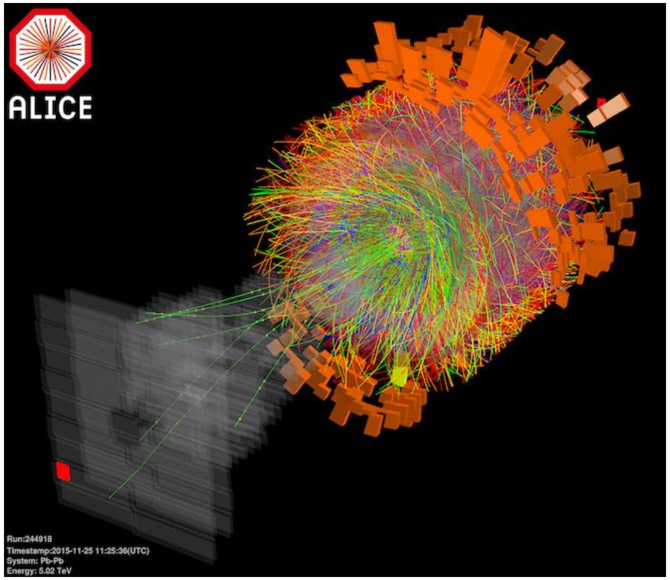
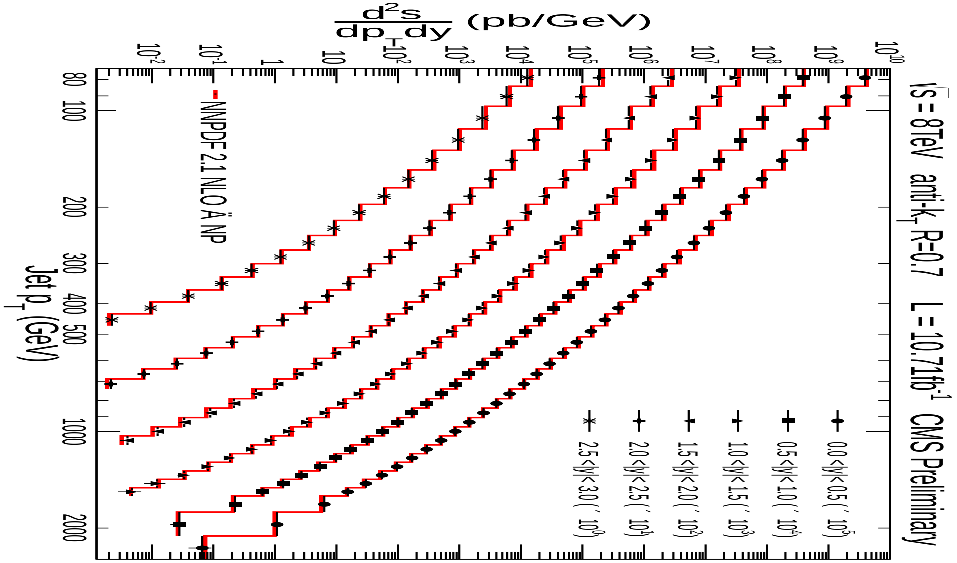
Jet quenching: what’s the endgame?

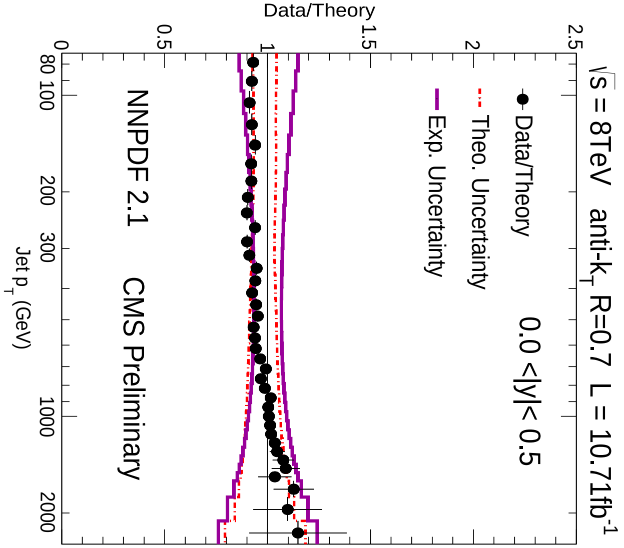
Peter Jacobs

LBNL



Jets in vacuum





Magnificent achievement of QCD

- needed 30 years of development in theory, experiment, and algorithms to connect the two

IRC jet reconstruction algorithms:

- Integrate out all hadron degrees of freedom
- Same procedures applied pQCD theory and experiment
- Enables direct, precise and improvable comparison of theory/experiment

➔ jets measure partons

Quenching via jet reconstruction

Can we study jet quenching with the same rigorous theory/experiment connection as achieved in vacuum?

Initial concept (Bjorken, Gyulassy, Wang,…):

precision in vacuum ➔well-controlled probe of the plasma, both theoretically and experimentally

Jet reconstruction integrates all hadronic degrees of freedom

➔ Measure energy flow and redistribution: jet quenching at the partonic level

A common theoretical picture of jets in-medium

Yacine M-T
EIC Workshop Jan ‘16

There are no pions in this picture

Jet quenching is a partonic phenomenon
➔measure it at the partonic level

In g of QCD-factorization theorem?
ium length L

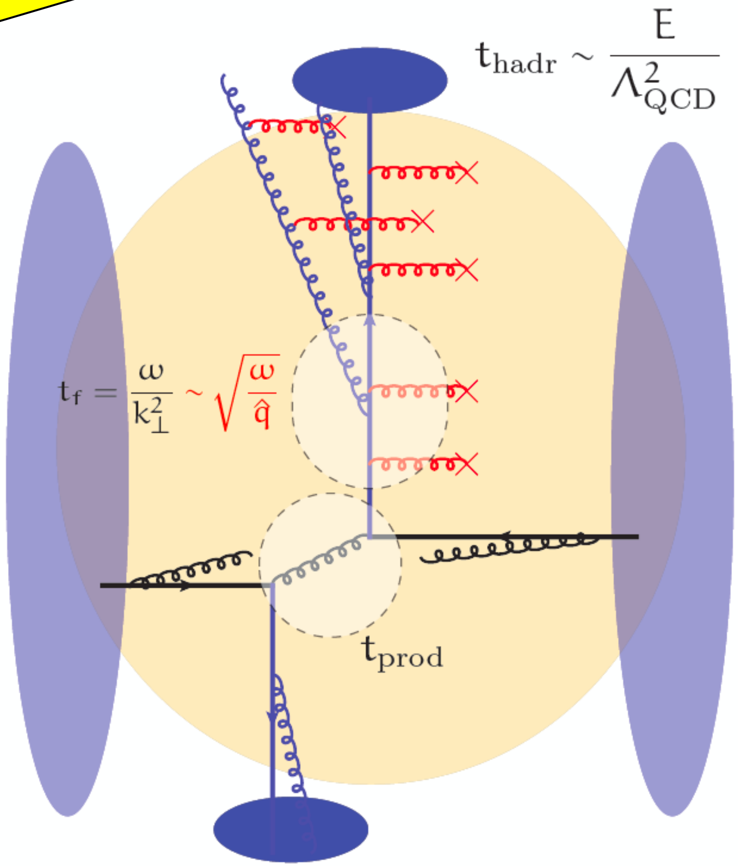
e of
D medium:

- Final state rescattering

$$\langle p_\perp^2 \rangle \equiv \hat{q}\, L$$

- Coherent medium-induced soft gluon radiation: no logarithm enhancement but length enhancement

$$\omega \frac{dN}{d\omega} = \alpha_s \frac{L}{t_f} \equiv \alpha_s N_{eff}$$



[Guylassy, Wang, Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov, Vitev, Levai, Wiedemann, Arnold ,Moore, Yaffe (1992-2000)]

My checklist for rigorous heavy ion jet measurements

Observables should be calculable in field theory

- at least in vacuum: start from rigorous basis, then extend to in-medium

Minimize the need for Monte Carlo modeling, to the degree possible

- "Infrared-safe" and collinear-safe observables: very low cuts on hadron p_T (preferably at limit of tracking)
- Minimize fragmentation bias on reported jet population
- Correct measurement for background fluctuations rather than trying to model background

Trigger bias should be transparently calculable without modeling of backgrounds

- Triggers reject events: require large S/B, no p_T smearing
  - Good triggers: hadron, photon, Z
  - Maybe good triggers: electron, muon
  - Not very good trigger: jet

Rigorous heavy ion jet measurements: preferred observables

An impossible task? No.

Partial list of observables that meet these criteria:

- Inclusive cross sections and their ratios vs R
- Semi-inclusive measurements: ratio of incl. cross sections for coincidence and trigger
- Moliere scattering in-medium
- Jet mass
- Subjets
- …?

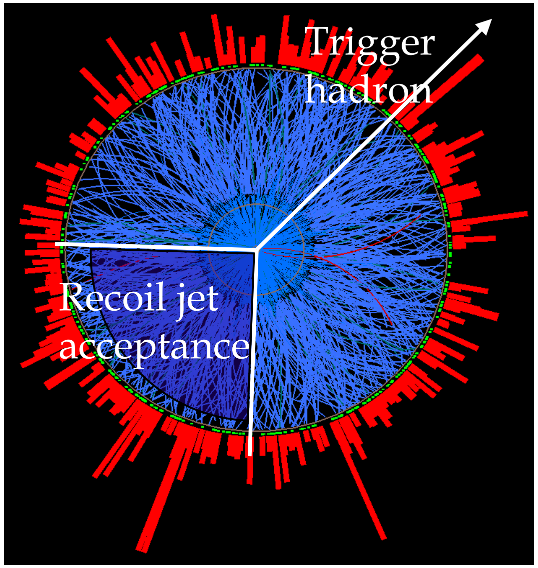
Choice of trigger: use to vary geometric and other biases

Absent from this list: hadron-specific observables ("Fragmentation Functions", CMS-like large-angle hadrons, etc)

Key outstanding issue: hadronization of jets (R-dependent)

Example: semi-inclusive h+jet correlations

Trigger-normalized yield of jets recoiling from a high p_T hadron trigger



$$\frac{1}{N_{trig}^{h}}\frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{AA\rightarrow h+X}}\frac{d\sigma^{AA\rightarrow h+jet+X}}{dp_{T,jet}}$$

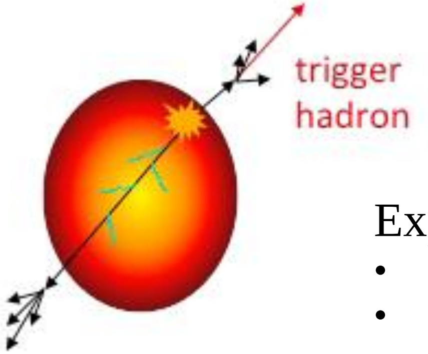
Measured — Calculable in pQCD

Semi-inclusive: event selection only requires trigger hadron

- experimentally clean; trigger bias theoretically calculable

Count all recoil jet candidates:

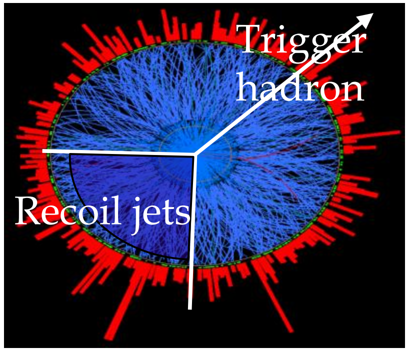
- uncorrelated background corrected at level of ensemble-averaged distributions
- jet selection does not impose fragmentation bias



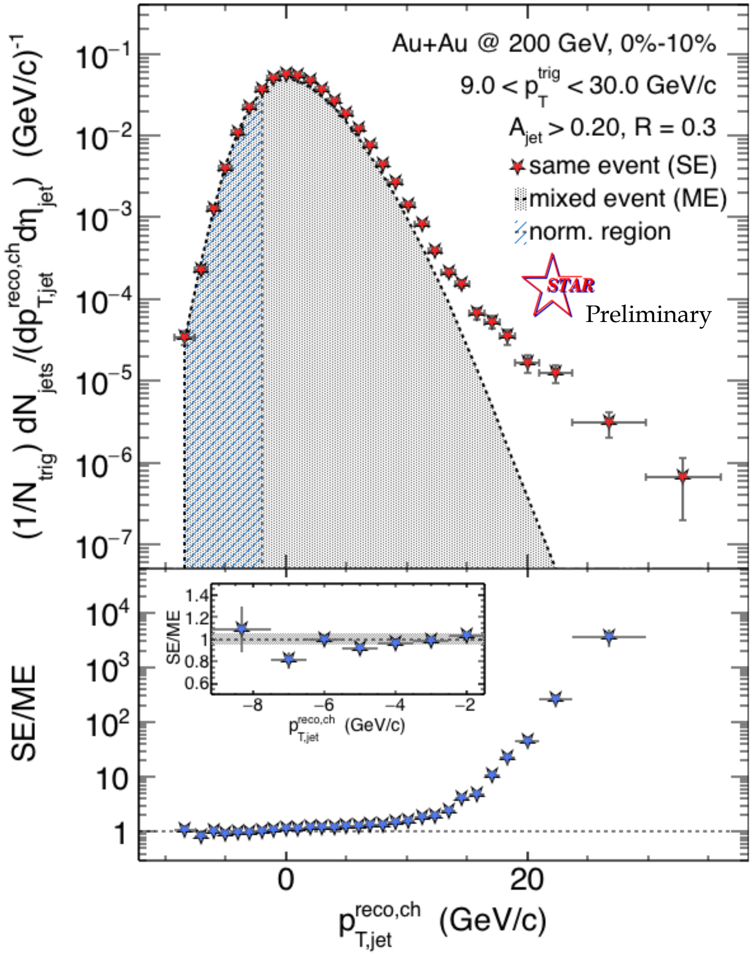
Expected geometric bias: surface, not tangential

