First LHC Results on Hadronic Jets via Angular Correlations

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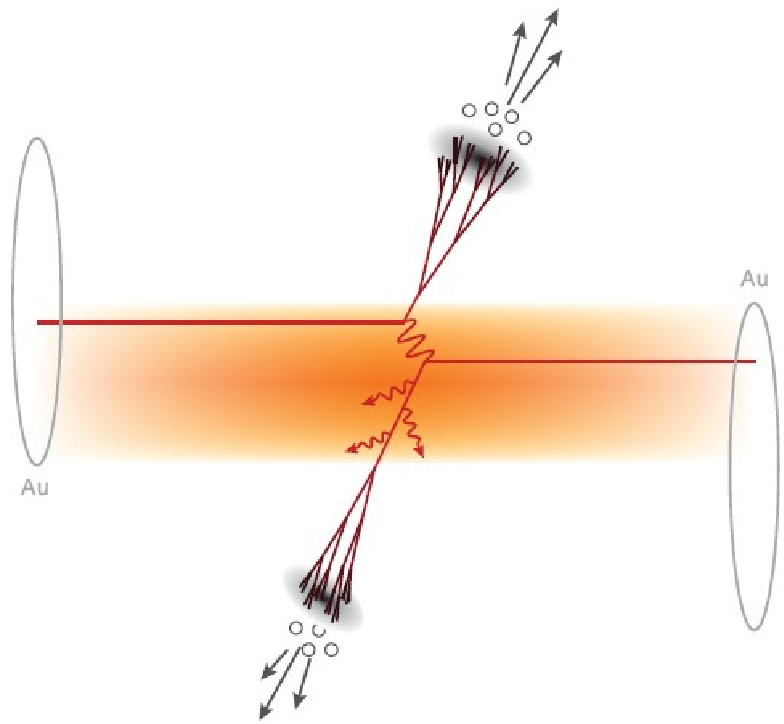
- Results from RHIC
- Results from p-p at 0.9&7TeV
- Results from Pb-Pb at 2.76TeV

The QGP Search via Hadronic Jets Modification

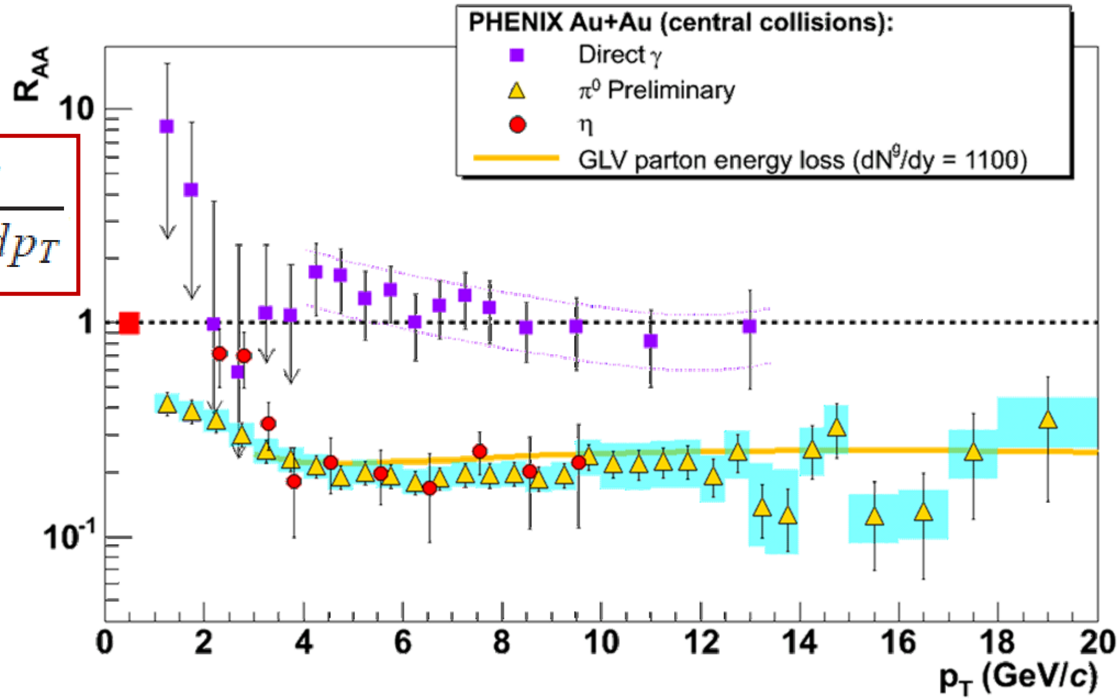
- One of the most awaited RHI analyses: test bench for parton energy loss
- Anticipated: high p_T hadron suppression (R_{AA}) and angular distribution modification (correlations)
- Surprises: medium response (the "shoulder" and the "ridge"), large hadron v_2 at high p_T, lack of broadening at high p_T, …



High p_T Hadron Suppression at RHIC!

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$



- consistency: $R_{AA}(\eta) \sim R_{AA}(\pi)$
- control: $R_{AA}(\gamma) \sim 1$, $R_{dA}(\pi) \geq 1$
- GLV Model: Theory~Data for $dN_g/dy=1100$

However…

Little Discerning Power…

Several pQCD models of high-p_T parton interaction with an expanding QGP:

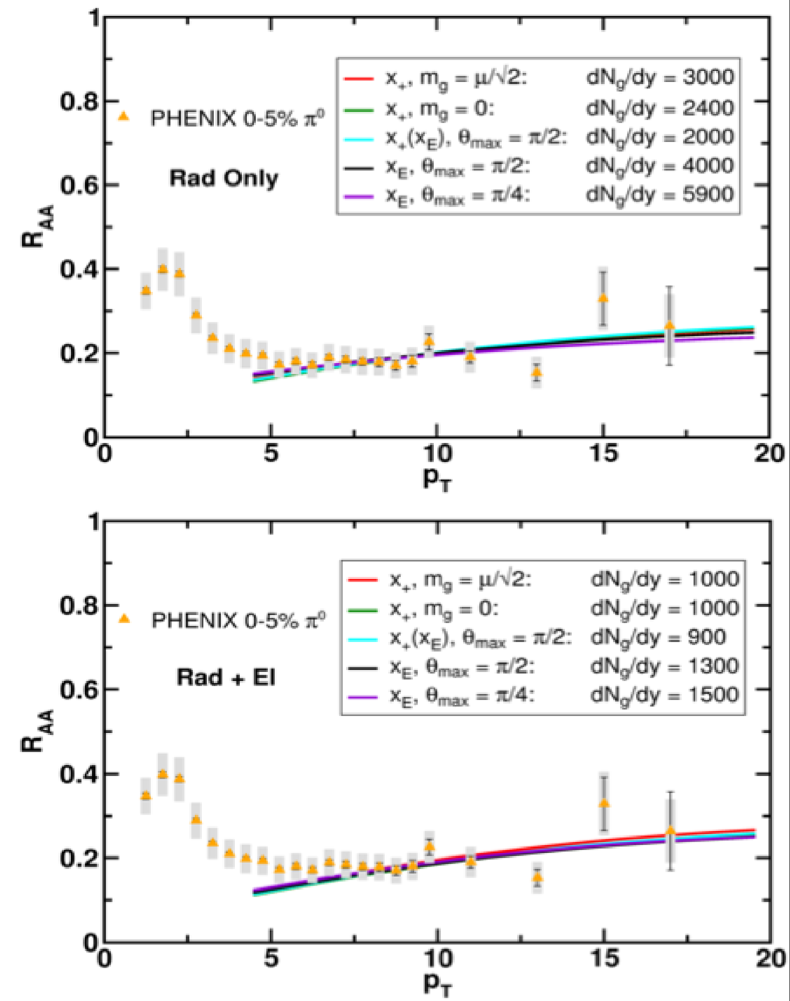
- Opacity expansion (GLV) PLB 538 (2002)
- Multiple soft scattering (BDMPS-Z-ASW) *NPB 588 (2000)*
- Higher-twist (HT) *PRL 85, 3591 (2000)*
- Thermal field theory (AMY) JHEP 11, 001(2000)

All successfully describe the jet quenching:

- very different physics assumptions, same results
- large theoretical uncertainty in QGP parameters

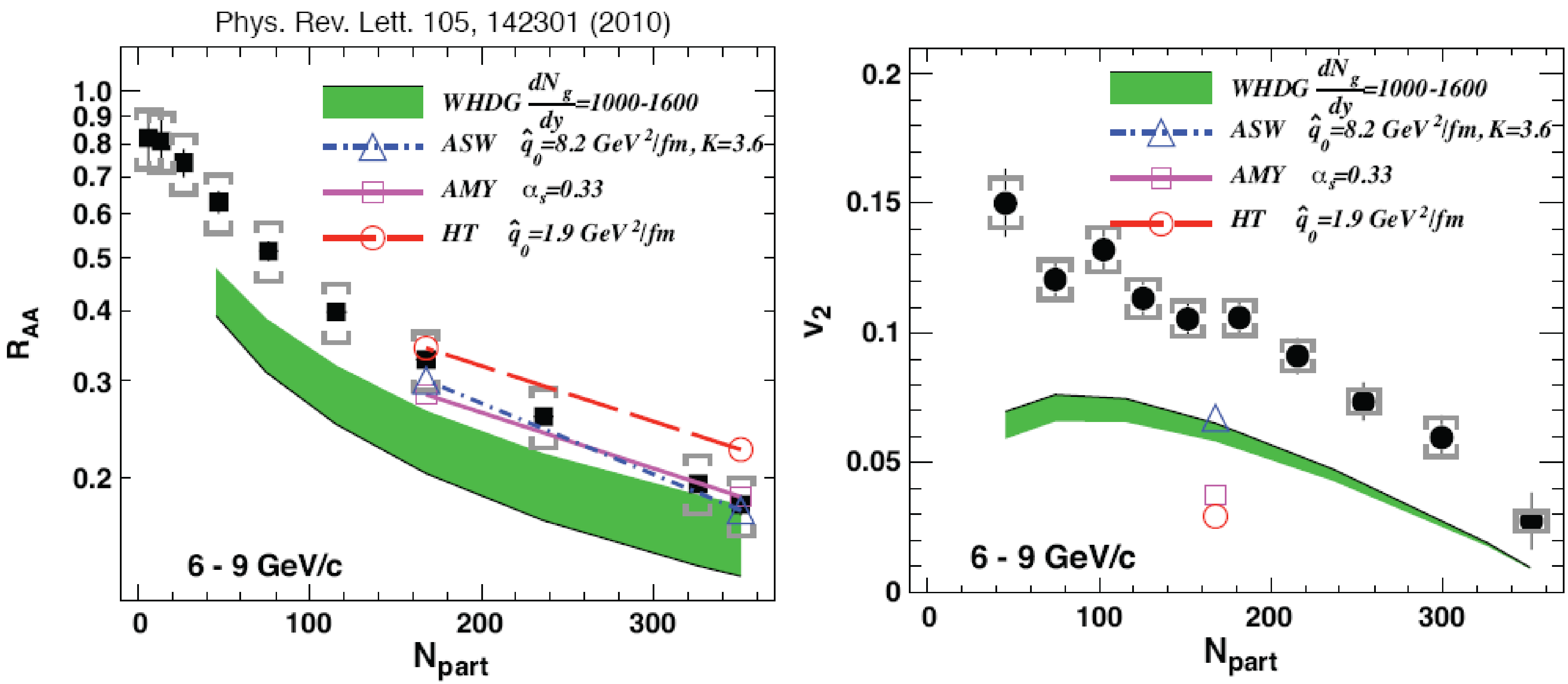
Horowitz, Cole, PRC 81, 024909 (2010)

Renk Phys. Rev. C 79, 054906 (2009)



Horowitz, Cole, PRC 81, 024909 (2010)

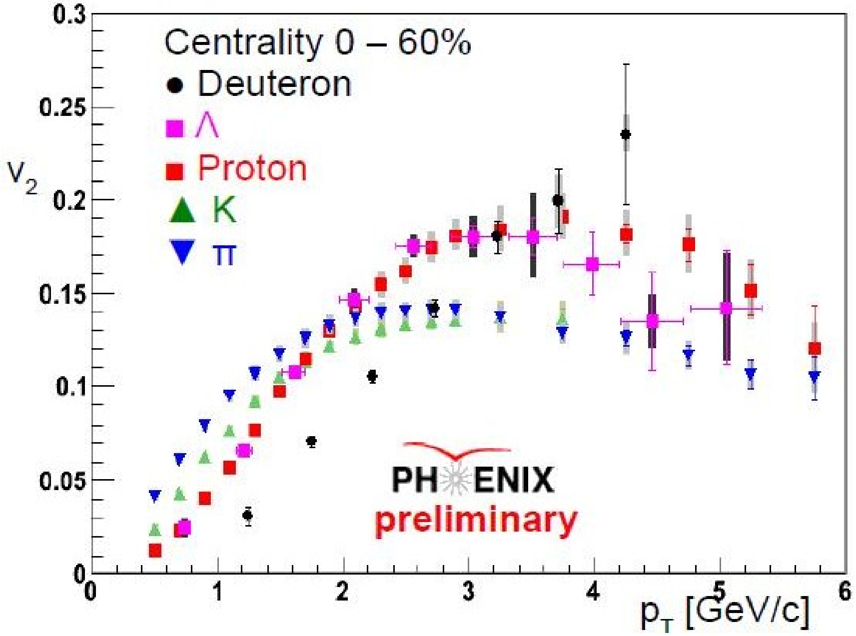
Not Everything Fits

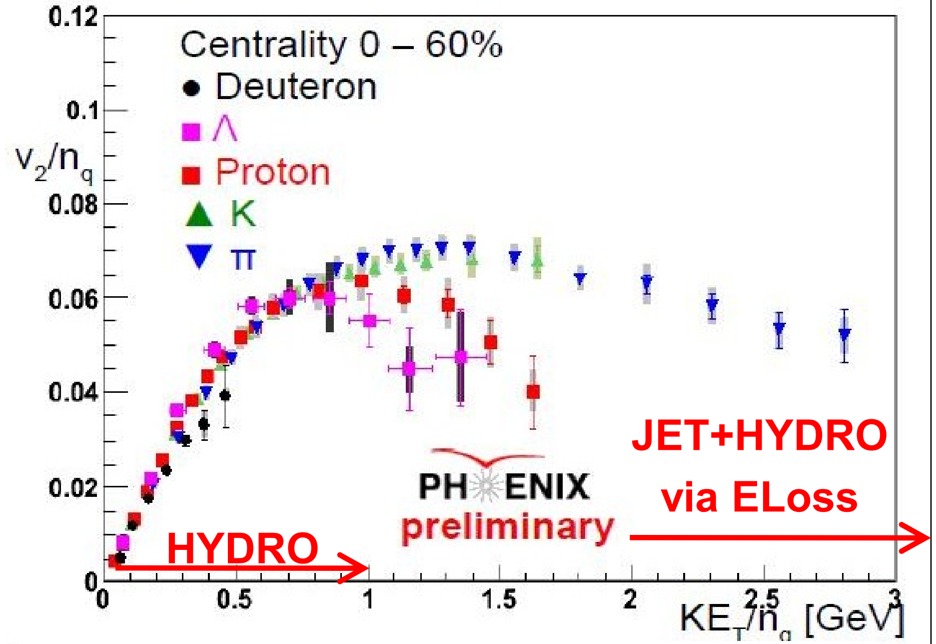


Reasonable average suppression

Too little reaction-plane dependence

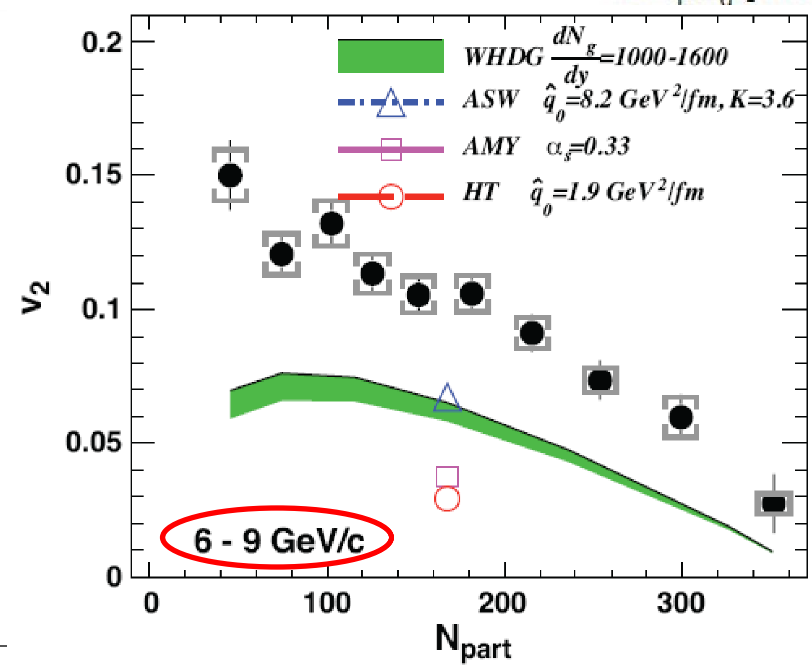
Large Hadron V_2 at High p_T





Elliptic flow vs. kinetic energy KE_T scales with the quark number (n_q=2,3 for meson/baryon): hydrodynamics for partons up to ~1GeV

Hadron elliptic flow above ~2-3GeV is from jet coupling to RP due to parton energy loss

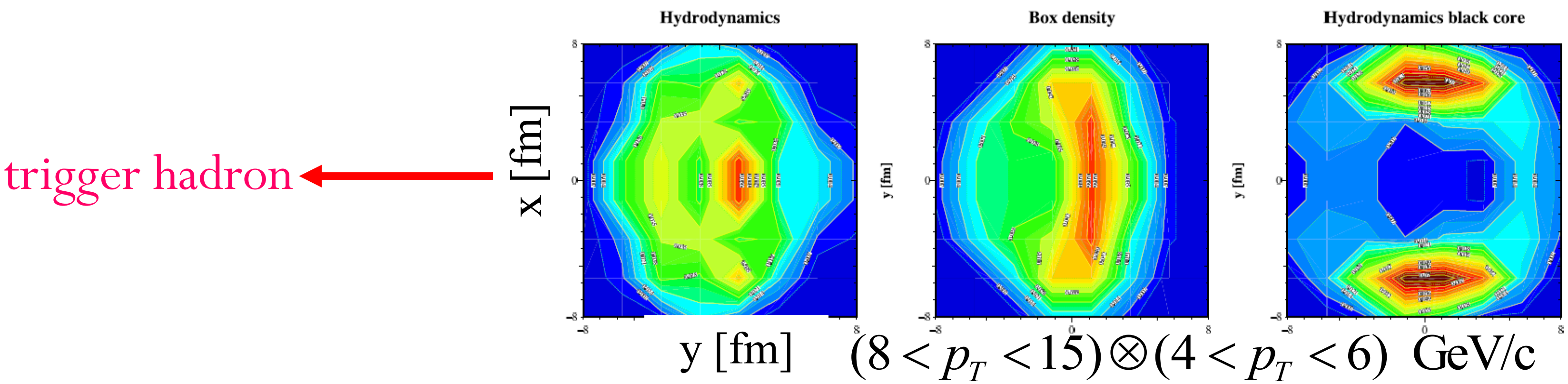


More discriminative measurements: Angular Correlations

Dihadron correlations: trigger on high p_T hadron, associate with lower p_T hadron

Less surface bias. Information on jet broadening.

