Soft QCD and the Production of Secondary Cosmic Rays

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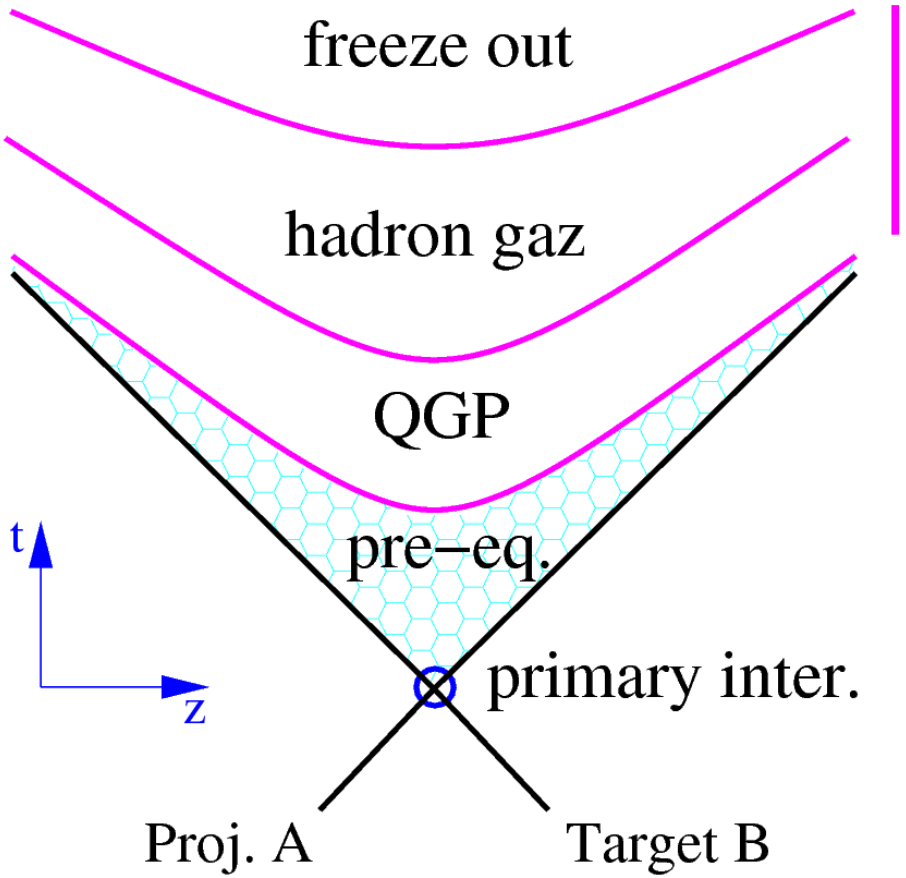
High Energy Hadronic Interactions



Collective Effects

General case : not only AA valid for pp if enough particles are produced !

Collective Hadronization

- 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

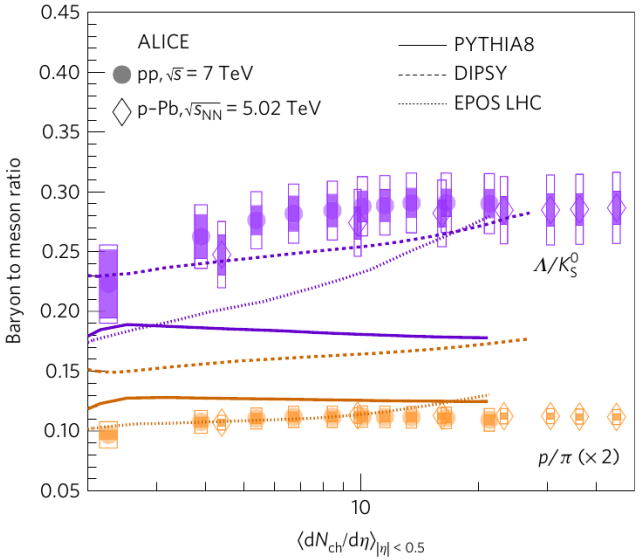
- mainly because azimuthal anisotropies (particle correlations) can be explained on the basis of ideal hydrodynamics (mass splitting, ridge, etc ...)

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

Global Approach

Moving from projectile/target to energy density (particle number)

- New point of view on particle production
- Continuity in particle ration evolution between pp, pPb and PbPb
- No model can reproduce every thing
  - PYTHIA : string only
  - DIPSY : overlapping strings with modified parameters
  - EPOS LHC : core/corona



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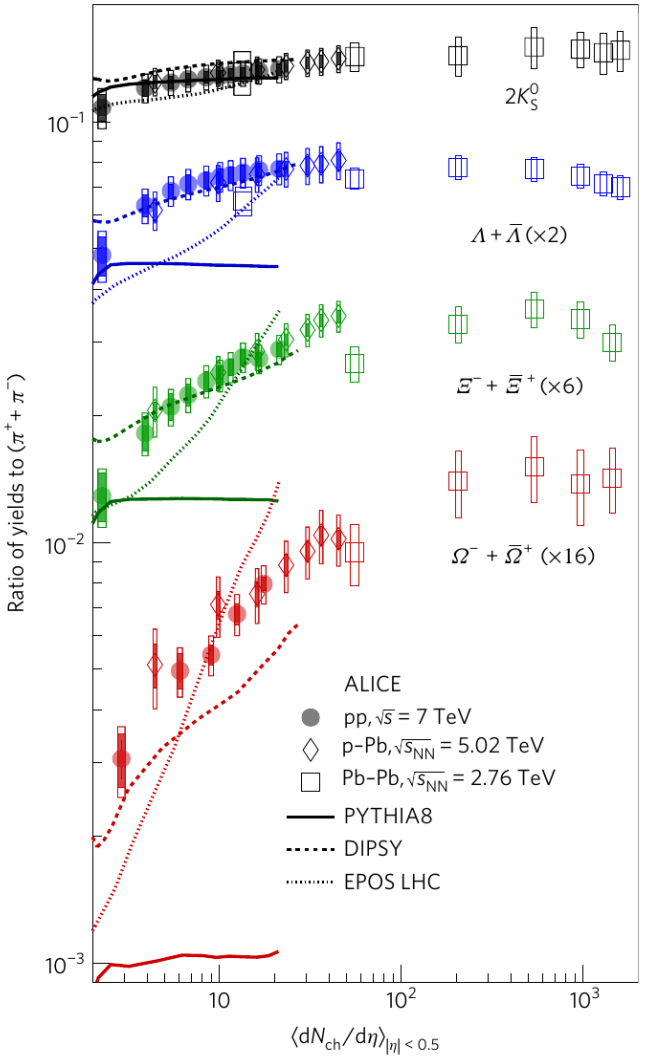
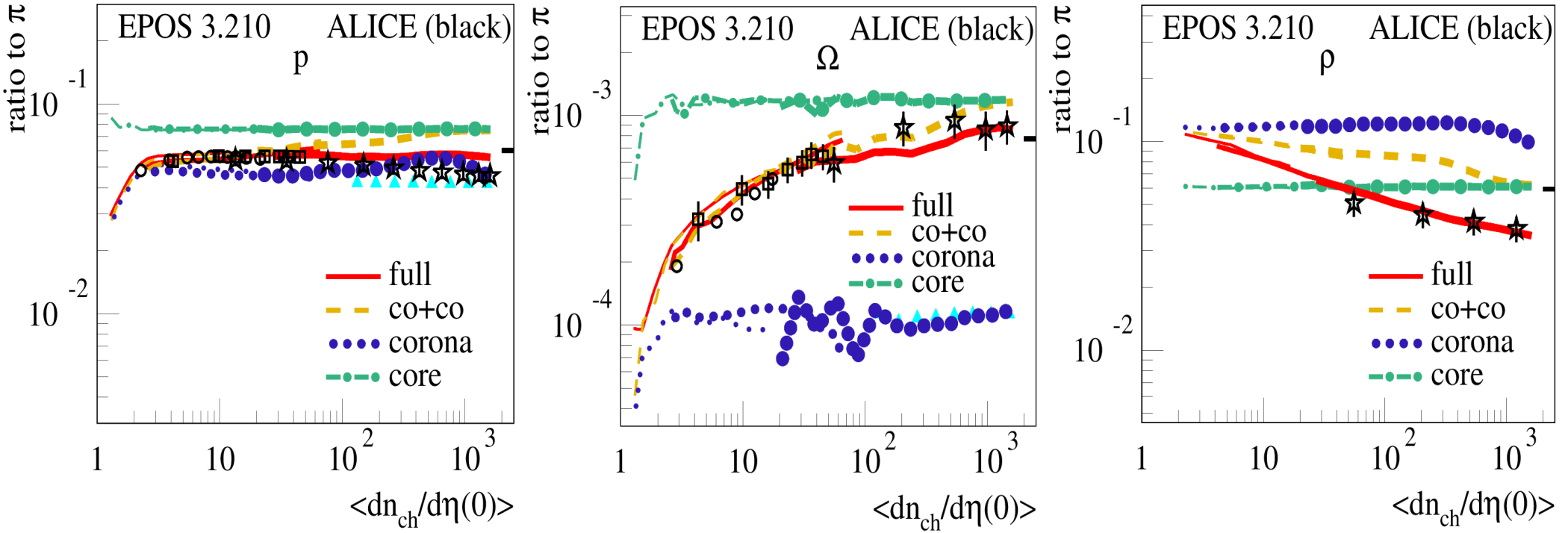


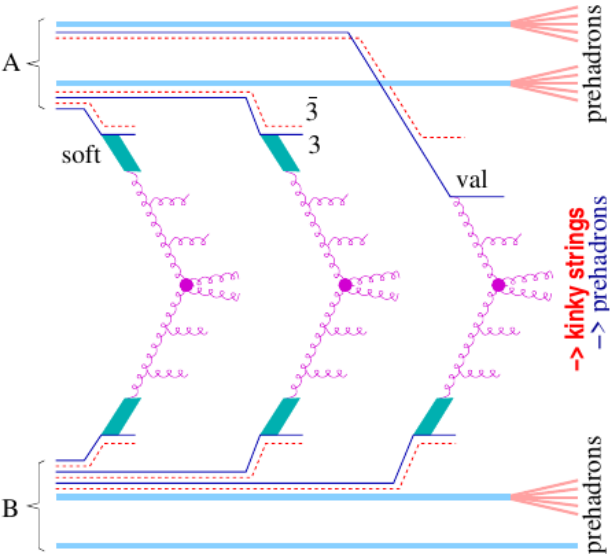
Global Approach : Core+Corona

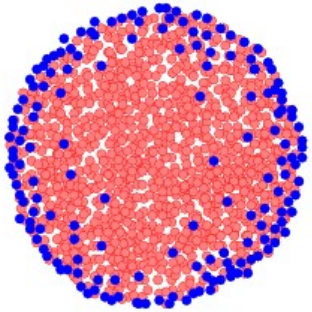
Moving from projectile/target to energy density (particle number)

- New point of view on particle production
- Good description achieved with core/corona + hadron reinteractions (hadron gas)
  - Same physics for all systems but different mixtures of the 2 components (low + high energy density hadronization)



The EPOS4 Project





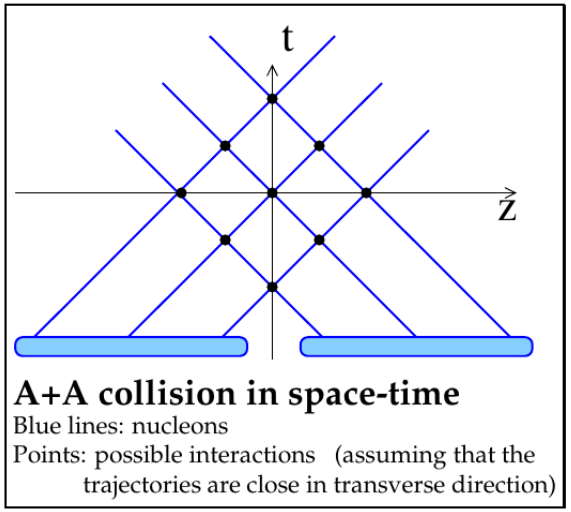
- NOT provide “another model” to study flow
- BUT a “complete” event generator
  - to do normal pp physics (total cross section, light flavor spectra, jets, charm,…)
  - which in addition accounts for collective effects in small systems
  - which in addition can handle nuclear scatterings from LHC to RHIC
- To check if we get a consistent overall picture

EPOS4 is designed as a general purpose approach (SPS, RHIC, LHC for pp or Heavy Ion), with conceptual problems of earlier EPOS versions being solved.

Parallel and Sequential Scattering in AA

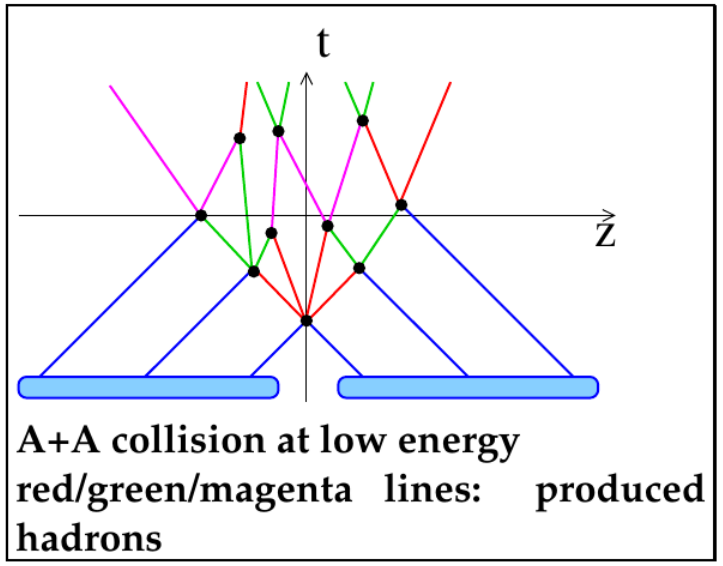
Crucial time scales

- $\tau_{collision}$ is the duration of the AA collision
- $\tau_{interaction}$ is the time between two NN interactions
- τ_{form} is the hadron formation time after the interaction of 2 nucleons



A+A collision in space-time
Blue lines: nucleons
Points: possible interactions (assuming that the trajectories are close in transverse direction)

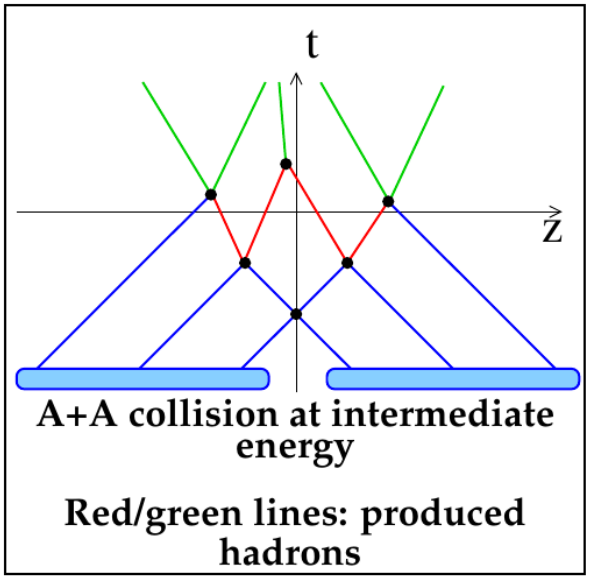
$\tau_{form} < \tau_{interaction}$



A+A collision at low energy
red/green/magenta lines: produced hadrons

- Sequential Collisions (cascade)

$4 < \sqrt{s_{NN}} < 24$ GeV

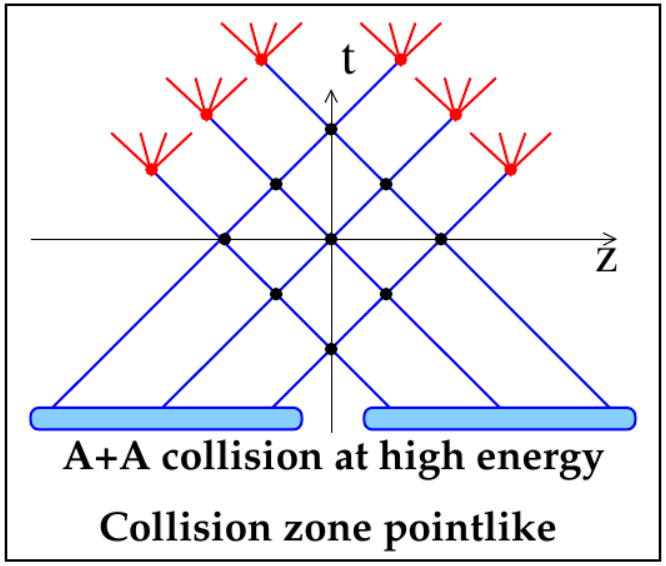


A+A collision at intermediate energy

Red/green lines: produced hadrons

- "partially parallel approach"

$\tau_{form} >> \tau_{collision}$



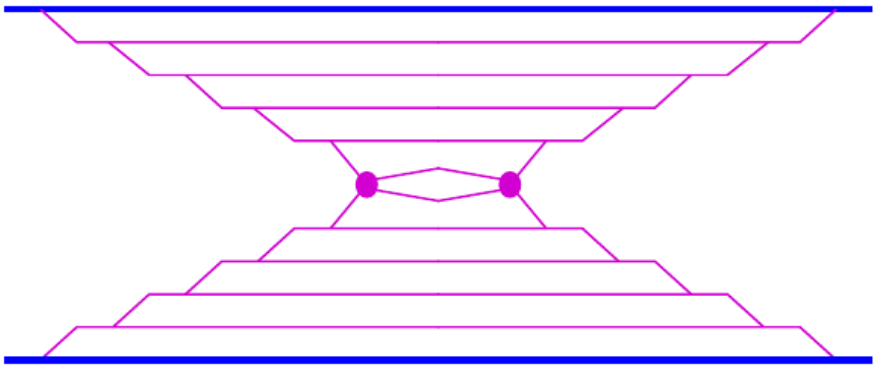
A+A collision at high energy

Collision zone pointlike

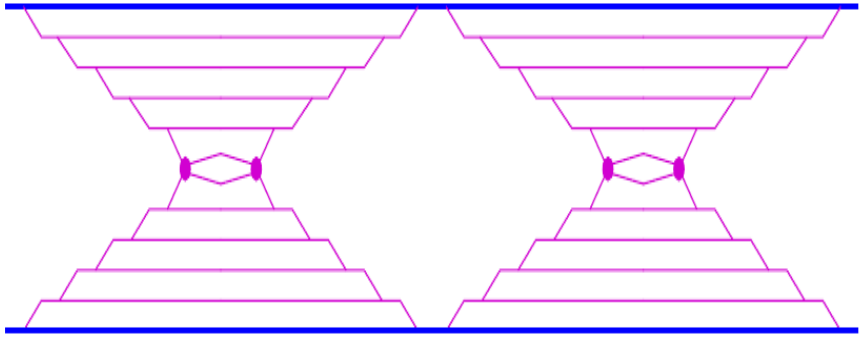
- Parallel interactions (simultaneous)

Parallel Approach in pp

- **At LHC energy**
  - Interaction = successive parton emissions
  - Large gamma factors
  - very long lived ptls
- **The complete process takes a very long time**



pp collision
Exchange of parton ladder



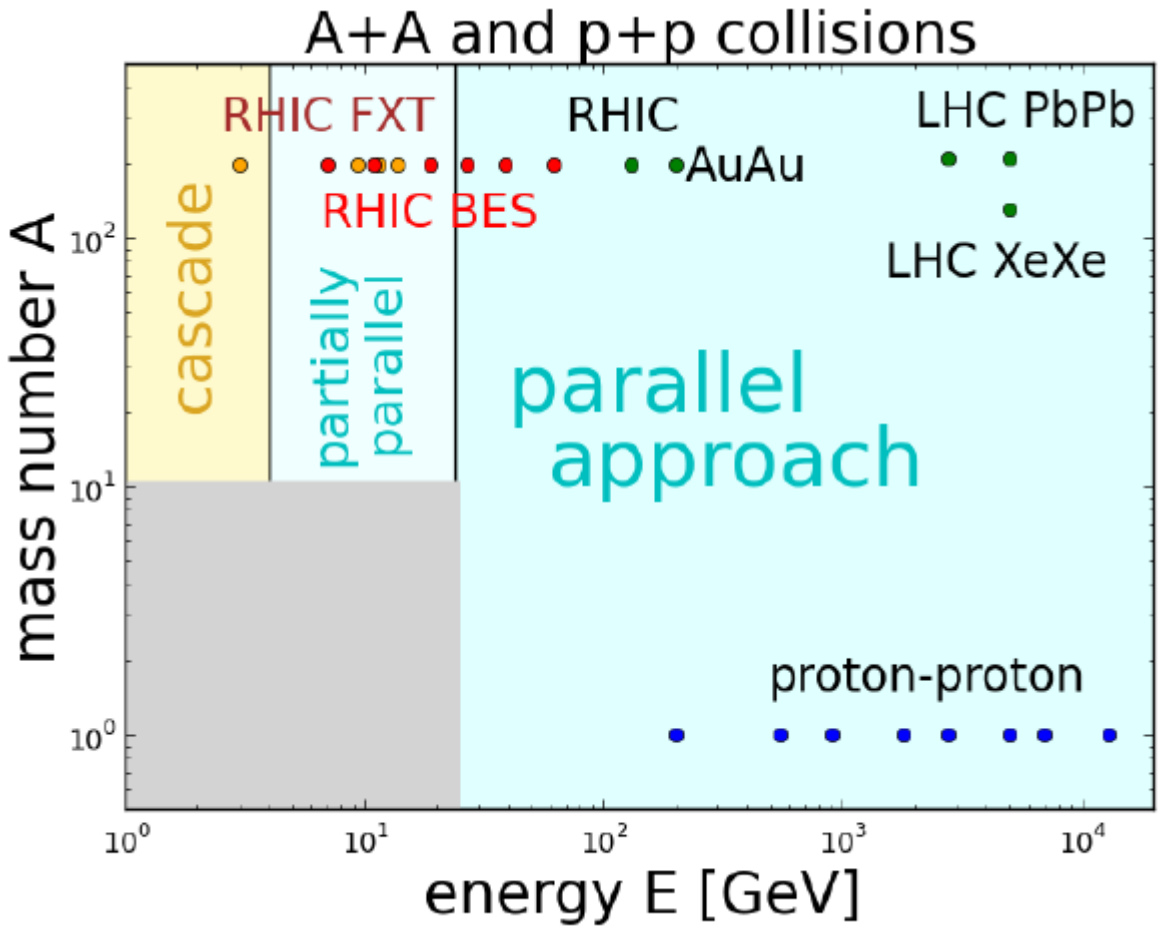
- **Impossible to have several of these interactions in a row**
  - So also in pp: High energy approach
    - parallel interactions

- **In High energies approach** (= parallel primary interactions for pp and AA)**, one can completely separate**
  - primary interactions (at t ≈ 0)
  - and secondary interactions (core-corona, hydro evolution, had. rescat., etc)

EPOS: Parallel Scattering

From very elementary time scale arguments:

- parallel scheme needed everywhere beyond 25 AGeV
- partly beyond 4 AGeV



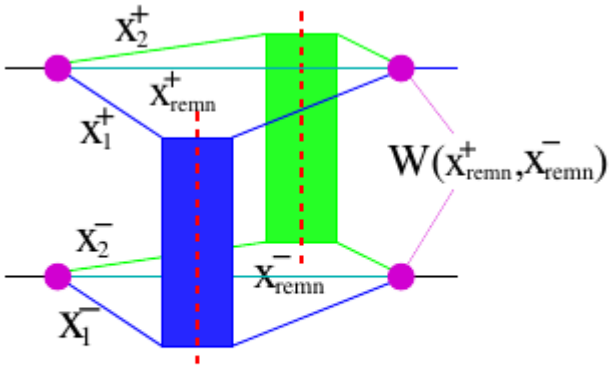
EPOS:
Primary scatterings (at t = 0)
parallel scattering approach based on S-matrix theory

From comparison with data :
Below 20 GeV “parallel scattering” fails, “partially parallel scattering” should be implemented (in principle straight-forward), definitely needed at 7.7 GeV. Below 4 GeV no point to use EPOS4 (see arXiv:2401.11275).

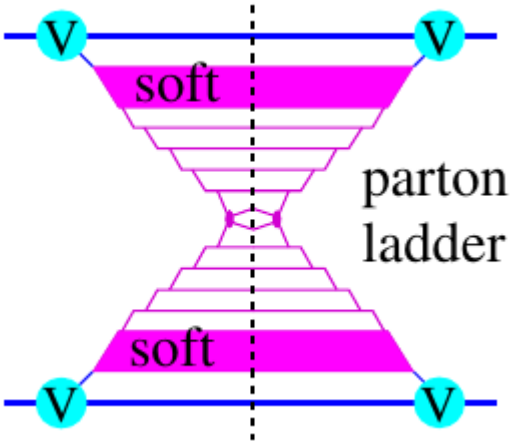
EPOS4 S-matrix Approach

Very compact summary (details: arXiv:2301.12517)

- Start: elastic scattering T-matrix *T* for pp scattering
- = product of "elementary" T-matrices (parton-parton scatterings)
  - pp->AA trivial: product of T-matrices per NN pair
  - Taking into account energy sharing in each pairs
- Connection to inelastic: optical theorem / cutting rules
  - cross section = sum of products of "cut Pomerons"
- cut Pomeron = squared inelastic amplitude = G
  - Pomeron linked to QCD object (DGLAP) = G_{QCD}
  - ends up as two (or more) kinky strings



two cut Pomerons
(QCD inside)

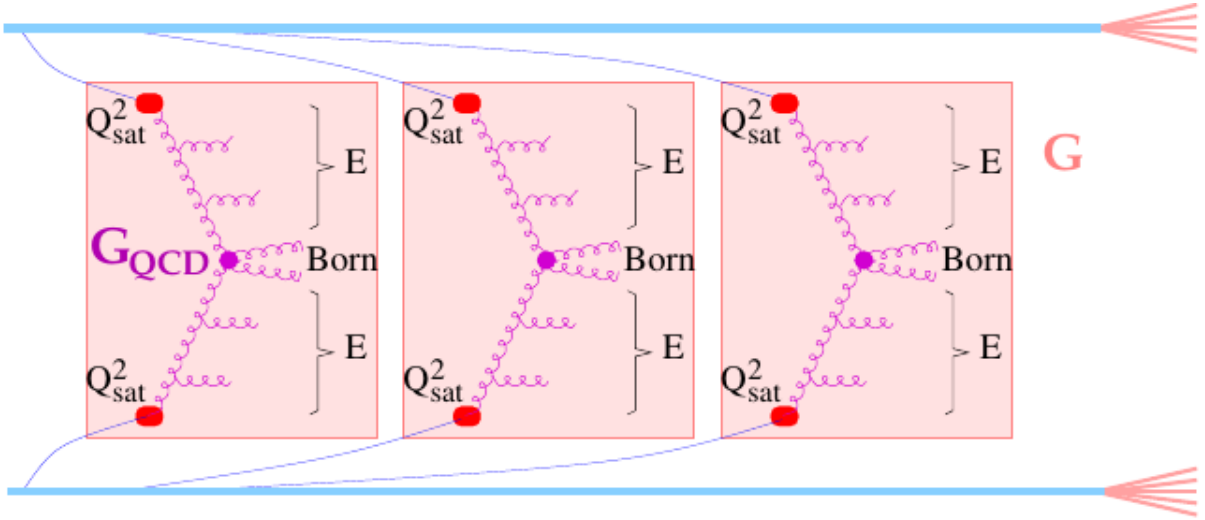


*) Relation S-matrix - T-matrix: $\mathbf{S}_{fi} = \delta_{fi} + i(2\pi)^4 \delta(p_f - p_i)\mathbf{T}_{fi}$
$T = \mathcal{F}[\mathbf{T}_{ii}]/(2s)$ (Fourier transform w.r.t. to transv. momentum , depends on b)

Primary Scatterings: Connecting GR+ and pQCD

Expressing G in terms of G_{QCD}

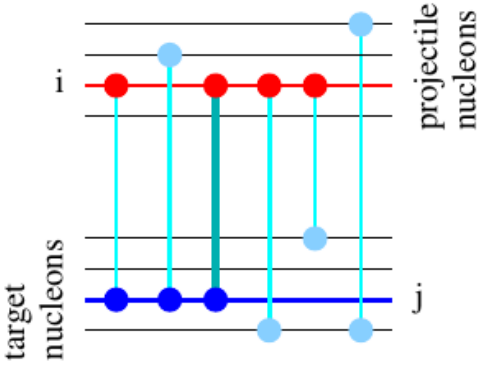
➡ $G = G_{QCD}$ not working in case of energy sharing



G = imaginary part of T-matrix over s in impact parameter representation ("cut diagram")

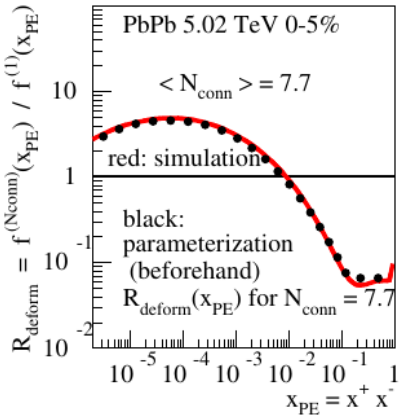
Not trivial to recover AGK (->binary scaling, factorization)

solution : $$G(x) = \frac{1}{R_{\mathrm{deform}}(N_{\mathrm{conn}}, x)} \times G_{\mathrm{QCD}}\left(Q^2_{\mathrm{sat}}(N_{\mathrm{conn}}, x),\ x\right)$$



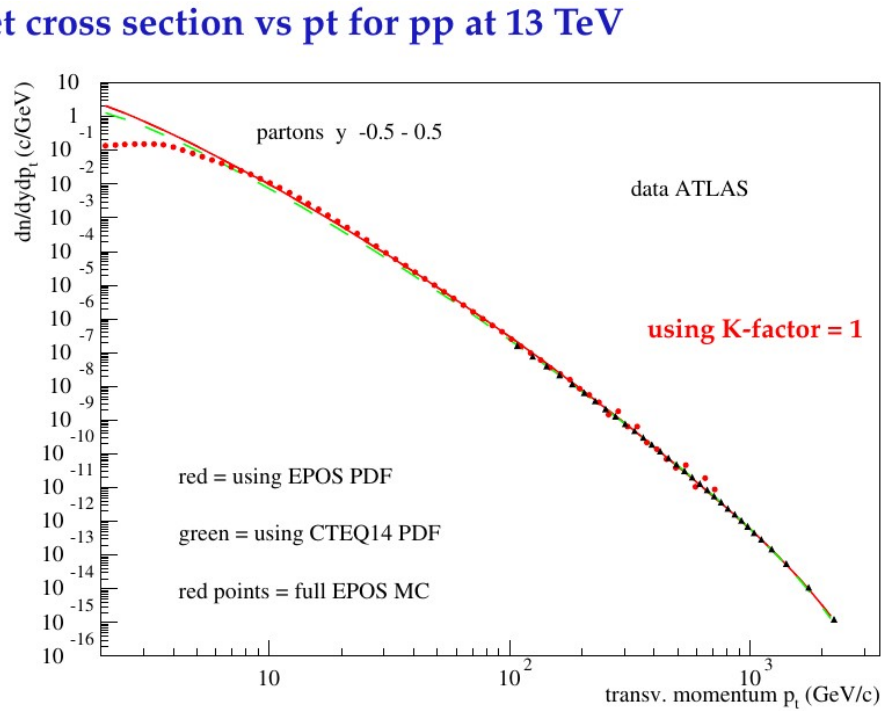
➡ N_{conn} = number of Pomerons connected to same nucleons (in AA)

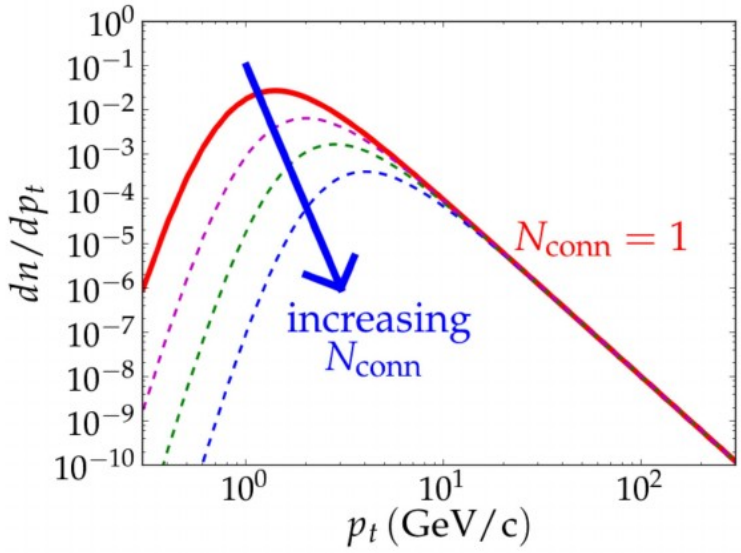
➡ R_{deform} = modification of Pomeron's energy distribution ($x = s_{Pom}/s$)

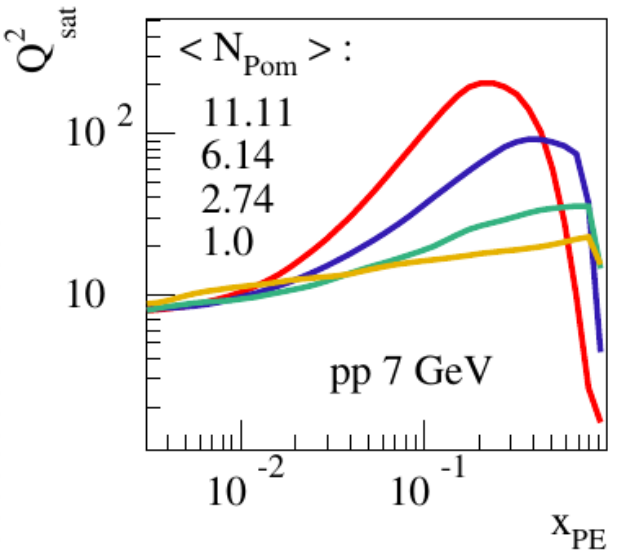


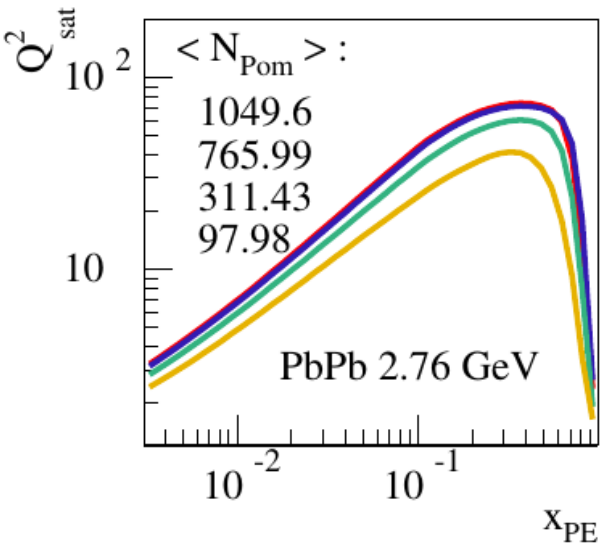
Saturation Scale Q^2_{sat}

- **G does not depend on N_{conn}**
  - Q^2_{sat} depends on x+ ,x − , N_{conn}
  - which perfectly solves the "R_{AA} problem"
- **the model can be used to study hight pt and low pt phenomena**
  - For large N_{conn}, low pt is suppressed, the Pomeron gets "hard".



