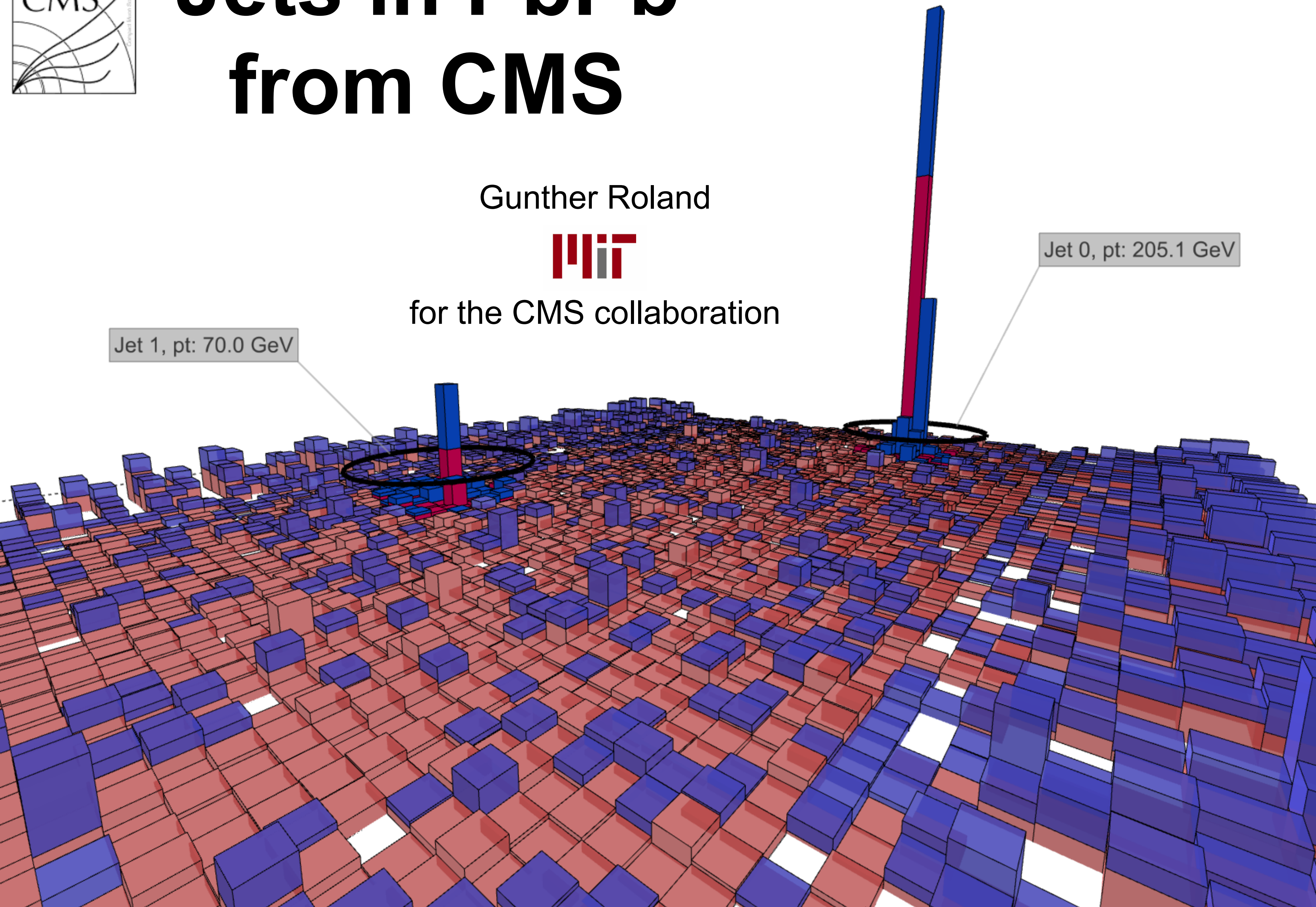
Jets in PbPb from CMS

Gunther Roland

MIT

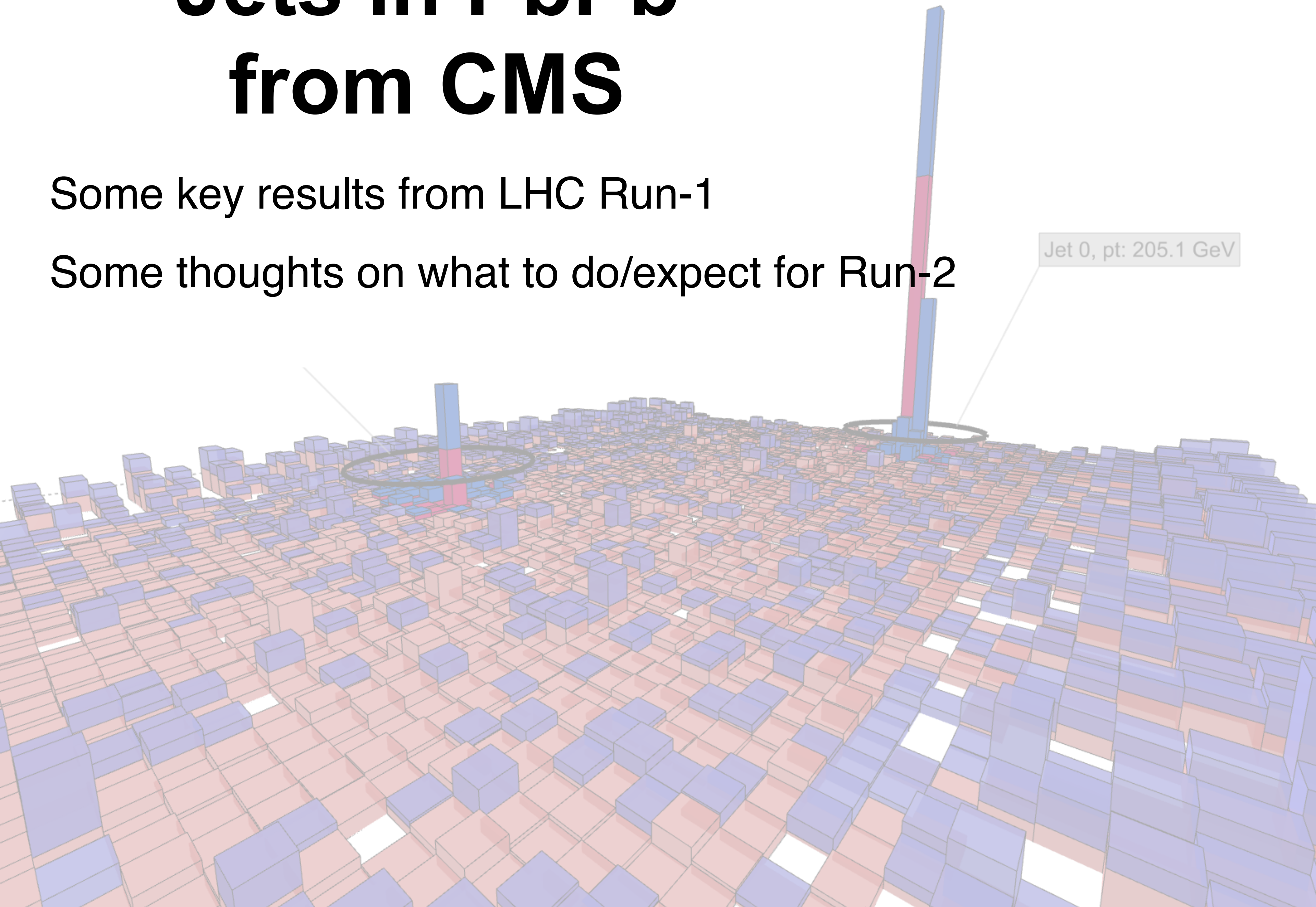
for the CMS collaboration

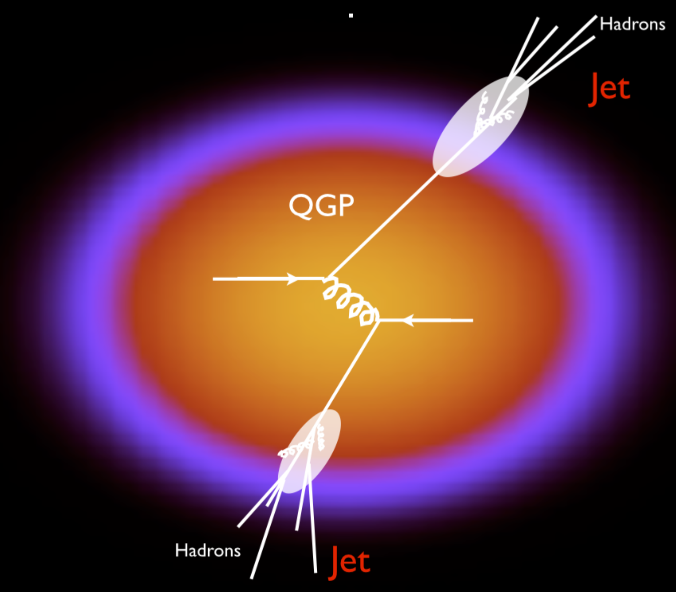


Jets in PbPb from CMS

Some key results from LHC Run-1

Some thoughts on what to do/expect for Run-2





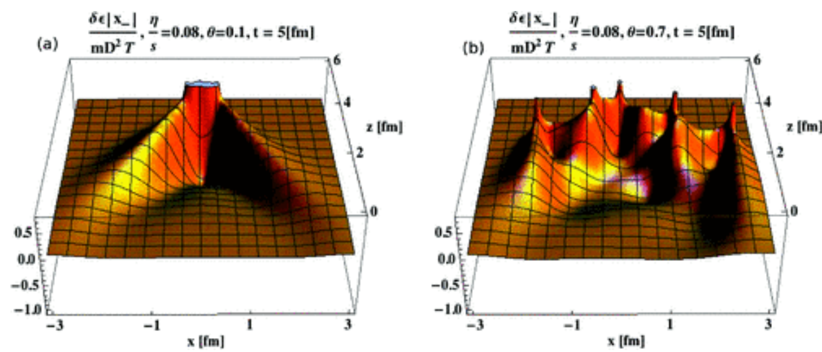
Jets as tools to ***characterize*** QGP

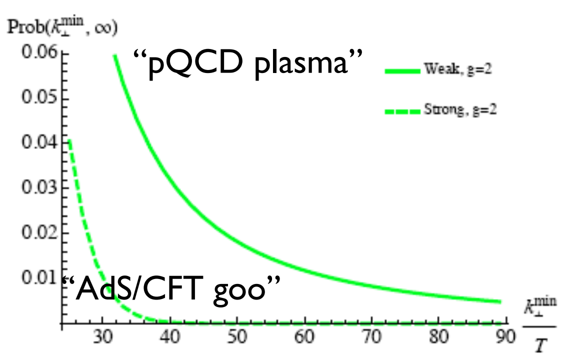
Medium effects on jets allow extraction of QGP transport coefficients:

- $\hat{q}$: 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?