T. Renk, K. Eskola hep-ph/0610059



$(8 < p_T < 15) \otimes (4 < p_T < 6)$ GeV/c

Direct photon-hadron correlations: trigger on isolated high p_T photon

Tag the hadronic jet with a direct photon. Difficult to isolate direct photons.

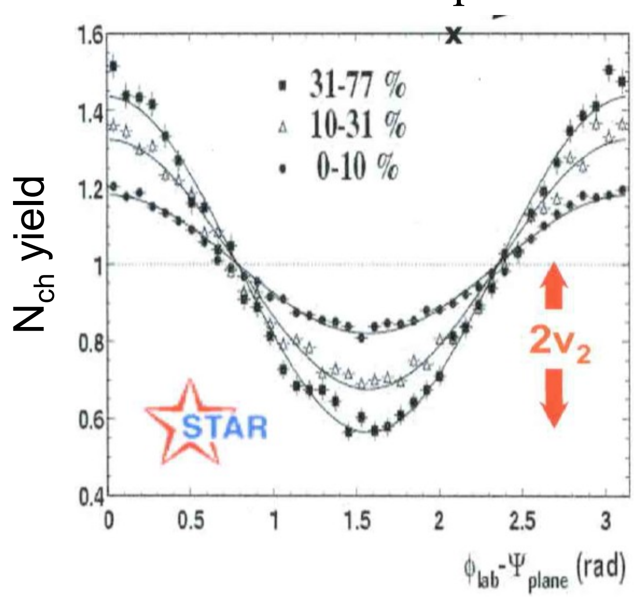
Jet-hadron correlations: trigger on a reconstructed jet

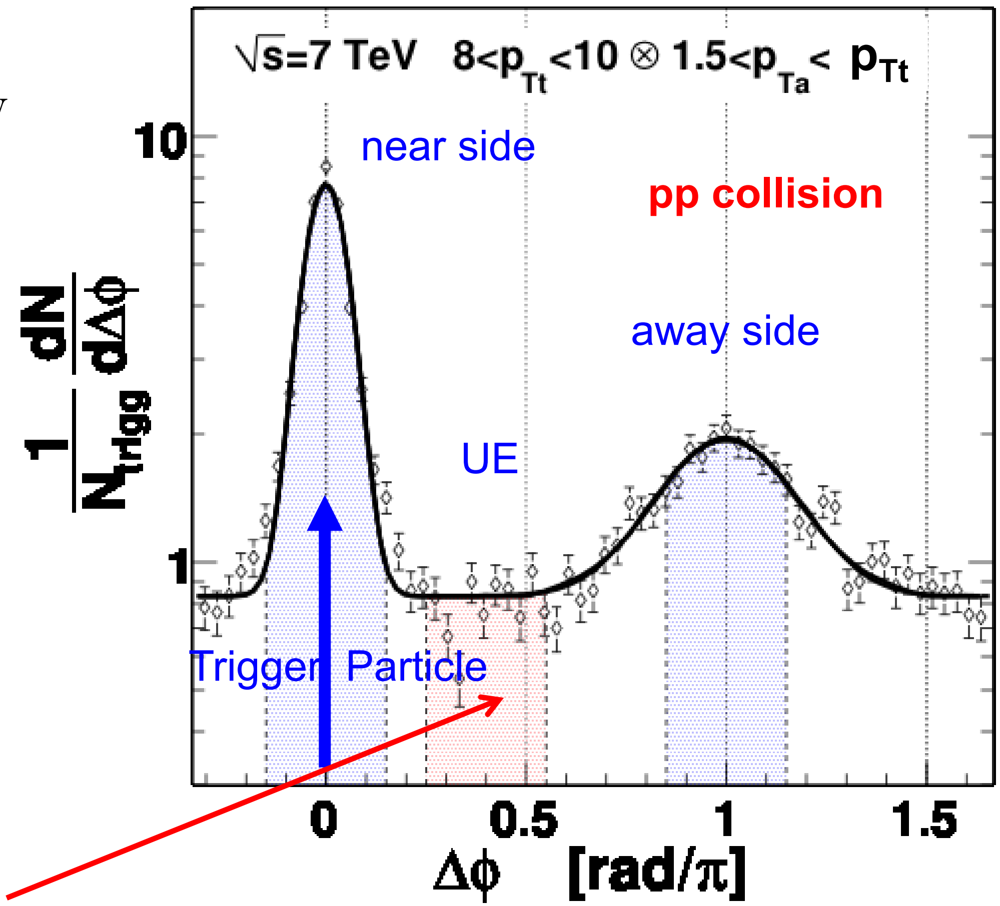
Direct measurement of jet properties. Difficult to reconstruct in high backgrounds.

Two-Particle Angular Correlations

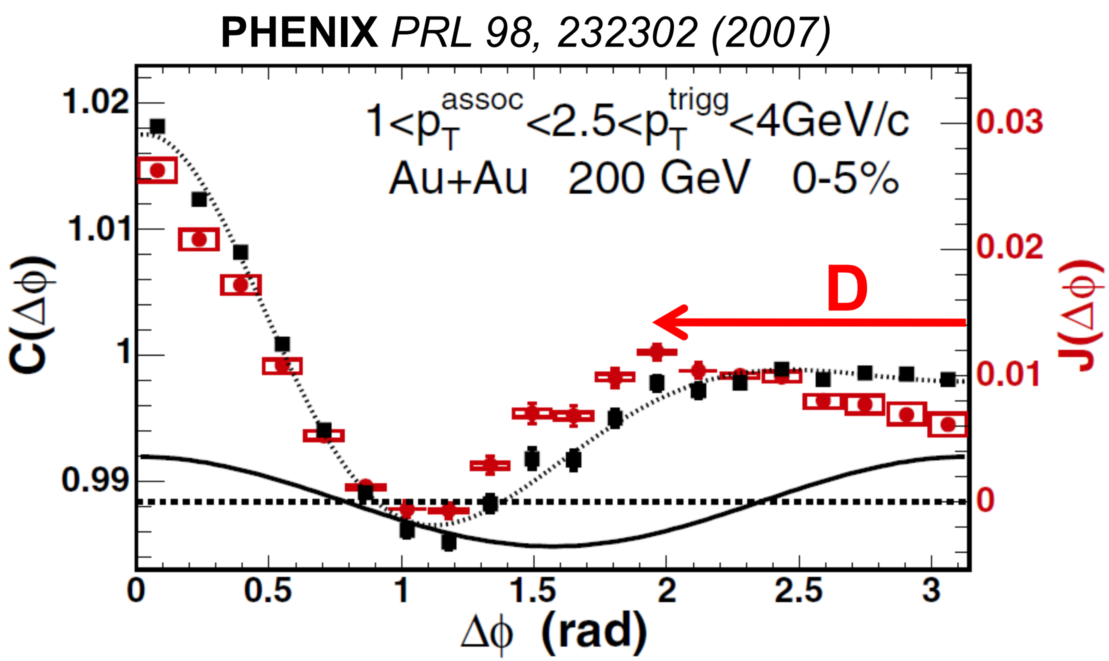
$\Delta\phi=\phi_{trigg}-\phi_{assoc}$ distributions divided by mixed-event $\Delta\phi$ distributions from the same collision class and normalized per trigger particle.

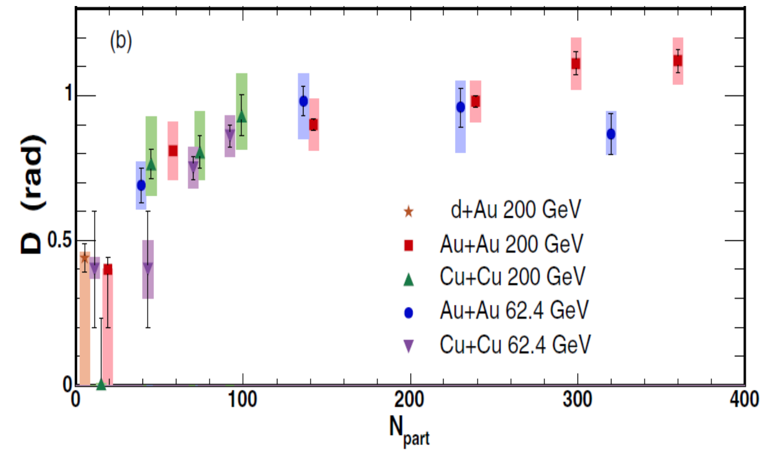
In **HI**: anisotropic UE





Background Subtraction: the "Shoulder"



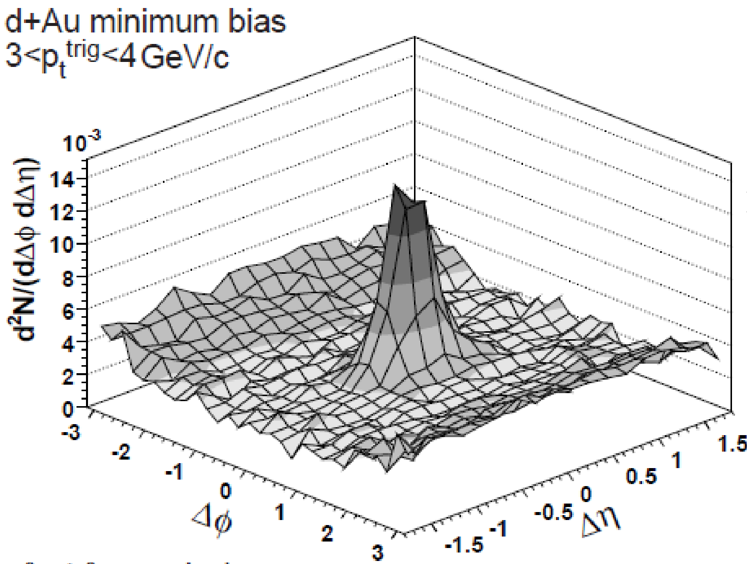


What v_2 should be used? Non-flow and flow fluctuation effects should be reduced…

After subtraction, a surprise at intermediate p_T: the "shoulder" = away-side peak shifted by ~1rad from $\Delta\phi=\pi$.

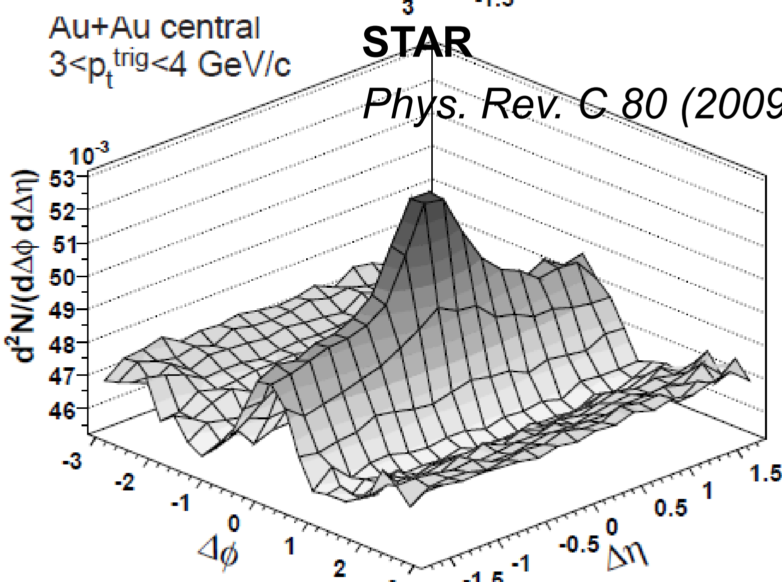
The "shoulder" is independent on momentum and collision centrality, energy, system.

Rapidity Correlations: the "Ridge"



The "Ridge": a wide flat $\Delta\eta$ plateau in the near-side ($\Delta\phi\sim0$) also present only in Au-Au collisions and only for intermediate p_T (1-4GeV)

PHOBOS: ridge extends up to $|\Delta\eta|<4$



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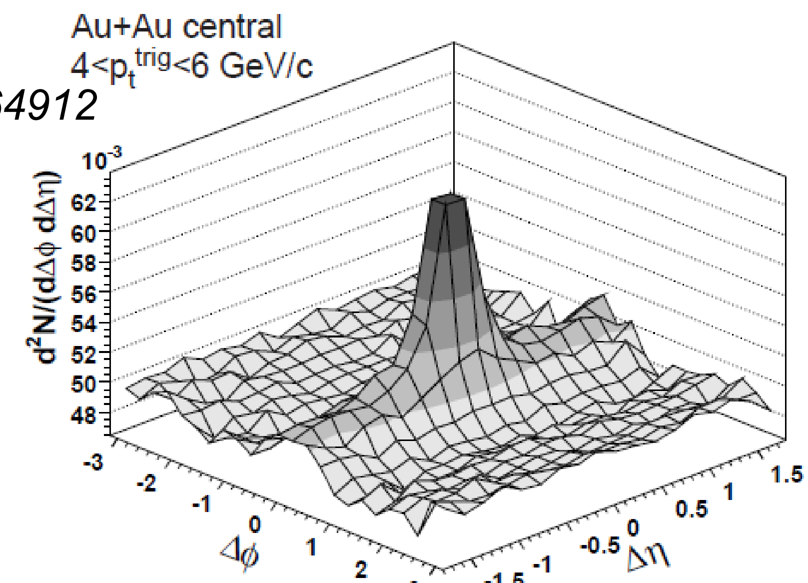
Phys. Rev. C 80 (2009) 64912



The "Shoulder" and the "Ridge": Medium Response to Jets?

Both are associated with mini-jets but have **medium like** properties (<p_T>, hadron composition): describe **medium-response** to jets?

Many medium-response models on the market for both… Leading contenders:

- the "shoulder": sonic shock waves (from supersonic partons)

Casalderrey-Solana et al *Nucl Phys A774, 577 (2006)*; Renk et al *Phys Lett B646, 19 (2007)*

- the "ridge": color flux tubes (from CGC initial state)

Dumitru et al *Nucl Phys A810, 91 (2008)*; Gavin et al *Phys Rev C79, 051902 (2009)*

Energy loss models have succeeded also to produce similar angular features

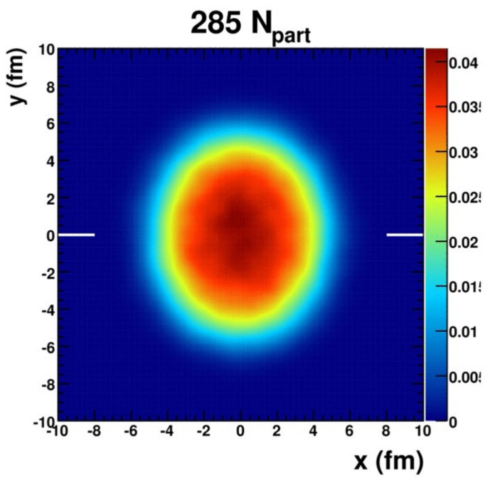
Salgado and Polosa *Phys Rev C75, 041901(R) (2007)*; Vitev *Phys Lett B630, 78 (2005)*

HOWEVER, a simpler explanation could be…

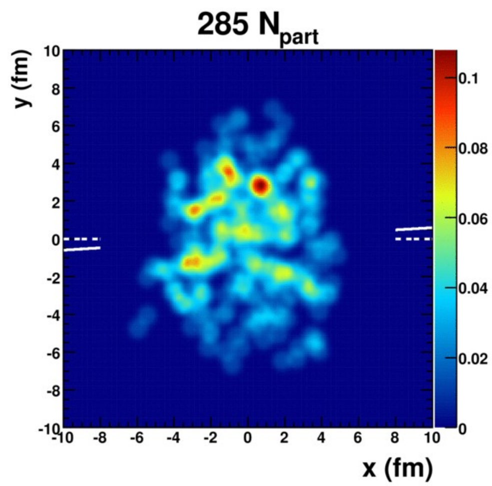
... or flow fluctuations?

