Multiplicity-dependent jet modification in p+p collisions at LHC energies

arXiv:1805.03101

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with

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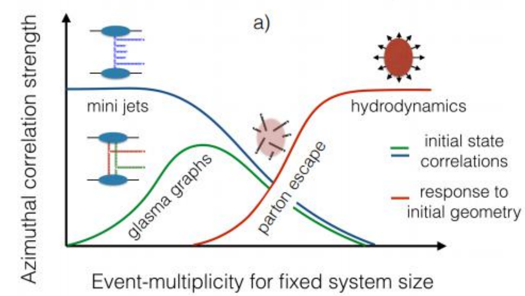
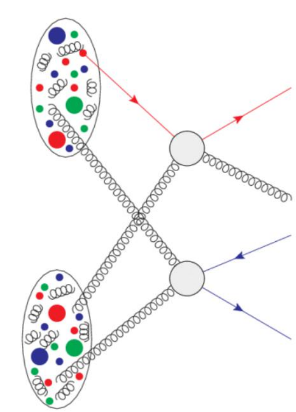
Motivation

- High-multiplicity p+p at LHC energies: **unexpected findings**
  - Long-range correlations
  - Substantial v_n (comparable to that in HI with same multiplicity)
    eg. L. Yan, J. Y. Ollitrault, PRL 112, 082301 (2014).
  - Stronger-than-linear dependence of HF production with event multiplicity
    ALICE Collaboration, JHEP 1608, 078 (2016).



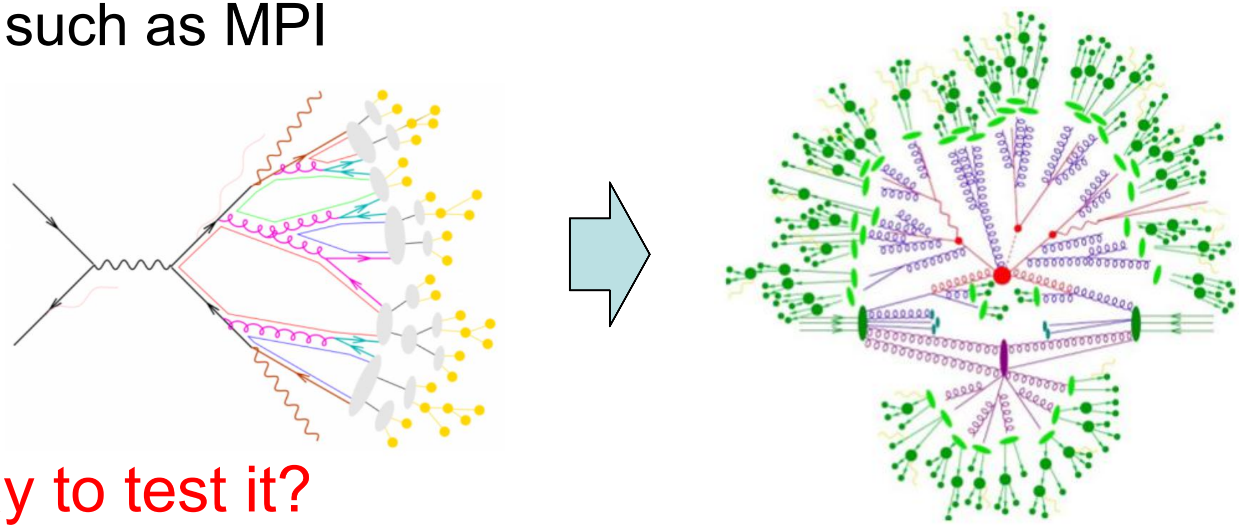
S. Schlichting, arXiv:1601.01177

- Current understanding:
  - Collectivity can arise from features other than QGP
  - Pure QCD can generate it at the soft-hard boundary
  - Eg. in the form of Multiple Parton Interactions (qualitatively explain HF enhancement)



Effect on jets

- Jet modification as a key QGP signature - what about pp?
  - Features in pp traditionally associated by QGP questions the role of pp as a reference
  - Jet quenching is not excepted without QGP in a larger volume, but...
  - The development of jets may be influenced by semi-hard processes such as MPI



- Is there a way to test it?

Look for nontrivial modification of jet structures

Our study: Simulation and jet reco.

- pp collisions at $\sqrt{s}$ = 7 TeV
- Simulation with PYTHIA 8.2
  - CTEQ6.6 PDF sets, all hard QCD processes
  - Tunes:
    - Monash (as default) - tuned for a large set of LHC data
    - Monash* - former CUETP8M1, based on underlying events)
    - 4C - a different tune based on key LHC observables and UE observables
  - Multiple Parton Interactions: *on* and *off*
  - Color Reconnection schemes:
    0: MPI-based scheme (default in PYTHIA and our study),
    1: QCD-based string length minimisation scheme,
    2: gluon-move scheme.
    off: we don't use it.
- Full jet reconstruction with R=0.7 (using standalone FastJet)
  - anti-k_T algorithm (default in this study)
  - Cambridge-Aachen algorithm
  - k_T algorithm

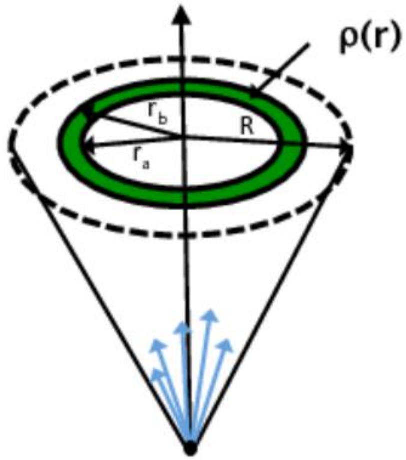
Jet shape measurables

CMS, JHEP 06, 160 (2012).

- Differential jet shape

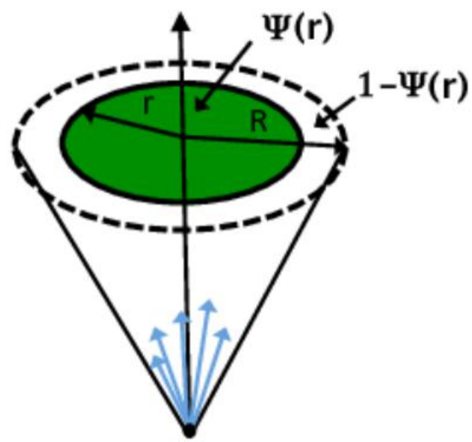
$$\rho(r) = \frac{1}{\delta r} \frac{1}{p_{\mathrm{T}}^{\mathrm{jet}}} \sum_{r_a < r_i < r_b} p_{\mathrm{T}}^{i}$$

$$r_i = \sqrt{(\phi_i - \phi_{\mathrm{jet}})^2 + (\eta_i - \eta_{\mathrm{jet}})^2}$$



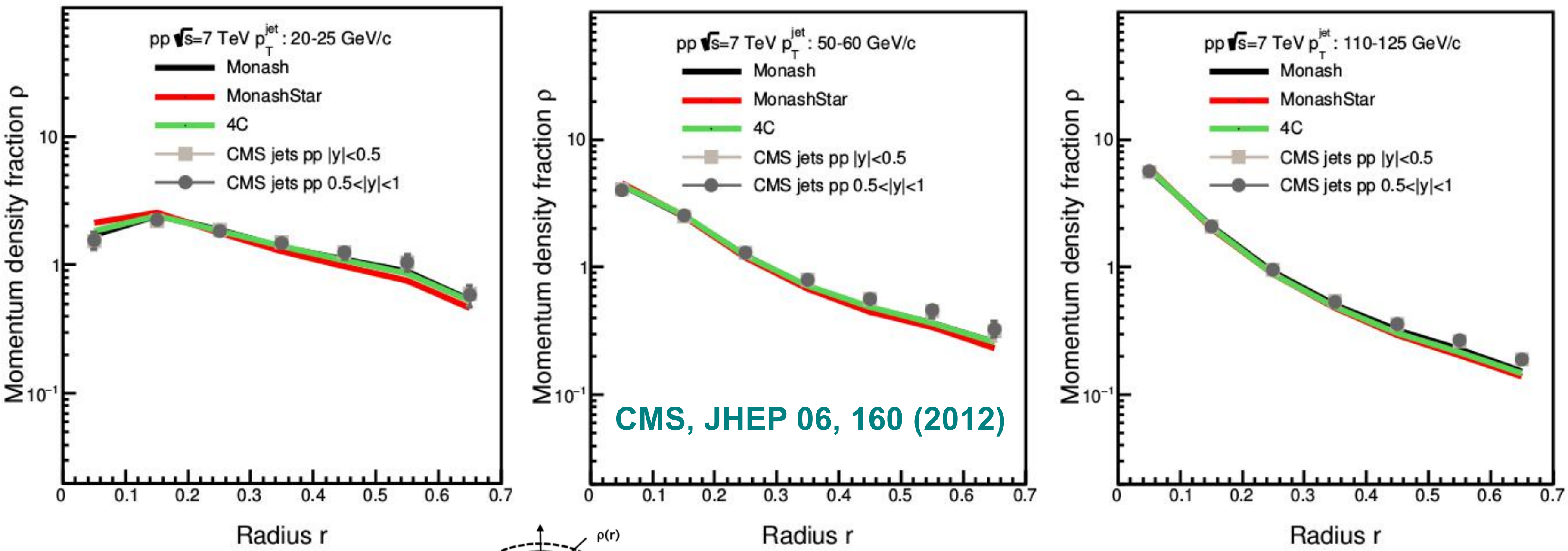
- Integral jet shape

$$\psi(r) = \frac{1}{p_{\mathrm{T}}^{\mathrm{jet}}} \sum_{r_i < r} p_{\mathrm{T}}^{i}$$

