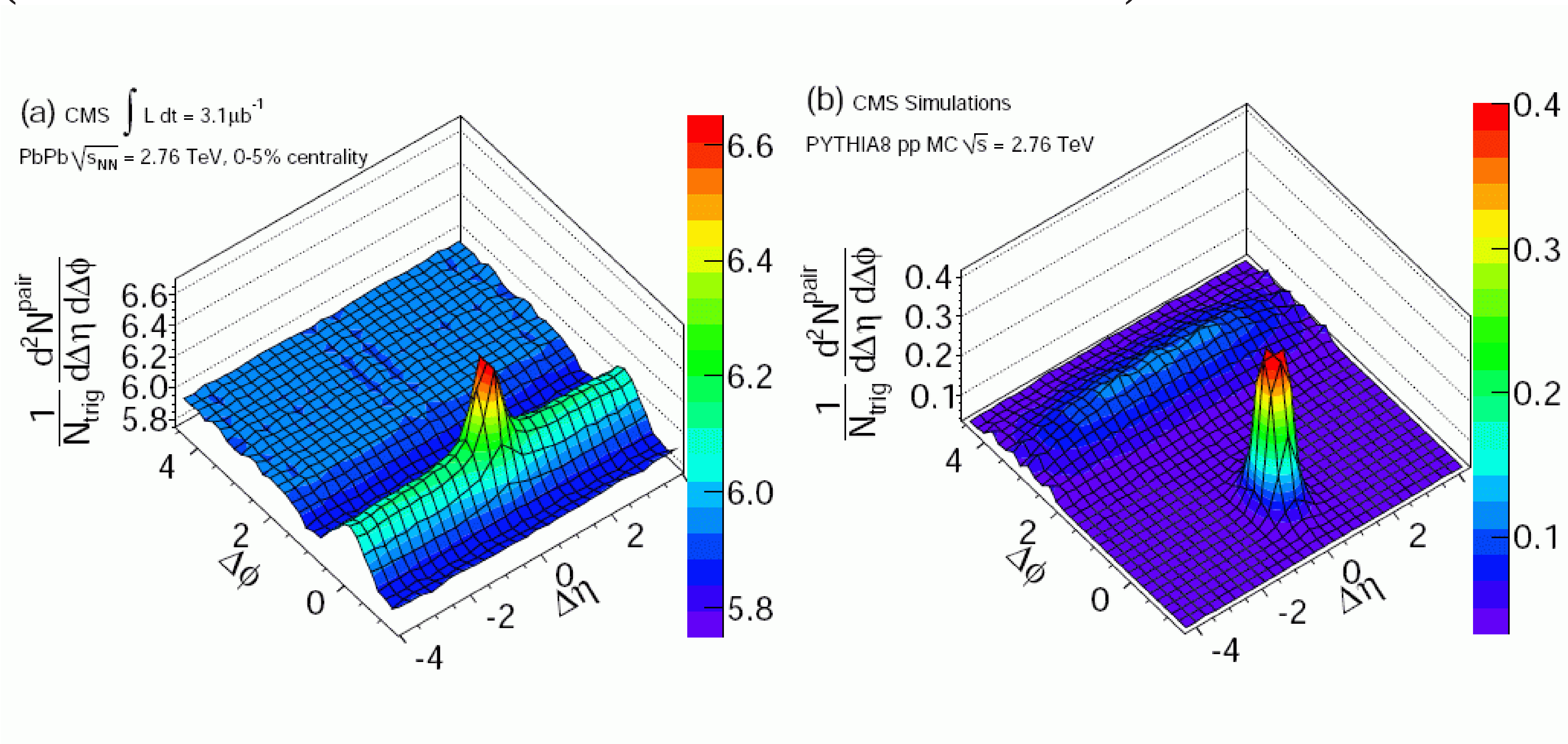
Jets, Bulk Matter, and their Interaction in Heavy Ion Collisions at the LHC

Klaus Werner <werner@subatech.in2p3.fr>

in collaboration with

Iu. Karpenko, T. Pierog, S. Porteboeuf,
M. Bleicher, K. Mikhailov

Motivation: Dihadron correlations: PbPb 2.76 TeV (CMS: CERN-PH-EP/2011-056 2011/05/13)



$4 < p_t^{\text{trigg}} < 6\,\text{GeV/c},\ 2 < p_t^{\text{assoc}} < 4\,\text{GeV/c}$

Ridge for small trigger pt:

- □ irregular initial energy density in transverse plane
- □ + little variation longitudinally (flux tubes)
- □ translates into long range transverse flow correlation

Ridge at higher pt ???

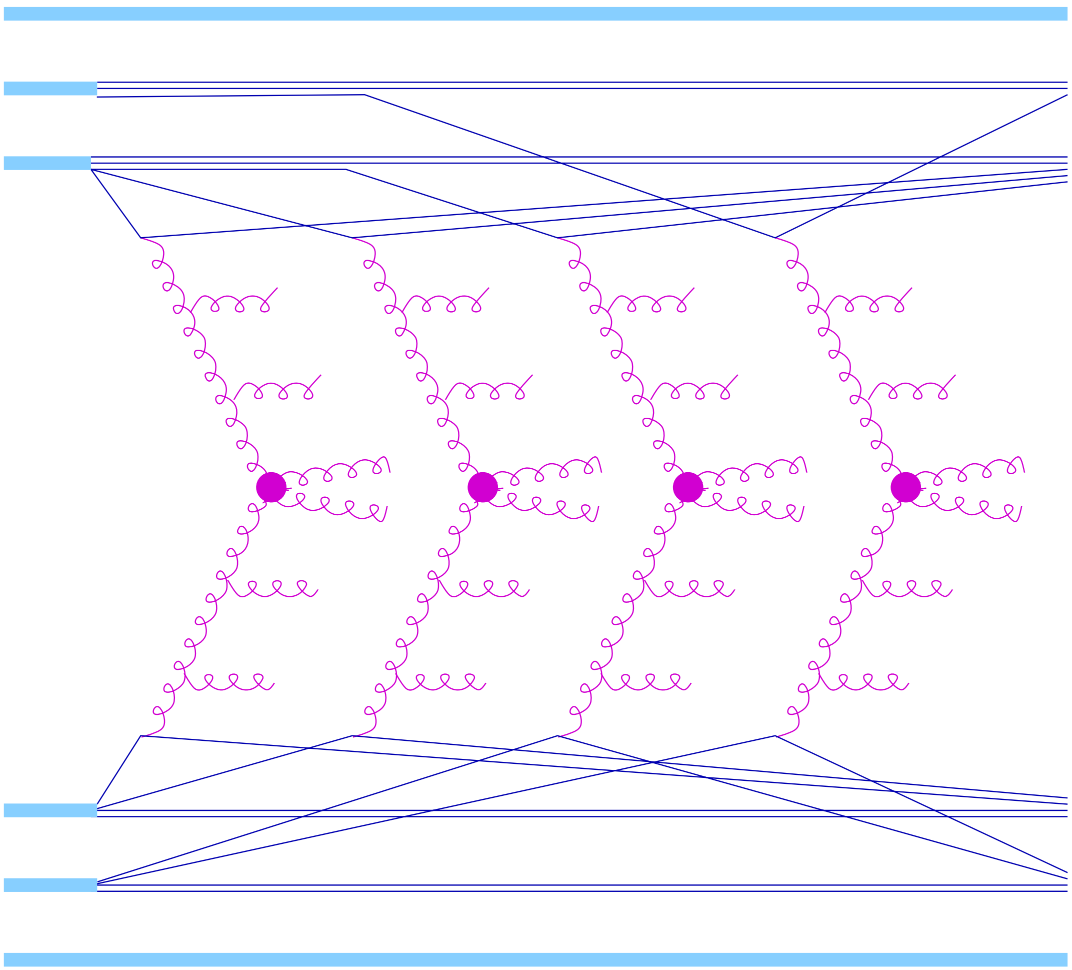
- □ One observes "factorization" of $v_n(p_t^t, p_t^a)$ in certain cases,
- □ which does not explain the phenomenon.

=> some new ideas about bulk, jets, and their interaction

arXiv:1203.5704, Jets, Bulk Matter, and their Interaction in HIC at Several TeV
arXiv:1204.1394, Lambda over Kaon Enhancement in HIC at Several TeV
arXiv:1205.3379, V2 Scaling in PbPb Collisions at 2.76 TeV

Basis: Multiple scattering approach (EPOS):

marriage of pQCD and Gribov-Regge, with energy sharing



Many collisions in parallel

Single scattering

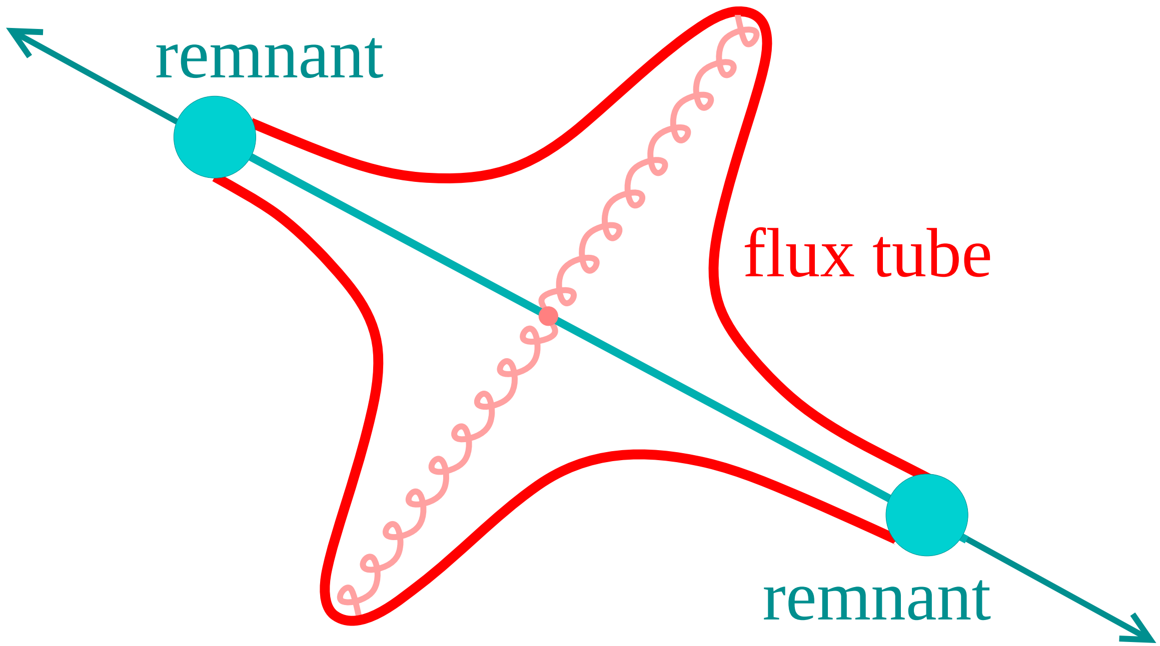
= hard scattering
+ IS + FS radiation
+ high density effects (screening)

= parton ladder

= color flux tubes

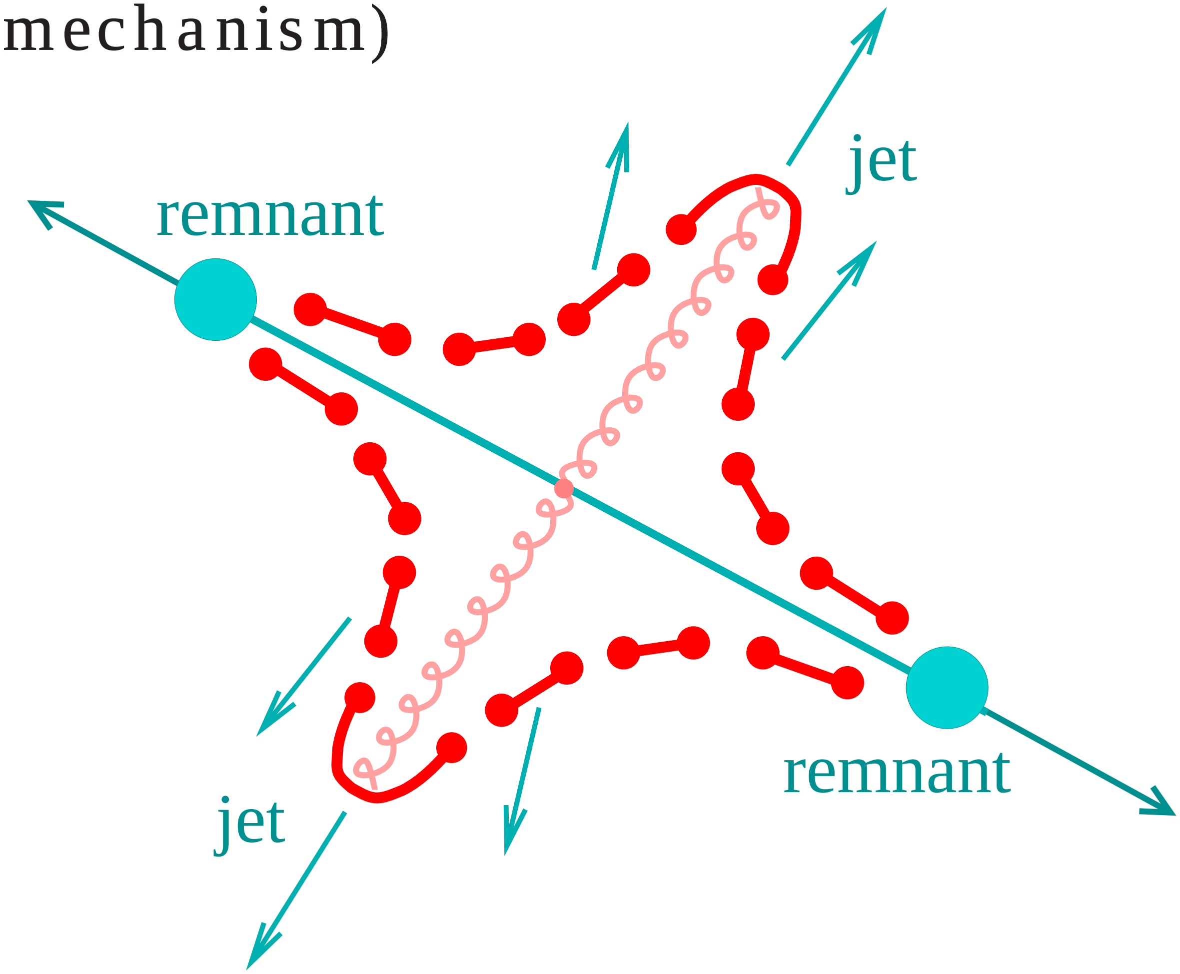
Realization: Cutting rules + Markov chain techniques

