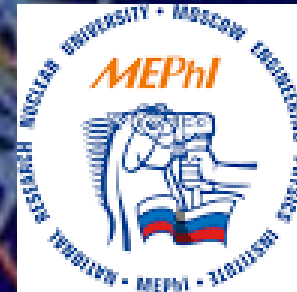
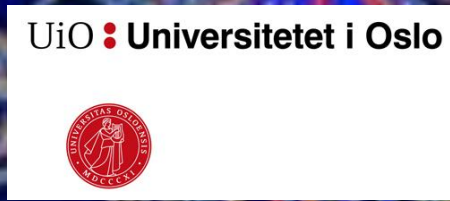


# ***BASIC FEATURES OF PP INTERACTIONS AND RFT- BASED QUARK-GLUON STRING MODEL***

***J.Bleibel, L.Bravina, E.Zabrodin***

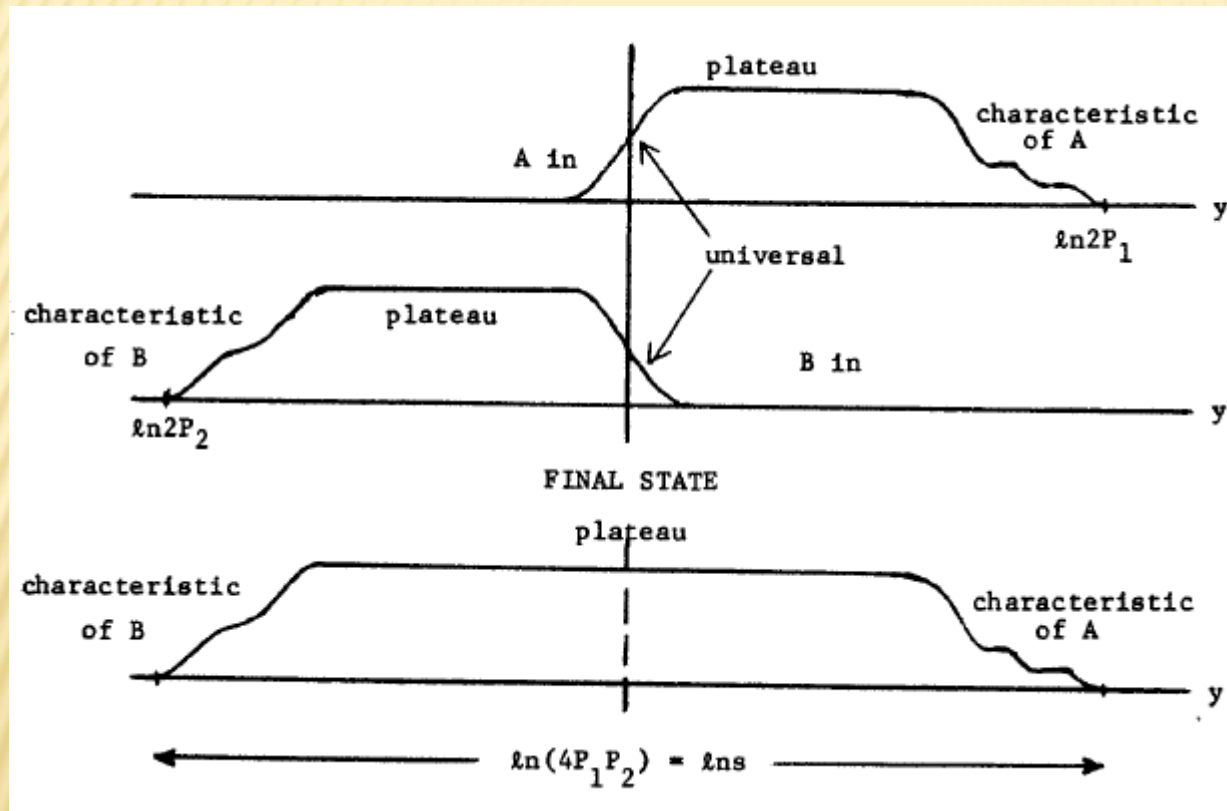


# Outline

- I. Motivation. Scaling hypotheses and relations: Feynman scaling, extended longitudinal scaling, Koba-Nielsen-Olesen scaling
- II. Quark-gluon string model
- III. Multiplicity, rapidity and  $P_T$  spectra
- IV. Violation of FS and KNO scaling
- V. Particle freeze-out
- VI. Forward-backward multiplicity correlations
- VII. Conclusions

# HYPOTHESIS OF FEYNMAN SCALING

R. Feynman, PRL 23 (1969) 1415; also in "Photon-hadron interactions"



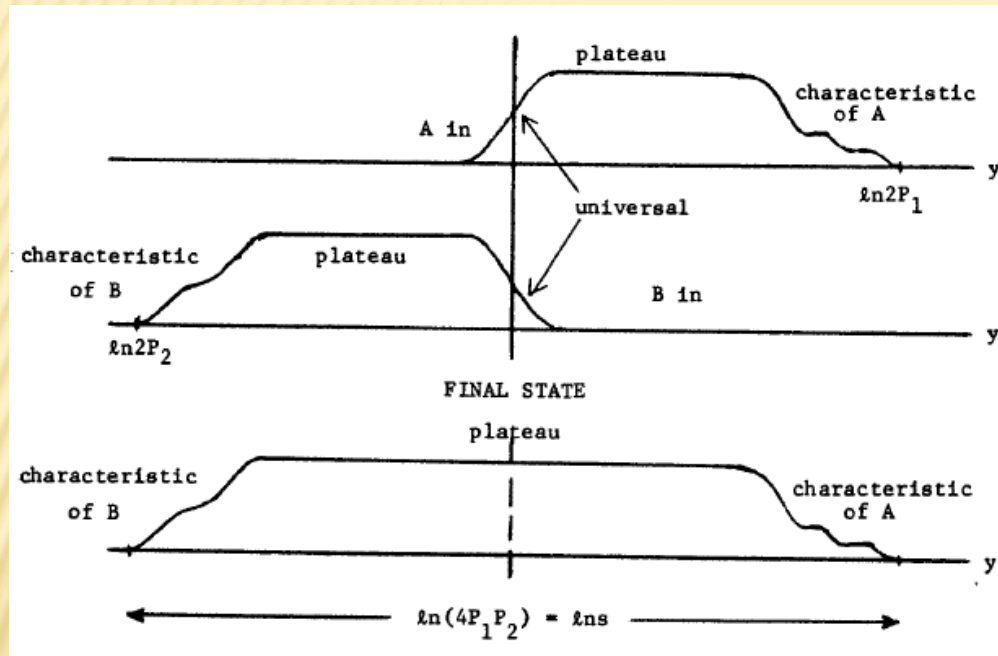
**Basic assumption:**  
scaling of inclusive spectra within the whole kinematically allowed region of  $x_F$  (or c.m.  $y$ )

**In addition:**  
existence of central area  $-x_0 \leq x_F \leq x_0$ , where  $x_0 \approx (0.1-0.2)$  is assumed.

**In terms of rapidity**

$$-\ln[x_0 \sqrt{s} / m_T] \leq y^* \leq \ln[x_0 \sqrt{s} / m_T]$$

# CONSEQUENCES OF FEYNMAN SCALING



- (1) Logarithmic rise of the central rapidity region with energy

$$(\Delta y^*) \approx 2 \ln(x_0 \sqrt{s} / m_T)$$

- (2) Fragmentation regions are fixed

$$(\Delta y^*) \approx \ln(1 / x_0)$$

- (3) Main contribution to mean multiplicity comes from the central area

$$\langle n \rangle \propto \ln(x_0 \sqrt{s} / m_T)$$

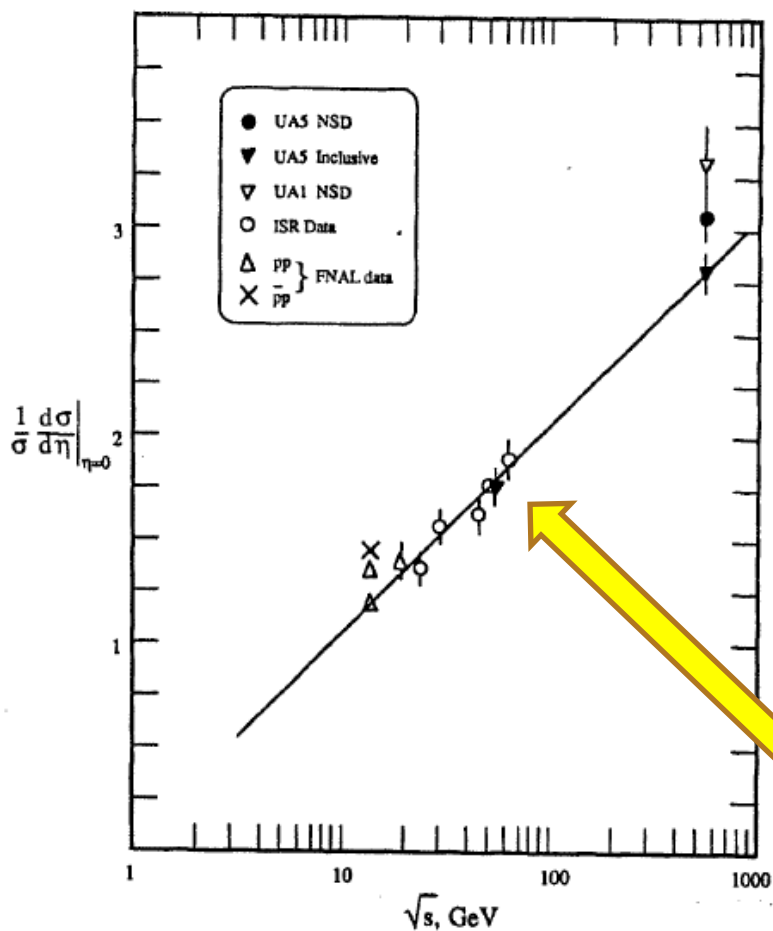
- (4) In the central area particle density does not depend on energy and rapidity

$$\rho(y^*, p_T; \sqrt{s}) = \rho(p_T)$$

- (5) Contribution from the fragmentation regions is energy independent

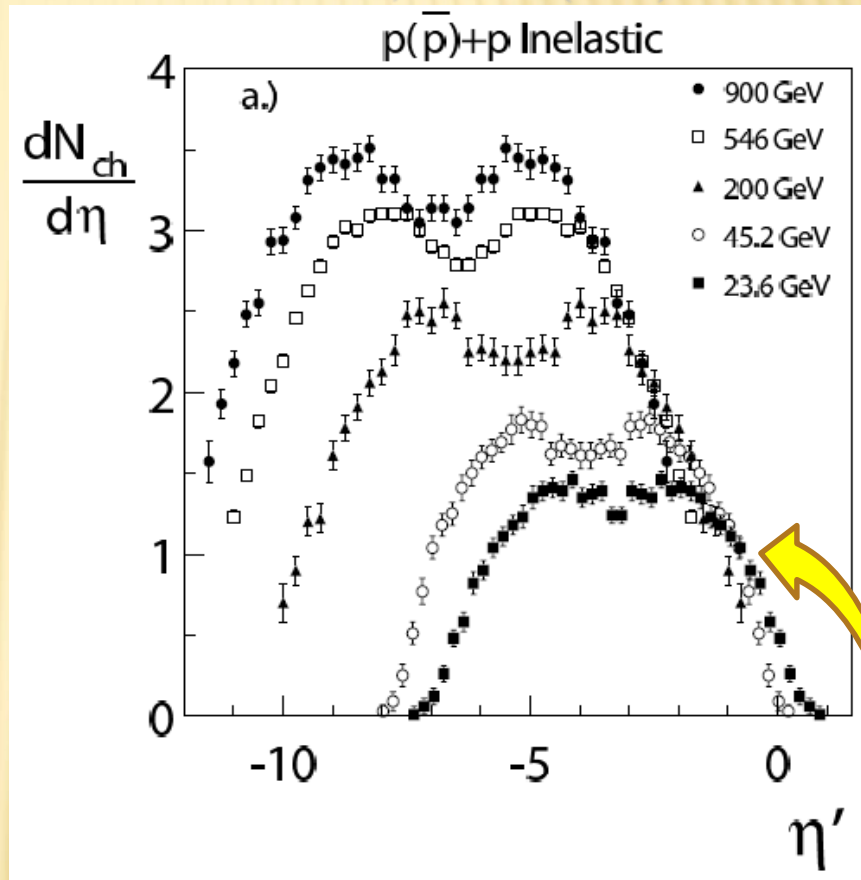
# VIOLATION OF FEYNMAN SCALING

UA5 Collab., Phys. Rep. 154 (1987) 247



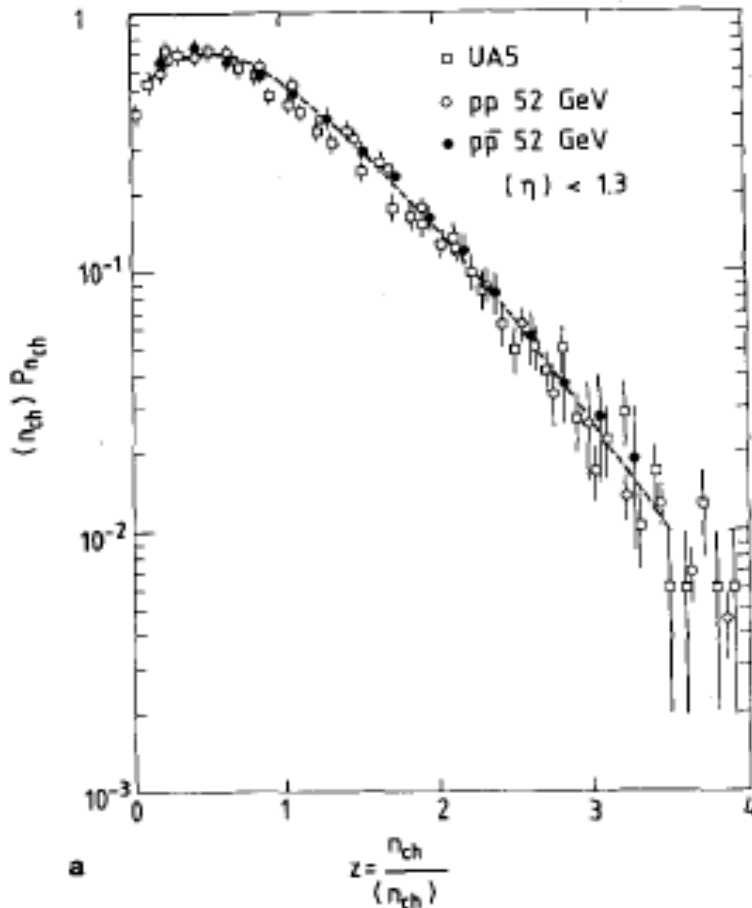
Charged particle pseudorapidity density at  $|\eta| = 0$  as a function of  $\sqrt{s}$

W. Busza, JPG 35 (2008) 044040



Violation of Feynman scaling, but ext. long. scaling holds?!

# KOBA-NIELSEN-OLESEN (**KNO**) SCALING



Z.Koba, H.B.Nielsen, P.Olesen, NPB 40 (1972) 317

They claim that the **multiplicity distributions** are independent of **energy** except through the variable

$$z = n / \langle n \rangle$$

$$P_n(s) = \frac{\sigma_n(s)}{\sigma_{tot}(s)} = \frac{1}{\langle n \rangle} \Psi \left( \frac{n}{\langle n \rangle} \right)$$

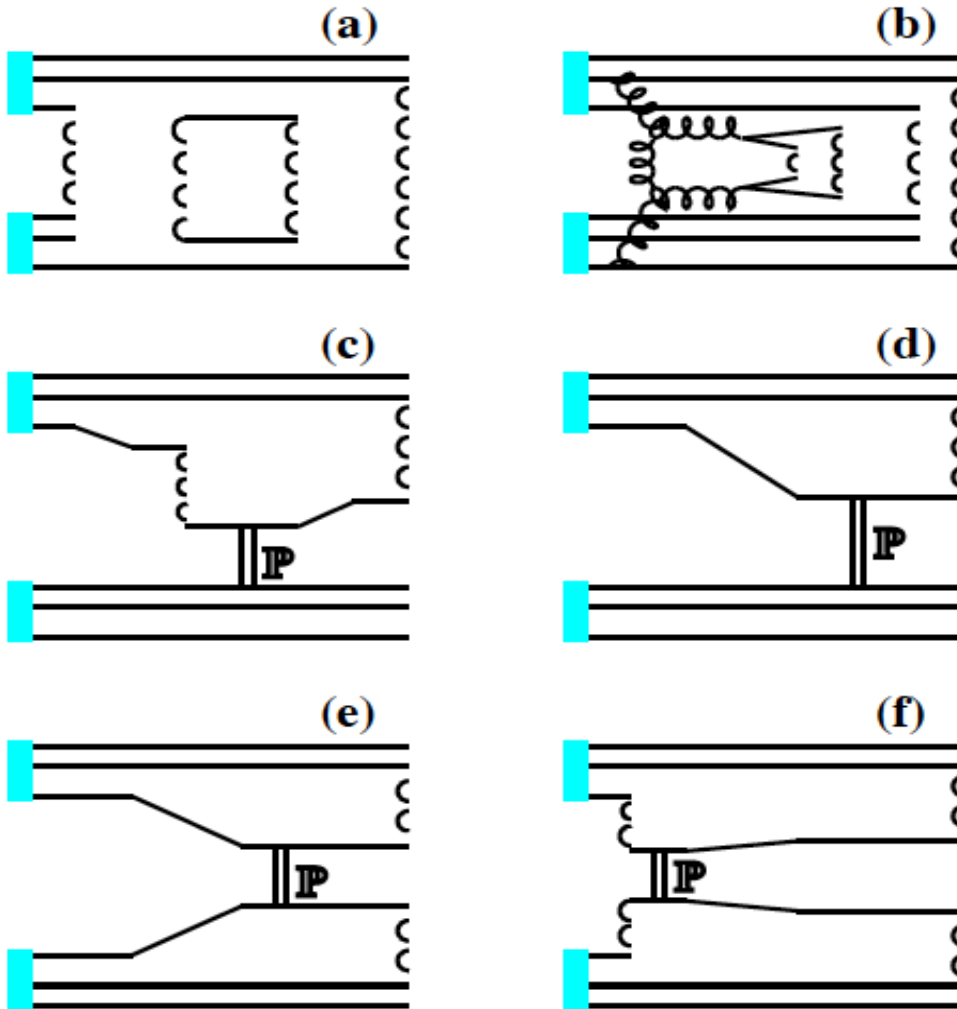
Experimental data: KNO scaling holds in  $hh$  collisions up to  $\sqrt{s} = 53$  GeV (ISR)

