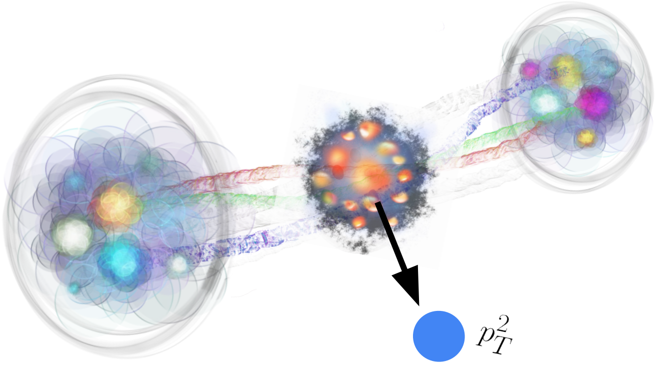
Producción de partículas en colisiones ultrarelativistas desde la perspectiva de la física estadística

HEP-phenomenology group, BUAP

D. Rosales Herrera, J. R. Alvarado García, **J. E. Ramírez**, A. Fernández Téllez



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21/01/2026

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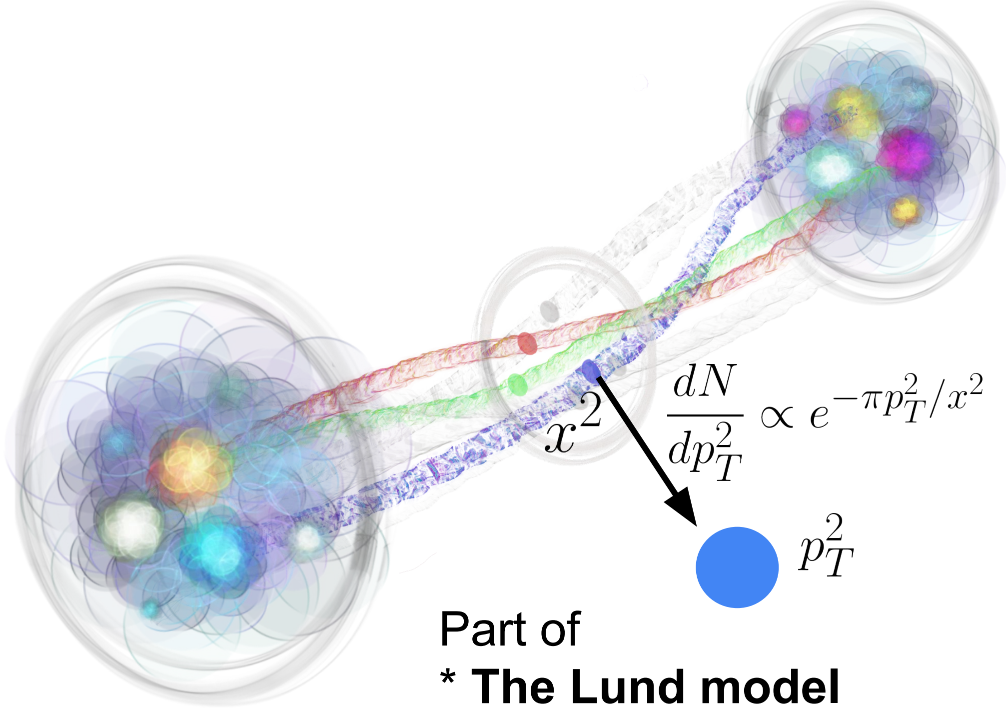
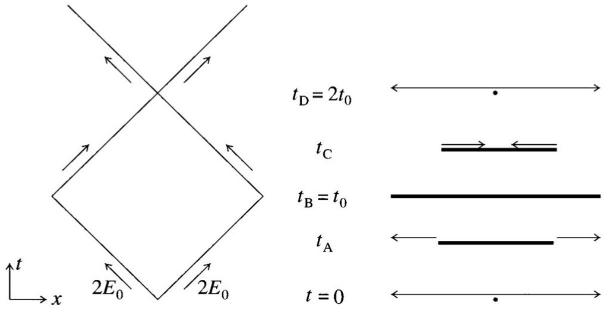
Outline

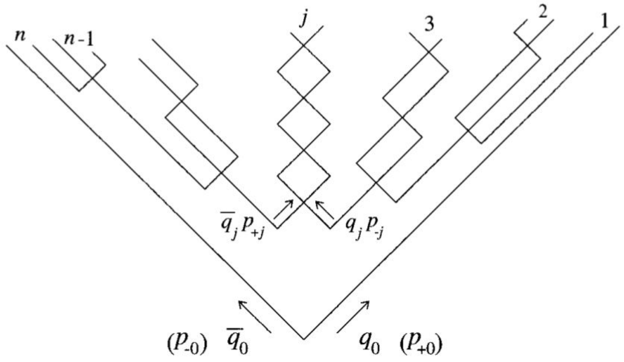
- Fragmentation of color strings and the Schwinger mechanism
    - Nonextensive description of the initial state
    - Nonthermal description of the pT spectrum
- Thermodynamics from the pT spectrum:
    - Entropy and heat capacity for minimum bias pp collisions
    - Equation of state (nonlinear in T)
- Softened hadron production (signal for collective phenomena?)
- Other origins for temperature fluctuations
- Concluding remarks

Particle production from Schwinger mechanism



Part of
* **The Lund model**
Implemented in
* **PYTHIA**





J. Schwinger, Phys. Rev. 128, 2425 (1962).

B. Andersson, T. Sjöstrand, et al, Phys. Rep. 97, 31 (1983).
B. Andersson, The Lund Model (Cambridge University Press, Cambridge, 1998)

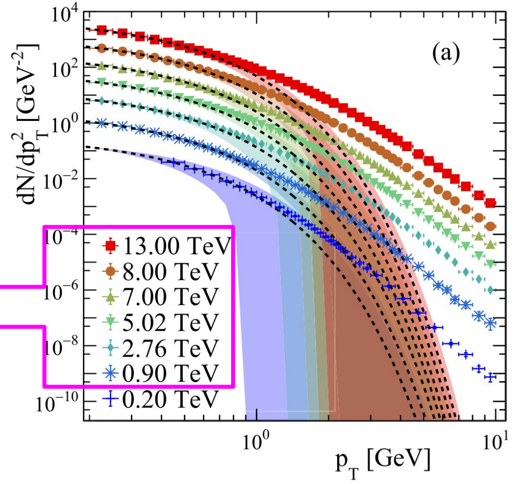
Nonextensive particle production

Gaussian fluctuations

$$P(x) \propto e^{-x^2/2\sigma^2} \Rightarrow \frac{dN}{dp_T^2} \propto e^{-p_T/T}$$

A. Bialas, Phys. Lett. B 466, 301 (1999).

ALICE data
Phys. Lett. B 845, 138110 (2023).



