

# Two component model for hadroproduction in high energy collisions

*Alexander Bylinkin*

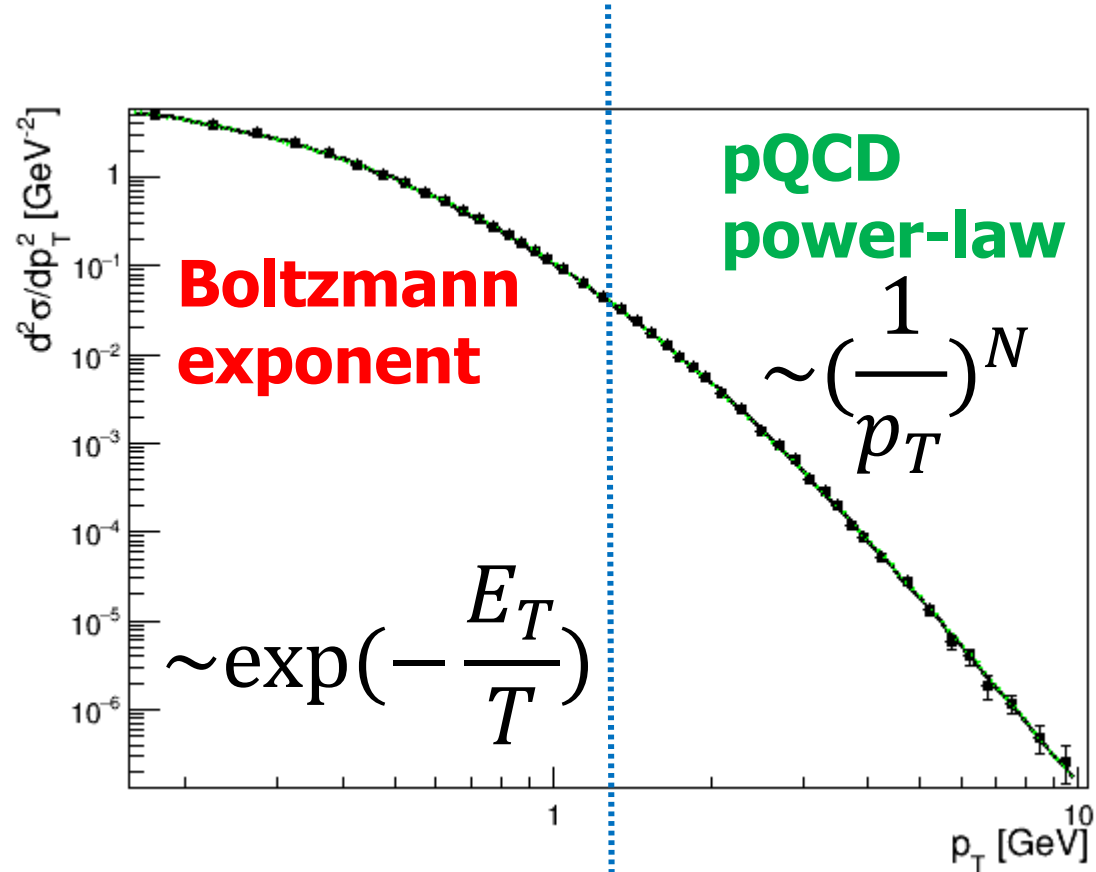
**Moscow Institute of Physics and Technology, Moscow, Russia**

International Conference on High Energy Physics,  
3-10 August, Chicago, USA

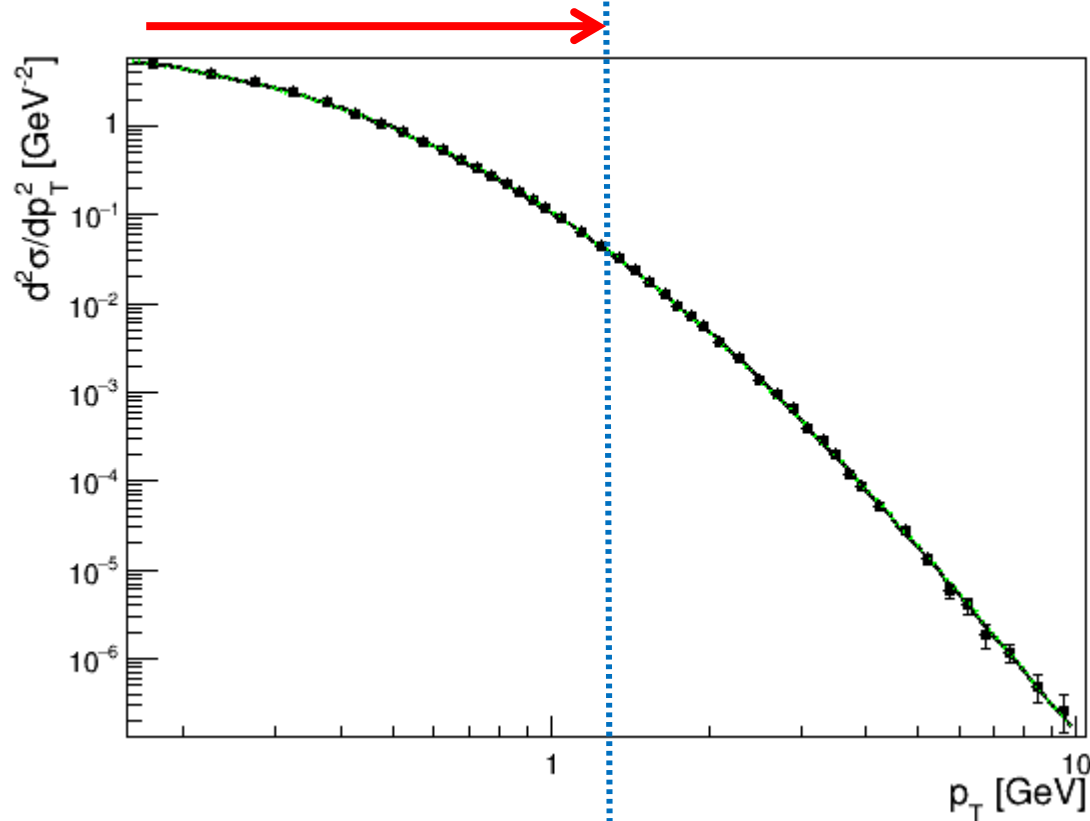
# Outline

- Particle production spectra and phenomenological models
- Two component model and spectra variations with:
  - Type of the collisions
  - Type of produced particle
  - Energy
  - Multiplicity
  - Pseudorapidity
- Predictions and possible interpretation

# Particle production spectra

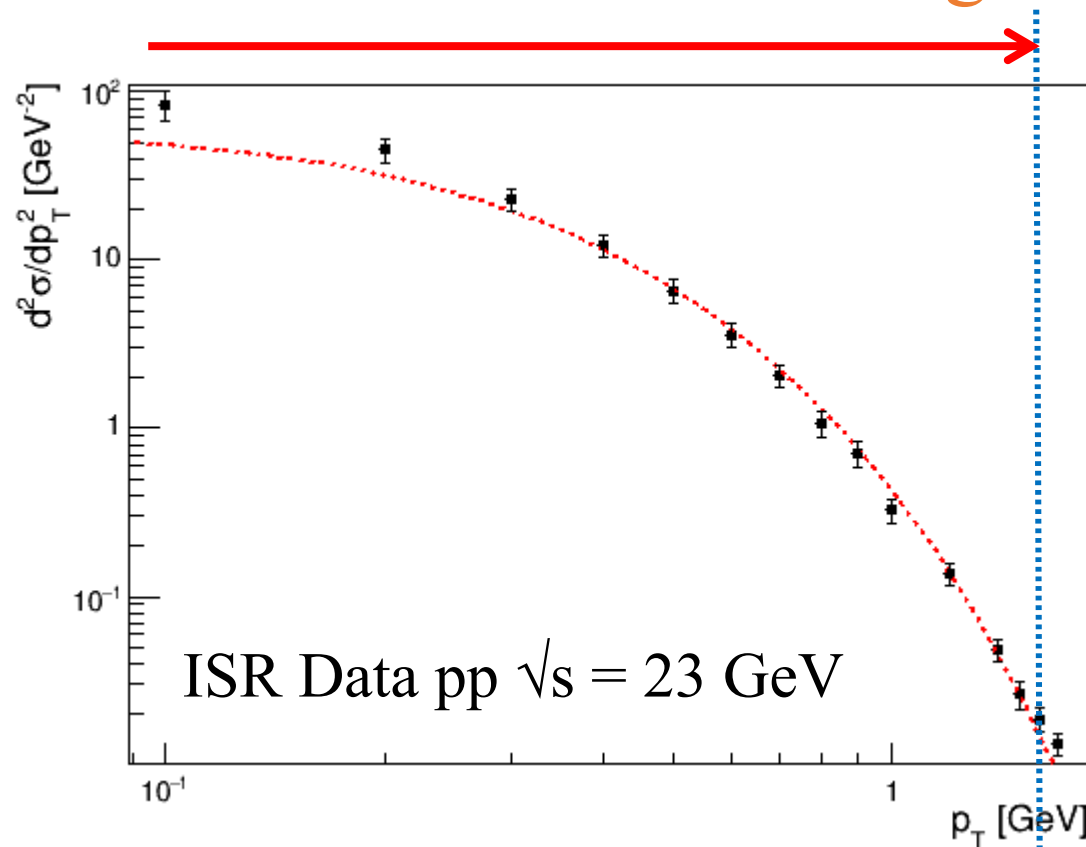


# Particle production spectra: Phenomenological models



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

# Particle production spectra: Phenomenological models

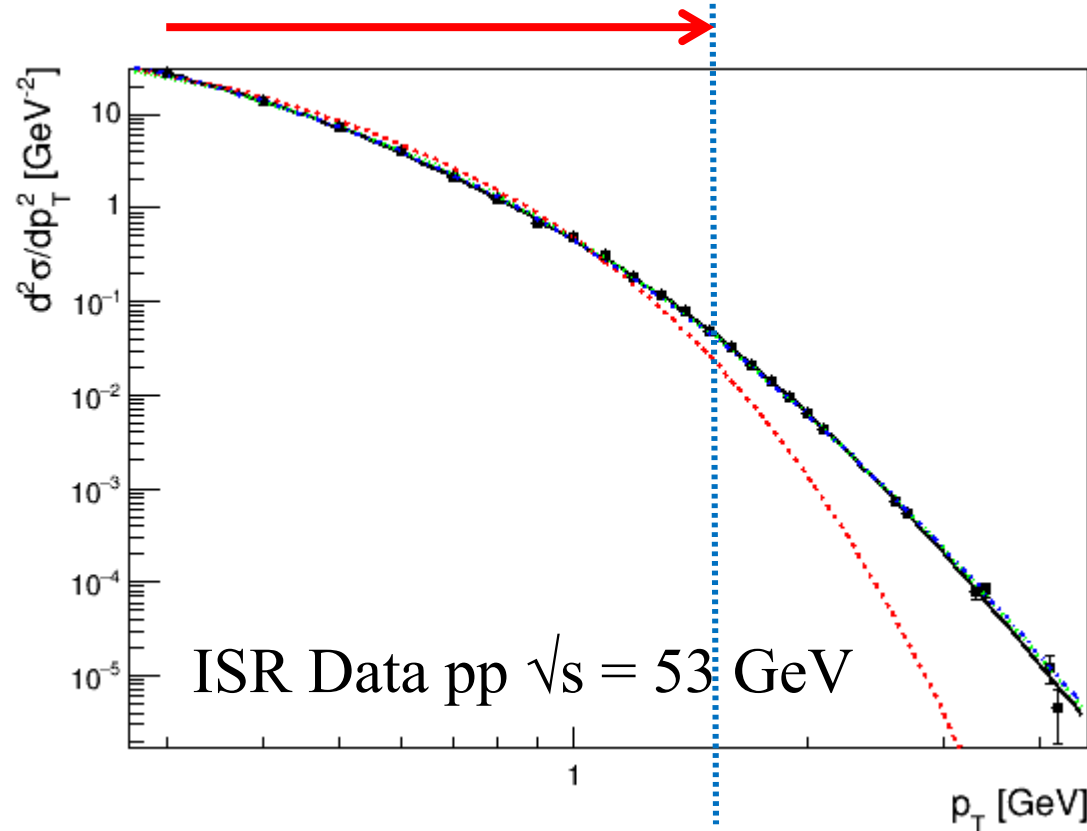


1952 E. Fermi  
 $\sim \exp\left(-\frac{E_T}{T}\right)$

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

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

# Particle production spectra: Phenomenological models

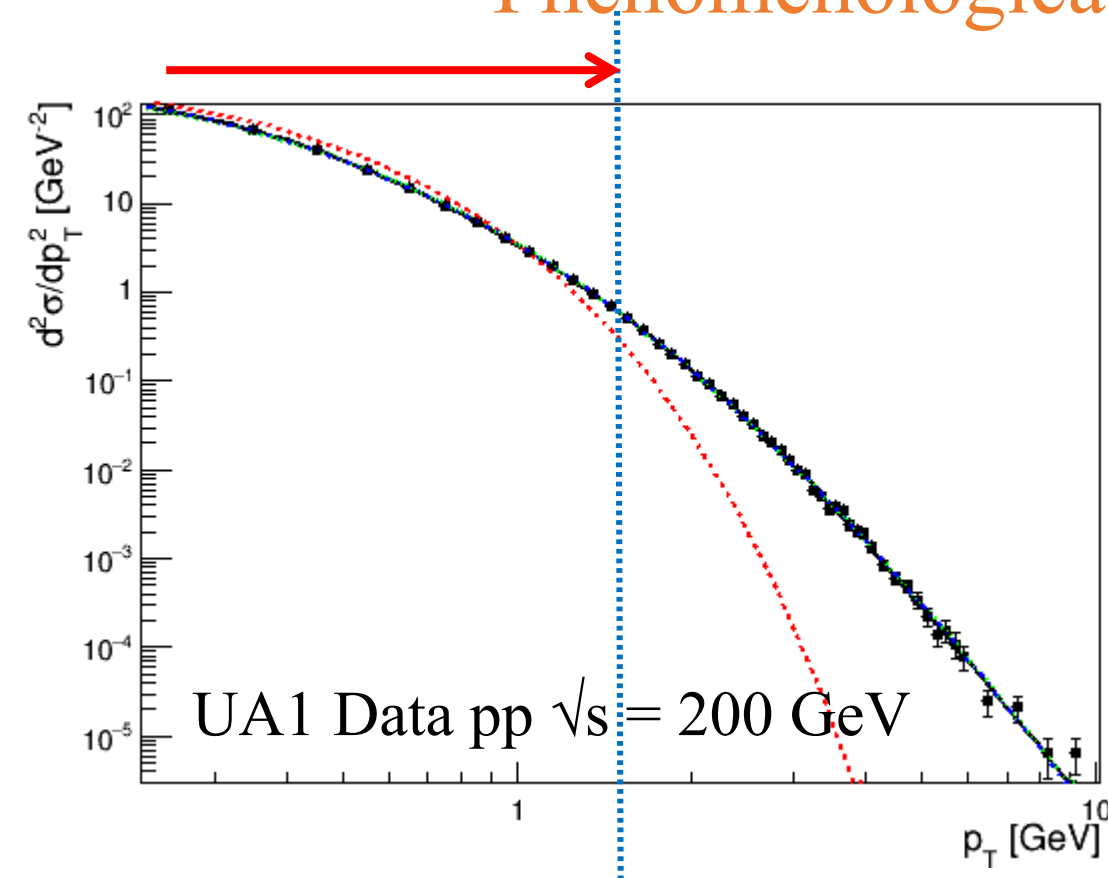


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 $\sim \exp\left(-\frac{E_T}{T}\right)$

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



1952 E. Fermi  
 $\sim \exp\left(-\frac{E_T}{T}\right)$

1983 R. Hagedorn  
 $\sim \left(\frac{p_0}{p_0 + p_T}\right)^N$

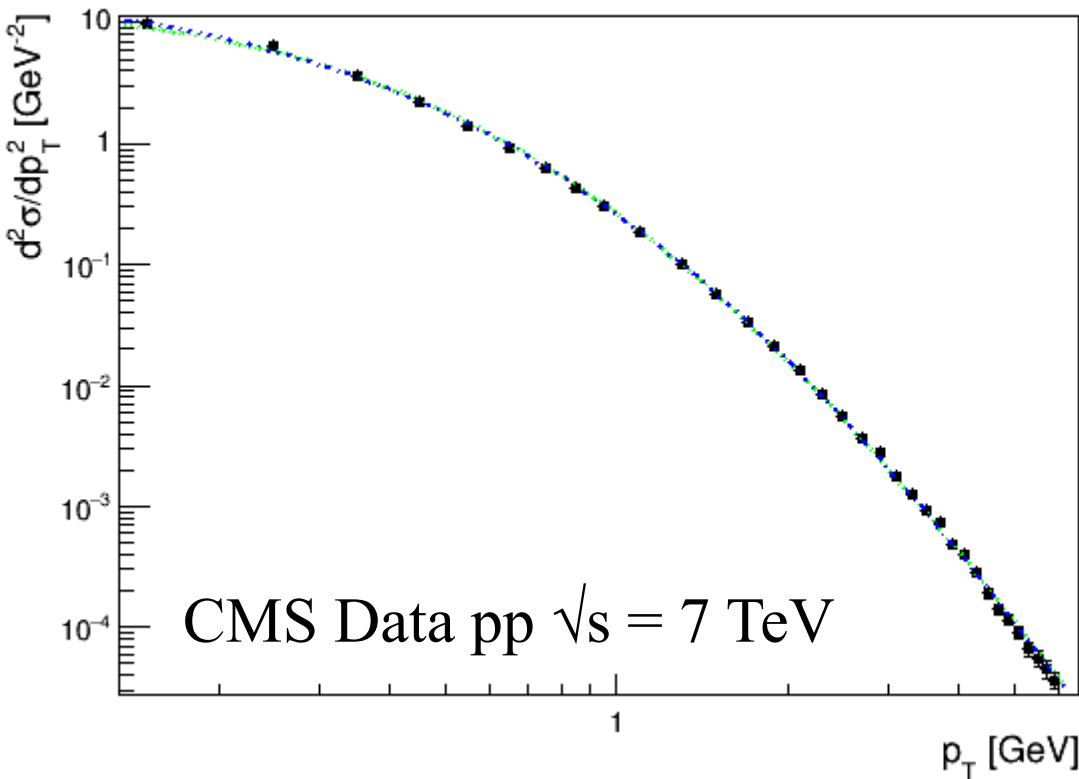
1987 C. Tsallis  
 $\sim \left(\frac{1}{1 + \frac{E_T}{T \cdot N}}\right)^N$

Further measurements have shown that high- $p_T$  particles observe different hadroproduction dynamics (pQCD power-law).

Modification of the statistical approach was necessary.

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

# Particle production spectra: Phenomenological models



1952 E. Fermi  
 $\sim \exp\left(-\frac{E_T}{T}\right)$

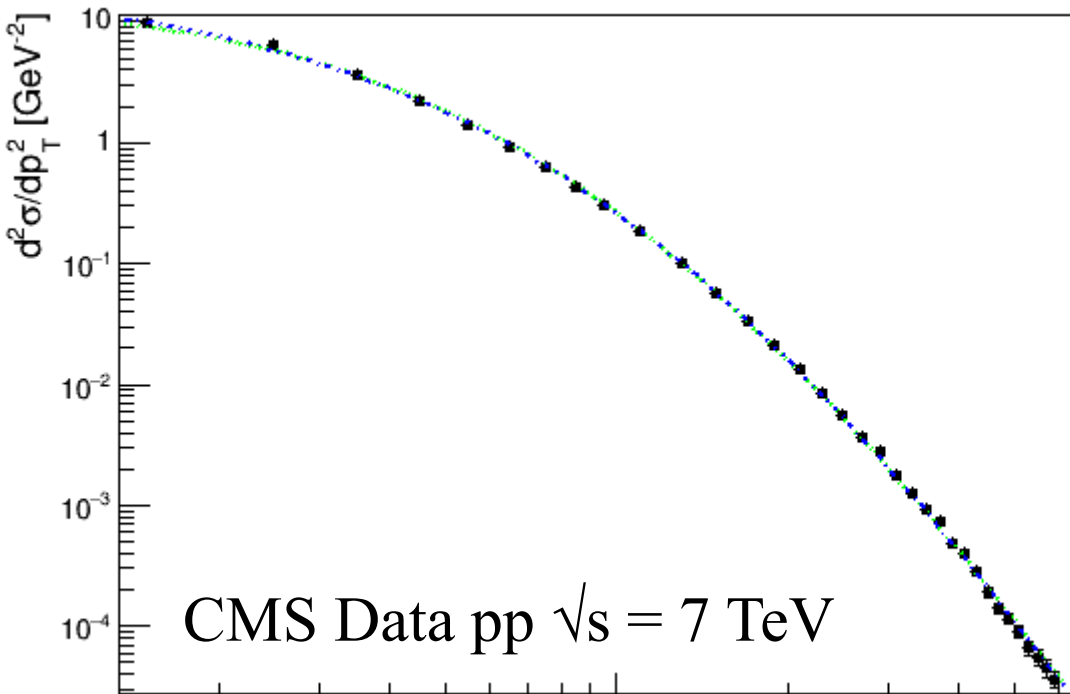
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2010 ???