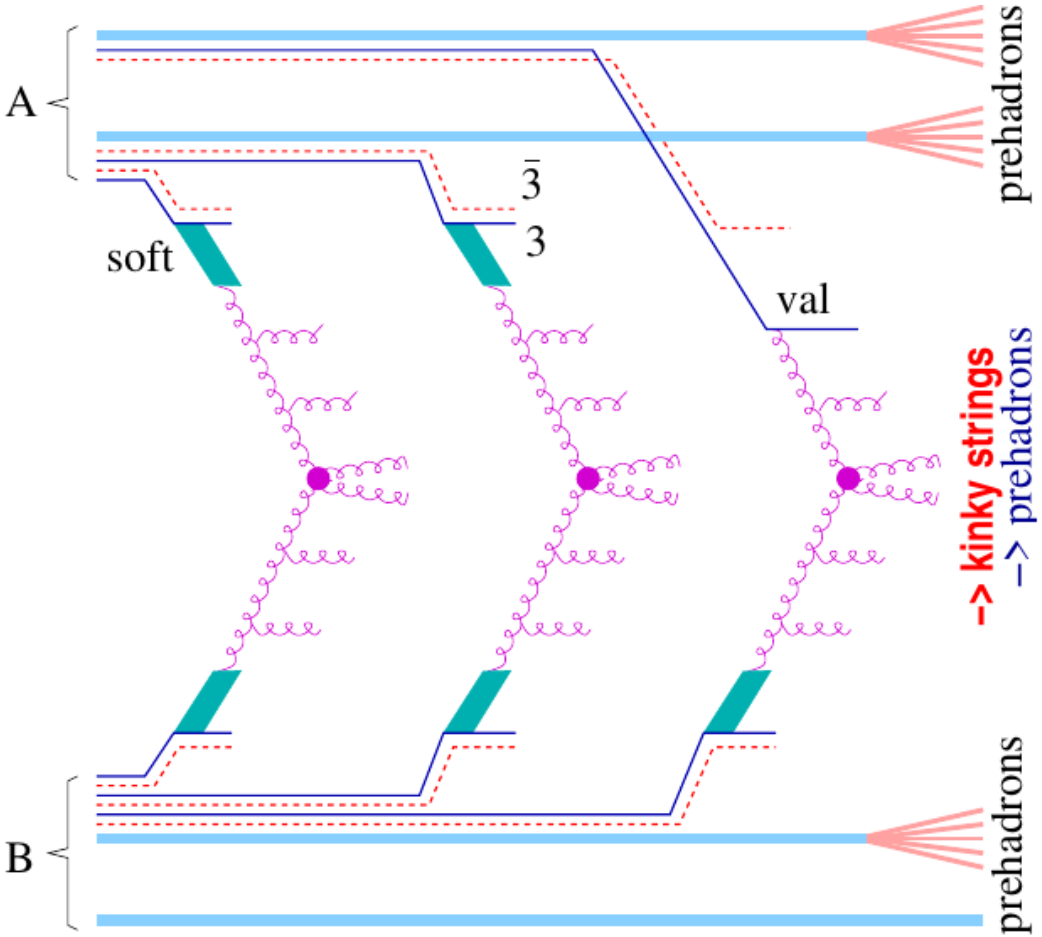






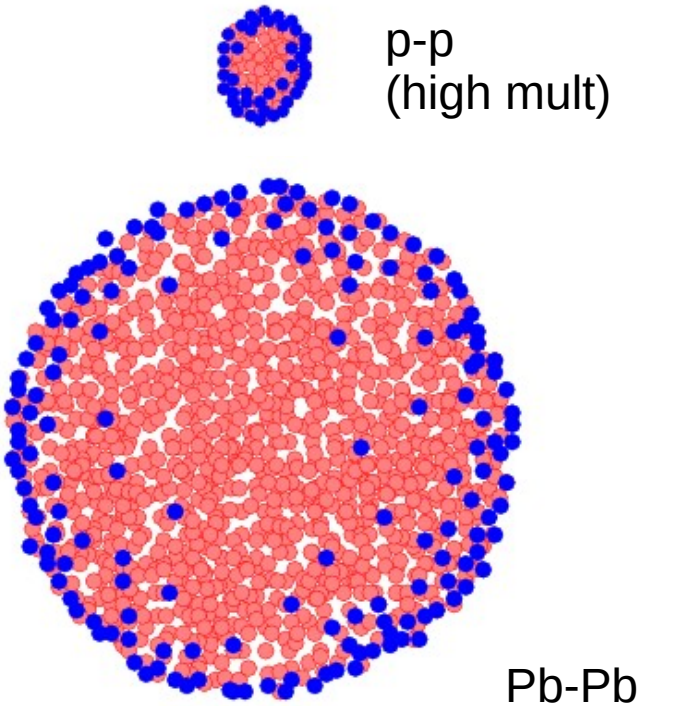
From Pomerons to Prehadrons

- **Very compact summary** (details: arXiv:2306.02396) :
  From multiple Pomeron configurations, after making the link with pQCD, we get partonic configurations
  - color flow diagrams
  - parton chains
  - kinky strings
  - Prehadrons
- **also: remnants**
  - Prehadrons
- **At the end: many prehadrons**



Core-corona separation (1)

- **We consider all prehadrons (at given τ). For each one, we estimate its energy loss if it would move out of this system**
  - If the energy loss is bigger than the energy of the prehadron, it is considered to be a "core prehadron"
  - If the energy loss is smaller than the energy, the prehadron escapes, it is called "corona prehadron"
- **The core prehadrons constitute "bulk matter"**
  - which will be treated via hydrodynamics and decays eventually microcanonically (NEW)
- **The corona prehadrons become simply hadrons**
  - propagate with reduced energy
- **Details: arXiv:2306.10277**



p-p
(high mult)

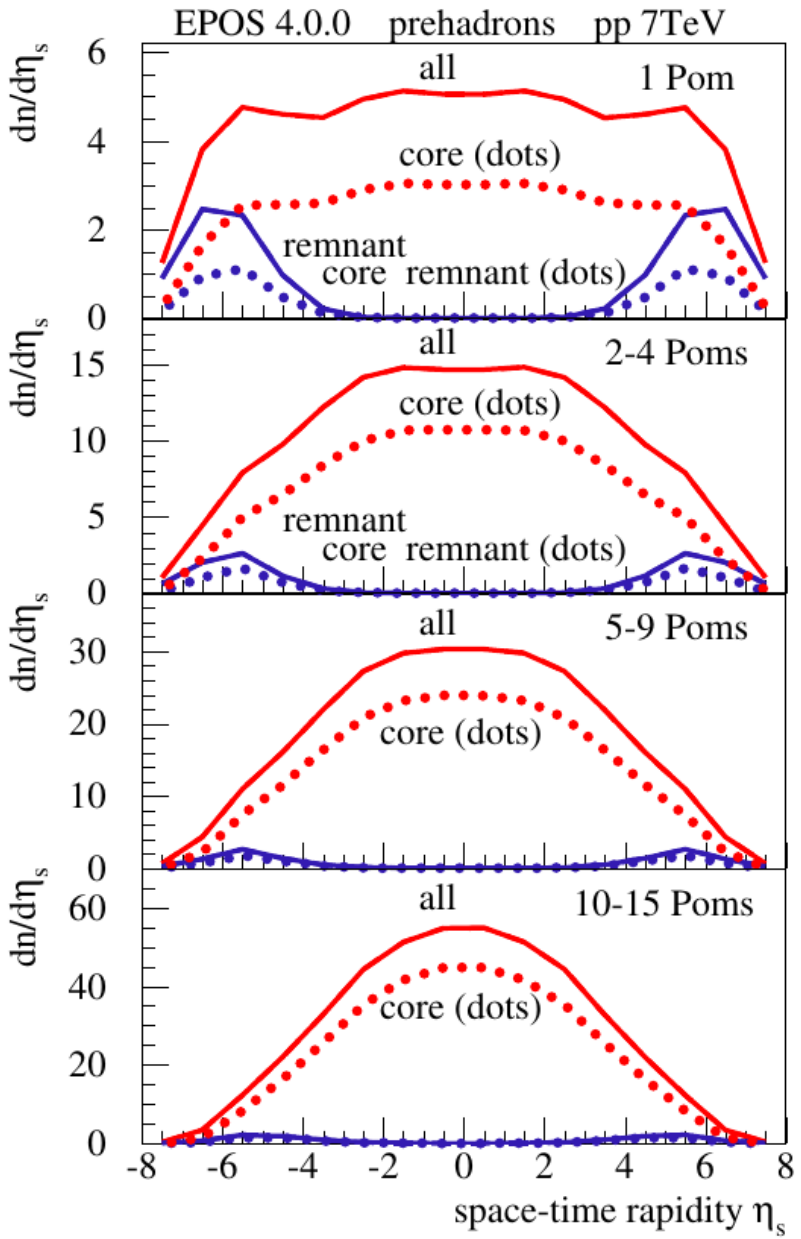
Pb-Pb
(central)

Core-corona separation (2)

- **The prehadron yield as a function of space-time rapidity, for different Pomeron numbers in proton-proton collisions at 7 TeV.**

- **Prehadrons**
  - all (red full)
  - core (red dotted)
  - remnant (blue full)
  - core remnant (blue dotted)

- **For core:**
  - compute $T^{\mu\nu}$ and flavor flow vector
  - then hydro evolution.



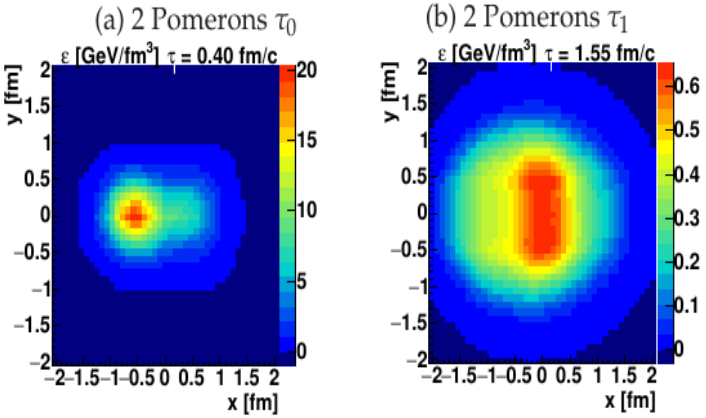
Microcanonical Hadronization of Core (1)

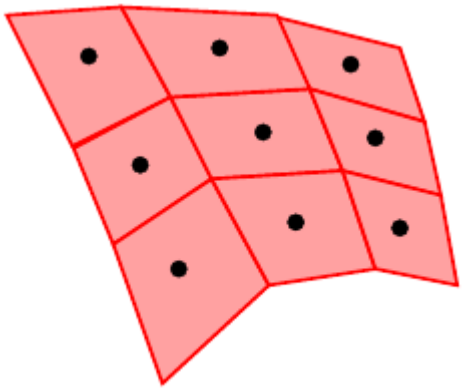
- **After Hydro evolution**

- **Based on flow of momentum vector dP^{μ} and conserved charges dQ_A through the hypersurface element $d\Sigma_{\mu}$ †**

  (hypersurface Σ defined via constant energy density)

  - Real hadronization (not transition fluid-particles)
    - (sudden statistical decay)
  - Energy-momentum and flavor conservation
    - (important for small systems)
  - Extremely fast
    - (major technical impovements in EPOS4)





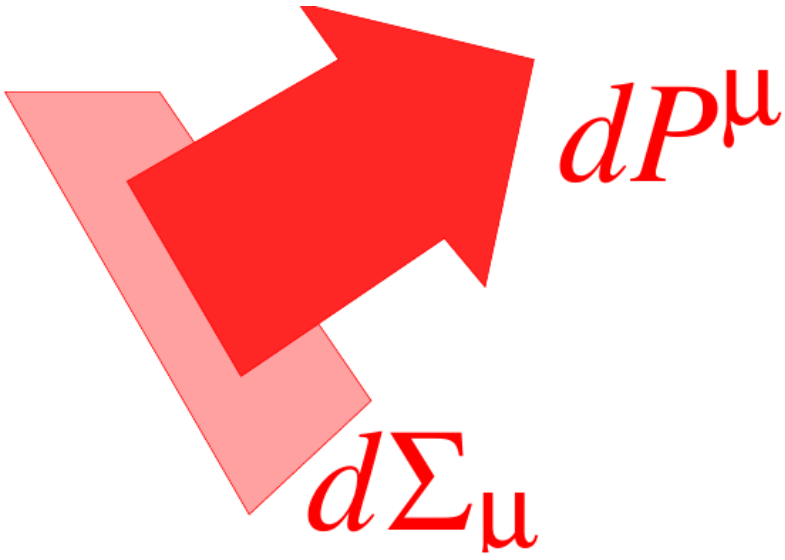
†) $d\Sigma_\mu = \varepsilon_{\mu\nu\kappa\lambda} \frac{\partial x^\nu}{\partial \tau} \frac{\partial x^\kappa}{\partial \varphi} \frac{\partial x^\lambda}{\partial \eta} d\tau\, d\varphi\, d\eta$

Surface: $x^0 = \tau \cosh \eta$, $x^1 = r \cos \varphi$, $x^2 = r \sin \varphi$, $x^3 = \tau \sinh \eta$, with $r = r(\tau, \varphi, \eta)$

Microcanonical Hadronization of Core (2)

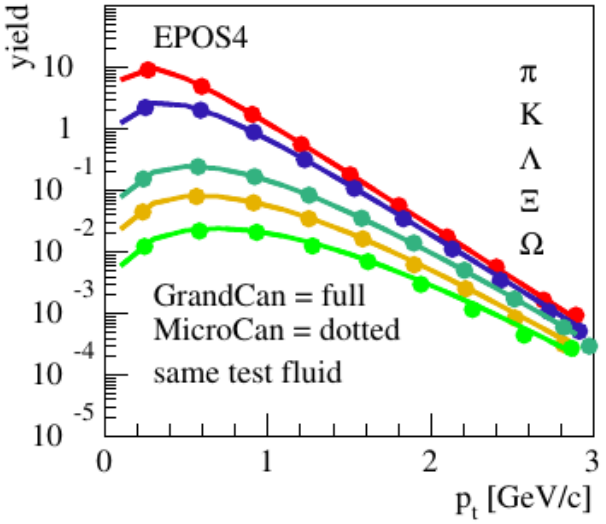
$$dP^\mu = T^{\mu\nu} d\Sigma_\nu$$
$$dQ_A = J^\nu_A d\Sigma_\nu$$

with conserved charges
$A \in \{C, B, S\}$



Construct an effective mass by summing surface elements:
$M = \int_{\text{surface area}} dM,$

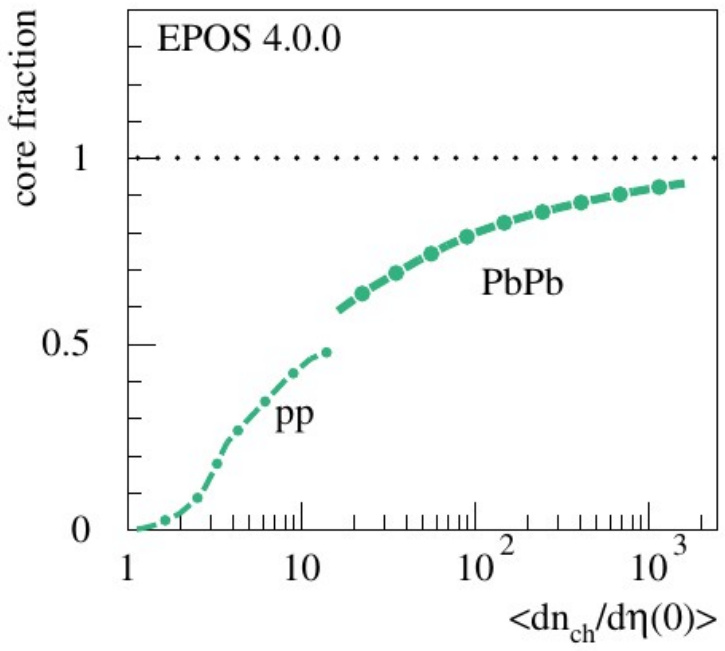
Decay M microcanonically



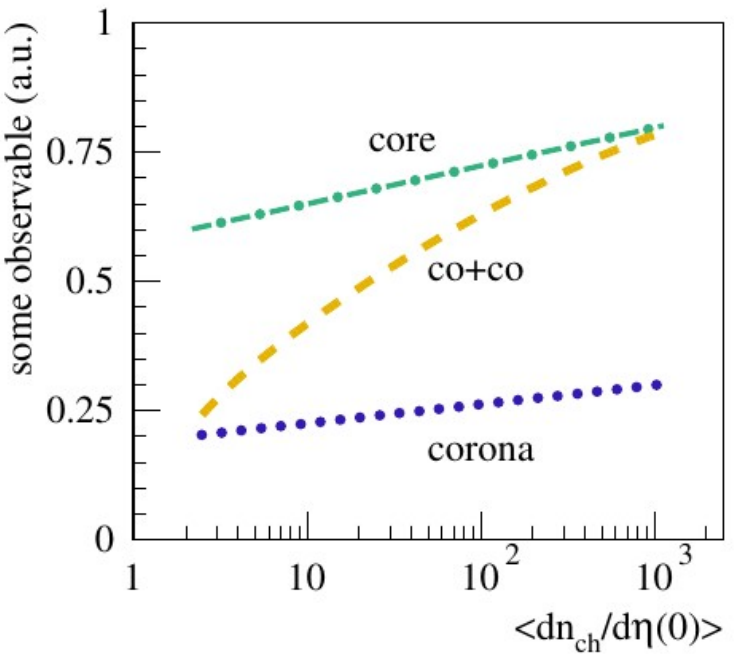
- **"give back" flow**
  - by placing particles on Σ following dM/dτdφdη
  - boosting them according to $U^\mu(\tau,\varphi,\eta) = dP^\mu / dM$
- **Details: arXiv 2306.10277**

Core + corona results - multiplicity dependencies

Core fraction



Core + corona (co+co) results (sketch)



Almost continuous!

- see DCCI2, Y. Kanakubo et al Phys. Rev. C 105 (2022) 2, 024905

Transition from corona core

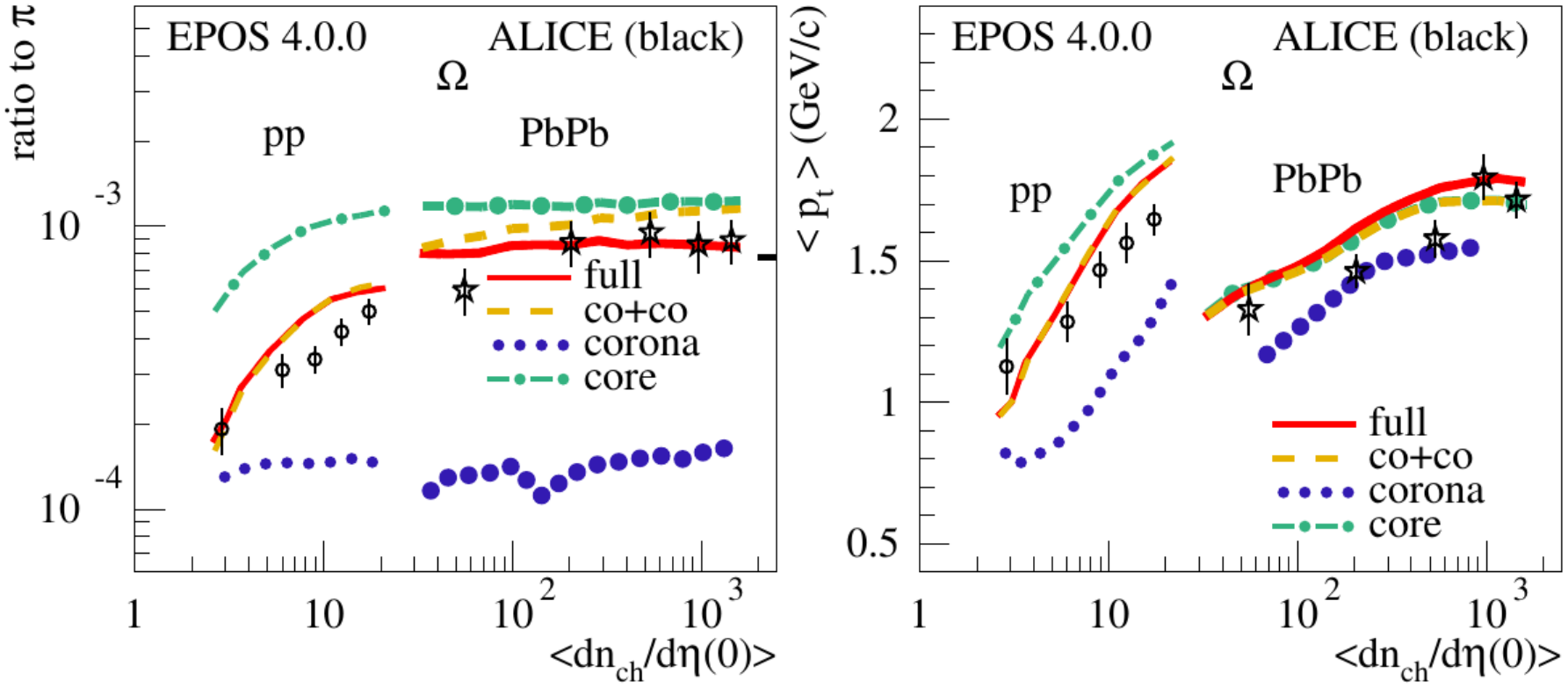
- Attention ! Core and corona curve continuous ... or not (depends on variable)

- On top: effects from hadronic cascade (UrQMD, S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 225 (1998), M. Bleicher et al., J. Phys. G25, 1859 (1999))

Yield Ratio and <pt>

continuous curve

jump



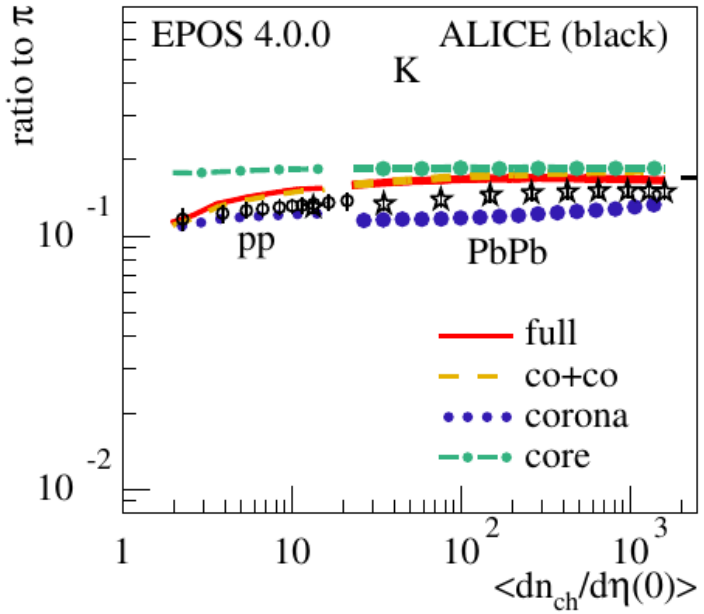
Yields affected by:

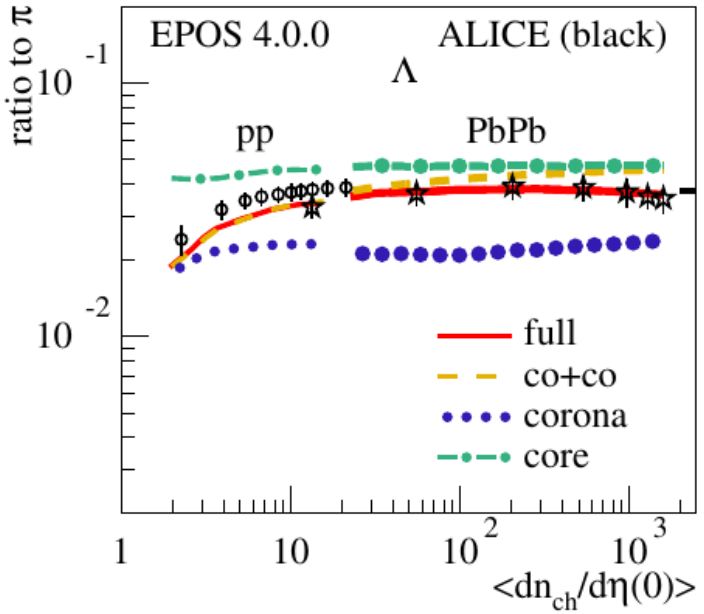
- core-corona
- microcanonical
- hadronic cascade (UrQMD)

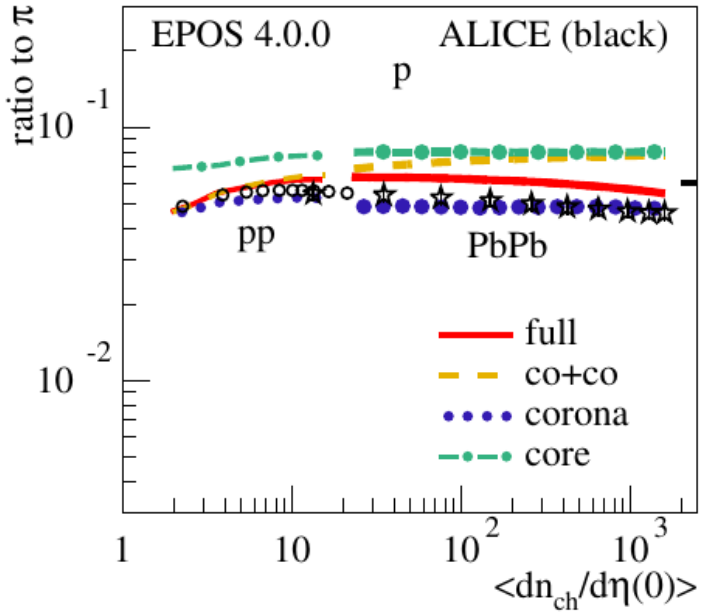
<pt> affected by

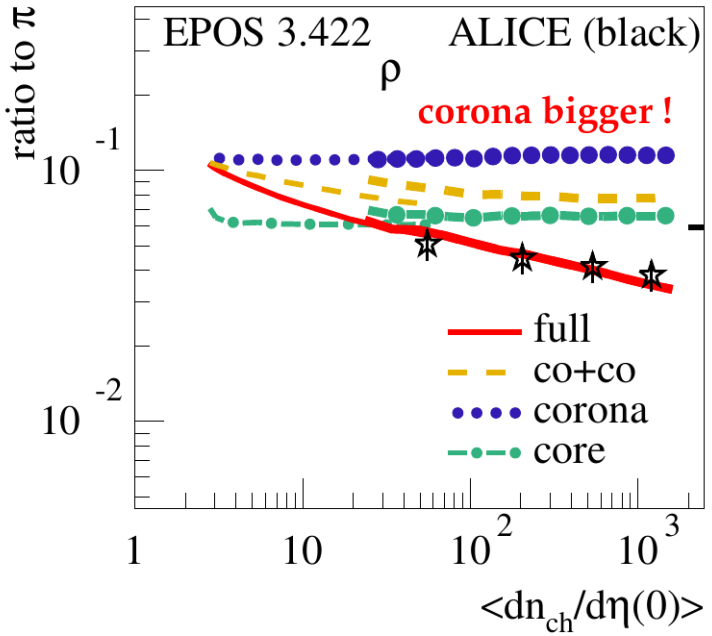
- saturation
- flow
- core-corona

Yield Ratio : Continuous









continuous curves

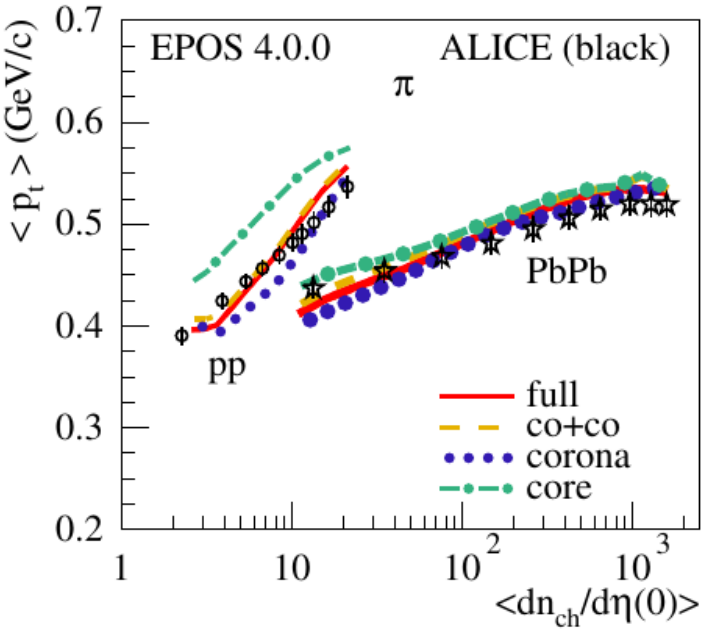
Affected by:

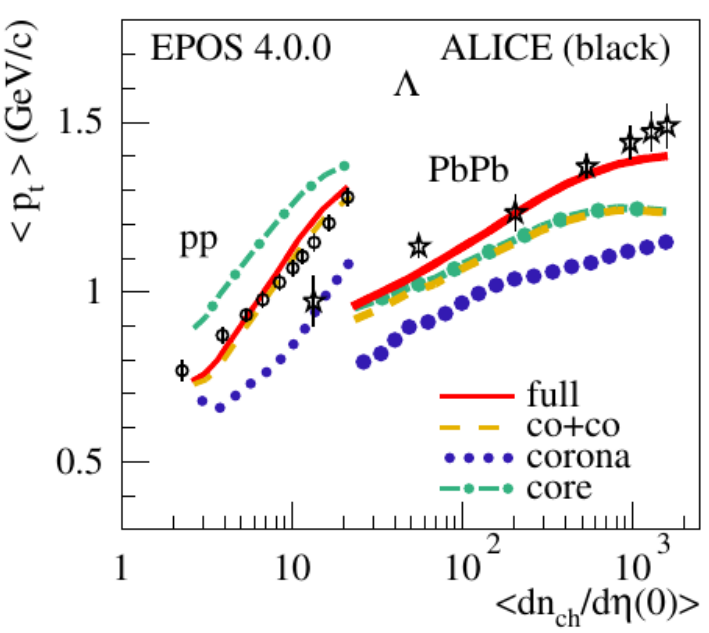
core-corona

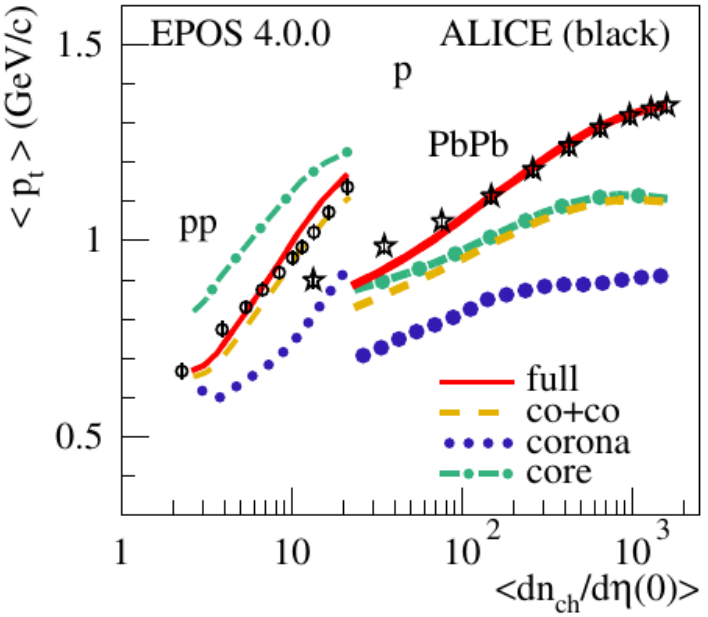
microcanonical

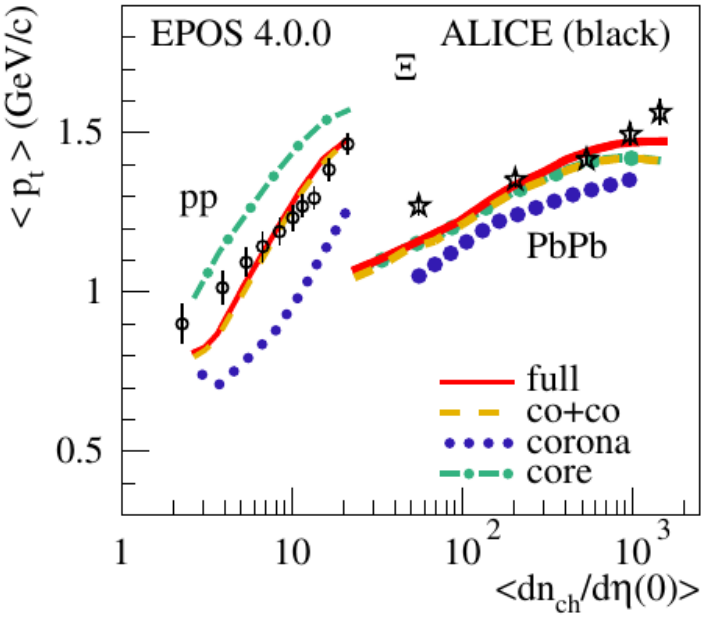
hadronic cascade

<pt> : Discontinuities









discontinuities

curves affected by:

saturation

flow

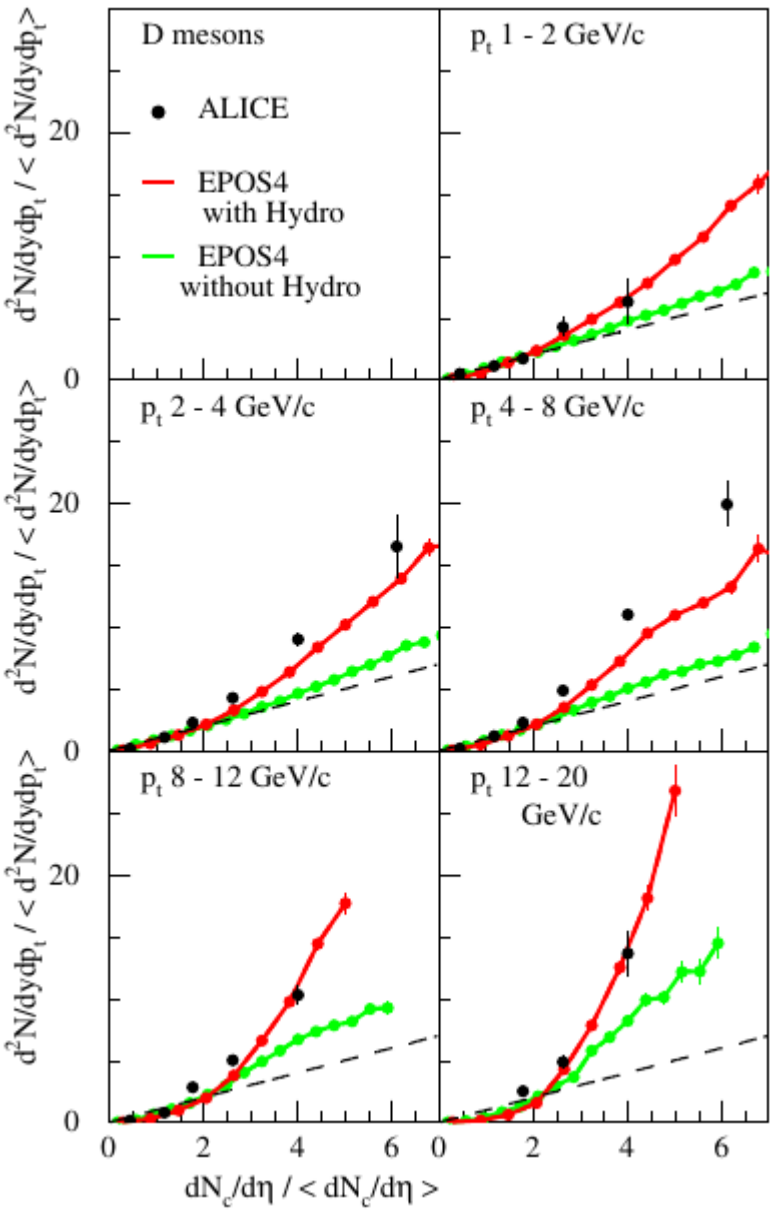
core-corona

hadronic cascade

Multiplicity dependence of charm production

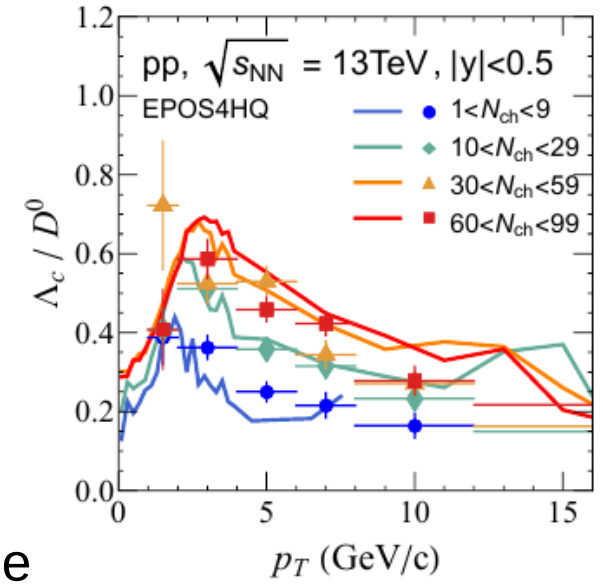
- **pp 7TeV**
  - Self-normalized D meson multiplicity for different transverse momentum ranges
  - versus self-normalized charged particle multiplicity
  - compared to ALICE data

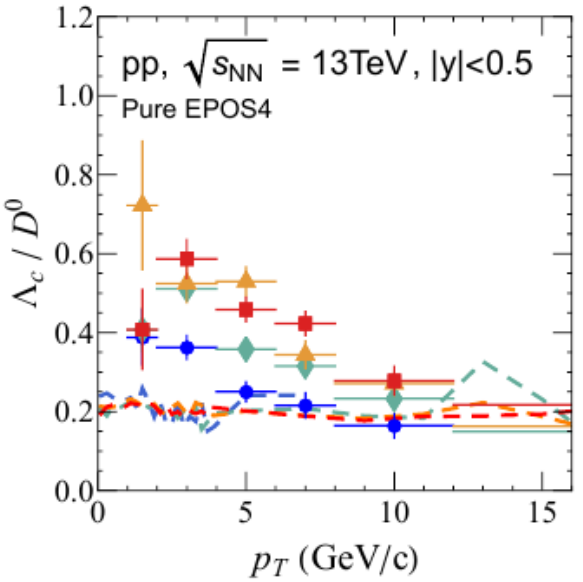
- **saturation and flow effect**
  - Saturation linked to increase without hydro
    - Harder Pomeron at high multiplicity
  - Hydro reduces apparent multiplicity for a given number of Pomerons
    - More hard scattering at a given mult.
  - Non-perturbative effect on heavy flavor !