parton ladder = color flux tubes = kinky strings



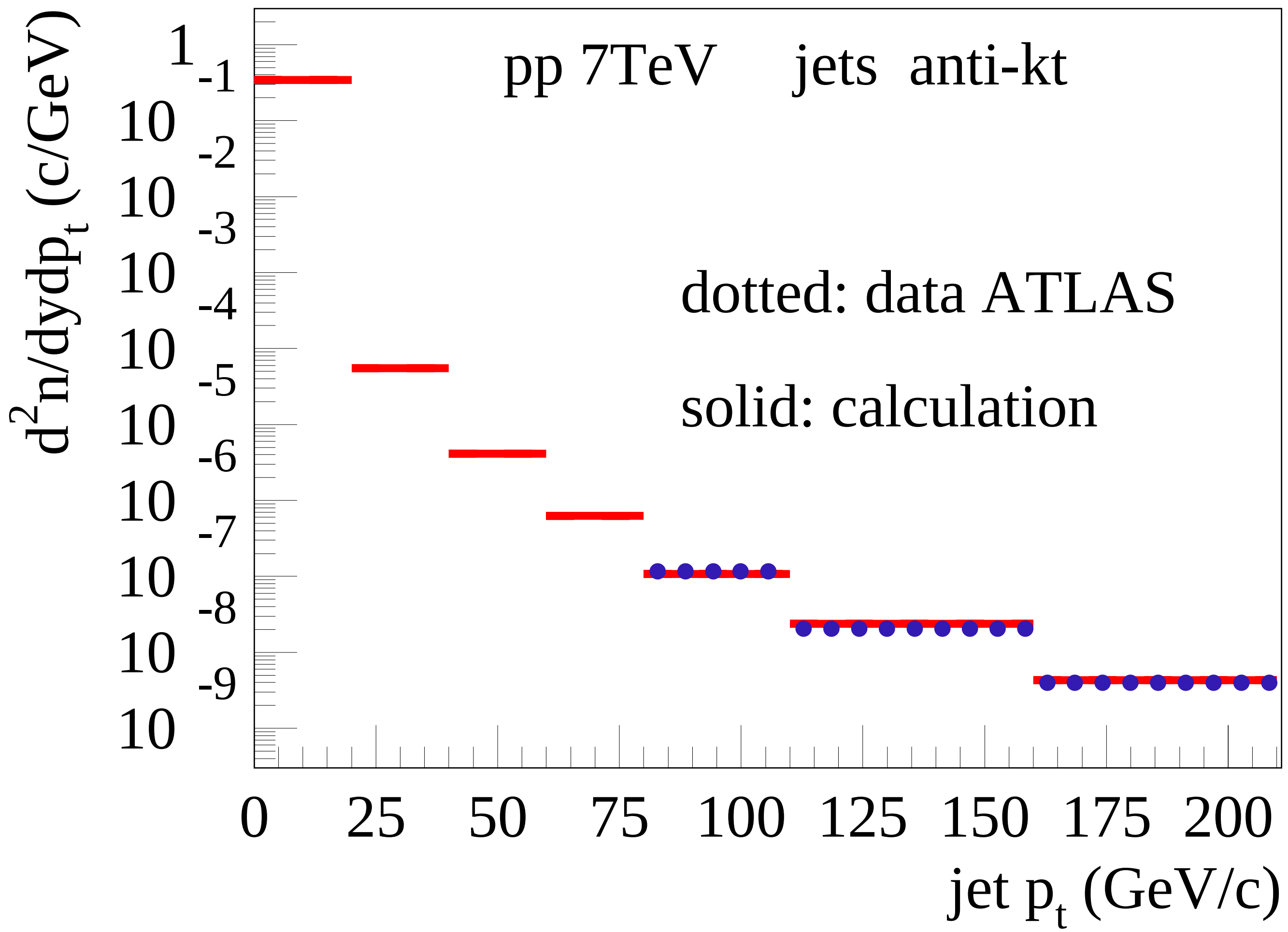
here no IS radiation, only hard process producing two gluons

which expand and break
via the production of quark-antiquark pairs
(Schwinger mechanism)

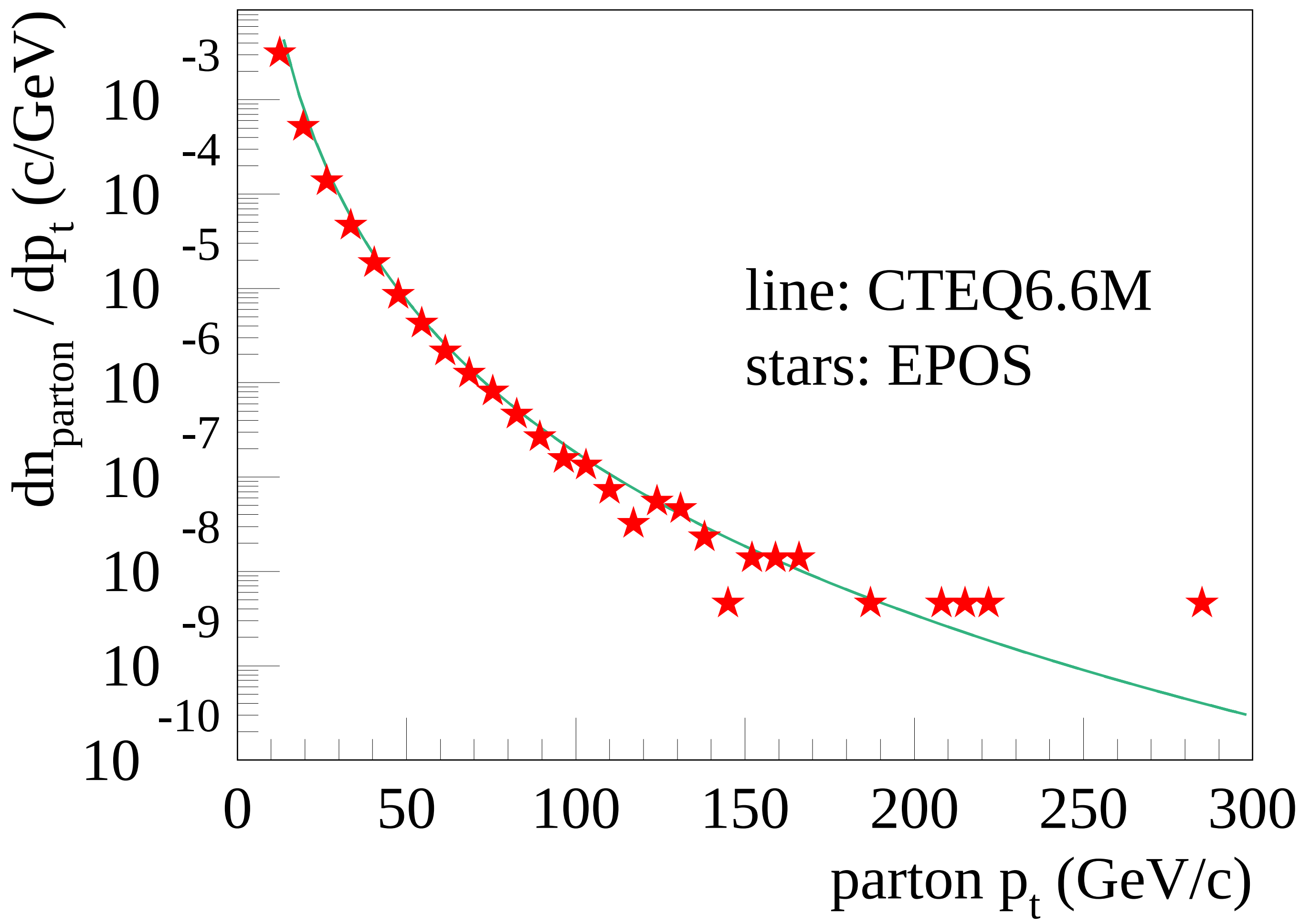


String segment = hadron. Close to “kink”: jets

Check: jet production in pp at 7 TeV



Comparison with parton model calculation using CTEQ PDFs for pp at 7 TeV



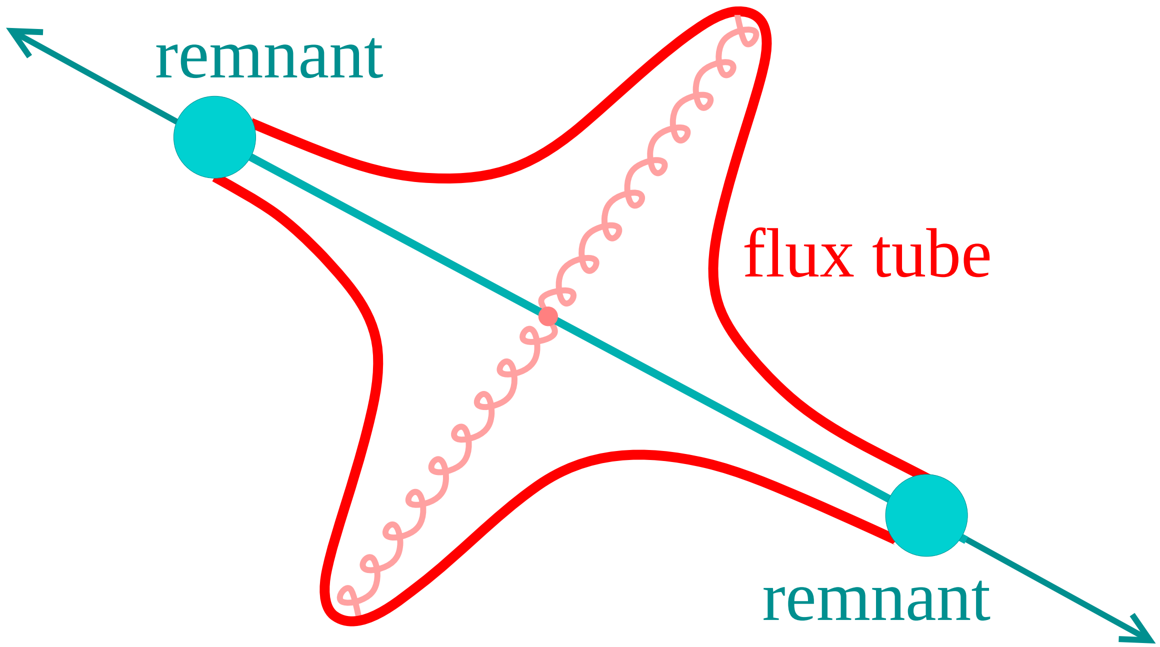
Heavy ion collisions or high energy & high multiplicity pp events:

- the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently

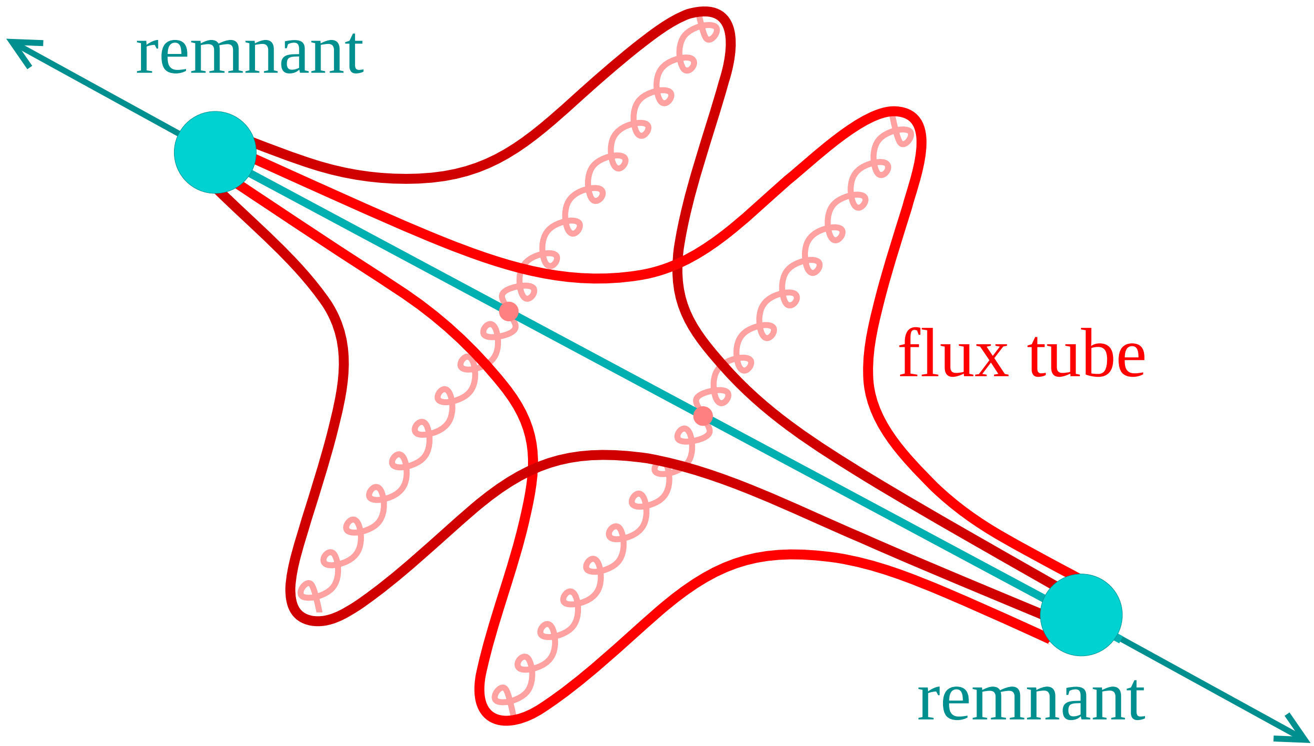
Some string pieces will constitute bulk matter, others show up as jets (jet-bulk separation)

These are the same strings (all originating from hard processes at LHC) which constitute BOTH jets and bulk !!

again: single scattering => 2 color flux tubes



... two scatterings => 4 color flux tubes



... many scatterings (AA) => many color flux tubes

=> matter + escaping pieces (jets)

Consider one flux tube in "matter"

(= high density of other flux tubes, which then thermalize)

Three possibilities:

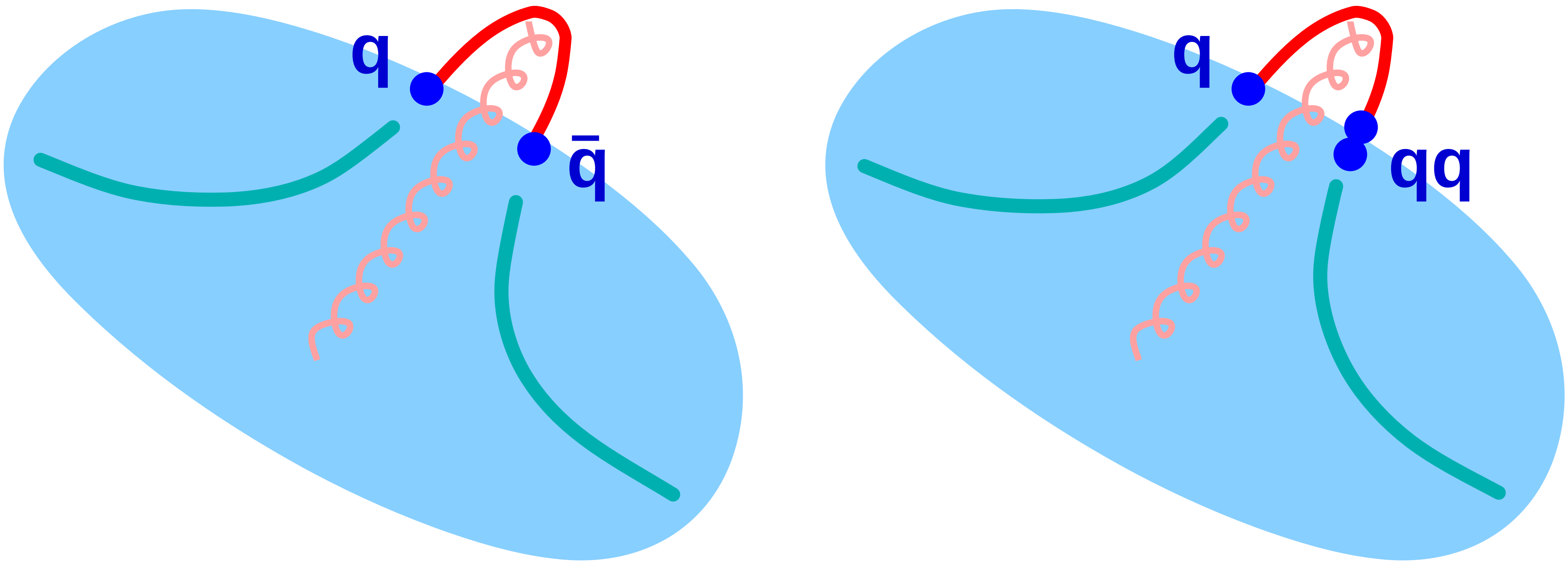
(A) String segments which have not sufficient energy to escape will constitute matter ($\Delta E > E$).
They lose their character as individual strings. This matter will evolve hydrodynamically and hadronize; hadrons still interact ("soft hadrons").

