Yale
Wright
Laboratory

Jet Quenching Measurements at RHIC

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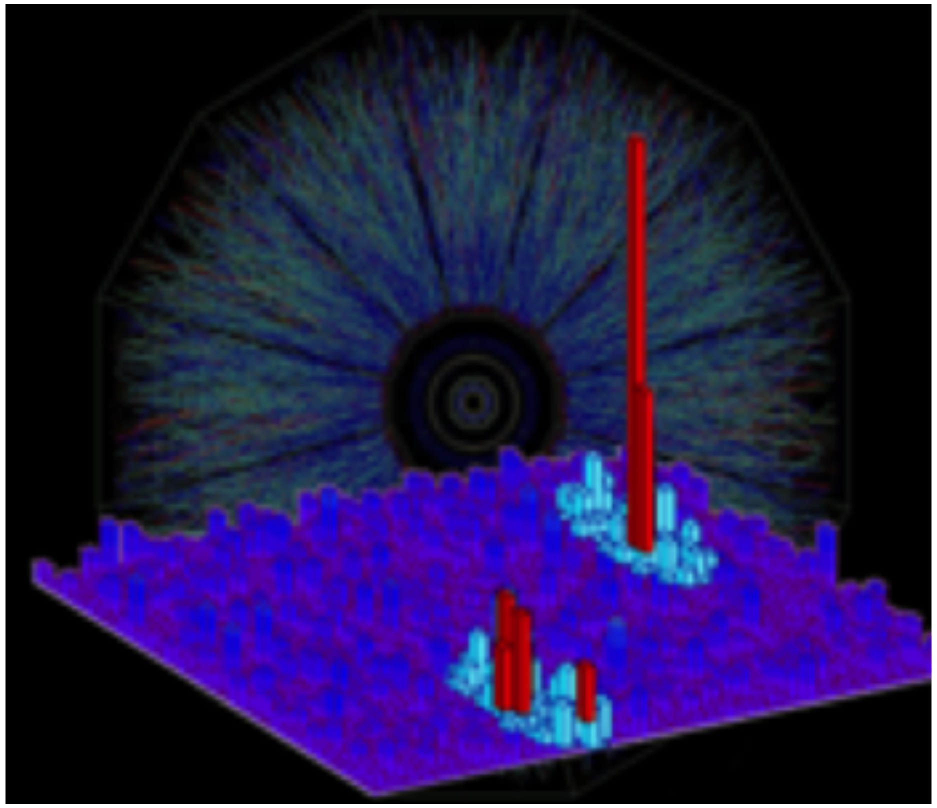
Yale University
JETSCAPE Workshop
LBNL, Jan 2018

JETSCAPE

Outline



Establishing the baseline

How much energy is lost?

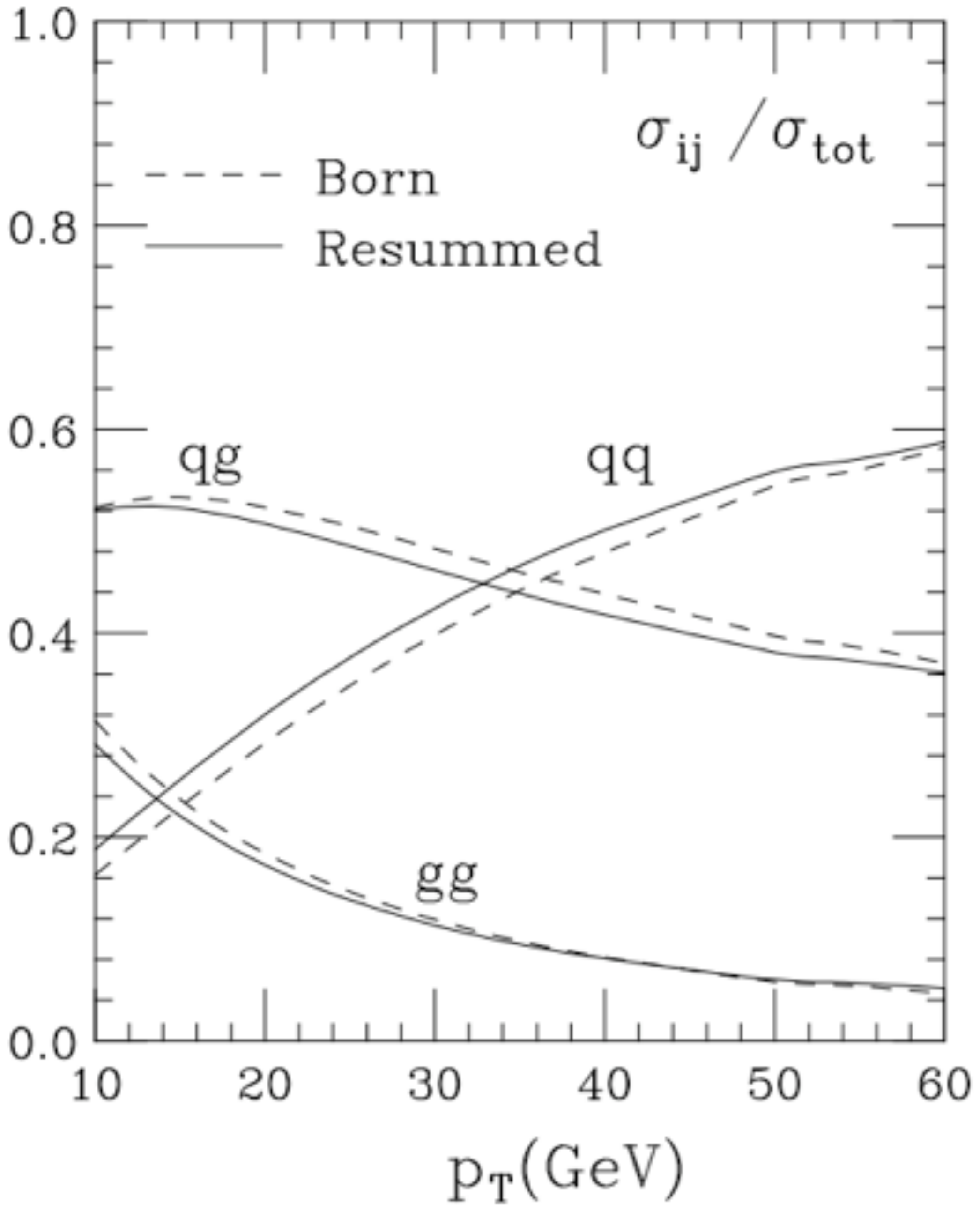
How does it reemerge?

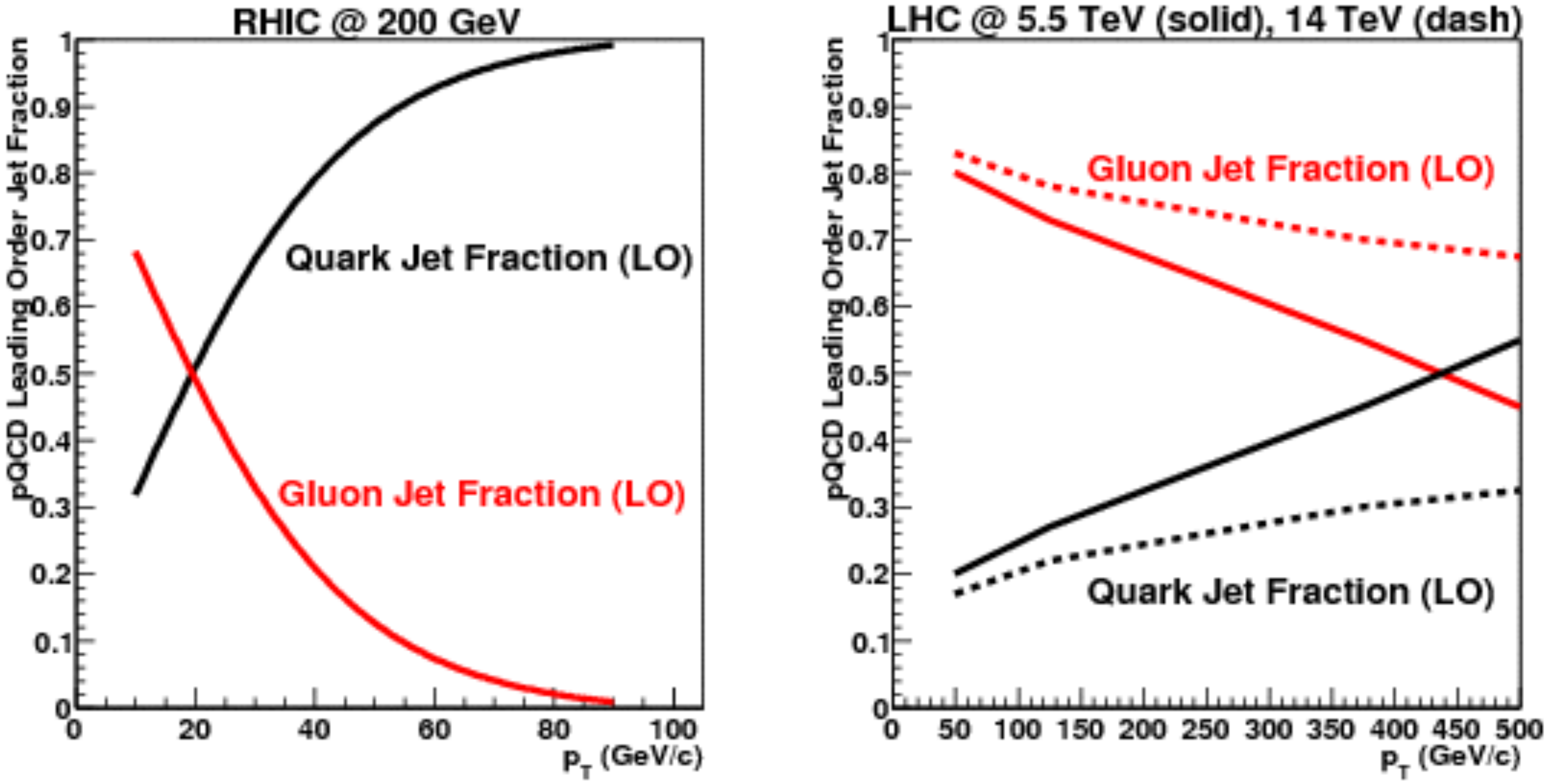
What about small systems?

Remaining opportunities

Hard scatterings at RHIC

pp collisions at 200 GeV and R = 0.4





Quark jets dominate

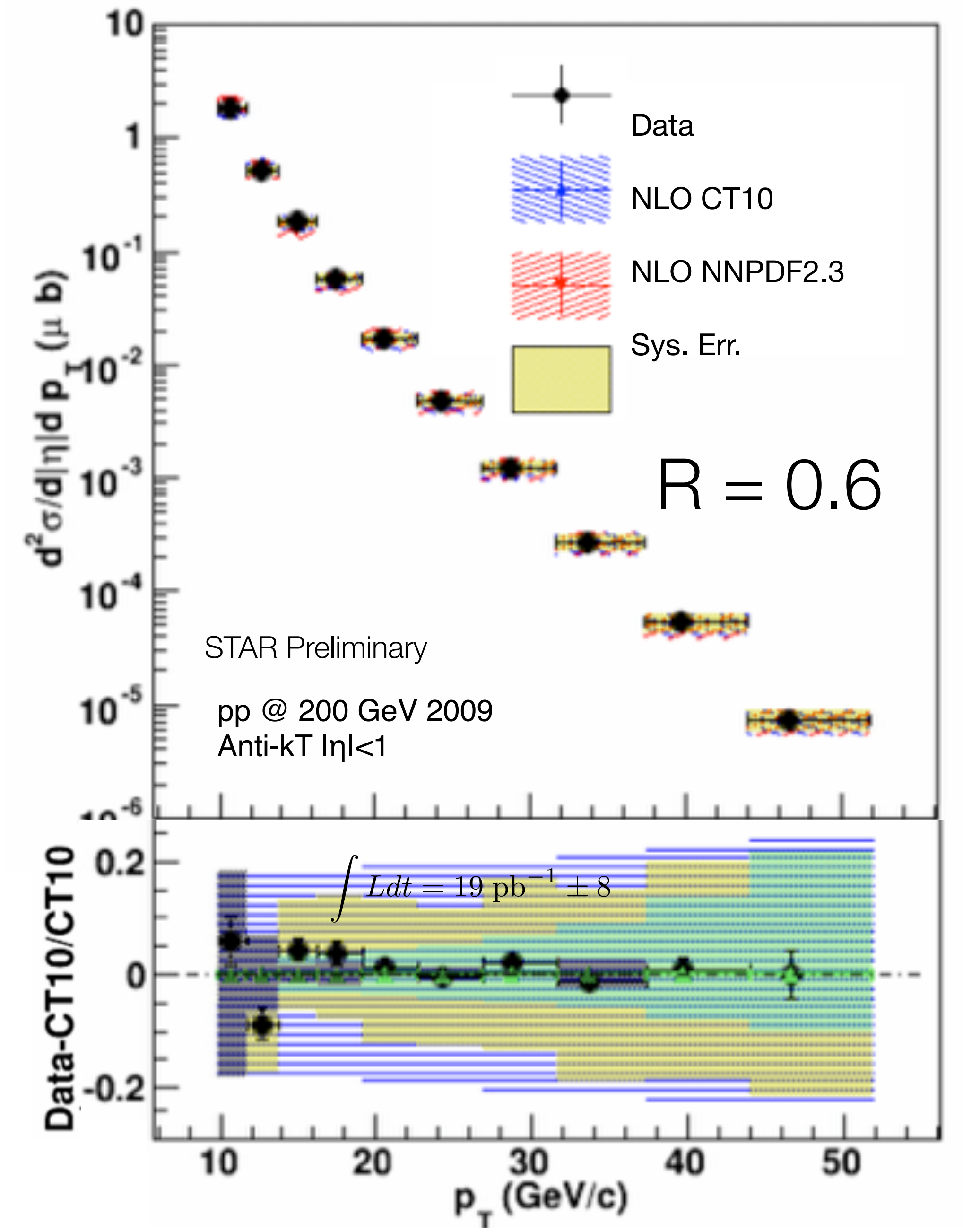
Florian and Vogelsang: PRD76. 074031
PHENIX: arXiv:1501.06197

Jets in vacuum

Inclusive Jet

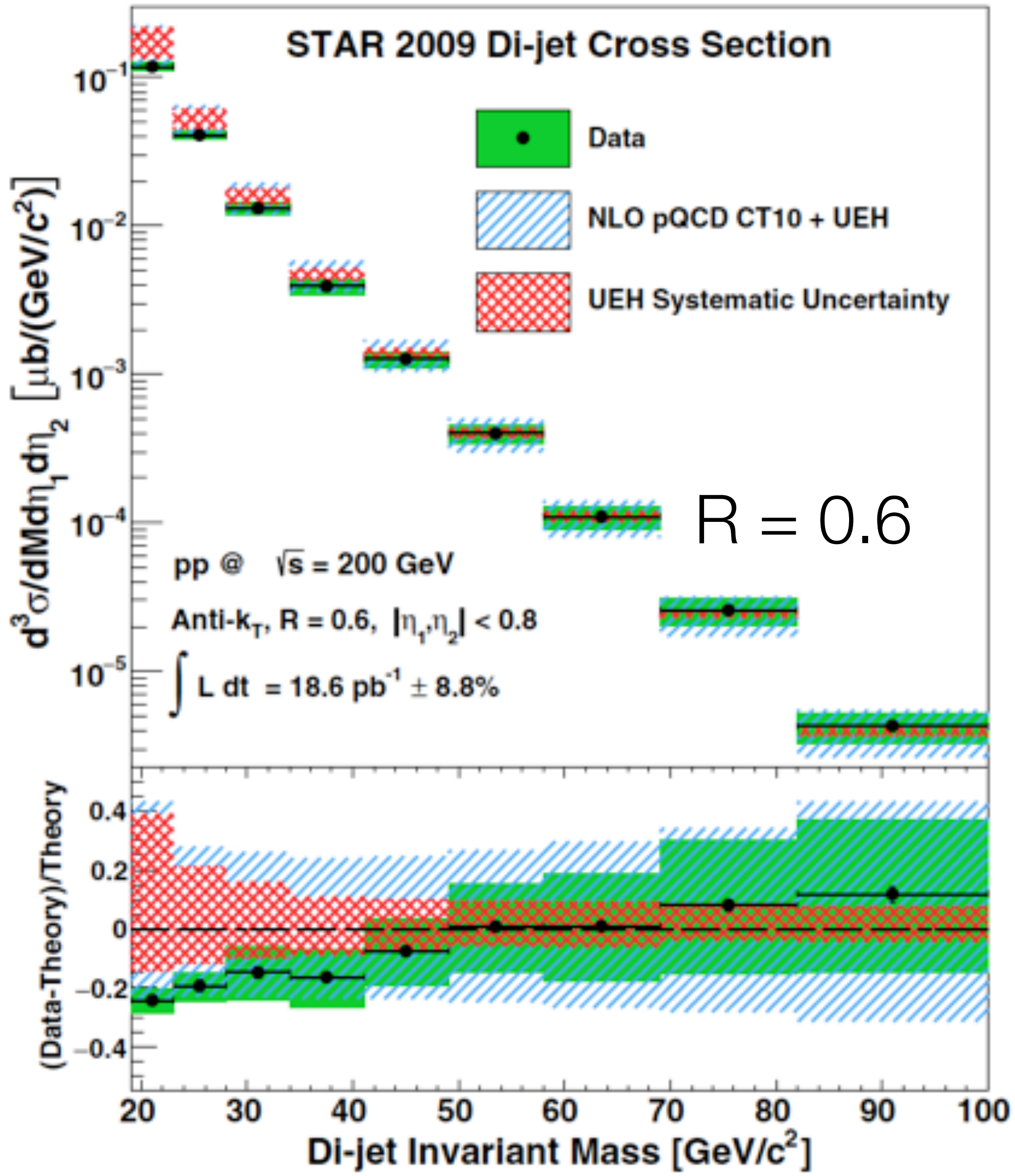
First mid-rapidity Dijet

jet cross section



ratio: color band for various sys. err.

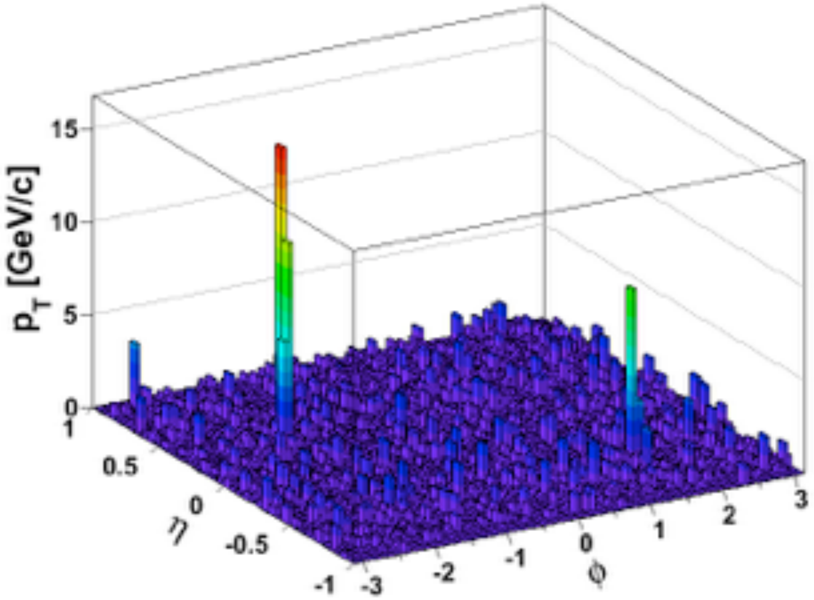
dijet cross section

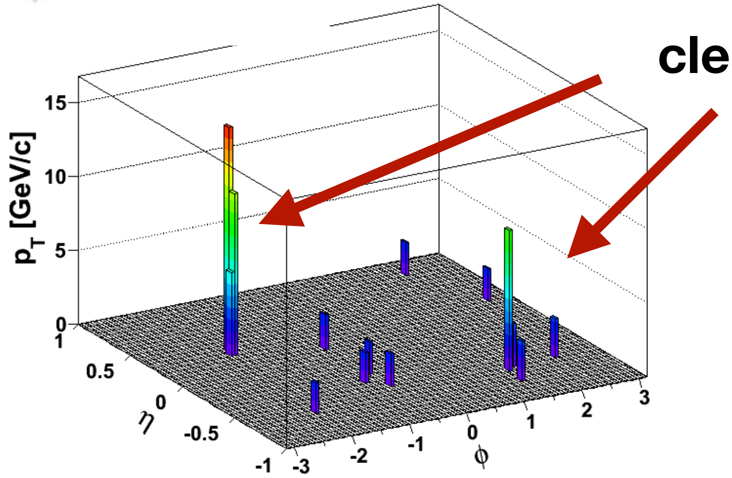


Well described by NLO pQCD → Jets as high precision tool

STAR: PRD95 071103(R) (2017)

