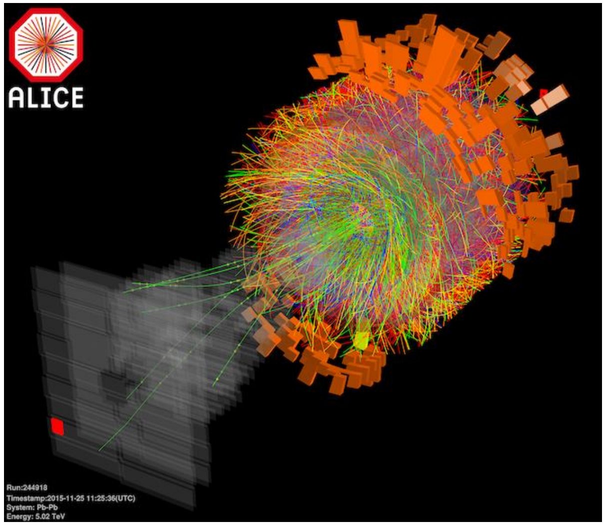
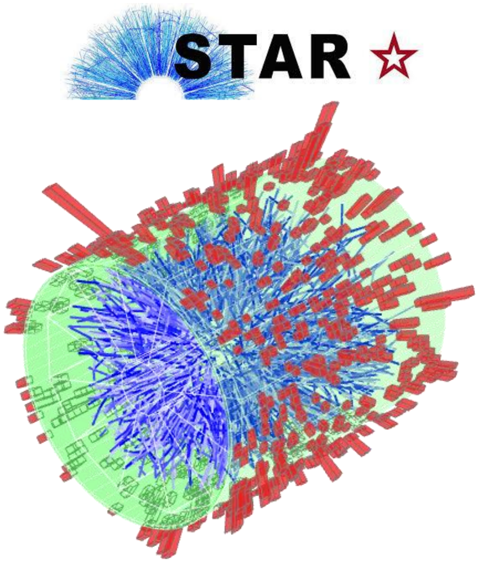
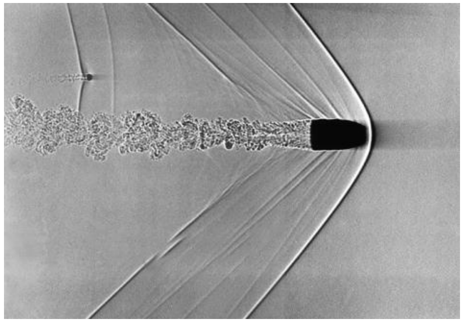
Heavy ion jets at RHIC and LHC: a common approach

Peter Jacobs

Lawrence Berkeley National Laboratory

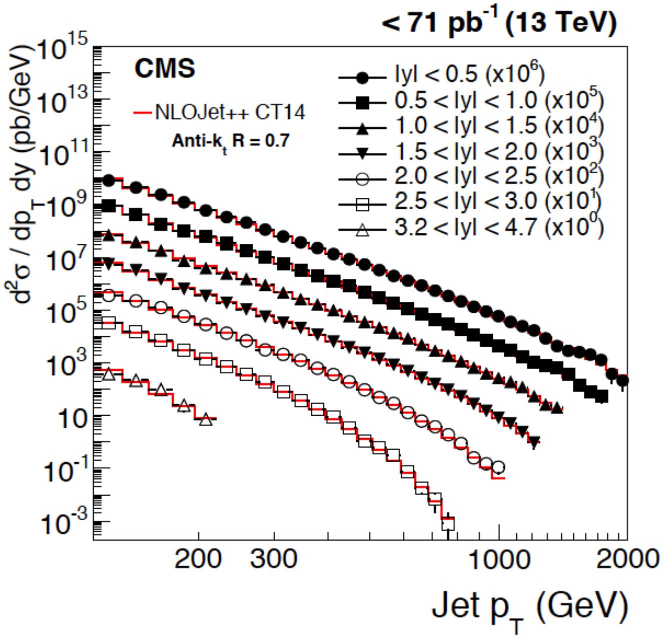


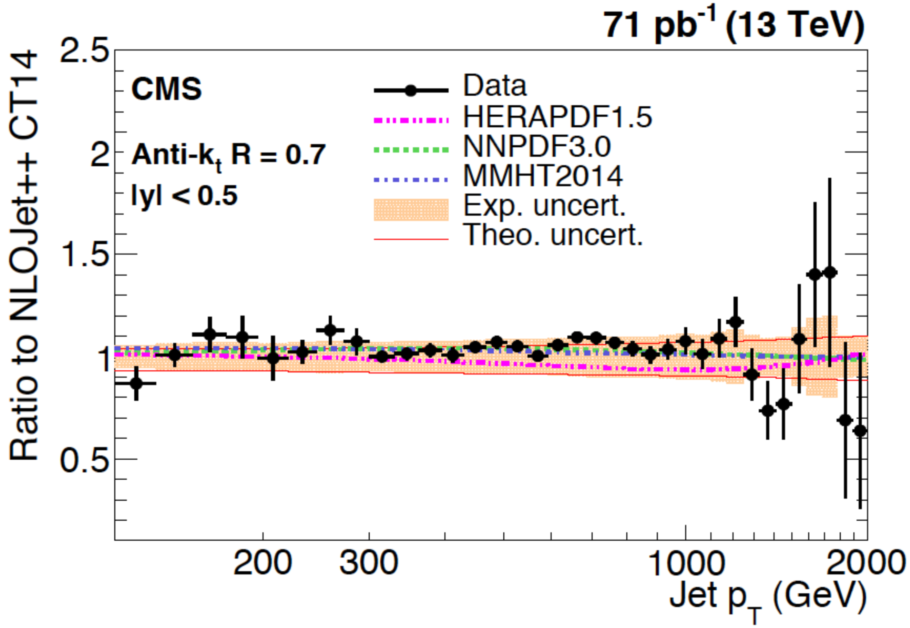




Jets in vacuum

CMS, Eur. Phys. J C76 (2016) 451





Magnificent achievement of QCD

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

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

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

➔ jets measure partons

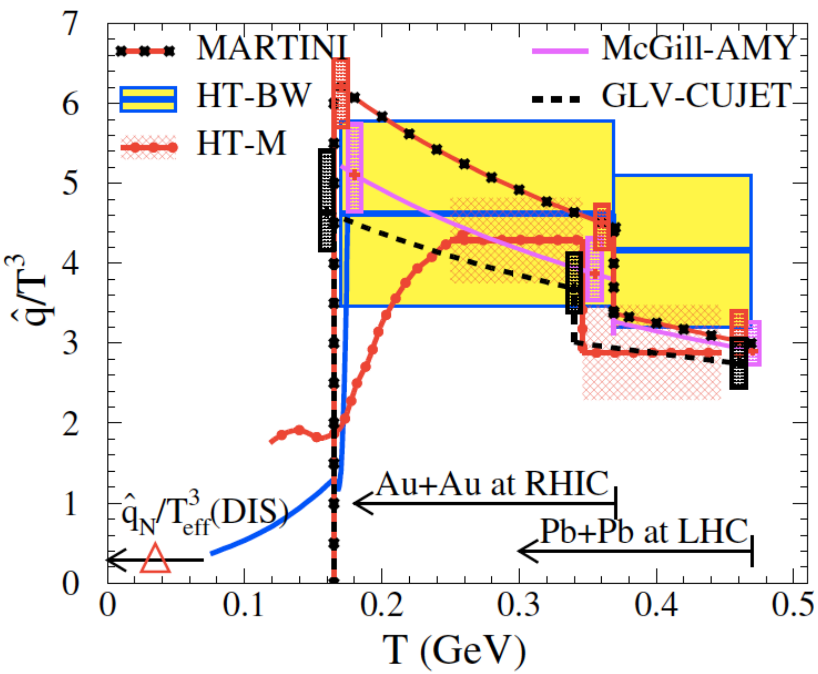
Jet quenching theory vs experiment: current example

Extraction of q^ via data + modeling

JET Collaboration
Phys.Rev. C90 (2014) 1, 014909

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

No consideration of correlations or jets



For a 10 GeV light quark at time 0.6 fm/c:

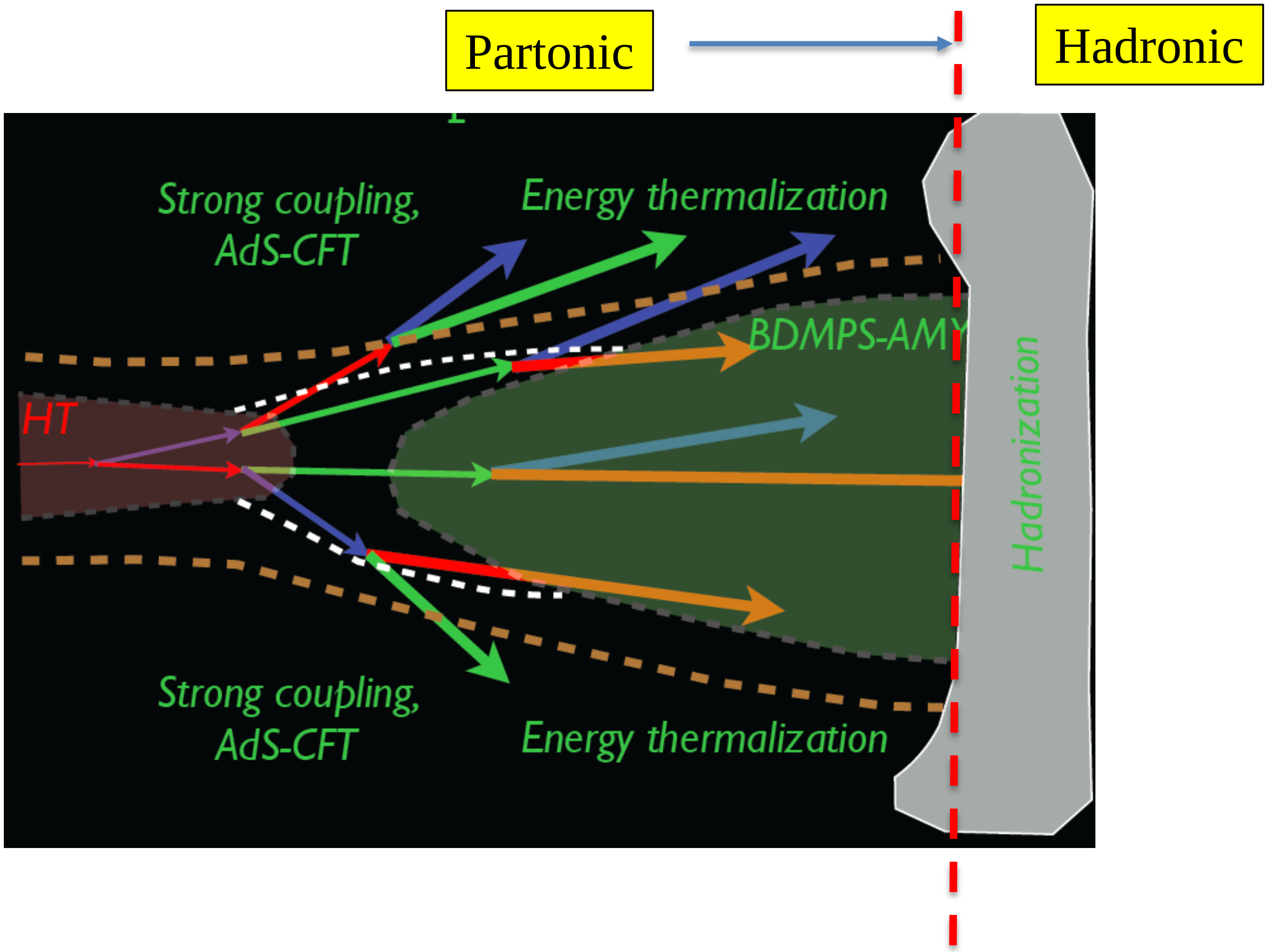
$$\mathrm{RHIC}: \ \hat{q} \approx 1.2 \pm 0.3 \ \mathrm{GeV}^2/\mathrm{fm}$$

