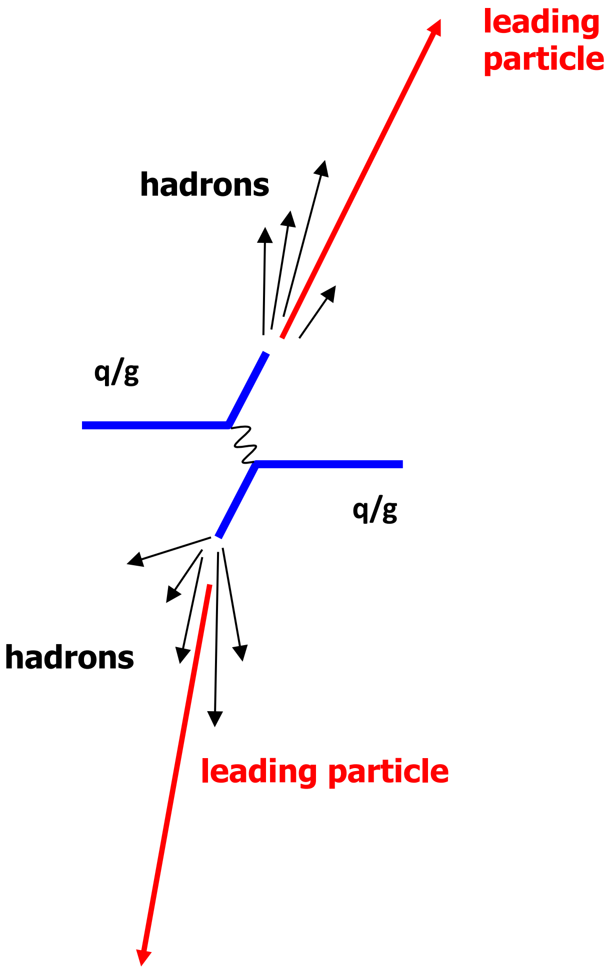
Introduction to Heavy Ion Collisions – Experimental

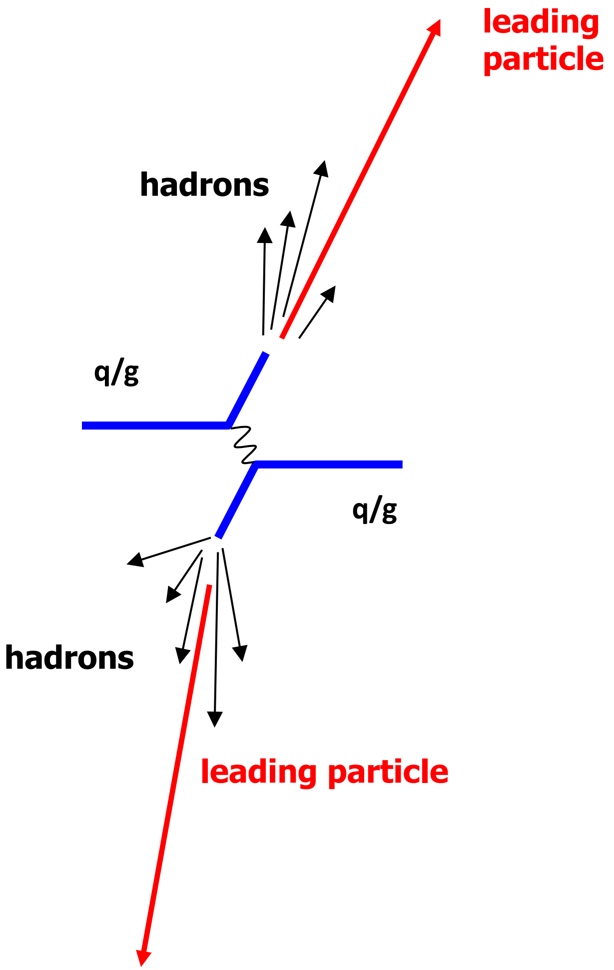
Part2 Jet

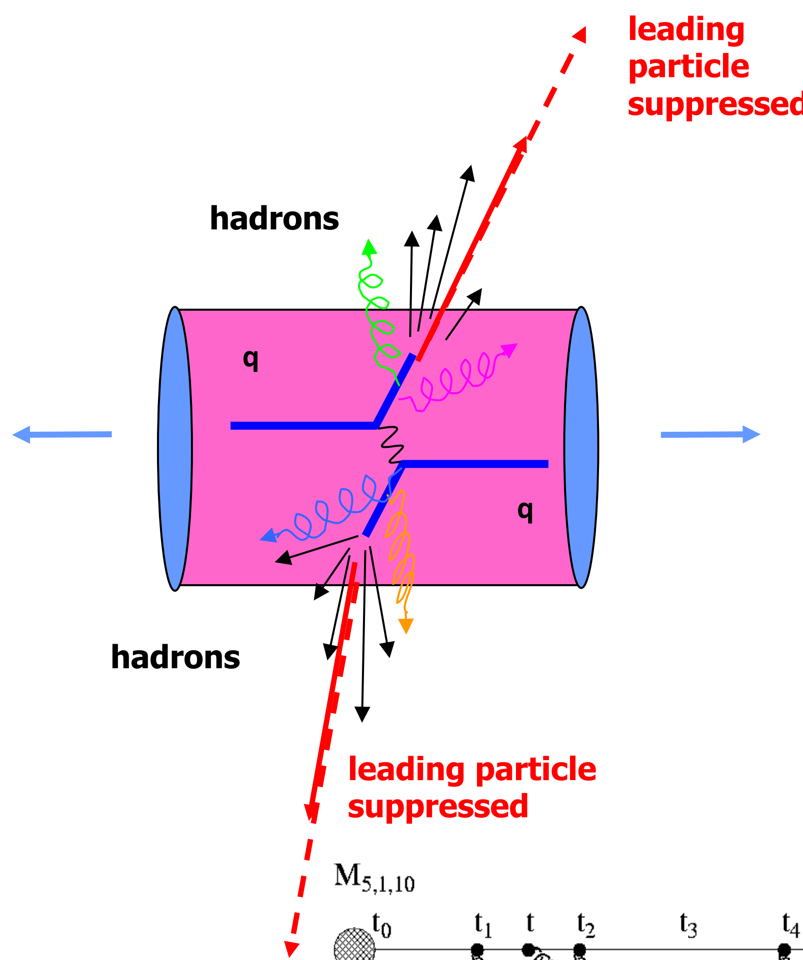
陈震宇
山东大学

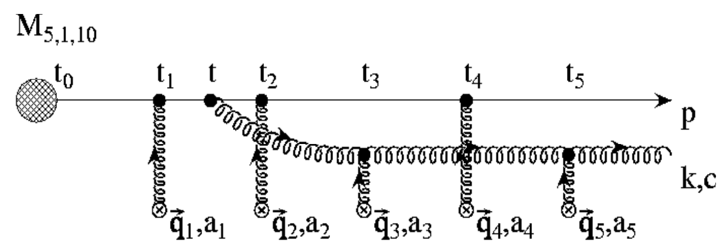
What is jet?



What is jet quenching?