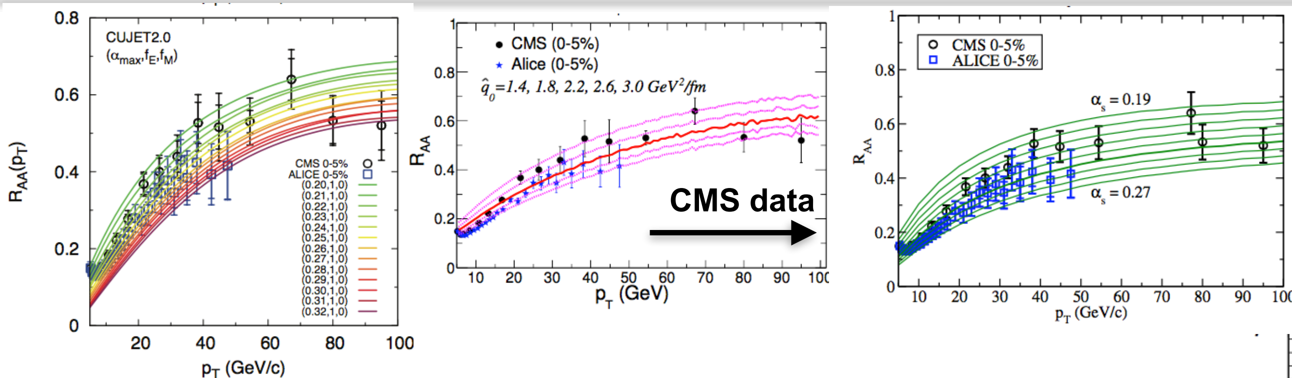
- Jets probe QGP at different (controllable) length scales
- Scattering sensitive to quasi-particle nature of the medium

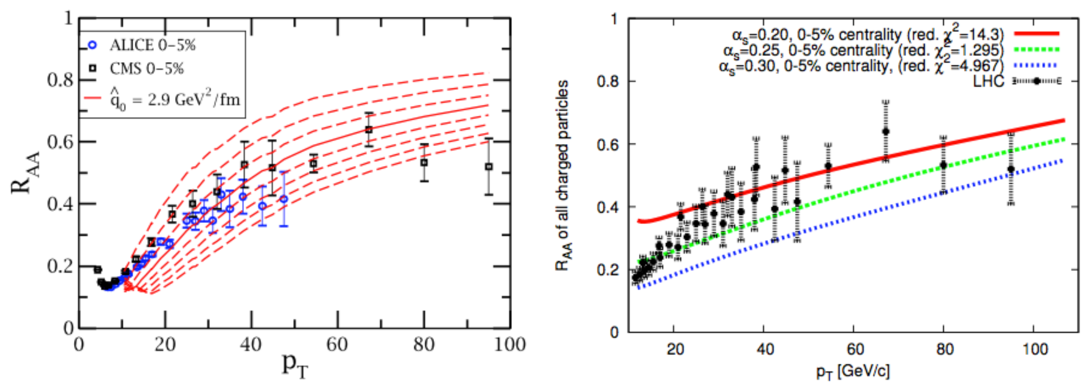
Recommendation #1:

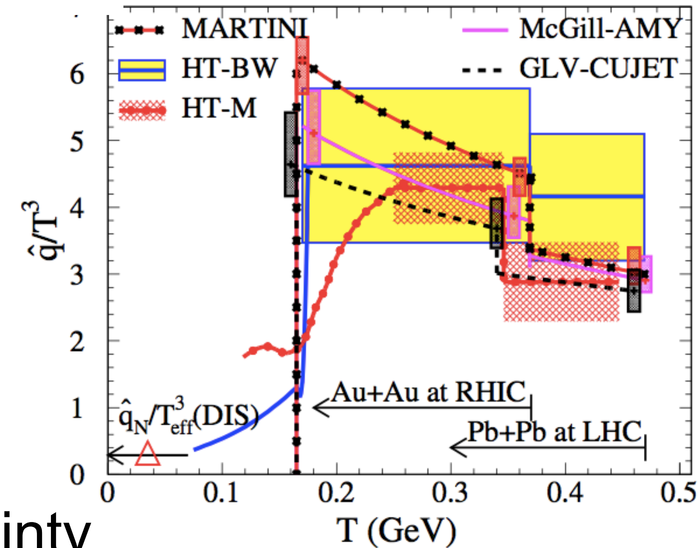
The discoveries of the past decade have posed or sharpened questions that are central to understanding the nature, structure, and origin of the hottest liquid form of matter that the universe has ever seen. As our highest priority we recommend a program to complete the search for the critical point in the QCD phase diagram and to exploit the newly realized potential of exploring the QGPs structure at multiple length scales with jets at RHIC and LHC energies.

Hot QCD White paper
US NP 2015 LRP

Extracting QGP transport coefficients







$\hat{q}$ determined with about 35% quoted uncertainty

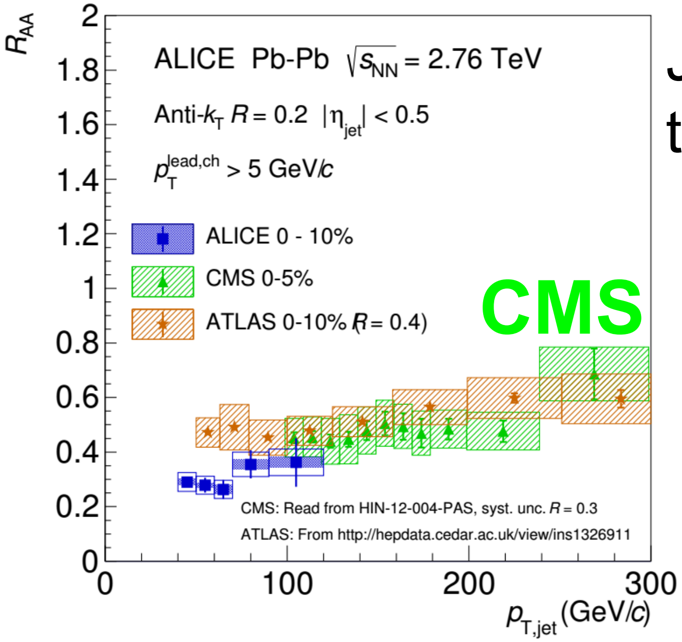
Combined RHIC and LHC data:

- Test model consistency
- First hint of temperature dependence

Systematic multi-model, multi-experiment comparison: Need more!

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

Jet Physics with Jets: Jet R_{AA} and Dijet Asymmetry

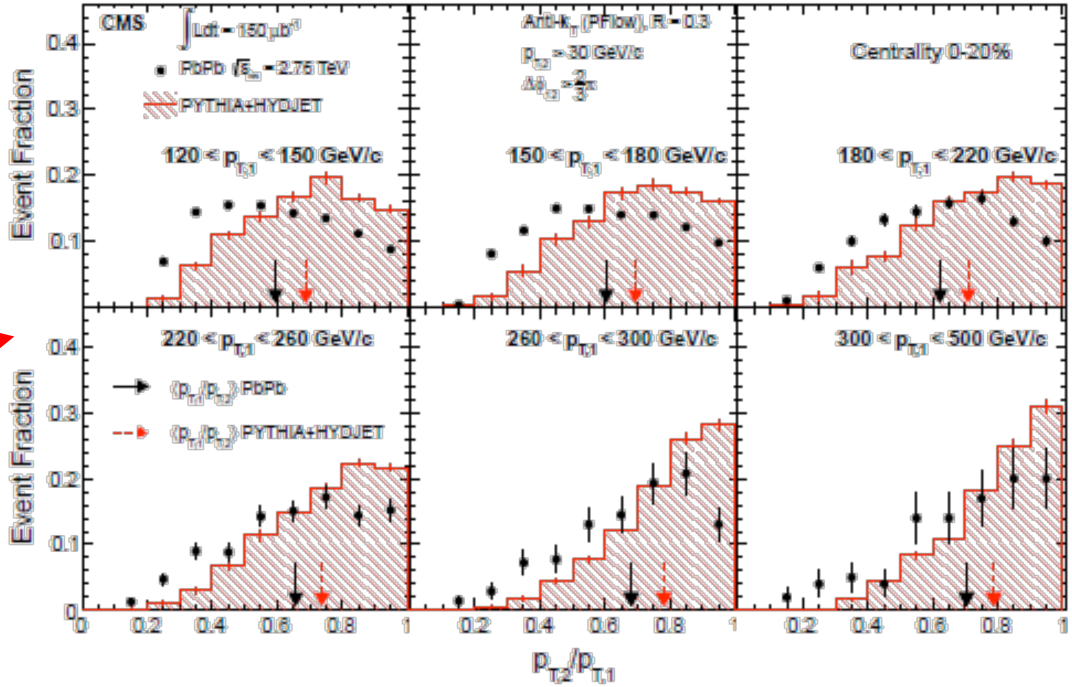


Jet R_{AA} numerically similar to hadron R_{AA} at high p_T

<Aj> carries similar information as R_{AA}

But: Wider range of theoretical tools for hadron R_{AA}

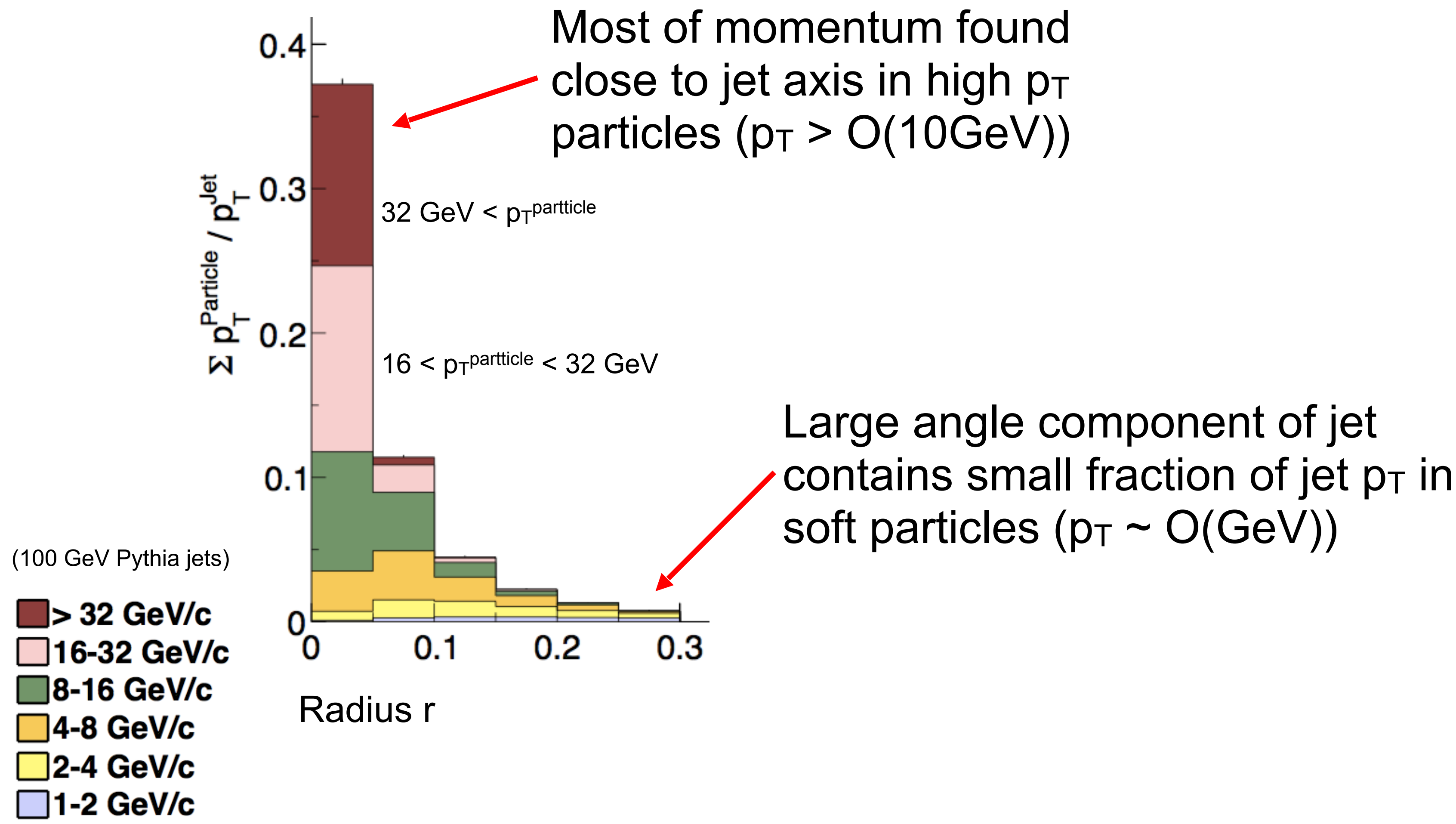
$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$