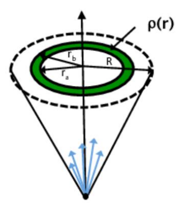


$$\psi(R) = \int_0^R \rho(r')dr' = 1$$

Validation: compare to CMS data



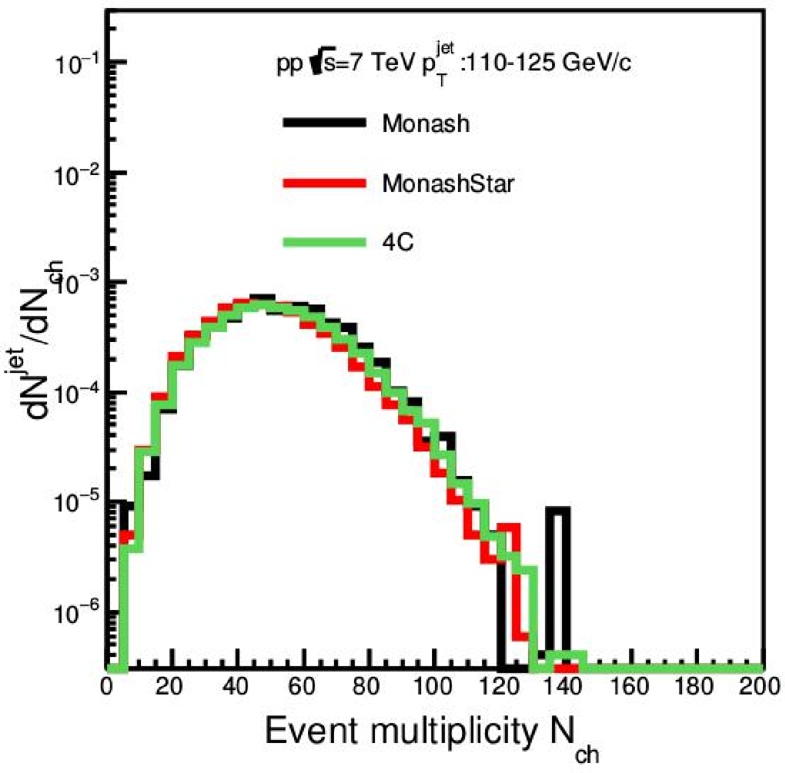
CMS, JHEP 06, 160 (2012)

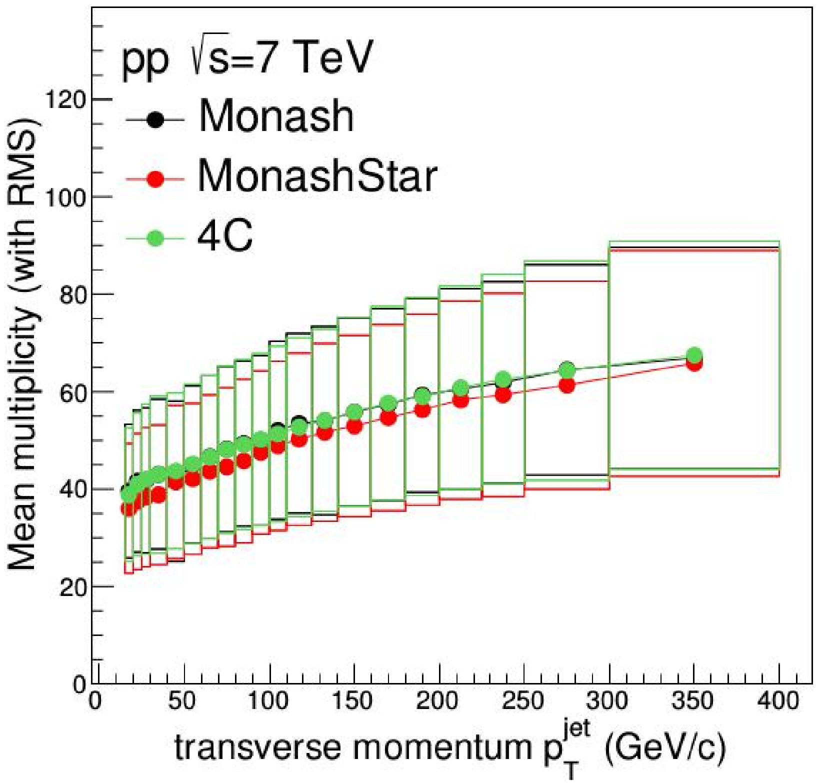


ρ(r)

- The three different "stock" tunes reproduce CMS |*y*|<1 p+p data at 7 TeV within uncertainty
- Between 15 < p_T < 400 GeV/*c* (3 examples shown)
  - *Note: our setup (acceptance, jet reco. etc) follows the CMS analysis*

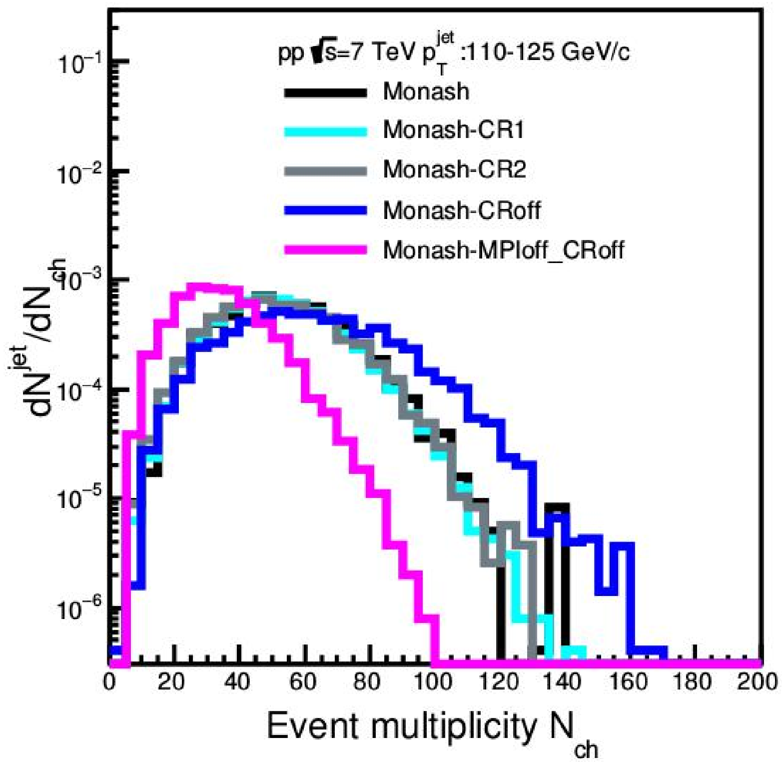
Event charged multiplicity (at mid-η)