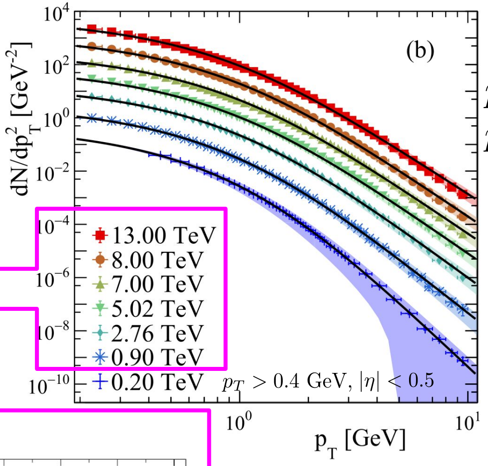
$|\eta| < 0.8$
$p_T < 10$ GeV
$p_T > 0.15$ GeV

q-Gaussian fluctuations

$$P(x) \propto \left[1 + \frac{(q-1)x^2}{2\sigma^2}\right]^{\frac{1}{1-q}} \Rightarrow \frac{dN}{dp_T^2} \propto U\left(\frac{1}{q-1} - \frac{1}{2}, \frac{1}{2}, \pi p_T^2 \frac{q-1}{2\sigma^2}\right)$$

C. Pajares and J. E. Ramírez, Eur. Phys. J. A 59, 250 (2023).

ALICE data
Phys. Lett. B 845, 138110 (2023).



$|\eta| < 0.8$
$p_T < 10$ GeV
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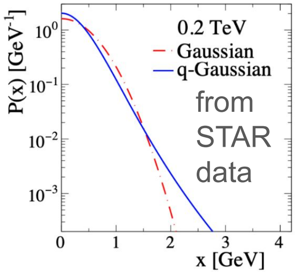
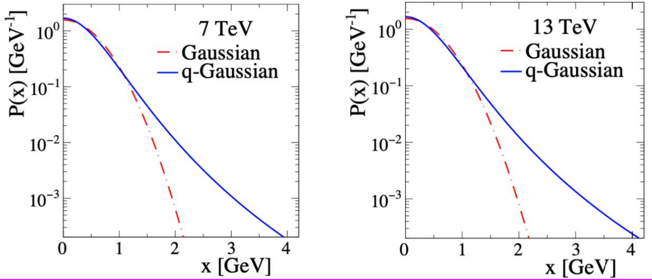
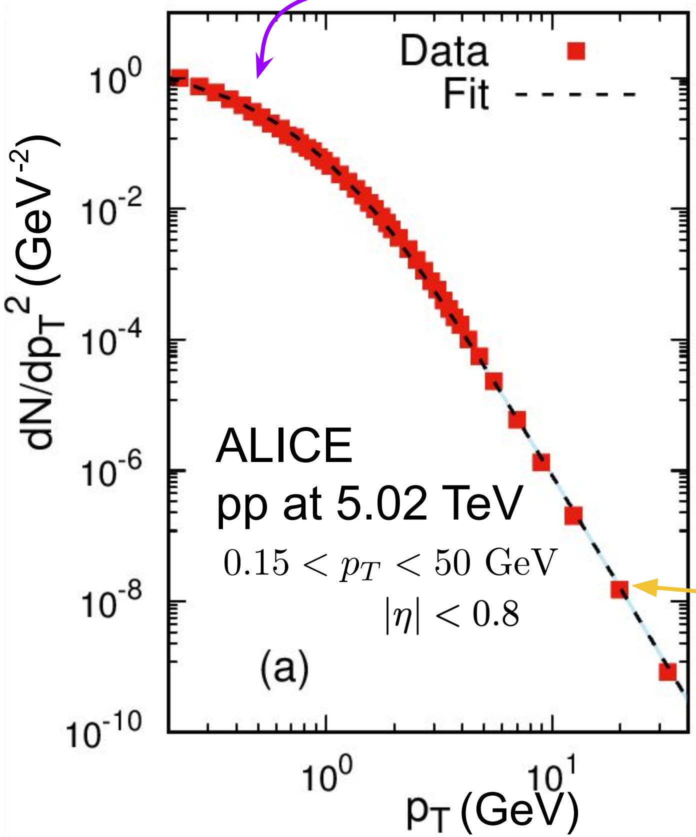




D. Rosales Herrera, et al, Phys. Rev. C 109, 034915 (2024).

Asymptotic behaviors



Low pT particles:

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

Effective temperature

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

High pT particles:

$$\frac{dN}{dp_T^2} \propto \left(p_T^2\right)^{\frac{1}{2}-\frac{1}{q-1}}$$

C. Pajares and J. E. Ramírez, Eur. Phys. J. A 59, 250 (2023).
J. R. Alvarado García, D. Rosales Herrera, et al, J. Phys. G: Nucl. Part. Phys. 50, 125105 (2023).

Hagedorn also comes from fragmentation of strings

We found:

$$(1 + p_T/p_0)^{-m} = \int_0^{\infty} e^{-\pi p_T^2/x^2} P_{\text{Hag}}(x)dx$$

where

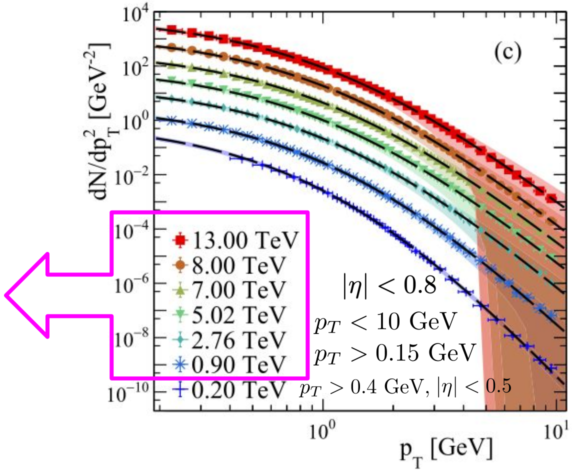
$$P_{\text{Hag}}(x) = \frac{m p_0^m \pi^{\frac{m-1}{2}}}{x^{m+1}} U\left(\frac{m+1}{2}, \frac{1}{2}, \frac{\pi p_0^2}{x^2}\right)$$