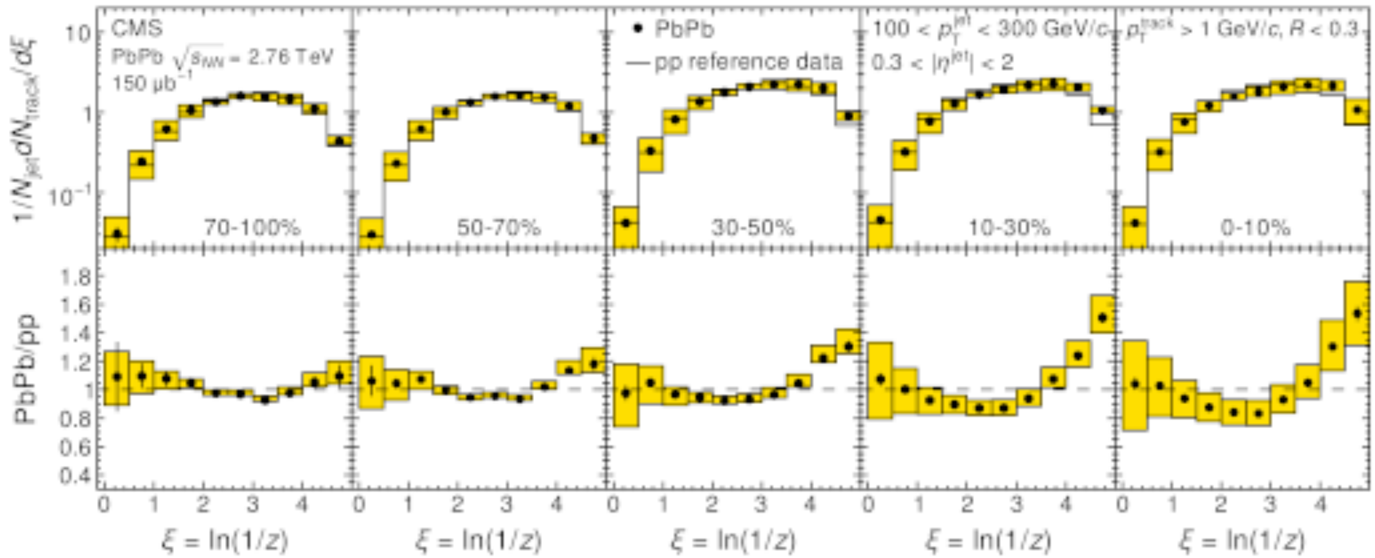
Jet quenching persists for p_T >300GeV jets

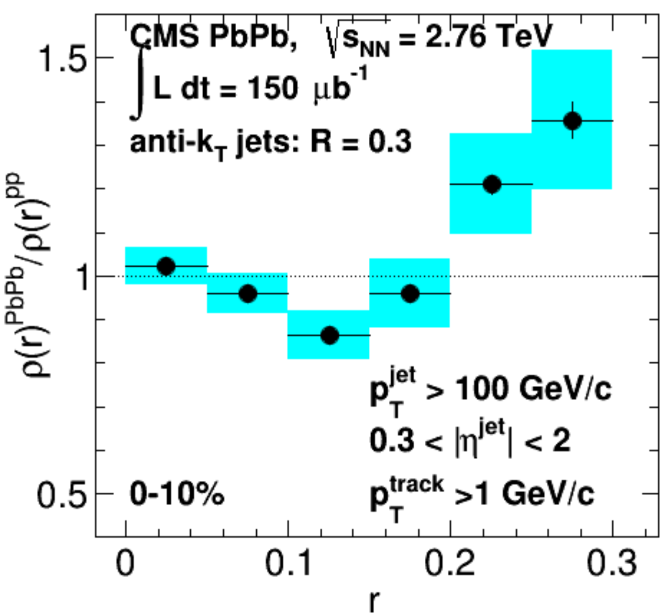
Jet Anatomy

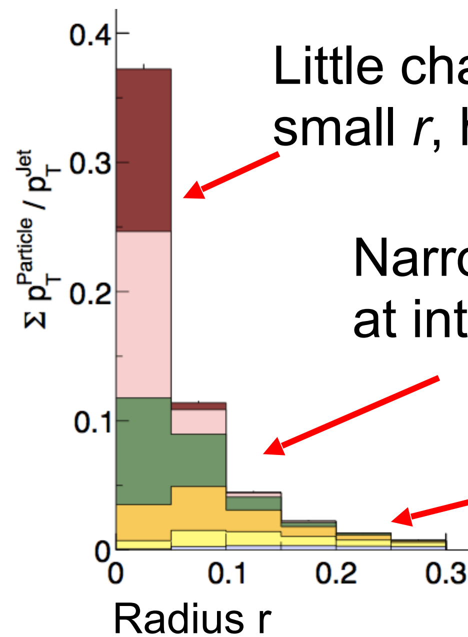
Jets are extended objects with momentum and angular structure



Jet Anatomy modifications







Little change at small r, high p_T

Narrowing/depletion at intermediate r, p_T

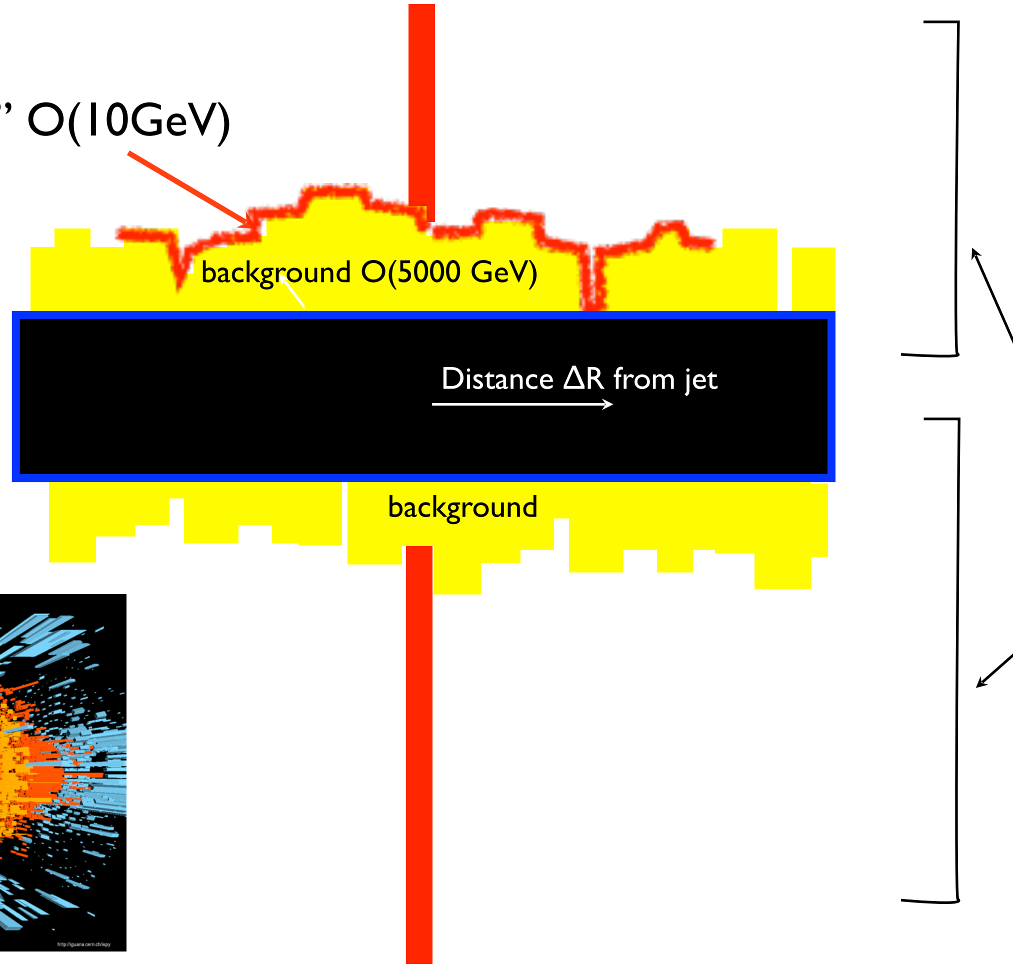
Broadening/excess at large r, low p_T

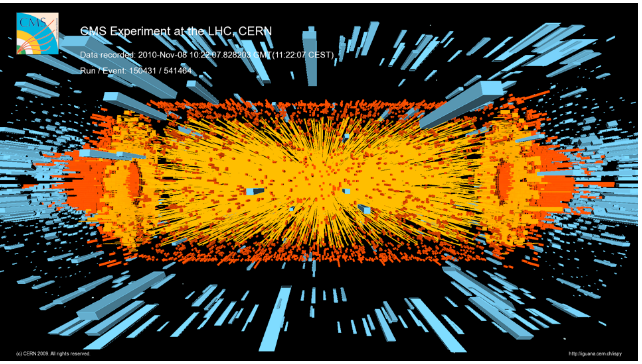
(~2% of jet energy)

Where is the “lost energy”?

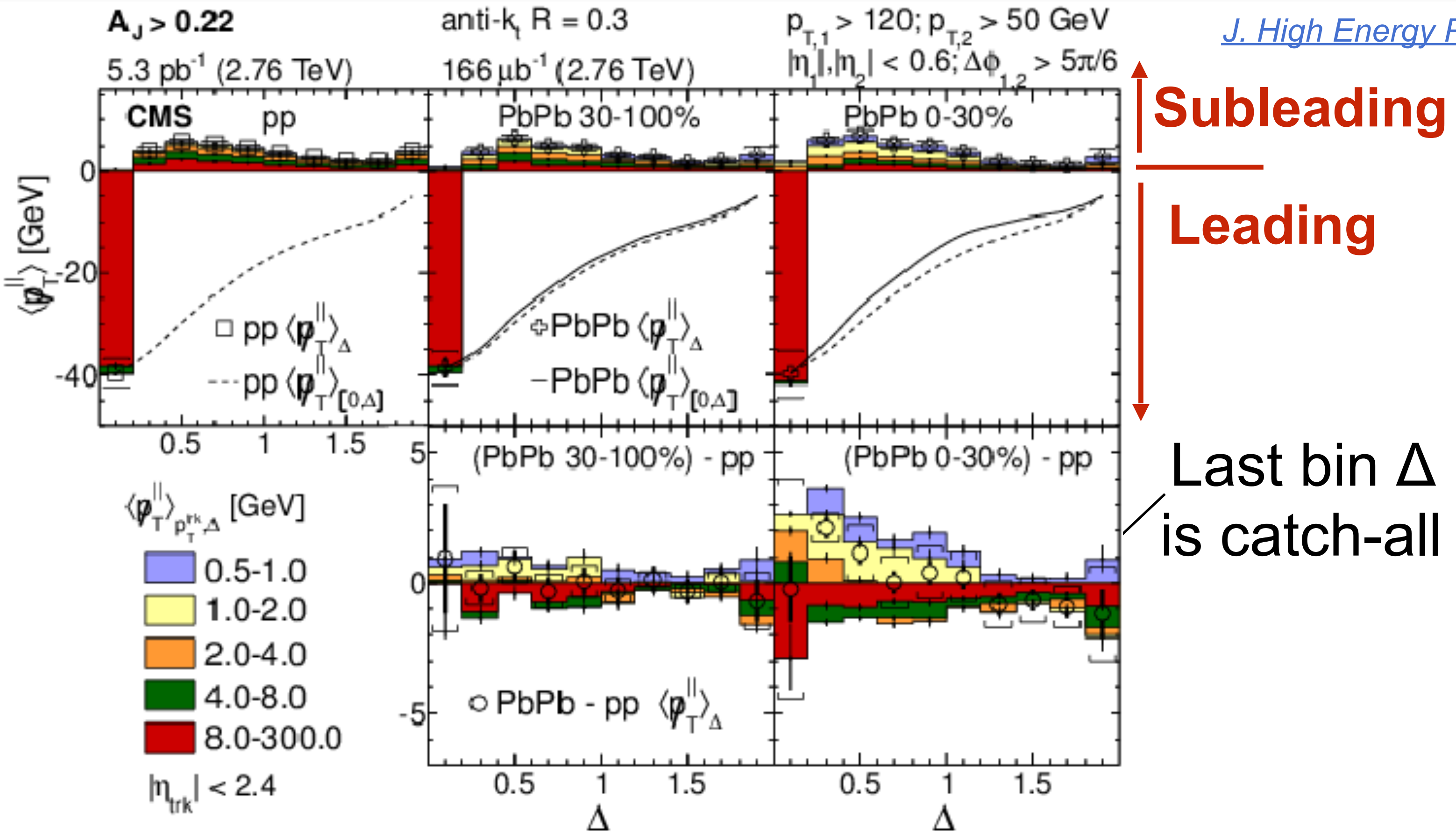
Use momentum-conservation to study momentum balance in the event: “Missing p_T”