# Particle production spectra: Phenomenological models

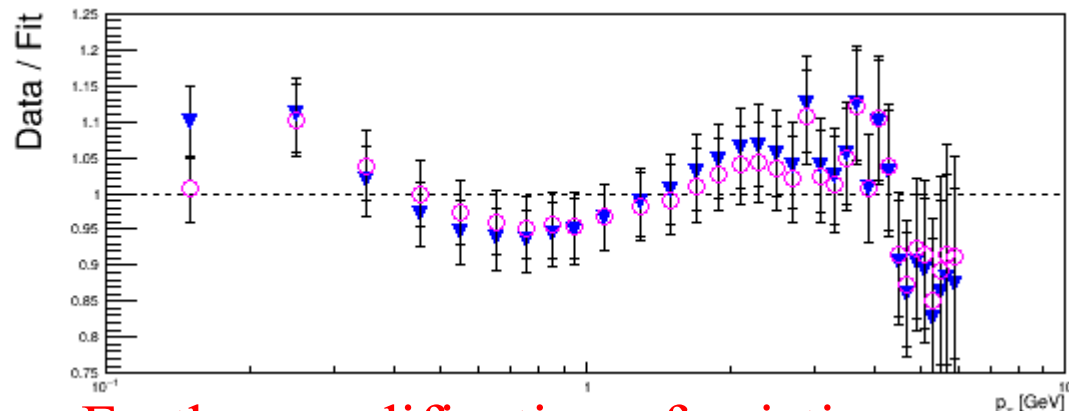


1952 E. Fermi  
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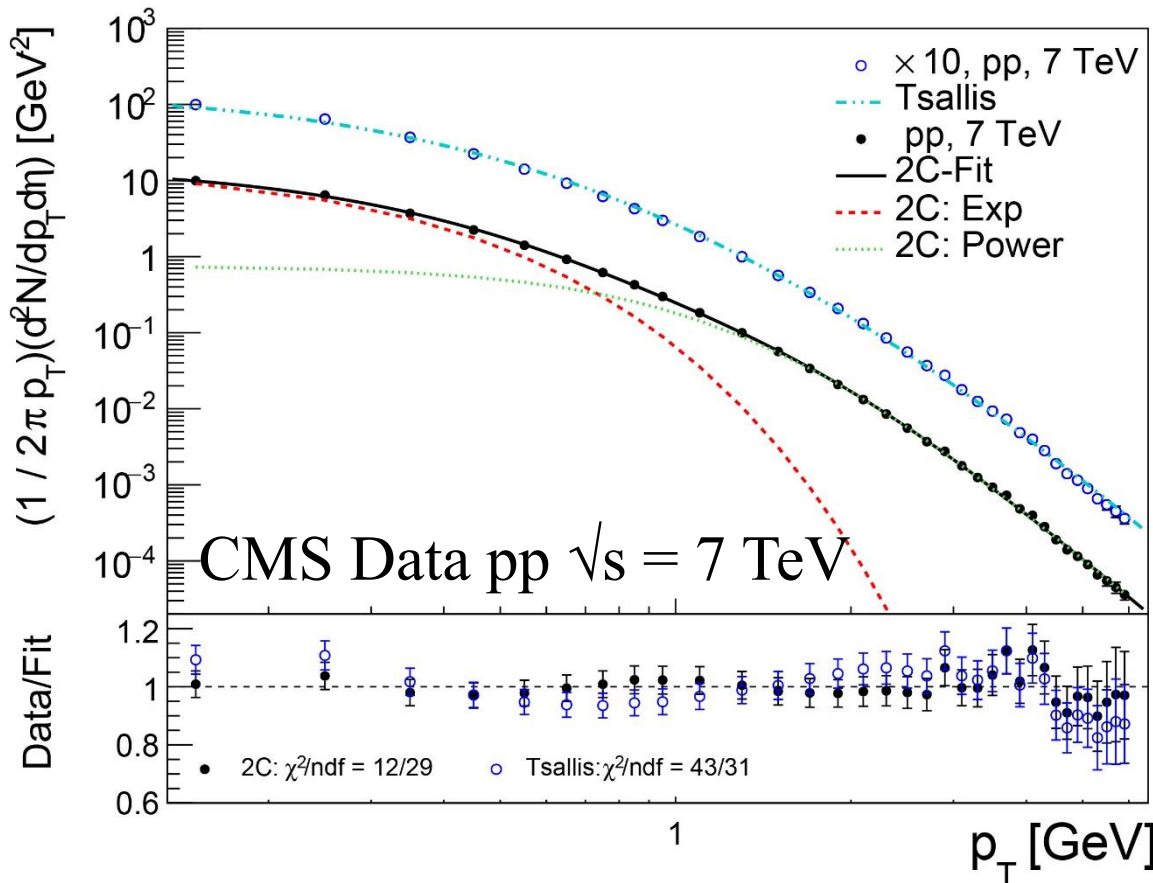
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2010 ???



Further modification of existing approaches is needed.

# Particle production spectra: Phenomenological models



1952 E. Fermi  
 $\sim \exp(-\frac{E_T}{T})$

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

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2010 A. Bylinkin &  
 A. Rostovtsev

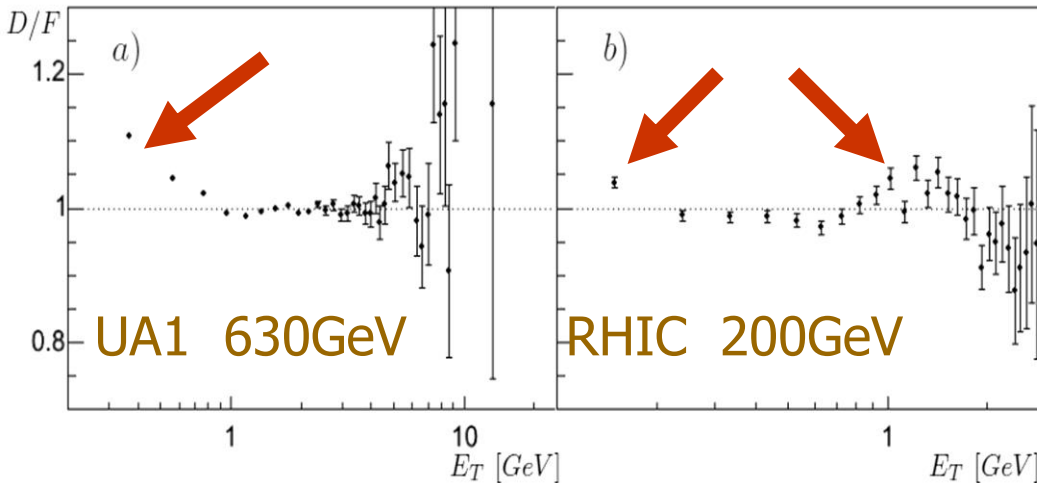
$$\frac{d^2\sigma}{\pi dy(dp_t^2)} = A_1 \exp(-E_{Tkin}/T_e) + \frac{A_2}{(1 + \frac{P_T^2}{T^2 N})^N}$$

Not just increased number of free parameters

# Not just increased number of free parameters

## Systematic defects with traditional approach in all datasets

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



$\chi^2/\text{ndf} = 288/44$      $\chi^2/\text{ndf} = 87/25$

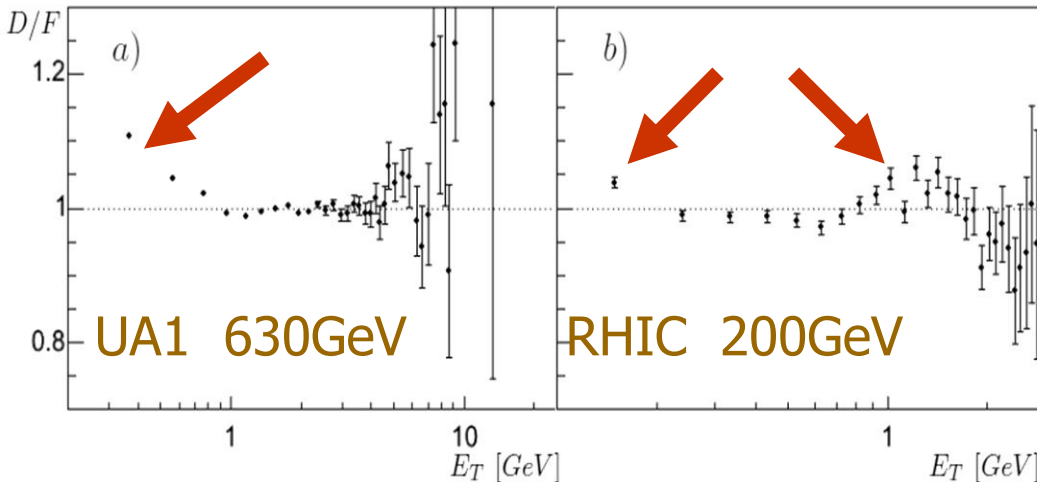
Tsallis fit

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

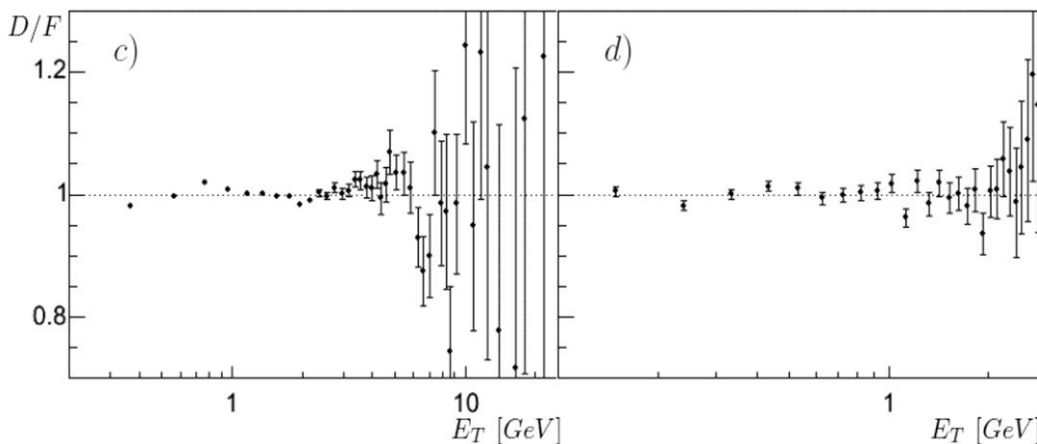
# Not just increased number of free parameters

## Systematic defects in the data description using traditional approach

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



$\chi^2/\text{ndf} = 288/44$      $\chi^2/\text{ndf} = 87/25$



$\chi^2/\text{ndf} = 54/42$      $\chi^2/\text{ndf} = 22/23$

New approach provides much better description of the data.

Tsallis fit

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

New approach

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

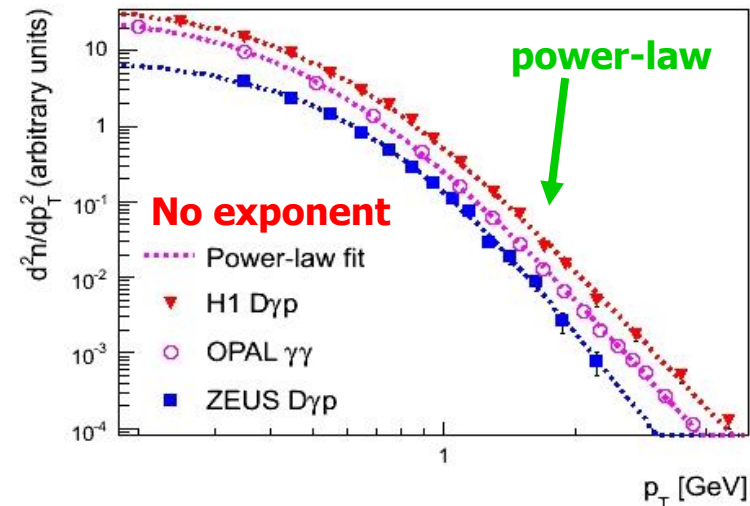
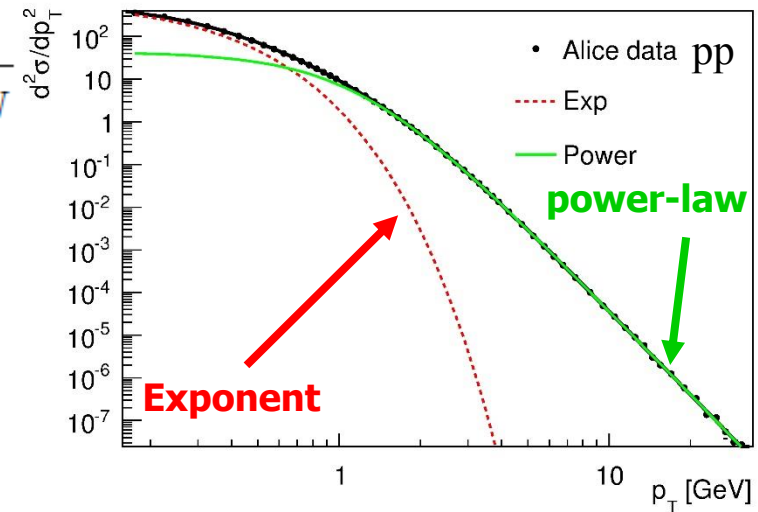
A. Bylinkin and A. Rostovtsev  
Phys. Atom. Nucl 75 (2012) 999-1005

Two components  $\longleftrightarrow$  Two mechanisms

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

# Two components $\leftrightarrow$ Two mechanisms

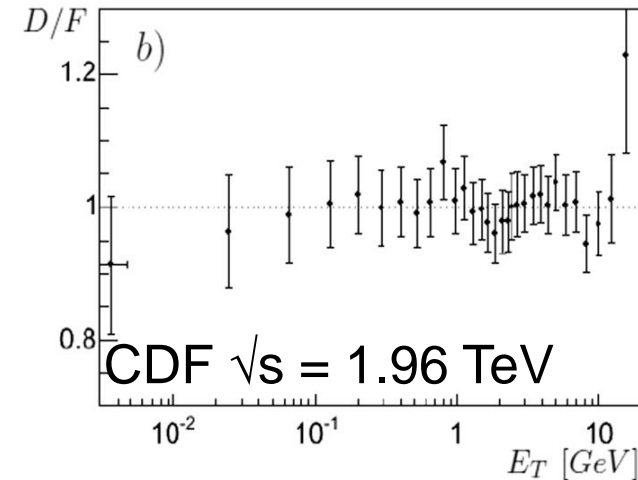
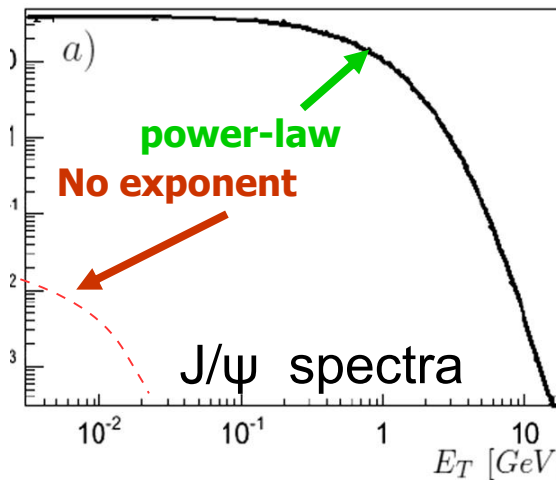
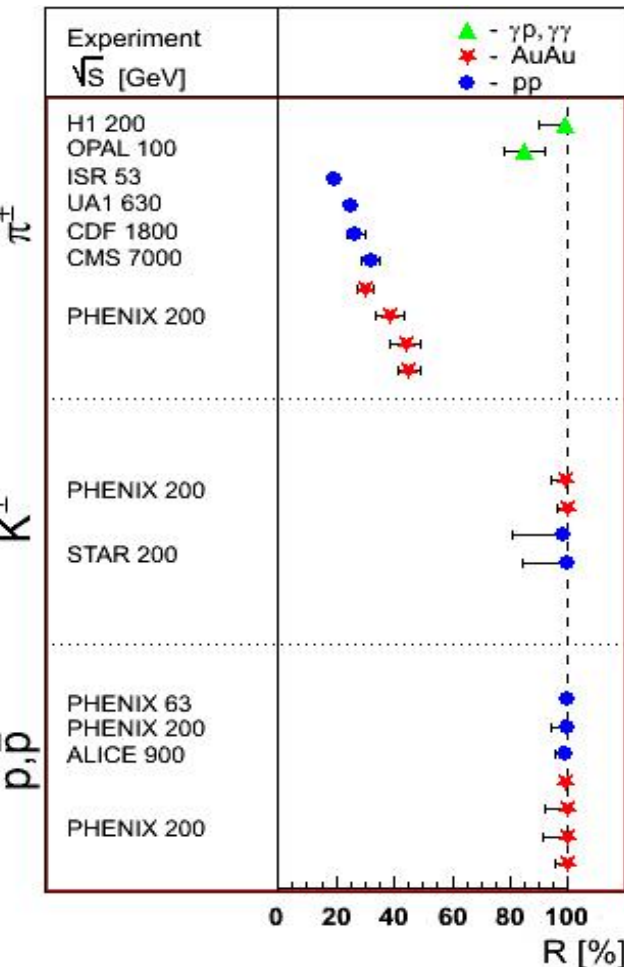
$$\frac{d^2\sigma}{\pi dy(dp_t^2)} = A_1 \exp(-E_{Tkin}/T_e) + \frac{A_2}{(1 + \frac{P_T^2}{T^2 N})^N}$$



# Two components $\leftrightarrow$ Two mechanisms

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

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



**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

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

Two components behave differently as a function of experimental setup:

calculated separately for exponential and power-law terms

- Charged particle densities  $d\sigma/d\eta$
- Mean transverse momenta  $\langle p_T \rangle$
- Collision energy,  $s$
- Charge particle multiplicity,  $N_{ch}$
- Pseudorapidity region,  $\eta$

# Energy dependences

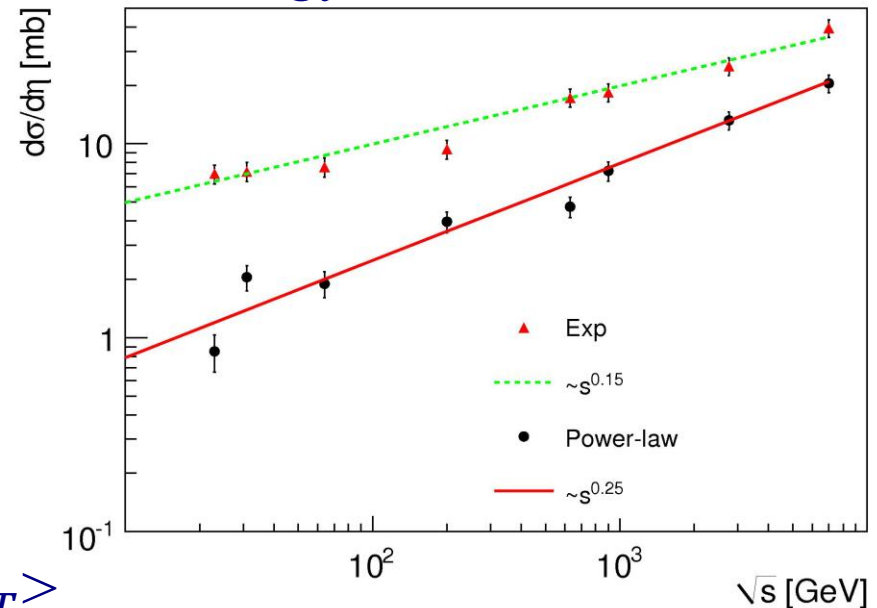
Charged particle densities  $d\sigma/d\eta$  grow with energy  $\sim s^\Delta$  :

- **Power-law:**  $\Delta \sim 0.25$

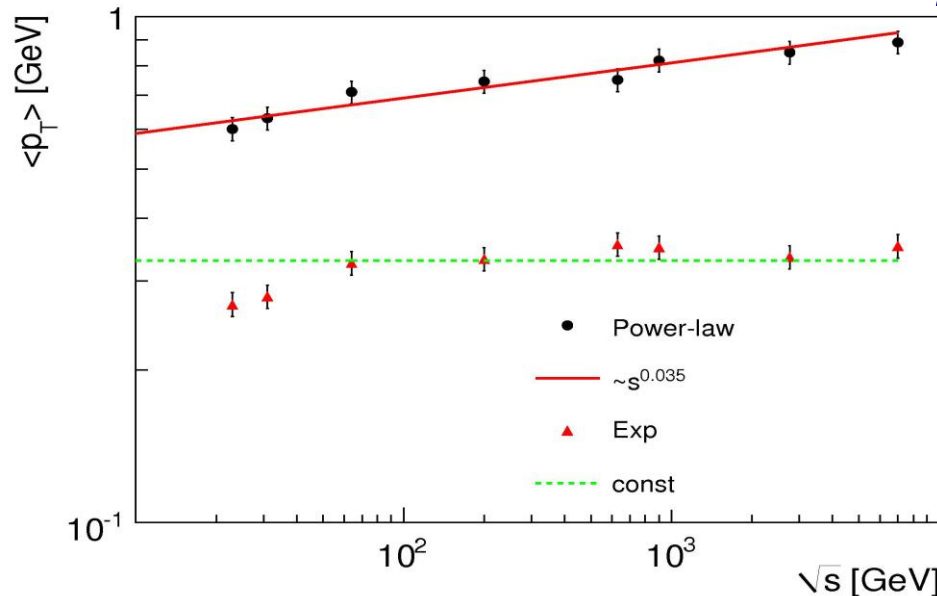
the pQCD (BFKL) pomeron after the resummation of the NLL corrections.

- **Exponent:**  $\Delta \sim 0.15$

strongly affected by absorptive corrections.