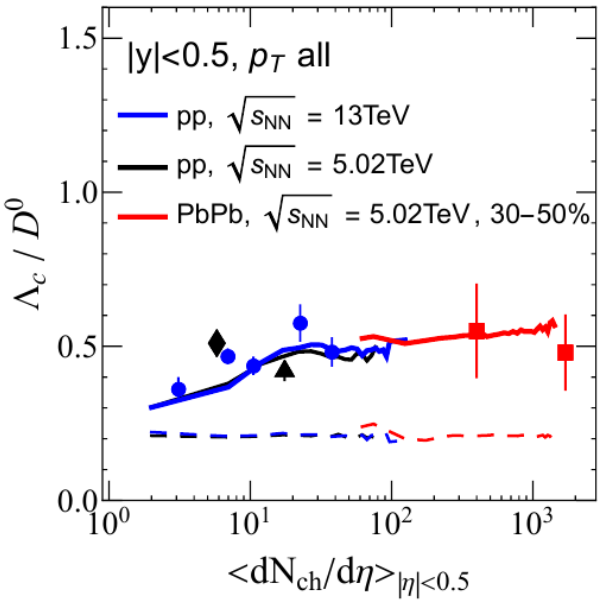


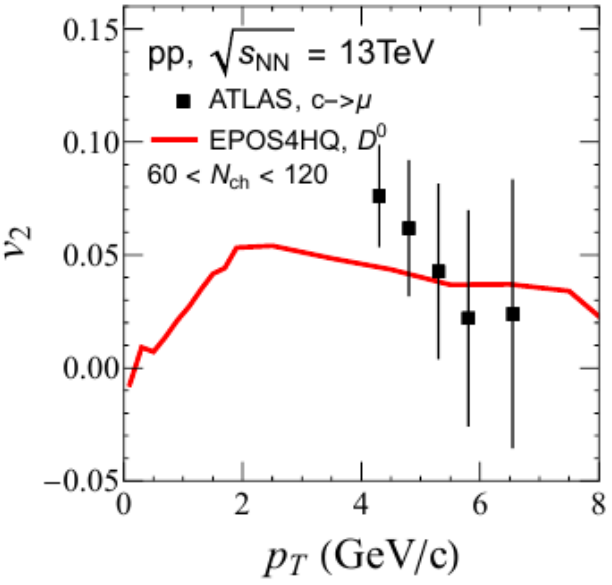
Charm Baryon Production

- **Do Charm flows ?**
  - Tests with EPOS HQ
  - Details: arxiv 2310.08684
- **Charm baryon yield**
  - Large increase observed
  - Consistent with coalescence of heavy quarks with light quarks
  - “In medium” effect
  - Follow core-corona
- **Azimuthal flow**
  - V2 predicted in pp





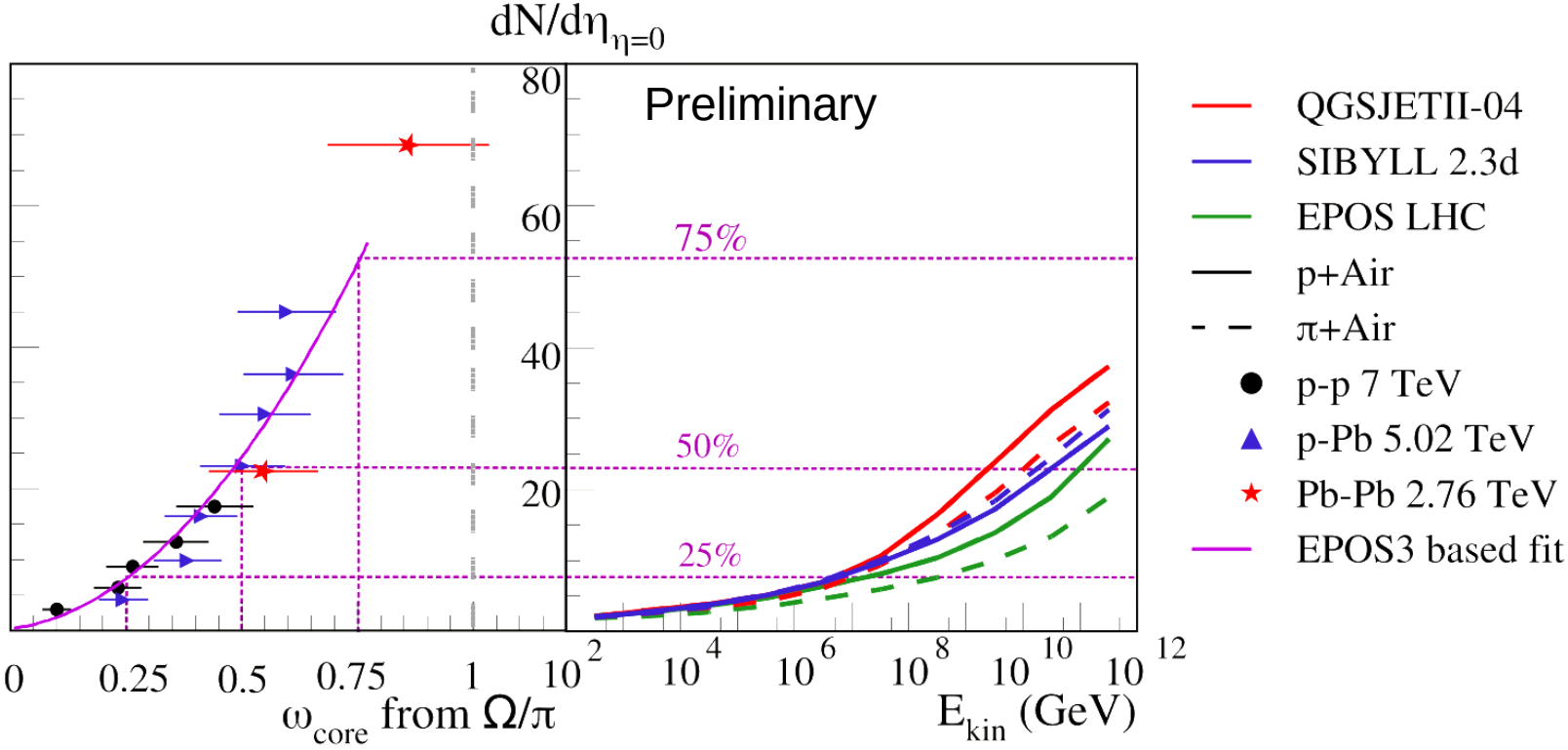




Particle Densities in Air Showers

Is particle density in air shower high enough to expect core formation ?

- Core formation start quite early according to ALICE data
- Cosmic ray primary interaction likely to have 50% core at mid-rapidity … but forward can be different !



Core-Corona appoach and EAS

To test if a QGP like hadronization can account for the missing muon production in EAS simulations a core-corona approach can be artificially apply to any model

- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization:

$$N_i = \omega_{\text{core}}\, N_i^{\text{core}} + (1-\omega_{\text{core}})\, N_i^{\text{corona}}$$

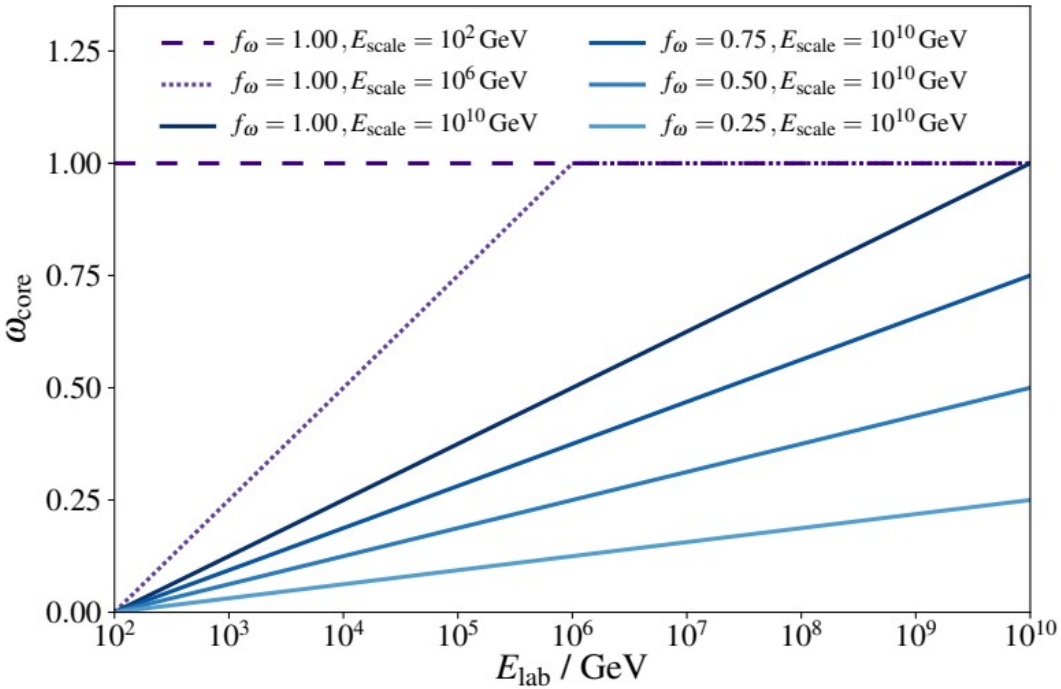
$$\omega_{\text{core}}(E_{\text{lab}}) = f_\omega \underbrace{F(E_{\text{lab}}; E_{\text{th}}, E_{\text{scale}})}$$

$$\frac{\log_{10}(E_{\text{lab}}/E_{\text{th}})}{\log_{10}(E_{\text{scale}}/E_{\text{th}})} \text{ for } E_{\text{lab}} > E_{\text{tl}}$$

$$E_{\text{th}} = 100\,\text{GeV}$$

Different scenarii can be studied playing with f_ω and E_{scale}.

Note : the leading particle is NOT modified (projectile remnant)

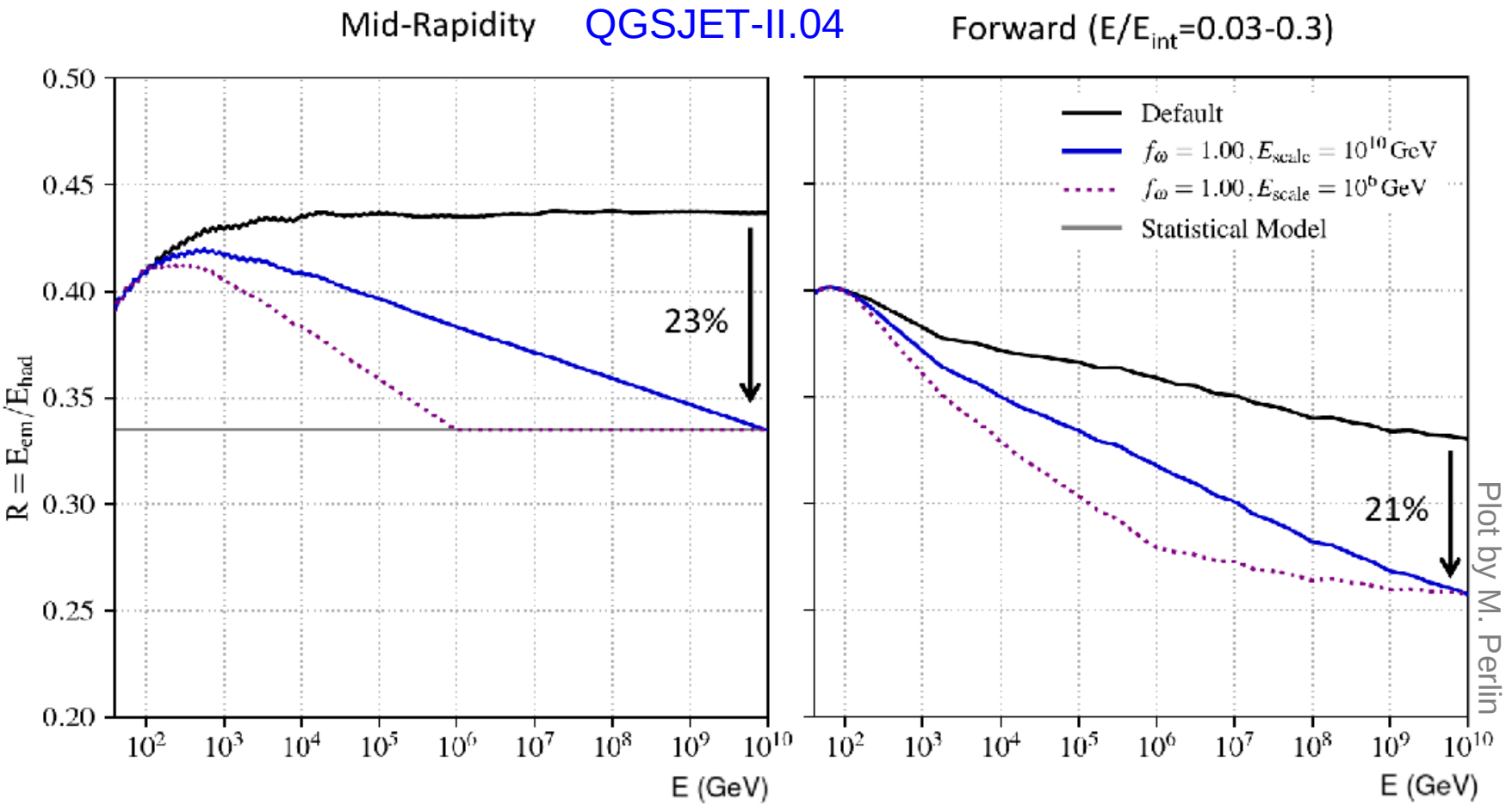


Evolution of hadronization from core to corona

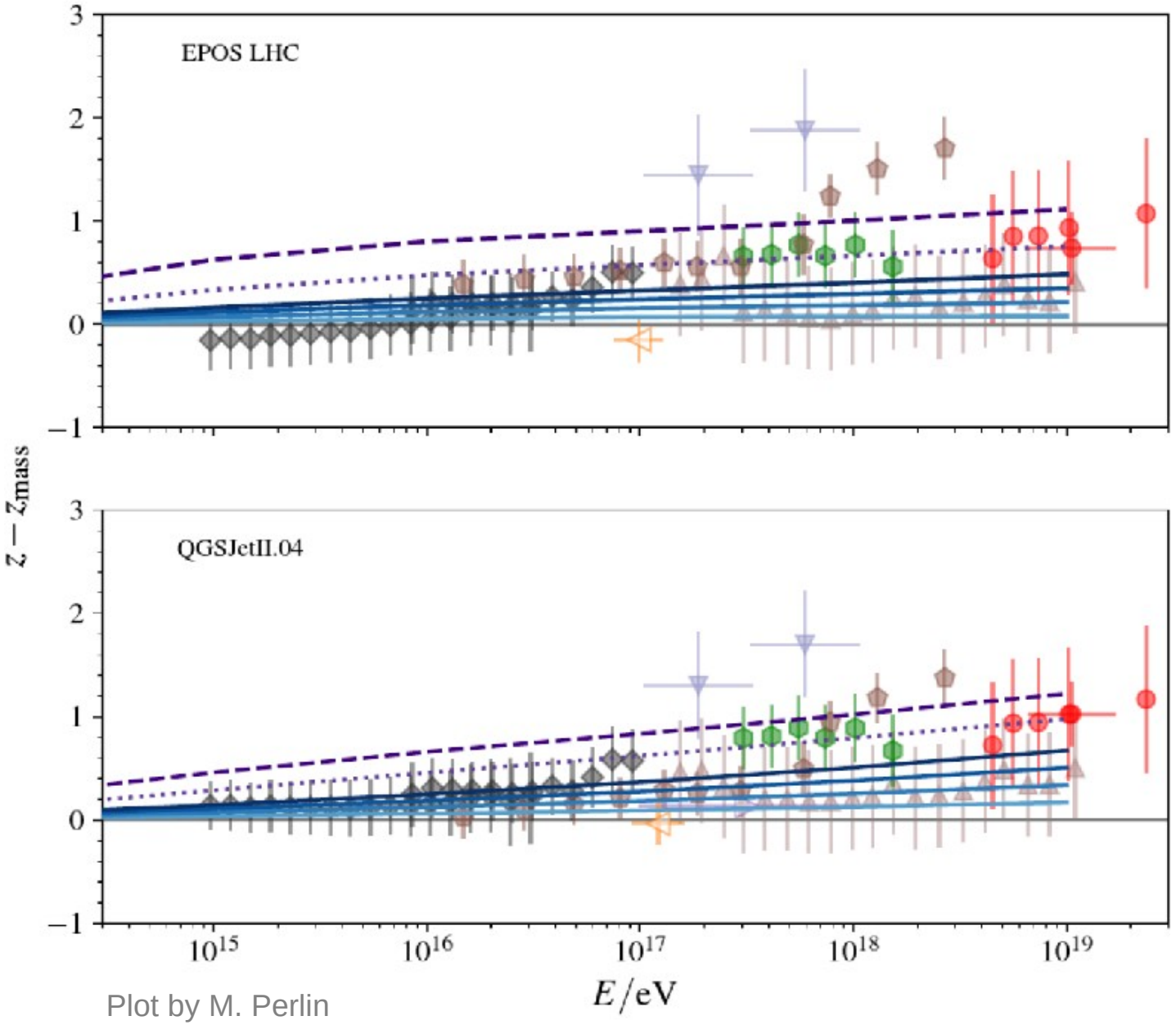
The relative fraction of π^0 depends on the hadronization scheme

- Change of ω_{core} with energy changes $c = \frac{N_{\pi^0}}{N_{mult}}$ or $R(\eta) = \frac{\langle dE_{\text{em}}/d\eta \rangle}{\langle dE_{\text{had}}/d\eta \rangle}$

  which define the muon production in air showers.



Results for z-scale



Plot by M. Perlin

$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$

- $f_\omega = 1.00$, $E_{scale} = 10^2$ GeV
- $f_\omega = 1.00$, $E_{scale} = 10^6$ GeV
- $f_\omega = 1.00$, $E_{scale} = 10^{10}$ GeV
- $f_\omega = 0.75$, $E_{scale} = 10^{10}$ GeV
- $f_\omega = 0.50$, $E_{scale} = 10^{10}$ GeV
- $f_\omega = 0.25$, $E_{scale} = 10^{10}$ GeV
- $f_\omega = 0$ (Default model)

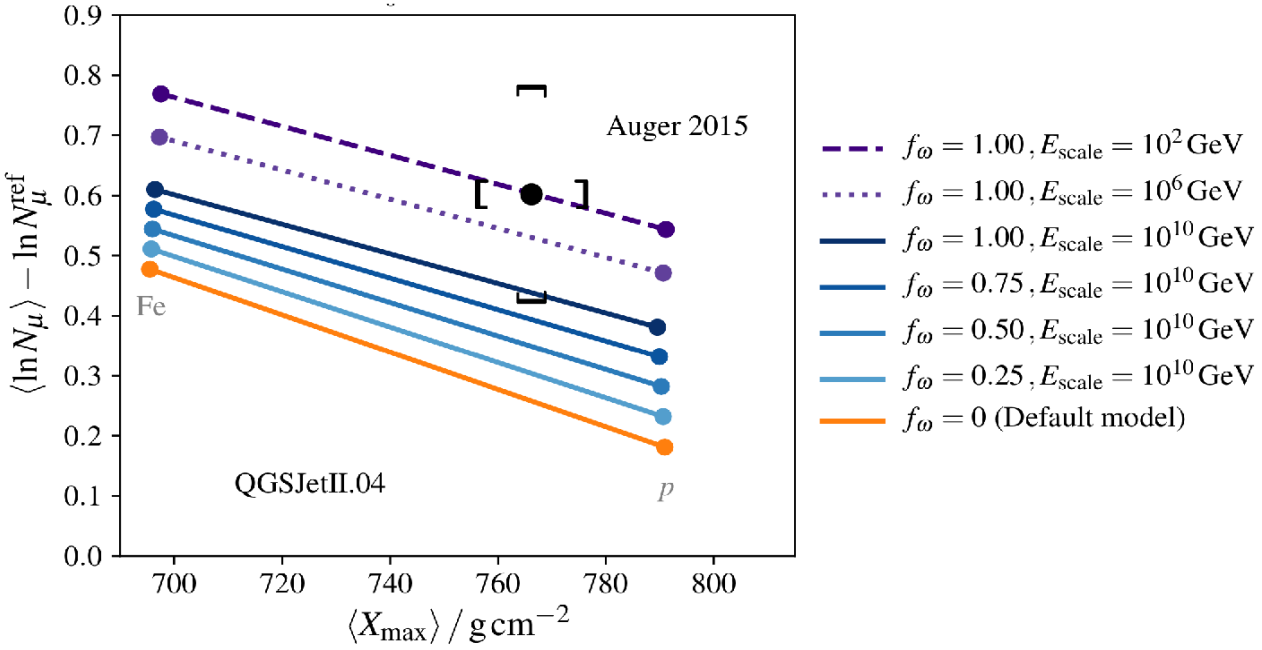
- Pierre Auger MD+SD [Preliminary]
- IceCube [Preliminary]
- NEVOD-DECOR
- Pierre Auger FD+SD
- SUGAR
- Yakutsk [Preliminary]
- EAS-MSU
- KASCADE-Grande

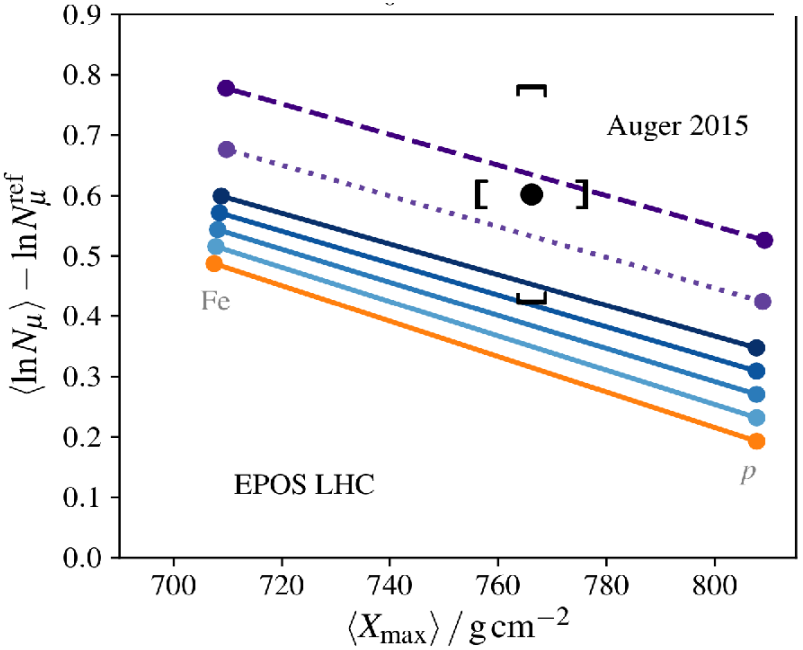
$$z_{\mathrm{mass}} = \frac{\langle \ln A \rangle}{\ln 56}$$

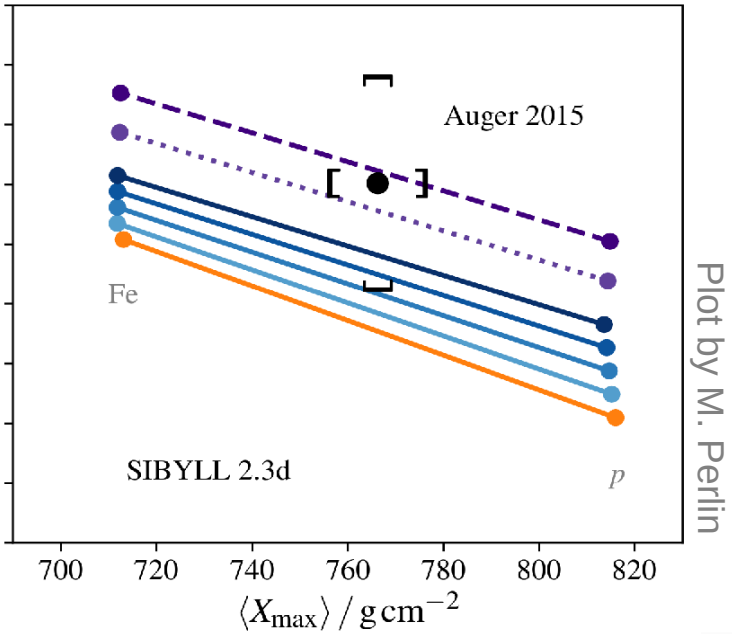
Complete Picture and Muon Puzzle

Significant effect on EAS observed if core-corona introduced in models

- No change in X_{max}
- Needs a large part of core hadronization at maximum energy to reach Auger point
- Sibyll with higher mass (deep X_{max}) need less







Plot by M. Perlin

Summary

EPOS4 allows (for the first time!) to accommodate simultaneously

Energy conservation + Parallel scattering + factOrization + Saturation

- **Now we can do in one single ("general purpose") approach**
  - "normal" pp physics (high pt jets etc) (where factorization comes into play)
  - high multiplicity pp events (where saturation plays a crucial role)
  - AA scattering at LHC and RHIC
- **Multiplicity dependencies: a wealth of information**
  - allowing to disentangle and better understand different phenomena, as
    - Core-corona separation, radial flow,
    - saturation effects, hadronic rescattering
- **Possible cosmic ray applications**
  - a fast version exists, PFE (parameterized fluid expansion), but there are still "technical issues"
  - First "retune" of EPOS LHC(-R) taking into lessons from EPOS 4

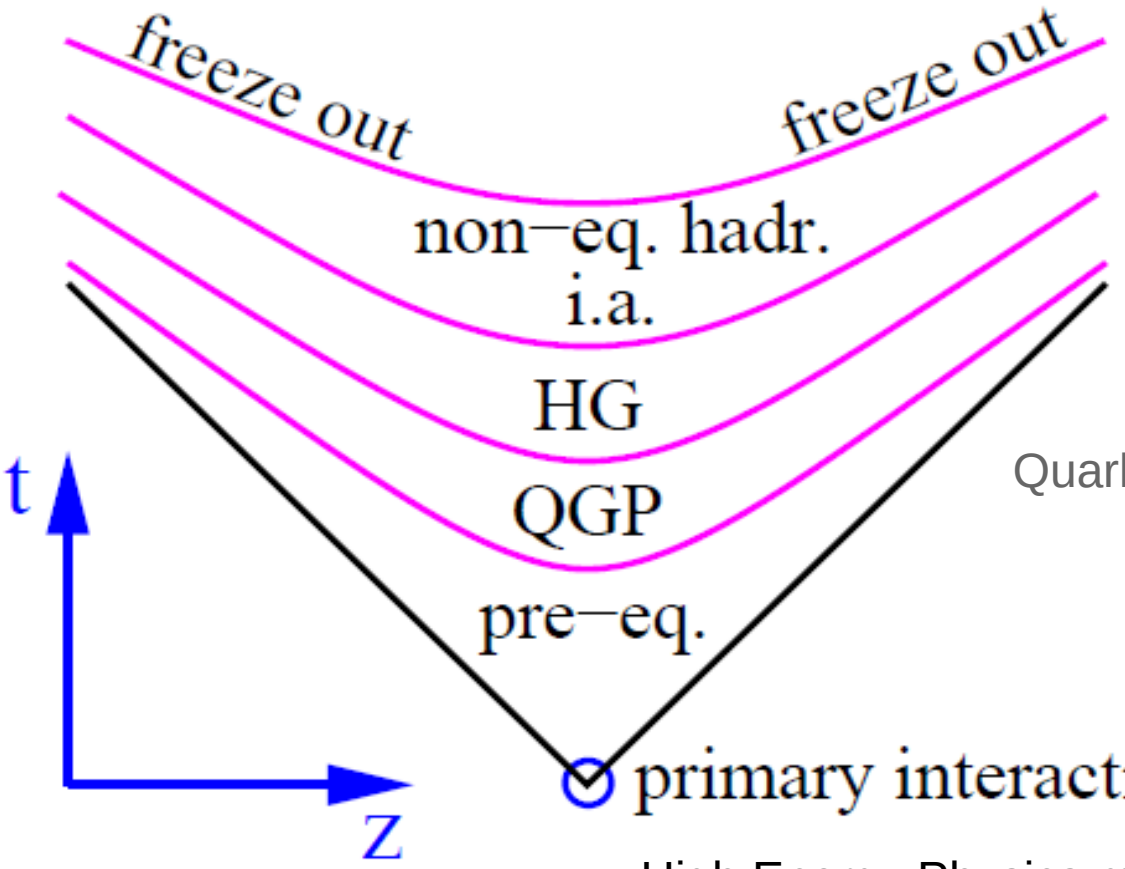
References

- **Web page (download): https://klaus.pages.in2p3.fr/epos4/**
- **EPOS4 overview**
  - arXiv:2301.12517, published in Phys. Rev. C 108, 064903 (2023)
- **Internal Pomeron structure in terms of QCD (link between the multiple scattering formalism and QCD)**
  - arXiv:2306.02396, published in Phys. Rev. C 108, 034904 (2023)
- **Very detailed and rigorous treatment of the multiple scattering formalism based on Pomerons**
  - arXiv:2310.09380, published in Phys. Rev. C 109, 034918 (2024)
- **Core-corona procedure and microcanonical hadronization in EPOS**
  - arXiv:2306.10277, published in Phys. Rev. C 109, 014910 (2024)
- **Does charm flow, even in small systems?**
  - arXiv:2310.08684, published in Phys. Rev. D 109, 054011 (2024)
- **Systematic comparison of open heavy flavor data with EPOS4HQ simulations**
  - arXiv:2401.17096

References for High Energy Models (new)

- **DPMJET III**
  - J. Ranft, R. Engel, S. Roesler, Nucl. Phys. B Proc. Suppl.122, 392 (2003)
  - A. Fedynitch, Cascade equations and hadronic interactions at very high energies. PhD thesis, KIT, Karlsruhe, Dept.Phys. (2015)
  - A. Fedynitch, R. Engel, 14th Inter-national Conference on Nuclear Reaction Mechanisms:Varenna, Italy, p. 291. CERN, Geneva (2015)
- **EPOS LHC**
  - T. Pierog at al., Phys. Rev. **C92** (2015) 034906 arXiv:1306.0121 [hep-ph]
- **QGSJETII-04**
  - S. Ostapchenko, Phys. Rev. **D83** (2011) 014018
  - S. Ostapchenko, Phys. Rev. **D89** (2014) 074009
- **SIBYLL 2.3d**
  - F. Riehn et al. Phys. Rev. **D102** (2020), 063002 arXiv:1912.03300 [hep-ph]

High Energy Hadronic Interactions



Collective Effects

Elastic hadronic reinteractions

Hadron Gas

Quark Gluon Plasma

High Energy Physics models

References :

Ralph Engel PhD Thesis (1997)
K. Werner, Phys.Rept. 232, Nos. 2-5 (1993) 87-299
K. Werner, arXiv:hep-ph/0206111v1

back-up

Core, corona, full
PbPb at 5.02 TeV
(AuAu at 200GeV similar)

pions, kaons, protons, lambdas (top to bottom)

Green: $\frac{\text{core}}{\text{core}+\text{corona}}$

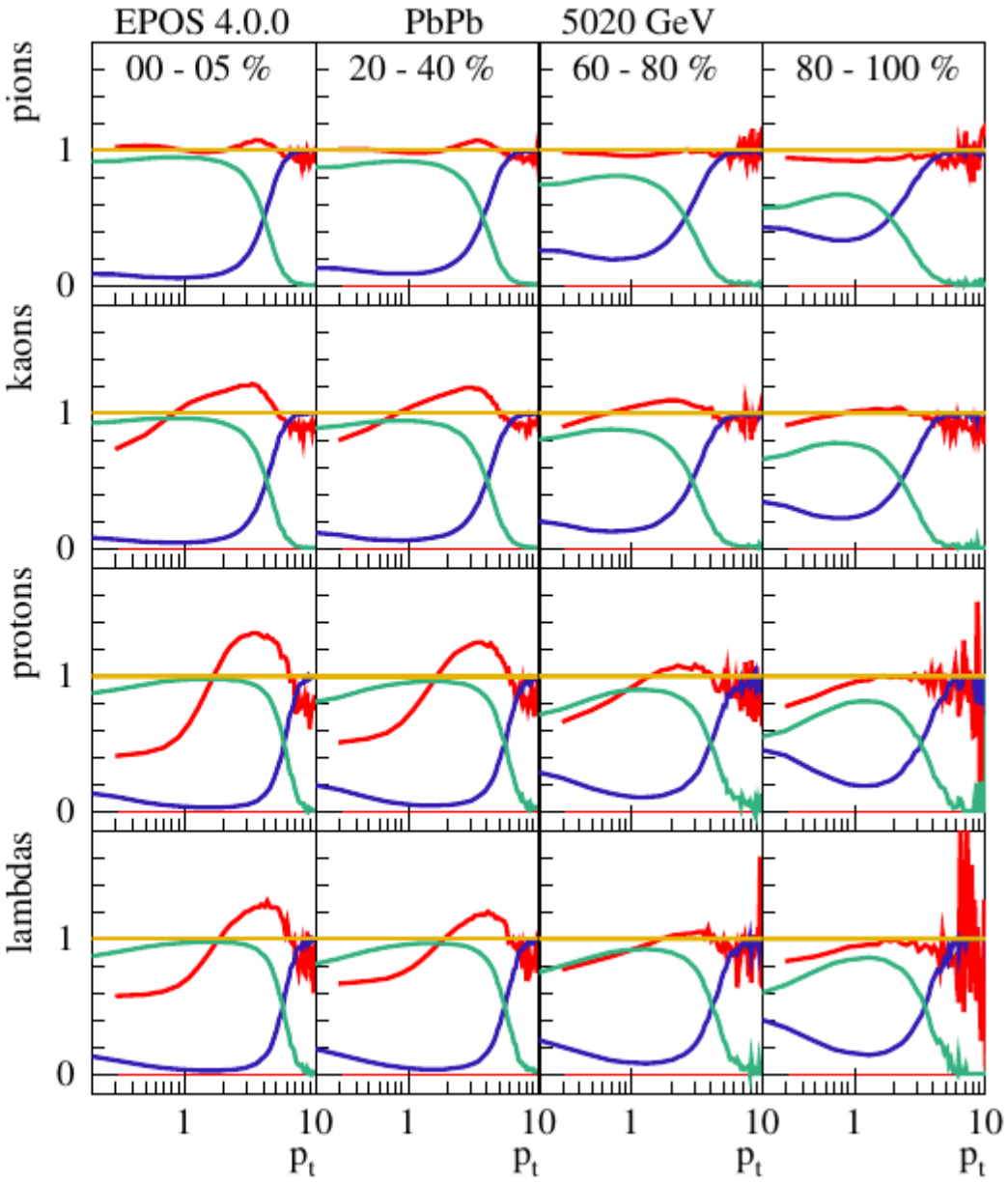
Blue: $\frac{\text{corona}}{\text{core}+\text{corona}}$

Red: $\frac{\text{full}}{\text{core}+\text{corona}}$

Core reaches to higher pt for baryons

Core has maximum at intermediate pt (flow)

Rescattering important



Core, corona, full
AuAu at 11.5 GeV

K^+, K^-, p, $\bar{p}$
(top to bottom)

