Tsallis distribution in high-energy heavy ion collisions

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Hot & Cold Baryonic Matter 2010, Budapest 15-19 August 2010

O U T L I N E

- Motivation:

- High & low-p_T hadron spectra

- Can non-extensive thermodyn. resolve this?

- Notes on hadronization

- Simple joint models, tests & outlook

M O T I V A T I O N – for the future

- Measuring jet fragmentation (PID)

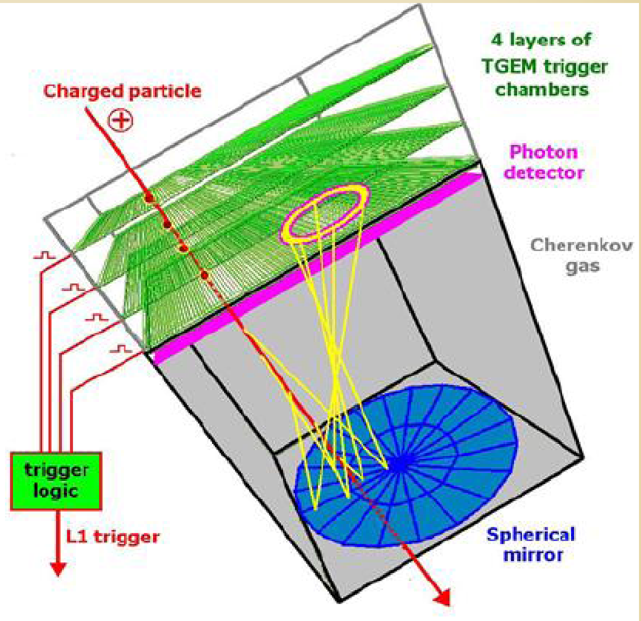
  Available: PID & jet fragmentation can be measured via jet analysis, data are from: DESY, Tevatron, RHIC, LHC...
  See: more on D. Berényi's poster

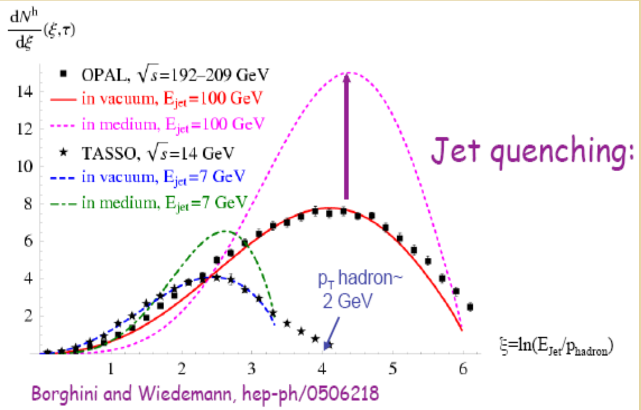
- Future PID measurement in HIC

  Under development: ALICE VHMPID detectors might measure it See more on: S. Pochybová, A. Agócs

- Fragmentation in ''matter''

  Aim/dream: Measure differential jet-parameters, identifying final state effects (jet-quenching modifications).





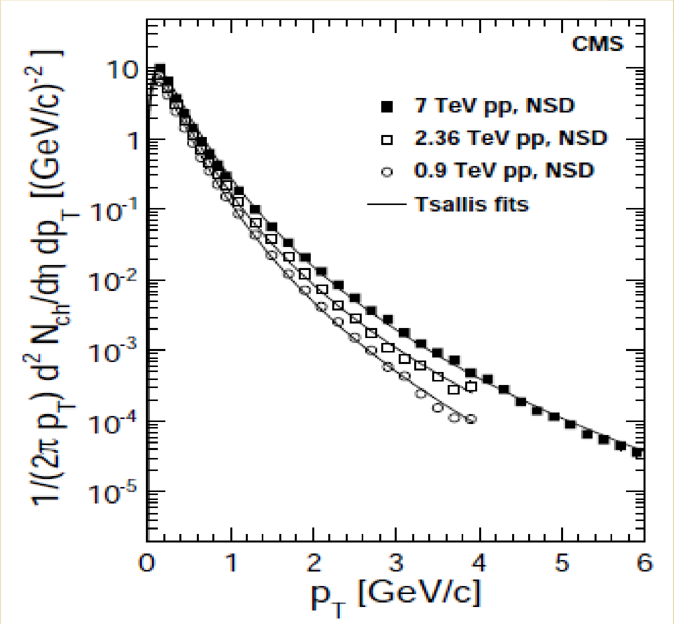
M O T I V A T I O N – recently

- New LHC pp data (CMS)

  JHEP 1002:041(2010)

  fitted Tsallis distribution for p_T spectra:

$$E\frac{d^3N_{\rm ch}}{dp^3} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N_{\rm ch}}{d\eta dp_T} = C(n,T,m)\frac{dN_{\rm ch}}{dy}\left(1+\frac{E_T}{nT}\right)^{-n}$$



  Parameters:

  0.9 TeV T= 130 MeV, q=1.13

  2.36 TeV T= 140 MeV, q=1.15 $n := (q-1)^{-1}$

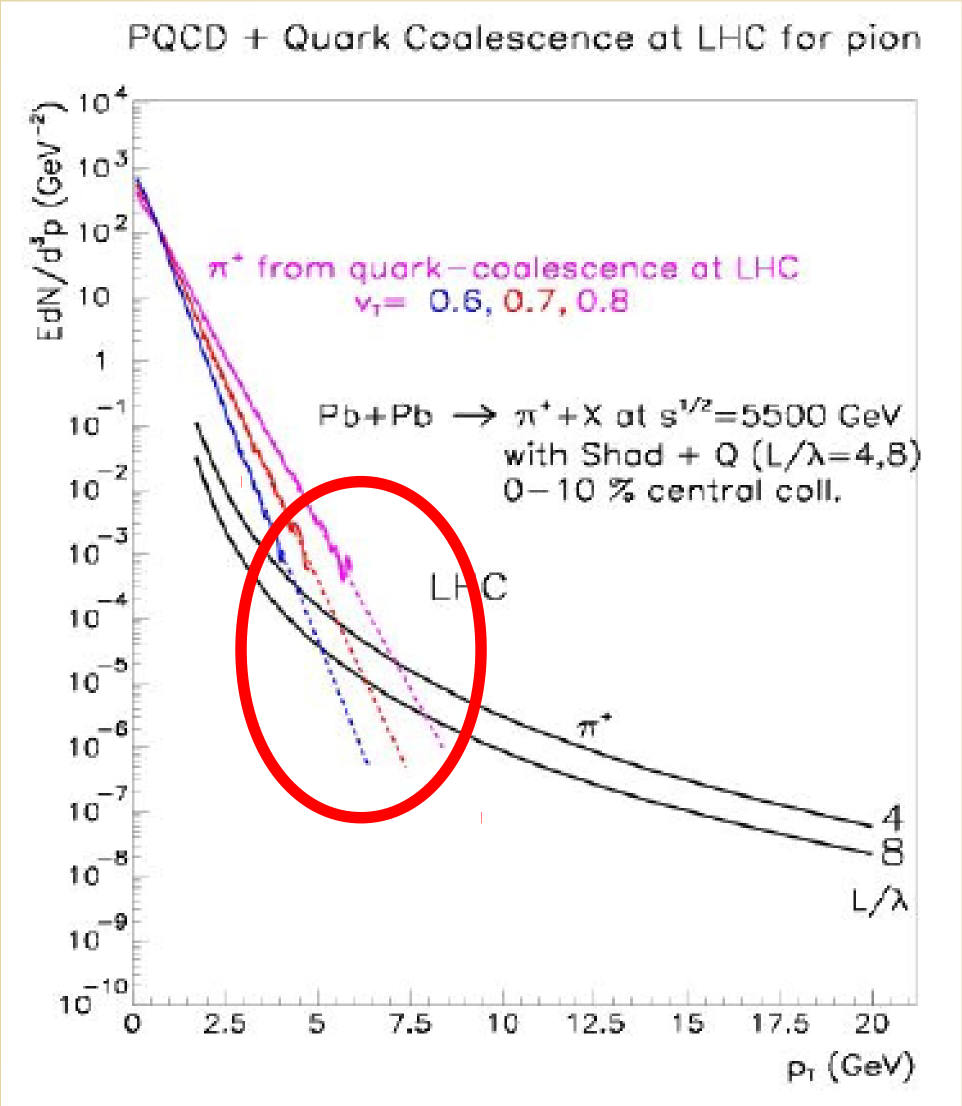
- RHIC analysis on AuAu data (y=0)

  Cooper-Frye model: K. Ürmössy, T.S. Bíró: PL B689 14 (2010)

