Hydrodynamical evolution based on fluctuating flux tube initial conditions:

Separating jets from bulk matter

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in collaboration with

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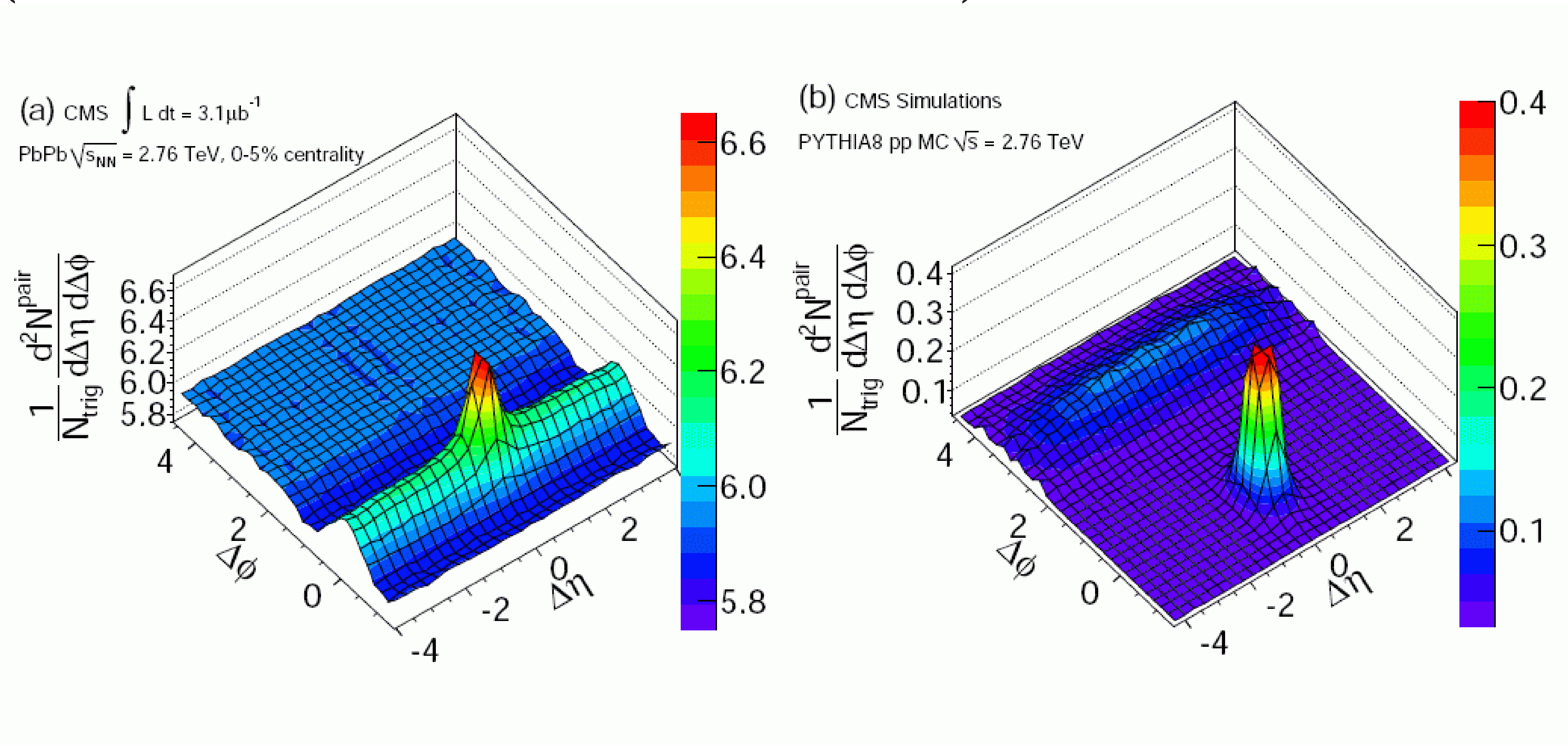
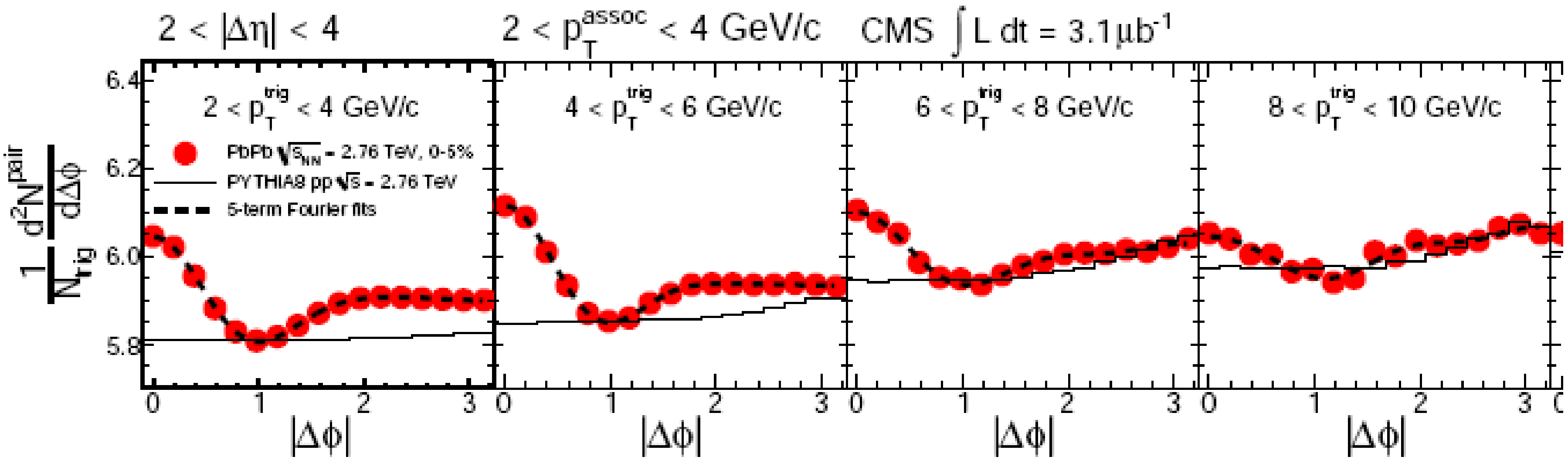
CMS dihadron correlations: PbPb 2.76 TeV (CERN-PH-EP/2011-056 2011/05/13)



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

$\Delta\eta$ integrated ($2 < |\Delta\eta| < 4$)



Ridge for small trigger pt:

irregular initial energy density in transverse plane + little variation longitudinally translates into long range flow correlation

Ridge at high pt ??? MUST involve jets

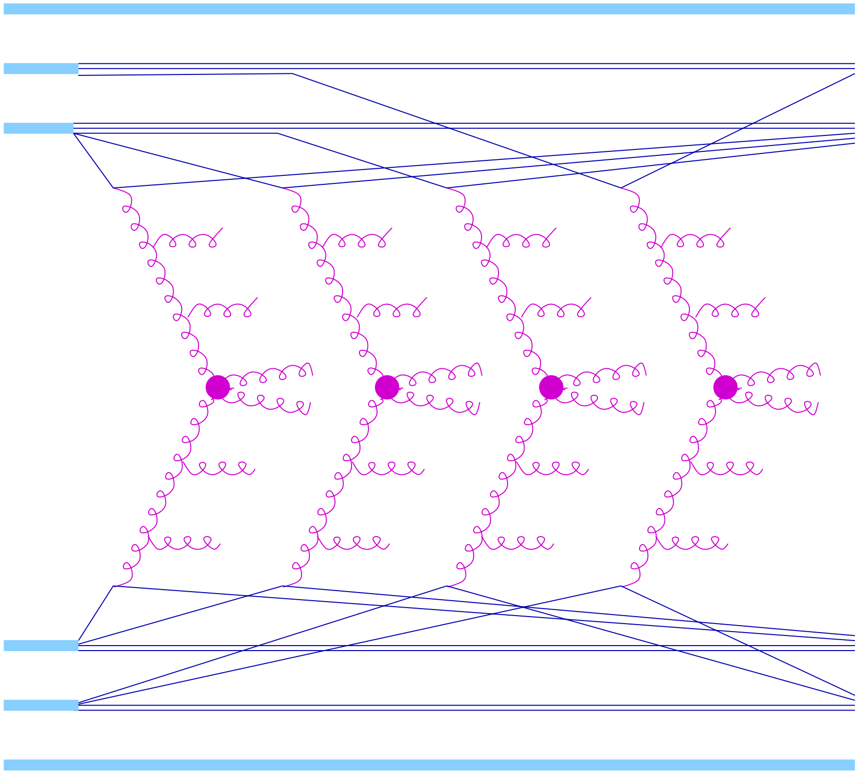
We will try to understand this

Contents

1 Basis: Flux tubes from MS approach

Multiple scattering approach (EPOS):

marriage of pQCD and Gribov-Regge, with energy sharing

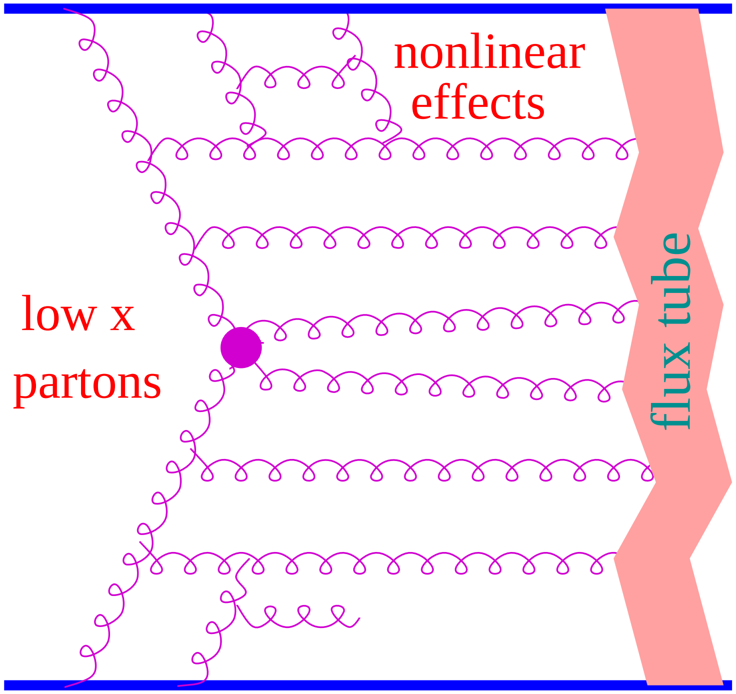


Many elementary collisions in parallel

Not just rescattering of hard partons!

