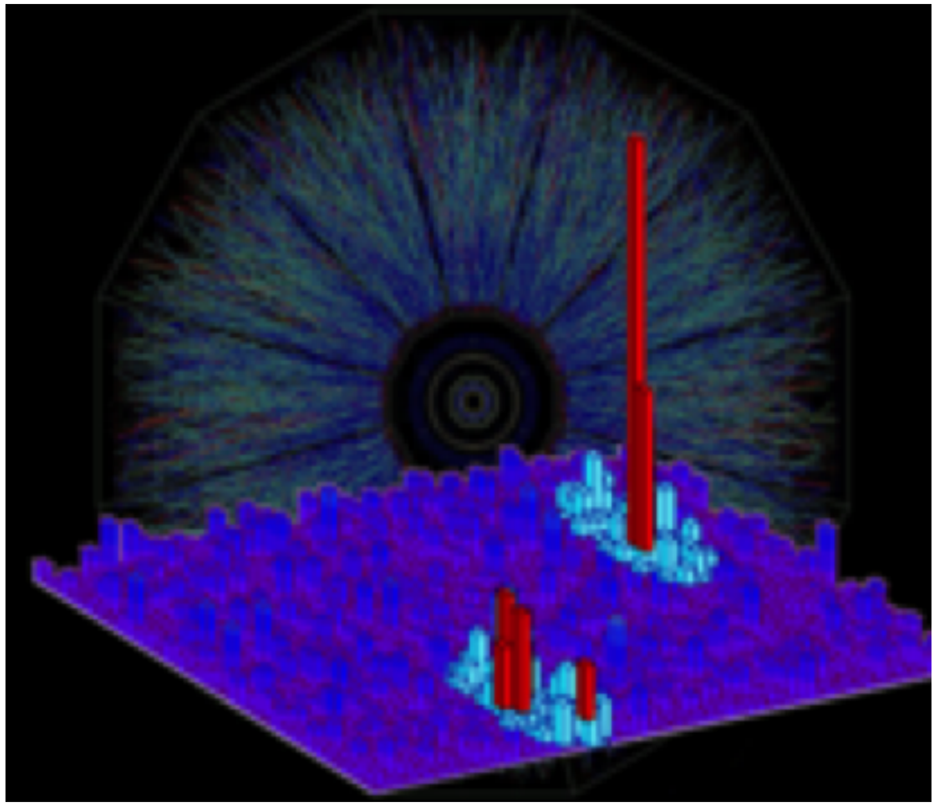
Recent High-p_T and Jet Results from STAR

Li Yi
Yale University
High p_T Workshop 2017

STAR

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

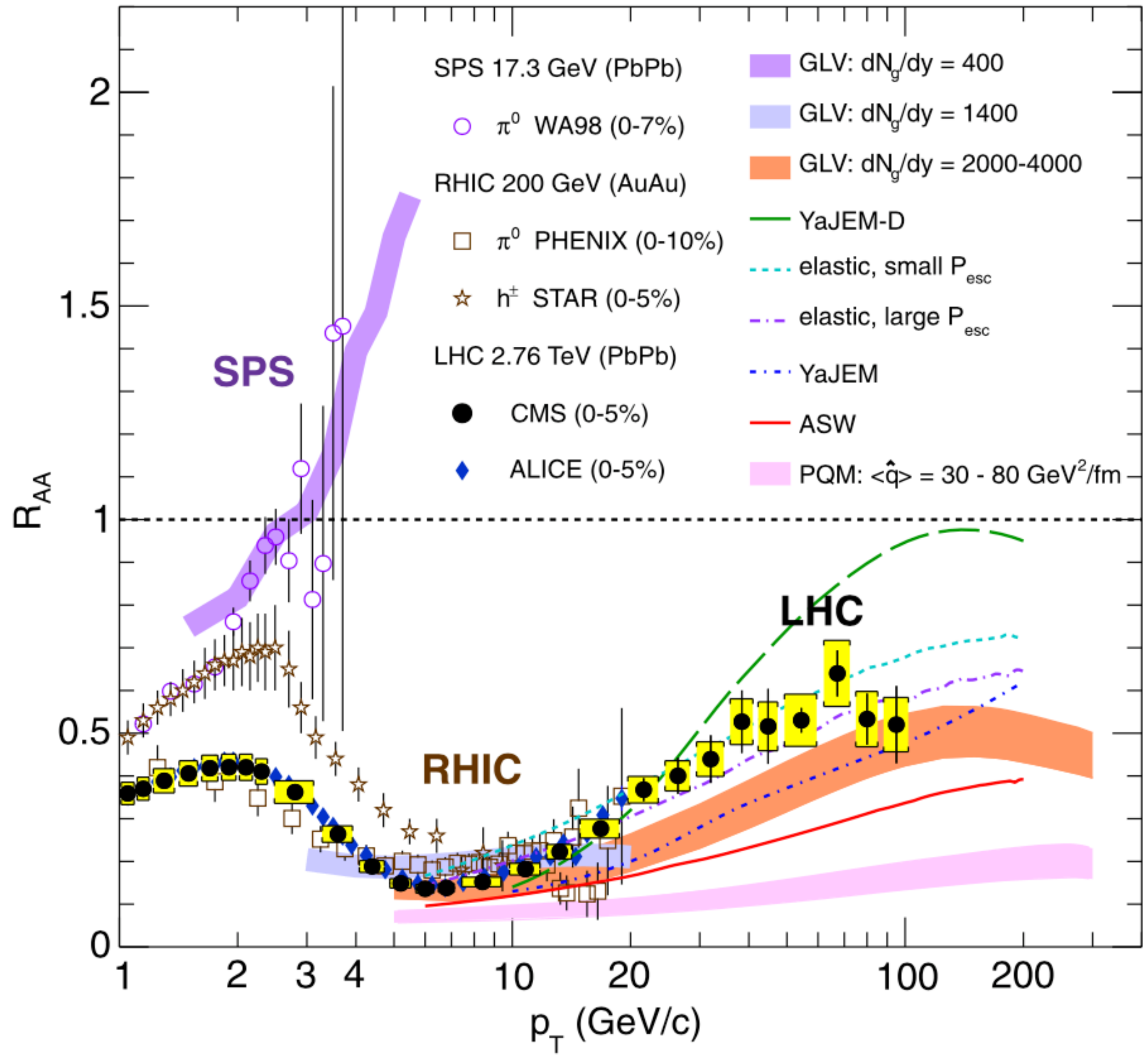


- high p_T hadron @BES
- pp jets vs pQCD
- h-jet energy loss
- ɣ-hadron energy ‘calibrated’
- Dijets energy imbalance
- z_g substructure

Single Hadron High p_T Suppression

CMS, EPJC (2012) 72:1945

Connors, Nattrass, Reed, Salur, arXiv 1706.01974

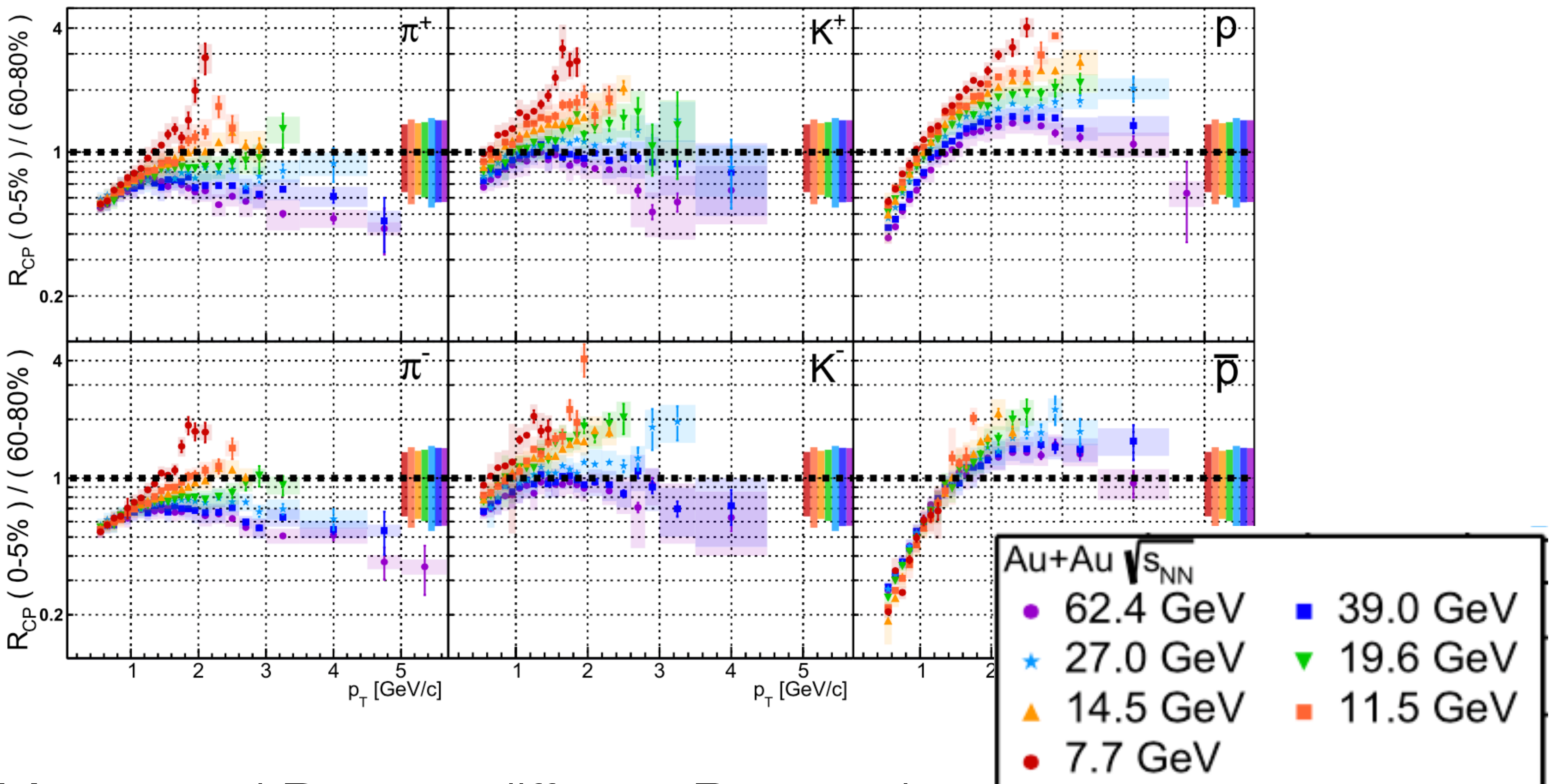


High p_T hadron suppression at RHIC and LHC energies

Single Hadron High p_T Suppression @ BES

feed-down subtracted

STAR, arXiv:1707.01988



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

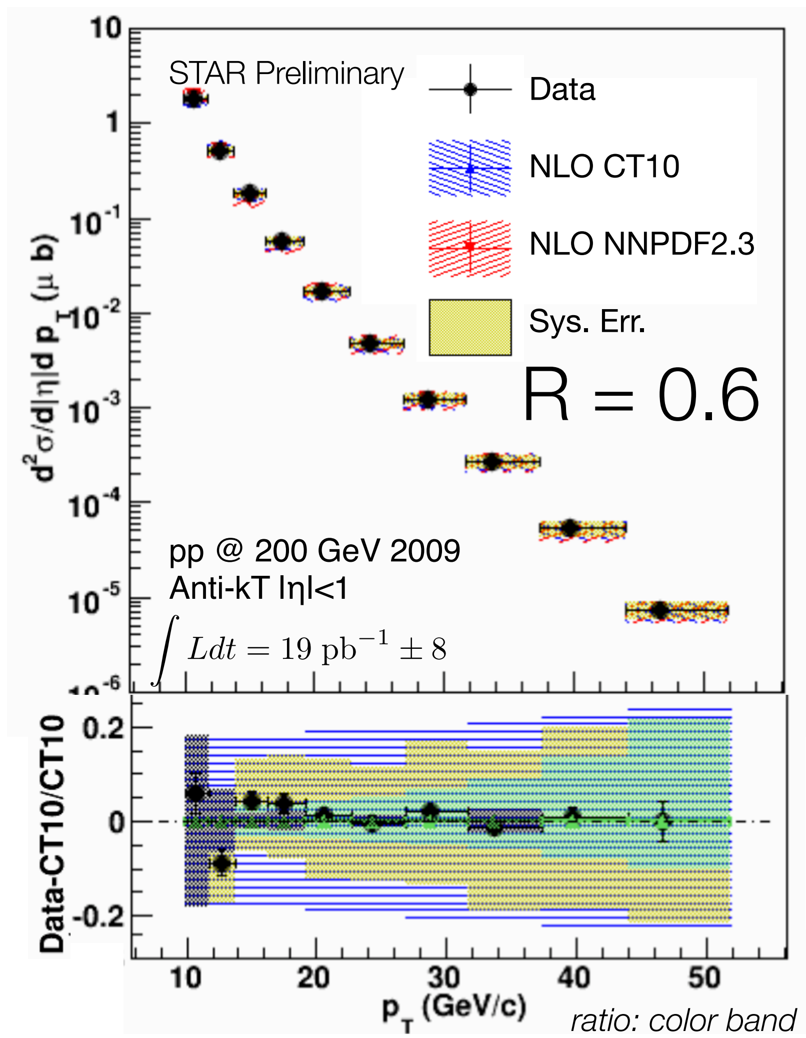
Jets in Vacuum: pp@200 GeV

Jets: reduce complexity of many hadrons to single objects

Inclusive Jet

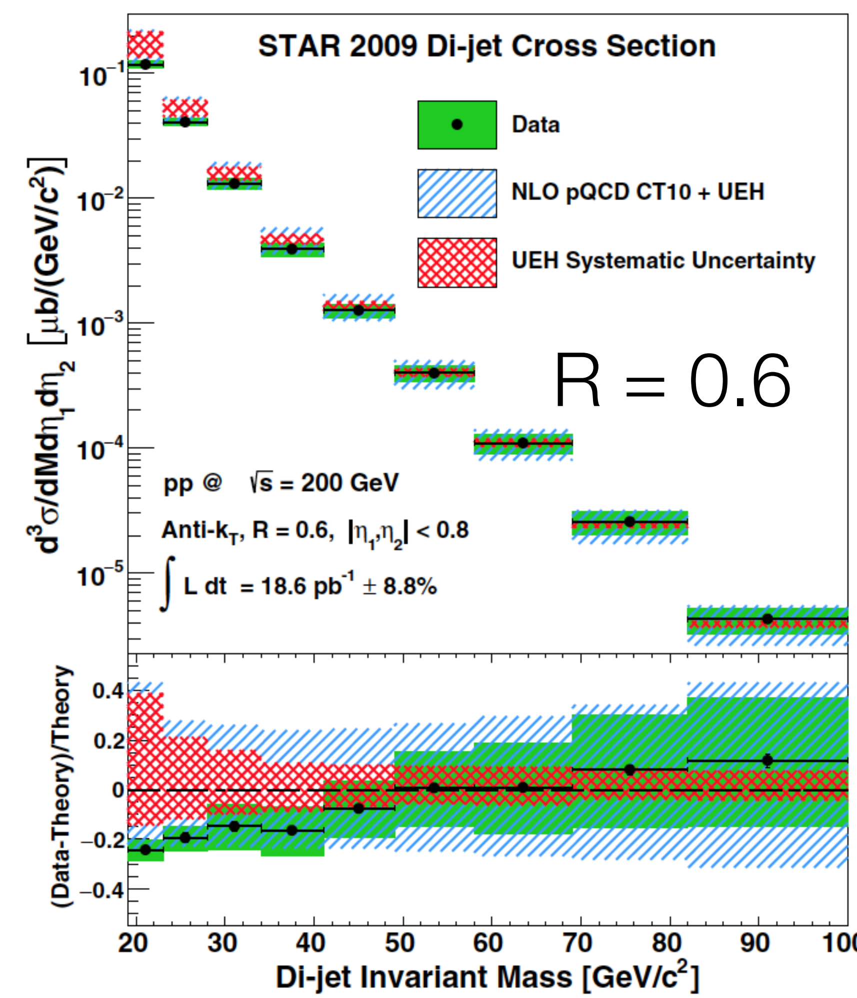
Dijet

jet cross section



ratio: color band for various sys. err.