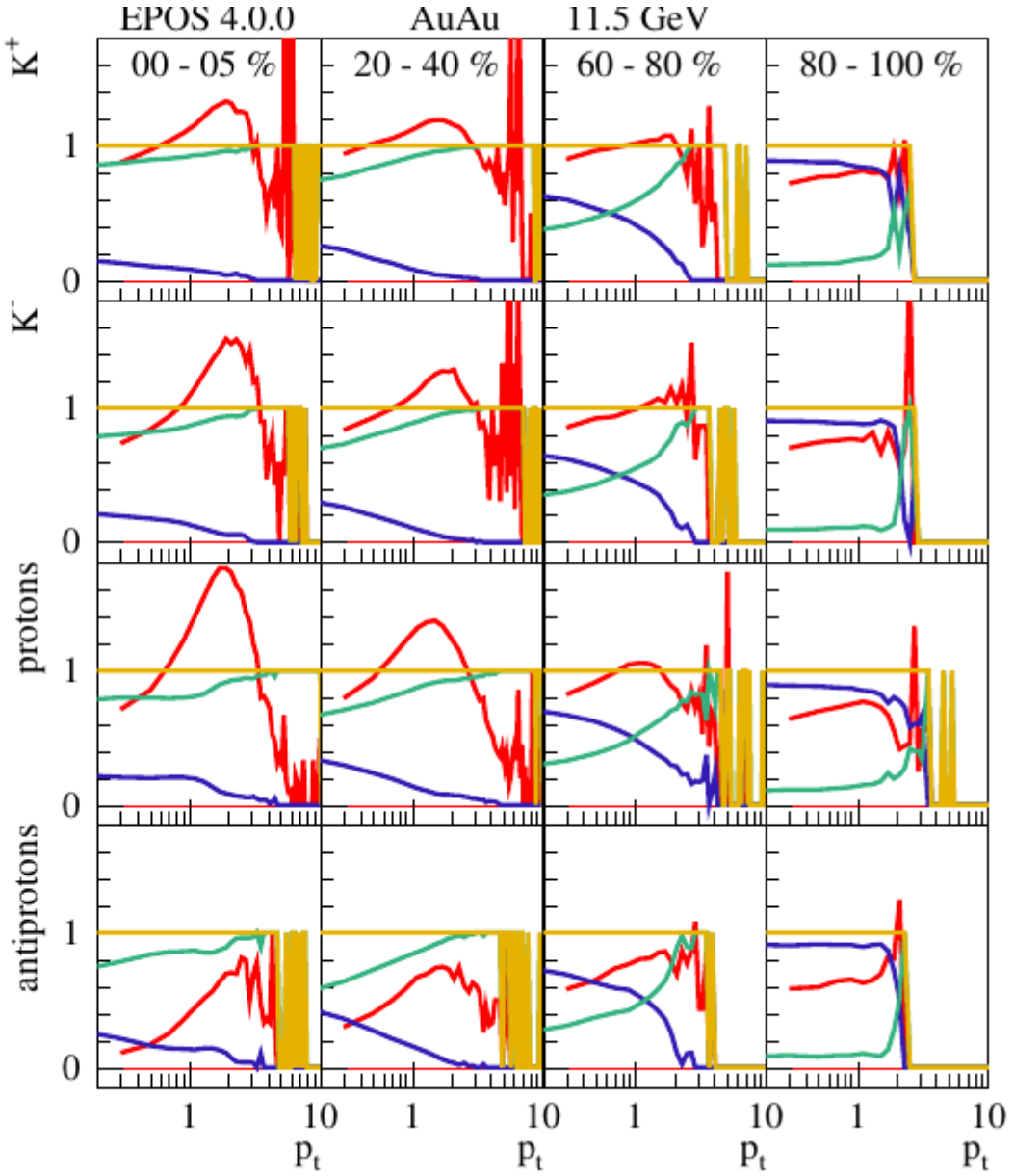
Green: $\frac{\text{core}}{\text{core}+\text{corona}}$

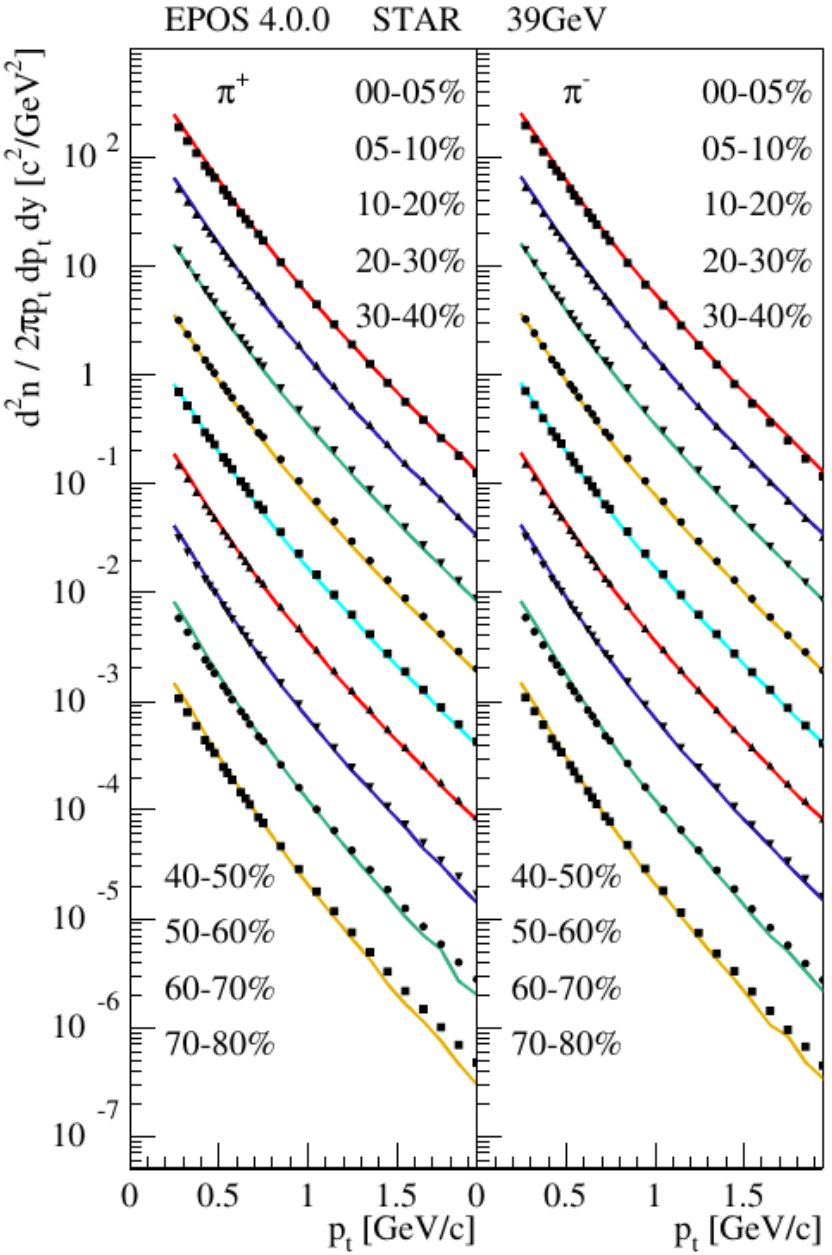
Blue: $\frac{\text{corona}}{\text{core}+\text{corona}}$

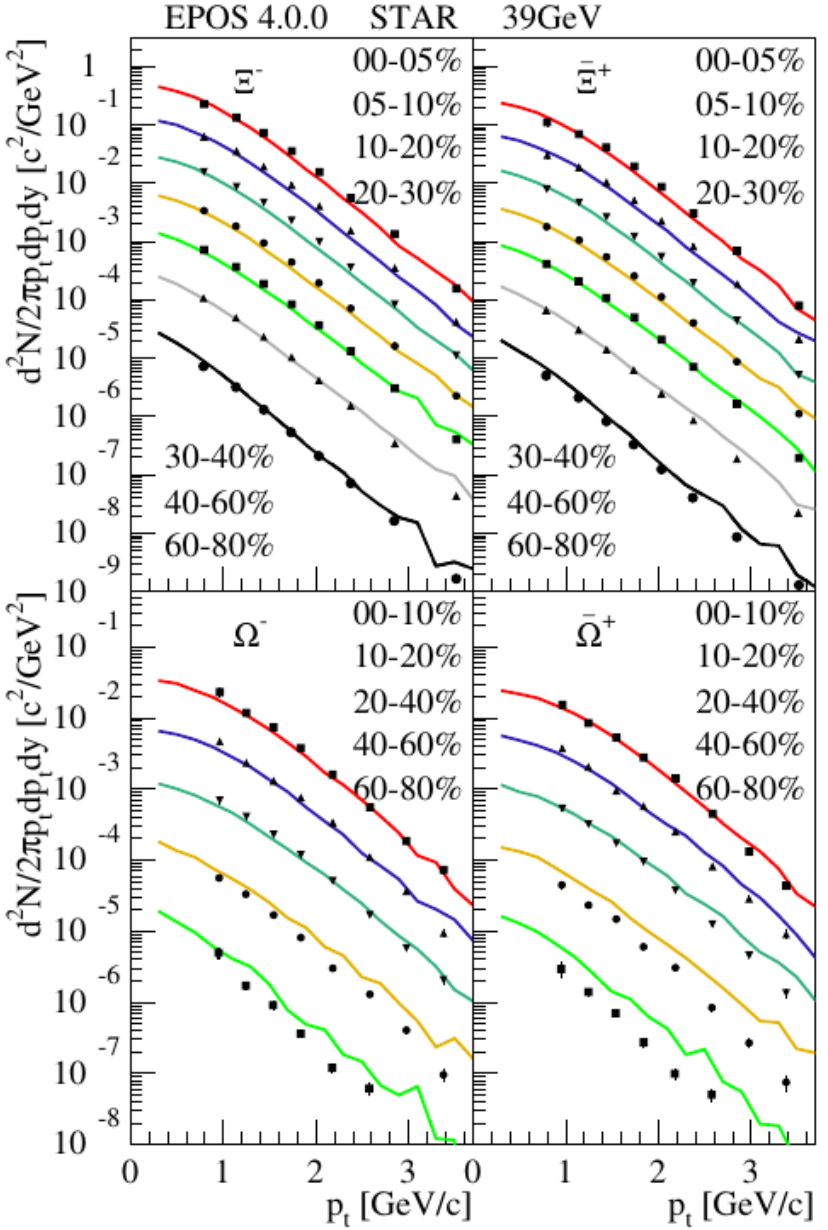
Red: $\frac{\text{full}}{\text{core}+\text{corona}}$

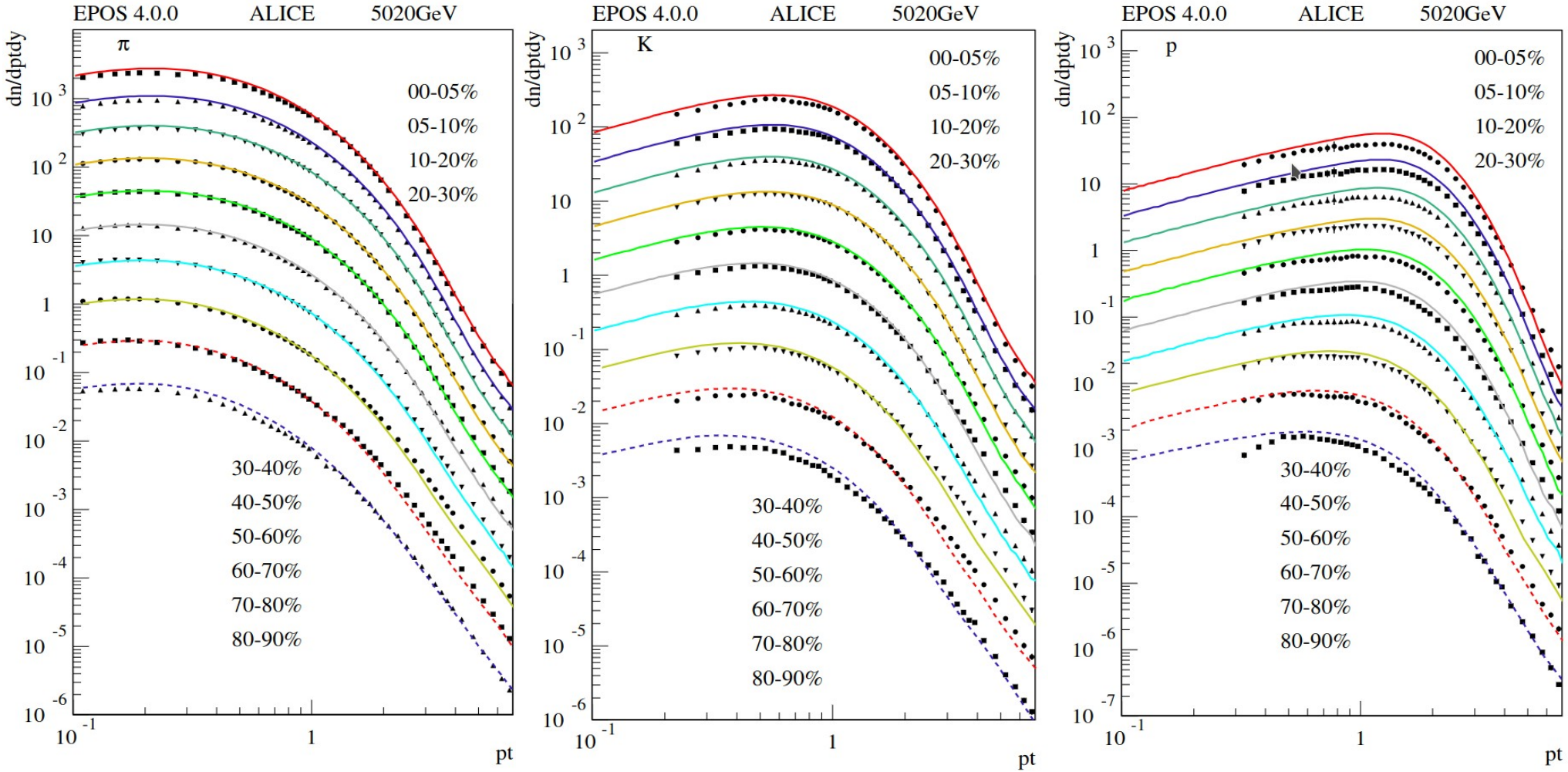
Core-corona similar to 39 GeV, core maximum at intermediate pt (flow)

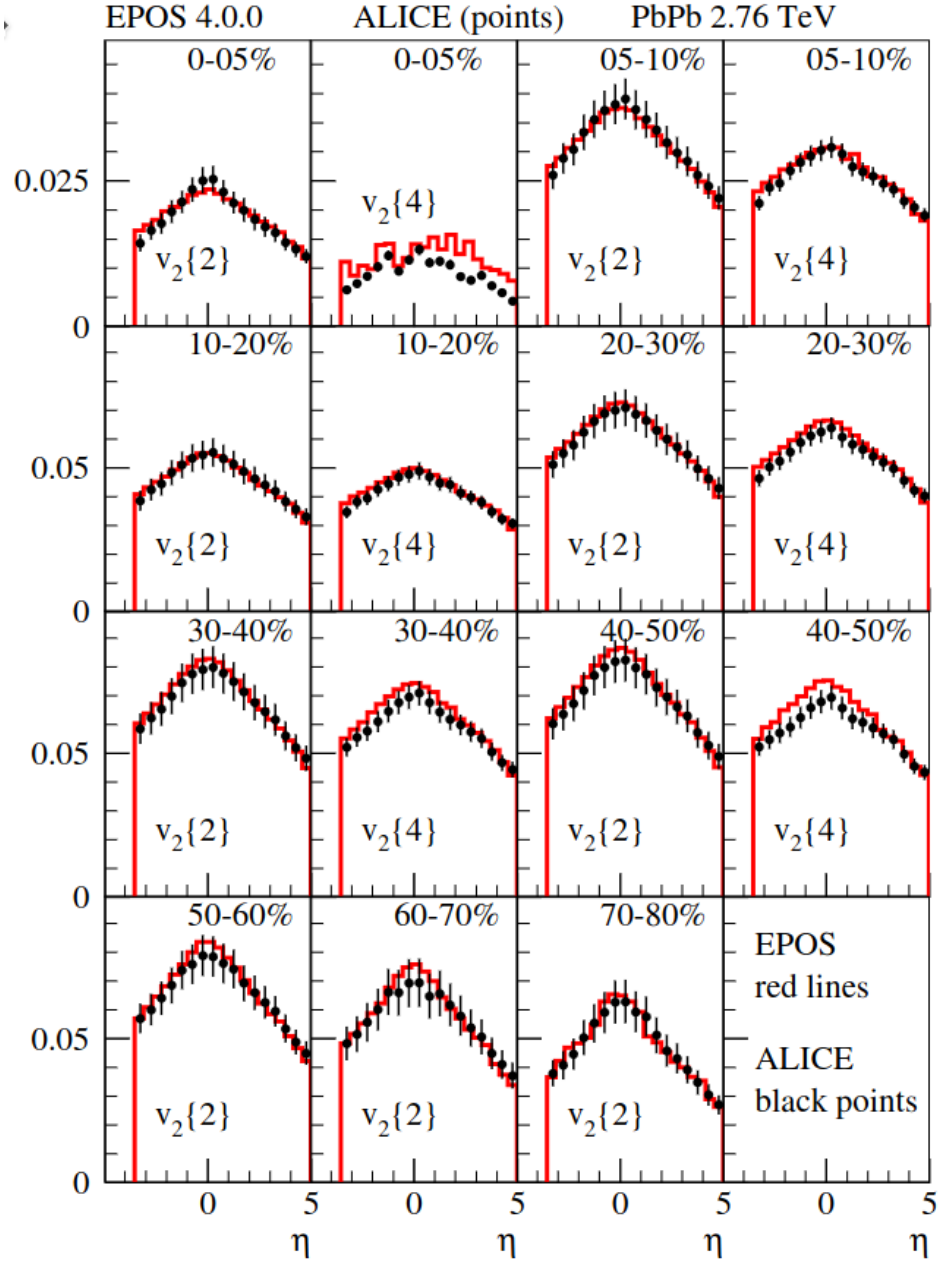
Huge rescattering effect, big difference between p and $\bar{p}$

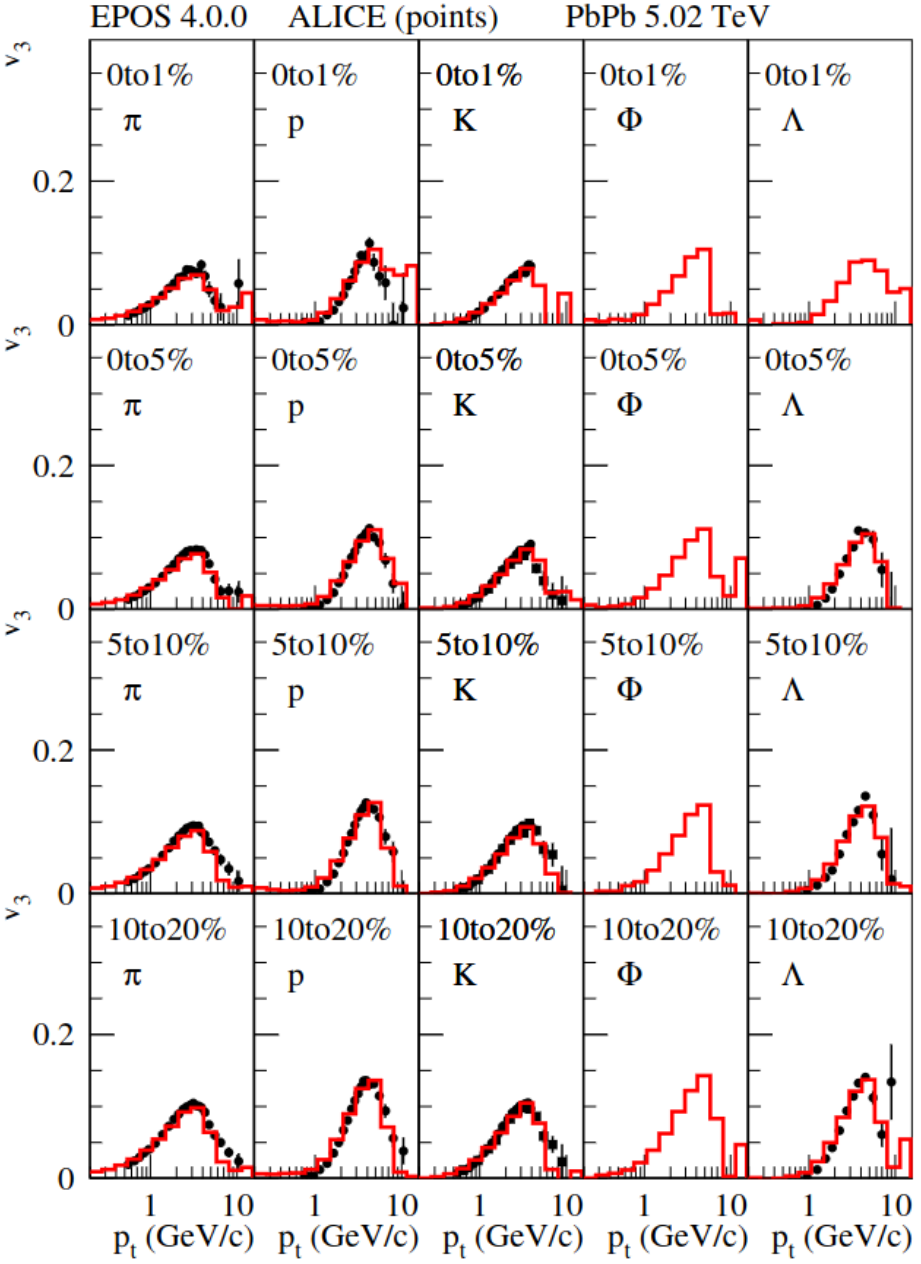



EPOS 4.0.0 STAR 39GeV
π^+
π^-
00-05%
05-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
70-80%
$d^2n / 2\pi p_t\, dp_t\, dy\ [c^2/GeV^2]$
p_t [GeV/c]

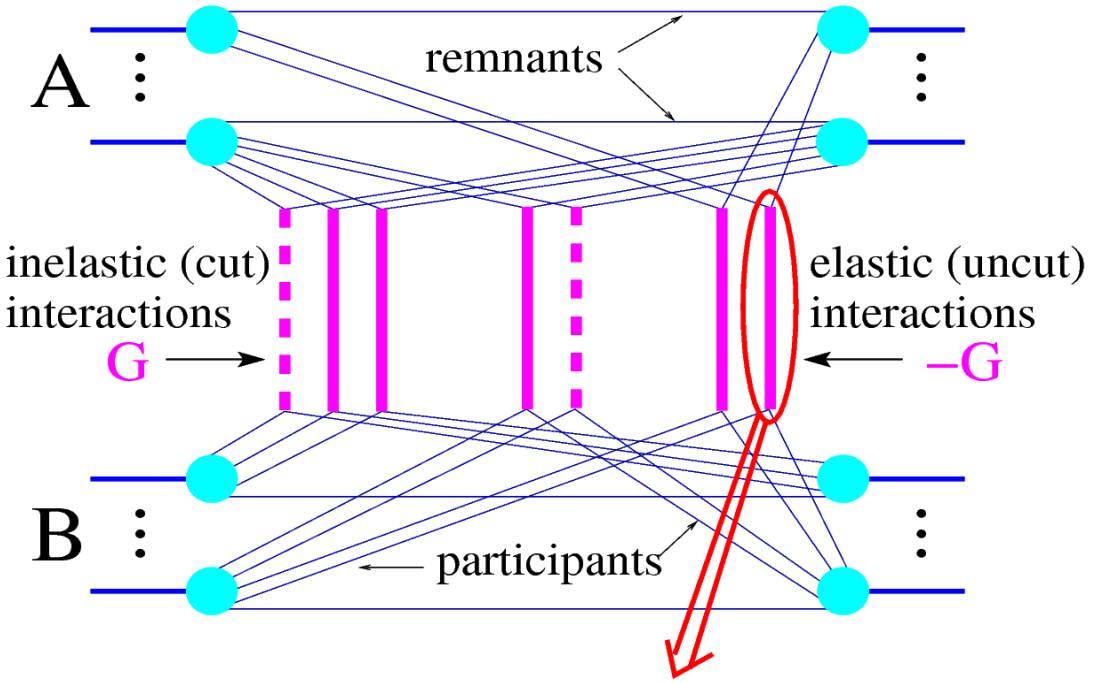

EPOS 4.0.0 STAR 39GeV
Ξ^-
$\bar{\Xi}^+$
Ω^-
$\bar{\Omega}^+$
00-05%
05-10%
10-20%
20-30%
30-40%
40-60%
60-80%
00-10%
20-40%
$d^2N/2\pi p_t dp_t dy\ [c^2/GeV^2]$
p_t [GeV/c]


EPOS 4.0.0 ALICE 5020GeV
π
K
p
dn/dptdy
pt
00-05%
05-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
70-80%
80-90%


EPOS 4.0.0
ALICE (points)
PbPb 2.76 TeV
0-05%
0-05%
05-10%
05-10%
10-20%
10-20%
20-30%
20-30%
30-40%
30-40%
40-50%
40-50%
50-60%
60-70%
70-80%
$v_2\{2\}$
$v_2\{4\}$
0.025
0.05
0
5
η
EPOS
red lines
ALICE
black points

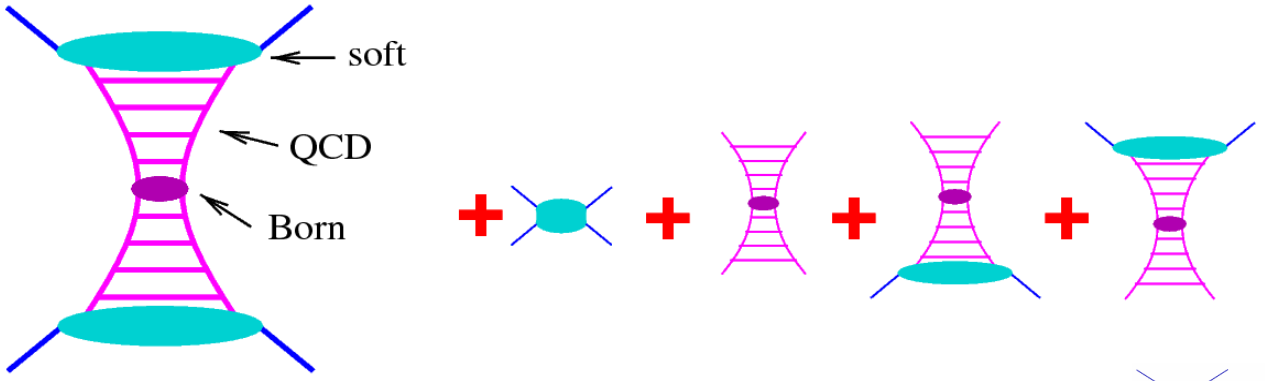

EPOS 4.0.0
ALICE (points)
PbPb 5.02 TeV
v_3
0to1%
0to5%
5to10%
10to20%
π
p
K
Φ
Λ
0.2
0
1
10
p_t (GeV/c)

Parton-Based Gribov-Regge Theory

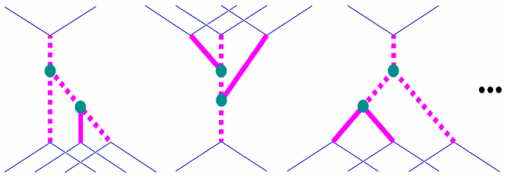


Energy sharing at the cross section level

- 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)

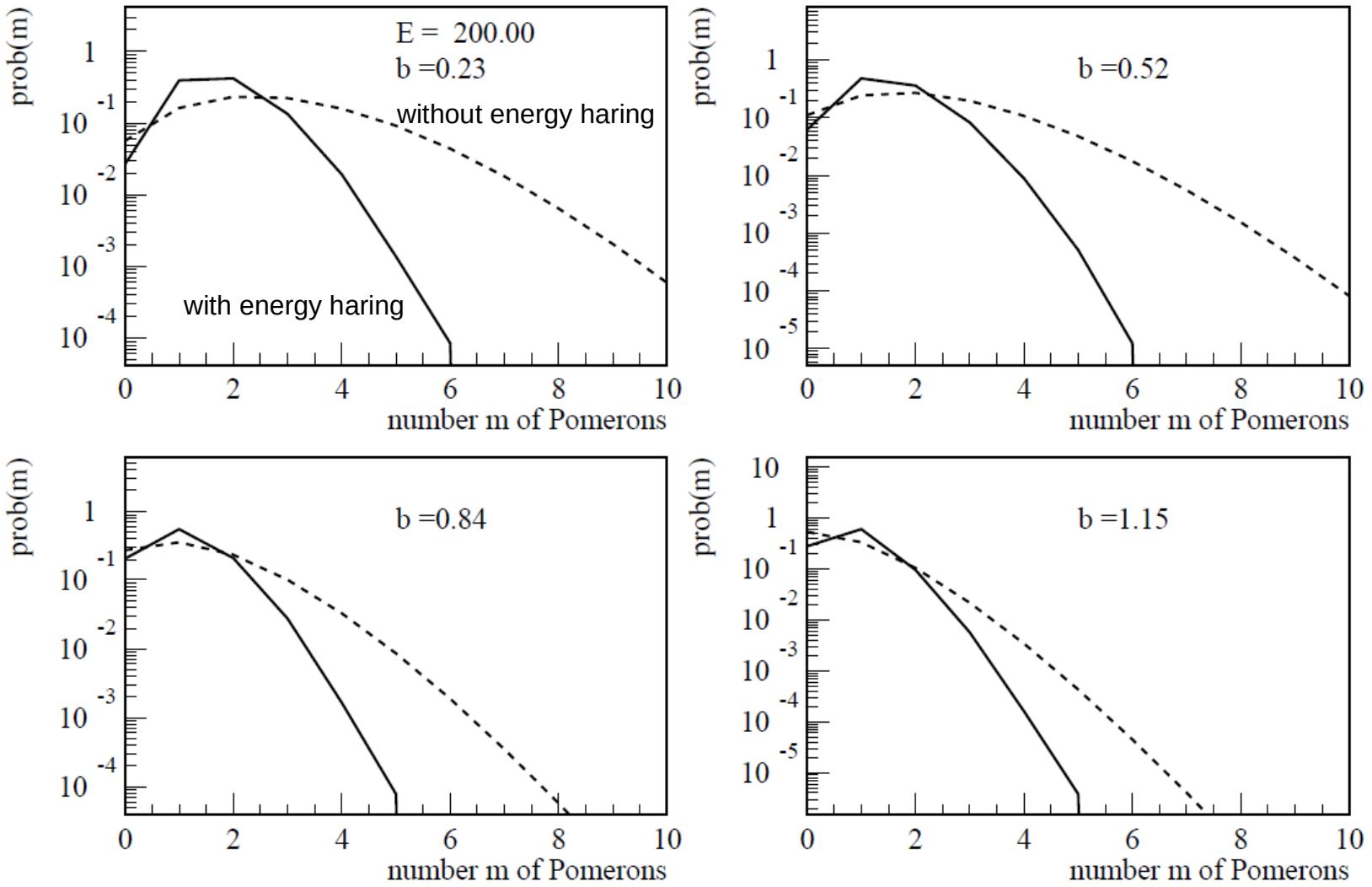


Non-linear effect (screening) absorbed in modified vertex functions



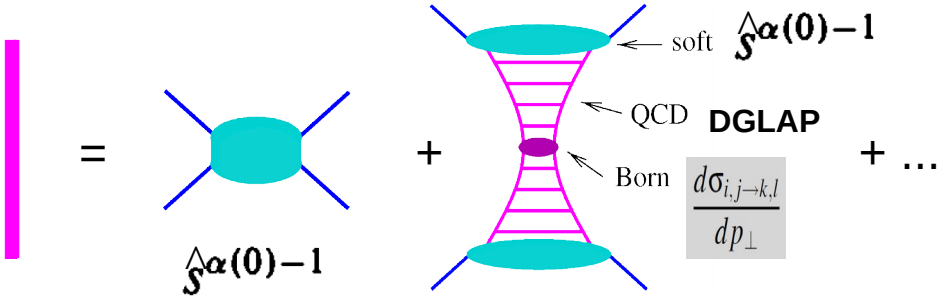
Number of cut Pomerons

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

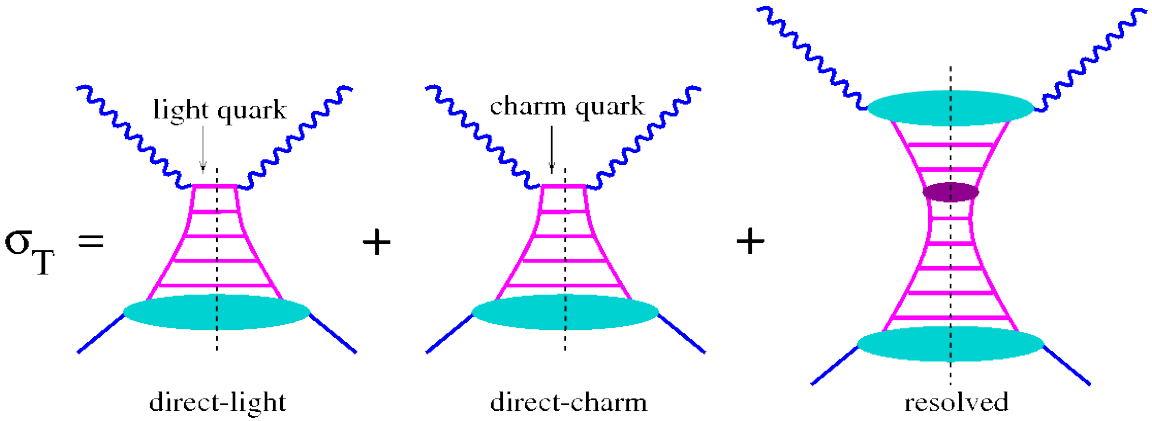


EPOS : Pomeron definition

Semi-hard Pomeron :



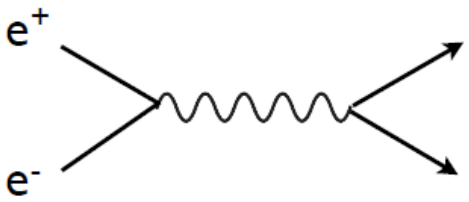
Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)



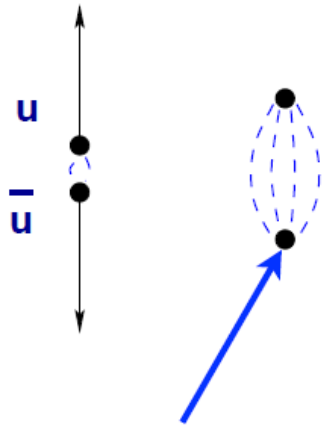
- Theory based Pomeron definion
  - pQCD based so large increase at small x (no saturation)
  - produce too high cross section
  - corrections needed using enhanced diagrams (triple Pomeron vertex)
    - effective coupling vertex

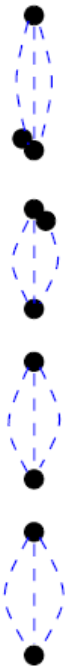
Simplest case: e^+e^- annihilation into quarks

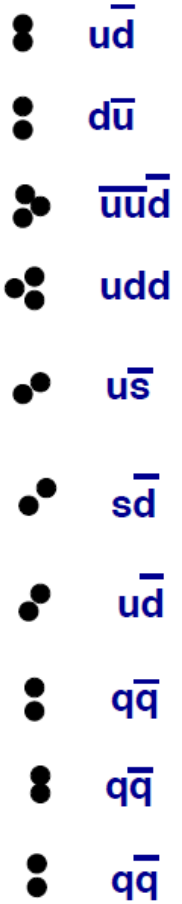
Annihilation at high energy



Quarks together are color-neutral system







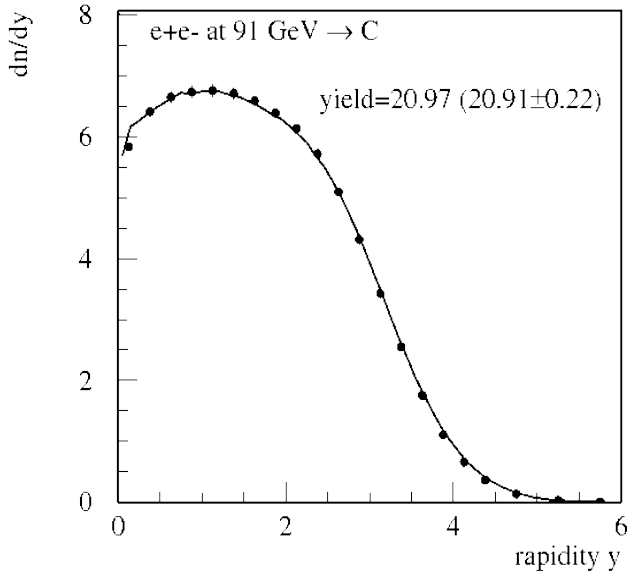
Area law used in EPOS (not Lund)