# QUARK-GLUON STRING MODEL

A.B. Kaidalov, K.A.Ter-Martirosyan, PLB 117 (1982)

N.S.Amelin, L.V.Bravina, Sov.J.Nucl.Phys. 51 (1990) 133

N.S.Amelin, E.F.Staubo, L.P.Csernai, PRD 46 (1992) 4873



At ultra-relativistic energies:  
multi-Pomeron scattering,  
single and double diffraction,  
and jets (hard Pomeron  
exchange)

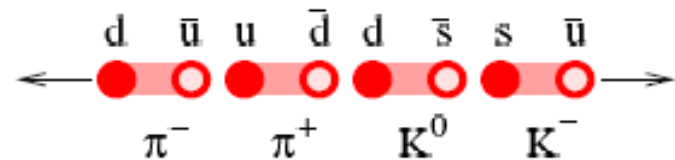
Gribov's Reggeon Calculus  
+ string phenomenology

QGSM is similar to DPM,  
NEXUS, PHOJET, QGSJET

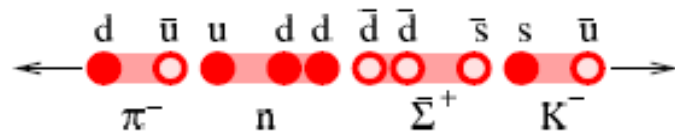
# STRING FRAGMENTATION: FIELD-FEYNMAN MECHANISM

Decay of strings - production of mesons and baryons:

- ▶ the colorfield between a quark and a antiquark gets "stretched"
- ▶ a meson (baryon) with some transverse momentum is formed and gets a fraction  $z$  of the primordial momentum of the string
- ▶  $z$  is generated from the fragmentation function
- ▶ the rest of the string either decays further or forms a cluster



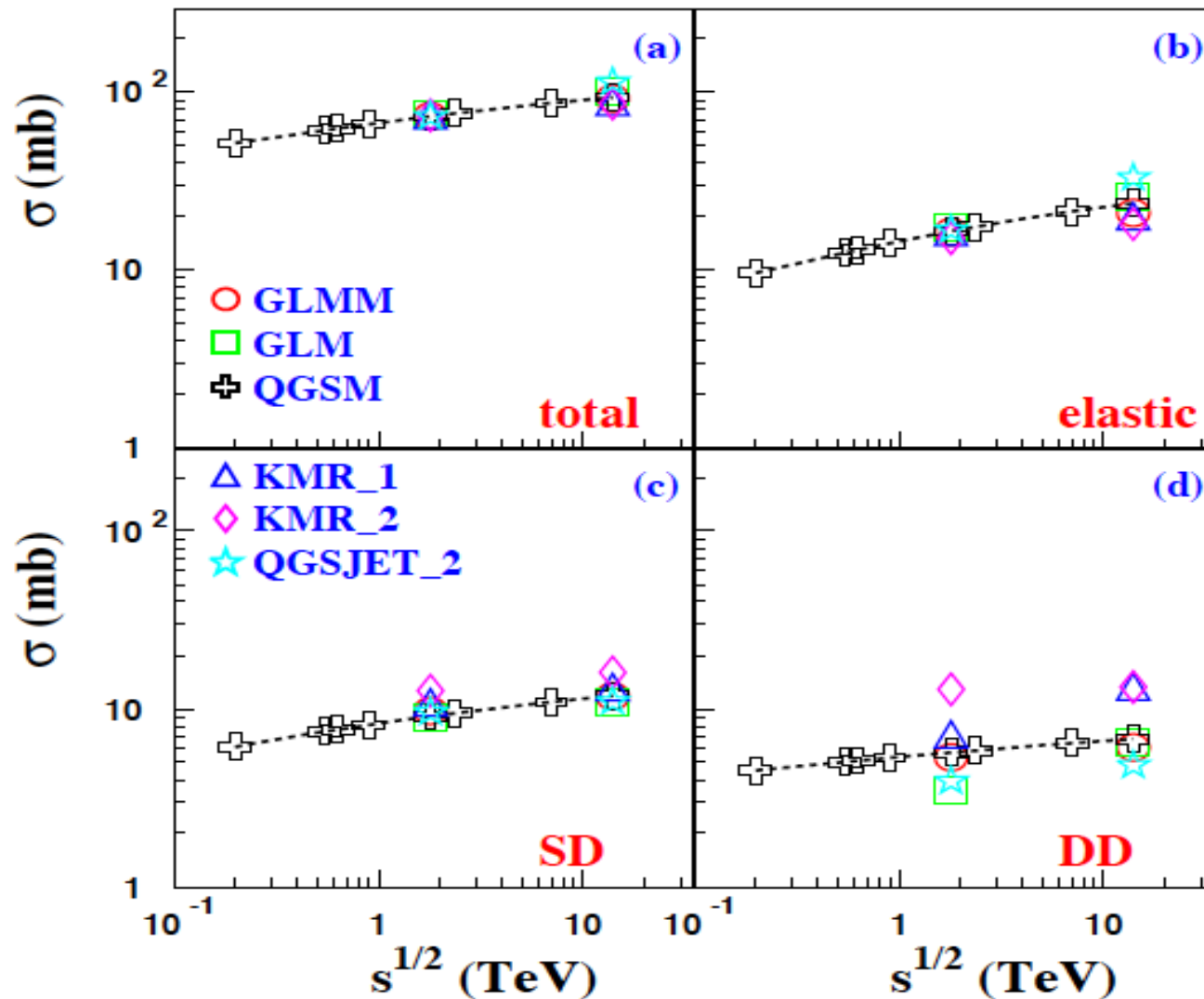
production of mesons



production of baryons

**Decay of strings and particle production**

# COMPARISON WITH OTHER RFT-BASED MODELS



GLMM:

E.Gotsman et al.,  
EPJC 57 (2008) 689

GLM:

E.Gotsman, E.Levin,  
U.Maor, EPJC 71 (2011)  
1553

KMR\_1:

M.Ryskin, A.Martin,  
V.Khoze, EPJC 54 (2008)  
199

KMR\_2:

M.Ryskin et al.,  
JPG 36 (2009) 093001

QGSJET\_2:

S.Ostapchenko,  
PRD 83 (2011) 014018

Agreement is good. Some deviations are present for DD cross section

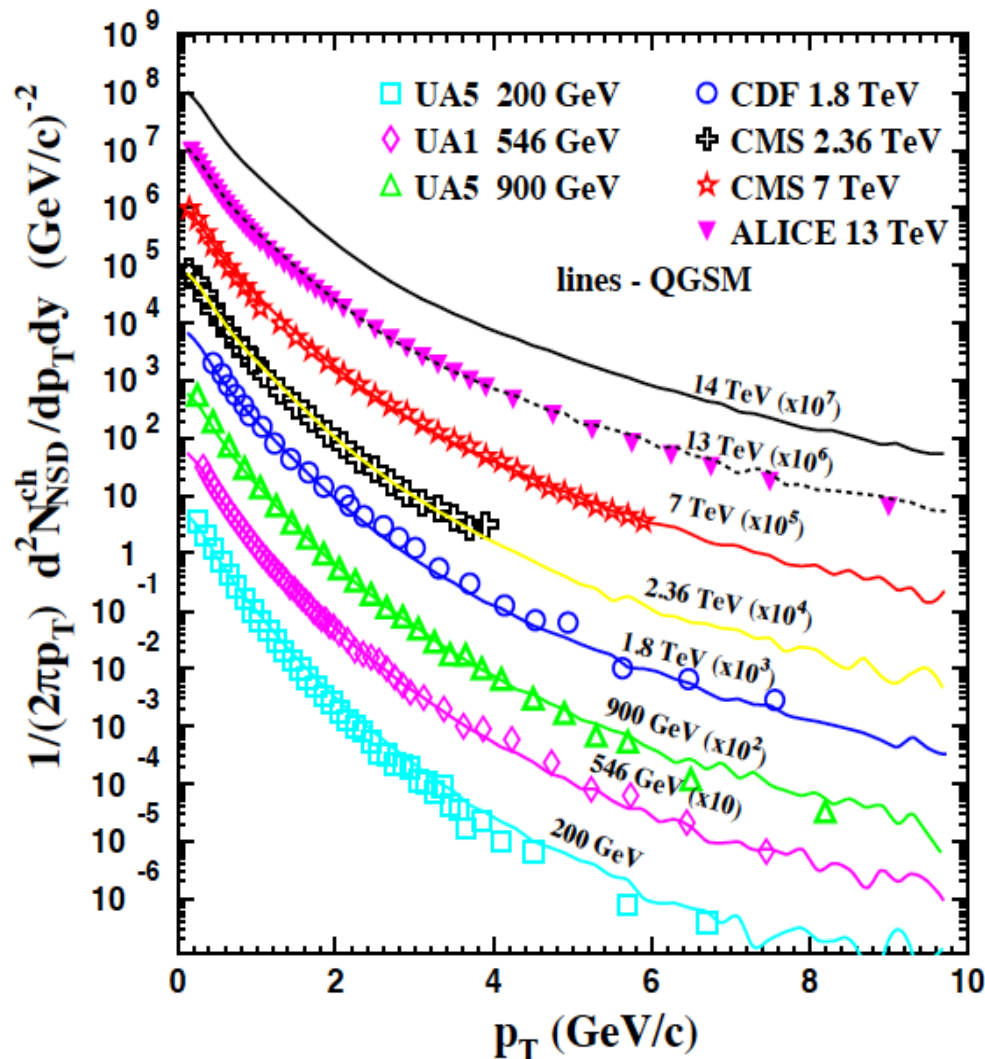
# ***EXPERIMENTAL DATA:***

- UA5 Collaboration:** G.Alner et al., Phys. Rep. 154 (1987) 247
- UA1 Collaboration:** G.Arnison et al., PLB 118 (1982) 167  
C.Albajar et al., NPB 335 (1990) 261
- CDF Collaboratio:** F.Abe et al., PRL 61 (1988) 1818; PRD 41 (1990) R2330
- E735 Collaboration:** T.Alexopoulos et al., PRD 48 (1983) 984
- ALICE Collaboration:** K.Aamodt et al., EPJC 68 (2010) 89; EPJC 68 (2010) 345;  
PLB 693 (2010) 53  
B.Abelev et al., EPJC 73 (2013) 2456  
J.Adam et al., PLB 753 (2016) 319
- CMS Collaboration:** K.Khachatryan et al., JHEP 02 (2010) 041;  
PRL 105 (2010) 022002; PLB 751 (2015) 143
- CMS + TOTEM:** K.Khachatryan et al., EPJC 74 (2014) 3053
- TOTEM Collaboration:** G.Antchev et al., Europhys. Lett. 101 (2013) 21002
- LHCb Collaboration:** R.Aaij et al., JHEP 02 (2015) 129

