Hadroproduction in high energy collisions

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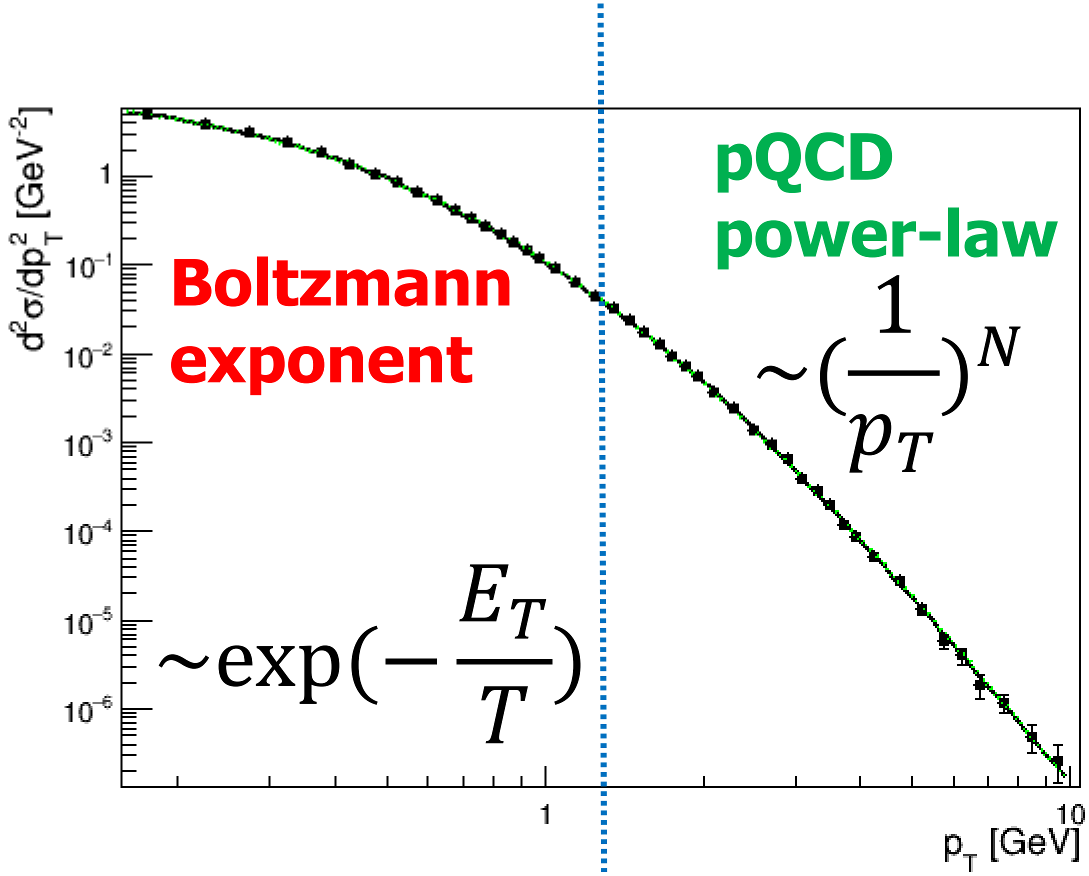
25th International Workshop on Deep Inelastic Scattering and Related Topics
3-7 April, Birmingham, United Kingdom

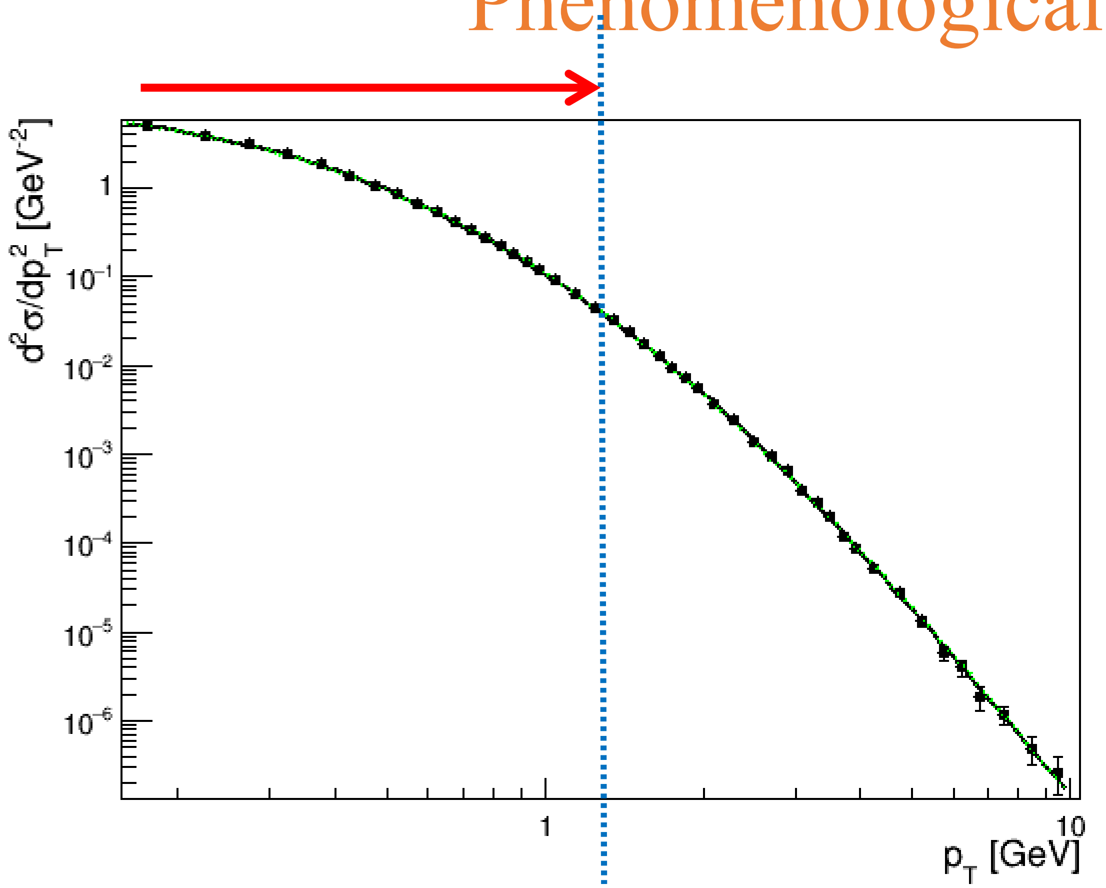
Outline

- Particle production spectra and phenomenological models
- New two component model and detailed study of spectra variations with:
  - Type of the collisions
  - Type of the produced particle
  - Energy of the collision
  - Multiplicity
  - Pseudorapidity
- Predictions from the two component model

Particle production spectra

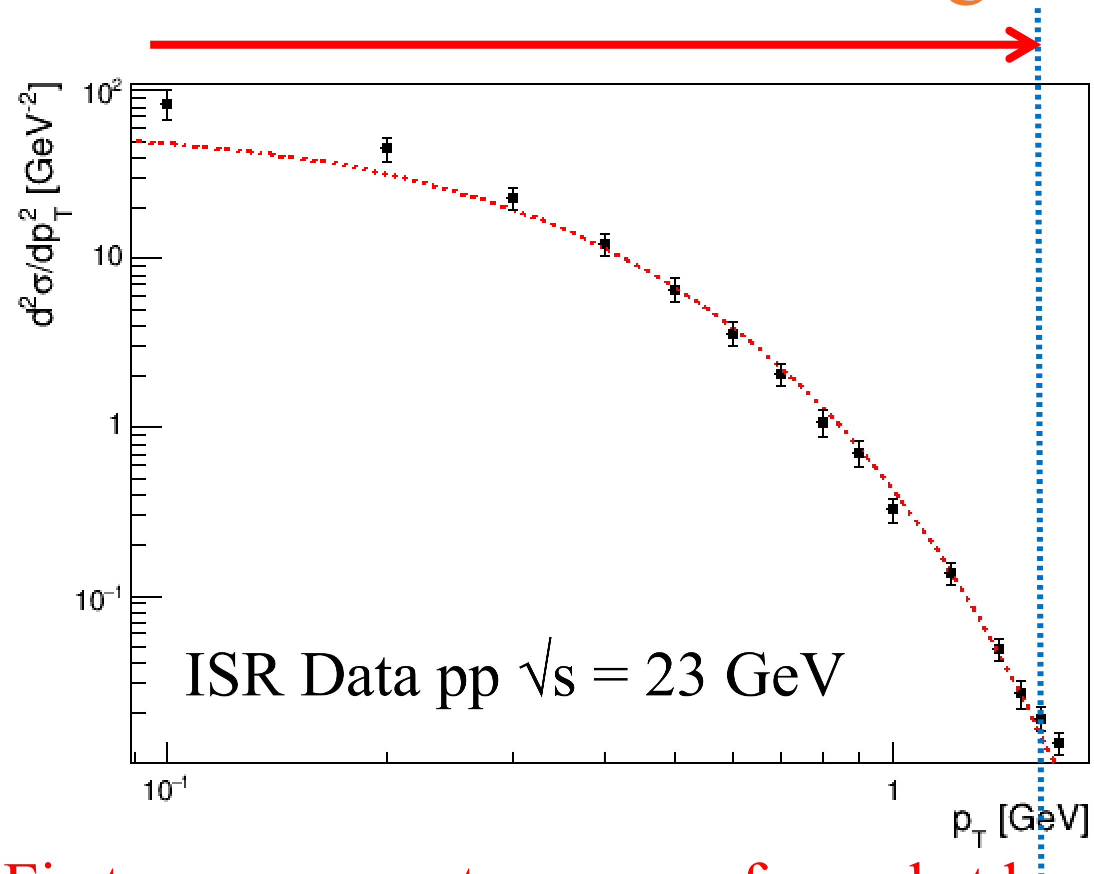


Particle production spectra:
Phenomenological models



First measurements were performed at low collision energies and in the limited kinematic region *(p_T < 1-2 GeV)* only.

Particle production spectra: Phenomenological models



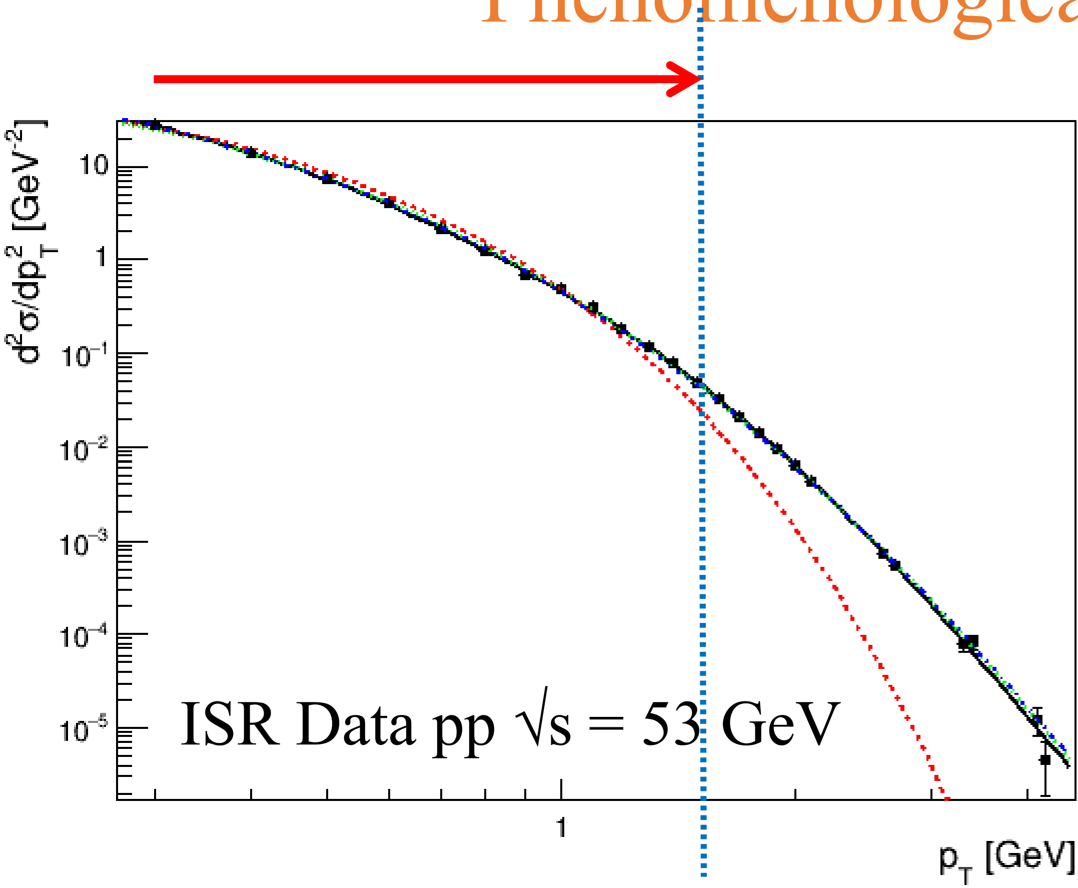
1952 E. Fermi

$$\sim \exp(-\frac{E_T}{T})$$

First measurements were performed at low collision energies and in the limited kinematic region *(p_T < 1-2 GeV)* only.

Experimental data could be fairly well described by the statistical approach.

Particle production spectra: Phenomenological models



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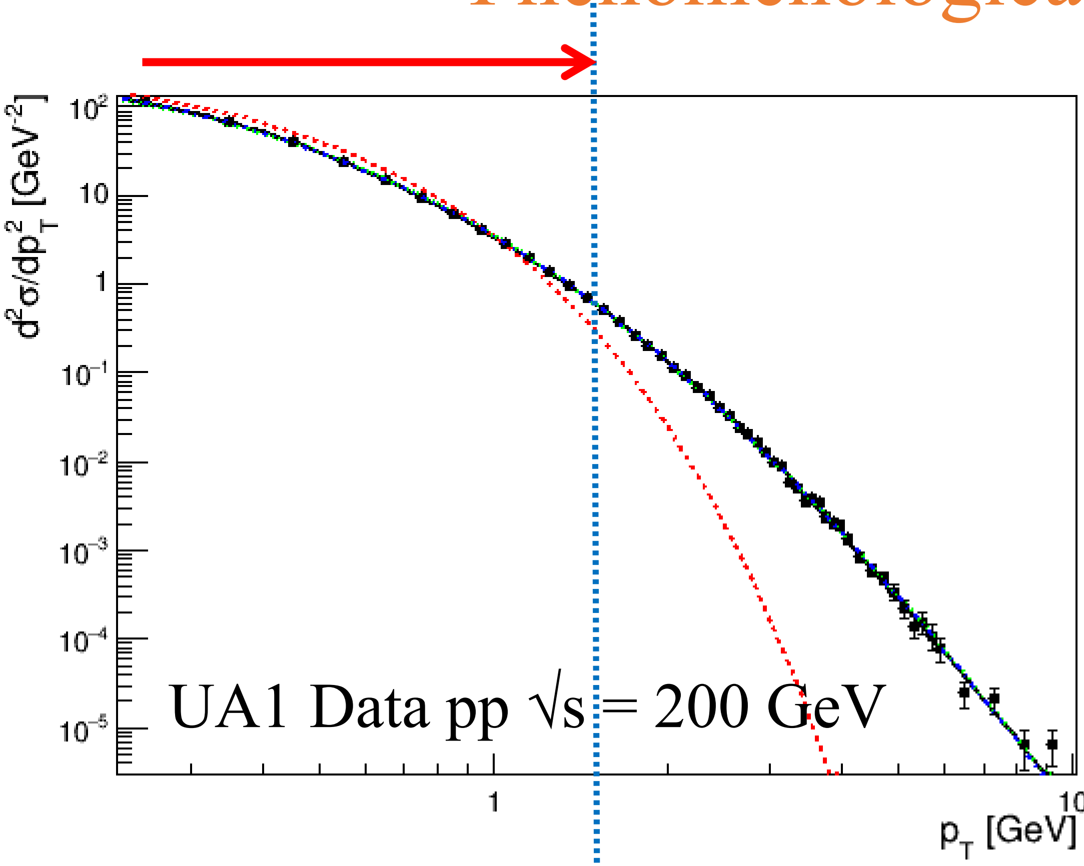
Further measurement have shown that high-pt particles observe different hadroproduction dynamics (pQCD power-law).

Modification of the statistical approach was necessary.

Particle production spectra: Phenomenological models



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$$\sim \exp\left(-\frac{E_T}{T}\right)$$

1983 R. Hagedorn

$$\sim \left(\frac{p_0}{p_0 + p_T}\right)^N$$

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$$\sim \left(\frac{1}{1 + \frac{E_T}{T \cdot N}}\right)^N$$

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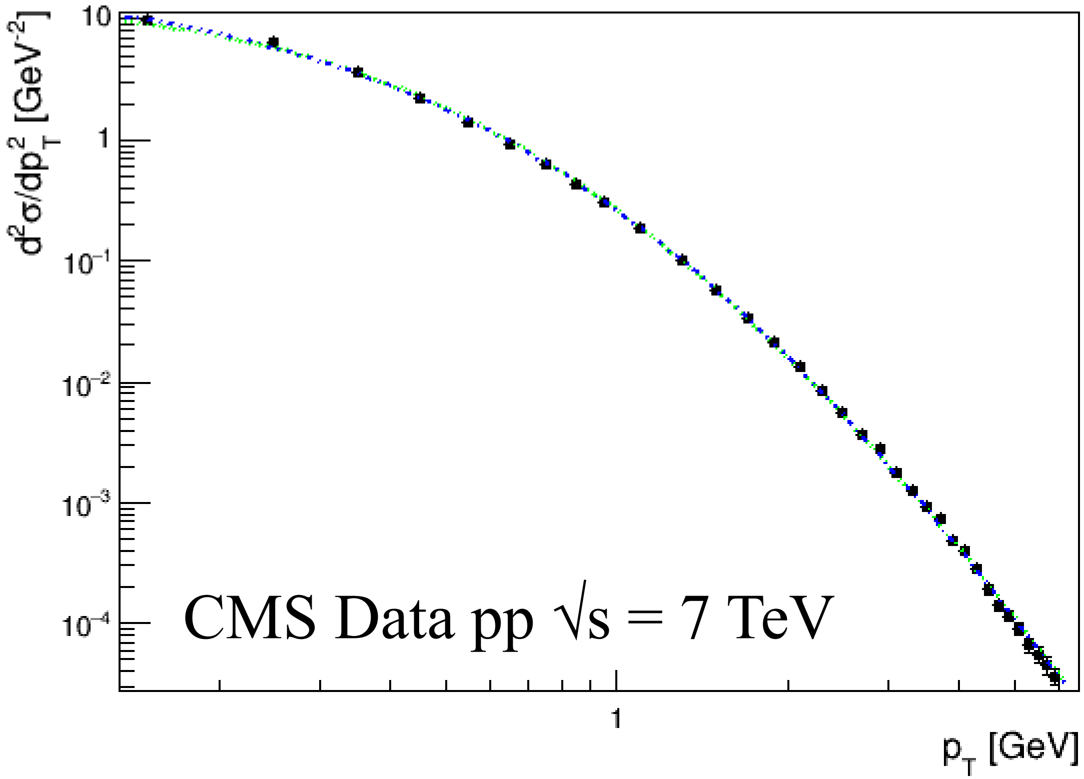
Modification of the statistical approach was necessary.

Tsallis and Hagedorn parameterizations combining exponential and power-law behaviors appeared.

Particle production spectra: Phenomenological models



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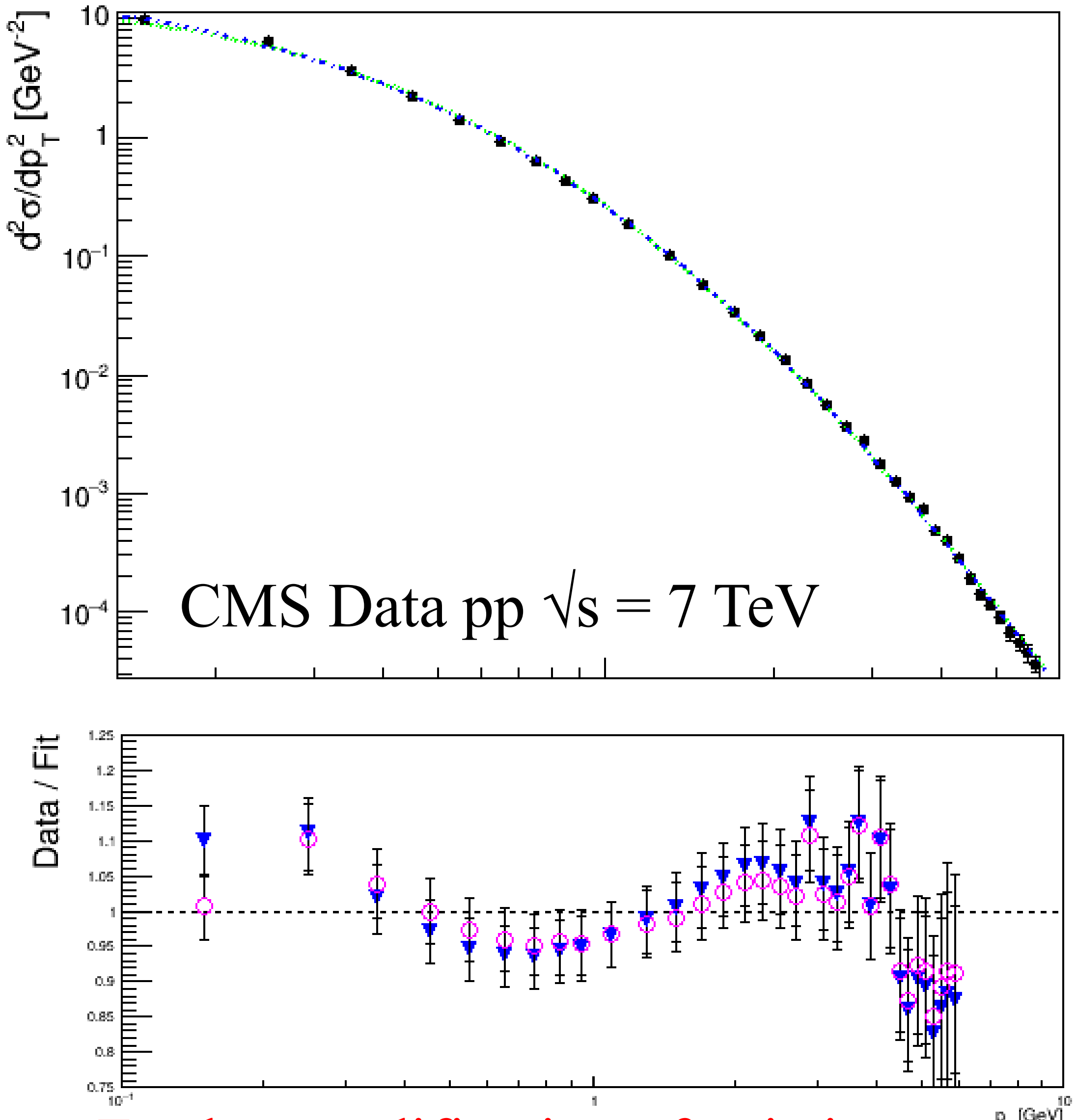
2010 ???

