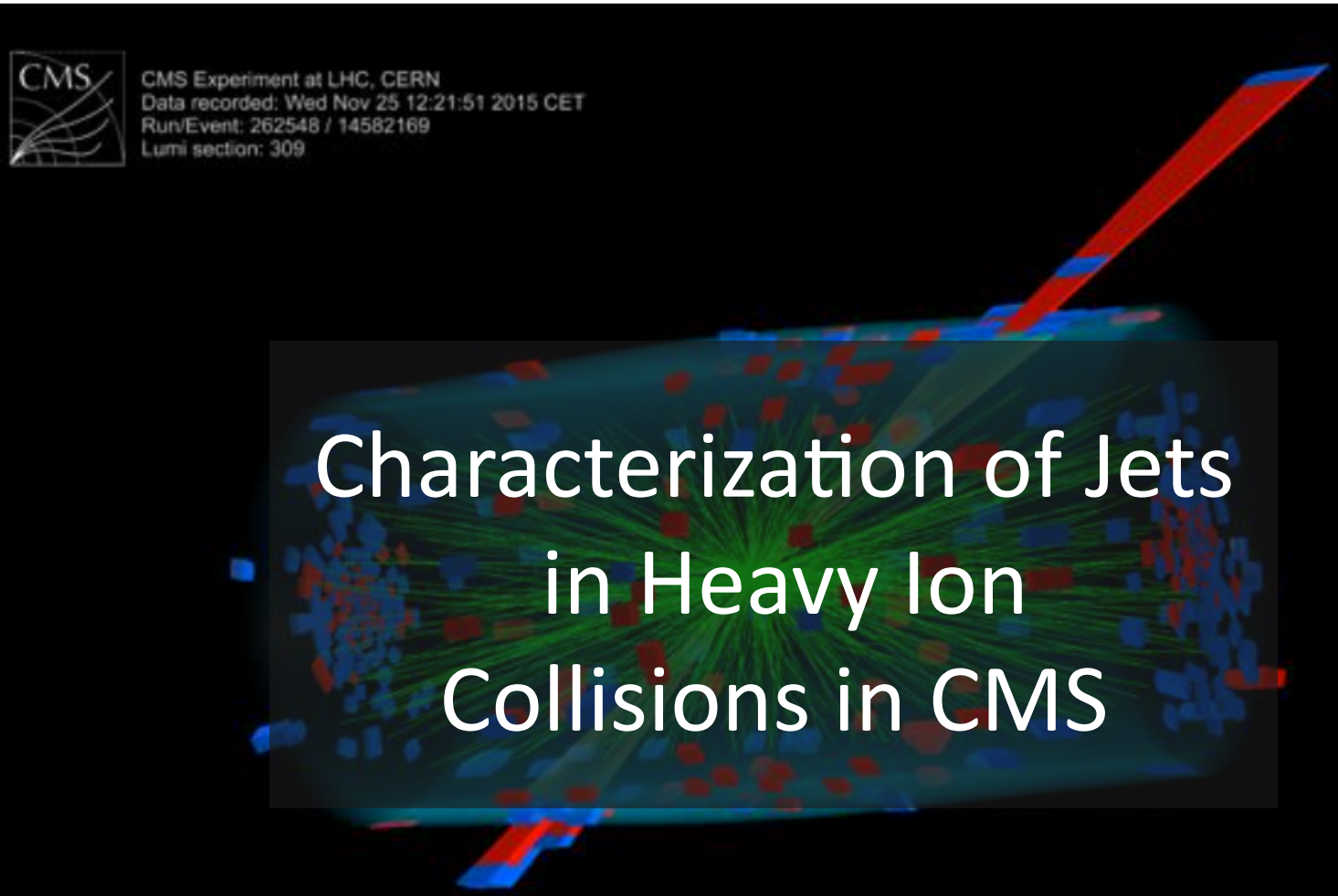


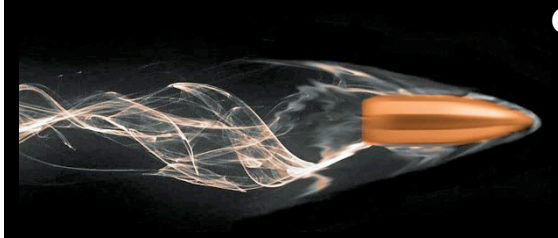
Characterization of Jets in Heavy Ion Collisions in CMS

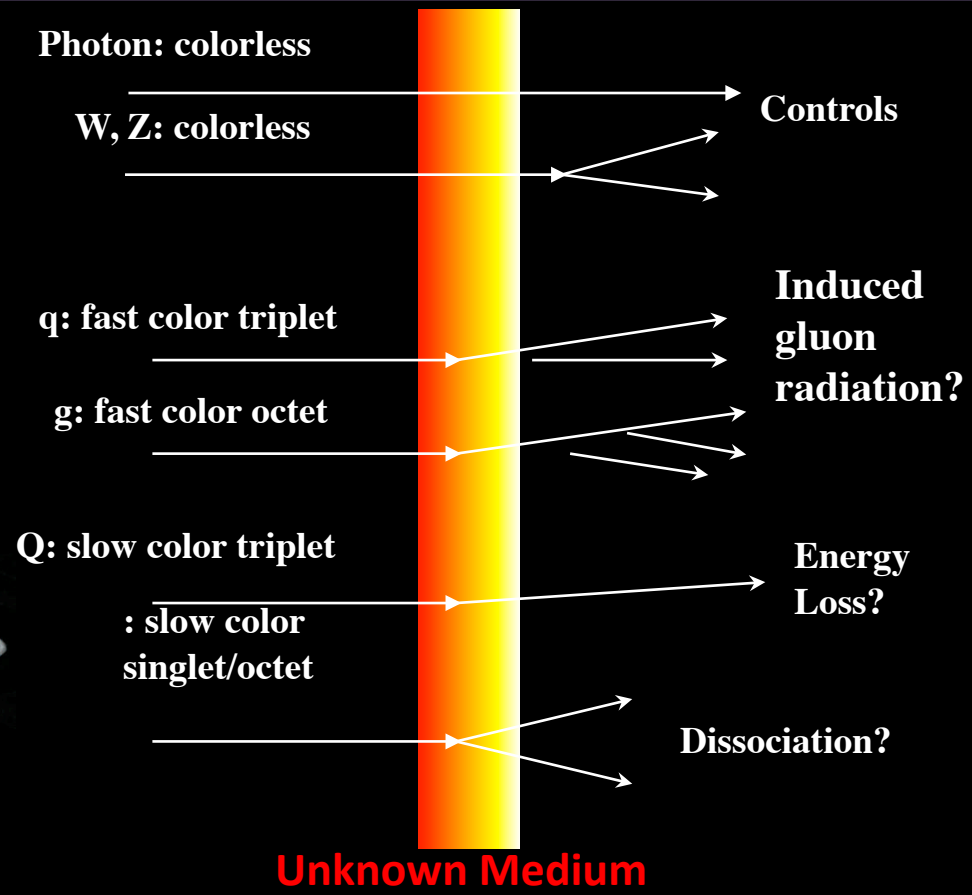
Sevil Salur

Rutgers University

Why Jets in heavy ion collisions?

probe IN
(known from
pp, pA+ pQCD)





probe
OUT

Probing non-perturbative QCD physics with perturbative objects

Diagnosing QCD medium: (simplified idea)
pass a QCD-sensitive probe through it, then look for any modifications due to the medium.

Jets as tools to *study* QGP.

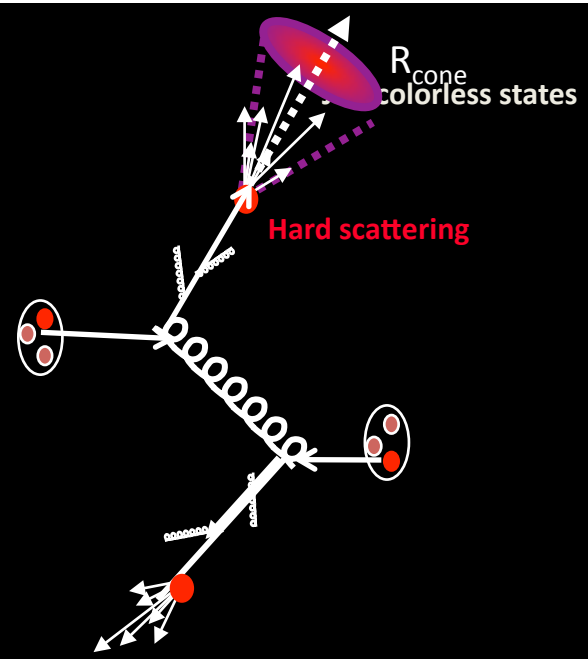
Jets in hadronic colliders is not a new phenomena

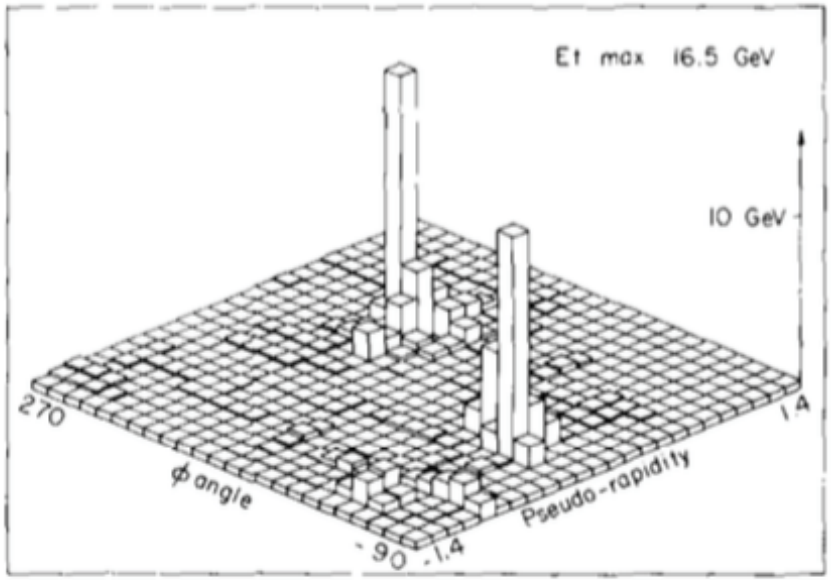
Volume 123B, number 1,2 PHYSICS LETTERS 24 March 1983

25 years head start !

OBSERVATION OF JETS IN HIGH TRANSVERSE ENERGY EVENTS AT THE CERN PROTON ANTIPROTON COLLIDER

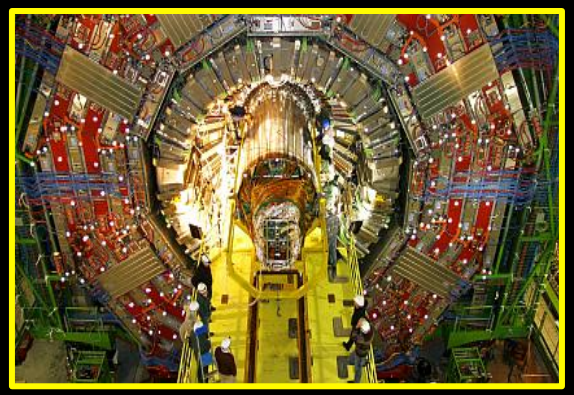
UA1 Collaboration, CERN, Geneva, Switzerland

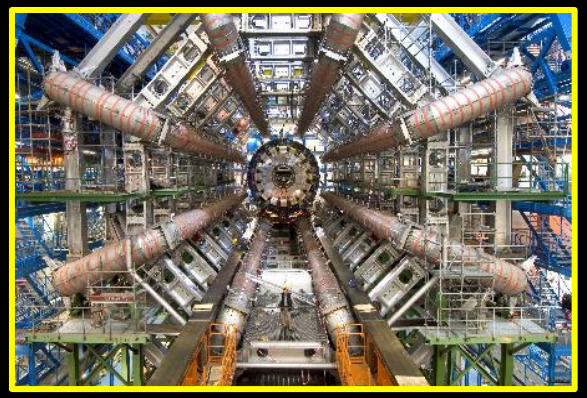


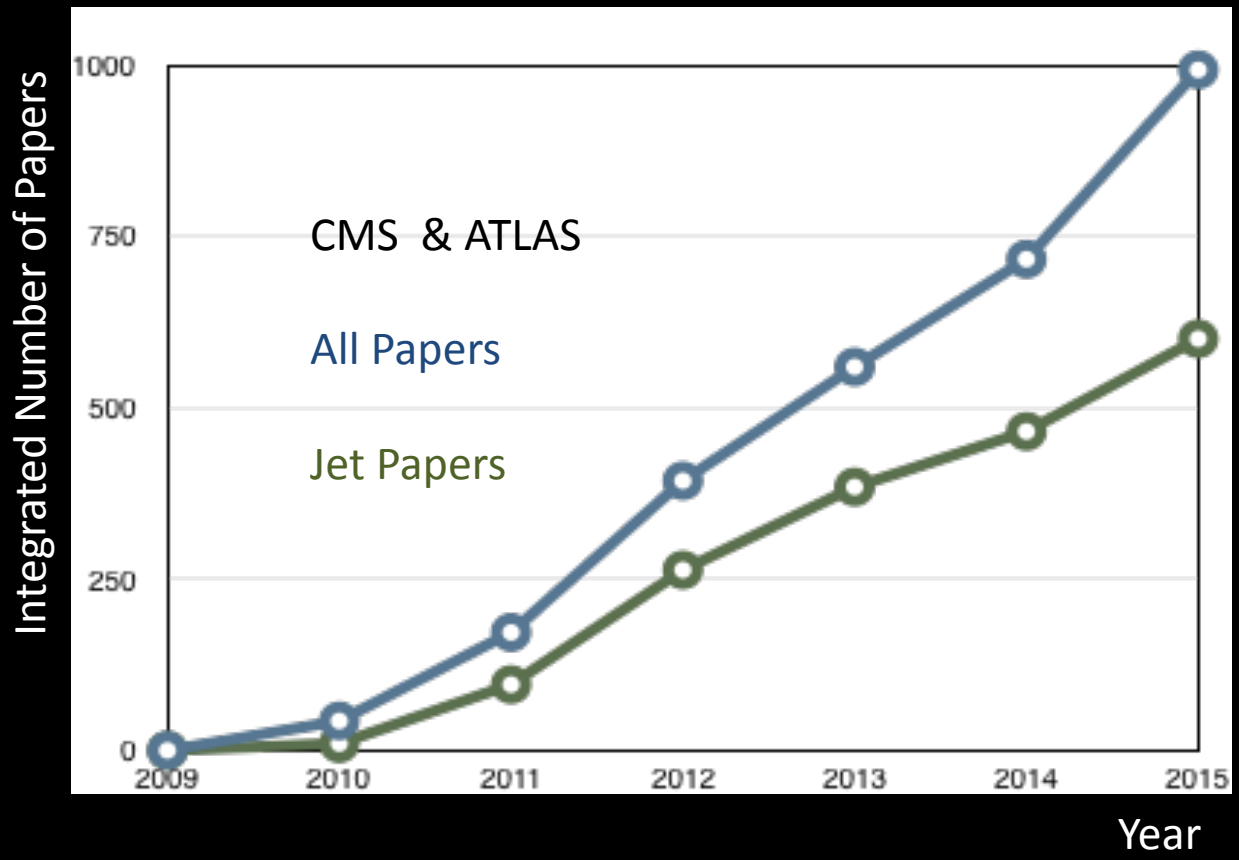


Jets are the experimental signatures of quarks and gluons!
They are expected to reflect kinematics and topology of partons.

> 50% of ATLAS & CMS papers use jets



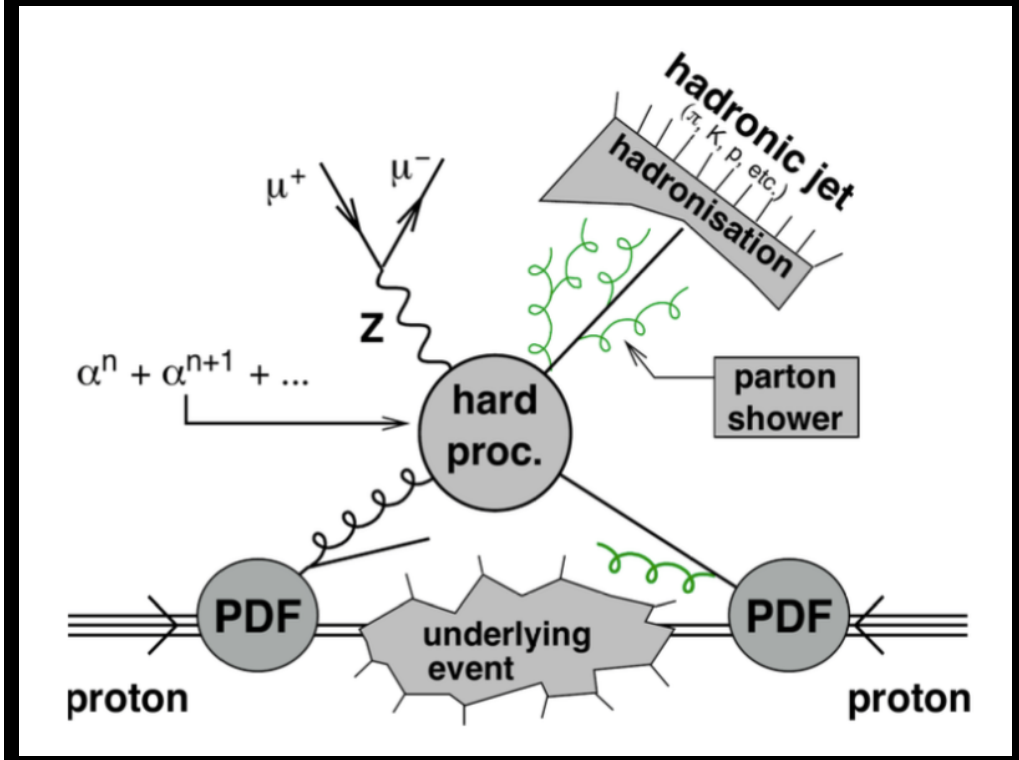




Any analysis that require, quark, gluon, i.e., parton or their absence in an event.

Many powerful set of discriminative jet tools are available!

However, QCD is not simple.



The whole event is color connected and at higher orders radiation can even be emitted!

A lot of complications!

