Systematic study of inclusive hadron production spectra in collider experiments

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There exists a large body of high precision experimental data on hadron production in high energy particle collisions.

Collisions	Energy Range	Experiments
Proton – Proton	23 – 7000 GeV	ISR, SppS, CDF, LHC
Gamma - Proton	200 GeV	HERA: H1, ZEUS
Gamma - Gamma	100 GeV	LEP: Opal, L3
DIS	120 – 213 GeV $7 < Q^2 < 28$ GeV^2	HERA: H1, ZEUS
Aurum - Aurum	200 Gev	RHIC

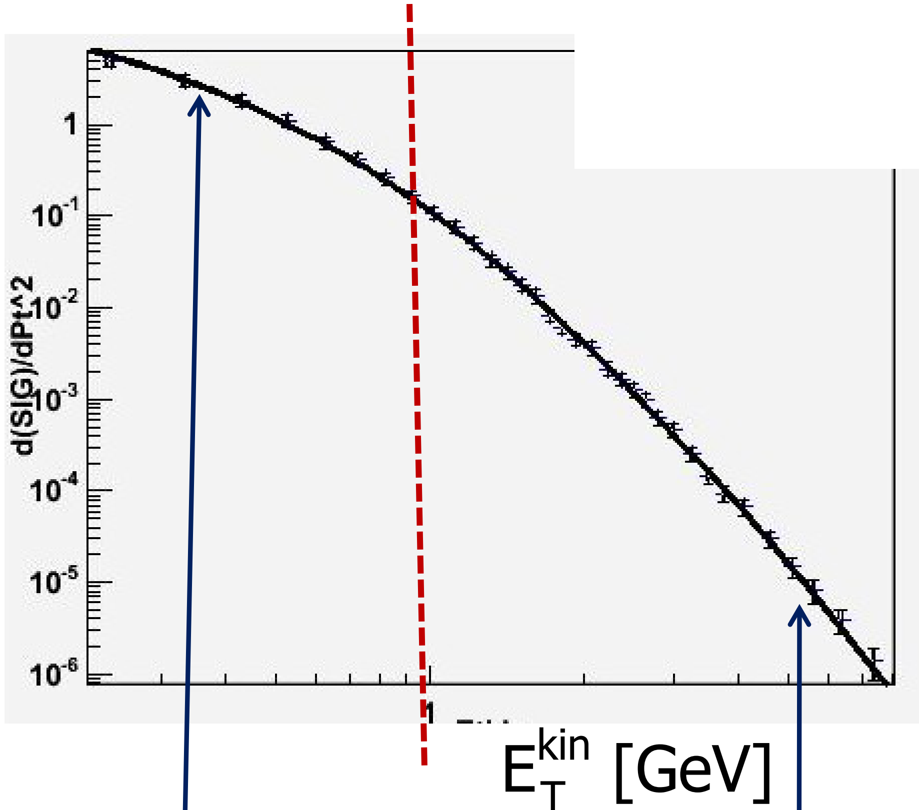
Aim: to find an universal parameterization of the spectra and to draw a parameter map.

Transverse Momentum Spectra of Charged Particles

(Differential Invariant Cross-Section)

A common statistical power-law distribution in the Nature.

(Kappa, Levy, Tsallis, …)



$$E\frac{d^3\sigma}{d^3p}(y\approx 0)=\frac{A}{\left(1+\frac{E_T^{kin}}{T\cdot N}\right)^N}$$

$$E_T^{kin}=\sqrt{p_T^2+m_\pi^2}-m_\pi$$

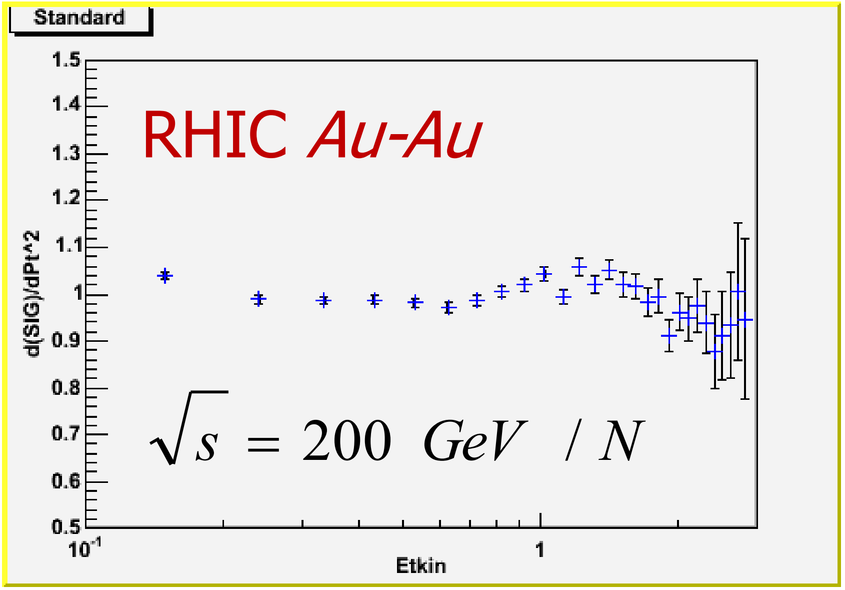
Nonperturbative thermodynamics

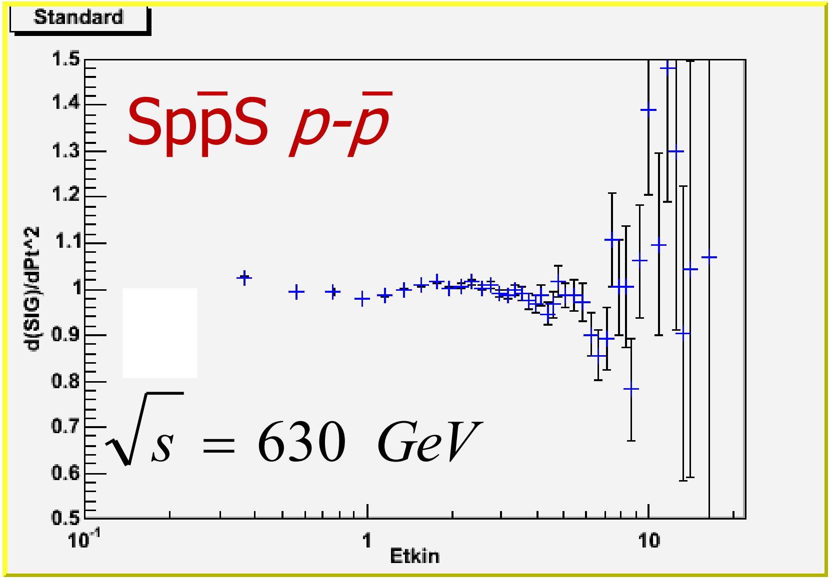
pQCD

A single smooth Tsallis-type function approximates the data in the whole kinematical region

Does Tsallis-type power law distribution really describe the hadron production spectra?

