EPOS Model and Collective Flow in (a)p-p Collisions

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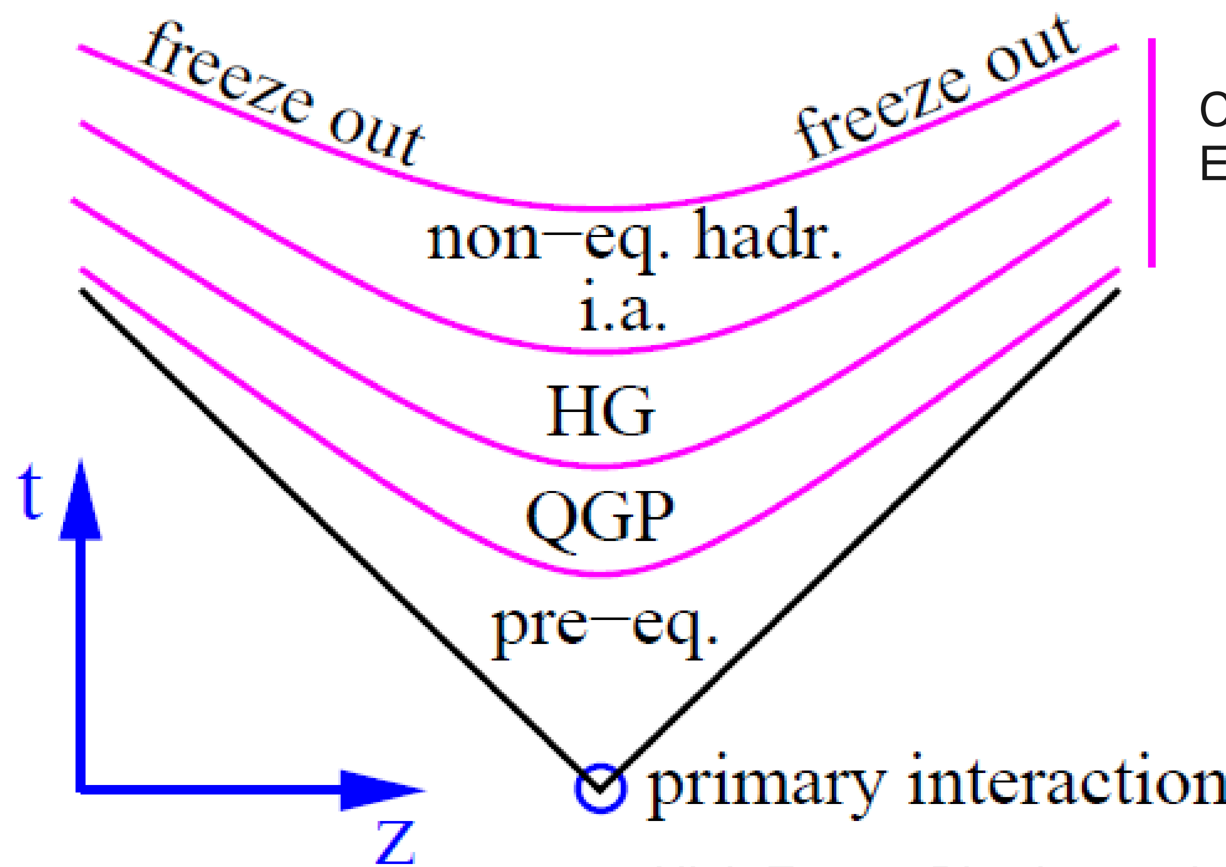
High Energy Hadronic Interactions



Collective Effects

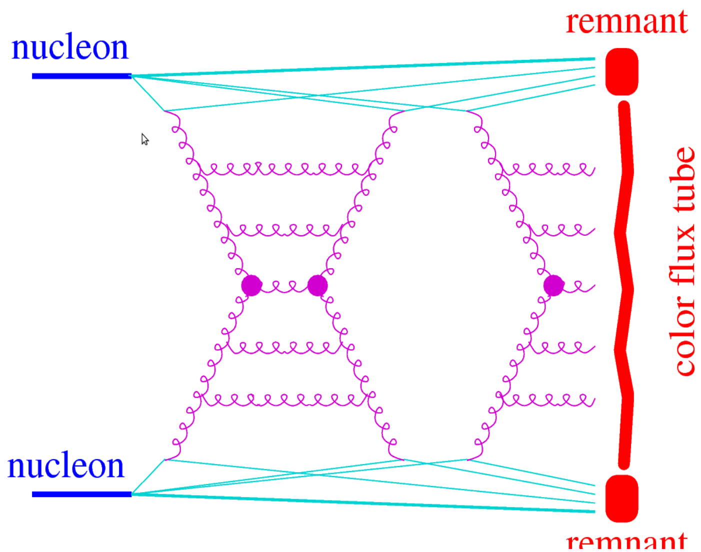
High Energy Physics models

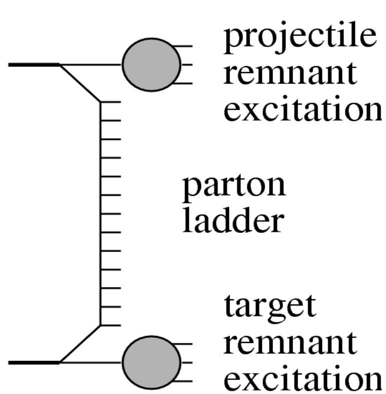
General case : valid for pp if enough particles are produced !

Outline

- **EPOS model**
  - ➜ **Introduction**
  - ➜ **Primary interaction**
    - Energy sharing
    - Parton multiple scattering
    - Outshell remnants
    - Screening, Shadowing and Strings
  - ➜ **Collective Effects**
    - Real hydrodynamical calculation
    - Simplified (effective) scheme

The EPOS Model





EPOS* is a parton model, with many binary parton-parton interactions, each one creating a parton ladder.

- Energy-sharing : for cross section calculation AND particle production
- Parton Multiple scattering
- Outshell remnants
- Screening and shadowing via unitarization and splitting
- Collective effects for dense systems

EPOS can be used for minimum bias hadronic interaction generation (h-p to A-B) from 100 GeV (lab) to 1000 TeV (cms) : used for air shower !

EPOS designed to be used for particle physics experiment analysis (SPS, RHIC, LHC) for pp or Heavy Ion

*T.Pierog, S. Porteboeuf and K. Werner

EPOS : History

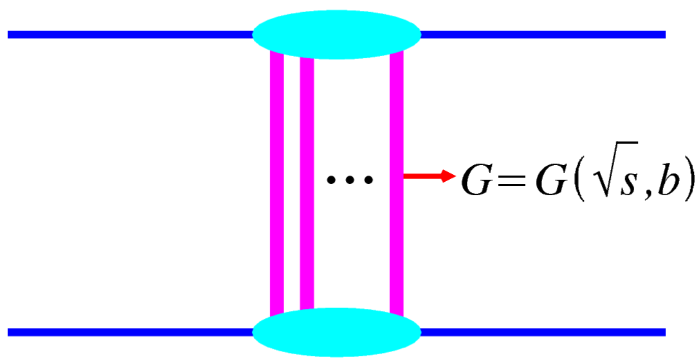
- **Evolution of models by K. Werner et al. :**
  - VENUS (93) : soft physic
  - NEXUS 2 (00): first realization of Parton-Based Gribov-Regge Theory (PBGRT) with soft, semi-hard and hard Pomerons
  - NEXUS 3.97 (03) : enhanced diagrams in PBGRT and new remnant treatment.
  - EPOS 1.6 (06) : PBGRT + remnants + Effective treatment of higher order effect and high density effect + new diffraction ...
  - EPOS 1.99 (09) : Correction of cross section and inelasticity for air showers.
  - EPOS LHC (12) : Re-tune using LHC data and correction of effective flow.
  - EPOS 2 : 2010 - ??? (still under development)
    - High mass diffraction
    - Real event by event hydro calculation (includ. pp)
    - Better parton distribution functions

EPOS : Parameters

- **Data used to constrain parameters (~100) :**
  - ➜ string fragmentation : e+e- data,
  - ➜ hard Pomeron : DIS data,
  - ➜ soft Pomeron and vertices : pp,πp,Kp, pA cross sections
  - ➜ diffraction : pp low energy diffraction and multiplicity distributions
  - ➜ excitation functions : multiplicity in pp from SPS to Tevatron,
  - ➜ string ends and remnants : NA49 data
  - ➜ collective and screening effects : RHIC and LHC

- **One set of parameters for all energies and system**
  - ➜ not designed to be tuned by users

Gribov-Regge Based Models



Multiple elementary scattering

- **Using Gribov-Regge** (GR) : cross section from optical theorem :

$$\sigma_{ine}(\sqrt{s})=\int d^2b(1-\exp(-G(\sqrt{s},b)))$$

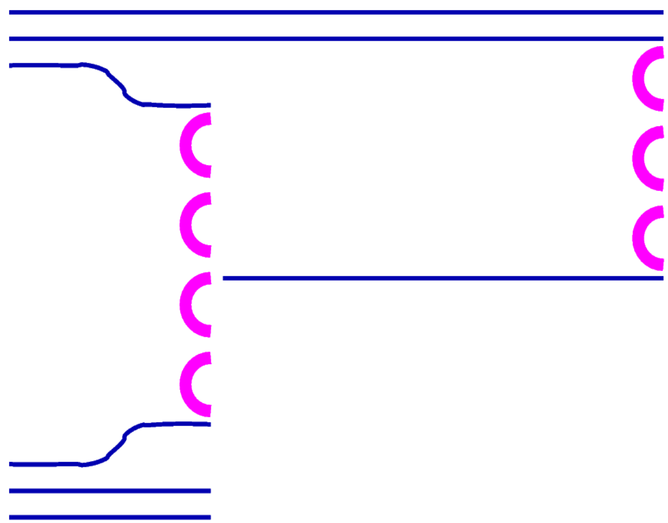
where G(energy,impact parameter) = elementary interaction

- Probability for the number of elementary interactions (Pomeron) per event

Successful description of hadronic cross-sections
But
Energy conservation NOT considered between the elementary interactions G

No possibility to deduce directly particle production !

Particle Production in GR based Models



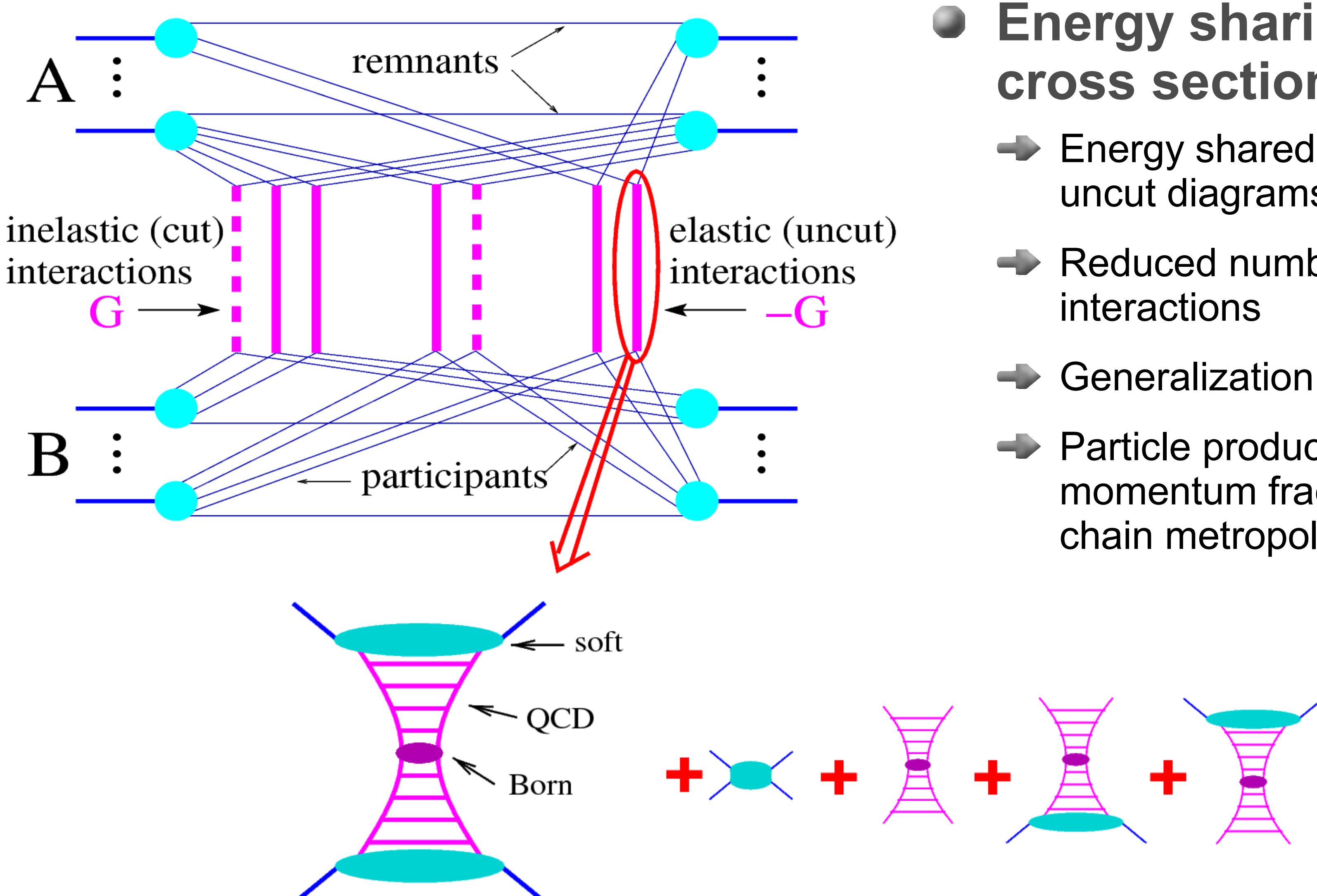
- **Number of strings from GR**
  - ➔ No energy conservation
- **Energy sharing**
  - ➔ Not consistent with cross-section
- **String fragmentation**
  - ➔ Proper energy conservation

Link between cross-section and particle production not consistent !

Parton-Based Gribov-Regge Therory* (PBGRT) developed to solve the problem :
same formalisme for cross section and particle production
used first in NEXUS and now in EPOS

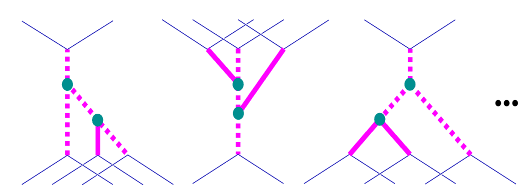
* H.J. Drescher et al., Phys.Rep. 350:93-289 (2001)

Parton-Based Gribov-Regge Theory



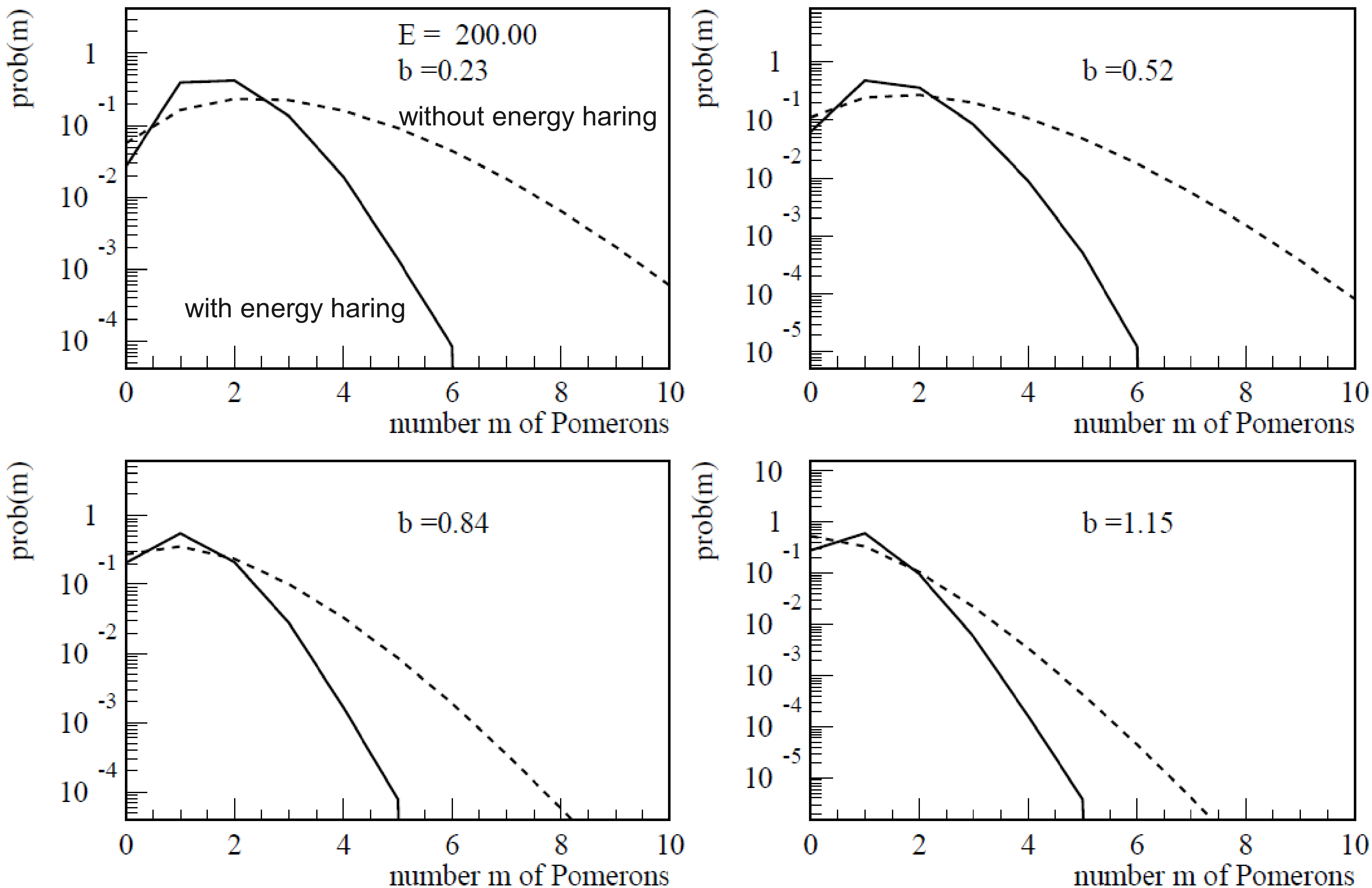
- **Energy sharing at the cross section level**
  - Energy shared between cut and uncut diagrams (Pomeron)
  - Reduced number of elementary interactions
  - Generalization to (h)A-B
  - Particle production from momentum fraction matrix (Markov chain metropolis)

Non-linear effect (screening) absorbed in modified vertex functions



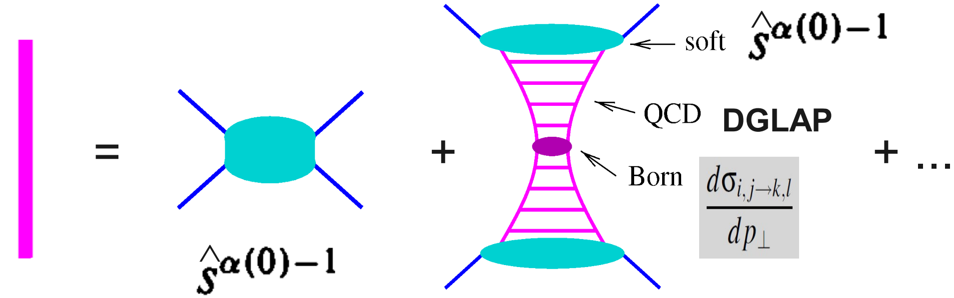
Number of cut Pomerons

Fluctuations reduced by energy sharing (mean can be changed by parameters)

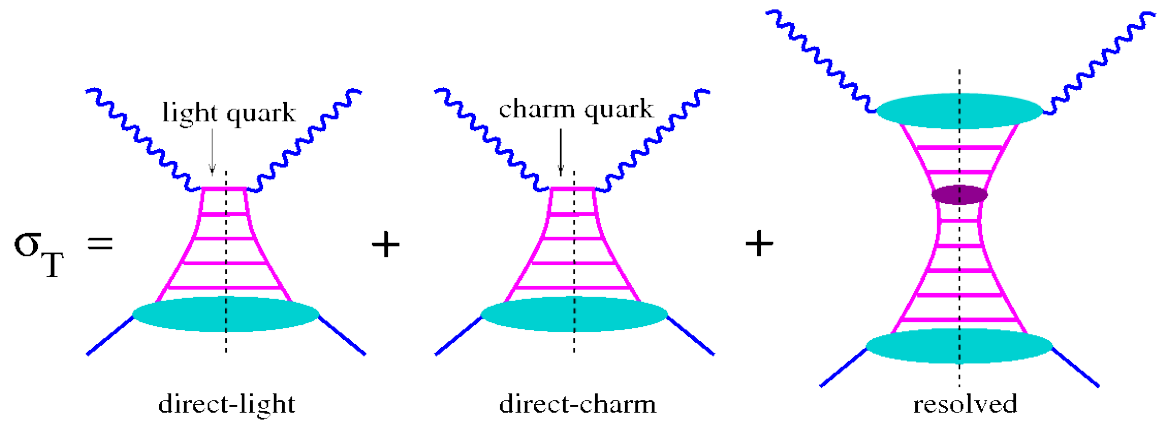


EPOS : Pomeron definition

Semi-hard Pomeron :

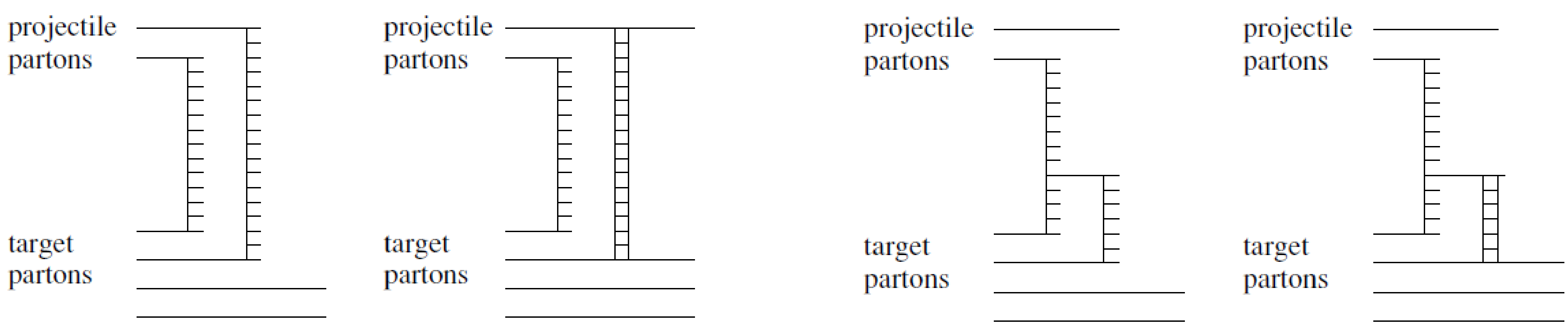


Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)



- Theory based Pomeron definion
  - pQCD based so large increase at small x (no saturation)
  - produce too high cross section
  - corrections needed using enhanced diagrams (triple Pomeron vertex)
    - effective coupling vertex

EPOS – high parton density effects

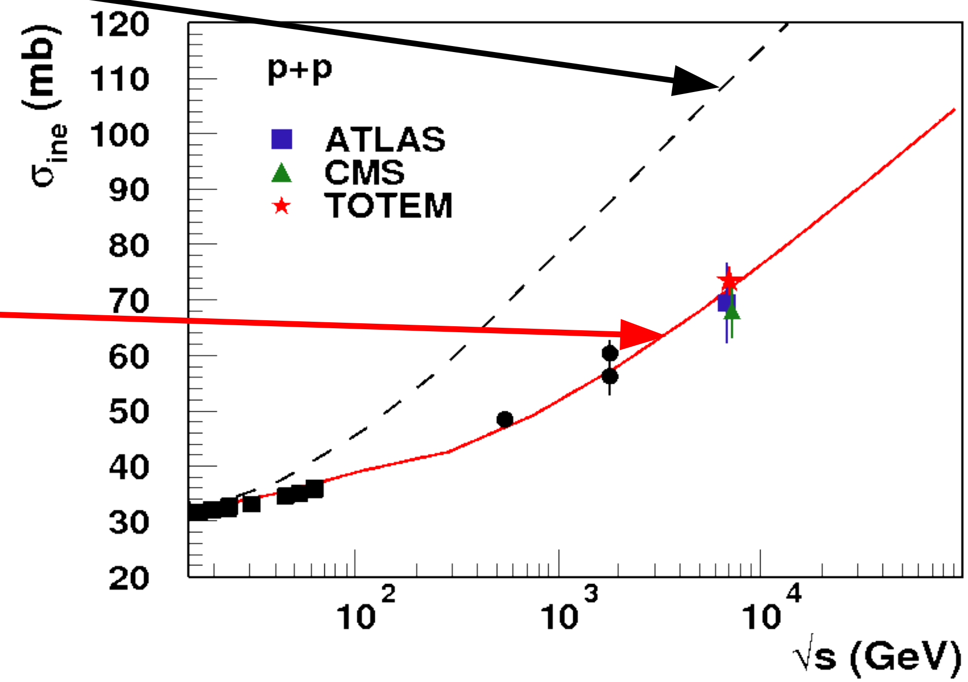


No effective coupling

$$A_{\mathrm{pom}} \sim (x_1 x_2)^{\beta}$$

With effective coupling

$$A_{\mathrm{pom}} \sim x_1^{\beta} x_2^{\beta-\varepsilon}$$



Parametrization

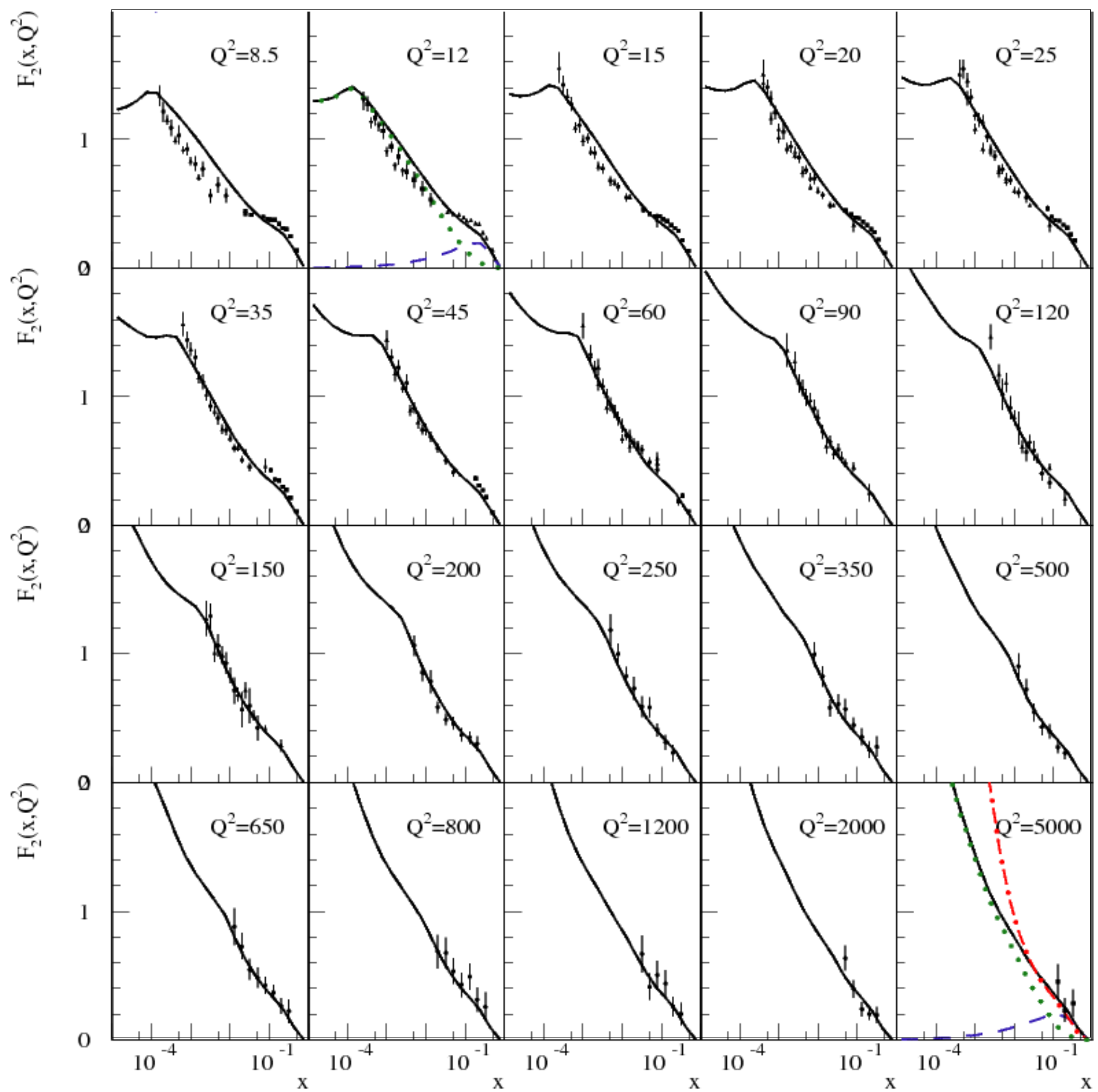
$$\varepsilon_S = a_S\, \beta_S\, Z(\mathrm{s,b})$$

$$\varepsilon_H = a_H\, \beta_H\, Z(\mathrm{s,b})$$

Parton Distribution Function

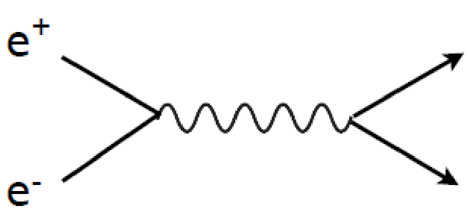
- **PDF based and DGLAP and initial soft parametrization with corrections**