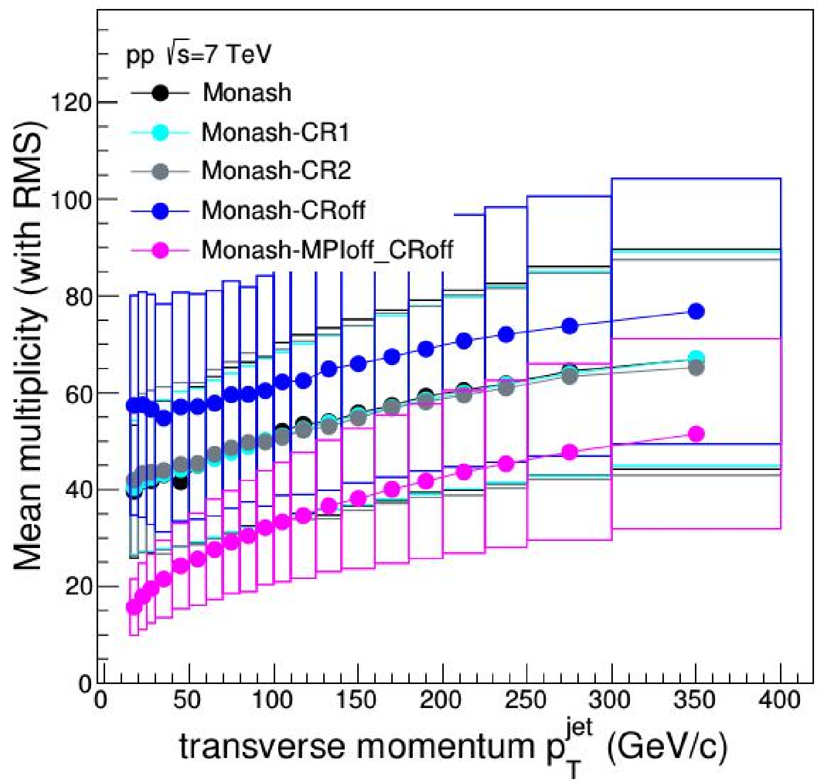




- The three different "stock" tunes show similar multiplicity dependences (all tuned to describe data)
- A rising trend with p_T (expected)

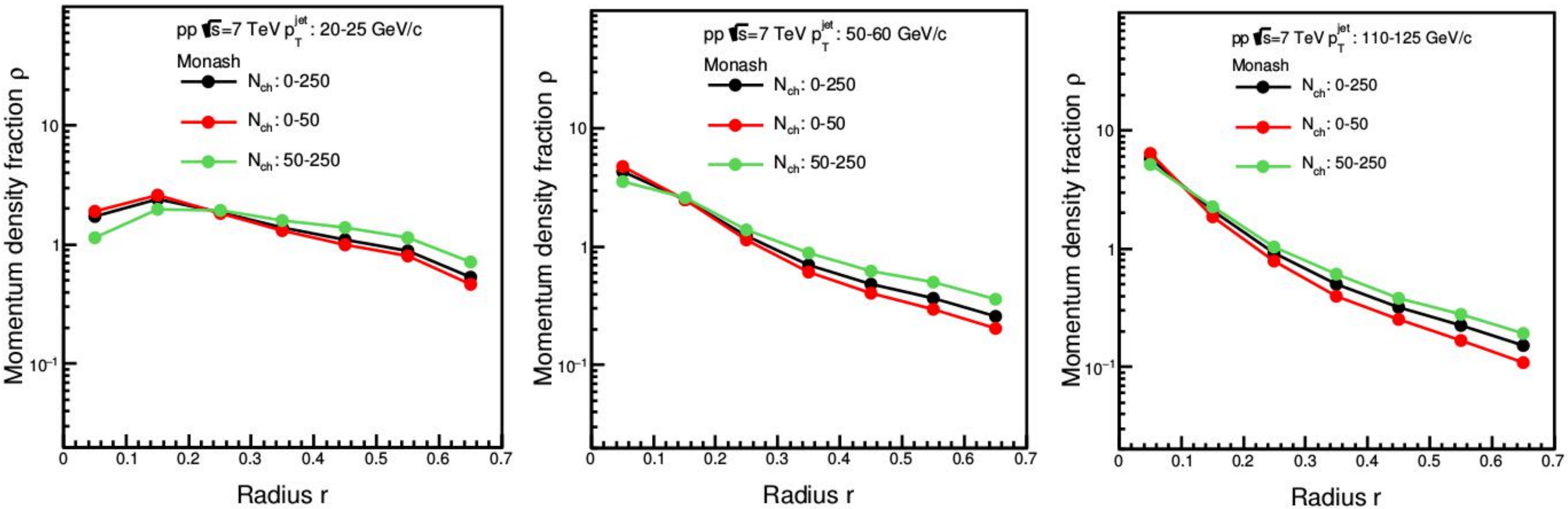
Event charged multiplicity (at mid-η)





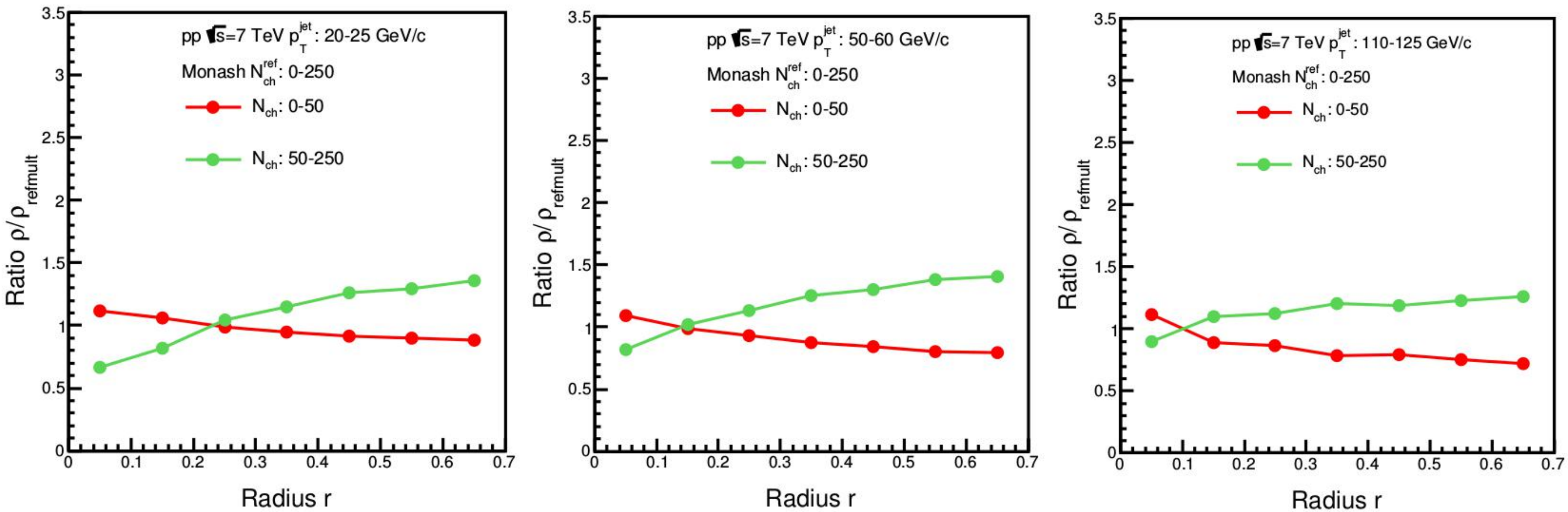
- Different CR-schemes also yield similar N_{ch} distributions
- MPI:off and CR:off are nonphysical settings
  - MPI:off (no CR) yields less multiplicity on the average
  - CR:off (with MPI:on) yields more

Jet structure for different multiplicities



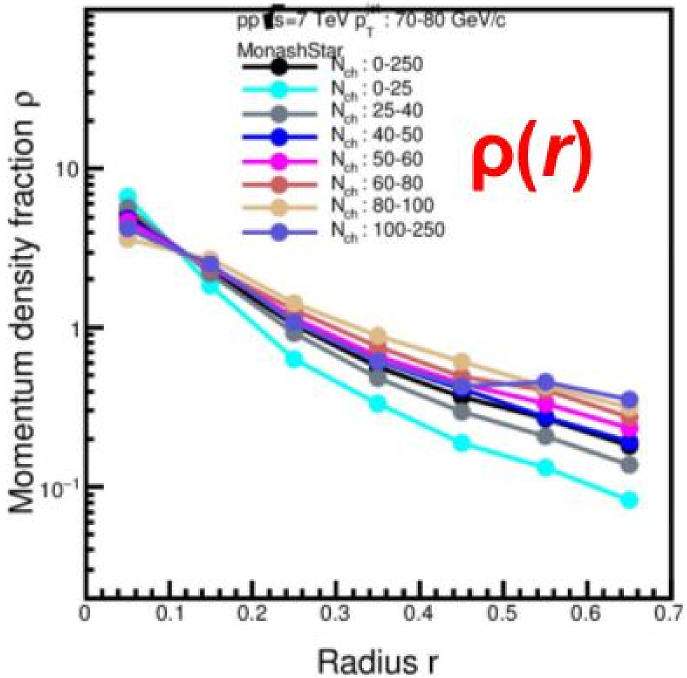
- Multiplicity dependence of differential jet shape ρ(r)
  - $\rho_{\text{any-Nch}} \equiv \rho_{\text{MB}}$; $\rho_{\text{low-Nch}}$; $\rho_{\text{high-Nch}}$
    Note: MB "minimum bias" just means no selection on mult./cent. contains certain biases introduced by the p_T selection,
- This is the expected, trivial behavior:
  - Event N_{ch} correlates with jet multiplicity, that correlates with ρ(r)
  - Lower-multiplicity jets are more concentrated than higher-mult jets

