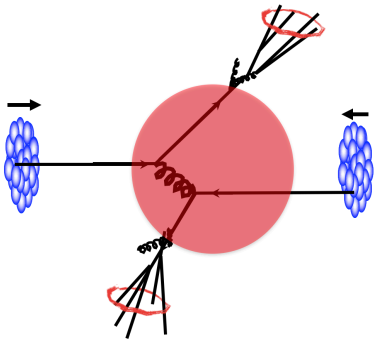
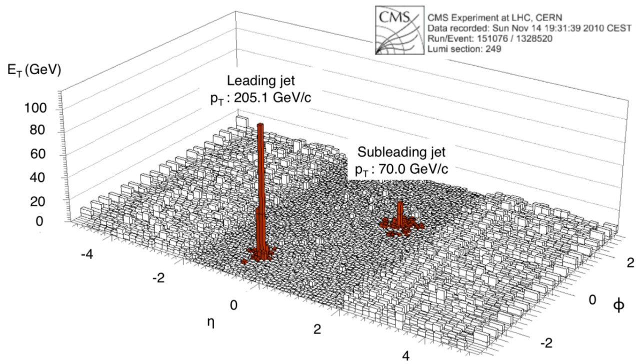
Overview of recent jet results in heavy ion collisions at LHC

Yongsun Kim (Korea University)

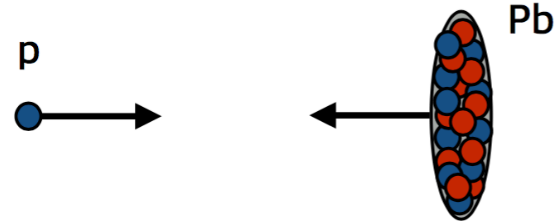
ISMD2016, Jeju Island, Korea, 2016.09.01

Introduction





- Jet has been one of the most popular object in Heavy Ion communitiy in LHC era for its plenty
- From 2010, More than 30 papers/notes were born from ATLAS and CMS
- This was enabled by virtue of not only the superb detecting apparatus, but the enormous development of jet finding techniques, especially UE background subtraction as well as researchers' efforts
- In this presentation, jet results during LHC Run I phase are overviewed and the new results from **PbPb@5.02TeV** are introduced
- Remind that only CMS and ATLAS results are discussed but ALICE also published several jet measurements via charged particle jets



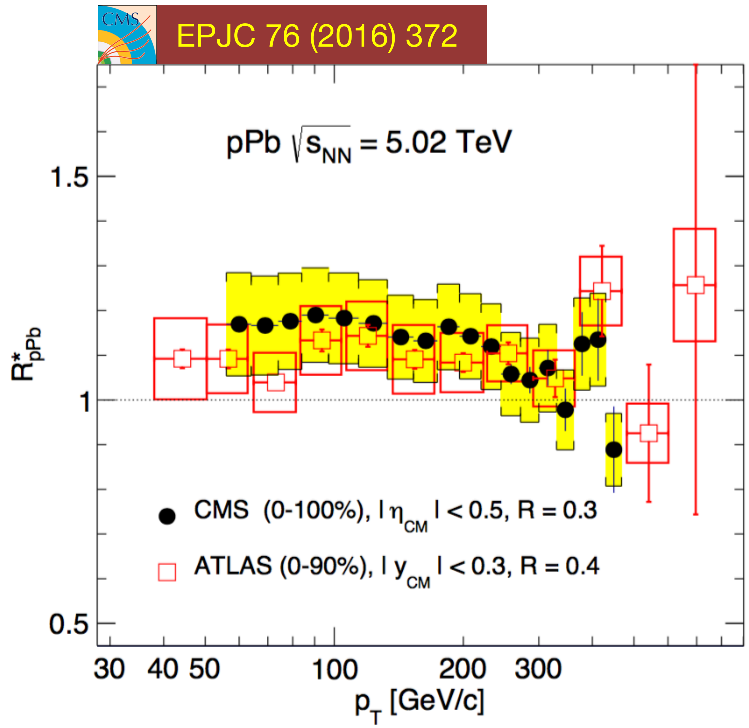
Part I

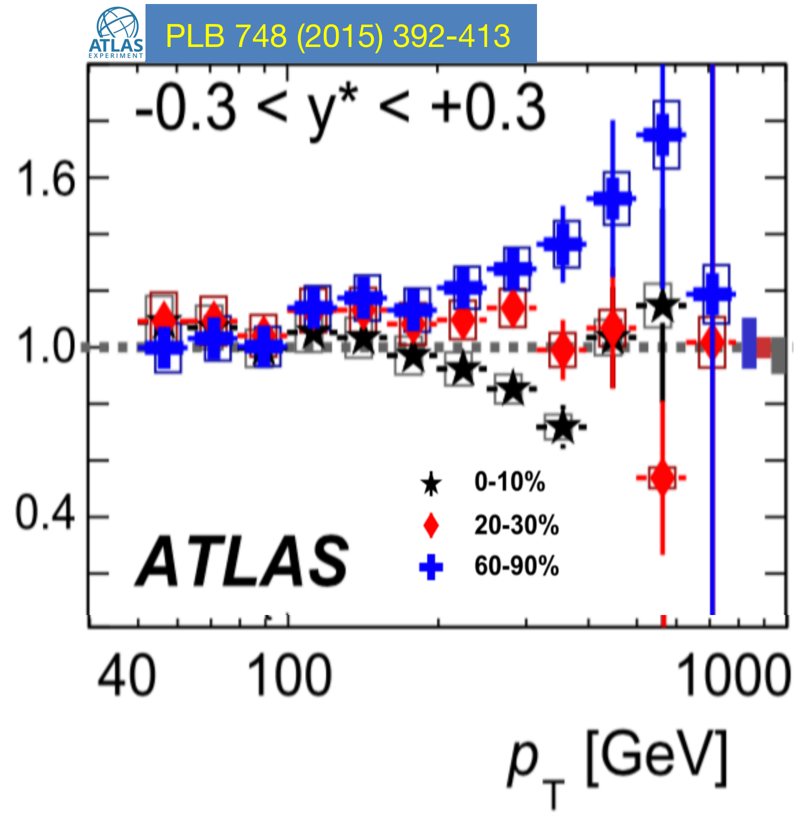
Jets in pPb at 5.02TeV

Outline

1. Jet $R_{pA,}$ and R_{CP}
2. Charm and bottom tagged jets
3. Di-Jet and nPDF

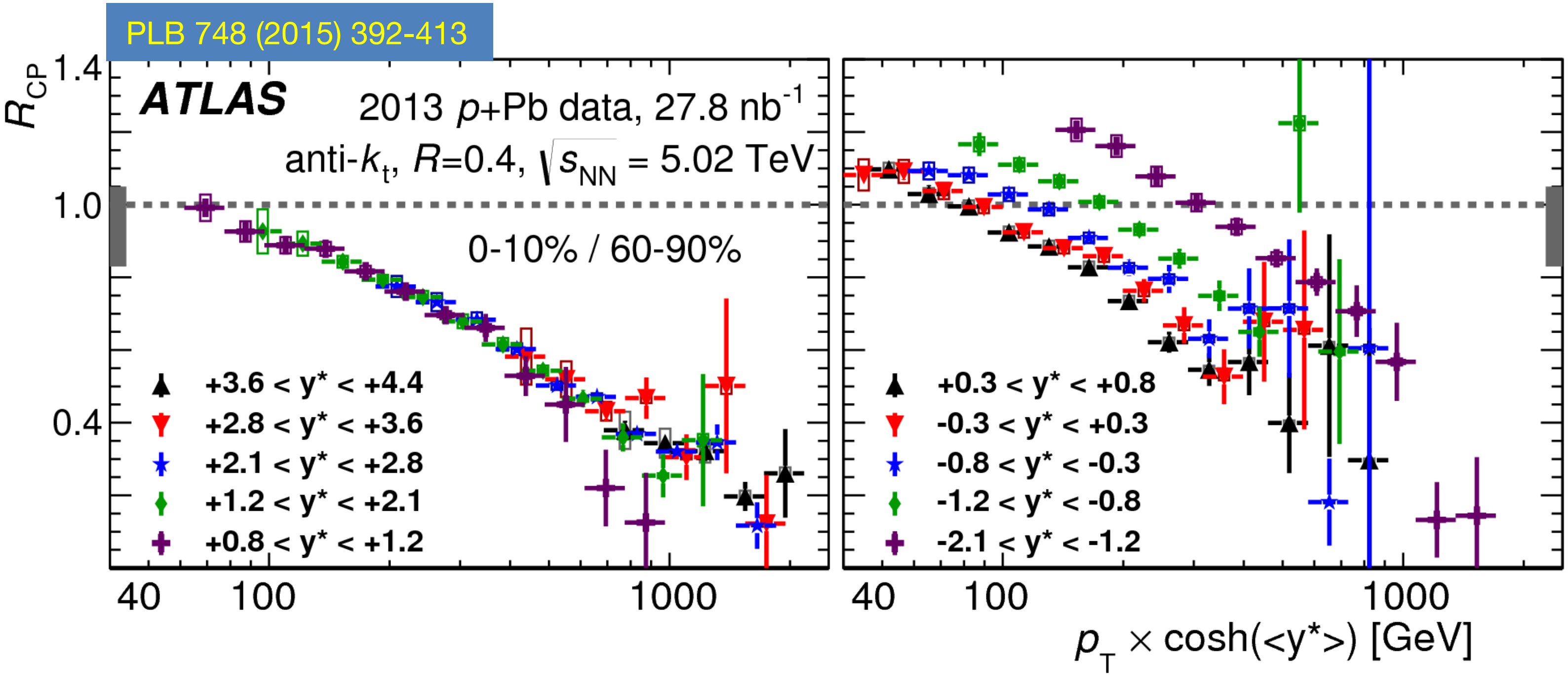
Jet R_{pA}





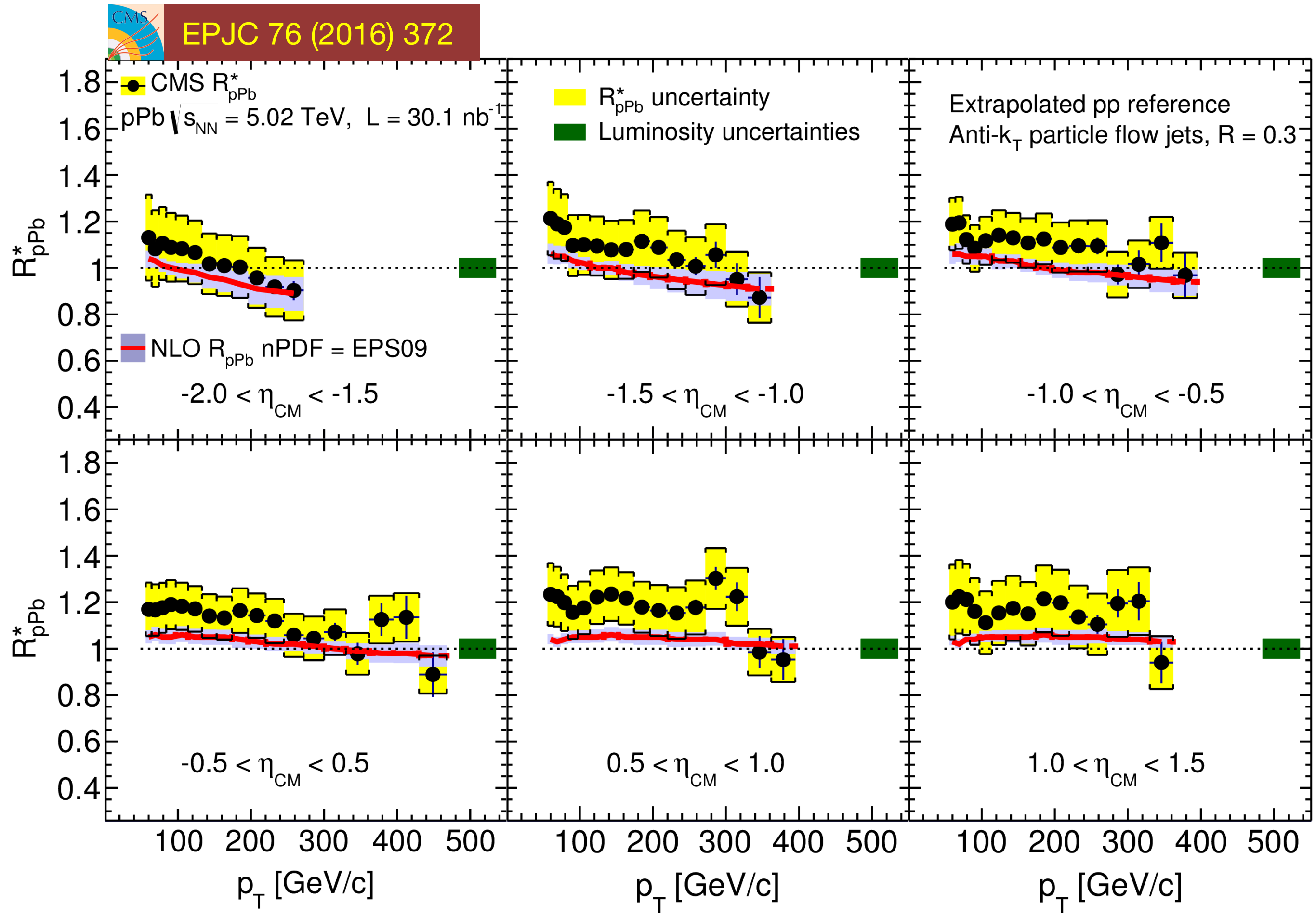
- R_{pPb} in centrality integrated collision is slightly above the unity, possibly due to interpolated pp reference
- ATLAS result indicates a strong centrality dependent reduction in the yield of jets in central collisions which is pronounced at high p_T

