Jets at RHIC and LHC today and tomorrow

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MIT

QCD Town Meeting
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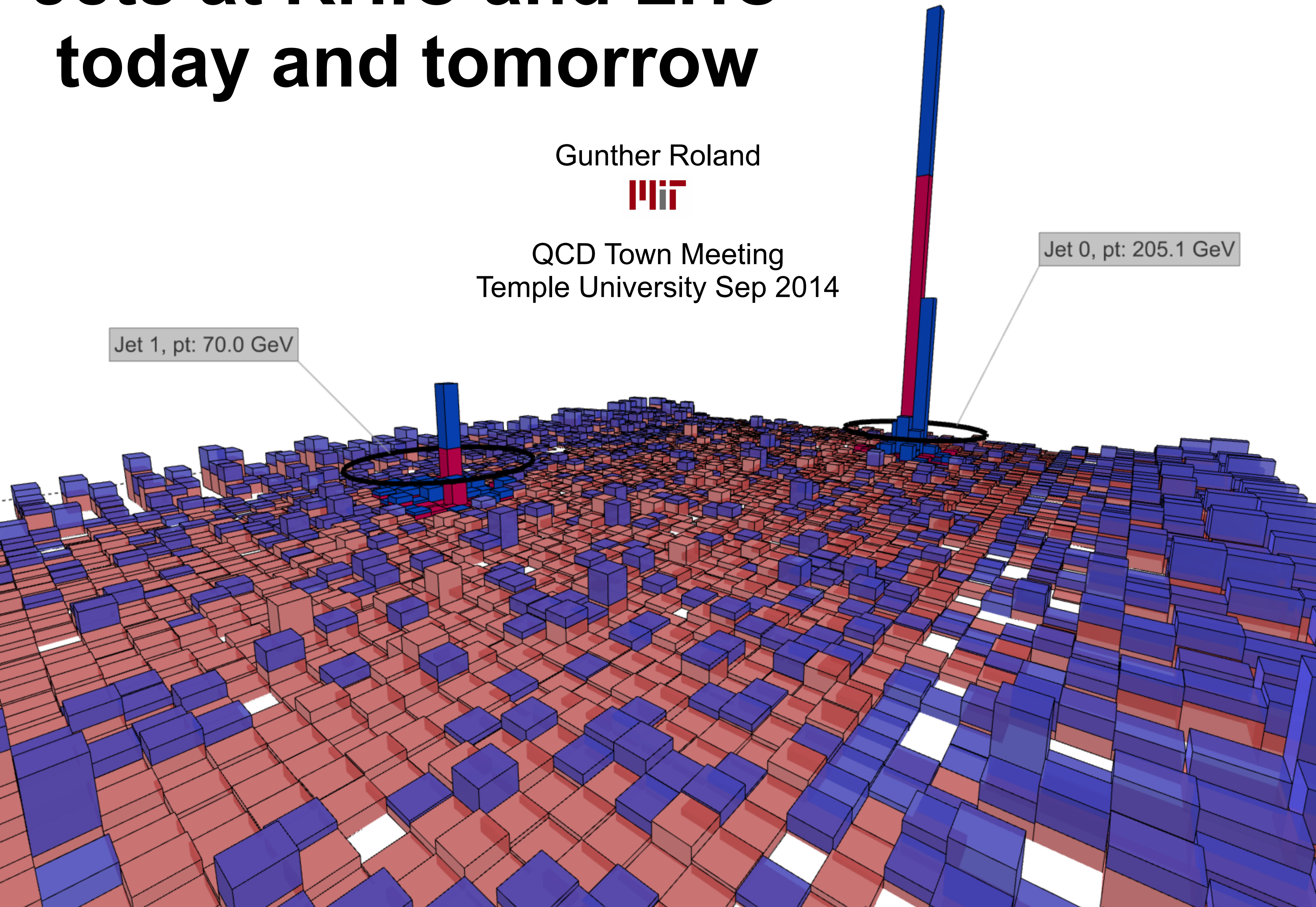
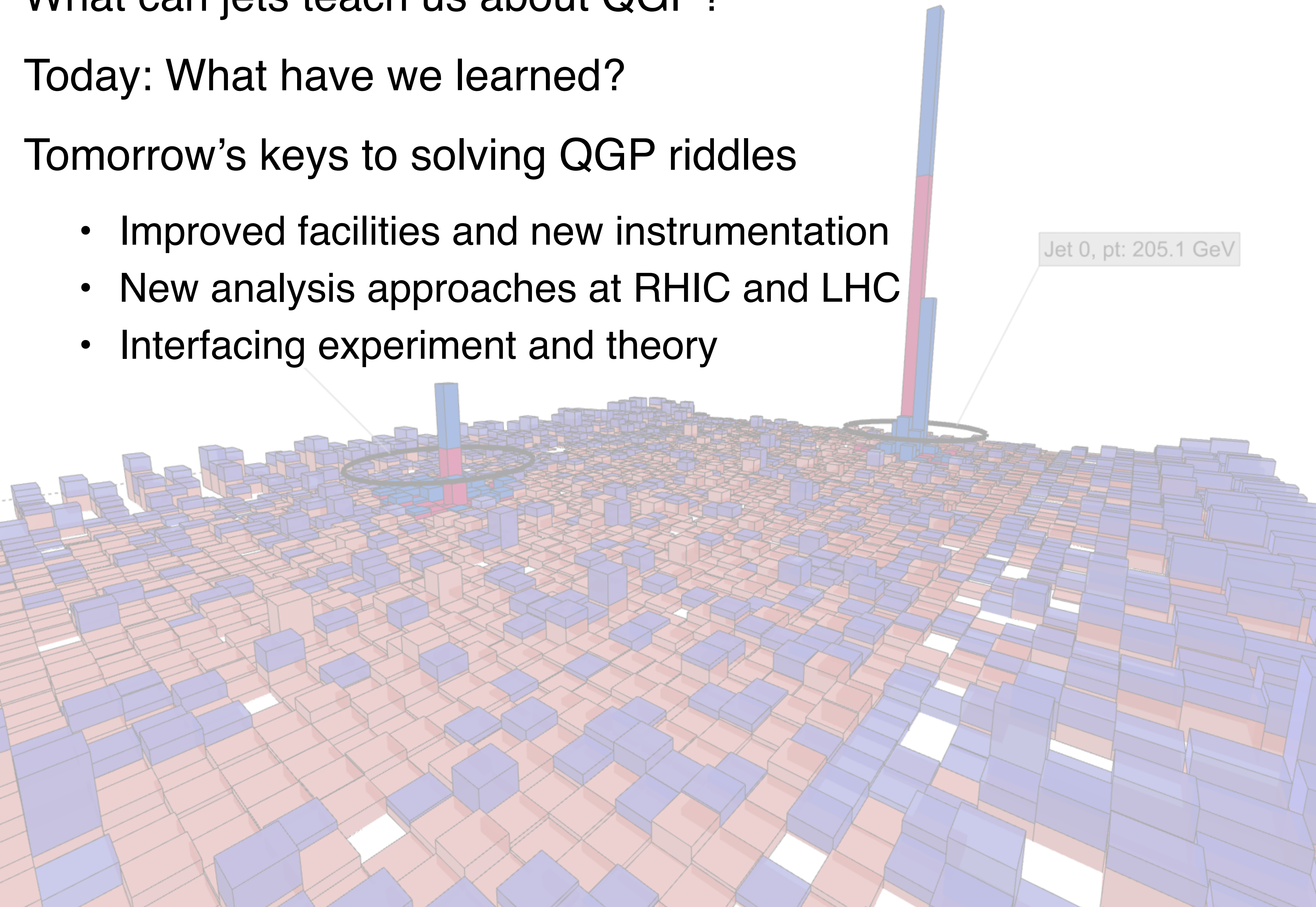