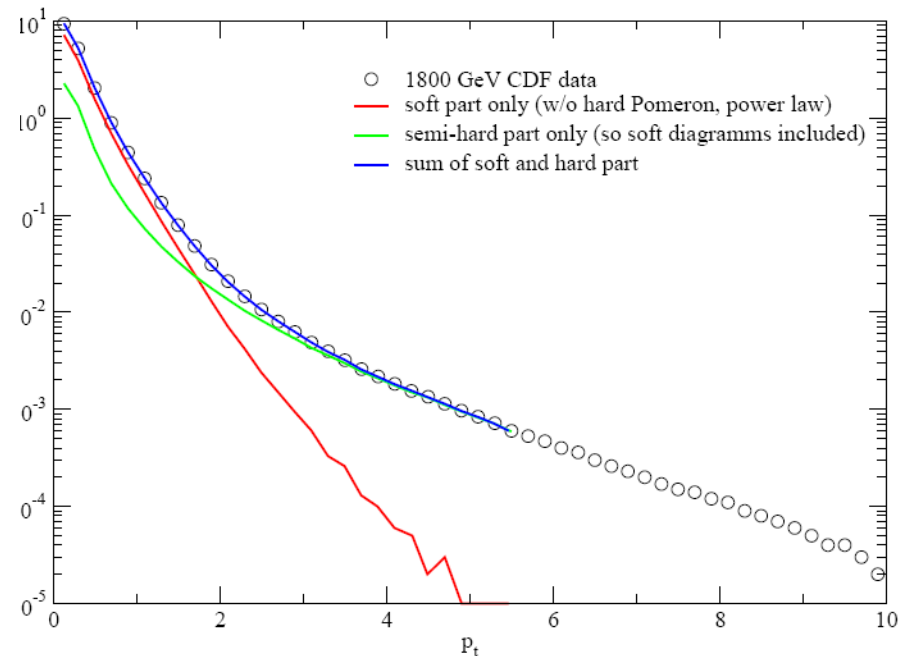
# $P_T$ SPECTRA: MODEL VS. DATA

## Transverse momentum spectra

J.Bleibel, L.Bravina, E.Z.,  
PRD 93 (2016) 114012

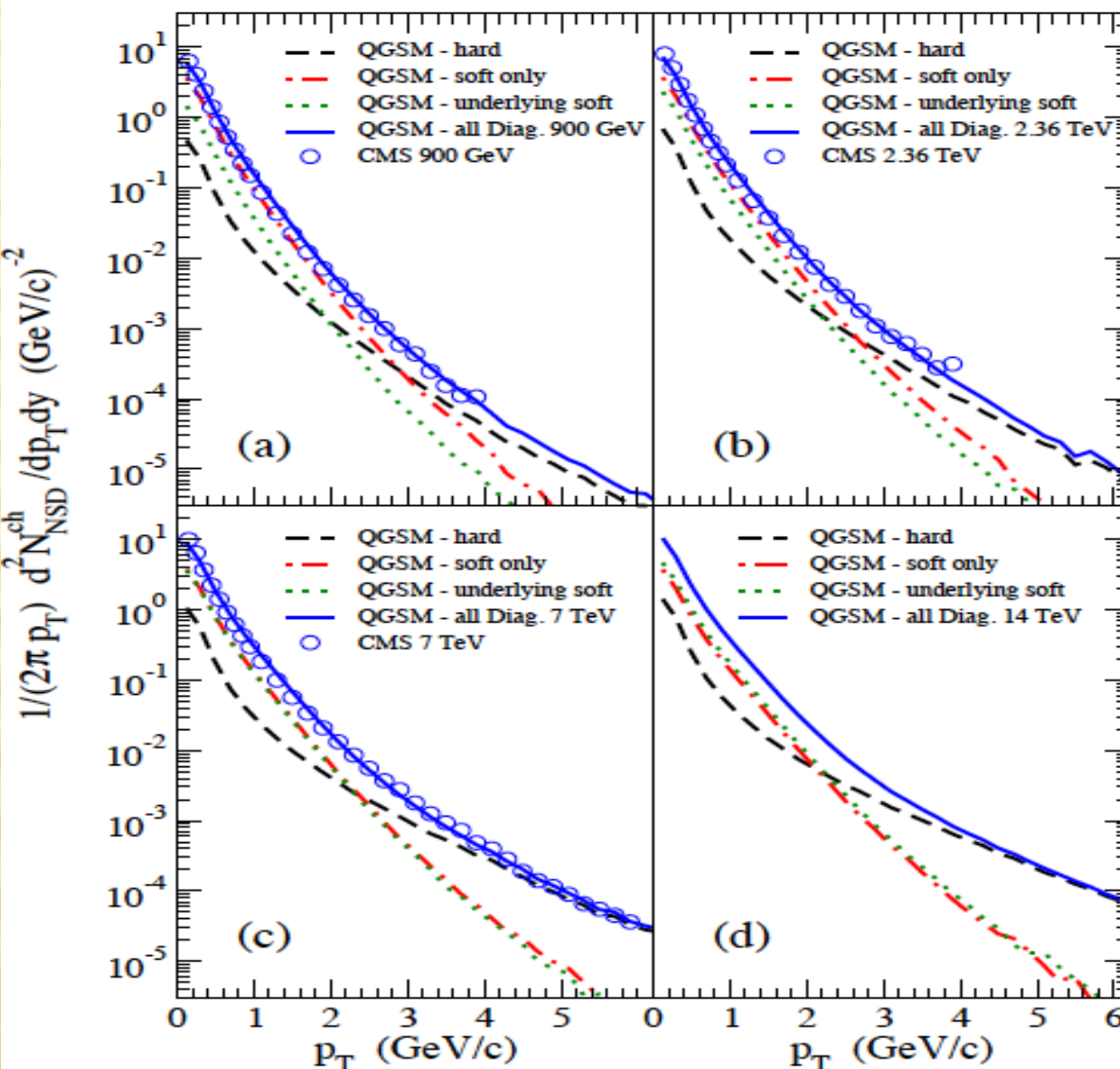


## Hard and soft components



Description of  $P_T$  spectra  
seems to be good

# $P_T$ SPECTRA: CONTRIBUTIONS OF SOFT AND HARD COMPONENTS



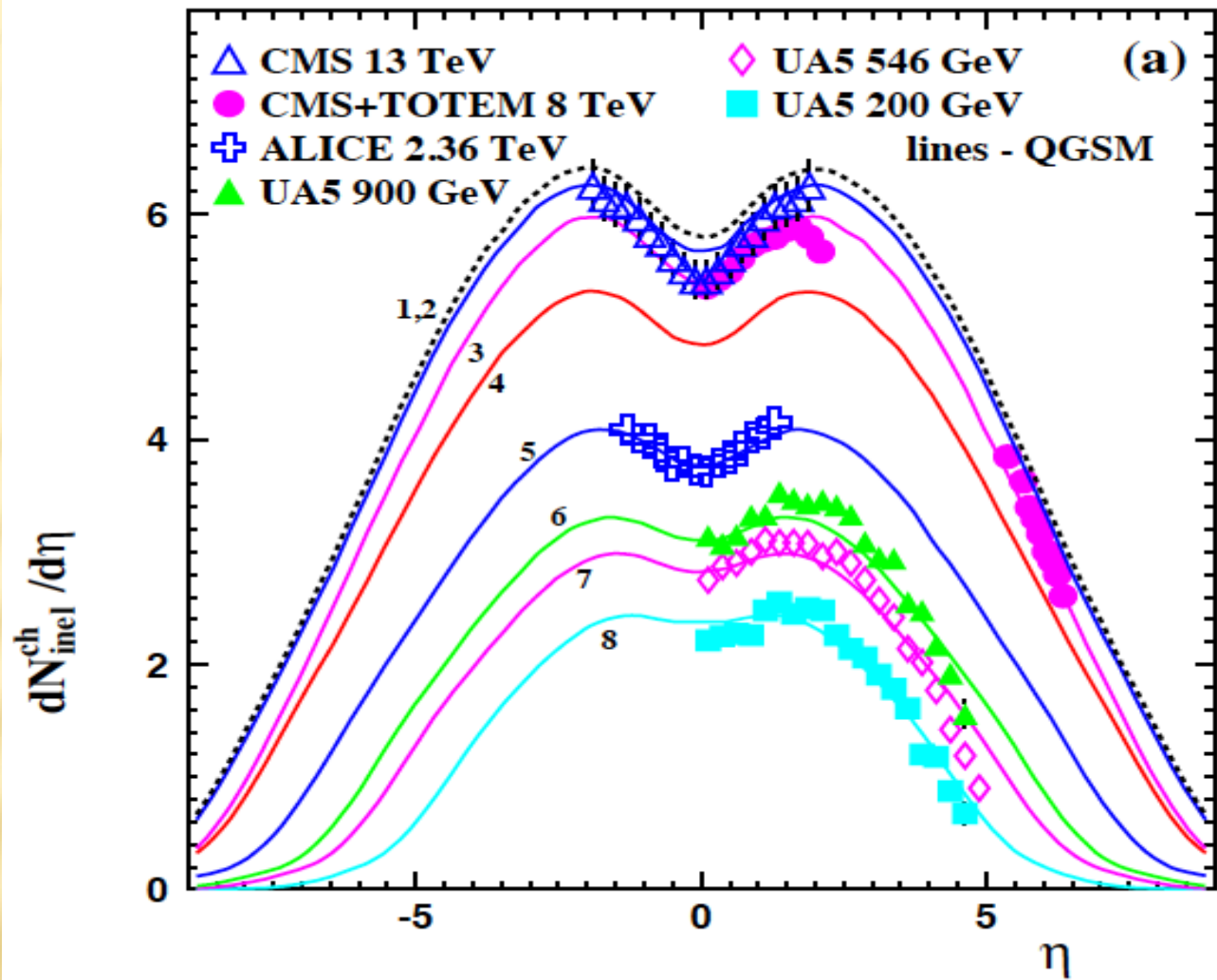
Hard and soft components from

$$\sqrt{s} = 900 \text{ GeV}$$

up to 14 TeV

# RAPIDITY SPECTRA: MODEL VS. DATA

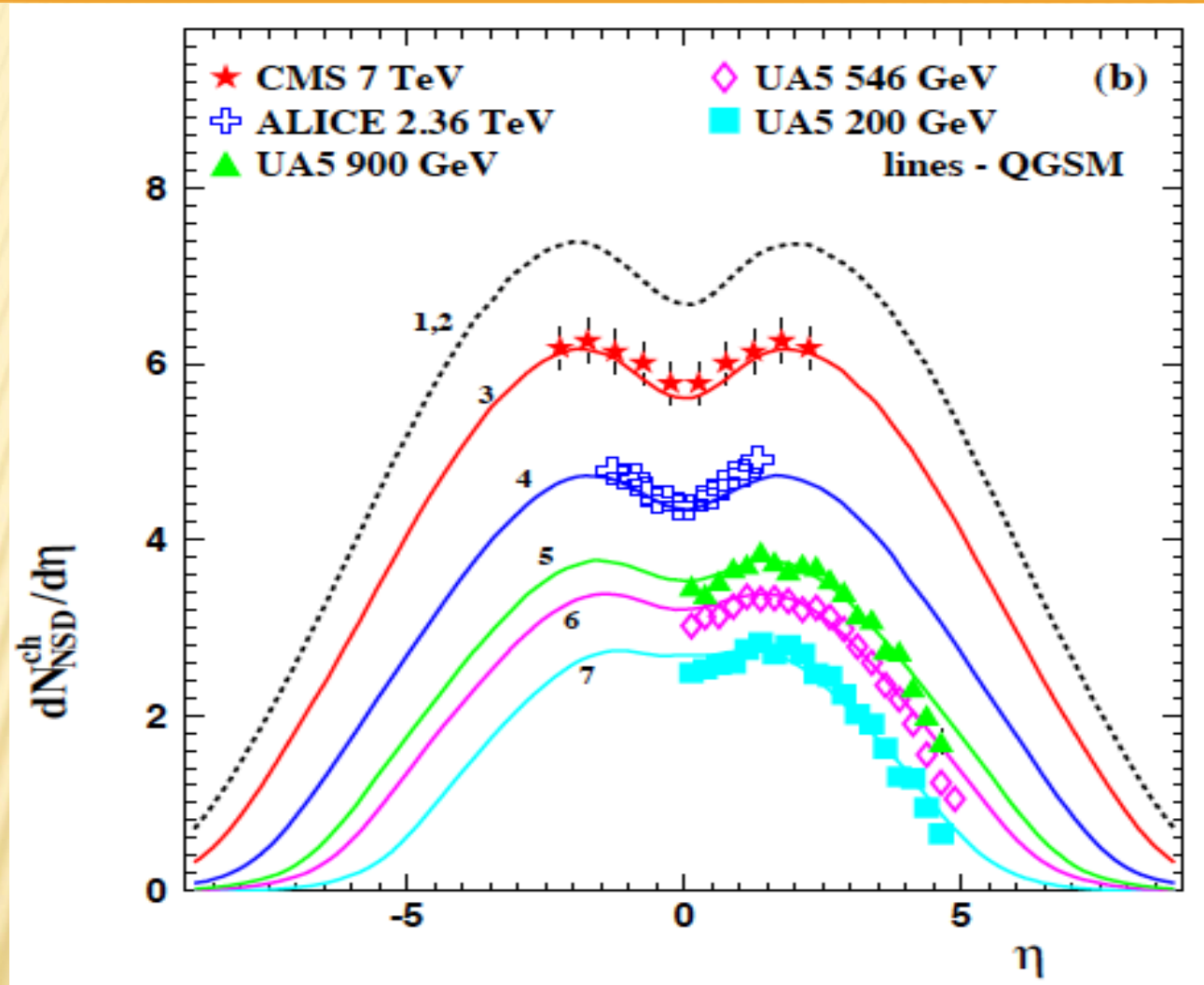
Inelastic collisions



Description of pseudorapidity spectra also seems to be good

# RAPIDITY SPECTRA: MODEL VS. DATA

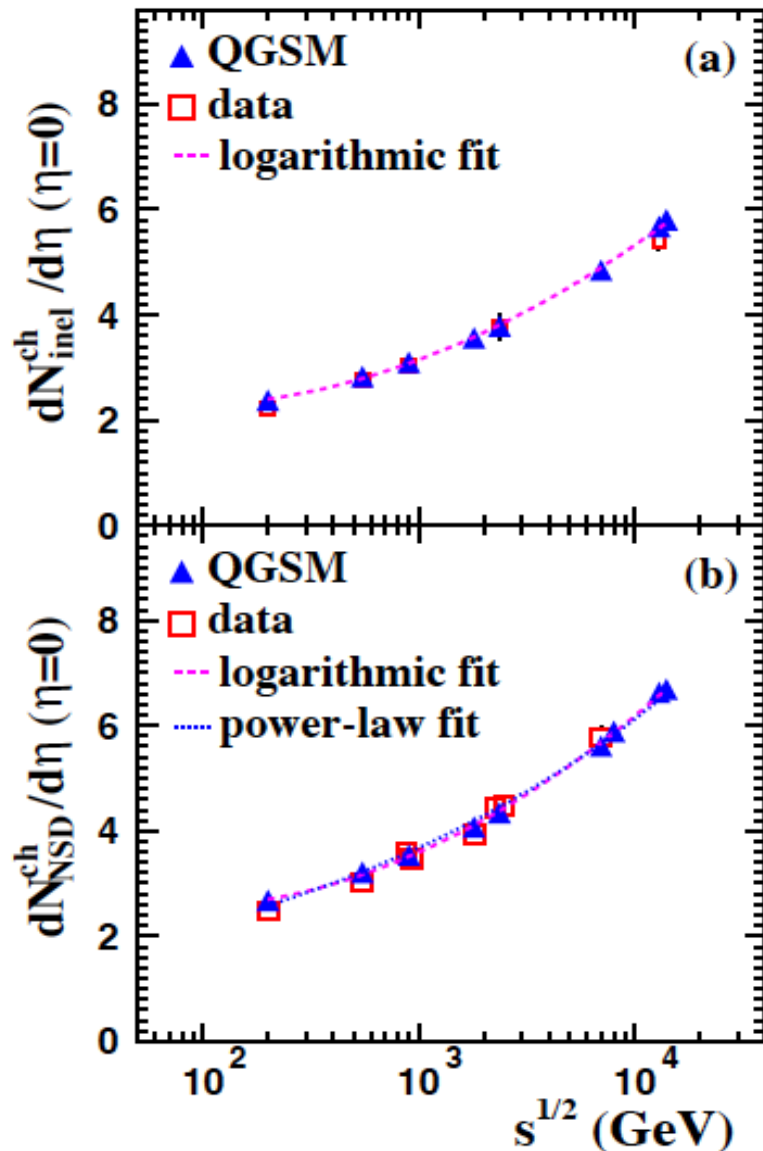
NSD  
collisions



J.Bleibel, L.Bravina, E.Z., PRD 93 (2016) 114012

Description of pseudorapidity spectra also seems to be good

# FIT TO DATA: LOGARITHMIC OR POWER-LAW ?



**Data:** CMS Collab., K.Khachatryan et al.,  
PRL 105 (2010) 022002

$$\left. \frac{dN_{inel}}{d\eta} \right|_{\eta=0}(s) = 4.36 - 0.507 \ln s + 0.03 \ln^2 s$$

$$\left. \frac{dN_{NSD}}{d\eta} \right|_{\eta=0}(s) = 5.015 - 0.60 \ln s + 0.036 \ln^2 s$$

$$\left. \frac{dN_{NSD}}{d\eta} \right|_{\eta=0}(s) = 0.77 E^{0.22} .$$

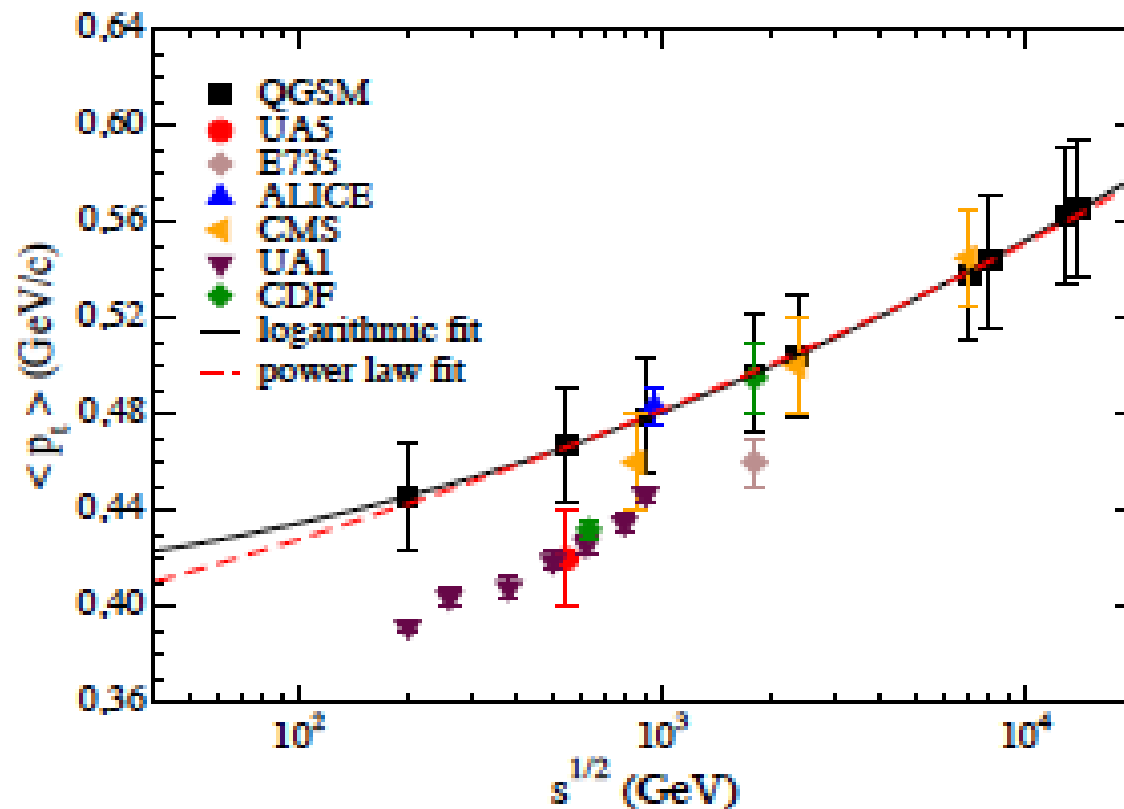
**Power-law:**

E.Levin, A.Rezaeian, PRD 82 (2010) 014022;

L.McLerran, M.Praszalowicz, Acta Phys. Polon.  
B 41 (2010) 1917

**No difference between the fits**

# FIT TO DATA: LOGARITHMIC OR POWER-LAW ?



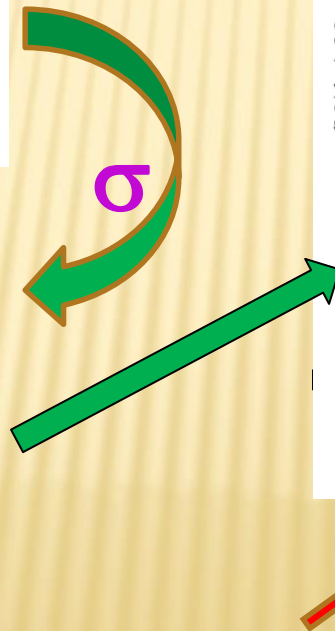
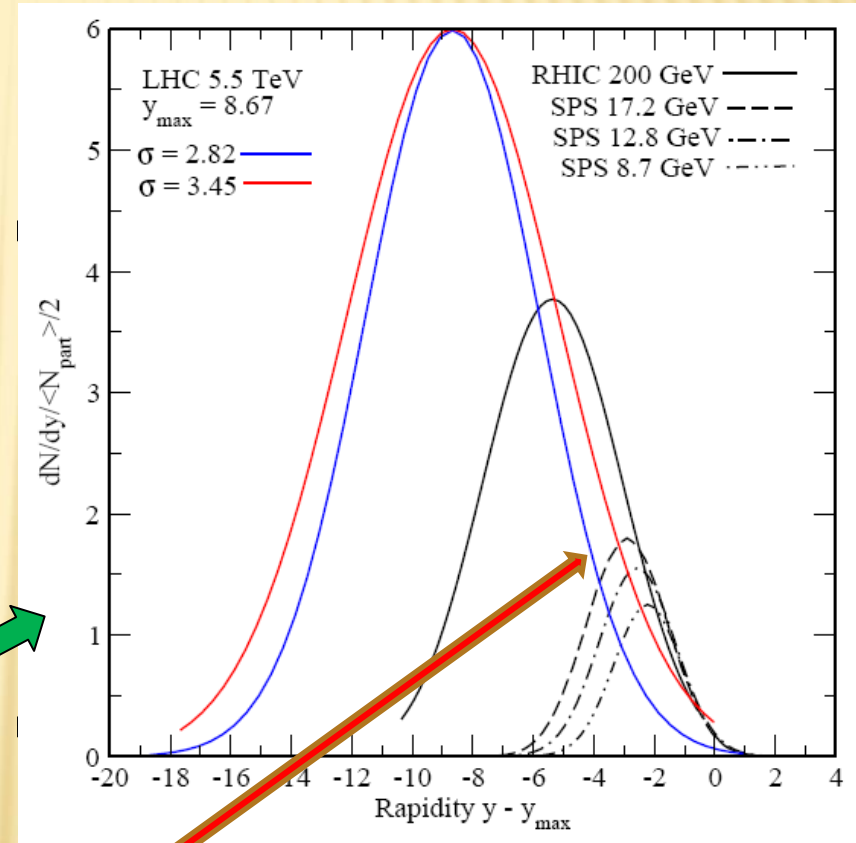
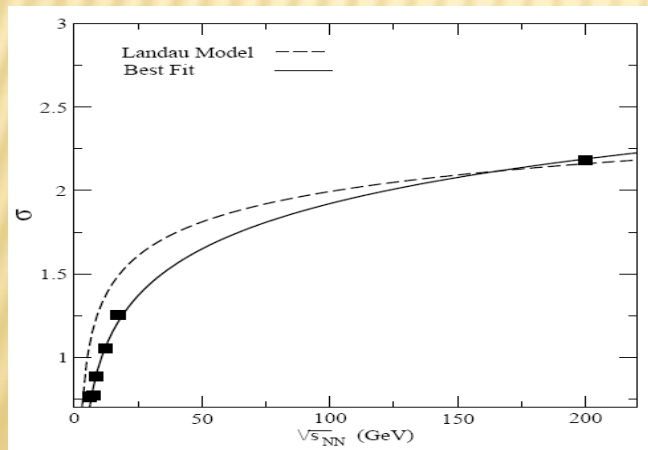
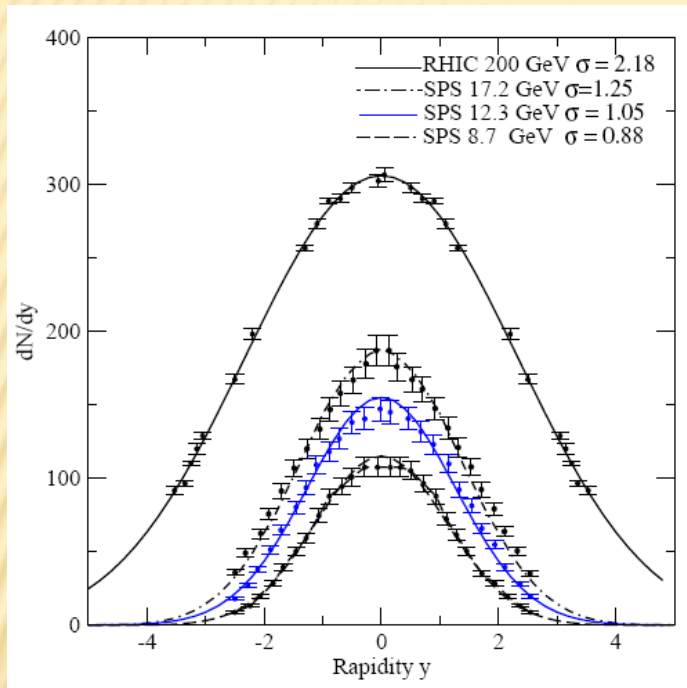
It is impossible to distinguish between these two fits even at 14 TeV