- Large path length for recoil
- Model studies: T. Renk, PRC74, 024903; H. Zhang et al., PRL98 212301;…

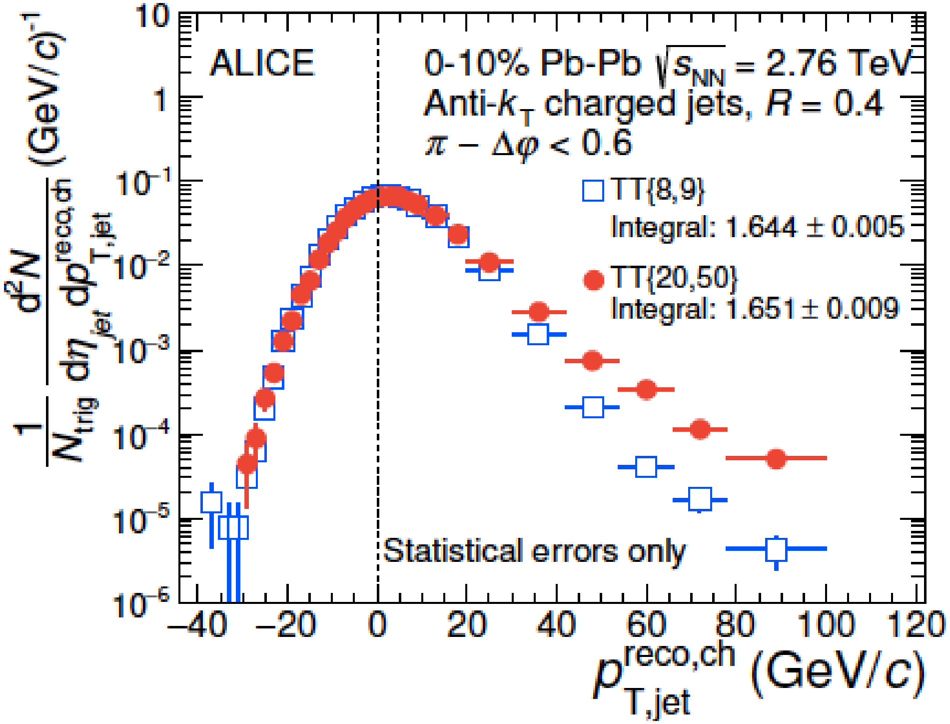
Recoil jet spectrum: STAR/ALICE



arXiv:1512.08784



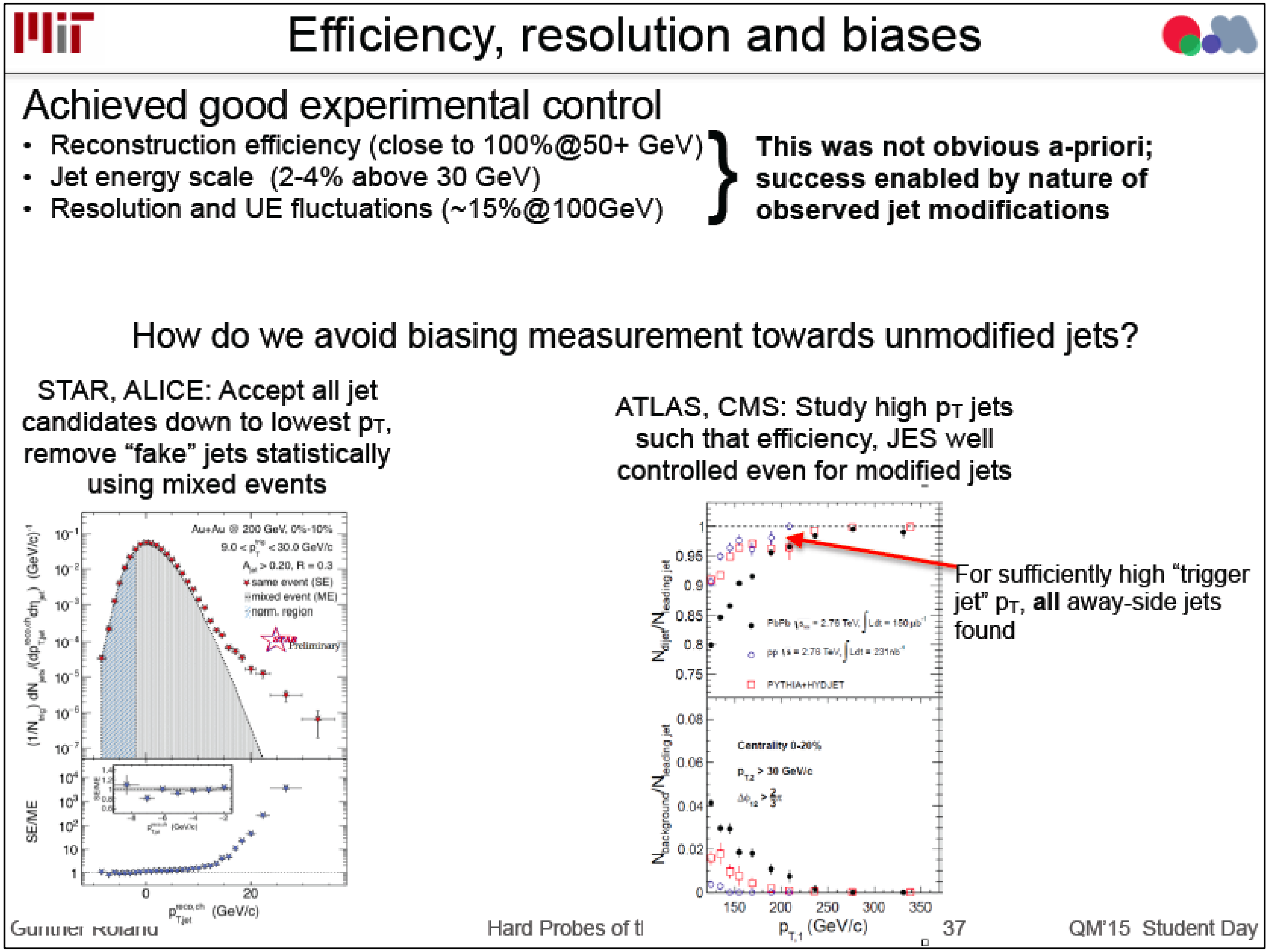
JHEP 09 (2015) 170



Contrary to conventional wisdom: heavy ion jet measurements have the same level of difficulty at RHIC and LHC ➔ can do precisely the same measurements

Comparison of techniques: ALICE/STAR vs ATLAS/CMS

Gunther Roland, QM15 Student Day



Efficiency, resolution and biases

Achieved good experimental control

- Reconstruction efficiency (close to 100%@50+ GeV)
- Jet energy scale (2-4% above 30 GeV)
- Resolution and UE fluctuations (~15%@100GeV)

This was not obvious a-priori; success enabled by nature of observed jet modifications

How do we avoid biasing measurement towards unmodified jets?

STAR, ALICE: Accept all jet candidates down to lowest p_T, remove “fake” jets statistically using mixed events

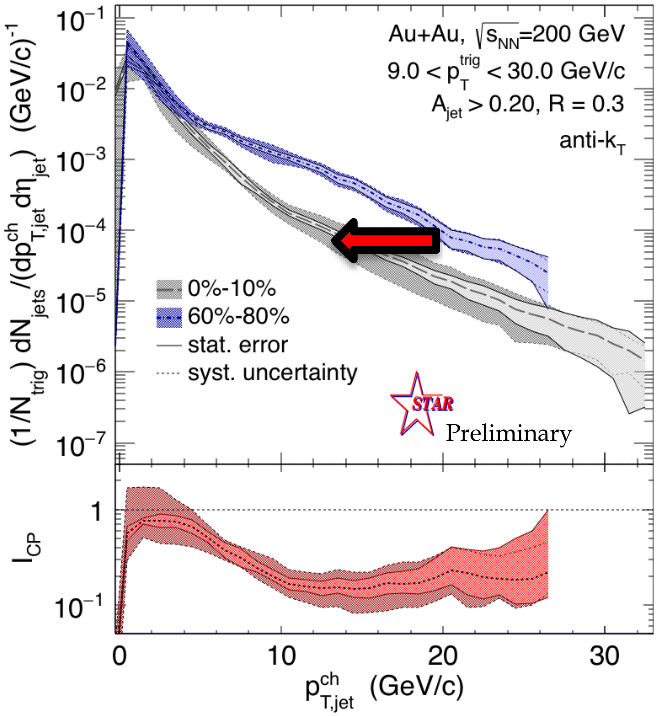
ATLAS, CMS: Study high p_T jets such that efficiency, JES well controlled even for modified jets

For sufficiently high “trigger jet” p_T, **all** away-side jets found

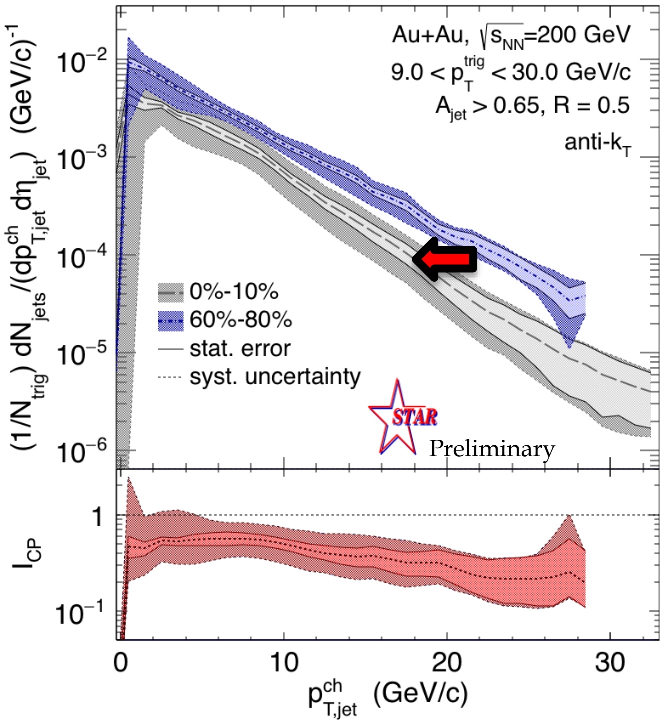
Gunther Roland   Hard Probes of t   37   QM'15 Student Day

Recoil yield suppression

R=0.3



R=0.5



Calculate spectrum shift

- requires distributions ~ exponential, ratio ~ flat

Spectrum Shift Periph/pp ➔Central

	$p^{ch}_{T,jet}$ range [GeV]	**Shift R=0.3 [GeV]**	**Shift R=0.5 [GeV]**
Au+Au @ 200 GeV	[10,20]	**-6.3** ± 0.6 ± 0.8	**-3.8** ± 0.5 ± 1.8
Pb+Pb @ 2.76 TeV *ALICE JHEP 09 (2015) 170*	[60,100]		**-8** ± 2

RHIC: smaller shift for larger R

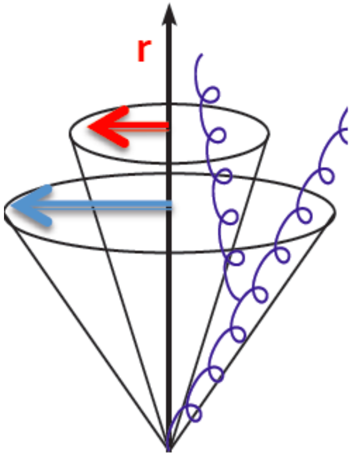
R=0.5: smaller shift at RHIC than LHC

Out-of-cone energy transport ?

