Recent results from CMS Heavy Ions

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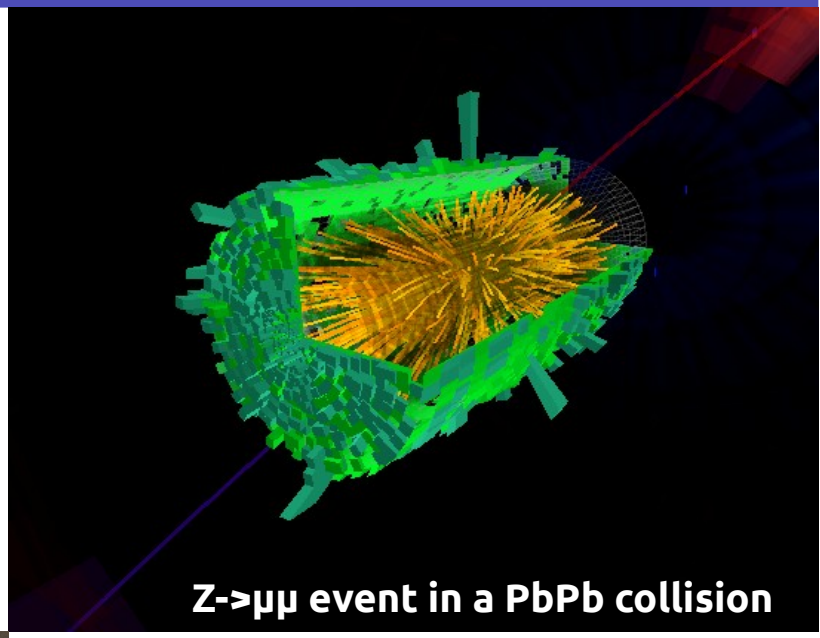
On behalf of the CMS Collaboration

foreword

The CMS Heavy Ion Group in 2015/2016 was **busy**:

- Recording new 5 TeV PbPb + pp data
- Excellent run preparation and operation
- Wrapping-up Run 1 analyses (pp, pPb, PbPb)

- Plenty of Run 2 data coming out in papers

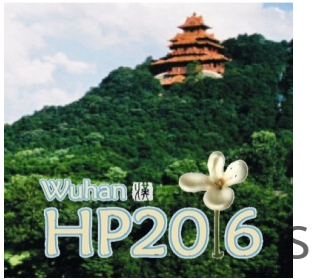


Z->μμ event in a PbPb collision

- **<u>Today</u>**: CMS-HI results from Run 1 & Run 2

- Selected results in correlations, heavy flavor/quarkonia and jets!

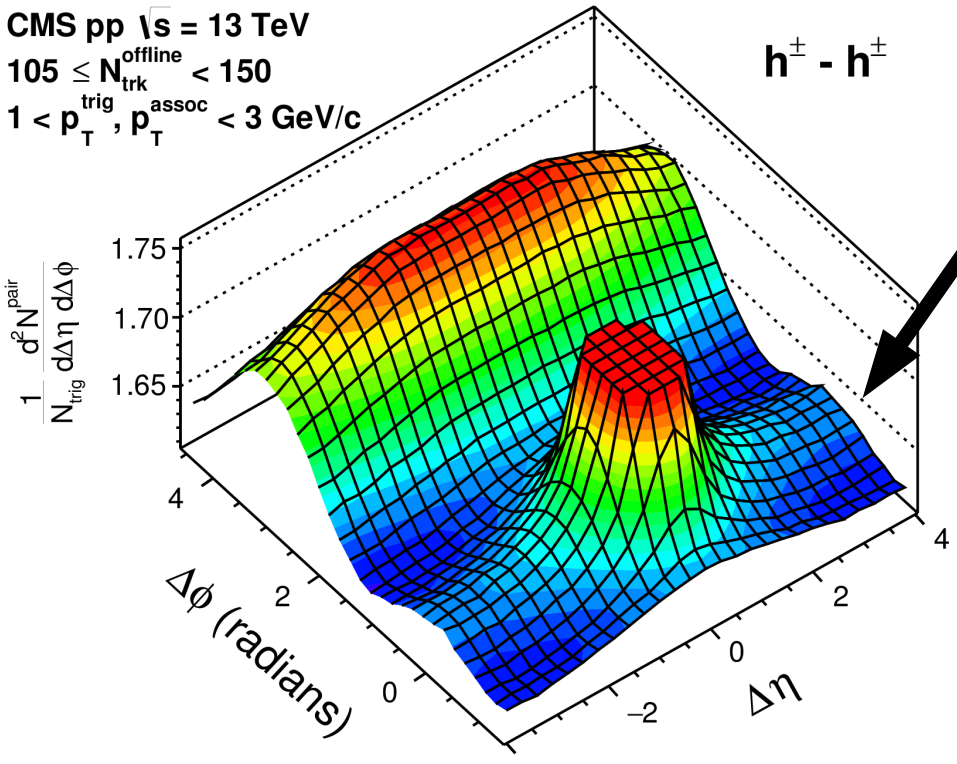
Teaser for **next week's HardProbes2016!**



Collectivity

Collectivity in pp collisions ?