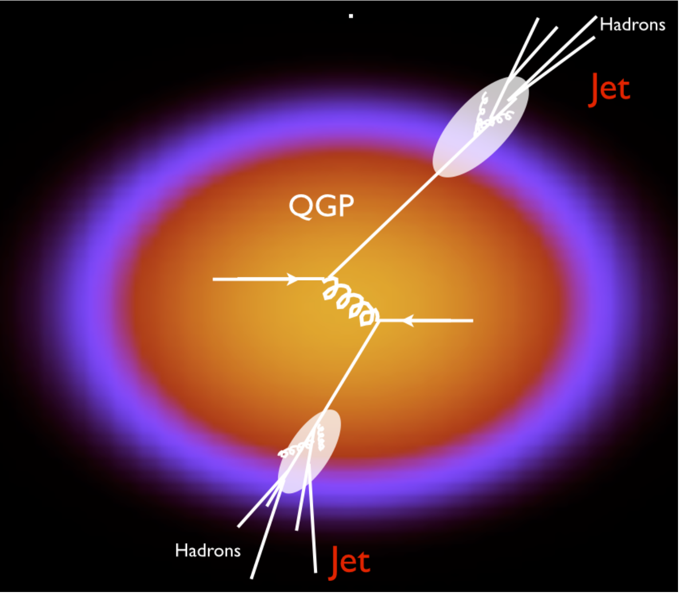
What can jets teach us about QGP?

Today: What have we learned?

Tomorrow’s keys to solving QGP riddles

- Improved facilities and new instrumentation
- New analysis approaches at RHIC and LHC
- Interfacing experiment and theory





Jets as tools to ***characterize*** QGP

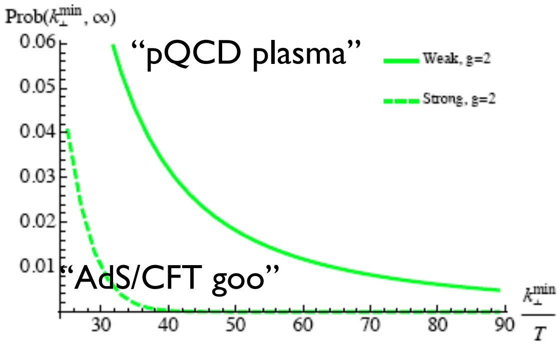
Medium effects on jets allow extraction of QGP transport coefficients:

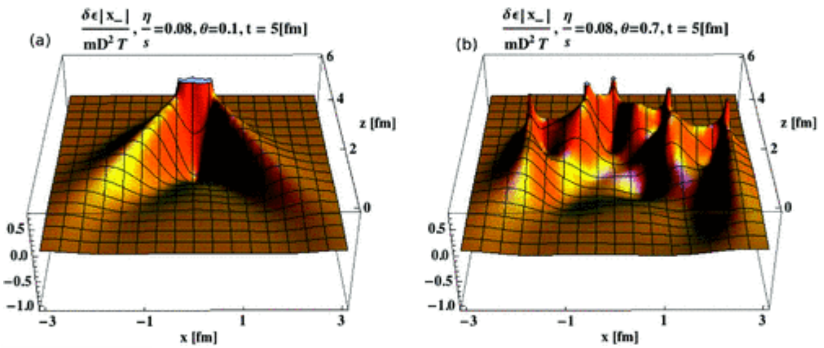
- $\hat{q}$: transverse momentum diffusion (*radiative energy loss*)
- $\hat{e}$: longitudinal drag (*collisional energy loss*)

Jets as tools to ***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

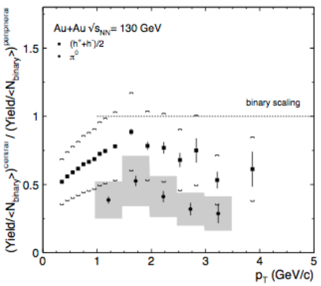




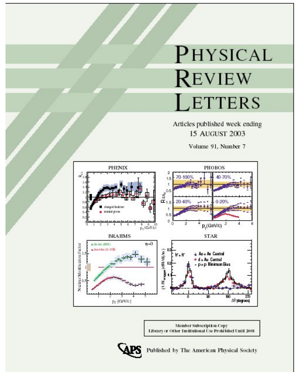
Jets as tools to ***manipulate*** QGP

How does QGP respond to local energy deposition by jets?

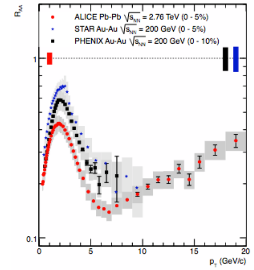
High p_T suppression in AuAu



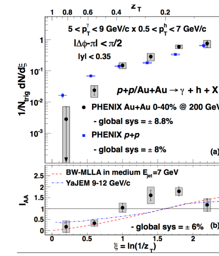
No high p_T suppression in dAu



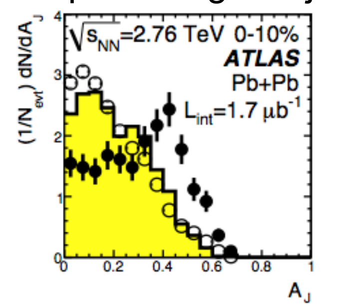
High p_T suppression at LHC

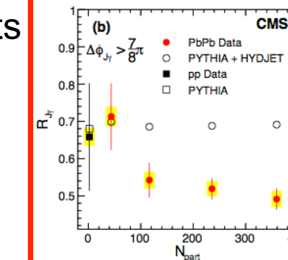


Photon-hadron correlations



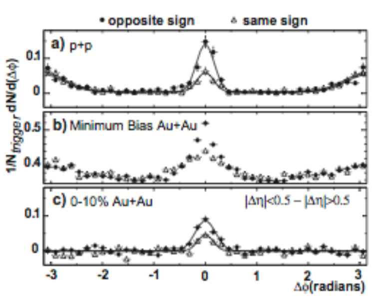
Jet quenching in dijets



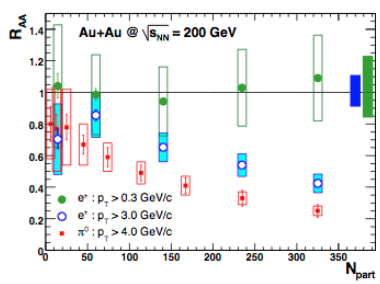


Photon-jet correlations

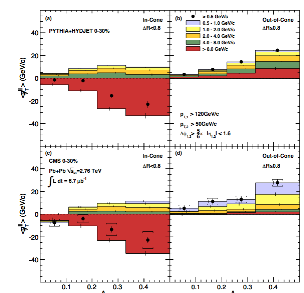
2000 2004 2008 2012



Disappearance of away-side correlations in AuAu

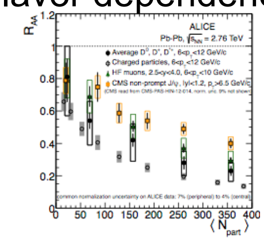


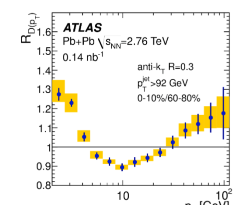
Suppression of heavy-flavors using single electrons