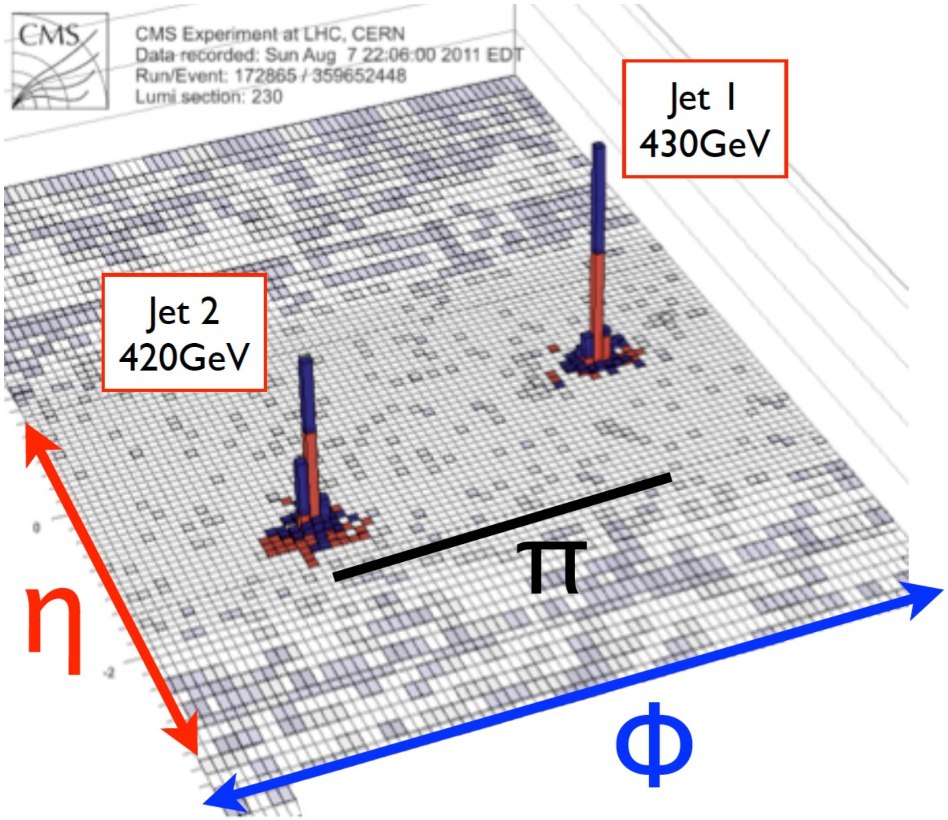


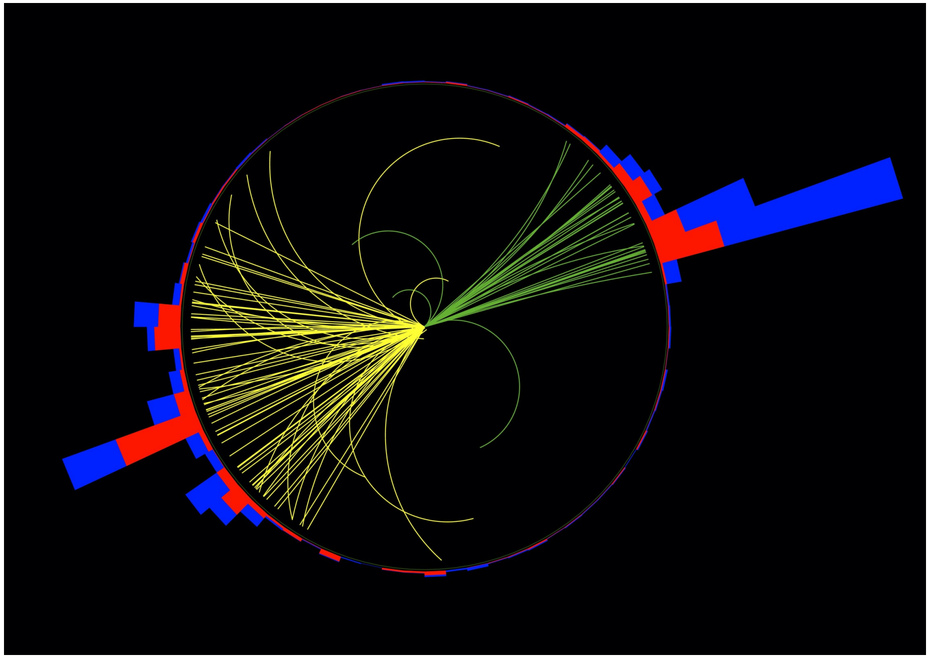




Source of energy loss: medium-induced gluon Bremsstrahlung + elastic scattering

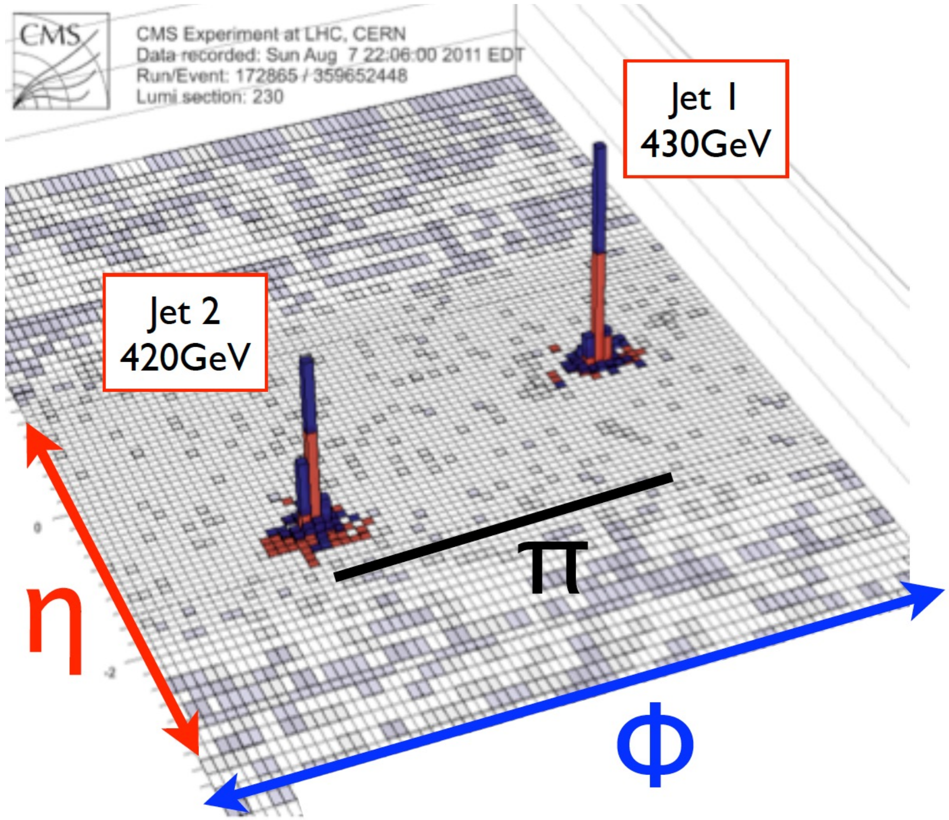
Jets seen by detectors

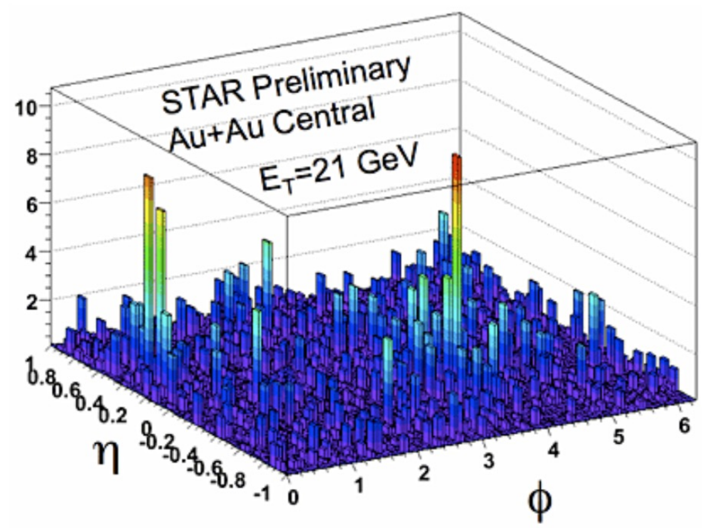




Jet finding is easy
High pT jets, pp collision

Jets seen by detectors



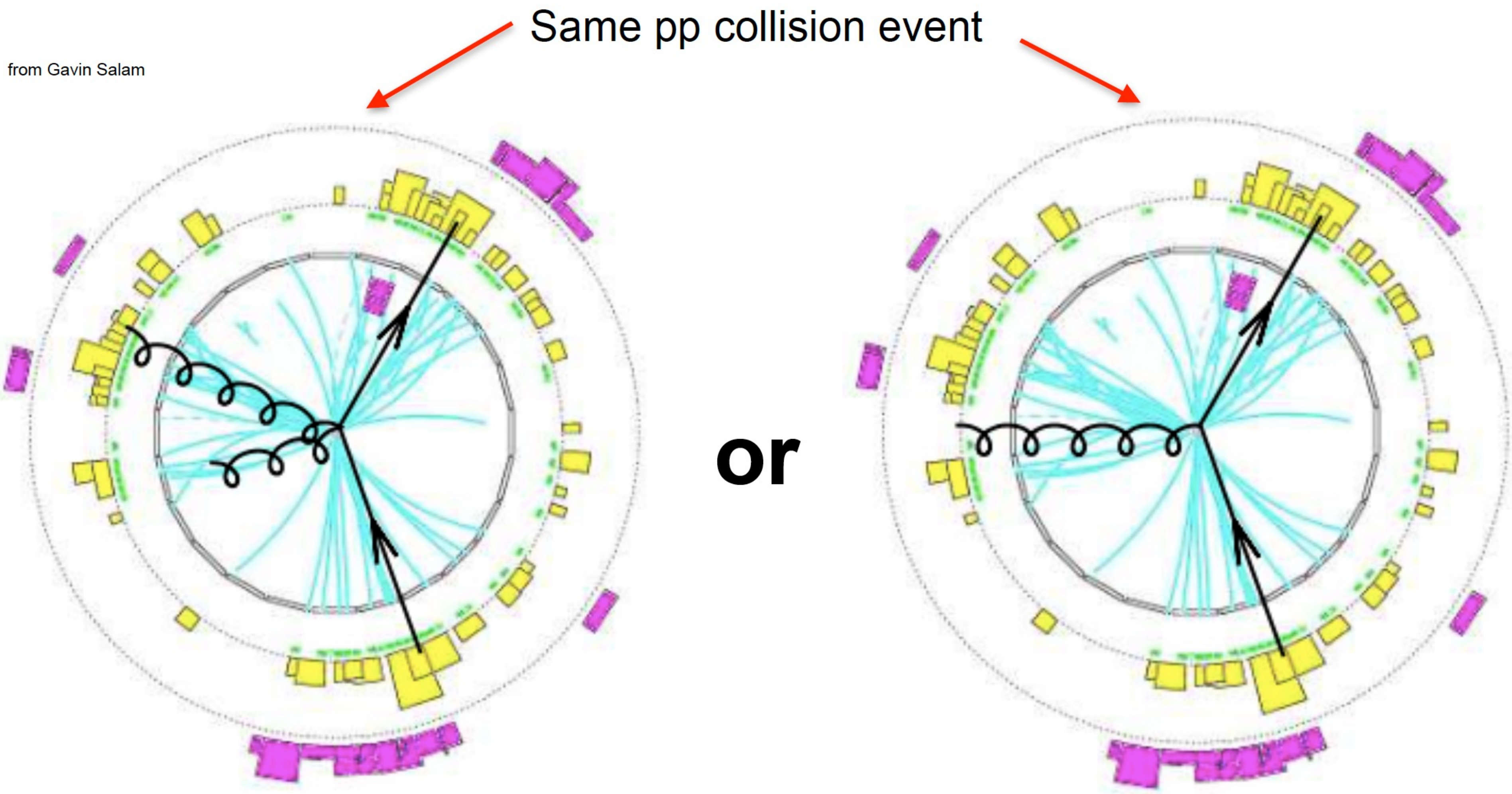


Jet finding is easy
High pT jets, pp collision

…until it is not
Low pT jets, heavy-ion collision underlying events

Jets seen by detectors

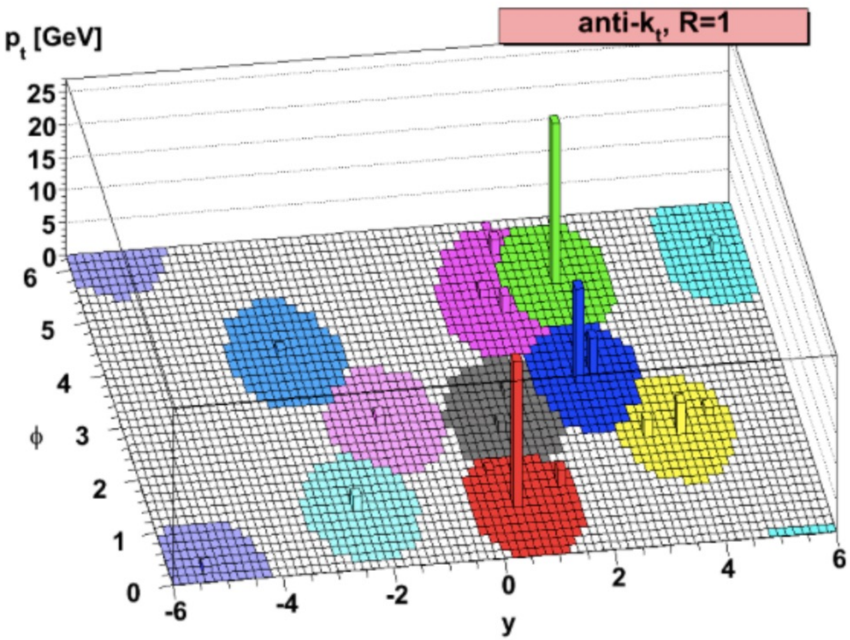
from Gavin Salam



Need to **define** jet in experiment **and** theory

Jet reconstruction

A jet is what Cacciari, Salam & Soyez say it is!



2008 Fastjet revolution JHEP 0804 (2008) 063

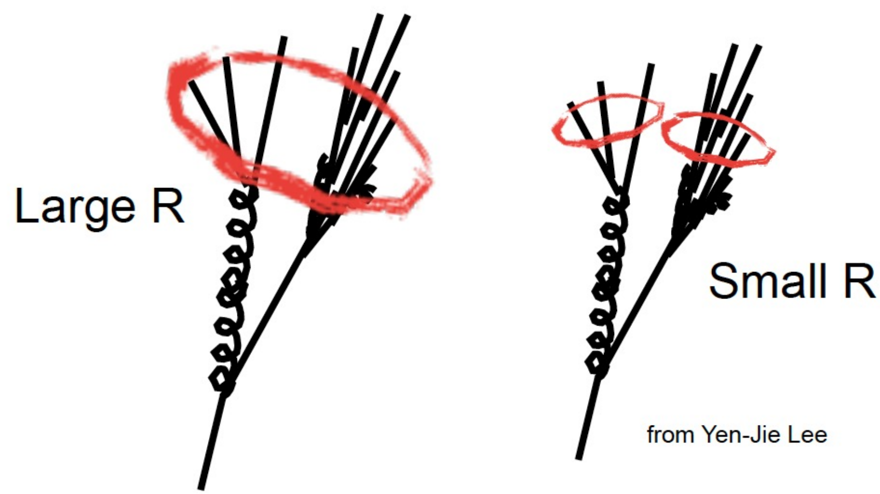
"anti-kT" replaces zoo of prior algorithms:

- Conceptually simple
- Theoretically sound
  - Infrared safe
  - Colinear safe
- Computationally efficient & robust
- Ready-to-use package

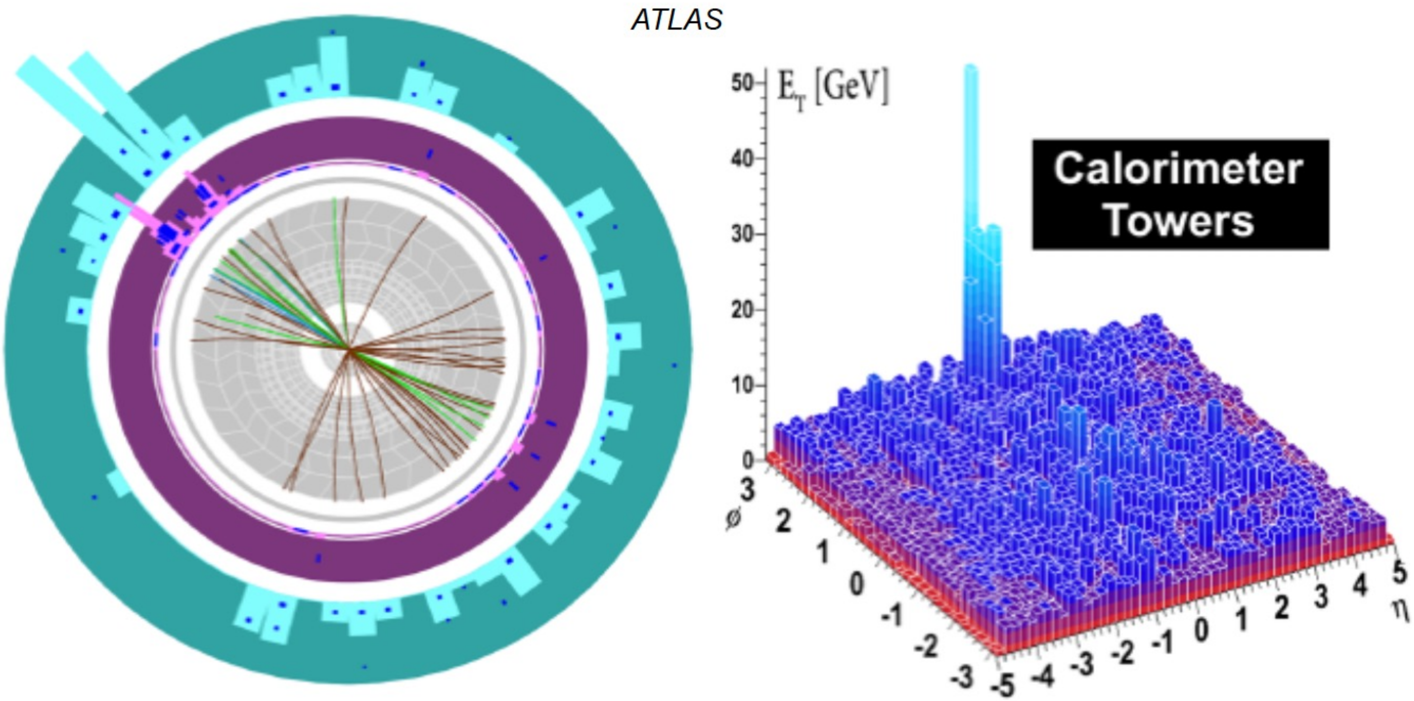
Anti-k_T:

Sequential clustering of objects in event (calo towers, tracks etc) with a particular distance R

Results in cone-shaped, approximately R-sized jets



Jet reconstruction in heavy-ion collisions



Jets sit on top of large underlying event (UE)
Need to decide which particles are part of jet and which belong to UE:
UE subtraction

Current methods assume UE under jet is same as elsewhere in the event
i.e. UE modification due to jets manifest as part of jet

Jet physics without jet

First RHIC Run: Charged Hadron R_{AA}

The start of jet physics in Heavy Ion in 2001

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum”}}$$

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

$\langle T_{AA}\rangle = N_{coll}/\sigma_{inel}^{NN}$

N_{coll}: Number of binary nucleon-nucleon collisions

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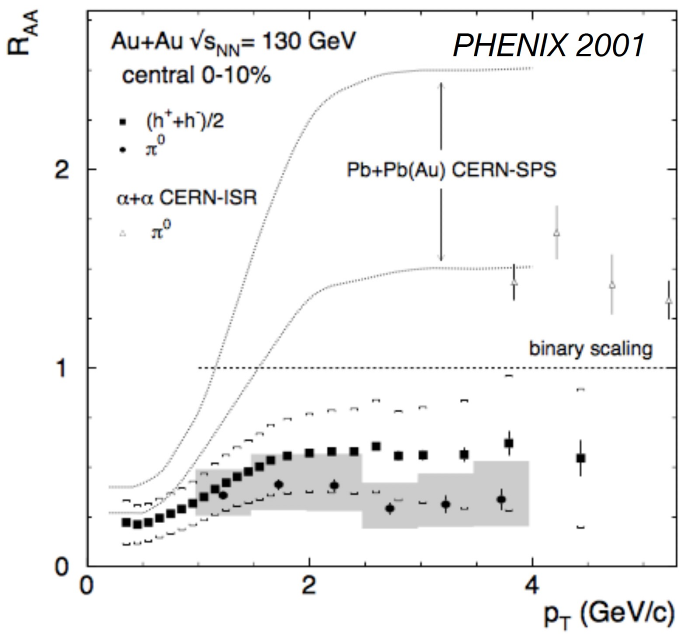

High pT particle as proxy of fragmenting parton

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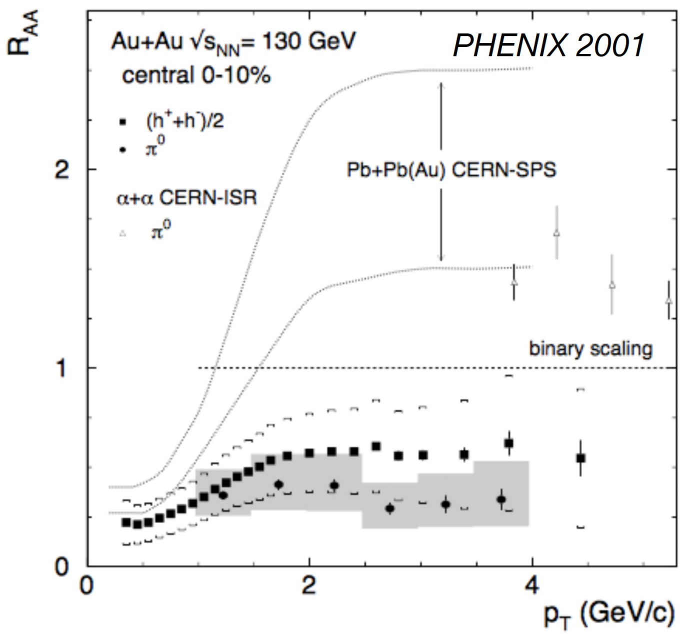
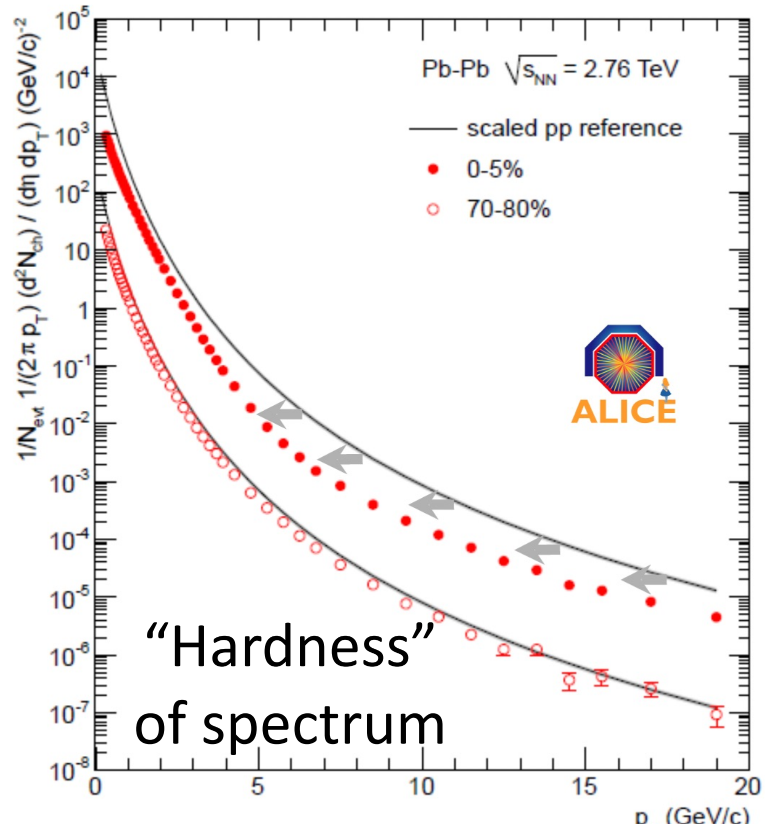
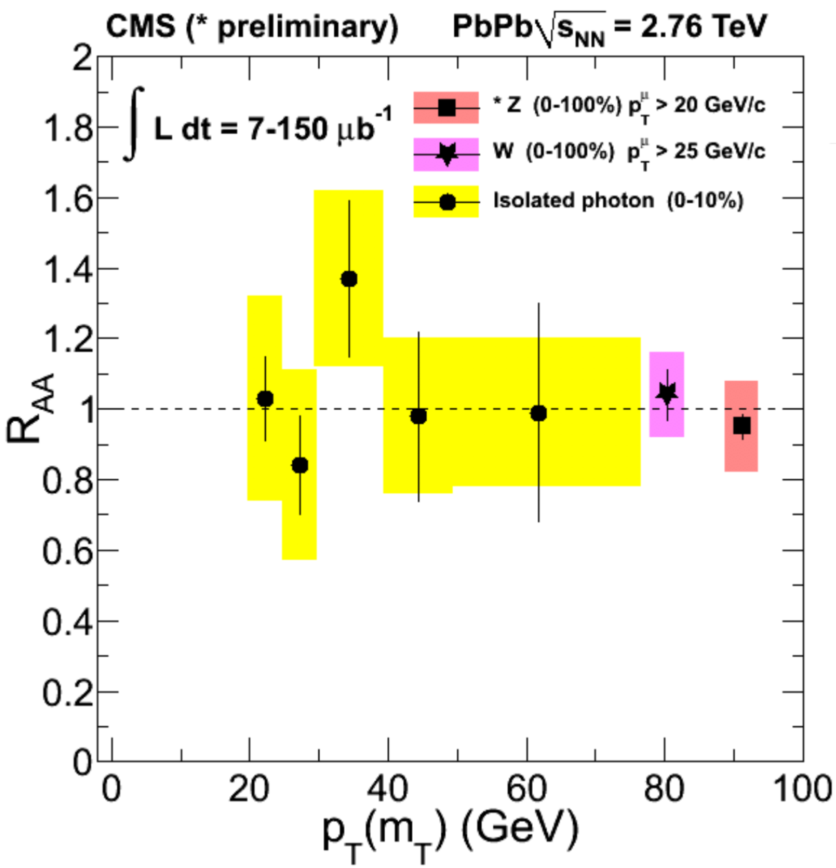


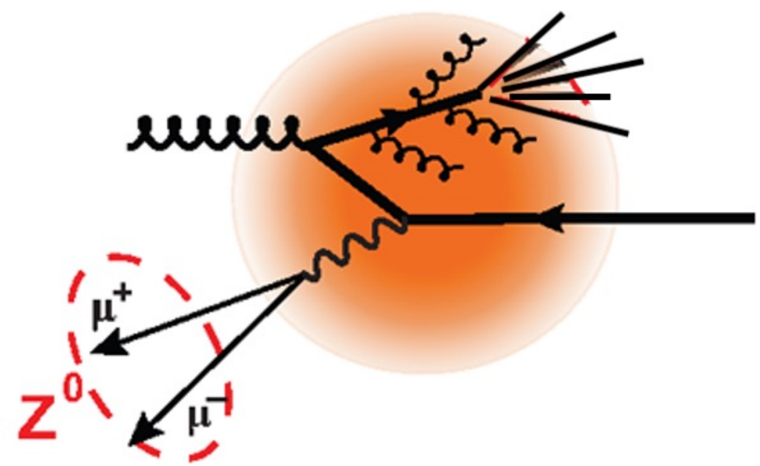
High pT particle as proxy of fragmenting parton



