

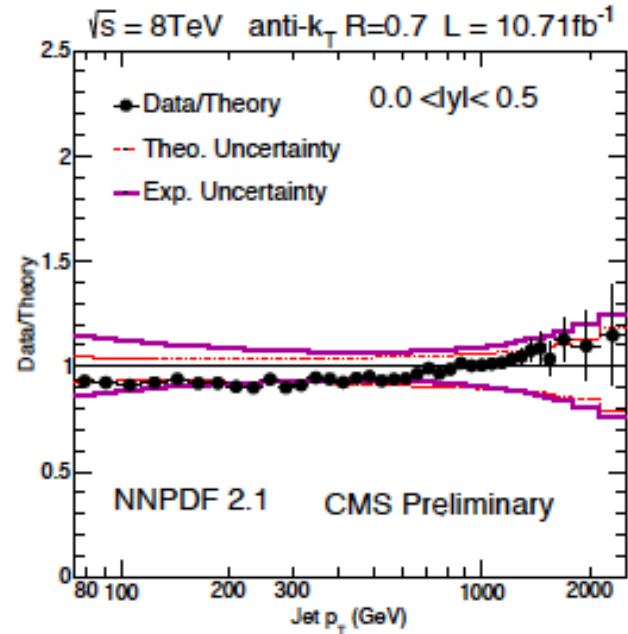
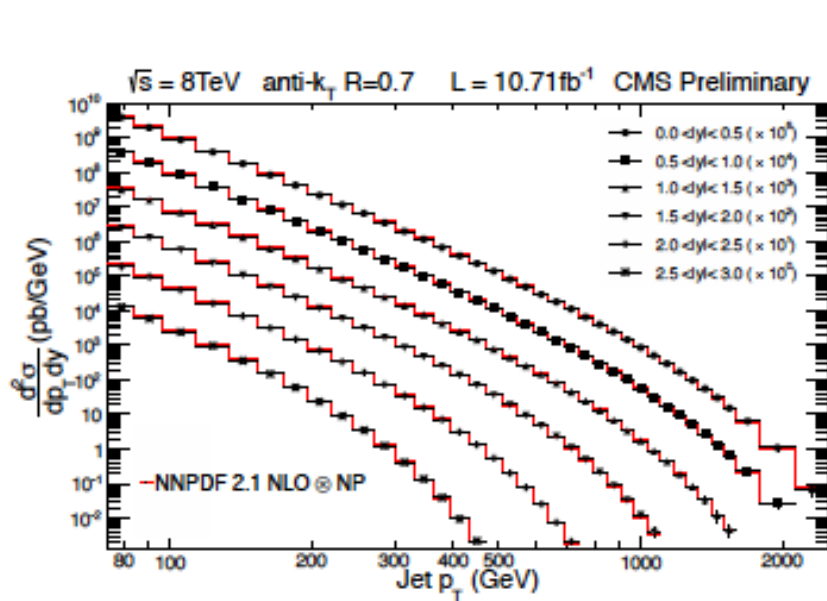
Jets in the medium: Uli's playground

Peter Jacobs

Lawrence Berkeley National Laboratory



Jets in vacuum



Magnificent achievement of QCD

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

Infrared and collinear-safe (IRC) jet reconstruction algorithms:

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

→ jets measure partons

Jet quenching via jet reconstruction

Initial concept:

Jets are a precision tool for QCD in vacuum

→ well-controlled probe of QGP, both theoretically and experimentally

Jet reconstruction integrates all hadronic degrees of freedom

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

Can we use reconstructed jets to study jet quenching with precise connection between theory and experiment?

The technology of jet reconstruction is complex, especially in the heavy ion environment

- If, in the end, jet measurements and their interpretation are just really complicated, we will not have succeeded
- Ultimately, their interpretation must be transparent in order for us to see clearly what these measurements are telling us about the Quark-Gluon Plasma
- Uli's leadership is essential for this program to succeed

Partonic jet quenching: observables

Observables should be calculable in field theory

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

Minimize the need for Monte Carlo modeling

- “Infrared-safe” and collinear-safe observables: very low cuts on hadron p_T (preferably at limit of tracking)
- Minimize fragmentation bias of jet population

Trigger bias should be calculable without modeling of backgrounds

- Preferred triggers: hadron (selected “inclusively”), photon, Z

Partonic jet quenching: observables (cont'd)

Partial list of observables:

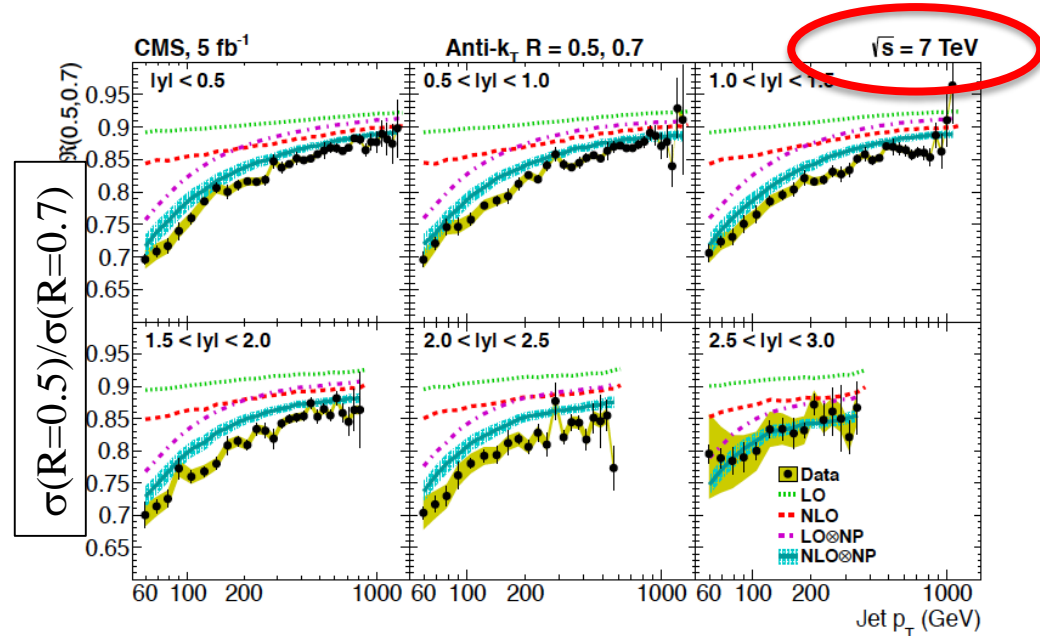
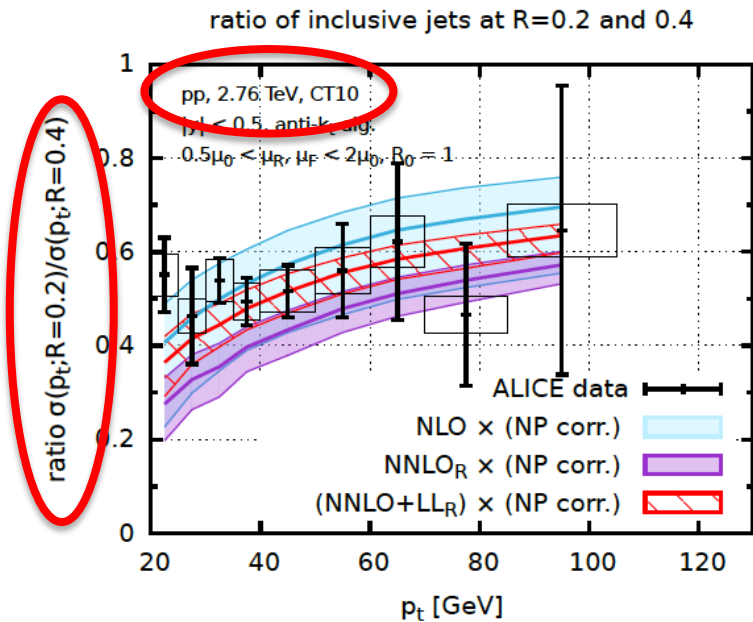
- Inclusive high p_T hadrons (parameterized by collinear FFs)
- Inclusive jet cross sections and semi-inclusive jet yields
 - R_{AA}, I_{AA}, \dots
 - Variation with R
- Moliere scattering in-medium
- Jet mass
- Subjets
- ...?

Coincidence observables: choice of trigger varies geometric and flavor biases

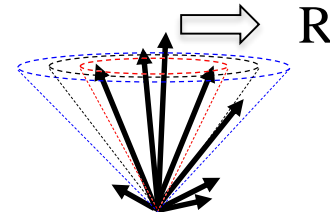
Transverse jet shape: inclusive jets in vacuum

arXiv:1602.01110

Phys Rev D90 (2014) 7, 072006



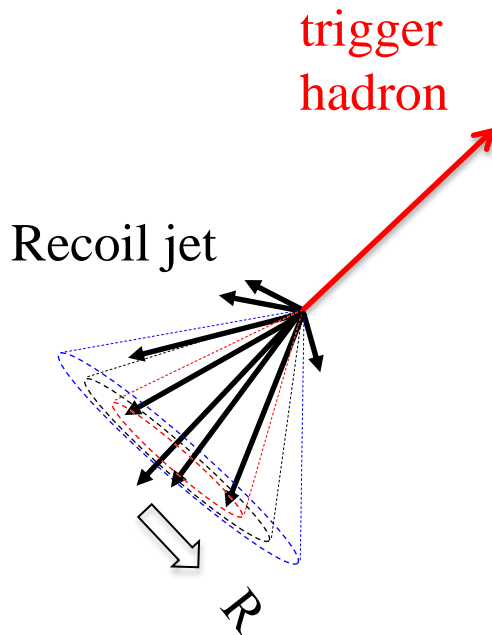
Jets with different R sensitive to different components of shower



- Incl cross section vs. R is sensitive probe of intra-jet structure
- Calculable in vacuum at NNLO + LL resummation

Coincidence observable: hadron+jet correlations

Phys.Rev. D79 (2009) 114014
arXiv:0904.4402



Next-to-leading order QCD corrections to
hadron+jet production in pp collisions at RHIC

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Facultad de Ciencias Exactas y Naturales

Universidad de Buenos Aires

Initial motivation: spin dependence of h+jet inclusive cross section
in polarized pp collisions

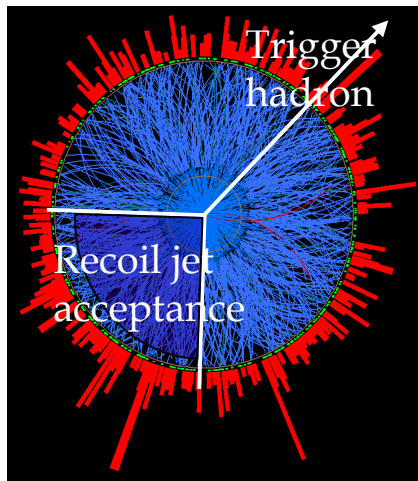
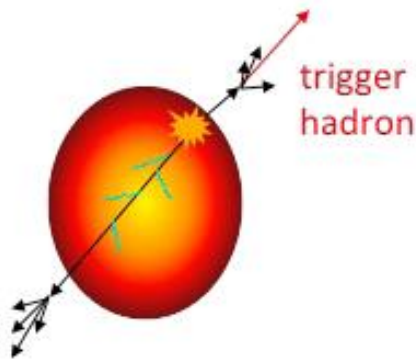
Measuring jet quenching with h+jet: semi-inclusive recoil jet yield