- comparison requires similar trigger bias ➔ theory calculation

Jet shapes: conventional approach

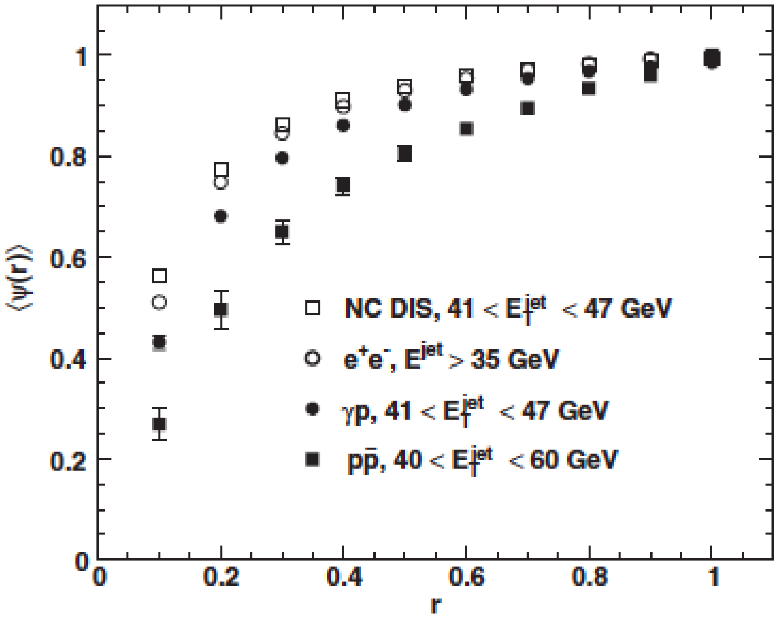
Self-normalized observable (Ellis ’93)



$$\Psi_{\rm int}(r;R) = \frac{\sum_i (E_T)_i \Theta(r-(R_{\rm jet})_i)}{\sum_i (E_T)_i \Theta(R-(R_{\rm jet})_i)}$$

$$\psi(r;R) = \frac{d\Psi_{\rm int}(r;R)}{dr} .$$

The transverse energy density inside a jet



Jet shapes via SCET

I. Vitev
EIC Workshop Jan ‘16

H-n. Li et al. (2011)

$$\Psi_\omega(r) = \frac{\langle E_r \rangle_\omega}{\langle E_R \rangle_\omega} = \frac{J_\omega^{E_r}(\mu)/J_\omega(\mu)}{J_\omega^{E_R}(\mu)/J_\omega(\mu)} = \frac{J_\omega^{E_r}(\mu)}{}$$

- To
acc
evo

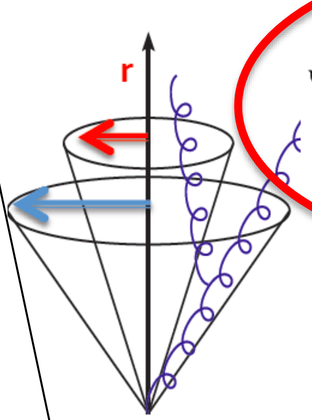
$$\frac{dJ_\omega^{qE_r}(\mu)}{d\ln\mu} = \Big[$$

$$\frac{dJ_\omega^{gE_r}(\mu)}{d\ln\mu} = \Big[$$

So what’s the problem in heavy ions?

Answer: observable is self-normalized. We cannot accurately know E_T event-by-event in the presence of large background – uncontrolled issue except at very high E_T

Y.-T. ... et al. (2014)



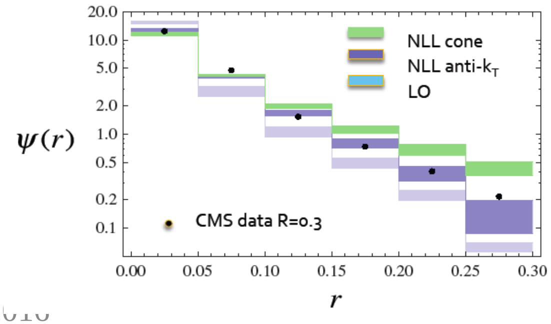
$$\Psi_{\text{int}}(r;R) = \frac{\sum_i (E_T)_i \Theta(r - (R_{\text{jet}})_i)}{\sum_i (E_T)_i \Theta(R - (R_{\text{jet}})_i)}$$

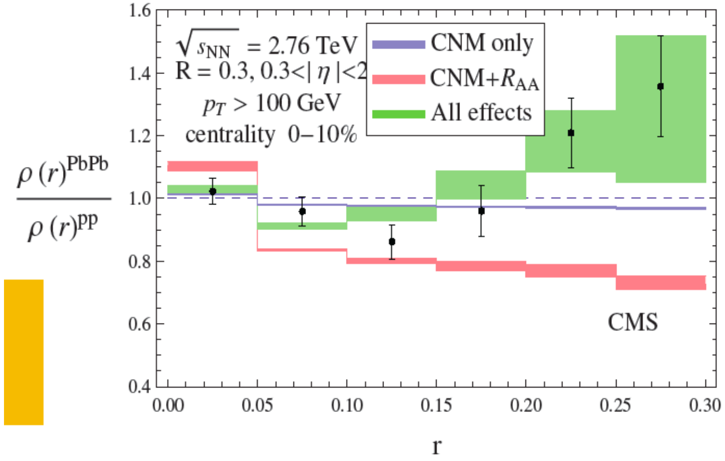
$$\psi(r;R) = \frac{d\Psi_{\text{int}}(r;R)}{dr}.$$

The transverse energy density inside a jet

$$J^i_{\omega,E_r}(\mu) = \sum_{i,k} \int_{PS} dx dk_\perp \mathcal{P}_{i\to jk}(x,k_\perp) E_r(x,k_\perp)$$

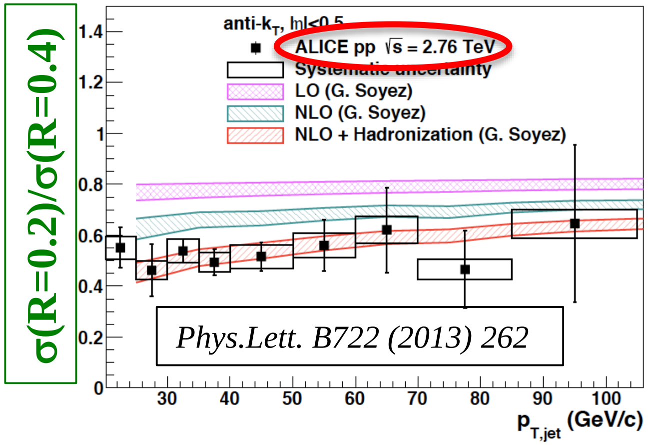
$$J_{\omega,E_r}(\mu) = J^{vac}_{\omega,E_r}(\mu) + J^{med}_{\omega,E_r}(\mu).$$



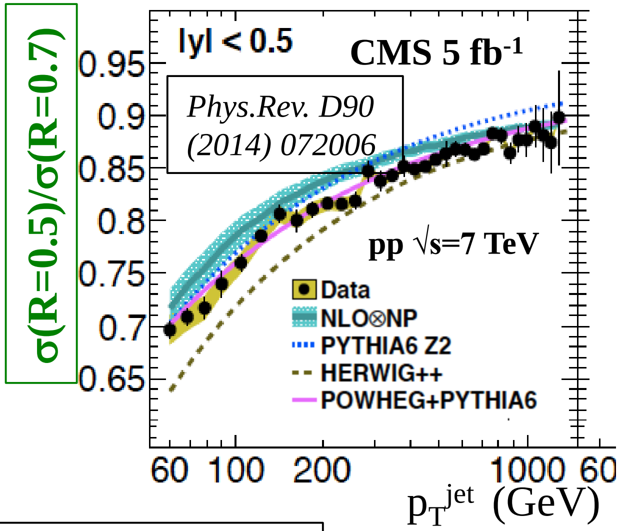


Alternative approach to jet shapes: cross section ratios for different R values

Inclusive jets, pp √s= 2.76, 7 TeV

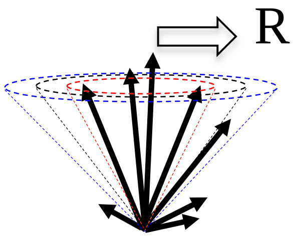


Phys.Lett. B722 (2013) 262



Phys.Rev. D90 (2014) 072006

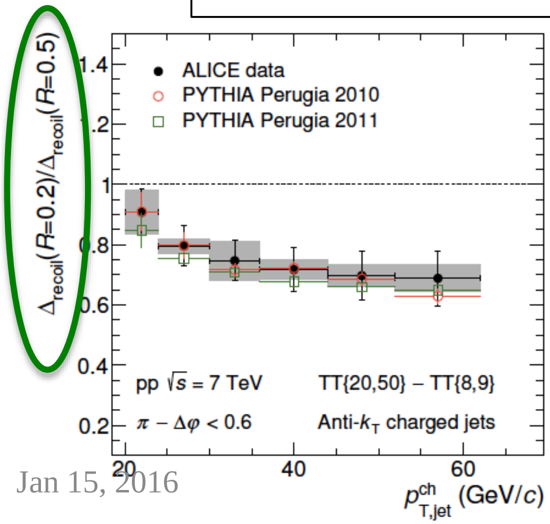
Jets with different R sensitive to different components of shower

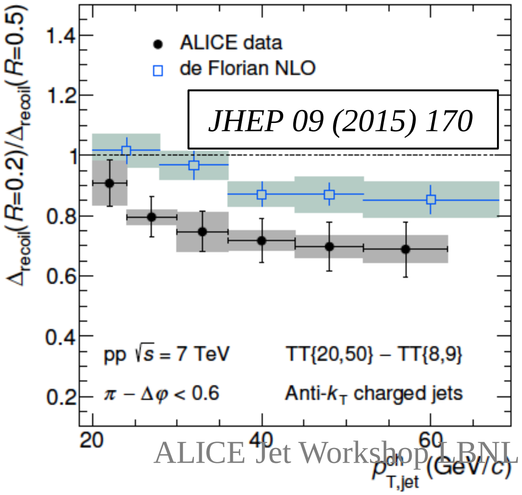


Calculable perturbatively:

- require (N)NLO + non-pert. corrections
- MC models ~OK

Semi-inclusive h+jet, pp √s=7 TeV





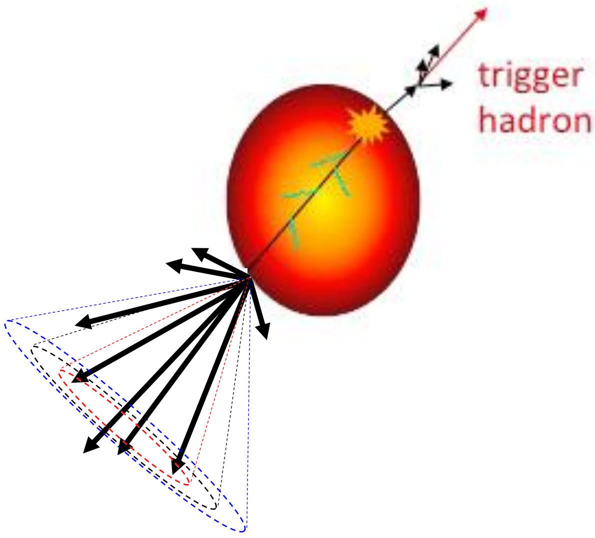
JHEP 09 (2015) 170

Ratios in vacuum

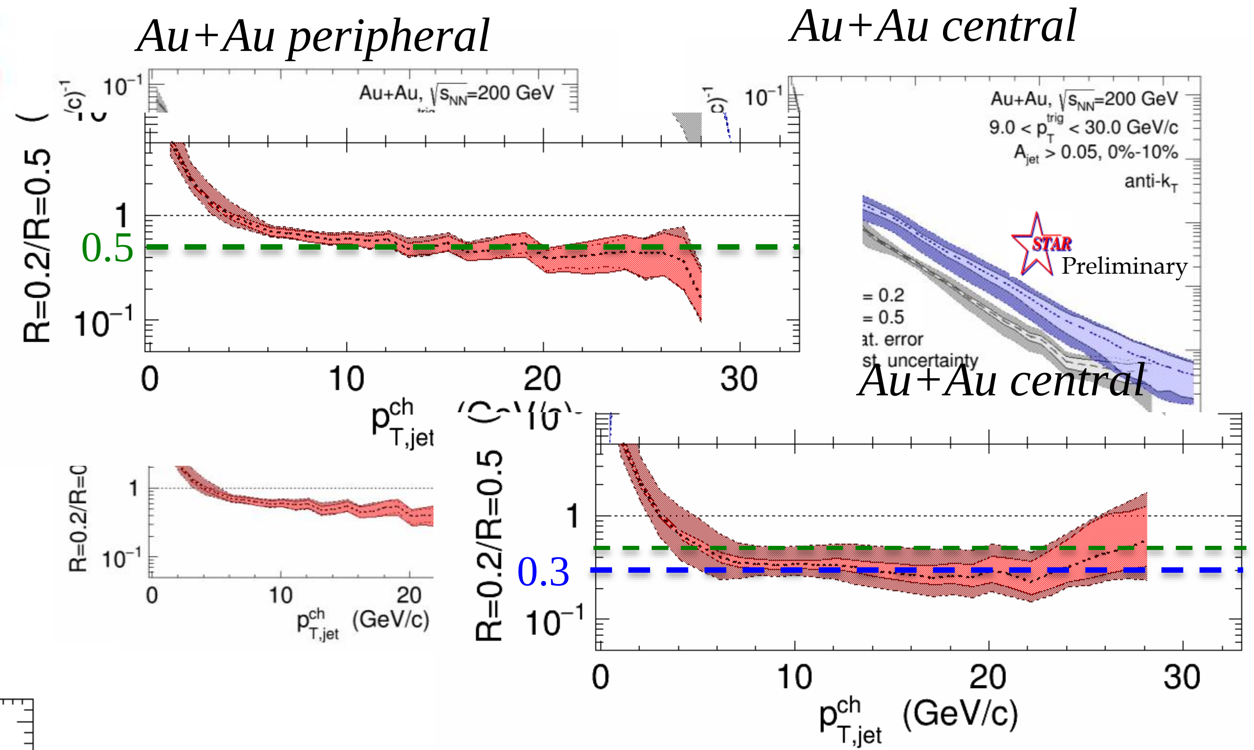
- sensitive to transverse jet structure
- rigorous data/theory comparison