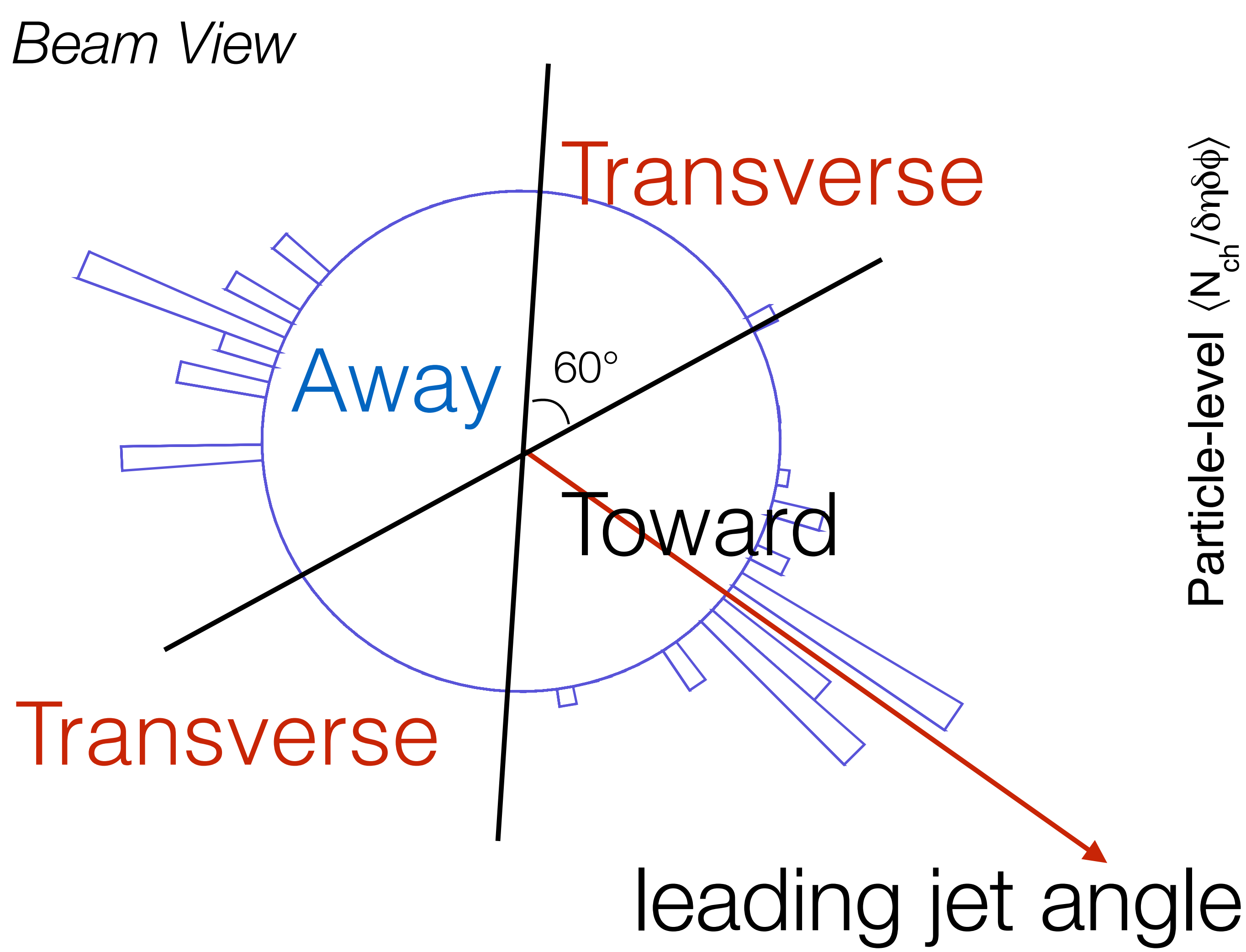
dijet cross section



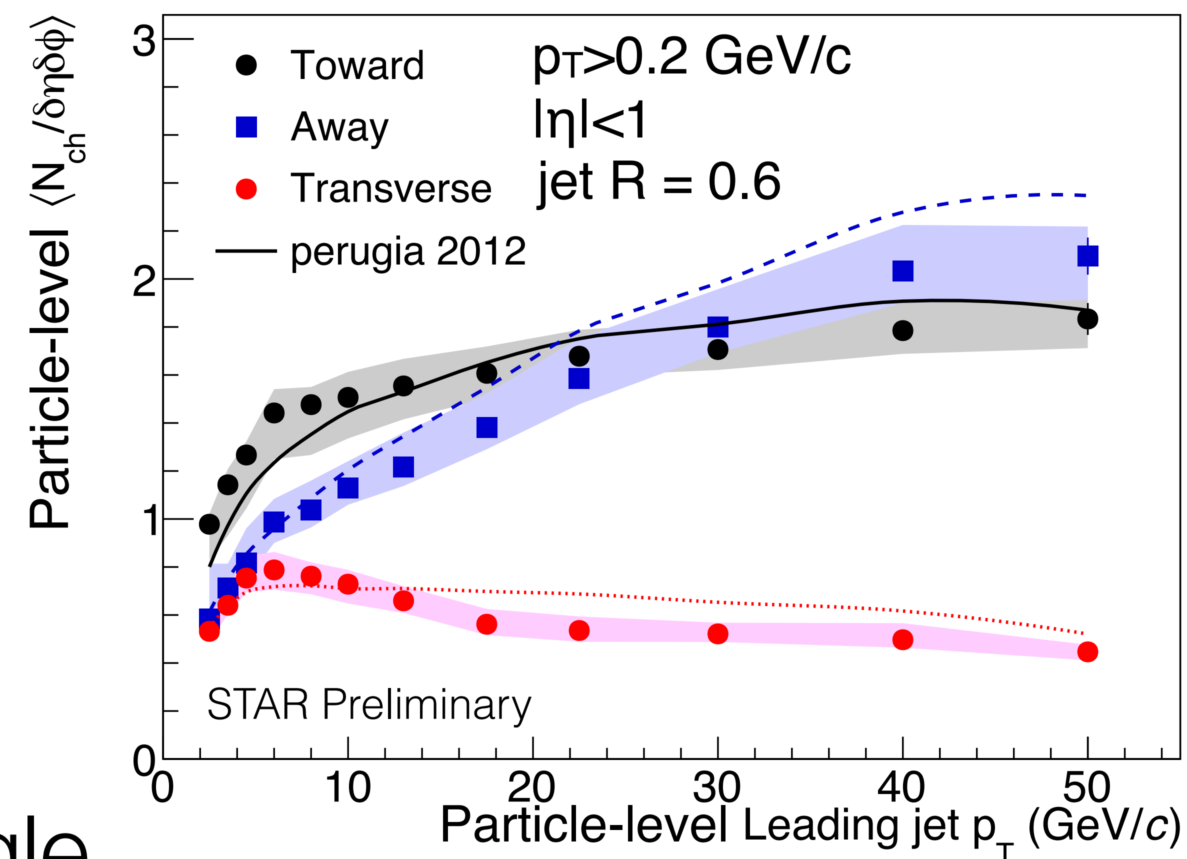
STAR, PRD. **95**, 071103(R) 2017

Well described by NLO pQCD → Jets as high precision tool

Background Activity in pp



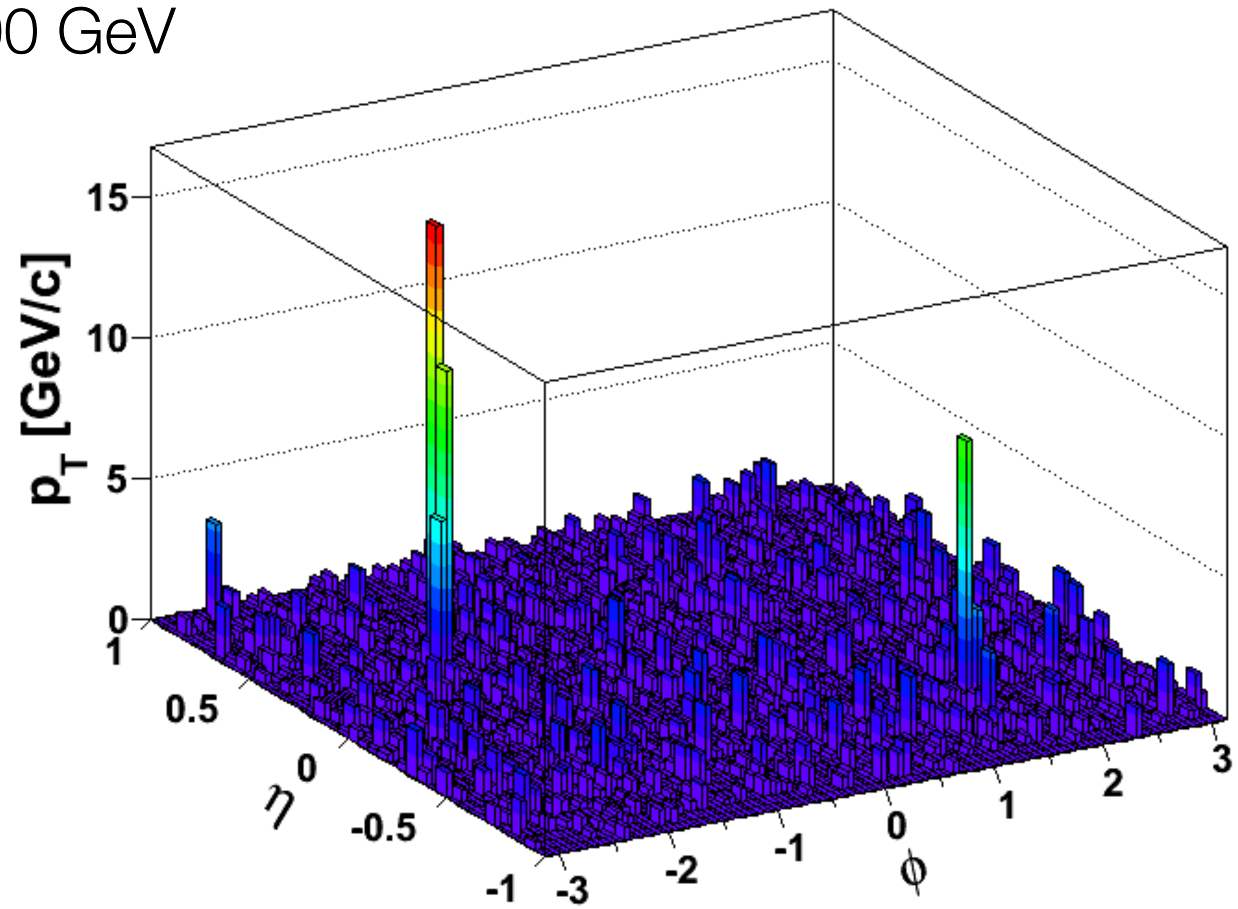
p+p@200 GeV



Underlying event only weakly depends on jet energy

Background Activity in A+A

STAR, Au+Au@200 GeV



0-10% <ρ^{ch}> ~ 34 GeV/c

Challenges: large fluctuating background

-> modified JES + smeared JER + **combinatorial jets**

important for low p_T jets

Experiment methods:

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

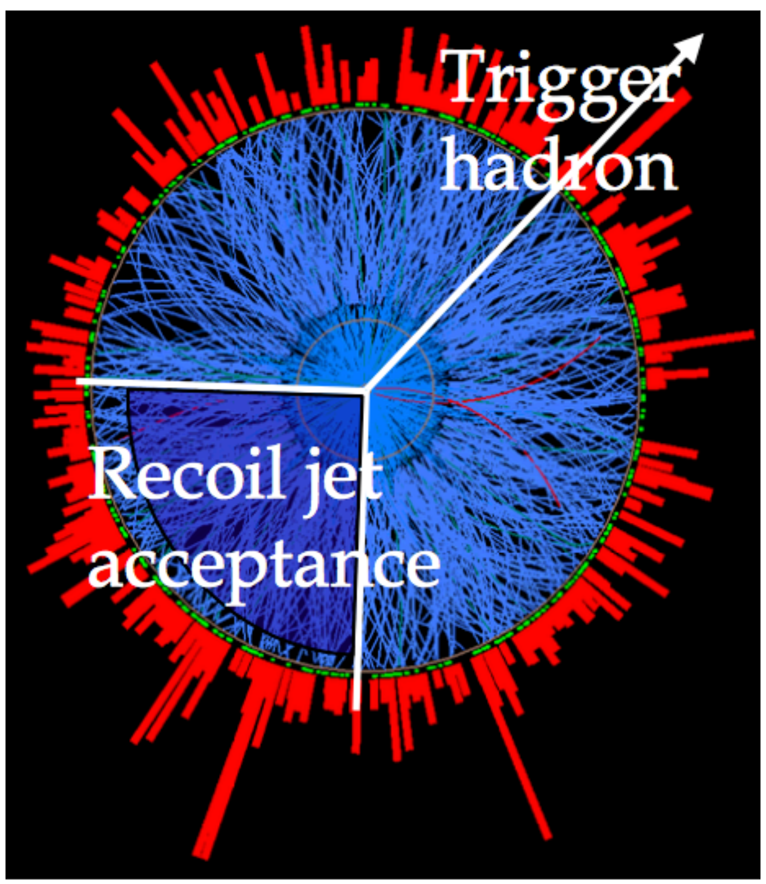
Semi-inclusive Jet Measurements

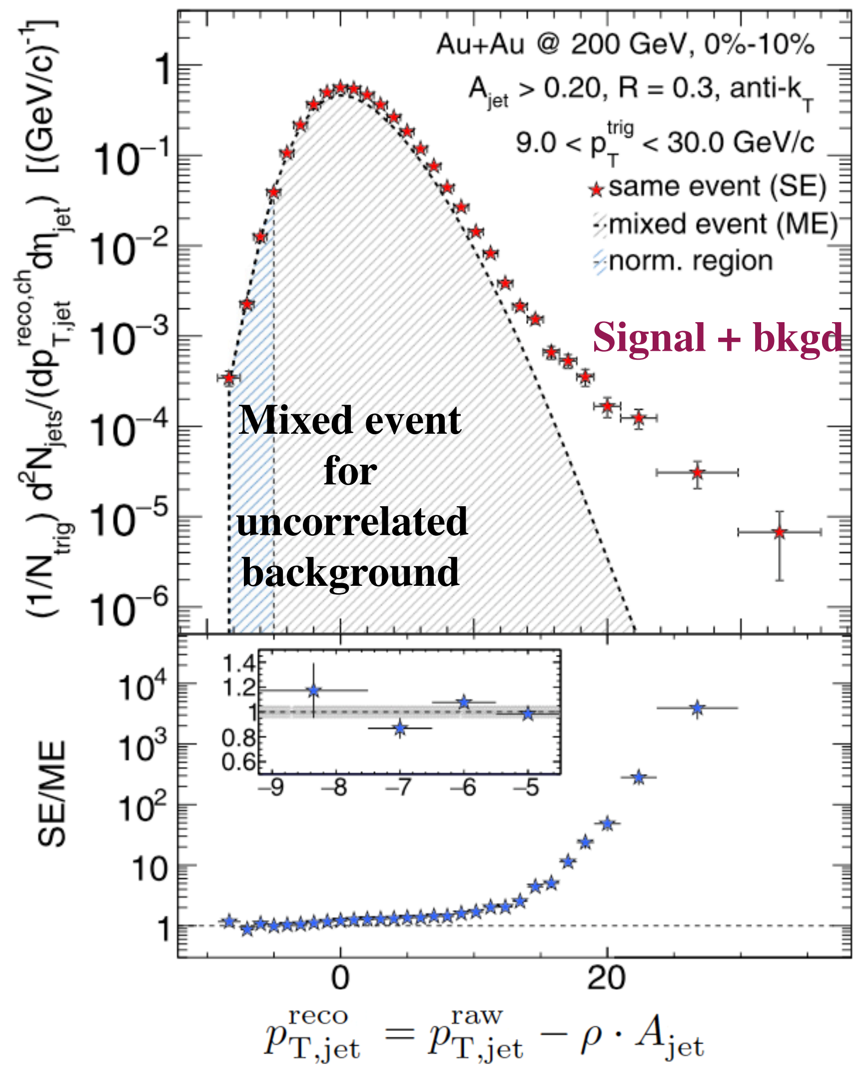
STAR, PRC **96**, 024905 (2017)

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

Measurable

Calculable in pQCD (in vacuum)





