QCD jets in heavy ion collisions: new approaches

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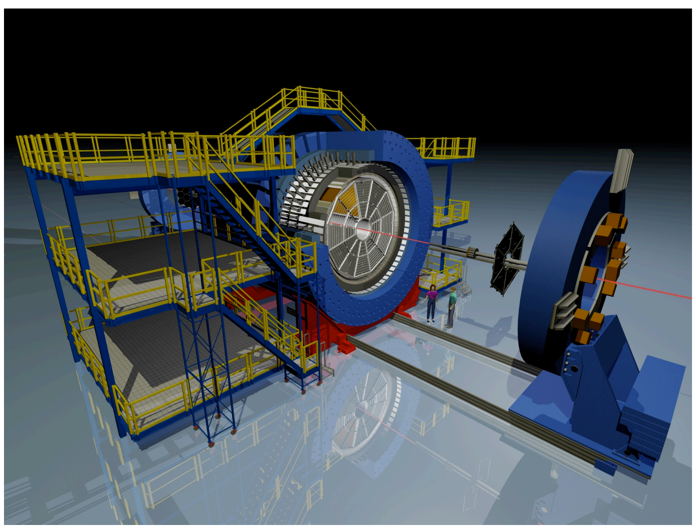
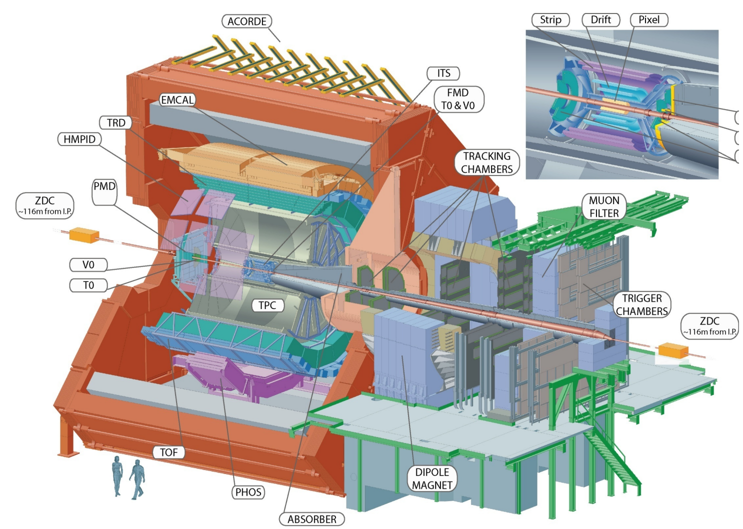
STAR @ RHIC



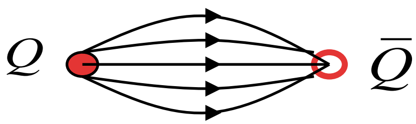
ALICE @ LHC

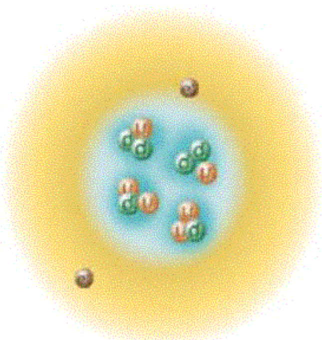


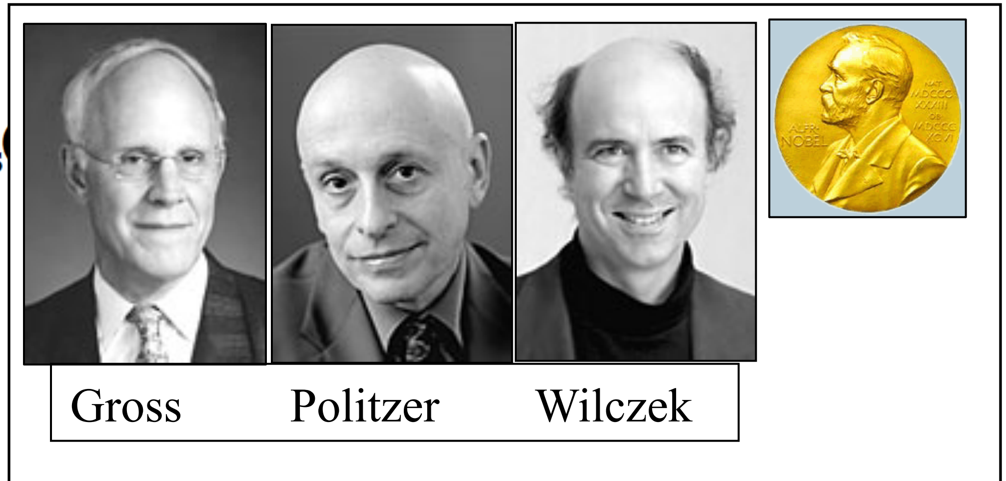
QCD: running of α_s

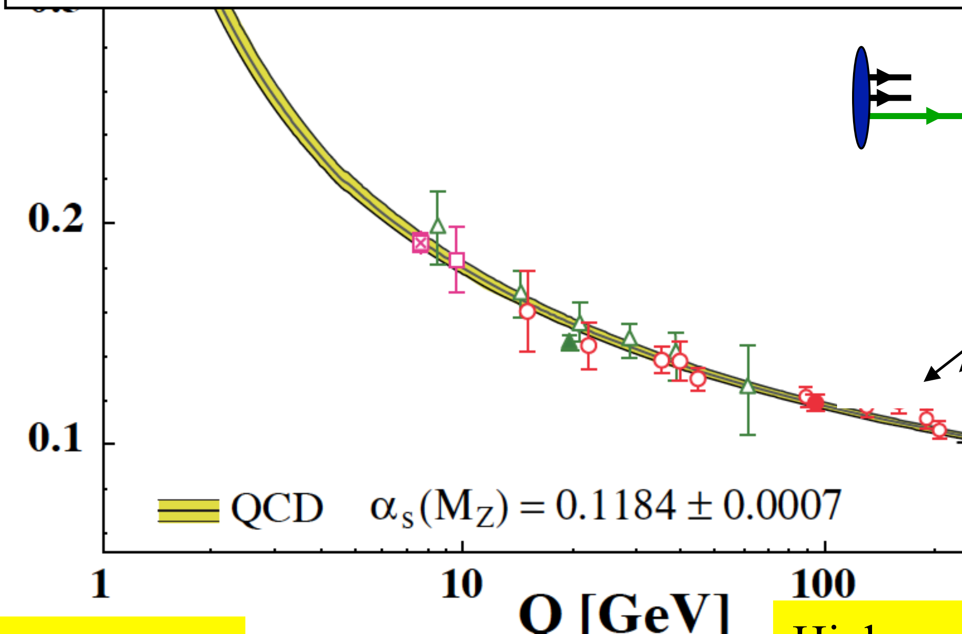
Asymptotic Freedom

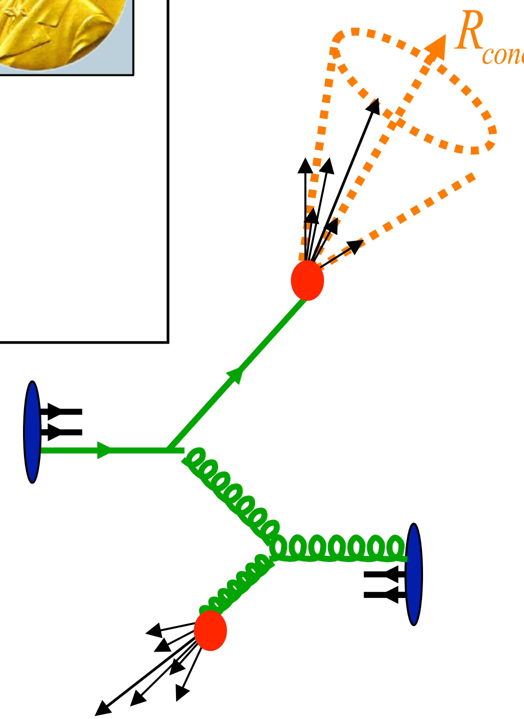
Confinement

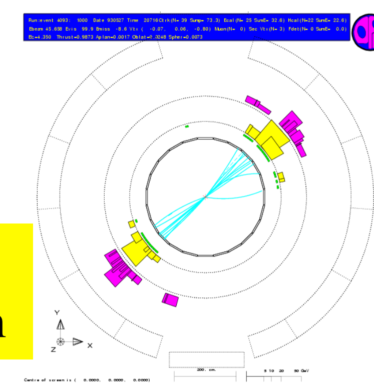








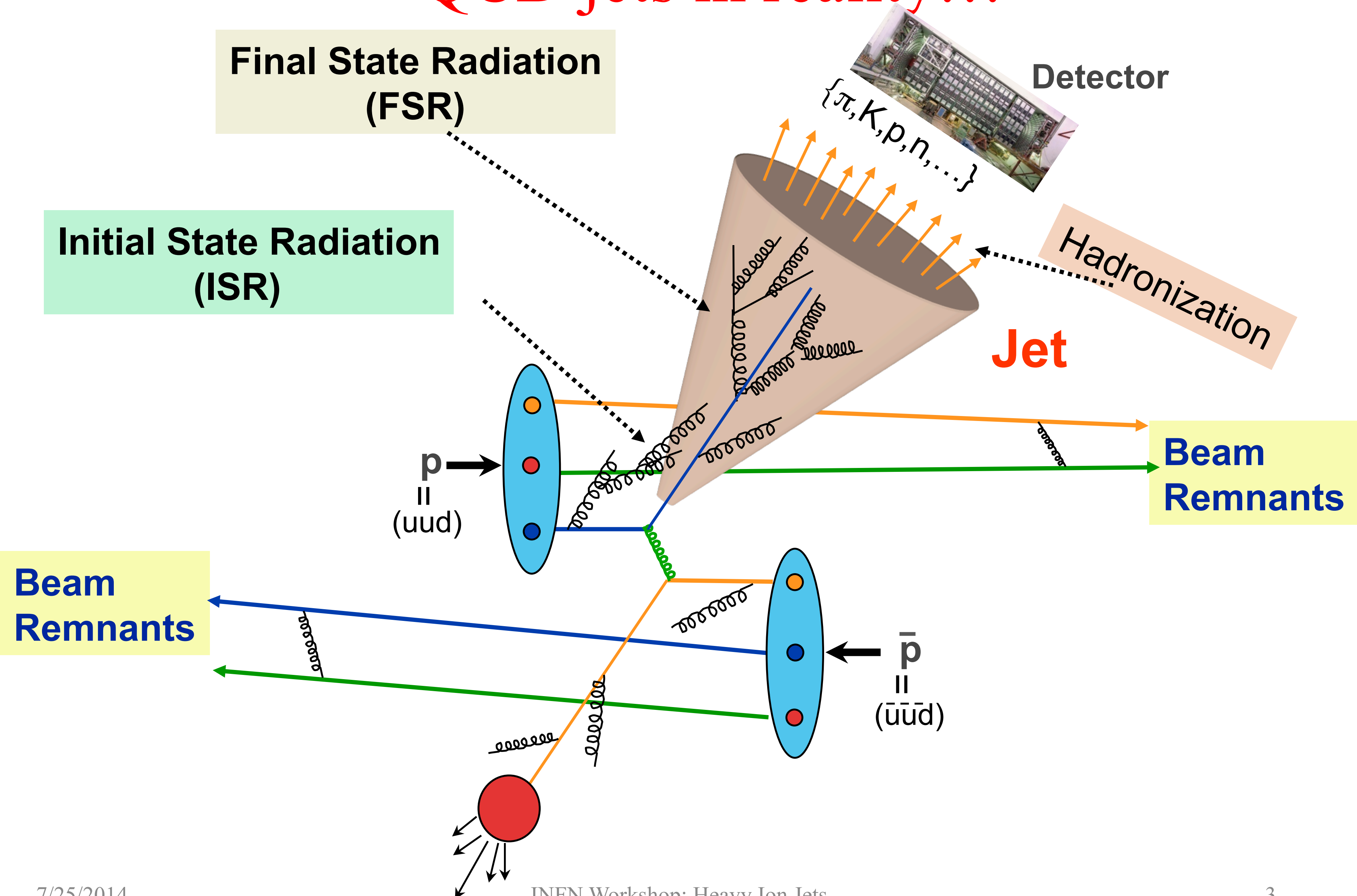




Low momentum

High momentum

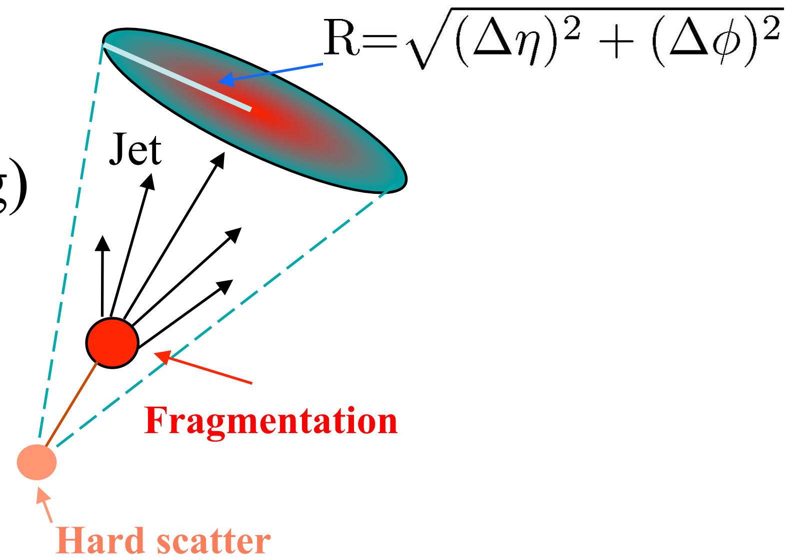
QCD jets in reality…



Modern jet reconstruction algorithms

- Cone algorithms
  - Mid Point Cone (merging + splitting)
  - SISCone (seedless, infra-red safe)

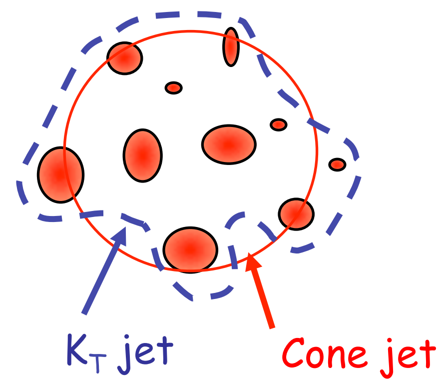
- Sequential recombination algorithms
  - k_T
  - **anti-k_T**
  - Cambridge/ Aachen



Algorithms differ in recombination metric:

→ different ordering of recombination

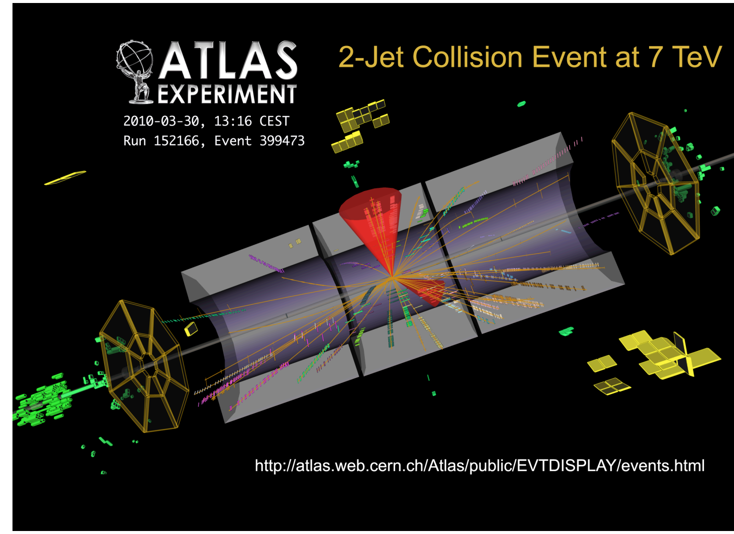
→ different event background sensitivities



What everyone now uses: FastJet (M. Cacciari, G. Salam, G. Soyez JHEP 0804:005 (2008))

Jet production in proton-proton collisions

Good agreement with pQCD @ NLO over a broad kinematic range



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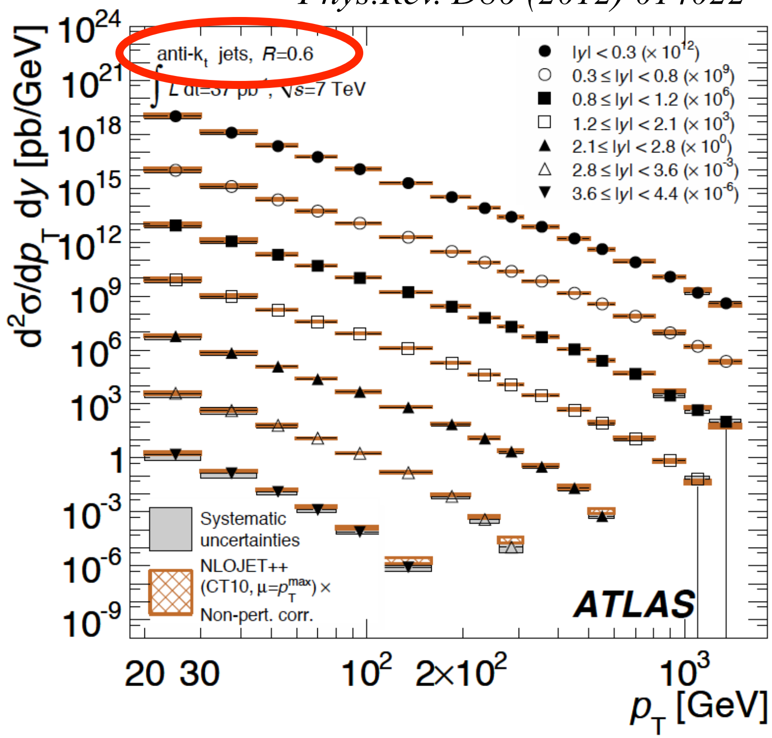
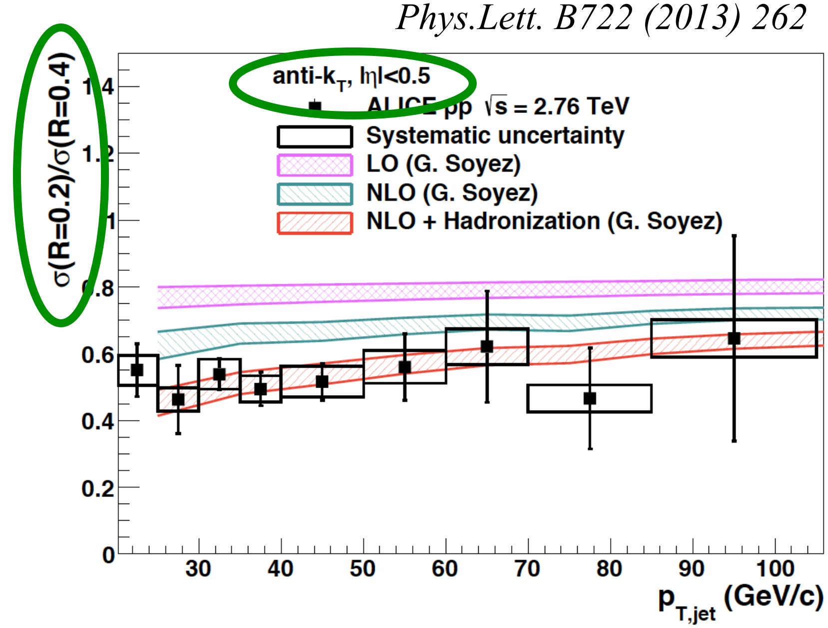
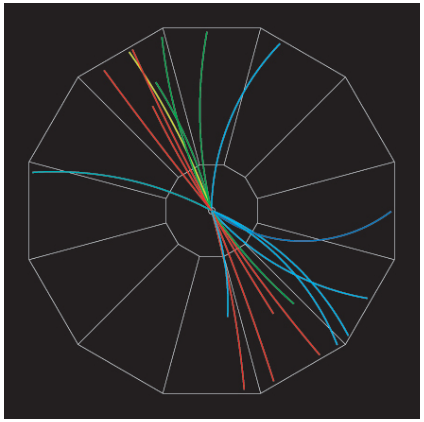
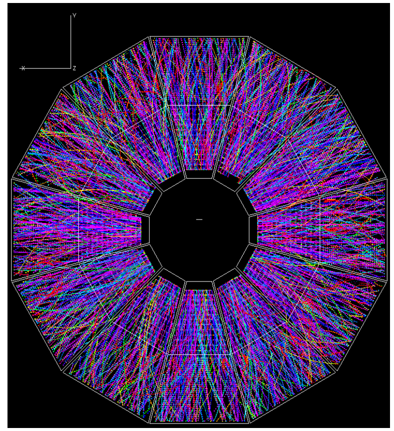