Jet R_{CP}



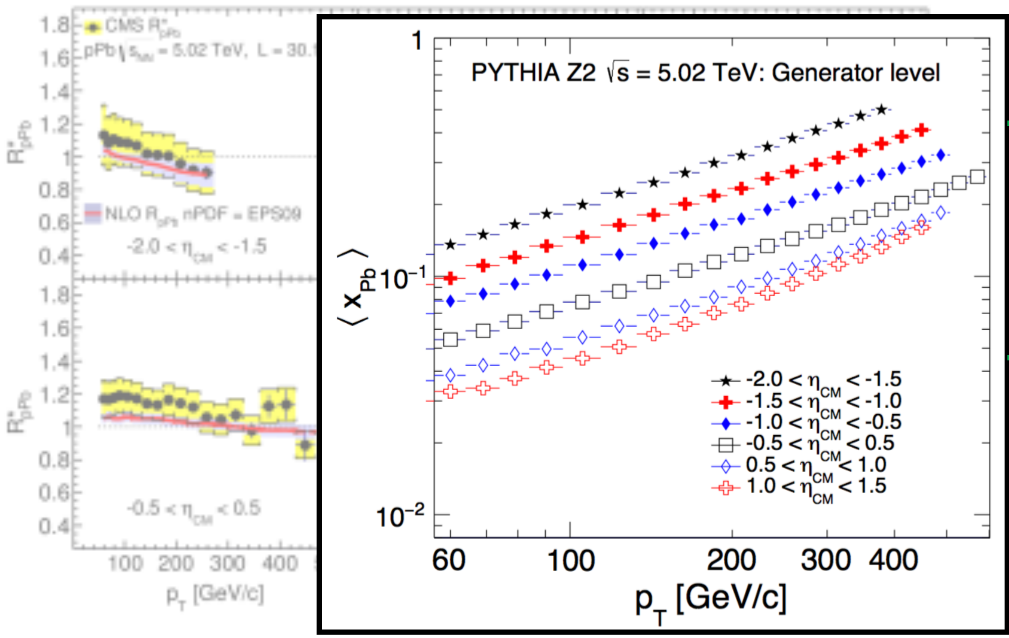
And interesting scaling behavior of Energy (not E_T) was observed in R_{CP} which was measured by ATLAS

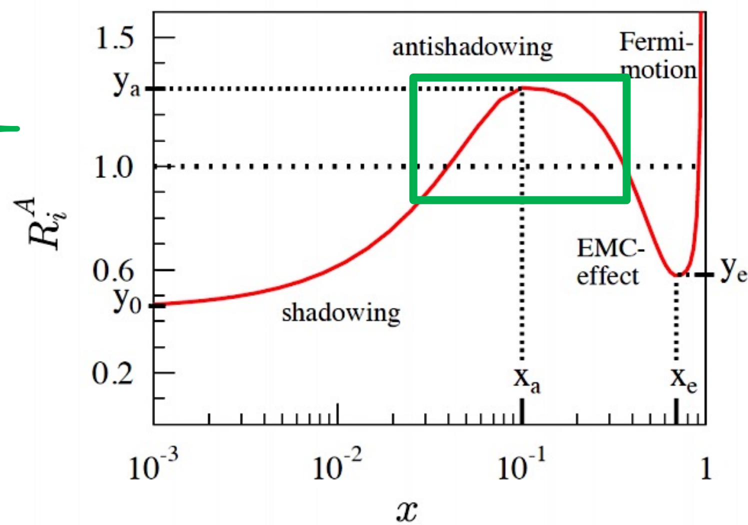
Lesson about nPDF from jet R_{pA}



The CMS R_{pA} result contains the trend favoring the NLO calculation w/ EPS09, while overall amplitue is slightly above within uncertainty.

Jet p_T translated into Bjorken-x

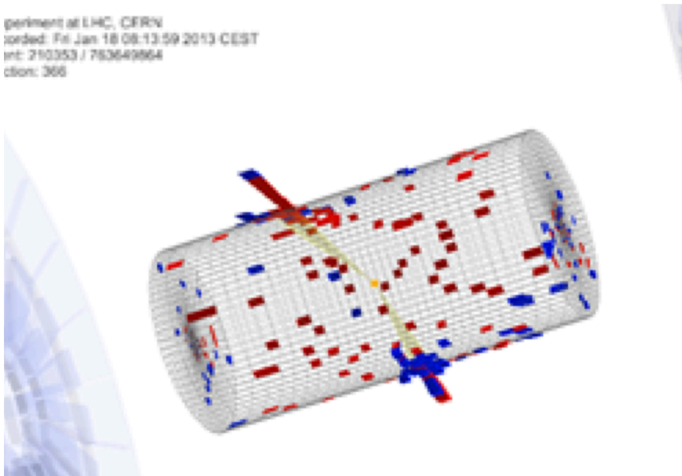




…covering the **anti-shadowing** region as well as the onset of the EMC effect regime.

BTW, There is a better tool for PDF study, which has two variables.....

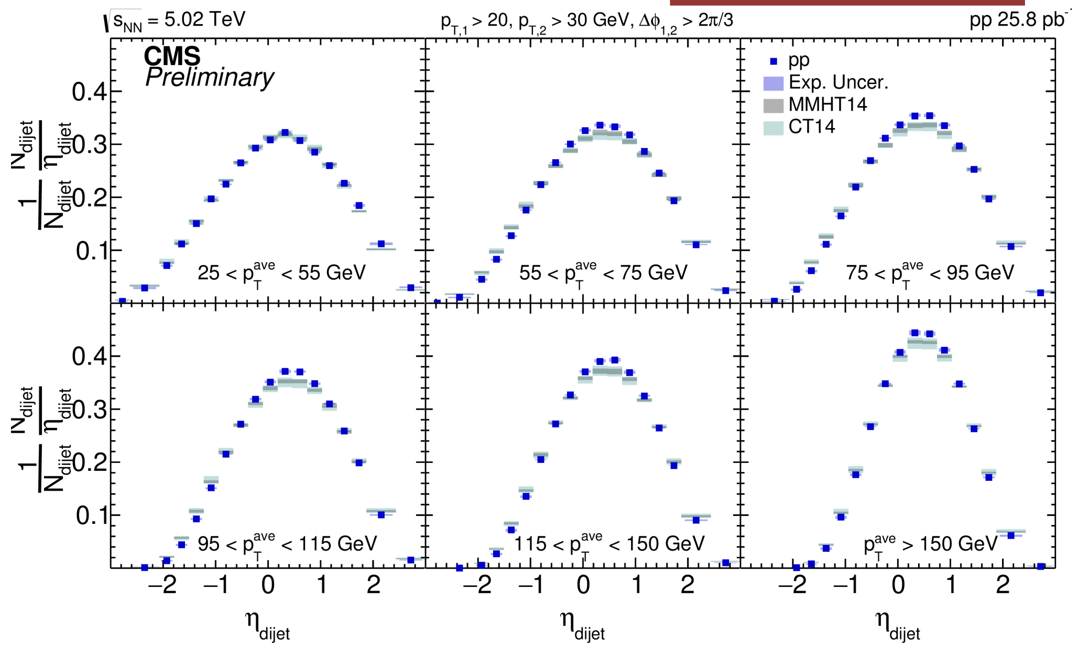
nPDF via di-jet pairs



Di-jet (back-to-back)

New pp results @5.02TeV

CMS-HIN-16-003



Why di-jet is good probe for PDF?

PDF is a two-dimentional function in (x, Q^2), and Di-jet momentum provides 2-dimensional information for PDF

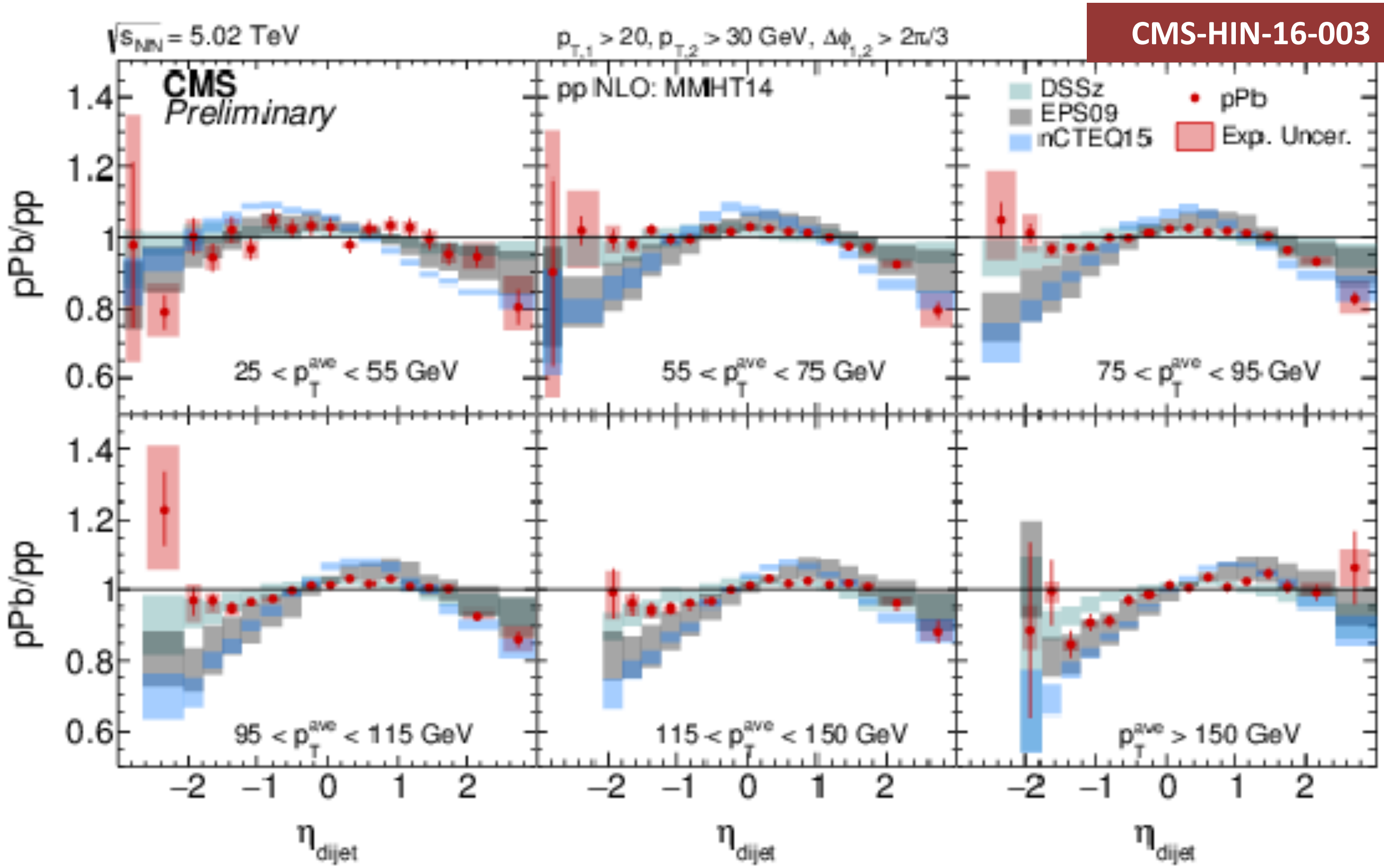
- x reflects $\eta_{dijet} = (\eta_1 + \eta_2)/2$ and $\mathbf{Q^2}$ by $p_T^{ave} = (p_T^1 + p_T^2)/2$

And back-to-back requriement suppresses complicated scatterings

This analysis used Run II pp data @5.02TeV as the reference, so the analysis also provides constraints for pp PDF models

nPDF via di-jet pairs

CMS-HIN-16-003



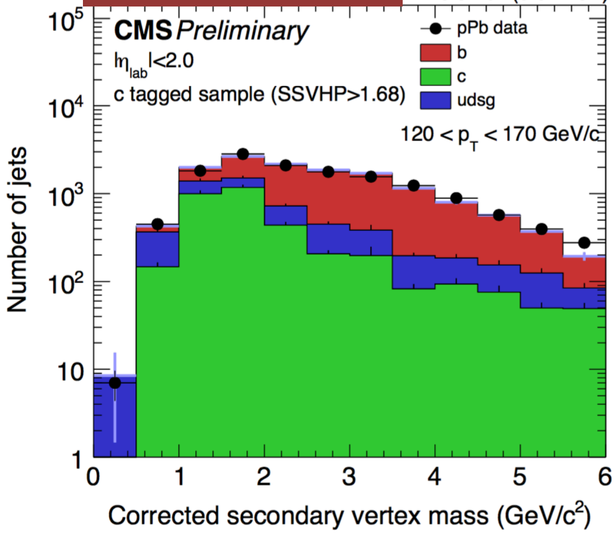
pPb/pp ratio is compared to NLO calcuations from several nPDF models.