$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$





[J. High Energy Phys. 01 (2016) 006]

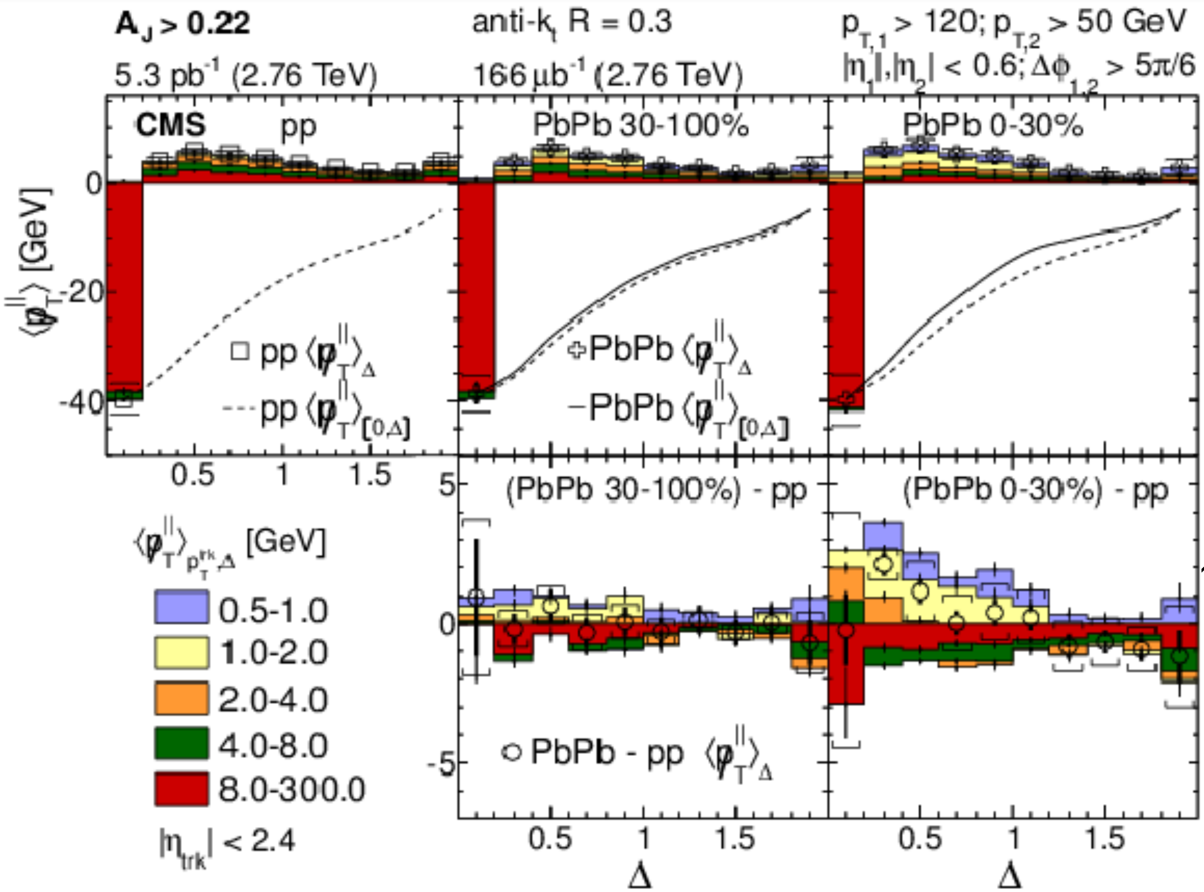


Detailed study of radial and track momentum distribution of leading-subleading jet momentum *difference*

As in pp, difference spread over large radial distance
Unlike in pp, difference is found in low p_T particles

“Missing p_T” analysis

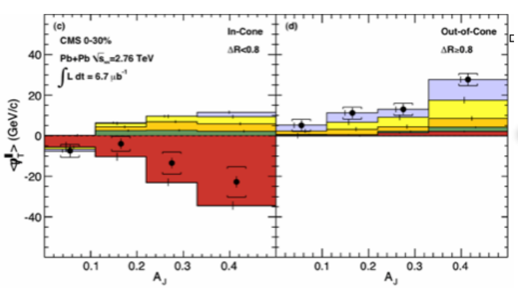
J. High Energy Phys. 01 (2016) 006



Subleading

Leading

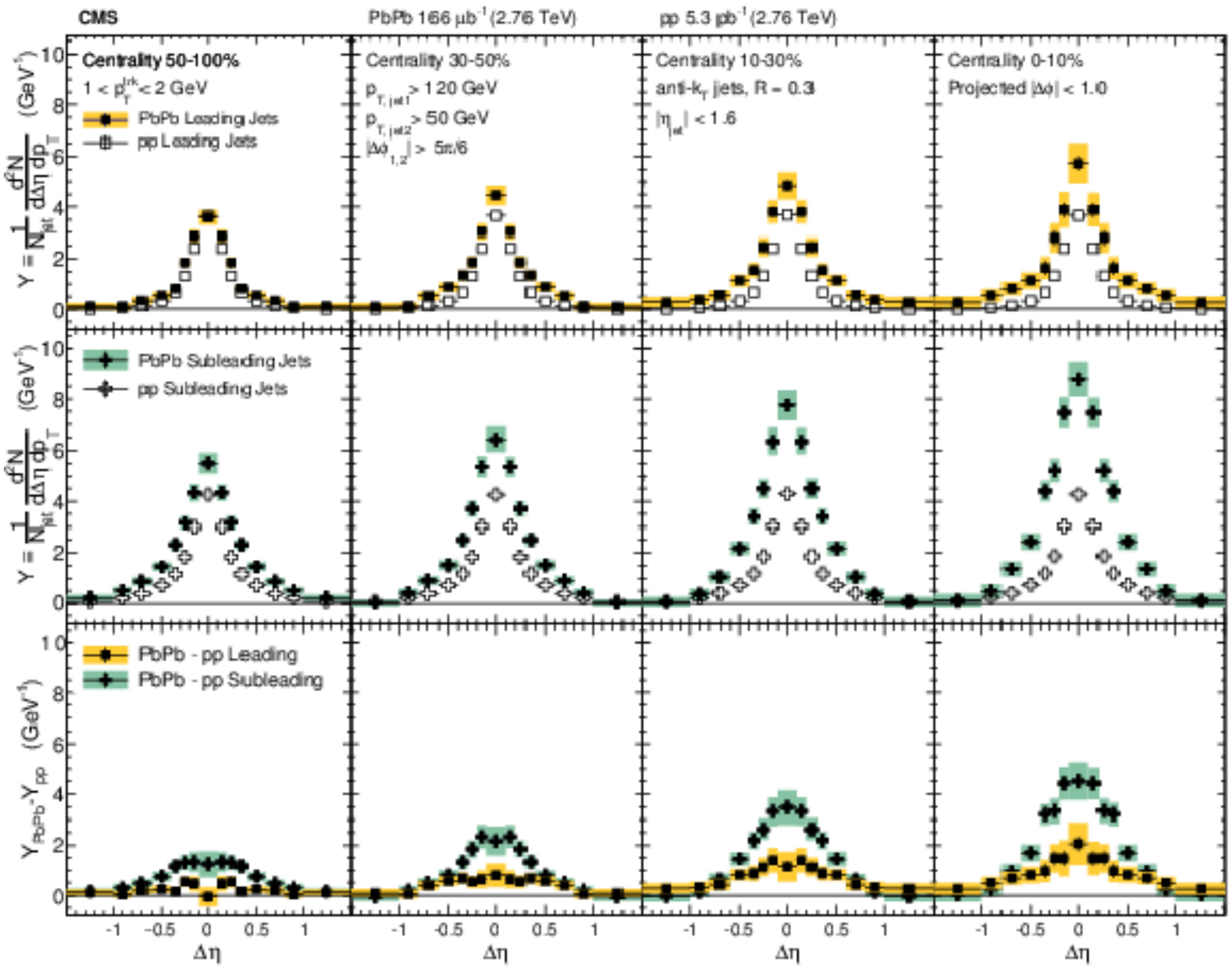
Last bin Δ is catch-all



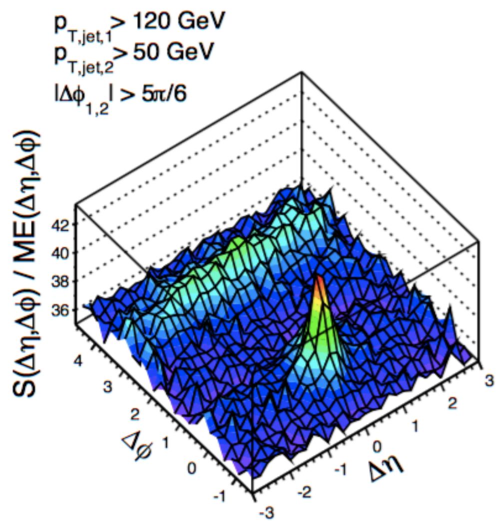
~10 person-years

First MPT measurement (2011)

