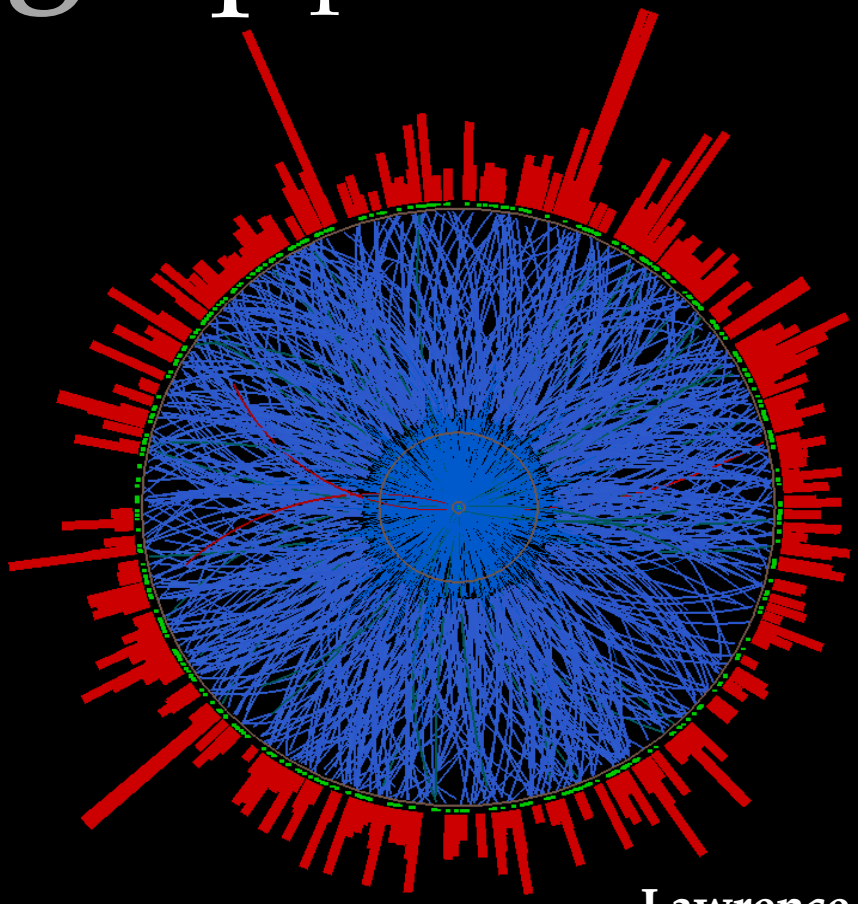
High p_T Correlations



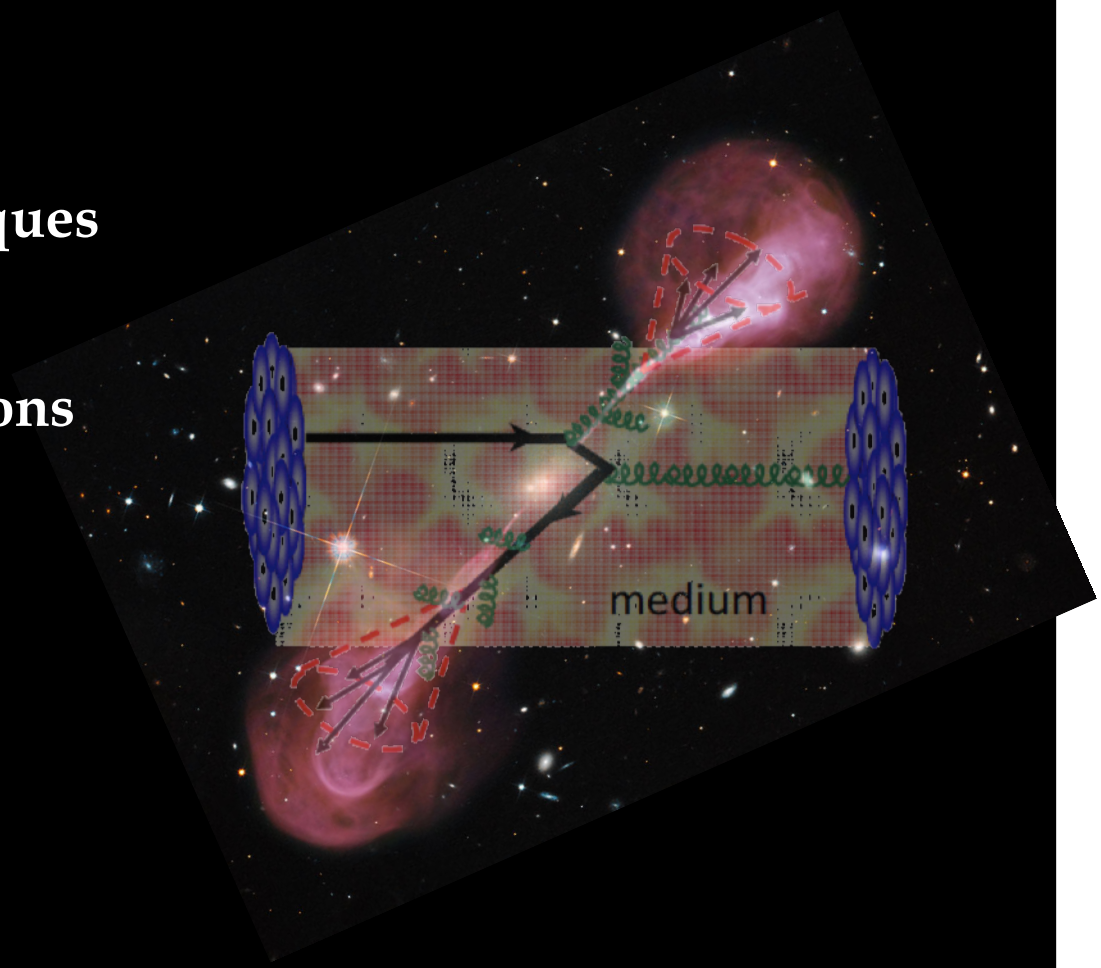
Alexander Schmah
Lawrence Berkeley National Lab

Hard Probes 2016 in Wuhan

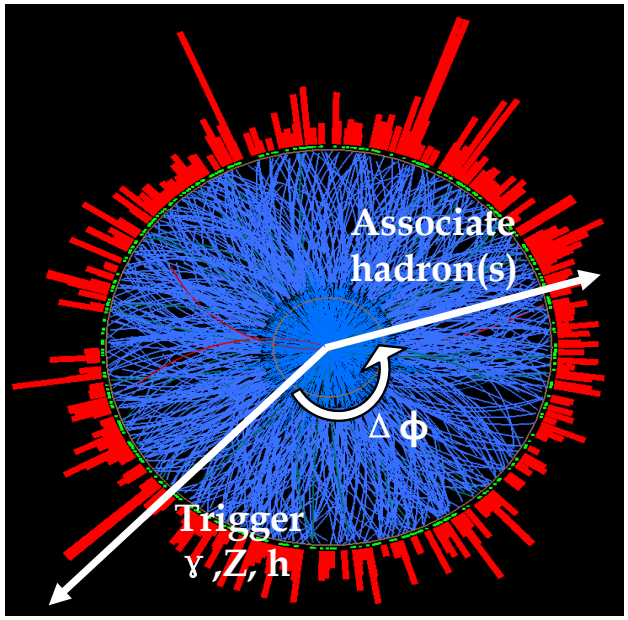
Berkeley Lab
U.S. Department of Energy

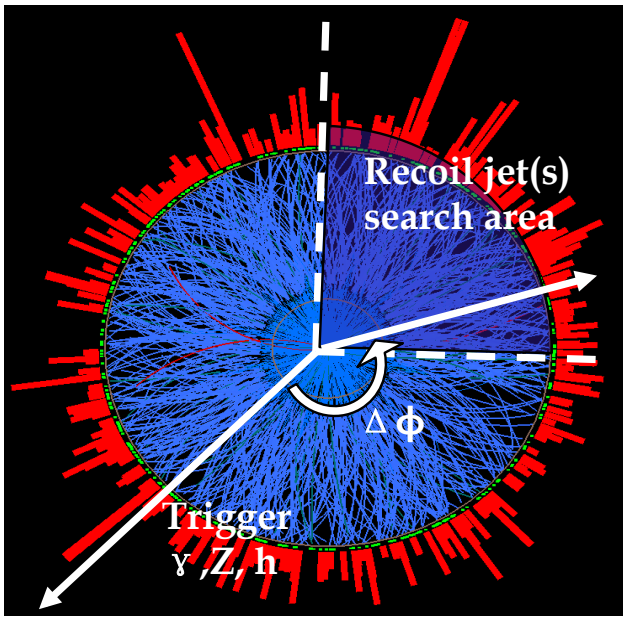
Outline

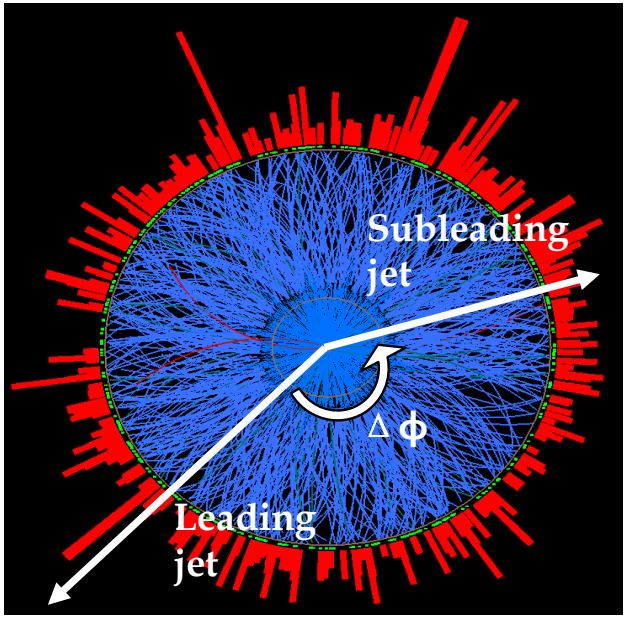
- **Reminders and some techniques**
- **γ/Hadron-Hadron Correlations**
- **γ/Z/Hadron-Jet Correlations**
- **Dijet Asymmetries**



Observables







- Straight forward and well know technique
- Δϕ
- Measure of recoil jet fragmentation function
- **No direct connection to initial parton kinematics on the associate side**
- **Limited information**

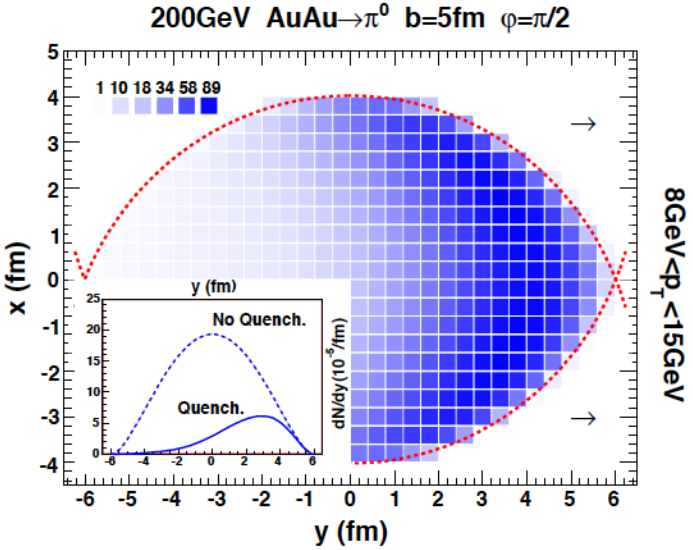
- Semi-inclusive measurement →calculable via pQCD
- High p_T trigger particle is proxy for jet axis
- Δϕ, energy imbalance
- **Combinatorial background jets must be subtracted**
- **Unfolding for detector effects and background**