(B) String segments having sufficient energy to escape and being formed outside the matter, constitute jets ("jet-hadrons").

(C) String segments produced inside matter or at the surface, but having enough energy to escape and show up as jets ("jet-hadrons").
They are affected by the flowing matter ("fluid-jet interaction").

Jet-hadrons produced inside matter or at the surface

(Type C)



End point partons from fluid, instead of Schwinger

=> adds flow, changes chemistry

Technical realization in two steps

Estimate initially which segments constitute the bulk (= initial condition for hydro), from

$$\Delta E > E$$

E=energy of the segment,
ΔE= energy loss along trajectory, with $dE \propto \rho^{3/8}\max(1, \sqrt{E/E_0})dL$ [1])

[1]) inspired by BDMPS, Peigne arXiv0806.0242

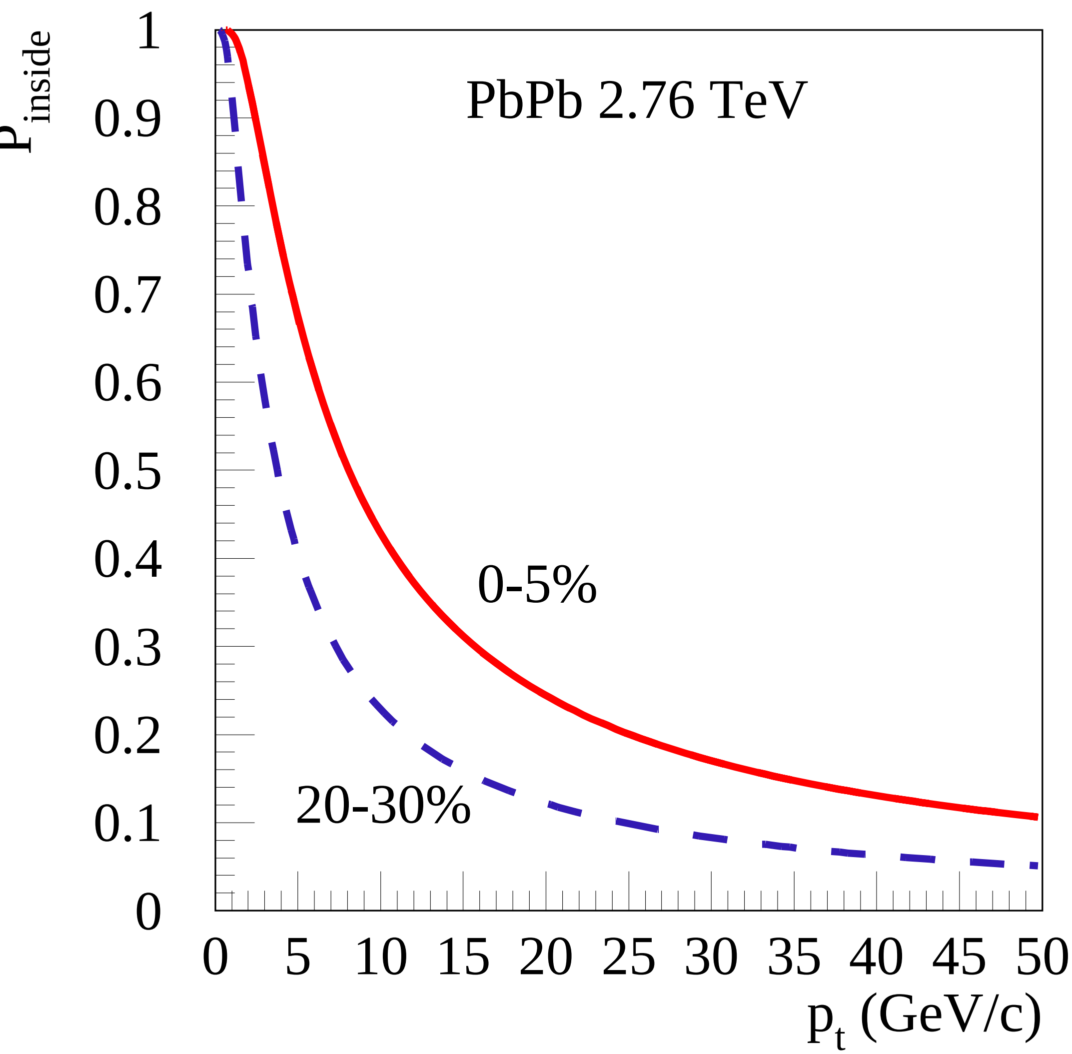
After hydro evolution:

Reconstruct for the ”jet segments” produced inside the matter (formation time) their escape points $(t, \vec{x})$,

replace Schwinger q/qbar by thermal ones, “flowing” with $\vec{v}(t, \vec{x})$.

Crucial: formation time !

Probability to form a hadron inside matter:



Simple estimate (ptl moving $\|\vec{b}$)

$$P_{\text{inside}} = 1 - \exp\left(-\frac{(r_{\text{Pb}} - b/2)\, m}{p_t\, \tau_{\text{form}}}\right).$$

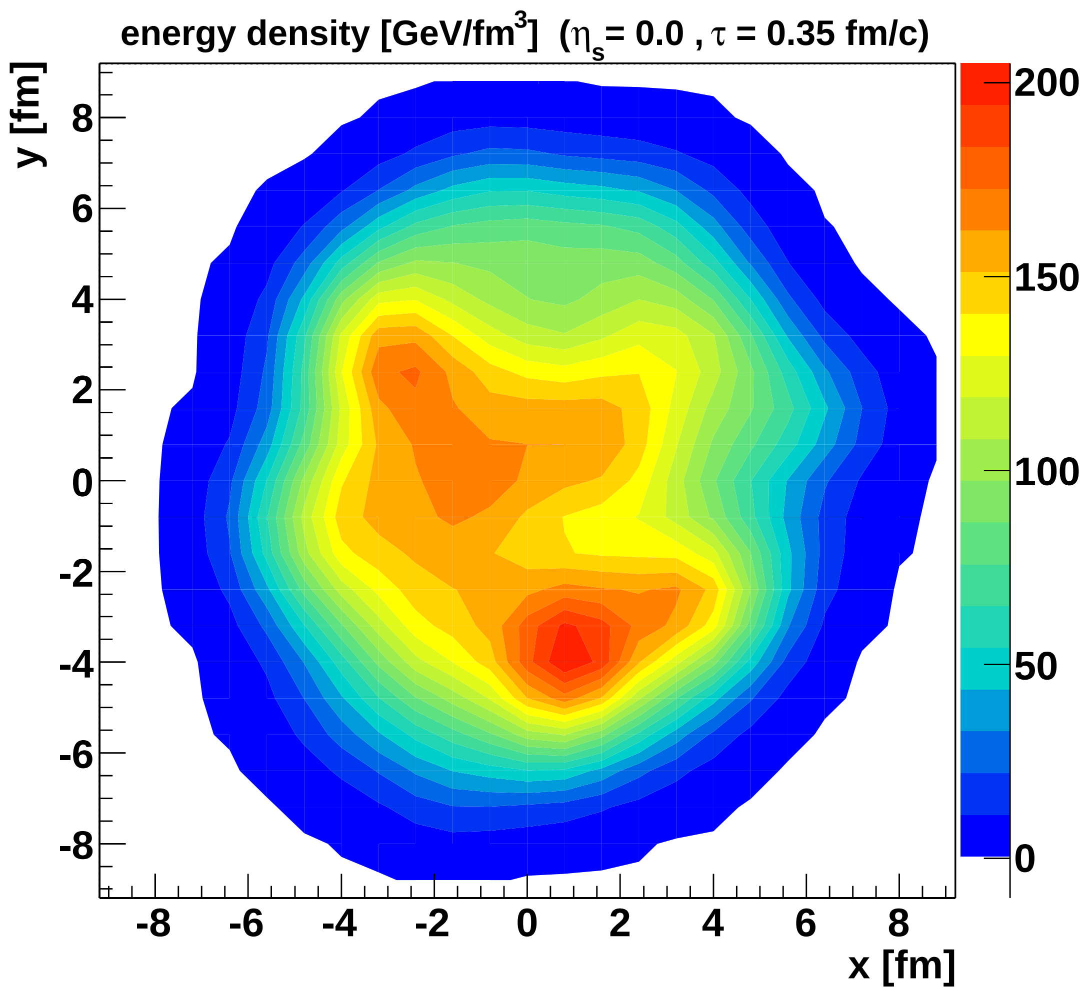
with $c\tau_{\text{form}} = 1\,\text{fm}$, $mc^2 = 1\,\text{GeV}$,

Using ideal hydro
v2 20-30% too big

(standard param setting:
flux tube radii 0.2 fm)

mimic viscous effects by taking artificially large values of the flux tube radii (we take 1 fm),

=> smoother initial conditions.



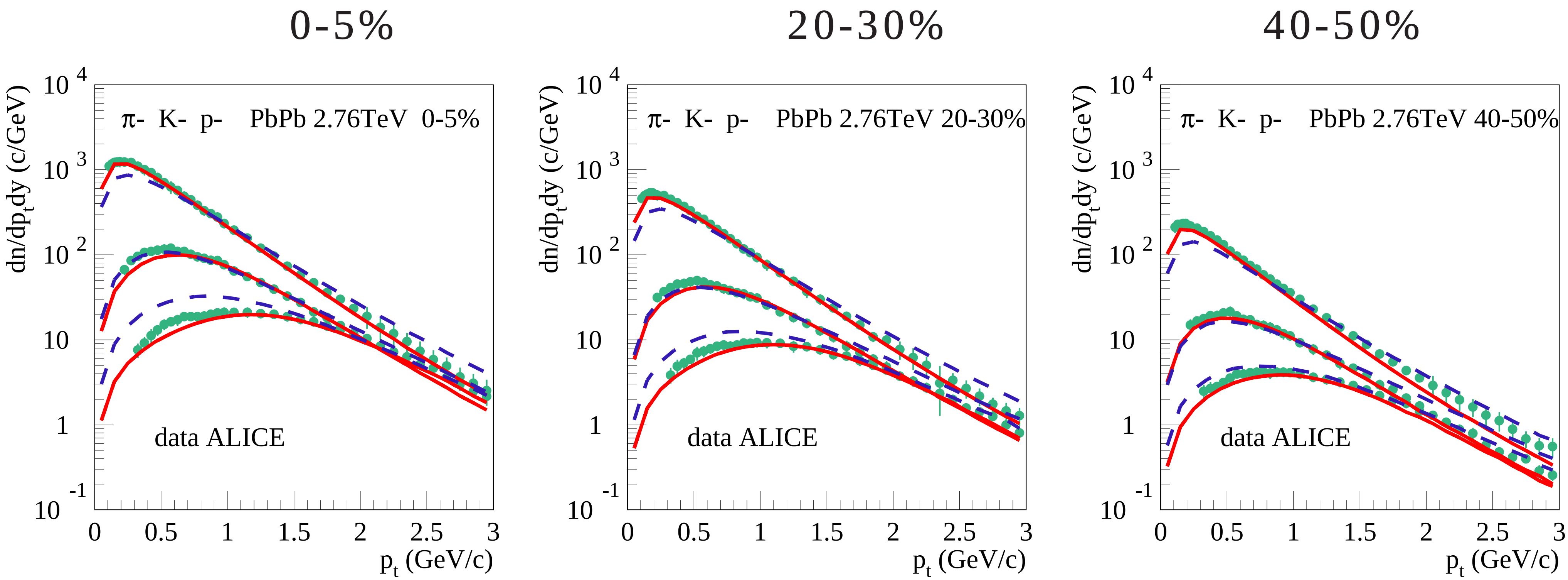
- The heavy ion results shown are based on 2000000 events simulated with EPOS2.17v3.

- A central (0-5%) PbPb event takes on the average around 2 HS06 hours CPU time (15 minutes on the machines of our computing farm).

- Difficult to make “tuning”, results are based on a “good guess of parameters” ...