Jet-track correlation analysis

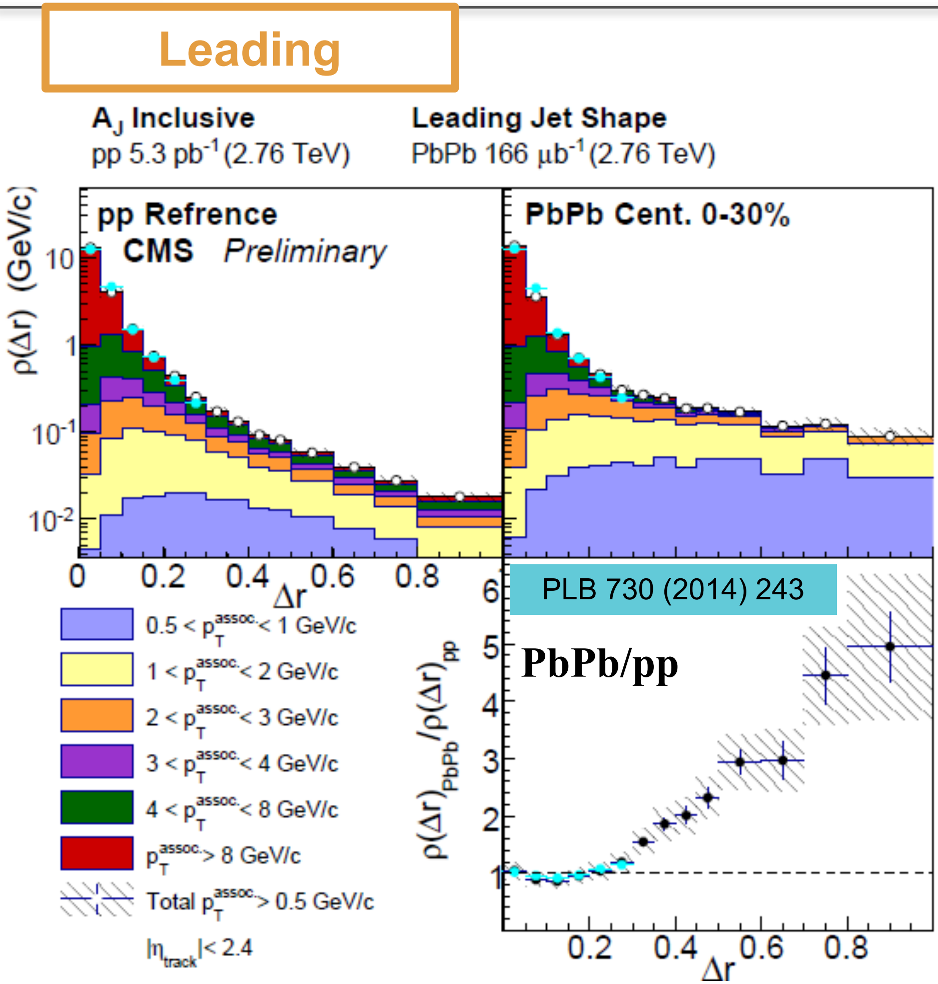


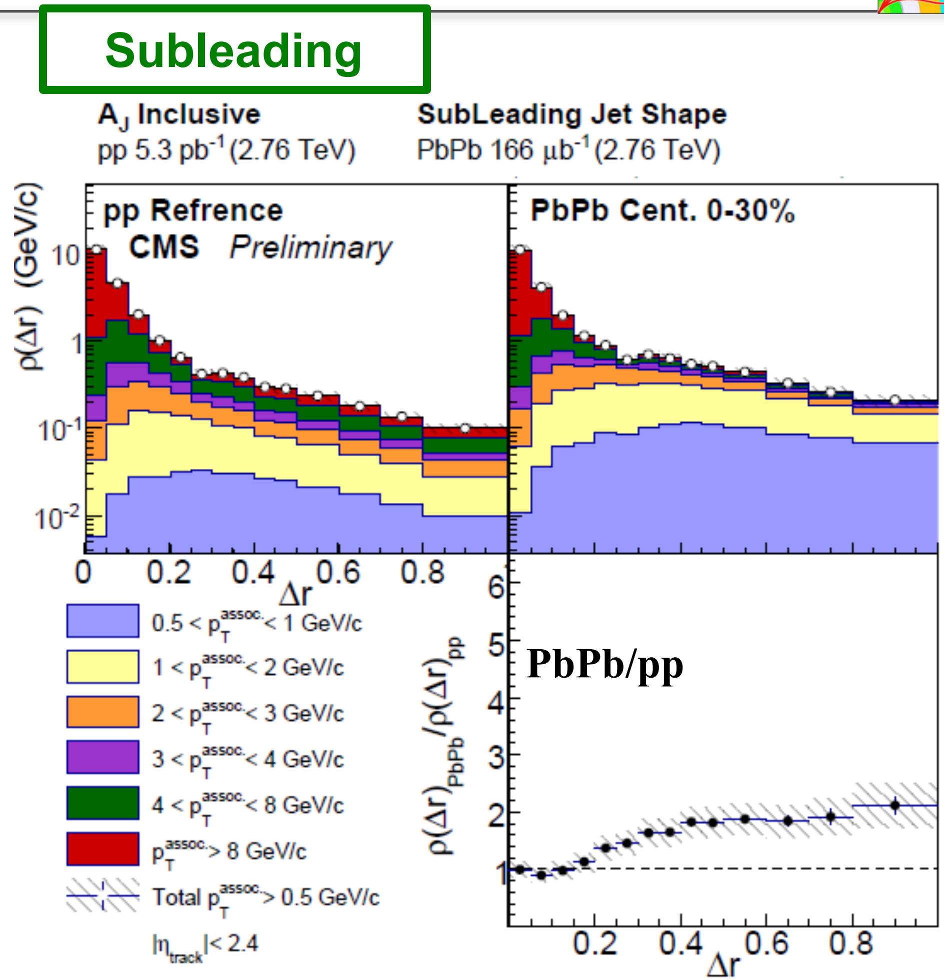
CMS-PAS HIN-14-016
submitted to JHEP



- Excess yield largest at low p_T, turns into depletion for p_T>8GeV/c
- Larger effects for subleading jets and in central events

Jet shapes from Jet-track correlations



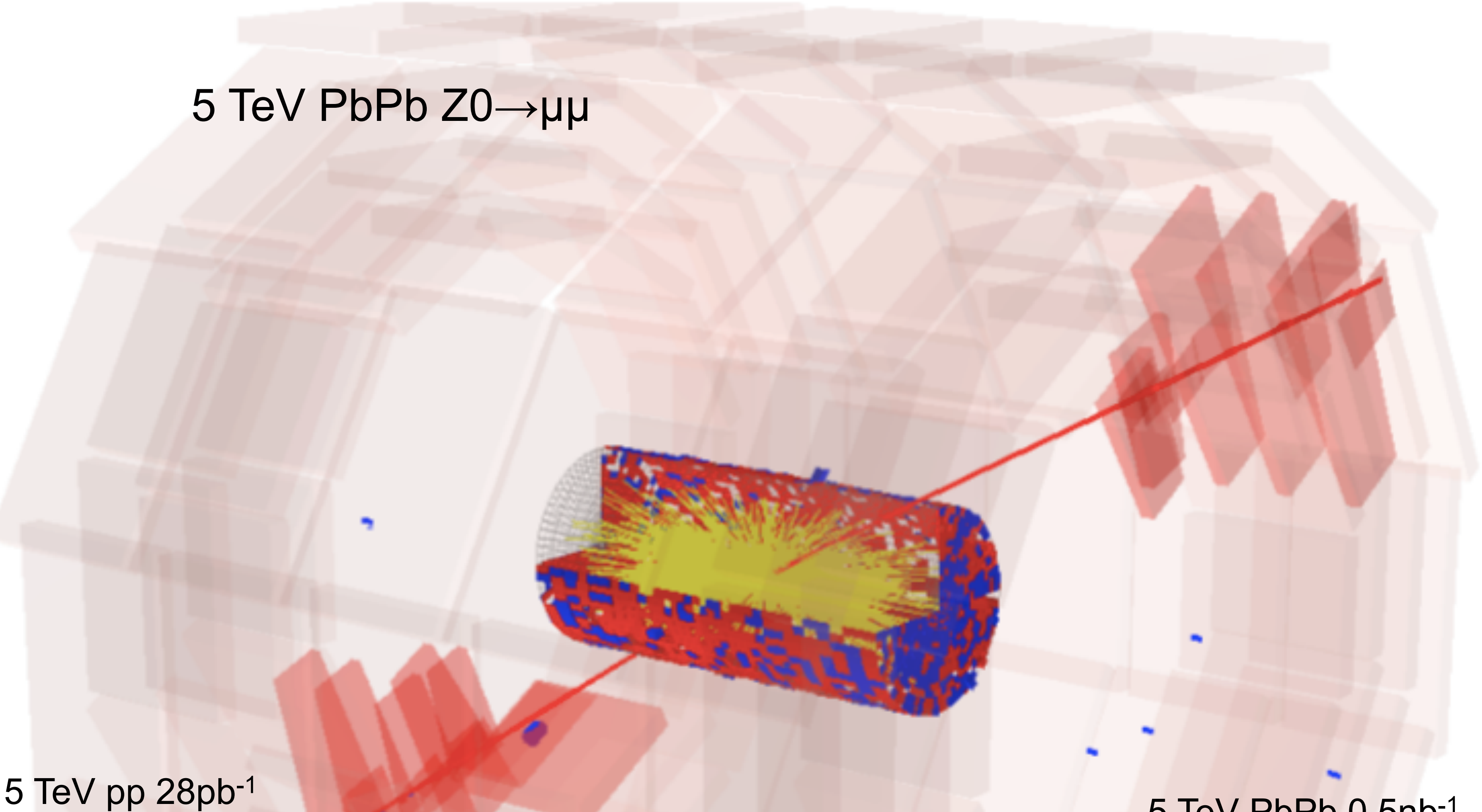


- Correlation functions can be integrated to yield e.g. jet shapes

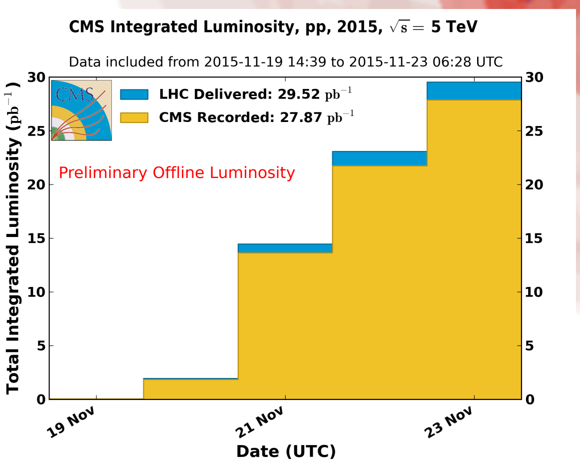
CMS-PAS HIN-15-011

What will the future hold?

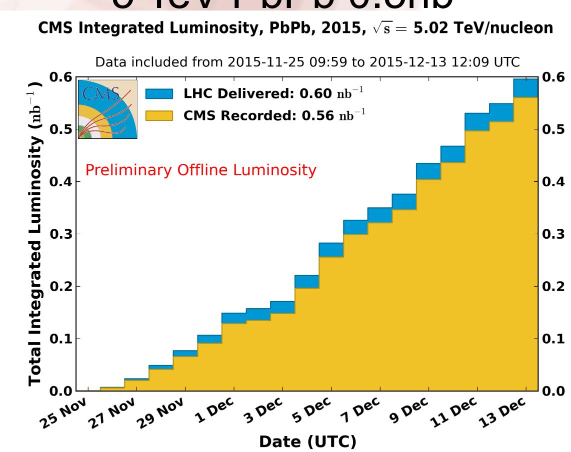
5 TeV PbPb Z0→μμ



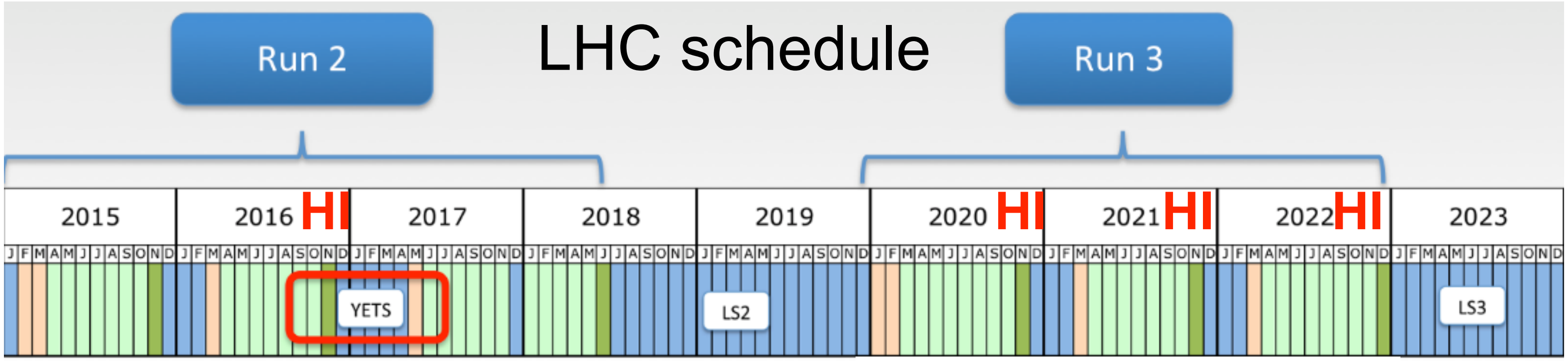
5 TeV pp 28pb^{-1}



5 TeV PbPb 0.5nb^{-1}



LHC Run 2 (and beyond)



