

Jets at RHIC and LHC today and tomorrow

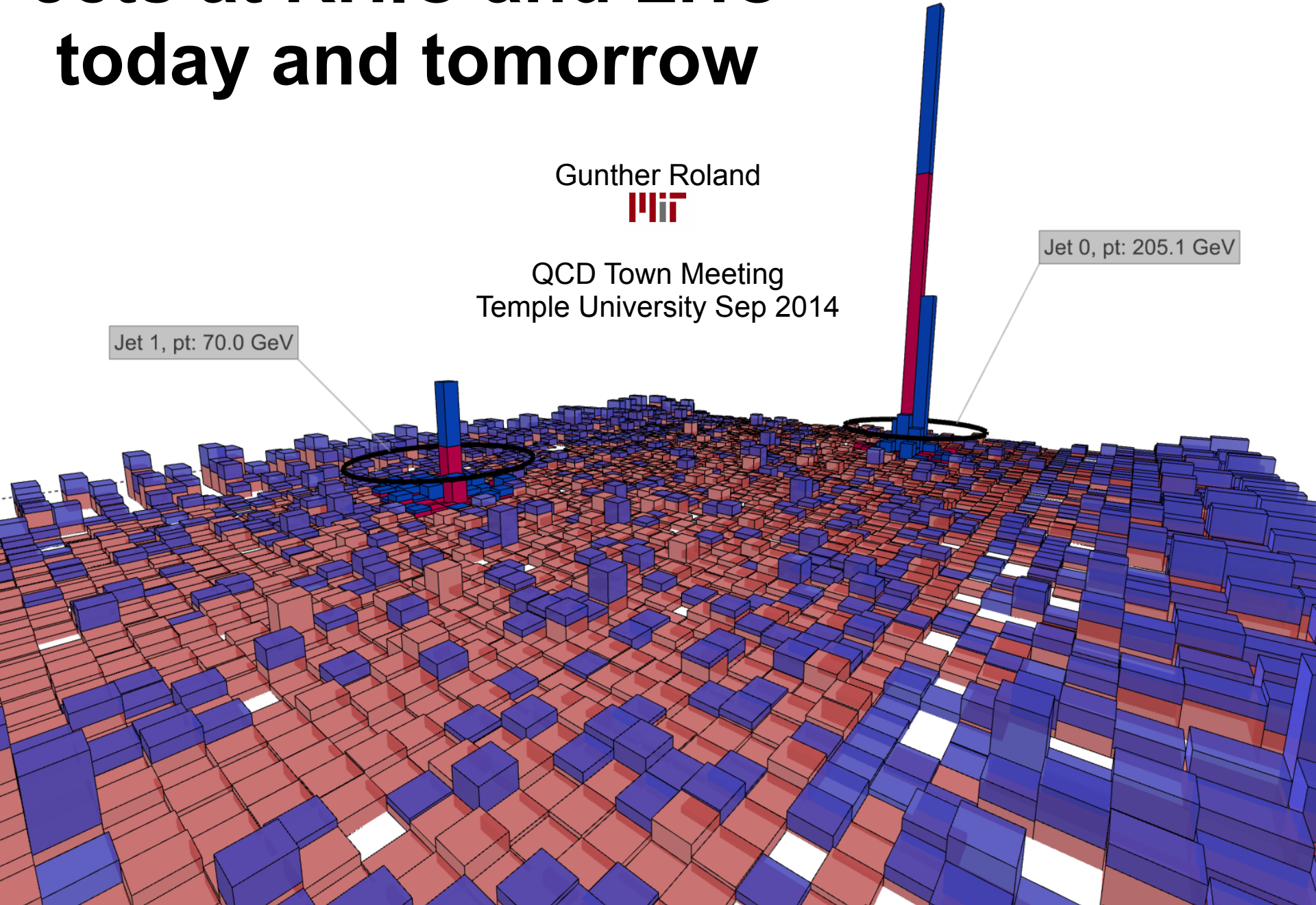
Gunther Roland



QCD Town Meeting
Temple University Sep 2014

Jet 1, pt: 70.0 GeV

Jet 0, pt: 205.1 GeV

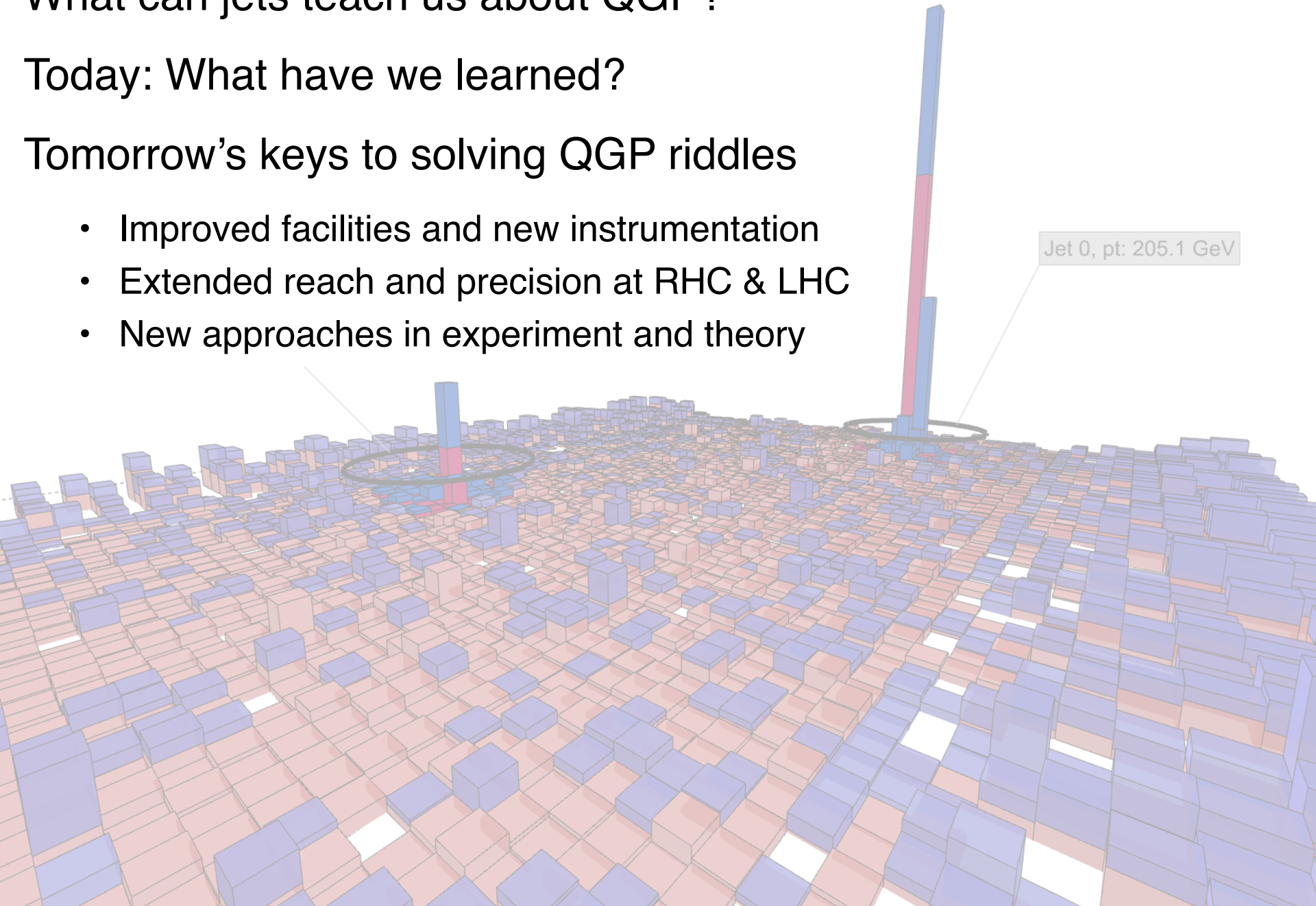


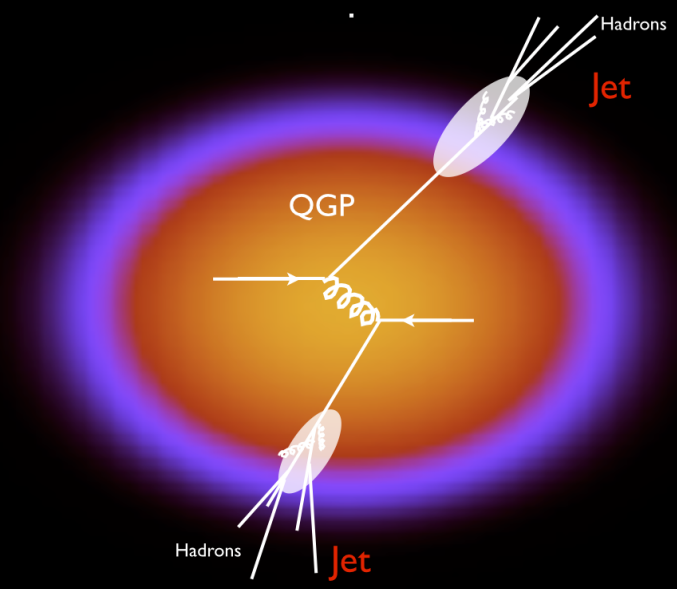
What can jets teach us about QGP?