Preliminary from EPOS 2

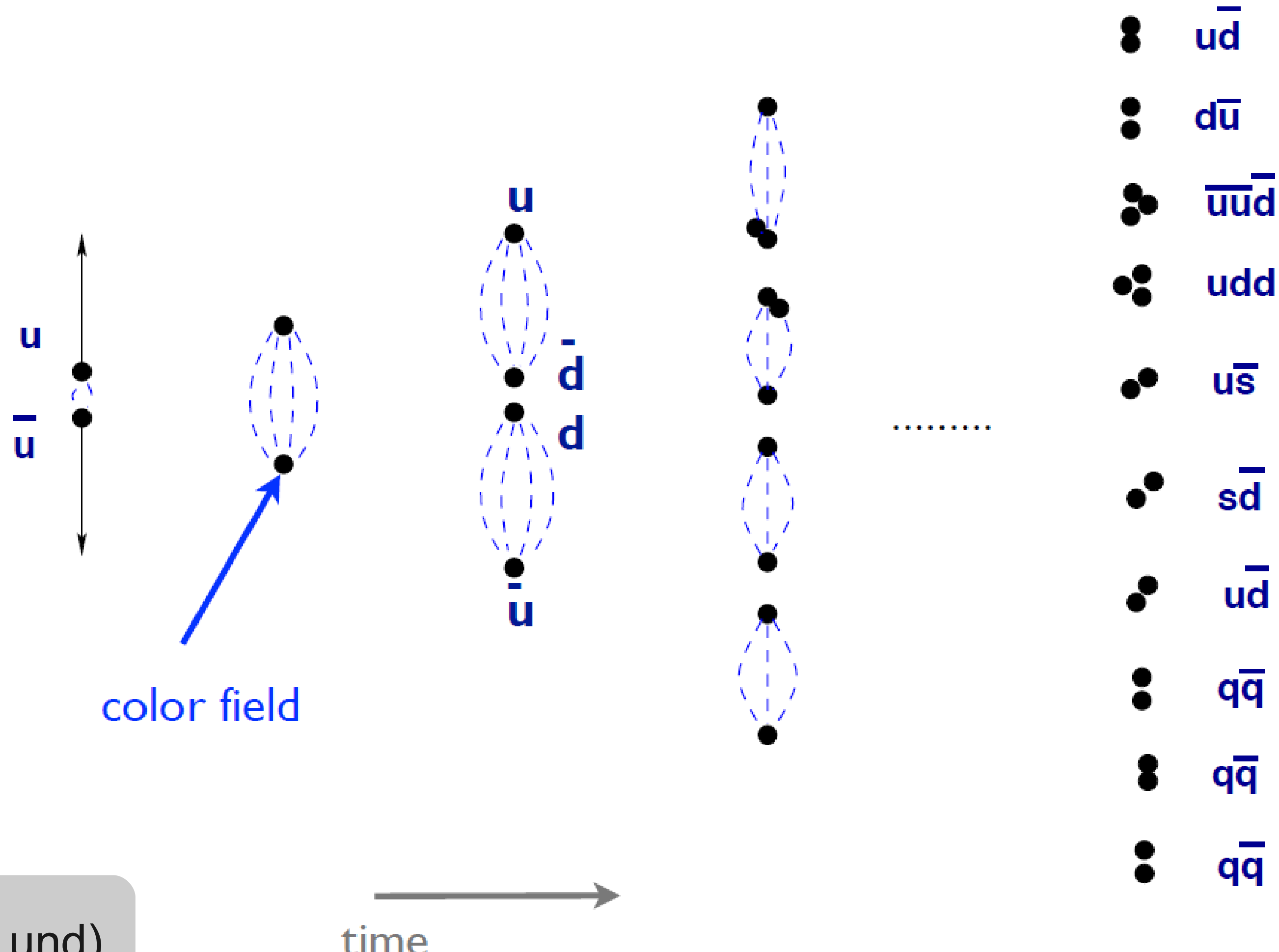


Simplest case: e^+e^- annihilation into quarks

Annihilation at high energy



Quarks together are color-neutral system

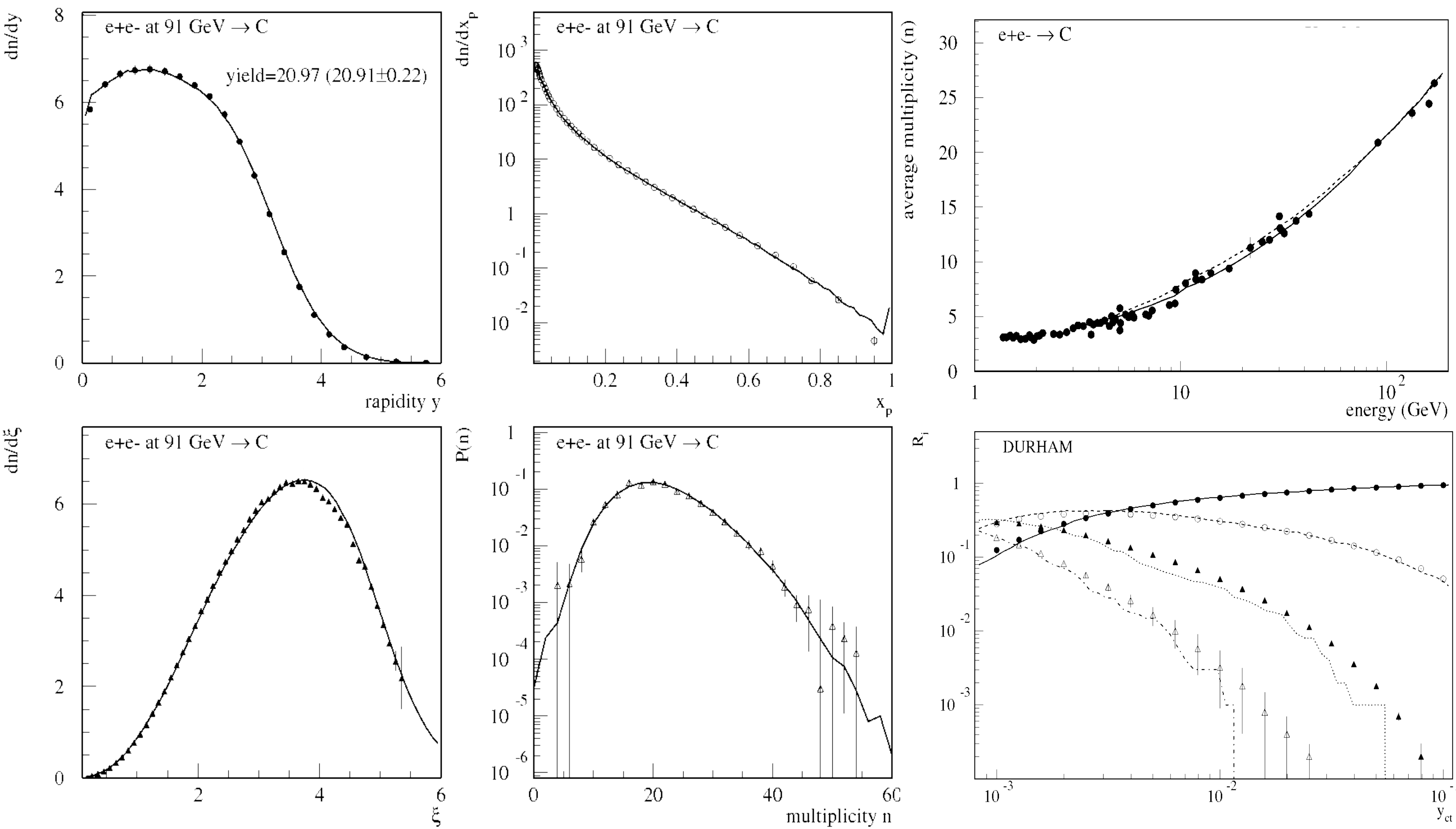


Area law used in EPOS (not Lund)

Chain of hadrons

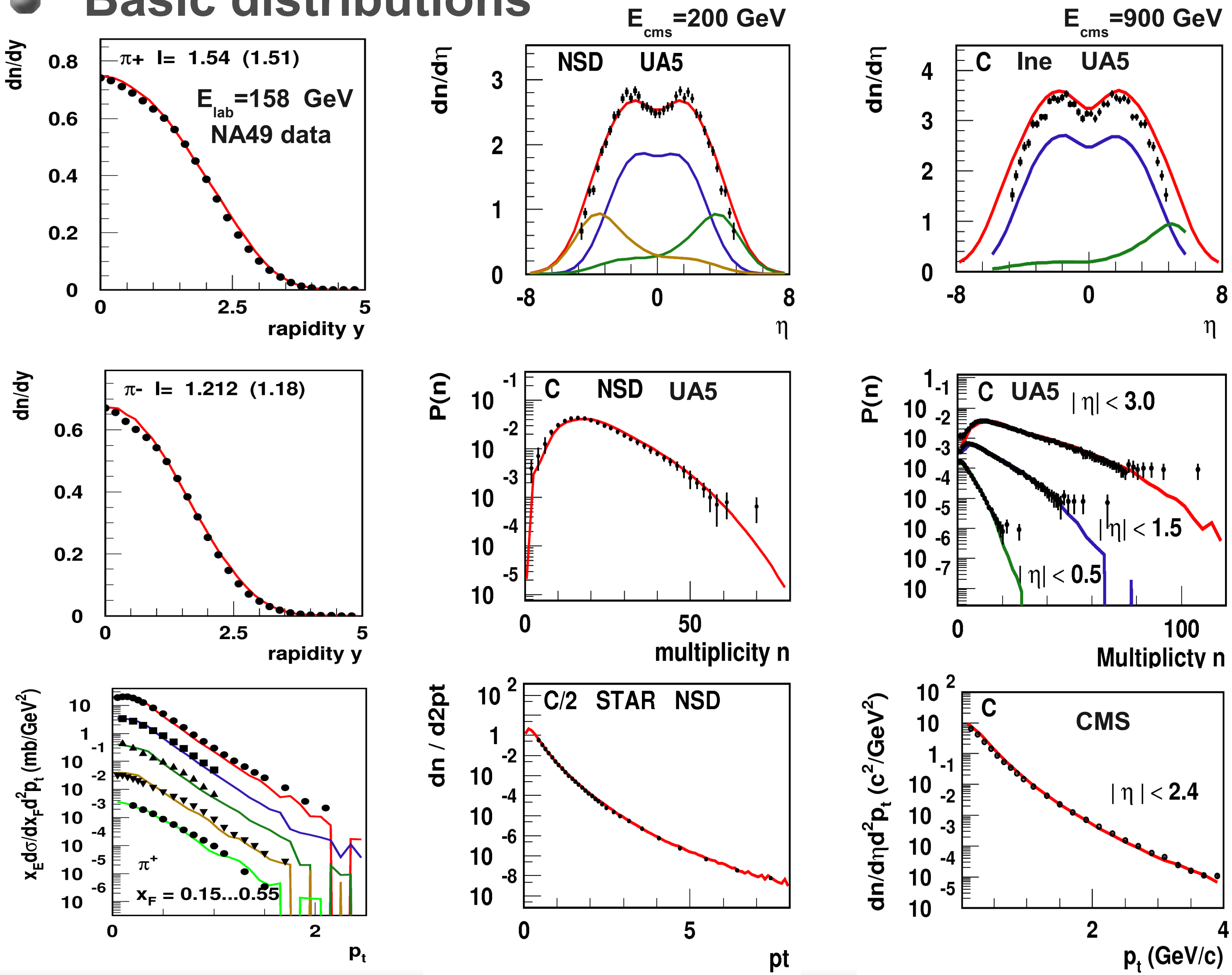
String fragmentation

Test at LEP


e+e- at 91 GeV → C
yield=20.97 (20.91±0.22)
dn/dy
rapidity y
dn/dx_p
x_p
e+e- → C
average multiplicity ⟨n⟩
energy (GeV)
dn/dξ
ξ
P(n)
multiplicity n
DURHAM
R_i
y_ct

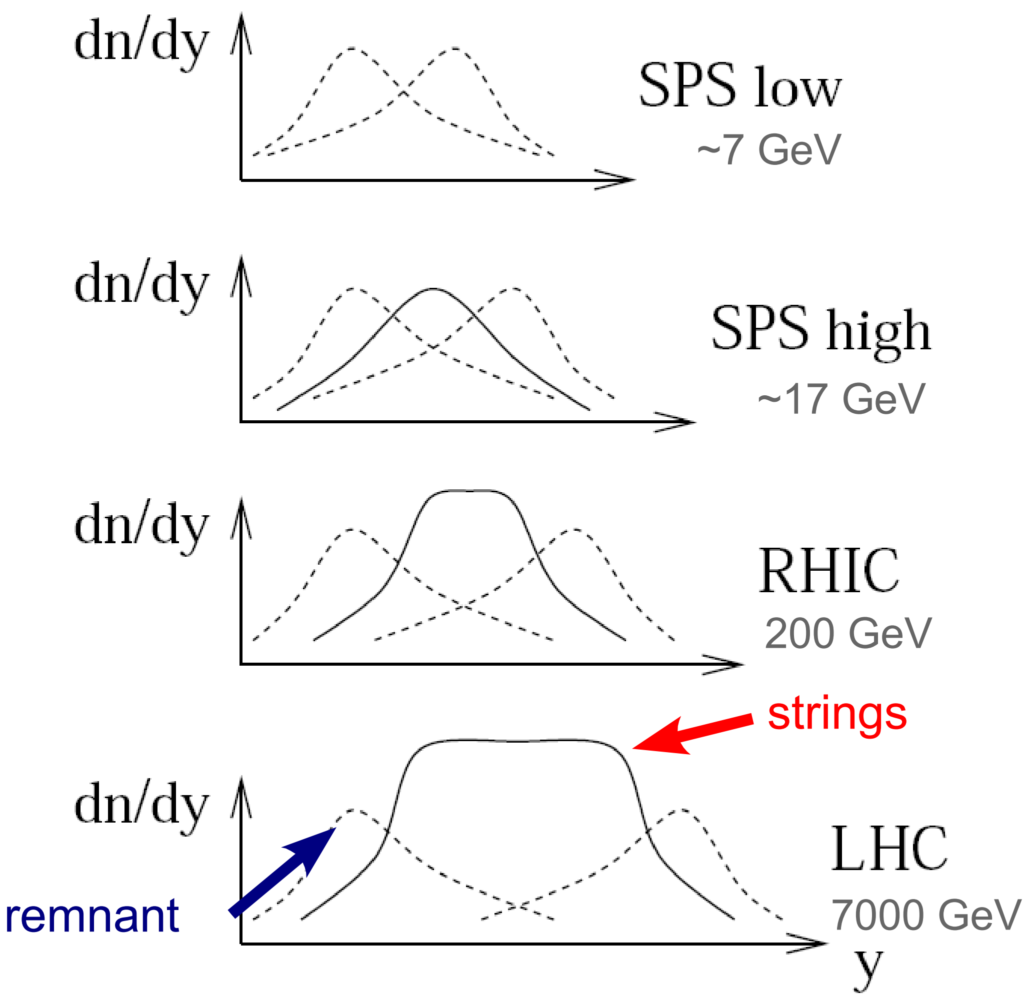
Basic Distributions

- ## Basic distributions



Remnants

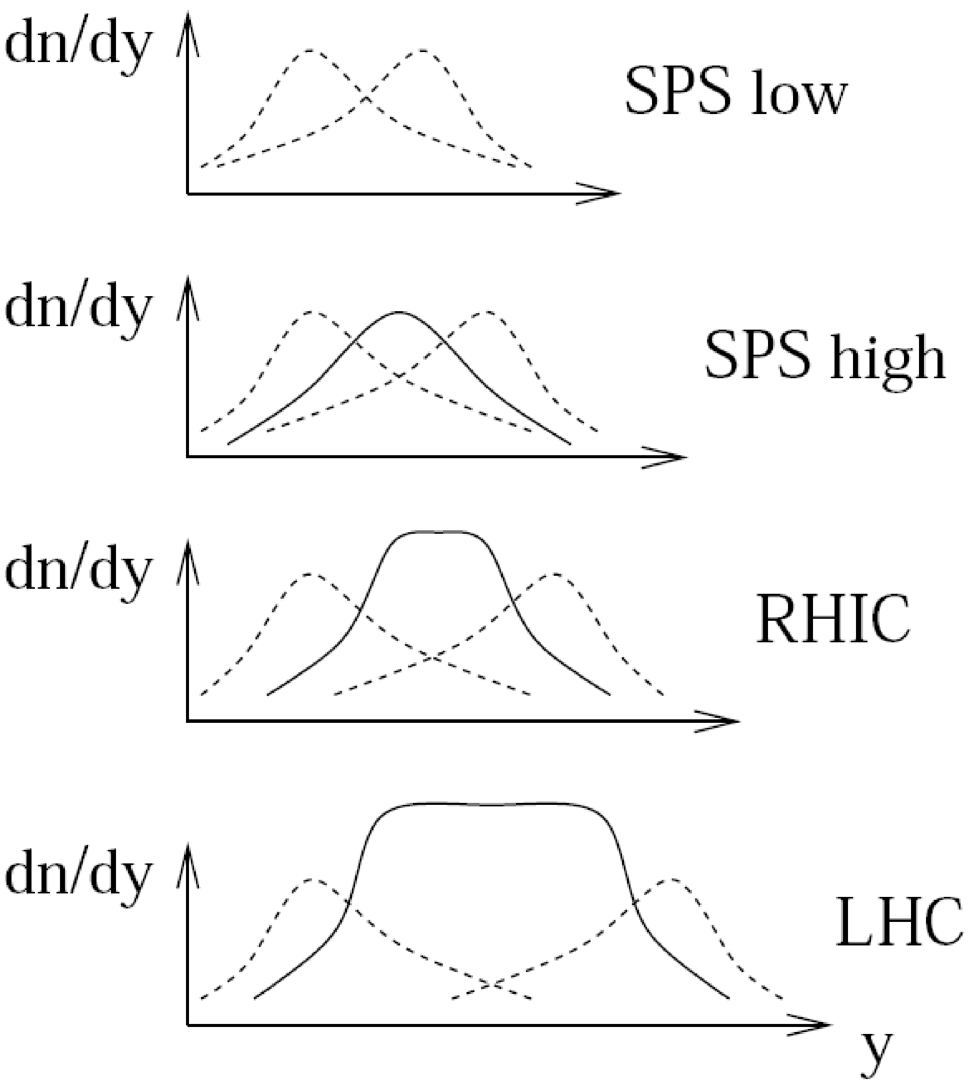
Forward particles mainly from projectile remnant



- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

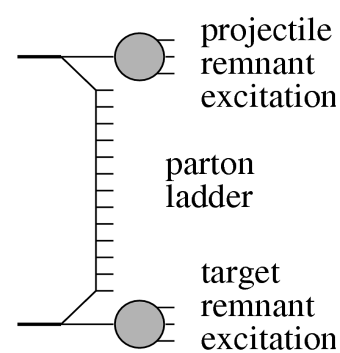
Different contributions of particle production at different energies or rapidities

Remnants



Free remnants in EPOS:

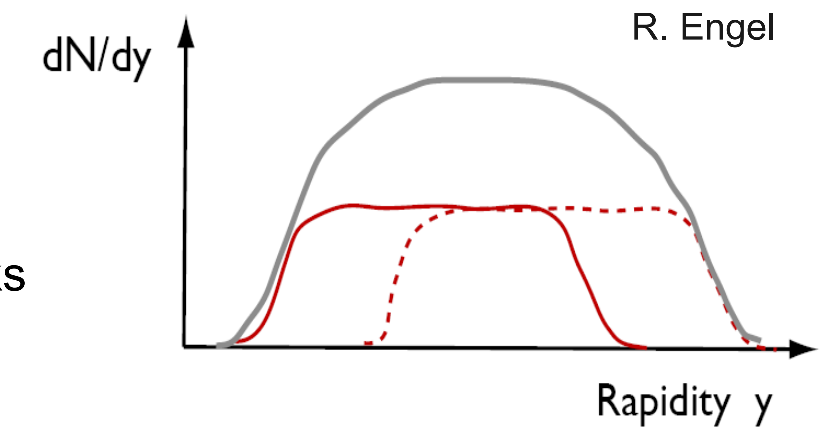
- from both diffractive or inelastic scattering
- excited state with $P(M) \sim 1/(M^2)^\alpha$
- very large contribution at low energy
- forward region at high energy
- depending on quark content and mass (excitation):
  - resonance
  - string
  - droplet (if #q>3)
  - string+droplet

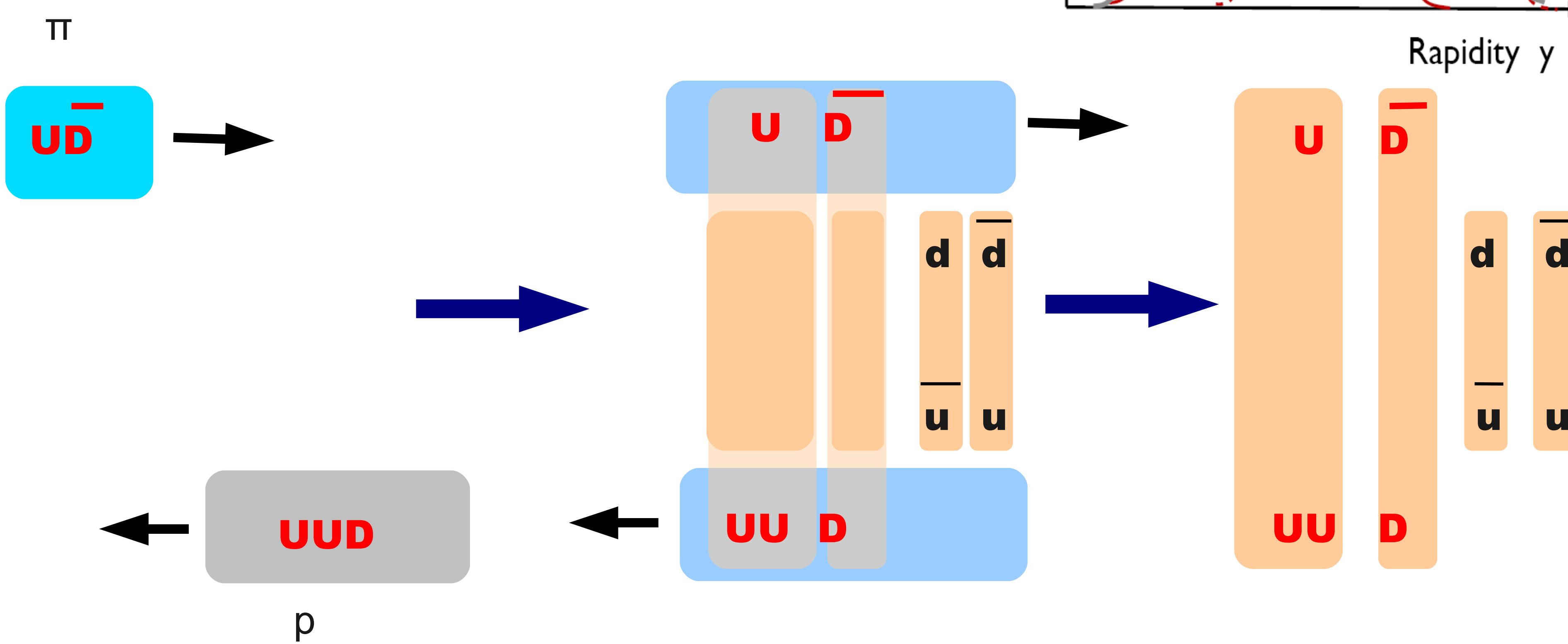


Remnants in PYTHIA

In PYTHIA : valence quarks attached to main string

- limited quark exchange
- very hard baryon and meson spectra
- string fragmentation
  - forward particle limited by valence quarks

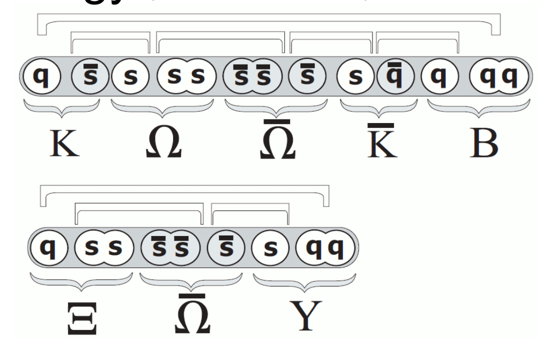




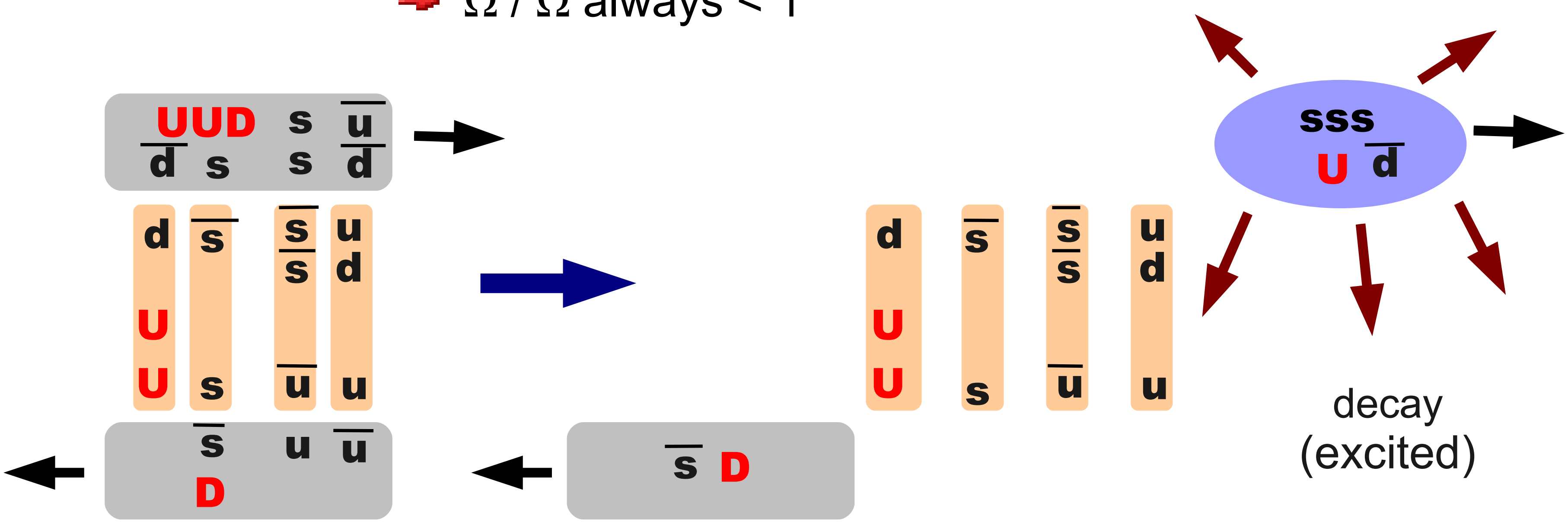
Baryons and Remnants

Parton ladder string ends :

- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :
    - $\bar{\Omega}$ / Ω always > 1
    - But data < 1 (Na49)

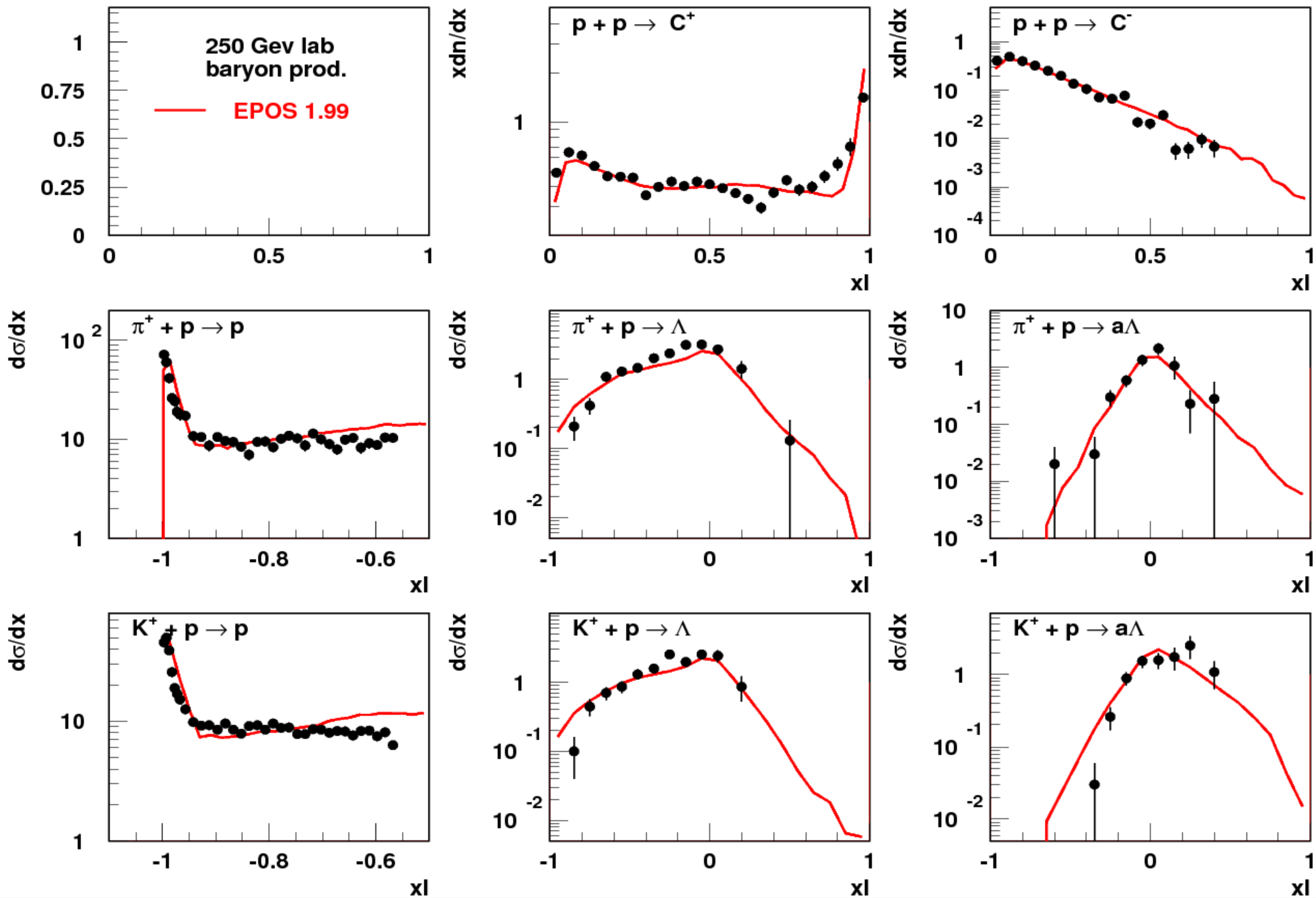


- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - $\bar{\Omega}$ / Ω always < 1

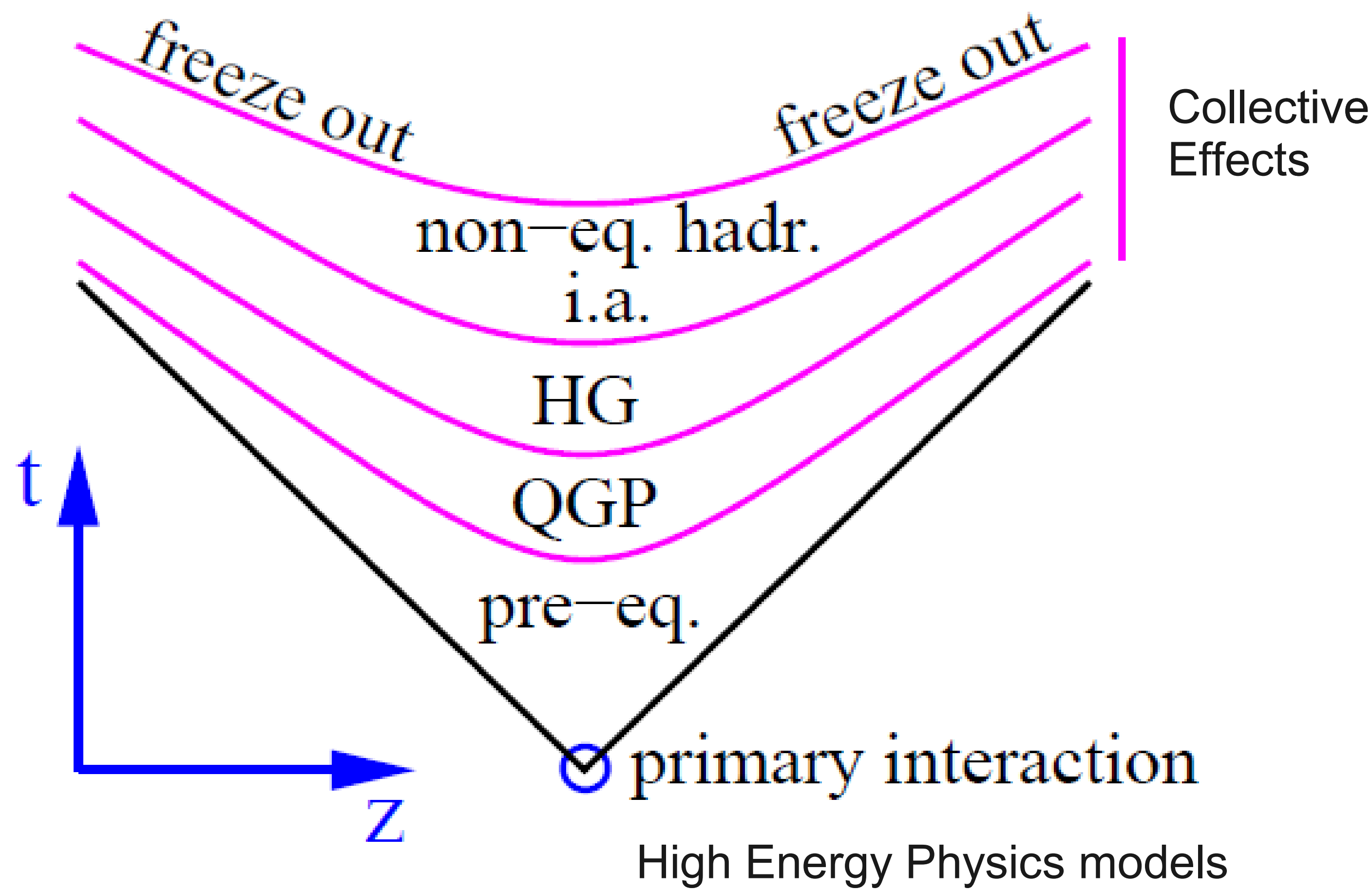


Baryon Production

- Baryon production for fixed target exp.



High Energy Hadronic Interactions



References : arXiv:1004.0805, arXiv:1010.0400, arXiv:1011.0375

Collective effects

- One decade of RHIC experiments (heavy ion, pp, and dAu scattering,up to 200 GeV)

heavy ion collisions produce matter which expands as an almost ideal fluid

- mainly because azimuthal anisotropies can be explained on the basis of ideal hydrodynamics (mass splitting etc)

LHC pp results: first signs for collective behavior as well ...

Approach (1)

- **pp@LHC treated as Heavy Ion:**
  - Multiple scattering approach EPOS (marriage of pQCD and Gribov-Regge) :
    - initial condition for a hydrodynamic evolution if the energy density is high enough
  - event-by-event procedure
    - taking into the account the irregular space structure of single events :
      - ridge structures in two-particle correlations
  - core-corona separation :
    - only a part of the matter thermalizes;
  - 3+1 D hydro evolution
    - conservation of baryon number, strangeness, and electric charge

Approach (2)

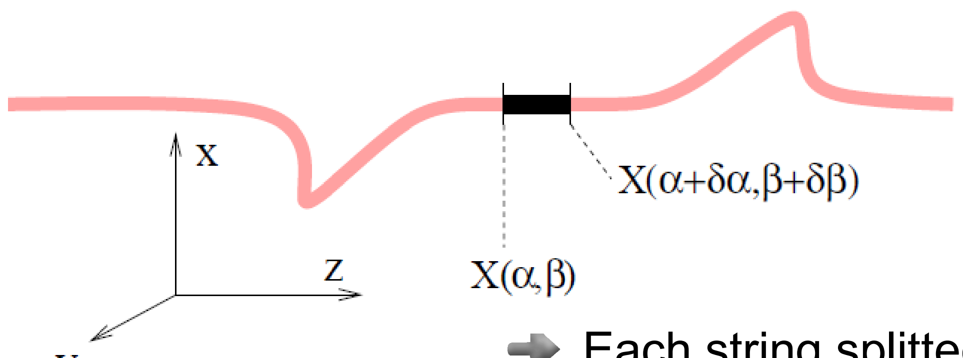
- **pp@LHC treated as Heavy Ion:**
  - parton-hadron transition
    - realistic equation-of-state, compatible with lattice gauge results
    - cross-over transition from the hadronic to the plasma phase
  - hadronization,
    - Cooper-Frye, using complete hadron table
    - at an early stage (166 MeV, in the transition region)
    - with subsequent hadronic cascade procedure (UrQMD)

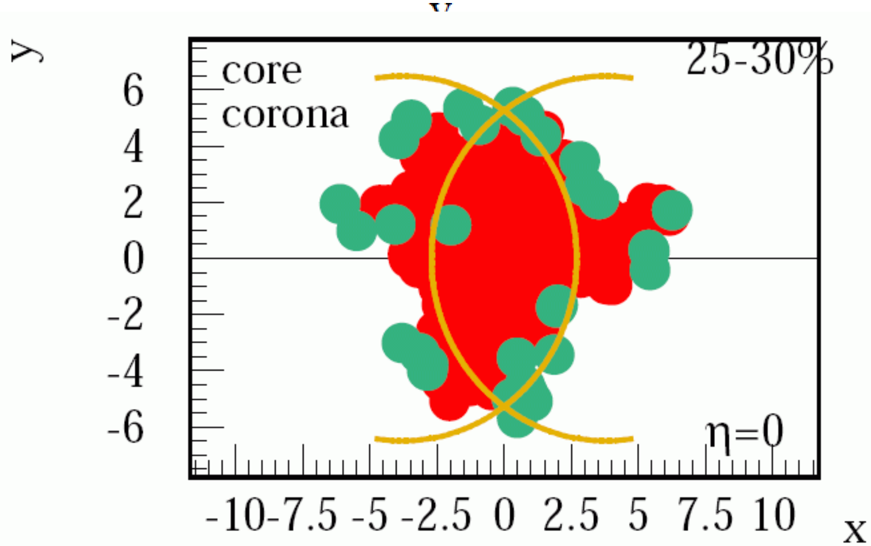
- **details see:**
  - arXiv:1004.0805, arXiv:1010.0400, arXiv:1011.0375 (ridge in pp)

    arXiv:1203.5704 (jet-bulk interaction)

High Density Core Formation

- **Heavy ion collisions or very high energy proton-proton scattering:**
  - the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently : **core**





- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
- If low density (corona)
  - segments remain hadrons

Energy Density

- **Initial conditions at proper time $\tau=\tau_0$**
  - Energy tensor :

$$T^{\mu\nu}(x) = \sum_i \frac{\delta p_i^\mu \delta p_i^\nu}{\delta p_i^0} g(x - x_i), \quad \delta p = \left\{ \frac{\partial X(\alpha,\beta)}{\partial \beta} \delta\alpha + \frac{\partial X(\alpha,\beta)}{\partial \alpha} \delta\beta \right\}$$

  - Flavor flow :

$$N_q^\mu(x) = \sum_i \frac{\delta p_i^\mu}{\delta p_i^0} q_i \, g(x - x_i), \quad q \in \{u, d, s\}$$

- **Evolution according to the equations of ideal hydrodynamics:**

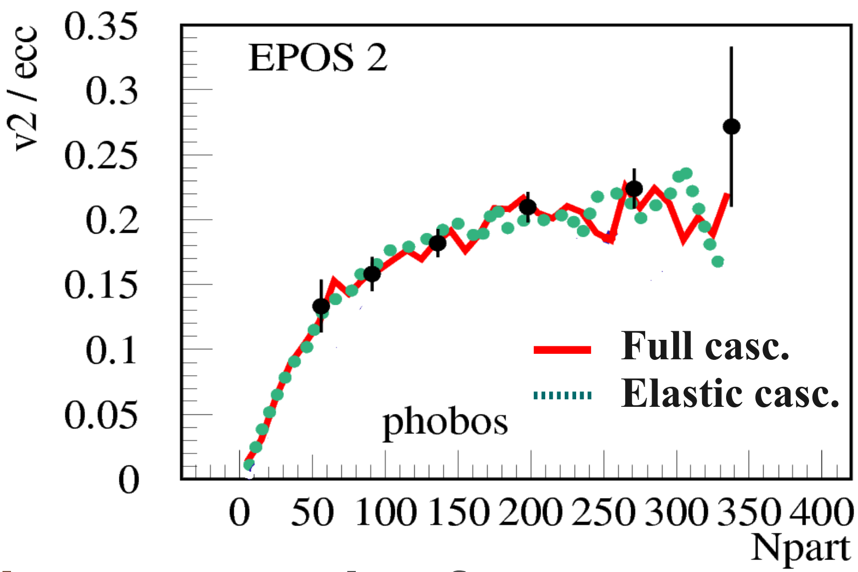
$$\partial_\mu T^{\mu\nu} = 0, \quad \text{using } T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p\, g^{\mu\nu}$$

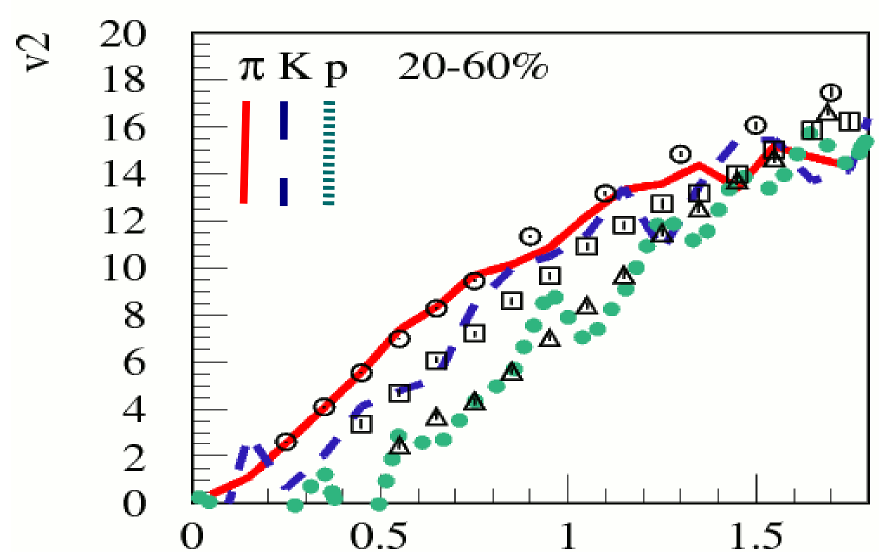
$$\partial N_k^\mu = 0, \quad N_k^\mu = n_k u^\mu,$$

with $k = B, S, Q$ referring to respectively baryon number, strangeness, and electric charge.

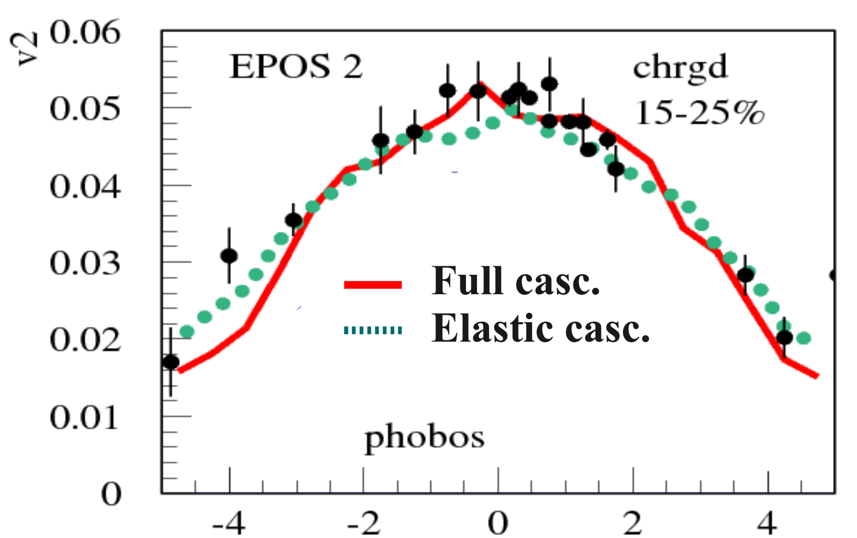
Check with Heavy Ions : AuAu@RHIC

➡ Early freeze-out (166MeV) + hadr. cascade





Important role of core-corona effect (K. Werner et al. J.Phys.G36:064030,2009)

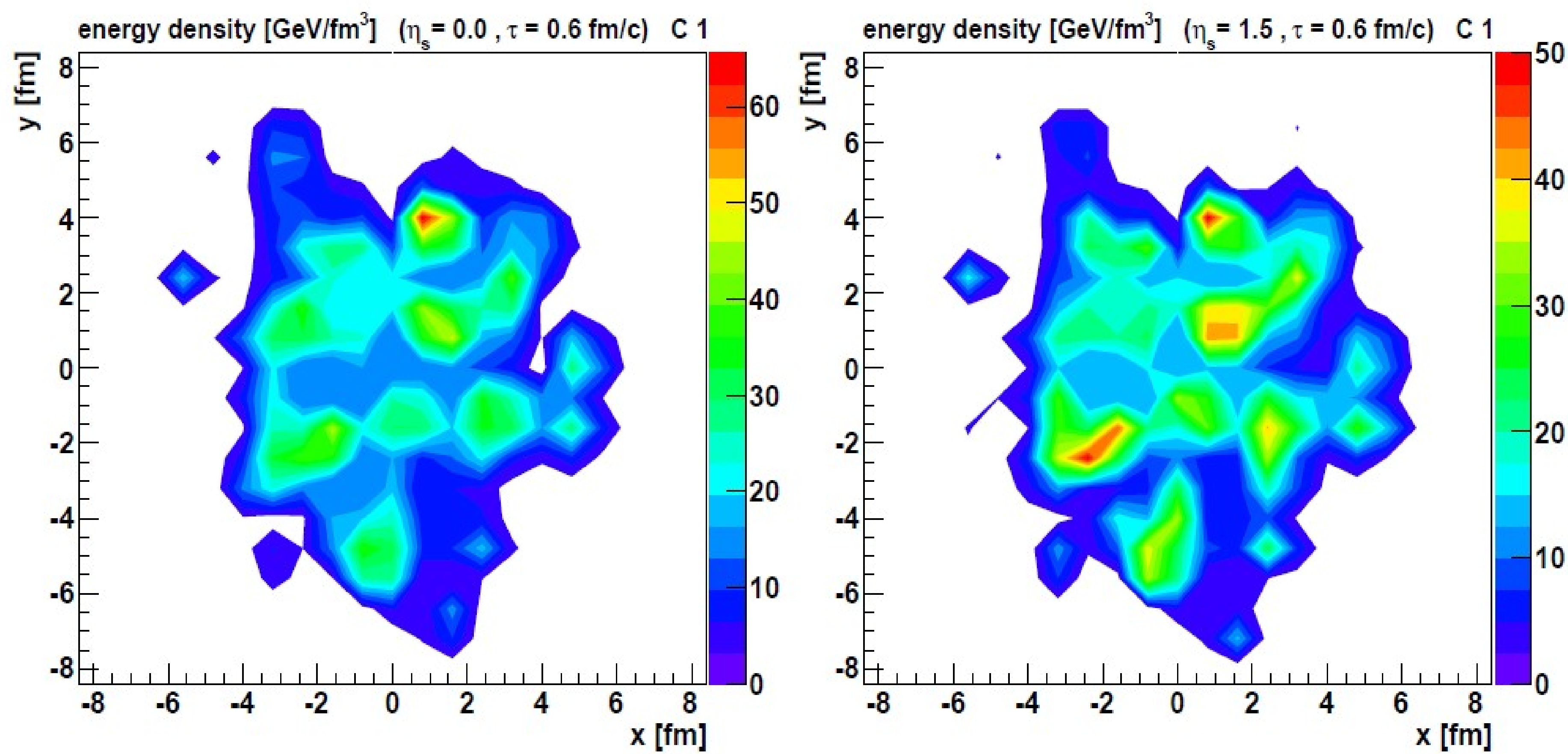


- **After checking successfully hundreds of particle spectra in AuAu**

➡ Event-by-event analysis

Event-by-Event Energy Density : AuAu

- Bumpy structure of energy density in transverse plane, but translational invariance
  - pseudorapidity extension of flux tubes



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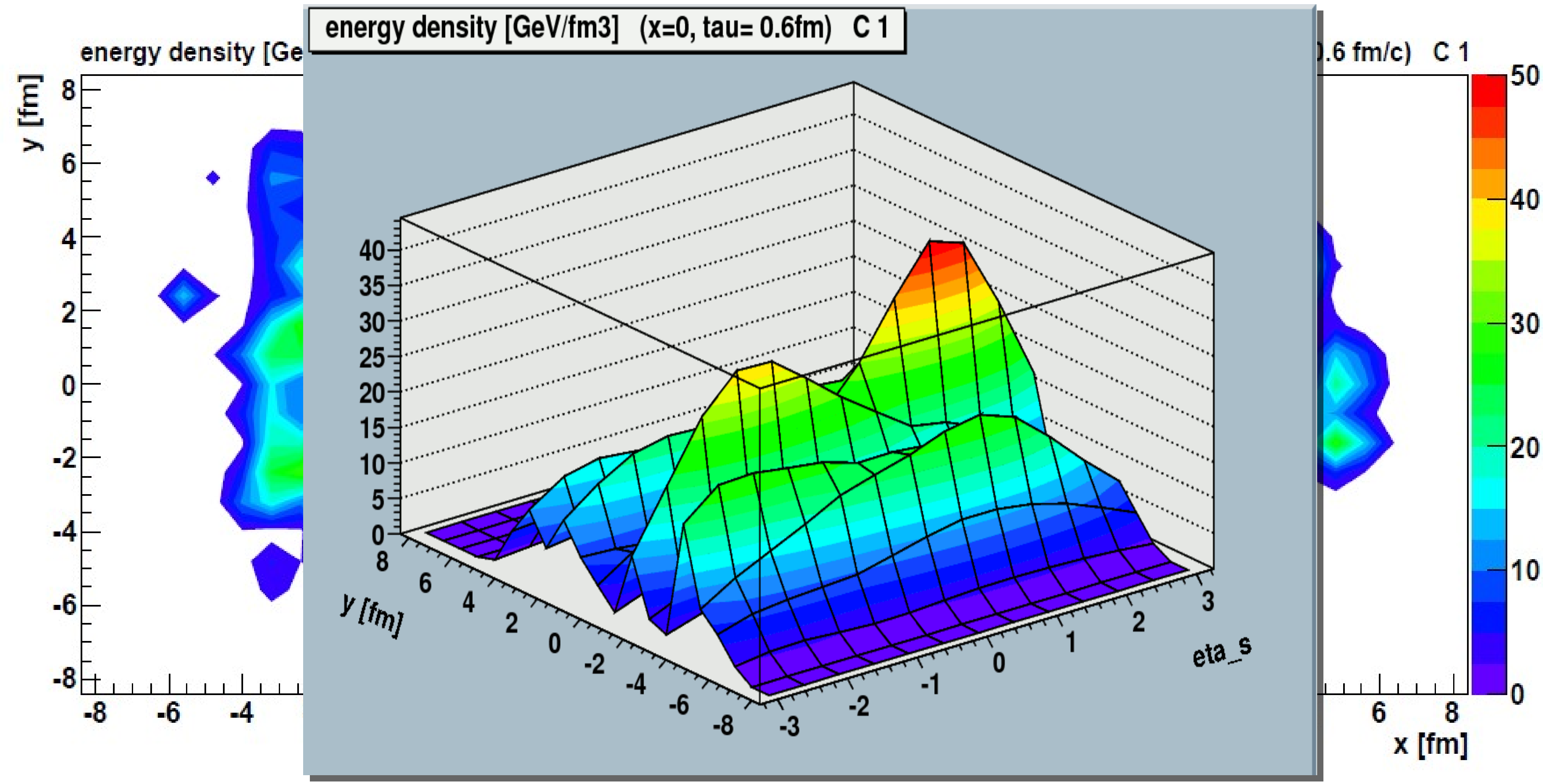
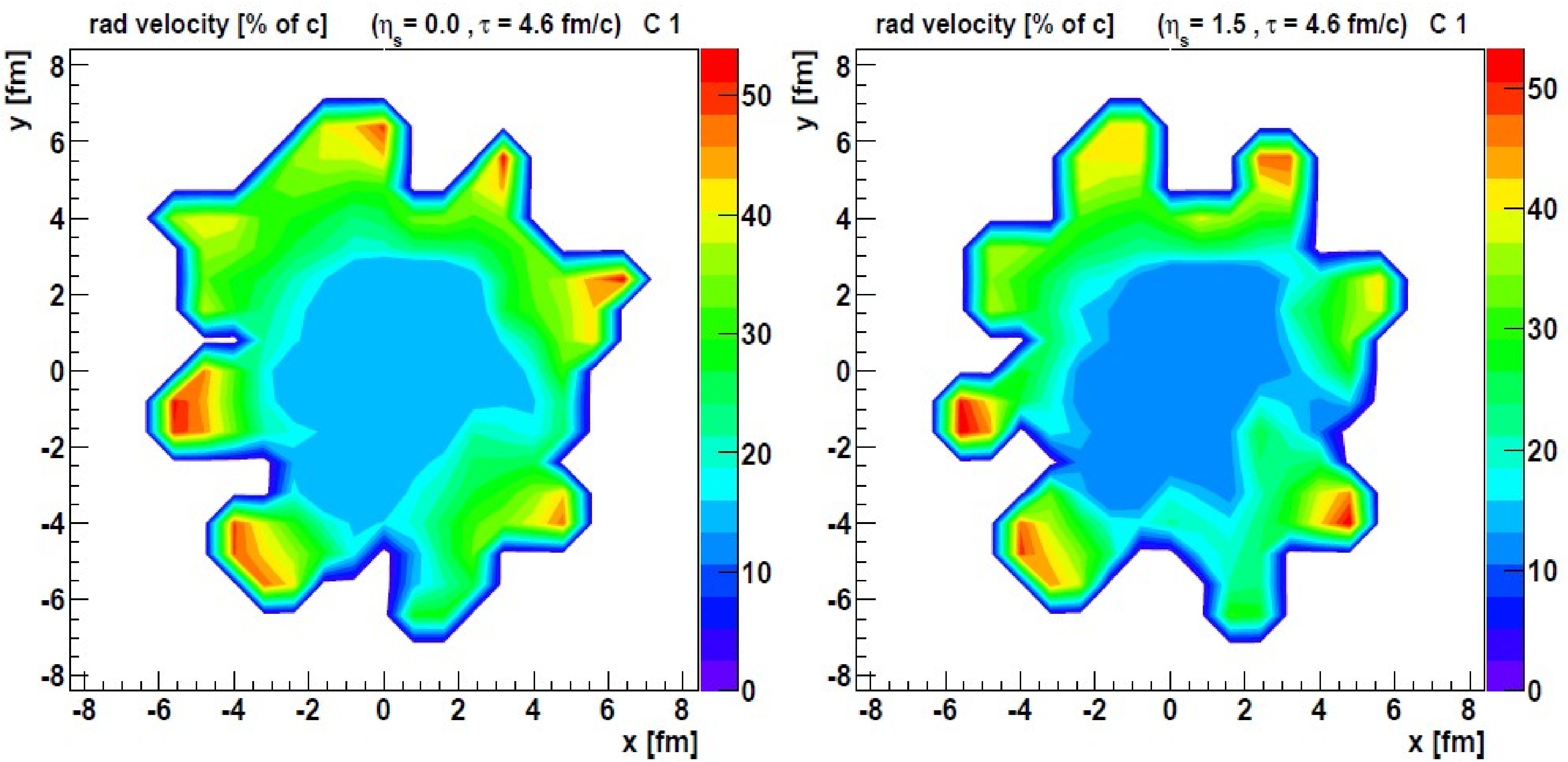


