Heavy ion jet measurements in STAR: status and outlook

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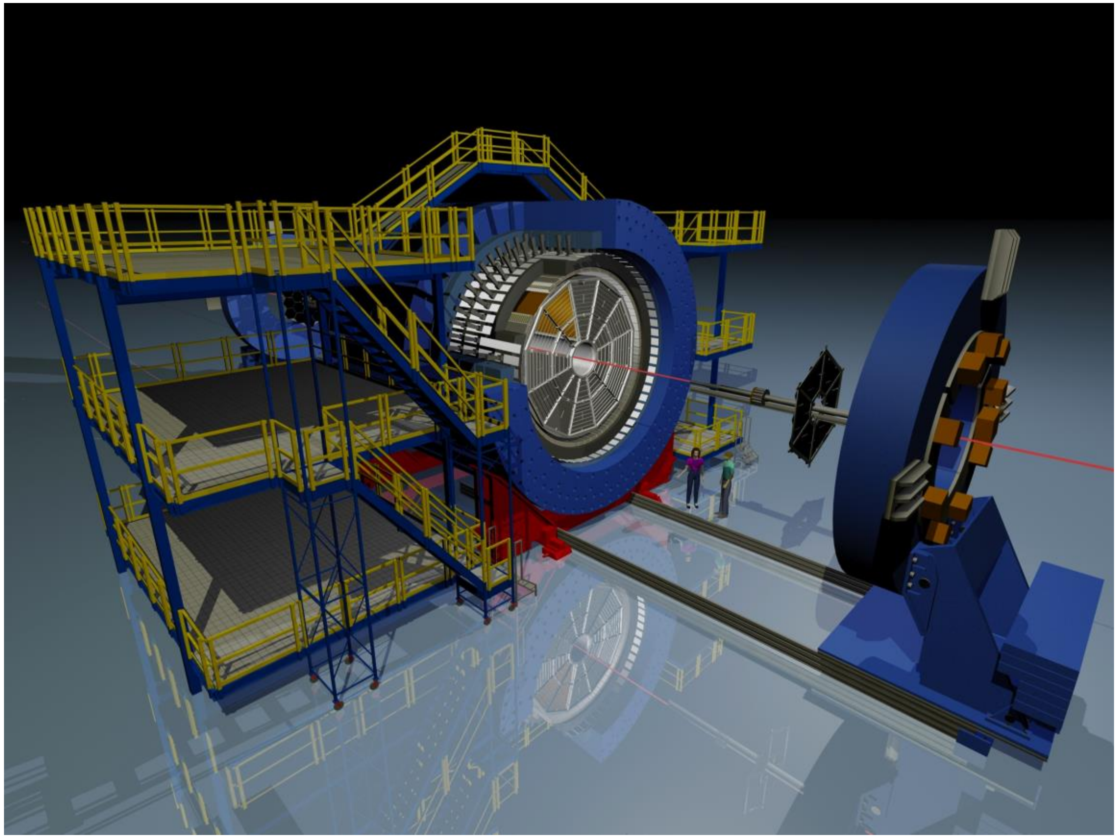


B. Mueller, sPHENIX Science Review

Hot QCD matter properties

Which **properties of hot QCD matter** can we hope to determine and how ?

Difficulty	Quantity	Observable
Easy for LQCD	$T_{\mu\nu} \Leftrightarrow \varepsilon, p, s$	**Equation of state**: spectra, coll. flow, fluctuations
	$\eta = \frac{1}{T}\int d^4x \langle T_{xy}(x) T_{xy}(0) \rangle$	**Shear viscosity**: anisotropic collective flow
Very Hard for LQCD	$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0) \rangle$ $\hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle i U^\dagger \partial^- A^{a+}(y^-) U A^{a+}(0) \rangle$ $\kappa = \frac{4\pi\alpha_s}{3N_c} \int d\tau \langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b \rangle$	**Momentum/energy diffusion**: parton energy loss, jet fragmentation
Hard for LQCD	$\Pi_{\rm em}^{\mu\nu}(k) = \int d^4x\, e^{ikx} \langle j^\mu(x) j^\nu(0) \rangle$	**QGP Radiance**: Lepton pairs, photons
Easy for LQCD	$m_D = -\lim_{\lvert x\rvert\to\infty} \frac{1}{\lvert x\rvert} \ln \langle U^\dagger E^a(x) U E^a(0) \rangle$	**Color screening**: Quarkonium states

General considerations for heavy ion jets (not STAR-specific)

Simple, transparent selection of jet population: what biases are we imposing?

Correction of jet distributions to particle level for all background and instrumental effects ("unfolding")

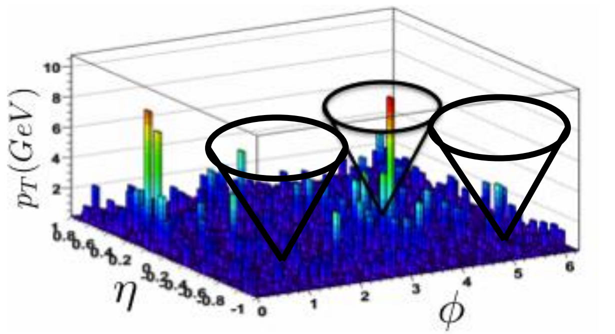
➔ Direct comparison to theory (no requirement to model background or instrumental effects)

Same algorithms and approach at both RHIC and LHC

➔ well-controlled over the full jet kinematic range (p_T^{jet} > ~20 GeV)
➔ energy evolution of quenching

Jets in Heavy Ion Collisions: STAR approach

Assignment of any given track or calorimeter cell to either background or jet signal is not meaningful on an event-wise basis



Only ensemble-averaged distributions of background-corrected signal are meaningful

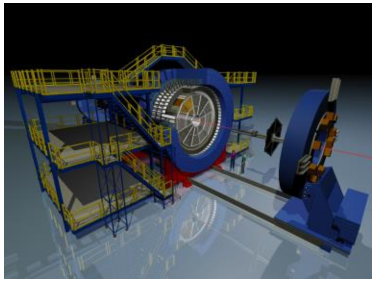
➔No jet selection/rejection based on background-corrected jet energy

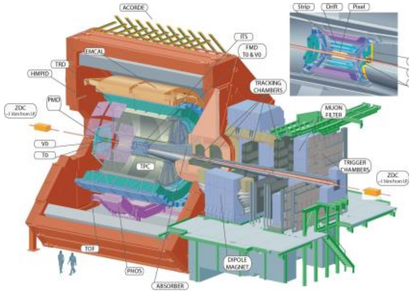
Instrumentation:

- Measurements based on EM calorimetry and tracking
- Why? Infrared safety:

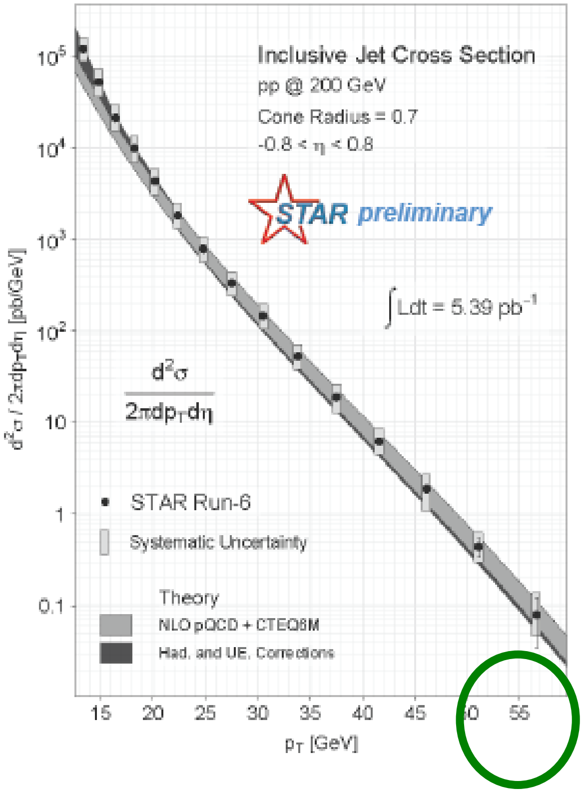
  ➔can measure individual jet consituents down to p_T~200 MeV (tracks, EMCal)
- Collinear safety – negotiable

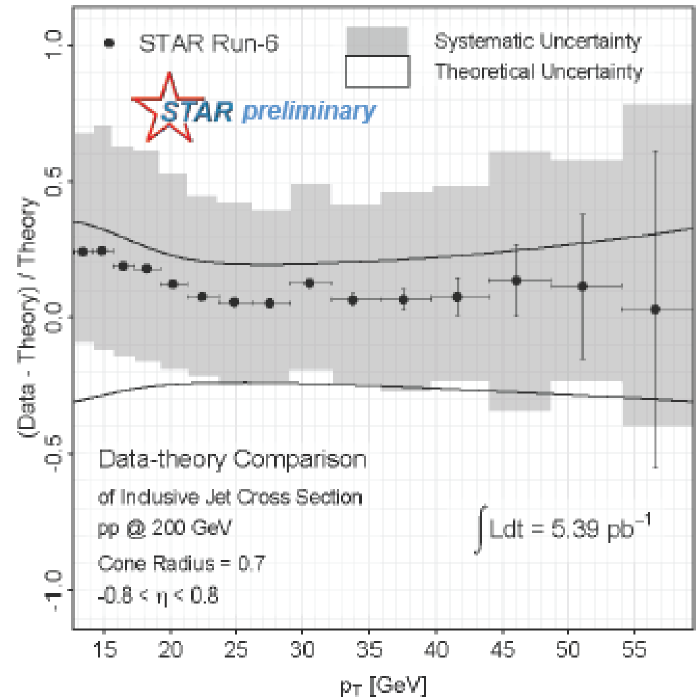
Same approach for STAR@RHIC and ALICE@LHC





STAR current performance: inclusive jet cross section in 200 GeV p+p





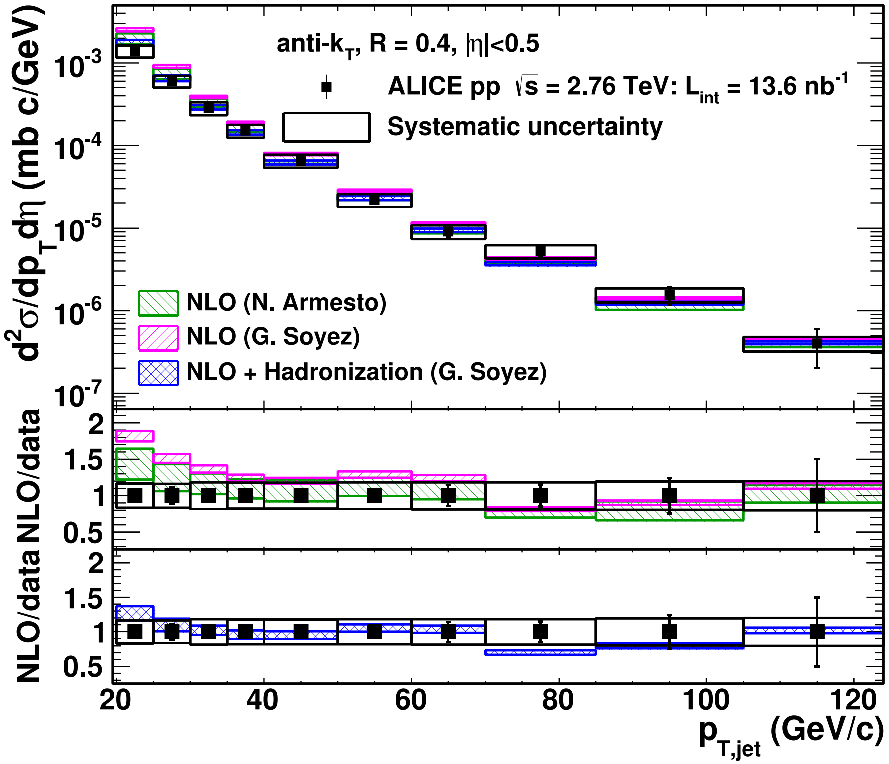
Well-described by NLO pQCD+Hadronization+Underlying Event

