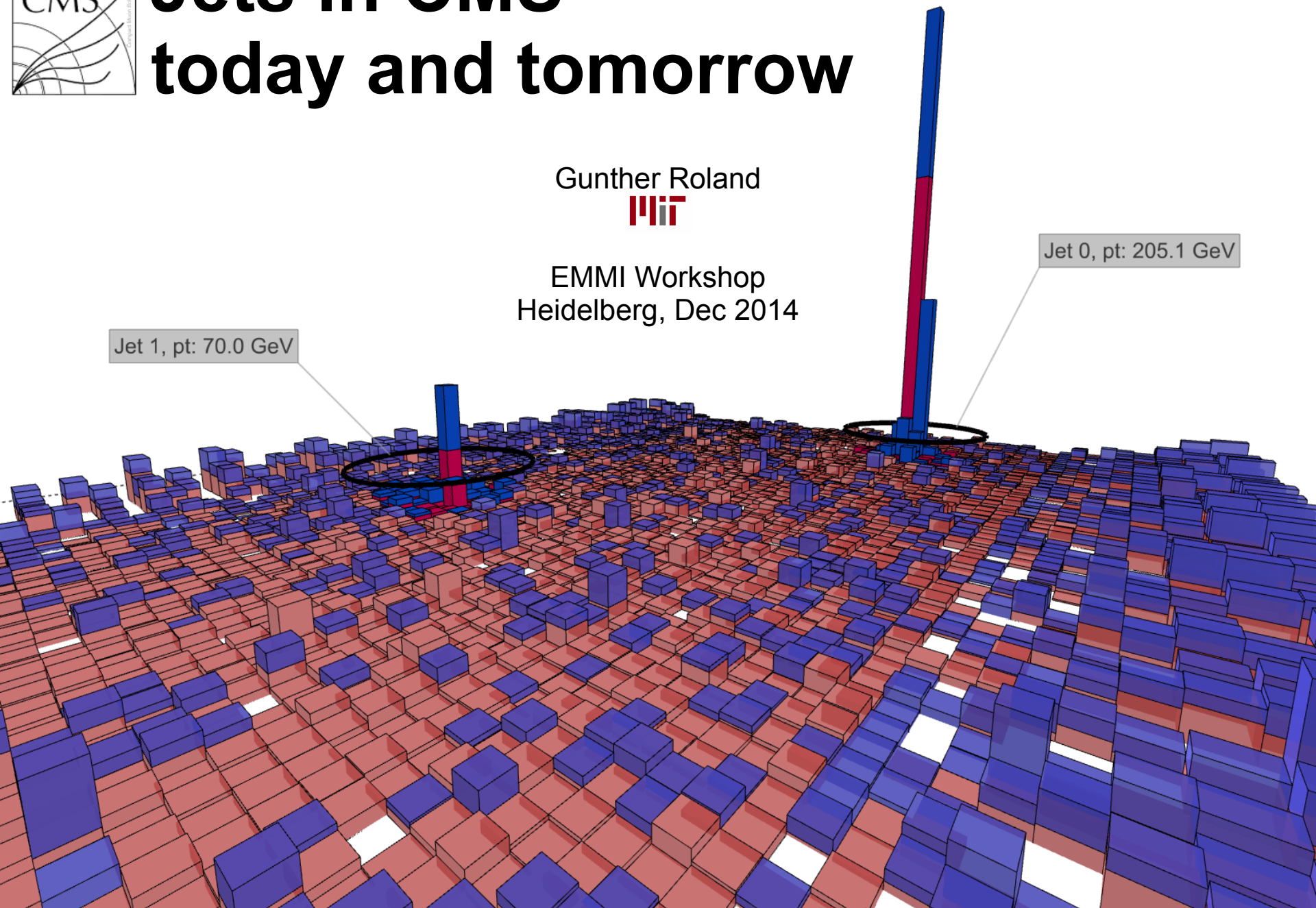
Jets in CMS today and tomorrow

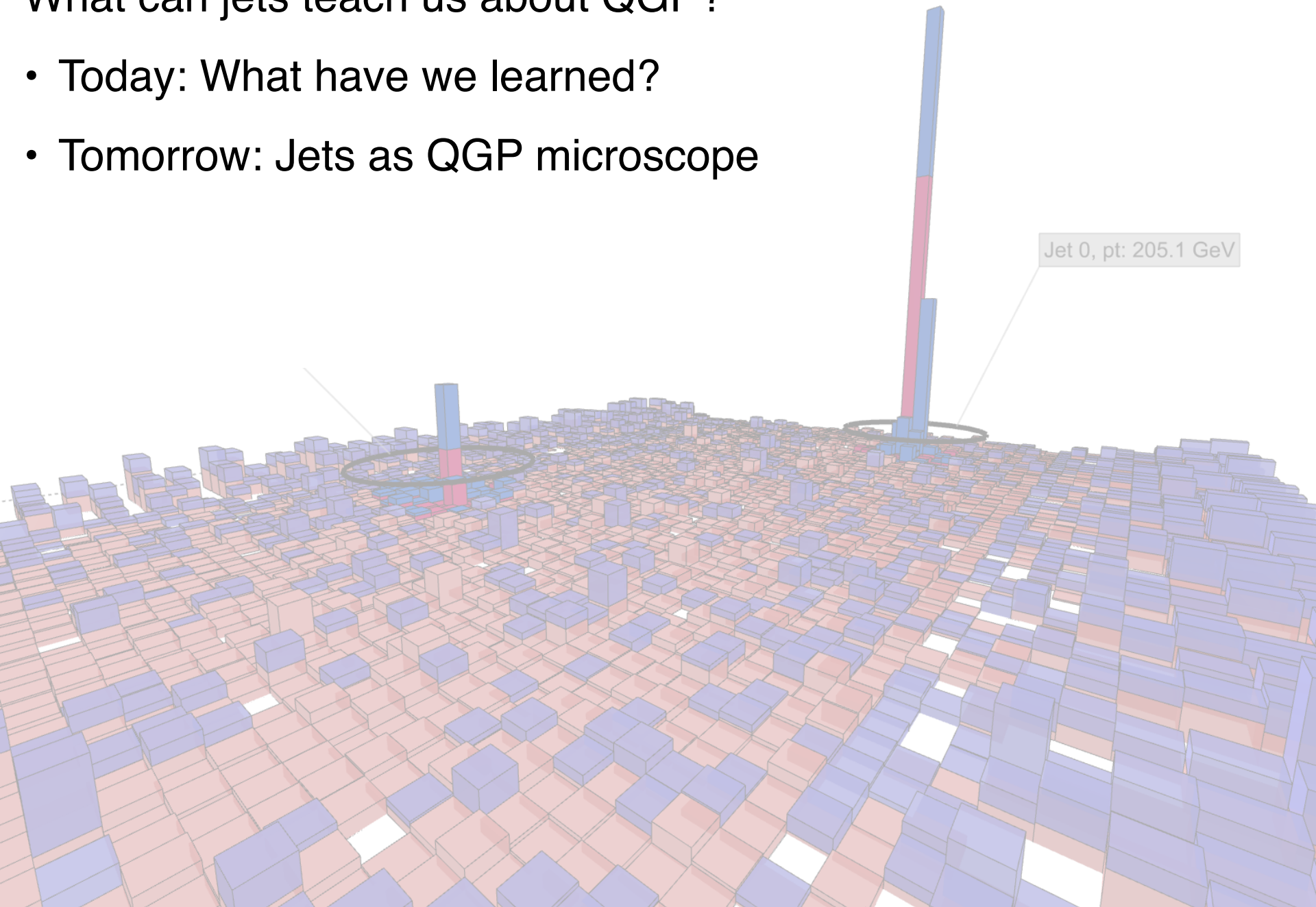
Gunther Roland
MIT

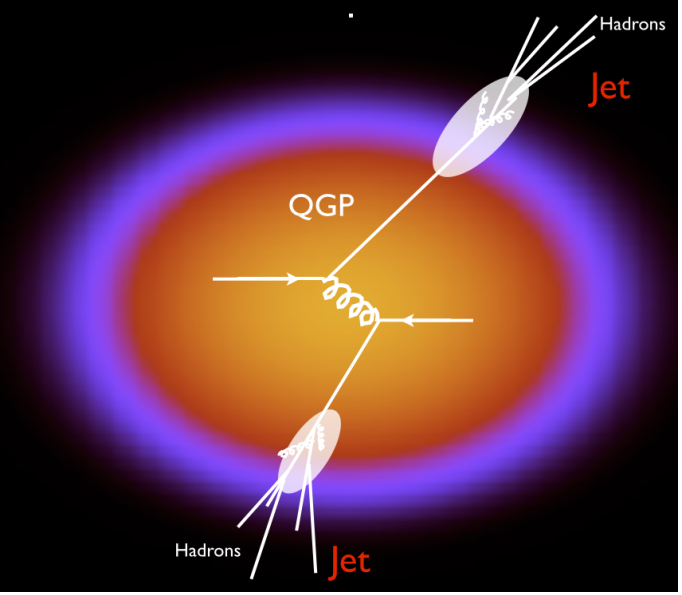
EMMI Workshop
Heidelberg, Dec 2014



What can jets teach us about QGP?

- Today: What have we learned?
- Tomorrow: Jets as QGP microscope





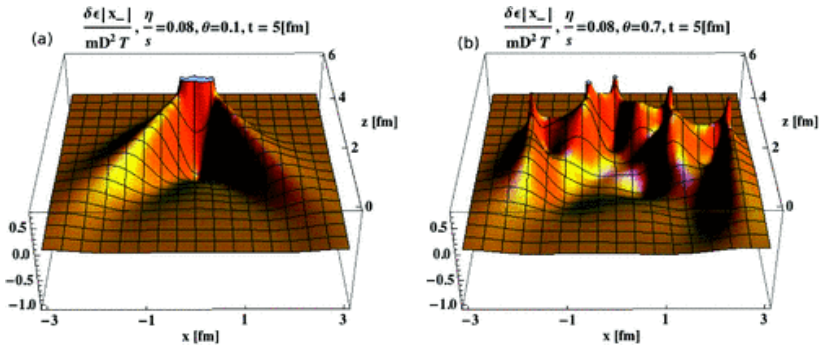
Jets as tools to ***characterize*** QGP

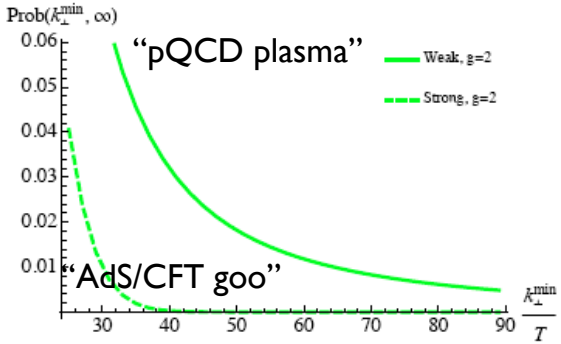
Medium effects on jets allow extraction of QGP transport coefficients:

- $\hat{q}$: 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?