Today: What have we learned?

Tomorrow's keys to solving QGP riddles

- Improved facilities and new instrumentation
- Extended reach and precision at RHC & LHC
- New approaches in experiment and theory





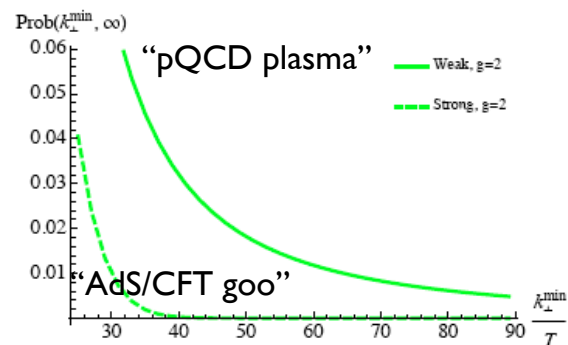
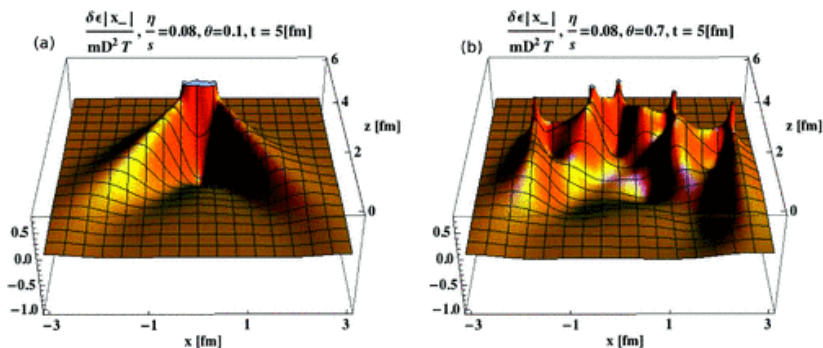
Jets as tools to *characterize* QGP

Medium effects on jets allow extraction of QGP transport coefficients:

- \hat{q} : transverse momentum diffusion (*radiative energy loss*)
- \hat{e} : longitudinal drag (*collisional energy loss*)

Jets as tools to *manipulate* QGP

How does QGP respond to local energy deposition by jets?

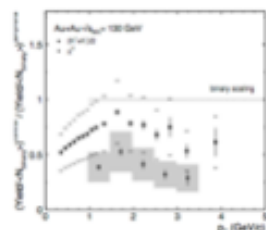


Jets as tools to *understand* QGP

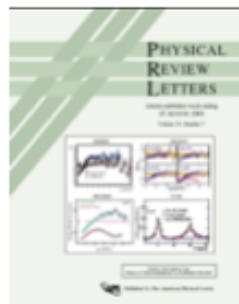
How does the strongly coupled liquid emerge from QCD?

- Jets probe QGP at different (controllable) length scales
- Scattering sensitive to quasi-particle nature of the medium

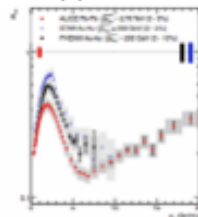
High p_T suppression in AuAu



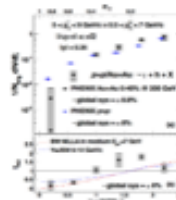
No high p_T suppression in dAu



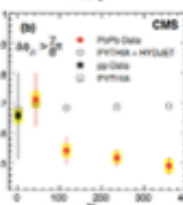
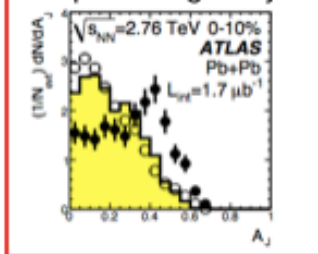
High p_T suppression at LHC



Photon-hadron correlations



Jet quenching in dijets



Photon-jet correlations

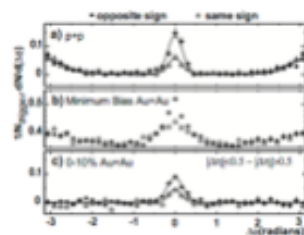
Now

2000

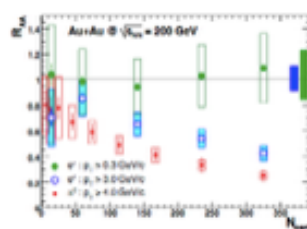
2004

2008

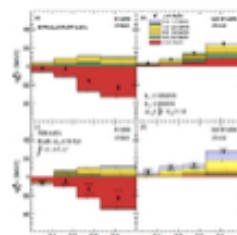
2012



Disappearance of away-side correlations in AuAu

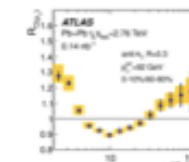
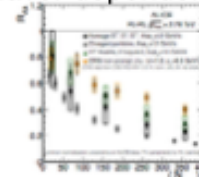


Suppression of heavy-flavors using single electrons



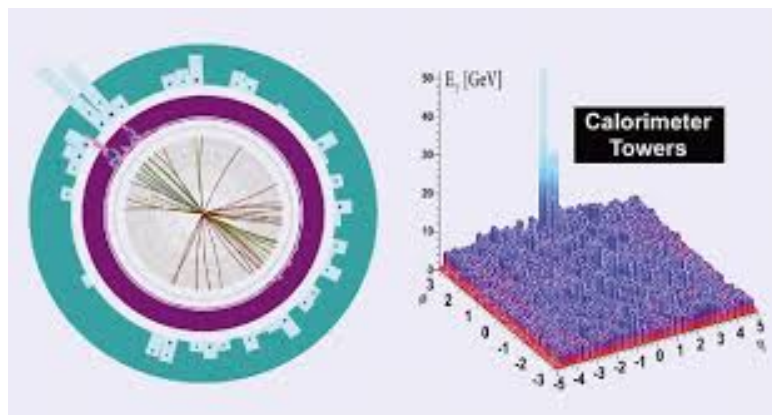
Observation of low p_T , large angle radiation

Flavor dependence



Fragmentation functions

We can measure jets in heavy ion collisions



Jet measurement approach:

- Clustering with anti- k_T algorithm
- Subtraction of event-by-event background energy estimate
- Jet energy corrections using pp calibration and MC correction factors

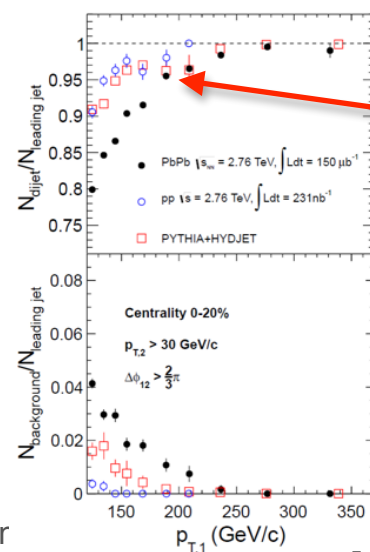
Achieved good experimental control

- Reconstruction efficiency (close to 100% @ 50+ GeV)
- Jet energy scale (2-4% above 30 GeV)
- Resolution and UE fluctuations ($\sim 15\%$ @ 100 GeV)

This was not obvious a-priori; success enabled by nature of observed jet modifications

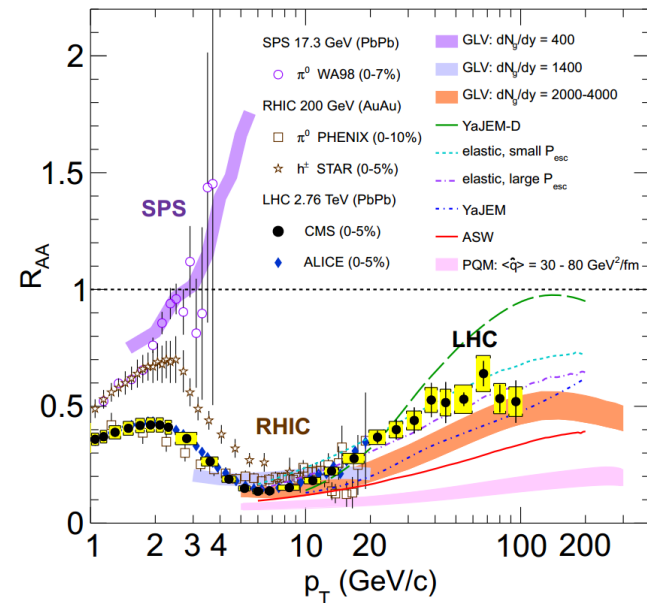
Complementary approaches to reconstruction biases