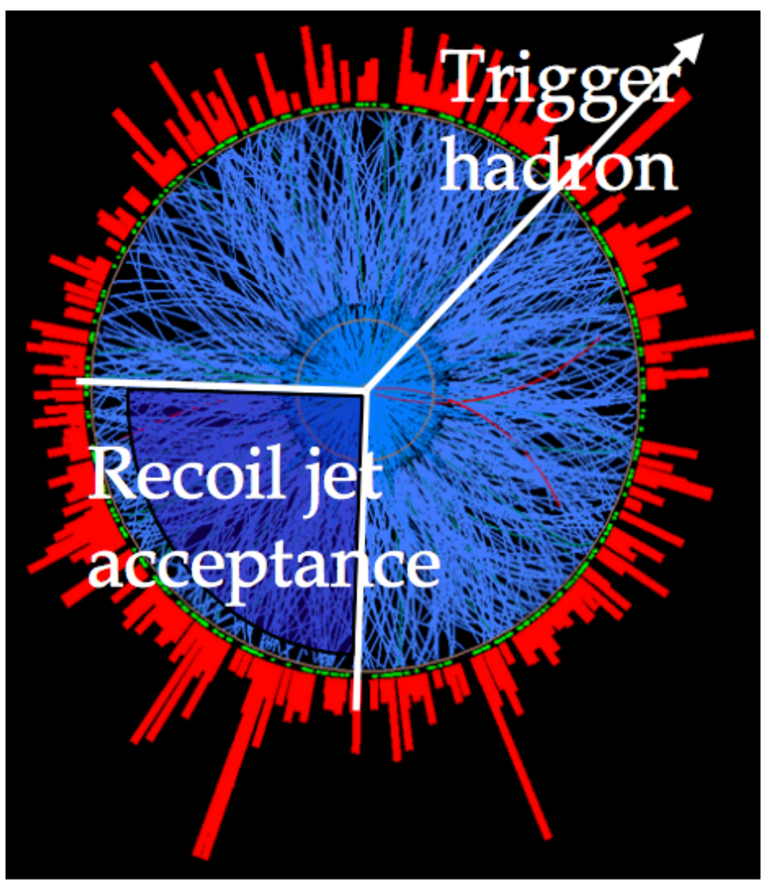
charged jet
R = 0.3

Semi-inclusive Jet Measurements

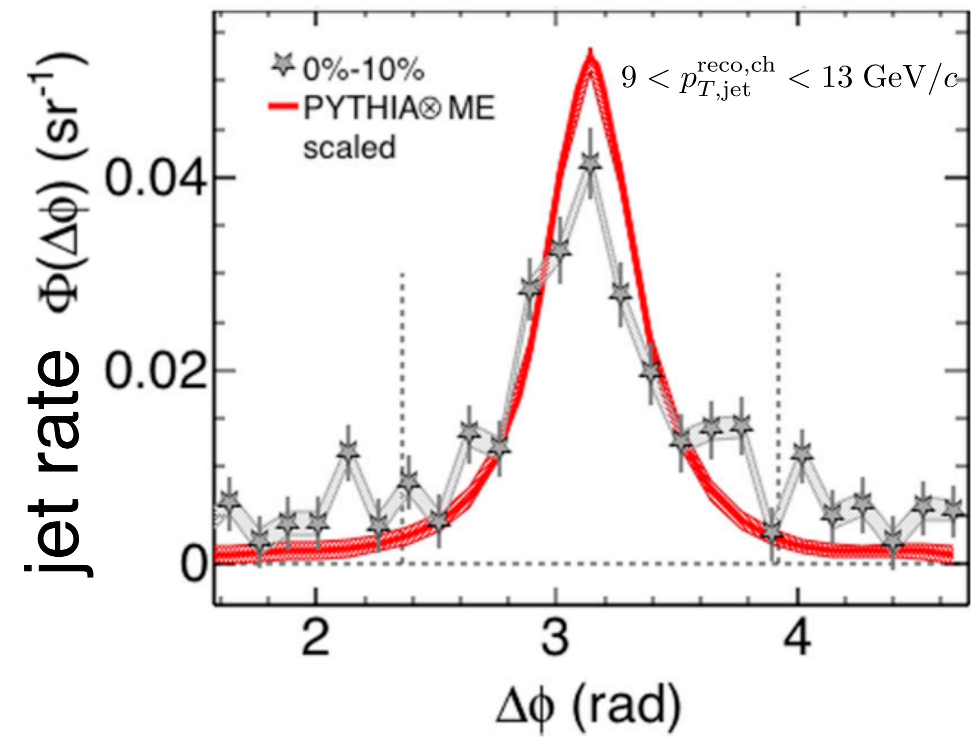
STAR, PRC **96**, 024905 (2017)

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

Measurable — Calculable in pQCD (in vacuum)



background subtracted



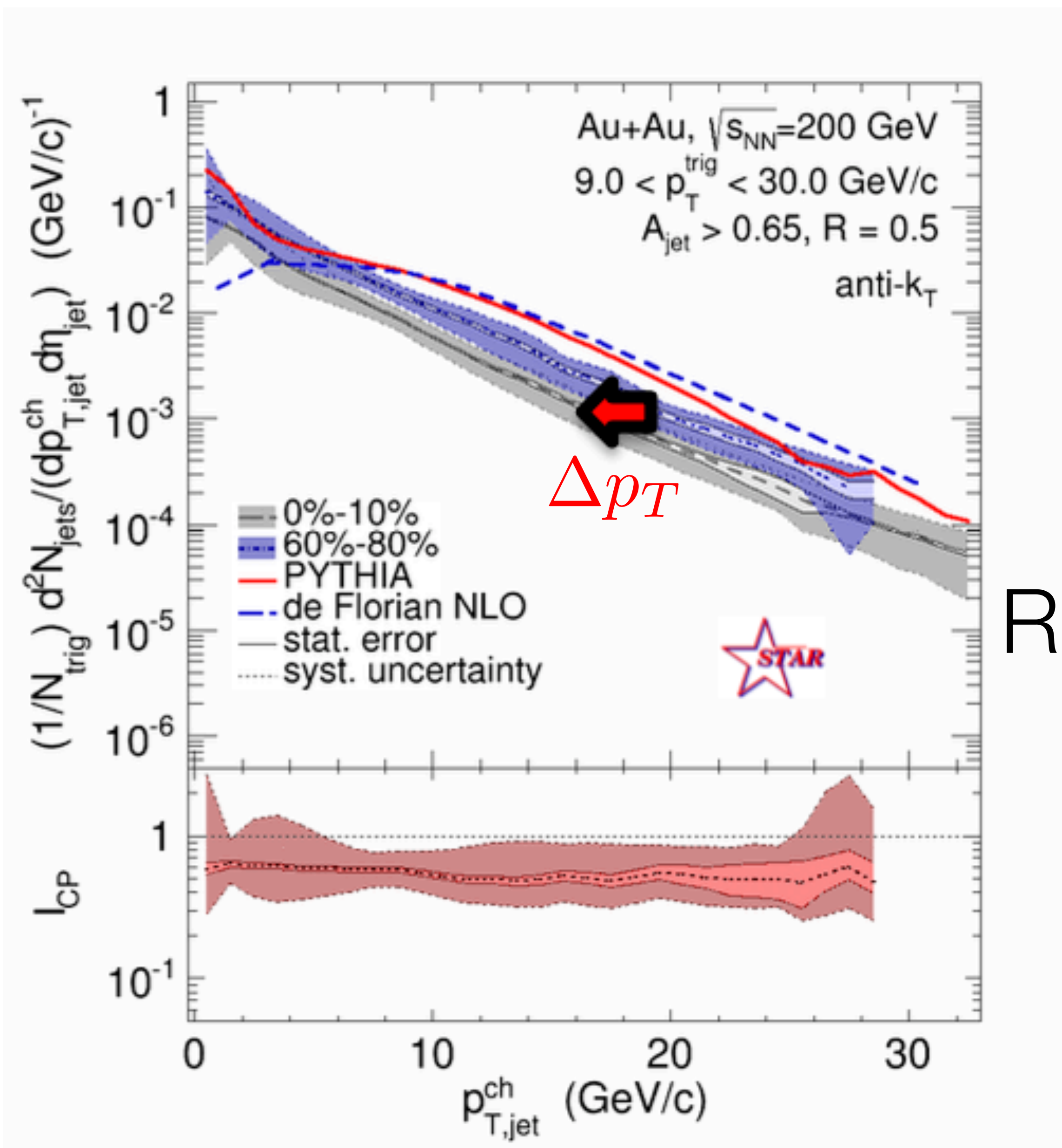
charged jet
R = 0.3

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

D'Eramo, *et al.* JHEP (2013) 2013: 31

Energy Shift Out of Cone

R=0.5



STAR, PRC **96**, 024905 (2017)

Spectrum shift → energy transport out-of-cone

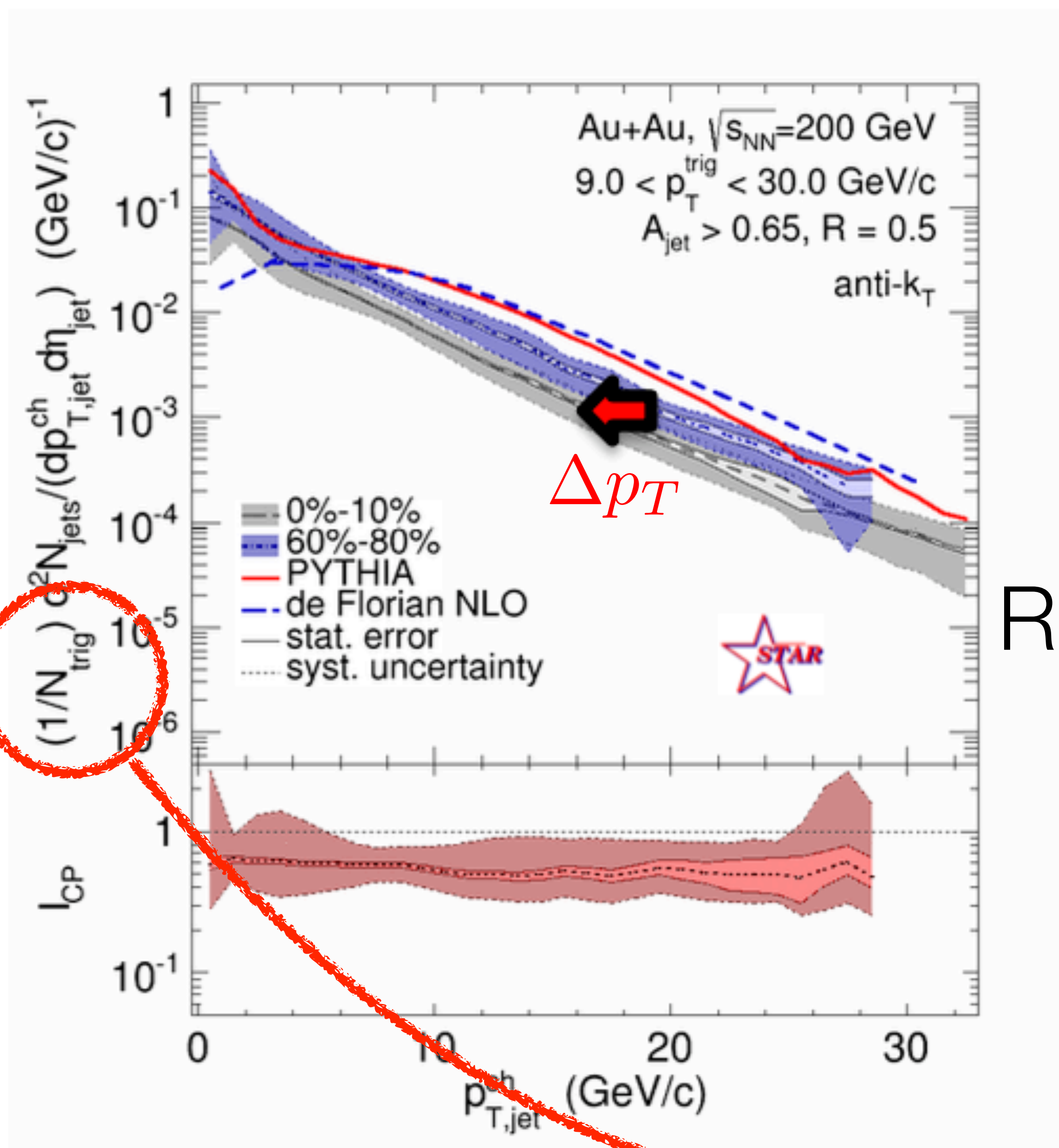
System		Au+Au $\sqrt{s_{NN}}$ = 200 GeV	Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$p_{T,jet}^{ch}$ range (GeV/c)		[10,20]	[60,100]
		p_T-shift of Y $\left(p_{T,jet}^{ch}\right)$ (GeV/c)	
		peripheral→central	p+p→central
R	0.2	$-4.4 \pm 0.2 \pm 1.2$	
	0.3	$-5.0 \pm 0.5 \pm 1.2$	
	0.4	$-5.1 \pm 0.5 \pm 1.2$	
	0.5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

ALICE, JHEP 09 (2015) 170

R=0.5: smaller shift at RHIC than LHC
→ lower energy loss at RHIC
but larger $\Delta p_T / p_T^{jet}$ at RHIC

Energy Shift Out of Cone

R=0.5



STAR, PRC **96**, 024905 (2017)

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

ALICE, JHEP 09 (2015) 170

R=0.5: smaller shift at RHIC than LHC

→ lower energy loss at RHIC

but larger $\Delta p_T / p_T^{jet}$ at RHIC

Not a cross section measurement per trigger instead of per event

Trigger Particle Normalization

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

In the case of no nuclear effect

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

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

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

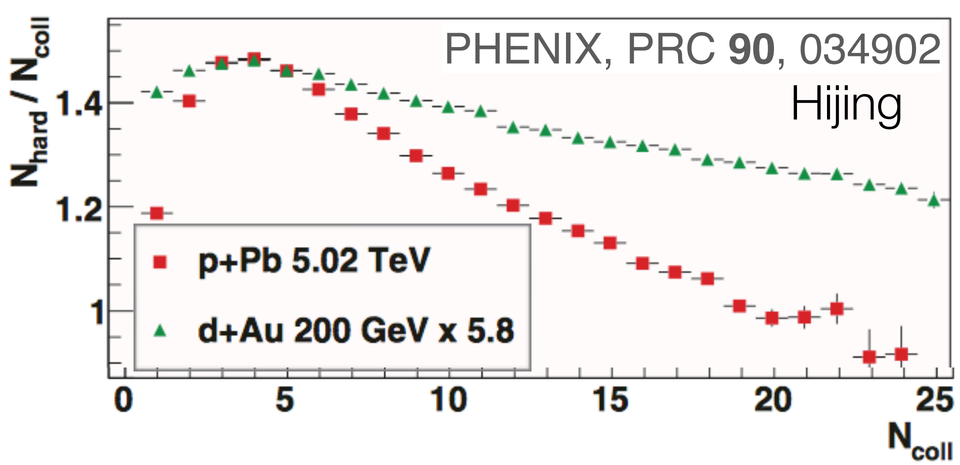
ALICE, arXiv:1706.07612
ALICE, PRC **91**, 064905
Loizides, Morsch, PLB **773** (2017) 408

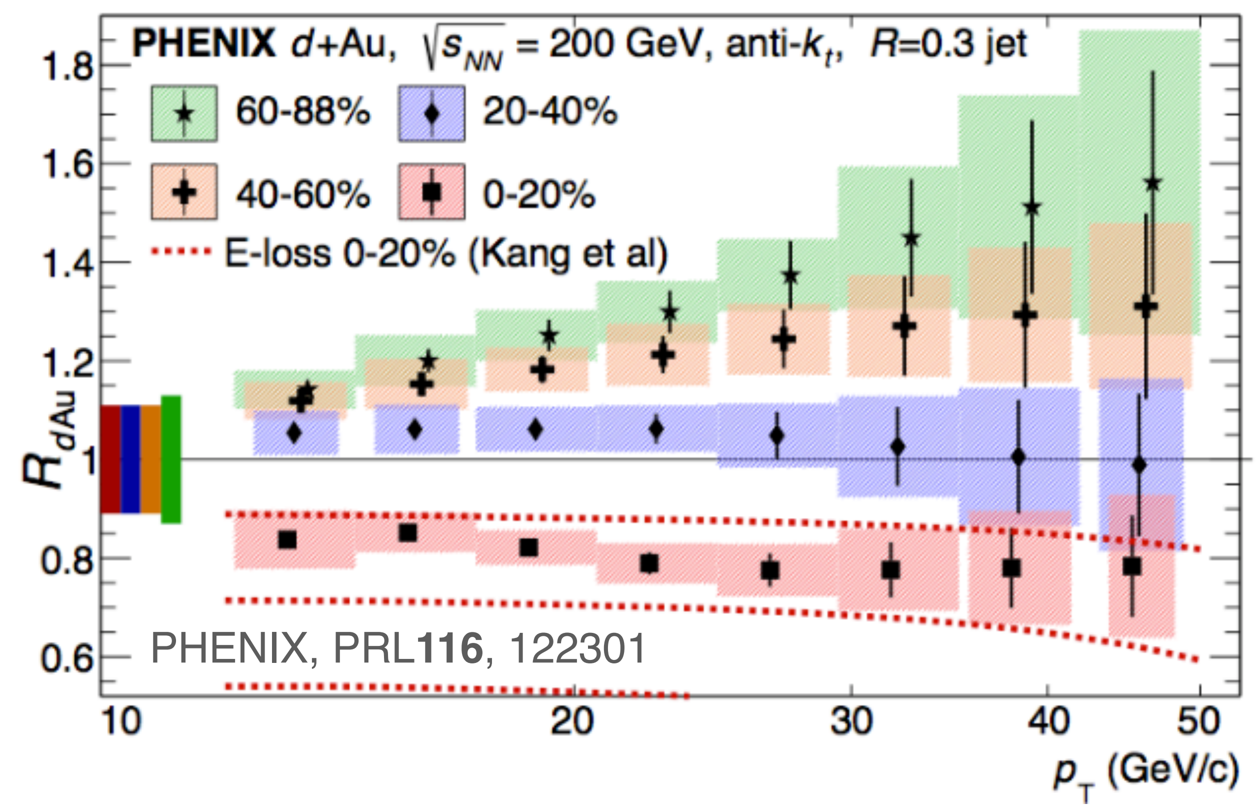
STAR

RHIC Jet in p/d+Au?