Event-by-Event Radial Flow : AuAu

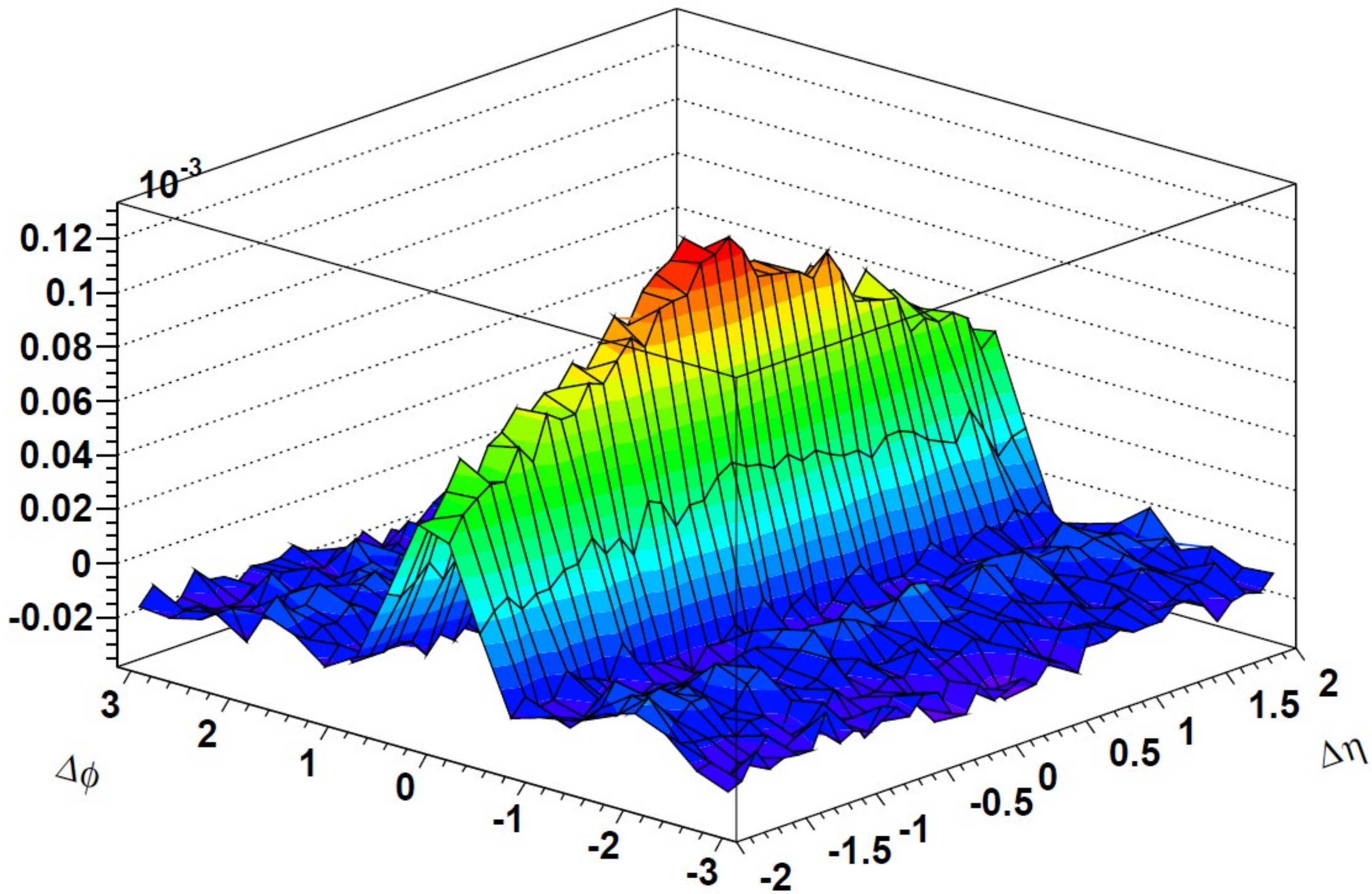
- **Leads to translational invariance of transverse flows**



➡ give the same collective push to particles produced at different values of η_s at the same azimuthal angle

AuAu : Di-hadron correlation

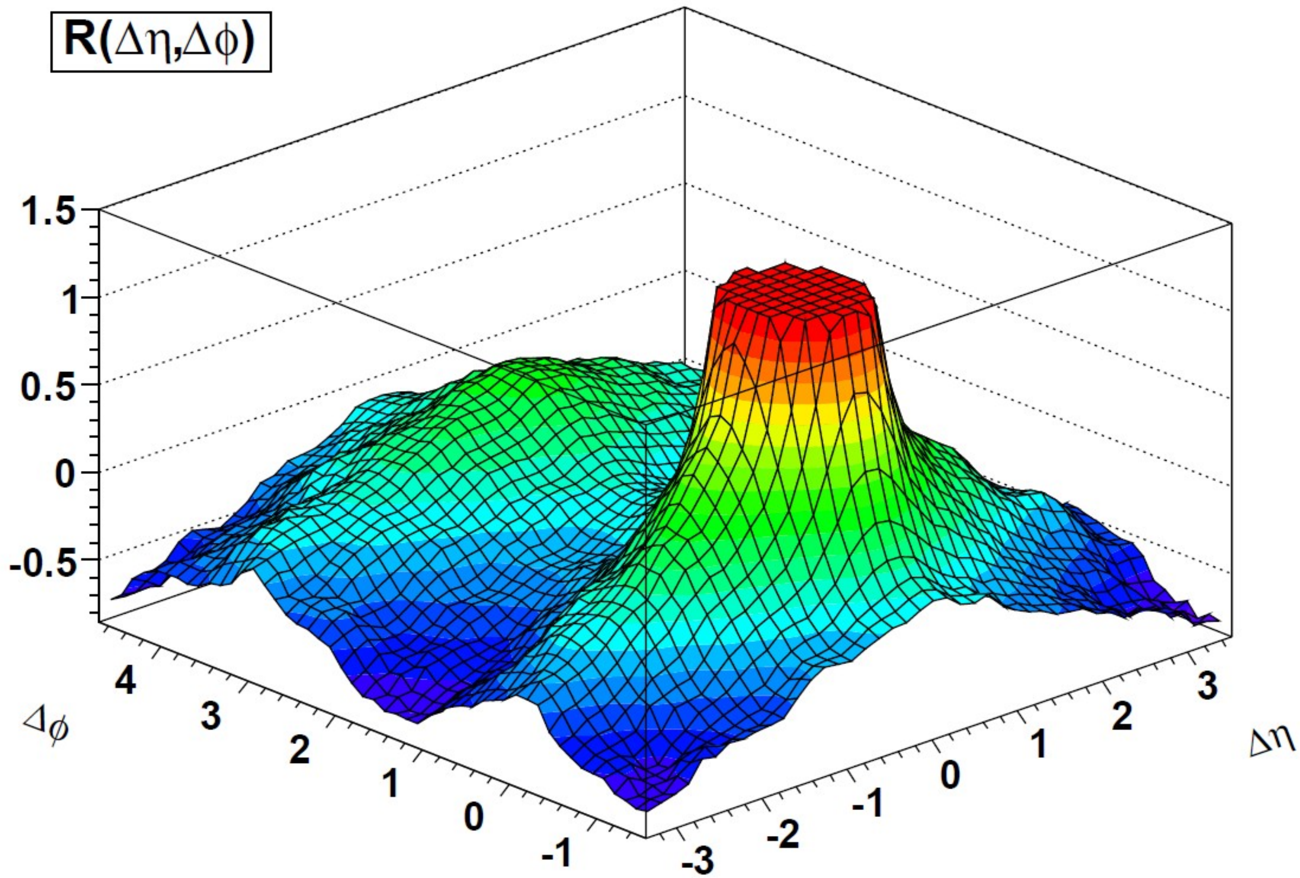
➜ ridge-structure in the dihadron correlation dN/dΔηdΔφ for free



AuAu 0-10%, $3 < p_t^{\mathrm{trig}} < 4\,\mathrm{GeV/c}$ $2 < p_t^{\mathrm{assoc}} < p_t^{\mathrm{trig}}$

pp@7 TeV : Di-hadron correlation

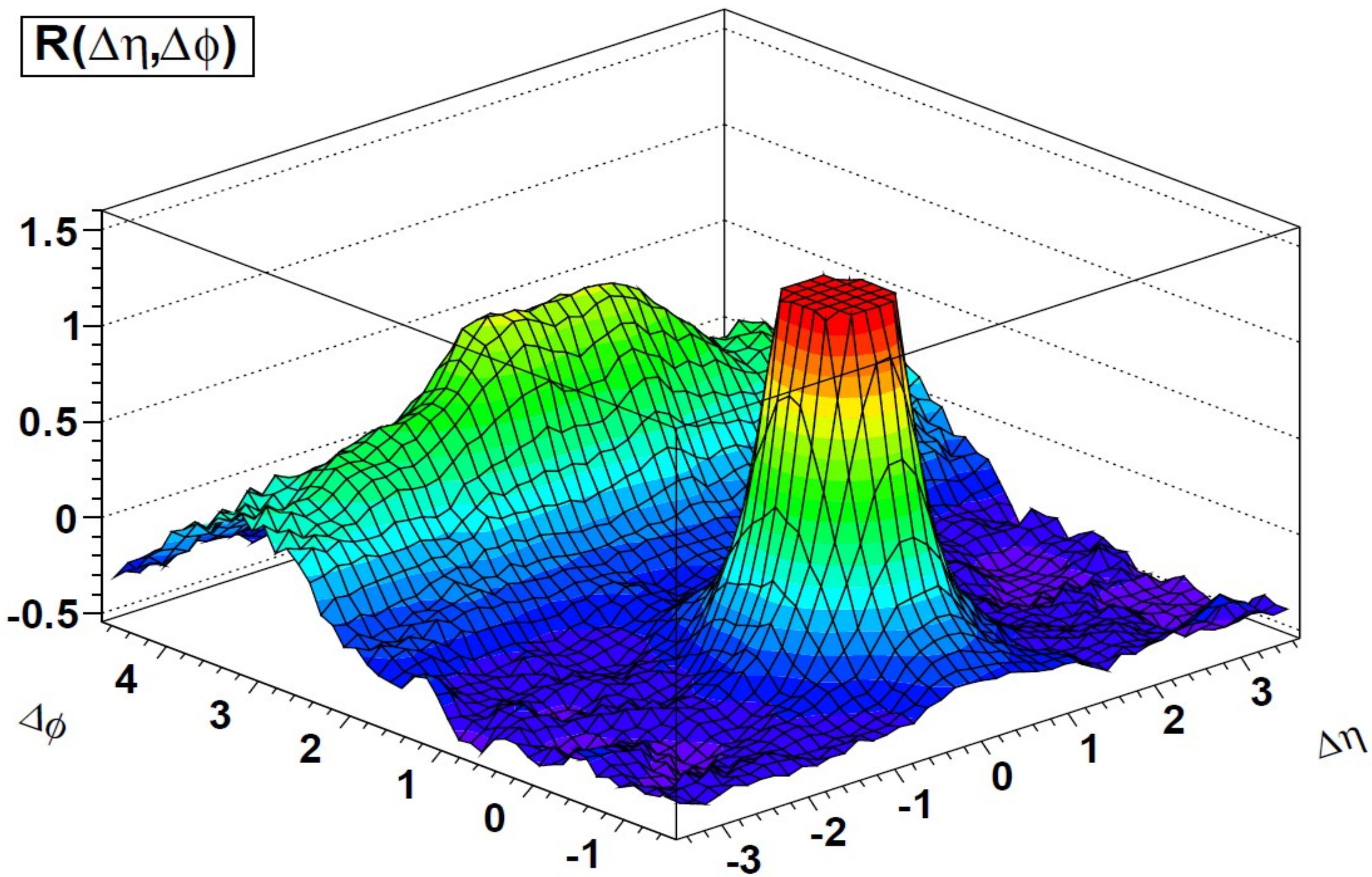
- Our calculation provides a similar ridge structure in pp@LHC using particles with 1 < pt < 3GeV/c, for high multiplicity events



close in form and magnitude compared to the CMS result (5.3 times mean multipl., compared to 7 in CMS)

pp@7 TeV : no Hydro

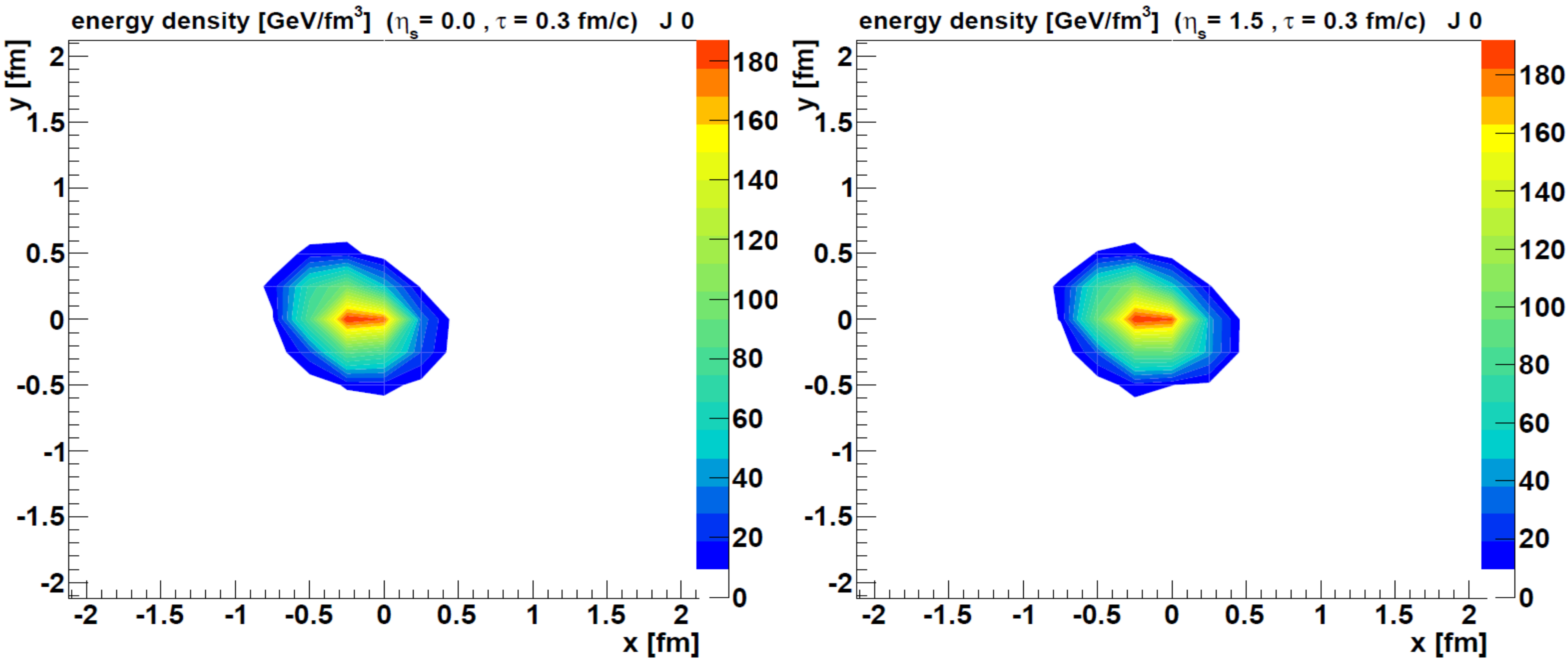
- Calculation without hydro => NO RIDGE



hydrodynamical evolution “makes” the effect! HOW?

Event-by-Event Energy Density : pp

- Random azimuthal asymmetries of initial energy density but translationally invariant
  - pseudorapidity extension of flux tubes



Initial energy density in the transverse plane for two different η_s

Event-by-Event Energy Density : pp

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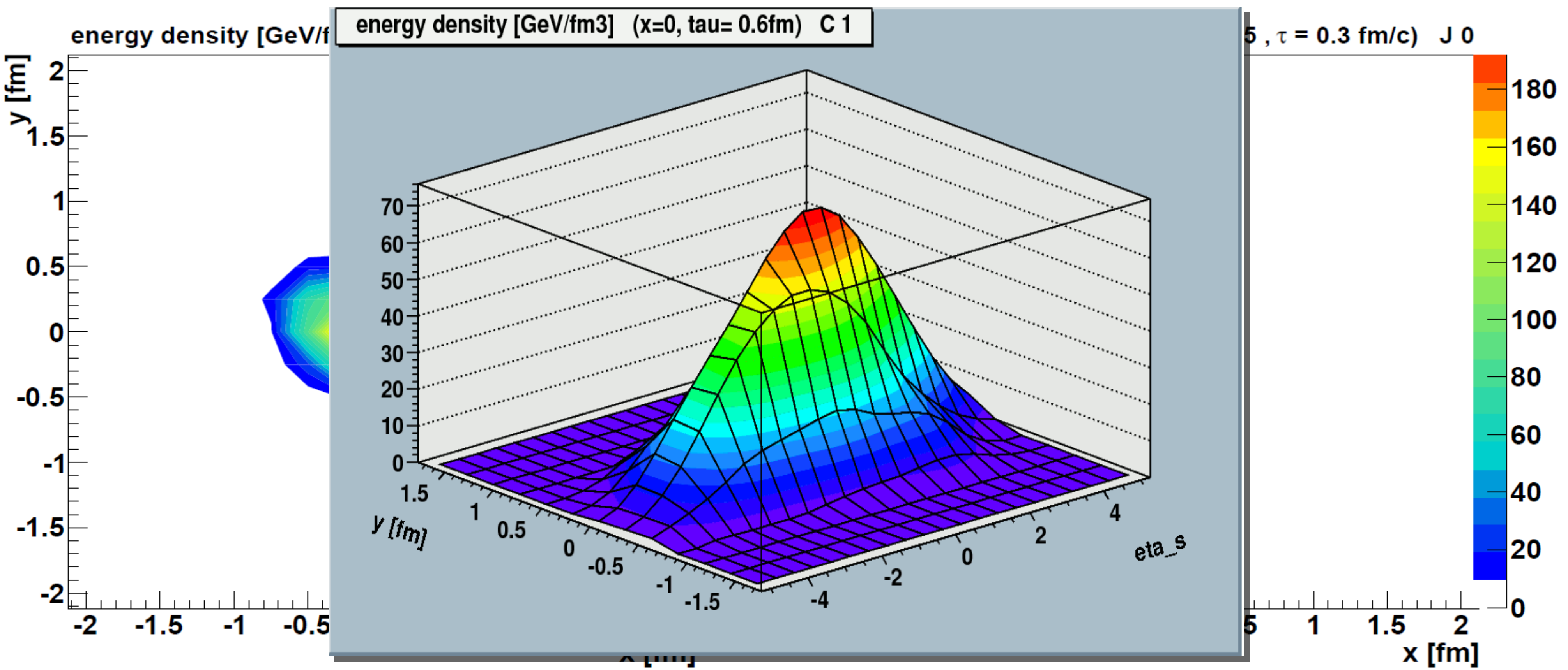
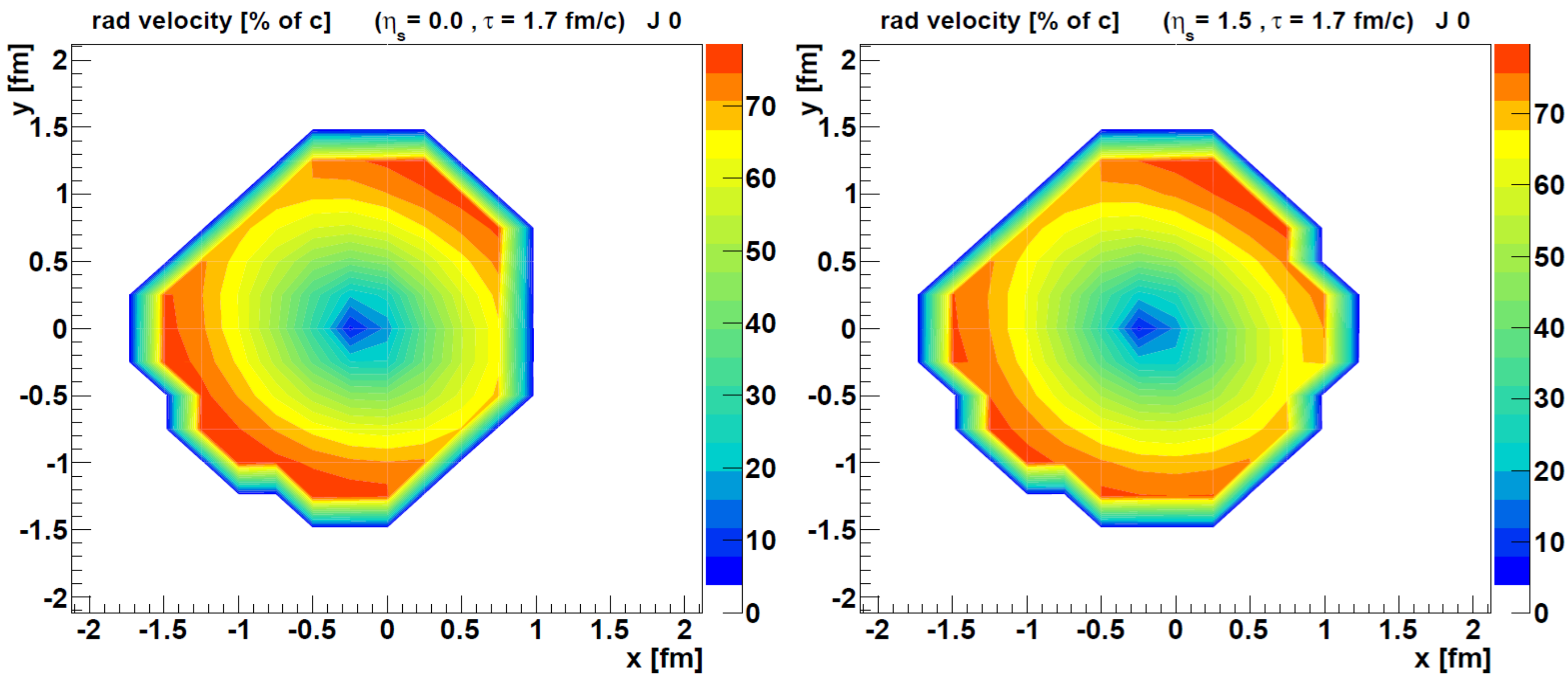


Initial energy density in the transverse plane for two different η_s

Event-by-Event Radial Flow : pp

- Elliptical initial shapes leads to asymmetric flows as well translationally invariant (in η_s)



Radial flow velocity at a later time in the transverse plane

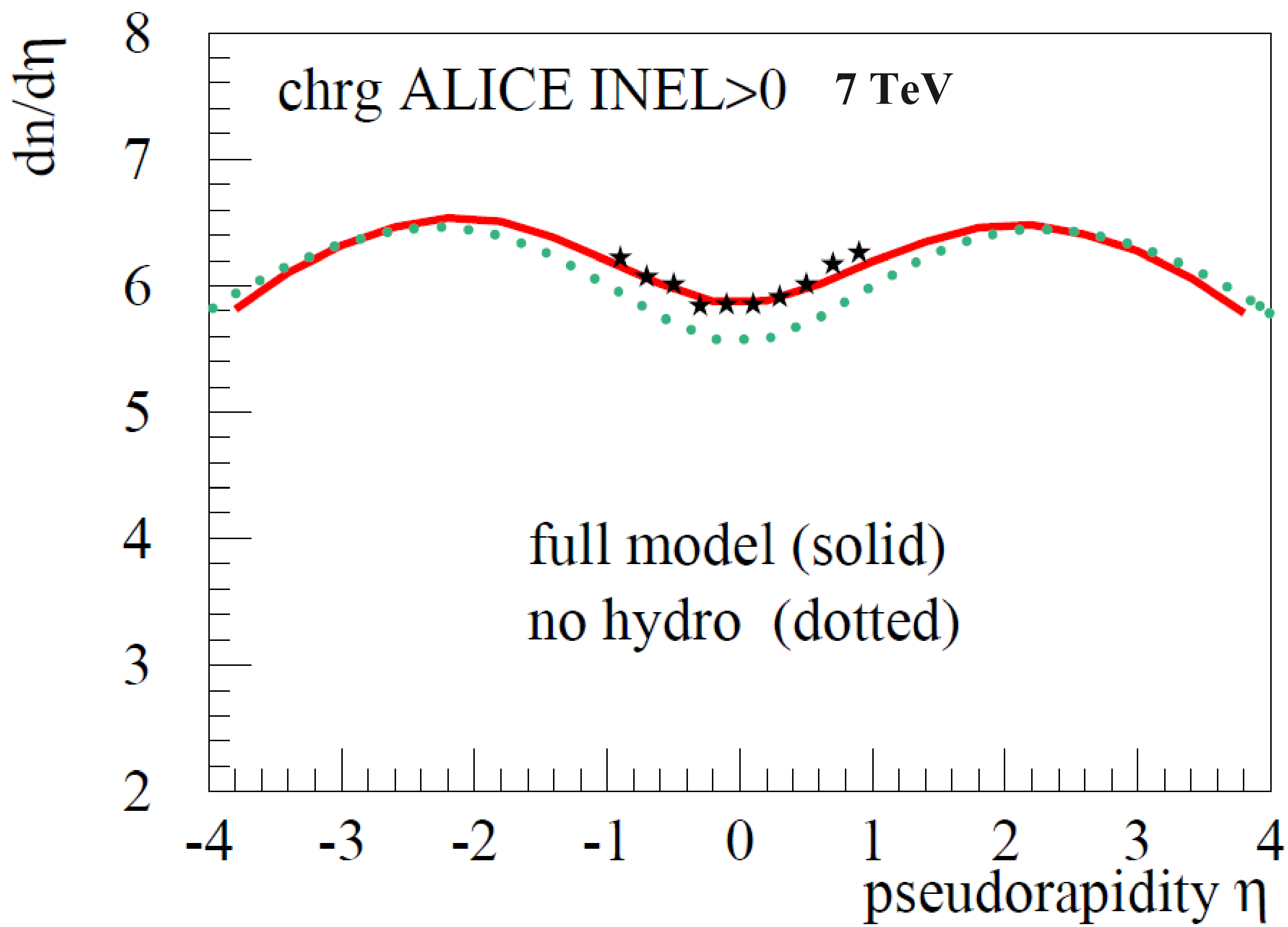
Summary Ridge in pp

- **Translational invariance of the flow asymmetry means:**
  - The system gives an increased collective push
  - to particles produced at different values of ηs
  - at the same azimuthal angle corresponding to a flow maximum

