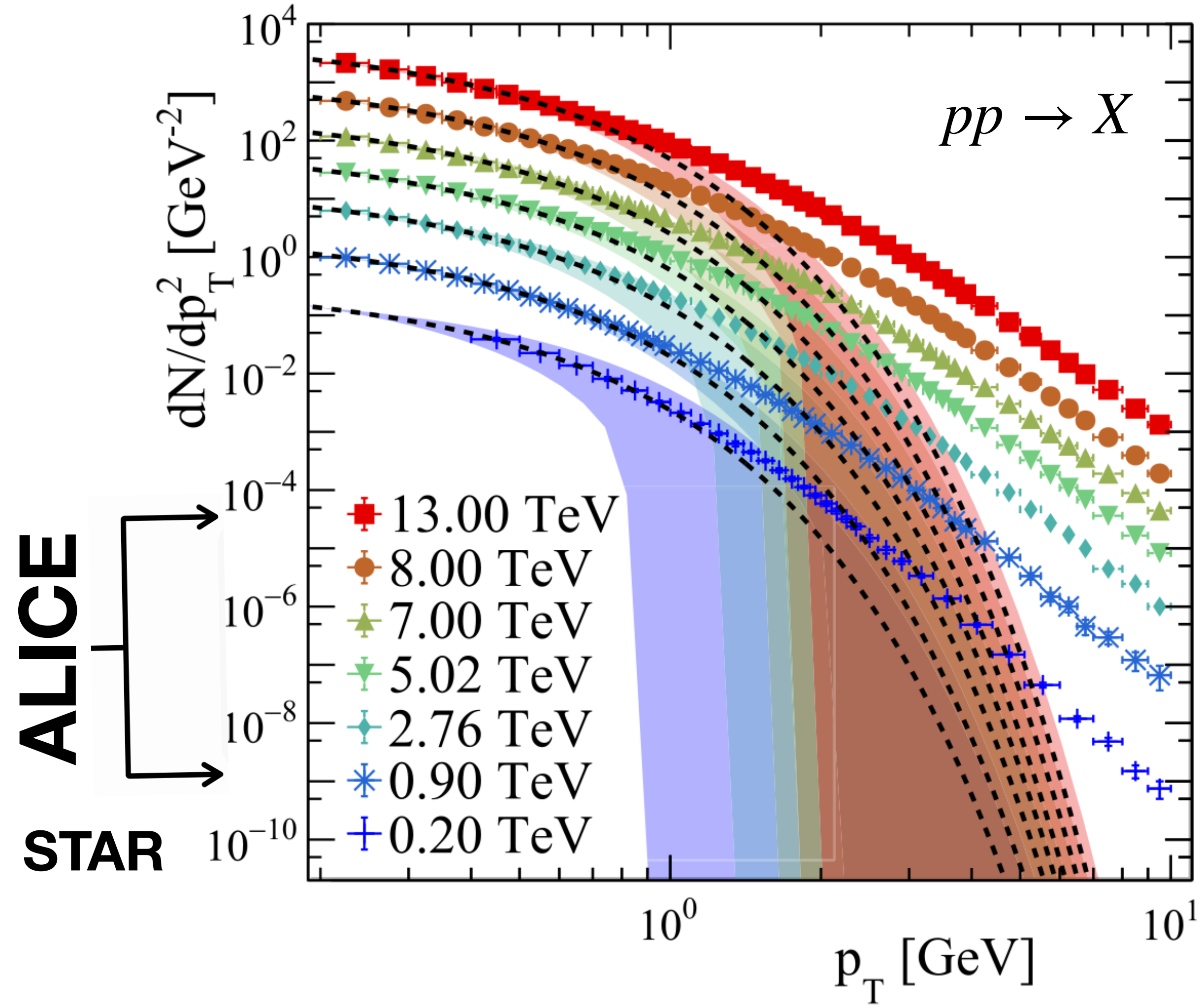
Schwinger Mechanism

String tension fluctuations

The Schwinger mechanism represents the probability of observing a particle with transverse momentum p_T produced by the fragmentation of strings with tension x^2 that may fluctuates.

Schwinger J 1962 Phys. Rev. 128 2425 // Bialas A 1999 Phys. Lett. B 466 301

String tension fluctuations



Thermal distribution

$$\frac{dN}{dp_T^2} \sim \exp\left(-p_T\sqrt{\frac{2\pi}{\langle x^2\rangle}}\right)$$

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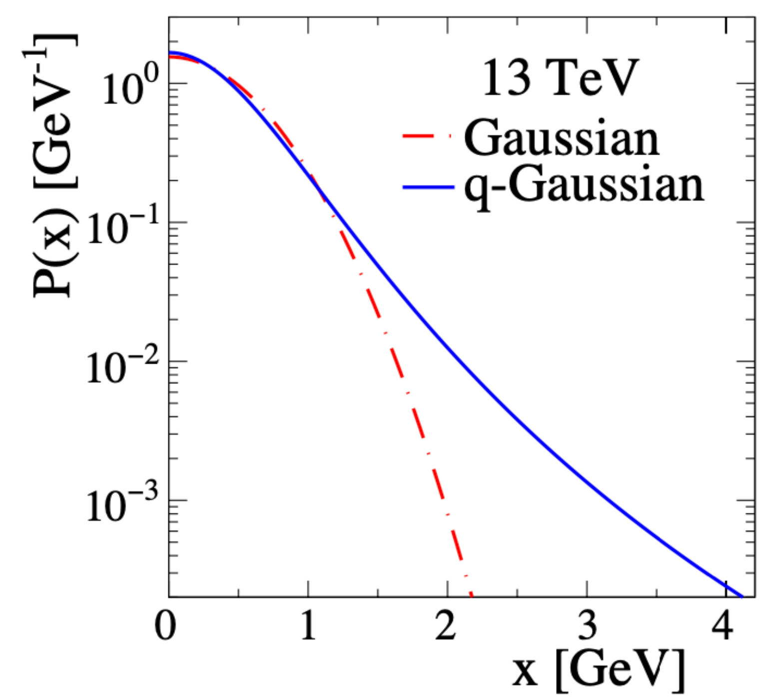


q-Gaussian string tension fluctuations

$$P(x) \sim \left(1 + \frac{(q-1)x^2}{2\sigma^2}\right)^{\frac{1}{1-q}}$$

Heavy tailed!