Elementary scattering = parton ladder

Elementary scattering - flux tube



- ☐ Parton evolutions from the projectile and the target side towards the center (small x)
- ☐ Evolution is governed by an evolution equation, in the simplest case according to DGLAP.
- ☐ Parton ladder may be considered as a quasi-longitudinal color field, a so-called flux tube, conveniently treated as a relativistic string.
- ☐ Intermediate gluons are treated as kink singularities in the language of relativistic strings, providing a transversely moving portion of the object.
- ☐ flux tubes decay via the production of quark-antiquark pairs, creating in this way fragments – which are identified with hadrons

Quantum mechanical treatment of multiple scattering

quite involved ... in particular when the energy sharing between the parallel scatterings is taken into account

Details:

Parton-based Gribov-Regge Theory, H. J. Drescher,
M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner,
Phys. Rept. 350 (2001) 93-289

☐ Based on cutting rule techniques,
one obtains partial cross sections for exclusive event classes,

☐ which are then simulated with the help of Markov chain techniques.

Parton ladder -> flux tube -> kinky string:

The relativistic classical string picture is very attractive, because its dynamics (Lagrangian) is essentially derived from general principles as covariance and gauge invariance (Nambu 69, Rebbi 74, Scherk 75)

Simplest possible string: a two-dimensional surface

$$X(\alpha,\beta)$$

in 3+1 dimensional space-time, with piecewise constant initial conditions,

$$V(\alpha)\equiv\frac{\partial X}{\partial\beta}(\alpha,\beta=0)=V_k,\ \text{in}\ [\alpha_k,\alpha_{k+1}],$$

referred to as kinky string.

The dynamics is governed by the Nambu-Goto string action.

Mapping partons onto strings:

☐ we identify the ladder partons with the kinks of a kinky string,

☐ such that the length of the α-interval is given by the parton energies E_k (divided by the string tension),

☐ and the kink velocities are just the parton velocities, p_k^μ / E_k.

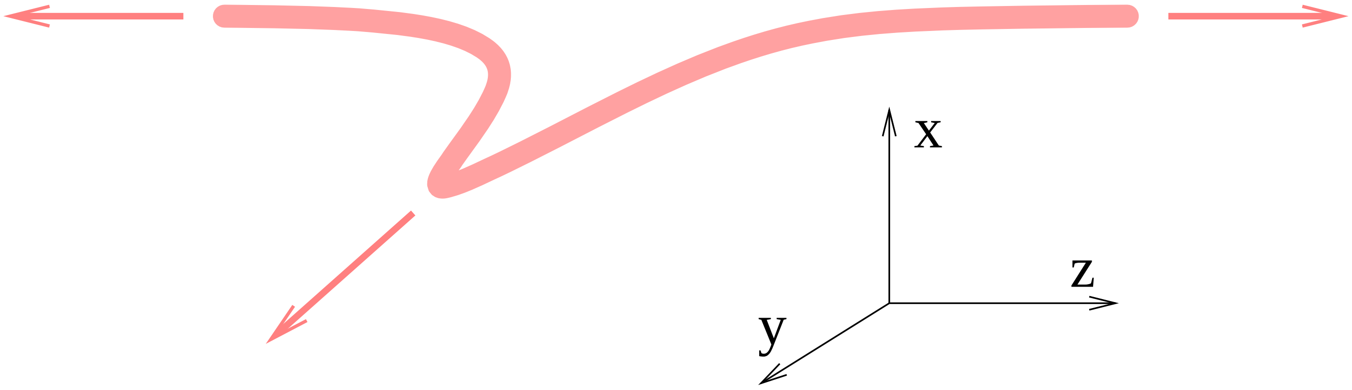
The string evolution is then completely given by these initial conditions

$$X(\alpha, \beta) = X_0 + \frac{1}{2}\left[\int_{\alpha-\beta}^{\alpha+\beta} V(\xi)\, d\xi\right].$$

Space components of the string in $\mathbb{R}^3$ space (at given proper time τ_0):

mainly longitudinal object (here parallel to the z-axis)

but due to the kinks: **string pieces moving transversely** (in y-direction in the picture).



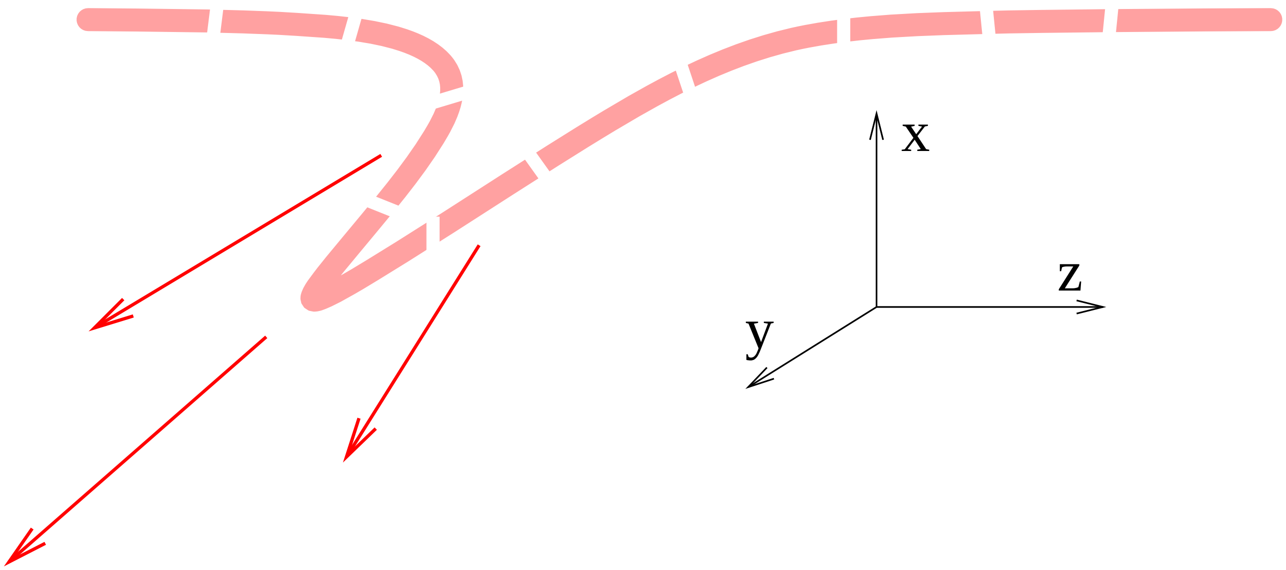
But despite these kinks, most of the string carries only little transverse momentum!

In case of elementary reactions

Strings break via q-$\bar{q}$ production, string fragments are identified with hadrons.

- ☐ String breaks within a surface area dA with probability $dP = p_B\, dA$ (area law, Artru 74, 83, Morris 87)
- ☐ Flavor dependence via probabilities $\exp(-\pi m_q^2/\kappa)$,

String pieces close to a kink constitute the jets of hadrons (arrows)



Heavy ion collisions
or very high energy proton-proton scattering:

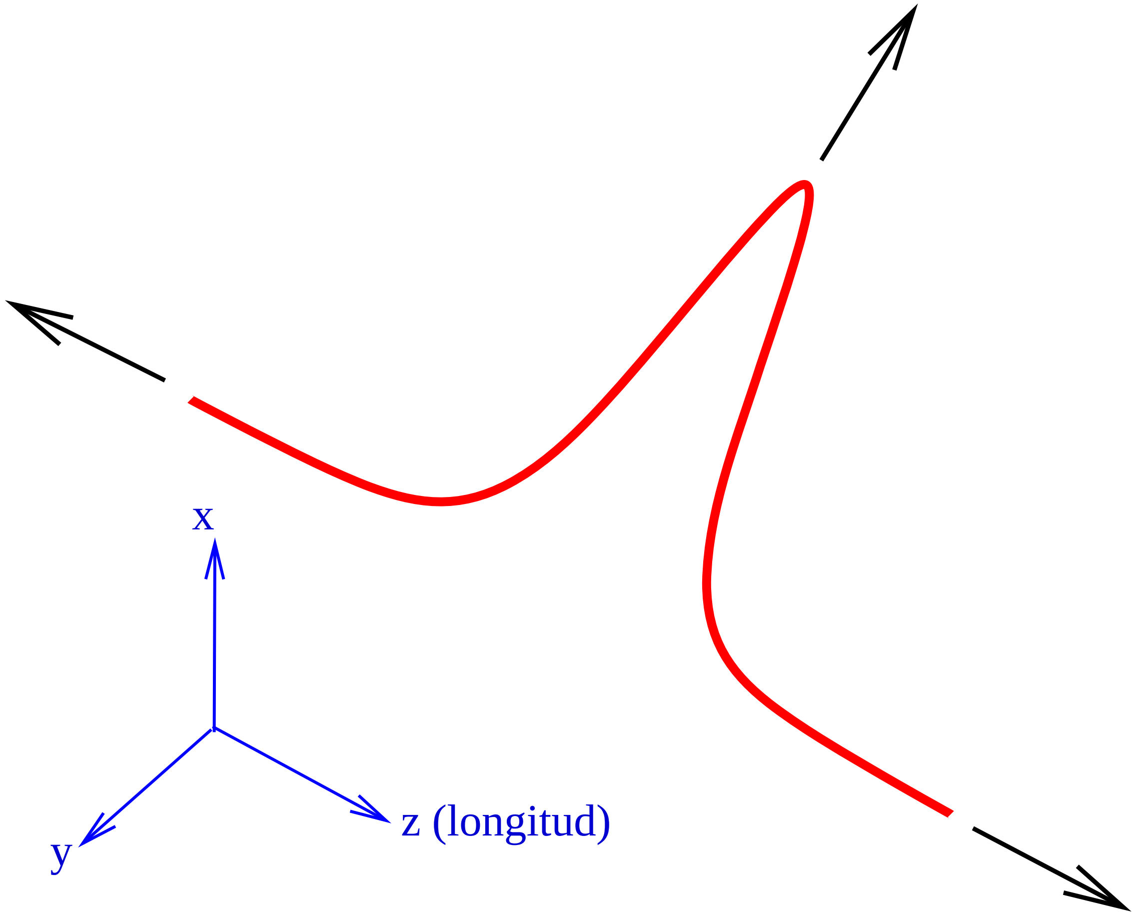
- ☐ the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently

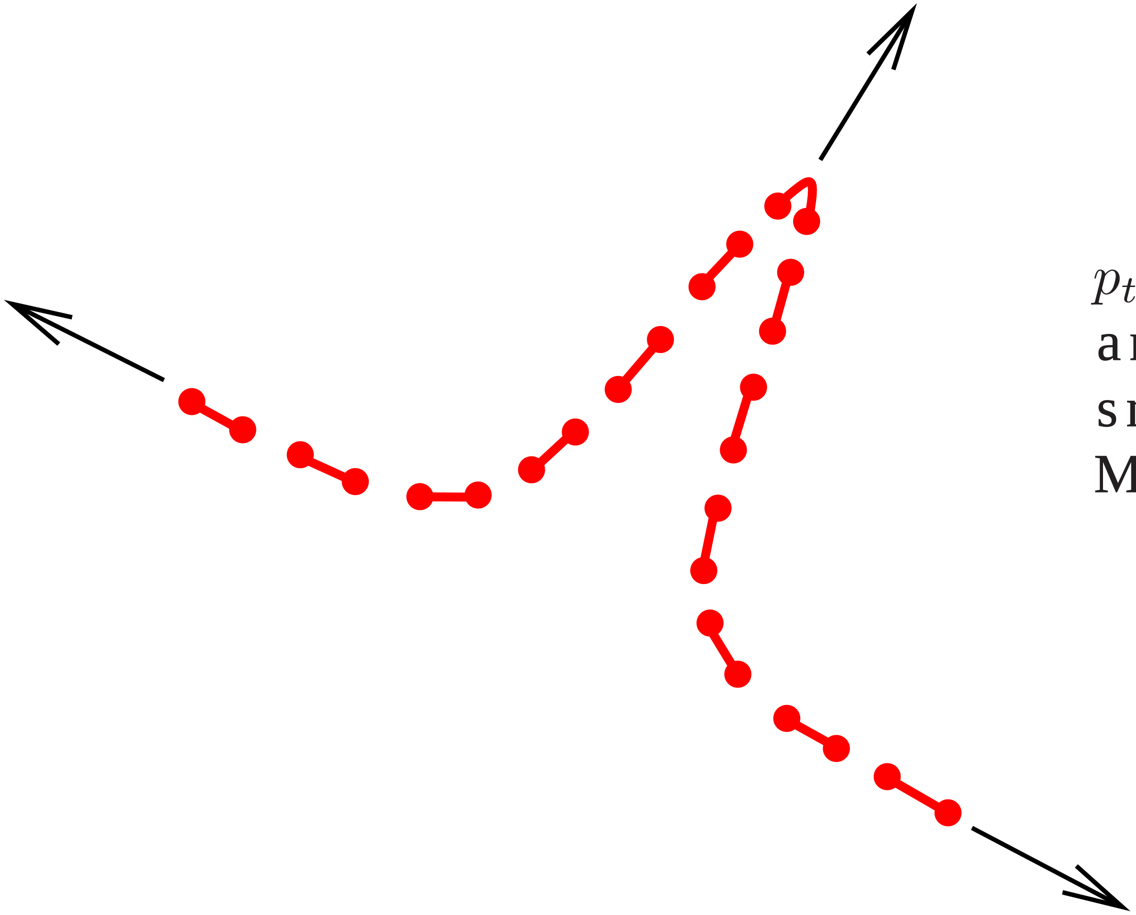
Some string pieces will constitute bulk matter,
others show up as jets
(jet-bulk separation)

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

2 Jet-bulk separation

consider first again an ordinary kinky flux tube (a single one)

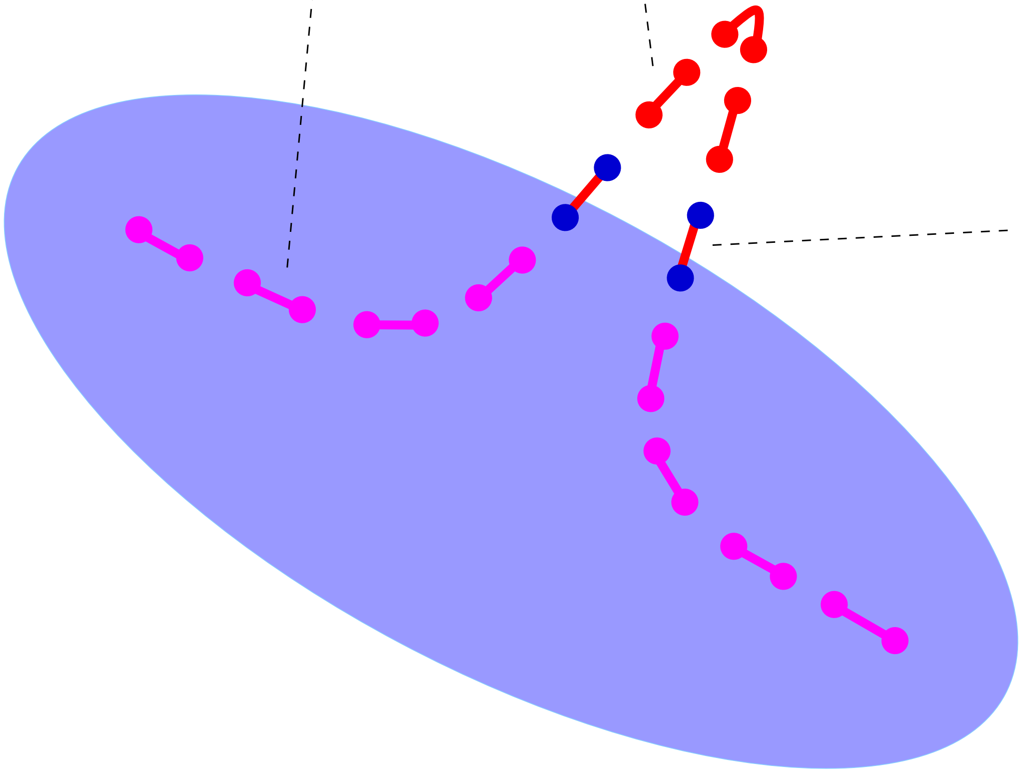




string breaks via
q-qbar production
(Schwinger mechanism)

p_t of created quarks and antiquarks are small (few hundred MeV)

In matter: three types of segments



inside, low pt: stay inside (contribute to bulk)

high pt: produced outside via Schwinger mechanism

produced close to the surface: pick up q-qbar from the (flowing) matter

Technical realization in two steps

Estimate initially which segments constitute the bulk, 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 $\vec{v}(t, \vec{x})$.

From the initially estimated “bulk segments” compute $T^{\mu\nu}$

$$\boxed{\begin{aligned} T^{\mu\nu}(x) &= \sum_i \frac{\delta p_i^\mu \delta p_i^\nu}{\delta p_i^0} g(x-x_i), \quad \delta p = \left\{ \frac{\partial X(\alpha,\beta)}{\partial \beta}\delta\alpha + \frac{\partial X(\alpha,\beta)}{\partial \alpha}\delta\beta \right\} \\ N_q^\mu(x) &= \sum_i \frac{\delta p_i^\mu}{\delta p_i^0} q_i\, g(x-x_i), \quad q \in \{u,d,s\} \end{aligned}}$$

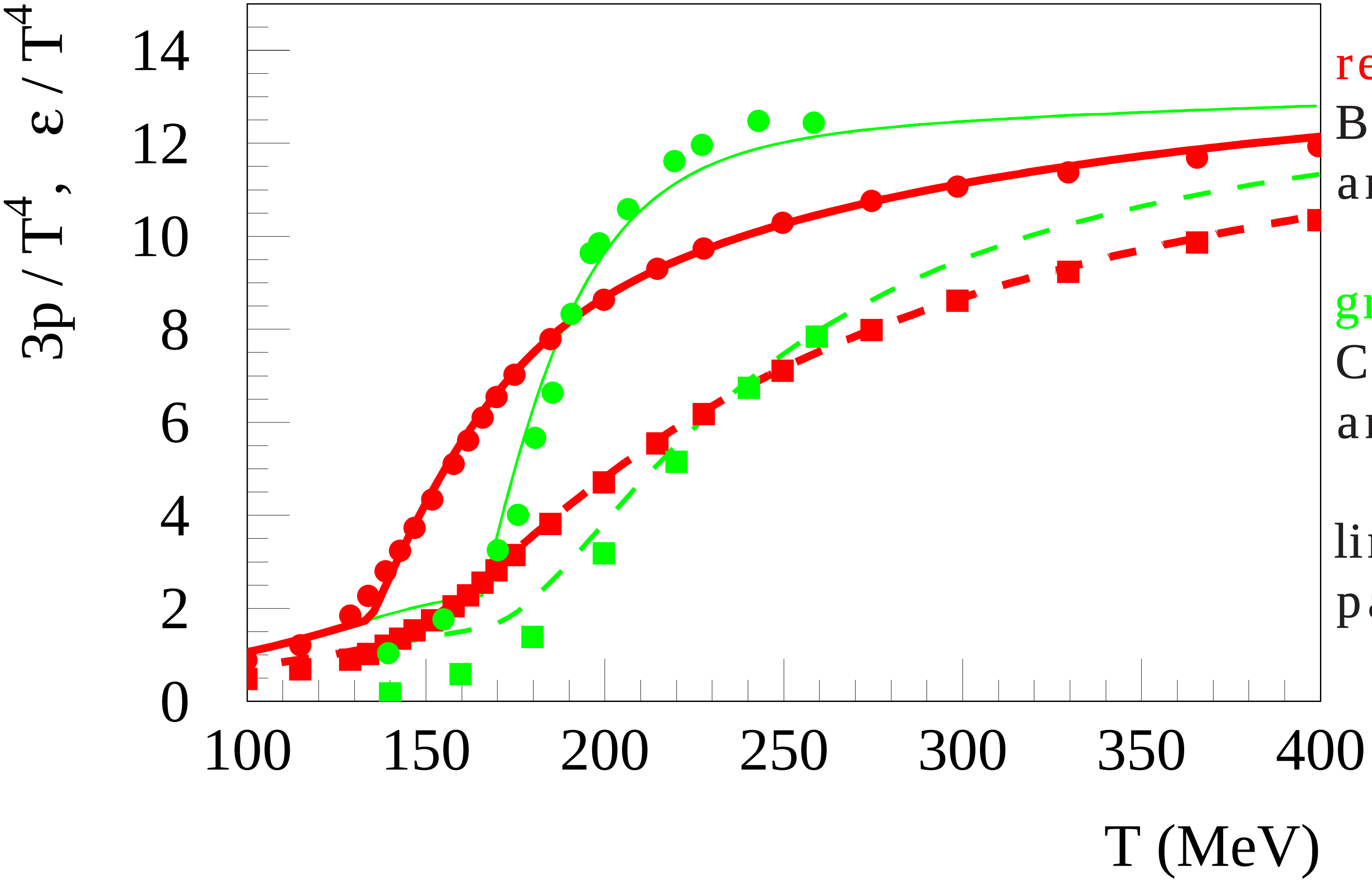
Evolution according to the equations of ideal hydrodynamics:

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

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

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

Important: equation of state (not well known)



red points:
Borsanyi et al,
arXiv:1007.2580

green points:
Cheng et al.,
arXiv:0911.2215

lines: our parametrizations

In our calculations: usually the red version (early FO)

3 Nuclear modification factor in PbPb at 2.76 TeV

Aim: understand R_{AA} from low to high p_t, with

$$R_{AA} = \frac{dn_{AA}/d^2p_t}{N_{coll}\, dn_{pp}/d^2p_t}$$

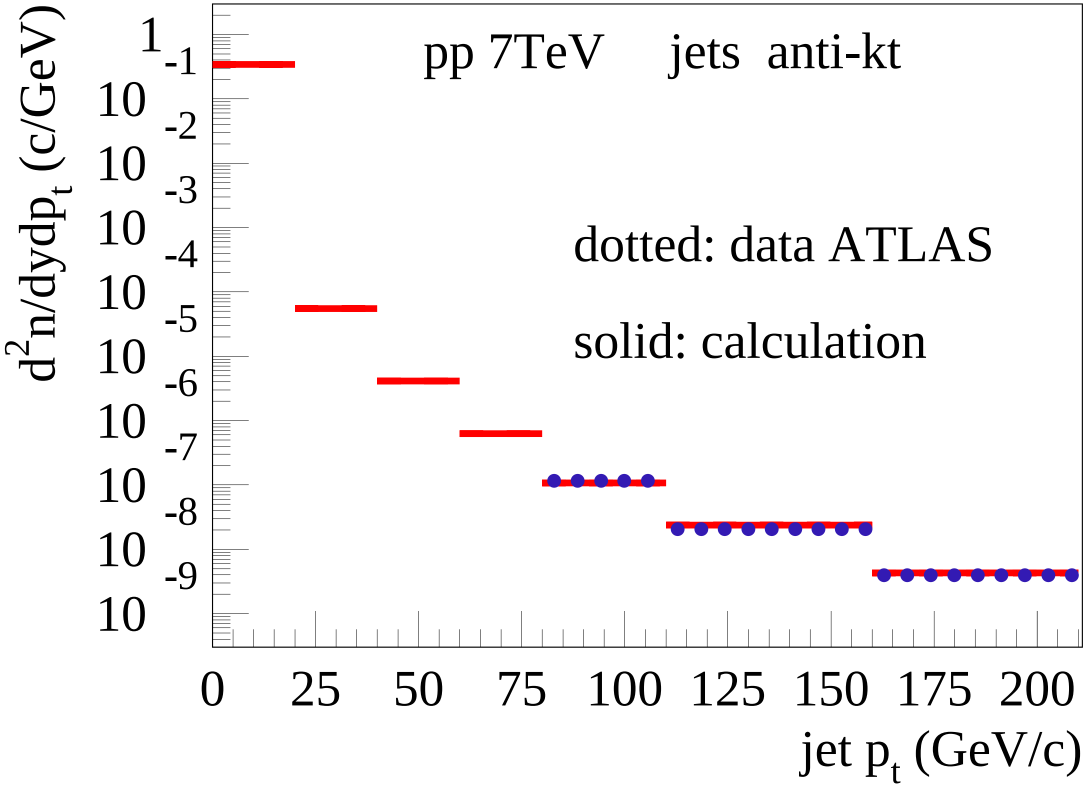
First (not shown): Checks for pp, see:

☐ pp@0.9TeV: arXiv:1010.0400, PRC 83, 044915

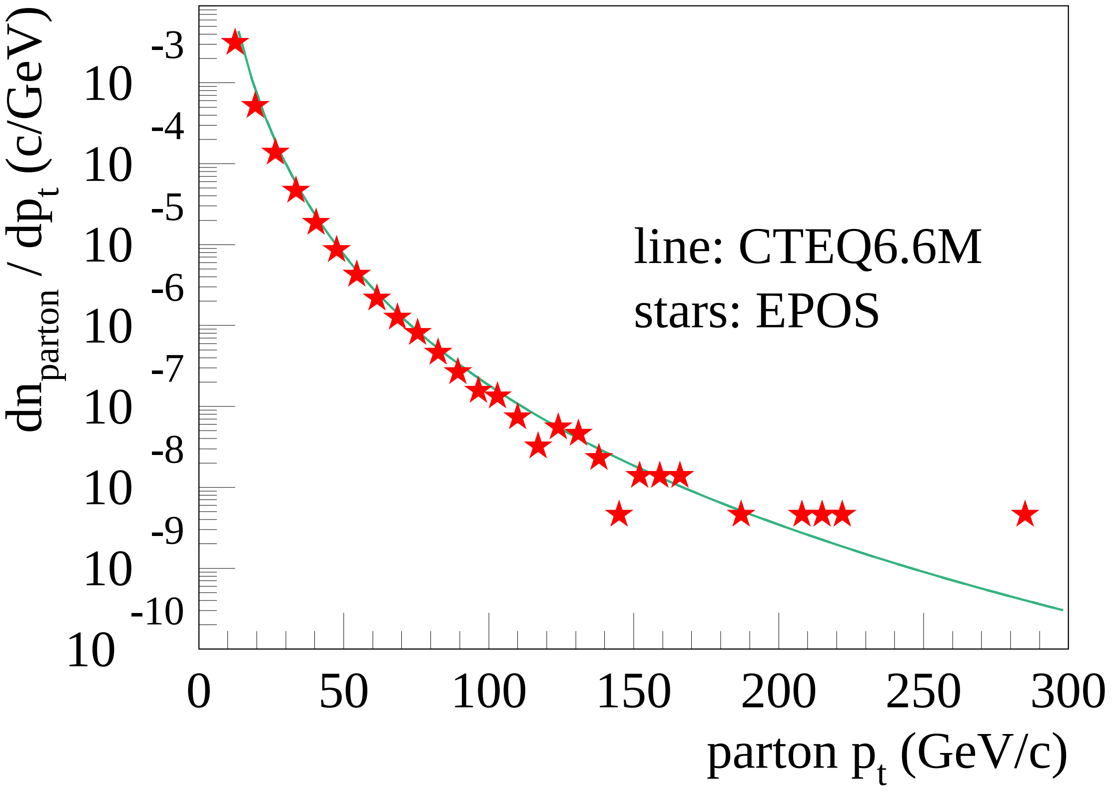
☐ pp@7TeV: arXiv:1011.0375, PRL 106:122004,201 and arXiv:1104.2405

☐ We also check pp@2.76 TeV compared to the ALICE pp reference

As consistency check, we also look at jet production in pp (unpublished)



And we compare with a parton model calculation using CTEQ PDFs for pp at 7 TeV

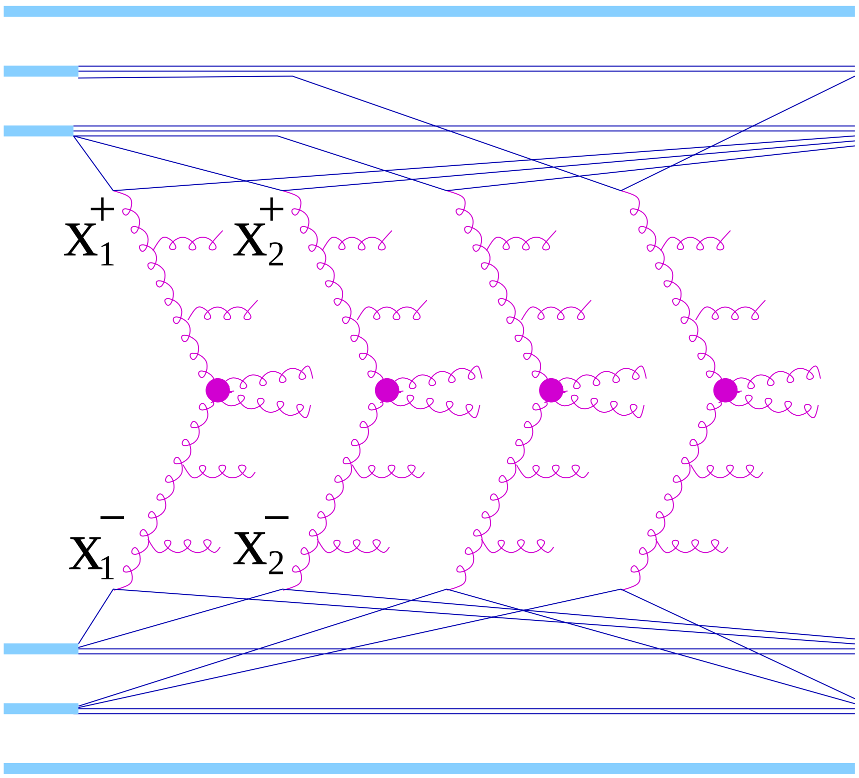


pp seems to be under control

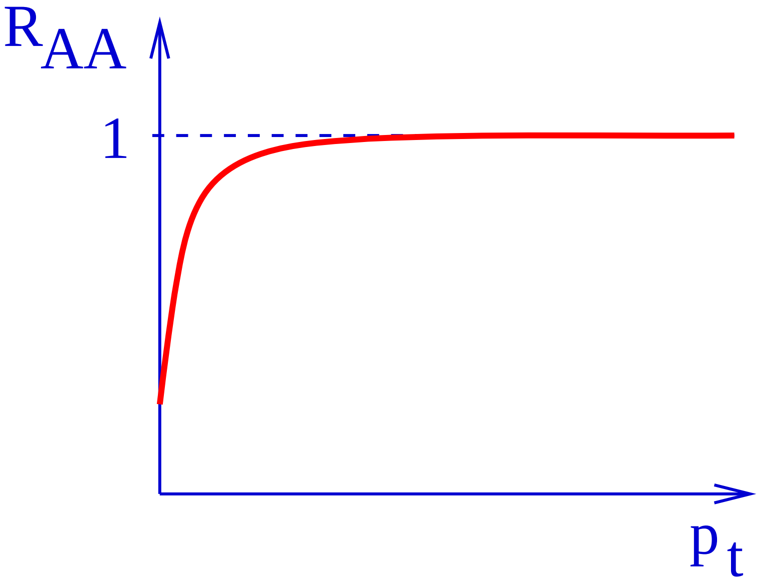
Energy sharing in AA :