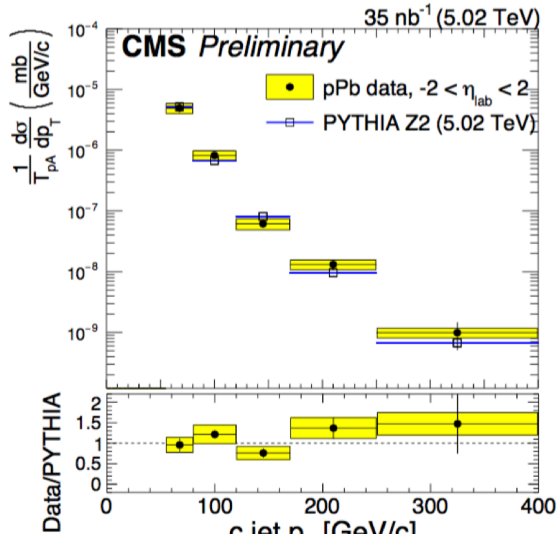
- Recall that the nPDF are usually demonstrated by ratio to pp

Comparisons with DSSZ, EPS09, nCTEQ15 (nPDF) and CT14, MMHT14 (PDF) are presented in the note

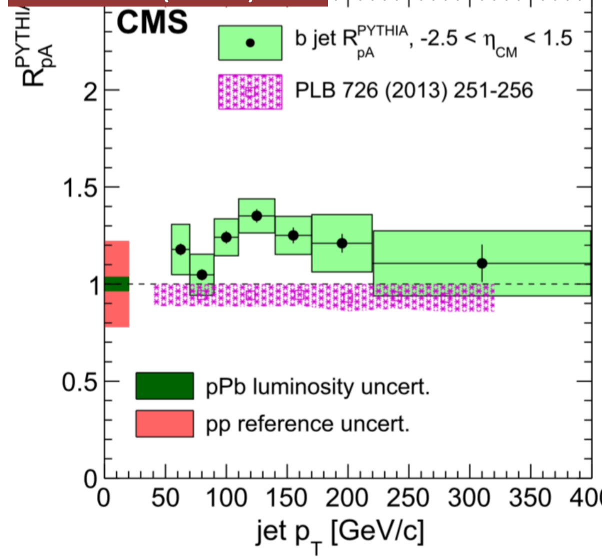
R_{pA} of heavy quark jets

CMS-HIN-15-012

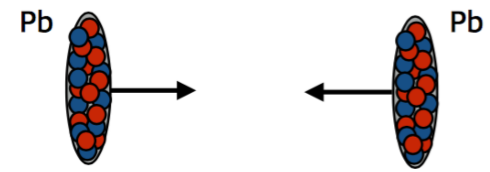




PLB 754 (2016) 59

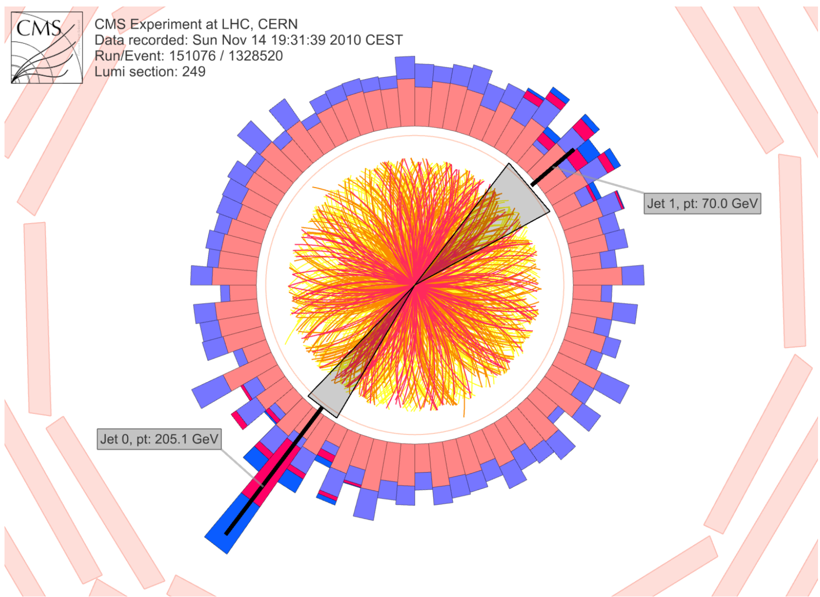


- The secondary vertex is used for b-tagging and c-tagging
  - c**τ** ~ 100 μm is discriminable with CMS silicon tracker
  - Find the secondary vertex where 2+ (or 3+) tracks are merged
- Distributions of the "corrected secondary vertex mass" are fit
- R_{pPb} , evaluated from PYTHIA reference, is consistent to unitiy within uncertainties, yet their central points are slightly above 1



Part II

Jet quenching in PbPb

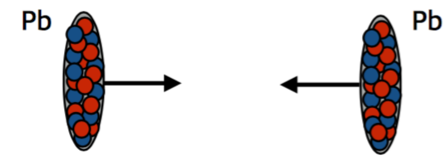


Did you notice that?

One of first jet quenching di-jet pairs in the first PbPb run

Jet library for PbPb

CMS **ATLAS**



Jet R_{AA}	PRL 113 (2014) 132301 **b-jet R_{AA}**	CMS-HIN-12-004 **RAA (PYTHIA reference)**	
	PLB 719 (2013) 220-241 **R_{CP}**	PRL 114 (2015) 072302 **R_{AA}**	
Fragmentation function	PLB 730 (2014) 243 **Jet shape**	PRC 90 (2014) 024908 **dN/dz (pT > 1GeV)**	JHEP 10 (2012) 087 **dN/dD(ξ) (p_T > 4GeV)**
	PLB 739 (2014) 320-342 **dN/dD(ξ)**	ATLAS-CONF-2015-055 **dN/dD(ξ) (pp referece)**	PLB (2015) 376 **Jet splitting**
Jet-track correlation	JHEP 1602 (2016) 156 **Jet-track correlation**	JHEP 01 (2016) 006 **Missing vs jet R**	CMS-HIN-15-011 **Dependence on A_J**
Di-jet	PRC 84 (2011) 024906 **Momentum imbalance**	PLB 712 (2012) 176 **p_T dependence**	ATLAS-CONF-2015-021 **A_J vs event plane**
	PRL 105 (2010) 252303 **Momentum imbalance**	ATLAS-CONF-2015-052 **p_T dependence**	PRL 111, 152301 (2013) **Jet v_2**
Boson-jet correlation	ATLAS-CONF-2012-119 **Z-jet**	CMS-HIN-13-006 **Gamma-jet in PbPb**	CMS-HIN-13-006 **p_T dependent gamma-jet**
New 2015 5TeV PbPb dataset	CMS-HIN-16-005 **Di-b-jet correlation**	CMS-HIN-15-013 **Z-jet correlation**	CMS-HIN-16-006 **Jet spiliting**

Outline

1. Jet quenching in Boson-jet pair

| ATLAS-CONF-2012-119
Z-jet | CMS-HIN-13-006
Gamma-jet in PbPb | CMS-HIN-13-006
p_T dependent gamma-jet |
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Z-jet correlation | | |

2. Momentum imbalance in di-jet

PRC 84 (2011) 024906 Momentum imbalance	PLB 712 (2012) 176 p_T dependence	ATLAS-CONF-2015-021 A_J vs event plane
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CMS-HIN-16-005 Di-b-jet correlation		

3. Momentum re-distribution

| JHEP 1602 (2016) 156
Jet-track correlation | JHEP 01 (2016) 006
Missing vs jet R | CMS-HIN-15-011
Dependence on A_J |

4. Jet hadronization (fragmentation)

| PLB 730 (2014) 243
Jet shape | PRC 90 (2014) 024908
dN/dz (pT > 1GeV) | JHEP 10 (2012) 087
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5. Jet splitting

| CMS-HIN-16-006
Jet spiliting | PLB (2015) 376
Jet splitting |

R_{AA} is skipped…

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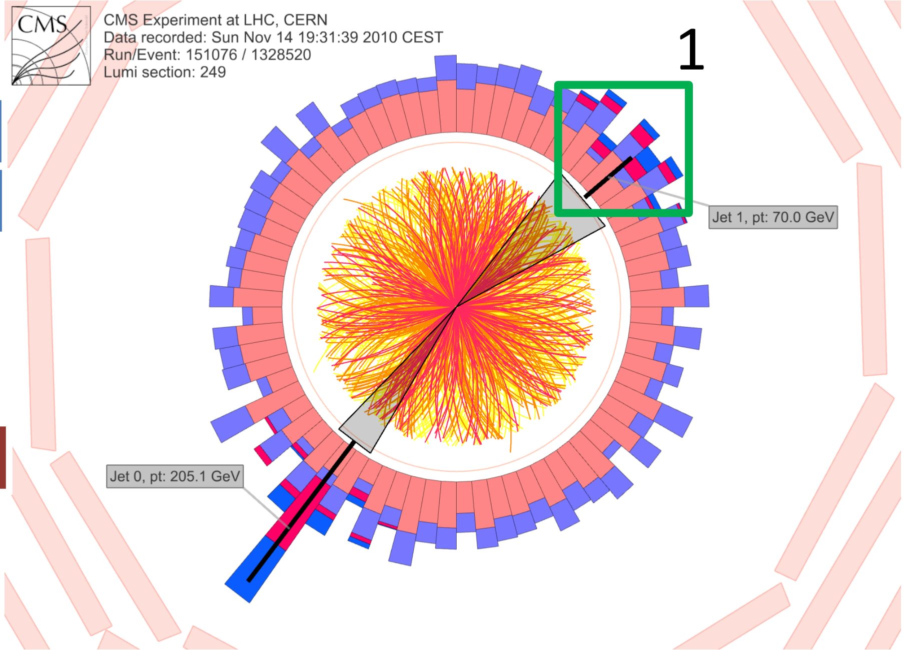
PRL 105 (2010) 252303 **Momentum imbalance**	ATLAS-CONF-2015-052 **p_T dependence**	PRL 111, 152301 (2013) **Jet v_2**
CMS-HIN-16-005 **Di-b-jet correlation**		



3. Momentum re-distribution

JHEP 1602 (2016) 156 **Jet-track correlation**	JHEP 01 (2016) 006 **Missing vs jet R**	CMS-HIN-15-011 **Dependence on A_J**

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CMS-HIN-16-006 **Jet spiliting**	PLB (2015) 376 **Jet splitting**

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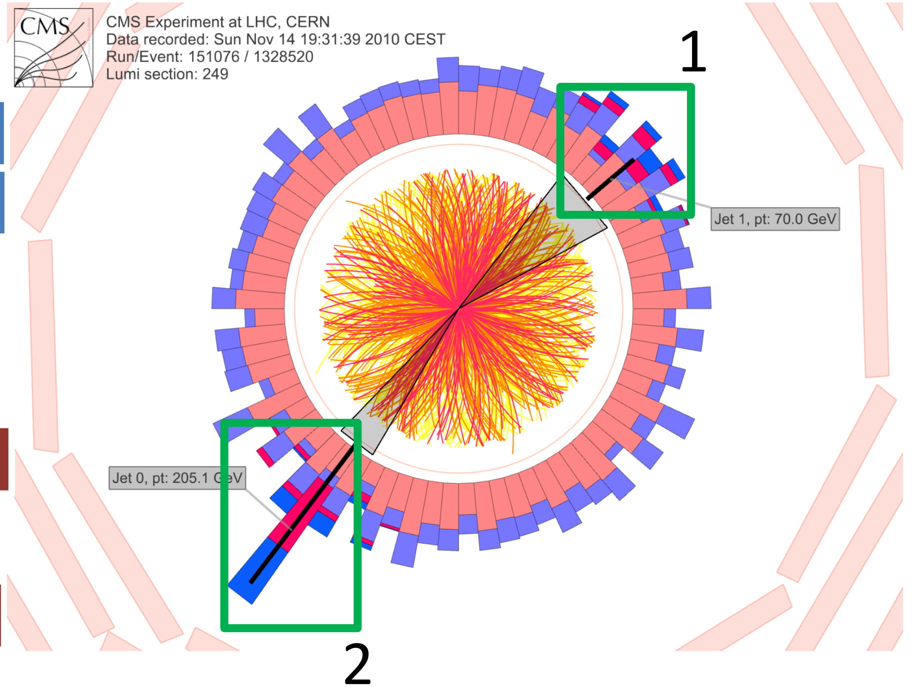