Mean transverse momenta  $\langle p_T \rangle$



- **Power-law:**  $\sim s^{0.05}$

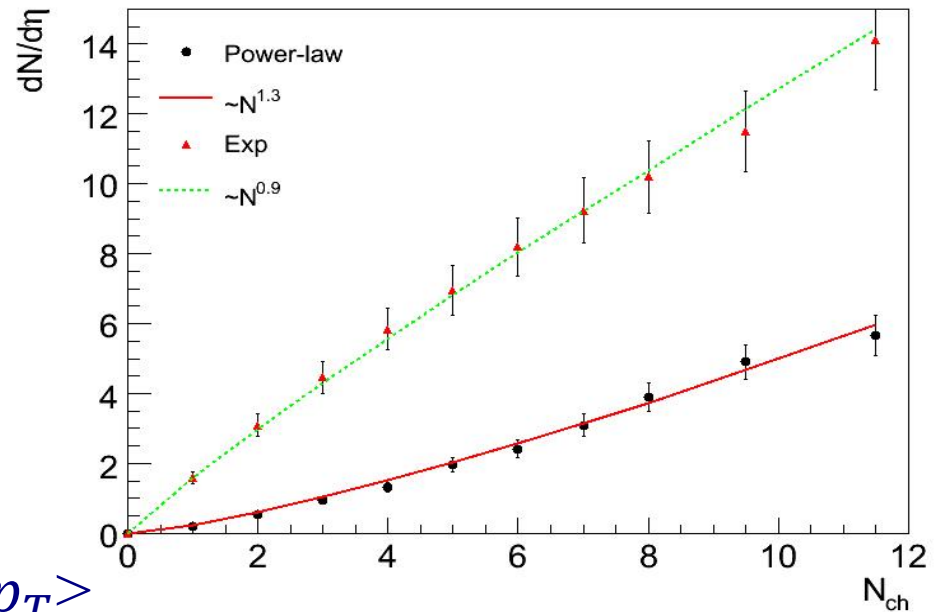
growth of the typical transverse momenta of mini-jets

- **Exponent:** constant

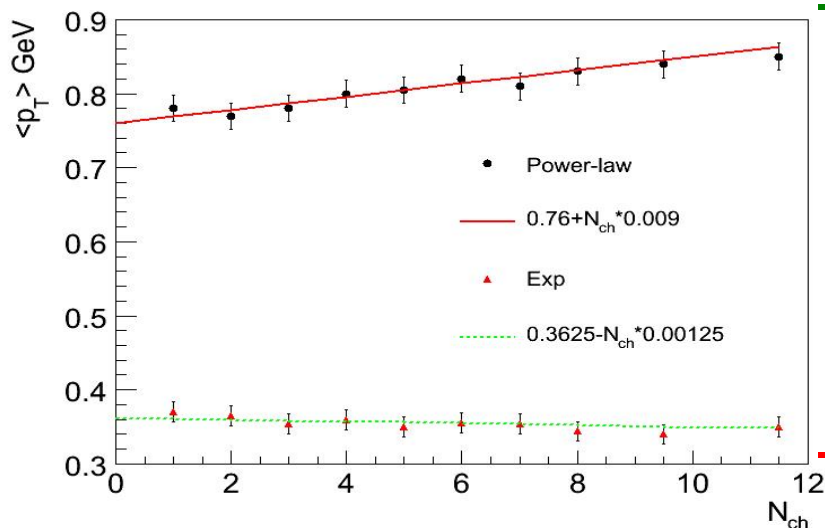
# Multiplicity dependences

## Charged particle densities $d\sigma/d\eta$ :

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



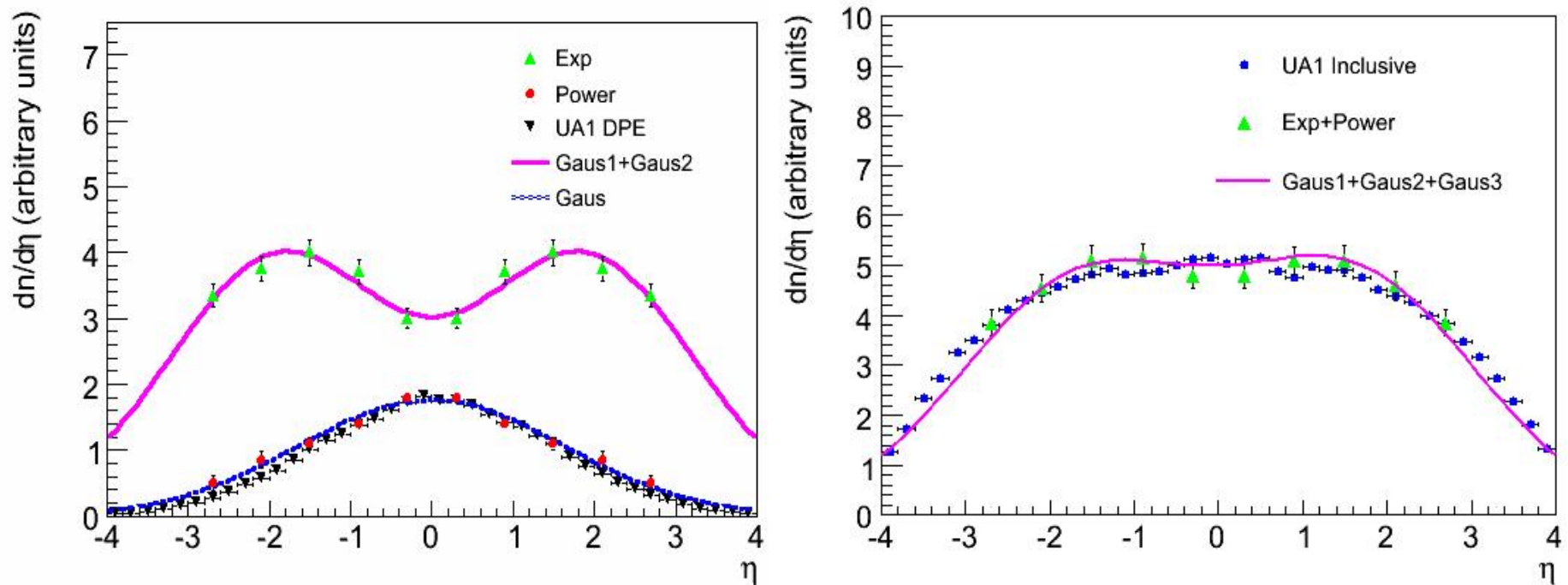
## Mean transverse momenta $\langle p_T \rangle$



- **Power-law:** Within the Regge theory the higher multiplicity events have a larger number,  $n$ , of 'cut' pomerons ( $N_{ch} \sim n$ ). Accounting for mini-jet contribution the  $\langle p_T \rangle$  should increase with  $N_{ch}$  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 ( $\eta \sim 0$ )**, while those coming from the **proton fragmentation** are expected to dominate at **high values of  $\eta$**  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*

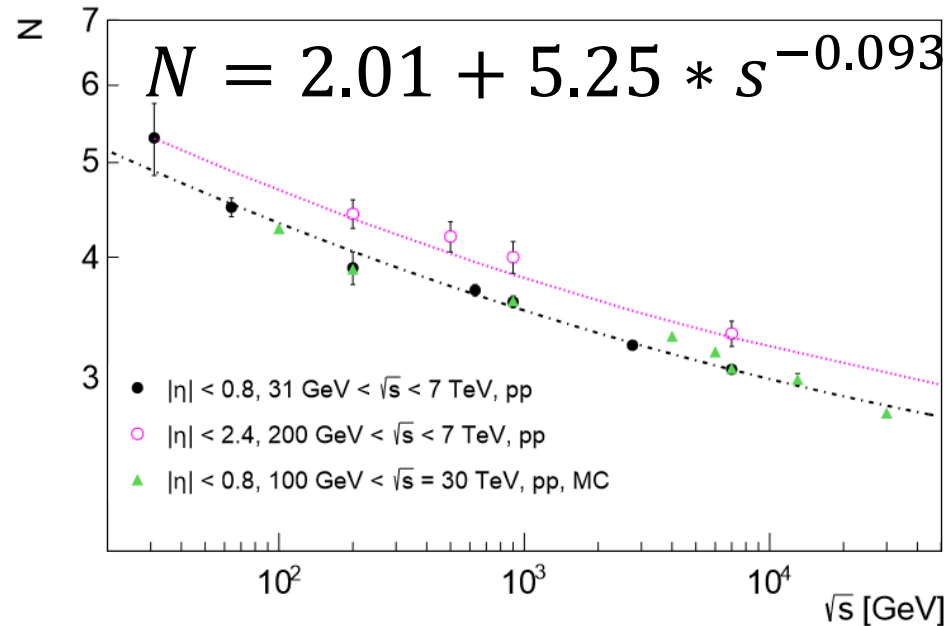
→ **existence of plateau in a pseudorapidity distribution**

# Parameter dependences

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

# Parameter dependences

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



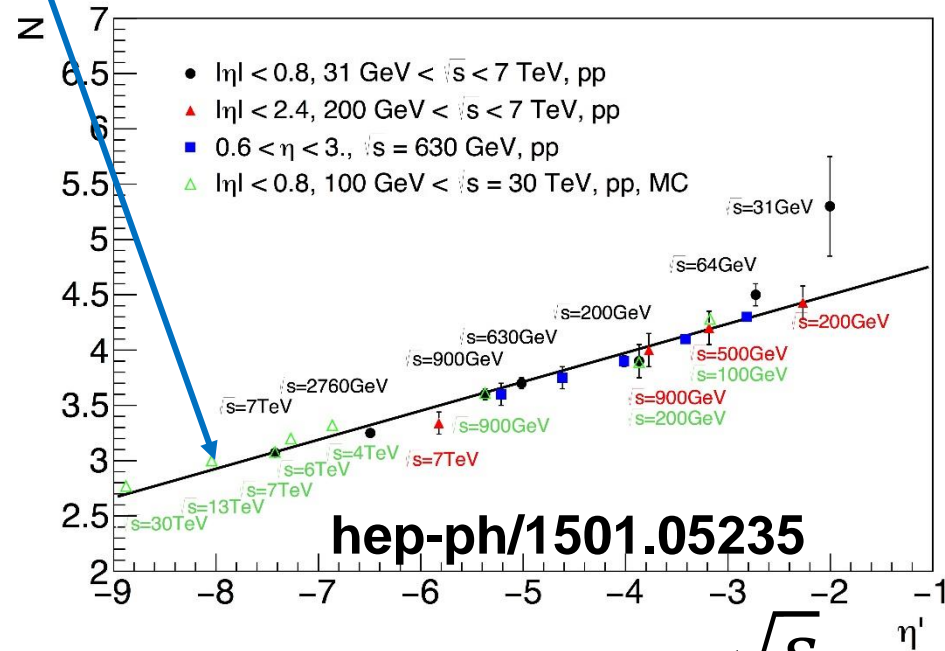
Remarkably, in the  $s \rightarrow \infty$  limit  $N \rightarrow 2$ , which corresponds to  $d^2\sigma/dp_T^2 \propto 1/p_T^4$  in the proposed parametrization.

Such behaviour can be expected just from dimensional counting in pQCD.

# Universal dependence

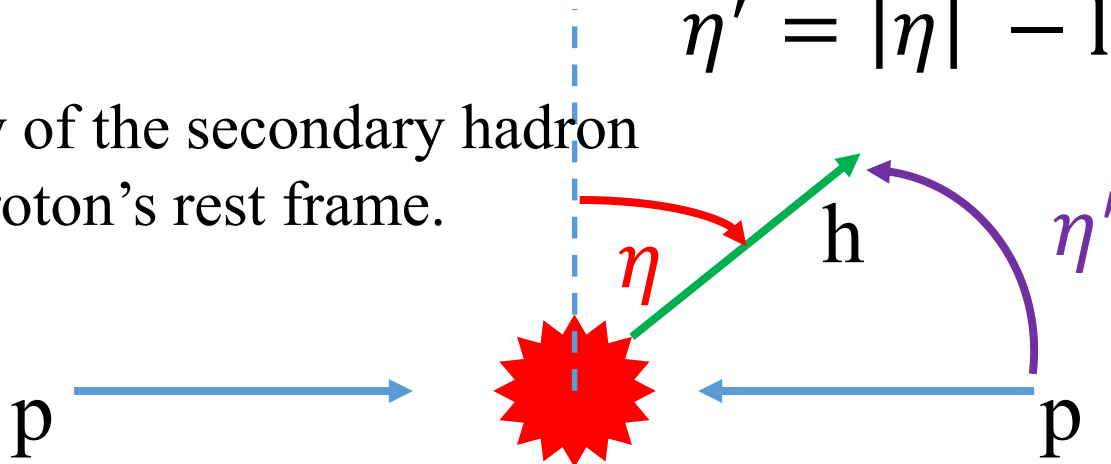
$$A_1 \exp(-E_{Tkin}/T_e) + \frac{A_2}{(1 + \frac{P_T^2}{T^2 N})} N$$

A. Bylinkin *et. al.*



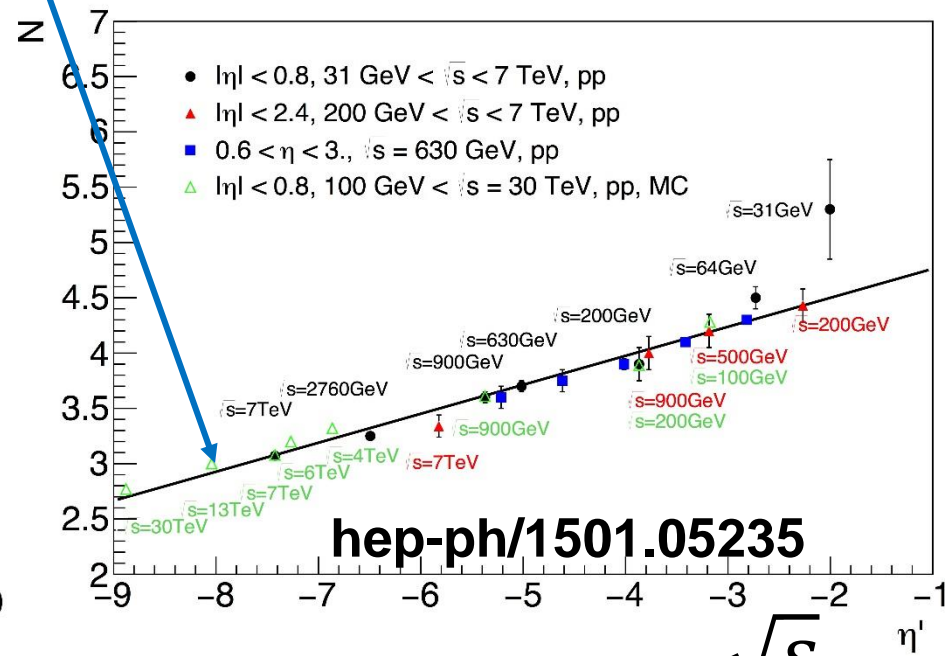
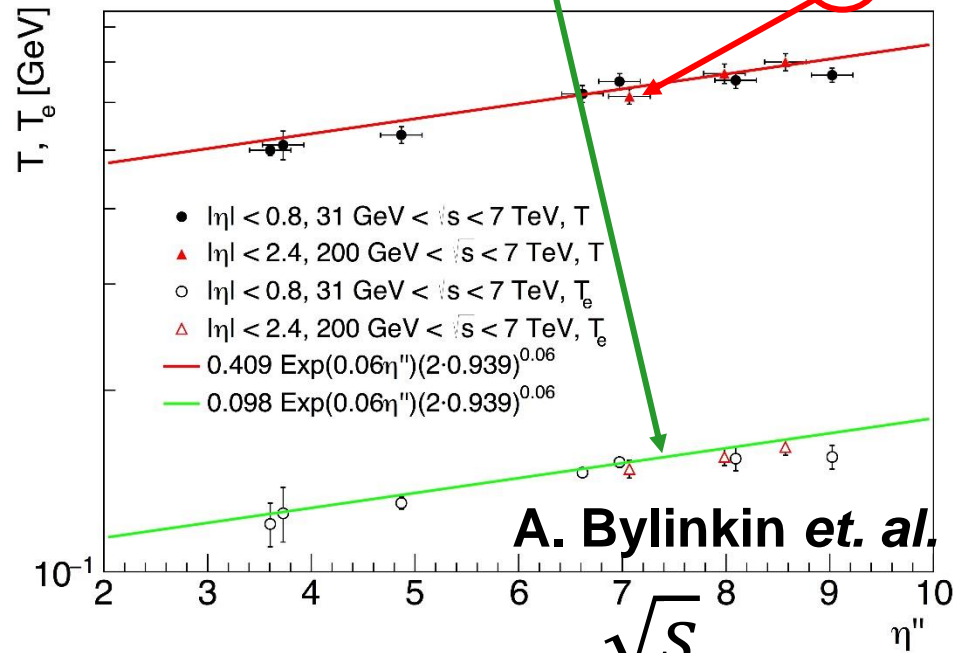
$$\eta' = |\eta| - \log\left(\frac{\sqrt{s}}{2m_p}\right)$$

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



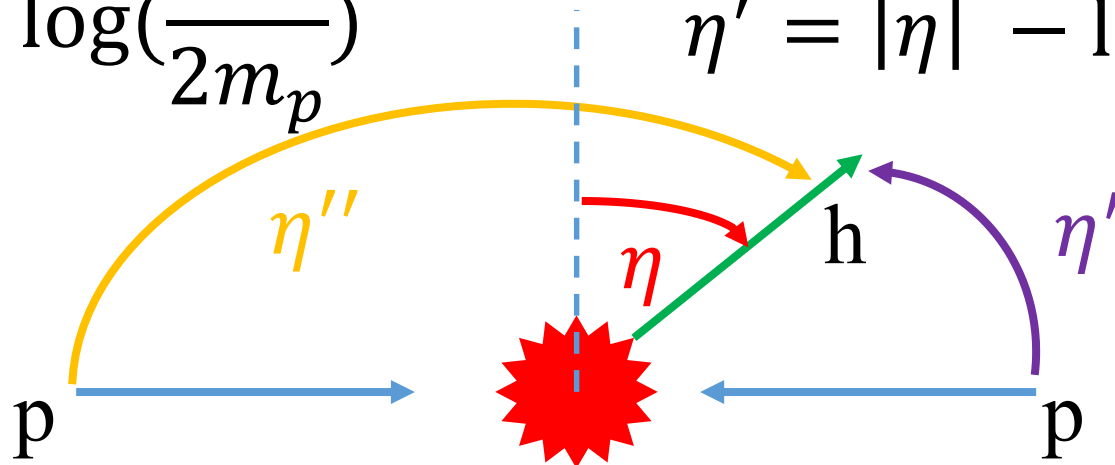
# Universal dependence

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



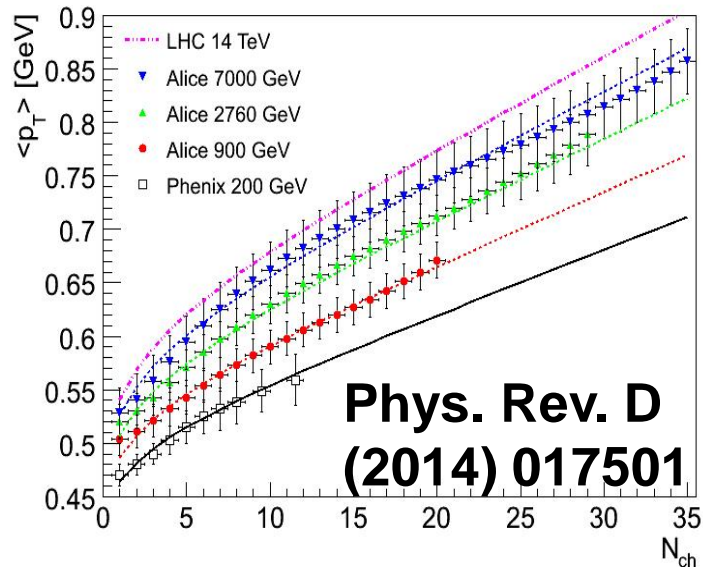
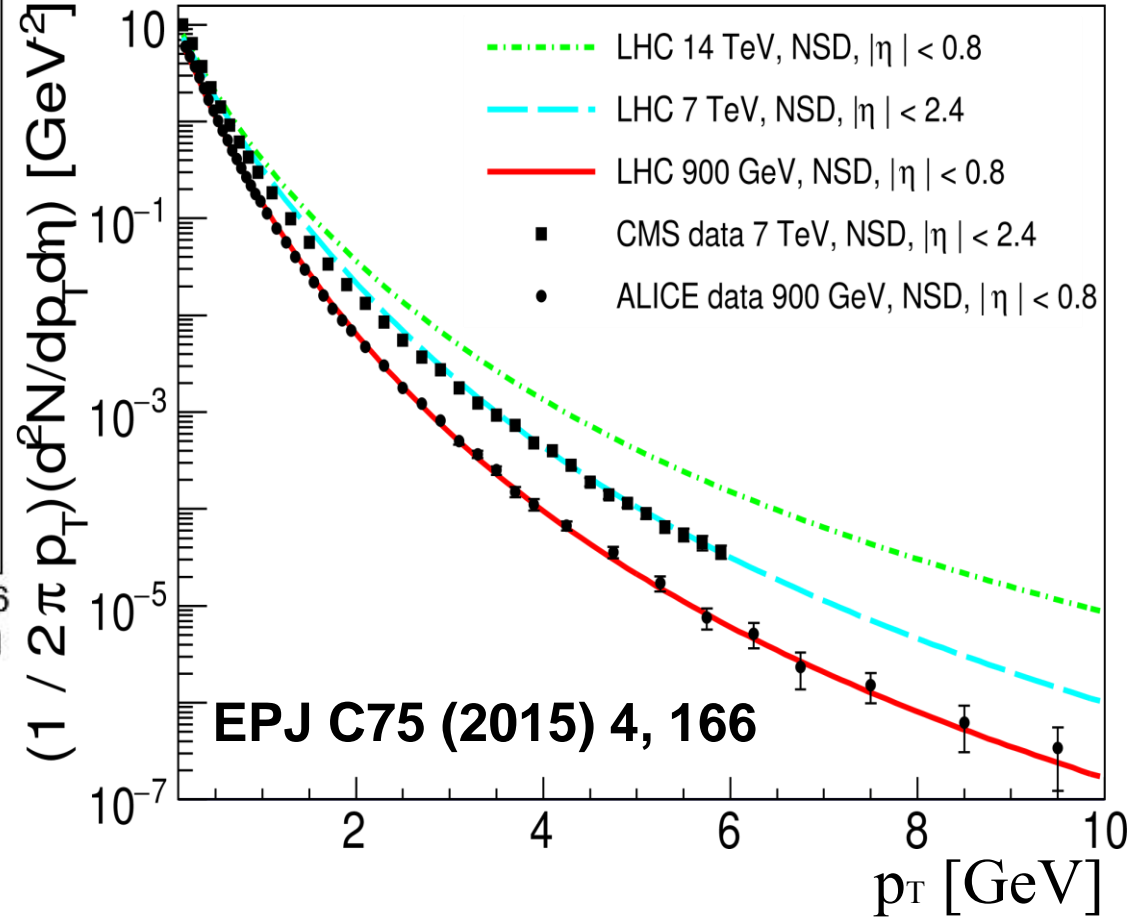
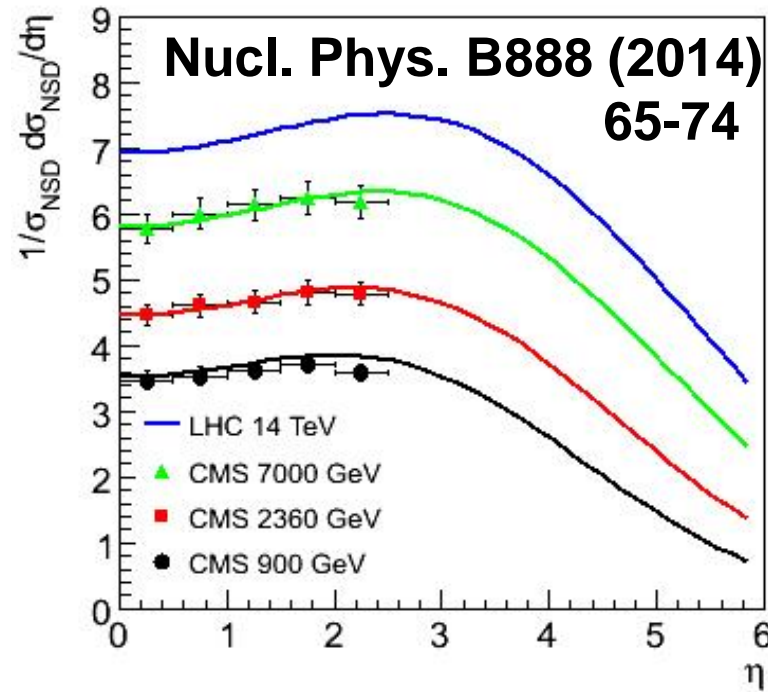
$$\eta'' = |\eta| + \log\left(\frac{\sqrt{s}}{2m_p}\right)$$

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





# Predictions of the model



Very good agreement between the available experimental data and the predictions of the model for  $\eta$  distributions,  $\langle p_T \rangle$  as a function of multiplicity and transverse momentum spectra is observed.