For all nucleons i

$$\sum_{\text{all ladders } k \text{ connected to nucleon } i} x_k^{\pm} < 1$$

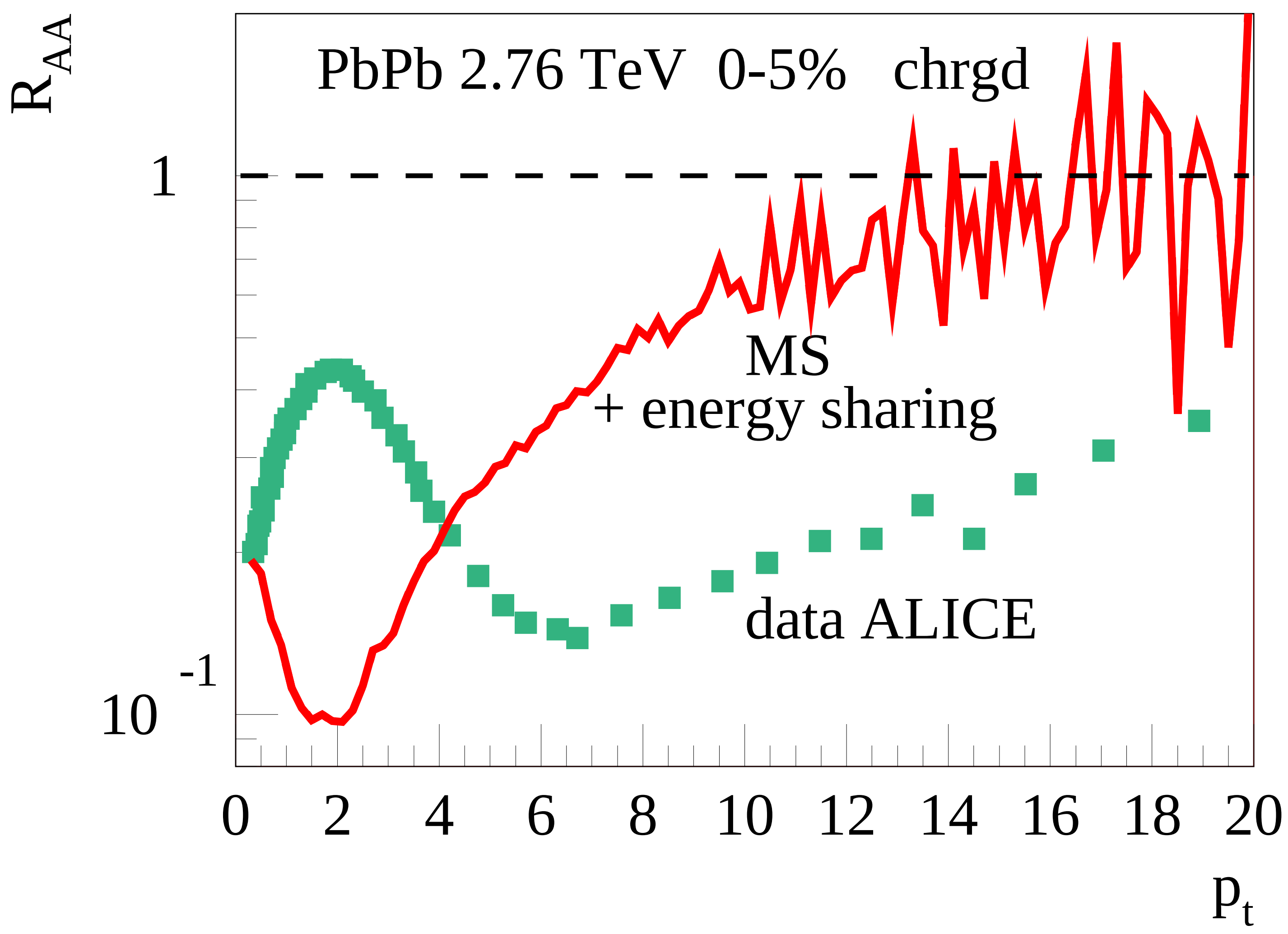


Leads to deviation
from perfect binary scaling
at low pt

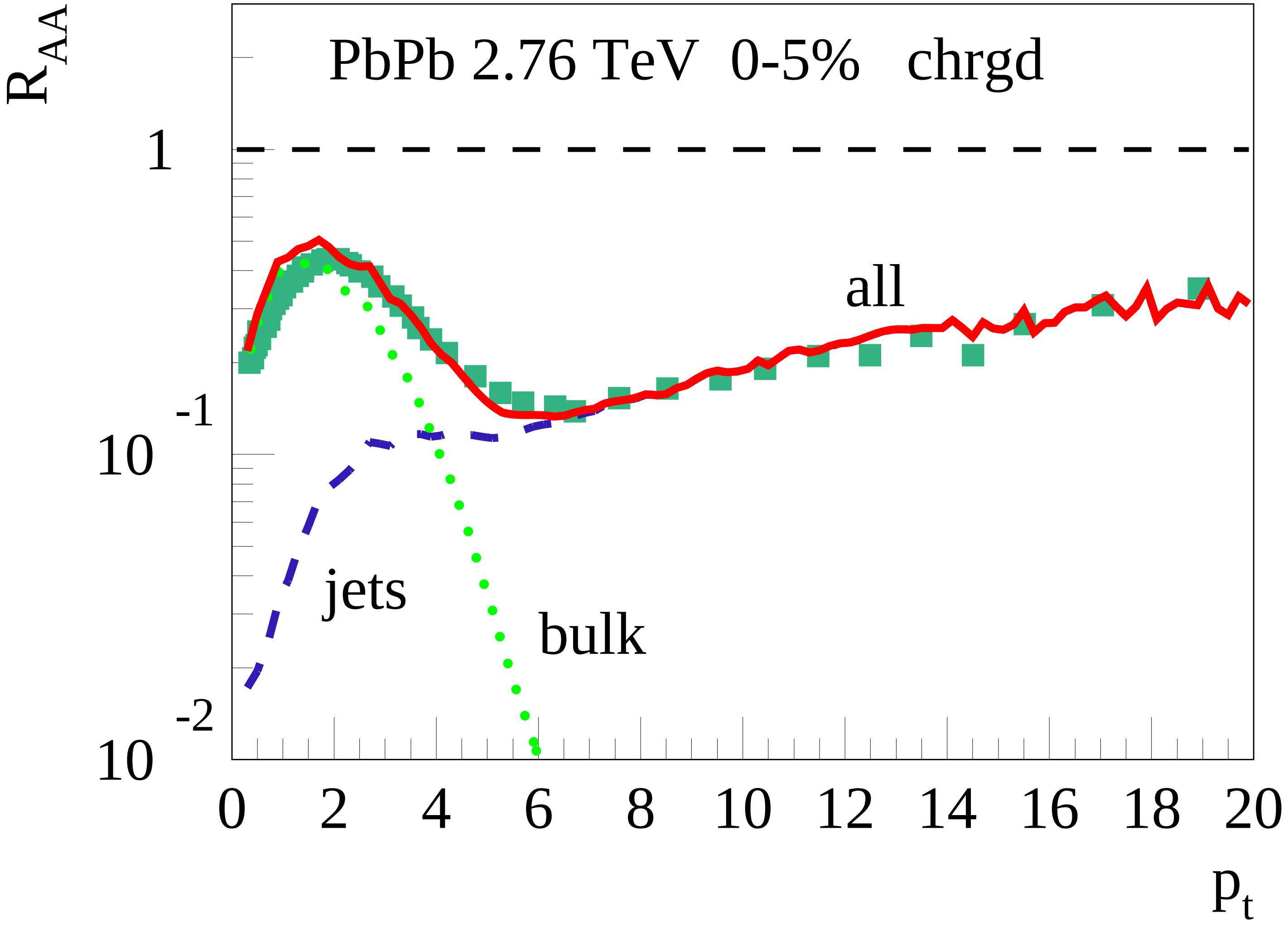


details about energy sharing
see Phys. Rept. 350 (2001) 93

R_{AA} for basic multiple scattering model with energy sharing (EPOS), without hydro



R_{AA} with hydro, using jet-bulk separation via energy loss (one free parameter)



4 Dihadron correlations in PbPb at 2.76 TeV

Dihadron correlation function $R(\Delta\eta,\Delta\phi)$ in PbPb:
Same definition as in experiment (CMS):