Particle production spectra: Phenomenological models



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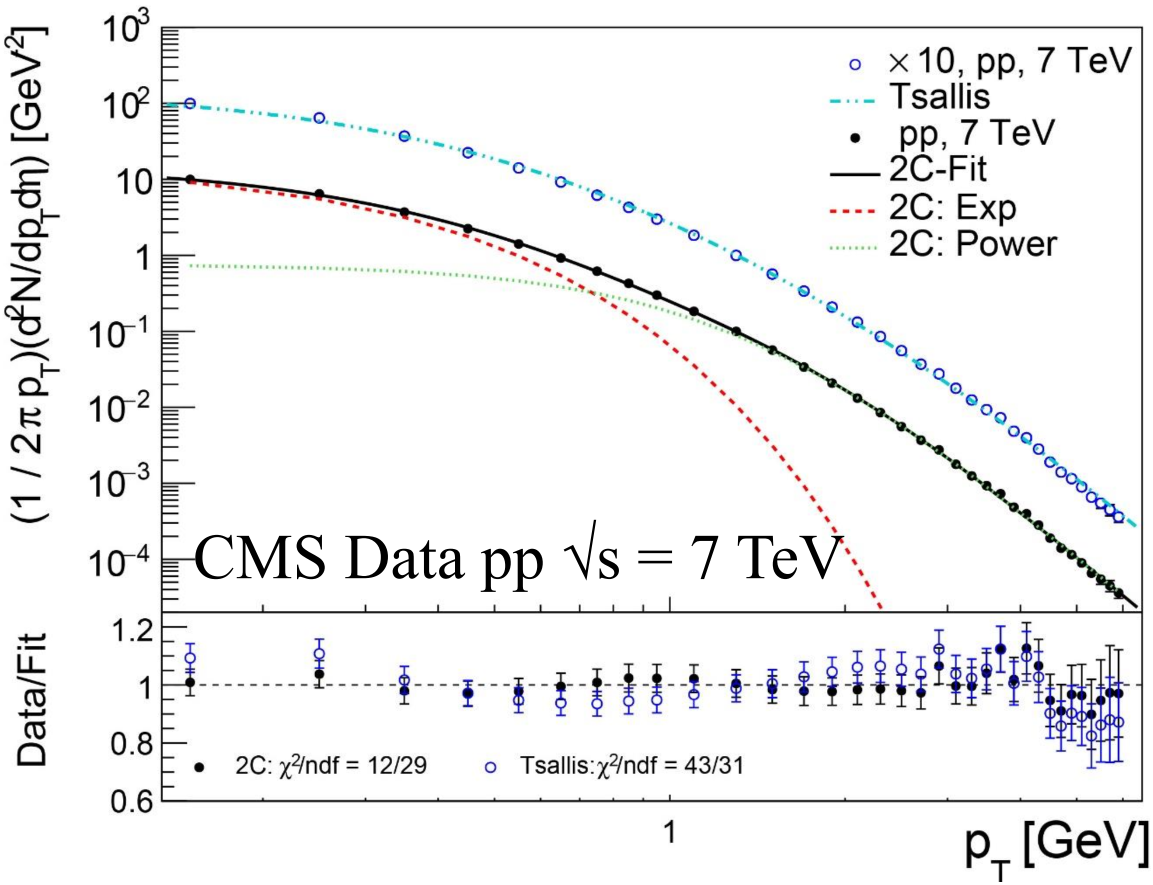
2010 ???

Further modification of existing approaches is needed.

Particle production spectra: Phenomenological models



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2010 A. Bylinkin & A. Rostovtsev

$$\frac{d^2\sigma}{\pi dy(dp_t^2)} = A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1 + \frac{P_T^2}{T^2 N})^N}$$

Not just increased number of free parameters

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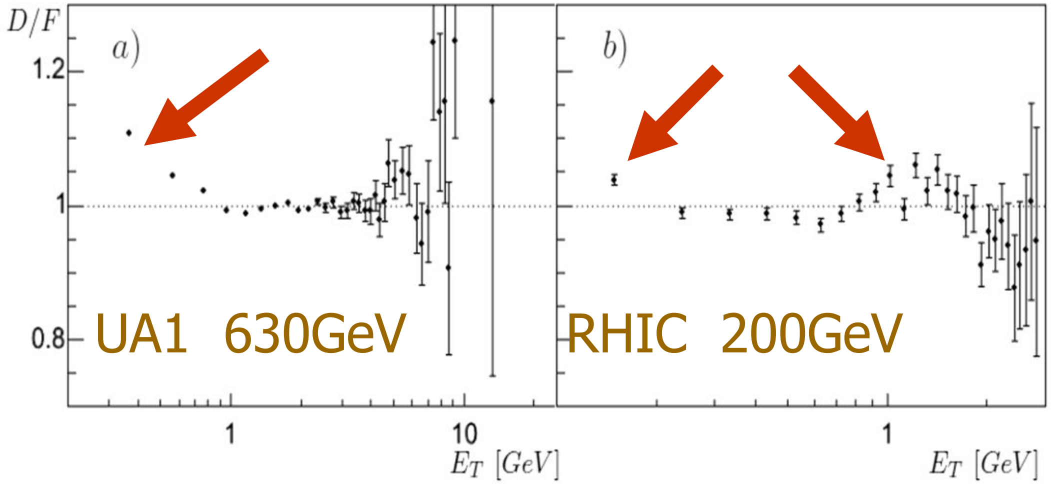
Systematic defects with traditional approach in <u>all</u> datasets

Experimental data divided over the values of the fit function in corresponding points



χ^2/ndf = 288/44 **χ^2/ndf = 87/25**

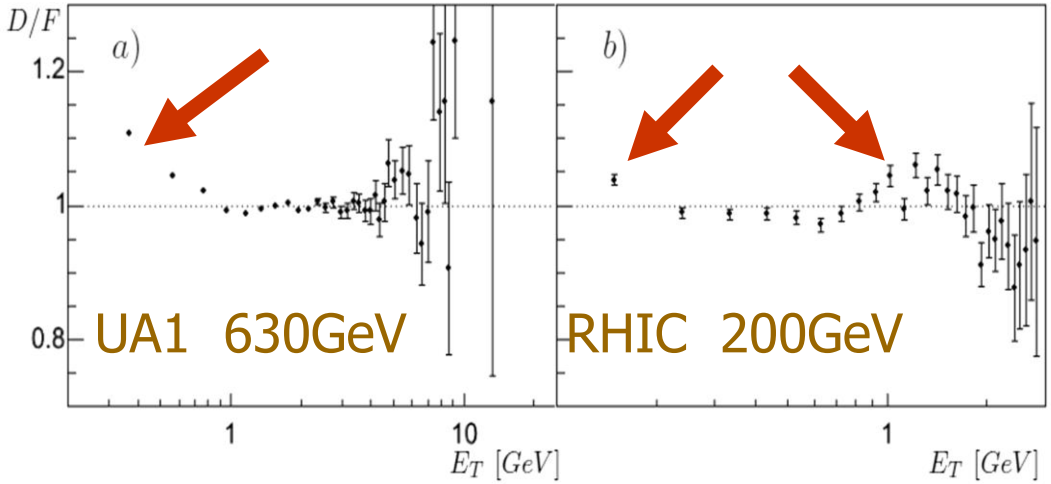
Tsallis fit

$$\frac{A}{\left(1+\frac{E_{Tkin}}{T*N}\right)^{N}}$$

Not just increased number of free parameters

Systematic defects in the data description using traditional approach

Experimental data divided over the values of the fit function in corresponding points



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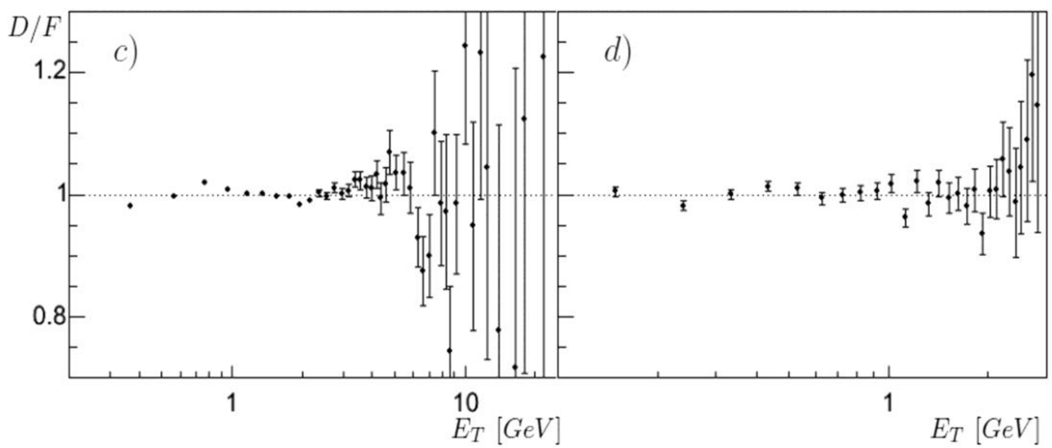

χ^2/ndf = 54/42 **χ^2/ndf = 22/23**

Tsallis fit

$$\frac{A}{(1+\frac{E_{Tkin}}{T*N})^N}$$

New approach

$$A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1+\frac{P_T^2}{T^2 N})^N}$$

A. Bylinkin and A. Rostovtsev
Phys. Atom. Nucl 75 (2012) 999-1005

New approach provides much better description of the data.

Two components $\longleftrightarrow$ Two mechanisms

$$\frac{d^2\sigma}{\pi dy(dp_t^2)} = A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1+\frac{P_T^2}{T^2N})^N}$$

Two components ↔ Two mechanisms

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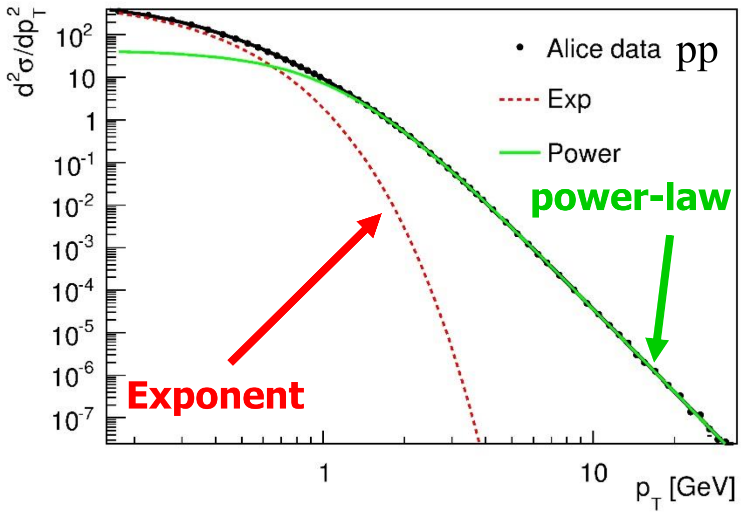

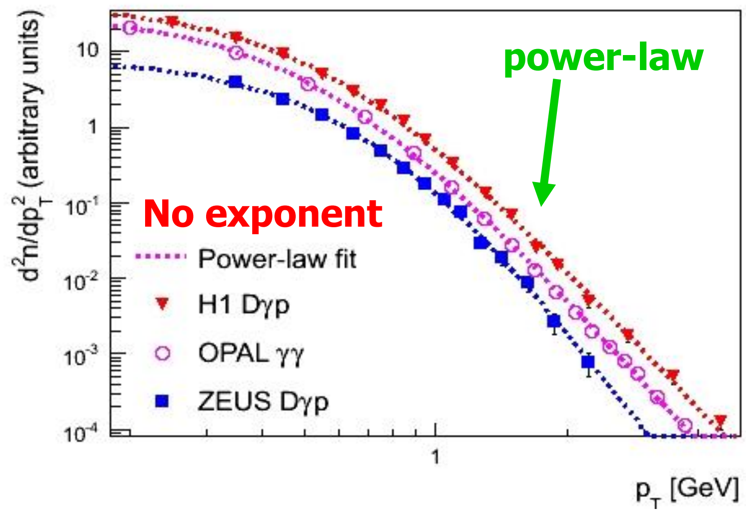

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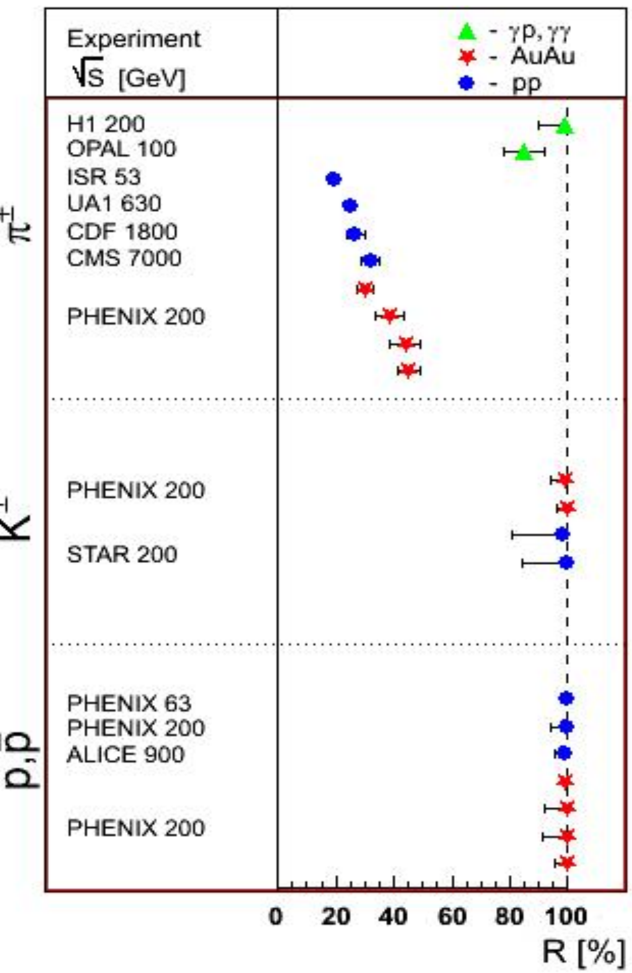
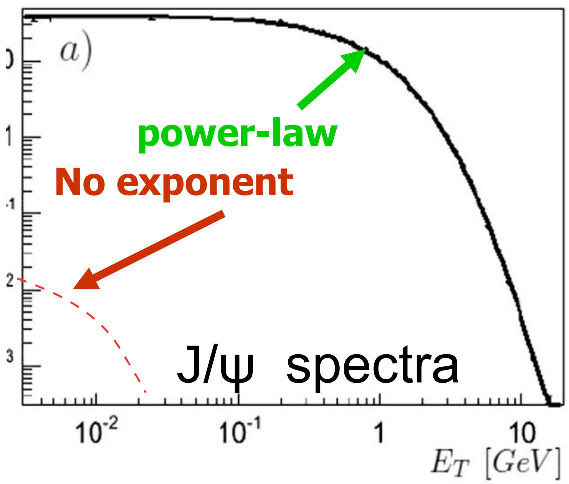
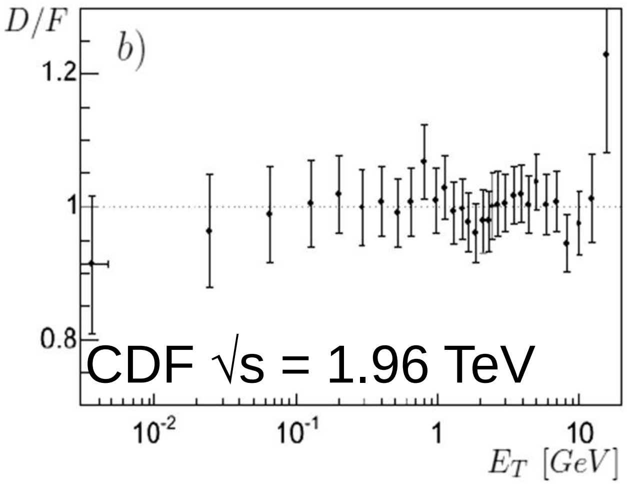
$$\frac{d^2\sigma}{\pi dy(dp_t^2)} = A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1+\frac{P_T^2}{T^2 N})^N}$$

$$R = \frac{\text{Power-law}}{\text{Exp + Power-law}}$$







Exponential contribution is related to the thermalized partons preexisted long before the interaction

Power-law contribution is related to the QCD vacuum fluctuations described by exchange of Pomerons

Two components $\longleftrightarrow$ Two mechanisms

$$\frac{d^2\sigma}{\pi dy(dp_t^2)} = A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1+\frac{P_T^2}{T^2 N})^N}$$

Two components behave differently as a function of experimental setup:

calculated separately for exponential and power-law terms

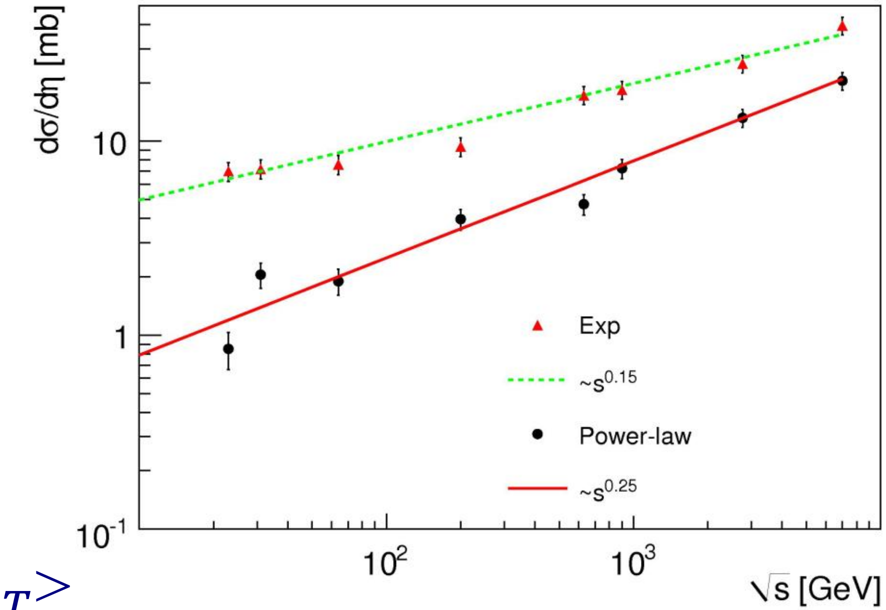
- Charged particle densities dσ/dη
- Mean transverse momenta $<p_T>$

- Collision energy, $\sqrt{s}$
- Charge particle multiplicity, N_{ch}
- Pseudorapidity region, η

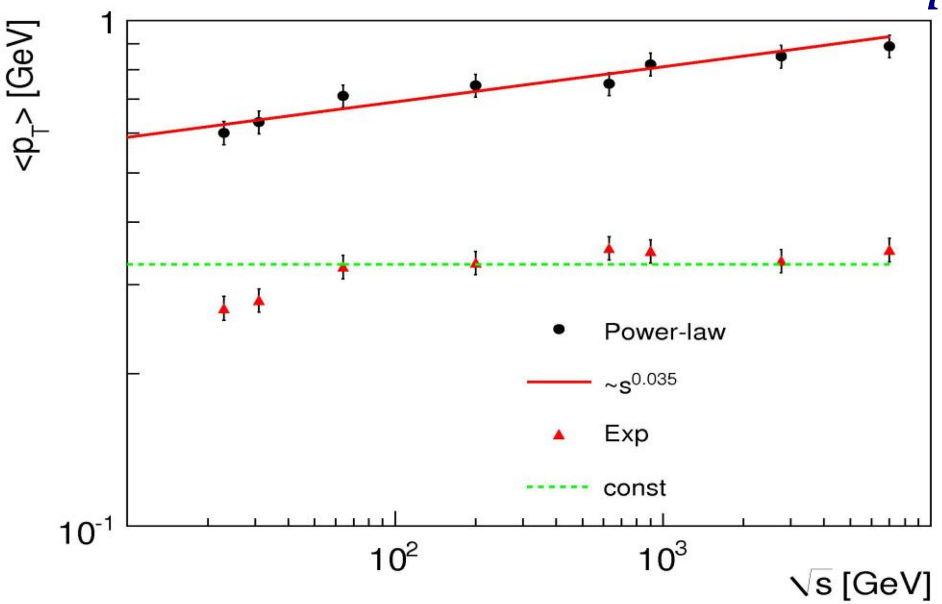
Energy dependences

Charged particle densities dσ/dη grow with energy $\sim s^{\Delta}$:

- **Power-law:** **Δ~0.25**
  the pQCD (BFKL) pomeron after the resummation of the NLL corrections.
- **Exponent: Δ~0.15**
  strongly affected by absorptive corrections.



Mean transverse momenta $<p_T>$

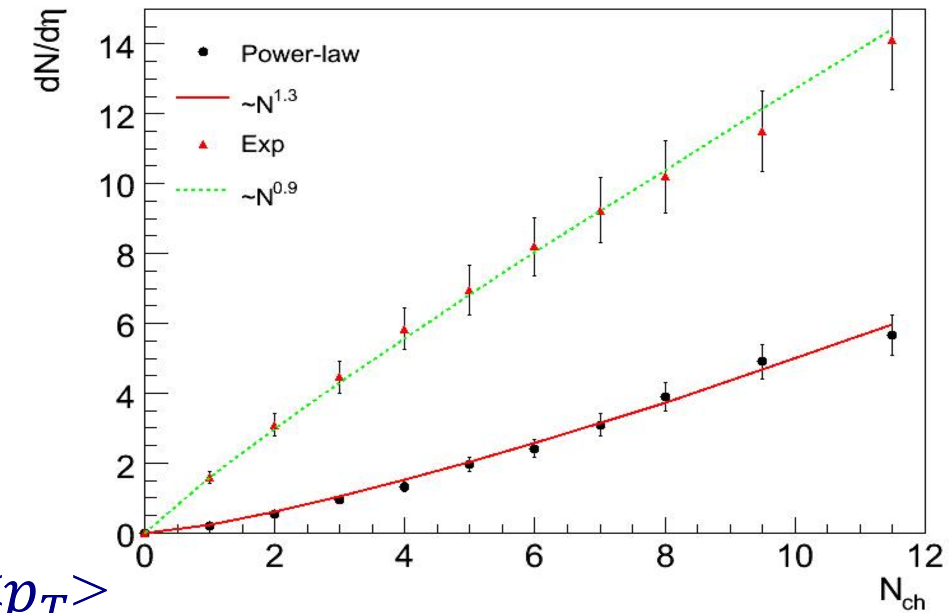


- **Power-law:** $\boldsymbol{\sim s^{0.05}}$
  growth of the typical transverse momenta of mini-jets
- **Exponent:** **constant**

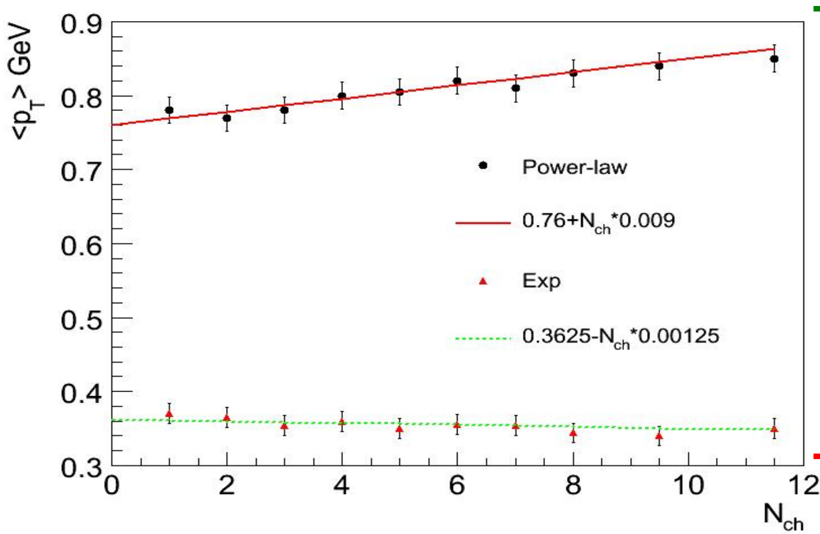
Multiplicity dependences

Charged particle densities dσ/dη:

Charge multiplicity is proportional to the number of 'cut' pomerons involved.
→ the contribution from the **power-law** component (mini-jets) **grows faster** than that from the **exponential** one