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

$$\mathrm{Cold\ matter\ (HERMES\ DIS)}: \ \hat{q} \approx 0.02 \ \mathrm{GeV}^2/\mathrm{fm}$$

Certainly interesting, but can we learn more?

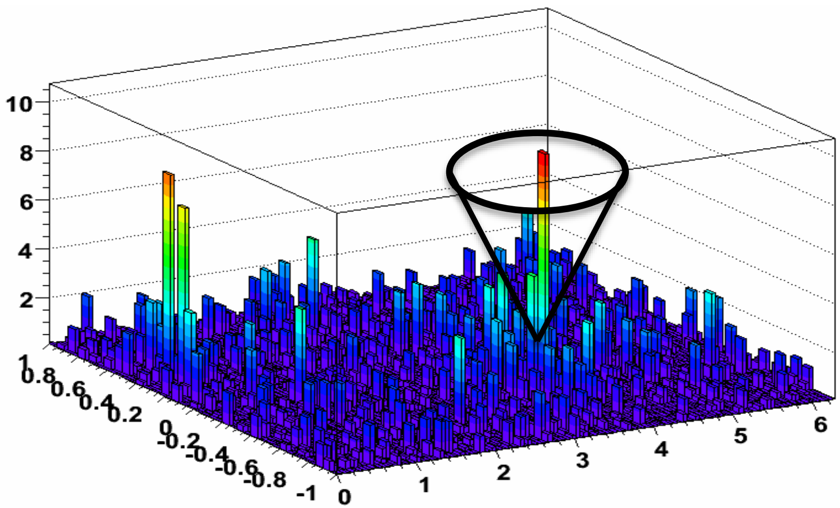
Jet quenching at the partonic level (JETSCAPE version)



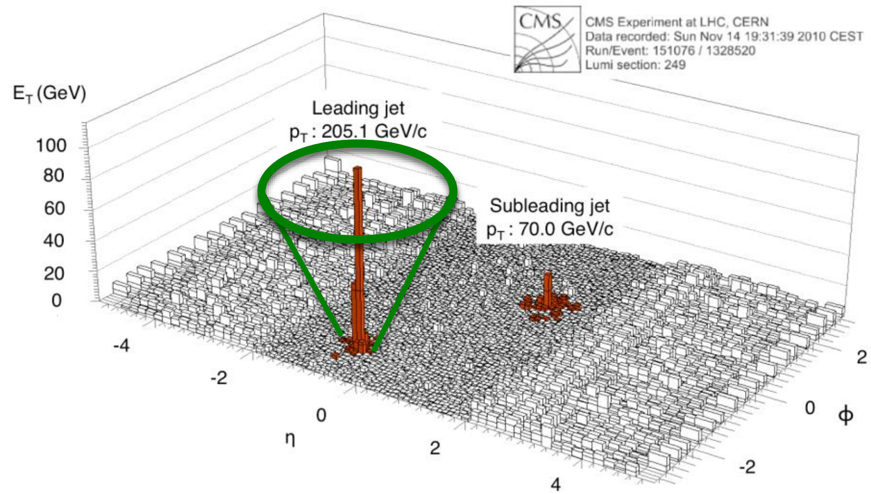
Define quenching observables that integrate out hadronic DOF

Jets in real heavy ion collisions

RHIC/Star



LHC/CMS



Visual identification of energetic jets above background is fairly easy

Much harder: accurate measurement of jet energy and structure within finite cone

- Pb+Pb at LHC: ~100 GeV of uncorrelated background energy in cone R=0.4
- Uncorrelated background has complex structure, including multiple overlapping jets at multiple energy scales
- Very challenging…

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

- Prefered 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},…
  - Variation with R
- Moliere scattering in-medium
- Jet mass
- N-subjettiness
- Groomed subjets
- INYTO (ideas not yet thought of…)

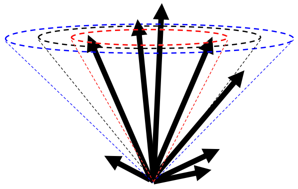
Coincidence observables: choice of trigger varies geometric and flavor biases

Not on this list: soft hadron distributions, "fragmentation functions"

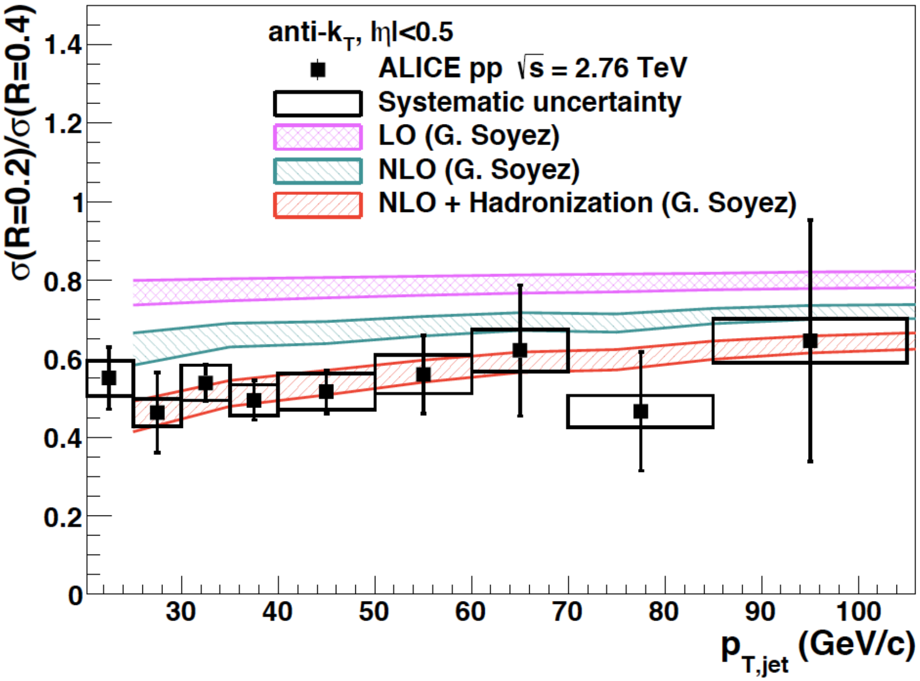
Warm-up example: "jet shape" via R-dependence of inclusive cross section in p+p collisions

Ratio of inclusive cross sections in 2.76 TeV p+p collisions

$$\text{Ratio} = \frac{\left[\frac{d\sigma^{pp\rightarrow jet+X}}{dp_{T,jet}}\right]_{R=0.2}}{\left[\frac{d\sigma^{pp\rightarrow jet+X}}{dp_{T,jet}}\right]_{R=0.4}}$$