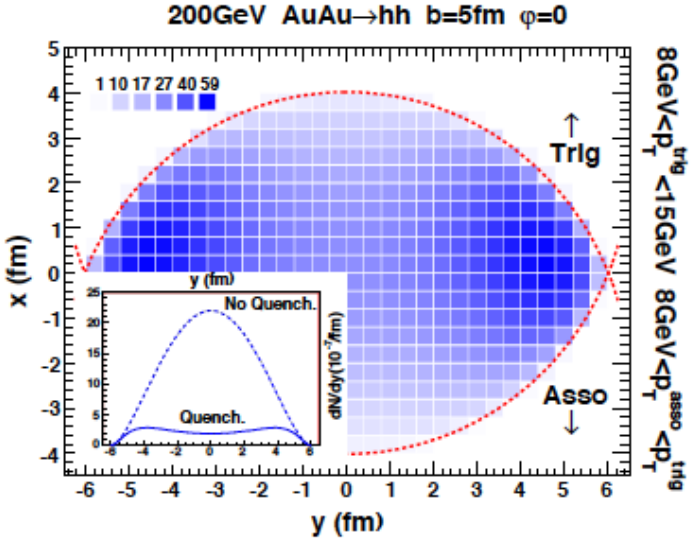
- Full jet reconstruction → ~initial parton kinematics
- Δϕ, energy imbalance
- **Unfolding for detector effects and background**

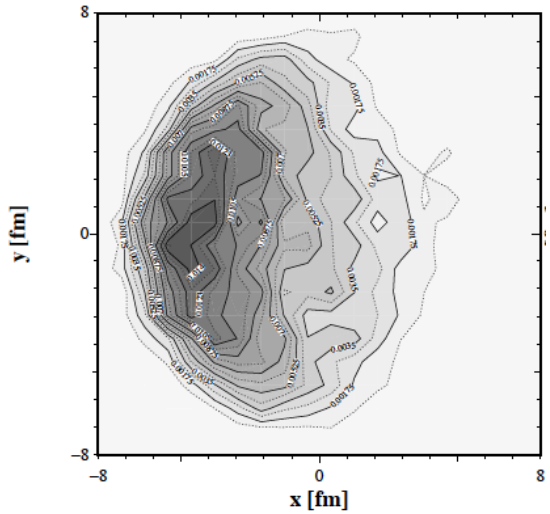
Jet/di-jet triggers: selection bias

Reminder: Production Vertex Bias

Phys.Rev.Lett. 98 (2007) 212301







Phys.Rev. C74 (2006) 024903

- Single hadron trigger: Surface bias
- Di-hadron trigger: Less surface bias
- Gamma/Z trigger: No bias

→ All of those are interesting!
→ Different recoil path lengths

γ/Hadron-Hadron Correlations

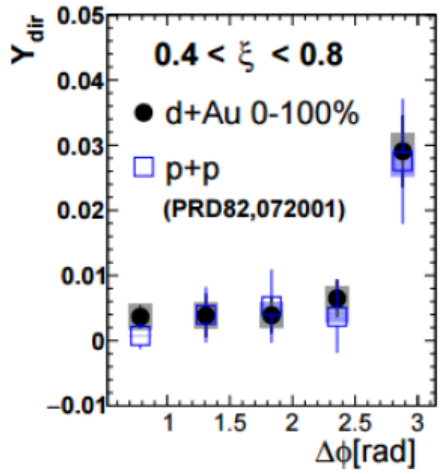
Direct Photon-Hadron Correlations

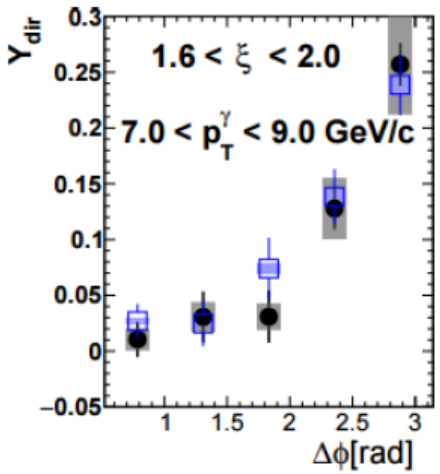
hard

soft

Huijun Ge, PHENIX

p+p
d+Au

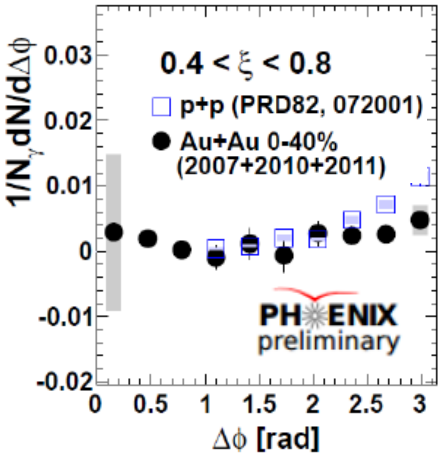


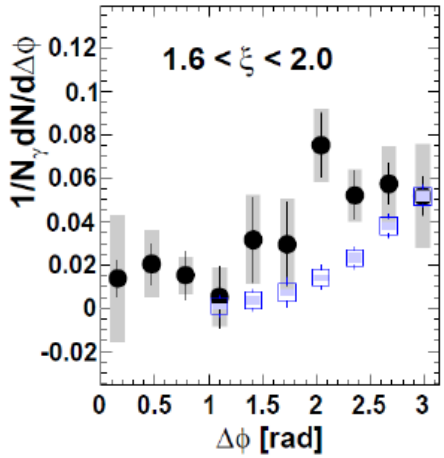


$$z_T = \frac{p_T^h}{p_T^\gamma}$$

$$\xi = \ln(1/z_T)$$

p+p
Au+Au

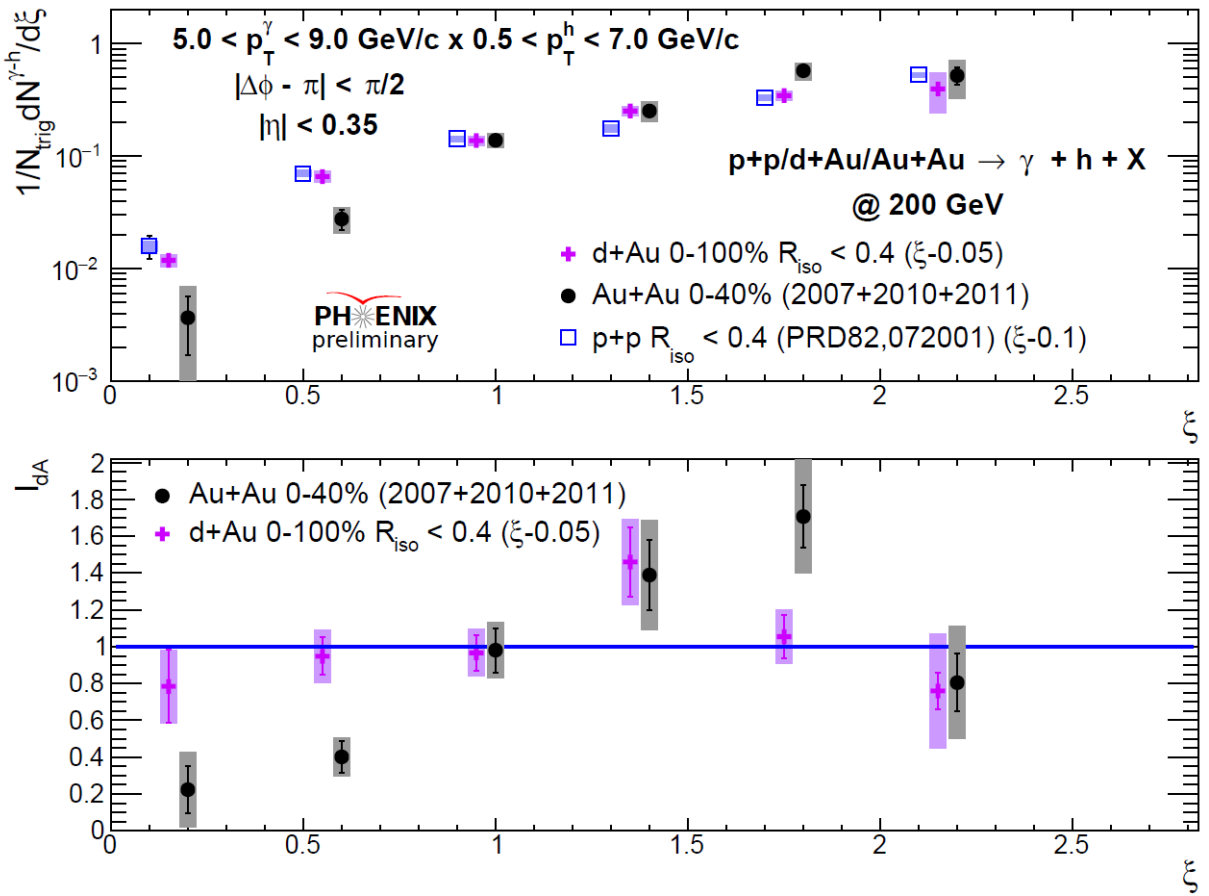




- d+Au and p+p in agreement → cold nuclear matter effect negligible
- Differences between p+p and Au+Au

I_{dA}/I_{AA} of Photon-Hadron Correlations

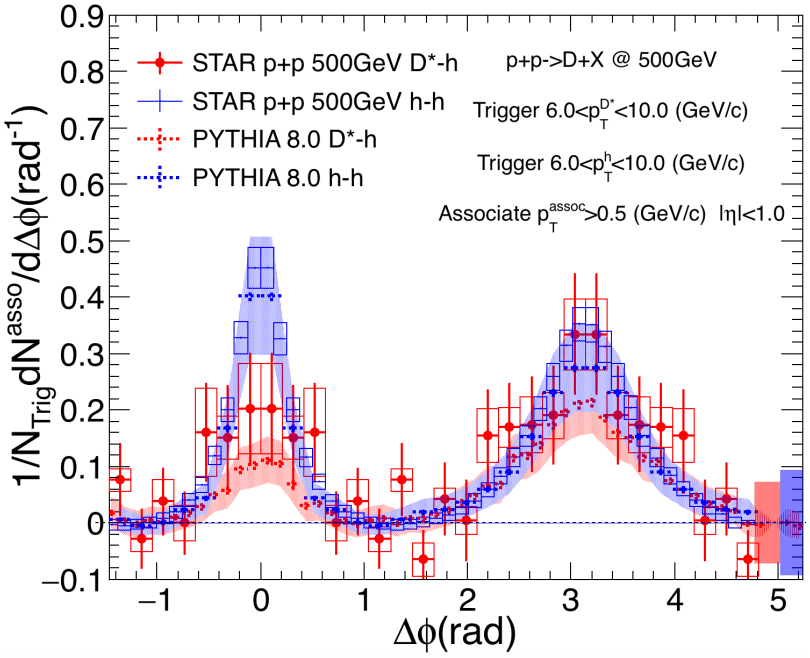
Huijun Ge, PHENIX

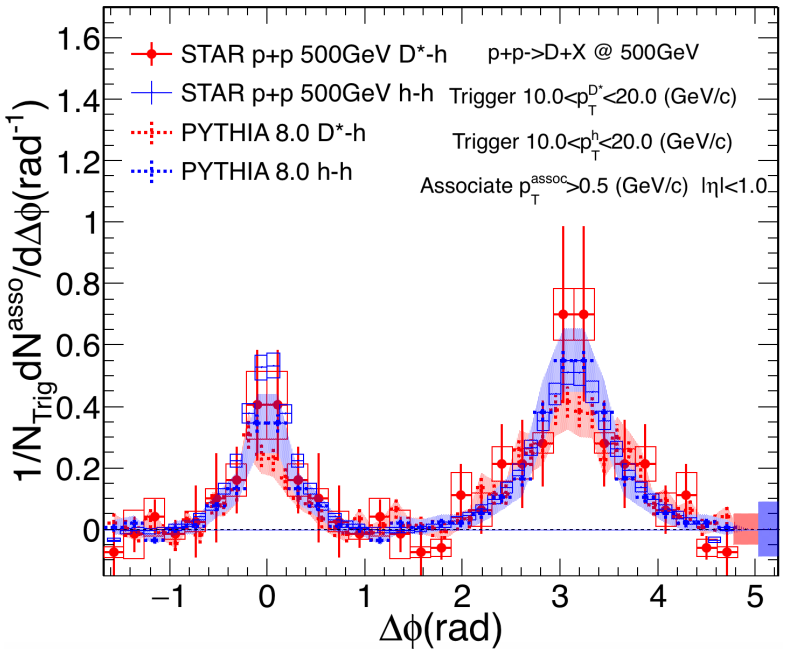


- d+Au I_{dA} consistent with no modification
- Modification in Au+Au:
  - Suppression at low ξ and enhancement at high ξ