- At low p_T : efficiency vs fake jets
- Restrict measurement to high p_T (CMS/ATLAS)
- Ensemble-based measurement with combinatorial correction (ALICE/STAR)



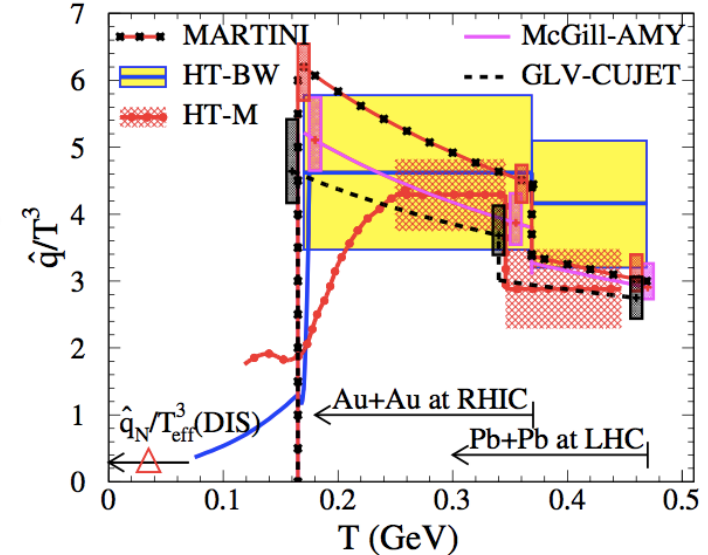
For sufficiently high trigger p_T , all away-side jets are found

We can extract QGP transport coefficients from jet quenching measurements



Systematic evaluation of single hadron suppression data from RHIC and LHC in perturbative framework

Similar information from jet R_{AA} , dijet asymmetries, γ -jet momentum shift



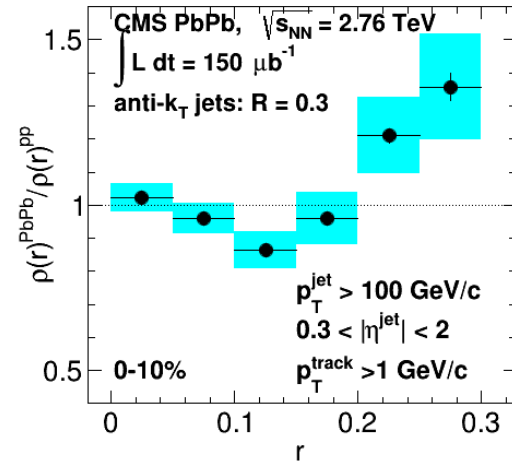
\hat{q} determined with about 35% uncertainty
Combined RHIC and LHC data:

- Test model consistency
- First hint of temperature dependence

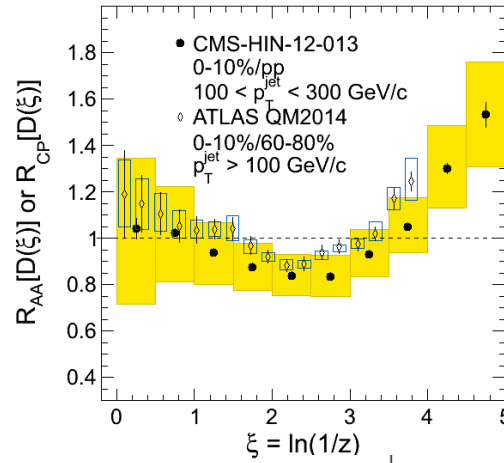
Quantitative extraction of \hat{e} awaits more precise heavy flavor data

We can observe medium modifications of jet momentum and angular structure

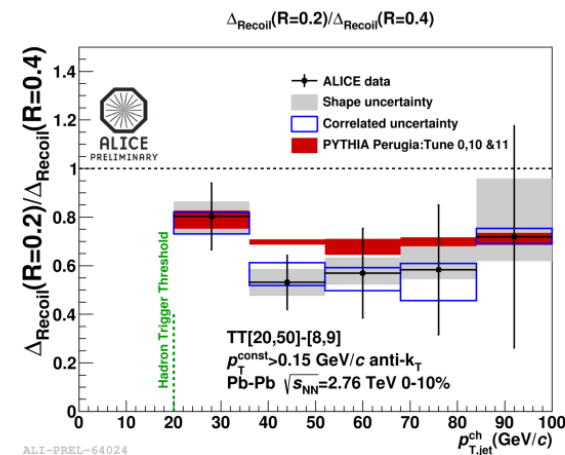
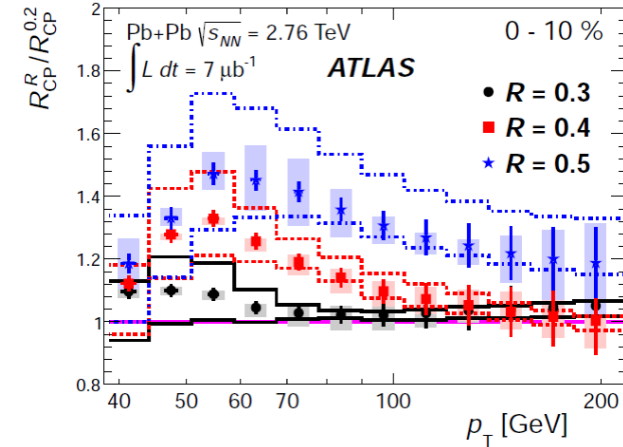
Jet shapes



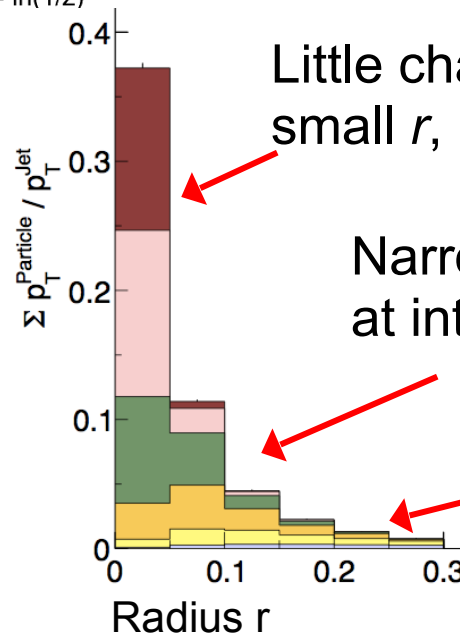
Fragmentation functions



R_{AA} radius dependence



Δ_{Recoil} radius dependence



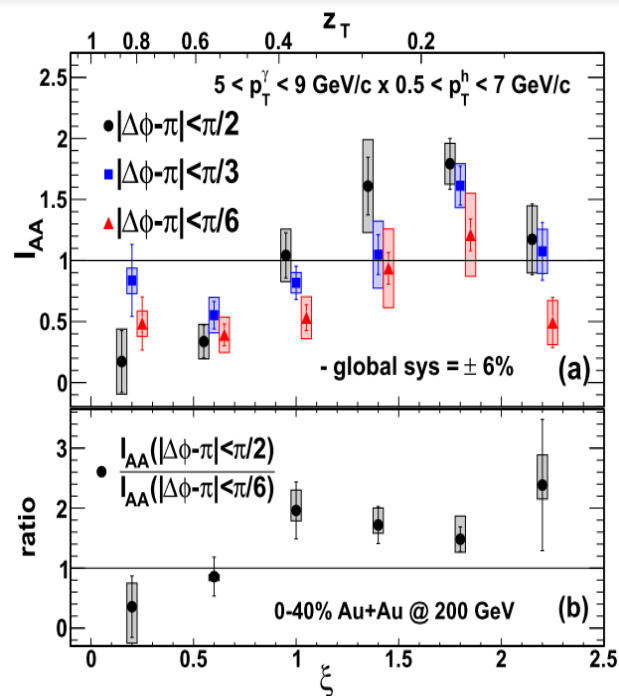
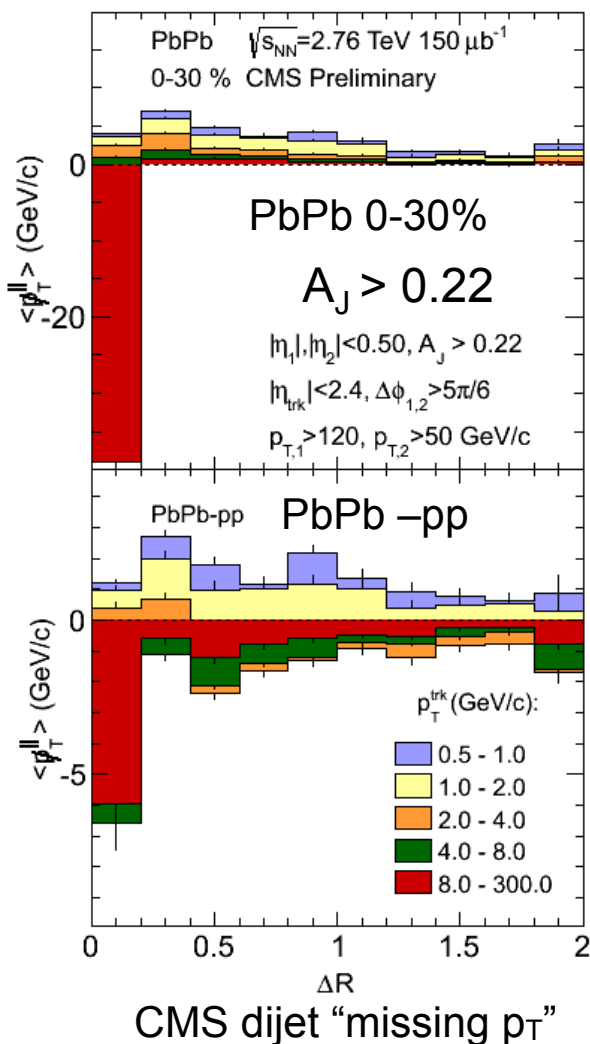
Little change at small r , high p_T