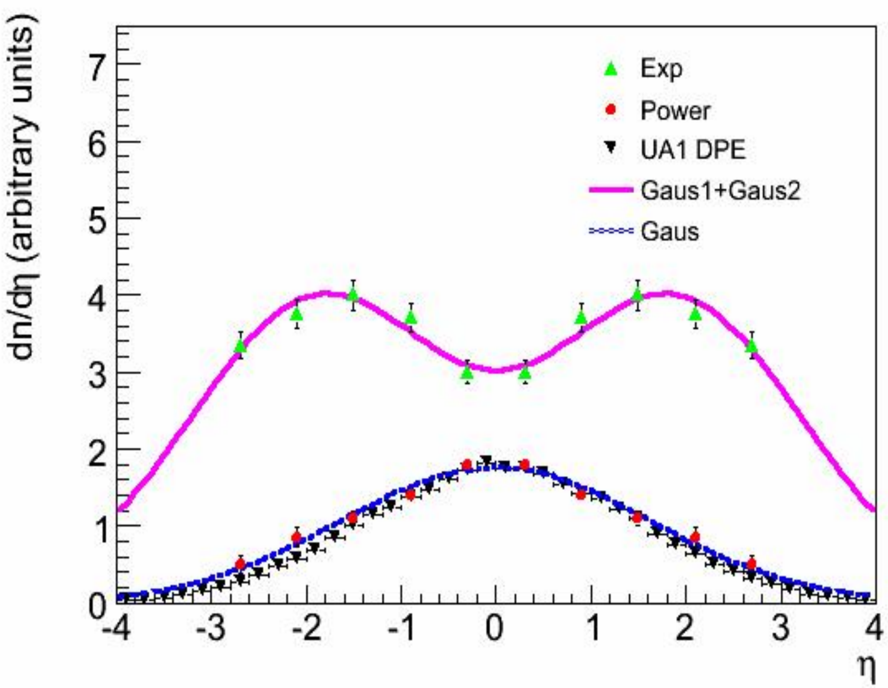
Mean transverse momenta $<p_T>$

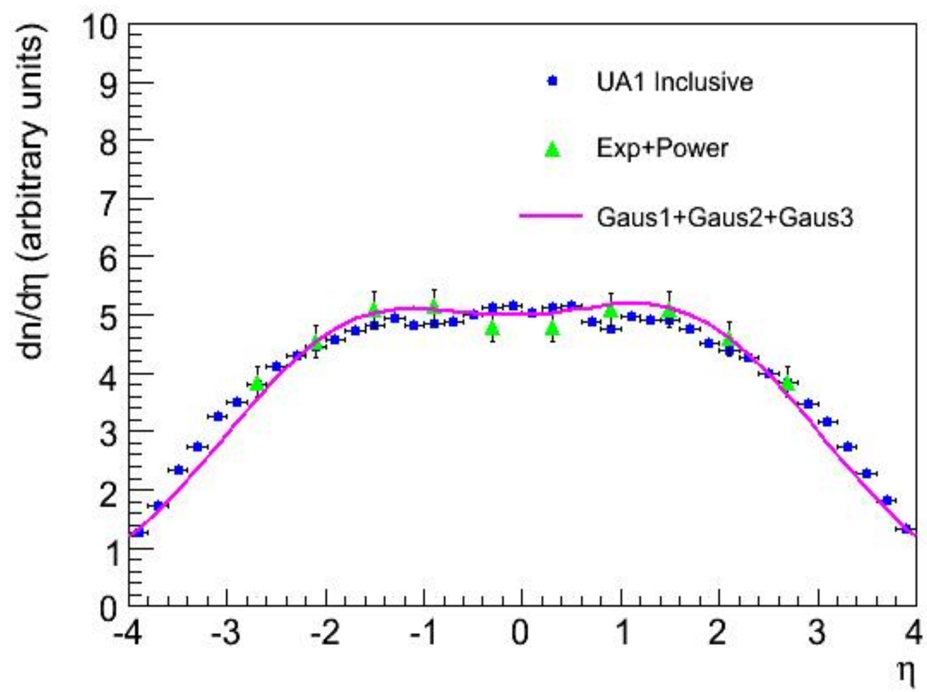


- **Power-law:** Within the Regge theory the higher multiplicity events have a larger number, n, of 'cut' pomerons (Nch ~ n). Accounting for mini-jet contribution the $<p_T>$ should increase with Nch since **another way to enlarge multiplicity is to produce mini-jets with larger E_T.**
- **Exponent: constant**

Pseudorapidity distributions

Hadrons produced via the **mini-jet fragmentation** should be concentrated in the **central rapidity region (η~0)**, while those coming from the **proton fragmentation** are expected to dominate at **high values of η** due to non-zero momenta of the initial partons along the beam-axis.





Gaussian distribution for Double Pomeron Exchange (DPE) events
Sum of **THREE Gaussians** for Minimum Bias (MB) events *in pp-collisions*
→existence of plateau in a pseudorapidity distribution

Parameter dependences

$$A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1 + \frac{P_T^2}{T^2 N})^N}$$

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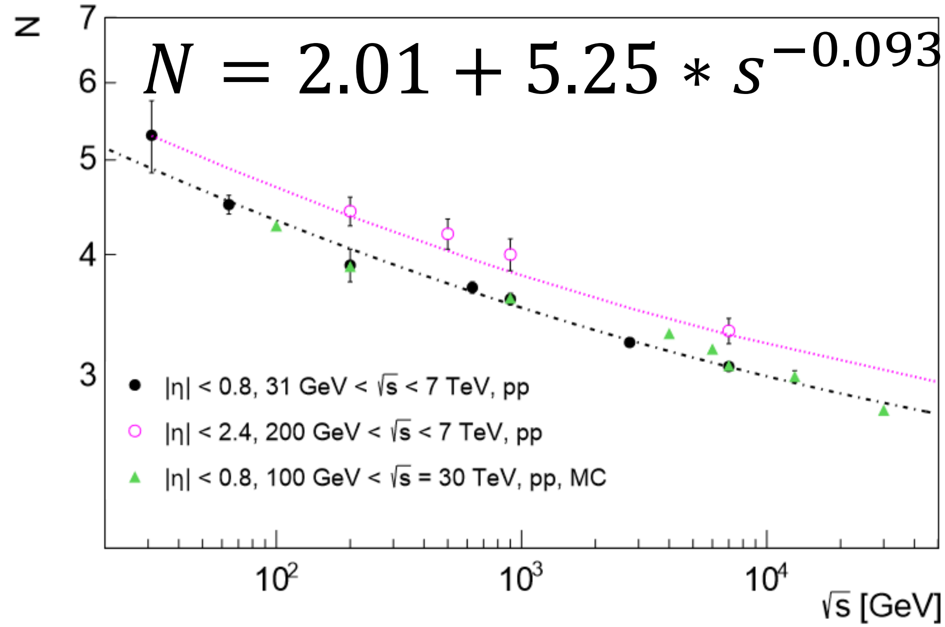
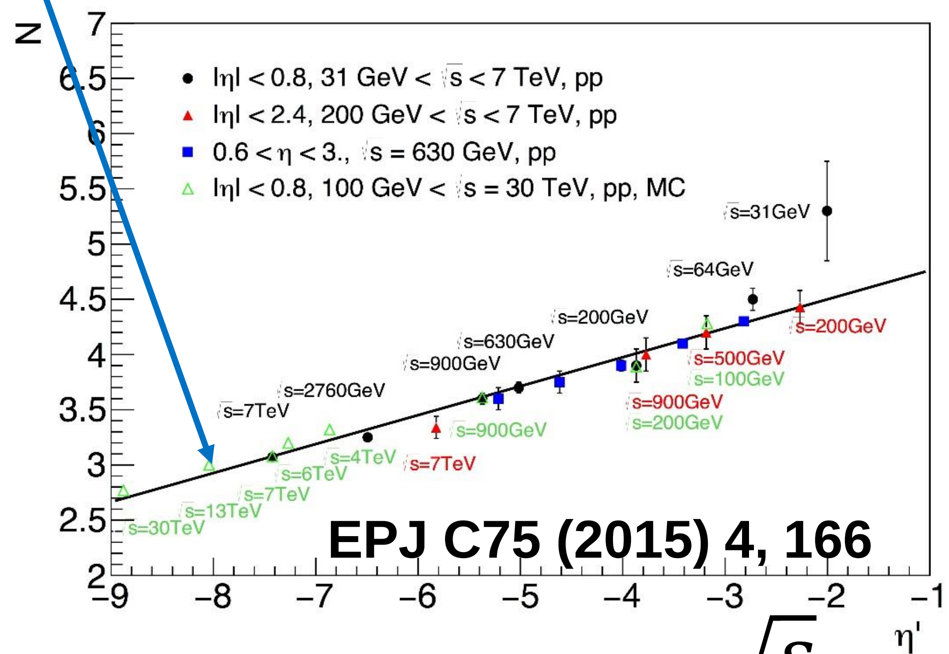


Remarkably, in the s →∞ limit N → 2, which corresponds to $d^2\sigma/dp_T^2 \propto 1/p_T^4$ in the proposed parametrization.
Such behaviour can be expected just from dimensional counting in pQCD.

Universal dependence

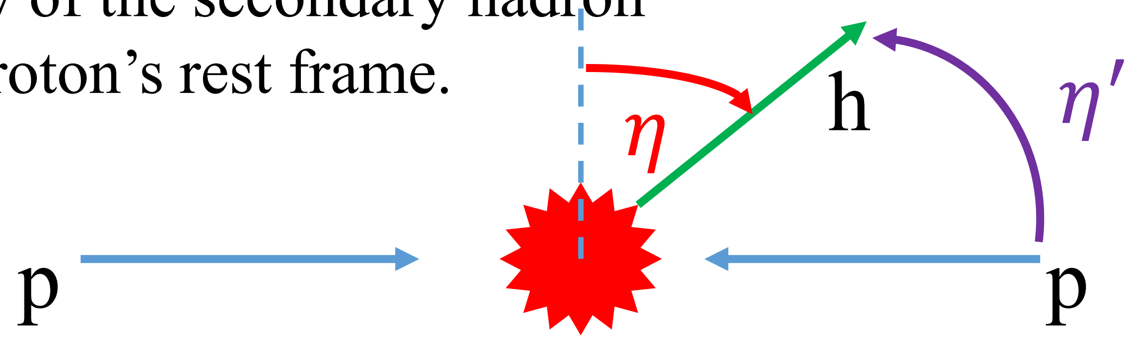
$$A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1+\frac{P_T^2}{T^2 N})^N}$$



A. Bylinkin *et. al.* **EPJ C75 (2015) 4, 166**

$$\eta' = |\eta| - \log(\frac{\sqrt{s}}{2m_p})$$

Pseudorapidity of the secondary hadron in the initial proton's rest frame.



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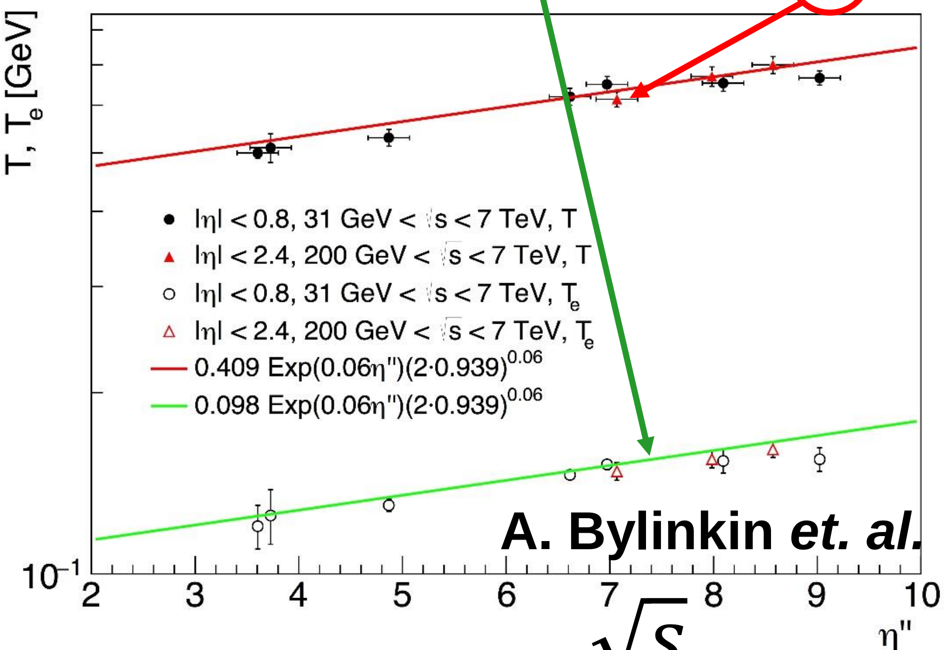
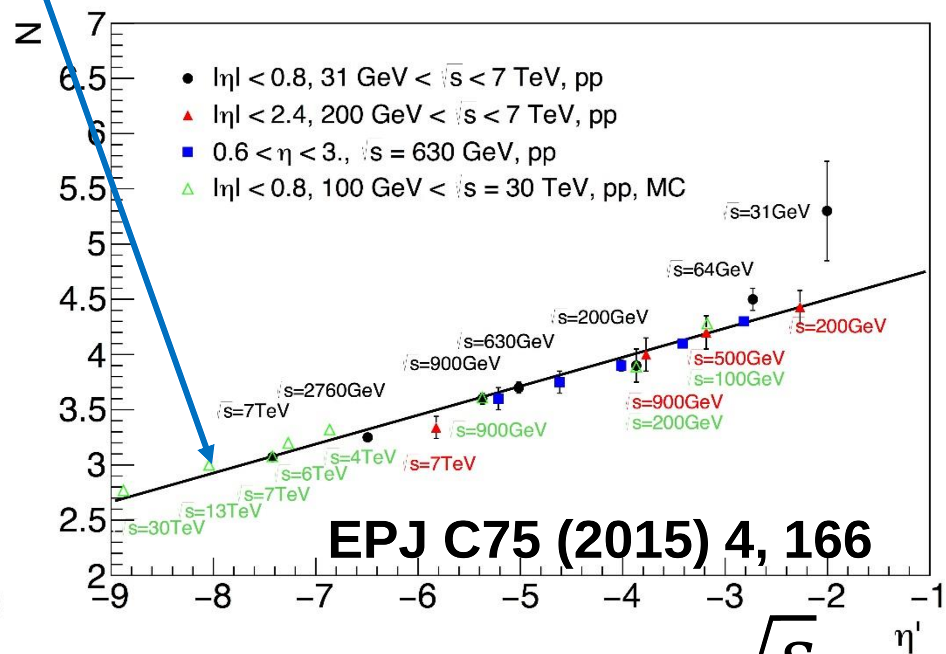
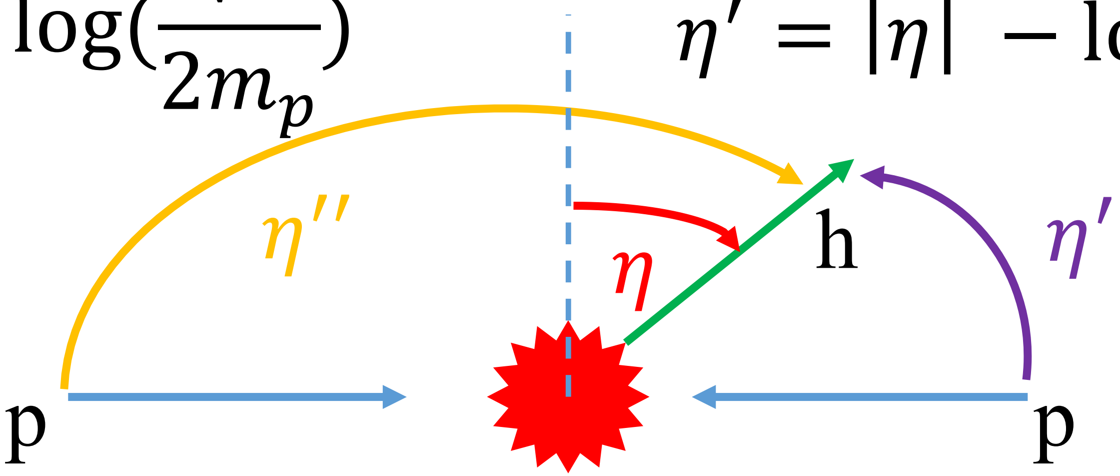


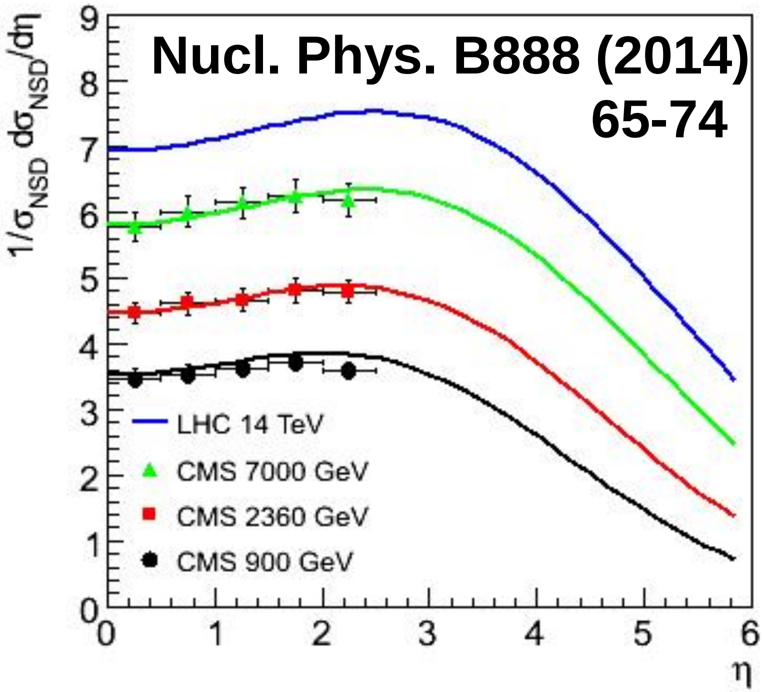


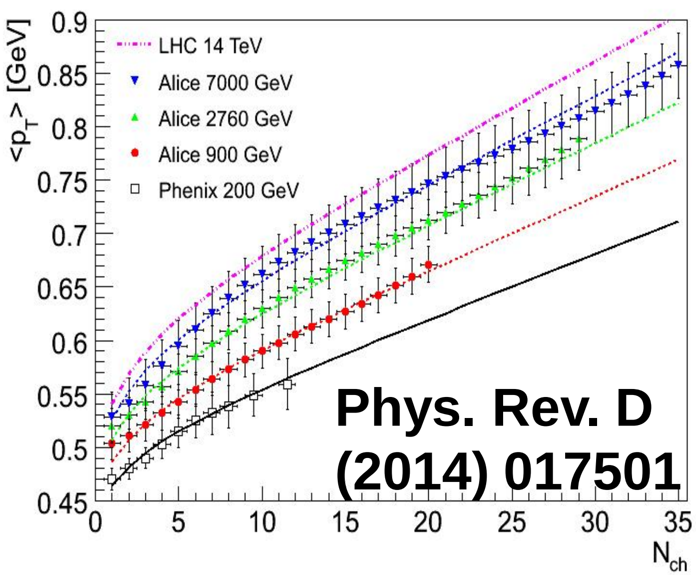
$$\eta'' = |\eta| + \log(\frac{\sqrt{s}}{2m_p})$$

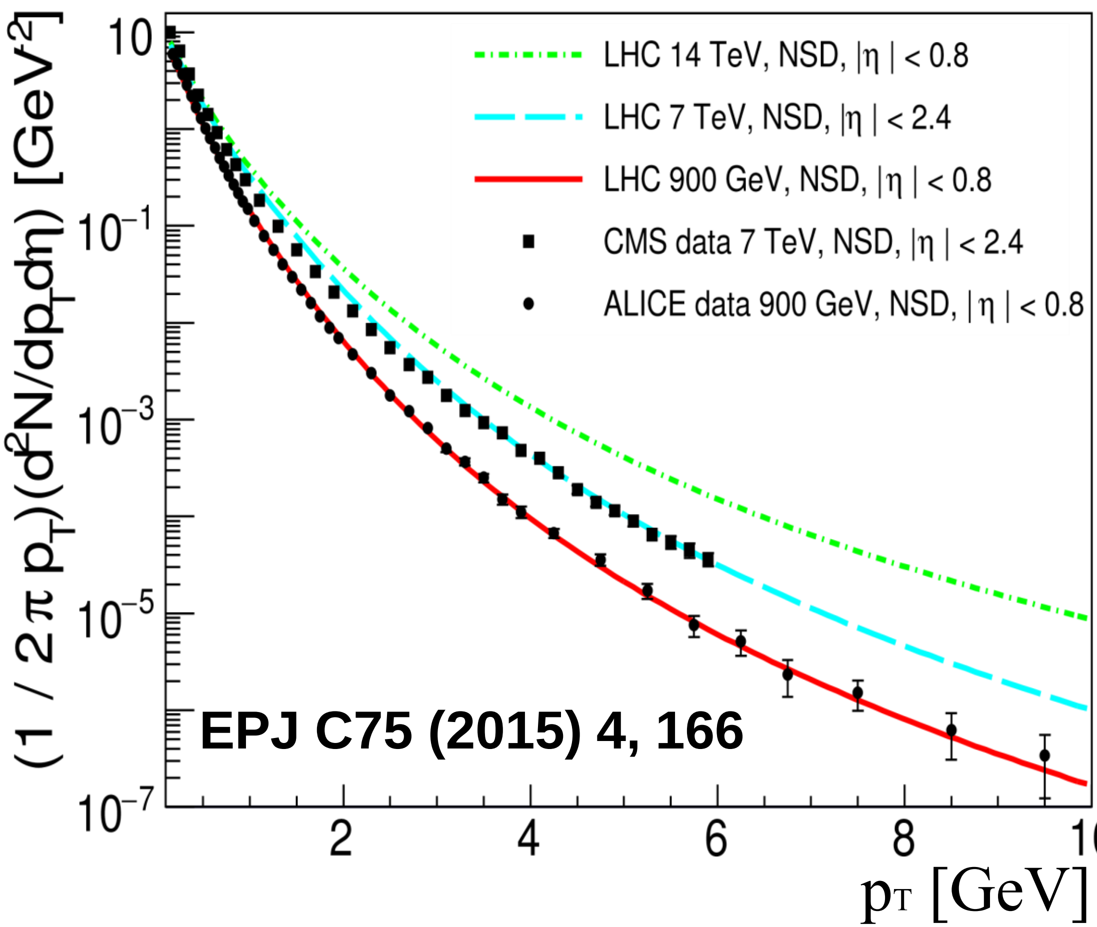
$$\eta' = |\eta| - \log(\frac{\sqrt{s}}{2m_p})$$



Predictions of the model







Very good agreement between the available experimental data and the predictions of the model for η distributions, <p_T> as a function of multiplicity and transverse momentum spectra is observed.

Conclusions

- The two component model for hadroproduction has been introduced
- It was shown to provide the best description of the available experimental data in comparison with other models
- Two components stand for two distinct mechanisms of hadroproduction
- Pseudorapidity of a secondary hadron in the initial's proton rest frame is found to be a universal parameter to describe the shape of the spectra
- Predictions on the pseudorapidity distributions, mean transverse momenta as a function of multiplicity and transverse momentum spectra were made and tested on the available experimental data

Many thanks to my co-authors: A. Rostovtsev, M. Ryskin, D. Kharzeev and N. Chernyavskaya

Thank you for your attention!

Additional slides

Two component model

Best fit to experimental data ✓

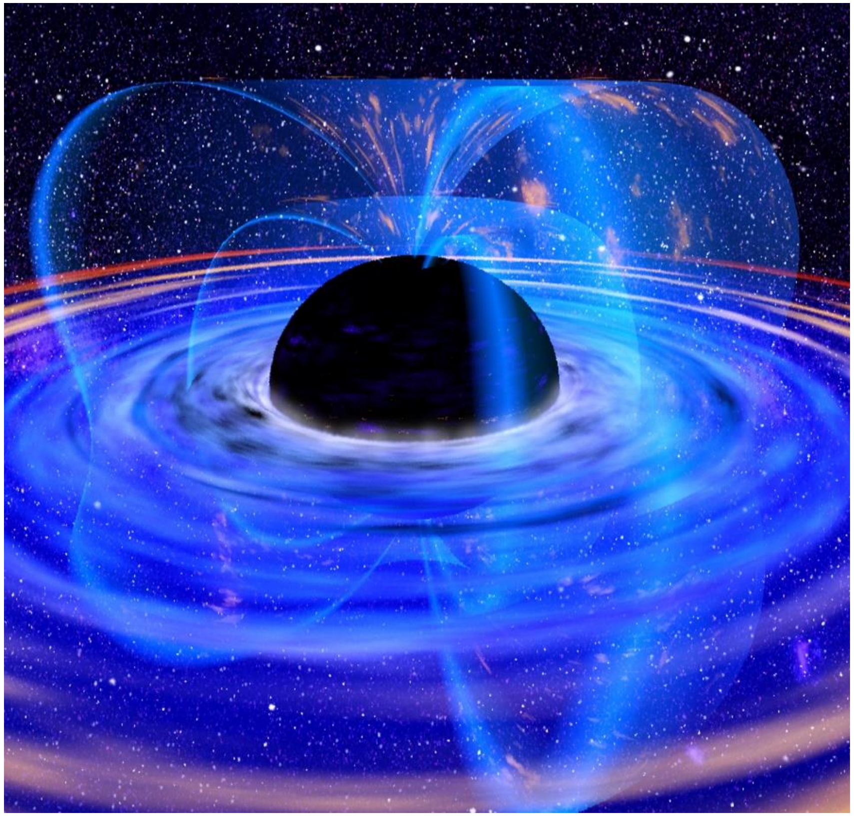
Nice predictions for further measurements ✓

Physical interpretation ?