D*-Hadron Correlations in p+p

Long Ma, STAR





- D*-hadron correlations at high p_T are similar to h-h correlations
- Difference on the near side at $6<p_T<10$ GeV/c
- Good agreement with PYTHIA 8.0 calculations
  → next step: Au+Au and D-h correlations with Heavy Flavor Tracker

- **Suppression and enhancement observed as a function of ξ, some evidence of medium response.**

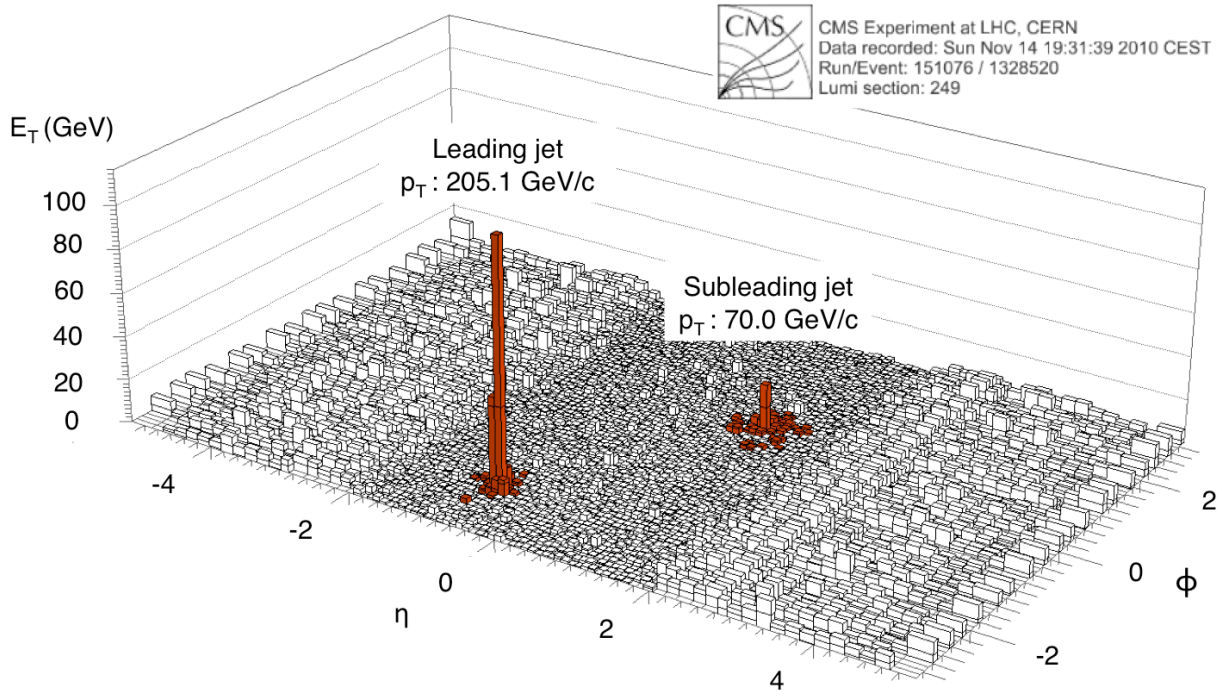
- **D might give some insights into charm fragmentation.**

- γ, Z are considered to be golden probes (no strong interaction, ~initial parton kinematics, no surface bias).

  → Can we quantify those effects?
  → Also one needs to take into account their low cross sections → larger errors compared to h-triggers.

γ/Z/Hadron-Jet Correlations

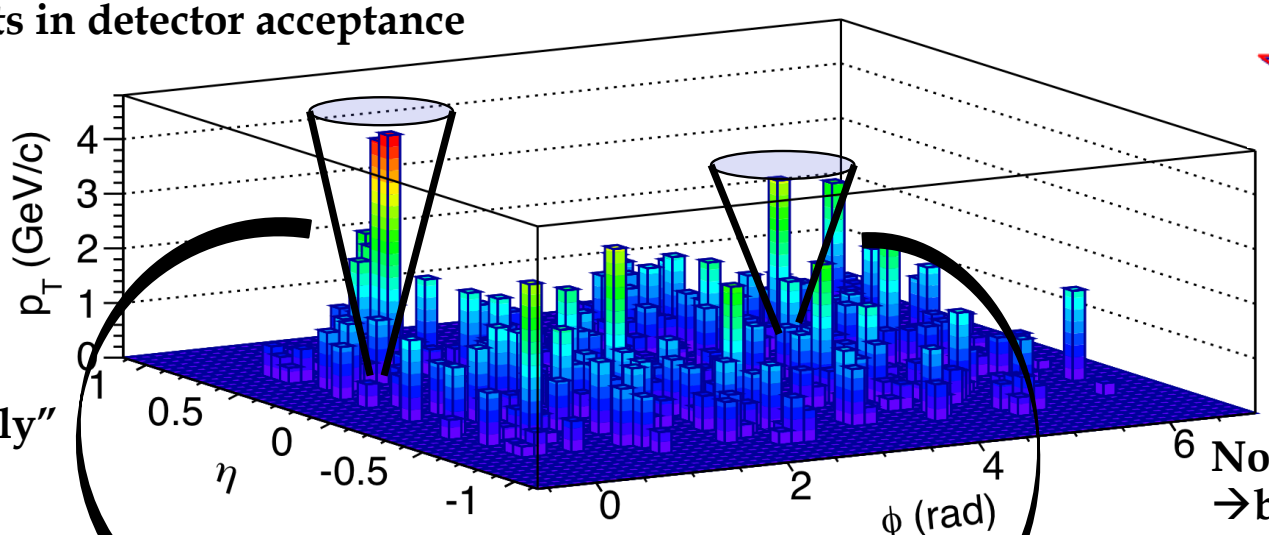
Jet Finding at High p_T



- High p_T objects, clearly seen over of heavy-ion background
  → Clear jet identification (at high p_T)
  → But measuring is not straight forward (background and detector smearing)

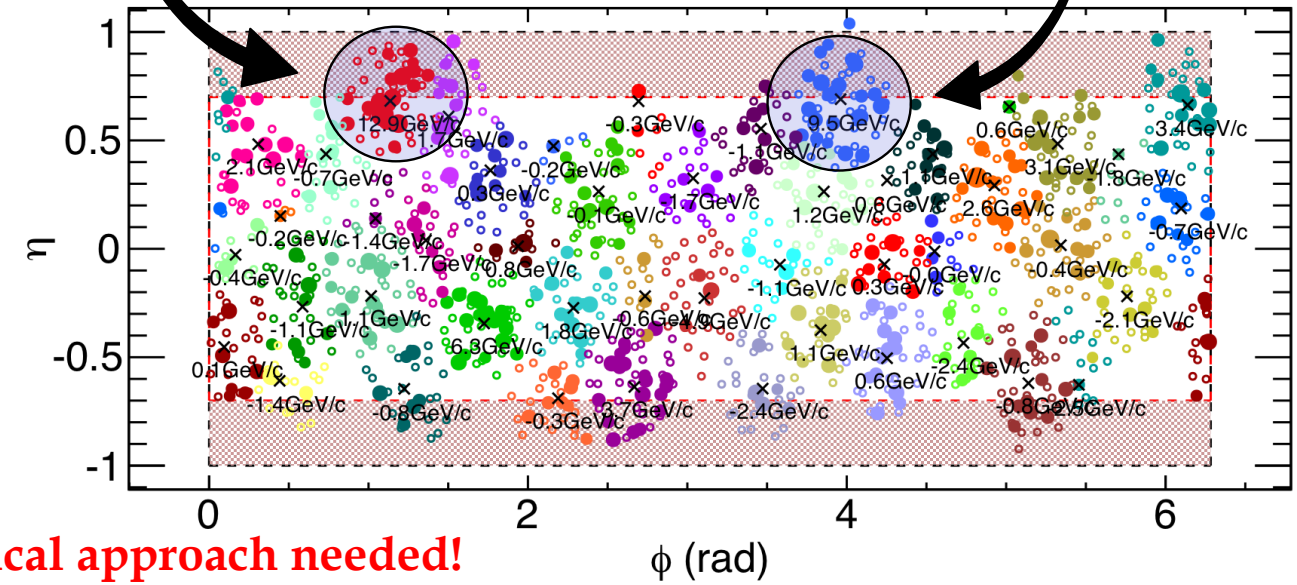
Jet Finding at low p_T

Tracks and jets in detector acceptance



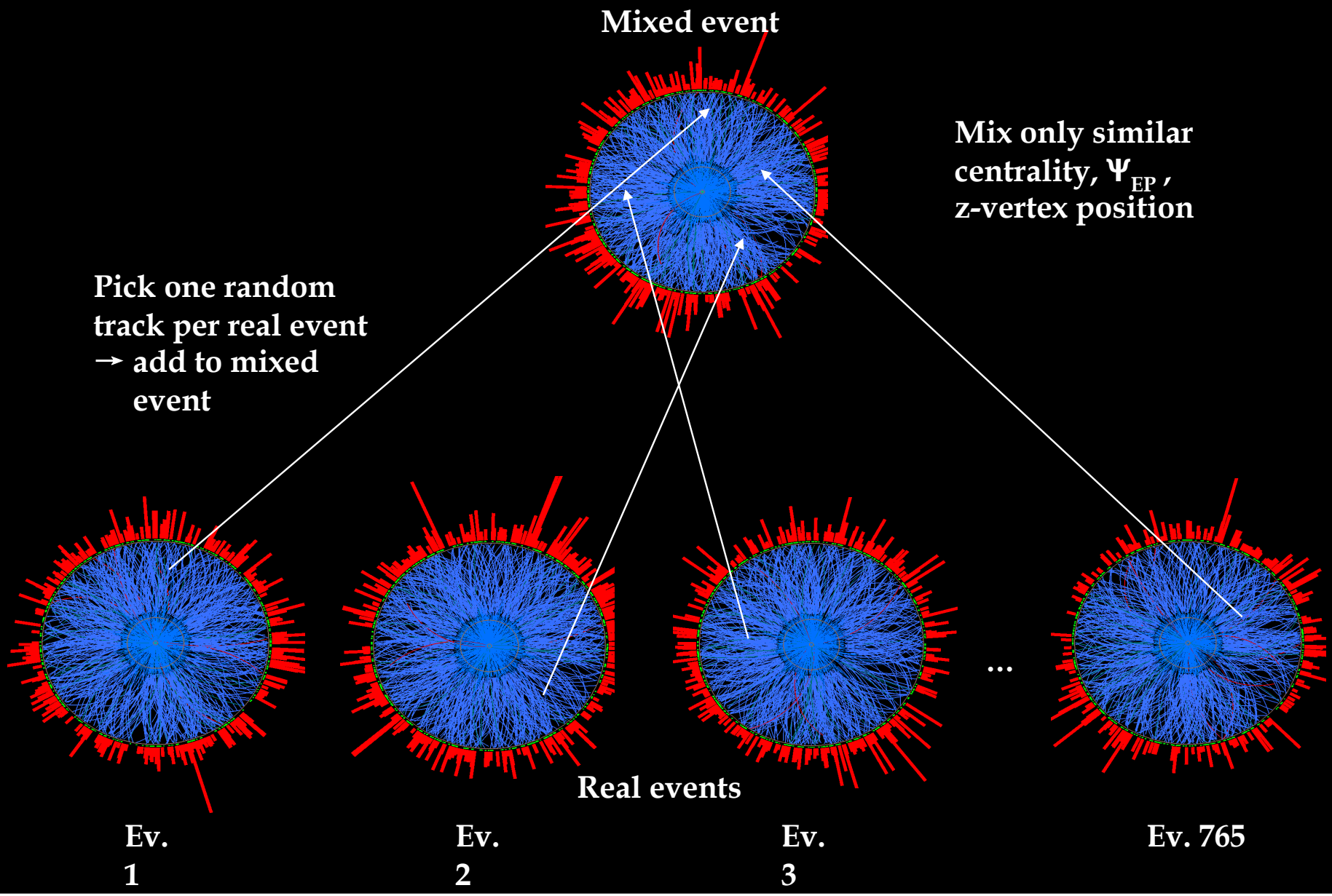
Can be "visually" identified

Not obvious →background is huge!