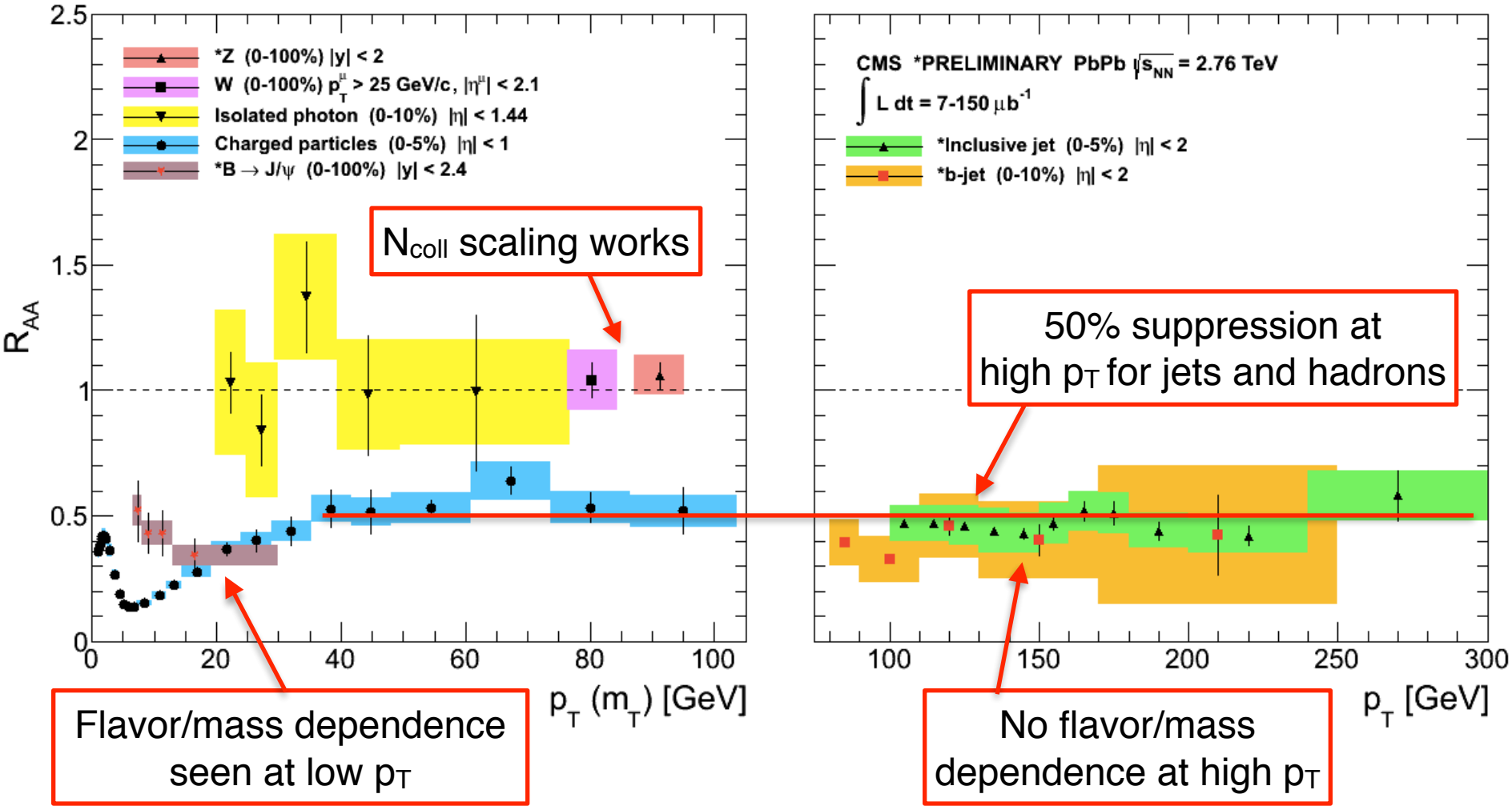
- Jets probe QGP at different (controllable) length scales
- Scattering sensitive to quasi-particle nature of the medium