“Hardness” of spectrum

Verifying N_{coll} scaling



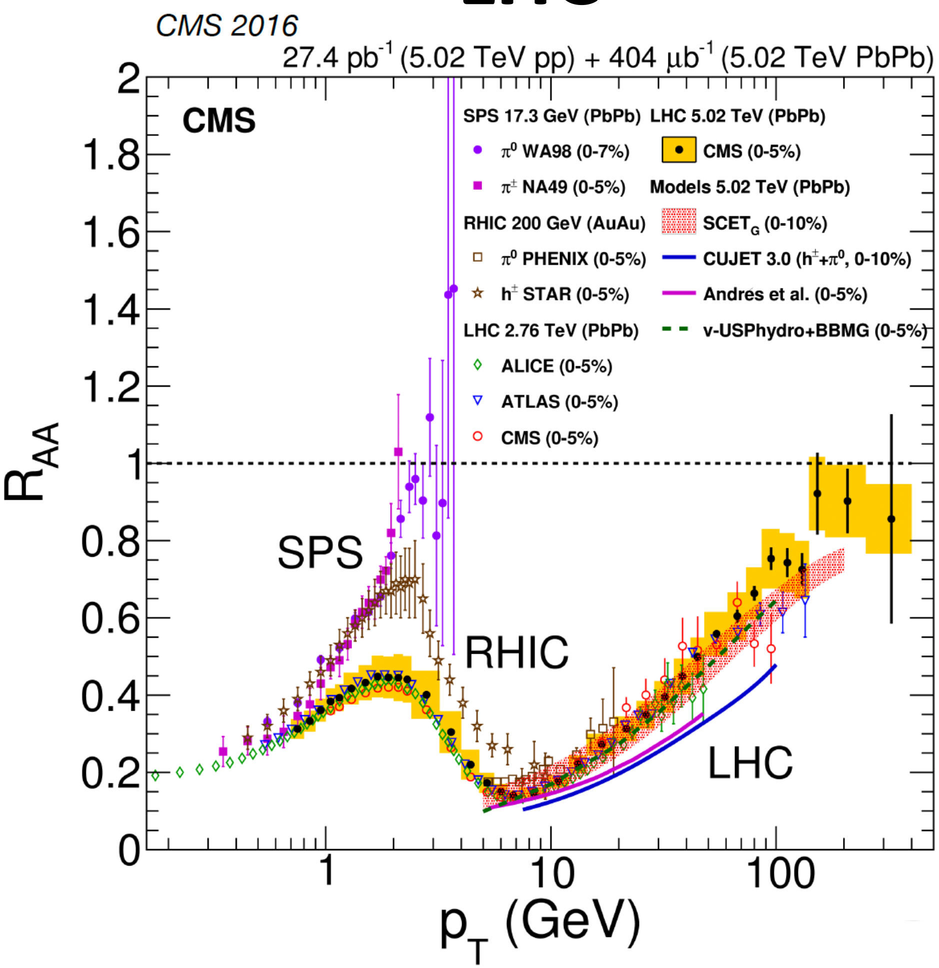


High pT photons, Z and W bosons produced in initial N+N collision

Escape QGP without interaction -> R_{AA} = 1

Up-to-date R_{AA} measurements

LHC



Precise measurement up to very high pT

Up-to-date R_{AA} measurements

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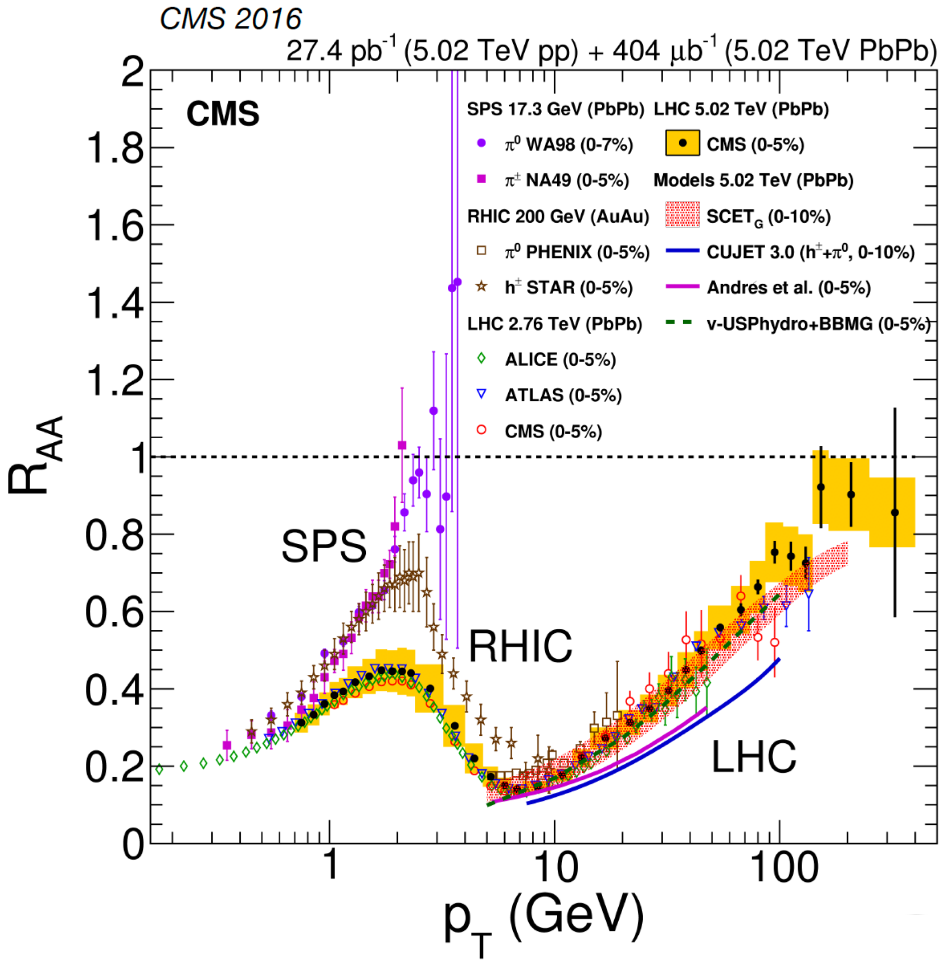
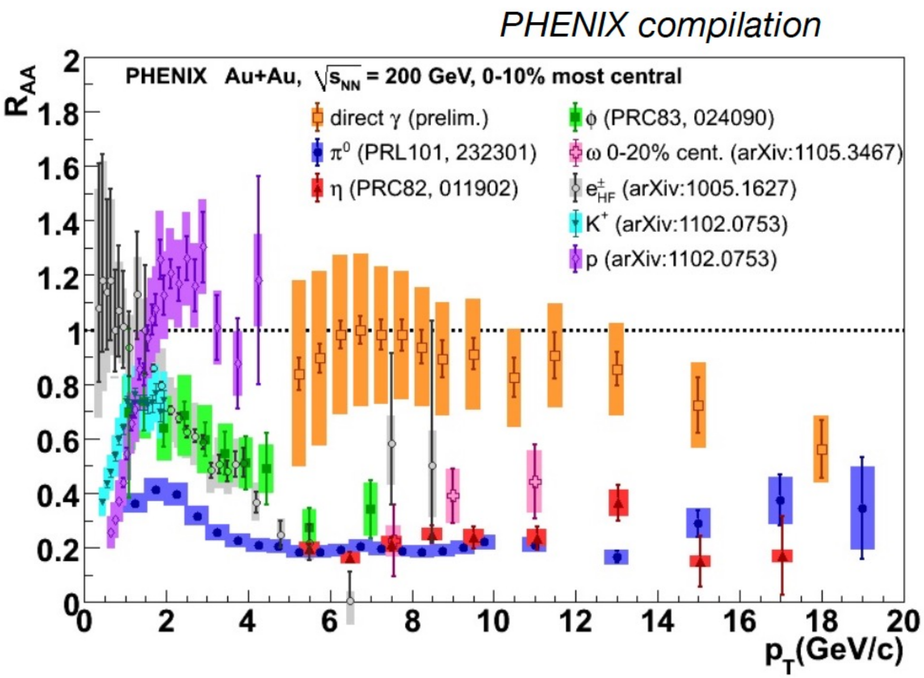


RHIC

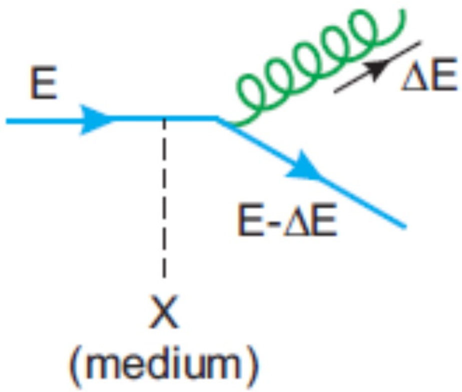


Precise measurement up to very high pT

Also for identified particles

QGP transport coefficients

Radiative
energy loss

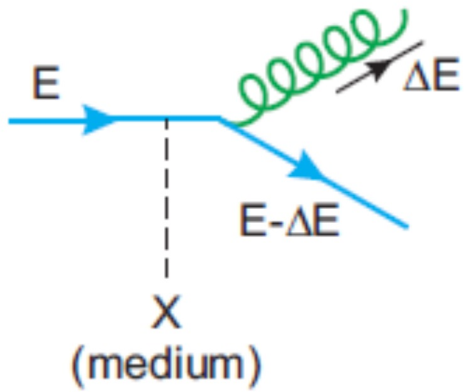


Medium effects on jets allow extraction of QGP transport coefficients:

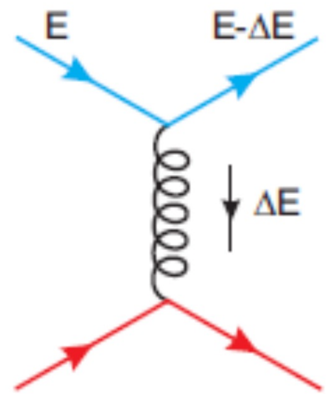
q: radiative energy loss
Induced gluon emission in medium

QGP transport coefficients

Radiative energy loss



Collisional energy loss

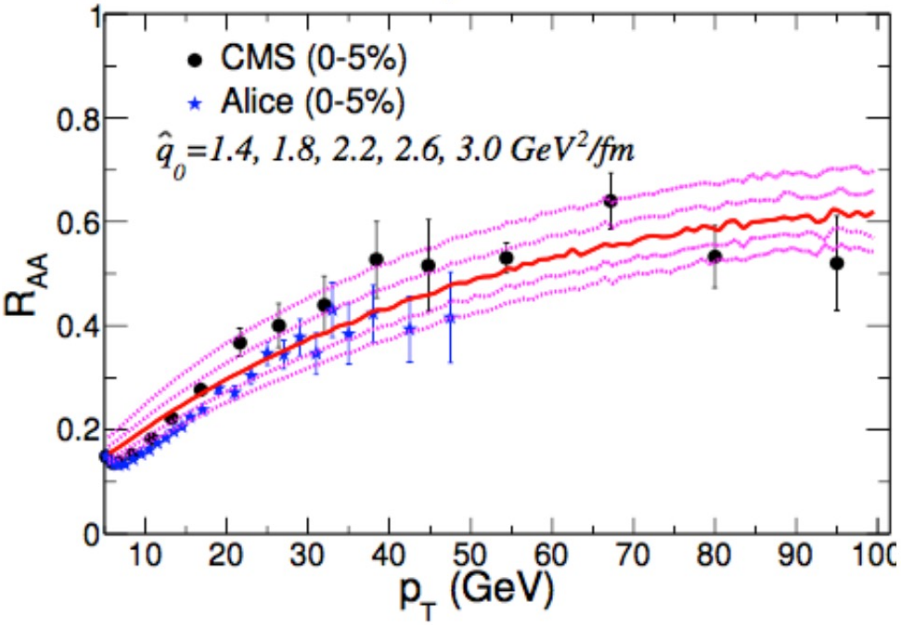


Medium effects on jets allow extraction of QGP transport coefficients:

q: radiative energy loss
Induced gluon emission in medium

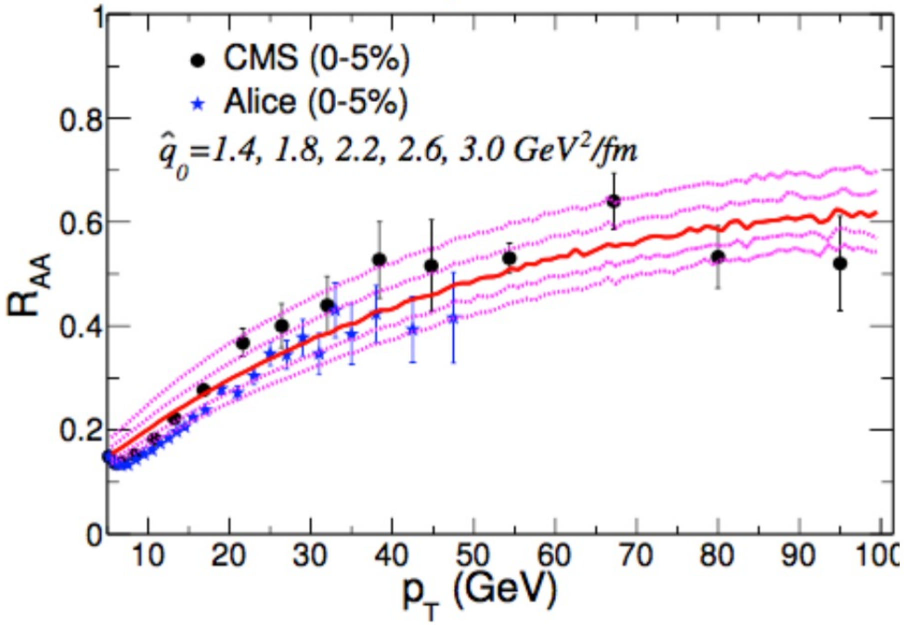
e: collisional energy loss
Collisions with medium partons

QGP transport coefficients

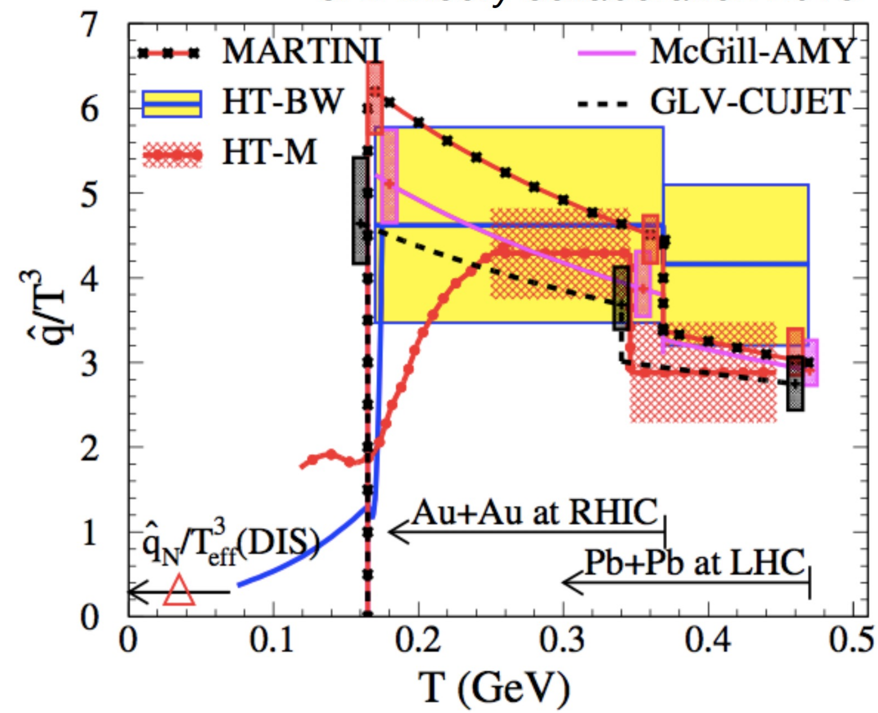


Combined RHIC and LHC data provide test for model consistency

QGP transport coefficients

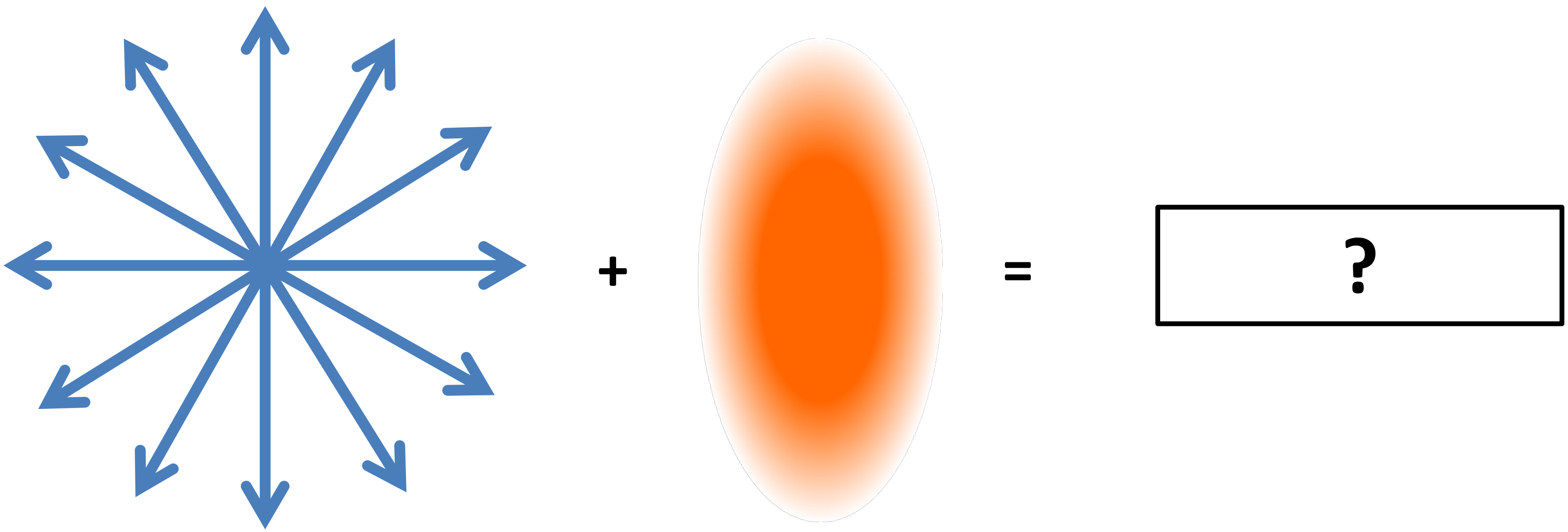


JET theory collaboration 2013



Combined RHIC and LHC data provide test for model consistency
q determined with about 35% uncertainty (in 2013)