Evolution of structure: ratio to MB

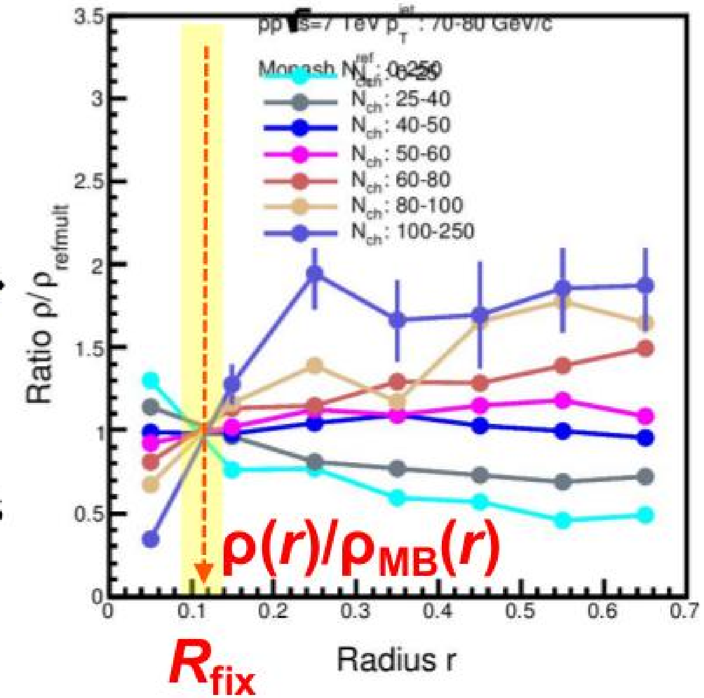


- Multiplicity dependence of jet shape ratios to MB:
  - Curves are $\rho_{low\text{-}Nch}/\rho_{MB}$; $\rho_{high\text{-}Nch}/\rho_{MB}$
- Intersection of the two curves at unity (trivial for two curves)
- Evolution with p_T: higher-momentum jets are narrower

More multiplicity classes



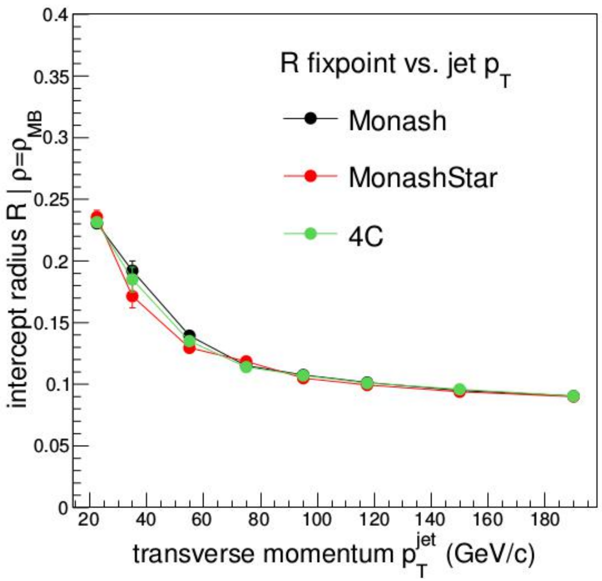
Compare to
Minimum Bias

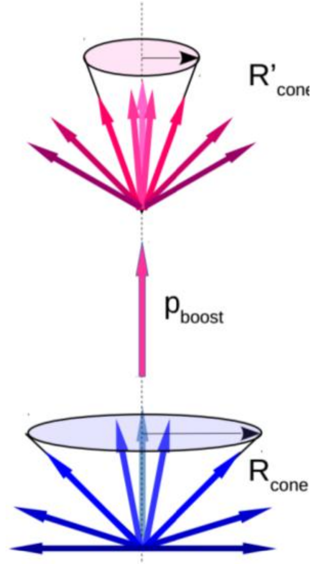


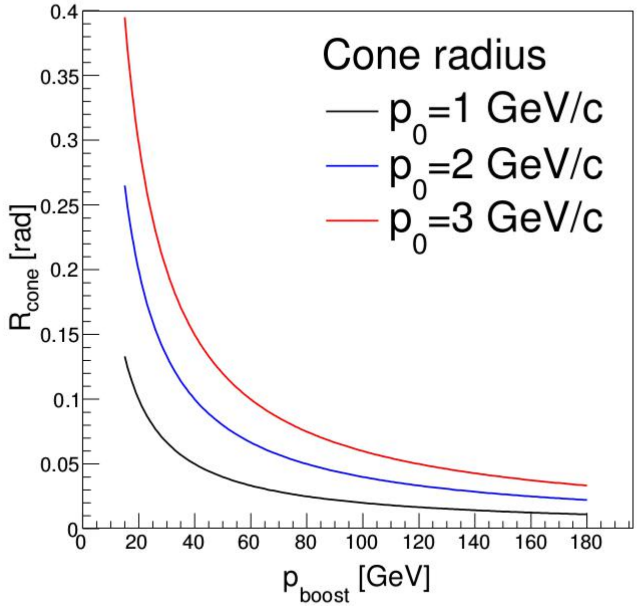
- All curves intersect at a given point
- This is non-trivial -> a given ratio R_{fix}

- Evolution with p_T?
- How strongly does it depend on simulation settings?

R_{fix} versus jet momentum

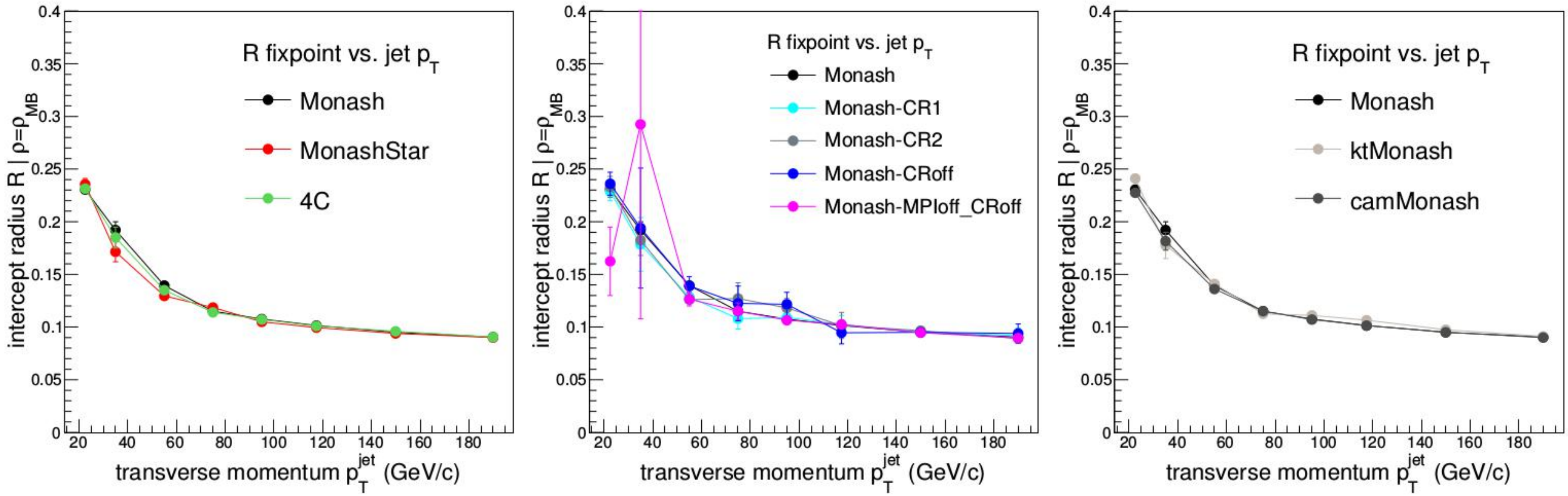






- Toy model to understand $R_{fix}(p_T)$ evolution
  - Jet consisting of particles with equal momenta p_0,
  - Boosted toward the jet axis with p_{boost}
- High-p_T : qualitatively similar behaviour to the MC
- Low-p_T : blow-up - not expected in data because jet reconstruction is limited by R and also angular cut-off in splitting

R_{fix} - is it universal?