PHag behaves as a power law in the limit of high string tension values:

$$P_{Hag} \propto x^{-(m+1)}$$

D. Rosales Herrera, et al, Phys. Rev. C 110, 015205 (2024).

ALICE data



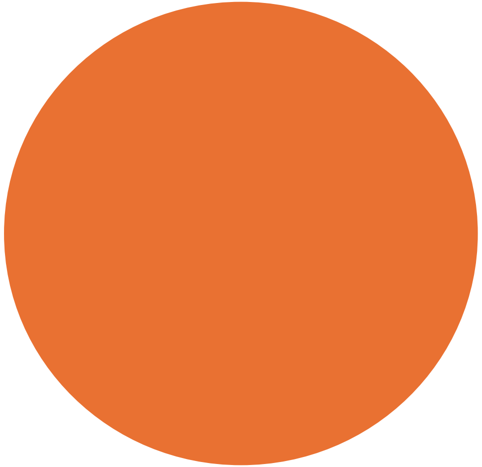
D. Rosales Herrera, et al, Phys. Rev. C 109, 034915 (2024).

High pT particle production requires heavy tailed string tension fluctuations!

Temperature fluctuations

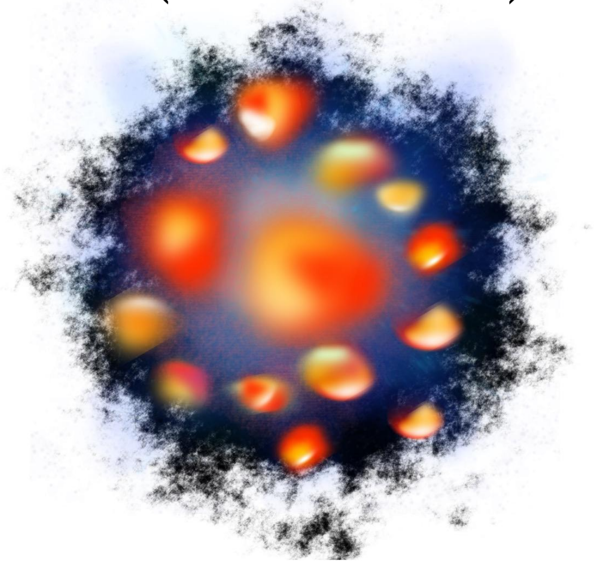
Gaussian fluctuations

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



q-Gaussian fluctuations

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

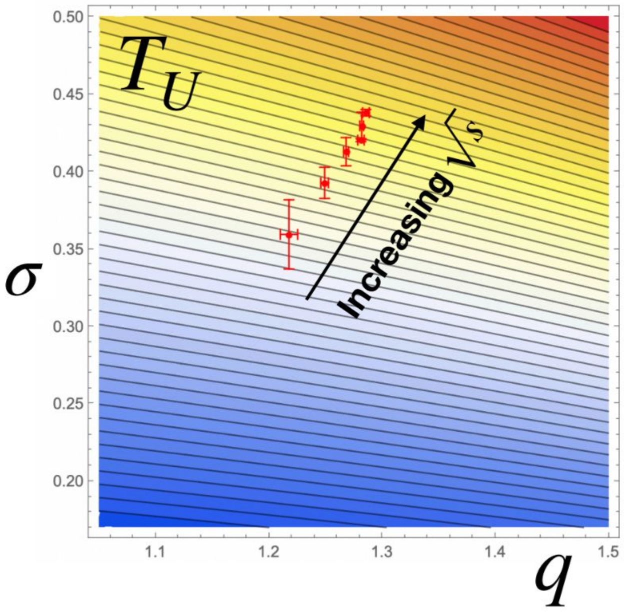


Nonextensive particle production implies a nonthermal description of the system!

D. Rosales Herrera, et al, Phys. Rev. C 110, 015205 (2024).

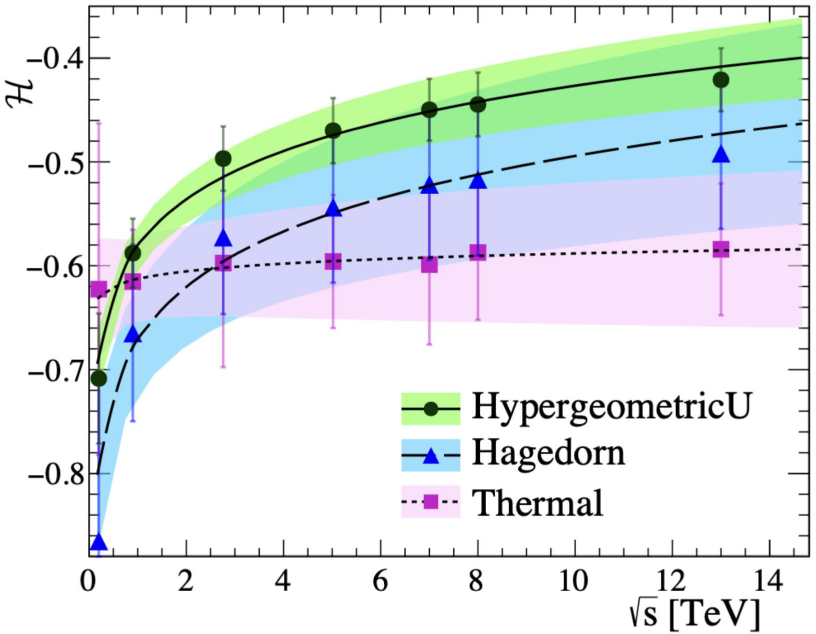
Thermodynamics from the pT spectrum

Temperature of min bias pp collisions (at LHC energies)