Collectivity of high p_T particle



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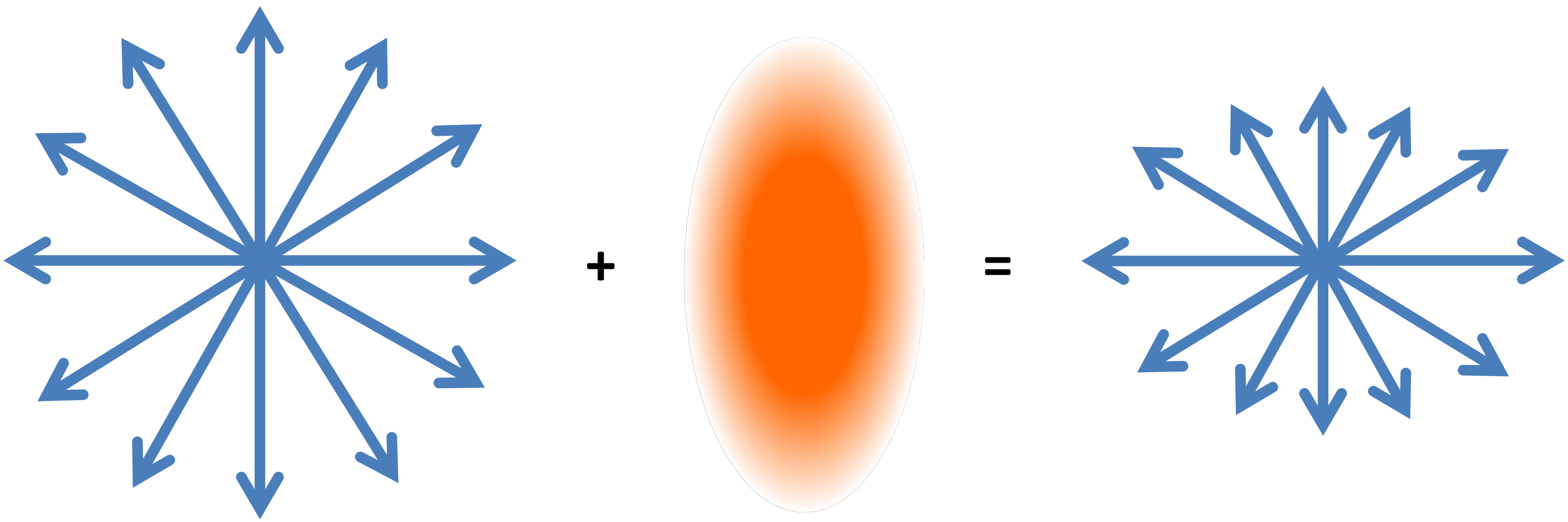
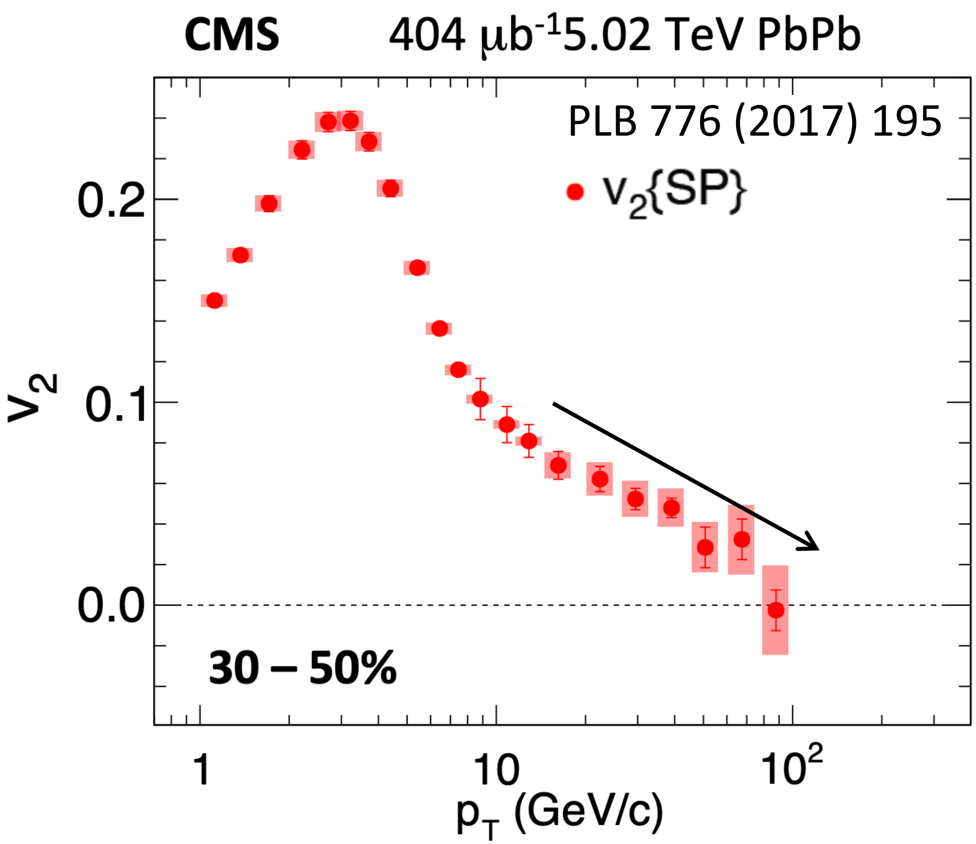


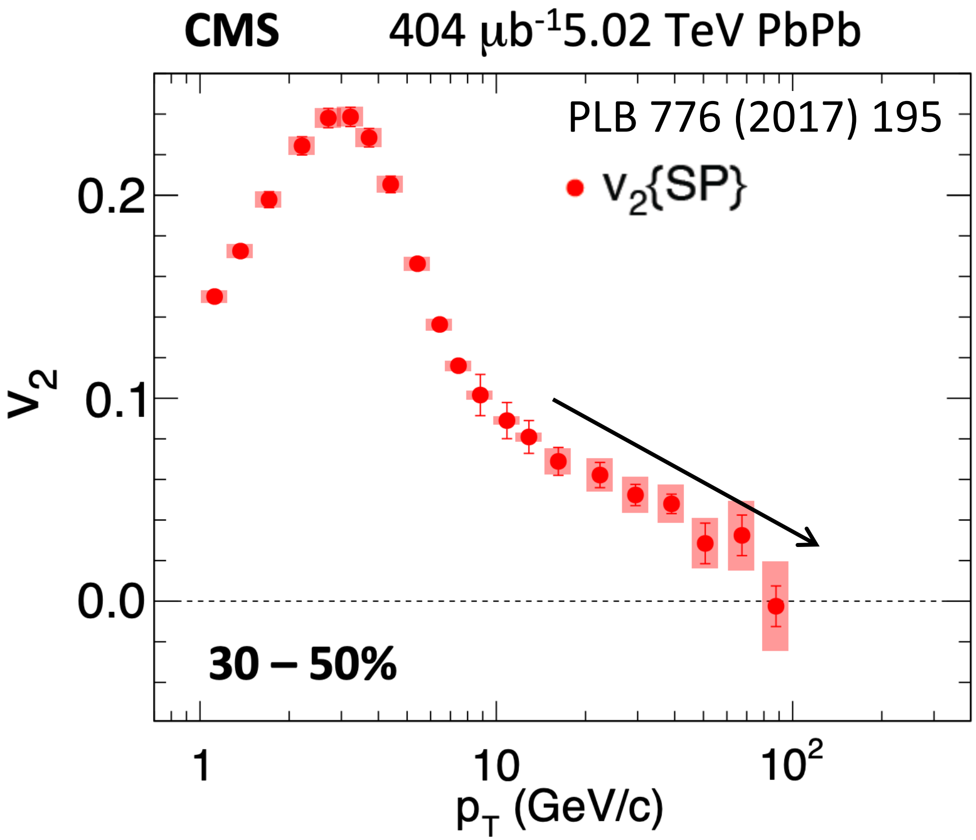
Anisotropic azimuthal distribution of high-p_T particles
Path length dependence of energy loss

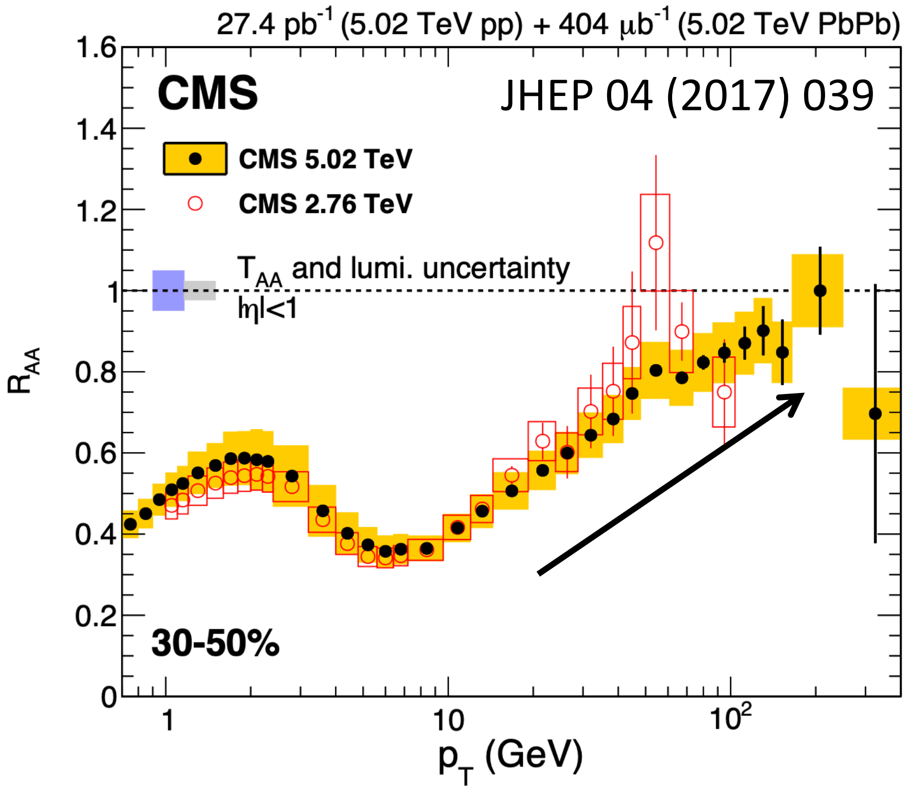
Collectivity of high p_T particle



Sizable v_2 up to 100 GeV

Collectivity of high p_T particle

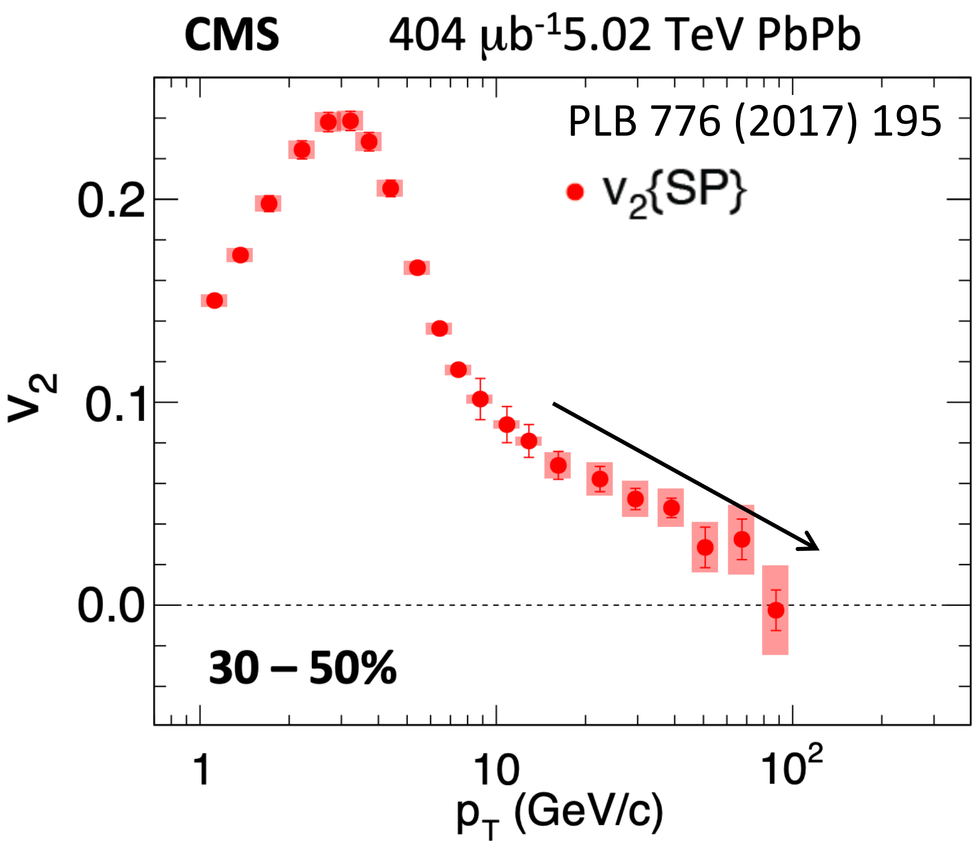


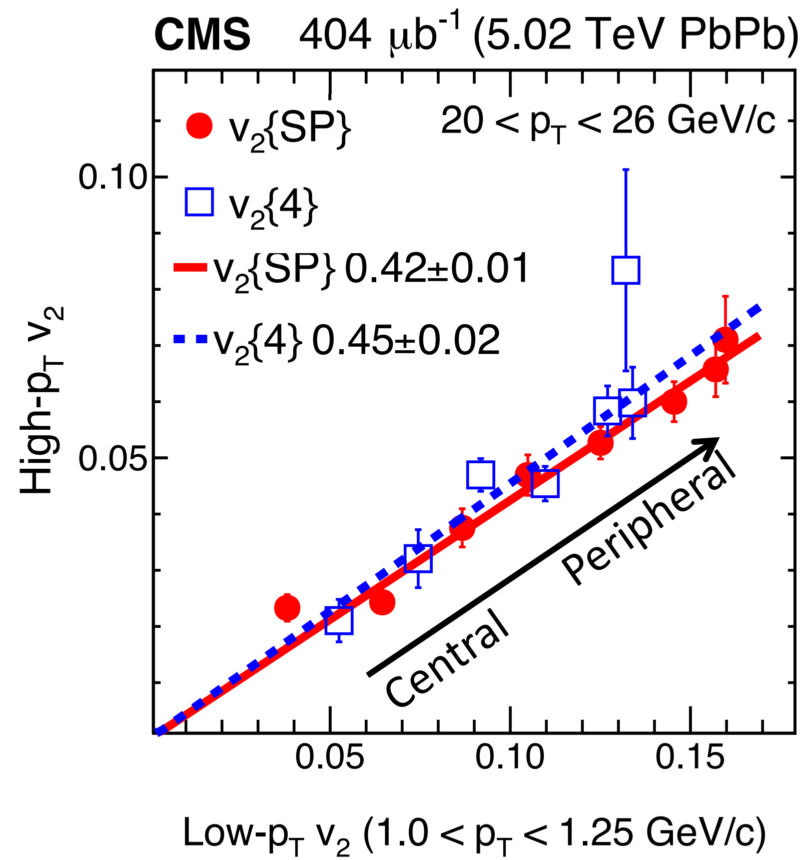


Sizable v_2 up to 100 GeV

Higher p_T particles less suppressed -> v_2 approach 0

Collectivity of high p_T particle





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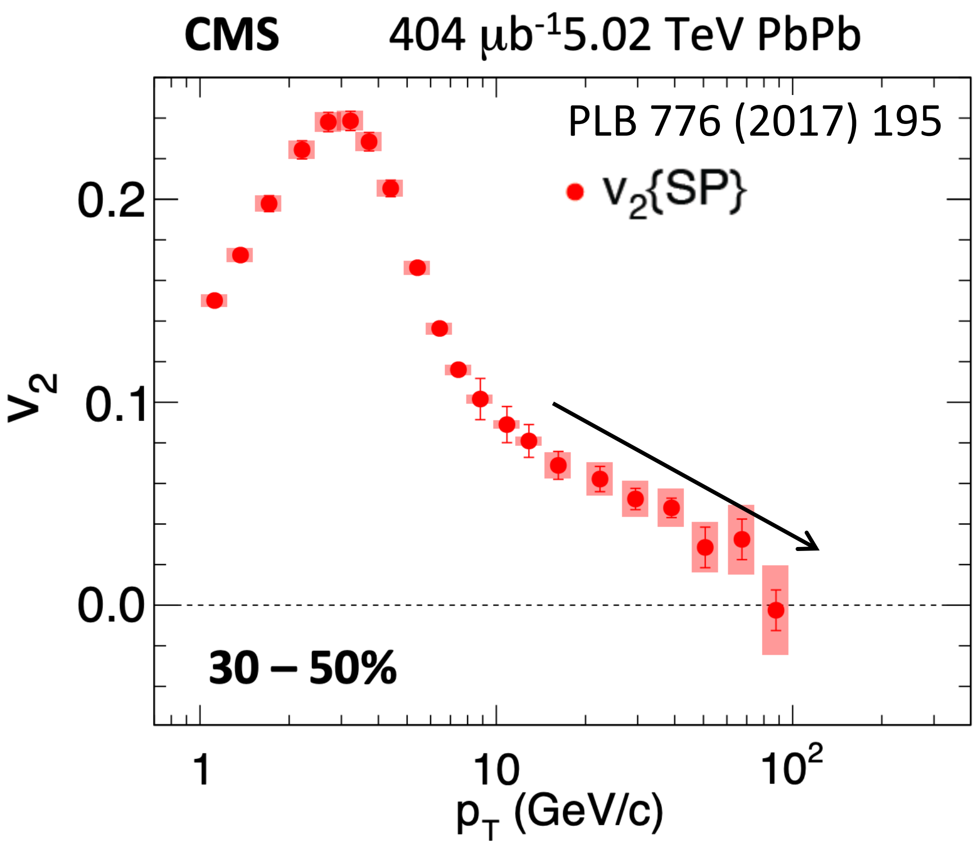
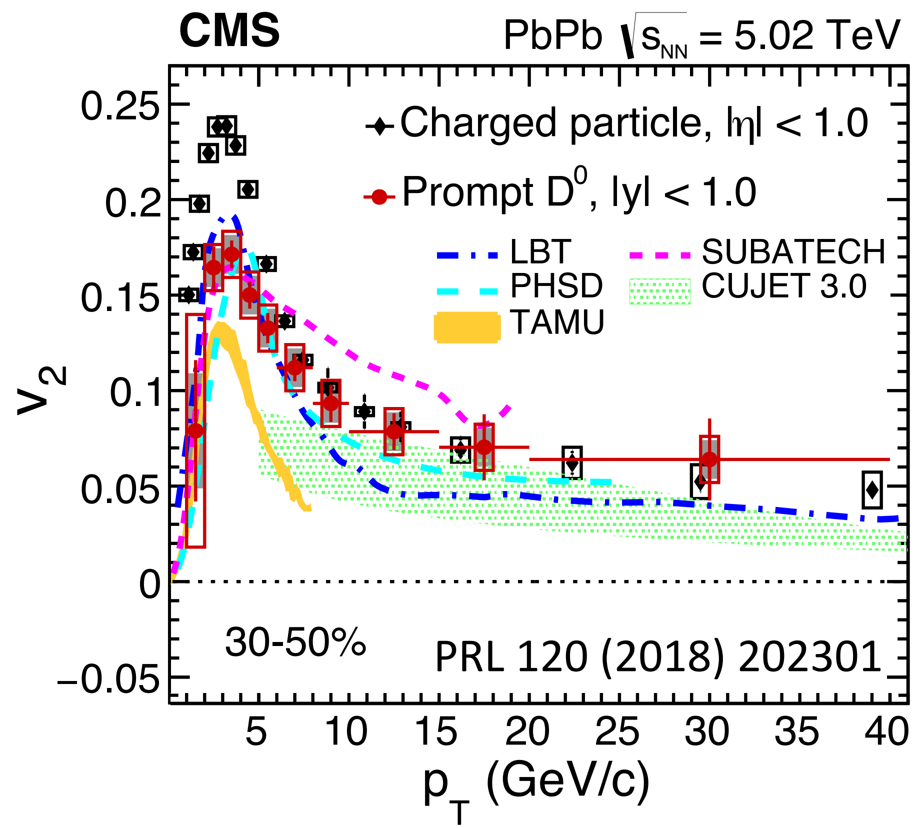
Strong correlation between low & high p_T v_2