It is motivated by phenomena raising the high p_T particle production, such as hard gluon emission from strings

D. Rosales Herrera, et al 2024 *Phys. Rev. C*, *109*(3), 034915

Nonextensive p_T -spectrum description

Tricomi function

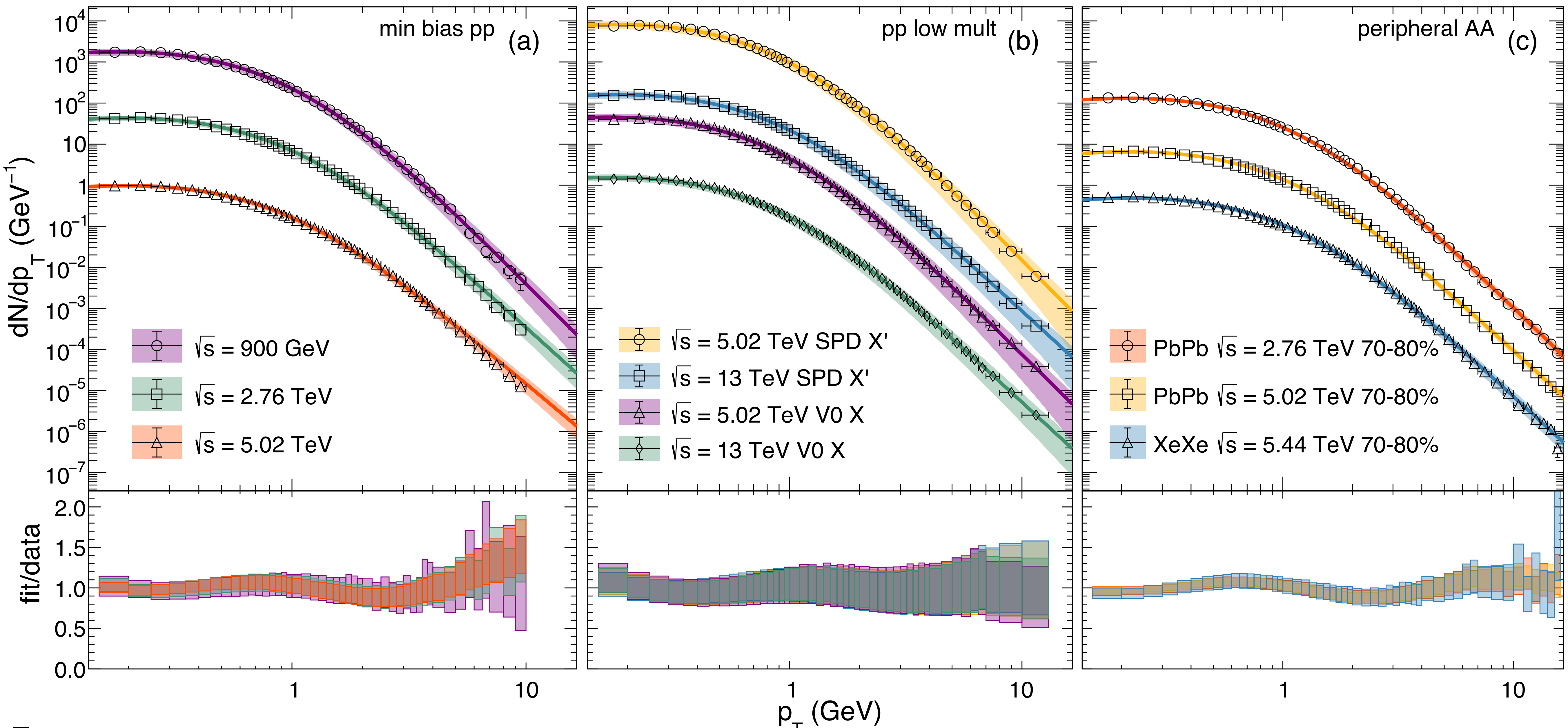
$$\frac{dN}{dp_T^2} \sim U\left(\frac{1}{q-1} - \frac{1}{2}, \frac{1}{2}, \pi p_T^2 \frac{q-1}{2\sigma^2}\right)$$

with p_T scale $\quad T_U = \sigma \dfrac{\Gamma\left(\frac{1}{q-1} - \frac{1}{2}\right)}{\sqrt{2\pi(q-1)}\,\Gamma\left(\frac{1}{q-1}\right)}$

q marks the departure of the thermal distribution and describes the p_T -spectrum tail

$$1 < q < 3/2$$

Higher values of q implies higher effective temperature



J.E. Ramírez, et al, *Eur. Phys. J. A* **59**, 250 (2023). Alice Collaboration Phys. Lett. B 845, 138110 (2023). D. Rosales, et al, EPJ C 85:760 (2025).

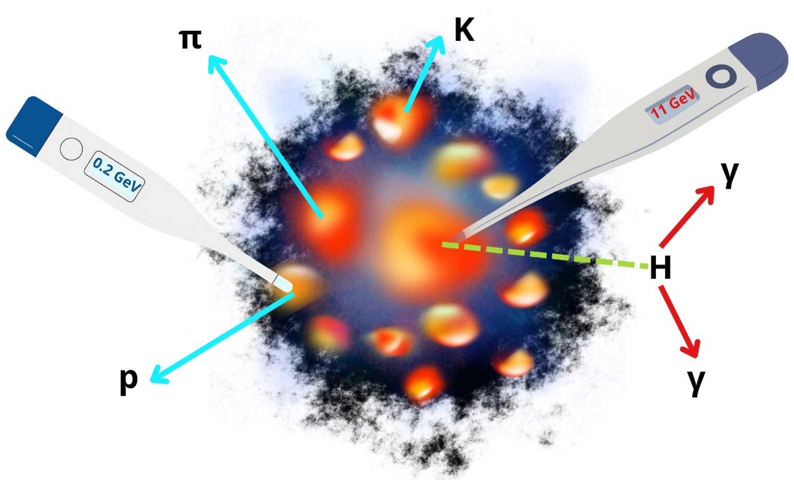
Nonextensive p_T -spectrum description

The production of high p_T particles requieres that the system departs from the thermal behavior