Today

CMS hadron and jet R_{AA}

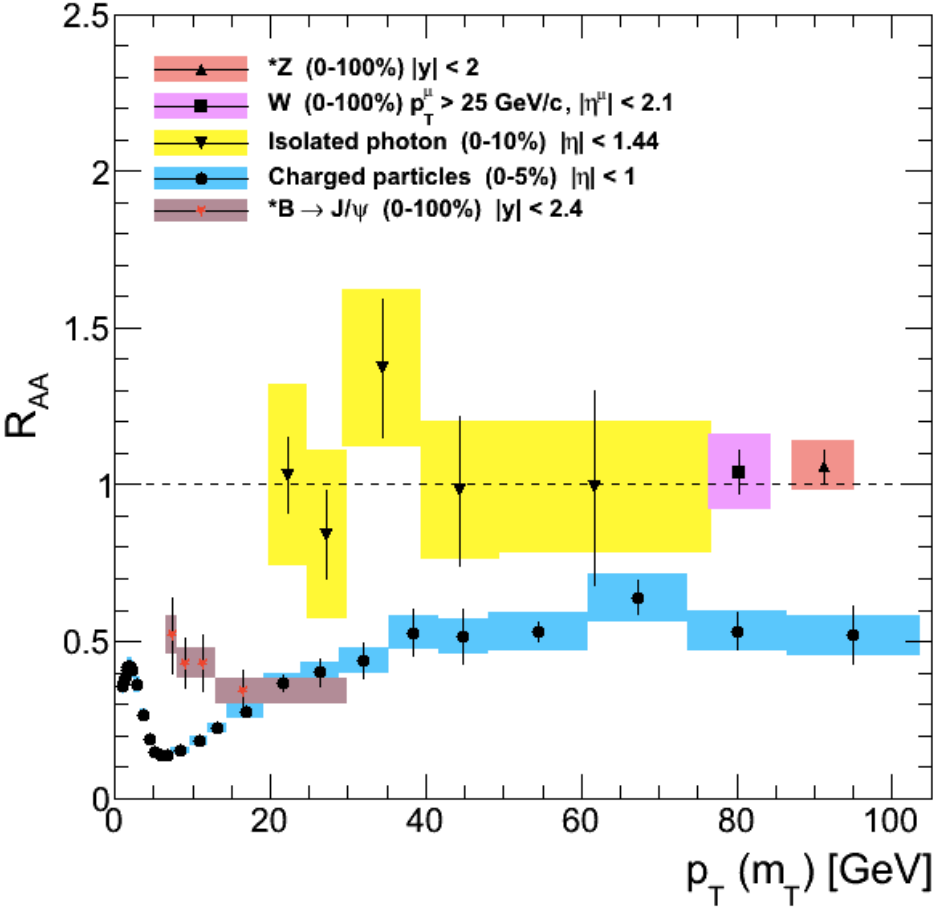
Charged Particles

Anti-k_T R=0.3 Jets

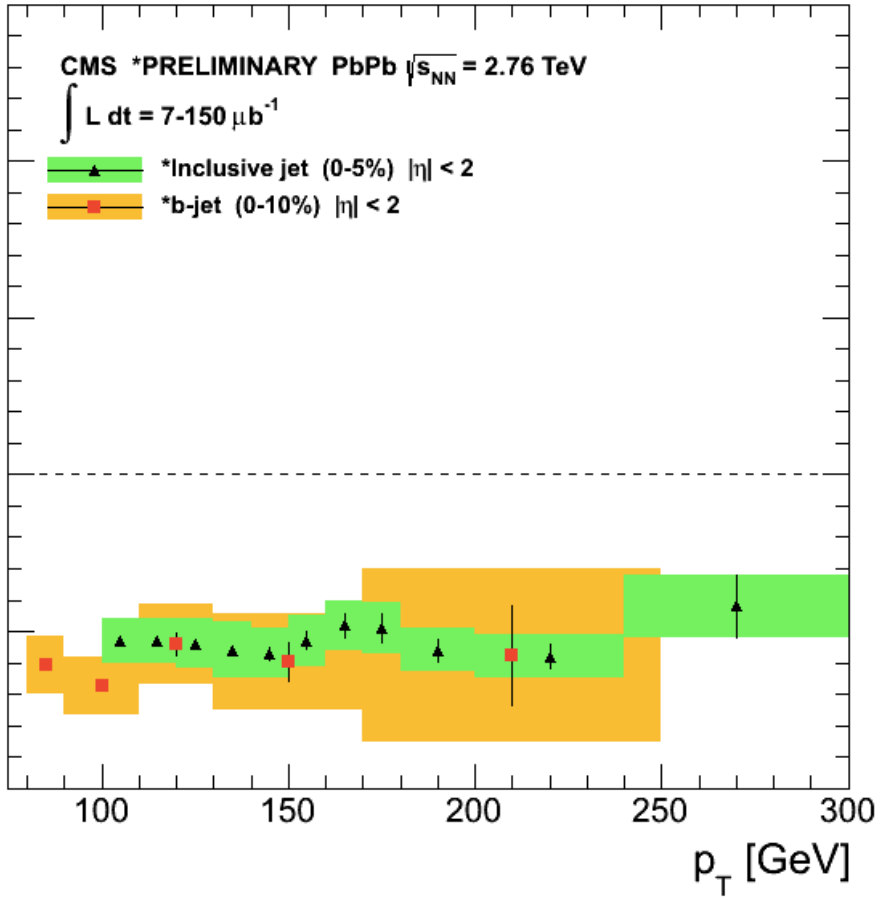


CMS hadron and jet R_{AA}

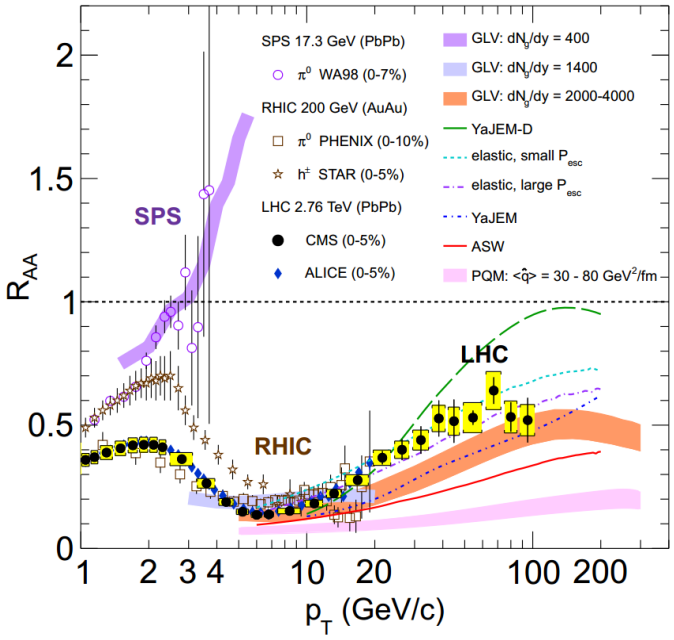
Charged Particles



Anti-k_T R=0.3 Jets

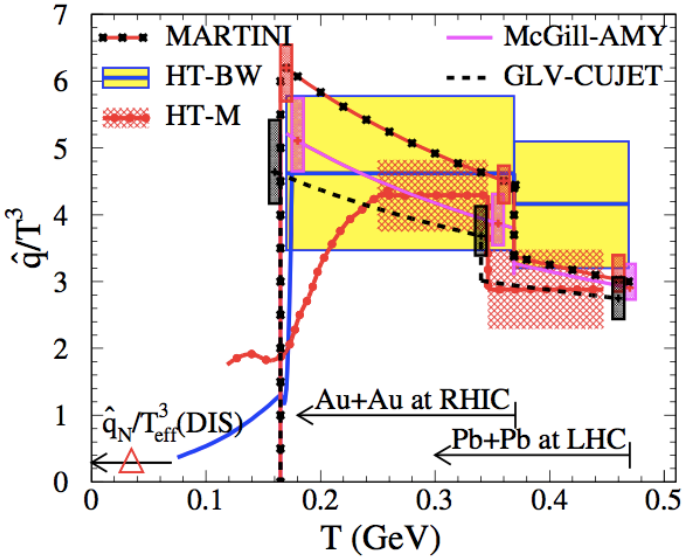


QGP transport coefficients from jet quenching measurements



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

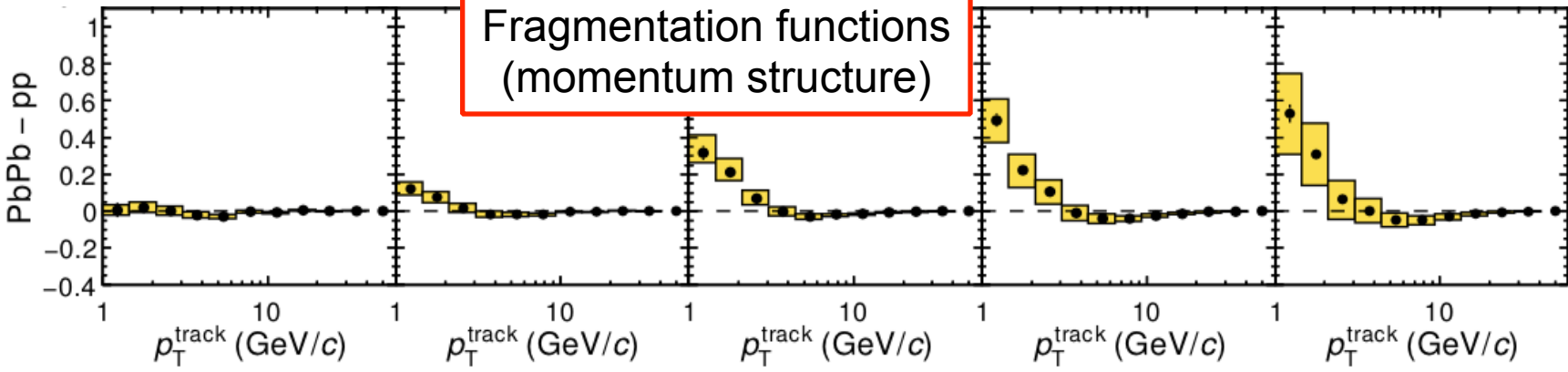
Combined RHIC and LHC data:

- Test model consistency
- First hint of temperature dependence

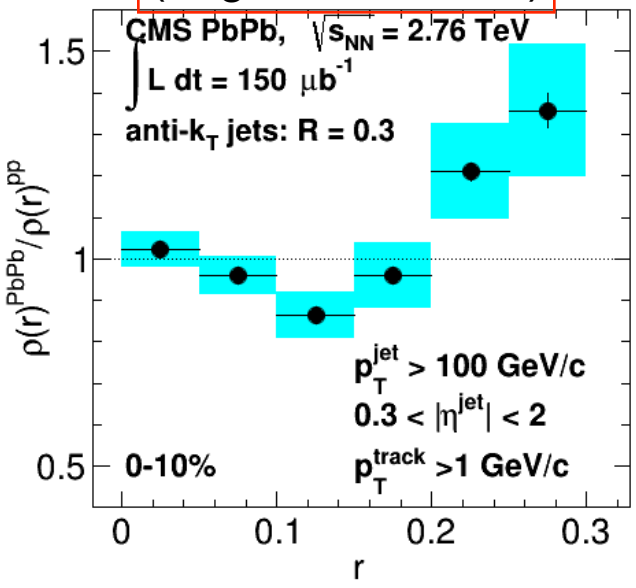
Quantitative extraction of $\hat{e}$ awaits more precise heavy flavor data

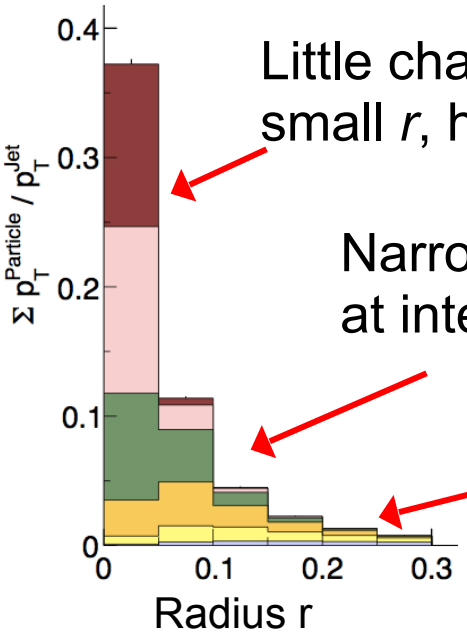
Medium modifications of jet momentum and angular structure

Fragmentation functions (momentum structure)



Jet shapes (angular structure)





Little change at small *r*, high p_T

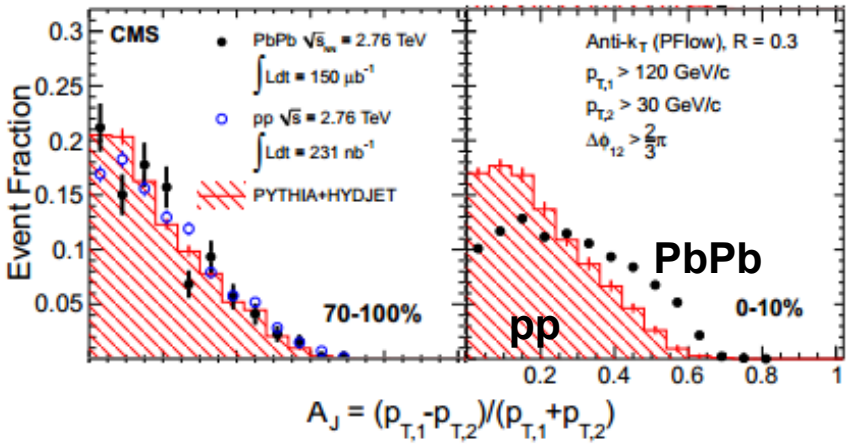
Narrowing/depletion at intermediate *r*, p_T

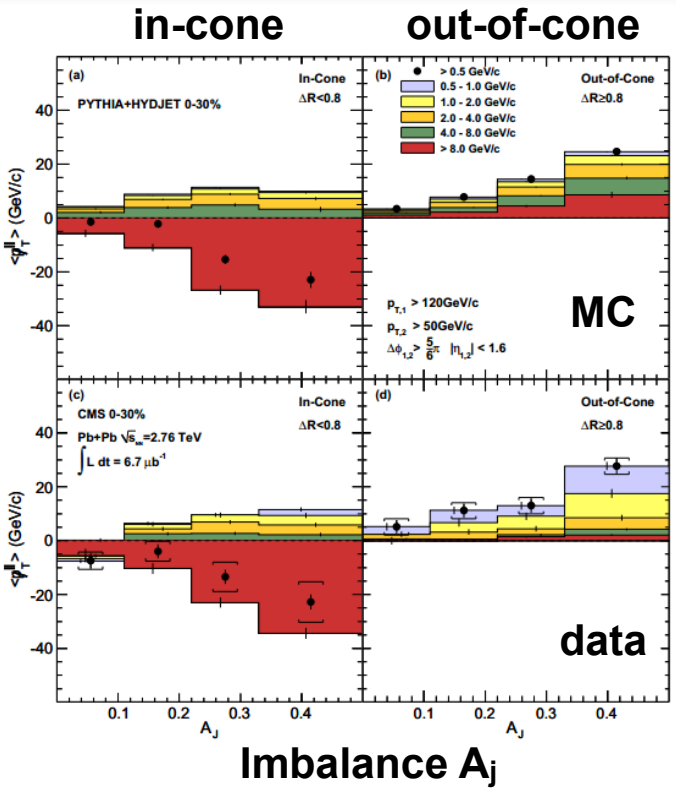
Broadening/excess at large *r*, low p_T

(~2% of jet energy)