➔ Now use to measure intra-jet broadening due to quenching

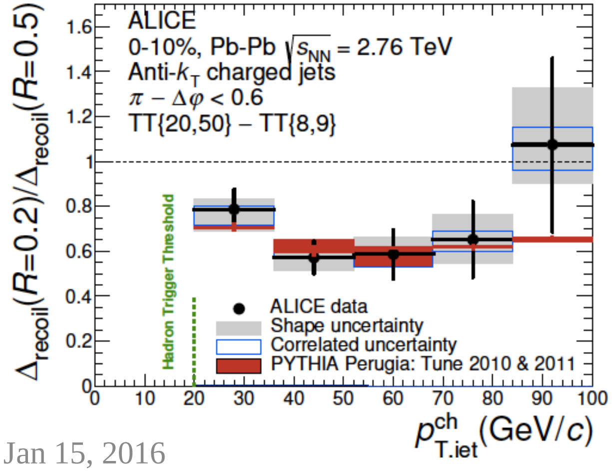
Intra-jet broadening: recoil yield vs. R



Redistribution of jet energy transverse to jet axis



JHEP 09 (2015) 170



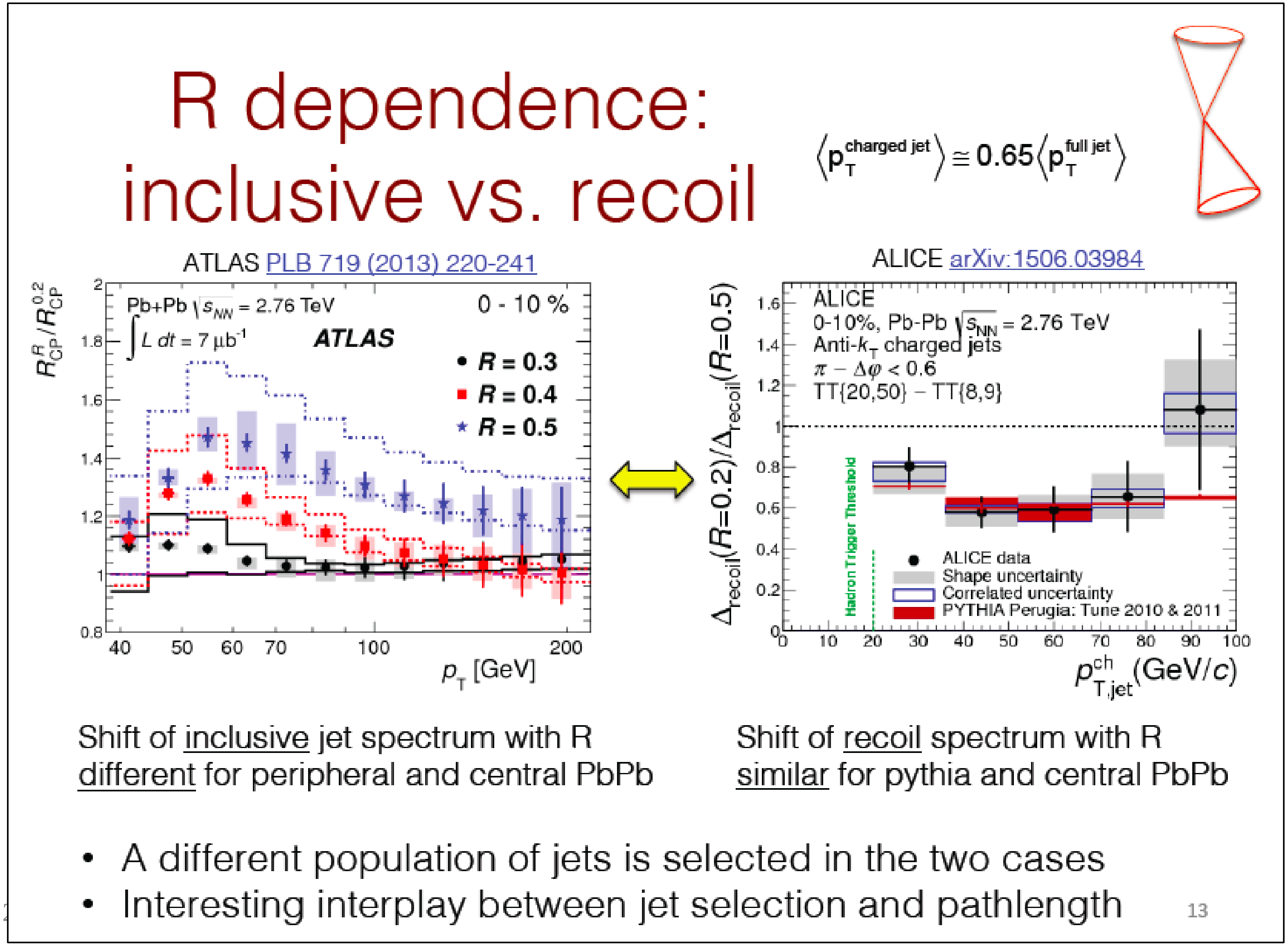
Ratios for peripheral and central are consistent within uncertainties

- compatible with some broadening within R<0.5
- future measurement (higher stats): reduce uncert.

ALICE: similar picture in overlapping p_T range

In-medium broadening: ATLAS vs ALICE

Matt Nguyen, QM15 Plenary Talk



R dependence: inclusive vs. recoil

$\langle p_T^{\text{charged jet}} \rangle \simeq 0.65 \langle p_T^{\text{full jet}} \rangle$

ATLAS PLB 719 (2013) 220-241

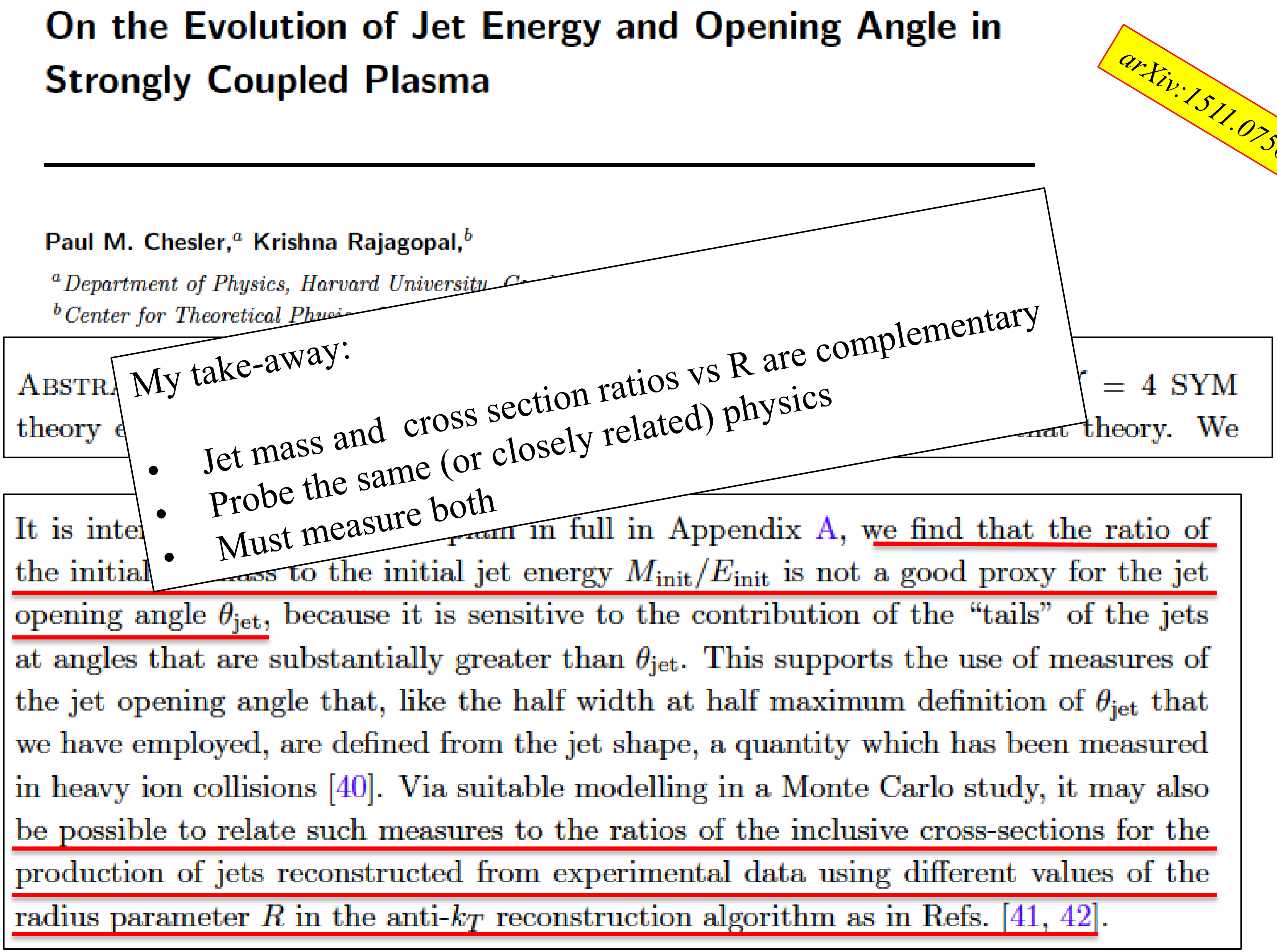
ALICE arXiv:1506.03984

Shift of inclusive jet spectrum with R different for peripheral and central PbPb

Shift of recoil spectrum with R similar for pythia and central PbPb

- A different population of jets is selected in the two cases
- Interesting interplay between jet selection and pathlength

13



On the Evolution of Jet Energy and Opening Angle in Strongly Coupled Plasma

Paul M. Chesler,[a] Krishna Rajagopal,[b]

[a] *Department of Physics, Harvard University*

[b] *Center for Theoretical*

ABSTRA

$\mathcal{N} = 4$ SYM

theory e

theory. We

It is inter

in full in Appendix A, we find that the ratio of the initial

to the initial jet energy $M_{\mathrm{init}}/E_{\mathrm{init}}$ is not a good proxy for the jet opening angle θ_{jet}, because it is sensitive to the contribution of the "tails" of the jets at angles that are substantially greater than θ_{jet}. This supports the use of measures of the jet opening angle that, like the half width at half maximum definition of θ_{jet} that we have employed, are defined from the jet shape, a quantity which has been measured in heavy ion collisions [40]. Via suitable modelling in a Monte Carlo study, it may also be possible to relate such measures to the ratios of the inclusive cross-sections for the production of jets reconstructed from experimental data using different values of the radius parameter R in the anti-k_T reconstruction algorithm as in Refs. [41, 42].