Mid-point cone, R=0.7; reach beyond 50 GeV

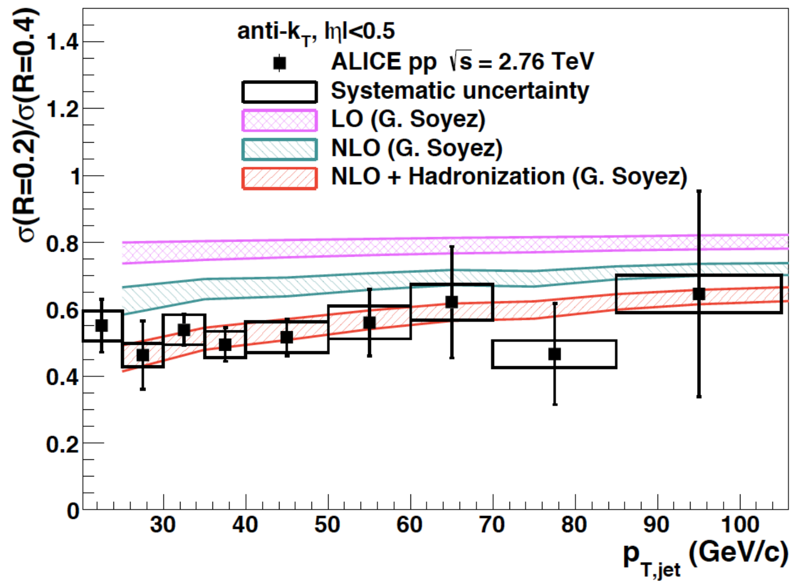
This measurement (2006, mid-point cone): JER ~23%, JES uncert~2-3%

2009 data, anti-k_T (+ other changes) ➔ JER ~ 18%

Inclusive jet cross section in 2.76 TeV p+p collisions (ALICE)



Phys Lett B722 (2013)262



Similar measurement technique: tracking + EMCal

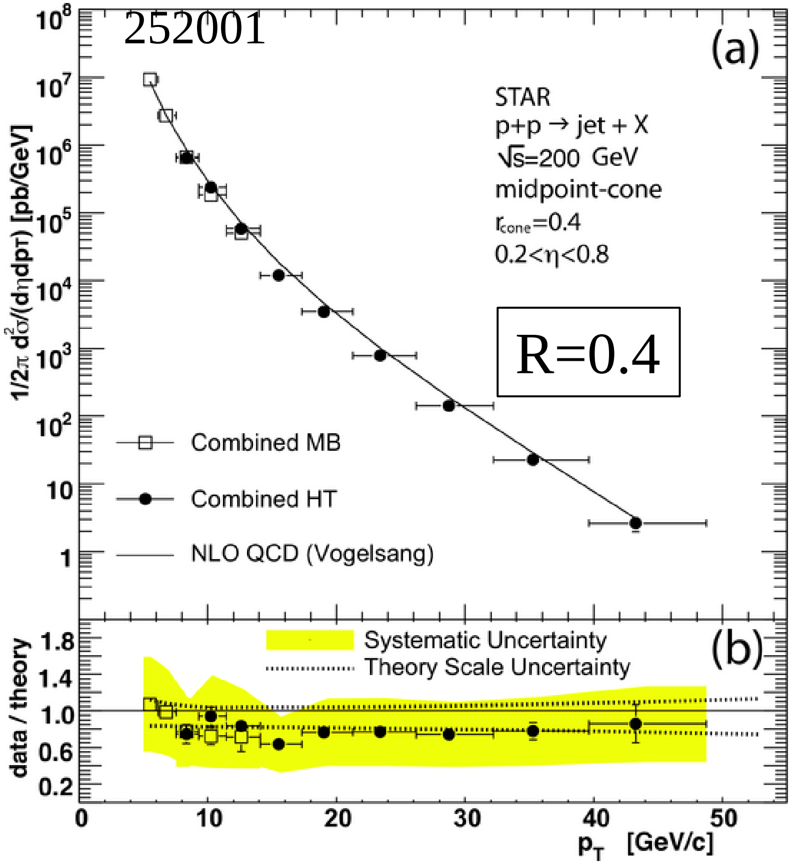
Anti-k_T, R=0.4:

- JER ~ 18%
- JES uncert < 3.6%

Similar performance to STAR p+p 2009

Estimated jet yields in STAR for 2011 and 2016 central Au+Au

Phys. Rev. Lett. 97 (2006) 252001



Run 11 Au+Au integrated luminosity ~ 2.8/nb

Estimate jet production yield (i.e. R_{AA}=1)

$$\sim T_{AA} \cdot \frac{d\sigma_{pp}^{jet}}{dp_T d\eta}$$

10% central Au+Au: ~2K jets with p_T>50 GeV (no quenching)

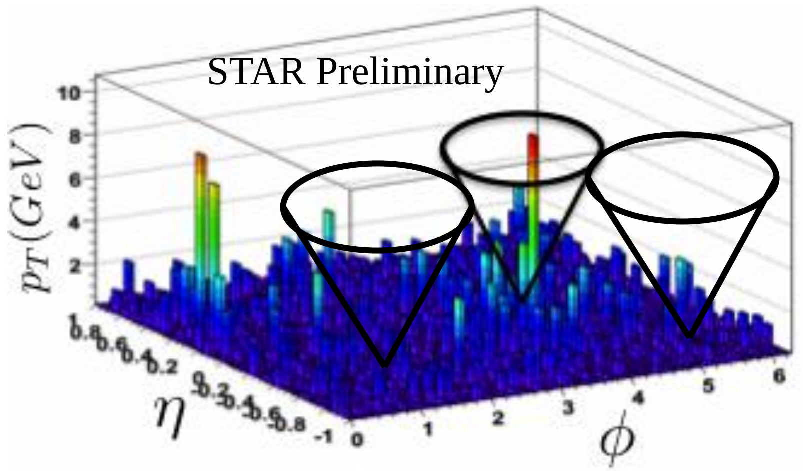
- Run 14 Au+Au @ 200: ~few /nb on tape
- STAR BUR Run 16 Au+Au @ 200: 10/nb
  ➔Central Au+Au: ~ 6K jets with p_T>50 GeV

Heavy ion jets: background density

For each event:

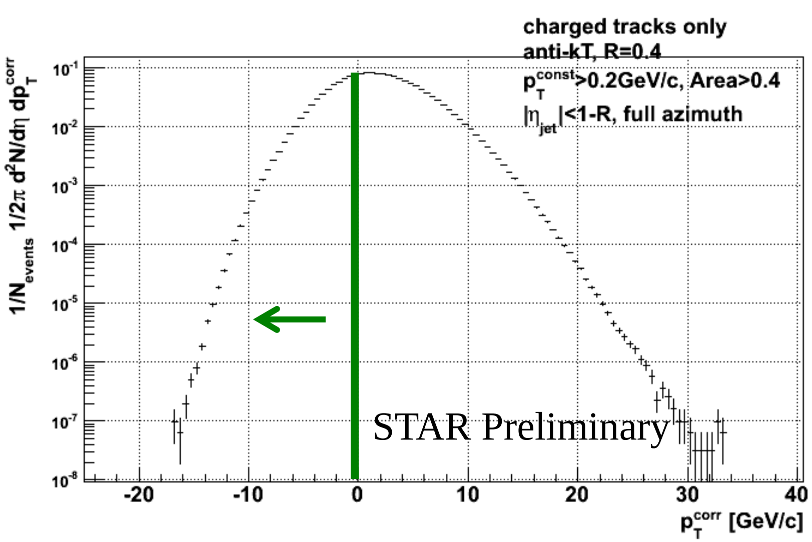
- Run jet finder, collect all jet candidates
- Tabulate jet energy $p_{T,i}^{jet}$ and area A_i^{jet}
- Event-wide median energy density:

$$\rho = \text{median}\left\{ \frac{p_{T,i}^{\text{jet}}}{A_i^{\text{jet}}} \right\}$$



Jet candidate p_T corrected event-wise for median background density:

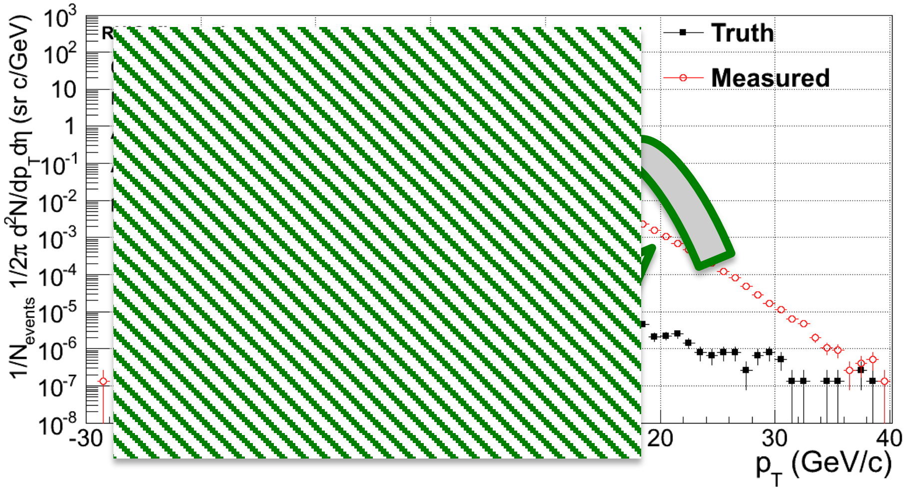
$$p_{T,i}^{\langle corr \rangle} = p_{T,i} - \rho \cdot A_i$$



~half the jet population has $p_T^{<corr>} < 0$

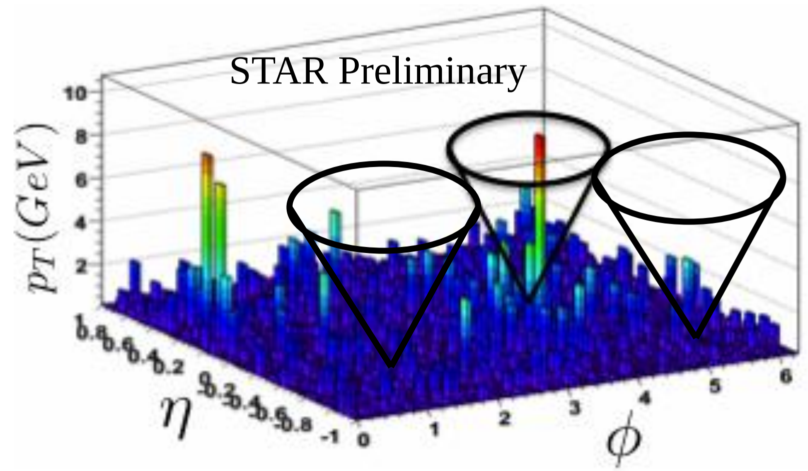
- Not interpretable as physical jets
- But we do not reject this component explicitly by a cut in $p_T^{<corr>}$:
  - Contains crucial information about background or "combinatorial" jets
  - Rejected at later step by imposition of a specific (transparent) bias on candidates