Transverse momentum dependence of particle yields

Pion, kaons, protons vs pt, in PbPb 2.76 GeV:



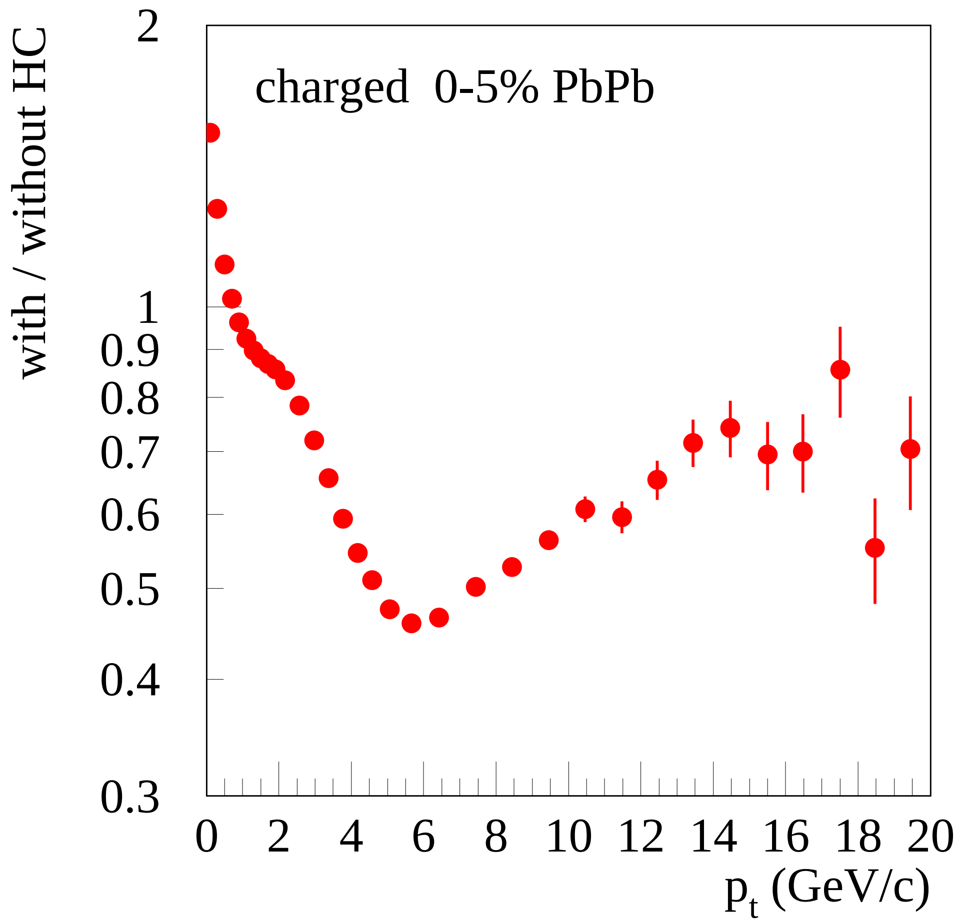
blue dashed lines: calculation without hadronic cascade,

red solid lines: full calculation

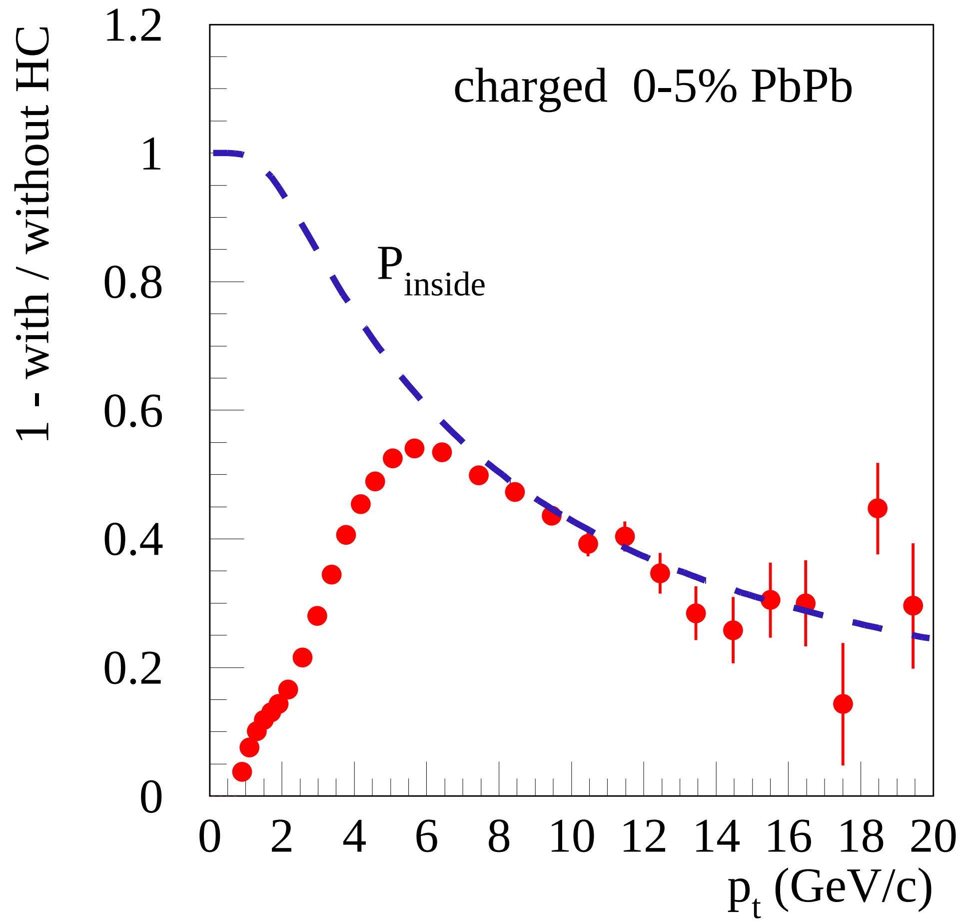
green points: data ALICE

Hadronic cascade important ! HC=UrQMD

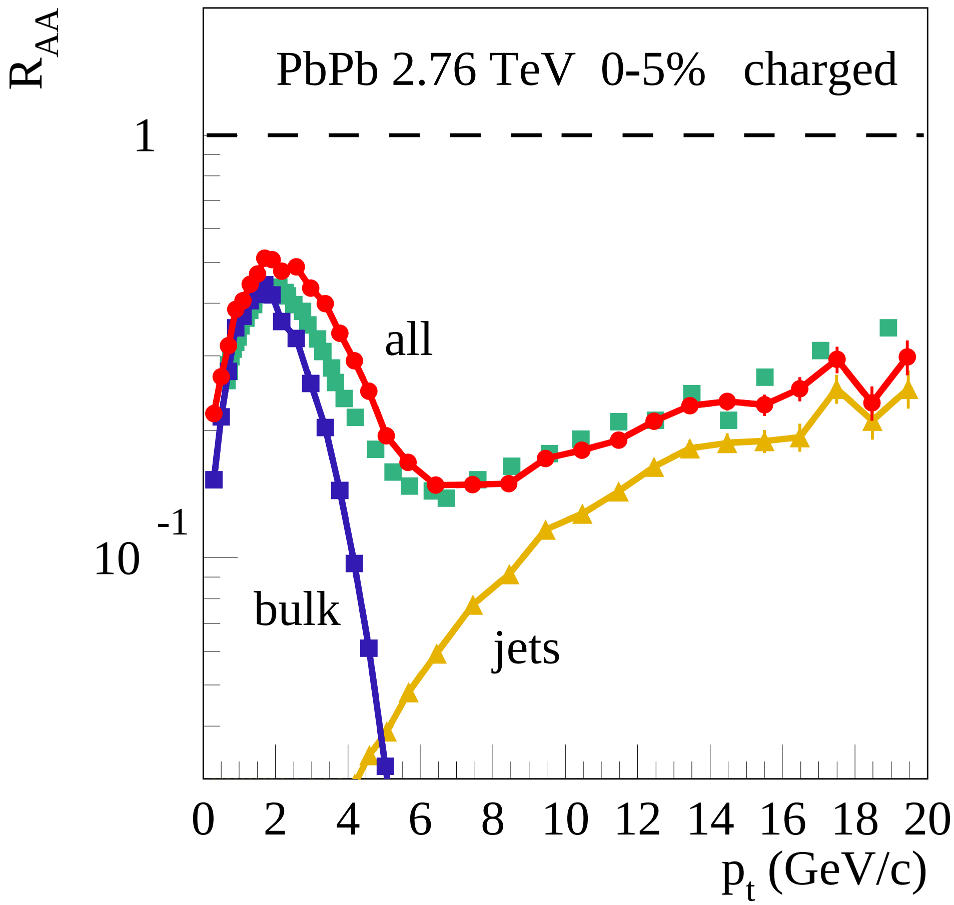
Ratio of charged particle spectra: full model / calculation without HC