Observation of low p_T, large angle radiation

Flavor dependence

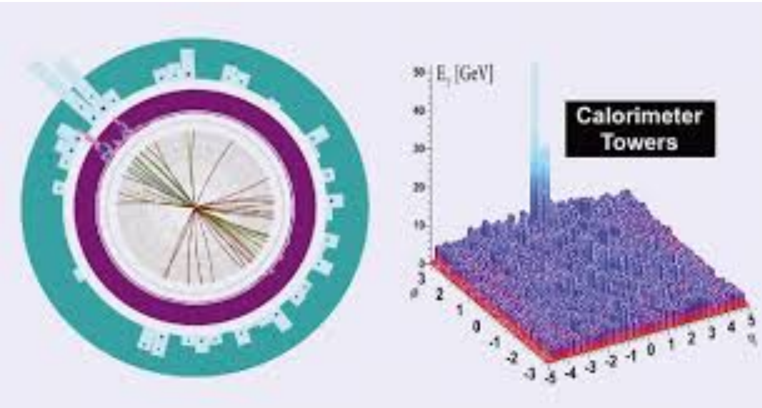




Fragmentation functions

Today

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
- JEC using pp calibration and MC correction factors

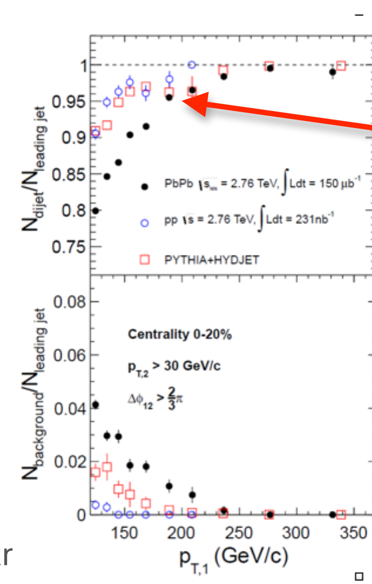
Achieved good experimental control

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

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

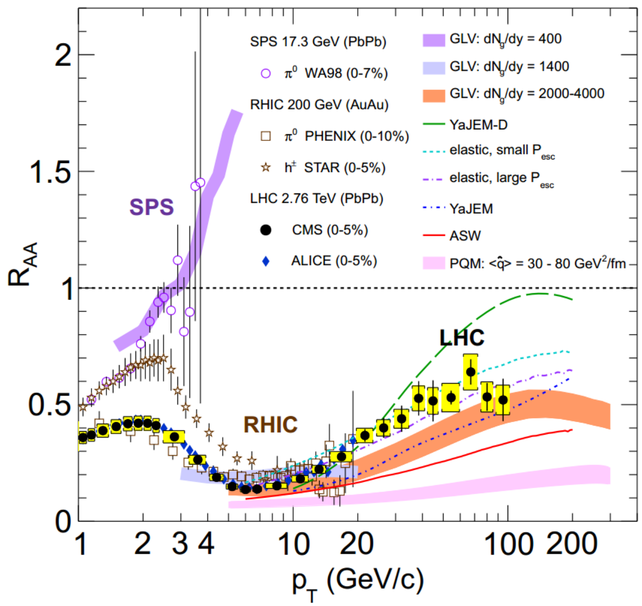
Complementary approaches to reconstruction biases

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



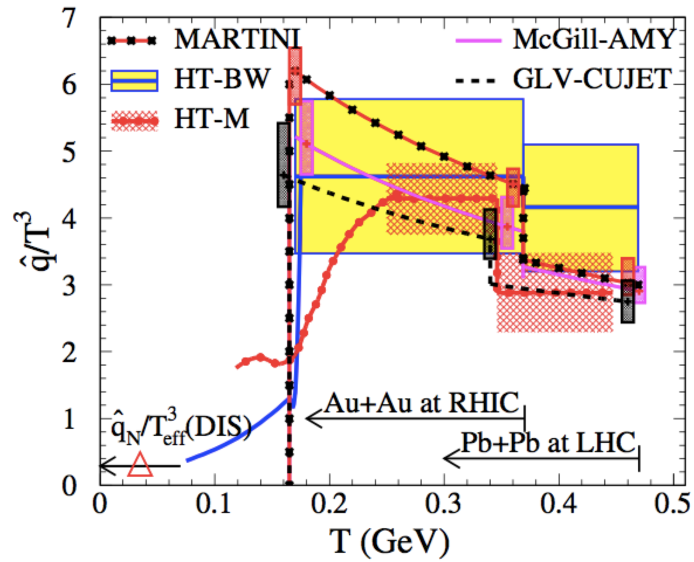
For sufficiently high trigger p_T, all away-side jets are found

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 50% uncertainty

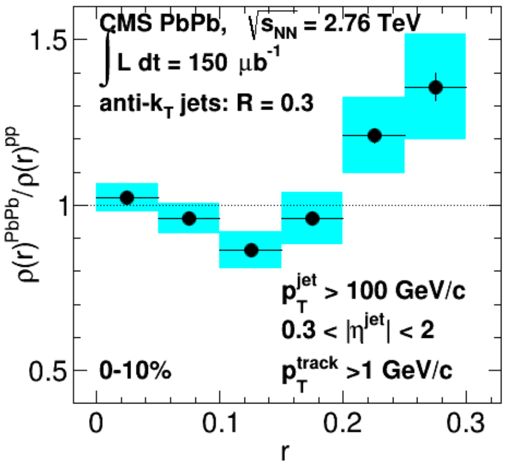
Combined RHIC and LHC data:

- Test model consistency
- First hint of temperature dependence

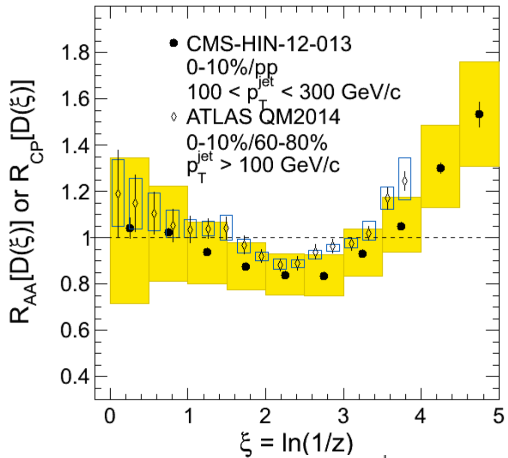
Quantitative extraction of $\hat{e}$ awaits more precise heavy flavor data