CMS-PAS-HIN-16-010
arXiv:1606.06198

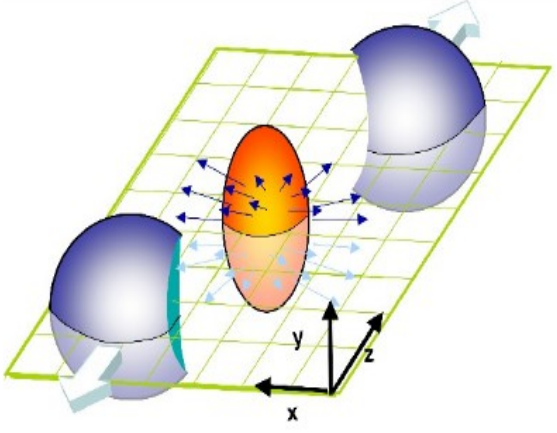


The 'ridge': correlation between particles that are produced far away from each other

Large $|\Delta\eta|$, small $|\Delta\varphi|$

- Correlation: Fourier harmonics v_2 (elliptic flow), v_3 (triangular flow):
  → geometry of initial stage of the collision
- First observed in AA collisions, then in pA & pp
- In pp: study the dynamics of the initial stage

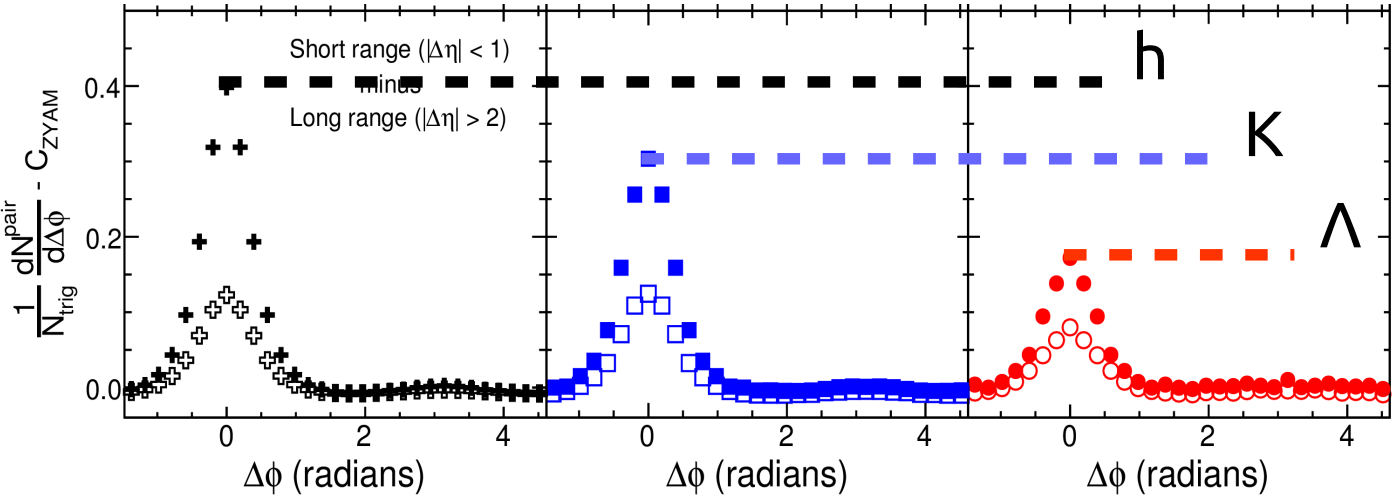
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy} \times \left(1 + \sum_{n=1}^{\infty} 2v_n(p_T, y)\cos\left[n\left(\varphi - \Psi_R\right)\right]\right)$$