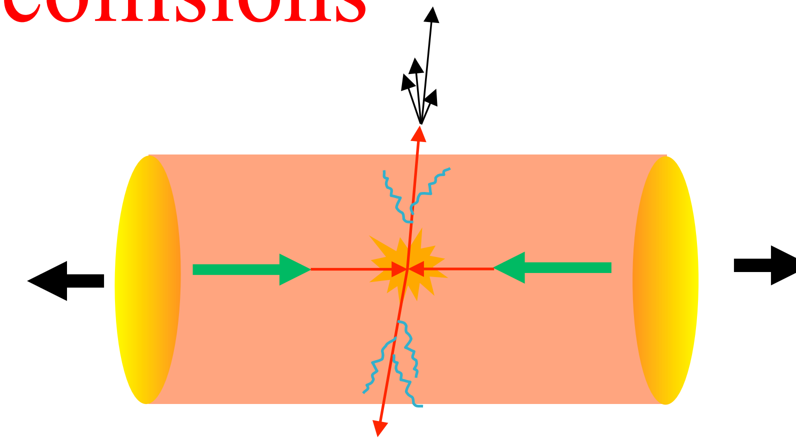
R. Ma, Ph.D. Thesis
Phys.Lett. B722 (2013) 262



Jets in heavy ion collisions



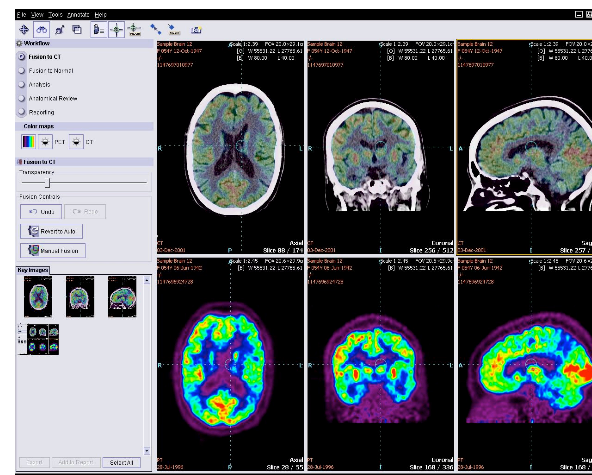




Controlled "beams" with well-calibrated intensity

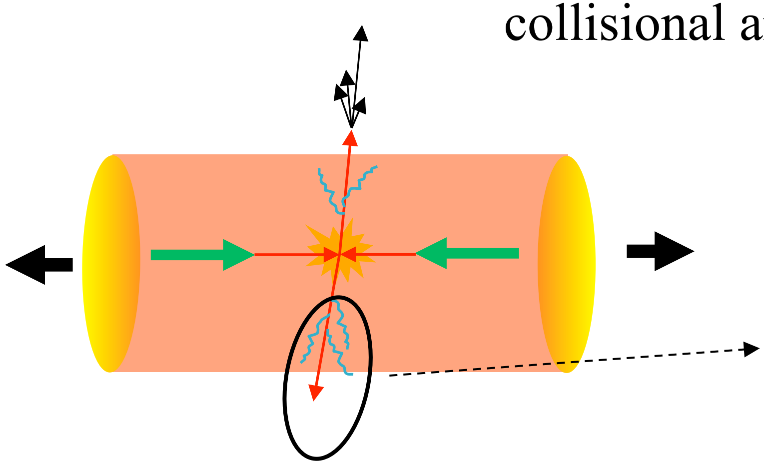
Final-state interactions with colored matter are calculable

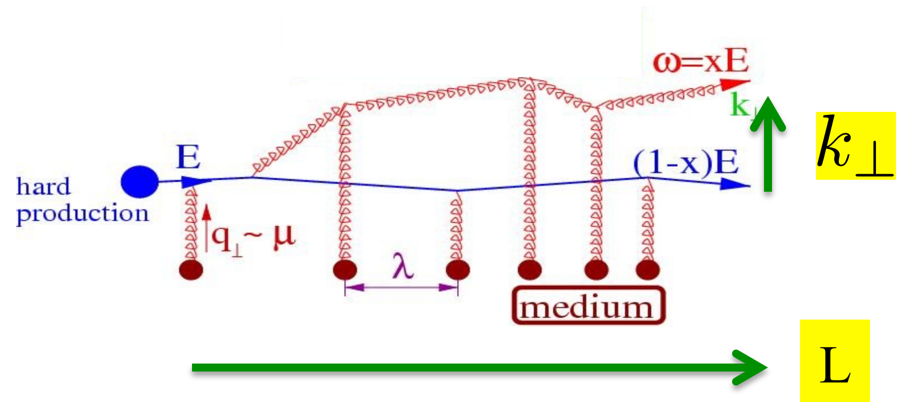
"Jet quenching": quasi-tomographic probe of the Quark-Gluon Plasma



Jet quenching in QCD

collisional and radiative energy loss





Probability distribution of $k_\perp$

$$P\left(k_\perp\right) = \int d^2 x_\perp e^{-i k_\perp \cdot x_\perp} W_R\left(x_\perp\right)$$

$W_R\left(x_\perp\right)$ = expectation value of Wilson loop of spatial extent L (incorporates effects of the medium)

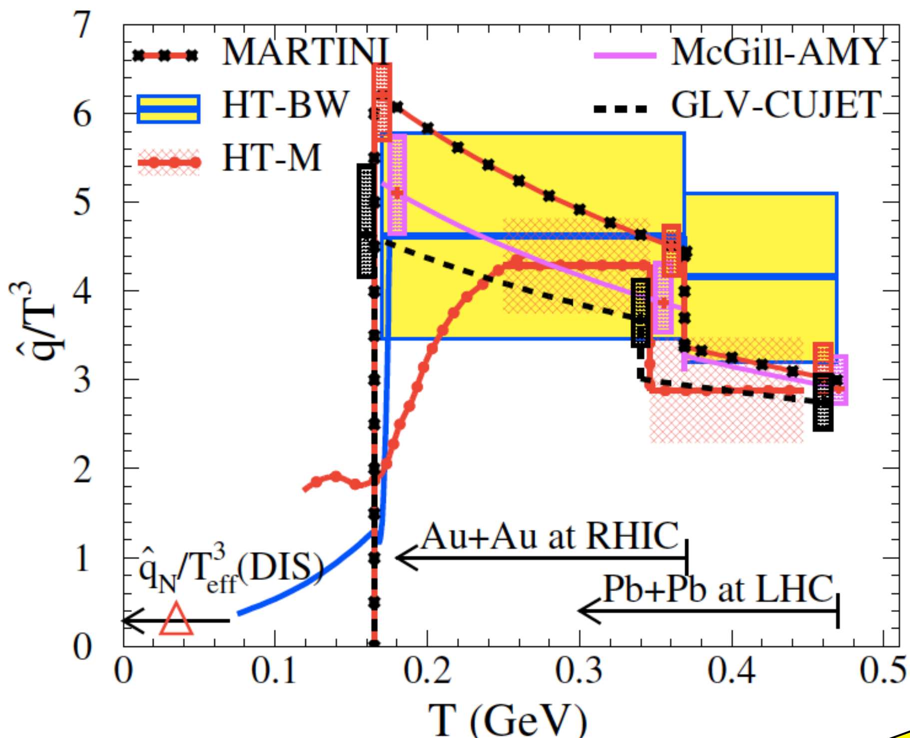
Second moment: $$\hat{q} \equiv \frac{\langle k_\perp^2 \rangle}{L} = \frac{1}{L} \int \frac{d^2 k_\perp}{(2\pi)^2} k_\perp^2 P\left(k_\perp\right)$$

Total medium-induced jet energy loss (multiple soft scattering):

$$\Delta E_{med} \sim \alpha_s \hat{q} L^2$$

Determination of $\hat{q}$: data + modeling

JET Collaboration, arXiv:1312.5003



Fit pQCD-based models to **single-hadron suppression** data at RHIC and LHC

Reconstructed jet measurements were not taken into account for this result

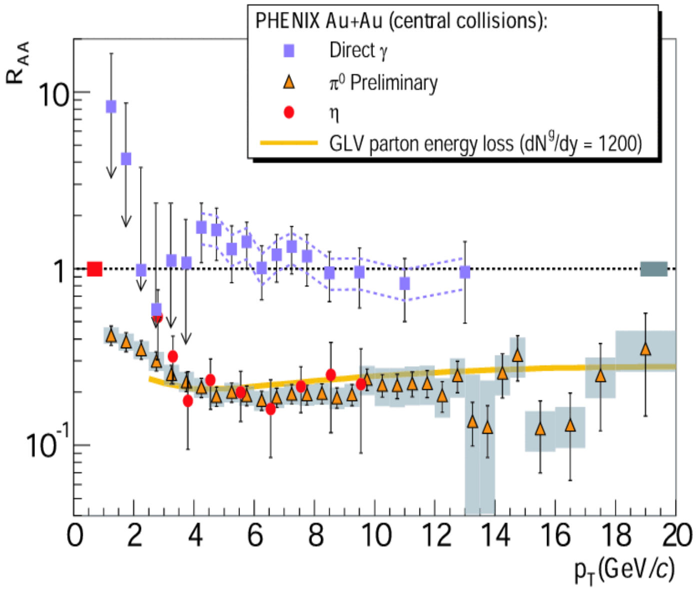
For a 10 GeV light quark at

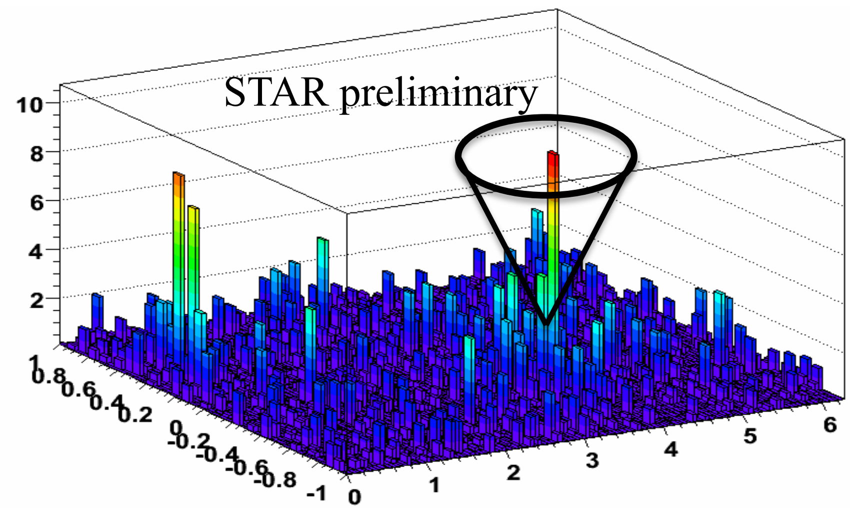
RHIC : ... GeV^2/fm

LHC : $\hat{q}$ ... $1.9 \pm 0.7\ \text{GeV}^2/\text{fm}$

Compared to 5 years ago: significant improvement in precision due to LHC data

So why bother with fully reconstructed jets?





High p_T hadron suppression is a ***disappearance*** measurement:
we largely observe the relics of those jets that have ***not interacted***

We want a complete dynamical understanding of jet quenching:

- Jet energy is not “lost”: where does it go?

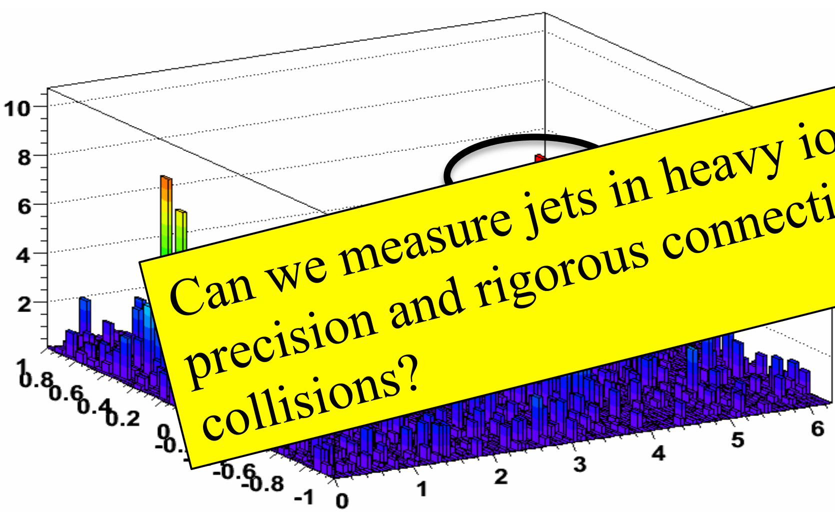
Jets and jet quenching are partonic in nature

- Hadrons are an annoyance that may screen the essential physics

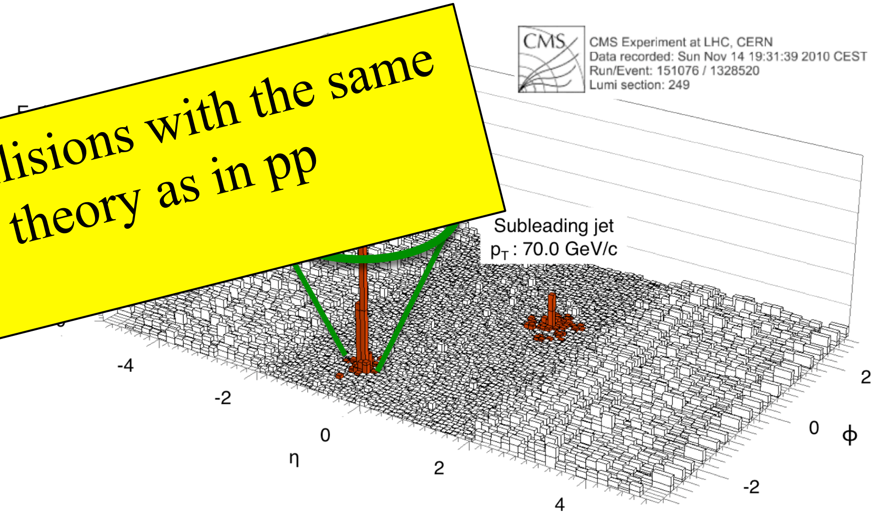
Jet quenching at the partonic level ➔ fully reconstructed jets

Jets in real heavy ion collisions

RHIC/Star



LHC/CMS

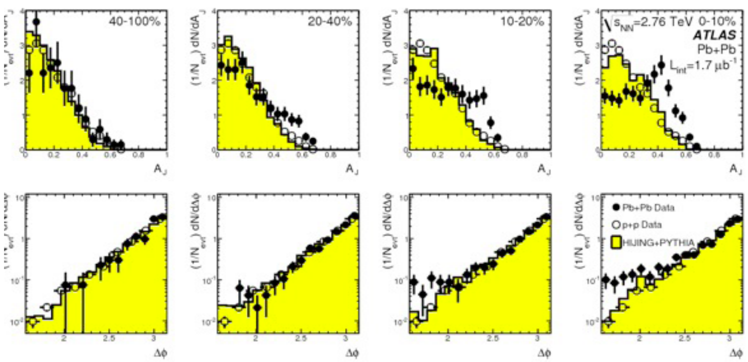


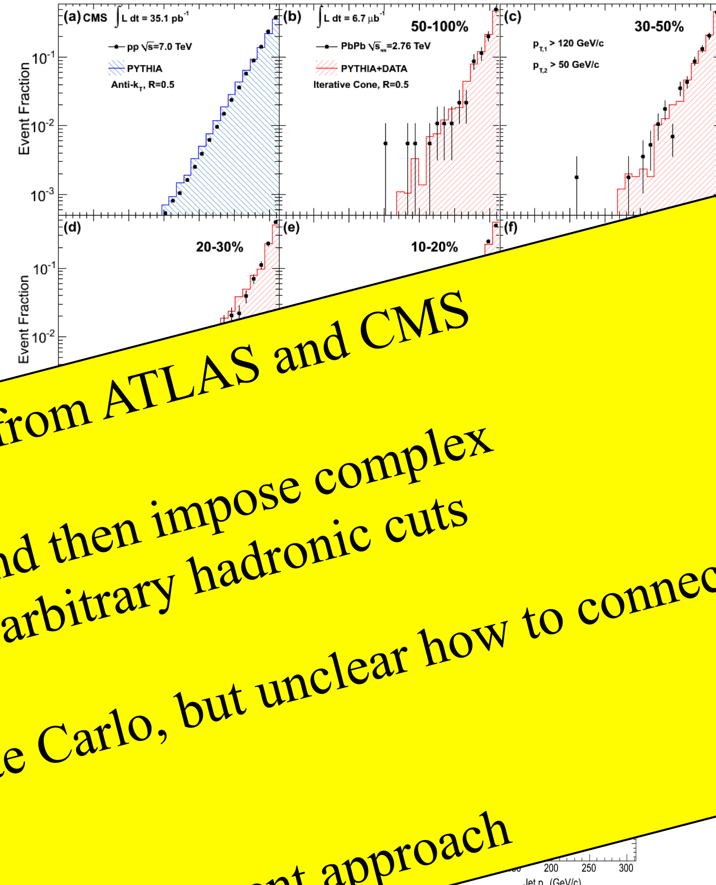
Can we measure jets in heavy ion collisions with the same precision and rigorous connection to theory as in pp collisions?