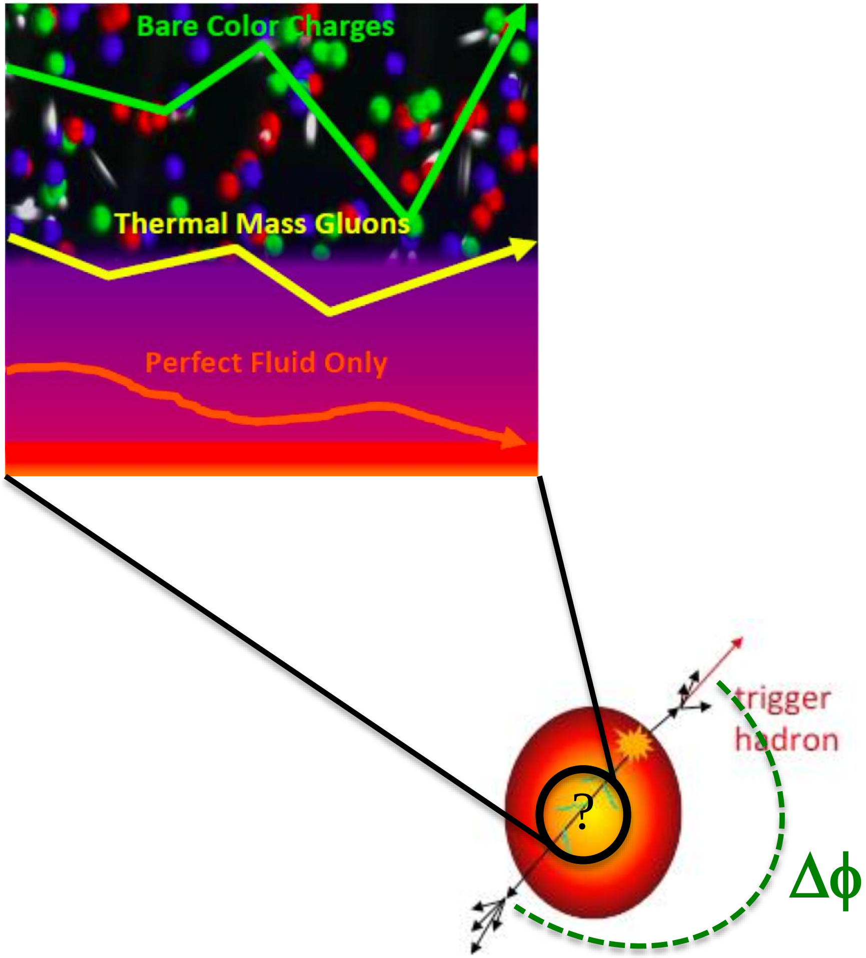
arXiv:1511.07567

My take-away:

- Jet mass and cross section ratios vs R are complementary
- Probe the same (or closely related) physics
- Must measure both

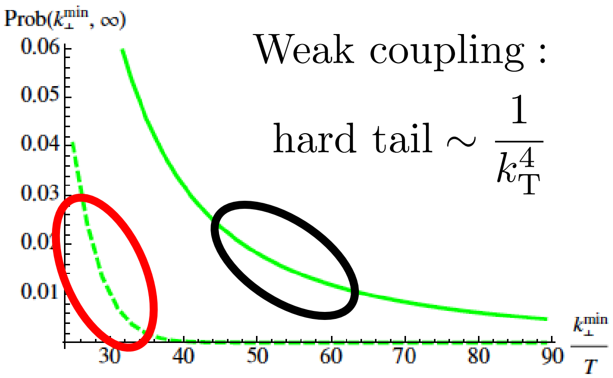
Inter-jet broadening: secondary scattering off the QGP

Discrete scattering centers or effectively continuous medium?



d'Eramo et al, arXiv:1211.1922

Distribution of momentum transfer k_T



Weak coupling :

hard tail $\sim \frac{1}{k_T^4}$

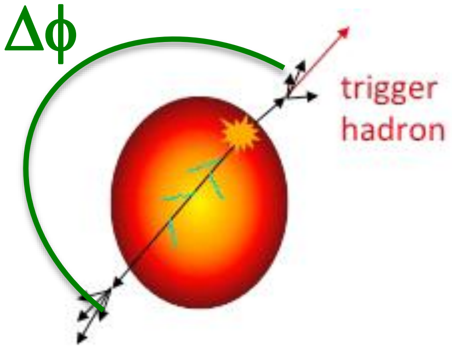
Strong coupling:
Gaussian distribution

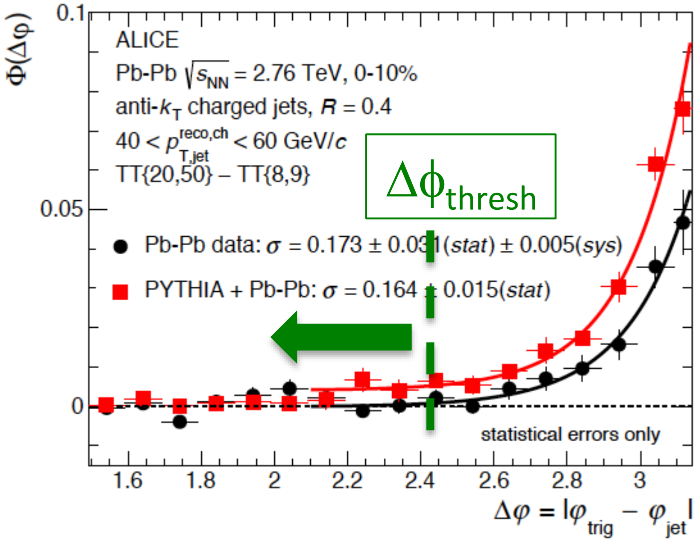
Conjecture for weak coupling: Δϕ distribution dominated by single hard Molière scattering at "sufficiently large" Δϕ

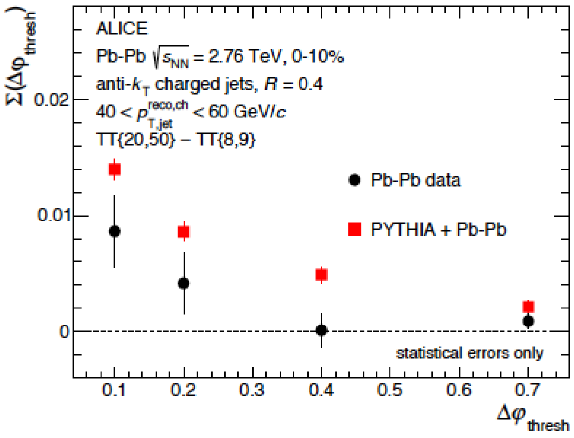
- vacuum QCD effects fall off more rapidly
- "sufficiently large" not yet known

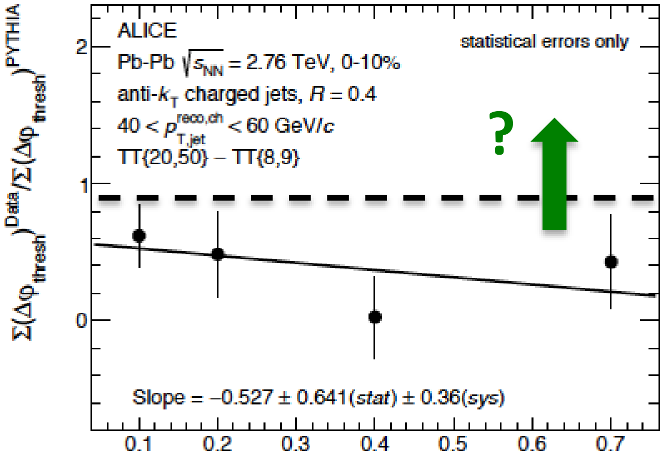
Interjet broadening: ALICE

JHEP 09 (2015) 170









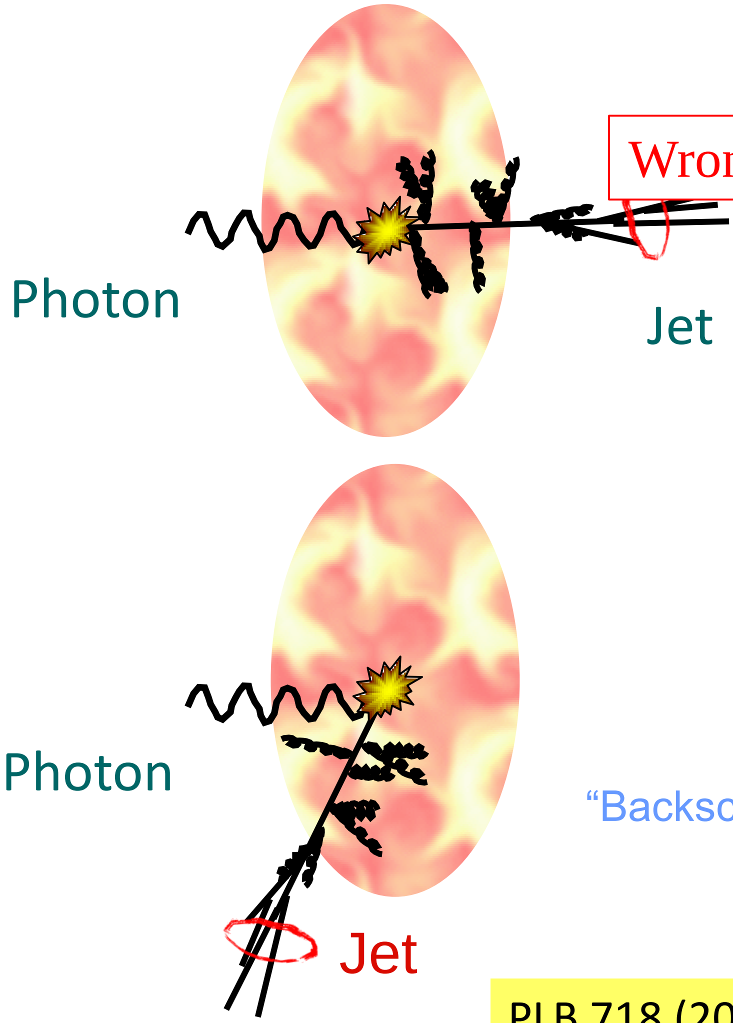
- No indication thus far for Moliere scattering
- Run 2 gives significant improvement in precision and reach
- Measurement technique enables lower p_T^{jet}, larger Δϕ (limit is only statistical)

CMS : photon-jet angular correlation

"QGP Rutherfold experiment"

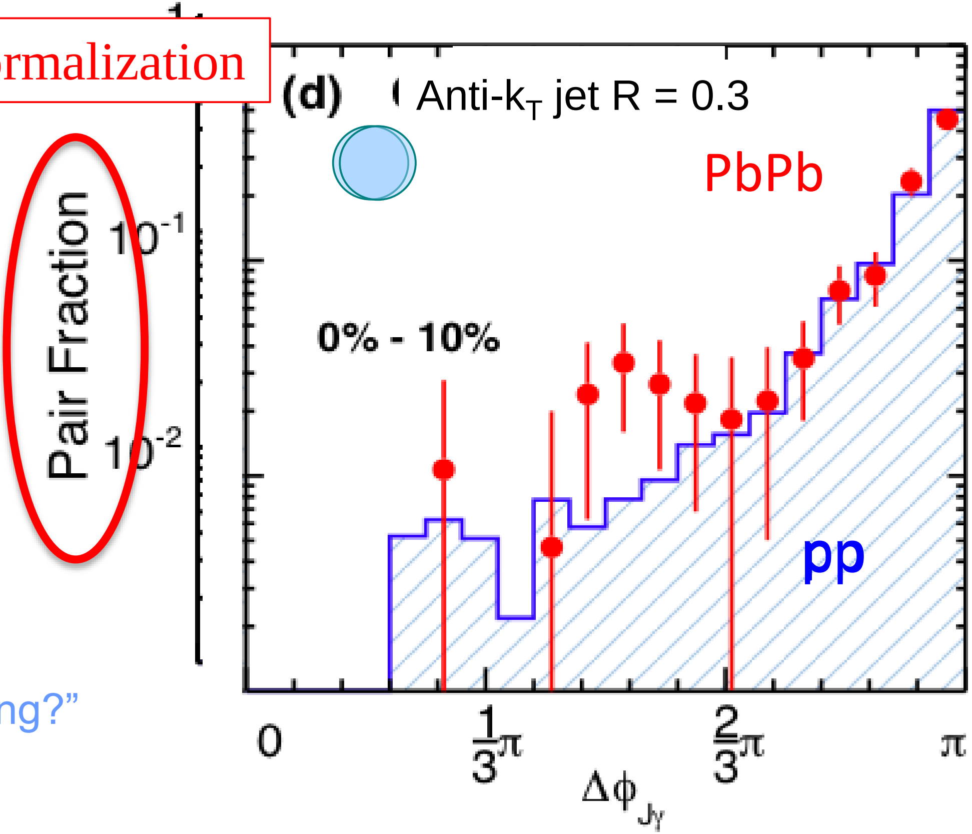
$$p_T^{\gamma} > 60 \text{ GeV/c}$$

$$p_T^{jet} > 30 \text{ GeV/c}$$



"Backscattering?"