– Underlying event

– Pileup

– Initial + final state radiation

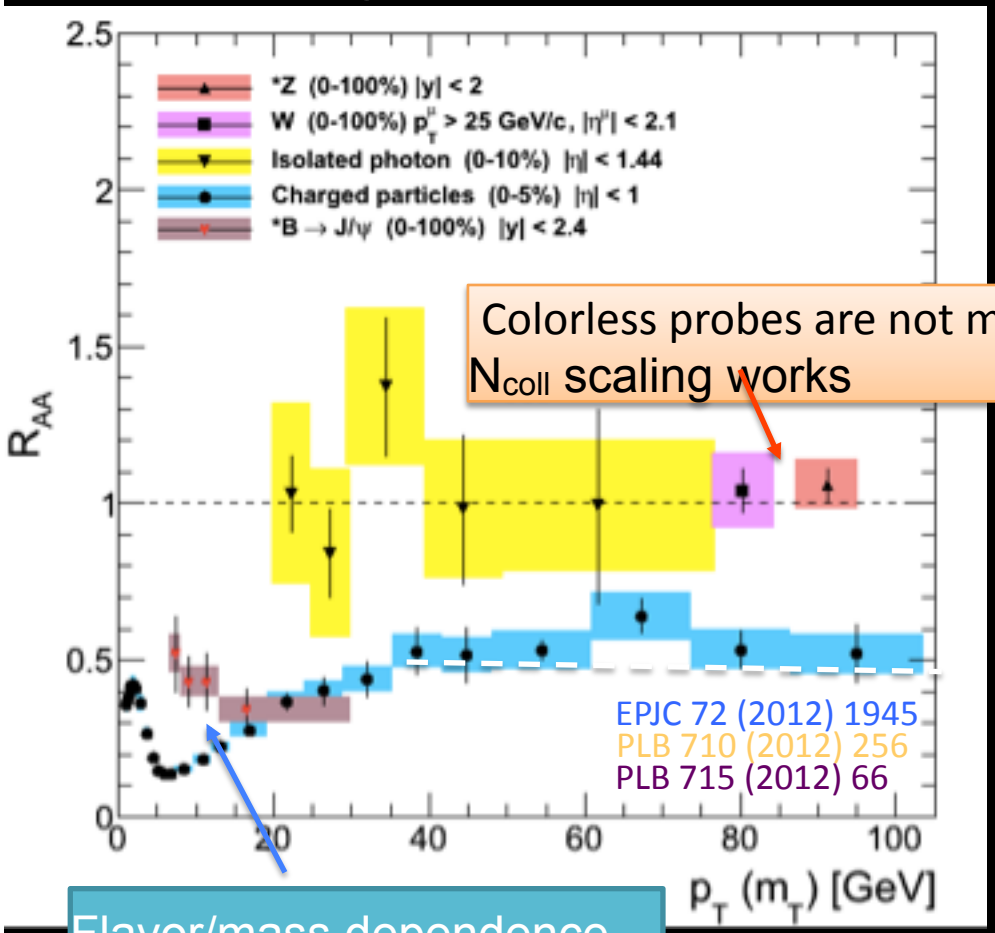
Graphics Courtesy to Gavin Salam

Hadronic jets carry information about partons but forget about correcting to the parton level!

Jet Measurements: Measurements of jet-like hadron production

Jet Quenching in PbPb Collisions w/o jets

Charged Particles



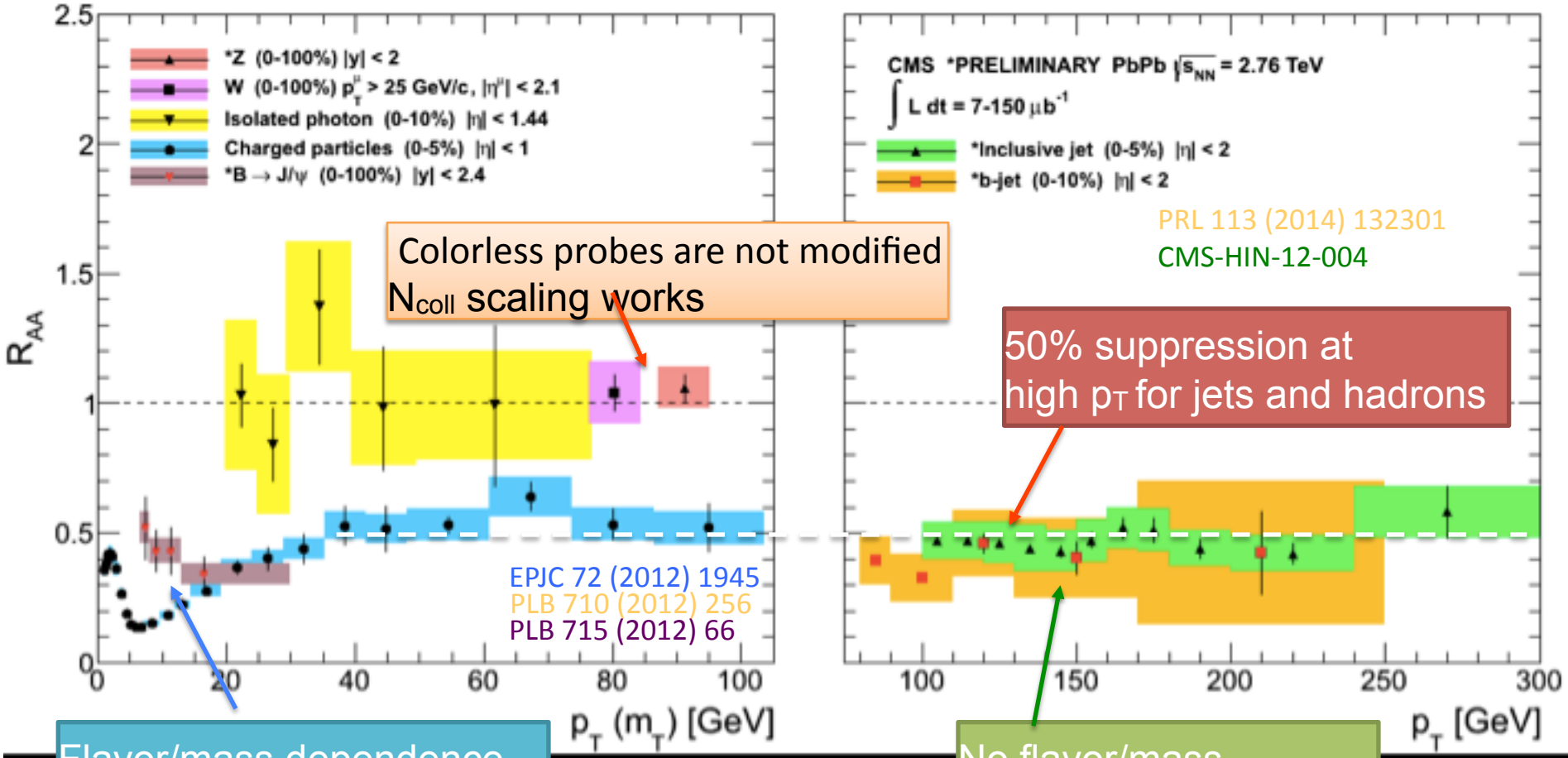
Colorless probes are not modified
N_{coll} scaling works

EPJC 72 (2012) 1945
PLB 710 (2012) 256
PLB 715 (2012) 66

Flavor/mass dependence seen at low p_T

Jet Quenching in PbPb Collisions w/o jets

Charged Particles | Anti-k_T R=0.3 Jets



Colorless probes are not modified
N_{coll} scaling works

PRL 113 (2014) 132301
CMS-HIN-12-004

50% suppression at high p_T for jets and hadrons

EPJC 72 (2012) 1945
PLB 710 (2012) 256
PLB 715 (2012) 66

Flavor/mass dependence seen at low p_T

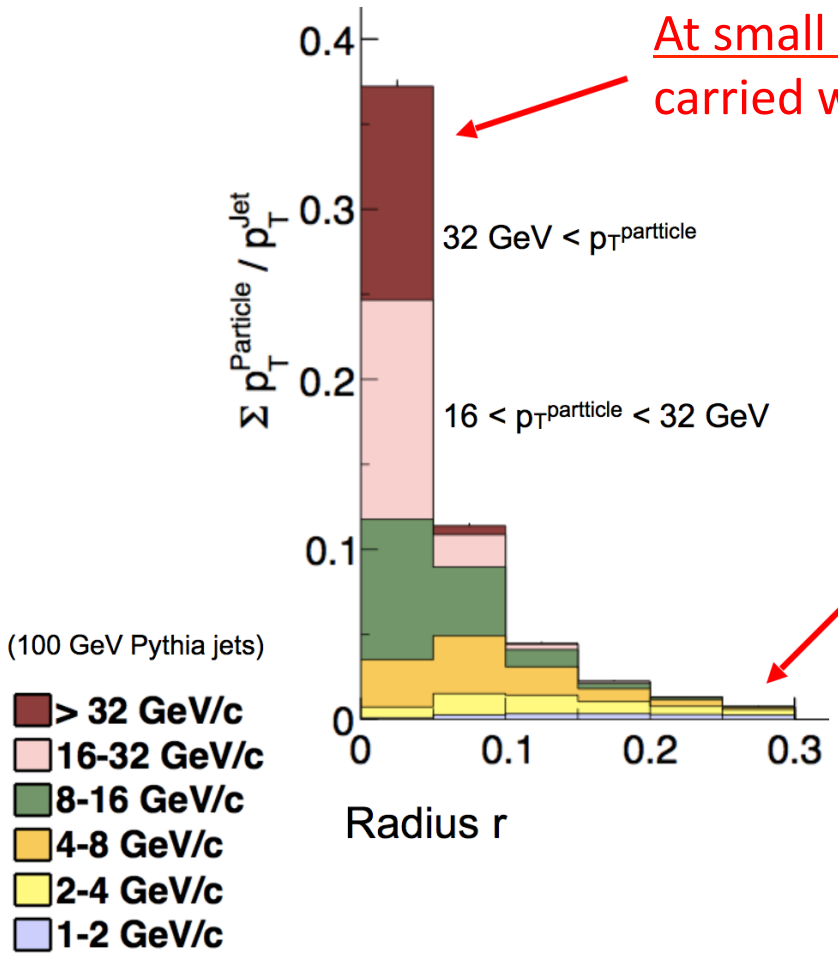
No flavor/mass dependence at high p_T

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

Is this random luck?

Jet Morphology:

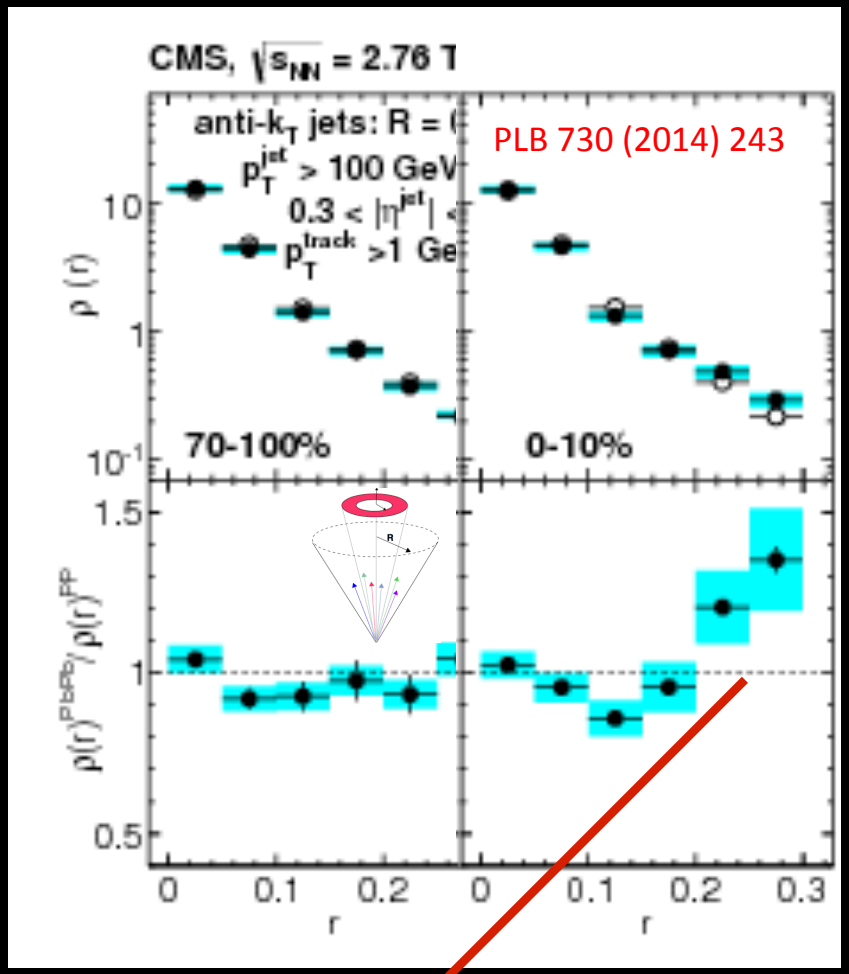
Angular and Momentum Structures

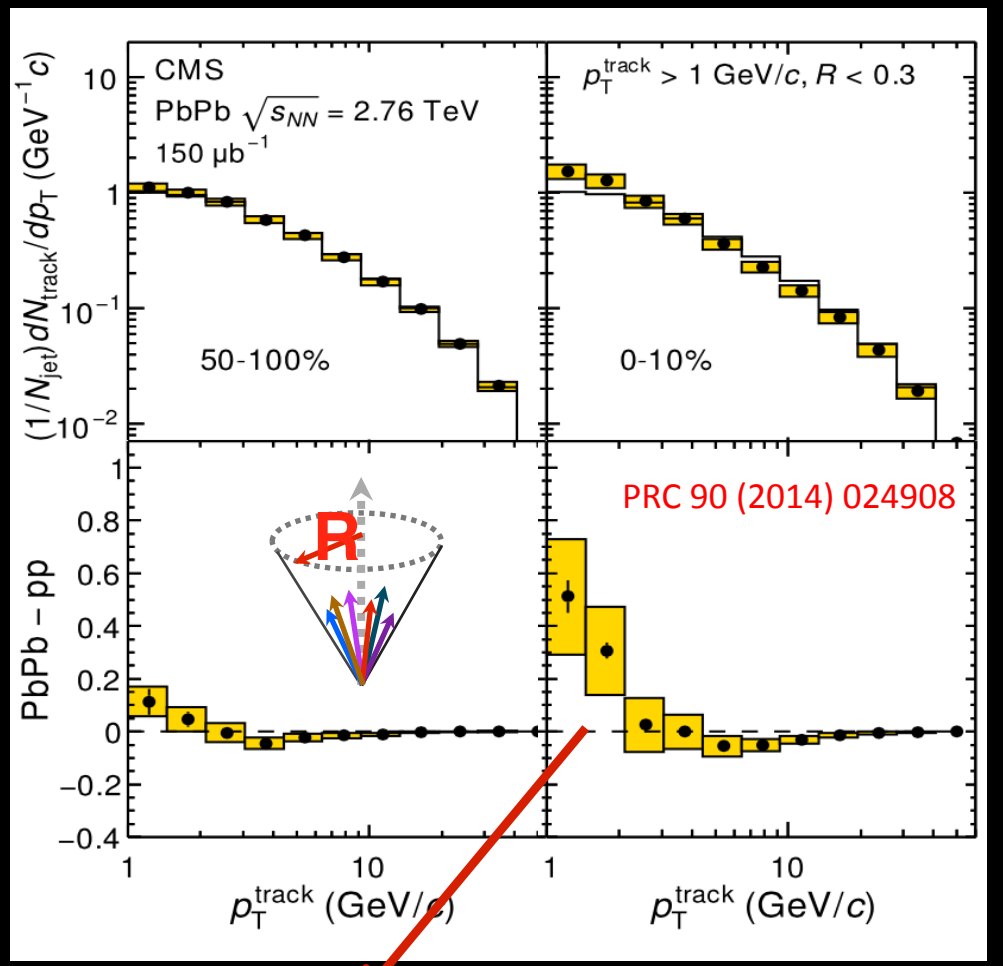


At small angles: Most of the p_T and carried with high p_T constituents

At large angles: Small fraction of p_T and carried with softer constituents

Change in Jet Morphology as seen with CMS:

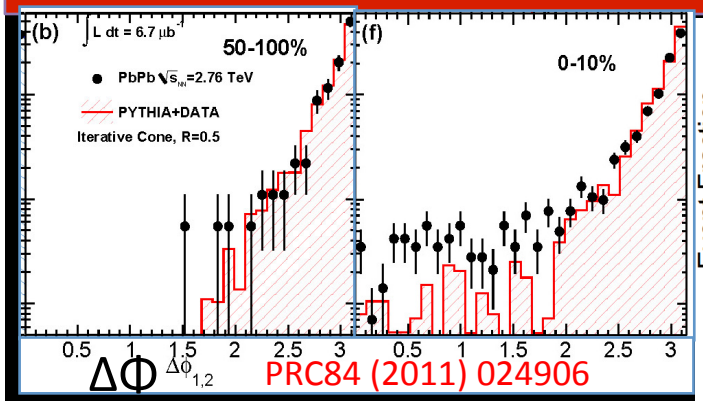




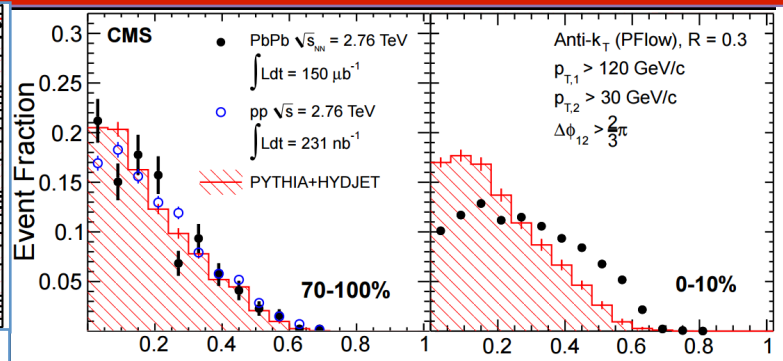
Jet Shapes: Structure of reconstructed jets modified towards an excess of particles far from the jet axis

Fragmentation Functions: Structure of reconstructed jets is modified towards an excess of particles at low p_T.