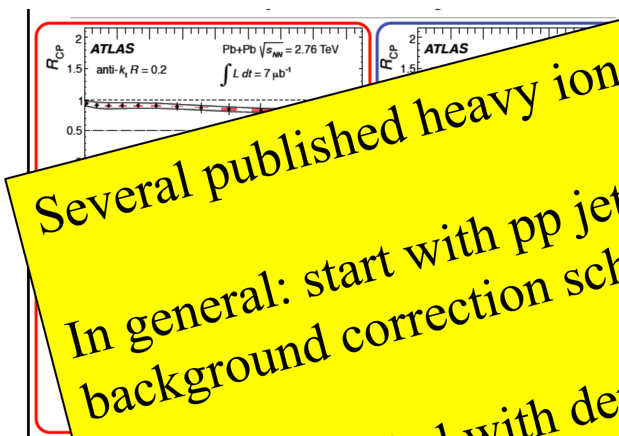
Visual identification of energetic jets above background is fairly easy

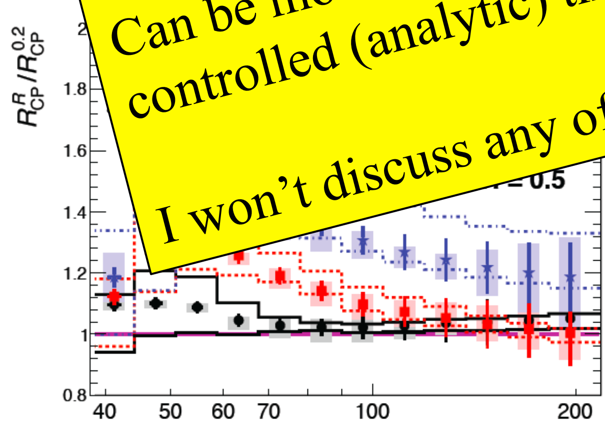
Much harder: accurate measurement of jet energy within finite cone

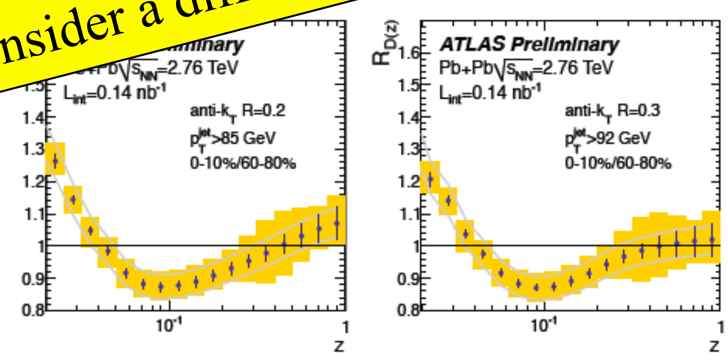
- Pb+Pb at LHC: on average over 100 GeV of uncorrelated background energy in cone R=0.4
- Uncorrelated background has complex structure, including multiple overlapping jets at all momentum scales











Several published heavy ion jet results from ATLAS and CMS

In general: start with pp jet analysis and then impose complex background correction schemes with arbitrary hadronic cuts

Can be modeled with detailed Monte Carlo, but unclear how to connect to controlled (analytic) theory….?

I won't discuss any of them: consider a different approach

Rethink the problem: general requirements for heavy ion jet measurements

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

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

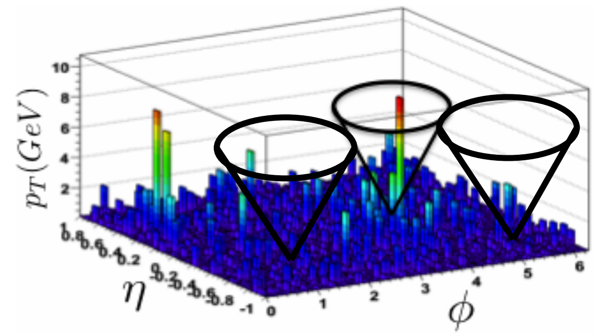
➔ Direct comparison to theory (no requirement to model background or instrumental effects)

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/ALICE approach

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

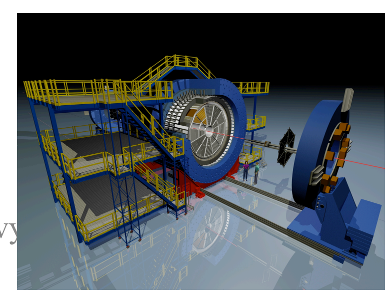


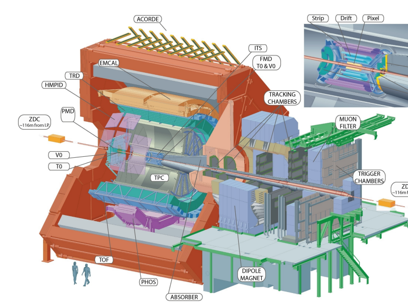
Only ensemble-averaged distributions of background-corrected signal are meaningful

➔No jet selection/rejection based on background-corrected jet energy (contrast ATLAS/CMS)

Instrumentation:

- Measurements based on EM calorimetry and tracking (no hadronic calorimetry: contrast ATLAS/CMS)
  - Why? Infrared safety:
    ➔can measure individual jet consituents down to p_T~200 MeV (tracks, EMCal)
  - Same approach for STAR@RHIC and ALICE@LHC
- Collinear safety – see later



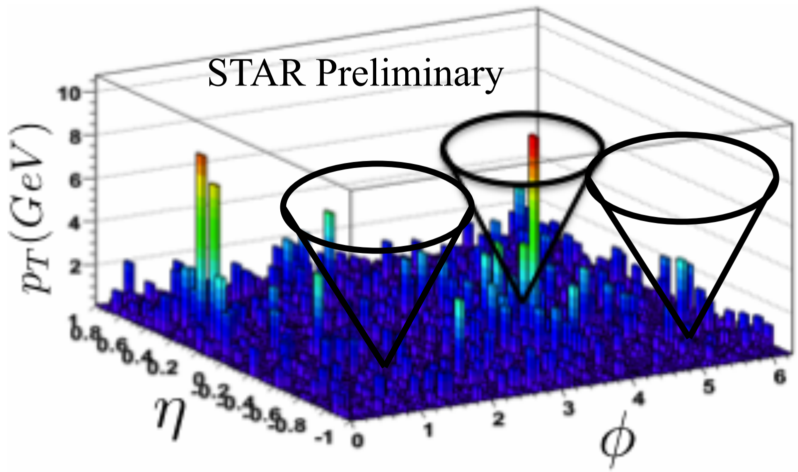


Background density estimate

For each event:

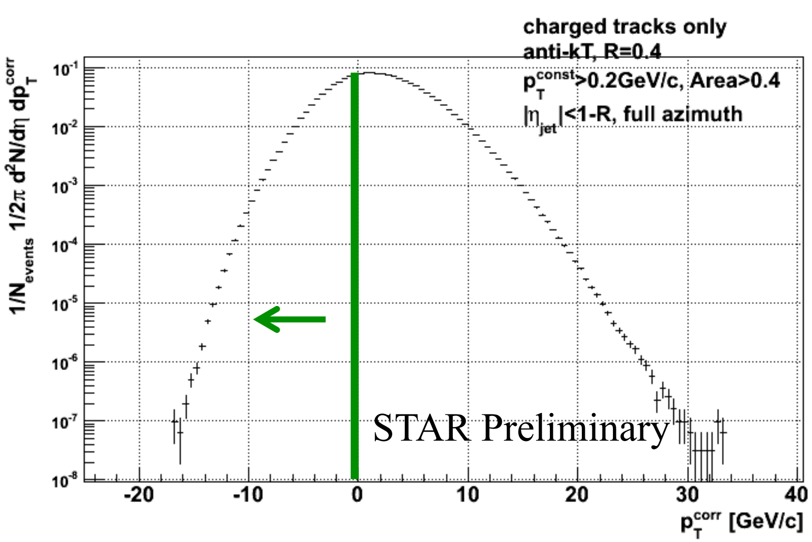
- Run jet finder, collect all jet candidates
- Tabulate jet energy $p_{T,i}^{jet}$ and area A_i^{jet}
- Event-wide median energy density:

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



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

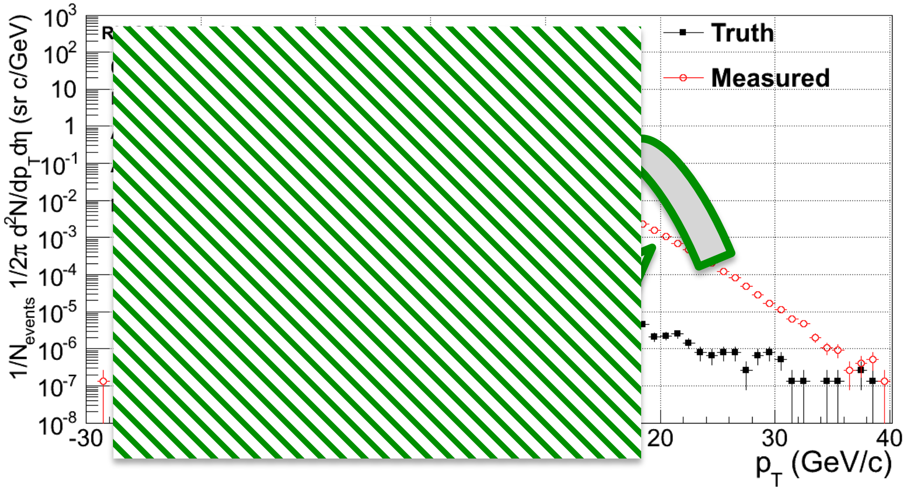
$$p_{T,i}^{\langle corr \rangle} = p_{T,i} - \rho \cdot A_i$$



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

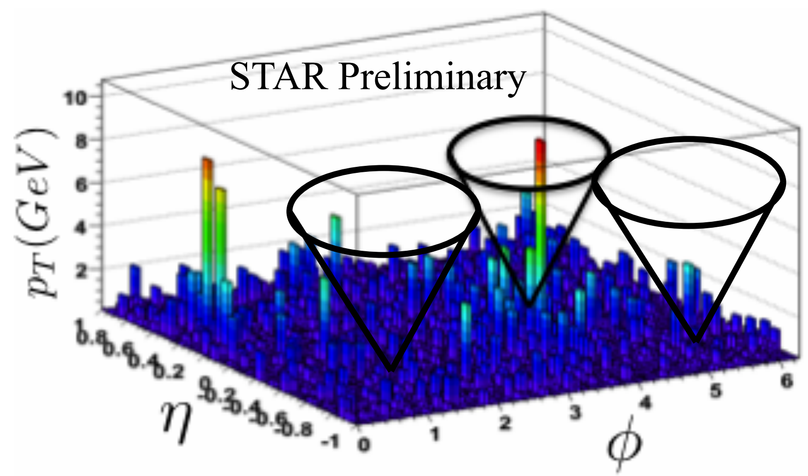
- Not interpretable as physical jets
- But we do not reject this component explicitly by a cut in $p_T^{<corr>}$:
  - Contains crucial information about background or "combinatorial" jets
  - Rejected at later step by imposition of a specific (transparent) bias on candidates

True and measured jet spectra



ATLAS/CMS algorithm:

- reject jet candidates based on $p_T^{\langle corr \rangle}$
- Correct for missing yield by simulation



STAR/ALICE:

- keep entire $p_T^{\langle corr \rangle}$ distribution
- Reject background based on other observables

Analysis steps:

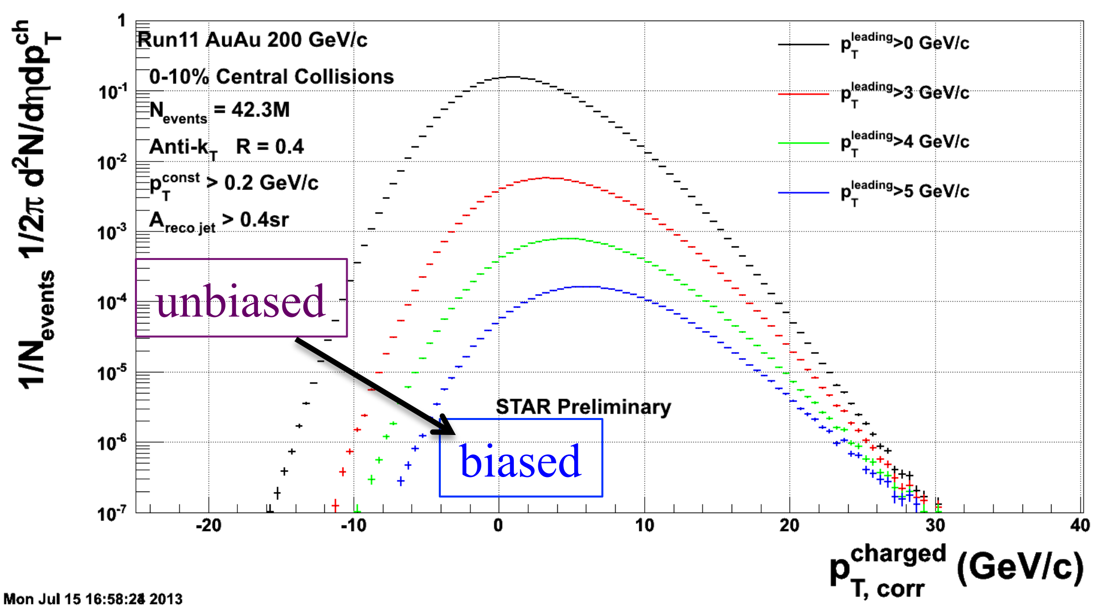
1. Isolate the real hard jet component and suppress combinatorial component
2. "Unfold" the effects of energy smearing on the hard jet component

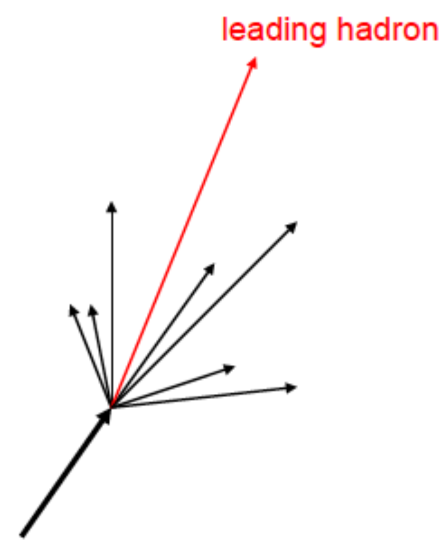
Inclusive jet spectrum: isolation of hard jet component

G. De Barros et al., arXiv:1208.1518

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

- Imposition of momentum scale discriminating hard from non-hard 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





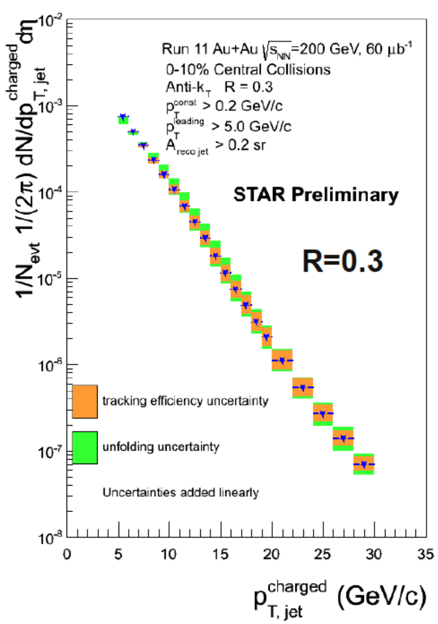
Quasi-inclusive jet spectrum in central heavy ion collisions at RHIC and LHC

Jan Rusnak
HP13

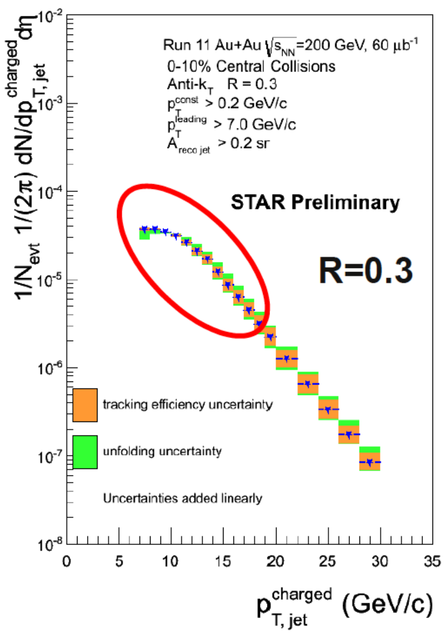
STAR central Au+Au
$\sqrt{s_{NN}}$=200 GeV
Charged jets R=0.3

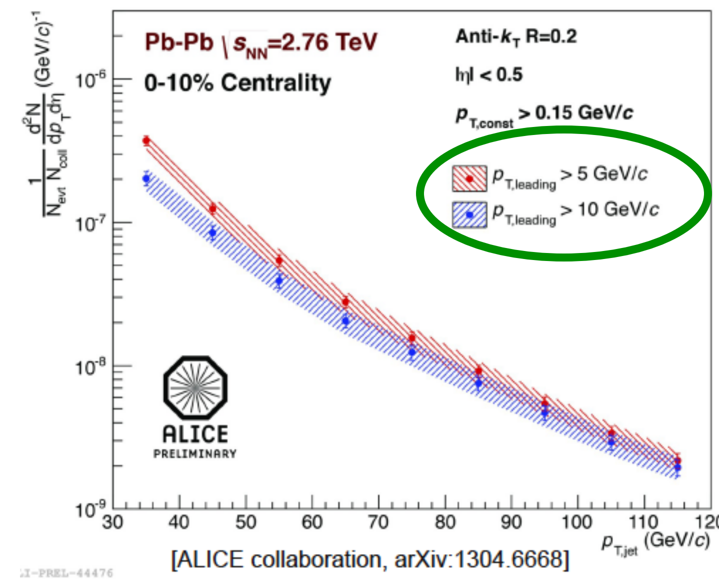
ALICE central Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
Full jets R=0.2

p_T^{thresh}=5 GeV



p_T^{thresh}=7 GeV





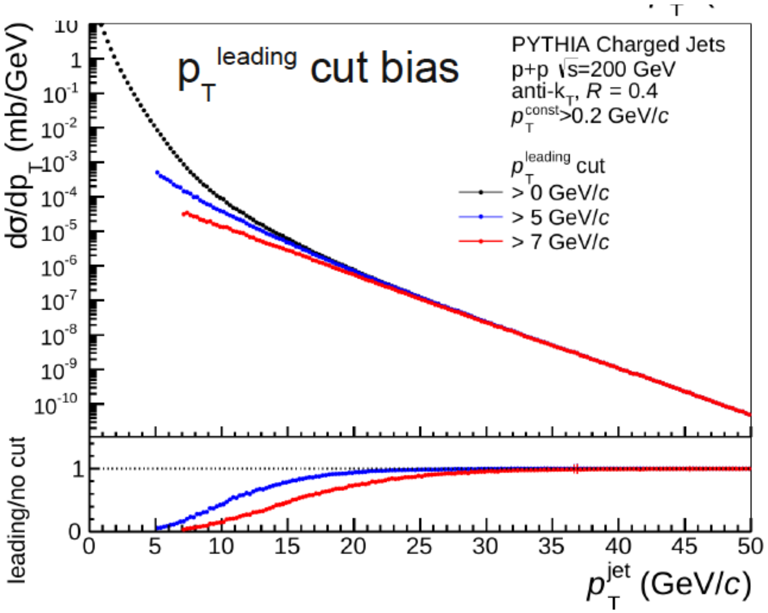
- Proof of principle: quasi-inclusive jet spectra can be measured with well-controlled systematics over a broad kinematic range at both RHIC and LHC
  - In progress: full jets (STAR), larger R at both energies, kinematic reach,…
- Effect of leading hadron bias is visible

Inclusive jets at RHIC: compare Au+Au and p+p

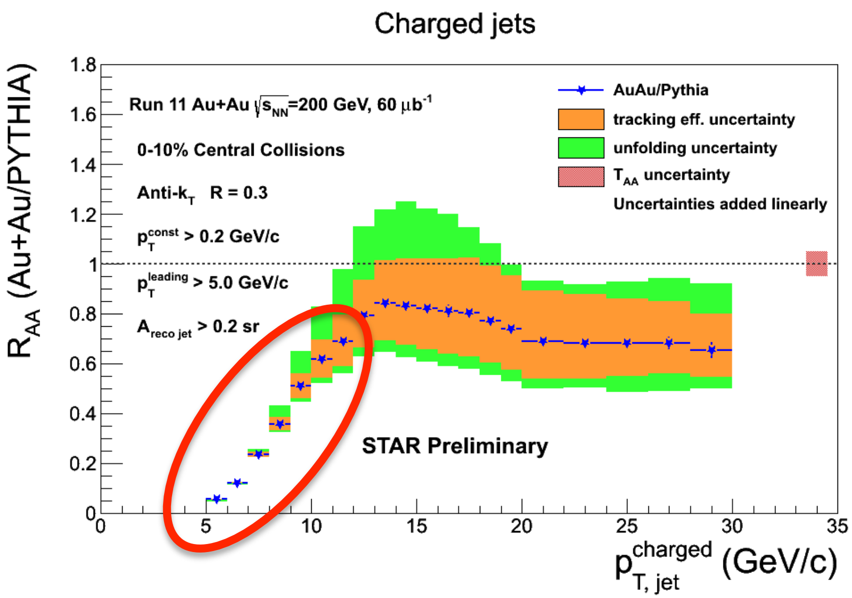
Ratio of heavy ion jet yield to p+p jet cross section