Narrowing/depletion at intermediate r , p_T

Broadening/excess at large r , low p_T

(~2% of jet energy)

We see out-of-cone momentum flow relative to jet



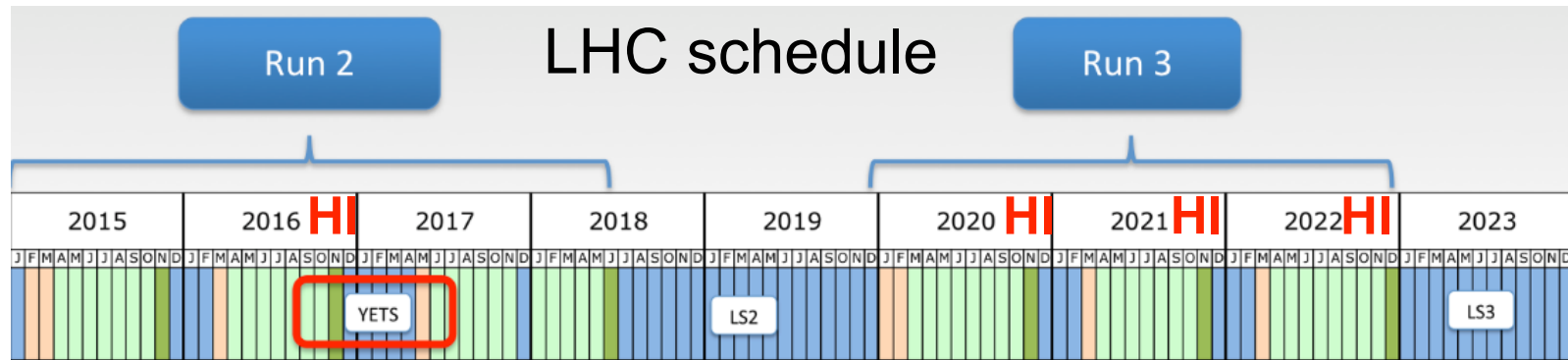
PHENIX
 γ -hadron
correlations

Enhancement of low- p_T correlated yields at large angles to jet axis

Is this “trivial” jet-medium coupling or signature of modified QCD branching (“turbulent flow”)?

Tomorrow

Future program enabled by accelerator development



HI $\sqrt{s} = 5\text{TeV}$

PbPb Collision rate $\approx 20\text{kHz}$

$L_{\text{int}} \approx 3/\text{nb}$

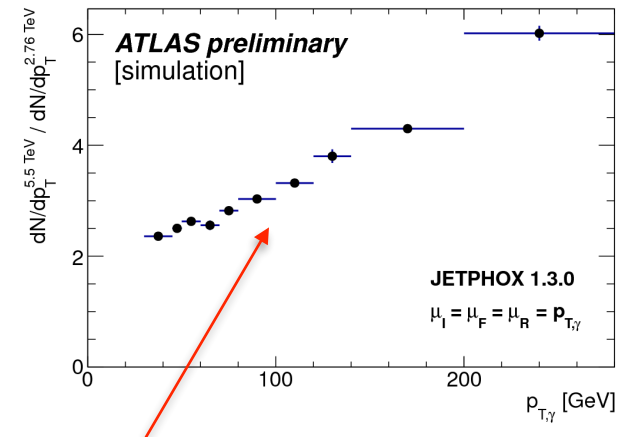
HI

$\sqrt{s} = 5.5\text{TeV}$

Collision rate $\approx 50\text{kHz}$

$L_{\text{int}} \approx 10/\text{nb}$ (run 2+3)

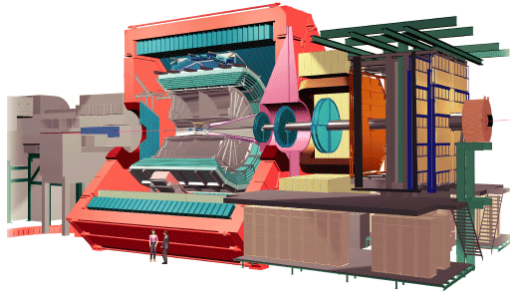
	2010–2011 2.76 TeV 160 μb^{-1}	HL-LHC 5.5 TeV 10 nb^{-1}
Jet p_T reach (GeV/c)	~ 300	~ 1000
Dijet ($p_{T,1} > 120$ GeV/c)	50k	$\sim 10\text{M}$
b-jet ($p_T > 120$ GeV/c)	~ 500	$\sim 140\text{k}$
Isolated γ ($p_T^\gamma > 60$ GeV/c)	$\sim 1.5\text{k}$	$\sim 300\text{k}$
Isolated γ ($p_T^\gamma > 120$ GeV/c)	—	$\sim 10\text{k}$
W ($p_T^W > 50$ GeV/c)	~ 350	$\sim 70\text{k}$
Z ($p_T^Z > 50$ GeV/c)	~ 35	$\sim 7\text{k}$



Compared to LHC Run1: x60 due to higher luminosity; x3 due to higher \sqrt{s}

Major upgrades to all LHC experiments

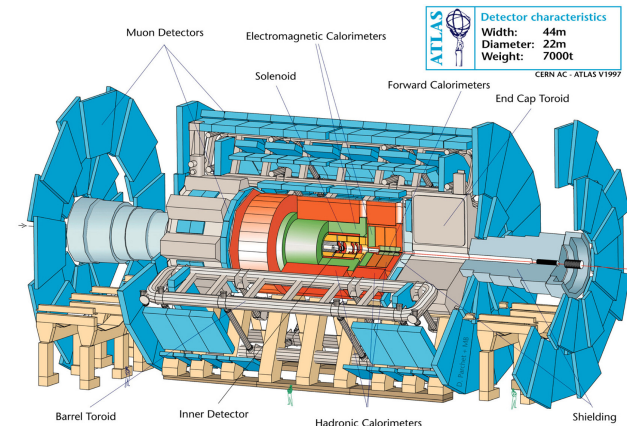
ALICE



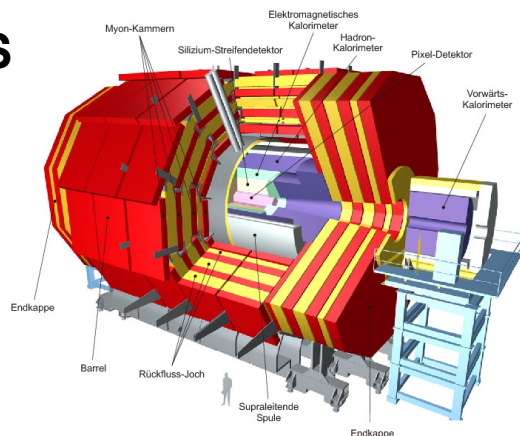
Expanded calorimetry
New inner tracker
Faster TPC readout
Improved data acquisition rate