Collectivity of high p_T particle





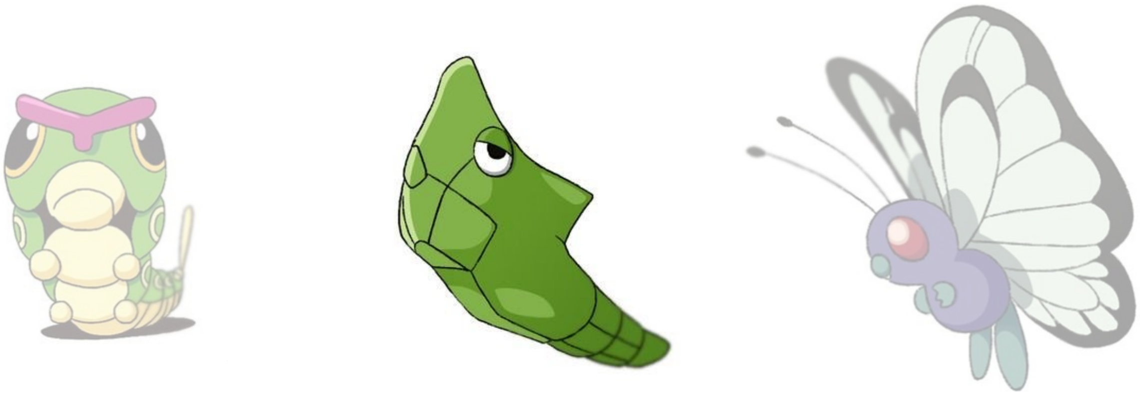
Sizable v_2 up to 100 GeV

Higher p_T particles less suppressed -> v_2 approach 0

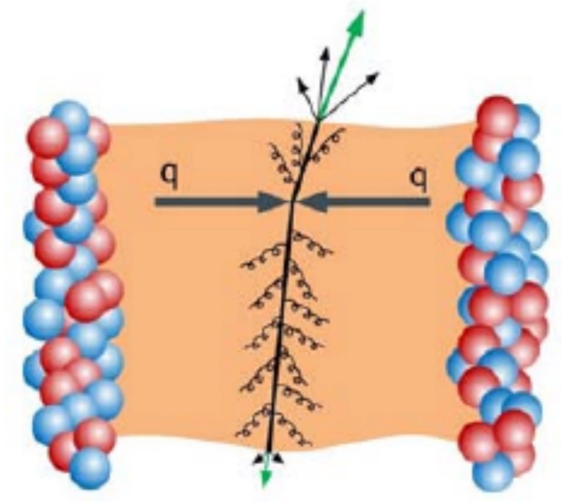
Strong correlation between low & high p_T v_2

Stringent constraints for energy loss models

Jet physics with jets



Dijet asymmetry



Dijet momentum imbalance

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

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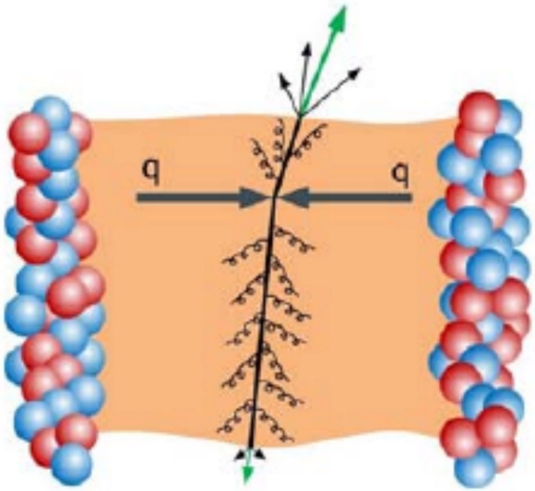

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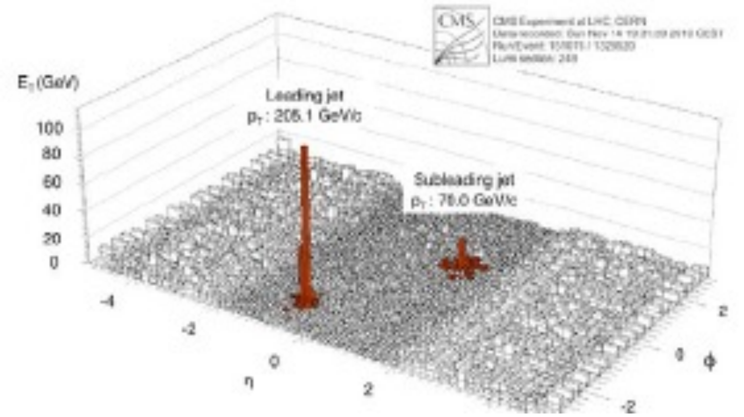

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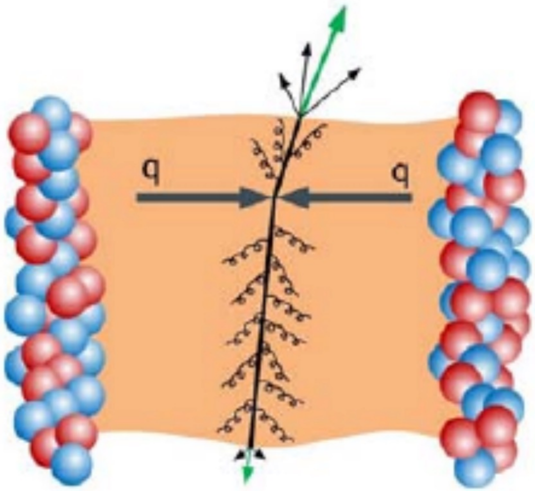

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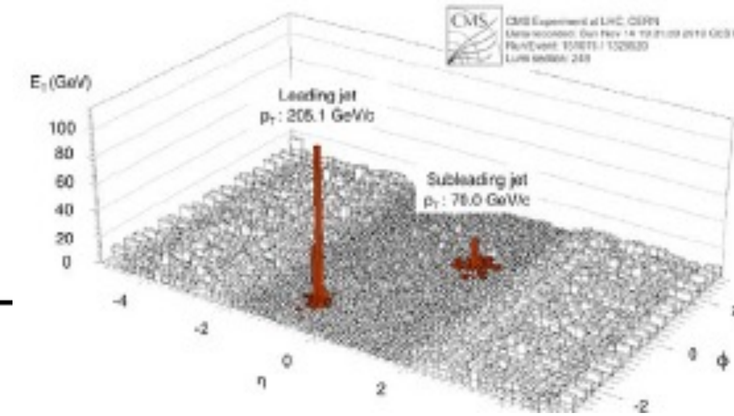
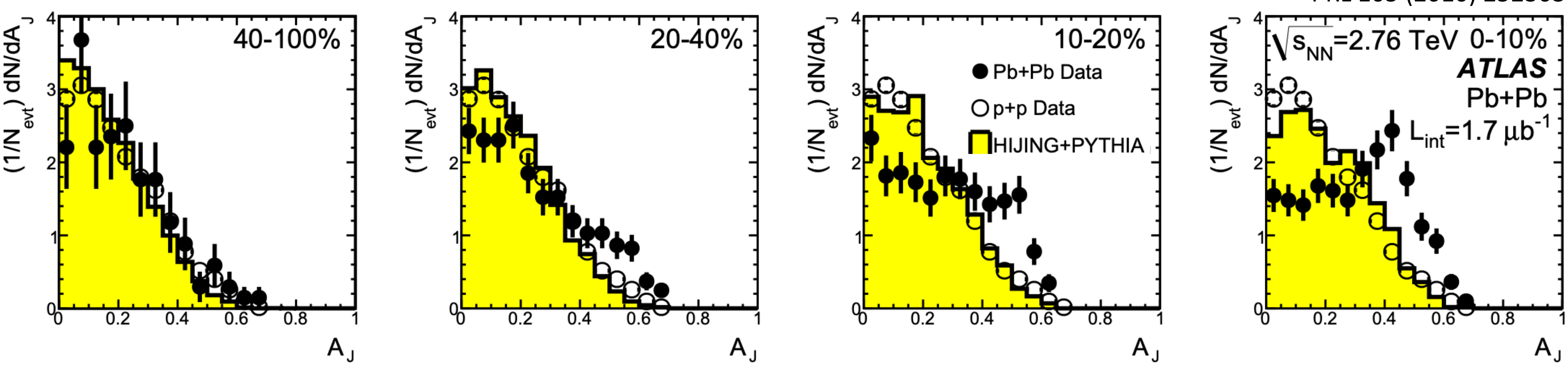
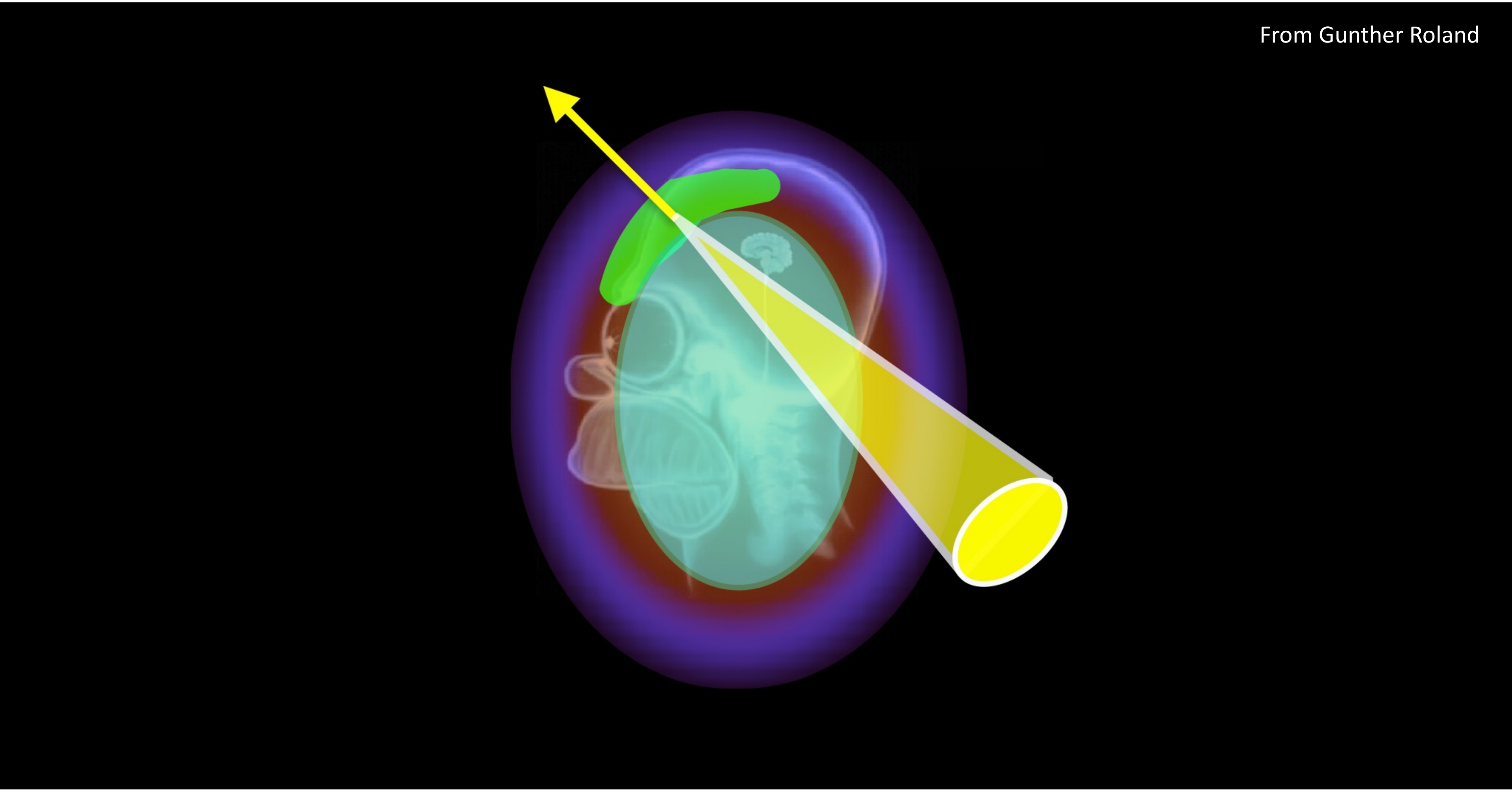


PRL 105 (2010) 252303

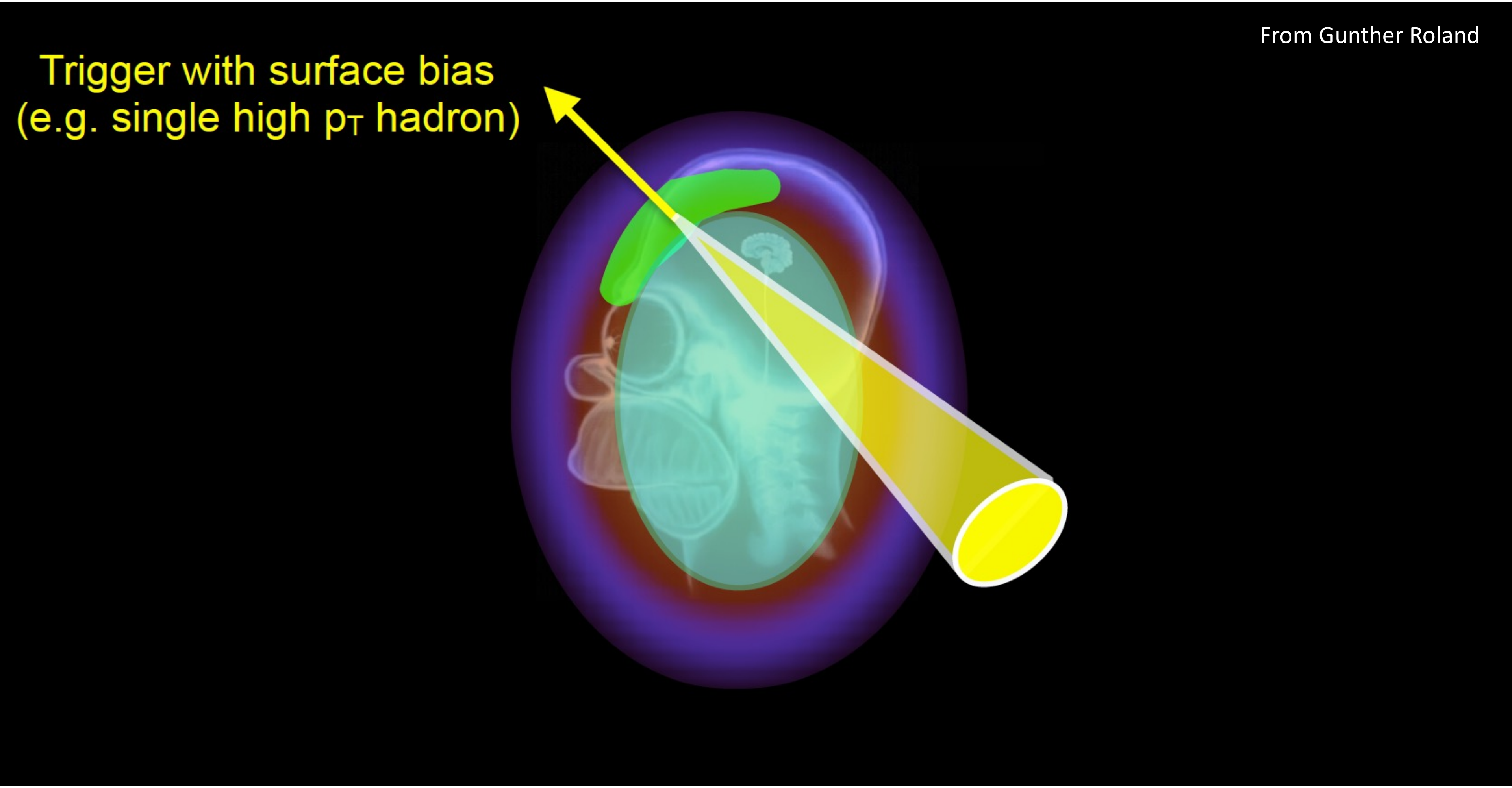


QGP tomography



Use pT, centrality, path length, collision energy, trigger bias…
to isolate different processes in time, coordinate and momentum space