True and measured jet spectra



ATLAS/CMS/some ALICE:

- reject jet candidates based on $p_T^{<corr>}$
- Correct for missing yield by simulation



STAR/some ALICE:

- keep entire $p_T^{<corr>}$ distribution
- Reject background based on other observables

Background correction procedure:

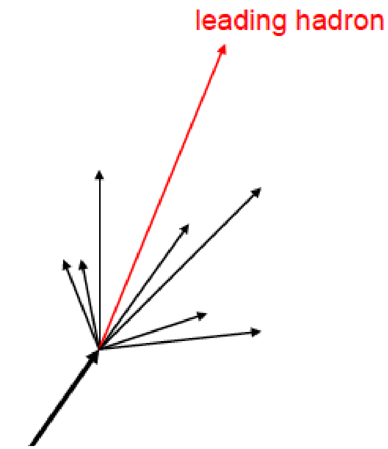
1. Isolate the real hard jet component and suppress combinatorial component
2. “Unfold” the effects of energy smearing on the hard jet component

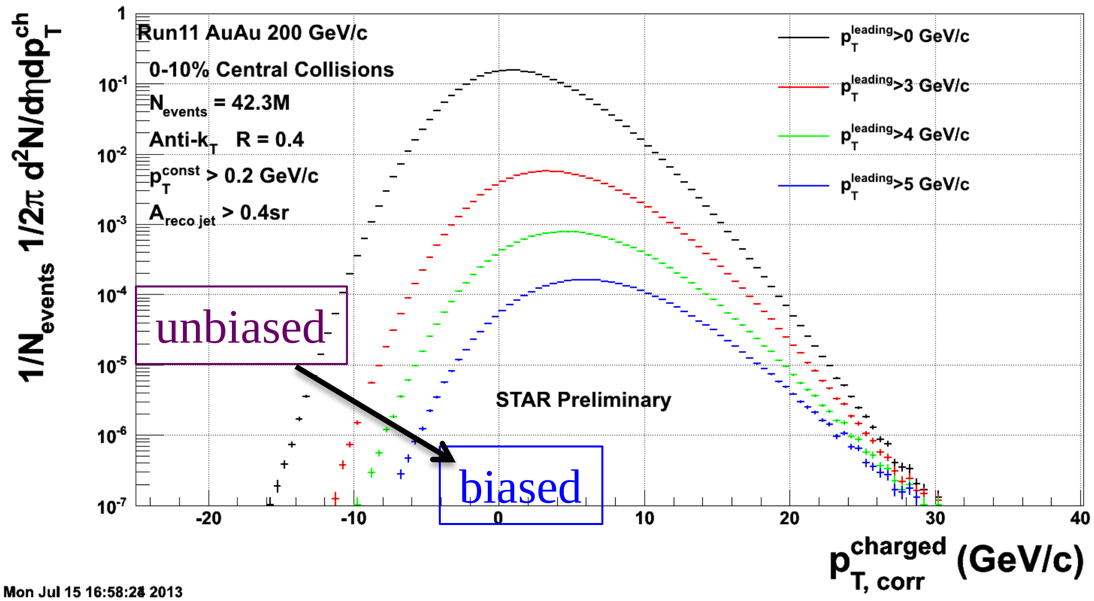
Inclusive jet spectrum: isolation of hard jet component

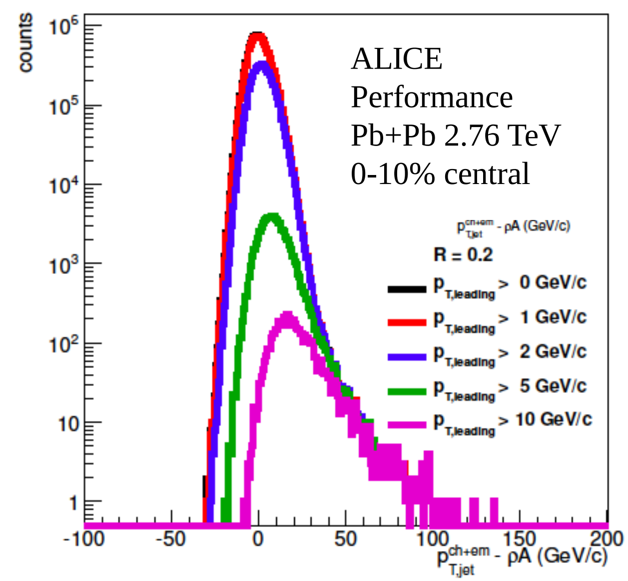
G. De Barros et al., arXiv:1208.1518

Require leading hadron of each jet candidate to be above p_T threshold

- Impose momentum scale discriminate hard/bkgd jets
- Infrared-safe: large fraction of jet energy can still be carried by very soft radiation (down to ~200 MeV)
- Collinear-unsafe: minimize p_T cut and vary it to assess its effect







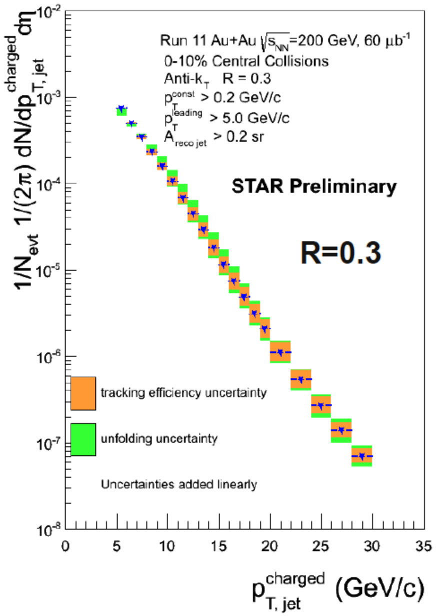
Quasi-inclusive jet spectrum in central heavy ion collisions at RHIC and LHC

Jan Rusnak
HP13

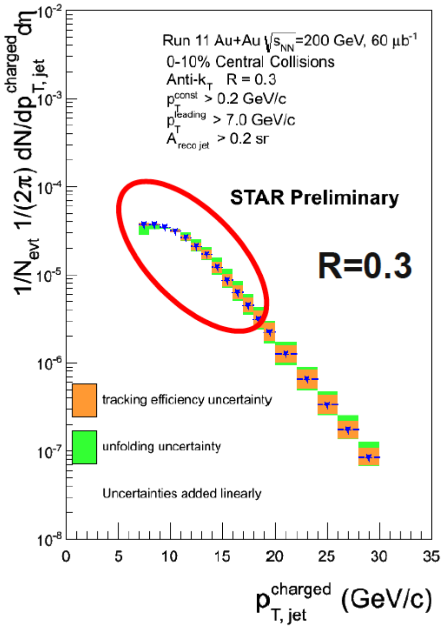
STAR central Au+Au
$\sqrt{s_{NN}}$=200 GeV
Charged jets R=0.3

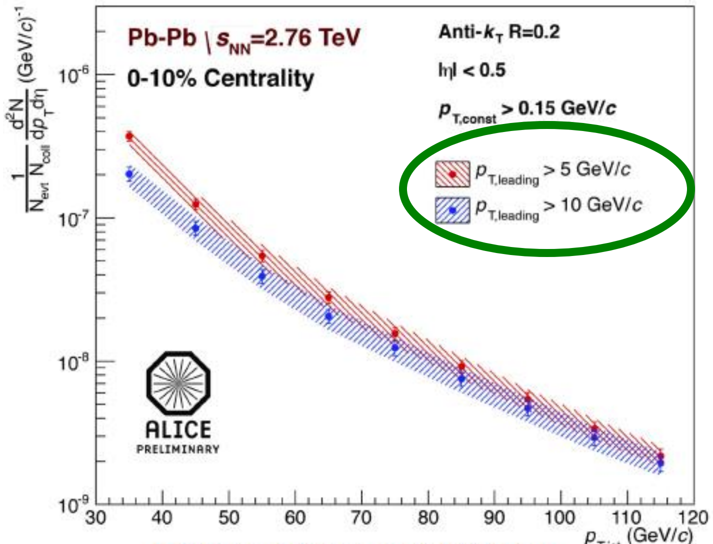
ALICE central Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
Full jets R=0.2

p_T^{thresh}=5 GeV



p_T^{thresh}=7 GeV



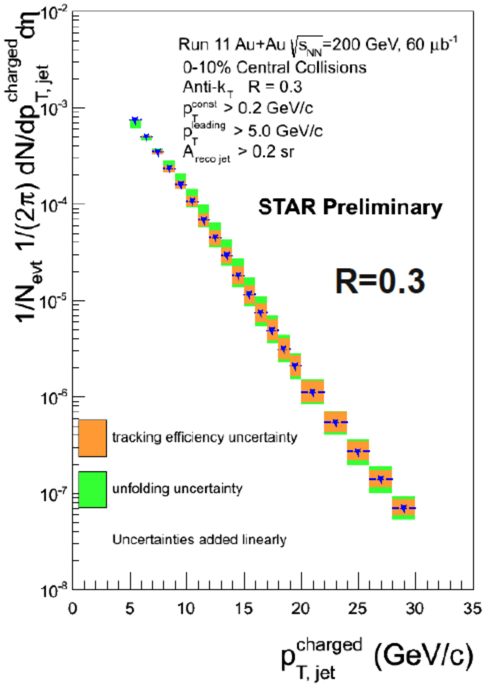


[ALICE collaboration, arXiv:1304.6668]

