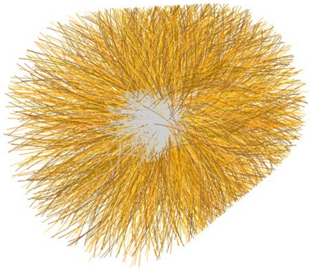


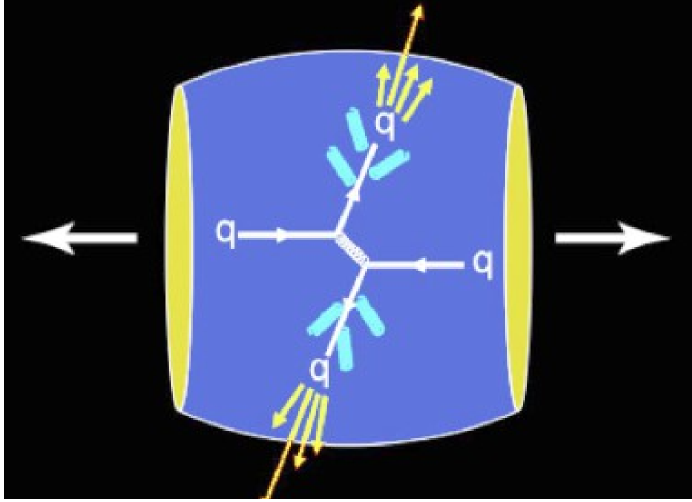
In-Medium Energy Loss and Correlations in Pb-Pb Collisions at 2.76 TeV with ALICE

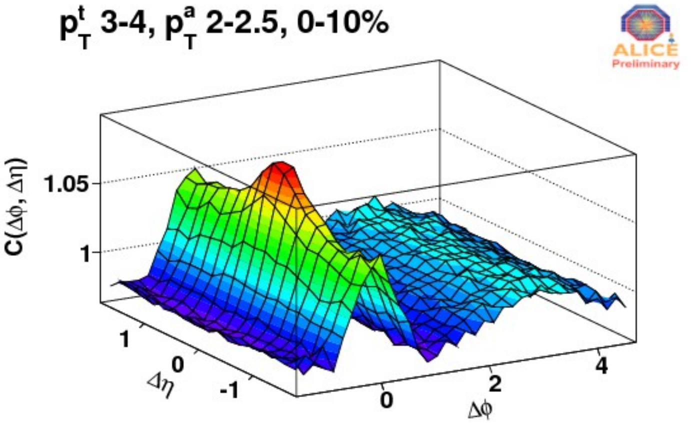
Jan Fiete Grosse-Oetringhaus
CERN/PH
for the ALICE Collaboration

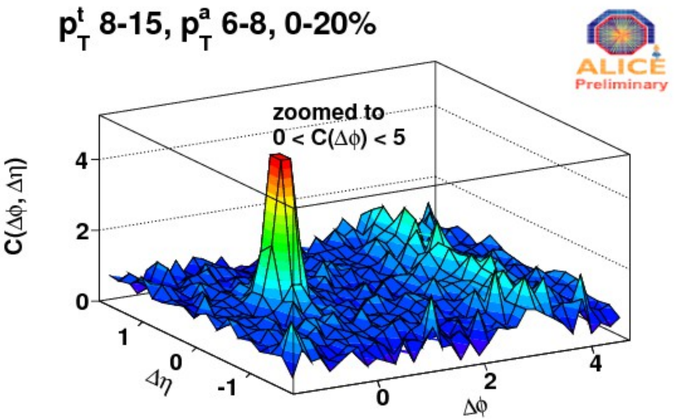
Heavy Ions: Experiments Confront Theory
Copenhagen, 8th November 2011

Motivation

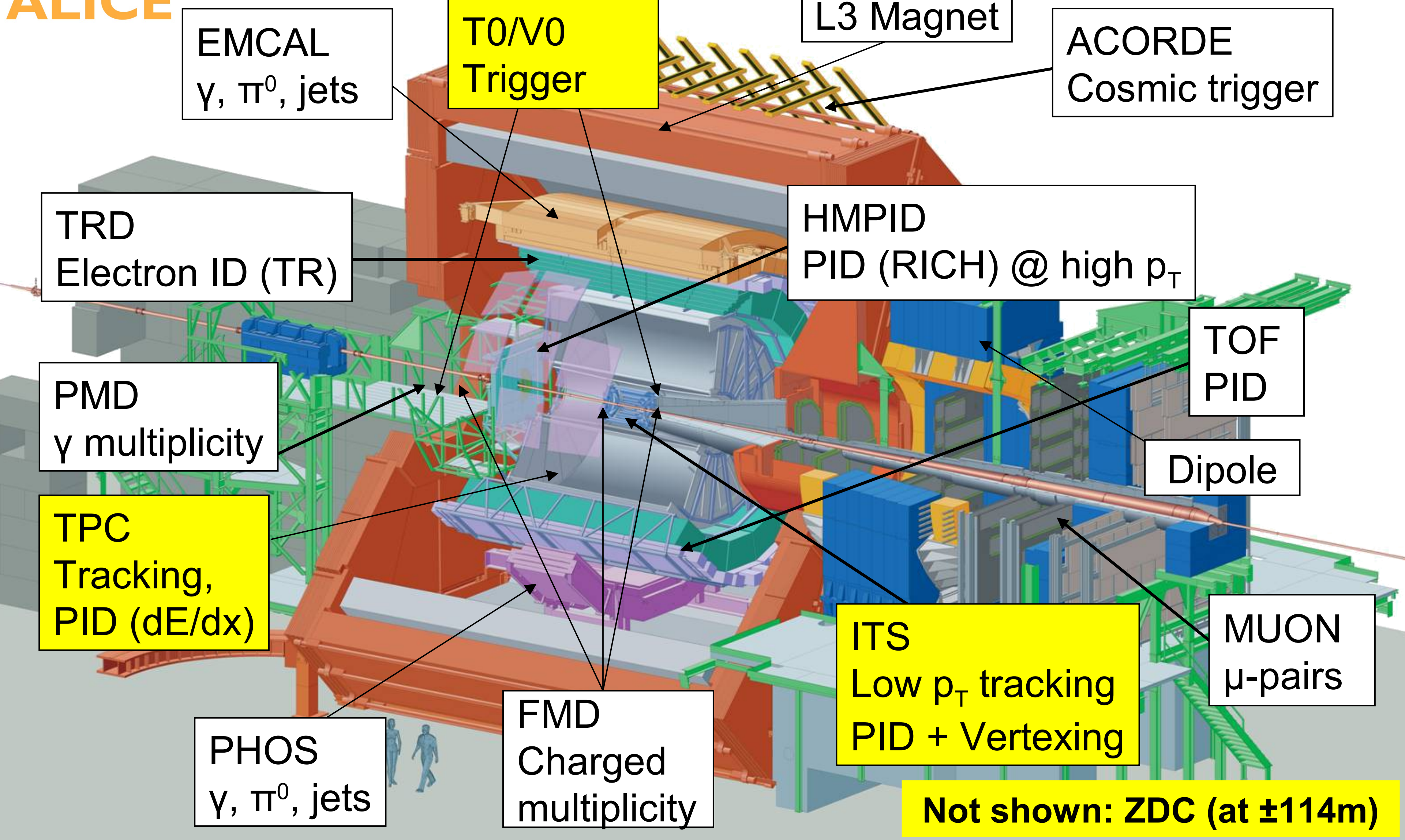
- Ultrarelativistic heavy-ion collisions at LHC probe QCD matter at unprecedented energy densities
- High p_T partons are produced in the very early stage of the collisions and traverse the hot and dense medium (quark-gluon plasma) → jet tomography
- Experimental tools
  - Single-particle distributions
    - High p_T suppression (R_{AA})
  - Two-particle correlations
    - Collective effects, ridge at lower p_T
    - Suppression/quenching at higher p_T (I_{AA})
- Aim: understand medium properties and evolution, constrain energy-loss mechanisms







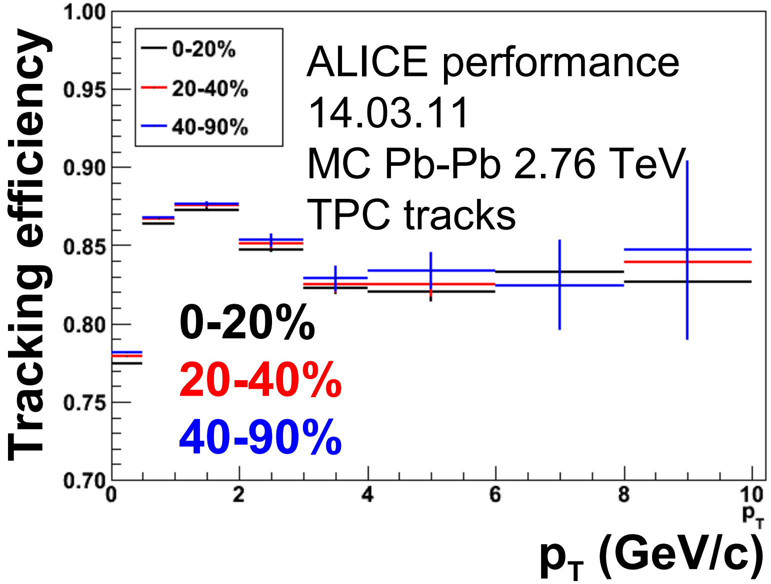
A Large Ion Collider Experiment

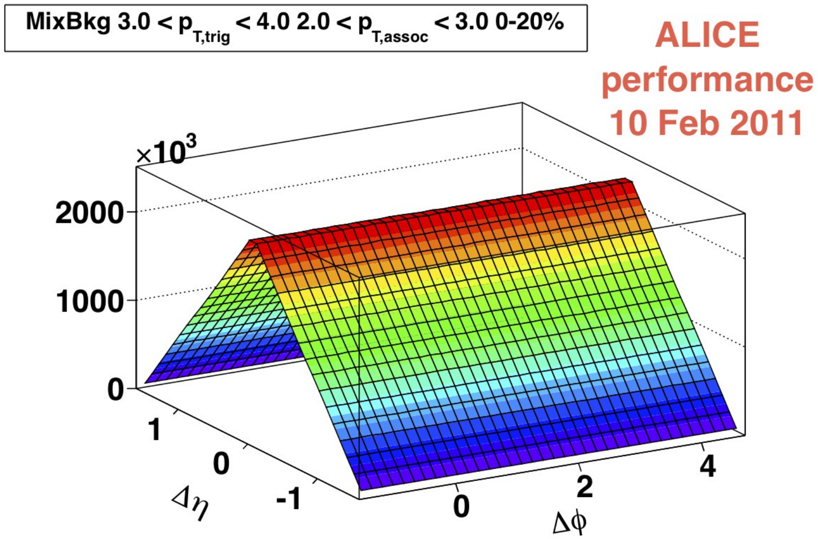


Not shown: ZDC (at ±114m)