  Parameters: $f(E) = A[1+(q-1)E/T]^{-1/(q-1)}$

  200 GeV T= 51 MeV, q= 1.062 (fit for p_T < 6 GeV/c)

M O T I V A T I O N – past…

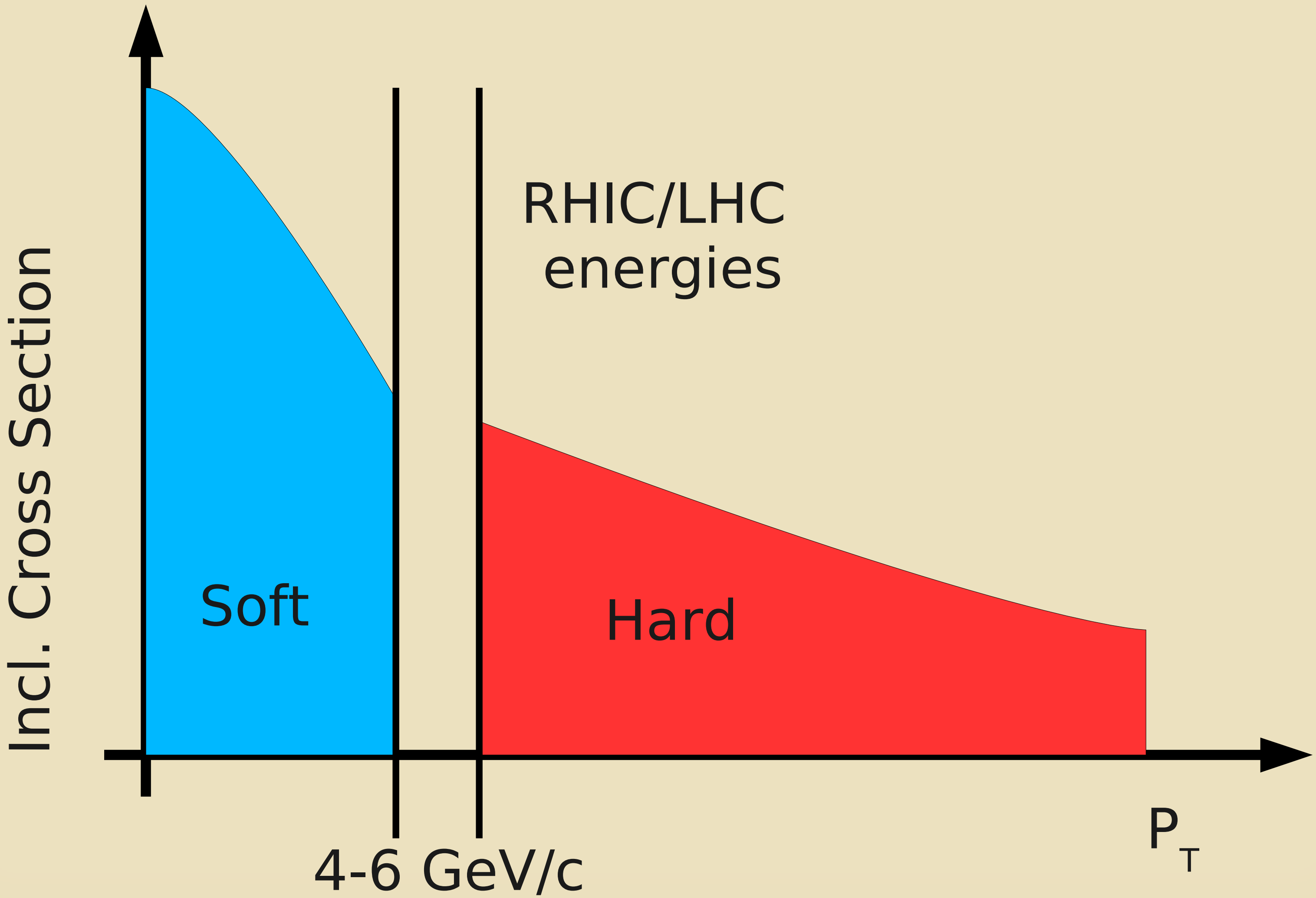


- pQCD based parton model:
  - QCD at T → 0 temperature
  - power law distribution
  - strong dependence on FF
  - good for high-p_T hadrons
- Quark-coalescence model
  - Thermal, finite temperature
  - exponential distribution $e^{-m/T}$
  - parton-hadron duality
  - good for high-p_T hadrons

P. Lévai, GGB, G. Fai: JPG35, 104111 (2008)

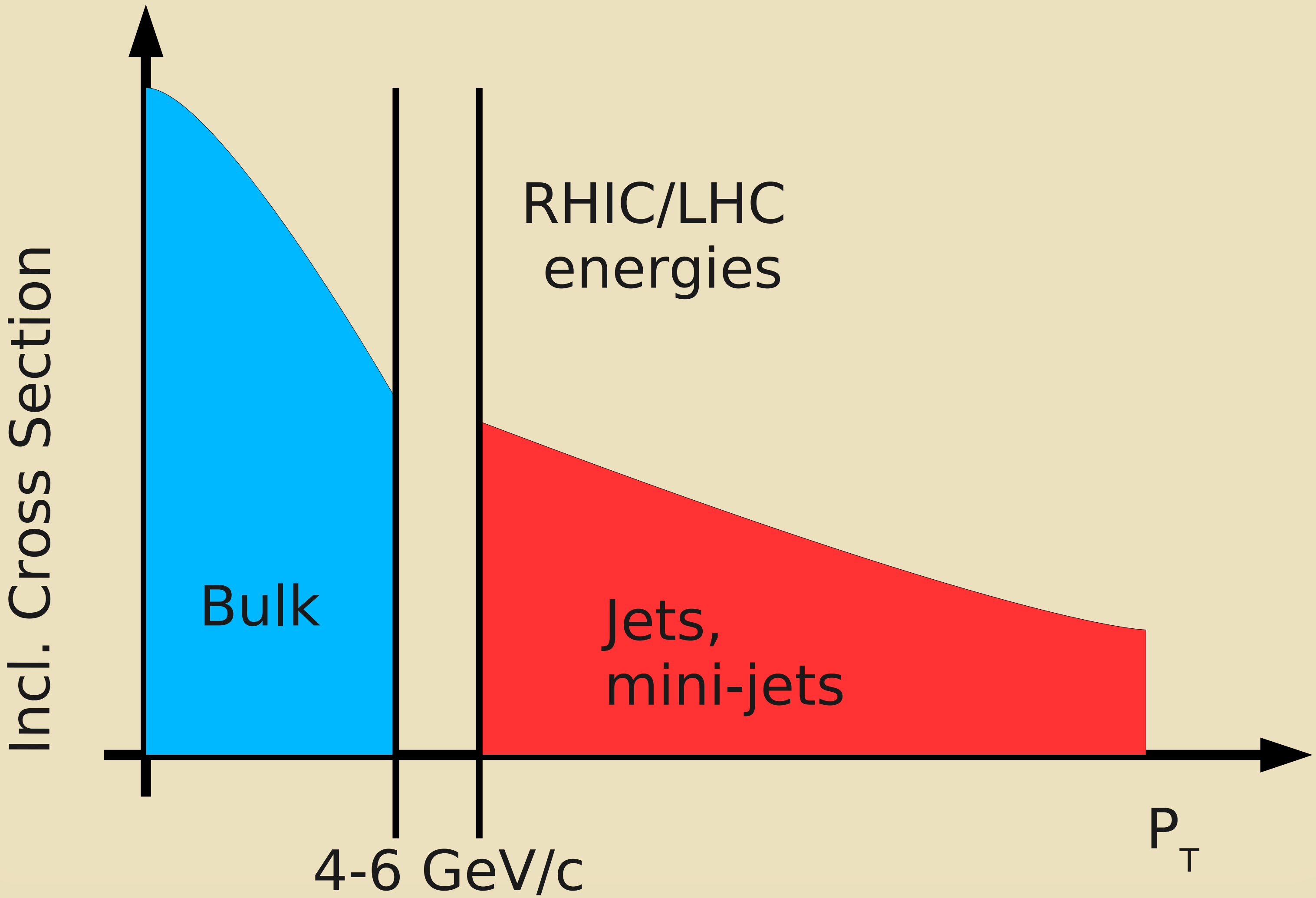
High & low p_T hadron spectra

- 1. interpretation 'soft' & 'hard' processes



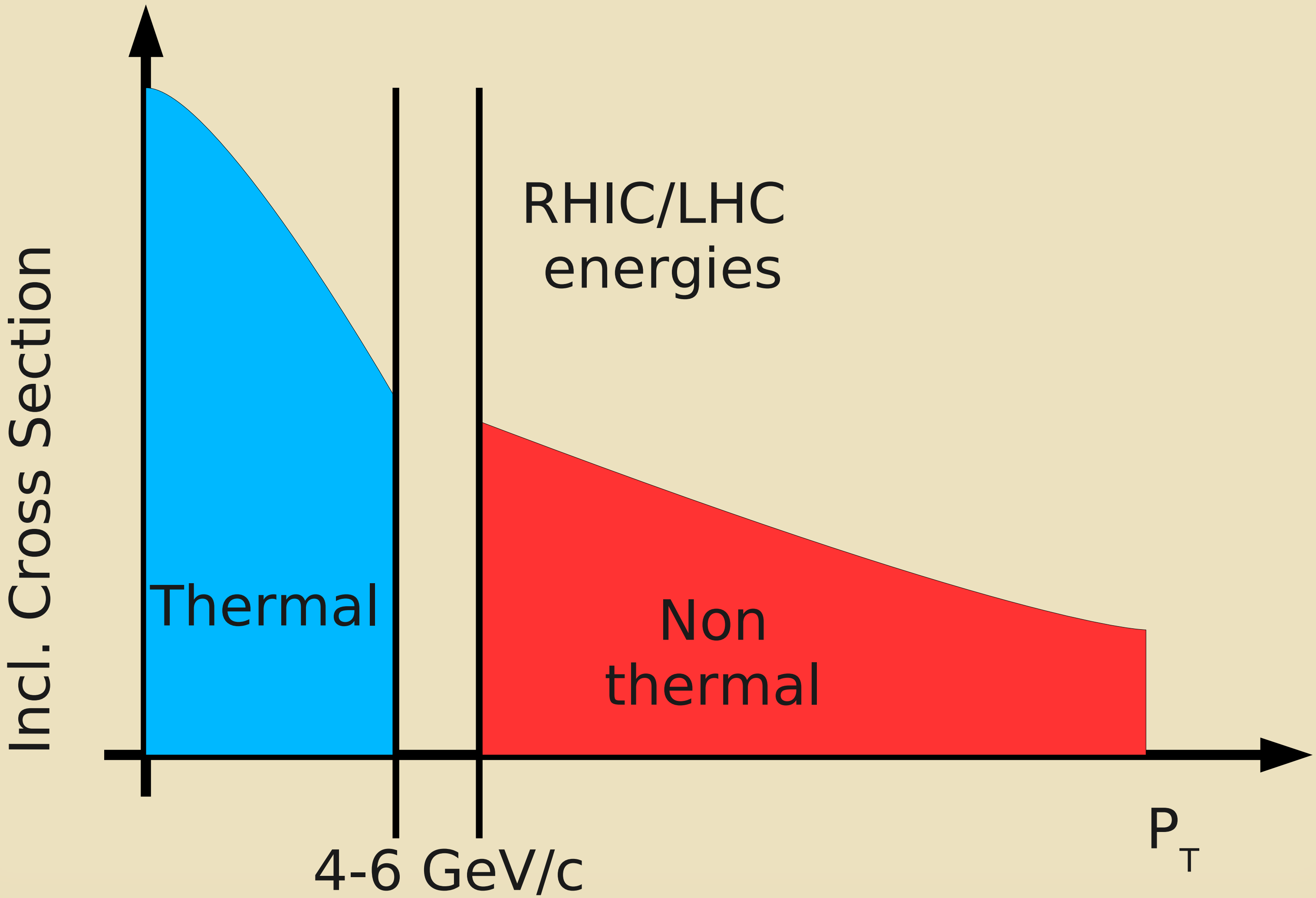
High & low p_T hadron spectra

- 2. interpretation 'bulk' & 'jet-like' processes



High & low p_T hadron spectra

- 3. interpretation 'thermal' & 'non-thermal' models




How can Tsallis
(re)solve this?