# Two component model

Best fit to experimental data



Nice predictions for further measurements



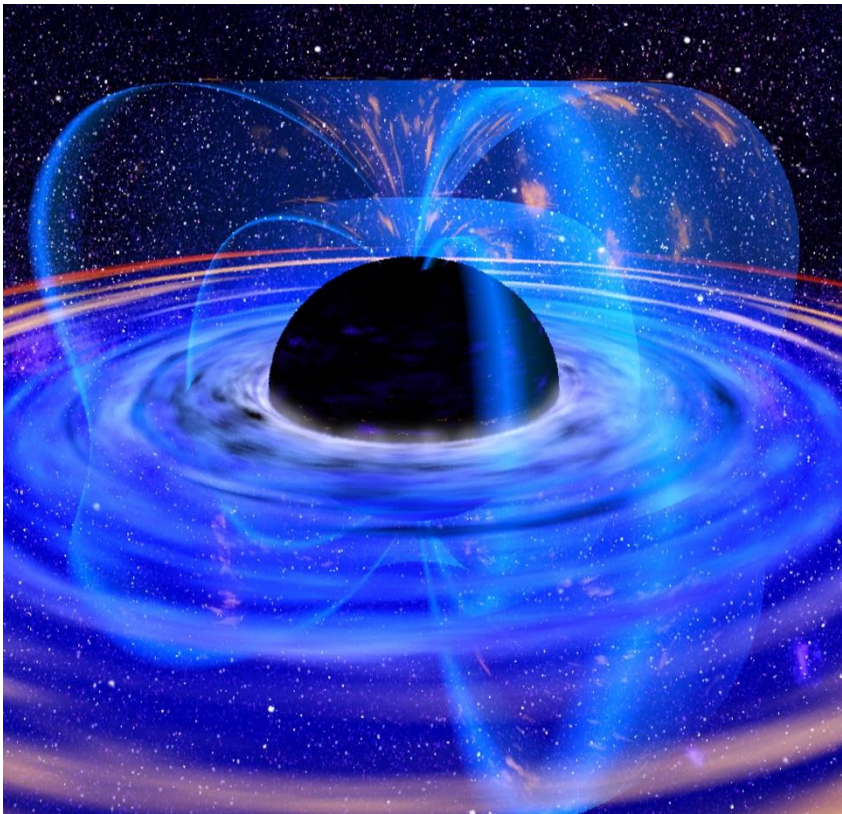
Physical interpretation



# “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:

Gravity  $\longleftrightarrow$  Acceleration in a non-inertial frame



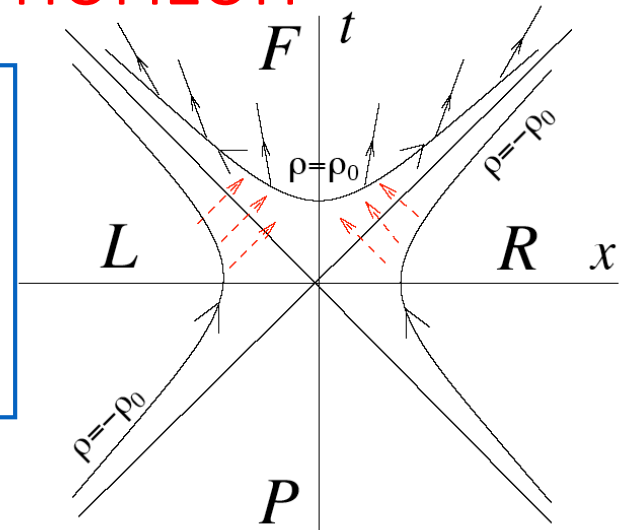
An observer moving with an acceleration  $a$  detects  
a thermal radiation with temperature

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

W.Unruh '76

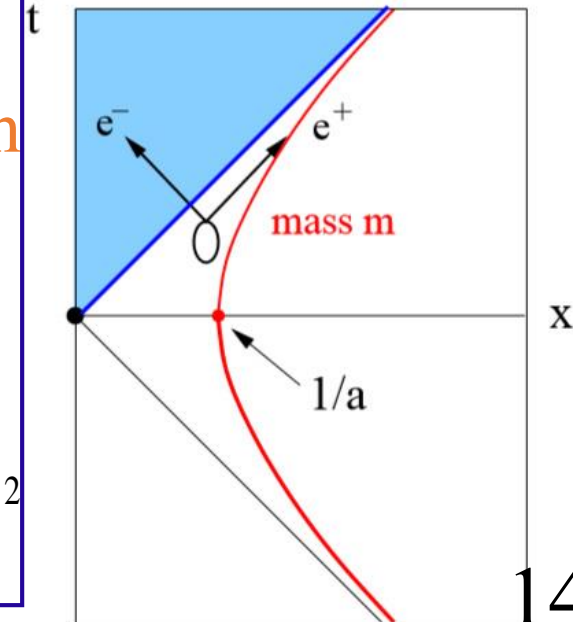
In both cases the radiation is due to the presence of **event horizon**

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



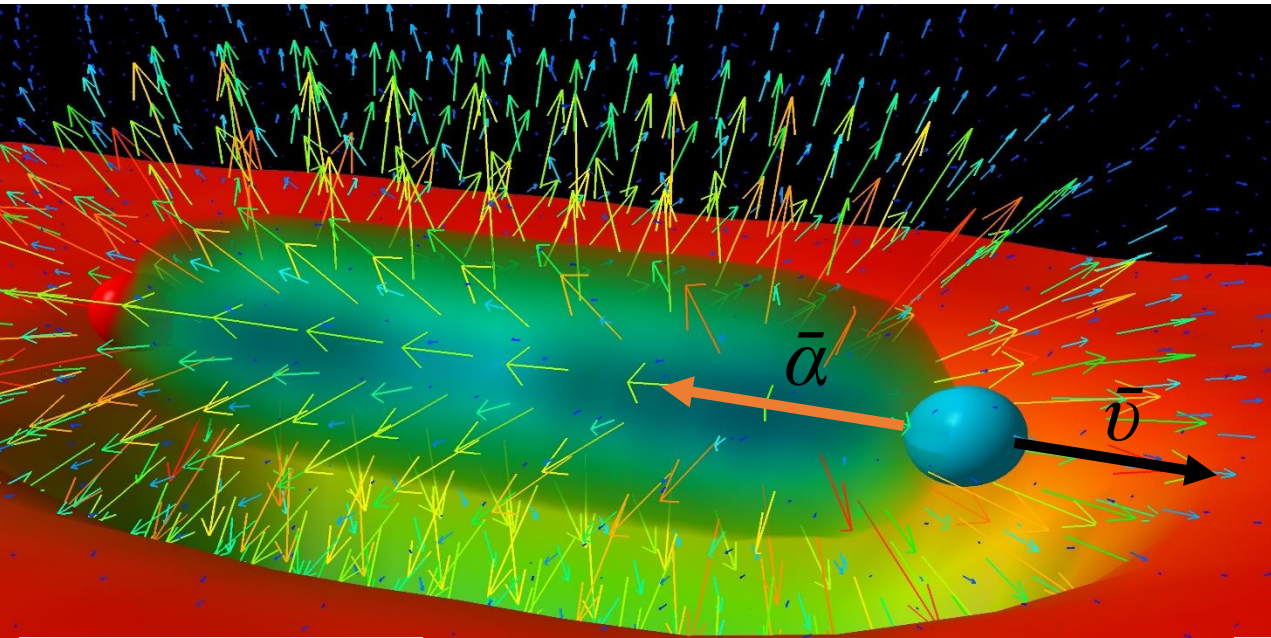
**Accelerated frame:** part of space-time is hidden (causally disconnected) from an accelerating observer;  
Rindler metric

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



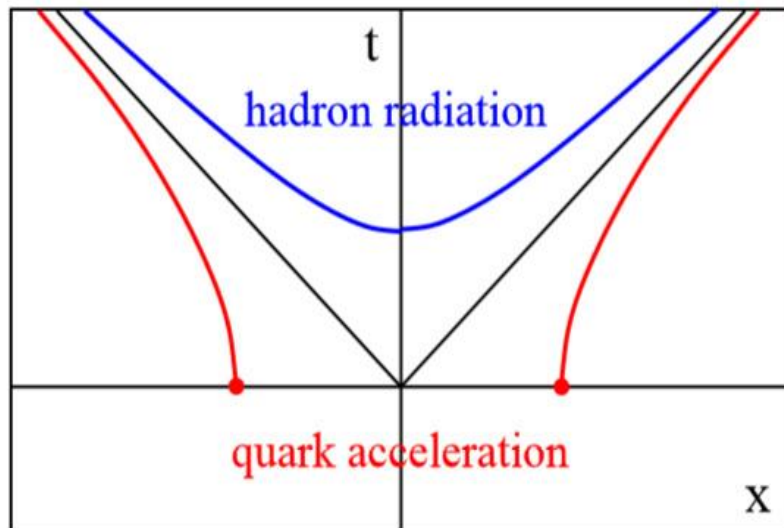


# Similar things happen in high energy collisions



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:

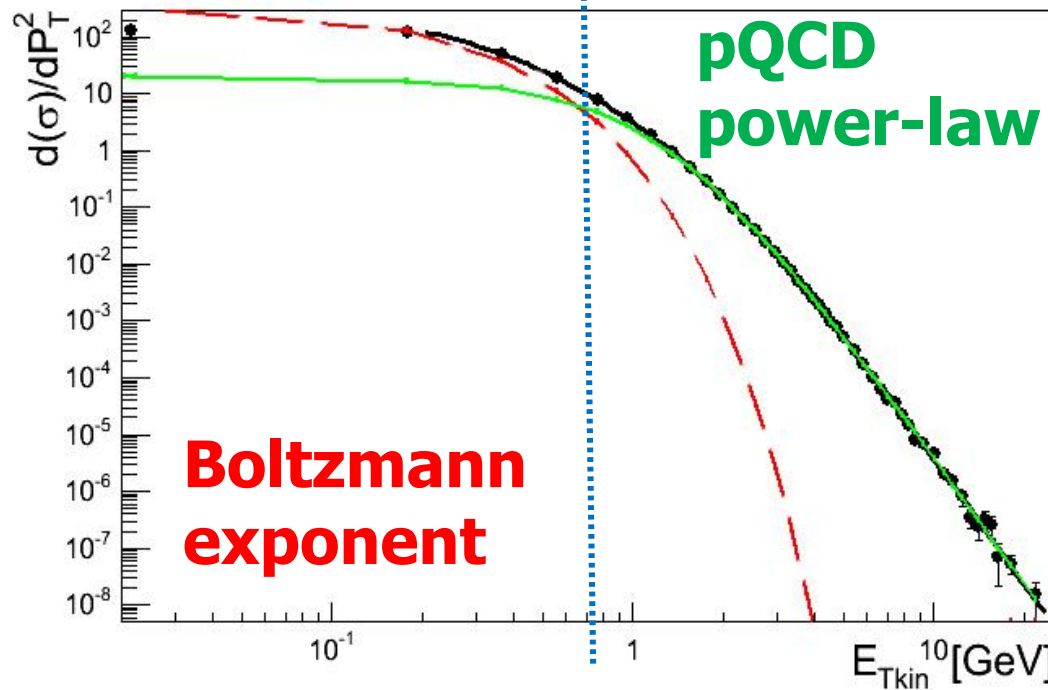
$$T_{th} = \frac{a}{2\pi} \sim 160 \text{ MeV}$$

# 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;

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

“Hard” radiation with saturation scale  $T \sim Q_s$



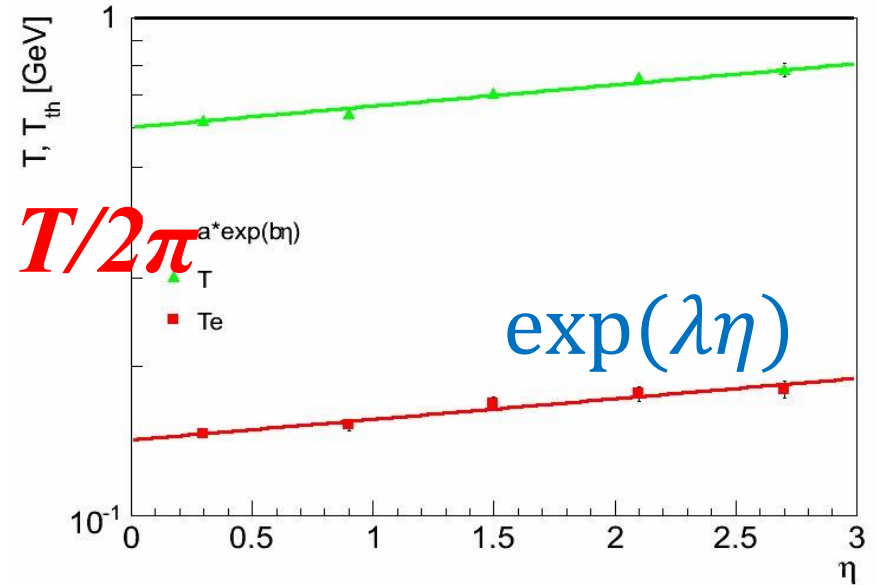
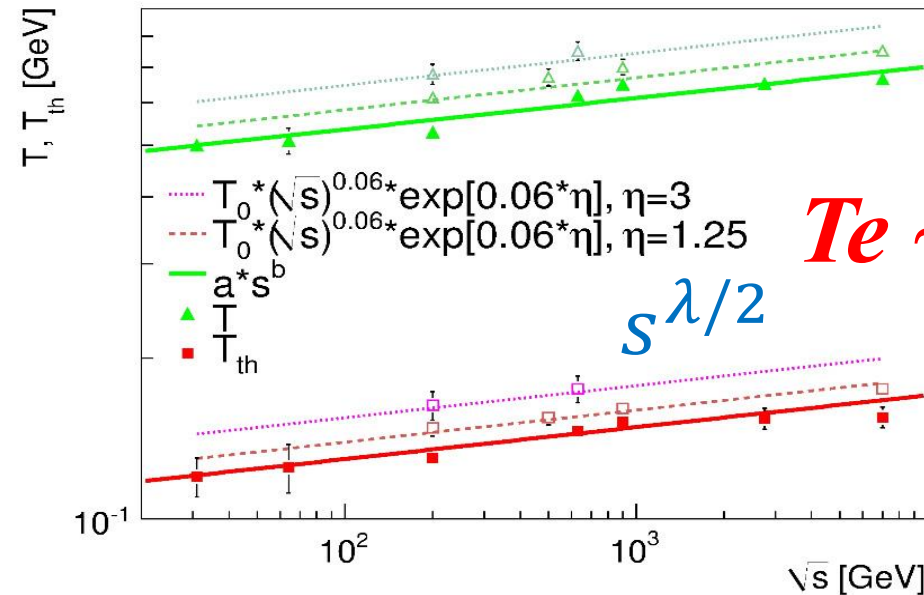
?

$$T_e \sim T/2\pi$$

$Q_s^2(s; \pm\eta) = Q_s^2(s_0; \eta = 0) \left(\frac{s}{s_0}\right)^{\lambda/2} \exp(\pm\lambda\eta);$  **Parton saturation scenario**  
**D. Kharzeev and E. Levin**  
**PLB 523, 79 (2001)**

# Two components in the “Black Hole” Interpretation

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



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

**Parton saturation scenario ( $\lambda=0.12$ )**

**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.**



# Conclusions

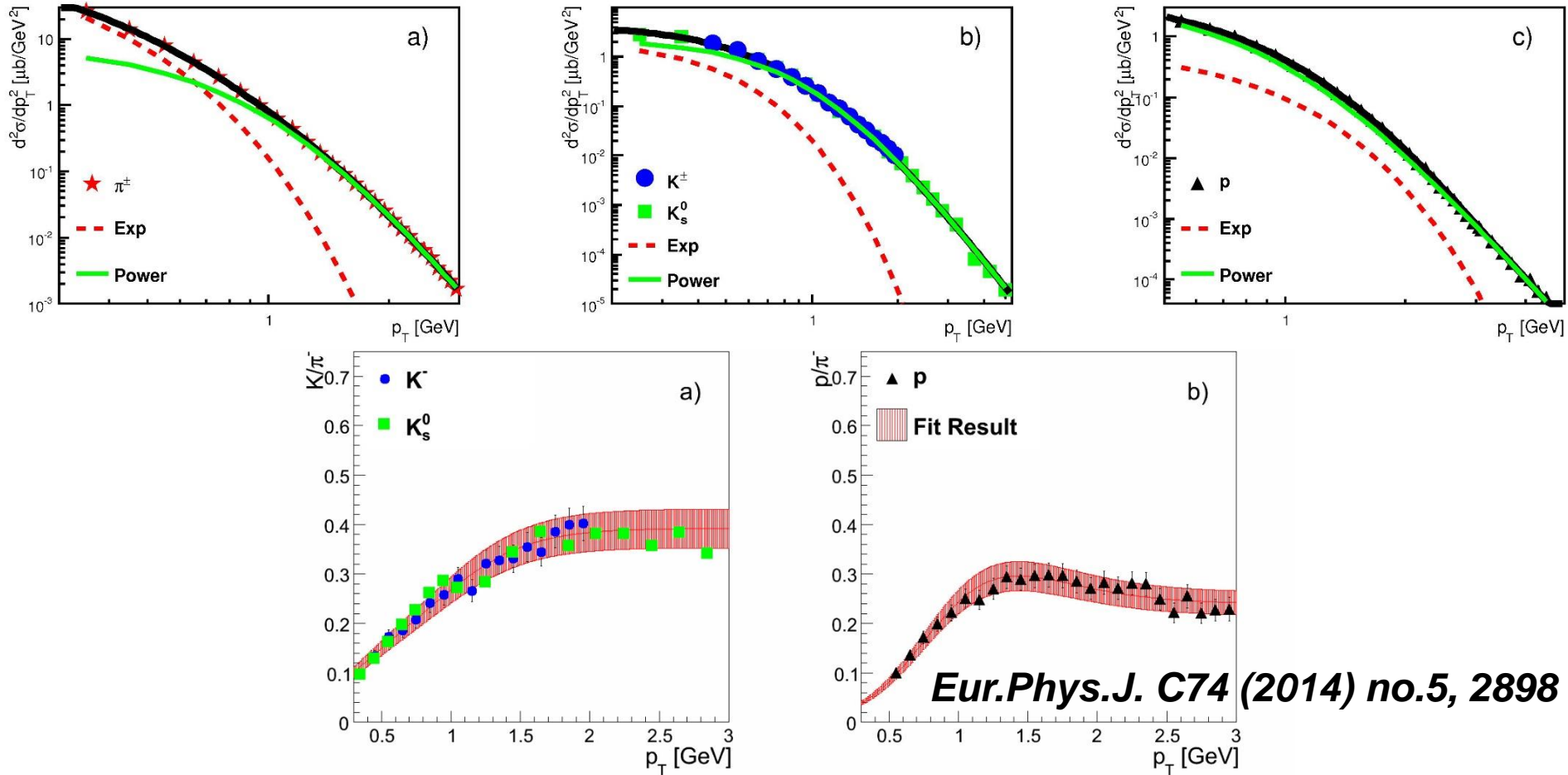
- The two component model for hadroproduction has been introduced
- It was shown to provide the best description of the available experimental data in comparison with other models
- Two components stand for two distinct mechanisms of hadroproduction
- Pseudorapidity of a secondary hadron in the initial's 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
- A possible link between General Relativity and QCD has been found

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

Thank you for your attention!

Additional slides

# Simultaneous fit of pion, kaon and proton spectra



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

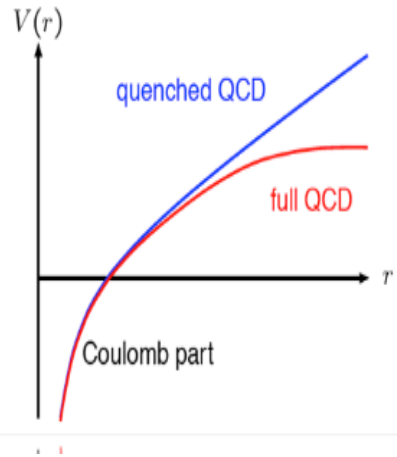
The large exponential contribution in pion spectra explains the peculiar shapes of  $K/\pi$  and  $p/\pi$  ratios as a function of transverse momentum.