Analysis

- ~14M Pb-Pb MB events used
- Centrality determination with V0 (forward scintillators)
- Tracking with Time Projection Chamber and Inner Tracking System in $|\eta| < 0.9$
- Tracking efficiency ~ 85% and only weakly centrality dependent
- Two-track effects small
- Flat ϕ acceptance
  - No mixed events needed for acceptance correction (in $\Delta\phi$ projection)





Nuclear Modification Factor R_{AA}

Nuclear Modification Factor

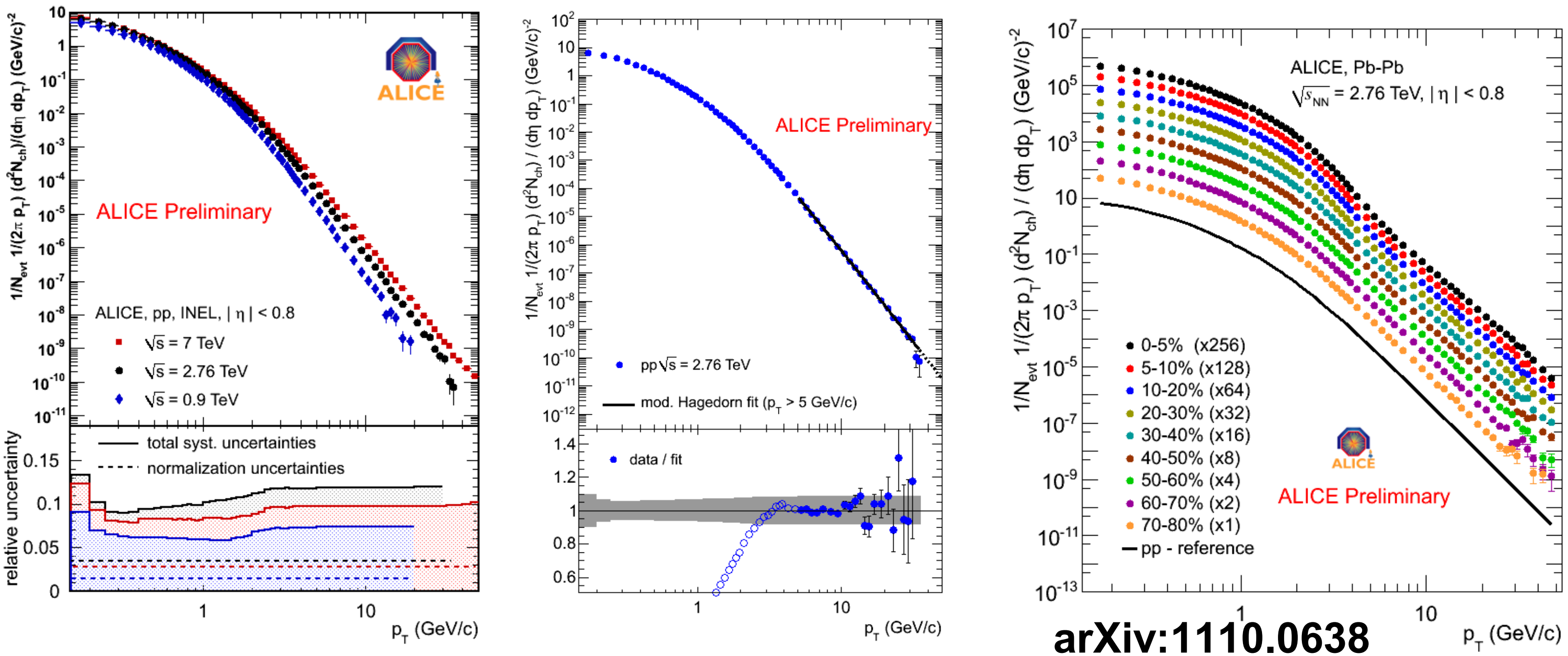
- Production cross section of hard probes in Pb-Pb collisions scale with the number of binary nucleus-nucleus collisions (Pb-Pb is superposition of pp)
- Medium affects initially produced (colored) probes
- Departure from binary scaling expectation quantifies medium effects
- Study in-medium energy loss by measuring inclusive particle spectrum (dN_{ch}/dp_T)
  - Compare Pb-Pb and pp collisions scaled with number of binary collisions (from Glauber calculation)

$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{coll} \rangle d^2N^{pp}/dp_T d\eta}$$

$$\langle N_{coll} \rangle = \langle T_{AA} \rangle \cdot \sigma_{pp}^{INEL}$$

dN_{ch}/dp_T Measurement

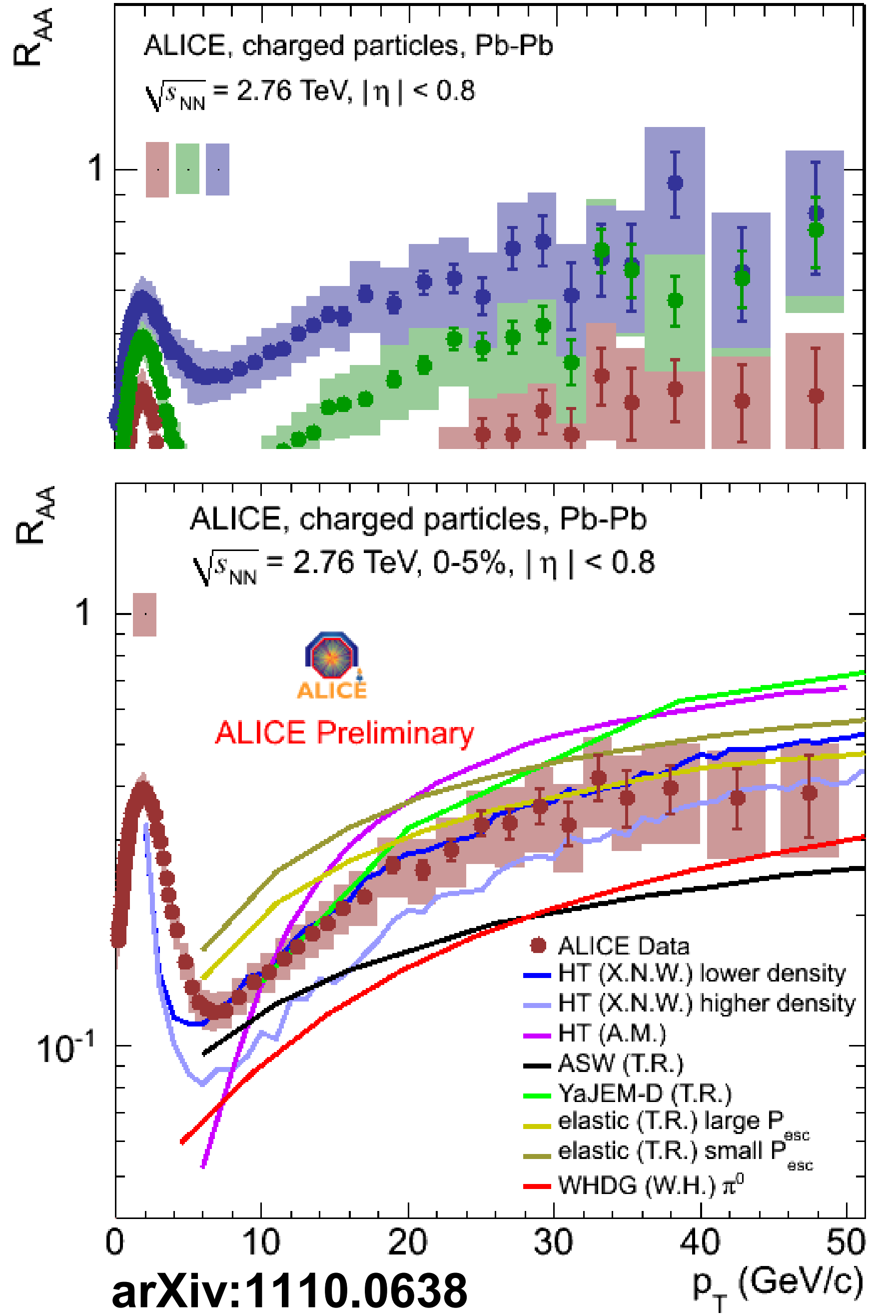
- pp reference distribution fitted with a modified Hagedorn function above 5 GeV/c
  - Used for extrapolation to higher p_T
- Pb-Pb distribution measured as function of centrality



arXiv:1110.0638

R_{AA}

- Pronounced centrality dependence observed
- Minimum (~0.12) reached at $p_T \approx$ 6-7 GeV/c
- Strong rise above 6 GeV/c
- Models
  - pQCD production
  - Medium density profile
  - Energy loss model
  - Hydro evolution
- Trends of data reproduced
- More systematic assessment needed for distinguishing power