Temperature fluctuations

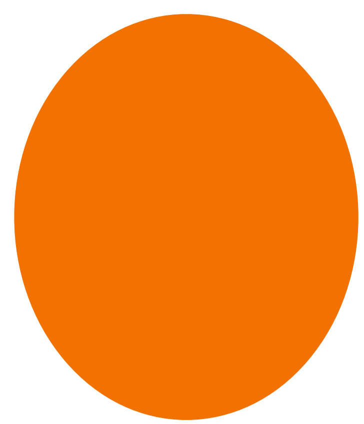
Nonextensive

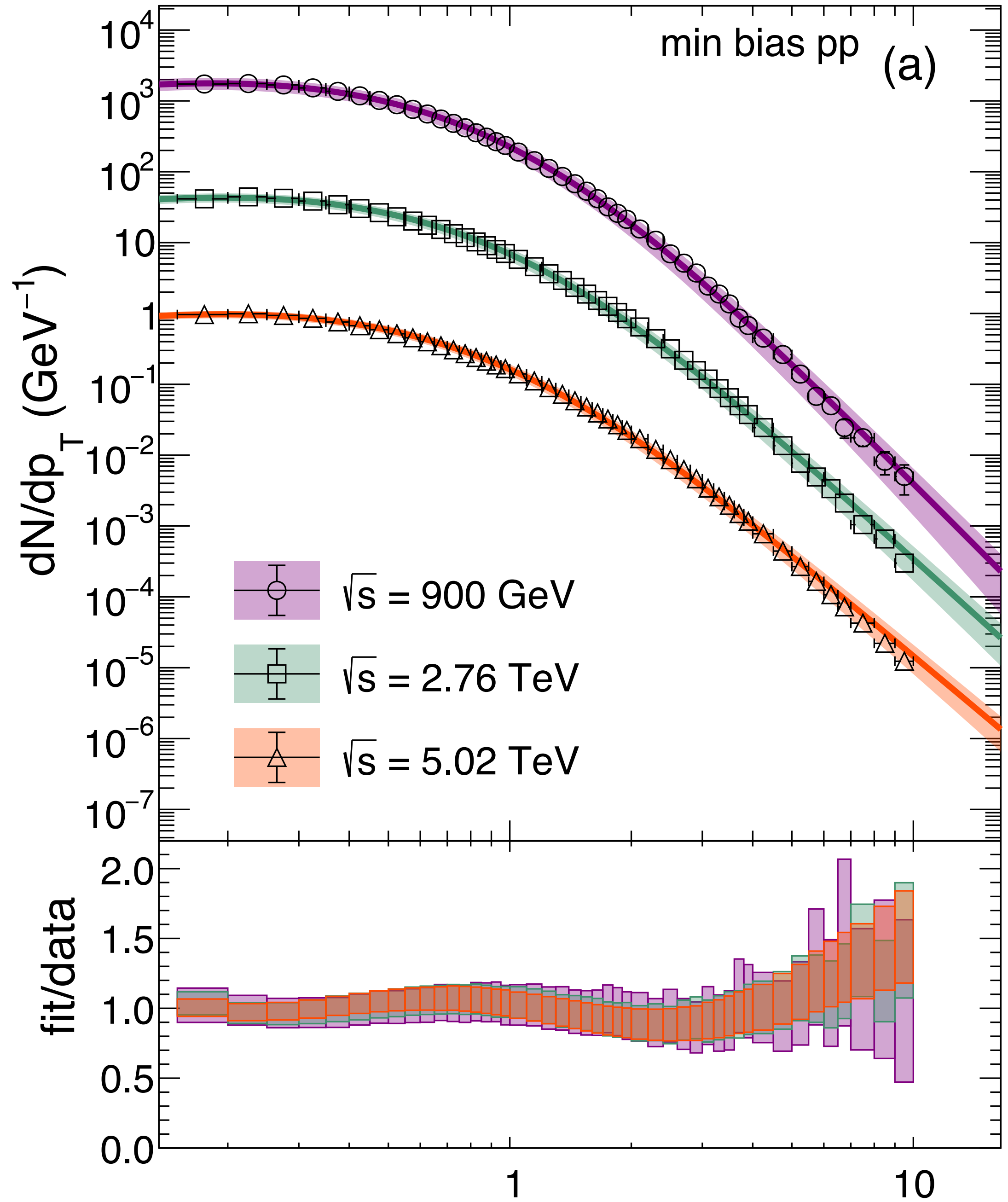
$$\mathscr{T}_U(T) = \frac{2}{T^3}\Gamma\left(\frac{1}{T^2}, \frac{1}{q-1} - \frac{1}{2}, \frac{1}{4z_0}\right)$$



Thermal dist.

$$\mathscr{T}_{th}(T) = \delta(T - T_{th})$$



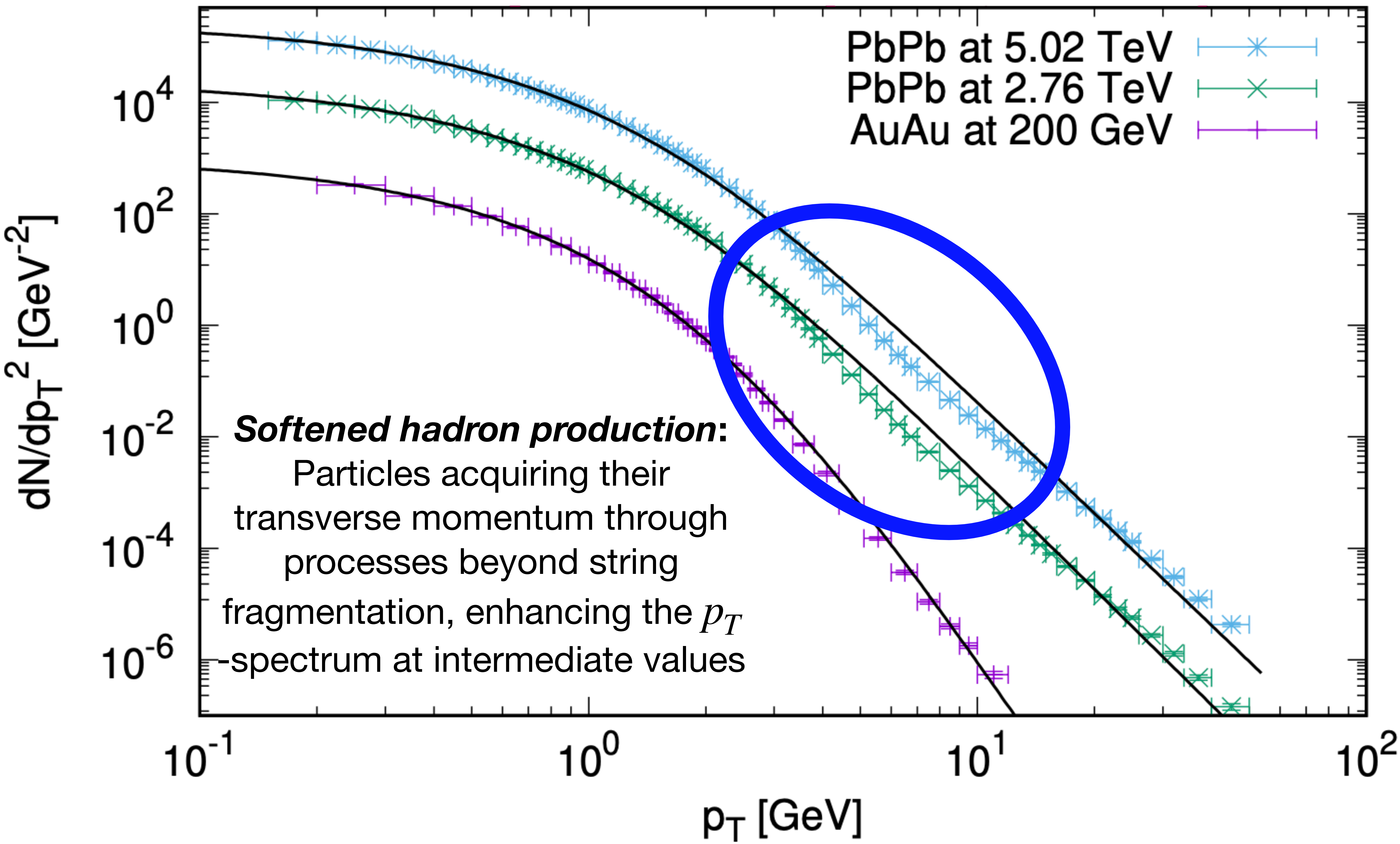


This is a mean field model type, where the production of high p_T particles is incorporated as the observation of rare events produced by the enhancement of having strings with higher tensions