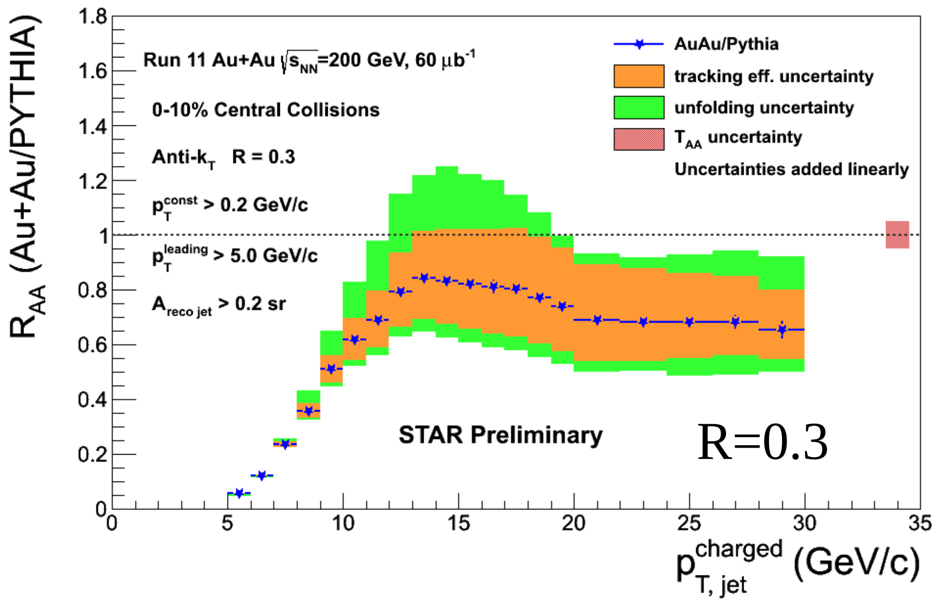
Jet R_{AA}: central Au+Au @ 200 GeV

J. Rusnak, HP2013

p_T^{thresh}=5 GeV



Charged jet R_{AA}, $p_T^{leading}$>5 GeV



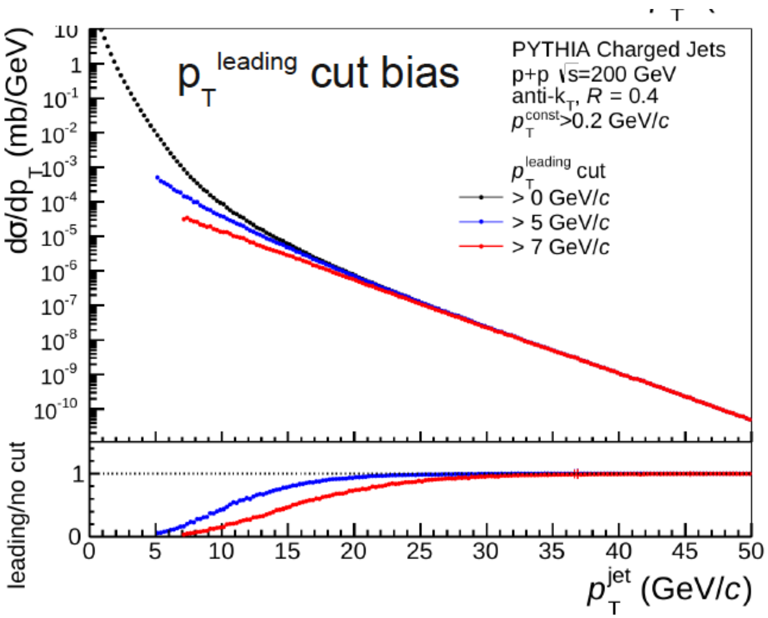
- Proof of principle: quasi-inclusive jet spectra can be measured with well-controlled systematics over a broad kinematic range
- In progress: full jets (w/ BEMC), larger R, kinematic reach,…

Inclusive jets : bias in p+p and Au+Au

Ratio of heavy ion jet yield to p+p jet cross section

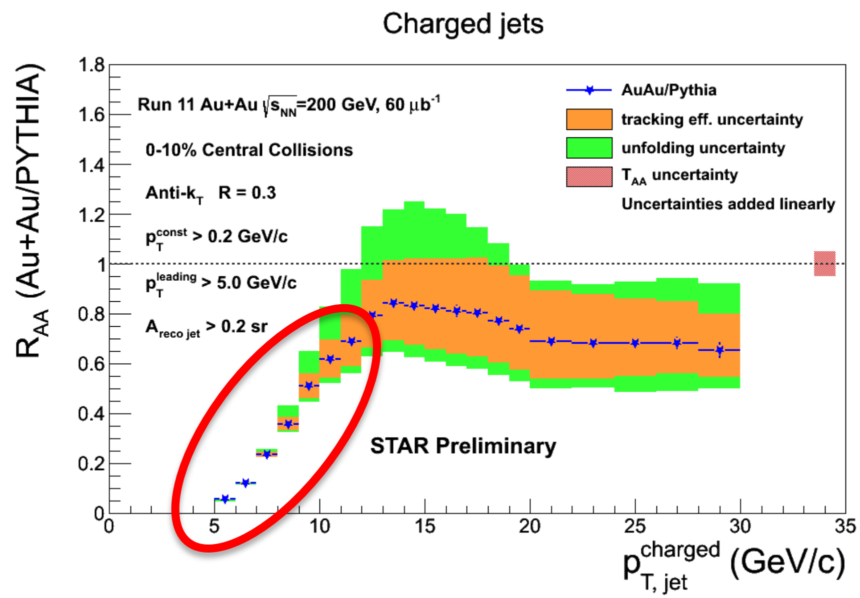
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

p+p spectrum with leading hadron bias



Bias persists to ~few times hadron p_T threshold

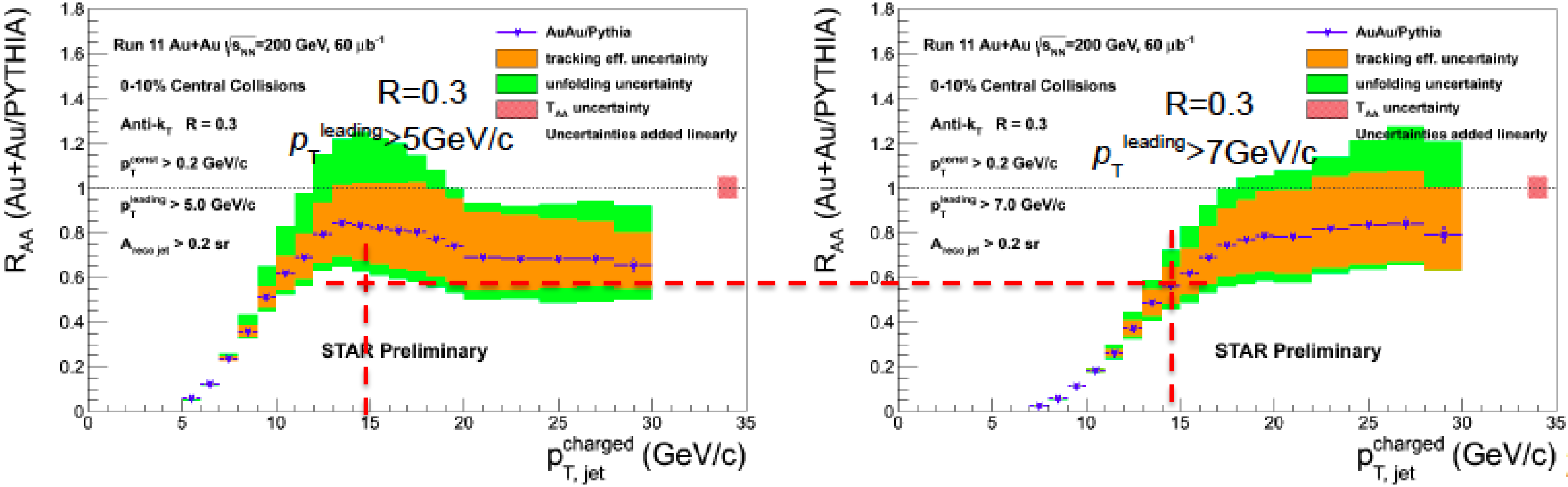
biased Au+Au/unbiased p+p



Bias in Au+Au not markedly different than in p+p

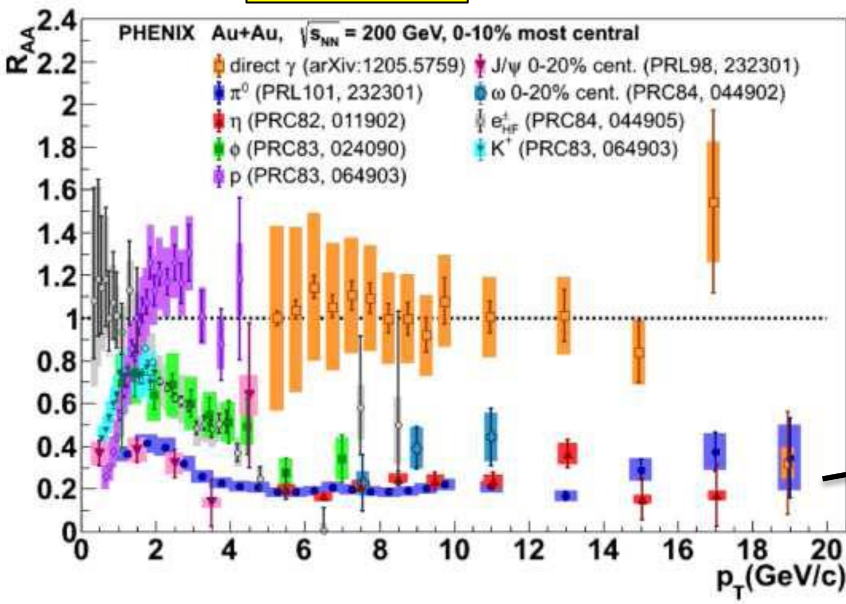
➔Vacuum-like jets?

Variation of $p_T^{leading}$ bias

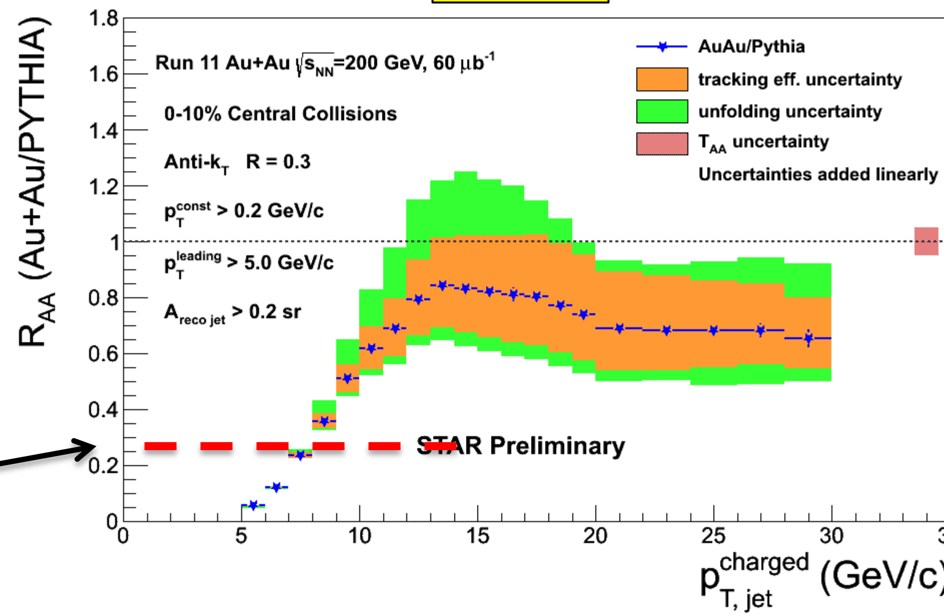


Hadron vs jet suppression at RHIC

Hadrons

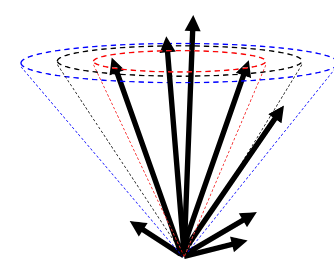


Jets



Jets are markedly less suppressed than hadrons at RHIC

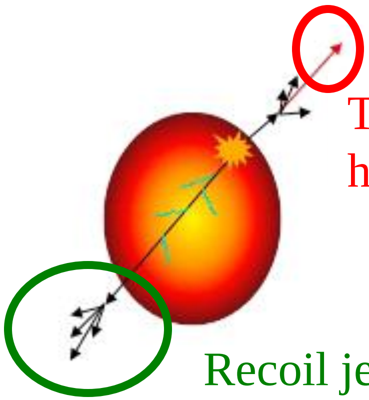
- Contrast LHC, where jet and hadron suppression are similar
  - ➔Less out-of-cone radiation at RHIC?

