An approach to test the core-corona model in EPOS 3 using multiplicity dependent particle production at LHC energies

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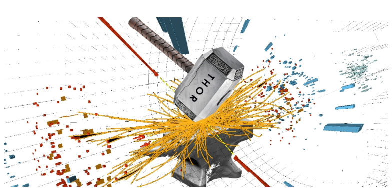


COST Action: CA15213

12 Dec 2017

Outline

- Motivation: collective-like behaviors in pp collisions at the LHC
- Radial flow-like effects in pp collisions at 7 TeV with EPOS 3 [1]
- Core-corona separation in EPOS 3 using transverse spherocity
  - Basic observables used for testing: identified p_T spectra and particle ratios versus charged particle multiplicities
- Power law exponent of p_T spectra versus multiplicity
- Summary

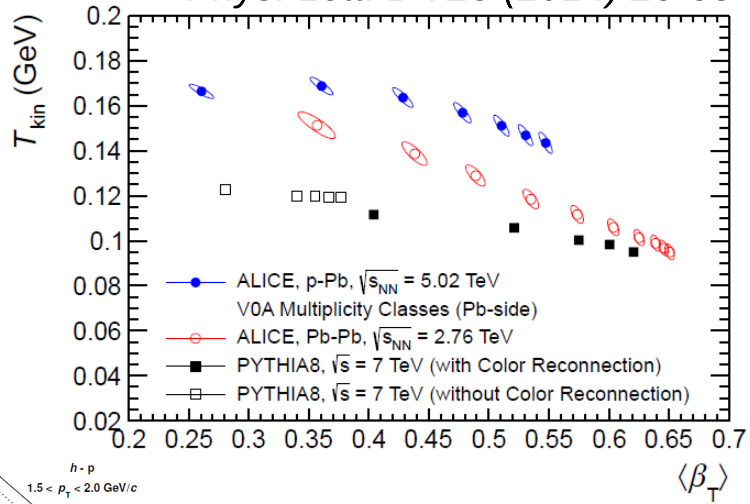
[1] J. Phys. G: **44** (2017) 065001

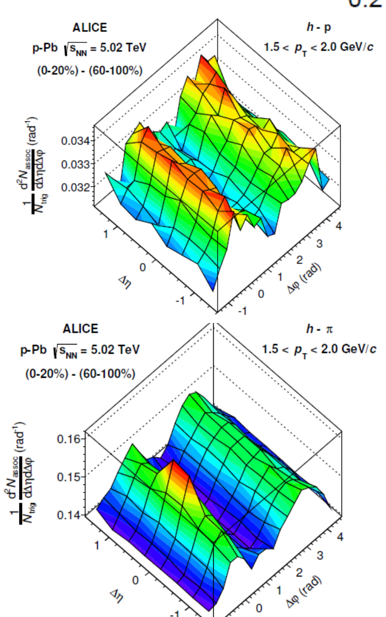
Motivation

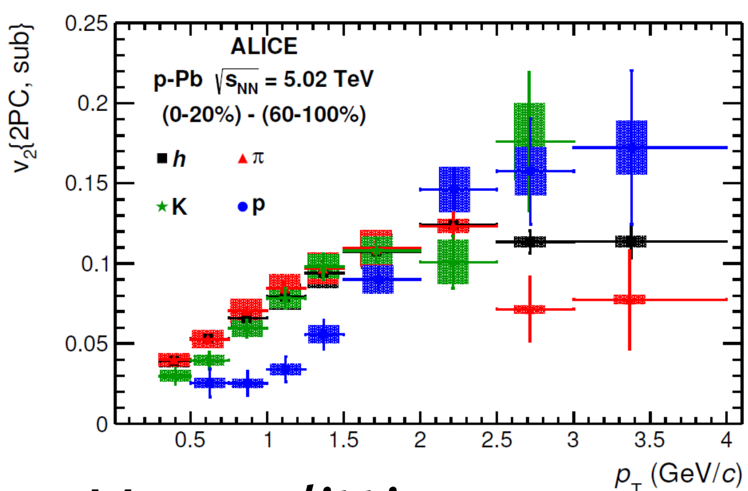
- ***Collective-like effects*** (in high multiplicity events) observed in small collision systems at the CERN LHC: radial fow signals, long-range angular correlations, strangeness enhancement
- No quantitative agreement between data and Monte Carlo models

Blast wave

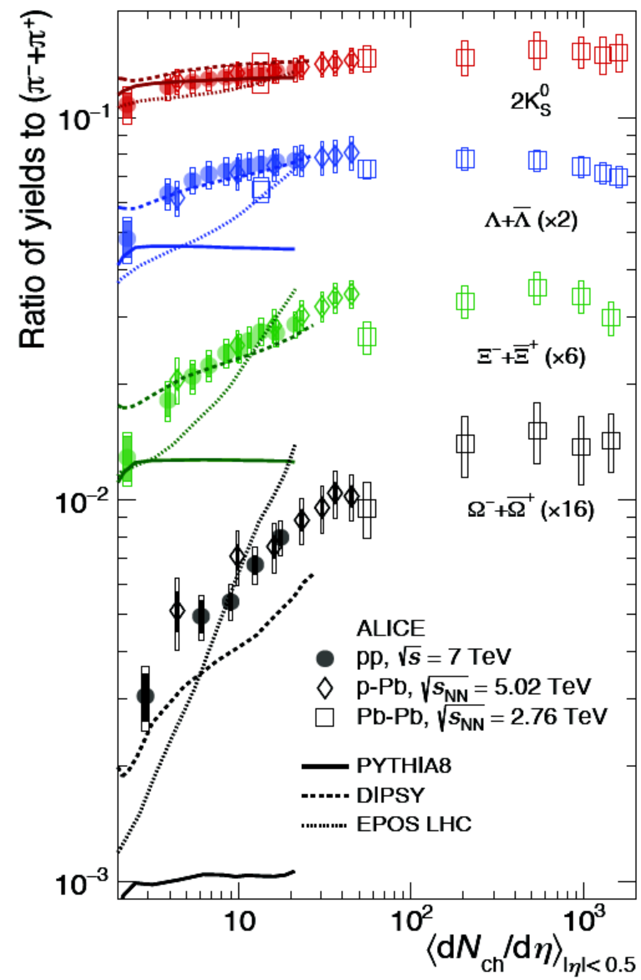
Phys. Lett. B 728 (2014) 25-38







Mass splitting



Strangeness enhancement

Observables and kinematic sets

1) Proton-proton collisions at 13 TeV

2) The *relevant observable* to study the radial flow is the transverse momenta (p_T) of the particles produced in the collisions at mid-rapidity $|y|<1$
   – $1/2\pi p_T \, d^2N/dydp_T$ invariant yield
   – Ratio of yields to pions

3) *Multiplicity selection:* z = dN/deta / <dN/deta> , z=0...1
   – Study observables for different values of z (low and high)

4) *Jet finder: FastJet 3,* selection of samples based on selection of p_T of a leading jet

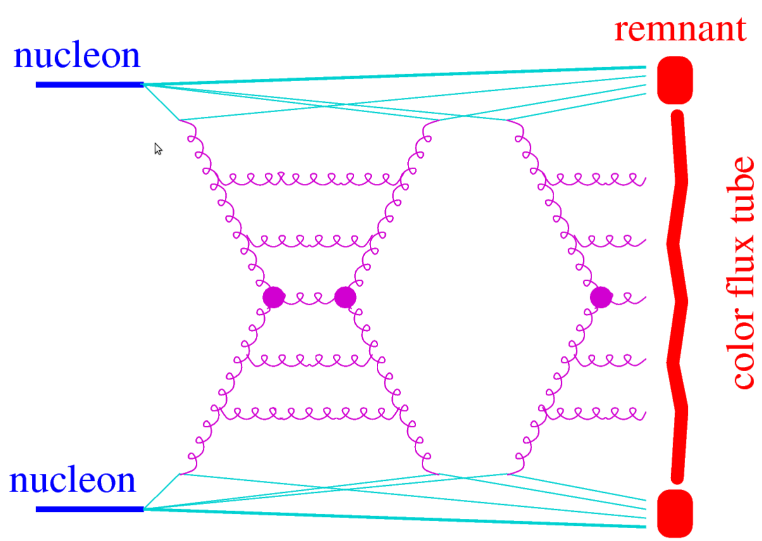
5) **S**pher**o**city: characterization of the event (being sensitive to soft physics)
   So < 0.3 → non-isotropic, So > 0.7 → isotropic

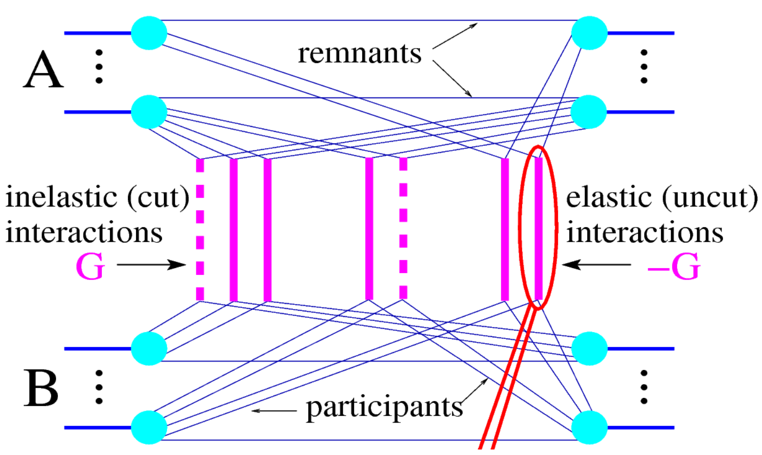
6) Sample: ~100M events (which were subsequently split into z classes)

7) Generator: EPOS 3.117 (hydro); EPOS 3.210 (hydro)

EPOS 3

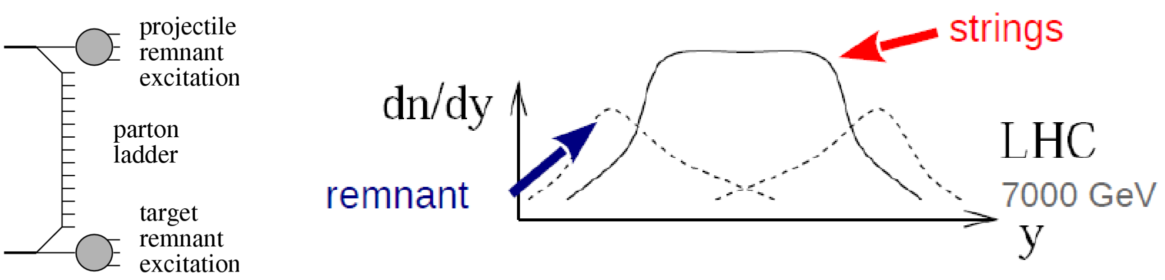
hydrodynamic core hadronisation





1) EPOS is designed to be used for particle physics experiments (SPS,RHIC, LHC) for pp and heavy ions

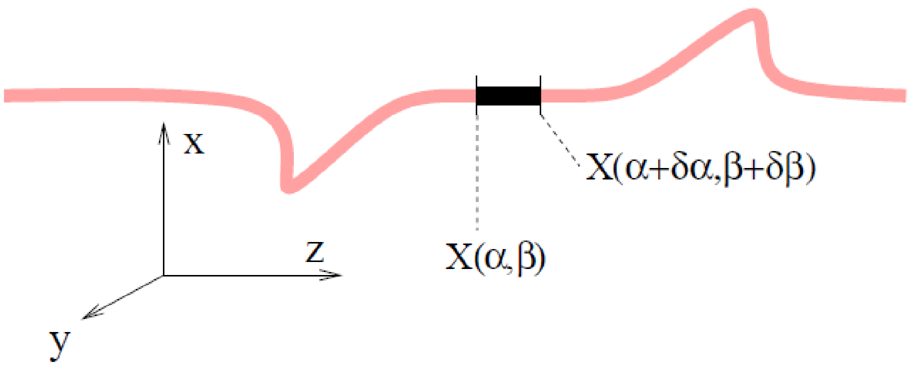
2) EPOS is a parton based (Gribov Regge theory) model where the partons initially undergo multiple scatterings:
   - each scattering is composed of hard elementary scattering with initial and final state linear parton emission forming parton ladder or "pomeron"
   - Parton ladder may be considered as a quasi-longitudinal color field, a so-called "flux tube", conveniently treated as a relativistic string

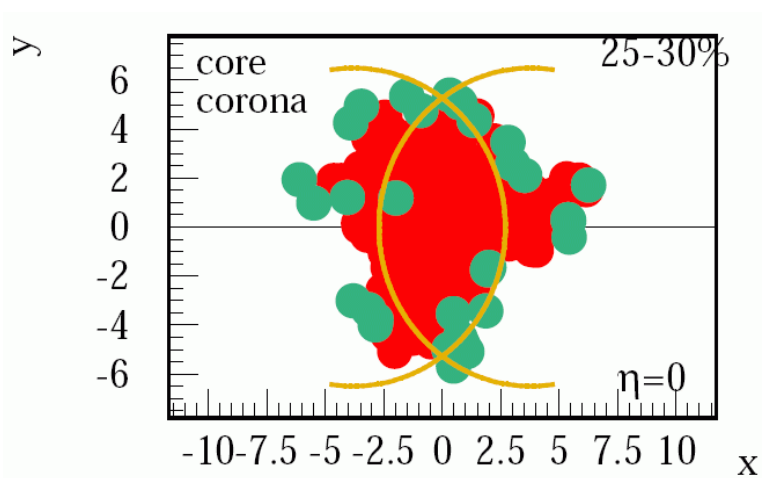


EPOS 3 basically contains a *hydrodynamical approach* based on flux tube initial conditions

This *flux tube* decays via the production of quark-antiquark pairs, creating in this way fragments which are identified with hadrons

EPOS 3
hydrodynamic core hadronisation





String hadronisation

- based on the local density of string segments per unit volume with respect to a critical-density parameter
- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- Each string is classified as being in either
  - a **low density coronal** region
  - or in a **high density core** region
- ***Corona*** hadronisation: via unmodified string fragmentation
- ***Core*** is subjected to a *hydrodynamic evolution*; i.e. it is hadronised including additional contributions from longitudinal and radial flow effects

Average pp collision (N_{ch}=30,|η|<2.4) at $\sqrt{s}$=7TeV, ~30 % of central particle production arises from the core region. This rises to 75 % for N_{ch}=100