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

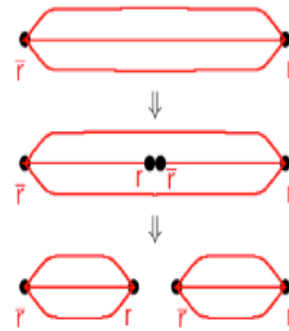
# Monte Carlo Generators

## Lund String Model

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



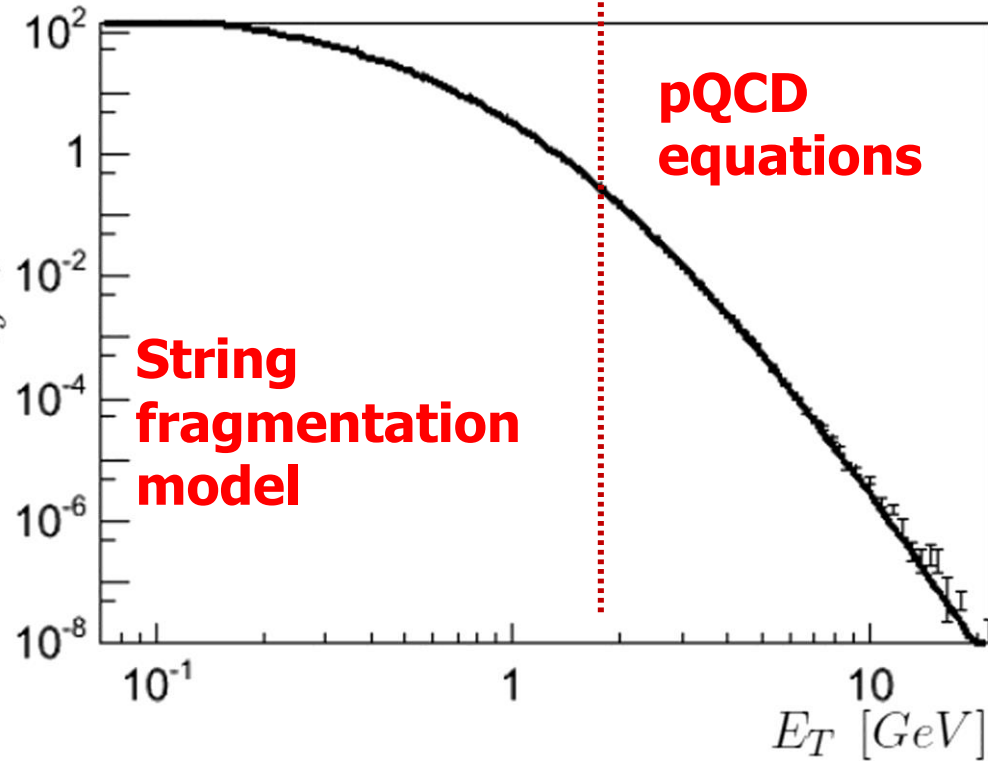
String Breaks:  
via Quantum Tunneling



(simplified colour representation)

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

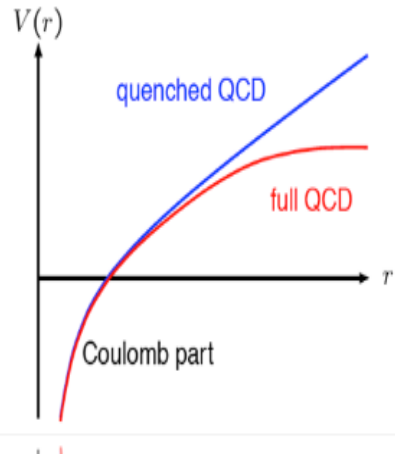
$$E \frac{d^2\sigma}{d^3P} \Big|_{y=0} [\mu b/GeV^2]$$



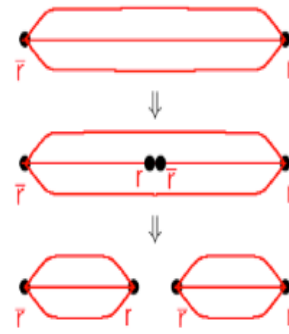
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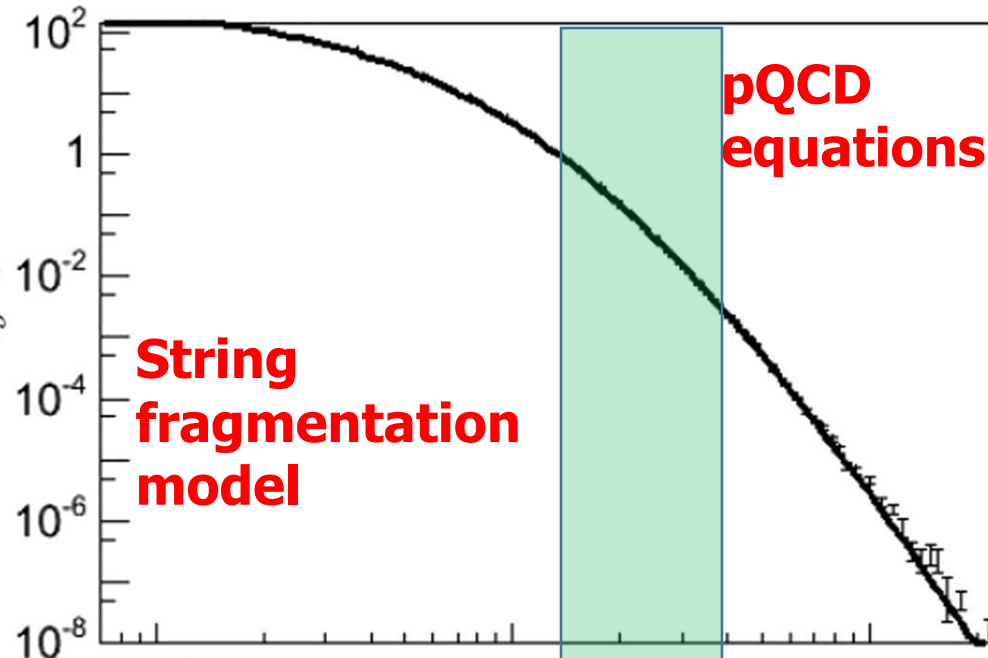
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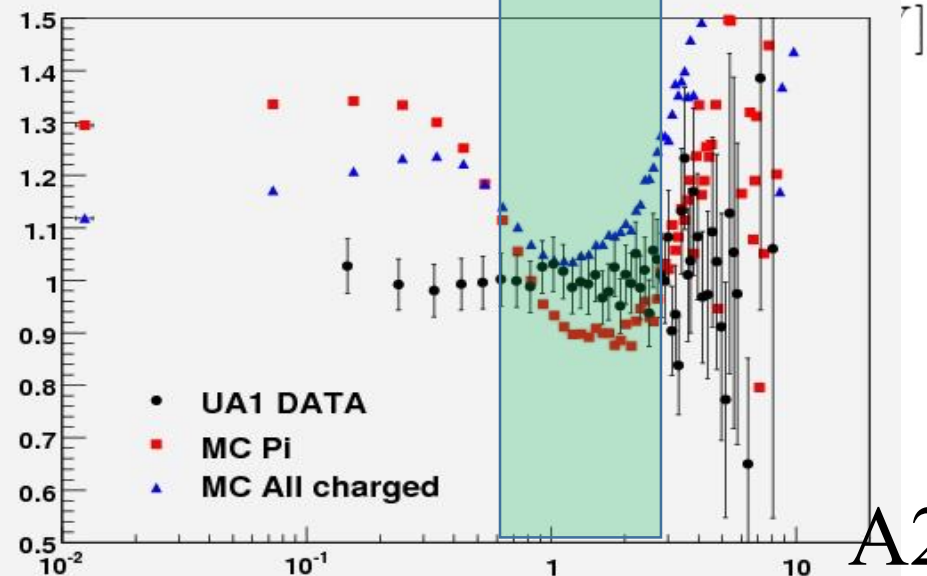
$$E \frac{d^2\sigma}{d^3P} \Big|_{y=0} [\mu b/GeV^2]$$



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

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

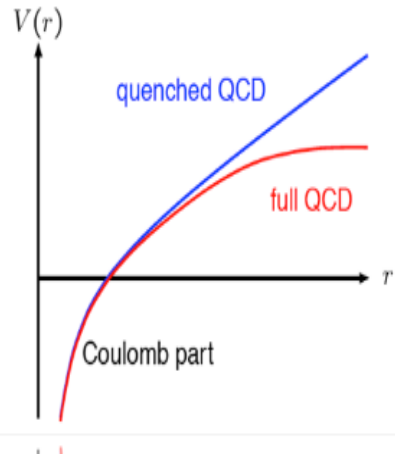
**MC does not describe the transition region between two dynamics**



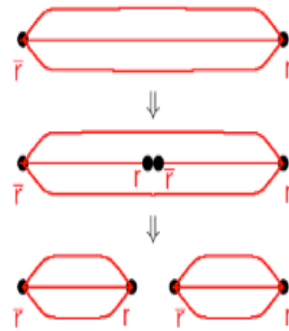
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String Breaks:  
via Quantum Tunneling



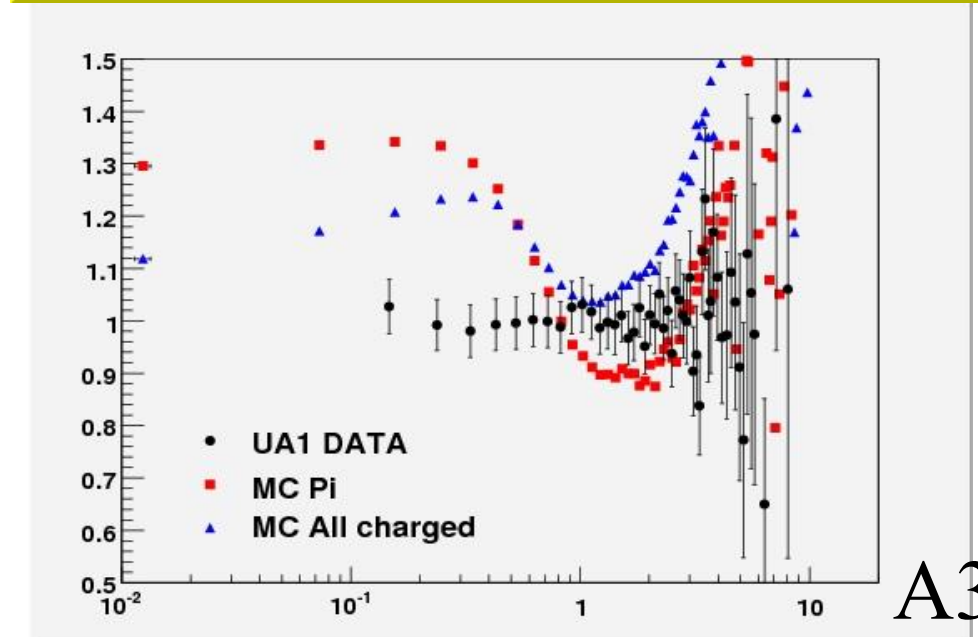
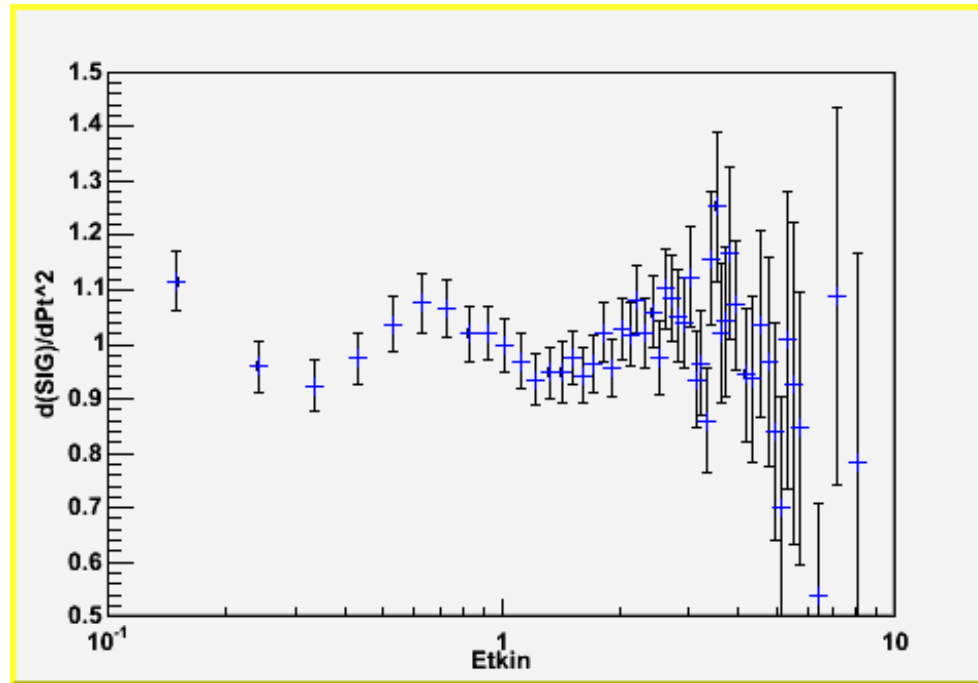
(simplified colour representation)

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



$$A_1 \exp\left(\frac{-m_q^2 - p_\perp^2}{\kappa/\pi}\right) + \frac{A_2}{\left(1 + \frac{P_T^2}{T^2 N}\right)^N}$$

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

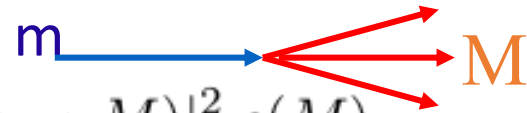


# Few words about heavy-ion collisions

# 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  $M \gg m$ ;




The probability of transition:  $P(m \rightarrow M) = 2\pi |\mathcal{T}(m \rightarrow M)|^2 \rho(M)$

Transition amplitude:  $|\mathcal{T}(m \rightarrow M)|^2 \sim \exp(-2\pi M/a)$

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

Unitarity:  $\sum P(m \rightarrow M) = \text{const},$

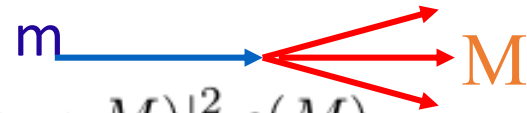
Limiting acceleration   $\frac{a}{2\pi} \equiv T \leq \frac{\sqrt{6}}{4\pi\sqrt{b}}$



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

Why it is interesting to look at heavy-ion collisions?

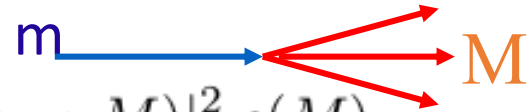
And why with the two component model?

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  $M \gg m$ ;



The probability of transition:  $P(m \rightarrow M) = 2\pi |\mathcal{T}(m \rightarrow M)|^2 \rho(M)$

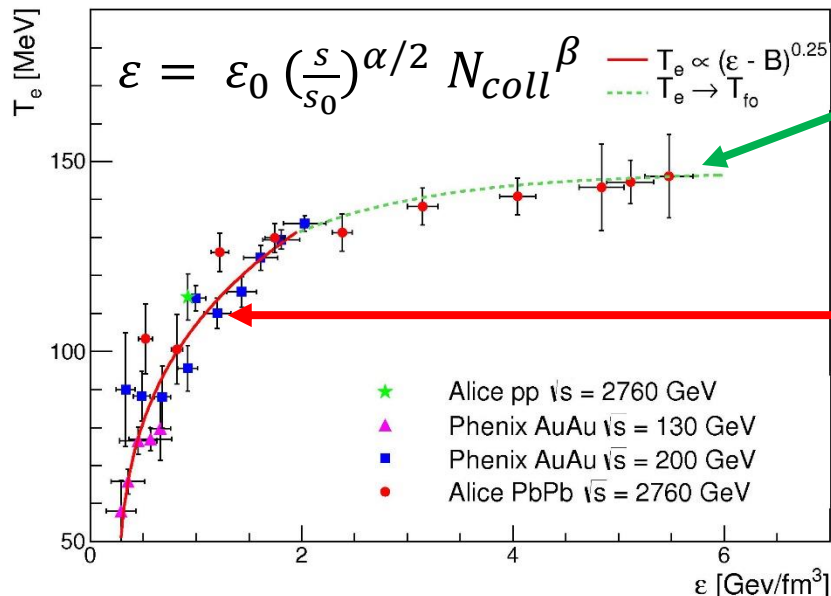
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Limiting acceleration  $\Rightarrow \frac{a}{2\pi} \equiv T \leq \frac{\sqrt{6}}{4\pi\sqrt{b}}$

Hagedorn temperature!



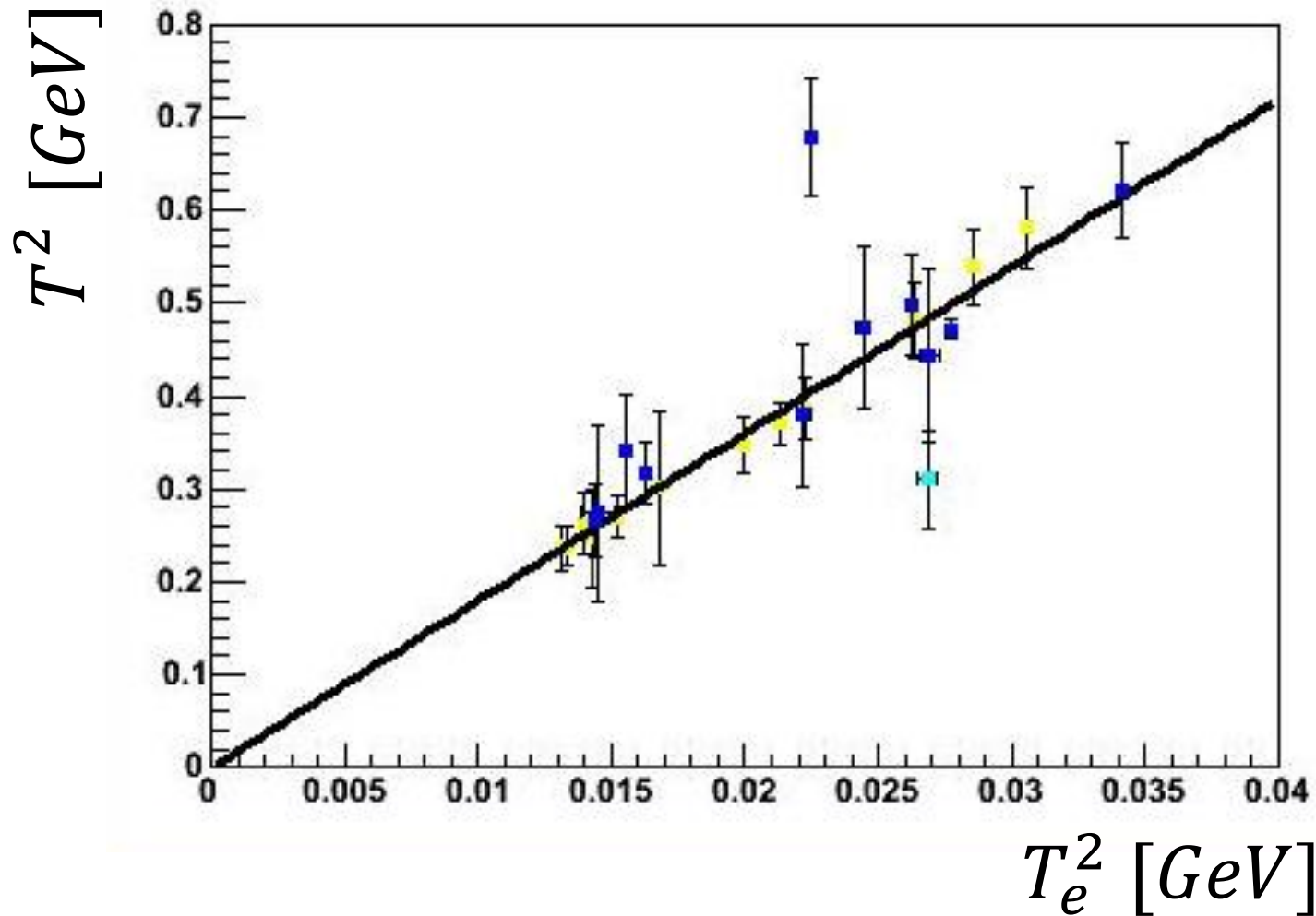
1.  $T_c \sim 150 \text{ MeV}$

Limiting acceleration or QGP phase transition???

2.  $\epsilon \sim T^4 + B$

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

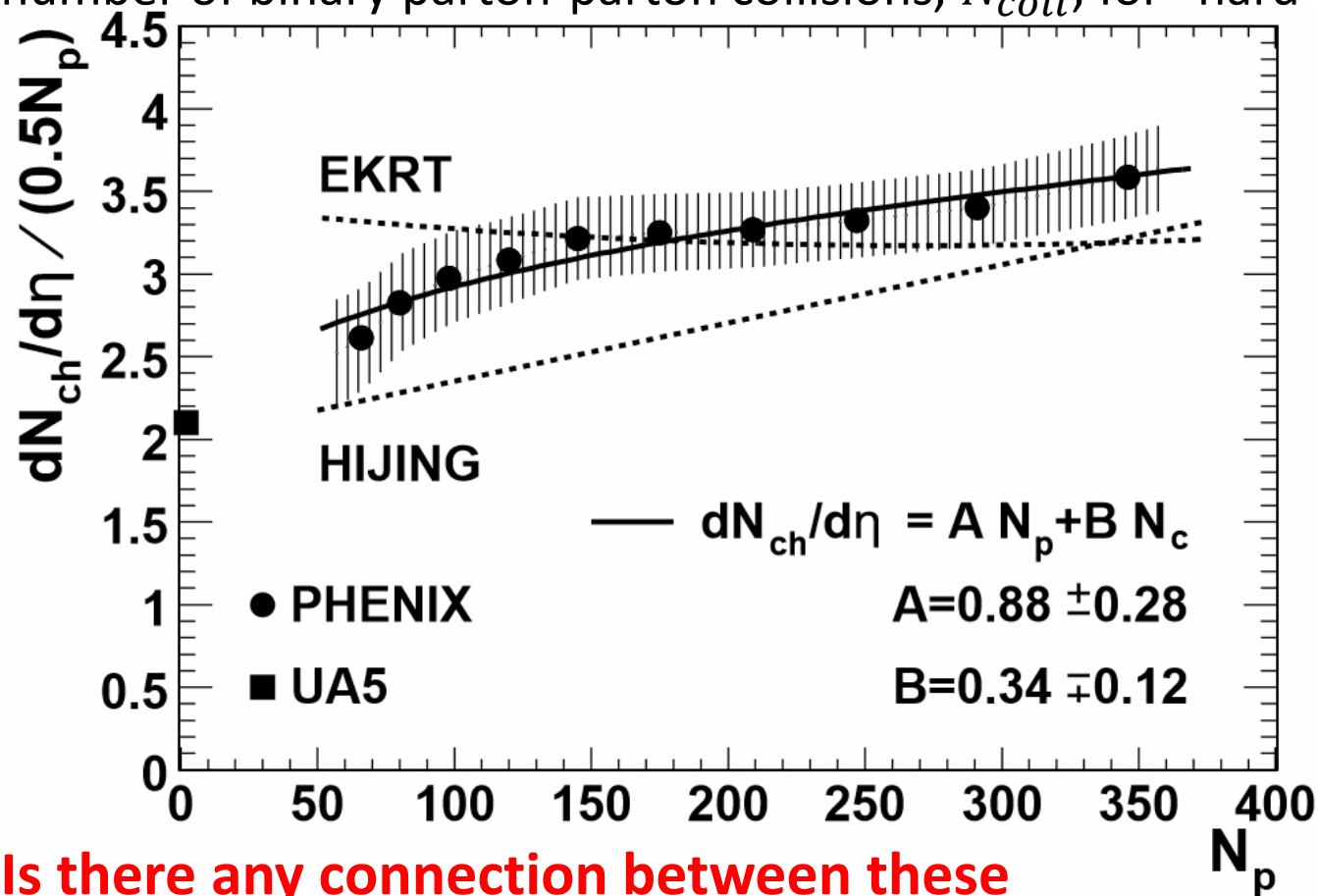
# Heavy-ion collisions



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

# Two components in heavy-ion collisions?

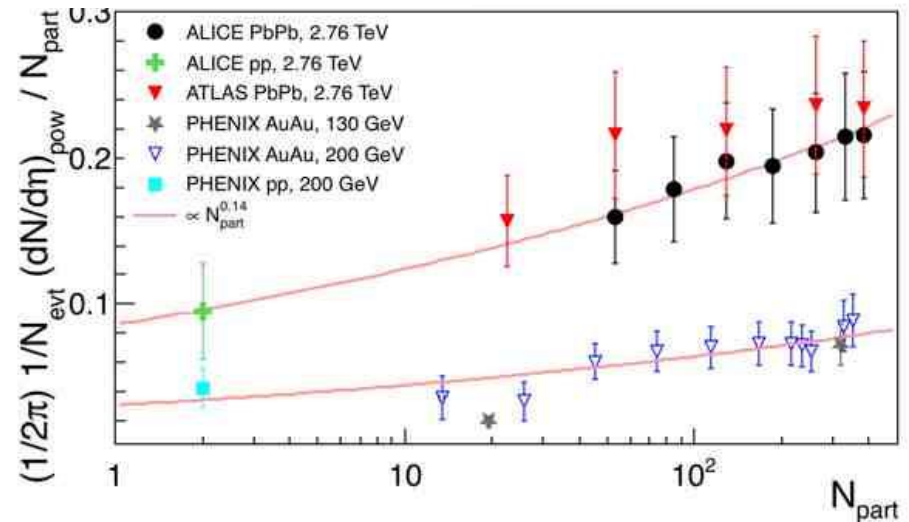
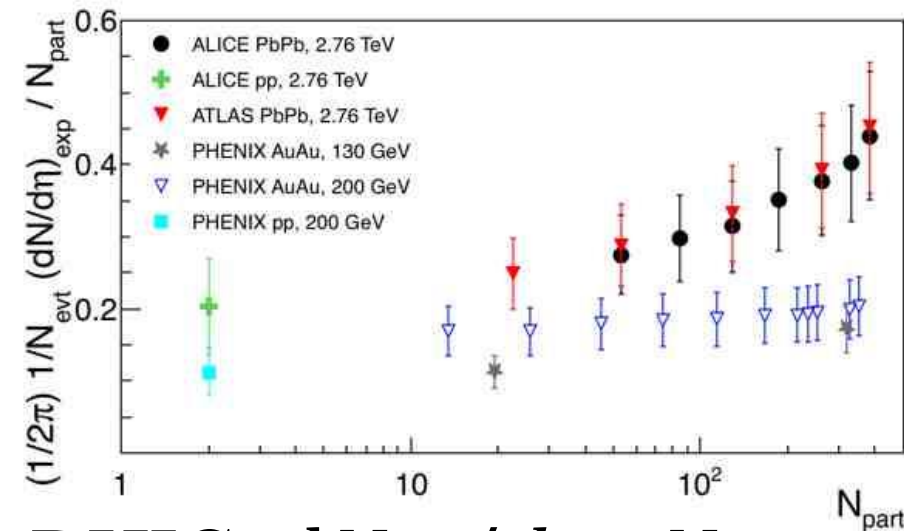
- Two component models have been used to describe heavy-ion collisions for a long time.
- Charged particle density,  $dN_{ch}/d\eta$ , is expected to scale with number of participating nucleons,  $N_{part}$ , for “soft” processes and with number of binary parton-parton collisions,  $N_{coll}$ , for “hard”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