We can observe medium modifications of jet momentum and angular structure

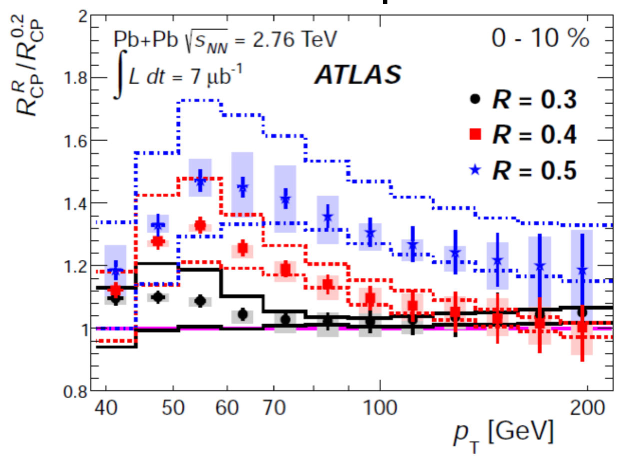
Jet shapes

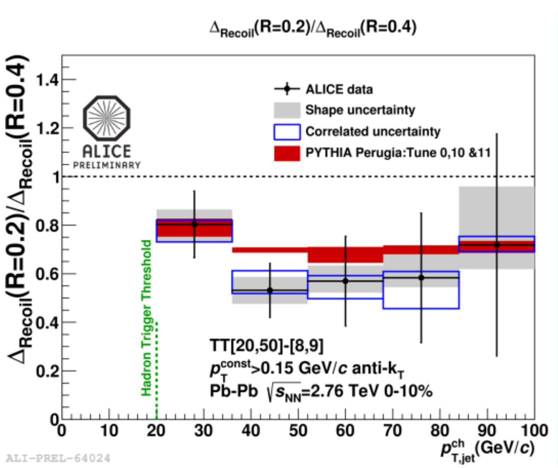


Fragmentation functions

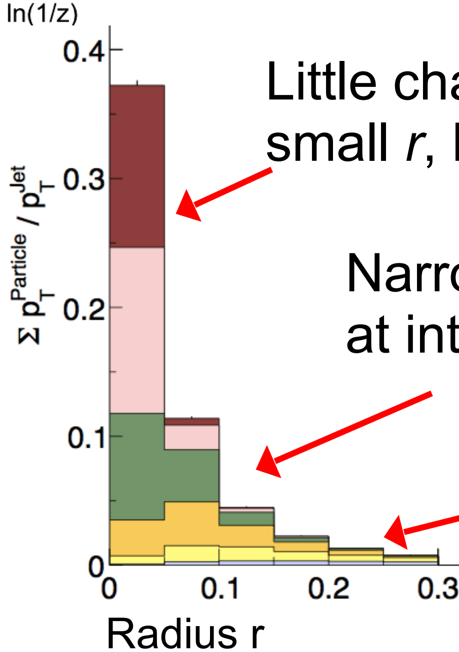


R_{AA} radius dependence





Δ_{Recoil} radius dependence



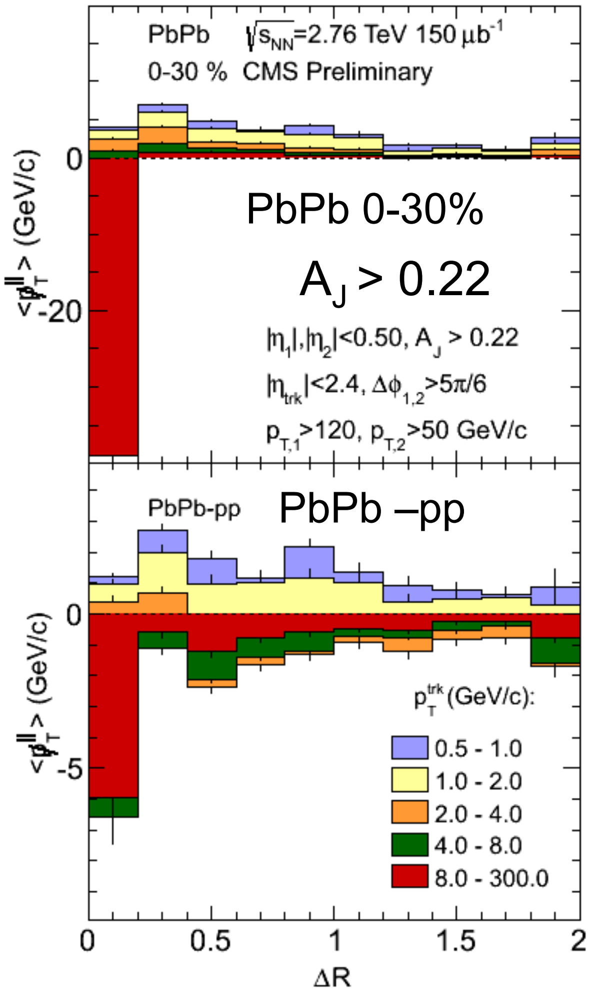
Little change at small *r*, high p_T

Narrowing/depletion at intermediate *r*, p_T

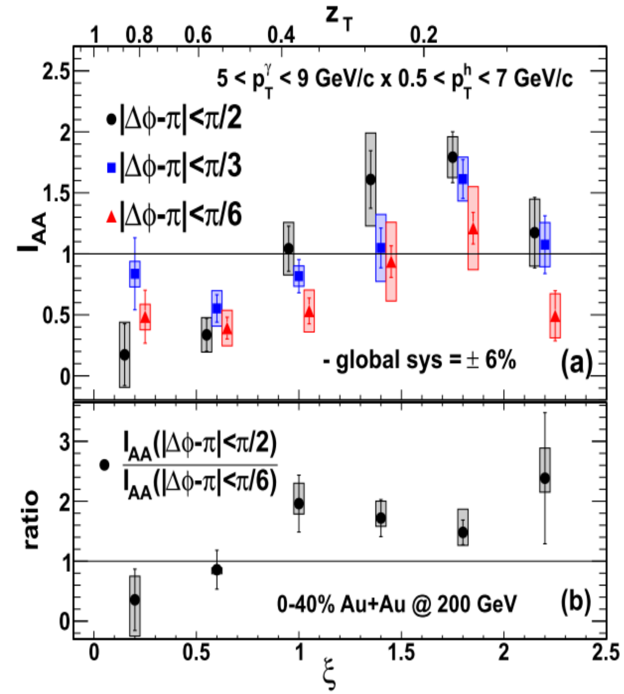
Broadening/excess at large *r*, low p_T

(~2% of jet energy)

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



CMS dijet "missing p_T"



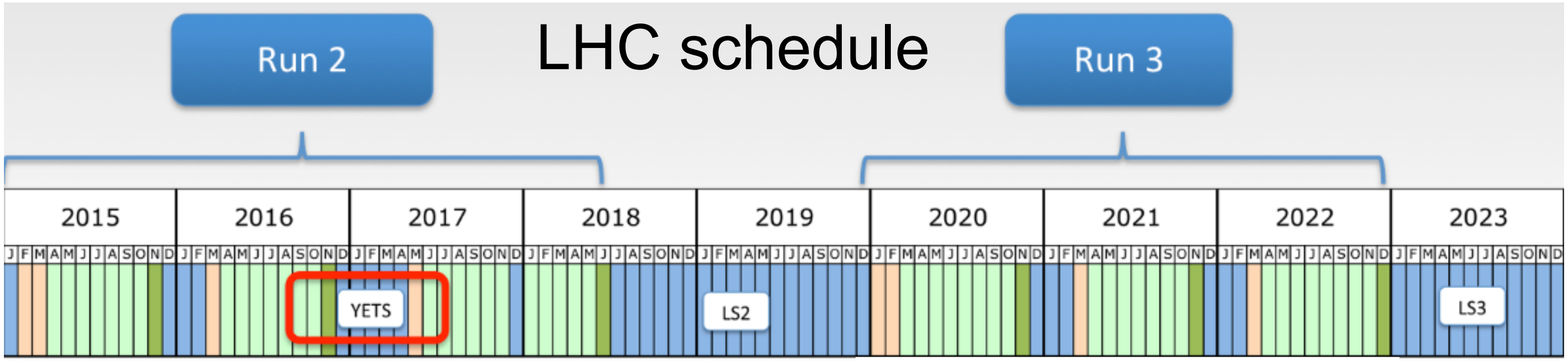
PHENIX
γ-hadron
correlations

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")?