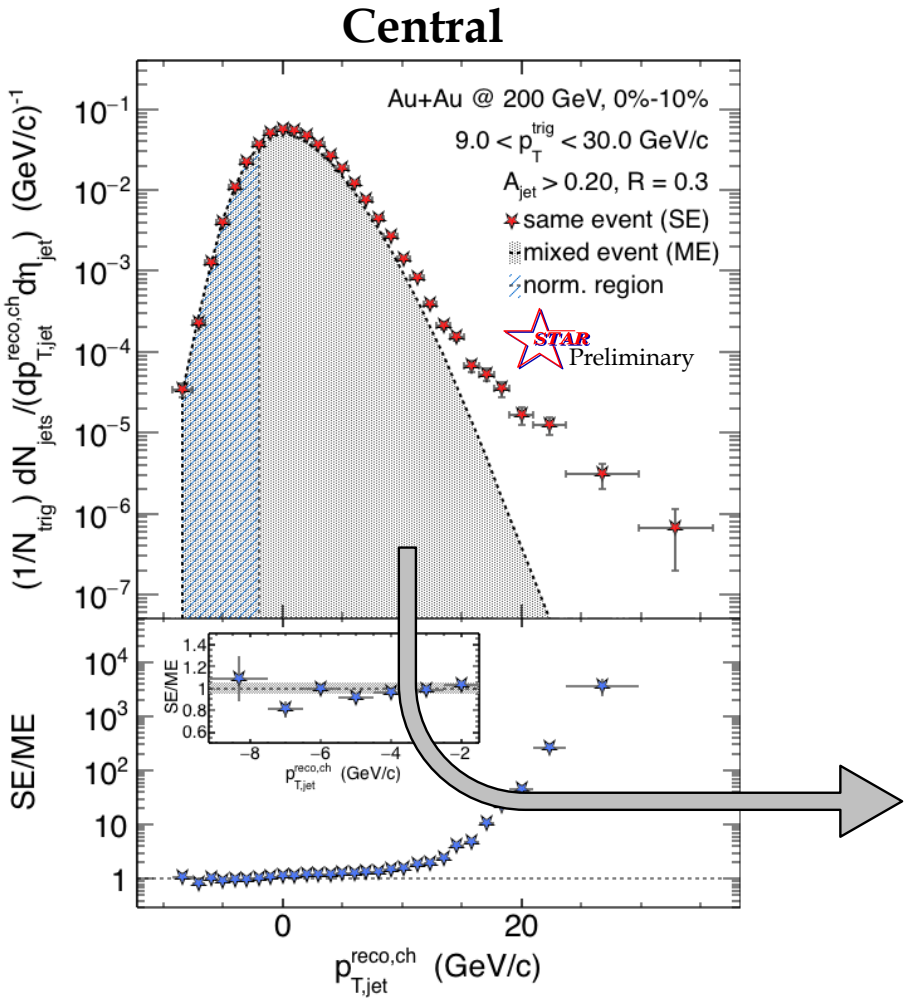


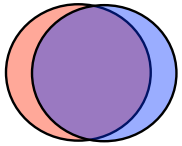
→ Statistical approach needed!

Background Description: Example Mixed Event Generation for Jets



Charged Raw Recoil Jet Spectrum: Central

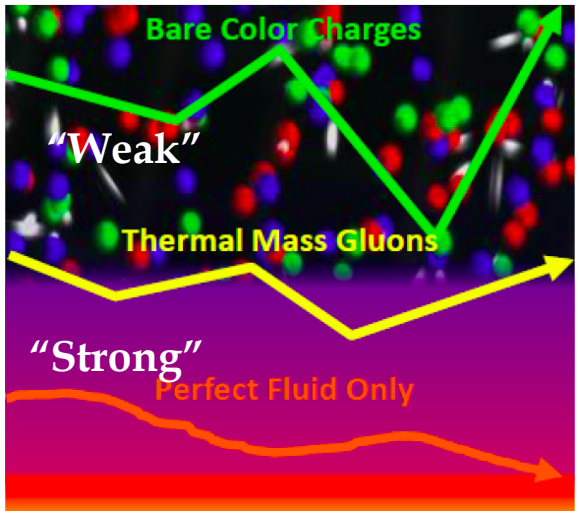




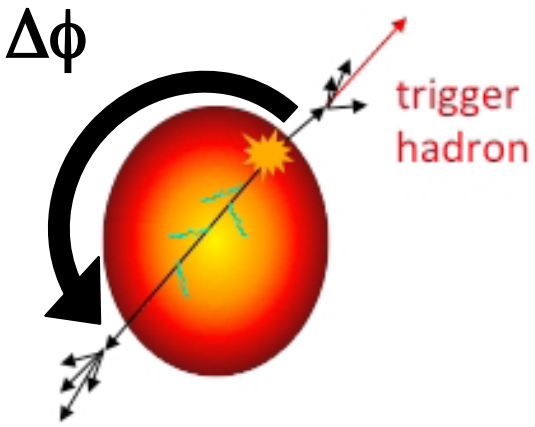
- Excellent description of low p_T SE spectrum with ME
- Normalization region varied systematically
- Significant jet signal at p_T-ρA > 10 GeV/c

Combinatorial jet background → statistically described by mixed event technique

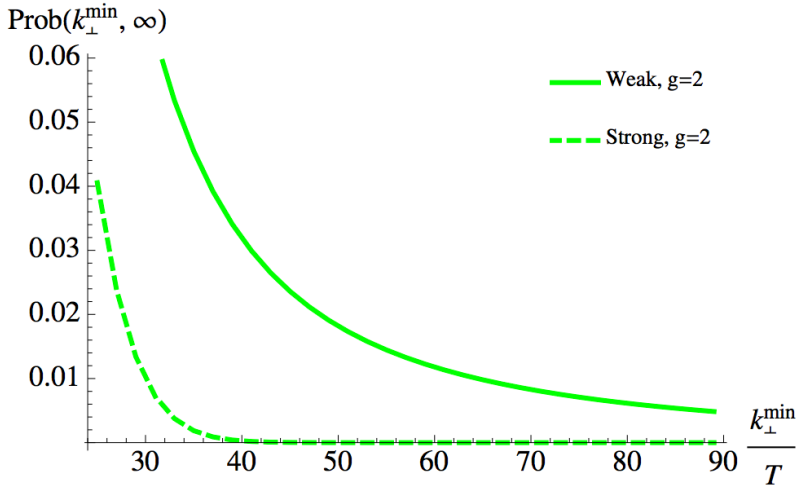
Large Angle Scattering off the QGP?



Discrete scattering centers or effectively continuous medium?

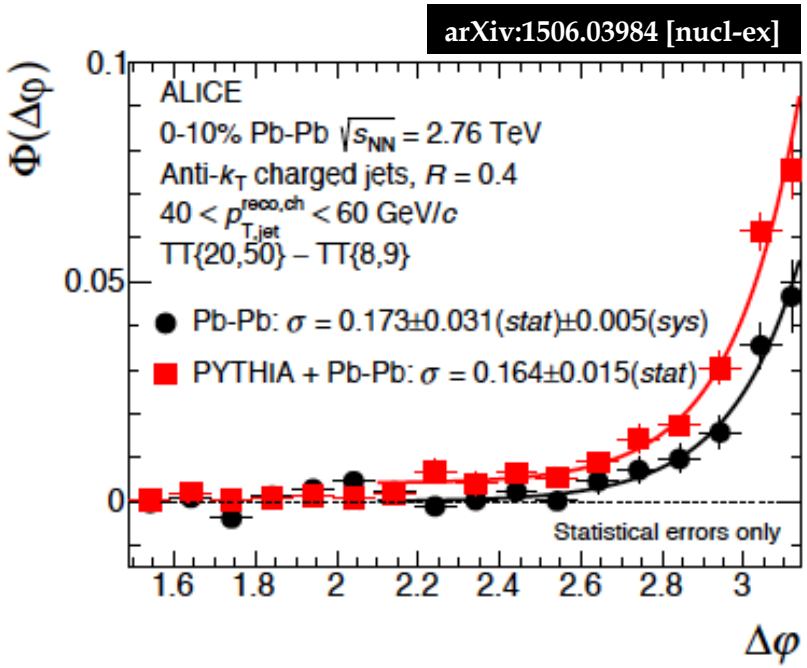


JHEP 1305 (2013) 031

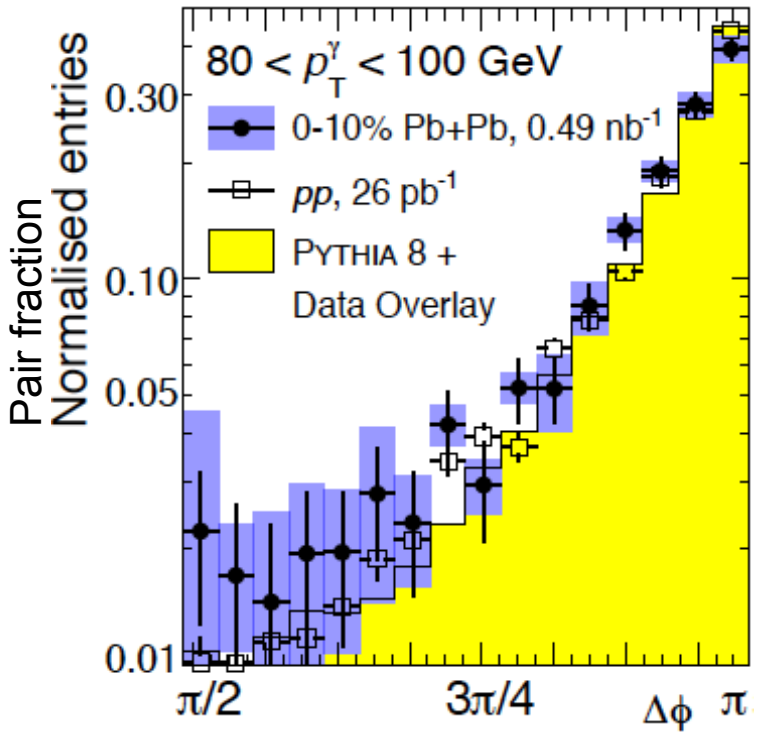


- Two components:
  → small angle due to soft radiation
  → large angle due to single Moliere scattering
- Scattering probability can give us important information about coupling
  → strongly/weakly coupled QGP
  → quasiparticles?