Improved trigger system
New/extended inner tracker

ATLAS



CMS



Improved trigger system
New/extended inner tracker

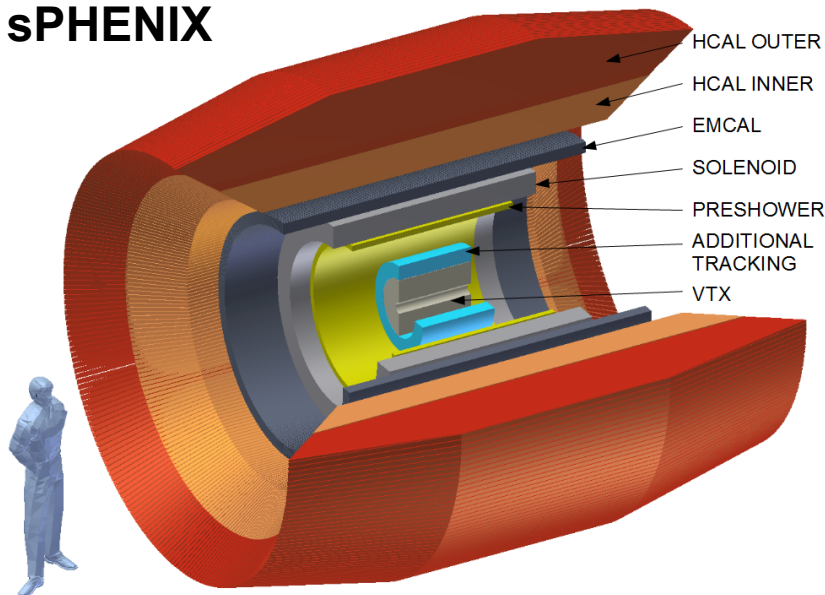
A state-of-the-art jet detector at RHIC

Use consistent experimental approach at RHIC and LHC to provide lever arm from $T \approx T_C$ to $T \gg T_C$

Study jet quenching vs medium temperature and density, parton p_T , flavor and pathlength

- to achieve a detailed characterization of QGP
- to understand how QGP properties arise from QCD

sPHENIX



Key capabilities

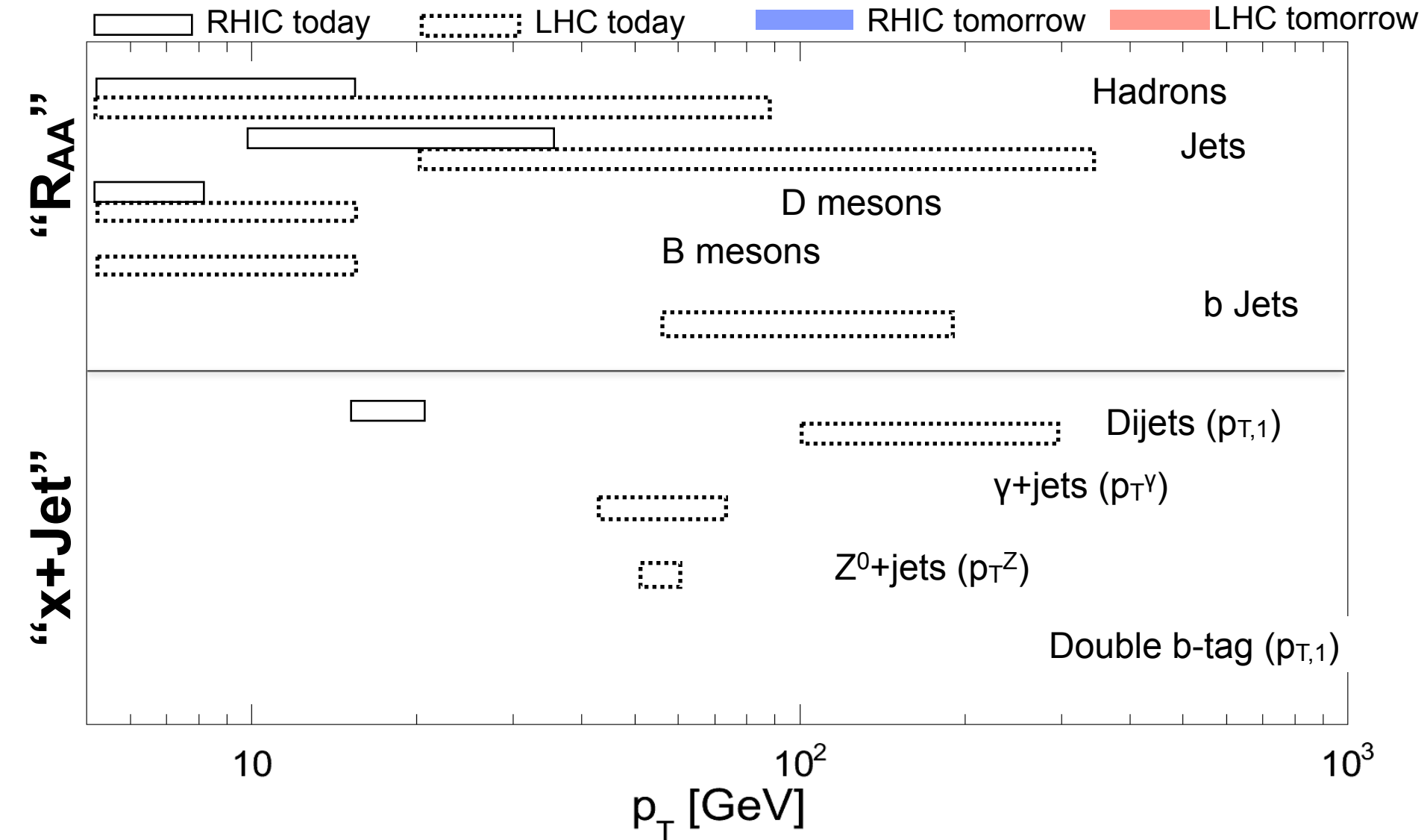
- Full calorimetry
- Tracking
- Rate capability

to exploit luminosity ($>50/\text{nb}$) and \sqrt{s} range (62-200 GeV) at RHIC

RHIC integrated luminosity up to x10 higher than LHC

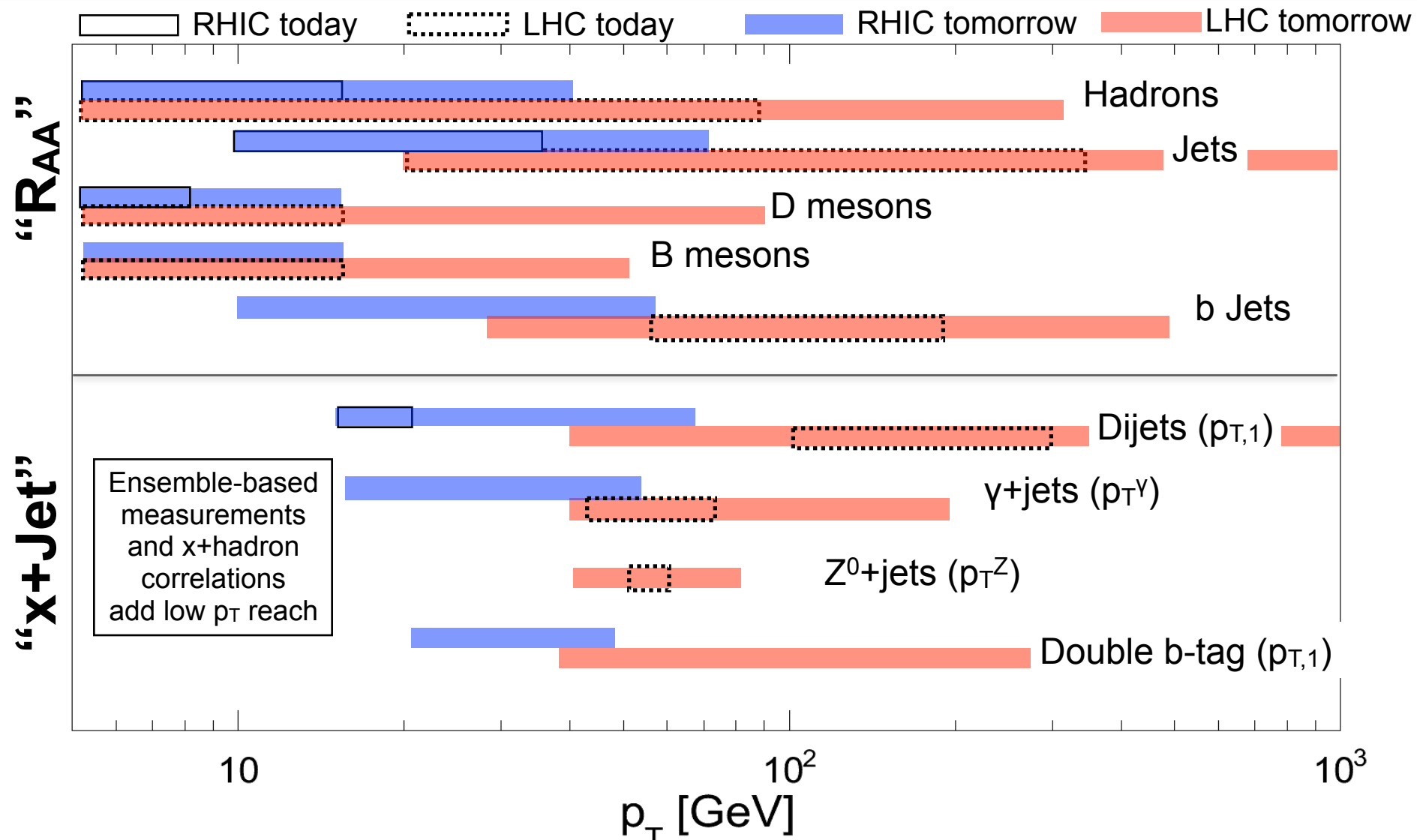
Kinematic reach: Now and tomorrow^(*)