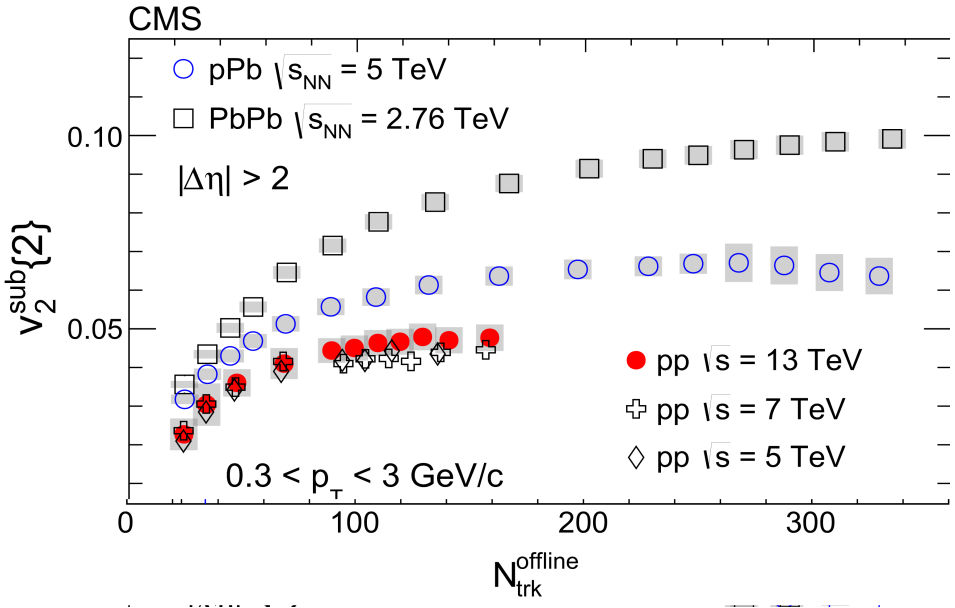
Collectivity in pp collisions

CMS-PAS-HIN-16-010
arXiv:1606.06198

- From the 2D distributions, extract background from low-multiplicity events:
  → 1D **correlation function** for light/strange hadrons



- Analysis of the correlation shape versus multiplicity:



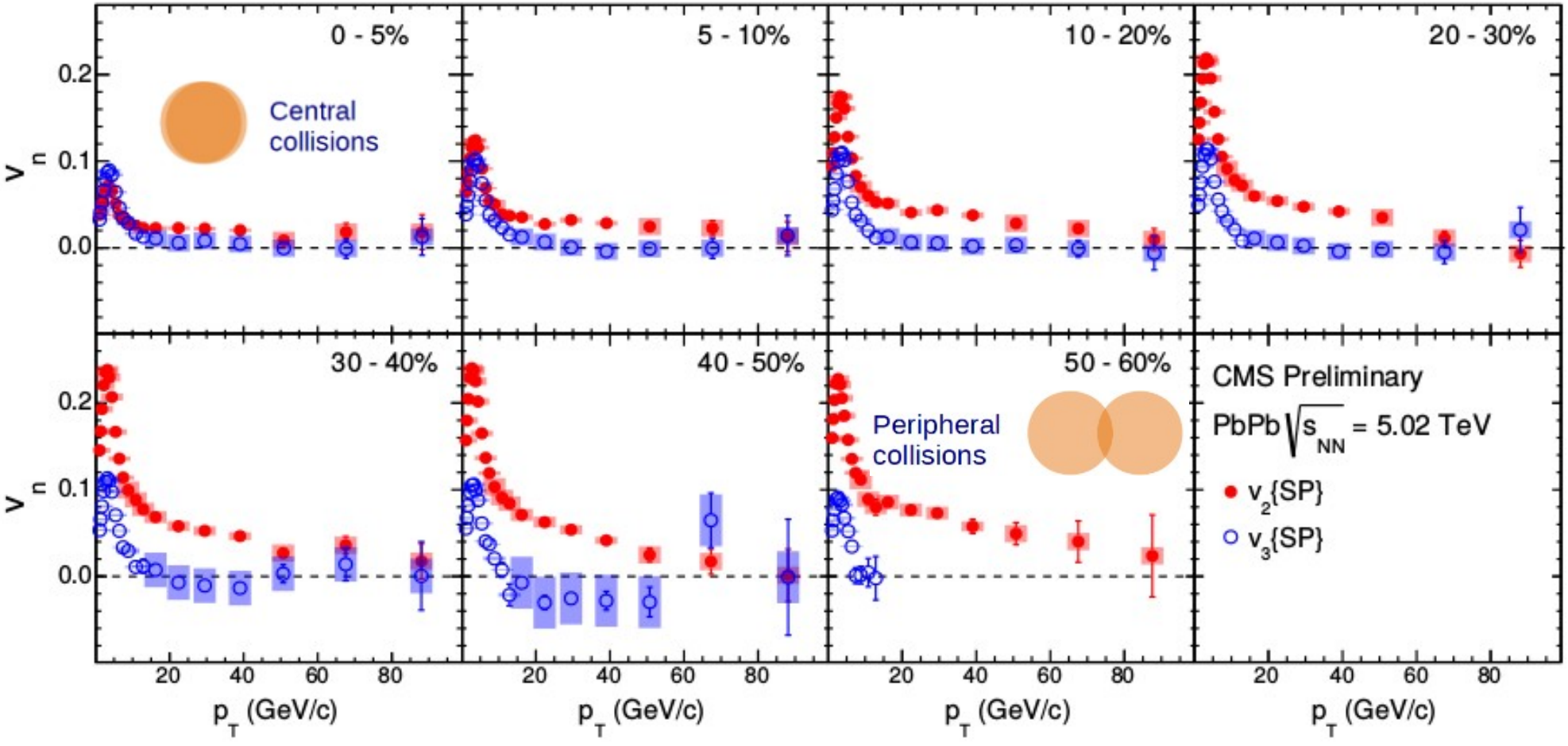
- Extracted non-zero v_2 and v_3 in pp
- Evidence for collectivity in long range |Δη|>2