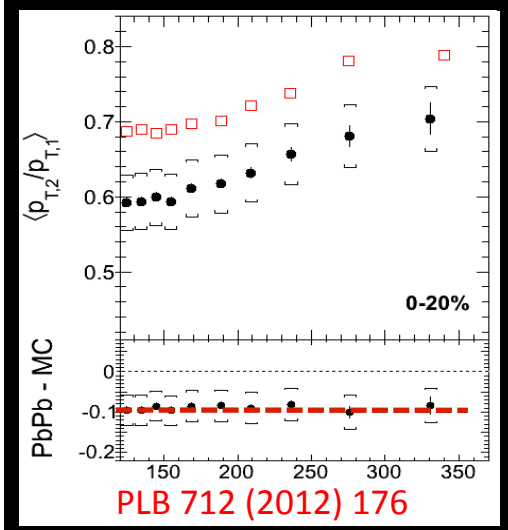
Jet modifications are seen with CMS via measurements of



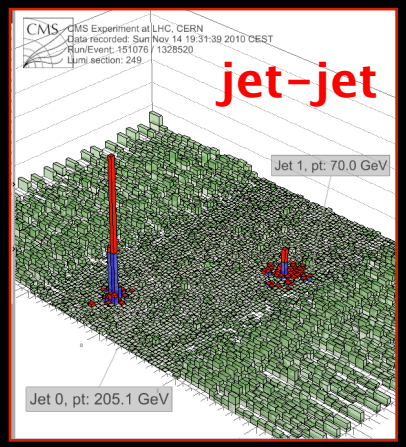
PRC84 (2011) 024906

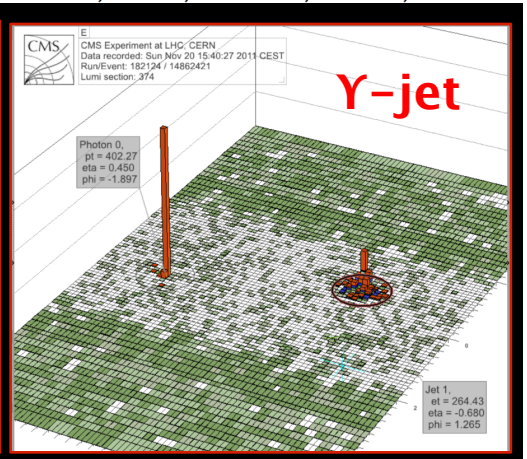


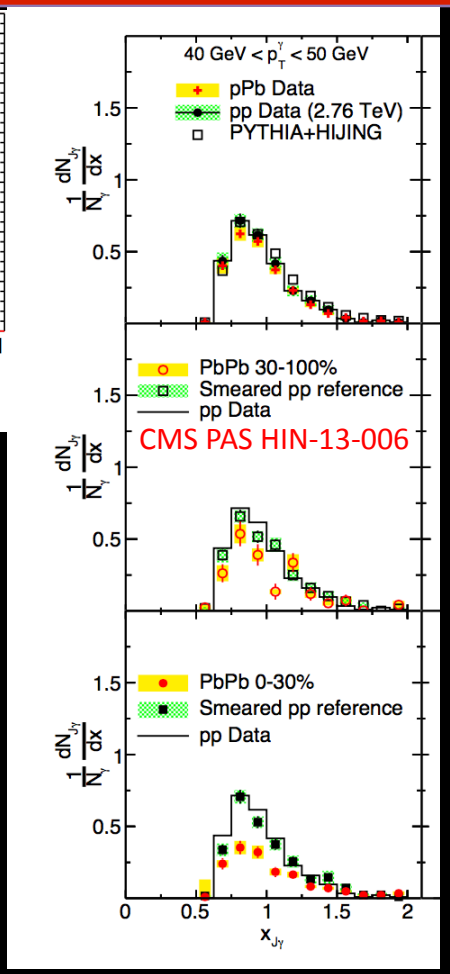
$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

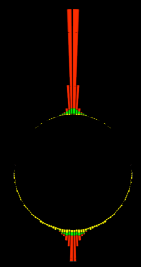


PLB 712 (2012) 176









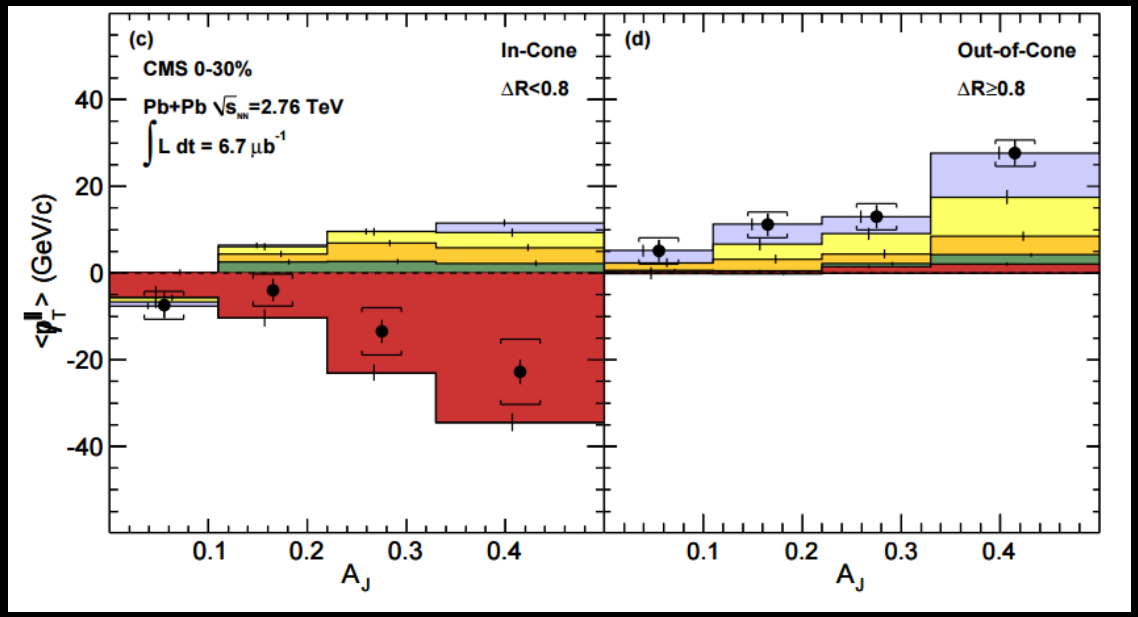
Dijet and ϒ−jet imbalance:

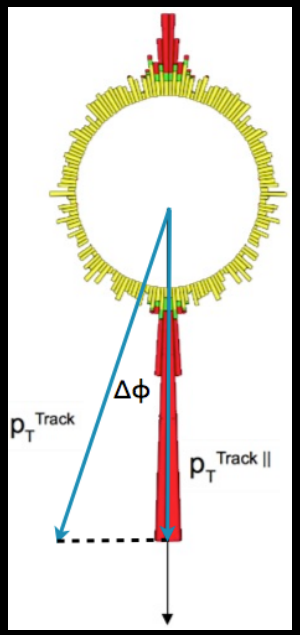
1. Jets are undeflected i.e., angular correlation is conserved.
2. Unambiguous evidence of energy loss of fast partons
3. Large imbalance of di-jet energies existing at all jet p_T.

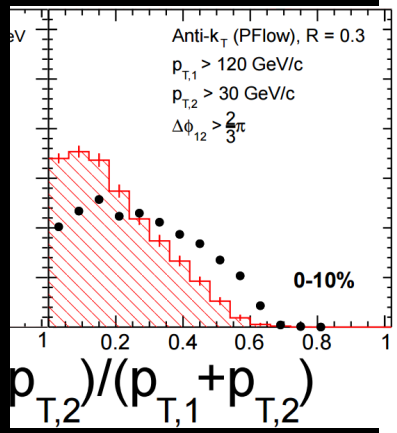
Change in Jet Morphology as seen with CMS

Missing p_T: Energy is carried away by low p_T particles far away from the jet axis. Average missing pt ~10 GeV/c.

In-cone (ΔR<0.8) Out-of-cone (ΔR>0.8)

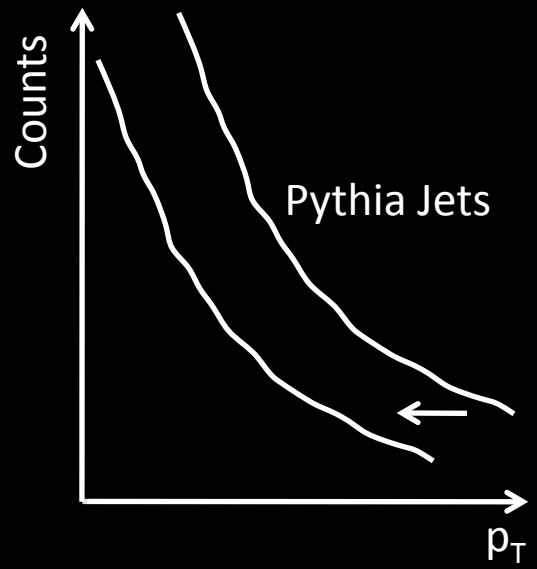


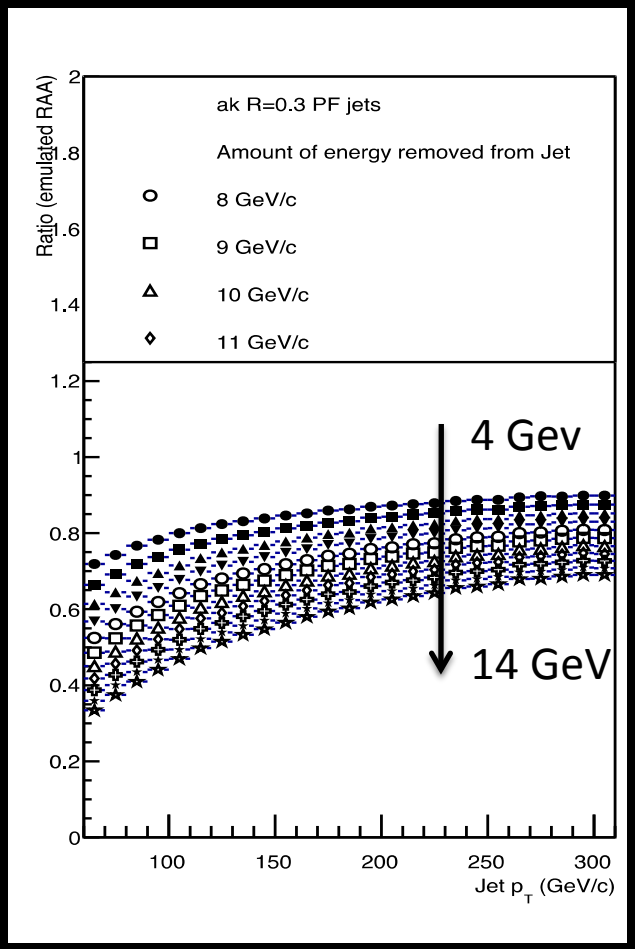


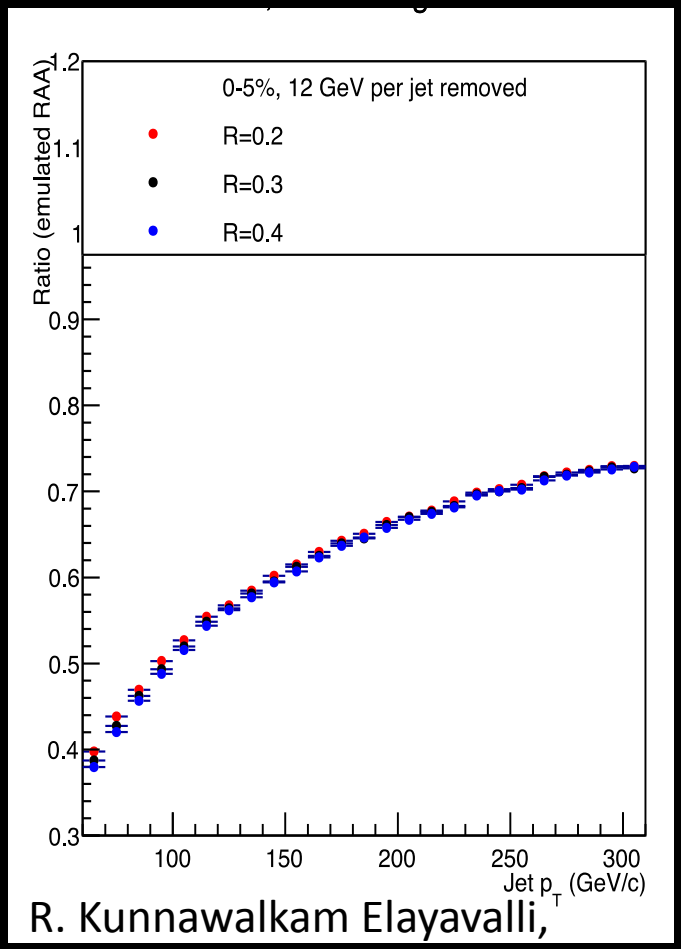


PRC 84 024906 (2011)

A Very Simple "Toy Model" of Energy Loss



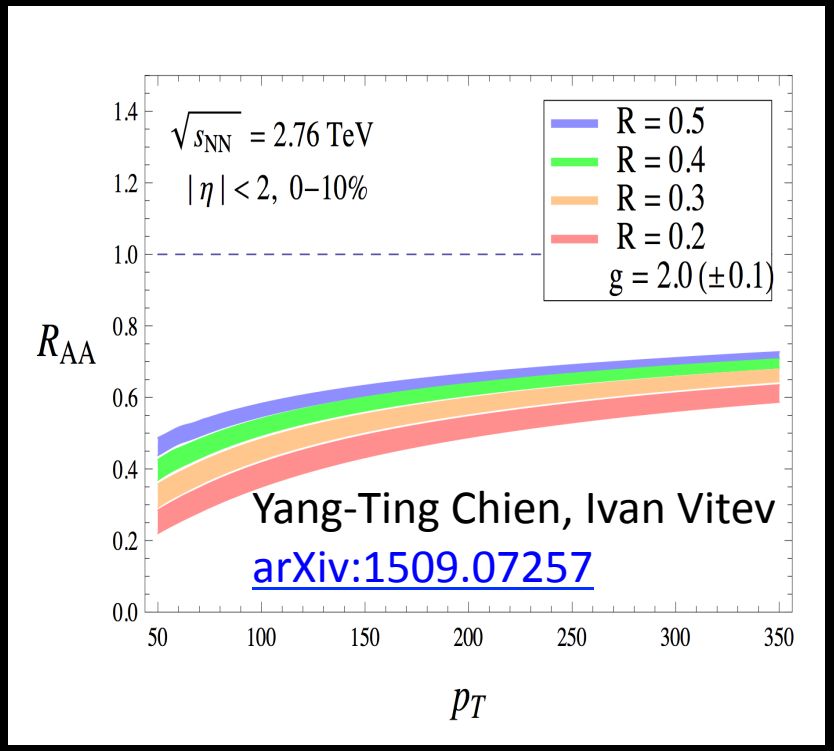


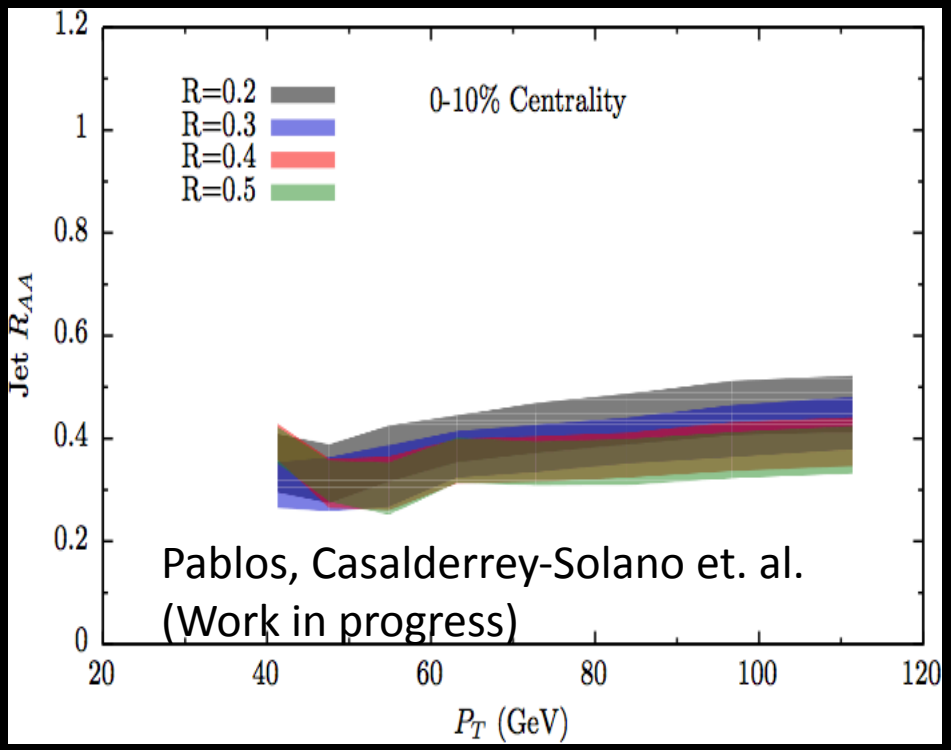


R. Kunnawalkam Elayavalli,

The choice of ΔE can emulate the RAA suppression.
Same shape of spectra: No R dependence: Same RAA for the same ΔE

Measurements meet Real Calculations ☺: An example



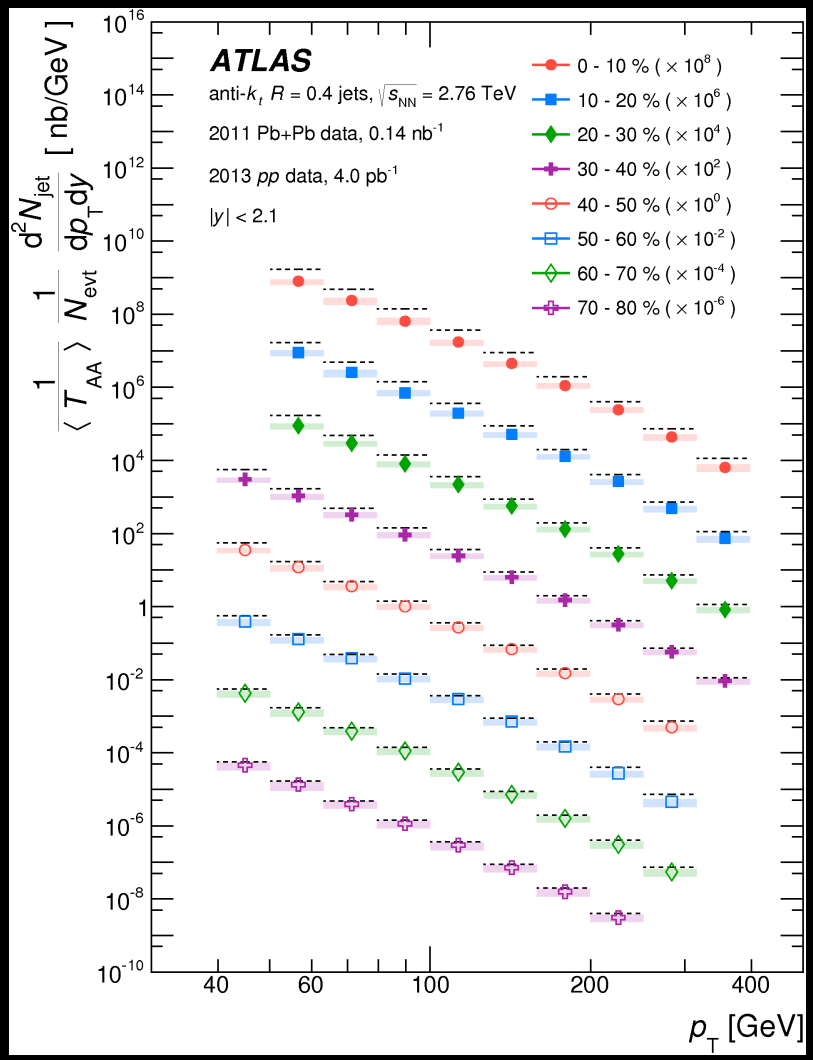


Radiated gluons don't interact
Intuitive ordering of R dependence!