γ/Hadron-Jet Correlations at high p_T



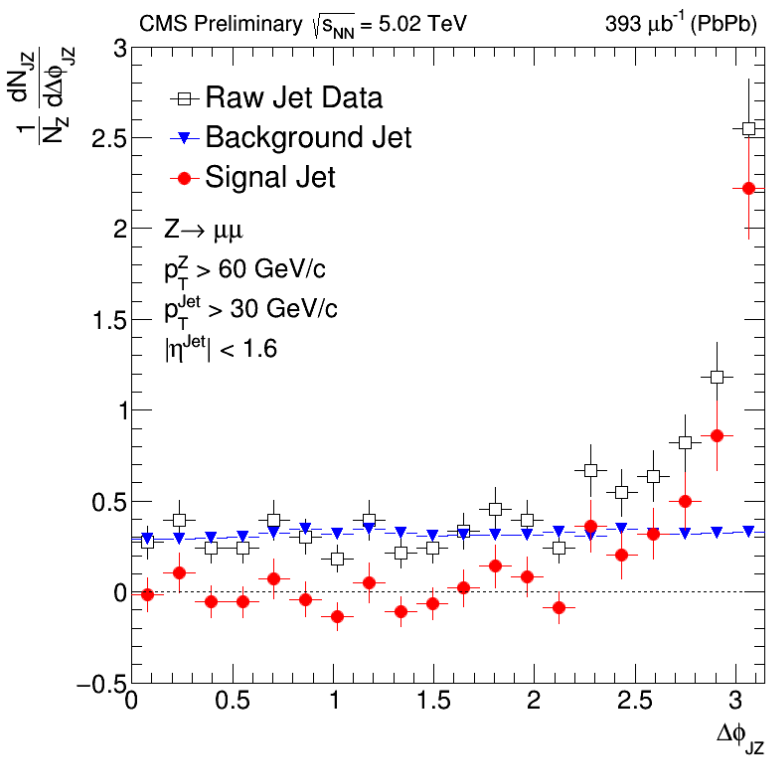
Brian Cole

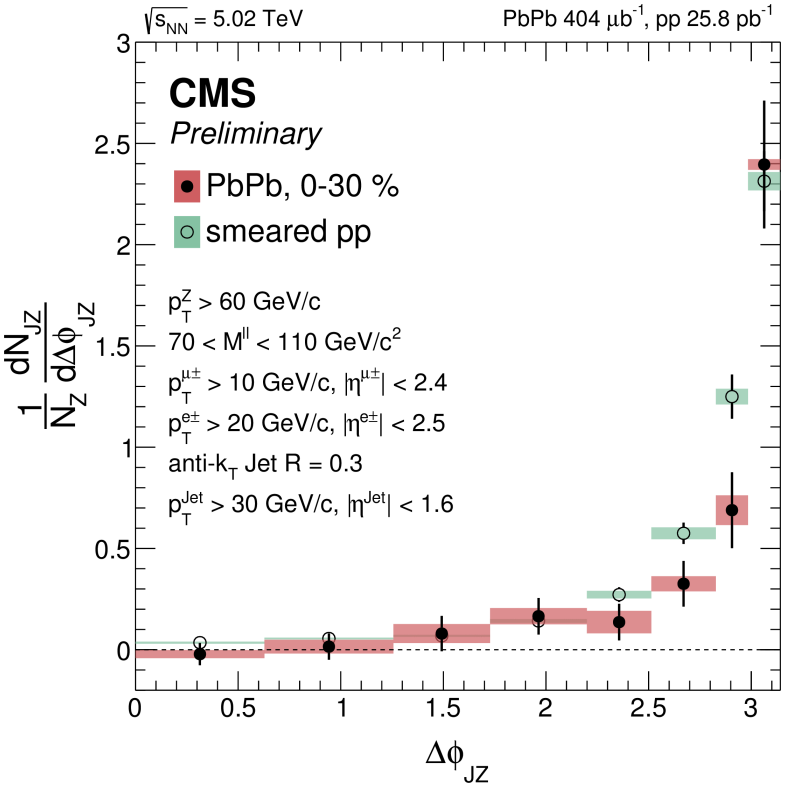


- No additional broadening observed in Pb+Pb compared to p+p so far
- No significant large angle scattering observed so far
- Background subtraction and normalization different

Z-Jet Correlation

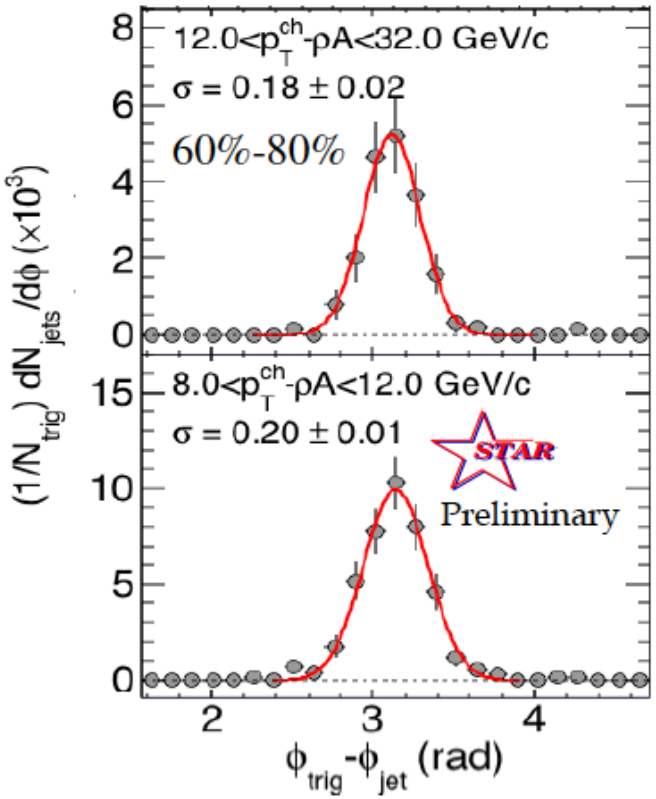
Kaya Tatar, CMS

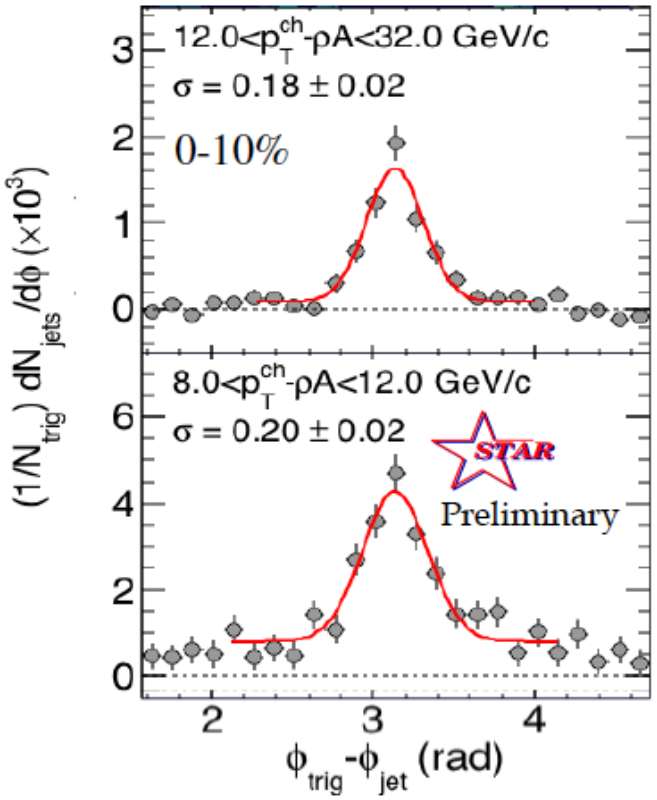




- Background subtraction via event mixing (different than STAR method!)
- Narrower shape in Pb+Pb compared to p+p

Hadron-Jet Correlations at low p_T





arXiv:1512.08784

- $\Delta\phi = \phi_{trig} - \phi_{jet}$
- Projections for different recoil jet p_T
- Background subtraction via 2D mixed event technique

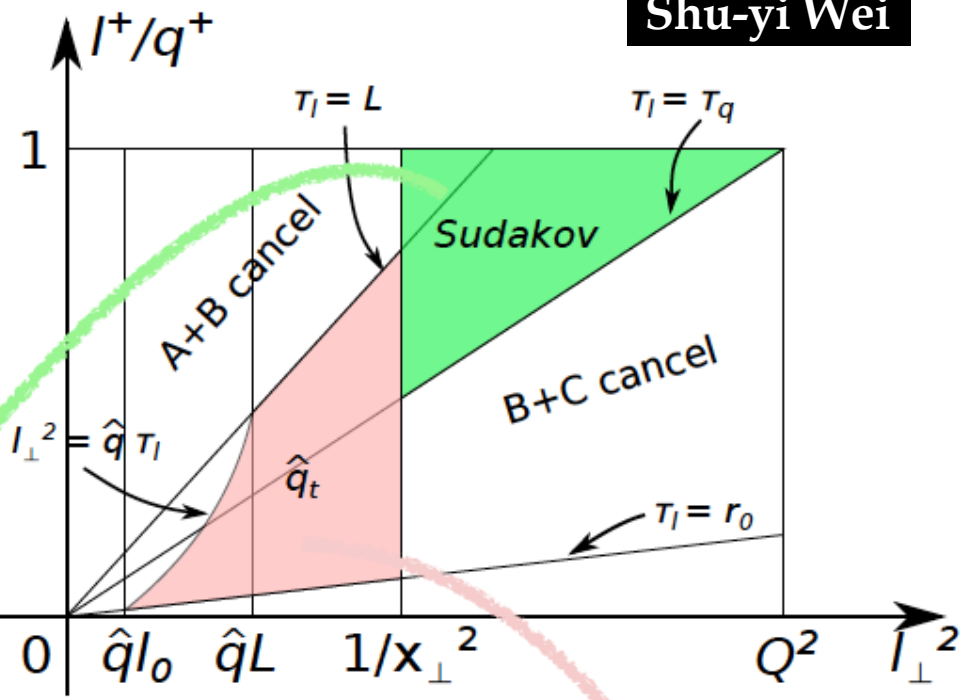
Calculation via Sudakov Resummation

Shu-yi Wei

From *pp* to *AA*

Mueller, Wu, Xiao, Yuan, arXiv:1608.07339

Considering one gluon radiation in the large medium,
Medium Induced Radiation and
Vacuum Parton Shower
can be separated.



hot medium

$$S_{AA}(Q,b) = S_{pp}(Q,b) + \frac{\langle \hat{q}L \rangle b^2}{4}$$

Vacuum parton shower

k_T broadening

Multiple scattering
Medium induced radiation

Transverse Momentum Broadening

arXiv:1607.01932

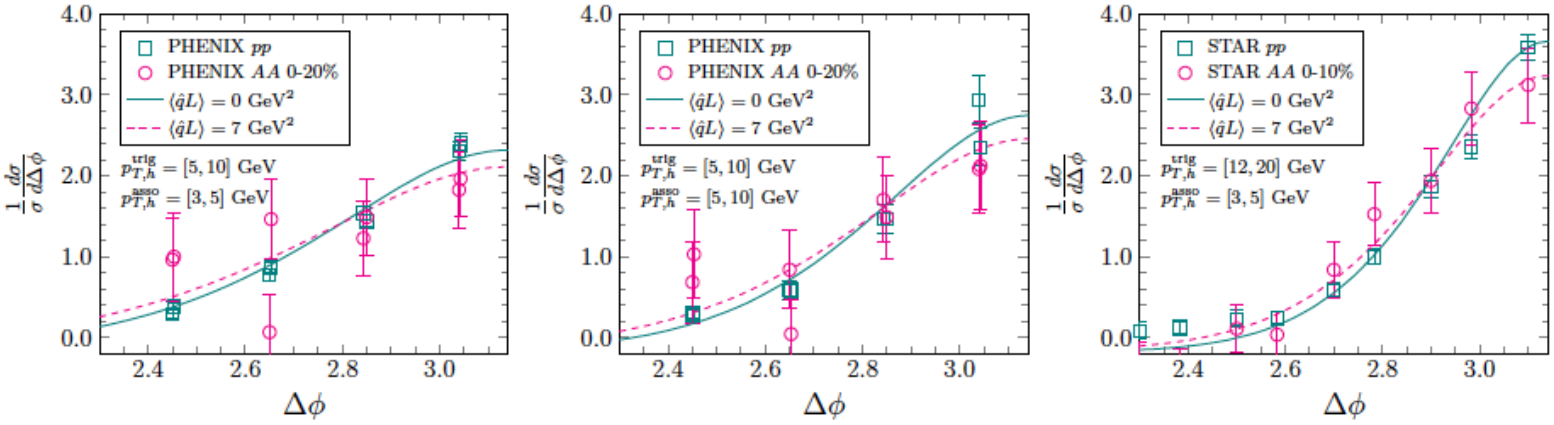
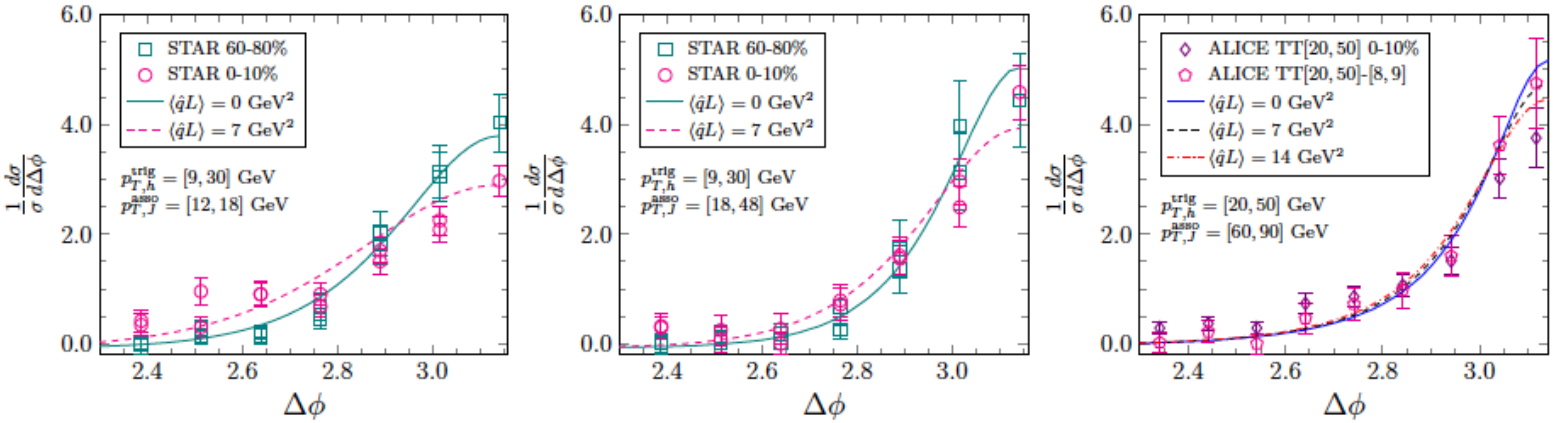