    → $\Delta\eta\Delta\varphi$ correlation

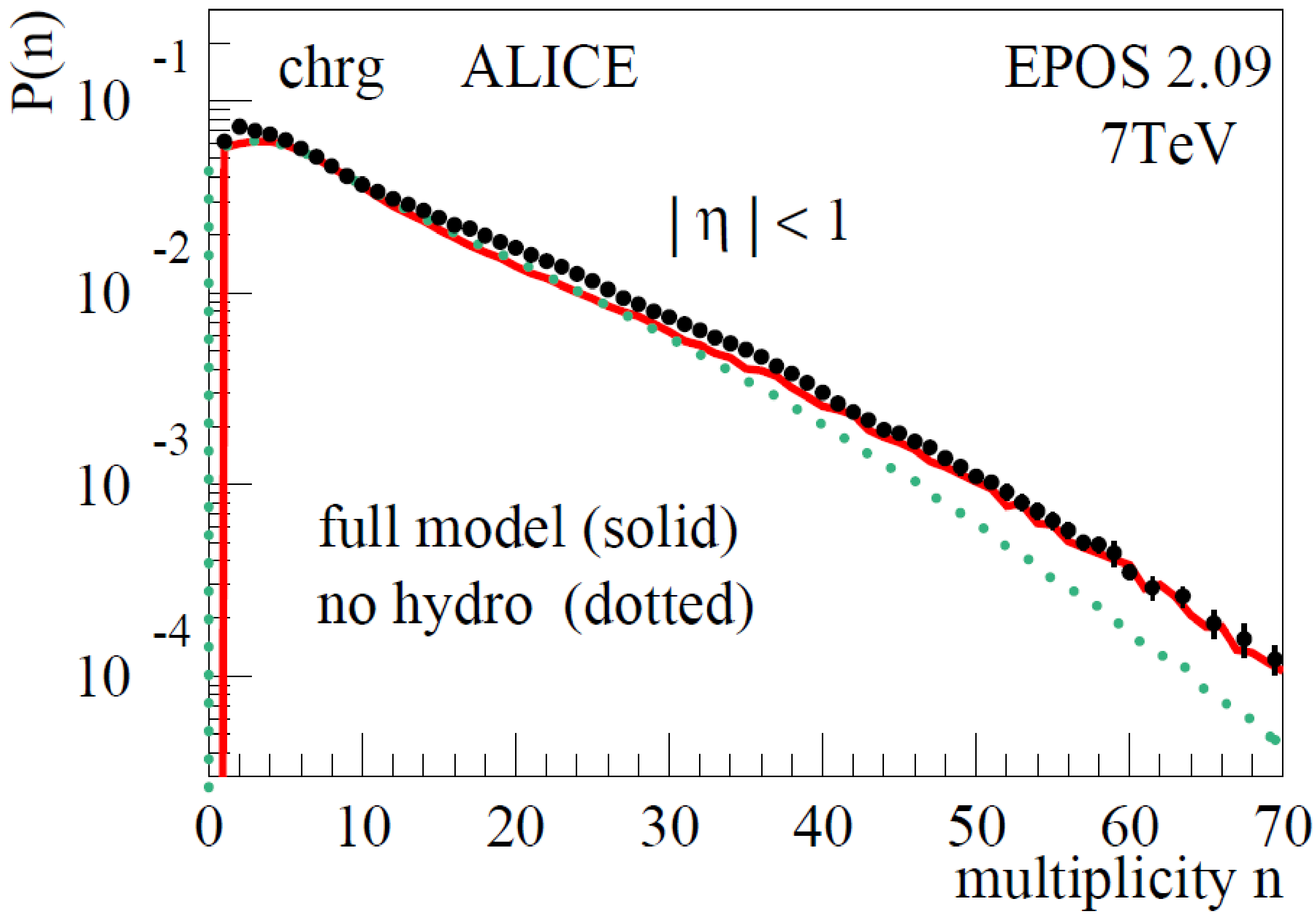
Pseudorapidity Distribution

- Little effect of hydro in MinBias dn/deta



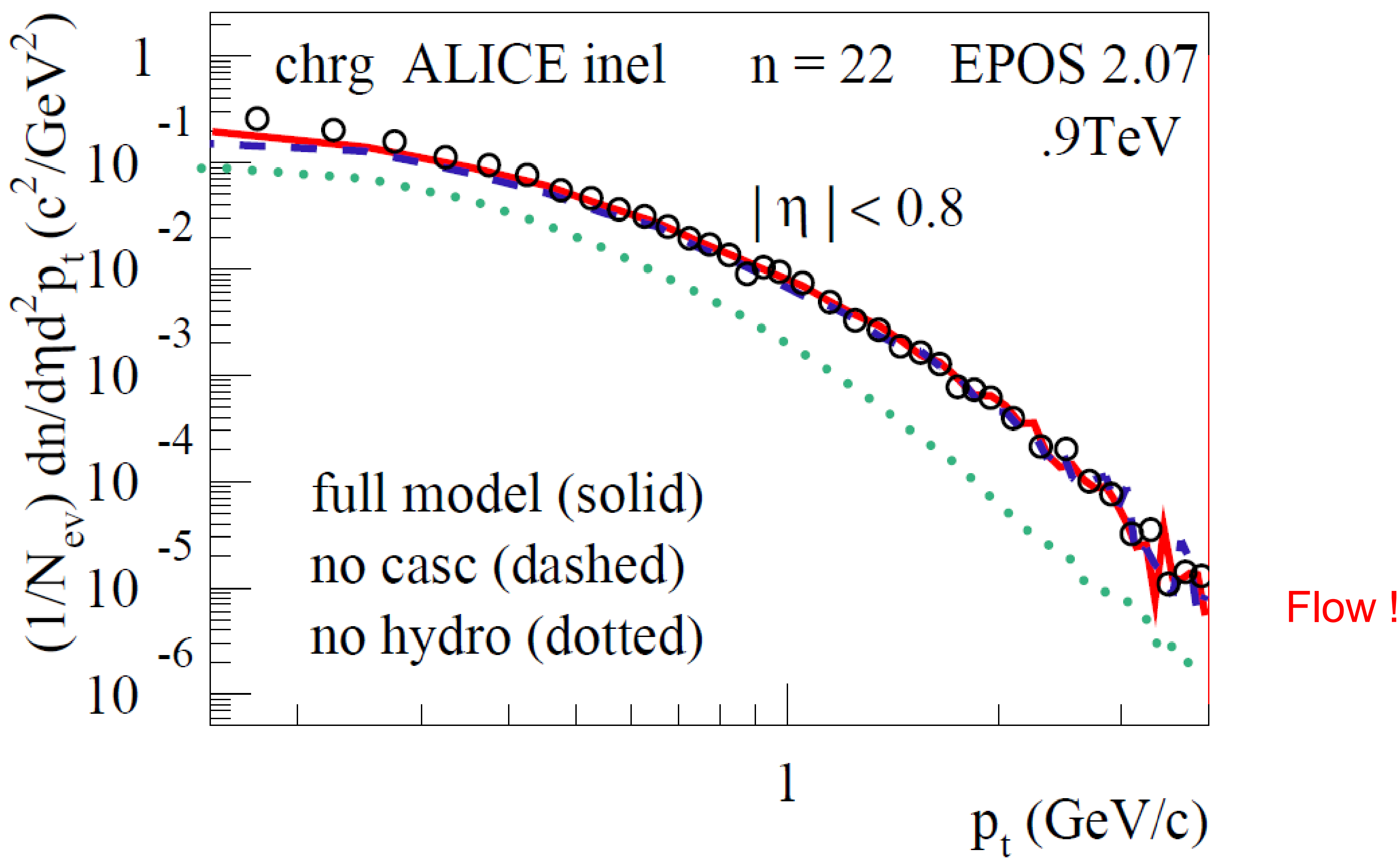
Multiplicity Distribution

➡ Little effect of hydro in MinBias dn/deta



Pt Distribution

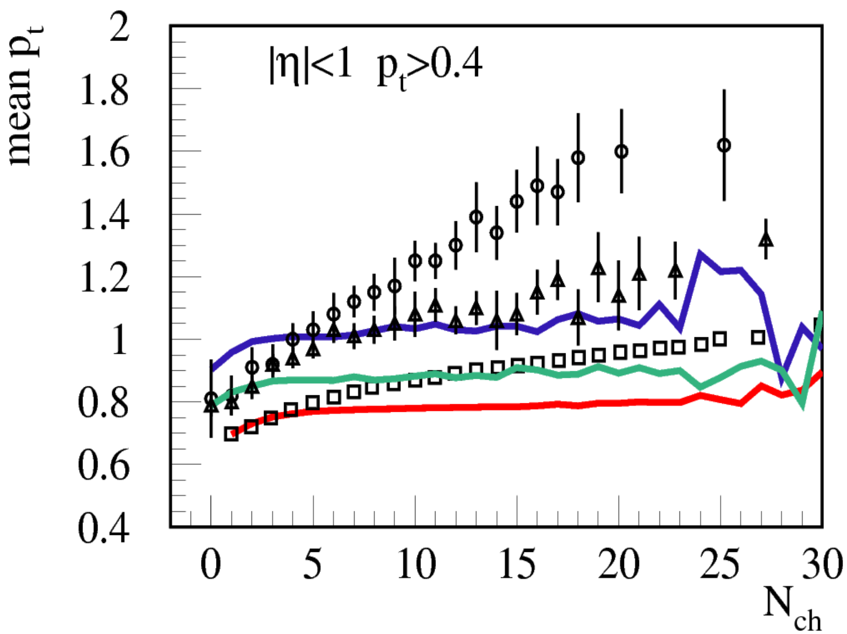
- Big effect for Pt distributions for high multiplicity events (here 900 GeV)



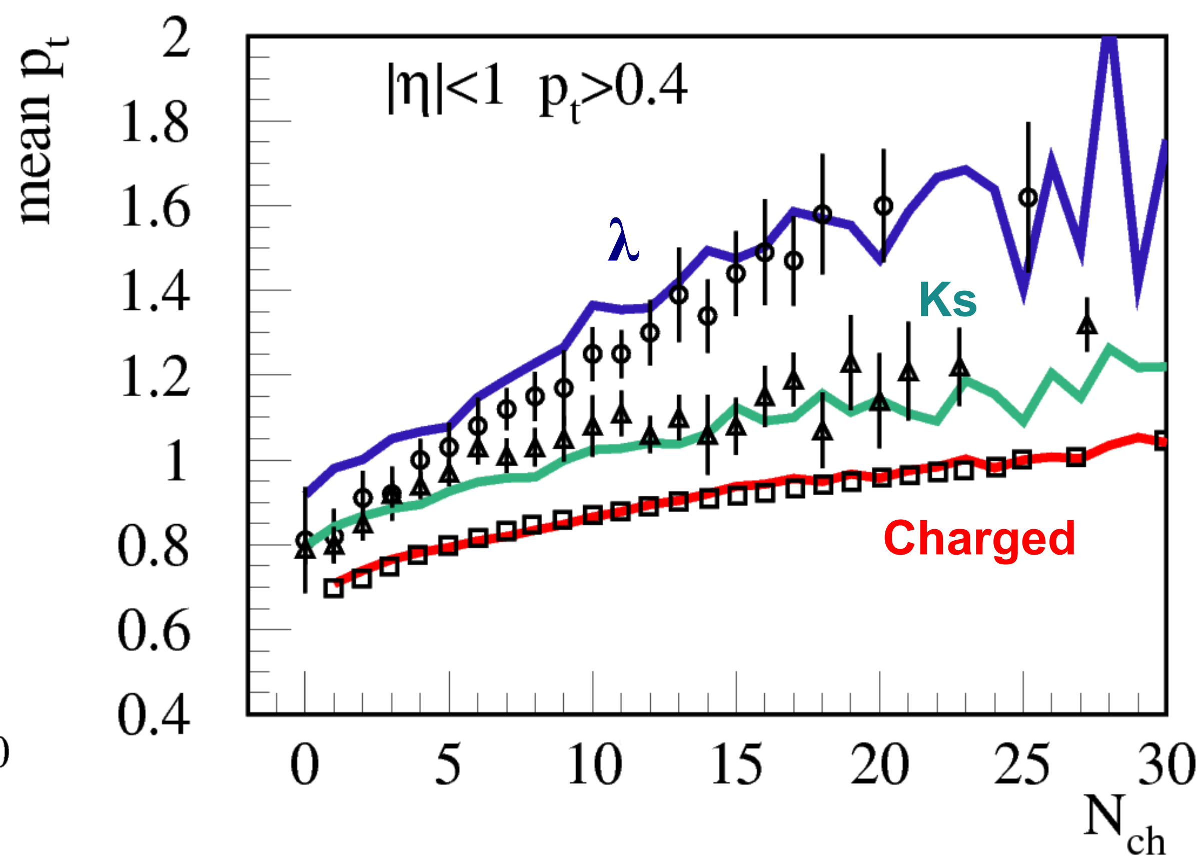
<p_t> vs multiplicity ap-p@1.8 TeV : EPOS 2

- **Using small flux tube size**
  - Very good description of CDF data
  - No additional parameter
  - Hadron mass dependence

No collective effects

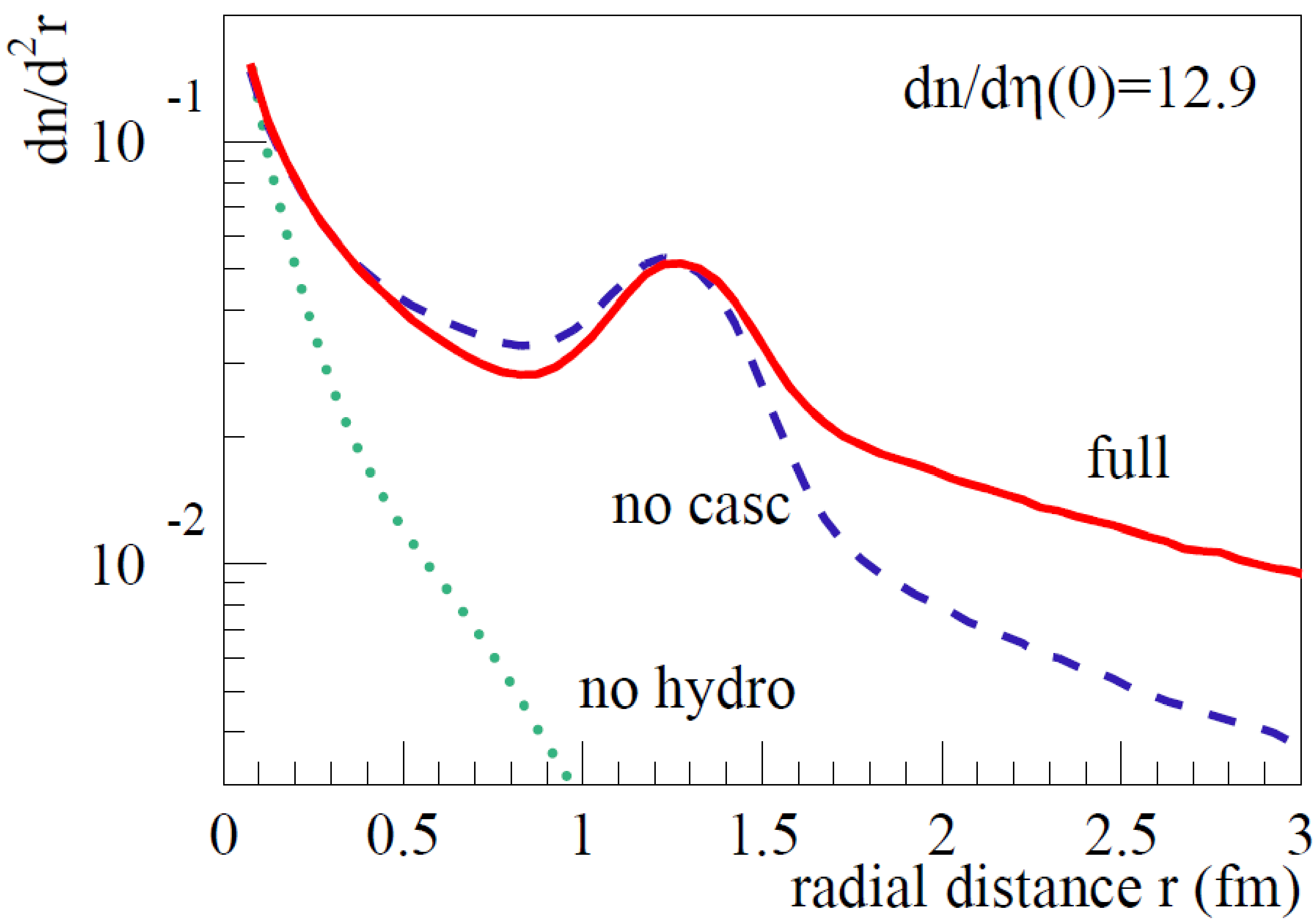


hydro+hadronic cascade



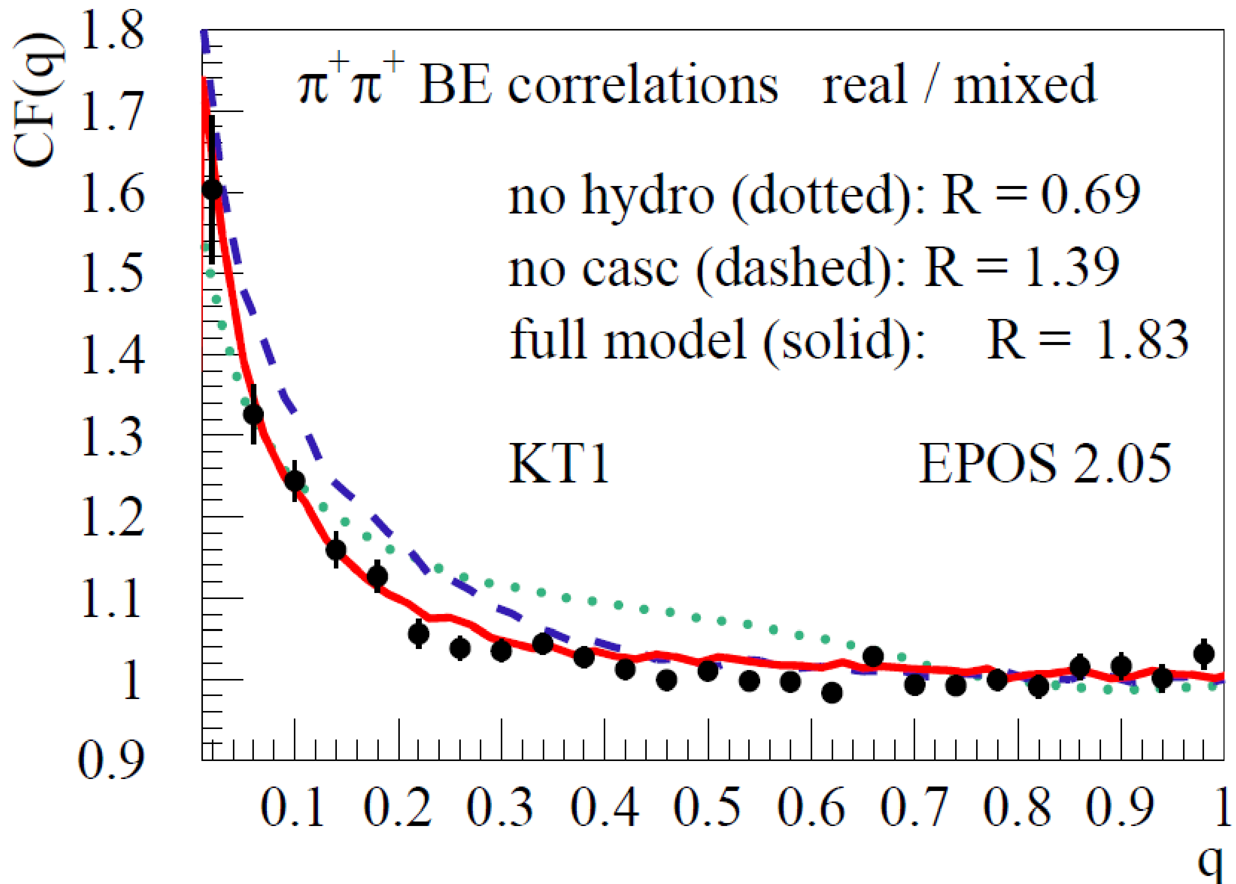
Radius of Particle Emission

➡ Space-time structure strongly affected (here 900 GeV)



Bose-Einstein Correlations

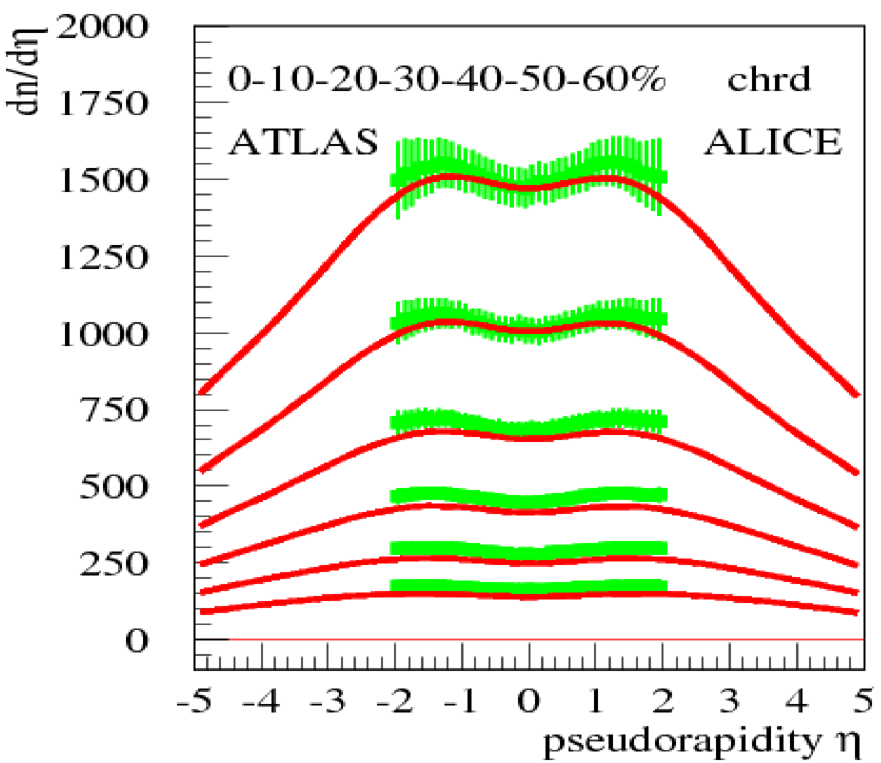
➡ Consequences for Bose-Einstein correlations

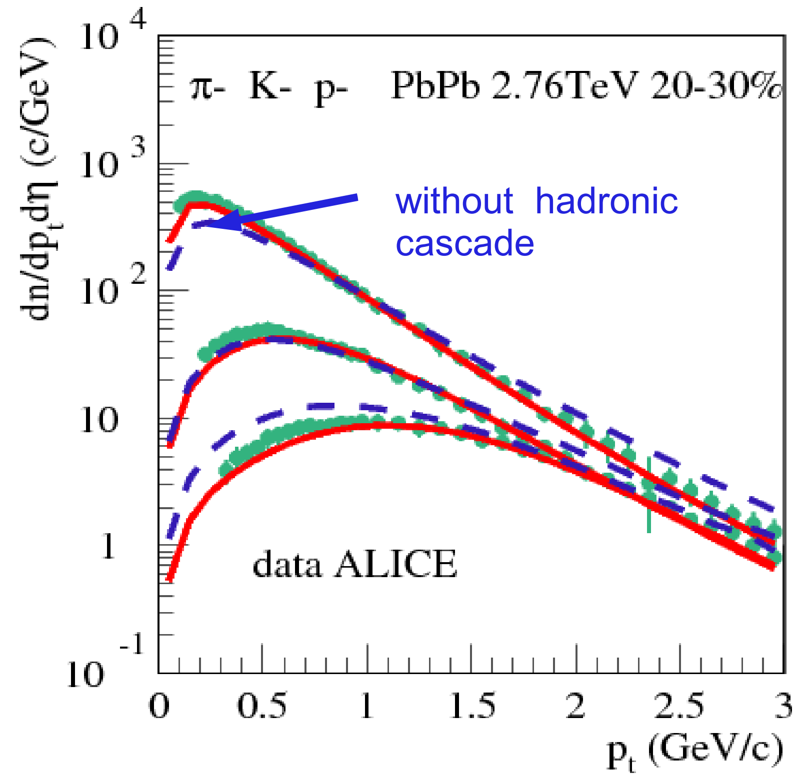


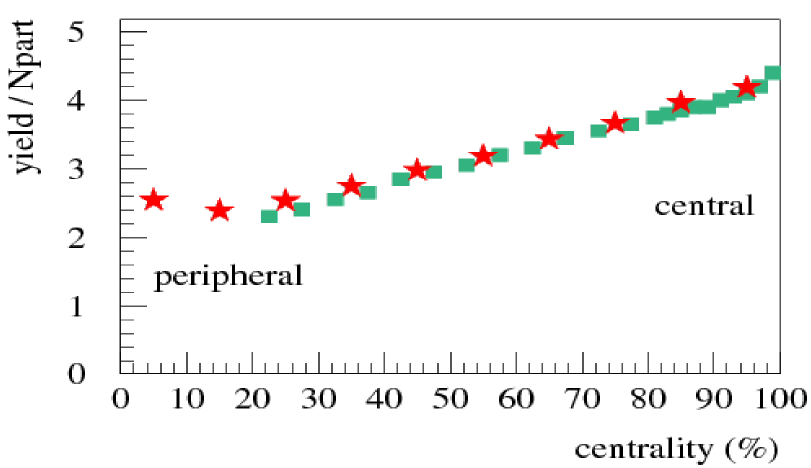
ALICE data.