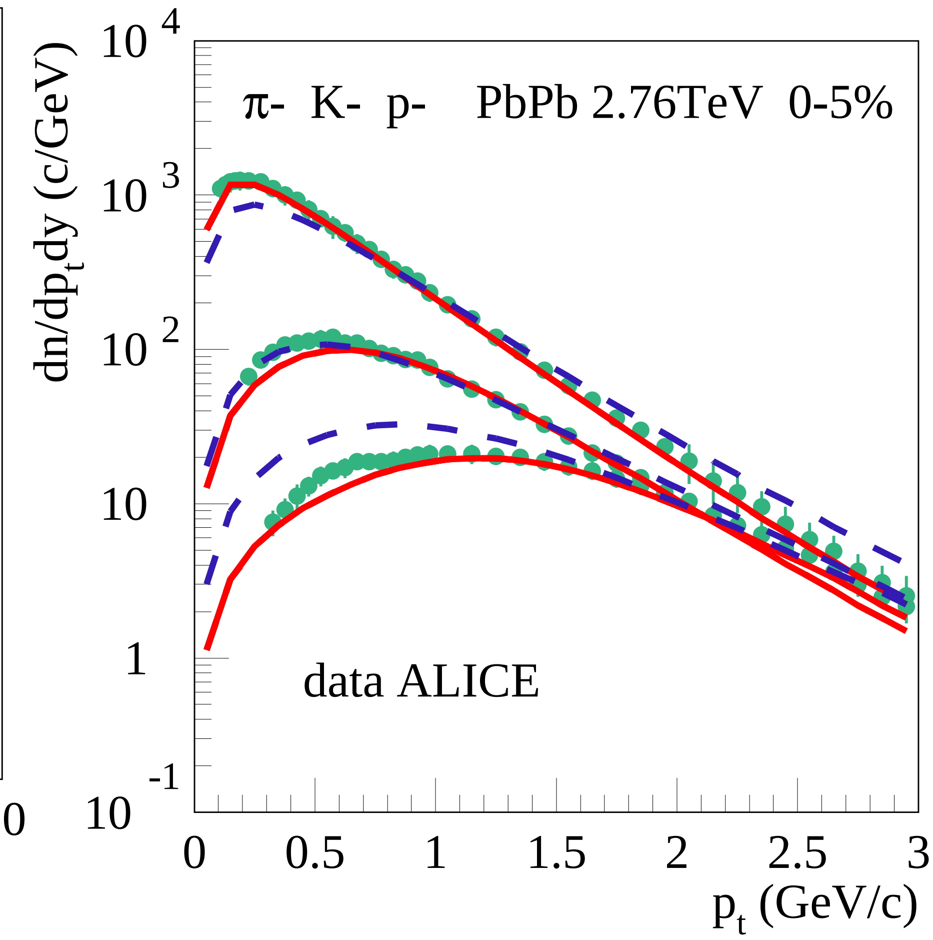
"1 - ratio" compared to P_{inside}

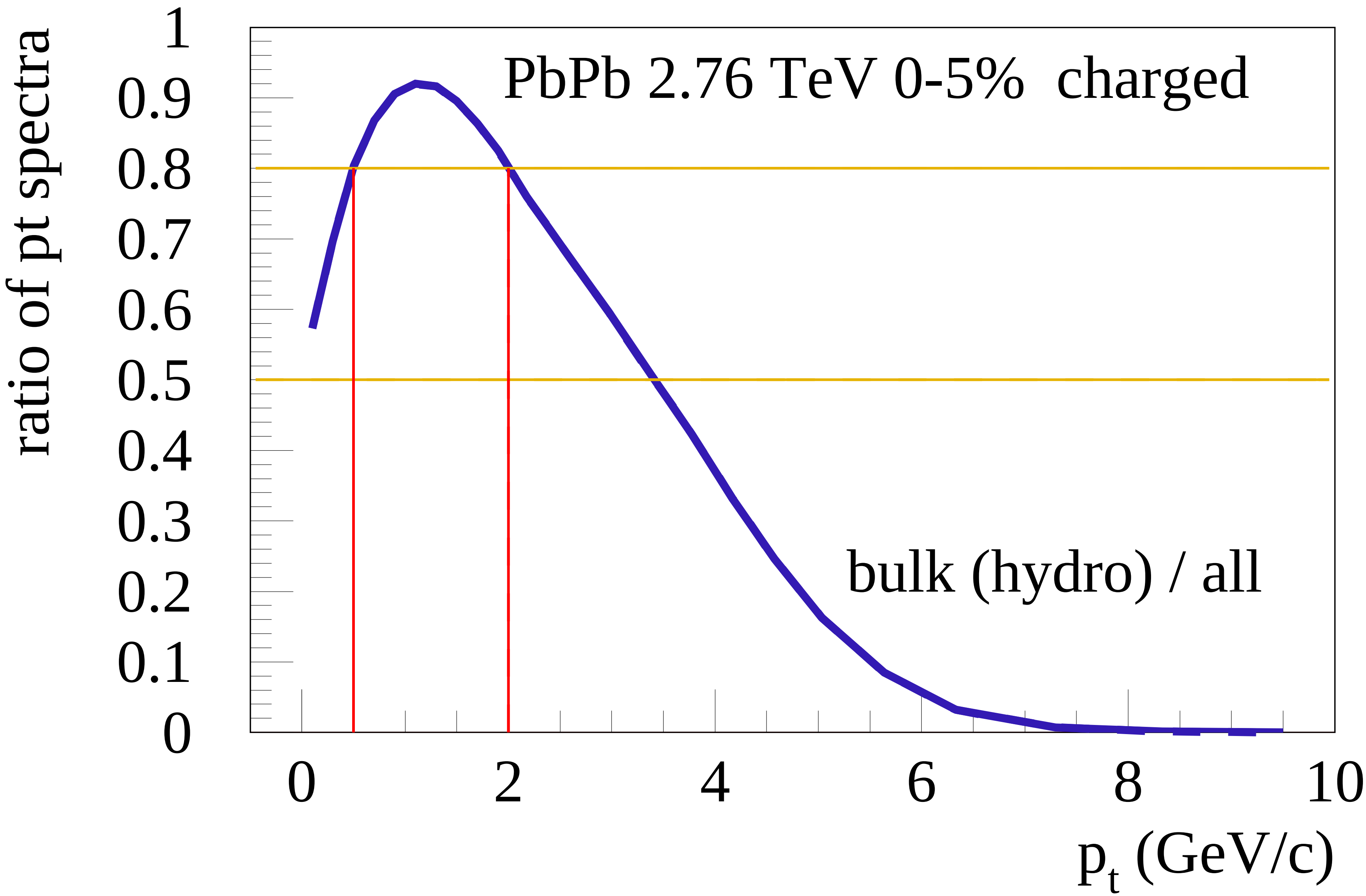


Charged particle R_{AA}



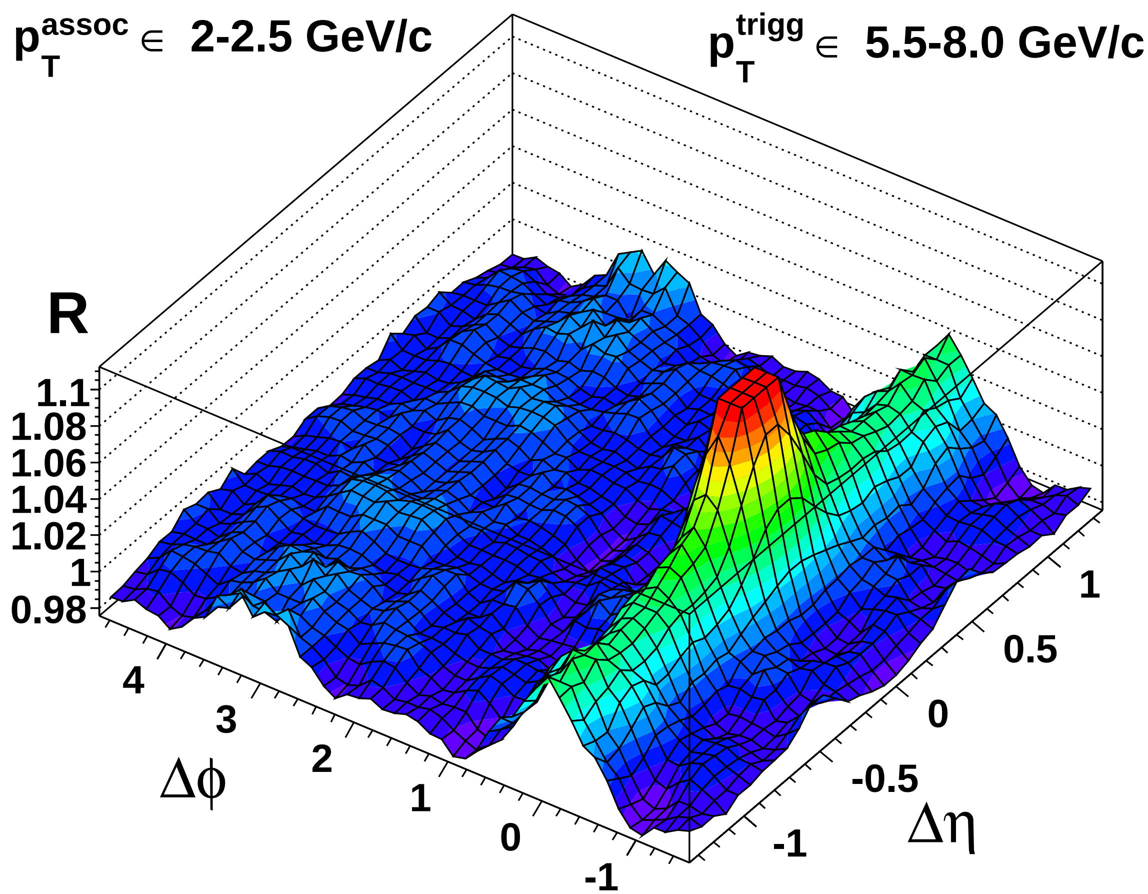
incompatible with PID results



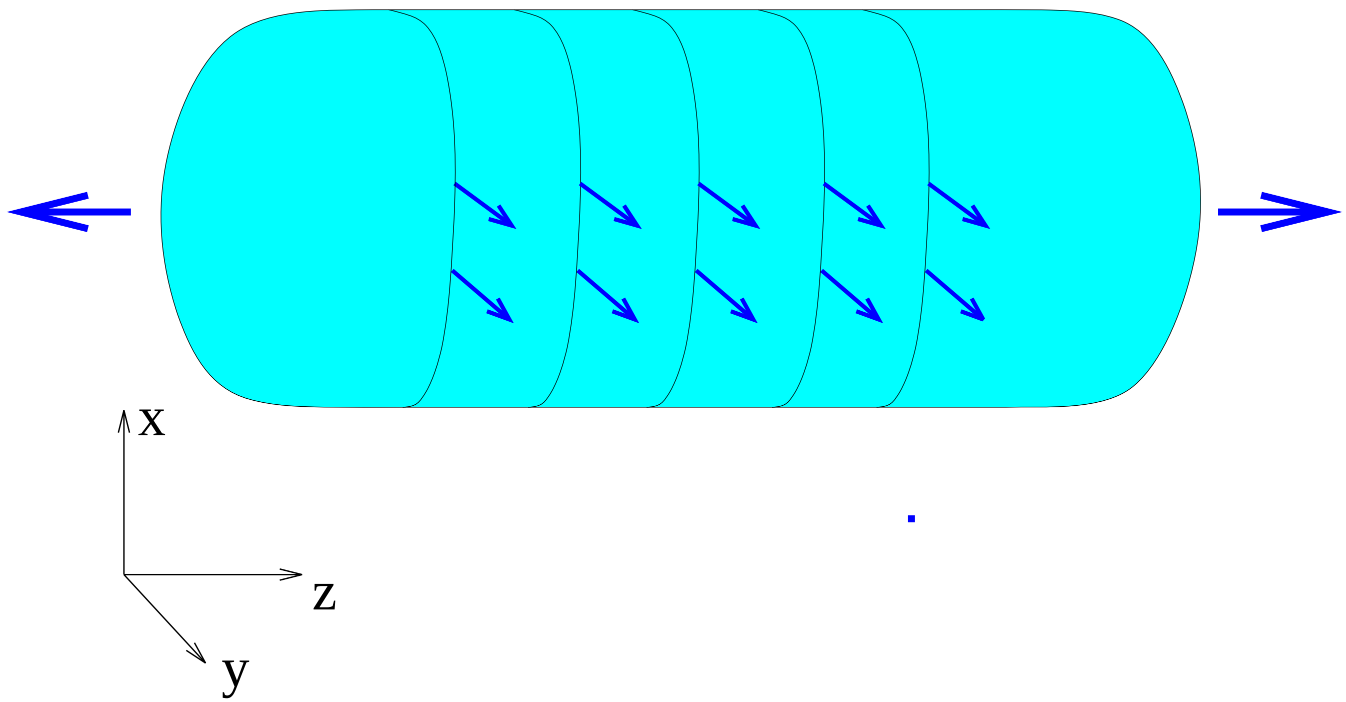

PbPb 2.76 TeV 0-5% charged
bulk (hydro) / all
ratio of pt spectra
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
p_t (GeV/c)

Dihadron correlations : ridges at high pt

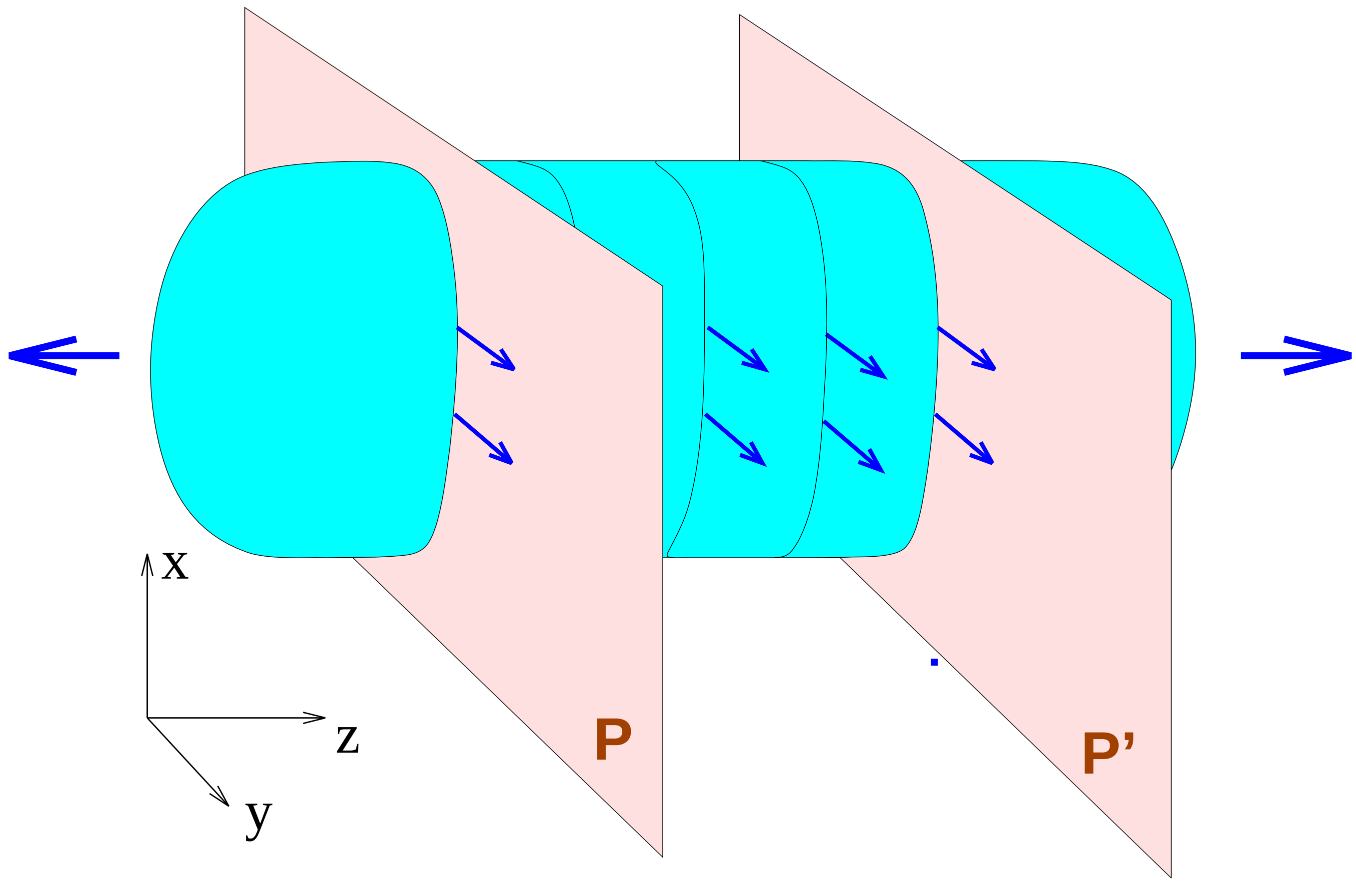
(0-5% PbPb)



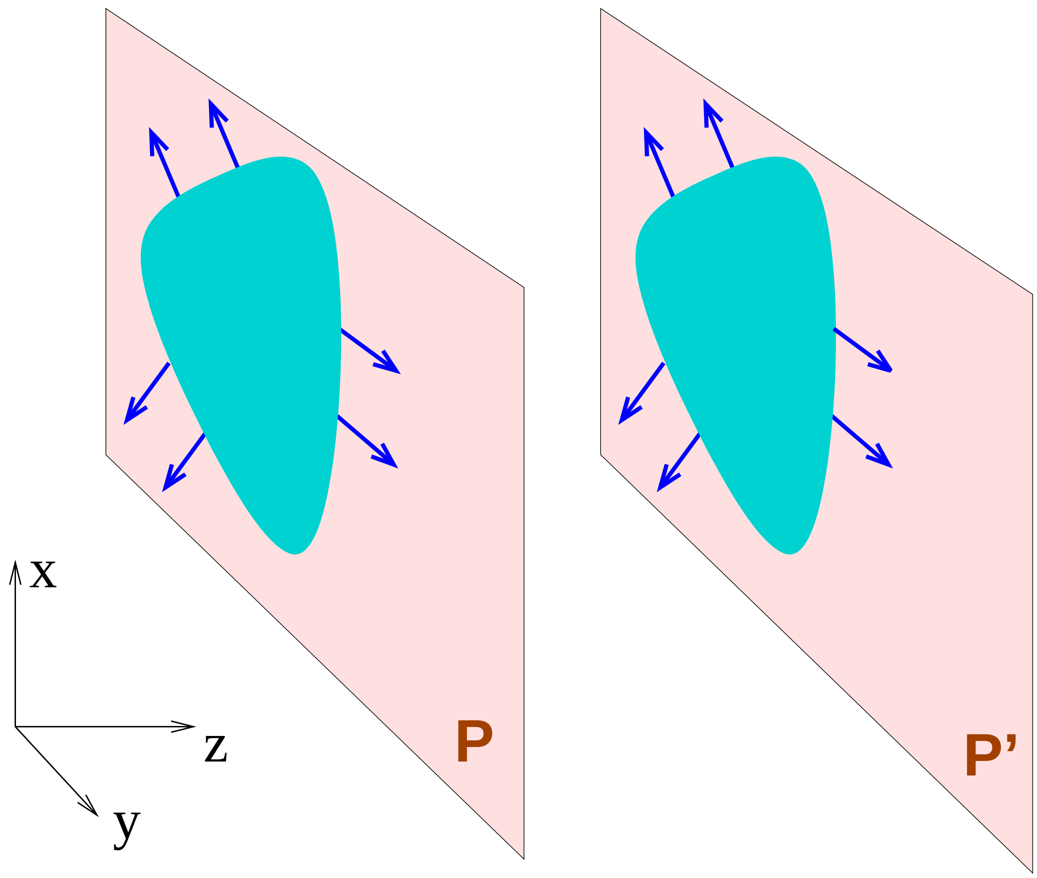
Freeze-out surface of fluid



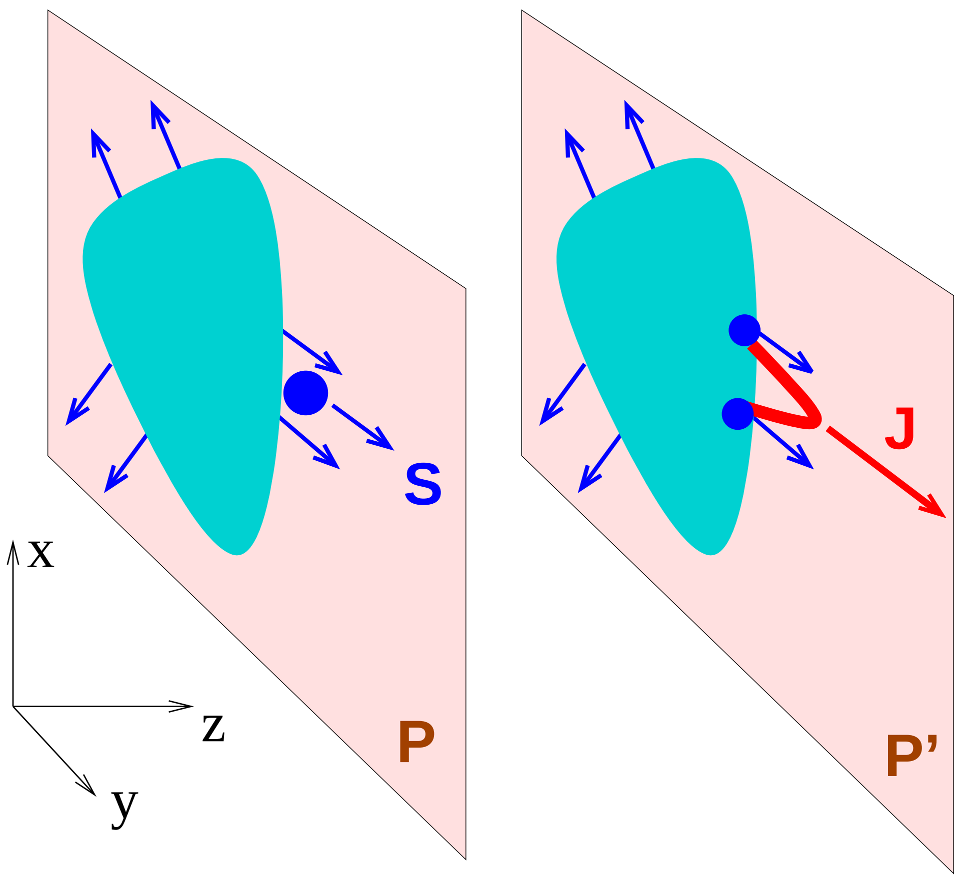
Cuts at two different z-values (P and P')