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

$$R_{dAu} = \frac{dN^{dAu}_{jet}}{N^{dAu}_{event}dp^{dAu}_{T}} / (N_{coll} \times \frac{dN^{pp}_{jet}}{N^{pp}_{event}dp^{pp}_{T}})$$





N_{coll} needed in R_{dAu} calculation

STAR's plan with 2B p+Au events from year 2015

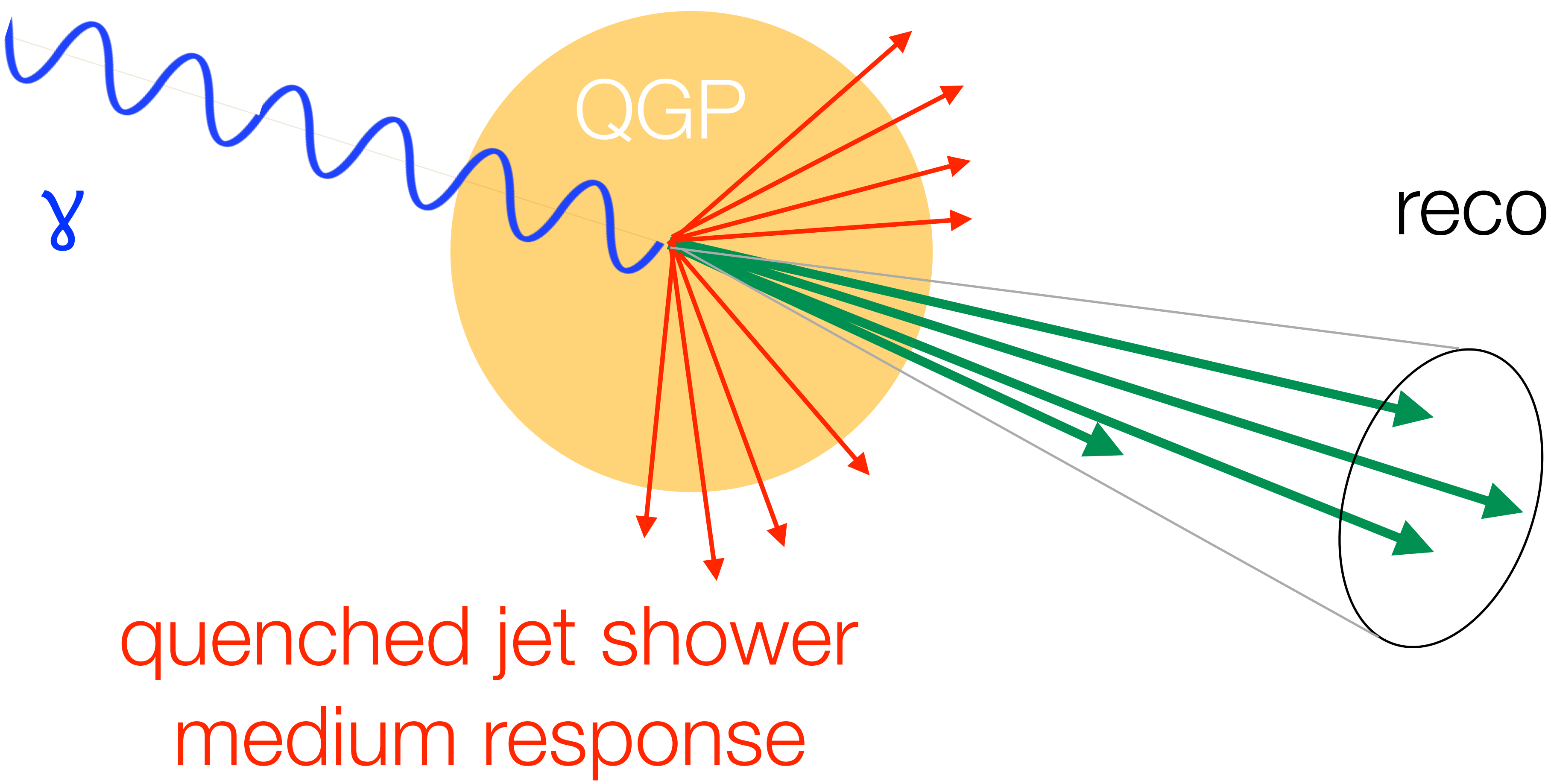
Semi-inclusive jet in p+Au to remove N_{coll} complication

Photon Triggered Recoil Jet

Select more quark recoil jets

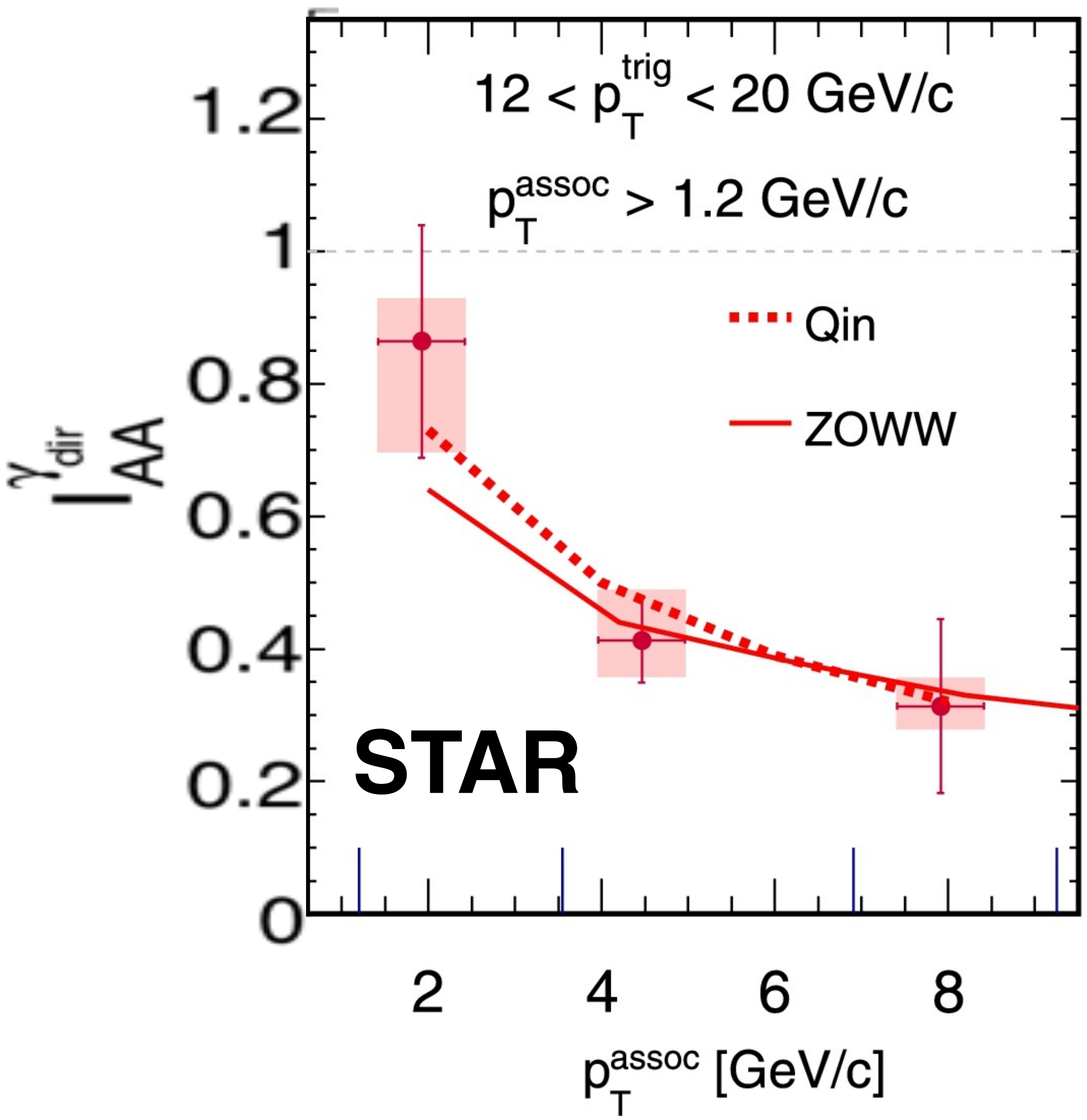
Avoid surface bias

Calibrate initial parton energy for study of energy loss, substructure modification