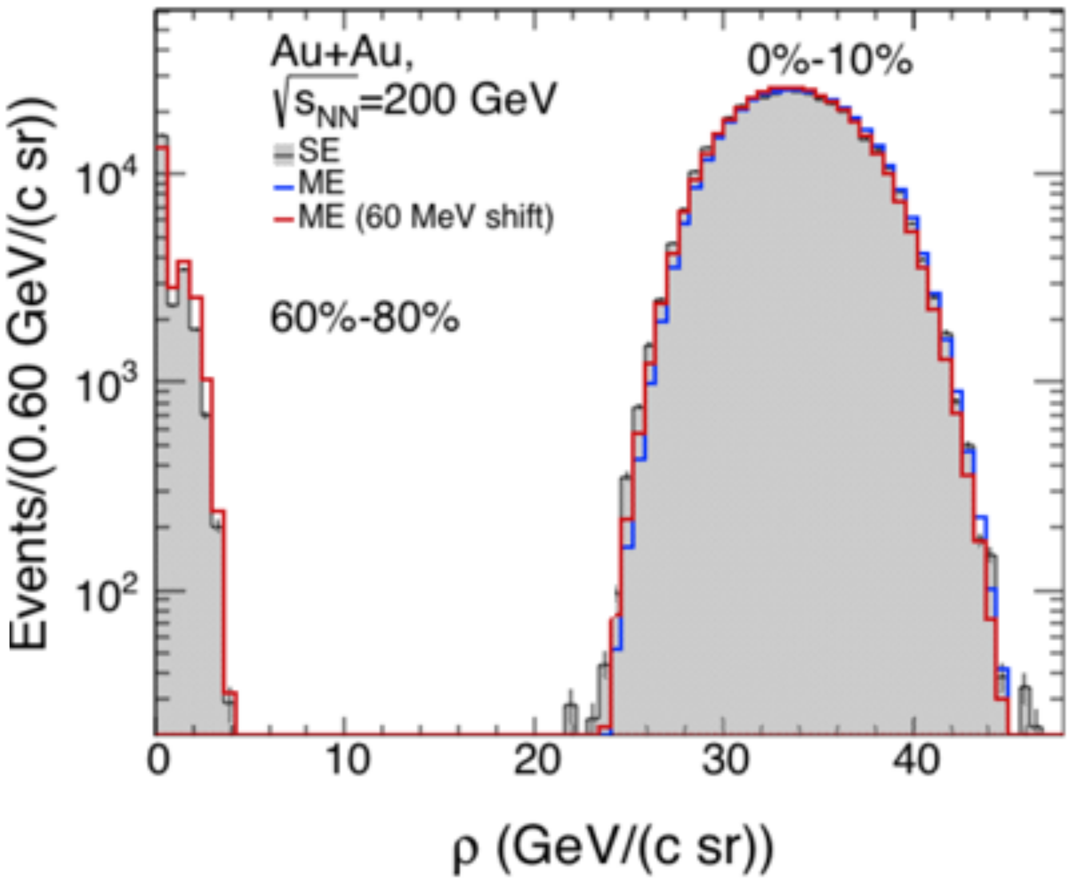
Background Activity in A-A





clear jet signal

STAR, Au-Au@200



0-10% $\langle \rho^{ch} \rangle \sim 35$ GeV/c

Challenges: large fluctuating background

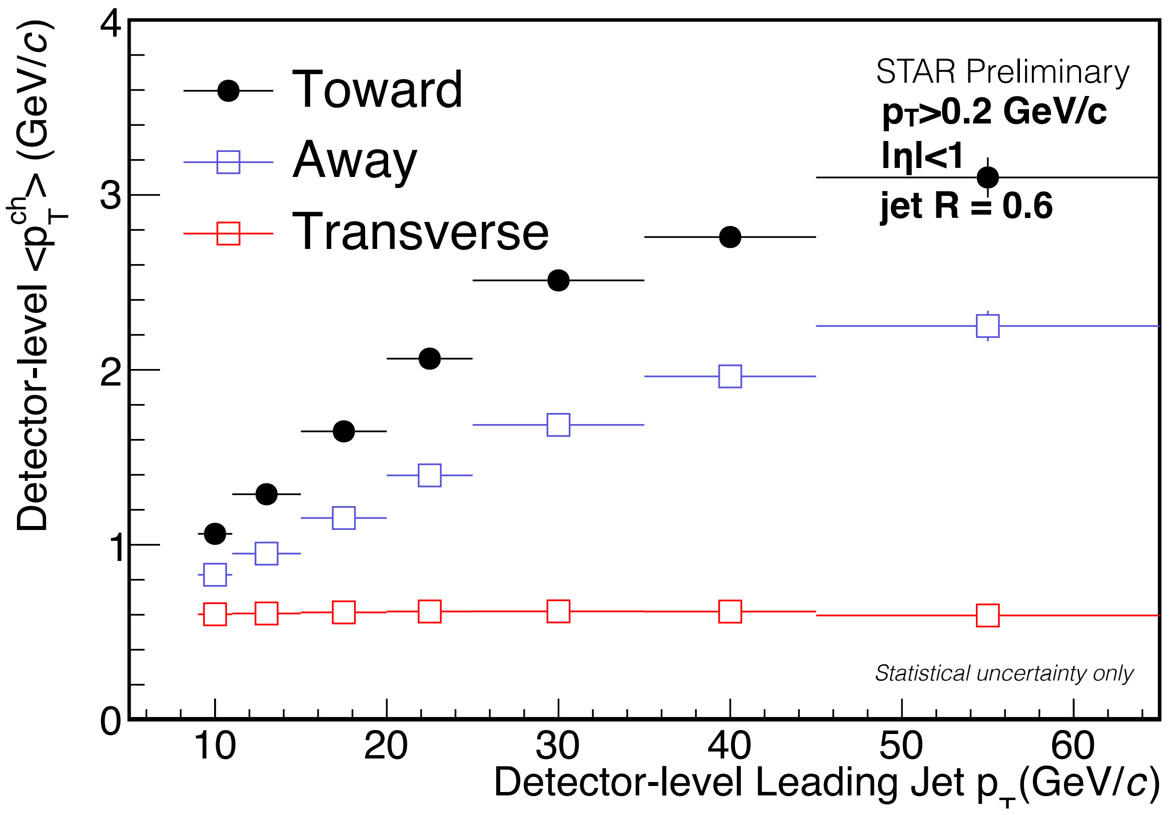
-> modified JES + smeared JER + combinatorial jets

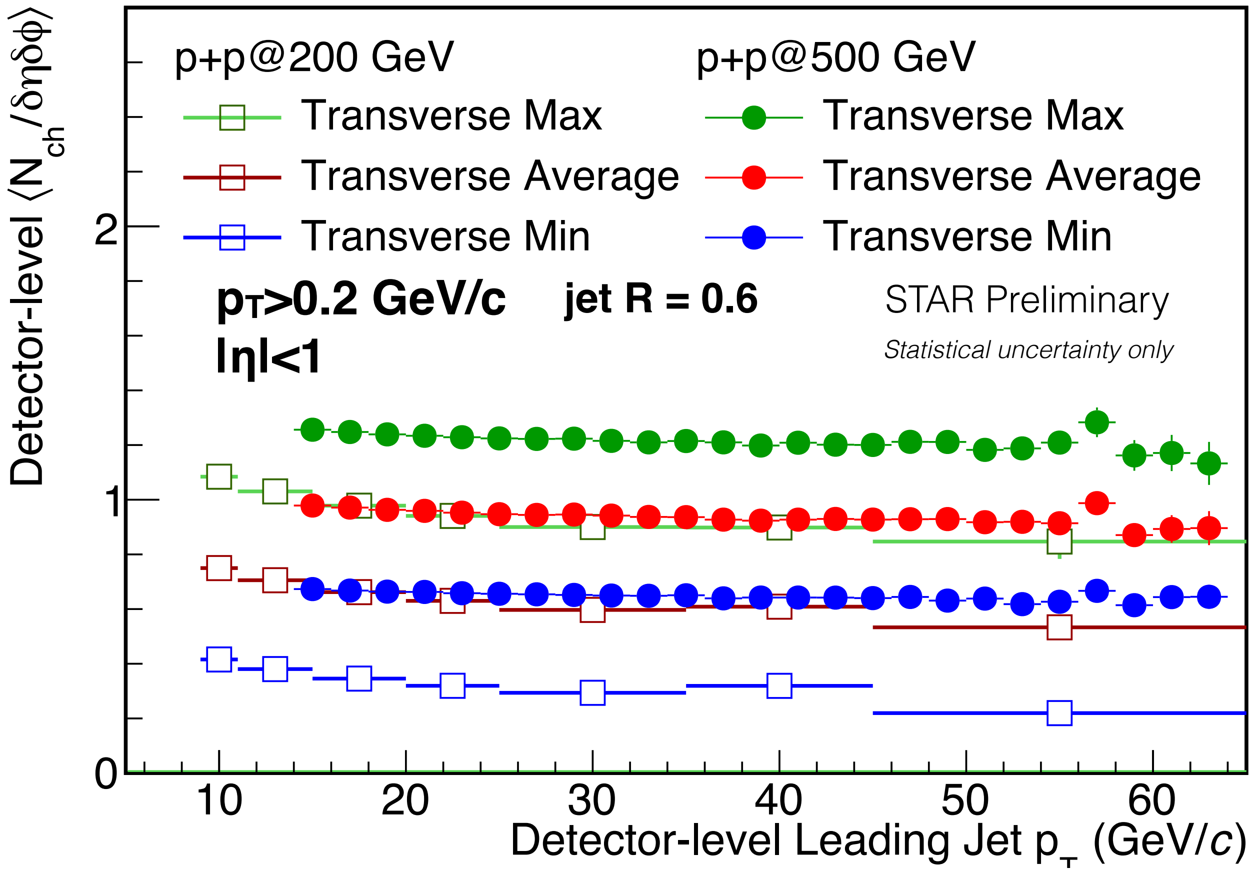
Experiment methods:

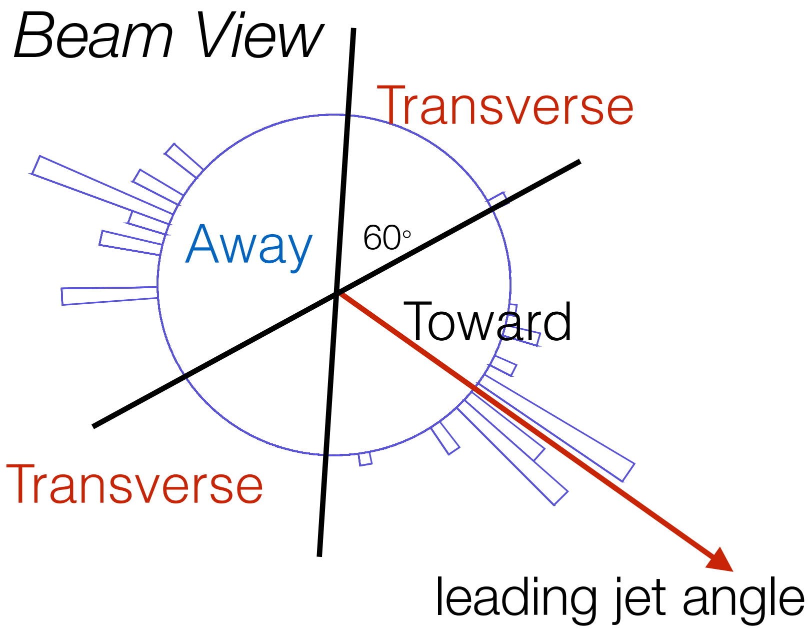
-> constituent cuts, high p_T particle match,.. mixed event

Most of the background is sub-2 GeV/c

Underlying event activity in pp







Underlying event:

Increases with beam energy

Weak dependence on jet energy

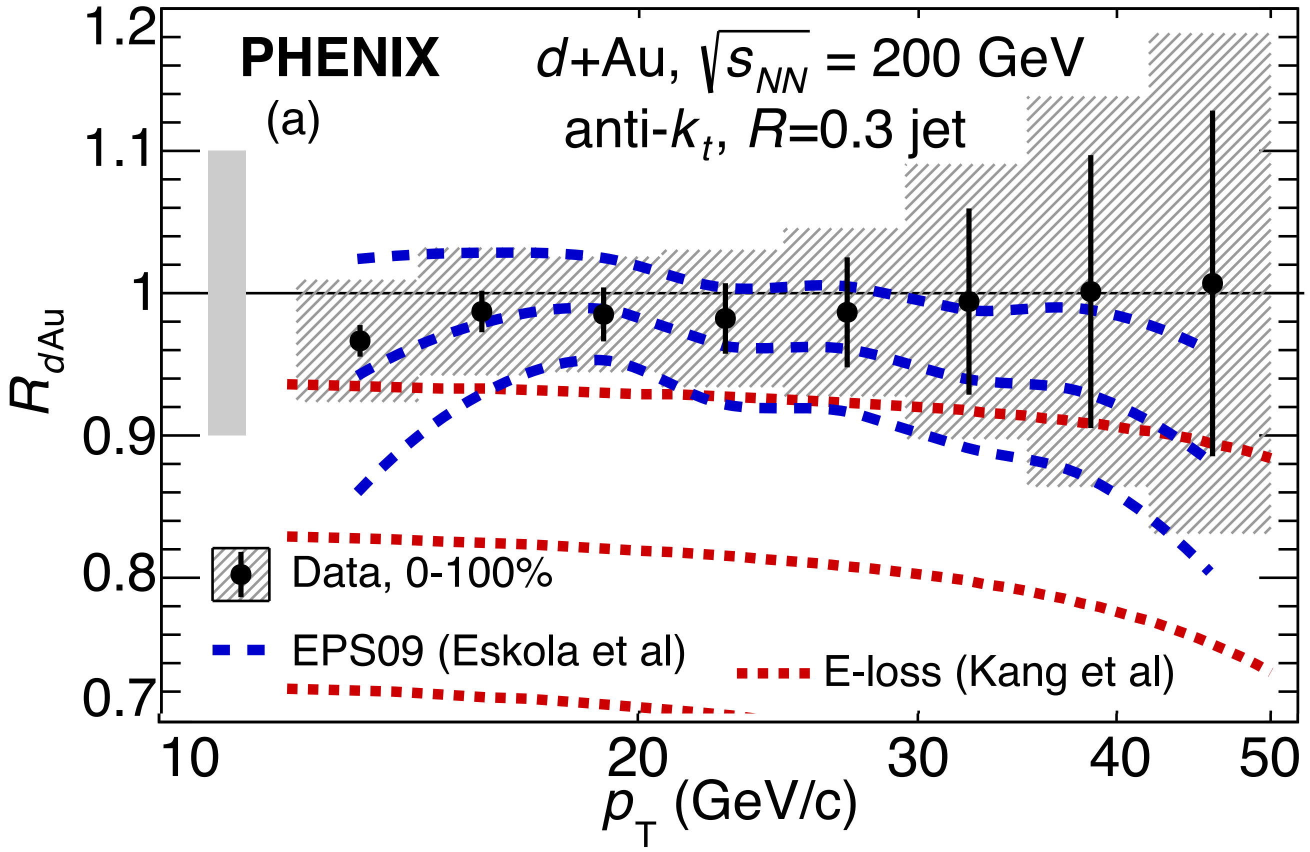
Slightly over predicted by PYTHIA

TransMin: BBR and MPI

TransMax: ISR and FSR

Little to no ISR/FSR contribution at RHIC

Measurements in minimum bias d-Au



Full jets

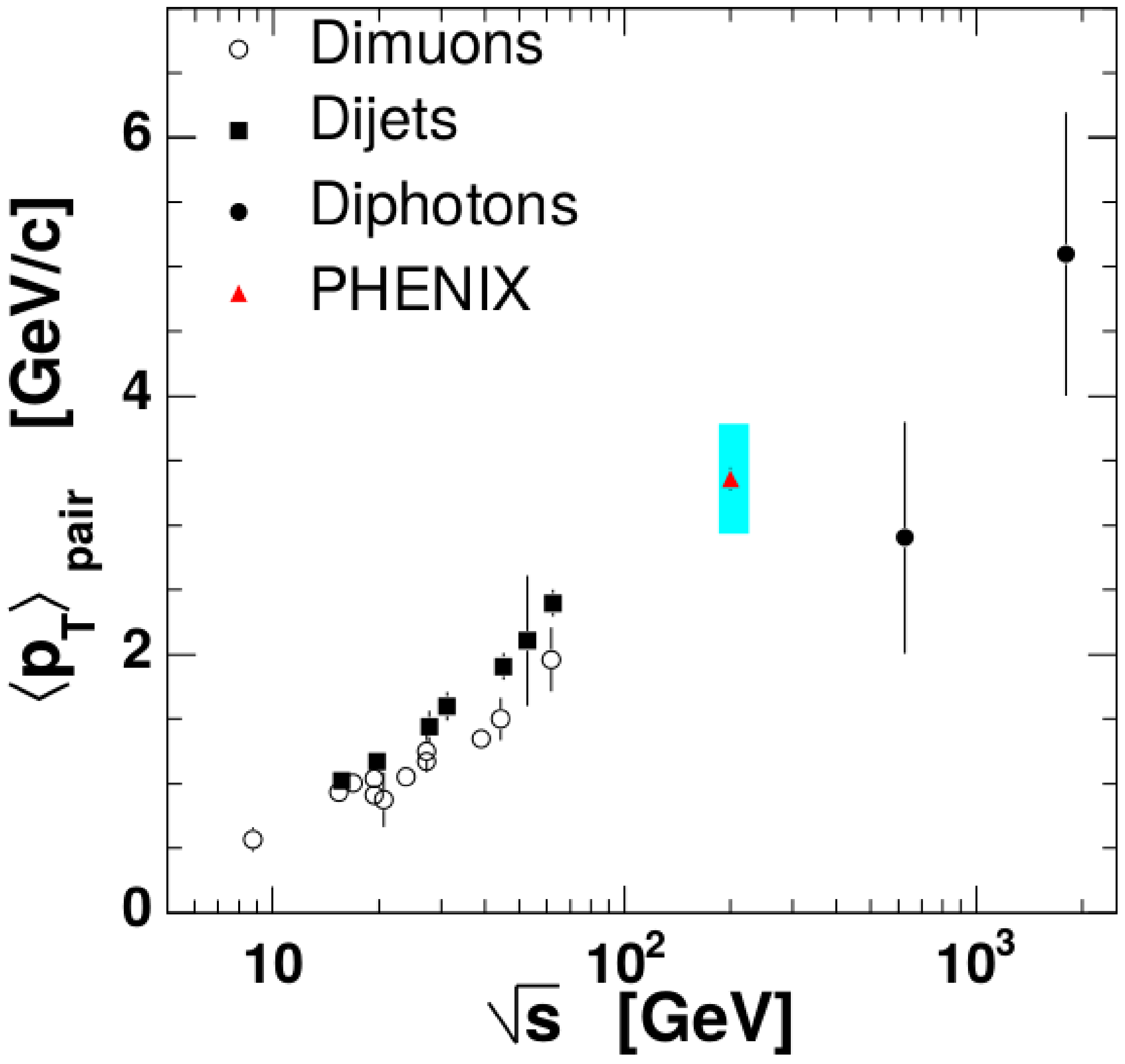
Consistent with NLO calculations using EPS09

di-hadron correlations

d-Au:

$$\langle\sqrt{k_T^2}\rangle = 2.68 \pm 0.07 \pm 0.34 GeV/c$$

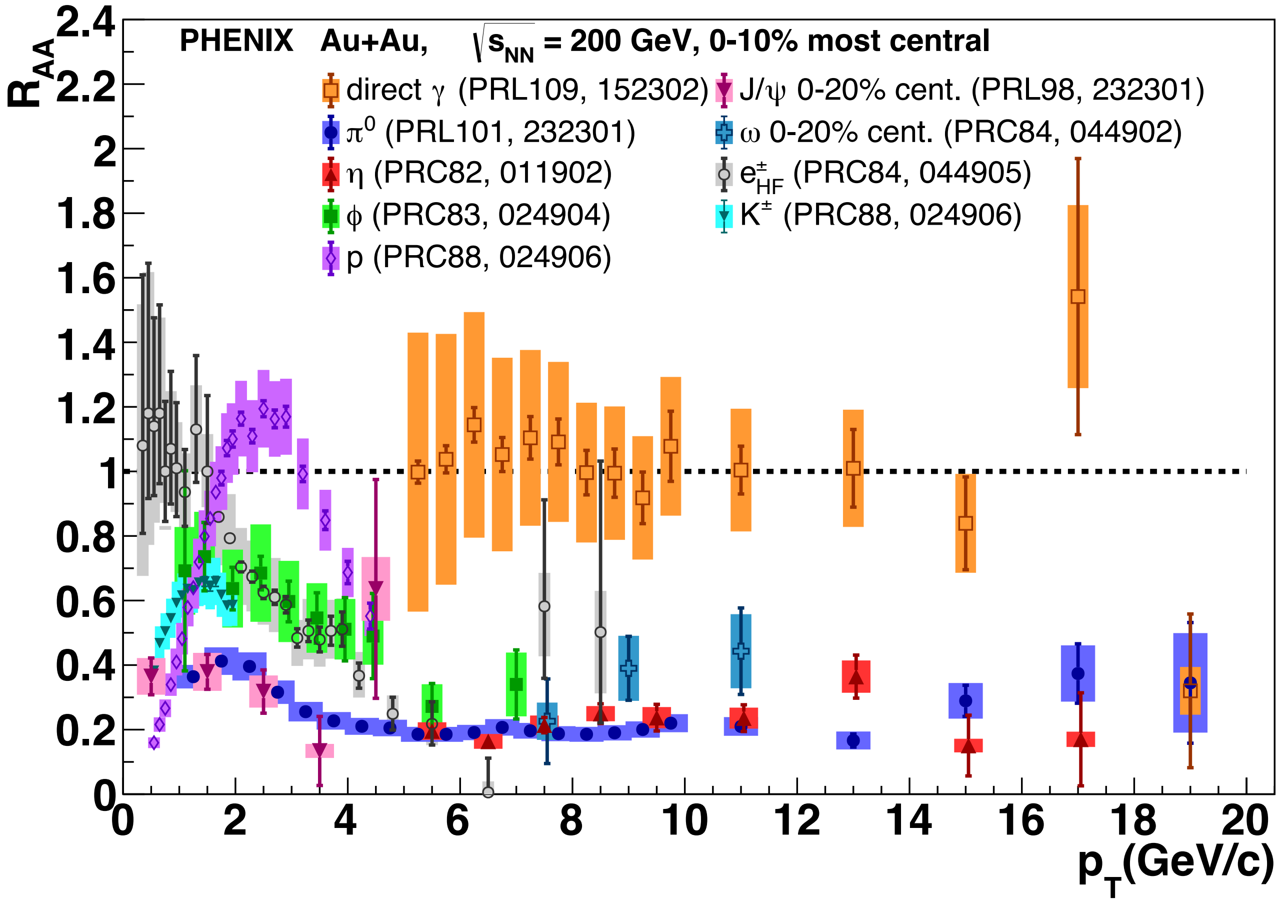
Consistent with trend for pp

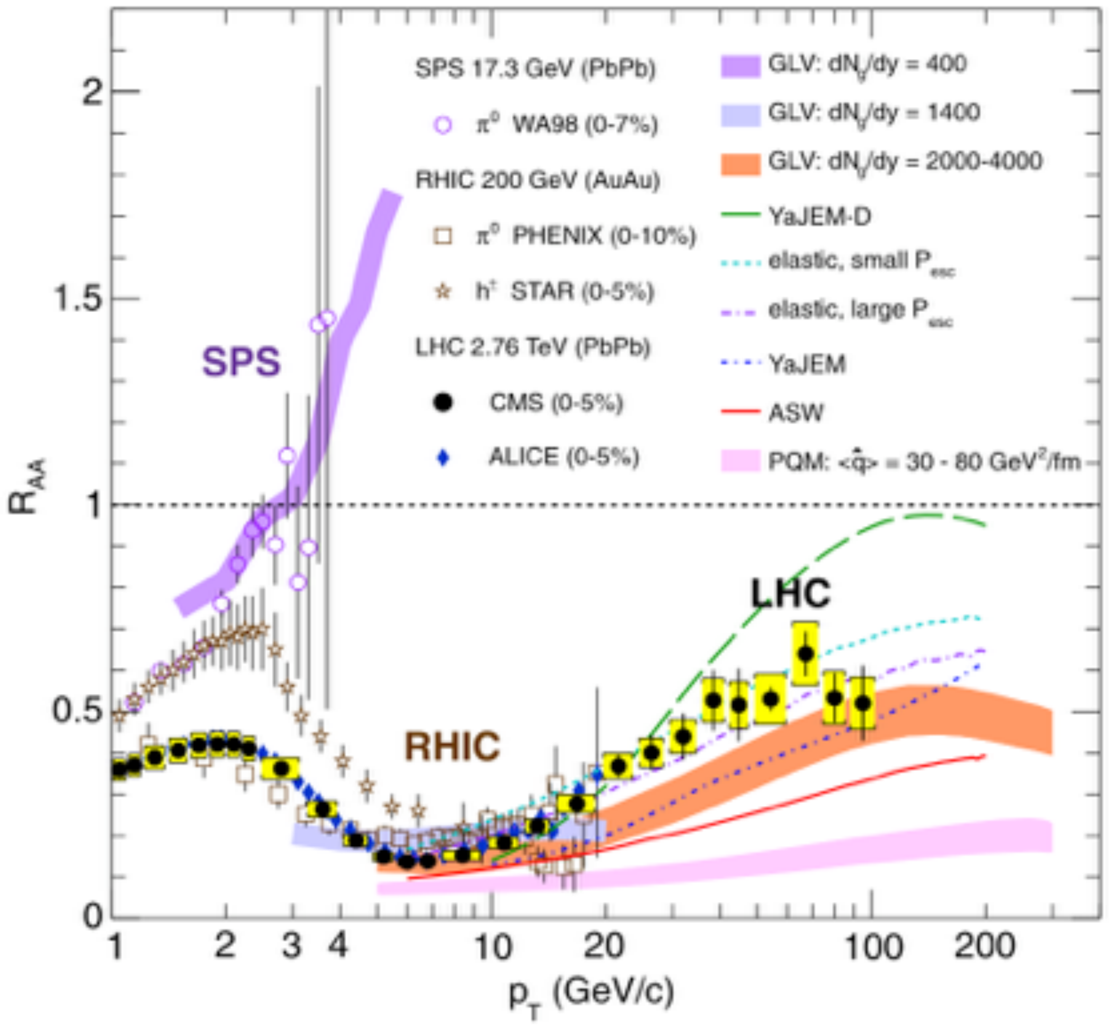


Nuclear effects small

PHENIX: PRD74. 072002 (2006)
PHENIX: PRL 116, 122301 (2016)

Single hadron high p_T suppression





All colored hadrons suppressed, including HF particles

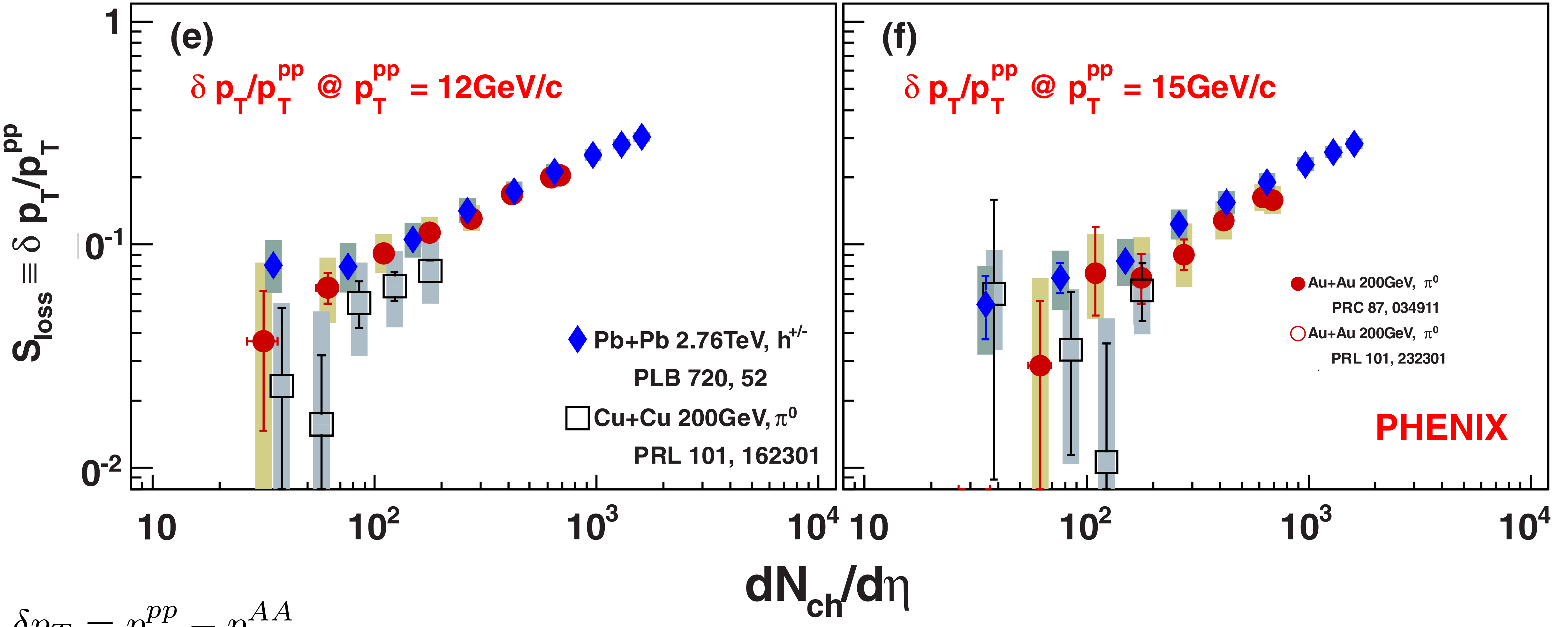
JET collaboration:

q-hat(RHIC) ~1.2±0.3 GeV²/fm
q-hat(LHC) ~ 1.9±0.7 GeV²/fm

for 10 GeV light quark at t=0.6 fm/c

JET: PRC90 1, 014909 (2014)
CMS: EPJC 72:1945 (2012)
Connors, Nattrass, Reed, Salur arXiv:1706.01974

Fractional partonic energy loss - S_{loss}



$$\delta p_T = p_T^{pp} - p_T^{AA}$$

At higher collision energies

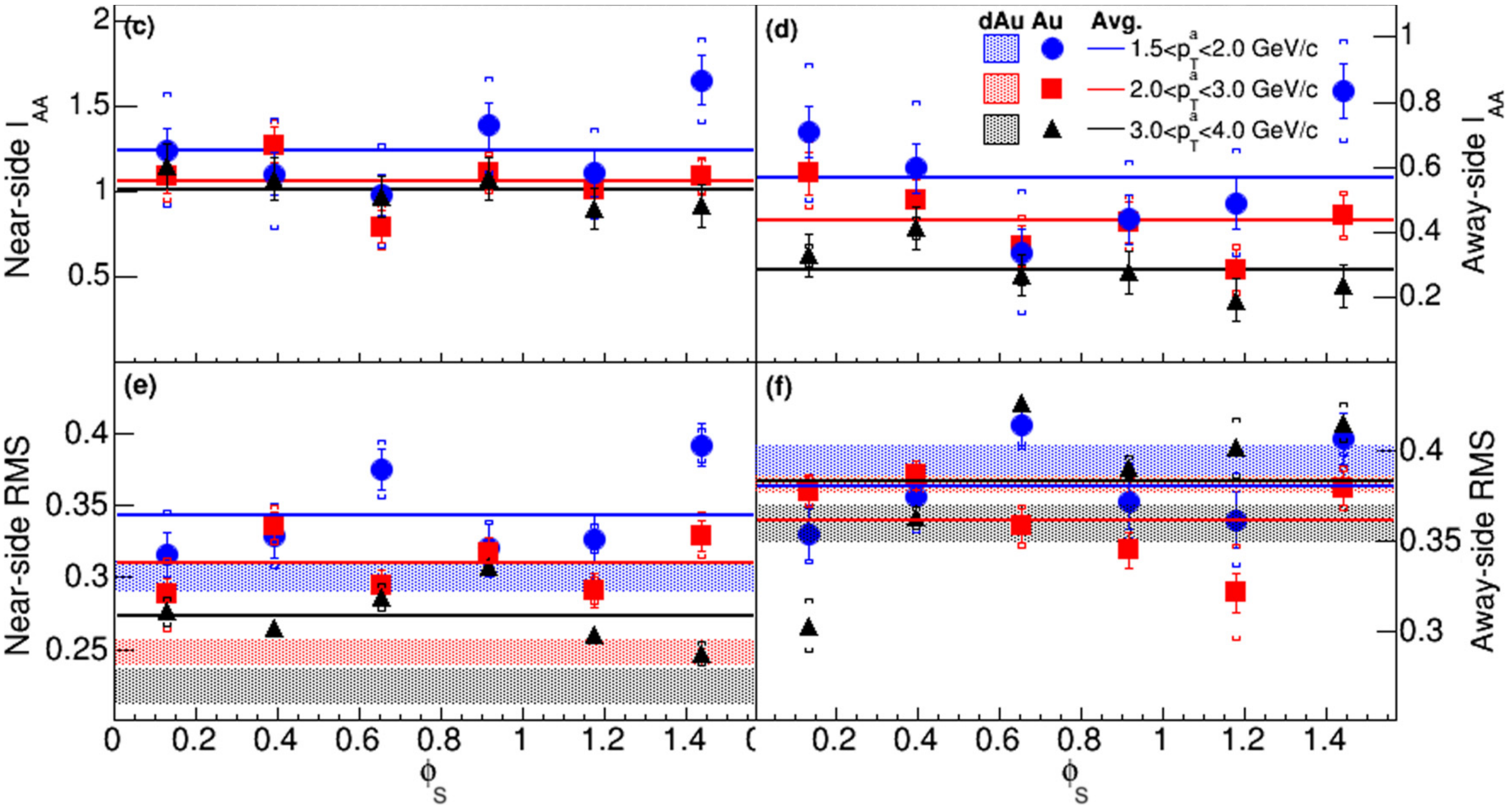
Apparent universal scaling of S_{loss} with $dN_{ch}/d\eta$

Independent of colliding species or energy

$dN_{ch}/d\eta$ ~ energy density ~ system opacity

PHENIX: PRC93. 024911 (2016)

Di-hadrons with respect to reaction plane



Away-side suppressed

Near-side width broader in Au-Au collisions than d-Au

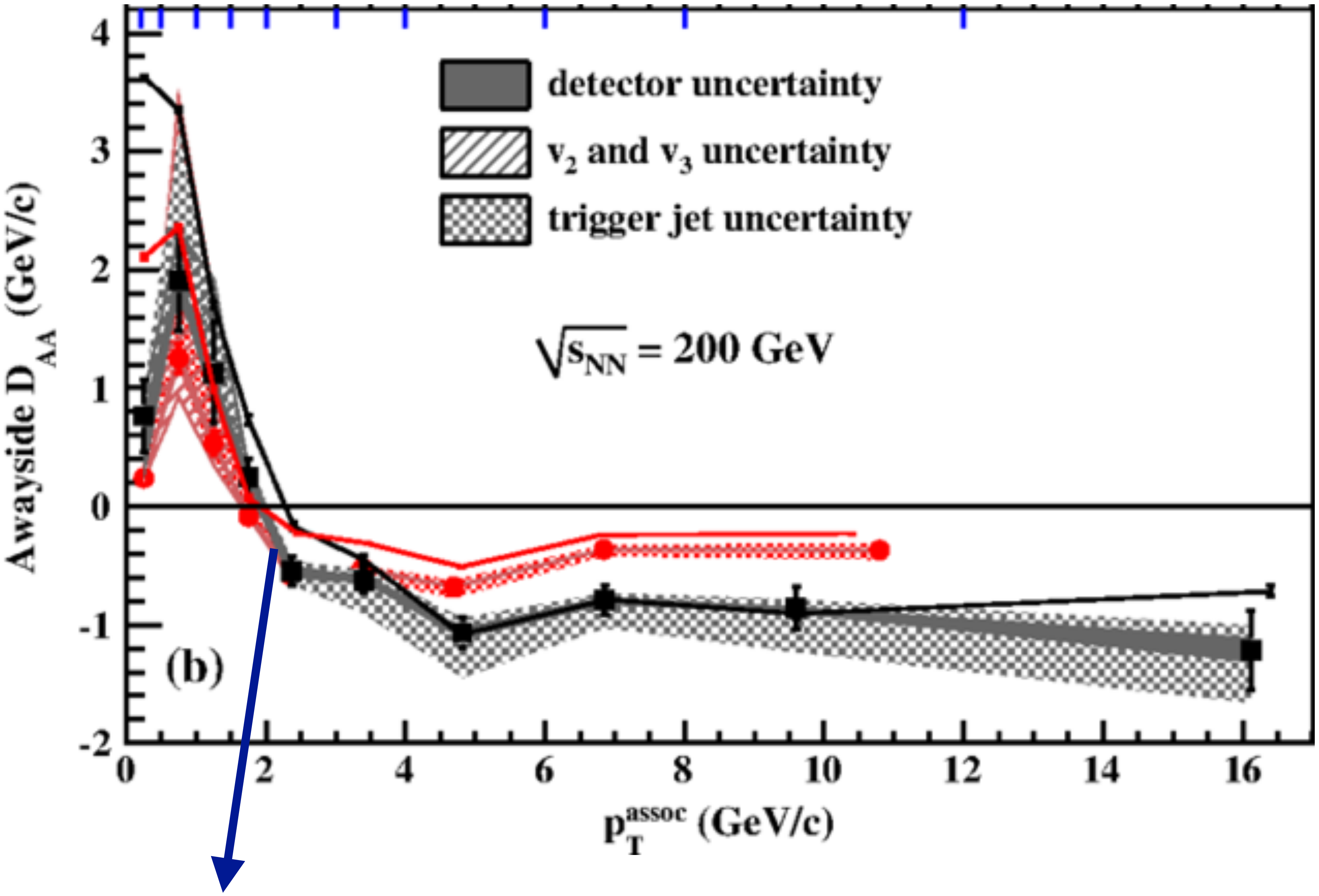
No strong dependence on reaction plane

E_{loss} fluctuations rather than path length differences

Nattrass et al.: PRC94. 011901 (2016)

How the energy reemerges

$$D_{AA}(p_T^{\text{assoc}}) \equiv Y_{\text{Au+Au}}(p_T^{\text{assoc}})\langle p_T^{\text{assoc}}\rangle_{\text{Au+Au}} - Y_{p+p}(p_T^{\text{assoc}})\langle p_T^{\text{assoc}}\rangle_{p+p}$$



Jet-hadron correlations:

Hard Core Jets:
High Tower trigger
E_T>5.4 GeV
+ p_{TCut} = 2 GeV/c

Trigger jet biased to surface

p_T^{assoc}~2 GeV/c

E_{loss} resurfaces as low p_T enhancement starting around 2 GeV/c

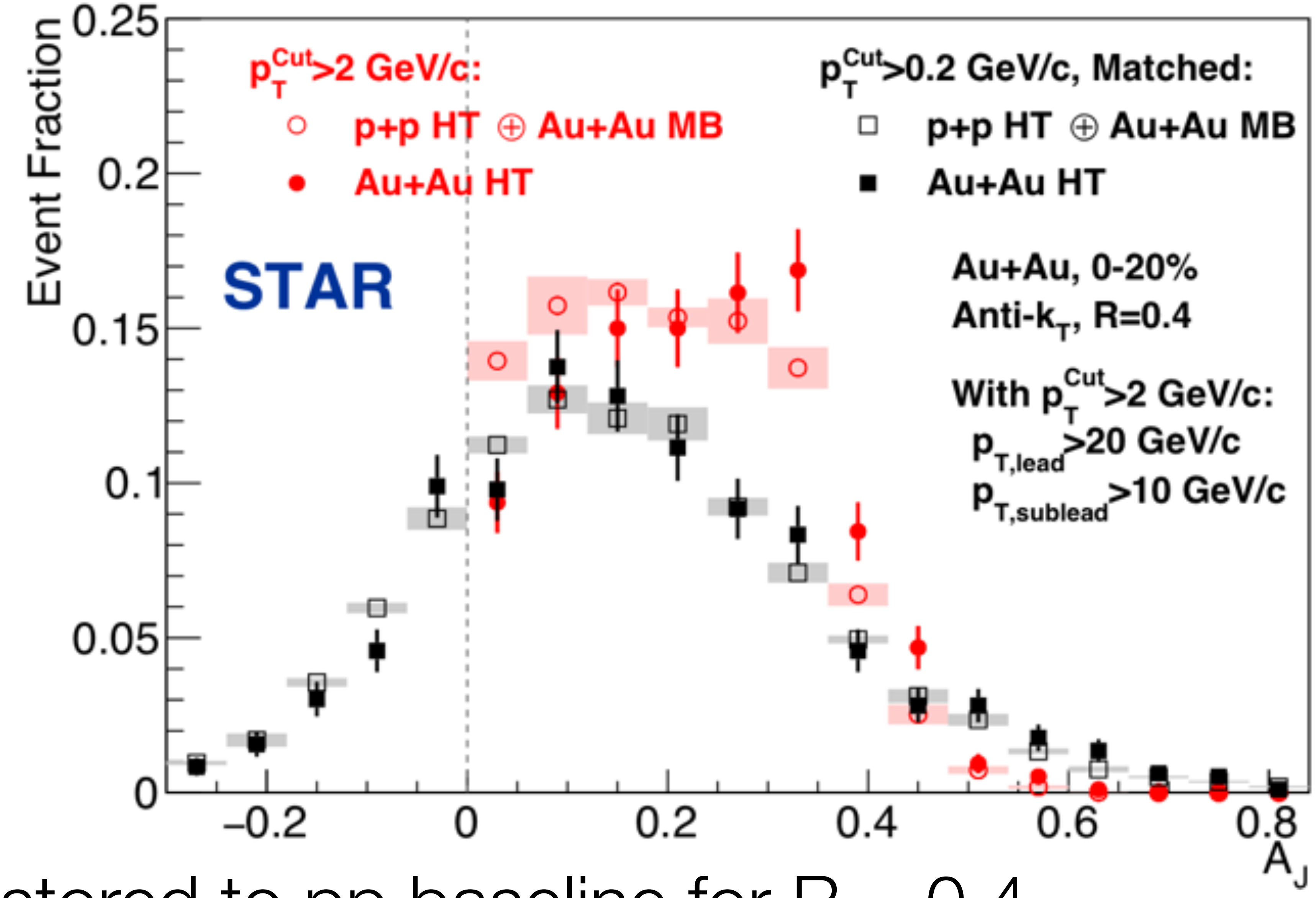
STAR: PRL 112 122301 (2014)

Dijets: restore balance with low p_T

Hard core matched dijets

$$A_J = \frac{p_T^{\mathrm{Lead}} - p_T^{\mathrm{SubLead}}}{p_T^{\mathrm{Lead}} + p_T^{\mathrm{SubLead}}}$$

credit: K. Jung

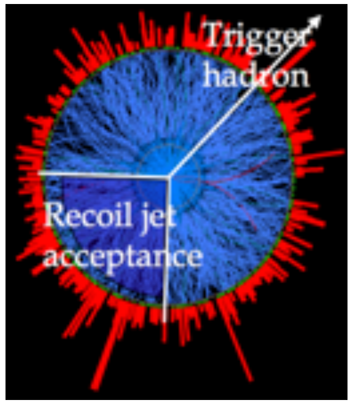


Momentum balance restored to pp baseline for R = 0.4,
after adding particles with < 2GeV/c