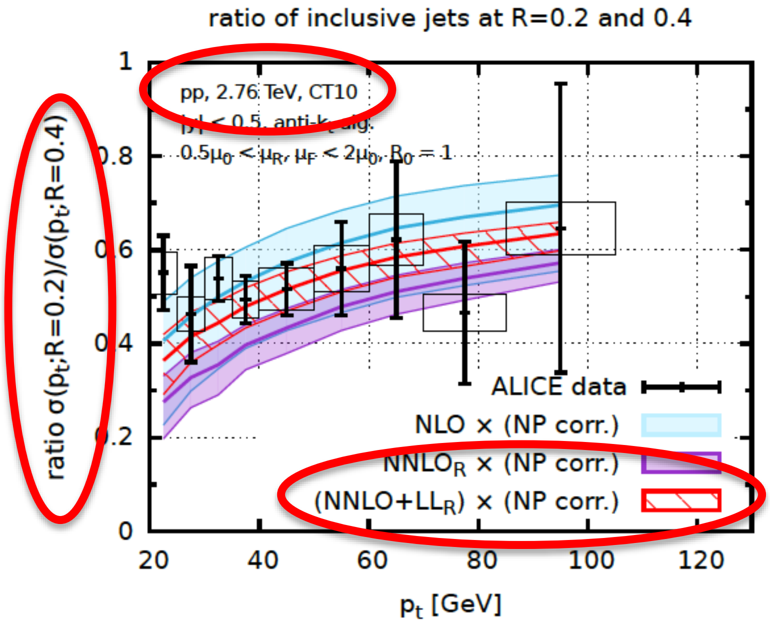


Phys.Lett. B722 (2013) 262-272

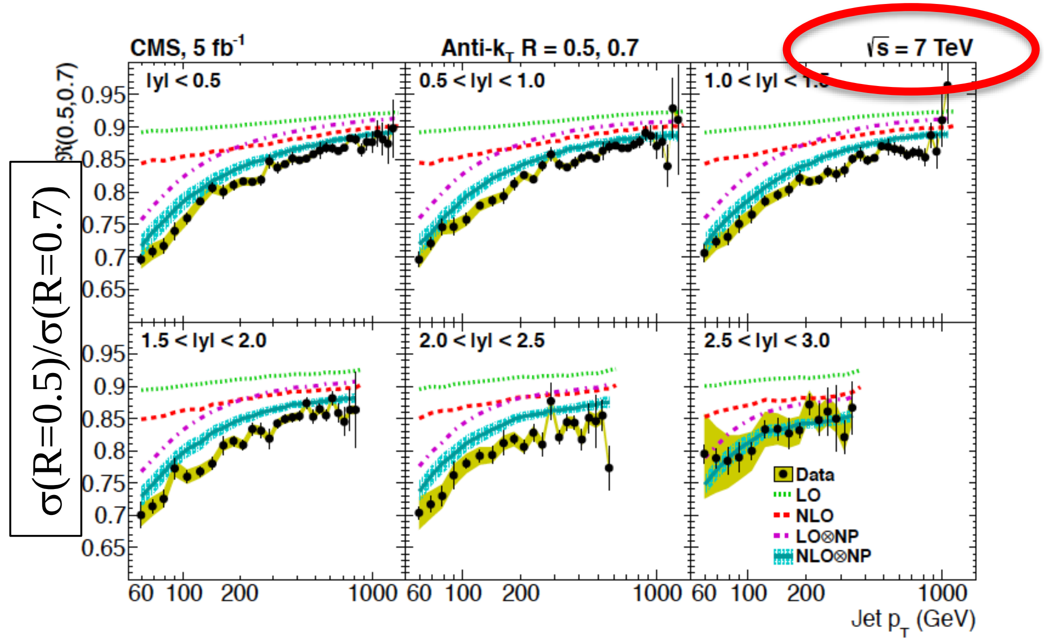


R-dependence of incl. jet xsection (cont'd)

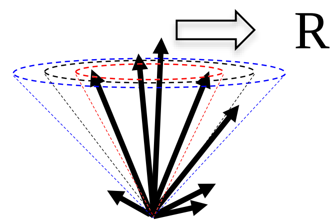
Dasgupta et al., JHEP 1606 (2016) 057



CMS, Phys Rev D90 (2014) 7, 072006



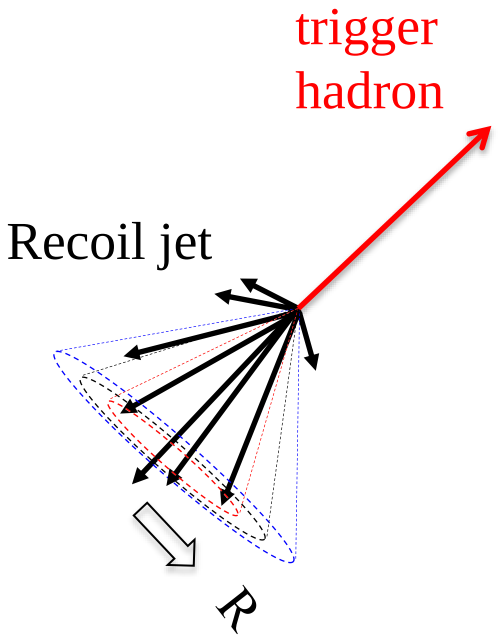
Jets with different R sensitive to different components of shower



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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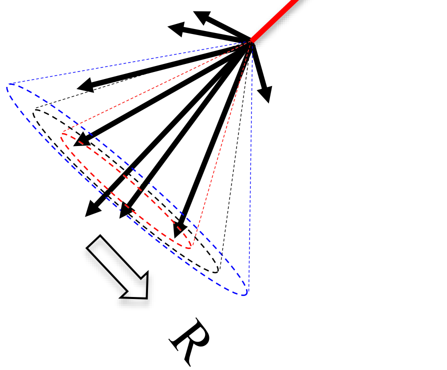
Departamento de Física
Facultad de Ciencias Exactas y Naturales
Universidad de Buenos Aires

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

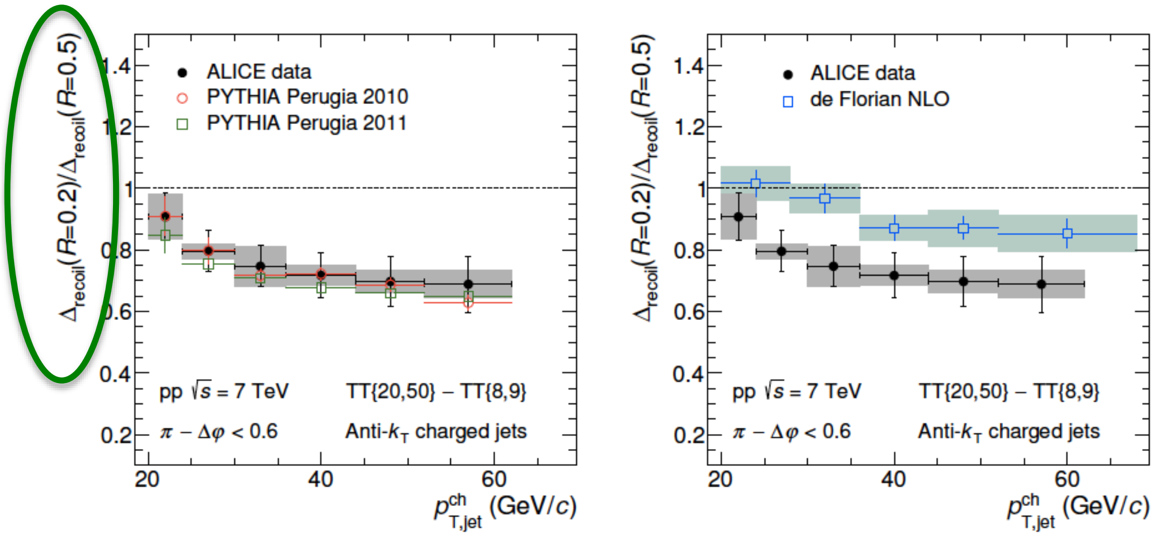
Shape of recoil jets in vacuum



Semi-inclusive h+jet, pp √s=7 TeV (unpolarized, of course)

- per-trigger recoil yield vs R

ALICE: JHEP 09 (2015) 170

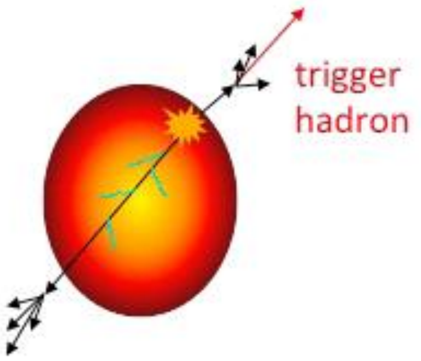


Picture similar to inclusive jet cross section ratio:

- well-described by PYTHIA
- less well-described by pQCD@NLO, needs NNLO

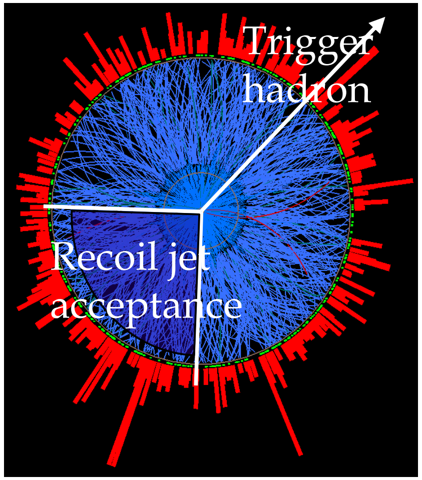
Measuring jet quenching with h+jet: semi-inclusive recoil jet yield

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



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

Measurable — Calculable in pQCD (in vacuum)



Semi-inclusive: event selection only requires trigger hadron

- Trigger hadron selected "inclusively"
- experimentally clean in heavy ion collisions: 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;…

JHEP

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Measurement of jet quenching with semi-inclusive hadron-jet distributions in central Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV

ALICE

The ALICE collaboration

E-mail: ALICE-publications@cern.ch

ALICE Collaboration
JHEP 09 (2015) 170

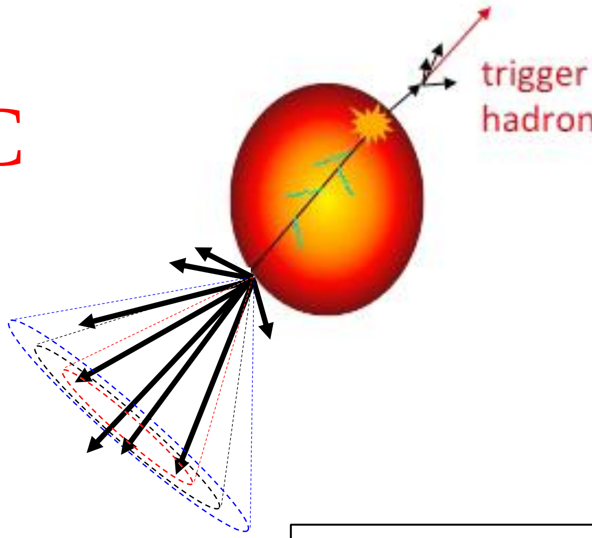
Measurements of jet quenching with semi-inclusive hadron+jet distributions in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV

L. Adamczyk,[1] J. K. Adkins,[19] G. Agakishiev,[17] M. M. Aggarwal,[31] Z. Ahammed,[50] N. N. Ajitanand,[40]
I. Alekseev,[15, 26] D. M. Anderson,[42] R. Aoyama,[46] A. Aparin,[17] D. Arkhipkin,[3] E. C. Aschenauer,[3] M. U. Ashraf,[45]
A. Attri,[31] G. S. Averichev,[17] X. Bai,[7] V. Bairathi,[27] A. Behera,[40] R. Bellwied,[44] A. Bhasin,[16] A. K. Bhati,[31]