Basics of non-extensive thermodynamics

Non-extensive thermodynamics (Based on: T.S. Biró: EPL84, 56003,2008)
associative composition rule, (non-additive) :

$$h(h(x,y),z) = h(x,h(y,z))$$

Then should exist a strict monotonic function, X(x) 'generalised logarithm' (an entropy-like quantity), for which:

$$h(x,y) = X^{-1}(X(x) + X(y)) \qquad X(h(x,y)) = X(x) + X(y).$$

Example: (i) Classical thermodynamics:

$$f(E) = e^{-\beta E}/Z \qquad h(x,y) = x + y.$$

(ii) Tsallis distribution

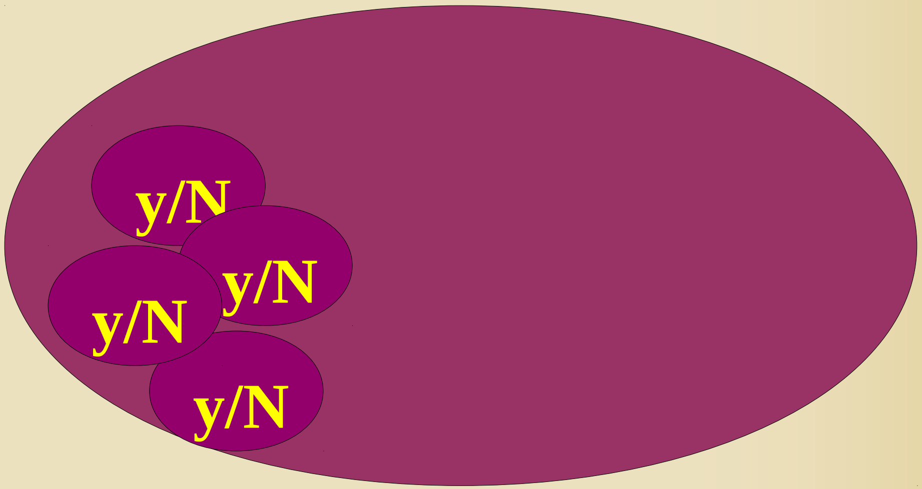
$$h(x,y) = x + y + axy \qquad a = q - 1$$

$$f(E) = \frac{1}{Z} e^{-\frac{\beta}{a}\ln(1+aE)} = \frac{1}{Z}(1+aE)^{-\beta/a} \qquad S = \int f \frac{e^{-a\ln(f)} - 1}{a} = \frac{1}{a}\int (f^{1-a} - f).$$

Associative composition ⇉ evolution eq.

Non-extensive Gibbs, generalised

logarithm: $f(x) = \frac{1}{Z} e^{-\beta X(x)}$.



Composition rule for sub-systems:

$$x_N(y) := \underbrace{h \circ \ldots \circ h}_{N-1} \left(\frac{y}{N}, \ldots, \frac{y}{N} \right)$$

Meanwhile satisfy: $\lim_{N \to \infty} x_N(y) < \infty$.

Assimptotically, if $N_1, N_2 \to \infty$:

$$x_{N_1+N_2} = \varphi(x_{N_1}, x_{N_2})$$

recursive equation can be given:

$x_n = h\left(x_{n-1}, \frac{y}{N}\right)$, where $h(x, 0) = x$.

$$x_n - x_{n-1} = h\left(x_{n-1}, \frac{y}{N}\right) - h(x_{n-1}, 0).$$

Evolution equation can carry out:

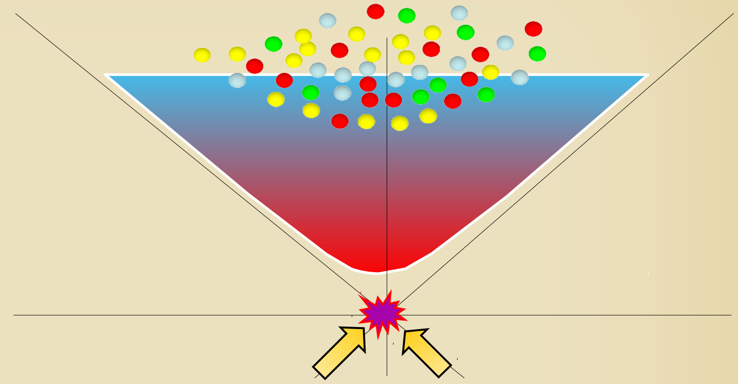
$$\frac{dx}{dt} = \frac{y}{t_f} h_2'(x, 0^+)$$

$$L(x) = \int_0^x \frac{dz}{h_2'(z, 0^+)} = y \frac{t}{t_f}.$$

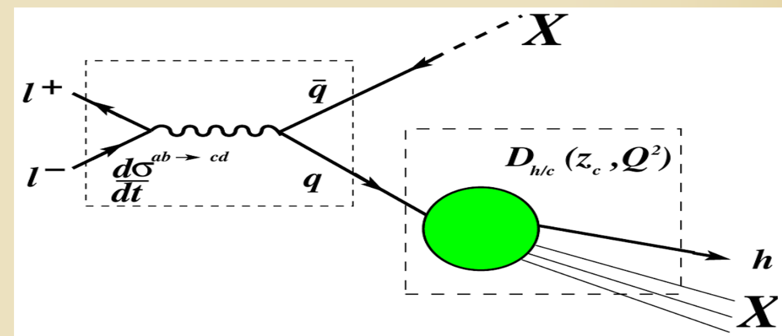
Notes on hadronization:

integrated vs. statistical

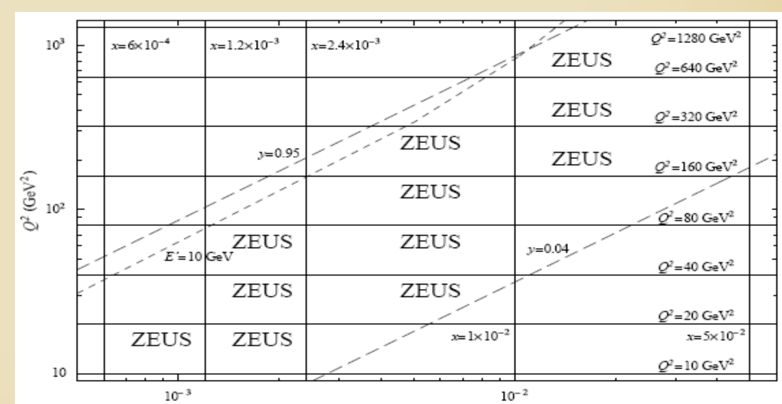
Hadronization processes & fragmentation



- Hadronization: requires a model, based on local parton-hadron duality (kvantum numbers & momenta connected to a cone around or to the leading particle.)



- Parton/hadron shower evolution comes from statistical processes (step-by-step MC evolution). → microscopical

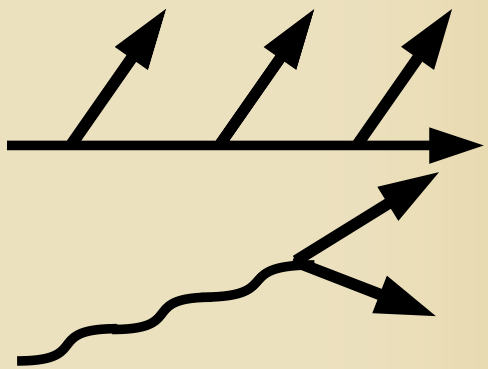


- Fragmentation function (FF) carries integrated (phenomenological) information on how parton fragment into hadron. → integradted distribution
- Measurement lepton-antilepton annihilation, HIC, etc...

Models for fragmentation

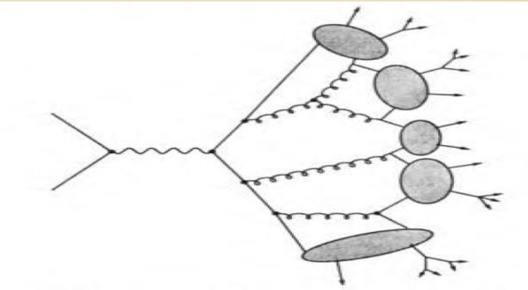
- Independent fragmentation model (Feynman - Field)

  Simplest model for fragmentation by
  Field & Feynman : q & g channels



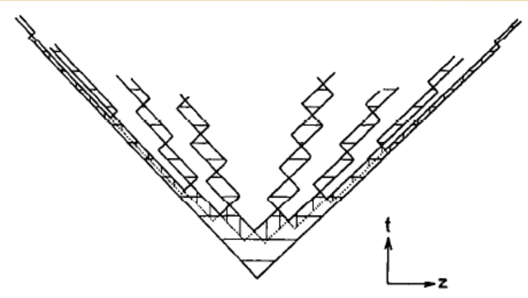
- (Quark) string model

  color strings between $q\bar{q}$, breaking into
  quark-antiquark pair → mesons



- Cluster model (Lund model)

  Lund model: phase-space separation,
  froming clusters: $q\bar{q}$ → M, qqq → B



Fragmentation processes in parton model

In a pQCD based parton model, fragmentation functions (FF) gives how parton (a) fragment into a hadron (h), $D_{h/a}(z,Q^2)$.

DGLAP scale evolution:

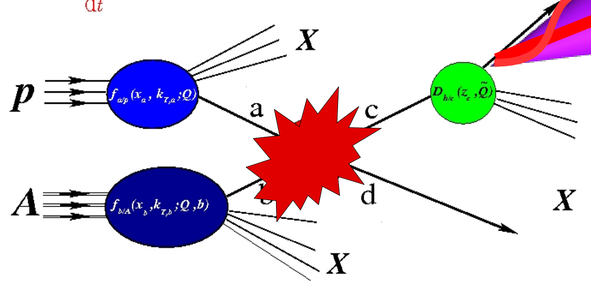
$$\frac{\partial}{\partial \ln Q^2} D_i^h(x,Q^2) = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_S}{4\pi} P_{ji}\left(\frac{x}{z}, Q^2\right) D_i^h(z,Q^2)$$