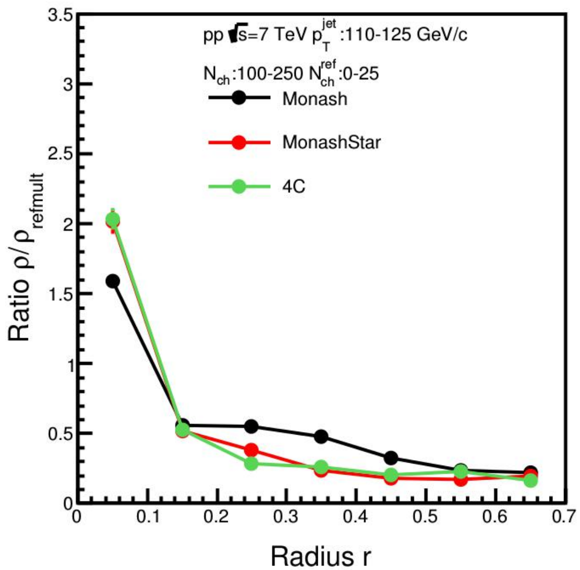


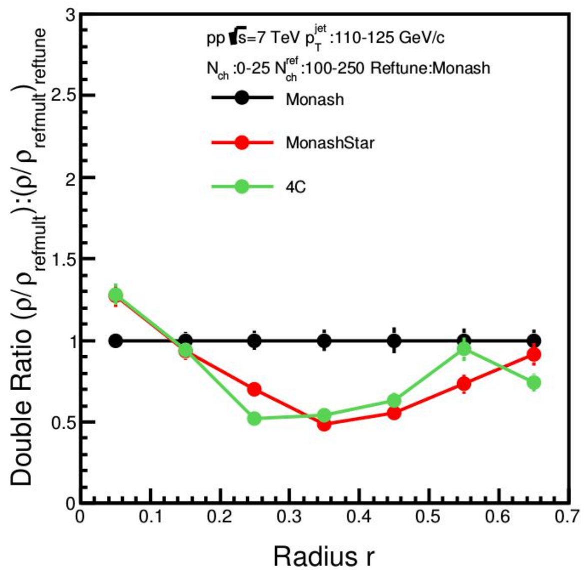
- *R_{fix}* does not depend on... (within uncertainties)
  - The choice of PYTHIA tune (Monash, Monash*, 4C)
  - CR schemes or even whether CR or MPI are on/off.
    Note: MPI:off is very different physics, different UE
  - Clustering algorithm (k_T, anti-k_T, Cambridge-Aachen)
    These algorithms create very different jets

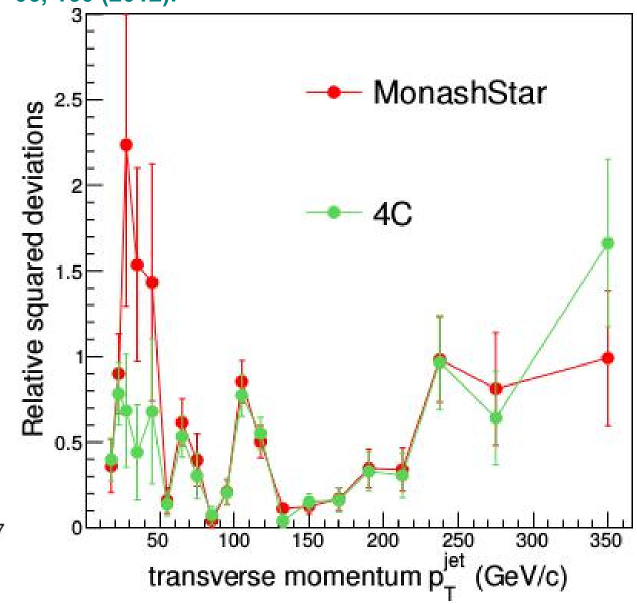
Will it hold in Heavy Ions?

Tune comparison: deviations vs. p_T

CMS, JHEP 06, 160 (2012).







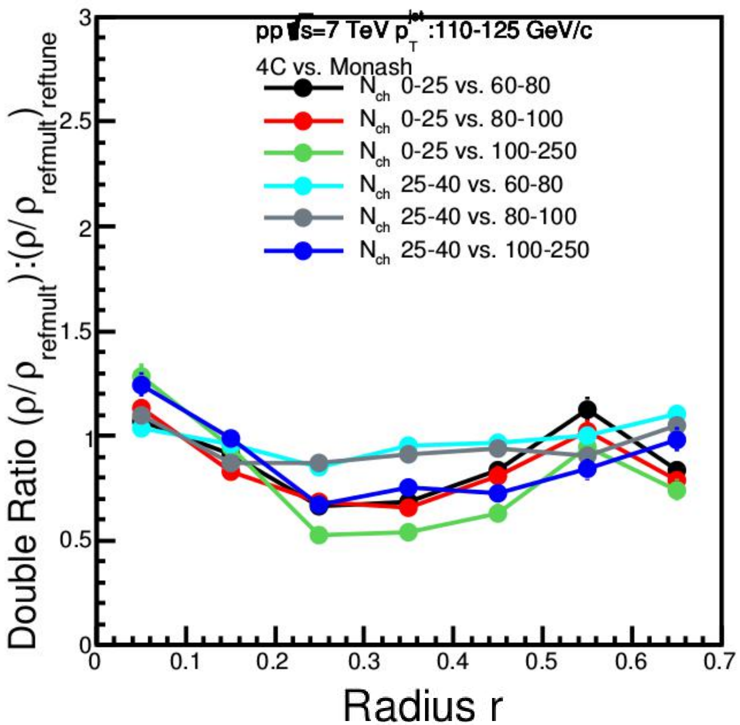
- Comparing $\rho_{\text{high-Nch}}/\rho_{\text{low-Nch}}$ ratios for different tunes
- **Double ratio** (given p_T)
  - Trivial multiplicity bias cancels
  - We find a significant effect at given p_T jet windows
  - Effect can be as large as a **factor of 2**!

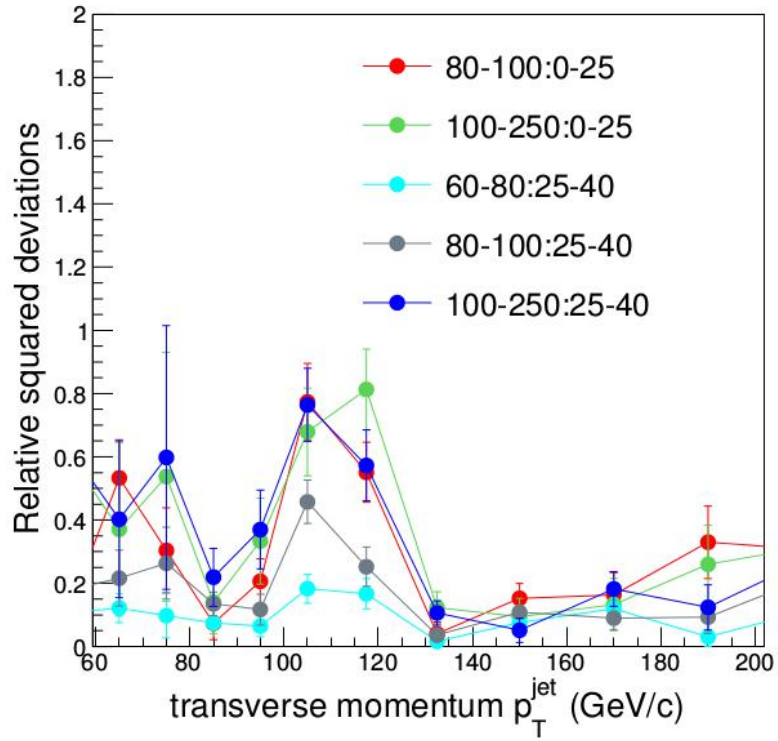
$$DR(r) = \frac{(\rho_{low}/\rho_{high})}{(\rho_{low}/\rho_{high})_{ref.tune}}$$