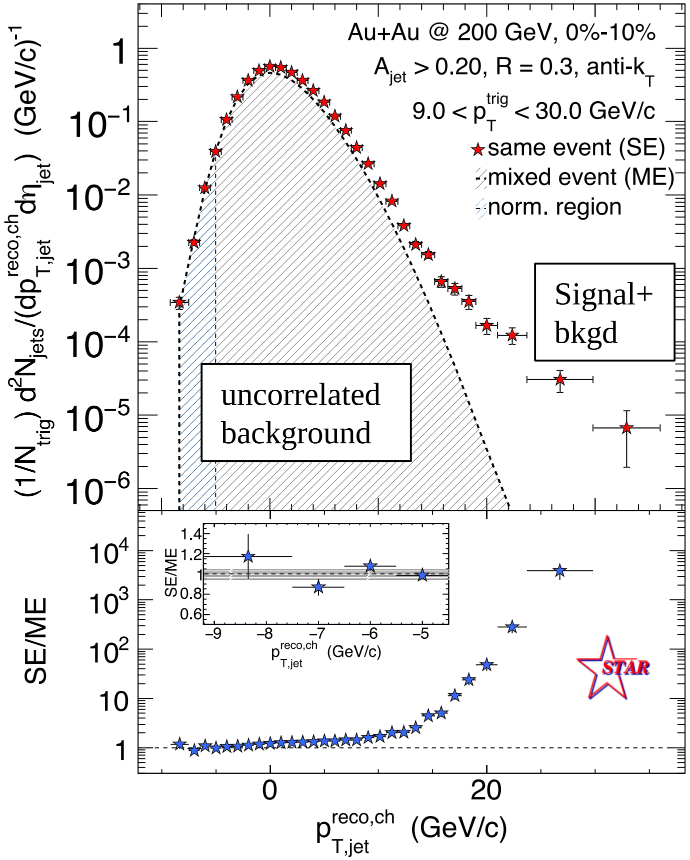
STAR Collaboration, arXiv:1702.01108

h+jet in heavy ions: raw recoil spectrum @ RHIC/LHC

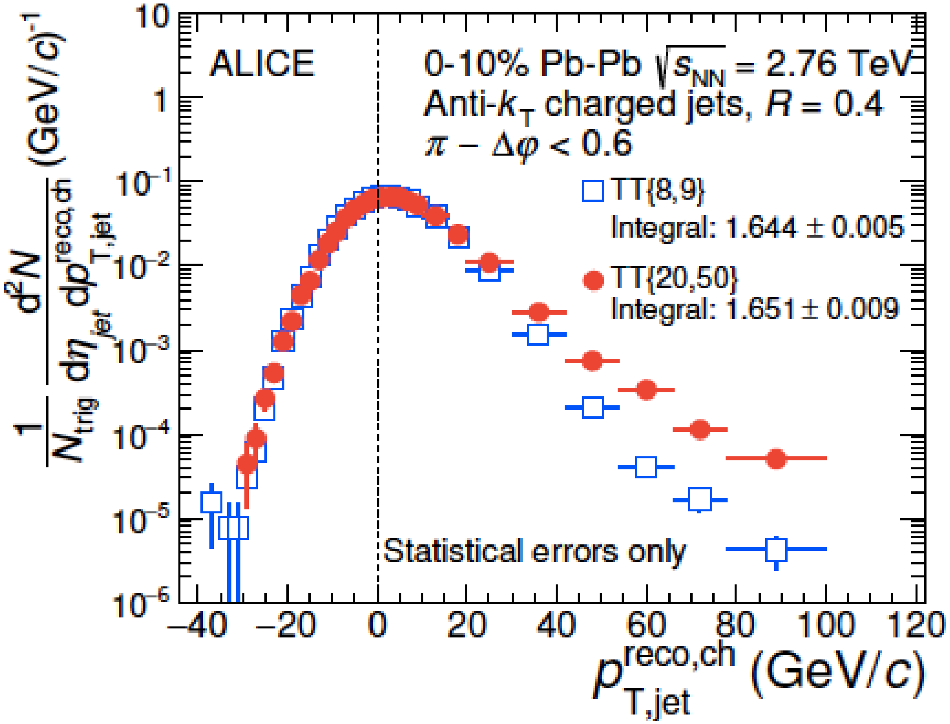
$$p_{\mathrm{T,jet}}^{\mathrm{reco,ch}} = p_{\mathrm{T,jet}}^{\mathrm{raw,ch}} - \rho \cdot A$$



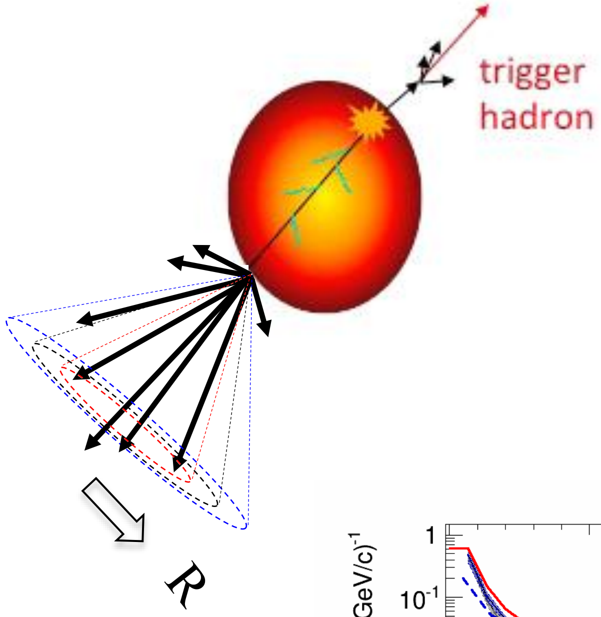
arXiv:1702.01108



JHEP 09 (2015) 170



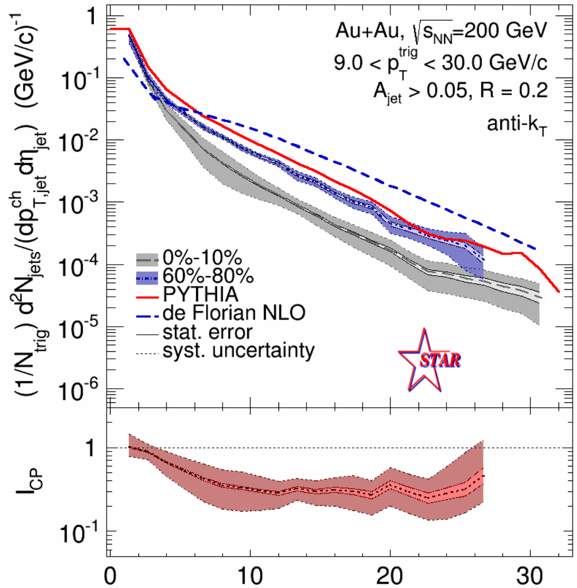
Corrected recoil jet spectra



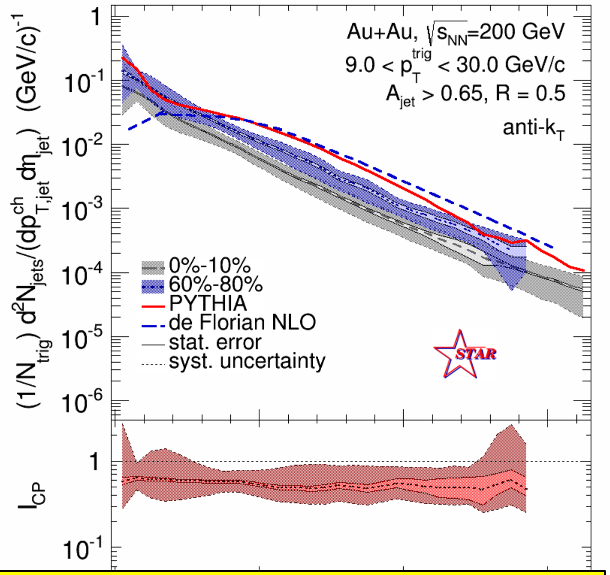
Measurements of full recoil jet spectra:

- all centralities, p_T, R
- No bias imposed by bkdg suppression
- Improvable systematic uncertainties