To answer this question let's plot a ratio = data / fit function





On both plots one observes a shallow dip at E_T values below 1 GeV followed by a broad bump above 1 GeV.

These defects are hidden on usual logarithmic plots!

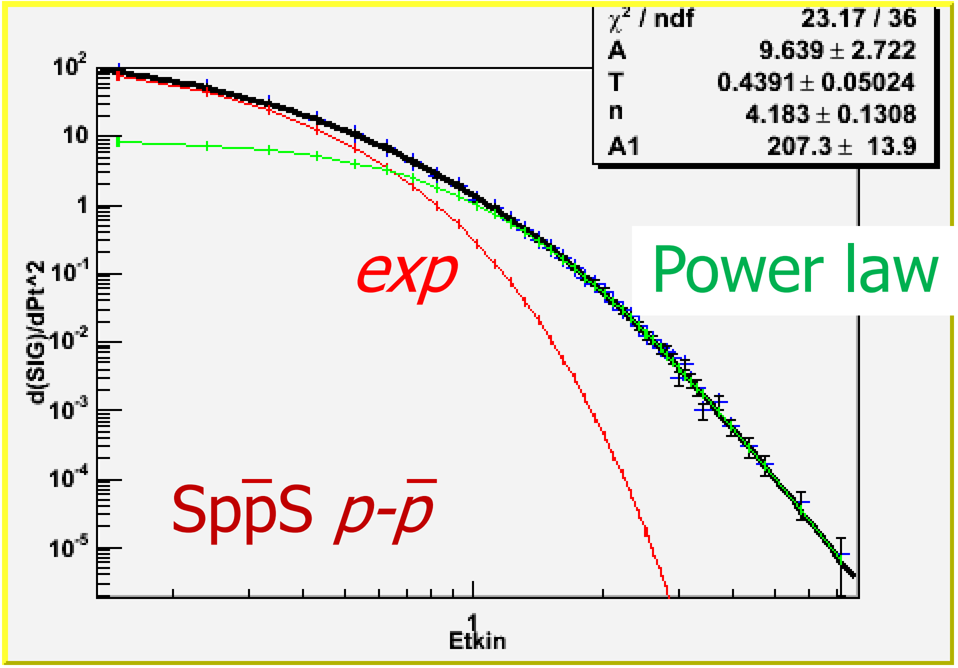
Observed systematic defects require a modification of fit function

A modification of the Tsallis function

Take two contributions: Exponential + Power law functions

Generalized forms: $\exp(-F(P_T)/T_e)$ $\quad 1/(1+F'(P_T)/TN)^N$

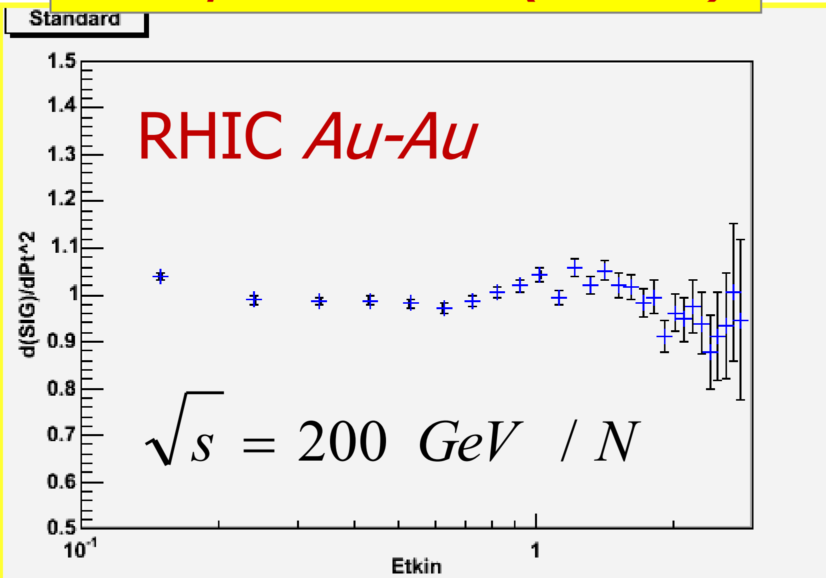
True scalars: $F, F' = P_T^2 \; or \; E_T^{kin} \quad (not \; P_T \; or \; P_T^3)$

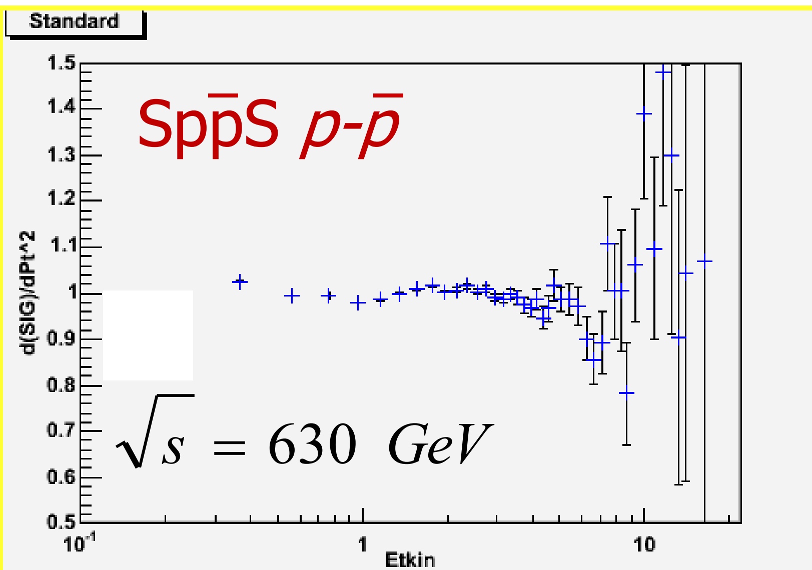


The best fits are given by $A_e \cdot \exp(-E_T^{kin}/T_e) + A/(1+P_T^2/T^2 N)^N$

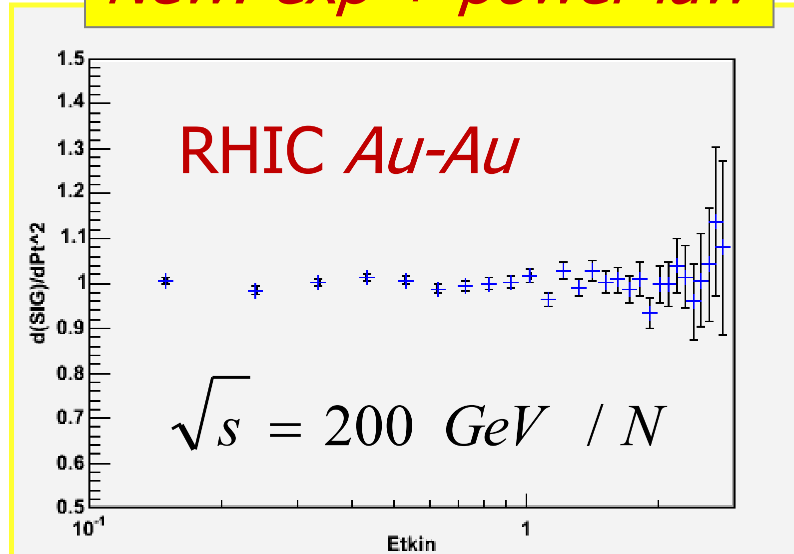
Looking back at the Ratios = data / fit function