HI √s = 5TeV HI

PbPb Collision rate ≈ 20kHz

L_{int} ≈ 3/nb

√s = 5.5TeV

Collision rate ≈ 50kHz

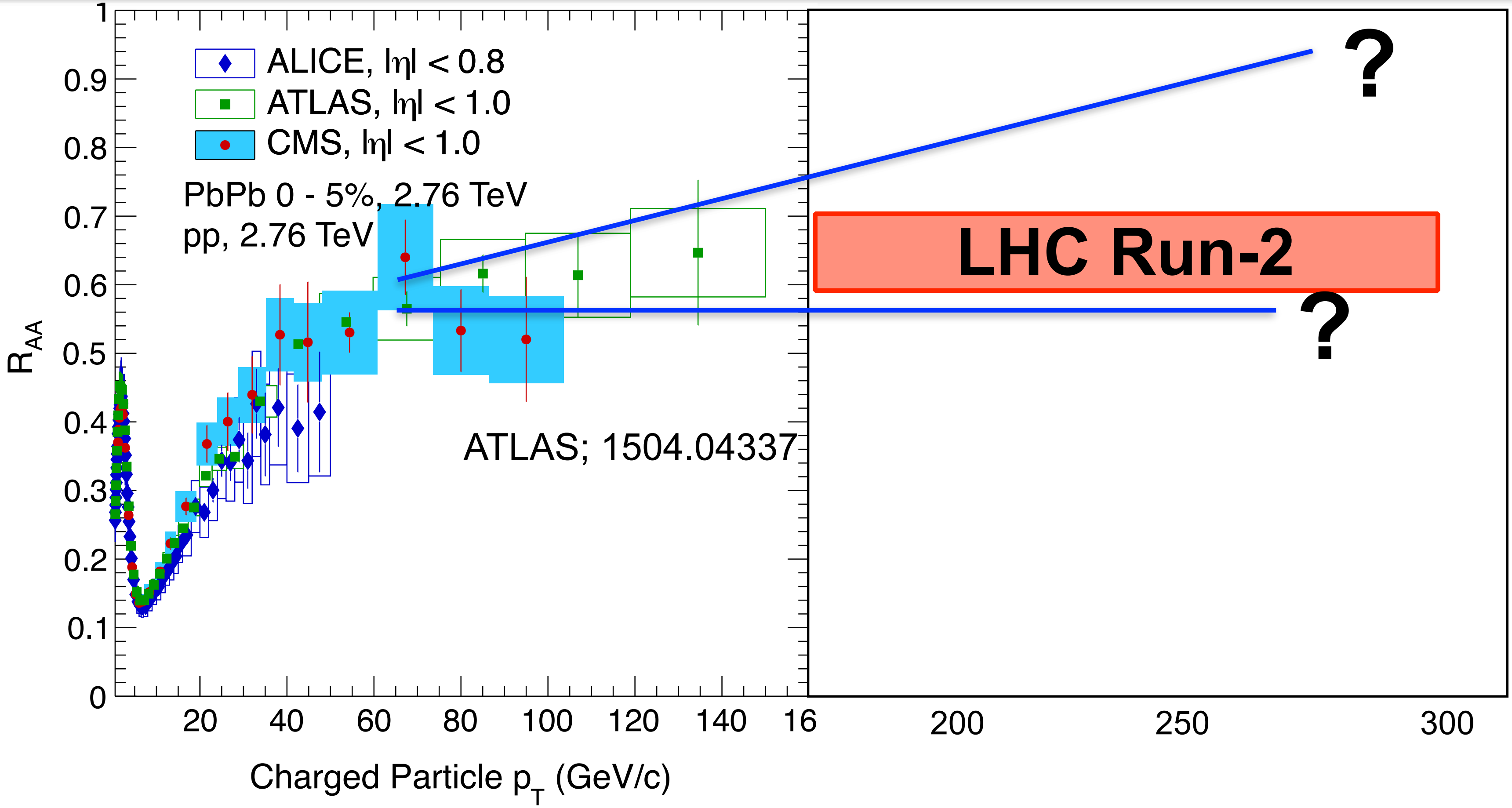
L_{int} ≈ 10/nb (run 2+3)

	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	$\sim$ 10M
b-jet ($p_T > 120$ GeV/c)	~ 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)	~ 350	$\sim$ 70k
Z ($p_T^Z > 50$ GeV/c)	~ 35	$\sim$ 7k

CMS collected 0.5 nb^{-1} in ’15
i.e., about 5% of Run 2+3 total,
factor 10 wrt Run 1 in HP stat’s

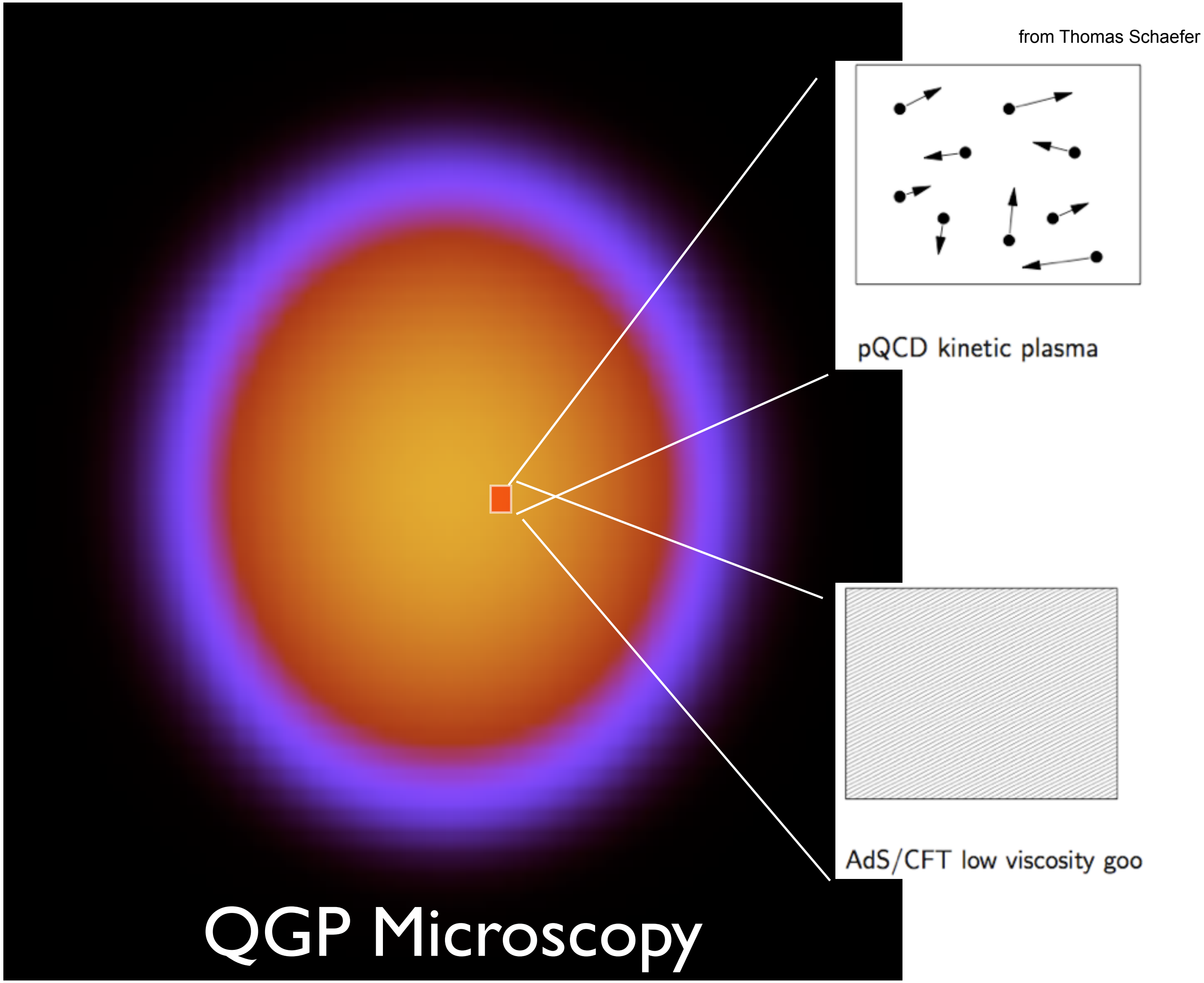
Compared to LHC Run 1: x60 due to higher luminosity; x3 due to higher √s

R_{AA} now and in Run-2

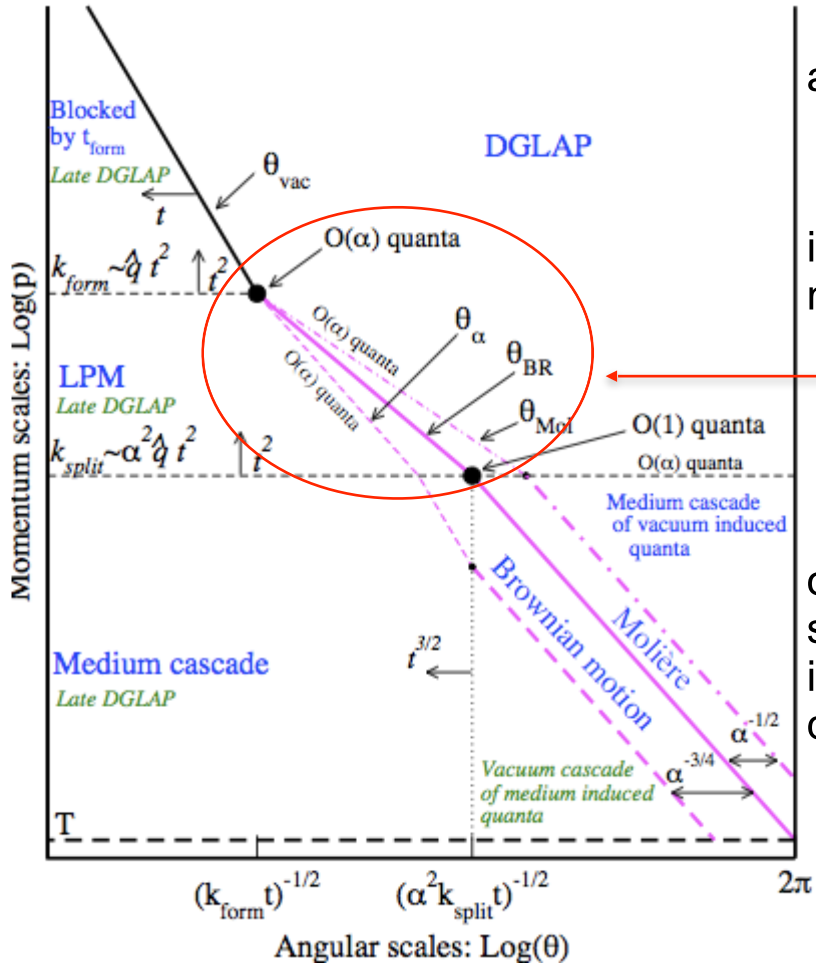


Essential to not let systematic, quantitative exp/theo comparison go stale

- Add new Run-1 data
- Predict/prepare for Run-2 data


from Thomas Schaefer
pQCD kinetic plasma
AdS/CFT low viscosity goo
QGP Microscopy

Angular and momentum structure
of intra-jet parton cascade



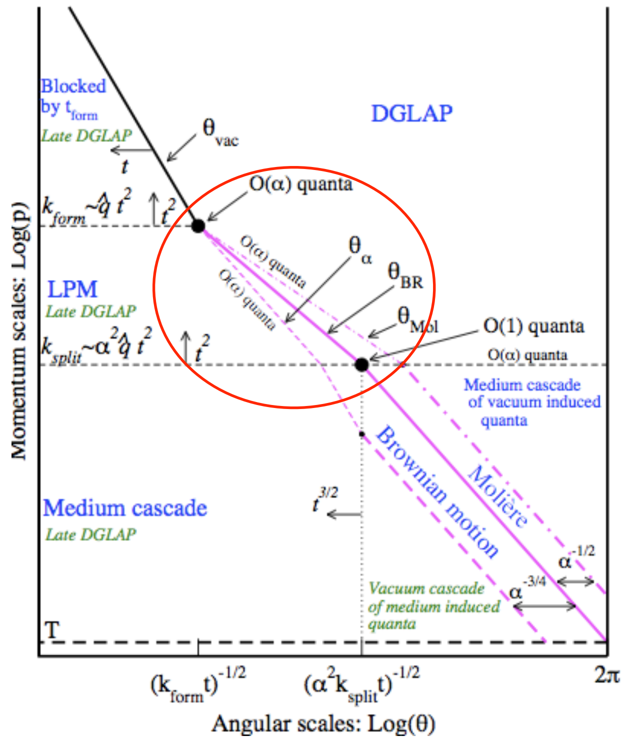
Jets evolve in momentum and angular space