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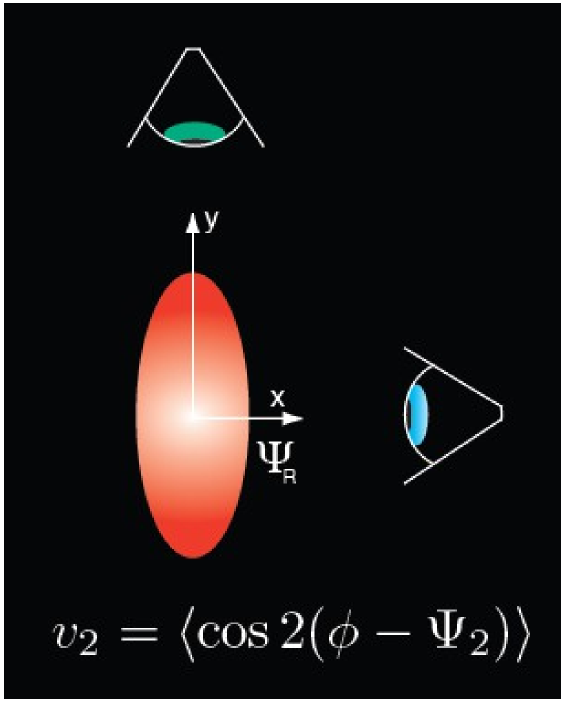
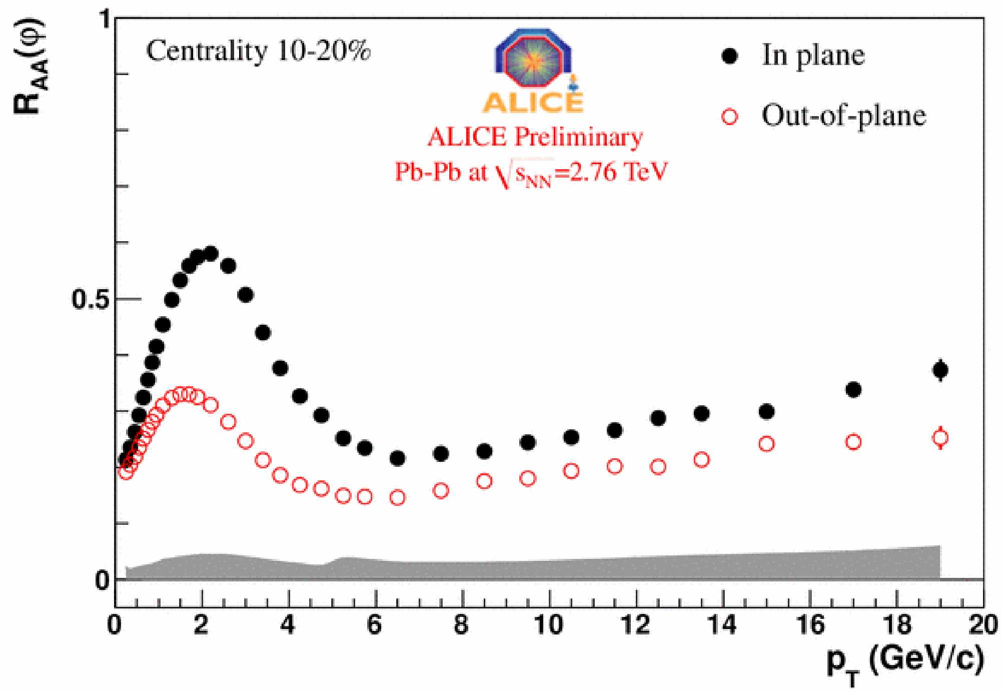
R_{AA} vs. Event Plane

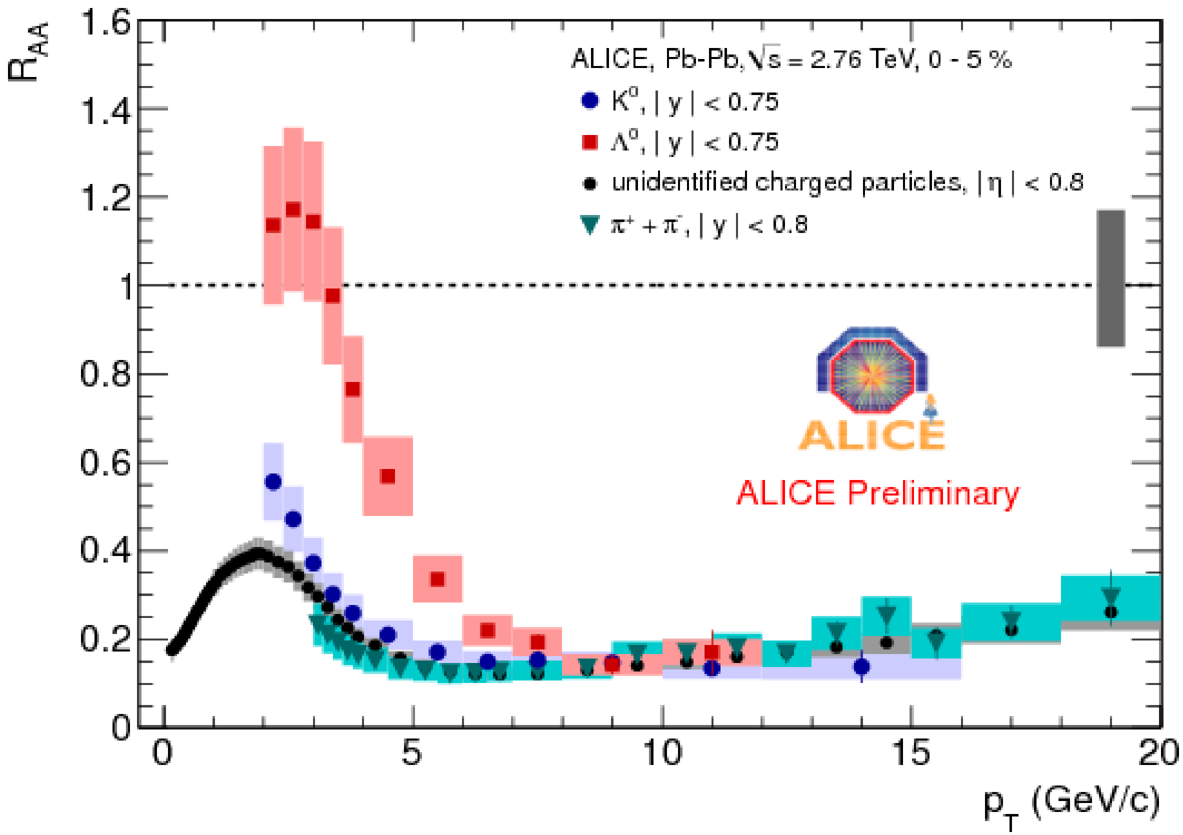




- Assess path-length dependent quenching
- Significant effect, even at 20 GeV
- Further constraints to energy-loss models
  - → Path-length dependence

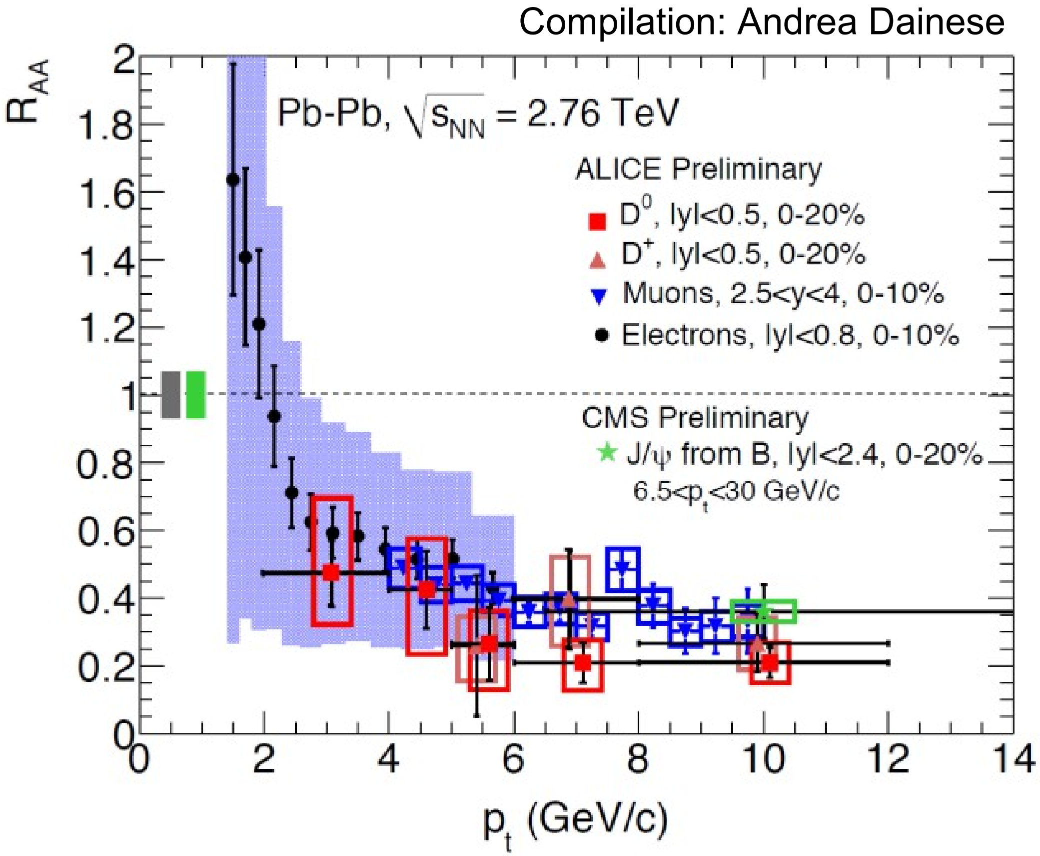
Identified Particle R_{AA}

- K similar to π
- K/Λ enhanced at low p_T
- Suppression becomes similar above 8 GeV/c



c and b Quenching at LHC

- Study parton mass and colour charge dependence of energy loss by looking at R_{AA} of charm and beauty mesons
- Substantial suppression of heavy flavour production at LHC
  - Including beauty