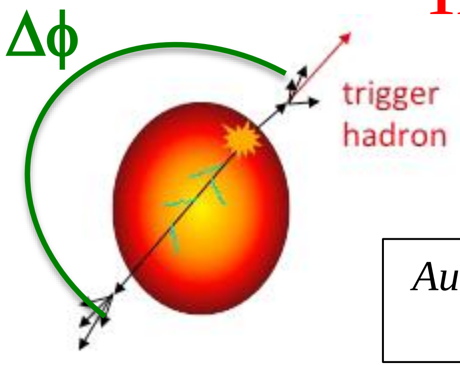
Wrong normalization



Azimuthal angle difference between photon and jet

PLB 718 (2013) 773

Inter-jet broadening: STAR

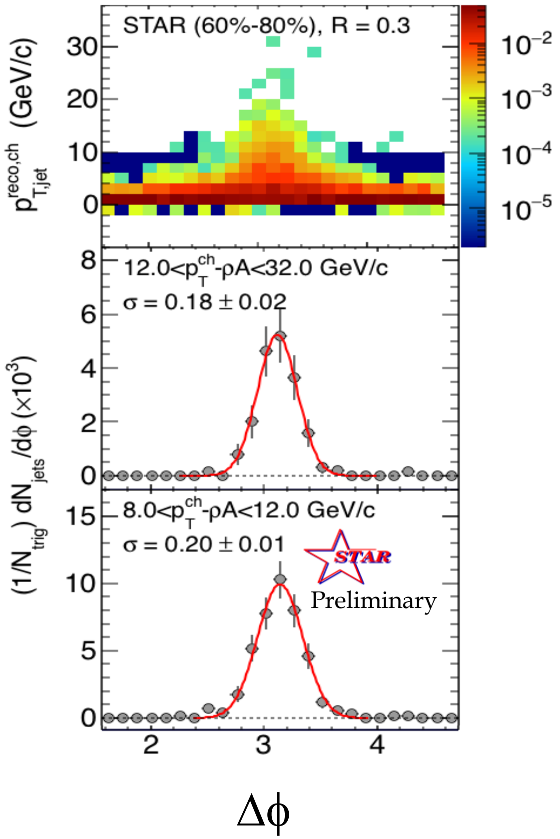


Quantitative search requires absolute normalization

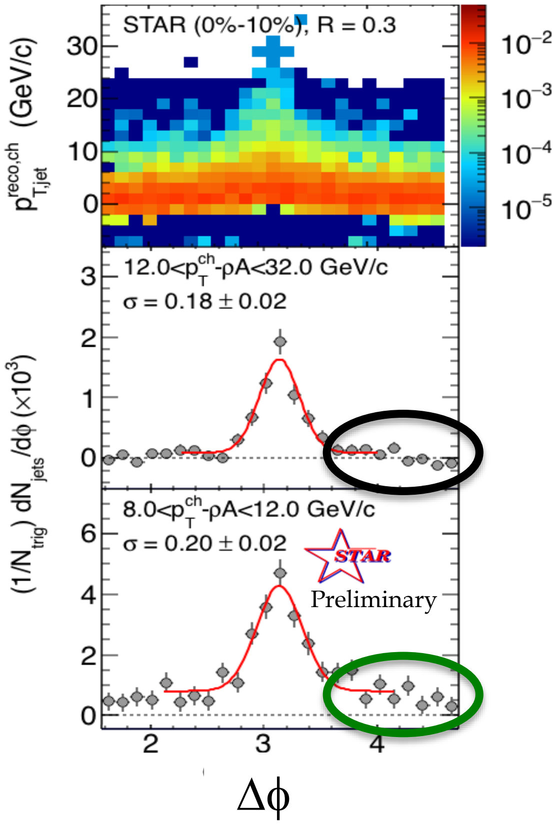
➔ semi-inclusive distribution

Au+Au $\sqrt{s_{NN}}=200$ *GeV*
$p_T^{trig}>9$ *GeV/c*

peripheral



central

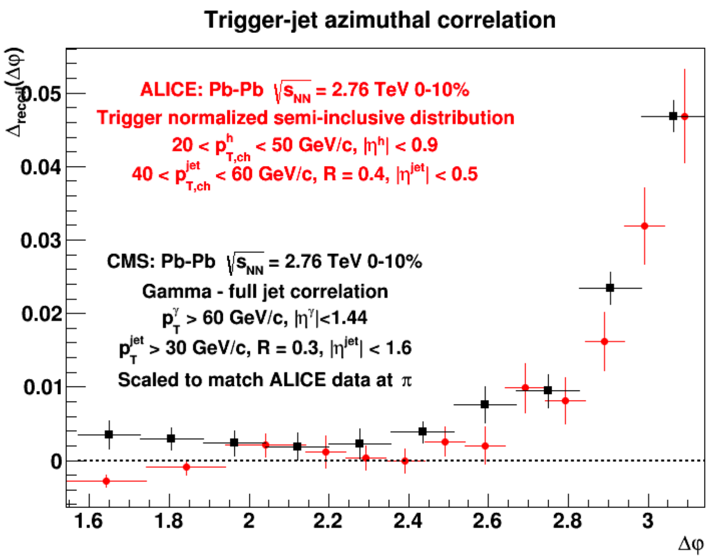


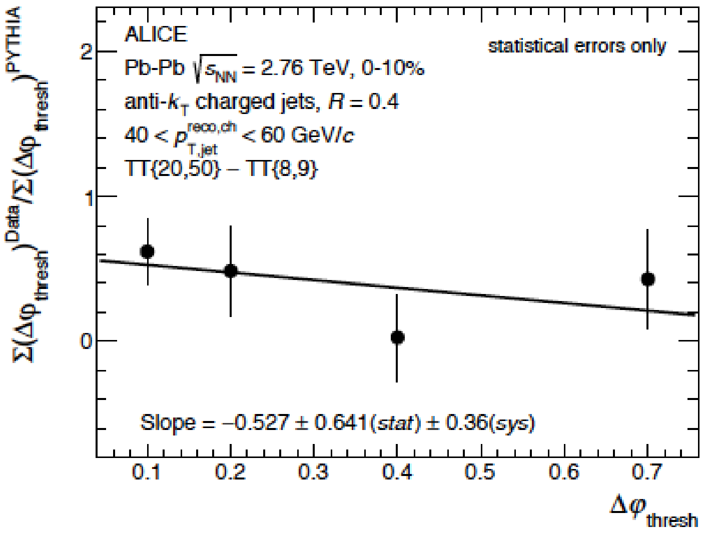
Consistent with zero at current precision

Low energies: hint of finite yield at large Δϕ yield at but not fully corrected for uncorrelated background

QCD calculation in progress (d’Eramo): will indicate integrated luminosity needed for significant measurement

Moliere scattering search: ALICE Run 2





Quantitative search requires absolute normalization

➔ semi-inclusive distributions

Systematics fully understood: limits are strictly statistical

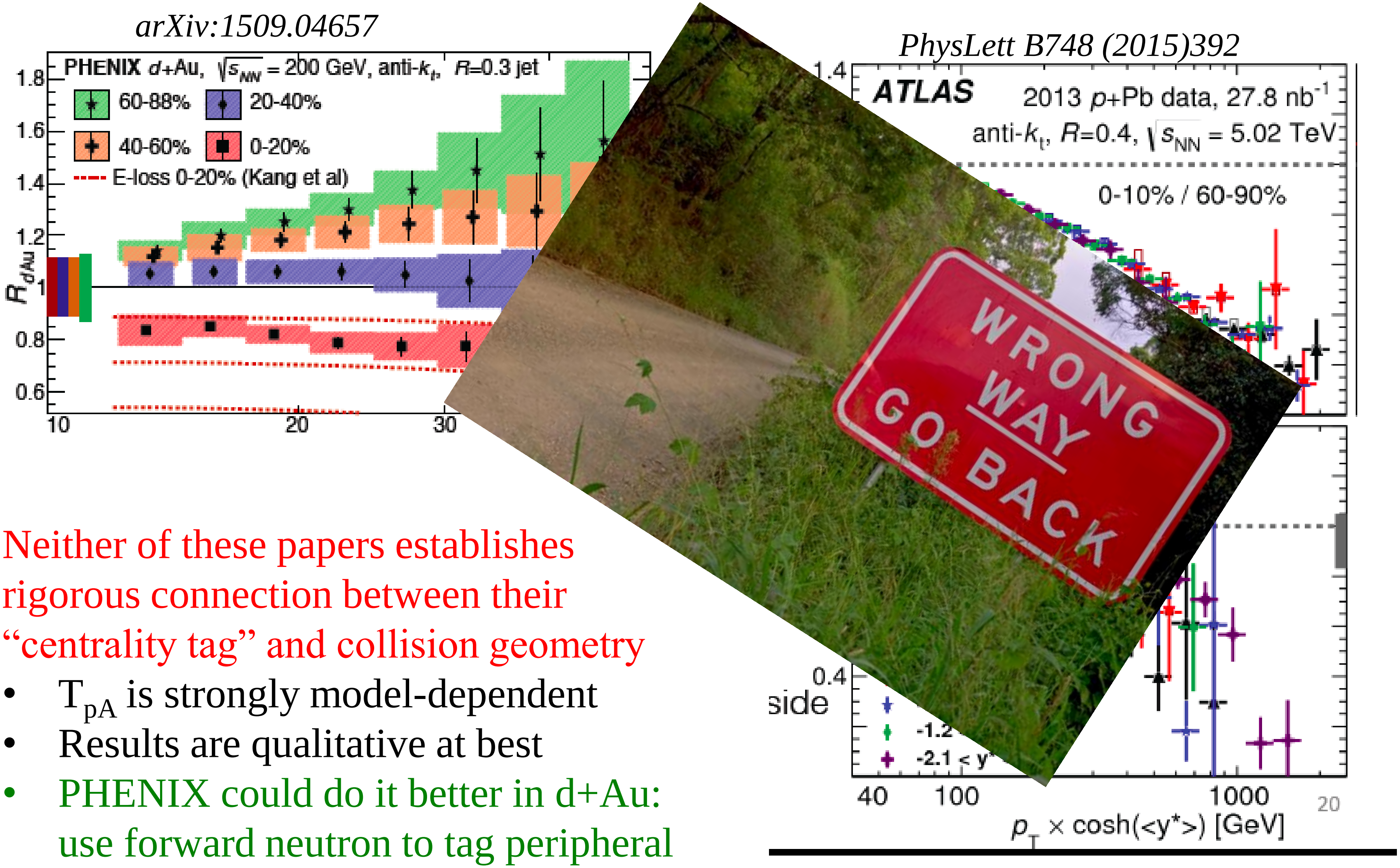
ALICE Run 2

- DCal trigger on γ/π^0
- Semi-inclusive jets in EMCal
- Factor 10 improvement in Pb+Pb precision
- Need similar precision in reference spectrum…?

Jet quenching in p+A: current approaches

arXiv:1509.04657

PhysLett B748 (2015)392



Neither of these papers establishes rigorous connection between their “centrality tag” and collision geometry

- T_{pA} is strongly model-dependent
- Results are qualitative at best
- PHENIX could do it better in d+Au: use forward neutron to tag peripheral collisions (but not yet done)

Jet quenching in p+A: the right approach

Semi-inclusive jet recoil spectrum

$$\frac{1}{N^{h}_{trig}}\frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{AA\to h+X}}\frac{d\sigma^{AA\to h+jet+X}}{dp_{T,jet}}$$

Why?

$$\overset{?}{=} \frac{1}{\sigma^{pp\to h+X}}\frac{d\sigma^{pp\to h+jet+X}}{dp_{T,jet}} \times \cancel{\frac{T_{pPb}}{T_{pPb}}}$$

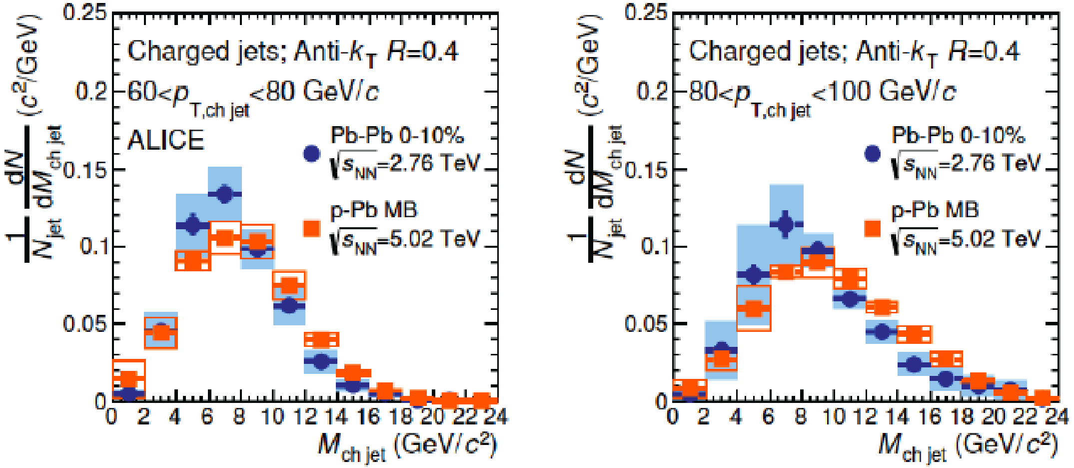
- Reference: both high p_T hadron and jet yields scale with T_{pPb}
- T_{pPb} cancels in the ratio: you don’t have to know it!