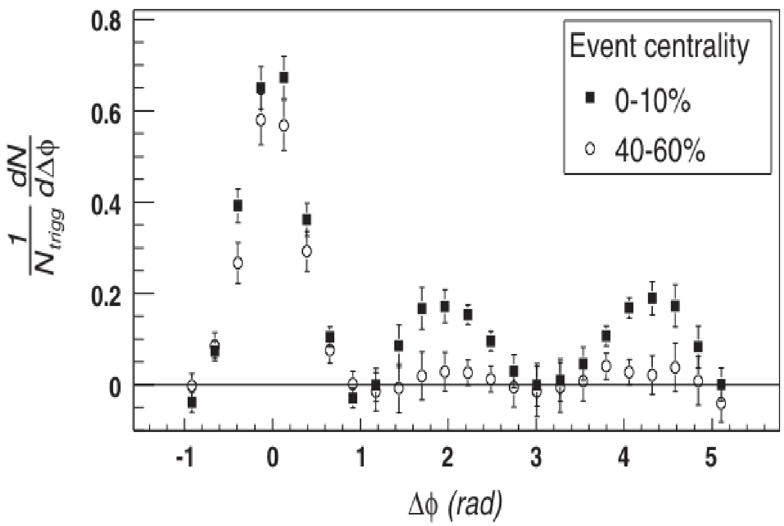
Hydrodynamic simulations: Takahashi et al *Phys Rev Lett 103, 242301 (2009)*

1000 event average



1 single event





- real collisions start from lumpy initial conditions that break symmetry
- no parton-medium coupling required
- generates both the "shoulder" and the "ridge"
- unclear yet if it fits with the rest

High p_T Correlations: "Normal" Away-Side

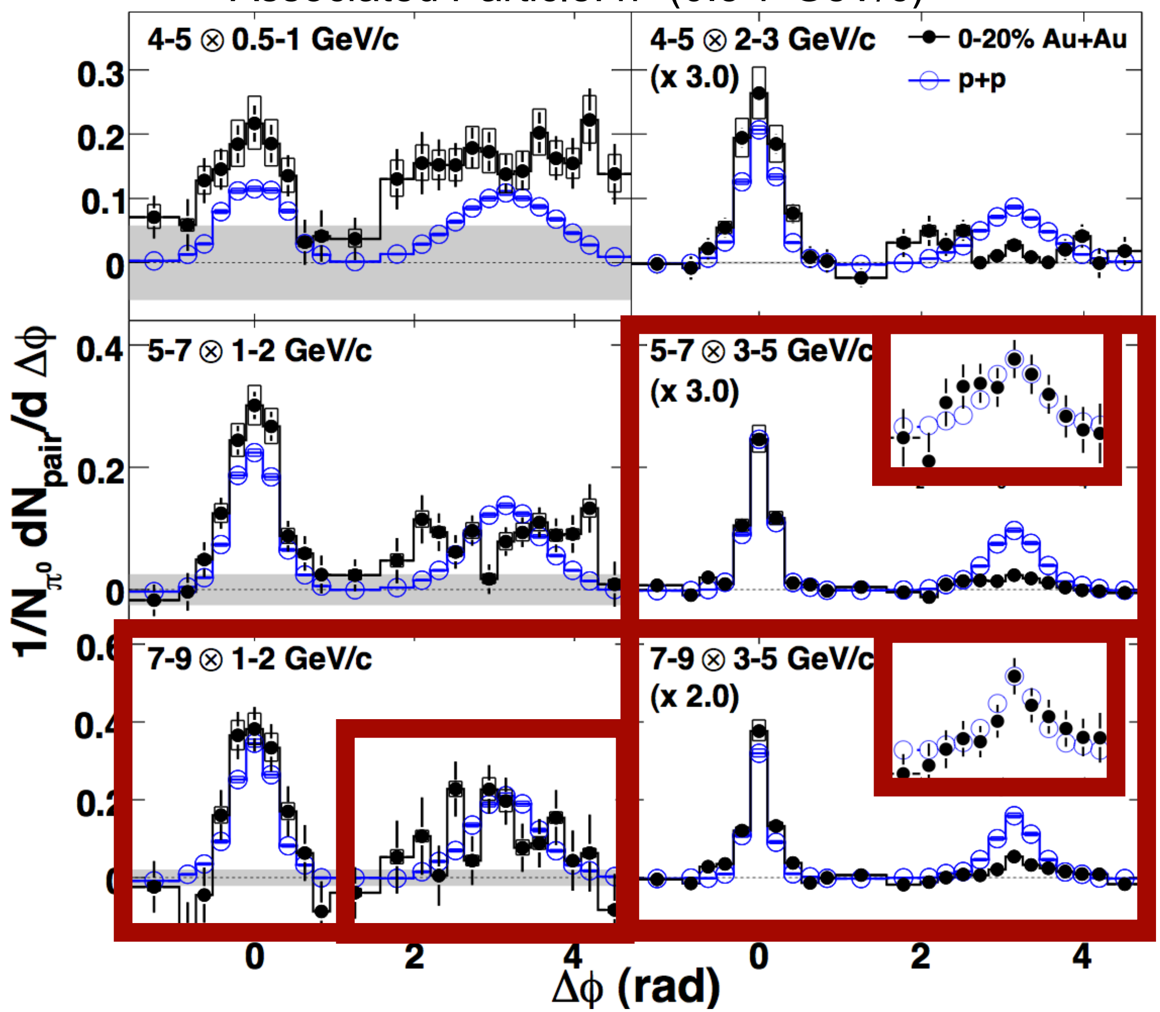
Broad range of trigger p_{Ttrigg}

p_{Ttrigg}>7GeV: back-to-back peaks for all measured associated p_T

No jet broadening

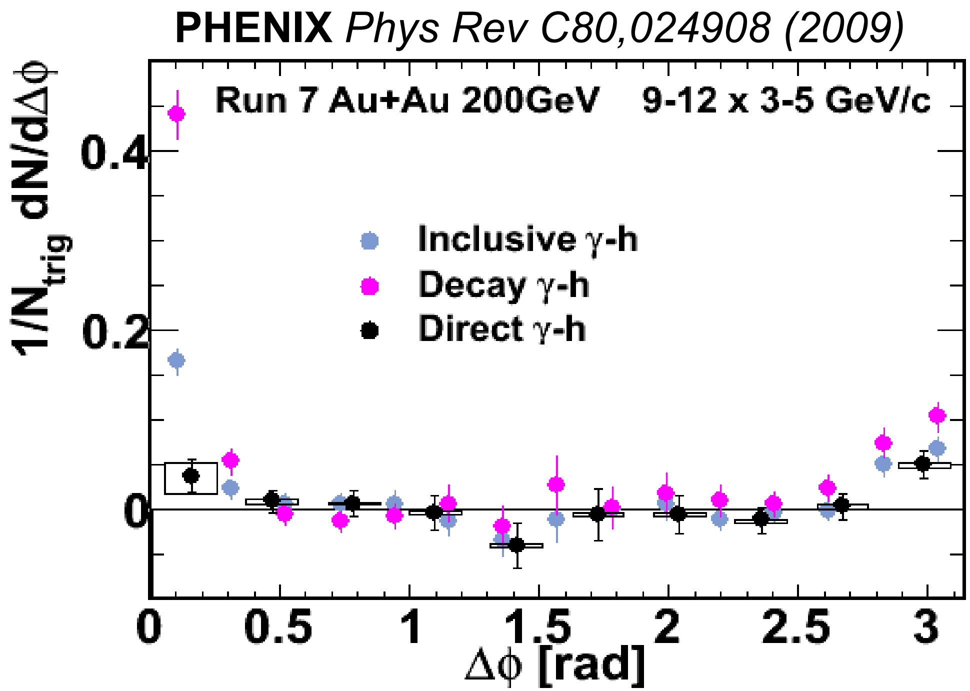
Away-side suppression at large associated p_T

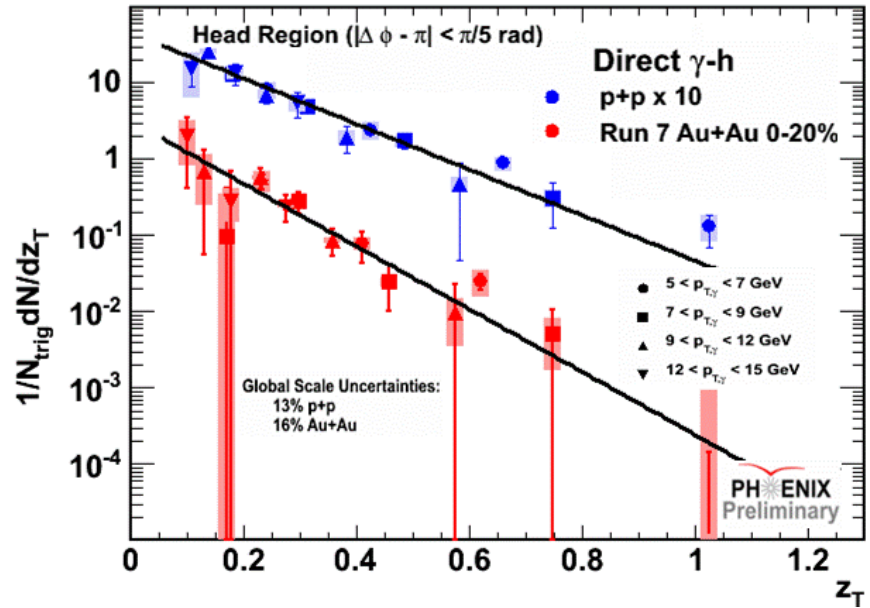
Trigger Particle: π^0 (4-9 GeV/c),
Associated Particle: $h^{\pm}$ (0.5-7 GeV/c)



Phys Rev Lett 104, 252301 (2010)

Direct γ-Hadron Correlations





Statistical subtraction method

Small near-side component (fragmentation γ)

Towards a fragmentation function: away-side per trigger yield vs $z_T = p_{Th}/p_{T\gamma}$.

Fit with $dN/dz_T = Ne^{-bz_T}$ gives:

$b_{pp} = 6.89 \pm 0.64$ (quark b=8)

$b_{AuAu} = 9.49 \pm 1.37$

High p_T Hadron Suppression: R_{AA} and I_{AA}

I_{AA} is the equivalent for R_{AA} that uses per trigger yields of correlated hadrons instead of single hadron yields in the AA/pp ratio.

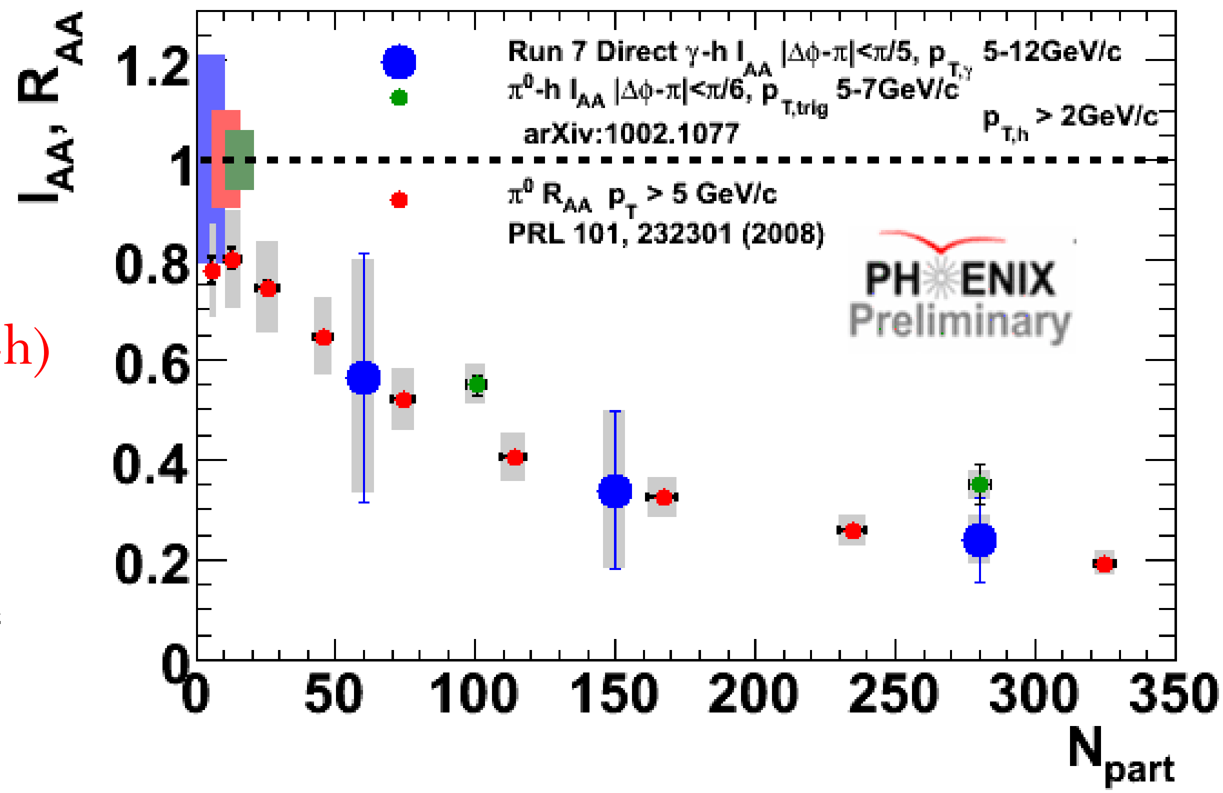
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{\mathrm{ch}}^{AA}/d\eta dp_T}{\langle N_{\mathrm{coll}}\rangle\, (1/N_{evt}^{pp})\, d^2N_{\mathrm{ch}}^{pp}/d\eta dp_T}$$

For p_{Ttrigg}>5GeV

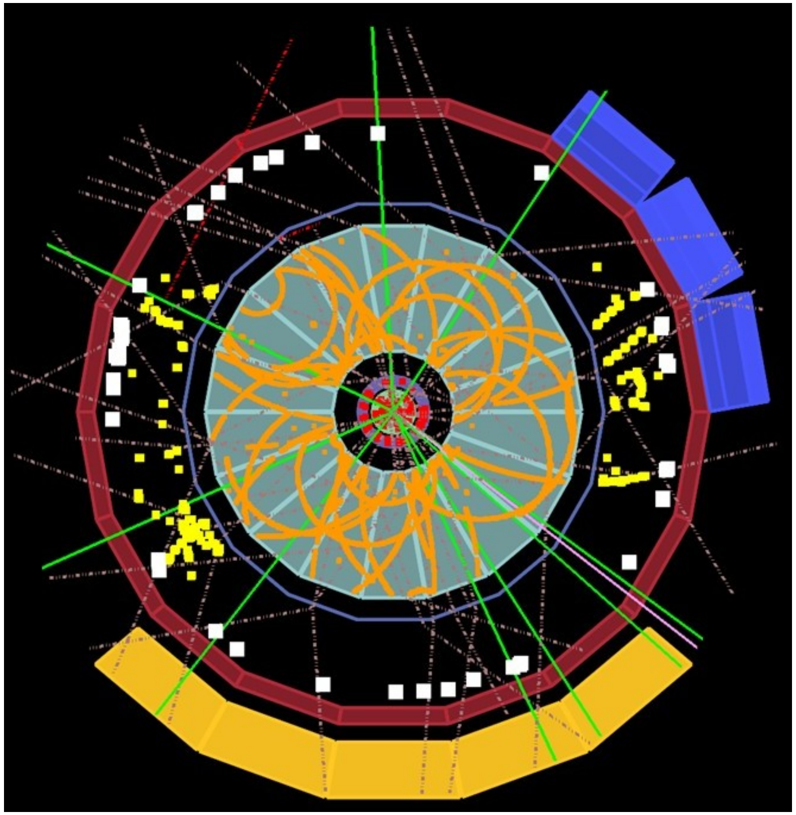
$R_{AA}(\pi^0)$~$I_{AA}(\pi^0\text{-h})$~$I_{AA}(\gamma\text{-h})$

with slightly higher $I_{AA}(\pi^0)$.