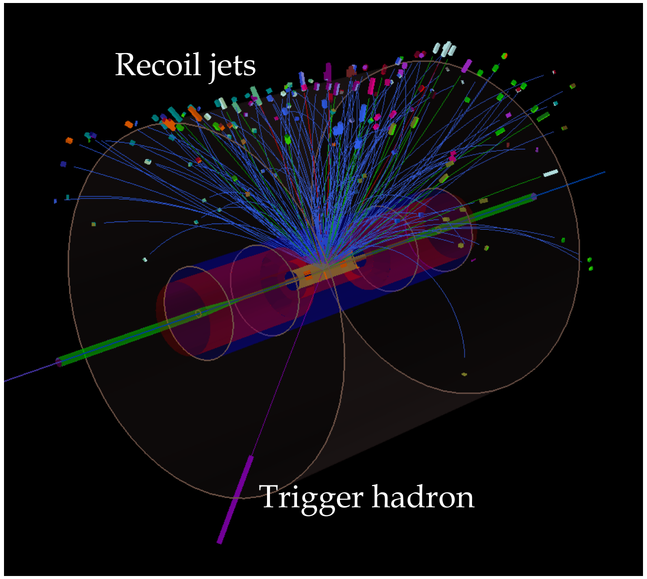


Instructive to compare and contrast similar jet measurements at RHIC and LHC

- Data-driven guidance on the nature of jet quenching
- Constraints on theory/modeling…?

h+jet correlations in STAR: 200 GeV Au+Au





Dataset: year 11 200 GeV Au+Au

- 70M 0-10%, 140M 60-80%

Charged hadron trigger: $9<p_T<19$ GeV/c

Charged particle jets:

- Anti-k_T R=0.3
- Constituents: track $p_T>0.2$ GeV/c

Jet recoil azimuth: $|\phi-\pi| < \pi/4$

Semi-inclusive observable: recoil jets per trigger

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

Measured

Calculable e.g. pQCD@NLO

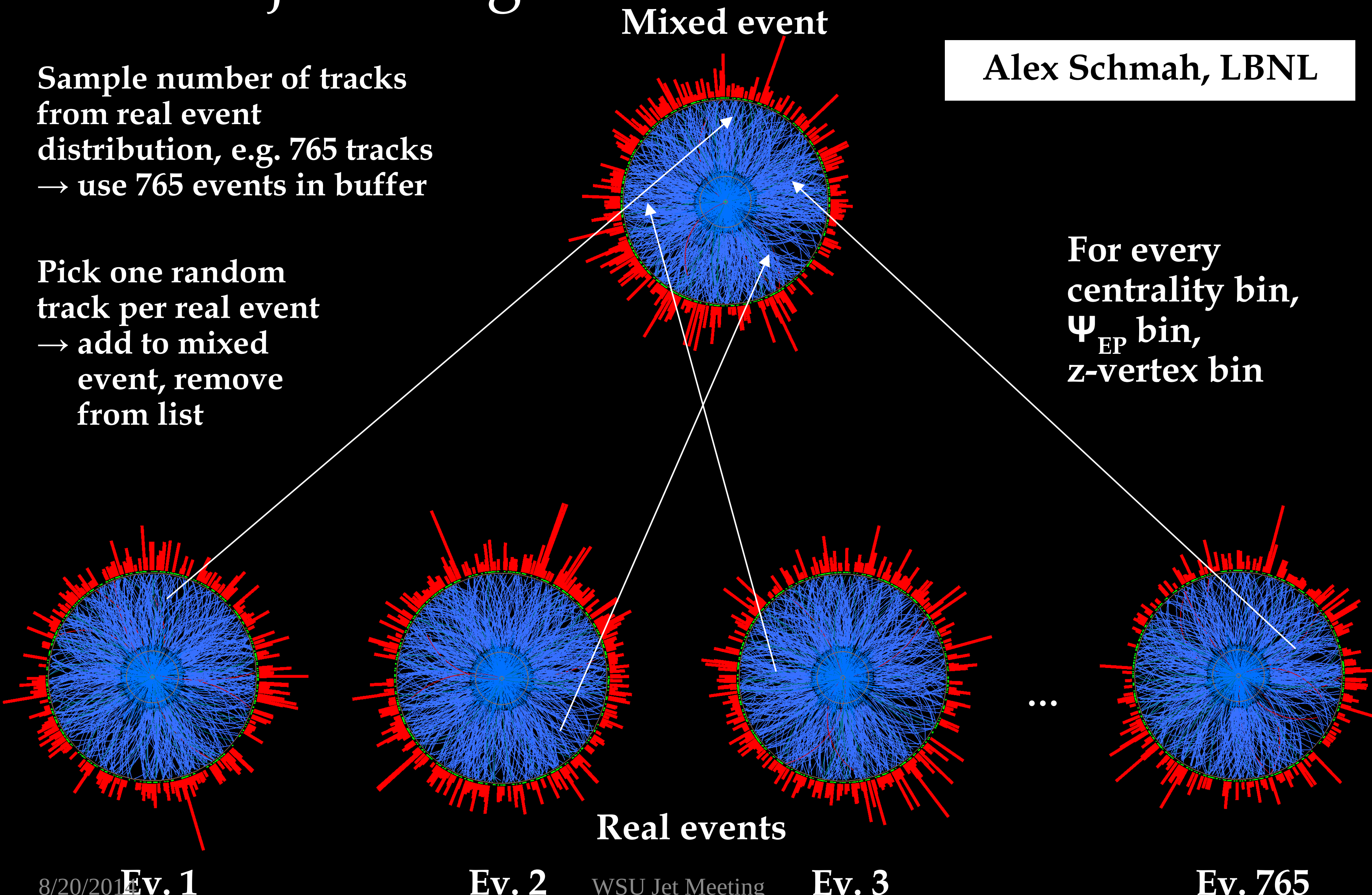
New method to measure combinatorial jet background: mixed events

Alex Schmah, LBNL

Sample number of tracks from real event distribution, e.g. 765 tracks
→ use 765 events in buffer

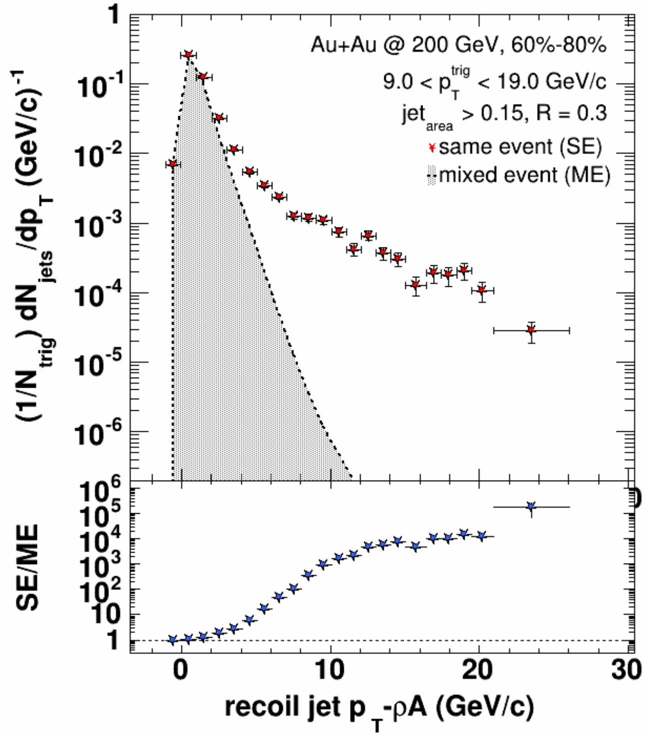
Pick one random track per real event
→ add to mixed event, remove from list

For every centrality bin, Ψ_{EP} bin, z-vertex bin

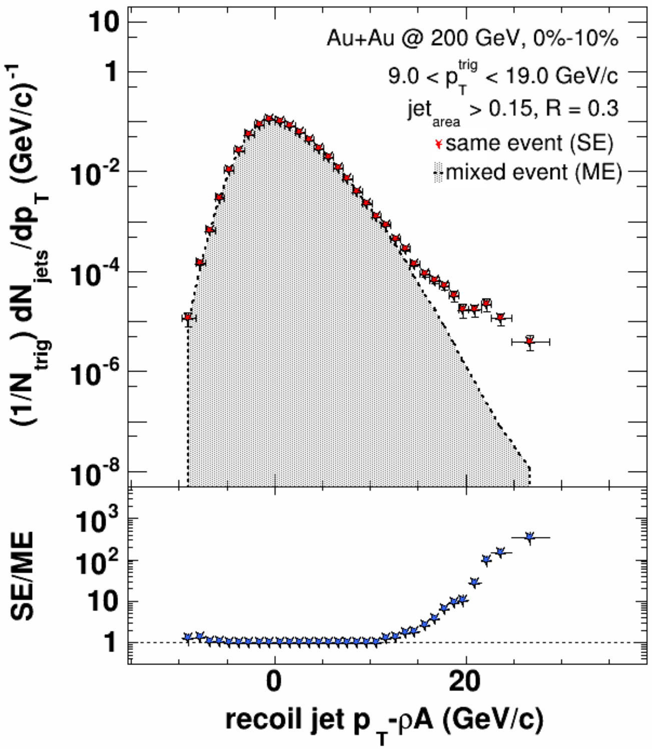


h+jet in STAR: data vs mixed events

Au+Au 60-80%



Au+Au 0-10%



Mixed events give good description of combinatorial background

➔Trigger-correlated recoil jet distribution: subtract ME from data

Comparable to ALICE h+jet measurement

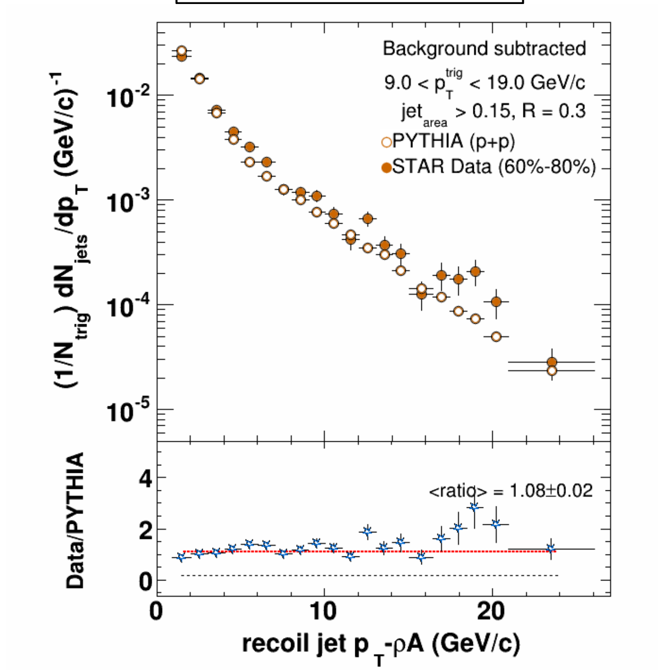
STAR h+jet: subtracted distributions

Ultimately: correct background-subtracted Au+Au distributions to the particle level