Measure recoil spectrum for minbias and high multiplicity collisions (no geometric interpretation required)

- In progress for charged and full jets (Filip K and pmj)

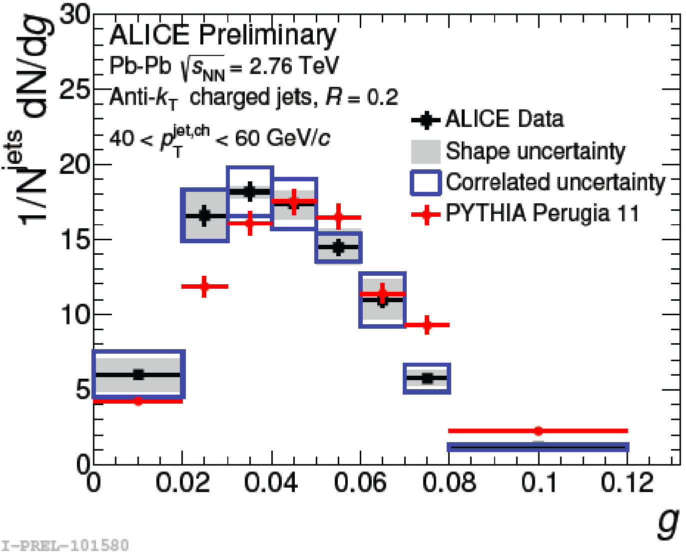
More differential IRC-safe jet observables

Jet mass



Jet shapes

$$g = \sum_{i \in jet} \frac{p_T^i}{p_T^{jet}} |r_i|$$



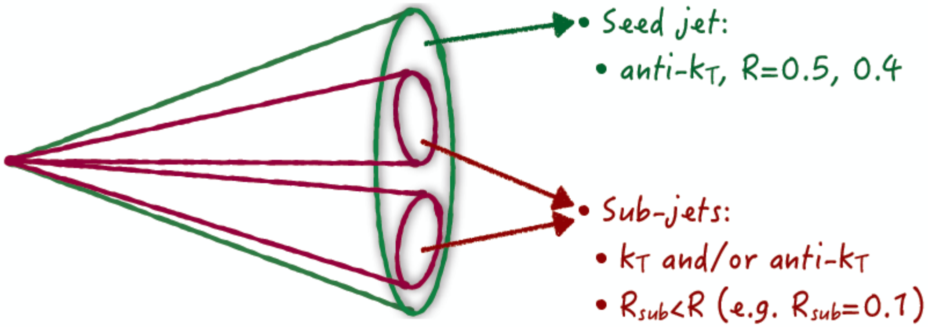
ALI-PREL-101580

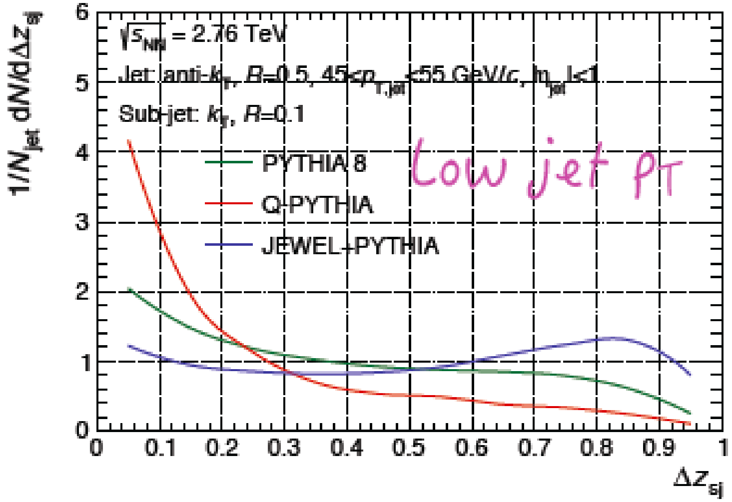
Radial moment shifted to lower values in Pb-Pb relative to PYTHIA Perugia11
→ indication of more collimated jet cores in Pb-Pb

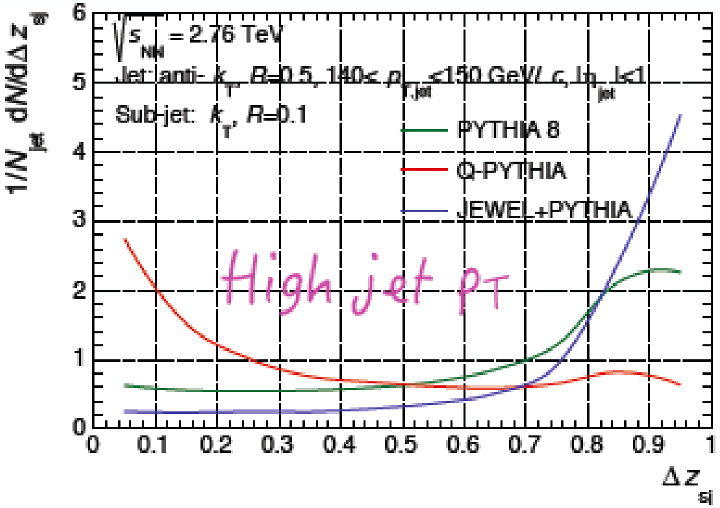
Subjets

Xiaoming Zhang, QM15

$$\Delta_{\mathrm{sj}} = p_{\mathrm{T,subjet}}^{\mathrm{1st\ leading}} - p_{\mathrm{T,subjet}}^{\mathrm{2nd\ leading}}, \quad \Delta z_{\mathrm{sj}} = \Delta_{\mathrm{sj}}/p_{\mathrm{T,jet}}$$



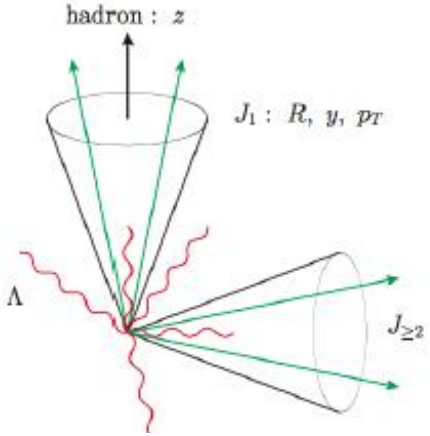




Fragmentation functions via SCET

I. Vitev, F. Ringer
EIC Workshop Jan ‘16

$$F_{\omega_1}(z, p_{T_i}) = \frac{d\sigma^h}{dy_i dp_{T_i} dz} \Big/ \frac{d\sigma}{dy_i dp_{T_i}} = \frac{\mathcal{G}^h_{\omega_1}(z,\mu)}{J_{\omega_1}(\mu)}$$



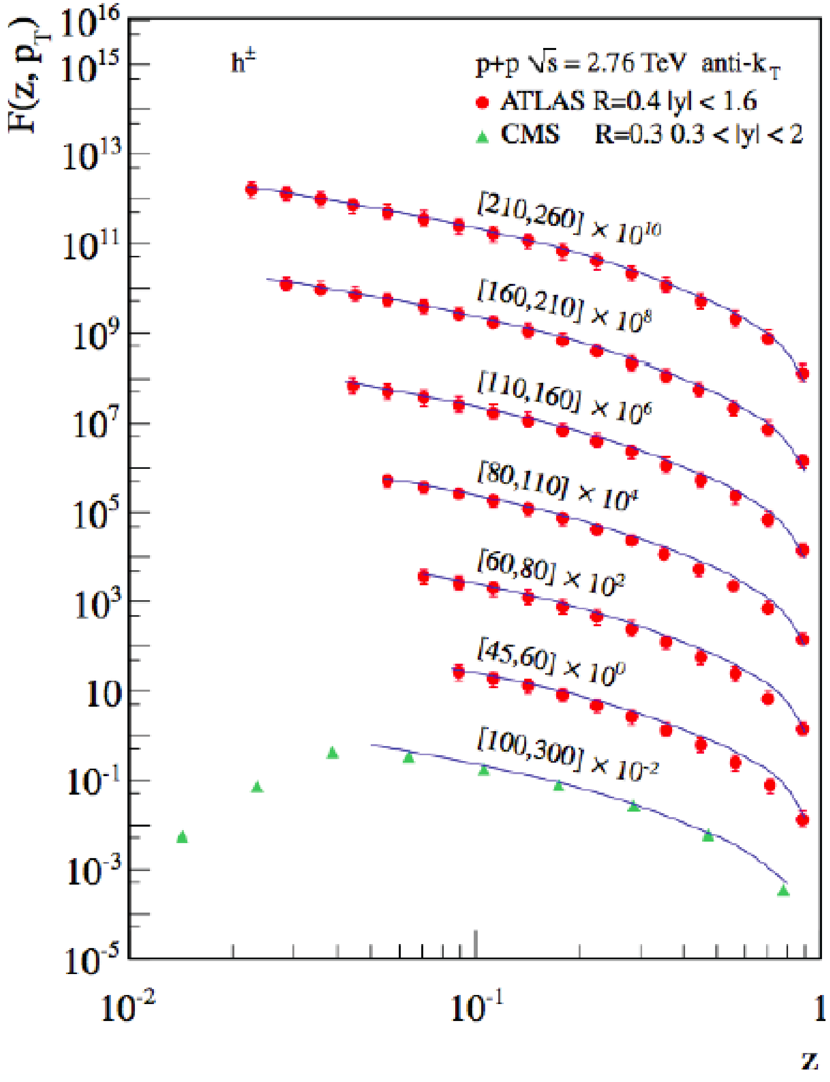
$$F(z,p_T) = \frac{1}{\sigma_{\text{total}}} \sum_{i=q,g} \int_{\text{PS}} dy\, dp_{T'} \frac{d\sigma^i}{dy\, dp_{T'}} \frac{\mathcal{G}_i^h(\omega,R,z,\mu)}{J^i(\omega,R,\mu)}$$

$$\mathcal{G}_i^h(\omega,R,z,\mu) = \sum_j \int_z^1 \frac{dx}{x} \mathcal{J}_{ij}(\omega,R,x,\mu)\, D_j^h\left(\frac{z}{x},\mu\right) + \mathcal{O}\left(\frac{\Lambda^2_{\text{QCD}}}{\omega^2 \tan^2(R/2)}\right)$$

Matching coefficients

Fragmentation functions

FF in SCET vs pp data



$$F(z,p_T) = \frac{d\sigma^h}{dydp_Tdz} / \frac{d\sigma^{\rm jet}}{dydp_T}$$

Works great! So what’s the problem in heavy ions?

Answer: observable is self-normalized:

$$z = \frac{p_T^h}{p_T^{\rm jet}}$$

We cannot accurately know $p_T^{\rm jet}$ event-by-event in the presence of large background – uncontrolled issue except at very high p_T

Outlook for (semi-)inclusive observables

New analysis techniques developed for heavy ion jet analysis

- Uncorrelated background corrected entirely at level of ensemble-averaged distributions

Suitable choice of observables:

- Inclusive cross sections and ratios, semi-inclusive
- clear connection to theory in vacuum
- well-controlled jet measurements for central AA collisions at RHIC and LHC at all R and all p_T

First measurements at ALICE and STAR of

- yield suppression
- intra-jet broadening
- inter-jet broadening
- search for Moliere scattering

Next steps:

- Extend techniques to fully calormetric jets
- Larger datasets (higher int lumi, calorimetric triggers)

My jet physics priorities for ALICE Run 2

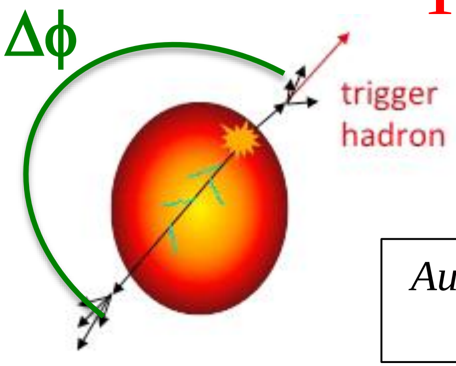
1. Inclusive jet R_{AA} in Pb+Pb@5 TeV
   - fully reconstructed, R=0.2 and 0.4 (0.5?)
   - complete kinematic range for periph and central
   - Analysis techniques are well-established
   - Needs EMCal jet trigger

2. Semi-inclusive h+Jet
   - Fully reconstructed jets in EMCal, R=0.2 to 0.5
   - Explore new event-mixing approach to uncorrelated background
   - Needs DCal single-shower trigger

3. More exclusive IRC-safe measurements
   - Subjets
   - Jet shapes
   - Jet mass
   - …
   - Needs single-shower and jet triggers

Extra slides

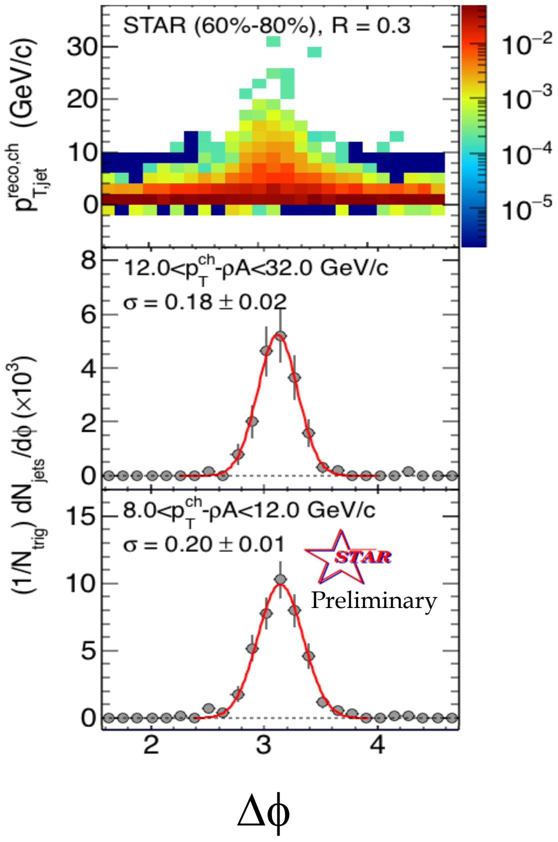
Inter-jet broadening: STAR



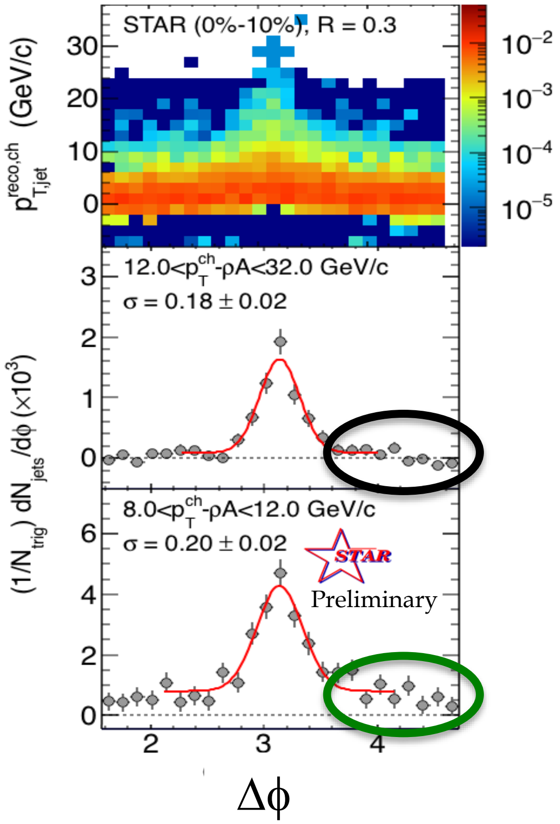
Quantitative search requires absolute normalization
➔ semi-inclusive distribution