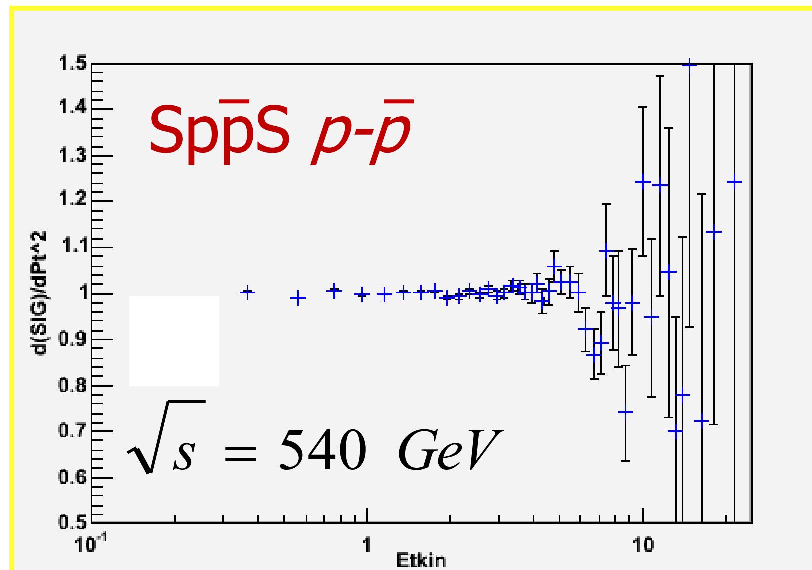
Old: power law (Tsallis)





New: exp + power law

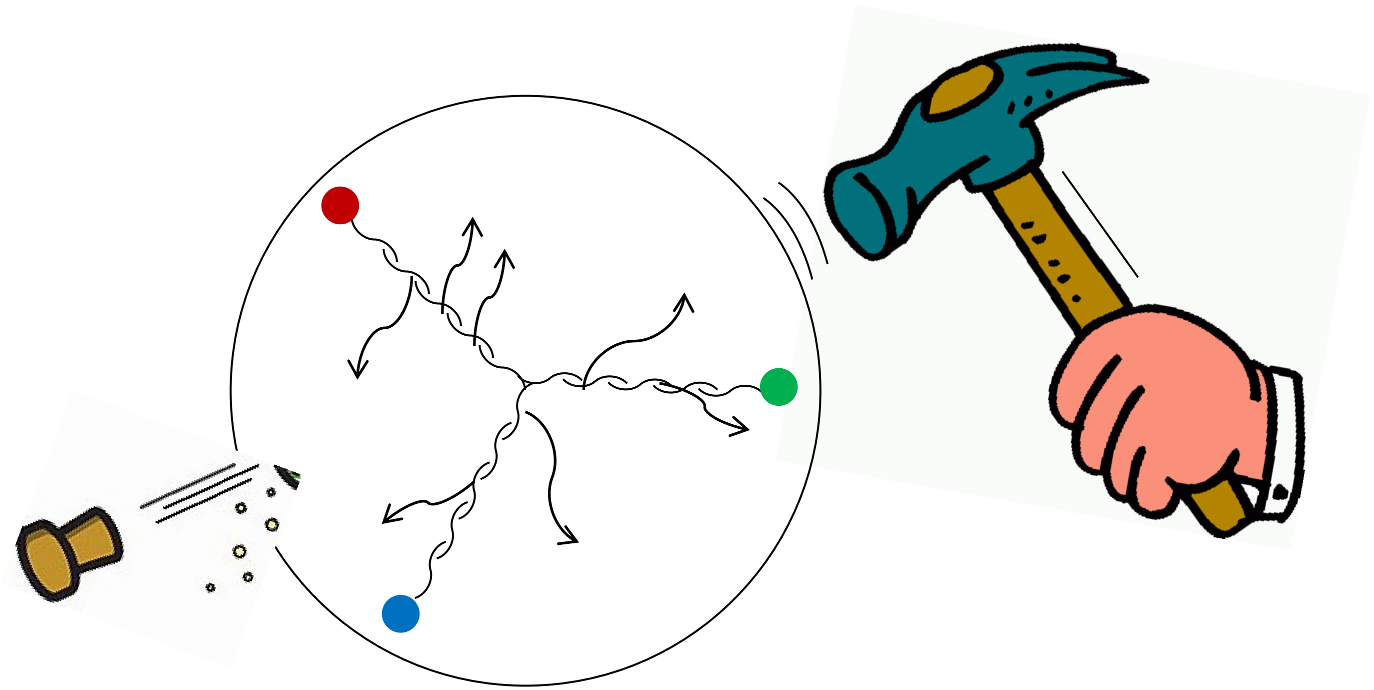




Toy-model Interpretation.

Exponential term – "thermolized" hadrons, or a hadronic gas accompanying the interactions. (Boltzmann-type radiation)

Power-law term – originates from partonic hard interactions?