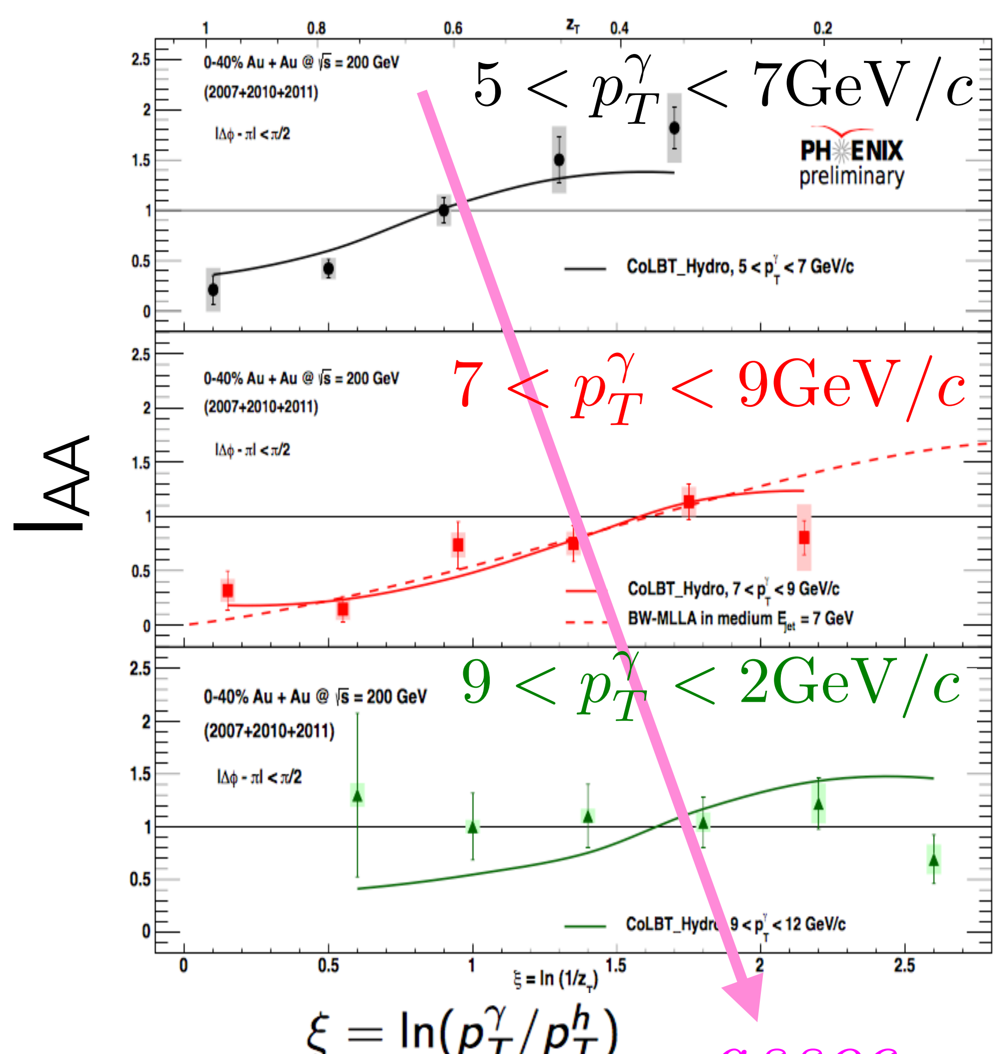
γ - hadron

STAR, PLB **760** (2016) 689



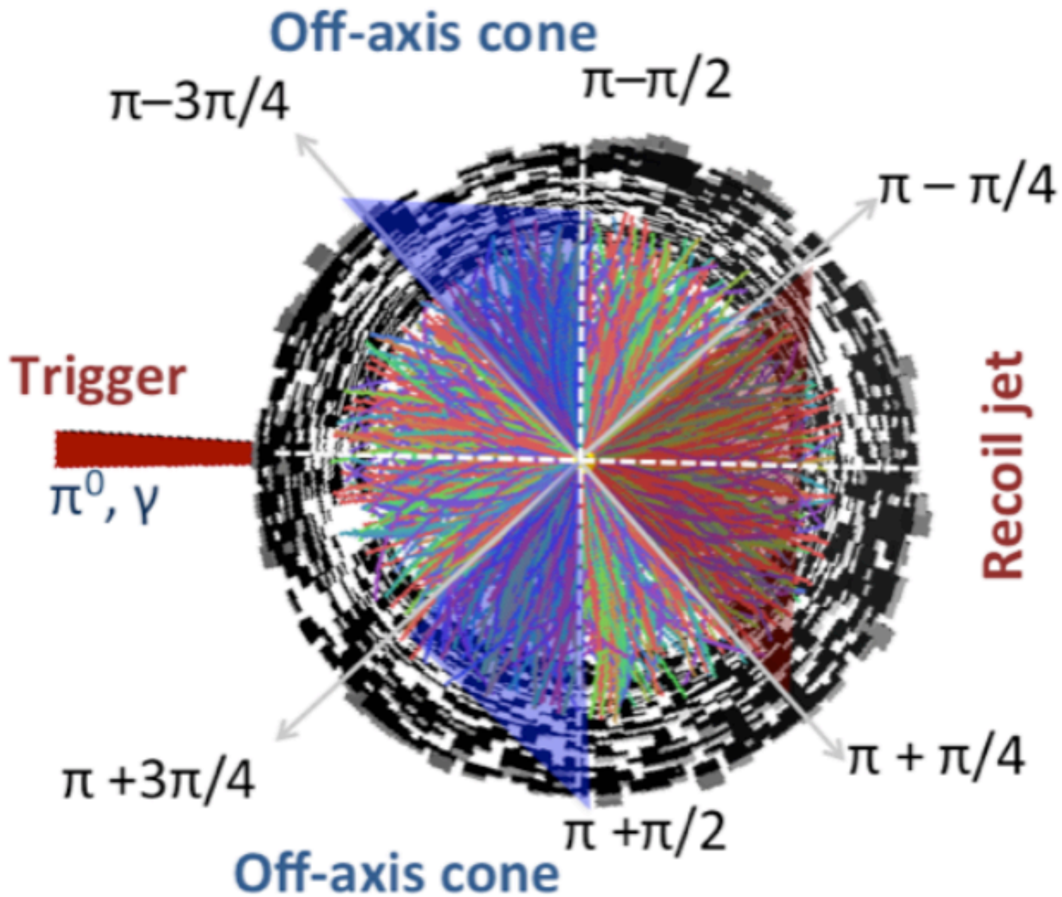
$z_T = p_T^{assoc}/p_T^{\gamma}$

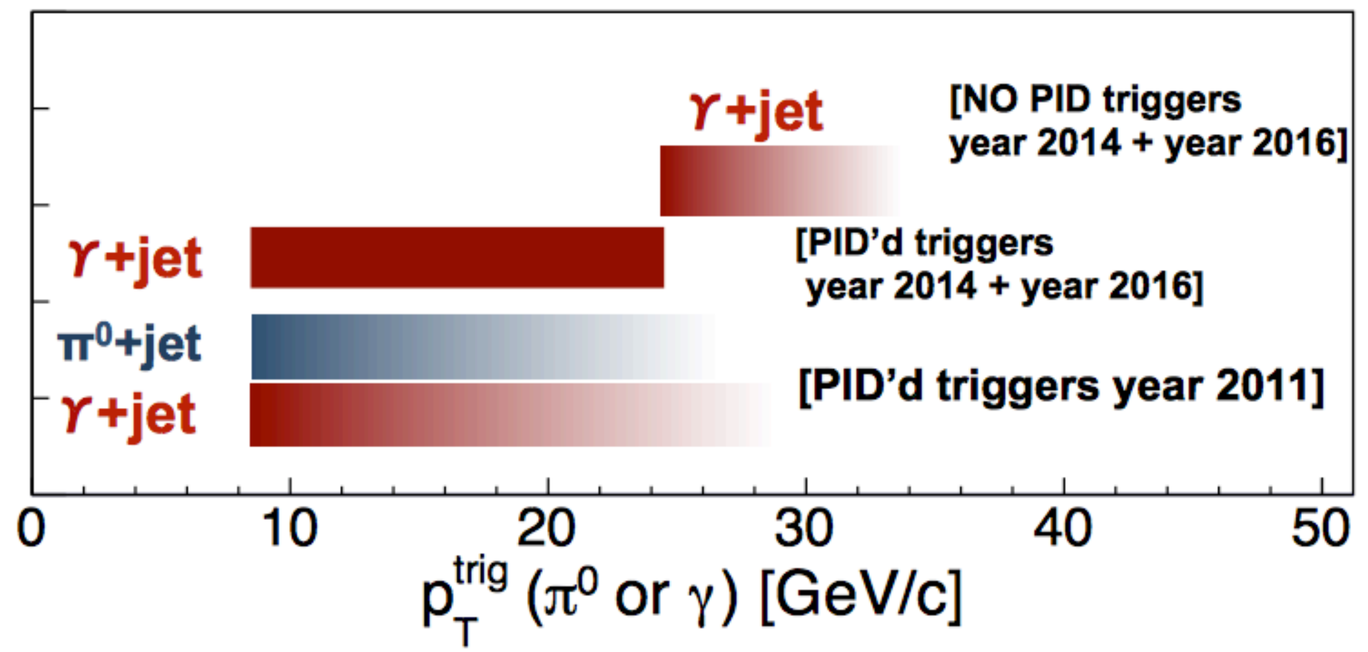
PHENIX, QM17



Absolute p_T rather than particle p_T fraction (z_T) more relevant

γ - jet





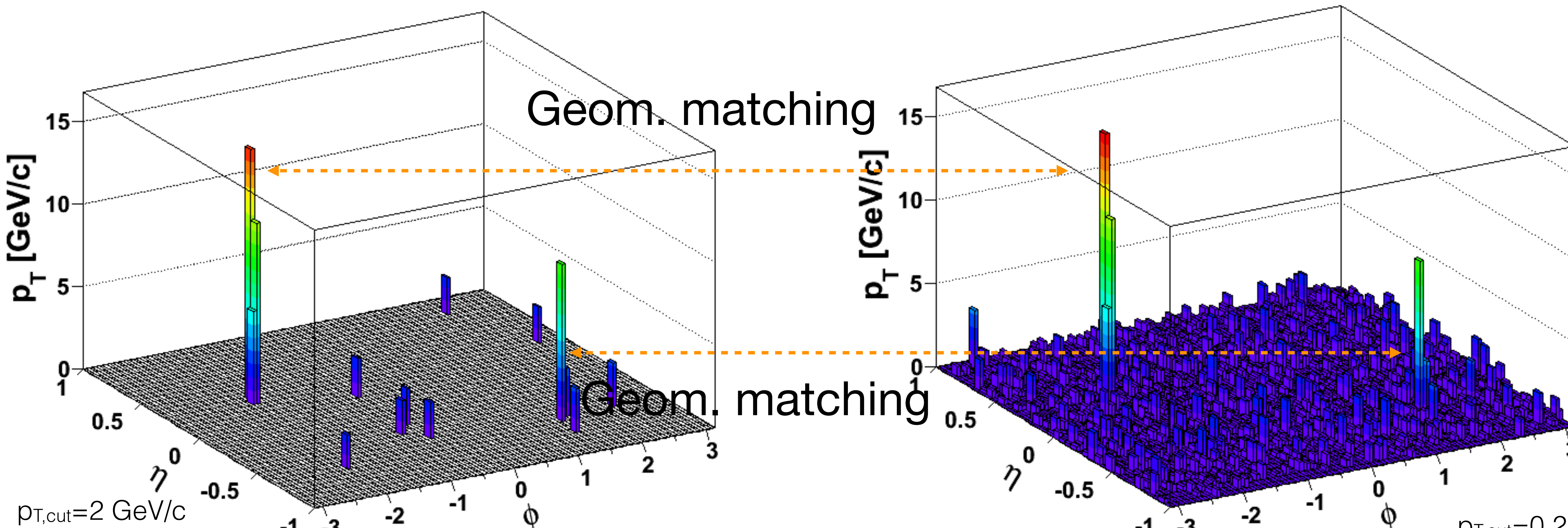
Background techniques: Mixed event; Off-axis cone

Uncorrelated vs correlated background

‘Hard Core’ Dijets

Au+Au w/o soft particles

Au+Au w/soft particles



$p_{T,cut}$=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

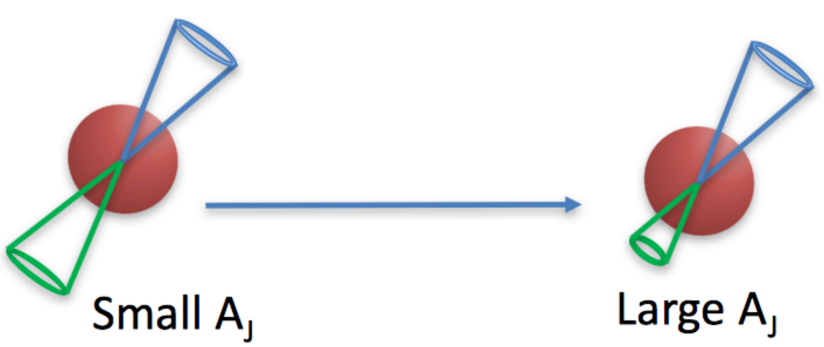
locate hard core dijets

reconstruct matched dijets

Dijets Restore Balance with Low p_T

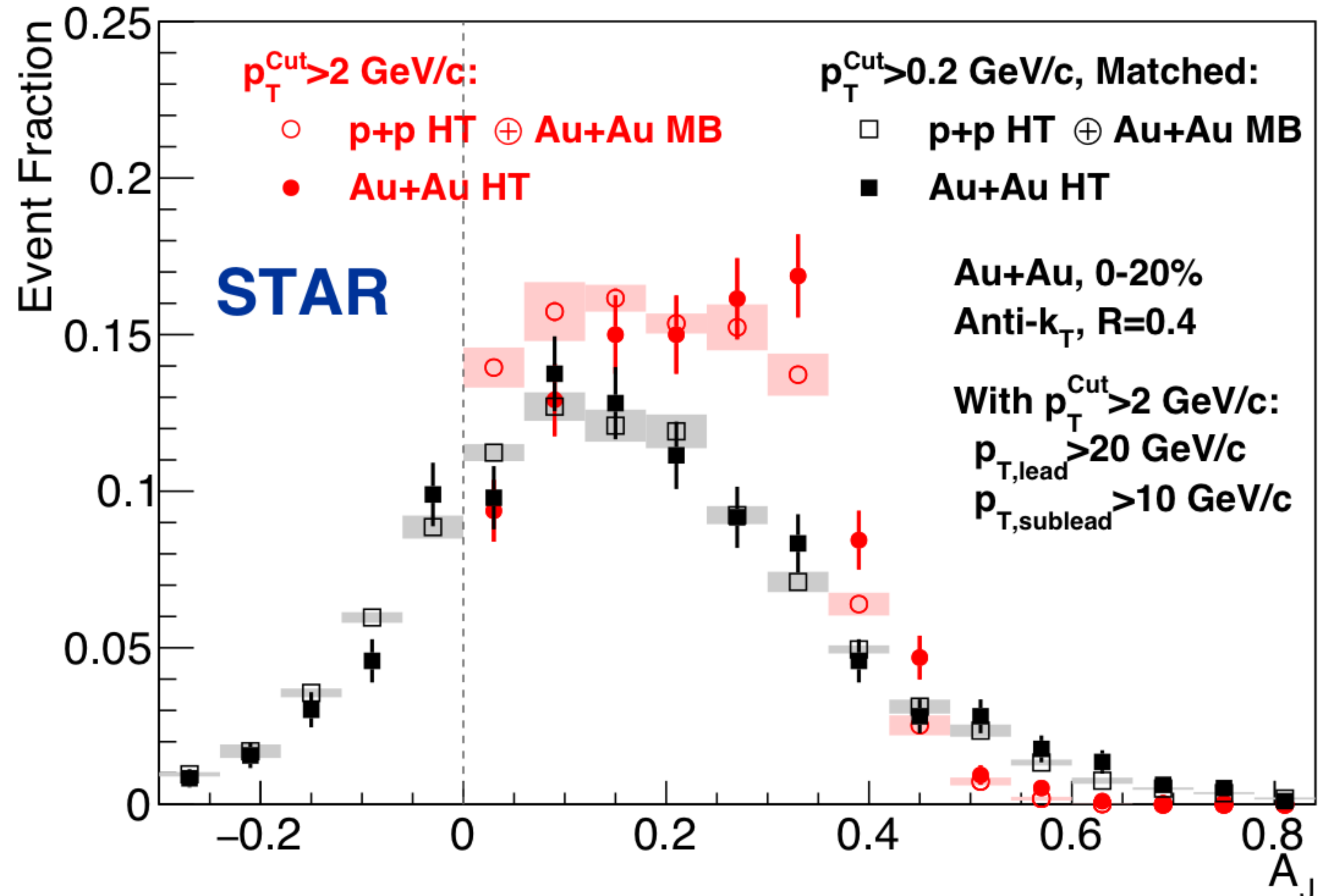
STAR, PRL **119**, 062301 (2017)

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



credit: K. Jung

for **hard core** matched dijets



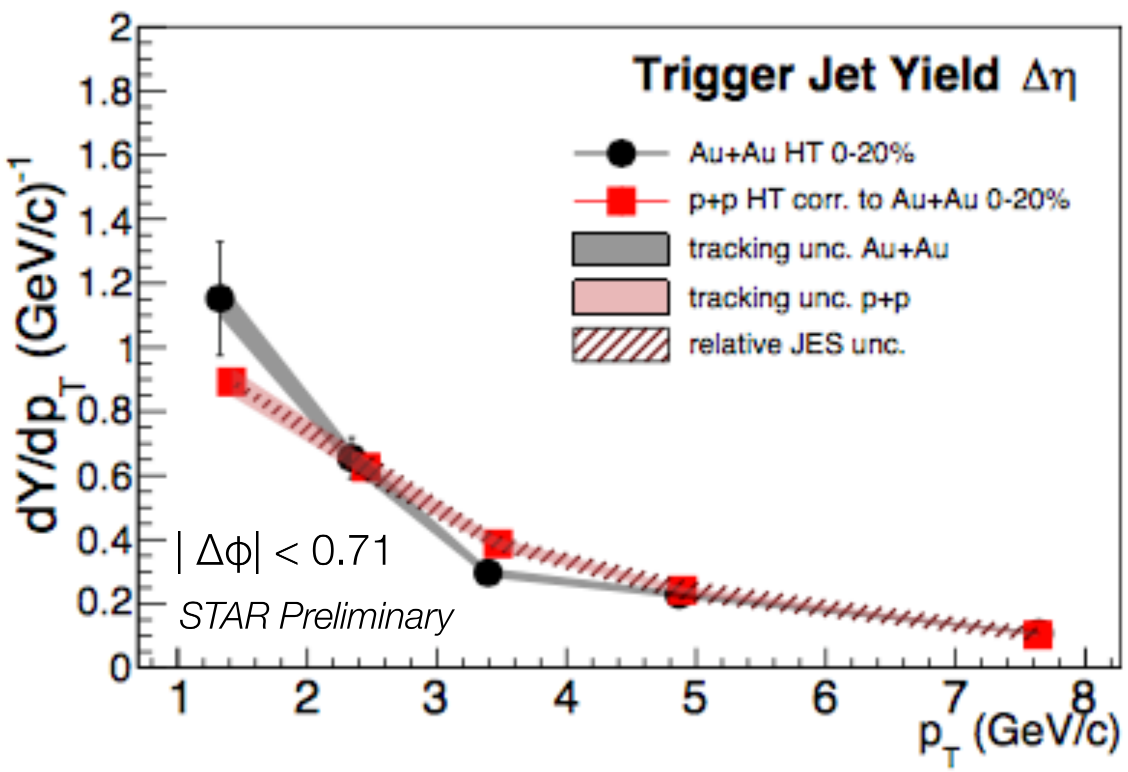
Momentum balance restored to pp baseline for R = 0.4, after adding particle < 2GeV/c