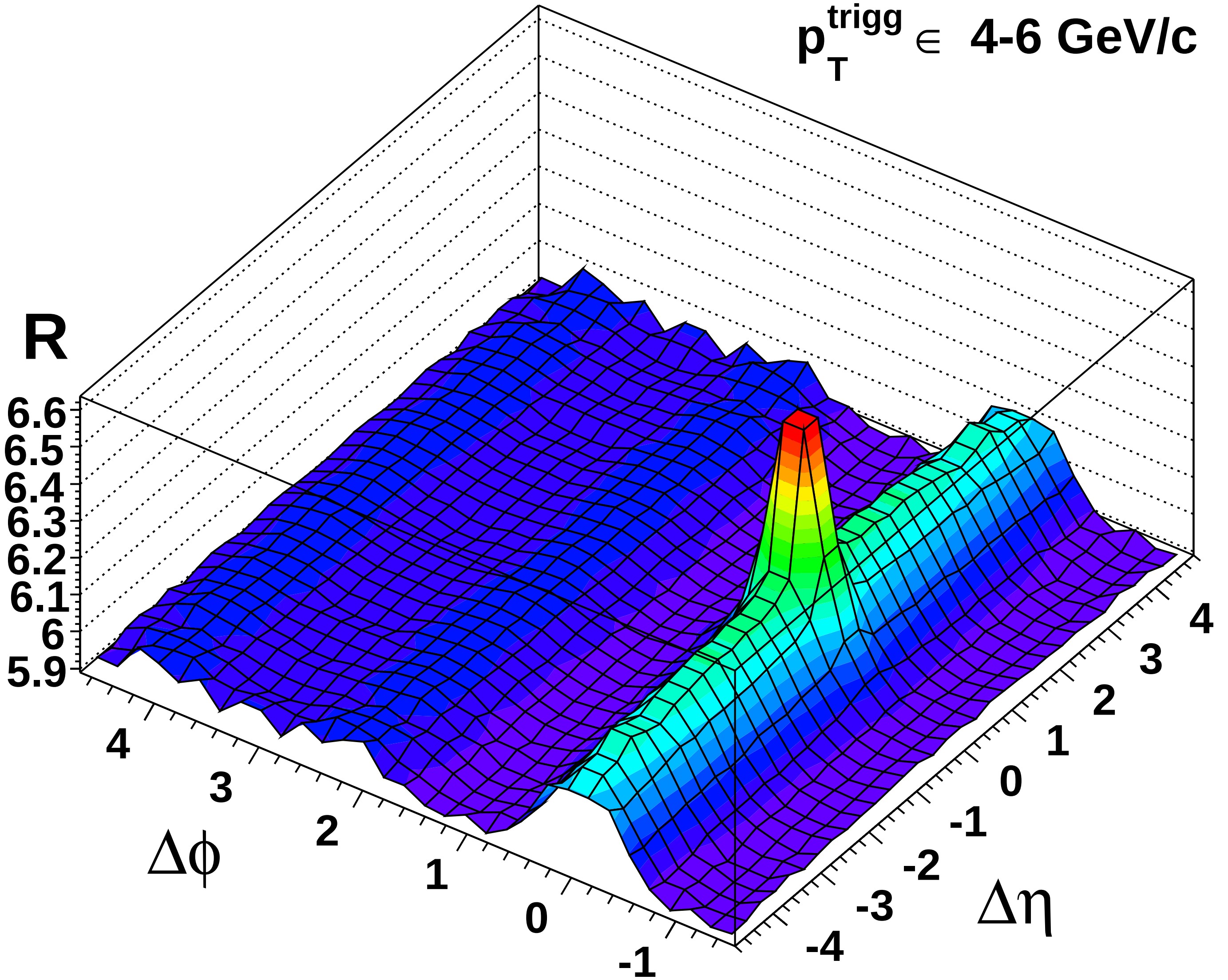
$$R(\Delta\eta,\Delta\phi) = B(0,0) \times \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

$S =$ # of pairs (real events), $B =$ # of pairs (mixed events)

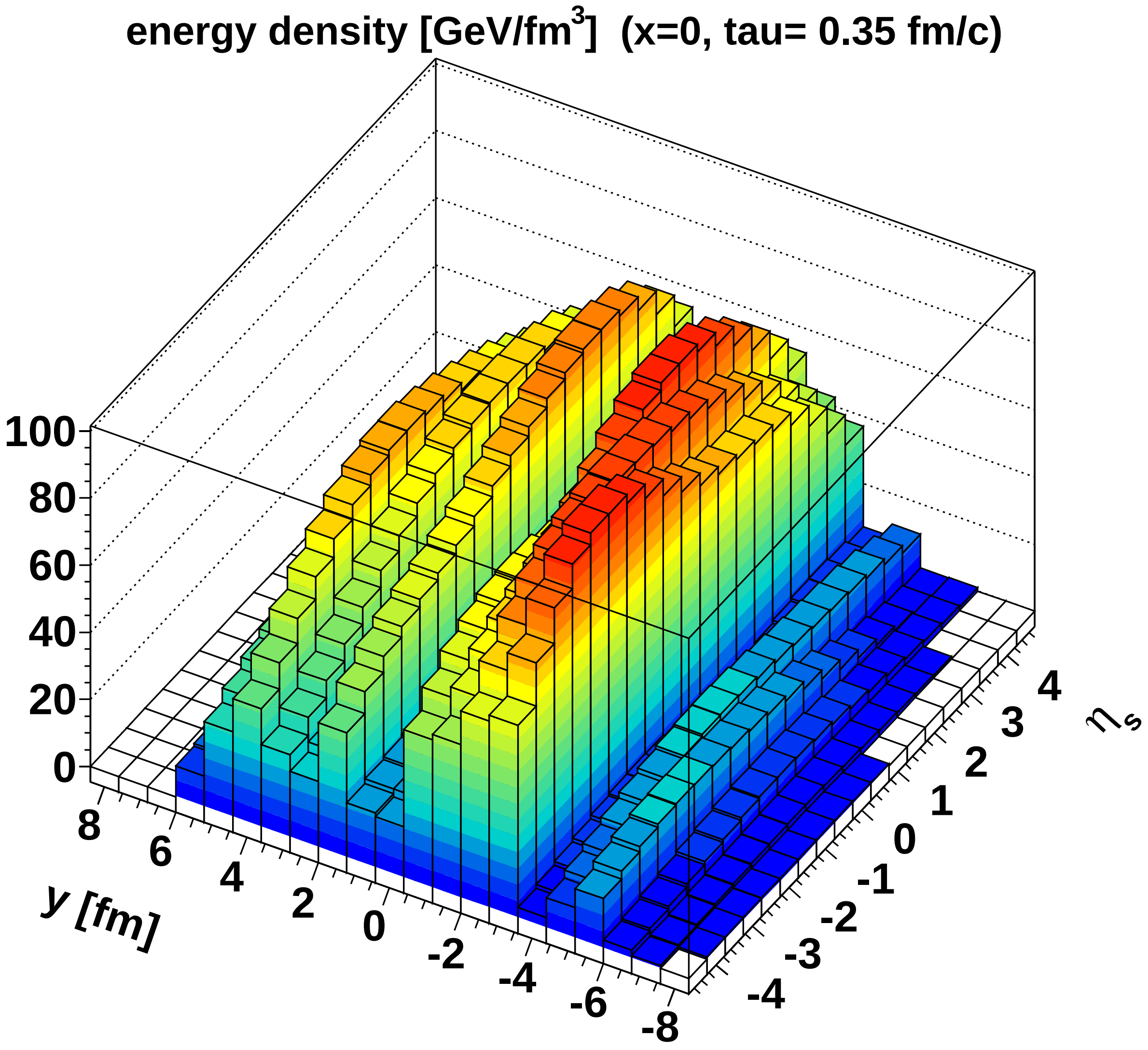
(Yield per trigger)

Calculation: no free parameter any more
after reproducing R_{AA}

Correlation function for $p_t^{assoc} \in 2-4\,\mathrm{GeV/c}$



Not trivial to get the completely flat ridge

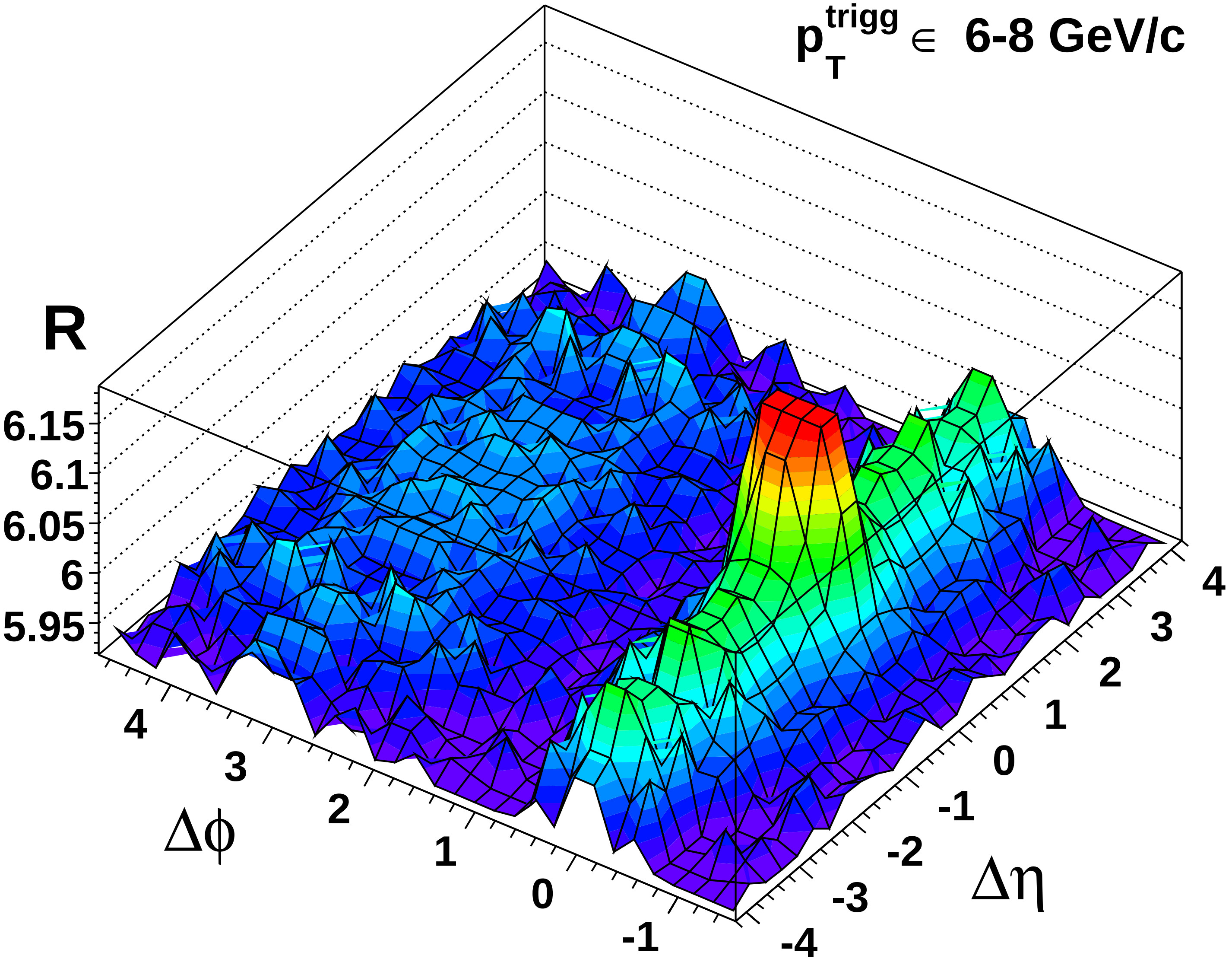


Strings must be treated as continuous objects to get smooth longitudinal structure (see fig)!