^(*)Artist's impression



Kinematic reach: Now and tomorrow^(*)

^(*)Artist's impression

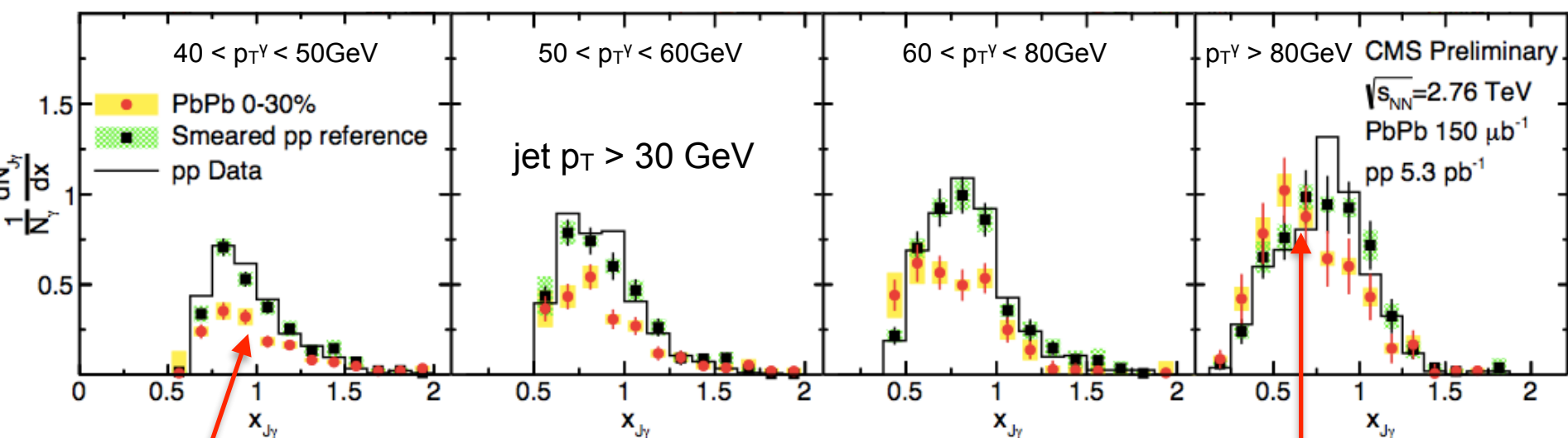


New observables; smaller uncertainties; broader p_T reach
RHIC+LHC overlap

The importance of photon-jet correlations

Using isolated photons to tag away-side jets

- determines initial parton energy to $\approx 15\%$
- determines initial direction of the parton
- tags parton to be a light quark



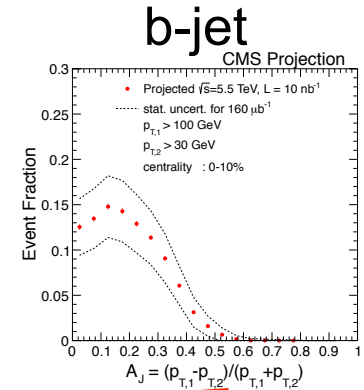
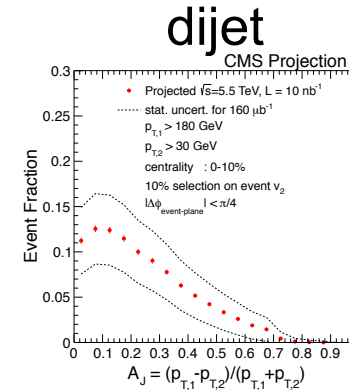
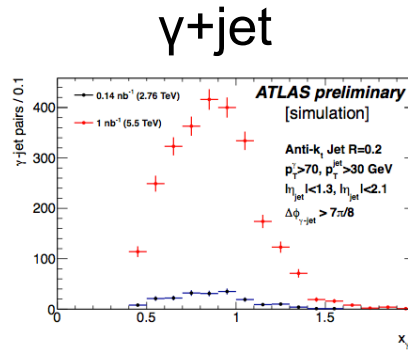
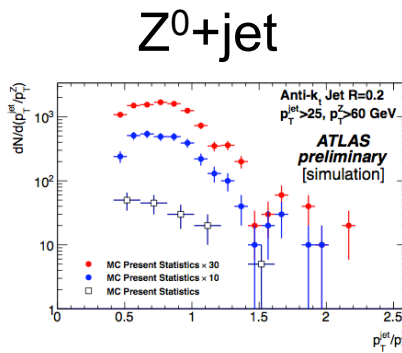
photon $p_T < 50 \text{ GeV}$:
Spectrum PbPb jets is
suppressed vs pp
Biased jet selection

photon $p_T > 80 \text{ GeV}$:
Spectrum of PbPb jets is
shifted vs pp
Unbiased jet selection

Sufficiently high γ p_T or sufficiently low jet p_T yield **unbiased** selection of jets

From Z^0 tags to B tags, and from LHC to RHIC

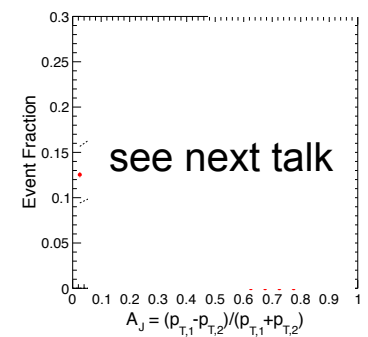
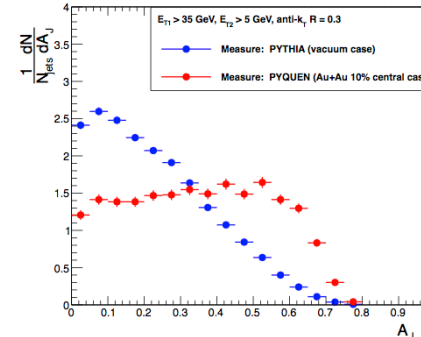
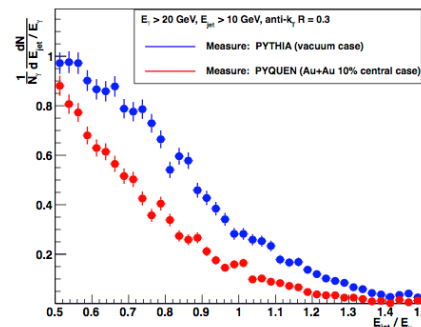
LHC



“Calibration”

Compare well-calibrated probes at RHIC/LHC to separate parton p_T , flavor dependence and medium conditions

RHIC

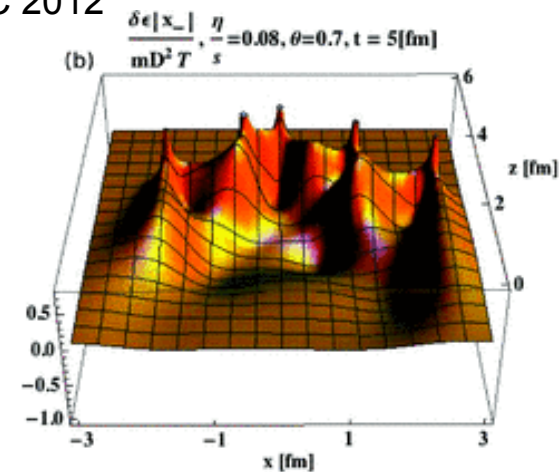
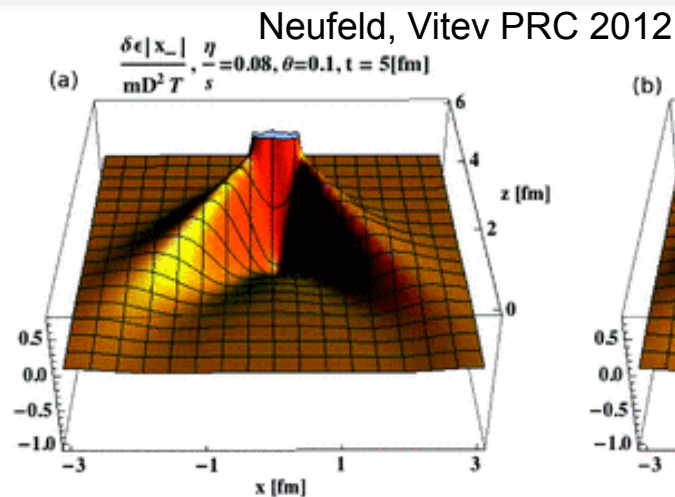
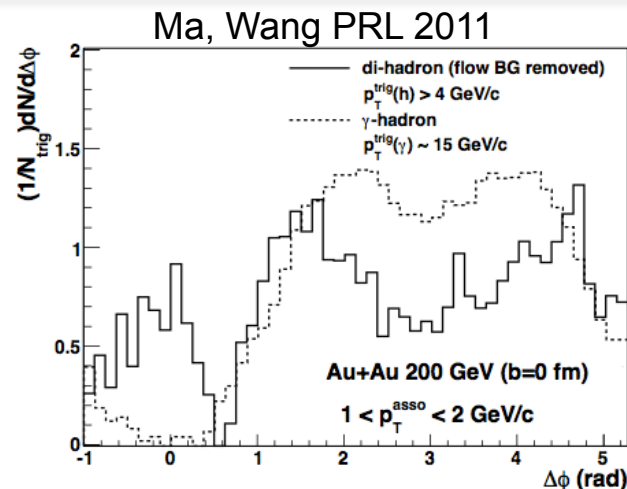