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

p+p spectrum with leading hadron bias



biased Au+Au/unbiased p+p

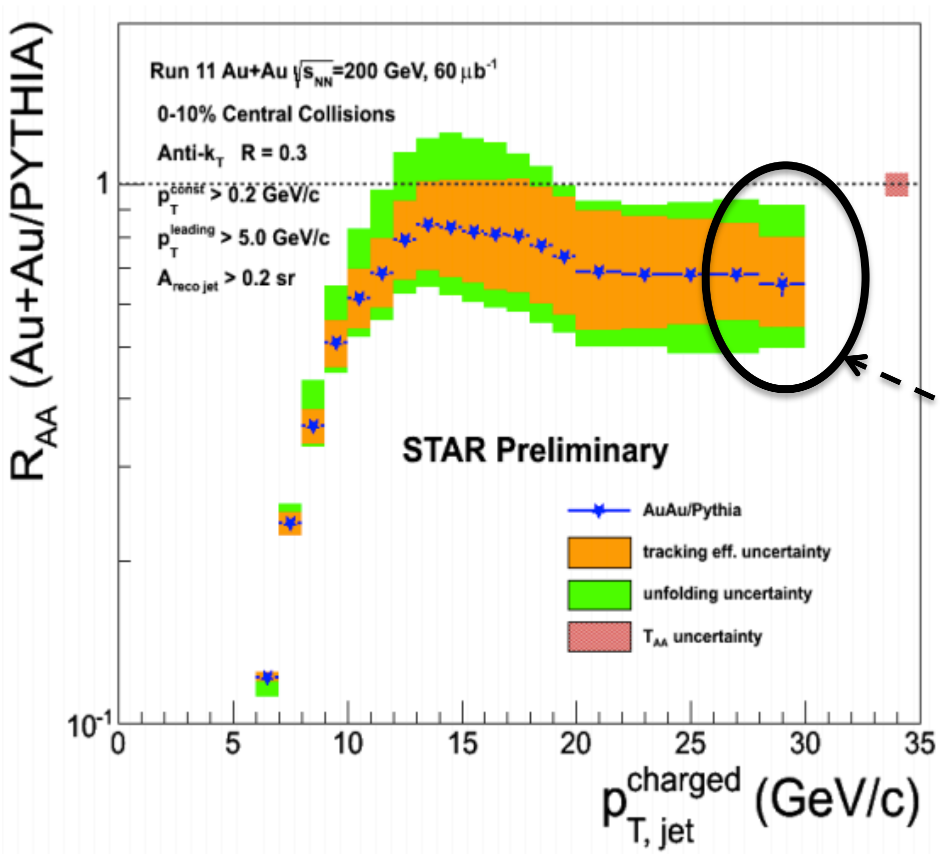


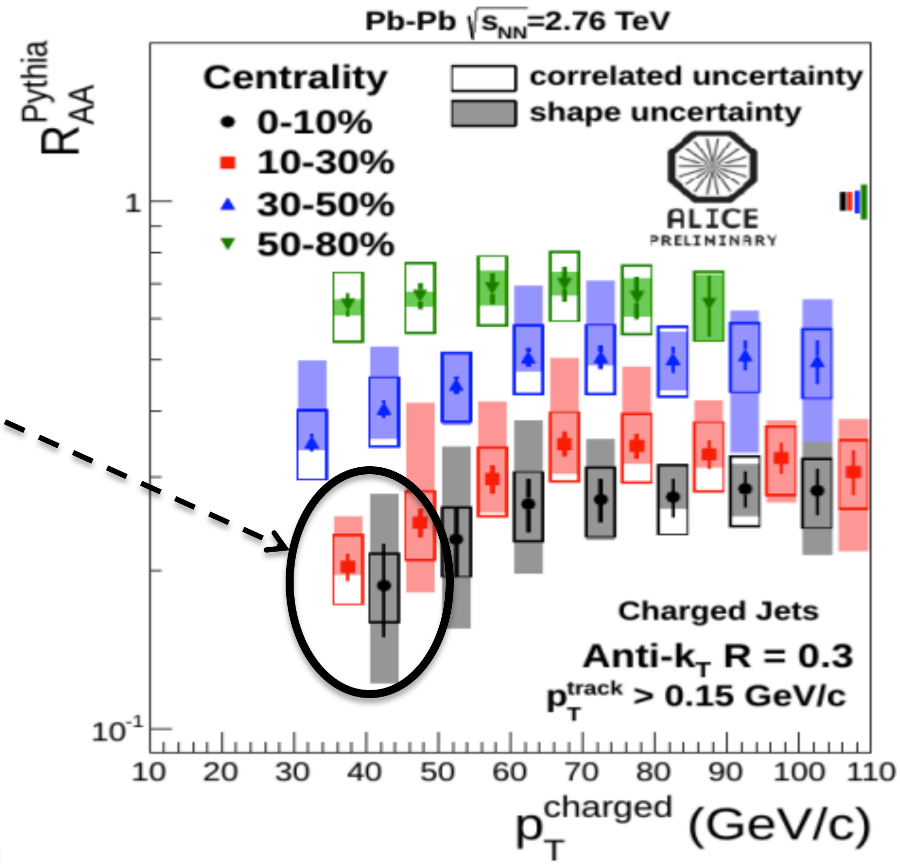
Bias persists to ~few times hadron p_T threshold

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

➔Vacuum-like jets?

Inclusive jet suppression: RHIC vs LHC



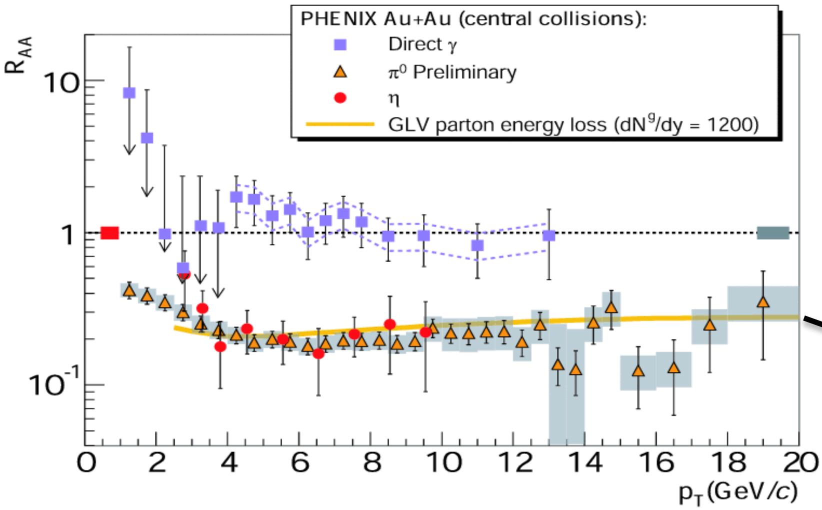


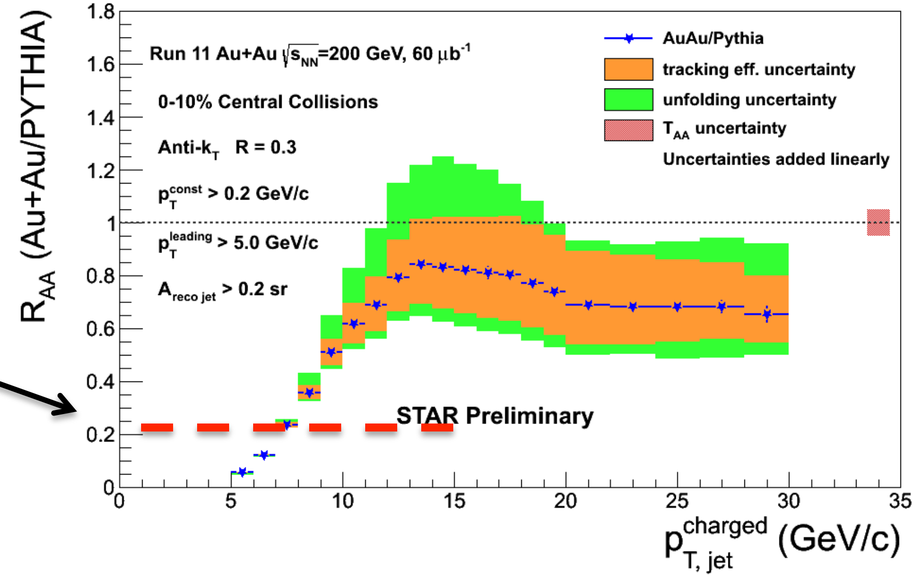
Markedly larger suppression of inclusive jet yield at LHC than at RHIC

Hadron vs jet suppression at RHIC

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

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

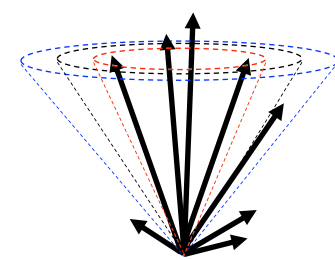




Jets are markedly less suppressed than hadrons at RHIC

- Contrast LHC, where jet and hadron suppression are similar

  ➔Less out-of-cone radiation at RHIC?

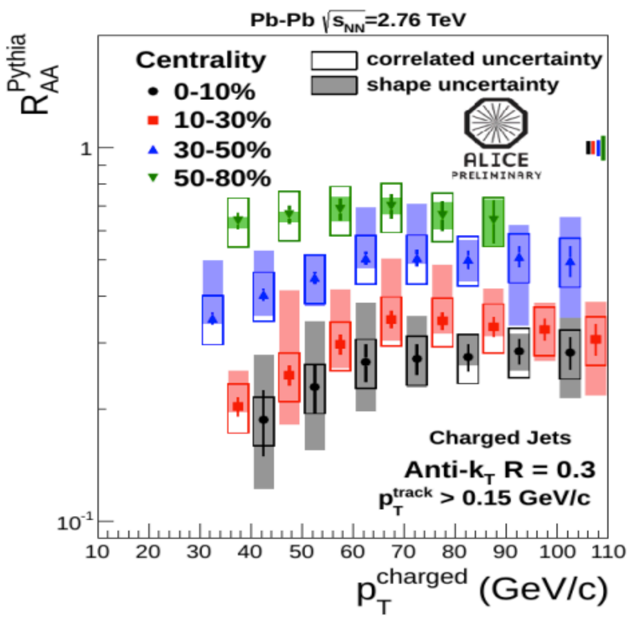


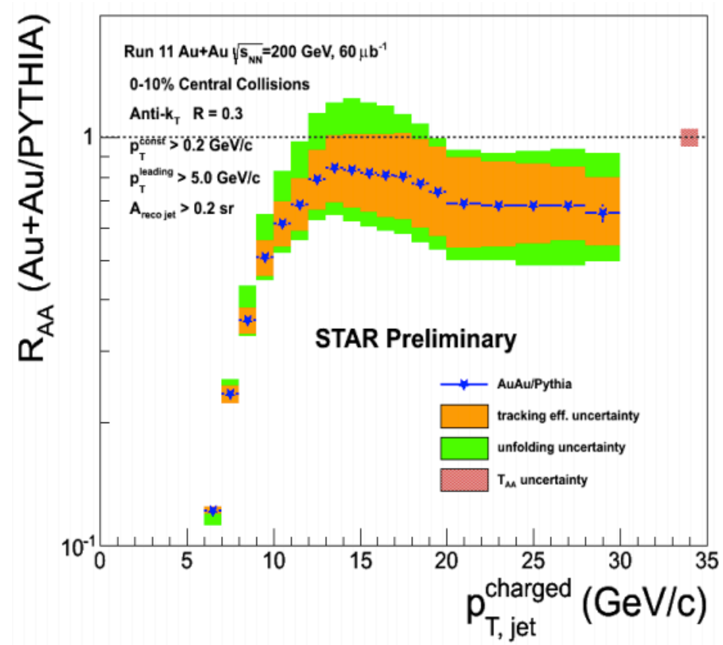
Result is suggestive; improved systematics and kinematic reach in progress

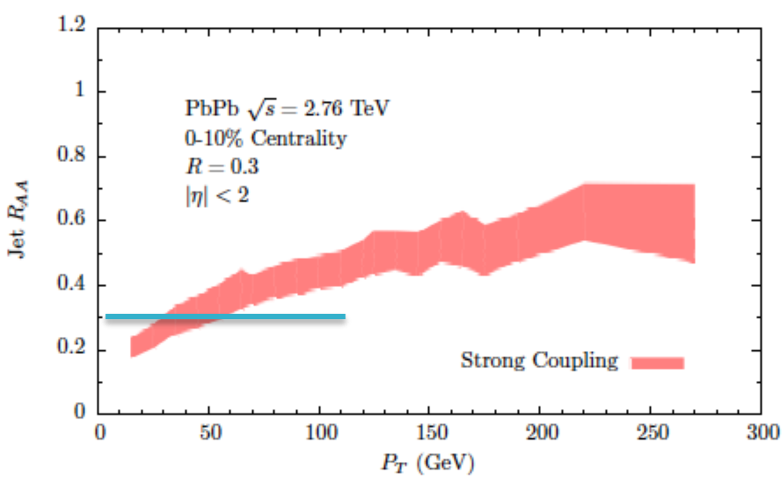
Next step: comparison to theory calculations

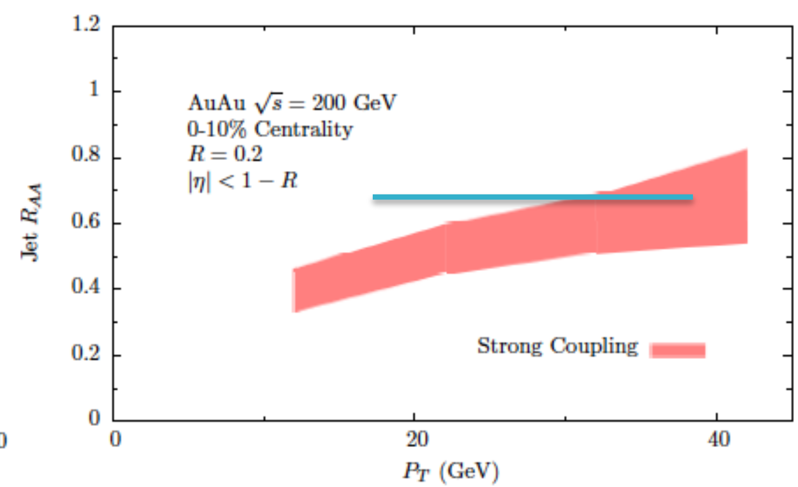
Jet RAA at RHIC and LHC: predictions

Casalderrey-Solana et al. arXiv:1405.3864



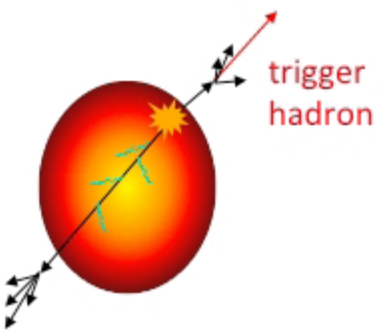






And now for something completely different: hadron+jet correlations

Semi-inclusive yield of jets recoiling from a high p_T hadron trigger

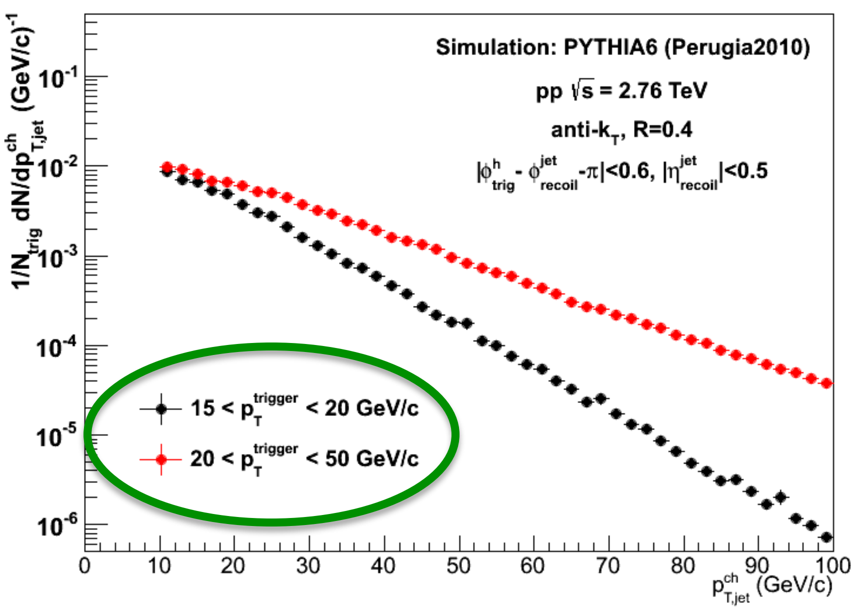


$$\frac{1}{N_{trig}^{h}} \frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{pp\rightarrow h+X}} \frac{d\sigma^{pp\rightarrow h+jet+X}}{dp_{T,jet}}$$

Measured

Calculable in fixed-order pQCD

p+p (Simulated)



Consider two different trigger p_T intervals

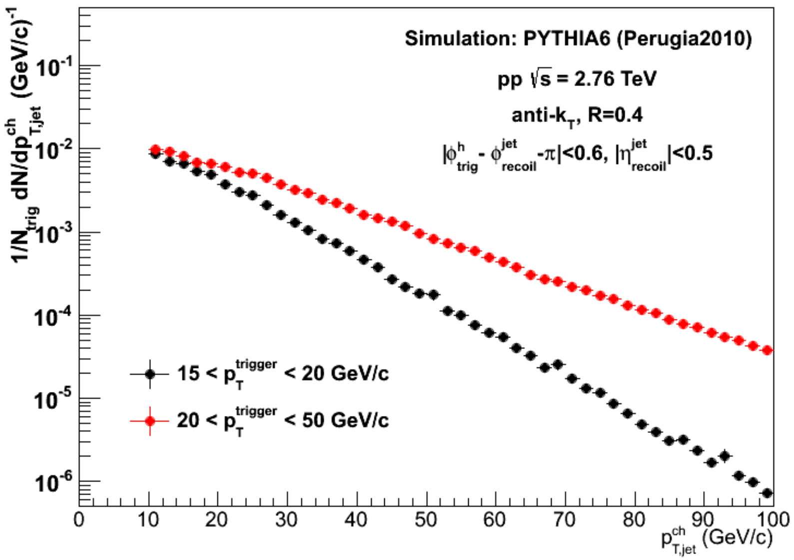
High $p_T^{trigger}$ ➔harder recoil spectrum