The string fragmentation is the baseline for the charge particle production

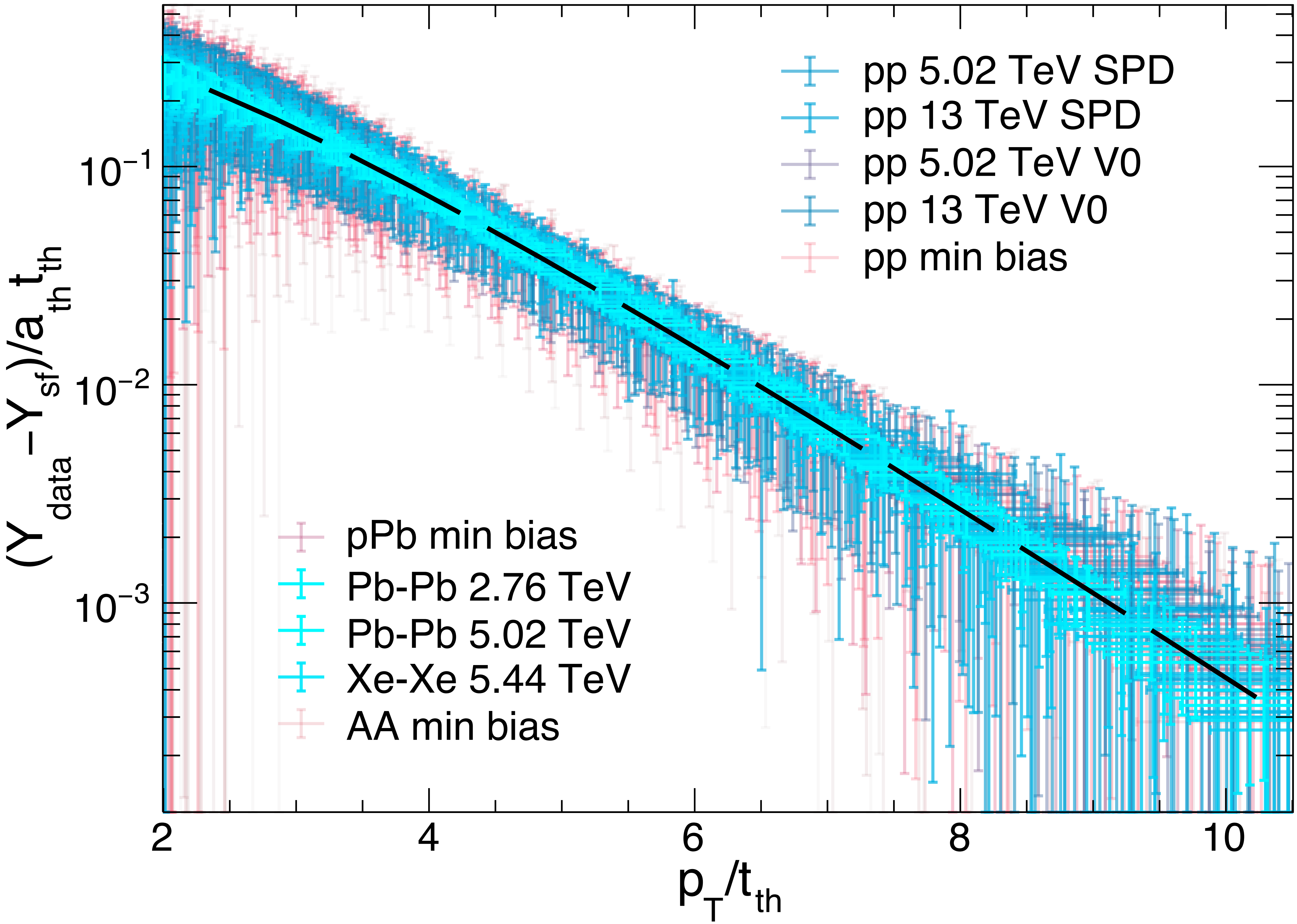
J.E. Ramírez, et al, *Eur. Phys. J. A* **59**, 250 (2023). Alice Collaboration Phys. Lett. B 845, 138110 (2023). D. Rosales, et al, EPJ C 85:760 (2025).

Central heavy ion collisions



J R Alvarado García, D. Rosales Herrera, et al, J. Phys. G: Nucl. Part. Phys. **50** 125105 (2023)   Alice Collaboration Phys. Lett. B 845, 138110 (2023).

Data-driven analysis at intermediate p_T values



The softened hadron produced in all the analyzed colliding systems collapse, following