Modification of the Jet Particle Yield

I_{AA} and I_{CP}

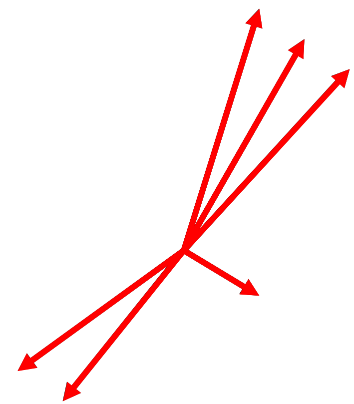
Triggered Correlations

- Choose a particle from one p_T region ("trigger particle") and correlate with particles from another p_T region ("associated particles") where $p_{T,assoc} < p_{T,trig}$ in bins of $p_{T,trig}$ and $p_{T,assoc}$
- Per-trigger yield (usually only as function of $\Delta\phi$)

$$Y(\Delta\varphi) = \frac{1}{N_{trig}} \frac{dN_{assoc}}{d\Delta\varphi}$$

- Correlation function

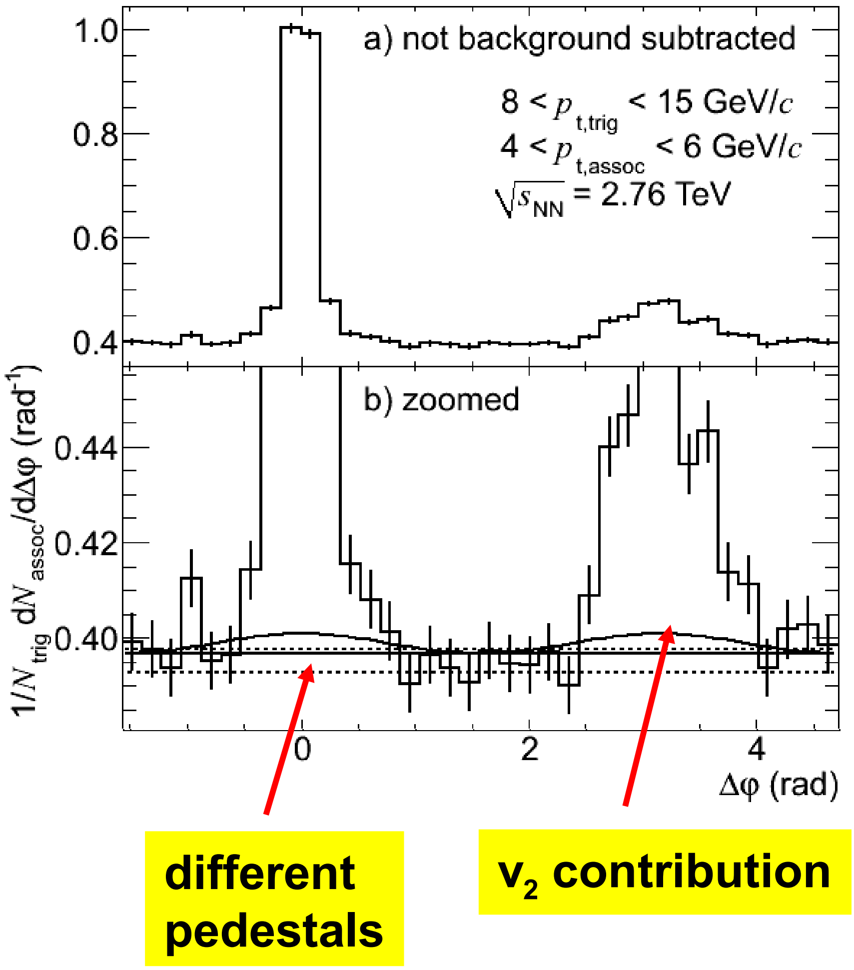
$$C(\Delta\varphi, \Delta\eta) = \left(\frac{1}{N_{pair}} \frac{d^2 N_{assoc}}{d\Delta\varphi d\Delta\eta} \right)_{same} \Bigg/ \left(\frac{1}{N_{pair}} \frac{d^2 N_{assoc}}{d\Delta\varphi d\Delta\eta} \right)_{mixed}$$



trigger particle
associated particle

Jet Particle Yields

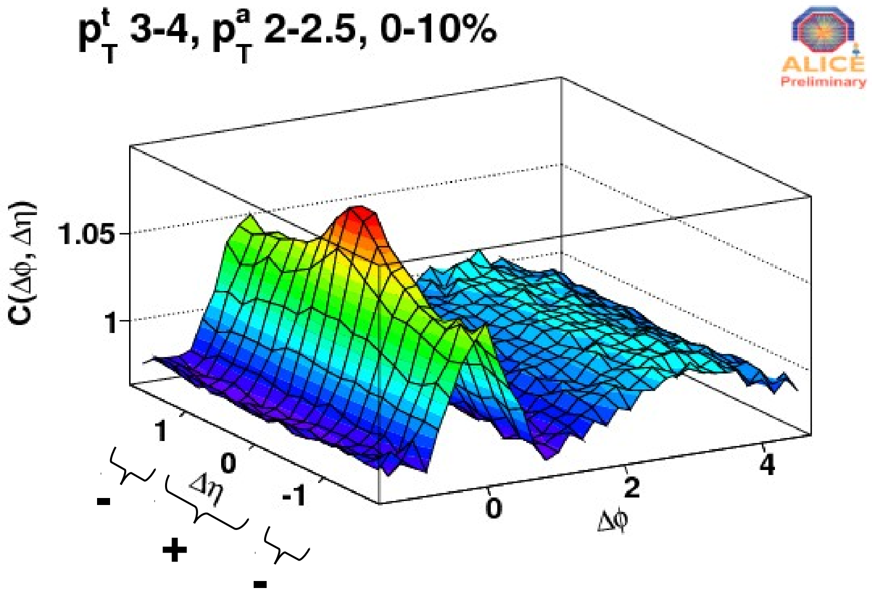
- Aim: Near and away-side jet yields from per-trigger yields
- Non-jet component (baseline) needs to be removed
  - No known assumption-free methods…
- 3 methods to determine pedestal
  - Flat pedestal around π/2 (ZYAM)
  - Pedestal with elliptic flow (v_2) contribution using ALICE flow result
  - Subtract $|\Delta\eta| > 1$ region (next slide)



arXiv:1110.0121

Baseline Determination

- On the near-side the jet peak is concentrated at $\Delta\eta = 0$
  - Estimate $\Delta\eta$-independent effects in long-range correlation region ($|\Delta\eta| > 1$)
  - Remove from short-range region ($|\Delta\eta| < 1$)
  - This corrects for all $\Delta\eta$-independent effects (including higher harmonics)

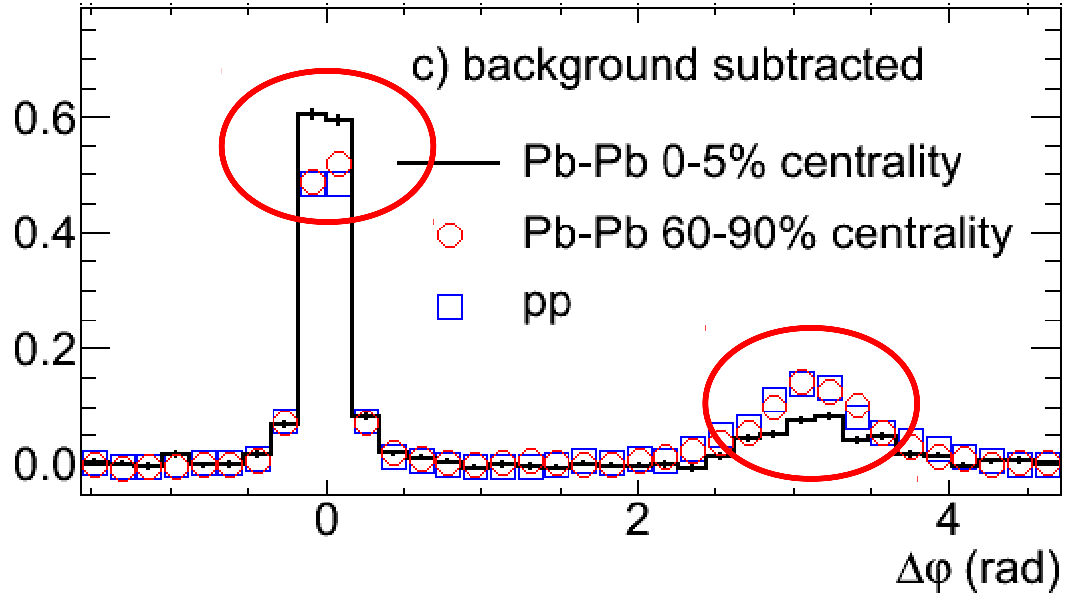


- Measure in a region where the signal dominates over pedestal and v_2 modulation (8 GeV/c < $p_{T,trig}$ < 15 GeV/c)