“Black Hole” Interpretation by Dmitry Kharzeev

Black holes radiate

S.Hawking ‘74



Black holes emit thermal radiation with temperature

$$T_{th} = \frac{\kappa}{2\pi}$$

acceleration of gravity at the surface, $(4GM)^{-1}$

Similar things happen in non-inertial frames

Einstein's Equivalence Principle:

$\boxed{\text{Gravity} \longleftrightarrow \text{Acceleration in a non-inertial frame}}$

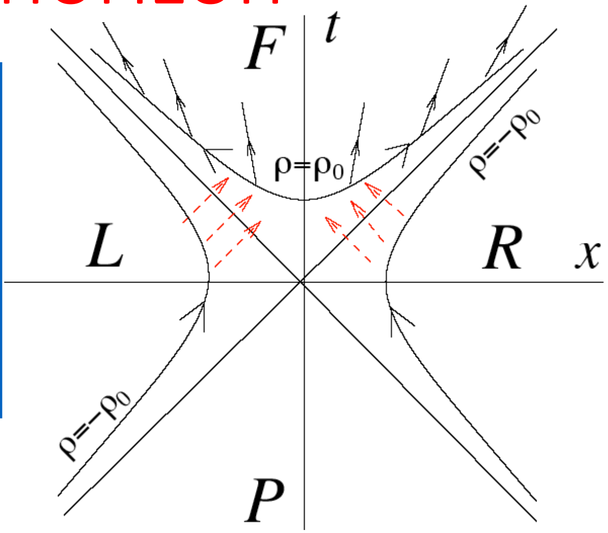
$\Downarrow$

An observer moving with an acceleration ***a*** detects a thermal radiation with temperature

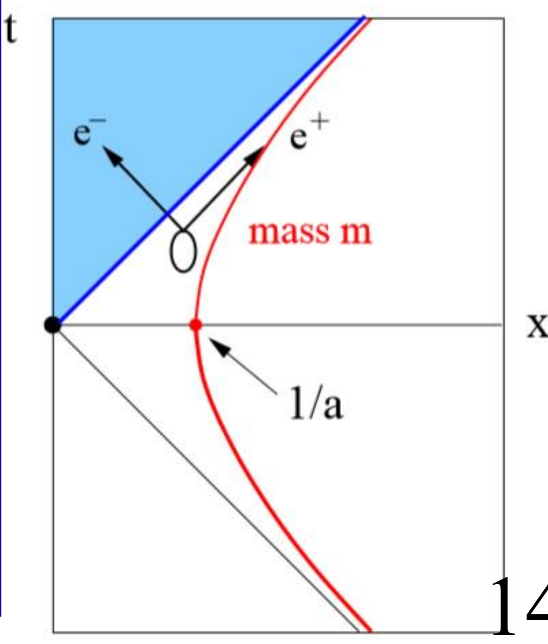
$$T_{th} = \frac{a}{2\pi}$$

W.Unruh '76

In both cases the radiation is due to the presence of event horizon



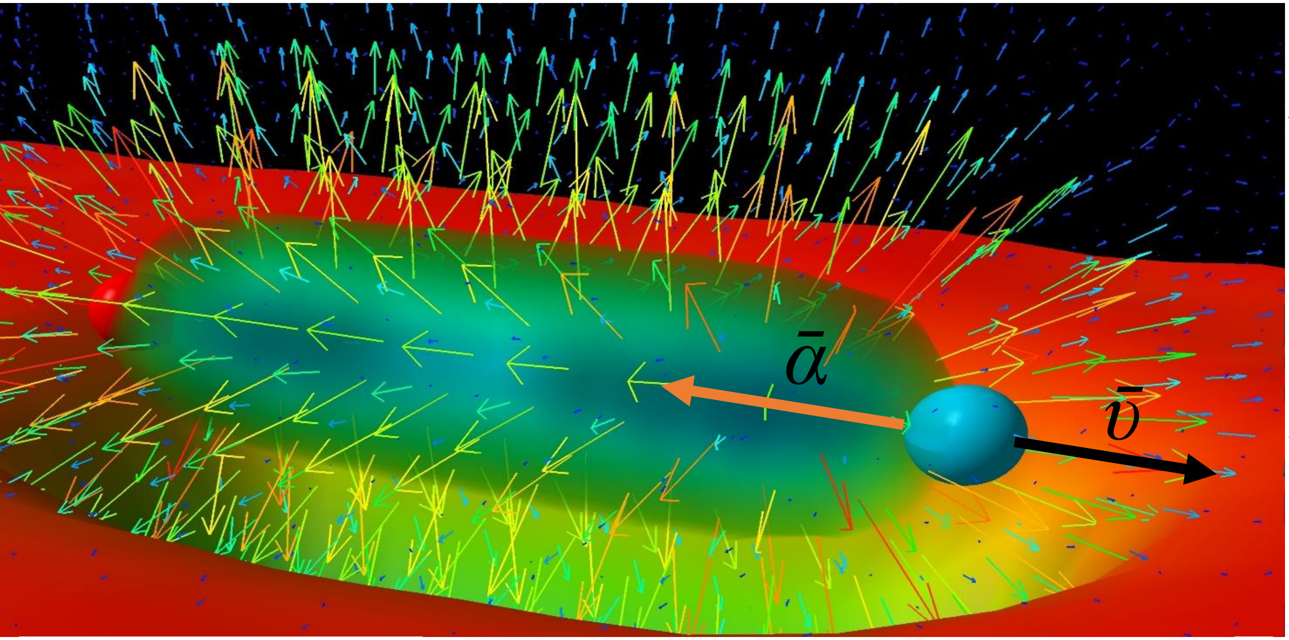
Black hole: the interior is hidden from an outside observer; Schwarzschild metric



Accelerated frame: part of space-time is hidden (causally disconnected) from an accelerating observer; Rindler metric

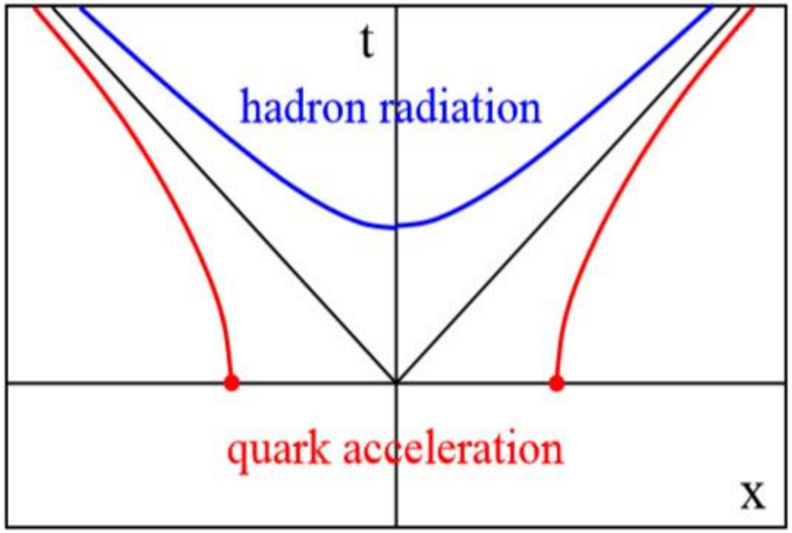
$$\rho^2 = x^2 - t^2, \quad \eta = \frac{1}{2}\ln\left|\frac{t+x}{t-x}\right| \quad ds^2 = \rho^2 d\eta^2 - d\rho^2 - dx_\perp^{\ 2}$$

Similar things happen in high energy collisions



Color string stretching between the colored fragments contains the longitudinal chromoelectric field, which decelerates the colored fragments.

$$v_{initial} \simeq c; \; v_{final} \simeq 0; \; \Delta t \simeq 1/Q_s; \;\; a \simeq Q_s \sim 1 \text{ GeV};$$



Confinement produces the effective event horizon for colored particles. Quantum fluctuations in its vicinity then result in the thermal hadron production:

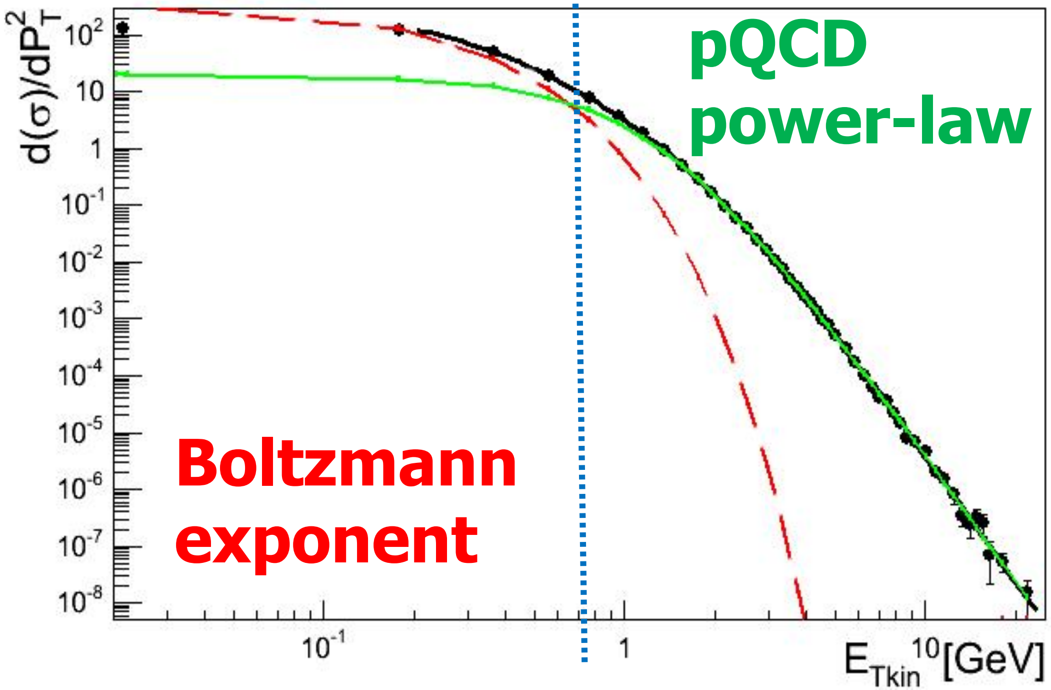
$$T_{th} = \frac{a}{2\pi} \sim 160 \text{ MeV}$$

Two components in the "Black Hole" Interpretation

"Thermal" Unruh-like radiation $T_e = \frac{a}{2\pi}$ with $a \simeq Q_s \sim 1$ GeV;

"Hard" radiation with saturation scale $T \sim Q_s$

$$A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1+\frac{P_T^2}{T^2 N})^N}$$



?

$T_e \sim T/2\pi$

$$Q_s^2(s;\pm\eta) = Q_s^2(s_0;\eta=0)\left(\frac{s}{s_0}\right)^{\lambda/2} \exp(\pm\lambda\eta);$$

Parton saturation scenario
D. Kharzeev and E. Levin
PLB 523, 79 (2001)

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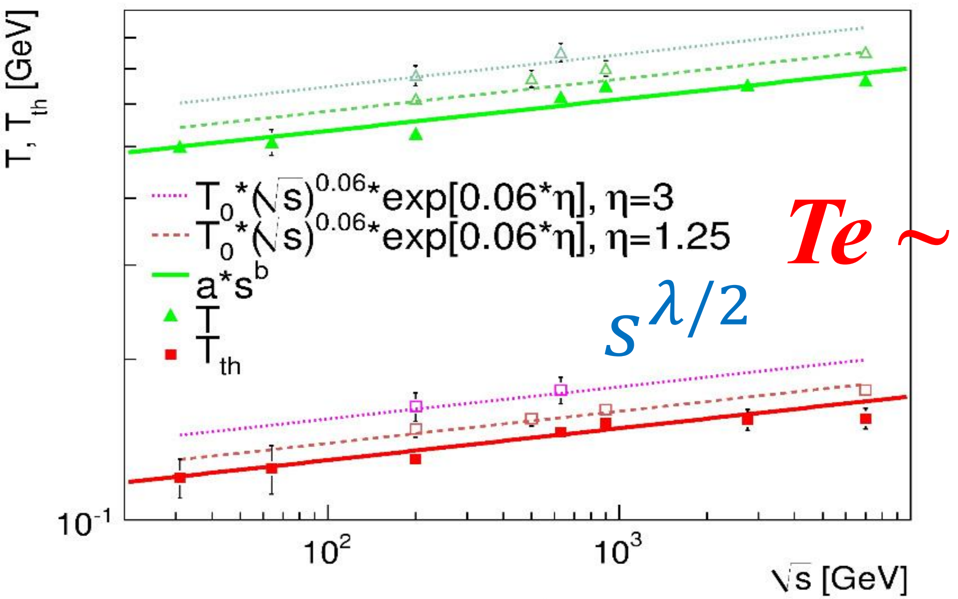
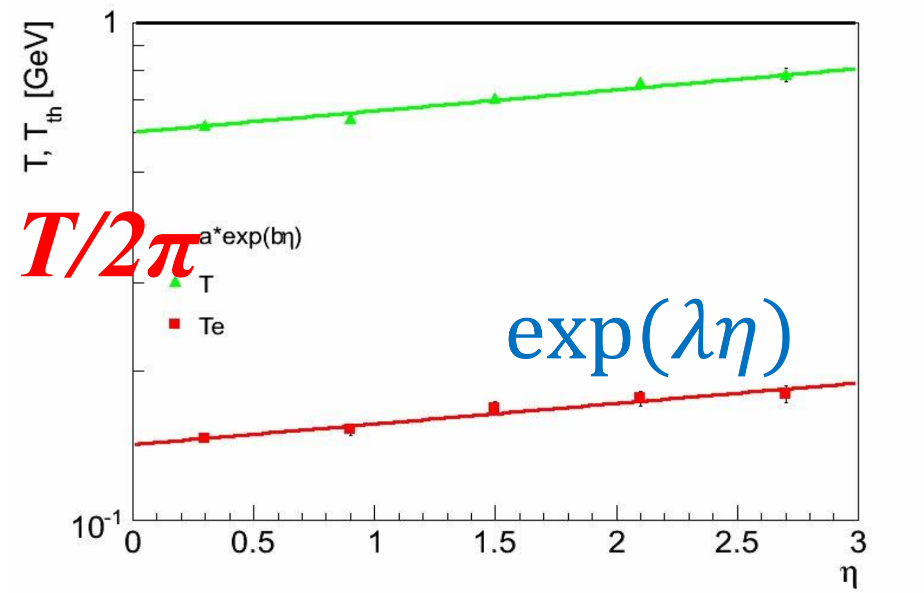


_Te ~ T/2π_



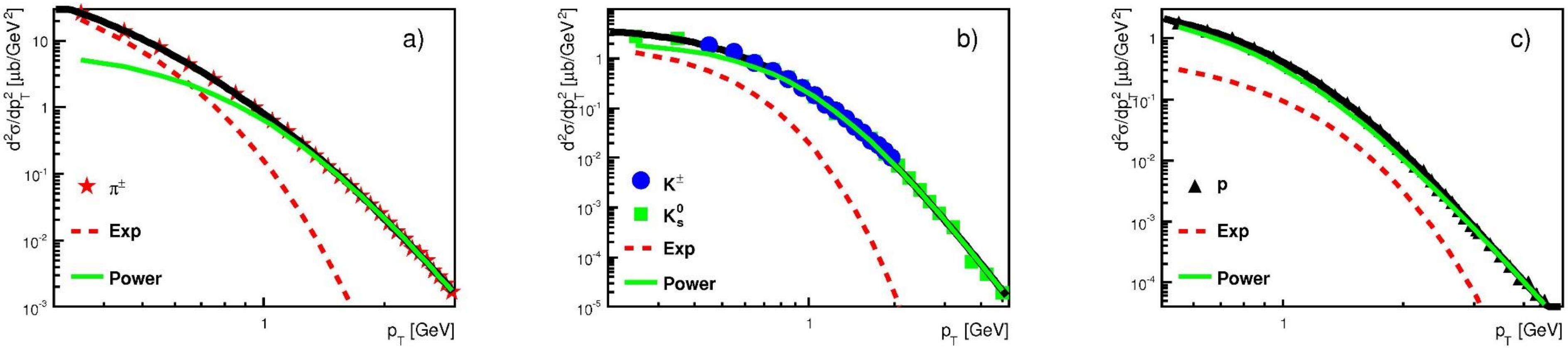
$$Q_s^2(s;\pm\eta) = Q_s^2(s_0;\eta=0)\left(\frac{s}{s_0}\right)^{\lambda/2} \exp(\pm\lambda\eta);$$

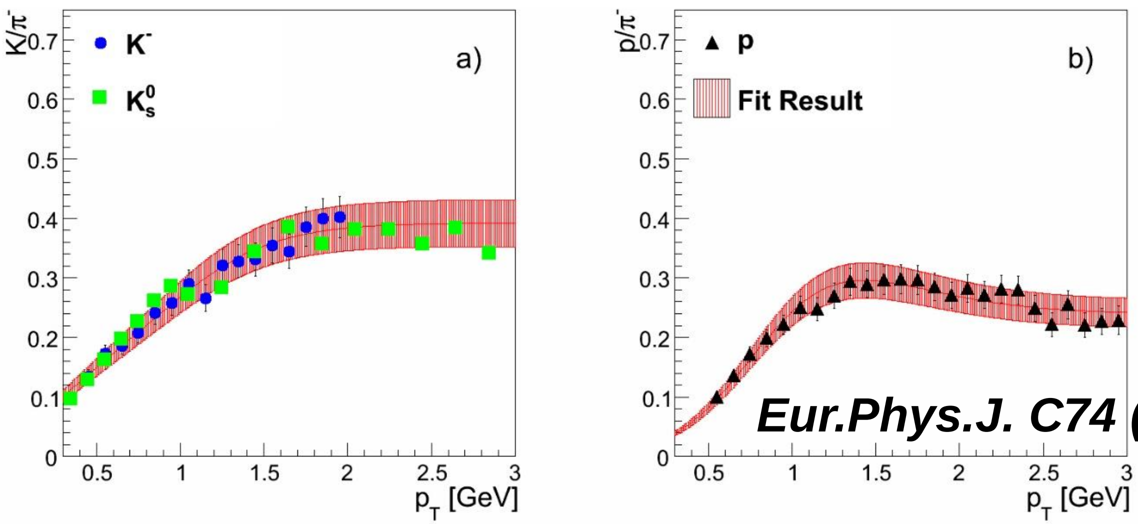
Parton saturation scenario *(λ=0.12)*
D. Kharzeev and E. Levin
PLB 523, 79 (2001)

The observed linear dependence between T and Te supports the suggested picture of charged hadron production.

A. Bylinkin, D. Kharzeev and A. Rostovtsev Int.J.Mod.Phys.E23 (2014) 0083

Simultaneous fit of pion, kaon and proton spectra





Eur.Phys.J. C74 (2014) no.5, 2898

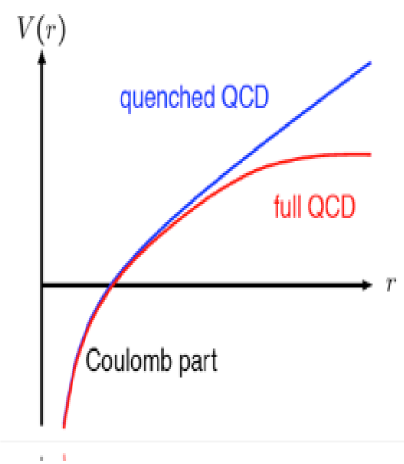
The large exponential contribution in pion spectra explains the peculiar shapes of K/π and p/π ratios as a function of transverse momentum.

The parameters of the power-law term, T and N, have the same values for all the species of produced hadrons.

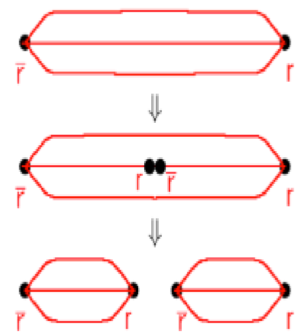
Monte Carlo Generators

Lund String Model

g→qq → The strings would break

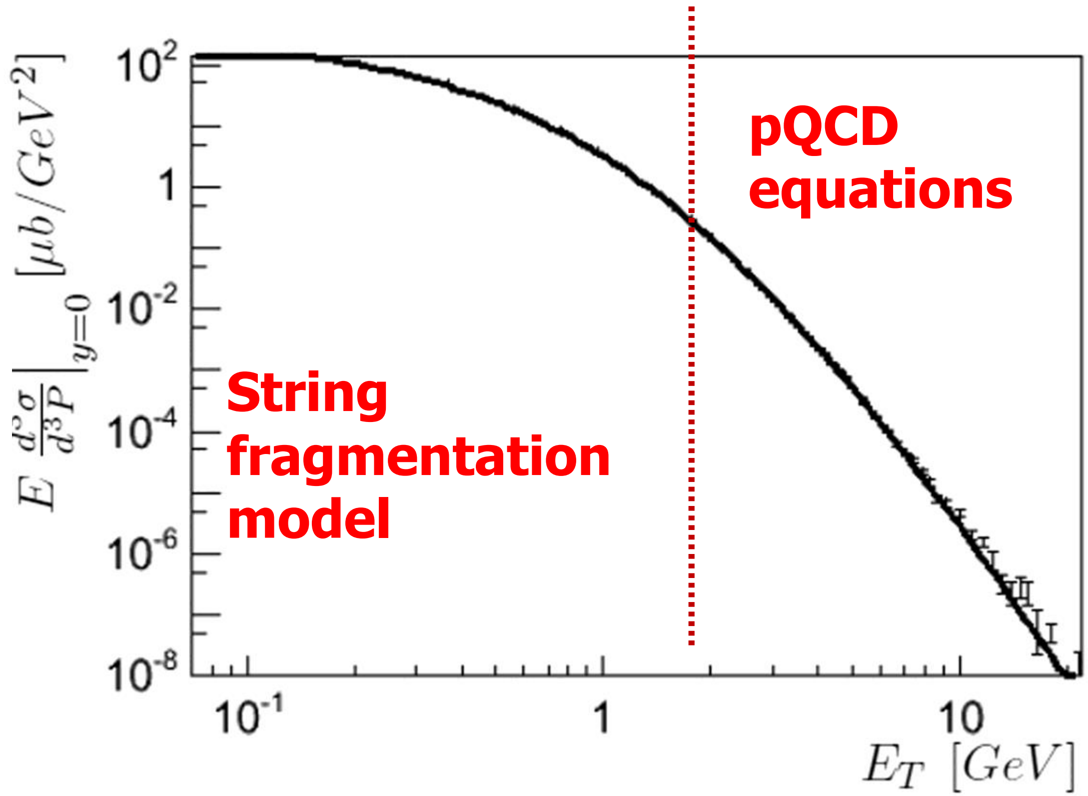


String Breaks:
via Quantum Tunneling



(simplified colour representation)

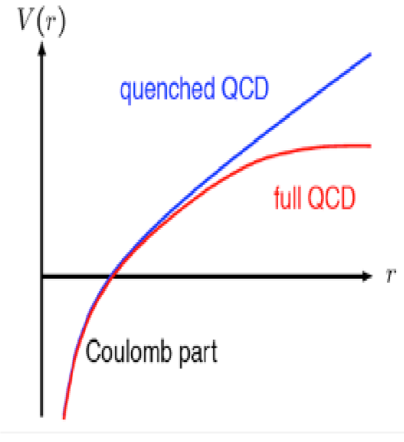
$$\mathcal{P} \propto \exp\left(\frac{-m_q^2 - p_\perp^2}{\kappa/\pi}\right)$$