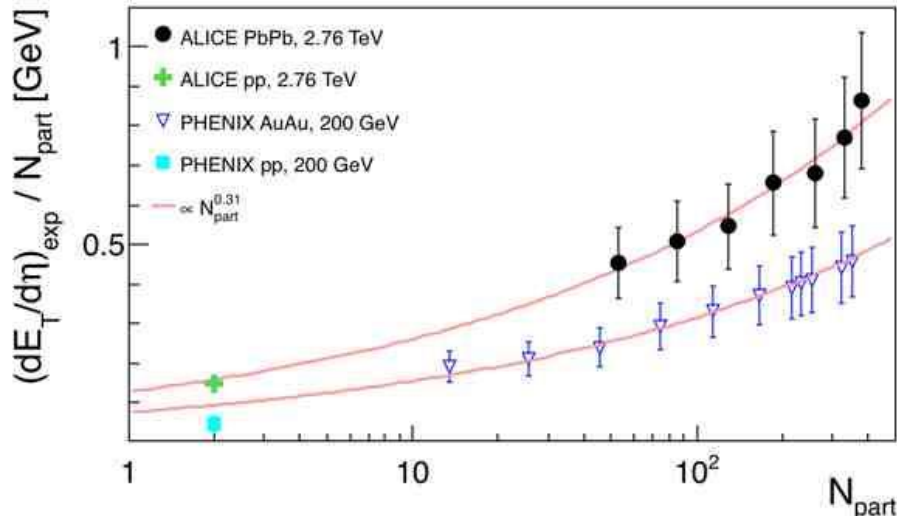
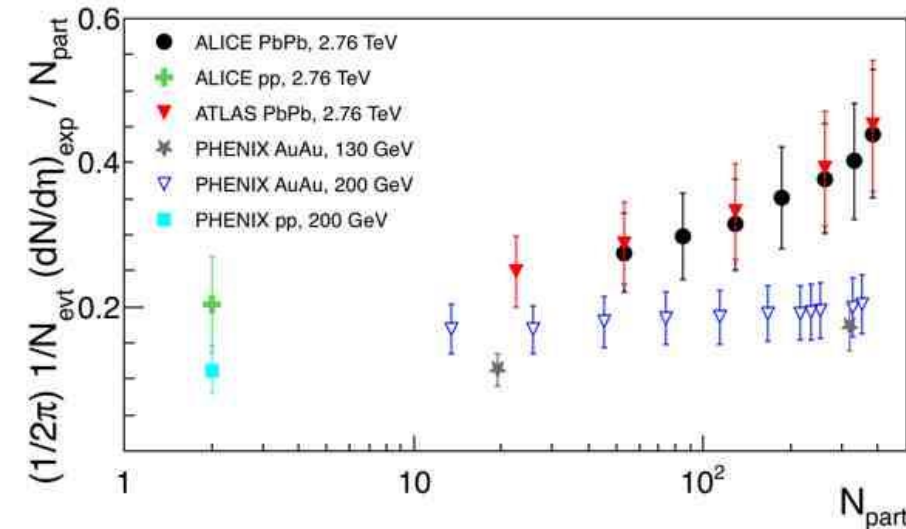
$$A_1 \exp(-E_{Tkin}/T_e) + \frac{A_2}{(1 + \frac{P_T^2}{T^2 N})^N}$$

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

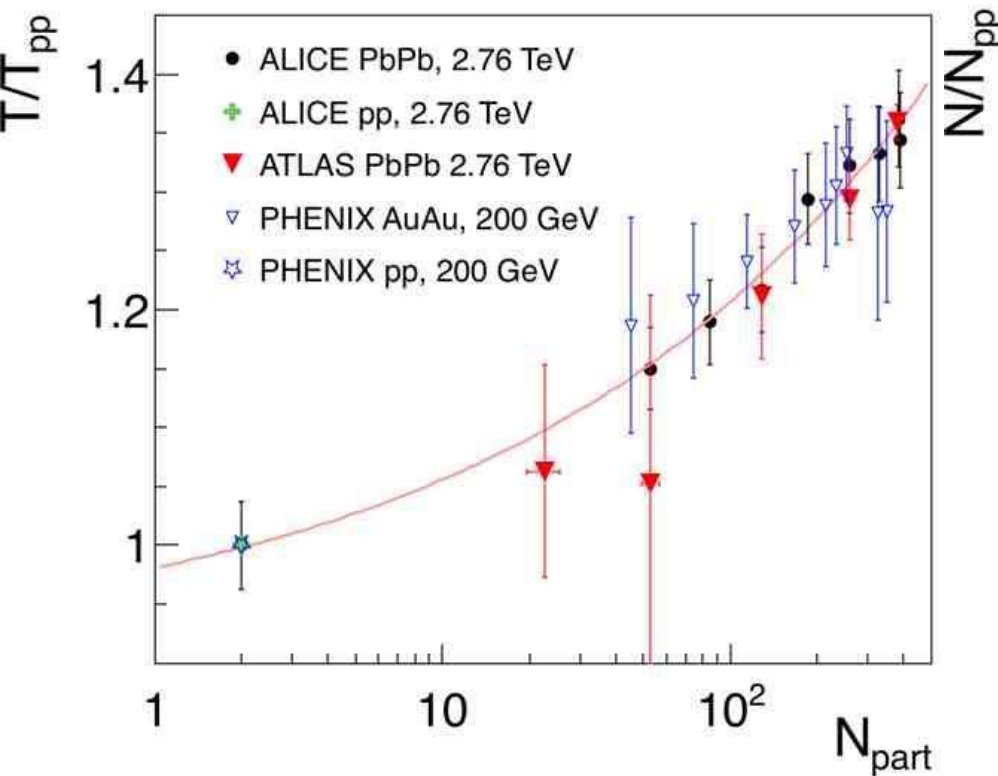
The same scaling of  $\Sigma E_T/d\eta$  both for RHIC and LHC energies.

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

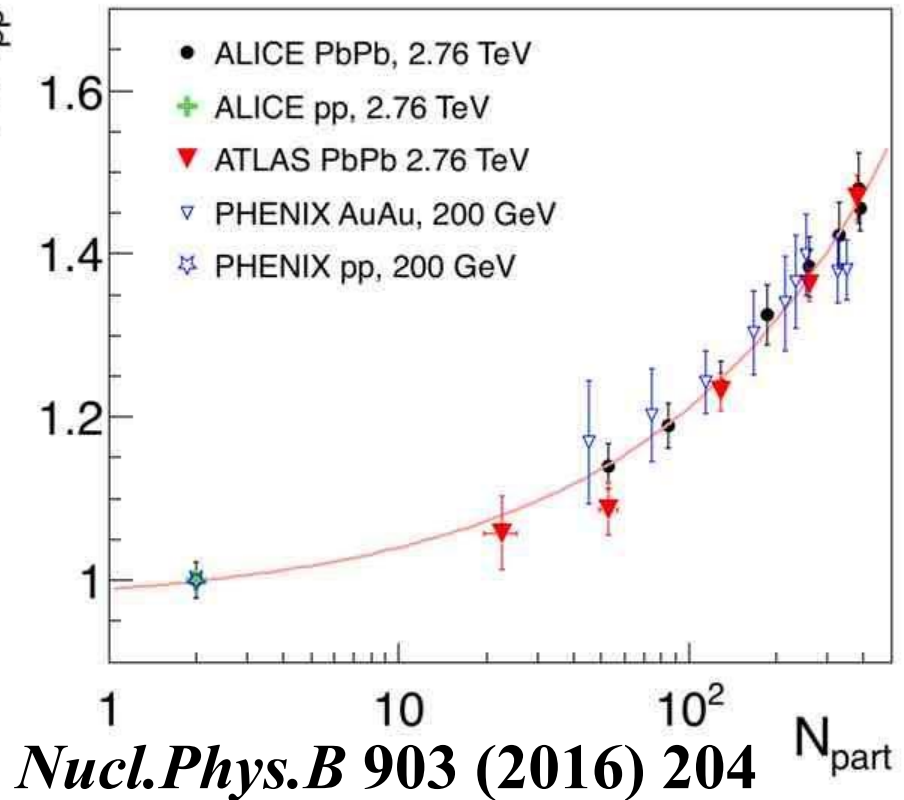
→ The two component model indeed reveal the underlying hadroproduction dynamics.



# 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 rescatterings 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

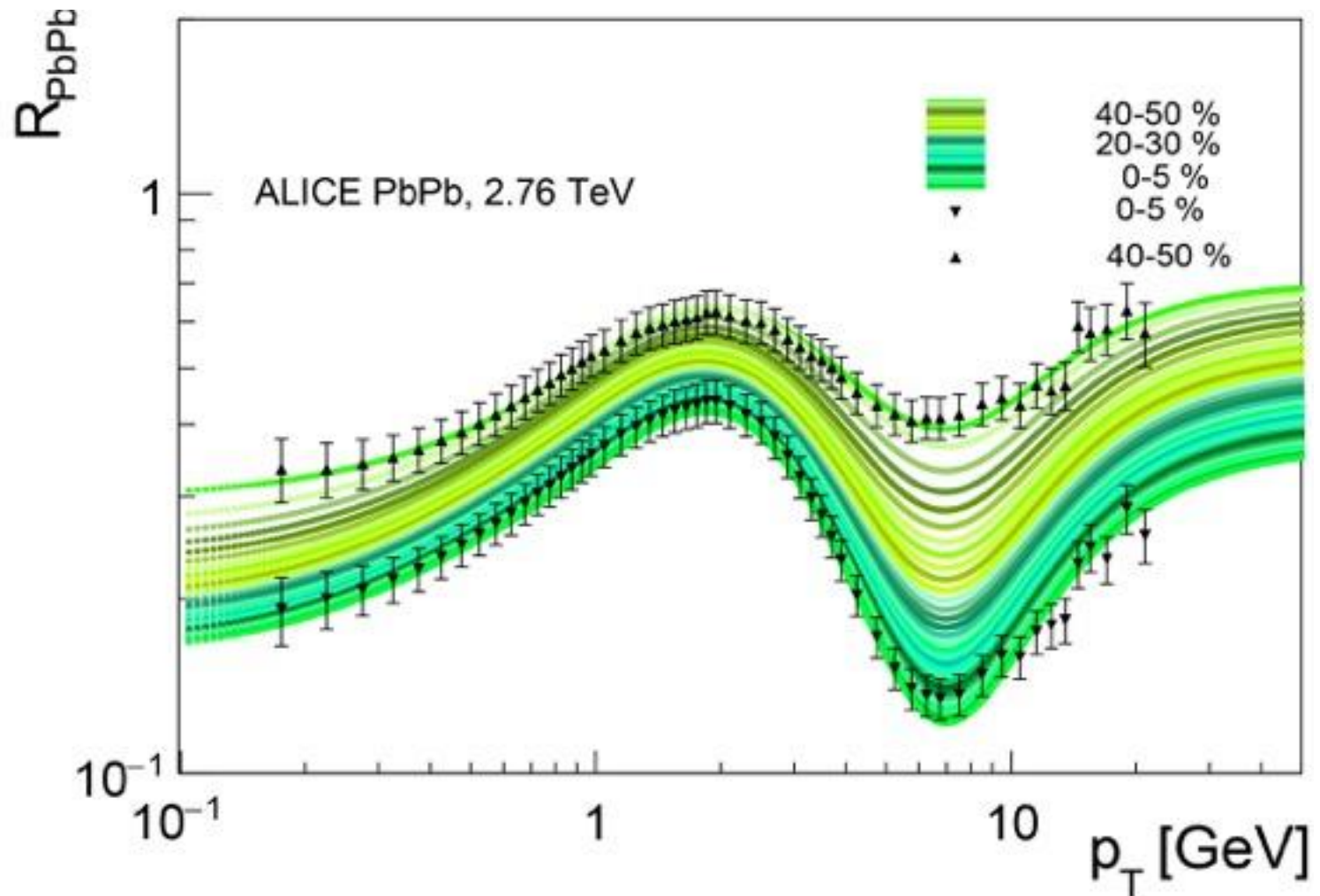
The same dependence for both RHIC and LHC data

The shape of  $R_{AA}$  can be predicted for all centralities 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





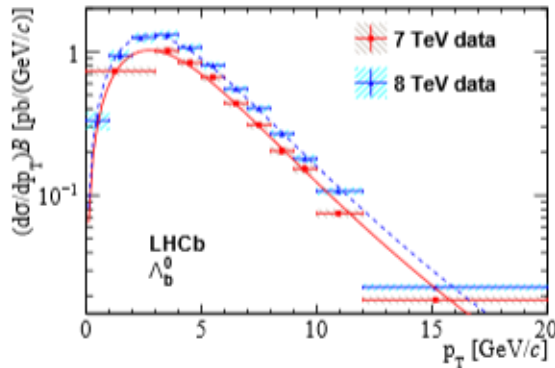
# Heavy flavour production

# Heavy flavour production



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

## Study of the production of $\Lambda_b^0$ and $\bar{B}^0$ hadrons in $pp$ collisions and first measurement of the $\Lambda_b^0 \rightarrow J/\psi p K^-$ branching fraction



$p_T$  distribution of the  $\Lambda_b^0$  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

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

For the 7 TeV (8 TeV) sample, the fit  $\chi^2$  is 21.0 (10.7) for 7 (9) degrees of freedom. The

Figure 4: Fit to the  $\Lambda_b^0$  distribution with the Tsallis function.

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](https://arxiv.org/abs/1501.07706).

# Why Tsallis works better for heavy flavor production?

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Tsallis

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

Two Component Model


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

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

$E_T$  - includes mass dependence

$p_T^2$  - no mass dependence

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Not expected to contribute  
to heavy flavor production

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

$p_T^2$  - no mass dependence

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

# Two Component Model with Mass

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

Mass dependence should be negligible for pion spectra

Let's check this explicitly



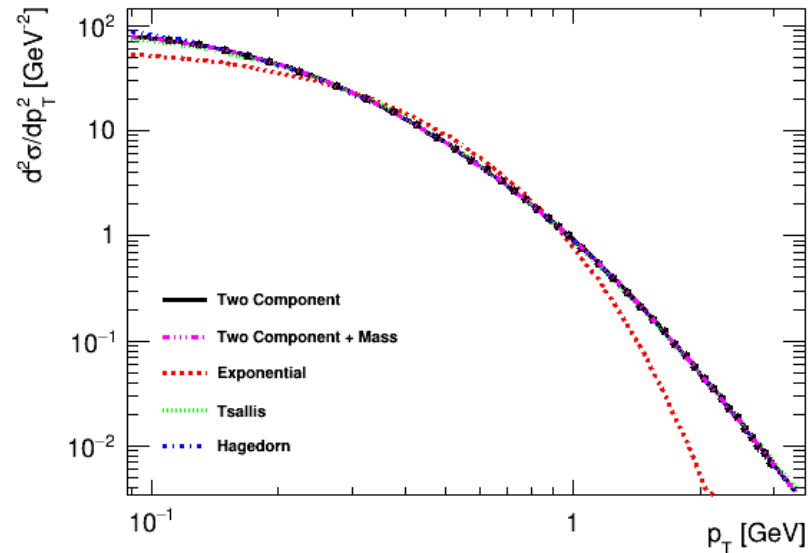
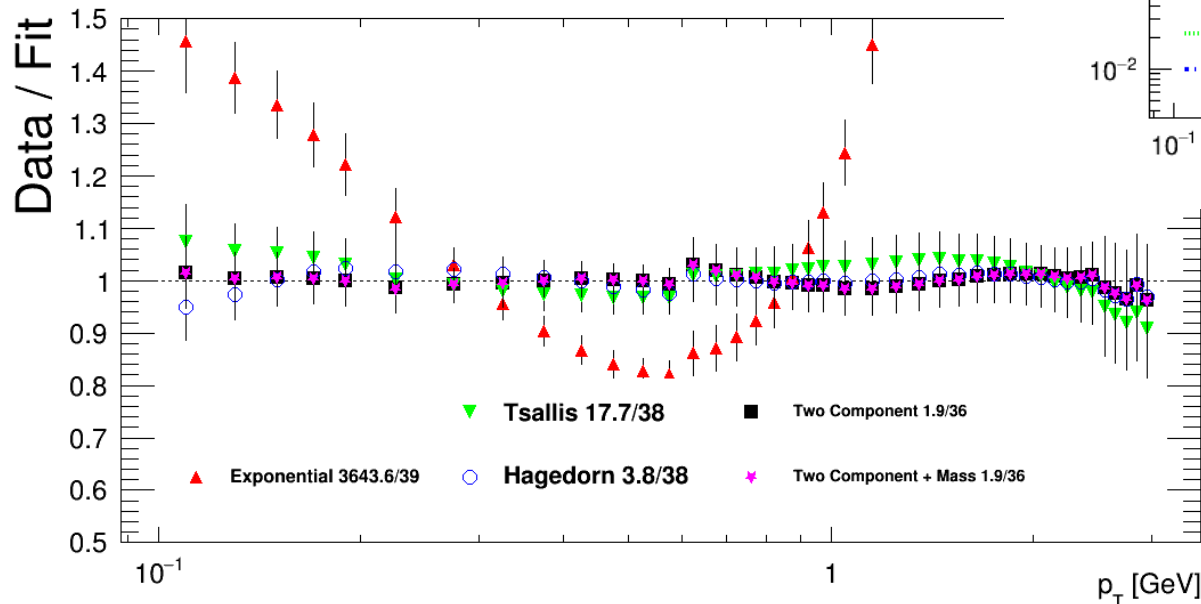
# Two Component Model with Mass

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Alice 7000 GeV, pion spectra



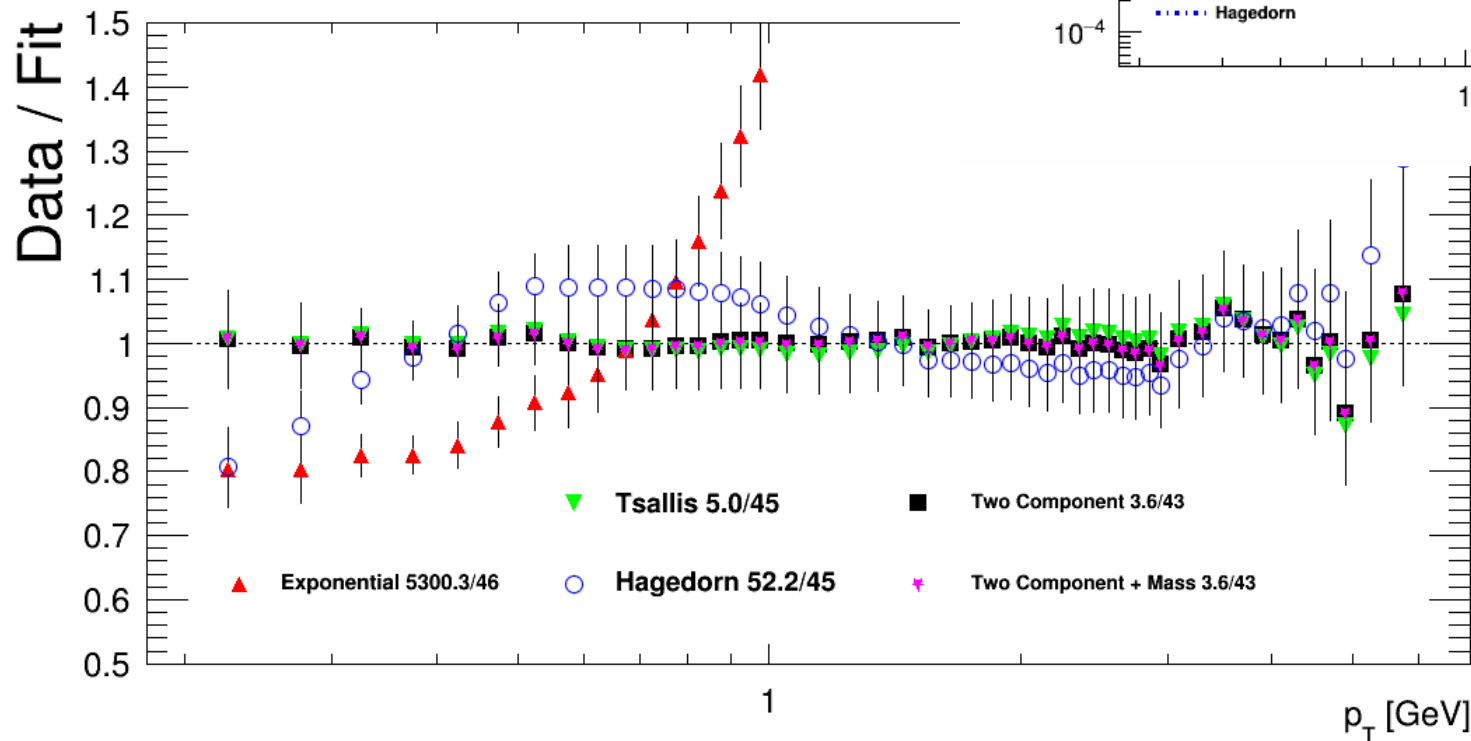
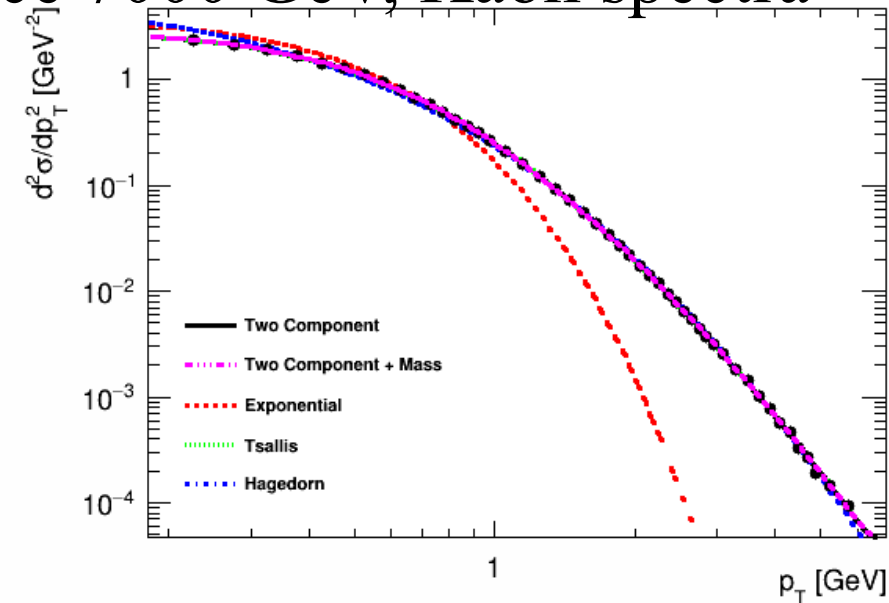
# Two Component Model with Mass