- biases towards higher Q^2 processes

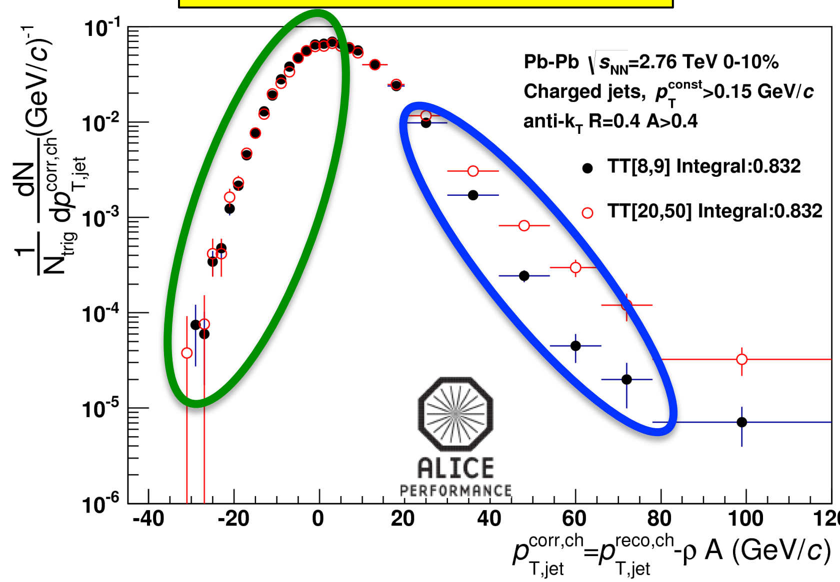
Semi-inclusive h+jet in p+p and Pb+Pb @ LHC

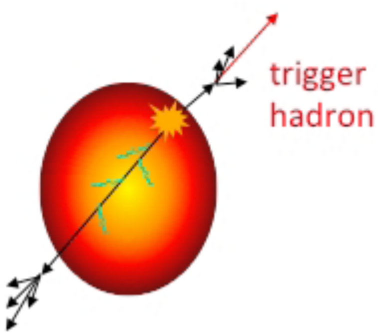
Leticia Qunqueiro, CERN
Rongrong Ma, BNL

p+p (Simulated)



Central Pb+Pb (data)





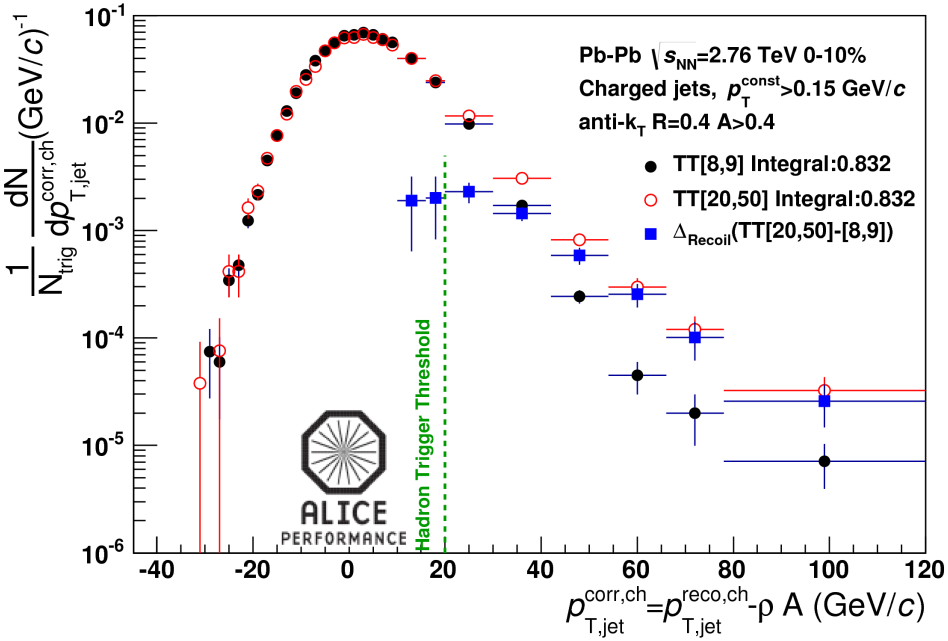
$p_T^{corr}<0$:

- 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: Δ_{Recoil}



G. De Barros et al., arXiv:1208.1518

Opportunity: take difference of spectra

- Precisely removes combinatorial jet contribution w/o jet selection bias
- Works robustly for R=0.5
- Correct to particle level for instrumental effects and bkgd fluctuations ("unfolding")

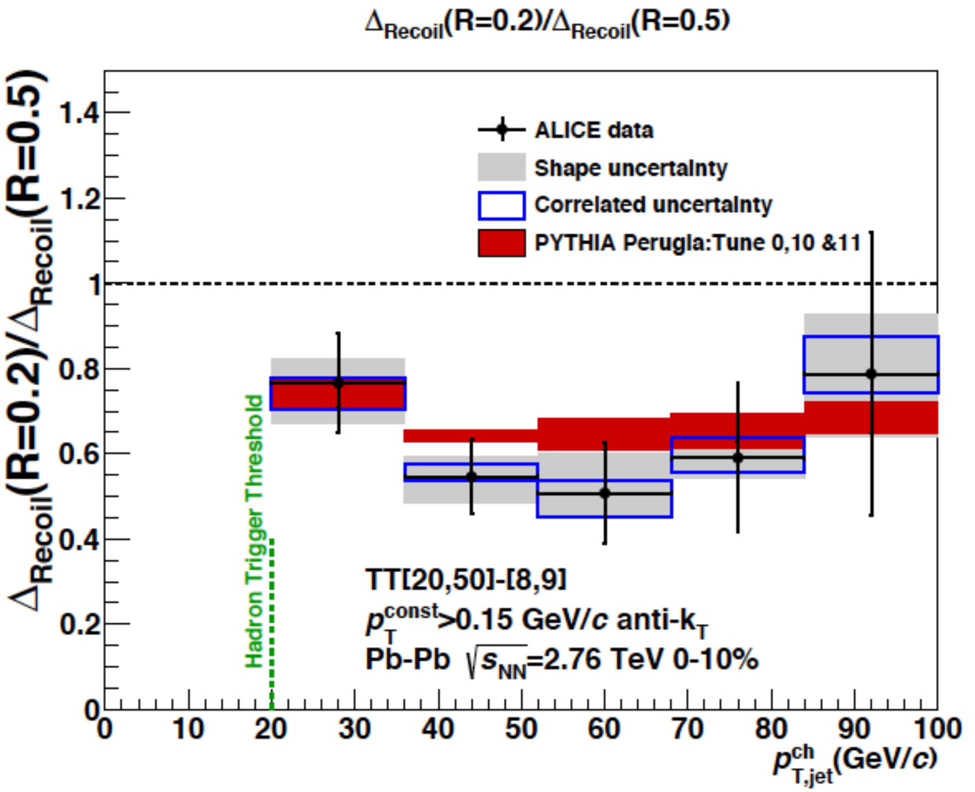
$$\Delta_{Recoil} = \left[\frac{1}{N_{trig}}\frac{dN_{Jet}}{dp_T^{jet}}\right]_{TT[20-50]} - \left[\frac{1}{N_{trig}}\frac{dN_{Jet}}{dp_T^{jet}}\right]_{TT[8-9]}$$

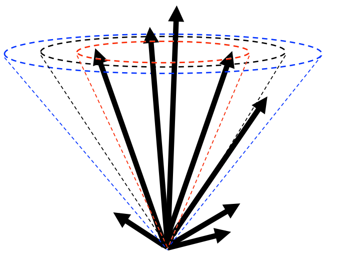
Ensemble-averaged analysis: no rejection of jet candidates on a jet-by-jet basis

- jet measurement is collinear-safe with low IR cutoff (0.2 GeV/c)
- directly comparable to pQCD calculations (vacuum and quenched)

But there is a price: this is the ***evolution*** of the recoil jet population with variation in p_T^{trig}

h+jet in p+p and Pb+Pb: jet broadening due to quenching?



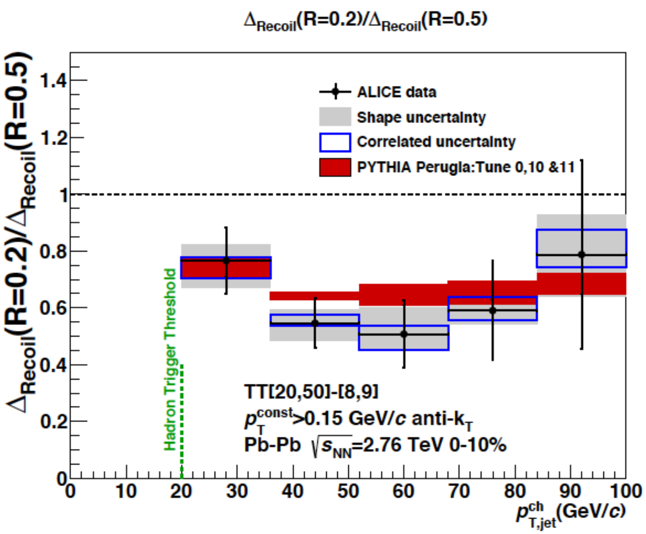


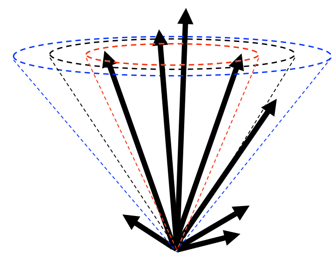
Ratio of differential recoil yields
R=0.2/R=0.5

Compare ratios for central Pb+Pb and p+p

No significant evidence of jet broadening due to quenching within R=0.5

Vacuum reference: NLO vs MC shower



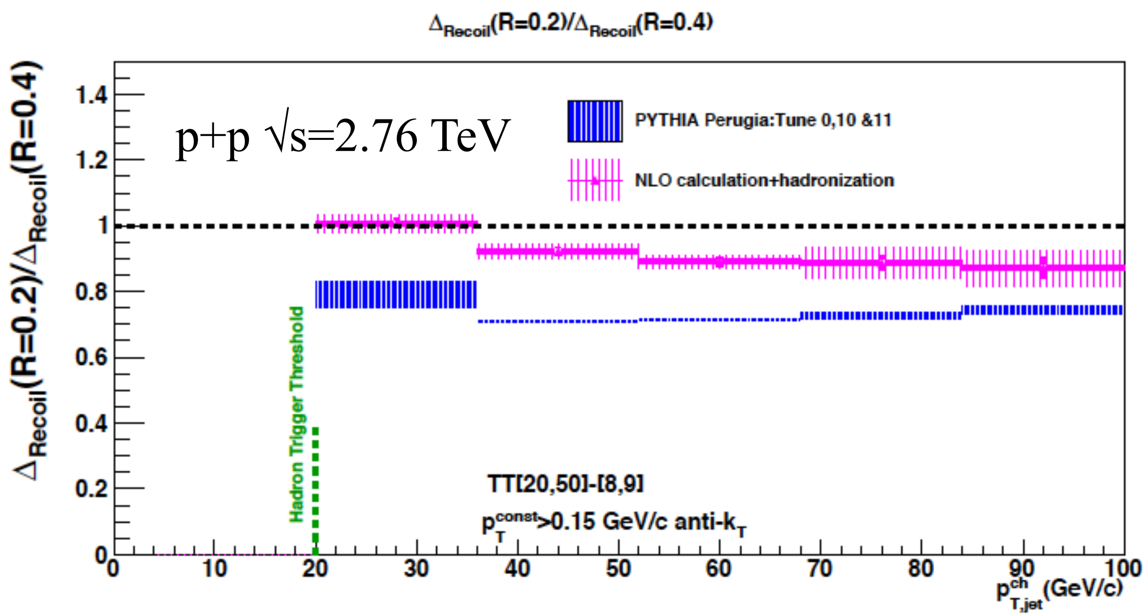


NLO: D. de Florian arXiv:0904.4402

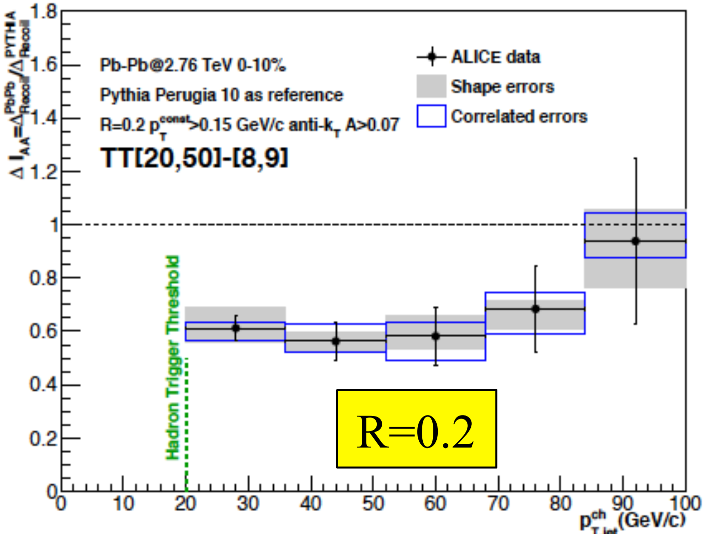
MC shower and NLO differ

Compare ALICE p+p@7 TeV (not shown): MC shower strongly favored

Important lesson for jet quenching via pQCD@NLO



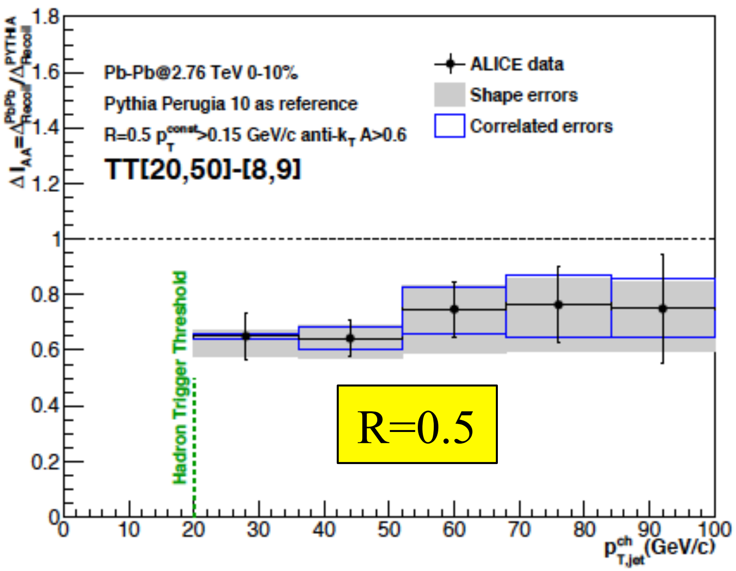
Recoil yield suppression: ΔI_{AA}

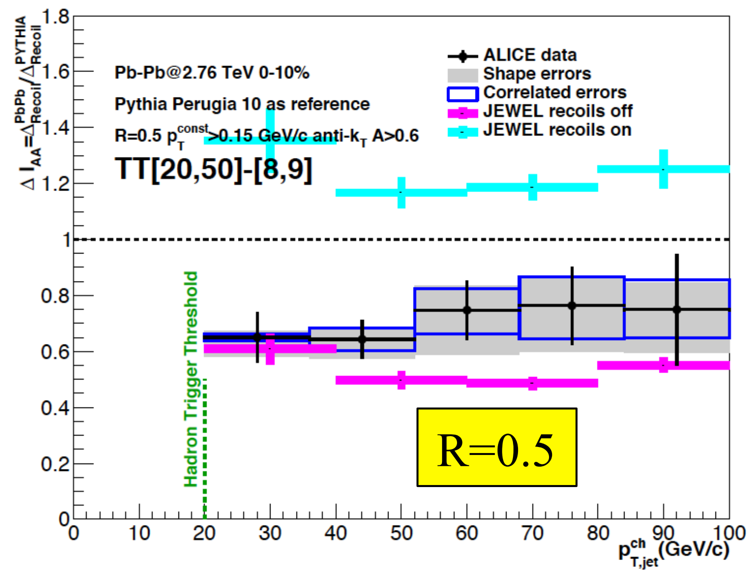


$$\Delta I_{AA} = \frac{\Delta^{PbPb}_{Recoil}}{\Delta^{pp}_{Recoil}}$$

pp reference: PYTHIA Perugia 10

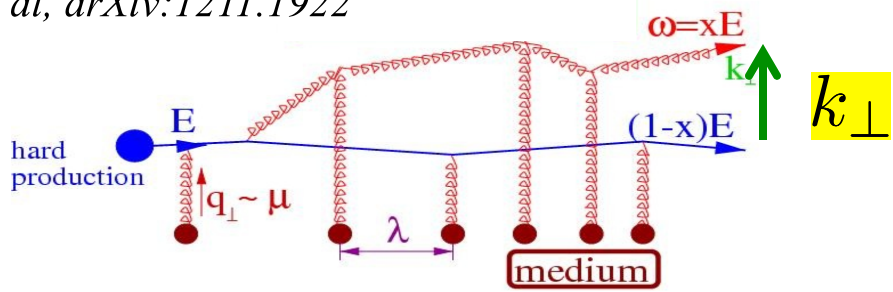
Compare to quenching MC: JEWEL



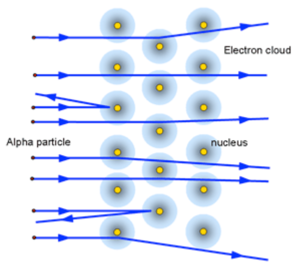


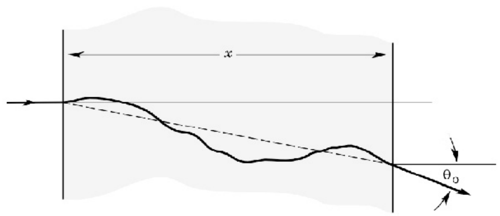
Large-angle scattering off the QGP

d'Eramo et al, arXiv:1211.1922



Discrete scattering centers or effectively continuous medium?





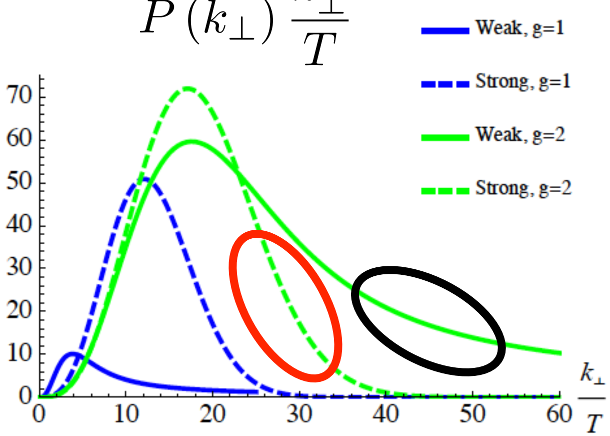
Look at the rate of large-angle deflections (DIS-like scattering off the QGP)

- What are the quasi-particles?