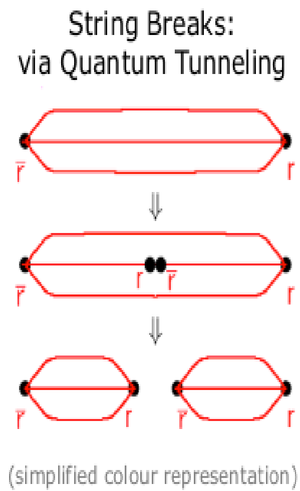


Monte Carlo Generators

Lund String Model

$g \to qq \to$ The strings would break





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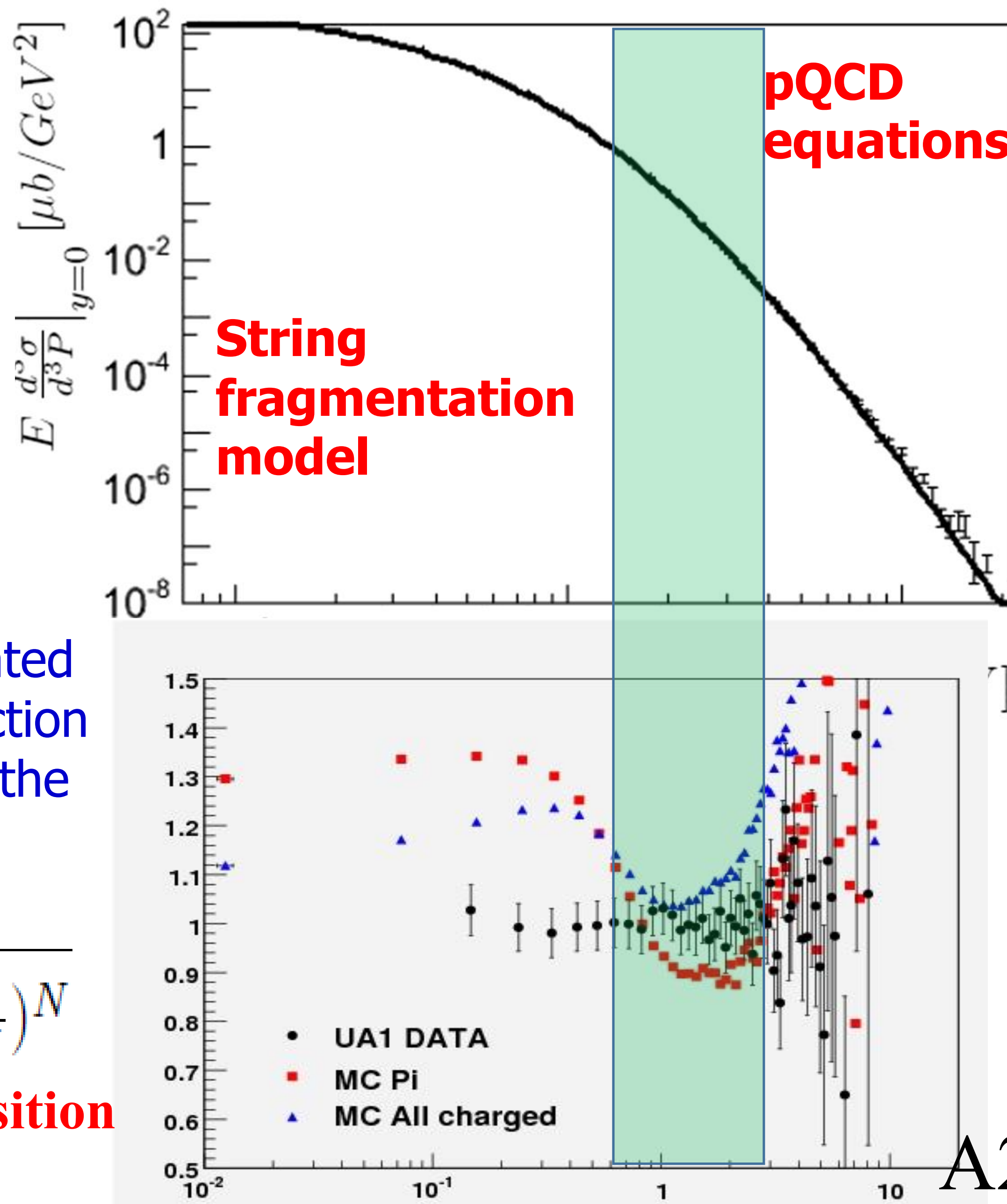


Experimental data and MC generated Spectrum divided over the fit function with the parameters obtained for the data.

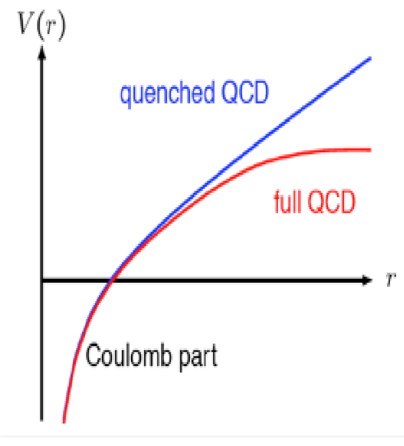
$$A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1 + \frac{P_T^2}{T^2 N})^N}$$

MC does not describe the transition region between two dynamics

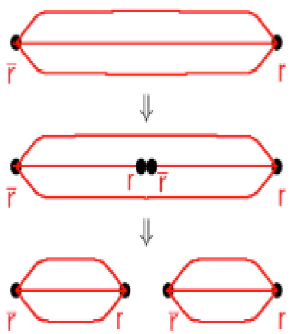
Monte Carlo Generators

Lund String Model

g→qq → The strings would break



String Breaks:
via Quantum Tunneling



(simplified colour representation)

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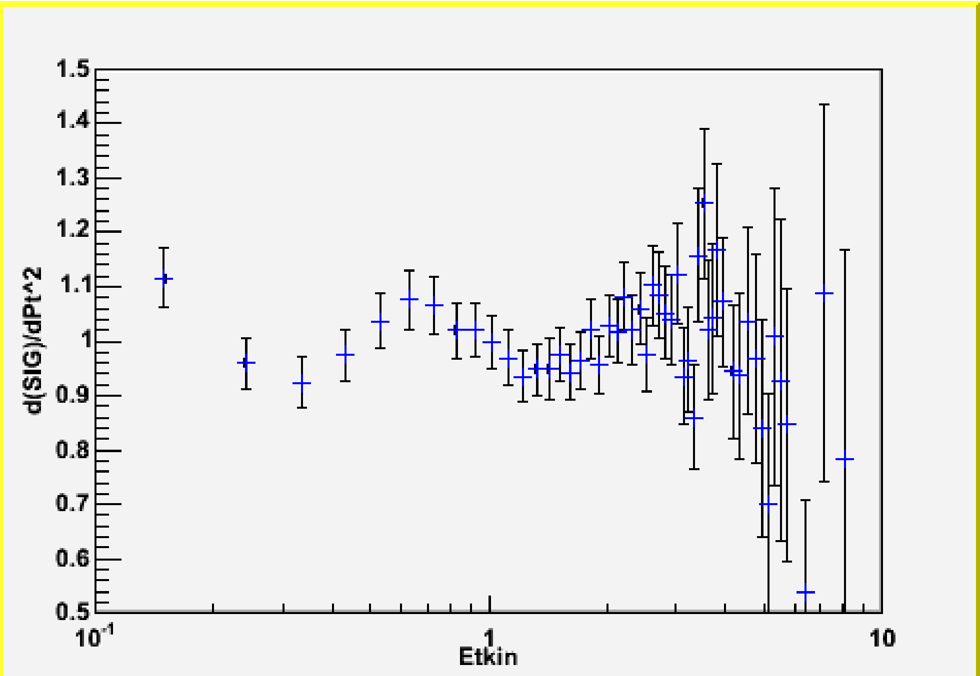

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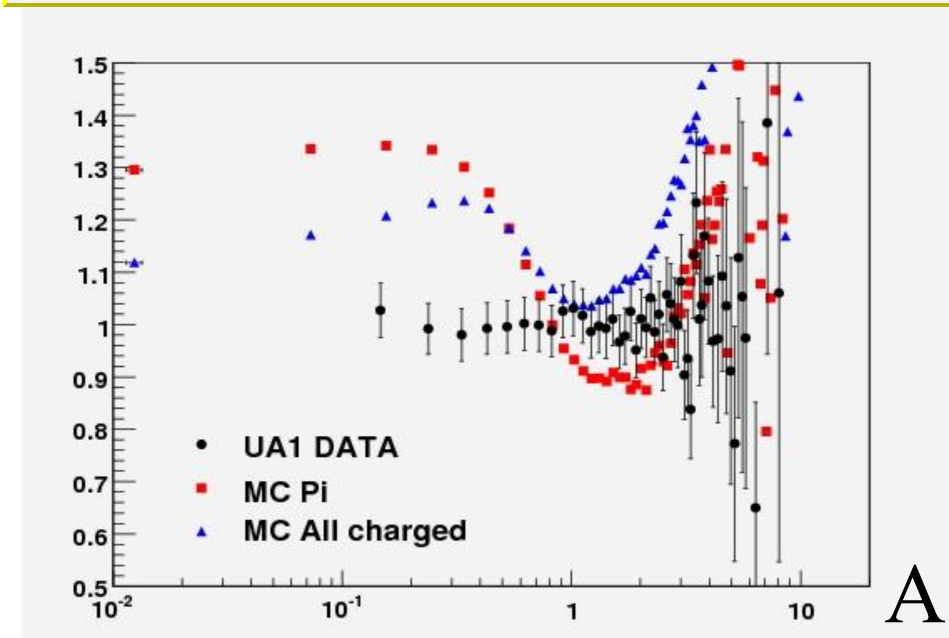


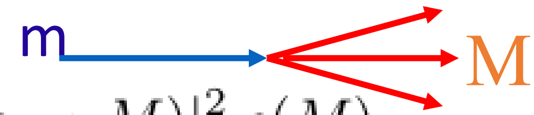
The reason is not the choice of the MC parameters, but in the different hadroproduction dynamics in MC.

A3

Few words about heavy-ion collisions

Few words about heavy-ion collisions
Limiting acceleration

Consider a dissociation of a high energy hadron of mass m into a final hadronic state of mass M>>m;



The probability of transition: $P(m \to M) = 2\pi |T(m \to M)|^2 \rho(M)$

Transition amplitude: $|T(m \to M)|^2 \sim \exp(-2\pi M/a)$

In dual resonance model: $\rho(M) \sim \exp(4\pi\sqrt{b}M/\sqrt{6})$

Unitarity: ΣP(m➔M)=const,

Limiting acceleration $$\frac{a}{2\pi} \equiv T \leq \frac{\sqrt{6}}{4\pi\sqrt{b}}$$

Few words about heavy-ion collisions

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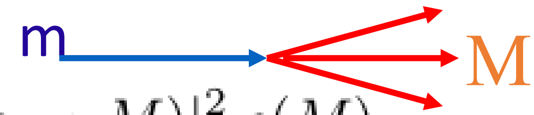

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Hagedorn temperature!

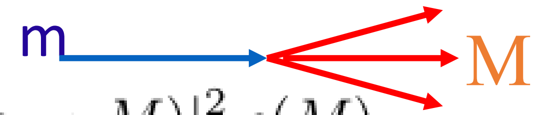
Why it is interesting to look at heavy-ion collisions?
And why with the two component model?

1. The maximum acceleration is obtained in heavy ion collisions.
2. The Two Component model allows to extract the "thermal" hadron production from the whole statistical ensemble.

Few words about heavy-ion collisions

Limiting acceleration

Consider a dissociation of a high energy hadron of mass m into a final hadronic state of mass M>>m;



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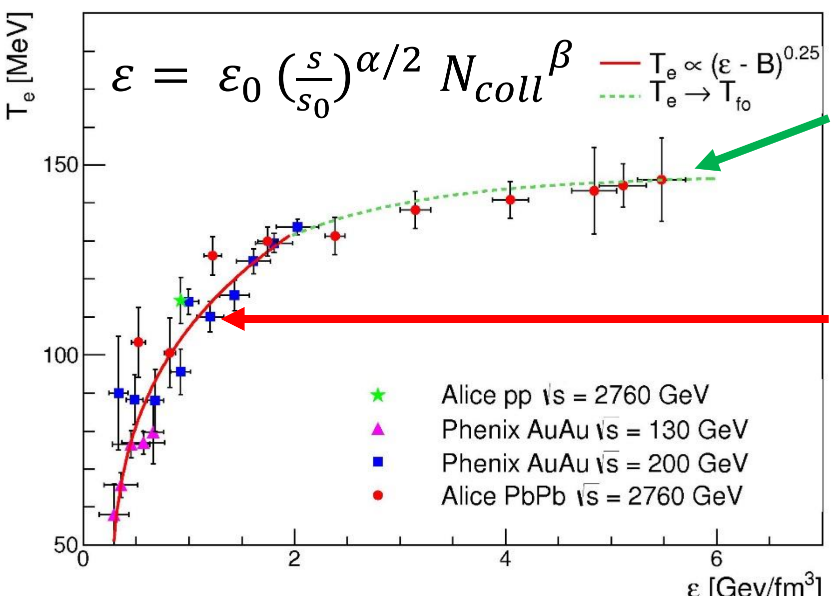


1. T_C ~ 150 MeV

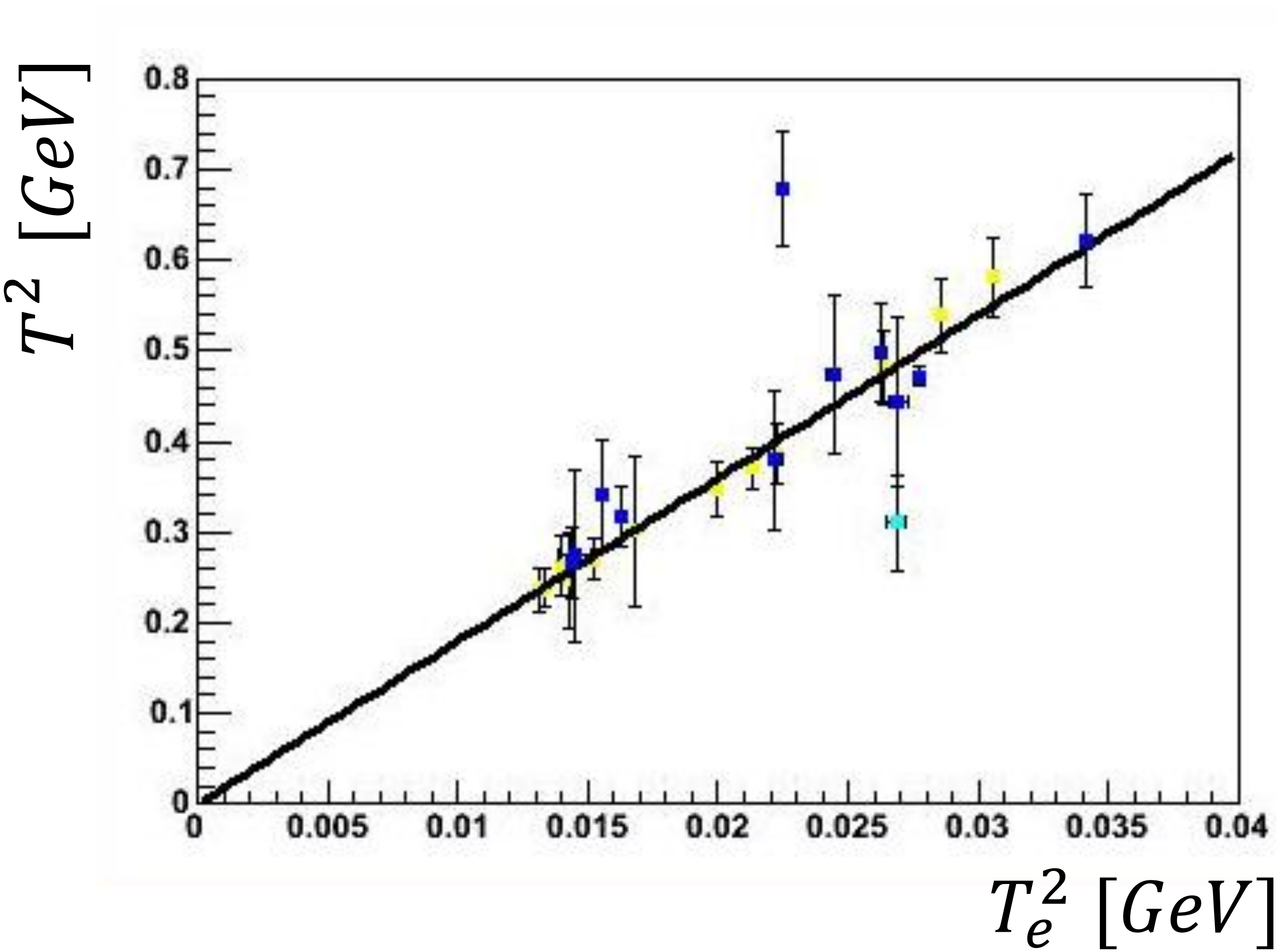
Limiting acceleration or QGP phase transition???

2. ε ~ T^4 + B

Good agreement with the Stefan-Boltzmann law for the Black Body radiation or the Bag model.

Phys. Rev. C 90 (2014) 018201 A.A.Bylinkin *et al.*

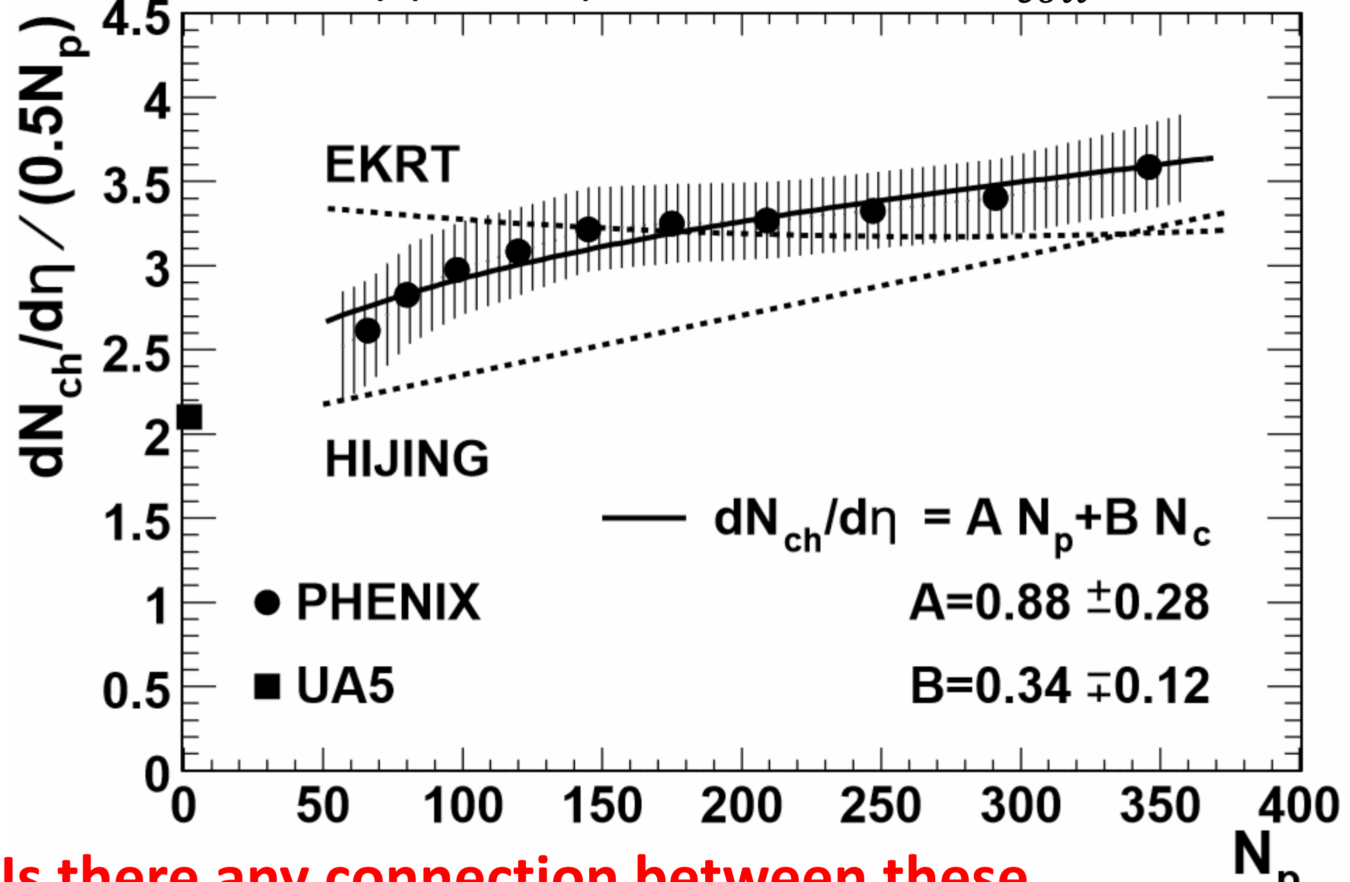
Heavy-ion collisions



The same linear dependence between T and Te both for pp and heavy-ion collisions.

Two components in heavy-ion collisions?

- Two component models have been used to describe heavy-ion collisions for a long time.
- Charged particle density, $dN_{ch}/d\eta$, is expected to scale with number of participating nucleons, N_{part}, for “soft” processes and with number of binary parton-parton collisions, N_{coll}, for “hard” regime.

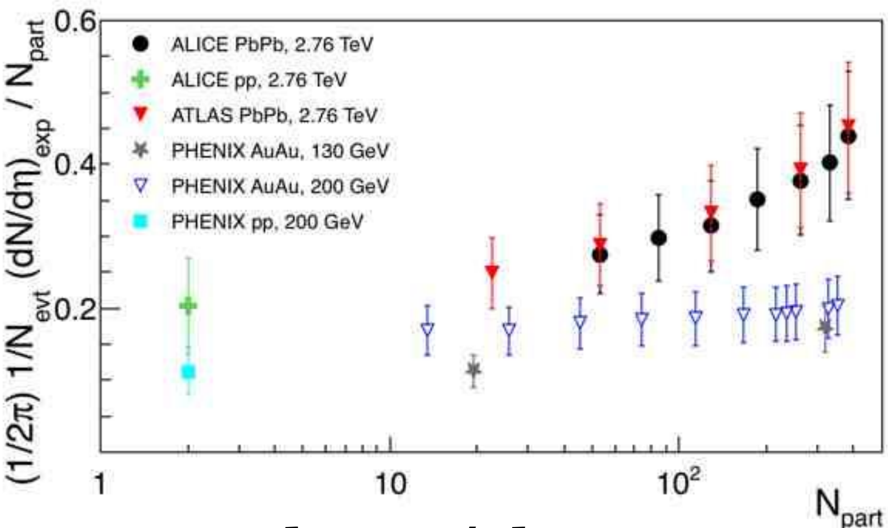


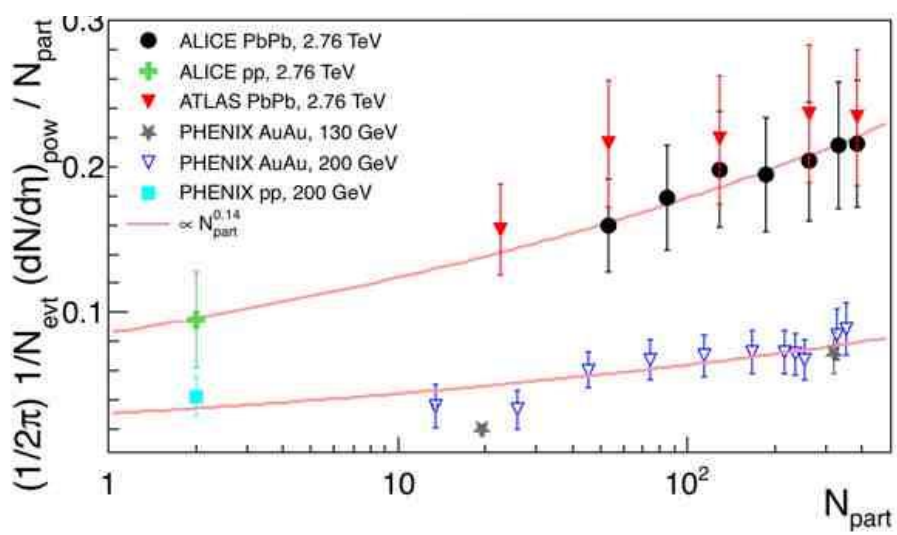
- **Is there any connection between these two component models?**

Two components in heavy ion collisions

calculated separately for exponential and power-law contributions to the transverse momentum spectra

$$A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1+\frac{P_T^2}{T^2 N})^N}$$





RHIC: $dN_{ch}/d\eta \sim N_{part}$

LHC: larger parton densities cause the increase of final state rescatterings

→ Produced secondaries start to thermalize

The universal scaling with $N_{part}^{1.14}$ indicates that the power-law is indeed related to the “hard” regime of hadroproduction.