Yet, **pp < pPb < PbPb**

Correlations in PbPb

CMS-PAS-HIN-15-014

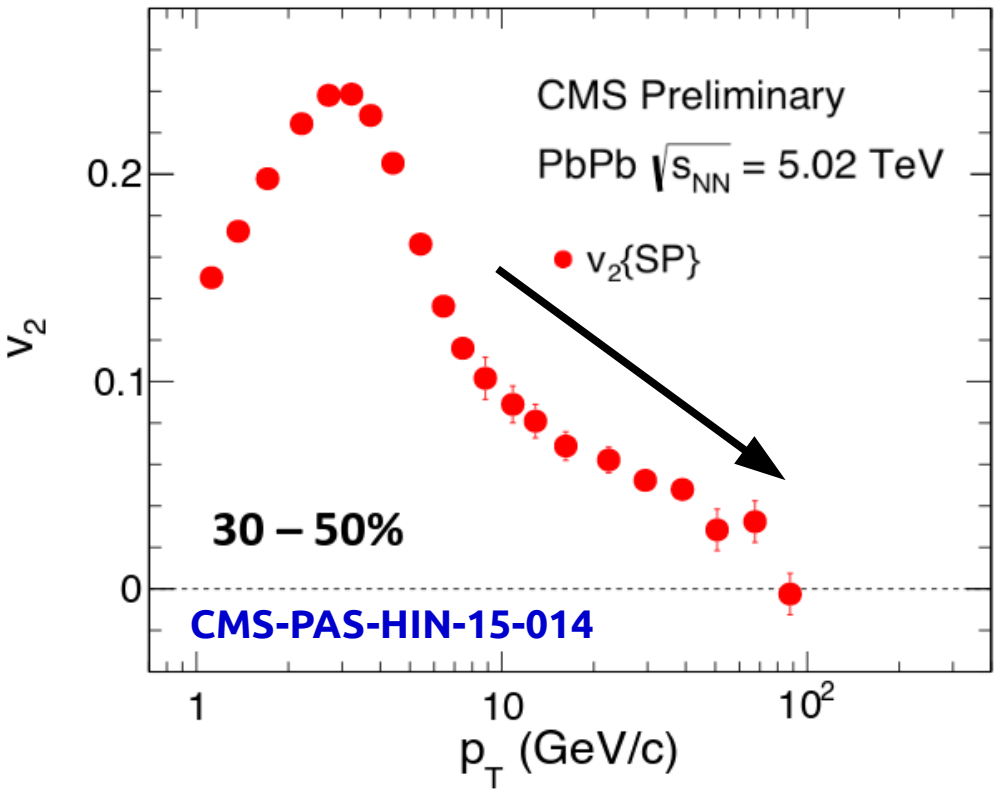
- v_2 and **first** v_3 measurement up to p_T ~100 GeV in PbPb at 5.02 TeV
- Consistent with no triangular flow above p_T > 30 GeV