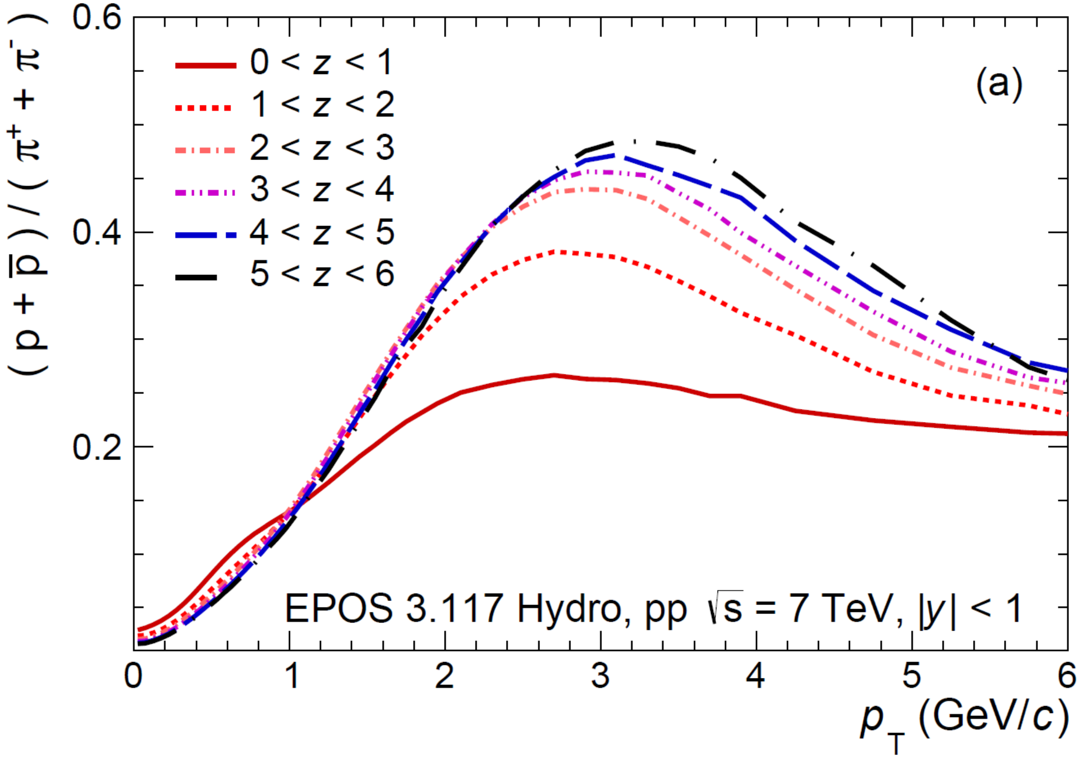
Radial flow-like effects in pp collisions at 7 TeV with EPOS 3

J. Phys. G ***44*** *(2017) 065001*

- ***Study how jets modify the low-p_T region***
  - Analyze mid-rapidity inclusive identified charged-hadron production as a function of $N_{ch,|y|<1}$ and $p_{T,jet}$ of the jet found within the same acceptance
  - Proton-to-pion ratio versus charged particle multiplicity and hardness of the event

EPOS 3 – testing flow observable: p/pi ratio

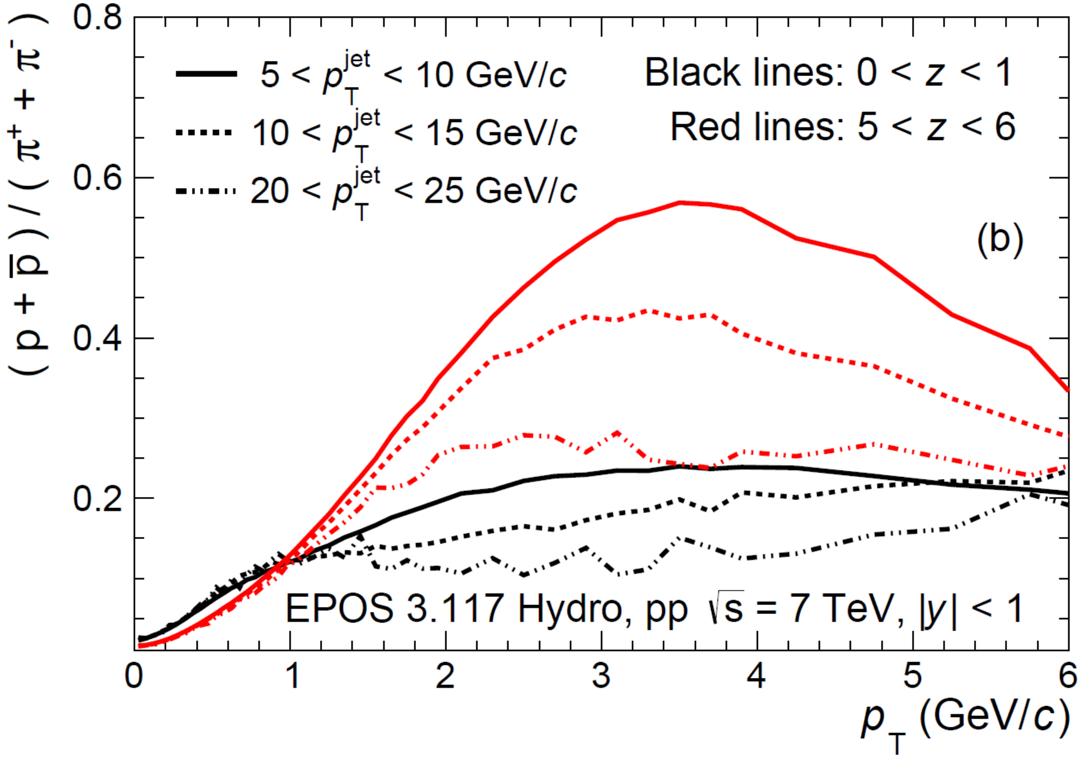
Results are shown for different multiplicity event classes in *z*



$\left\langle \frac{dN_{ch}}{d\eta} \right\rangle_{\lvert\eta\rvert<1}$	$\frac{d N_{ch}/d\eta}{\langle d N_{ch}/d\eta\rangle_{\lvert\eta\rvert<1}}$ $(\equiv z)$
2.12	$0 < z < 1$
8.12	$1 < z < 2$
13.6	$2 < z < 3$
19.0	$3 < z < 4$
24.4	$4 < z < 5$
29.8	$5 < z < 6$
35.2	$6 < z < 7$
40.6	$7 < z < 8$
46.1	$8 < z < 9$

- Depletion (increase) for p_T < 1 GeV/*c* (1 < p_T < 6 GeV/*c*)
- It can be attributed to radial flow (which modifies the spectral shape of the p_T distributions, depending on the hadron masses)

Proton-to-pion ratio versus multiplicity and $p_{T,jet}$



Low-z case:

- *EPOS shows weak or no response to the presence of jets*

High-z case:

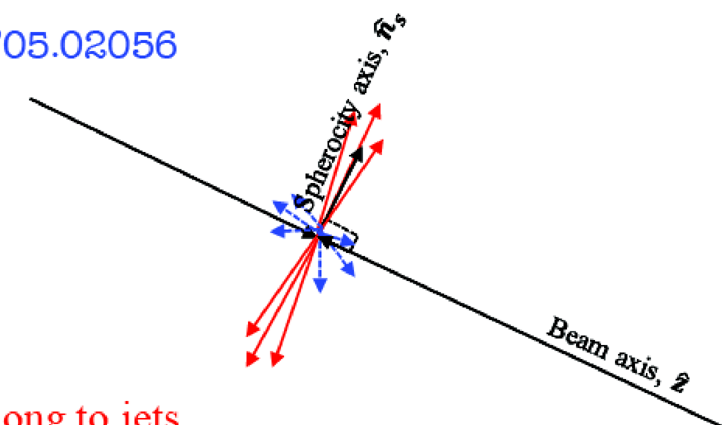
- Enhancement w.r.t. inlcusive case (w/o selection on $p_{T,jet}$)
- Higher $p_{T,jet}$: peak shifted to lower p_T → size of peak smaller than inclusive
- Difference between event classes can be attributed to difference between hadro-chemistry of "jet" and "bulk"

Study of core-corona separation (at low p_T)

Isolation of core-corona separation using transverse spherocity

- ***Transverse pherocity:***
  - Expectation: Spherocity might allow to enhance/suppress the core and corona contribution in EPOS → needs to be tested
  - So < 0.3 → non-isotropic (“jetty”-like) , So > 0.7 → isotropic

arXiv:1705.02056



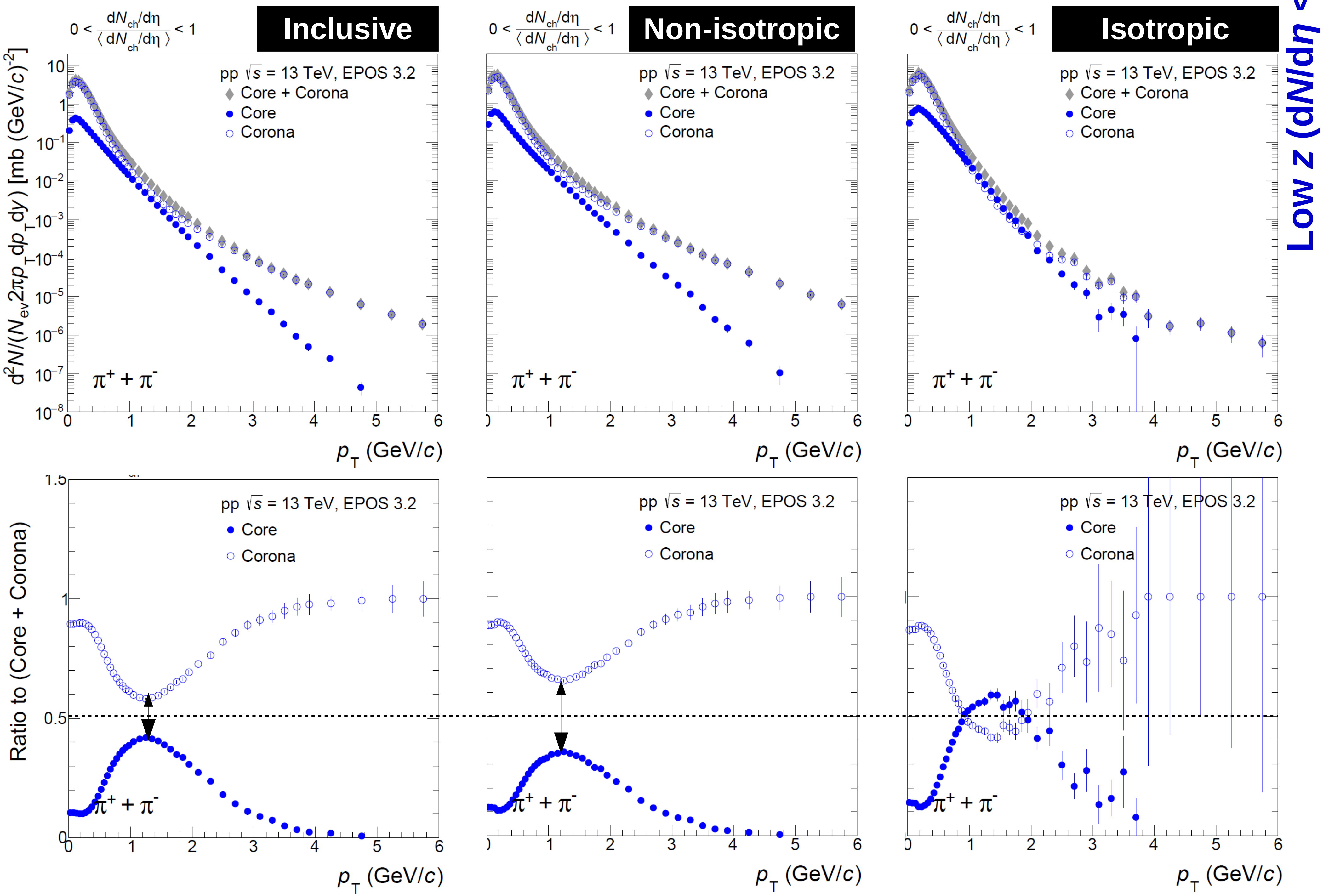
p_T's belong to jets
p_T's belong to UE

By definition, transverse spherocity is sensitive to soft physics

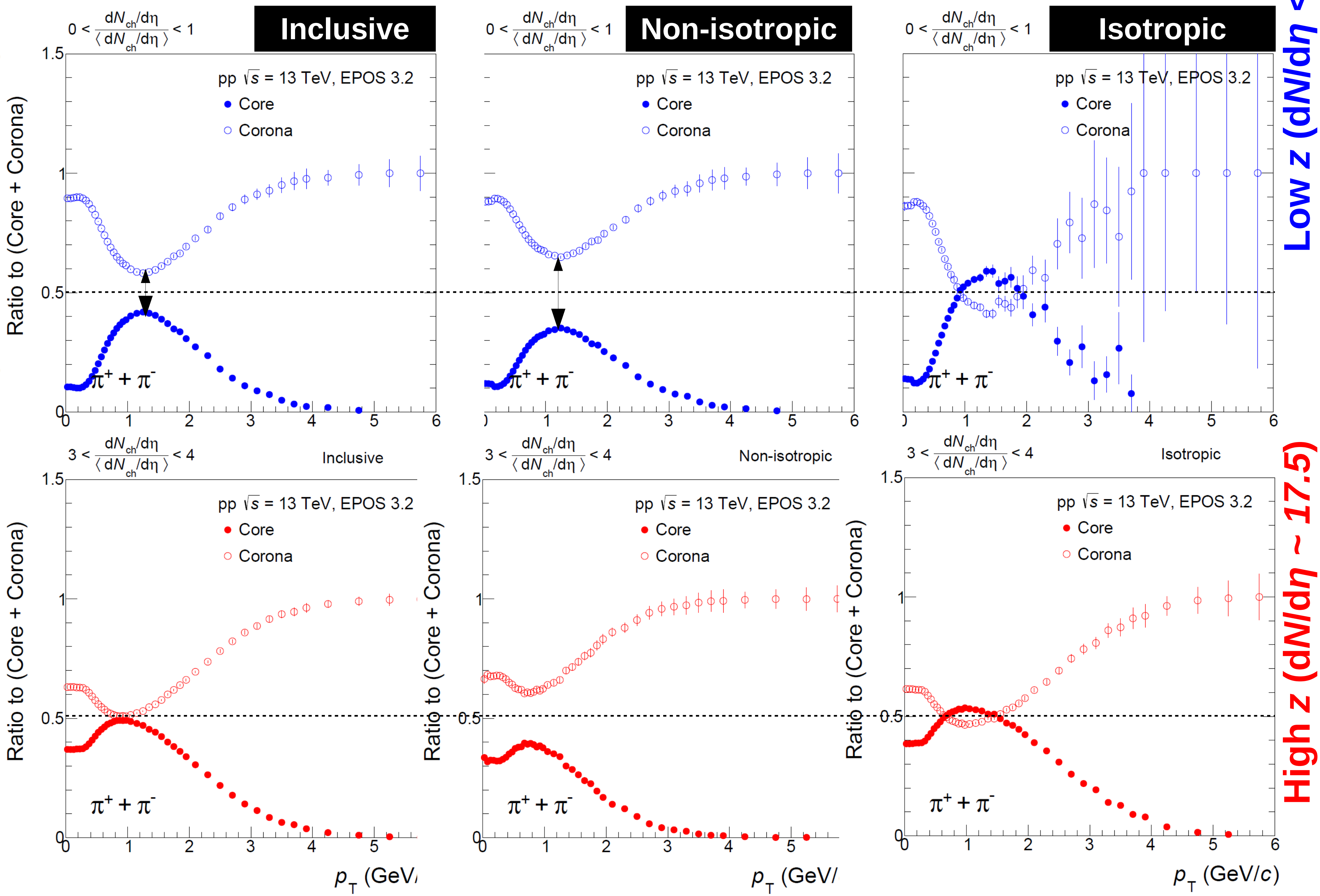
$$S_0 \equiv \frac{\pi^2}{4} \min_{\hat{\boldsymbol{n}}_s} \left(\frac{\sum_i^{N_{\rm ch}} |\vec{p}_{{\rm T},i} \times \hat{\boldsymbol{n}}_s|}{\sum_i^{N_{\rm ch}} p_{{\rm T},i}} \right)^2$$