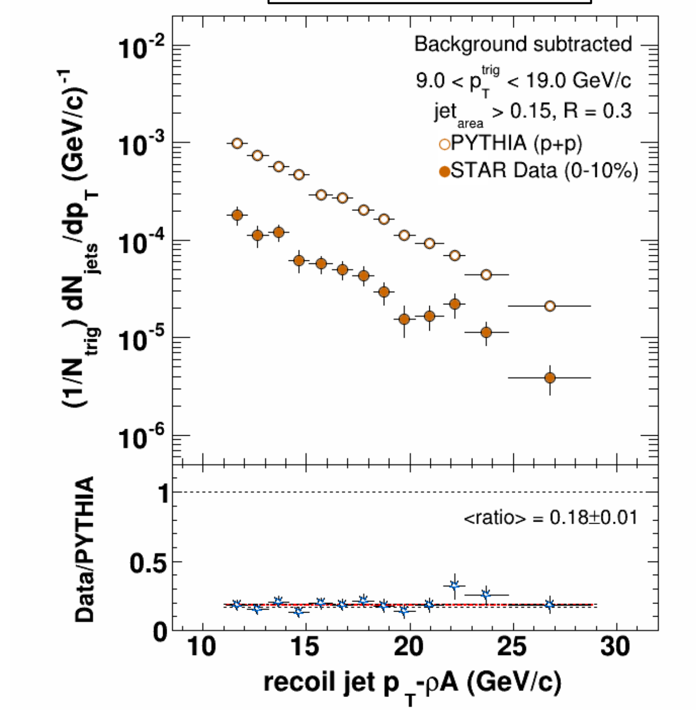
- not yet done

Currently: compare Au+Au background-subtracted distributions to PYTHIA p+p smeared by background fluctuations and detector effects

Au+Au 60-80%



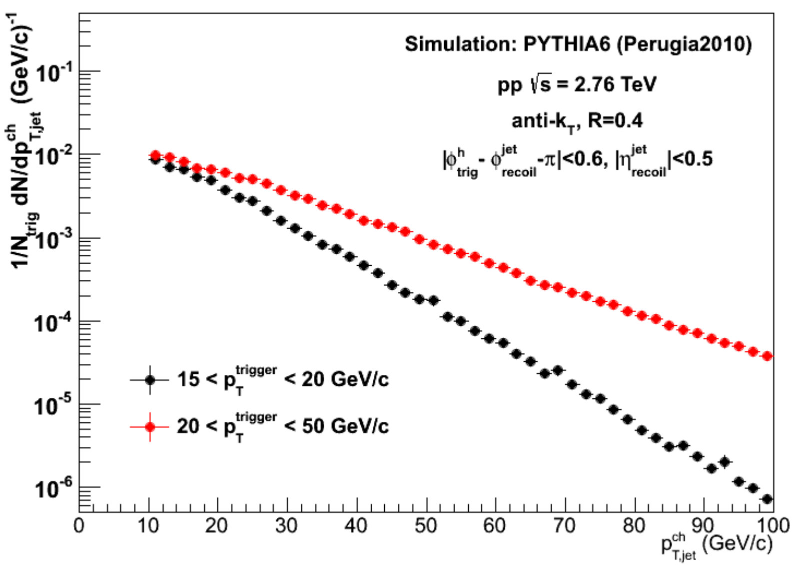
Au+Au 0-10%



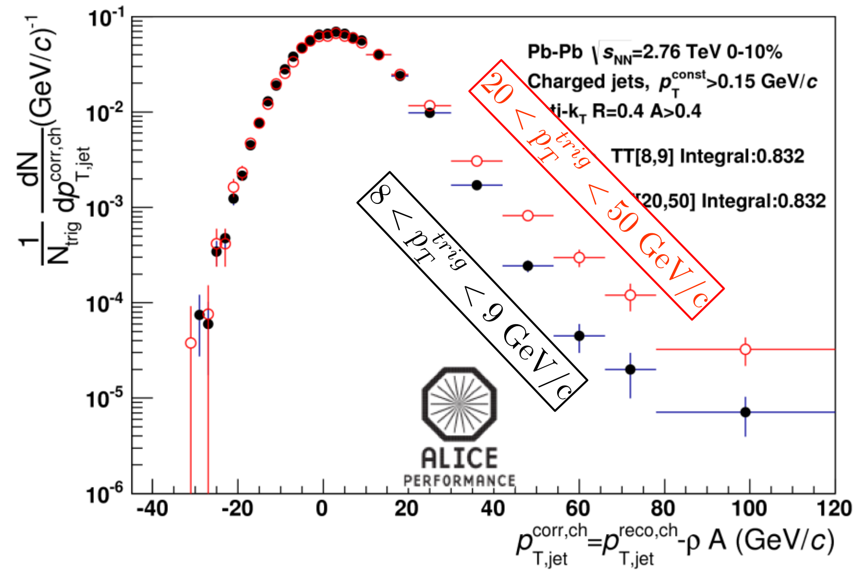
Peripheral Au+Au: good agreement between data and PYTHIA
Central Au+Au: strong suppression relative to PYTHIA

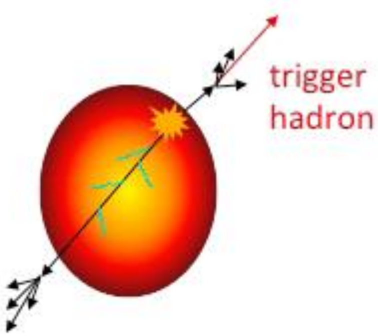
Semi-inclusive h+jet in ALICE

p+p (Simulated)



Central Pb+Pb (data)



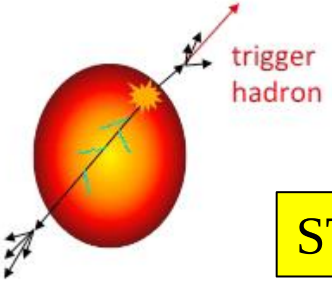


$p_T^{corr}<0$:

- Expectation: dominated by combinatorial (noise) jets
- Observation: distr. uncorrelated with $p_T^{trigger}$

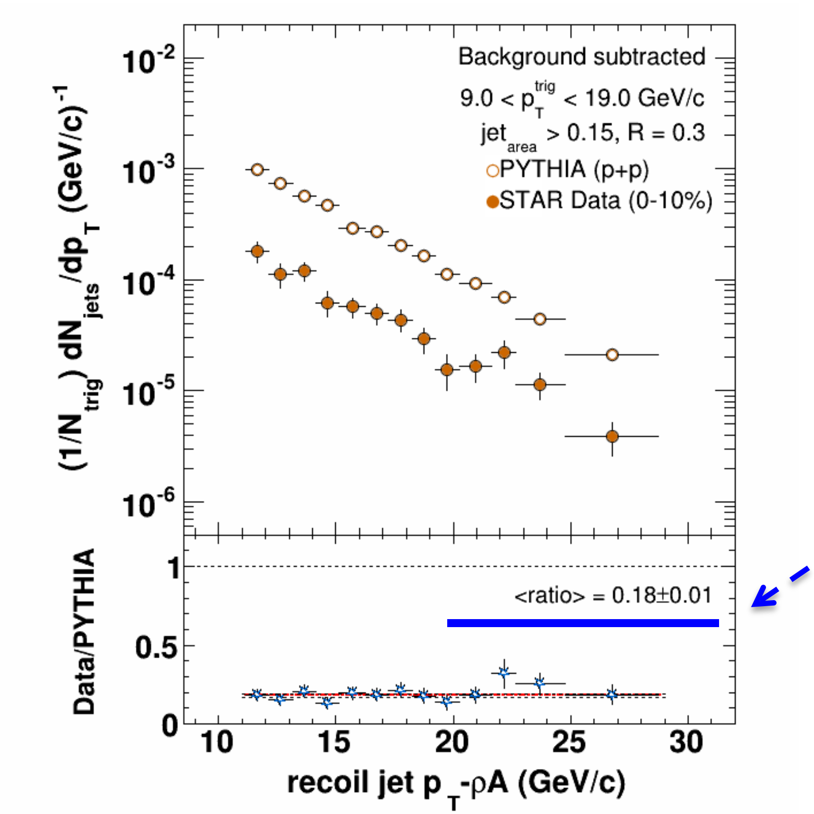
p_T^{corr} large and positive:

- Expectation: hard recoil jets from true coincidences
- Observation: distr. strongly correlated with $p_T^{trigger}$

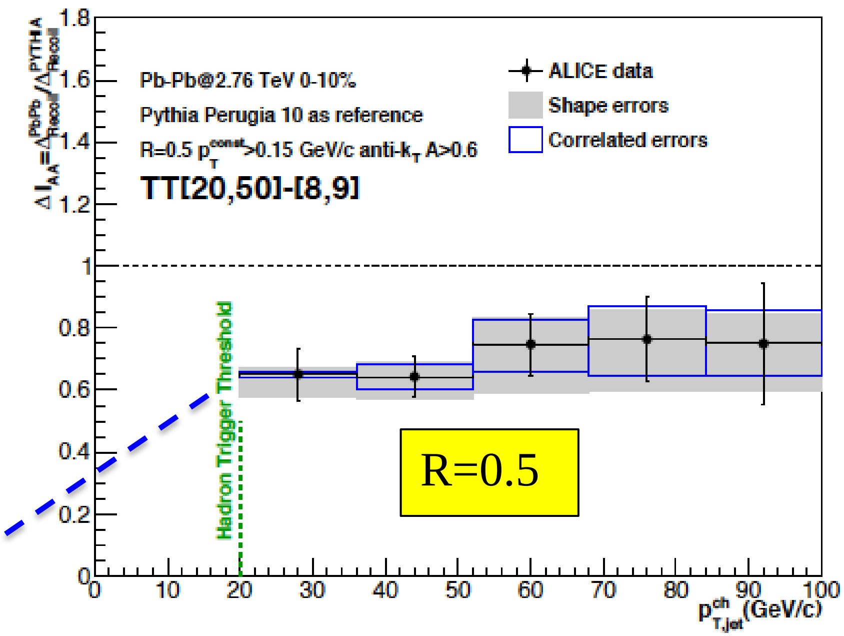


h+jet yield suppression: RHIC vs LHC

STAR central Au+Au



ALICE central Pb+Pb



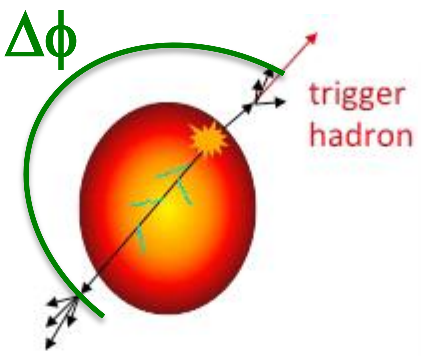
Are these consistent?