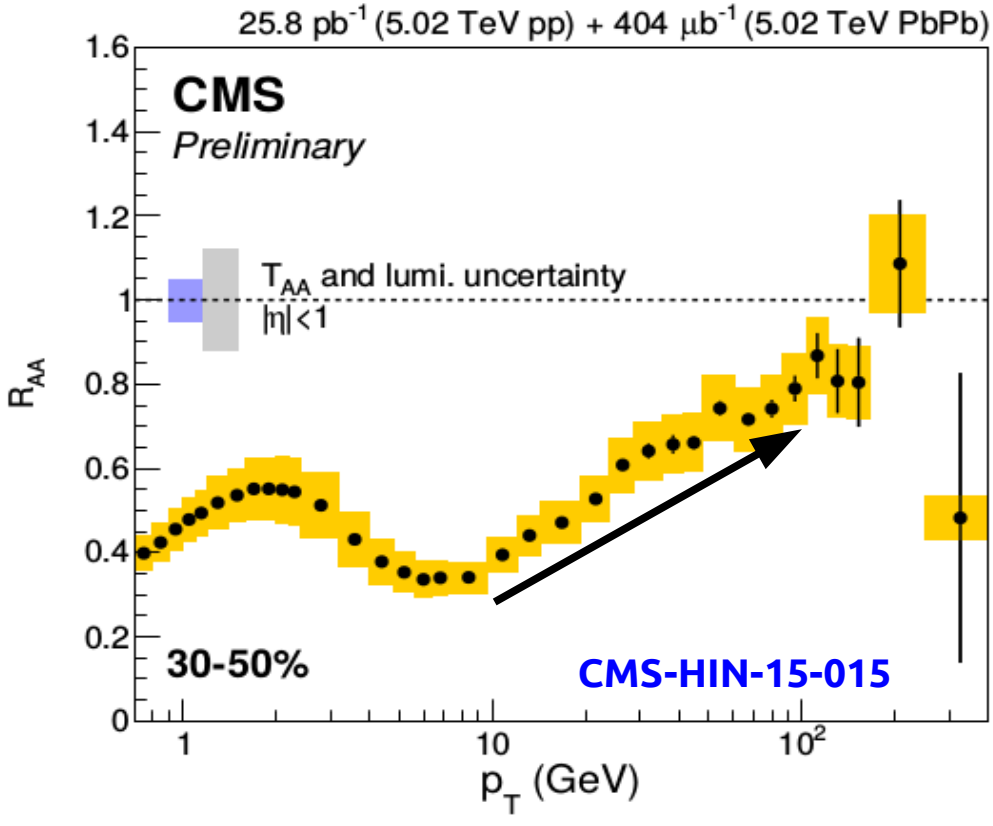


- Note: in comparison, v_2(pp) < 0.1, v_2(pPb) < 0.2 ~ v_2(peripheral PbPb)

v_2 and R_{AA} in PbPb

- Fourier harmonics of charged particles yields vs p_T: address azimuthal anisotropy in PbPb collisions
- Clear complementarity to R_{AA}, the nuclear modification factor:





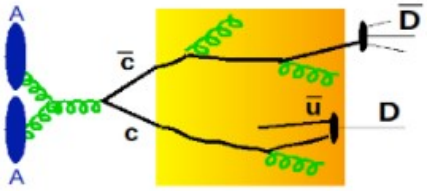
- At high-p_T, charged hadron production is more isotropic
  → decreasing elliptic flow