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

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

Measurable

Calculable in pQCD (in vacuum)



Semi-inclusive: event selection only requires trigger hadron

- Trigger hadron selected “inclusively”
- experimentally clean; trigger bias theoretically calculable

Count all recoil jet candidates:

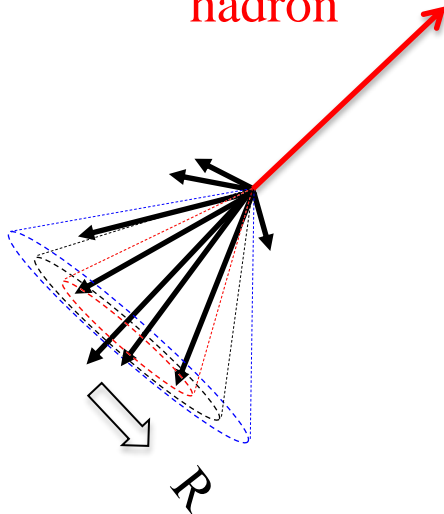
- uncorrelated background corrected at level of ensemble-averaged distributions
- jet selection does not impose fragmentation bias

Expected geometric bias: surface, not tangential

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

Transverse jet shape II: recoil jets in vacuum

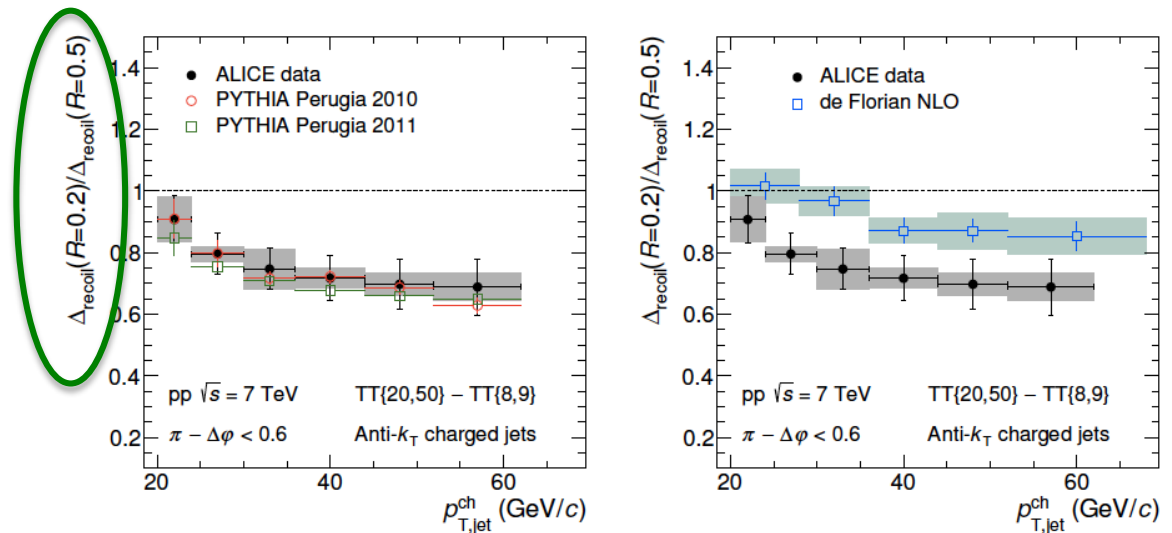
trigger
hadron



Semi-inclusive h+jet, pp $\sqrt{s}=7$ TeV

- ratio of recoil jet yield for different R

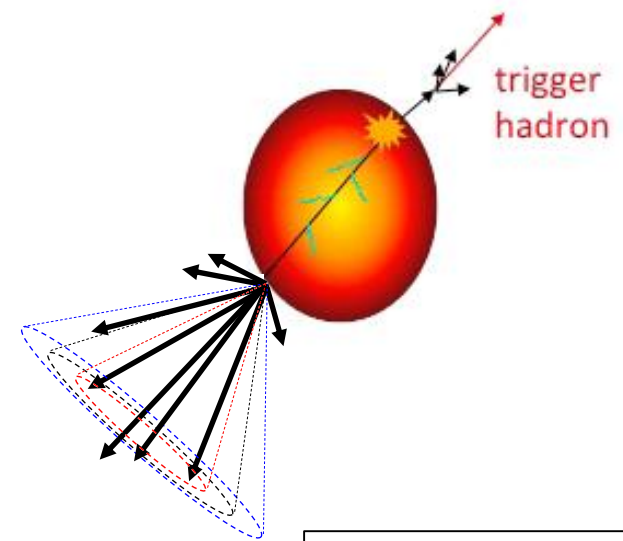
ALICE: JHEP 09 (2015) 170



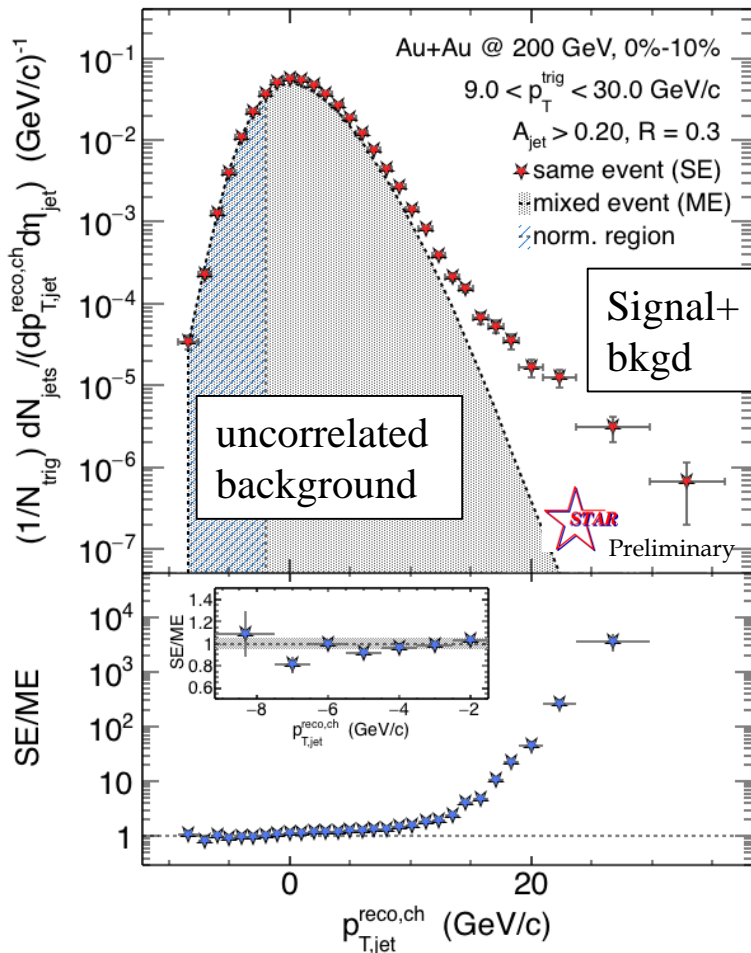
h+jet in vacuum: recoil yield vs R

- pQCD picture similar to inclusive cross section ratio: need NNLO
- Well-described by PYTHIA