Balance not restored for R=0.2

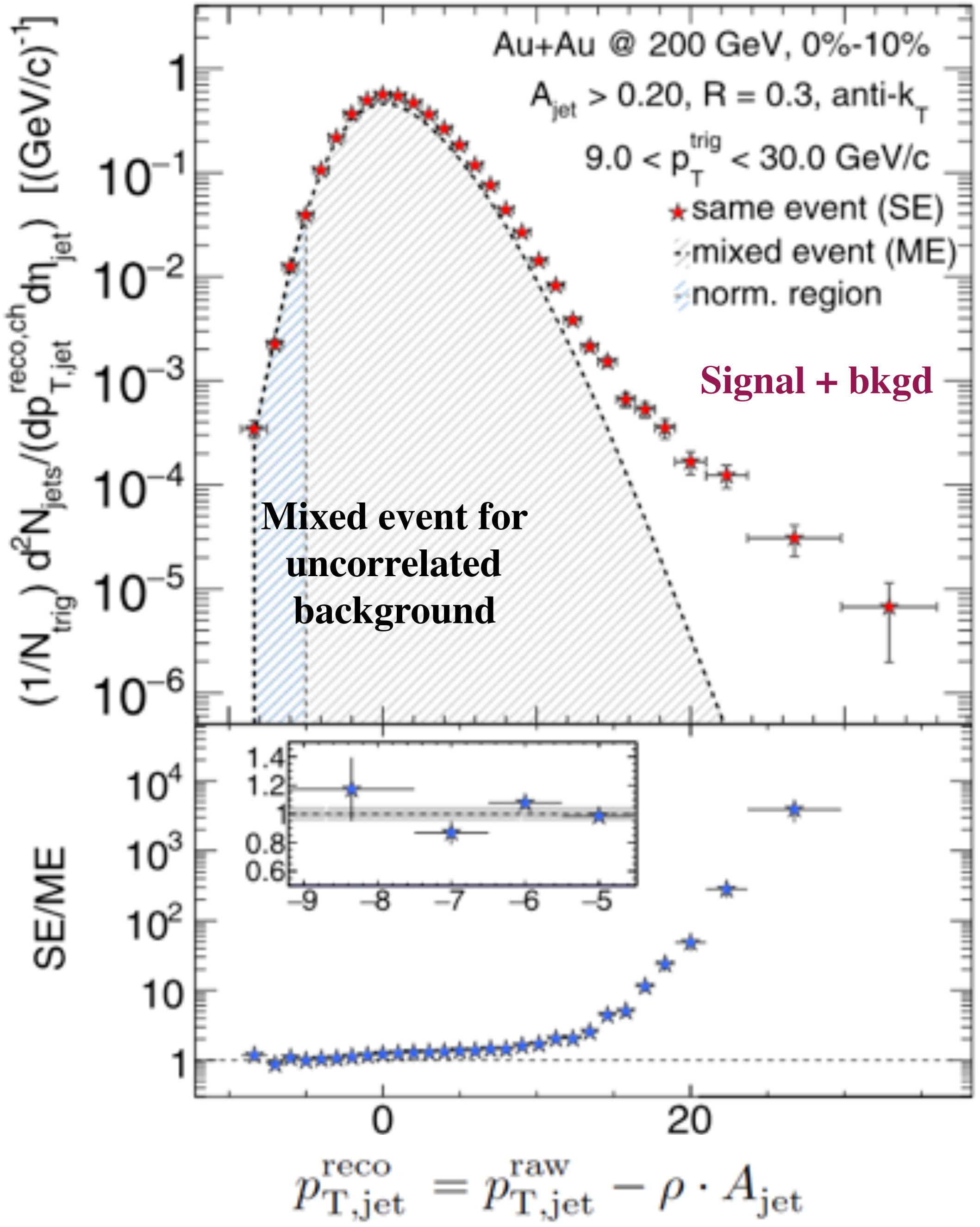
STAR: PRL119 062301 (2017)

Semi-inclusive jet measurements

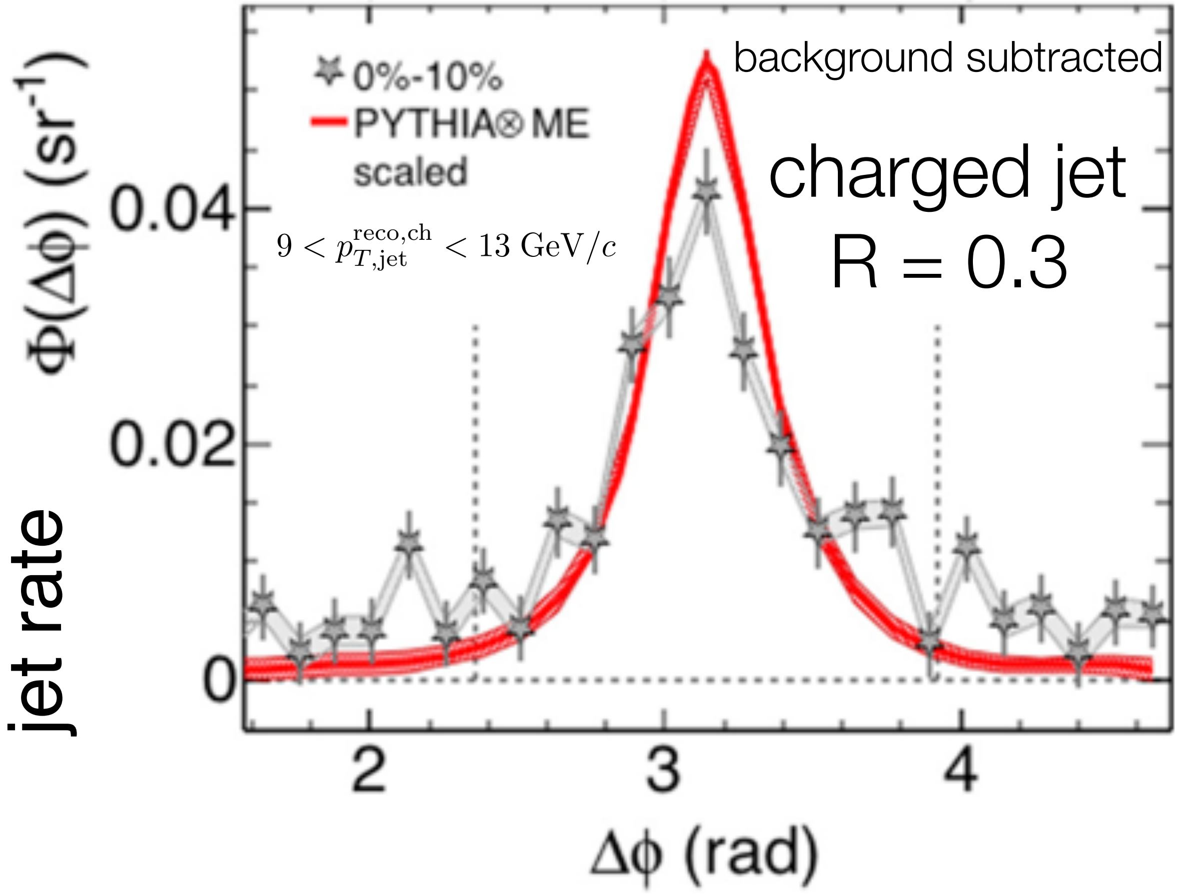


$$\frac{1}{N^h_{trig}}\frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{AA\to h+X}}\frac{d\sigma^{AA\to h+jet+X}}{dp_{T,jet}}$$

Measurable Calculable in pQCD (in vacuum)



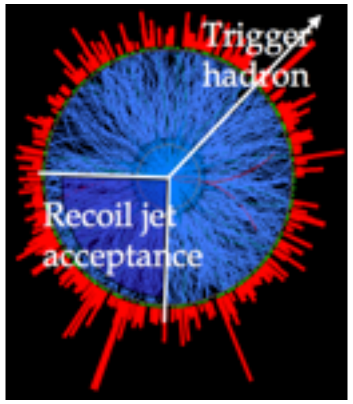
Access to low p_T jets



No significant evidence for large-angle scattering in central Au-Au

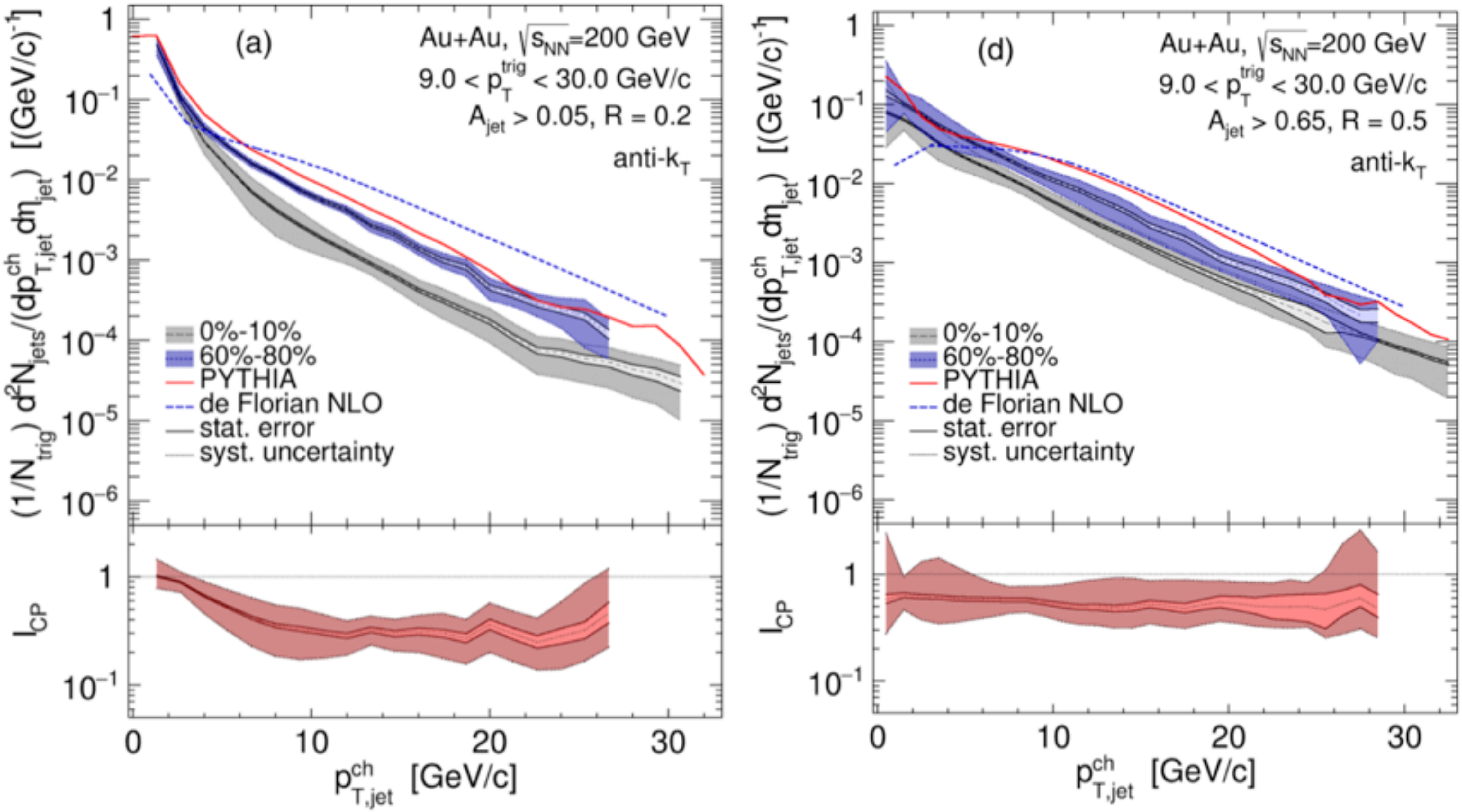
STAR: PRC96 024905 (2017)

Energy shift out of cone



R = 0.2

R = 0.5

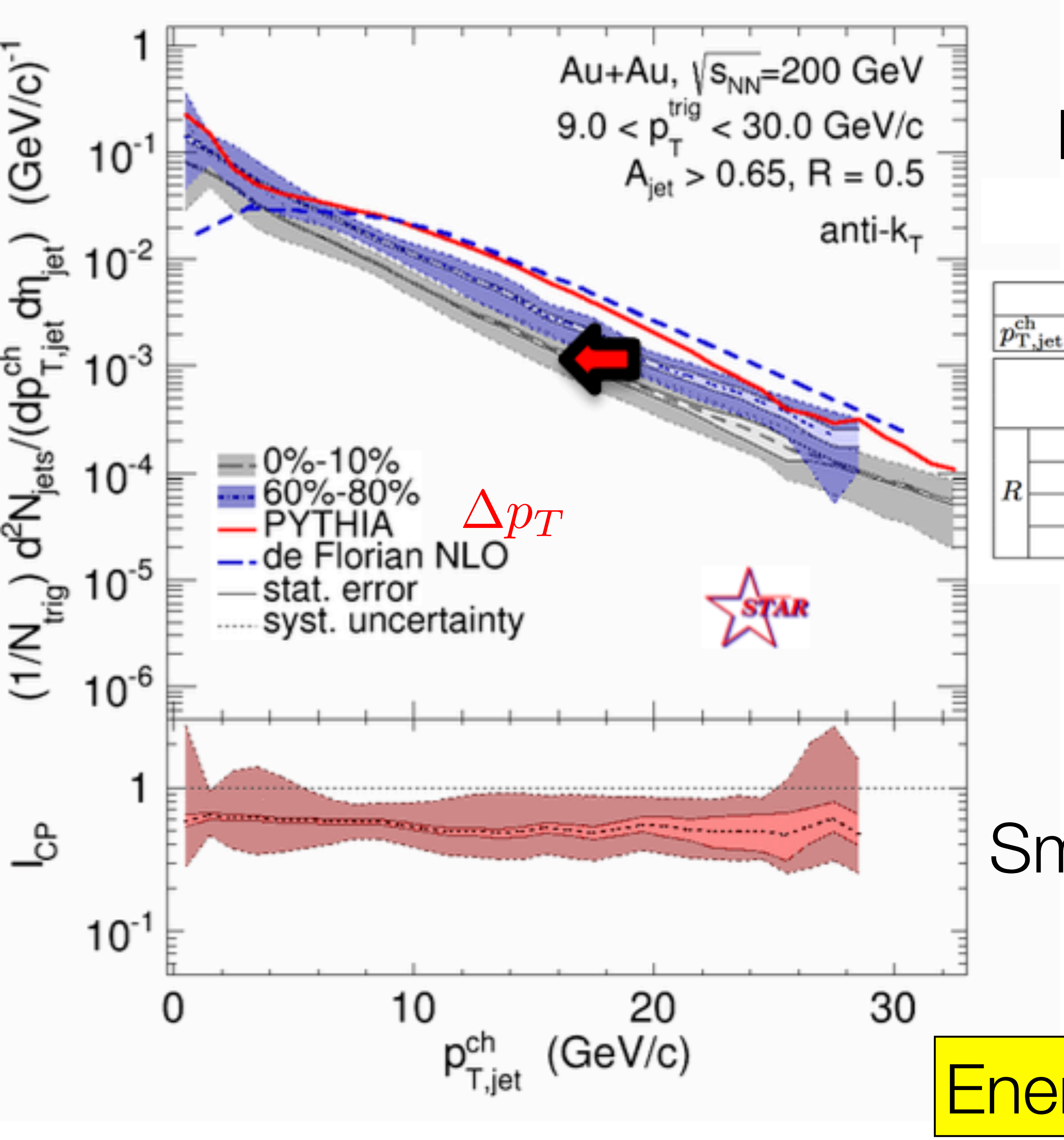


Recoil jet quenched in central 200 GeV Au-Au collisions

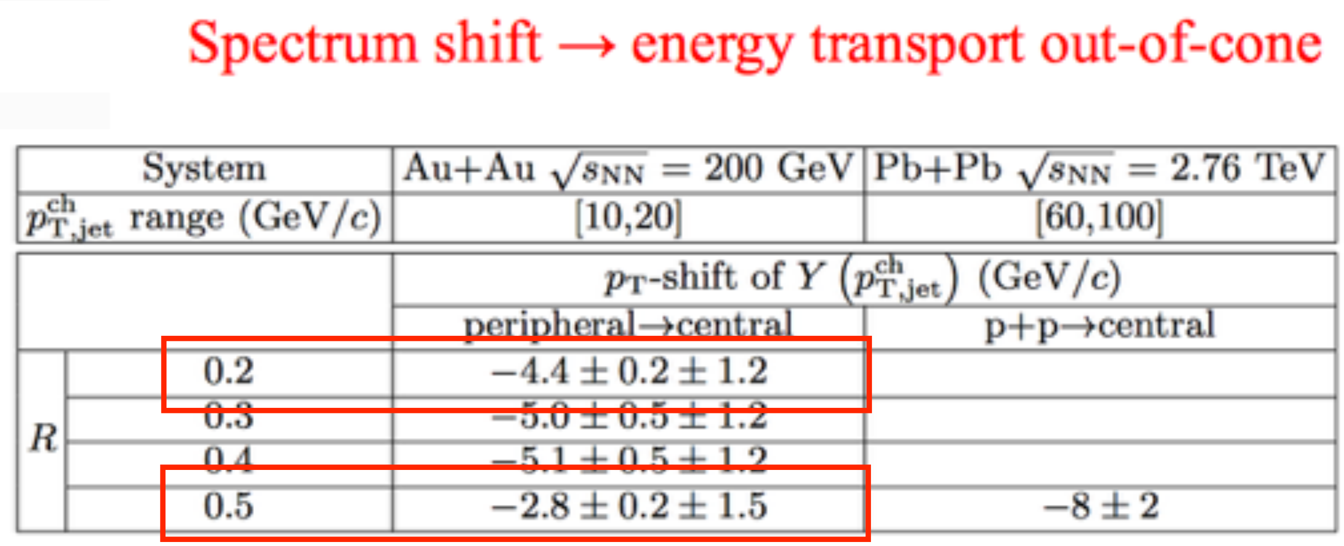
Smaller I_{cp} with R = 0.2

STAR: PRC96 024905 (2017)

Energy shift out of cone



Look at


Spectrum shift → energy transport out-of-cone

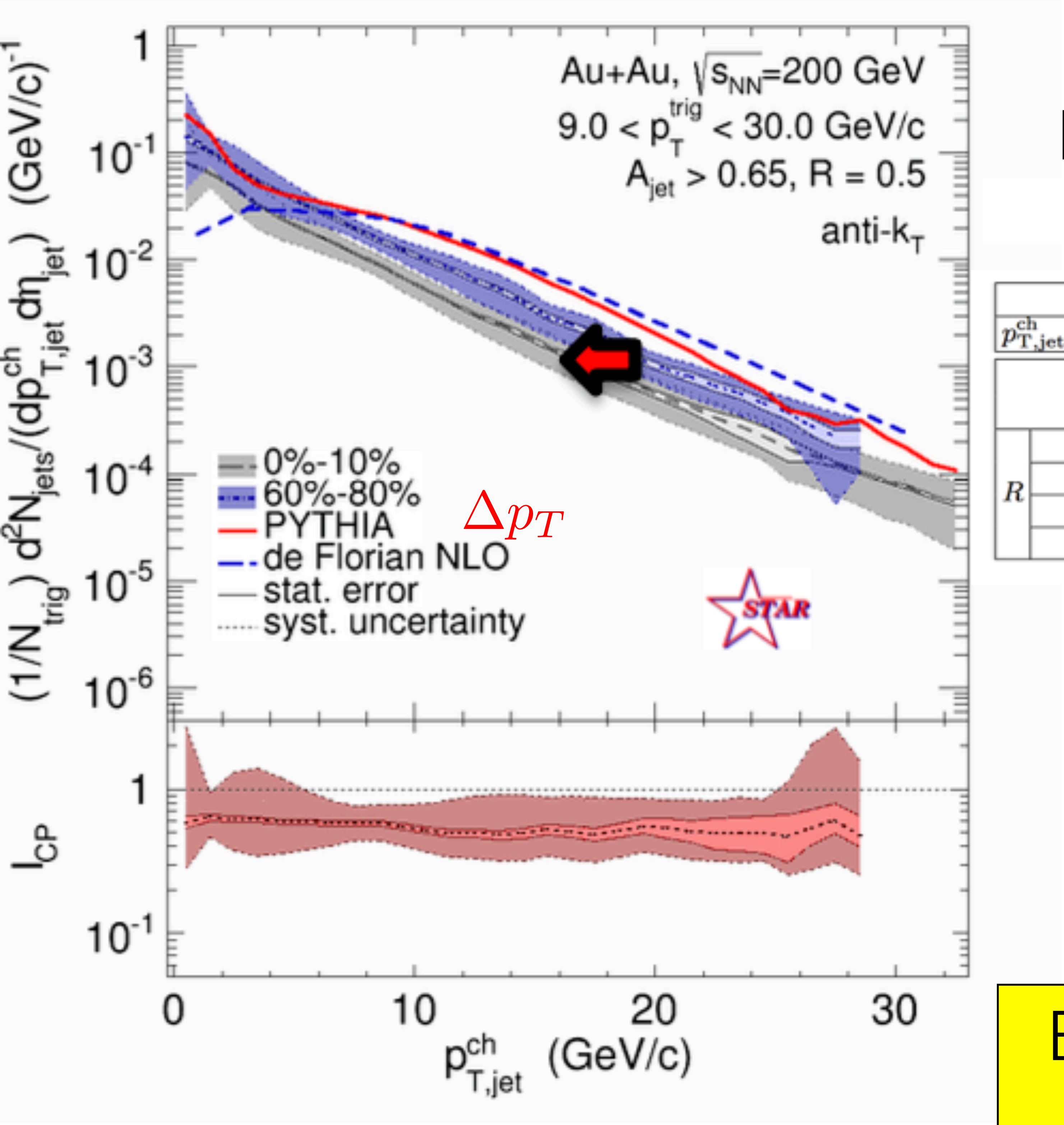
System		Au+Au $\sqrt{s_{NN}} = 200$ GeV	Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV
$p^{ch}_{T,jet}$ range (GeV/c)		[10,20]	[60,100]
		p_T-shift of $Y\left(p^{ch}_{T,jet}\right)$ (GeV/c)	
		peripheral→central	p+p→central
R	0.2	$-4.4 \pm 0.2 \pm 1.2$	
	0.3	$-5.0 \pm 0.5 \pm 1.2$	
	0.4	$-5.1 \pm 0.5 \pm 1.2$	
	0.5	$-2.8 \pm 0.2 \pm 1.5$	-8 ± 2

Smaller Δp_T for R = 0.5 than 0.2

Energy shift out of R = 0.2 -> 0.5

ALICE: JHEP 09 170 (2015)
STAR: PRC96 024905 (2017)