- Charged hadrons are less suppressed
  → R_{AA} rises

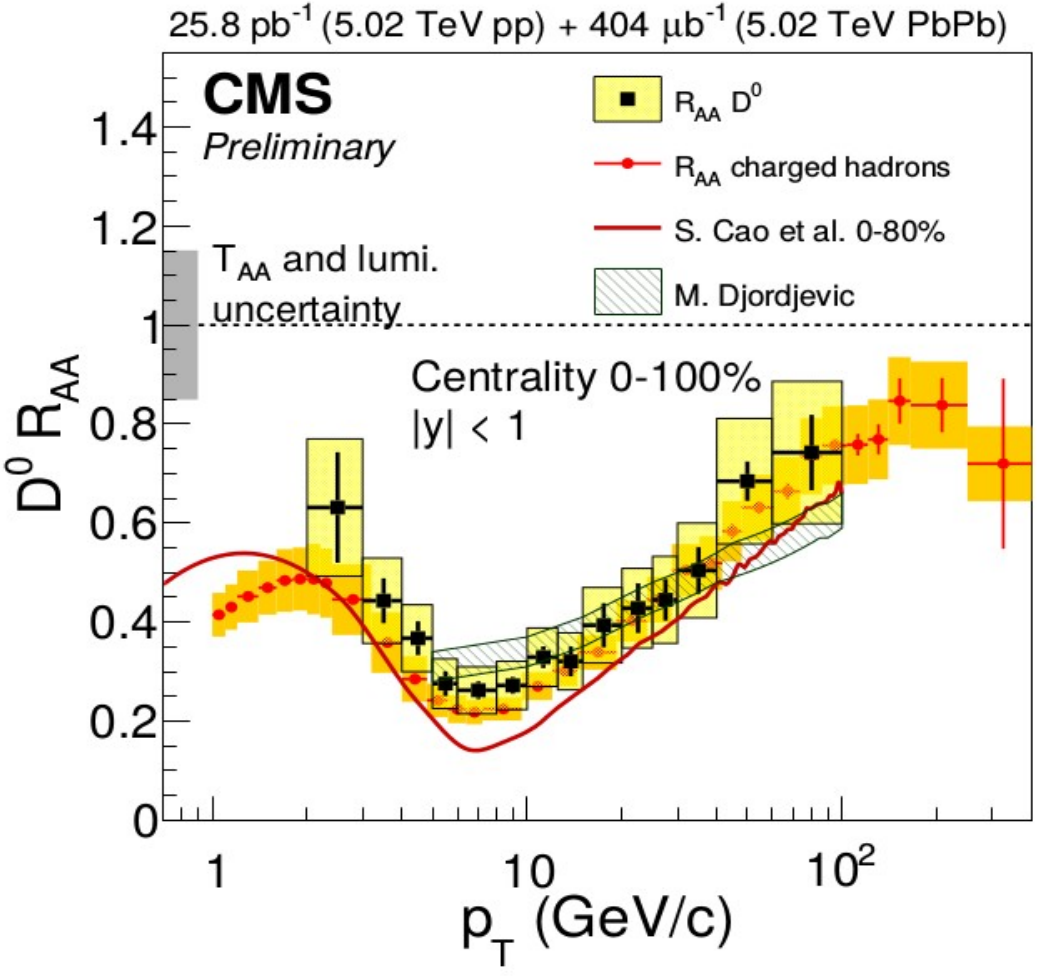
heavy flavour + quarkonia

D^0 meson R_{AA}

CMS-PAS-HIN-16-001



$$R_{\mathrm{AA}} = \frac{\mathcal{L}_{pp}}{T_{\mathrm{AA}} N_{\mathrm{MB}}} \cdot \frac{\mathrm{N}^{\Upsilon}_{\mathrm{PbPb}}}{\mathrm{N}^{\Upsilon}_{pp}} \cdot \frac{\varepsilon_{\mathrm{pp}}}{\varepsilon_{\mathrm{PbPb}}}$$



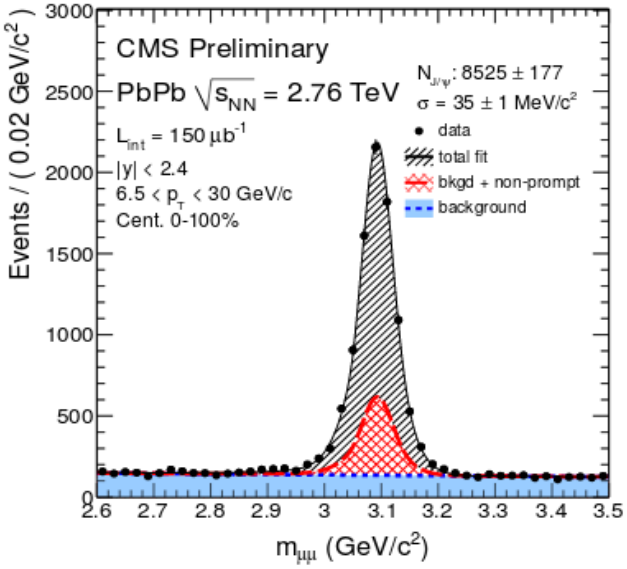
- Heavy quarks formed prior to thermalisation of the medium
- R_{AA} + v_2 necessary to get real insight on heavy quark energy loss
- D, B, Should be less suppressed than light quarks and gluons
- $R_{AA}(D^0)$ compatible with charged hadrons within uncertainties
- But, R_{AA} also contains nuclear absorption, shadowing...
- So, what about the v_2 ?

  … Stay tuned !