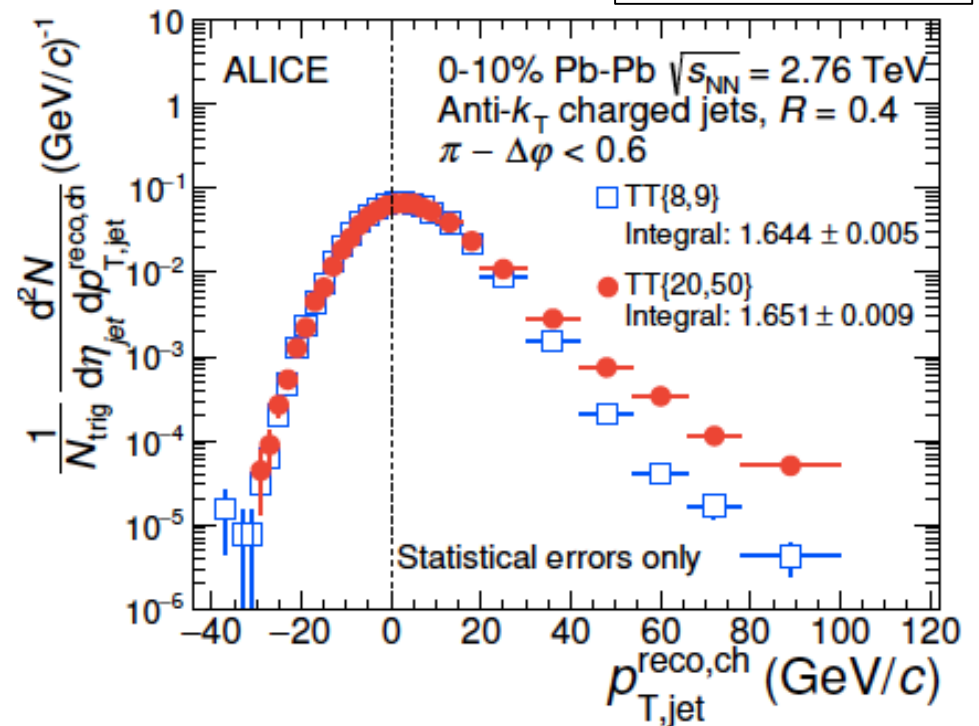
Recoil jet spectrum at RHIC and LHC



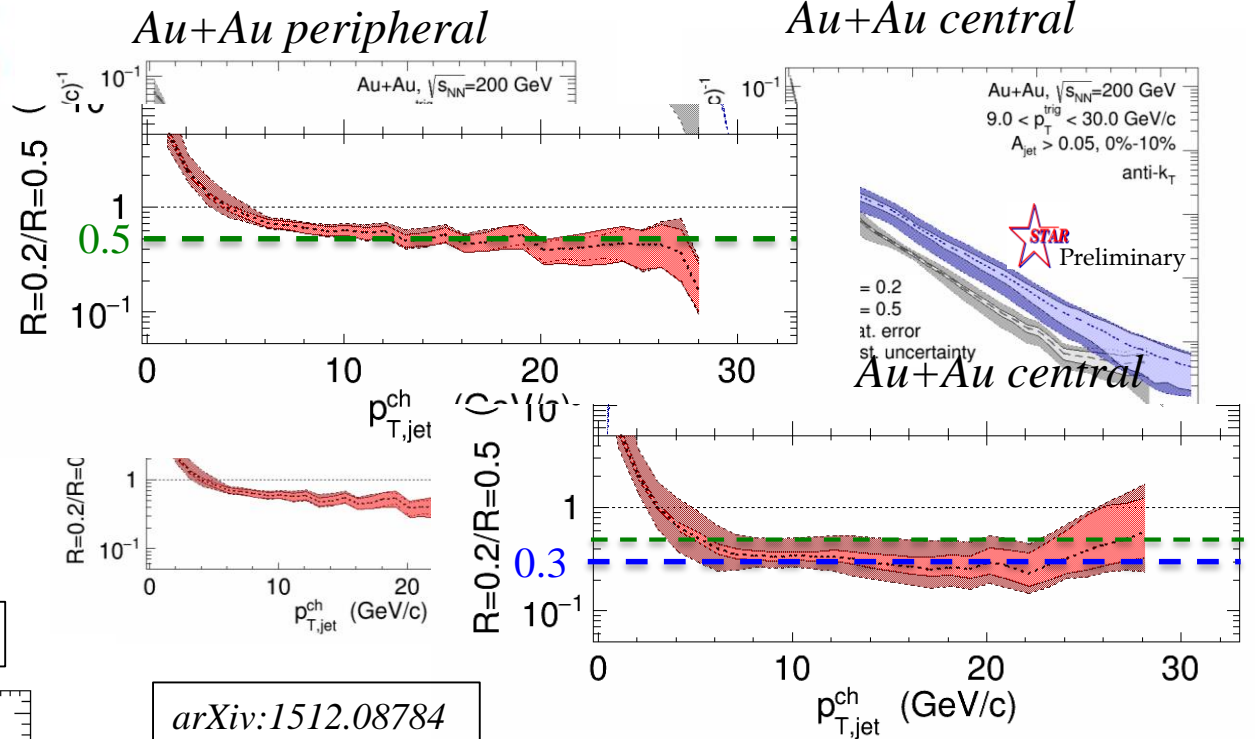
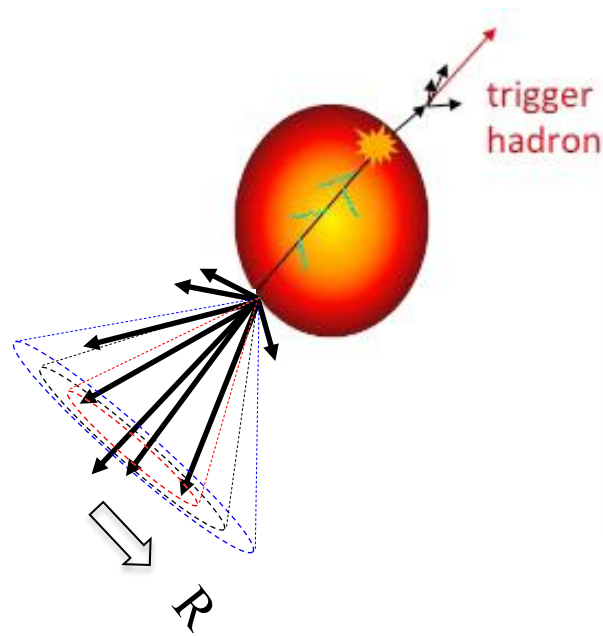
arXiv:1512.08784



JHEP 09 (2015) 170



Jet quenching: intra-jet broadening

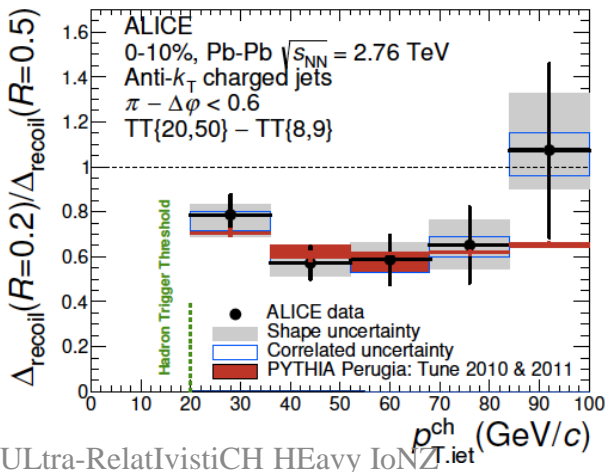


ALICE: JHEP 09 (2015) 170

arXiv:1512.08784