Same triangular shape and flow on P and P'

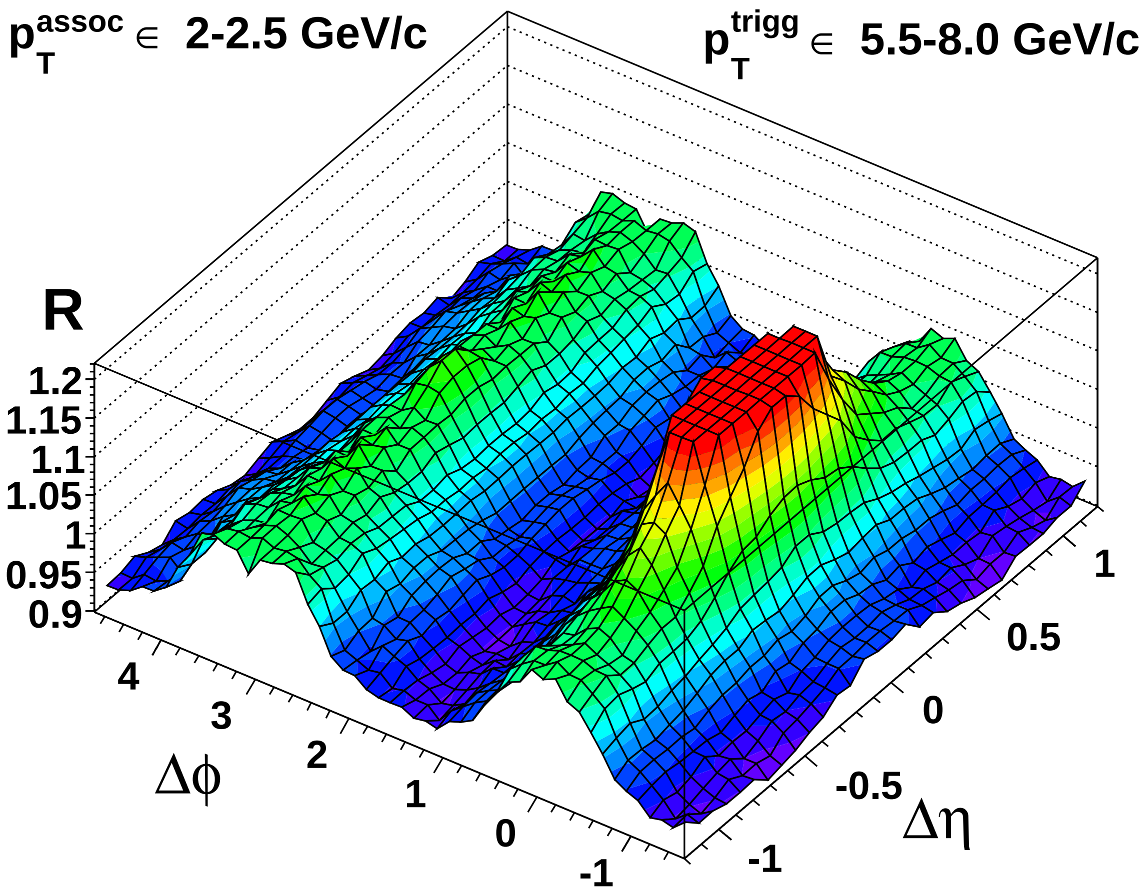


gives soft-jet correlation



also strong jet-soft correlation for peripheral events

(40-50% PbPb)

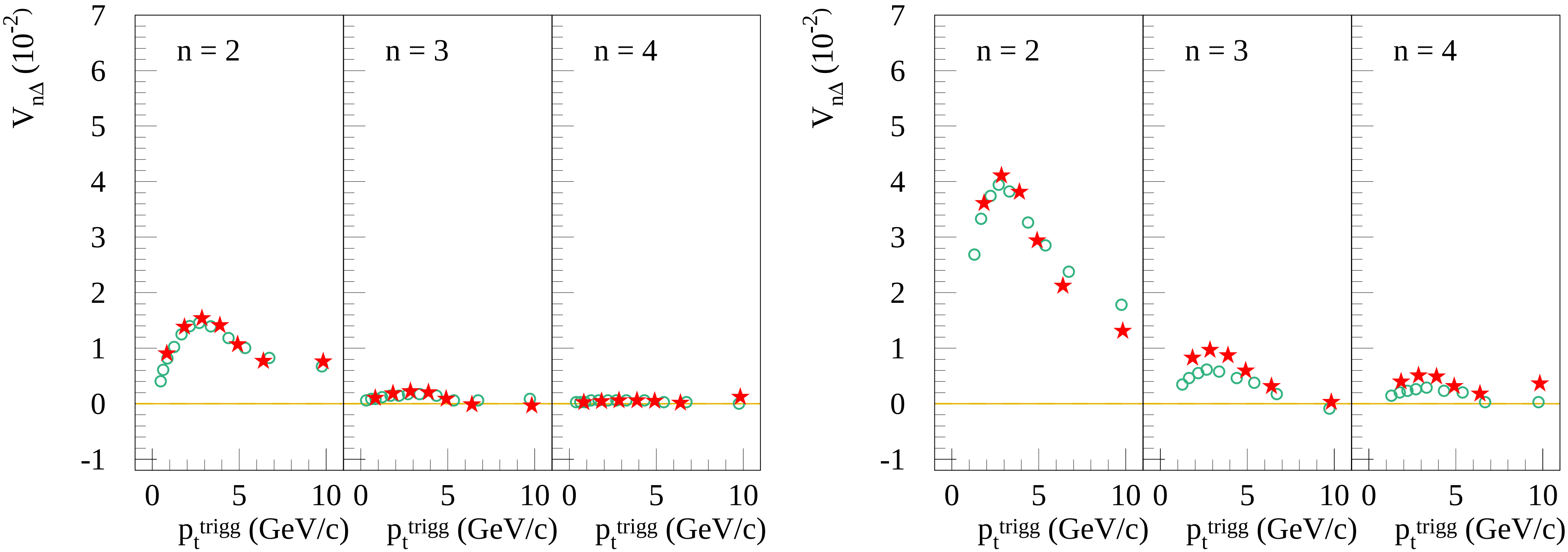


$$R(\Delta\phi) = \frac{1}{2(B-A)} \int_{A<|\Delta\eta|<B} R(\Delta\eta, \Delta\phi)\, d\Delta\eta$$

$$R(\Delta\phi) = 1 + \sum_{n=1}^{5} 2V_{n\Delta} \cos(n\Delta\phi)$$

40-50% PbPb

$p_t^{\text{assoc}} \in$ 0.25-0.5 GeV/c $\qquad$ $p_t^{\text{assoc}} \in$ 1.0-1.5 GeV/c

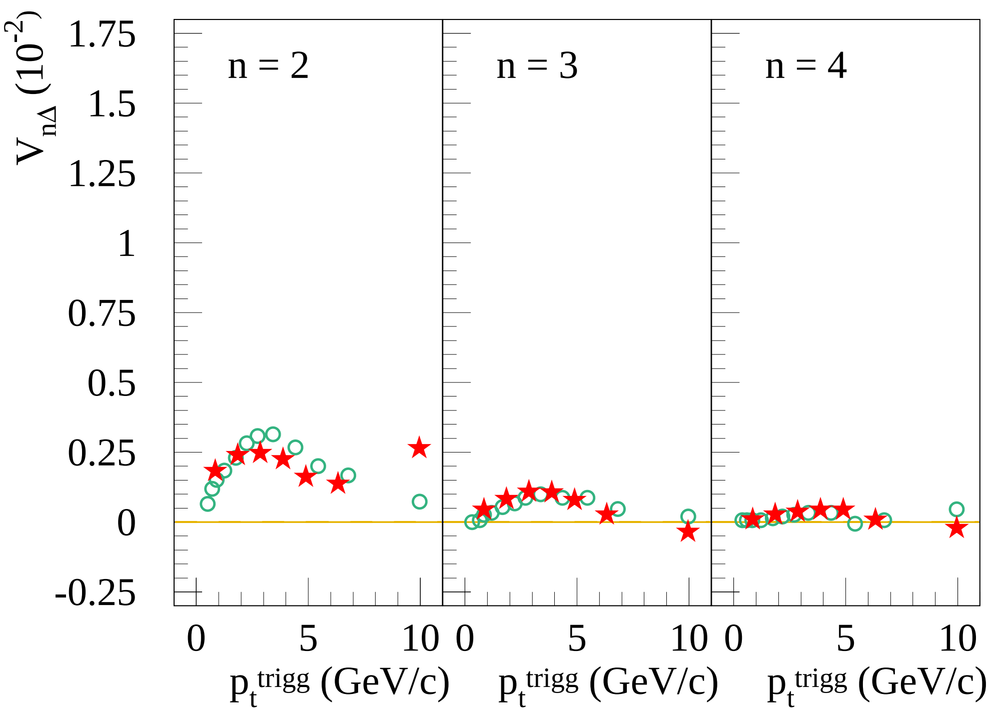


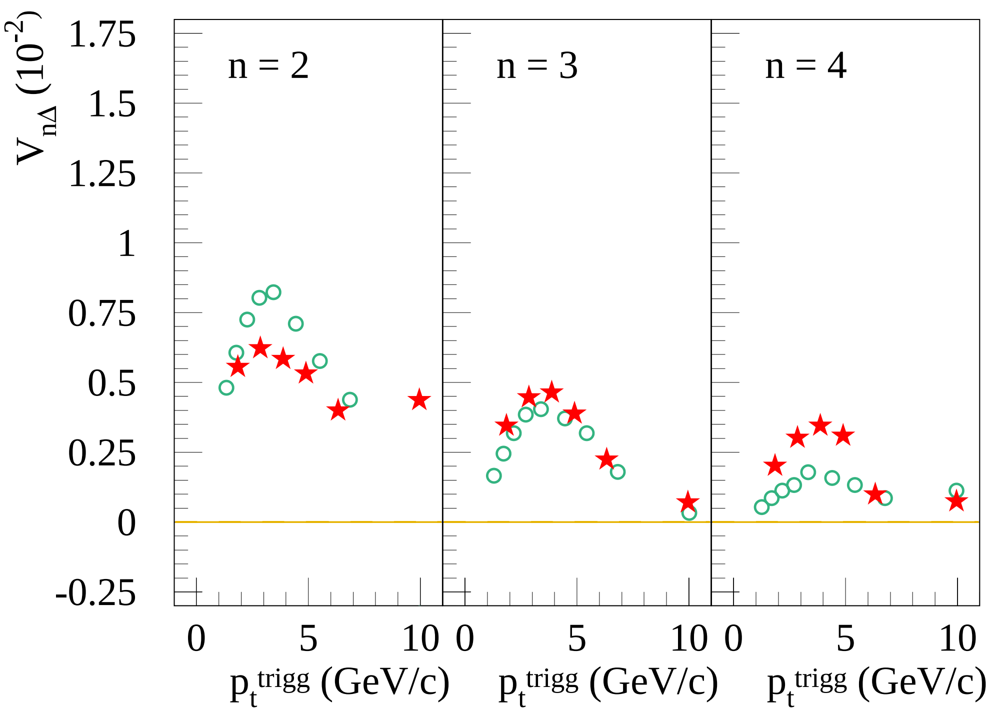
around 3 GeV/c: transition from soft-soft to soft-jet correlation