Energy shift out of cone



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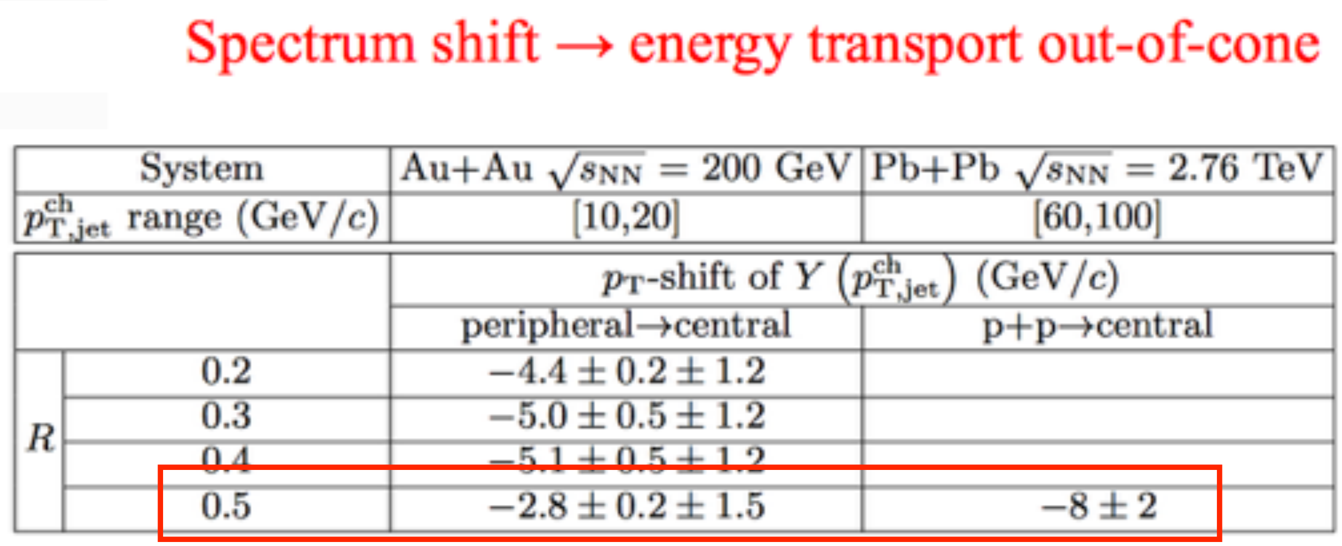
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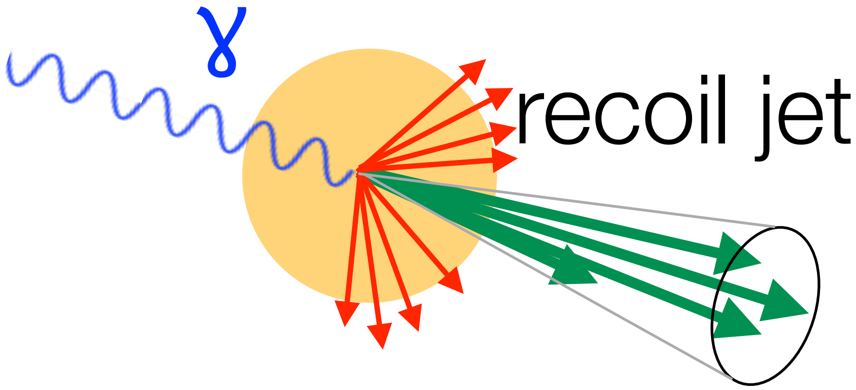
R=0.5:
Shift at RHIC < LHC

E_{loss} more focussed at RHIC than LHC

ALICE: JHEP 09 170 (2015)
STAR: PRC96 024905 (2017)

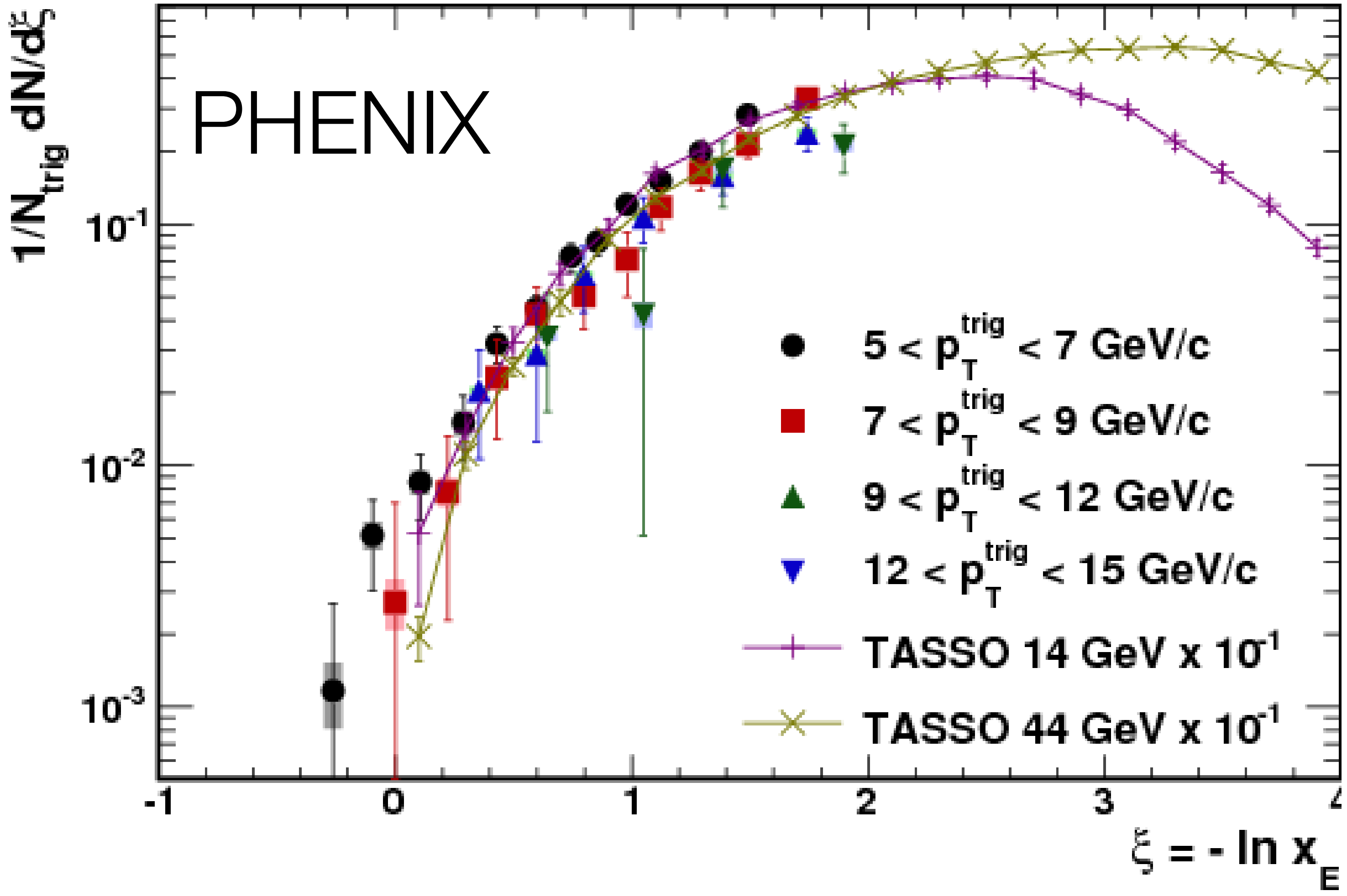
Photon triggered correlations



Recoiling parton highly biased towards being a quark

Avoids surface bias

$$x_E = - \mid \frac{p_T^a}{p_T^\gamma} \mid cos(\Delta\phi) \approx z$$

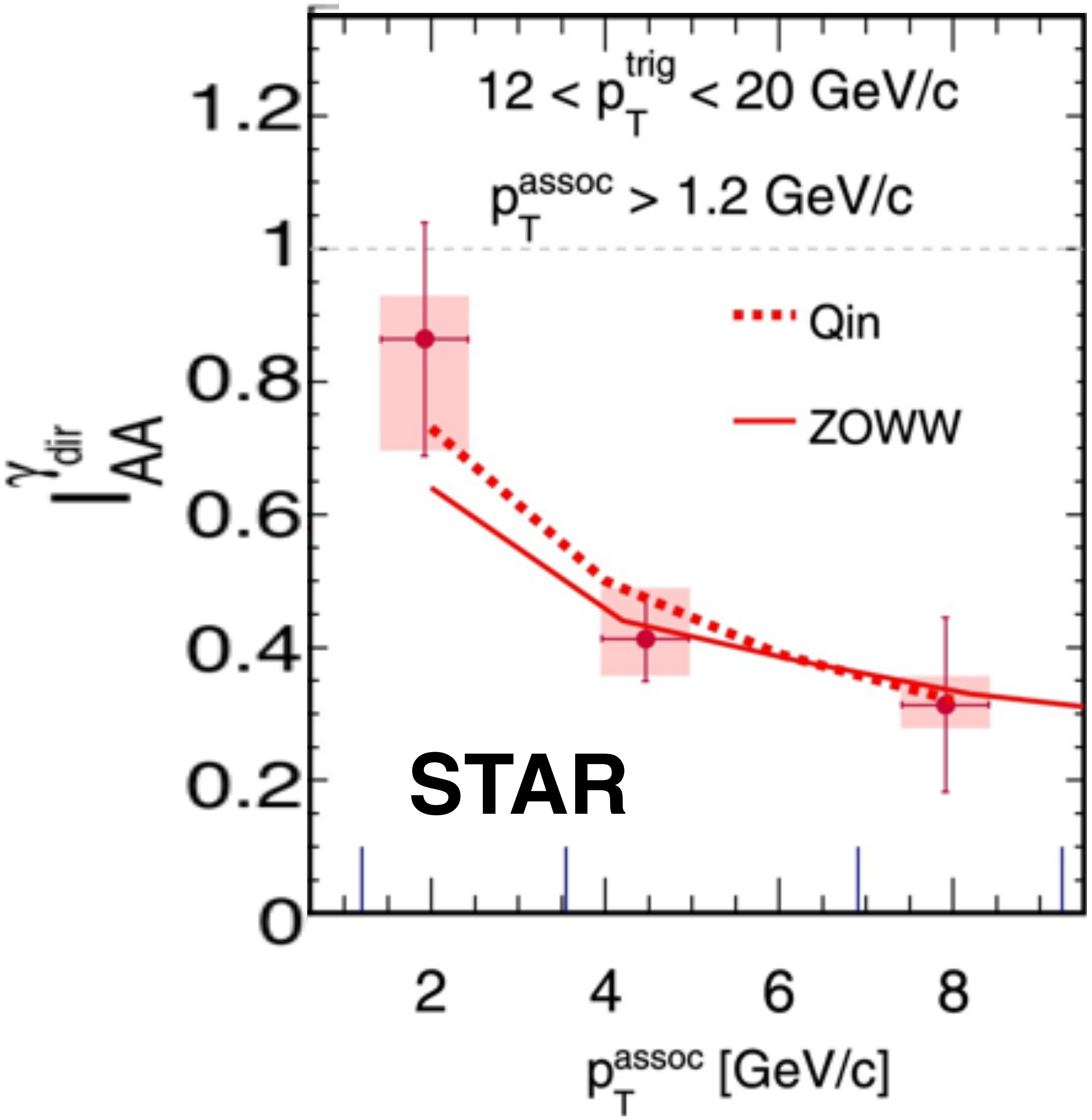


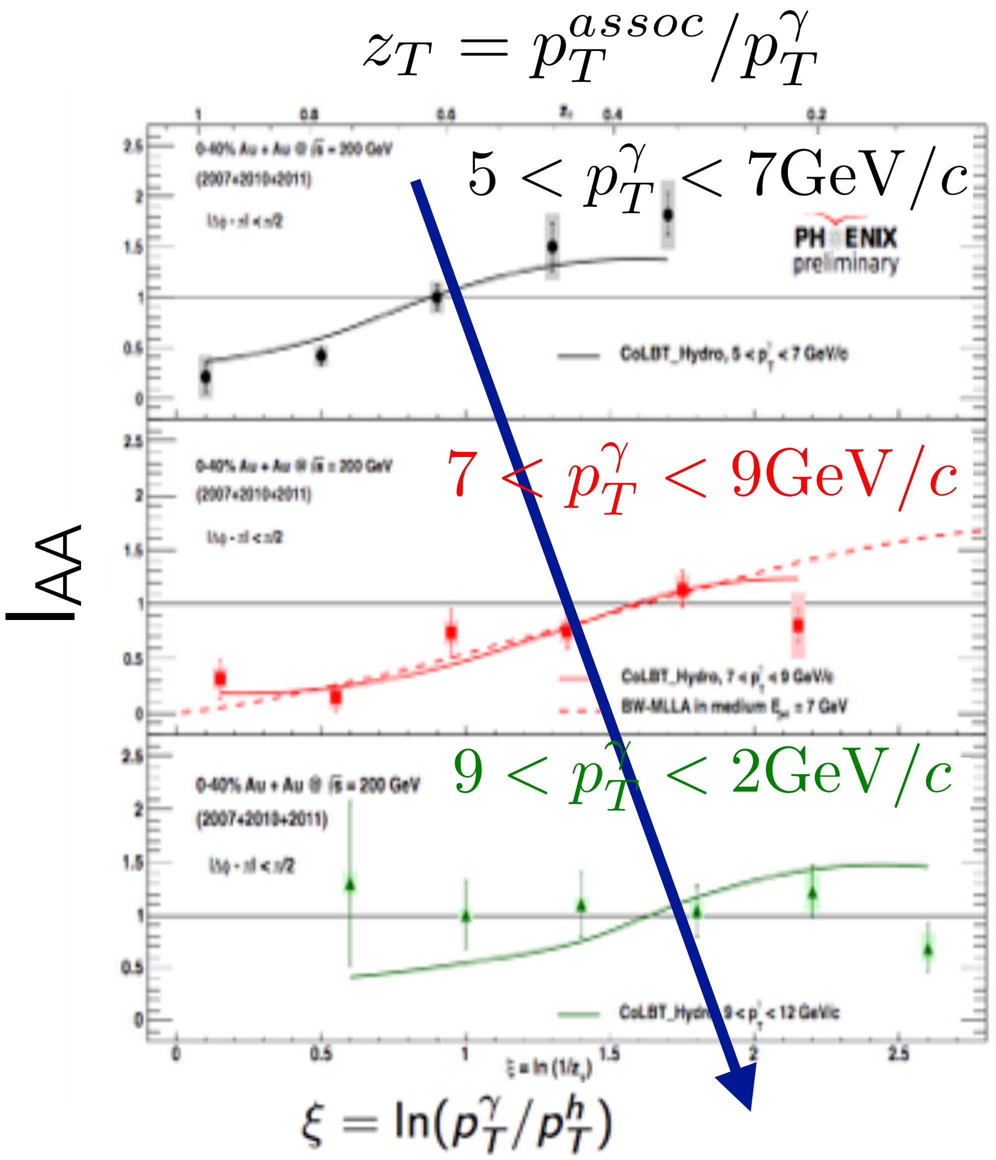
Good agreement between RHIC and TASSO measurements of q fragmentation

Fragmentation same in pp and e^+e^-

direct photons can be used to calibrate initial parton E

How energy reemerges





$z_T = p_T^{assoc}/p_T^{\gamma}$

$5 < p_T^{\gamma} < 7\mathrm{GeV}/c$

$7 < p_T^{\gamma} < 9\mathrm{GeV}/c$

$9 < p_T^{\gamma} < 2\mathrm{GeV}/c$

p_T^{assoc}~2 GeV/c

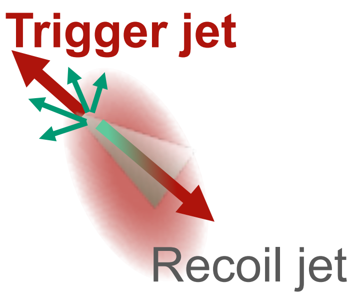
Suppression at high p_T again turns into enhancement at low p_T

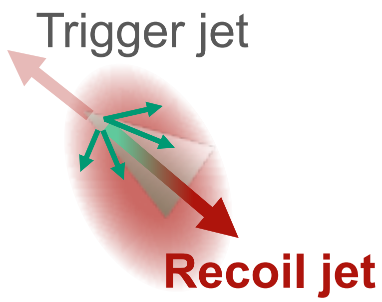
Absolute p_T not p_T fraction (z_T) relevant

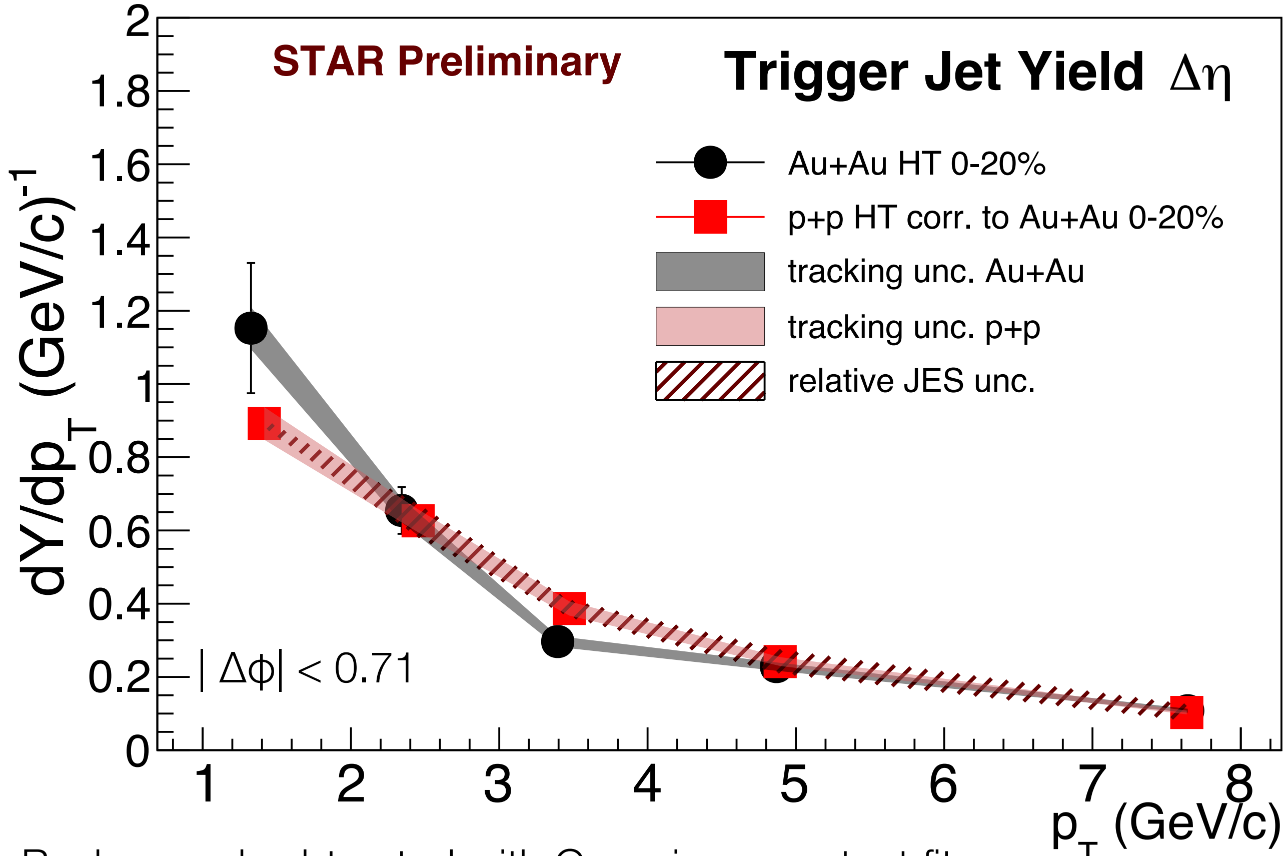
PHENIX: QM17
STAR: PLB760 689 (2016)