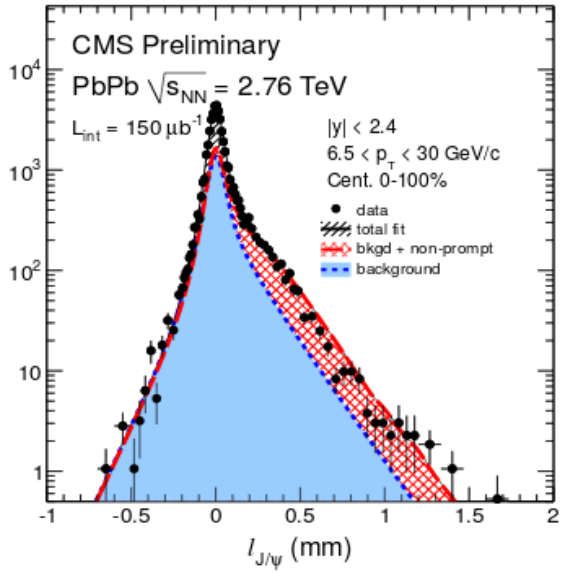
J/ψ in PbPb

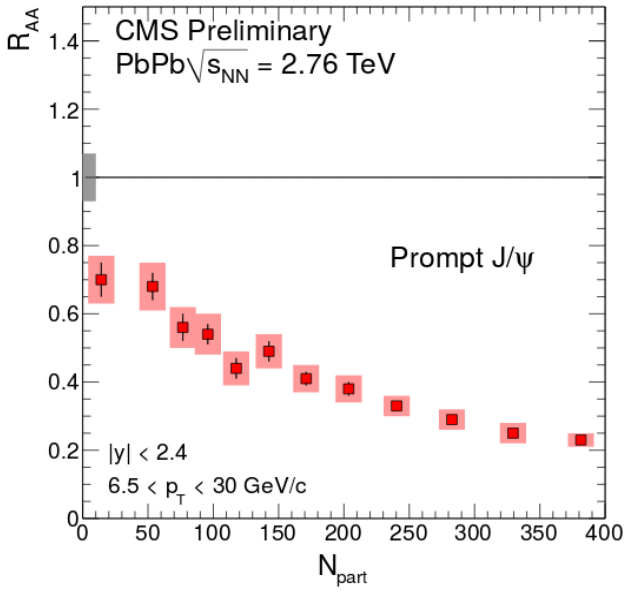
CMS-PAS-HIN-12-014
CMS-PAS-HIN-12-001
arXiv:16yy.xxx

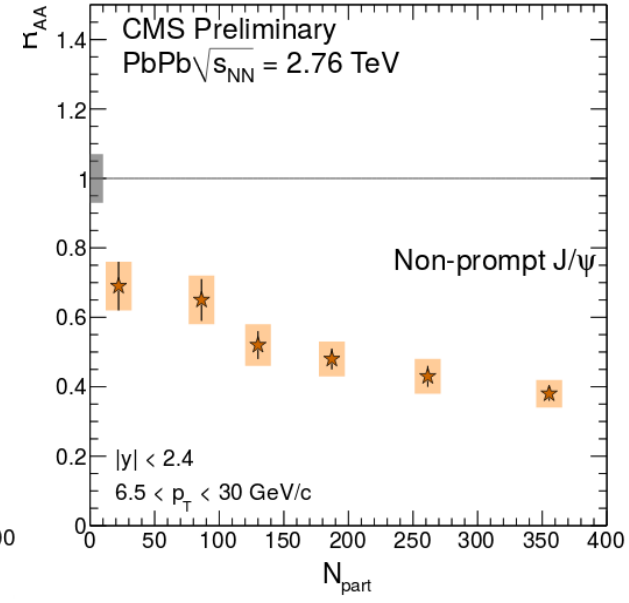
Prompt-J/ψ



'Non-prompt' J/ψ







- Quarkonium states put 'grades' on the QGP thermometer
- 3 < p_T(J/ψ) < 30 GeV/c
- Prompt J/ψ:
  → sequential melting?
  → regeneration?
- Non-prompt from B meson:
  → b-quark energy loss
  → flavor dependence?
- Legacy Run1 J/ψ R_{AA} & v_2 imminent …

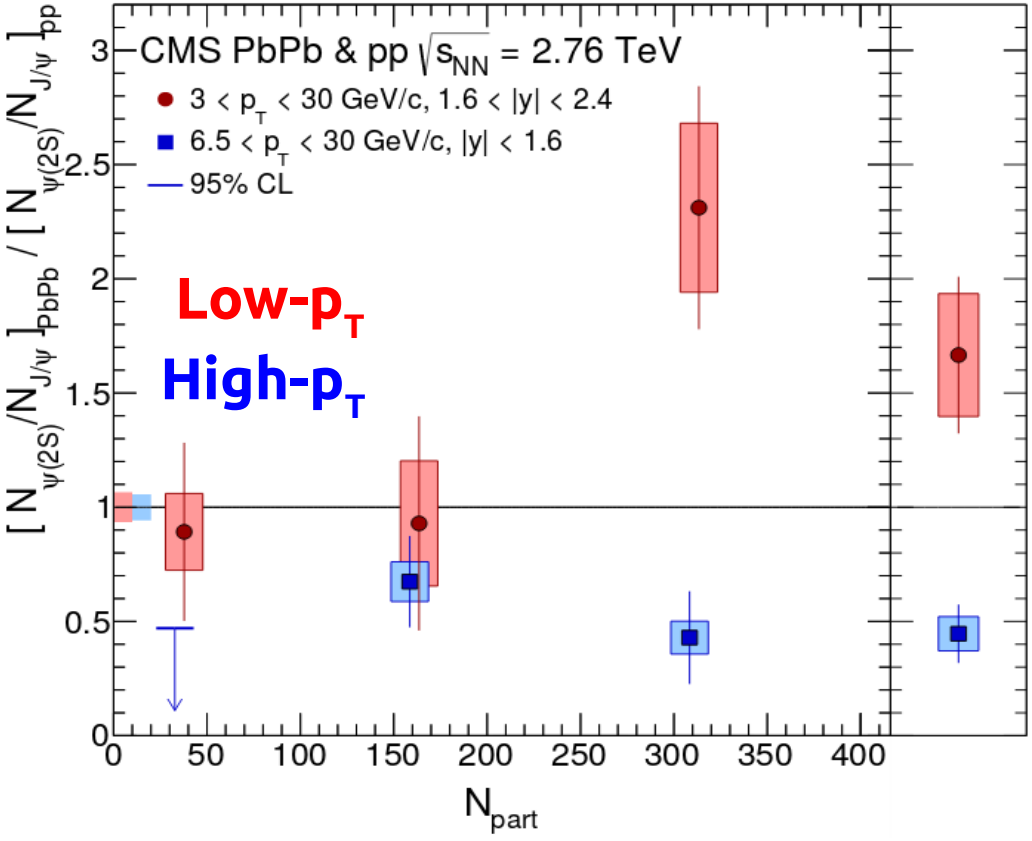
  … Stay tuned !