(events with more than 2 charged particles within $|\eta|<0.8$ and $p_T>0.15$ GeV/c)

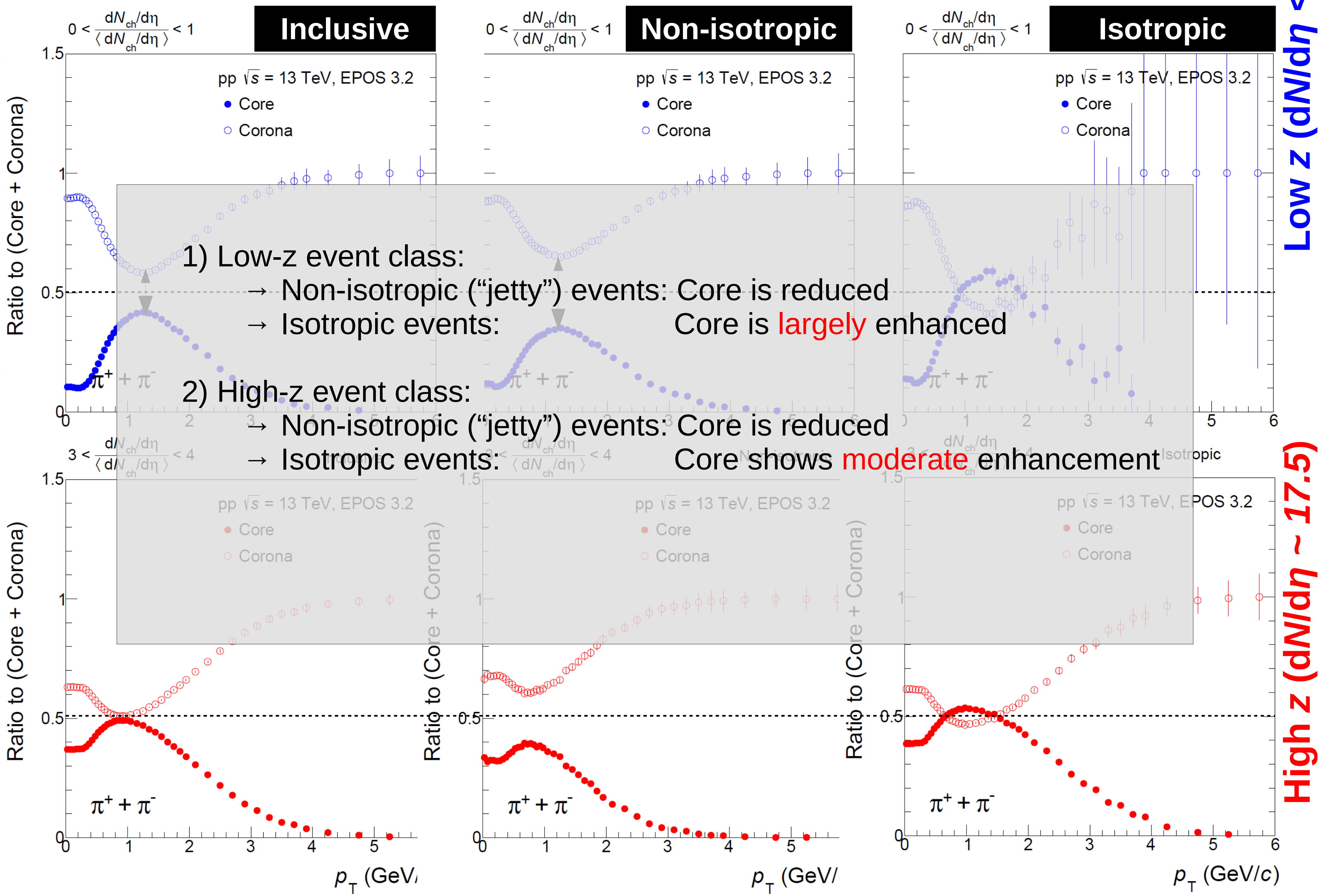
p_T spectra vs N_{ch} vs Spherocity vs Core-corona



p_T spectra vs N_{ch} vs Spherocity vs Core-corona



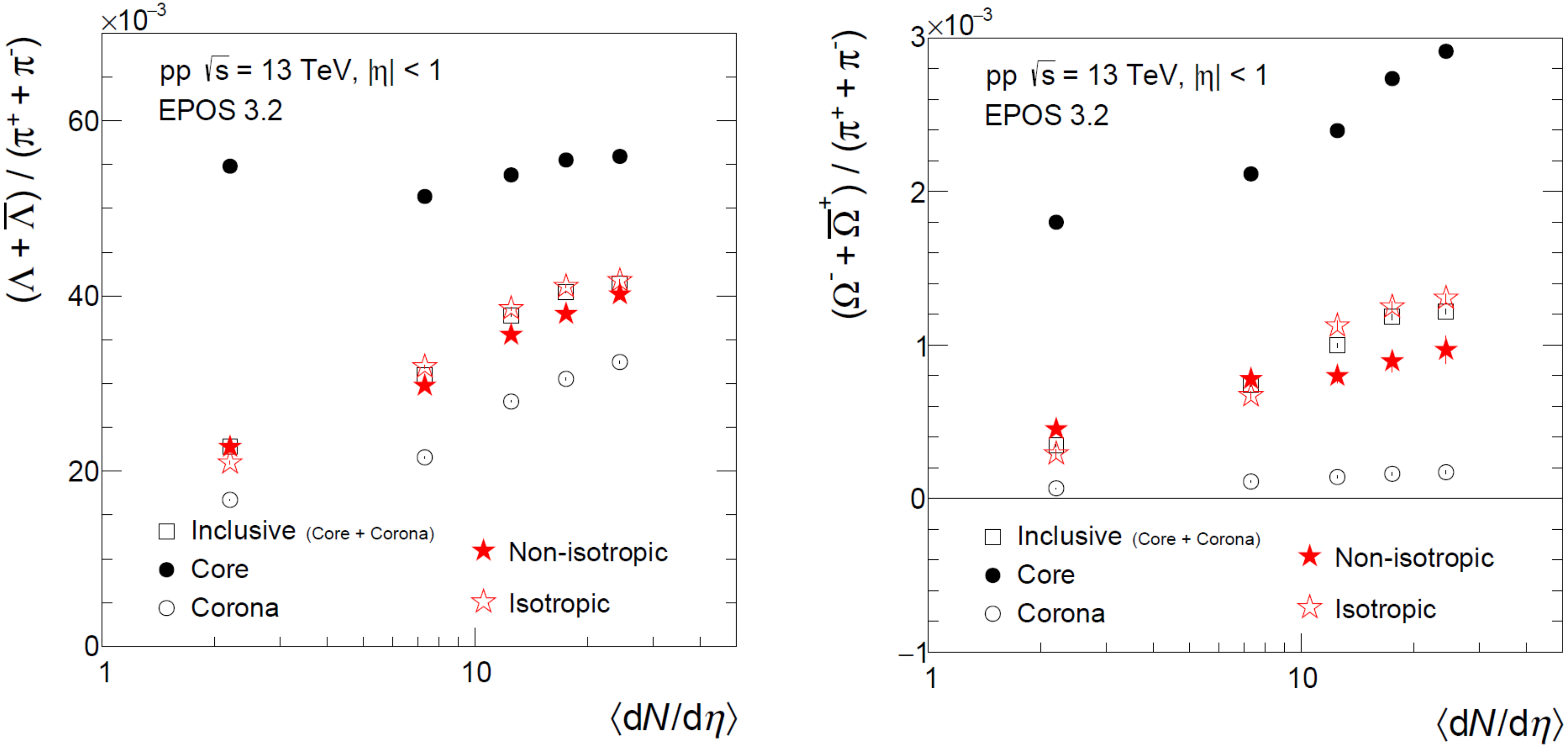
p_T spectra vs N_{ch} vs Spherocity vs Core-corona



1) Low-z event class:
→ Non-isotropic ("jetty") events: Core is reduced
→ Isotropic events: Core is largely enhanced

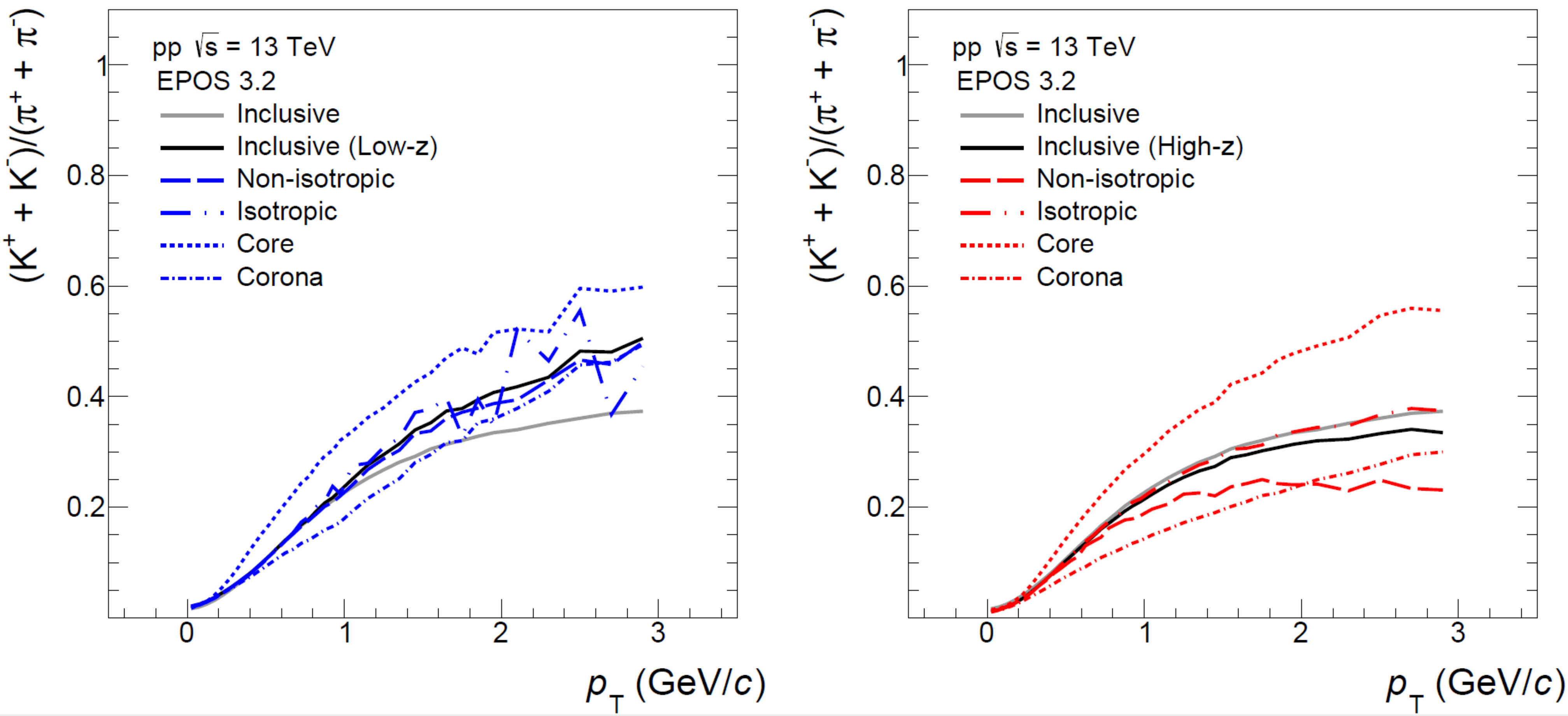
2) High-z event class:
→ Non-isotropic ("jetty") events: Core is reduced
→ Isotropic events: Core shows moderate enhancement

Yield ratios to pions versus N_{ch} – core-corona



- For high-z (dN/dη> 10) sizeable separation seen between non-isotropic and isotropic events
- "Jetty" events tend to be closer to those of corona, and isotropic events approach the core
- Effect is ~ 30% for Omega to pion ratio (right panel)

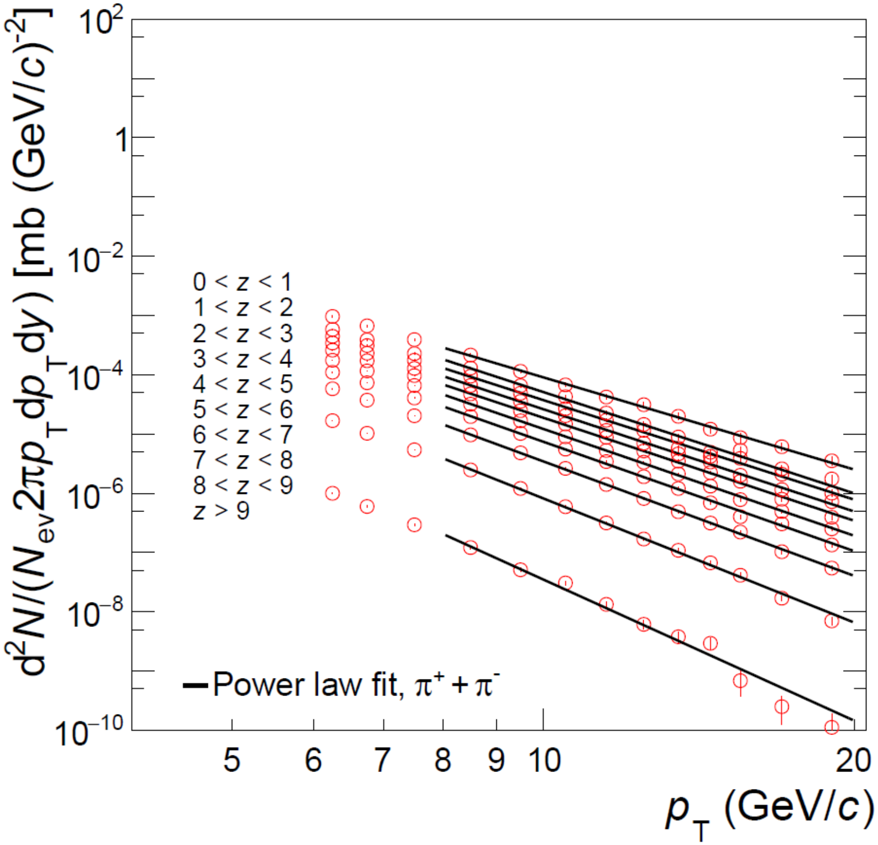
Particle ratios versus N_{ch} – core-corona