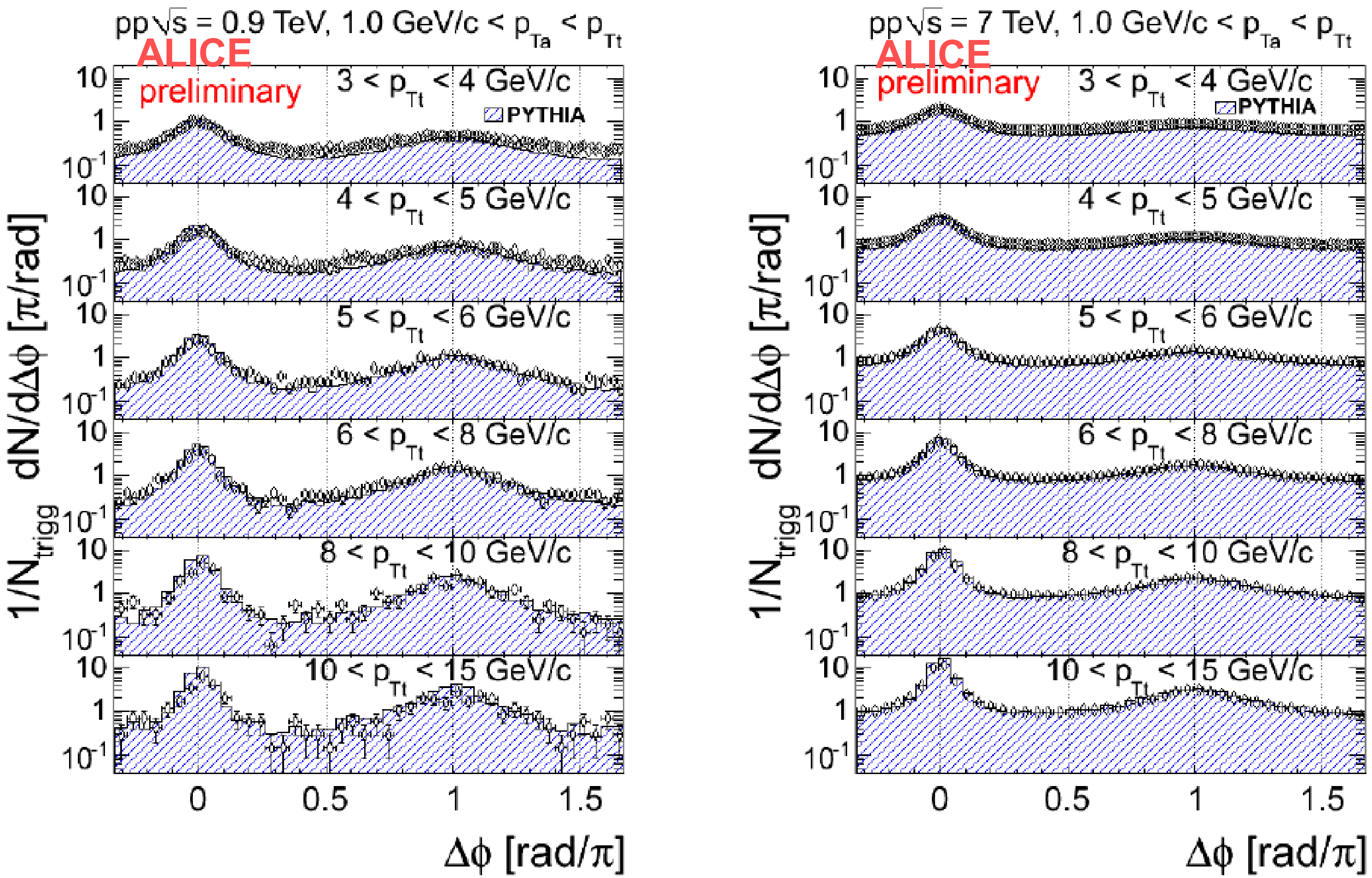
<u>This kind of complex set of measurements puts stringent constraints on models</u>.



LHC Results from pp Collisions at $\sqrt{s}$=0.9&7TeV



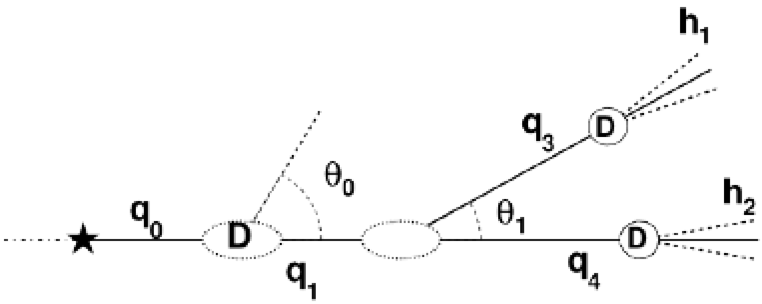
Dihadron Azimuthal Correlations in p-p



1. Pythia (Perugia tune) doesn't get right CFs below trigg. p_{Tt} ~ 4 GeV/s
2. Uncorrelated background much larger at 7TeV than at 0.9TeV.

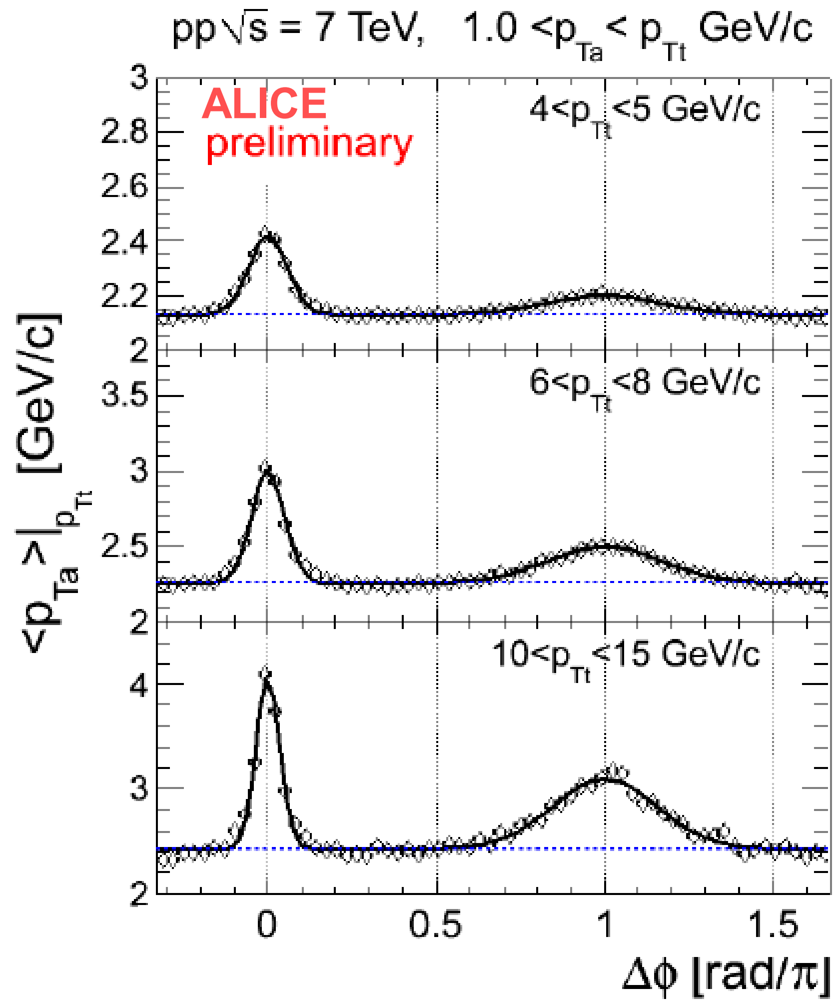
Fragmentation Angular Ordering

- Angular ordering

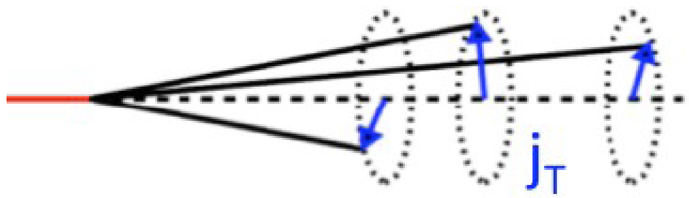


Dokshitzer, Y. L. et al:
Hard Processes in QCD
Phys.Rept., 1980, 58, 269-395
Fong, C.P., Webber, B.R.:
Phys.Lett.B 229 (1989) 289.

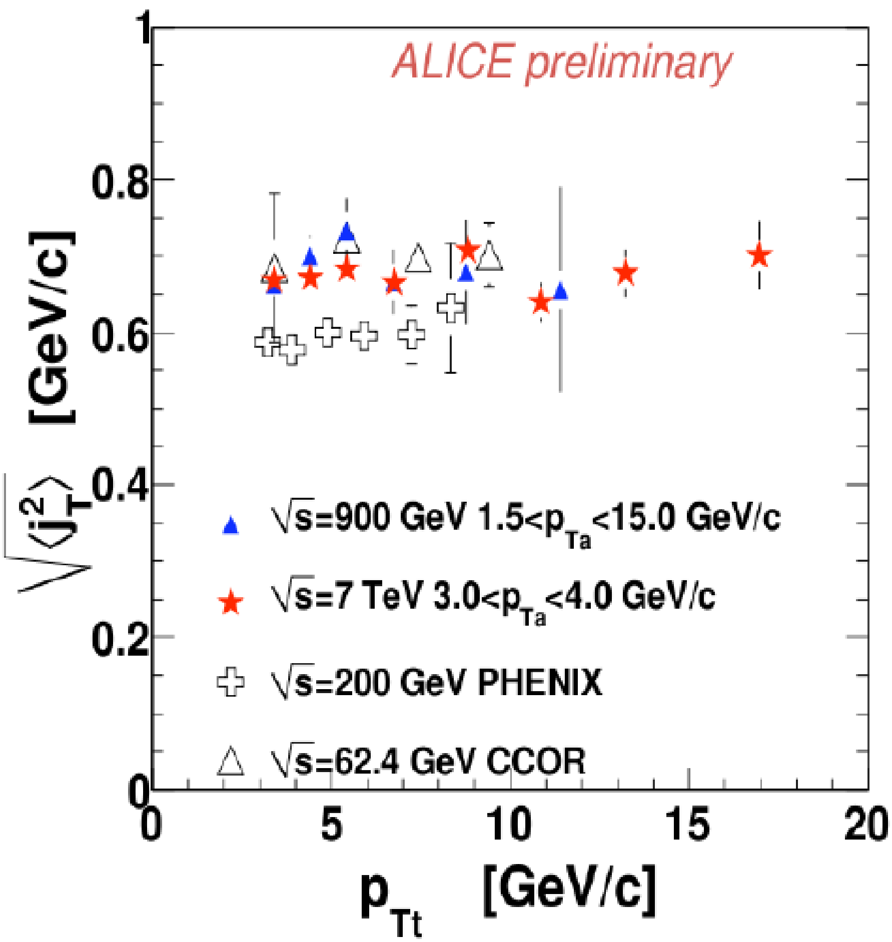
- Modified Leading Logarithmic Approximation MLLA



Fragmentation Transverse Momentum



- Dispersion of j_T from nearside width
- Average transverse momentum of fragmentation products relative to jet axis
- Expected independence on trigger particle p_T confirmed



$$\sqrt{\langle j_T^2 \rangle}_{900\text{ GeV}} = 678 \pm 12\ \text{MeV/c}$$

$$\sqrt{\langle j_T^2 \rangle}_{7\text{ TeV}} = 673 \pm 5\ \text{MeV/c}$$

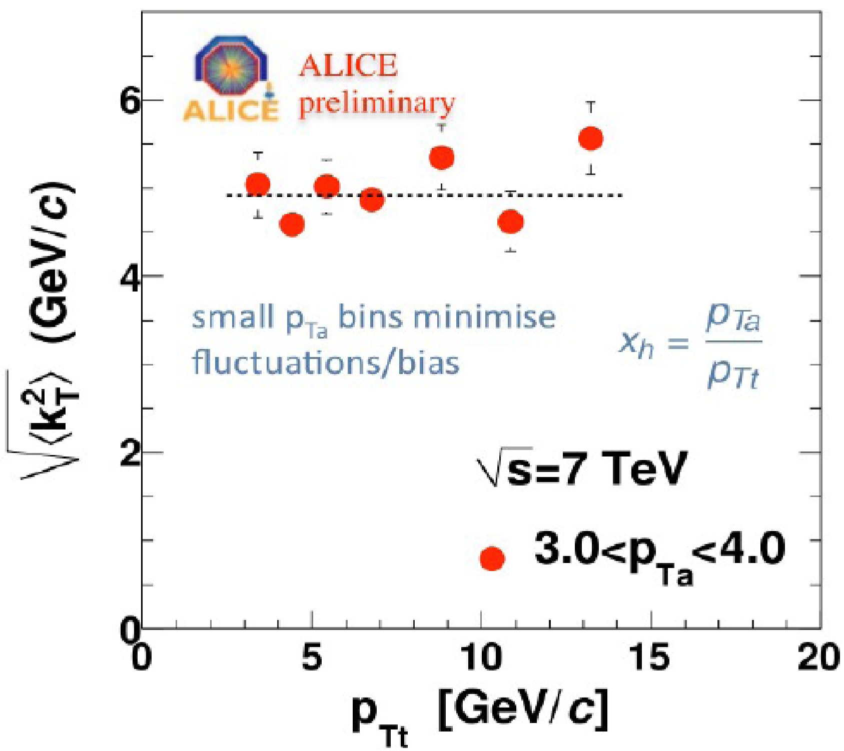
Partonic Transverse Momentum k_T

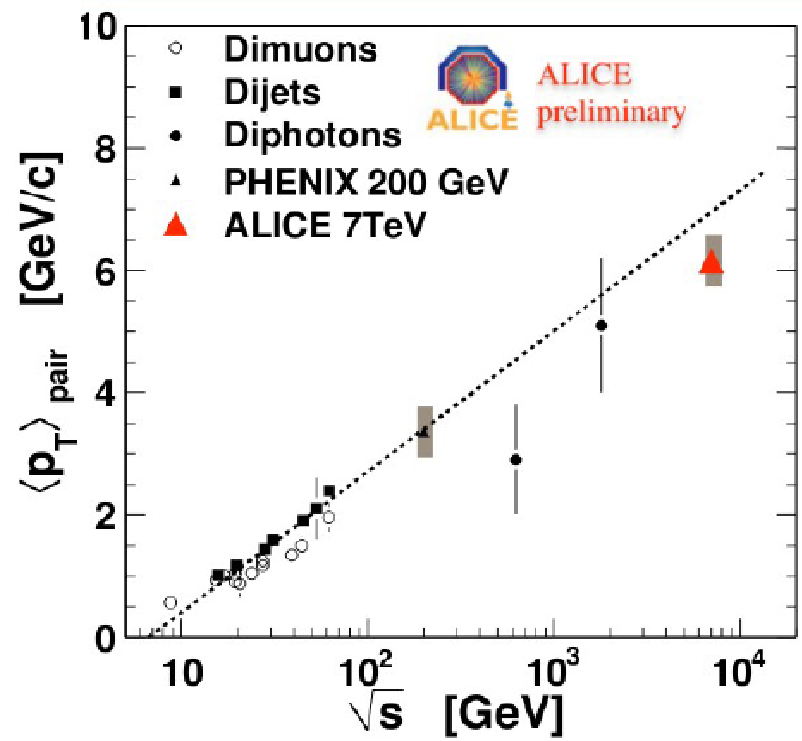
calculable *Phys Rev D74, 072002 (2006)*

$$\frac{\langle z_t\rangle}{\langle \hat{x}_h\rangle}\sqrt{\langle k_T^2\rangle} = \frac{1}{x_h}\sqrt{\langle p_{out}^2\rangle - \langle j_{Ty}^2\rangle(1+x_h^2)}$$

partonic hadronic/measured

$$\langle p_{T,\mathrm{pair}}\rangle = \sqrt{2}\times\langle k_T\rangle = \sqrt{\frac{\pi}{2}}\sqrt{\langle k_T^2\rangle}$$





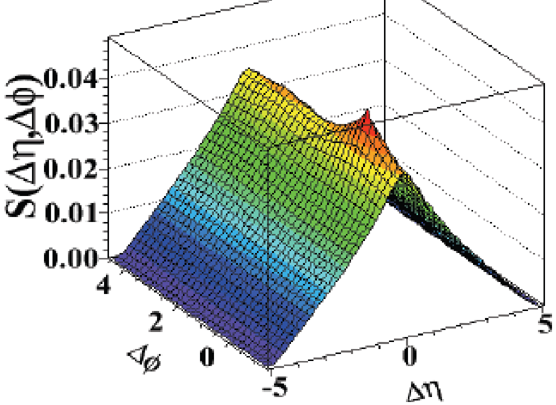
Confirmed expected increase of momentum imbalance of parton pair.

$$\sqrt{\langle k_T^2\rangle} = 4.9 \pm 0.1 \text{ GeV/c}$$

CMS: Angular Correlations in p-p at 7TeV

Signal distribution:

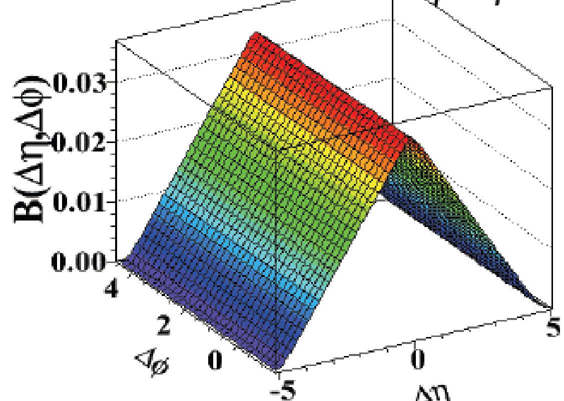
$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$



Same event pairs

Background distribution:

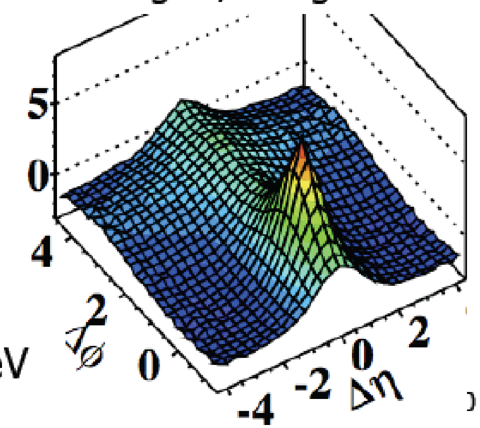
$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2}\frac{d^2N^{bkg}}{d\Delta\eta d\Delta\varphi}$$