$$Y_{\text{data}} - Y_{\text{sf}} = a_{th} p_T \exp(-p_T/t_{th})$$

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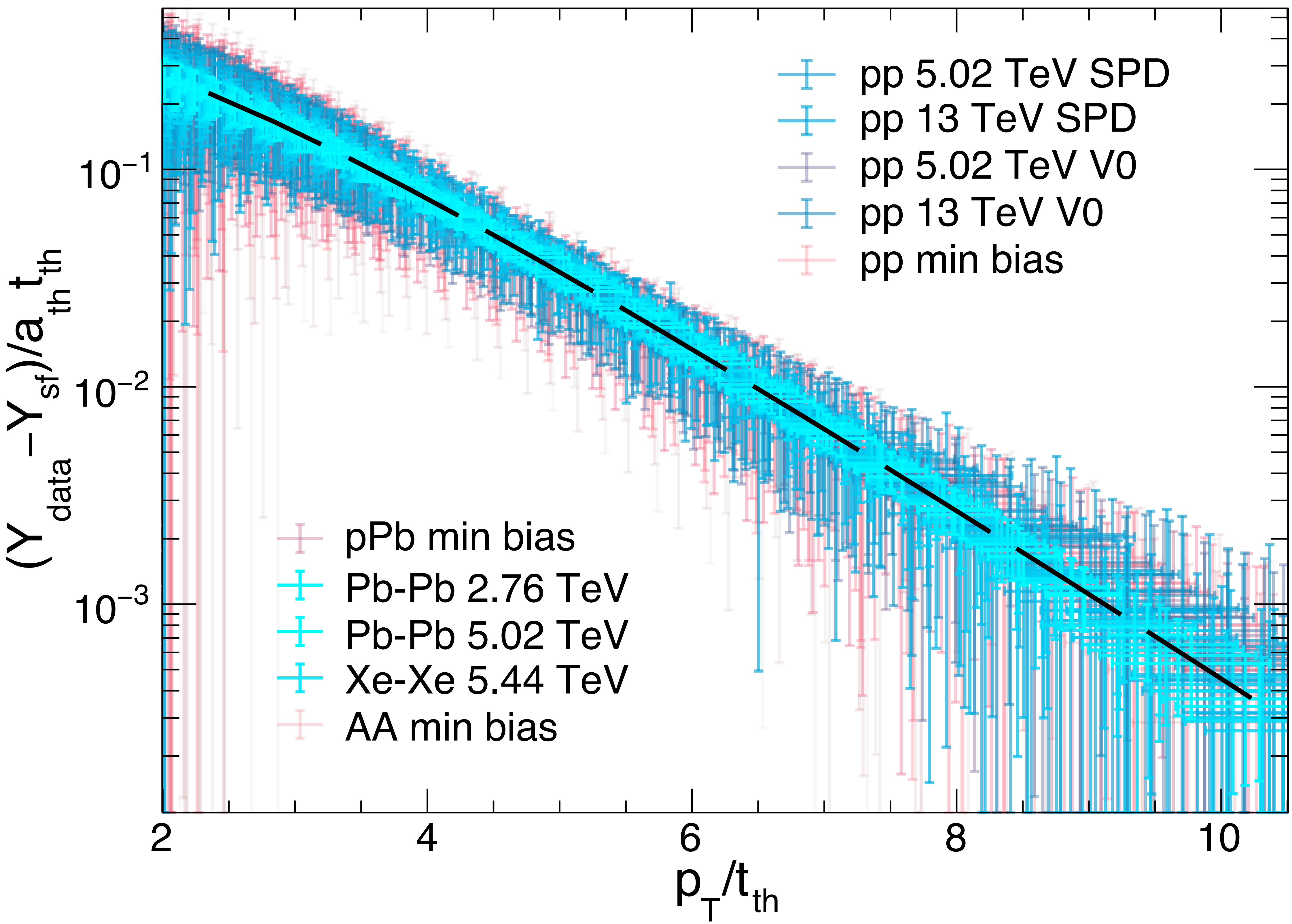
Data-driven analysis at intermediate p_T values



This does not imply that the production of softened hadrons comes from thermal processes, but these particles redistribute their transverse momentum in this form

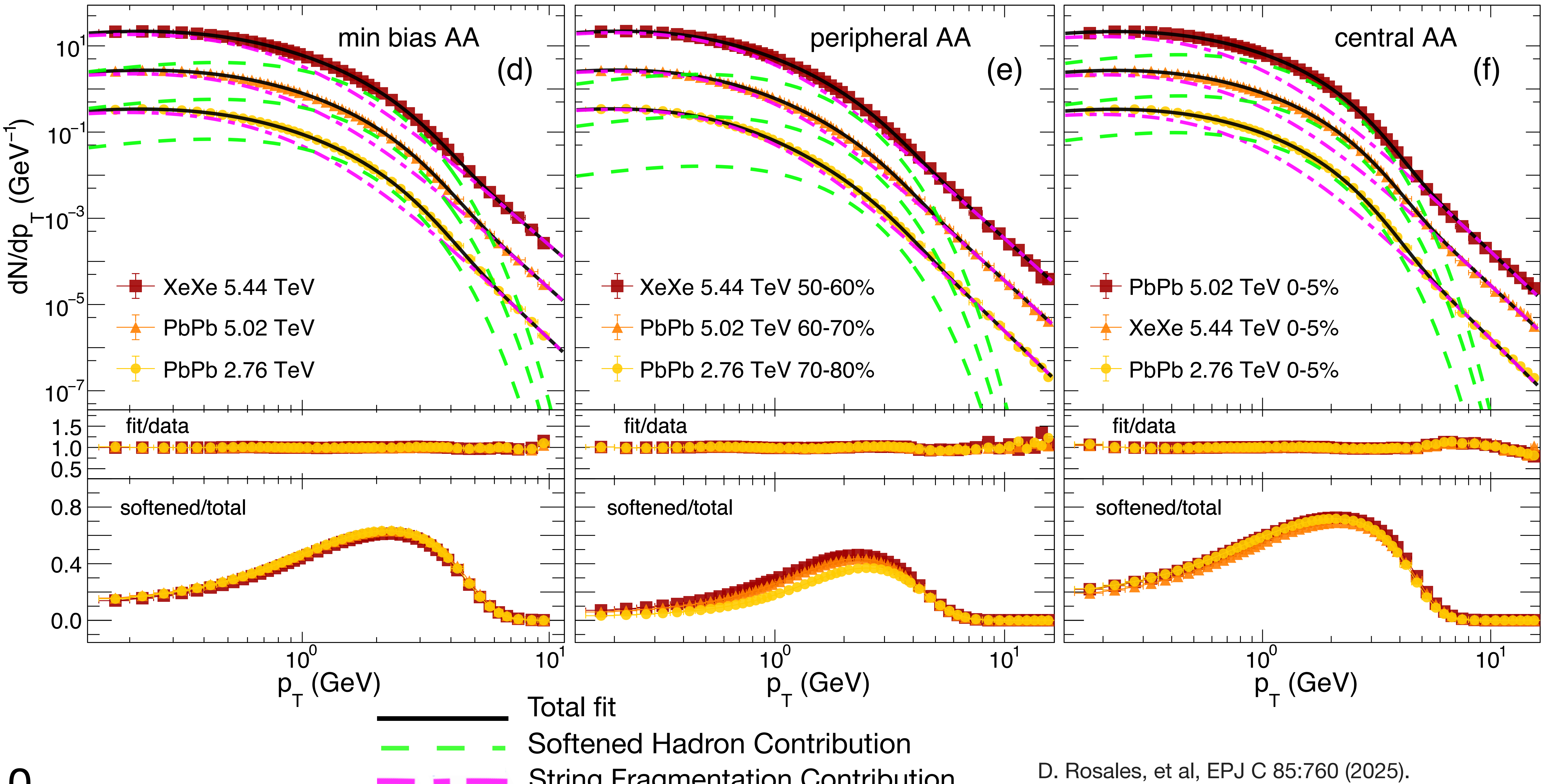
Two contributions to the p_T - spectrum

$$\frac{dN}{dp_T^2} = A_U U\left(\frac{1}{q-1} - \frac{1}{2}, \frac{1}{2}, \pi p_T^2 \frac{q-1}{2\sigma^2}\right) + A_{th}\exp(-p_T/T_{th})$$

p_T scale associated with the softened hadrons

Effective temperature linked to the complete p_T - spectrum

$$T_{\text{eff}}^{-1} = \frac{1}{A_U^* + A_{th}}\left(\frac{A_U^*}{T_U} + \frac{A_{th}}{T_{th}}\right) \quad \text{with} \quad A_U^* = \frac{A_U\sqrt{\pi}}{\Gamma\left(\frac{1}{q-1}\right)}$$