- Dependence on p_T complicated

$$RSD = \sqrt{\sum_{0<r_i<R} (DR(r_i) - 1)^2}$$

Tune comparison, varied N_{ch}-bin pairs



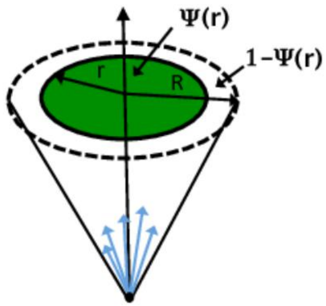


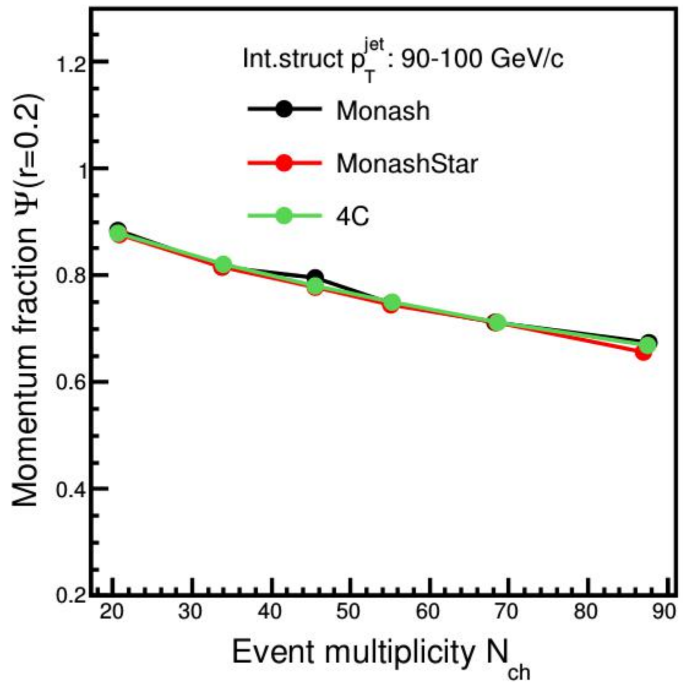
- Deviations are present in many {N_{ch}-low, N_{ch}-high} pairs

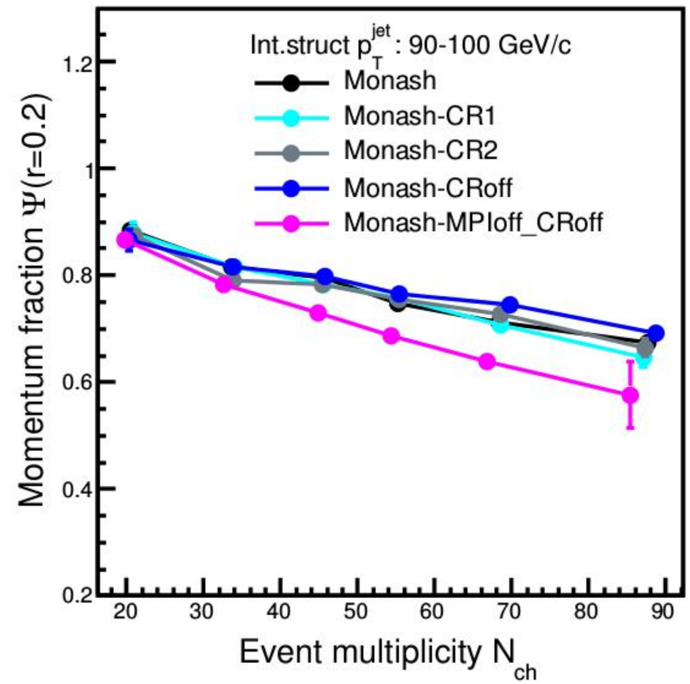
  Statistically independent samples => not accidental fluctuations!
- Extent of deviation is larger for more distant N_{ch} pairs

Predictions can serve as sensitive model tests

Integrated jet shapes vs. N_{ch} (r=0.2)







- No significant difference for 3 "stock" tunes or CR schemes
- **MPI:off case is significantly different at high N_{ch}**
  - not explained by the sizeable bin shift effect

Modification of jet structures by MPI

- Word of caution: effect can (partly) come from modified UE

Conclusions and outlook

- Multiplicity-differential jet structure measurements in pp collisions at LHC energies are **sensitive tests of MC models**
  - A way to differentiate between otherwise well-performing models
  - **Data up to high p_T would be essential**
- We see a **non-trivial modification of the jet shapes** by multiple parton interactions
  - The role of underlying events should be clarified
  - We are extending our study to **less UE-sensitive observables**
  - **Studies with heavy-flavor jets** are underway
- We suggest a **multiplicity-independent jet size** measure
  - Modification of R_{fix} in heavy-ion collisions may be tell-tale
  - Moving to **event generators with medium effects** (HIJING++)

...so please stay tuned :)

Thank you!

Acknowledgements:

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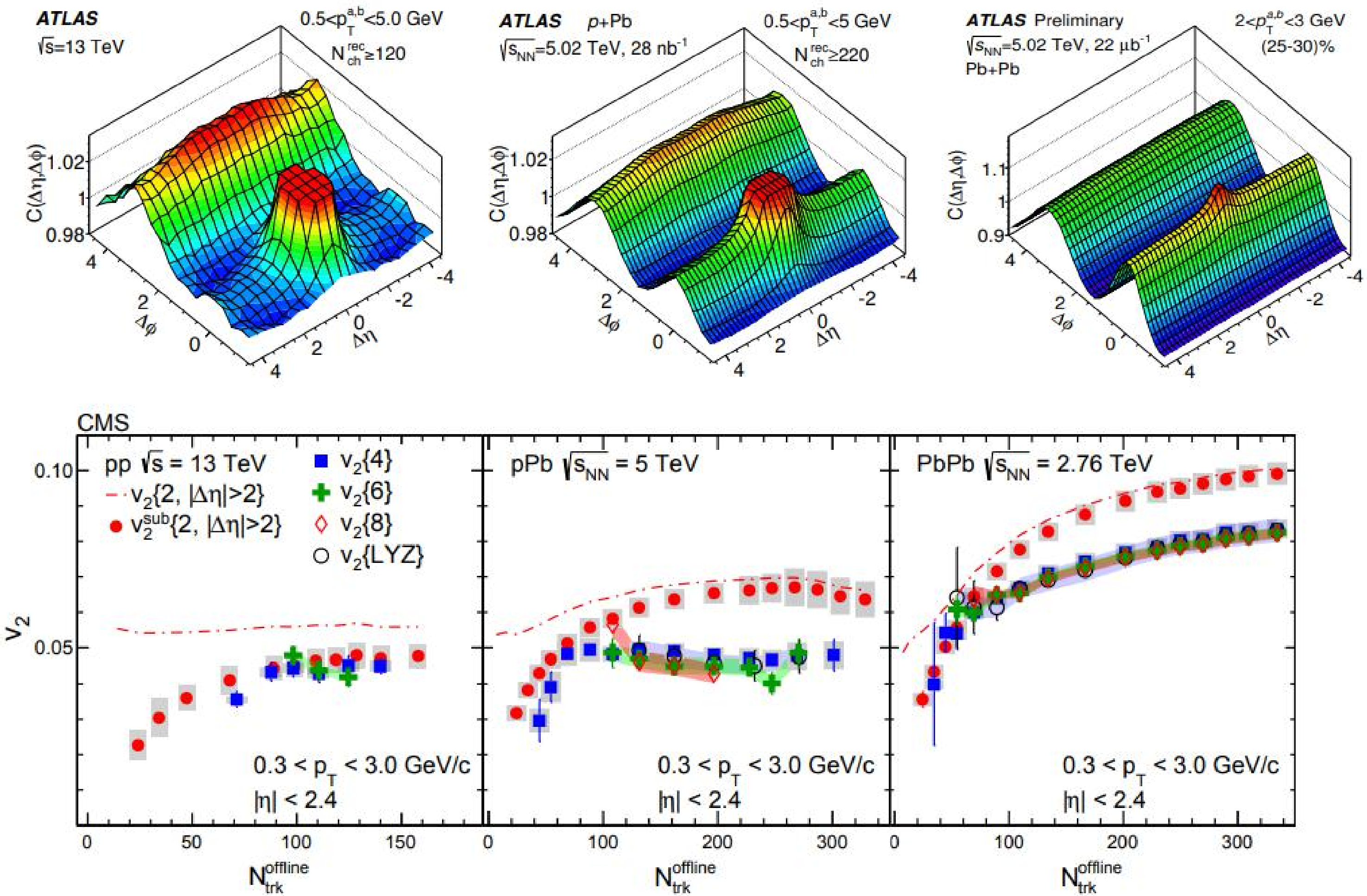
Supported by: **NKFIH/OTKA** K 120660 grant; **János Bolyai scholarship** of the Hungarian Academy of Sciences; **MOST-MTA** Chinese-Hungarian Research Collaboration