Ratio 0.2/0.5 for peripheral and central consistent within uncertainties

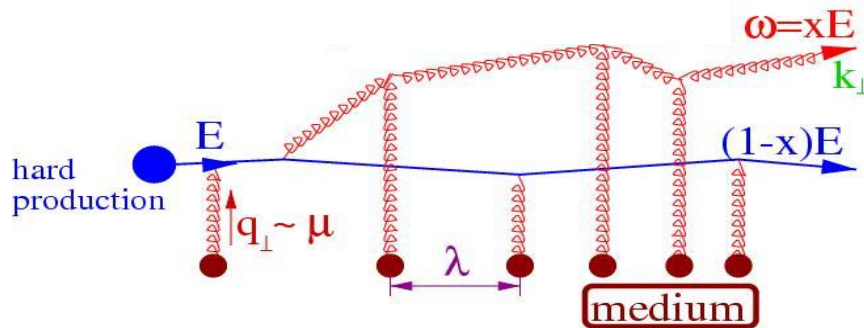
- compatible with some broadening within $R < 0.5$
- future measurements will reduce uncert.



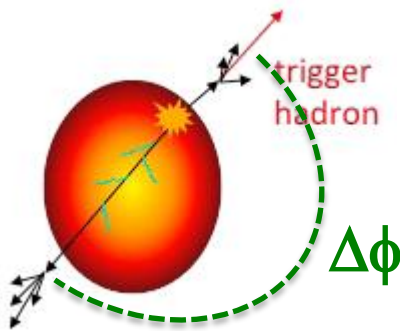
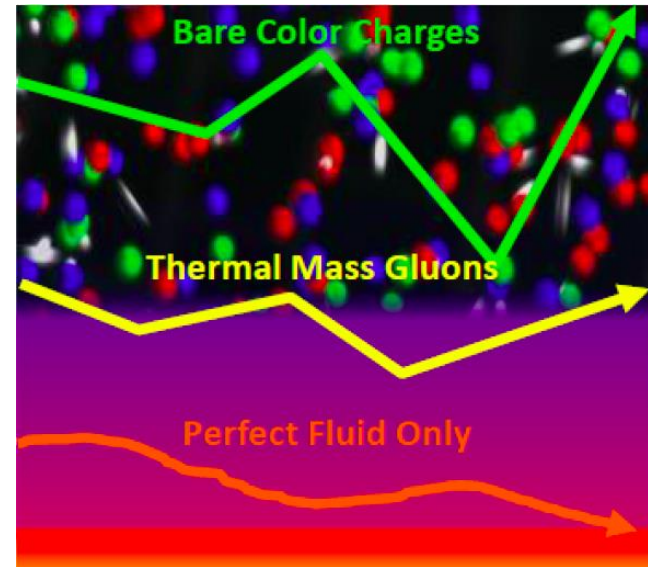
ALICE: similar picture in overlapping p_T range