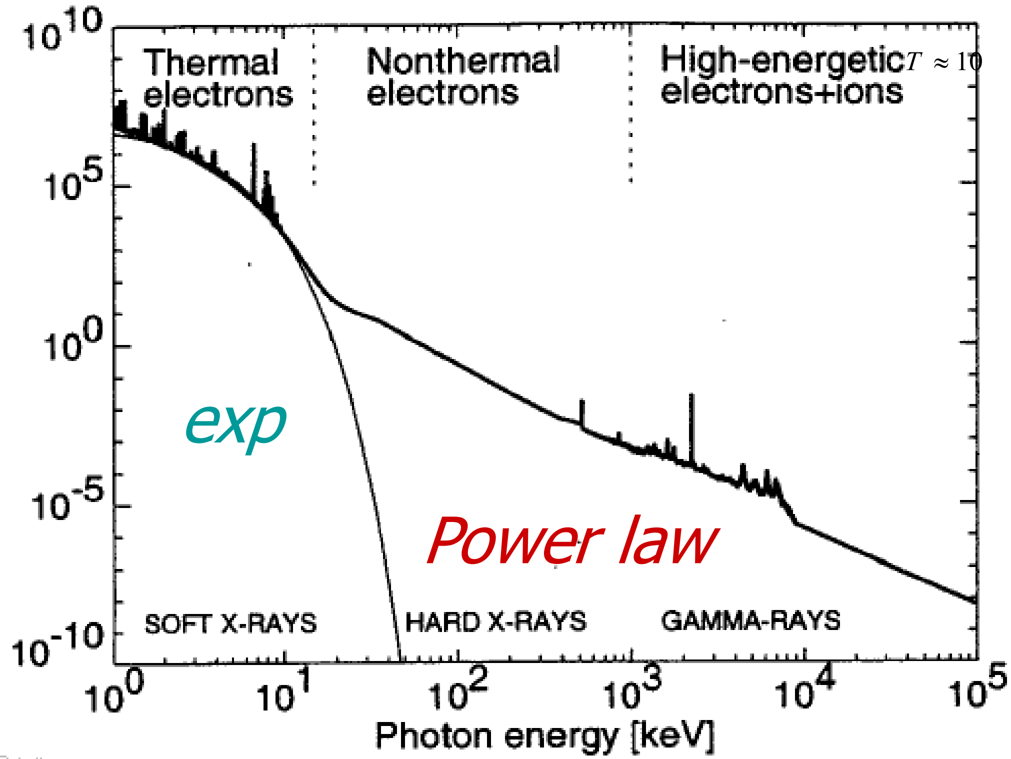


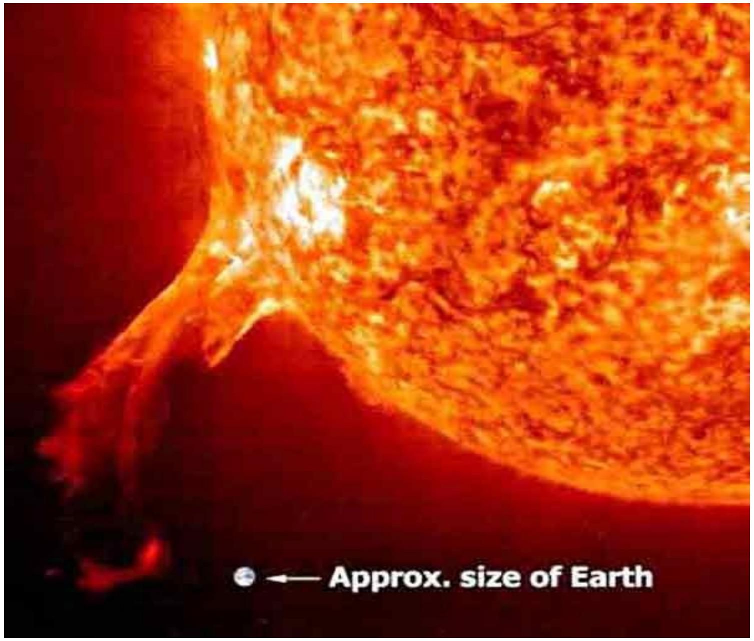
Are there any other similar phenomena in the Nature?

Solar Flares. Photon spectrum.

The observed spectra of photons from Solar flares is represented by a sum of the thermal and non-thermal emissions.

$$\frac{dN_\gamma}{dE_\gamma} = A_e \cdot e^{-E\gamma/T} + A_{pl} \cdot \frac{1}{E_\gamma^N}$$





The photons are emitted by:

A_e: Thermolized electrons in Sun Flare

T ~ 10 million degrees

A_{pl}: Accelerated electrons

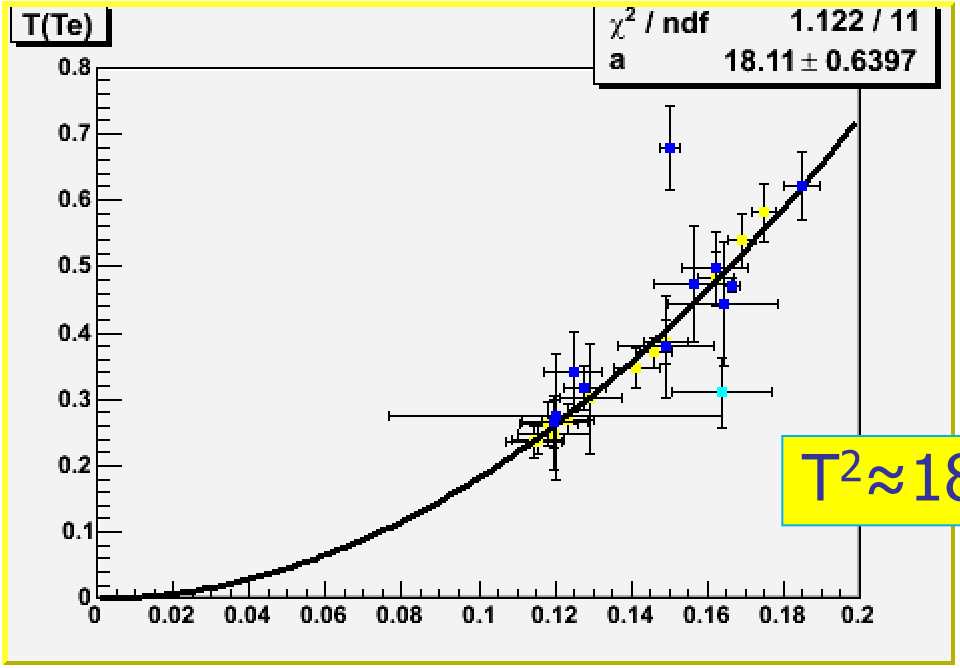
E ~ up to few GeV

A strong correlation between the fit-function parameters

Fit-function: $A_e \cdot \exp(-E_T^{kin}/T_e) + A/(1+P_T^2/T^2N)^N$

correlated

T² [GeV²]