Shannon entropy for the normalized TMD:

$$\mathcal{H} = -\int_0^\infty (\mathrm{TMD}/I_0)\ln(\mathrm{TMD}/I_0)dp_T$$

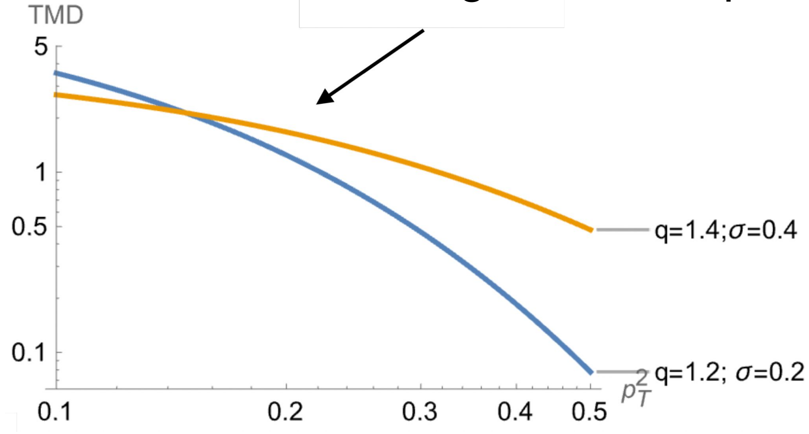


D. Rosales Herrera, et al, Phys. Rev. C 109, 034915 (2024).

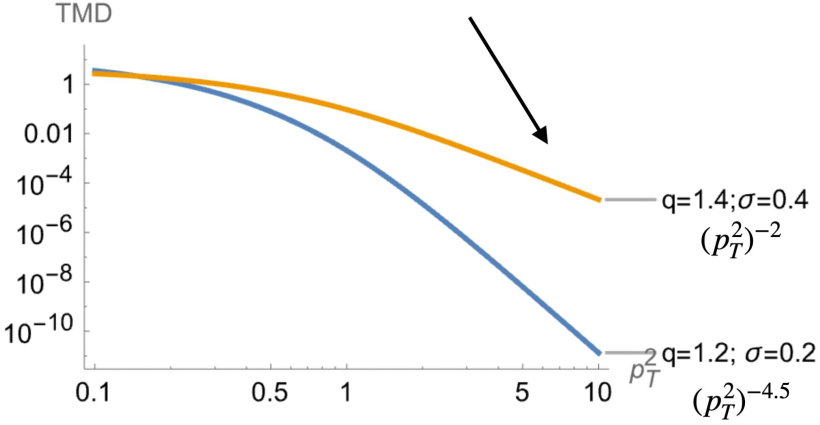
Heating the TMD

Heat capacity is a measure of how much energy is required for “heat up” the TMD

Flattening of the soft part



Enhancement of the TMD tail

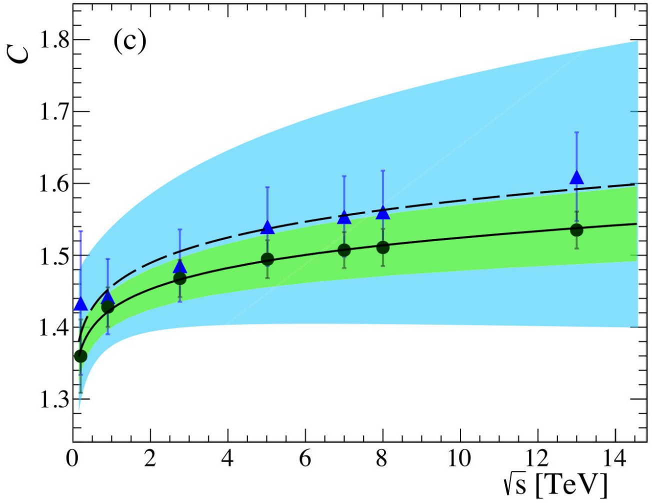


D. Rosales Herrera, et al, Phys. Rev. C 109, 034915 (2024).

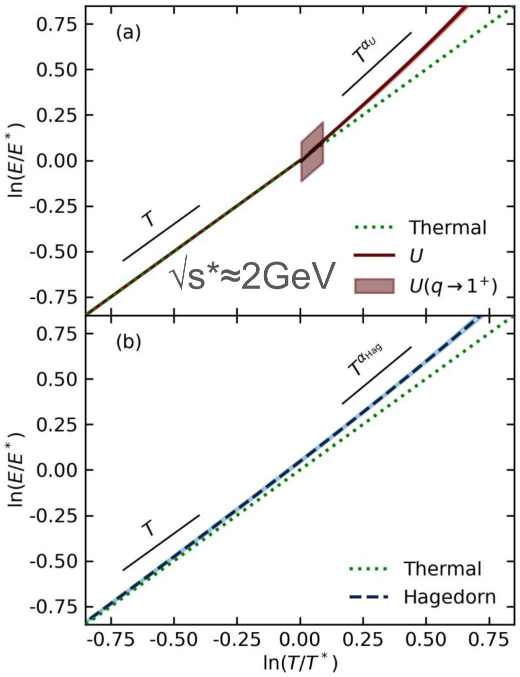
Thermodynamics from the pT spectrum

Heat capacity:

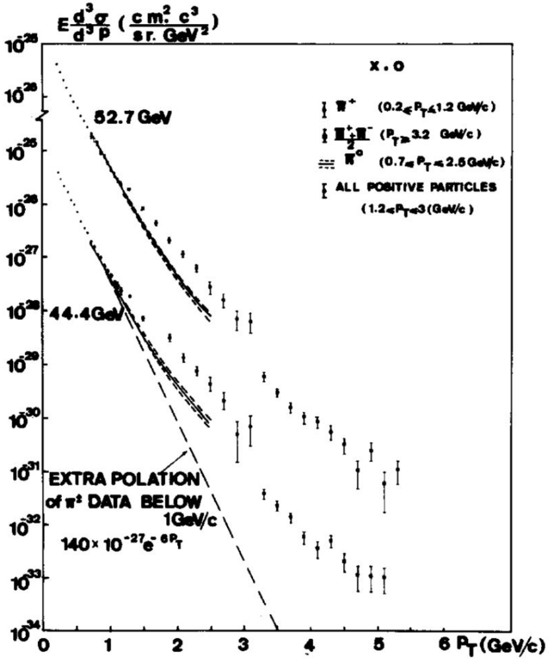
$$C = T\frac{d\mathcal{H}}{dT}$$



EOS: $$\frac{dE}{dT} = C$$

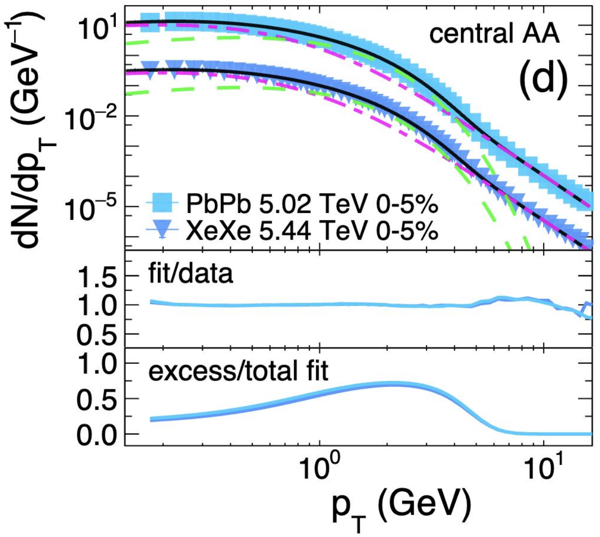


Pion production at ISR energies

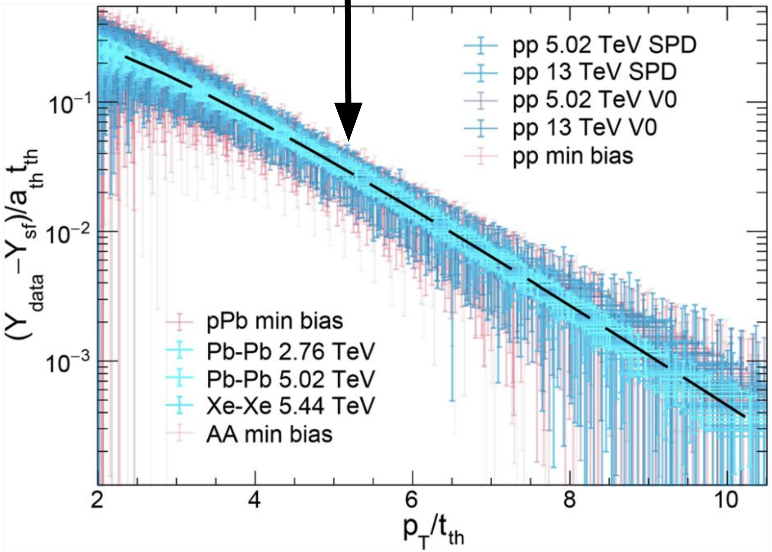


D. Rosales Herrera, et al, Phys. Rev. C 109, 034915 (2024).
J. Alonso, et al, arXiv:2509.14175 (2025).
M. Banner, et al, Phys. Lett. 44B (6), 537 (1973).

Softened hadron production



xexp(-x)



Data reported by ALICE!

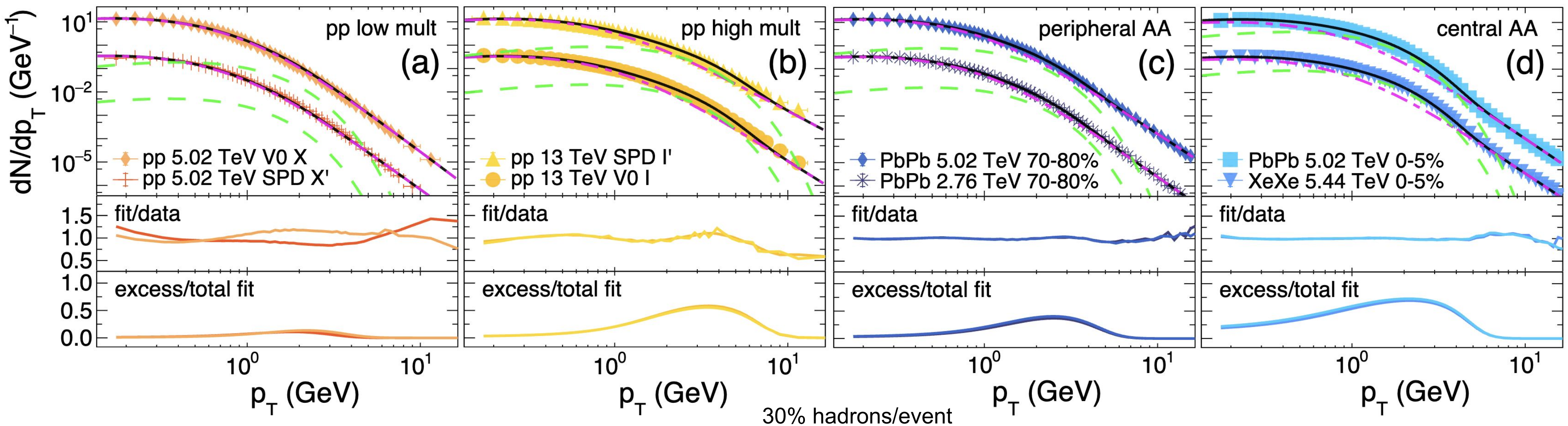
$$\frac{dN}{dp_T^2} = A_U U(a, 1/2, z_0 p_T^2) + A_{th} e^{-p_T/T_{th}}$$

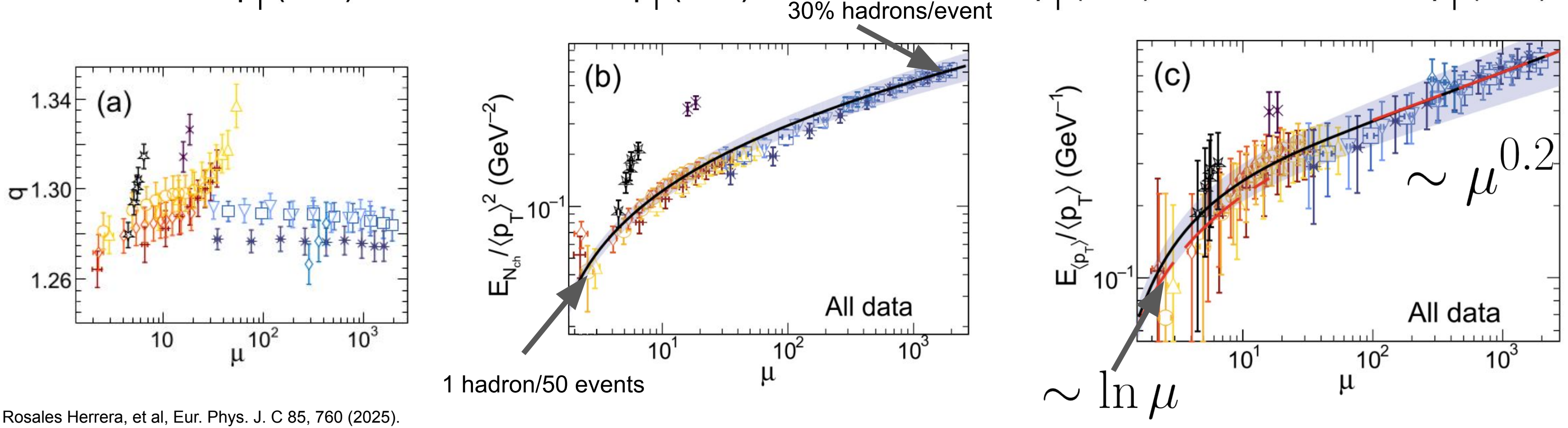
Particle production from collective effects