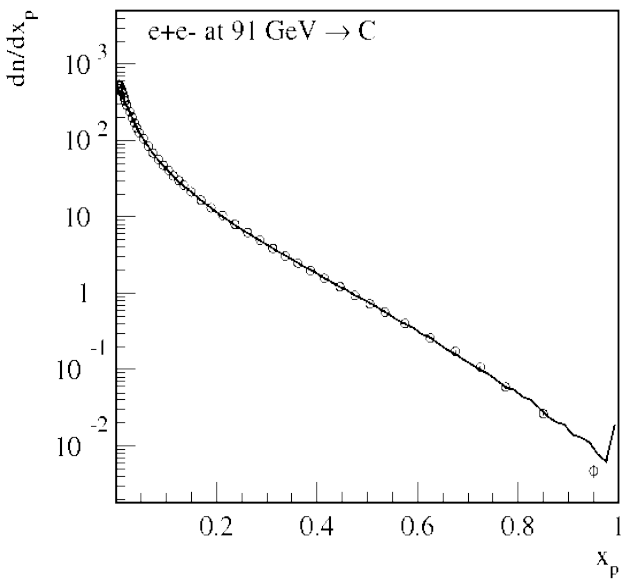
time

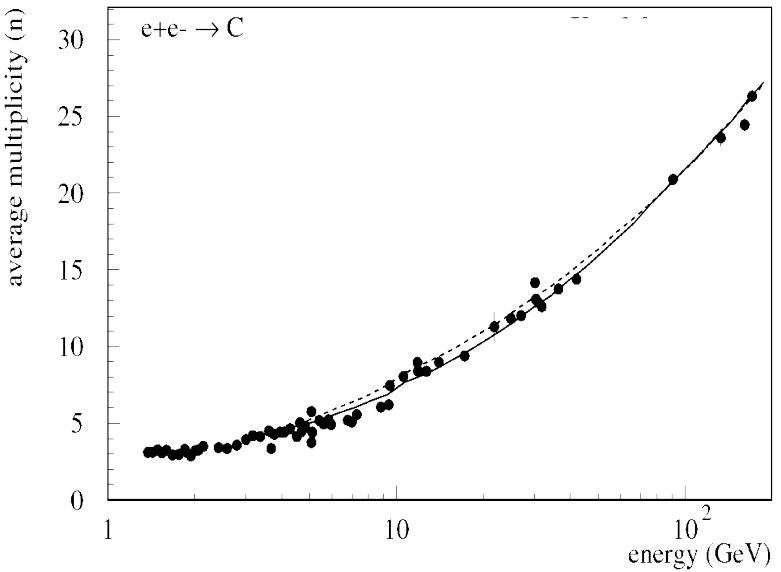
Chain of hadrons

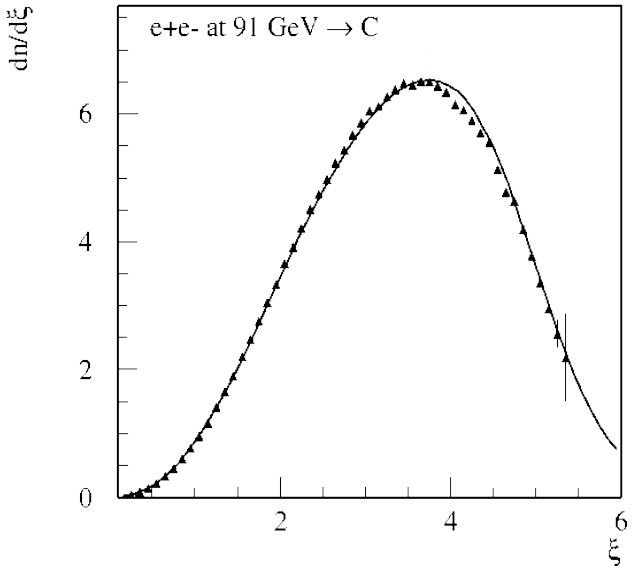
String fragmentation

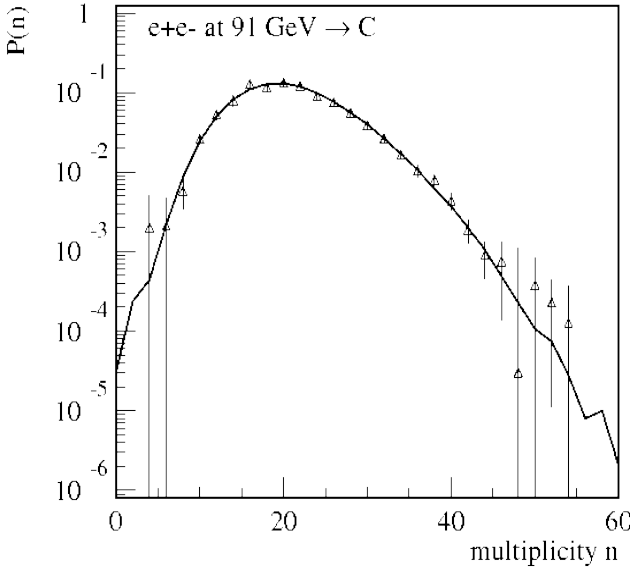
Test at LEP

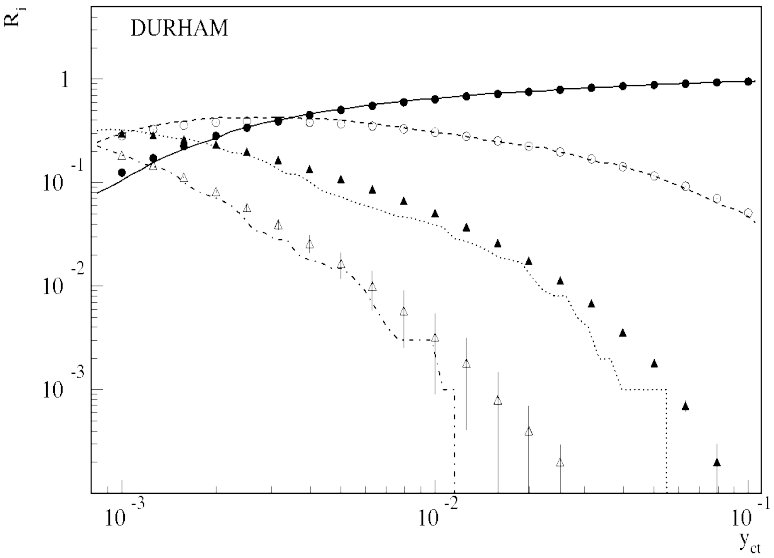

e+e- at 91 GeV → C
yield=20.97 (20.91±0.22)
dn/dy
rapidity y


e+e- at 91 GeV → C
dn/dx_p
x_p


e+e- → C
average multiplicity (n)
energy (GeV)

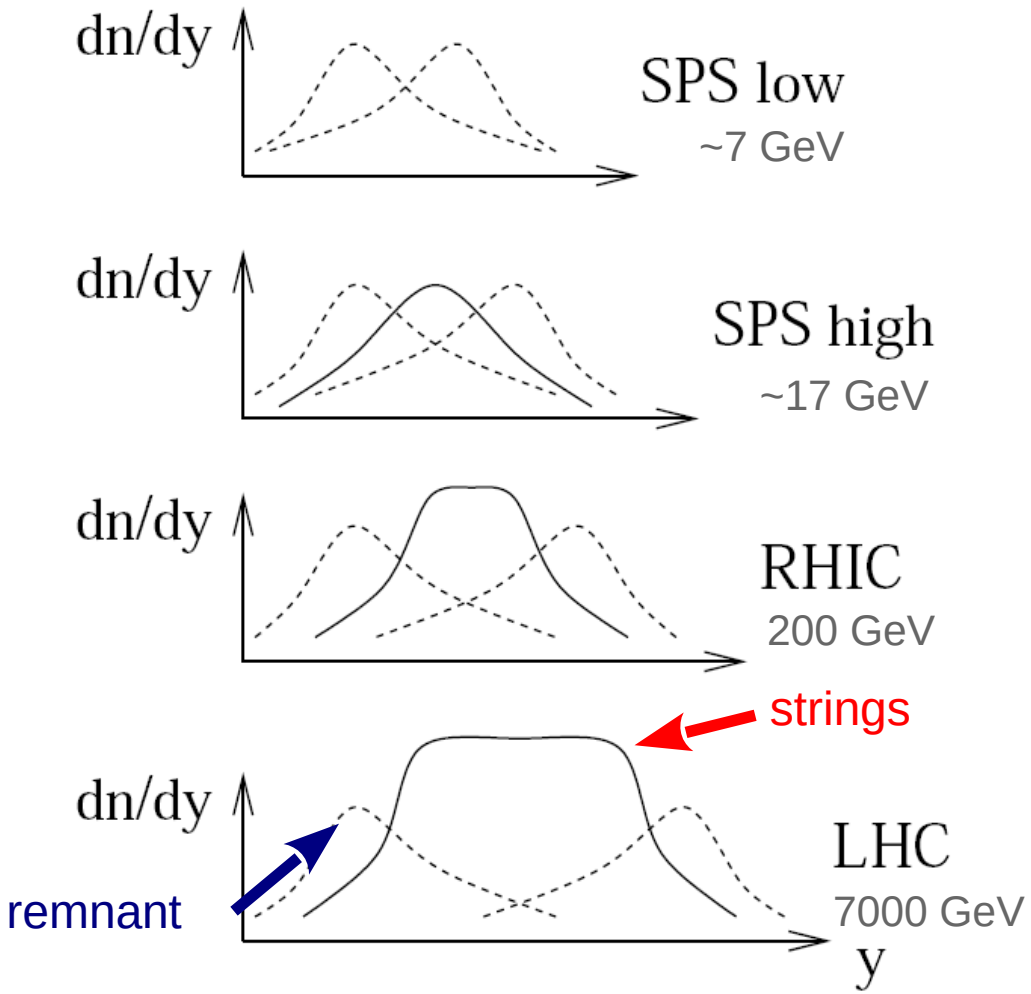

e+e- at 91 GeV → C
dn/dξ
ξ


e+e- at 91 GeV → C
P(n)
multiplicity n


DURHAM
R_i
y_cut

Remnants

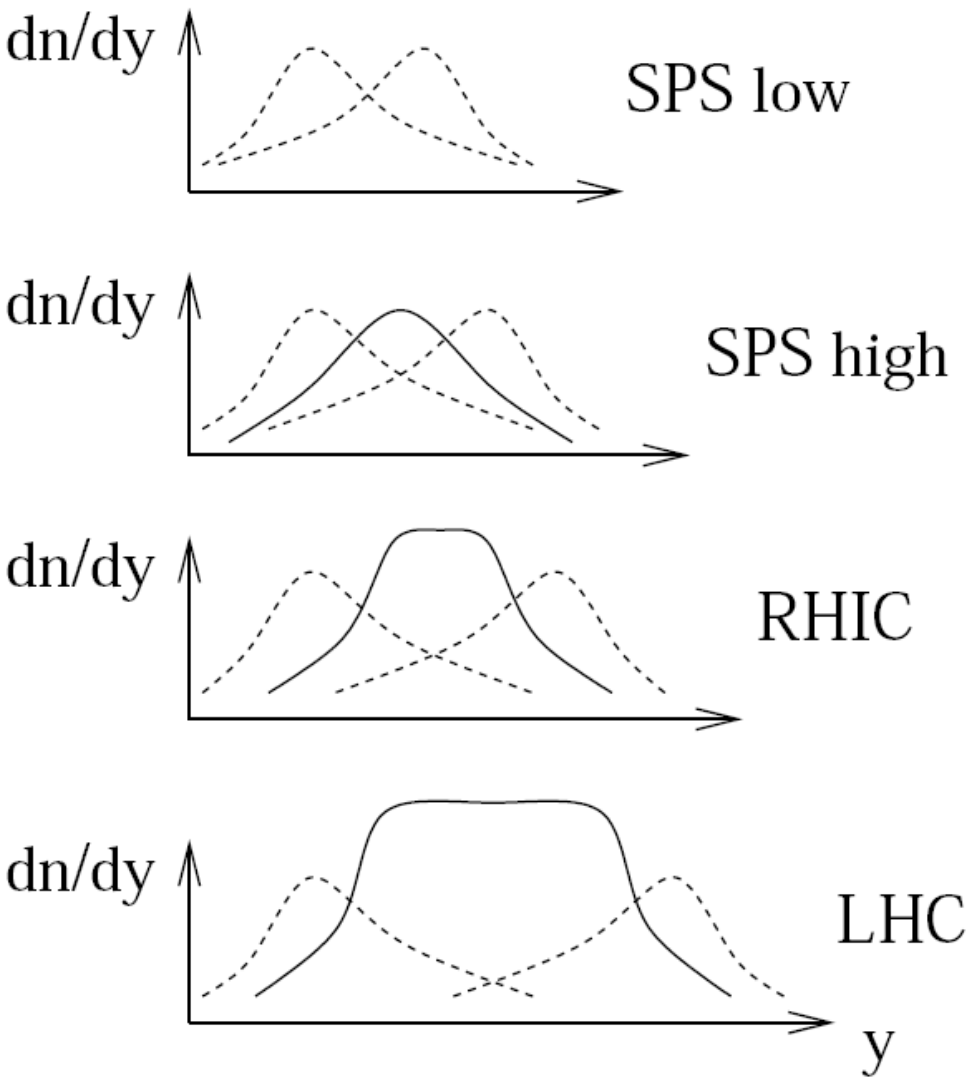
Forward particles mainly from projectile remnant



- 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)

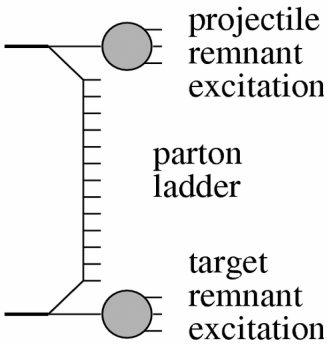
Different contributions of particle production at different energies or rapidities

Remnants



Free remnants in EPOS:

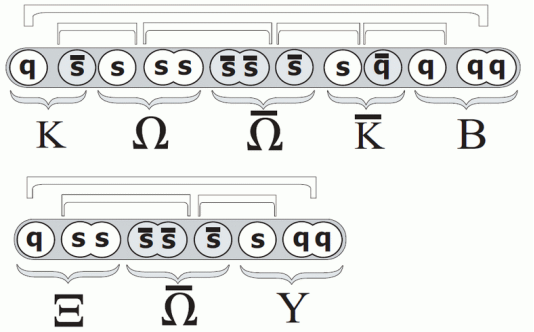
- from both diffractive or inelastic scattering
- excited state with $P(M) \sim 1/(M^2)^{\alpha}$
- dominant contribution at low energy
- forward region at high energy
- depending on quark content and mass (excitation):
  - resonance
  - string
  - droplet (if #q>3)
  - string+droplet



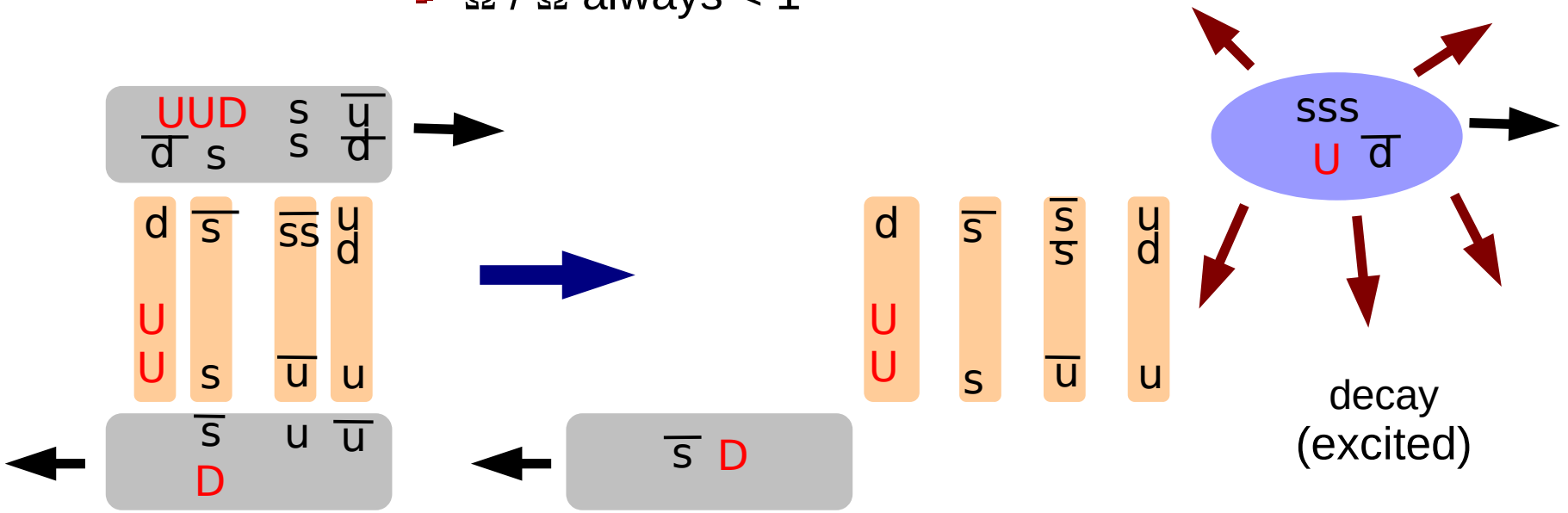
Baryons and Remnants

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)



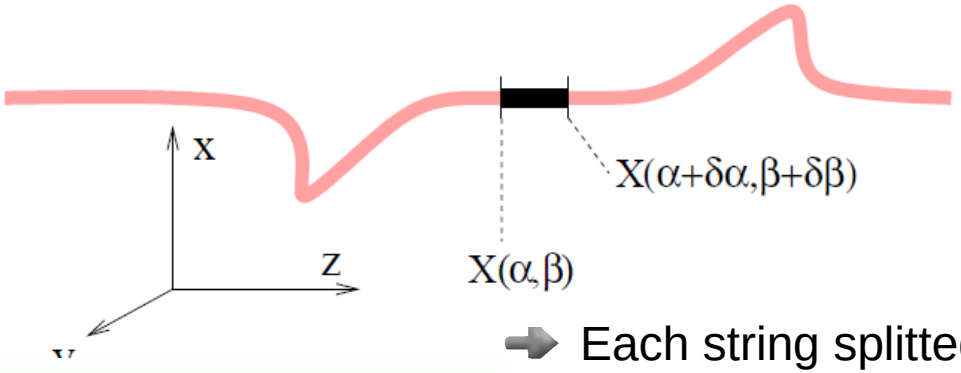
- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - $\bar{\Omega}$ / Ω always < 1

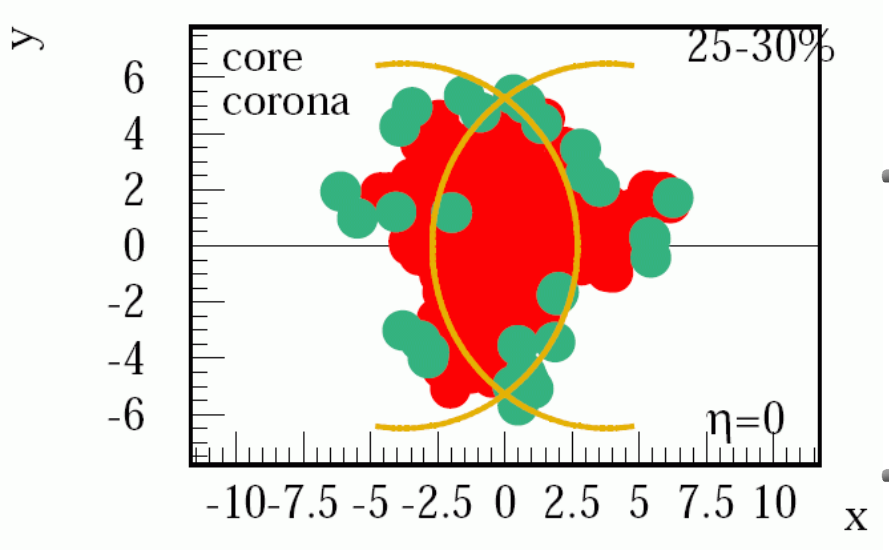


High Density Core Formation

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**



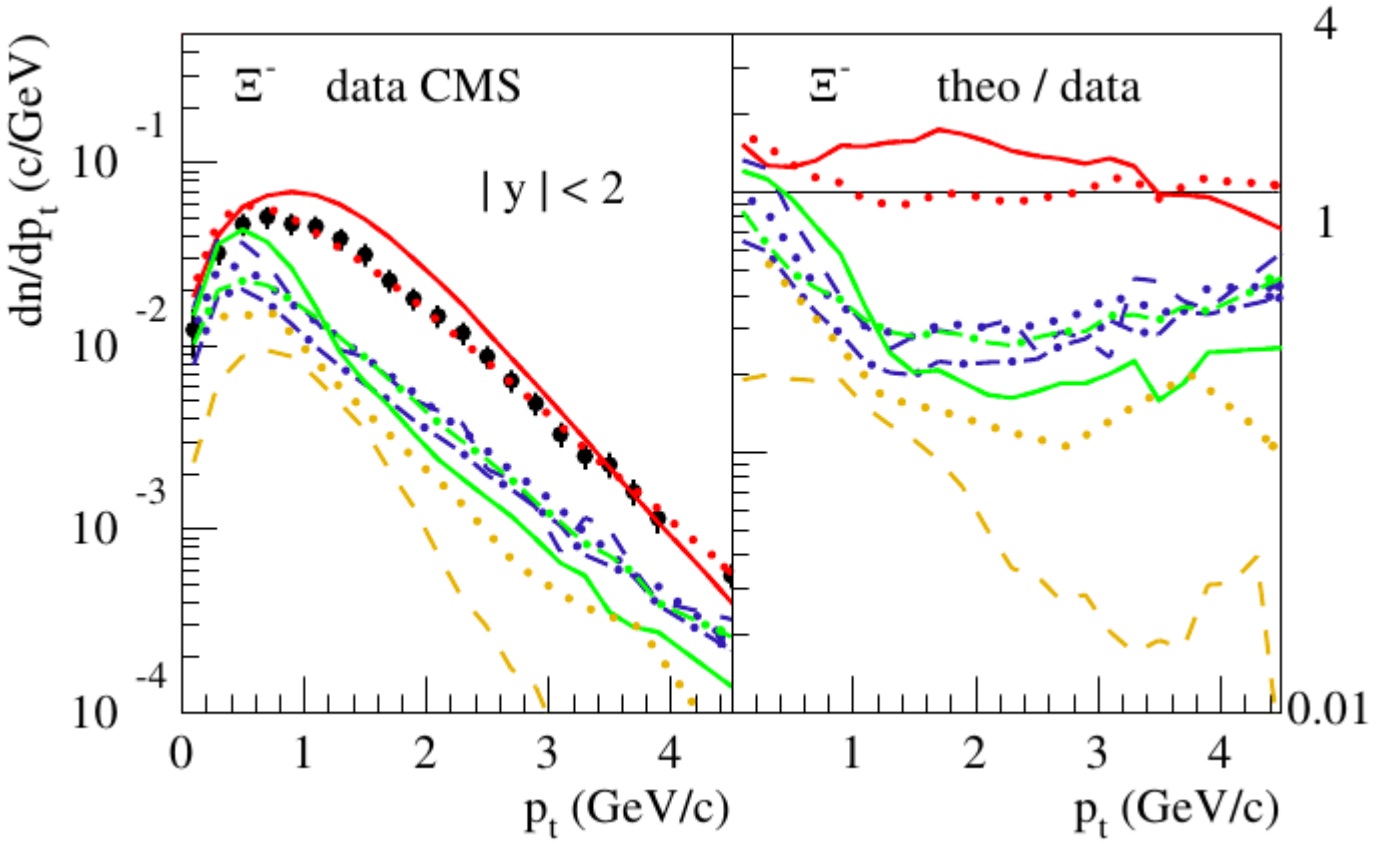


- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - flow from hydro-evolution
    - statistical hadronization
- If low density (corona)
  - segments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

Core in p-p

Detailed description can be achieved with core in pp

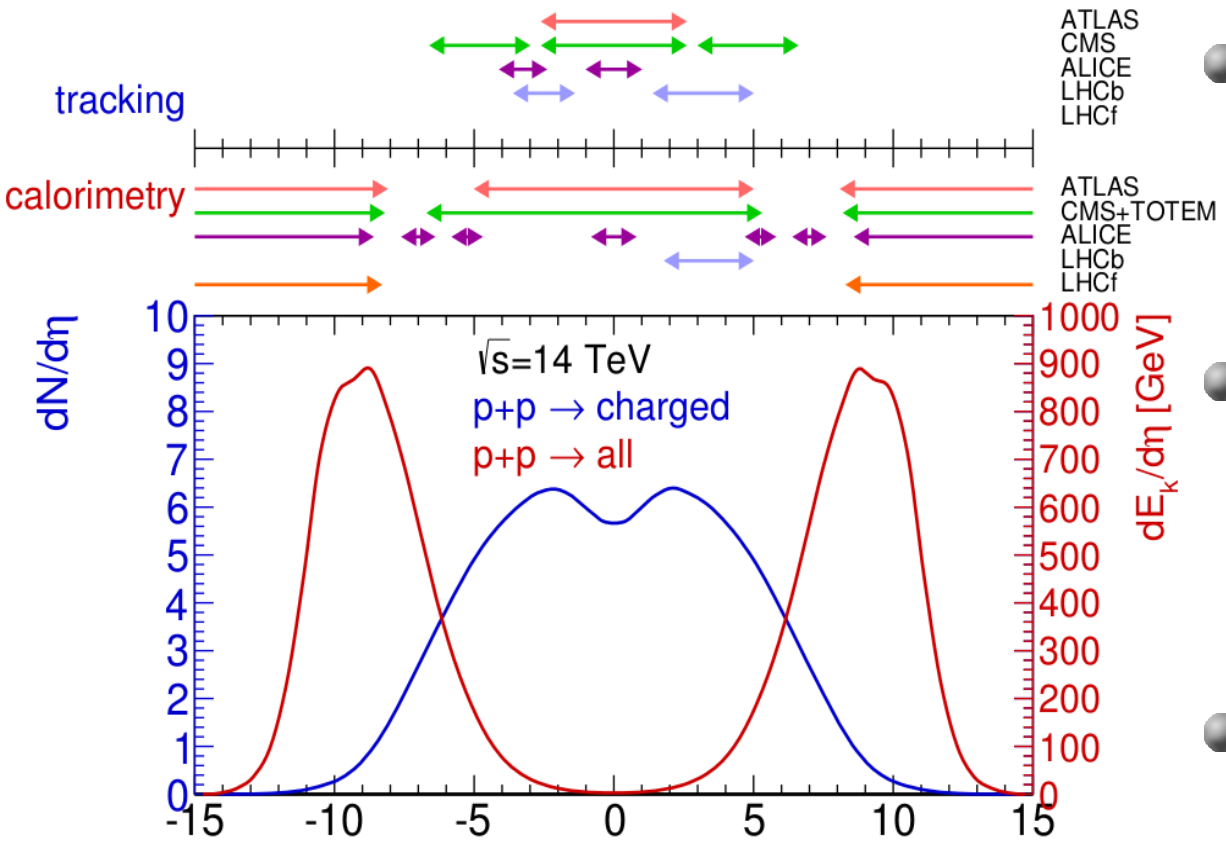
- identified spectra: different strangeness between string (low) and stat. decay (high)
- p_t behavior driven by collective effects (statistical hadronization + flow)
  - larger effect for multi-strange baryons (yield AND $<p_t>$)



p-p @ 7 TeV

EPOS3
EPOS LHC
QGSJETII
SIBYLL
AMPT
PHOJET
PYTHIA6
PYTHIA8
HERWIG++
SHERPA

Ideal Measurements for CR

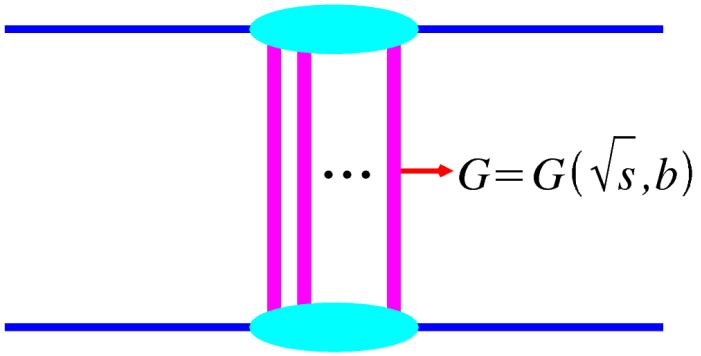


Direct measurement of particles important for air shower development difficult at LHC !

(excluded by kin. and techn. limits)

- **Inelastic cross-section (and all other obs.) for p-Air and pion-Air**
  - LHC: p-p or p-Pb … pO ?
- **Average elasticity/inelasticity** (energy fraction of the leading particle)
  - LHC: SD with proton tagging only
- **Multiplicity of id. particles in forward region (x_F~0.1)**
  - LHC: tracking for eta<7 (id<5)
- **EM/Had Forward Energy flow (x_F>0.1)**
  - LHC: ZDCs for neutral particles only

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

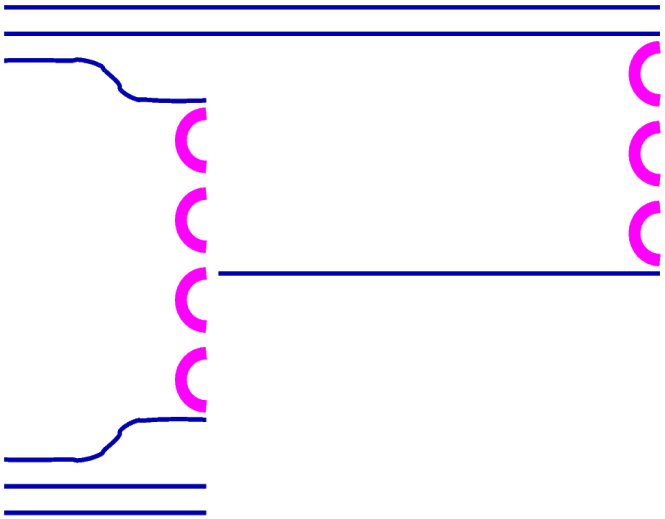
Successful description of hadronic cross-sections

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)

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)

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:**

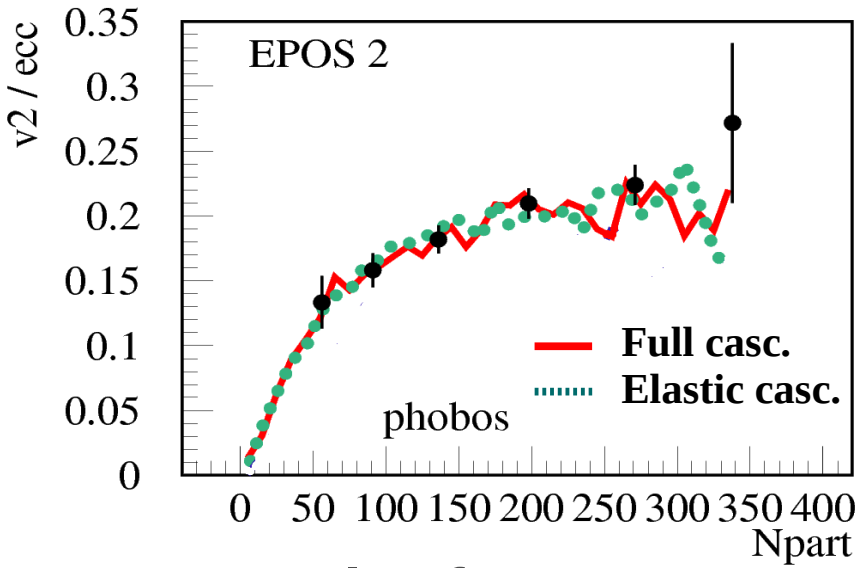
$$\partial_\mu T^{\mu\nu} = 0, \quad \text{using } T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p\, g^{\mu\nu}$$

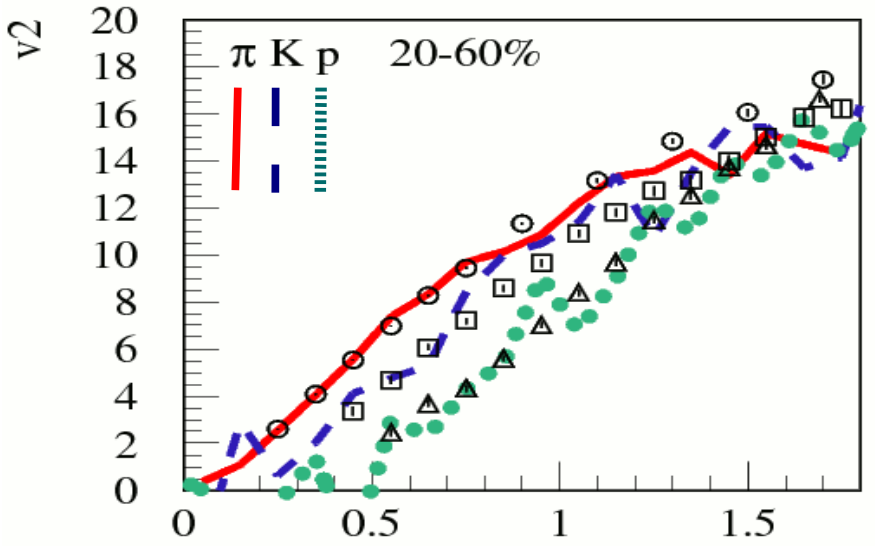
$$\partial N_k^\mu = 0, \quad N_k^\mu = n_k u^\mu,$$

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

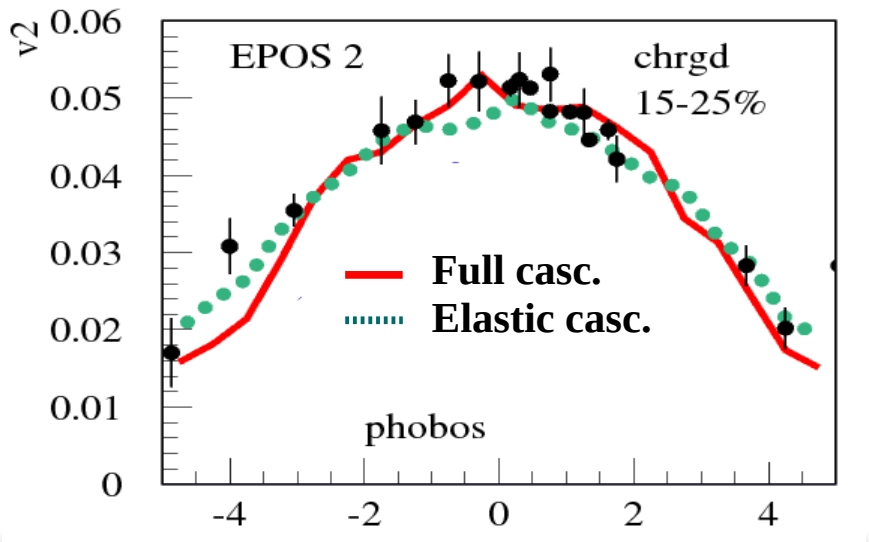
Check with Heavy Ions : AuAu@RHIC

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





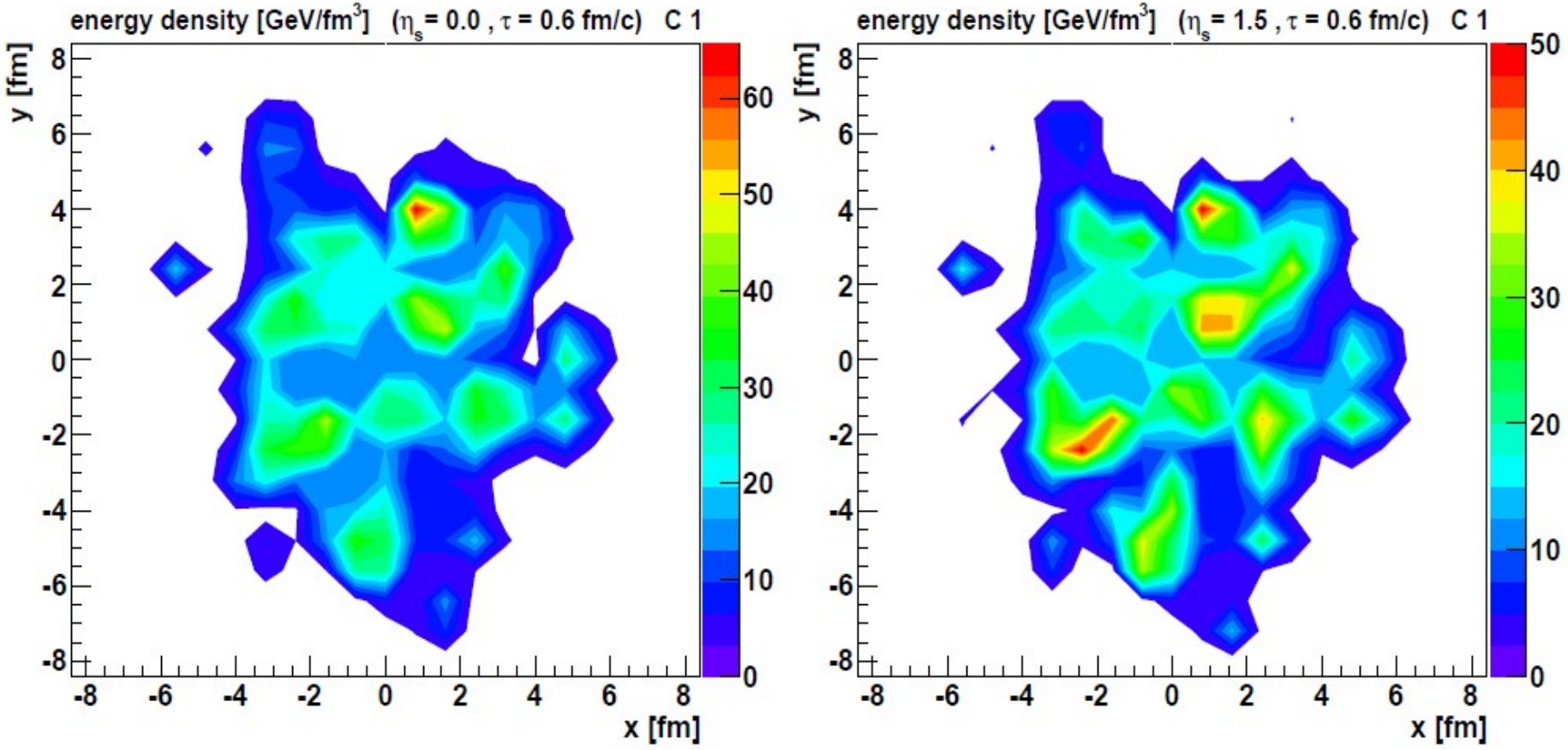
Important role of core-corona effect (K. Werner et al. J.Phys.G36:064030,2009)