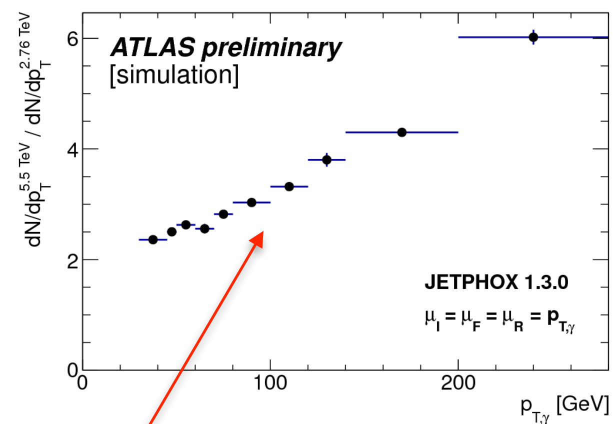
Tomorrow

Future program enabled by accelerator development



	$\sqrt{s}$ = 5TeV	$\sqrt{s}$ = 5.5TeV
PbPb	Collision rate ≈ 20kHz	Collision rate ≈ 50kHz
	L_{int} ≈ 3/nb	L_{int} ≈ 10/nb (run 2+3)

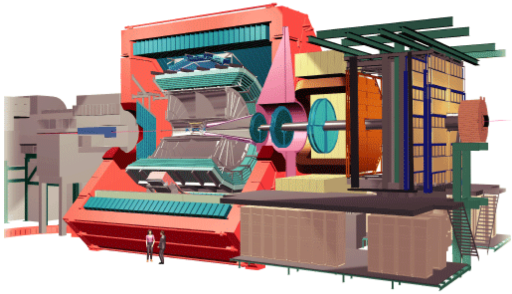
	2010–2011 2.76 TeV 160 μb^{-1}	HL-LHC 5.5 TeV 10 nb^{-1}
Jet p_T reach (GeV/c)	$\sim$ 300	$\sim$ 1000
Dijet ($p_{T,1} > 120$ GeV/c)	50k	$\sim$ 10M
b-jet ($p_T > 120$ GeV/c)	$\sim$ 500	$\sim$ 140k
Isolated γ ($p_T^\gamma > 60$ GeV/c)	$\sim$ 1.5k	$\sim$ 300k
Isolated γ ($p_T^\gamma > 120$ GeV/c)	–	$\sim$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



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

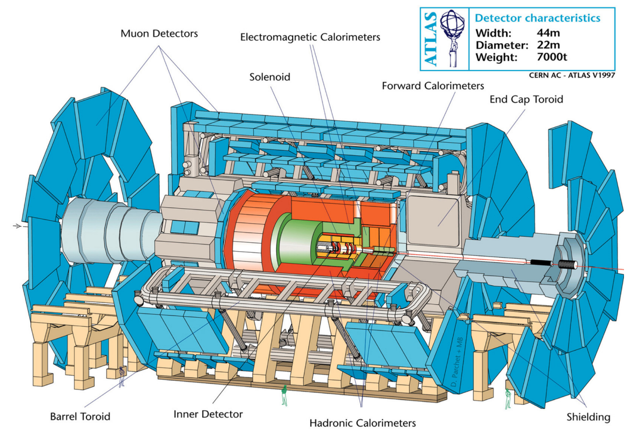
Major upgrades to all LHC experiments

ALICE



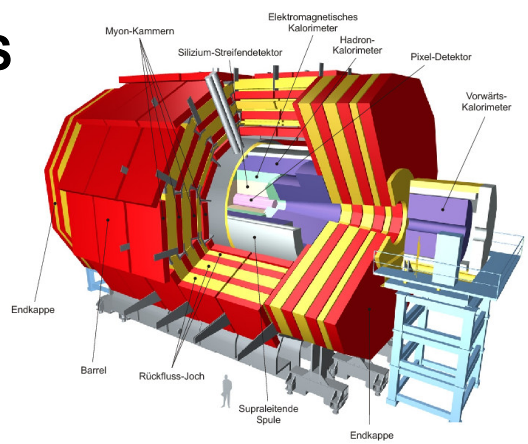
Expanded calorimetry
New inner tracker
Faster TPC readout
Improved data acquisition rate

ATLAS



Improved trigger system
New/extended inner tracker

CMS



Improved trigger system
New/extended inner tracker

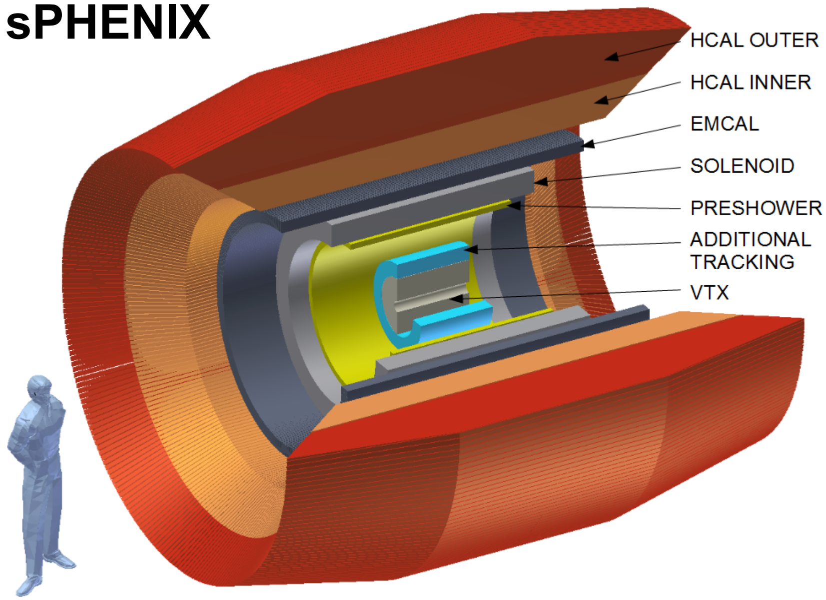
A state-of-the-art jet detector at RHIC

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



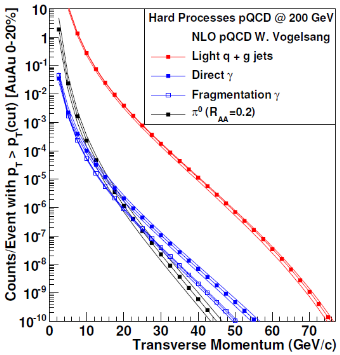
Key capabilities

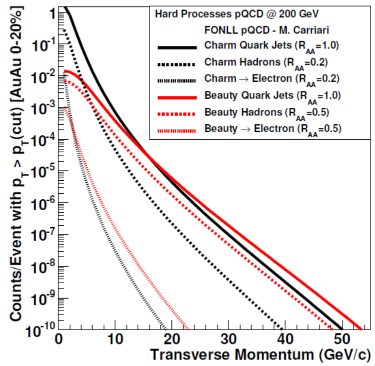
- Full calorimetry
- Tracking
- Rate capability

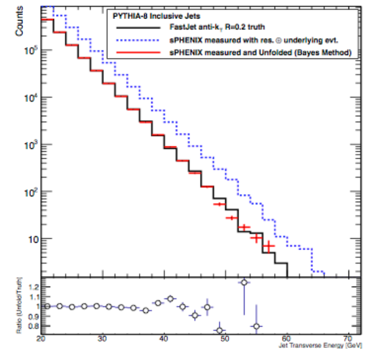
to exploit luminosity (>50/nb) and $\sqrt{s}$ range (62-200GeV) at RHIC