$T^2 \approx 18 \cdot T_e^2$

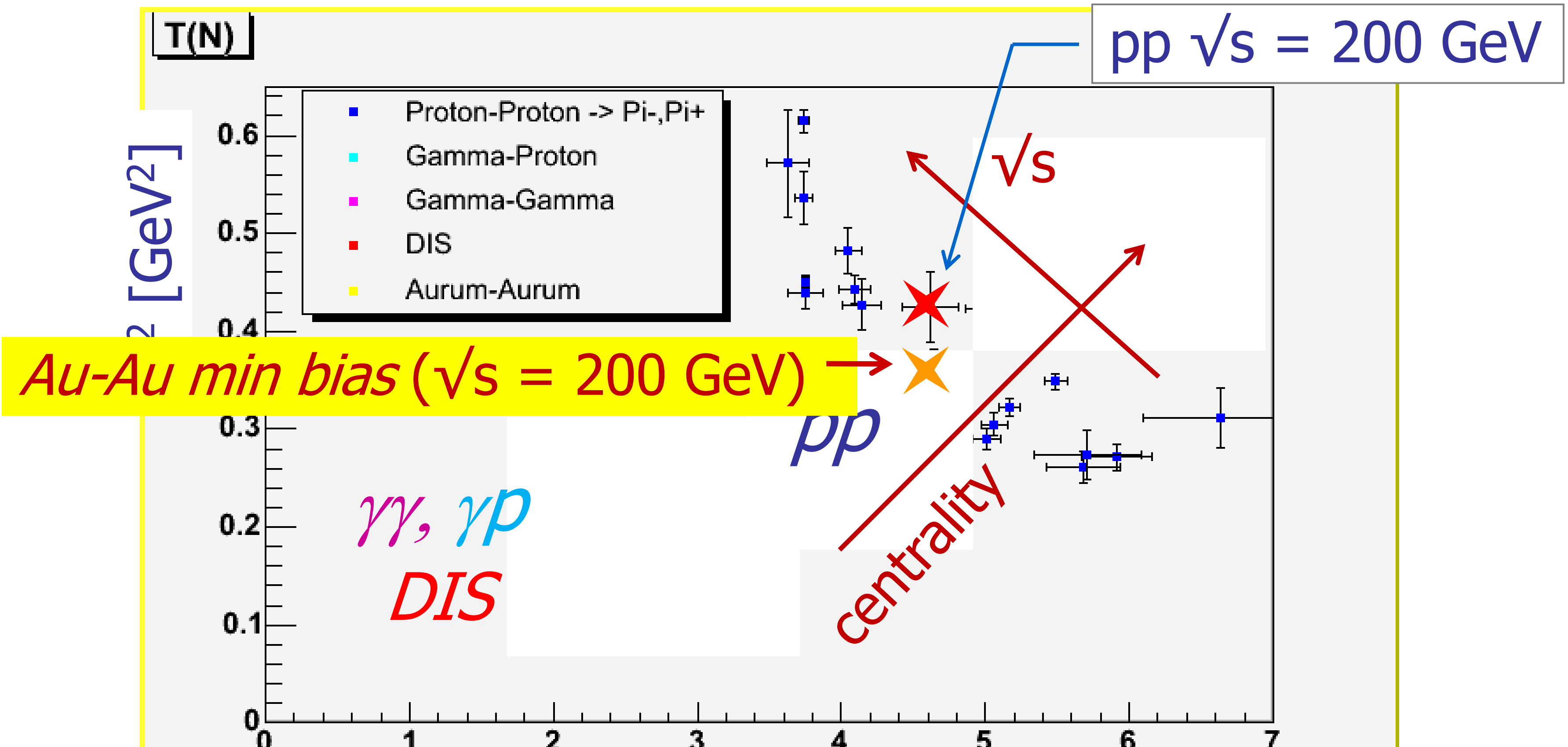
T_e [GeV]

Though an origin of the observed correlation is unknown, it might indicate that the exponential and power law terms are integral parts of more complicated function describing the true statistical distribution.

The fit-function parameter map

$$\frac{d\sigma}{dP_T^2} = A_e \cdot \exp(-E_T^{kin}/T_e) + A/(1 + P_T^2/(T^2 N))^N$$

$T^2 = 18.11 T_e^2$



Heavy Ion mid centrality (minimum bias) interactions look similar to single pp minimum bias interactions at the same collision energy!

But what makes *AuAu* and *pp* spectra different in shape??

Observations and surprises with the fit parameter map

1. There are two distinct trends:
   - with change of $\sqrt{s}$ in pp
   - for different colliding particles and fixed $\sqrt{s}$
2. The two trends cross each other in a point
   - with $\sqrt{s}$ = 200 GeV in pp and Au-Au
   - for minimum bias centrality in Au-Au
3. DIS, γp, $\gamma\gamma$ sit on the same band as Au-Au with different centralities and look similar to very peripheral Heavy Ion interactions

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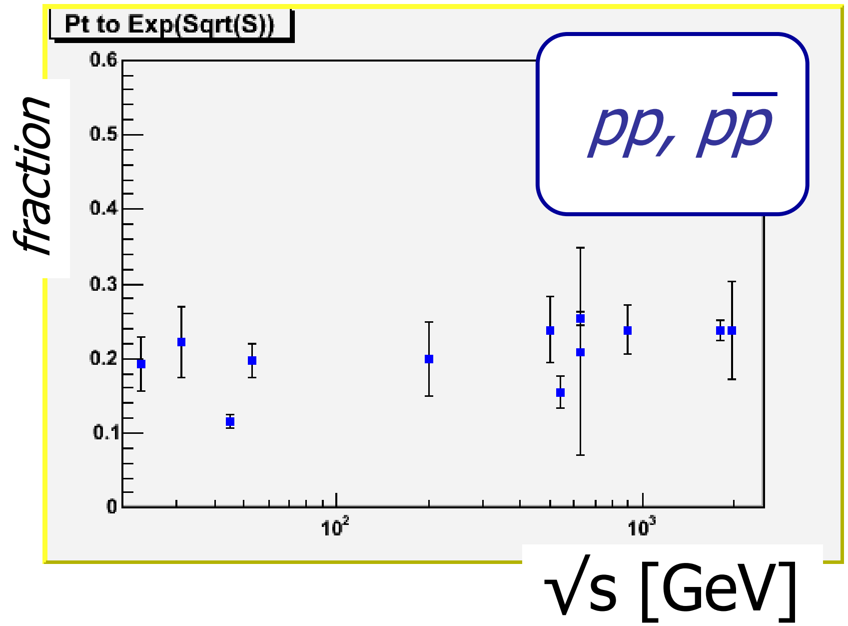
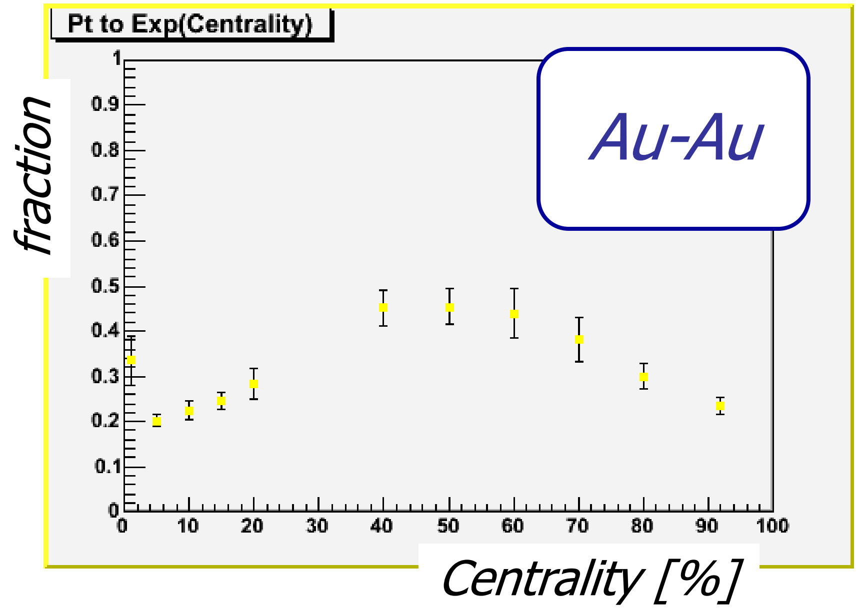
Further observations: relative contributions of the exponential and power-law terms in the spectra