Weak coupling: pQCD: finite temperature plays the role of mass to generate large angle scattering

Strong coupling: AdS/CFT

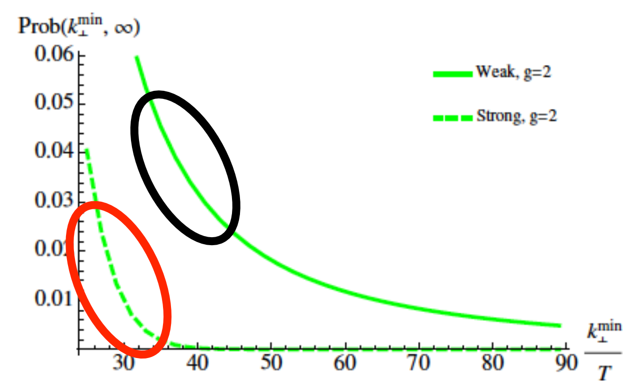
$$P\left(k_\perp\right)\frac{k_\perp^3}{T}$$



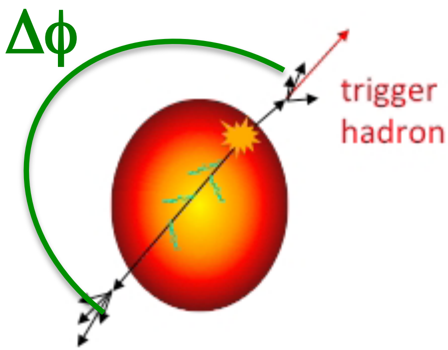
Strong coupling: Gaussian distribution

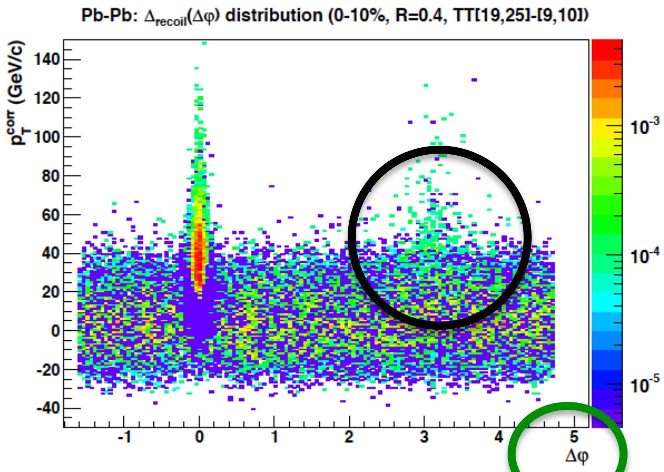
Weak coupling: hard tail $\sim \frac{1}{k_\perp^4}$

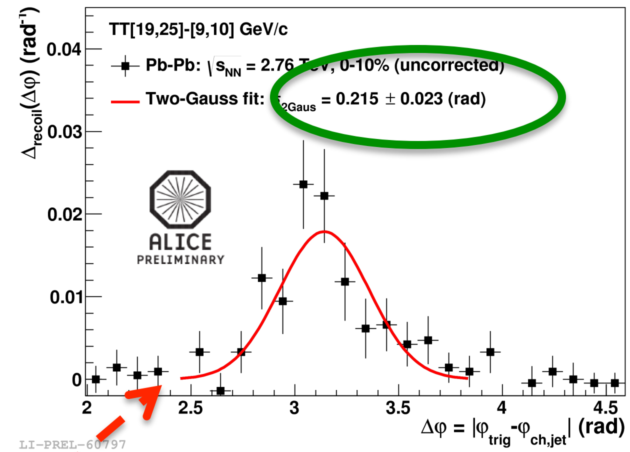
$$\mathrm{Prob}\left(k_\perp > k_\perp^{min}\right)$$

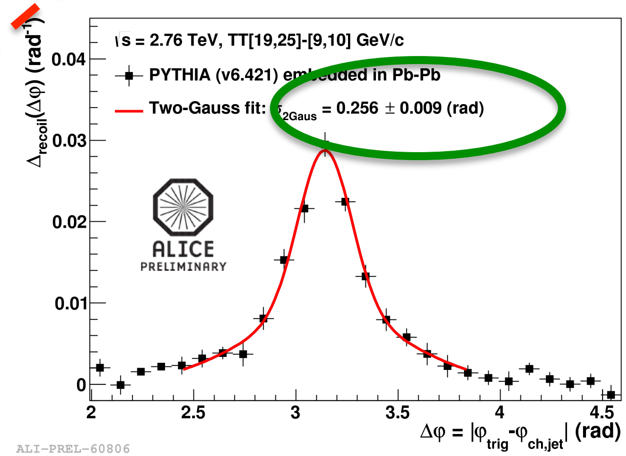


h+jet @ LHC: medium-induced acoplanarity?





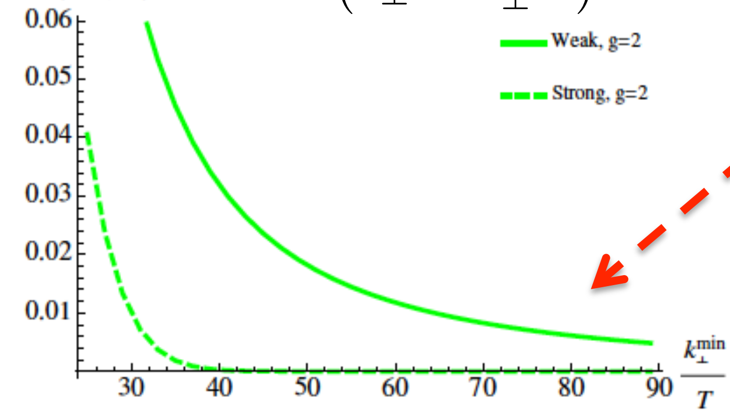




"DIS off the QGP": look at rate of large-angle scattering…?

Compare to p+p (PYTHIA)

$$\text{Prob}\left(k_\perp > k_\perp^{min}\right)$$



No evidence of medium-induced acoplanarity

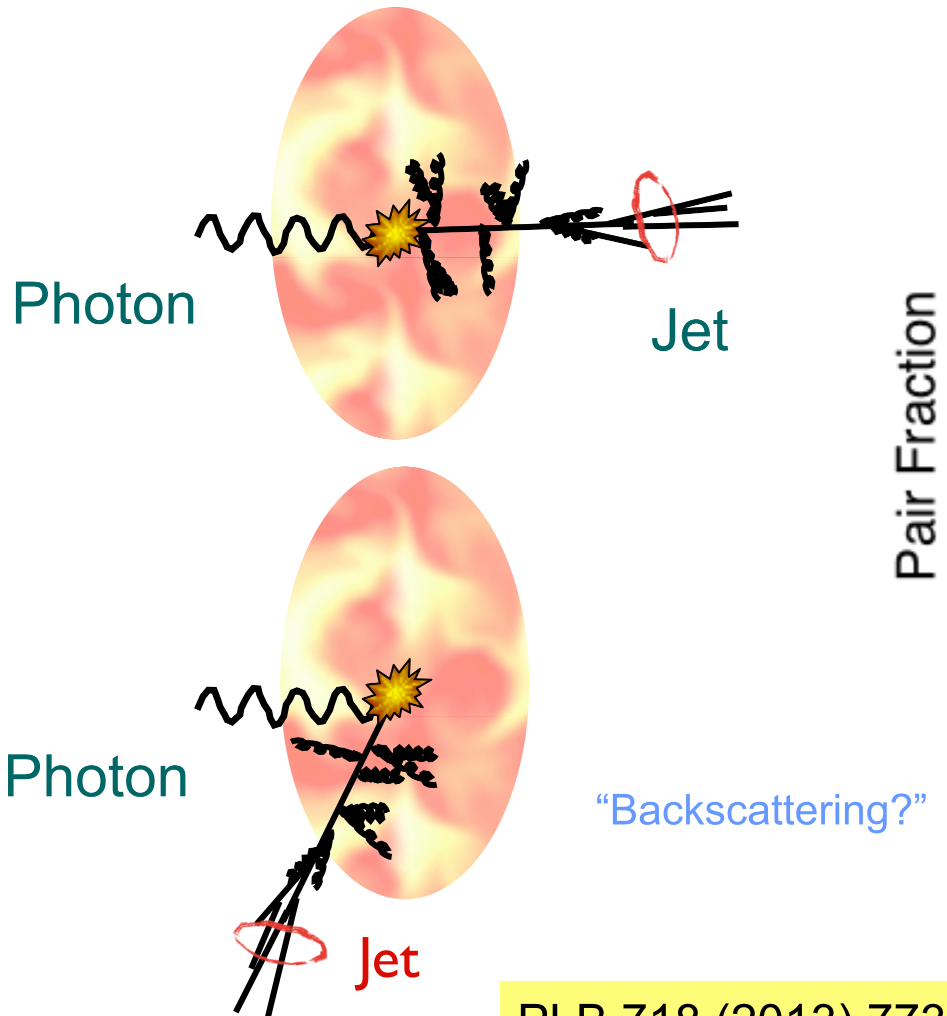
d'Eramo et al, arXiv:1211.1922

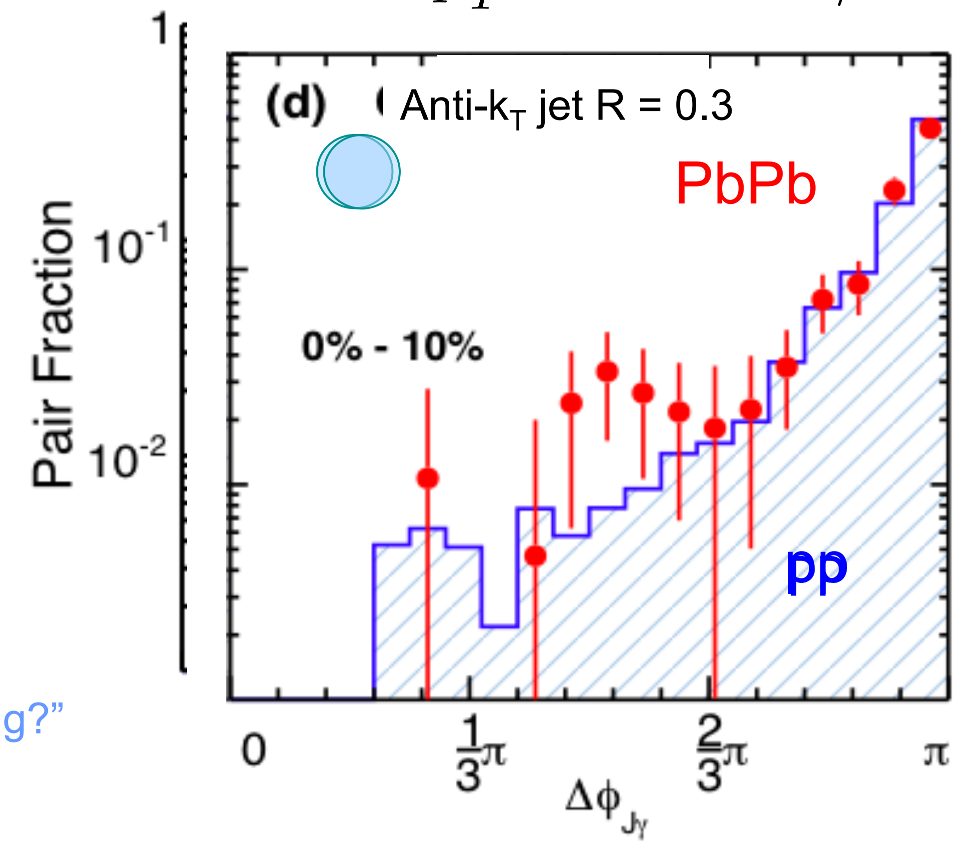
CMS : photon-jet angular correlation

"QGP Rutherfold experiment"

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

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

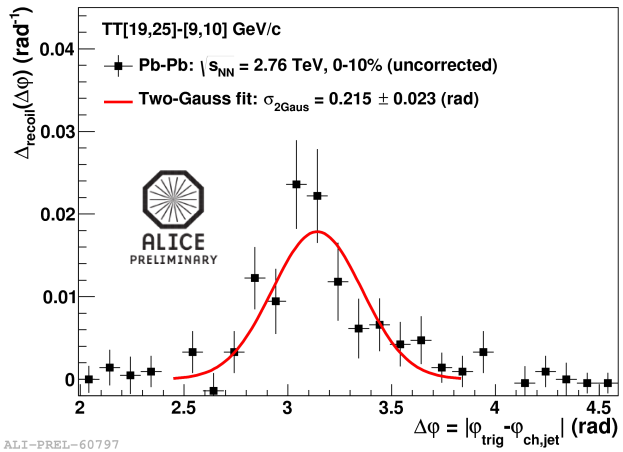


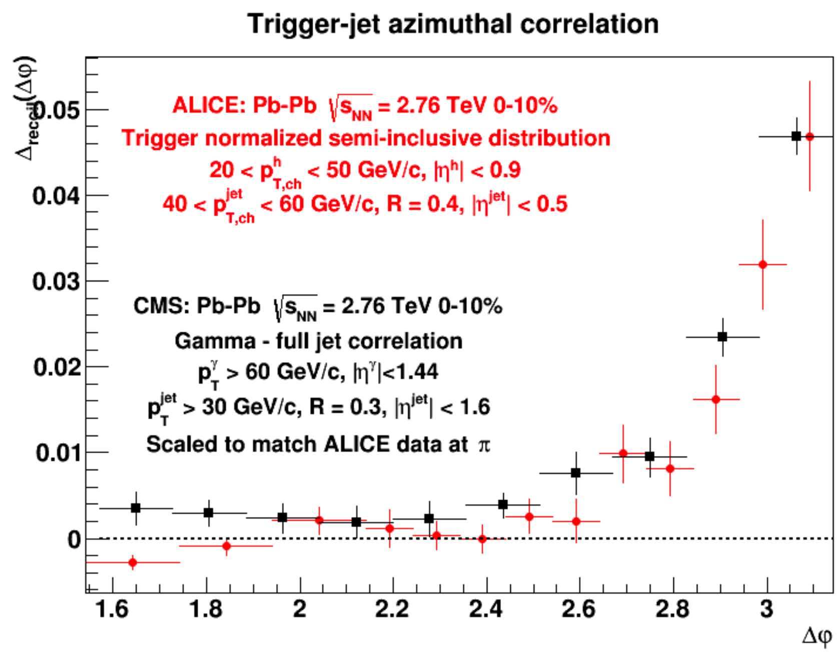


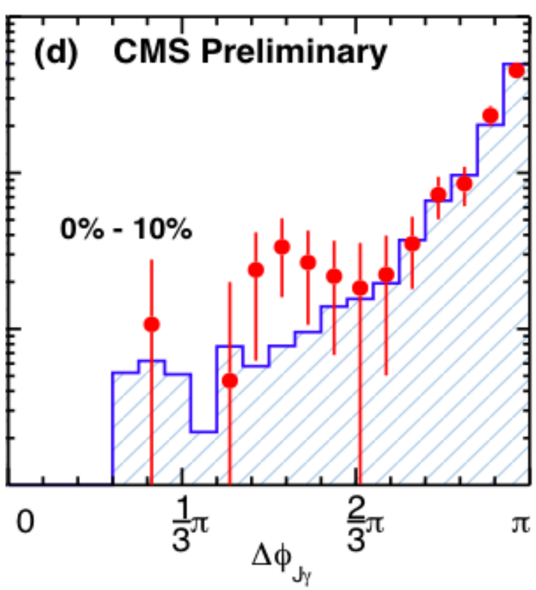
PLB 718 (2013) 773

Azimuthal angle difference between photon and jet

Compare CMS γ+jet/ALICE h+jet





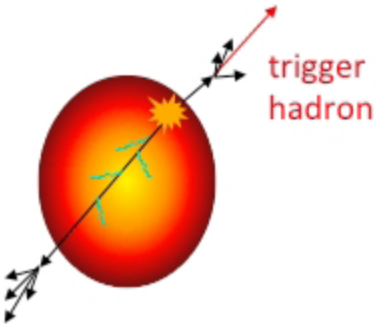


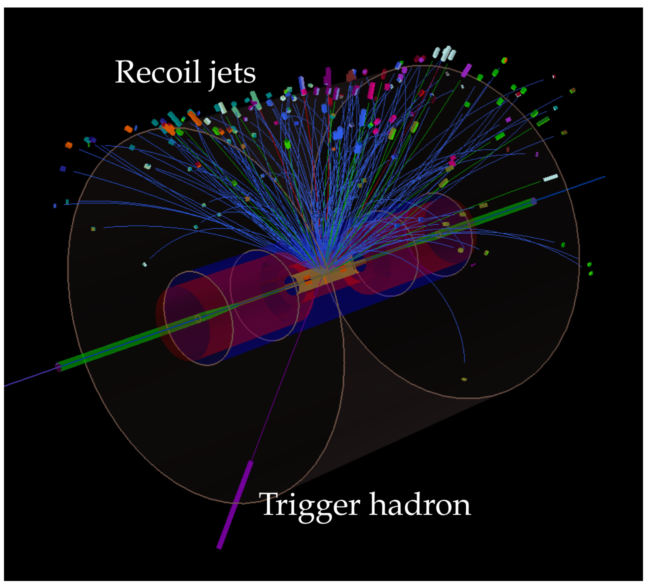
Many differences: trigger, jet kinematics, jet selection bias, parton flavor bias,…

But still: distributions are similar

- Difference in tails….?

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

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

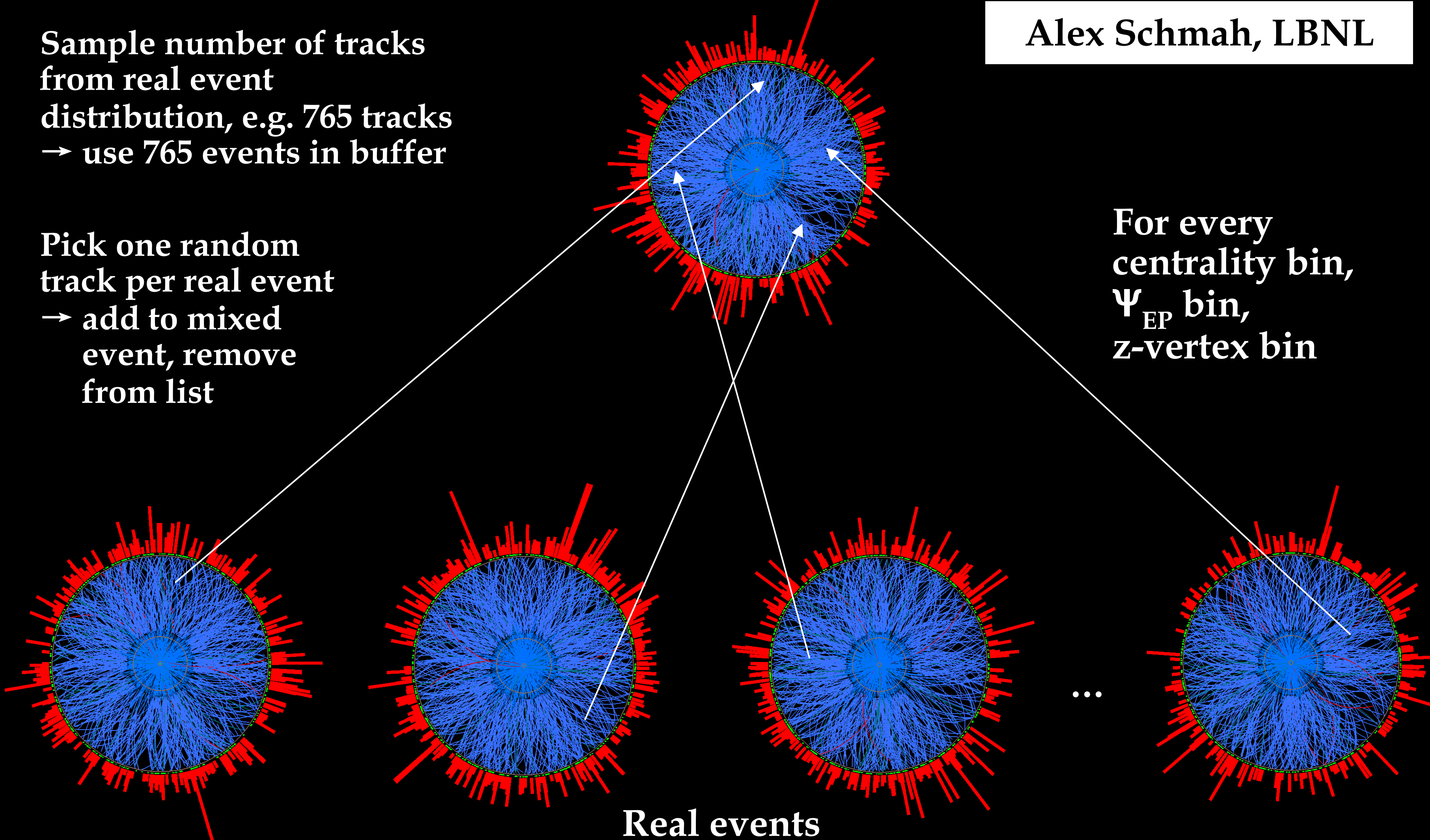
New method to measure combinatorial jet background: mixed events