Out-of-cone momentum flow relative to jet

PLB 712 (2012) 176



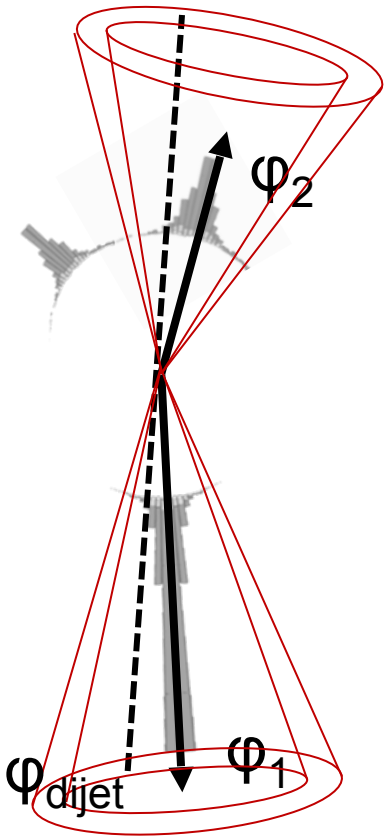


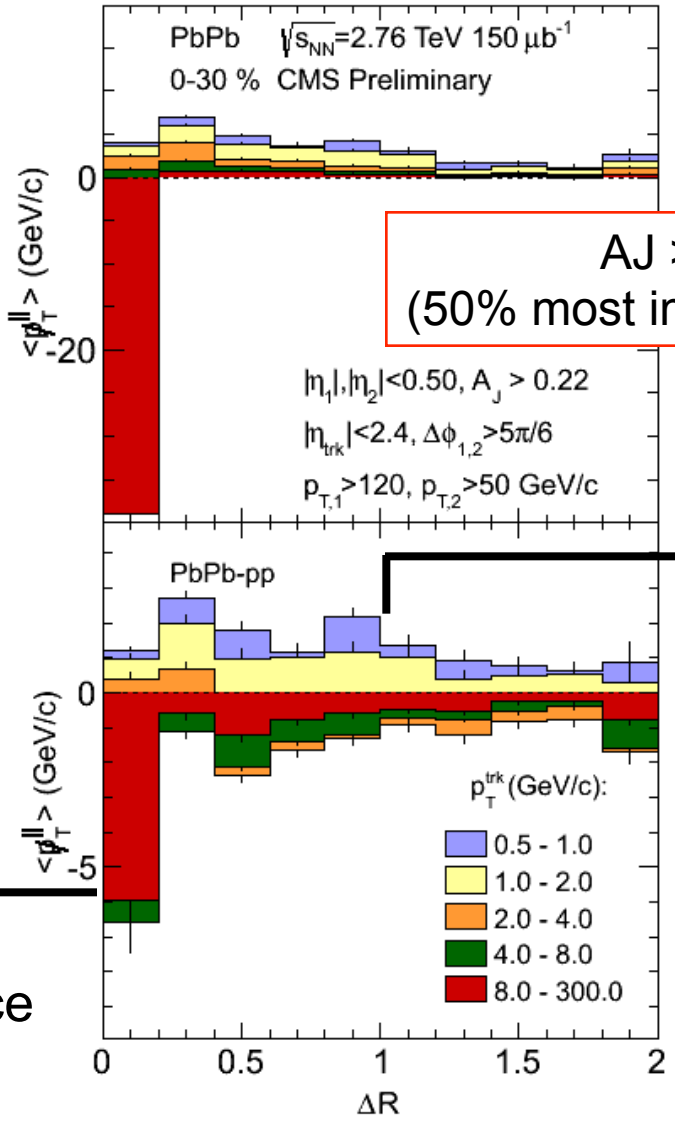
- Balance is not recovered inside a cone of ΔR<0.8.
- PbPb ⟶ Dijet imbalance is balanced by out-of-cone low p_T particles

- Next step: Measurement of missing p_T differential in ΔR
- What is the angular shape, p_T composition and multiplicity of the balancing spectrum?

PRC 84 (2011) 024906

Out-of-cone momentum flow relative to jet





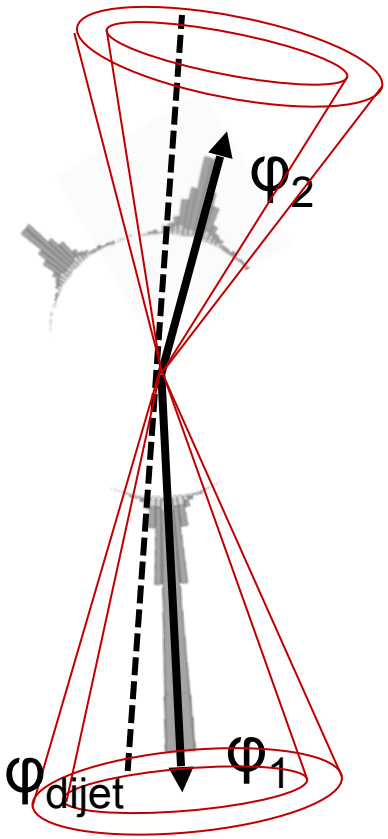
CMS-PAS-HIN-14-010

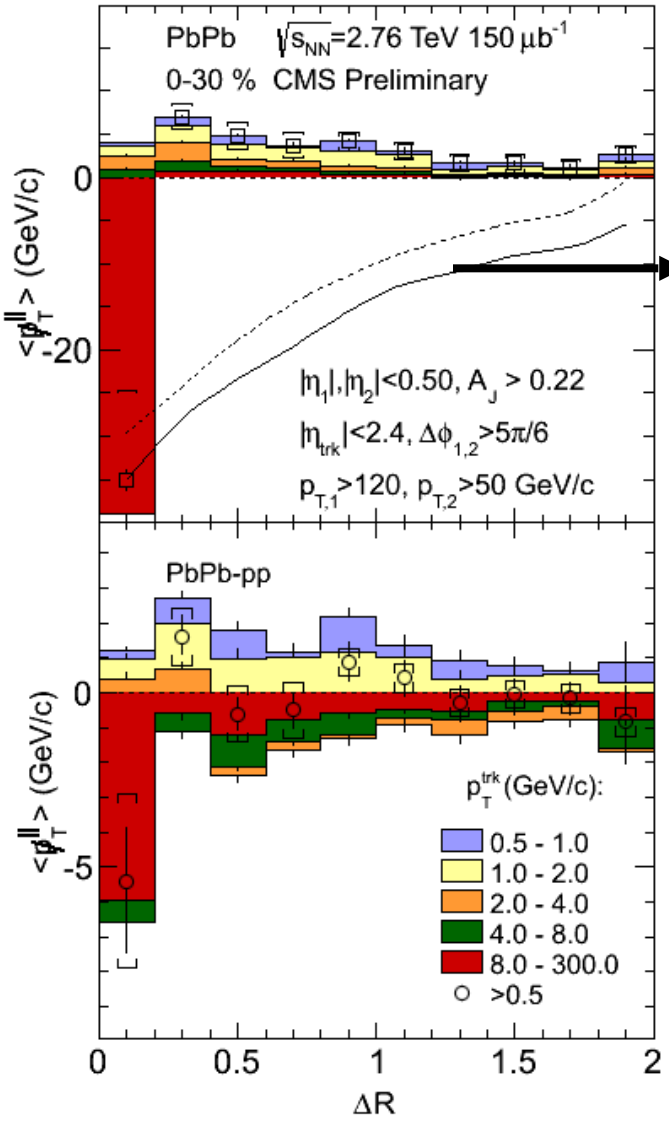
AJ > 0.22
(50% most imbalanced jets)