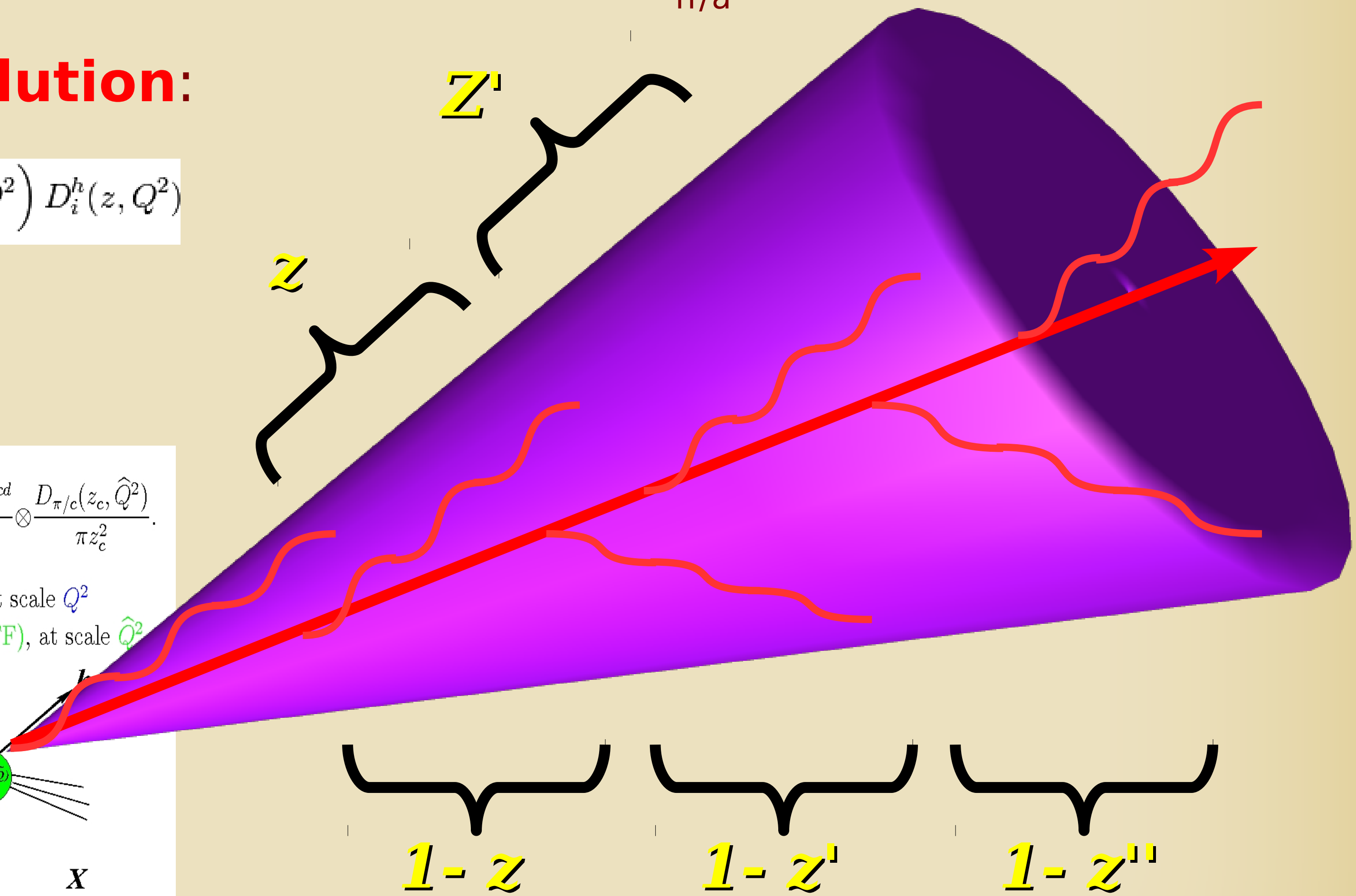
$$E_\pi \frac{d\sigma_\pi^{pA}}{d^3p_\pi} \sim f_{a/p}(x_a, Q^2; k_T) \otimes f_{b/A}(x_b, Q^2; k_T, b) \otimes \frac{d\sigma^{ab\to cd}}{d\hat{t}} \otimes \frac{D_{\pi/c}(z_c, \hat{Q}^2)}{\pi z_c^2}.$$

$f_{b/A}(x_a, Q^2; k_T, b)$: Parton Dist. Function (PDF), at scale Q^2

$D_{\pi/c}(z_c, \hat{Q}^2)$: Fragmentation Function for π (FF), at scale $\hat{Q}^2$

$\frac{d\sigma^{ab\to cd}}{d\hat{t}}$: Partonic cross section





Fragmentation via associative composition

Program:

1) Search and fit Tsallis distribution to data.

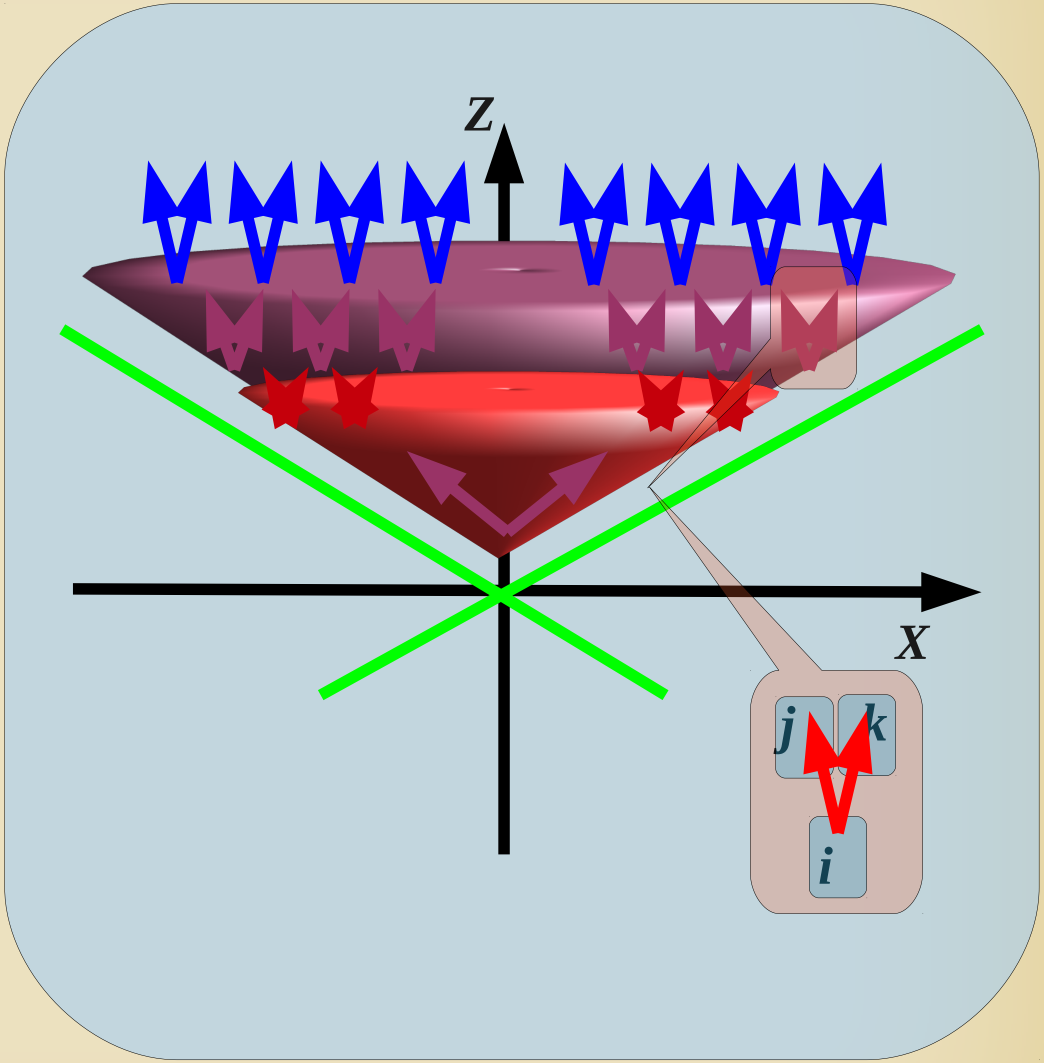
2) Search for physical meaning of T and q parameters.

3) Components of the sub-systems are e.g. 'splitting functions' P_{qg} , P_{gg}

4) Test: can a BFKL / DGLAP-like evolution equation be obtained?

$$D(x,Q^2) \sim f(E,T,q) * f(\ln(Q^2))$$

$$D(x,Q^2) \sim f(E,T(\ln(Q^2)),q(\ln(Q^2)))$$

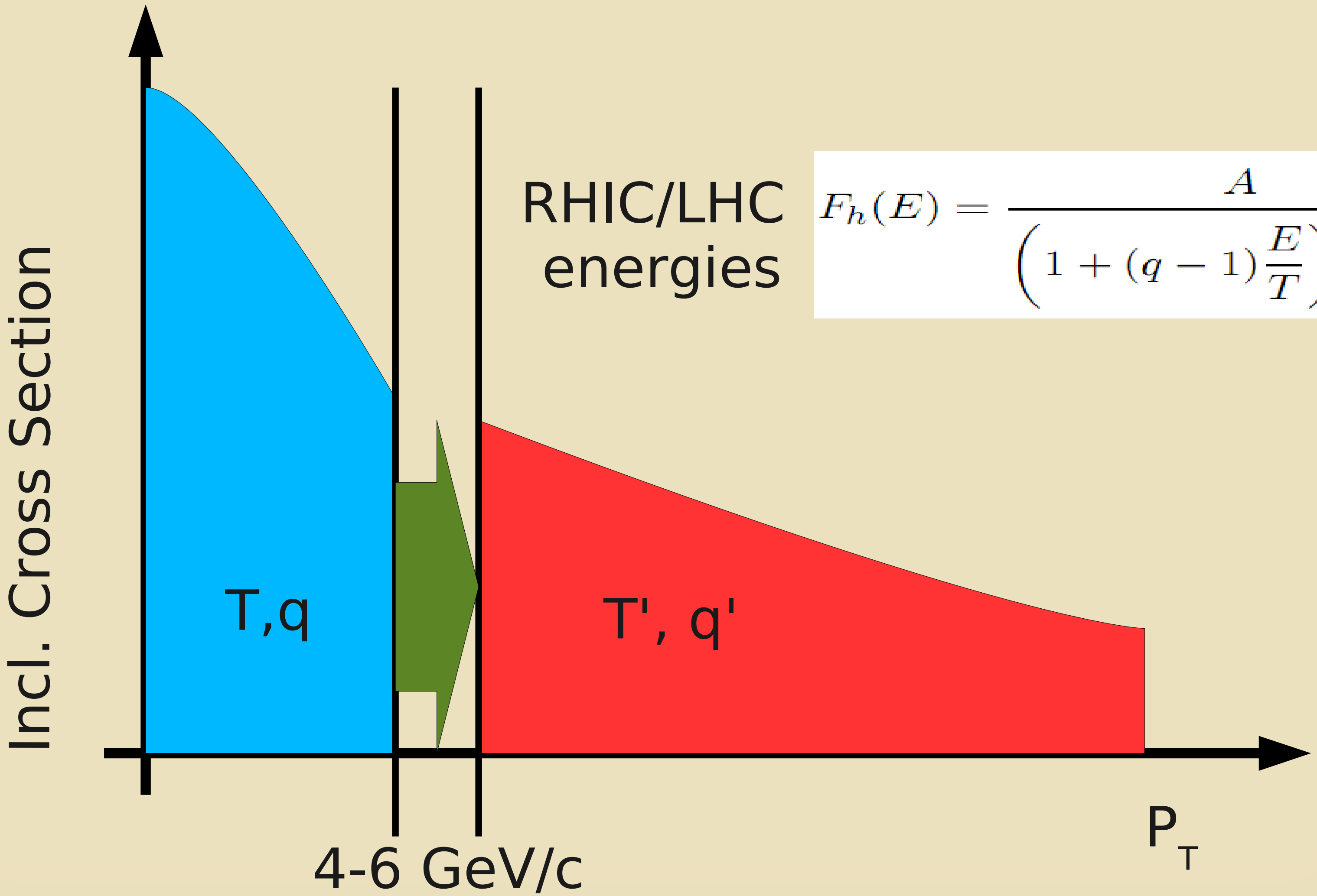


A test in two models

joint ideas…

1^{st} way: find the distribution

- A suggested new way: Tsallis (like) distribution



$$F_h(E) = \frac{A}{\left(1 + (q-1)\frac{E}{T}\right)^{1/(q-1)}}$$

1st joint model: recombination & pQCD in AA

Find a distribution for low & high momentum spectra:

$$\boxed{e^{-\beta E}} \longrightarrow F_h(E) = \frac{A}{\left(1 + (q-1)\frac{E}{T}\right)^{1/(q-1)}}$$

In AA collisions particle energy modified by the flow:

$$E = \gamma(m_t - v_{flow} p_t), \quad m_t = \sqrt{m^2 + p_t^2}$$

Slope for particle spectra can be fitted:

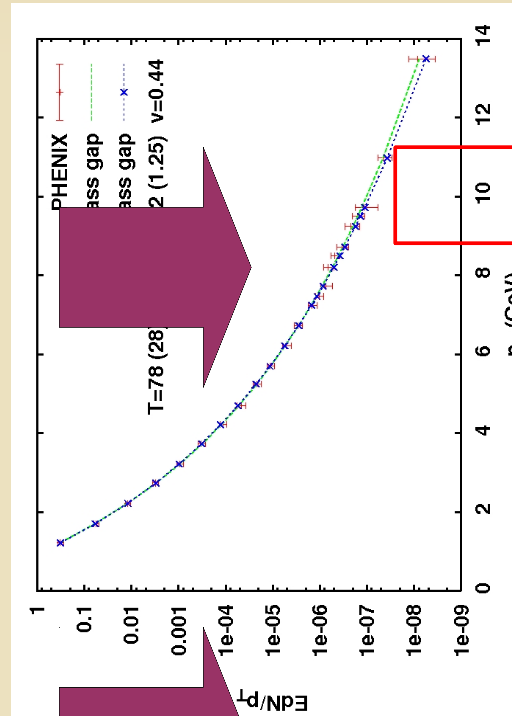
$$T_{slope} = -\frac{\partial E}{\partial ln(F_h(E))} = T(1 + aE) = T + (q-1)E$$

furthermore, if E>>m, then $T \rightarrow T\,[\,(1 + v)\,/\,(1 - v)\,]^{1/2}$

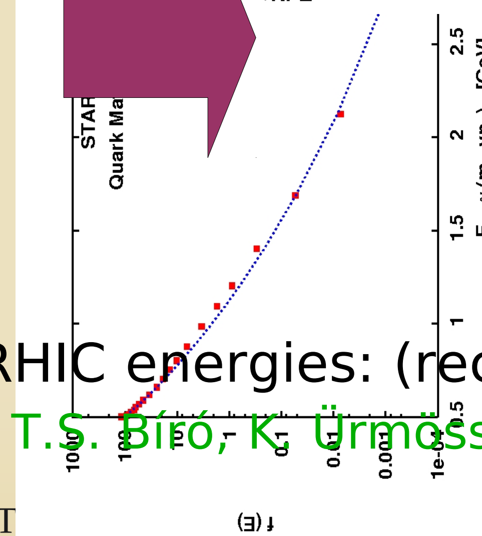
See more on details in talks by: K. Ürmössy and P. Ván

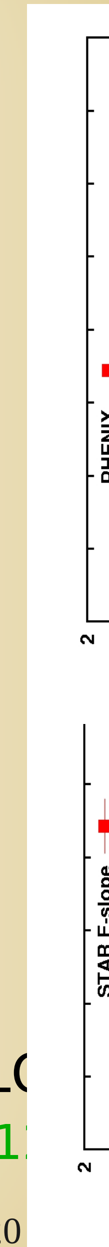
1st joint model: recombination & pQCD in AA

Pion spectrum



Kaon spectrum



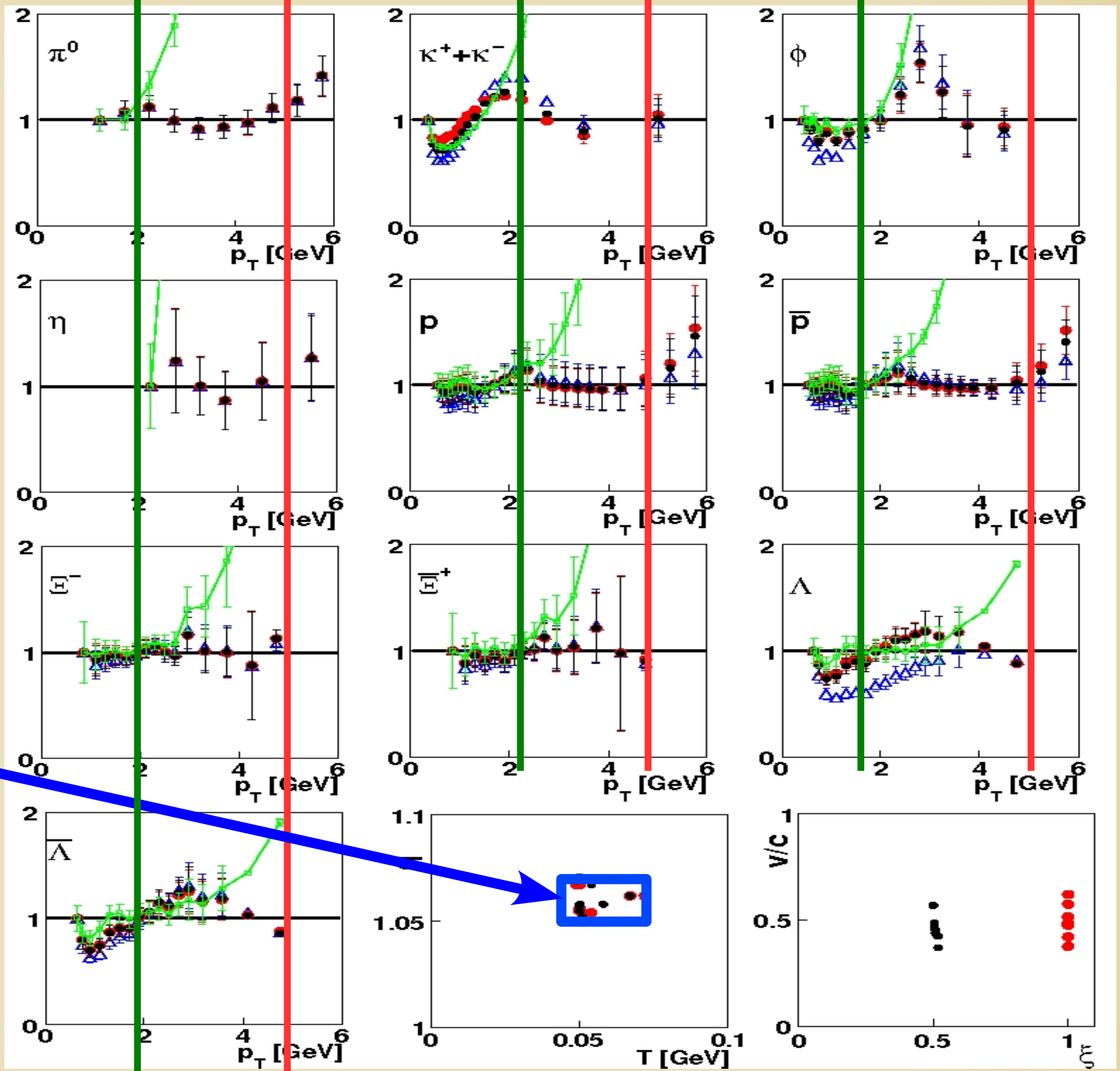


Fitted T & q Tsallis parameters at RHIC energies: (recombination and NL pQCD+AKK FF, *v=0.5* for kaons): T.S. Biró, K. Ürmössy, GGB: JPG35, 04401 (2008)