- **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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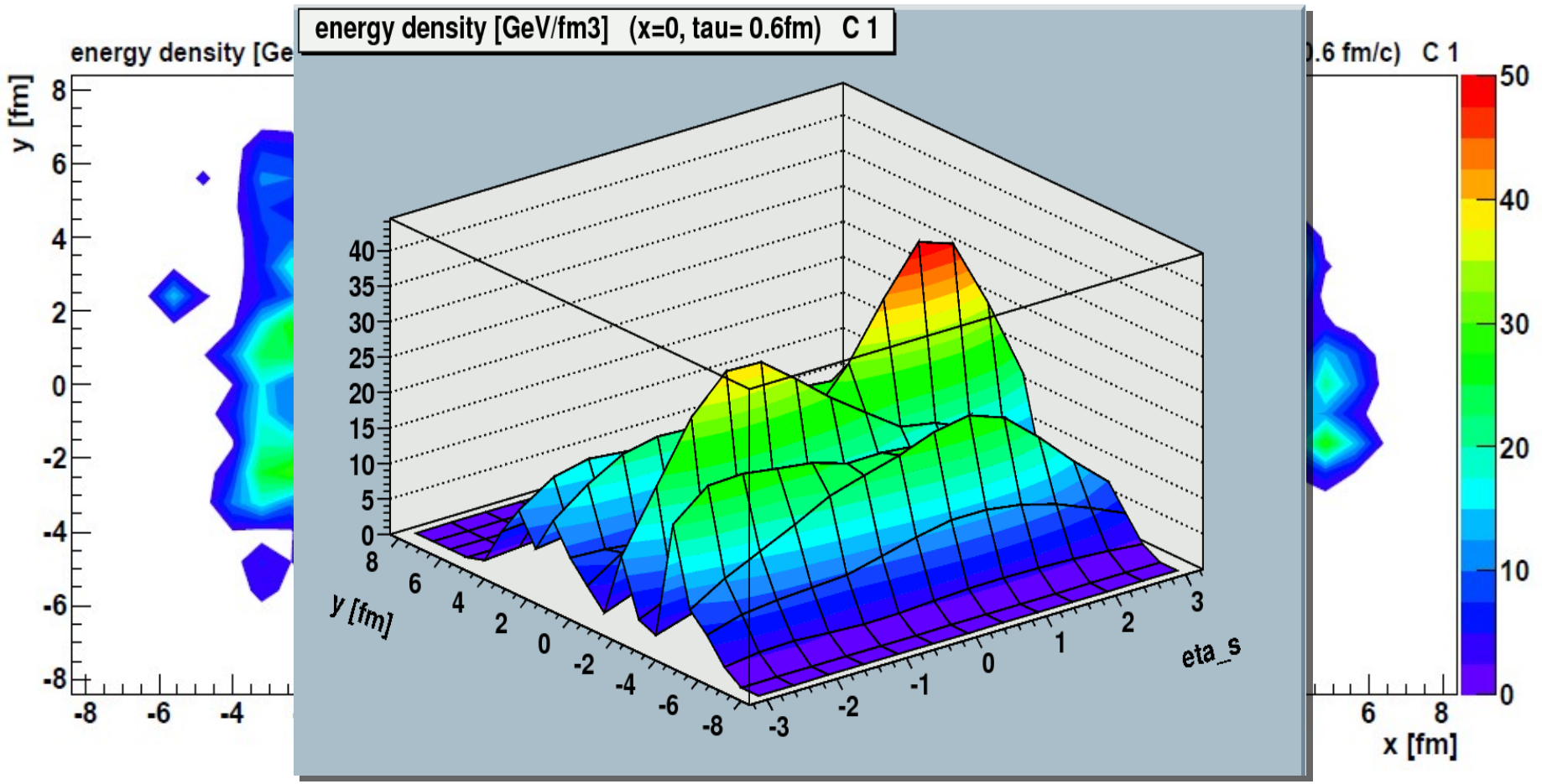
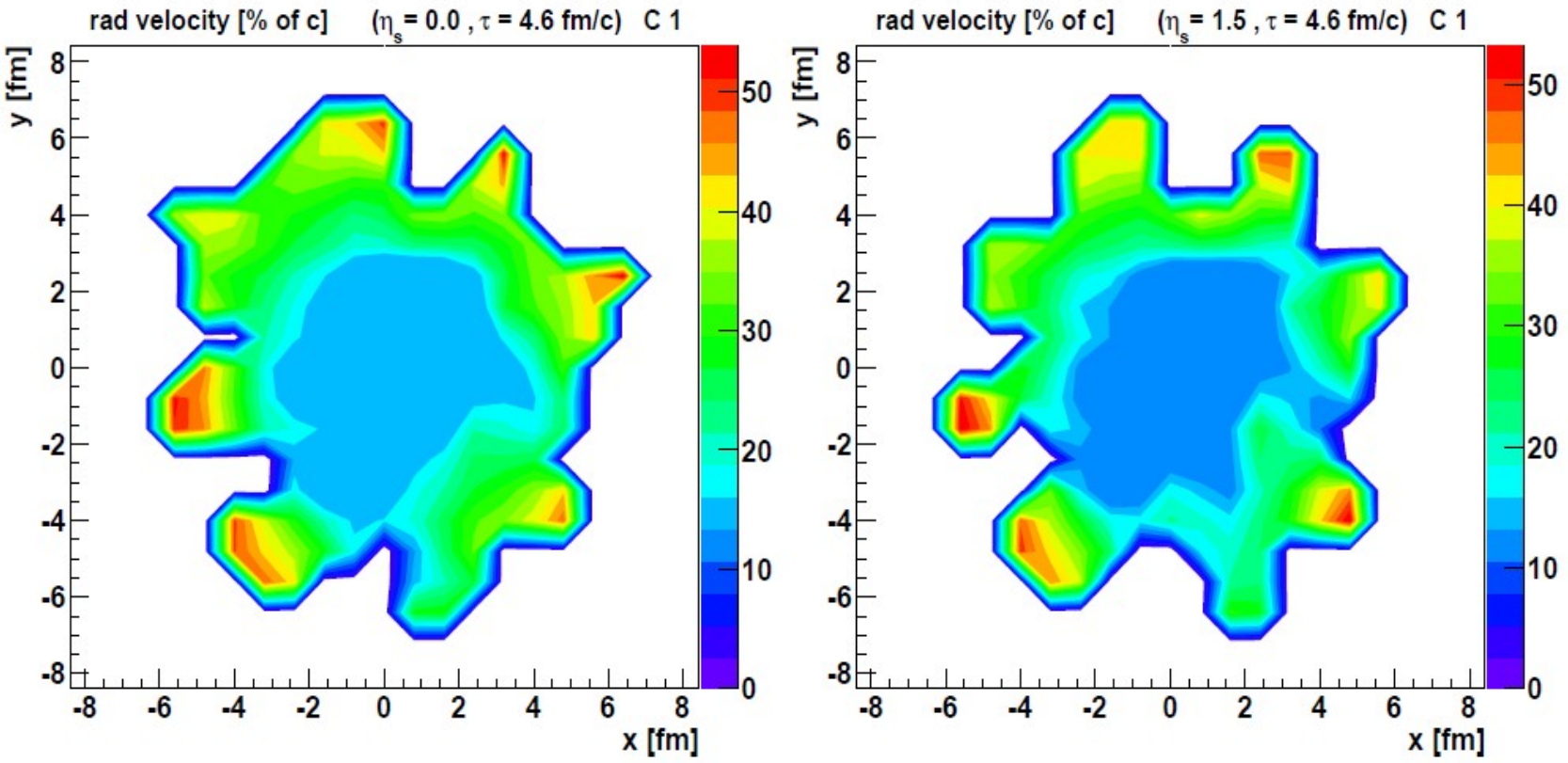


Event-by-Event Radial Flow : AuAu

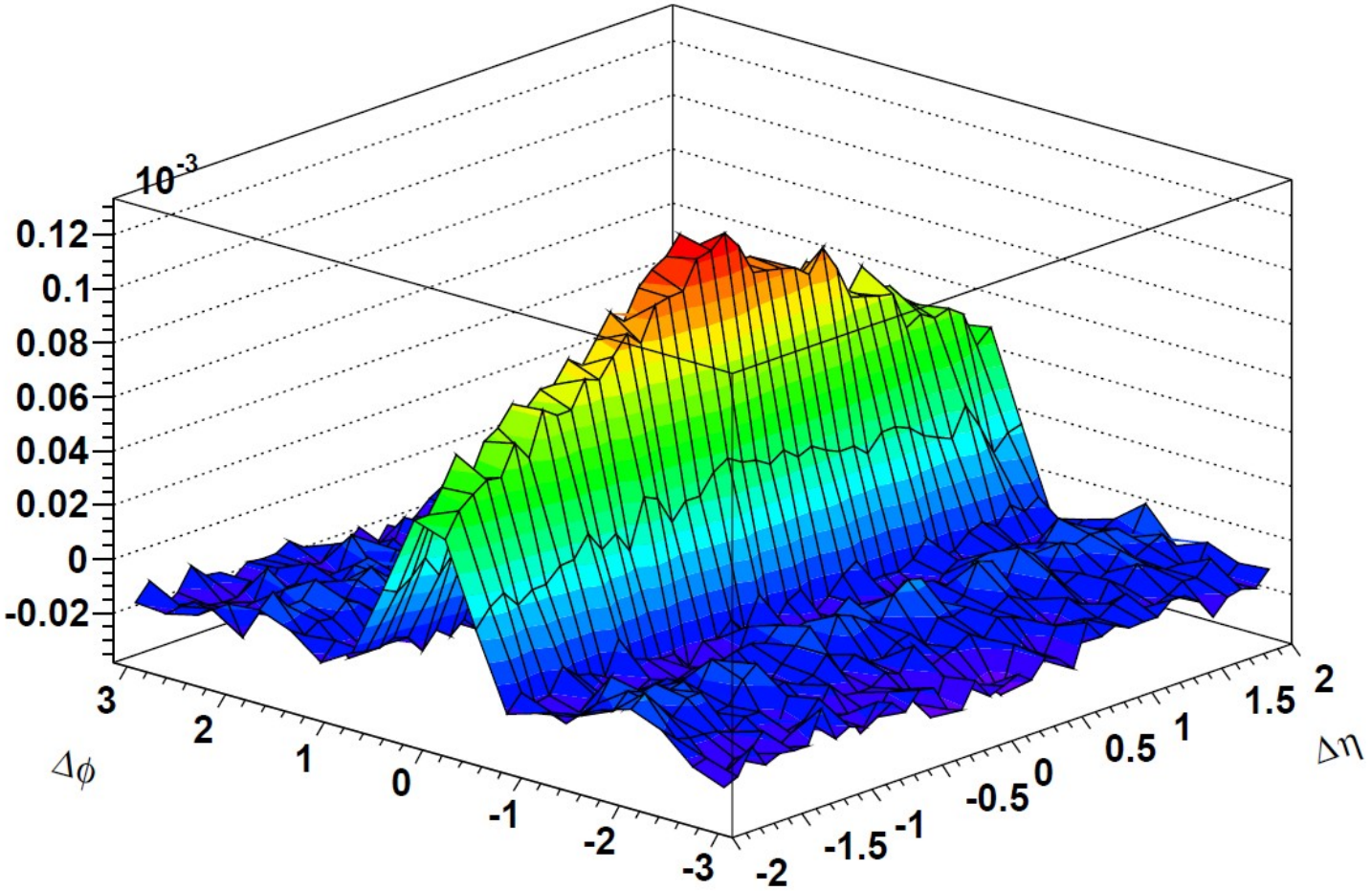
- **Leads to translational invariance of transverse flows**



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

AuAu : Di-hadron correlation

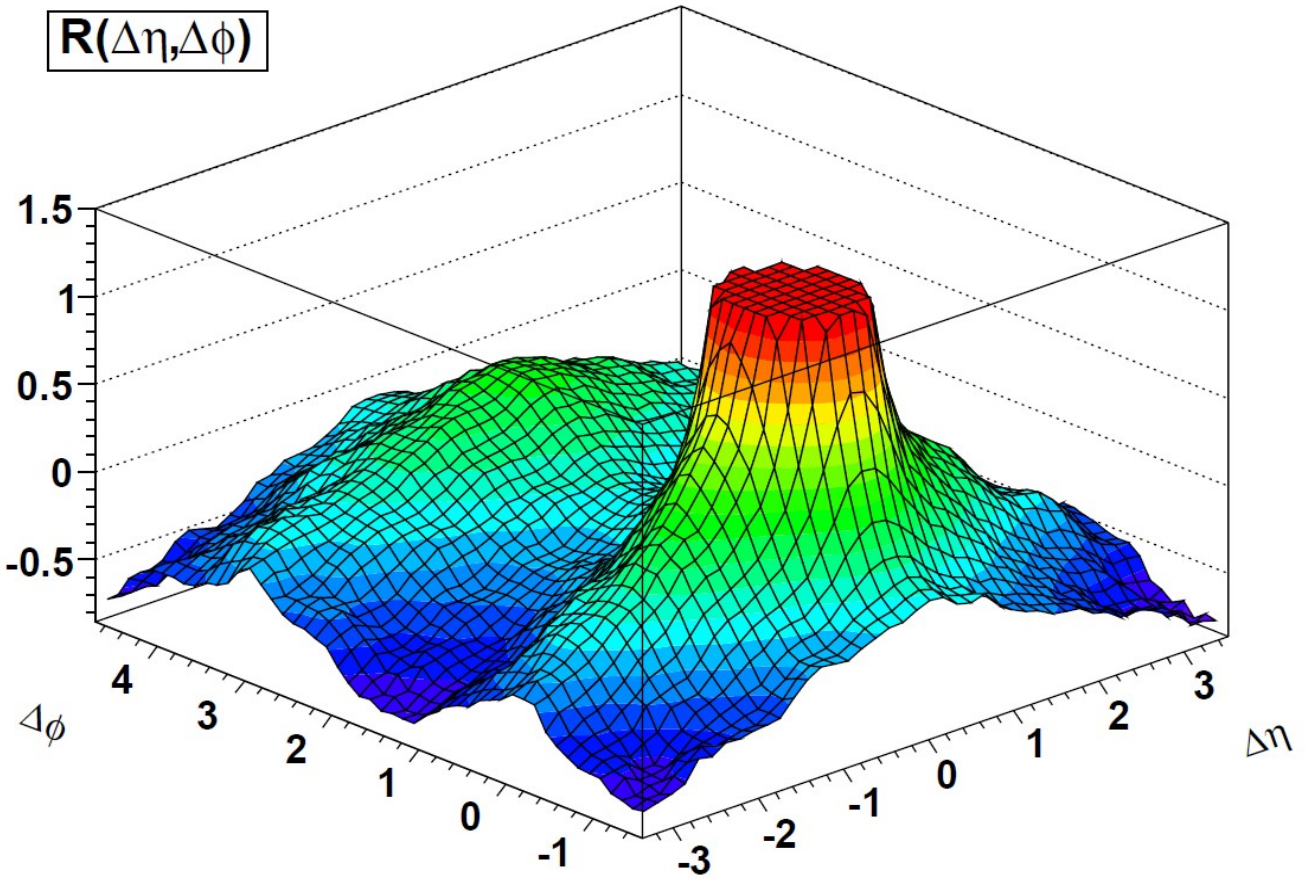
- ridge-structure in the dihadron correlation dN/dΔηdΔφ for free



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

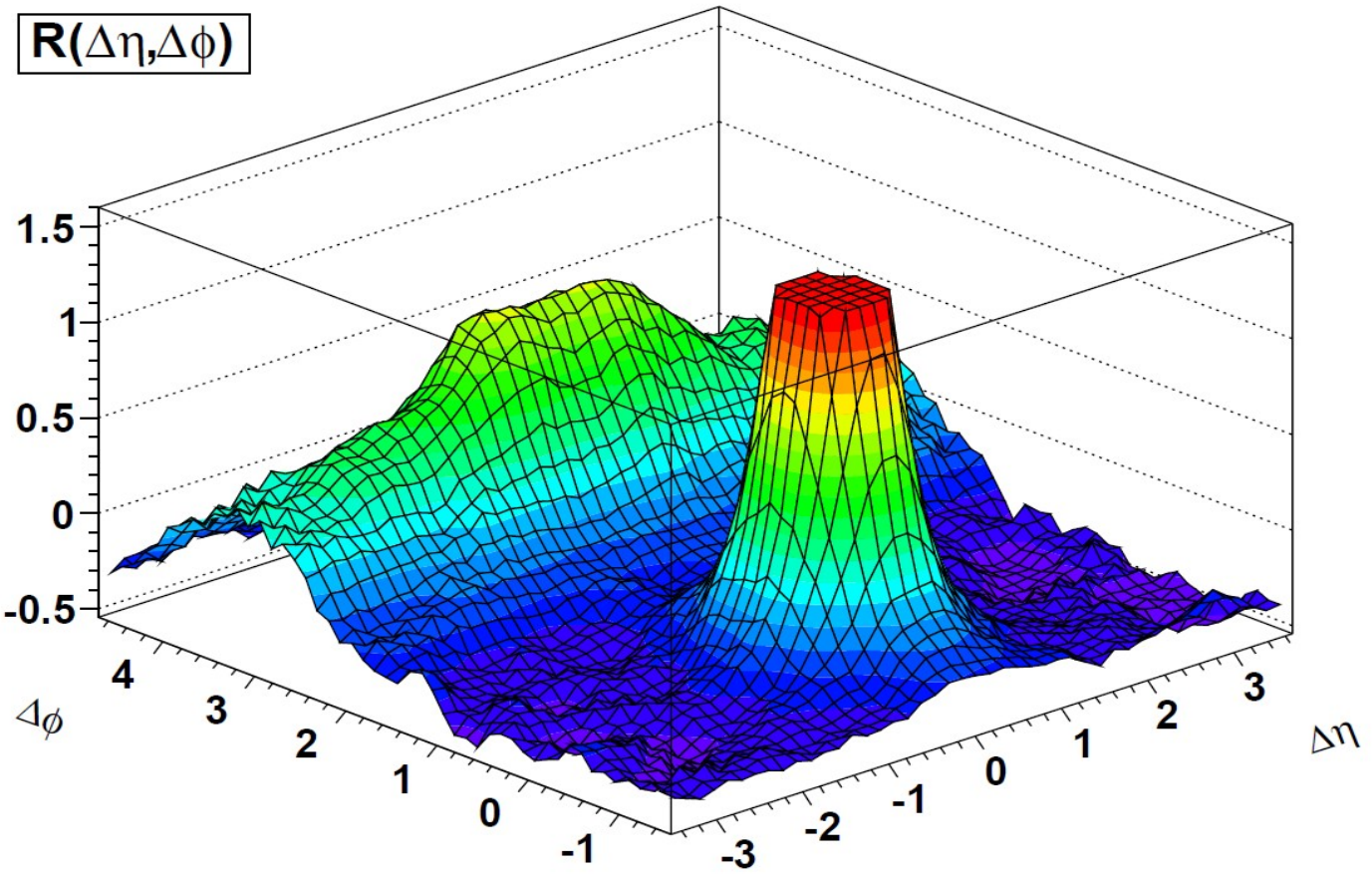
- Our calculation provides a similar ridge structure in pp@LHC using particles with 1 < pt < 3GeV/c, for high multiplicity events



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

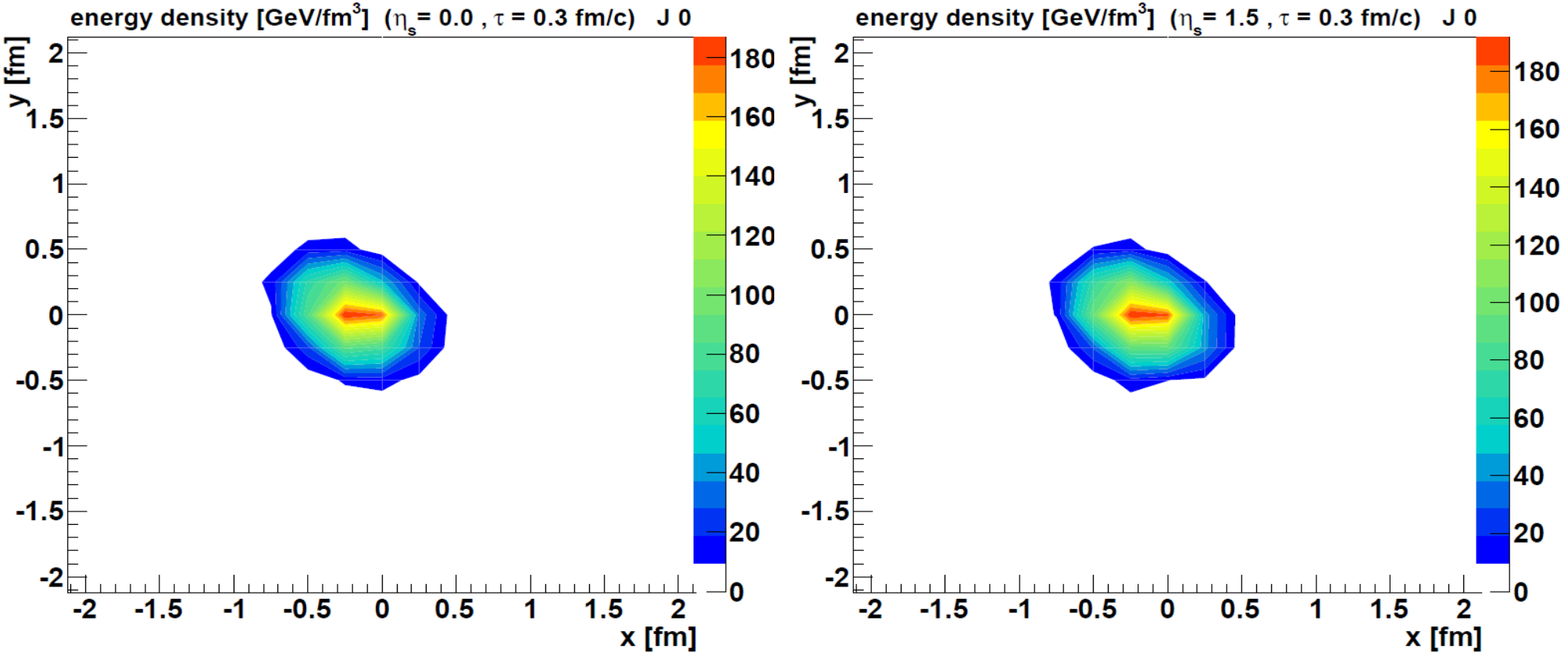
- Calculation without hydro => NO RIDGE



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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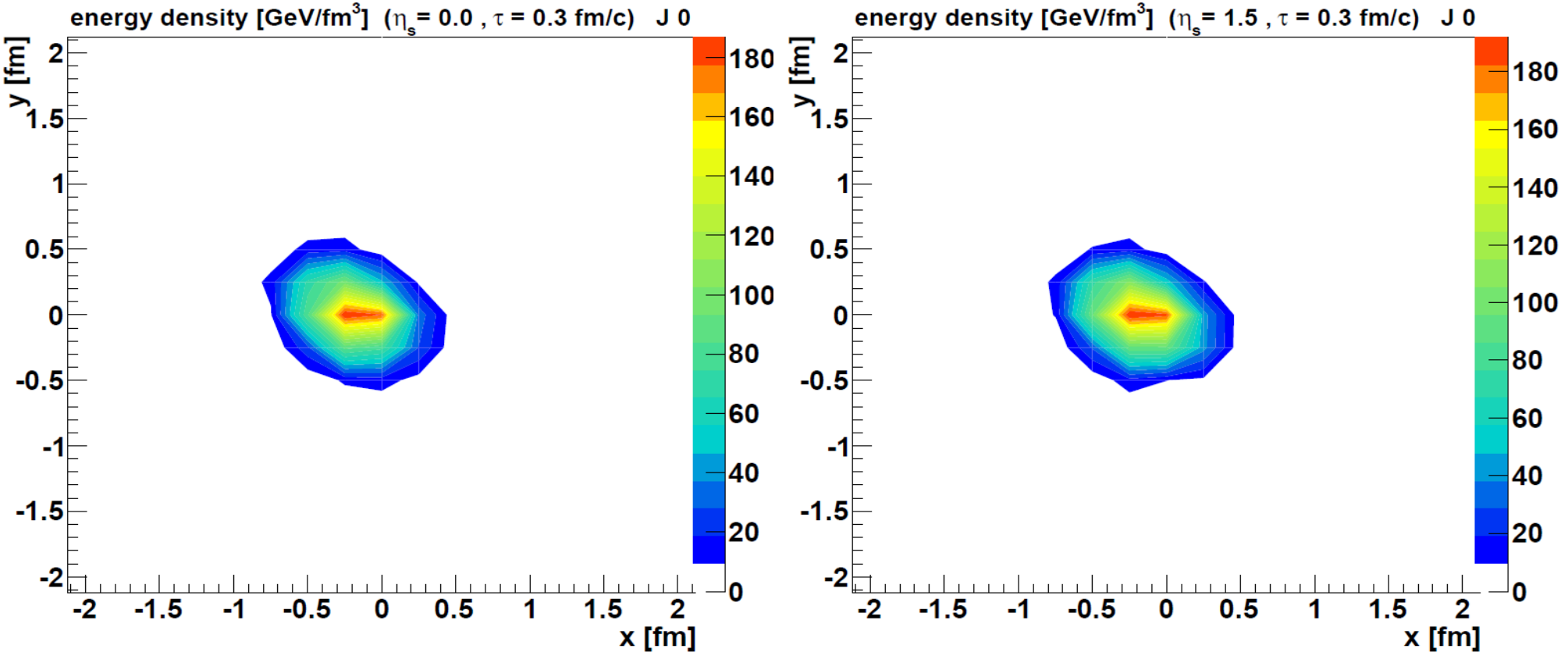

Initial energy density in the transverse plane for two different η_s

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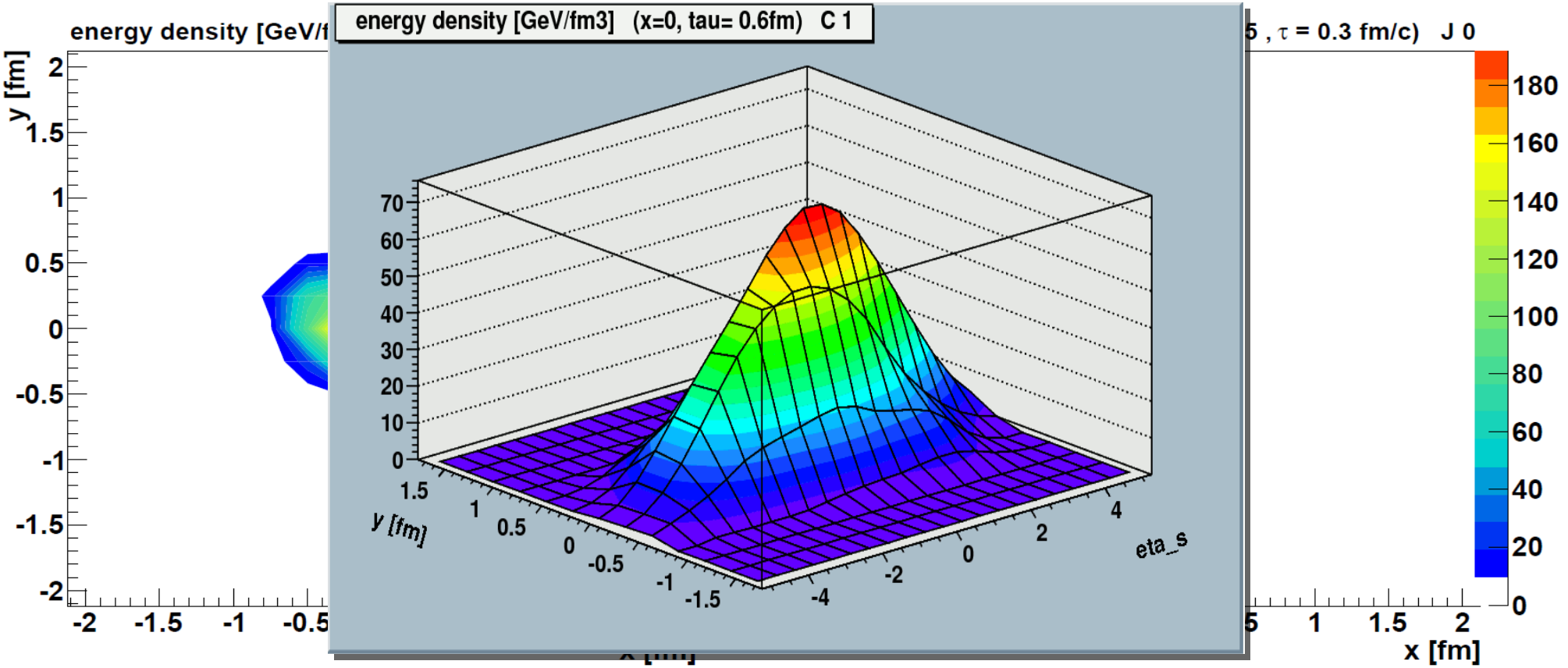
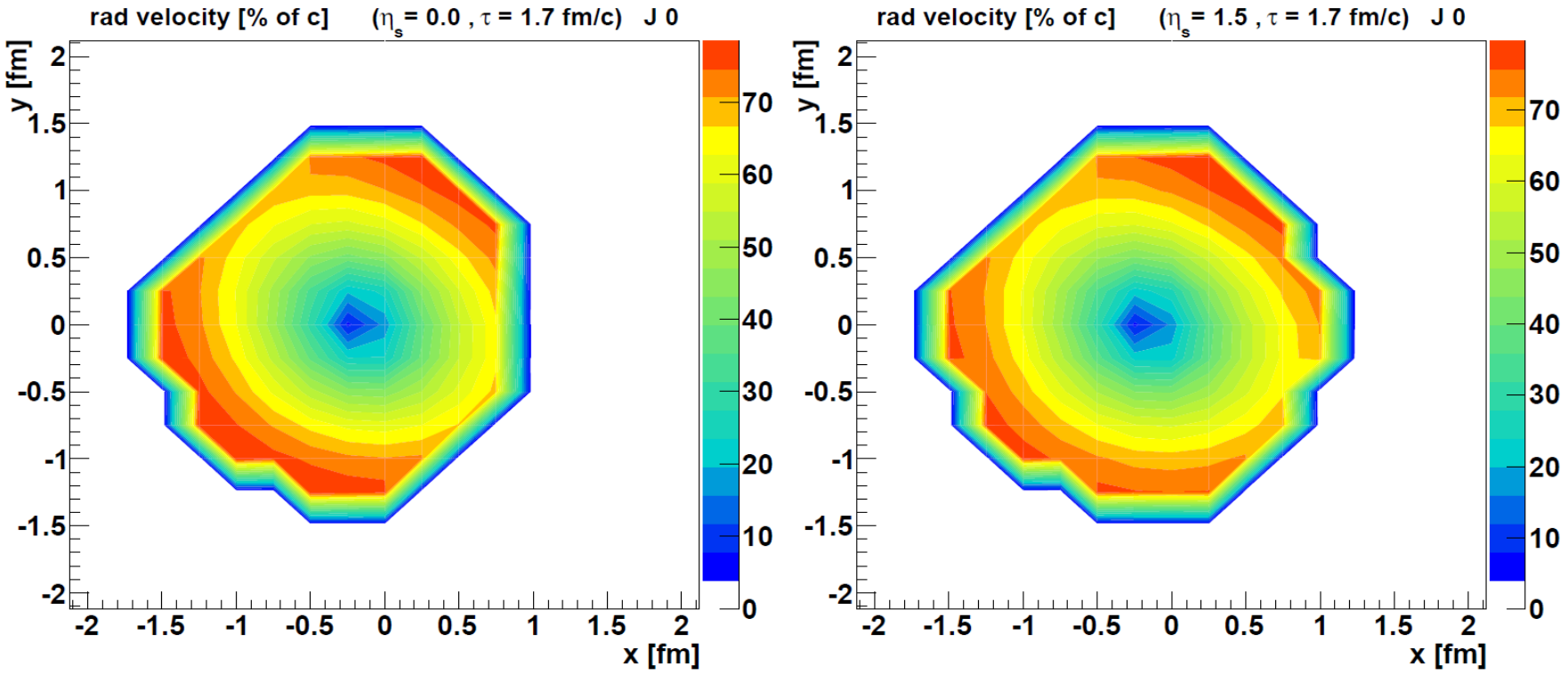


Initial energy density in the transverse plane for two different η_s

Event-by-Event Radial Flow : pp

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



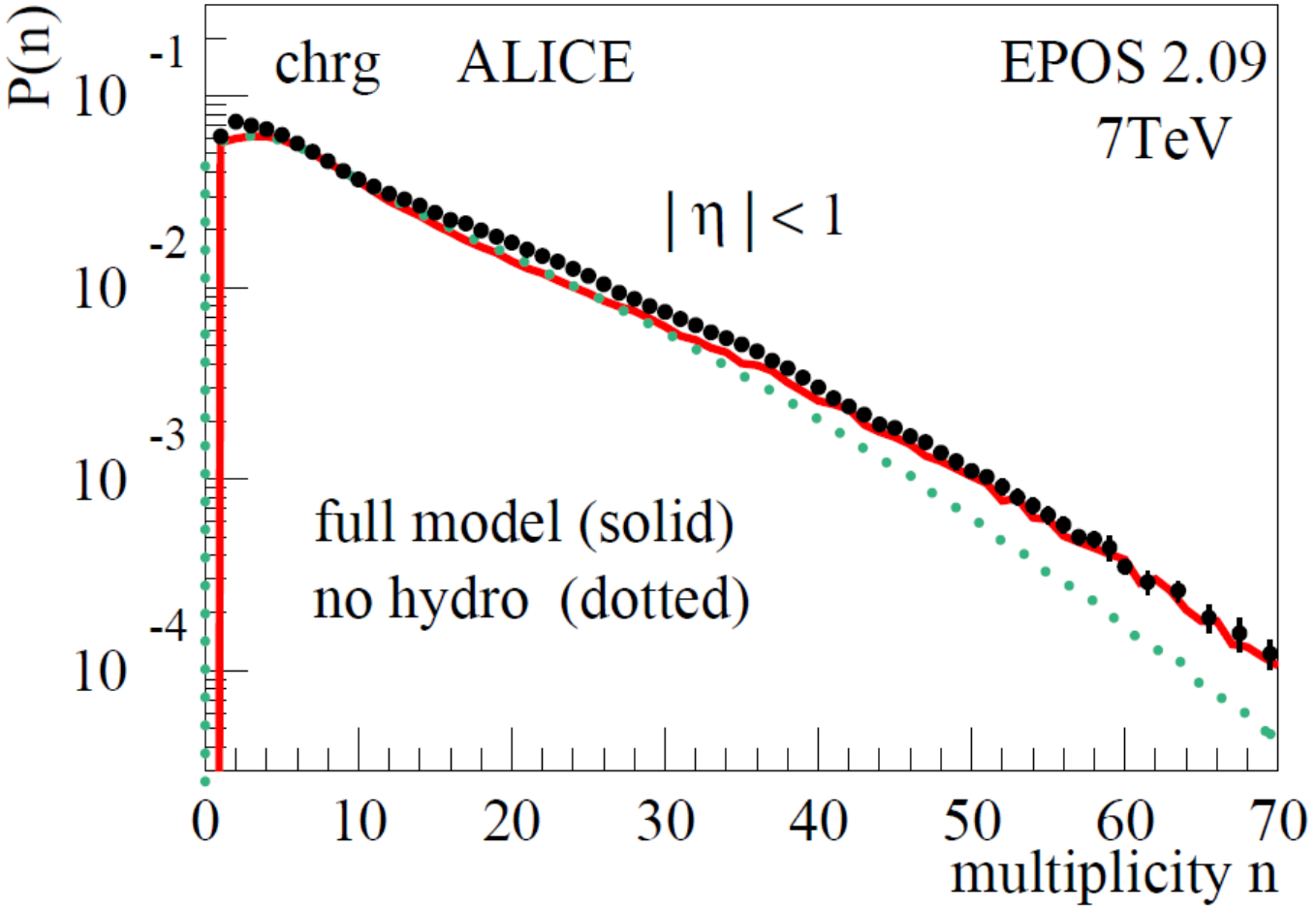
Radial flow velocity at a later time in the transverse plane