Radiated gluons continue to interact
non-intuitive ordering of R dependence

Need precision jet measurements!

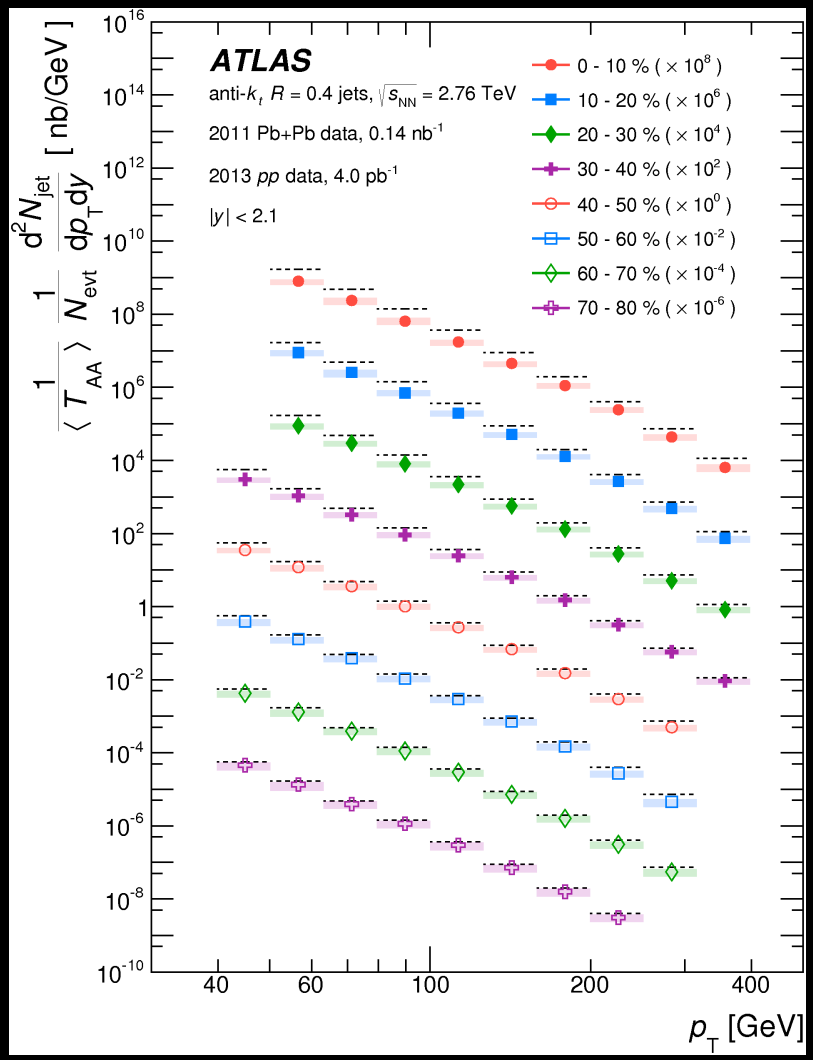
Beautiful "Inclusive" Jets!

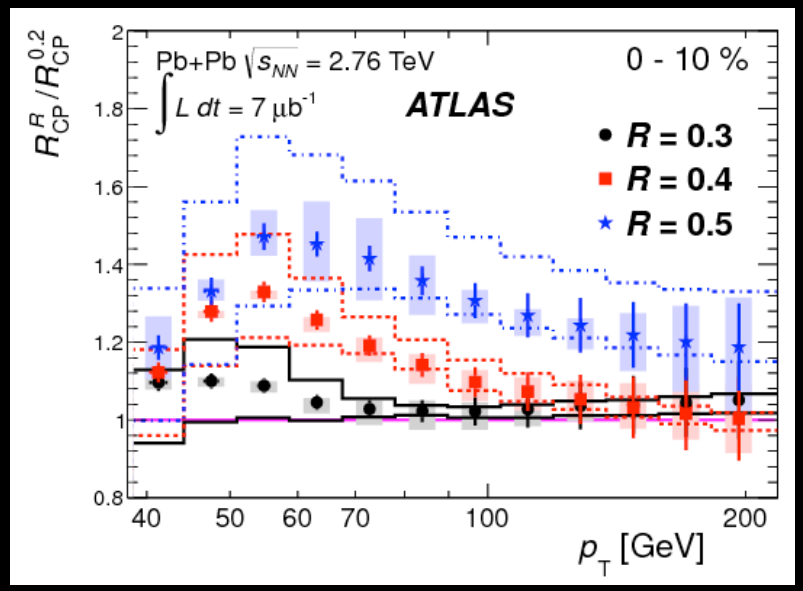


Phys. Rev. Lett. 114 (2015) 072302

Beautiful jet spectra with large kinematic reach.

Beautiful "Inclusive" Jets!





Phys.Lett. B719 (2013) 220-241

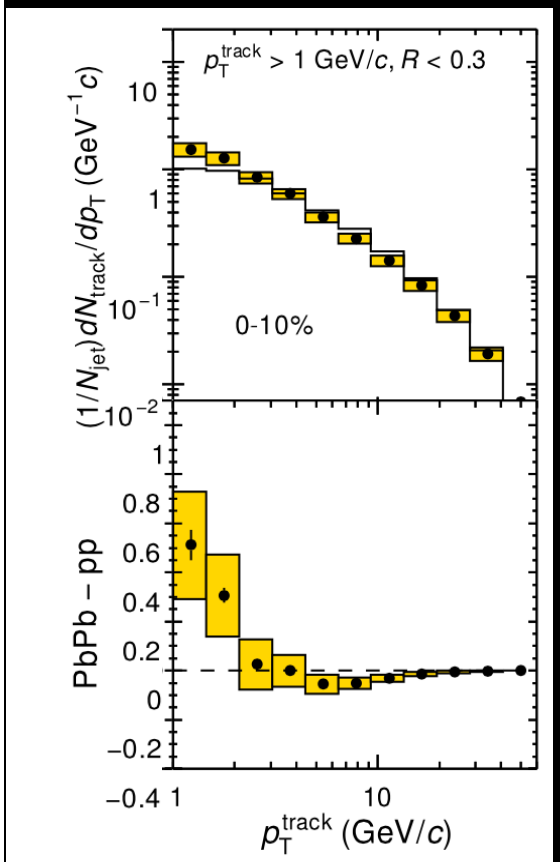
Intuitive ordering of R dependence!

Extremely Hard Measurements
–> large uncertainties

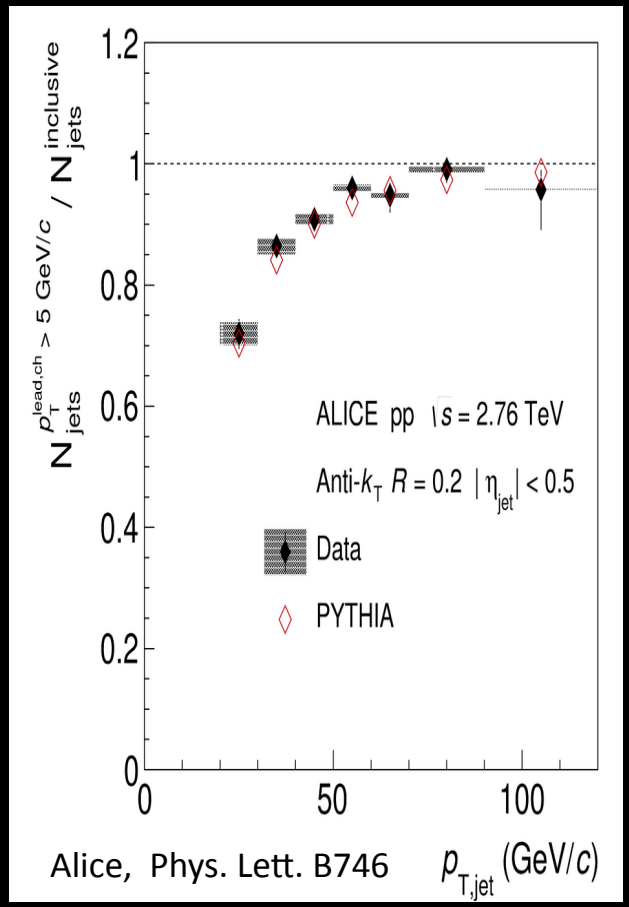
Phys. Rev. Lett. 114 (2015) 072302

Beautiful spectra with large kinematic reach.

Precision Measurements: Caveat
"Removal of Fake Jets"



CMS, PRC 90 (2014) 024908

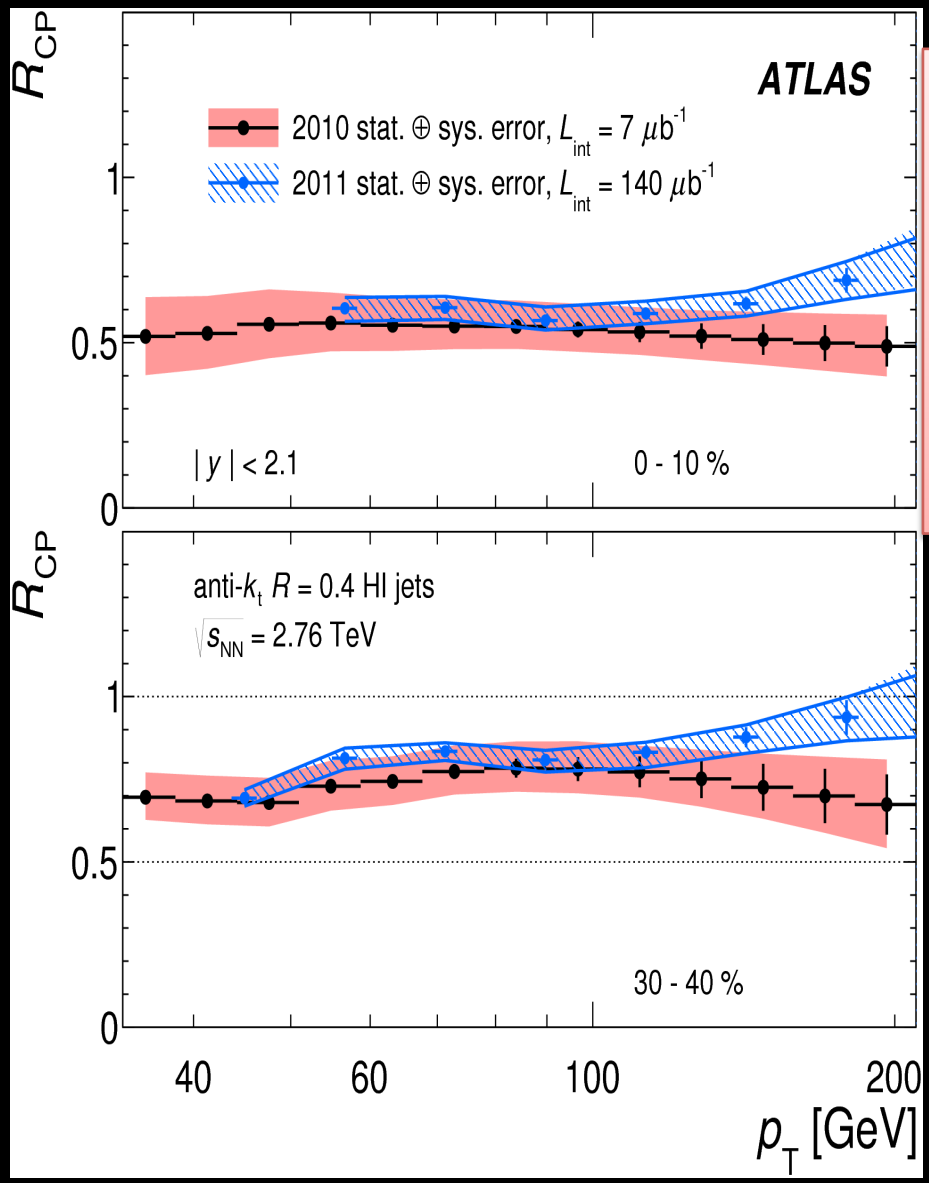


Alice, Phys. Lett. B746

All corrections including fake jets treatment ($p_T$constituent>5-8 GeV/c) done with Pythia fragmentation!

Are we throwing away the physics that we are interested in with these selections?

Precision Measurements: Caveat
"Experimental Corrections: eg. Unfolding"



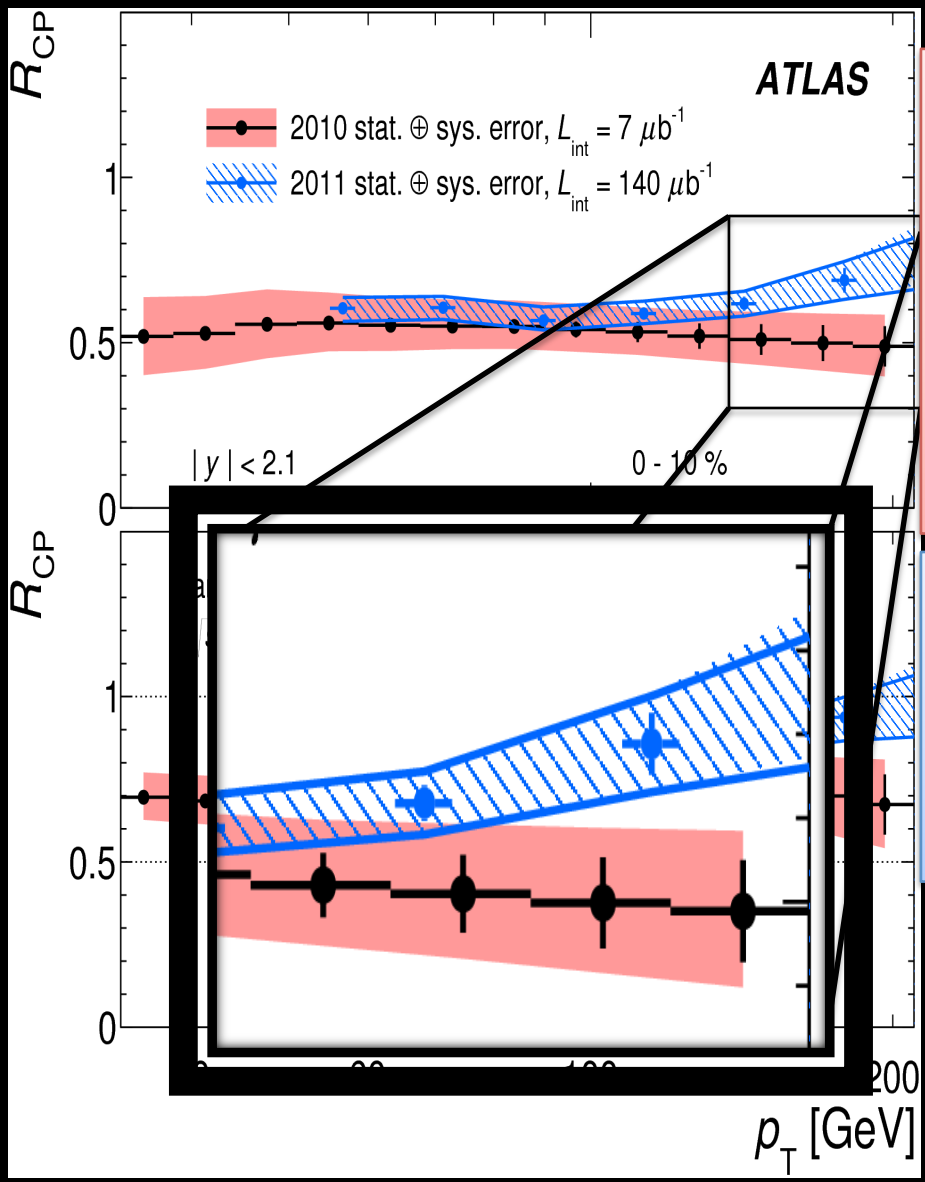
All corrections are done with Pythia fragmentation!

Unfolding corrections are not easy: Modeling of response matrix, choice of method, kinetic cut offs, statistics in samples ....

Phys. Rev. Lett. 114 (2015) 072302

Phys.Lett. B719 (2013) 220-241

Precision Measurements: Caveat
"Experimental Corrections: eg. Unfolding"



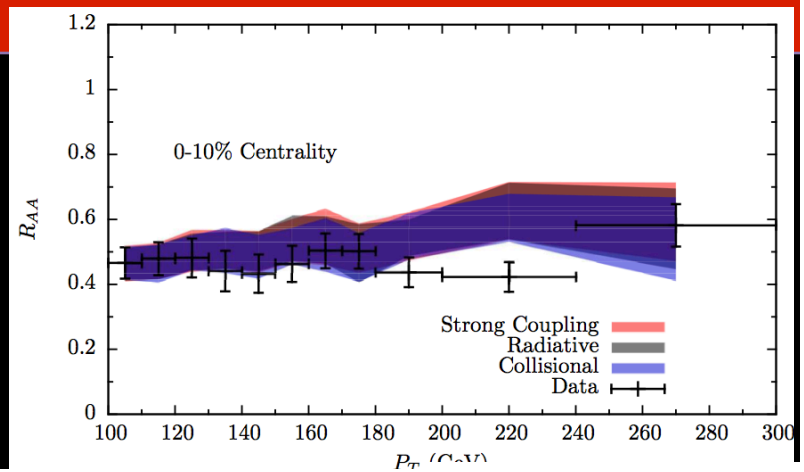
All corrections are done with Pythia fragmentation!
Unfolding corrections are not easy!
Modeling of response matrix, choice of method, kinetic cut offs, statistics in samples ....