1st joint model: recombination & pQCD in AA

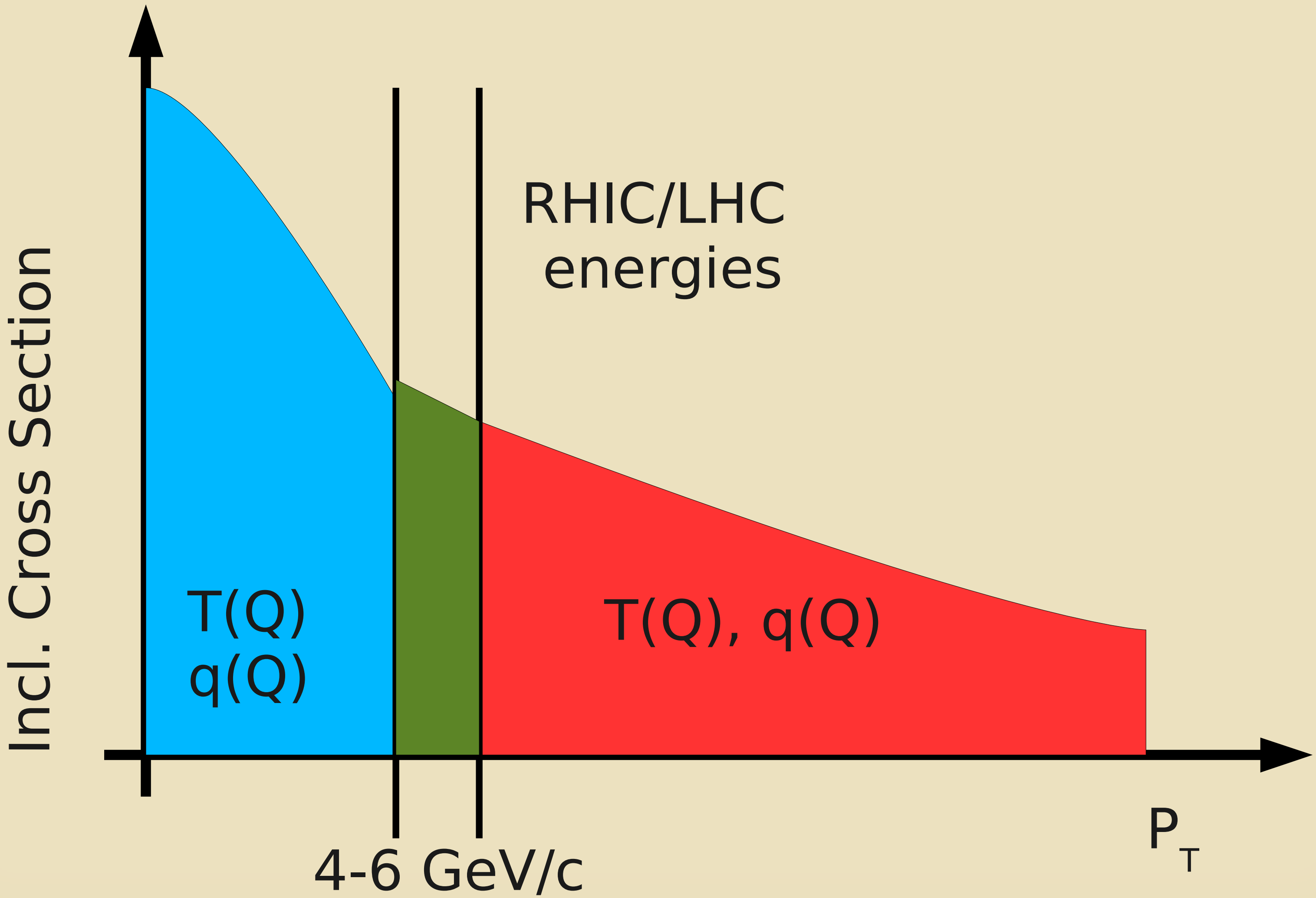
Analysing
Meson & Baryon
specta in
AuAu collisions

- Ratio of theoretical or experimental p_T spectra in y=0, AuAu collisions fitted by Tsallis distribution.
- T=50-70MeV, q=1.06-1.07
- Here the fit is only for $p_T < 6$ GeV/c.
- K. Ürmössy, T.S. Bíró: PLB689:14 (2010)



2nd way: to resolve the gap...

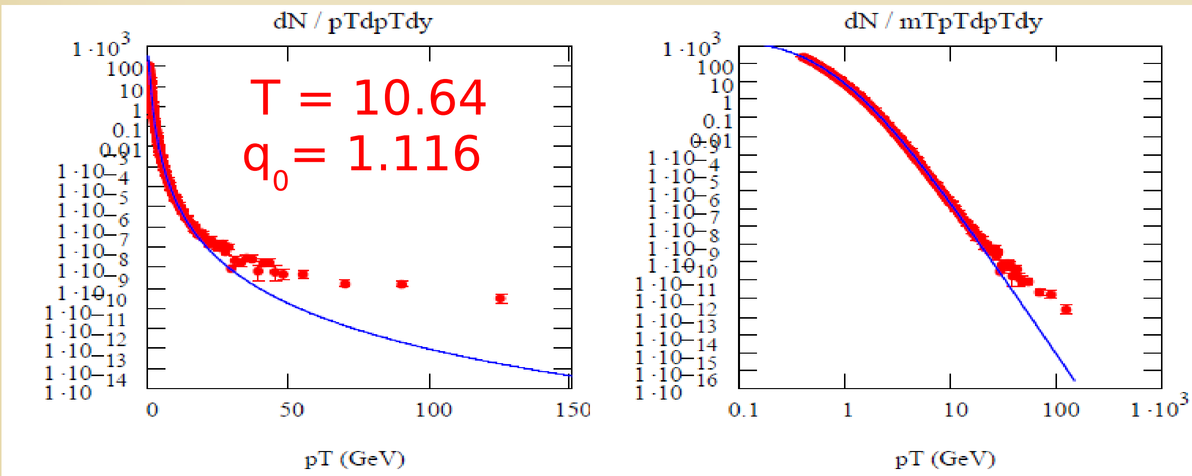
- Suggested interpetation: Tsallis + evolution