Using string fragmentation instead gives bumpy longitudinal structure
=> triangular shape rather than flat ridge

We need strings !!

Ridge still present for large trigger p_t (always $\mathrm{p_t^{assoc}} \in 2-4\,\mathrm{GeV/c}$)



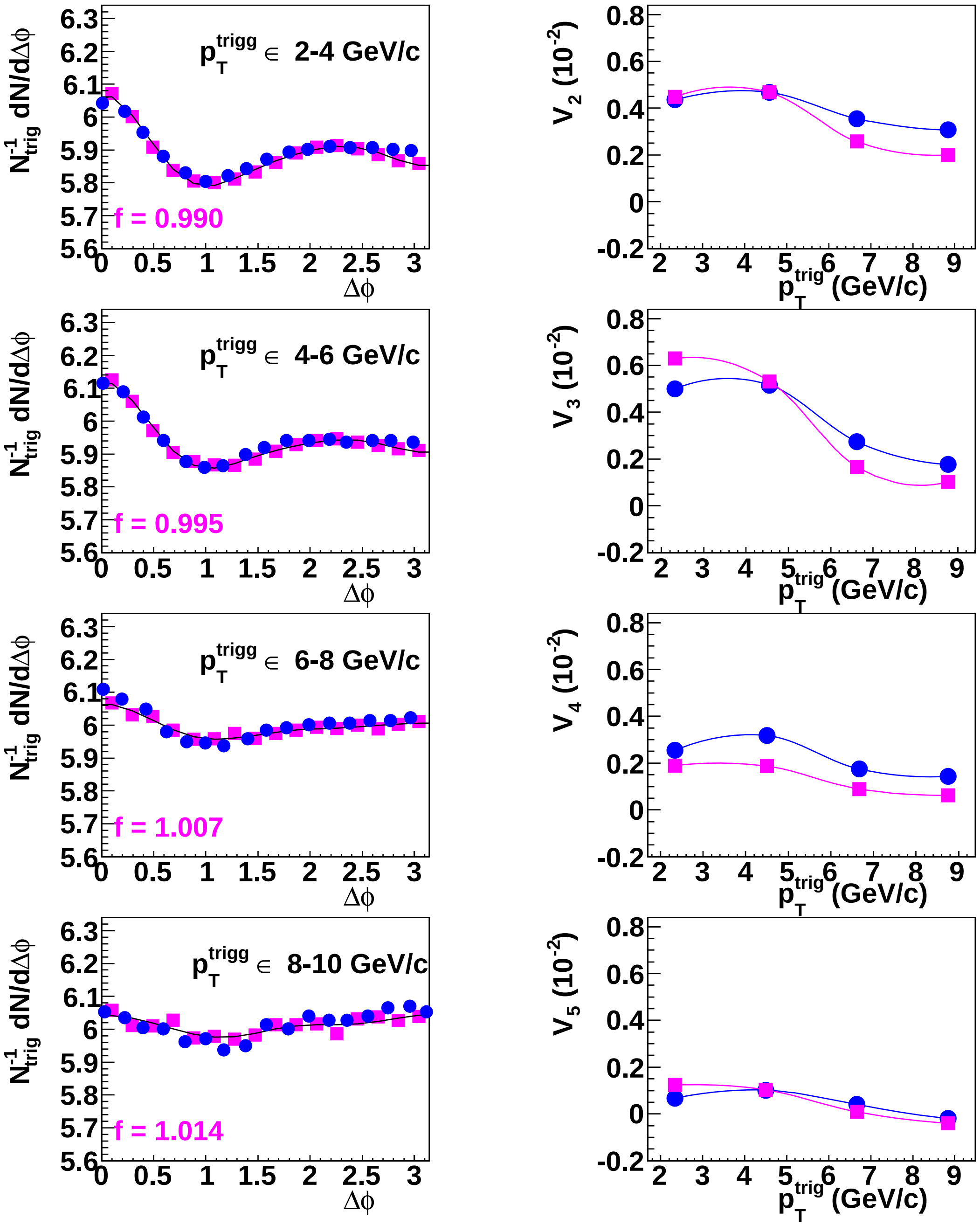
flowing jets ...

Quantitative analysis of the long range correlation:

left:
Integration over $2<|\Delta\eta|<4$
(away from jet)
calculations multipl by factor f

right:
Fourier coefficients
fit $\frac{N}{2\pi}\left\{1+\sum_{n=1}^{5}2V_n\cos(n\Delta\phi)\right\})$
V_2, V_3 dominate
(Alver, Roland 2010)

data: blue circles,
calc: magenta squares



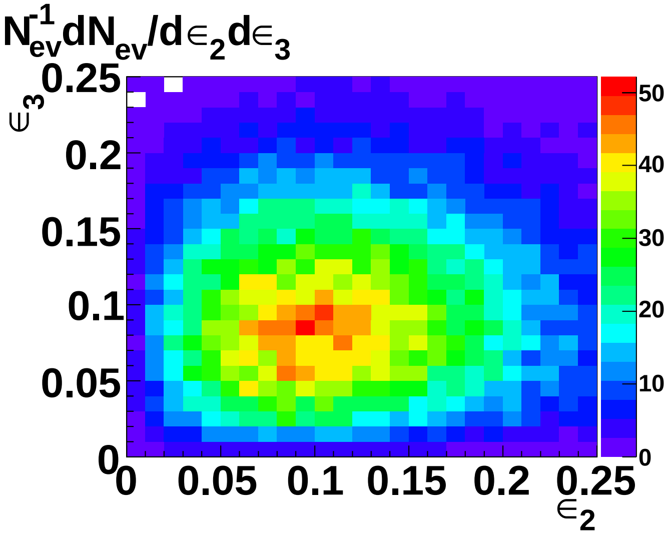
Correlations V_m – eccentricity ϵ_m ?

Eccentricities defined as

$$\epsilon_m e^{im\psi_m} = \frac{\int r^2\, e^{im\phi} \varepsilon\, r dr d\phi dz}{\int r^2\, \varepsilon\, r dr d\phi dz}$$

and harmonic flow coefficients v_m seem to be correlated (for $m = 2, 3$) (Alver,Roland 2010, Qiu, Heinz 2011 ...)

$\epsilon_2 - \epsilon_3$ distribution from our simulations:



To check V_m–$\epsilon_m$correlations, we trigger on events with large ϵ_2 (>0.1) and small ϵ_3 (<0.1)

Results for events
with large ϵ_2 and small ϵ_3

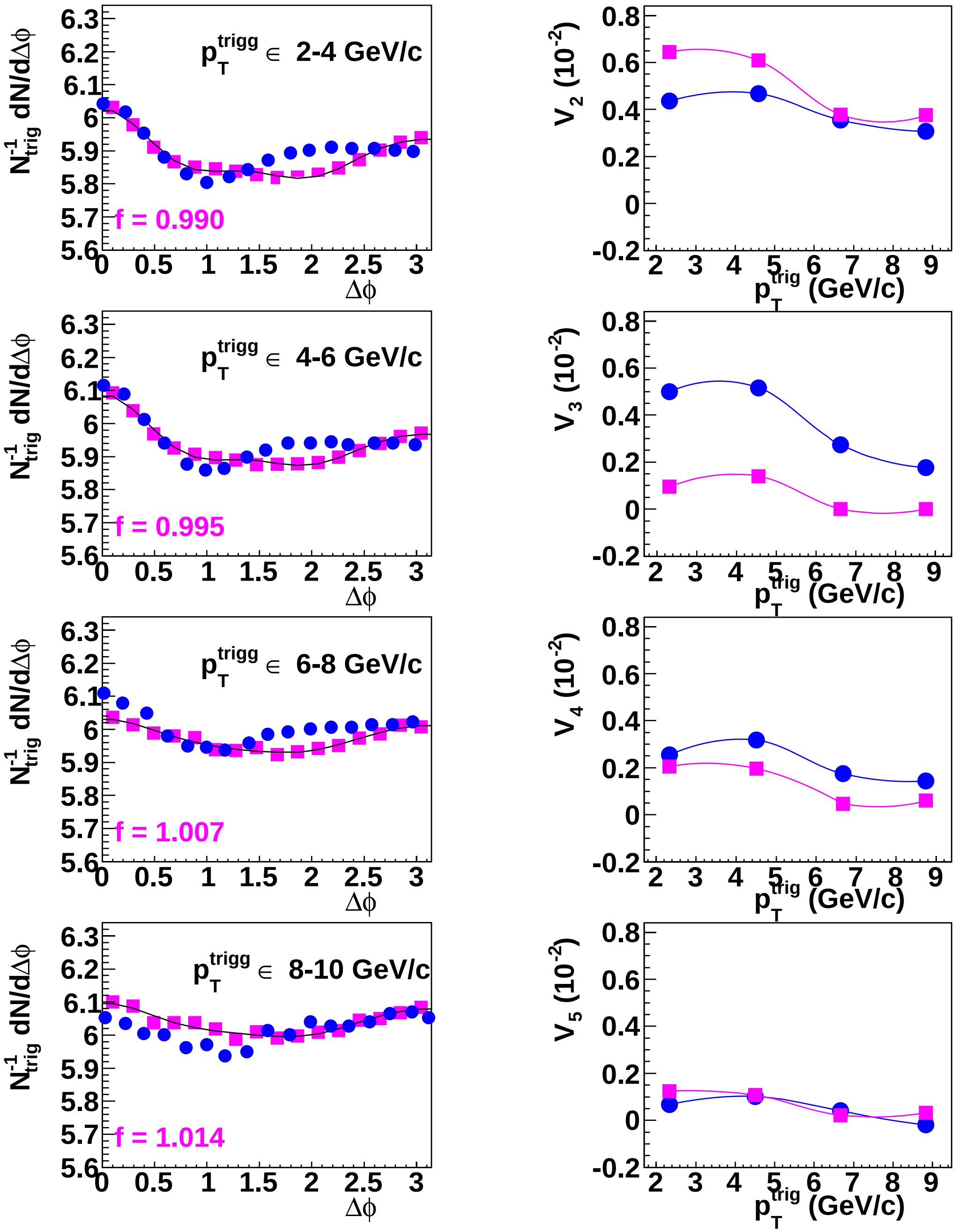
left:
Integration over $2<|\Delta\eta|<4$
(away from jet)