Two components in heavy ion collisions

calculated separately for exponential and power-law contributions

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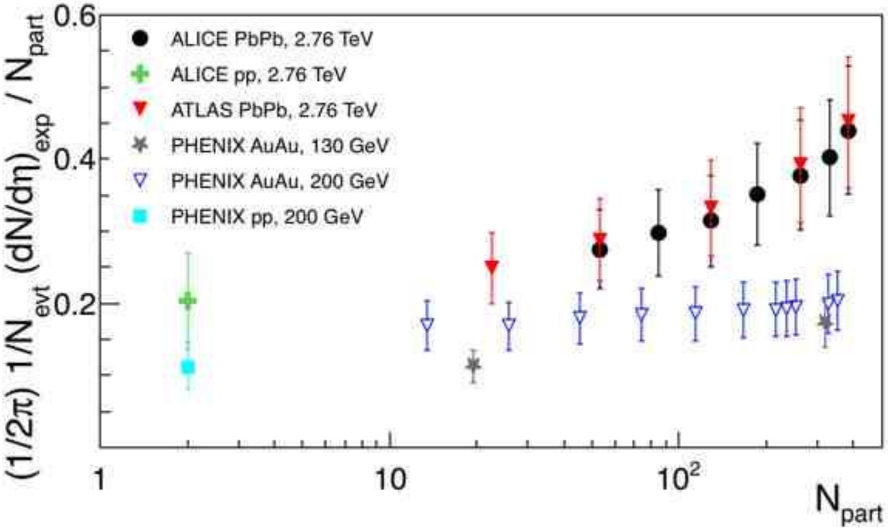
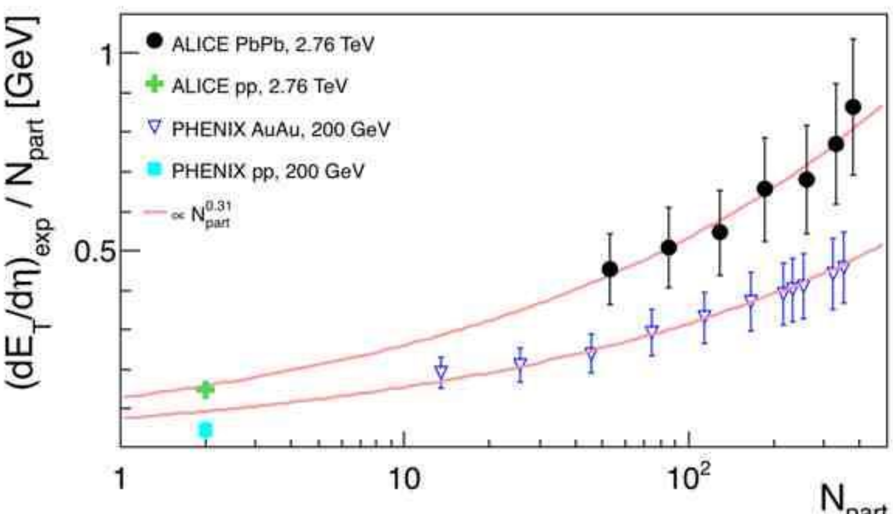




$$\Sigma E_T/d\eta \sim N_{part}^{1.31} \sim N_{coll}$$

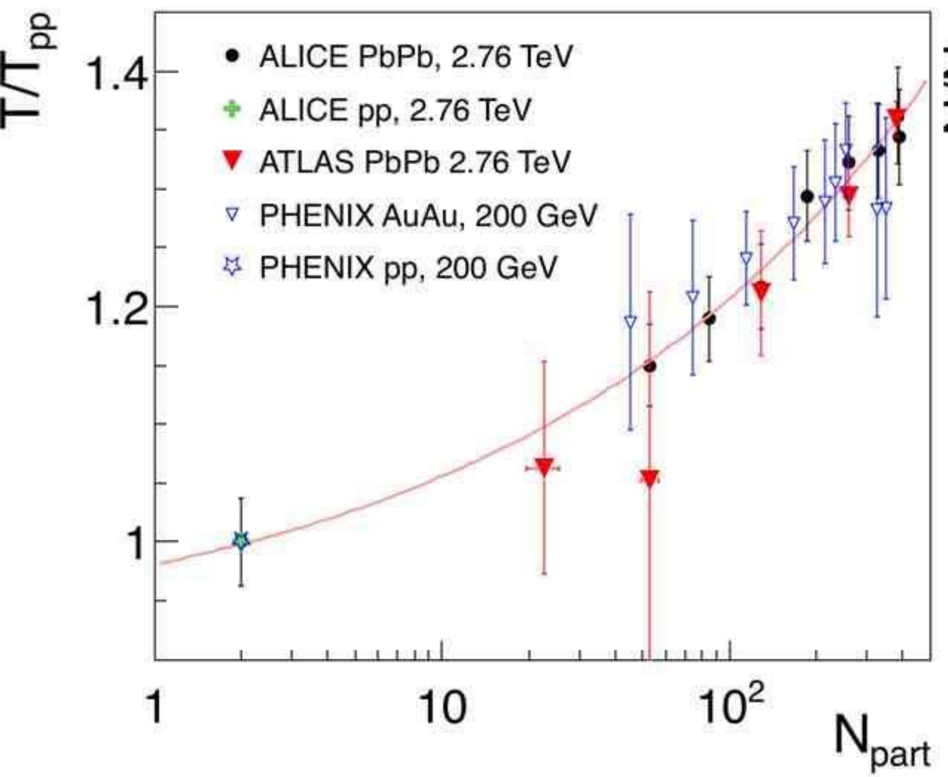
The same scaling of $\Sigma E_T/d\eta$ both for RHIC and LHC energies.

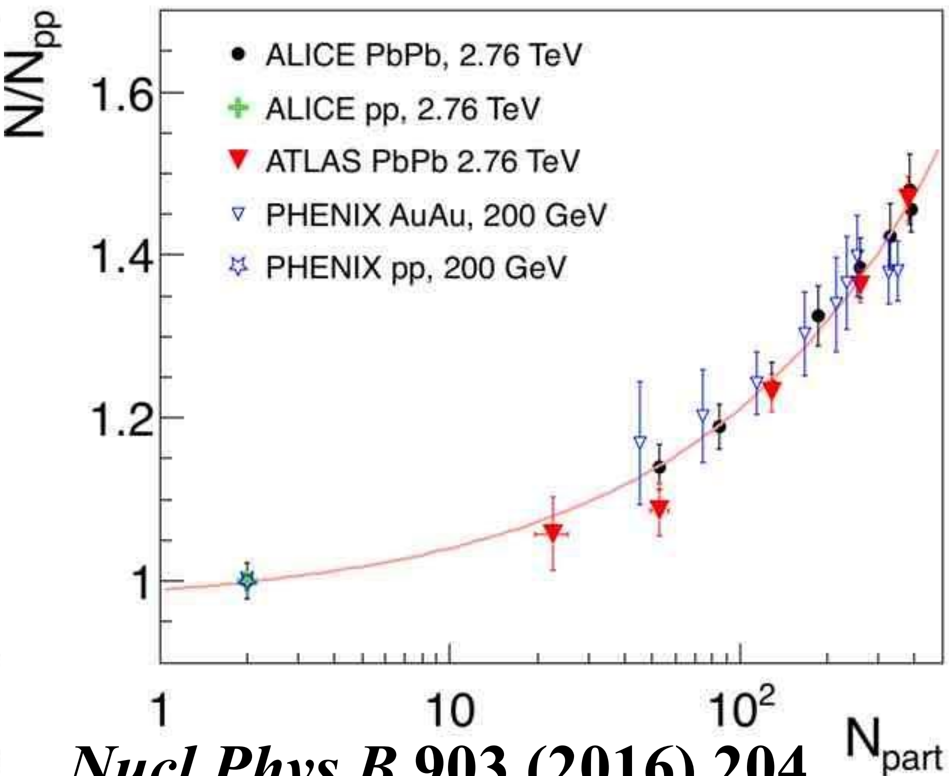
→ The observed deviation is related to a change in hadroproduction dynamics because of larger initial parton density

→ The two component model indeed reveal the underlying hadroproduction dynamics.

Quenching of hadron spectra

$$A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1+\frac{P_T^2}{T^2 N})^N}$$





***Nucl.Phys.B* 903 (2016) 204**

More rescaterrings occur for most central collisions - higher T and N values

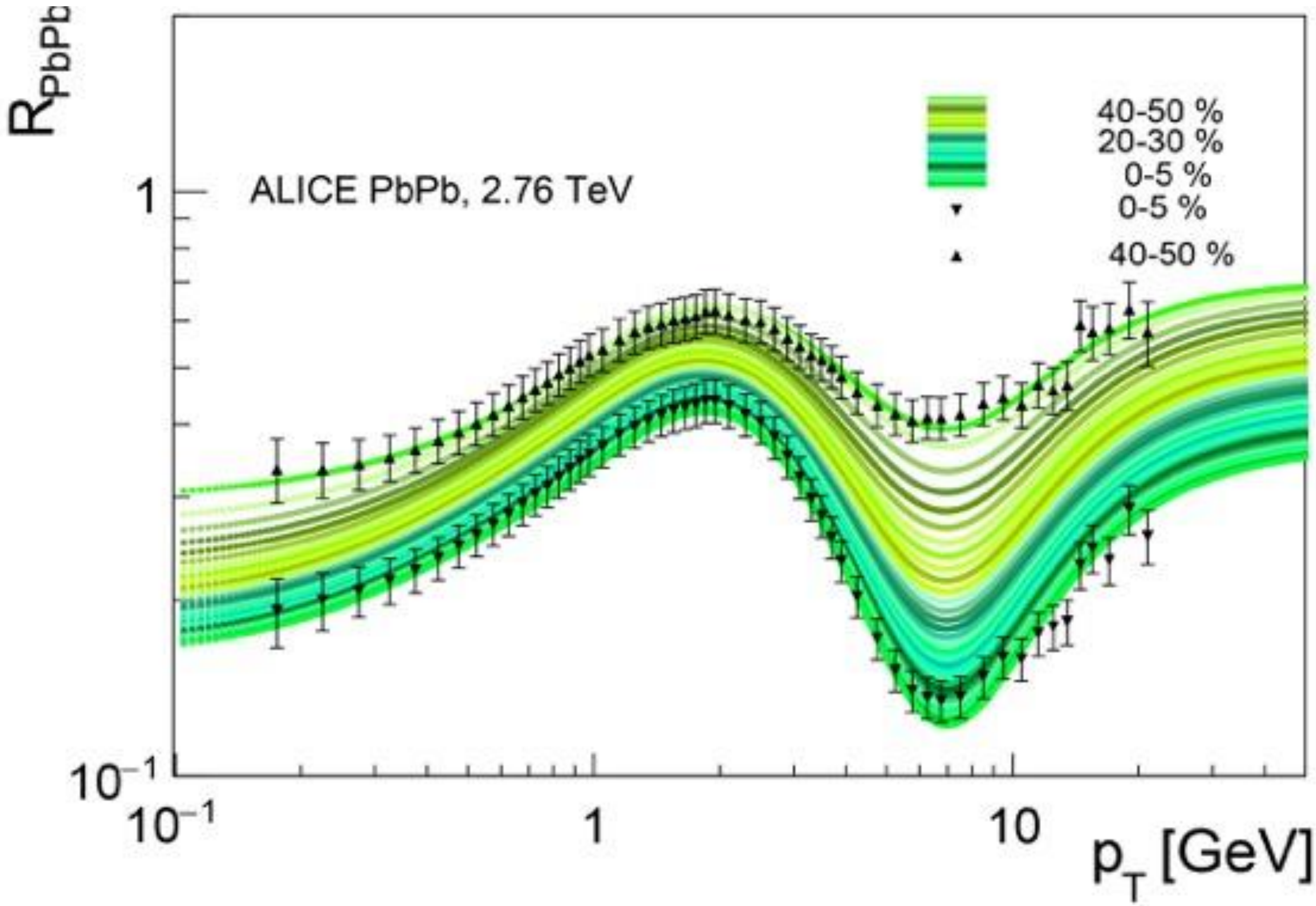
The values of T and N are nicely placed on the fit lines of PbPb-data at the same collision energy 2.76 TeV

The same dependence for both RHIC and LHC data

The shape of R_{AA} can be predicted for all centralitities just with the knowledge of the spectra shape in pp-collisions.

Prediction on Raa

Good agreement between the prediction from the proposed model and the experimental data



A10

Heavy flavour production

Heavy flavour production

CERN-PH-EP-2015-223
LHCb-PAPER-2015-032
25 January 2016

Study of the production of Λ_b^0 and $\overline{B}^0$ hadrons in pp collisions and first measurement of the $\Lambda_b^0 \to J/\psi\, pK^-$ branching fraction

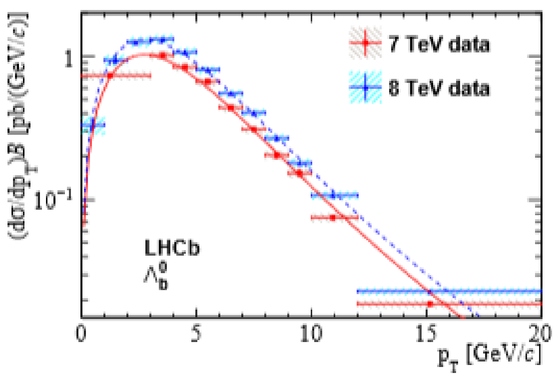


Figure 4: Fit to the Λ_b^0 distribution with the Tsallis function.

p_T distribution of the Λ_b^0 production, fitted by a power-law function with the Tsallis parameterisation [44,45]:

$$\frac{d\sigma}{p_T dp_T} \propto \frac{1}{[1 + E_{k\perp}/(TN)]^N}, \quad (6)$$

where T is a temperature-like parameter, N determines the power-law behaviour at large $E_{k\perp}$, and $E_{k\perp} \equiv \sqrt{p_T{}^2 + M^2} - M$ with M the mass of the hadron. The fit results are

$$T = 1.12 \pm 0.04 \text{ GeV} \qquad N = 7.3 \pm 0.5 \qquad (7\,\text{TeV}),$$
$$T = 1.13 \pm 0.03 \text{ GeV} \qquad N = 7.5 \pm 0.4 \qquad (8\,\text{TeV}).$$

For the 7 TeV (8 TeV) sample, the fit χ^2 is 21.0 (10.7) for 7 (9) degrees of freedom. The other and with the values found by CMS [5]. Other functions suggested in Ref. [46] do not give acceptable fits to the data. In Fig. 4 the data points are placed in the bin according

[46] A. A. Bylinkin and O. I. Piskounova, *Transverse momentum distributions of baryons at LHC energies*, arXiv:1501.07706.

Why Tsallis works better for heavy flavor production?

Why Tsallis works better for heavy flavor production?

Tsallis

$$\left(\frac{1}{1+\frac{E_T}{T\cdot N}}\right)^N$$

Two Component Model

$$A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1+\frac{P_T^2}{T^2 N})^N}$$

Why Tsallis works better for heavy flavor production?

Tsallis

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Not expected to contribute
to heavy flavor production

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$$\left(\frac{1}{1+\frac{E_T}{T\cdot N}}\right)^N$$

$$\frac{A_2}{(1+\frac{P_T^2}{T^2 N})^N}$$

E_T - includes mass dependence

p_T^2- no mass dependence

Why Tsallis works better for heavy flavor production?

Tsallis

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E_T - includes mass dependence

p_T^2- no mass dependence

$$\left(\frac{1}{1+\frac{m_T^2}{T^2\cdot N}}\right)^N$$

Two Component Model with Mass

$$A_1 exp(-E_{Tkin}/T_e) + \frac{A_2}{(1 + \frac{P_T^2}{T^2 N})^N} \rightarrow A_1 e^{-m_T/T_e} + \frac{A_2}{(1 + \frac{m_T^2}{T^2 \cdot N})^N}$$

Mass dependence should be negligible for pion spectra

Let's check this explicitly

Two Component Model with Mass

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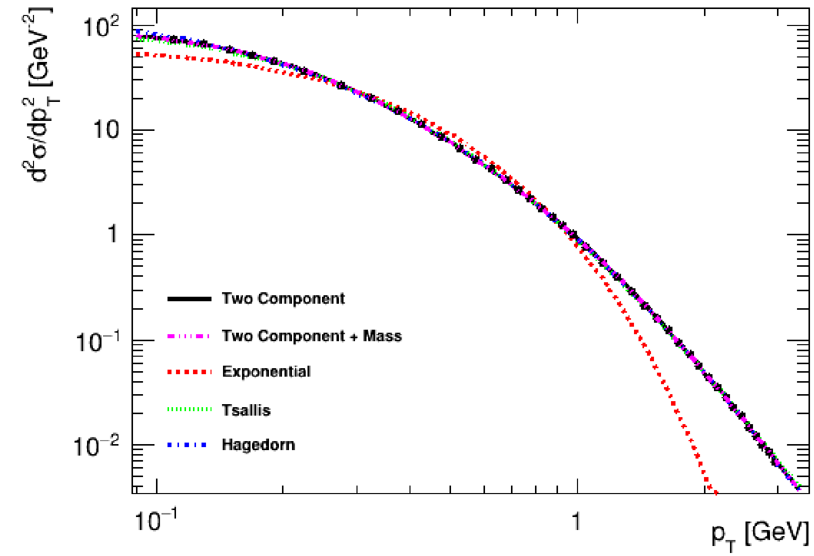
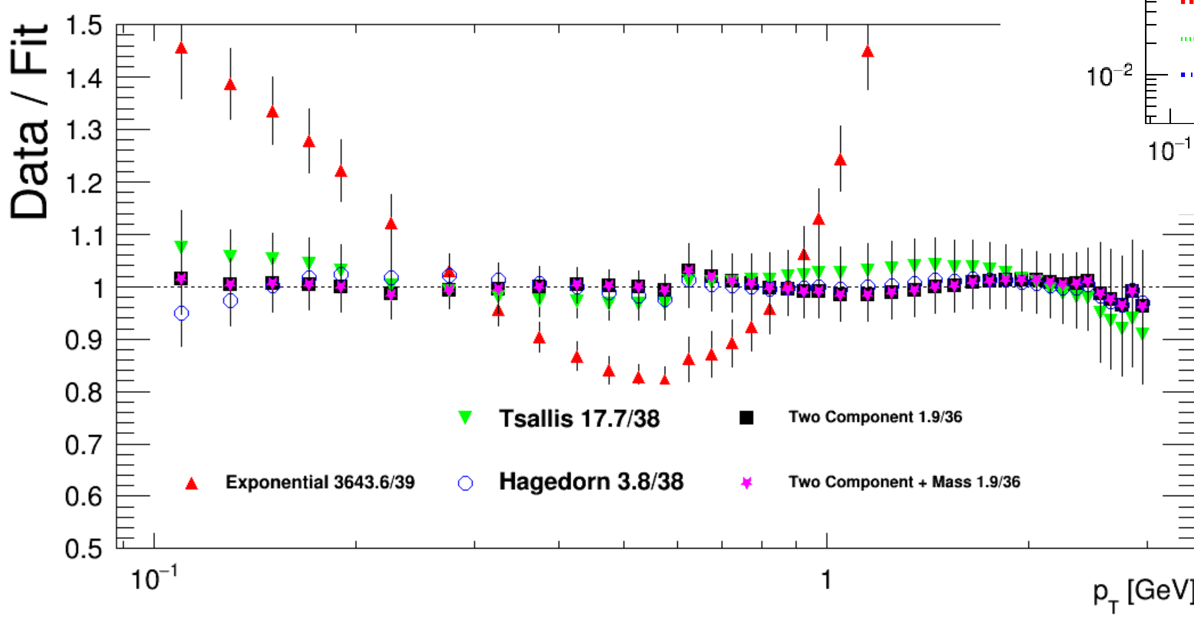