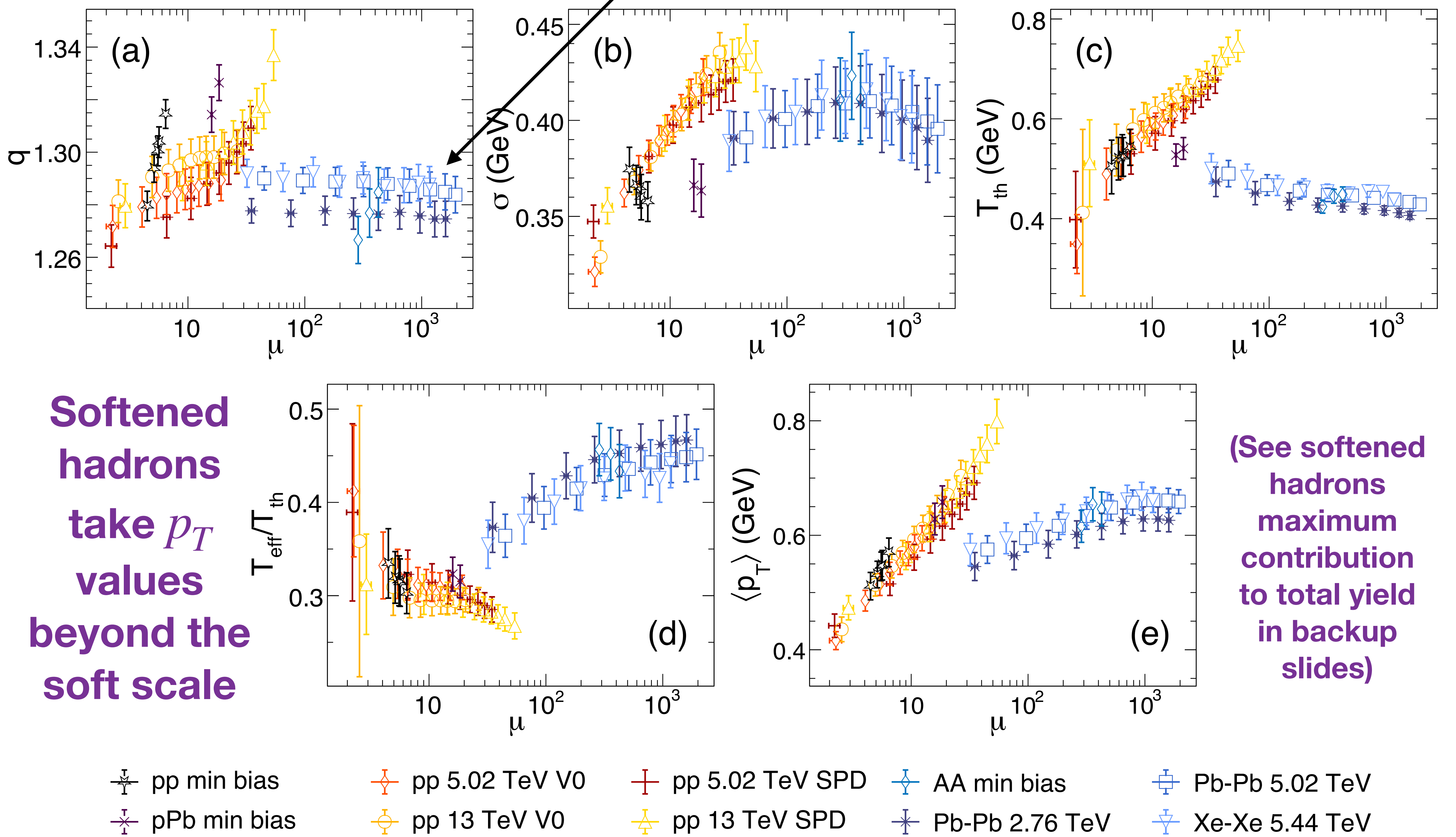


D. Rosales, et al, EPJ C 85:760 (2025).
Alice Collaboration Phys. Lett. B 845, 138110 (2023).

Physical meaning

Lower q values mean lower probability of producing high p_T hadrons

Suppression of high p_T particles at the most central AA collisions



Softened hadrons take p_T values beyond the soft scale

(See softened hadrons maximum contribution to total yield in backup slides)

D. Rosales, et al, EPJ C 85:760 (2025).

Softened hadron's contributions

$$E_n = \frac{A_{th}\int_0^\infty p_T^n e^{-p_T/T_{th}} dp_T}{\int_0^\infty p_T^n \frac{dN}{dp_T^2} dp_T}$$

$n = 0$	$n = 1$	$n = 2$
Weighted contribution of softened hadron's to the p_T -spectrum	Weighted contribution of softened hadron's to charged particles produced N_{ch}	Weighted contribution of softened hadron's to mean p_T
$E_{\frac{dN}{dp_T^2}}$	$E_{N_{ch}}$	$E_{\langle p_T \rangle}$

$E_n = 0$ means that all the particle production comes from the fragmentation of color strings.

D. Rosales, et al, EPJ C 85:760 (2025).

Scaling laws

$$E_{\frac{dN}{dp_T^2}} \propto (\mu \langle p_T \rangle)^{\beta_3}$$

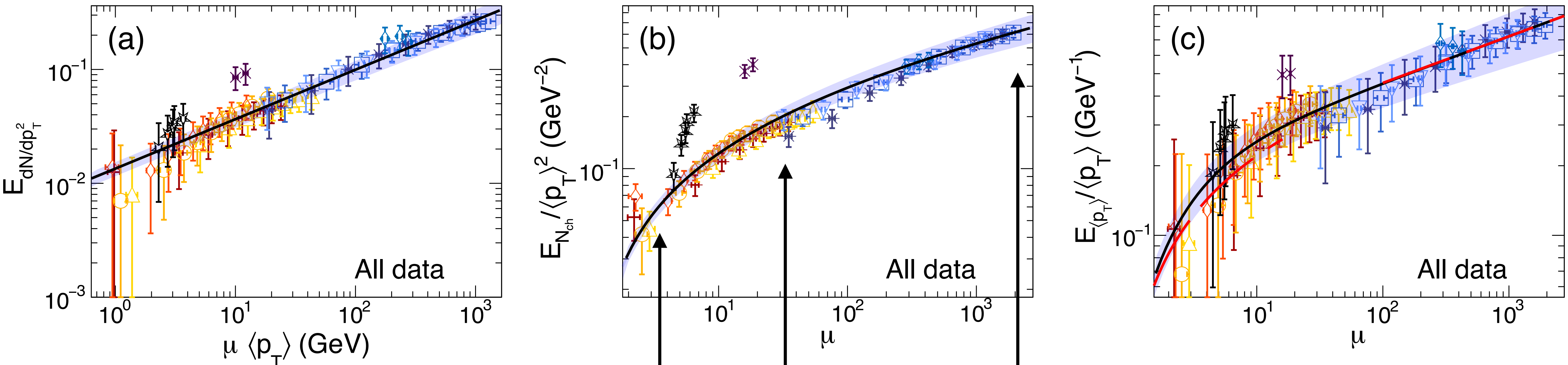
$$\beta_3 = 0.43(1)$$

$$E_{N_{ch}} \propto \mu^{\beta_4}$$

$$\beta_4 = 0.08(1)$$

$$\frac{E_{\langle p_T \rangle}}{\langle p_T \rangle} \propto \mu^{\beta_5} + e^{-2/\mu} - 1$$

$$\beta_5 = 0.20(1)$$



1 particle per 50 events

30% of softened hadrons

Softened hadron production increases with $\mu \langle p_T \rangle$

Highest multiplicity pp collisions have comparable values with peripheral AA collision