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

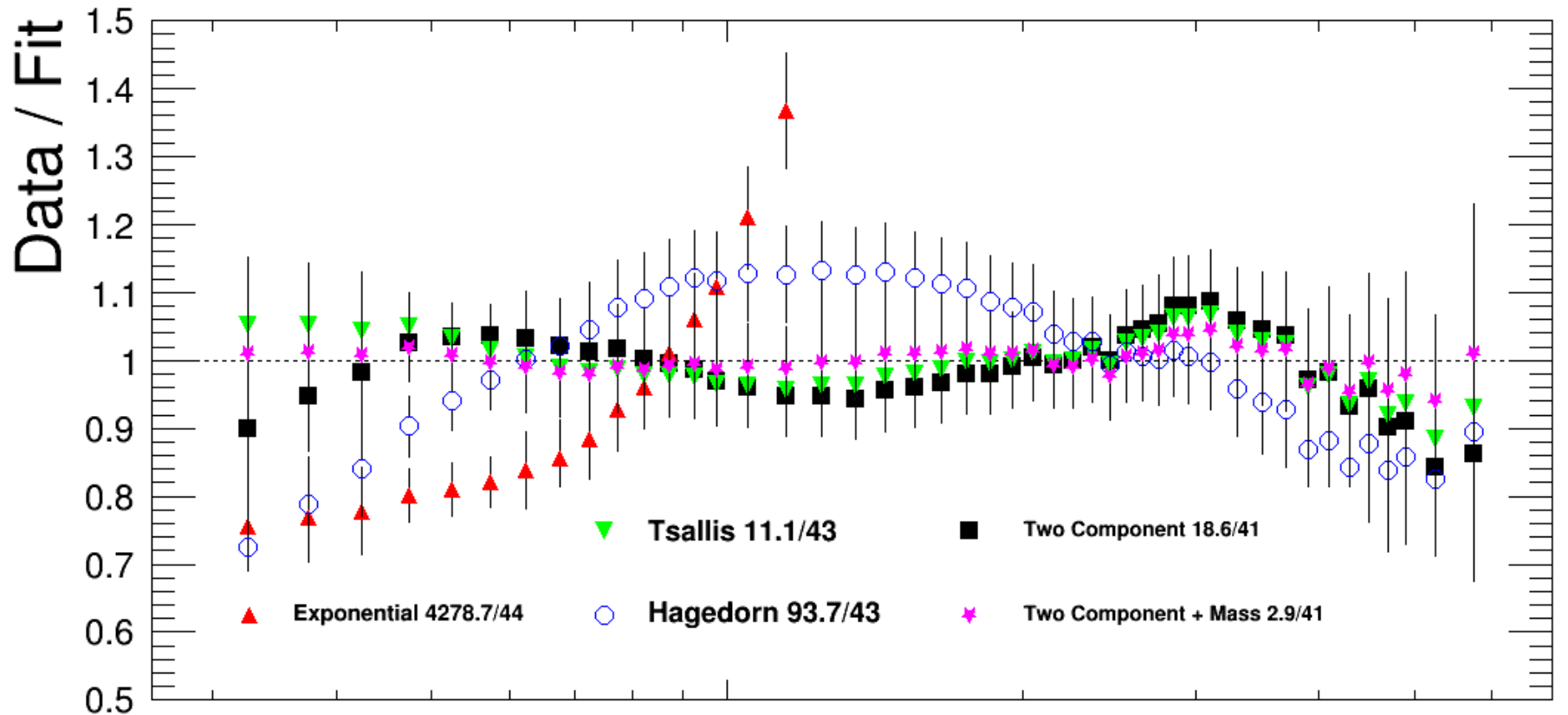
Alice 7000 GeV, Kaon spectra



# Two Component Model with Mass

Let's go step by step

Alice 7000 GeV, proton spectra



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

Difference appears starting from proton spectra.

And what about LHCb data?

LHCb 8 TeV,  $\Lambda_b^0$  spectra

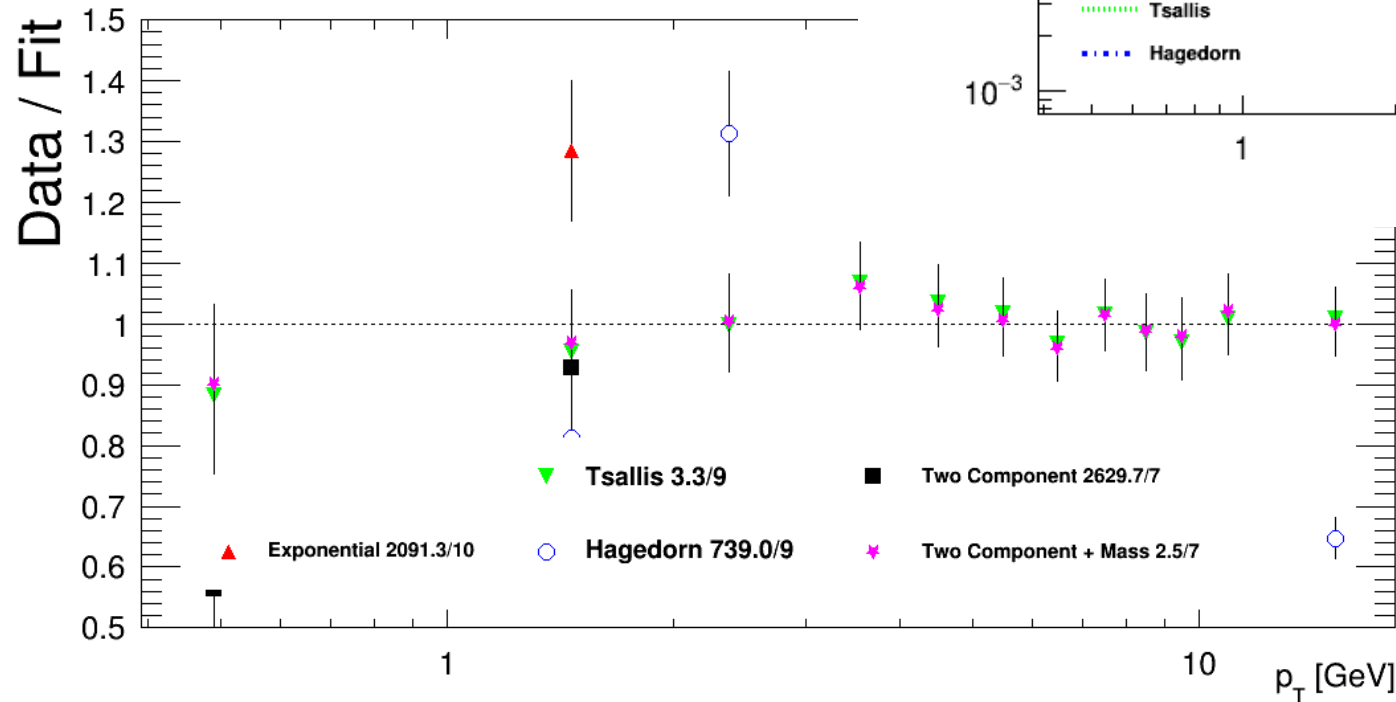
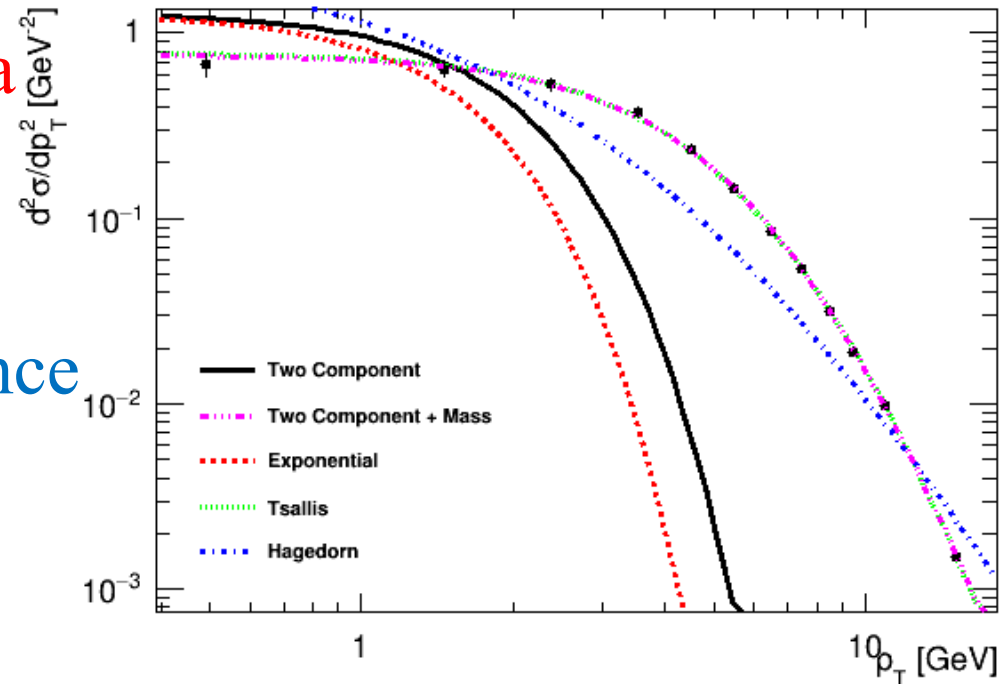
# And what about LHCb data?

## LHCb 8 TeV, $\Lambda_b^0$ spectra

The old two component approach does not fit the data

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

Formula with mass dependence works as well as Tsallis

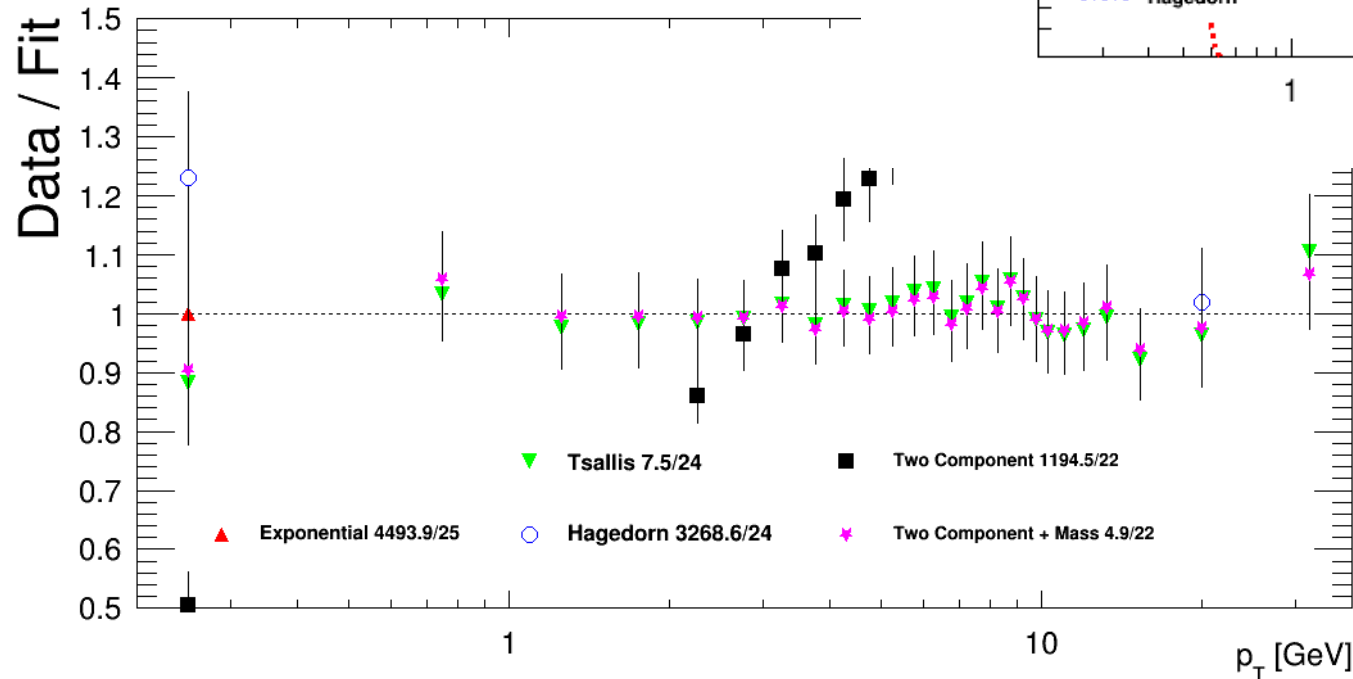
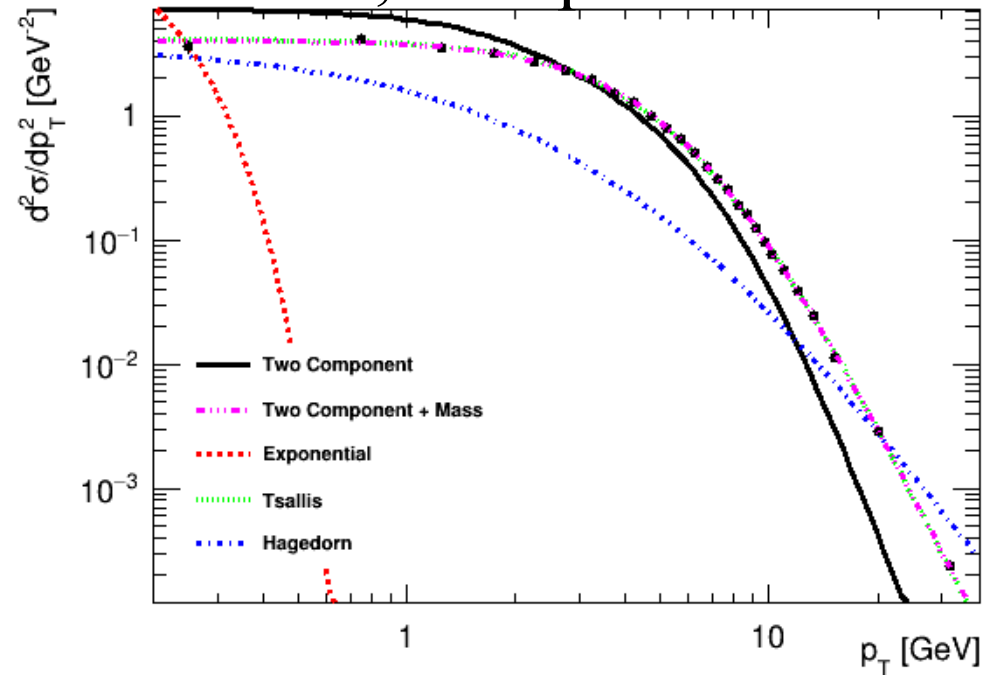


# And what about LHCb data?

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

The mass dependence is also crucial for the fit

## LHCb 7 TeV, $B^0$ spectra



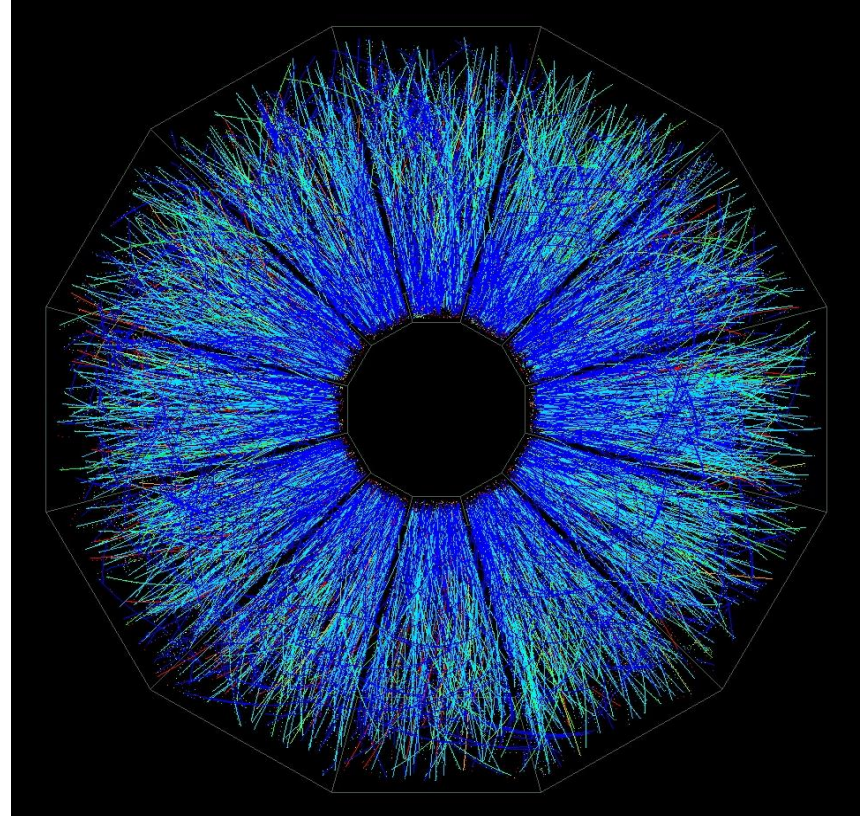
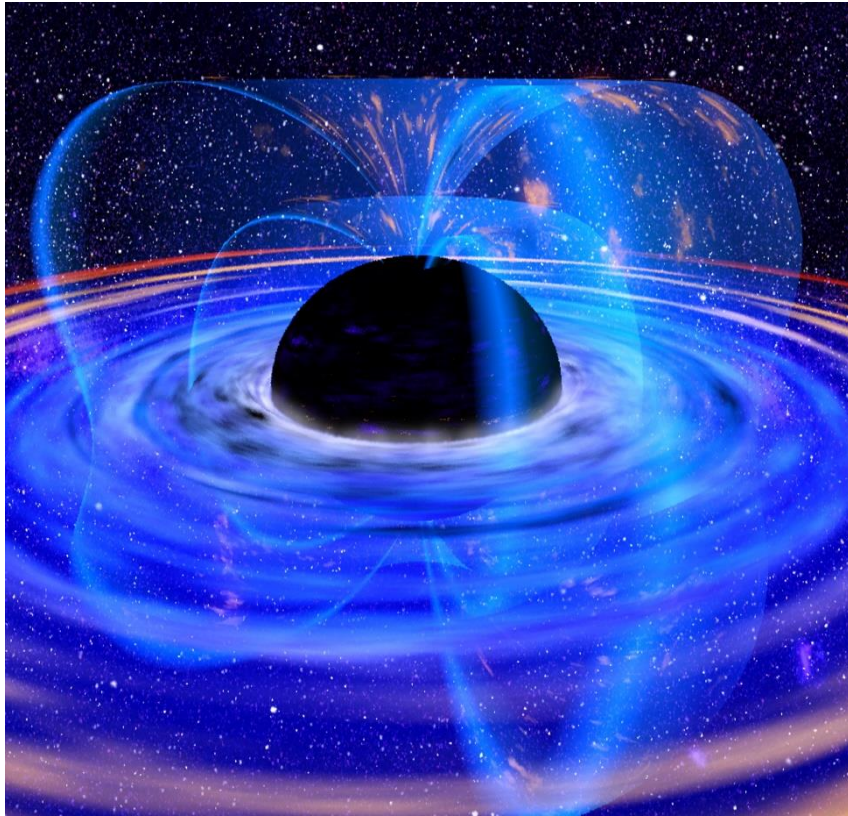


# A link between General Relativity and QCD? solution to some of the LHC puzzles?

Black holes



Heavy-ion collisions



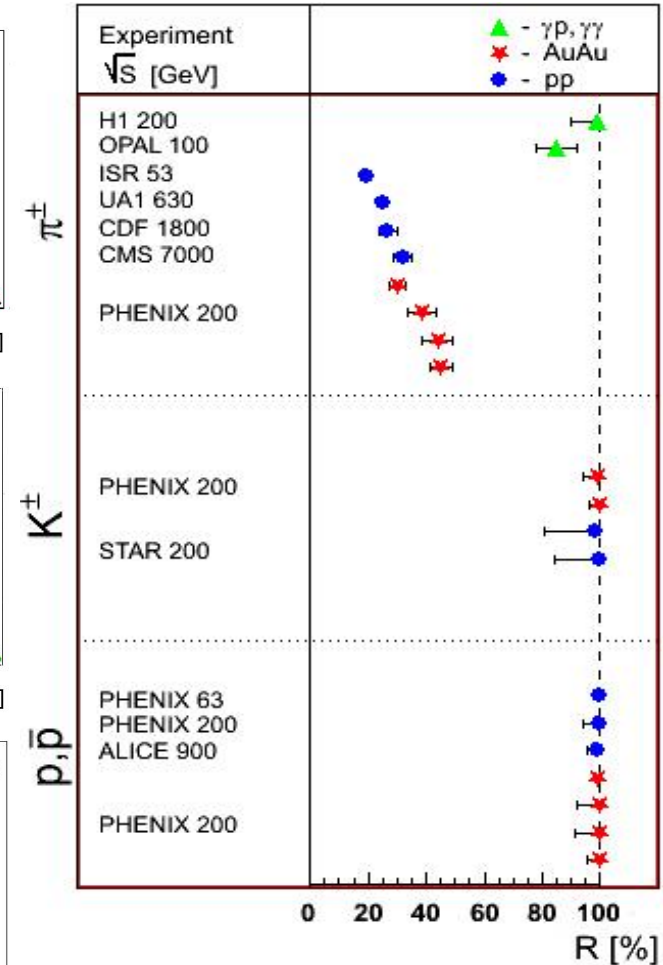
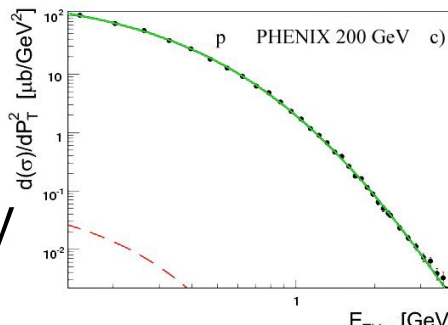
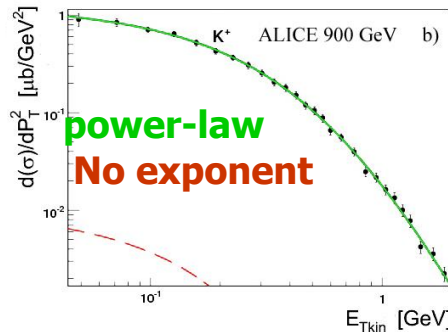
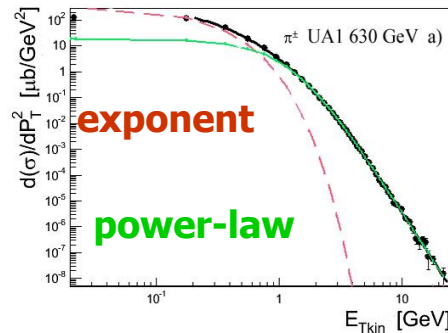
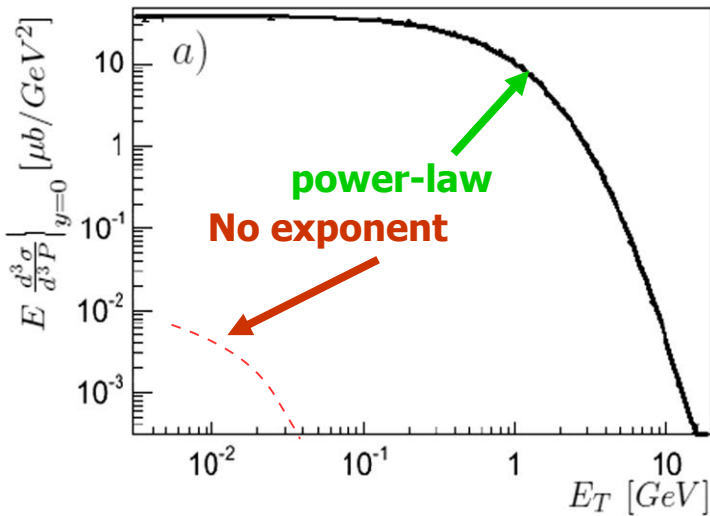
In astrophysics, Hawking-Unruh radiation has so far never been observed. The thermal hadron spectra in high energy collisions may thus indeed be the first experimental instance of such radiation, though in strong interaction instead of gravitation.