right:
Fourier coefficients

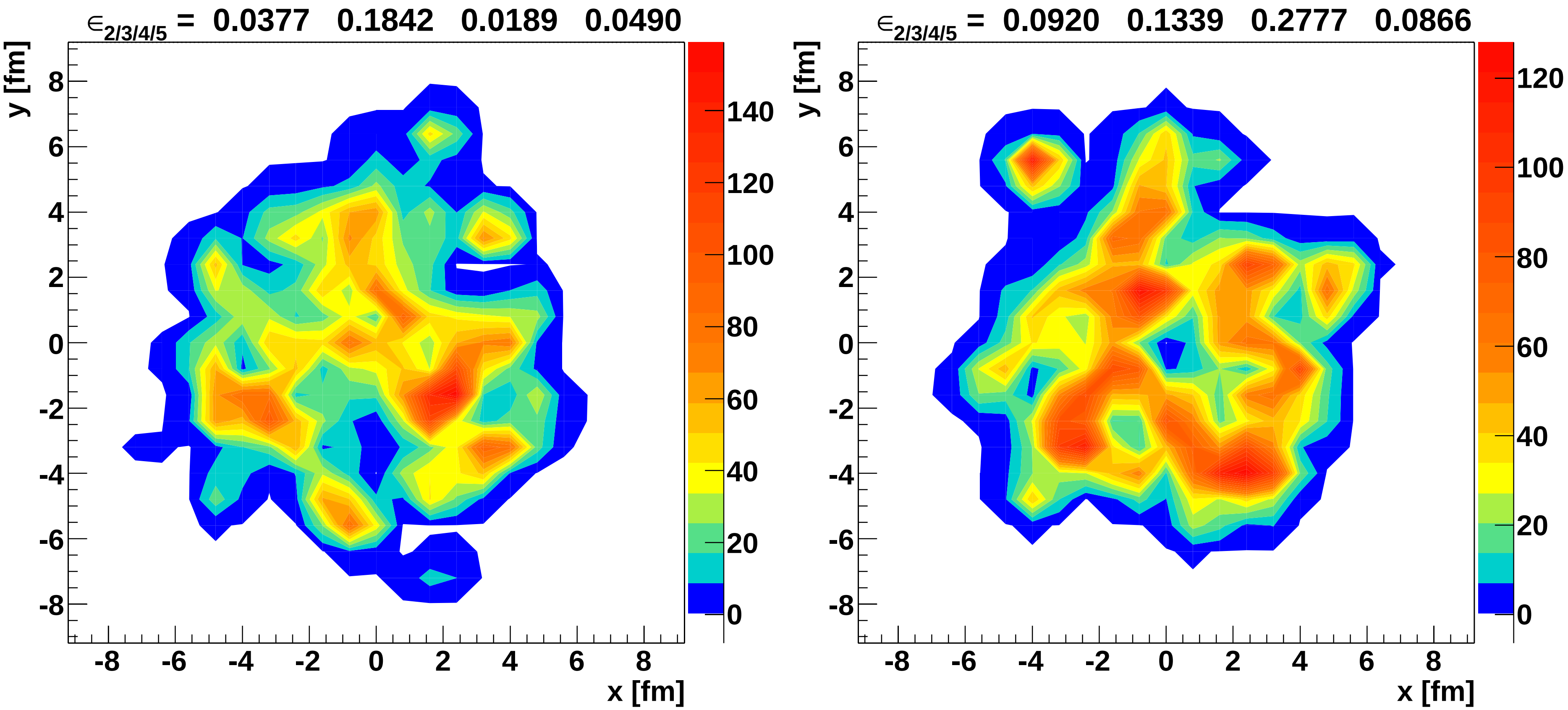
Indeed
V_3 drops (considerably)
V_2 increases (slightly)

large V_3 consequence
of large initial ϵ_3

But: near-side ridge
almost unchanged !



BTW: events with large ϵ_3 and small ϵ_2 do not necessarily look triangular...



The shape of the “hot spots” or better “hot tubes” counts

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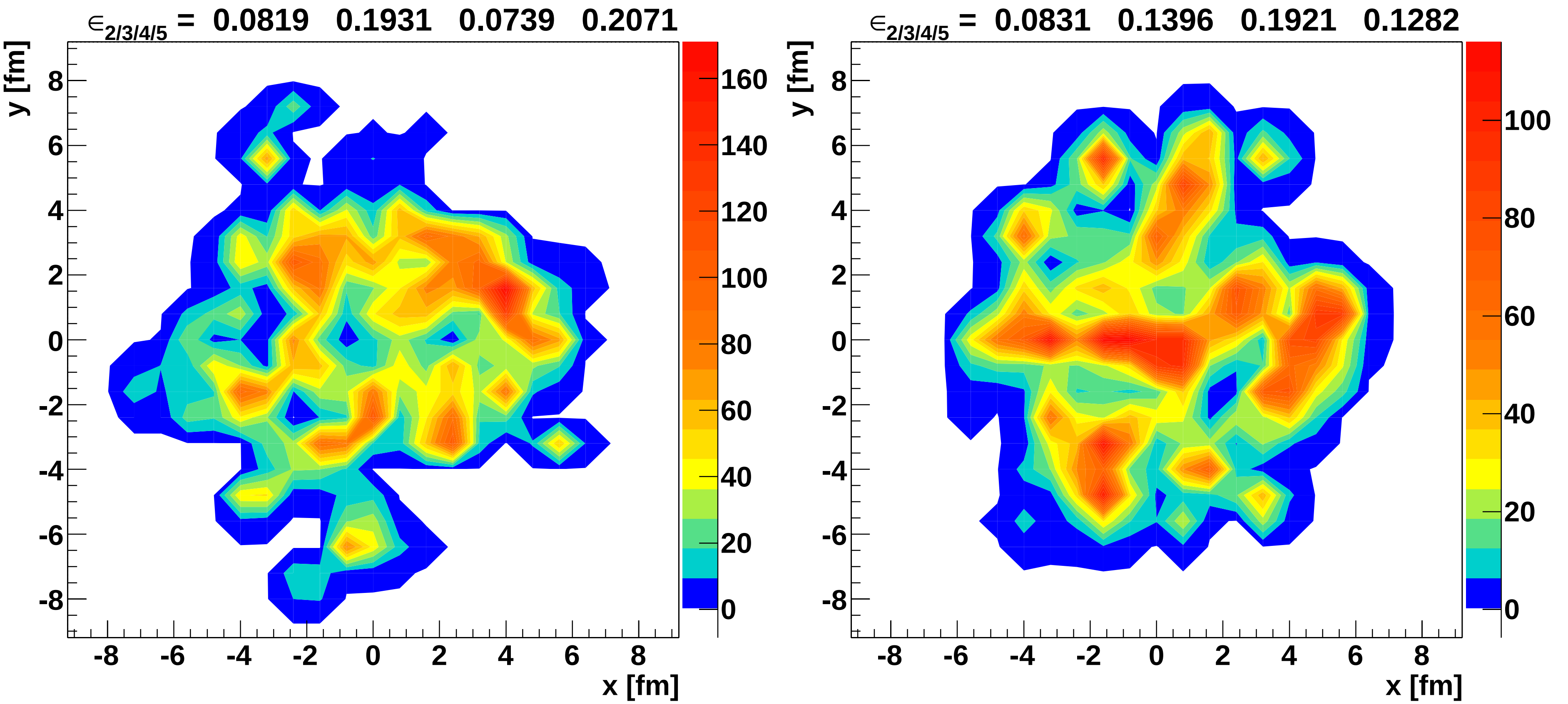
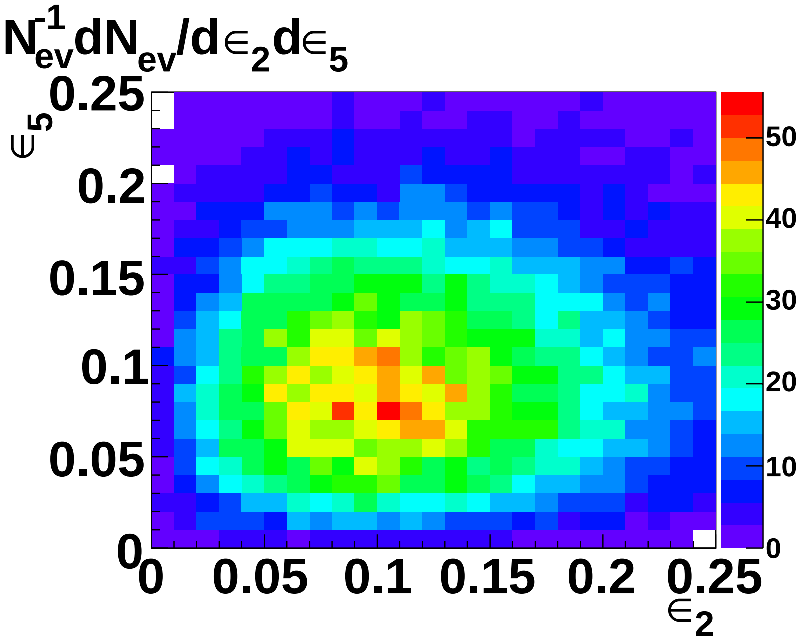


The shape of the “hot spots” or better “hot tubes” counts

Although V_5 is small, we see quite often large ϵ_5!



Distribution confirms: large V_5 is not rare,

but does not shop up as large V_5

Summary

Multiple scattering approach => multiple flux tubes (=> strings)

All flux tubes originate from hard processes (at LHC), the high pt partons manifest themselves as transversely moving string pieces

These strings constitute both “jets” and “bulk matter”

Jet-bulk separation mechanism based on energy loss describes R_AA between 0 and 20 GeV

Jets communicate with the flowing bulk, since the strings breaking close to the fluid surface pick the q-qbar pairs from the fluid instead of employing the Schwinger mechanism

Jet-bulk cross talk visible in dihadron correlations as ridge for high pt triggers (less triangular than low pt)

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