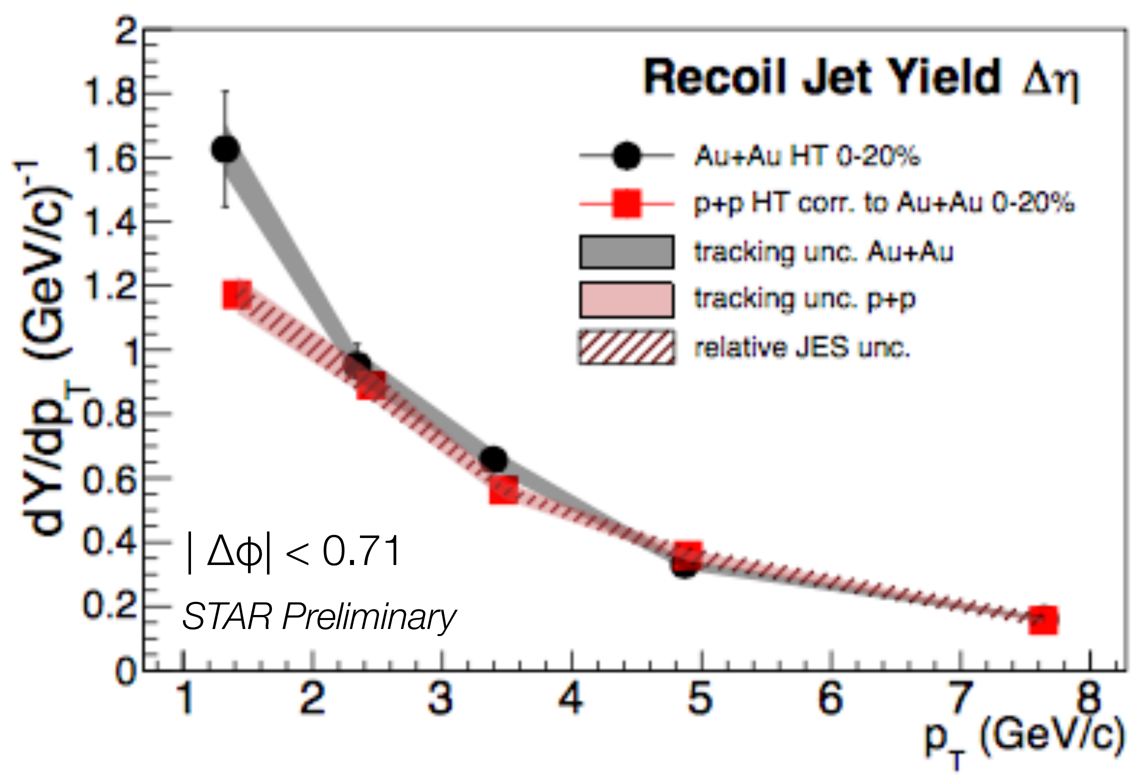
Dijet-Hadron Correlations

for **hard core** matched dijets

Background subtracted with Gaussian+constant fit

STAR, QM17





HT: E_T>4.5 GeV

No significant difference for jet constituent multiplicity

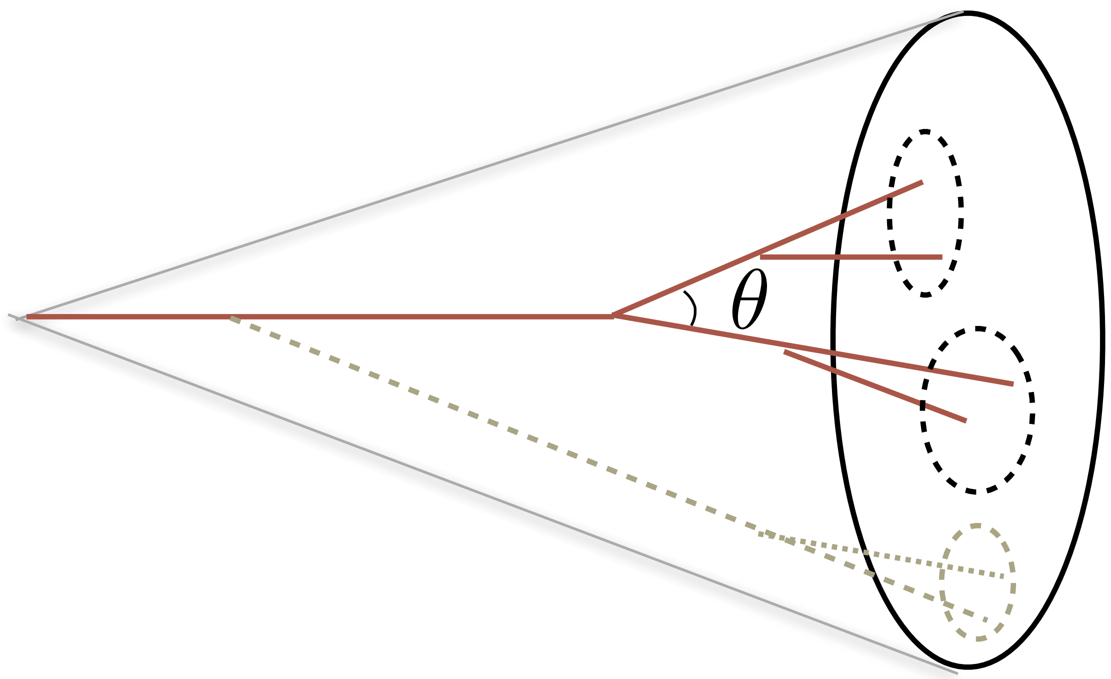
But jet energy changed — A_J different

→ Extend p_T coverage, study A_J dependence

Jet Substructure: Soft Drop z_g

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

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



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

energy threshold

angular exponent

Credit: Marta Verweij

Large-angle soft radiation + background are removed

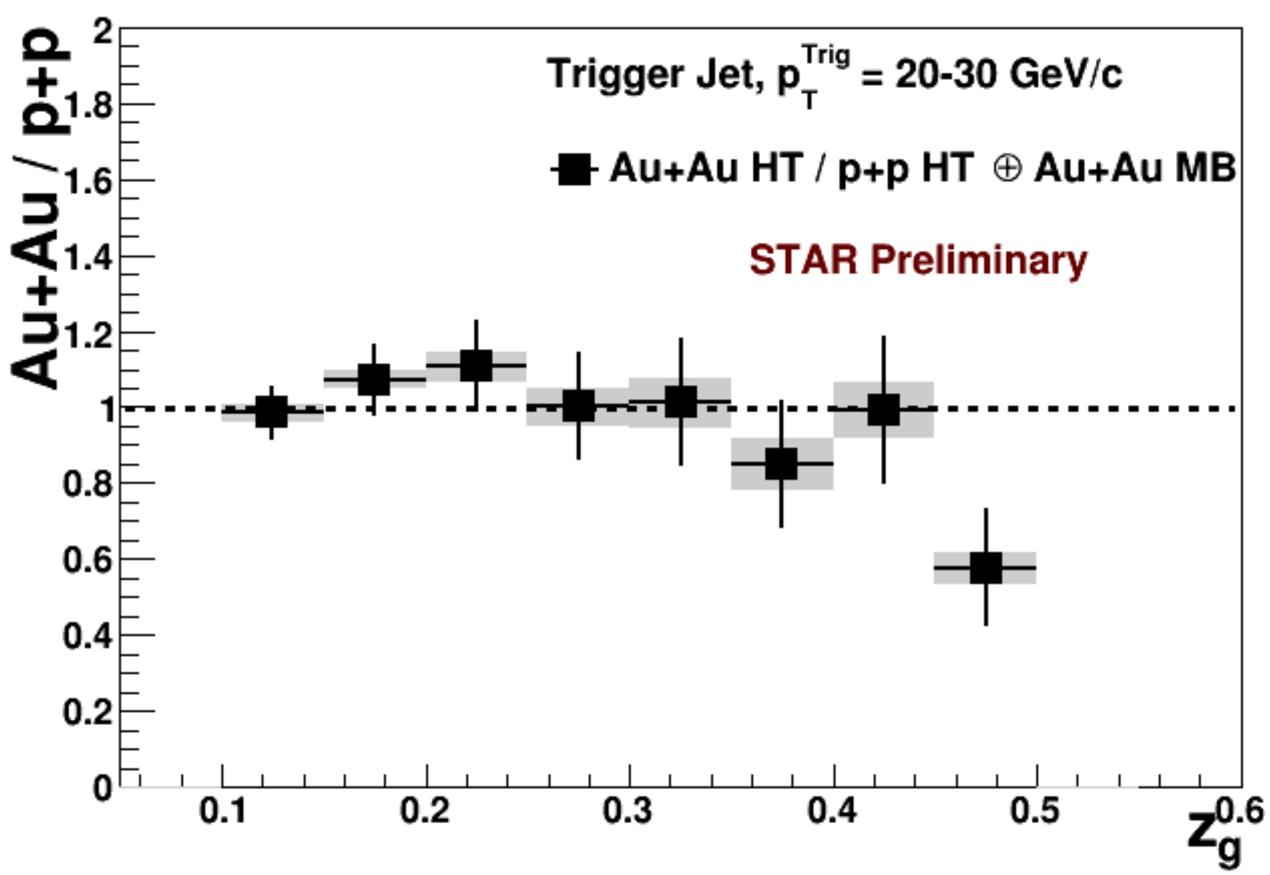
Goal: to search for modification of hardest jet splitting

Dijet Substructure z_g

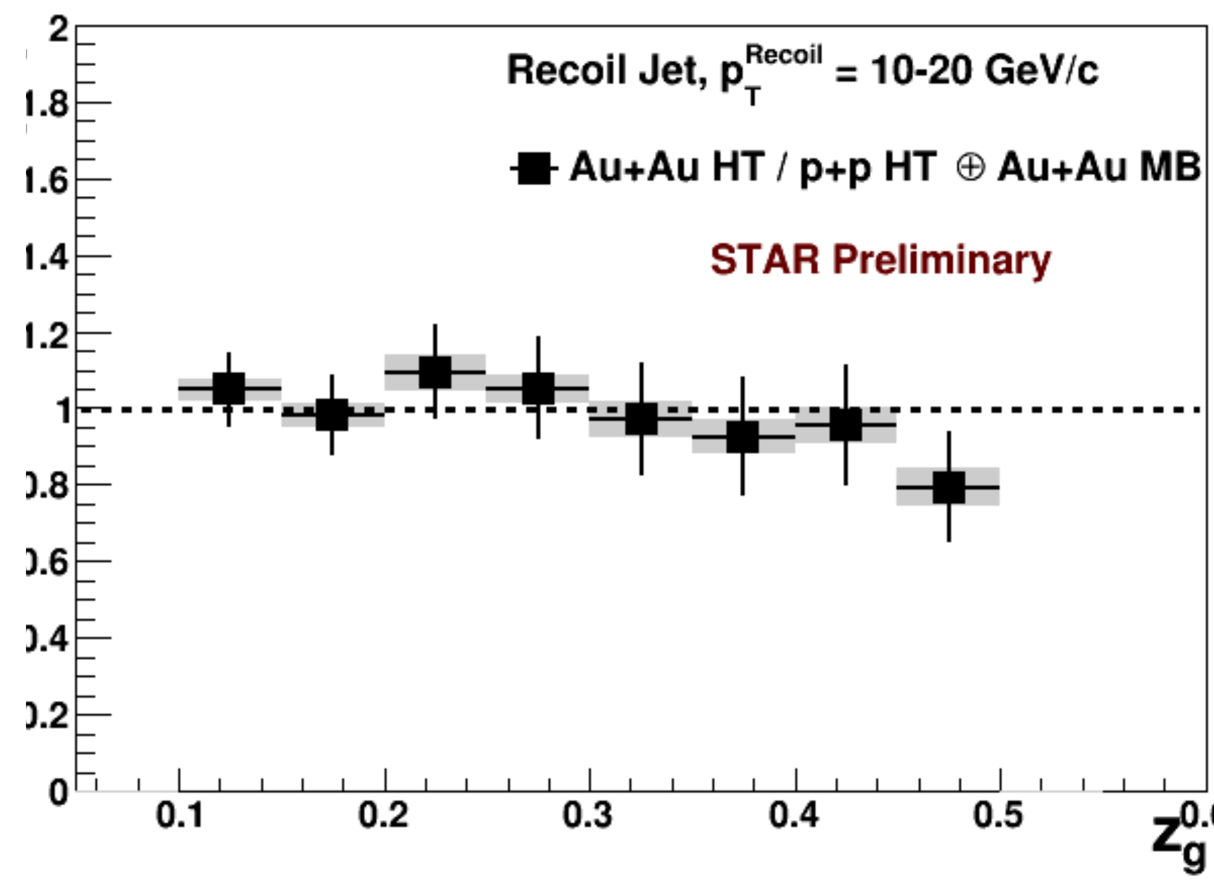
z_g in hard core matched dijets with $p_{T,cut}$ > 0.2 GeV/c

STAR, QM17

Trigger Jet

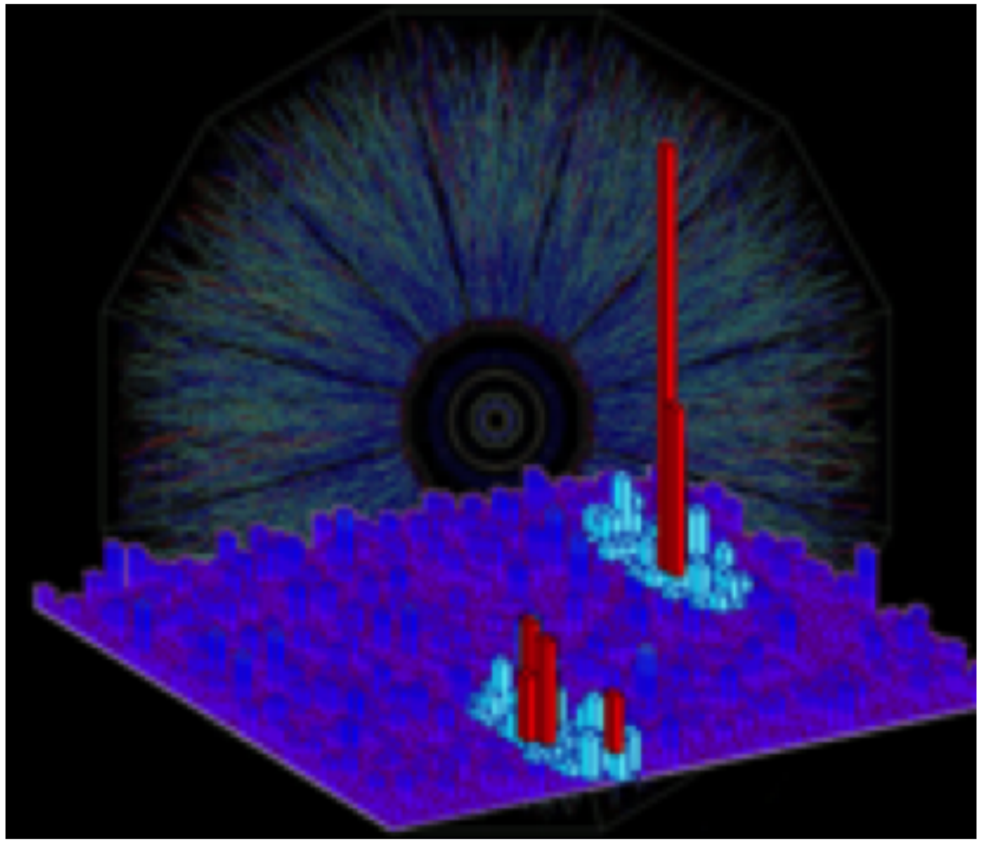


Recoil Jet



No significant splitting modification on near- or away-side

Probing the jet modification at RHIC



Significantly enhanced understanding of jet modifications at RHIC

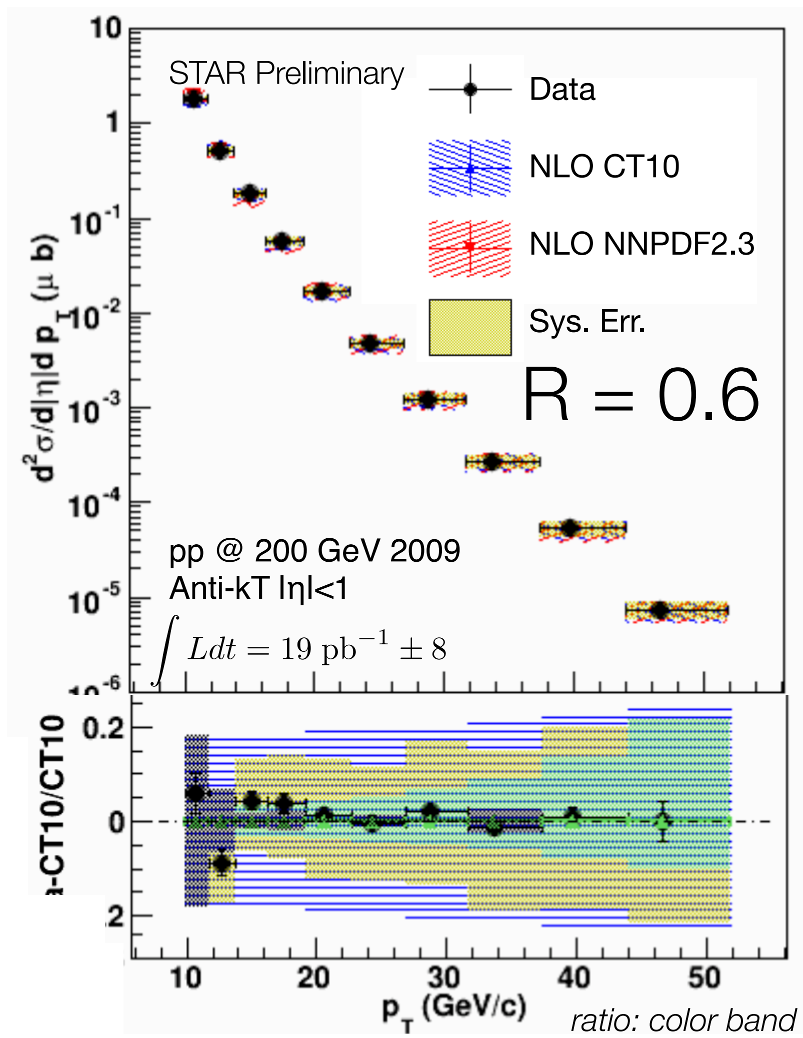
- High p_T hadron suppression at BES
  (arXiv:1707.01988)
- pp in very good agreement with theory
  (Di-jets, *PRD 95 (2017) 71103 (R)*)
- Unbiased recoil jets highly suppressed due to medium induced broadening
- Total E_{loss} less than at LHC
  (Hadron-jet correlations, *PRC 96 (2017) 24905)*
- Lost energy re-emerges at low p_T **not** z_T
  (γ-hadron correlations, *PLB 760 (2016) 689)*
- Di-jet energy imbalance largely recovered within R=0.4 when low p_T hadrons included
  (Di-jet A_J, *PRL 119 (2017) 062301* - Editor's suggestion)
- z_g unmodified for hard core jets
  (preliminary release)
- γ-jet, jet in small systems, flavor jet …
  (stay tuned)

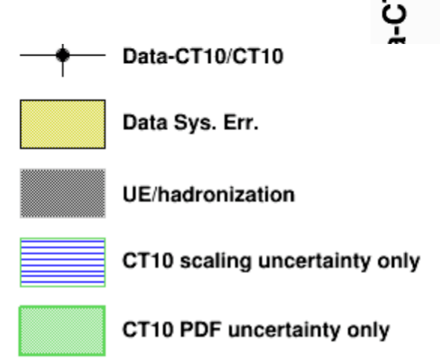
Jets in Vacuum: pp@200 GeV

Jets: reduce complexity of many hadrons to single objects

Inclusive Jet

jet cross section

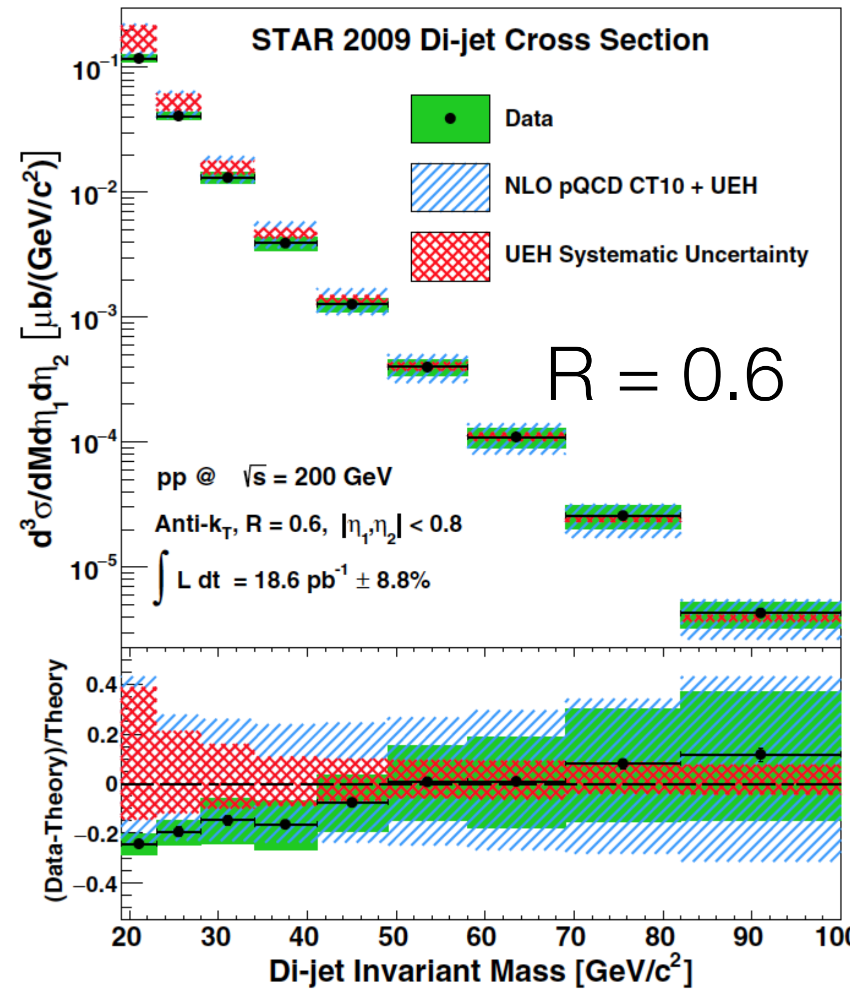




ratio: color band for various sys. err.