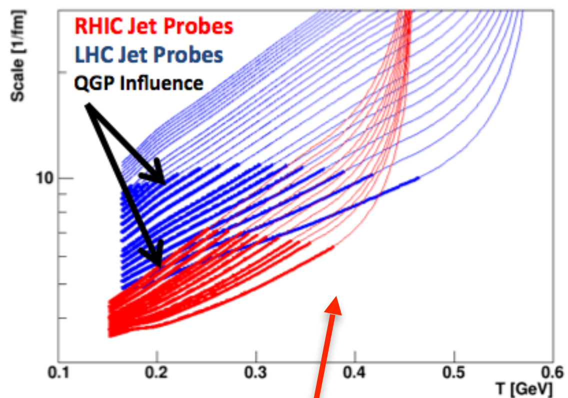
At different scales, evolution is dominated by different mechanisms:
- vacuum evolution
- (jet-constituent)-medium scattering
- in-medium cascade

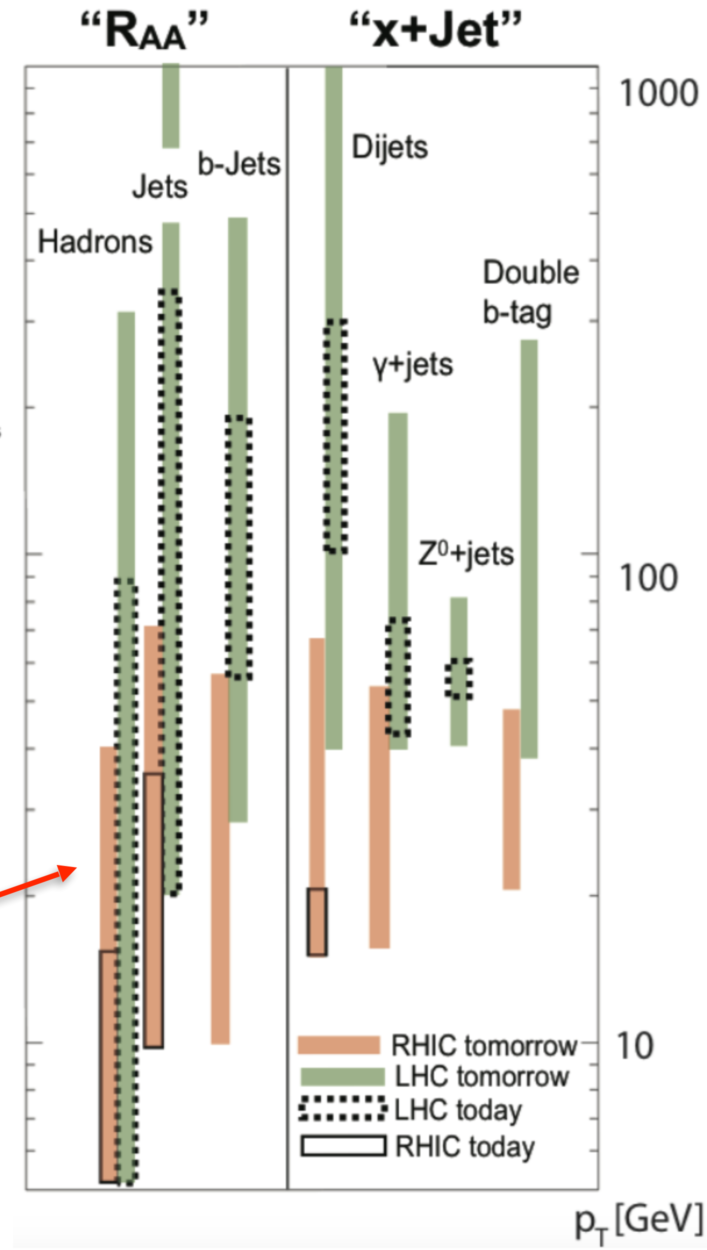
Detailed understanding of jet modifications on all scales may allow to isolate interactions with “QGP quasiparticles”

Kurkela, Wiedemann, arXiv:1407.0293

Force Multiplier: Jets at RHIC **and** LHC

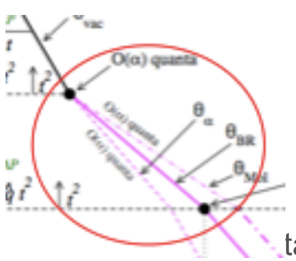






Future RHIC vs LHC Run 2:
- Probe different paths of QGP evolution
- Overlap in observables/kinematics

Isolate this

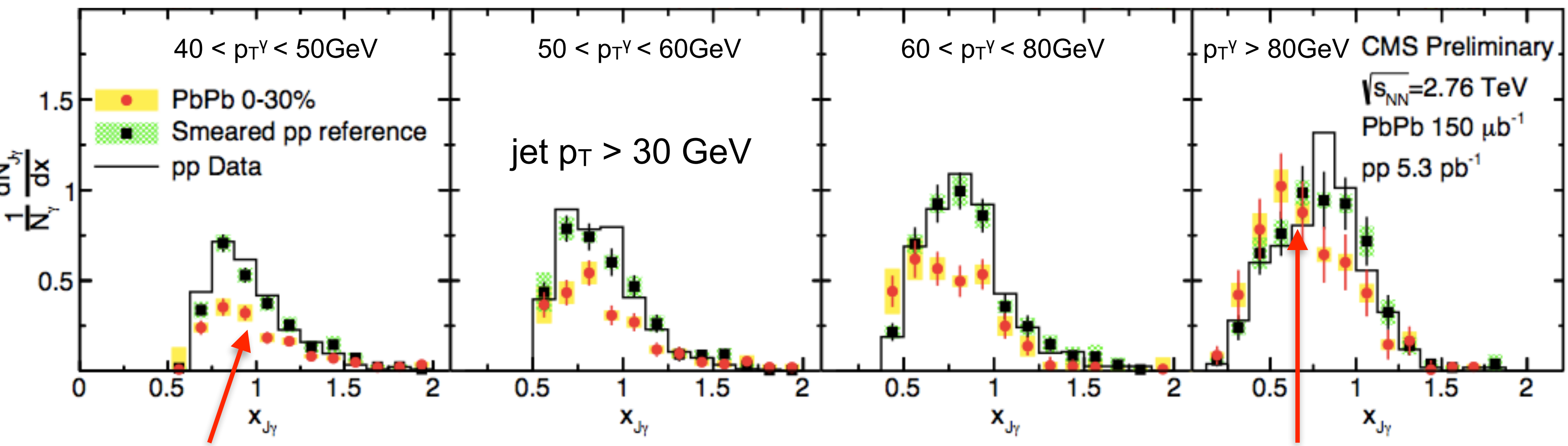


Run-2: Qualitative step forward for gamma-jet

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

Run 1 data

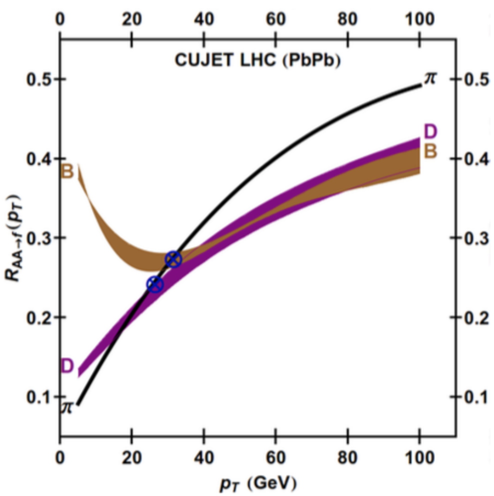


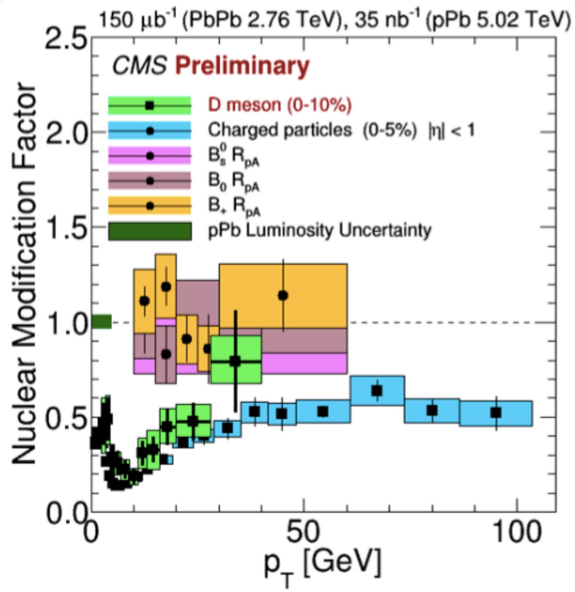
photon p_T <50GeV:
Spectrum of PbPb jets is **suppressed** vs pp
Biased jet selection

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

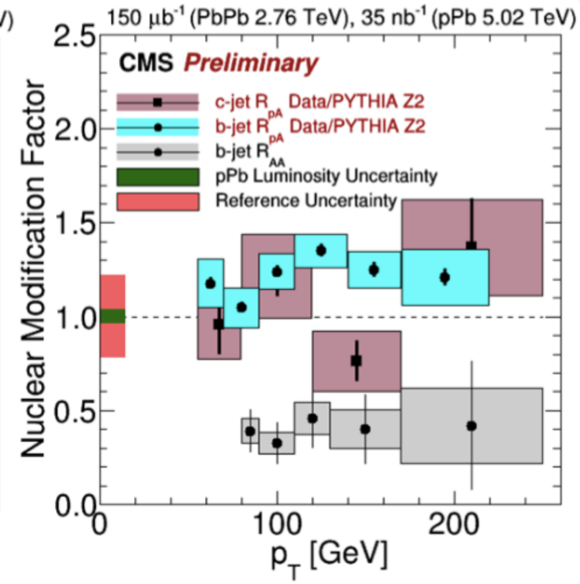
Run-2: Qualitative step forward for HF





B in pPb: arXiv 1508.06678

Prompt D^0 in PbPb: CMS-HIN-15-005



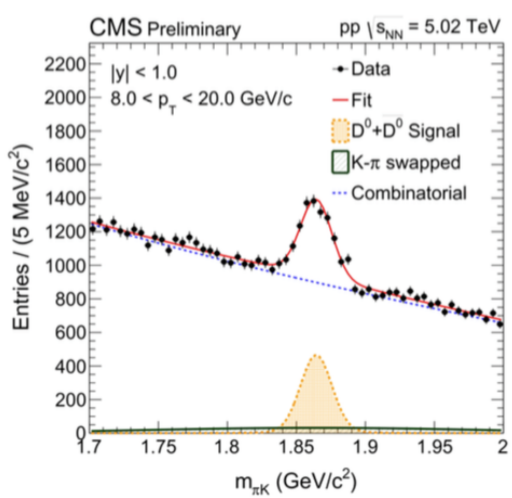
c-jet in pPb: CMS-HIN-15-012

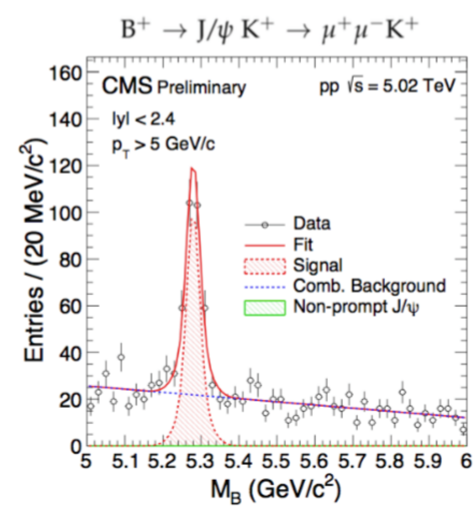
b-jet in pPb: CMS-HIN-14-007

b-jet in PbPb: PRL 113, 132301 (2014)