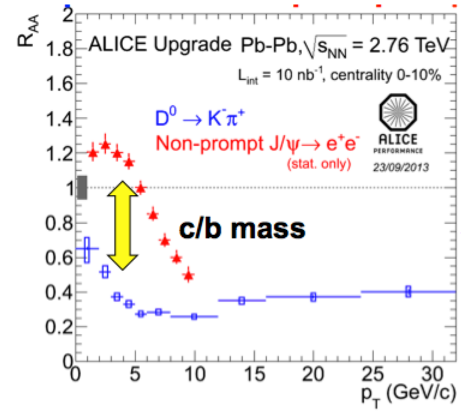
RHIC integrated luminosity up to x10 higher than LHC

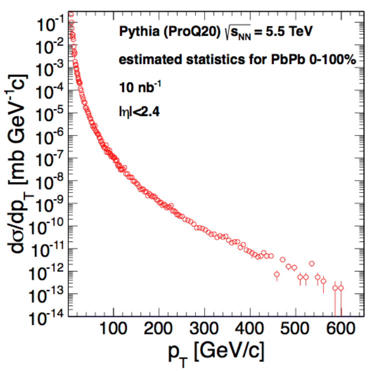
Kinematic reach at RHIC and LHC

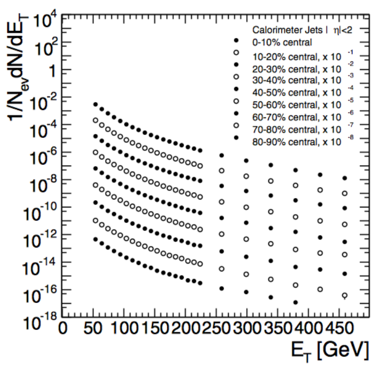


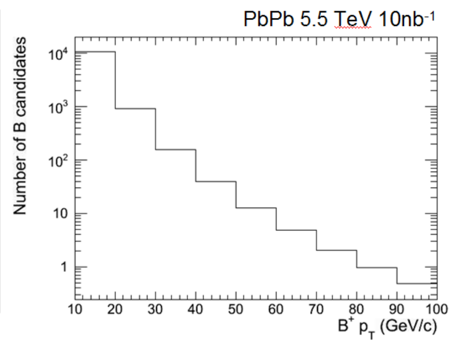




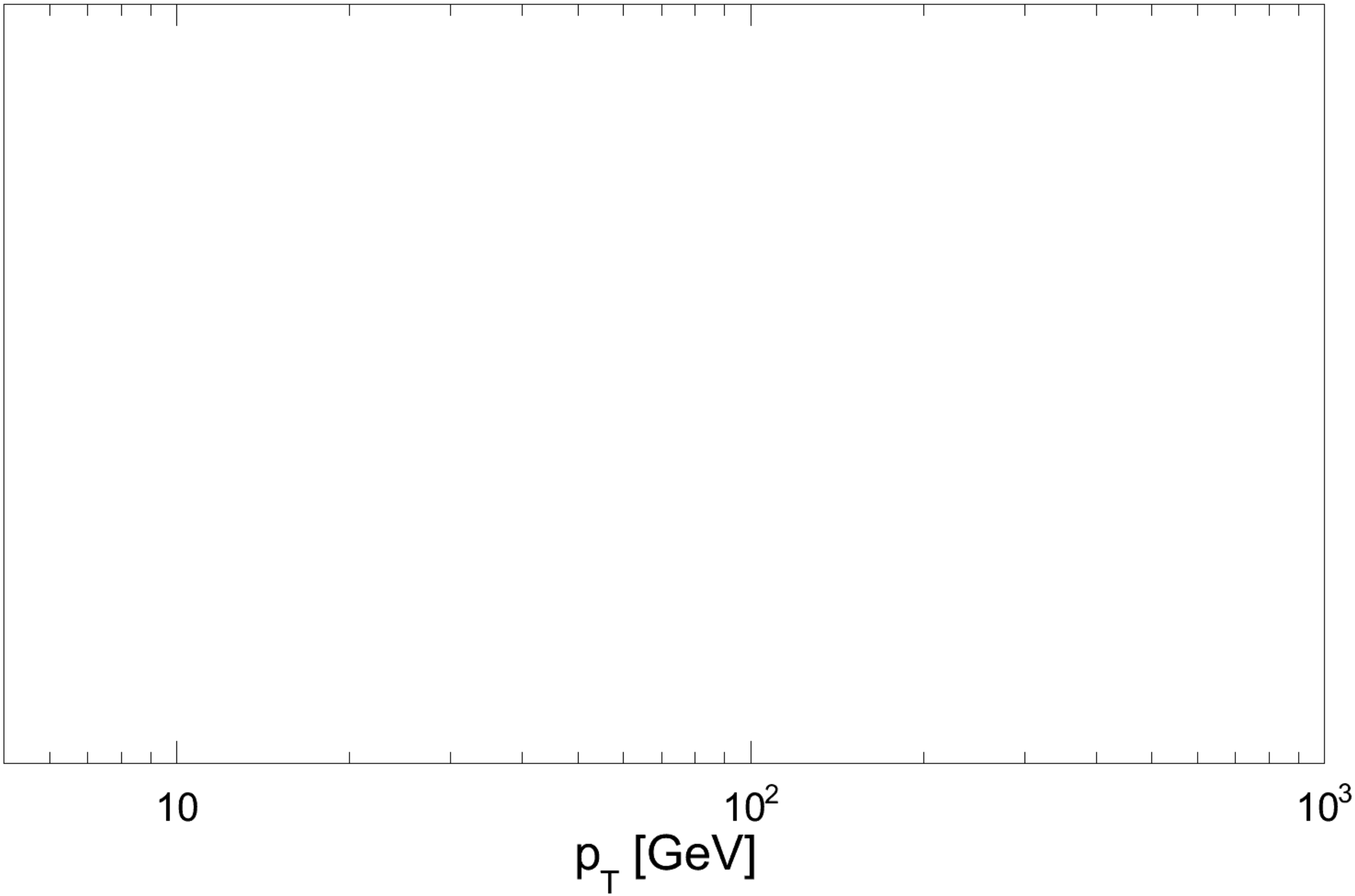








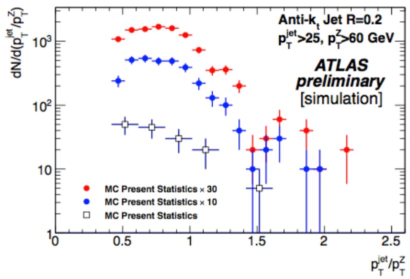
Kinematic reach: Today and tomorrow



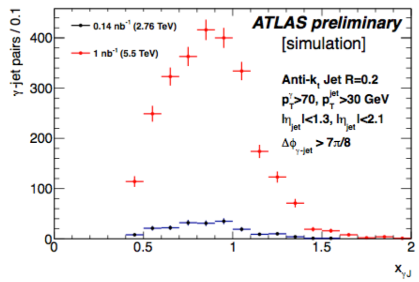
From Z^0 tags to B tags, and from LHC to RHIC