Convert vertical suppression into horizontal shift: energy transport out of jet cone

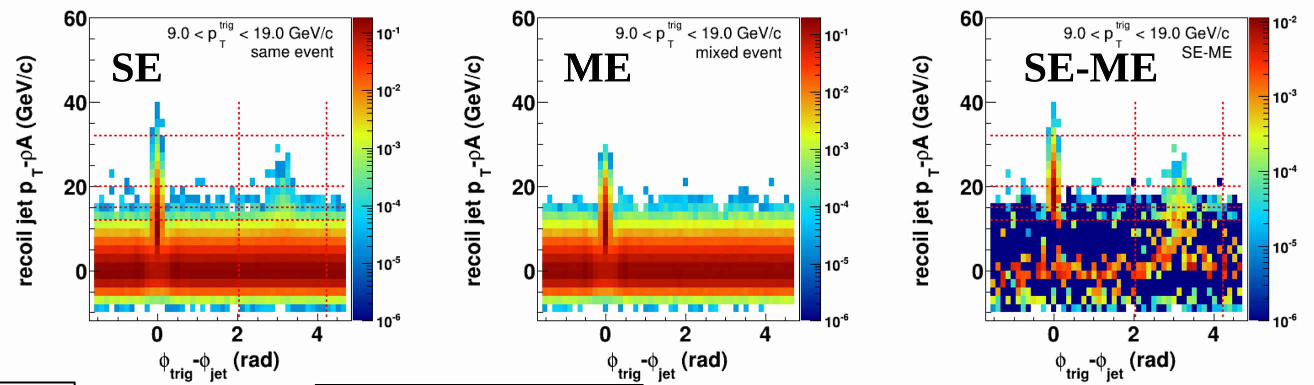
RHIC: ΔE ~ 5 GeV
LHC: ΔE ~ 7 GeV

"Chi-by-eye", to be done more precisely

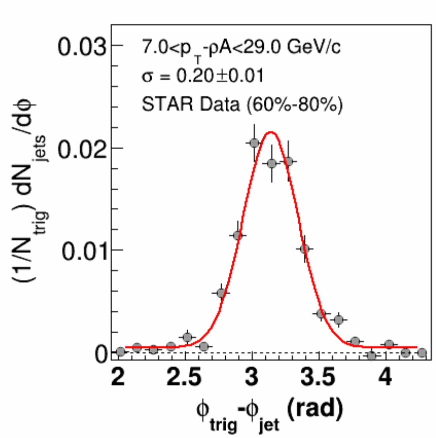
h+jet azimuthal distributions: RHIC vs LHC



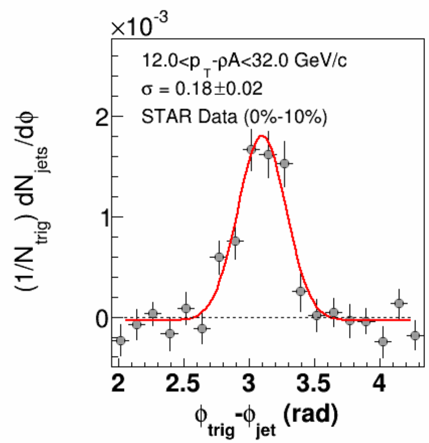
200 GeV Au+Au 0-10%



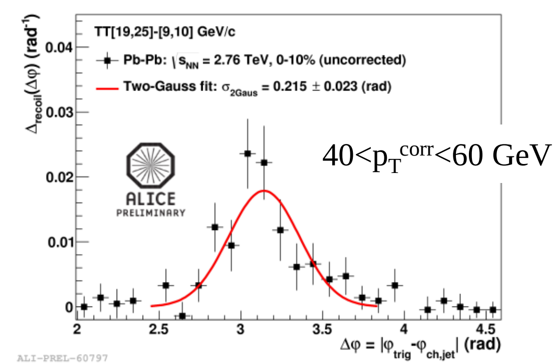
Au+Au 60-80%



Au+Au 0-10%



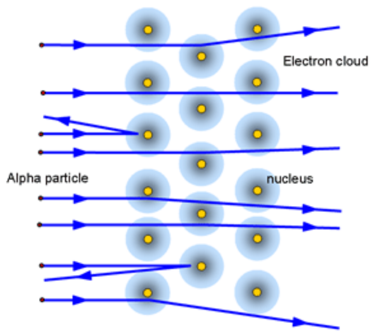
Pb+Pb 2.76 TeV 0-10%

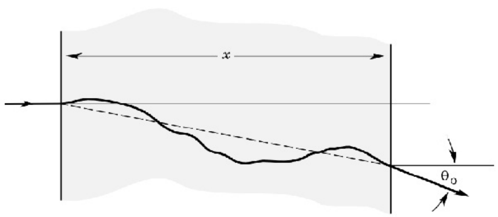


- AuAu central vs peripheral: No evidence of large-angle scattering
- RHIC vs LHC: comparable widths
- Current precision is limited but dominant uncert. is systematic: "systematically improvable"

Large-angle scattering off the QGP?

d'Eramo et al, arXiv:1211.1922





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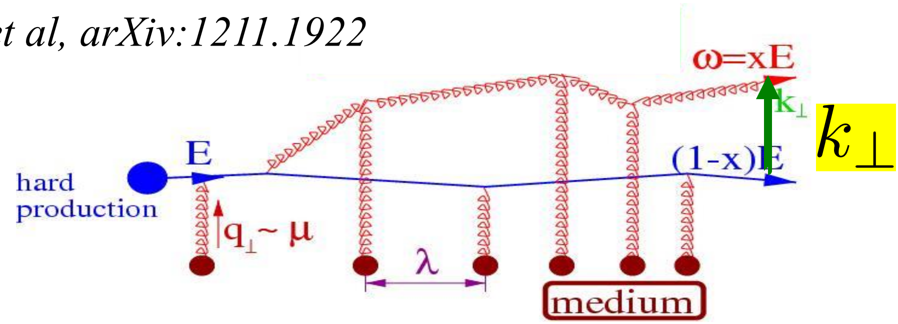
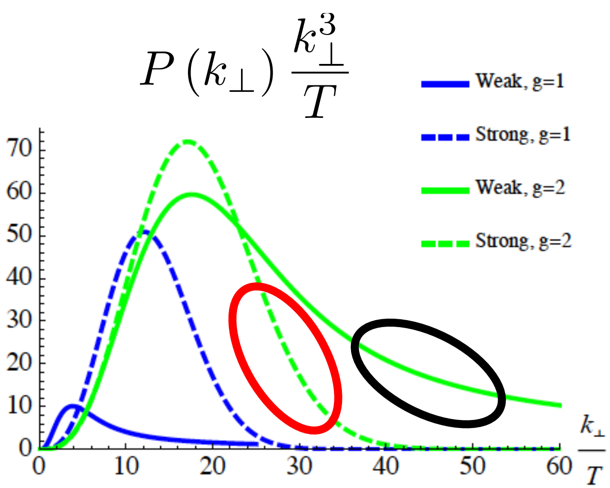


Look at the rate of large-angle deflections (DIS-like probe of the QGP)

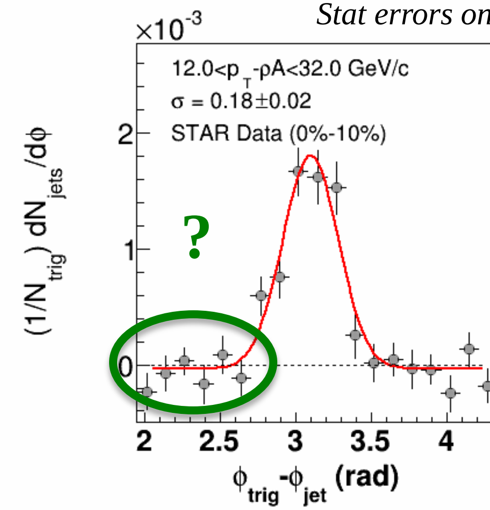
- Weak coupling: pQCD
- Strong coupling: AdS/CFT



Strong coupling:
Gaussian distribution

Weak coupling:
hard tail $\sim \frac{1}{k_\perp^4}$

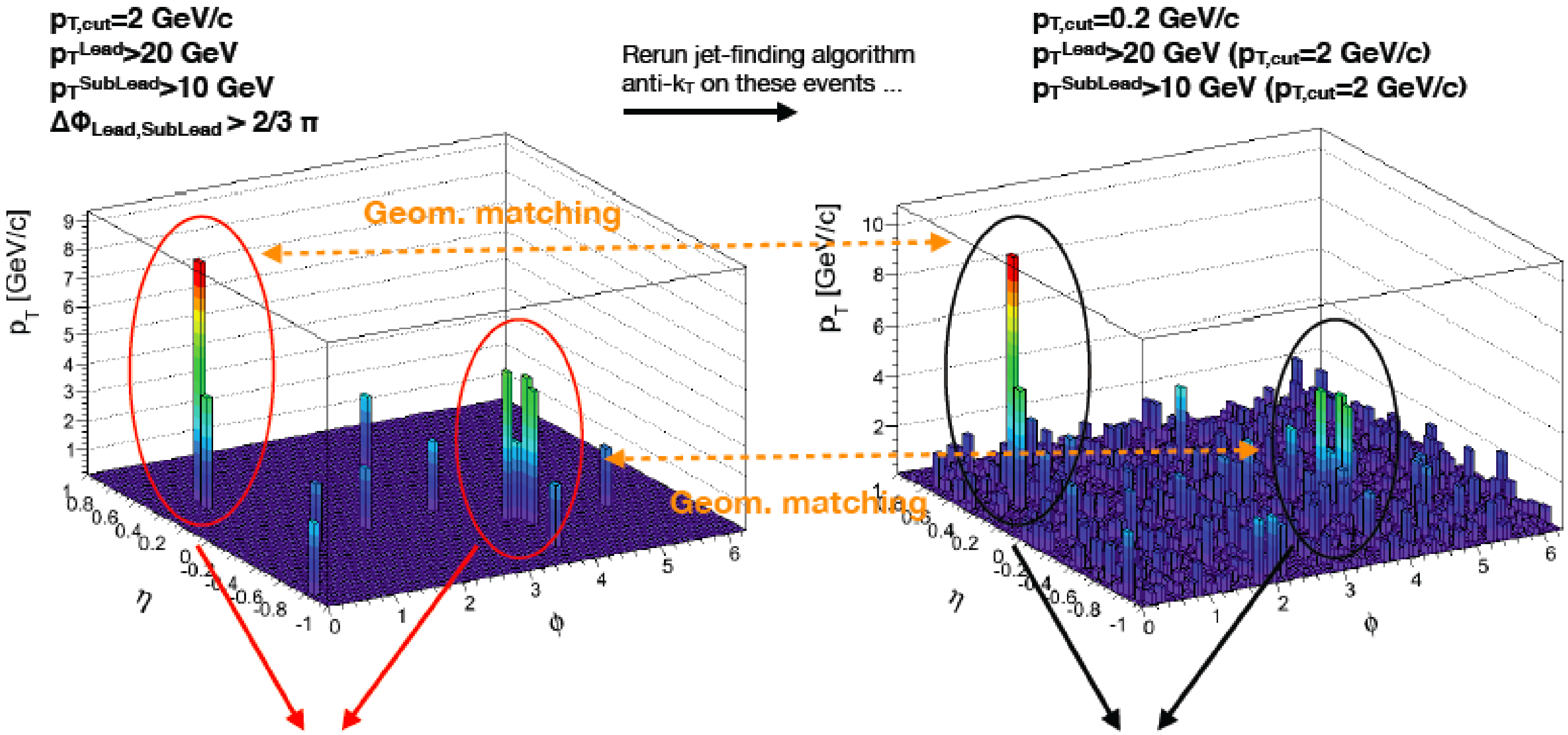
STAR preliminary
Stat errors only



A_J at RHIC

J. Putschke, QM2014

Full jets (with BEMC), Run 7 data



Calculate A_j with constituent $p_{T,cut}$>2 GeV/c

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \qquad p_T = p_T^{rec} - \rho \times A$$

Calculate "matched" $|A_j|$ with constituent $p_{T,cut}$>0.2 GeV/c.