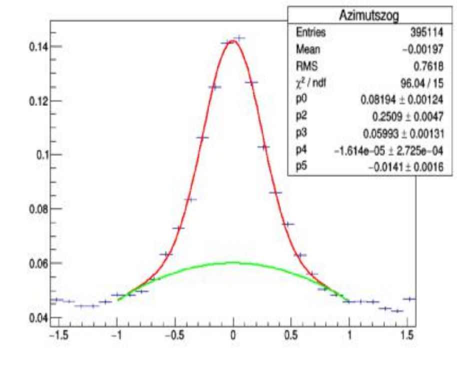
Correlations and v_2



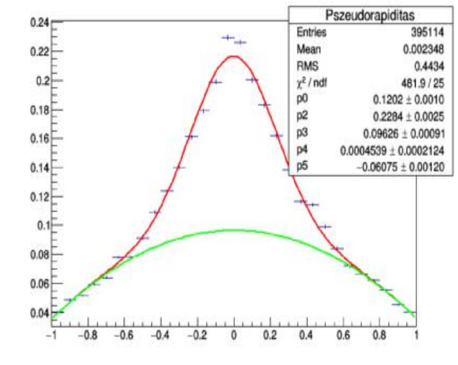
W. Li, arXiv:1704.03576, to appear in NPB

h-h correlations, near-side Gaus+p2 fit

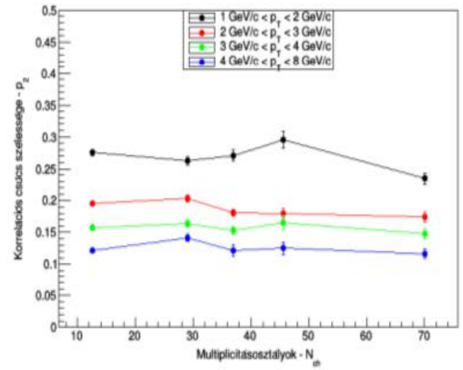
Miklós Kovács, BSc. Thesis, Budapest University of Technology and Economics (2018)



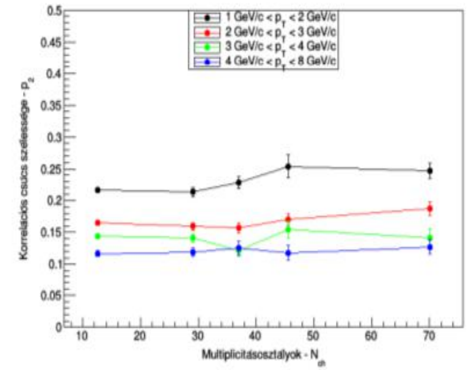
(a) $\Delta\phi$-irány
$1\ \mathrm{GeV}/c < p_T < 2\ \mathrm{GeV}/c\ ;\ 50 < N_{ch}$



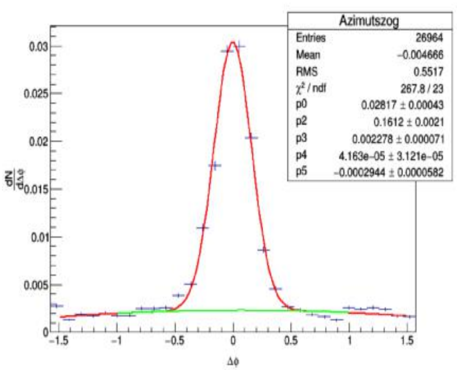
(b) $\Delta\eta$-irány
$1\ \mathrm{GeV}/c < p_T < 2\ \mathrm{GeV}/c\ ;\ 50 < N_{ch}$



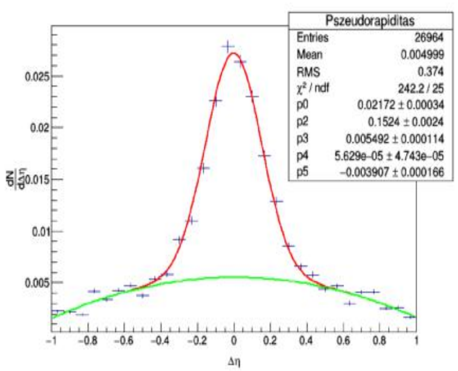
(a) $\Delta\phi$-irány , MPI: off , CR: off



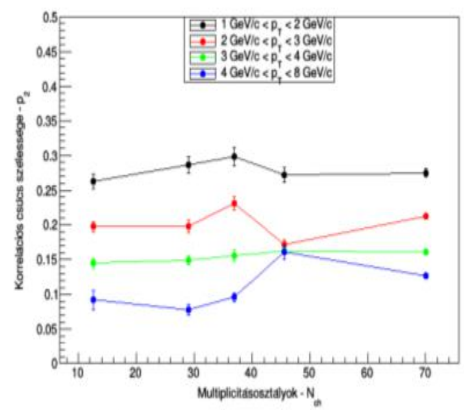
(b) $\Delta\eta$-irány , MPI: off , CR: off



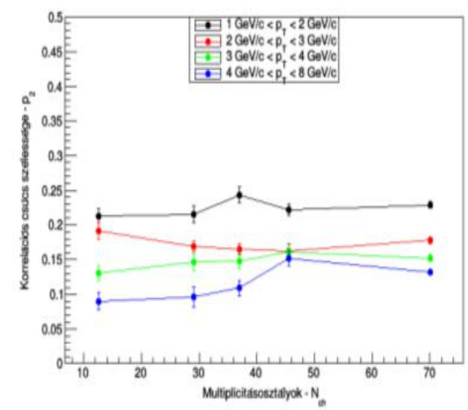
(c) $\Delta\phi$-irány
$4\ \mathrm{GeV}/c < p_T < 8\ \mathrm{GeV}/c\ ;\ 50 < N_{ch}$



(d) $\Delta\eta$-irány
$4\ \mathrm{GeV}/c < p_T < 8\ \mathrm{GeV}/c\ ;\ 50 < N_{ch}$



(e) $\Delta\phi$-irány , MPI: on , CR: on

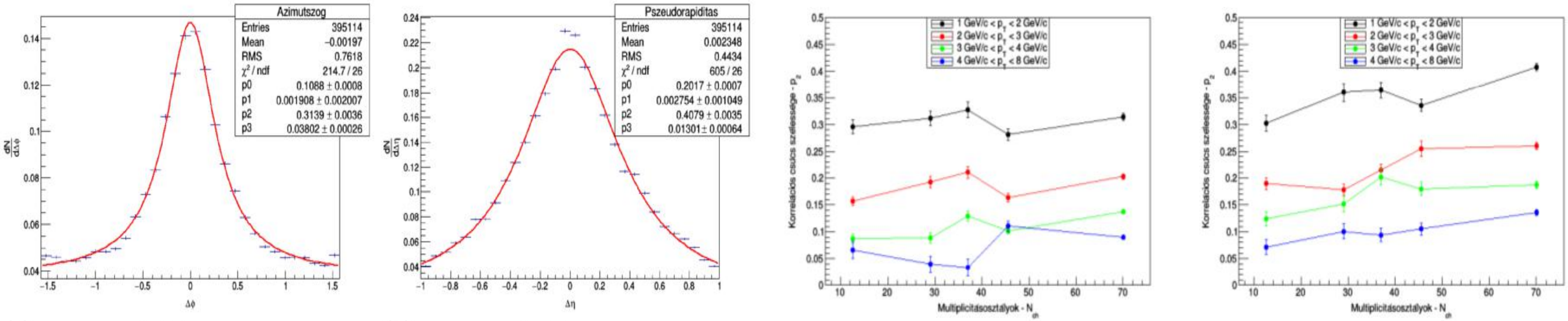


(f) $\Delta\eta$-irány , MPI: on , CR: on

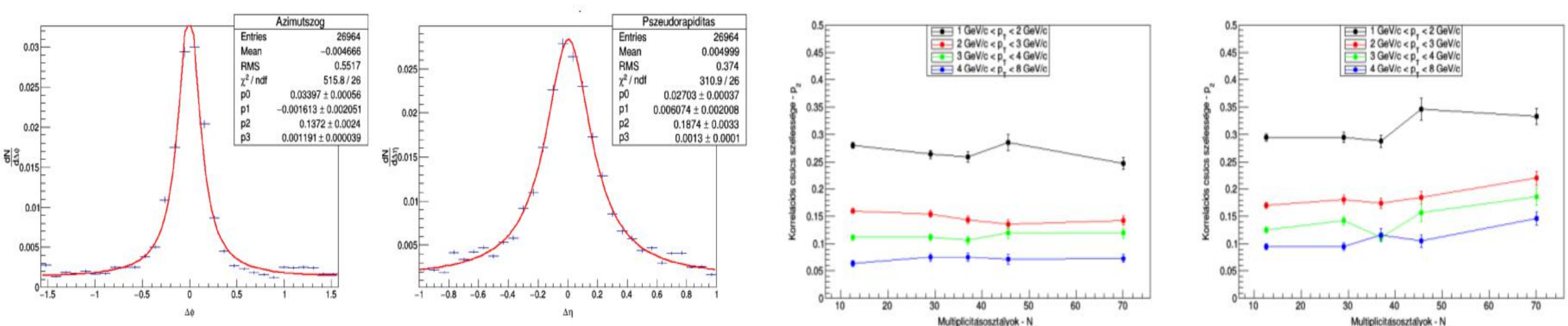
- Peak mostly includes fragmentation components,
- Long-range initial stage is in the parabolic backgound
- Broadening by MPI moderate

h-h correlations, near-side Cauchy fit

Miklós Kovács, BSc. Thesis, Budapest University of Technology and Economics (2018)