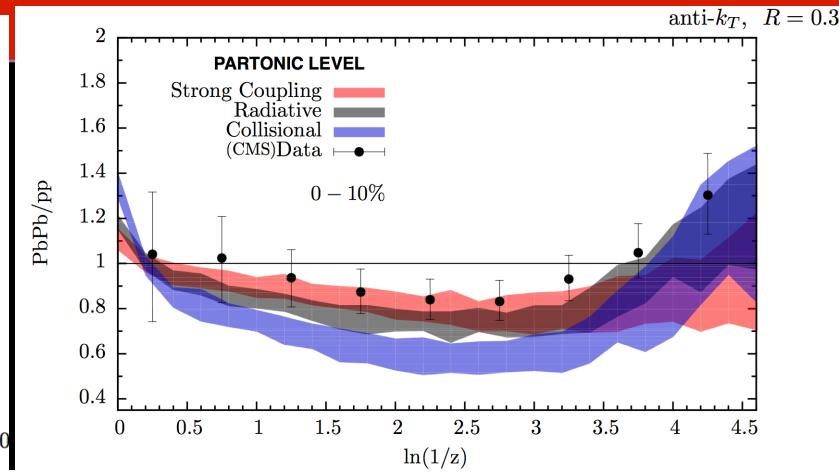
Disagreement? with 2010 vs 2011 data in the same experiment!
We are still learning to make **precision jet measurements**! CMS?

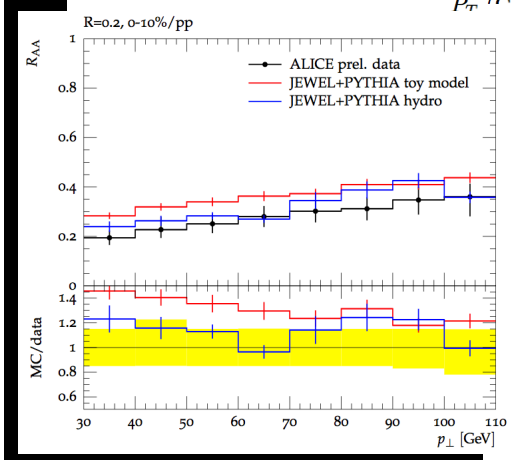
Phys. Rev. Lett. 114 (2015) 072302

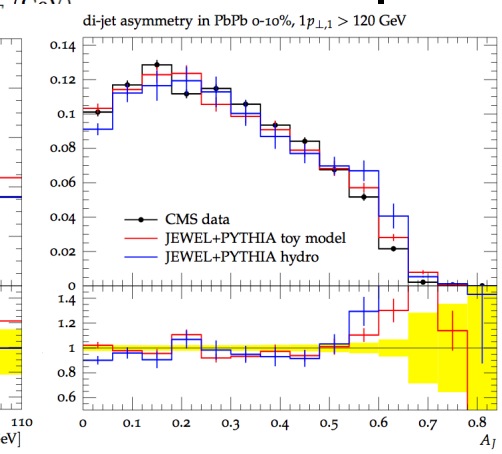
Phys.Lett. B719 (2013) 220-241

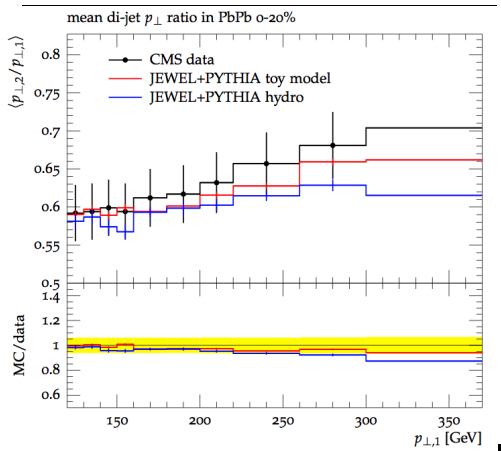
Measurements meet Models: other examples!

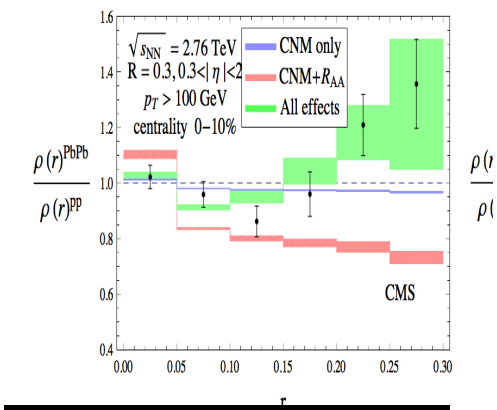








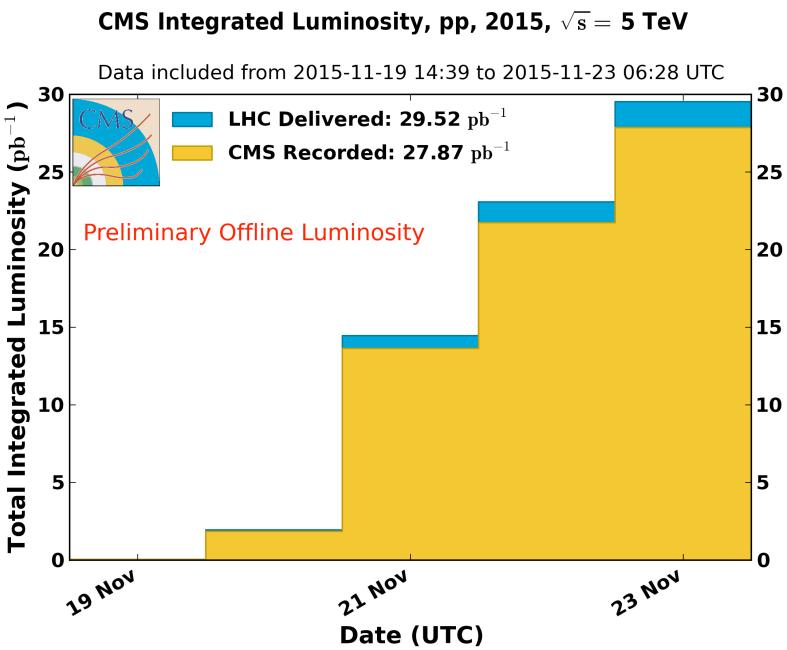


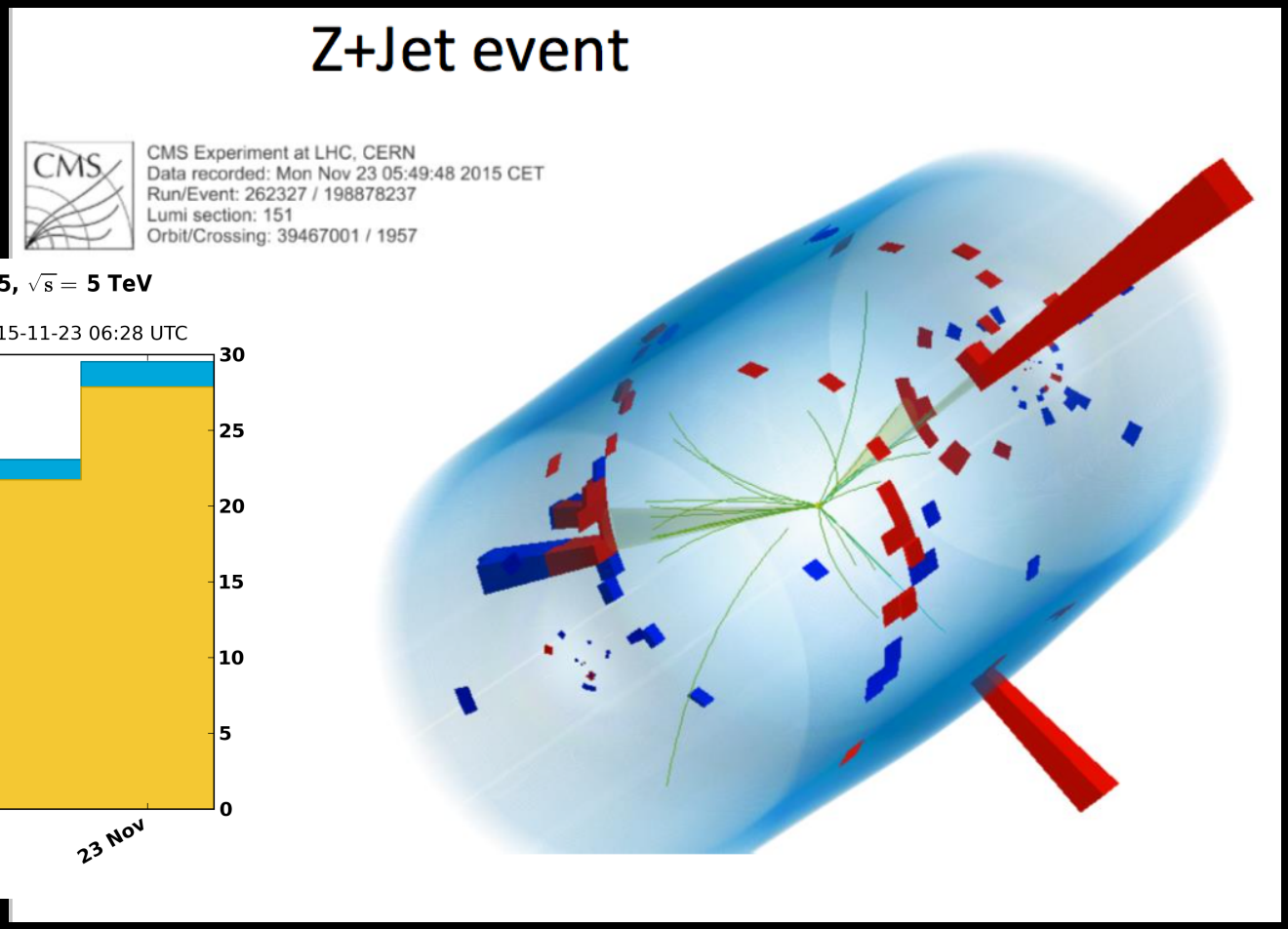


And many other recent theoretical developments!

- We can construct jet-based observables in heavy-ion collisions.
- Quantitative comparison of data and theory started!
- Observables related to jet structure seem to show sensitivity.

What about near future?



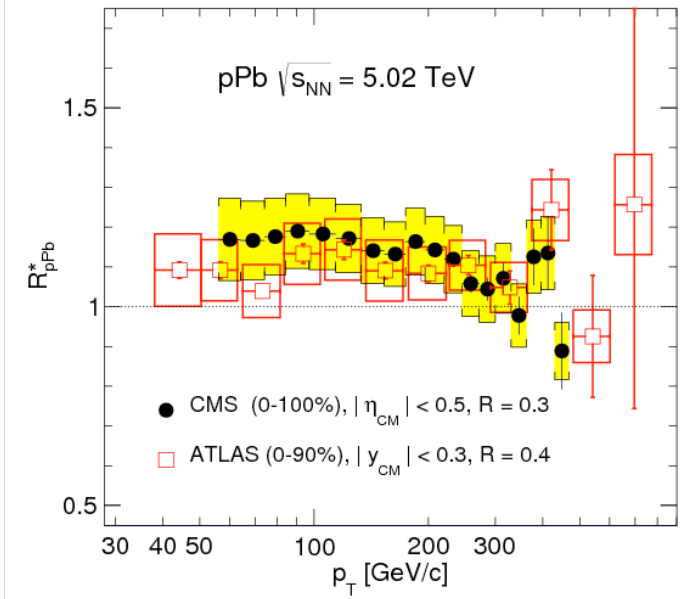


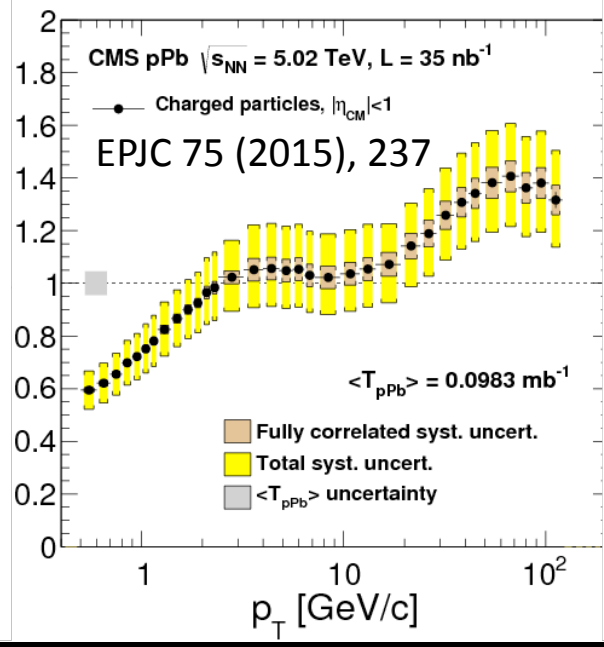
28 pb-1 of data recorded in 5 days!
Essential for HI program at LHC!

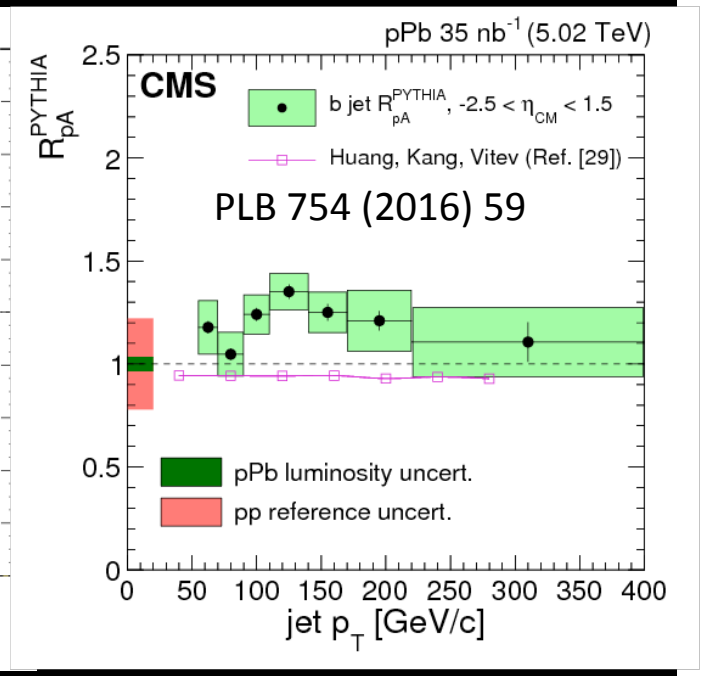
Initial state effects?

Inclusive jet, charged and b-jet R_{pPb}

CMS-HIN-14-001, arXiv:1601.02001







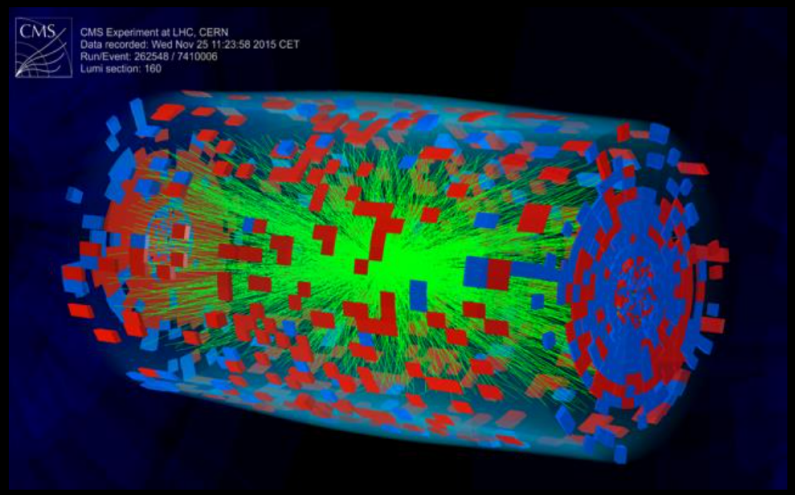
Charged particle R_{pPb}: Show a curious rise!

Jets: Consistent with no effect when the reference is extrapolated or pythia!

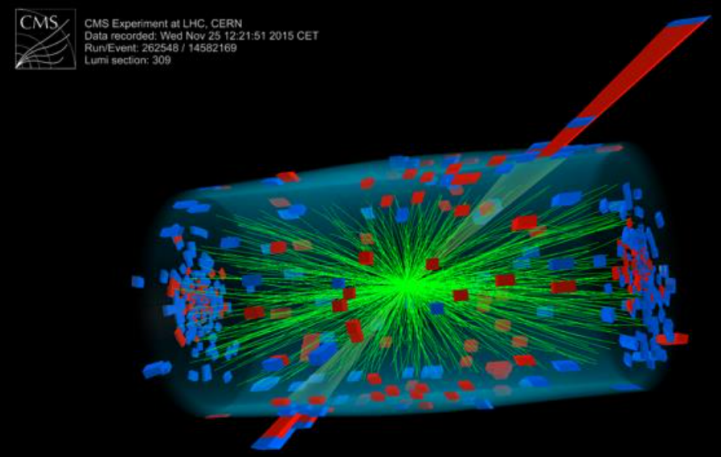
Data is collected and REAL pp data reference ☺ is in the works!

What about further down the road?