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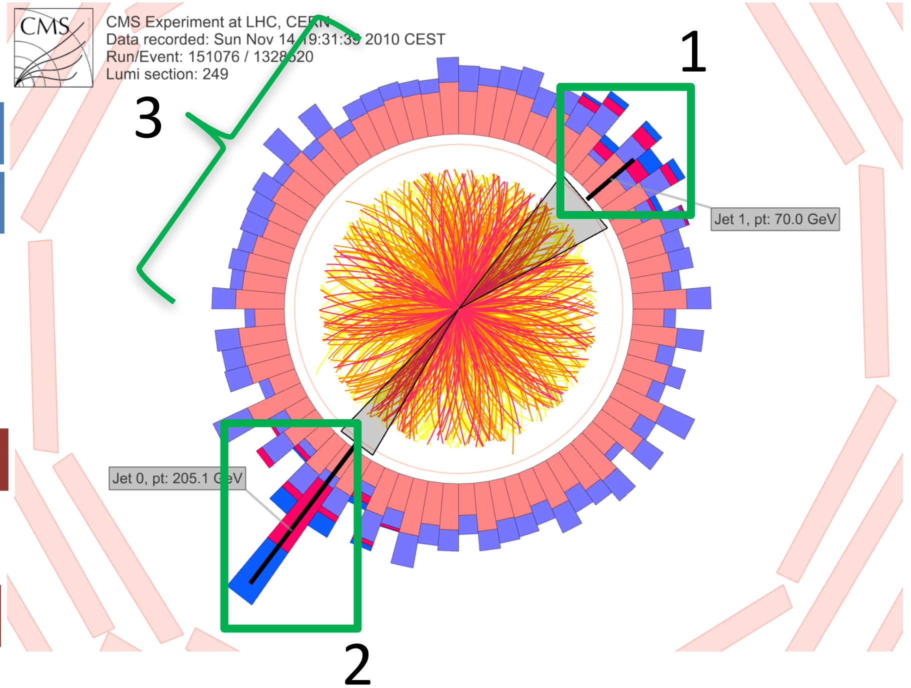
CMS-HIN-16-006 **Jet spiliting**	PLB (2015) 376 **Jet splitting**



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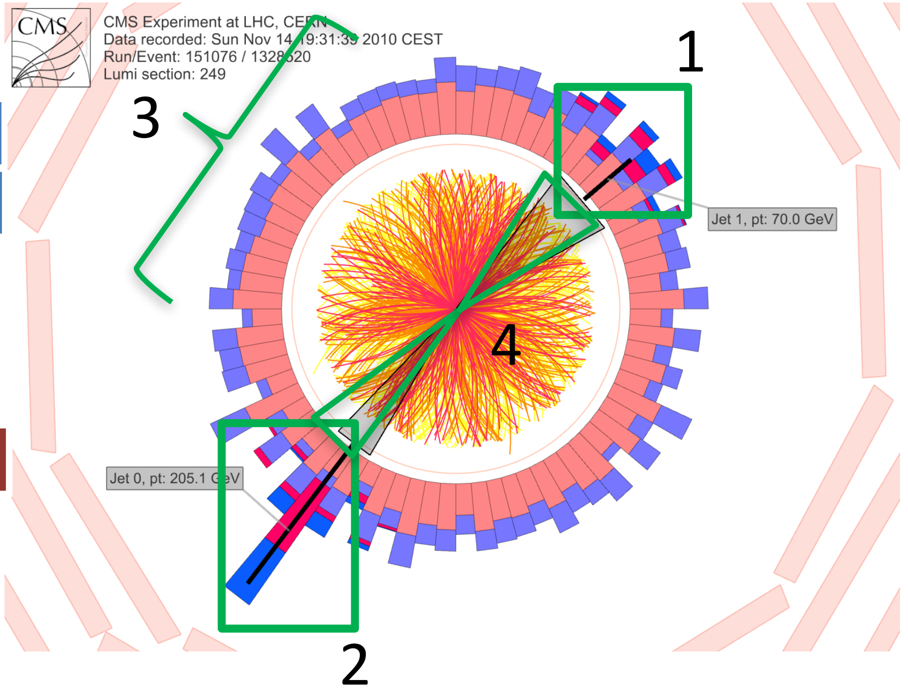


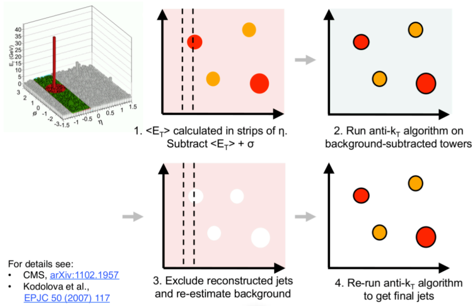
Before moving to the results…

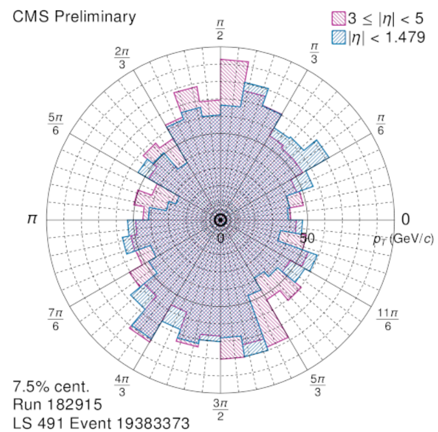
A series of evolution in UE background energy subtraction technique

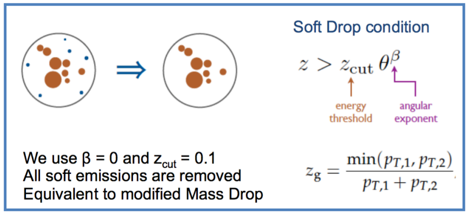
~2010) UE background estimated from the average in η ring

~2012) Flow component taken in account
- CMS : Background ρ estimated from event training and Voronoi sectioning
- ATLAS : Data-driven correction for modulation

~2016) Constituent Subtraction[1]
- background ρ, ρ_m from kT clustered soft jets
- particle-by-particle 4-vector subtraction
- first used by ALICE for jet shape study and in CMS for jet splitting study







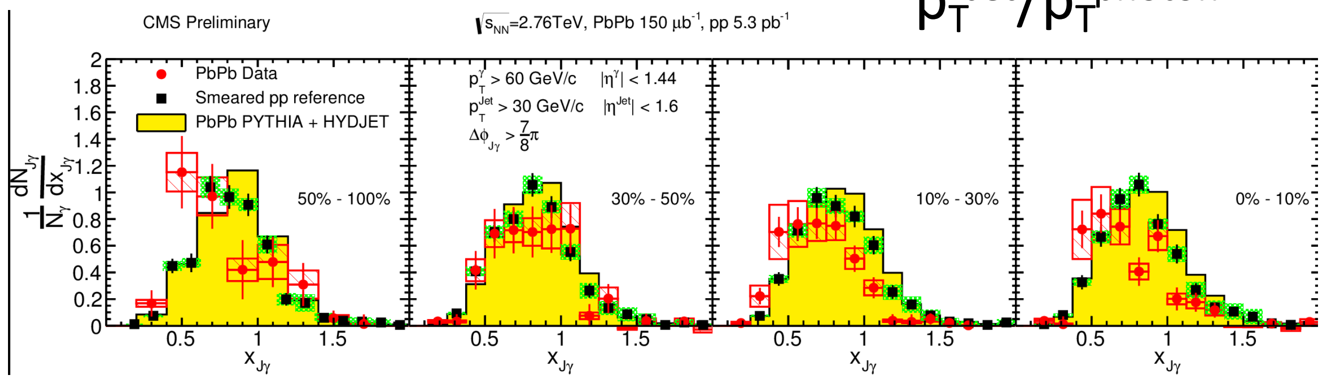
[1] Berta et al, JHEP 1406 (2014) 092

1. Previous results of boson-jet correlation

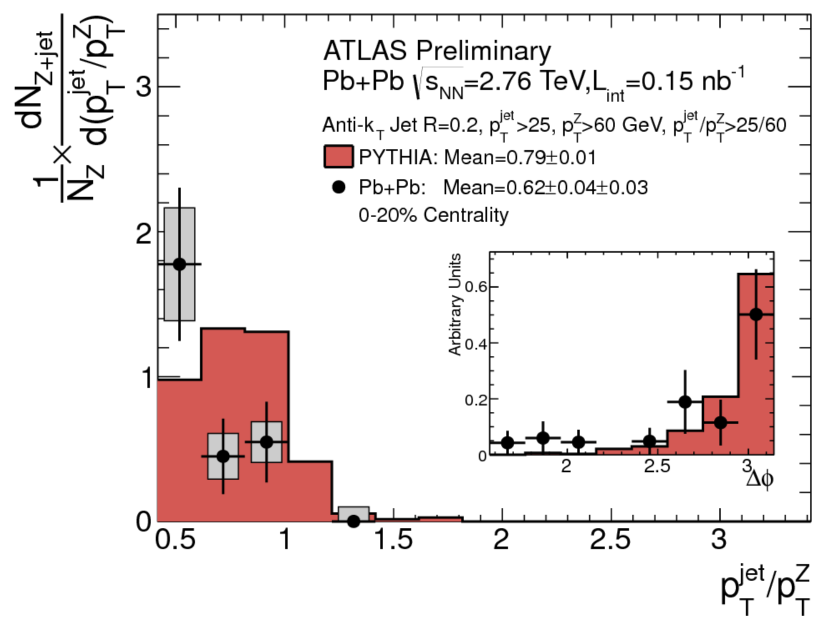
Most direct measurement of jet quenching
via boson-jet