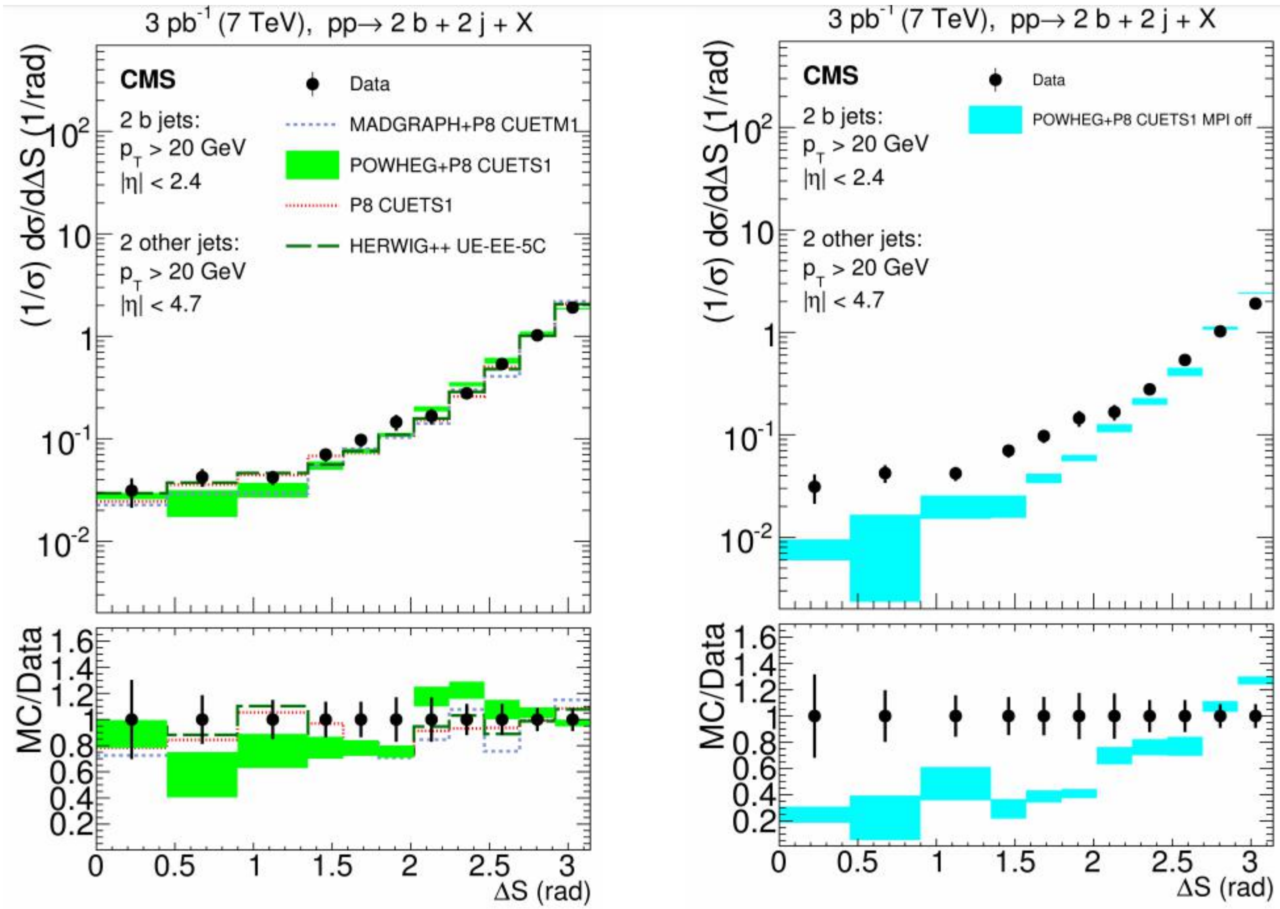
(a) $\Delta\phi$-irány 1 GeV/$c < p_T <$ 2 GeV/c ; $50 < N_{ch}$
(b) $\Delta\eta$-irány 1 GeV/$c < p_T <$ 2 GeV/c ; $50 < N_{ch}$
(e) $\Delta\phi$-irány , MPI: on , CR: on
(f) $\Delta\eta$-irány , MPI: on , CR: on



(c) $\Delta\phi$-irány 4 GeV/$c < p_T <$ 8 GeV/c ; $50 < N_{ch}$
(d) $\Delta\eta$-irány 4 GeV/$c < p_T <$ 8 GeV/c ; $50 < N_{ch}$
(a) $\Delta\phi$-irány , MPI: off , CR: off
(b) $\Delta\eta$-irány , MPI: off , CR: off

- Peak includes early-stage and fragmentation components
- Sizeable broadening by MPI

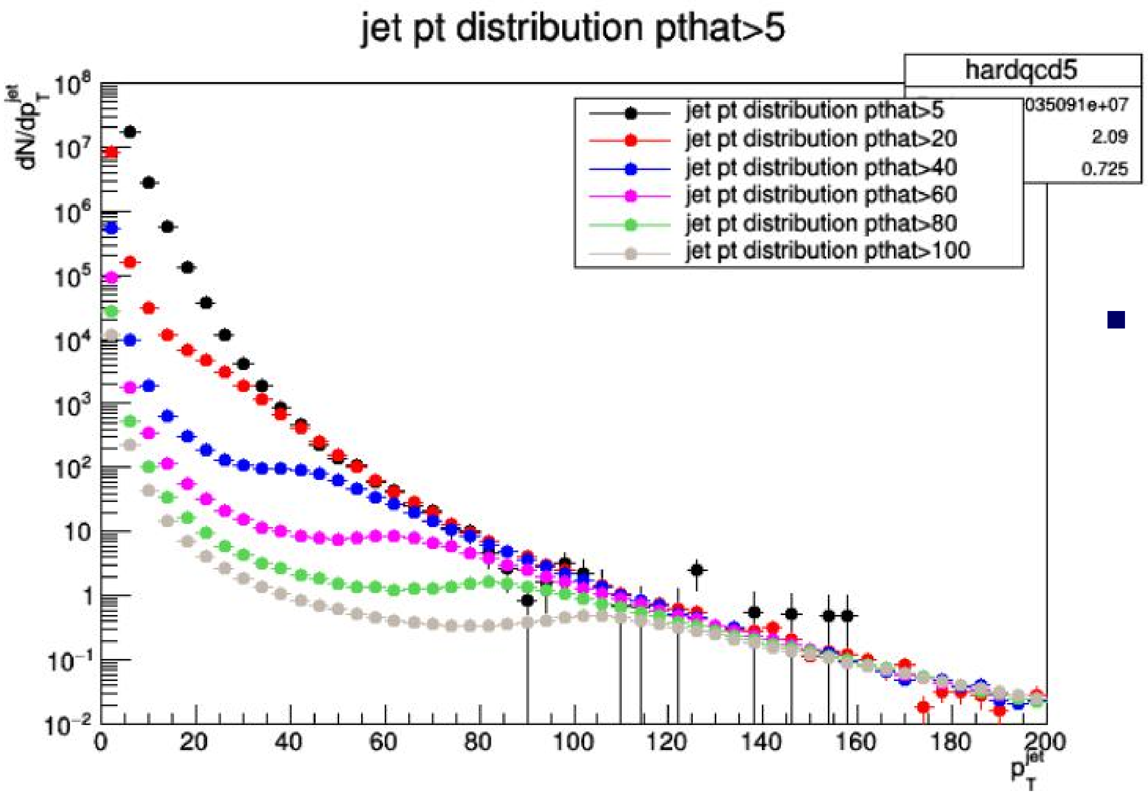
CMS 2j+2b dijet azimuthal angle ΔS



CMS, PRD94, 112005 (2016)

- Sensitive to MPI
- Robust regarding UE, choice of simulations

p_T^{jet} spectum and choices of $p_T\hat{}_{min}$



- p^T_{jet} spectra with different values of $p_T\hat{}_{min}$

- choices of $p_T\hat{}_{min}$ for given p_{Tjet} windows used in the analysis

p_t^{jet}	$\hat{p}_t$
20 - 25	5 $\leq$
30 - 40	5 $\leq$
50 - 60	20 $\leq$
70 - 80	20 $\leq$
90 - 100	40 $\leq$
110 - 125	40 $\leq$
140 - 160	80 $\leq$
180 - 200	80 $\leq$
225 - 250	80 $\leq$