Enhancement of low p_T particles
Contributions from very large ΔR

Larger imbalance in PbPb

Out-of-cone momentum flow relative to jet

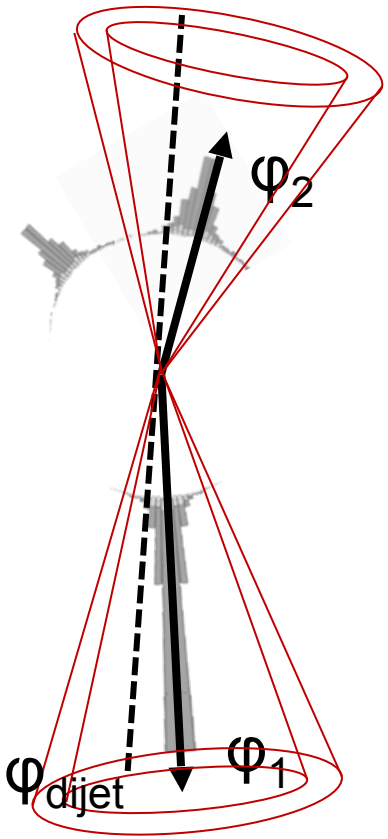


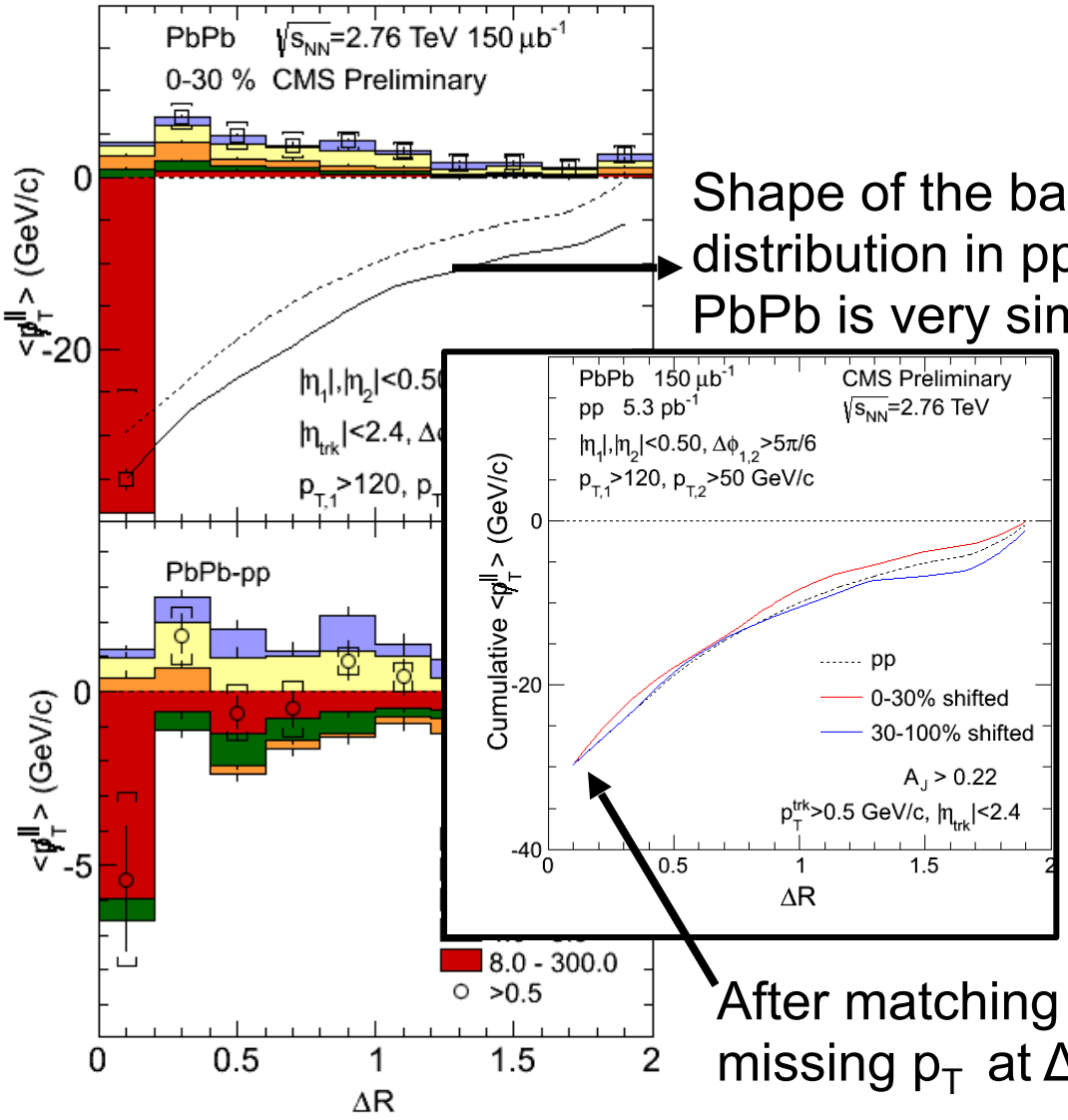


CMS-PAS-HIN-14-010

Shape of the balancing distribution in pp and PbPb is very similar

Out-of-cone momentum flow relative to jet



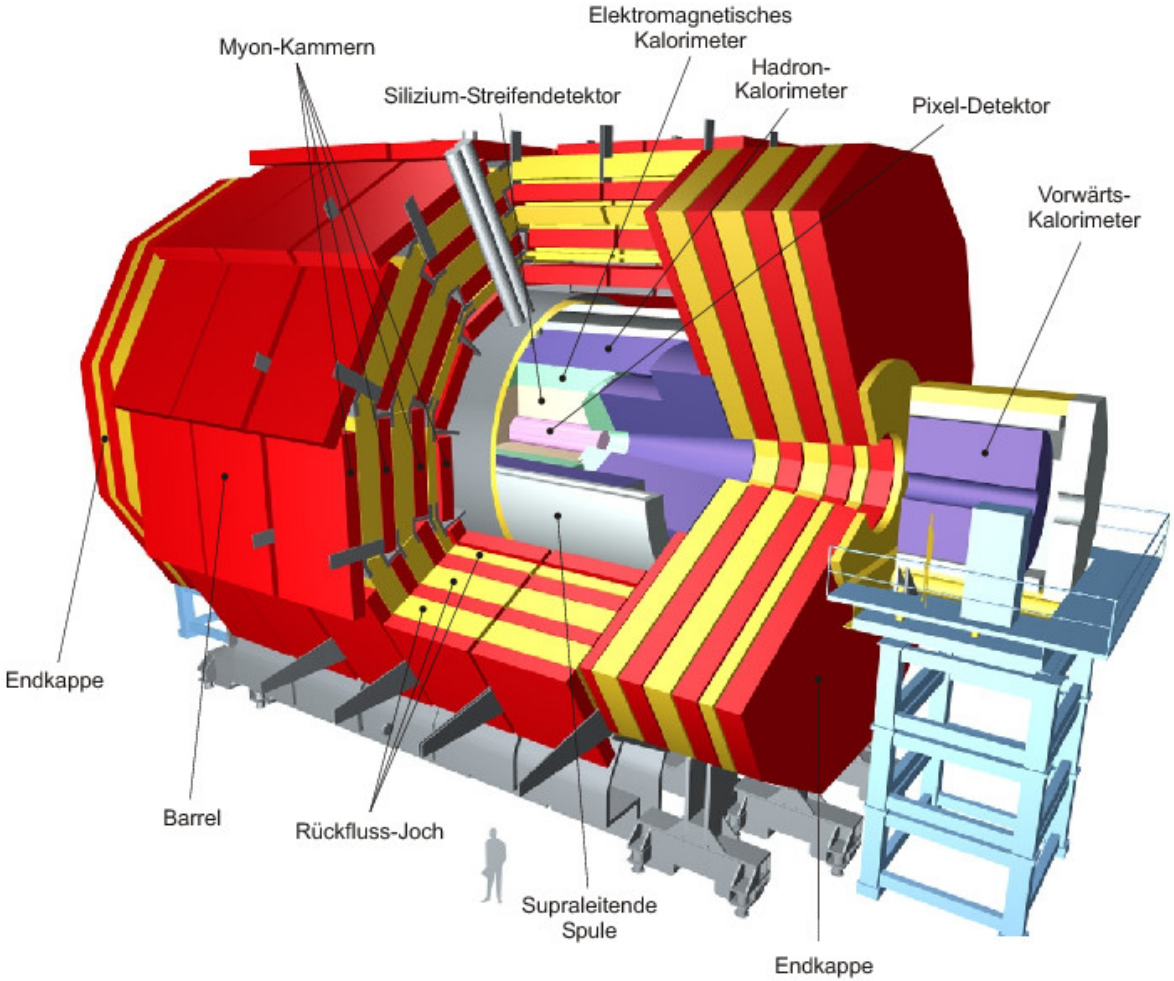


Shape of the balancing distribution in pp and PbPb is very similar

After matching the missing p_T at ΔR<0.2

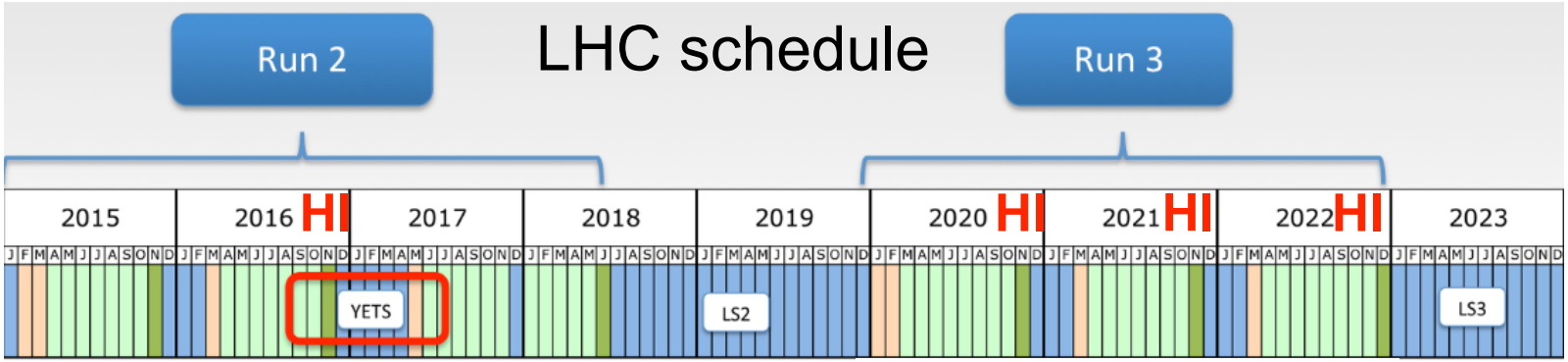
Tomorrow

Major CMS upgrades



Improved trigger system
New/extended inner tracker

Future program enabled by accelerator development



PbPb

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

Collision rate ≈ 20kHz

L_{int} ≈ 3/nb

$\sqrt{s}$ = 5.5TeV

Collision rate ≈ 50kHz

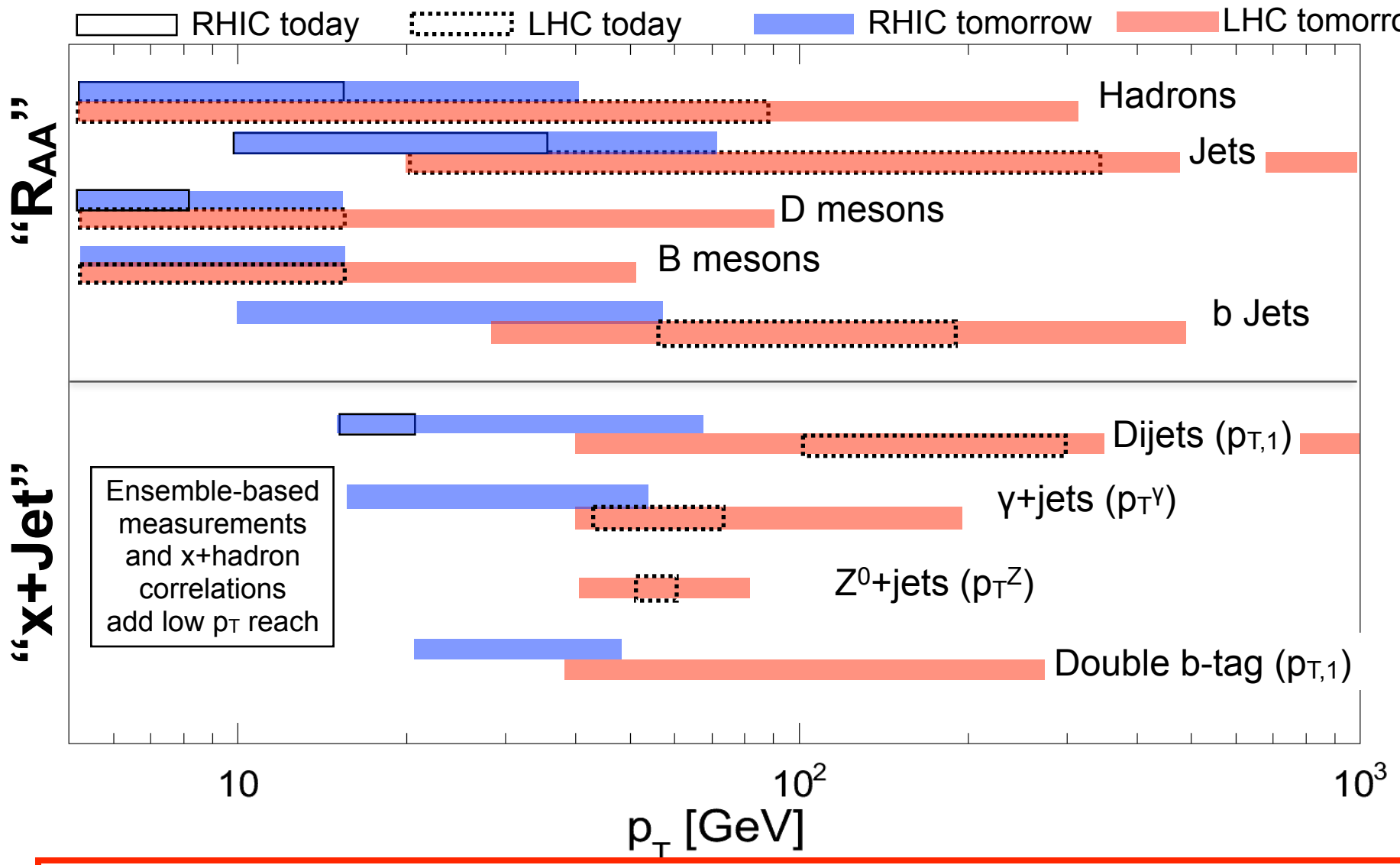
L_{int} ≈ 10/nb (run 2+3)

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

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

Kinematic reach: Now and tomorrow(*)

(*)Artist's impression

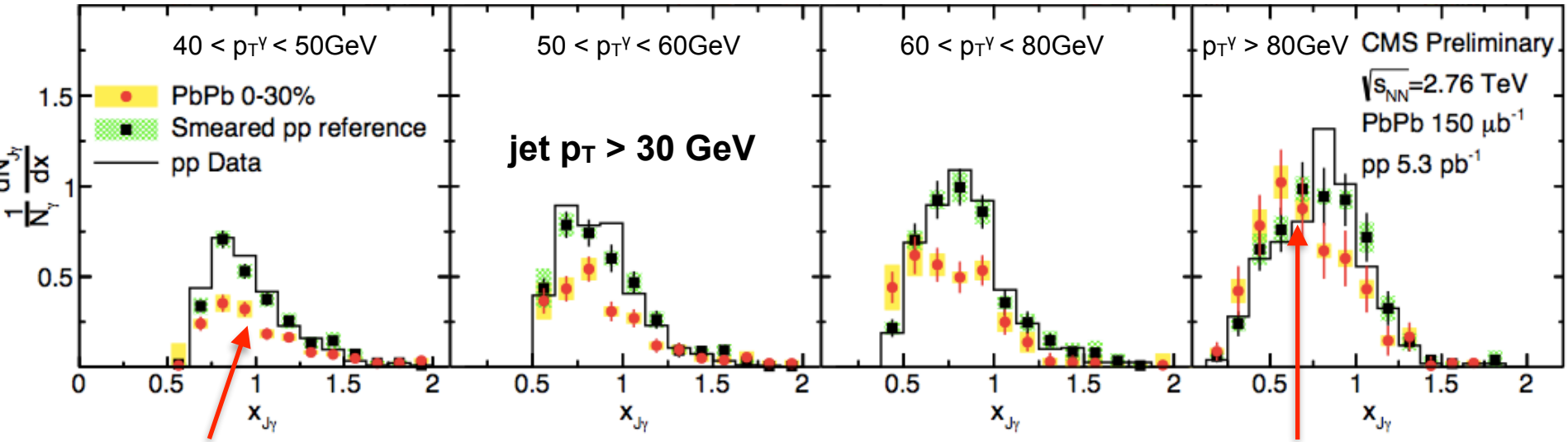


New observables; smaller uncertainties; broader p_T reach