Alex Schmah, LBNL

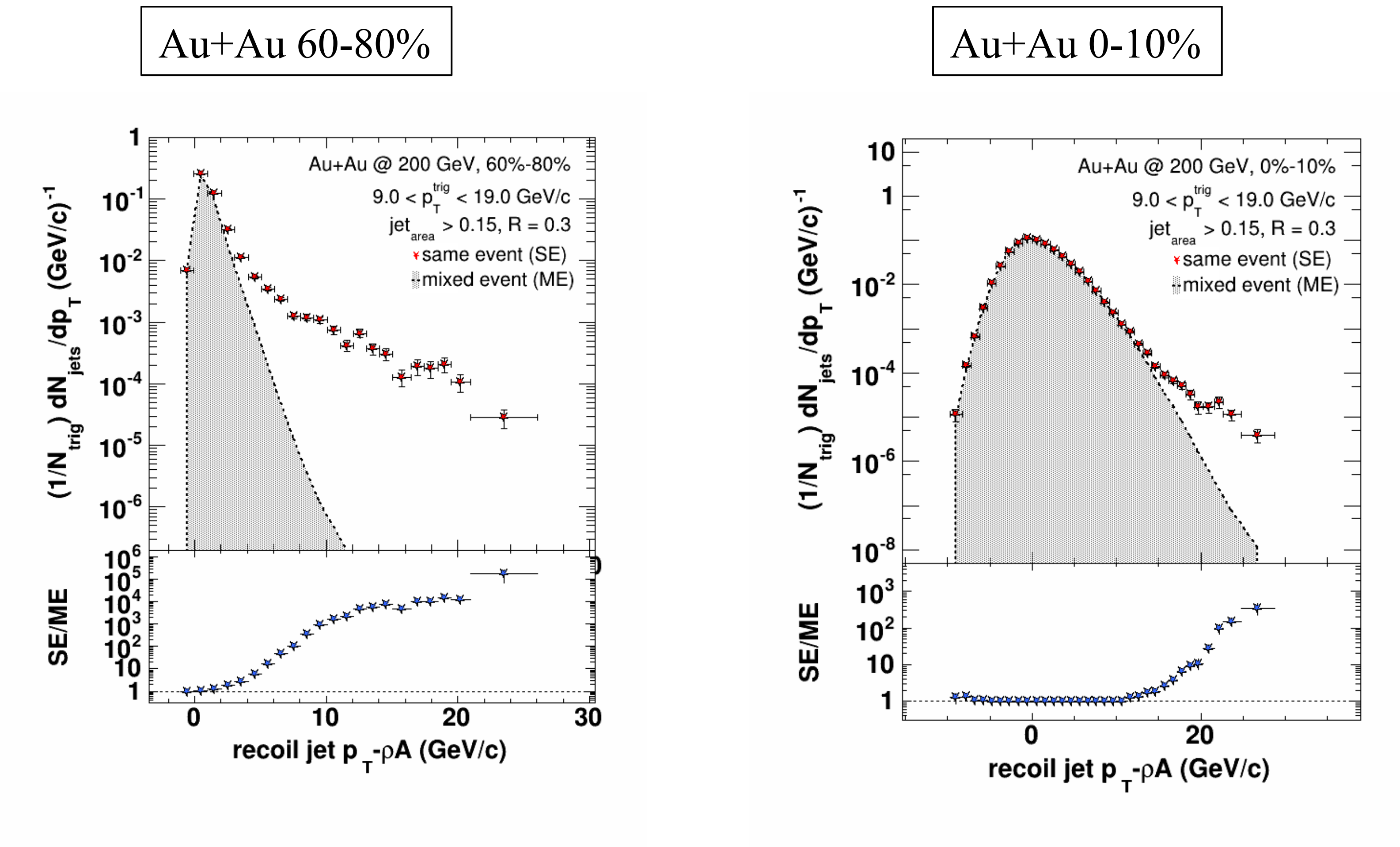
Sample number of tracks from real event distribution, e.g. 765 tracks → use 765 events in buffer

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



Mixed events give precise description of combinatorial background

➔Trigger-correlated jet distribution: subtract ME from data

Compare ALICE h+jet: difference is absolute recoil yield (not trigger-differential)

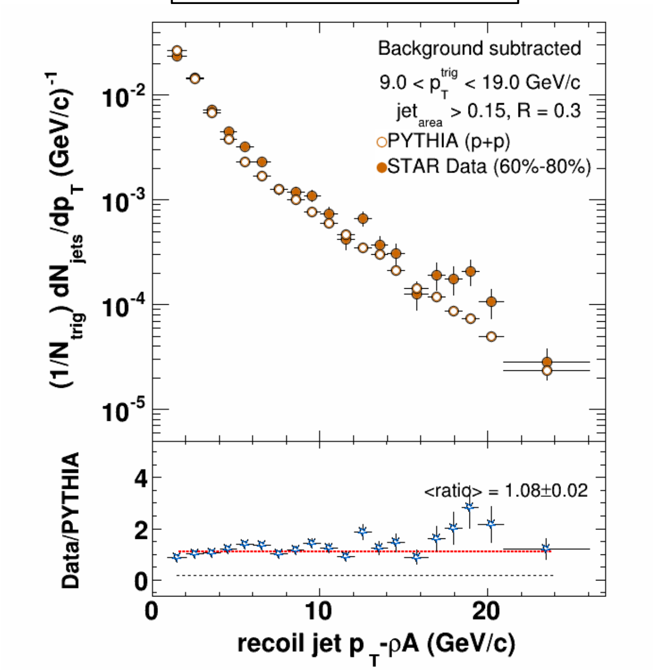
Background-subtracted distributions

Compare to theory: should correct background-subtracted Au+Au distributions to the particle level

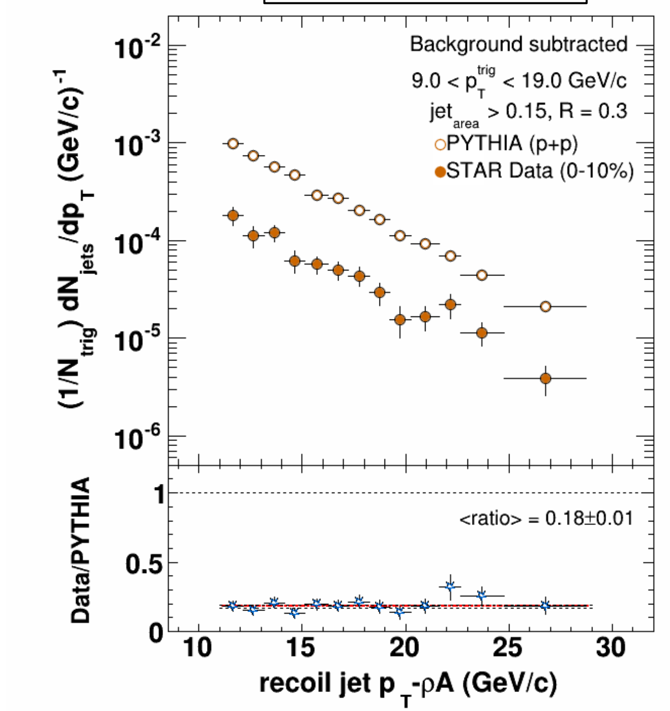
- unfold for background fluctuations and detector effects
- but not yet done

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

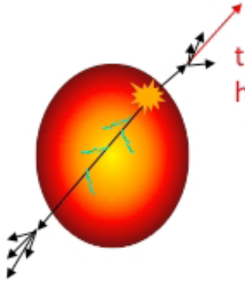
Au+Au 60-80%



Au+Au 0-10%

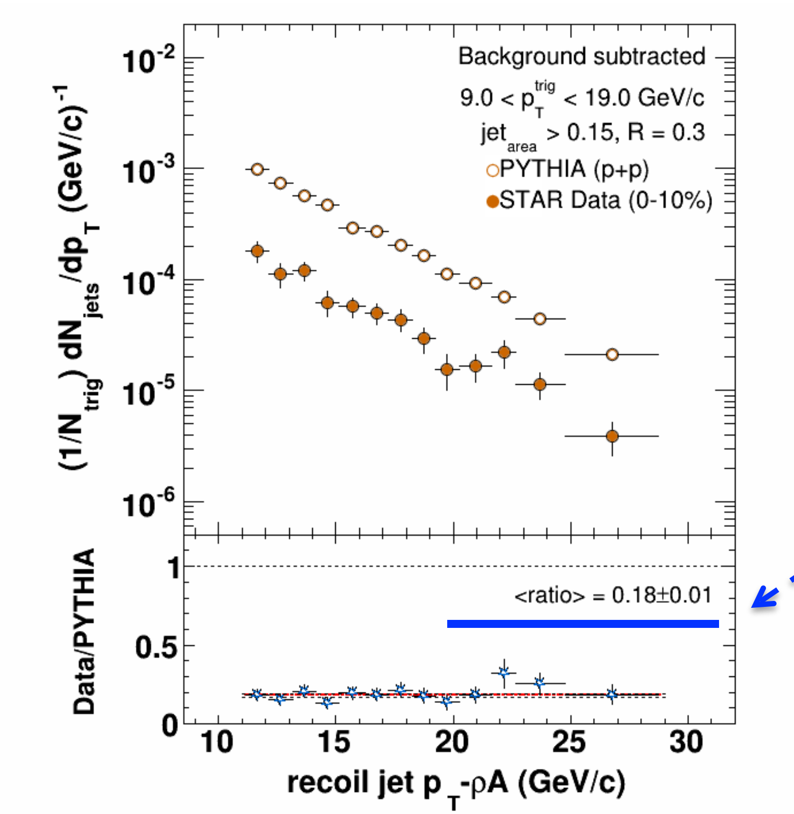


Peripheral Au+Au: good agreement between data and PYTHIA
Central Au+Au: strong suppression relative to PYTHIA

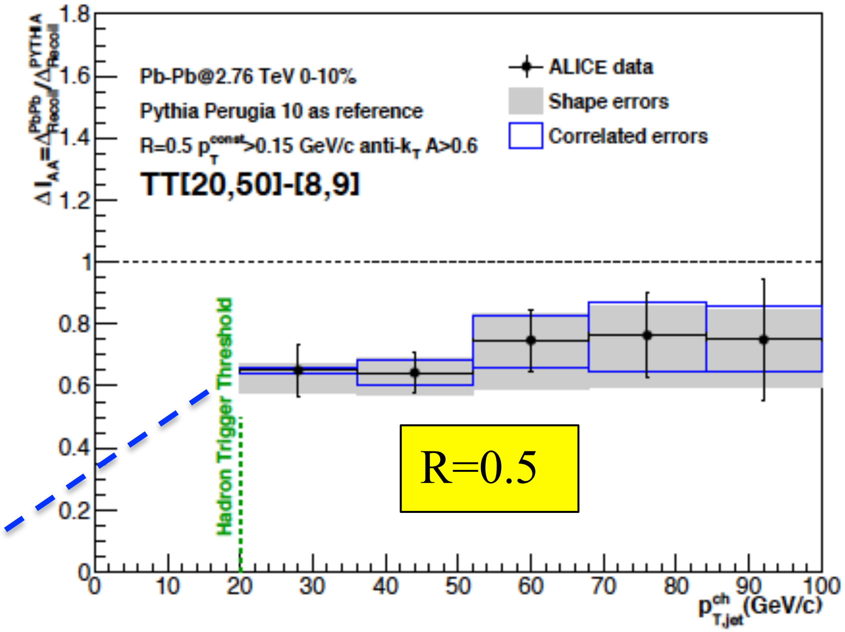


h+jet yield suppression: RHIC vs LHC

STAR central Au+Au



ALICE central Pb+Pb



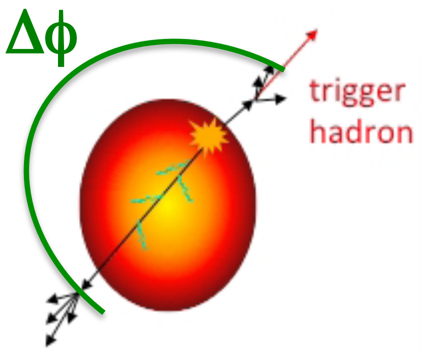
Are these consistent?

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

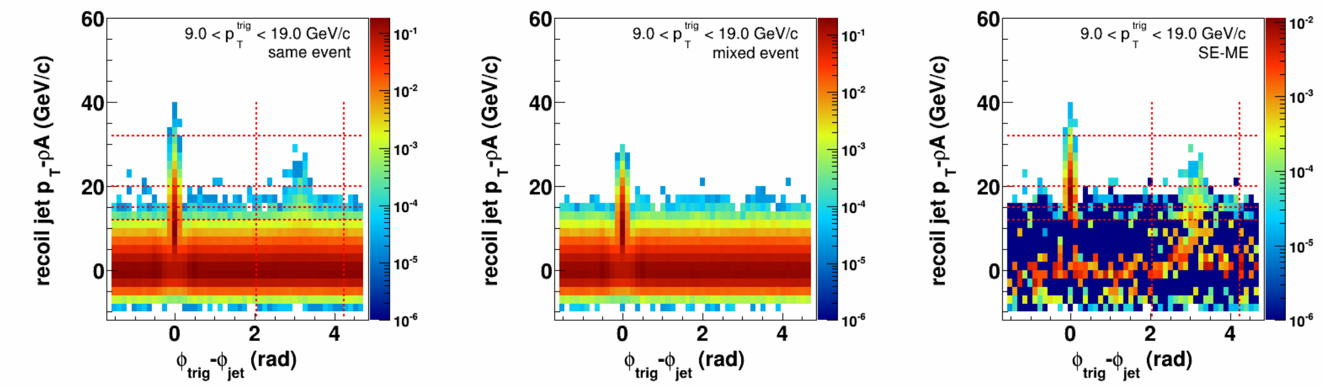
RHIC: $\Delta E \sim 5$ GeV
LHC: $\Delta E \sim 7$ GeV

"Chi-by-eye", needs to be done carefully

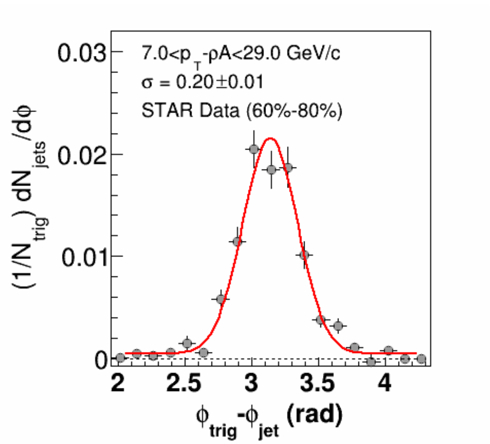
h+jet azimuthal distributions: RHIC vs LHC



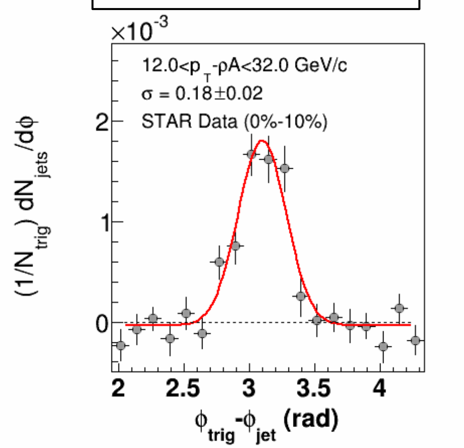
Au+Au 0-10%



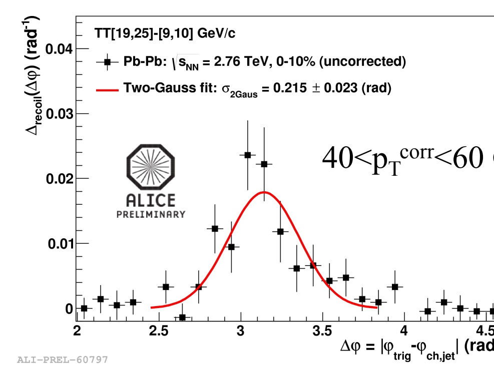
Au+Au 60-80%



Au+Au 0-10%



Pb+Pb 2.76 TeV 0-10%



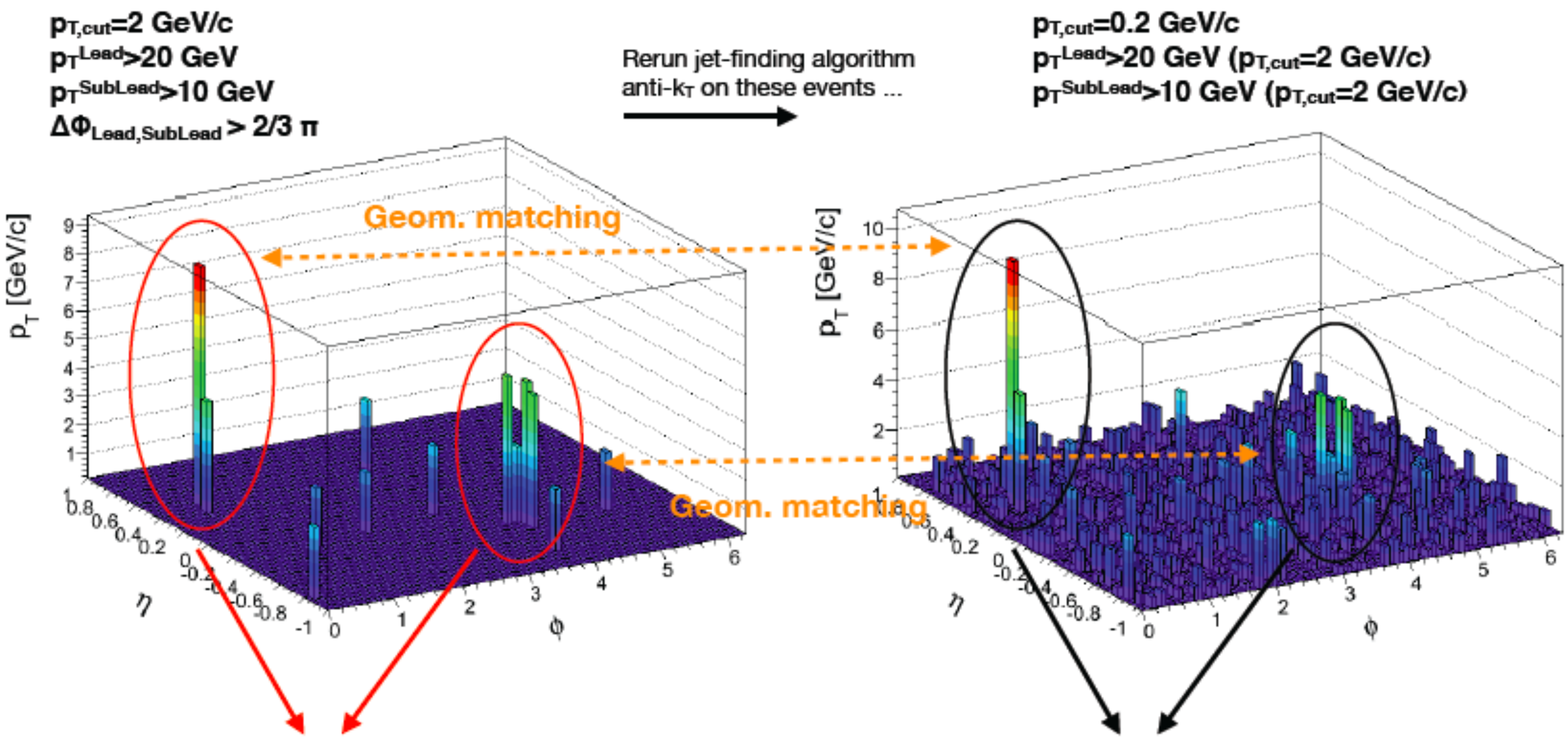
40<p_T^{corr}<60 GeV

- AuAu central vs peripheral: No evidence yet of large-angle scattering
  - (N)NLO pQCD calculations underway (d'Eramo + Rajagopal)
- RHIC vs LHC: comparable widths…expected or not?