Power law term fraction in pp spectra as function of √s

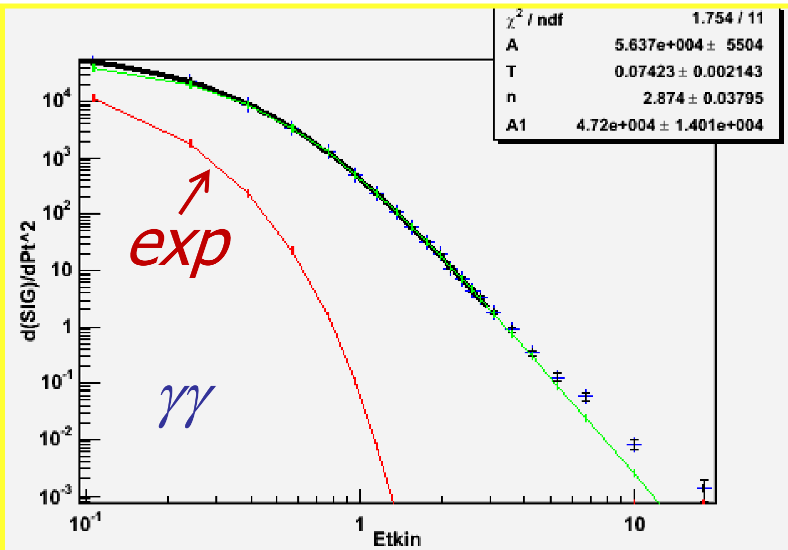


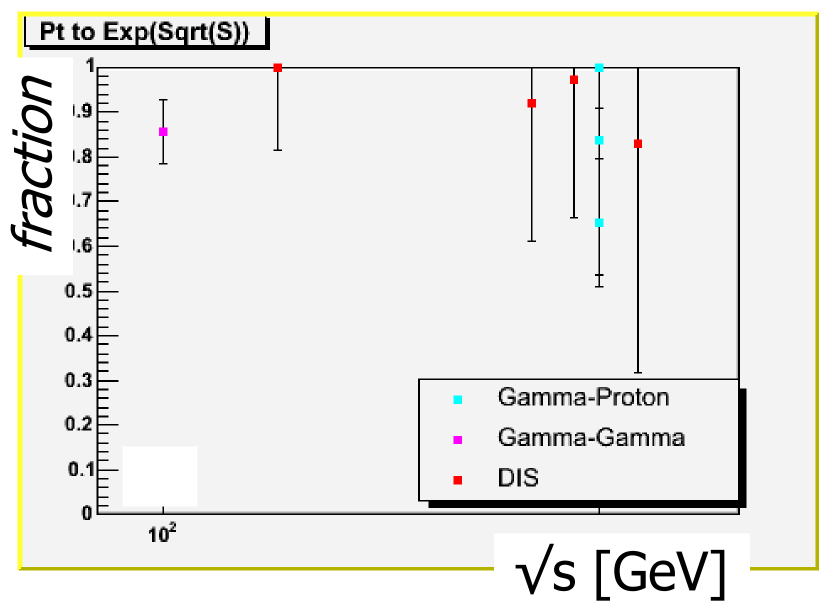
Power law term fraction as function of centrality in Au-Au at √s=200 GeV



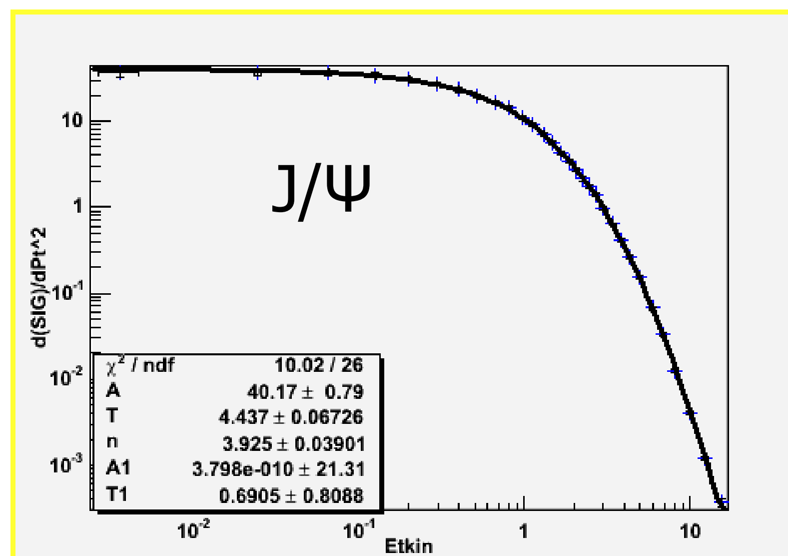
- In pp interactions: power-law contribute ~20% independent of √s
- In Heavy Ions: power-law contribution is maximal (~50%) at mid centralities and minimal (~20%) for very central and very peripheral int's.
- What is about "point-like" interactions?

In DIS, γp, γγ the power-law contribution dominates (~100%)