QGP tomography



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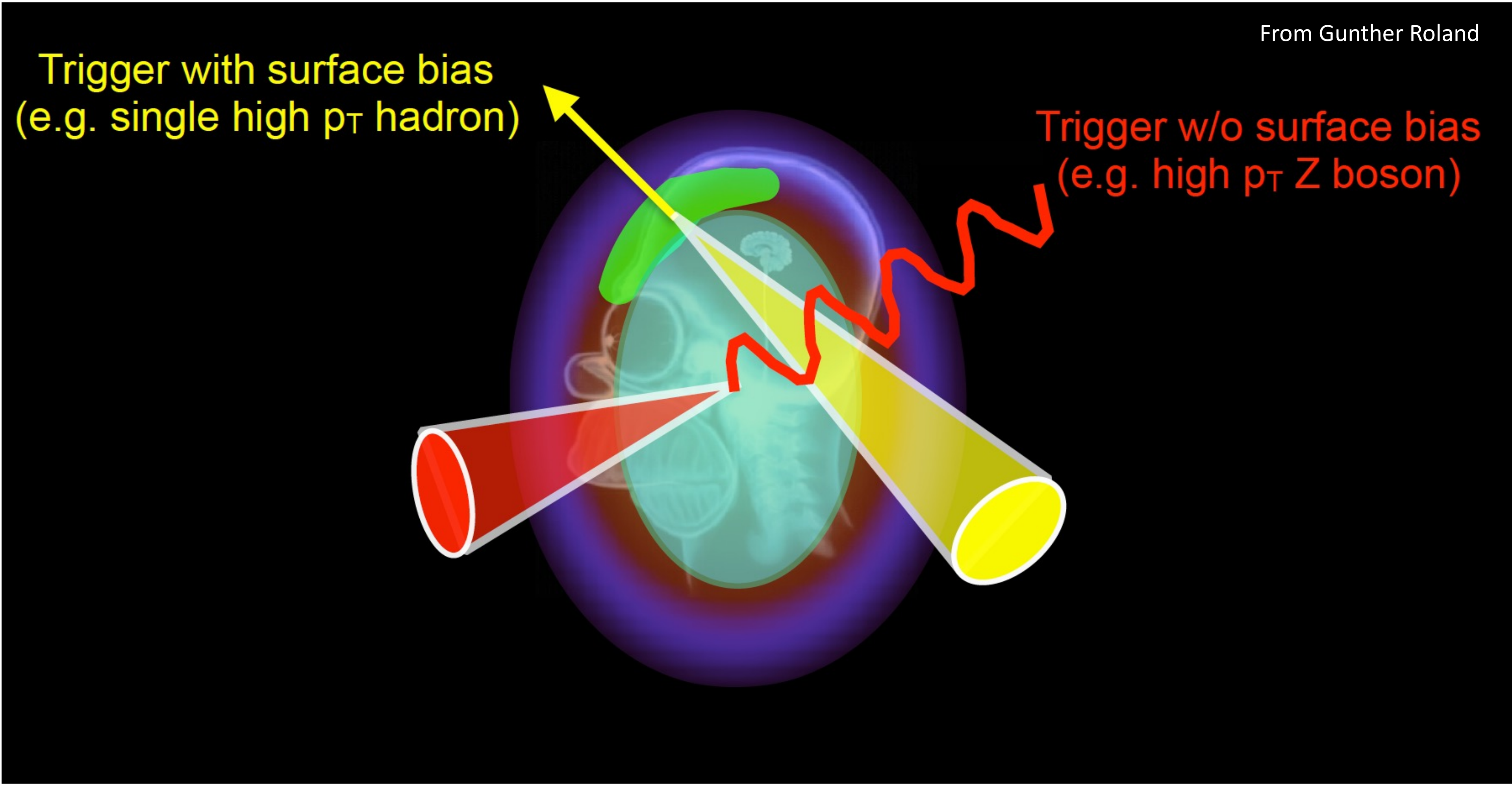

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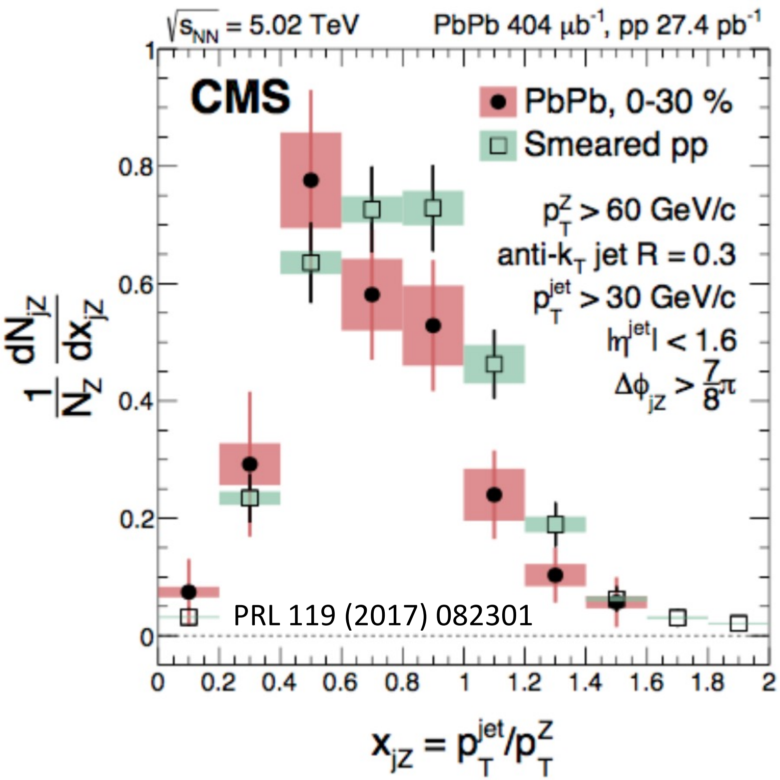
Jet+X correlations

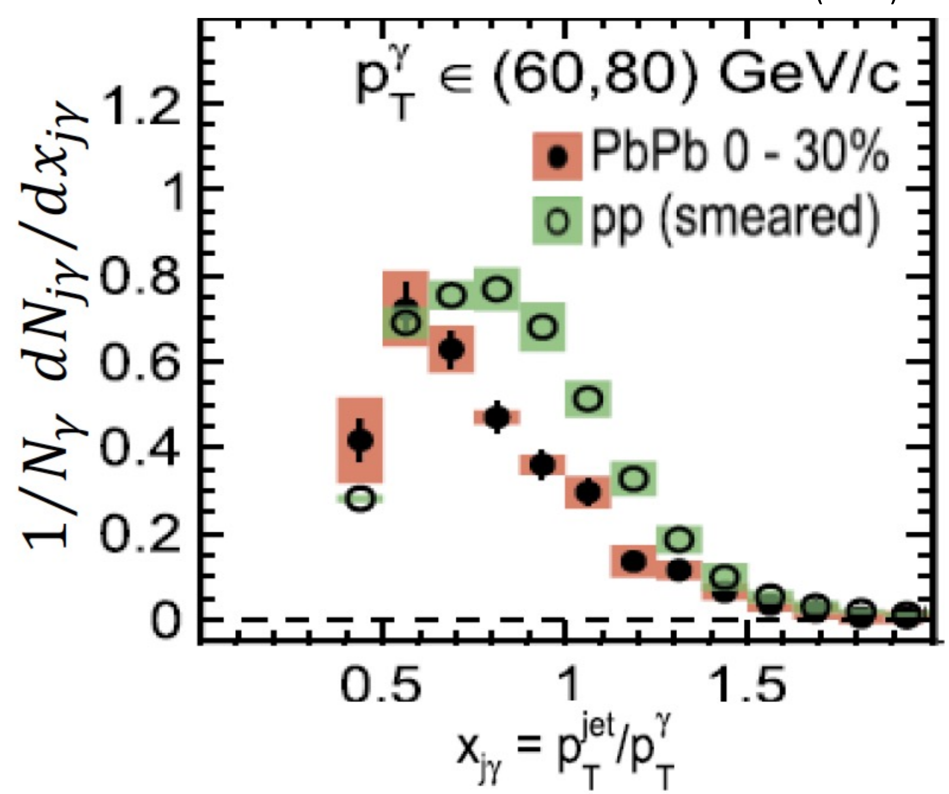
Z+jet

CMS 2017



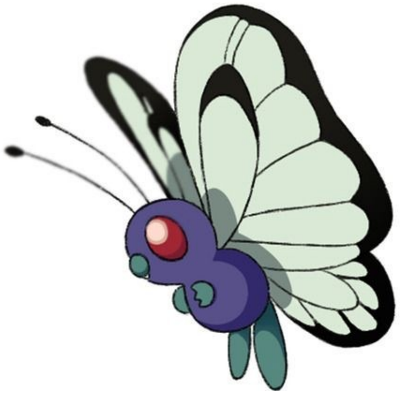
Photon + jet

PLB 785 (2018) 14



Shift of final state jet momentum relative to initial parton momentum without geometry bias

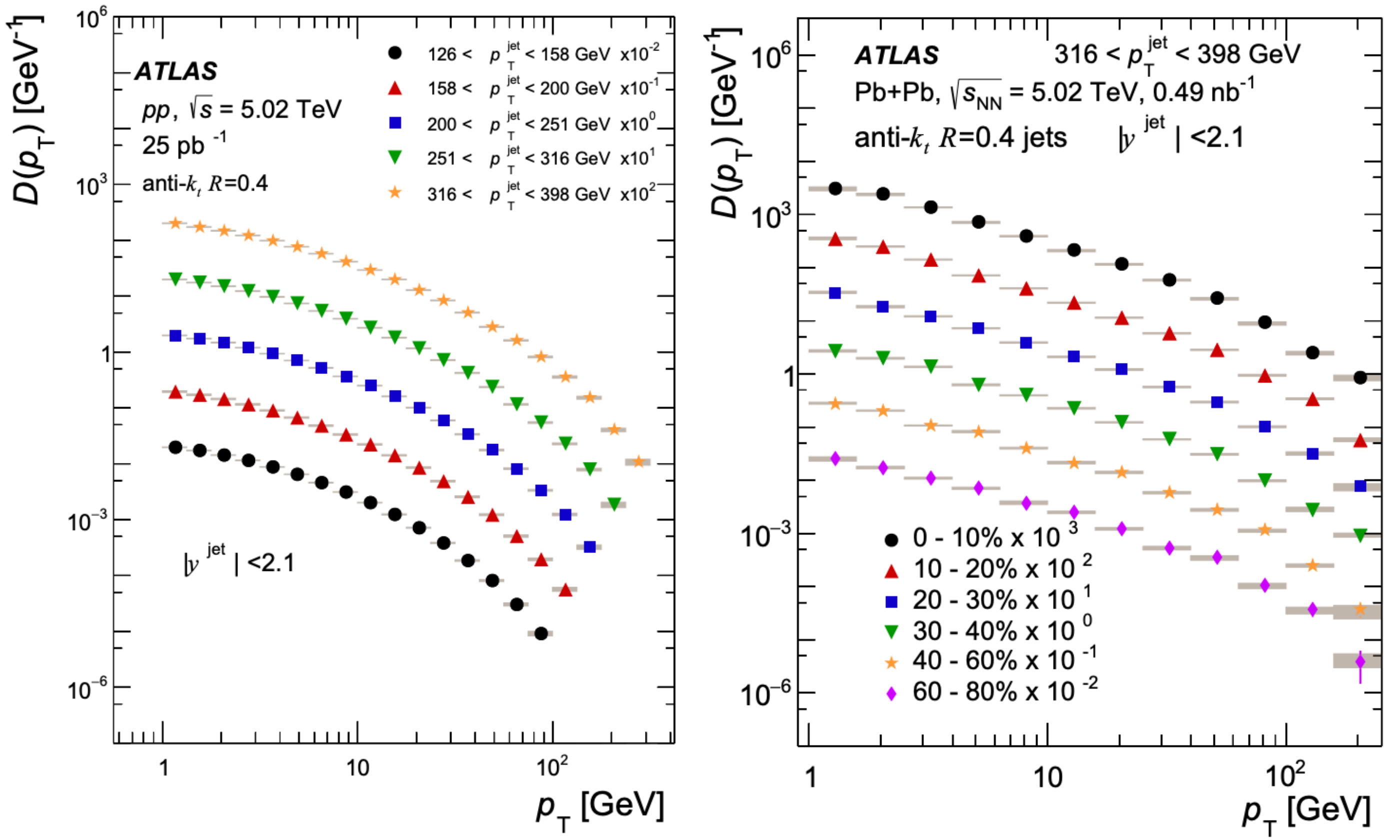
Jet inner workings



Jet longitudinal structure

PRC 98 (2018) 024908

$$D(p_{\mathrm{T}}) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{dn_{\mathrm{ch}}}{dp_{\mathrm{T}}}$$



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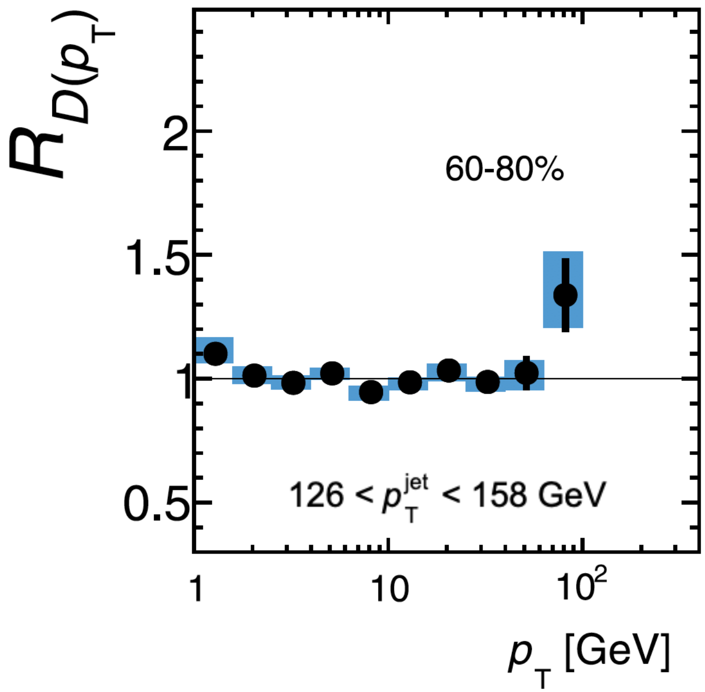

Little/no medium effects in peripheral events

Jet longitudinal structure

PRC 98 (2018) 024908

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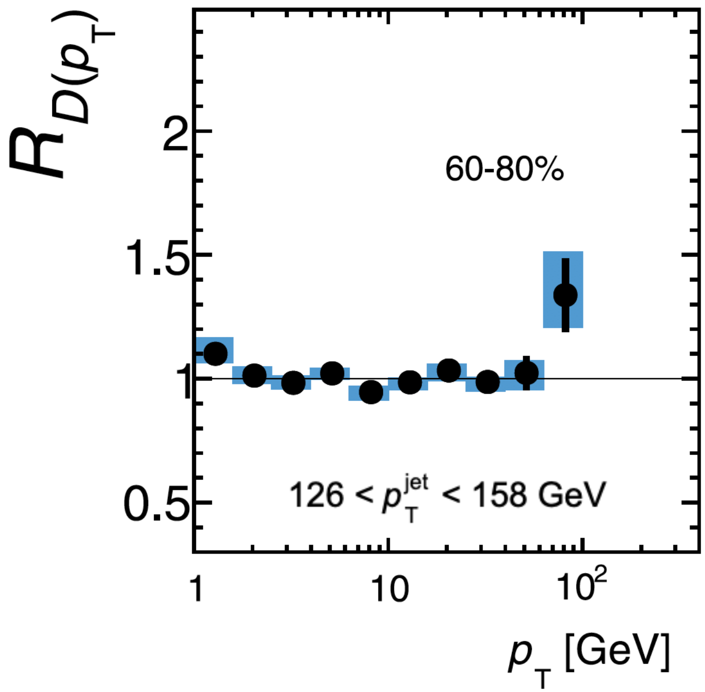
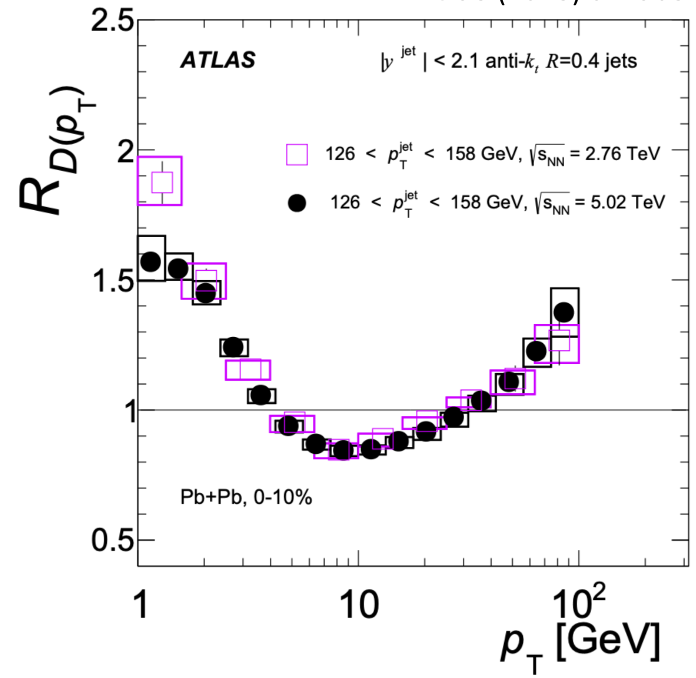




Little/no medium effects in peripheral events

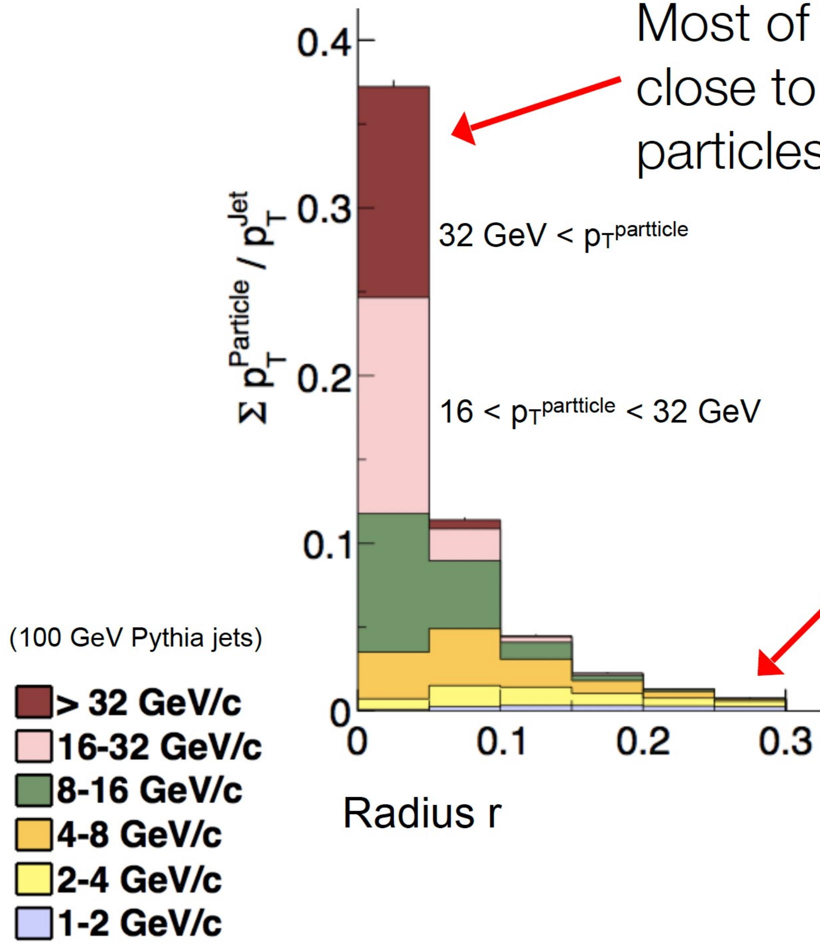
Excess of soft fragments

Depletion at intermediate momenta

Excess of high pT tracks – gluon/quark jets fraction diff?