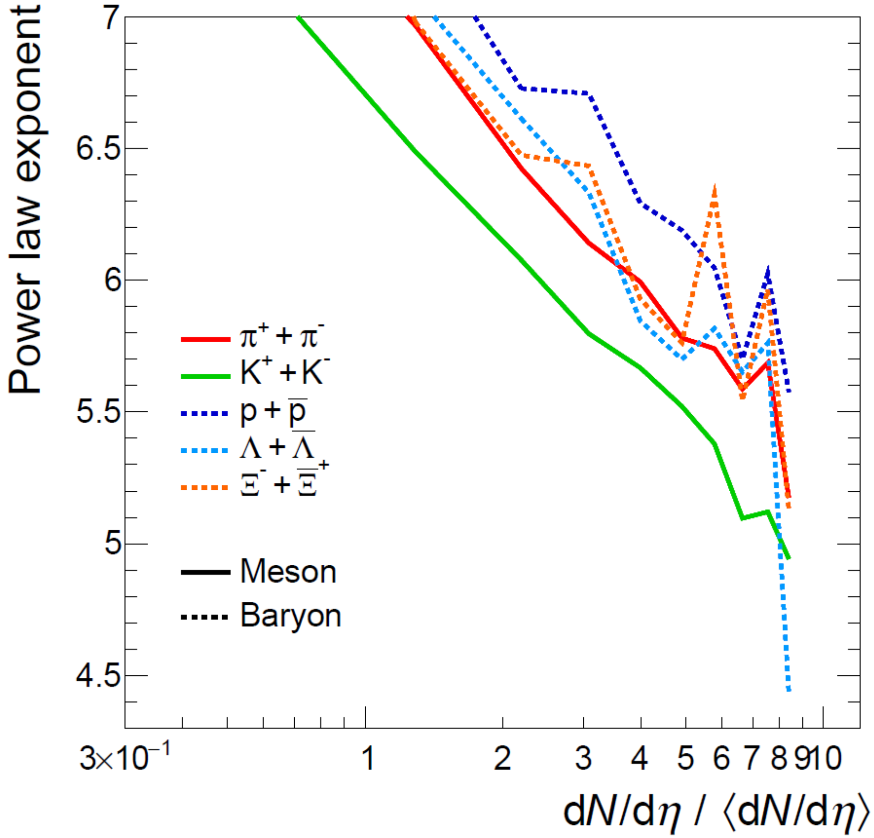


- Low-z events:
  - Spherocity selection show no sizeable deviation from inclusive case
  - Core and corona behave as seen in data (jet-bulk hadrochemistry): jets have reduced ratio
- High-z events:
  - Curve for corona is found near the region of that of “jetty”

Study of particle production at high p_T

Power law exponent versus multiplicity

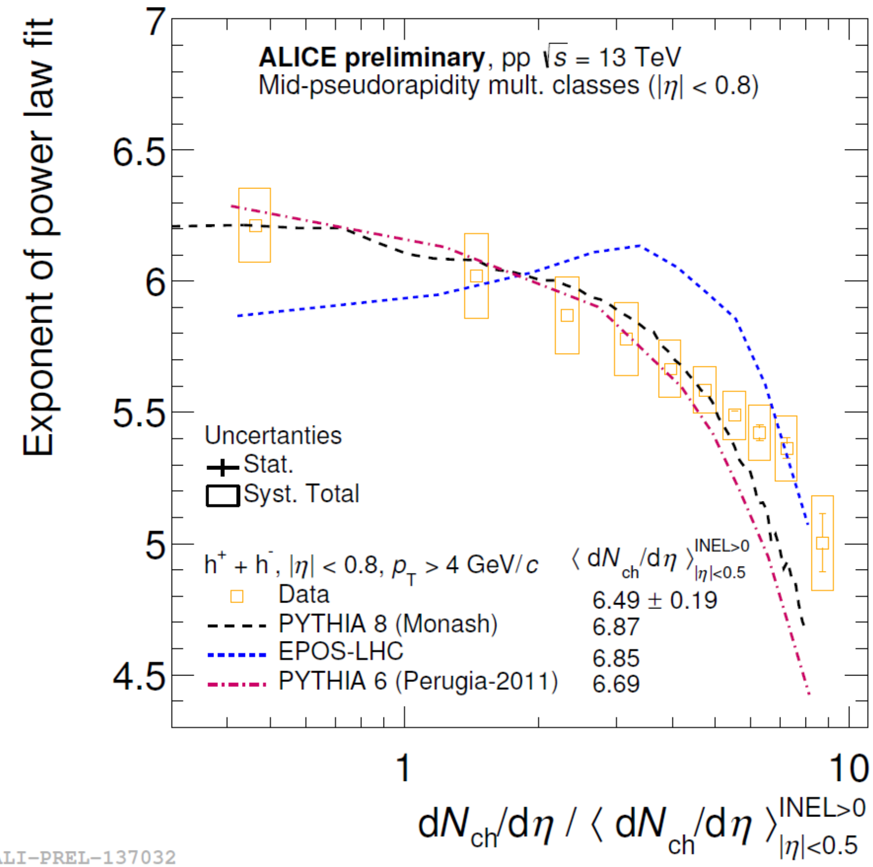


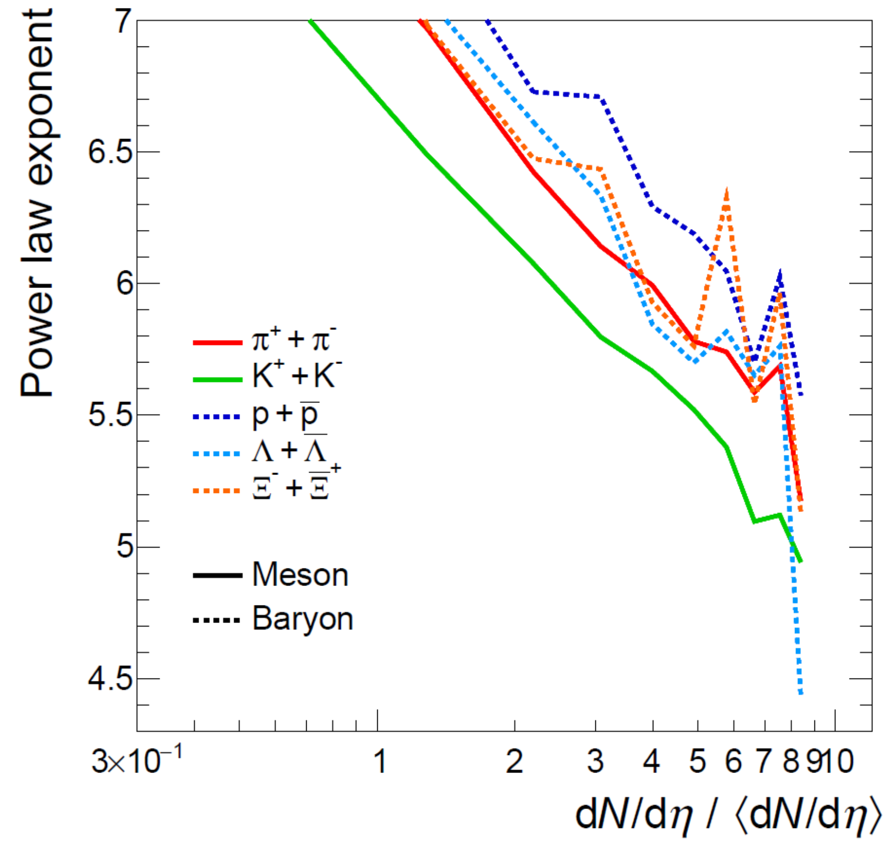


- **Inlcusive** p_T spectra for different particle species were fit with power law for p_T > 8 GeV/*c*, i.e. in the p_T region where the corona component dominates
- Power law exponent was extracted as a funtion of multiplicity

Power law exponent – pp 13 TeV

Ref. [1]





- At low multiplicity EPOS 3 shows continuously decreasing trend
- At high multiplicity EPOS 3 and EPOS-LHC indicate same behavior
- Clear separation is seen with the mass for different particle species

[1] Figure taken from Sergio I. (on behalf of ALICE Coll.), Initial Stages 2017

Summary

- We performed a double differential analysis to study identified particle production in EPOS 3
- We found that radial flow-like effects are present even in sub-class of events at low-multiplicity when we impose a selection on the hard scale in the event
- We found a tool which enables us to control core and corona separation using spherocity and it was successfully tested on bulk observables as a function of charged particle multiplicity

Backup slides

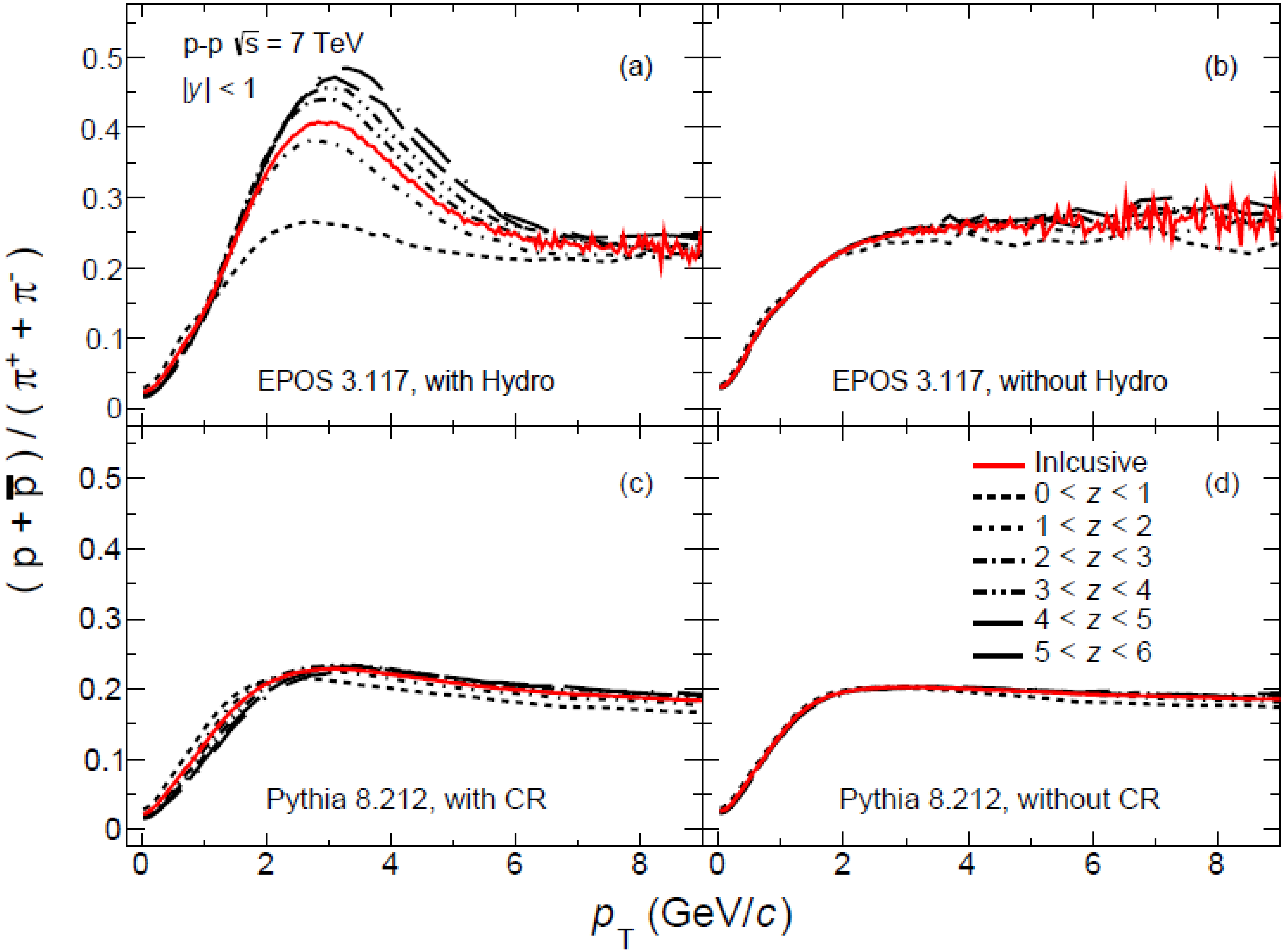


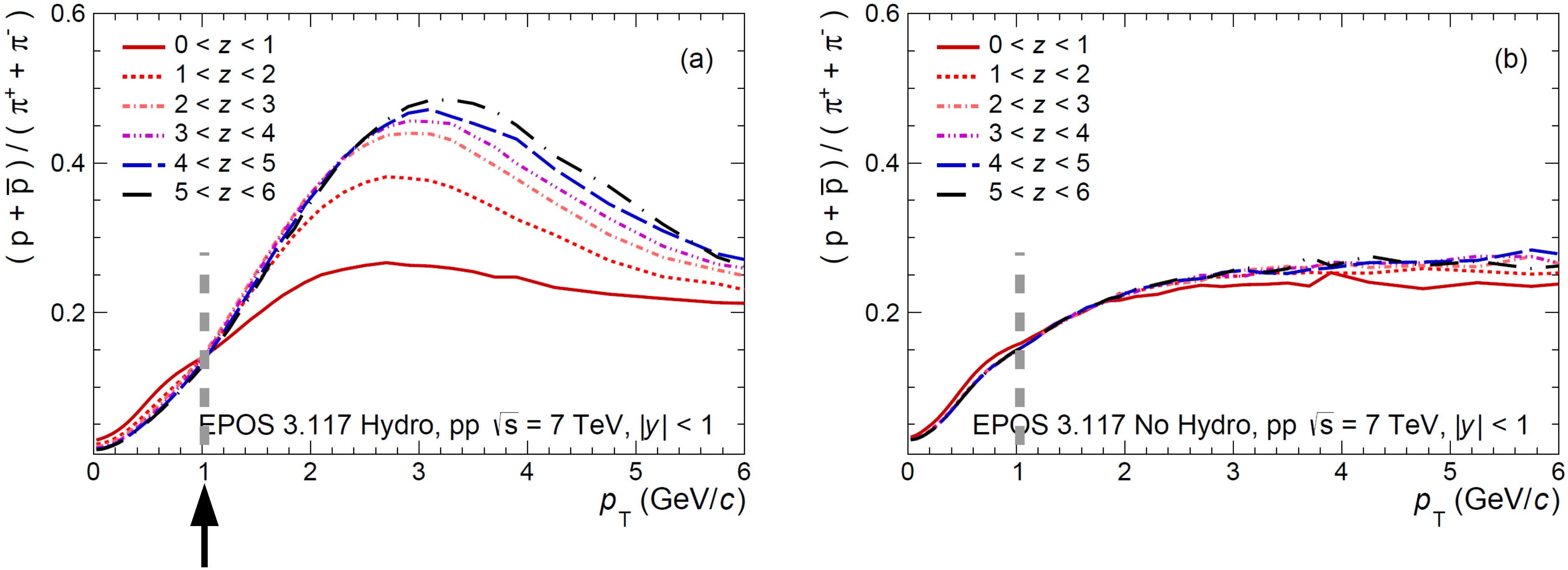
Figure 2: (Color online) Proton-to-pion ratio as a function of p_T for different multiplicity event classes. Results for pp collisions at $\sqrt{s} = 7$ TeV generated with EPOS 3 and PYTHIA 8 are presented. For PYTHIA 8 (EPOS 3) the ratios are displayed for simulations with and without color reconnection (hydrodynamical evolution of the system).