γ +jet

dijet

b-jet

Energy flow and medium response



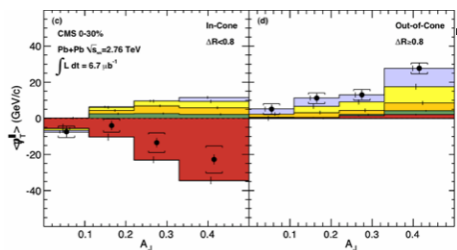
Do we have a medium, if there's no medium response?

Experimental and theoretical challenges:

- Strength and angular structure of medium response unknown
- Jets are correlated with the complex e-by-e flow fields through quenching
- How to distinguish medium-response from modified jet branching?

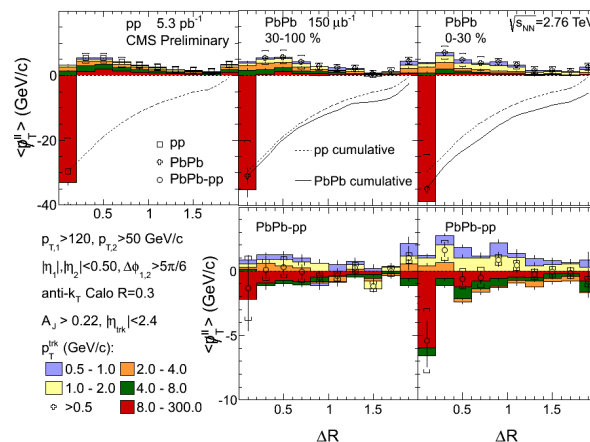
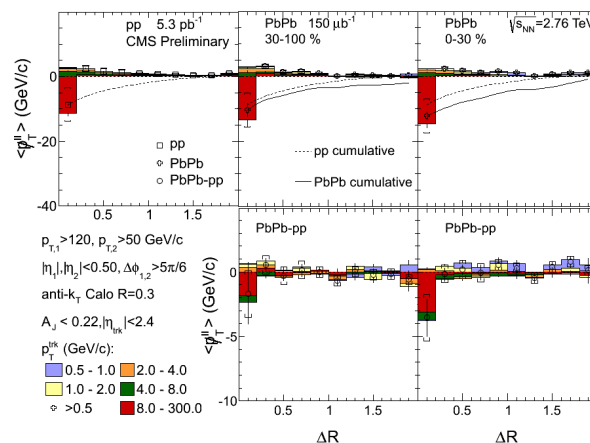
2011

- 0.015/nb
- 4 months analysis time
- in-cone vs out-of-cone
“missing p_T ” for dijets



2014

- 0.15/nb
- 2 years analysis time
- Improved tracking correction
- Improved jet bkg subtraction
- Detailed ΔR dependence of
“missing p_T ” for dijets



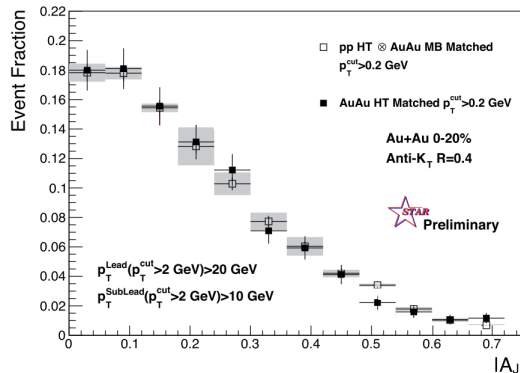
2015-2024

- 10/nb (LHC) 50/nb (RHIC)
- **γ +jet** (no flow correlations)
- MPT → **absolute correlated yields vs ($\Delta\eta$, $\Delta\phi$)**
- **Differential in e-by-e energy loss**
- **Different medium conditions at RHIC and LHC**

Indication of energy flow differences at RHIC vs LHC

RHIC (STAR)

Anti- k_T $R=0.4$, $p_{T,1} > 20$ GeV & $p_{T,2} > 10$ GeV with $p_{T,1}^{cut} > 2$ GeV/c



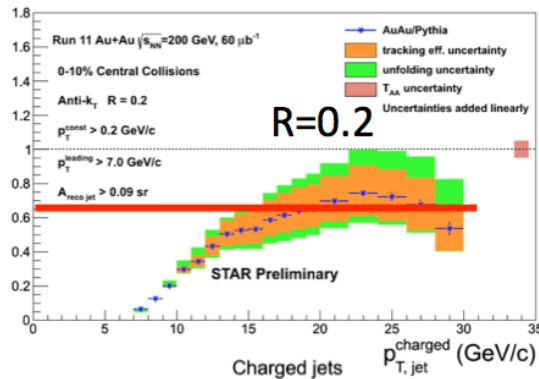
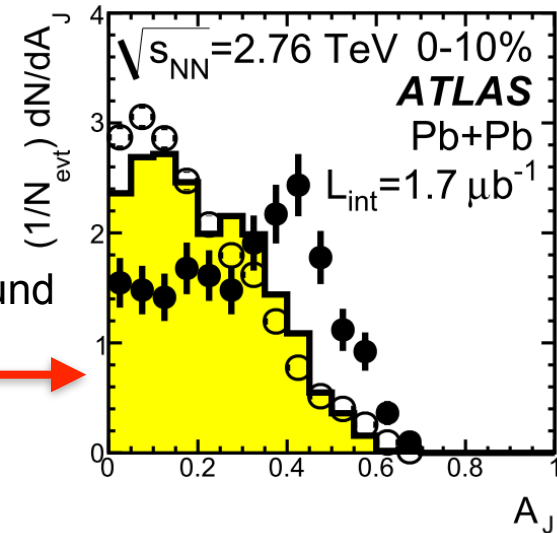
Jets balanced when including $p_T > 0.2$ GeV



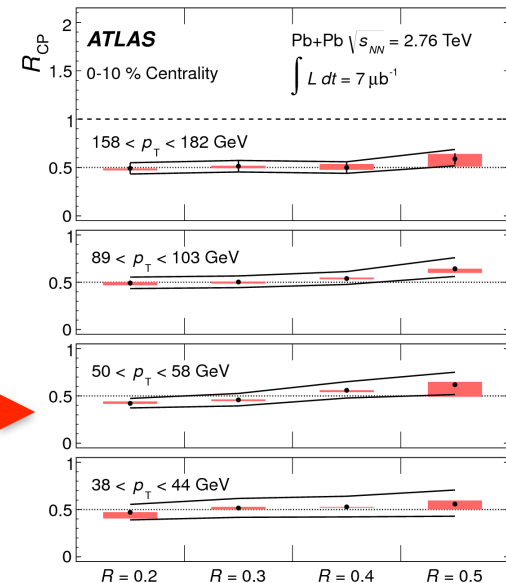
Energy balance found outside of jet cone



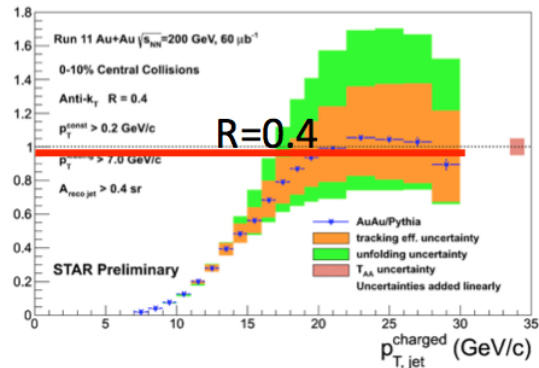
LHC (ALICE, ATLAS, CMS)