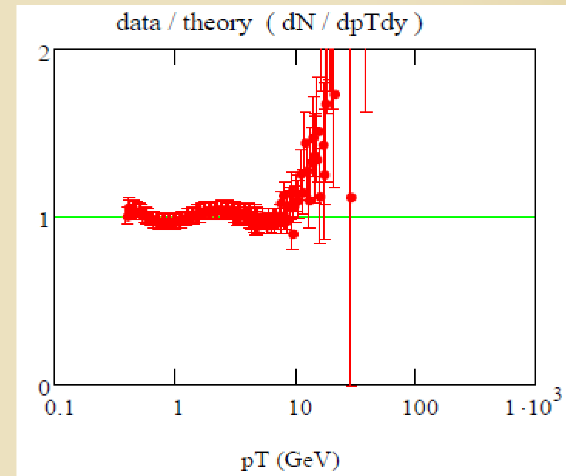


2^{nd} joint model: Tsallis with evolution

- TEST on CDF ch. hadron data in pp @ 1.96 TeV |y|<1

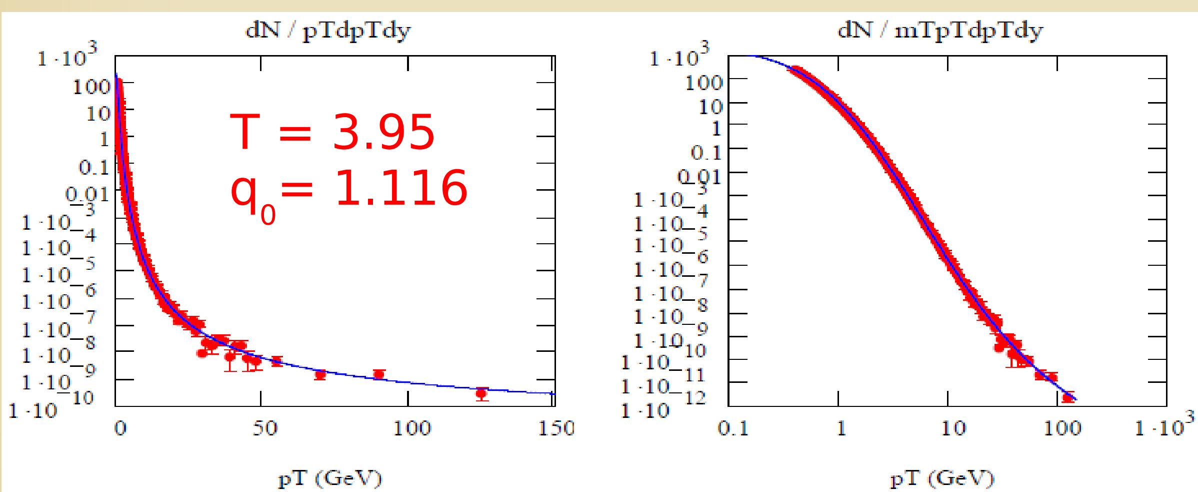
NO evolution

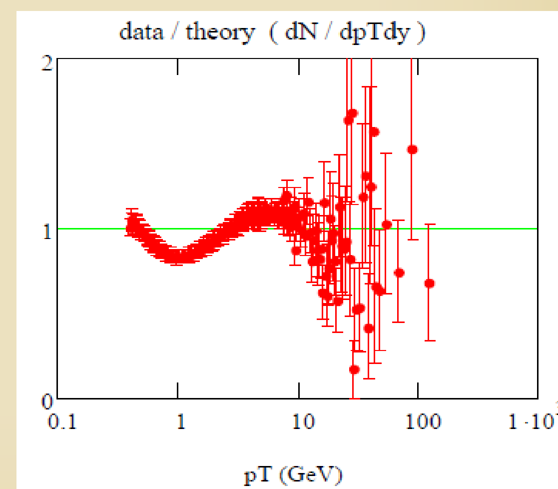




- DGLAP motivated evolution: $n = (q_0-1)^{-1} - 2*\log(\log(Q))$

With evolution

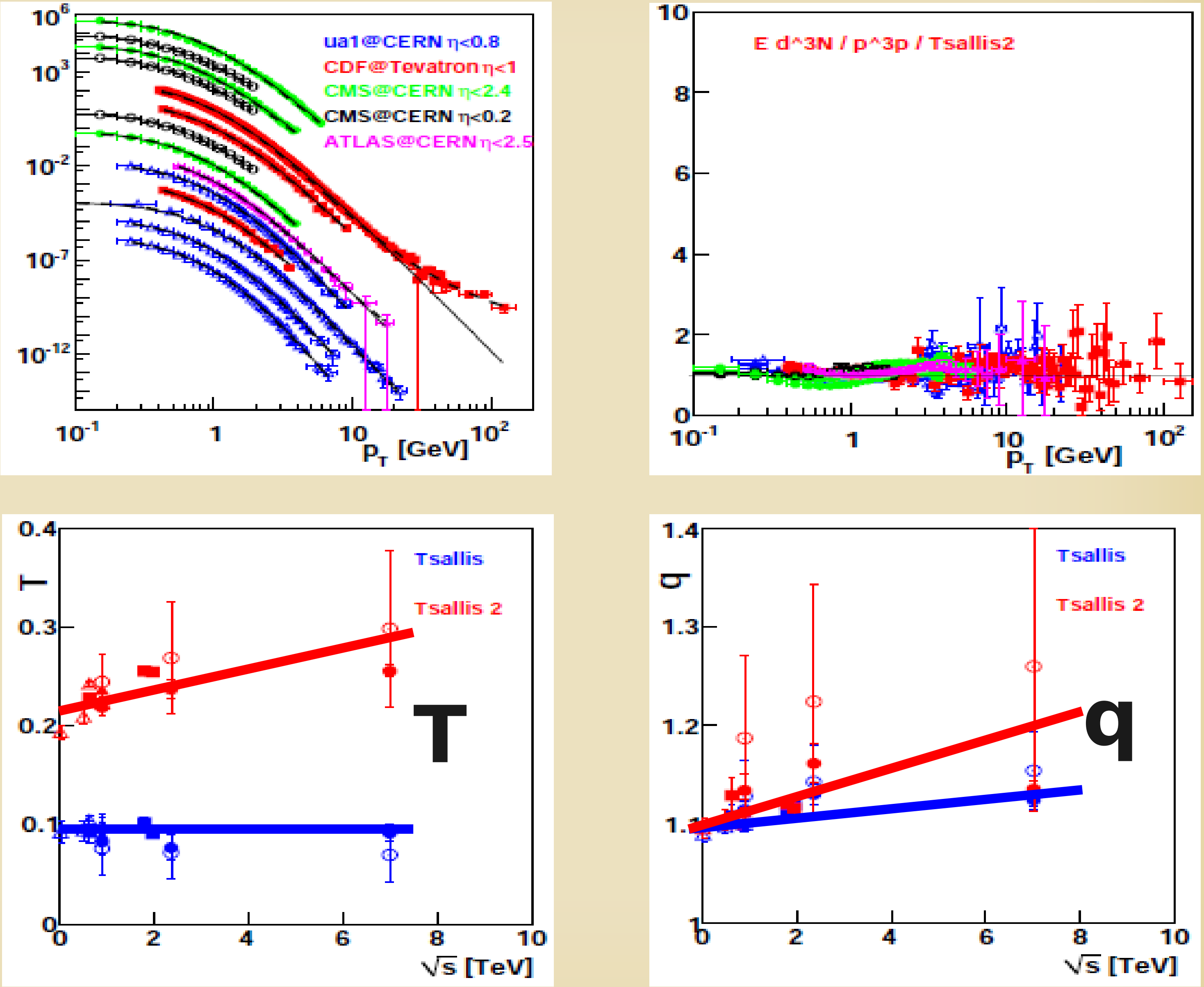




2nd joint model: Tsallis with evolution

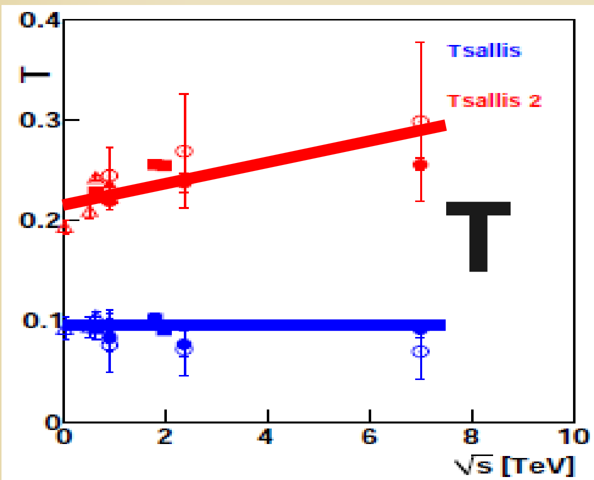
- More TEST: 0.2 - 7 TeV midrapidity data

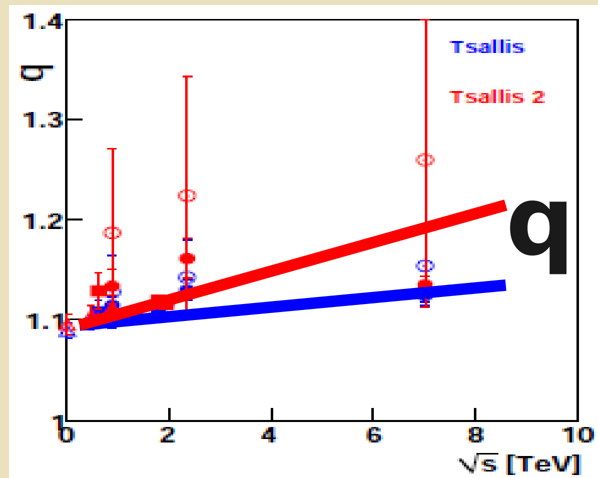
- C.m. Energy dependence of the T & q parameters

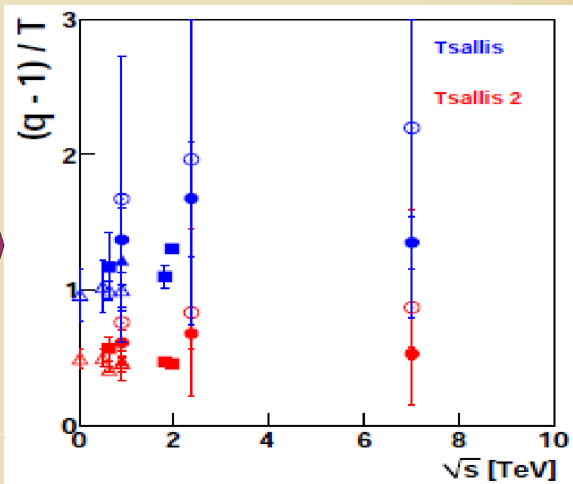


2^{nd} joint model: Tsallis on q-T plane

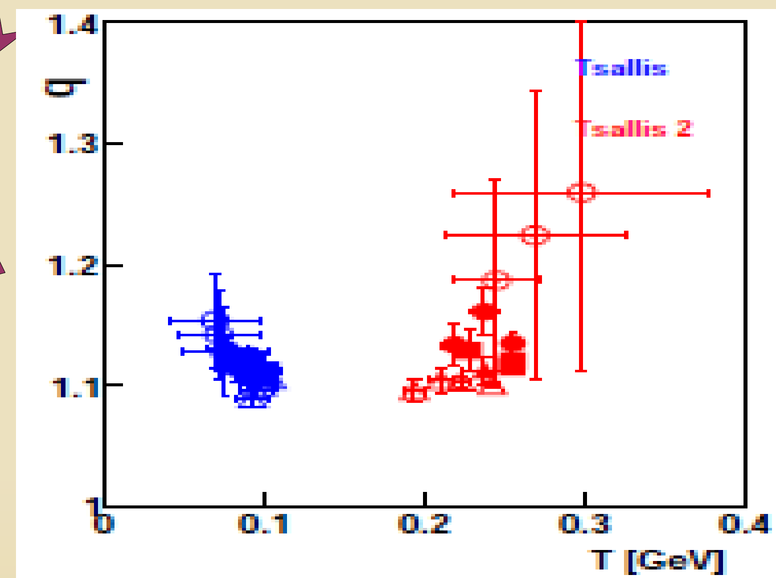
- TEST on various midrapidity data @ different cm