Universal scaling law for pp, pPb y AA collisions

D. Rosales, et al, EPJ C 85:760 (2025).

Conclusions

By considering a nonextensive description through q-Gaussian string tension fluctuations

$$\frac{dN}{dp_T^2} = A_U U\left(\frac{1}{q-1} - \frac{1}{2}, \frac{1}{2}, \pi p_T^2 \frac{q-1}{2\sigma^2}\right) + A_{th}\exp(-p_T/T_{th})$$

String fragmentation

Collective phenomena

The main results are the scaling laws for the contribution of the softened hadrons.

From this, we can conclude that the physical mechanisms producing the softened hadrons have similar origins for all colliding systems.

Thank you !

For more details:

[1] D. Rosales, et al, EPJ C 85:760 **(2025)**

[2] D. Rosales Herrera, et al, Phys. Rev. C 110, 015205 **(2024)**

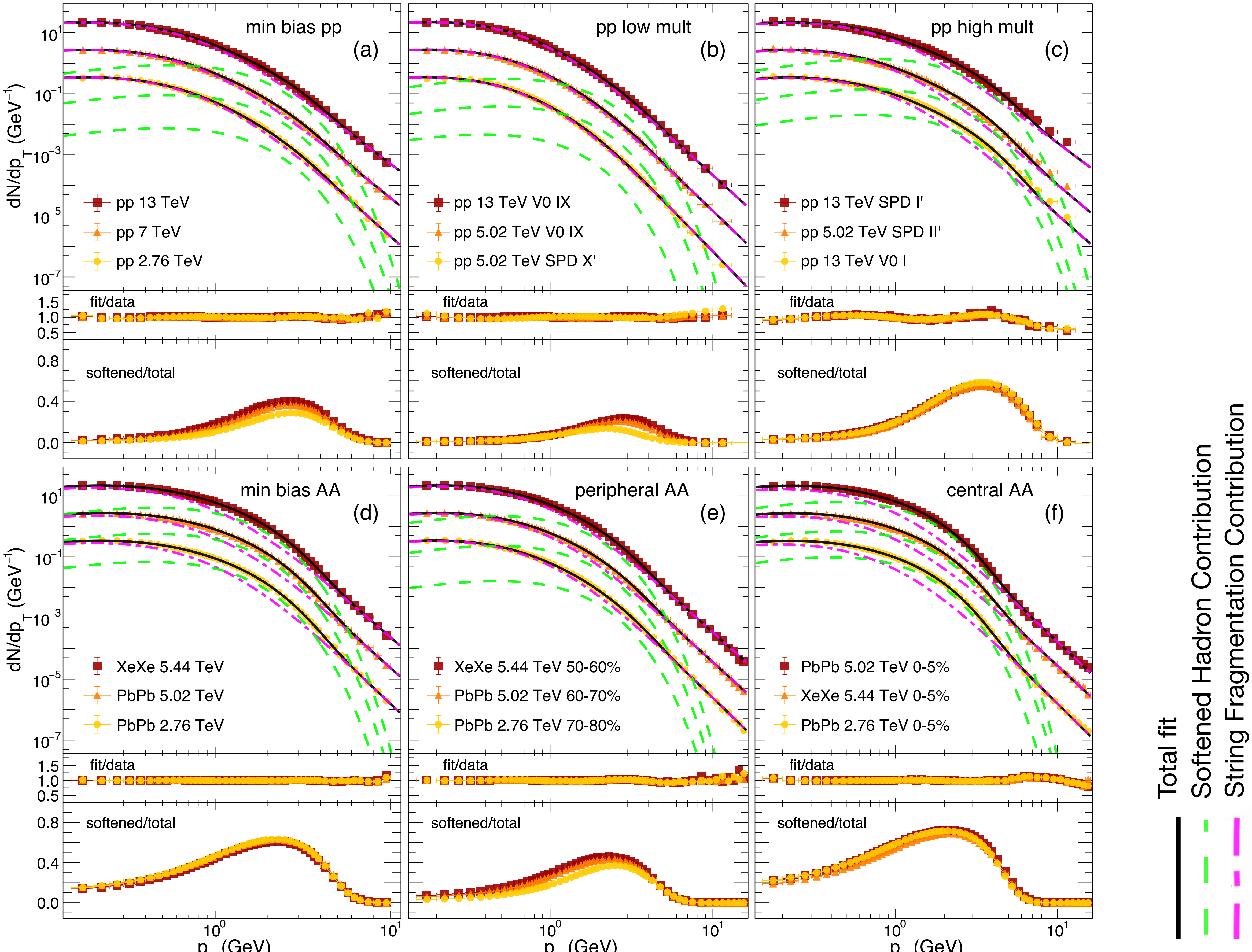
[3] D. Rosales Herrera, et al, Phys. Rev. C 109, 034915 **(2024)**

[4] J. R. Alvarado García, et al, J. Phys. G: Nucl. Part. Phys. 50, 125105 **(2023)**