Dijet

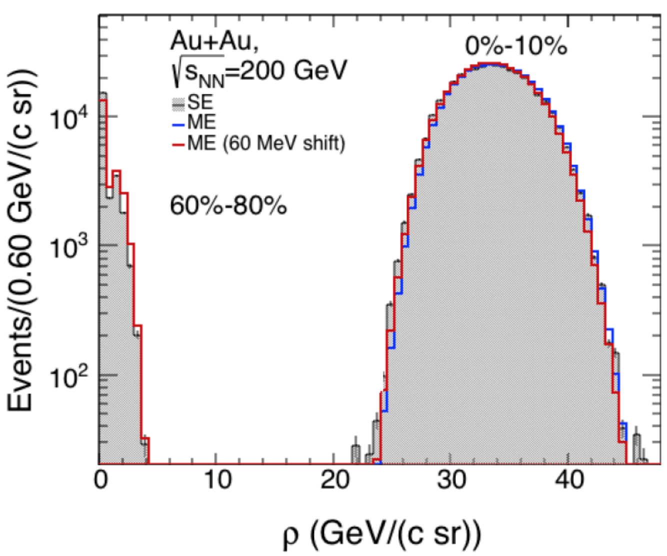
dijet cross section

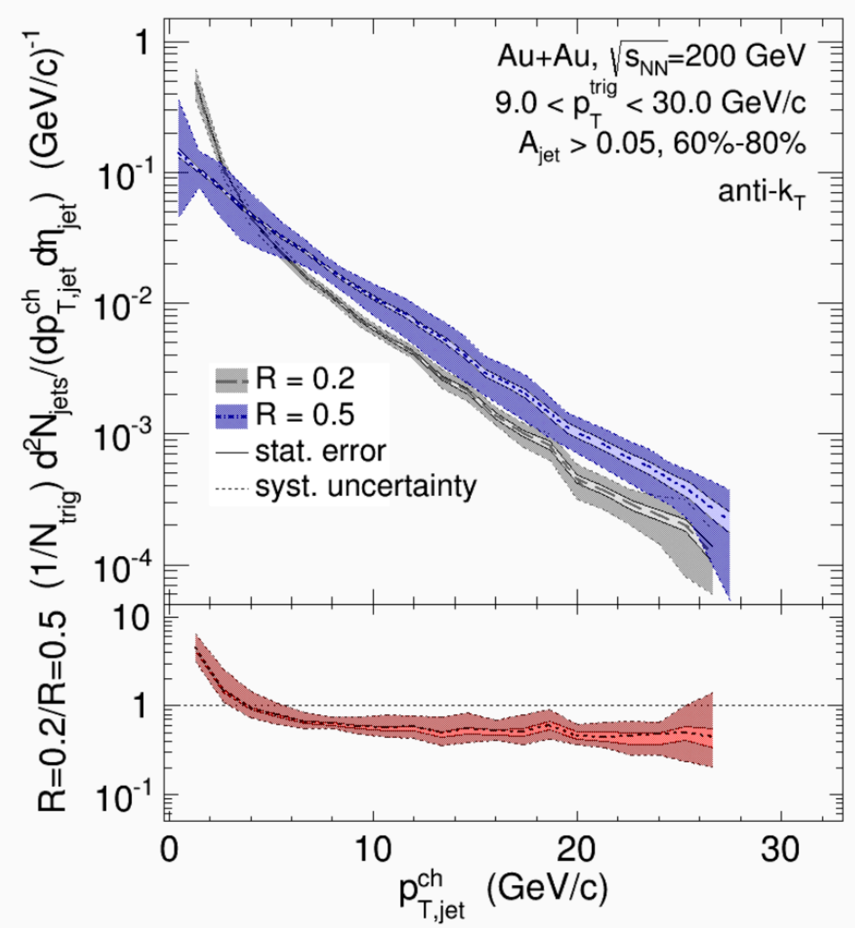


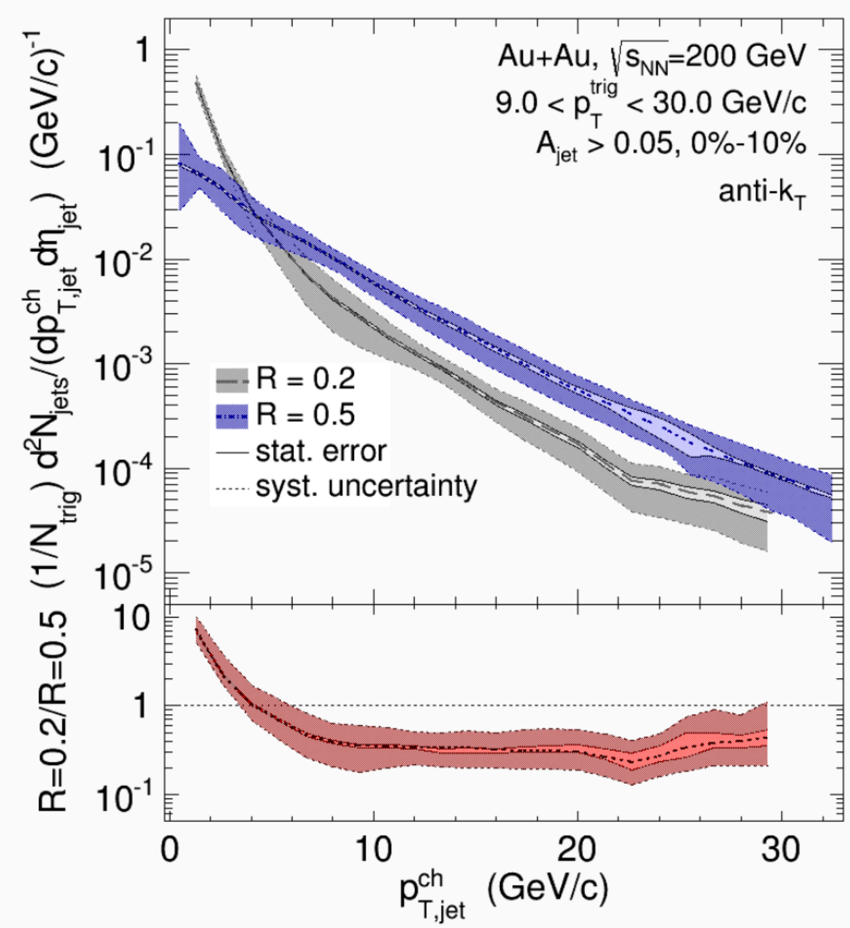
STAR, PRD. **95**, 071103(R) 2017

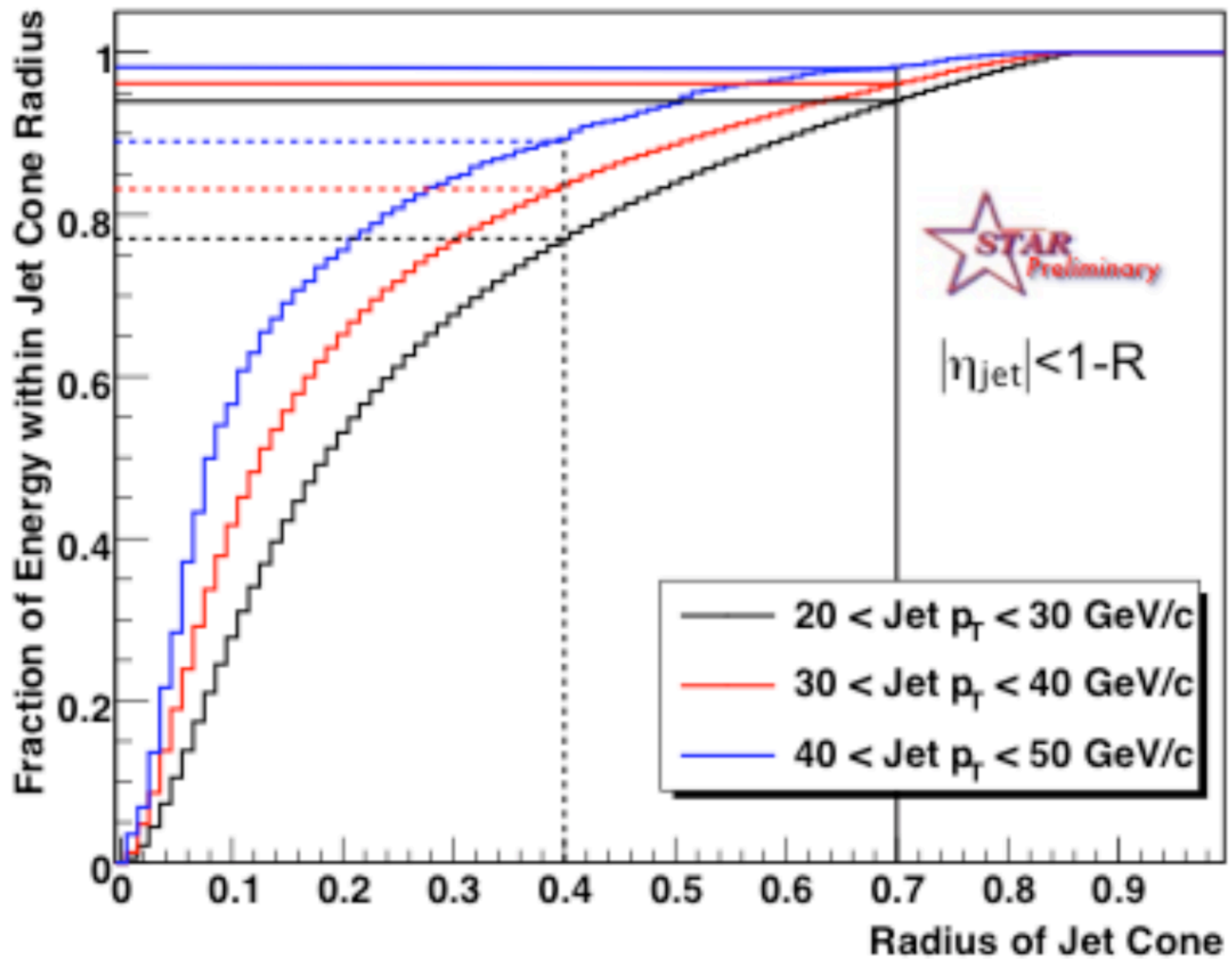
ll described by NLO pQCD → Jets as high precision tool

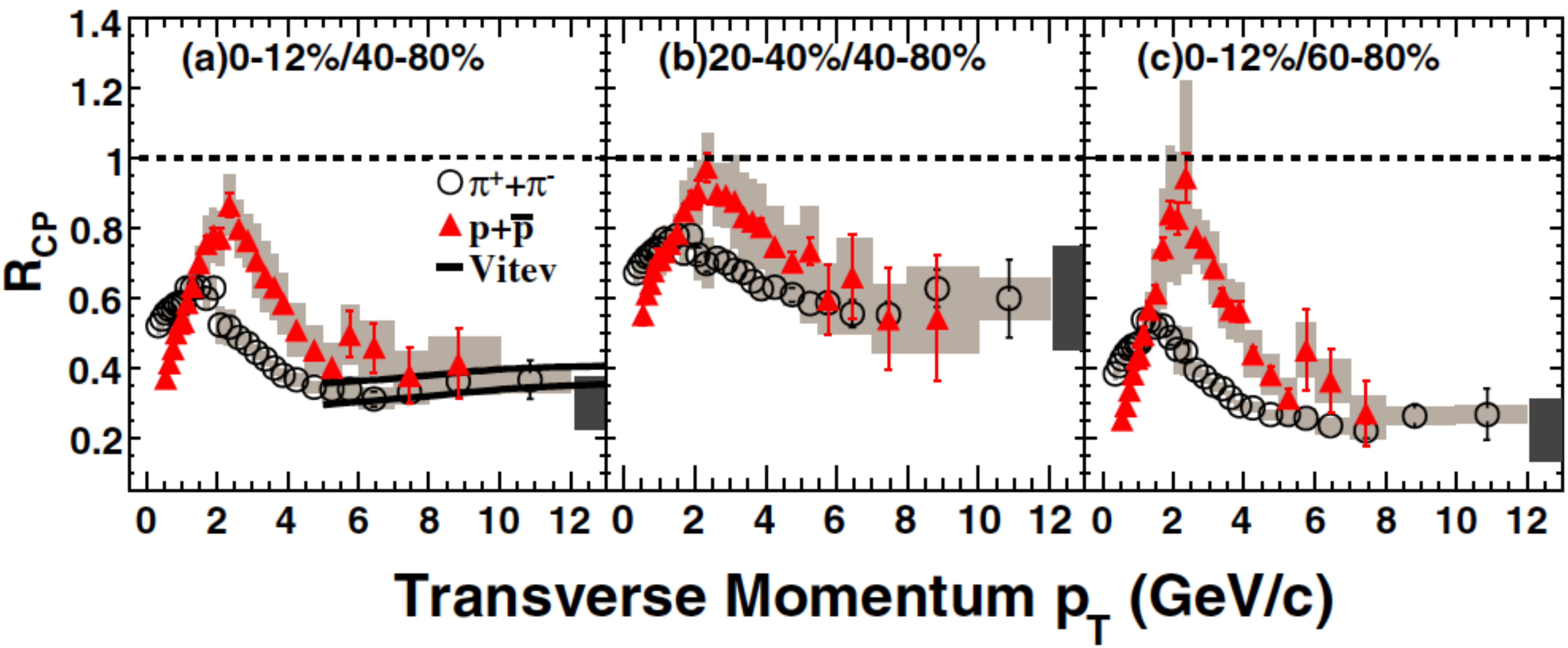
STAR, PRC **96**, 024905







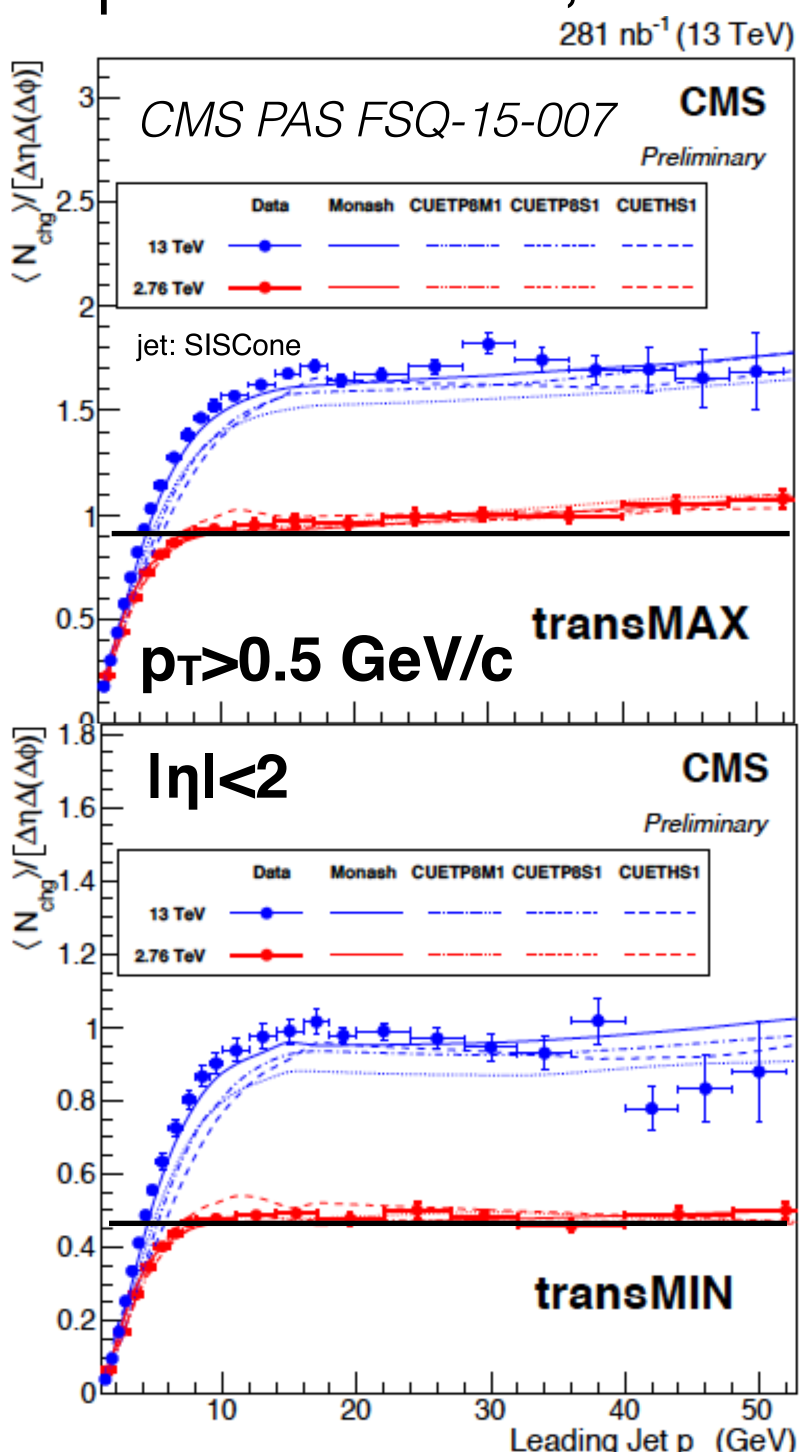

Fraction of Energy within Jet Cone Radius
Radius of Jet Cone
0
0.2
0.4
0.6
0.8
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
STAR Preliminary
$|\eta_{jet}|$<1-R
20 < Jet p_T < 30 GeV/c
30 < Jet p_T < 40 GeV/c
40 < Jet p_T < 50 GeV/c