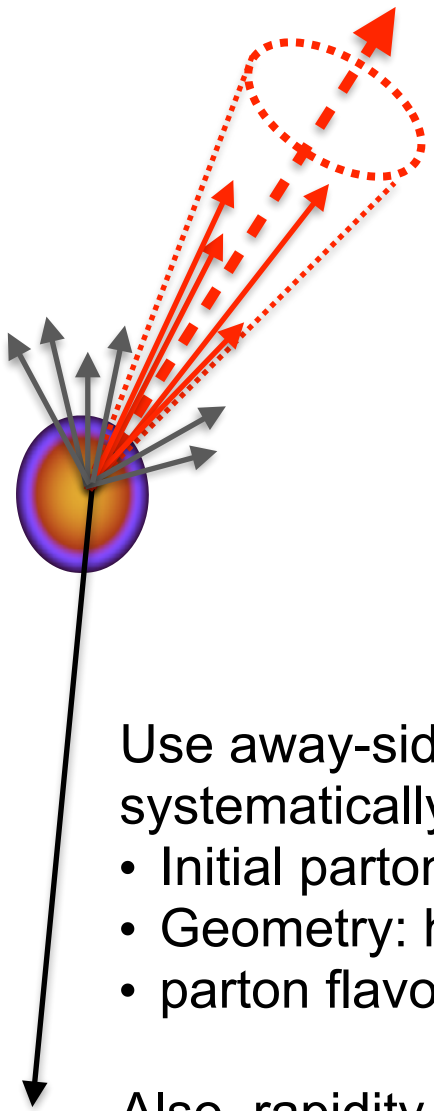
Run2:

- x10 higher statistics
- D from few GeV to > 100 GeV
- C-jets in PbPb
- Fully reco'd B in PbPb
- Double-tag b-dijets
- D,B's in jets
- ….





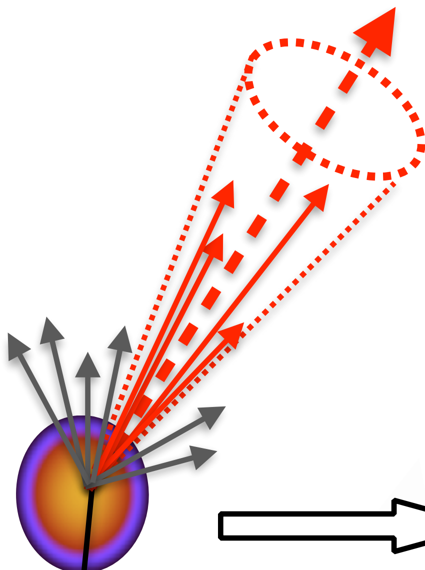
Theme for Run-2 (and sPHENIX) Jet Physics



Use away-side and/or same side tags to systematically control jet system:

- Initial parton energy, flavor: Z and γ tag
- Geometry: hadron vs jet vs Z/γ tag
- parton flavor/mass: D, B, c/b-tag, displaced J/ψ

Also, rapidity dependence to control flavor



Use charged tracks (and/or calo-based constituents) to characterize momentum flow relative to jet system

- Integrate to traditional jet shapes, fragmentation func's
- In-cone vs out-of-cone energy distributions
- Jet-substructure and jet-by-jet classifiers

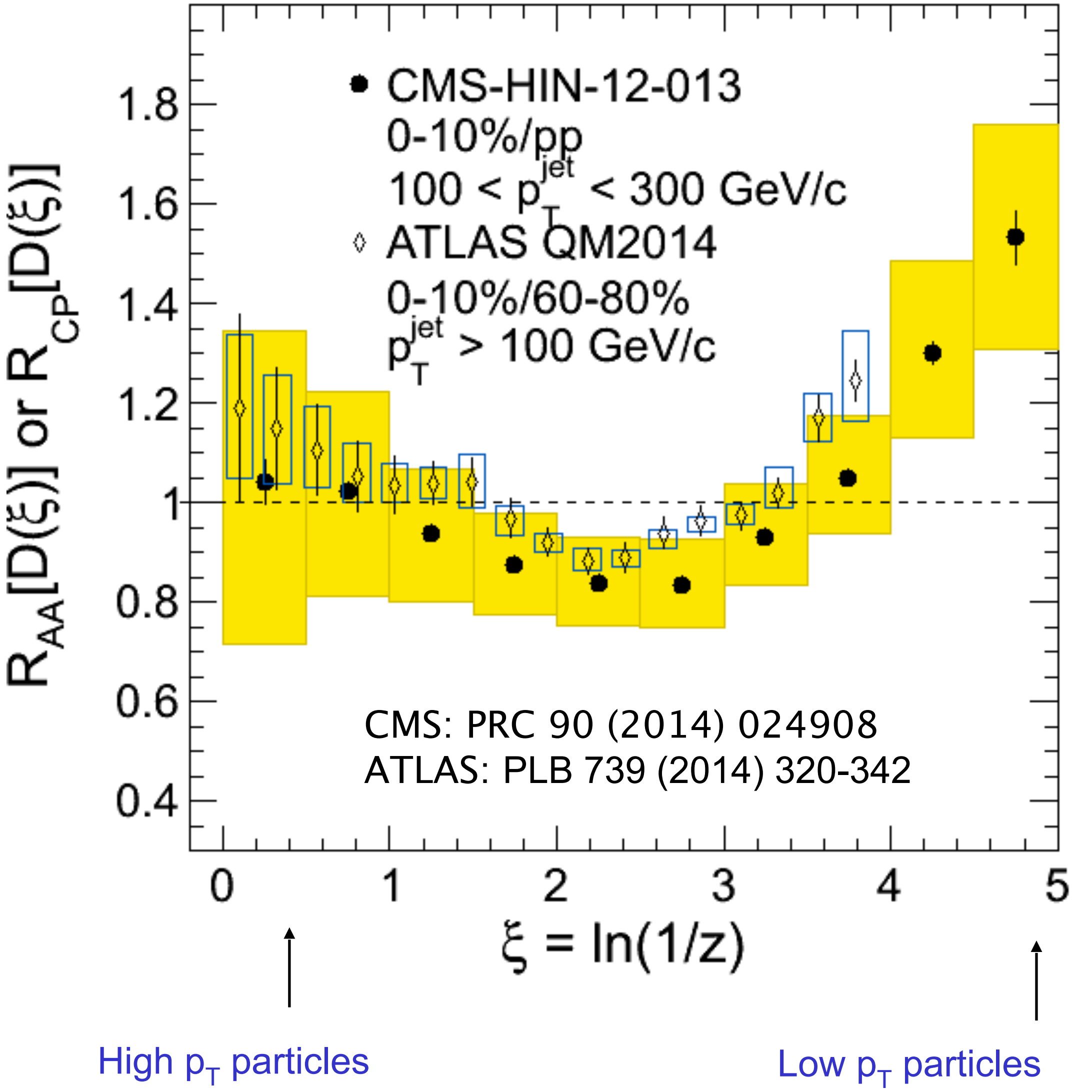
$C_2(p_T, \Delta\eta, \Delta\varphi)$

Use away-side and/or same side tags to systematically control jet system:

- Initial parton energy, flavor: Z and γ tag
- Geometry: hadron vs jet vs Z/γ tag
- parton flavor/mass: D, B, c/b-tag, displaced J/ψ

Also, rapidity dependence to control flavor

But there is a *long* road ahead…



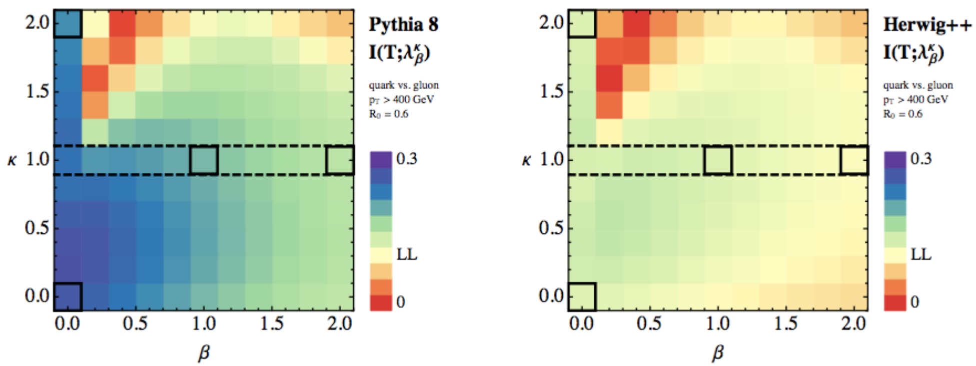
$Z = p_{||}^{Trk} / p^{Jet}$

Qualitative consistent results between CMS and ATLAS

But: Experiment-comparison suggests that we do NOT YET have sufficient control over systematics necessary for our decadal program

Jet structure in pp and PbPb

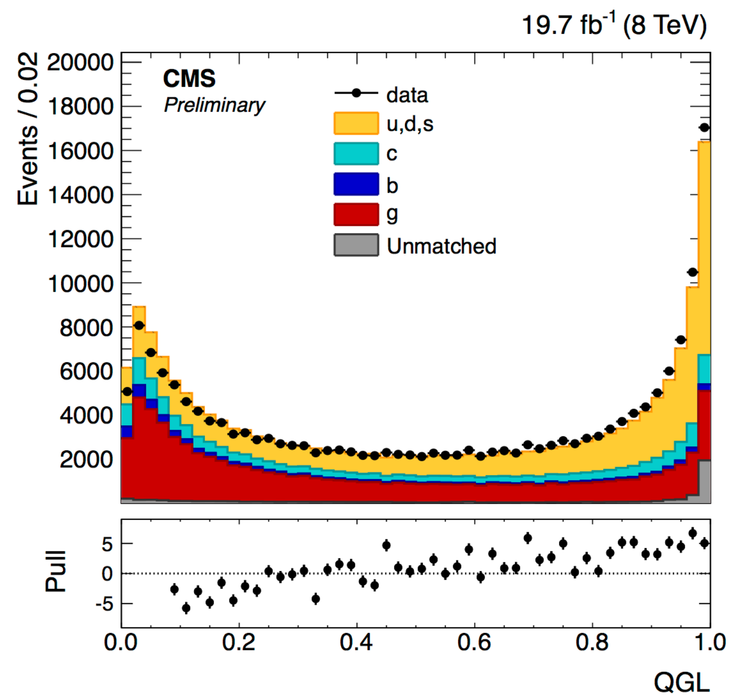
Jesse Thaler, Boost 2014



$$\lambda^\kappa_\beta = \sum_{i \in \mathrm{jet}} z_i^\kappa \theta_i^\beta$$

momentum fraction — angle to recoil-free axis

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



Quark/gluon discrimination in pp

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

Not directly applicable for g/q in AA
(use γ-jet, Z-jet, b/c tag, 3-jet)

Stability vs pp pileup is major issue

But: use QGL or similar to look jet-by-jet quenching

Convergence of AA and pp needs

Summary

- Rich harvest of CMS jet results from LHC Run-1
- Run-2 has started
  - 2015 run improves jet statistics by ~ order of magnitude
  - Allows detailed studies of tagged initial states
    - Z+Jet, photon-jet, HF jets,….
  - Complete characterization of final state
    - Jet-track correlations in-cone and out-of-cone
      - Jet shapes, FF, sub-structure
    - Jet tagging (c, b-jets)
- Need continuous experiment-theory dialog
- Need detector with excellent calorimetric/tracking/HF capabilities (@LHC & RHIC)