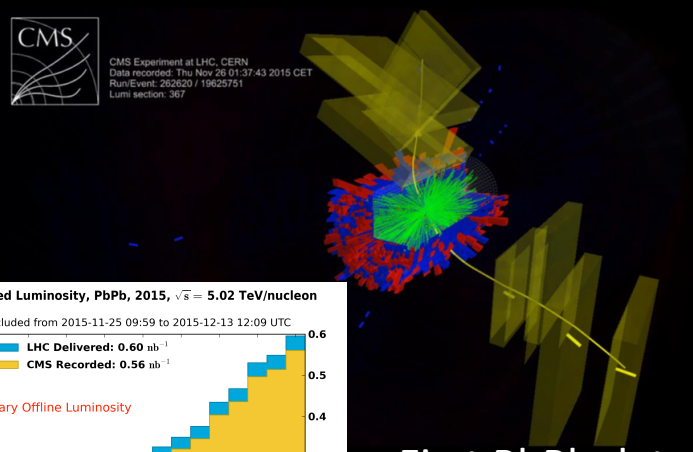
Head-on collision

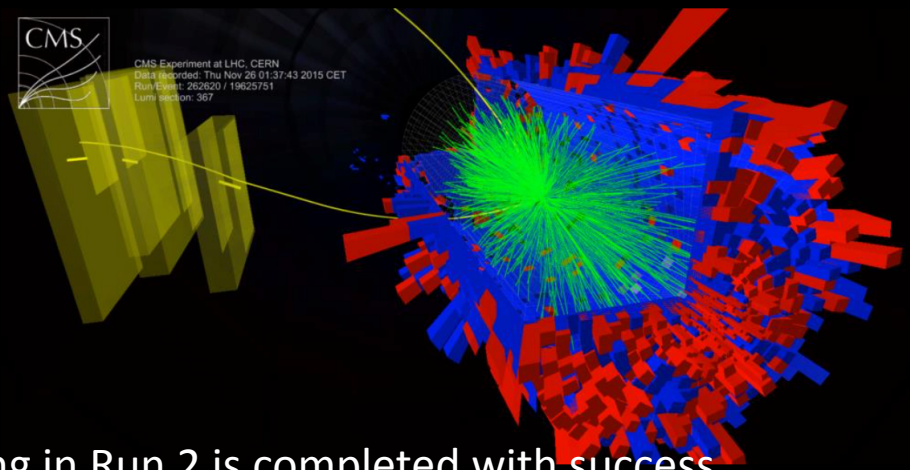


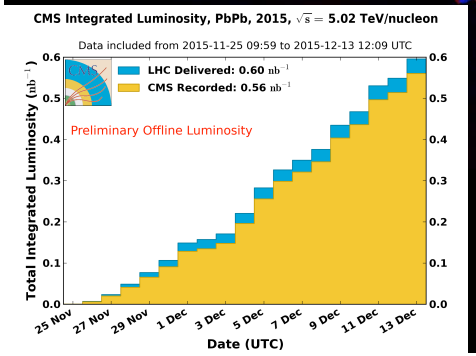
The first dijet event



The first Upsilon Candidate

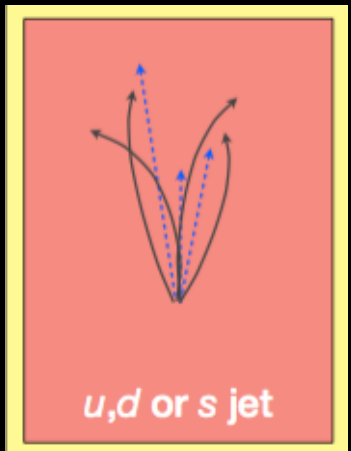


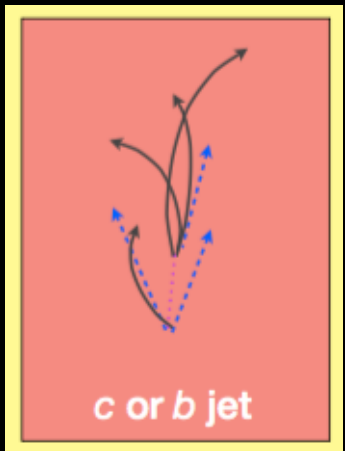




First PbPb data taking in Run 2 is completed with success.
Improvement on jet statistics by ~ order of magnitude.

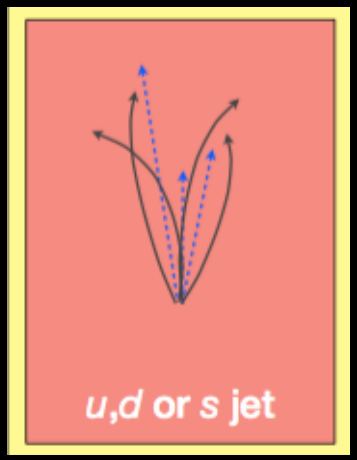
Other Jet Substructure Observables?





To what extent can the identities of underlying partons be deduced from properties of the jets they produce?

Quark-gluon discrimination:

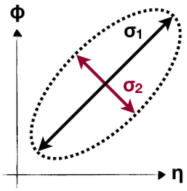


Compared to gluon jets,
quark jets in vacuum have:

1. Fewer constituents
2. Narrower shape
3. Harder fragmentation function

and less symmetric energy sharing among constituents

1. Multiplicity: Total, Charged, Neutral → Particle-Flow in CMS
2. Width Variables



obtained by diagonalizing

$$\frac{1}{\sum_i p_{\mathrm{T},i}^2} \sum_i p_{\mathrm{T},i}^2 \begin{pmatrix} (\Delta\phi_i)^2 & (\Delta\phi_i \Delta\eta_i) \\ (\Delta\eta_i \Delta\phi_i) & (\Delta\eta_i)^2 \end{pmatrix}$$

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$$

3. Energy Sharing Variables: Pull, R, p_TD

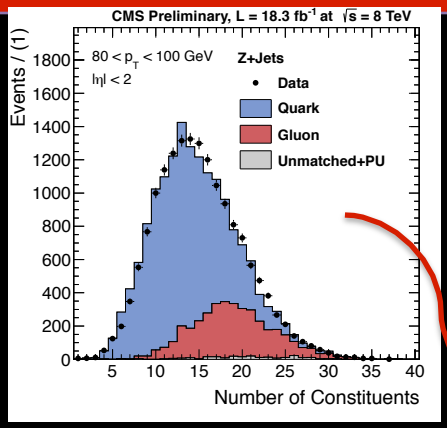
$$|\vec{t}| = \left| \frac{\sum_i p_{\mathrm{T},i}^2 \, |r_i| \, \vec{r}_i}{\sum_i p_{\mathrm{T},i}^2} \right| \qquad \vec{r}_i = (\Delta\eta_i, \Delta\phi_i)$$

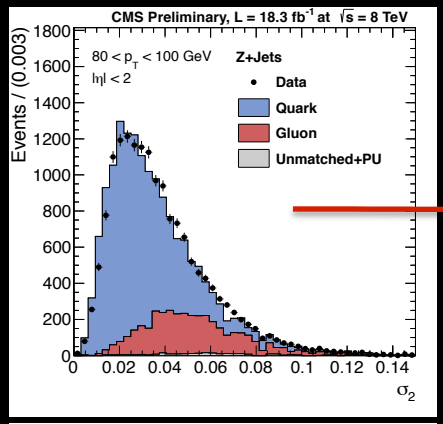
$$R = \frac{\max\left(p_{\mathrm{T},i}\right)}{\sum_i p_{\mathrm{T},i}} \qquad p_{\mathrm{T}}D = \frac{\sqrt{\sum_i p_{\mathrm{T},i}^2}}{\sum_i p_{\mathrm{T},i}}$$

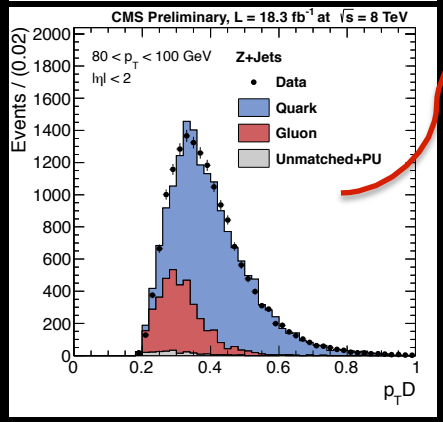
p_TD=1 single jet constituent
p_TD=0 ∞ number of jet constituents.

http://cds.cern.ch/record/1599732/files/JME-13-002-pas.pdf
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME13002

Quark-gluon discrimination:

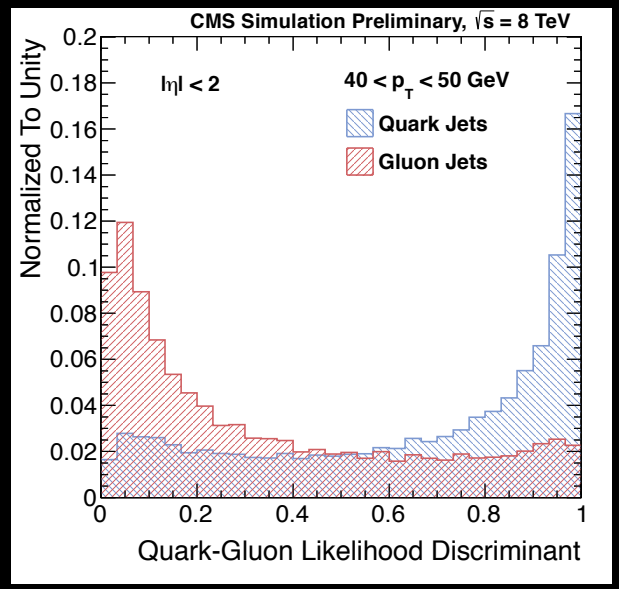


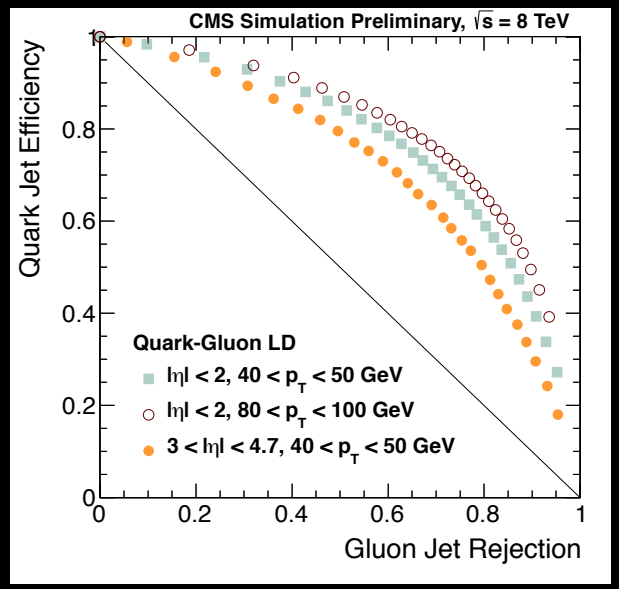




Likelihood based discriminator obtained by combining 3 variables:

- Total multiplicity
- Minor axis
- p_TD





Good background rejection and signal efficiency

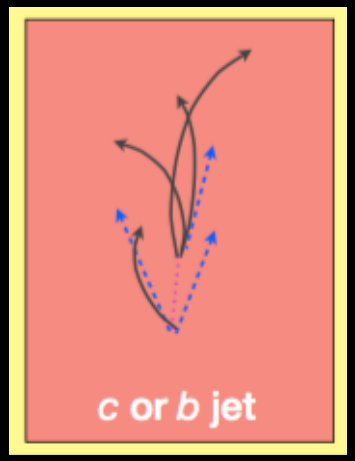
Stability vs pile-up is under investigation

Is not directly applicable to AA but combine it with other taggers.

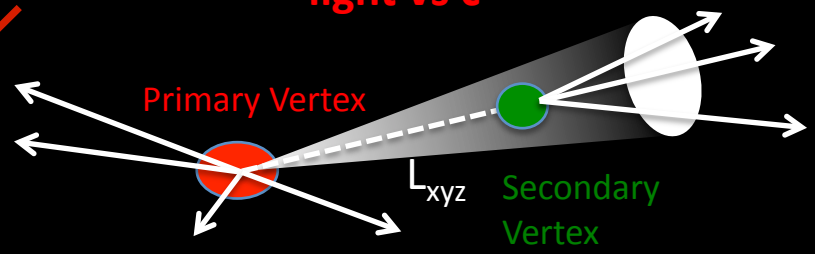
http://cds.cern.ch/record/1599732/files/JME-13-002-pas.pdf
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME13002

Heavy Flavour Parton Dependence

Bottom tagged jets are selected on displaced vertices.

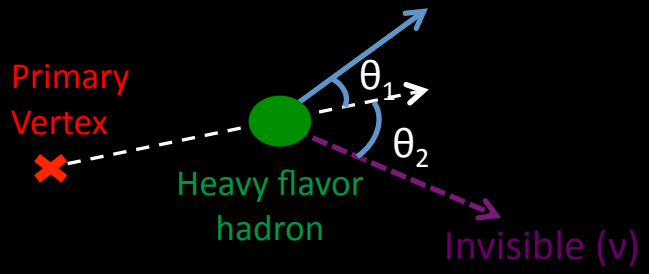


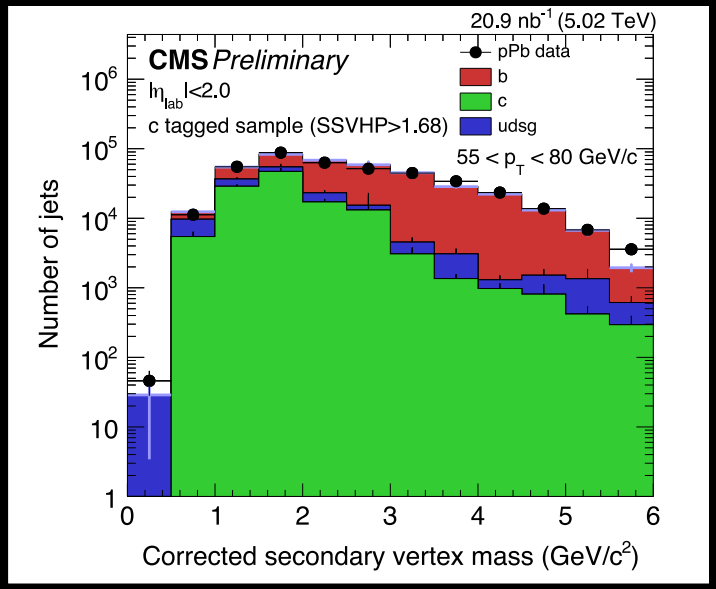
But charm jets also have small displacement
→ Additional discriminative variables: **3+ Body Secondary Vertex Tagging: light vs c**



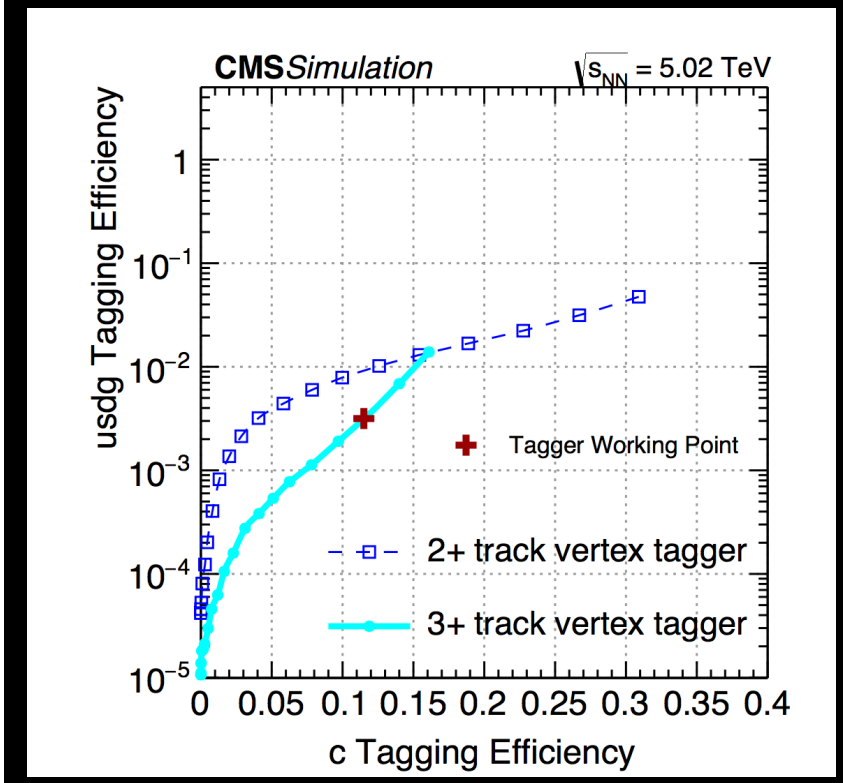
Feed into template shapes
charm jet contribution extracted