Mixed event pairs

arXiv:1009.4122v1

Ratio Signal/Background



CMS pp 7TeV

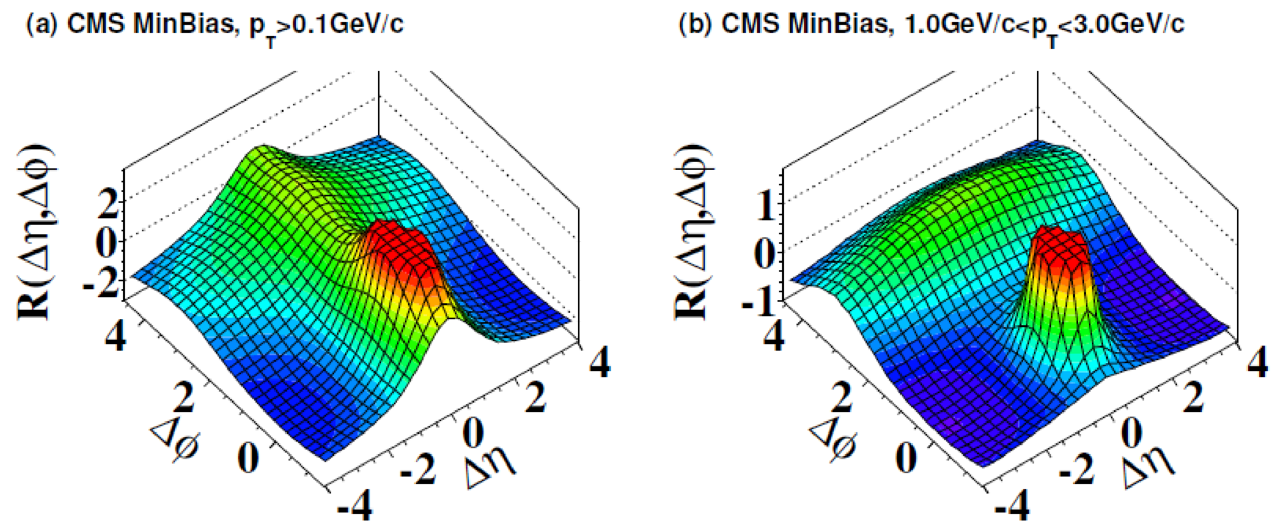
$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_N$$

$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$

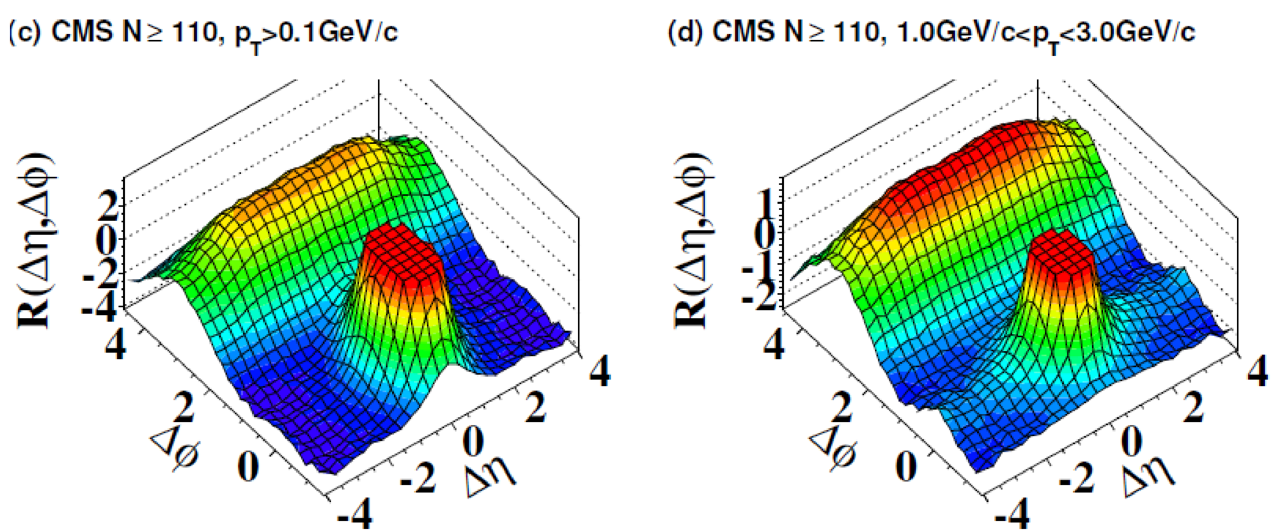
p_T-inclusive two-particle angular correlations in min bias collisions

CMS: Ridge in p-p at 7TeV (I)

The Ridge appears in pp collisions at high multiplicity (N>110) and intermediate p_T.



arXiv:1009.4122v1

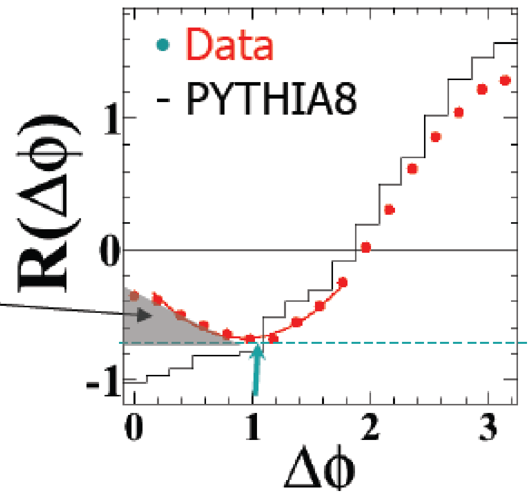


No structure around $\Delta\phi$=0 at large $\Delta\eta$ in Pythia6/8 and Herwig++

CMS: Ridge in p-p at 7TeV (II)

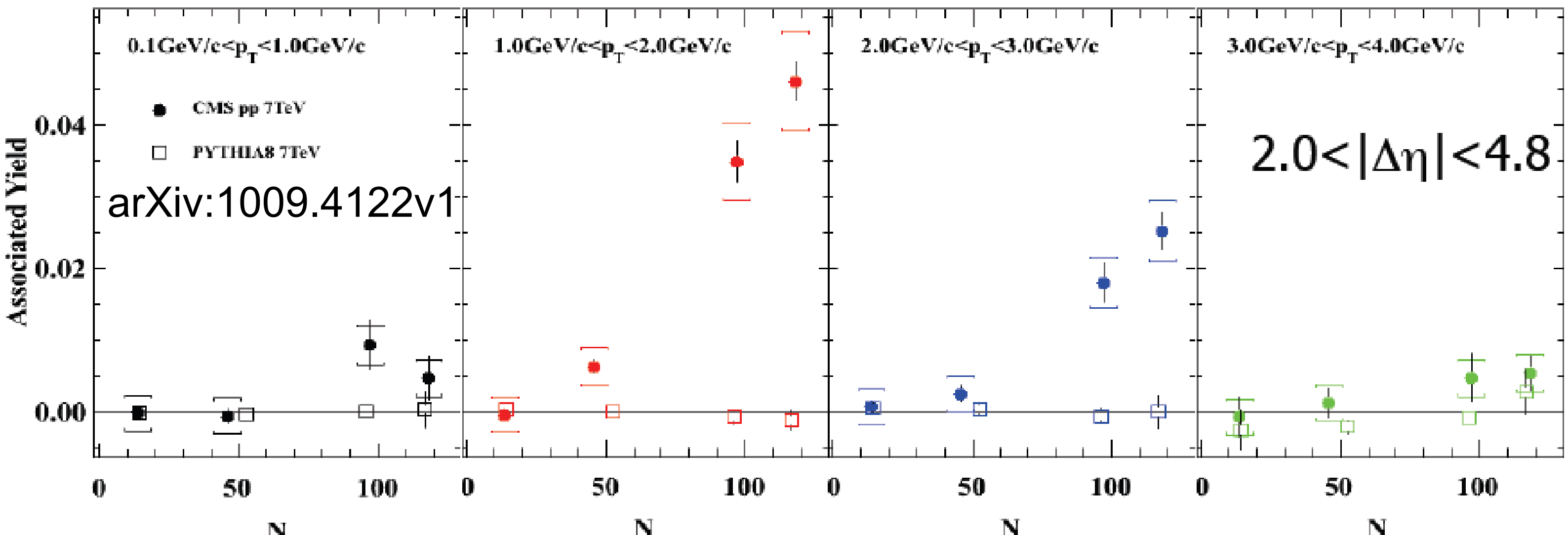
Zero Yield At Minimum (ZYAM)

Associated yield:
correlated multiplicity per particle



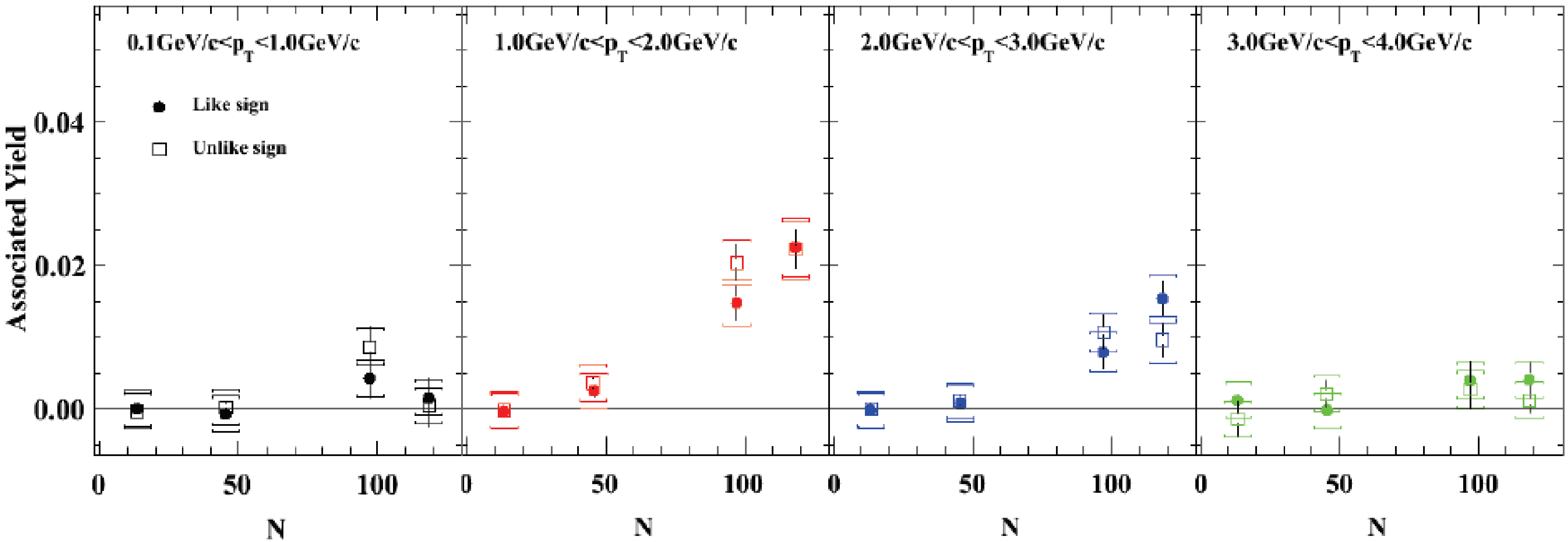
N>110
$2.0<|\Delta\eta|<4.8$
$1GeV/c<p_T<2GeV/c$

Minimum of R



Associated yield grows with increasing multiplicity

CMS: Ridge in p-p at 7TeV (III)

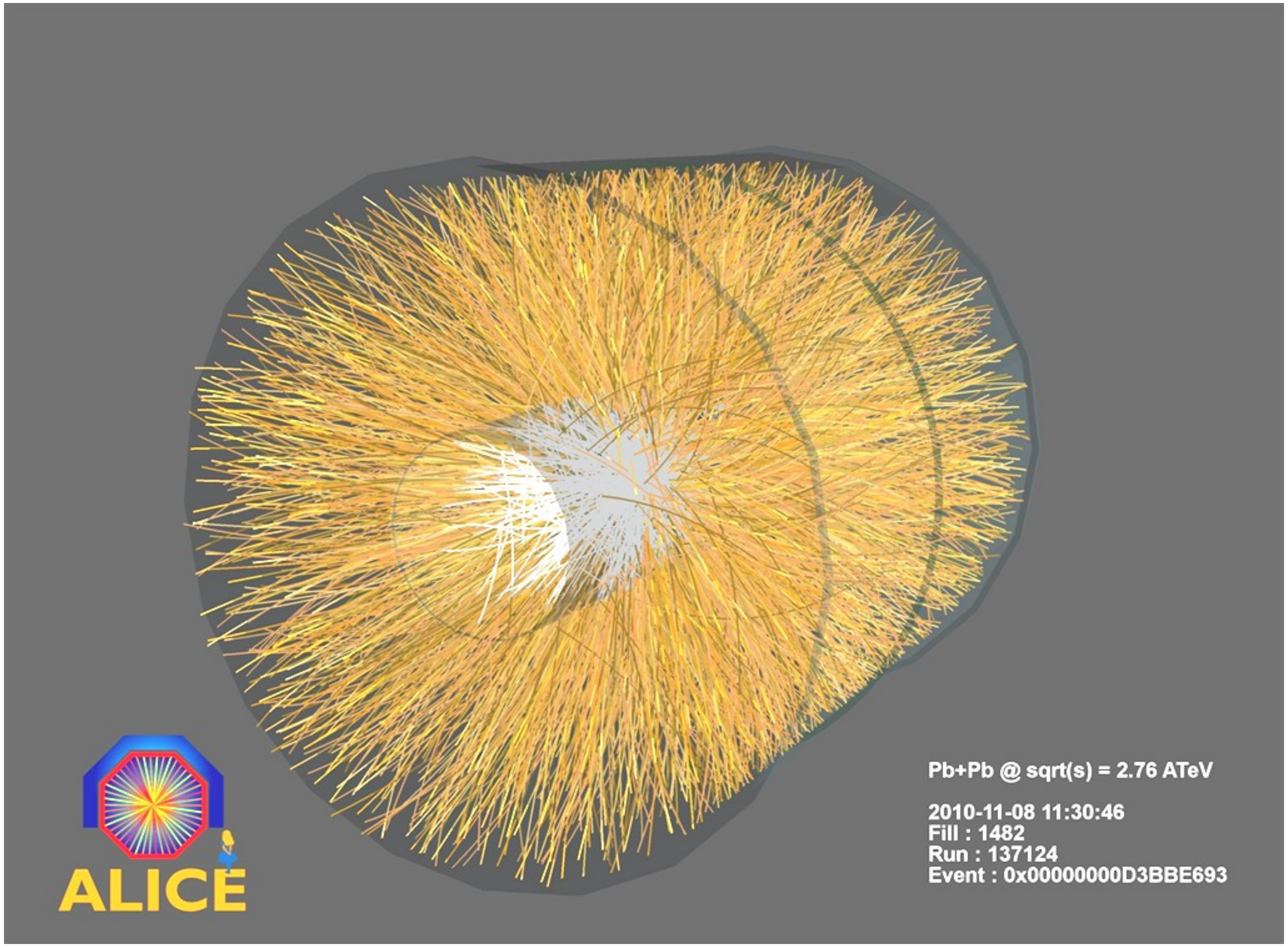


No dependence on relative charge sign

Interesting to see if it looks like jets or like "bulk" (<p_T>, hadron composition)

Ridge presence in pp collisions will constrain the models.

First LHC Results from Pb-Pb Collisions at $\sqrt{s_{NN}}$=2.76TeV



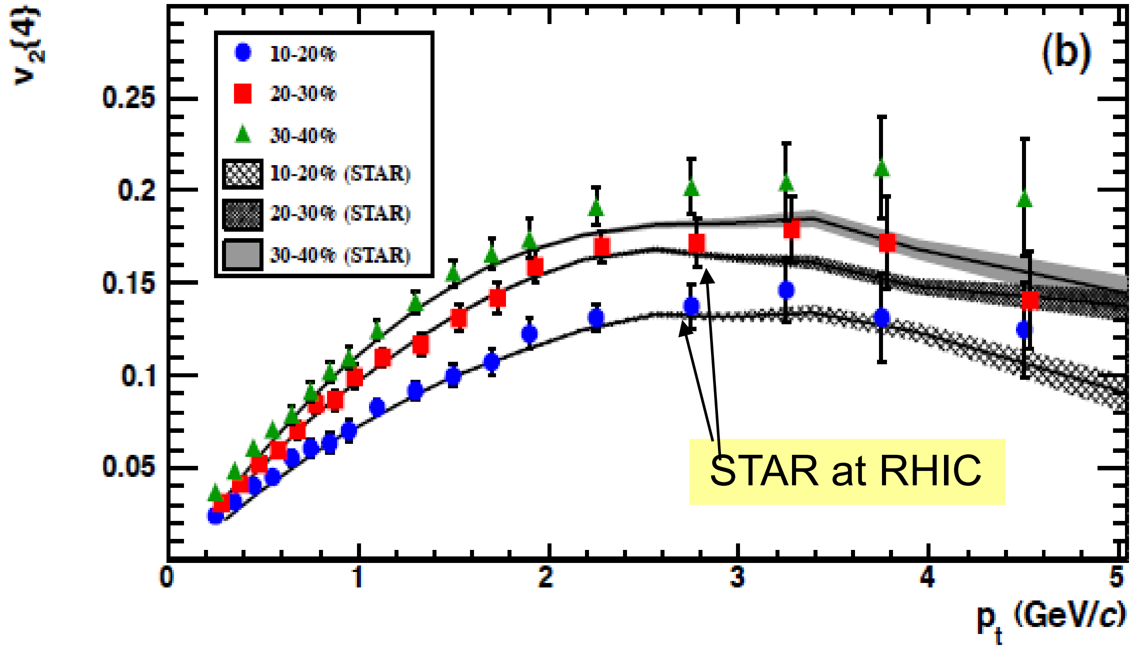
Elliptic Flow v_2

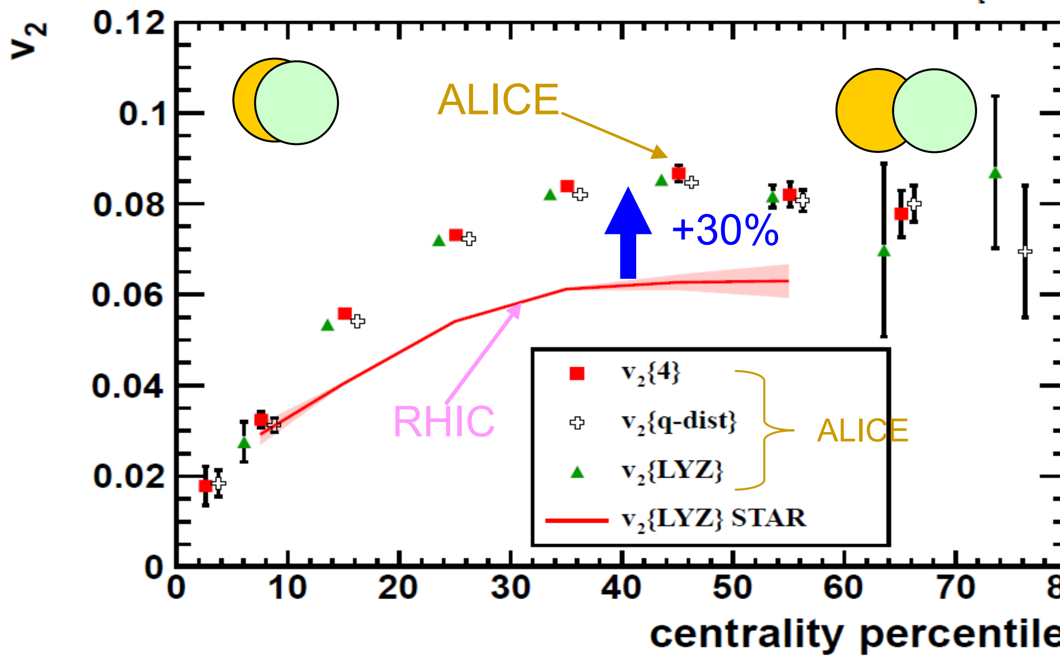
v_2 as function of p_t: very small difference compared to RHIC

v_2 integrated over pt

- 30% increase from RHIC
- In agreement with hydro limits

Phys Rev Lett 105, 252302 (2010)