EPOS 3 – testing flow observable: p/pi ratio

Results are shown

– for different multiplicity event classes in *z*

– for cases w/ and w/o hydro options

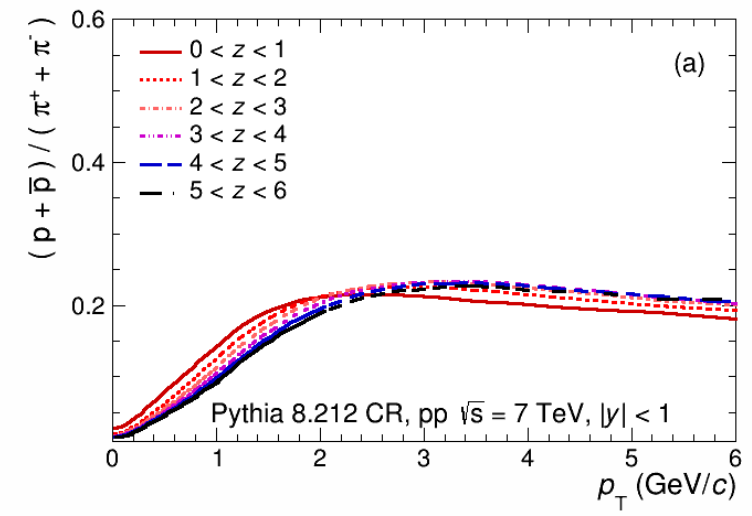


Depletion (increase) for p_T < 1 GeV/*c* (1 < p_T < 6 GeV/*c*)

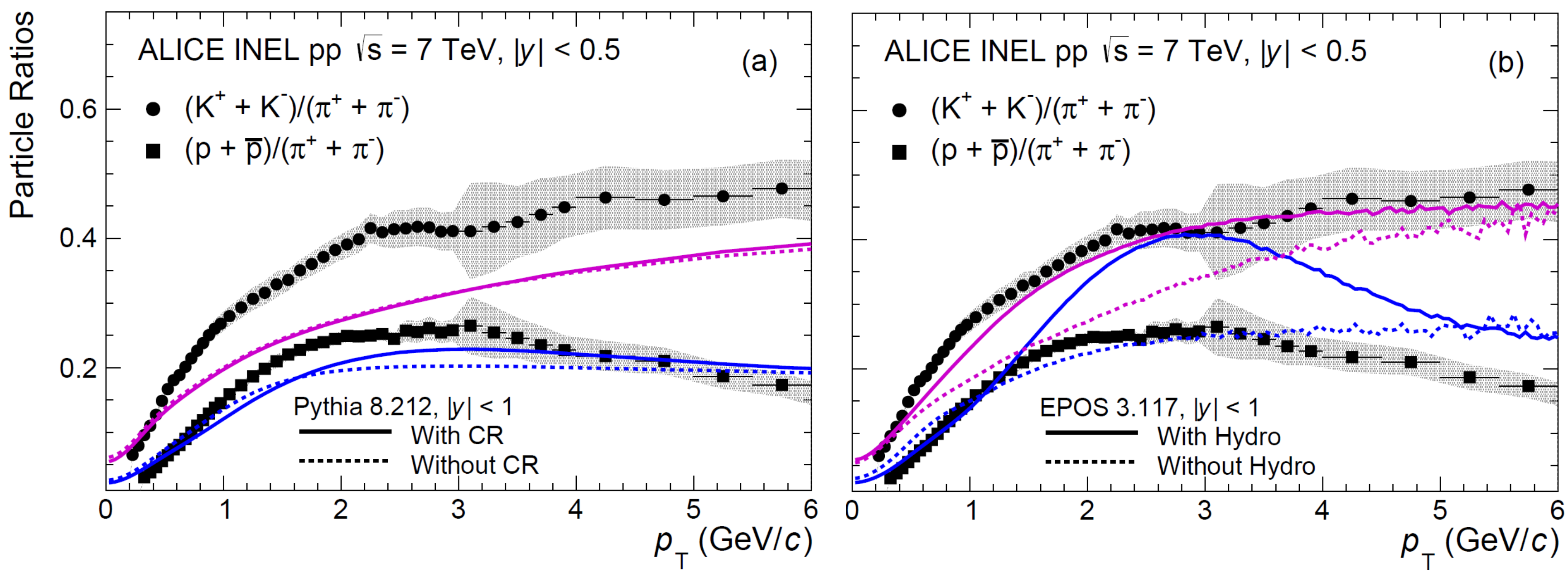
→ can be attributed to radial flow (which modifies the spectral shape of the p_T distributions, depending on the hadron masses)

*Without hydro*dinamical component *no modification* observed as a function of *z*

Pythia 8 – testing description of data

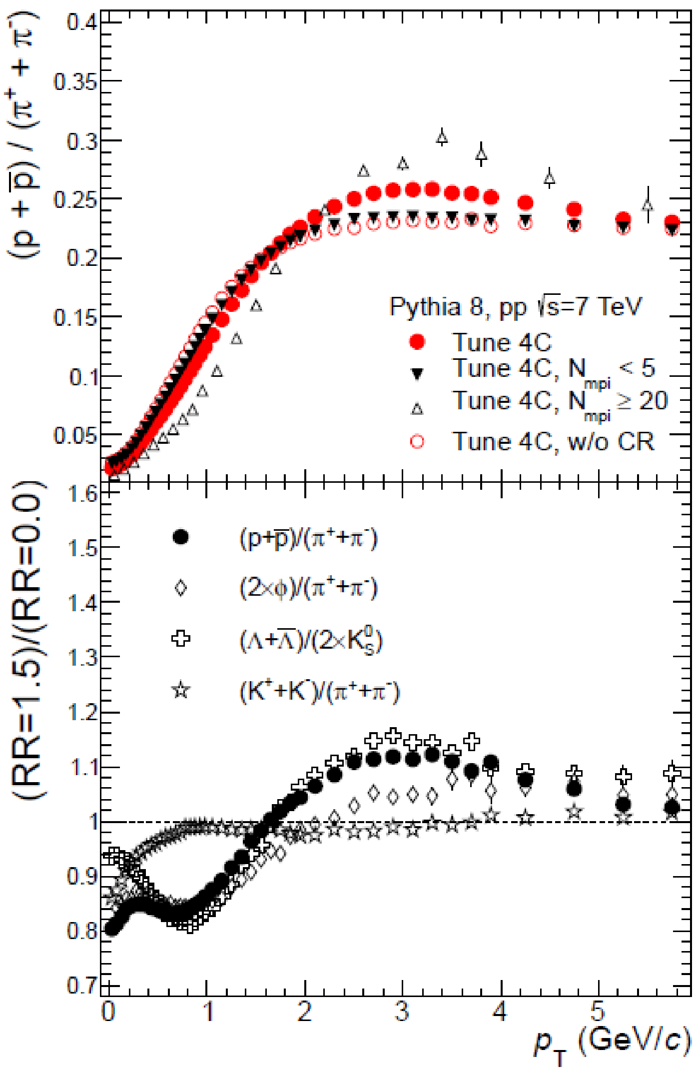


- Flow-like effects observed in pp are potentially connected to CR
- Qualitatively similar effect seen in the model as in heavy ion coll



In general both Pythia 8 and EPOS 3 describe the data qualitatively, whereas they fail to do so quantitatively

Pythia 8
Color reconnection and flow-like effects



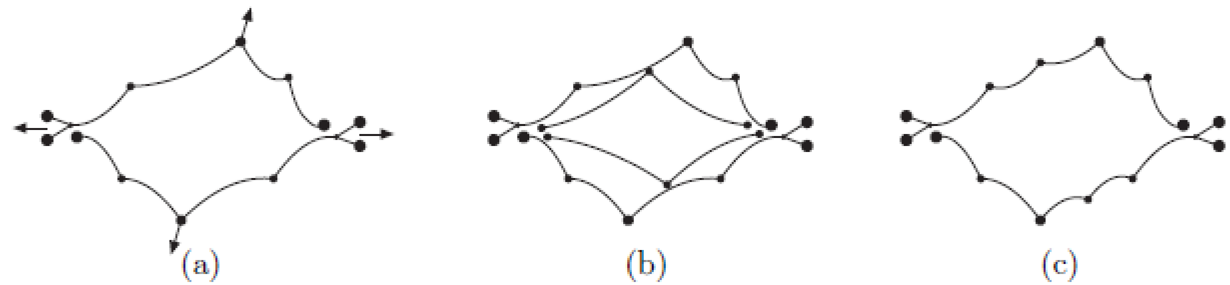


Fig. 2. (a) In a hard gluon-gluon subcollision the outgoing gluons will be colour-connected to the projectile and target remnants. Initial state radiation may give extra gluon kinks, which are ordered in rapidity. (b) A second hard scattering would naively be expected to give two new strings connected to the remnants. (c) In the fits to data the gluons are colour reconnected, so that the total string length becomes as short as possible.

- ***Description of soft-inclusive physics**:*
  - *by multiple perturbative parton–parton interactions (MPI) + p⊥-ordered parton showers*

- Pythia 8.185 Monash 2013 (Tune:ee=7; Tune:pp = 14)
  → CR MPI-based by default: allows partons to interact with probability of

$$\mathcal{P}(p_{\mathrm{T}}) = \frac{(R \times p_{\mathrm{T0}})^2}{(R \times p_{\mathrm{T0}})^2 + p_{\mathrm{T}}^2}$$

- Reconnection range, RR, which enters in the probability to merge a hard scale p_T system with one of a harder scale

- There is no a priori basis for guessing precisely what reconnection probability to choose, nor whether it should be constant at all CM energies

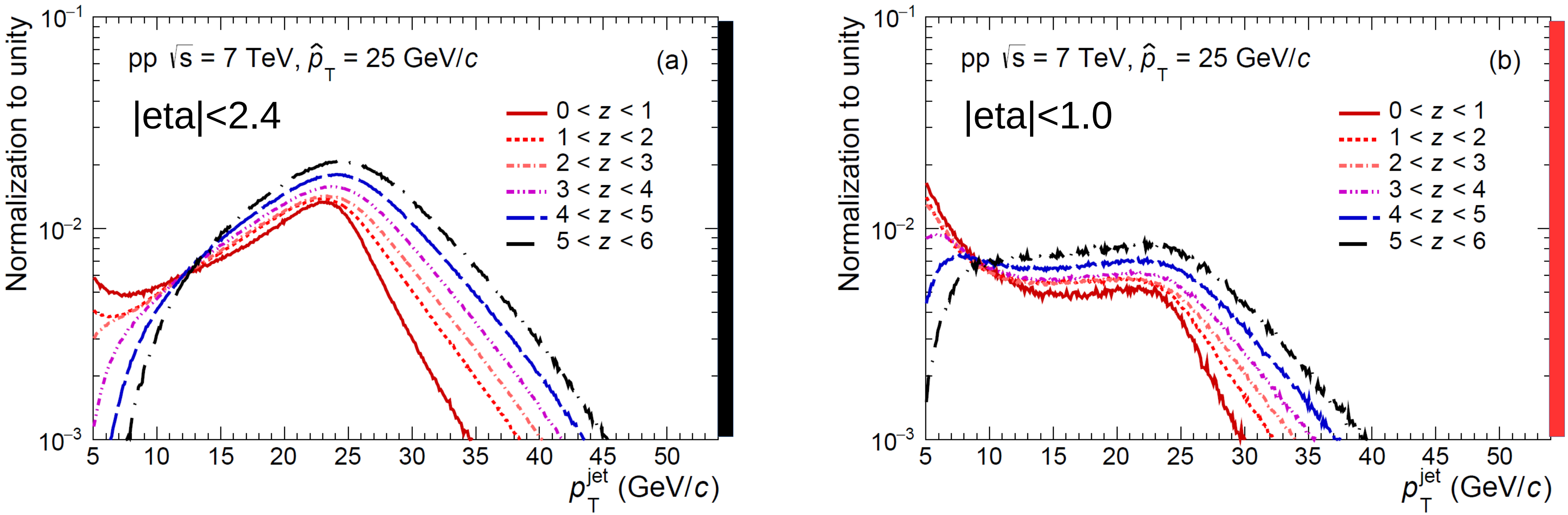
FASTJET 3.1.3 – hardness of the event: selection of jets

Multiplicity dependence of the leading jet p_T

Anti-k_T algorithm is used by requiring

– R=0.4 cone radius for jet searching

– $p_{T,min}$ = 5 GeV/*c (by ensuring the selection of semi-hard/hard events)*



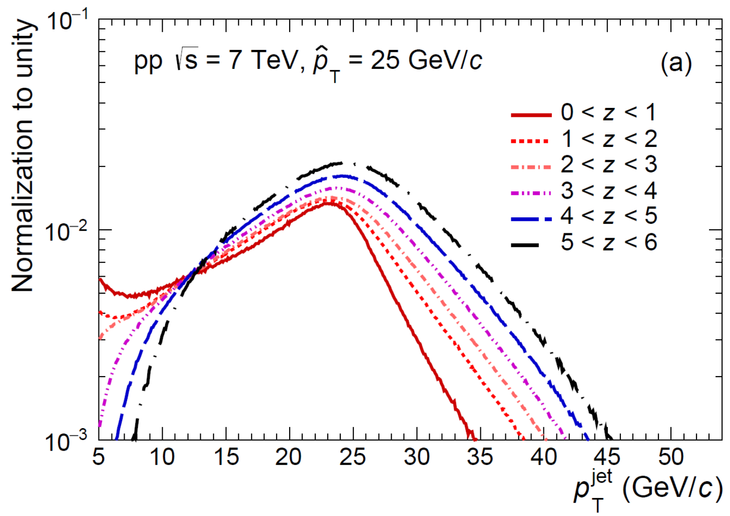
Testing the performance in high-mult events → Samples generated by Pythia8 by fixing the min and max invariant pT of the jet: p_T = 25-26 GeV/c

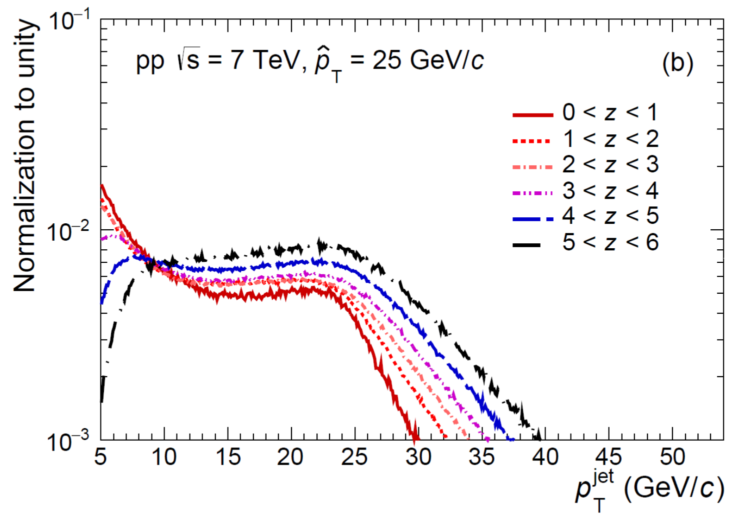
Left: clear peak around the expected pT is seen;
jets w/ pT = 5 GeV/c increases for low-mult case