Dijet-hadron correlations

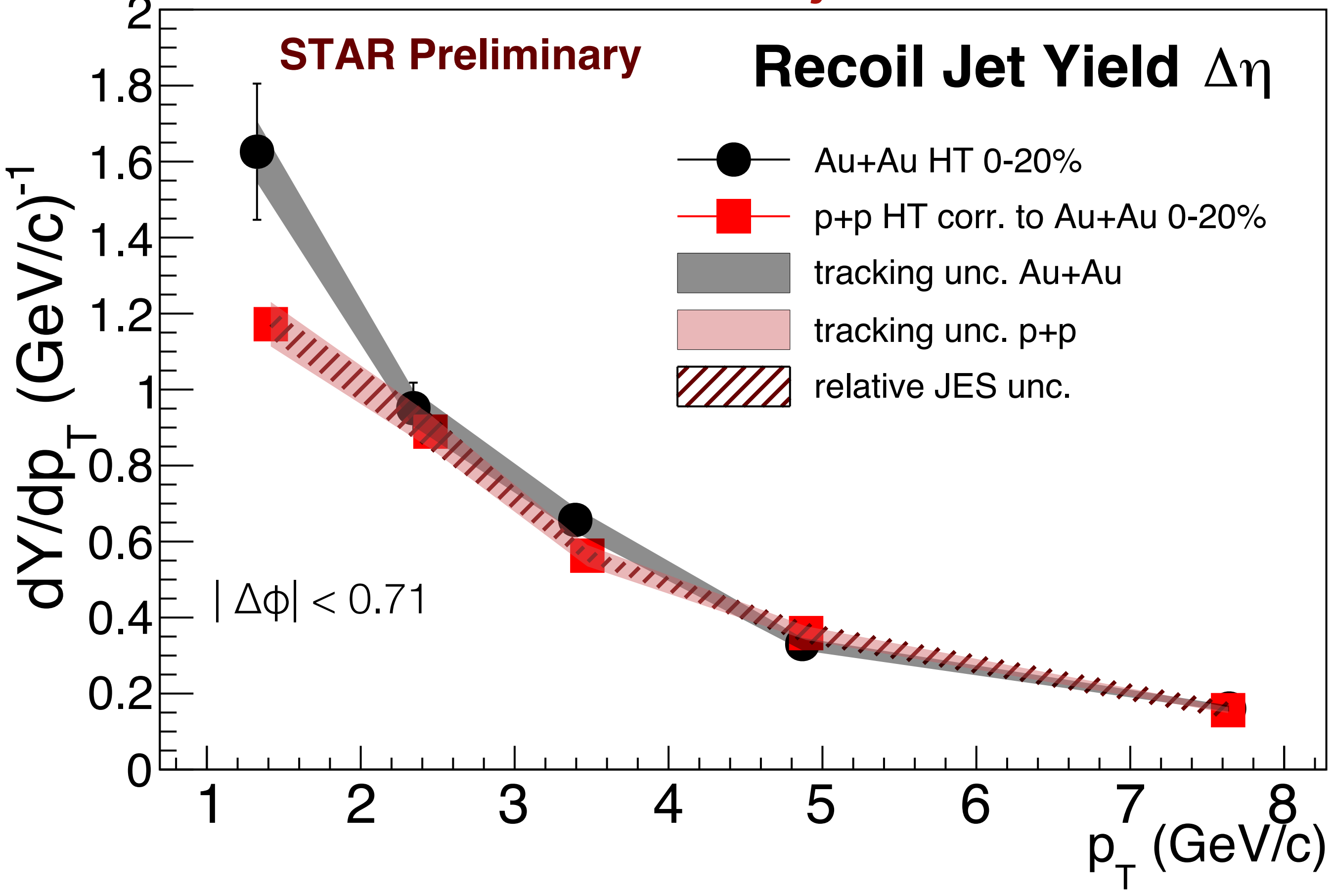
Hard core matched dijets but look at hadron correlation







Background subtracted with Gaussian+constant fit



No significant difference for jet constituent multiplicity hint for recoil p_T<2 GeV/c

But jet energy changed : A_J different

→ Extend p_T coverage, study A_J dependence

STAR: QM17

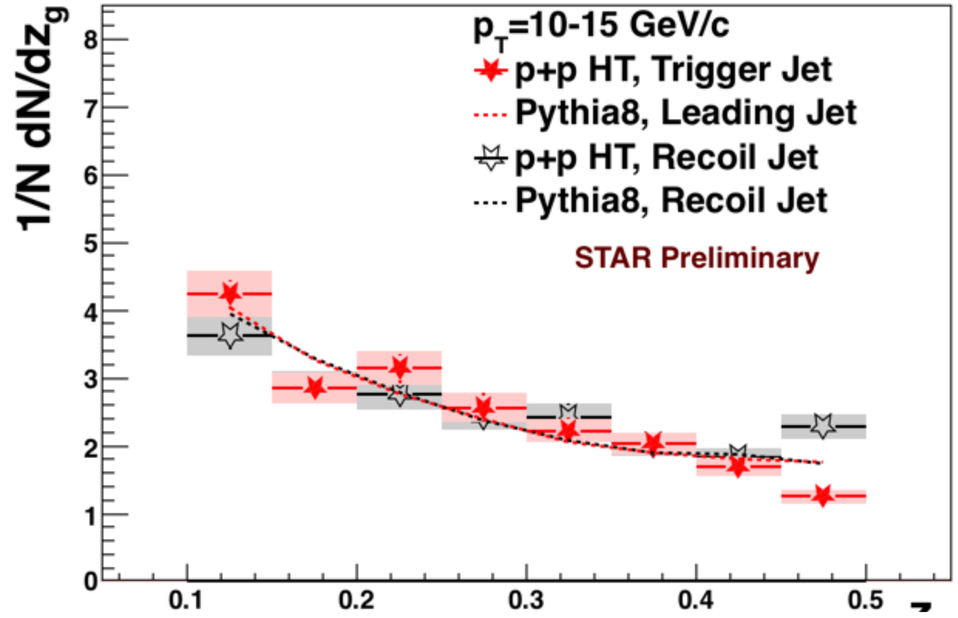
Dijet substructure z_g

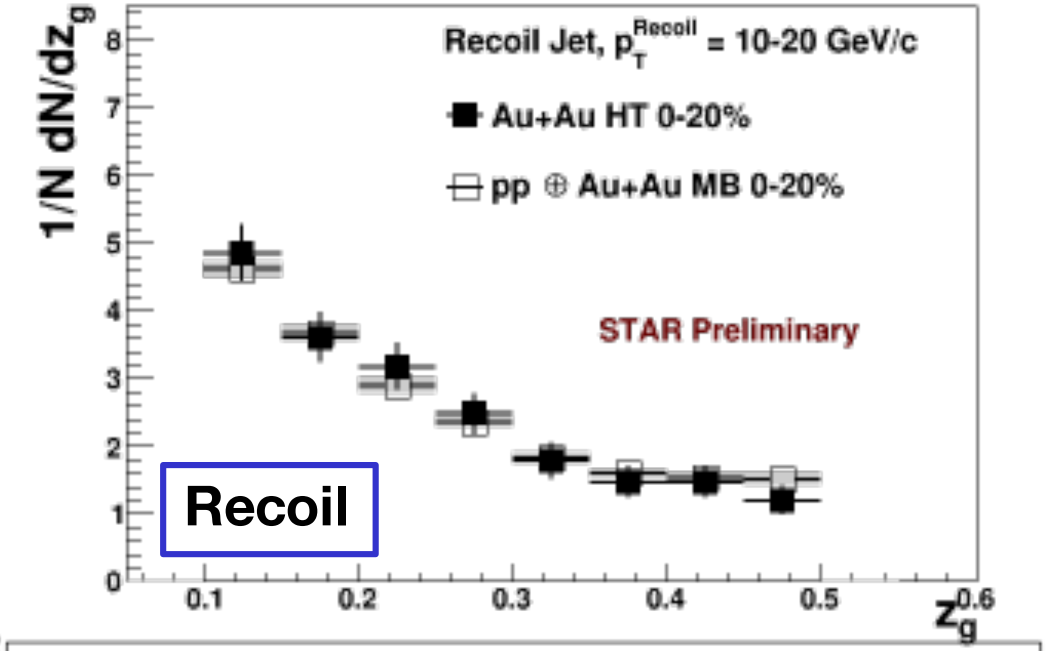
z_g in hard core matched diets

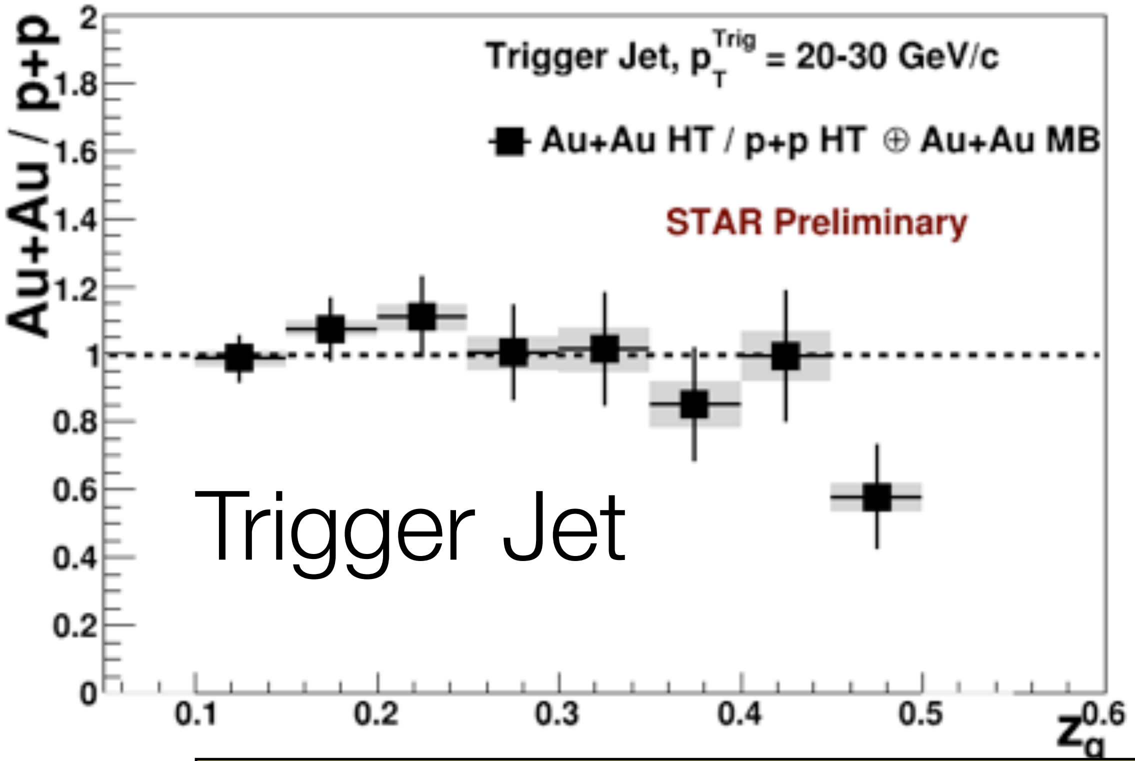
$$z_g = \frac{\boxed{\min}(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\mathrm{cut}}\, \theta^{\beta}$$

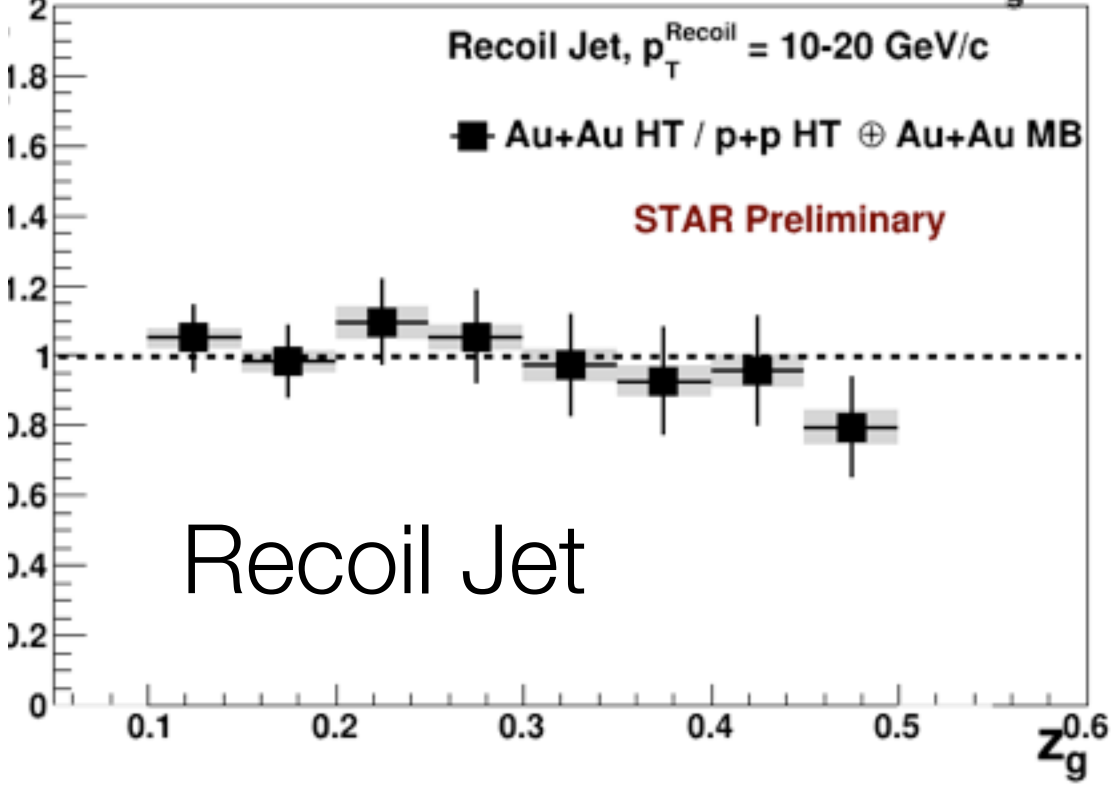
energy threshold

angular exponent





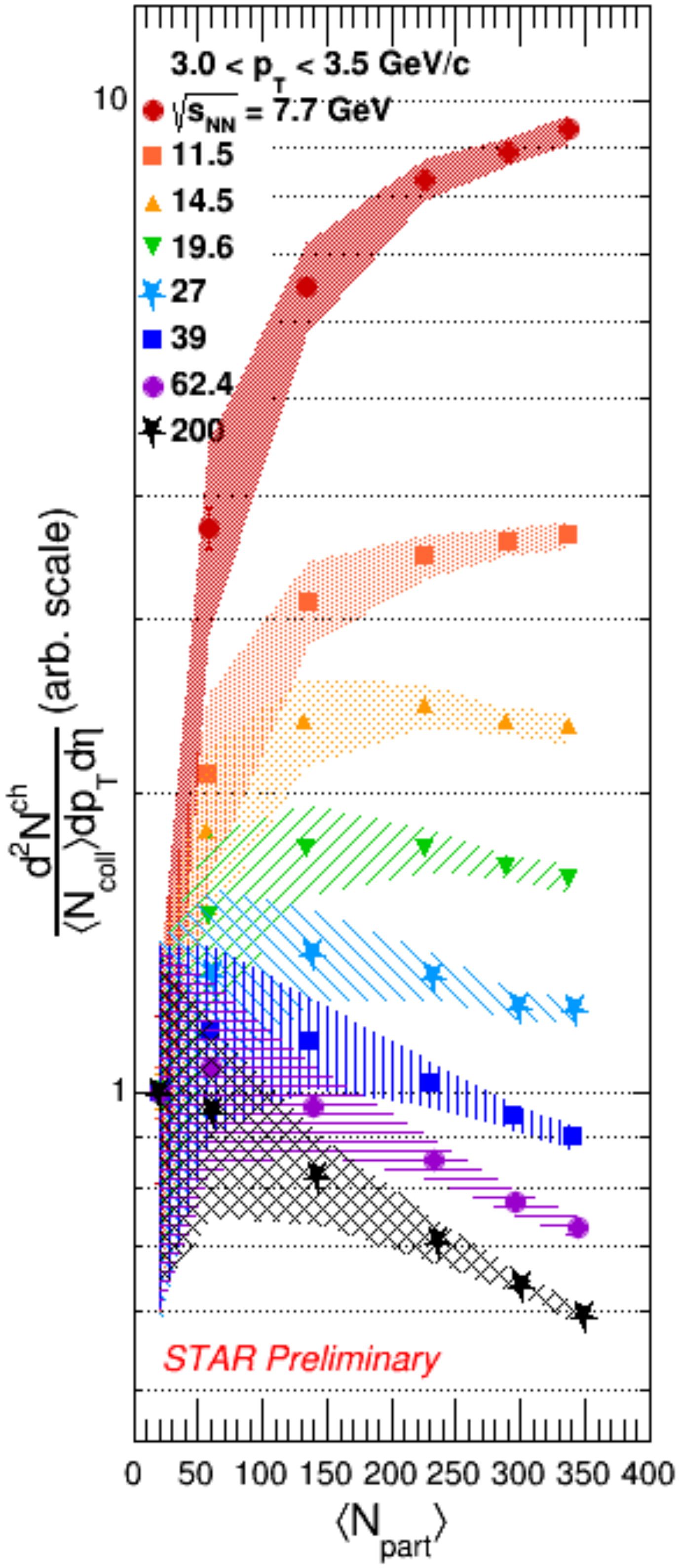


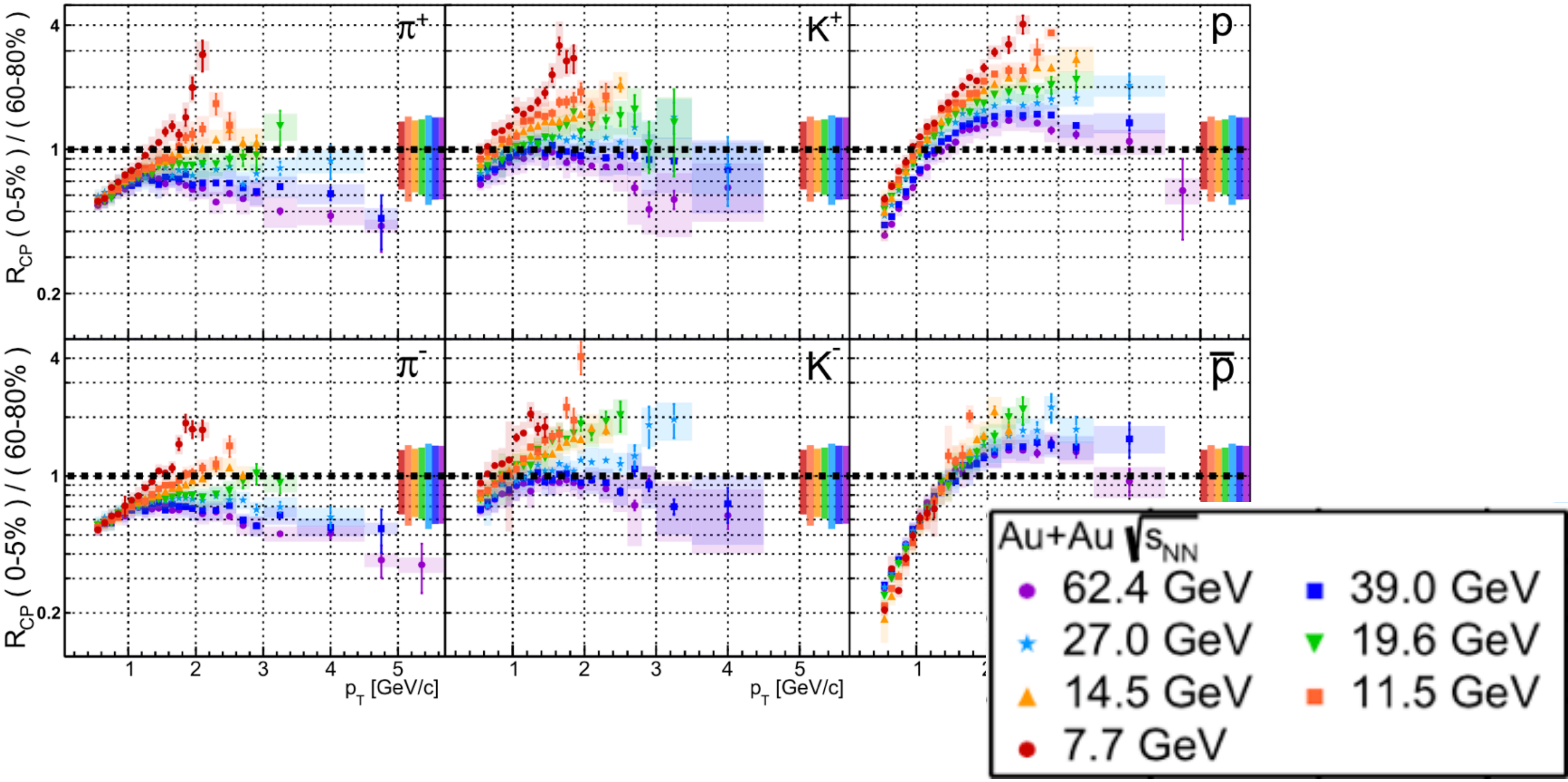


No significant splitting modification on near- or away-side

STAR: QM17

Single hadron high p_T suppression @ BES





Meson and Baryon: different R_{cp} trends

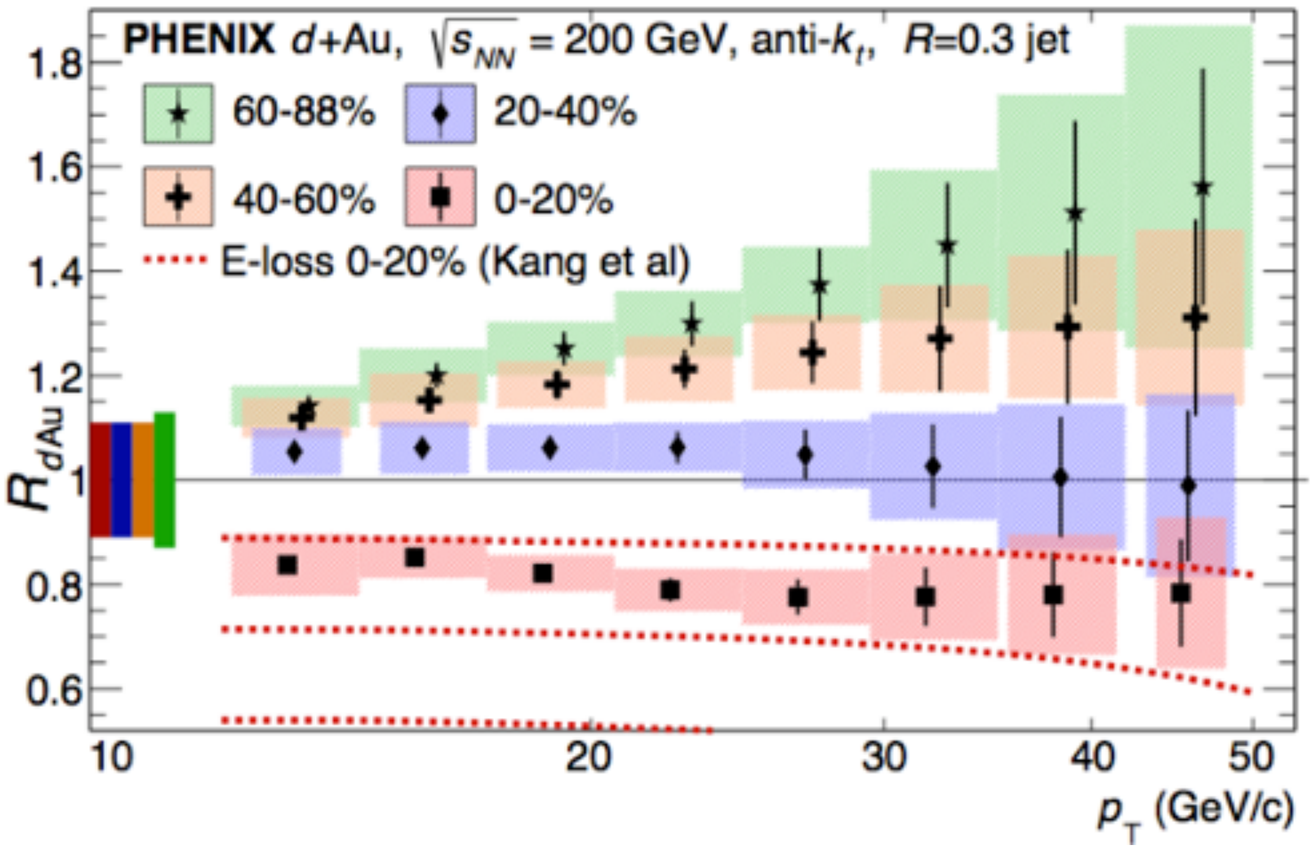
At high p_T: pion suppressed for $\sqrt{s_{NN}}$ > 27 GeV

proton enhanced at all BES energies

Most central high p_T yield suppressed compared to mid-central at $\sqrt{s_{NN}} > 14.5$ GeV