  → Difference between three methods small

I_{AA} and I_{CP}

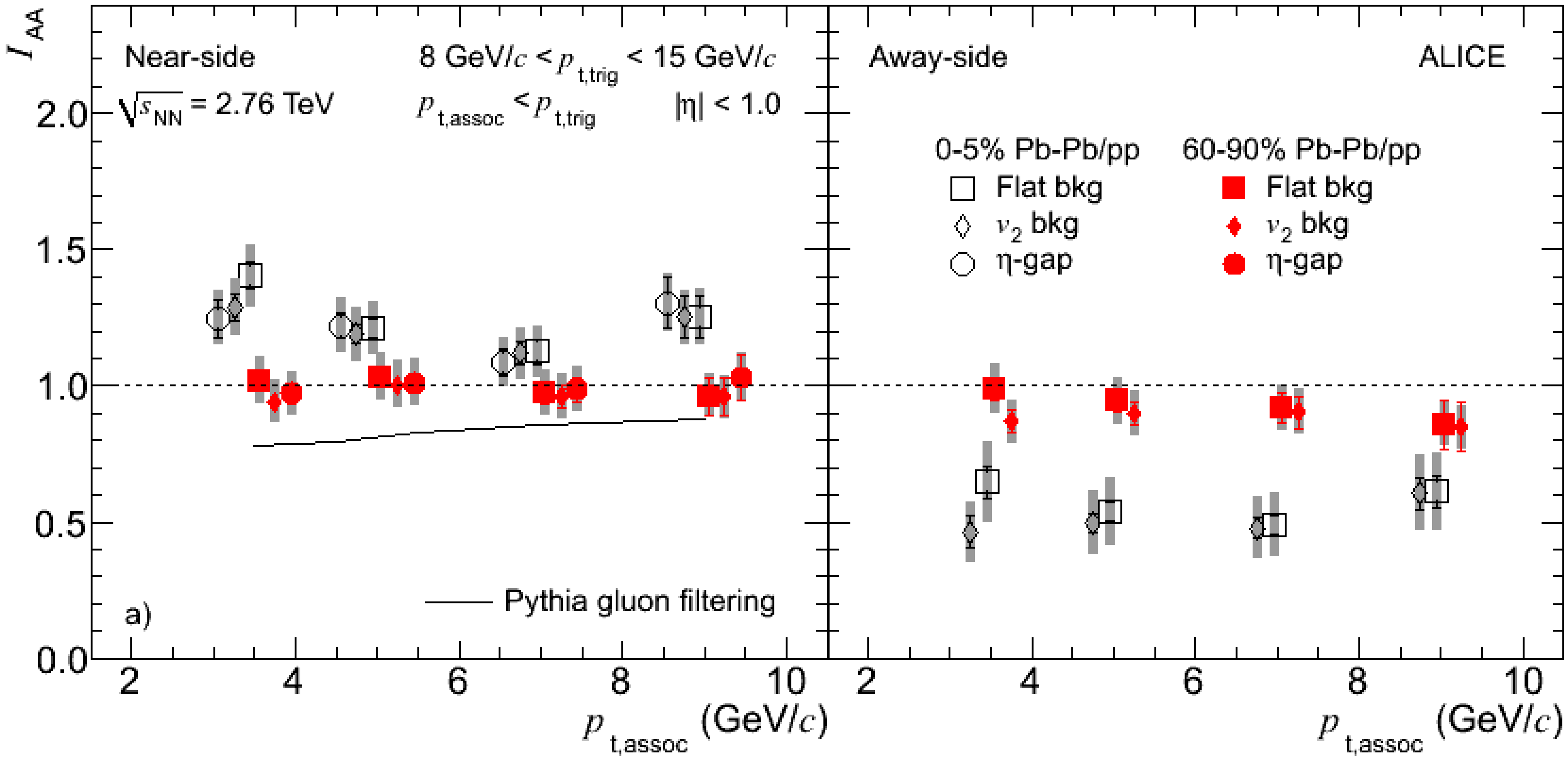
- After baseline subtraction, integrate yields
- Compare Pb-Pb and pp → $I_{AA} = \frac{Y^{AA}}{Y^{pp}}$
- Compare central and peripheral collisions → $I_{CP} = \frac{Y^{AA}_{central}}{Y^{AA}_{peripheral}}$



arXiv:1110.0121

I_{AA}

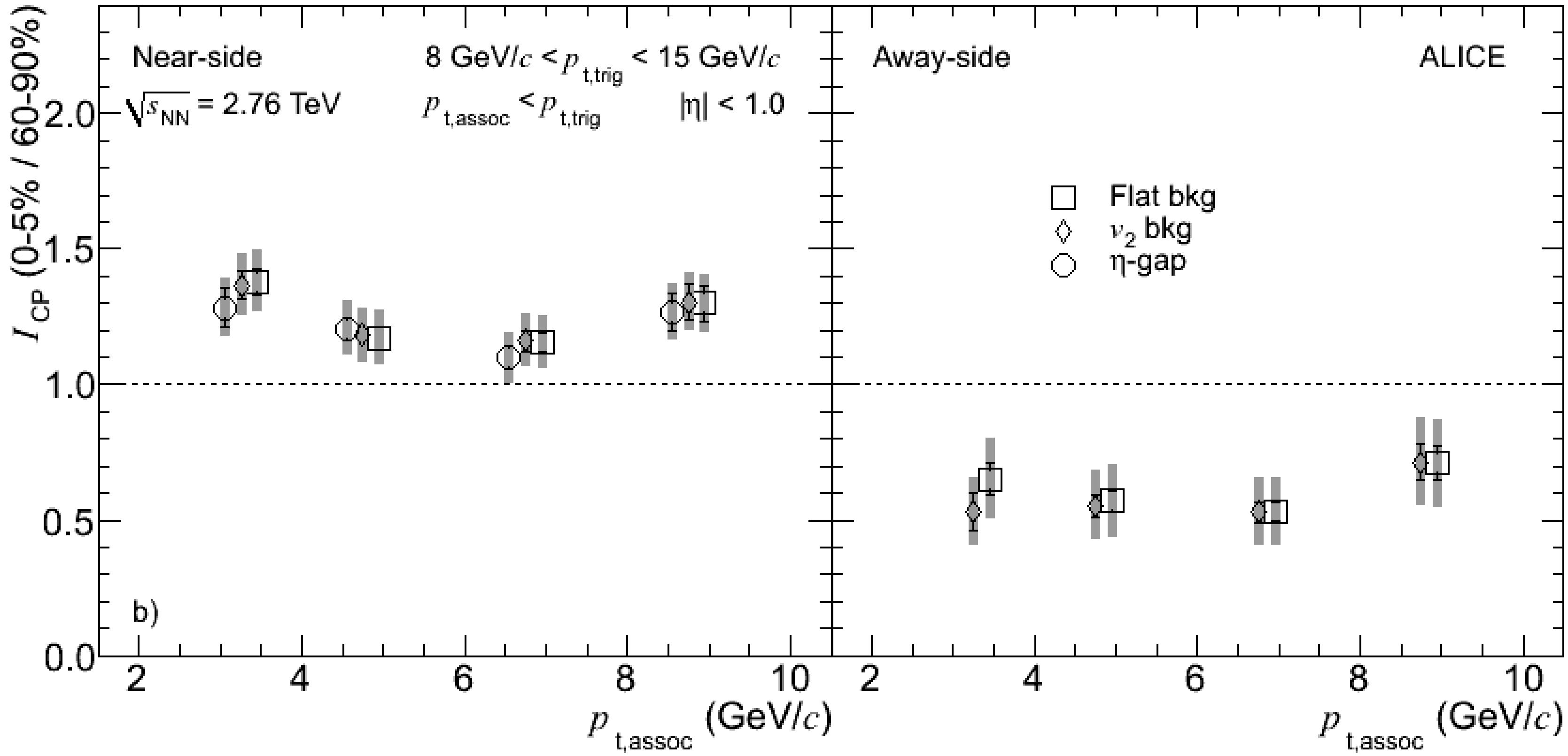
arXiv:1110.0121



- Near-side of central events slightly enhanced I_{AA} ~ 1.2 … surprising?
- Away-side of central events suppressed: I_{AA} ~ 0.6 … expected from in-medium energy loss

- Peripheral events consistent with unity
- Flow contribution small except in lowest bin