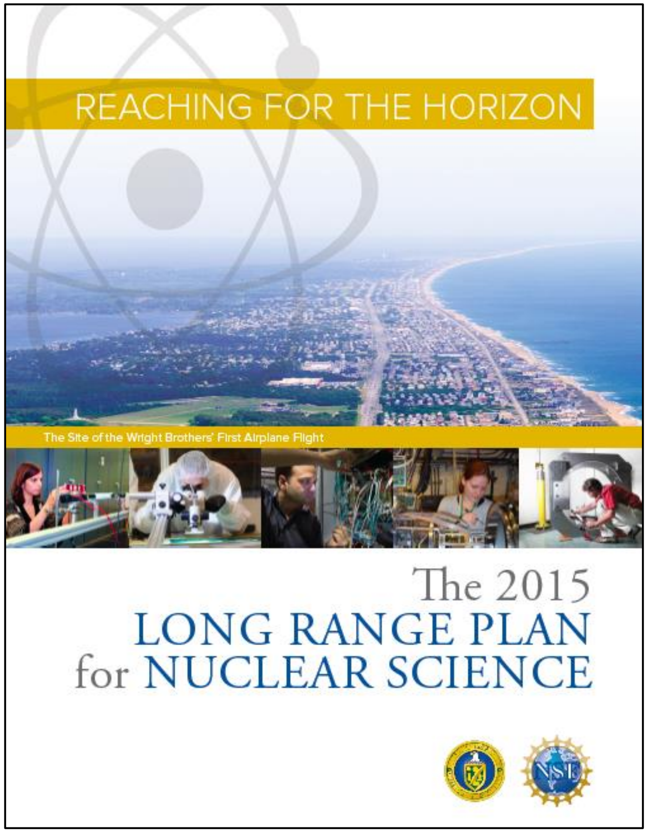
R=0.2

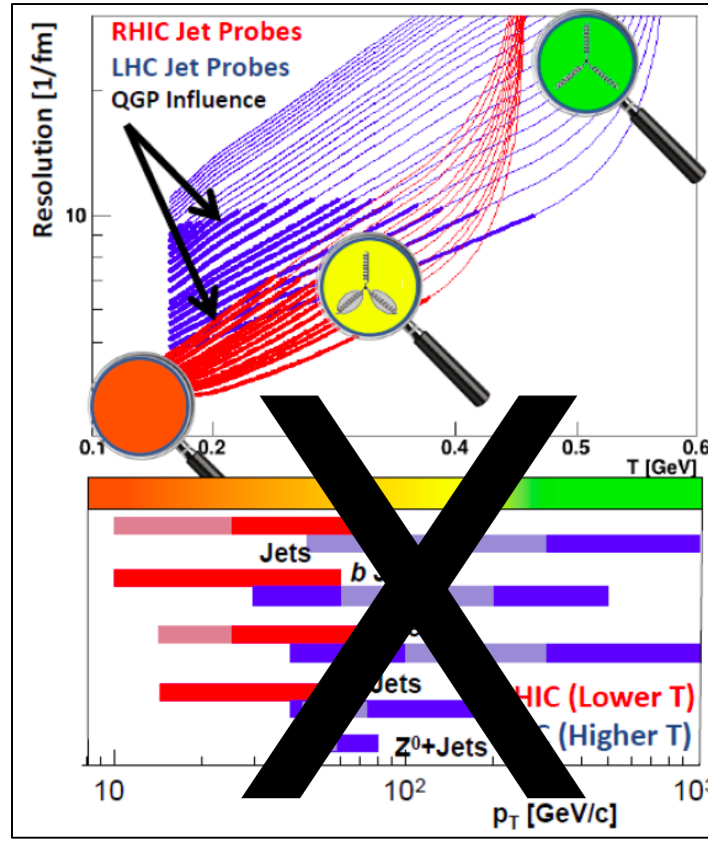


R=0.5



Effectively: IRC-safe jet measurements in heavy ion collisions





Common analysis approach: no limits in principle to reconstructed jet measurements at RHIC and LHC → full overlap in phase space achievable

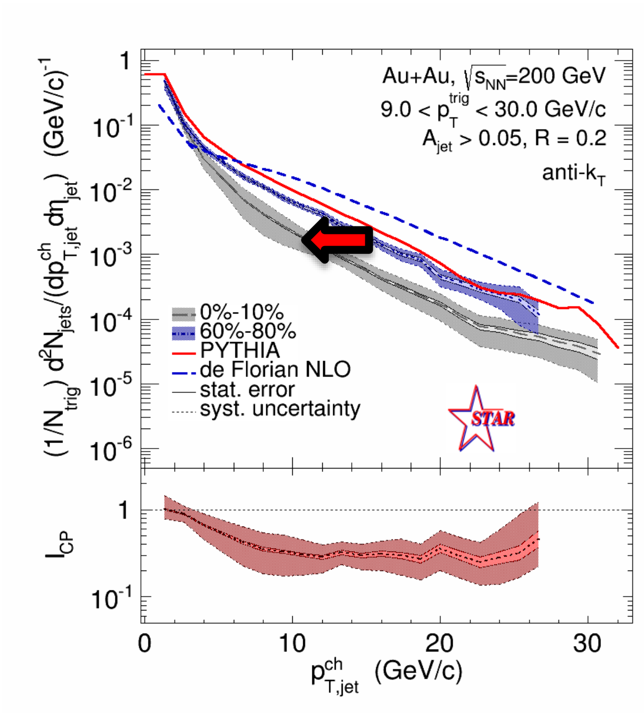
Practical limitations:

- Cross sections → kinematic reach
- Instrumentation: triggering, tracking/calo precision, corrections/systematic uncertainties,…

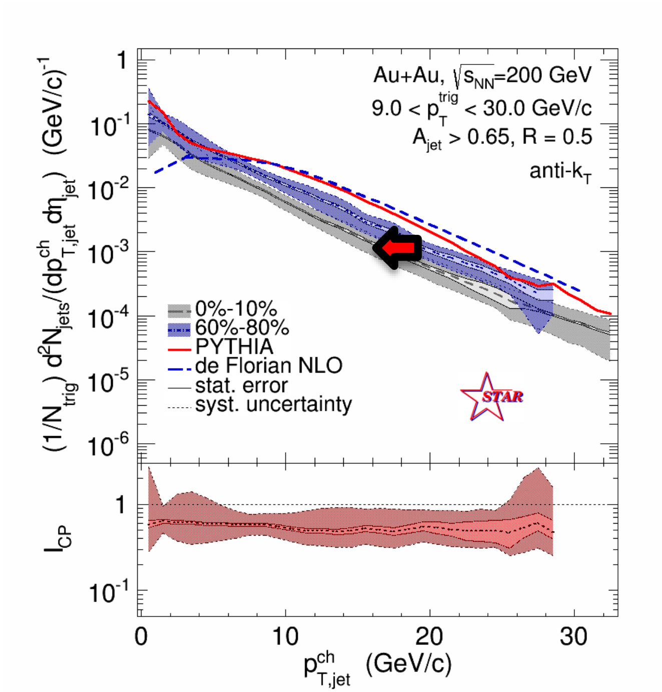
Compare ALICE/ATLAS/CMS; Compare STAR/sPHENIX → each has advantages

Recoil jet yield suppression

R=0.3



R=0.5



Spectrum shift → energy transport out-of-cone

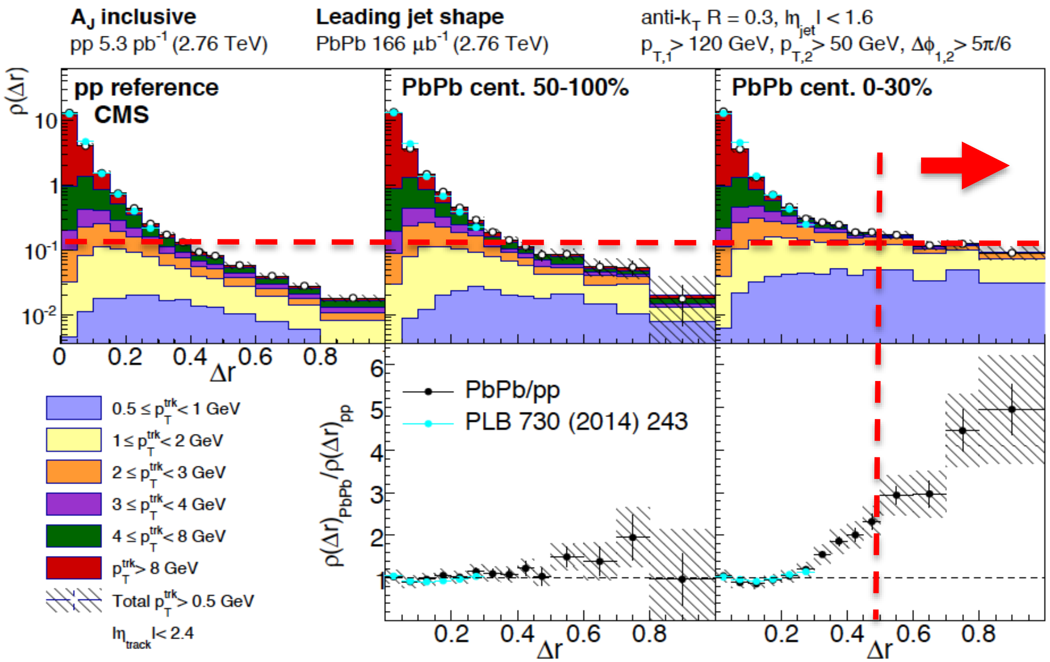
System		Au+Au $\sqrt{s_{NN}}$ = 200 GeV	Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$p^{ch}_{T,jet}$ range (GeV/c)		[10,20]	[60,100]
		p_T-shift of $Y\left(p^{ch}_{T,jet}\right)$ (GeV/c)	
		peripheral→central	p+p→central
R	0.2	$-4.4 \pm 0.2 \pm 1.2$	
	0.3	$-5.0 \pm 0.5 \pm 1.2$	
	0.4	$-5.1 \pm 0.5 \pm 1.2$	
	0.5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

RHIC: no significant dependence of shift on R for R<0.5

R=0.5: smaller shift at RHIC than LHC → lower energy loss at RHIC

Energy transport to large R: CMS vs ALICE

CMS, JHEP 1611 (2016) 055



$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jets}}}\Sigma_{\mathrm{jets}}\frac{\Sigma_{\mathrm{tracks}\in(r_a,r_b)}\,p_{\mathrm{T}}^{\mathrm{trk}}}{p_{\mathrm{T}}^{\mathrm{jets}}}.$$

$\rho(\Delta r)\sim 0.1$
$\delta r = 0.05$

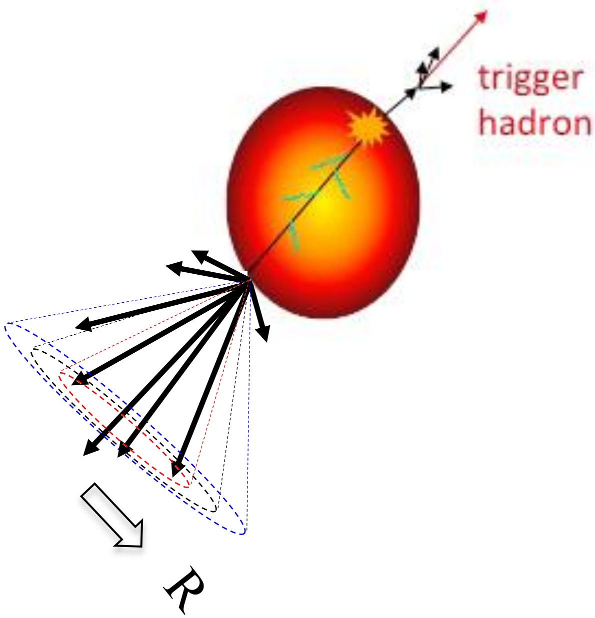
Integrate over $0.5<\Delta r<1.0$ (10 bins)

Estimated charged-energy for $0.5<\Delta r<1.0$ relative to leading jet (~150 GeV)

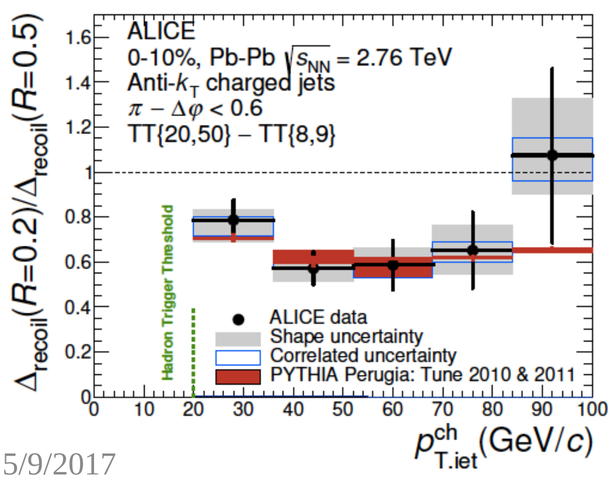
$$\sum_{tracks} p_{\mathrm{T}}^{\mathrm{trk}} = 150\ \mathrm{GeV}\ \times\ 0.1\ \times\ 0.05 \times\ 10\ \mathrm{bins} \sim\ 7.5\ \mathrm{GeV}$$

CMS excess relative to pp ~ factor 4 ➞ absolute excess ~ 6 GeV
Compare ALICE: charged energy transported to $\Delta r > 0.5$ is 8±2 GeV (!!)