0-10% PbPb

$p_t^{\rm assoc} \in$ 0.25-0.5 GeV/c

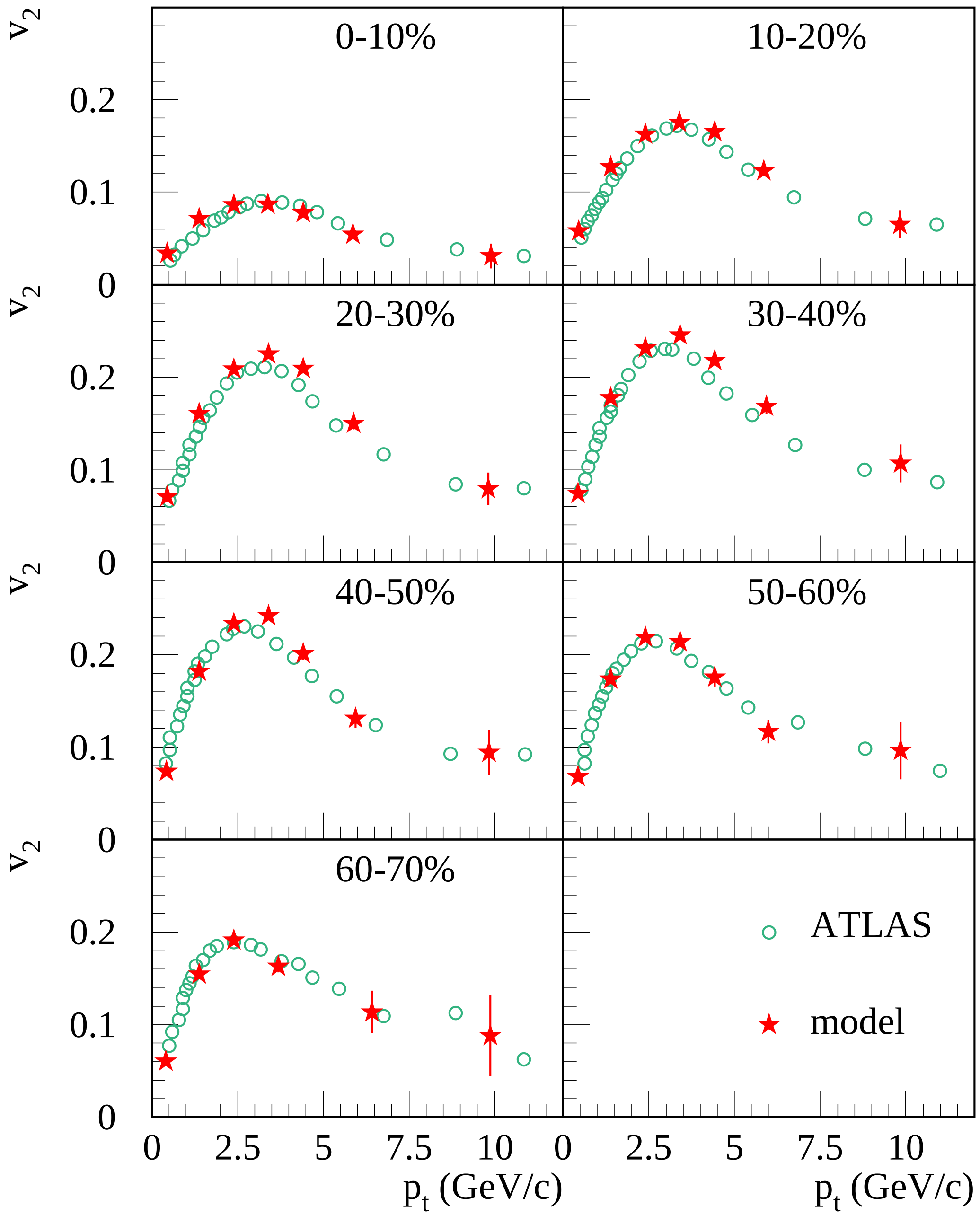
$p_t^{\rm assoc} \in$ 1.0-1.5 GeV/c



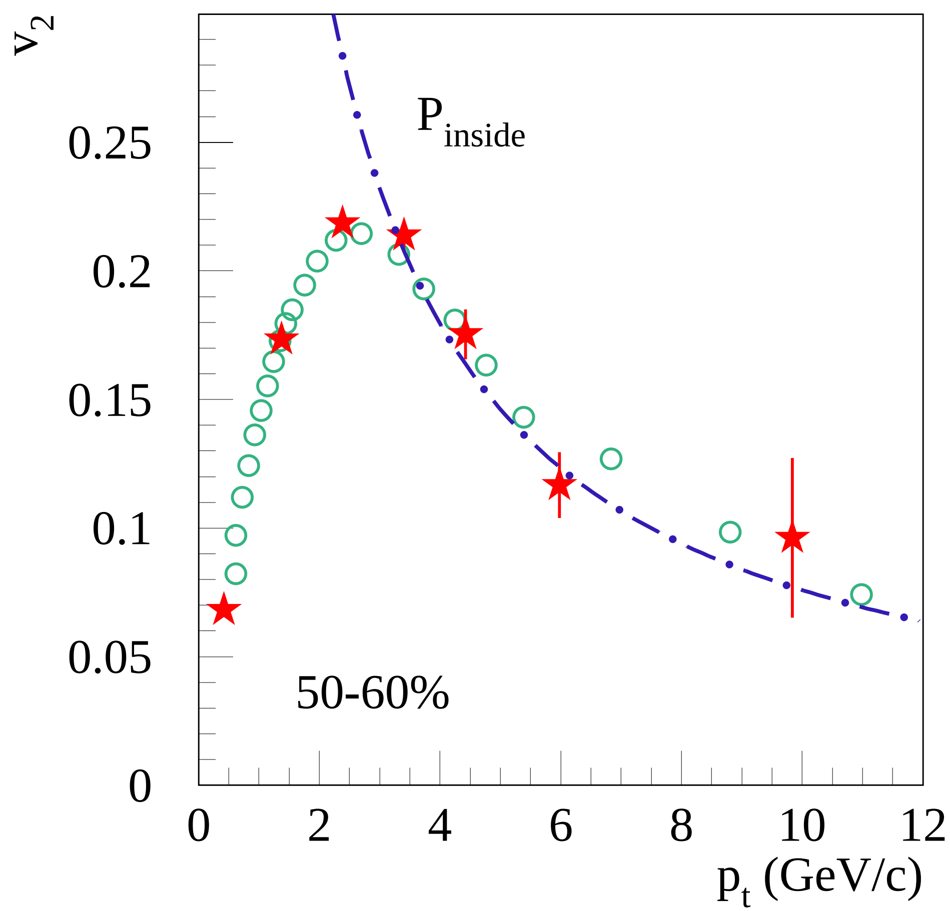


$$v_2 = \langle \cos[2(\phi - \phi_{\mathrm{Ref}})] \rangle$$

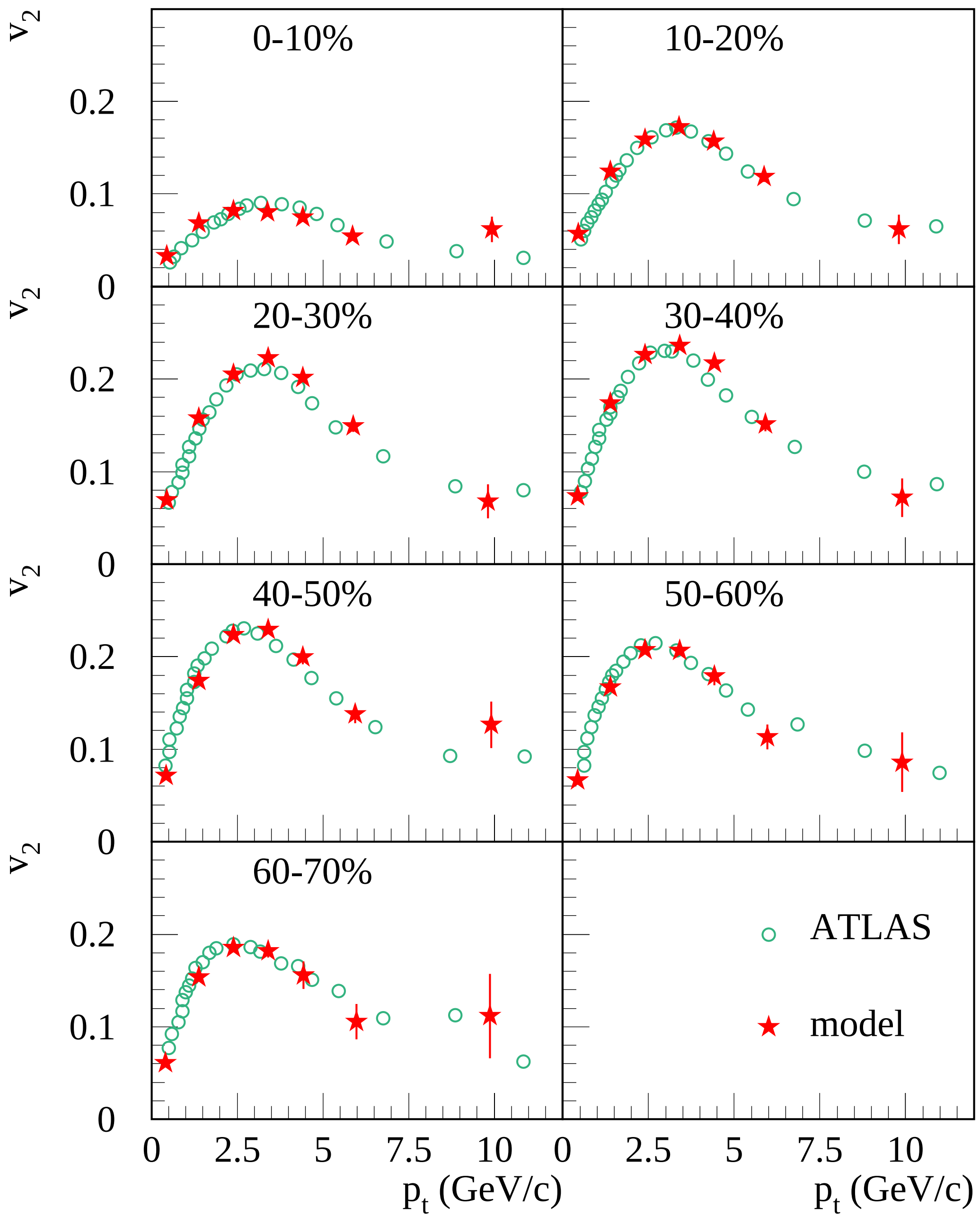
$$\phi_{\mathrm{Ref}} = \phi_{\mathrm{opposite\,hemisphere}} = \frac{1}{2} \tan^{-1} \frac{\langle \sin 2\phi \rangle}{\langle \cos 2\phi \rangle}$$


0-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
ATLAS
model
v_2
p_t (GeV/c)
0
0.1
0.2
2.5
5
7.5
10

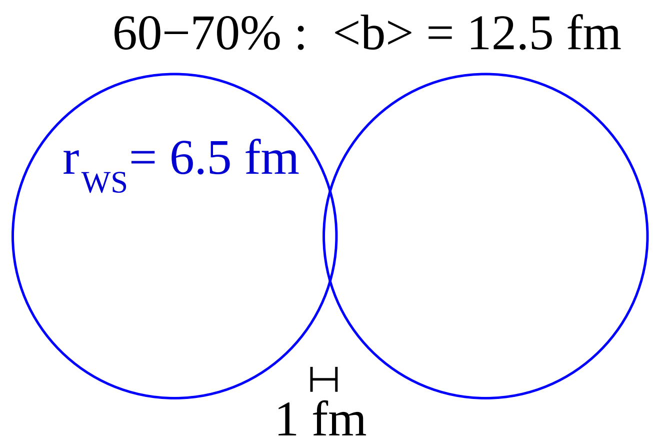
Tails again formation time driven:



VERY long tails

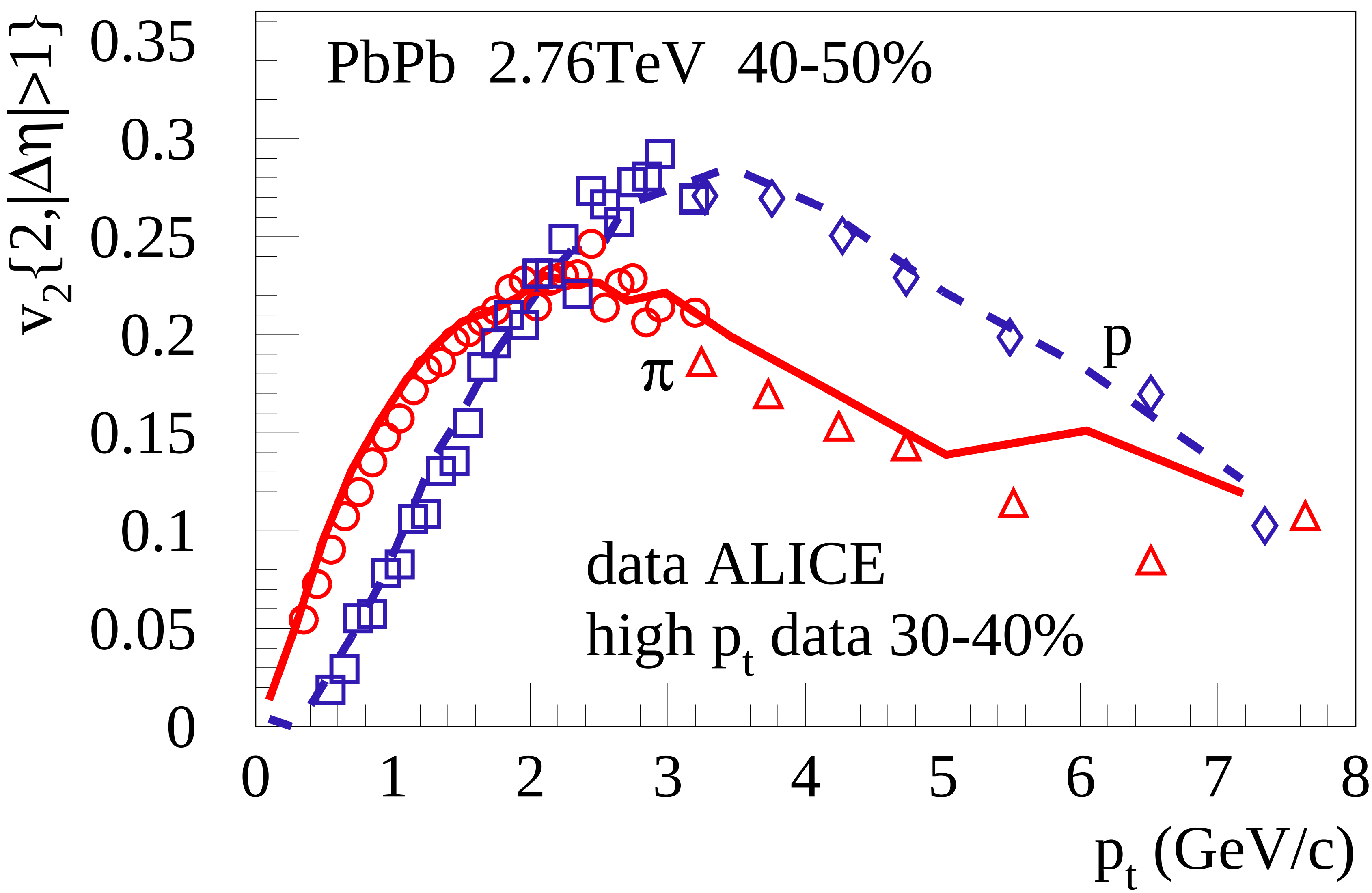


Interesting: Picture works up to peripheral collisions

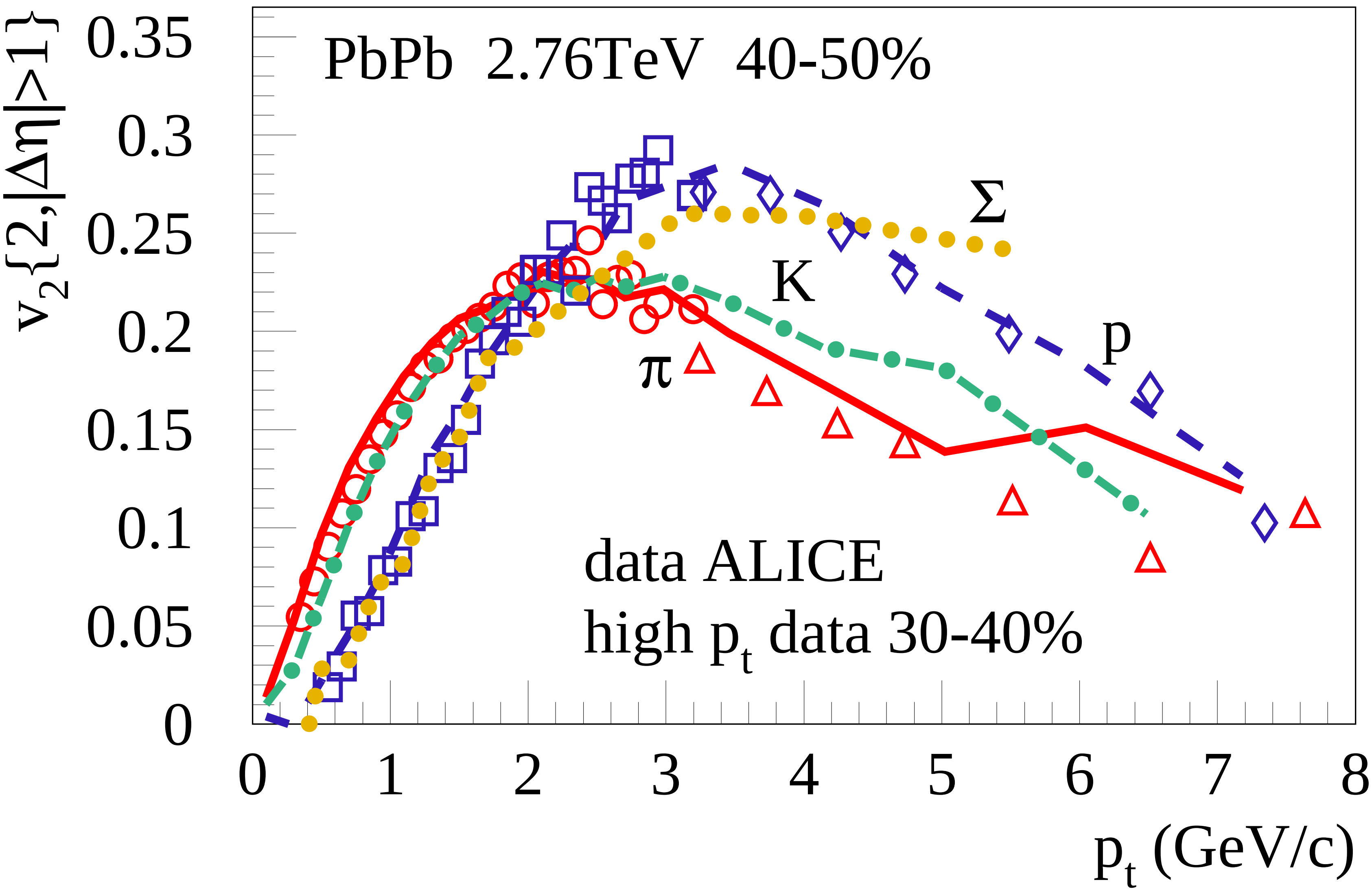


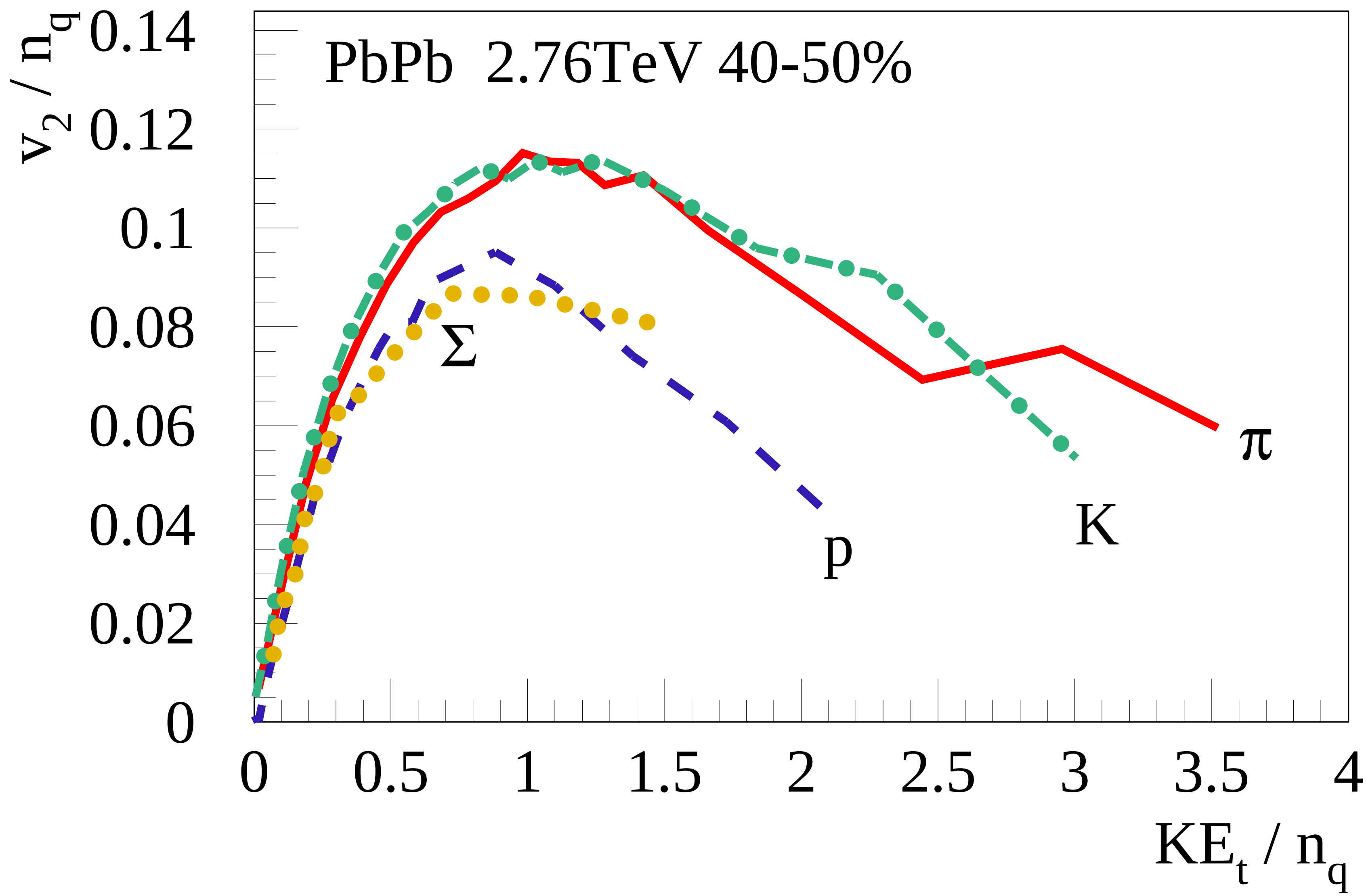
overlap like in pp!!

v2 scaling ???

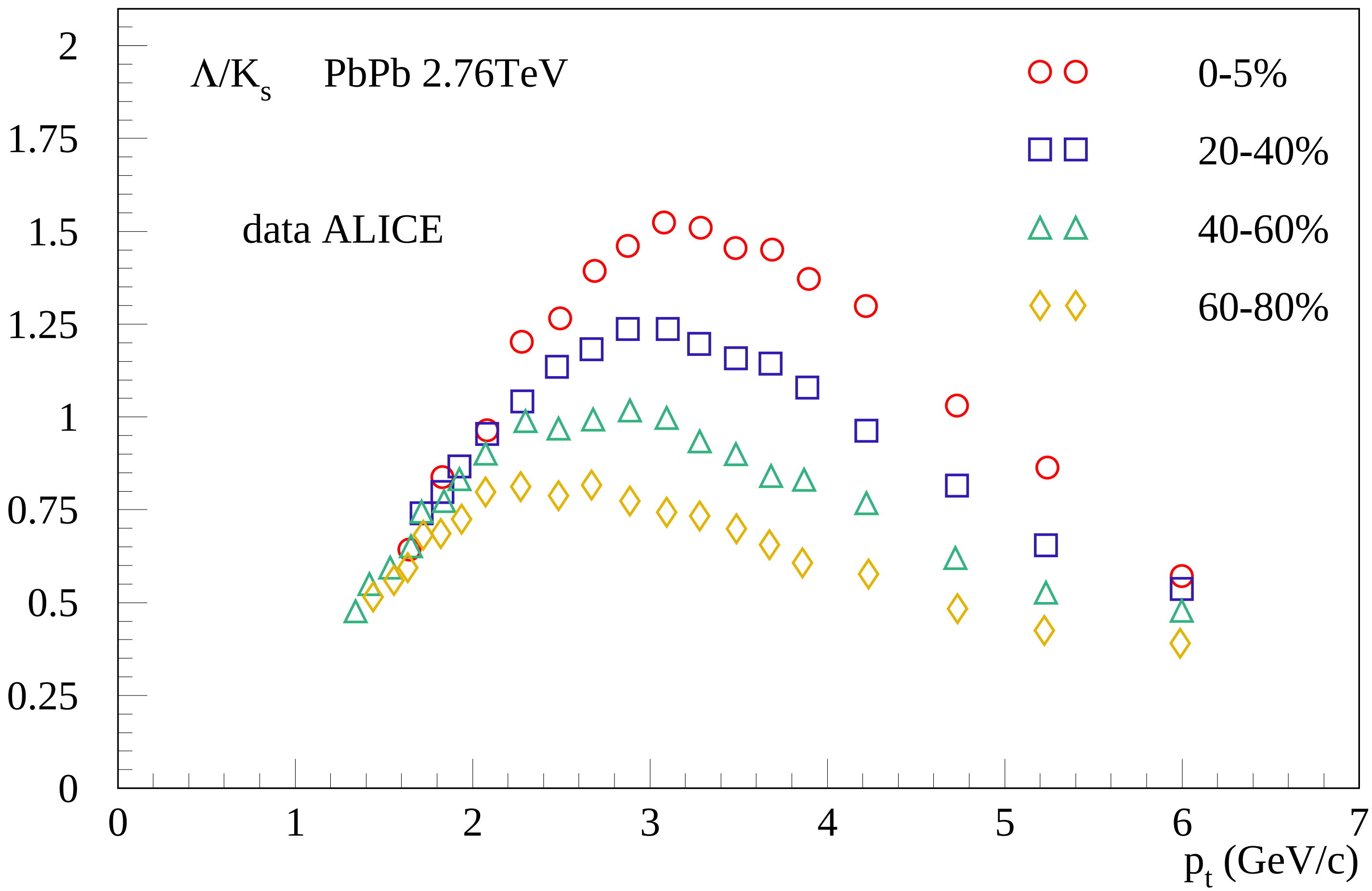


PbPb 2.76TeV 40-50%
data ALICE
high p_t data 30-40%
π
p
$v_2\{2,|\Delta\eta|>1\}$
p_t (GeV/c)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
6
7
8


PbPb 2.76TeV 40-50%
$v_2\{2,|\Delta\eta|>1\}$
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
6
7
8
p_t (GeV/c)
Σ
K
p
π
data ALICE
high p_t data 30-40%


PbPb 2.76TeV 40-50%
v_2 / n_q
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
3
3.5
4
KE_t / n_q
Σ
p
K
π

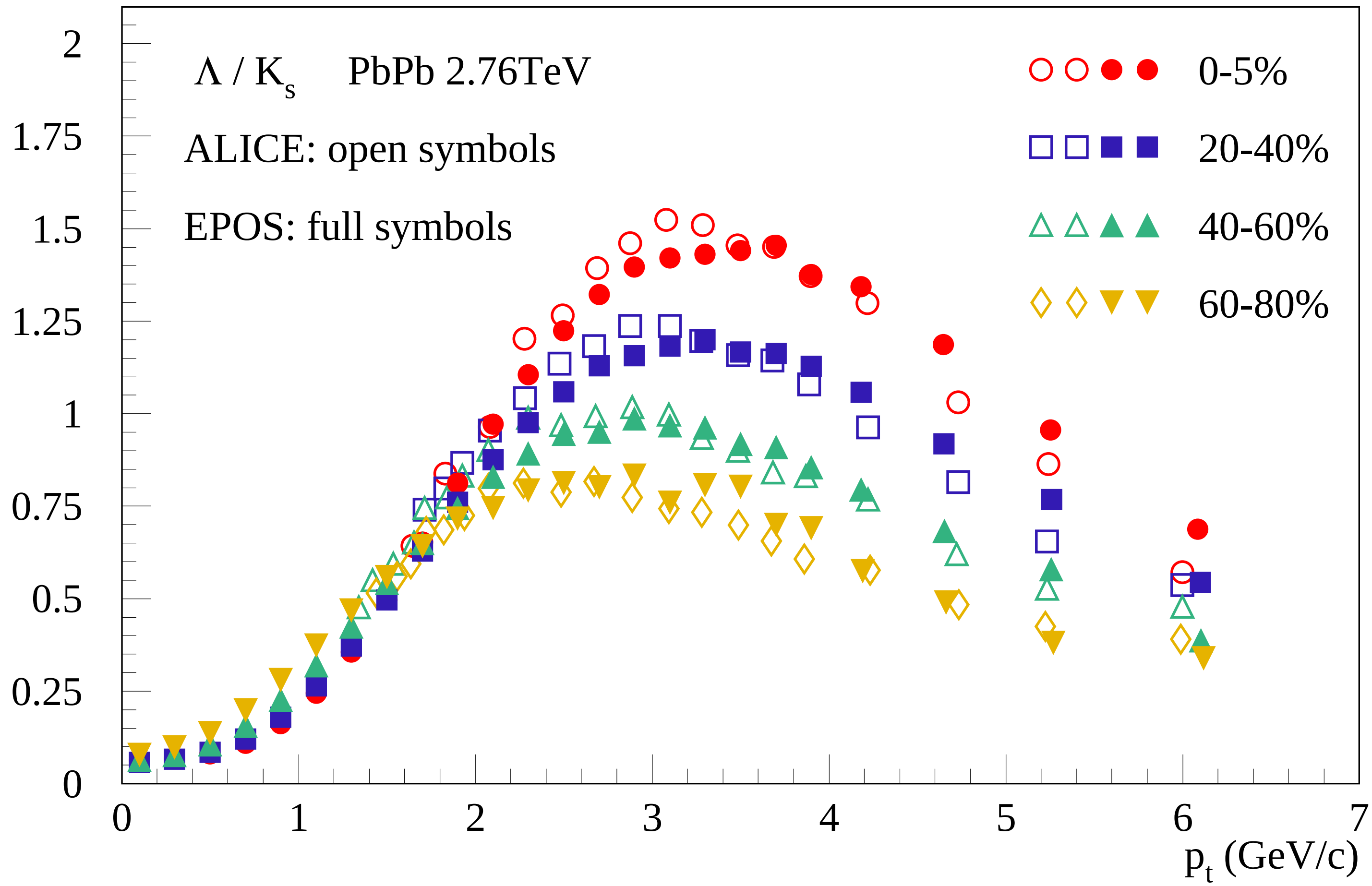
What about Lambda / kaon ratio??



One of the key observables at intermediate pt

We get for free:

Lambda/kaon ratio, PbPb at 2.76 TeV



size – formation time effect

intermediate pt particles are produced in the fluid

and carry plasma properties like flow, increased strangeness and diquark rate

Summary

- **We present a framework for treating bulk, jets, and their interaction.**
- **Jet-soft and fluid-jet interactions (jet = hadrons) affect particle productions VERY STRONGLY between 0 and 20 GeV/c (even up to 50 GeV/c). Parton energy loss dominant beyond.**
- **Reasonable quantitative description of yields, flow harmonics, dihadron correlations with small and large trigger pt, pion,proton v2, lambda/K ratio**

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Thank you !!