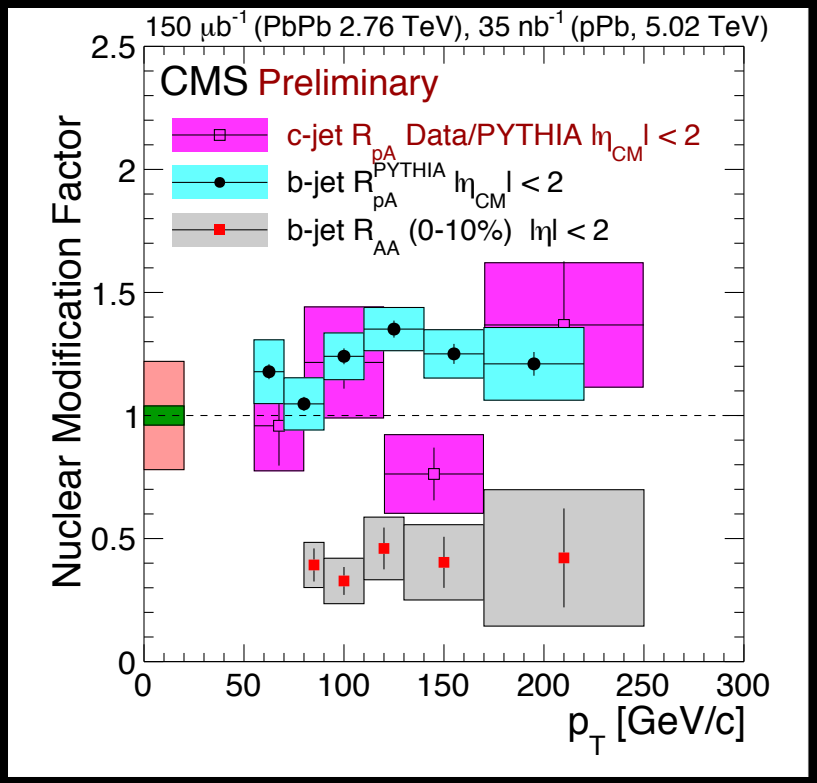
Corrected Secondary Vertex Mass: c vs b





Heavy Flavour Parton Dependence

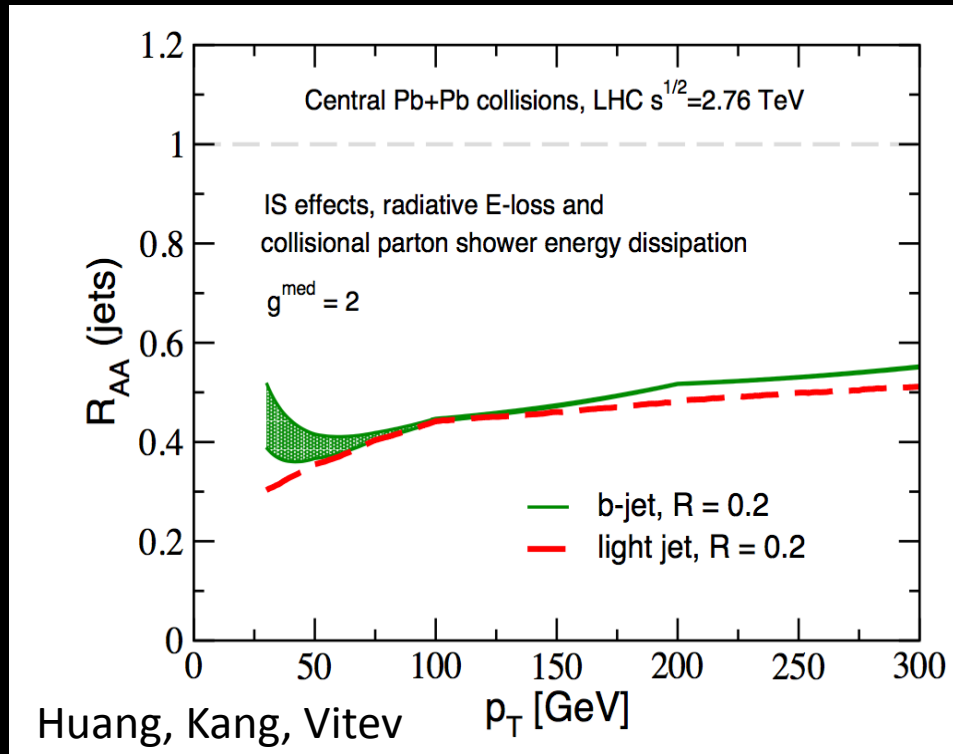




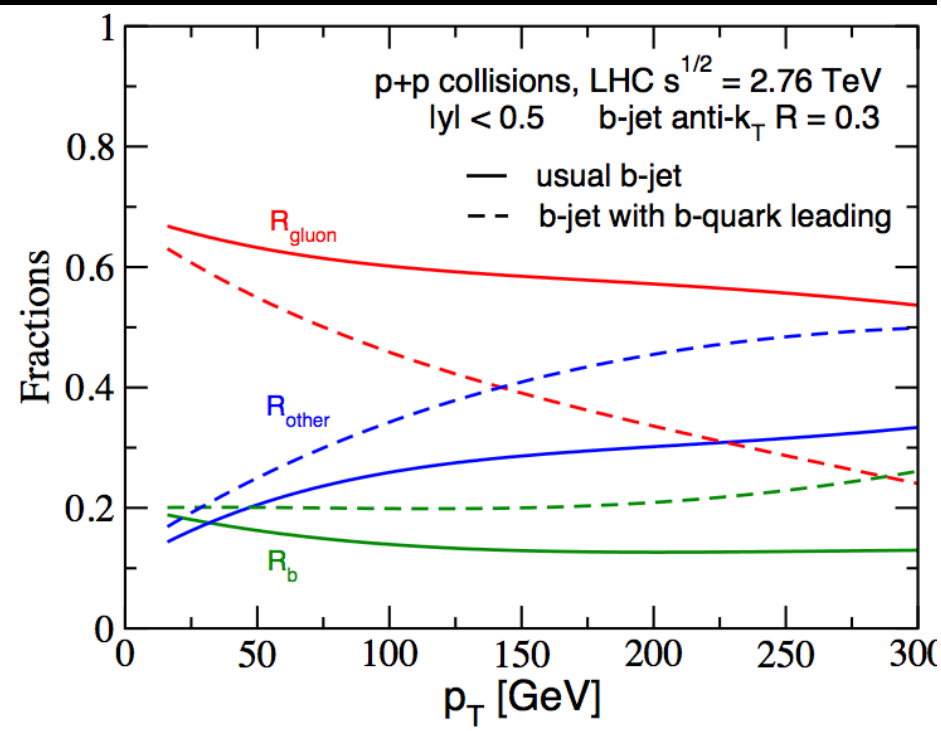
Reduction in the mistag rate
by a factor of 3 with HP SSV

Done with pp at 2.76 TeV and Pbp at 5 TeV
b/c look alike

Caveat: b/c jet might not be original!



Huang, Kang, Vitev



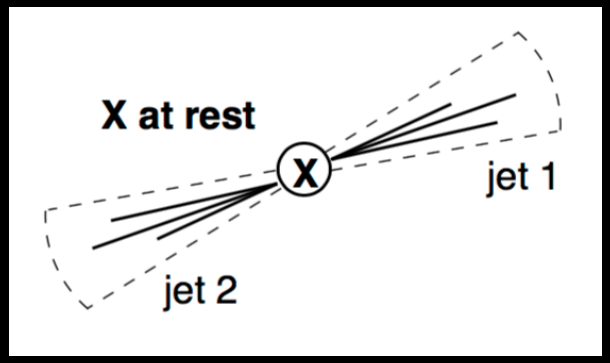
At high pt region, mass effect can be neglected

R_{gluon}:fraction of g->b
R_b :fraction of b->b
R_{other}:fraction of q->b

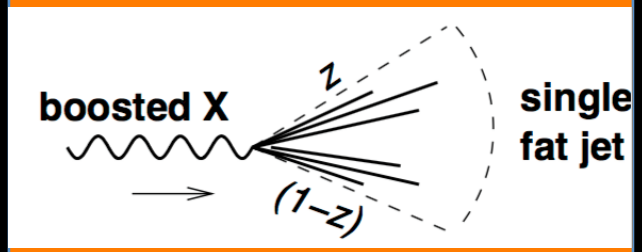
With high statistics Run 2: Explore multi tags such as c/b jet with D/B and γ.

Utilize tools developed for pp ☺ - Jet Grooming:

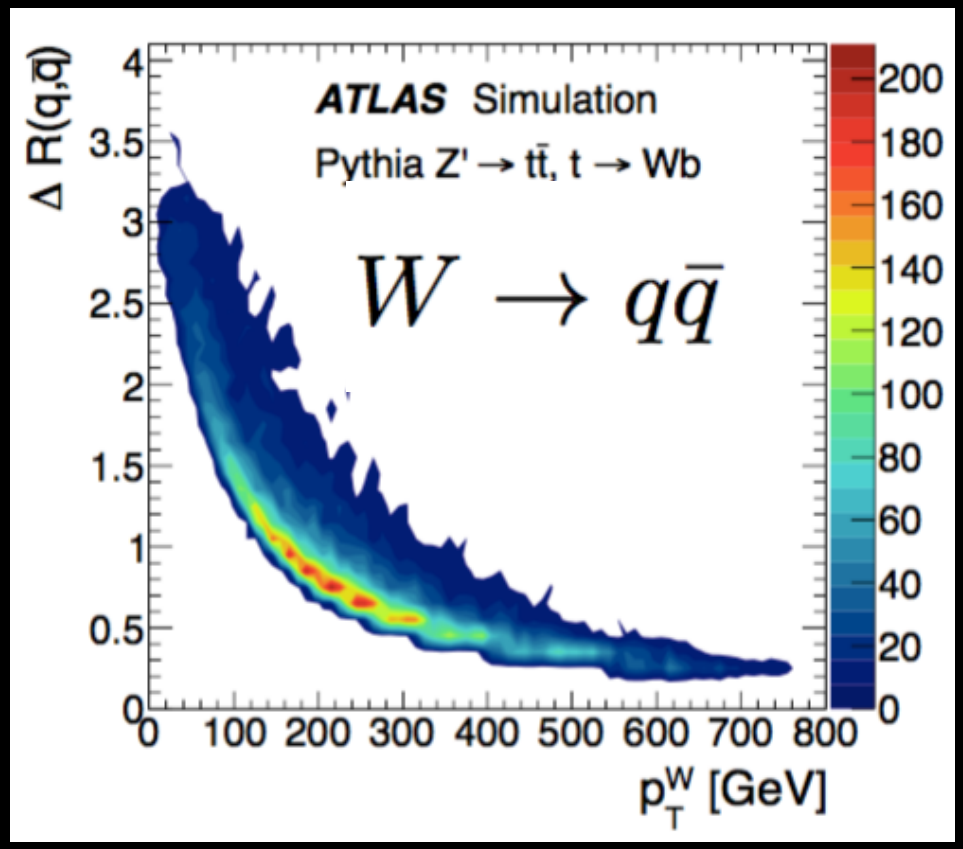
the systematic removal of a subset of the jet constituents
→remove soft and wide-angle radiation from the jet



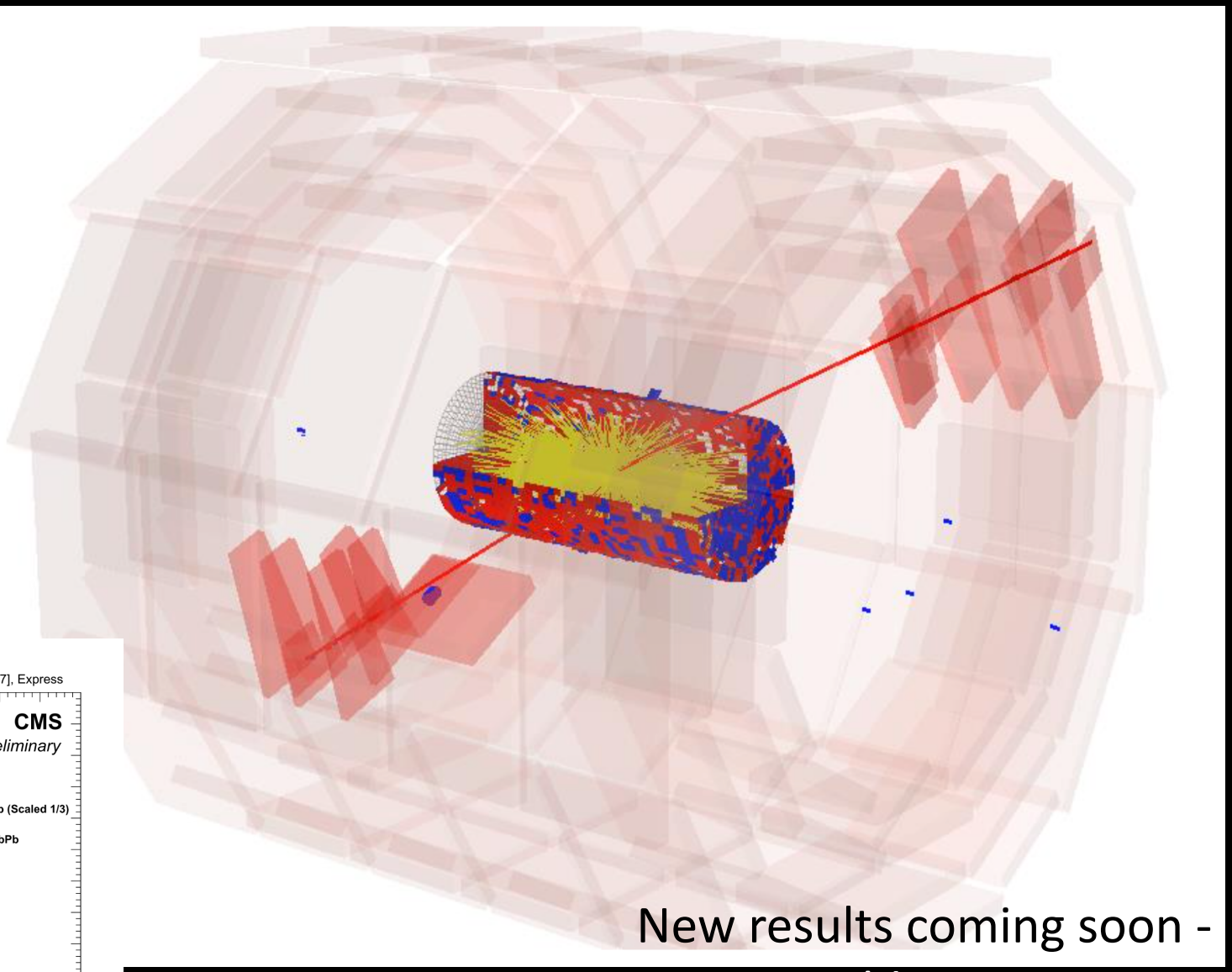
High-pT regime: p_T>2m/R

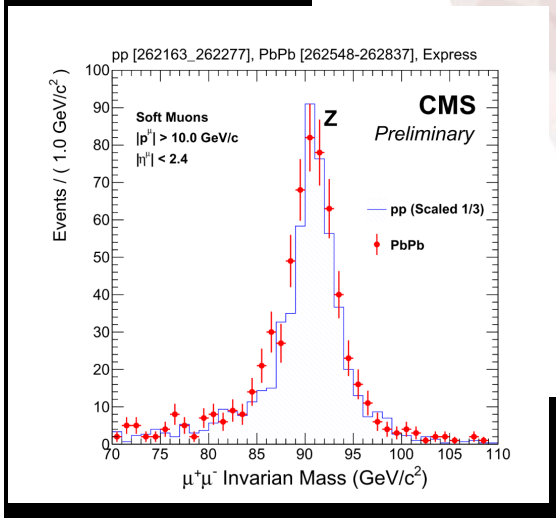


Decay is collimated i.e., qq are in the same jet.



Z+jets at 5 TeV PbPb





New results coming soon - Stay Tuned !

Summary

Run 1: (2010-2014)
Jet Tomography has been explored with multiple jet observables.

Run 2 (and beyond): (2015-2018)
Initial pp reference at 5 TeV is already collected.

- Detailed studies of jets for initial state effects with proper pp reference will be soon available for inclusive jets, γ+jet, c/b+jet but also for Z+Jet, additional tags with B/D …

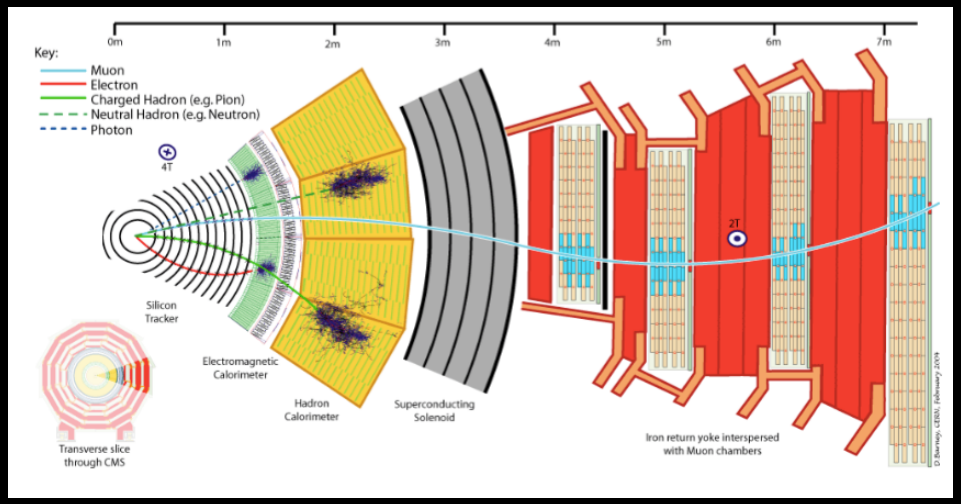
Improvement in jet statistics in PbPb.

- Explore underlying partons properties with reconstructed jets.
- Event plane dependent Jet Tomography with: Jet shapes, FF, sub-structure for a complete characterization of final state

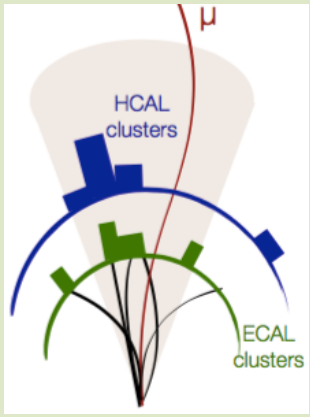
Need continuous interaction of experiment & theory!

Extras

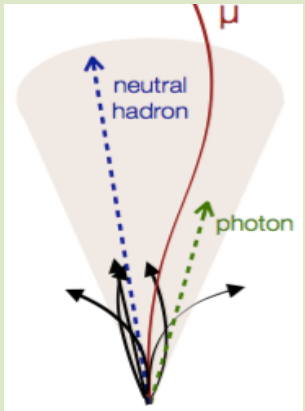
CMS Detector:



Every layer serves a purpose in particle identification and measurement.



CMS Particle Flow Algorithm



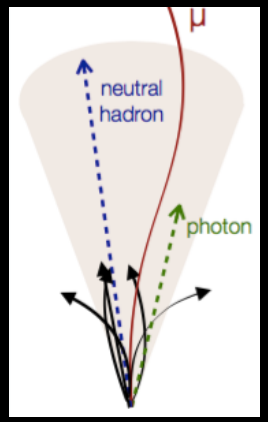
Tracks and calorimeter clusters

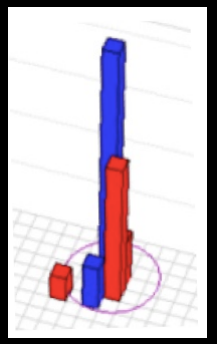
$\mu^{\pm}$, $e^{\pm}$, γ, h^{0}, $h^{\pm}$

Jet Reconstruction in CMS

A jet reconstruction algorithm is a set of mathematical rules that reconstruct unambiguously the properties of a jet.