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
    - ΔηΔφ correlation

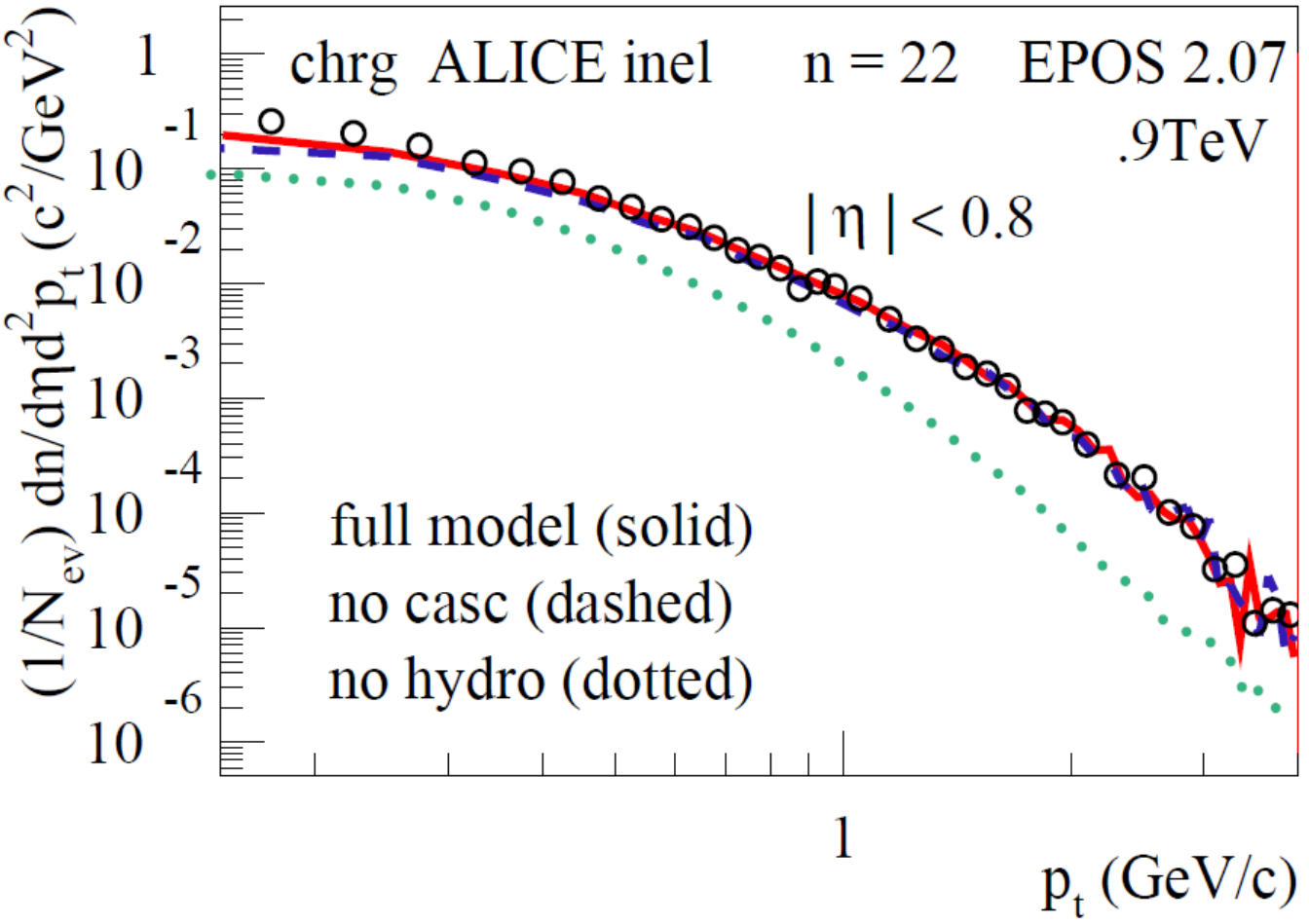
Multiplicity Distribution

- Little effect of hydro in MinBias dn/deta



Pt Distribution

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

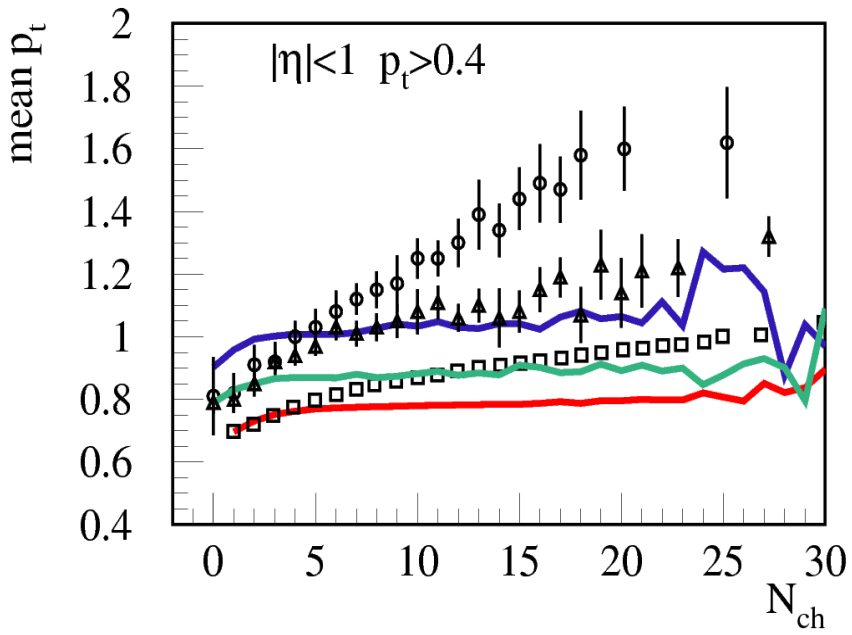


Flow !

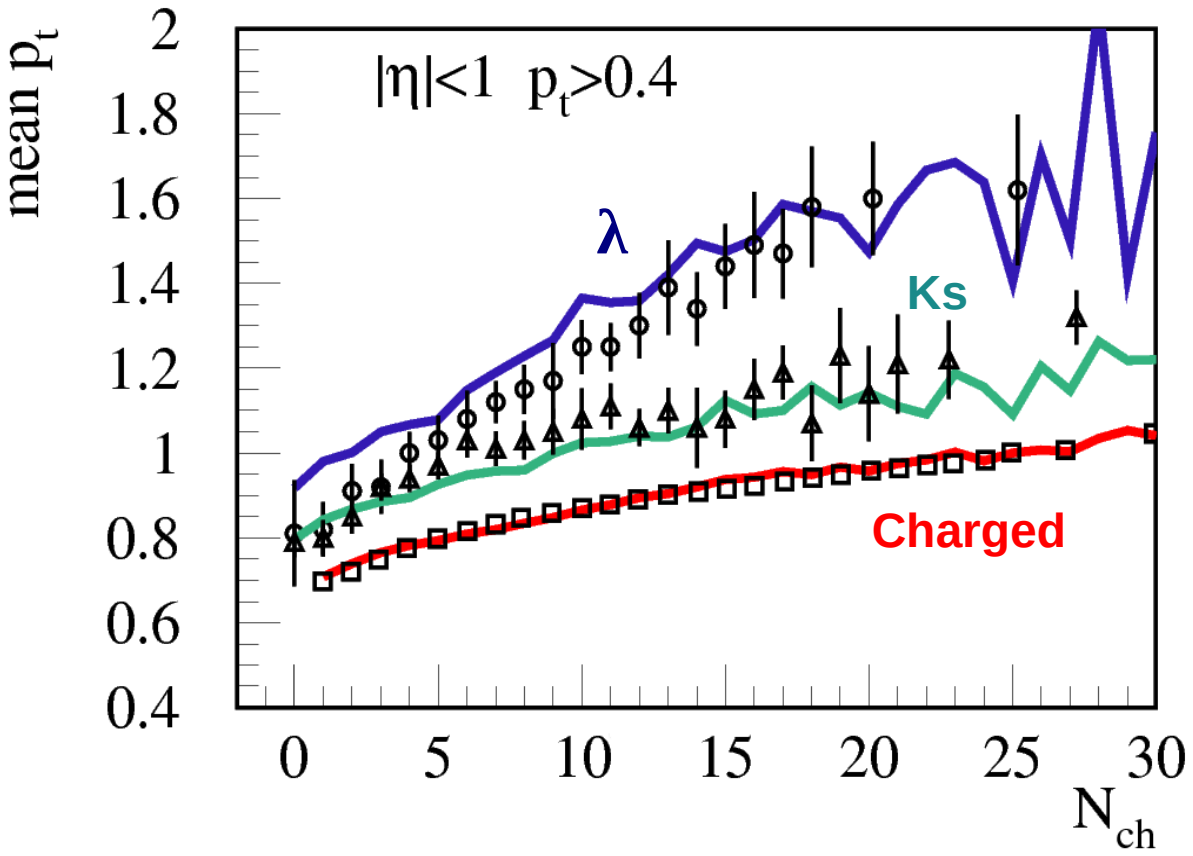
<p_t> vs multiplicity ap-p@1.8 TeV : EPOS 2

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

No collective effects

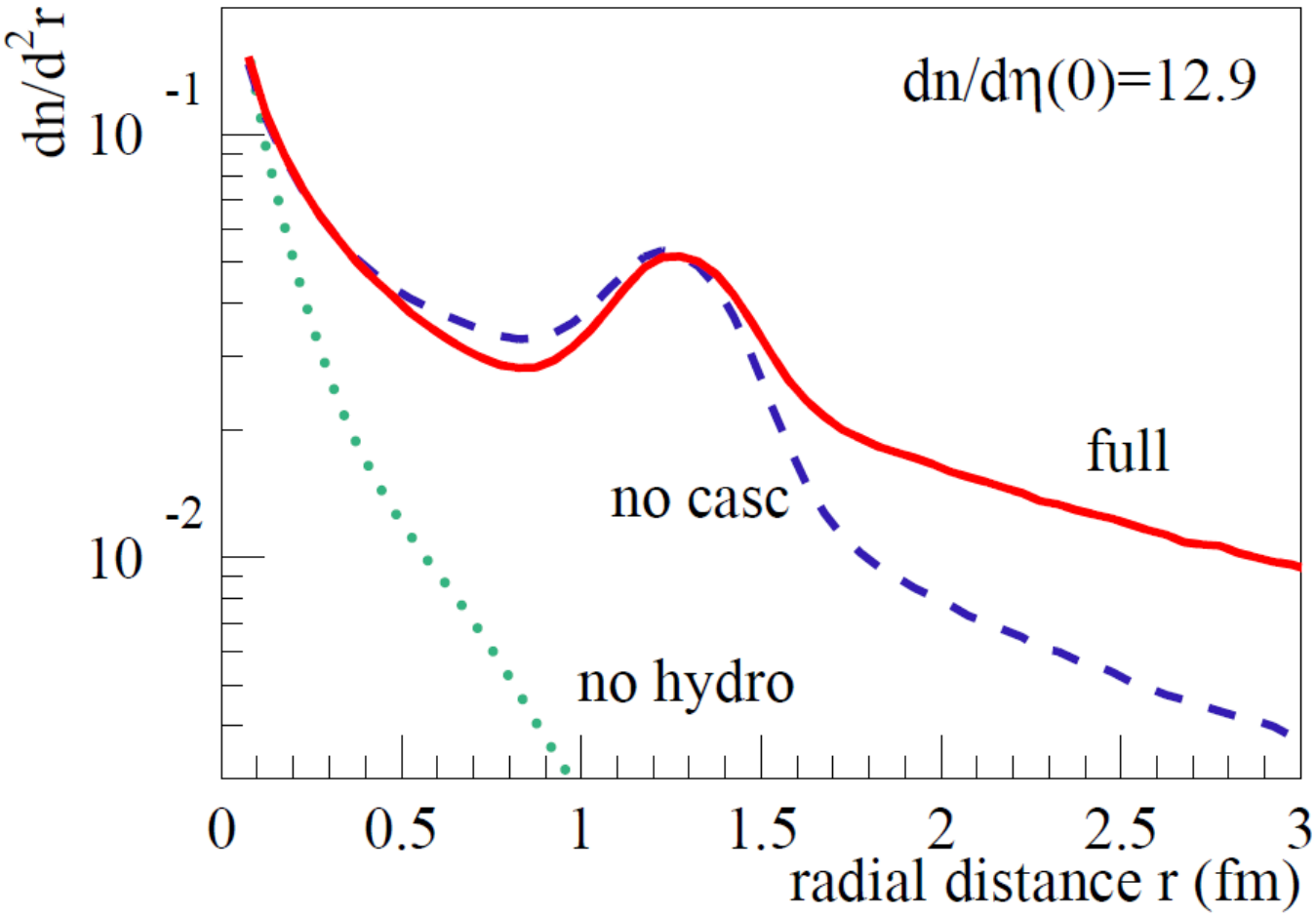


hydro+hadronic cascade



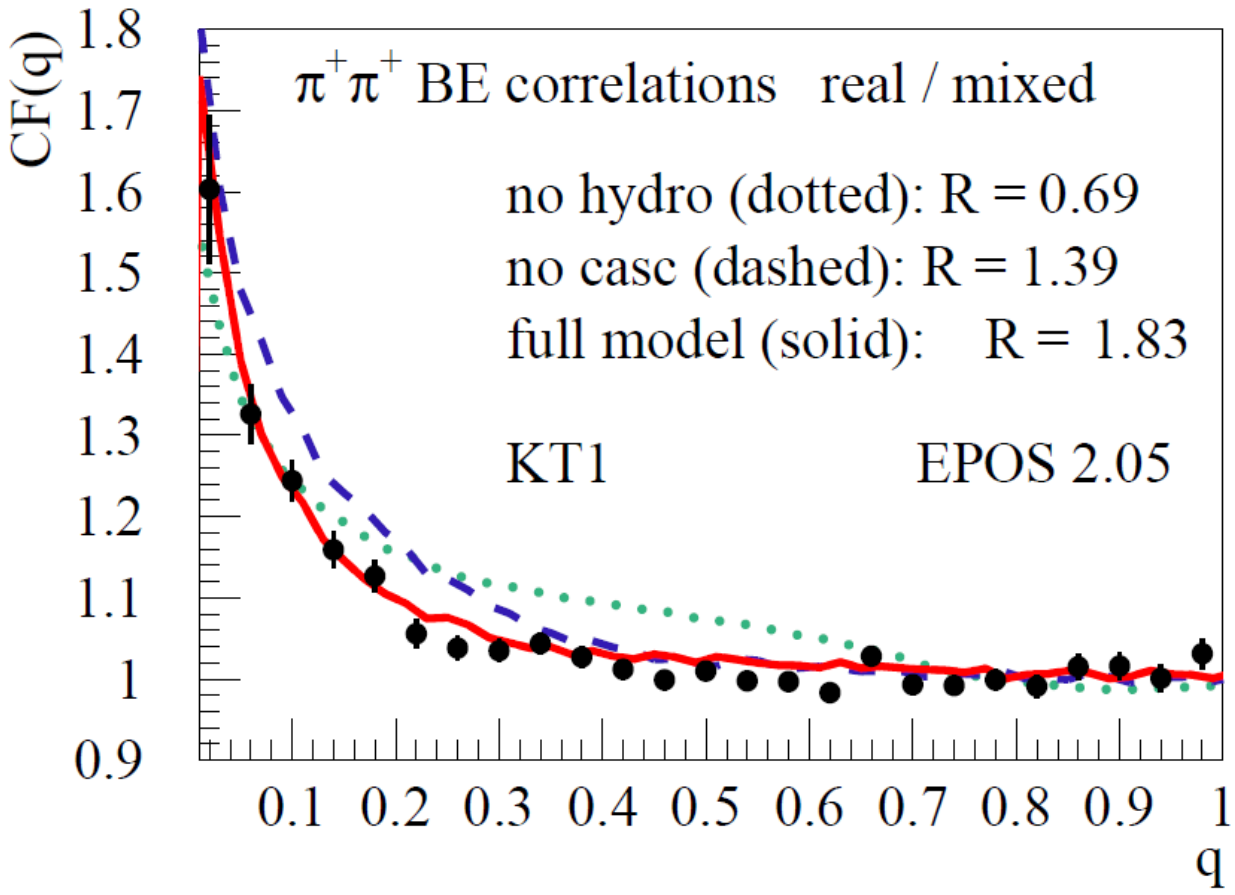
Radius of Particle Emission

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



Bose-Einstein Correlations

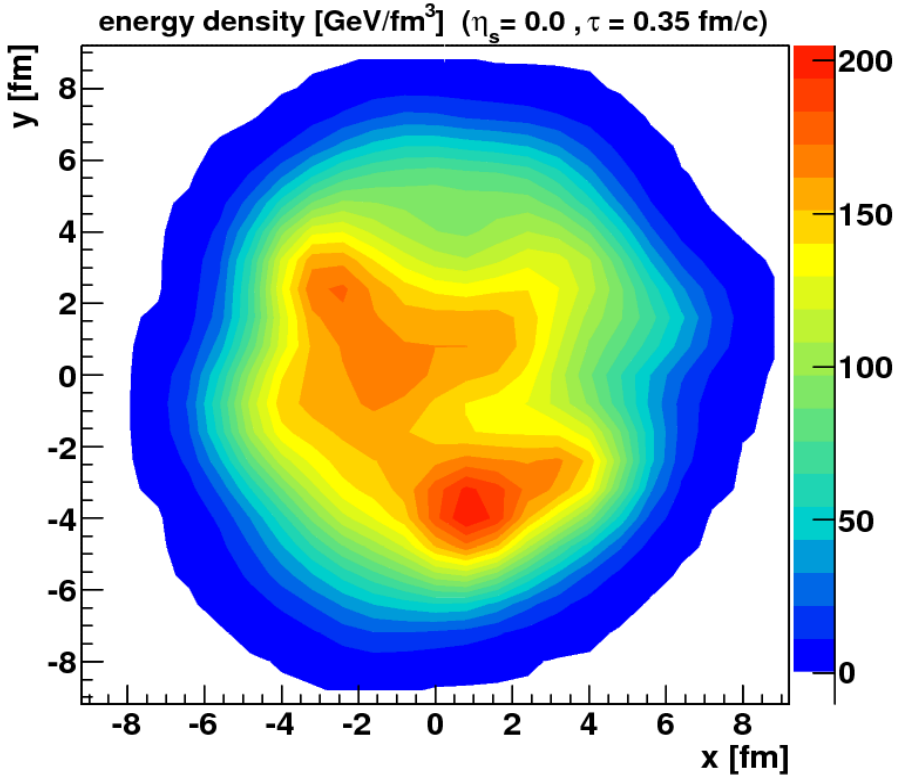
- Consequences for Bose-Einstein correlations

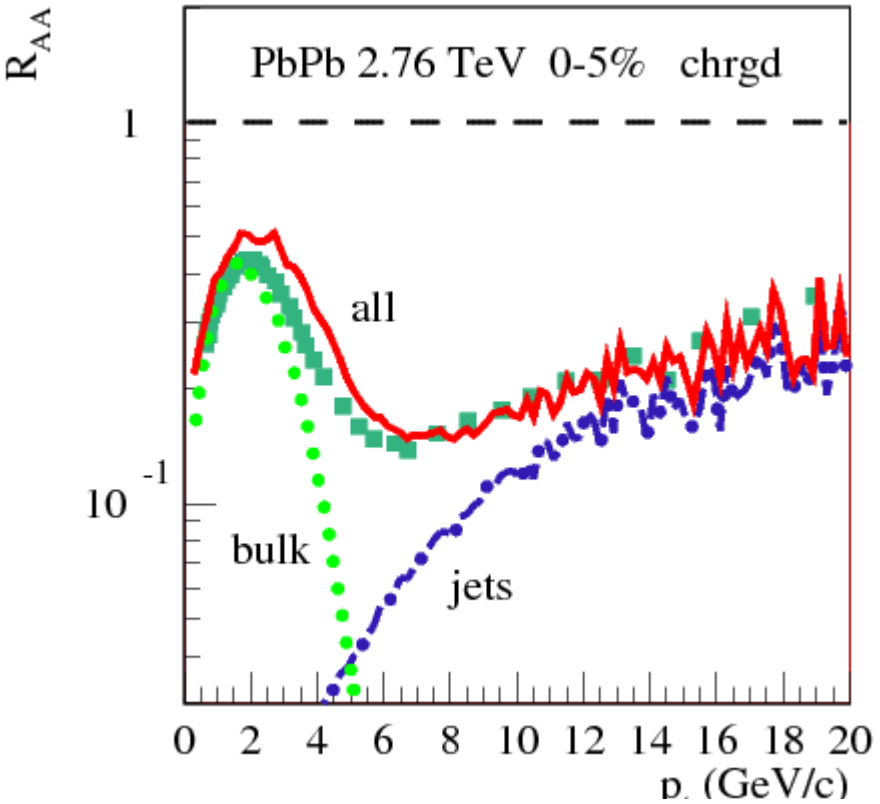


ALICE data.

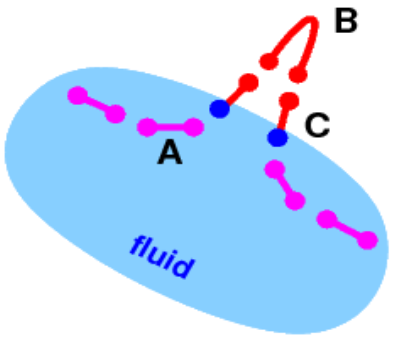
Radii R from exponential fit.
KT1= [100, 250], KT3= [400, 550], KT5= [700, 1000]

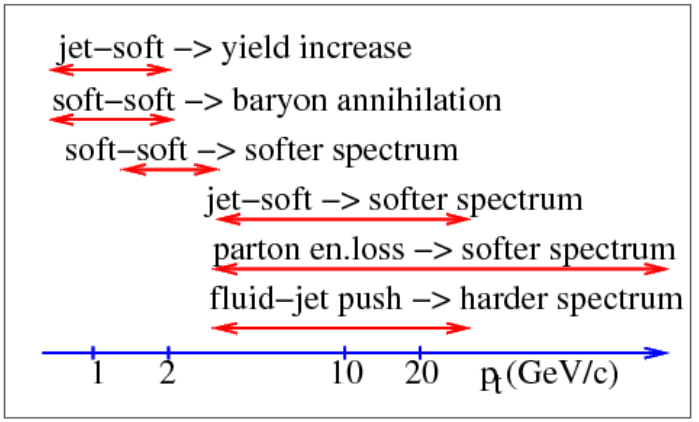
jets in PbPb @ LHC



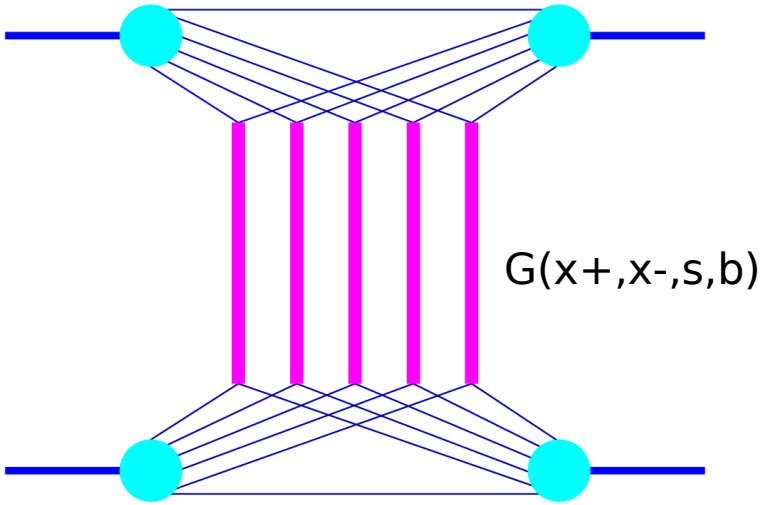


- **Jet interacts in bulk of matter**
  - parton energy loss
  - boost at the surface





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

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

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

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 :

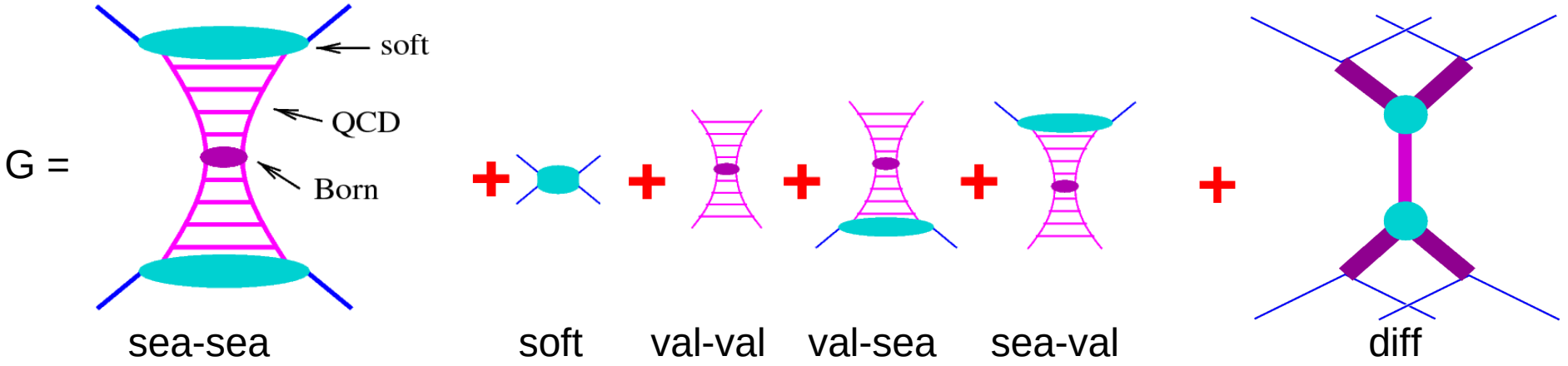
$$\Omega_{AB}^{(s,b)}(m, X^+, X^-) = \prod_{k=1}^{AB} \left\{ \frac{1}{m_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, b_k) \right\} \Phi_{AB}\left(x^{\text{proj}}, x^{\text{targ}}, s, b\right)$$

  - 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

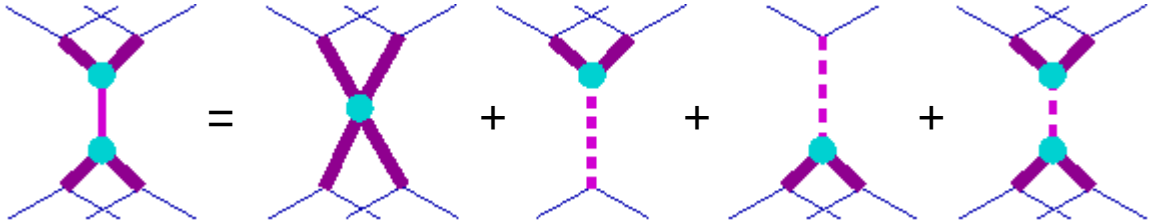
Consistent treatment of cross section and particle production:
number AND distribution of cut Pomerons depend on cross section

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

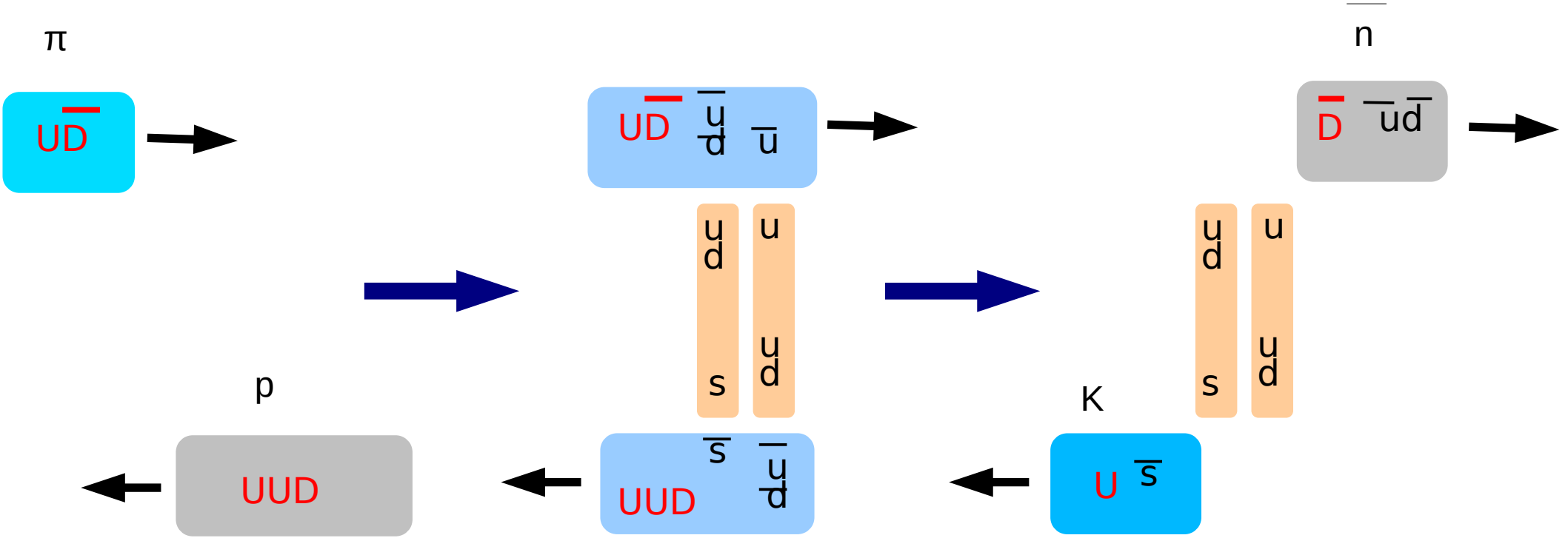


  - Parameters extracted from single diffractive (SD) cross-section
  - Events with only “diff” type diagrams are diffractive

Remnants in EPOS

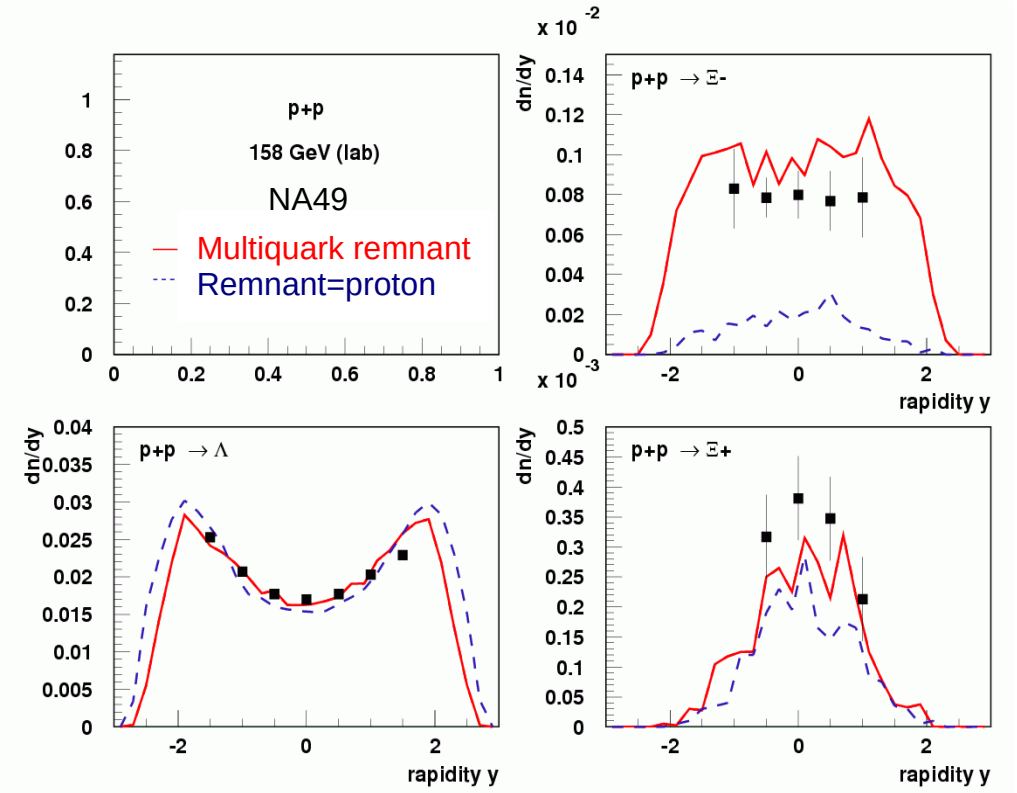
In EPOS : any possible quark/diquark transfer

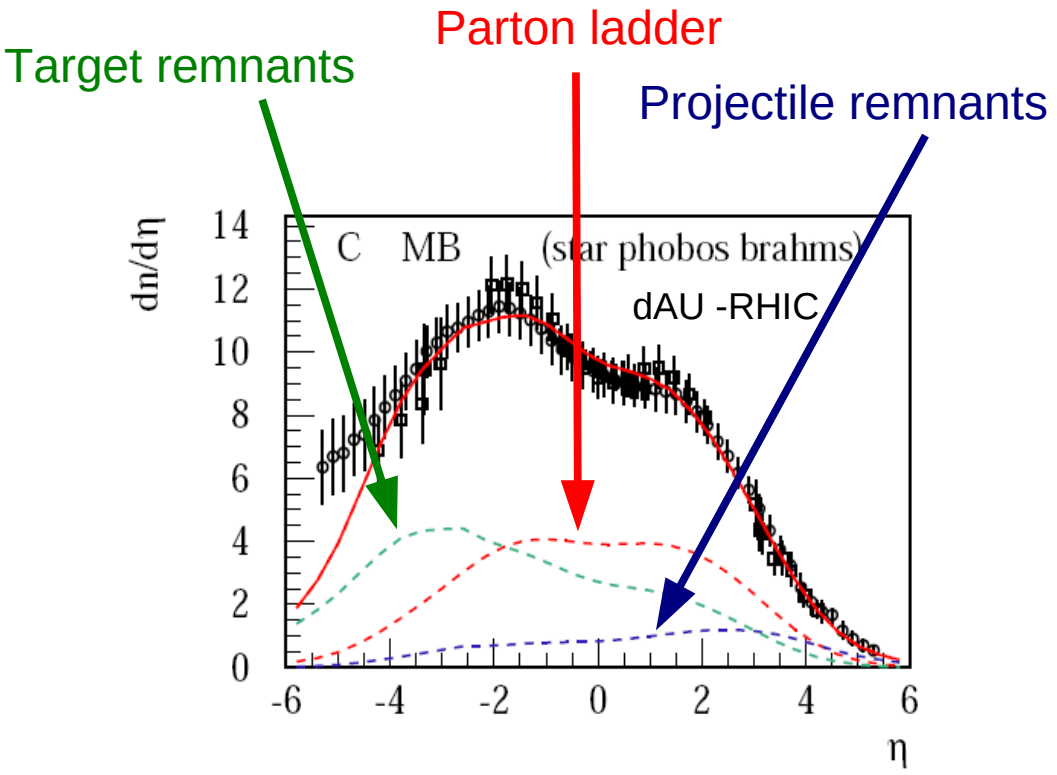
- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



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)