In-medium jet deflection

Multiple soft scattering



Single Moliere scattering



Measure recoil jet acoplanarity relative to trigger axis
(a.k.a. decorrelation)

Probing Transverse Momentum Broadening via Dihadron and Hadron-jet Angular Correlations in Relativistic Heavy-ion Collisions

Lin Chen,¹ Guang-You Qin,¹ Shu-Yi Wei,¹ Bo-Wen Xiao,¹ and Han-Zhong Zhang¹

¹Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China

arXiv:1607.01932

Vacuum parton shower: Sudakov resummation

Medium-induced broadening: $\langle \hat{q} L \rangle$

Vacuum broadening smaller at RHIC than LHC

Optimum observable: low jet p_T , vary R

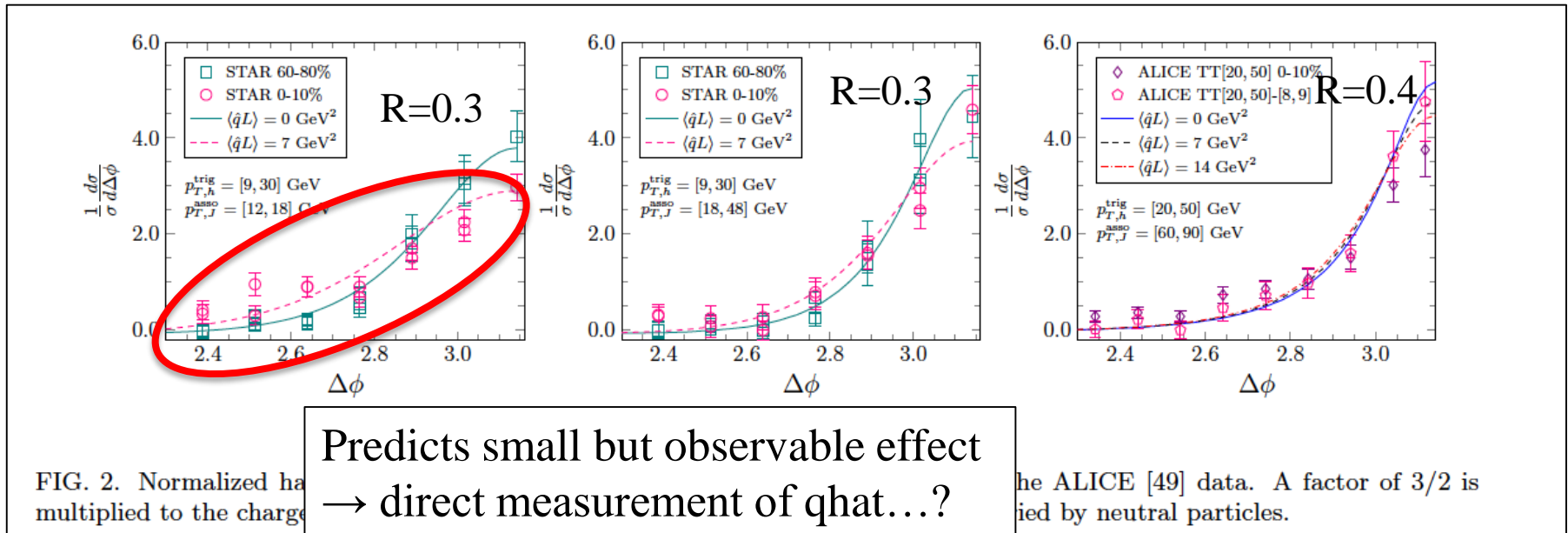
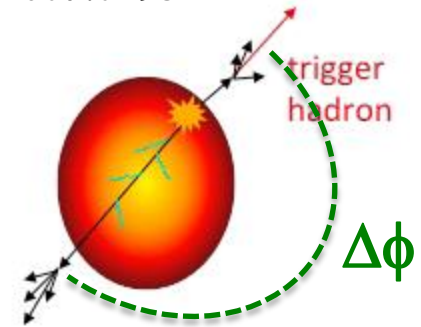


FIG. 2. Normalized hadron-jet angular correlations multiplied to the charge...

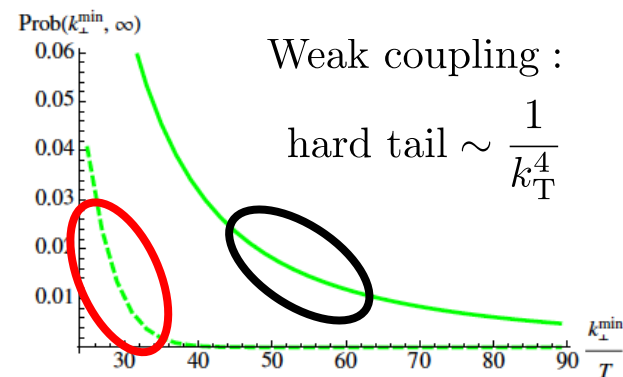
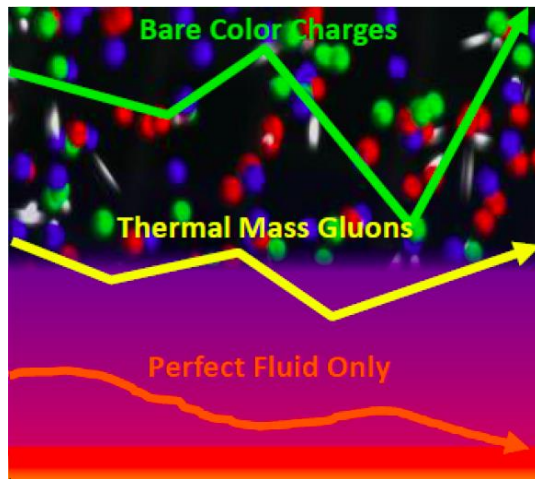
the ALICE [49] data. A factor of 3/2 is...
...ied by neutral particles.