1. Calorimeter Jet (calojet): from energy depositions grouped in HCAL & ECAL
2. Particle Flow Jets (PFJ): Reconstructed particles utilizing all sub-detectors "a la Generator Level"





CMS uses several Jet Algorithms:

- Anti-K_T (R = 0.2-0.5)
- Iterative Cone (R=0.5)

Underlying event subtraction

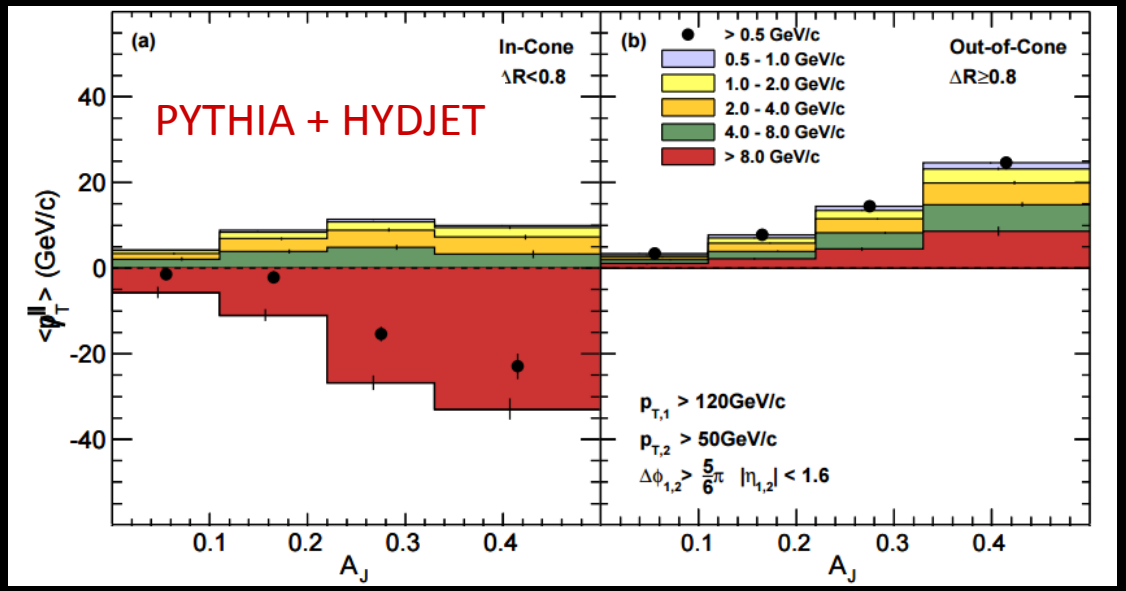
- Iterative PileUp subtraction
- HF/Vornoi and others

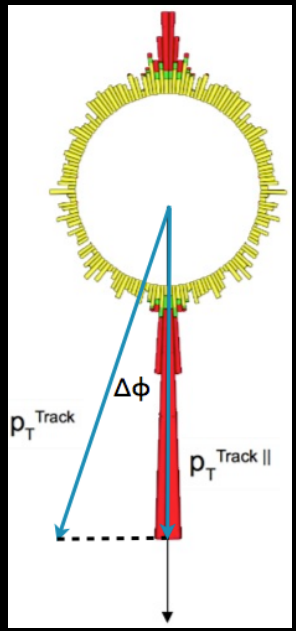
M. Cacciari, G. P. Salam, and G. Soyez, JHEP 04 (2008) 063
O. Kodolova, I. Vardanian, A. Nikitenko et al., Eur. Phys. J. C50 (2007) 117

Change in Jet Morphology as seen with CMS

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

In-cone (Δ R<0.8) Out-of-cone (Δ R>0.8)



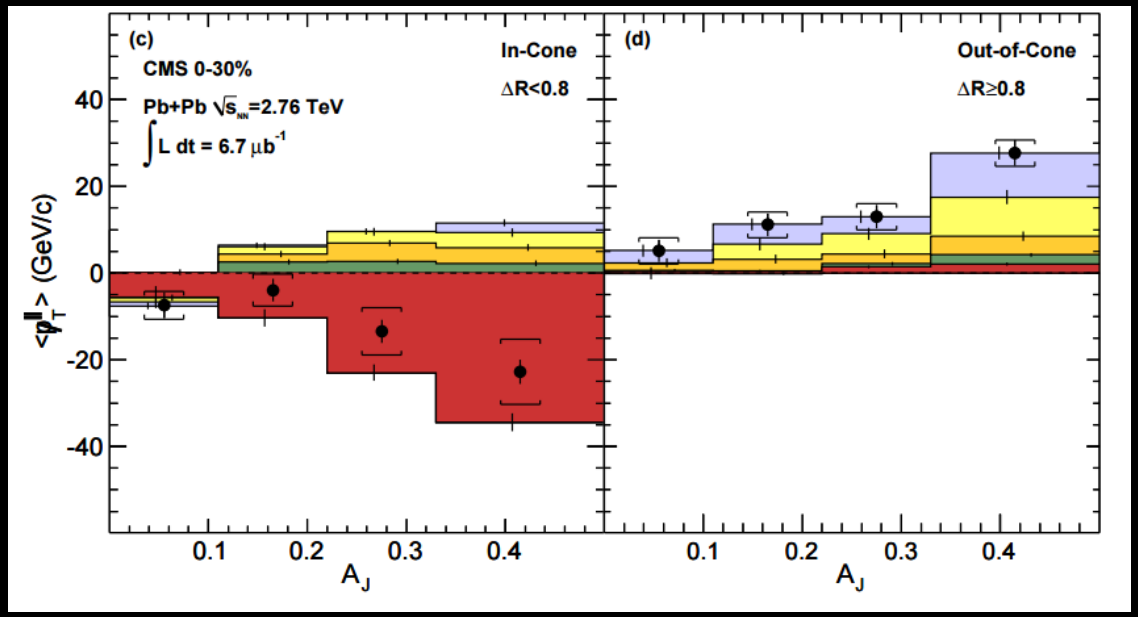


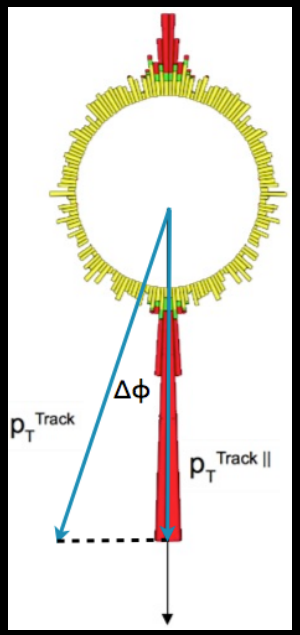
PRC 84 024906 (2011)

Change in Jet Morphology as seen with CMS

Missing p_T: Energy is carried away by low p_T particles far away from the jet axis.

In-cone (ΔR<0.8) Out-of-cone (ΔR>0.8)

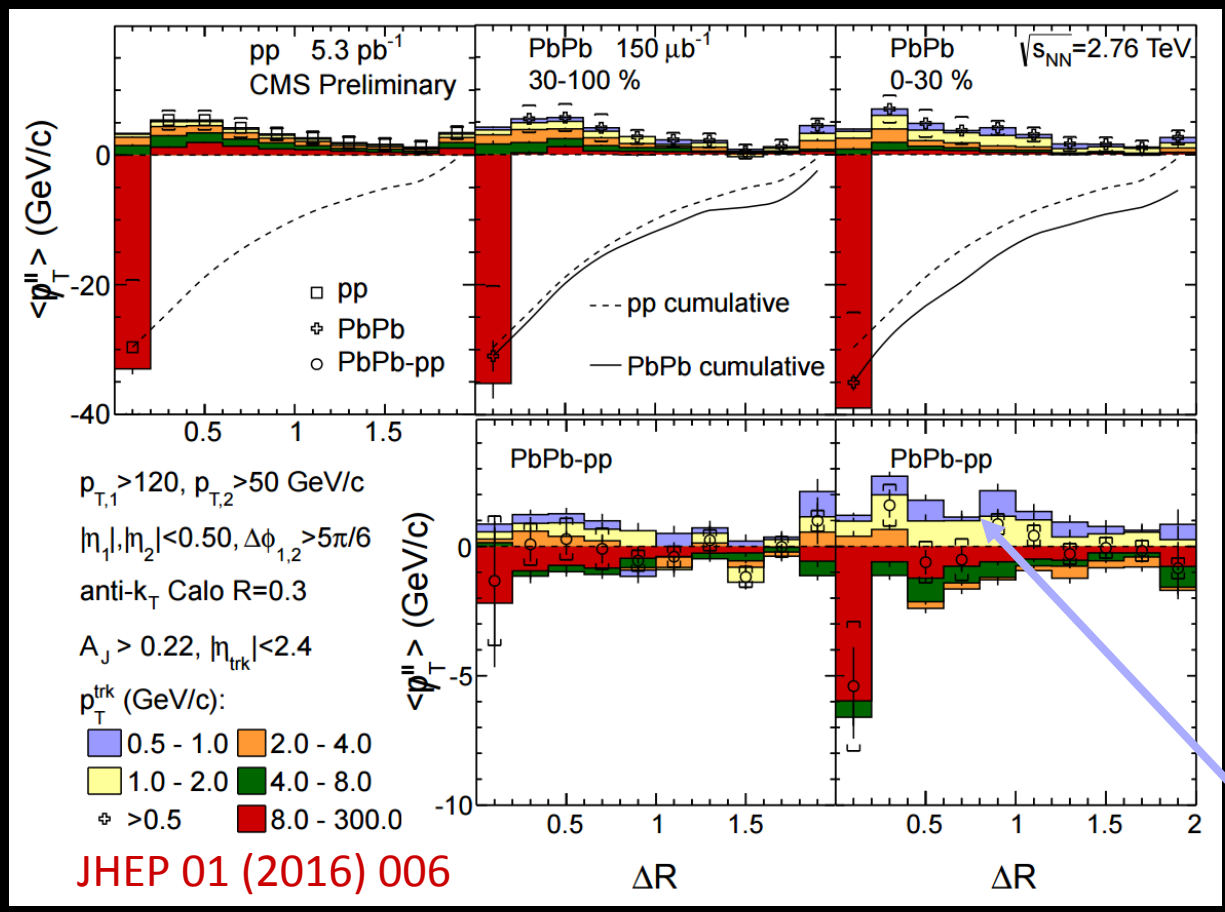




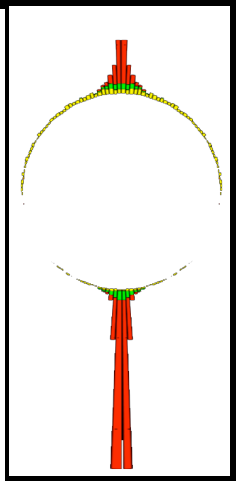
PRC 84 024906 (2011)

Extending Missing p_T analysis on ΔR dependence …

leading-subleading jet momentum *difference*



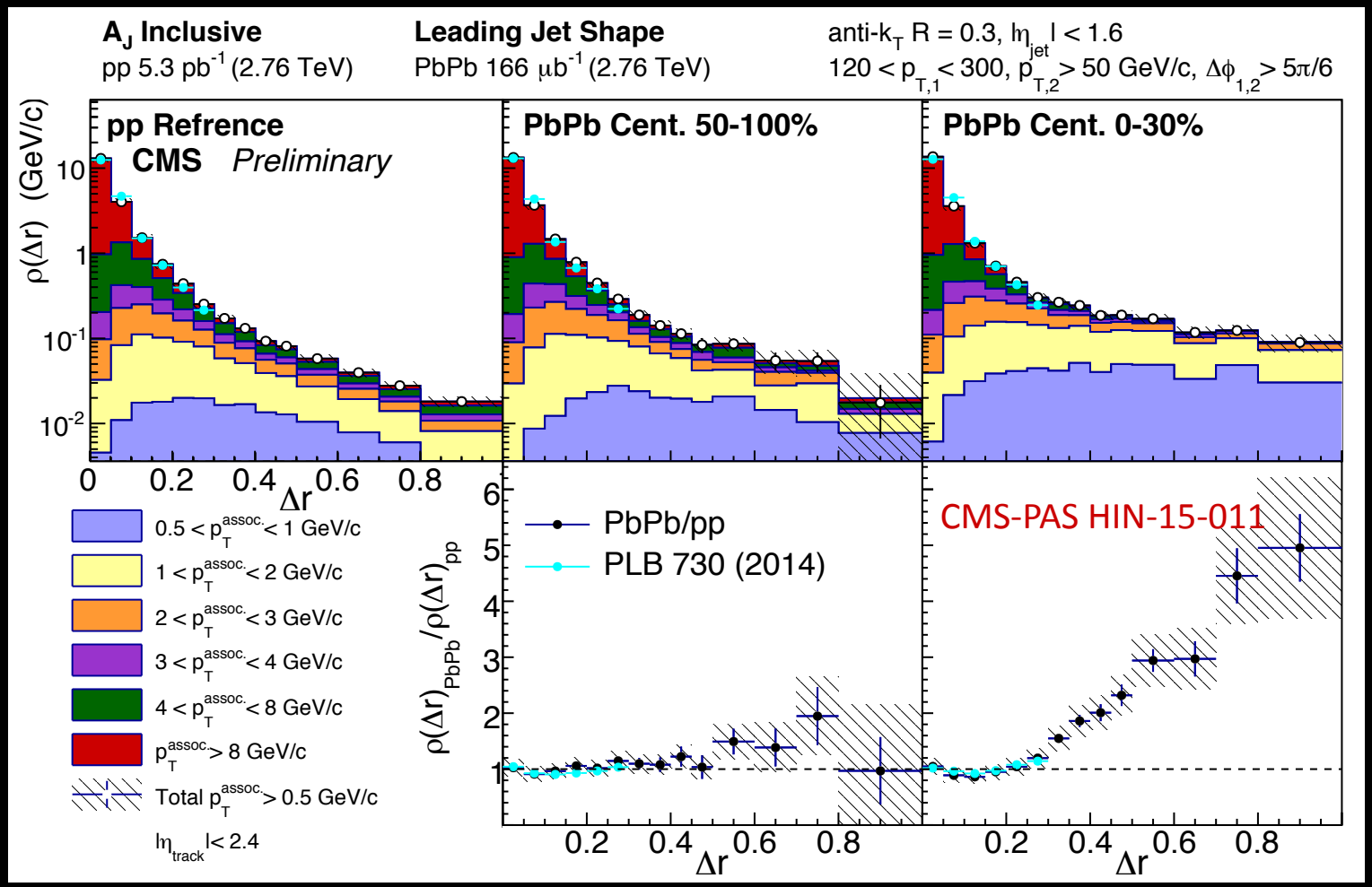
JHEP 01 (2016) 006



Balanced by low p_T particles in subleading jet direction
Extends upto large ΔR

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

Jet Shape Modifications from jet track correlations



$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\frac{\Sigma_{\text{tracks}\in(r_a,r_b)}p_T^{\text{track}}}{p_T^{\text{jet}}}$$

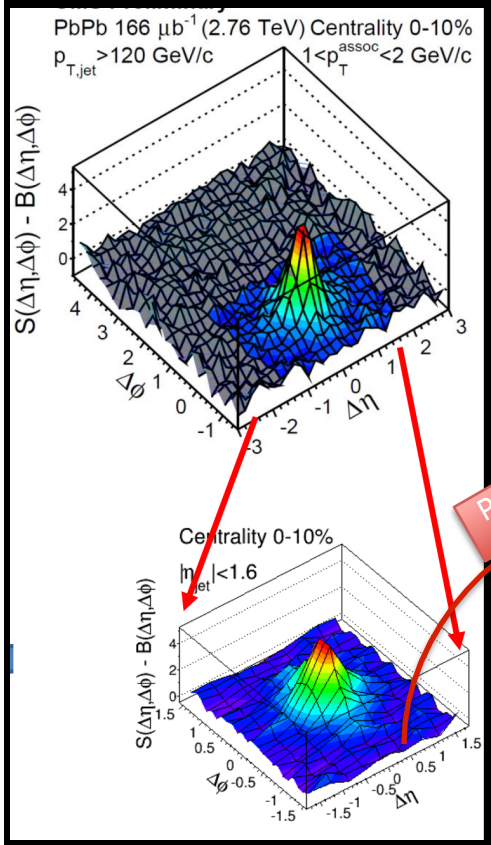
Integrated Correlations function

→ Jet shapes up to large radial distances

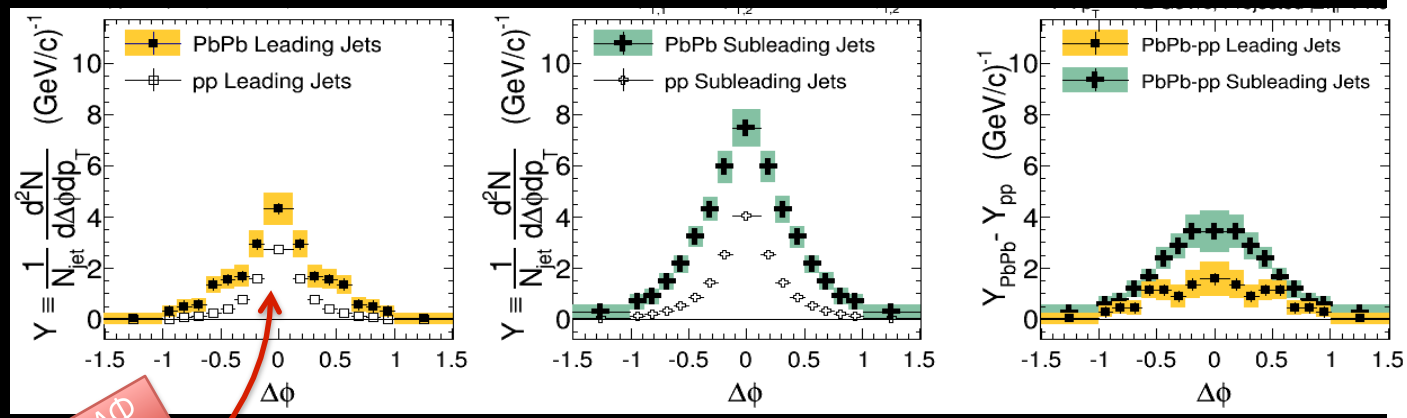
Preserved normalization of previous measurement:

set to integrate to unity for p_T>0.5 GeV/c in Δr<0.3

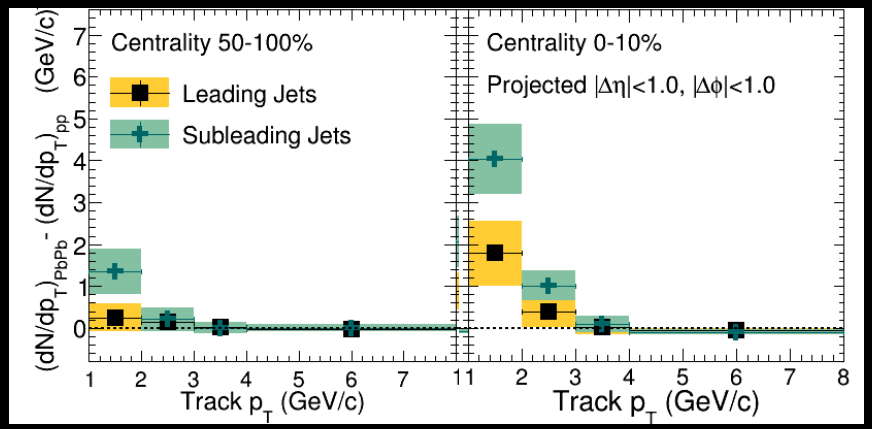
Jet Track Correlations:



Project into ΔΦ



Enhancement of low-p_T particles in PbPb vs pp



CMS-PAS HIN-14-016
arXiv:1601.00079

Excess yield drops with p_T,
Larger effects for subleading jets and in central events