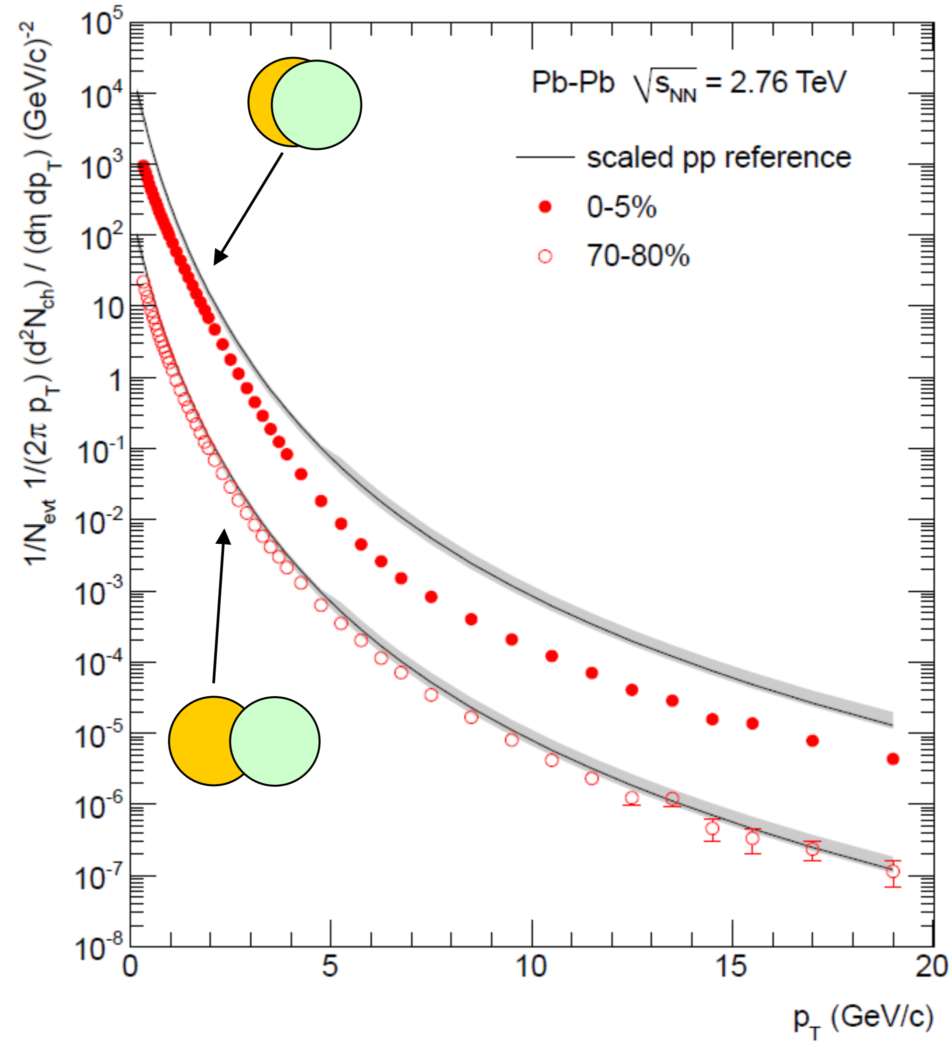
Jet quenching: High-p_T Hadron Suppression (I)

For the pp reference: data driven interpolation 900 GeV & 7 TeV
<u>or</u> using NLO for change in shape
7 TeV * NLO (2.76 TeV)/NLO(7 TeV).

Then, compute

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

Phys Lett B 696 (2011) 30-39

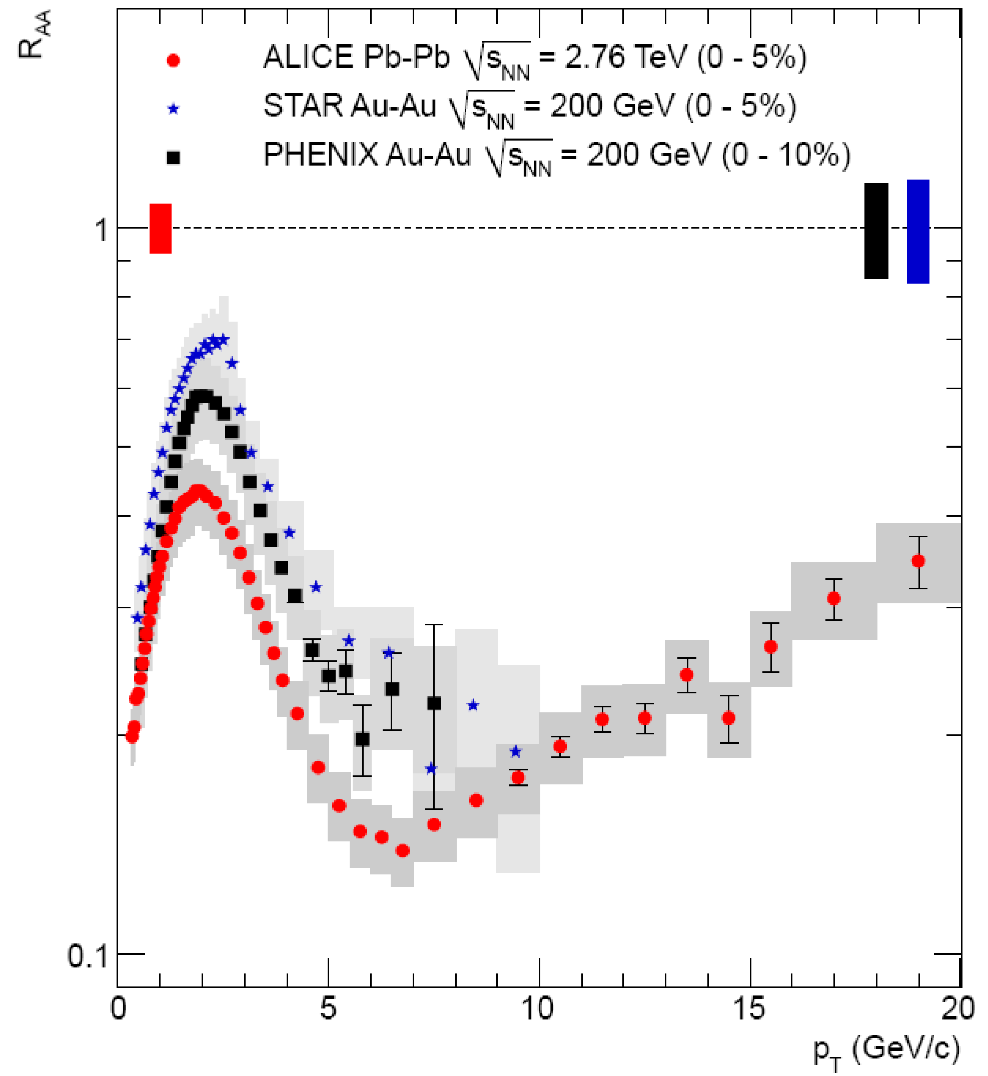


Jet quenching: High-p_T Hadron Suppression

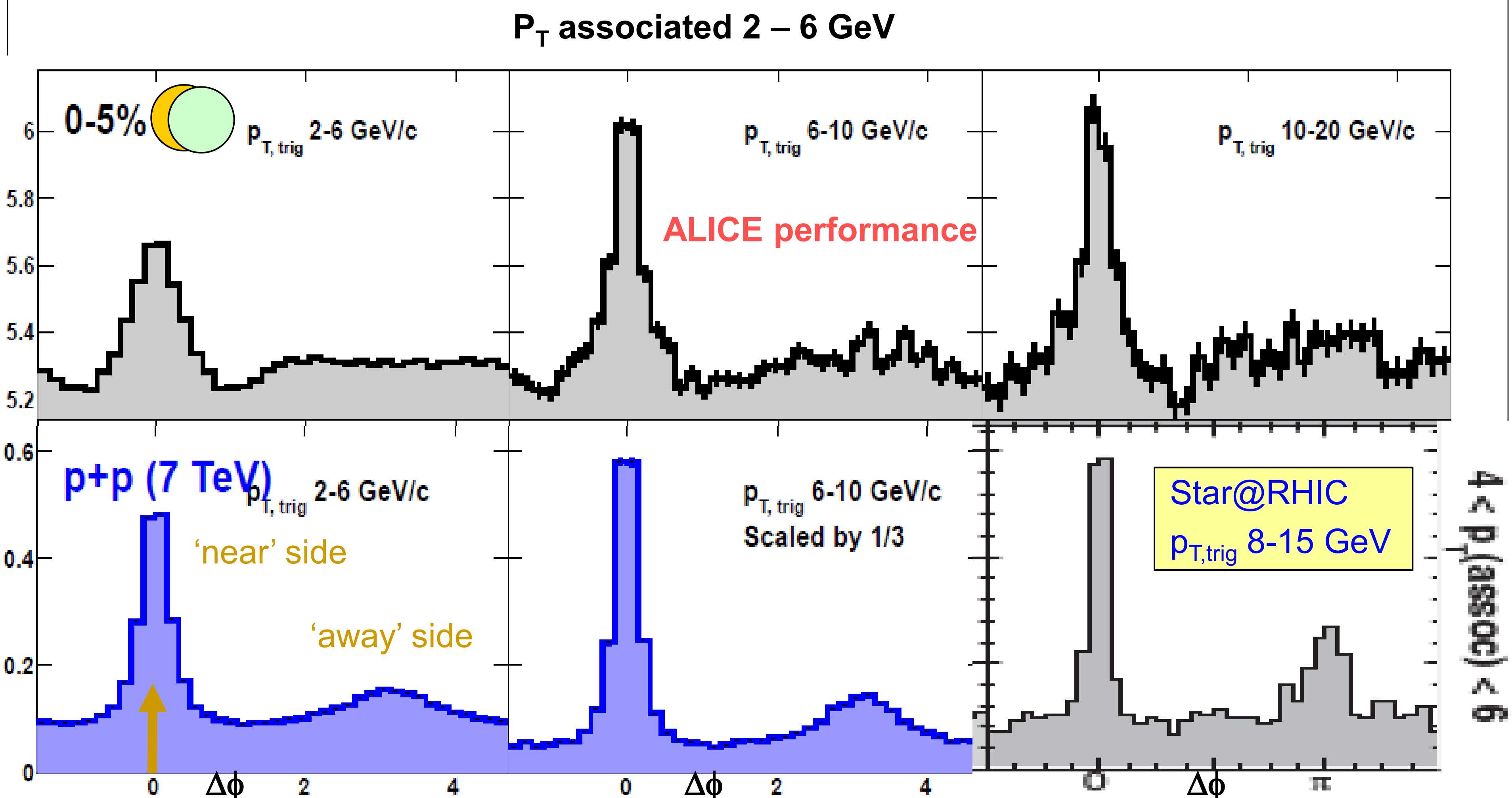
Significantly larger suppression than at RHIC (~1.5-2 larger)

Clear rising trend with p_T!

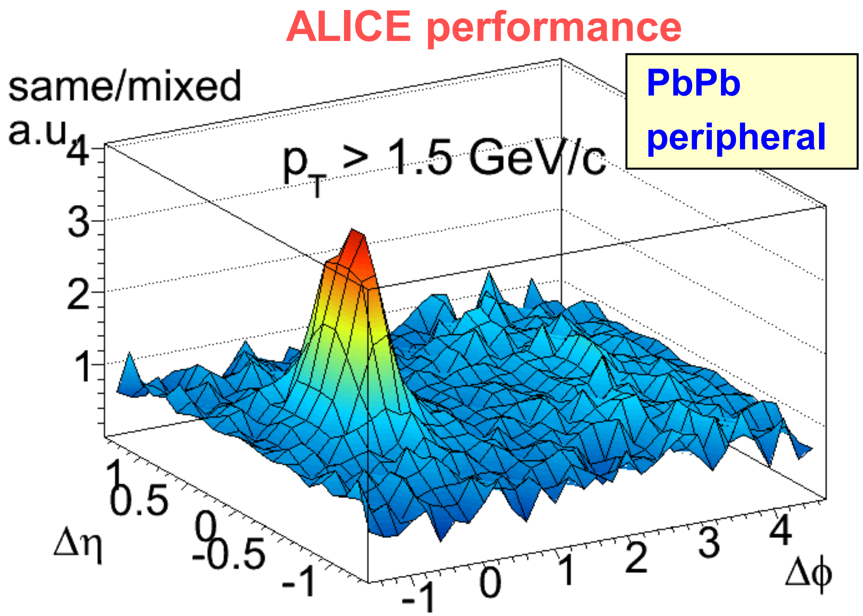
Phys Lett B 696 (2011) 30-39

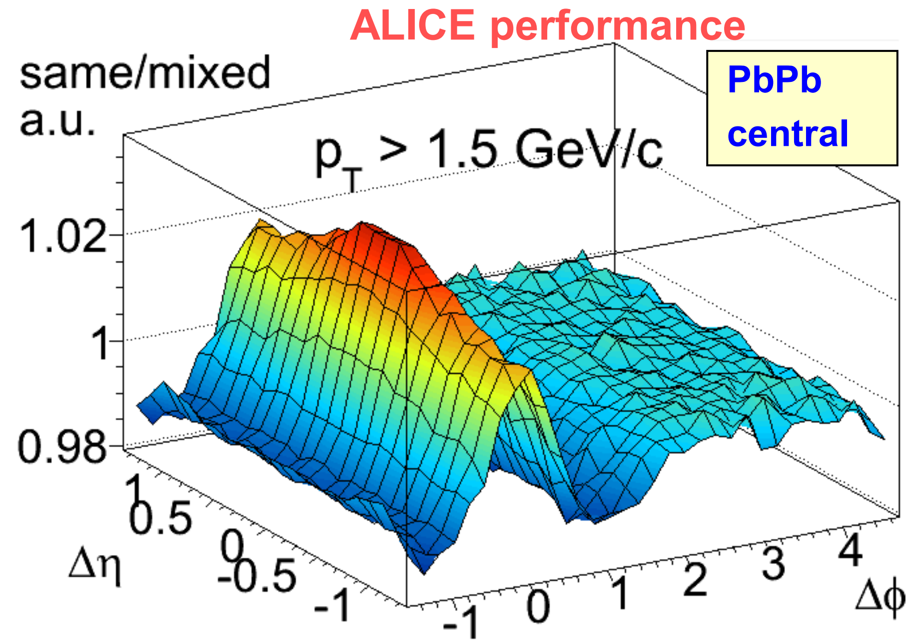


Jet quenching: Dihadron Correlations



The "Shoulder" and the "Ridge"