Inter-jet broadening: secondary scattering off the QGP

Discrete scattering centers or
effectively continuous medium?

d'Eramo et al, arXiv:1211.1922

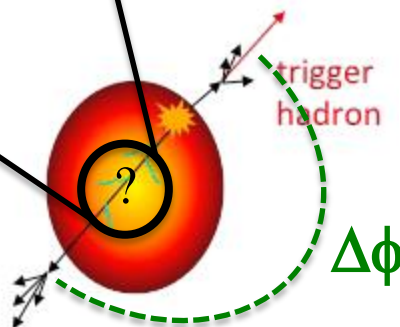
Distribution of momentum transfer k_T



Strong coupling:
Gaussian distribution

Conjecture for weak coupling: $\Delta\phi$
distribution dominated by single hard
Molière scattering at “sufficiently large” $\Delta\phi$

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



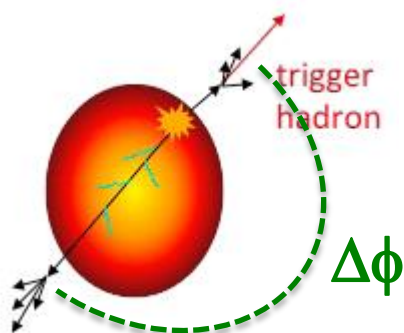
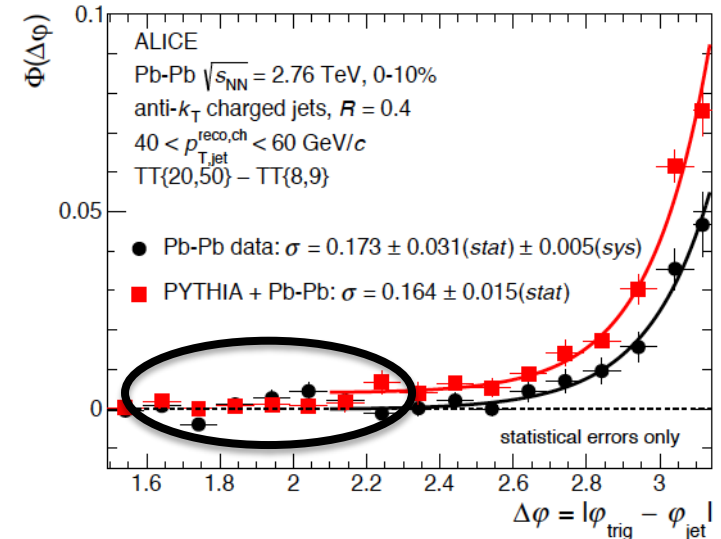
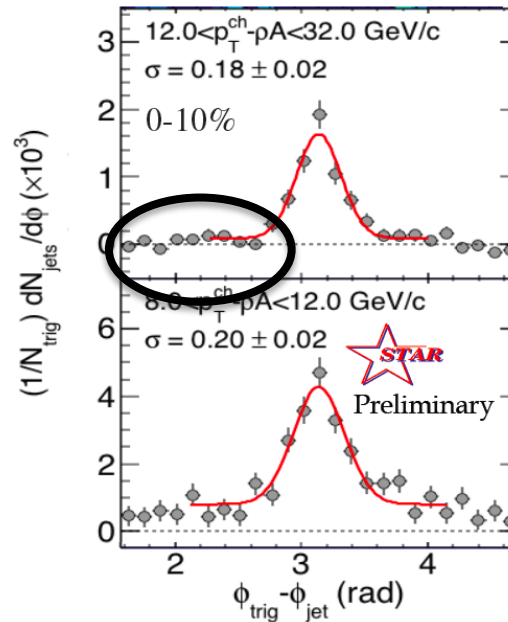
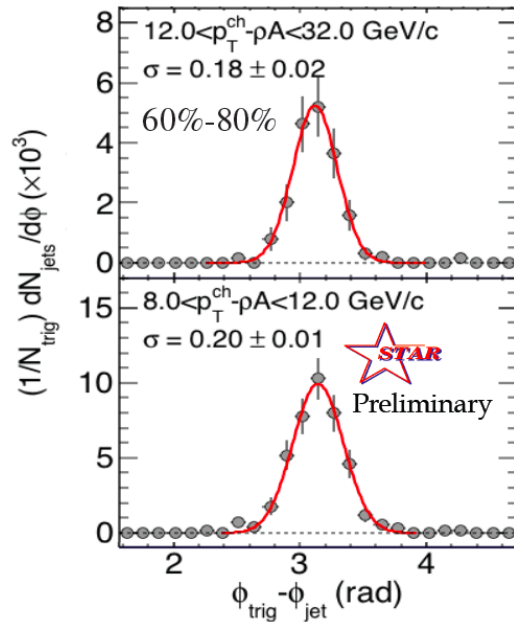
Interjet broadening: RHIC and LHC

AuAu $\sqrt{s_{NN}}=200$ GeV

PbPb $\sqrt{s_{NN}}=2.76$ TeV

arXiv:1512.08784

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Low jet p_T of special interest: largest effects expected