Alice 7000 GeV, pion spectra



A13

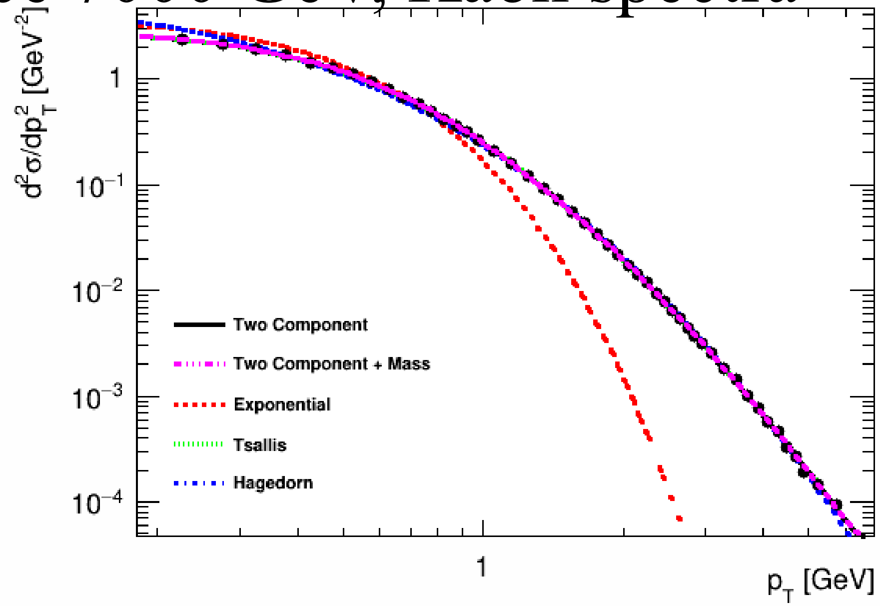
Two Component Model with Mass

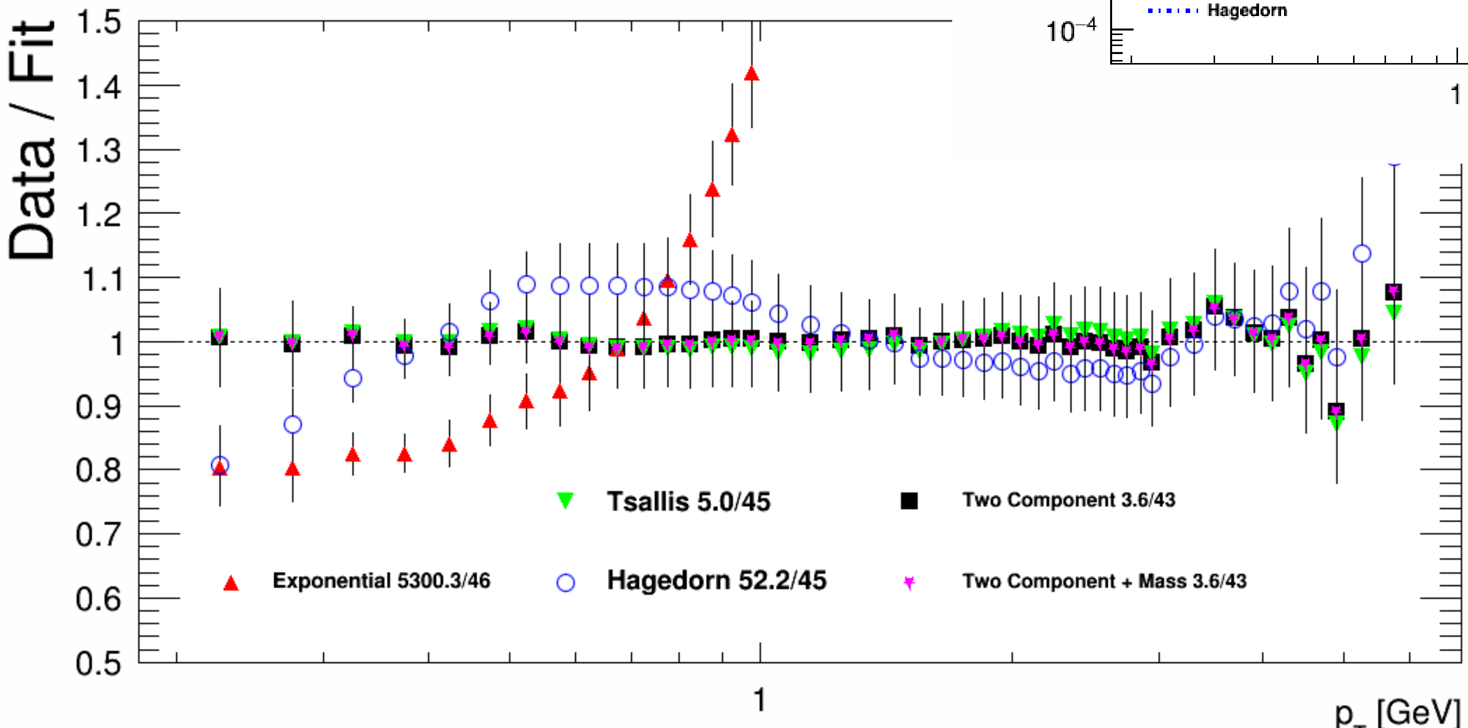
Let's go step by step

$$A_1 e^{-m_T/T_e} + \frac{A_2}{\left(1+\frac{m_T^2}{T^2\cdot N}\right)^N}$$

No difference even for Kaons

Alice 7000 GeV, Kaon spectra



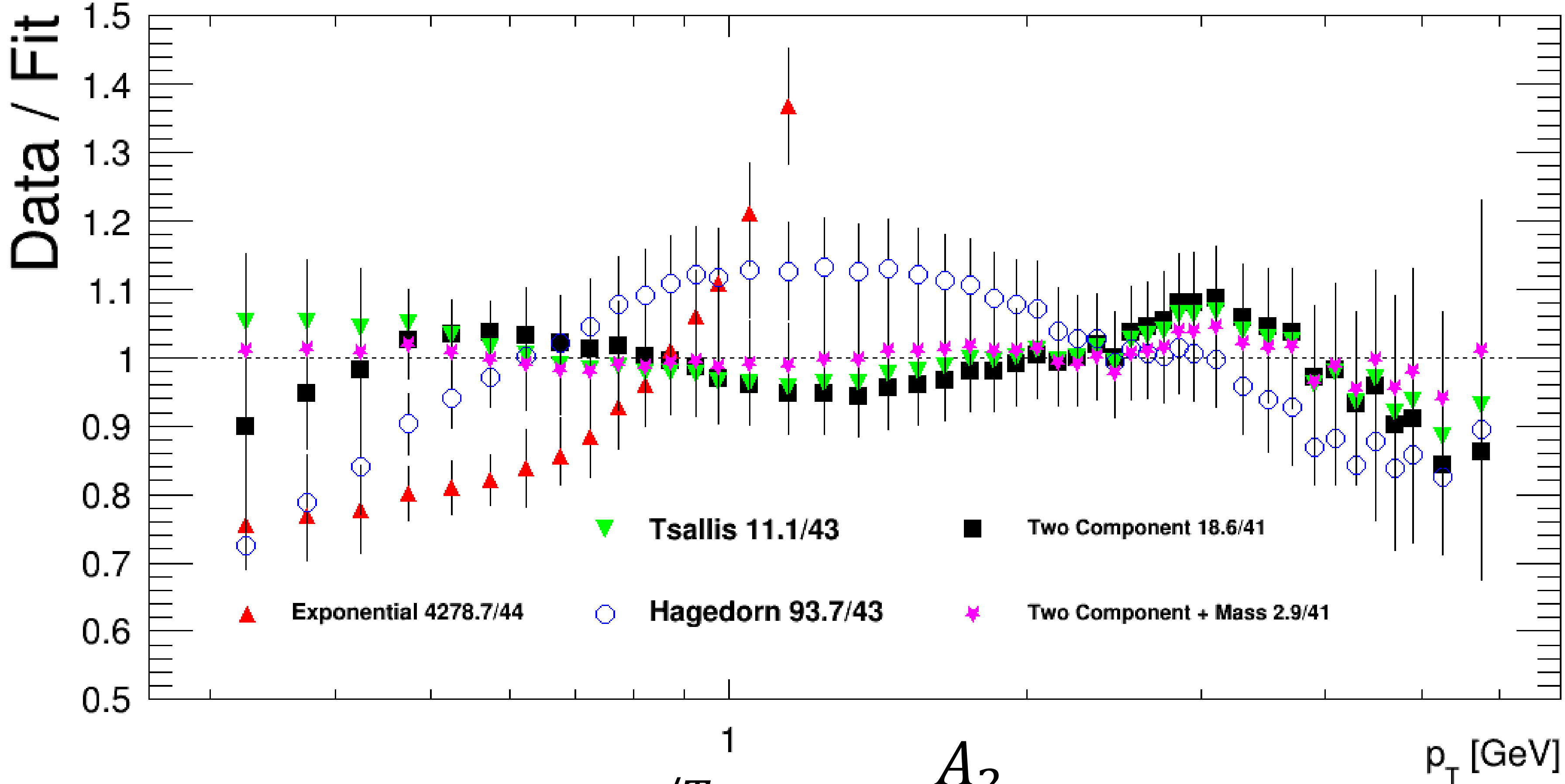


A14

Two Component Model with Mass

Let's go step by step

Alice 7000 GeV, proton spectra



$$A_1 e^{-m_T/T_e} + \frac{A_2}{(1 + \frac{m_T^2}{T^2 \cdot N})^N}$$

Difference appears starting from proton spectra.

And what about LHCb data?

LHCb 8 TeV, Λ_b^0 spectra

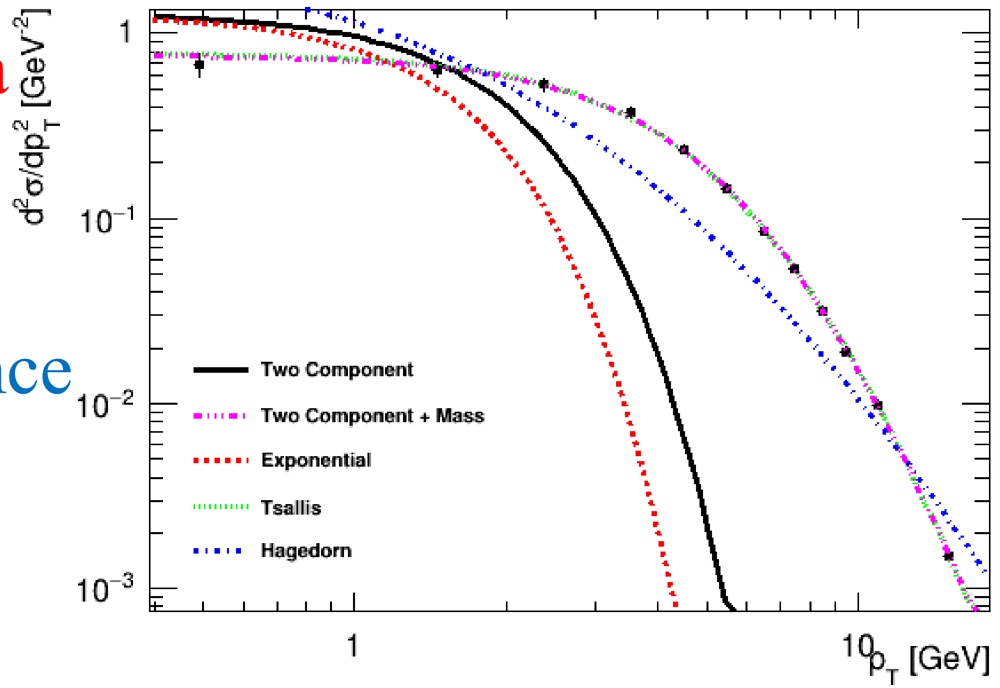
And what about LHCb data?

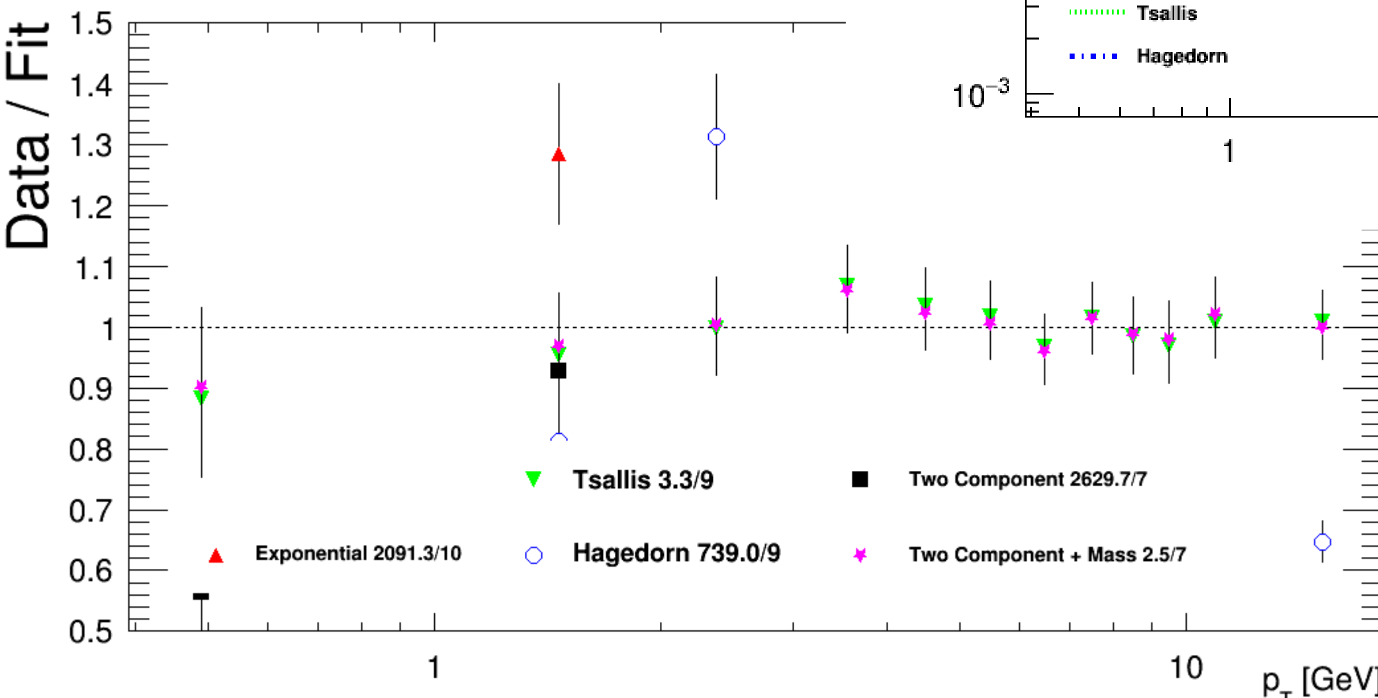
LHCb 8 TeV, Λ_b^0 spectra

The old two component approach does not fit the data

$$A_1 e^{-m_T/T_e} + \frac{A_2}{(1+\frac{m_T^2}{T^2 \cdot N})^N}$$

Formula with mass dependence works as well as Tsallis



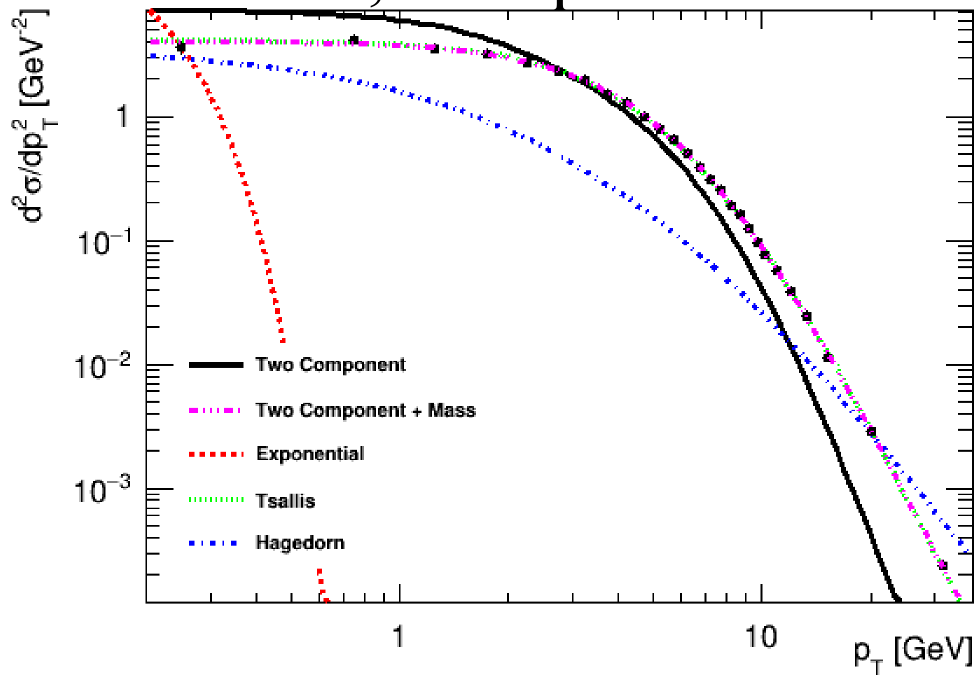


A16

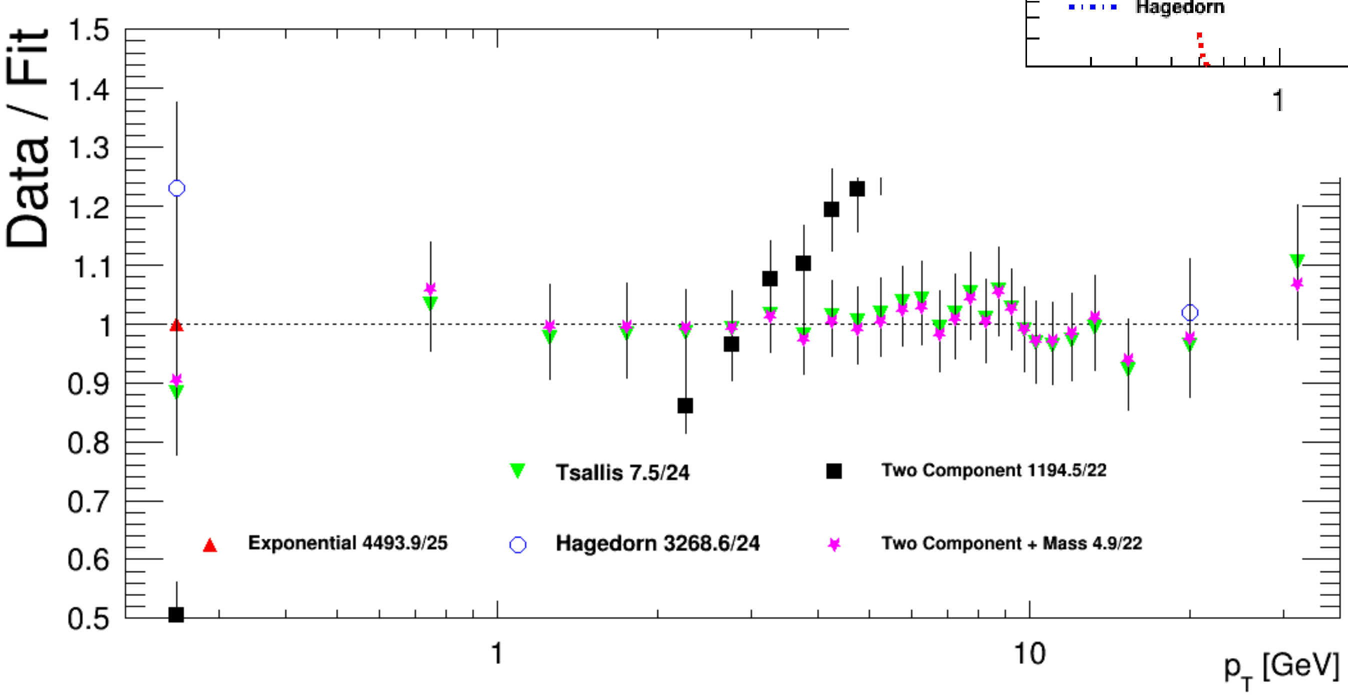
And what about LHCb data?

$$A_1 e^{-m_T/T_e} + \frac{A_2}{(1 + \frac{m_T^2}{T^2 \cdot N})^N}$$

LHCb 7 TeV, B^0 spectra



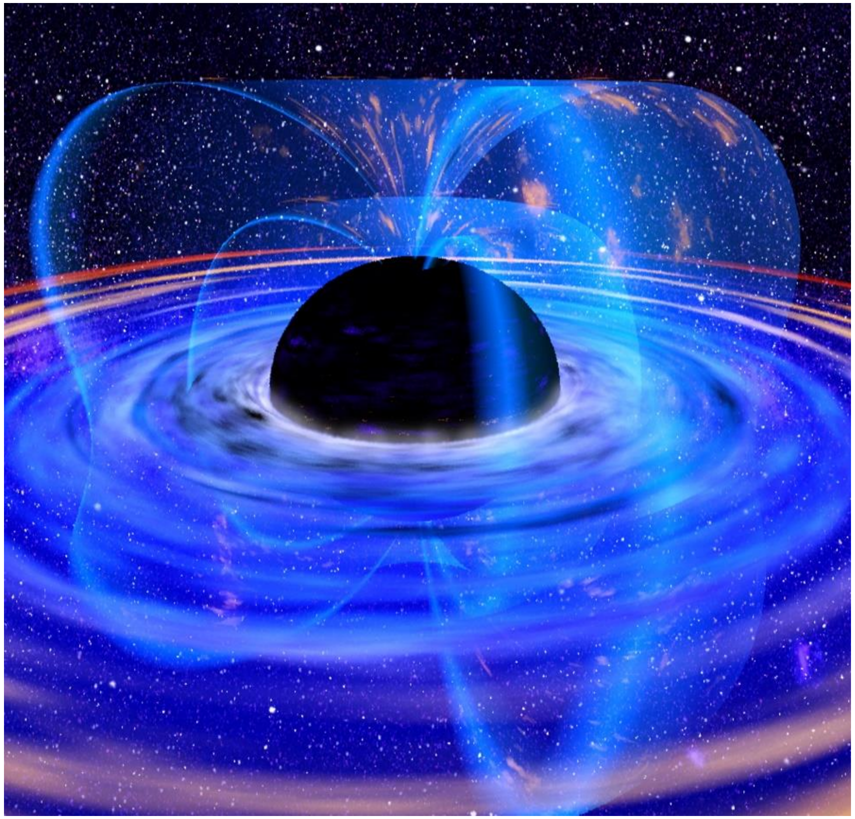
The mass dependence is also crucial for the fit

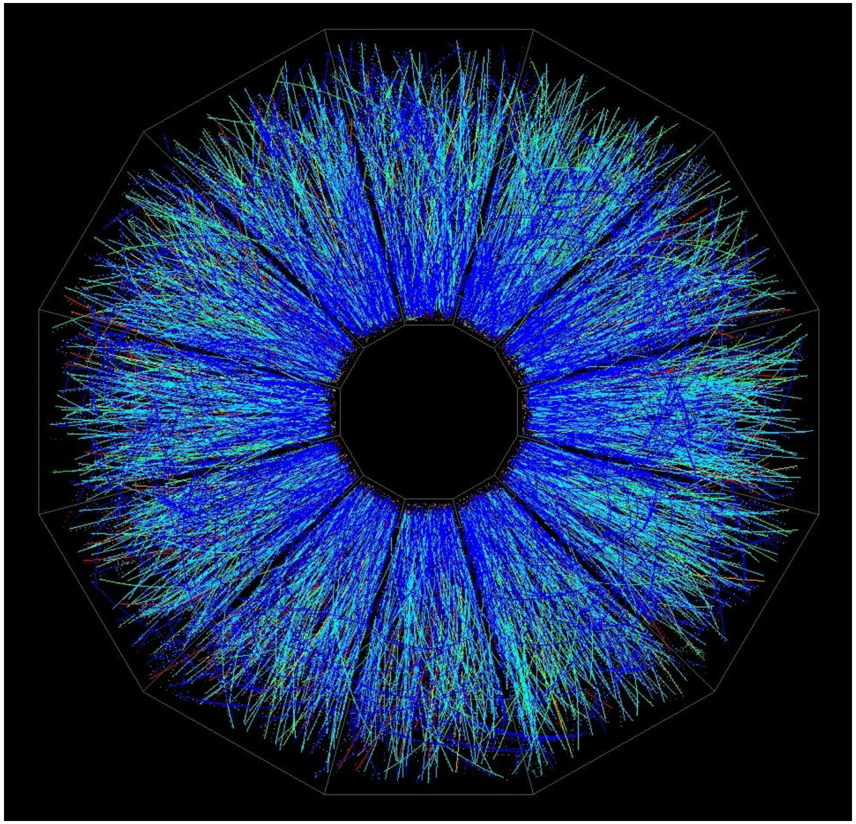


A17

A link between General Relativity and QCD? solution to some of the LHC puzzles?

Black holes ⟷ Heavy-ion collisions





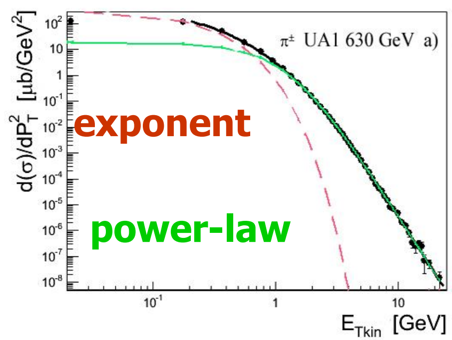
In astrophysics, Hawking-Unruh radiation has so far never been observed
The thermal hadron spectra in high energy collisions may thus indeed be the first experimental instance of such radiation, though in strong interaction instead of gravitation.