A_J at RHIC

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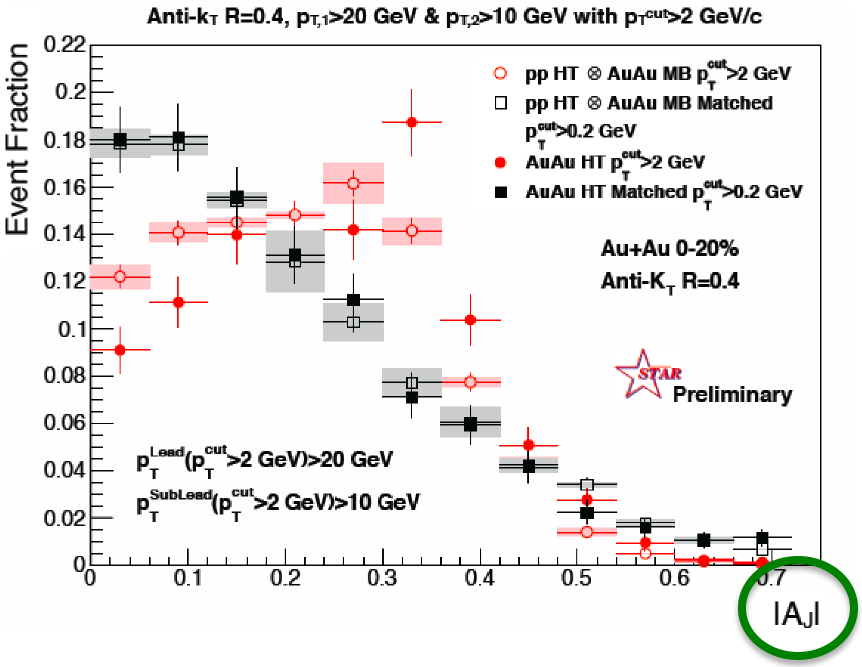
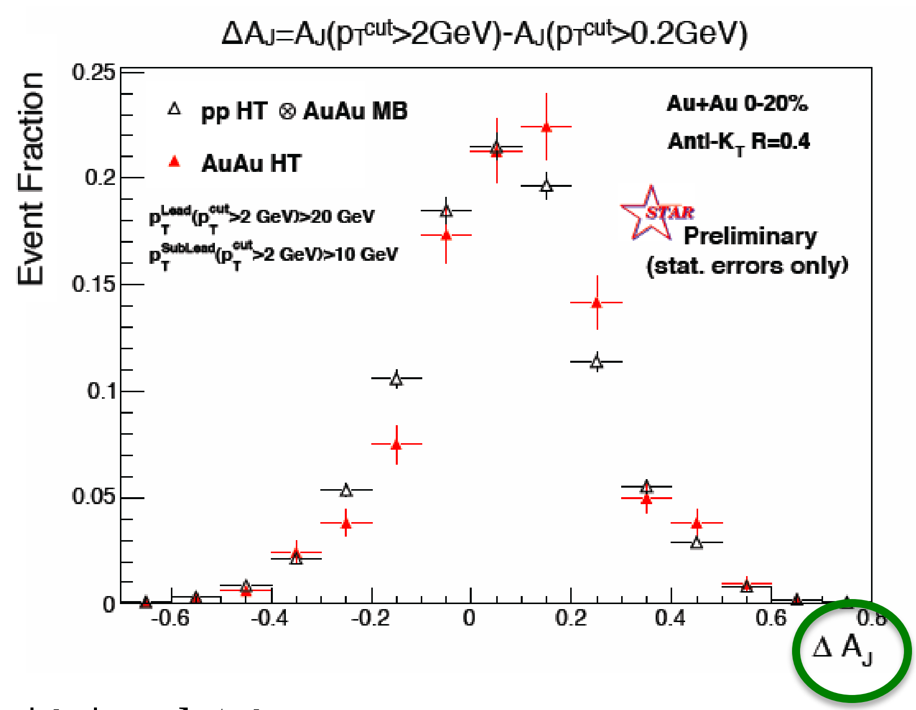




Alternative ways to look distribution: $|A_J|$ and ΔA_J

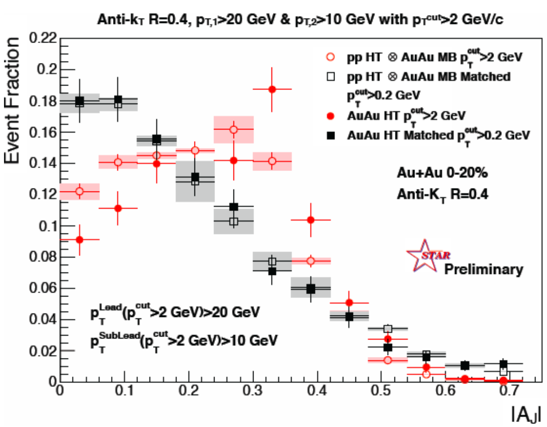
- ΔA_J = pair-by-pair shift in A_J w/ constituent cut 2 GeV ➔ 0.2 GeV

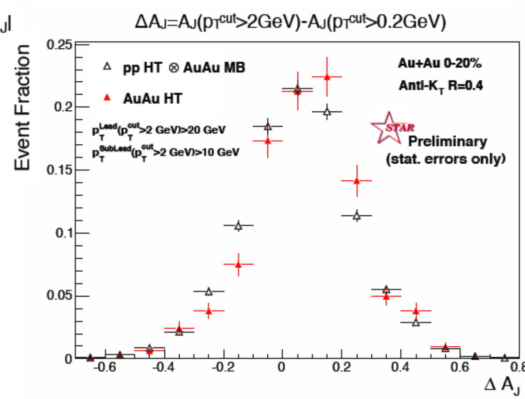
ΔA_J central Au+Au vs p+p: modest differences in overall shift

➔ vacuum like jets? Bias towards tangential pairs?

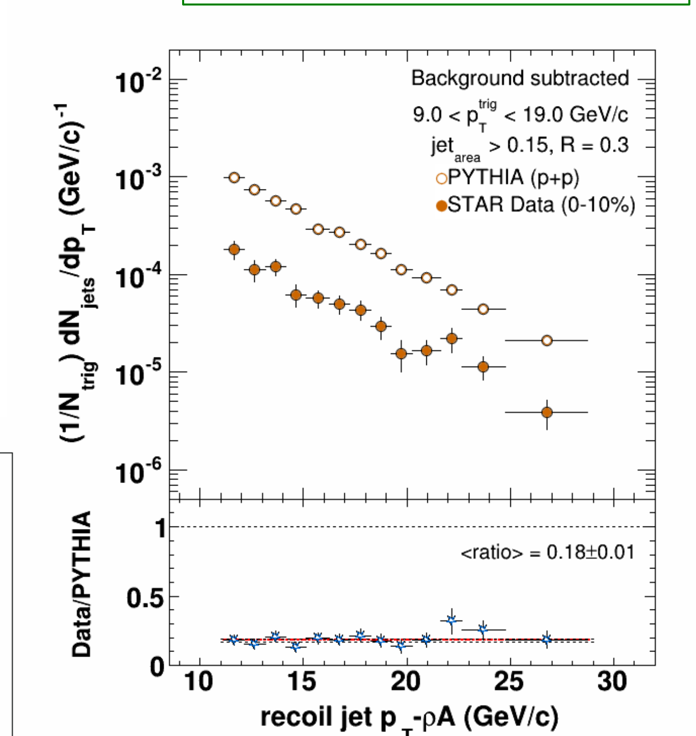
How important is jet selection bias?

A_J: biased pairs





h+jet: unbiased recoil



Strong yield suppression of central Au+Au vs p+p

Moderate differences between central Au+Au vs p+p

Biases play an important role and we can put them to use…

New idea: Fragmentation Function Moments

Jet Fragmentation Function Moments in Heavy Ion Collisions

Matteo Cacciari,[1,2] Paloma Quiroga-Arias,[1] Gavin P. Salam[3,4,1] and Gregory Soyez[5]

EPJ C73, 2319(2013)

Define event-averaged moments of hadron p_T distribution in jets:

$$M_N^{jet} = \frac{\sum_{i\in \text{jet}} \left(p_{T,i}\right)^N}{\left(p_{T,jet}\right)^N}$$

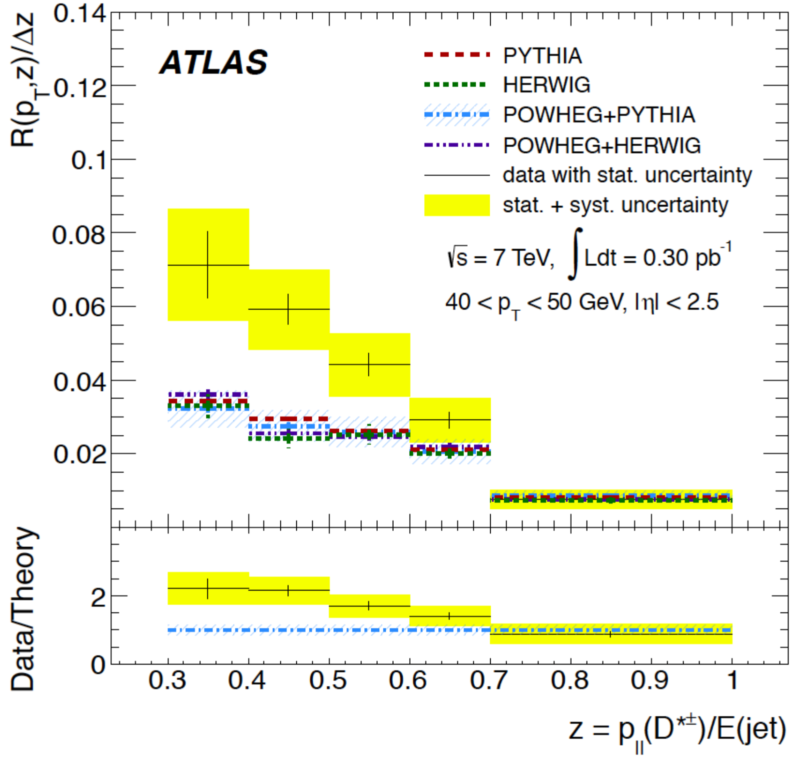
Moments are theoretically well-defined: DGLAP-like evolution

Heavy ion measurements: unfold bkgd fluctuations at the ensemble level

- in the same spirit as the STAR/ALICE approach to incl/semi-incl jet measurements
- systematically improvable precision

New idea: intrinsic charm in jets

D-meson fragmentation function: ATLAS, PRD 85, 052005 (2012)



Is this of interest in heavy ions?

- Perhaps: g->c+cbar may be a "direct messenger" from the parton shower
  - ➔ even more ambitious: c+cbar correlations
- New vertex detectors are crucial (HFT, PHENIX VTX)
- Very luminosity-hungry: STAR estimates TBD

STAR outlook

Several jet analyses in progress: inclusive R_{AA}, biased-jet A_J, h+jet

- RAA, h+jet: factor ~6 more data for fully reconstructed jets (BEMC)

Run 16: factor 3 increase in statistics over run 11

New instrumentation: HFT, MTD

- measure both leading and sub-leading HF in jets

Still to come (rate estimates and capabilities TBD)

- Jet shapes, substructure, Frag Function moments, …
- gamma+jet
- Tag B-jets with displaced J/Psi
- Tag g /q jets with photon and J/Psi triggers
- Charm FF,…

Theory developments needed:

- Connect calculations and measurements (JET Collaboration)
- Large-angle scattering (d'Eramo and Rajagopal, XN Wang et al.)
- Sub-leading HF in jets

Thoughts on LRP: strategic issues

Inevitable question: Why do we need RHIC in the LHC era?

- Why this is serious: easiest way to solve the Tribble II problem of too many facilities is to close RHIC and redistribute the funds to other NP efforts
  - Doesn't work that way in practice (e.g. NP budget contracted after LAMPF closure) but that can't be our answer

Need to present larger community with unified view of the future of heavy ion physics at both RHIC and LHC

BES-II @ RHIC is a relatively easy sell outside our community:
- physics questions are compelling
- issue is whether they can be probed experimentally
- RHIC is unique

Jets @ RHIC not as easy
- **What really are we learning about the QGP from these jet measurements?**
- Why aren't jets at LHC enough to answer the essential questions?