- current measurements consistent with zero yield

QCD calculation of scattering in q/g gas can indicate integrated luminosity needed for significant measurement

Assessment and next steps

Strategy: “IRC-safe” measurements of medium-induced shower broadening and scattering with reconstructed jets

- Full dynamic range of jet p_T and R at RHIC and LHC

⇒ Enables comparison to theory calculations without modeling of hadronization (beyond collinear FFs)

First results: proof of principle

- Charged-particle jets, small datasets: limited precision

Up next: calorimetric jets, higher int lumi (both RHIC and LHC)

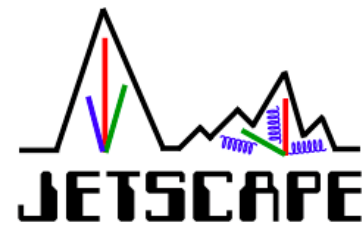
Theory/data comparison for precise constraints on quenching mechanisms, measurements of QGP parameters:

Embed theory calculations into accurate dynamical model of collision

- IS fluctuations, viscous hydro expansion, hadronization,...



JETSCAPE Collaboration



Consortium of theorists and experimentalists to create a next-generation heavy ion event generator

- Flexible framework for event generation
- Combine current MC simulators and fluid-dynamical models
- GPU parallelization for speed
- Statistical analysis using bayesian techniques

PIs:

Duke: Steffen Bass, Robert Wolpert

McGill: Charles Gale, Sangyong Jeon

MIT: Gunther Rolad

Ohio State: Uli Heinz

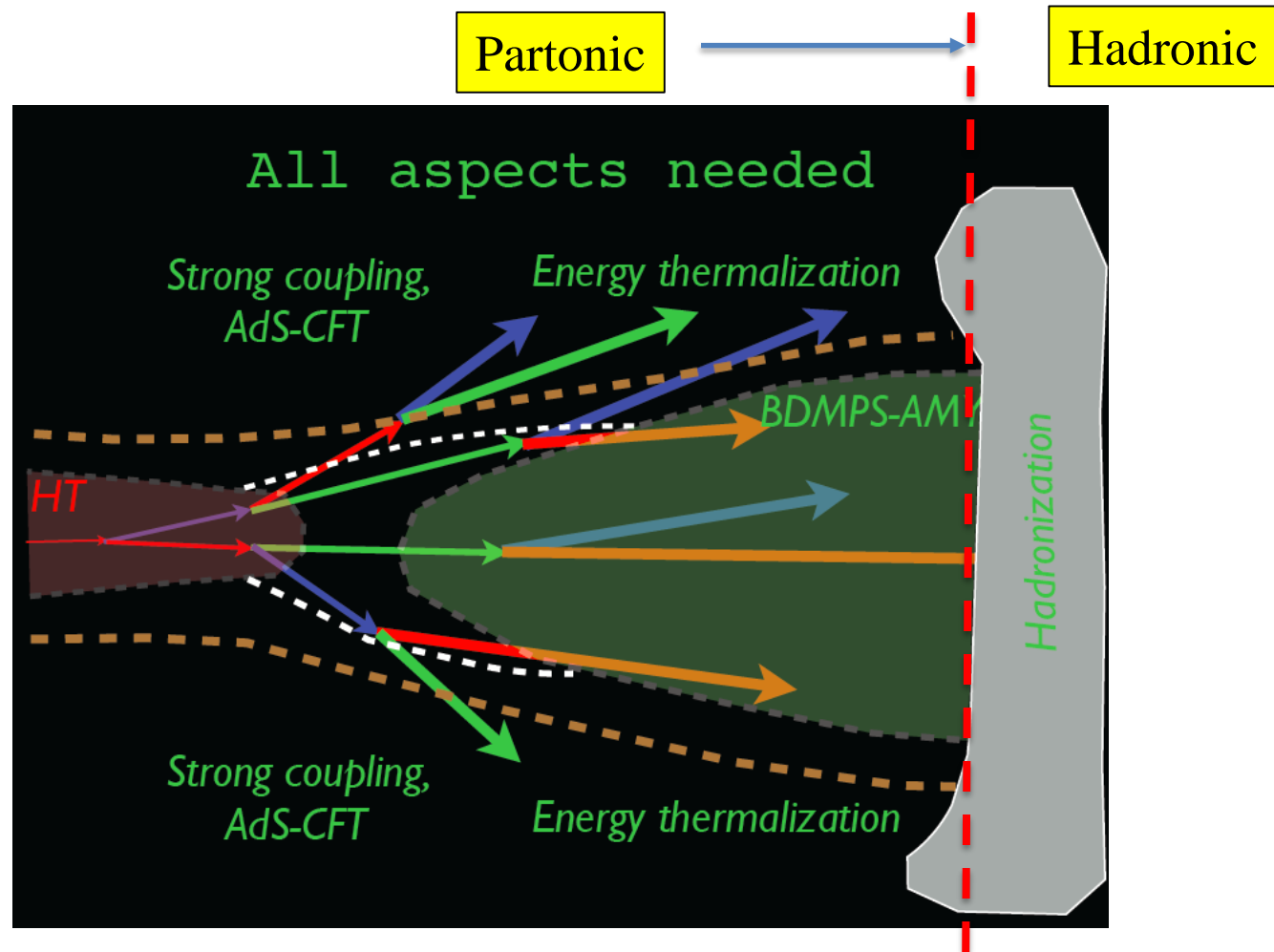
Texas A&M: Rainer Fries

LBNL: Barbara Jacak, Peter Jacobs, Xin-Nian Wang

Wayne State: Abhihit Majumder, Joern Putschke, Loren Schweibert

LLNL: Ron Soltz

Partonic jet quenching in JETSCAPE



Happy Birthday Uli !