Particle production coming from string fragmentation

D. Rosales Herrera, et al, Eur. Phys. J. C 85, 760 (2025).
ALICE Collaboration, Phys. Lett. B 845, 138110 (2023).

Softened hadron production

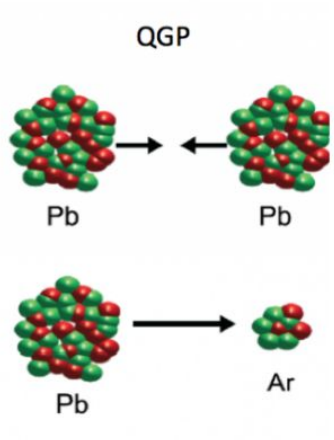




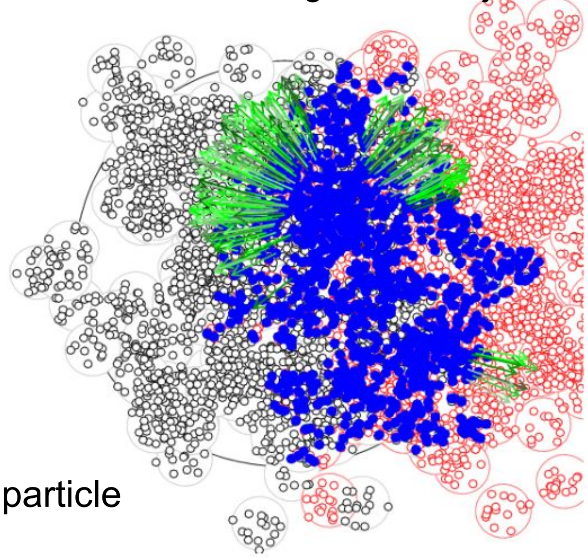
D. Rosales Herrera, et al, Eur. Phys. J. C 85, 760 (2025).

Color String Percolation Model (CSPM)

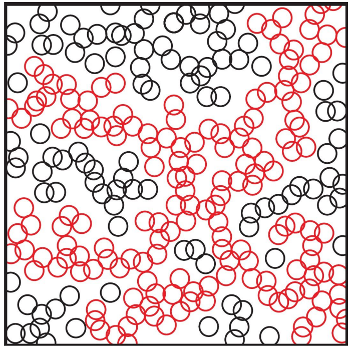
String percolation model



Strings=color objects



Continuum percolation

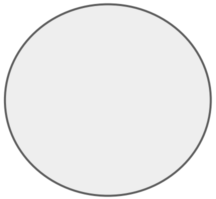


- Strings need to interact for particle production
- Corresponds to the initial state of the system

Chartrchyan et al., Phys. Rev. C, 2013
Feofilov et al., SHEPPXXII, 2015

Phenomenology of the CSPM

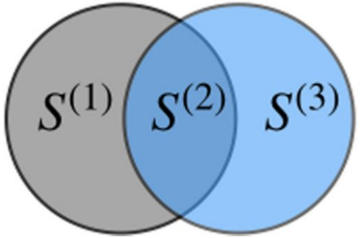
String



Properties

*color field Q0
*Transverse area S1
*Transverse momentu $\langle p_T^2 \rangle_1$
*Multiplicity μ_1

Cluster of two strings



Properties

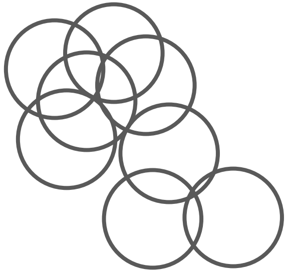
*Independent emission
*Multiplicity:

$$\mu/\mu_1 = 2(S^{(1)}/S_1) + \sqrt{2}(S^{(2)}/S_1)$$

*Transverse momentum:

$$\frac{\langle p_T^2 \rangle}{\langle p_T^2 \rangle_1} = \frac{2(S^{(1)}/S_1) + \sqrt{2}\sqrt{2}(S^{(2)}/S_1)}{2(S^{(1)}/S_1) + \sqrt{2}(S^{(2)}/S_1)}$$

Cluster of n strings



*Multiplicity:

$$\mu_n = \sqrt{\frac{nS_n}{S_1}}\mu_1,$$

*Transverse momentum:

$$\langle p_T^2 \rangle_n = \sqrt{\frac{nS_1}{S_n}}\langle p_T^2 \rangle_1$$

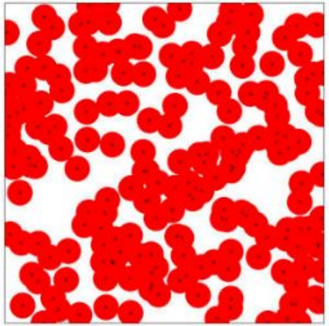
$$\mu = NF(\eta)\mu_1,$$

$$\langle p_T^2 \rangle = \frac{\langle p_T^2 \rangle_1}{F(\eta)}.$$

with

$$F(\eta) = \sqrt{\frac{\phi(\eta)}{\eta}}$$

$$\phi(\eta) = 1 - e^{-\eta}$$

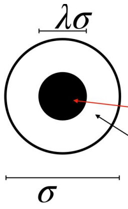


Percolation: Covered area by disks

Braun and Pajares, EPJC 16, 349 (2000)