$$\langle p_T \rangle = 0.417 - 0.0035 \ln s + 0.00059 \ln^2 s ,$$

$$\langle p_T \rangle = 0.243 + 0.12 E^{0.1107} .$$

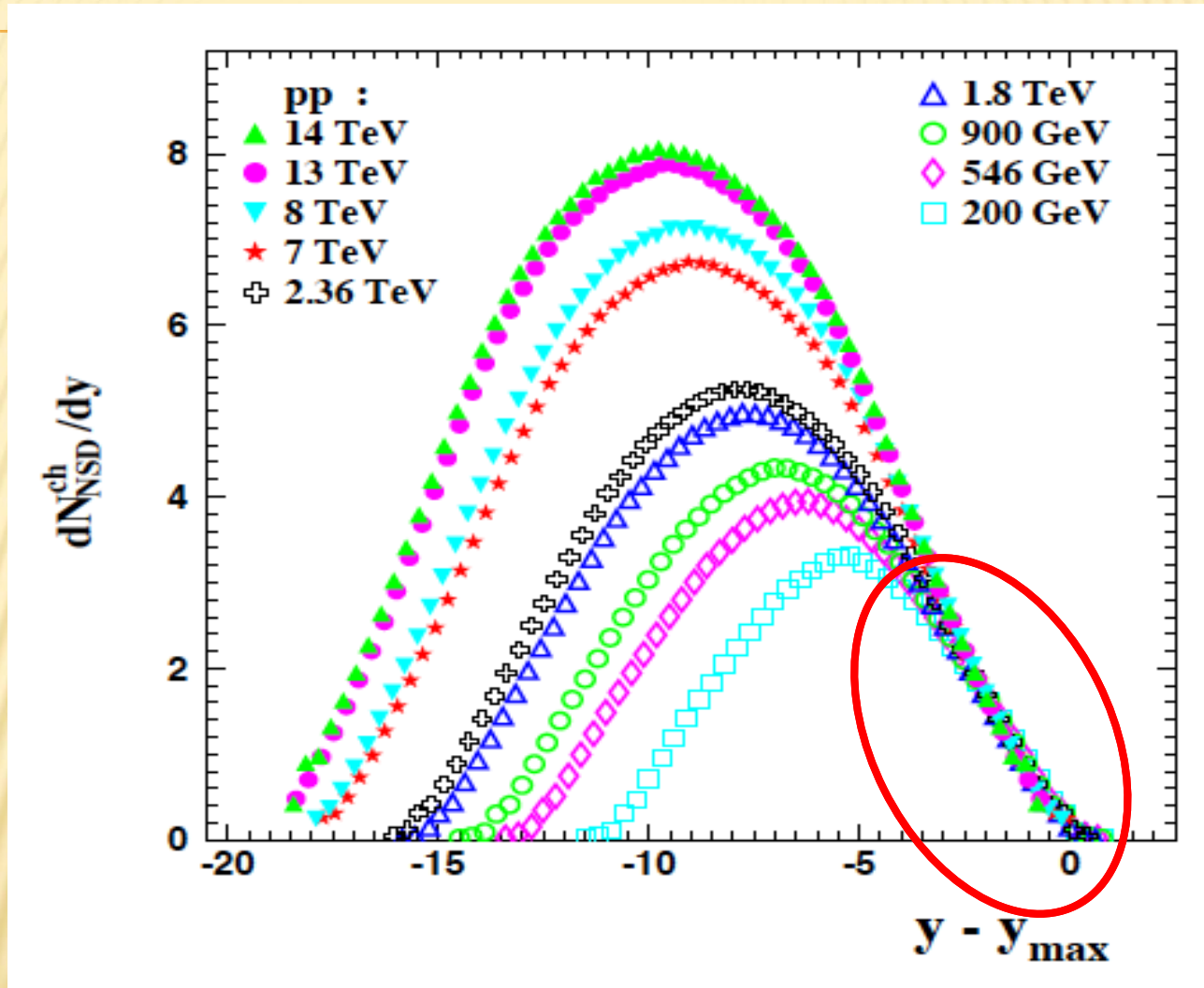
# VIOLATION OF ELS IN A+A AT LHC?

J. Cleymans, J. Struempfer, L. Turko, PRC 78 (2008) 017901



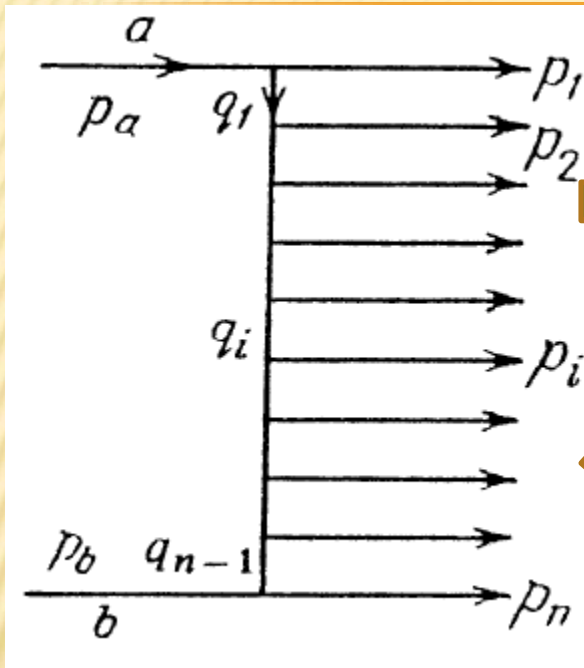
Statistical thermal model: ELS will be violated in A+A @ LHC. What about pp ?

# EXTENDED LONGITUDINAL SCALING @ LHC



QGSM: extended longitudinal scaling in pp collisions holds

# WHY SCALING HOLDS IN THE MODEL



$$x_F^{(i)} \equiv \frac{p_{i\Box}}{p_{\Box}^{\max}} \approx \exp\{-(y_1 - y_i)\}$$

therefore

$$\star n_i = \psi(x_F^{(i)}, p_{iT}^2)$$



Correlation function

$$C(y_i, y_j) \propto \exp\{-\lambda(y_i - y_j)\}$$

Particles are uncorrelated if

$$y_i - y_j \equiv \Delta y \gg 1$$

Consider now inclusive process

$$1 + 2 \rightarrow i + X$$

Particle inclusive cross section

$$f_i = \frac{d^2 \sigma(y_1 - y_i, y_i - y_2, p_{iT}^2)}{dy_i d^2 p_{iT}}$$

In the fragmentation region of particle 1

$$y_1 - y_i \approx 1, y_i - y_2 \approx y_1 - y_2 \gg 1$$

Inclusive density

$$n_i = f_i / \sigma_{inel} = \phi(y_1 - y_i, p_{iT}^2) \star$$

In string models both **FS** and **ELS** holds in the fragmentation regions

# VIOLATION OF KNO SCALING

E.M. Levin, M.G. Ryskin, *Yad. Fiz.* 19 (1974) 389

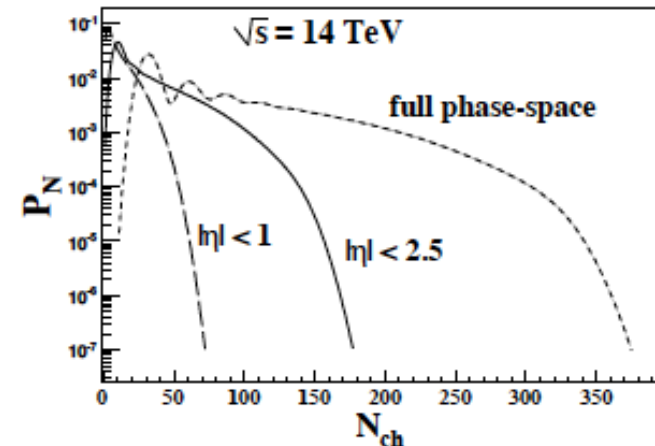
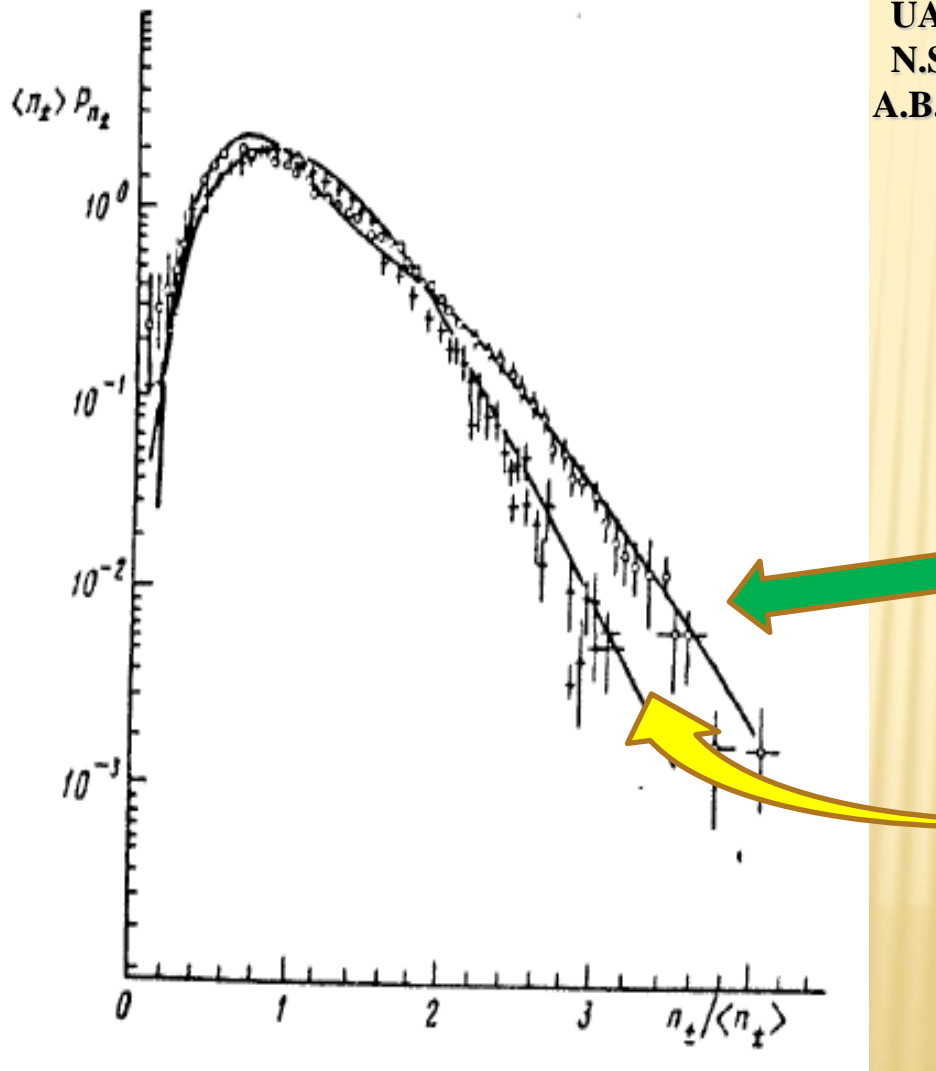
A.B. Kaidalov, K.A. Ter-Martirosyan, *PLB* 117 (1982) 247

UA5 Collaboration, *Phys. Rep.* 154 (1987) 247

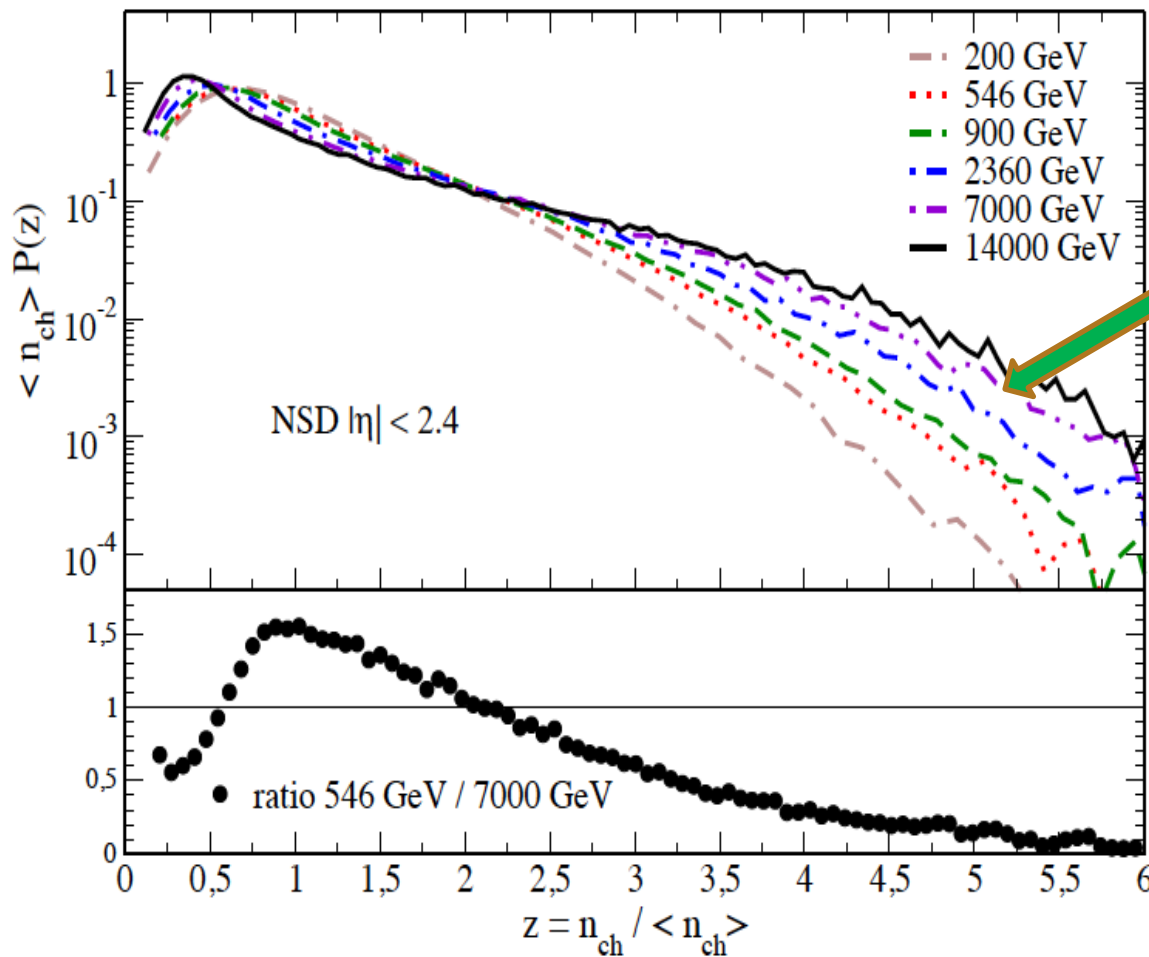
N.S. Amelin, L.V. Bravina, *Sov. J. Nucl. Phys.* 51 (1990) 133

A.B. Kaidalov, M.G. Poghosyan, *EPJC* 67 (2010) 397

**Charged-particle  
multiplicity distributions in  
the KNO variables in  
nondiffractive antiproton-  
proton collisions at  
 $\sqrt{s} = 546 \text{ GeV}$  and  $53 \text{ GeV}$**