FIG. 1. Normalized dihadron angular correlation compared with PHENIX [51] and STAR [52] data.



- Small change of distributions for h-h correlations and for high-p_T
- Strongest sensitivity for qL for h-jet correlations at low p_T (12-18 GeV/c)

- Low p_T recoil jets show sensitivity to medium interactions
→ acoplanarity, extraction of qL seems to be possible!

- Normalization of $\Delta\phi$ distributions is per trigger or per pair
→ per pair does not allow for limits at large angles and does hide the suppression (shape comparison)

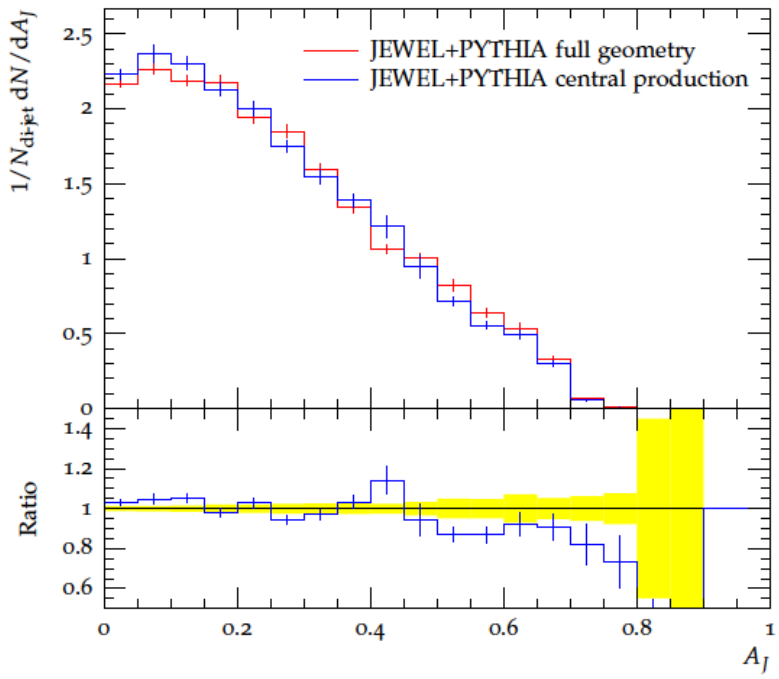
- Background normalization is not straight forward.

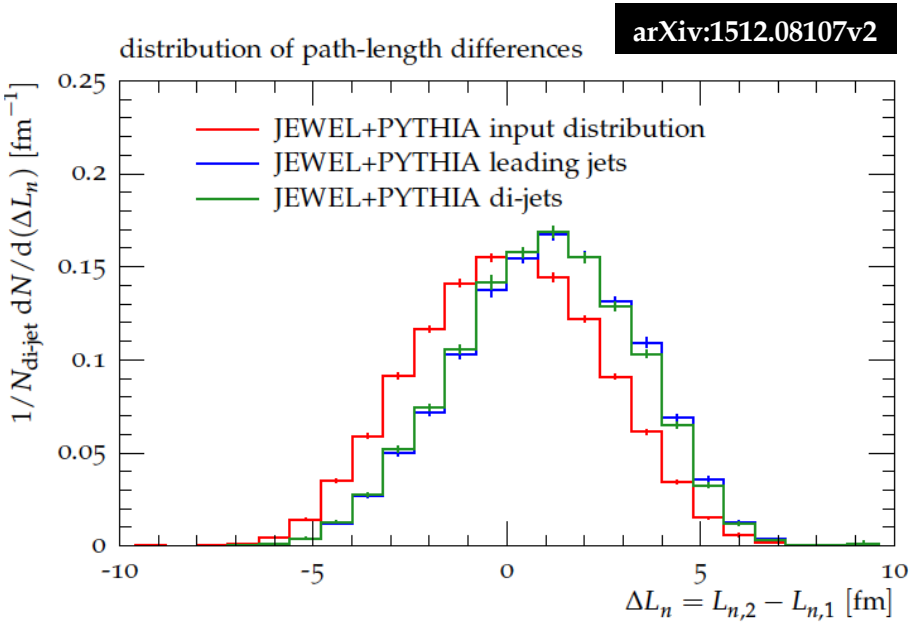
- 2D unfolding needs to be done in order to compare to theory calculations.

- Theory is using not unfolded distributions
→ extracted parameters for qL might be off

Dijet Asymmetries

Path Length Effect for Dijets



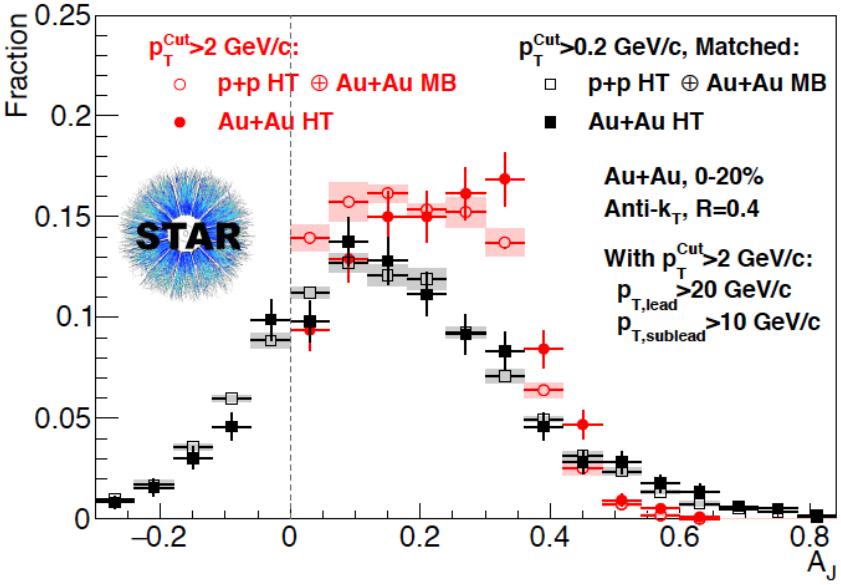


- Path length effect is small for dijet selection

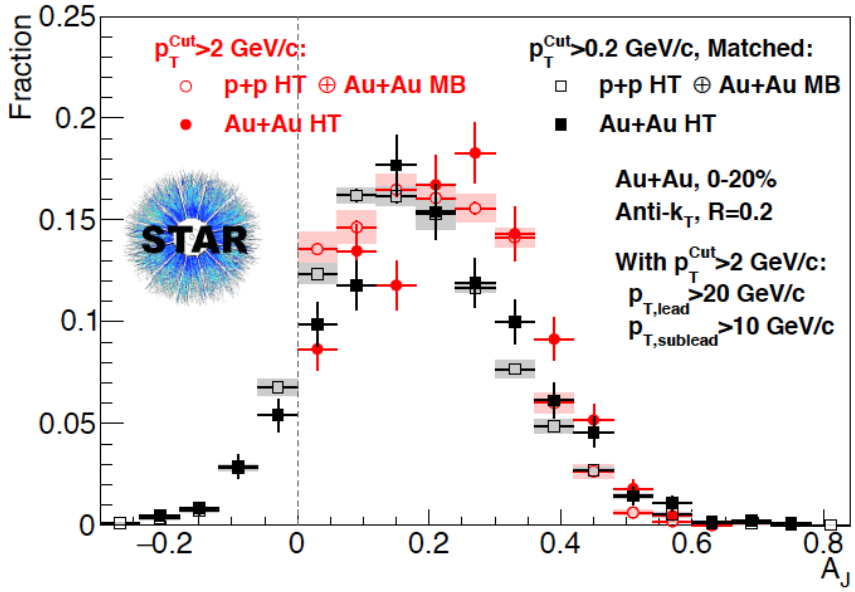
Di-Jet Imbalance at RHIC

arXiv:1609.03878

R = 0.4



R = 0.2

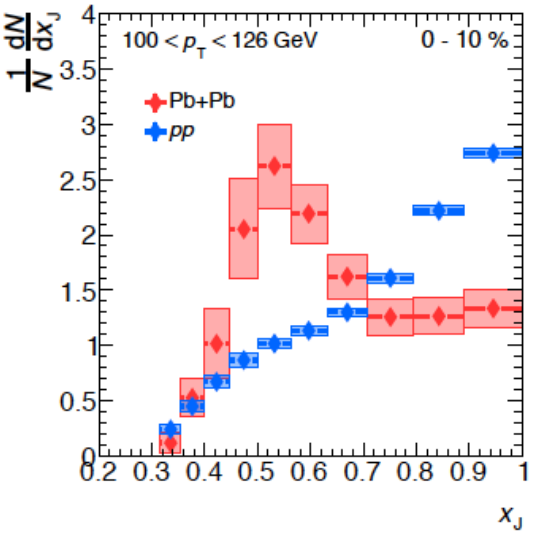


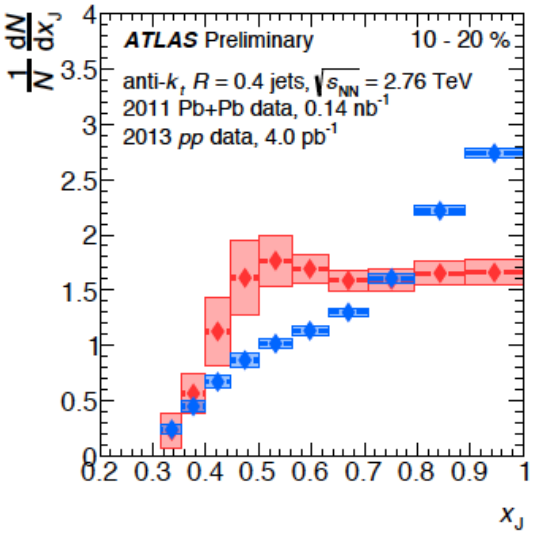
- Larger imbalance for Au+Au compared to p+p for R = 0.4 and pT > 2 GeV/c
- Same AJ distributions after soft particles are included
- Au+Au and p+p are different for R = 0.2
  → Some energy is transported to R > 0.2
  → Soft constituent particles needed to balance jets to the p+p level