CMS-HIN-13-006
Gamma-jet

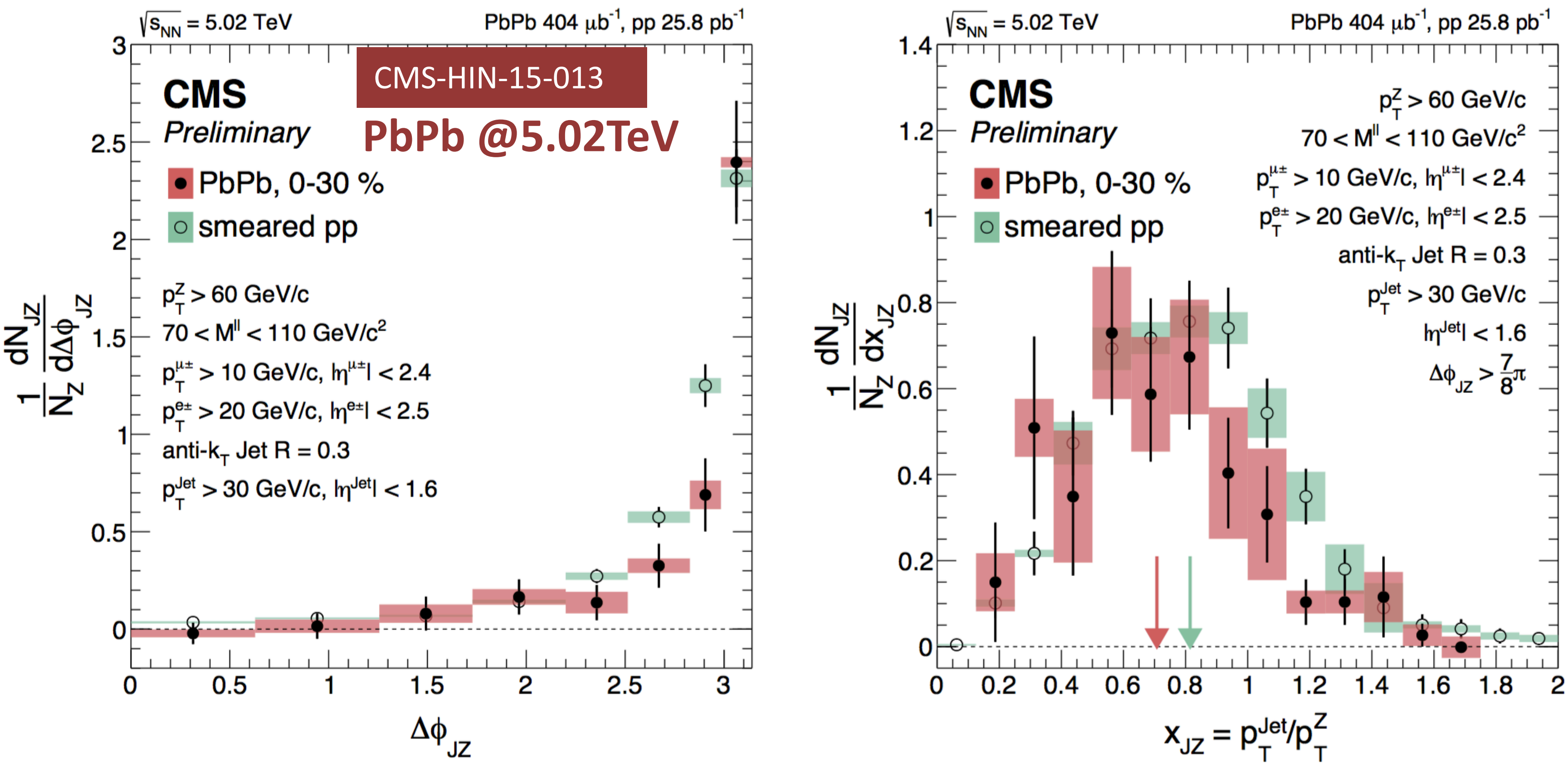
p_T^{Jet}/p_T^{photon}



ATLAS-CONF-2012-119
Z-jet



1. Z-jet @ 5.02 TeV

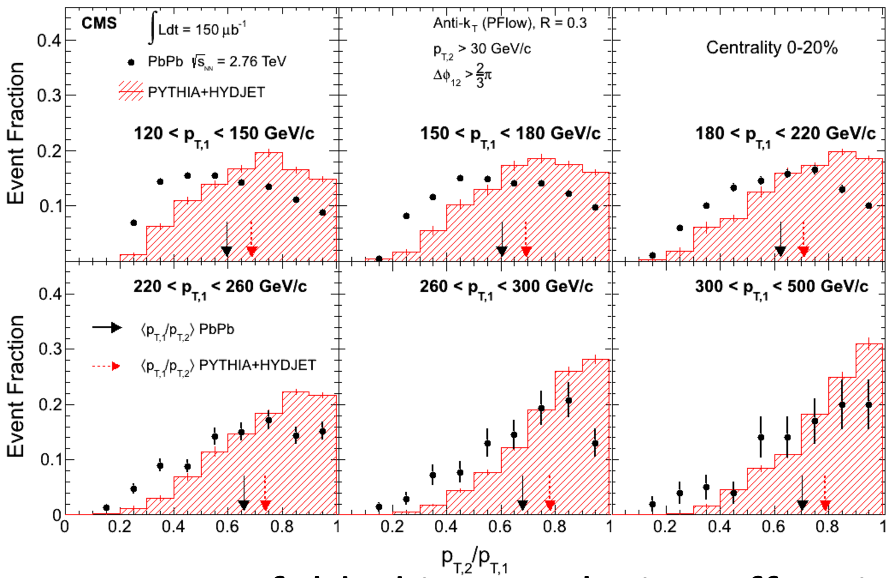


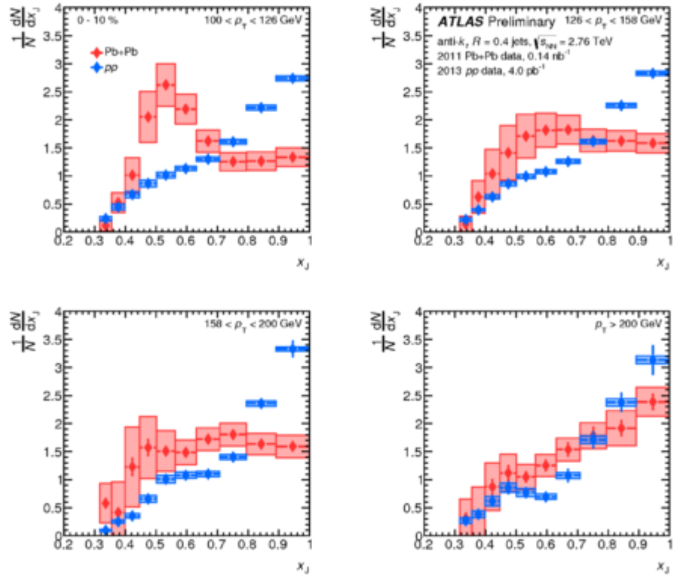
- Slightly narrower *ΔΦ* distribution in central PbPb collision than pp reference
- Jet quenching is in similar level with gamma-jet result in 2.76TeV
- Demonstrated the utility of Z boson for the quantitative study of jet quenching

2. Di-jet results

- Di-jet momentum imbalance study

PRC 84 (2011) 024906 **Momentum imbalance**	PLB 712 (2012) 176 **p_T dependence**
PRL 105 (2010) 252303 **Momentum imbalance**	ATLAS-CONF-2015-052 **p_T dependence**



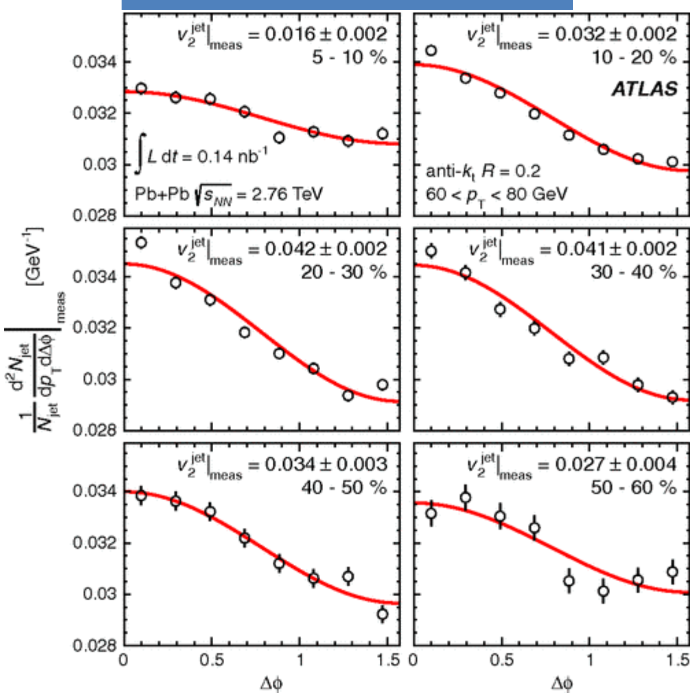


- ATLAS unfolded jet resolution effect in x_J (= p_T^2 / p_T^1) and found a peak at x_J ~0.5 for the central collisions
- di-jet imbalance vs $p_T^{leading}$ provides constrains in quenching models

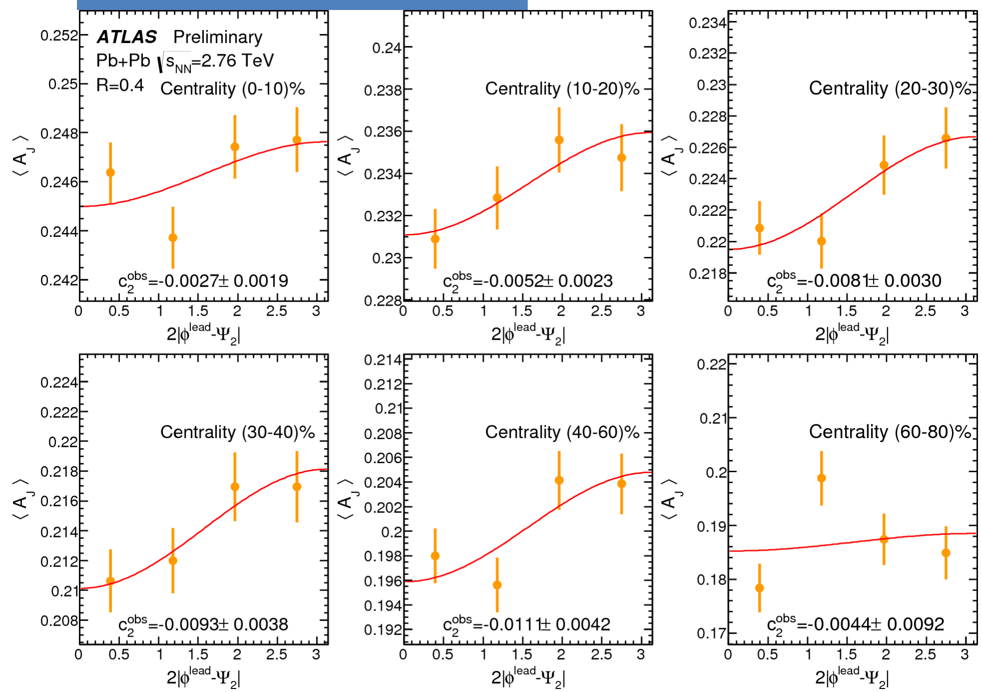
2. Di-jet results

- Correlation with event plane

PRL 111, 152301 (2013)
Jet v_2

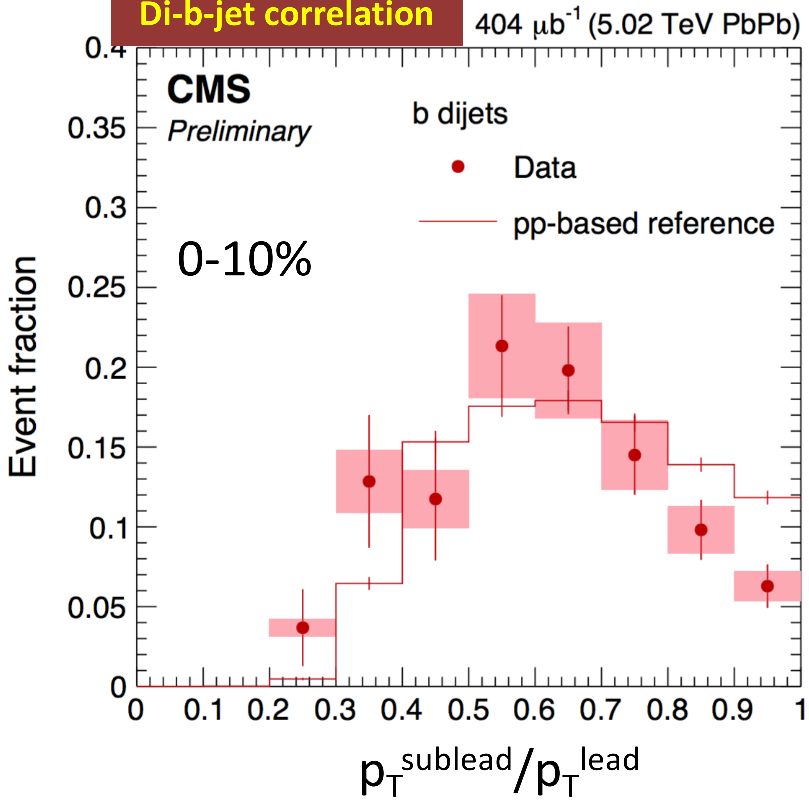


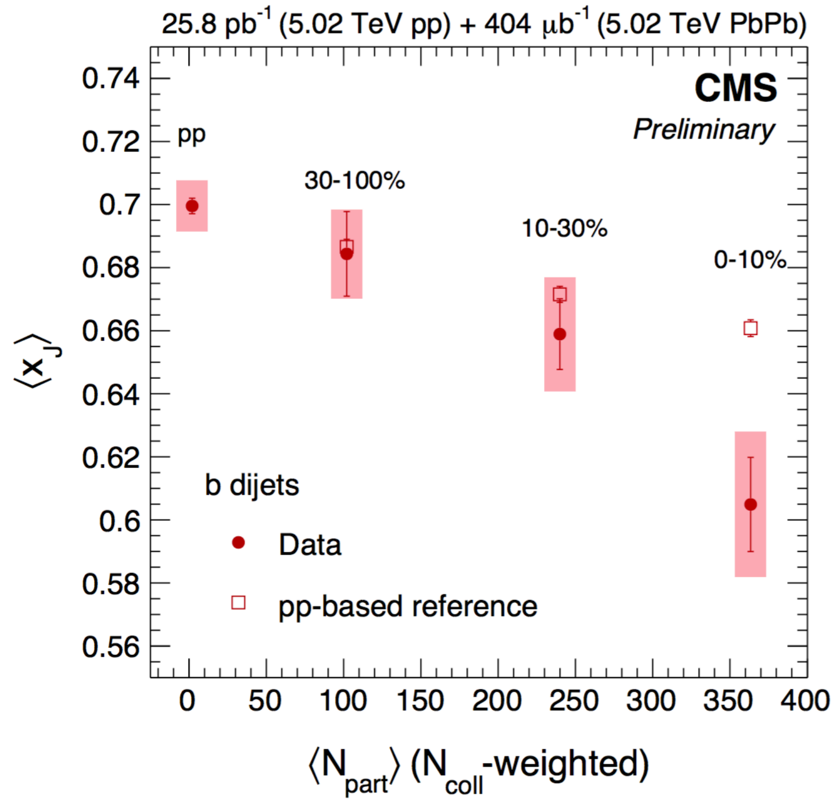
ATLAS-CONF-2015-021
A_J vs event plane



- Positive v2 for inclusive jets and the excess of momentum imbalance in out-of-plane
- The results supports the intuitive picture of the path-length dependence of energy loss : Longer path ➔ more energy loss and large fluctuation

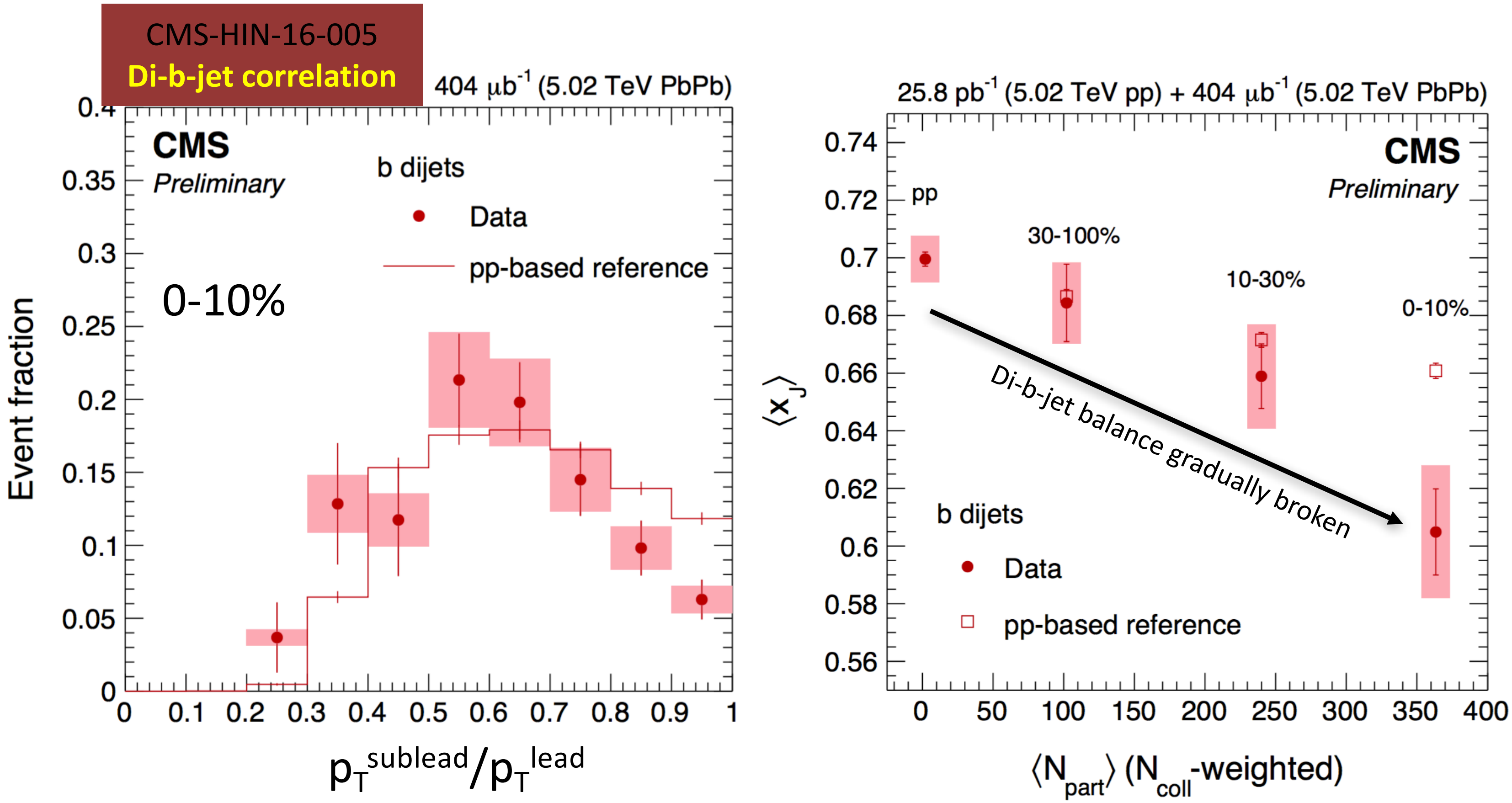
CMS-HIN-16-005
Di-b-jet correlation





- **The first measurement** of flavor identified di-jet correlation in AA
- Similar size of momentum imbalance with inclusive dijets
- Provides inputs to the modelling of quark-mass and flavour dependence of queching