Strong radius dependence of jet RAA

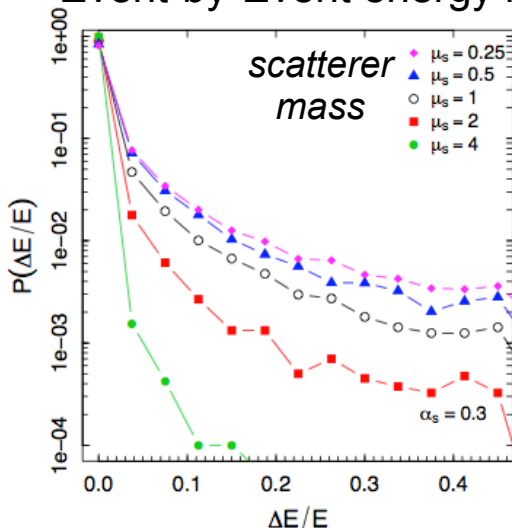


Weak radius dependence of jet RAA



Jet measurements as QGP microscope

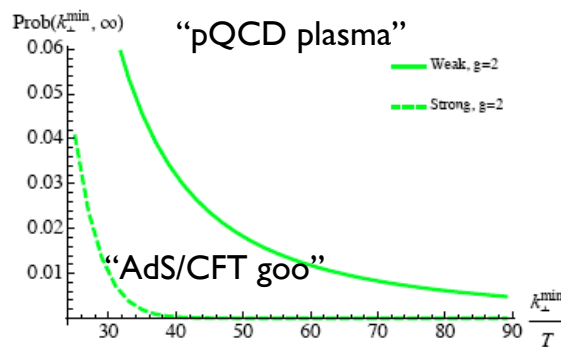
Event-by-Event energy loss



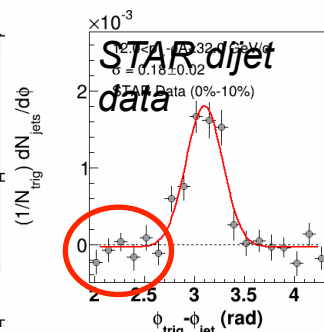
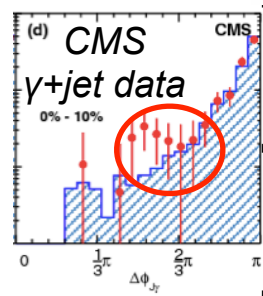
Coleman-Smith, Muller,
arXiv:1209.3328

Need $\approx \times 10$
better precision

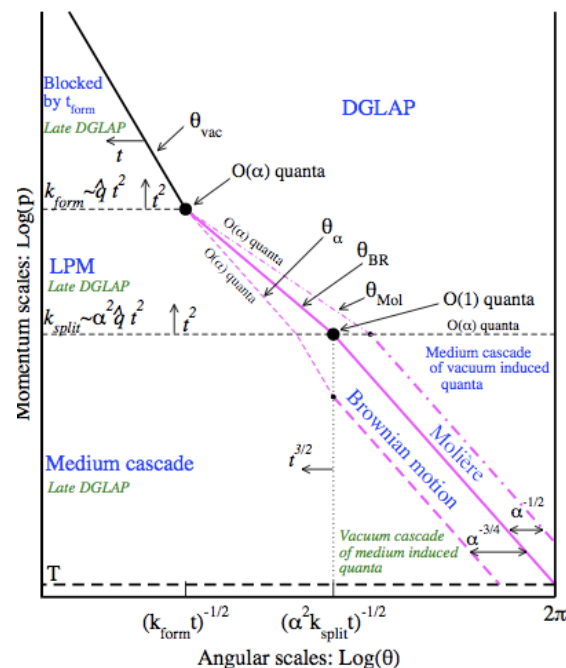
Large angle jet scattering



D'Eramo, Rajagopal, '12
updated calculation underway



Angular and momentum structure of parton cascade

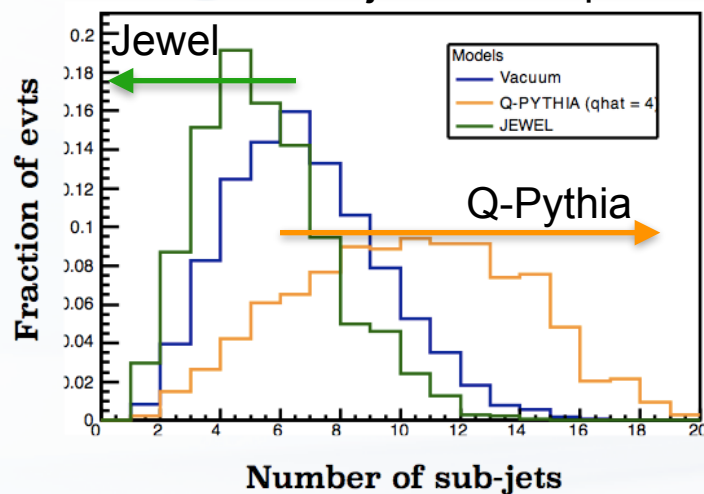


Kurkela, Wiedemann,
arXiv:1407.0293

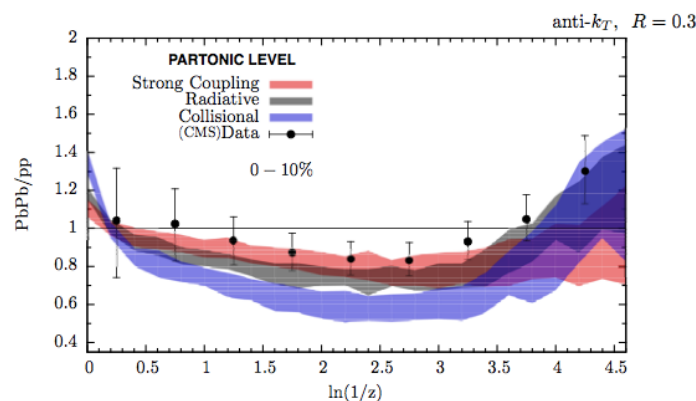
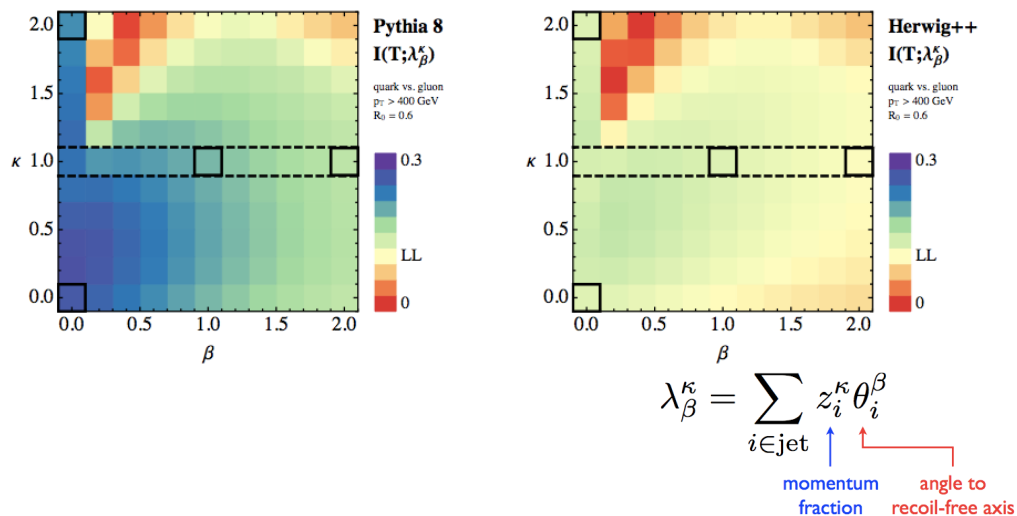
Differential (event-by-event) measurements may allow glimpse at "QCD Rutherford scattering" off QGP constituents

Jet structure in pp and PbPb

Liliana Apolinario
Lisbon HI jet workshop



Jesse Thaler, Boost 2014



Dani Pablos
Lisbon HI jet workshop

Jet structure variables sensitive to
(in-medium) shower evolution

Critical effort in pp highest sensitivity searches
(q/g and boosted object discrimination)

Stability vs pp pileup is major issue

Convergence of AA and pp needs

Summary

- Jets probe fundamental features of QGP
 - We reached an era of quantitative comparison of data and theory
 - We have learned how to construct jet-based observables in heavy-ion collisions
- Jets can solve fundamental questions in hot QCD
 - Precise measurement of transport properties
 - Further characterization of QGP liquid nature
 - Understanding the emergence of QGP nature from the underlying degrees of freedom
- High precision studies ahead at RHIC and LHC
 - Upgraded facilities, upgraded and new experiments
 - Close experiment/theory collaboration
 - Close collaboration with pp