[5] J. E. Ramírez, et al, Eur. Phys. J. A 59, 250 **(2023)**

Backup slides

Two contributions to the p_T - spectrum



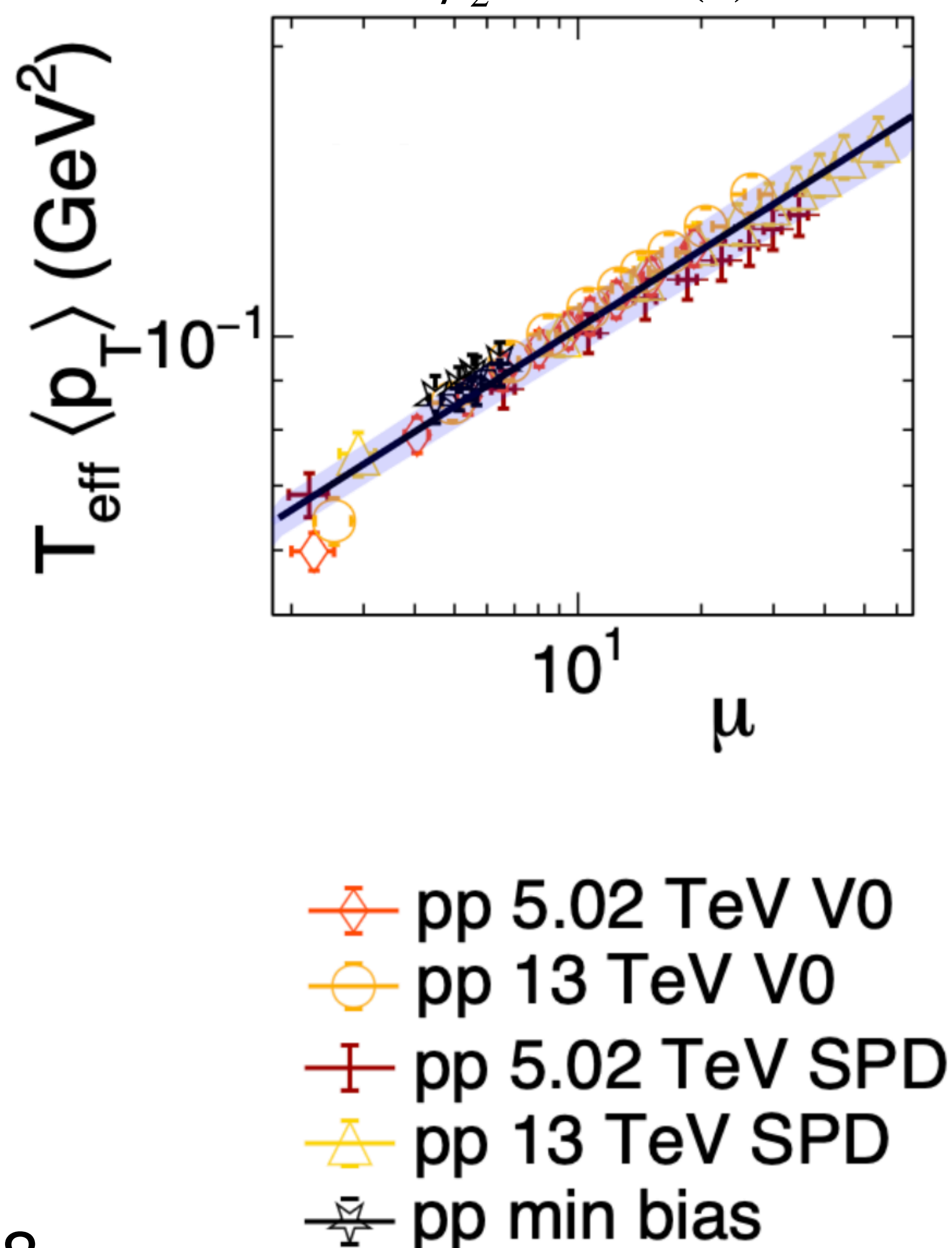
D. Rosales, et al, EPJ C 85:760 (2025).

Dissimilarities between small and large systems

Small systems

$$T_{eff} \propto \mu^{\beta_2}/\langle p_T \rangle$$

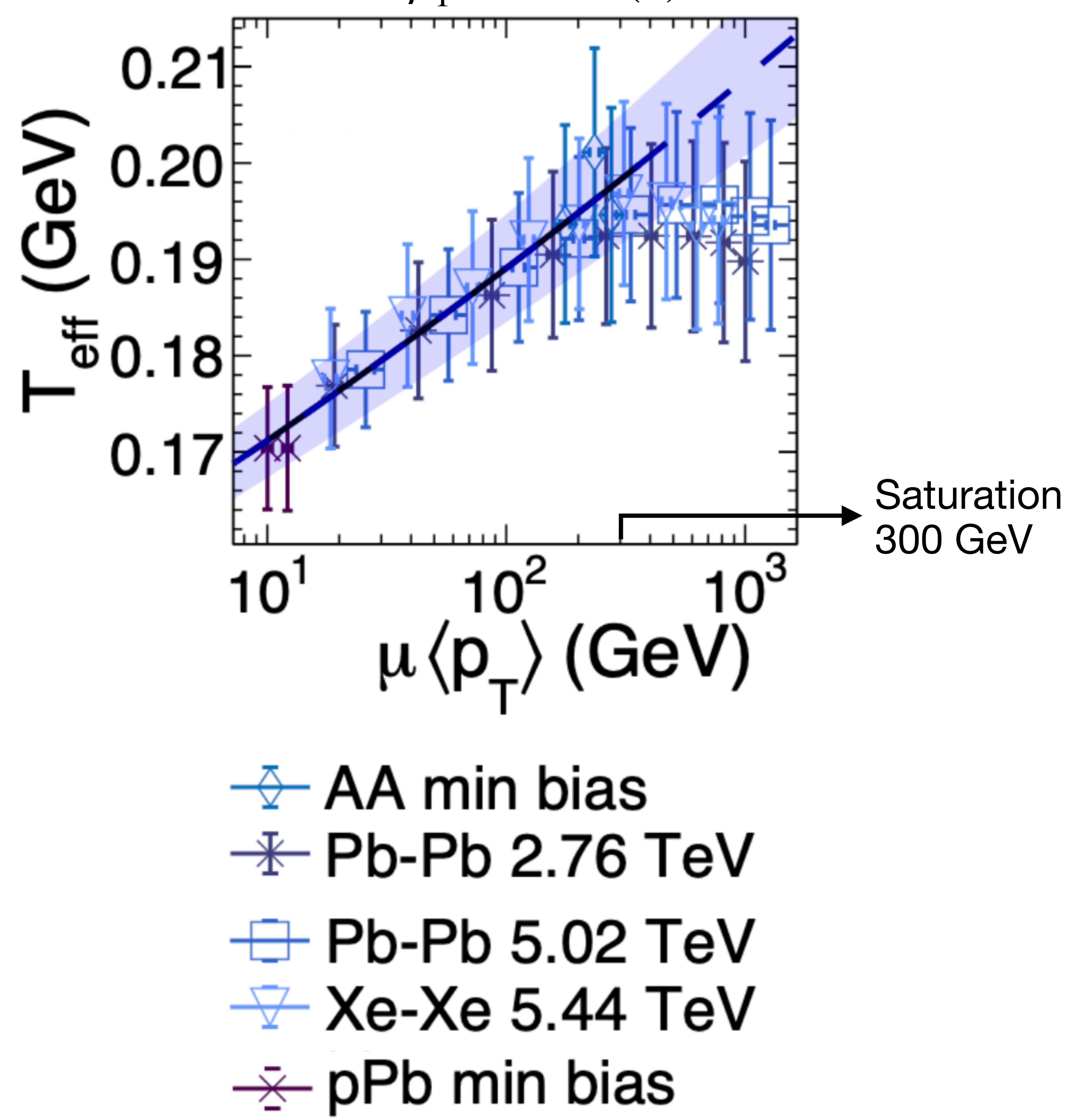
$\beta_2 = 0.270(9)$



Large systems

$$T_{eff} \sim (\mu\langle p_T \rangle)^{\beta_1}$$

$\beta_1 = 0.043(2)$



D. Rosales, et al, EPJ C 85:760 (2025).