2. Di-b-jet results in PbPb



- **The first measurement** of flavor identified di-jet correlation in AA
- Similar size of momentum imbalance with inclusive dijets
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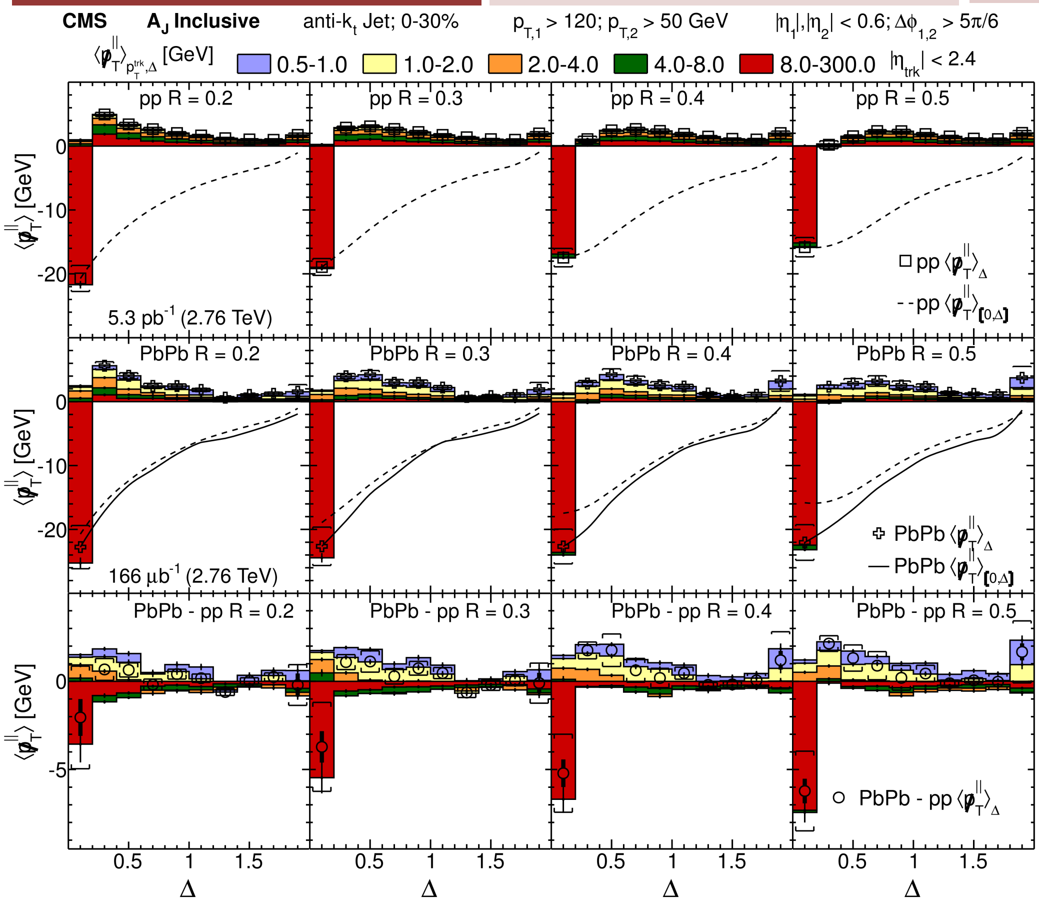
3. Chase of the missing energy (1/3)

- The devil is in the details! Hunting for the missing energy dissipated by jet quenching in several aspects

JHEP 01 (2016) 006	CMS-HIN-15-011	JHEP 1602 (2016) 156
Missing vs jet R	Dependence on A_J	Jet-track correlation

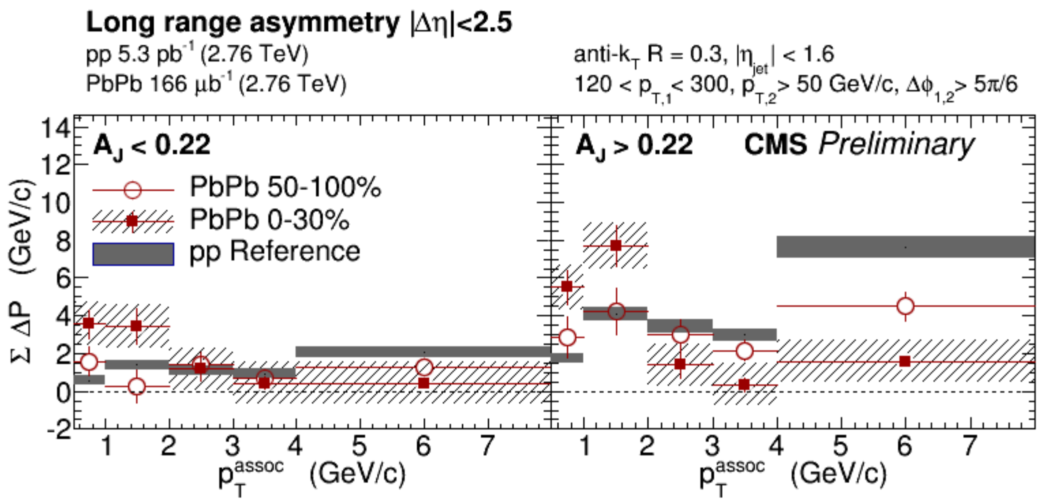


- Track p_T are projected to the di-jet axis
- Distributions depends on jet R and centrality
- However, when integrated they are all balanced

3. Chase of the missing energy (2/3)

- The devil is in the details! Hunting for the missing energy dissipated by jet quenching in several aspects

JHEP 01 (2016) 006 Missing vs jet R	CMS-HIN-15-011 Dependence on A_J	JHEP 1602 (2016) 156 Jet-track correlation

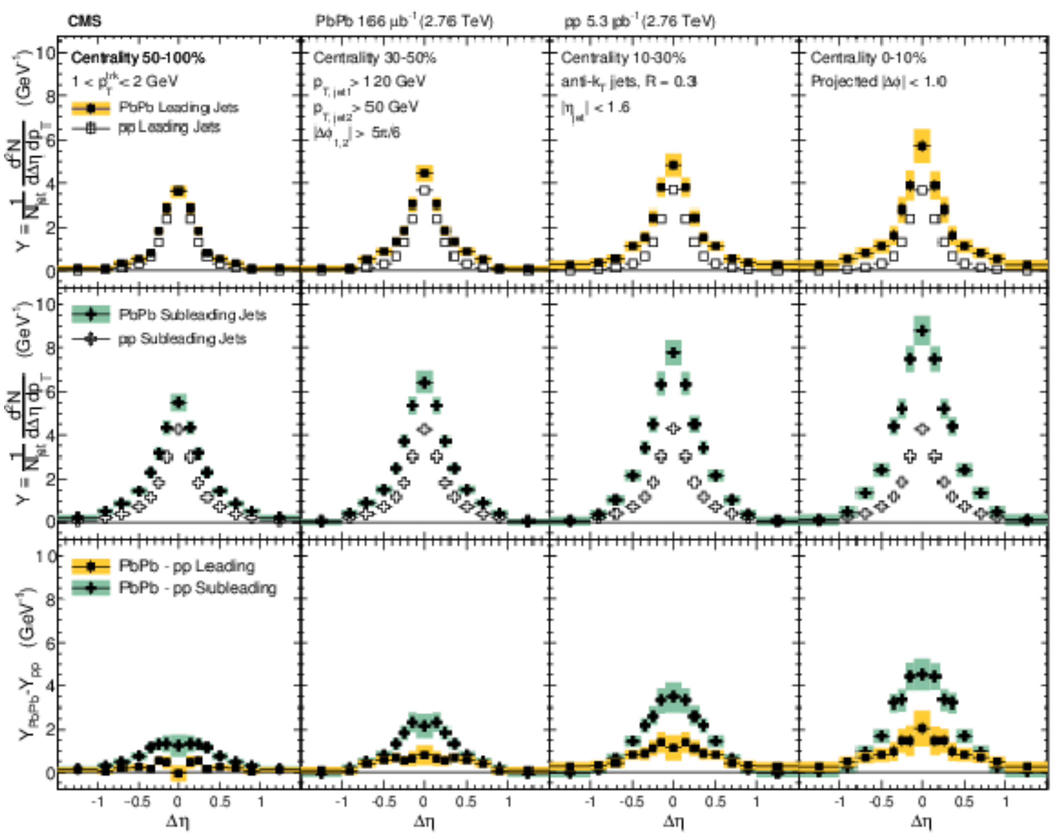


- Energy redistribution are decomposed in p_T bins for peak region and long-range regtion, and integrated over hemisphere
- Imbalanced di-jets in PbPb has , compared to pp, excess of soft particles reduction of high p_T particles (3-jet events)
- Jet shape measured

3. Chase of the missing energy (3/3)

- The devil is in the details! Hunting for the missing energy dissipated by jet quenching in several aspects

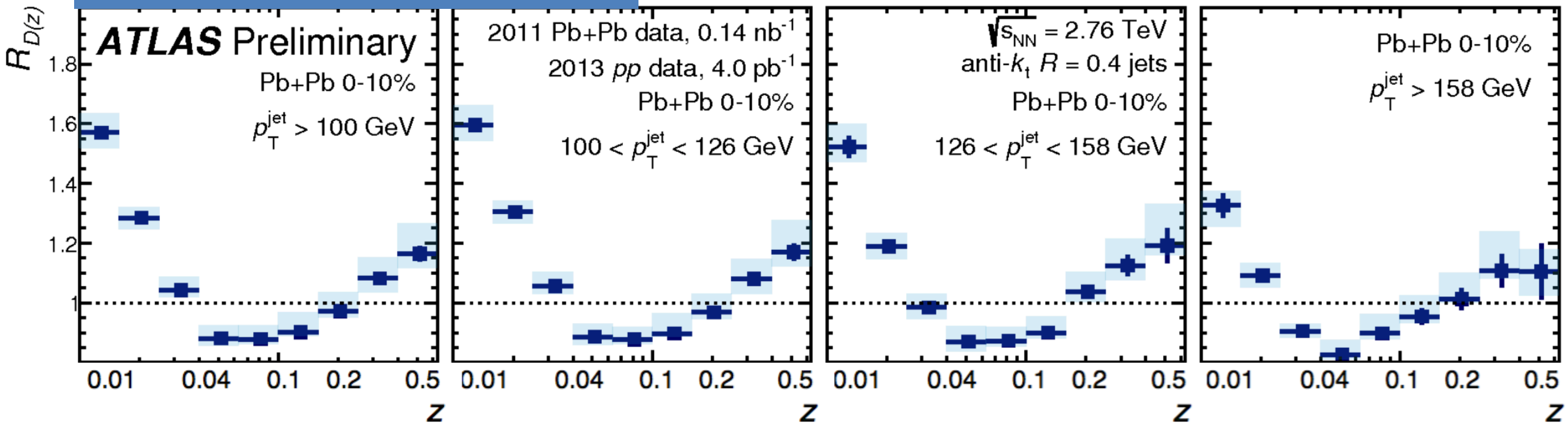
JHEP 01 (2016) 006 Missing vs jet R	CMS-HIN-15-011 Dependence on A_J	JHEP 1602 (2016) 156 **Jet-track correlation**