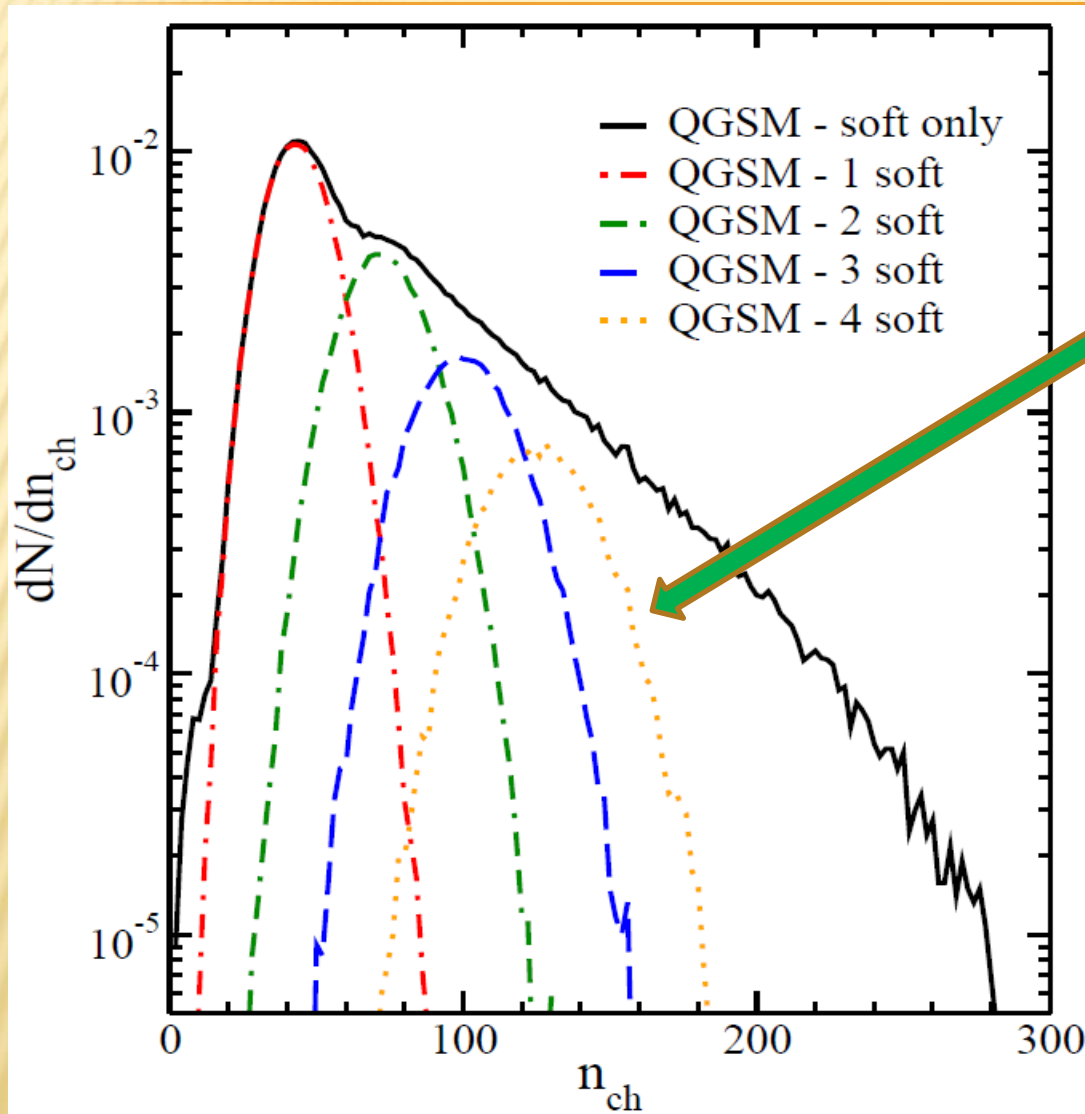
# ***VIOLATION OF KNO SCALING AT LHC***



**High-multiplicity tail is pushed up, whereas maximum of the distribution is shifted towards small values of  $z$**

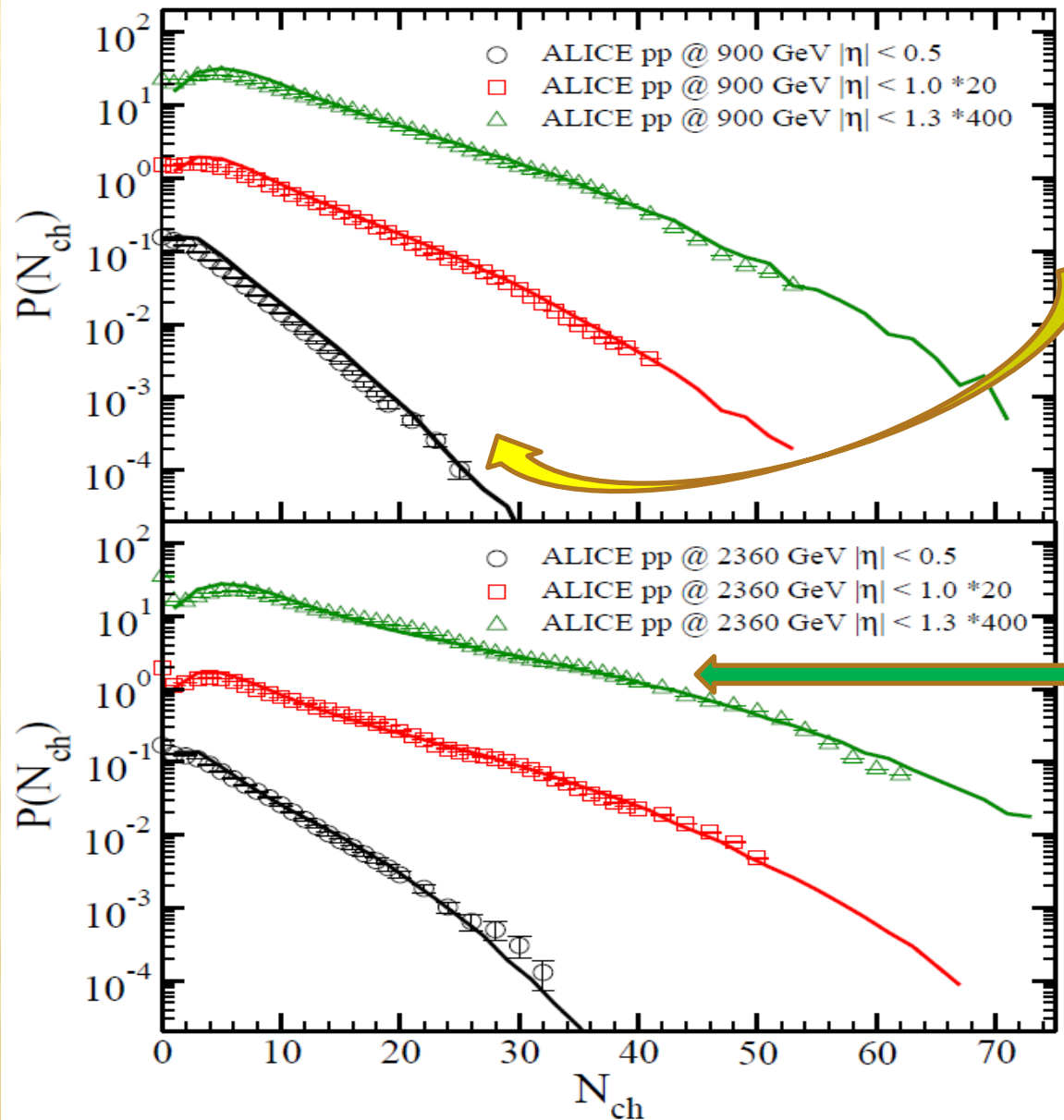
**Enhancement of high multiplicities**

# ***VIOATION OF KNO SCALING AT LHC***



**At energies below 100 GeV different contributions overlap strongly, whereas at higher energies – more multi-string processes**

# COMPARISON WITH EXPERIMENTAL DATA

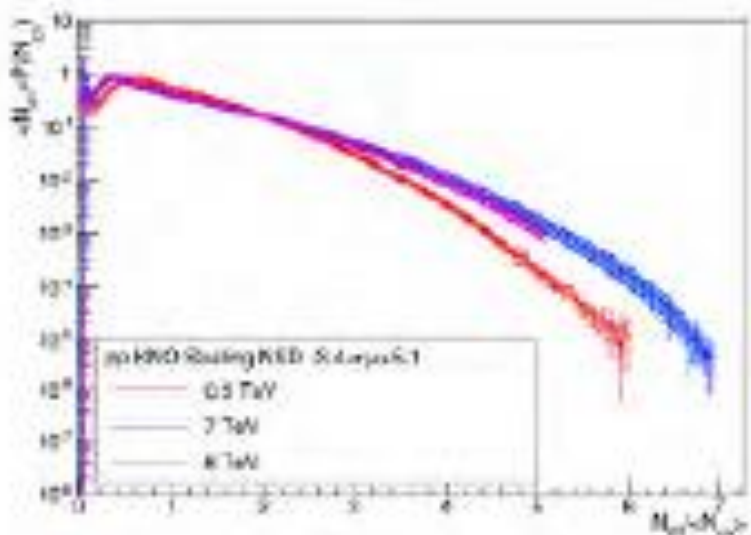
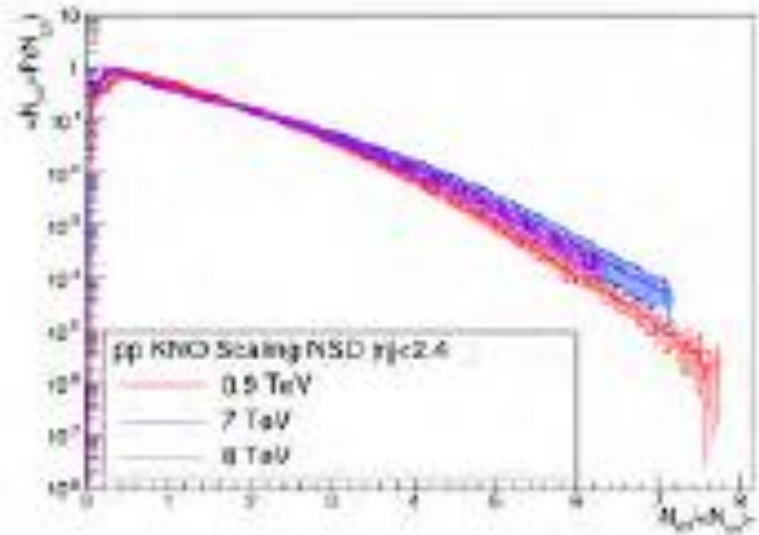
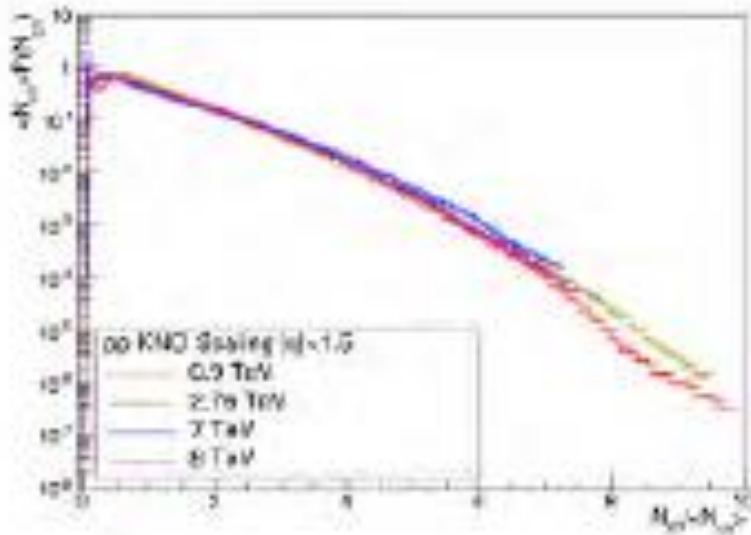


At midrapidity KNO scaling holds.

With the rise of the rapidity interval the high  $P_T$  tail of the distribution increases

# COMPARISON WITH EXPERIMENTAL DATA

V. Zaccolo, NBI, PhD thesis



All distributions seem to have a unique crossing point.

No oscillations yet.

# FREEZE-OUT OF PARTICLES AT LHC

M.S. Nilsson, UiO, PhD thesis

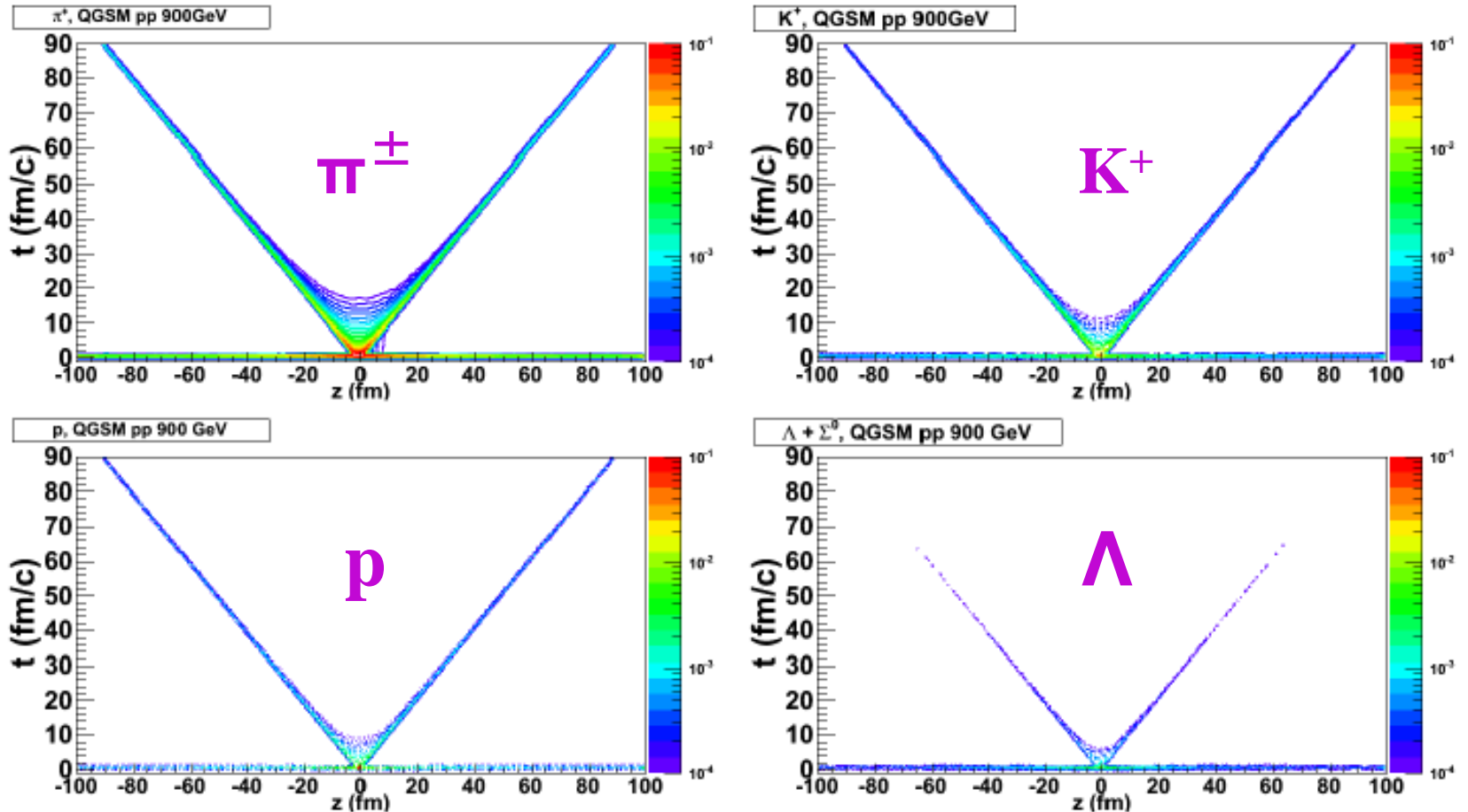


Figure 5.1:  $\frac{d^2N}{dzdt}$  distributions from  $pp$  900 GeV in QGSM

Mass hierarchy: heavier hadrons are frozen earlier

# FREEZE-OUT OF PARTICLES AT LHC

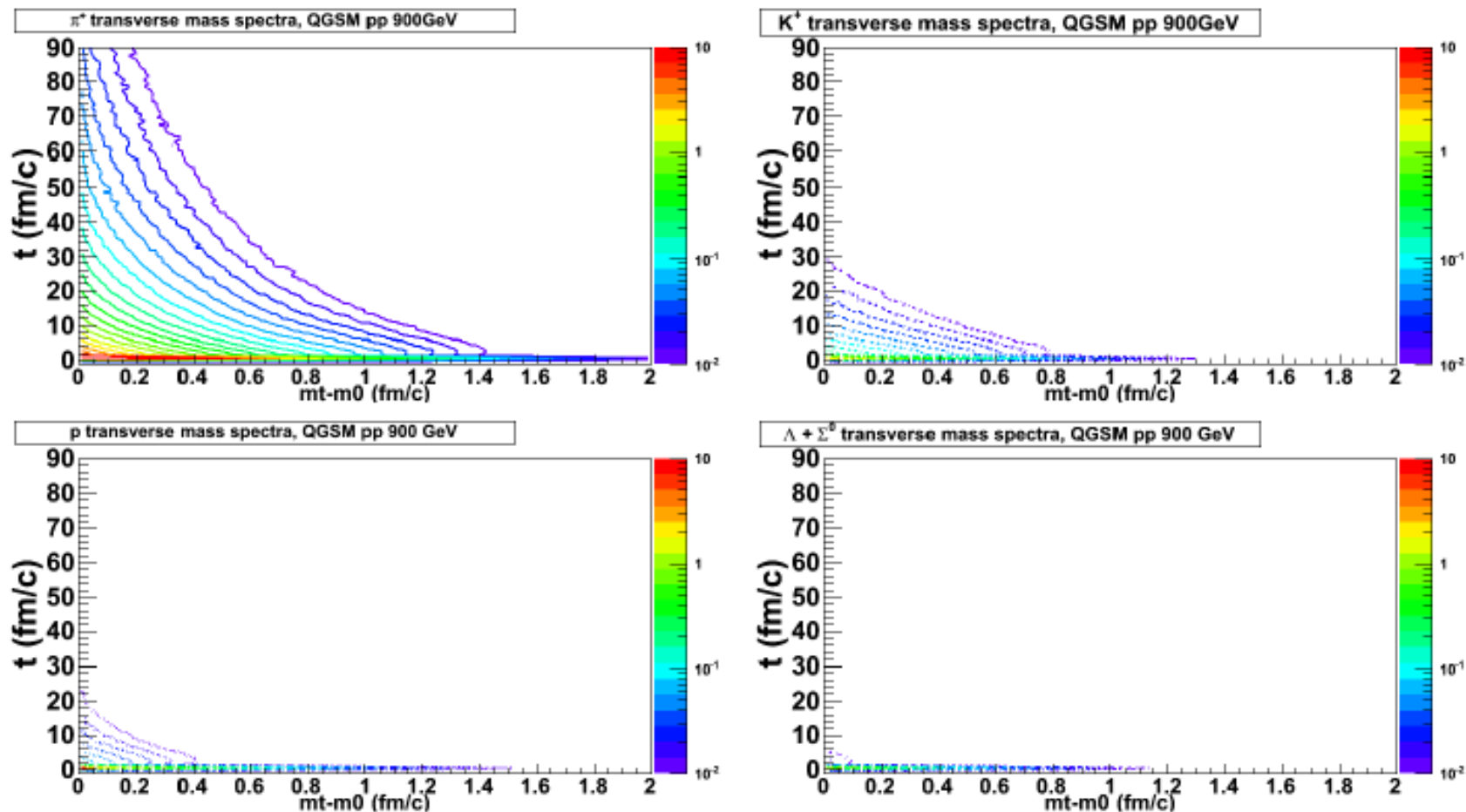


Figure 5.2:  $\frac{d^2 N}{m_T dm_t dt}$  distributions from  $pp$  900 GeV in QGSM