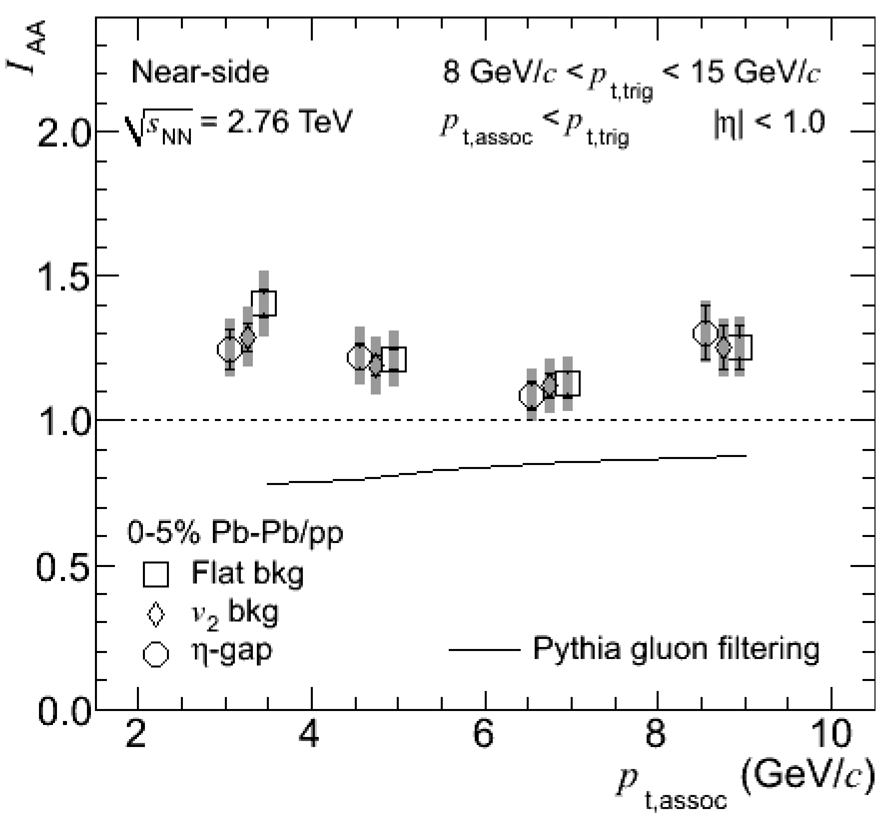
I_{CP}



I_{AA}(0-5%) consistent with I_{CP}:
Both indicate near-side enhancement and away-side suppression

arXiv:1110.0121

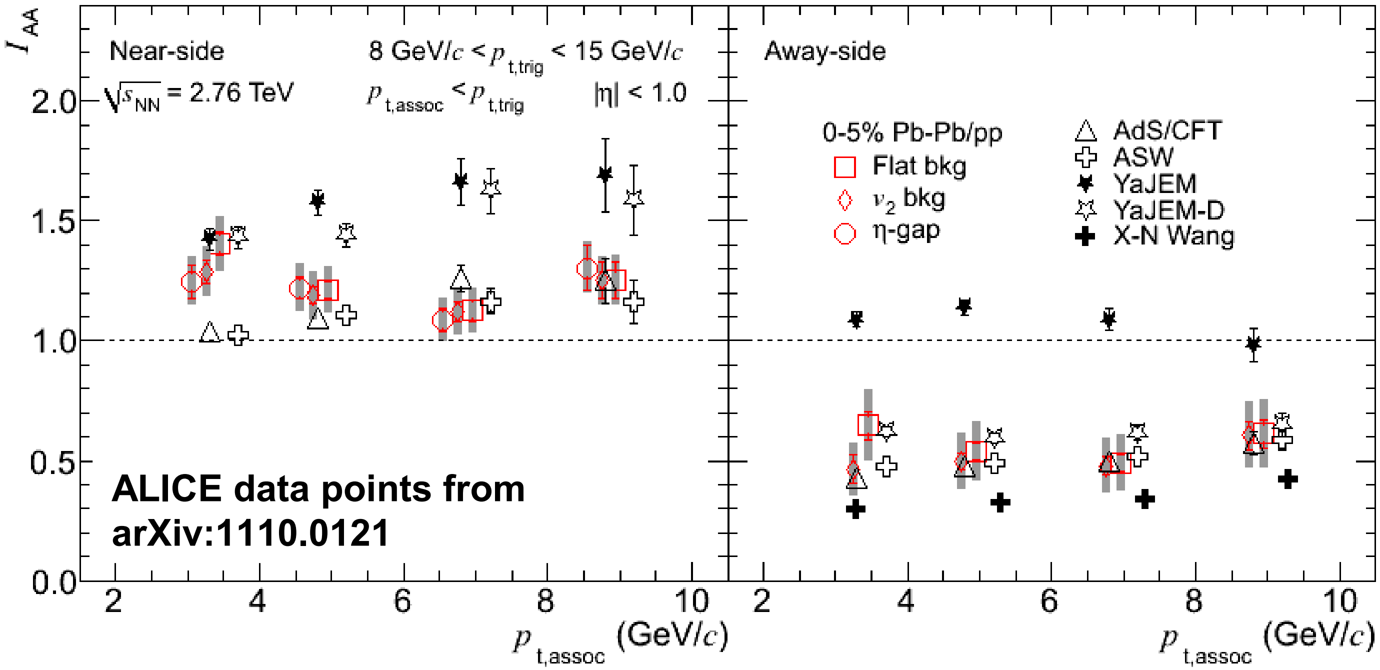
Near-Side Enhancement



arXiv:1110.0121

- R_{AA} small (~0.2) for trigger p_T range considered and rising with p_T
  - Hadron-pair suppression factor $R_{AA}(p_{t,T})\ I_{AA}(p_{t,T}, p_{t,A})$
  - If fragmentation unmodified, it depends only on $p_{t,T} + p_{t,A}$ and is approx. $R_{AA}(p_{t,T} + p_{t,A})$ on near side
  - → Rising R_{AA} leads to $I_{AA} > 1$, increasing with $p_{t,A}$
- Gluons couple stronger to the medium → larger energy loss
  - Trigger particles predominantly from quarks
  - Quarks have a harder fragmentation (<z> larger) than gluons → smaller associated yield
  - Quantified with Pythia 8 (tune 4C)

Theory Comparison



AdS/CFT,ASW, Yajem(-D):
- LO pQCD
- WS matter dist.
- Ideal 2+1d hydro
- Different e-loss scenarios

X N Wang:
- Hard sphere matter dist.
- NLO pQCD
- Avg. e-loss
- 1D expansion

Near-side enhancement:
- reproduced by AdS/CFT pQCD hybrid (L^3 path length dependence) and ASW (L^2 dependence)
- YaJEM(-D) too high

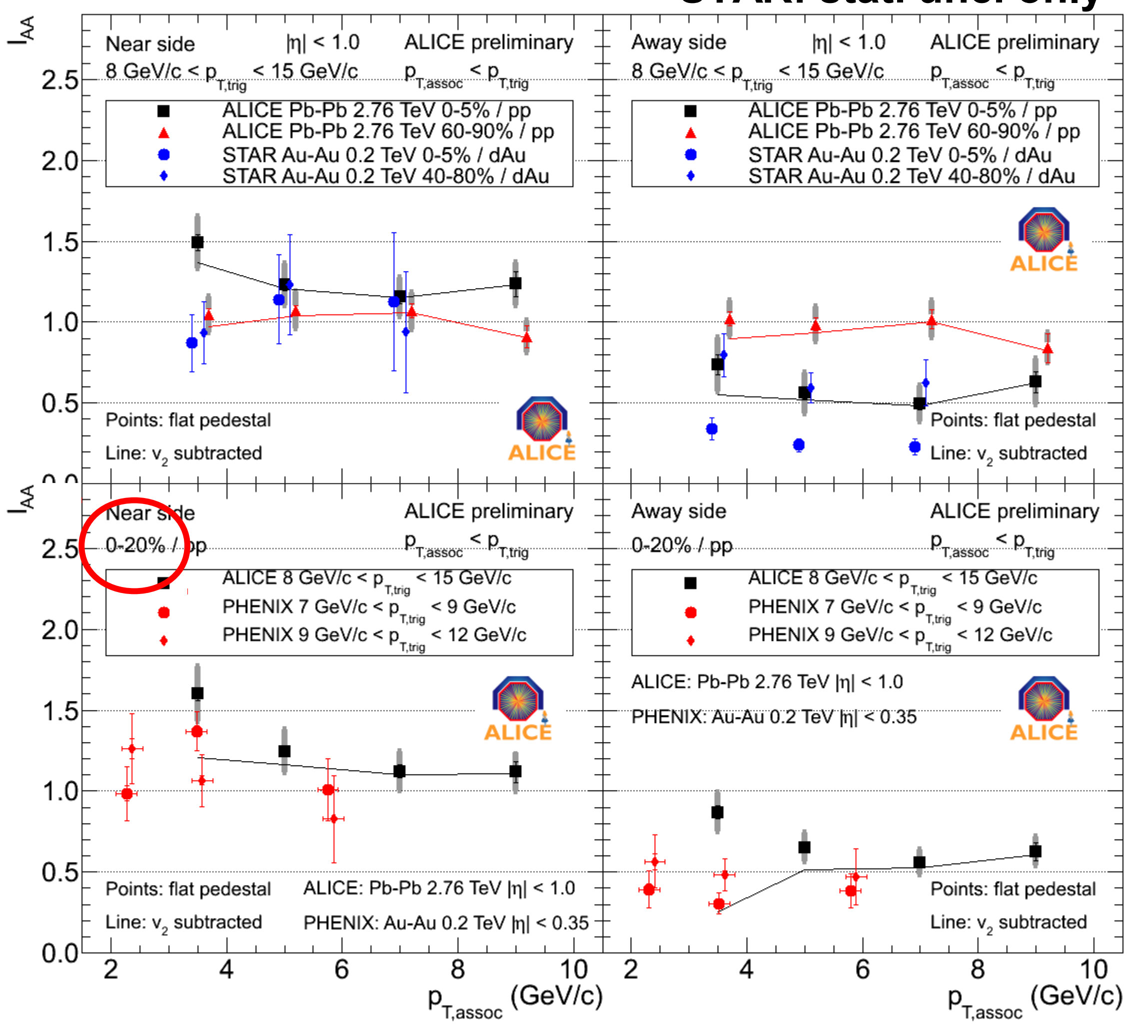
Away-side suppression:
- reproduced by AdS/CFT, ASW, YaJEM-D
- YaJEM too high (L dependence)
- X N Wang slightly too low

AdS/CFT,ASW,YaJEM(-D) simulations from T Renk [arXiv:1106.1740]
X N Wang [private communication, following calculation in PRL98:212301 (2007)]