Right: case corresponds to R=+-0.4; peak around 24 Gev/c;
higher probability of selection non-leading jets in the acceptance

FASTJET 3.1.3 – hardness of the event: selection of jets

Multiplicity dependence of the leading jet p_T



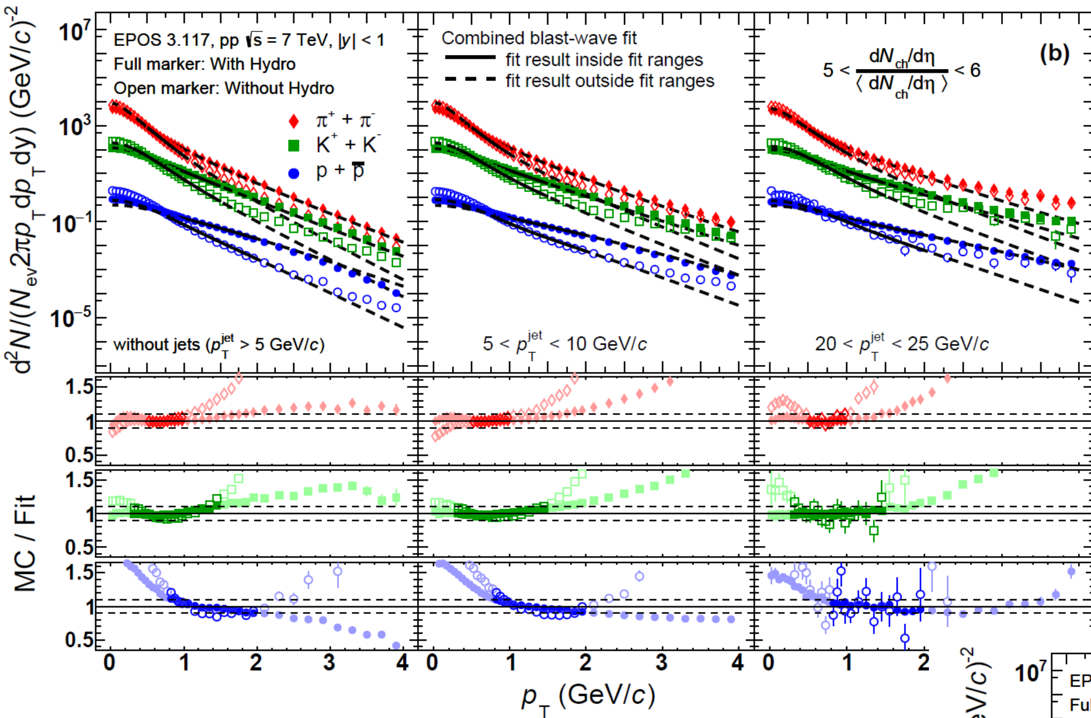


$\left\langle \frac{dN_{ch}}{d\eta} \right\rangle_{\lvert\eta\rvert<1}$	$\langle p_T^{jet} \rangle_{\lvert\eta\rvert<1}$ (GeV/c)	% of events with $p_T^{jet} > 5\,\mathrm{GeV}/c$
2.12	7.09	1.03
8.12	7.49	13.1
13.6	7.83	37.3
19.0	8.48	63.7
24.4	9.56	83.2
29.8	11.1	93.9
35.2	13.2	98.2
40.6	16.1	99.5
46.1	19.7	99.8

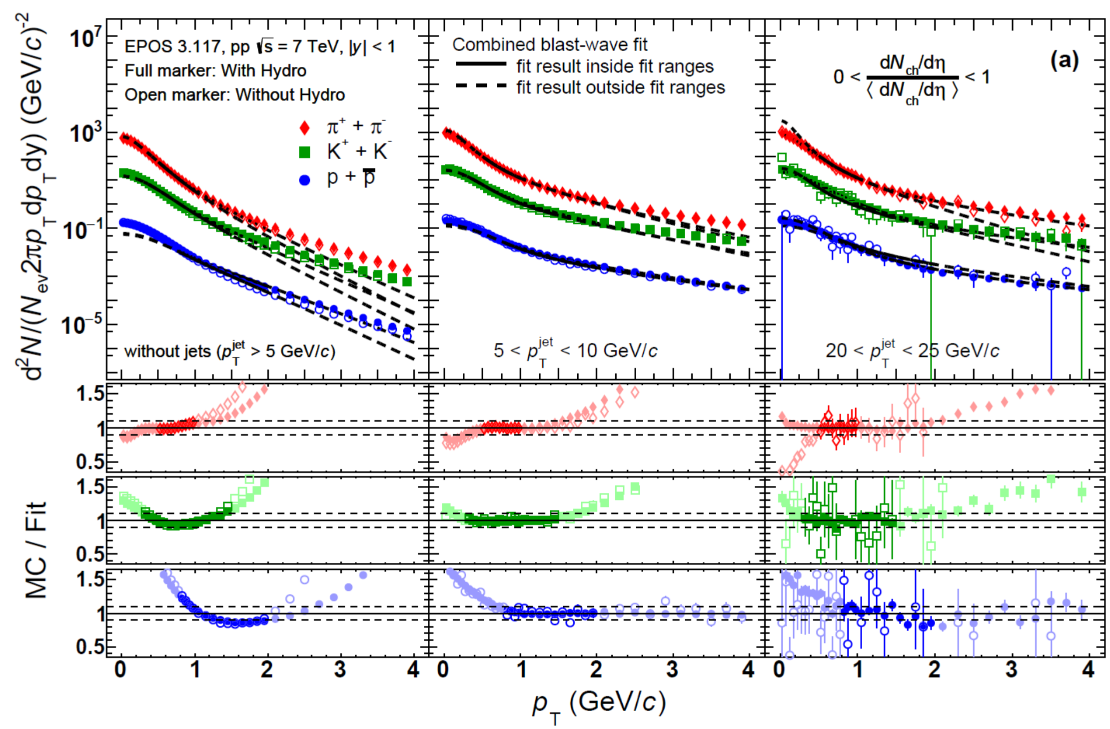
- The higher the multiplicity the larger average $p_{T,jet}$
- The higher the multiplicity the larger the # N_{MPI}
  → prob (hard parton-parton scattering) is larger
- Fraction (%) of events increases having jets within the acceptance

Results – Blast-wave model fits

EPOS 3

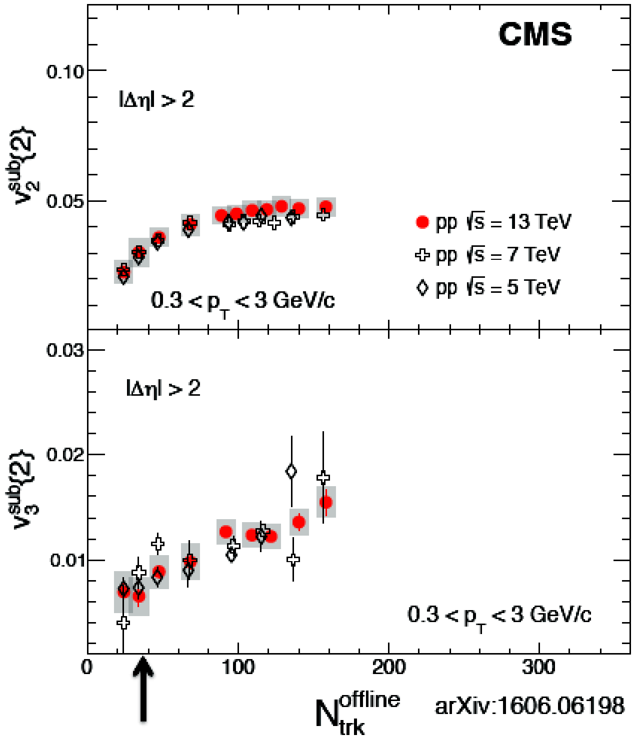


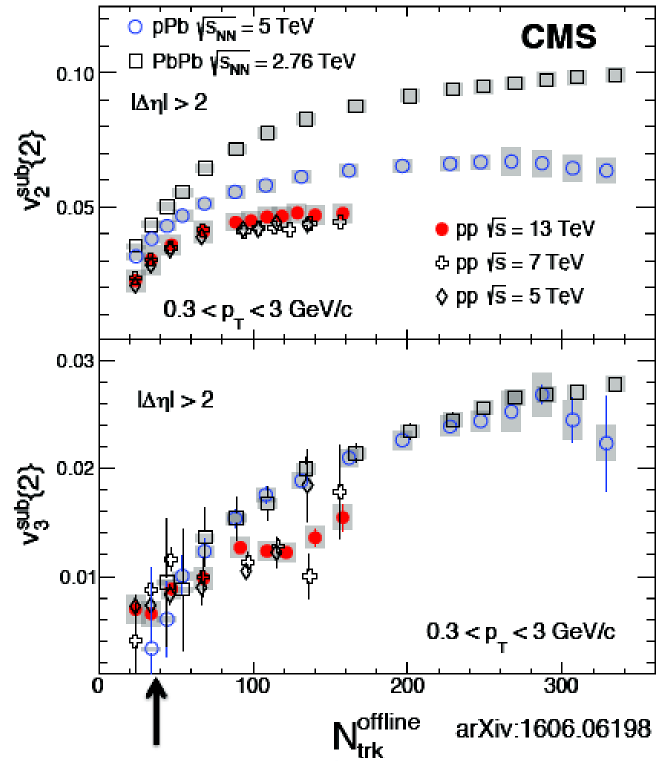
The jet contribution is less important for EPOS 3 than for Pythia 8



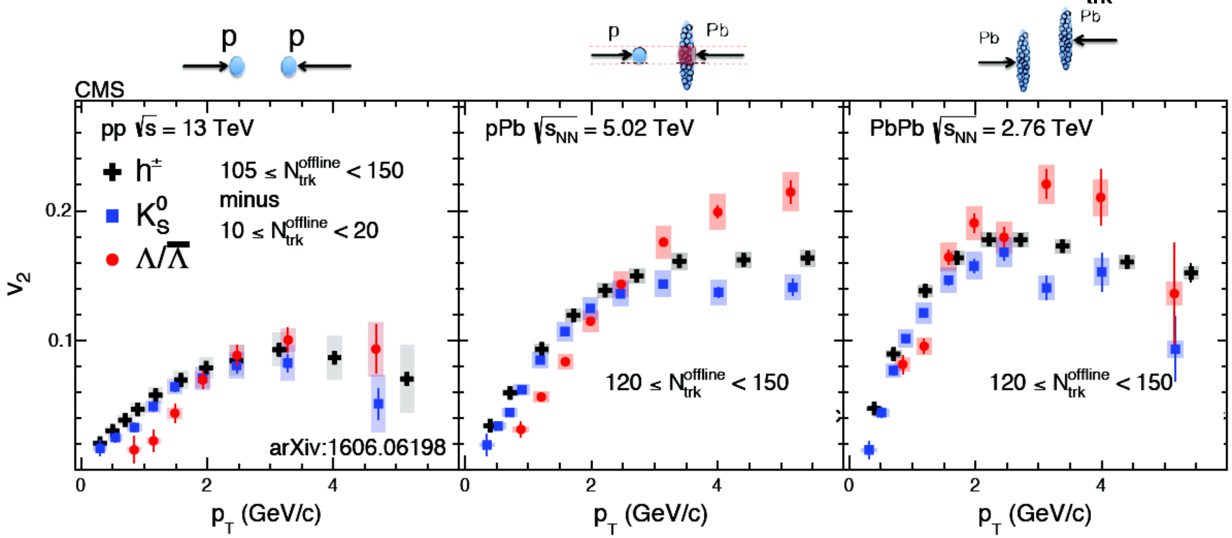
Collectivity in small systems

Flow signatures in small systems





- Both v_2 and v_3 arise from low to high N_{trk}
- Similar behaviors across all 3 systems

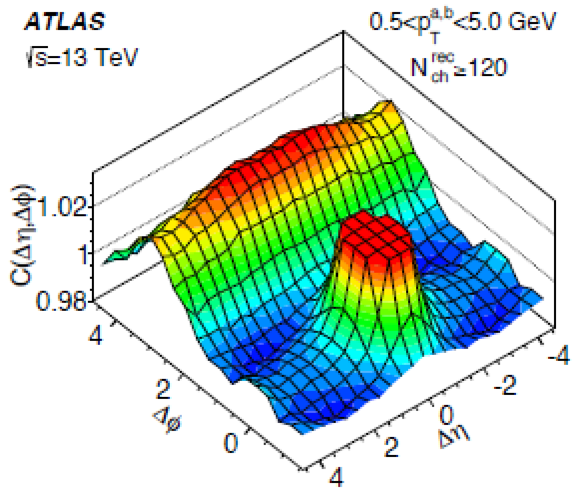


PLB 742 (2015) 200

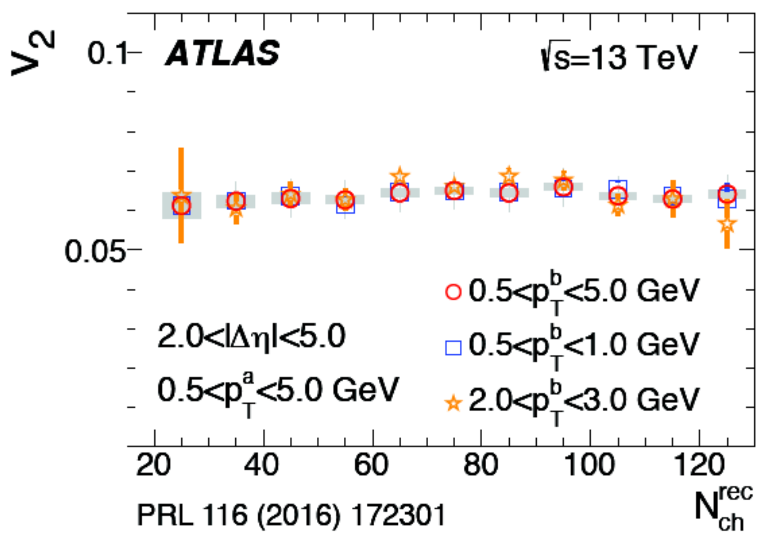
- Mass splitting of v_2
  - → Collective expanding source
- larger splitting in pp/p-Pb
  - → smaller system is more explosive at fixed N_{trk}