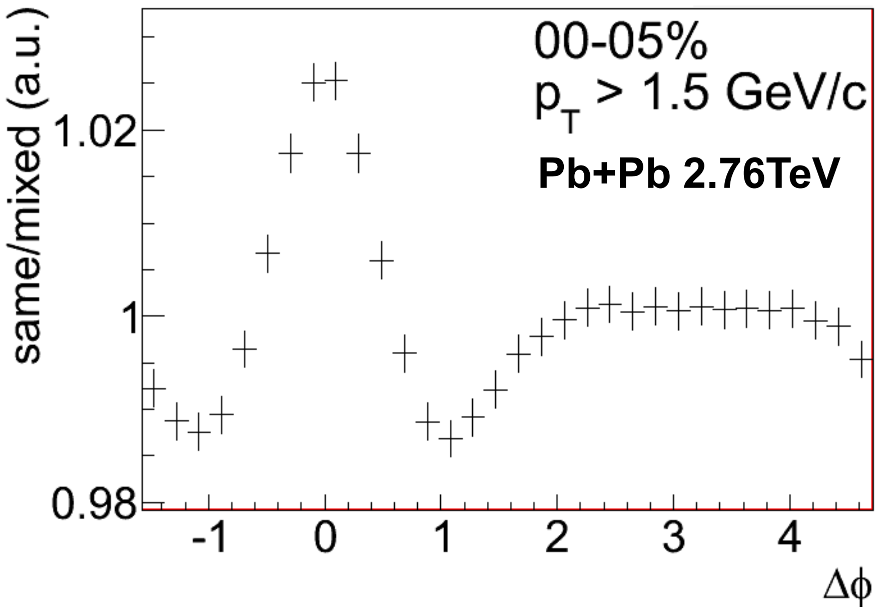


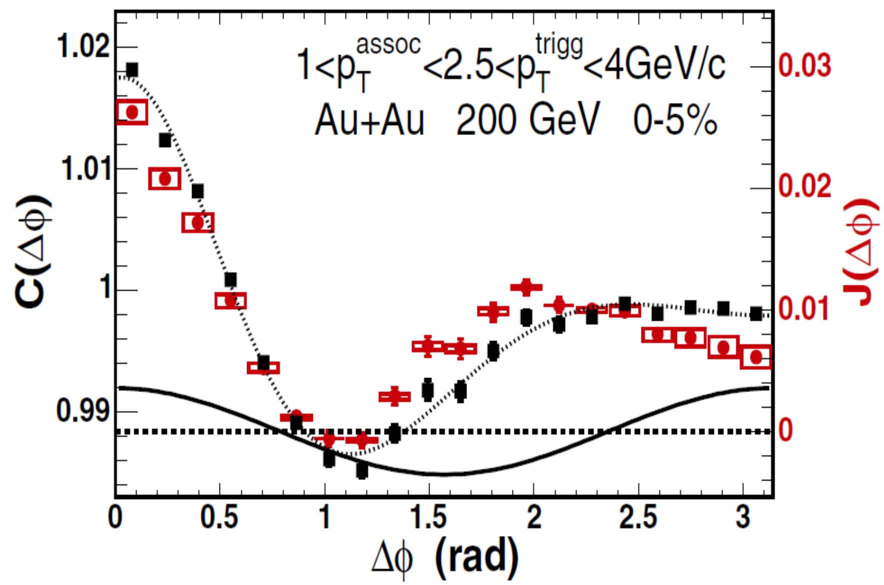


Results not even preliminary yet, but:

- clear near-side ridge in central collisions.
- away-side shoulder should develop in central collisions…

The "Shoulder" at LHC

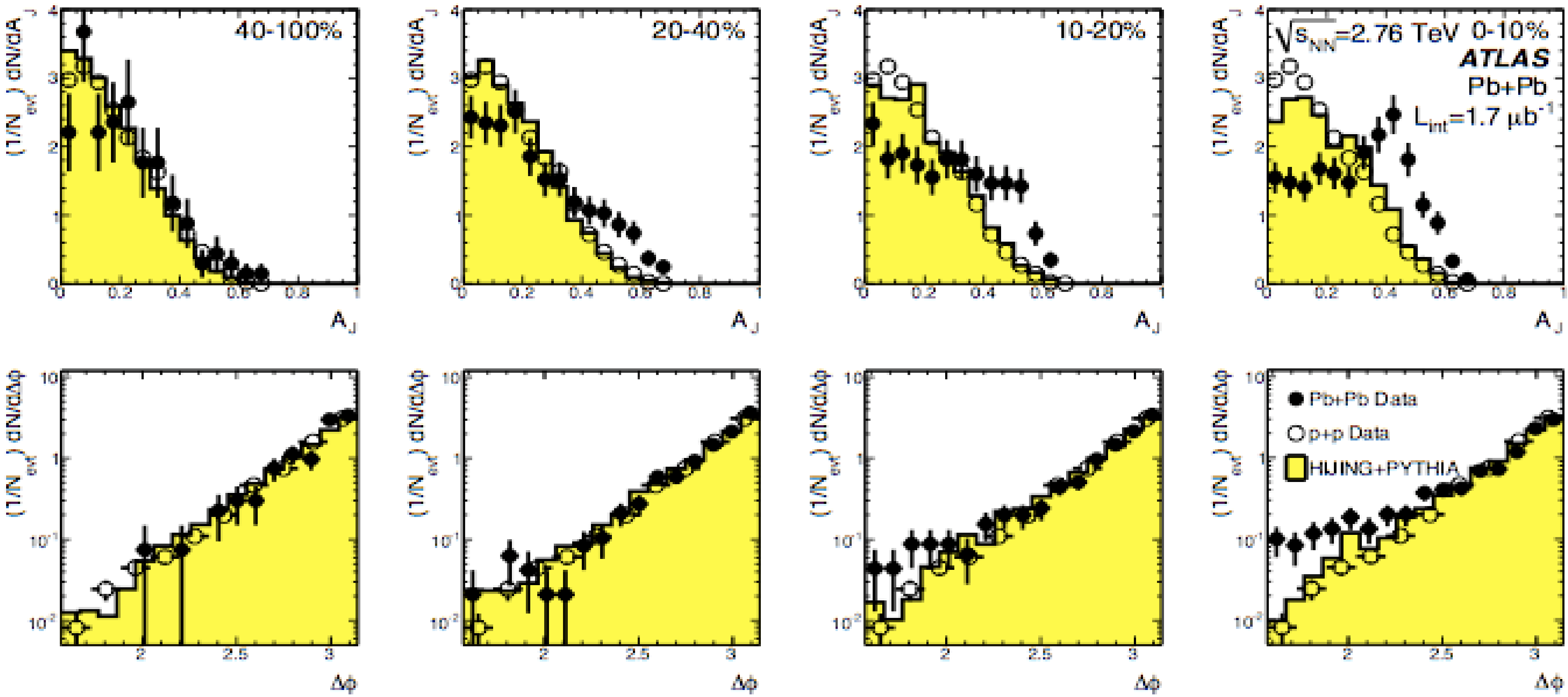




The wide flat plateau in the away-side before flow (mainly v_2) subtraction will lead to a shoulder similar to that at RHIC.

ATLAS&CMS: Jet Quenching via Dijet Assymetry

Use anti-k_T jets with leading jet (highest in event) E_{T1}>100GeV and sub-leading jet (highest in opposite hemisphere) E_{T2}>25GeV with $|\eta|<2.8$ and compute the dijet assymetry $A_J=(E_{T1}-E_{T2})/(E_{T1}+E_{T2})$ and relative azimuthal angle $\Delta\phi$:



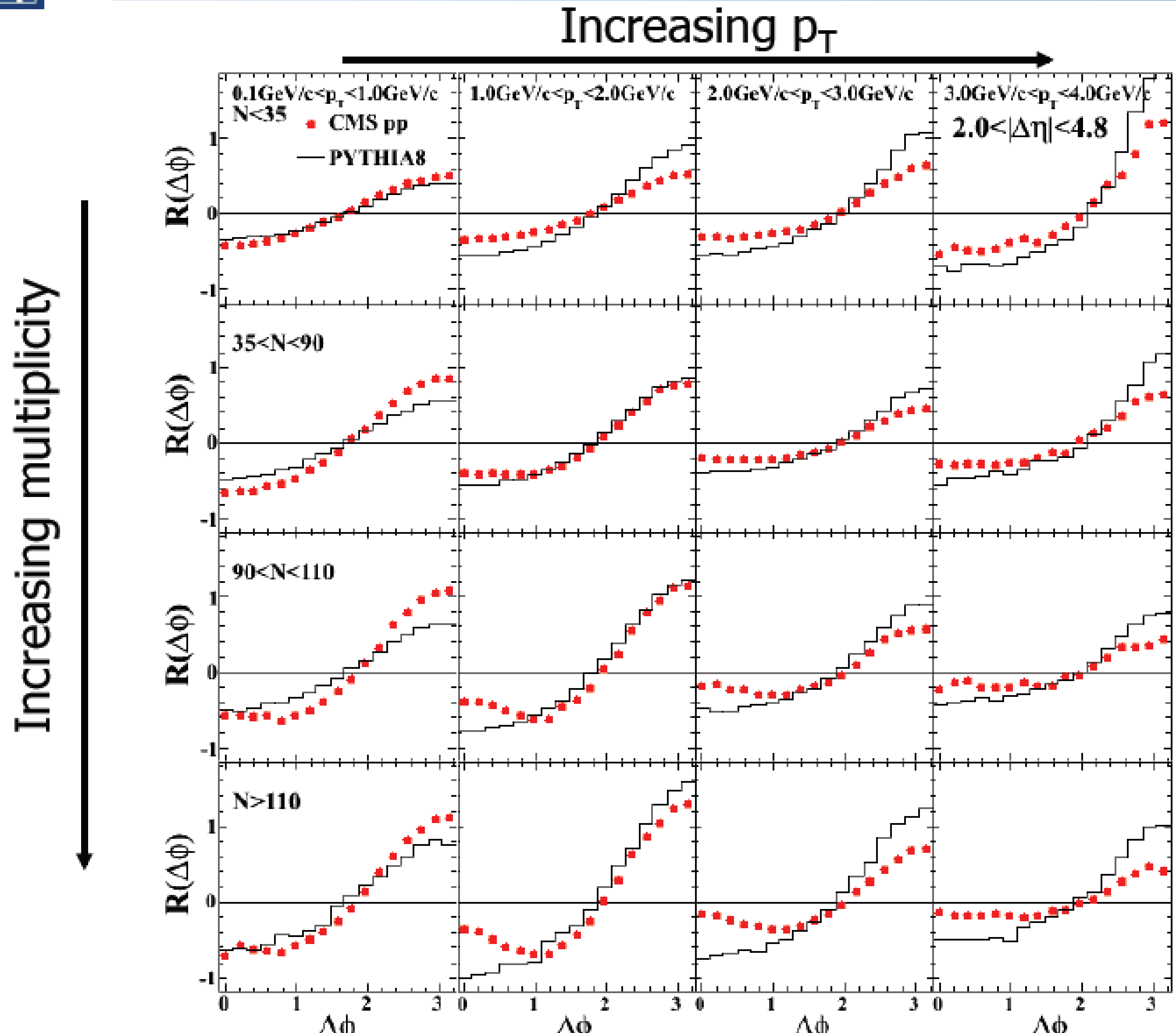
Comparison with PYTHIA dijet events embedded in HIJING. Similar results from CMS.

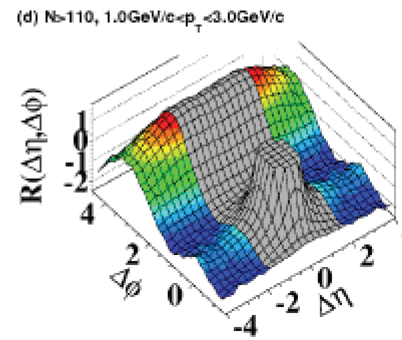
Lessons from RHIC and Outlook for LHC

- THE QGP model will require:
  - a large variety of precise measurements in all sectors of global and hard physics and, of course,
  - advanced theoretical models capable of simultaneous computation of all measured quantities
- Other programs will need to advance: p-Pb collisions (initial state), lattice QCD (EOS)

BACKUP SLIDES

Multiplicity- and p_T -Dependence





"Ridge" maximal for highest multiplicity and $1 < p_T < 3$ GeV/c

Multiplicity and Energy density e

$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy} < m_t >$$

- **$dN_{ch}/d\eta \sim 1600 \pm 76$ (syst)**
  - somewhat on high side of expectations
  - growth with √s faster in AA than pp (√s dependent 'nuclear amplification')
- **Energy density ≈ 3 x RHIC** (fixed τ)
  - lower limit, likely τ_0(LHC) < τ_0(RHIC)

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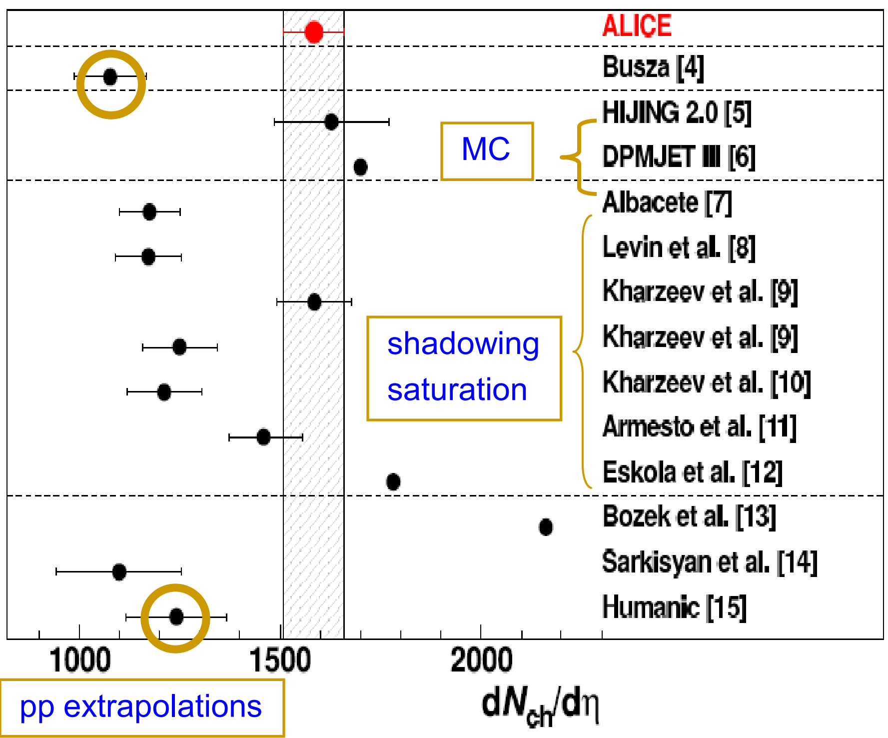
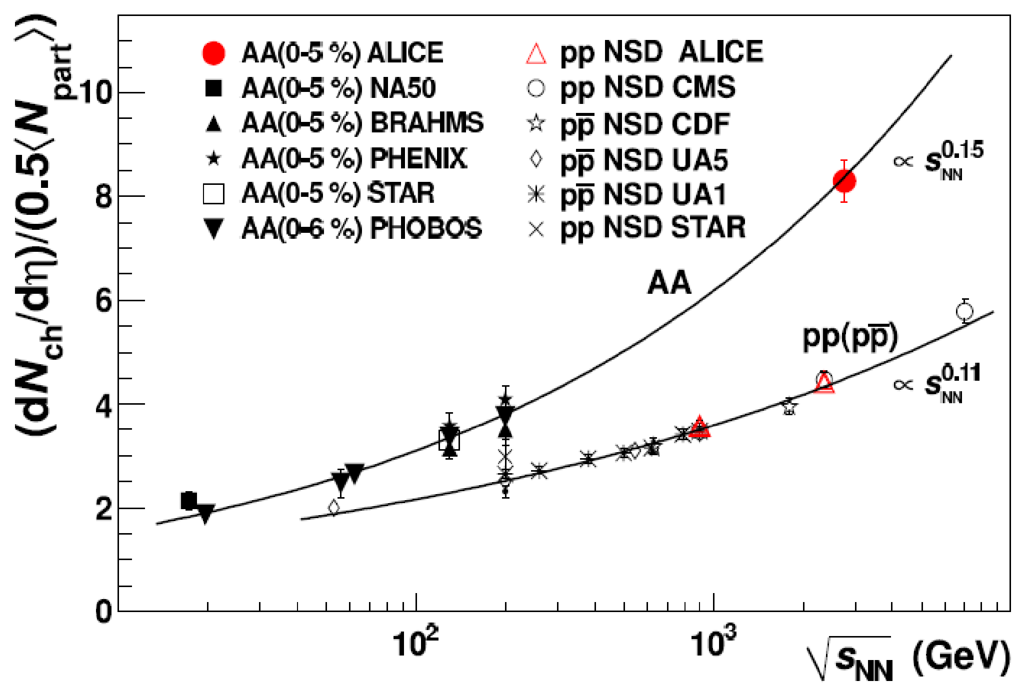
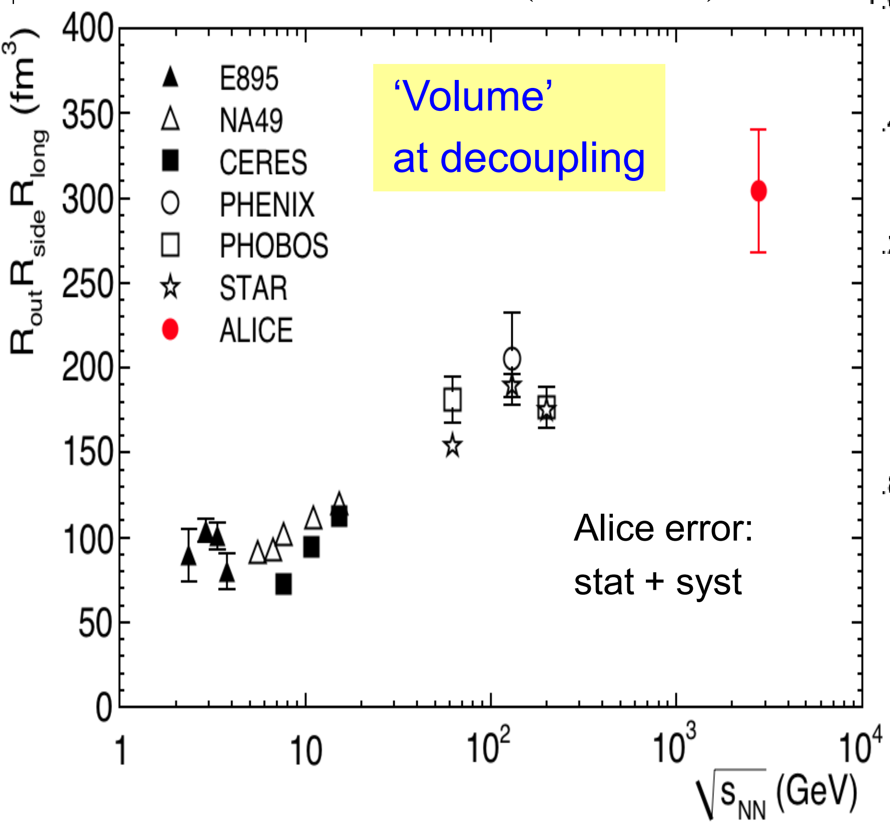