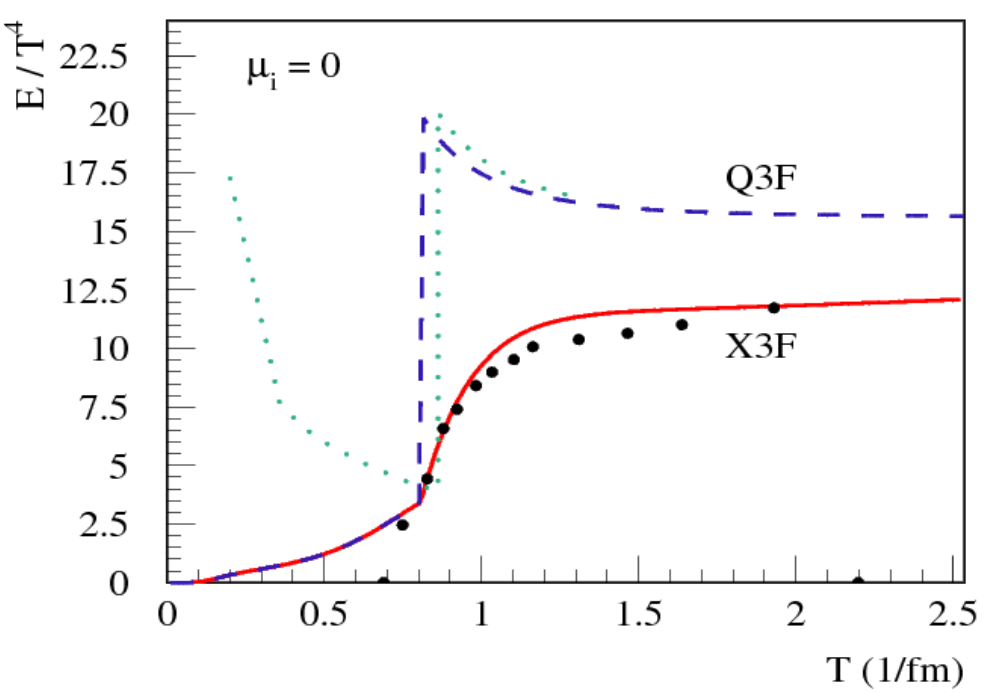
EoS

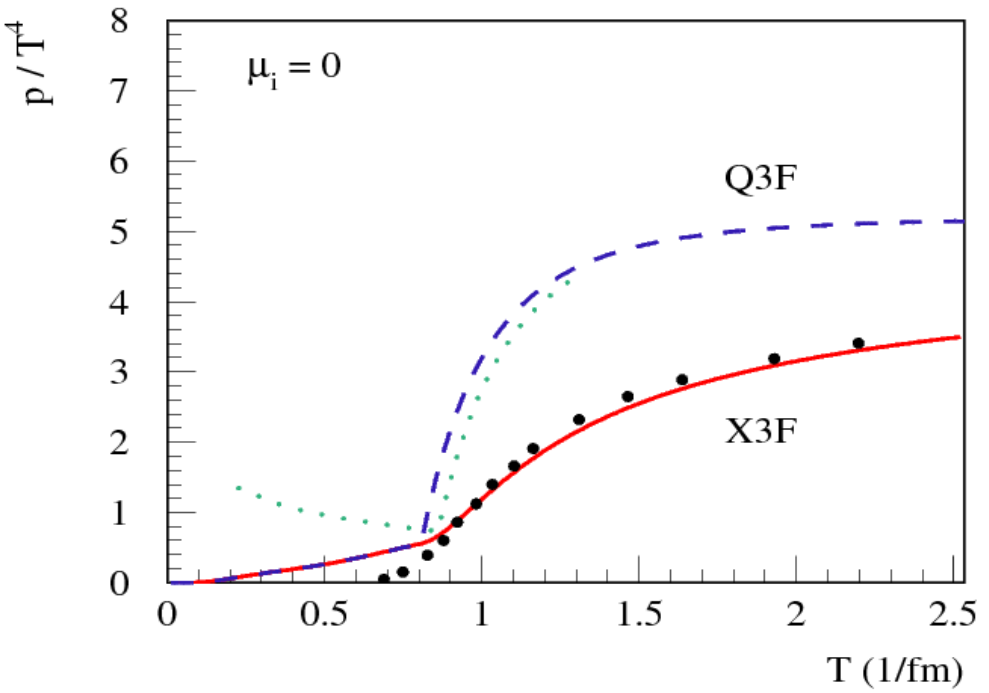
Hirano: QG & resonance gas => 1st order PT, PCE, $\mu_B = \mu_S = \mu_Q = 0$

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



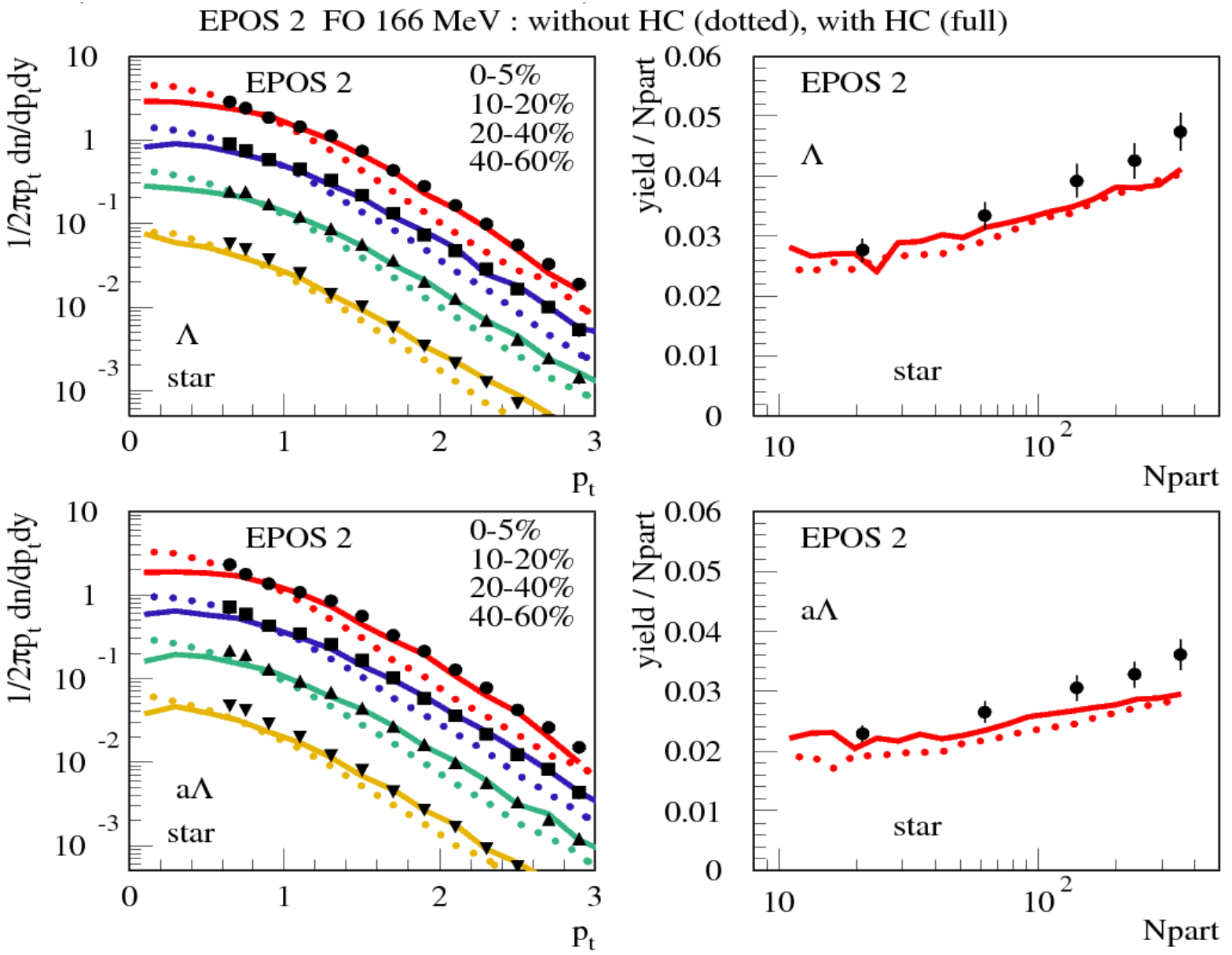


AuAu : Lambda

for better visibility:

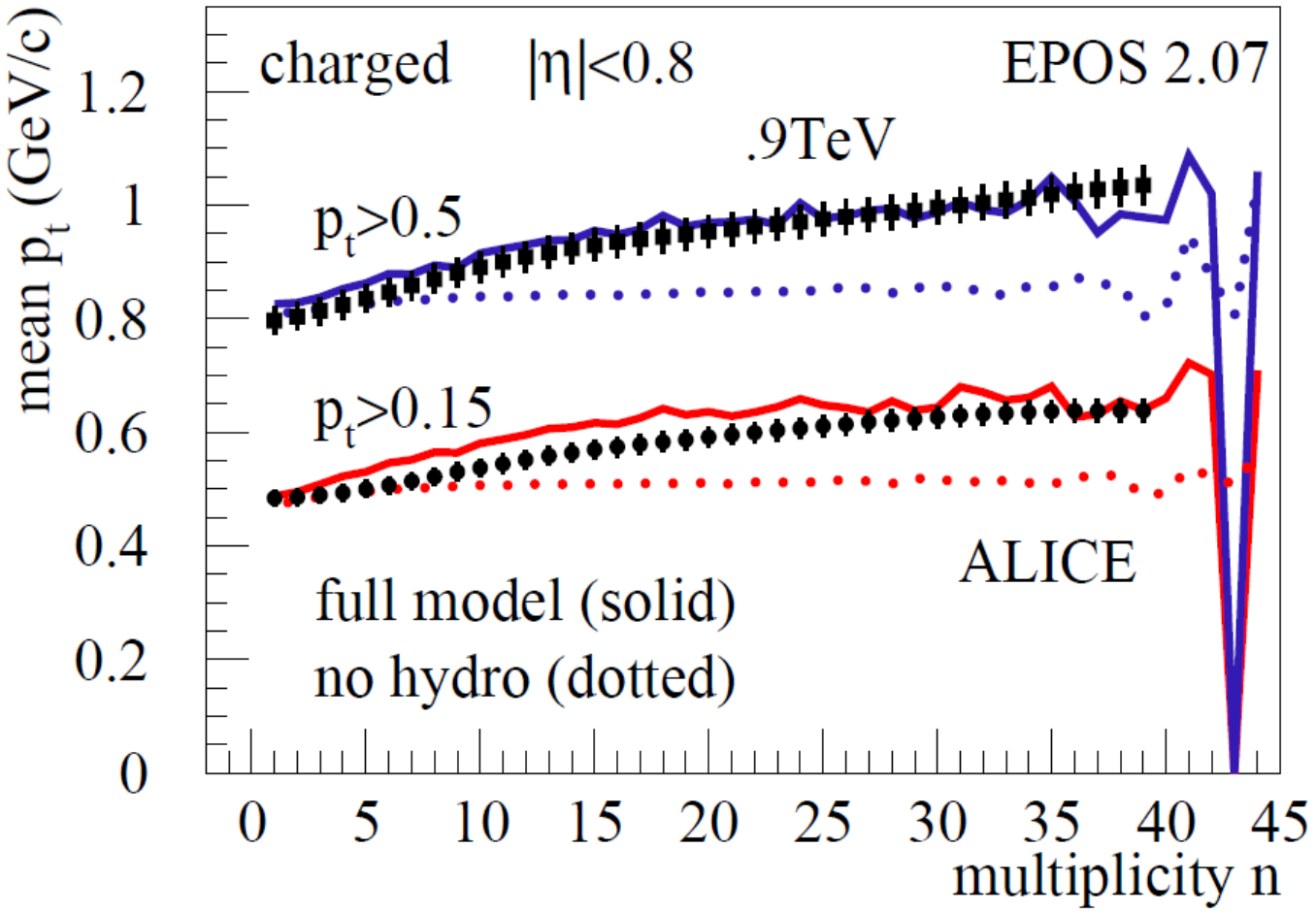
pt spectra scaled by

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



Pt Distribution

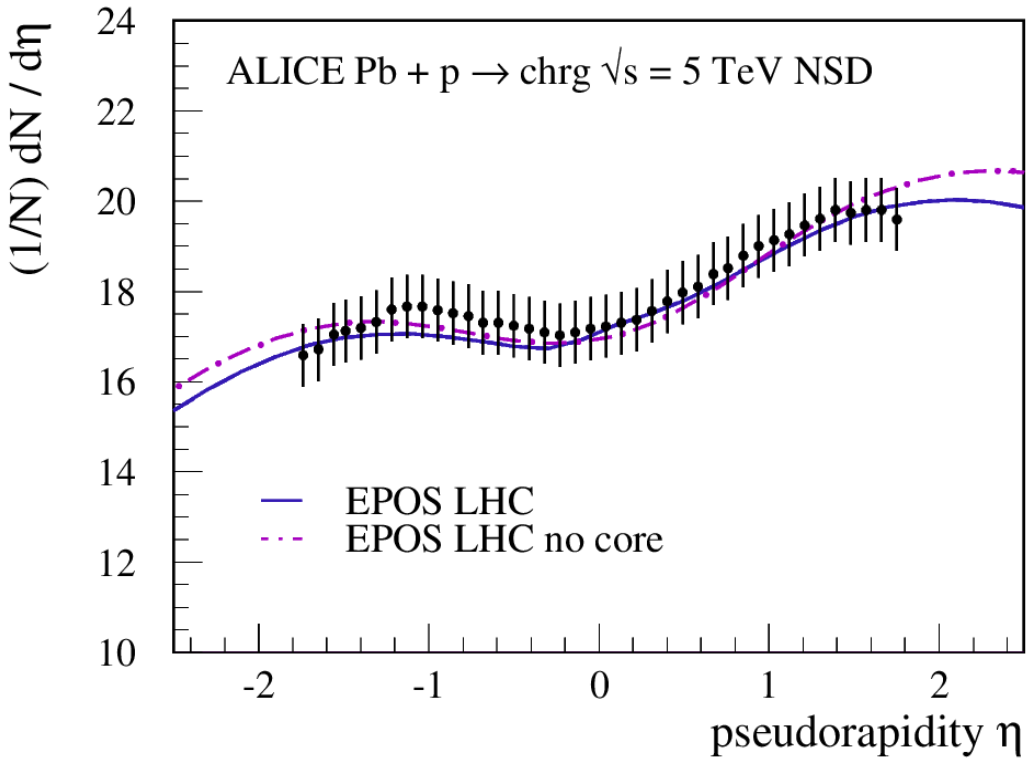
- Summarized in <Pt> versus multiplicity (here 900 GeV)

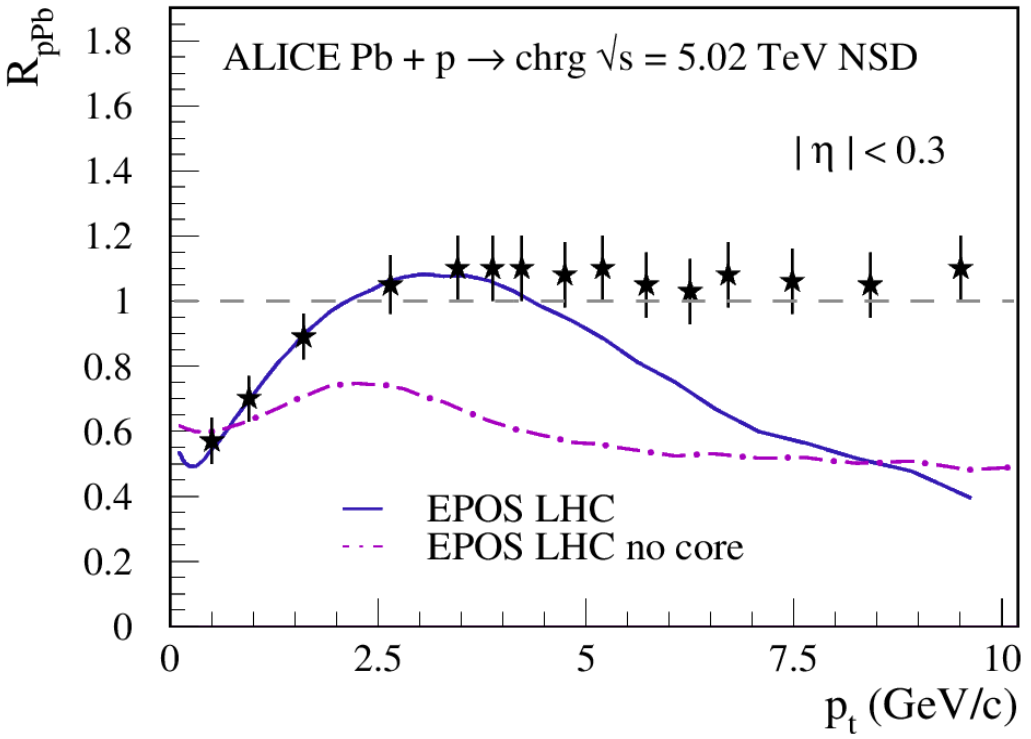


Saturation

Limitations in EPOS LHC

- Good results at low/medium p_t in Pb-p
- Problems for high p_t : no binary scaling
  - same correction for soft and hard scales
    - Q^2 dependent screening

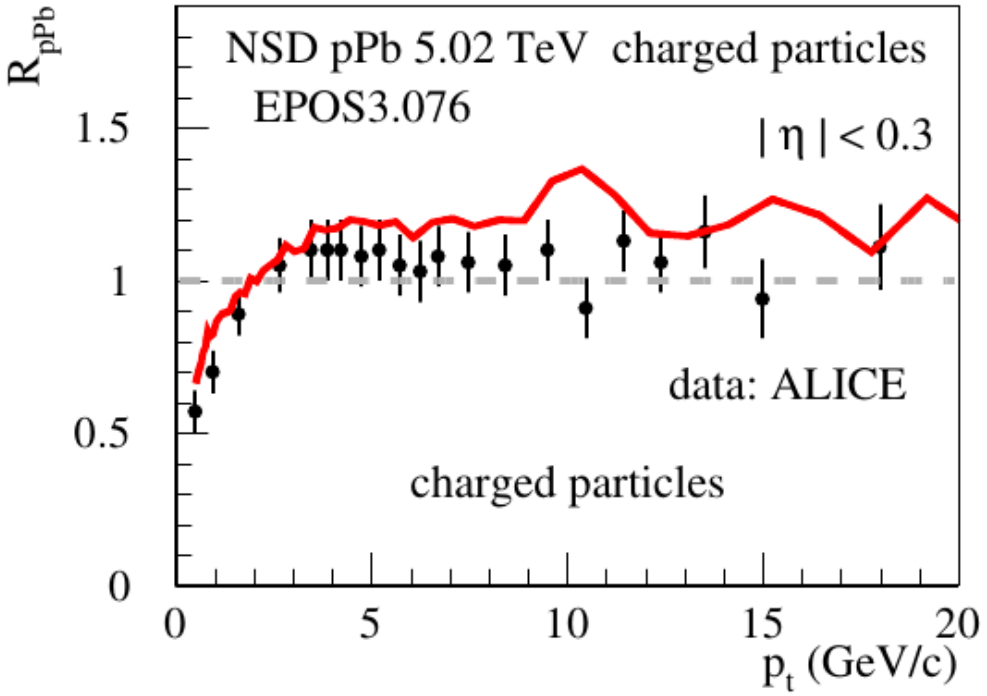


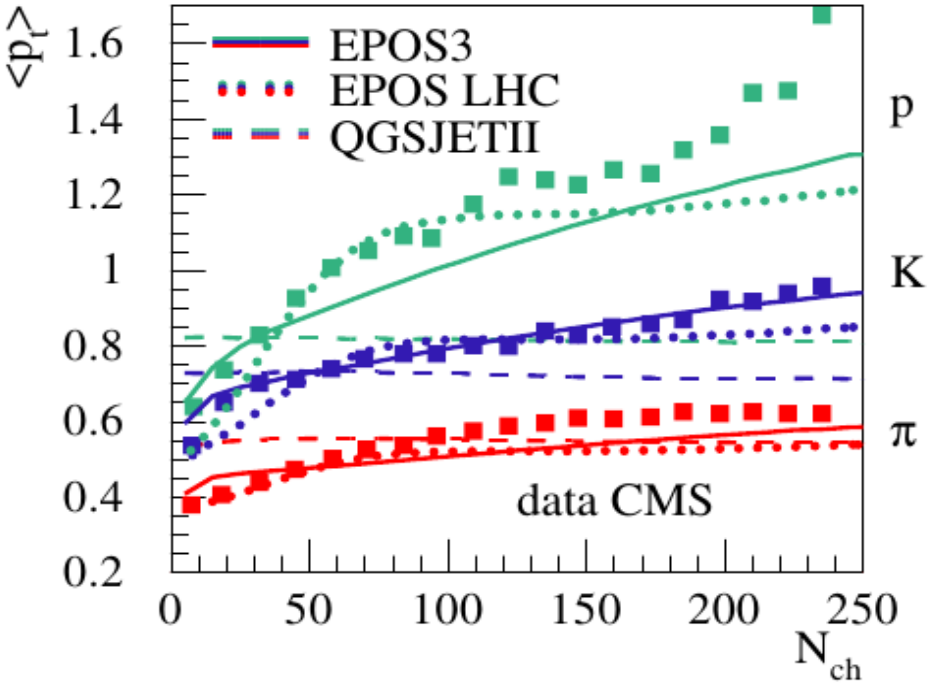


EPOS 3

Use saturation scale to have a Q^2 dependent screening

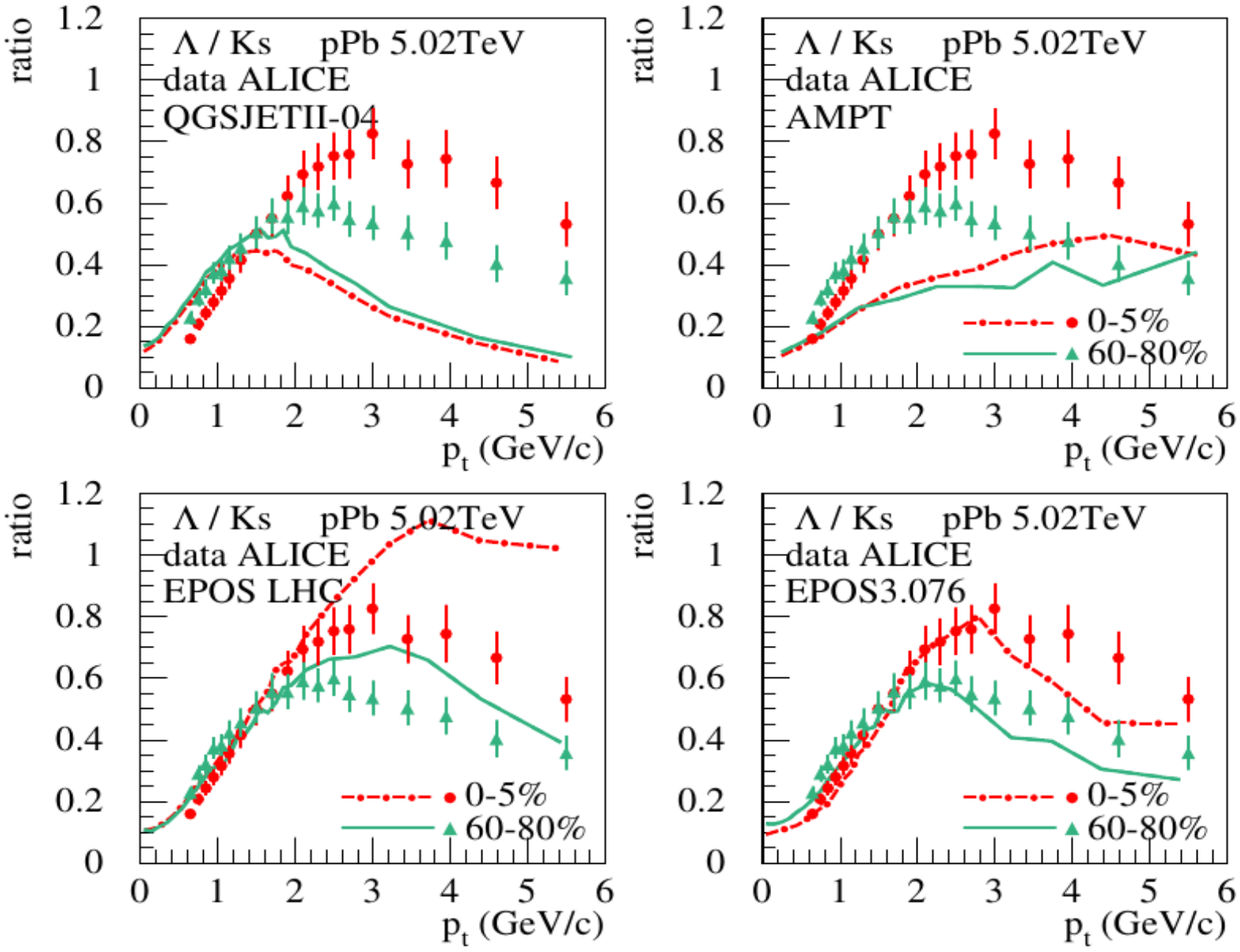
- restore binary scaling for high p_t
- intermediate p_t due to flow based on real hydro simulations
  - mass splitting



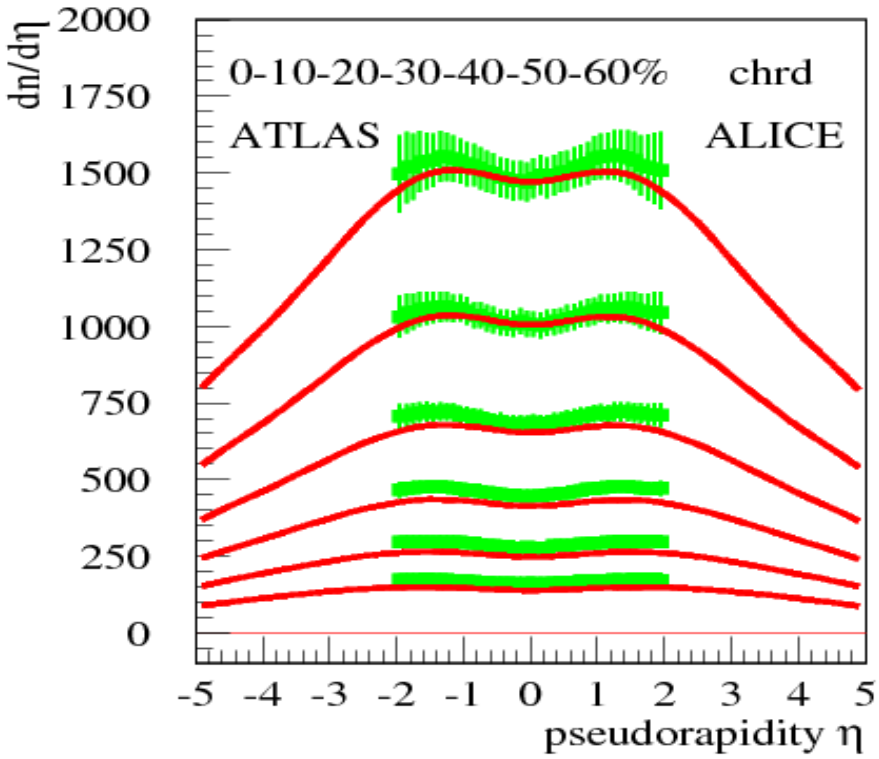


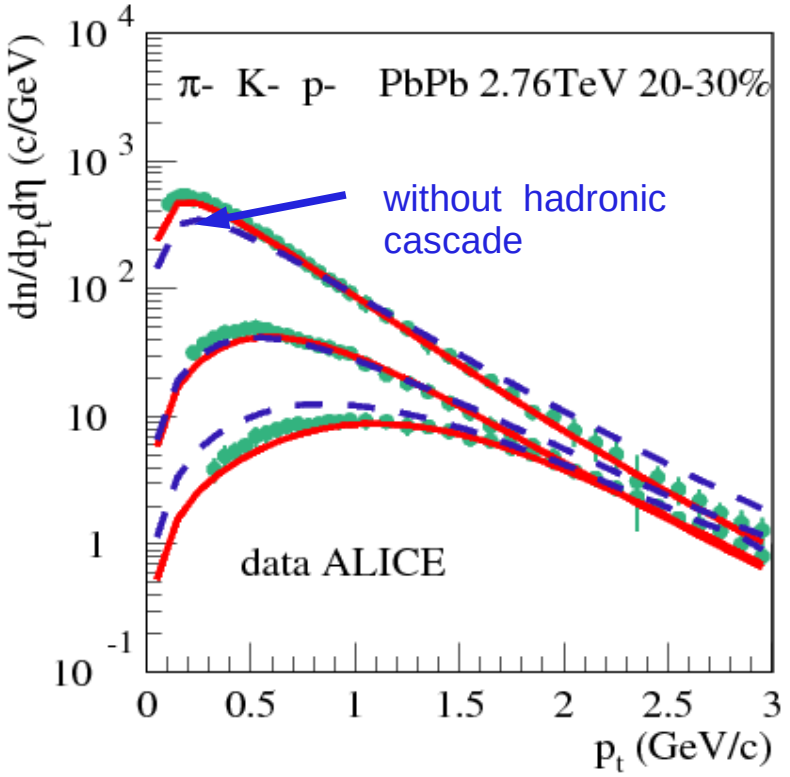
Real 3D Hydro

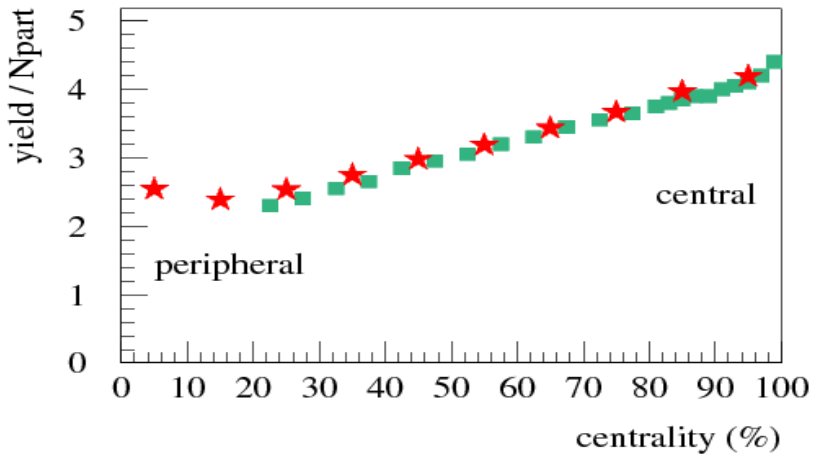
Particle ratio characteristic of collective flow effect.

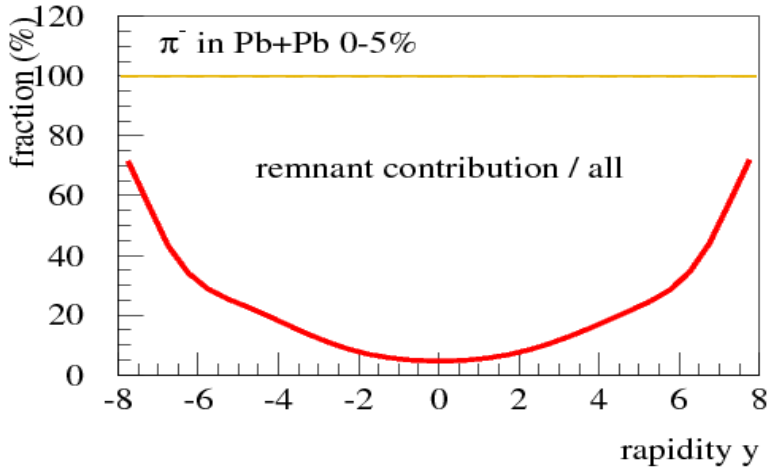


PbPb @ LHC

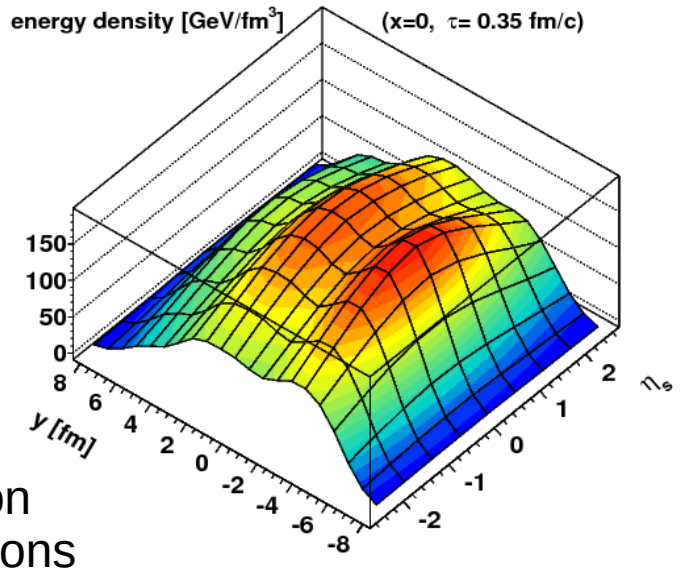

dn/dη
0-10-20-30-40-50-60%
chrd
ATLAS
ALICE
pseudorapidity η


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

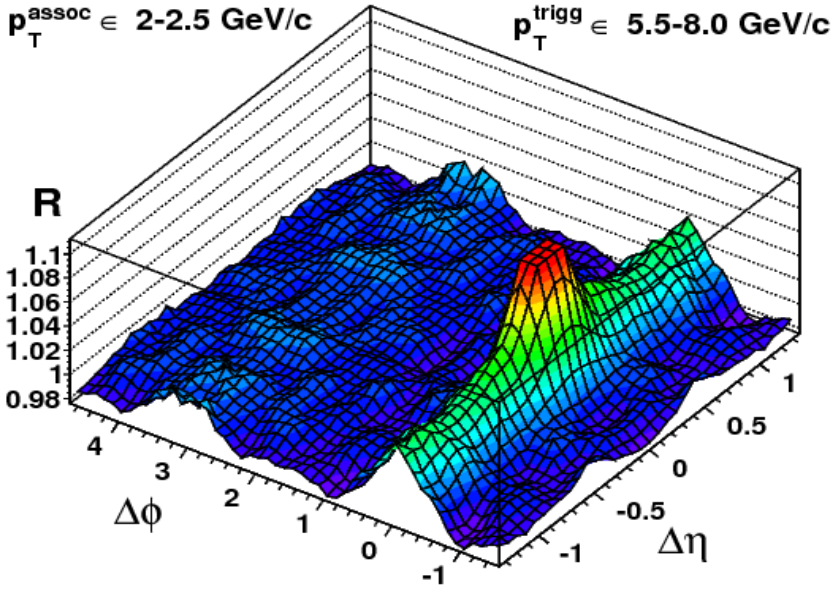
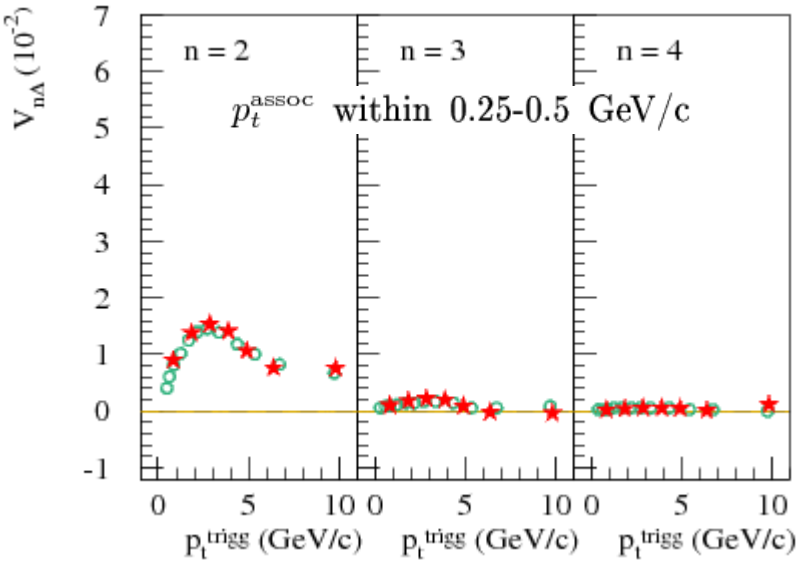
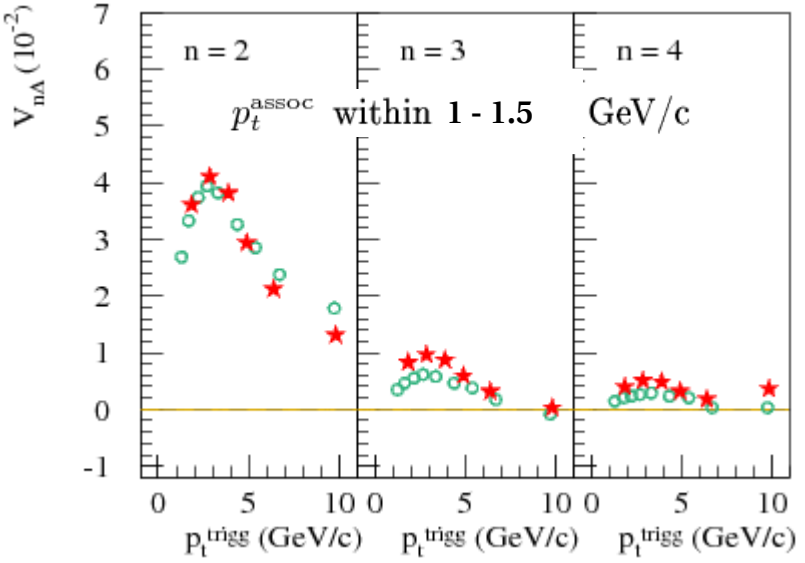

yield / Npart
peripheral
central
centrality (%)


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

Correlations in PbPb@LHC



di-hadron correlations



Fourier coefficient for most central events