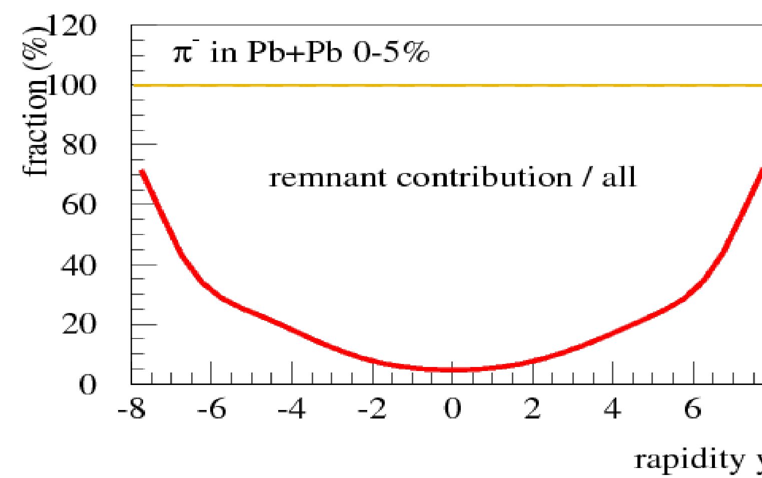
Radii R from exponential fit.
KT1= [100, 250], KT3= [400, 550], KT5= [700, 1000]

PbPb @ LHC

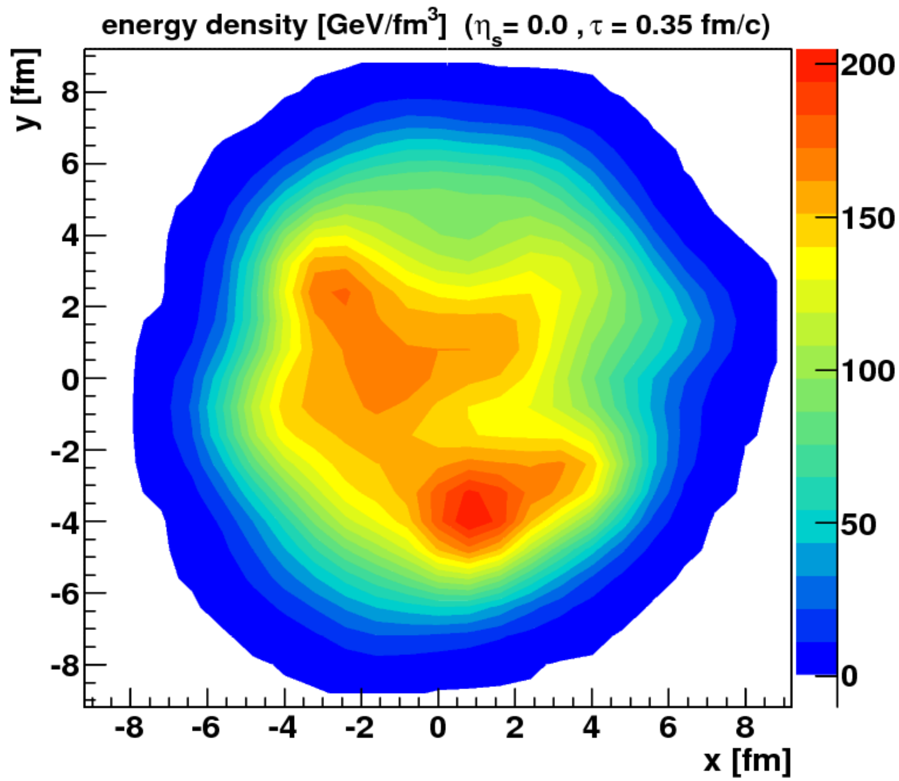

dn/dη
0-10-20-30-40-50-60% chrd
ATLAS ALICE
pseudorapidity η

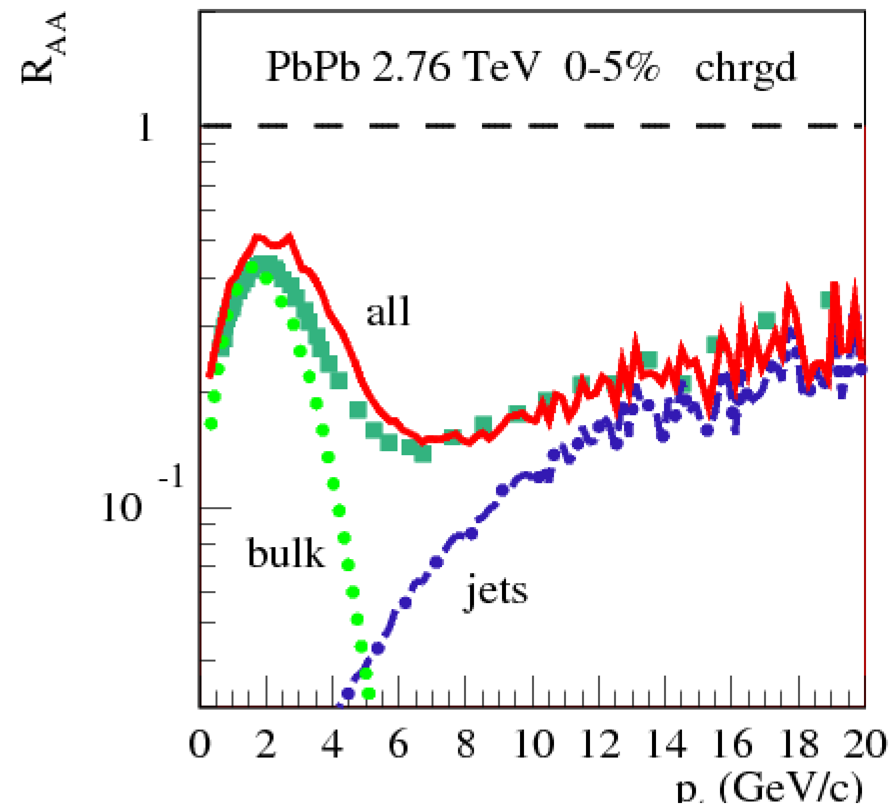

dn/dp_t dη (c/GeV)
π- K- p- PbPb 2.76TeV 20-30%
without hadronic cascade
data ALICE
p_t (GeV/c)

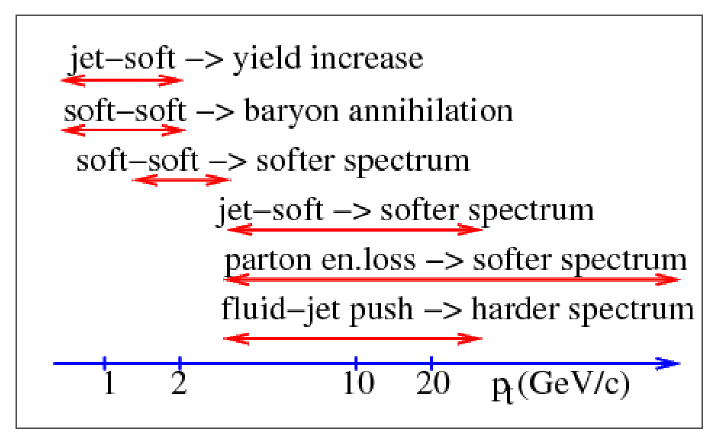

yield / Npart
central
peripheral
centrality (%)


fraction (%)
π⁻ in Pb+Pb 0-5%
remnant contribution / all
rapidity y

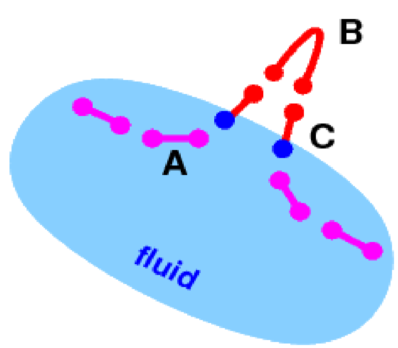
jets in PbPb @ LHC



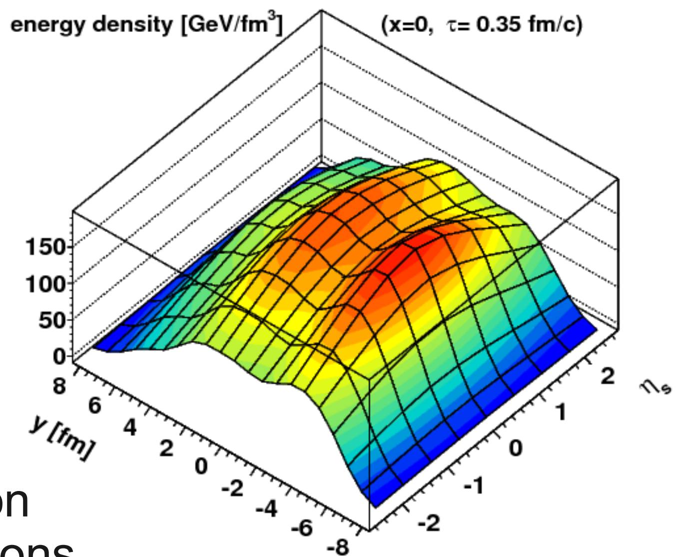




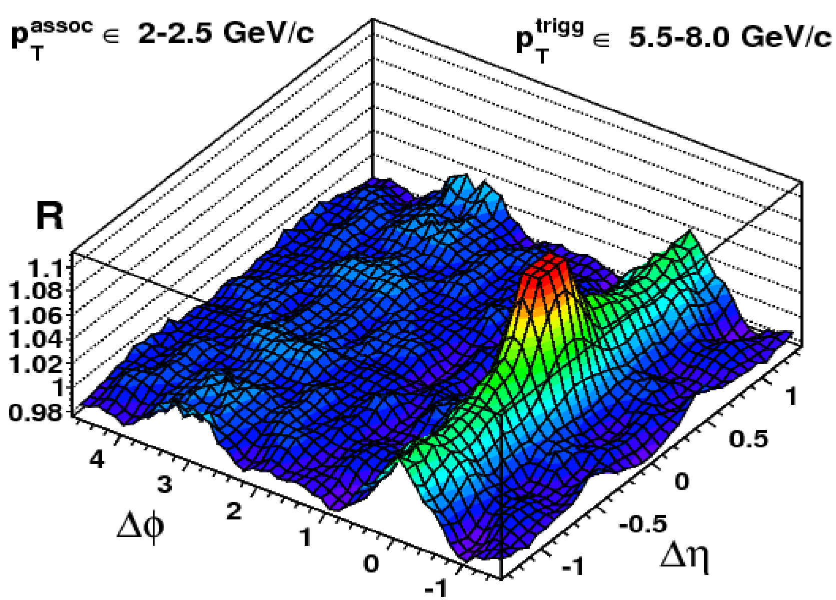
- **Jet interacts in bulk of matter**
  - parton energy loss
  - boost at the surface



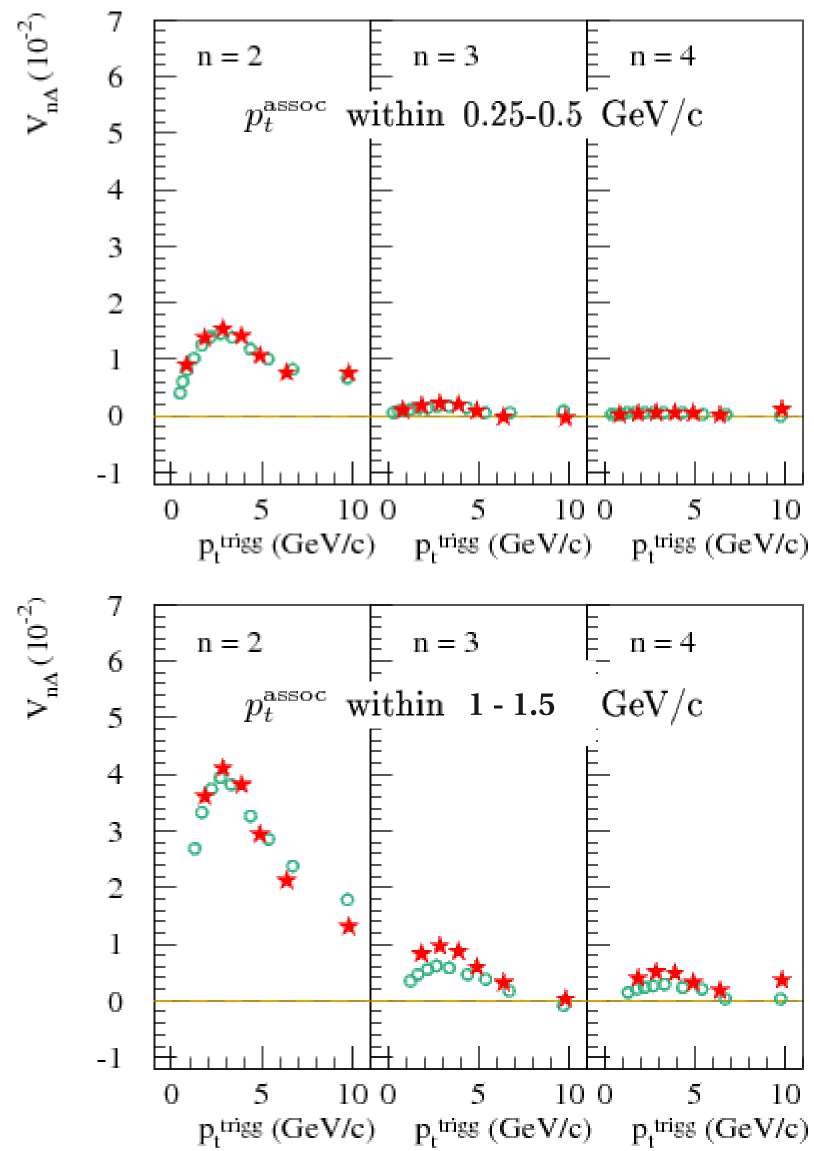
Correlations in PbPb@LHC



di-hadron correlations

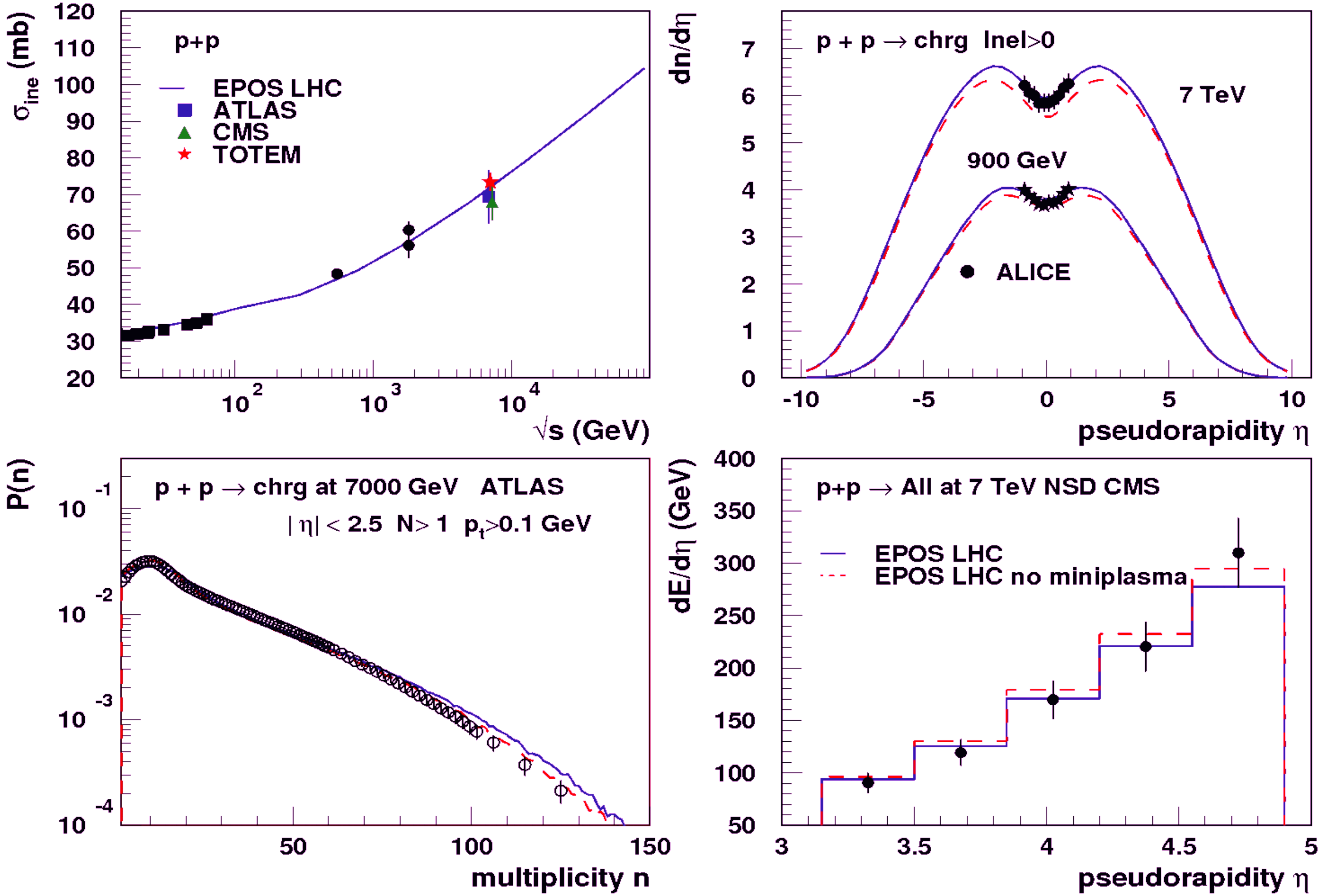


Fourier coefficient for most central events



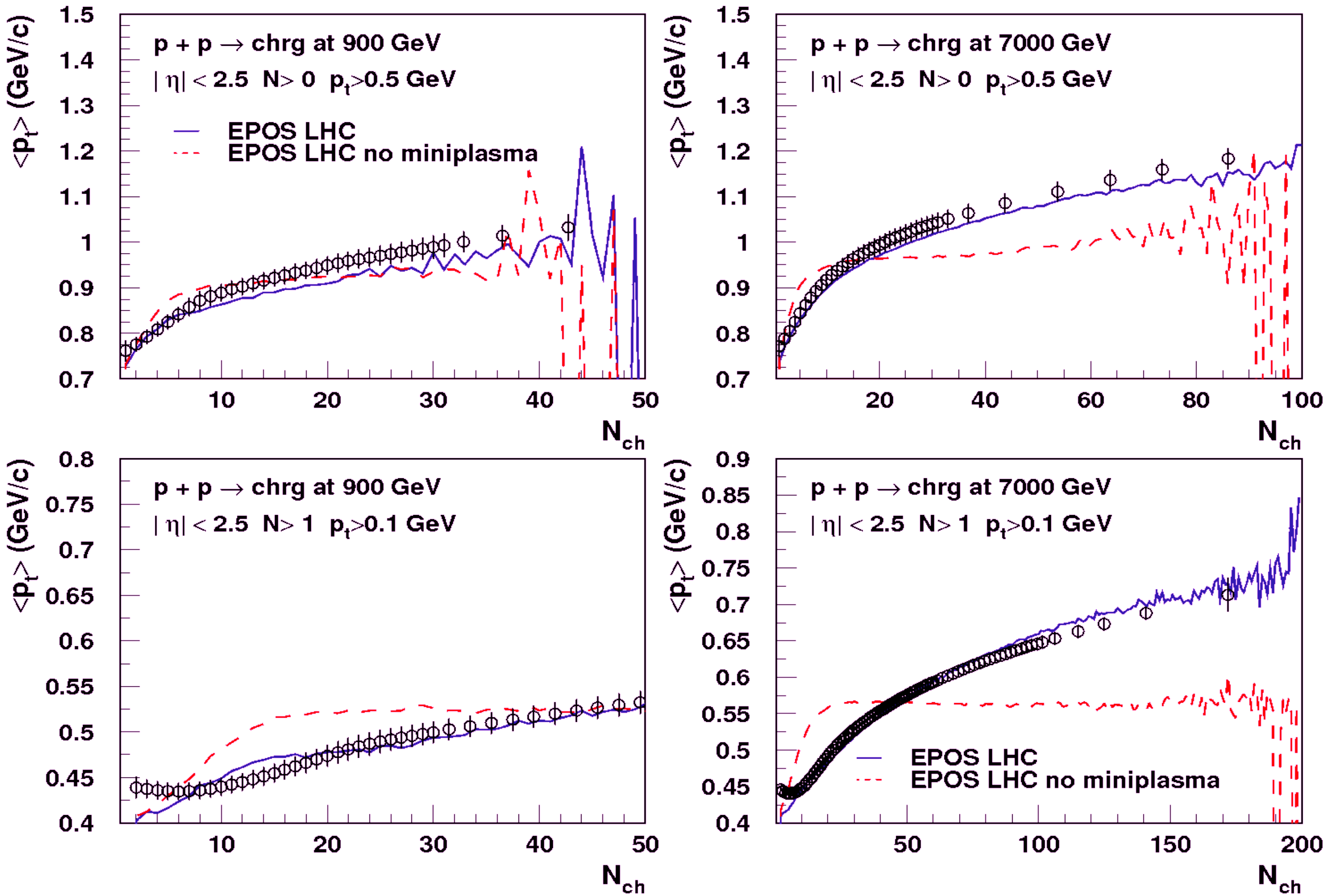
EPOS LHC

- **Effective flow treatment**



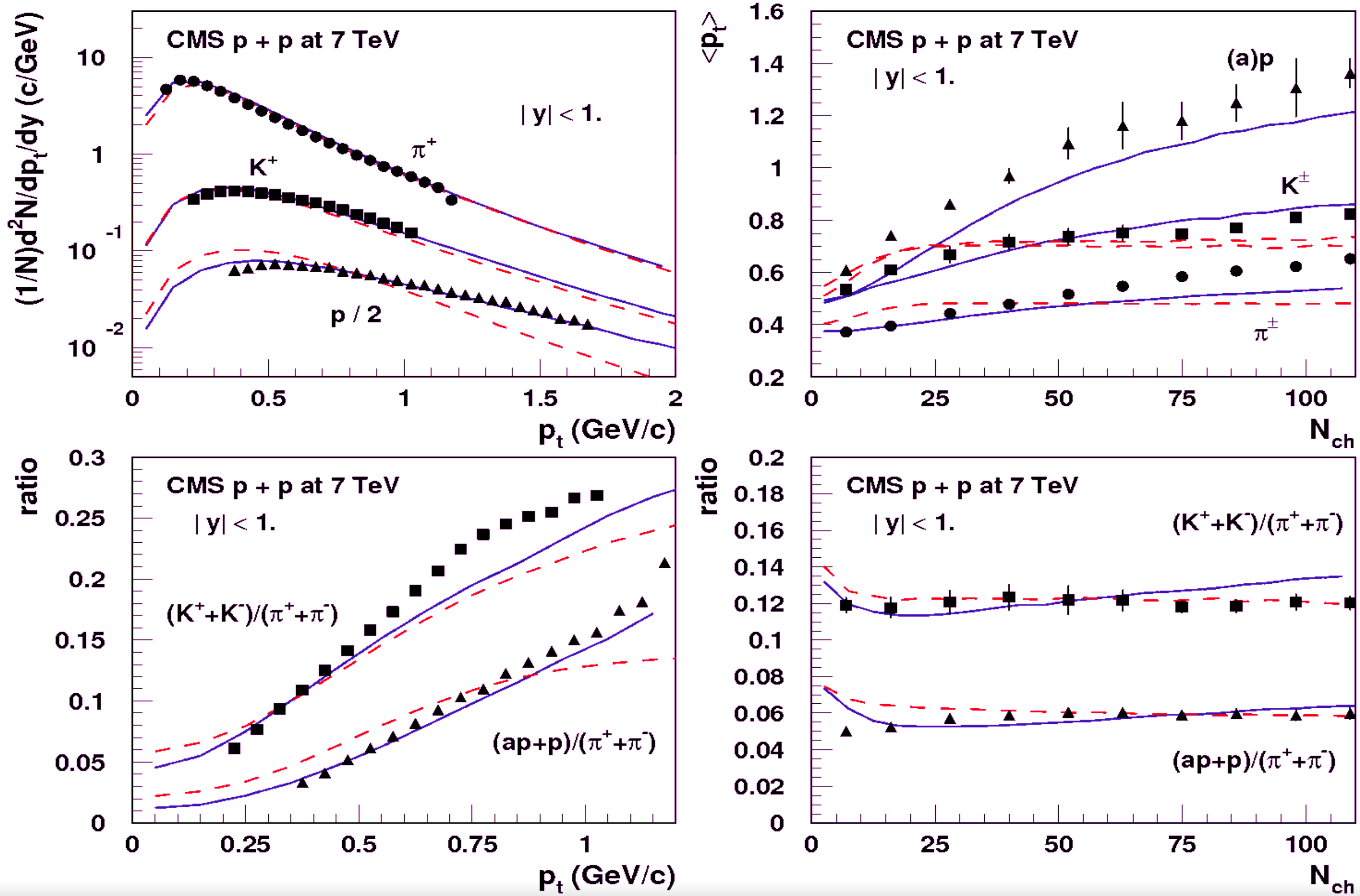
EPOS LHC

- Effective flow treatment



EPOS LHC

- **Detailed description can be achieved**
  - identified spectra
  - p_t behavior driven by collective effects (statistical hadronization + flow)



Summary

Hadronic interactions with EPOS :

- Consistent treatment for all kind of system : final state depends on the energy used for each event (multiplicity) not only on the energy available (collective hadronization when density of particles is high)

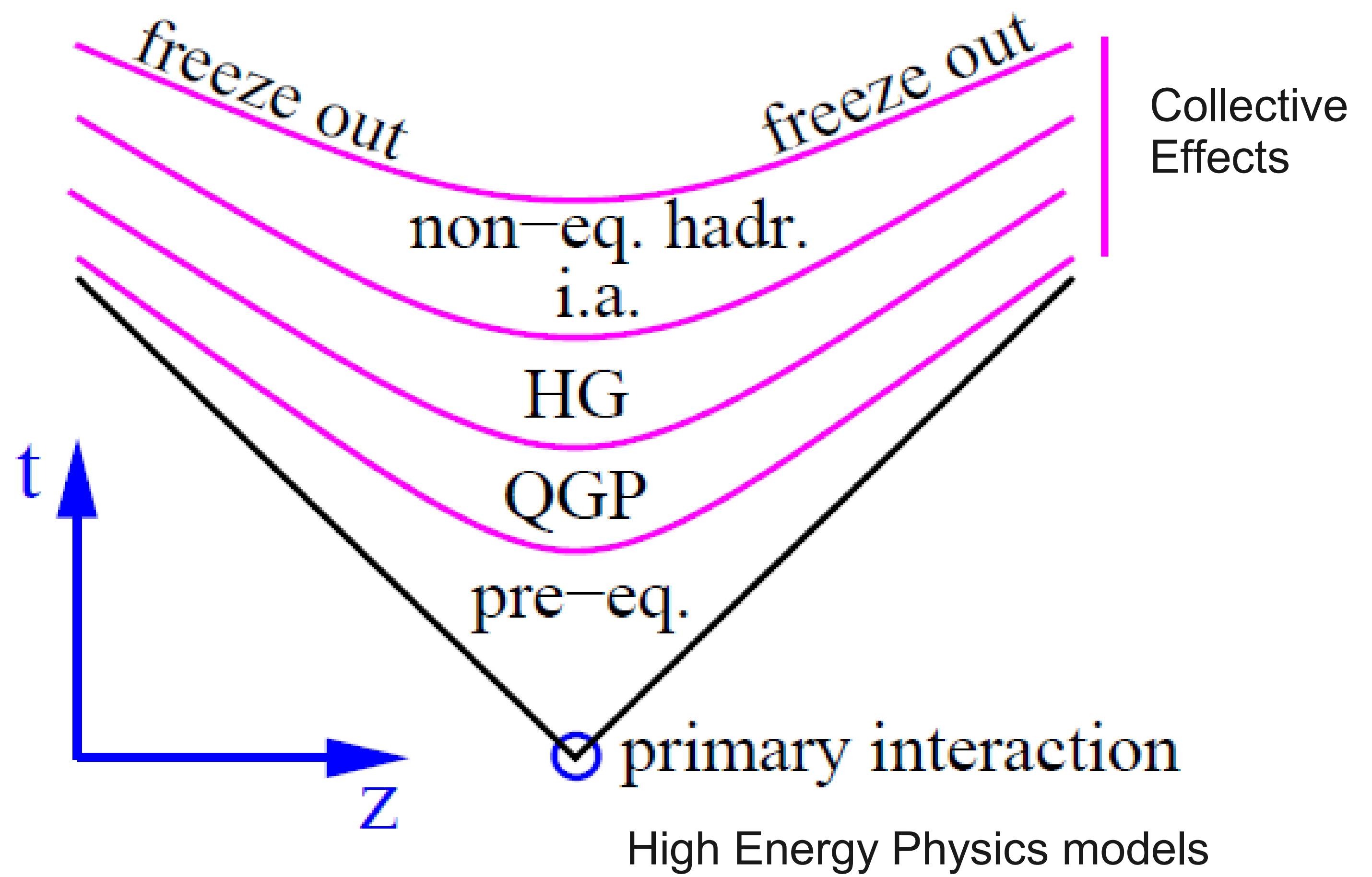
Hydro on event-by-event basis :

- for AuAu@RHIC or PbPb@LHC, explains naturally nontrivial features as “ridge” correlations, elliptical flow
- Explains some nontrivial pp results (ridge, BE correlations)

EPOS on-going developments :

- Test all Min Bias LHC data
- Improvement of hard events (jets) in MB
- Selection of hard processes (specific born Pt)
- Both at the same time : underlaying events
- Test with cosmic ray data

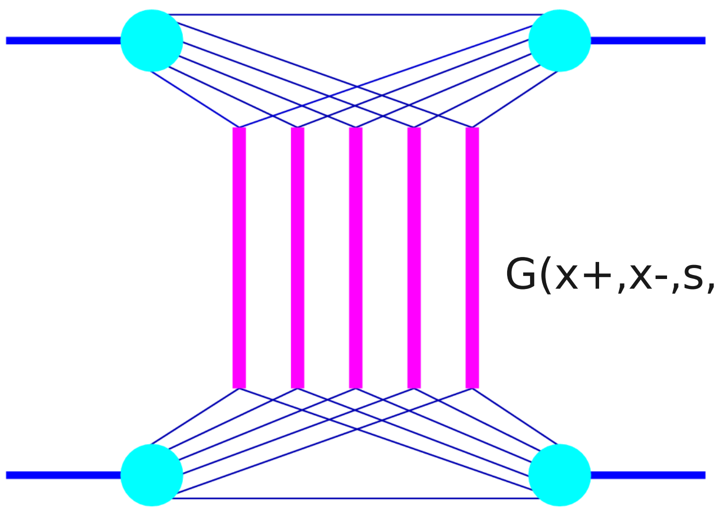
High Energy Hadronic Interactions



General case : valid for pp if enough particles are produced !