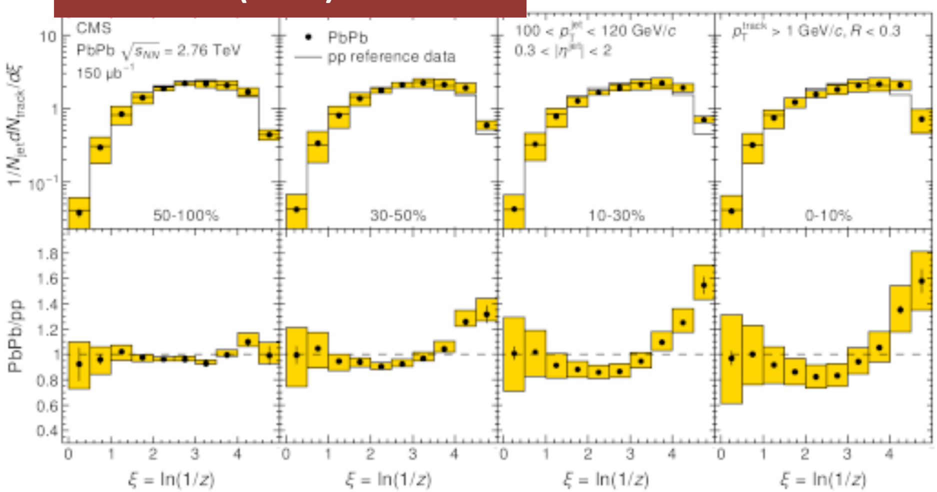
- Δη and ΔΦ between jet and chared particles
- Clear modification of distribution compared to pp
- **Different** behavior for leading jet and sub-leading jet

4. Fragmentation function

ATLAS-CONF-2015-055



PRC 90 (2014) 024908



Constituents of jets in PbPb

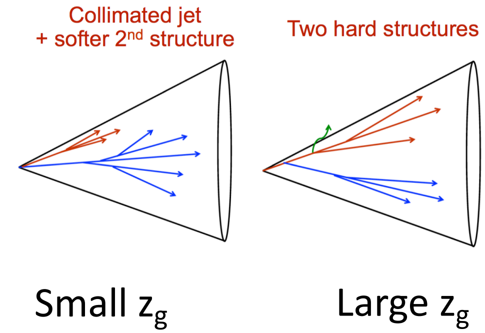
- more soft particles (z < 0.02)
- less intermediate p_T particles
- more harder particles (z > 0.2)

Detailed measurement by ATLAS

- in bins of **centrality, jet p_T** and **η**
- Fully unfolded jet p_T
- Gradual evolution of FF observed

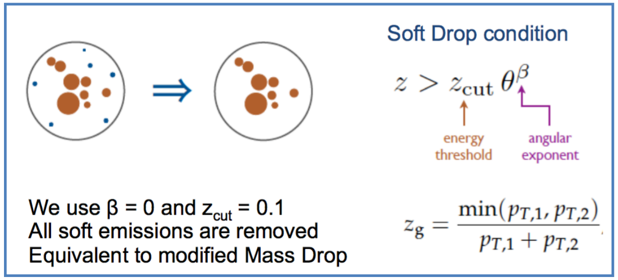
5. Analysis with sub-jets in a jet

Jet splitting Observable : $z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$



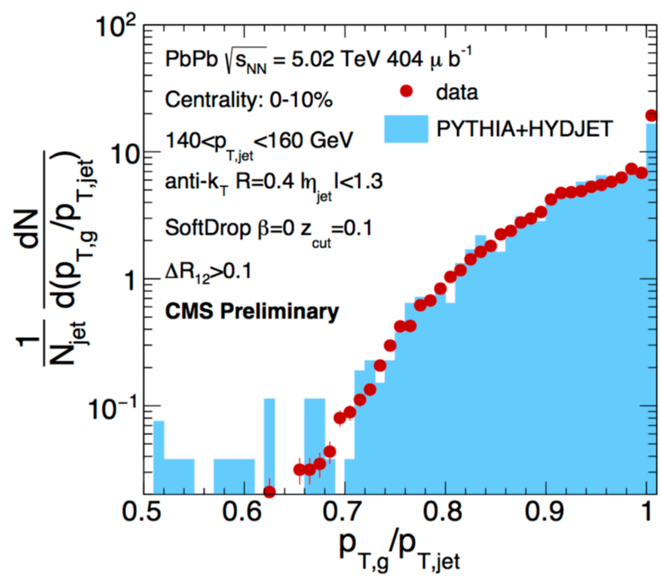
Why interesting?

- Hard branching delivers information in early stage of quenching (Vitev's talk on Wed)

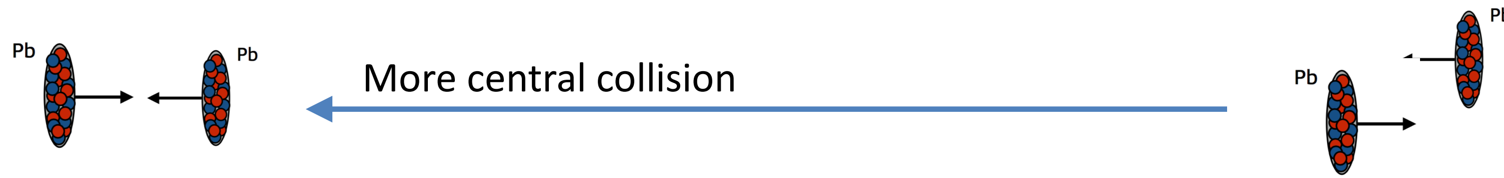


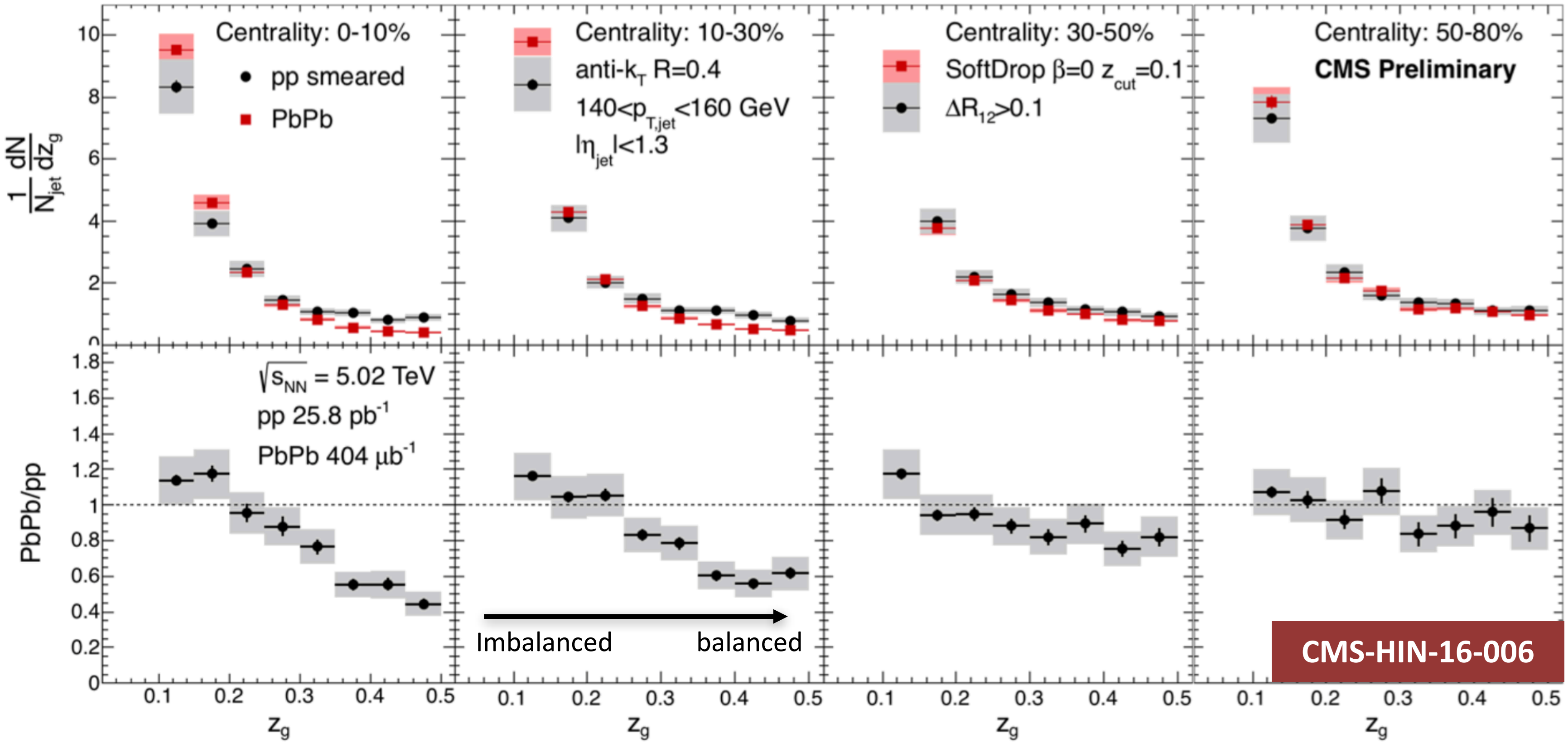
New Jet algo : Grooming with SoftDrop

- Removes soft divergences and remaining backgrounds
- This is the first anlaysis using this method in Heavy Ion research
- Grooming and sub-jet finding is done simultaneously



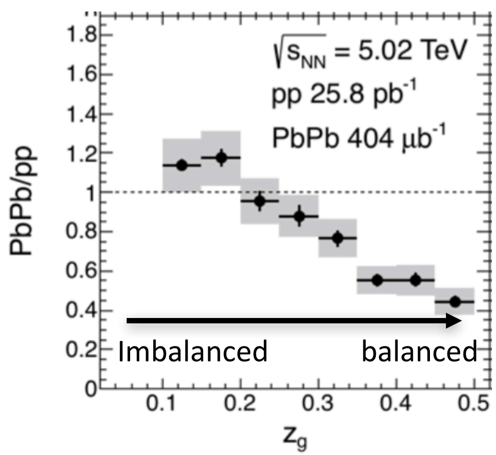
5. Jet splitting result at 5.02TeV

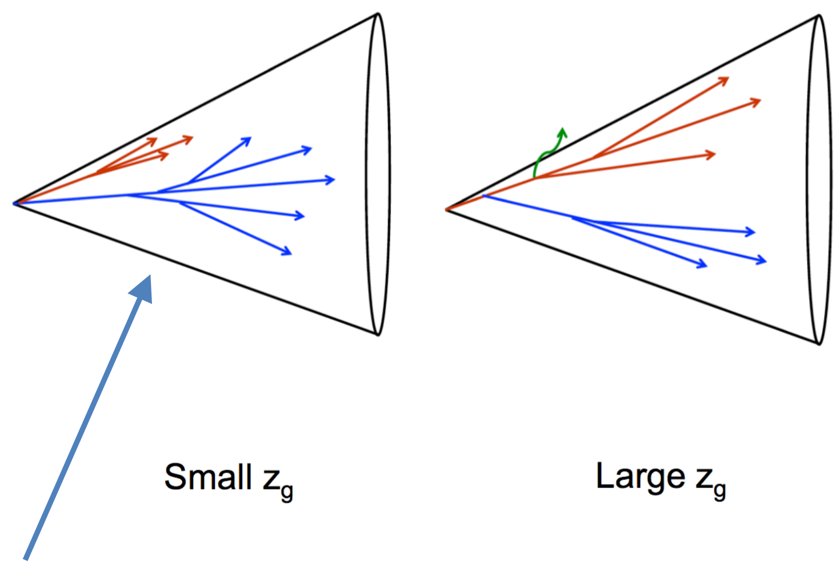




Compared to pp reference, the two subjets are more imbalanced in central PbPb collisions. The modification is less conspicuous for higher p_T.