Jet shapes

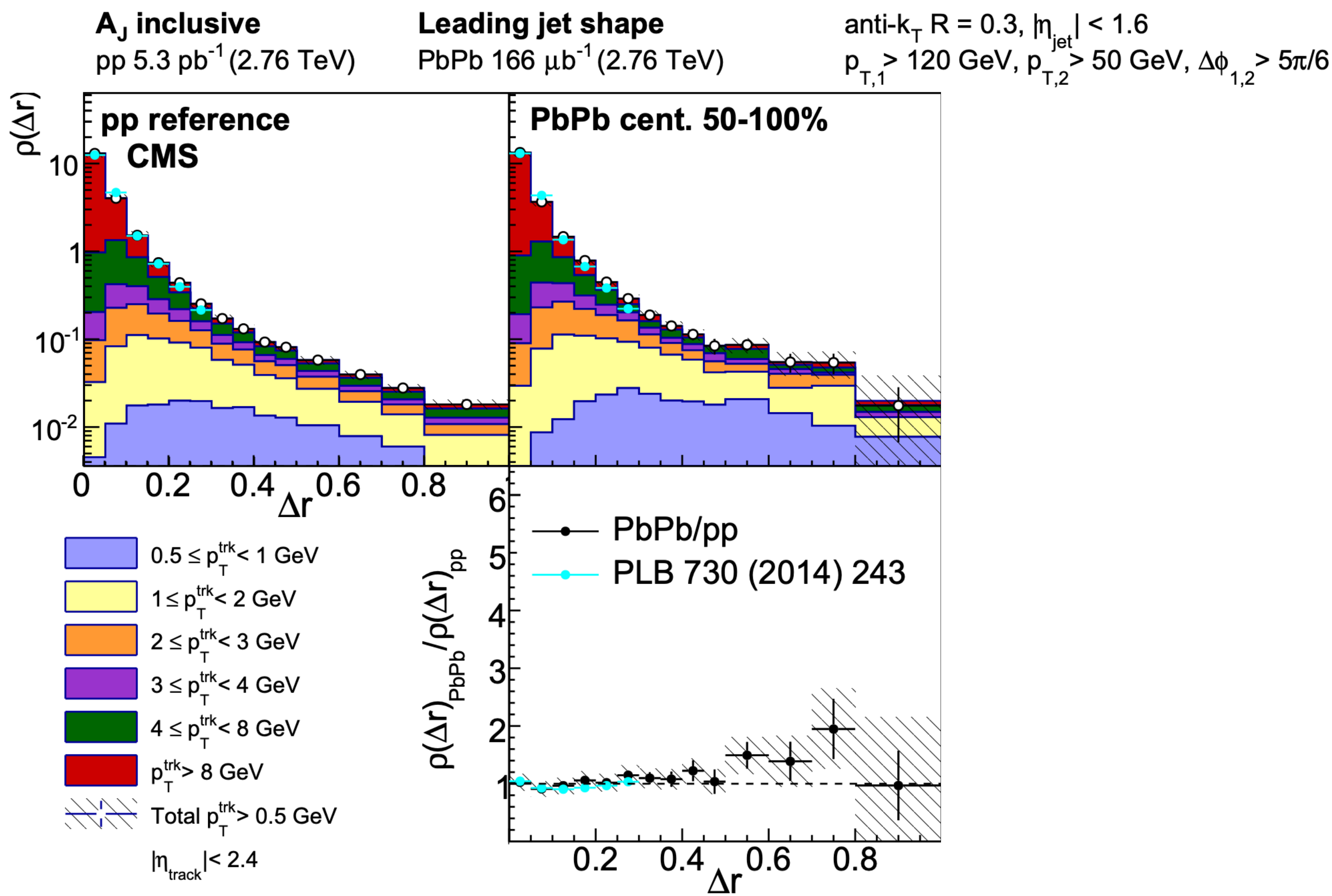
Jets are extended objects with momentum and angular structure



Most of momentum found close to jet axis in high p_T particles ($p_T > O(10GeV)$)

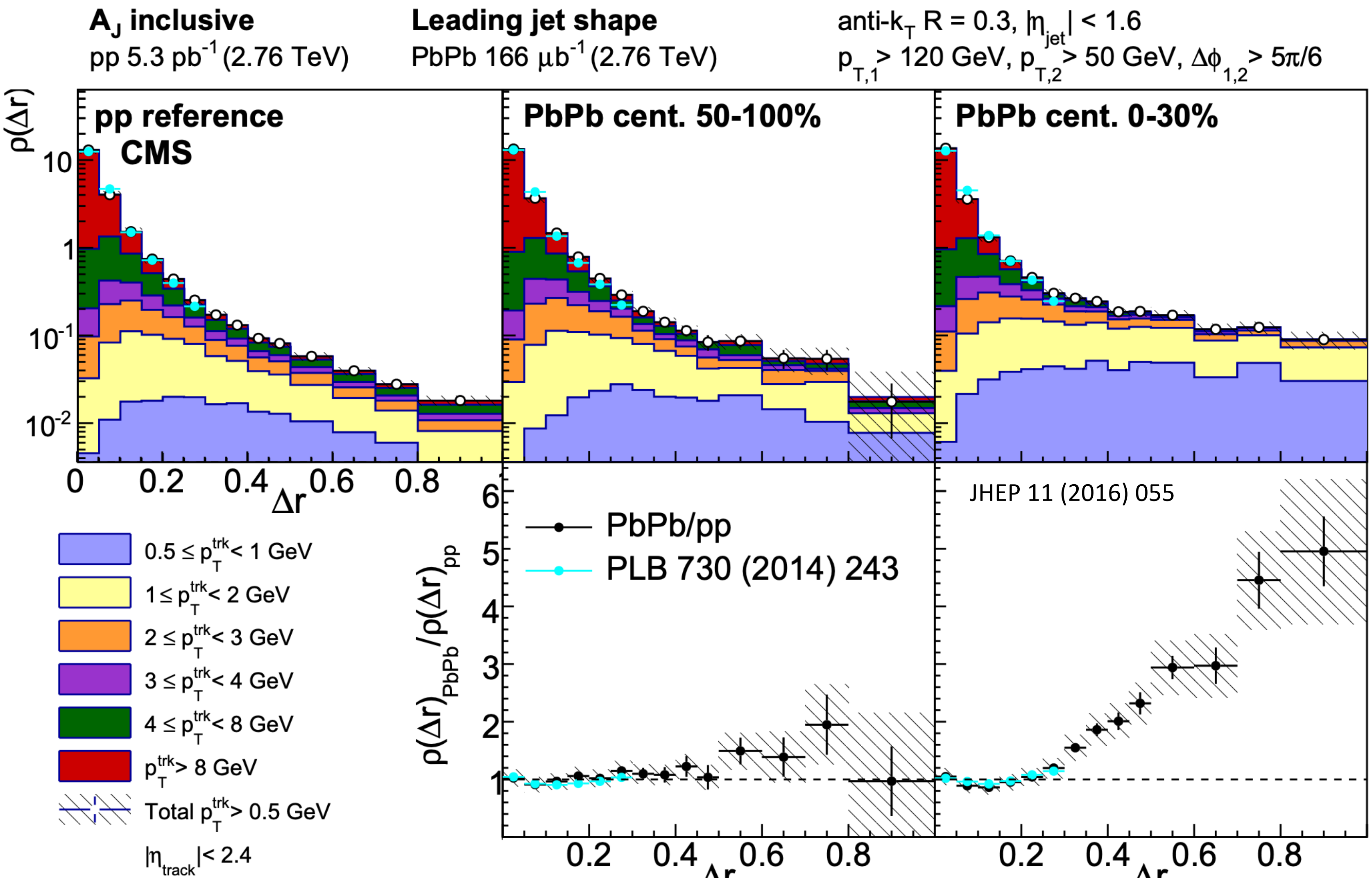
Large angle component of jet contains small fraction of jet p_T in soft particles ($p_T \sim O(1GeV)$)

Jet shapes



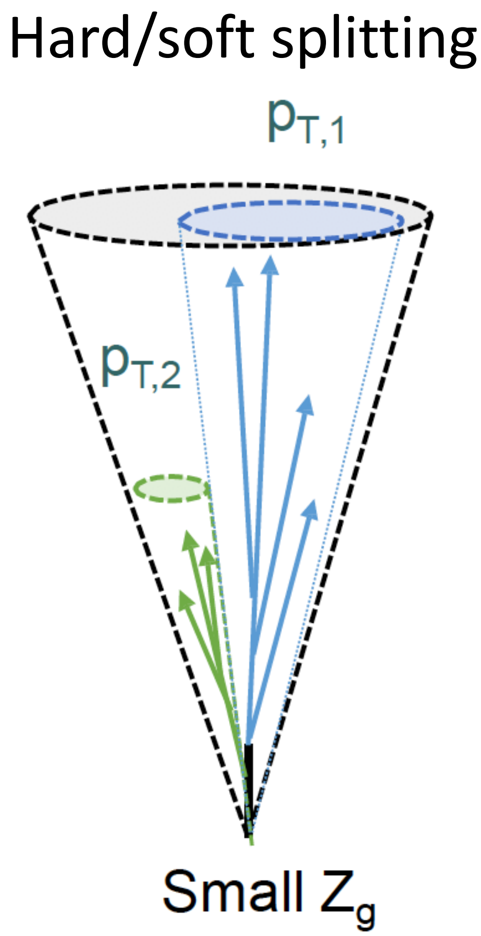
Enhancement at low pT and large r in central collisions

Jet shapes

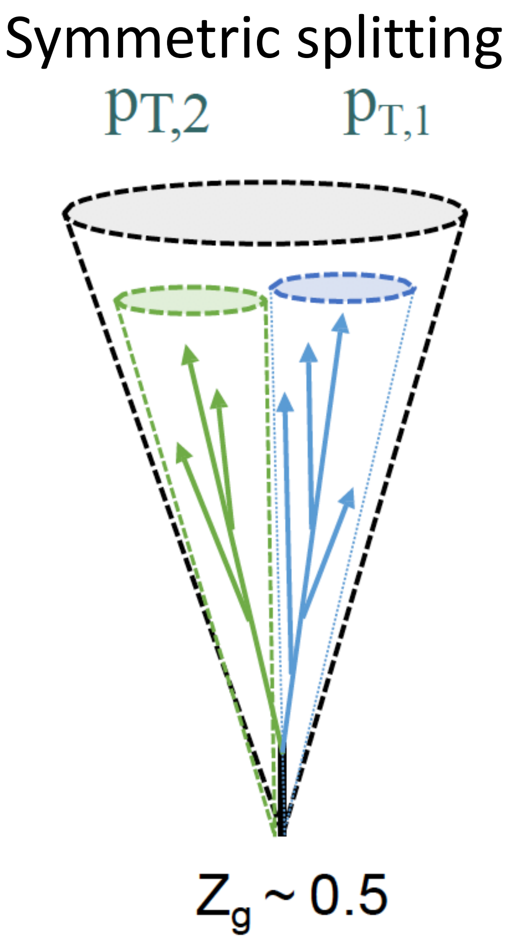


Enhancement at low pT and large r in central collisions

Jet substructure

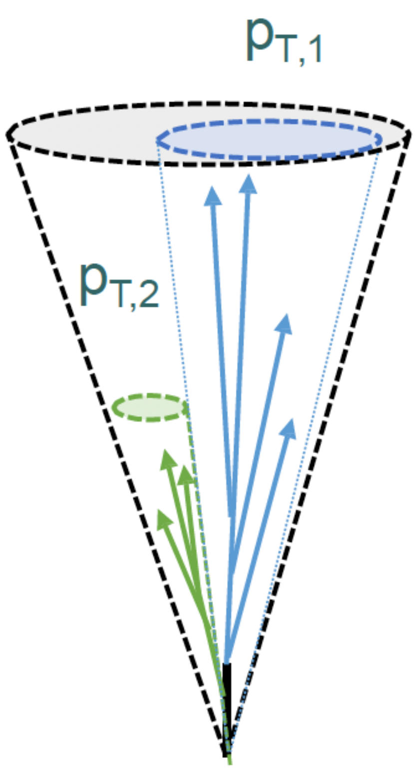


$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$



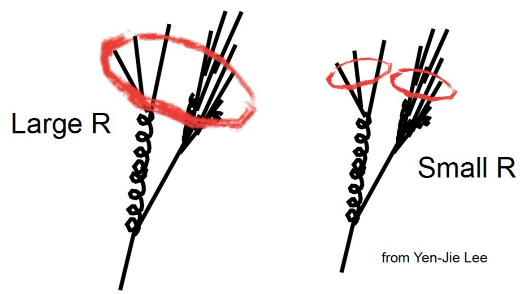
Jet substructure

Hard/soft splitting

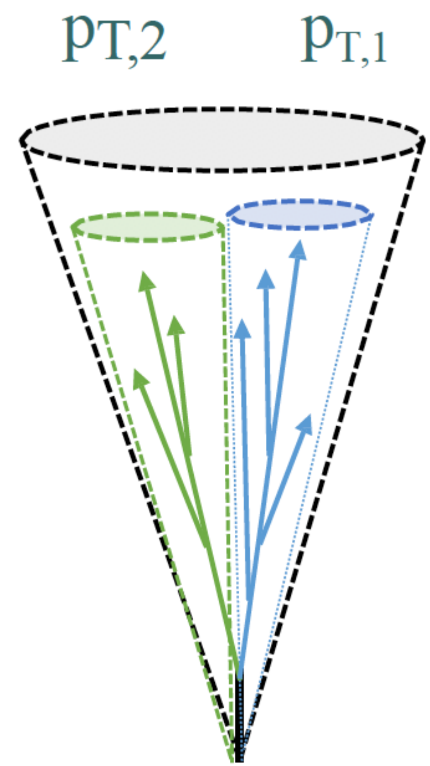


Small Z_g

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$



Symmetric splitting

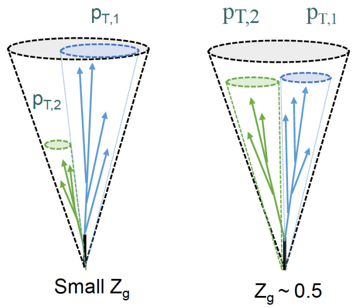


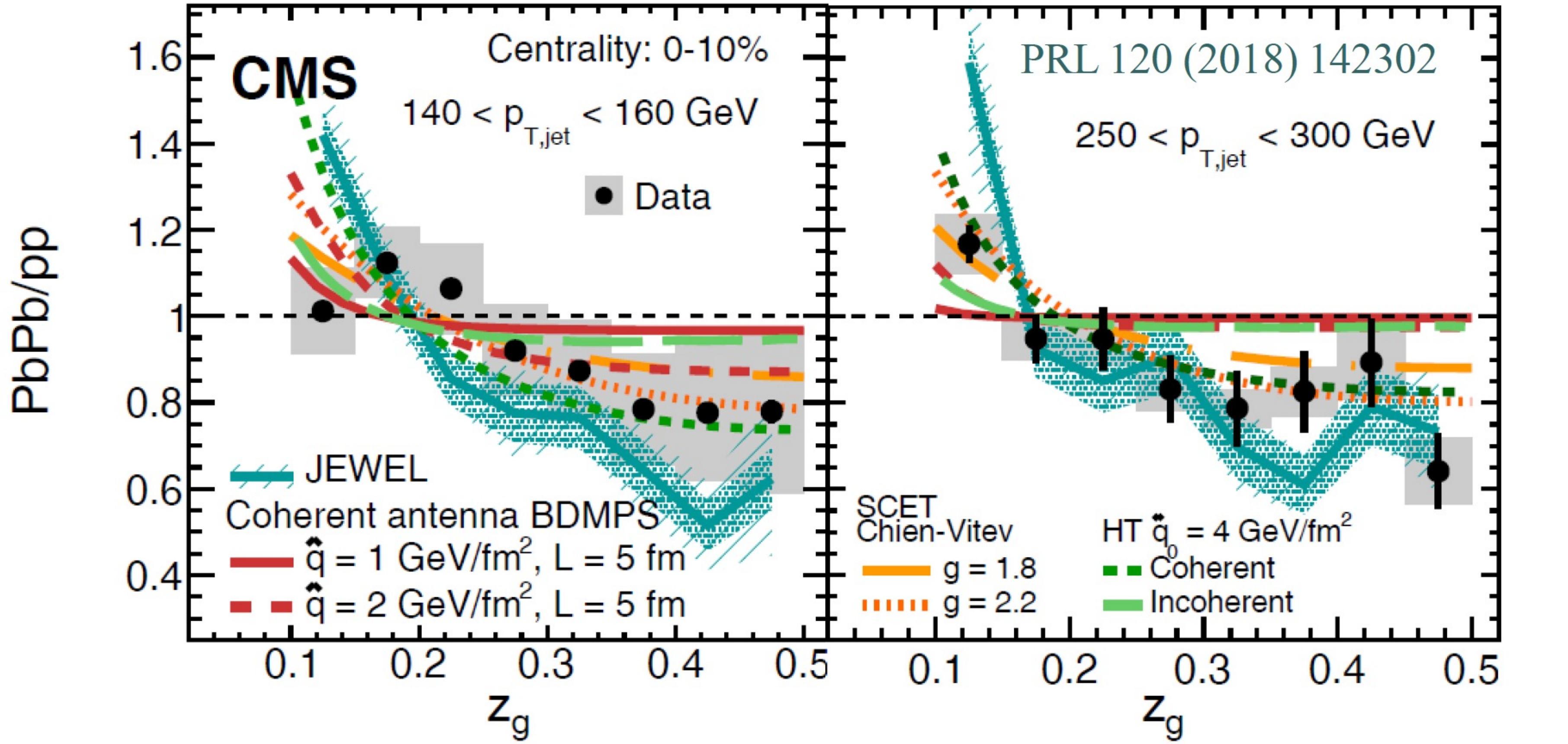
$Z_g \sim 0.5$

Grooming: isolate hard structure from soft background

Approaches: Filtering, trimming, pruning

Jet substructure





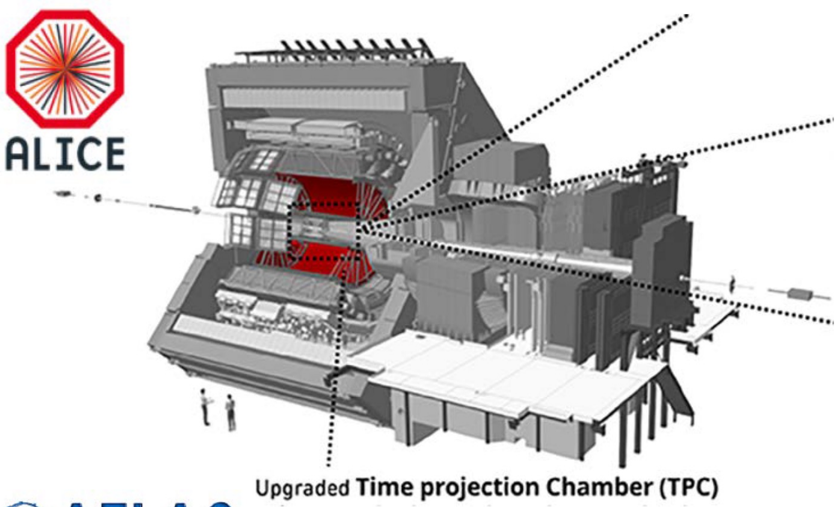
Higher suppression for jets with more symmetric splitting