Thank you

Cross Section Calculation : EPOS



- PBGRT : Gribov-Regge but with energy sharing at parton level
- amplitude parameters fixed from QCD and pp cross section (semi-hard Pomeron)
- cross section calculation take into account interference term

$$\sigma_{\mathrm{ine}}(s) \;=\; \int d^2b \,(1-\Phi_{\mathrm{pp}}(1,1,s,b))$$

$$\Phi_{\mathrm{pp}}\left(x^+,x^-,s,b\right) \;=\; \sum_{l=0}^{\infty}\int dx_1^+dx_1^- \ldots dx_l^+dx_l^- \left\{\frac{1}{l!}\prod_{\lambda=1}^{l} -G(x_\lambda^+,x_\lambda^-,s,b)\right\} \times\; F_{\mathrm{proj}}\left(x^+-\sum x_\lambda^+\right) F_{\mathrm{targ}}\left(x^--\sum x_\lambda^-\right).$$

can not use complex diagram with energy sharing:
non linear effects taken into account as correction of single amplitude G

Particle Production in EPOS

m number of exchanged elementary interaction per event fixed from elastic amplitude taking into account energy sharing :

- m cut Pomerons from :

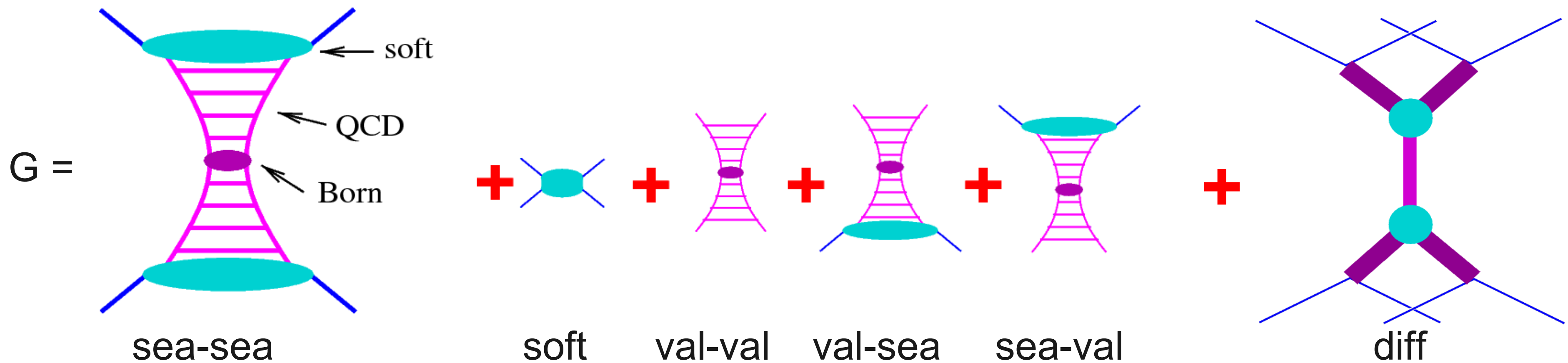
$$\Omega_{AB}^{(s,b)}(m,X^+,X^-) = \prod_{k=1}^{AB}\left\{\frac{1}{m_k!}\prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, b_k)\right\} \Phi_{AB}\left(x^{\text{proj}}, x^{\text{targ}}, s, b\right)$$

  - m and X fixed together by a complex Metropolis (Markov chain)
- $2m$ strings formed from the m elementary interactions
  - energy conservation : energy fraction of the $2m$ strings given by X
- consistent scheme : energy sharing reduce the probability to have large m

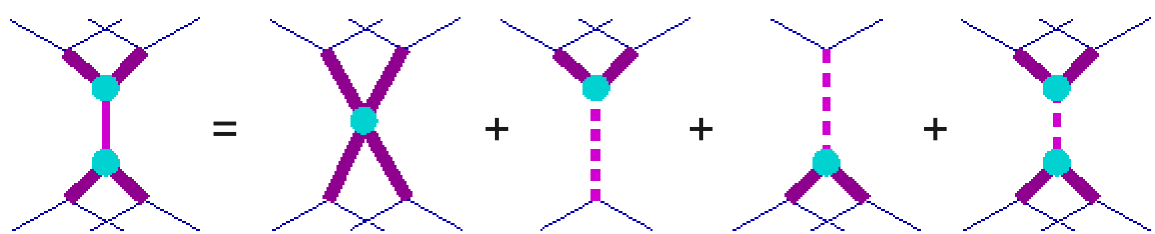
Consistent treatment of cross section and particle production:
number AND distribution of cut Pomerons depend on cross section

Diffraction in PBGRT

- **Using the same formalism**
  - Diffraction from an additional diagram

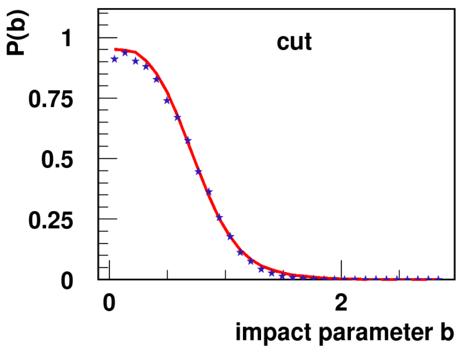


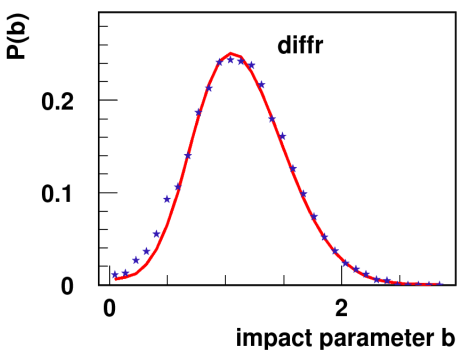
  - Same form as soft (Regge pole) but with different amplitude and width
  - Low mass and high mass diffraction from the same diagram



  - Parameters extracted from single diffractive (SD) cross-section
  - Events with only “diff” type diagrams are diffractive

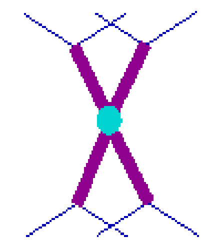
Low Mass Diffraction

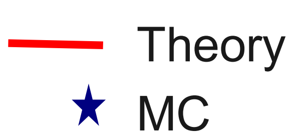


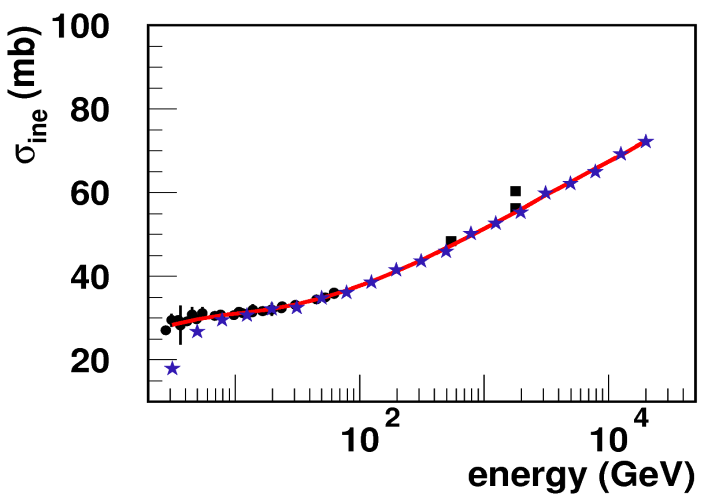


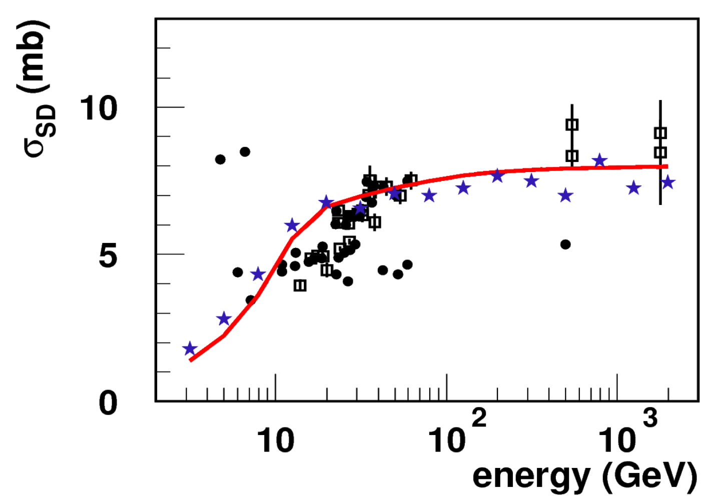
Diffractive event = event with only cut diff. diagrams

- Multiple cut-diff diagrams possible
- For each cut-diff diagram probability P_{dif} not to excite remnant
  - More cut-diff = more excitation : $(1-P_{dif}^{\ n})$
  - Important in pA
- No particle production directly from diagram
- P_{dif} (~0.25) fixes SD, DD (or elastic) probability.

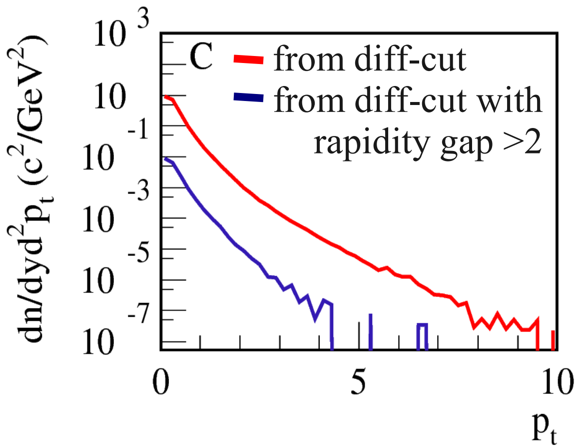








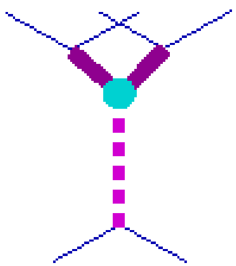
High Mass Diffraction



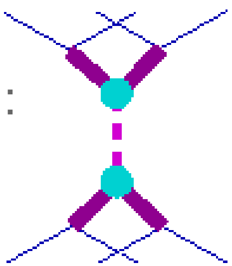
Same scheme but with particle production

- Do not change cross-section
- For each cut-diff probability P_{HM}(mass,b,...) to remain as real (soft or semi-hard) cut diagram
- 0, 1 or 2 rapidity gap depending on P_{dif}

Projectile not excited :
1 rapidity gap



Projectile and target not excited :
2 rapidity gaps

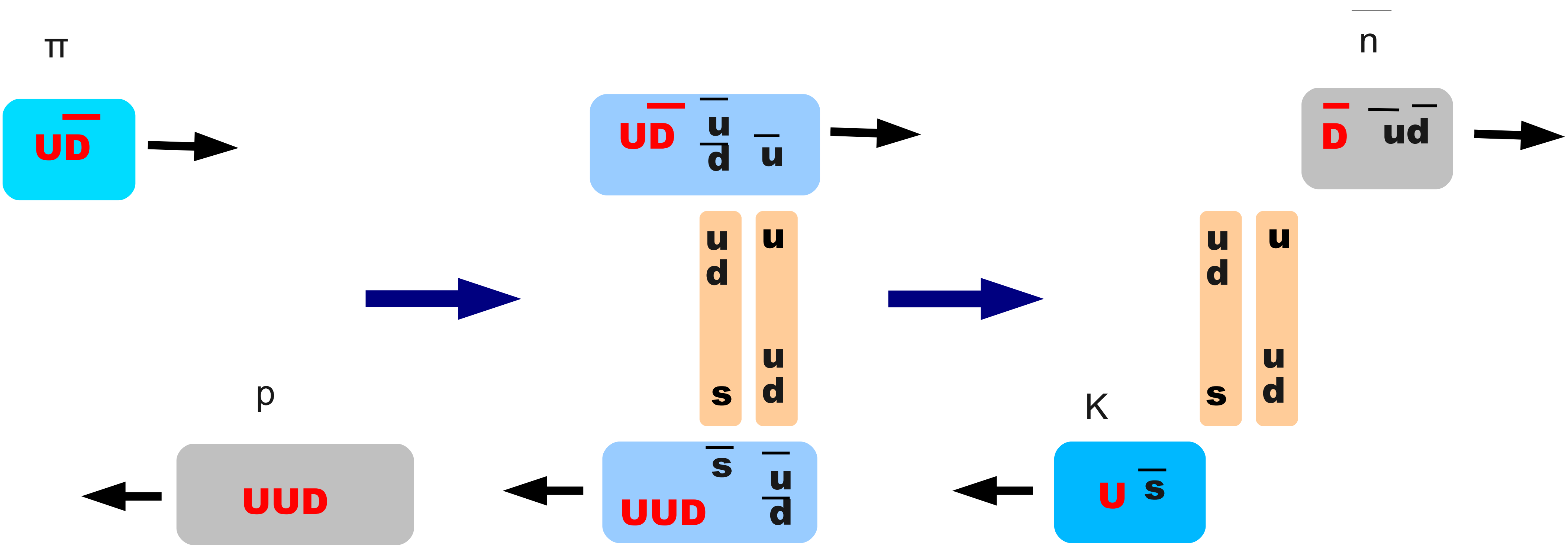


- Additional multiplicity contribution in ND events
- Work in progress

Remnants in EPOS

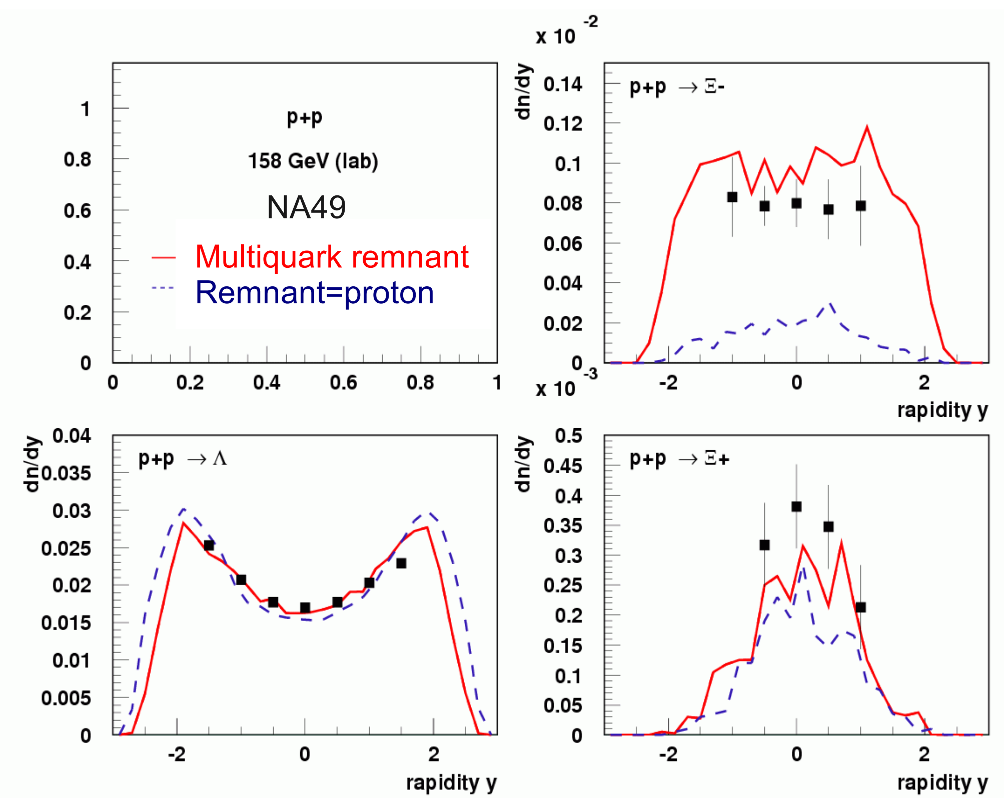
In EPOS : any possible quark/diquark transfer

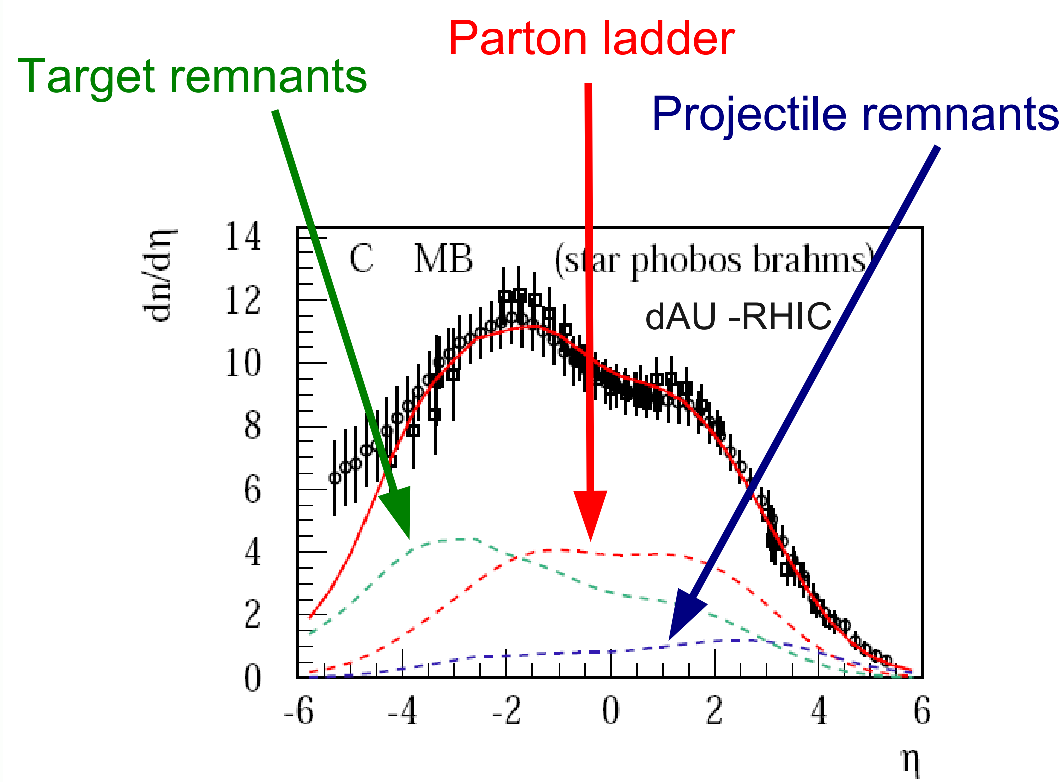
- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



Properties of Free Remnants

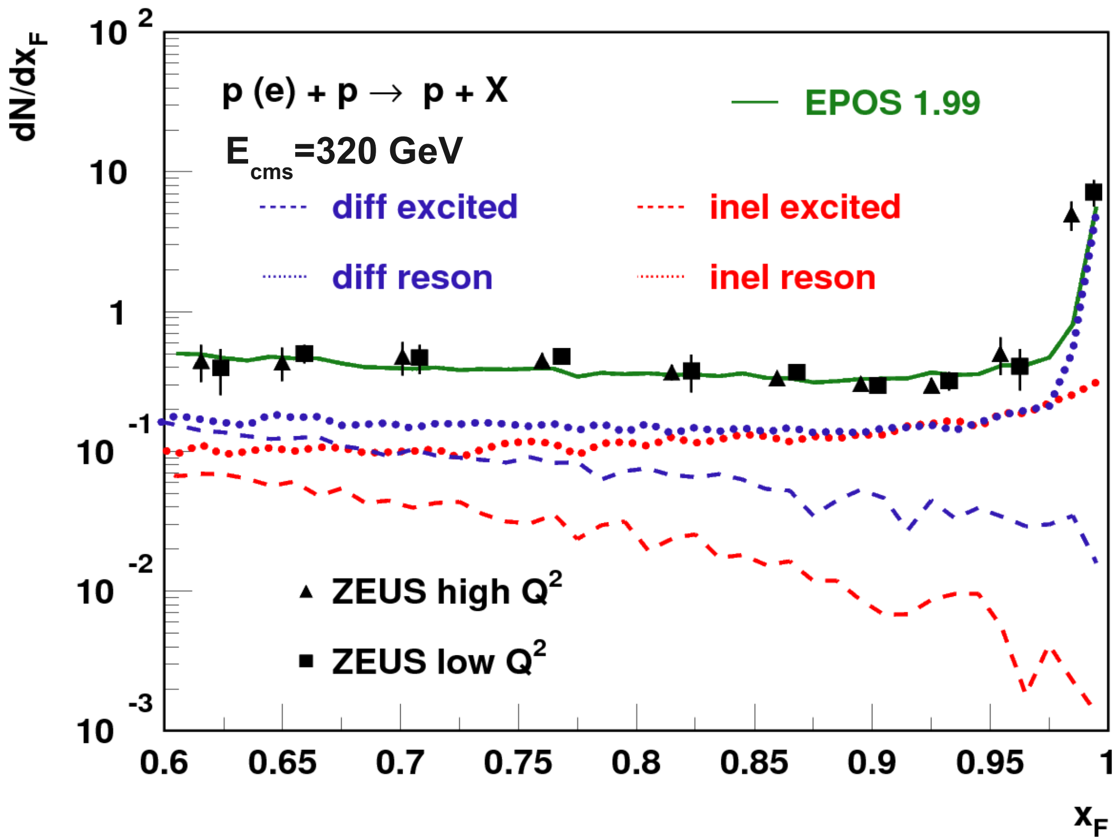
- **Valence quark not necessarily connected to parton ladder :**
  - ➜ Necessary to have aΩ/Ω < 1 (NA49 data)
  - ➜ Very broad remnant distribution
  - ➜ Can be used to describe effective enhanced diagrams (higher mass)
  - ➜ Very important for Cosmic Ray (leading particle)

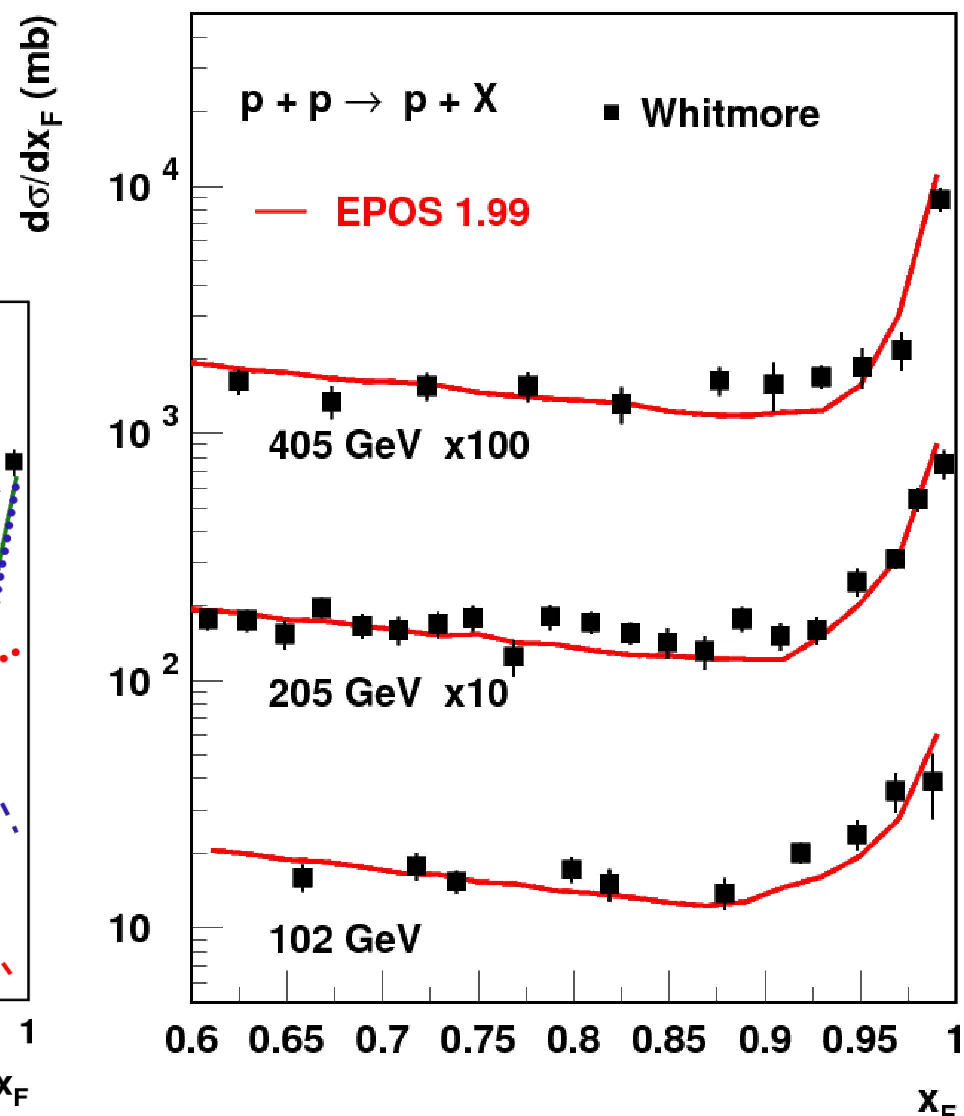




Proton Xf Distribution

- **Leading proton**
  - Tests from 100 GeV lab to 300 GeV cms
  - Very forward proton from ND events

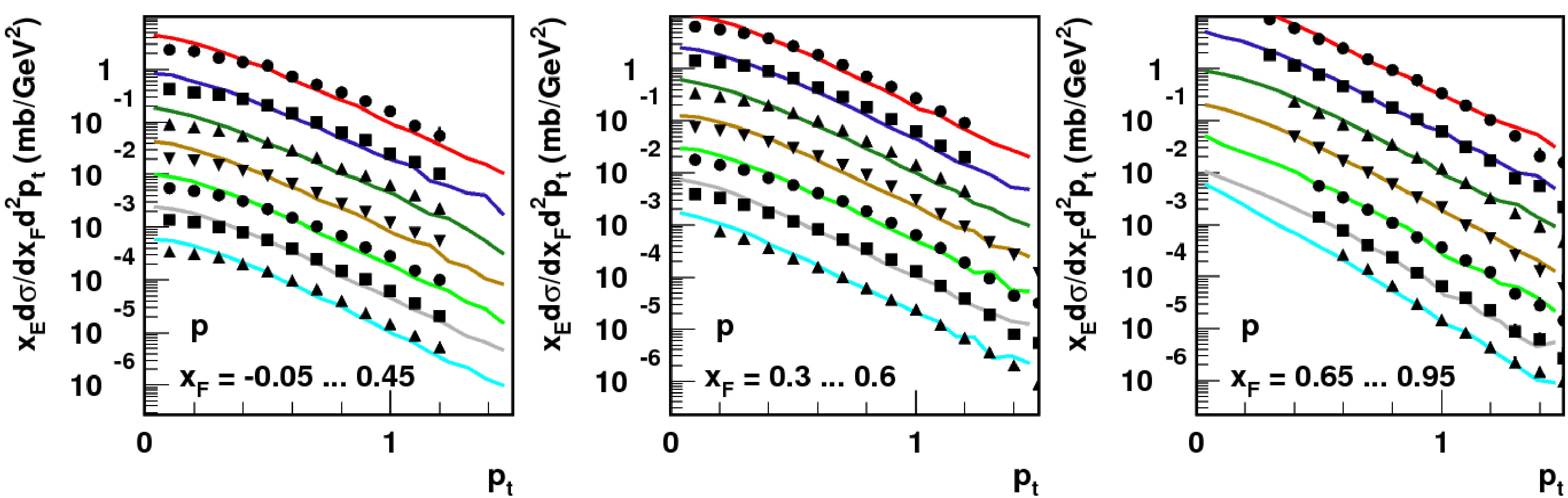




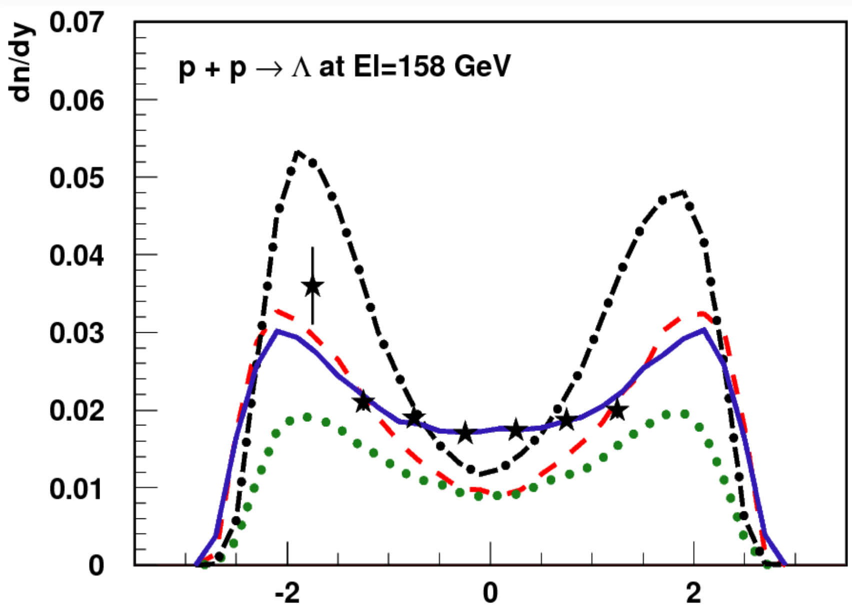
Proton Xf Distribution

- **Leading proton**
  - Tests from 100 GeV lab to 300 GeV cms
  - Very forward proton from ND events