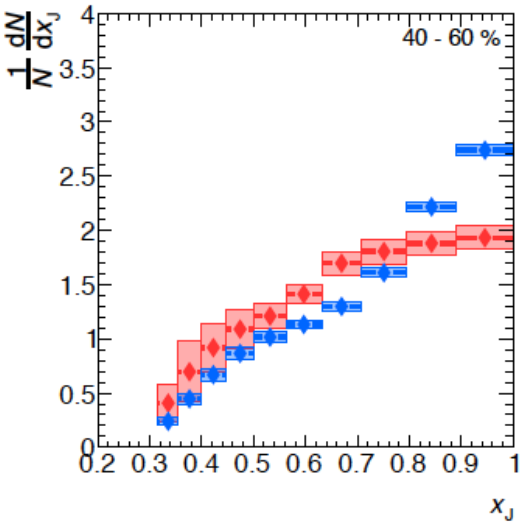
$$A_J = \frac{p_T^{Jet,1} - p_T^{Jet,2}}{p_T^{Jet,1} + p_T^{Jet,2}}$$

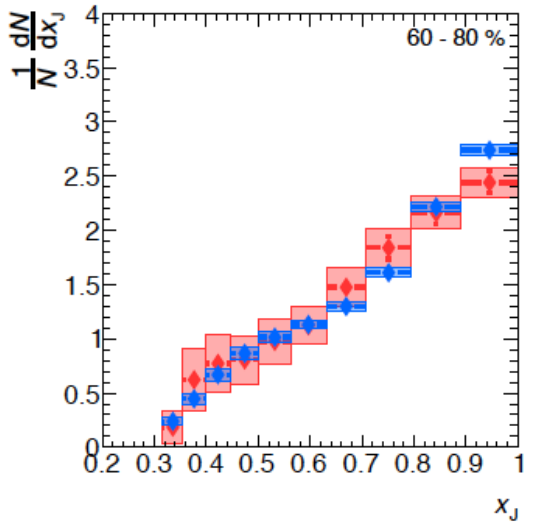
Di-Jet Energy Imbalance

Brian Cole









- Full 2D-unfolding
- Peripheral Pb+Pb and p+p are in agreement
- Di-jets in central Pb+Pb are clearly imbalanced compared to p+p

$$x_J = \frac{p_T^{Jet,sub}}{p_T^{Jet,lead}}$$

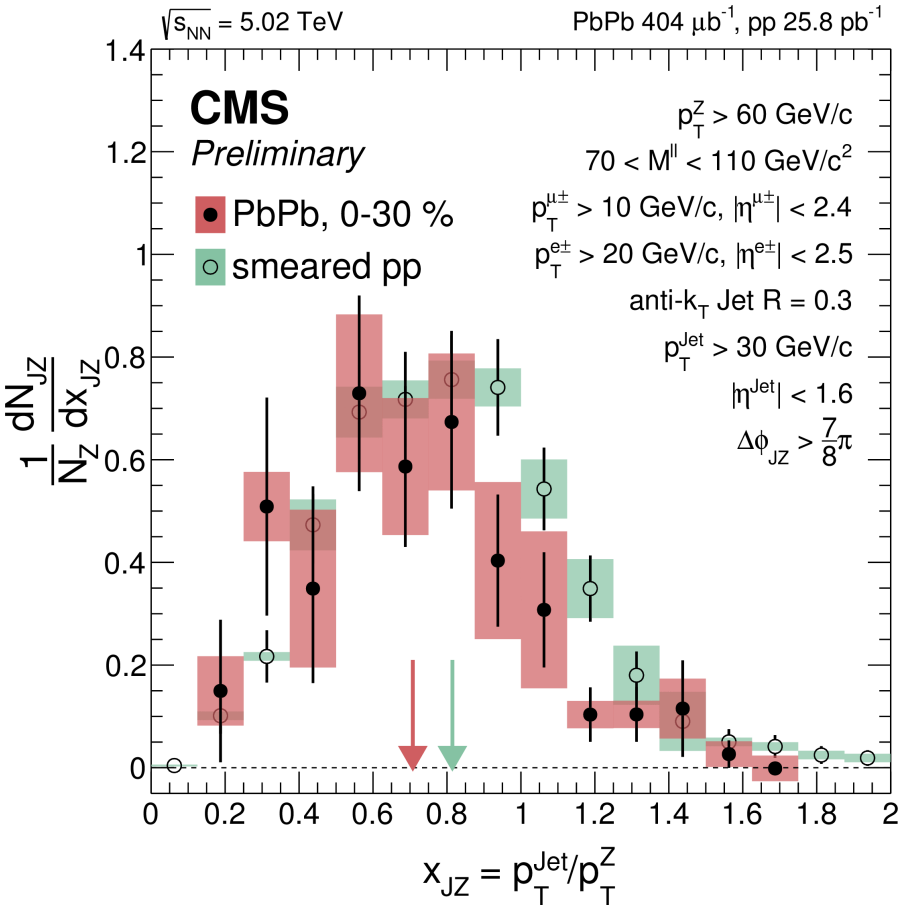
Z-Jet Energy Imbalance

Kaya Tatar, CMS

$$x_{JZ} = \frac{p_T^{Jet}}{p_T^Z}$$

- Z is an excellent probe for energy imbalance measurements:
  - no strong interaction
  - no background (from trigger)

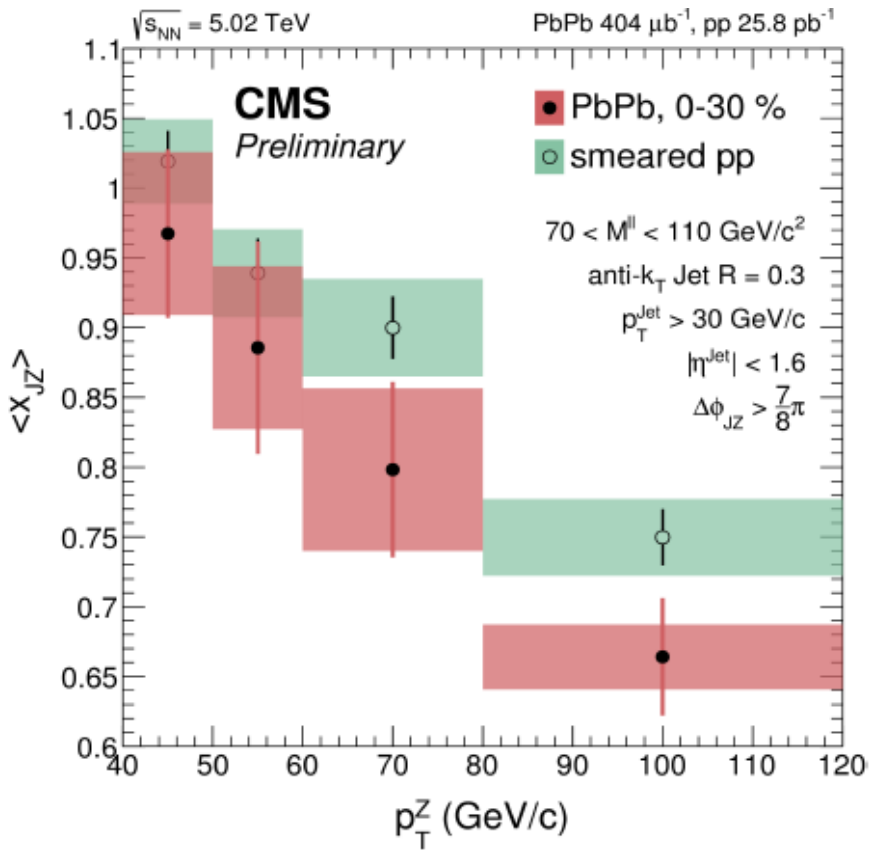
- Tendency of a larger imbalance for Pb+Pb compared to p+p



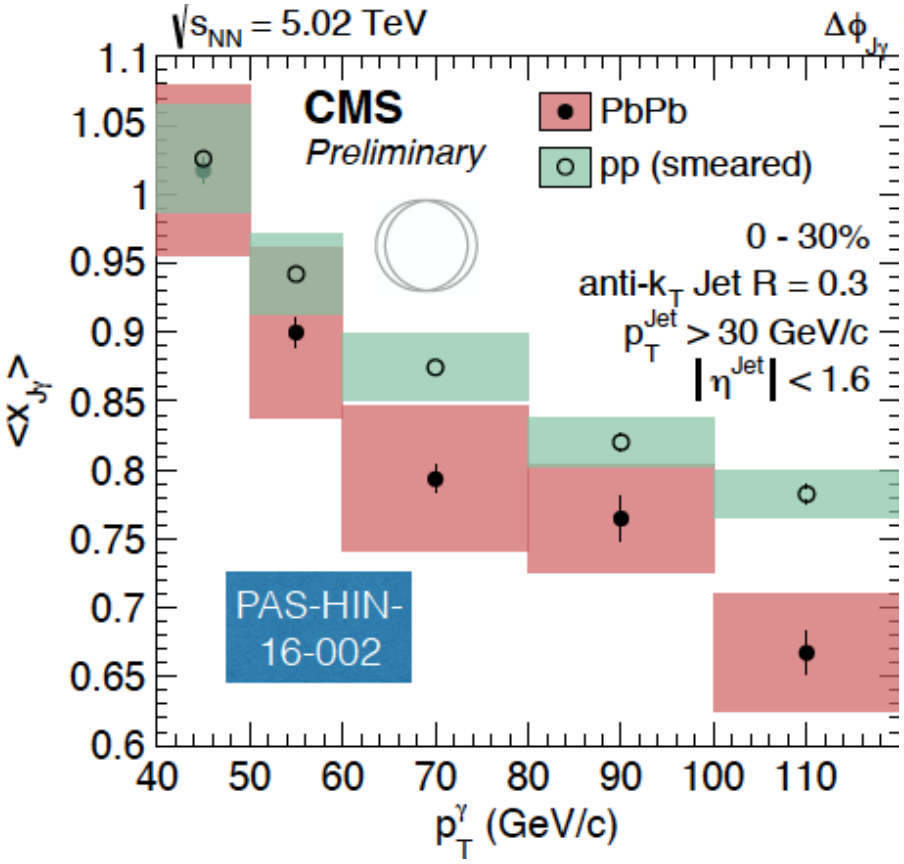
Pb+Pb, 0-30%: $\langle x_{JZ} \rangle$ = 0.71+/-0.04
p+p : $\langle x_{JZ} \rangle$ = 0.81+/-0.02