Comparison with RHIC

- Caveat: same trigger p_T probes different parton p_T at different $\sqrt{s_{NN}}$
- STAR and PHENIX subtract v_2 → compare with ALICE line
  - STAR I_{AA} w.r.t. to dAu reference
  - STAR has different centrality for peripheral events
  - Away side larger than at STAR
  - PHENIX has (slightly) different $p_{T,trig}$ ranges
- No evidence for near-side I_{AA} > 1 at RHIC, but not excluded

STAR: stat. unc. only

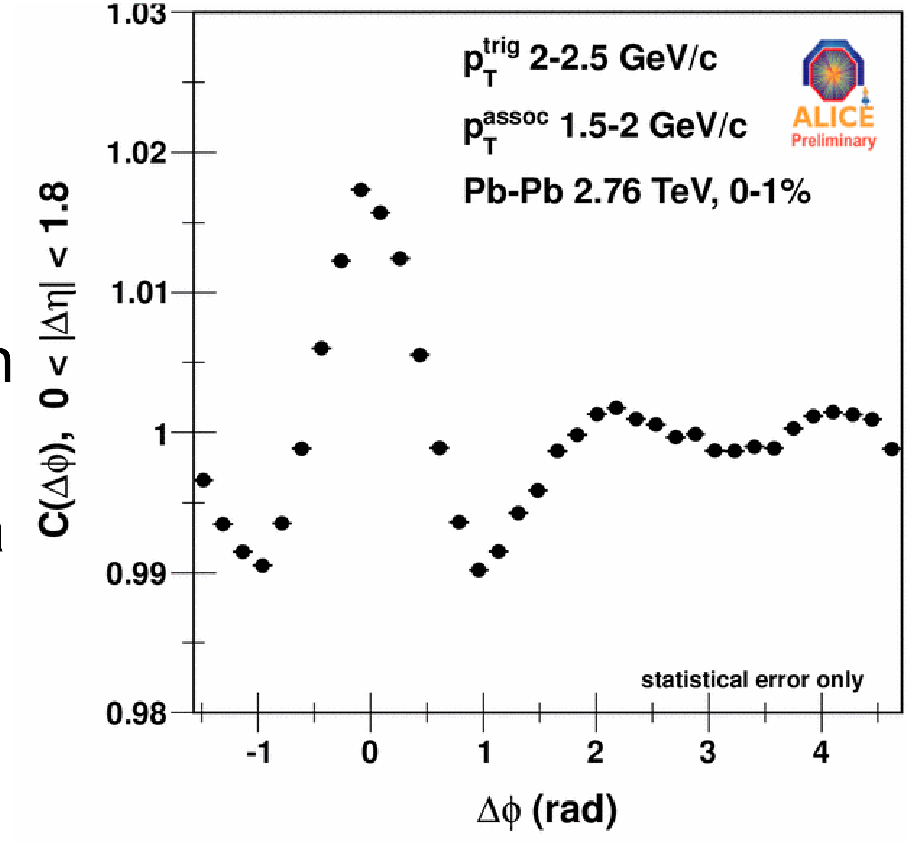


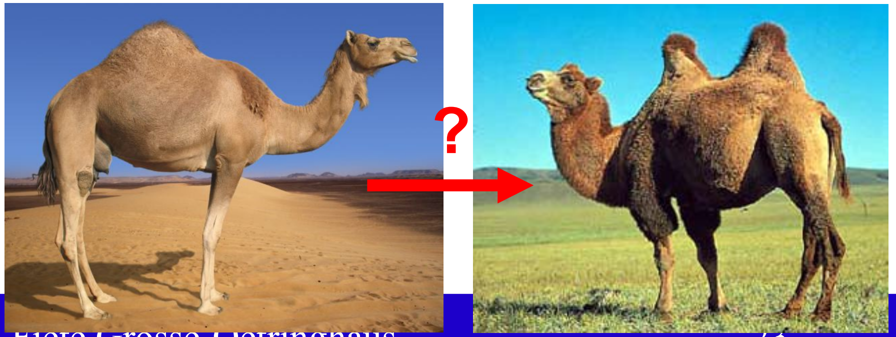
STAR, PRL97,162301 (2006) PHENIX, PRL 104, 252301 (2010)

Decomposition of Long-Range Correlations

Long η-range Correlations

- Study correlation function in long-range correlation region ($0.8 < |\Delta\eta| < 1.8$) where collective effects are dominan
- "Ultra-central" events: dramatic shape evolution in a very narrow centrality range
- Double-hump structure ("Mach cone") on away-side appears on 1% most central
  – Visible without v_2 subtraction!





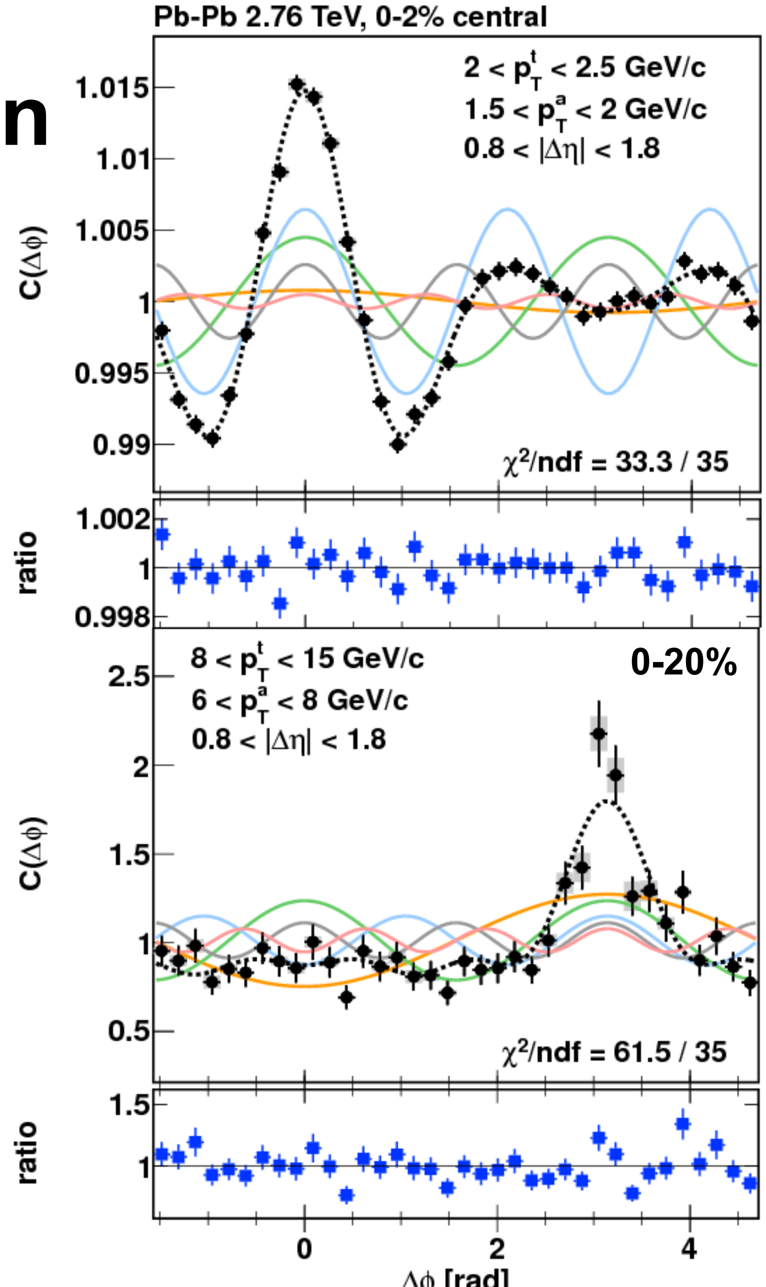
arXiv:1109.2501

Fourier Decomposition

- Fourier coefficients are calculated

$$V_{n\Delta} = \langle \cos n\Delta\varphi \rangle = \frac{\int d\Delta\varphi C(\Delta\varphi)\cos n\Delta\varphi}{\int d\Delta\varphi C(\Delta\varphi)}$$

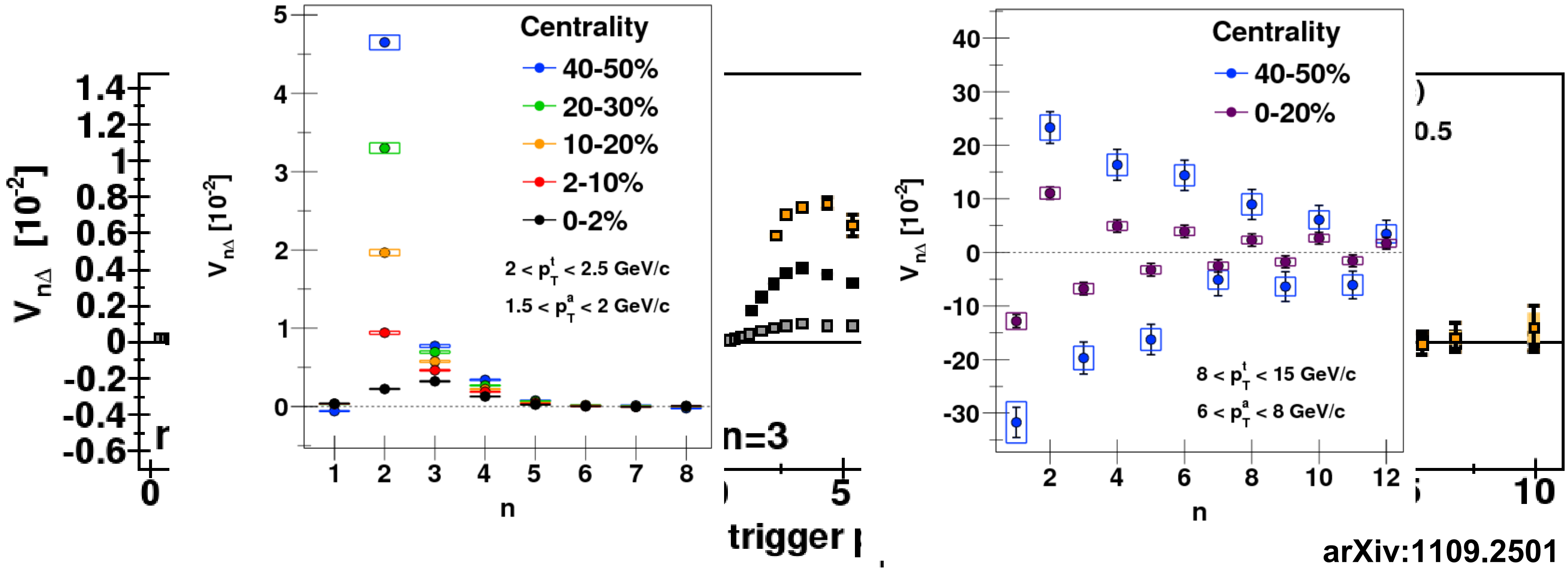
- Strong near-side ridge + double-peaked structure (in very central events) on away side at low p_T
  - 5 coefficients describe correlation well at low p_T
- Away-side peak dominates at high p_T
  - Higher coefficients improve description