$Au+Au\ \sqrt{s_{NN}}=200\ GeV$
$p_T^{trig}>9\ GeV/c$

peripheral



central

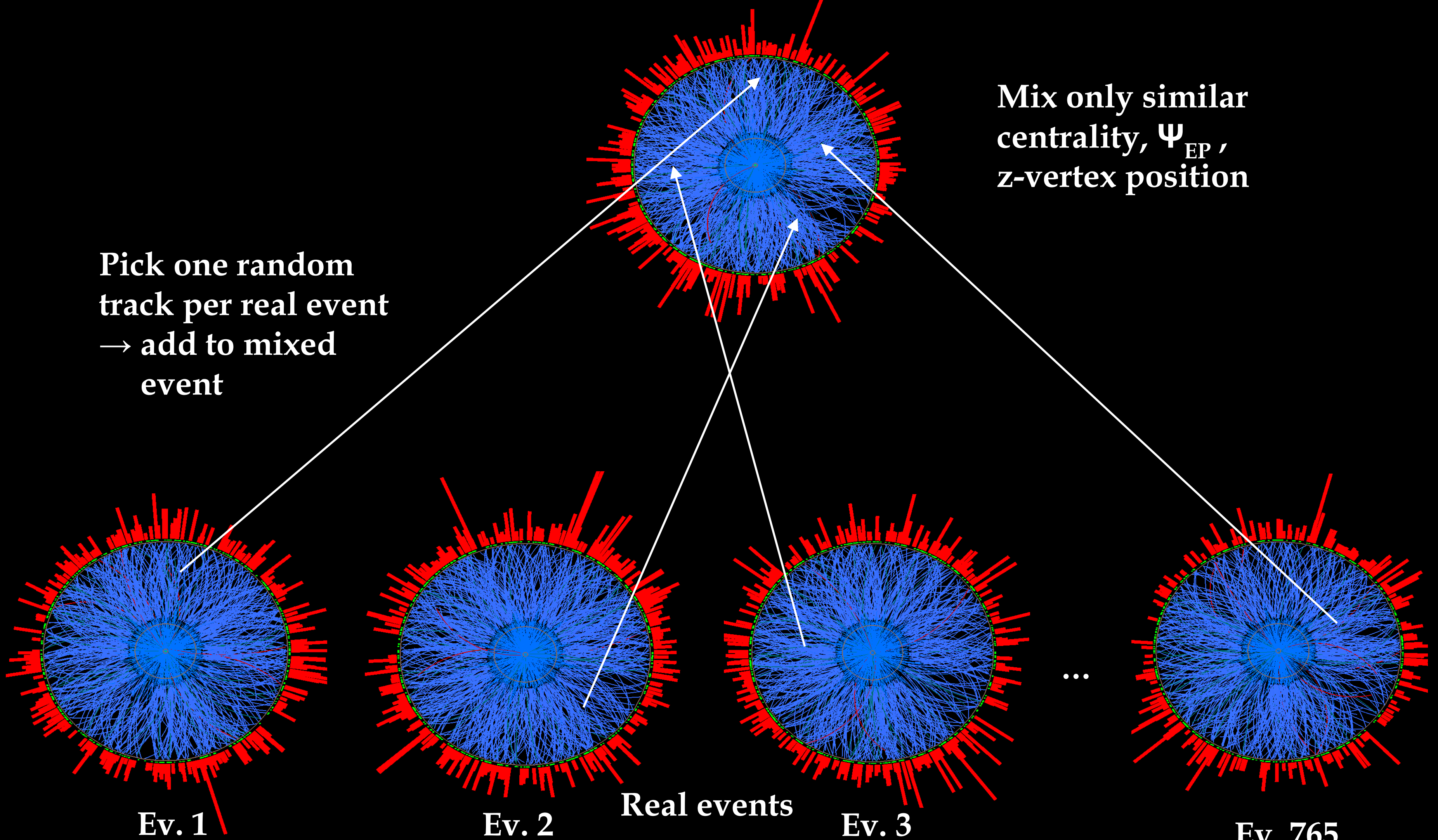


Consistent with zero at current precision

Low energies: hint of finite yield at large Δϕ yield at but not fully corrected for uncorrelated background

QCD calculation in progress (d’Eramo): will indicate integrated luminosity needed for significant measurement

New method for uncorrelated background: mixed events



Mixed event

Mix only similar centrality, Ψ_{EP} , z-vertex position

Pick one random track per real event → add to mixed event

Ev. 1

Ev. 2

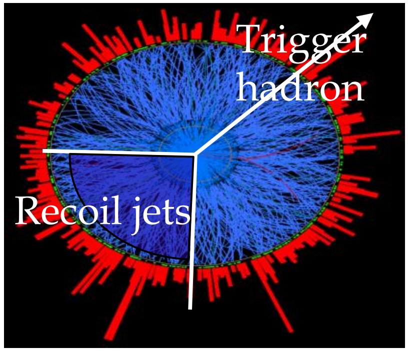
Real events

Ev. 3

…

Ev. 765

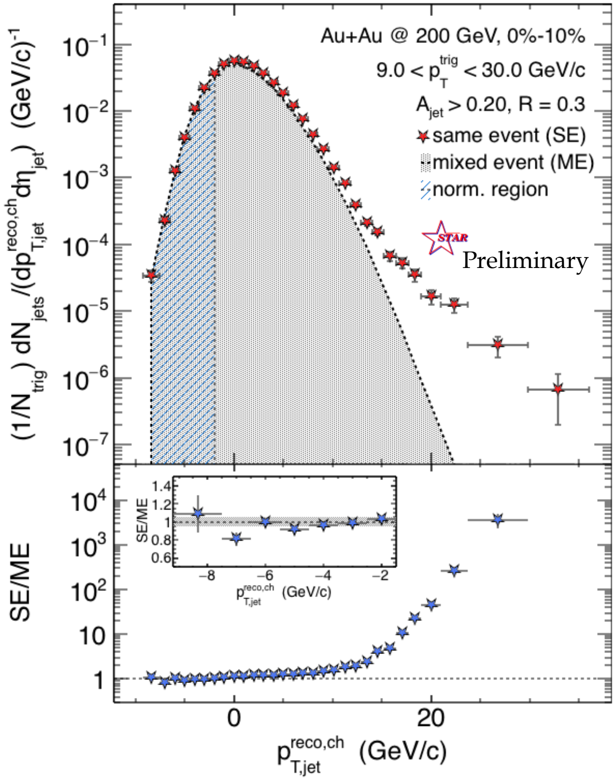
Recoil jet spectrum: STAR



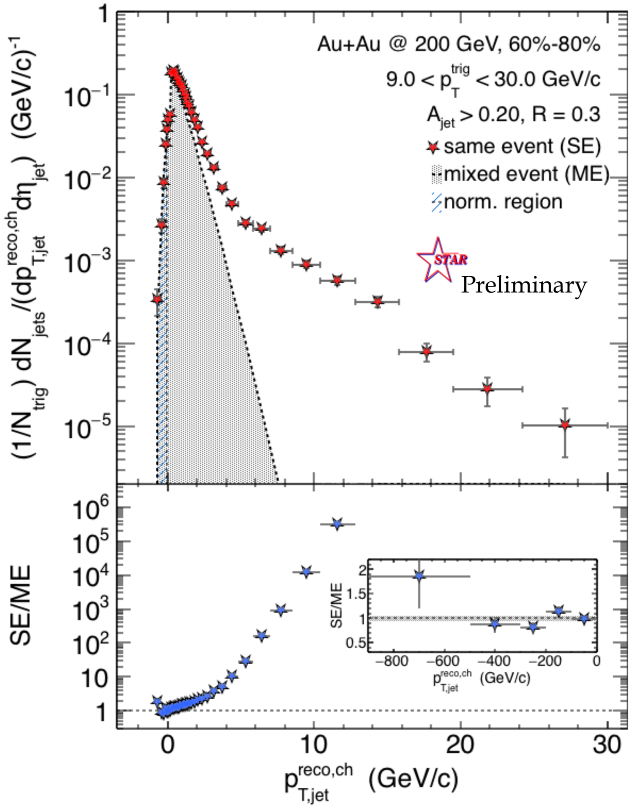
$$\boxed{p_{\mathrm{T,jet}}^{\mathrm{reco,ch}} = p_{\mathrm{T,jet}}^{\mathrm{raw,ch}} - \rho \cdot A}$$

ρ = estimated background energy density

Central Au+Au

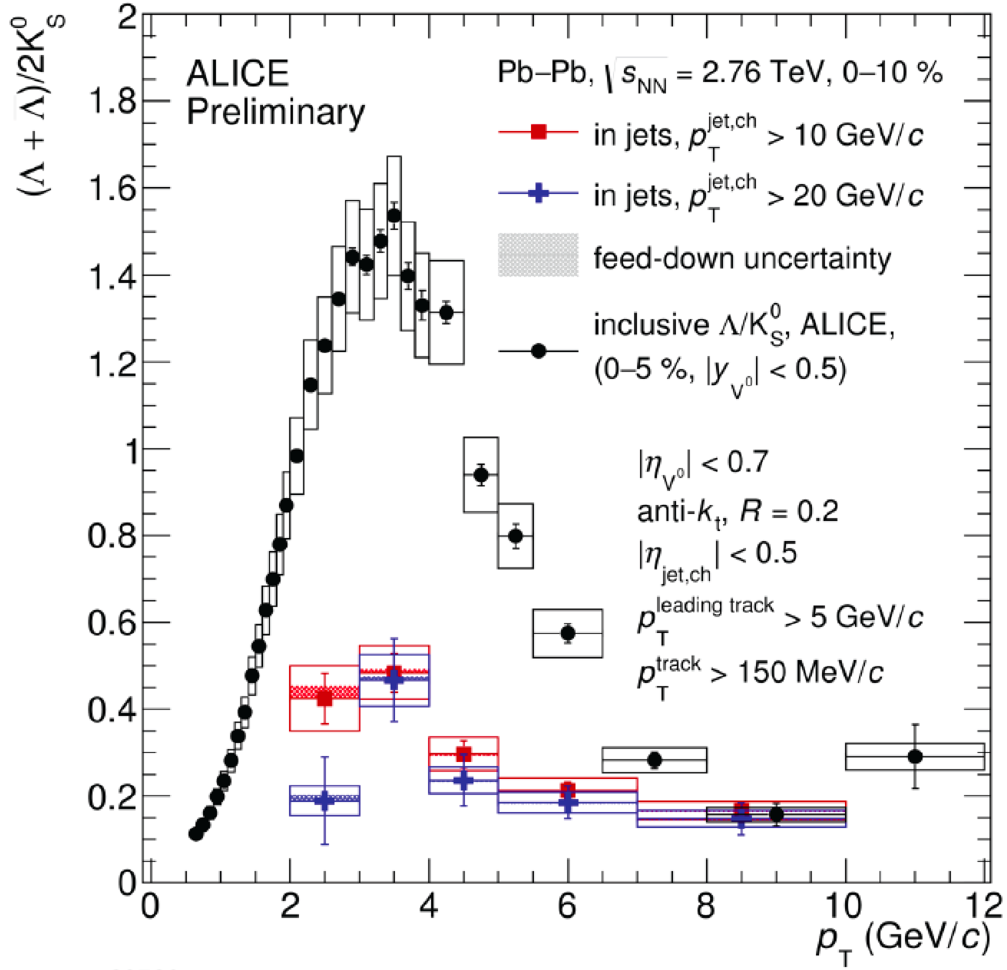


Peripheral Au+Au



Mixed event distribution is good description of combinatorial jet background

Other measurements: jet hadro-chemistry



ALI-PREL-93799