STAR: A_J of biased jets

J. Putschke, QM2014

Full jets (with BEMC), Run 7 data



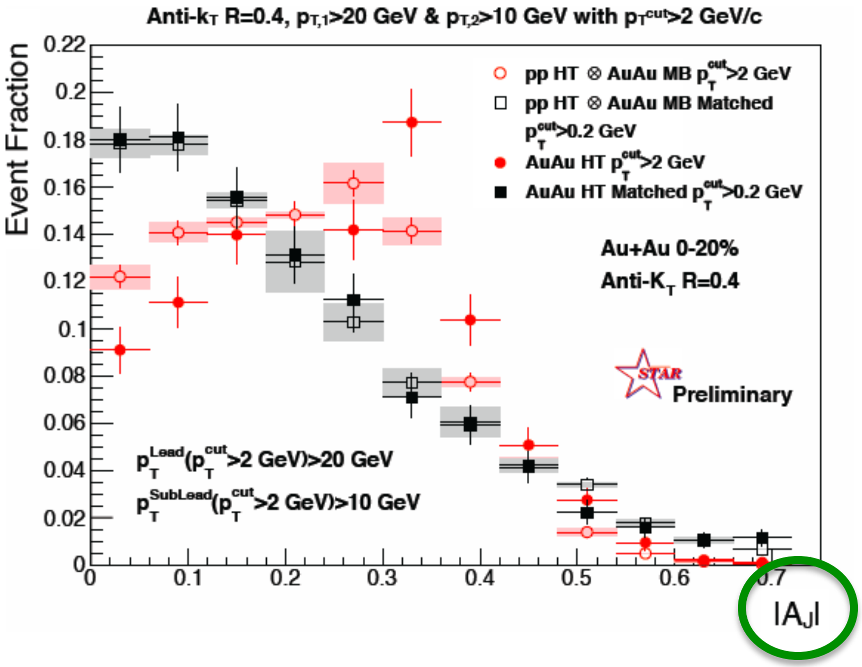
Calculate A_j with constituent $p_{T,cut}$>2 GeV/c

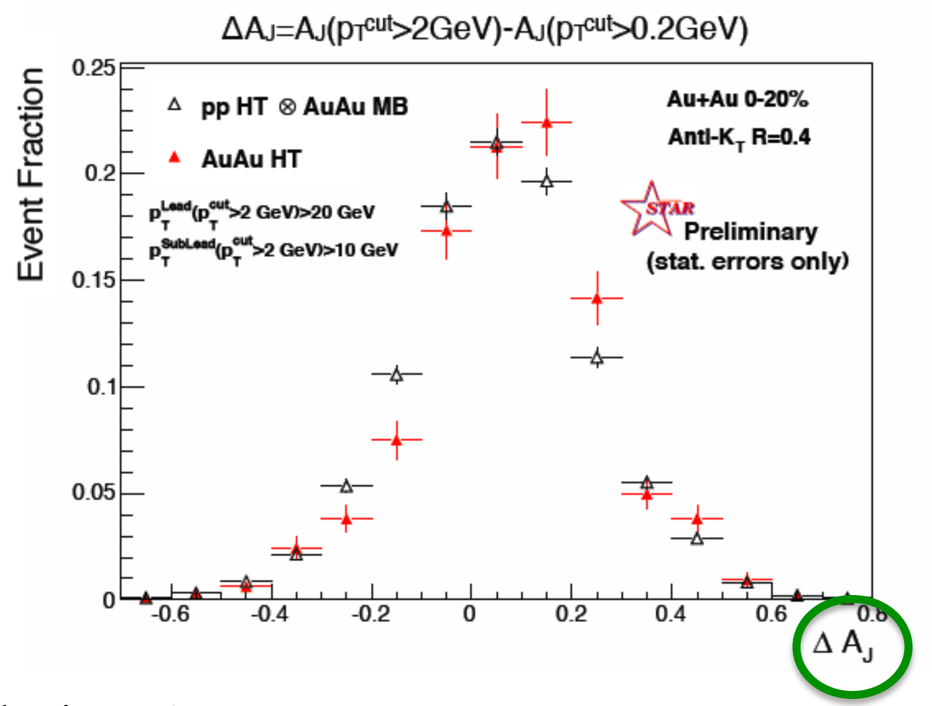
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \qquad p_T = p_T^{rec} - \rho \times A$$

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

A_J of biased di-jets

J. Putschke, QM2014





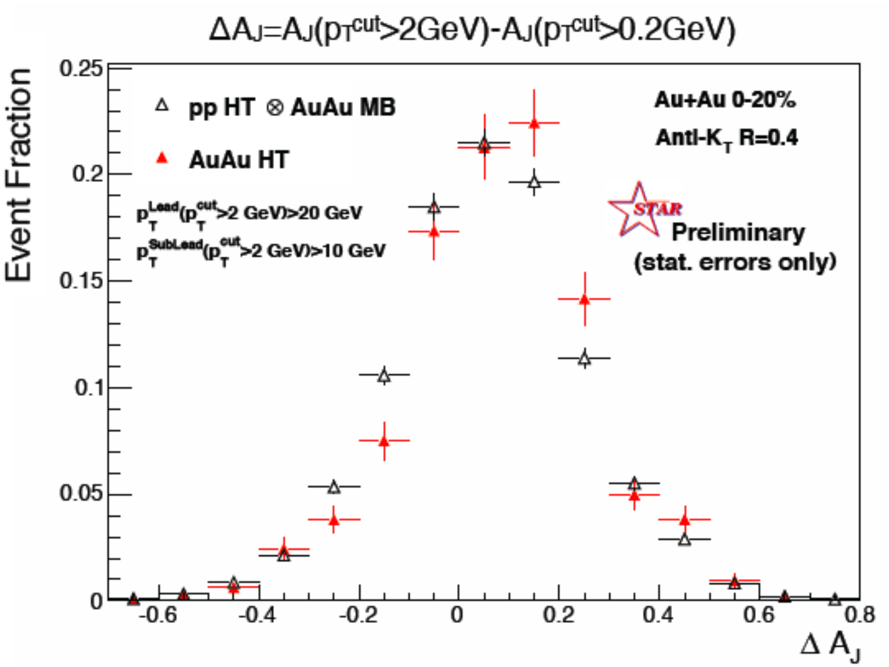
My preferred observable for this analysis: ΔA_J

- ΔA_J = shift in A_J with constituent cut 2 GeV ➔ 0.2 GeV
- Calculated on a pair-wise basis
- Includes negative shifts, flipping of trigger/recoil assignment

ΔA_J central Au+Au vs p+p: minor differences compared to overall shift
➔ vacuum like jets? Bias towards tangential pairs?

How important is jet selection bias?

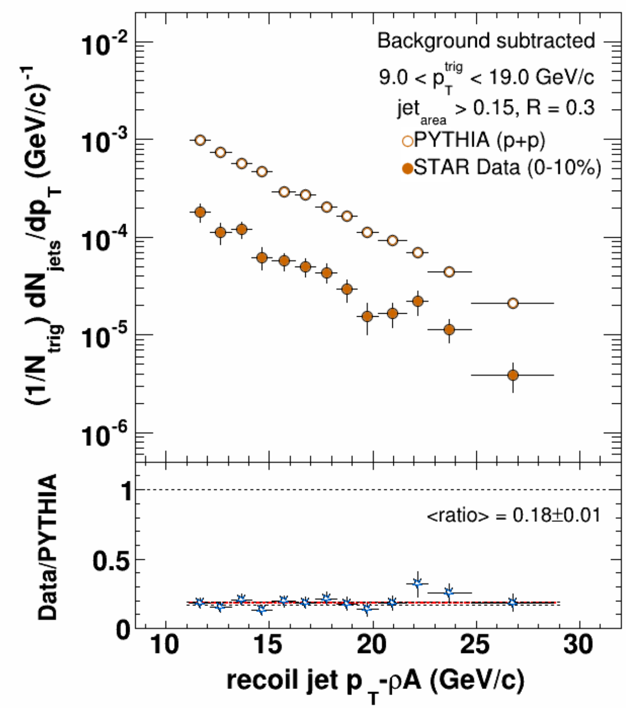
A_J: biased pairs



Little difference between central Au+Au vs p+p

- Vacuum-like: tangential pairs?
- Small if any out of cone radiation

h+jet: unbiased recoil



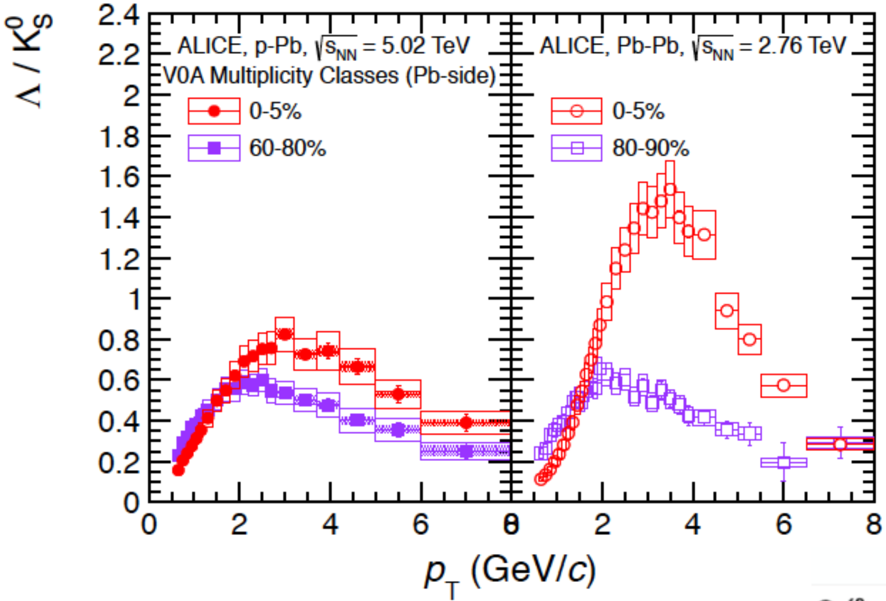
Strong yield suppression of central Au+Au vs p+p:

- large out-of-cone radiation

The bias matters…a lot!

ALICE: Λ/K^0_S ratio in jets

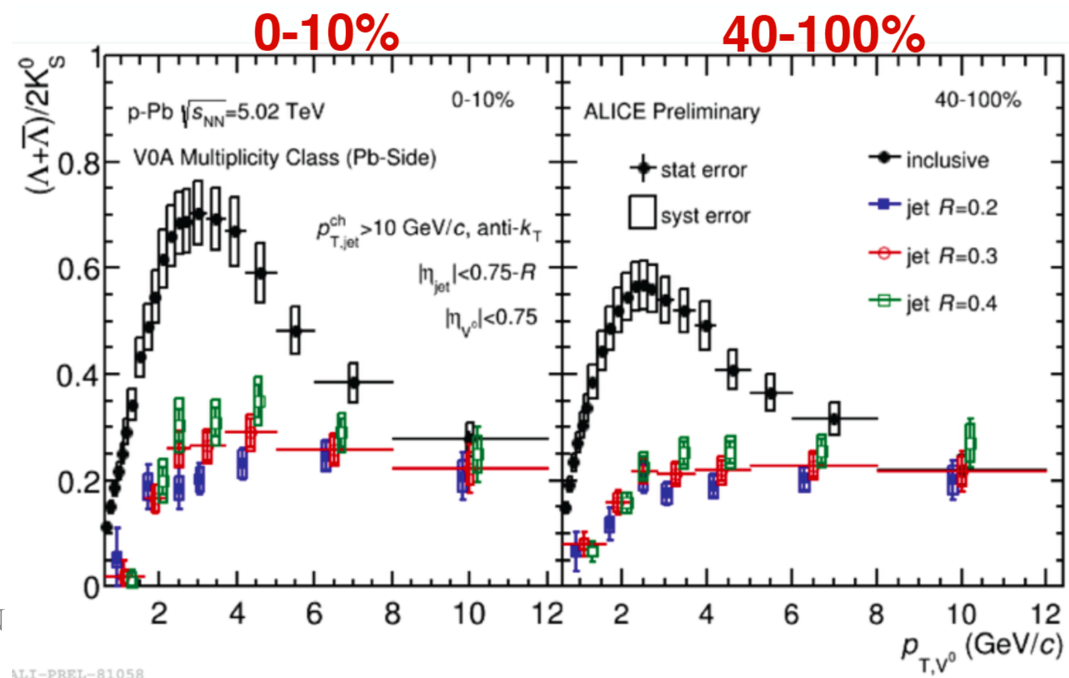
ALICE PhysLett B719 (2012) 29



Previous result: baryon enhancement (Λ/K) seen in high multiplicity p+Pb

X. Zhang, QM14

New analysis: look at Λ/K inside jets vs UE in p+Pb

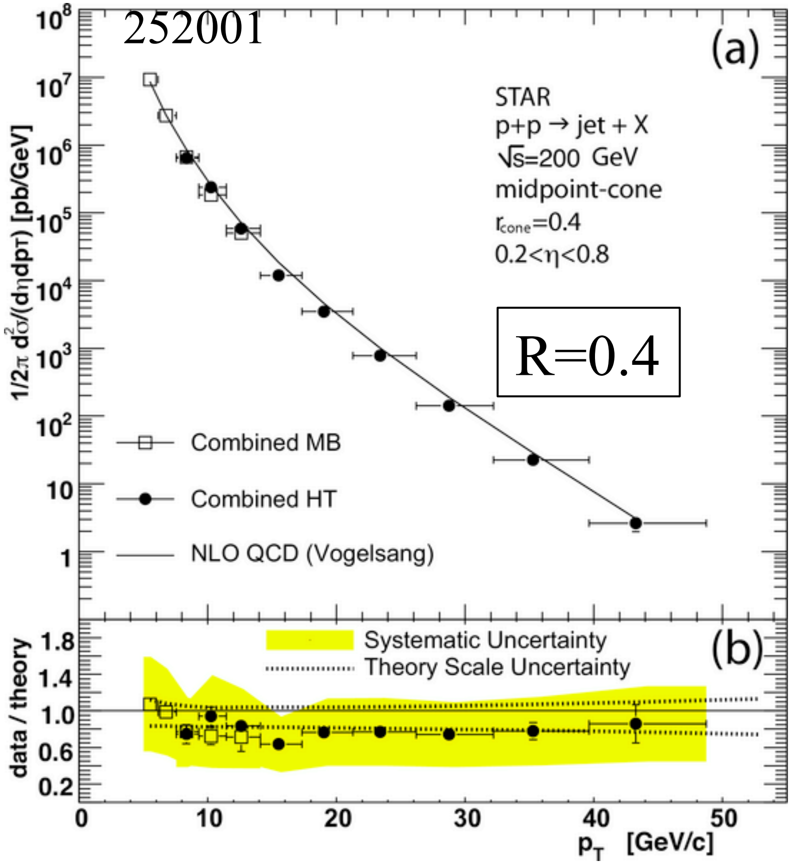


Conclusion: Λ/K enhancement is not correlated with jet production

➔Implications for coalescence models?

Estimated jet yields in STAR for central Au+Au: current and future data

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

New idea I:

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

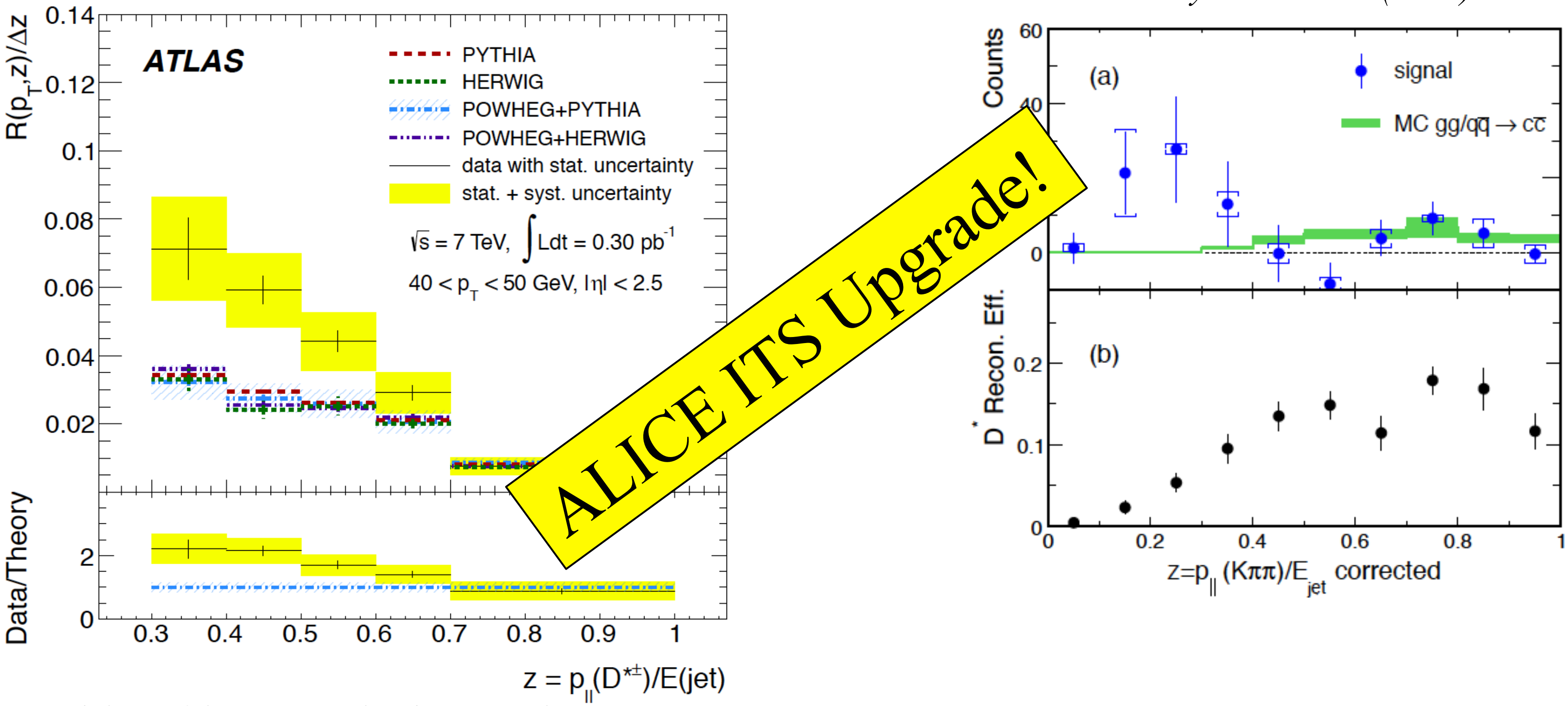
- in the same spirit as the STAR/ALICE approach to incl/semi-incl jet measurements
- systematically improvable precision

New idea II: intrinsic charm in jets

D-meson fragmentation function:

ATLAS, PRD 85, 052005 (2012)

*STAR Phys. Rev. D **79** (2009) 112006*



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: estimates TBD

Outlook

Jet quenching is a rich and compelling problem in QCD

- Field-theoretical basis, many interesting theory approaches
- Experiment: challenging measurements but promising new ideas

We have developed new techniques for robust measurements of true jets (not an approximation) over the full kinematic range at both RHIC and LHC

- Clear connection to theory
- Extensions under discussion, e.g. into heavy flavor sector

There is much interesting jet physics still to do in heavy ion collisions:

- new tools enable the first rigorous jet measurements