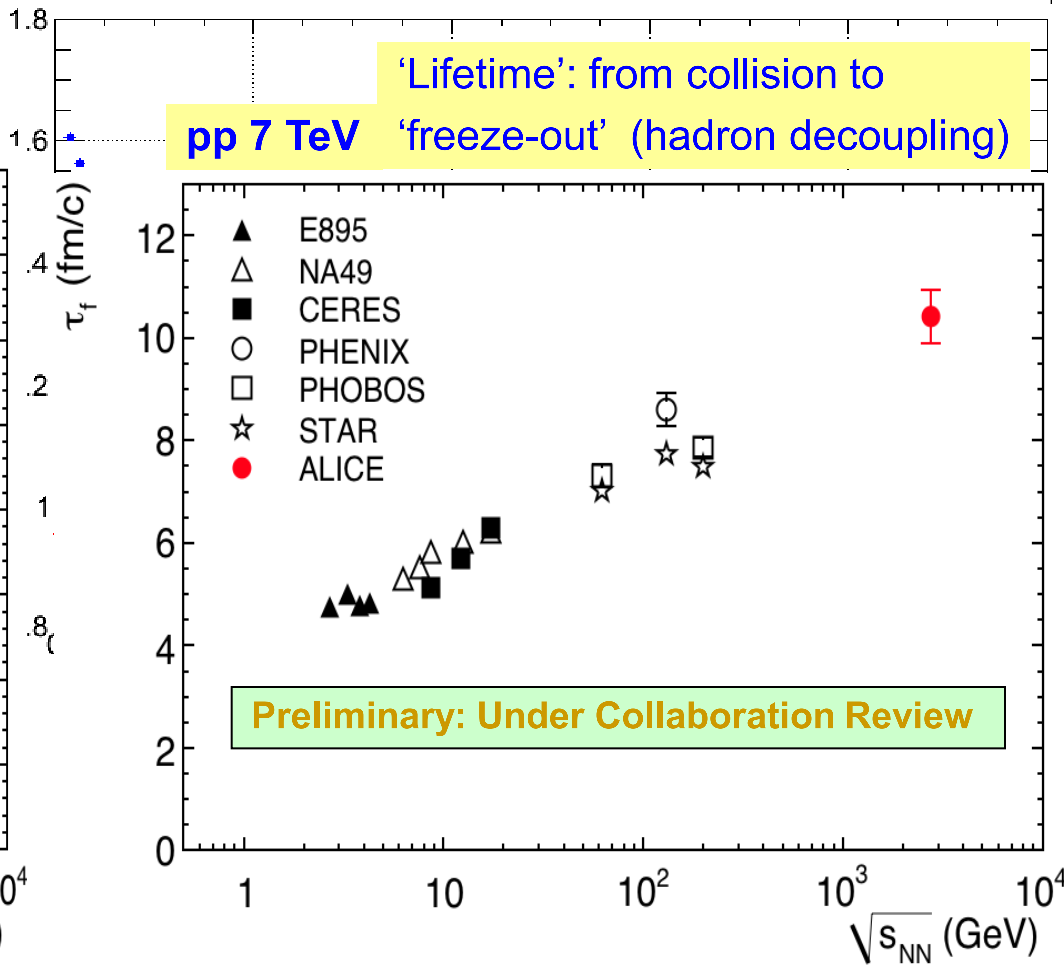


Volume and Lifetime from HBT

$$(E,\vec{\mathbf{p}}) \xrightarrow{\text{F.T.}} (\tau,\vec{\mathbf{X}})$$

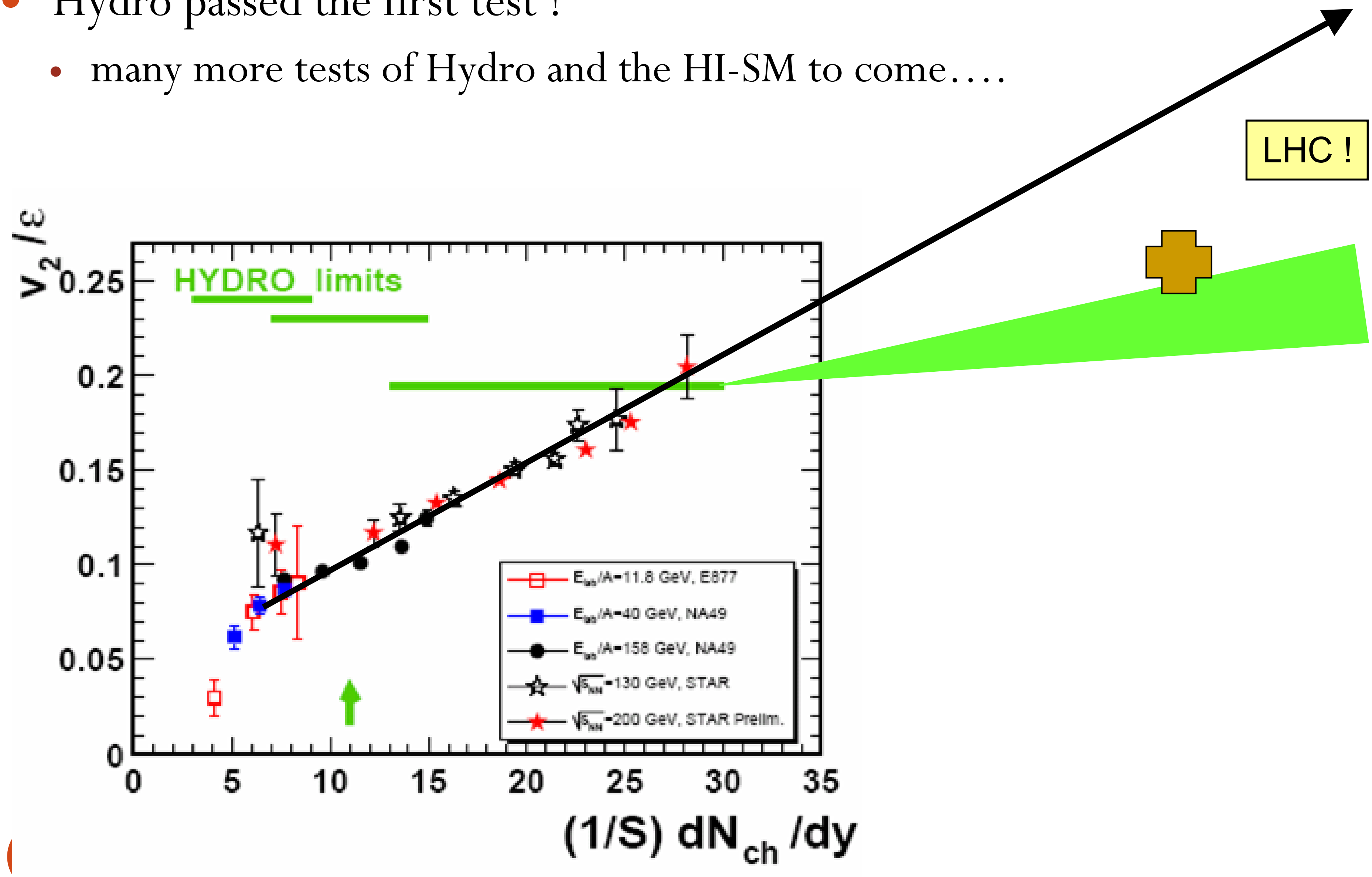
- Identical particle interferometry (HBT, Bose-Einstein correlations)
  - QM enhancement of identical Bosons at small momentum difference
  - measures Space-Time evolution of the 'dense matter' system in heavy ions coll.
- **Volume ≈ 2 x RHIC** (≈ 300 fm^3)
- **Lifetime ≈ +20%** (≈ 10 fm/c)





The Hydro Limits Passed…

- Hydro passed the first test !
  - many more tests of Hydro and the HI-SM to come….

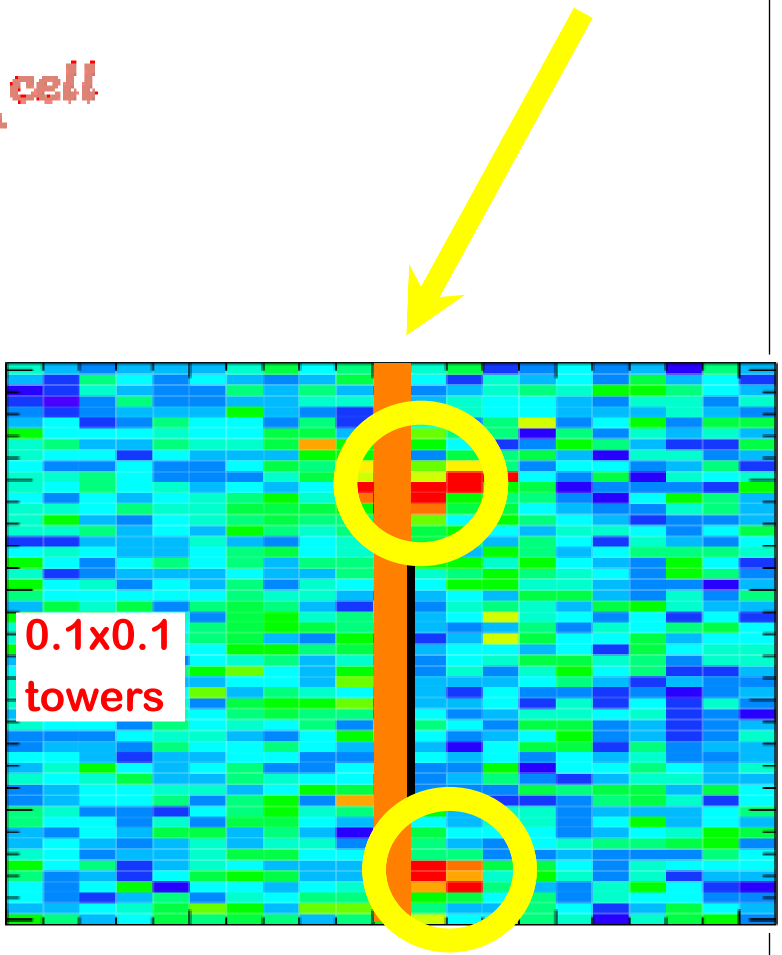


ATLAS: Jet Reconstruction

- Take maximum advantage of ATLAS segmentation
  - Underlying event estimated and subtracted for each longitudinal layer and for 100 slices of $\Delta\eta = 0.1$
    - $E_{T\,sub}^{cell} = E_T^{cell} - \rho^{layer}(\eta) \times A^{cell}$
  - ρ is energy density estimated event-by-event
    - From average over $0 < \varphi < 2\pi$
- Avoid biasing ρ due to jets
  - Using anti-kt jets:
    - Exclude cells from ρ if

$$D = E_{T\,max}^{tower} / \langle E_T^{tower} \rangle > 5$$

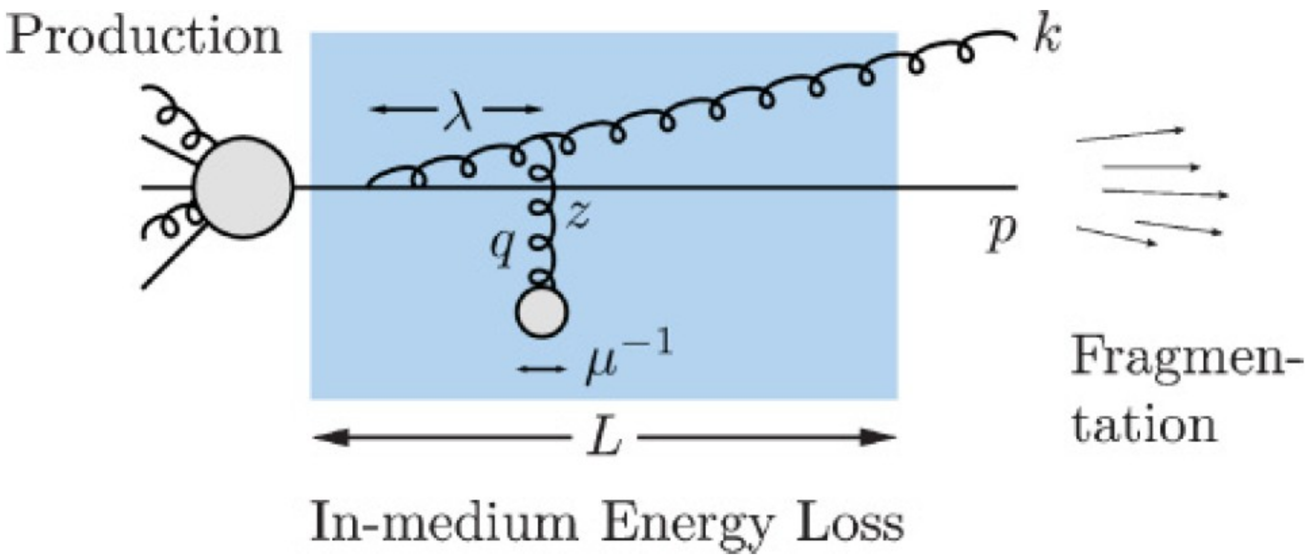
  - Cross check
    - Sliding Window algorithm



- NO jet removal on basis of D, or any other quantity

Parton Energy Loss in HI - Theory

Hard parton propagating through excited QCD: medium-induced gluon bremsstrahlung



Parton Energy Loss $\frac{dE}{dz} = -\frac{\alpha_S N_C}{4} p_\perp^2$

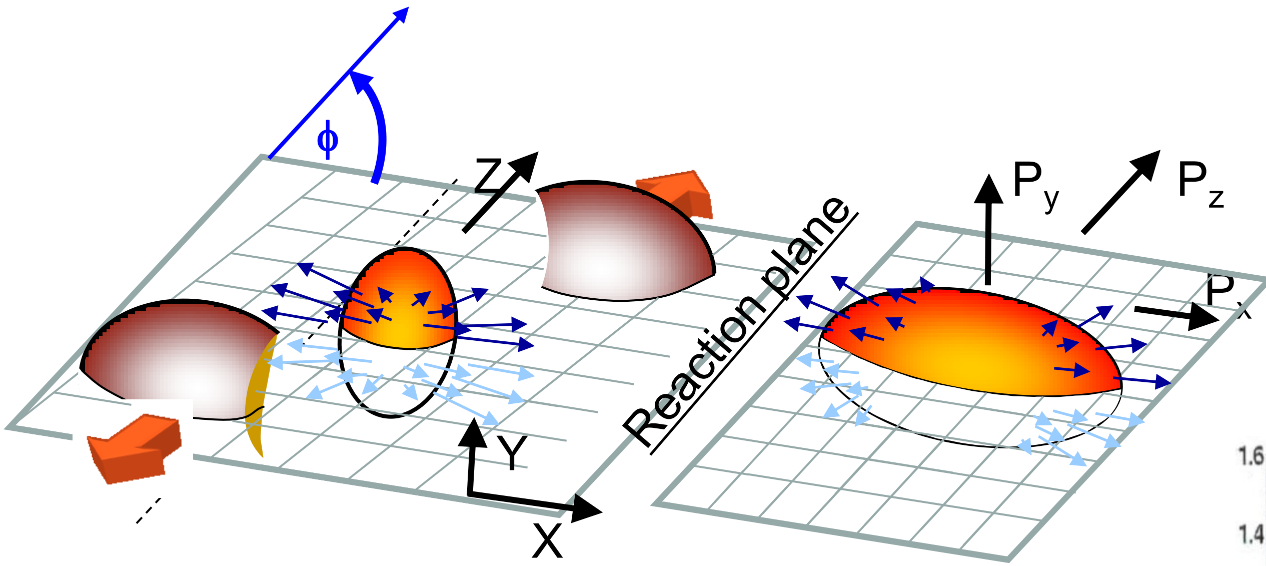
Momentum broadening $p_\perp^2 = \hat{q}L$

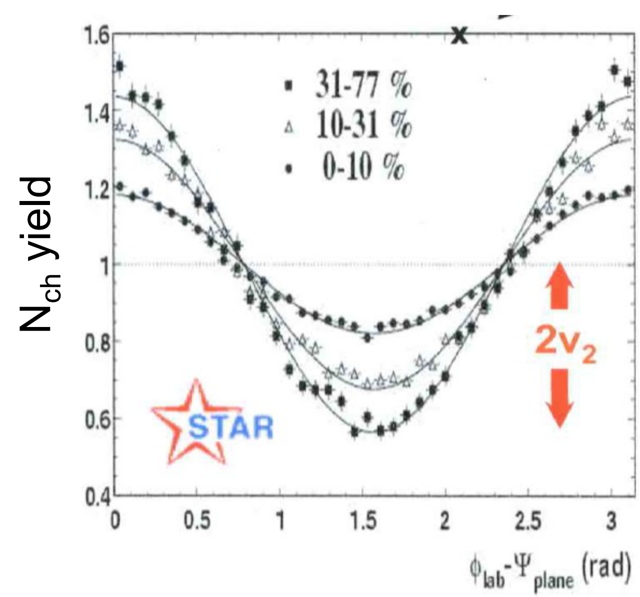
$\hat{q}$ transport coefficient
momentum kick
L medium size

Other energy loss mechanisms can be significant: collisional, dissociation.

Hadron Elliptic Flow v_2

Bulk hydrodynamics: initial spatial anisotropy is converted by pressure gradients into final momentum anisotropy reflected in hadron yield modulation w.r.t. collision RP.





Heavy quark suppression underpredicted