Early freeze-out of heavy particles

# FREEZE-OUT OF PARTICLES AT LHC

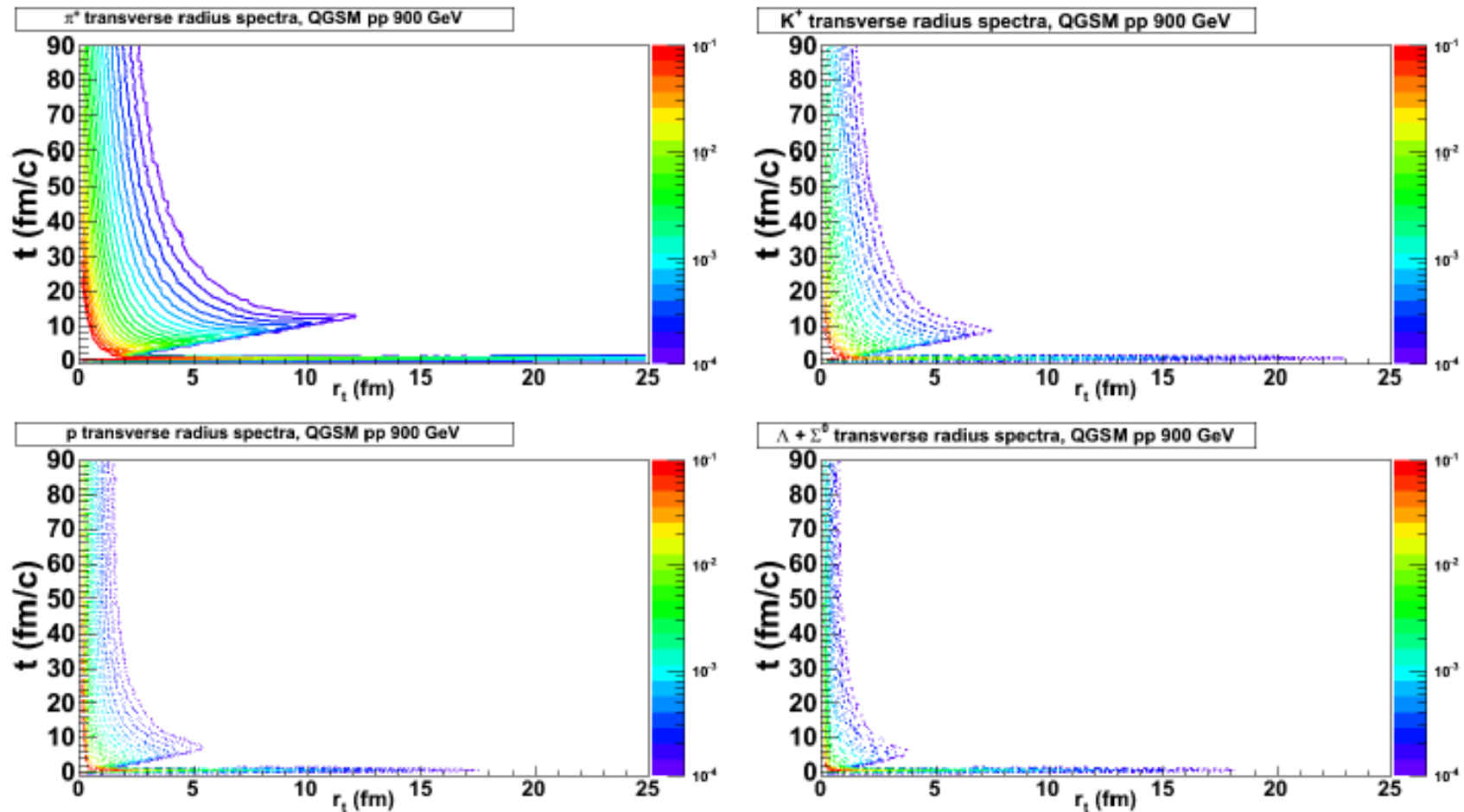


Figure 5.3:  $\frac{d^2N}{r_t dr_t dt}$  distributions from  $pp$  900 GeV in QGSM

Second peak – because of short-lived resonances

# SPACE-MOMENTUM CORRELATIONS

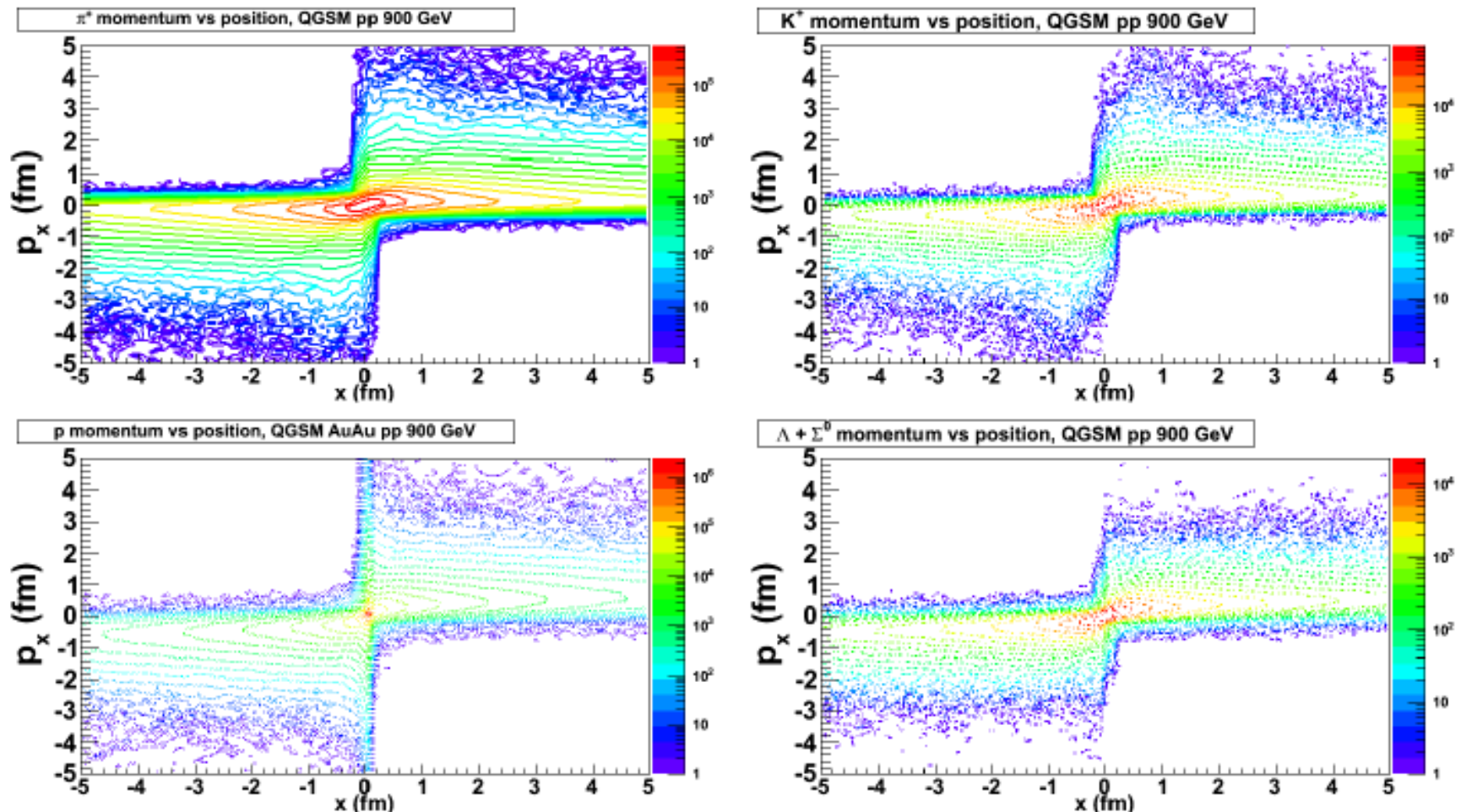
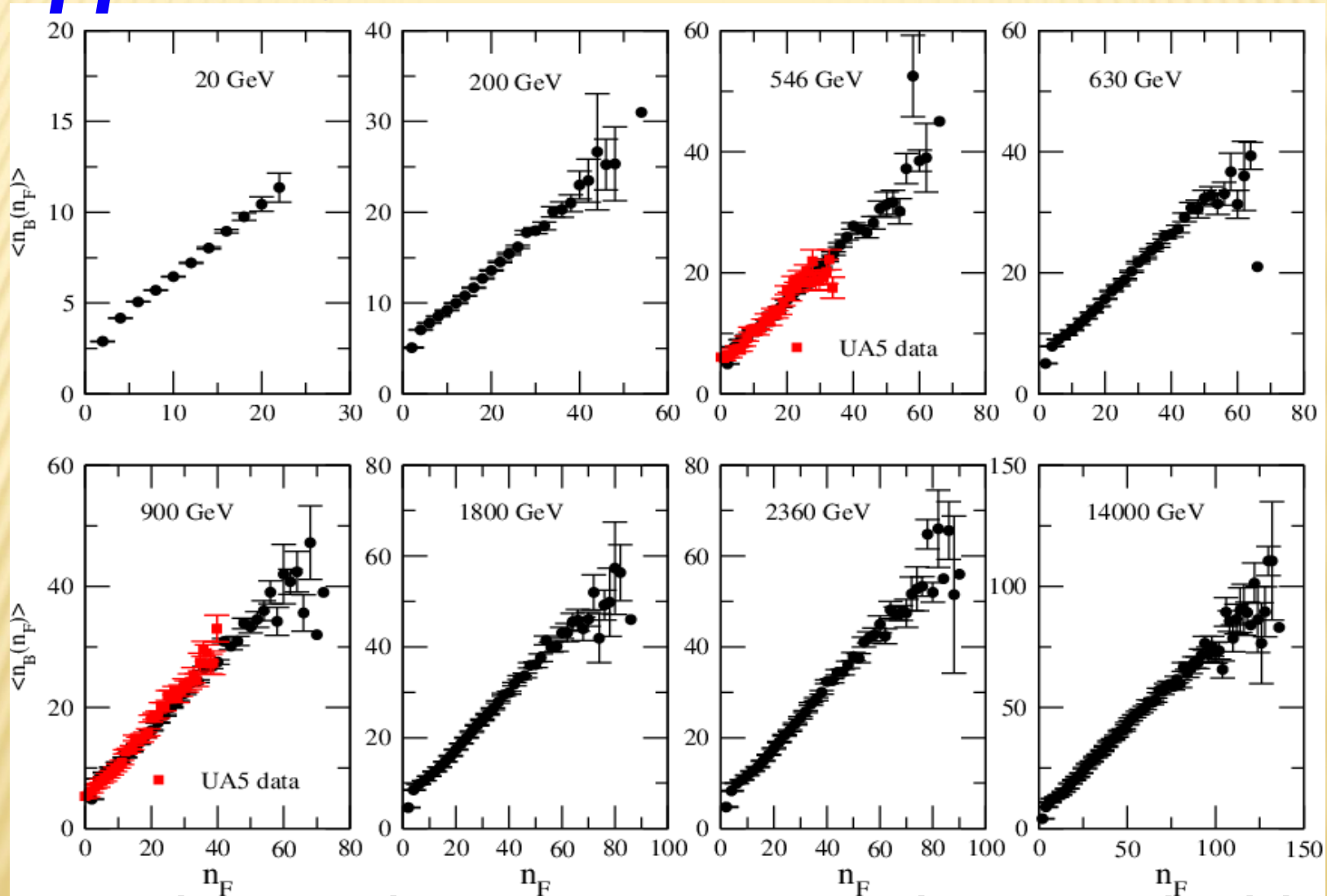


Figure 5.4:  $p_x - x$  distributions from  $pp$  900 GeV in QGSM

In hydrodynamics such correlations arise due to collective flow,  
in string models – due to dynamics of string fragmentation

# Forward-backward mult. correlations pp @ 20 GeV to 14 TeV



The slope is almost linear; slope parameter  $b$  increases with rising energy  
Why? – see talk by L. Bravina

# *Summary and perspectives*

- *Feynman scaling at midrapidity is not observed yet*
- *Extended longitudinal scaling holds*
- *It would be interesting to check the ELS for pp collisions within the statistical thermal model*
- *KNO scaling is strongly violated at LHC  
The origin of the violation is traced to multi-string processes*
- *Long-range forward-backward correlations arise because of addition of different multi-chain diagrams with different average multiplicities*

# ***BACK-UP SLIDES***

---

# A.B.Kaidalov Predictions for LHC.

1.  $\sigma^{(tot)}$       103 mb      ( $\sigma_{(s)}^{(tot)} \sim \ln^2 \frac{s}{s_0}$ )

2.  $\sigma^{(el)}$       26 mb      ( $\sigma_{(s)}^{(el)} \sim \ln^2 \frac{s}{s_0}$ )

3.  $B(0)$       21.5 GeV<sup>-2</sup>      ( $B(0) \sim \ln^2 \frac{s}{s_0}$ )

4.  $\rho = \frac{\text{Re} T(0)}{\text{Im} T(0)}$       0.11

5.  $\sigma_{SD}$       12 ÷ 13 mb      ( $\sigma_{SD} \sim \sigma_{DD} \sim \ln \frac{s}{s_0}$ )

6.  $\sigma_{DD}$       11 ÷ 13 mb

$$\sigma^{(el)} + \sigma_{SD} + \sigma_{DD} = 51 \text{ mb} \approx \frac{1}{2} \sigma^{(tot)}$$

## A.B.Kaidalov Predictions for LHC.

7.  $\langle n_{ch} \rangle$   $80 \div 100$

8.  $\left. \frac{dn_{sb}}{dy} \right|_{y=0}$   $5.5 \div 6.0$

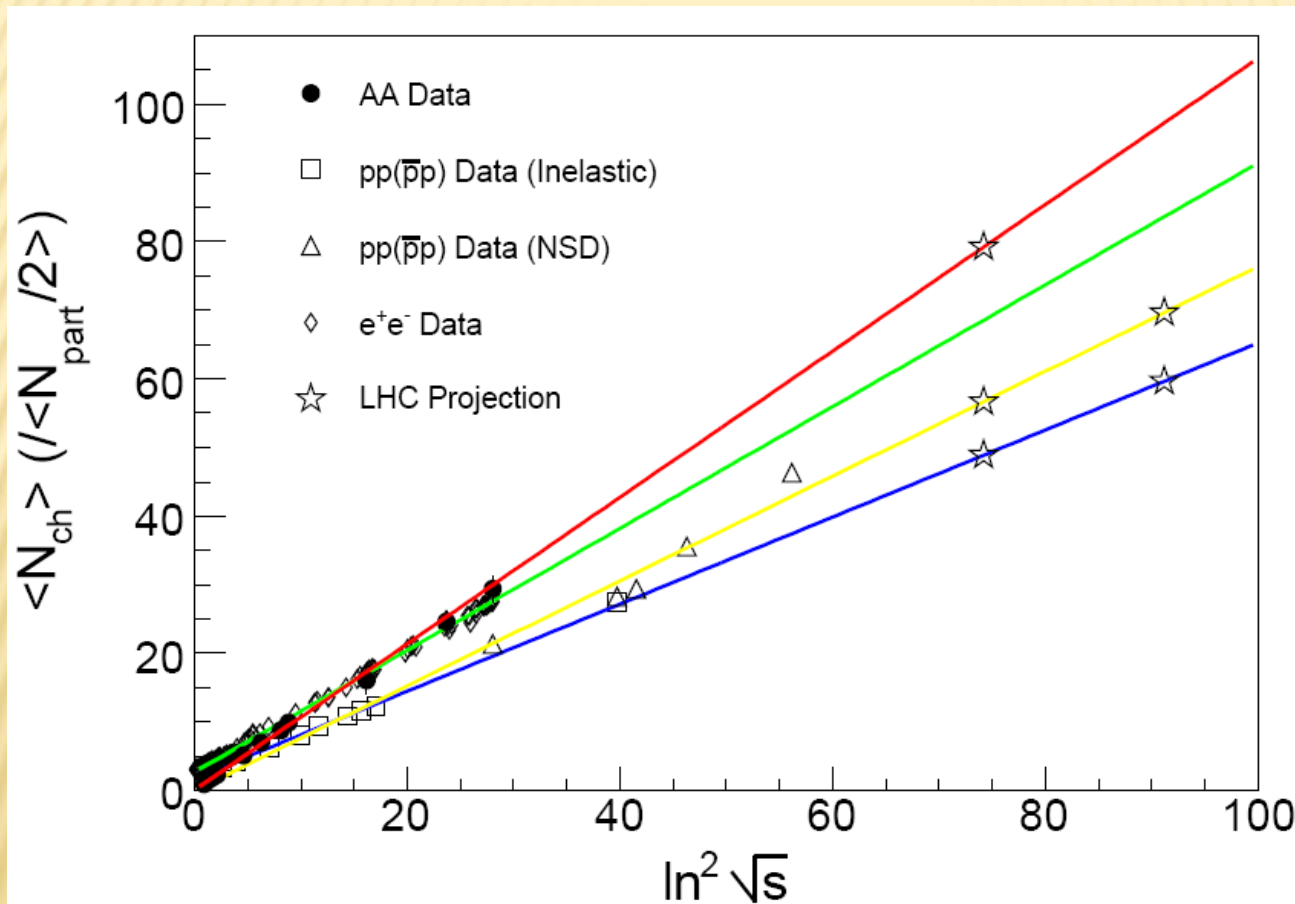
9. Structures in  $\sigma_n$

10. Strong long-range (in  $y$ ) correlations

11. Large amount of minijets.

# MOTIVATION: SCALING BEHAVIOR

W. Busza, JPG 35 (2008) 044040



Predictions for LHC

inelastic pp :