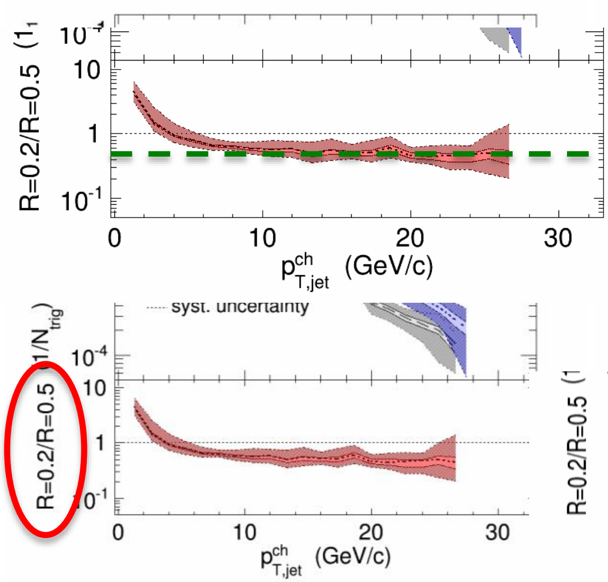
Jet quenching: intra-jet broadening



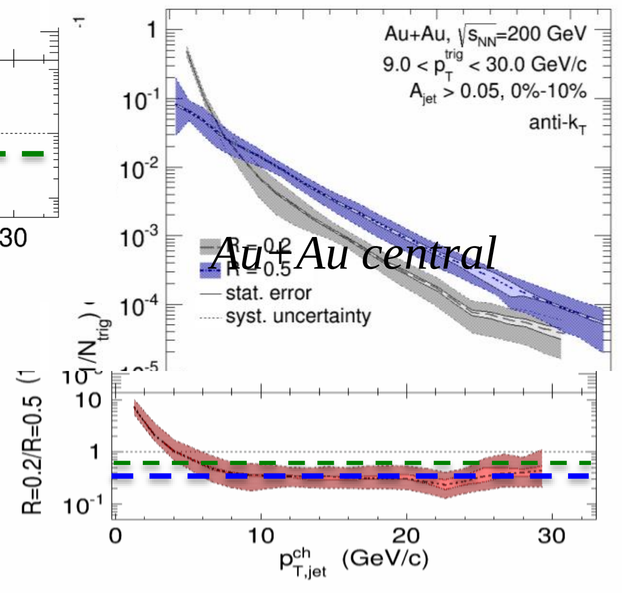
ALICE: JHEP 09 (2015) 170



Au+Au peripheral



Au+Au central



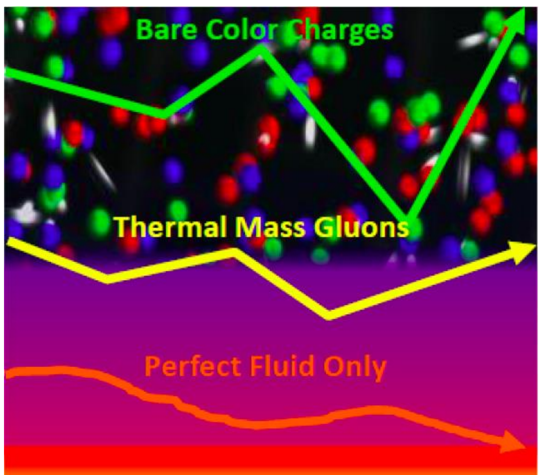
Ratio 0.2/0.5 for peripheral and central consistent within uncertainties

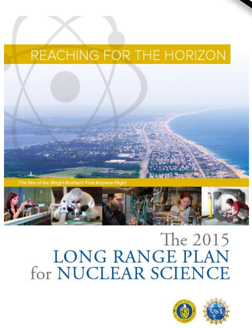
- compatible with some broadening within R<0.5
- future measurements will reduce uncert.

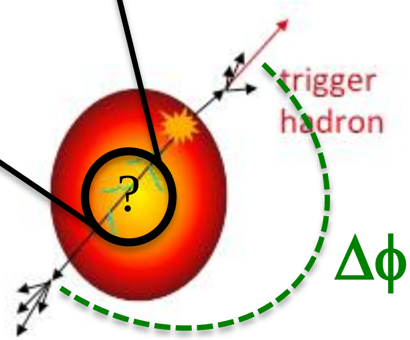
ALICE: similar picture in overlapping p_T range

Inter-jet broadening: secondary scattering off the QGP

Discrete scattering centers or effectively continuous medium?

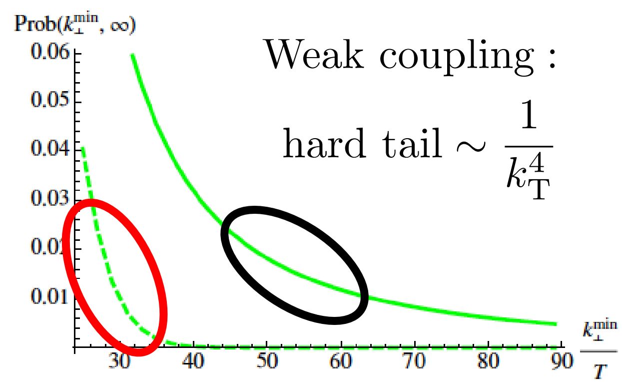






d'Eramo et al., JHEP 1305 (2013) 031

Distribution of momentum transfer k_T



Strong coupling:
Gaussian distribution

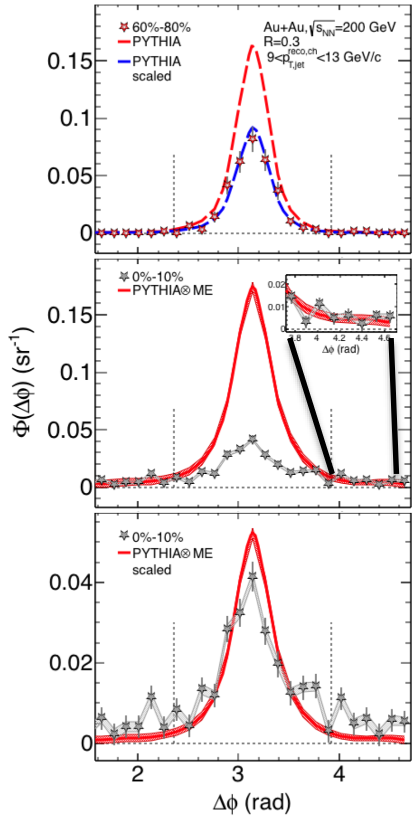
Conjecture for weak coupling: Δϕ distribution dominated by single hard Molière scattering at "sufficiently large" Δϕ