5. Jet splitting result at 5.02TeV





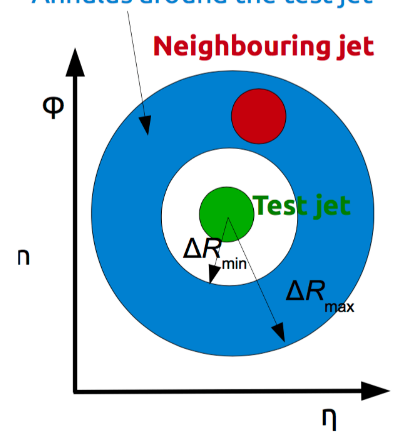
In general this is dominant.
And even more in PbPb compared to pp

5. Measurement of neighboring jets @ 2.76TeV

Motivation

- Search for two jets originated from the same parton shower, in annulus ΔR=(0.5-0.8)-1.6
- Two jets are thought of as trasversing the same path length in the medium, so isolate the size of fluctuation in energy loss

P. Steinberg

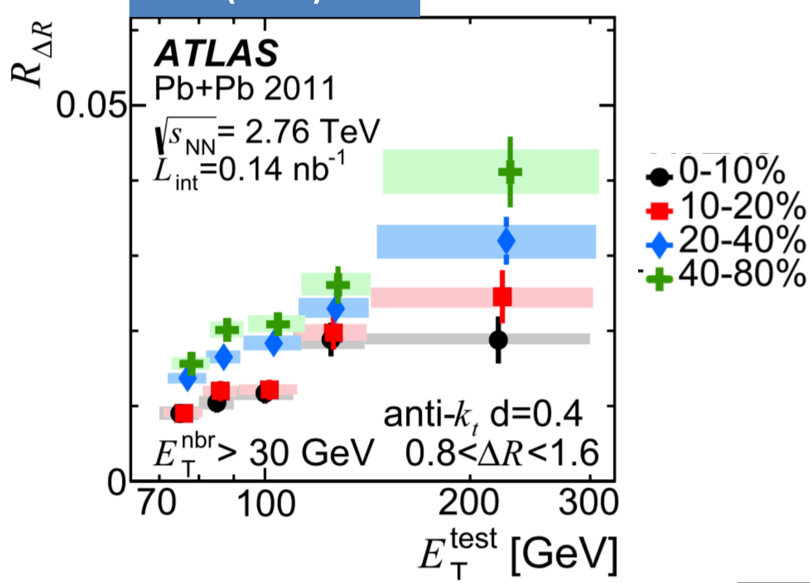


Observable :

$$R_{\Delta R}(E_{\mathrm{T}}^{\mathrm{test}}, E_{\mathrm{T}}^{\mathrm{nbr}}) = \frac{\sum_{i=1}^{N_{\mathrm{jet}}^{\mathrm{test}}} N_{\mathrm{jet},i}^{\mathrm{nbr}}(E_{\mathrm{T}}^{\mathrm{test}}, E_{\mathrm{T}}^{\mathrm{nbr}}, \Delta R)}{N_{\mathrm{jet}}^{\mathrm{test}}(E_{\mathrm{T}}^{\mathrm{test}})}$$

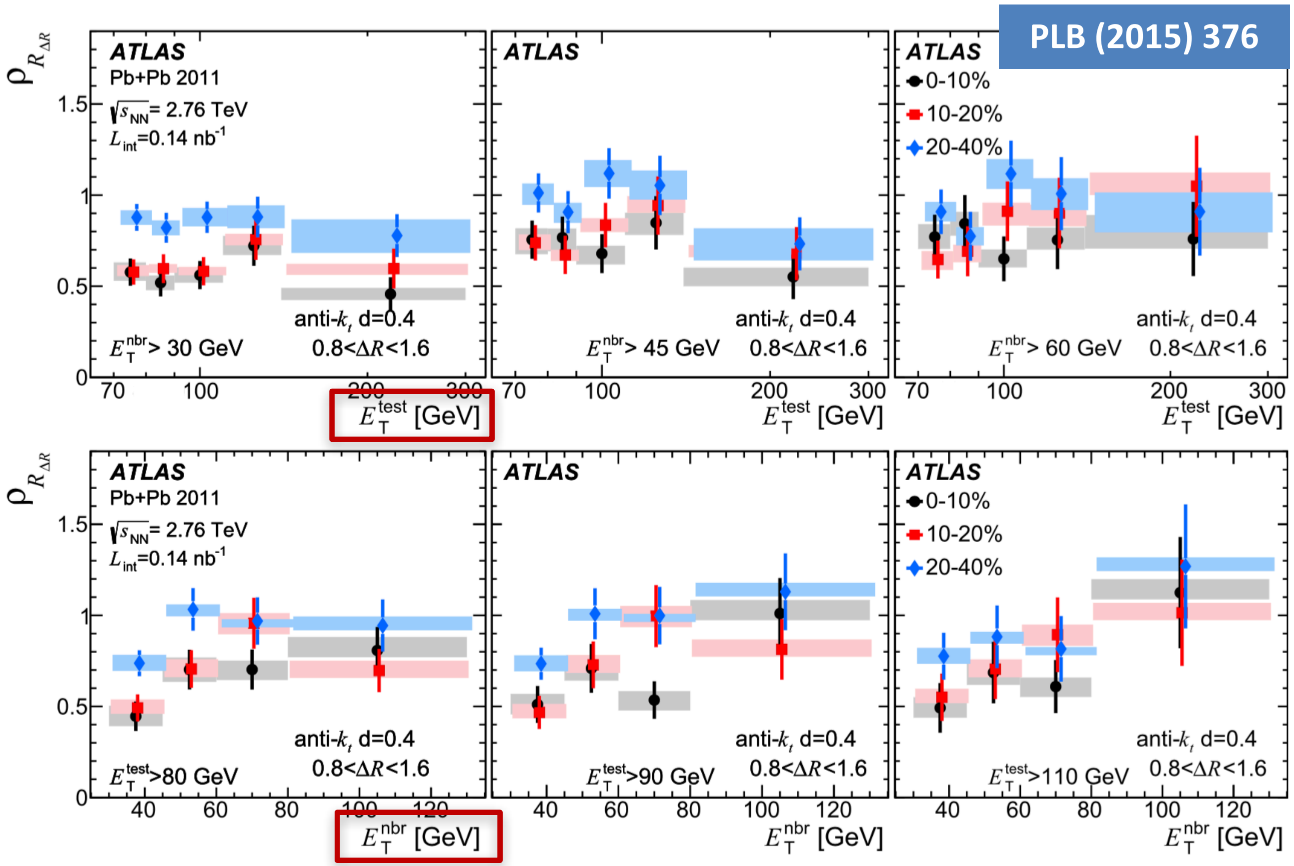
= The probability to find a neighboring jet near a test jet

PLB (2015) 376



5. Measurement of neighboring jets @ 2.76TeV

$$\rho_{R_{\Delta R}} = R_{\Delta R}|_{\mathrm{cent}} / R_{\Delta R}|_{40-80}$$ (Central – peripheral ratio)



Clear dependence of suppression on centrality, but independent of the test jet E_T

The suppression is decreasing with increasing neighbor jet E_T

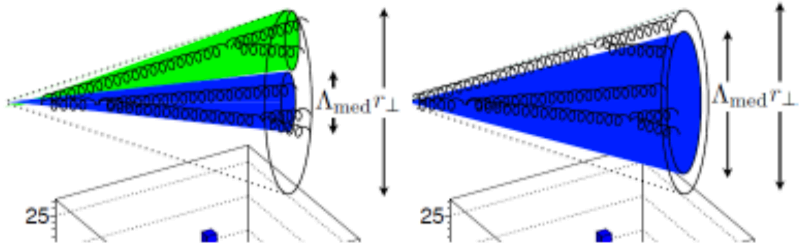
Summary

- The heavy ion jet results at 2.76TeV and 5.02TeV from CMS and ATLAS collaboration were reviewed
- The pPb nuclear modification factor of inclusive, b- and c-jet confirms that the strong suppression in PbPb collision is attributed to the hot medium effects. Along with di-jet results, they provide constrains for nPDF in anti-shadowing region
- In PbPb, ~20 literatures indicate the significant energy loss of high p_T jets and give quantitative clues where the lost energy are dissipated
- The new reuslts from LHC Run II phase arrived. Z-jet result at 5TeV proved the role of Z for more elaborate analyses in near future. Di-b-jet correlation results gave an insights of quark mass dependence
- CMS and ATLAS investigated the jet splitting nature using different analysis techniques in different distances within jet-pair
- There are tons of new results from brand new data @5TeV are waiting for us, so stay tuned!

BAKCUP

Latest jet finding algorithm in CMS

Phys.Lett.B 725 (2013) 357–360



2 coherent emitters
Color disconnected

1 coherent emitter
Color disconnected

Studies of jet splitting

- In antenna picture, the activity of (de)coherent emitters is affected by the temperature of medium

Jet Grooming with SoftDrop

- Removes soft divergences and remaining backgrounds
- This is the first anlaysis using this method in Heavy Ion research
- Extracts 2 branchs

Soft Drop condition

$$z > z_{\text{cut}}\ \theta^{\beta}$$

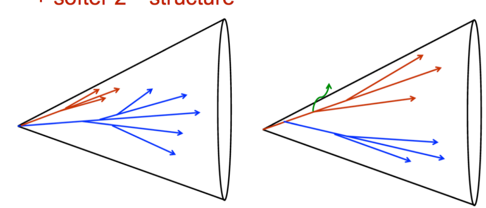
energy threshold — angular exponent

We use β = 0 and z_{cut} = 0.1
All soft emissions are removed
Equivalent to modified Mass Drop

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

Collimated jet + softer 2[nd] structure

Two hard structures

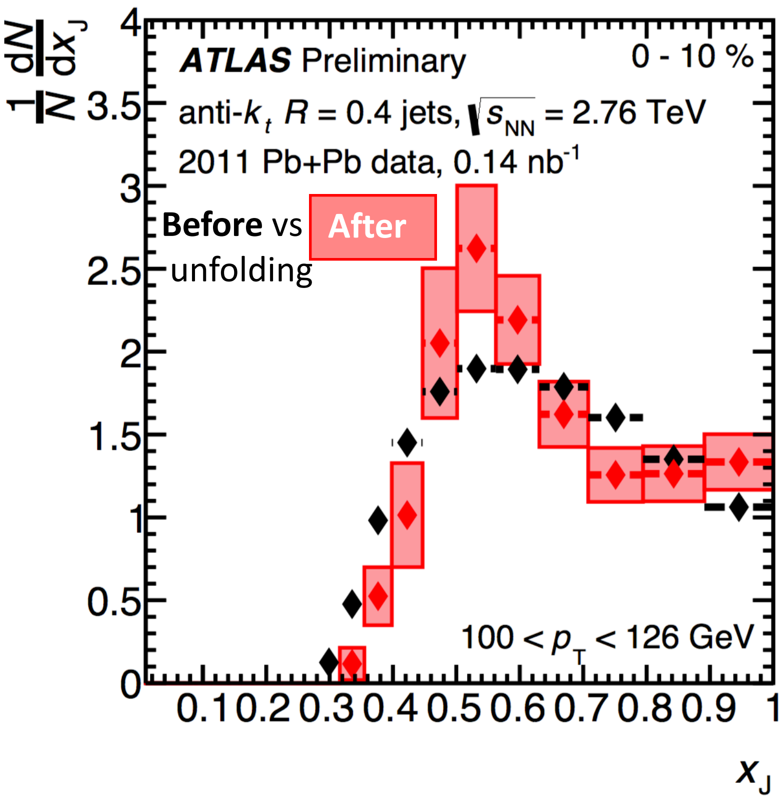


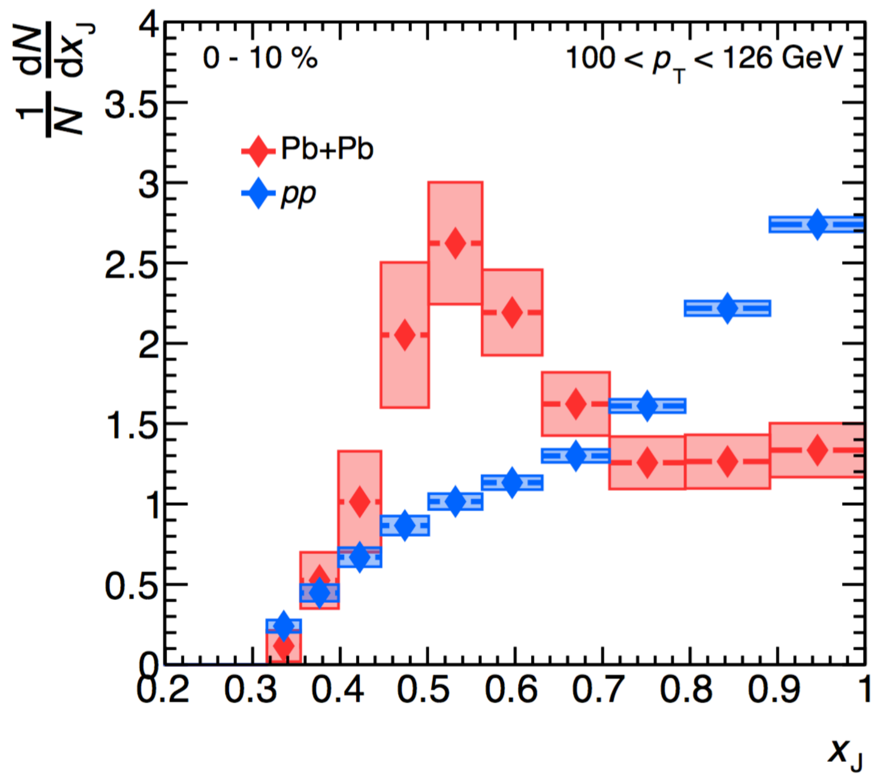
Small z_g

Large z_g

Observable : $$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

Unfolding of di-jet xJ distribution

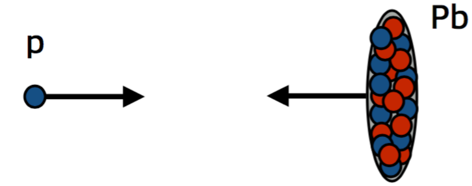




- ATLAS updated the di-jet correlation result with 0.14 nb^{-1} @2.76TeV
- x_J (= p_T^2 / p_T^1) is fully unfolded and found a peak at x_J =0.5 for the central PbPb collision
- The x_J distribution gets narrower for higher p_T pair indicating ΔE/E decrases with jet p_T

CMS

ATLAS



Jet results in pPb at 5.02TeV

1. Jet R_{pA}, and R_{CP}

PLB 748 (2015) 392-413
Jet R_{pA}

EPJC 76 (2016) 372
Jet R_{pA}

CMS-HIN-15-012
c-jet R_{pA}

PLB 754 (2016) 59
b-jet R_{pA}

2. Charm and bottom tagged jets

EPJC 74 (2014) 2951
η_{dijet}

CMS-HIN-16-003
η_{dijet} updated (+pp data)

3. Di-Jet and nPDF

ATLAS-CONF-2015-022
Fragmentation function

- CMS-HIN-15-004
Fragmentation function