LHC

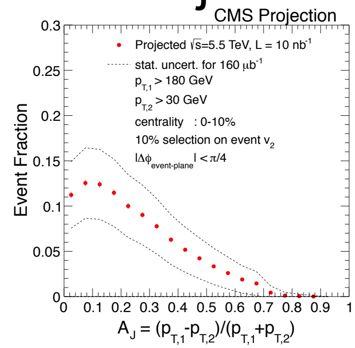
Z^0+jet



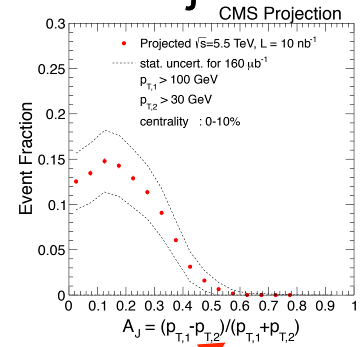
γ+jet



dijet



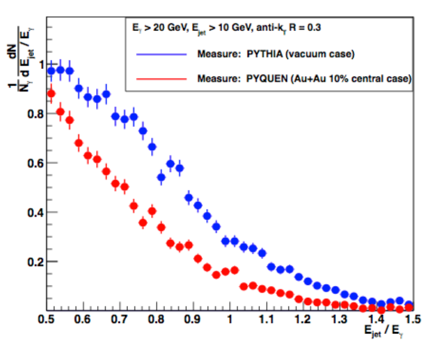
b-jet



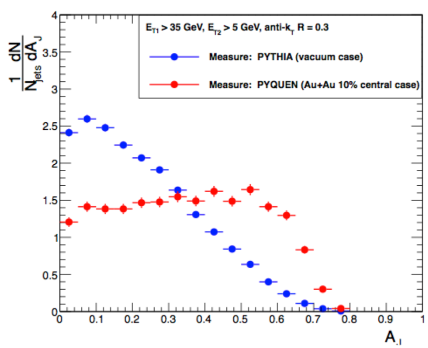
“Calibration”

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

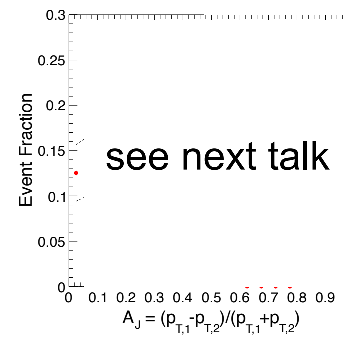
RHIC



γ+jet

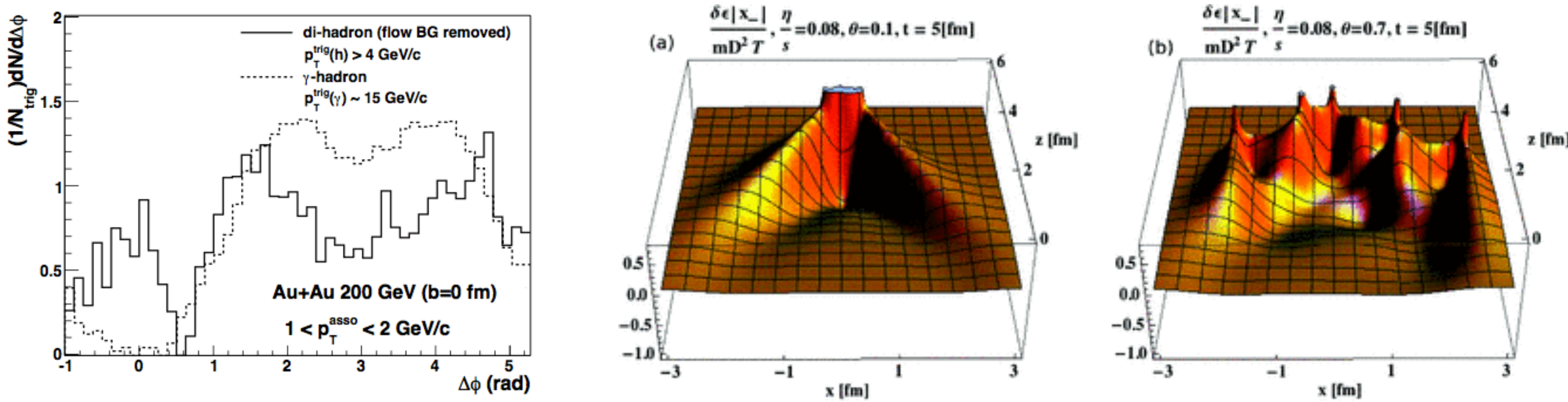


dijet



b-jet

Energy flow and medium response



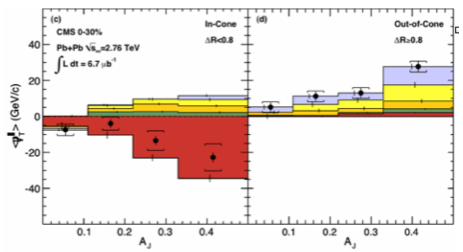
Do we have a medium, if there's no medium response?

Challenge:

- 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?

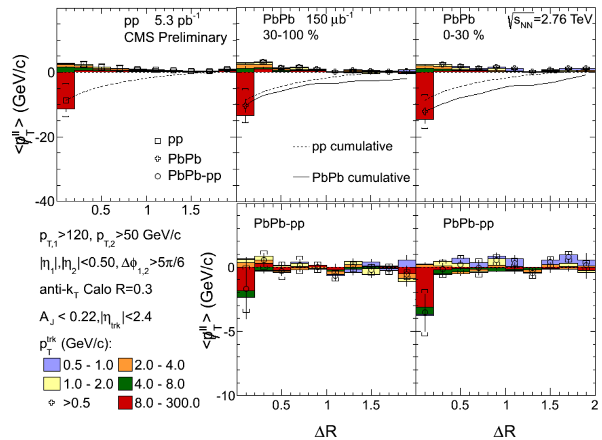
2011

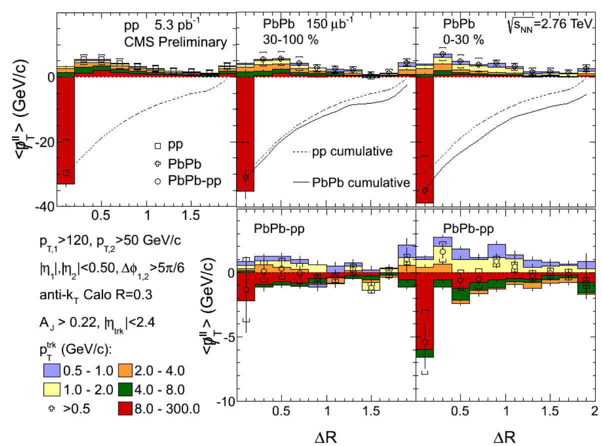
- 0.015/nb
- 4 months analysis time
- in-cone vs out-of-cone “missing p_T” for dijets



2014

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



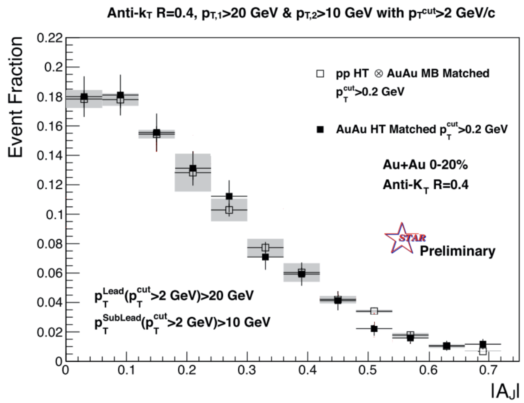


2015-2024

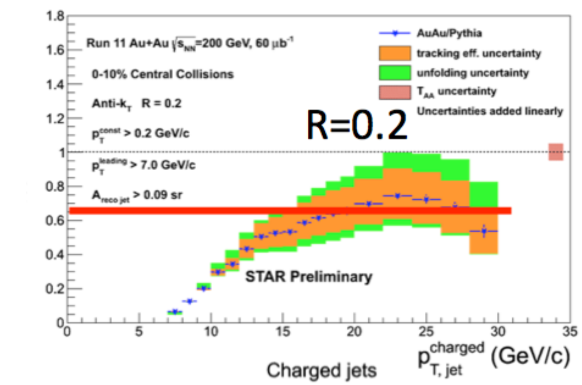
- 10/nb (LHC) 50/nb (RHIC)
- **γ+jet** (no flow correlations)
- MPT → **absolute correlated yields vs (Δη, Δφ)**
- **Differential in e-by-e energy loss**
- **Different medium** conditions at RHIC and LHC