Comparison of Z-Jet to γ-Jet

Kaya Tatar, CMS



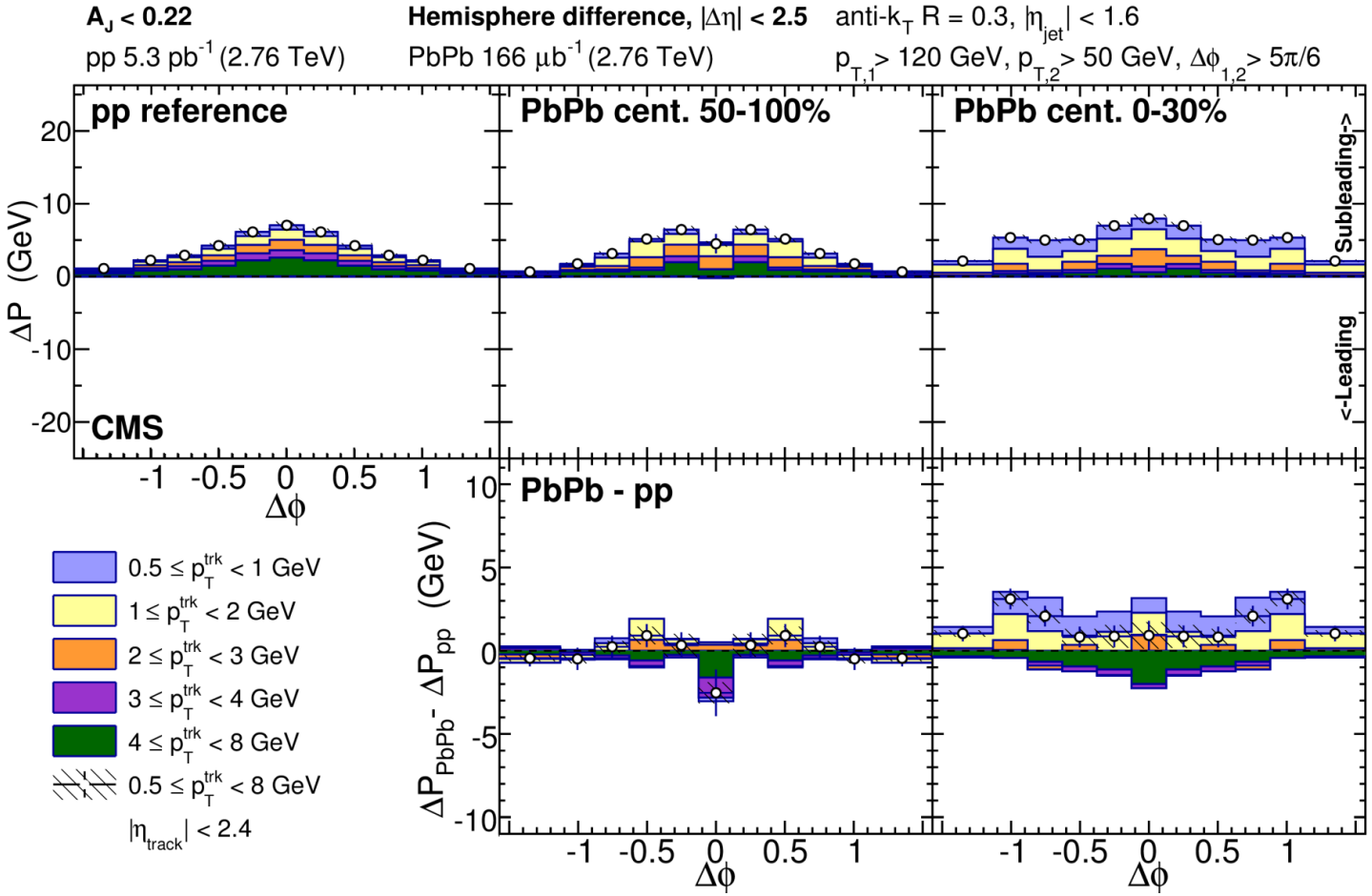
Chris McGinn, CMS



- Same kinematic selection for Z and γ
- Z and γ triggered distributions are identical within errors

"Di-Jet" Imbalance: $A_J < 0.22$

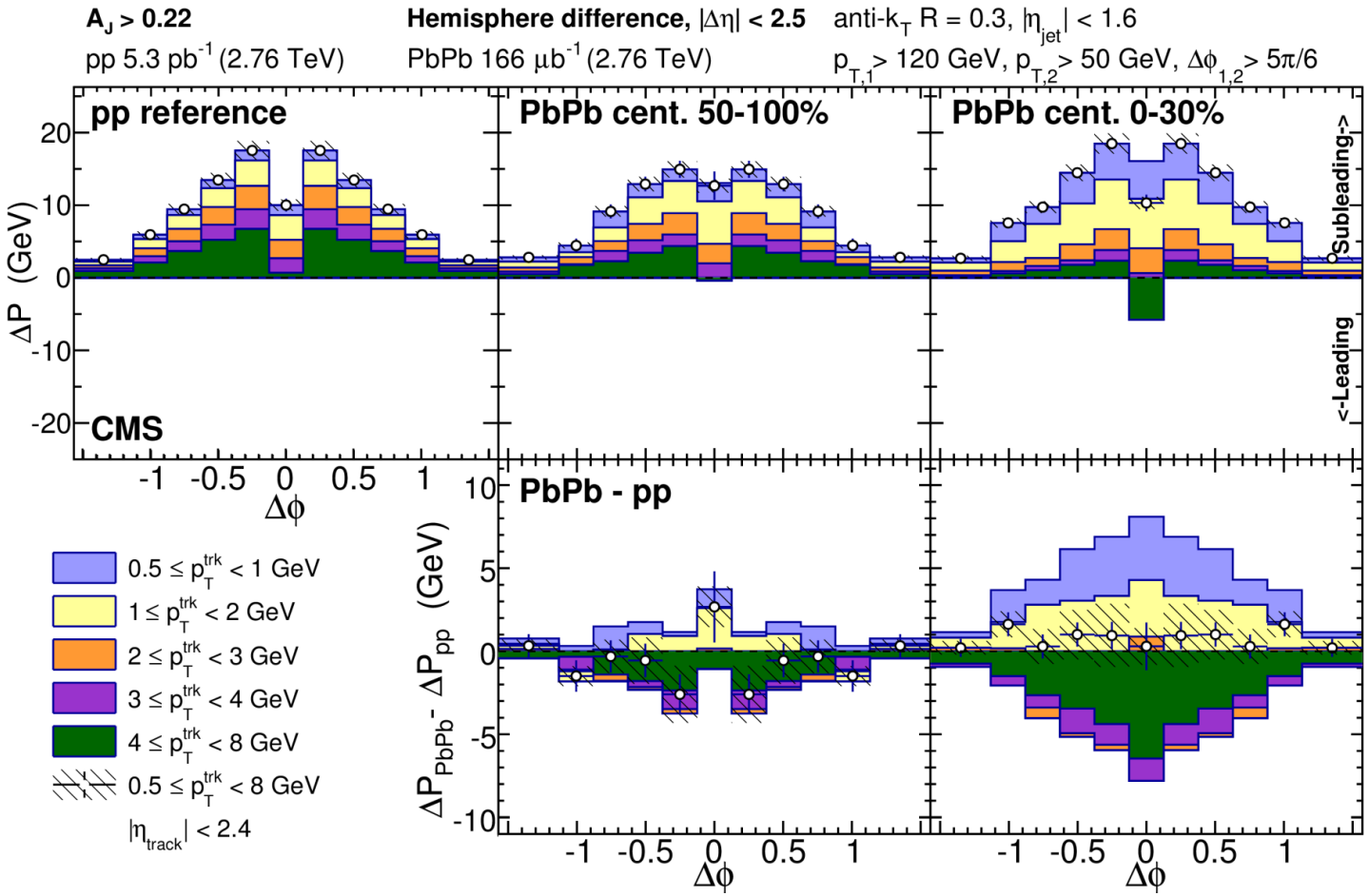
Dragos Velicanu, CMS



- Imbalance as a function of $\Delta\phi$
- Soft particles on the sub leading side go to large angles

"Di-Jet" Imbalance: $A_J > 0.22$

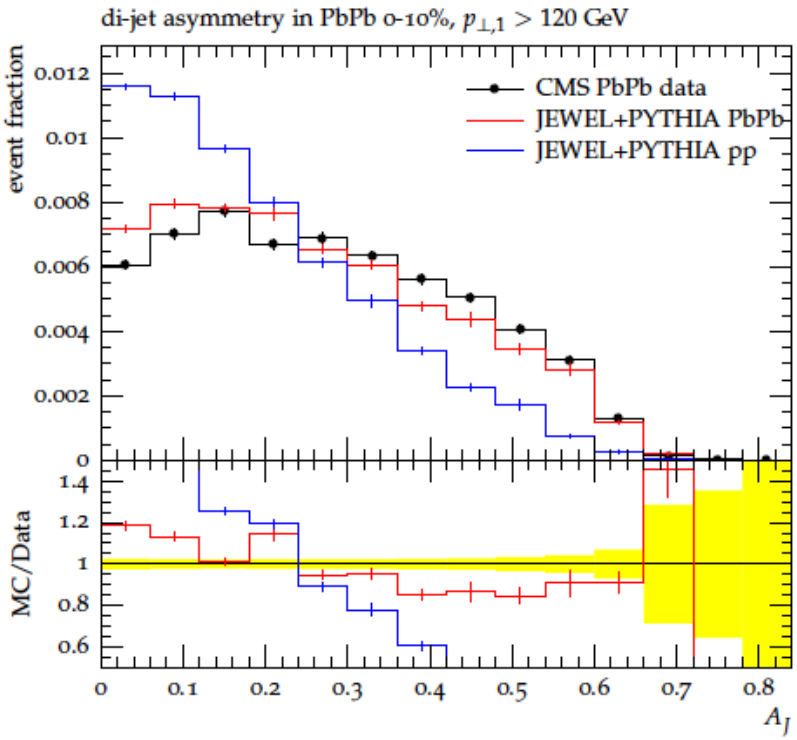
Dragos Velicanu, CMS



- Naturally also larger differential imbalance for $A_J > 0.22$
- $\Delta\phi$ dependent imbalance consistent between Pb+Pb and p+p

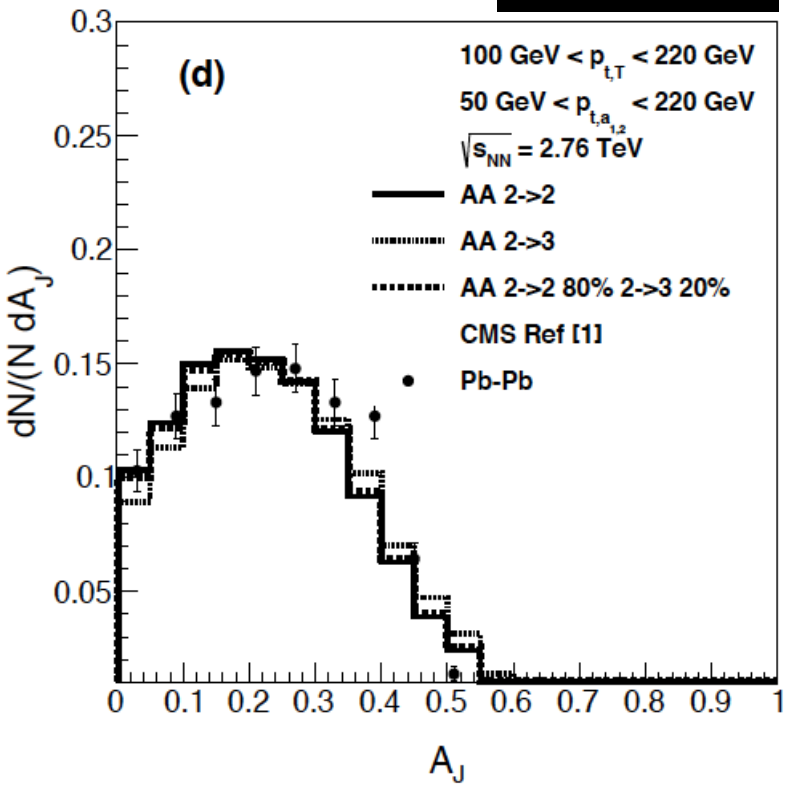
Di-Jet Imbalance: Models

arXiv:1512.08107v2



- Parametrized background
- Path length dependence was shown to be negligible
- A_J is mainly caused by fluctuations

arXiv:1503.06889v2



- Viscous hydrodynamics with constant energy loss per unit length
- Also includes 2→3 parton processes
- Emission of the leading hadron near the surface → maximum path length effect!

Model Conclusions

"This in turn can be explained as originating from the energy loss of the partons created in the hard scatterings and travelling in the plasma, including a slight enhancement produced by the contribution from 2 → 3 events."

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"This provides clear evidence that fluctuations, rather than systematic path-length differences, are most relevant in building up the asymmetry."

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- Very different model assumptions, both describe A_J reasonably well.

- Clear suppression observed in HI compared to p+p for all observables.

- Differential imbalance measurements done.

- For special selection of dijets energy can be recovered at RHIC within R = 0.4, not the case for LHC and other selection.

- How much are γ and Z triggered measurements different to h-triggered ones? Virtuallity, g,q content, and surface bias are different. Can we quantify those effects?

- Jets and di-jets suffer from selection bias.

- A_J, x_J are straight forward observables (in experiment) but how much are they sensitive to the detailed energy loss processes?

- High statistics runs are coming at LHC and RHIC (sPHENIX)!


Thanks!