RHIC+LHC overlap

The importance of photon-jet correlations

Using isolated photons to tag away-side jets

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



photon p_T <50GeV:
Spectrum PbPb jets is **suppressed** vs pp
Biased jet selection

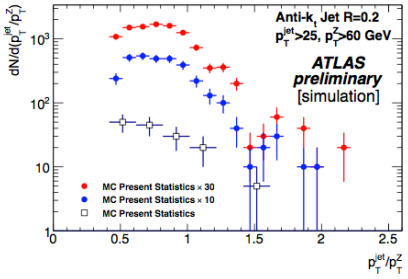
photon p_T >80GeV:
Spectrum of PbPb jets is **shifted** vs pp
Unbiased jet selection

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

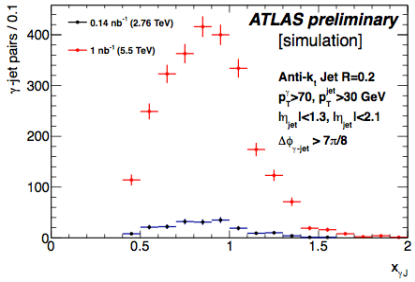
From Z^0 tags to B tags, and from LHC to RHIC

LHC

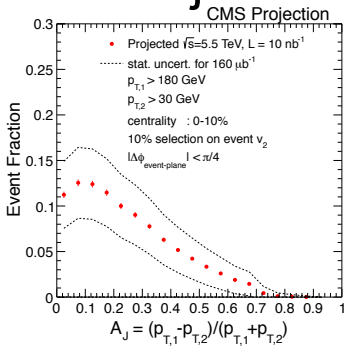
Z^0+jet



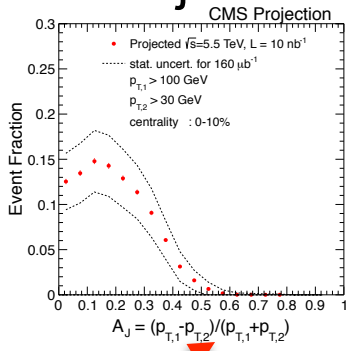
γ+jet



dijet



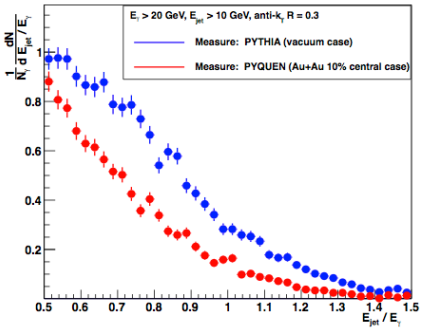
b-jet

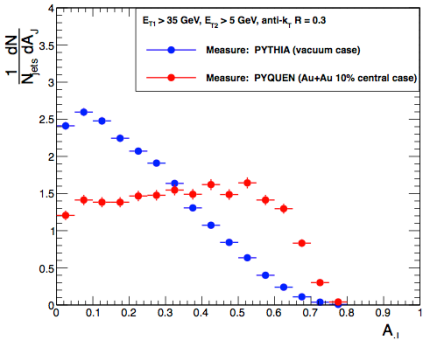


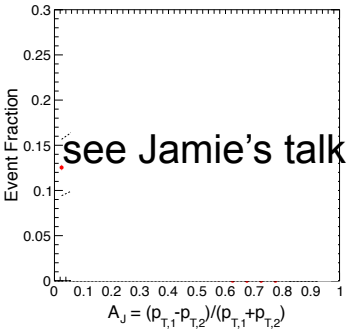
"Calibration"

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

RHIC



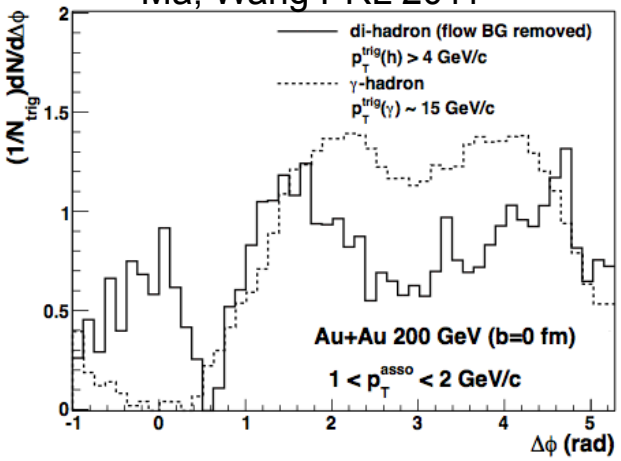




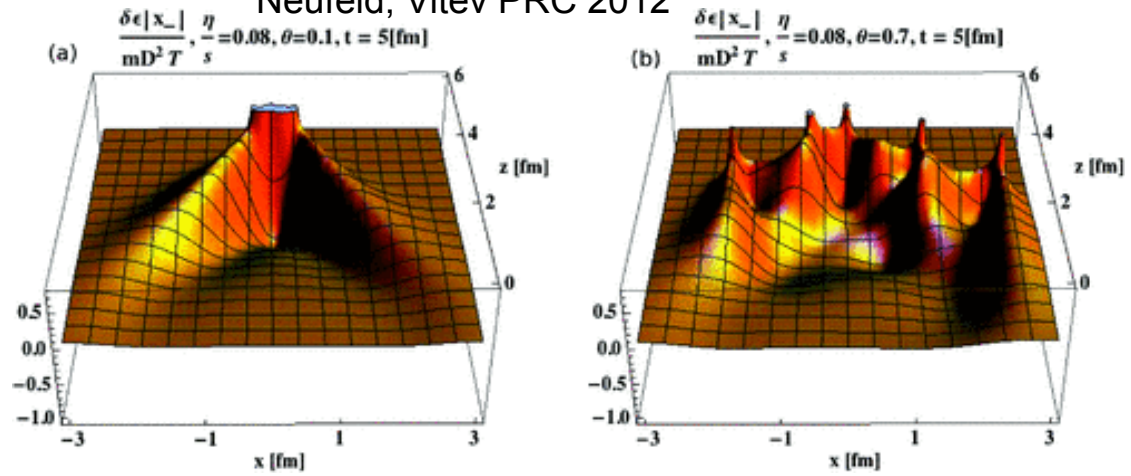
γ+jet dijet b-jet

Energy flow and medium response

Ma, Wang PRL 2011



Neufeld, Vitev PRC 2012



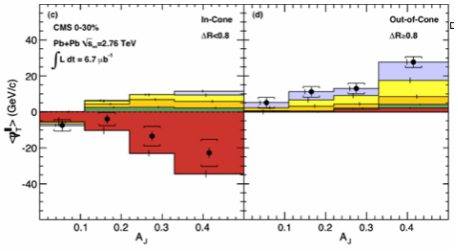
Do we have a medium, if there's no medium response?