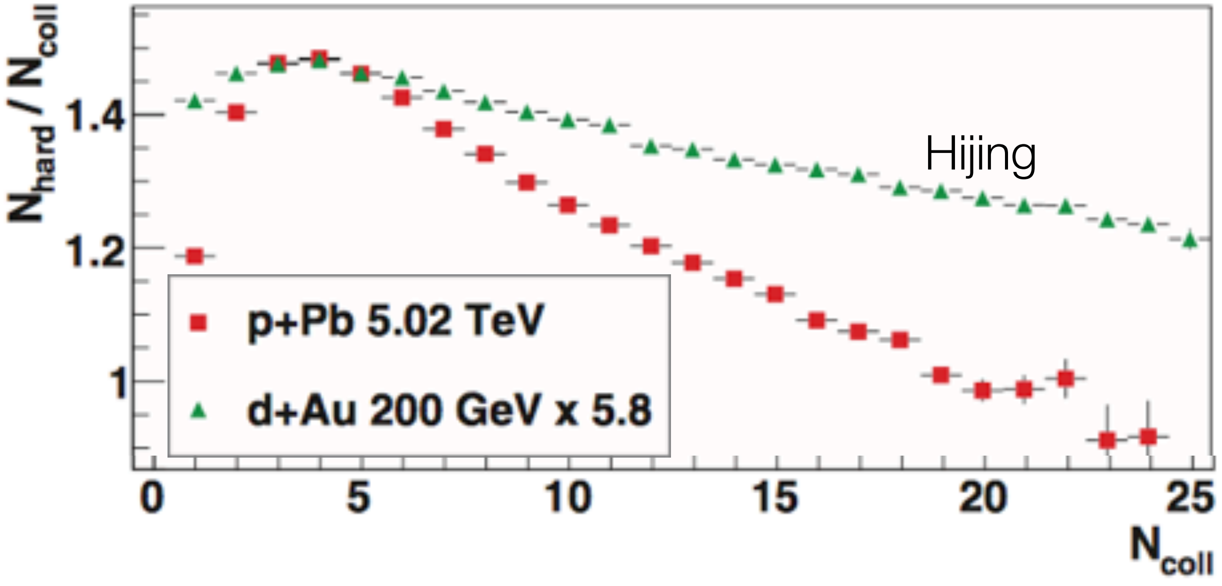
STAR: arXiv:1707.01988

Quenching in p/d-Au



Strong deviation from unity for centrality selected events when compared to expectations assuming geometric scalings

Unlikely to be from "centrality" definition bias as determined from pp



Model estimates smaller bias in d+Au@200 GeV than p+Pb@5.02 TeV

coincidental(?) cancelation of central suppression and peripheral enhancement

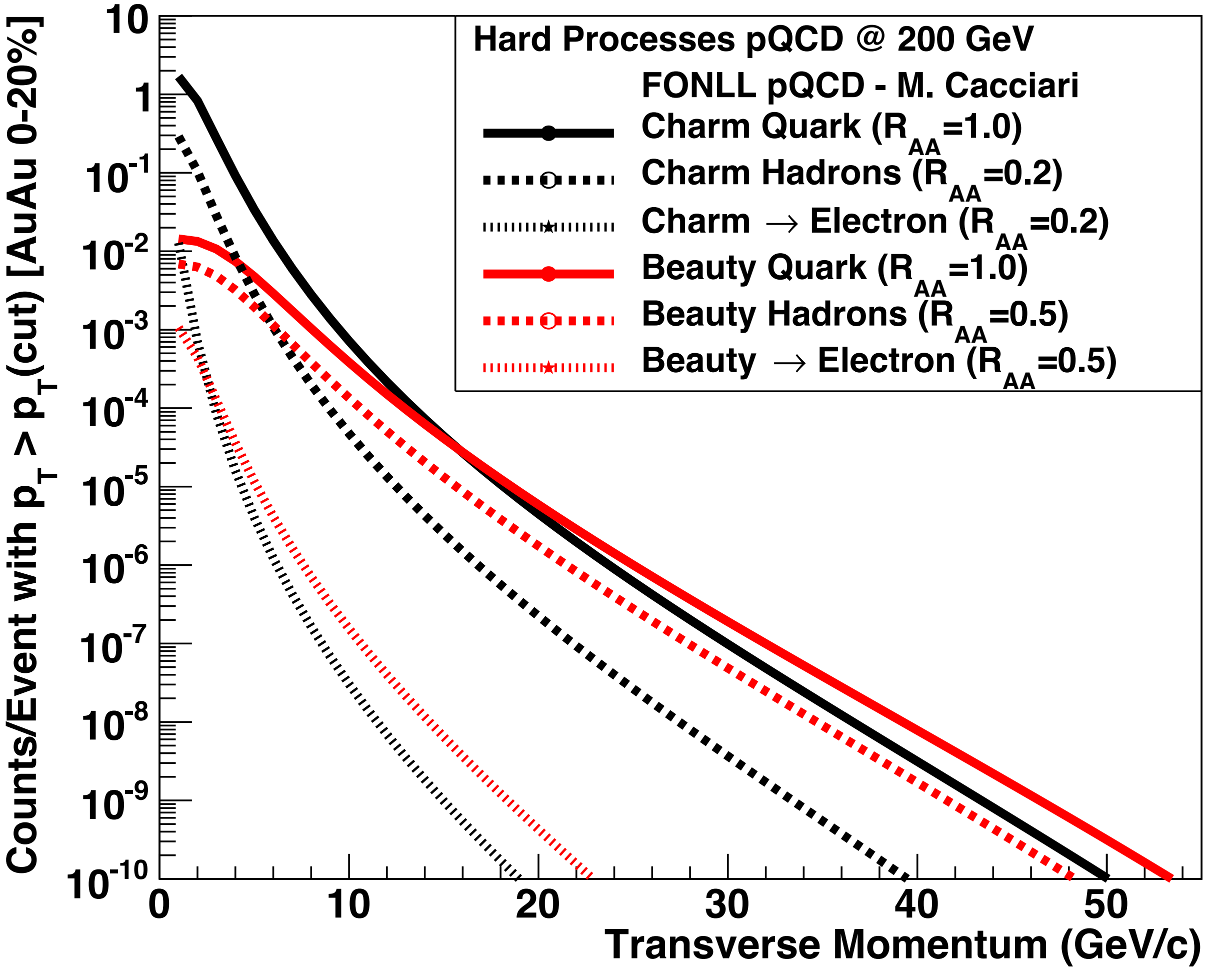
PHENIX: PRC **90**, 034902
PHENIX: PRL 116, 122301 (2016)

More results to come

High statistics Au-Au and asymmetric systems data already on tape

High statistics data from Run18

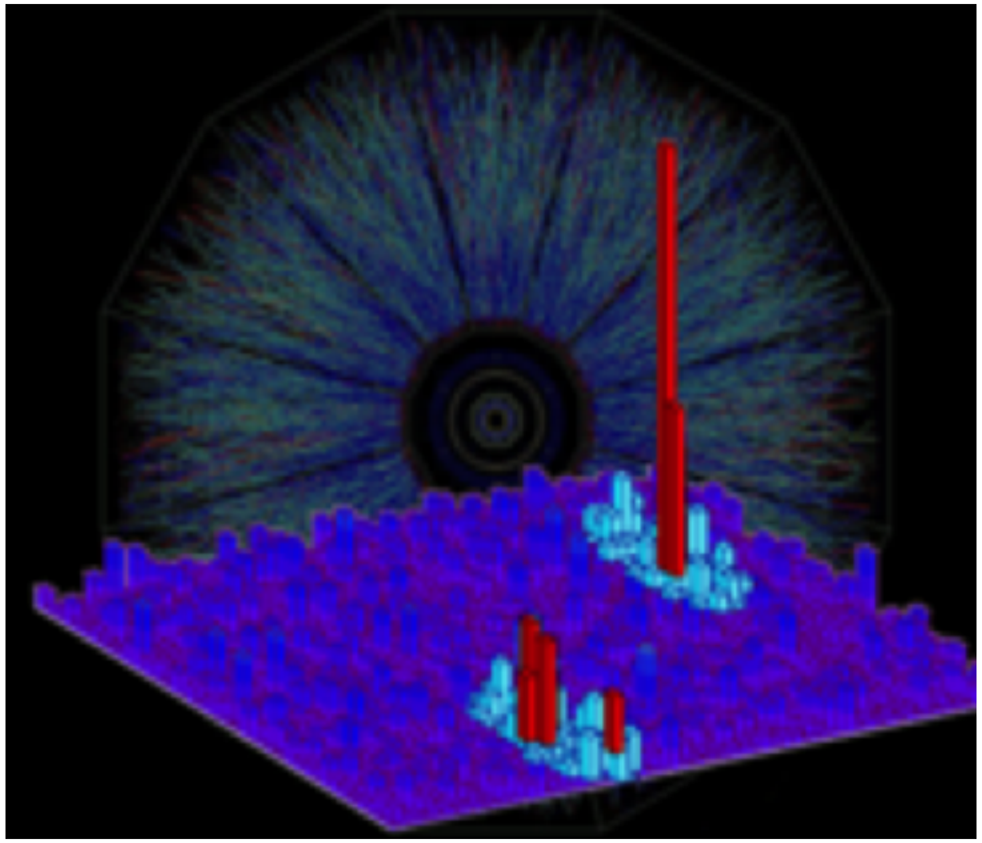
sPHENIX - CD1 expected in 2018



Forward upgrades could be in place by Run21

Access to: photon-jet
HF tagged jet
A_J selected jets
event-engineered studies
unbiased high p_T jets
large rapidity range….

Summary



Significantly enhanced understanding of jet modifications at RHIC

- pp in very good agreement with theory
- Unbiased recoil jets highly suppressed due to medium induced broadening
- Total E_{loss} less than at LHC
- Lost energy re-emerges at low p_T **not** z_T
- Di-jet energy imbalance largely recovered within R=0.4 when low p_T hadrons included
- z_g unmodified for hard core jets
- High p_T hadron suppression at BES
- Unexpected centrality dependence of jet R_{dAu}

BACK UP

Experimental aspects / differences

- jet reconstruction:
    - EM + hadron calorimeter based (ATLAS)
    - charged track + EMCal based (STAR + ALICE)
    - particle flow (CMS)

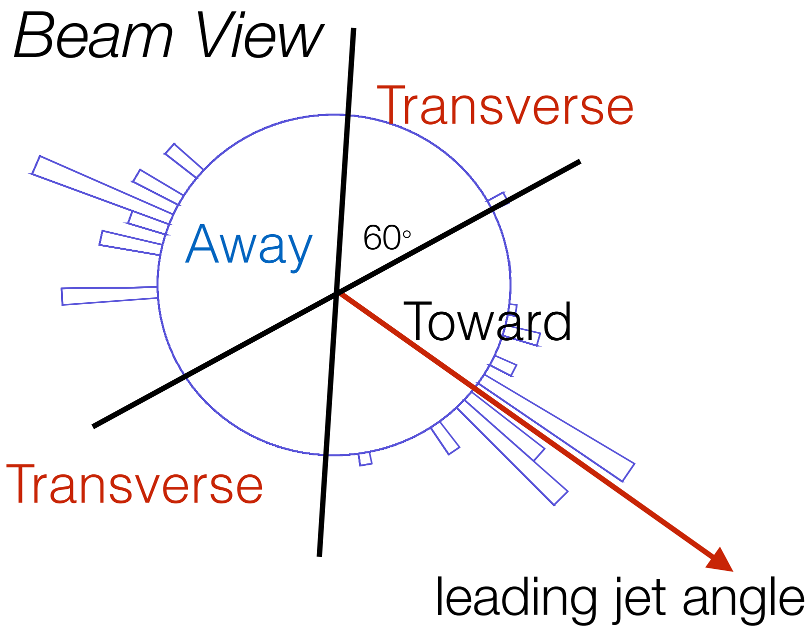
- fake jet rejection:
    - constituent p_T cuts
    - leading constituent bias / track jet matching
    - di-jet (hadron-jet) coincidence
    - subtraction
    - ….
    - consistently applied to the reference, but may introduce physics bias

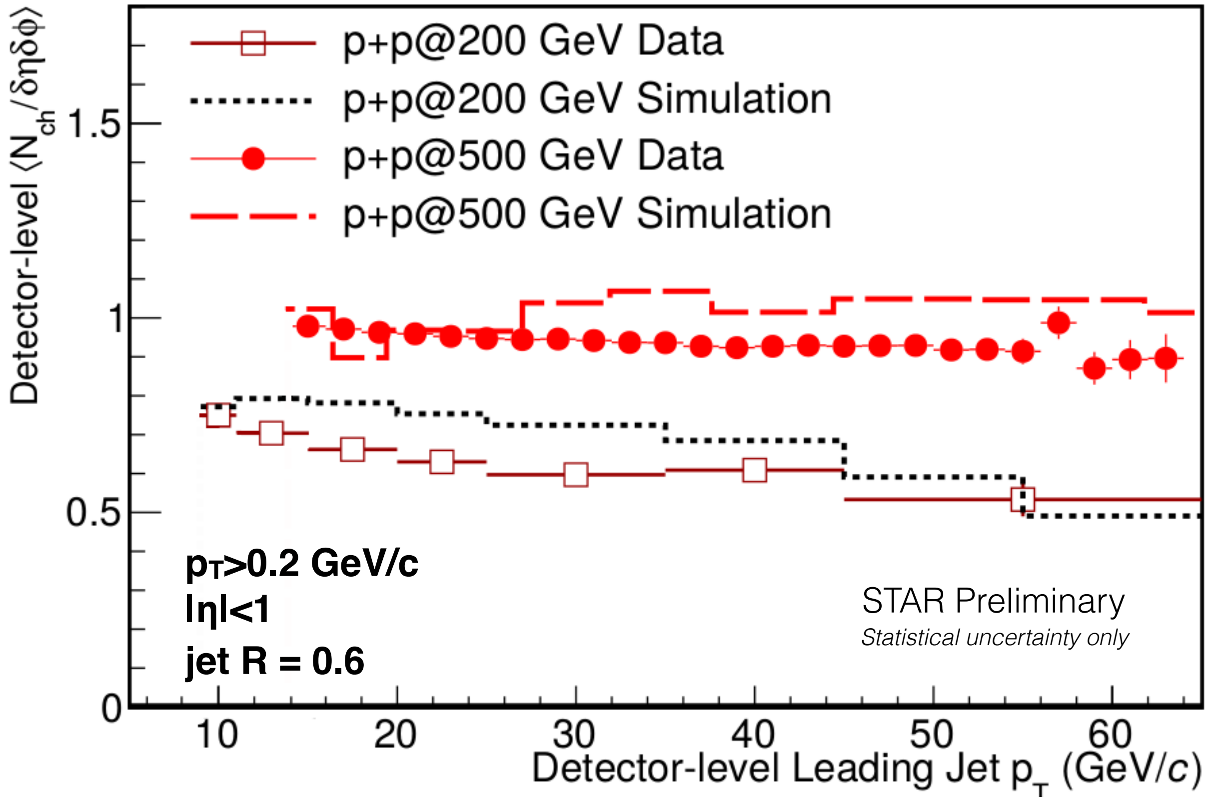
- background subtraction:
    - median density from clusters (ALICE, STAR)
    - iterative geometrical (ATLAS, CMS)

- corrections: for detector effects (efficiency, resolution) and background fluctuations (resolution-like)
    - typical: full corrections to particle level
    - sometimes: detector and/or background effects applied to a reference

O. Busch, INT 2017

Background Activity in pp

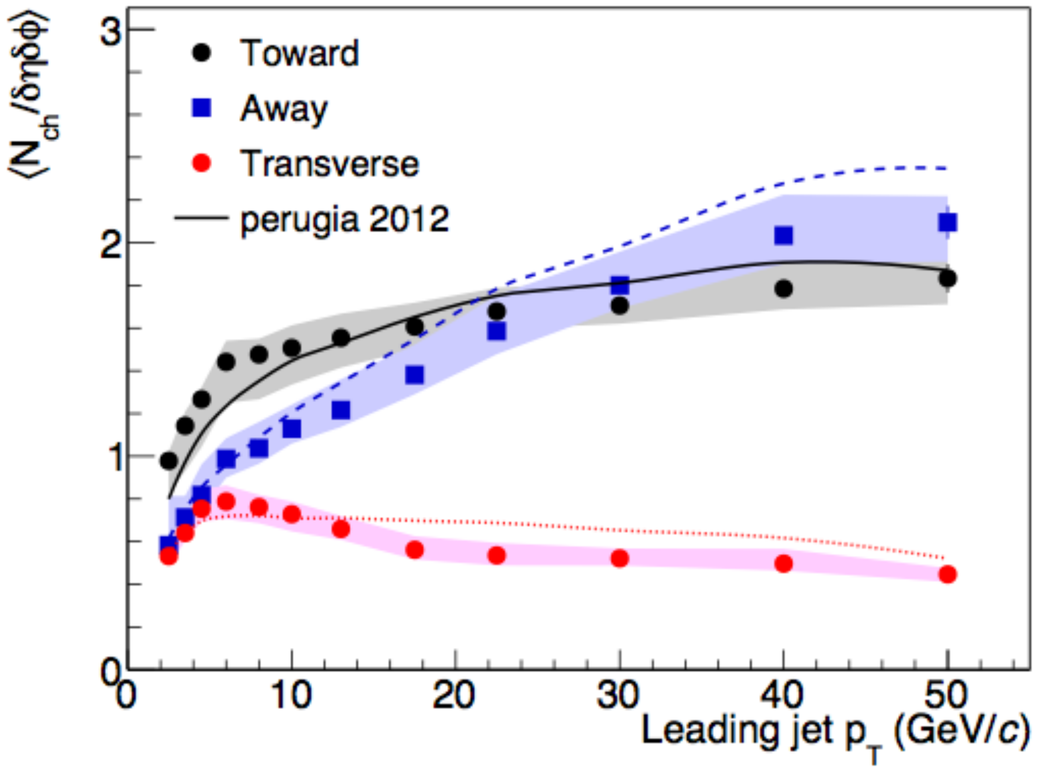




PYTHIA tunes into GEANT:

200GeV	perugia 2012 CTEQ6L1 PDF PARP(90)=0.213
500GeV	perugia 0

Underlying event only weakly dependent on jet energy

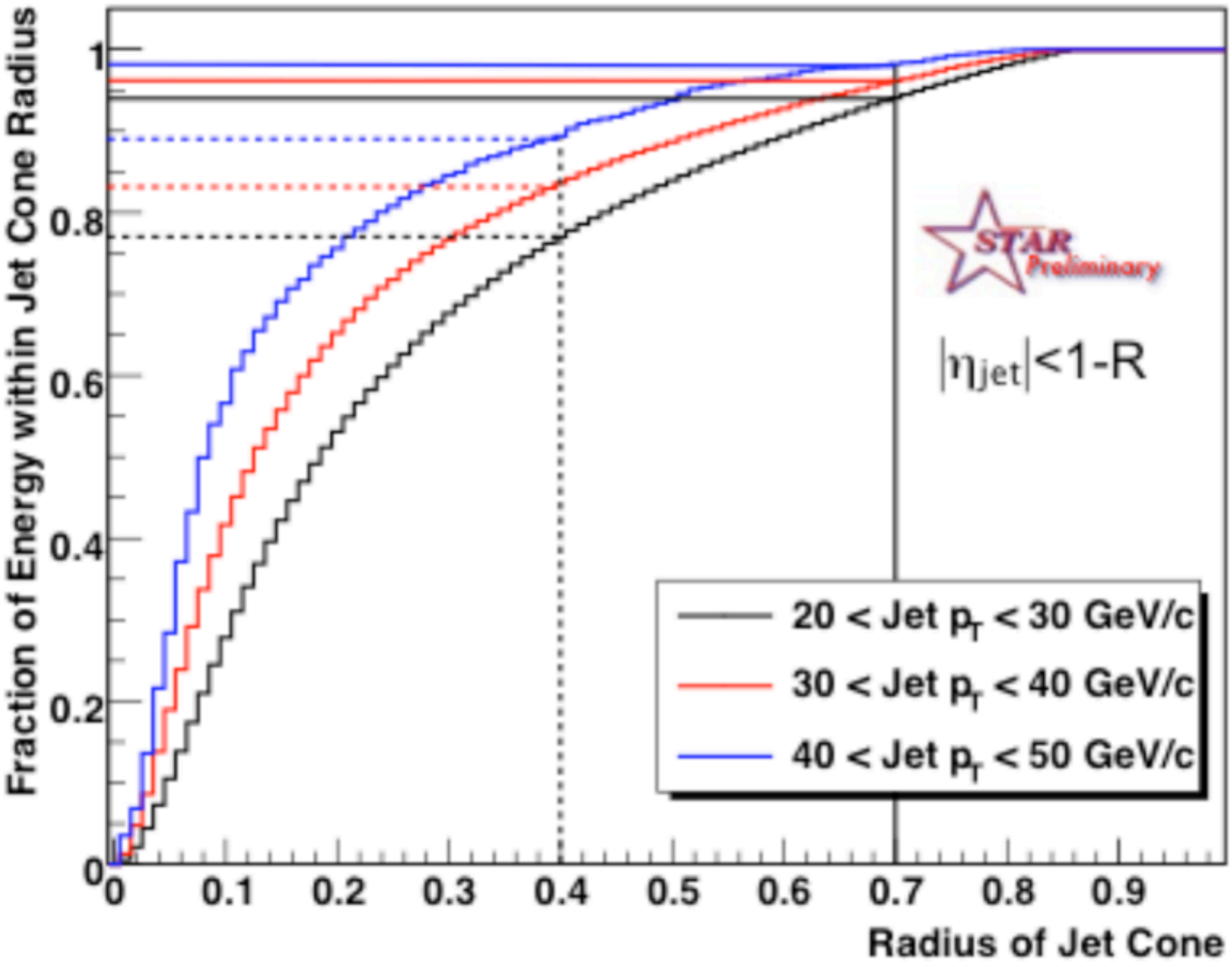


UE:

Increasing with beam energy

Slightly over predicted by PYTHIA

Radial energy distribution in pp jets



STAR hardcore jet definition

“Hard Core” Selection

High Tower trigger ET>5.4 GeV pTCut = 2 GeV/c

Reduce background

Reduce combinatorial jets

Jet pTLead>20 GeV/c Jet pTSubLead>10 GeV/c

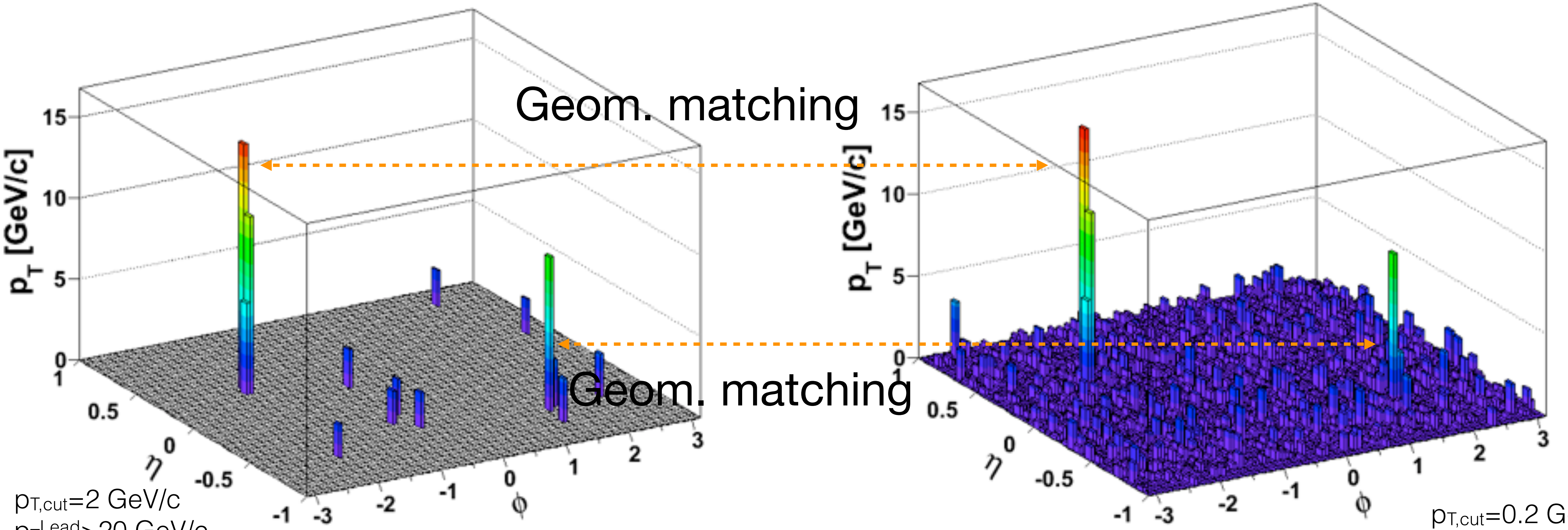
Recover soft component:

match to pTCut = 0.2 GeV/c Compared at detector level

‘Hard Core’ Dijets

Au+Au w/o soft particles

Au+Au w/soft particles



Geom. matching

Geom. matching

$p_{T,cut}$=2 GeV/c
p_T^{Lead}>20 GeV/c
$p_T^{SubLead}$>10 GeV/c
$|\Delta\phi-\pi|<0.4$

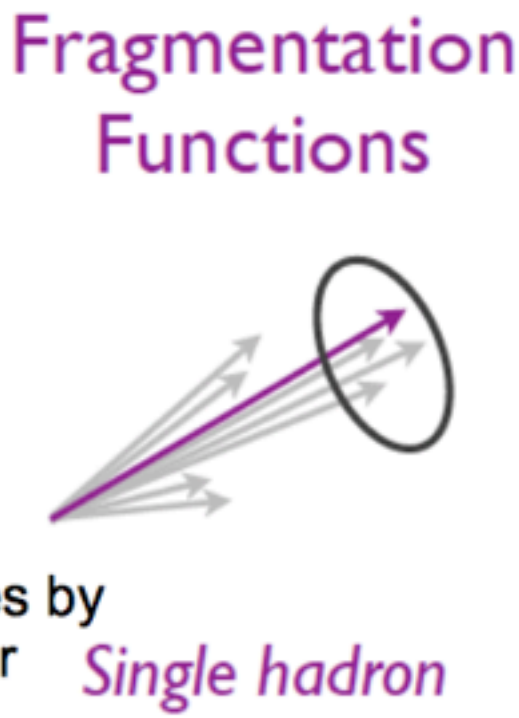
$p_{T,cut}$=0.2 GeV/c

locate hard core dijets

reconstruct matched dijets

Intra jet observables

Dynamics of particles inside the jet
Two scales: angular + momentum space

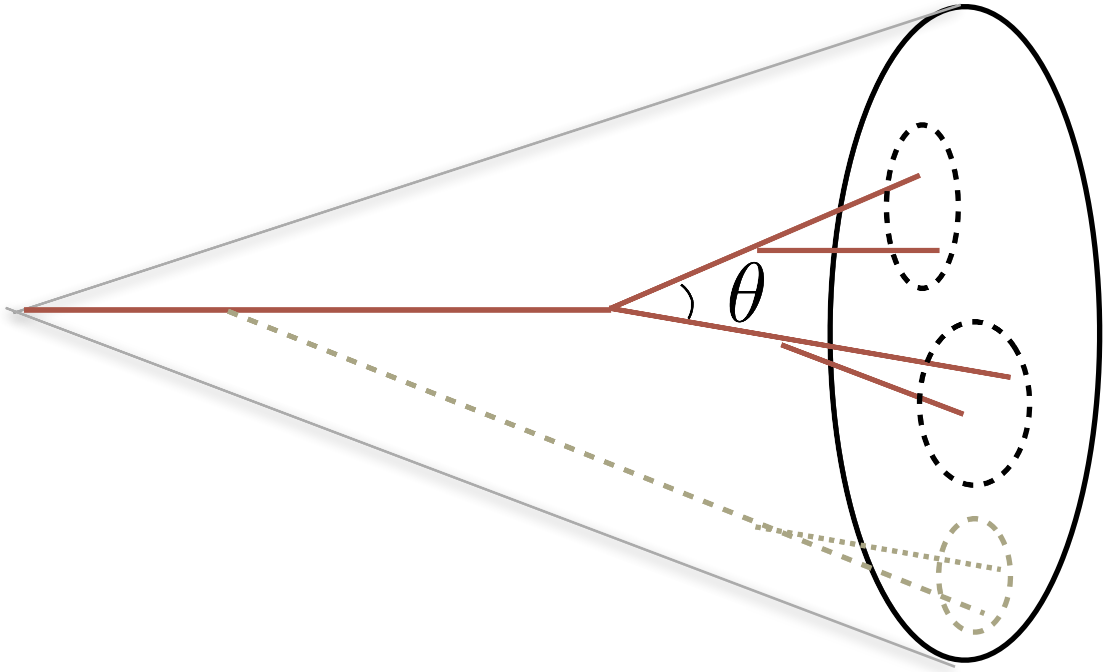


Sketches by
J. Thaler

Jet Substructure: soft drop z_g

Larkoski, *et al*, JHEP05(2014)146

Dasgupta, *et al,* JHEP09(2013)029



$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > \underset{\substack{\uparrow \\ \text{energy} \\ \text{threshold}}}{z_{\text{cut}}}\ \underset{\substack{\uparrow \\ \text{angular} \\ \text{exponent}}}{\theta^{\beta}}$$

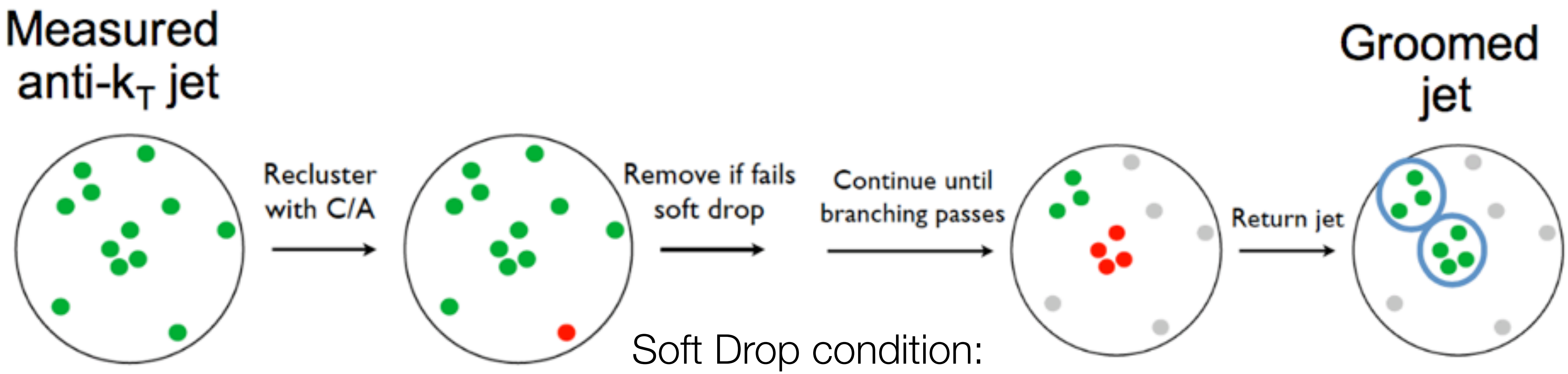
Credit: Marta Verweij

Large-angle soft radiation + background are removed

Goal: to search for modification of hardest jet splitting

What is z_g Soft Drop

Marta Verweij, QM17



Soft Drop condition:

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\mathrm{cut}}\ \theta^{\beta}$$

energy threshold

angular exponent

Large-angle soft radiation + background are removed

Goal: to identify hard jet splitting

Trigger Particle Normalization

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

In the case of no nuclear effect

$$\rightarrow \left(\frac{1}{\sigma^{pp\rightarrow h+X}}\cdot\frac{d\sigma^{pp\rightarrow h+jet+X}}{dp_{T,jet}^{pp}}\right)\times N_{coll}/N_{coll}$$

$$= \frac{1}{N_{trig}^{h,pp}}\frac{dN_{jet}^{pp}}{dp_{T,jet}^{pp}}$$

N_{coll}: number of binary nucleon-nucleon collisions

N_{coll} no longer needed for comparison to pp

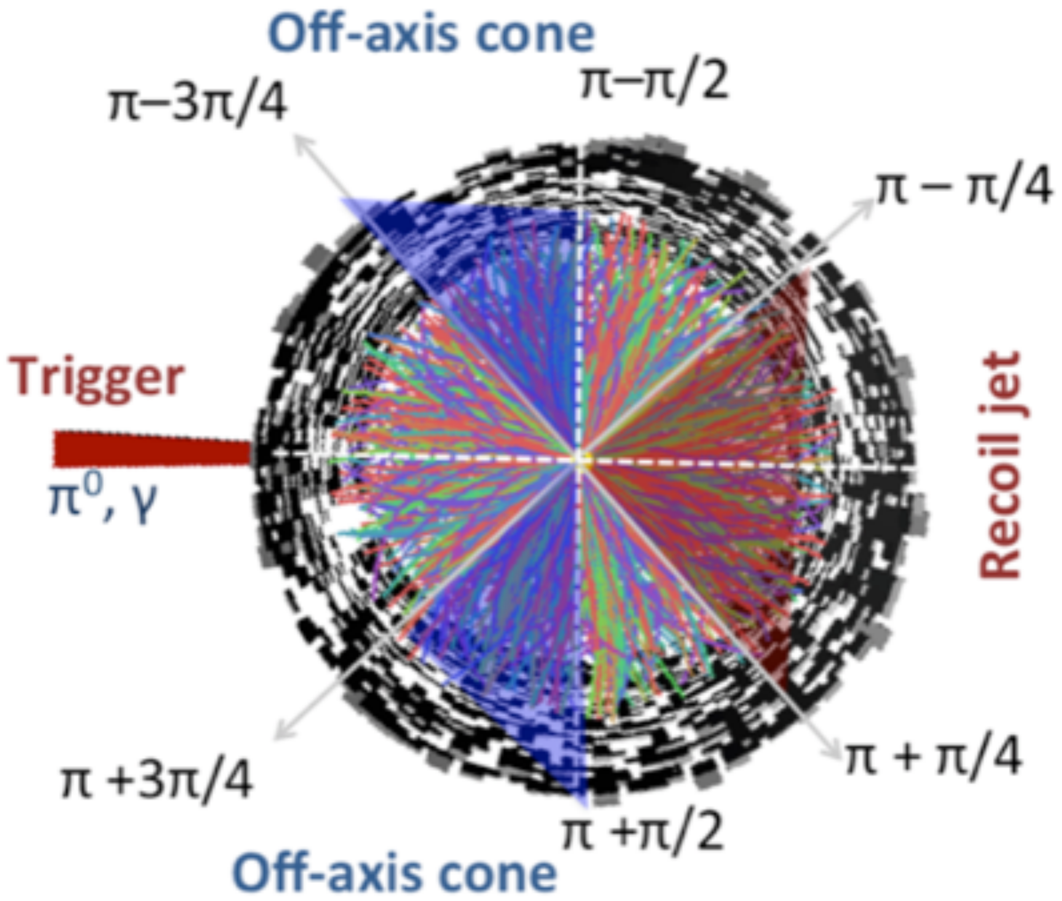
In p(d)A, various centrality biases depending on phase space selection

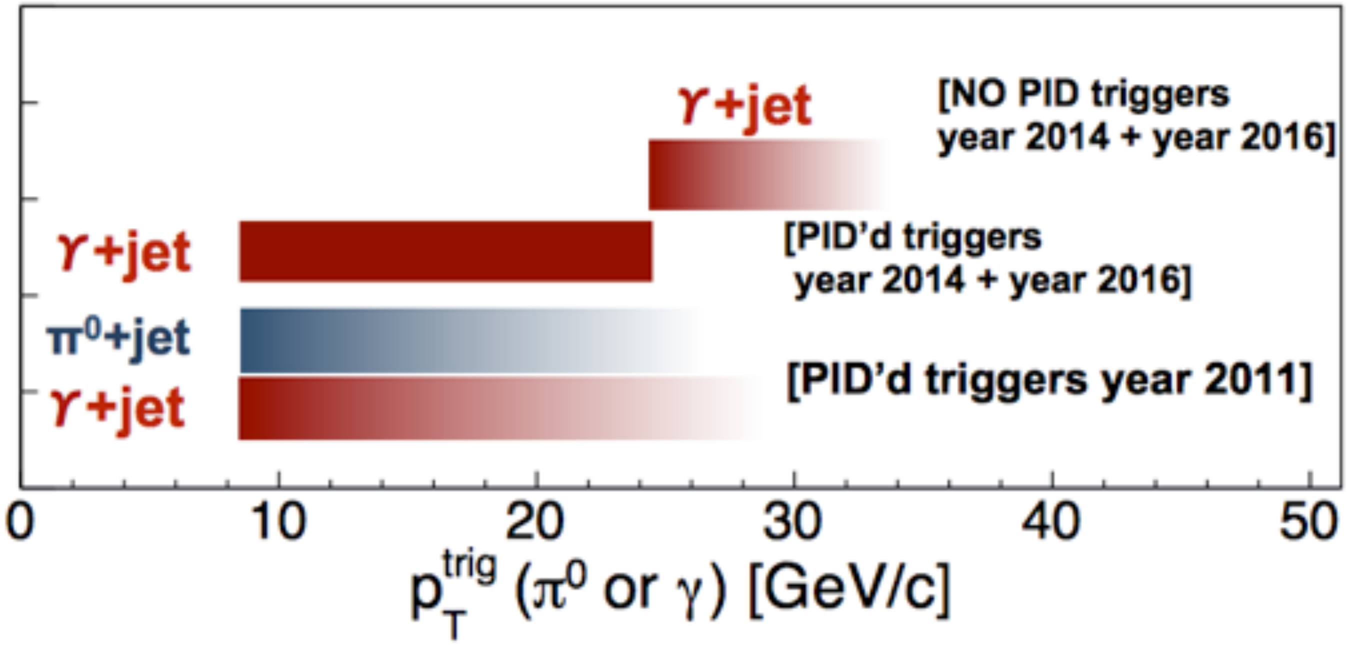
Bias could also be in peripheral AA

ALICE, arXiv:1706.07612
ALICE, PRC **91**, 064905
Loizides, Morsch, PLB **773** (2017) 408

γ - jet

Coming soon

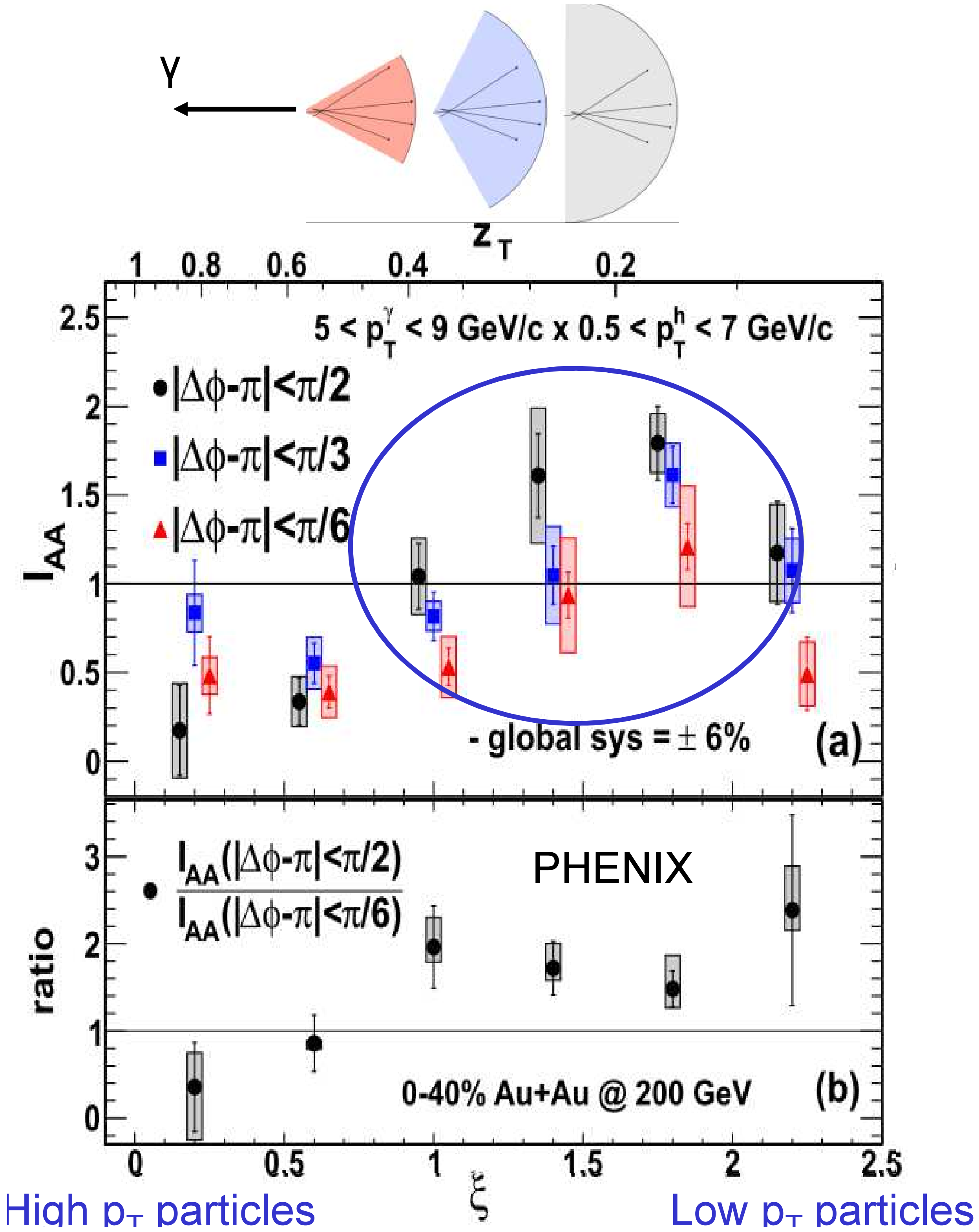




Background techniques: Mixed event; Off-axis cone

Uncorrelated vs correlated background

Reemergence of lost energy



Lost energy: found in large Δφ(ΔR) with respect to the away-side jet, converted to low p_T particles.