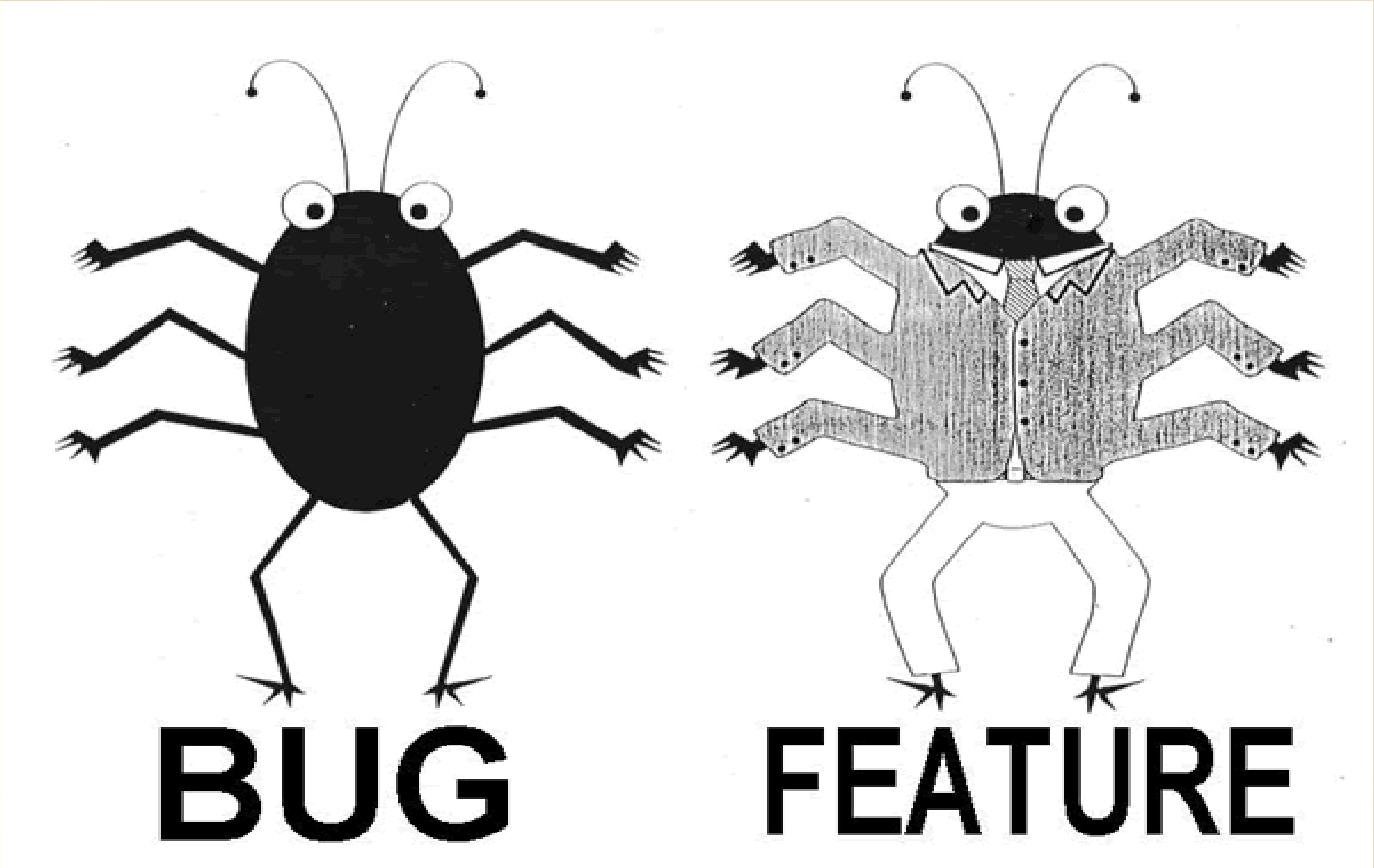




- The q-T plane

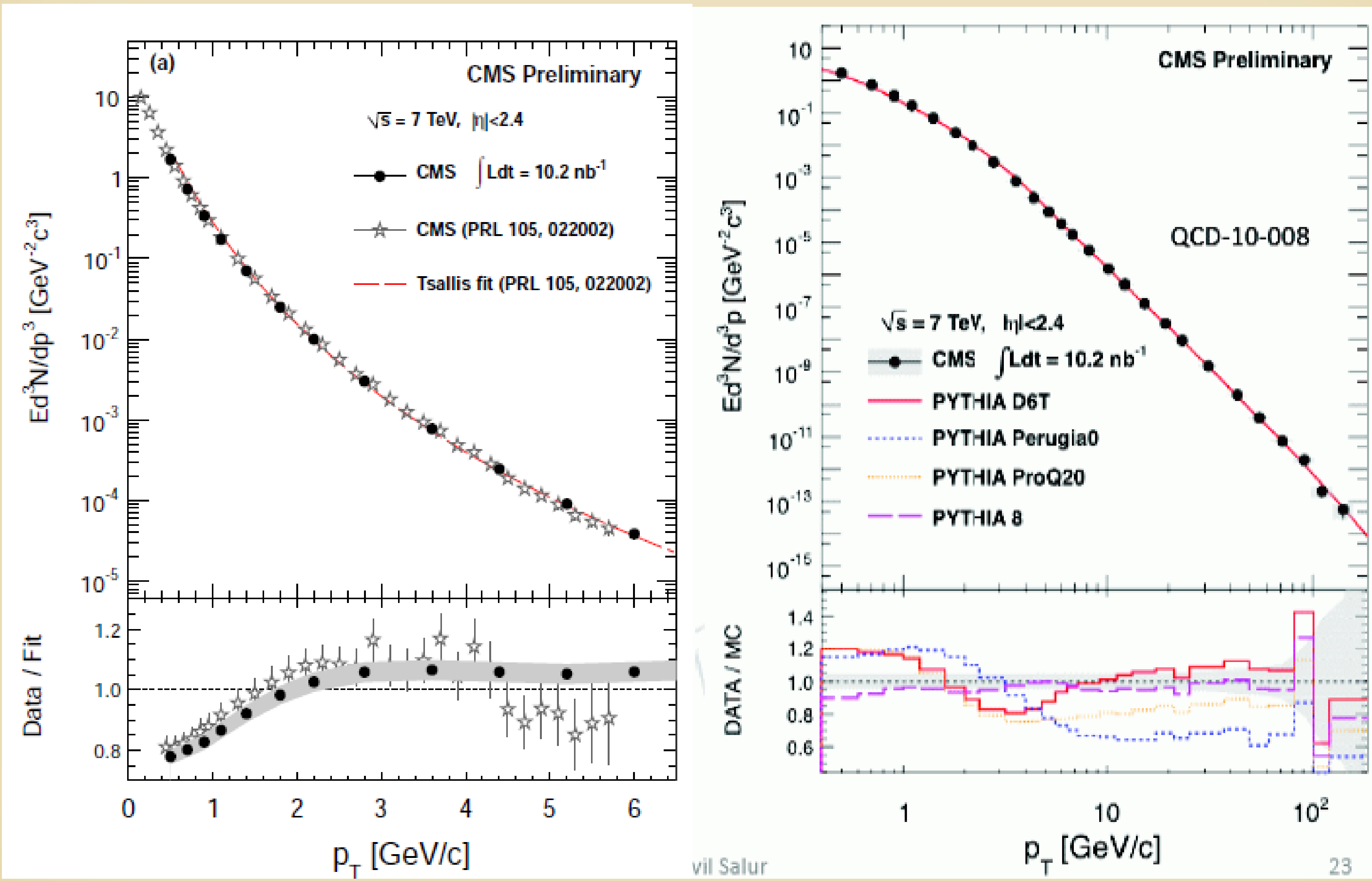


A new question on the market...



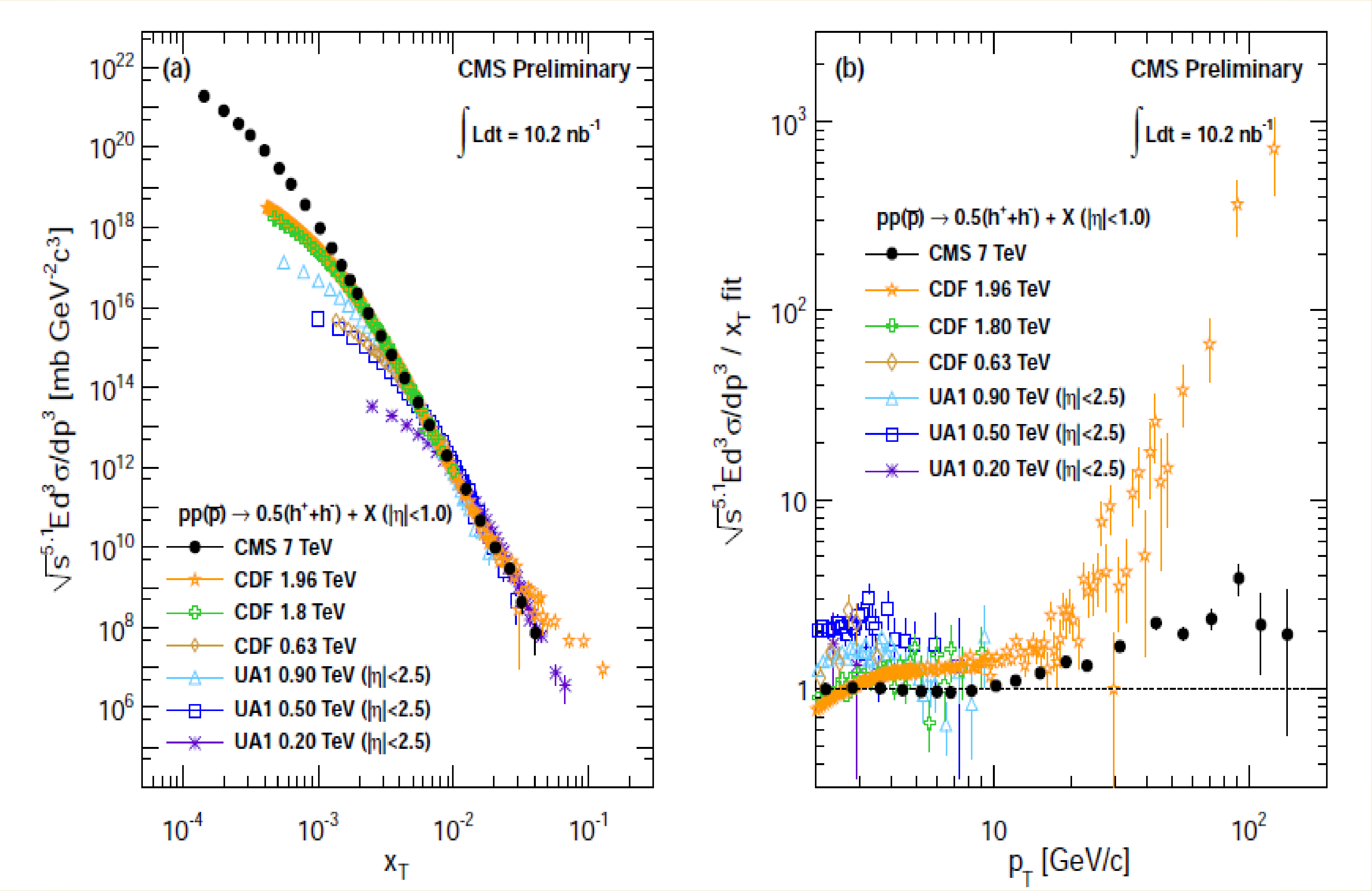
New (HOT) data at LHC energies – today

See: ALICE: Prague Jet workshop & CMS: QCD-10-008



Comparision in x_T: old/new data by Tevatron

See: CDF: PRD 79 112005 (2009) & CMS QCD-10-008



How to resolve this 'question'..

- Experimentalists' point: simply: wrong data
- Earlier signs:

  F. Arleo et al.: hep-ph/1003.2963v2 LAPTH-015/10, ICCUB-10-018

- P. Lévai et al.:

  See: P. Lévai's talk

- Our phenomenology:

  (i) Tsallis distribution fits well, but parameters vary by e.g. energy

  (ii) Need for evolution of the parameters: like e.g. in hadronization, (p)QCD based paron model (i.e. BFKL, DGLAP).

  Note, fits are good basically for hadrons...

S U M M A R Y

- High & low p_T spectra has different distribution..

  ...however hadronization should not work differently.

- Non-extensive (non-equilibrium) thermodynamic

  Can be applied generally. Based on composition rules, evolution eq. can be obtain even for non-thermalised case.

- Tests and models with Tsallis assumptions

  Seems working for hadron production up to intermediate p_T, and extension to the highest p_T region is still question.

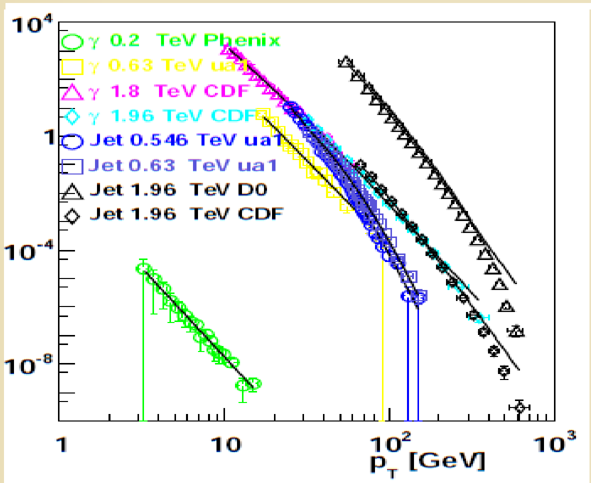
  .

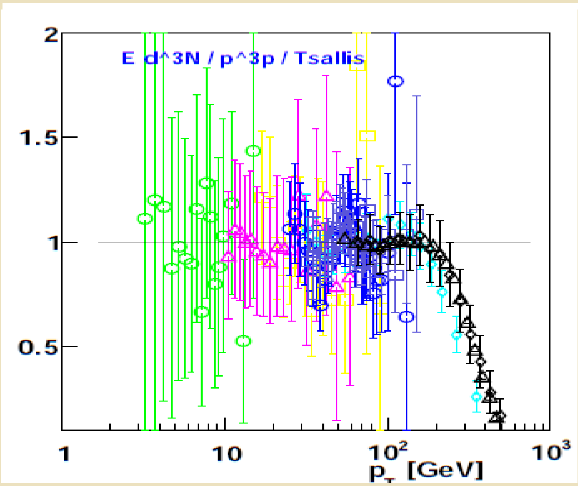
... so we hope...

BACKUP

An extra to 2nd joint model: Tsallis on jets

- TEST on jets and direct photon production – on q only





- Fits data with irrelevant T values, but tail is described