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

Interjet broadening: RHIC and LHC

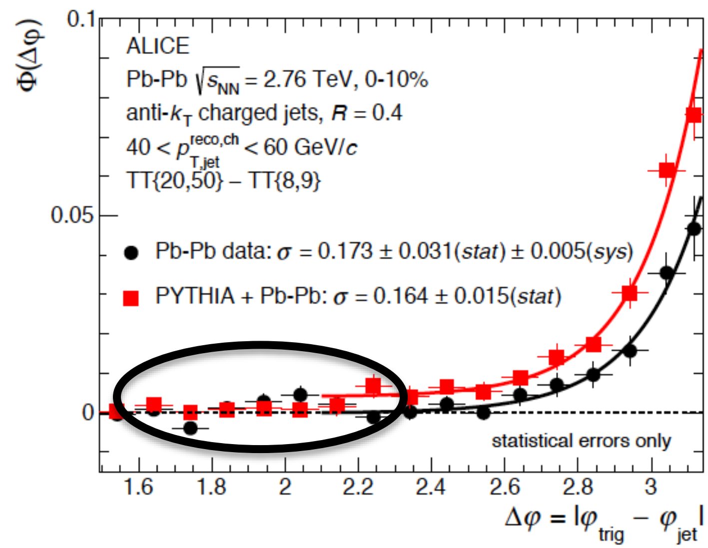
AuAu $\sqrt{s_{NN}}$=200 GeV

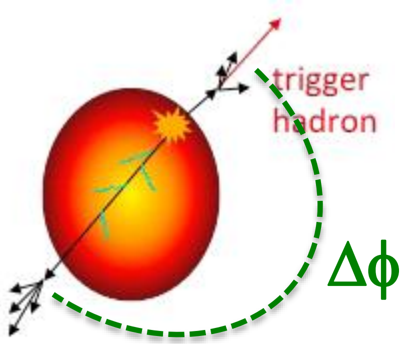
arXiv:1702.01108



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

JHEP 09 (2015) 170





Low jet p_T of special interest: largest effects expected

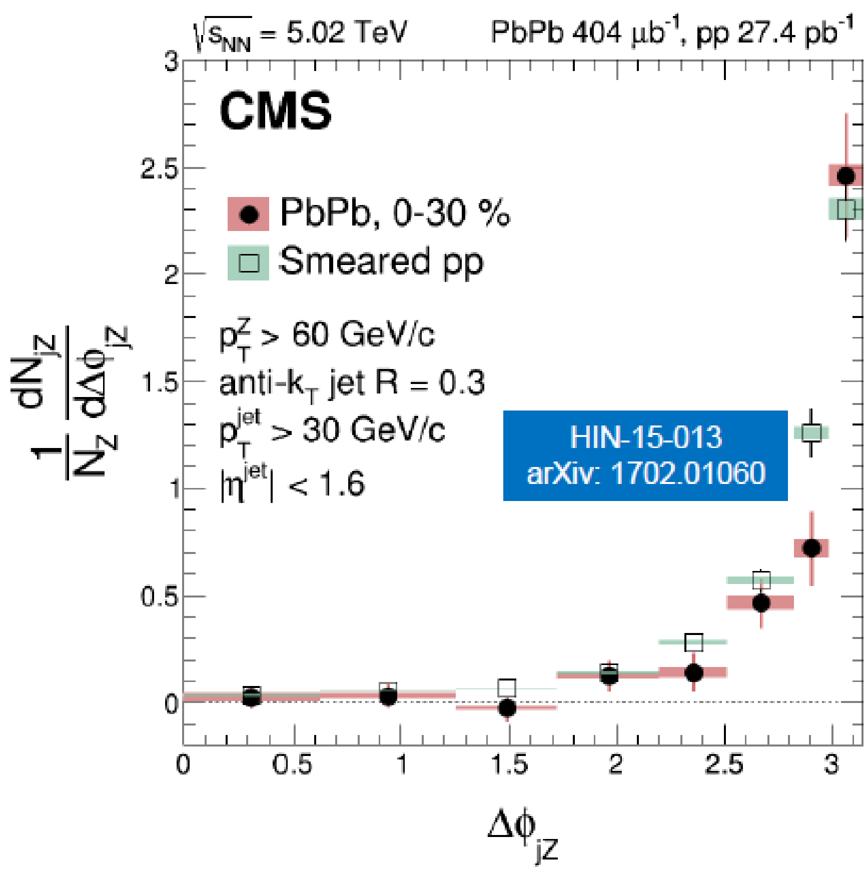
- current measurements consistent with zero yield

QCD calculation of scattering in q/g gas needed to estimate integrated luminosity needed for significant measurement

Acoplanarity in Z+jet

Ran Bi, CMS
QM17

Azimuthal correlation $\Delta\phi_{JZ}$ (Z-jet events)



- No broadening of the $\Delta\phi_{JZ}$ distribution within uncertainties
- **Not** statistically significant, p-value of 0.14

RAN BI QUARK MATTER 2017 7

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

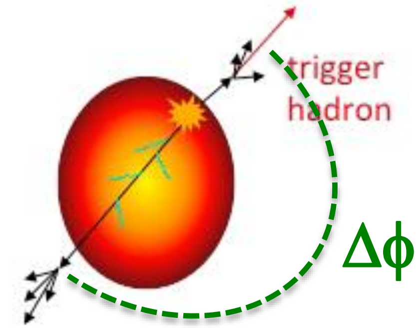
Lin Chen,[1] Guang-You Qin,[1] Shu-Yi Wei,[1] Bo-Wen Xiao,[1] and Han-Zhong Zhang[1]
[1] *Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China*

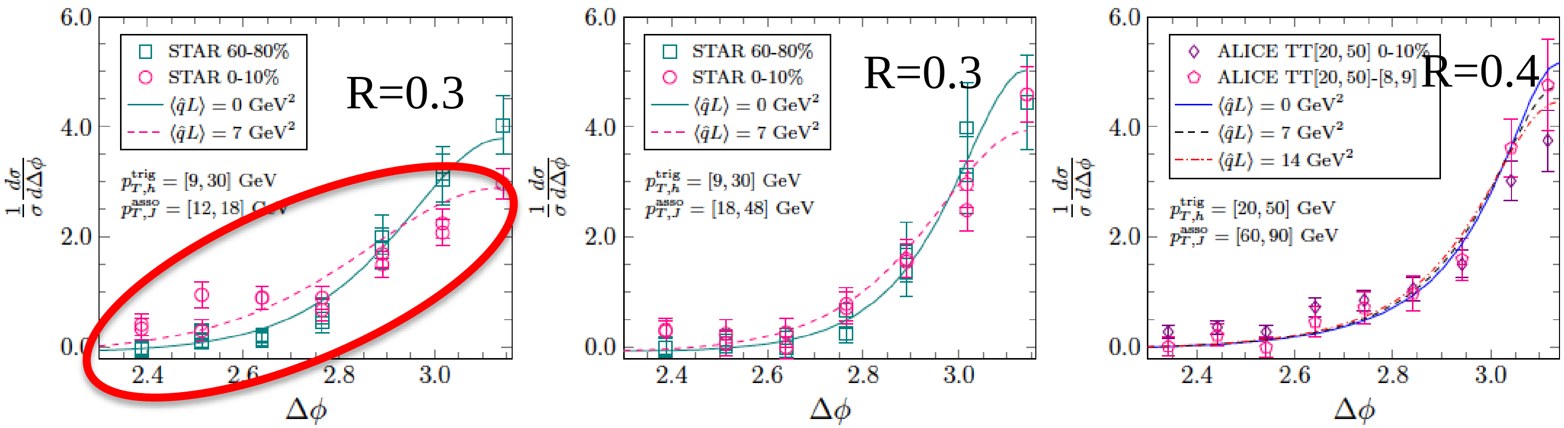
arXiv:1607.01932

Vacuum parton shower: Sudakov resummation
➞broadening of main recoil peak at |Δϕ-π|~small

Medium-induced broadening: <qhat*L>

Optimal kinematics: low jet p_T ~ 10 GeV





Predicts small but observable effect
→ direct measurement of <qhat*L>…?

FIG. 2. Normalized ha… …LICE [49] data. A factor of 3/2 is multiplied to the charg… …y neutral particles.

Sudakov broadening: RHIC vs LHC

Chen et al., *arXiv:1607.01932*

Sudakov broadening for the same kinematic objects in p+p collisions at RHIC and LHC

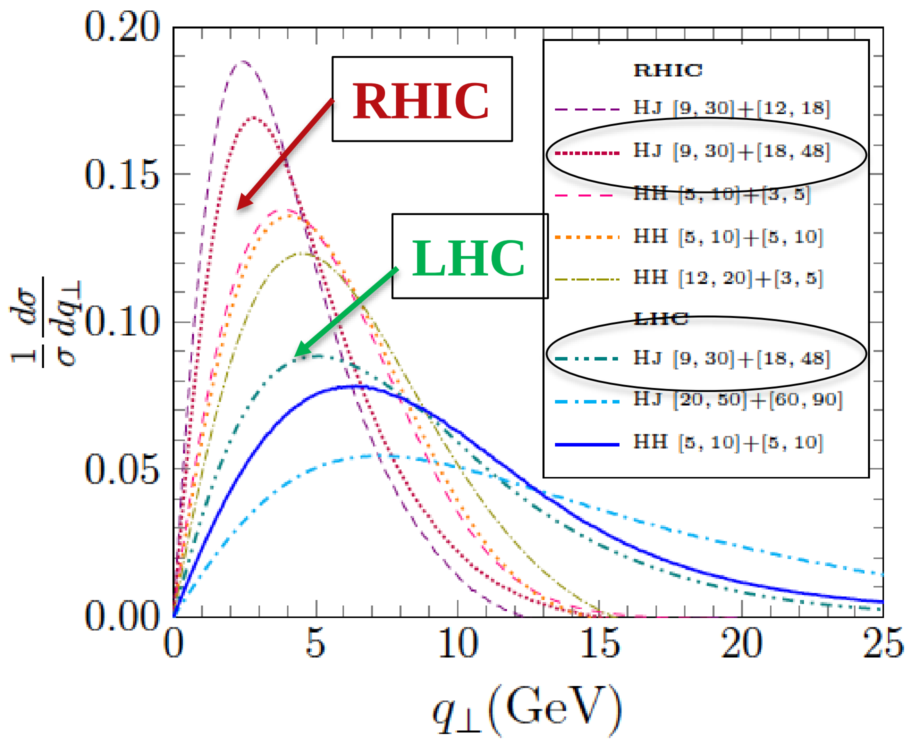


FIG. 3. Normalized $q_\perp$ distributions for dihadron and hadron-jet correlations in *pp* collisions at RHIC and the LHC.

h+jet:

- $9 < p_T^{trig} < 30$ GeV/c
- $18 < p_T^{recoil\ jet} < 48$ GeV/c

Significantly larger broadening at LHC than RHIC

→harder to pull out broadening due to <qhat*L>

Challenging measurement at both colliders

- Needs high statistical and systematic precision for low p_T jets

At minimum can set limit on <qhat*L>

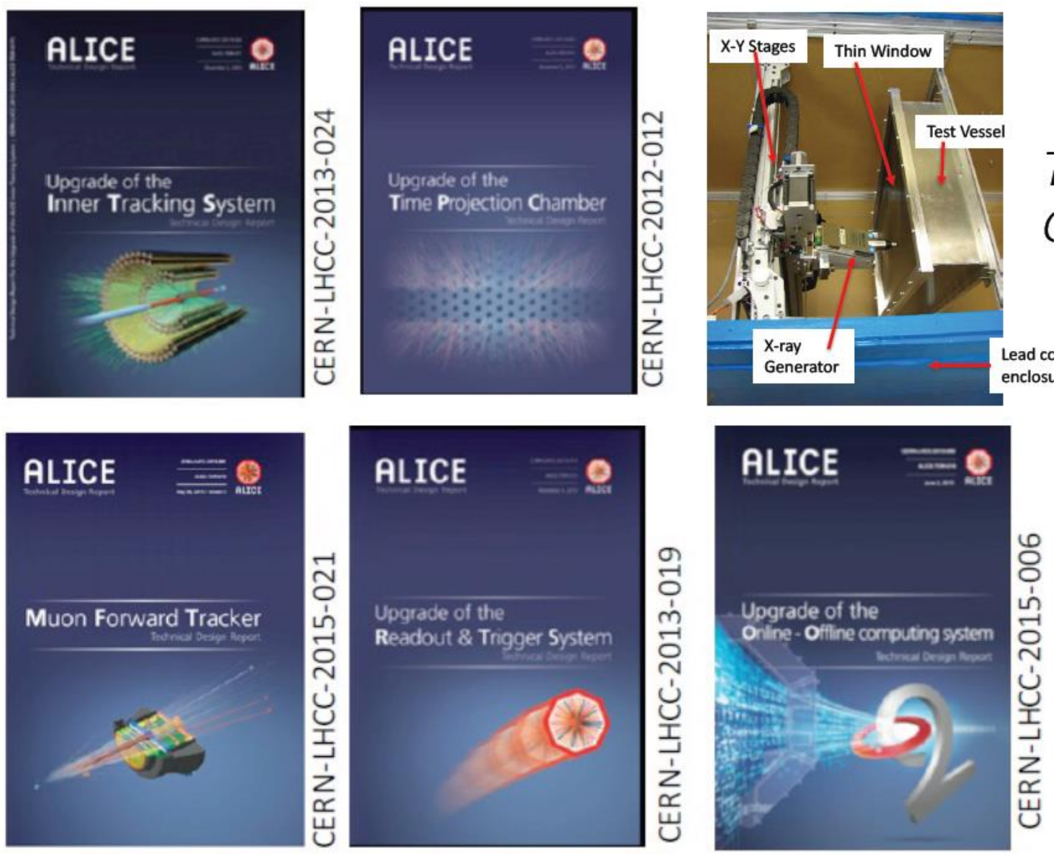
→ positive measurement possible?