arXiv:1109.2501

Fourier Coefficients

- Coefficients increase with increasing p_T
- First coefficient becomes negative at large p_T (influence of away-side jet)
- From central to peripheral, $v_{2\Delta}$ rises most



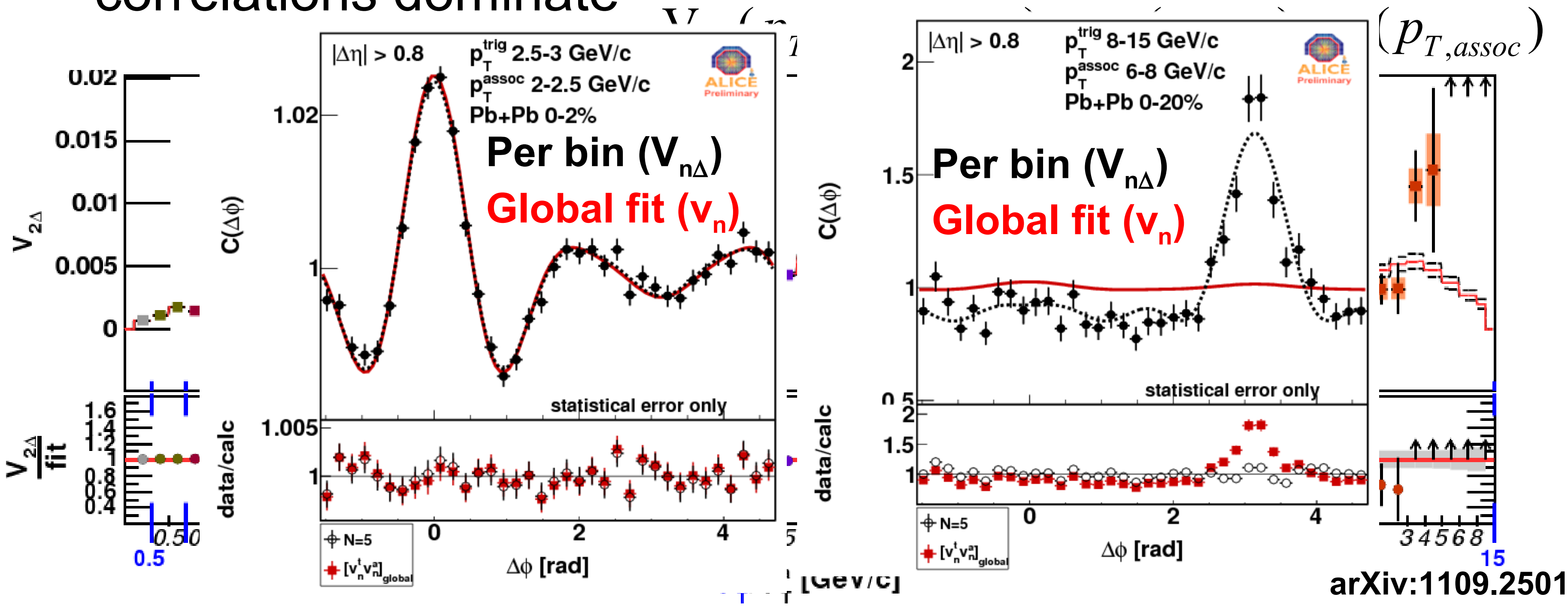
arXiv:1109.2501

Flow vs Non-Flow Correlations

- Flow-related effects imply correlation of two particles through a plane of symmetry ψ_n
  - $V_{n\Delta}$ factorizes: $V_{n\Delta}(p_{T,trig}, p_{T,assoc}) = v_n(p_{T,trig}) \cdot v_n(p_{T,assoc})$
- Jets cause correlations of a few energetic particles by fragmentation
  - There can be indirect correlations: length-dependent quenching
  - Would be largest w.r.t. ψ_2 since it reflects the collision geometry
- Assess flow vs. non-flow by testing the factorization relation $V_{n\Delta}(p_{T,trig}, p_{T,assoc}) = v_n(p_{T,trig}) \cdot v_n(p_{T,assoc})$
  - Calculate $V_{n\Delta}$ in each $p_{T,assoc}$ x $p_{T,trig}$ bin (N(N-1)/2=66 bins)
  - Allow only one v_n per p_T bin (12 parameters)

Flow vs. Non-Flow Correlations

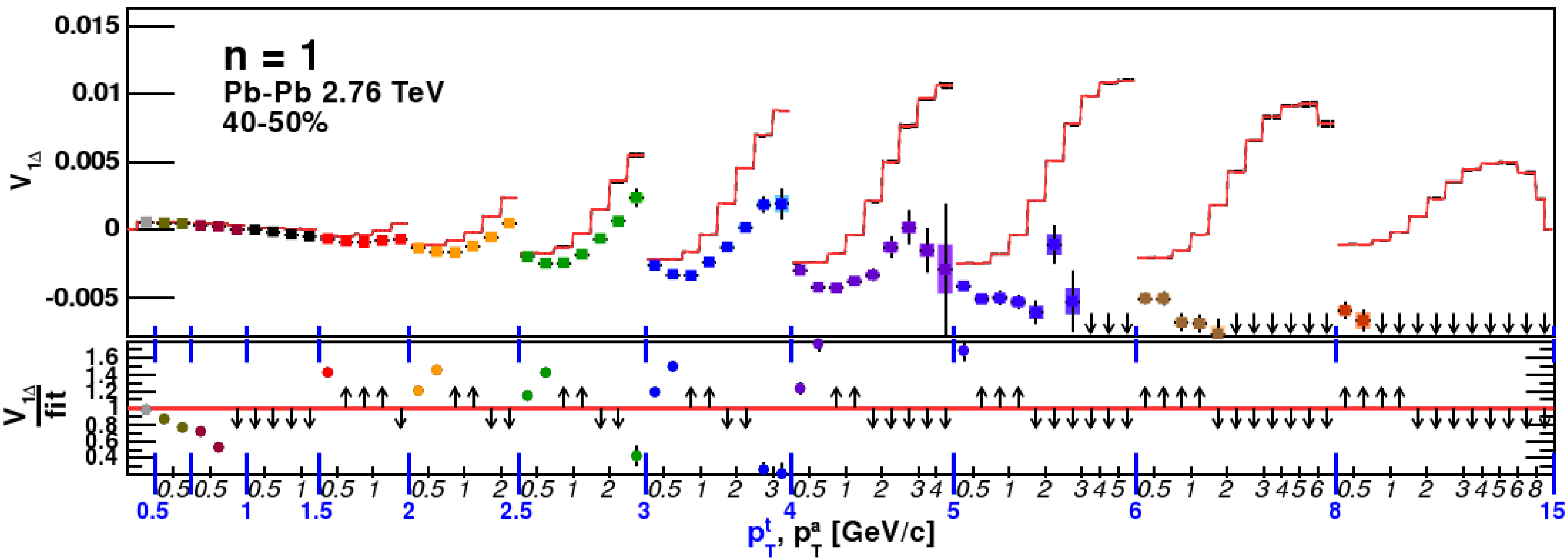
- Compare single calculated values with global fit
  - Good agreement suggests flow-type correlations, while a poor fit implies non-flow effects
- $v_{2\Delta}$ to $v_{5\Delta}$ factorize until p_T ~ 3-4 GeV/c, then jet-like correlations dominate



arXiv:1109.2501

Flow vs. Non-Flow Correlations (2)

- $v_{1\Delta}$ factorization problematic (influence of away-side jet)
  - $v_{1\Delta}$ magnitude of global fit strongly depends on included p_T range
- Collective effects may be present, but are not the dominant contribution



Summary

Summary

- Nuclear modification factor R_{AA} shows strong quenching in central collisions
  - Minimum (~0.12) at $p_T \approx$ 6-7 GeV/c and strong rise after
- Jet Particle Yield modification factor I_{AA}
  - Away-side suppression (~0.6) and near-side enhancement (~1.2) is measured for central collisions
  - The effect of the medium on the near side is visible at LHC
- Fourier decomposition of long-range correlations ($0.8 < |\Delta\eta| < 1.8$)
  - The flow factorization $V_{n\Delta} = v_{N,trig} v_{N,assoc}$ holds at low to intermediate p_T (< 3-5 GeV/c)
  - Jet correlations break the factorization at higher p_T