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?

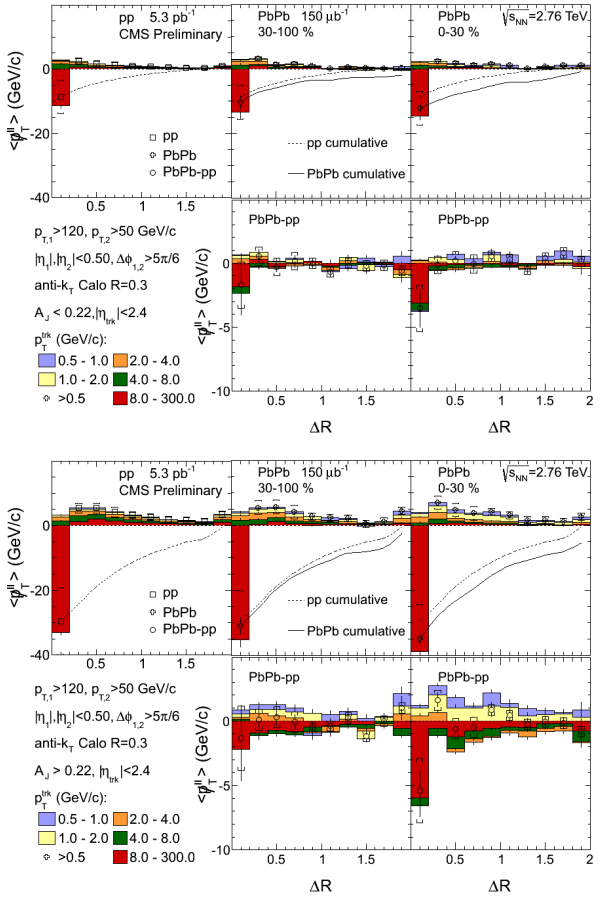
2011

- 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

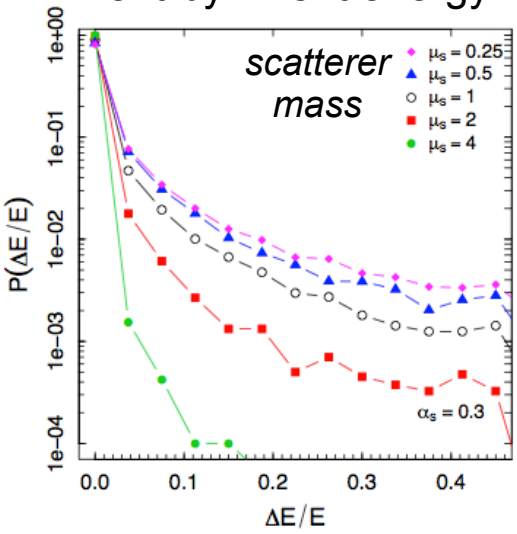


2015-2024

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

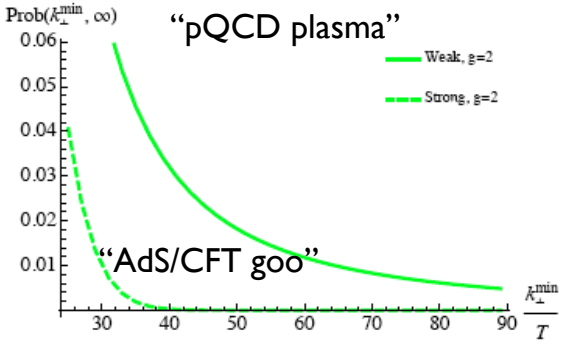
Jet measurements as QGP microscope

Event-by-Event energy loss



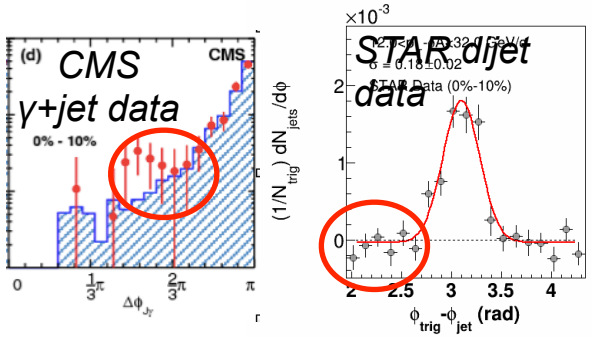
Coleman-Smith, Muller, arXiv:1209.3328

Large angle jet scattering

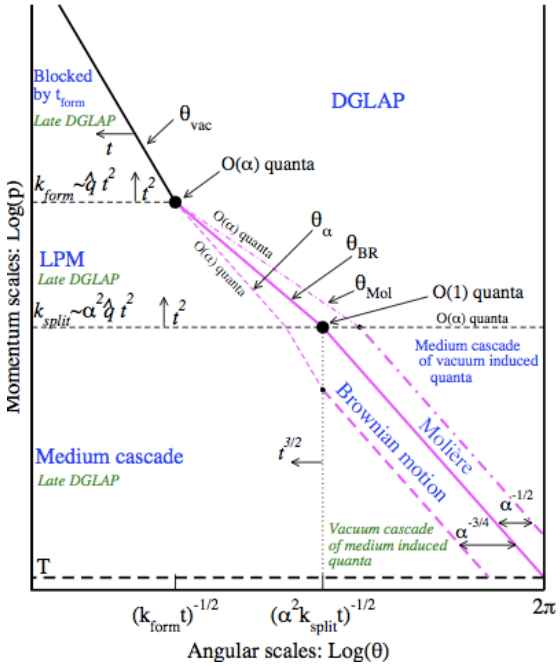


D'Eramo, Rajagopal, '12 updated calculation underway

Need ≈ x10 better precision



Angular and momentum structure of parton cascade

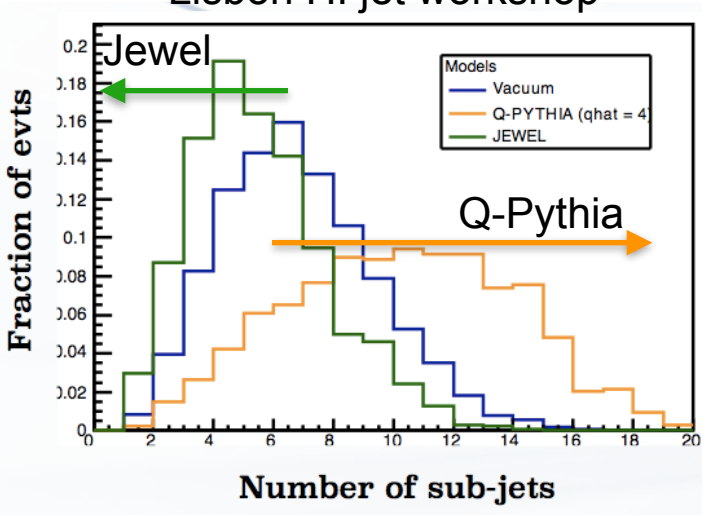


Kurkela, Wiedemann, arXiv:1407.0293

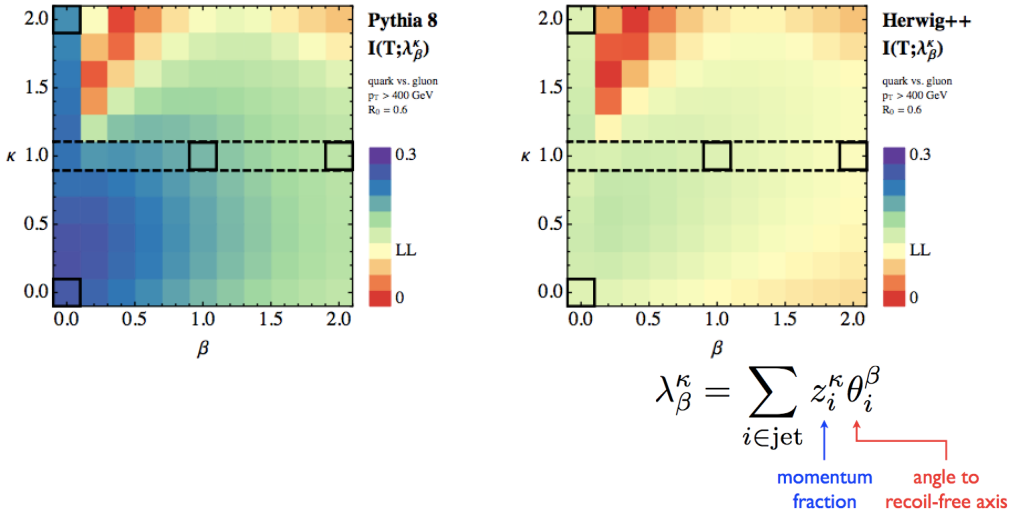
Differential (event-by-event) measurements may allow glimpse at "QCD Rutherford scattering" off QGP constituents