Creating the future…

LHC Run 3

Major LHC upgrade: factor 10 in Pb+Pb integrated lumi

Major ALICE upgrades; smaller upgrades for ATLAS/CMS

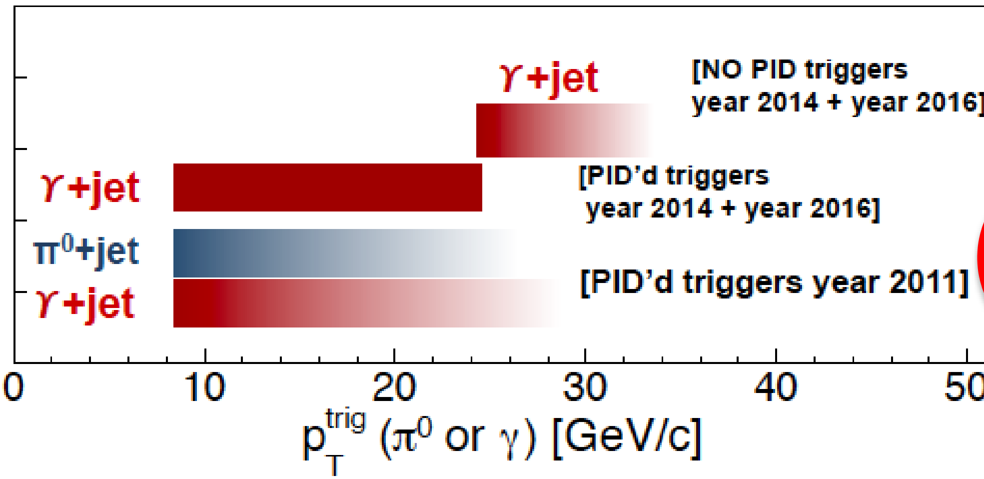


STAR Projections

Nihar Sahoo
QM17

Future measurements of π^0+jet vs. γ+jet

Au+Au collisions in the STAR experiment



Int. Lumininosity sampled by BEMC trigger
Year 2011: 2.8 nb^{-1}
Year 2014+ year 2016: ~25 nb^{-1} on tape(~10 times more statistics)

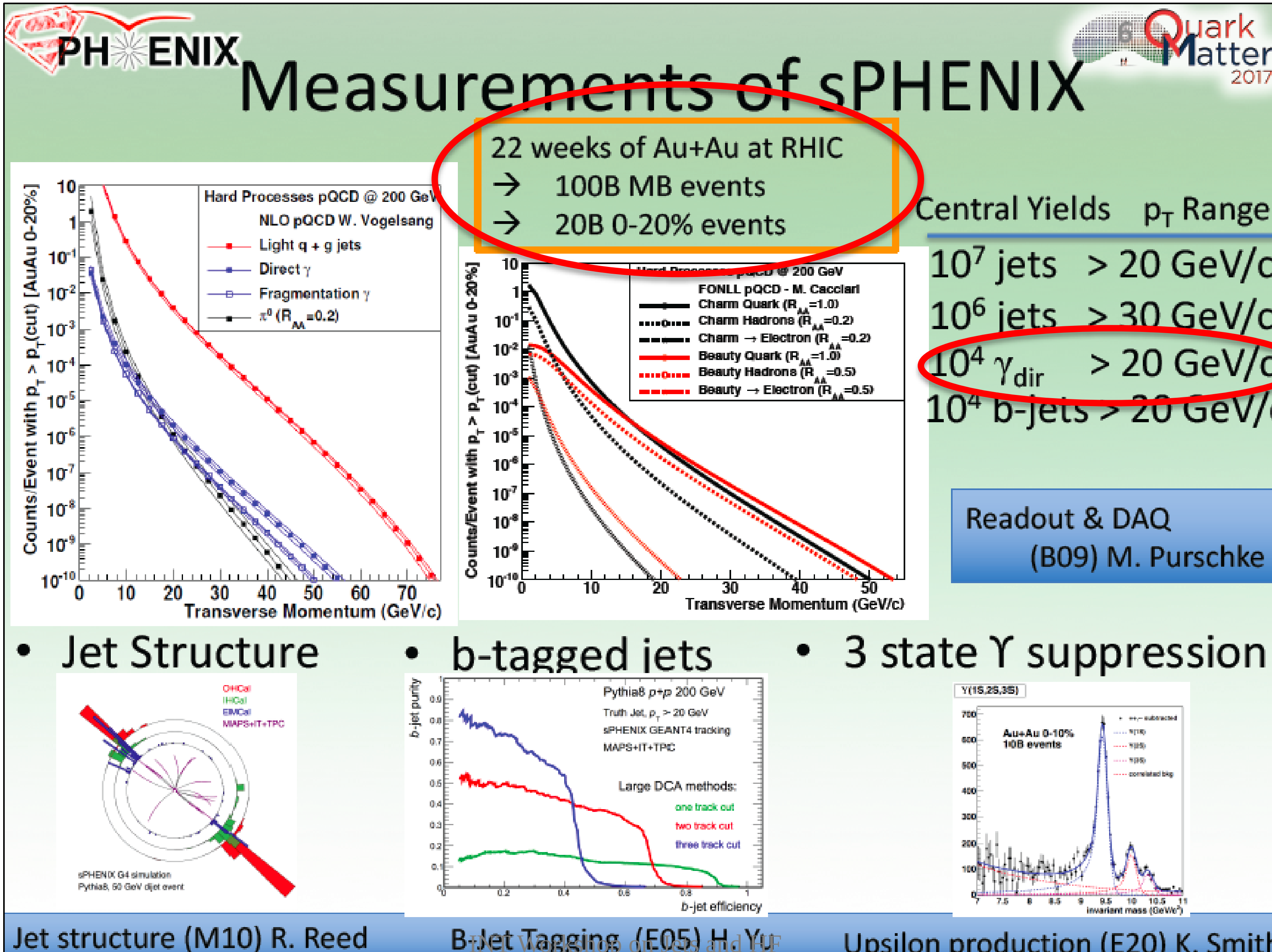
- ~25 nb^{-1} corresponds to 175 billion MB events

- For p_T > 9 GeV/c
  - Run11: γ+jet ~30K trigger (p_T > 9 GeV/c) events with tight PID cuts
  - Combining year 2014+ year 2016, we have 8 times year 2011 statistics on the tape.
- For p_T > 25 GeV/c
  - we don't need tight PID (Ratio γ/π^0 > ~2) and hence expect > 5K γ triggers

…Stay tuned

sPHENIX projections

Megan Connors
QM17



JETSCAPE: Jet Energy-loss Tomography with a Statistically and Computationally Advanced Program Envelope

Steffen Bass & Robert Wolpert	Duke University
Ron Soltz	Lawrence Livermore National Laboratory
Gunther Roland	Massachussetts Institute of Technology
Charles Gale & Sangyong Jeon	McGill University
Ulrich Heinz	Ohio State University
Rainer Fries	Texas A&M University
Barbara Jacak, Peter Jacobs & Xin-Nian Wang	University of California at Berkeley & Lawrence Berkeley National Laboratory
Abhijit Majumder, Joern Putschke & Loren Schwiebert	Wayne State University (Lead Institution)

http://jetscape.wayne.edu/jetscape/

Summary and Outlook

Jet measurements in vacuum: precise comparison to QCD requires IRC-safe observables · integrate out hadronic degrees of freedom

Partonic jet quenching measurements in heavy ion collisions:

- observables that are theoretically well-founded in vacuum
- what changes in-vacuum ➞in-medium?
- requires similar approaches in theory

Current focus: semi-inclusive h+jet measurements (γ+jet in progress)

- Statistical approach to background:
  - "IRC-safe": no fragmentation bias imposed by bkgd suppression
  - good and improvable systematic precision for all R + all p_T + all systems
- Applied at STAR/RHIC and ALICE/LHC
- Observables: yield suppression, medium-induced jet broadening, jet substructure,…

Next steps:

- Extend techniques to fully calormetric jets, higher int lumi RHIC+LHC
- Quantitative comparison to theory calculations

Backup slides

From sPHENIX Science Review, summer 2014

Current theoretical efforts have an overemphasis on medium modeling and phenomenological parameter tuning, specifically mock-up applications of energy loss or medium-induced parton showers not based on rigorous theory in Monte Carlo codes.

For jet and heavy flavor applications there is a need to put the emphasis back on field theory and QCD factorization. These should be priority areas for the next generation heavy ion theorists who should seek input and expertise from particle physics. The incorporation of recent advances in pQCD, SCET results in the largely phenomenological Monte Carlos should be encouraged.

From a neighboring field…

JHEP 1412 (2014) 009

Power Counting to Better Jet Observables

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1 Introduction

Over the past several years there has been an explosion in the number of jet observables and techniques developed for discrimination and grooming [1–3].

While the proliferation of jet observables is exciting for the field, the vast majority of proposed observables and procedures have been analyzed exclusively in Monte Carlo simulation. Monte Carlos are vital for making predictions at the LHC, but should not be a substitute for an analytical understanding, where possible. Because Monte Carlos rely on tuning the description of non-perturbative physics to data, this can obscure what the robust perturbative QCD predictions are and hide direct insight into the dependence of the distributions on the parameters of the observable. This is especially confusing when different Monte Carlo programs produce different results.

STAR approach to Uncorrelated Background: Mixed Events