Origins of the temperature fluctuations

Structure of the QGP for interacting color strings



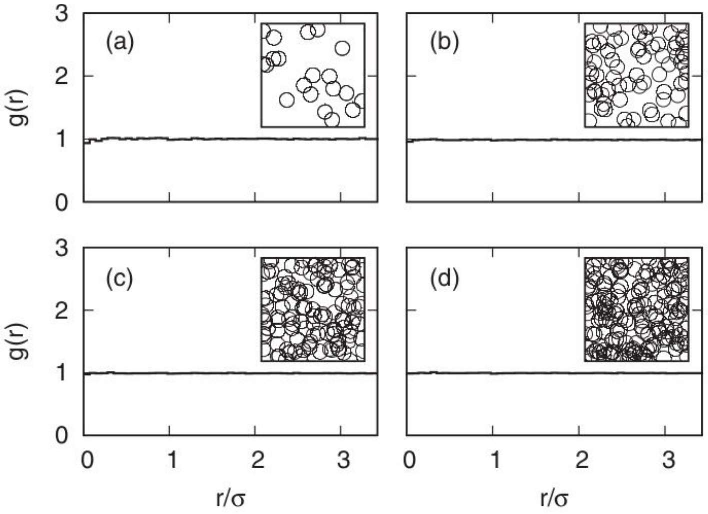
$0 < \lambda < 1$

Hard-core

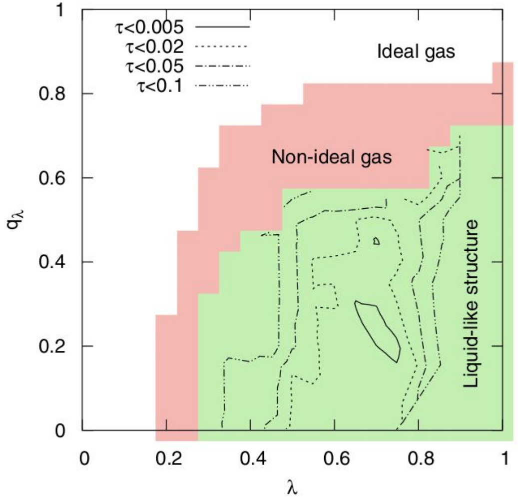
Overlapping region

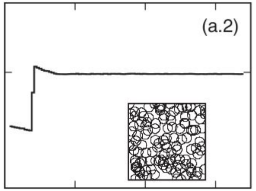
q_λ Probability of core-core interaction

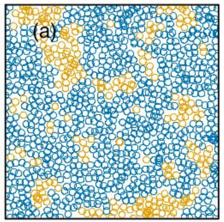
Structure of the QGP (fully overlapping string)

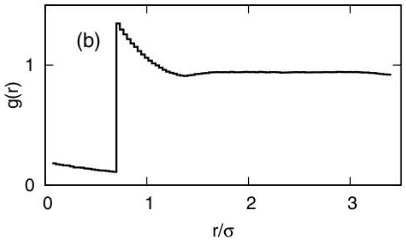


Ideal gas!!







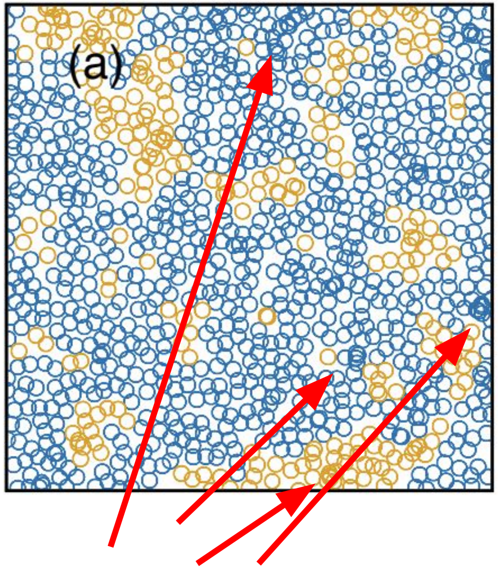


$$|T_c - T_c^*| < 1 \text{ MeV}$$

JE Ramírez et al, PRD, 094029 (2021)

Origins of the temperature fluctuations

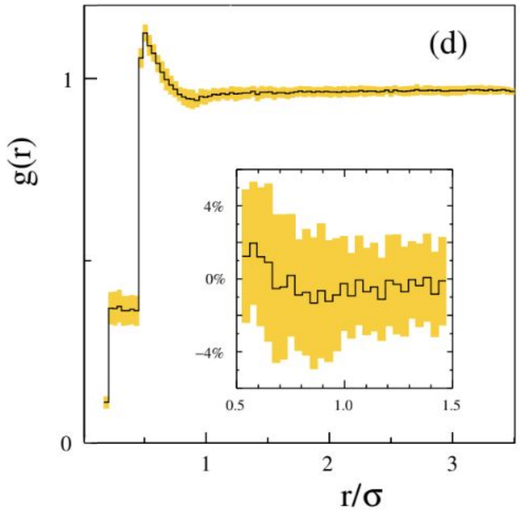
Percolation (of interacting color strings)



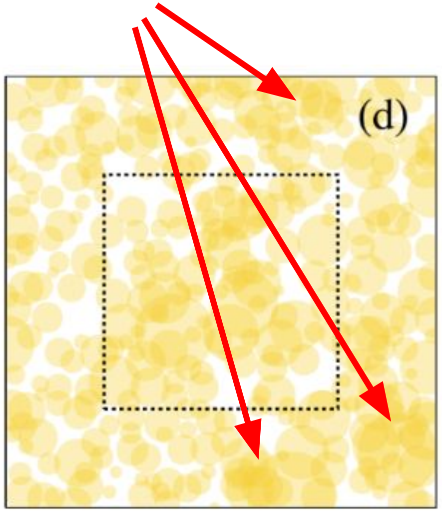
HOT SPOTS

JE Ramírez et al, PRD, 094029 (2021).
J.R. Alvarado García, et al, Universe 9, 291 (2023).