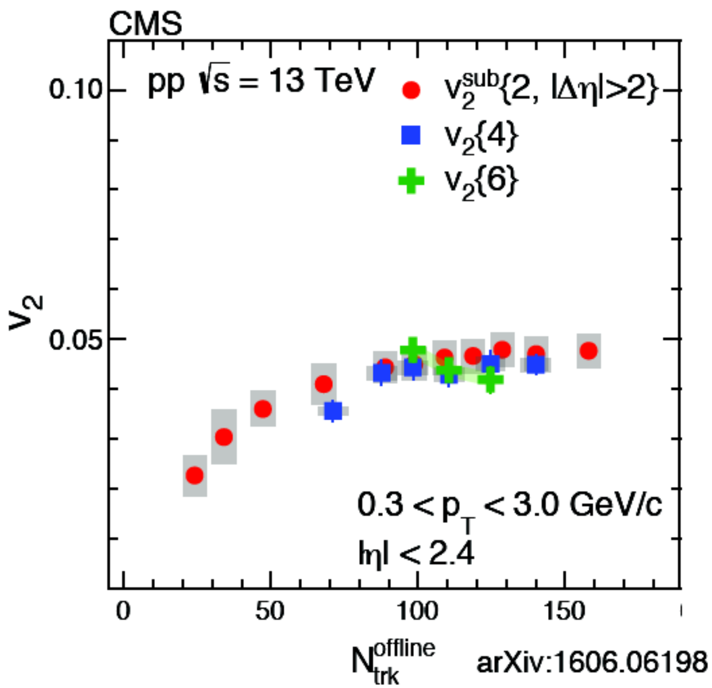
Collectivity in small systems

Long-range correlations – evidence of collectivity

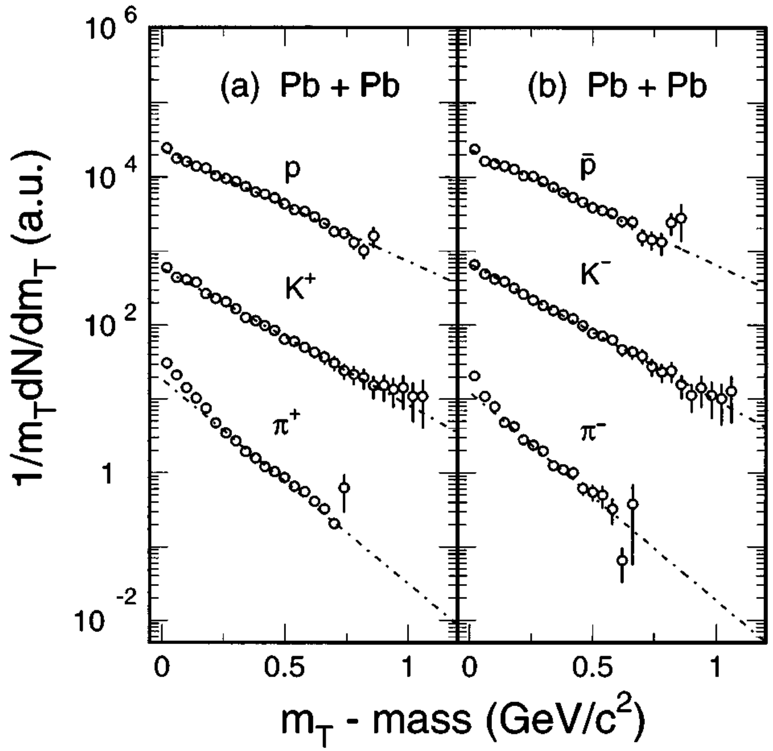


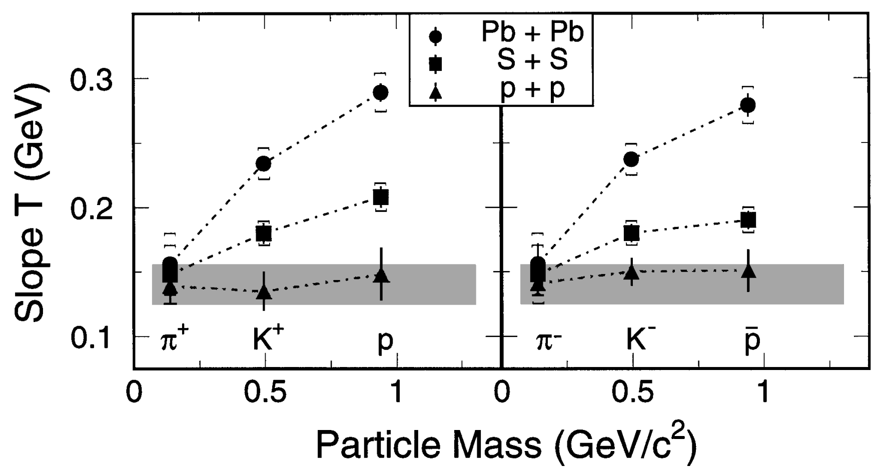
- *v_2 (or collectivity) constant or decreases as system becomes dilute (N_{trk} → 0)*
- *No strong radial flow or mass ordering at low N_{trk}*



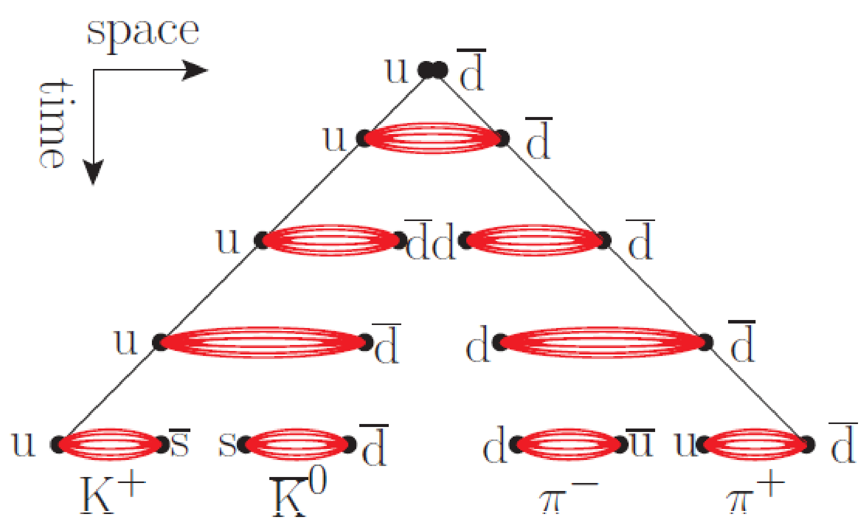


Collective phenomena in heavy ion collisions

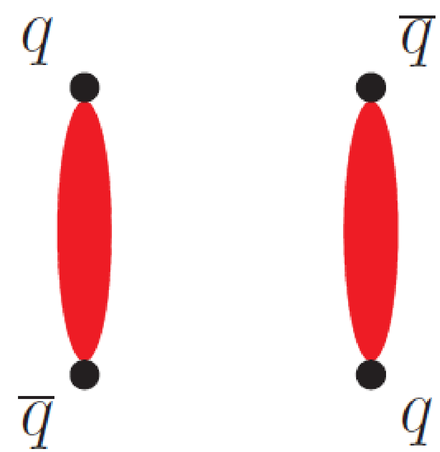


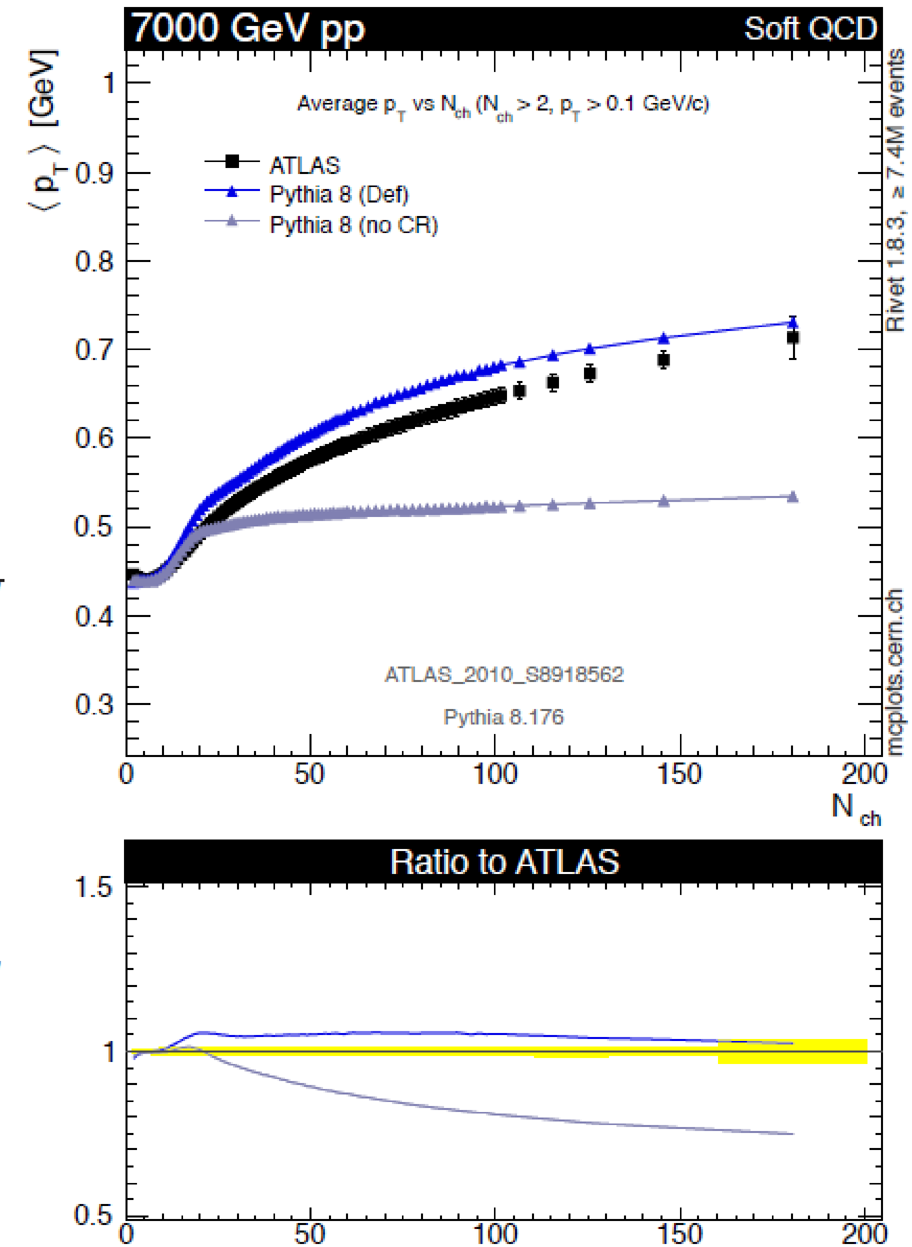


Pythia 8 – Hadronization and Color Reconnection



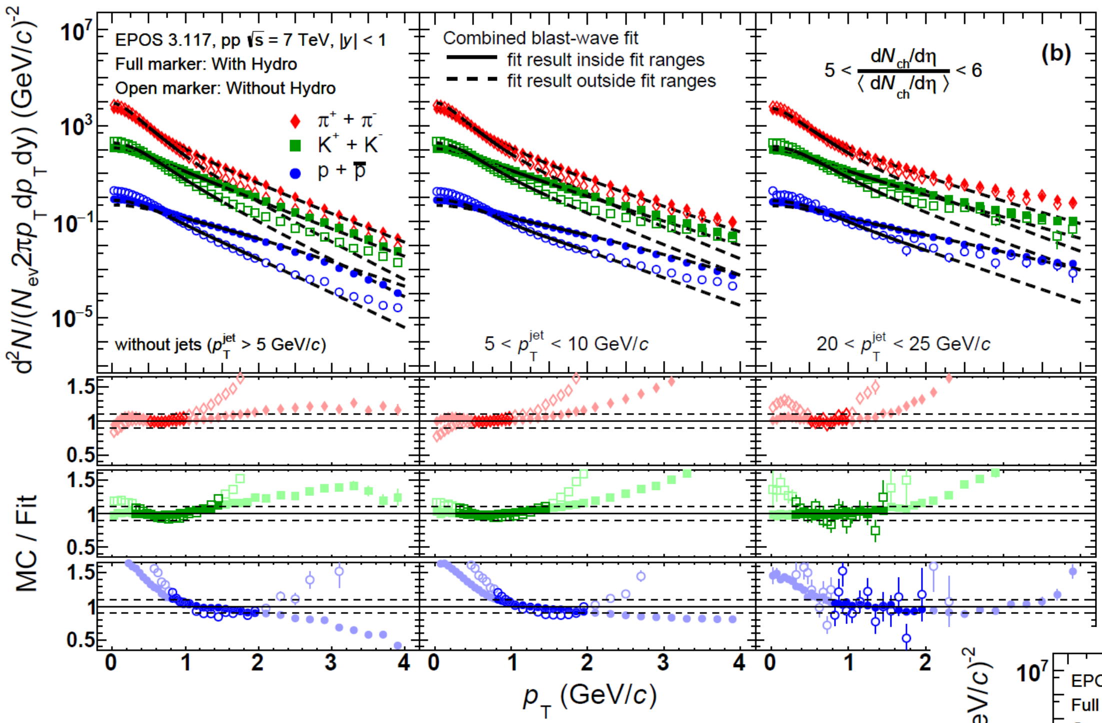
- What happens for multiple strings?
  - QCD quadropole? We have no idea how to hadronize this
  - Instead use several dipoles!
  - Multiple possible pairings $\Rightarrow$ Colour reconnection!