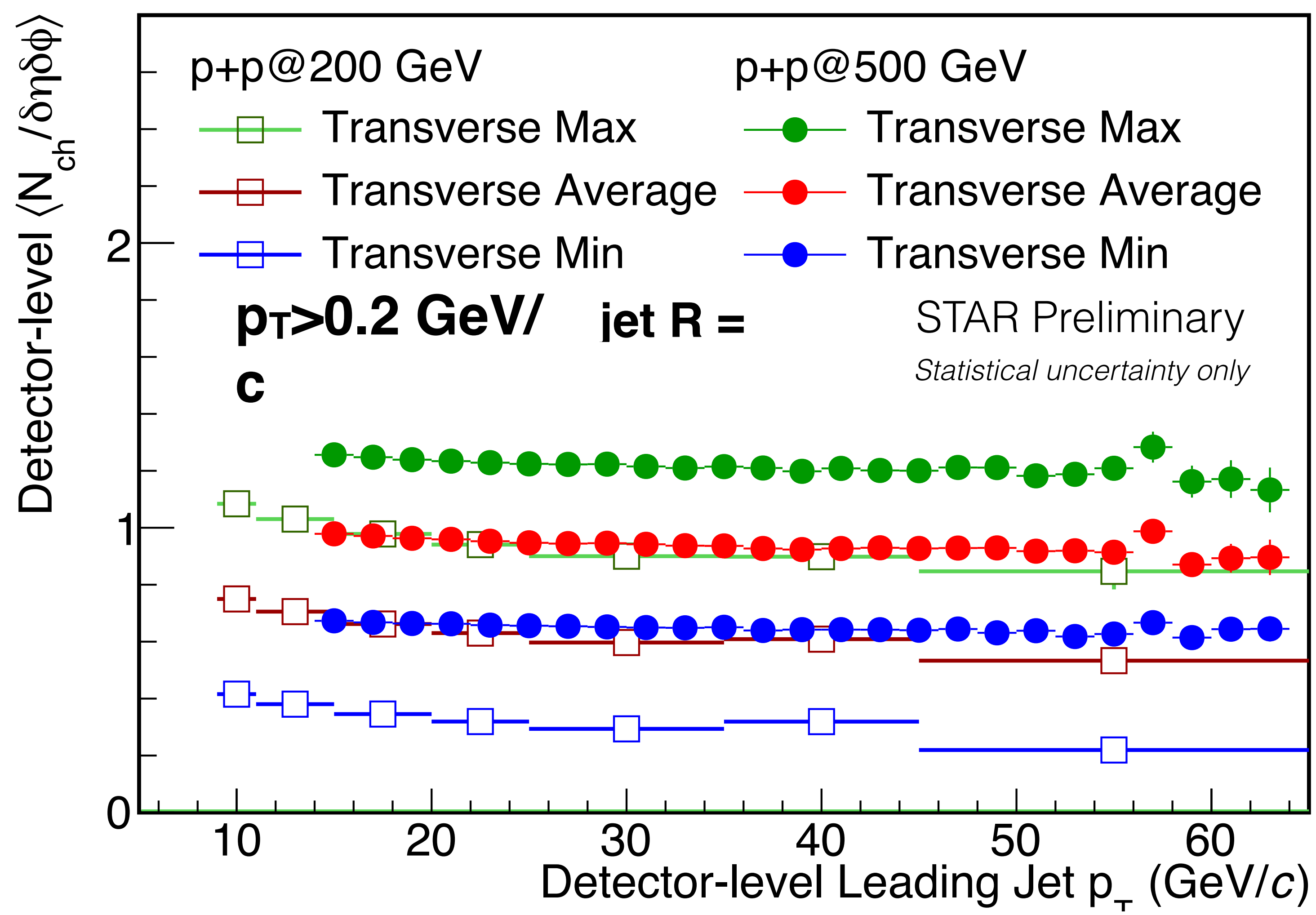
STAR, PRL 97, 152301 (2006)

Transverse Max Vs. Transverse Min

p+p@2.76TeV, 13TeV



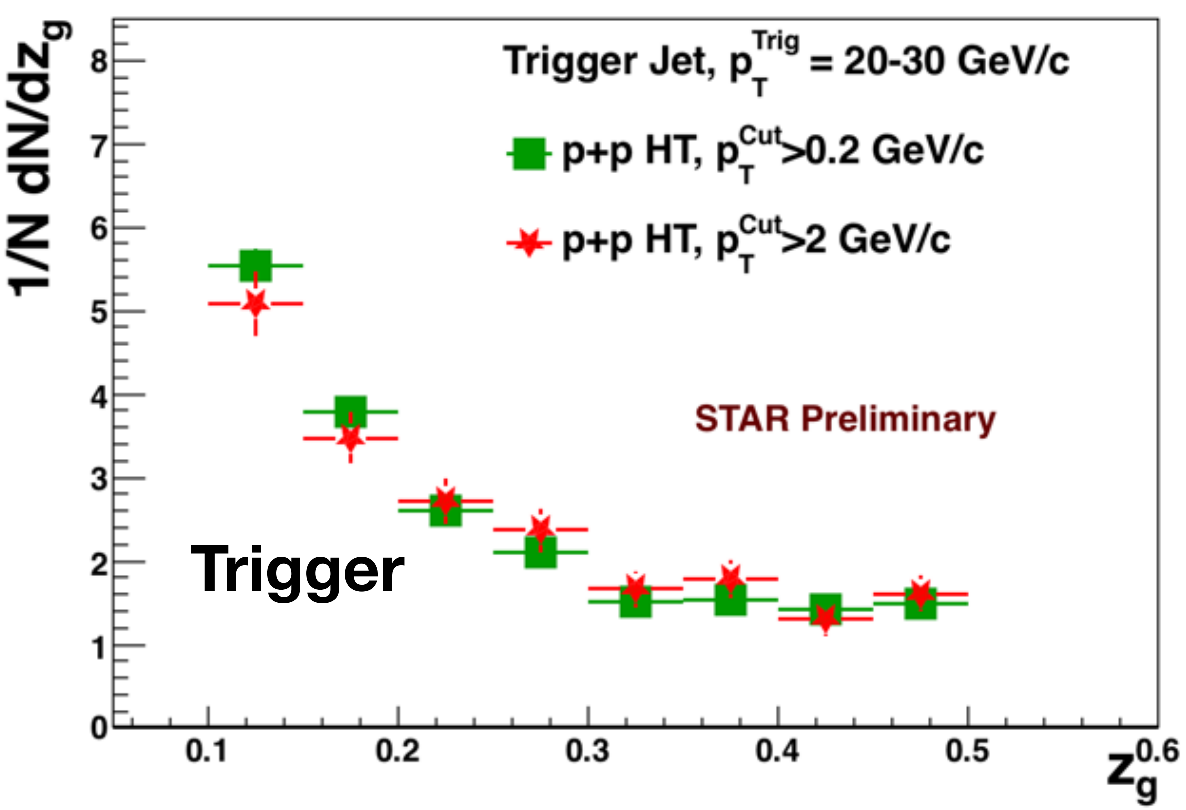
p+p@200GeV, 500GeV

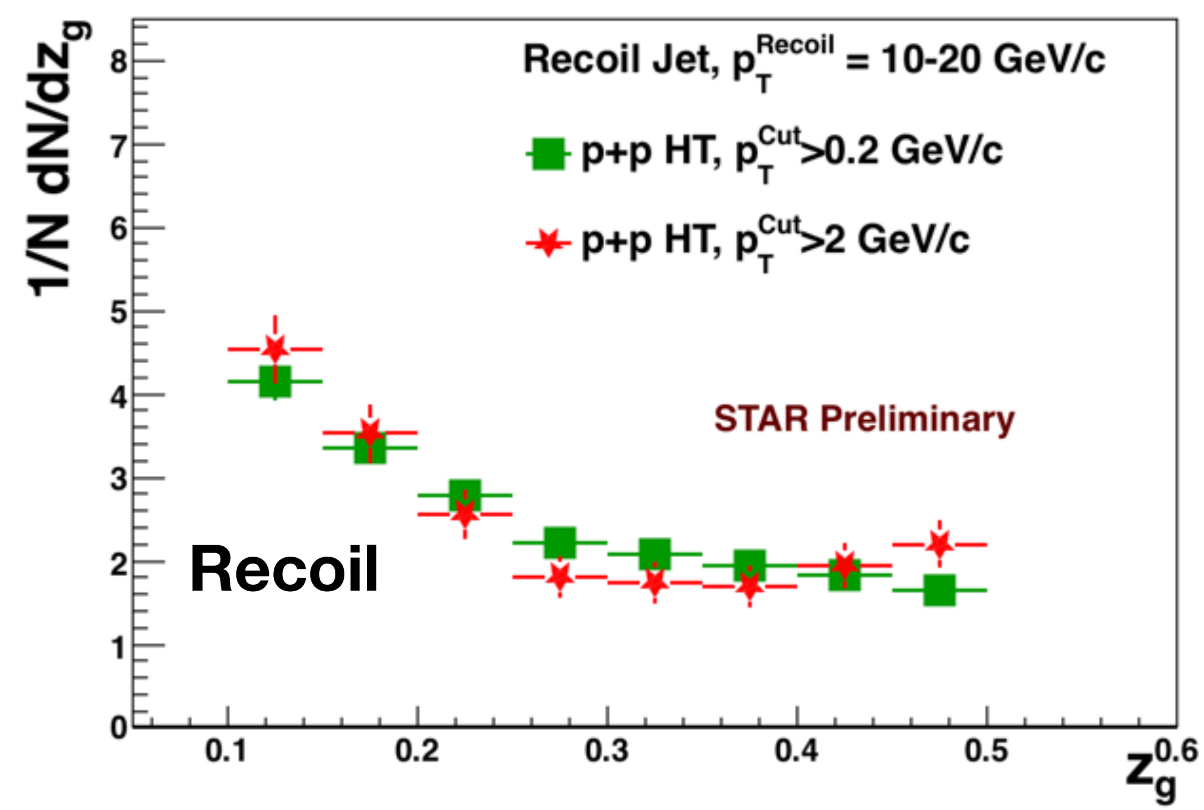


Hints of less Initial/Final State Radiation at RHIC energies

z_g for Hard Core Dijets in p+p at Detector Level

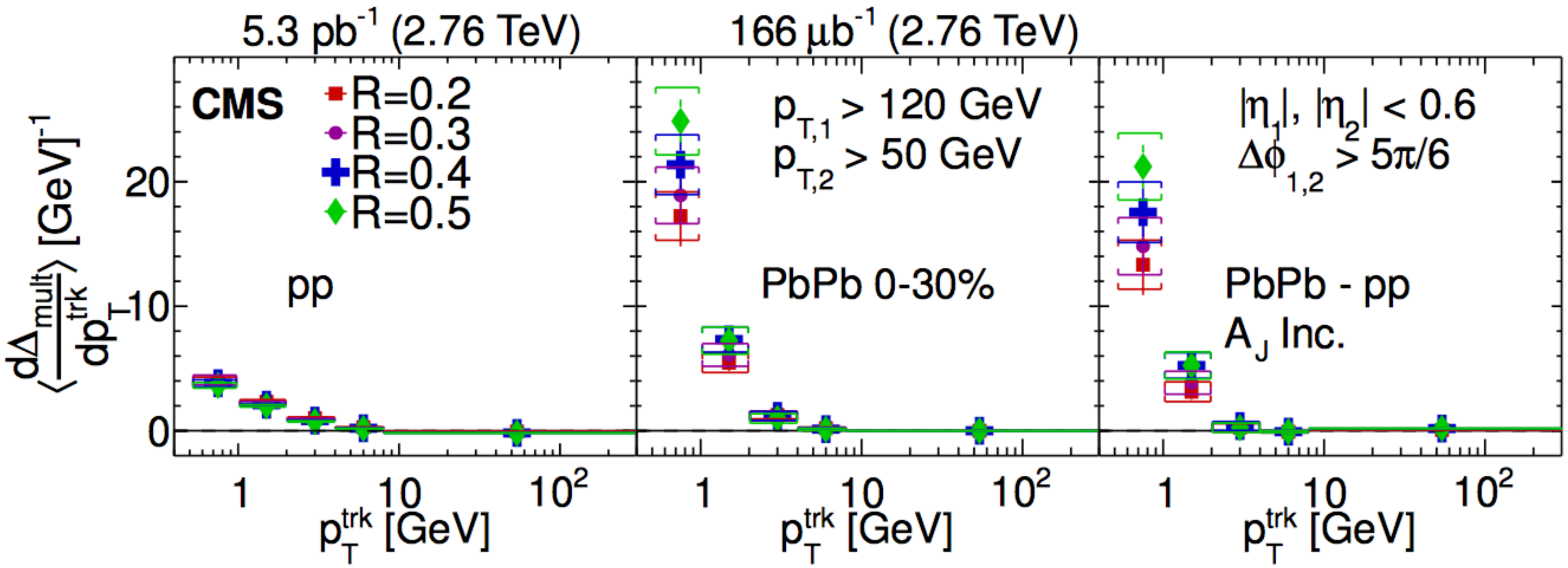
stat. errors only

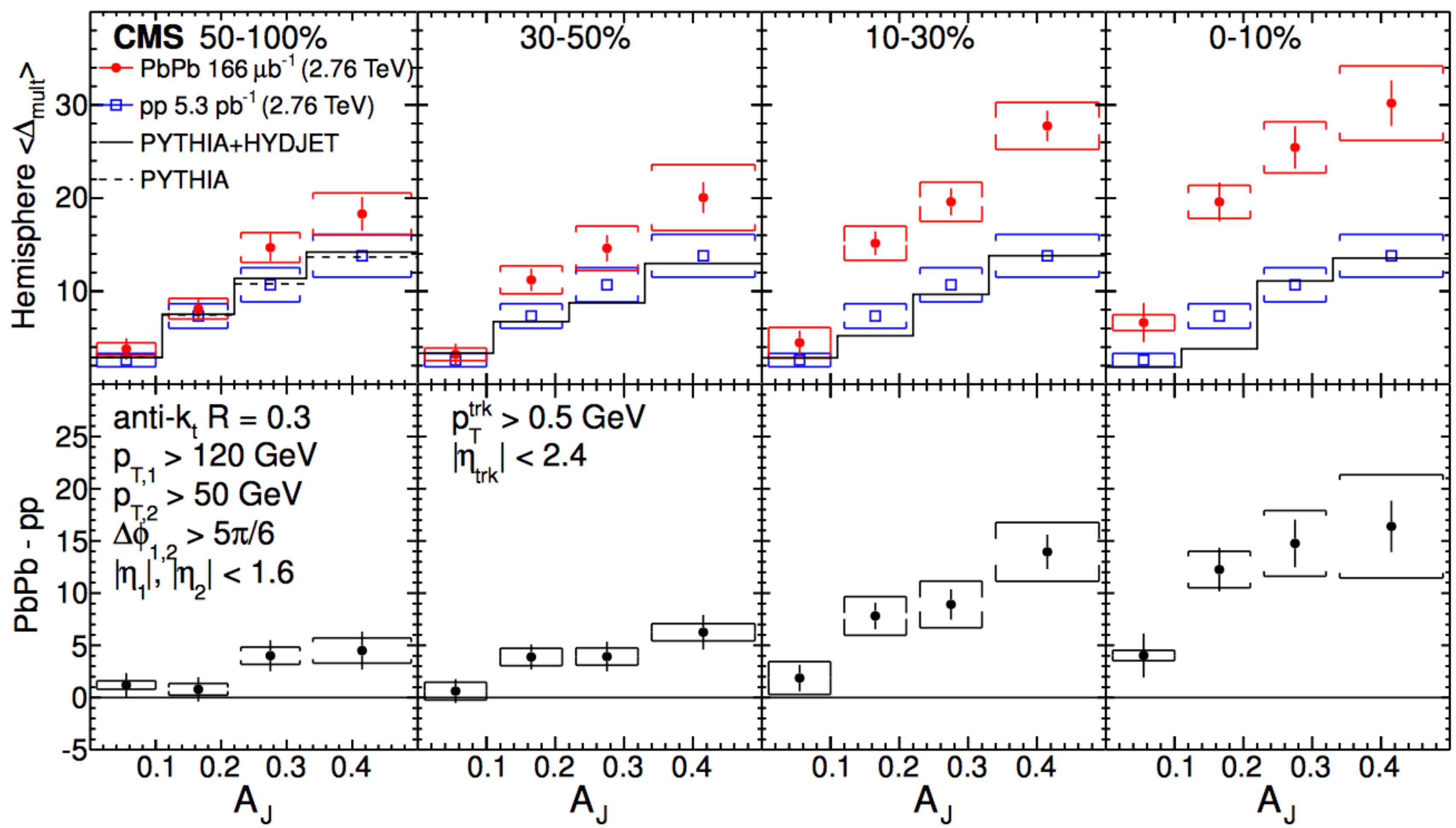




- Hard-core selection p_T^{Cut}>2 GeV/c shifts jet p_T and may bias toward different splitting pattern
  —> However, observe rather mild effect!

- Stat. uncertainty only, no unfolding


5.3 pb^-1 (2.76 TeV)
166 μb^-1 (2.76 TeV)
CMS
R=0.2
R=0.3
R=0.4
R=0.5
pp
pT,1 > 120 GeV
pT,2 > 50 GeV
PbPb 0-30%
|η1|, |η2| < 0.6
Δφ1,2 > 5π/6
PbPb - pp
AJ Inc.
pT trk [GeV]


CMS 50-100%
30-50%
10-30%
0-10%
PbPb 166 μb^-1 (2.76 TeV)
pp 5.3 pb^-1 (2.76 TeV)
PYTHIA+HYDJET
PYTHIA
Hemisphere <Δmult>
anti-kt R = 0.3
pT,1 > 120 GeV
pT,2 > 50 GeV
Δφ1,2 > 5π/6
|η1|, |η2| < 1.6
pT trk > 0.5 GeV
|ηtrk| < 2.4
PbPb - pp
AJ