Color Glass Condensate



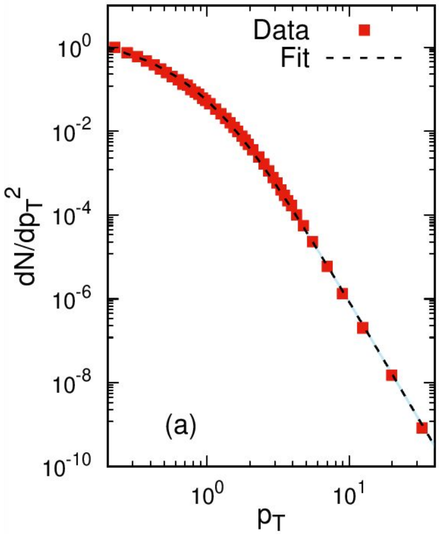
HOT SPOTS



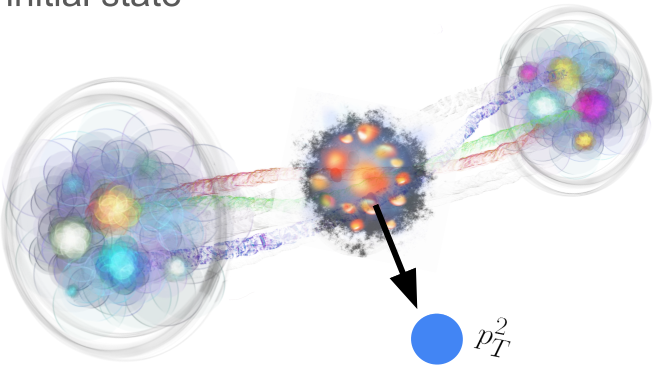
Fluctuating saturation scale (QS^2)
Central PbPb at 5.02 TeV

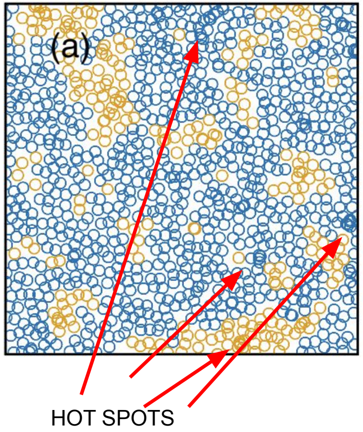
R. Venugopalan, et al, PRL, 108, 262001 (2012),
L. McLerran, et al, Nucl. Phys. A, 945, 216 (2016).

Concluding remarks



- A nonextensive description is required to accurately describe the pT spectrum
- The system created in ultrarelativistic collisions is out of equilibrium
- Source of fluctuations:
  - fluctuations in the intensity of color interactions
  - anisotropies of the initial state





Thank you

12.4 The phenomenological implications of the tunnelling process

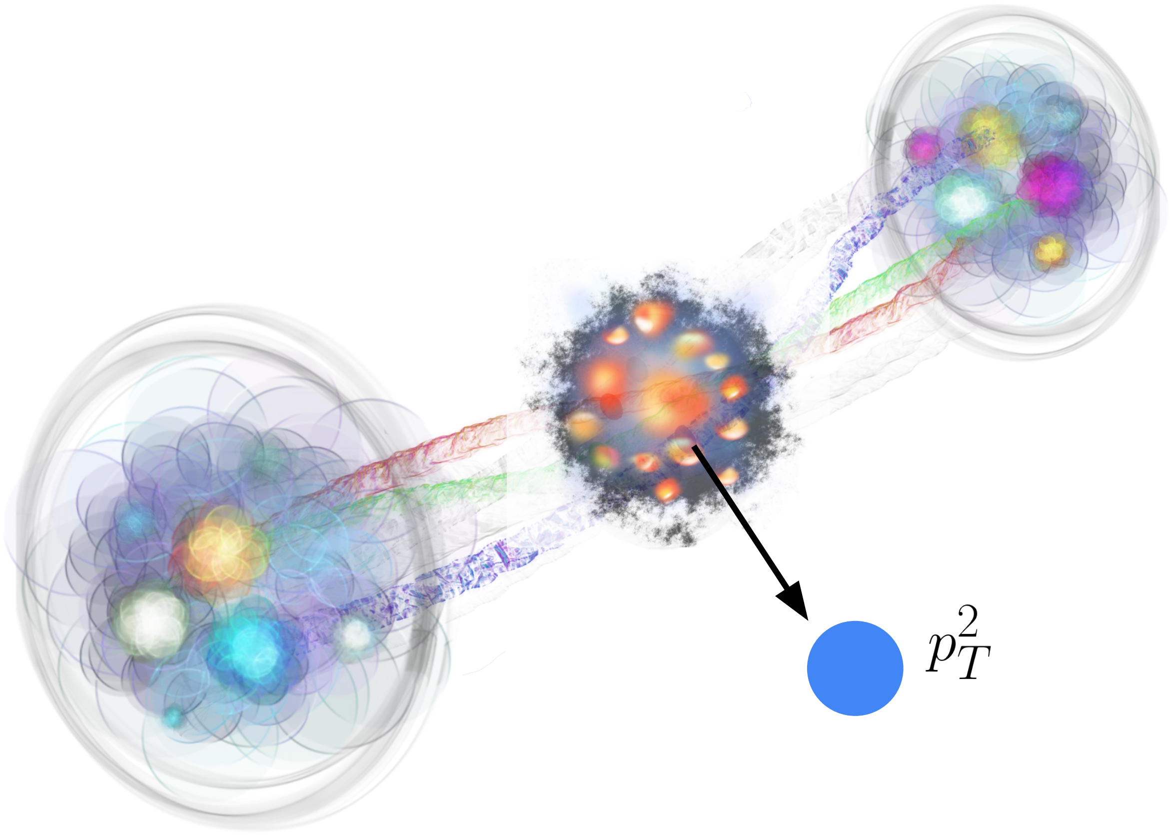
1 *The production of heavy flavors*

The results derived above are compatible with the WKB results, i.e. they are equivalent to Schwinger's result for the decay of the no-particle vacuum in the presence of an external electric field. We obtain for the $q\bar{q}$ production rate, with μ the mass and $\pm\mathbf{k}_\perp$ the transverse momenta of the pair,

$$dP \simeq d^2k_\perp \exp(-\pi E_\perp^2/\kappa), \quad E_\perp^2 = \mathbf{k}_\perp^2 + \mu^2 \tag{12.28}$$

The result in Eq. (12.28) has several different consequences.

The first is related to the relative abundance of different flavors in the fragmentation process. It is difficult to obtain precise mass-values for the unobservable $q\bar{q}$-particles but it is possible to obtain estimates.


p_T^2