# 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 than pion

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

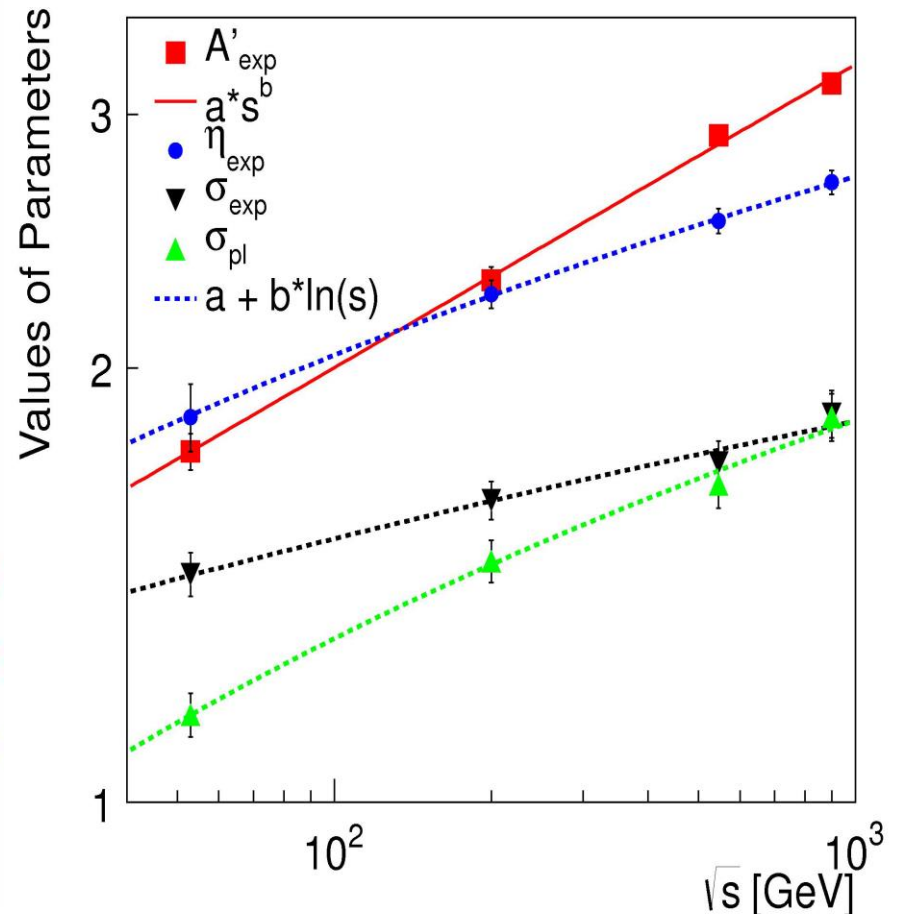
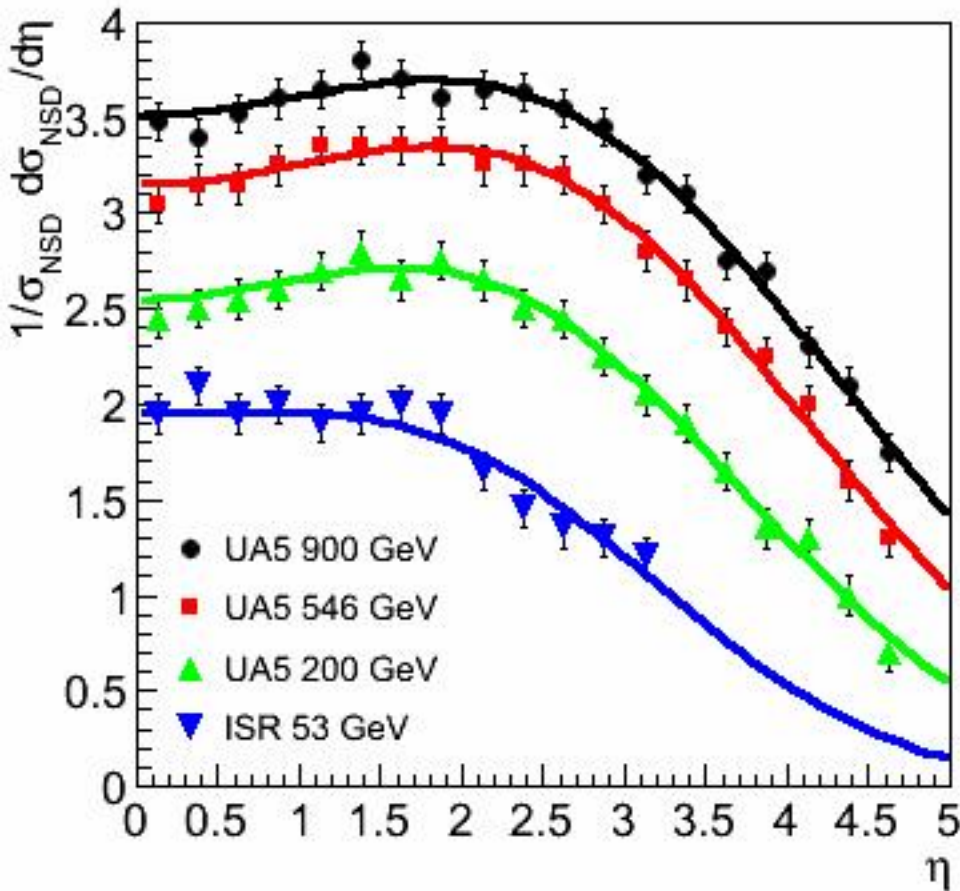


J/ψ spectra CDF  $\sqrt{s} = 1.96 \text{ TeV}$

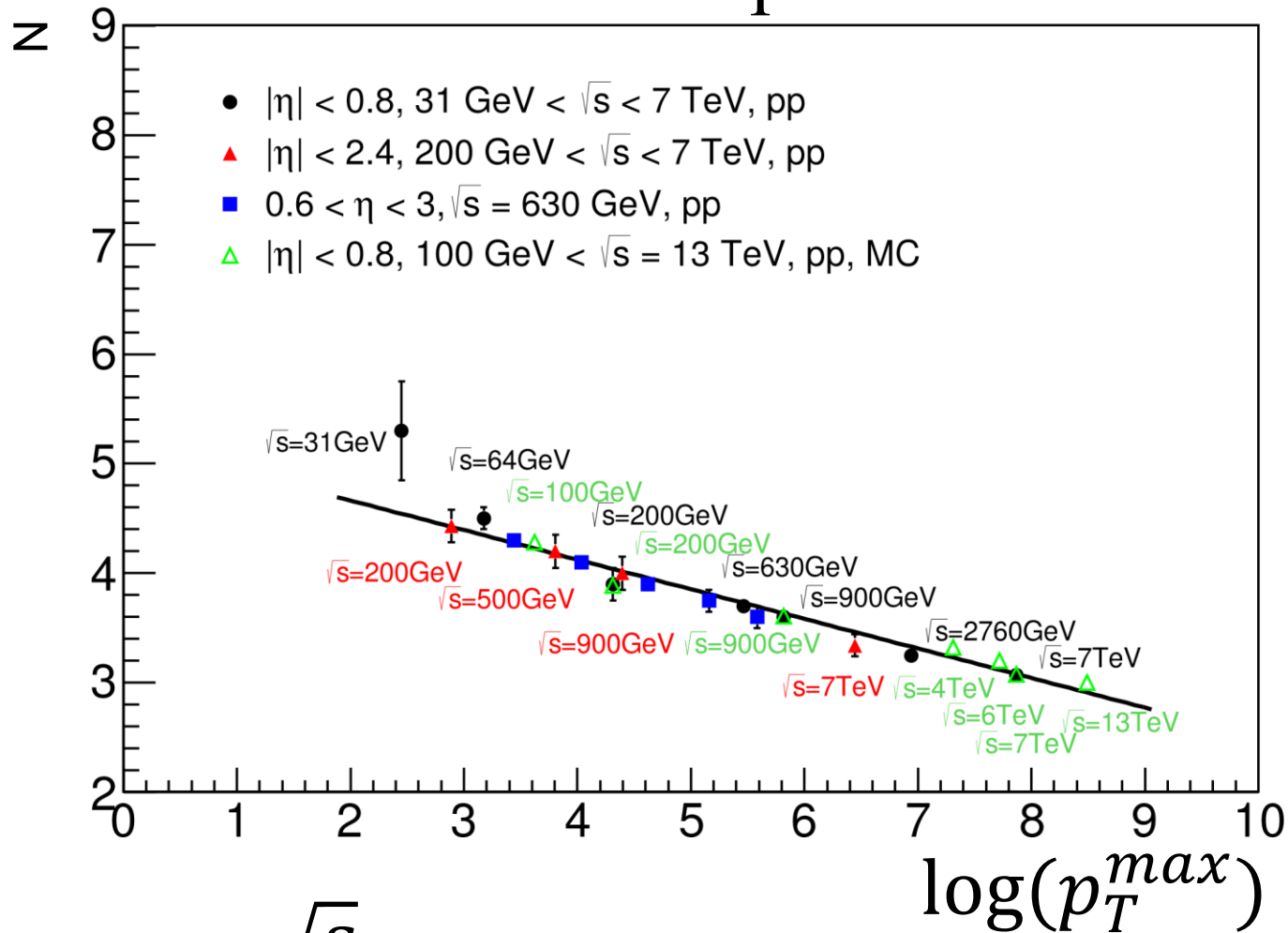


# Scaling of distributions

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



# 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  $x \rightarrow 1$  limit of PDFs, where the decrease of the perturbative cross section is modified by the fall-off of the parton distribution functions

# Universal dependence

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

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

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

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

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

The diagram illustrates a proton-proton collision. Two blue arrows labeled 'p' represent the incoming protons from the left and right. They meet at a central point marked with a red starburst. A vertical dashed blue line passes through this point. A green arrow labeled 'h' represents a secondary hadron produced in the collision. A red arc between the dashed line and the green arrow is labeled with the red symbol  $\eta$ . A larger yellow arc, spanning from the left proton's path to the green arrow, is labeled with the yellow symbol  $\eta''$ . To the right of the diagram, text reads: "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:

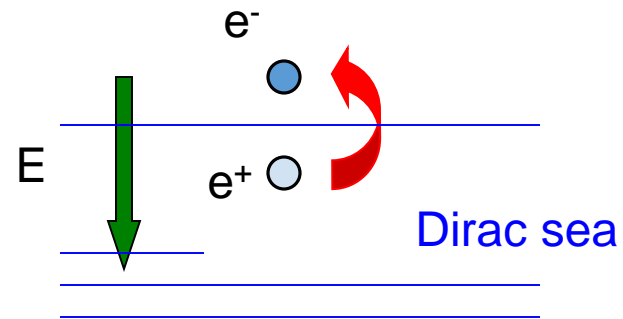
$$R \sim \exp \left( -\frac{2\pi m}{a} \right) = \exp \left( -\frac{2\pi m^2}{eE} \right)$$

What is this?

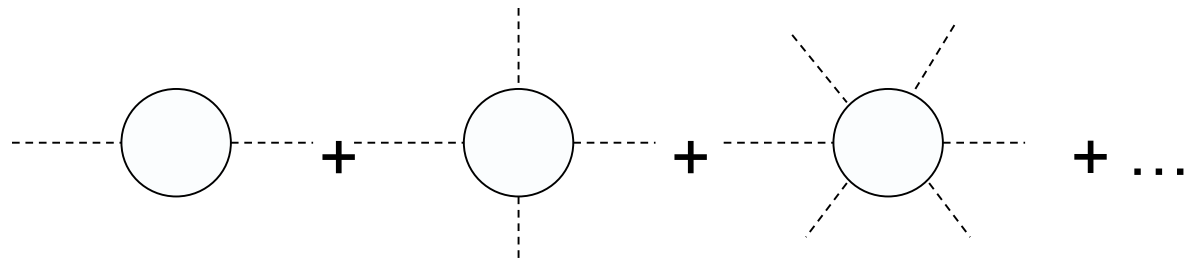
Schwinger formula for the rate of pair production;  
an exact **non-perturbative** QED result

factor of 2: contribution from the field

# The Schwinger formula



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



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...

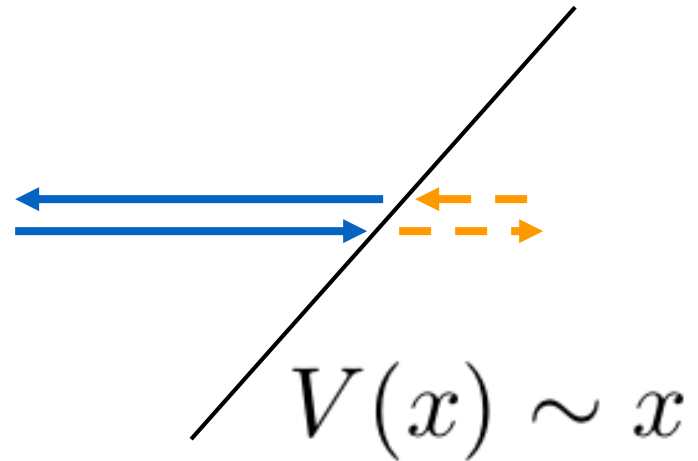
well, now we need some quantum mechanics, too:

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

The rate of tunneling under the potential barrier:

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

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



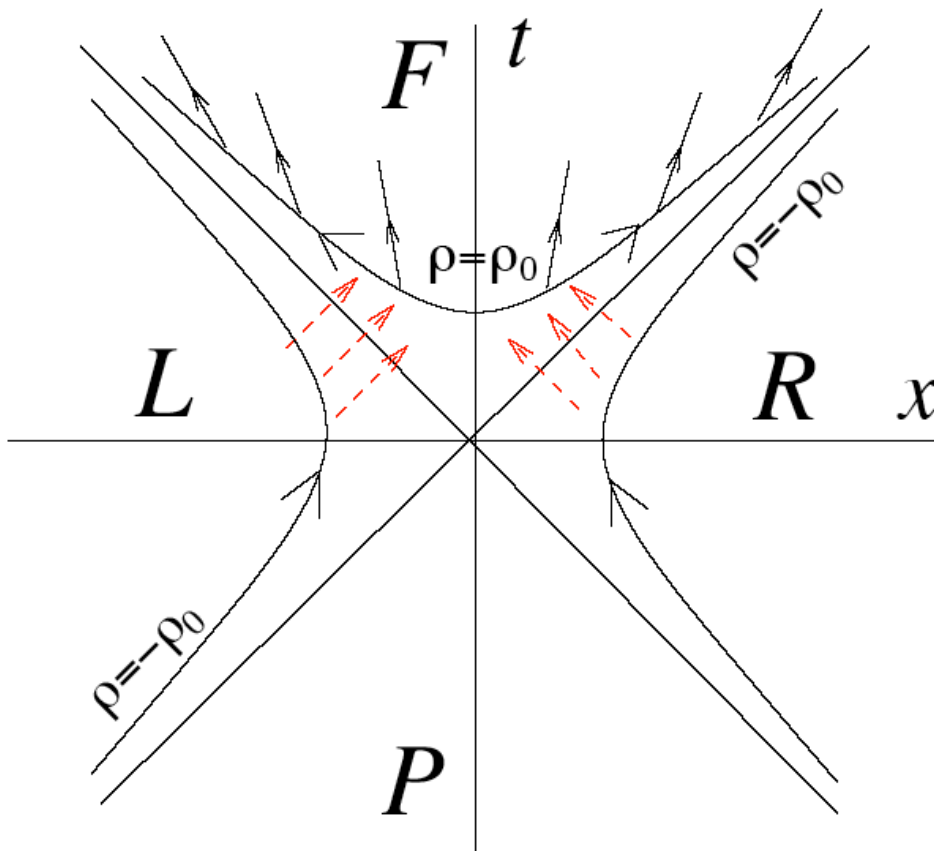


# Quantum thermal radiation at RHIC

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

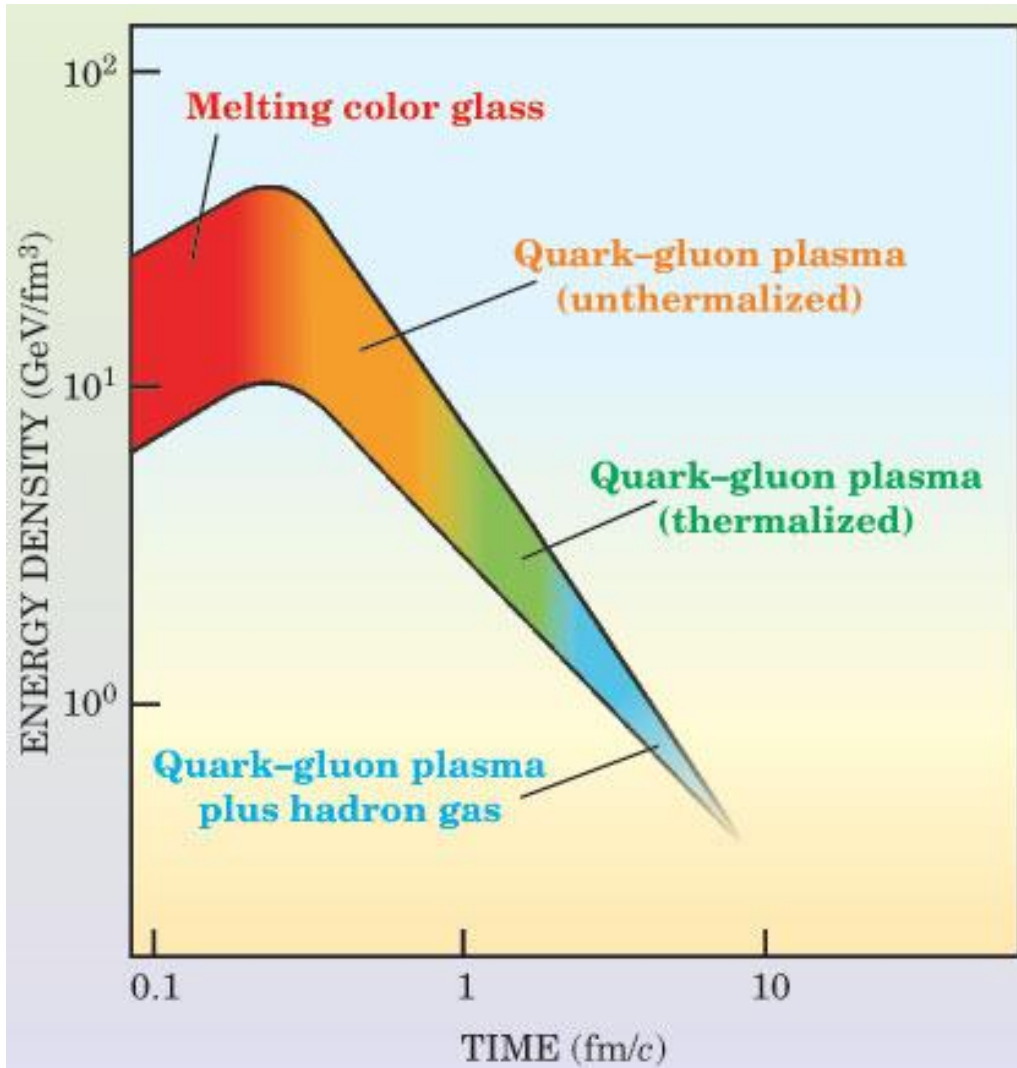
The event horizon emerges due to the fast deceleration  $a \simeq Q_s$  of the colliding nuclei in strong color fields;

Tunneling through the event horizon leads to the thermal spectrum



Rindler and Minkowski spaces

# 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

A17