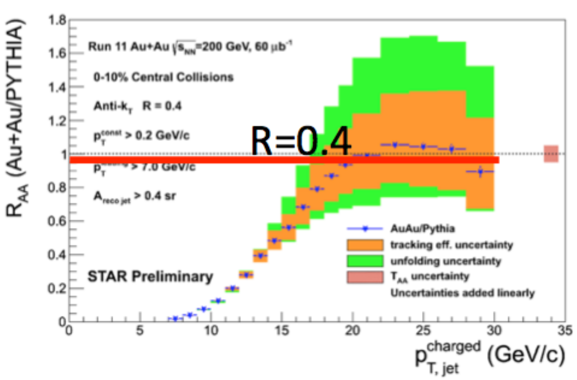
Indication of energy flow differences at RHIC vs LHC

RHIC (STAR)



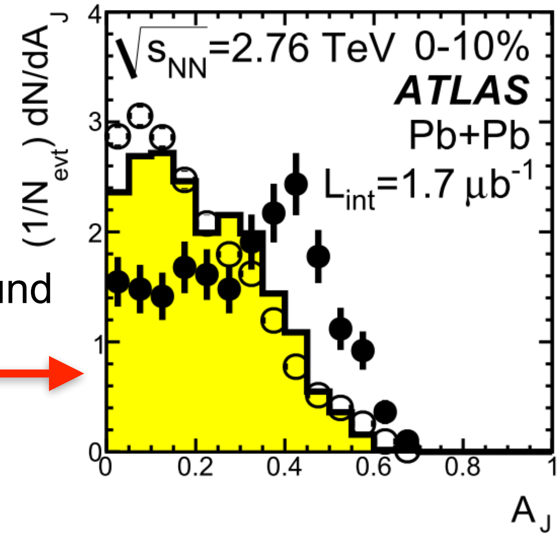
Jets balanced when including $p_T > 0.2$GeV



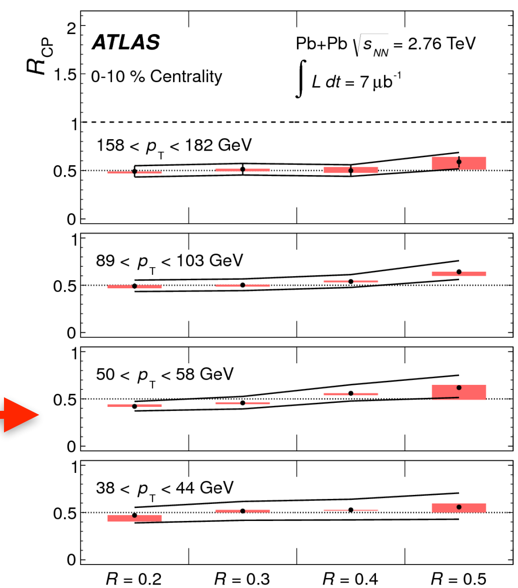


Strong radius dependence of jet RAA

LHC (ALICE, ATLAS, CMS)

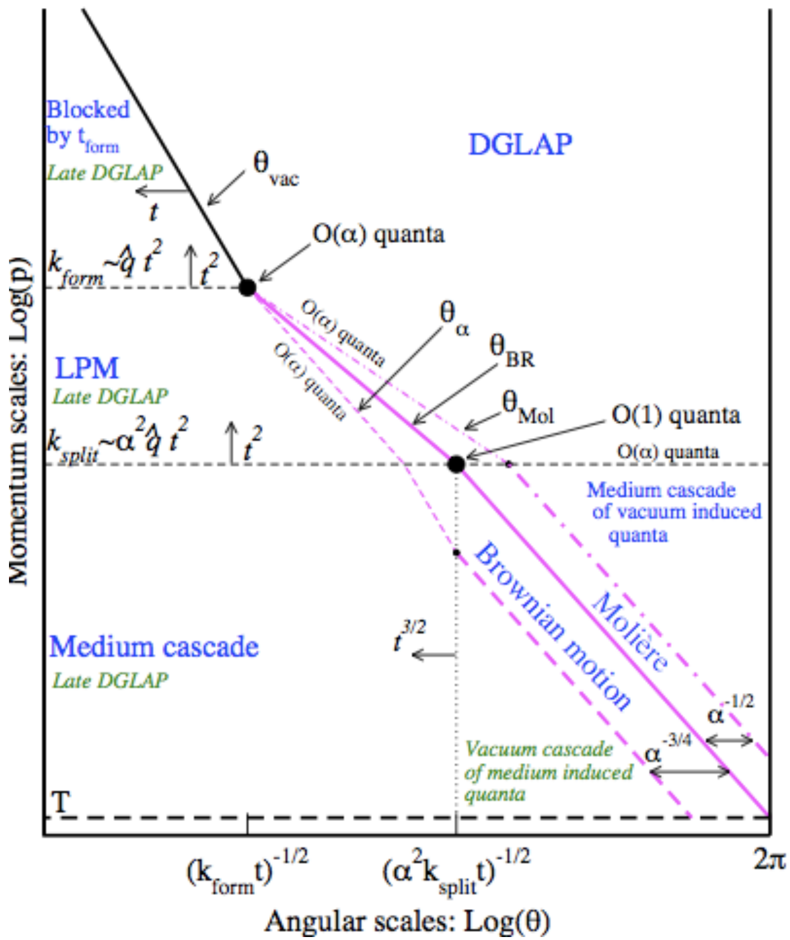


Energy balance found outside of jet cone

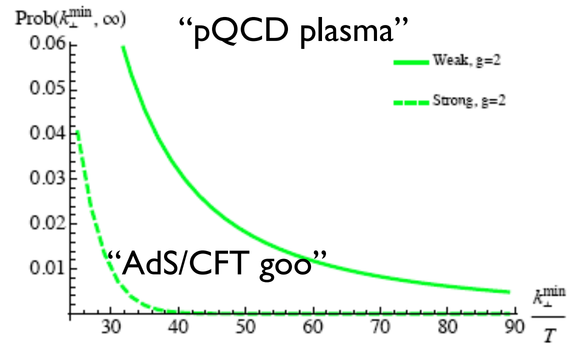


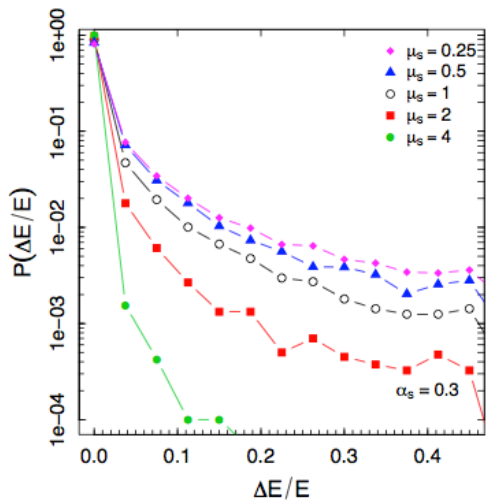
Weak radius dependence of jet RAA

Jet measurements as QGP microscope



Kurkela, Wiedemann, arXiv:1407.0293





Detailed jet studies, in particular of intra-jet and inter-jet angular structure, may reveal microphysics of QGP

Jet structure in pp and PbPb

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
  - Close coordination of RHIC and LHC efforts