$N_{ch} = 60 \pm 10$  (14 TeV)

$N_{ch} = 49 \pm 8$  (5.5 TeV)

NSD pp :

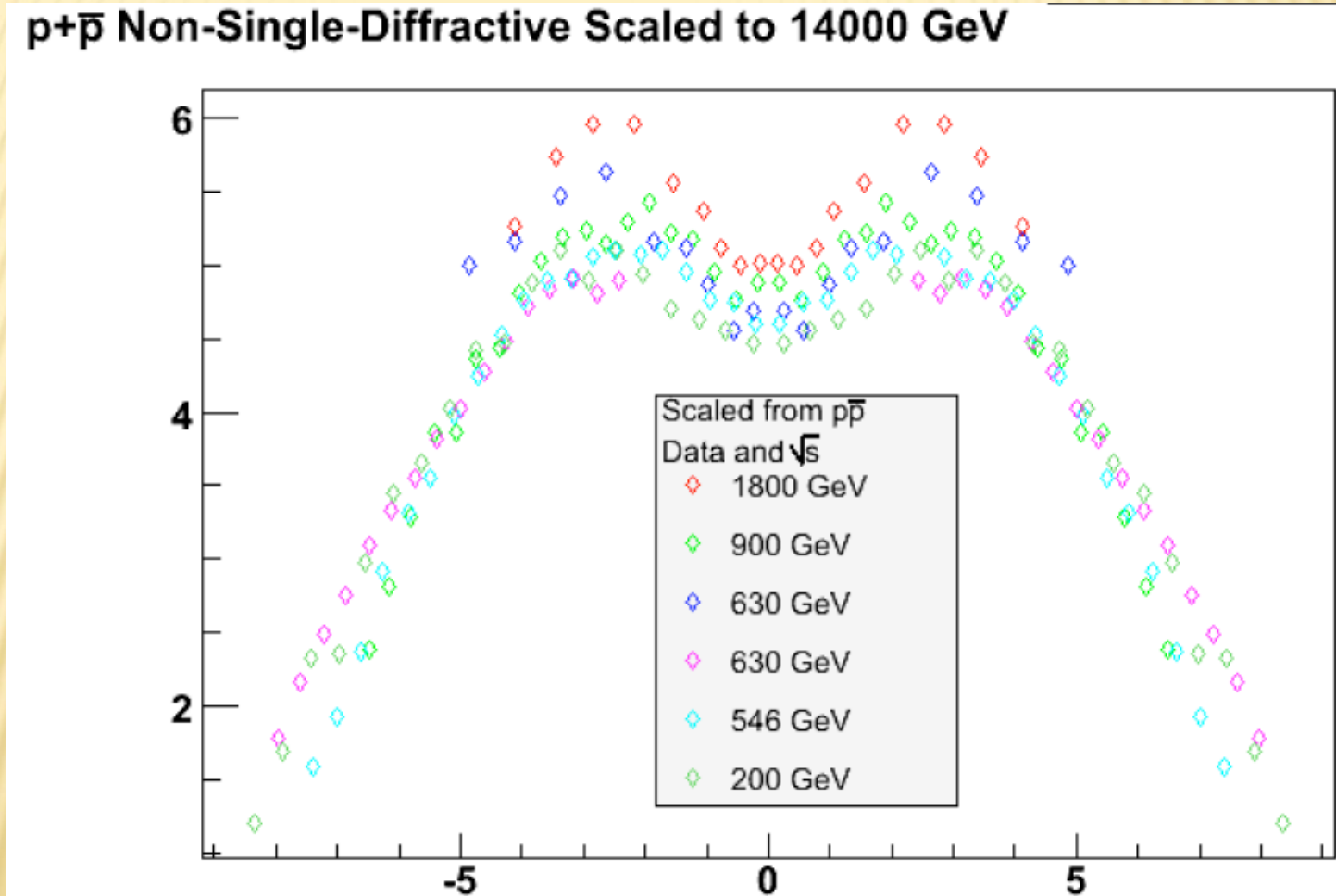
$N_{ch} = 70 \pm 8$  (14 TeV)

$N_{ch} = 57 \pm 7$  (5.5 TeV)

Energy dependence of particle multiplicities

# MOTIVATION: EXPERIMENTAL RESULTS

W. Busza, JPG 35 (2008) 044040

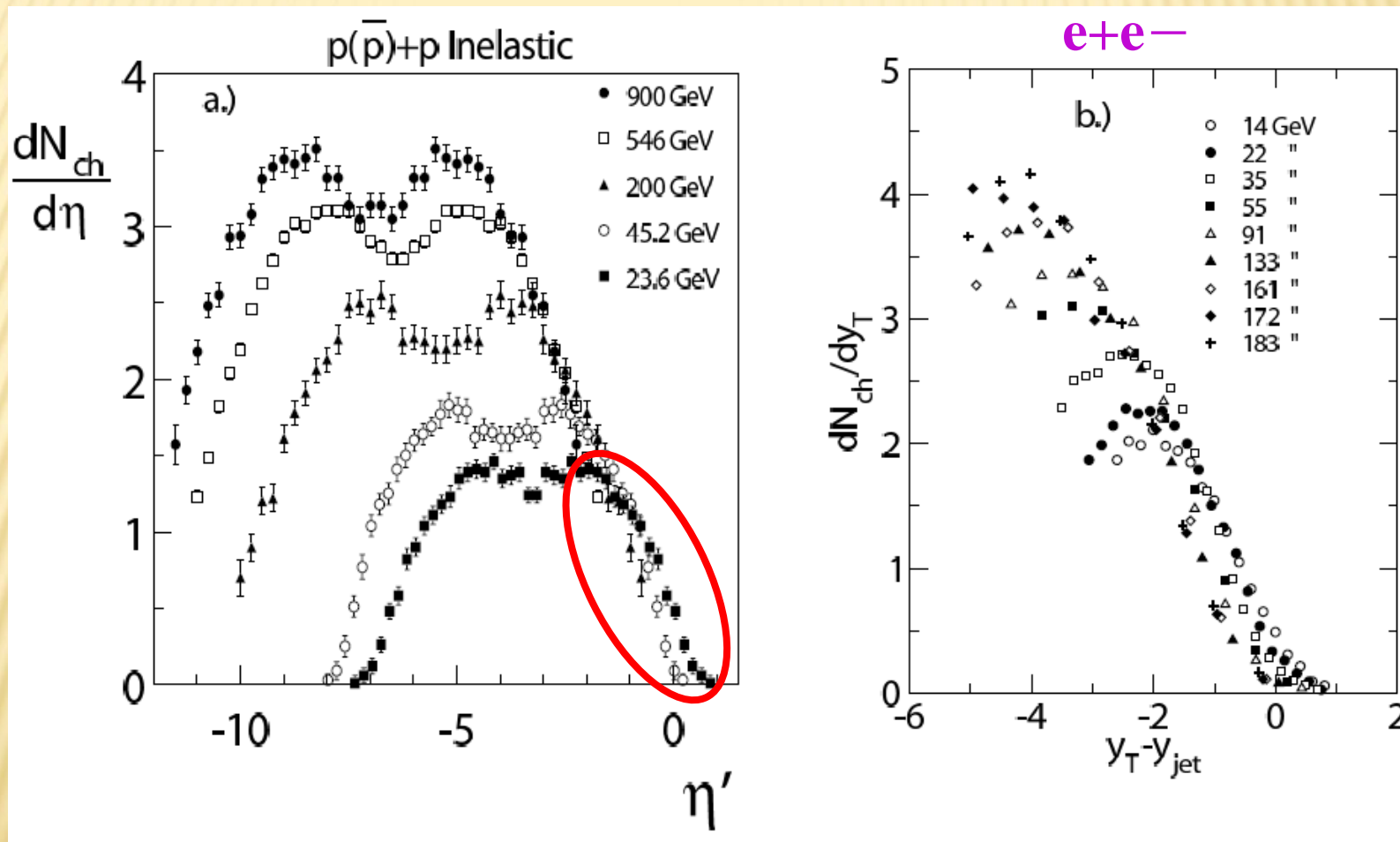


Extrapolation of NSD pp data to LHC using  $\ln\sqrt{s}$  scaling of the width and height of the distribution

# MOTIVATION: EXPERIMENTAL RESULTS

## Extended longitudinal scaling

W. Busza, JPG 35 (2008) 044040



Example of extended longitudinal scaling in different reactions

# QUARK-GLUON STRING MODEL

## Soft and hard eikonals

$$u(s, b) = u_{soft}(s, b) + u_{hard}(s, b)$$

$$\sigma_{inel}(s) = 2\pi \int_0^\infty \{1 - \exp[-2u^R(s, b)]\} b db .$$

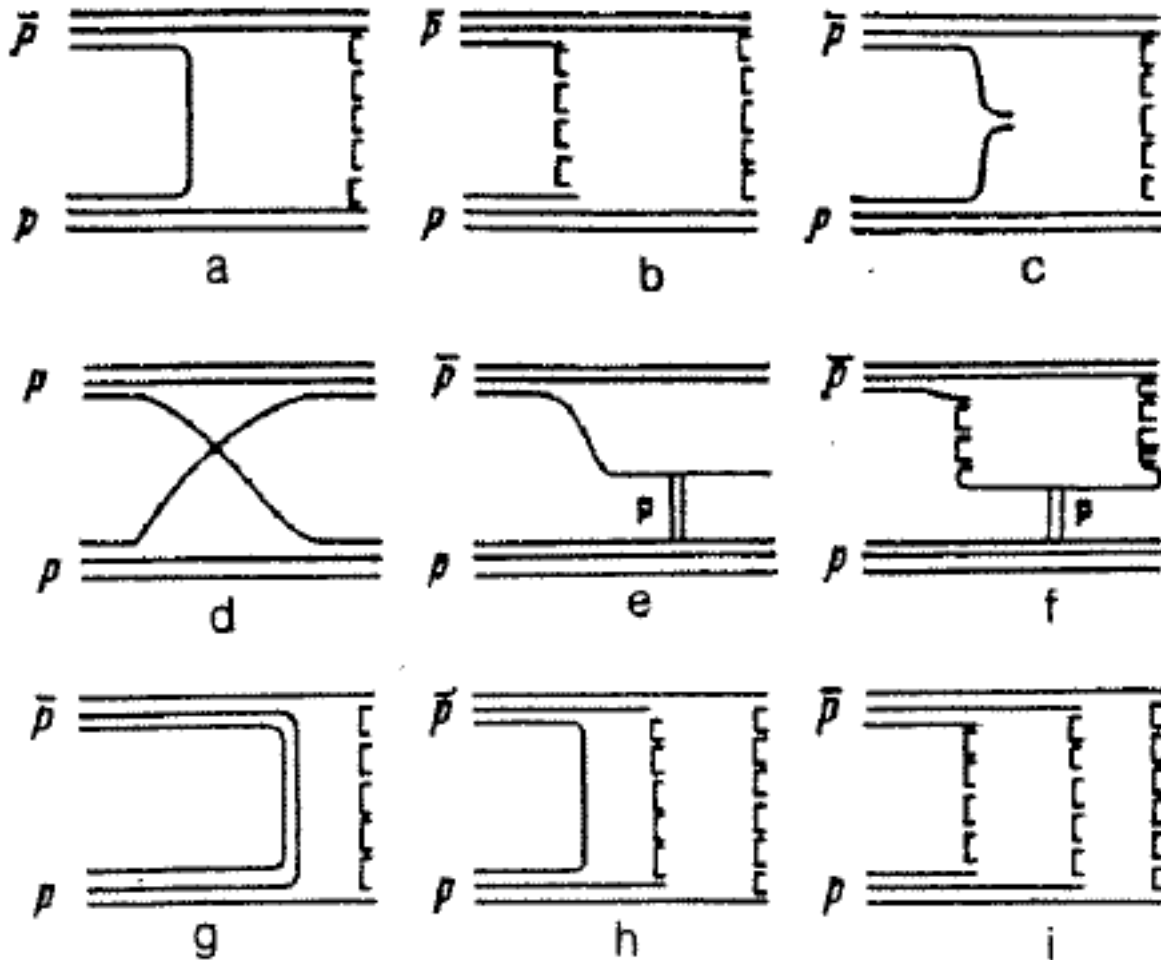
$$\sigma_{inel}(s) = \sum_{i,j=0; i+j \geq 1} \sigma_{ij}(s),$$

AGK cutting rules

$$\sigma_{ij}(s) = 2\pi \int_0^\infty b db \exp[-2u^R(s, b)] \\ \times \frac{[2u_{soft}^R(s, b)]^i}{i!} \frac{[2u_{hard}^R(s, b)]^j}{j!} .$$

number of cut soft and hard  
Pomerons => number of  
quark-gluon strings

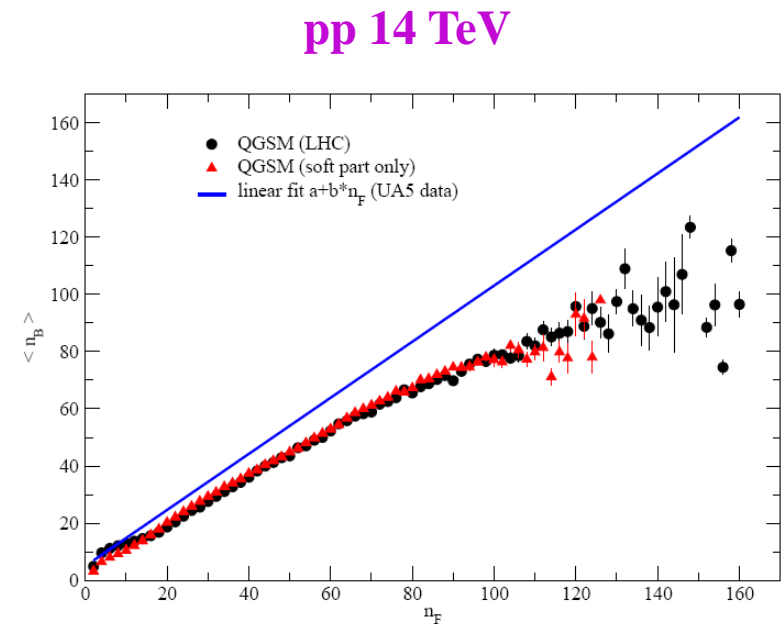
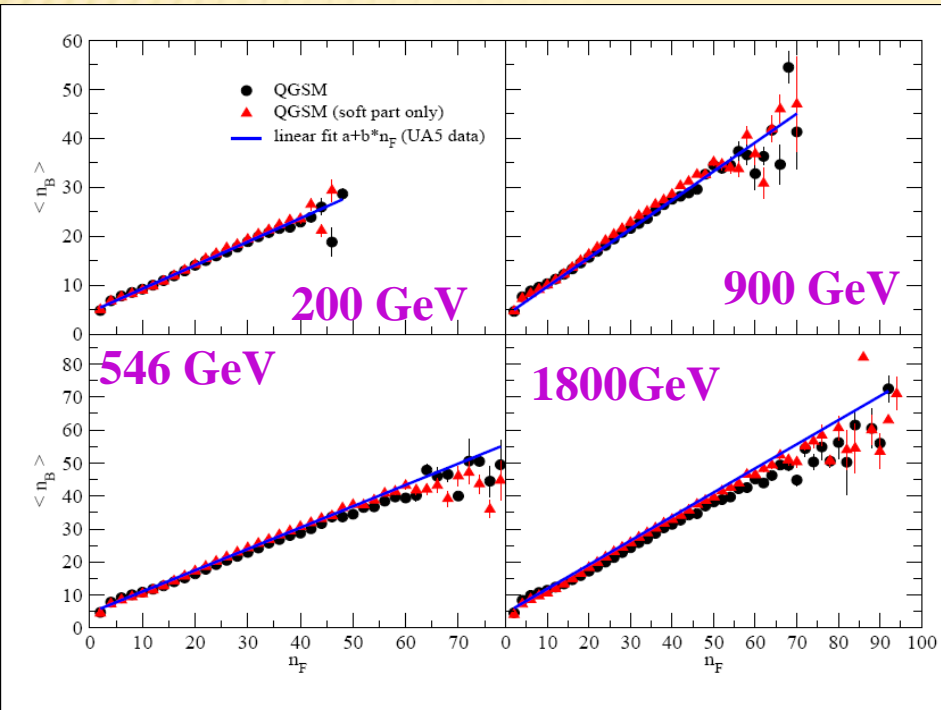
# Diagrams at intermediate energies



(a) -- planar  
 (b) -- cylindrical  
 (c) -- undeveloped cylinder  
 (d) -- quark rearrangement  
 (e) -- single diffraction of small mass  
 (f) -- single diffraction of large mass  
 (g)-(i) -- annihilation diagrams  
 + double diffraction diagrams similar to (e),(f)

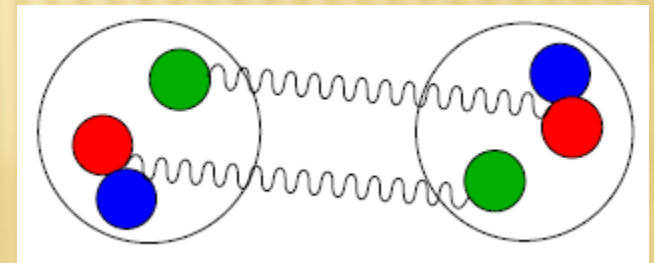
Because of the different sets of diagrams for pp and anti-pp collisions (particularly, annihilation) there should be a difference in FB multiplicity correlations for these two reactions.