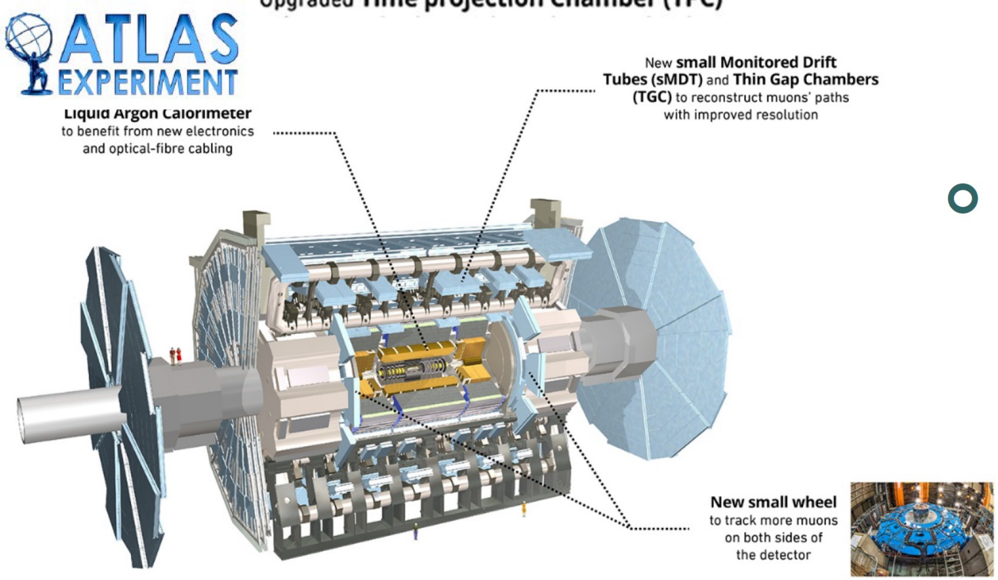
New insights on in-medium effects for theory

Medium recoil? Modified splitting?

Towards the future

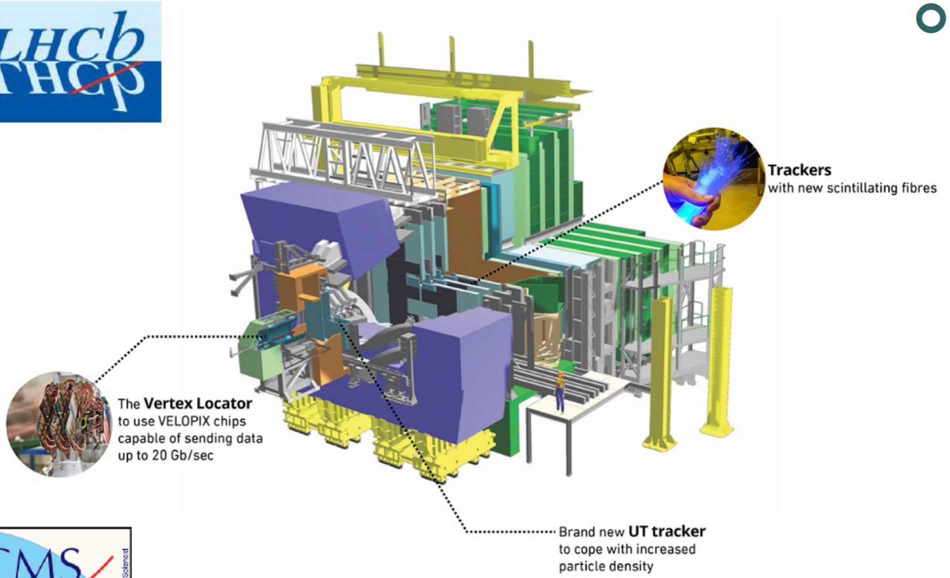
Towards the future

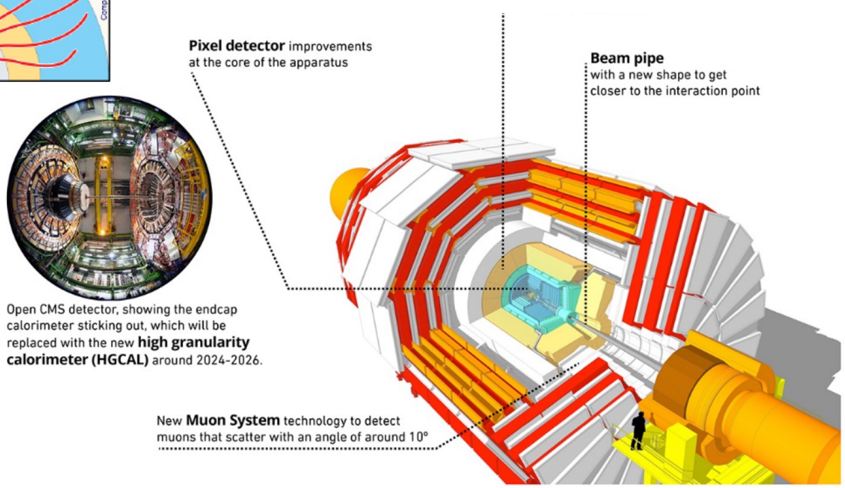




- ALICE
  - New Inner Tracking system (ITS)
  - Muon Forward Tracker (MFT) upgrade
  - New Fast Interaction trigger (FIT)
  - TPC (readout) upgrade
- ATLAS
  - Rebuilding Muon Wheels
  - Fast Tracker
  - Trigger, DAQ, electronics upgrades

Towards the future

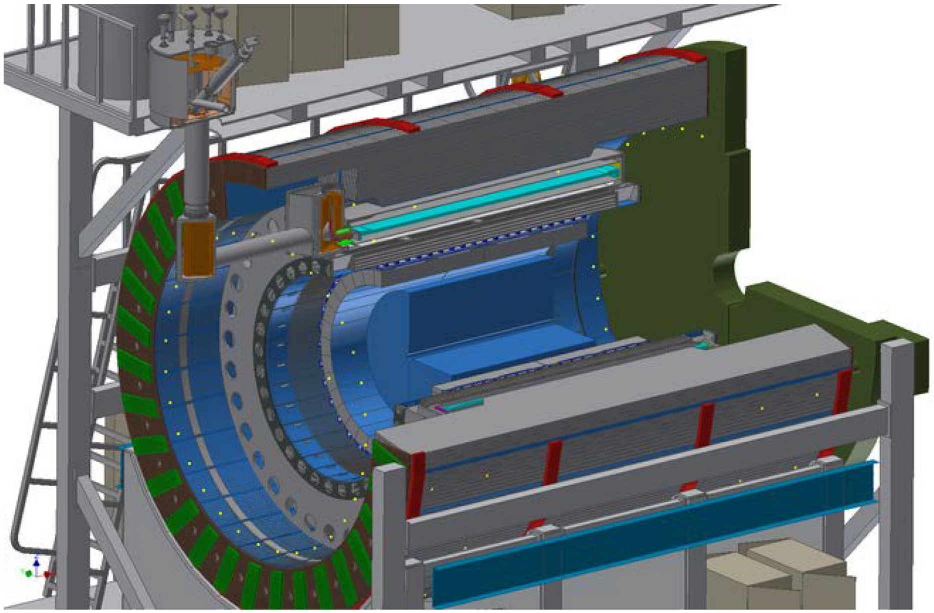




- LHCb
  - New (faster) vertex positioning detector (VeloPix)
  - RHIC detectors upgrade
  - New Tracker (silicon-microstrip and scintillating fibers (SciFi))
  - Read-out upgrade with fully software based trigger
- CMS
  - Pixel Detector improvements
  - Hadronic and EM Calorimeters upgrades
  - Muon System upgrade
  - New beam pipe

Towards the future

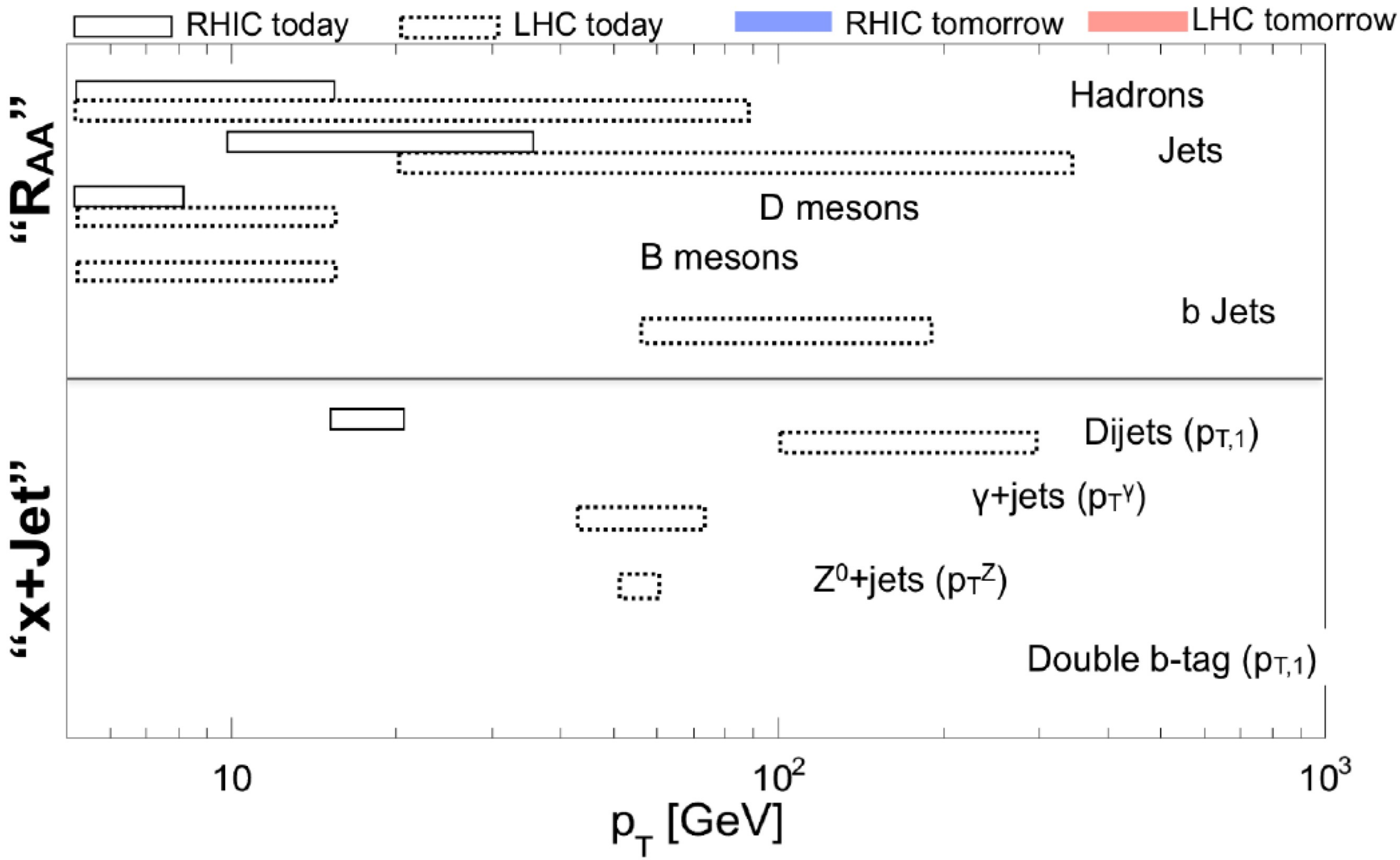
As we speak, a new "state-of-the-art jet detector at RHIC" is under construction at BNL



- sPHENIX:
  - 1.4T Magnetic Field
  - Large acceptance
  - Precision tracking
  - Hadronic & EM calorimetry

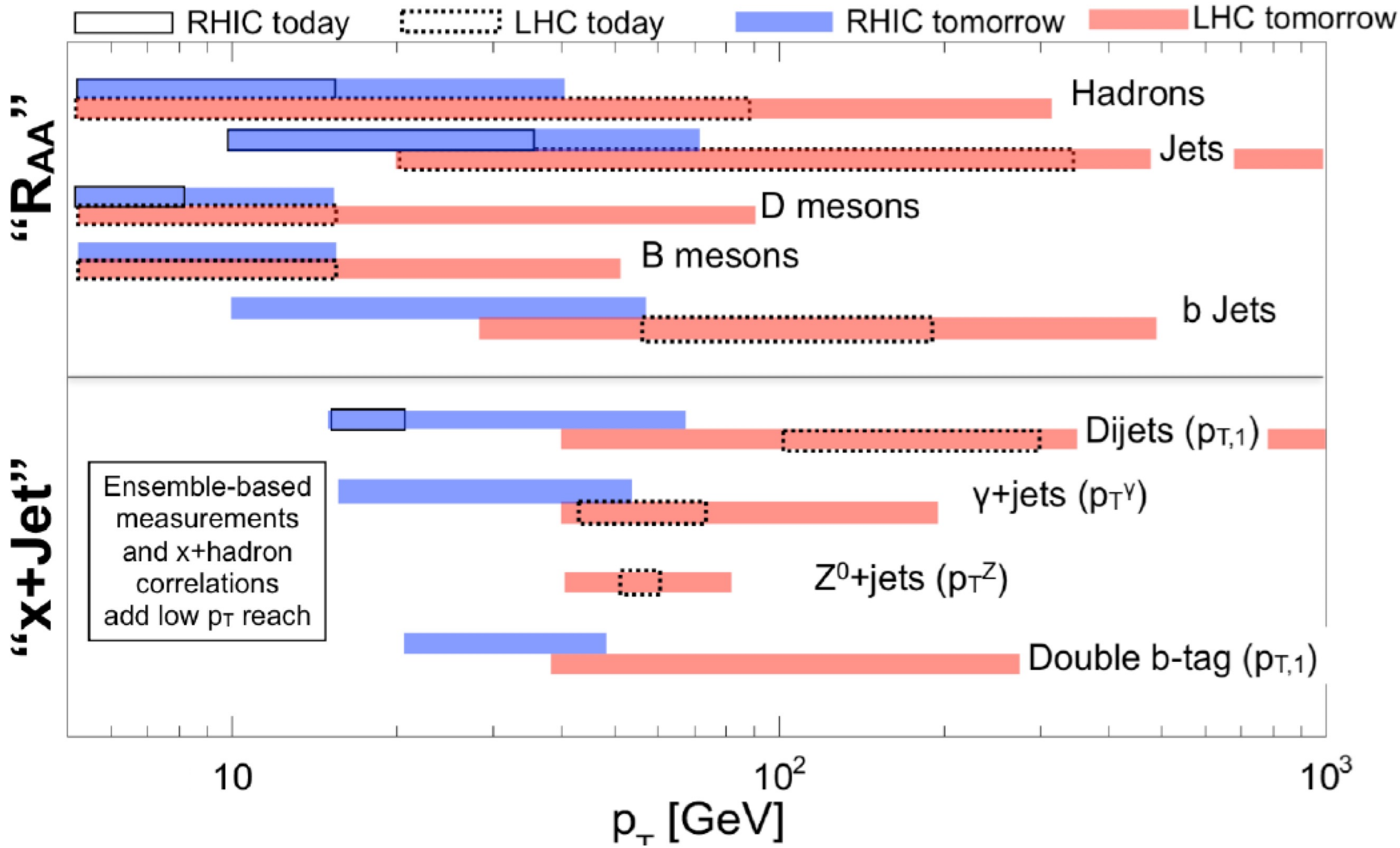
Early studies indicate substantial differences in jet quenching systematics at 200 GeV vs 5 TeV – unique opportunity to test QCD at variable T

Towards the future



Little LHC/RHIC overlap

Towards the future



Extended kinematic coverage and LHC/RHIC overlap
Make jet tomography really possible!