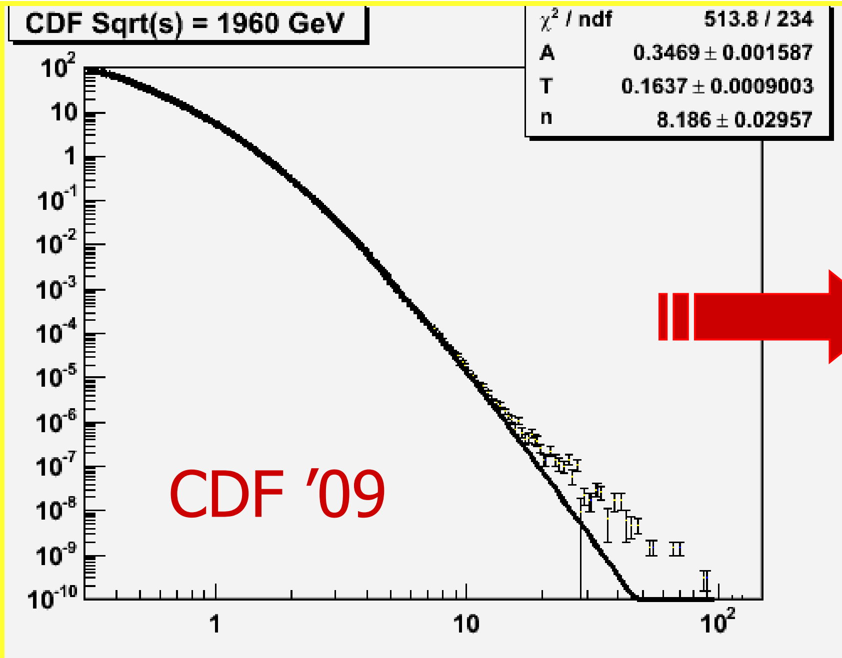


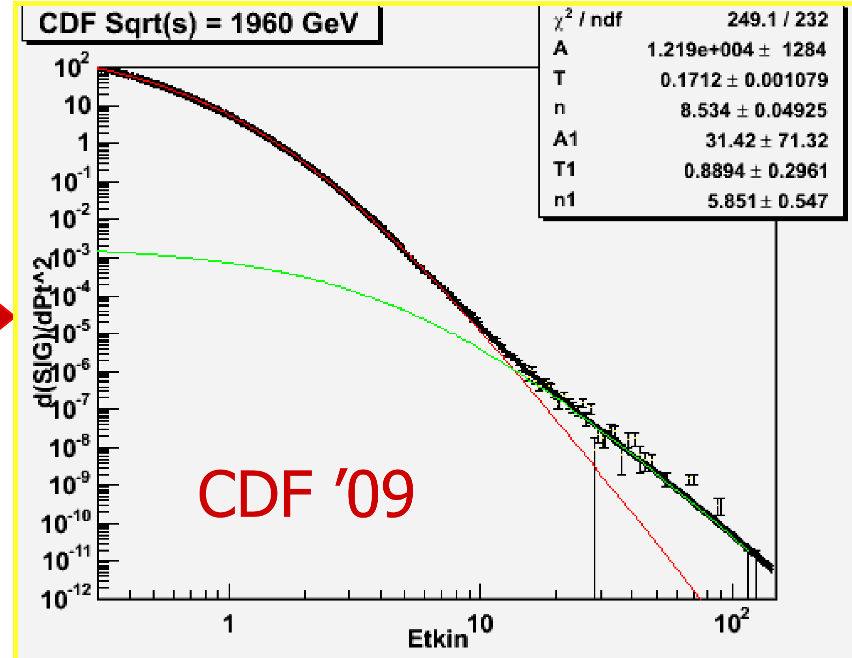


Inclusive J/Ψ production doesn't leave any room for the exponential term in the spectrum shape



More surprises in high-Pt data





$\chi^2/\text{ndf} = 513.8/234$ $\chi^2/\text{ndf} = 249.1/232$

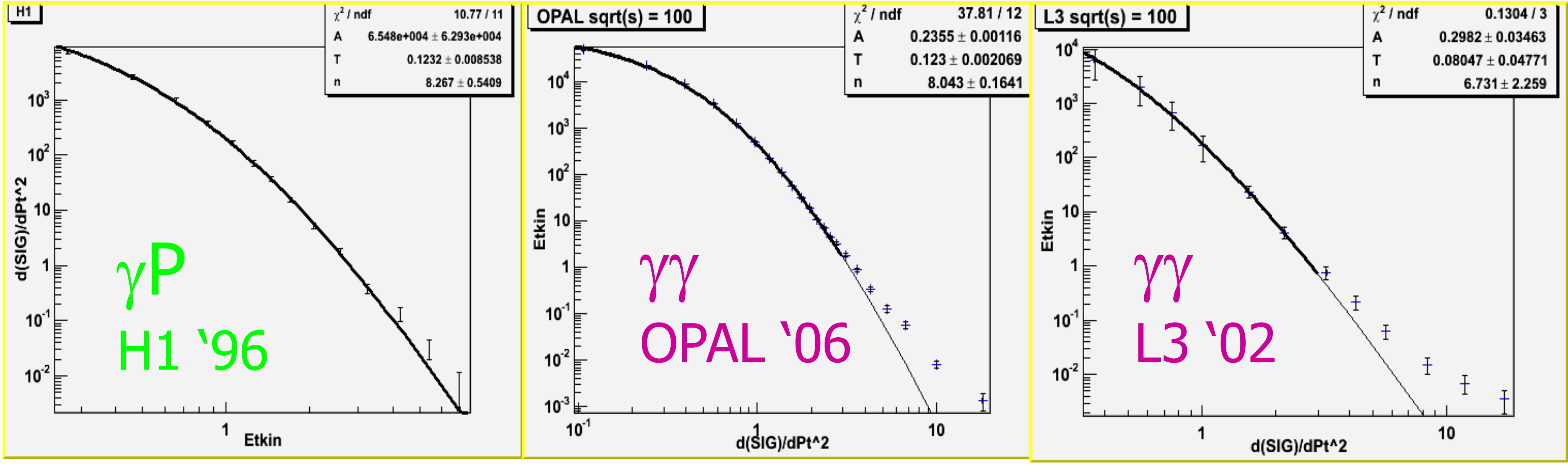
$$\frac{d\sigma}{dP_T^2} = A_1 \cdot (1 + P_T^2/(T_1^2 N_1))^{N_1} + A_2 \cdot (1 + P_T^2/(T_2^2 N_2))^{N_2}$$

Disagreement with CDF jet spectrum & Fragmentation (A.S.Yoon et al)

For P_T > 80 GeV is of order of inclusive jet cross section

At CDF only?

The onset of high-Pt power-law tail in gamma collisions



The onset of the extra high-P_T power-law term is visible for:

$P_T > 10$ GeV in pp - collisions

$P_T > 4$ GeV in γp - collisions

$P_T > 3$ GeV in $\gamma\gamma$ - collisions

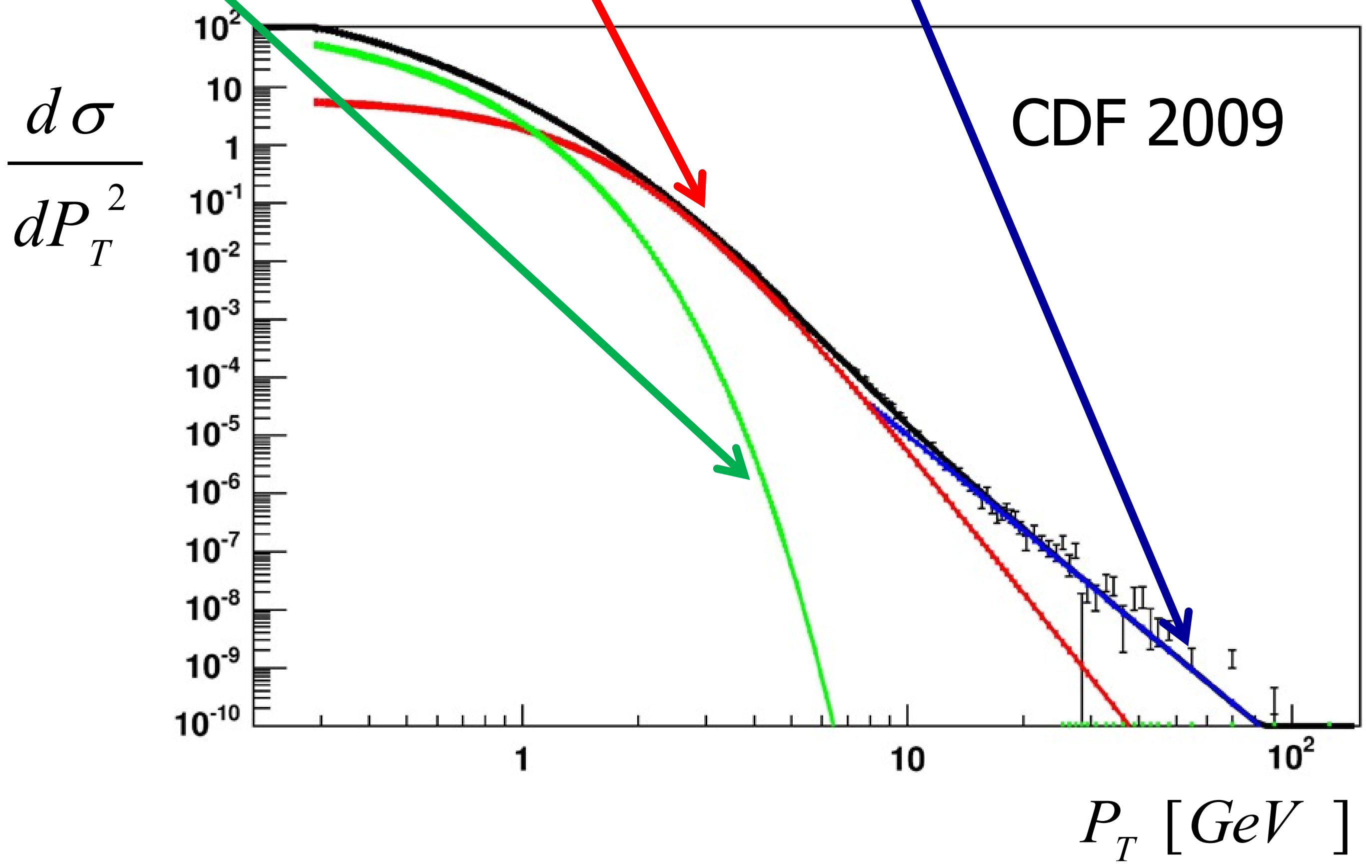
Two different regimes for charged hadron production?

Three contributions to hadron production spectra

- Exponential – *bulk of hadrons in nucl.-nucl. collisions*

1-st power law – *hadrons with moderate P_T*

2-nd power law – *high P_T tail*



Conclusions:

- the large body of high precision data on hadron production in collider experiments allow systematic measurements of the fine details of the spectra shape;
- a simple power law type statistical distribution (Tsllis) provides a good approximation, but fails to describe the details of spectra shape both at low and high Pt;
- a modified statistical distribution (exp + power law) is proposed
- curiosities – surprises:

1. *HI and pp data require "thermal" term. DIS and $\gamma\gamma$ – not.*
2. *Hadron production parameter map: similarity between HI and pp min bias events and between HI peripheral and DIS*
3. *High PT tails still not explained*
4. *Dips in spectra: reality or mismeasurements?*

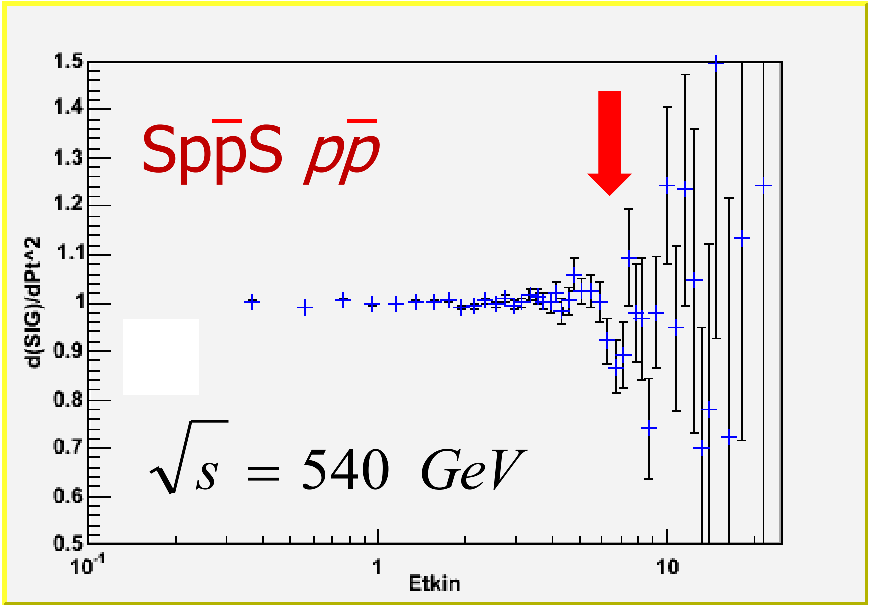
Wanted: High statistics LHC charged particle spectra.

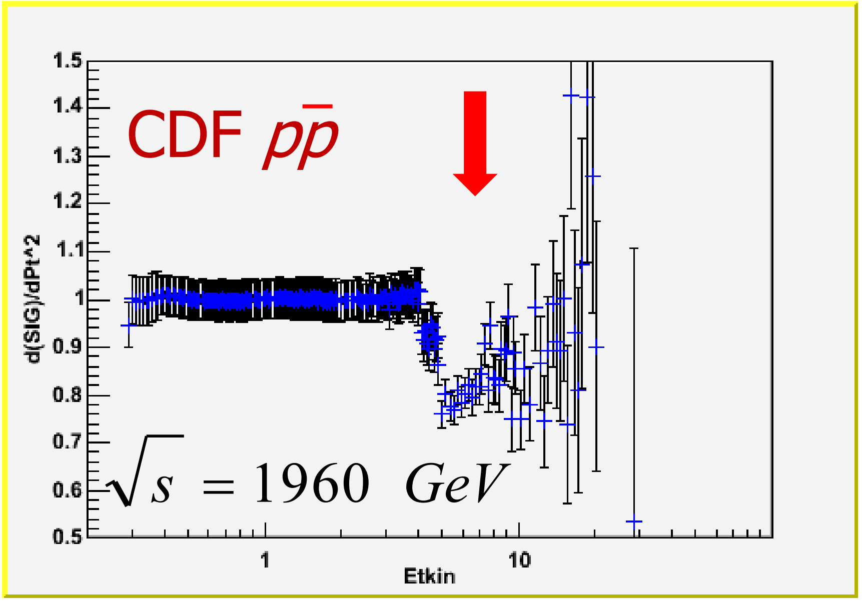
Recent Publication: e-Print: **arXiv:1008.0332** [hep-ph]

Diffraction-type dips in the inclusive particle spectra?

Provocative examples of the data to fit ratio:

The only two accurate sets of *pp*-data extended to high P_T





Looking forward to see high precision LHC (7 GeV) spectra soon.