Jet structure in pp and PbPb

Liliana Apolinario
Lisbon HI jet workshop

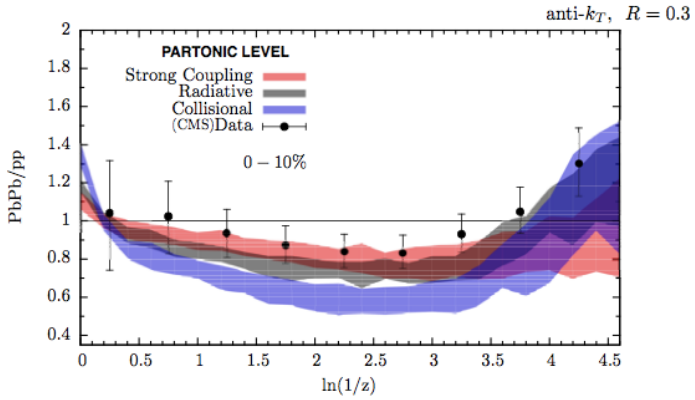


Jesse Thaler, Boost 2014



$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta$$

momentum fraction — angle to recoil-free axis



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)

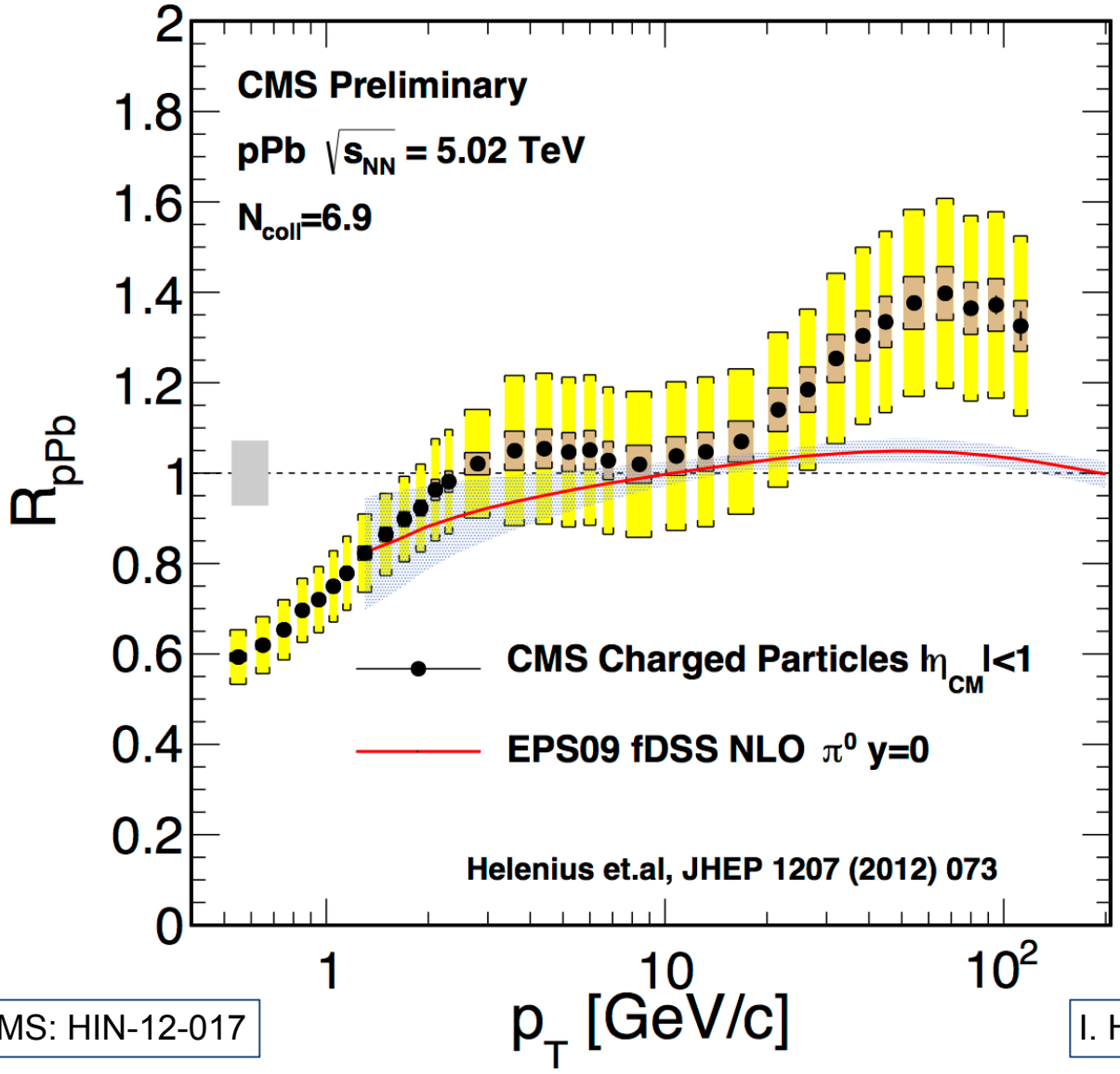
Stability vs pp pileup is major issue

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
  - CMS trigger and detect upgrades; LHC lumi increase
  - Close experiment/theory collaboration
  - Close collaboration with pp

Jet modification in pPb



Glauber (Scale) Uncertainty

Strongly Correlated Uncertainties

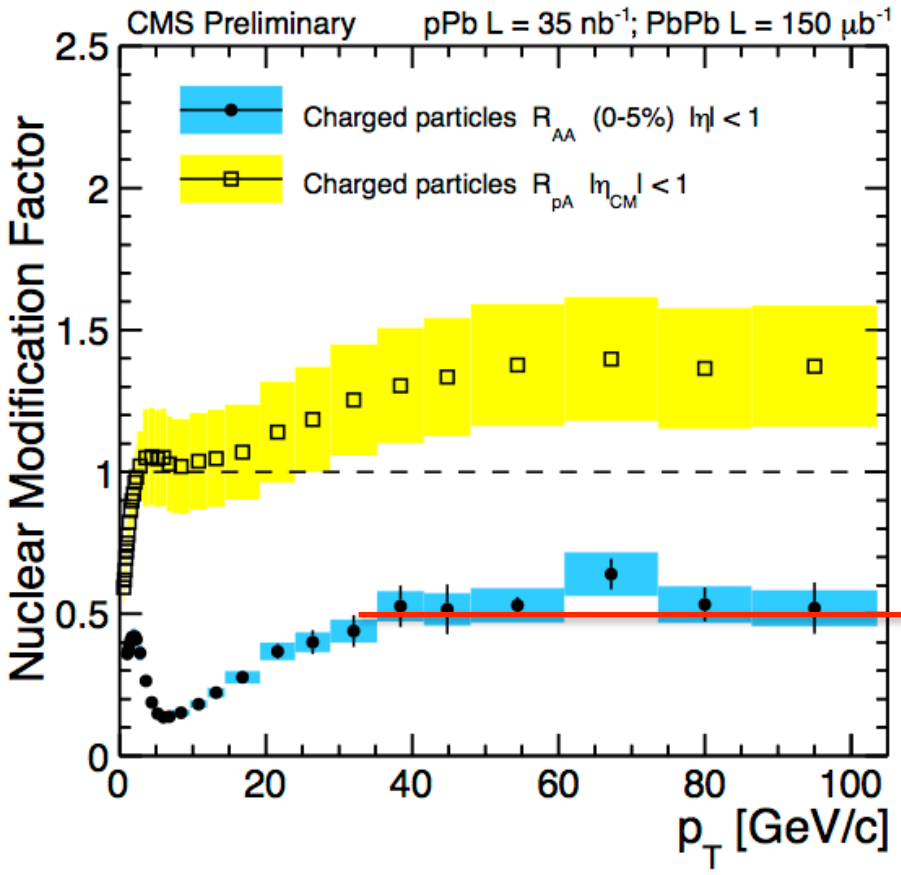
All Other Uncertainties

CMS: HIN-12-017

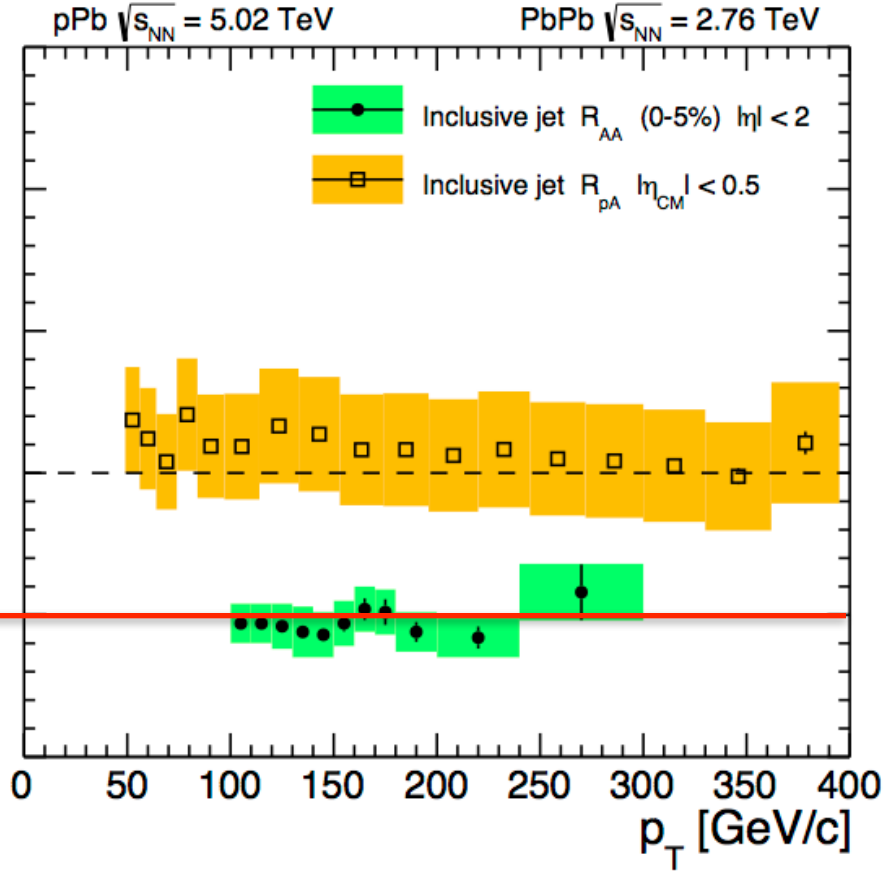
I. Helenius, et al. JHEP 07 (2012) 073

CMS hadron and jet R_{AA}

Charged Particles



Anti-k_T R=0.3 Jets



CMS: EPJC 72 (2012) 1945 , HIN-12-004, HIN-12-017, HIN-14-001