# FORWARD-BACKWARD MULTIPLICITY CORRELATIONS

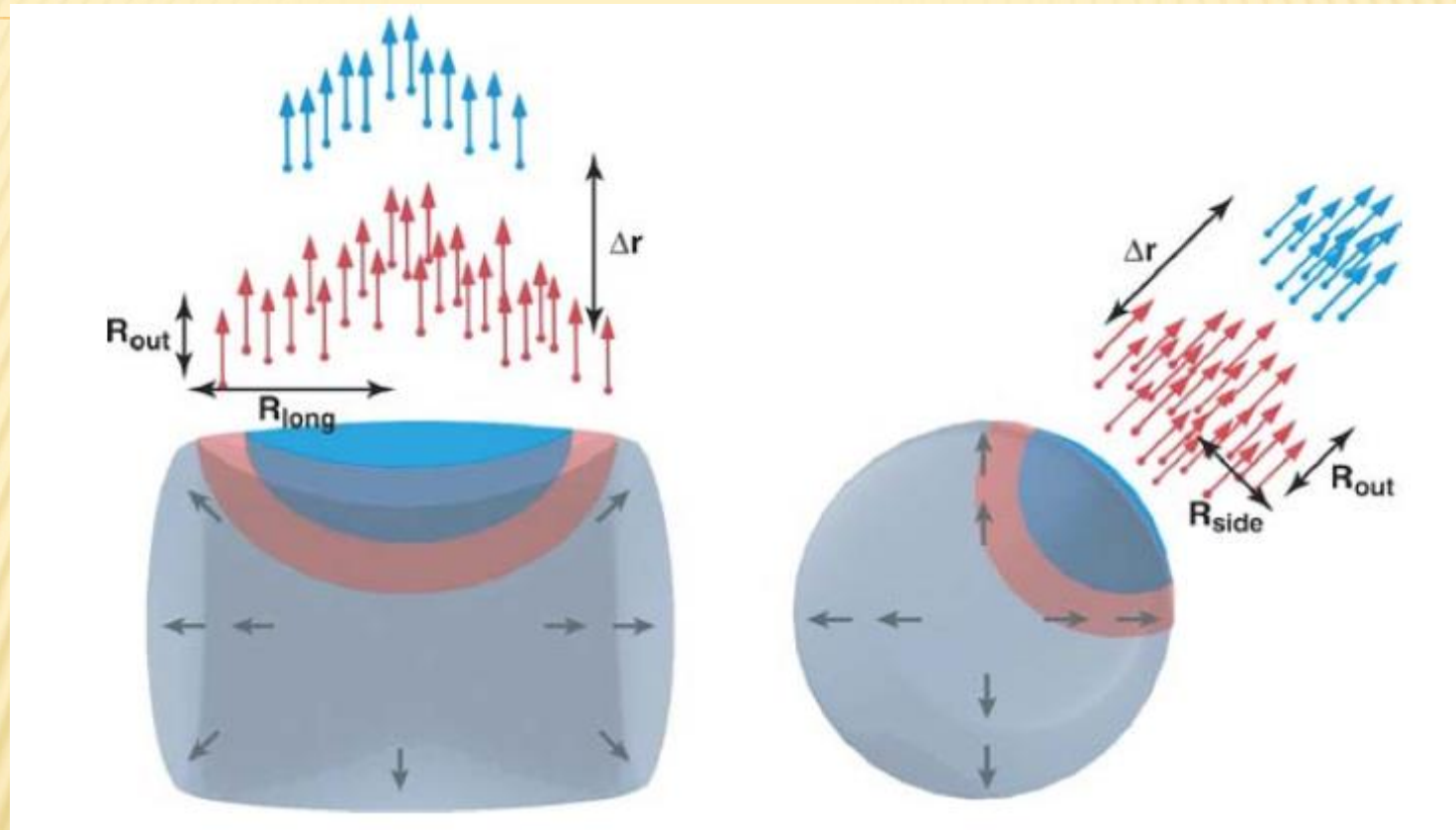


$\langle n_B(n_F) \rangle = a + b n_F$  is linear with increase of the slope  $b$  with energy due to

- 1) Multi-chain diagrams
- 2) Color exchange type of string excitation



# FEMTOSCOPY CORRELATIONS



$$CF(q) = 1 + \lambda \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)$$

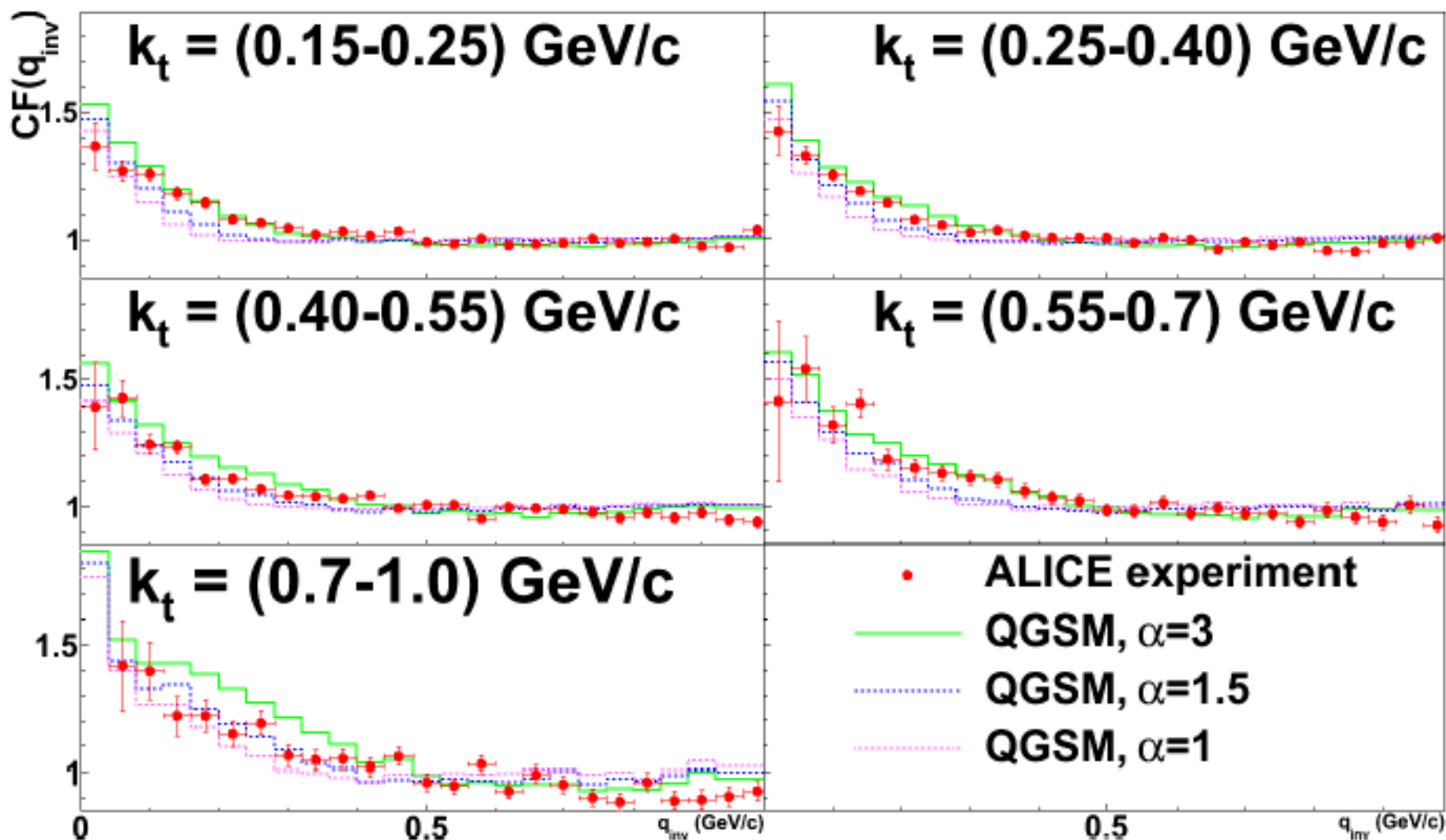
$$CF(q_{inv}) = 1 + \lambda \exp(-R_{inv}^2 q_{inv}^2)$$

$$P_1(p_i) = E_i \frac{dN_i}{d^3 p_i}$$

$$P_2(p_1, p_2) = E_1 E_2 \frac{dN_{12}}{d^3 p_1 d^3 p_2}$$

$$CF(p_1, p_2) = \frac{dN_{12}/(d^3 p_1 d^3 p_2)}{(dN_1/d^3 p_1)(dN_2/d^3 p_2)}$$

# FEMTOSCOPY CORRELATIONS



# FEMTOSCOPY CORRELATIONS

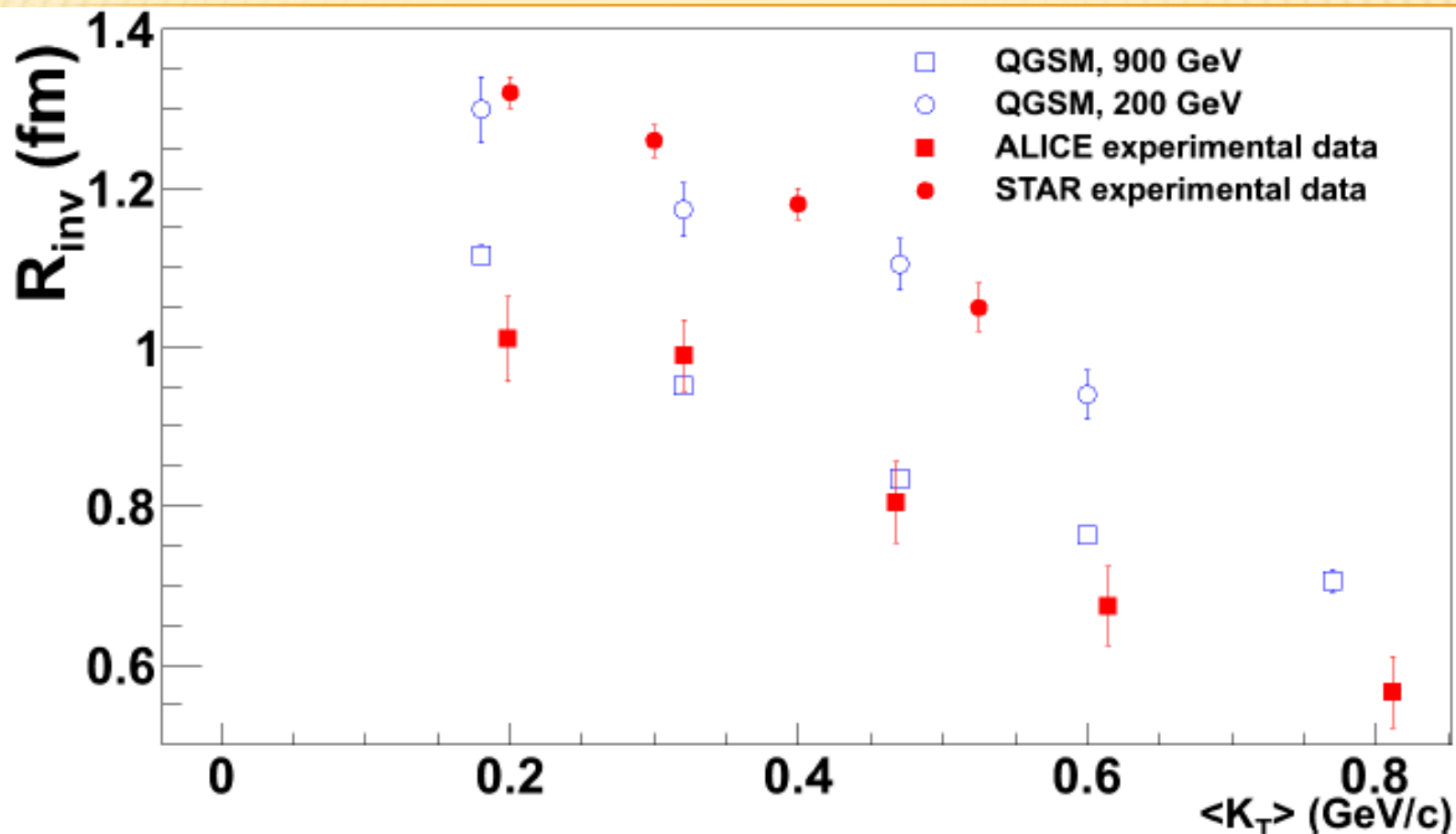
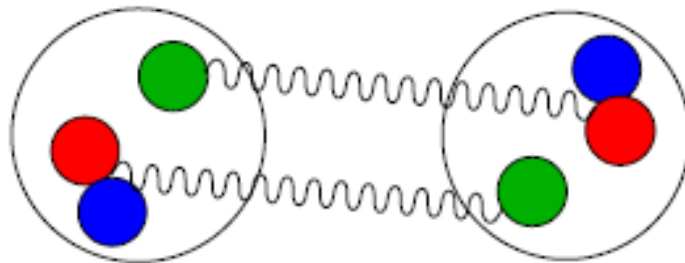


Figure 5.10: One-dimensional  $\pi^+\pi^+$  correlation radii as functions of  $K_T$  in  $pp$ -collisions at  $\sqrt{s} = 200$  GeV and  $\sqrt{s} = 900$  GeV, compared with STAR [67] and ALICE [71] experimental data. Both model results and experimental data are obtained from a fit using a flat baseline.

# QUARK-GLUON STRING MODEL

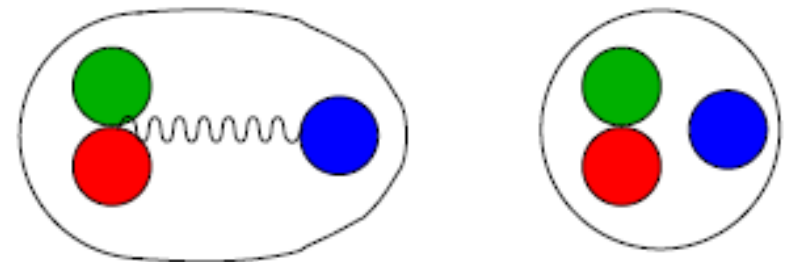
two different mechanisms:

- ▶ excitation due to exchange of pomerons (color exchange)
- ▶ transverse strings



- ▶  $n$  cut pomerons give  $2n$  strings

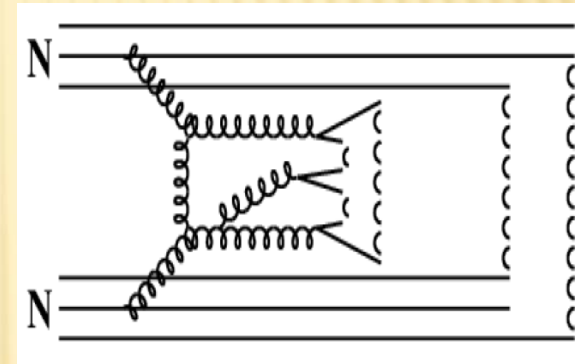
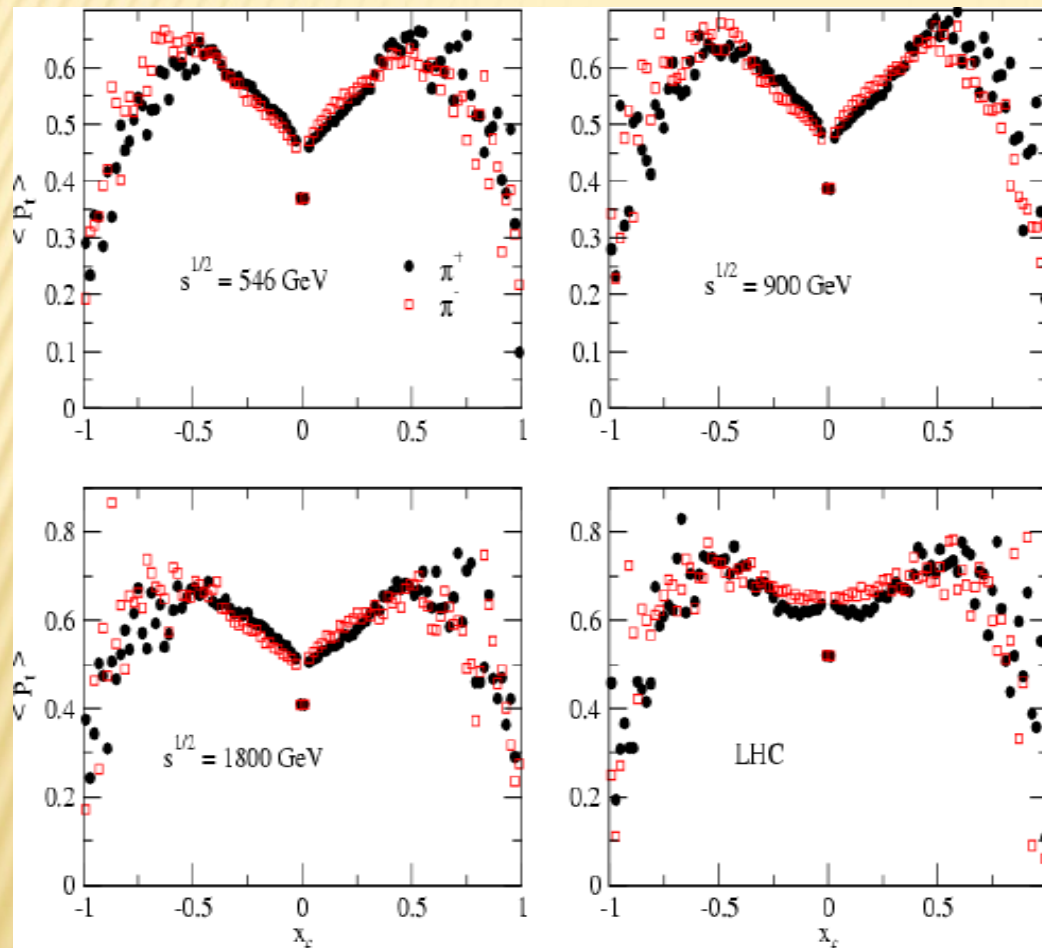
- ▶ excitation due to transfer of momentum to a single parton
- ▶ longitudinal string



- ▶ purely phenomenological process

**Excitation of color neutral strings**

# STRONG SEA-GULL EFFECT $\langle PT(XF) \rangle$



Sea-gull effect becomes more pronounced with energy