E_{lab}=158 GeV NA49 data

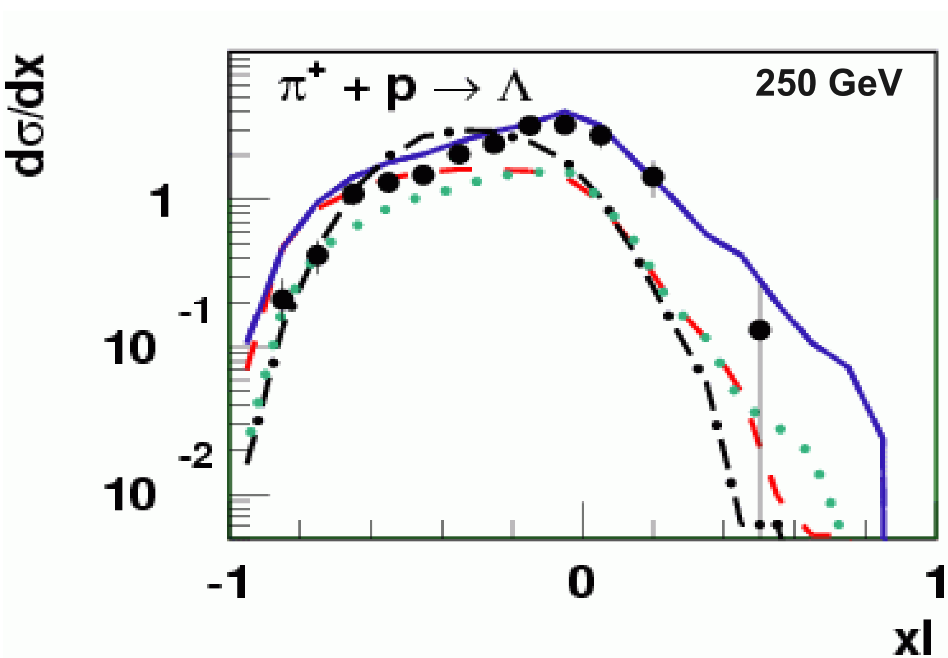


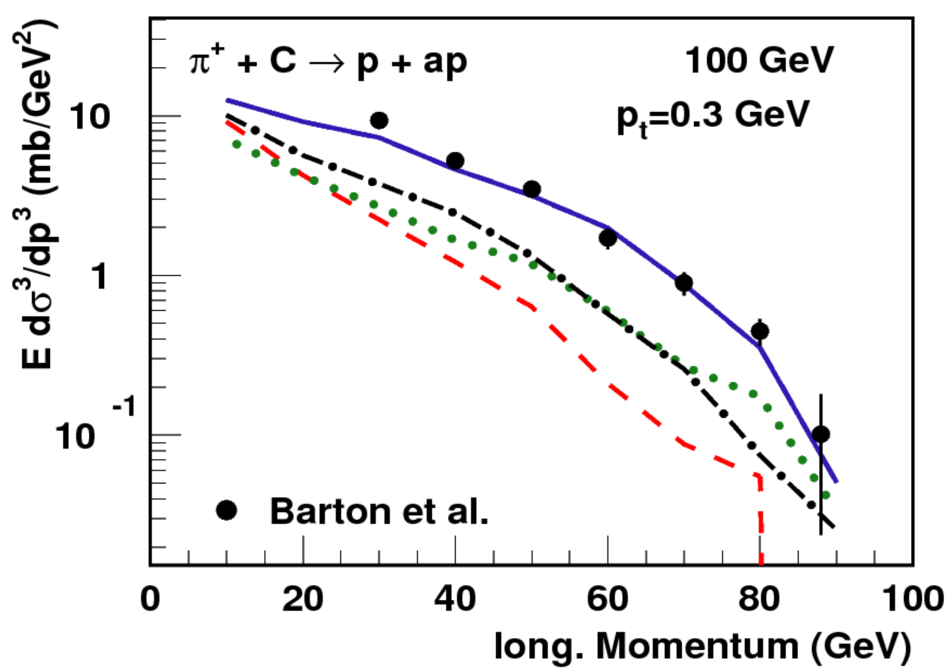
Baryon Spectra



- Large differences between models
- Need a new remnant approach for a complete description (EPOS)
- Problems even at low energy
- No measurement at high energy !

> Without remnant string fragmentation has to be changed for baryon production

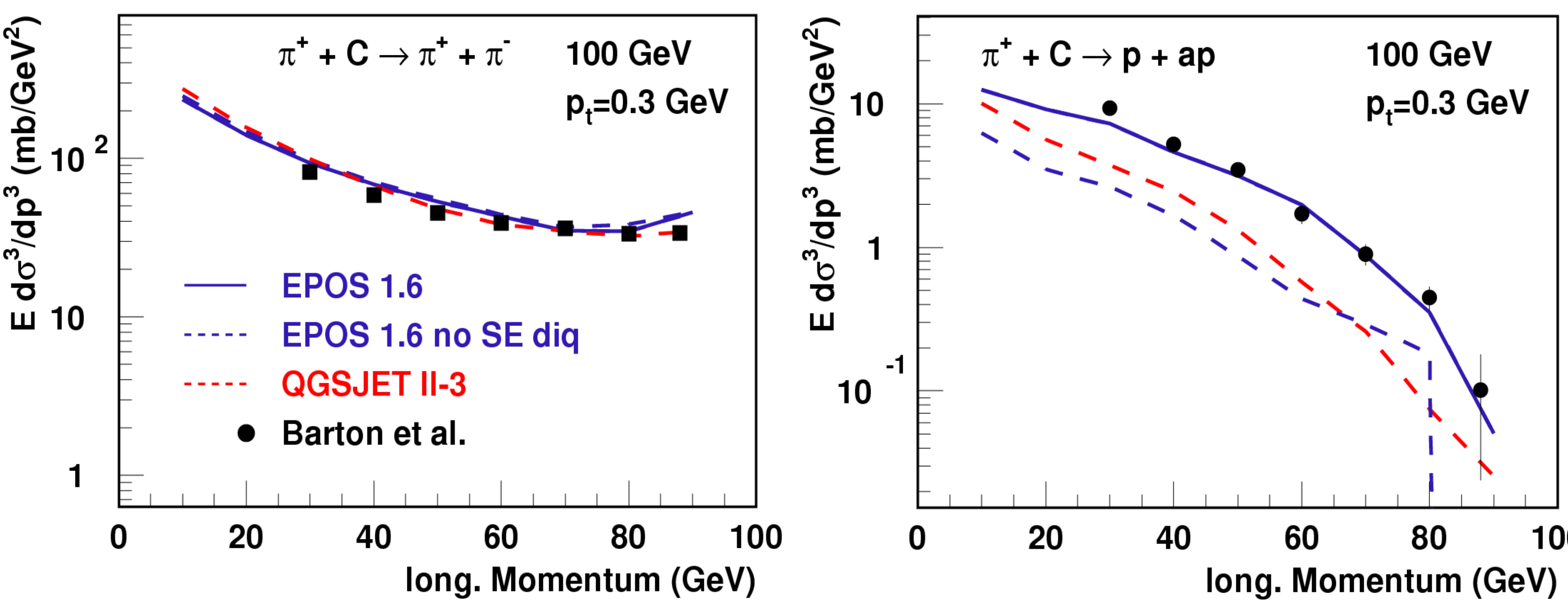




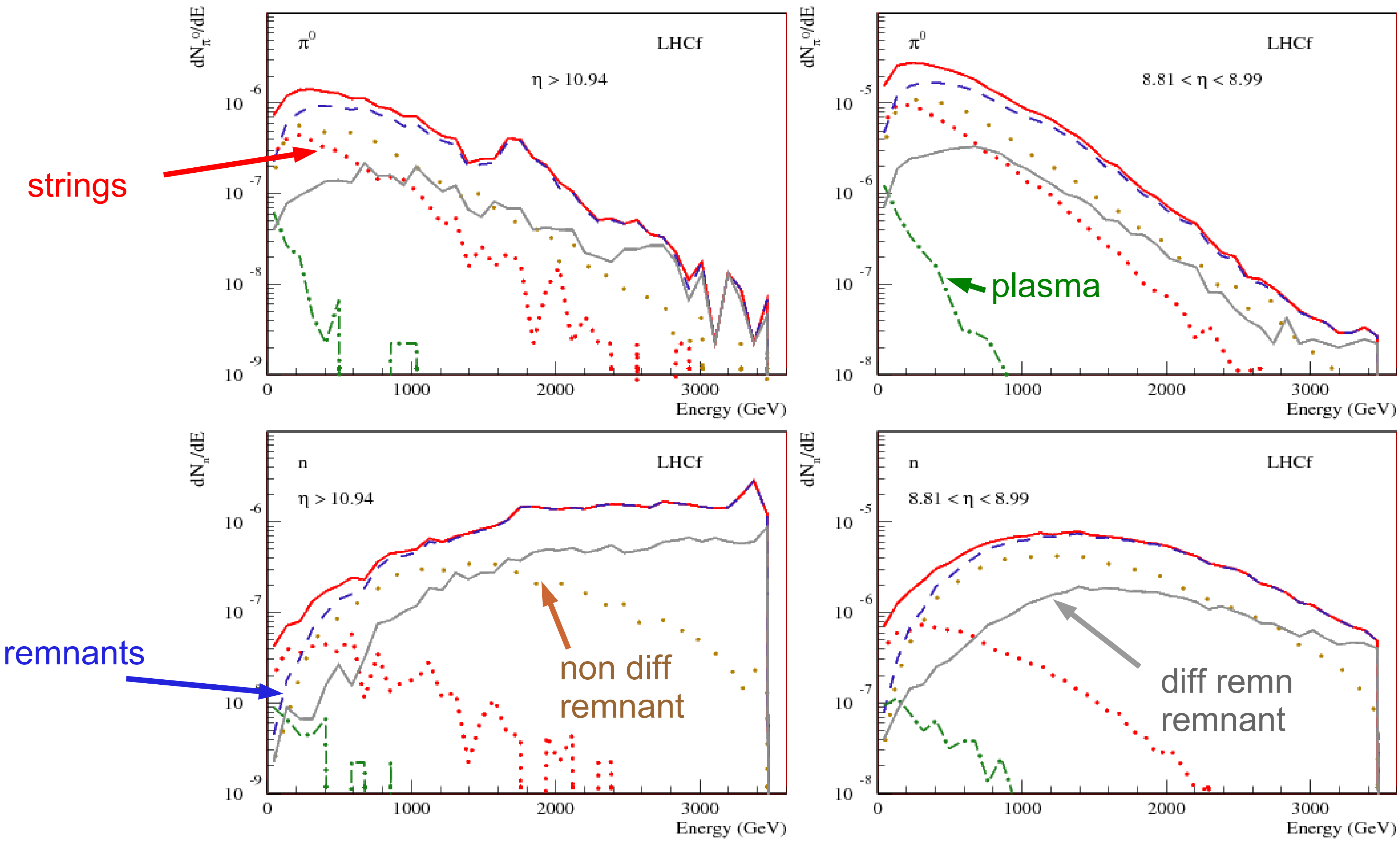
Baryons in Pion-Carbon

Very few data for baryon production from meson projectile, but for all :

- strong baryon acceleration (probability ~20% per string end)
- proton/antiproton asymmetry (valence quark effect)
- target mass dependence



Remnant contributions in LHCf



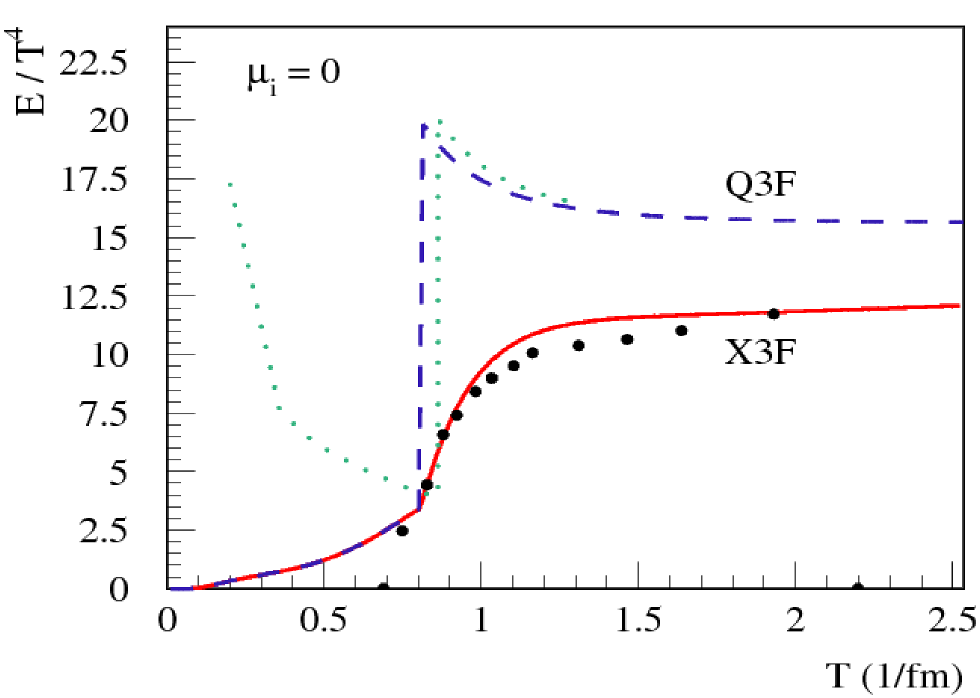
EoS

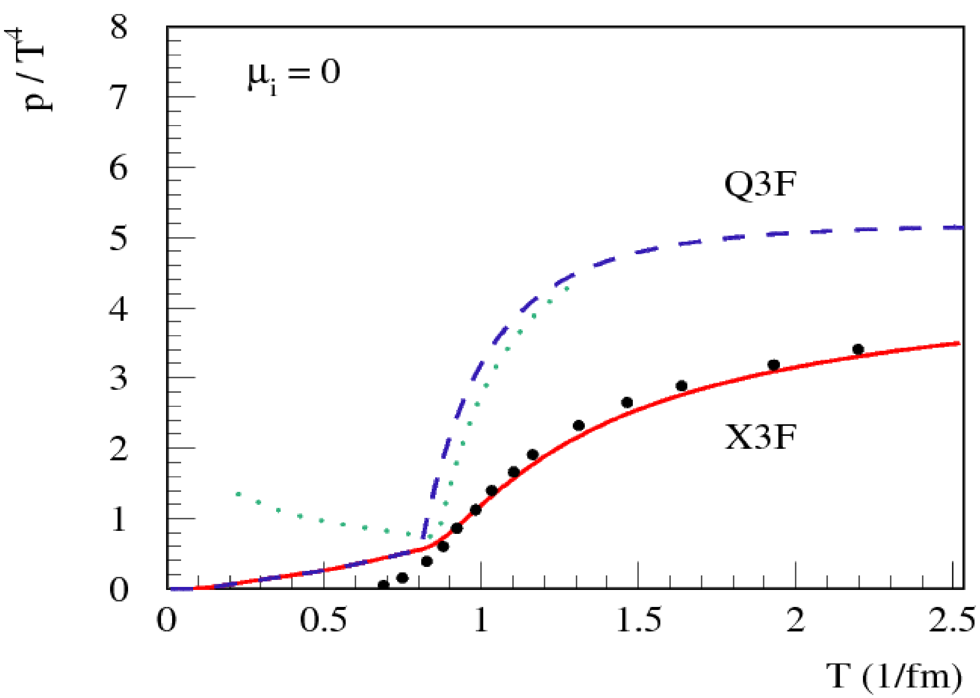
Hirano: QG & resonance gas => 1st order PT, PCE, $\mu_B = \mu_S = \mu_Q = 0$

Q3F: QG & "complete" resonance gas => 1st order PT, excl volume correction, μ_B, μ_S, μ_Q considered, parameters as in Spherio

X3F: crossover : $p = p_Q + \lambda(p_H - p_Q)$, $\lambda = \exp(-\frac{T-Tc}{\delta})\theta(T - T_c) + \theta(T_c - T)$

"data": Y. Aoki, Z. Fodor, S.D. Katz , K.K. Szabo, JHEP 0601:089,2006



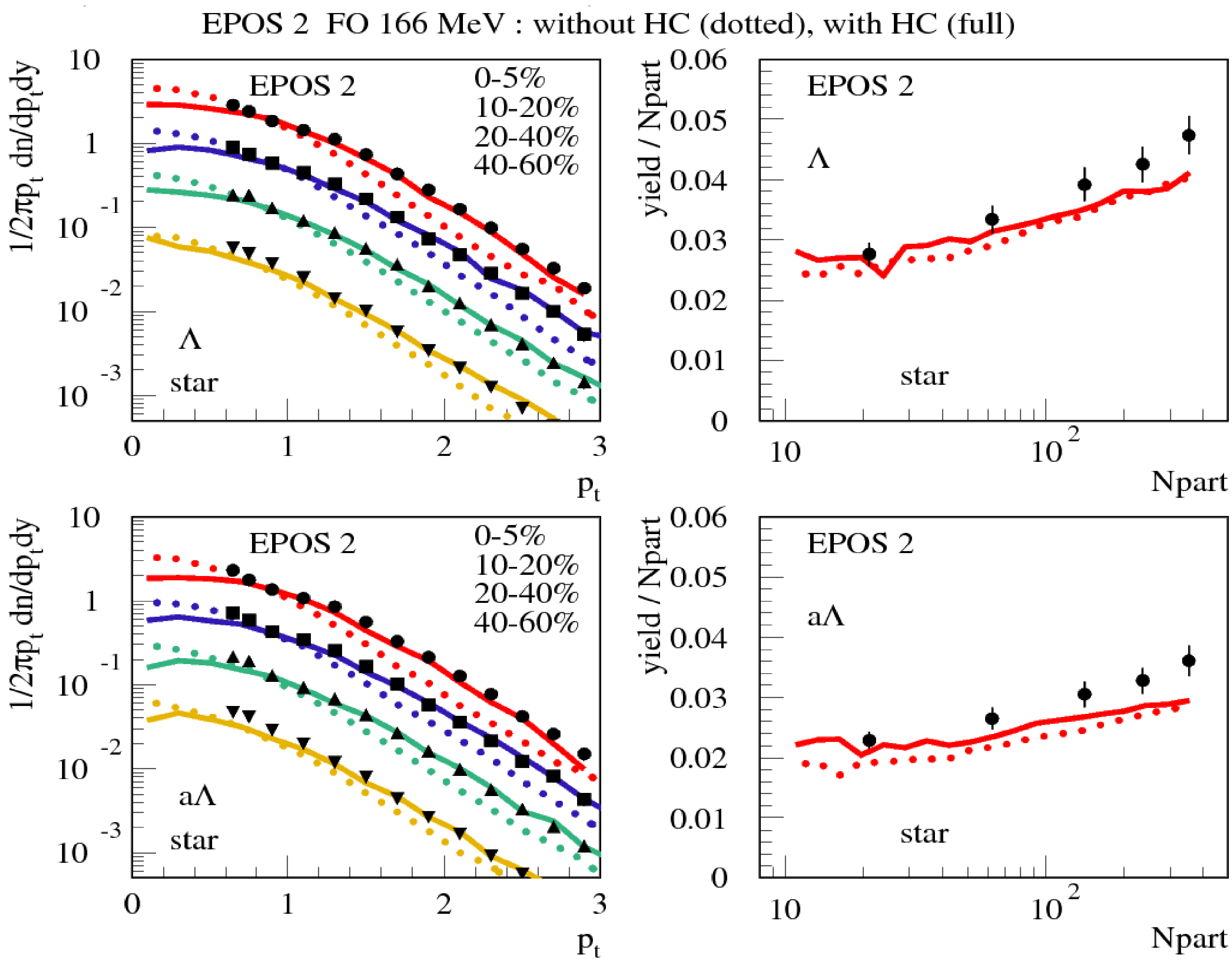


AuAu : Lambda

for better visibility:

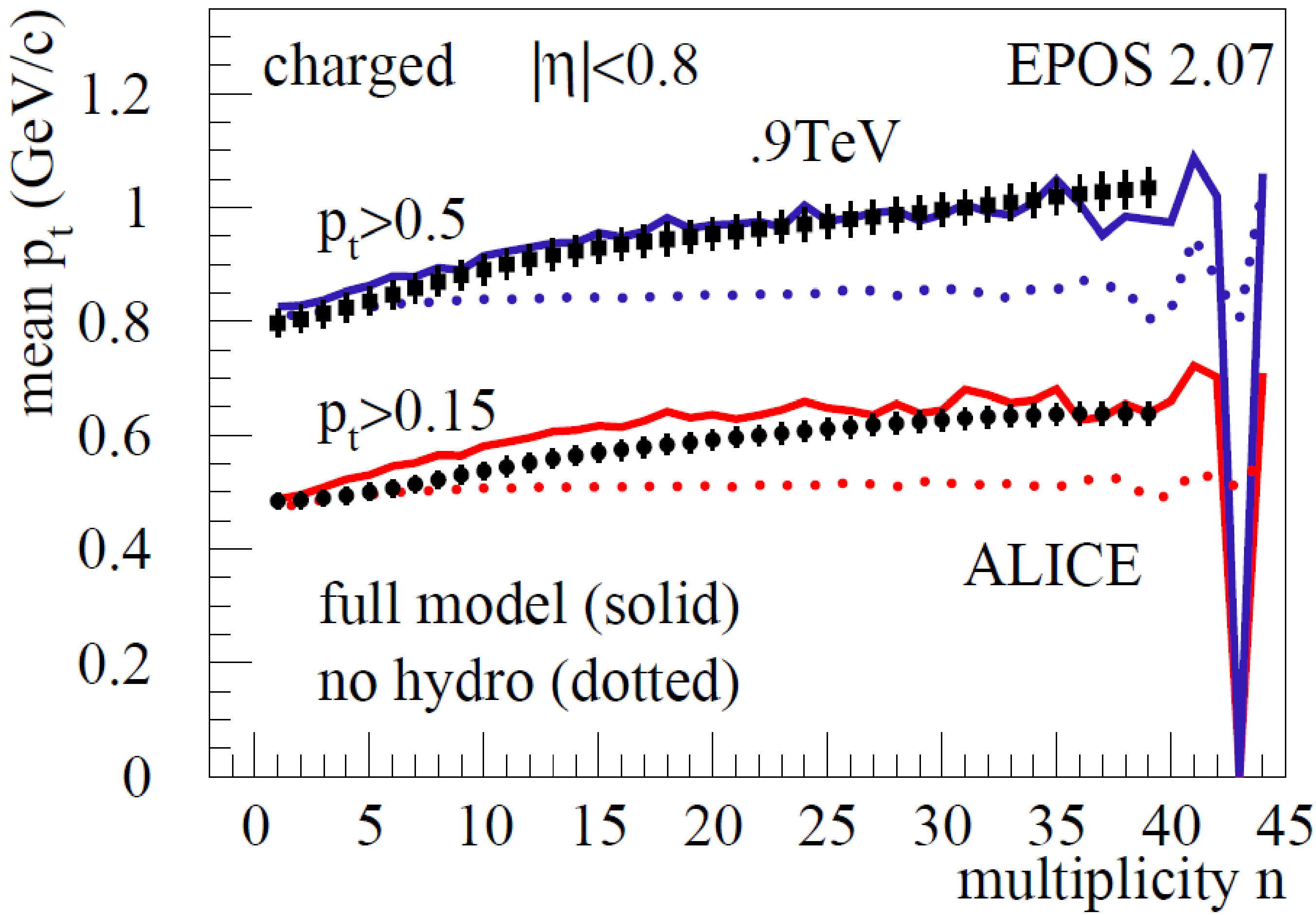
pt spectra scaled by

1/2 (10-20%)
1/4 (20-40%)
1/8 (40-60%)

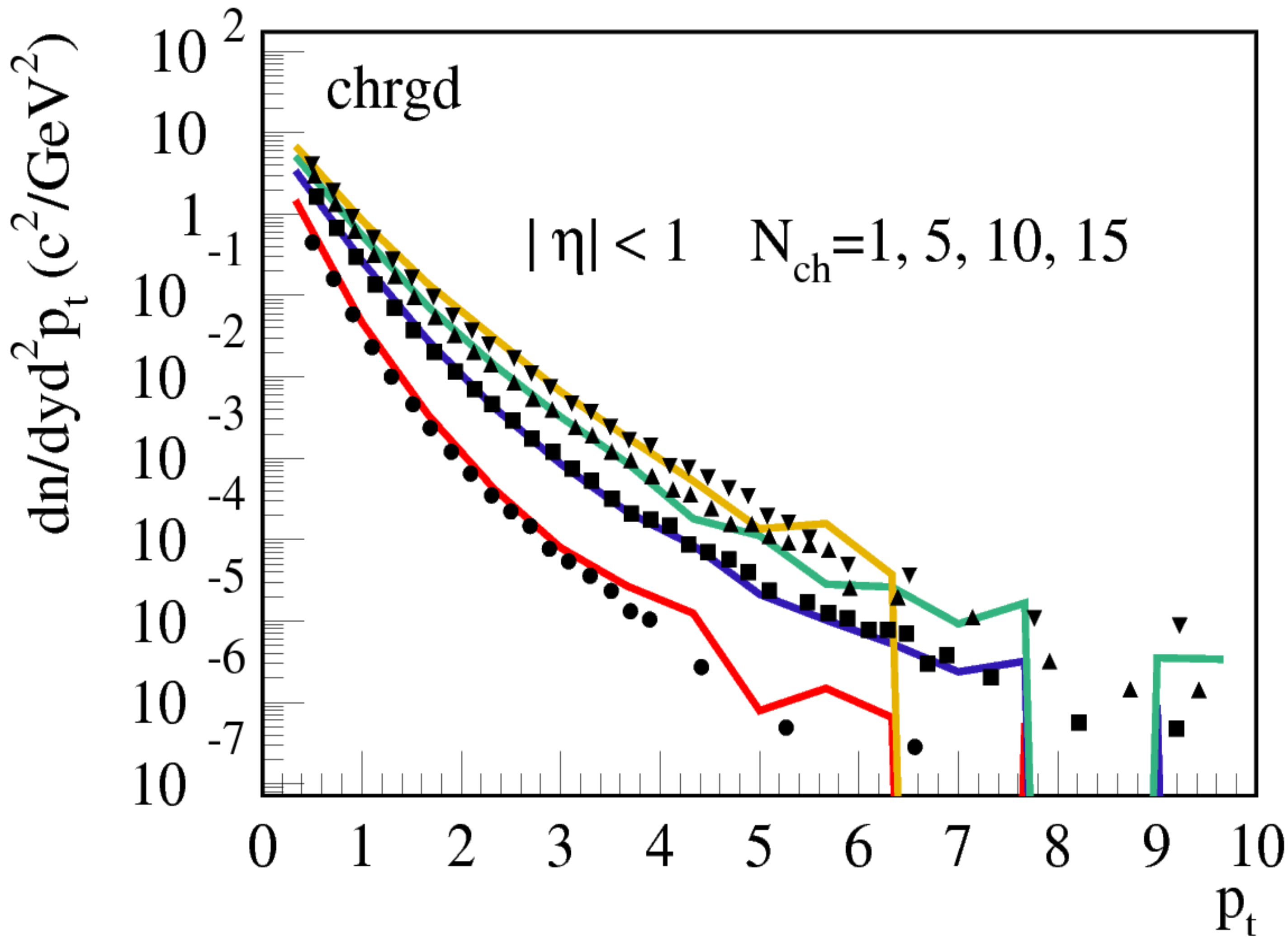


Pt Distribution

➡ Summarized in <Pt> versus multiplicity (here 900 GeV)



Pt distribution CDF ap-p@1.8 TeV with Hydro



Pt distribution CDF ap-p@1.8 TeV without Hydro