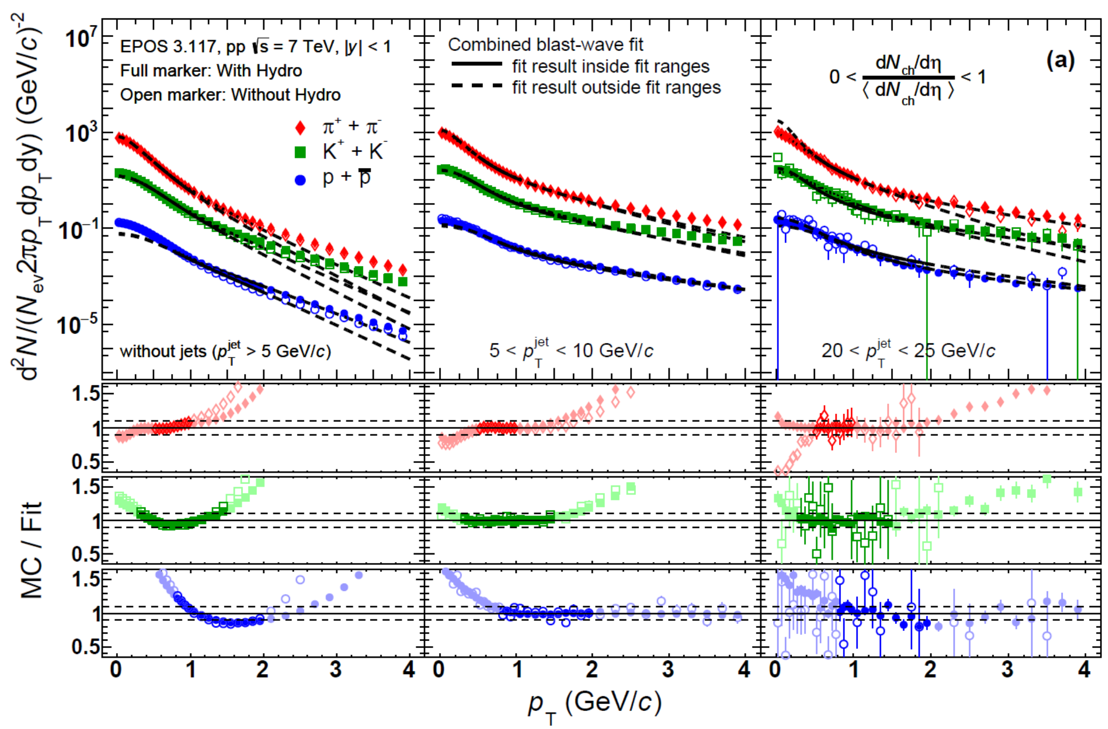


Results – Blast-wave model fits

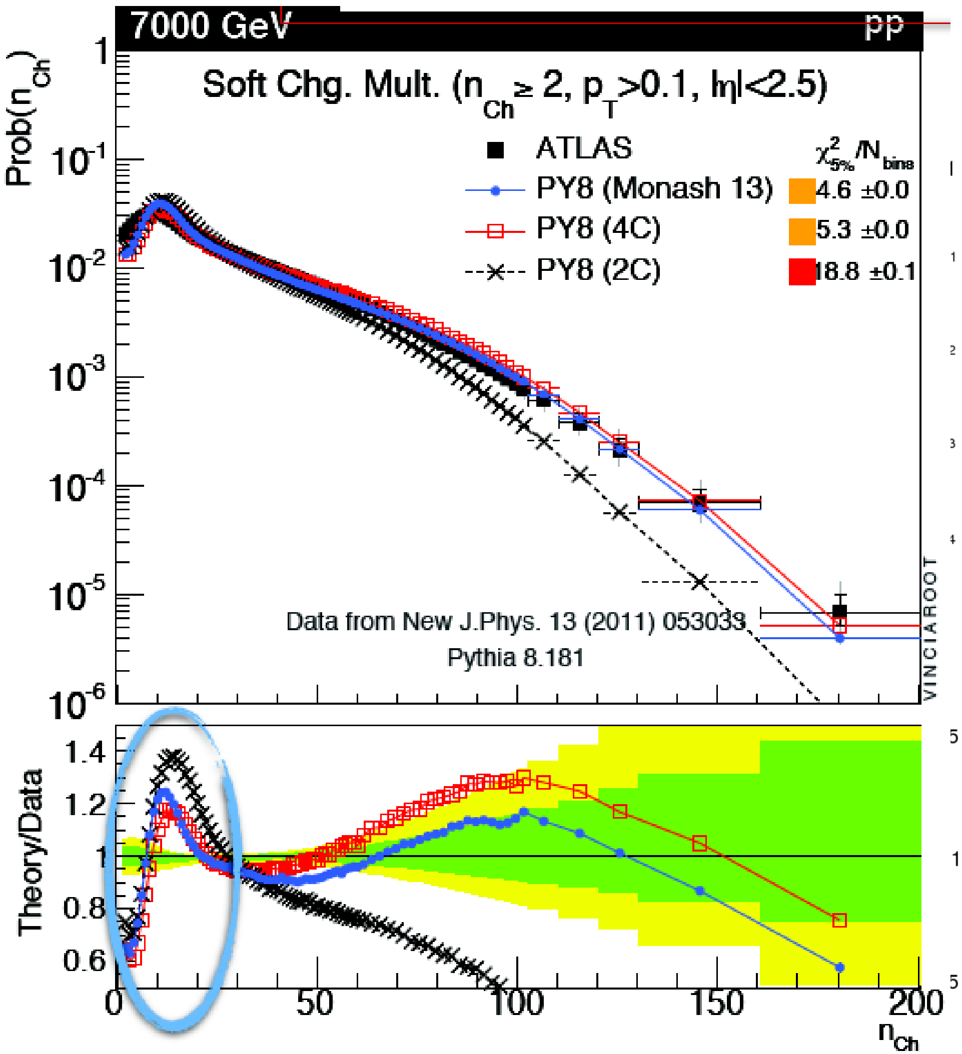
EPOS 3

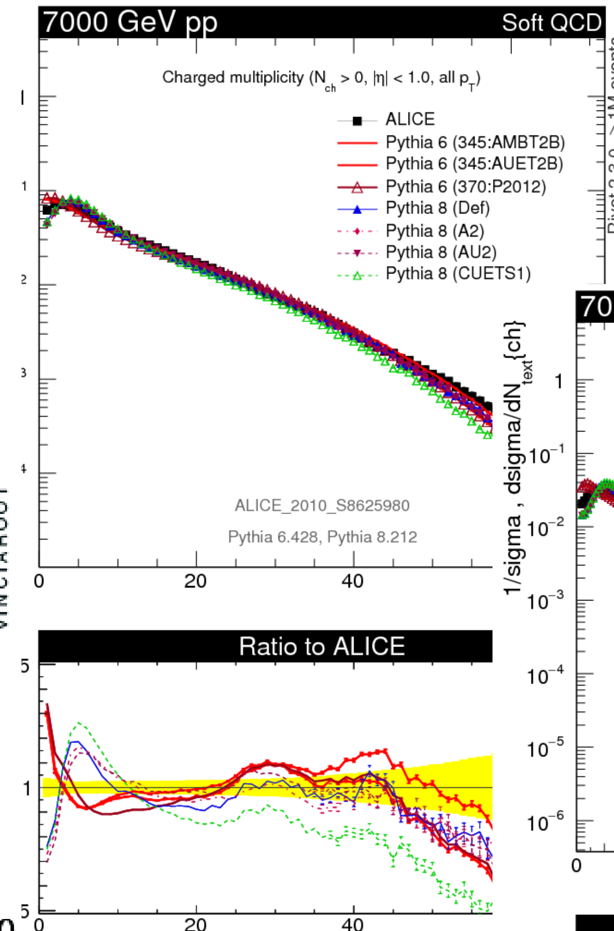


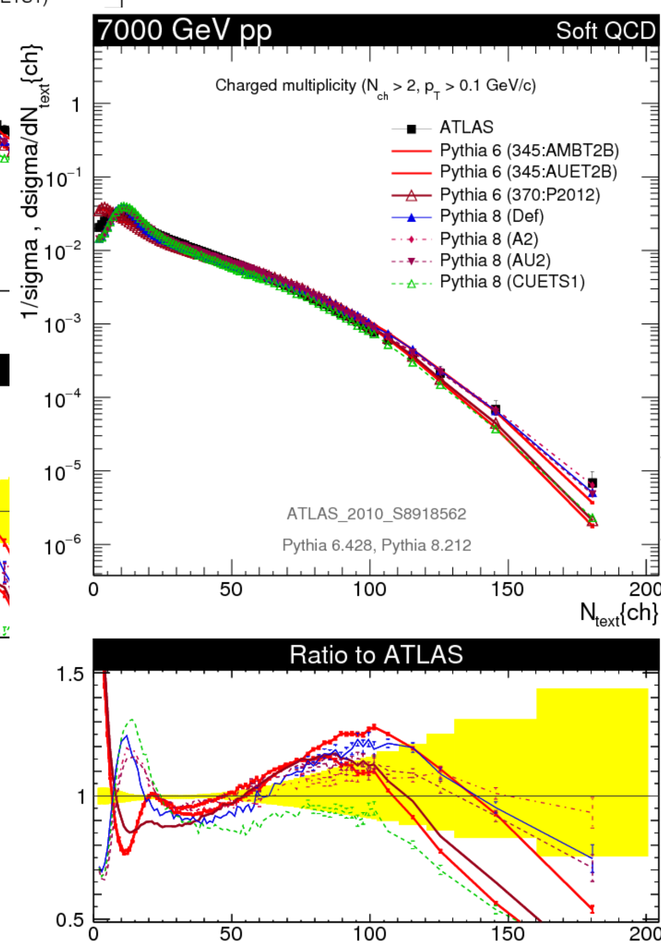
The jet contribution is less important for EPOS 3 than for Pythia 8



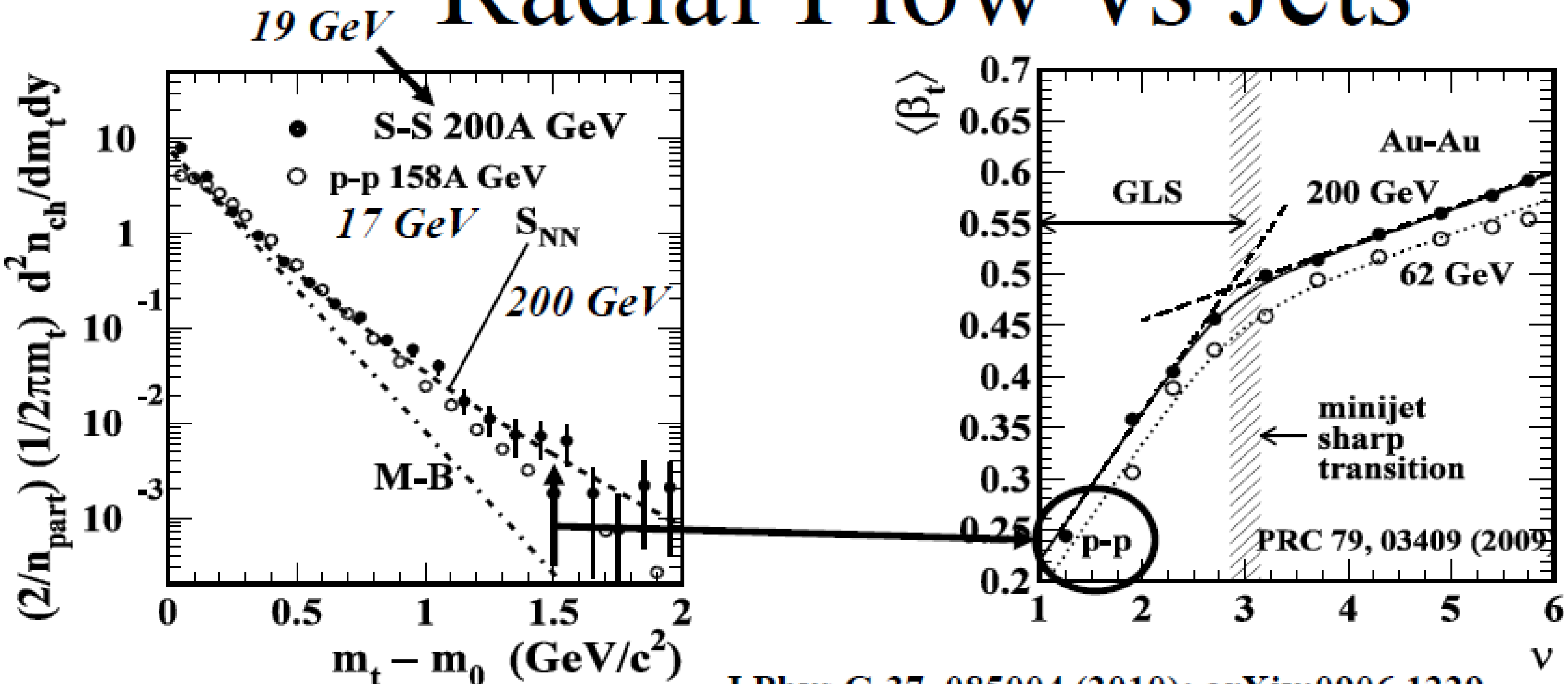
Pythia 8 – Charged-Particle Multiplicities
Tunes: Monash vs 4C







Radial Flow vs Jets



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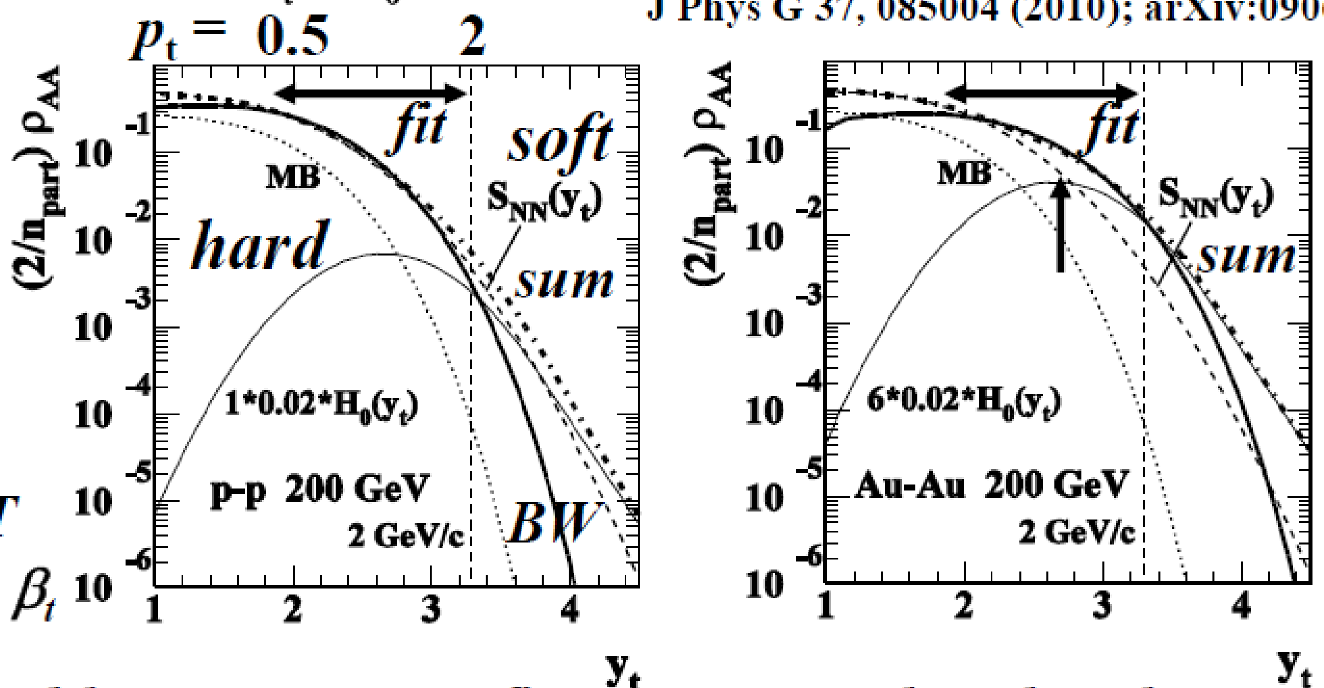
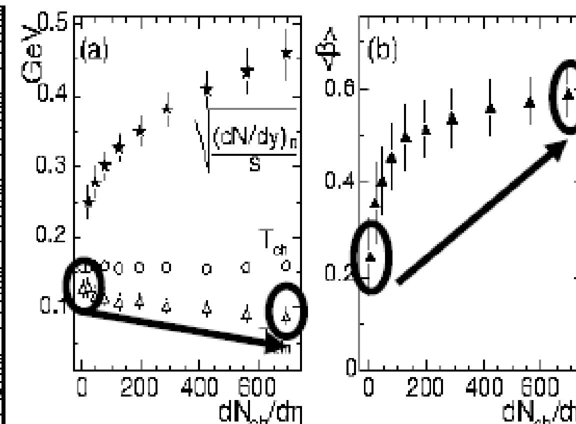
slope break is jet effect



larger T smaller β_t



smaller T larger β_t

blast-wave BW fits accommodate hard component – jets