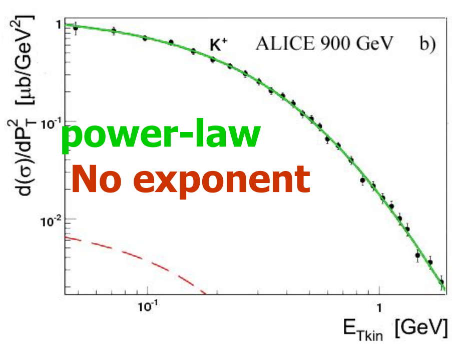
Type of produced particle

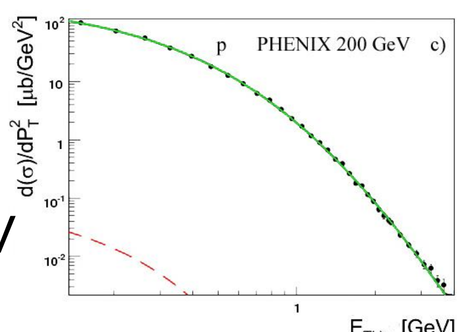
•QCD-fluctuations are democratic to quark flavour while valence quark radiation can't produce heavy flavours

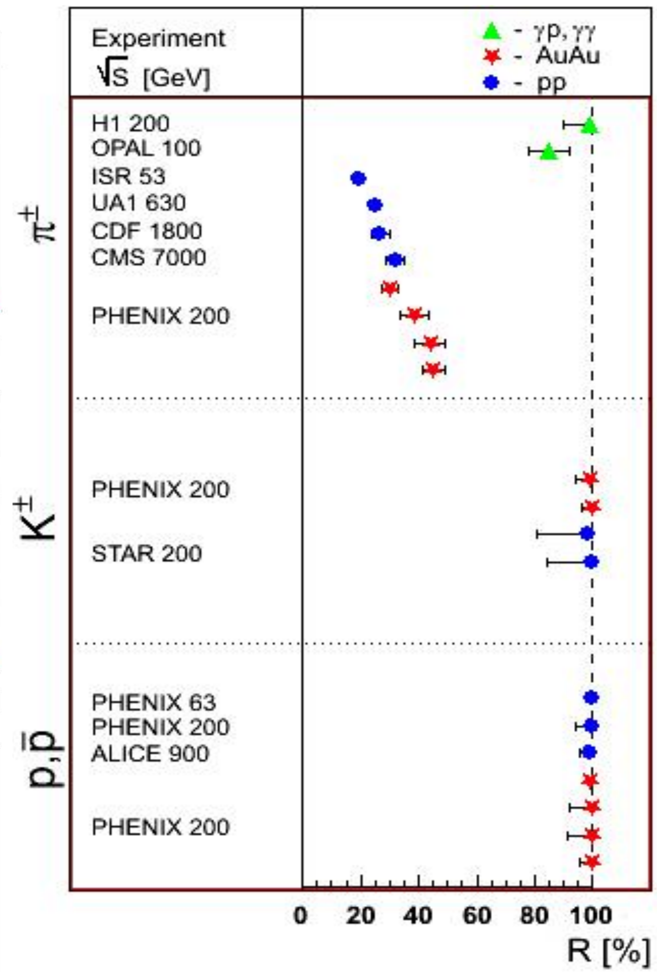
Prediction: Kaon (and J/ψ) spectra should have less exponential contribution then pion

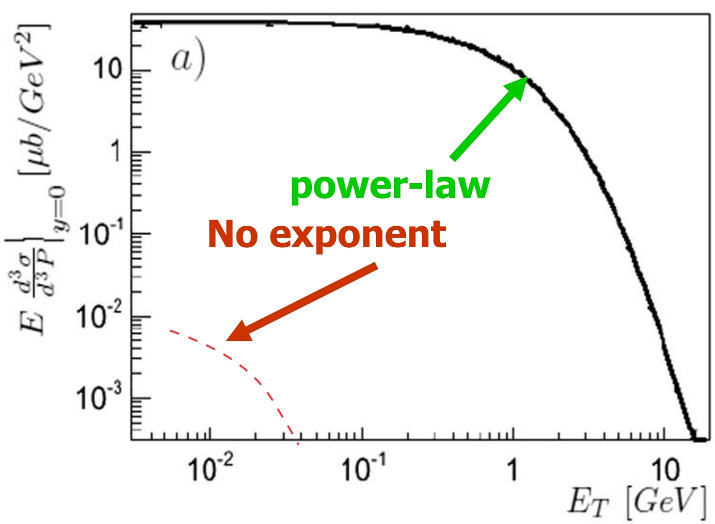
$$R = \frac{\text{Power-law}}{\text{Exp + Power-law}}$$







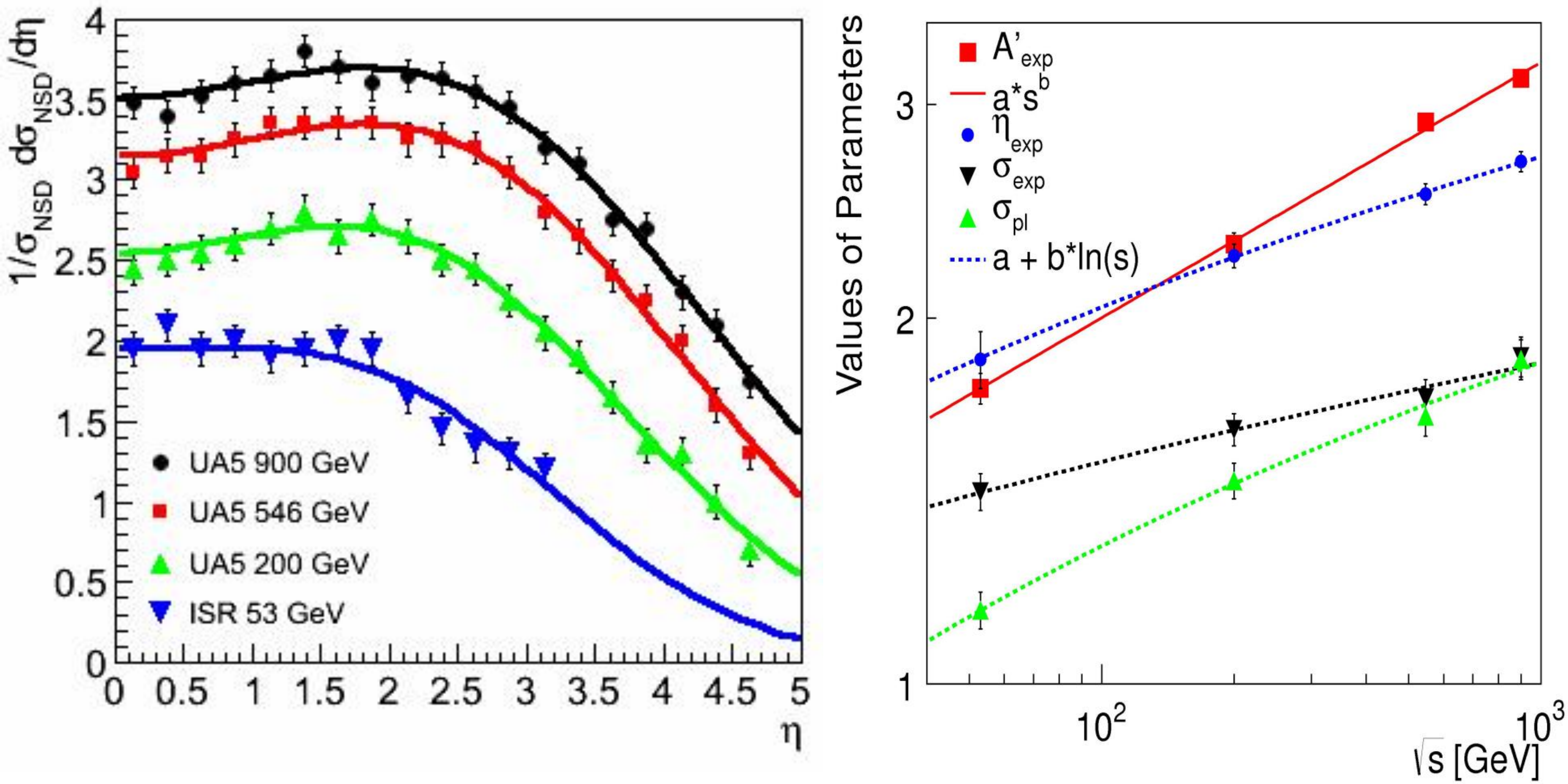




J/ψ spectra CDF √s = 1.96 TeV

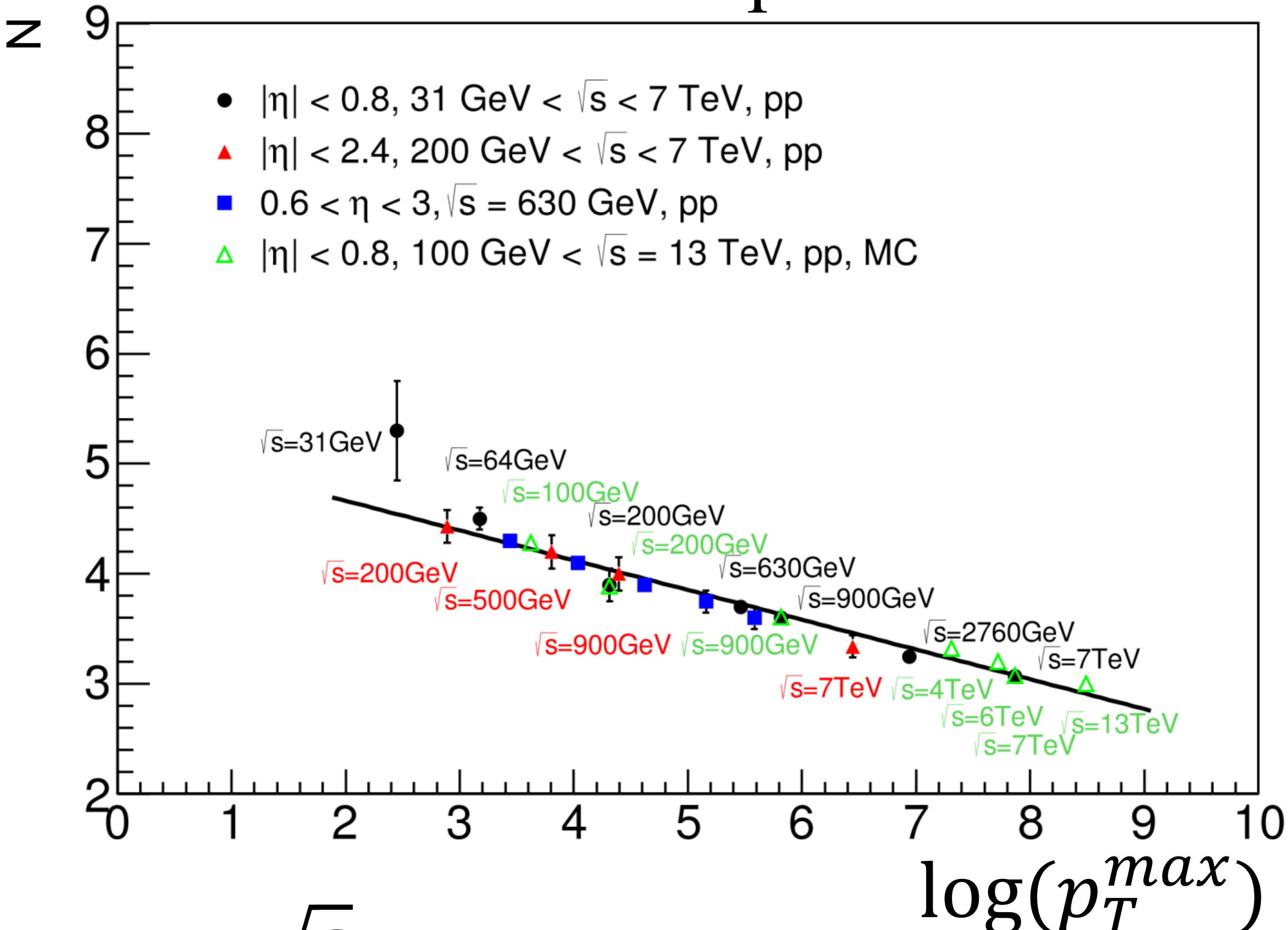
Scaling of distributions

Data on pseudorapidity distributions *measured under the same experimental conditions* by the UA5 Detector.



A10

Power-law parameter N



$$p_T^{max} = \frac{\sqrt{s}}{2}\sin[2 * tan^{-1}(\exp(-|\eta|))]$$

Larger N corresponds to smaller p_T^{max}. That should correspond to the x → 1 limit of PDFs, where the decrease of the perturbative cross section is modified by the fall-off of the parton distribution functions

Universal dependence

$$\boldsymbol{T}(\boldsymbol{s};\boldsymbol{\eta}) \sim C * T(s_0;\eta = 0)\, s^{\lambda/2} \exp(\lambda\eta)$$

Universal dependence

$$\boldsymbol{T}(\boldsymbol{s};\boldsymbol{\eta}) \sim C * T(s_0;\eta = 0)\, s^{\lambda/2} \exp(\lambda\eta)$$

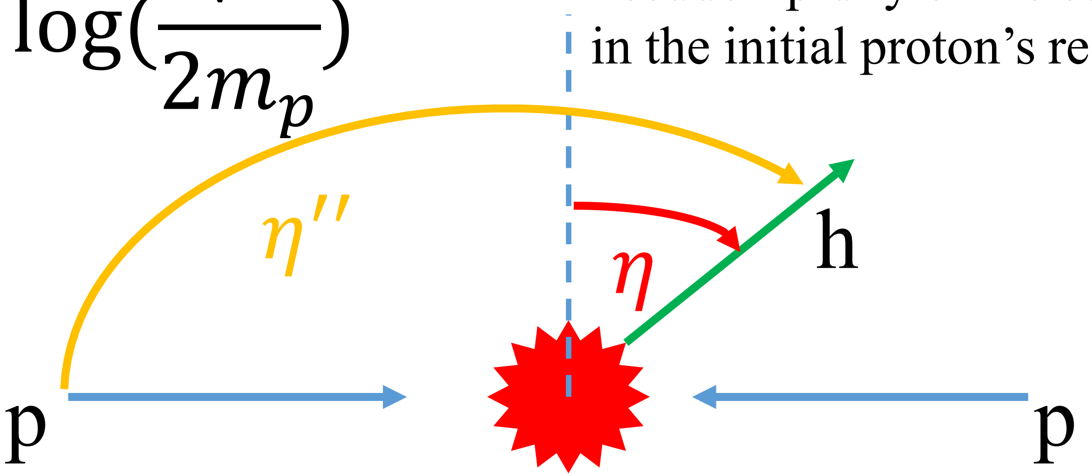
$$T(s;\eta) \sim C * T\,(s_0;\eta = 0) \exp(\lambda\eta + \ln s^{\lambda/2})$$

$$T(s;\eta) \sim C * T\,(s_0;\eta = 0) \exp(\lambda(\eta + \ln s^{1/2}))$$

$$\boldsymbol{T}(\boldsymbol{s};\boldsymbol{\eta}) = \boldsymbol{T}(\boldsymbol{\eta}'') \sim C * T\,(s_0;\eta = 0) \exp(\lambda\eta'')$$

$$\eta'' = |\eta| + \log(\frac{\sqrt{s}}{2m_p})$$

Pseudorapidity of the secondary hadron in the initial proton's rest frame.



An example: electric field

The force:

$$F = ma = eE$$

The acceleration:

$$a = \frac{eE}{m}$$

The rate:

$$\boxed{R \sim \exp\left(-\frac{2\pi m}{a}\right) = \exp\left(-\frac{2\pi m^2}{eE}\right)}$$

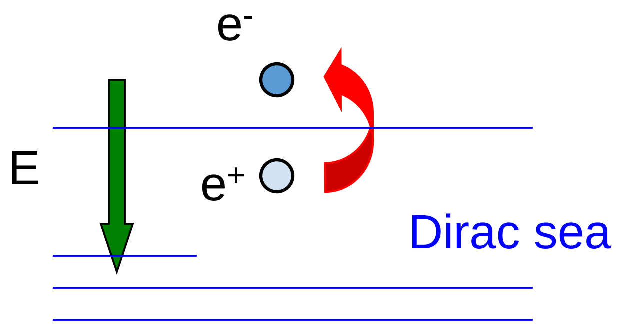
What is this?

Schwinger formula for the rate of pair production;

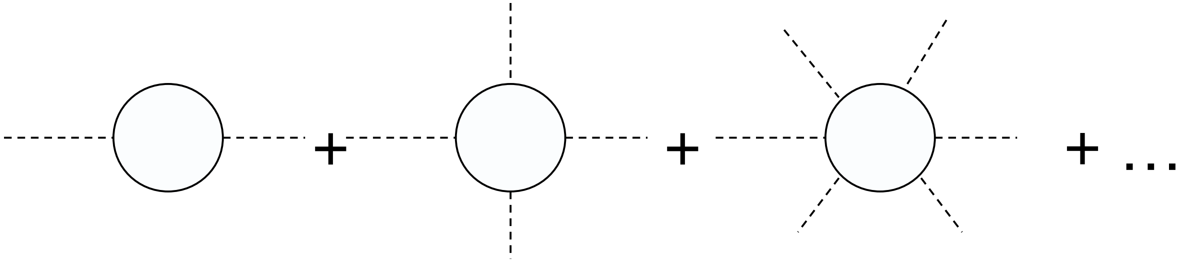
an exact non-perturbative QED result

factor of 2: contribution from the field

The Schwinger formula



$$R \sim \exp\left(-\frac{\pi m^2}{eE}\right)$$



A13

Thermal radiation can be understood as a consequence of tunneling through the event horizon

Let us start with relativistic classical mechanics:

$$v(t) = \frac{a\,t}{\sqrt{1 + a^2 t^2}}$$

velocity of a particle moving with an acceleration a

classical action:

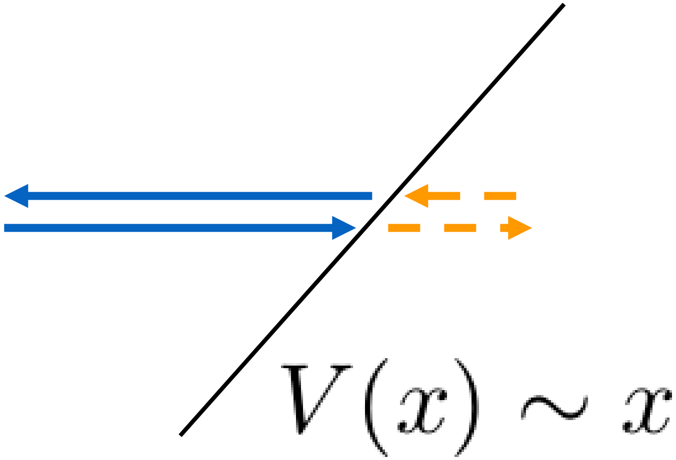
$$S(\tau) = -m \int^{\tau} dt\, \sqrt{1 - v^2(t)}$$

$$= -\frac{m}{a} \operatorname{arcsinh}(a\,\tau)$$

it has an imaginary part…

well, now we need some quantum mechanics, too:

$$\mathrm{Im}\, S(\tau) = \frac{m\,\pi}{a}$$



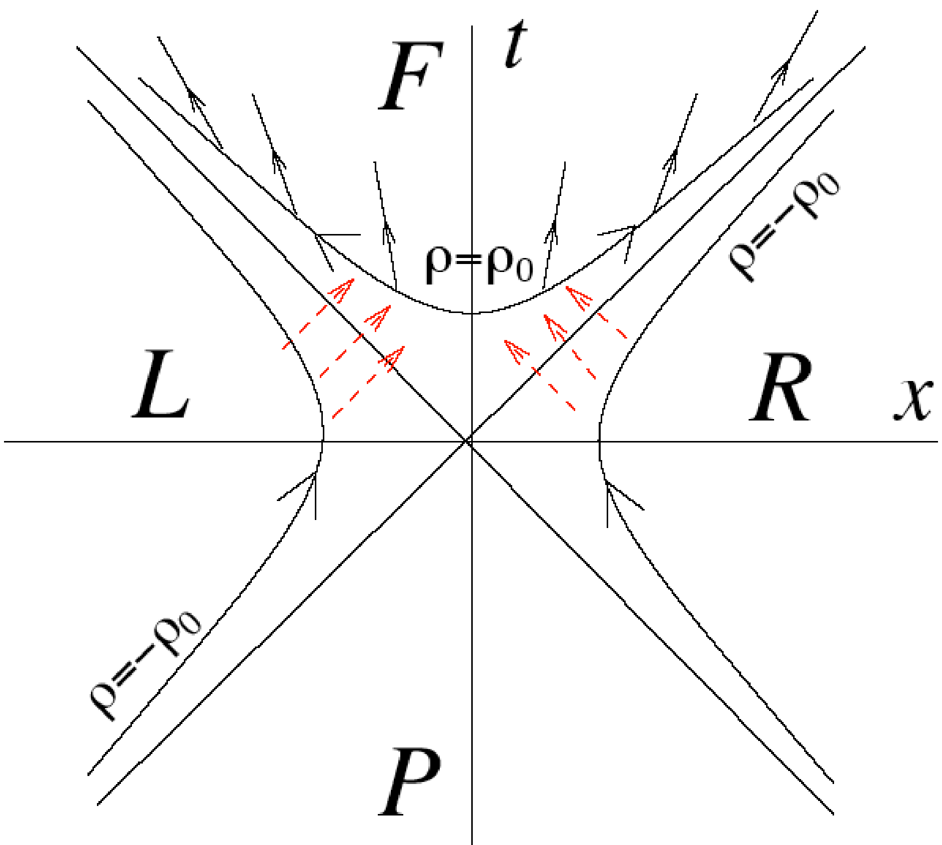
The rate of tunneling under the potential barrier:

$$R \sim \exp(-2\ \mathrm{Im} S) = \exp\left(-\frac{2\pi\ m}{a}\right)$$

This is a Boltzmann factor with $T = \dfrac{a}{2\pi}$

Quantum thermal radiation at RHIC

$$\boxed{T = \frac{a}{2\pi} \simeq \frac{Q_s}{2\pi}}$$

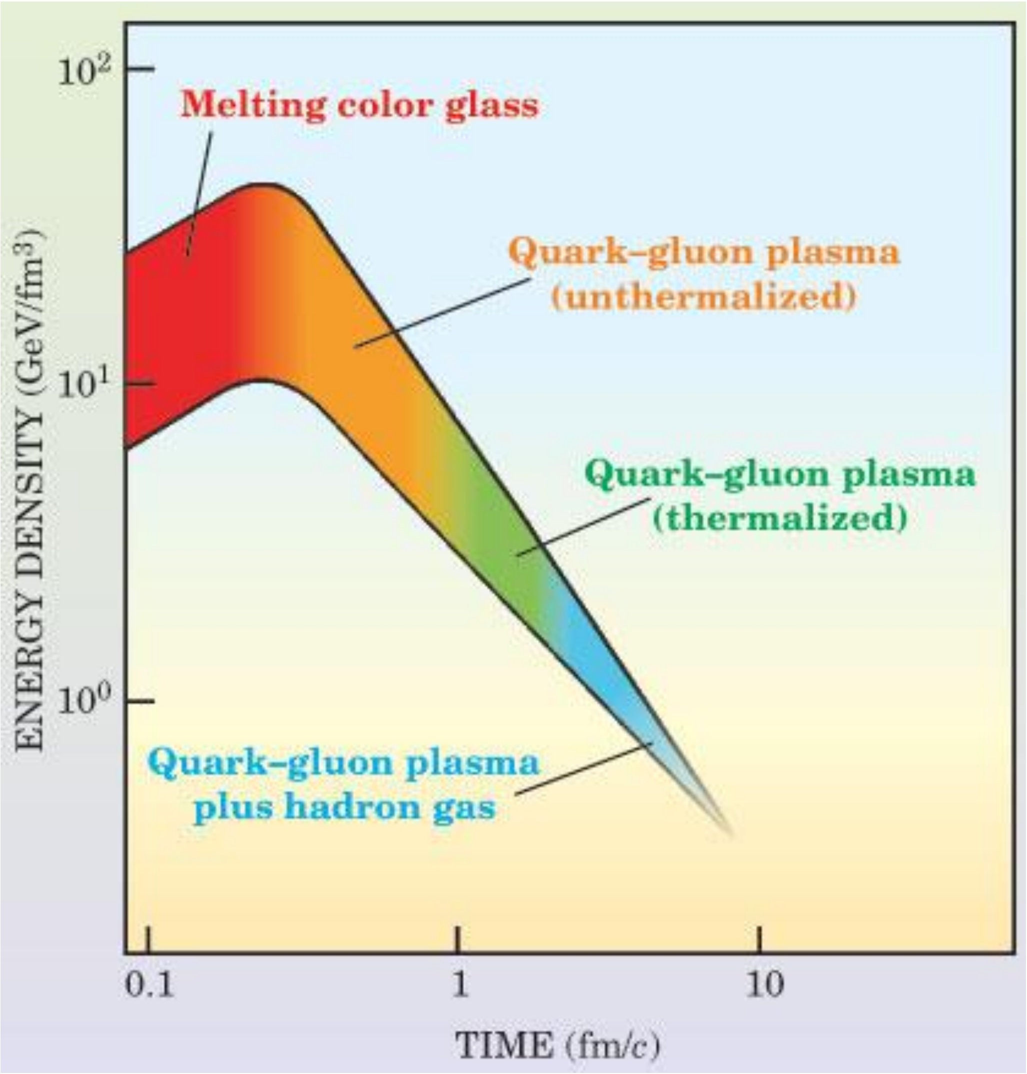


Rindler and Minkowski spaces

The event horizon emerges due to the fast decceleration $a \simeq Q_s$ of the colliding nuclei in strong color fields;

Tunneling through the event horizon leads to the thermal spectrum

The emerging picture



Big question:

How does the produced matter thermalize so fast?

Non-perturbative phenomena in strong fields?

T. Ludlam, L. McLerran, Physics Today '03