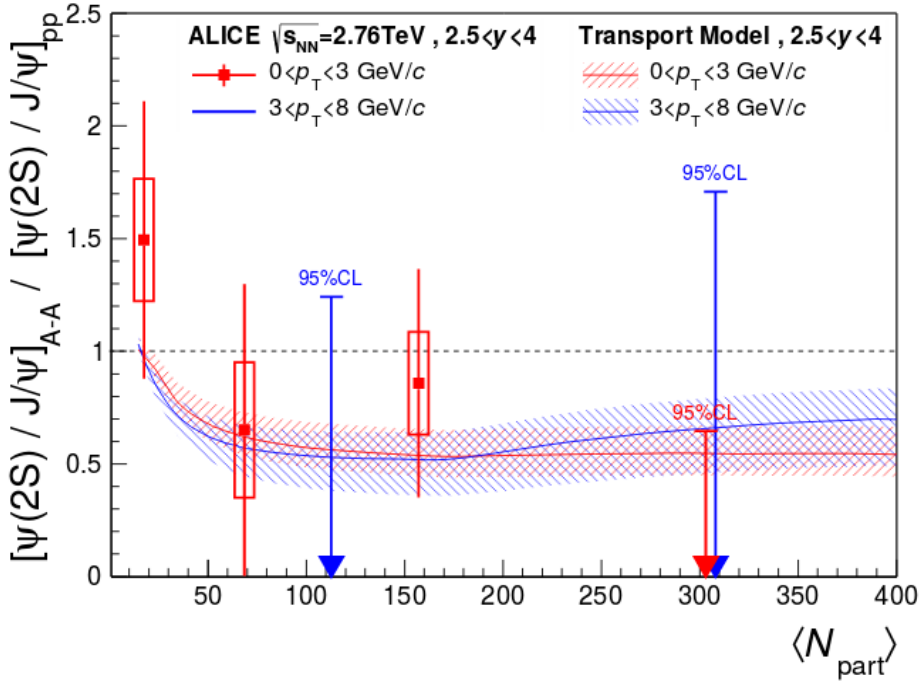
ψ(2S) in PbPb

PRL 113 (2014) 262

- Sequential melting: excited states suppressed more than ground states
  → R_{AA} (ψ(2S)) / R_{AA} (J/ψ) < 1 (*double ratio*)

- Run 1 riddle: charmonium double ratio > 1, at low p_T, in CMS ?!
  → Larger luminosity in 2015 PbPb @ 5 TeV … wait and see!





JHEP 05(2016)179

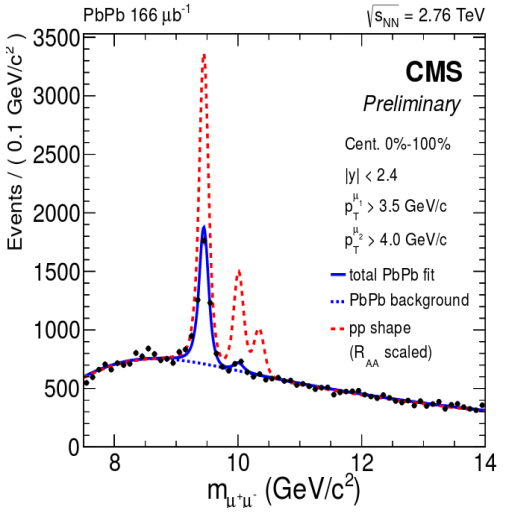
Bottomonia in pp, PbPb

- Upsilon family: ideal probe for deconfinement
  → R_{AA} (Y(1S)) > R_{AA} (Y(2S)) > R_{AA} (Y(3S))

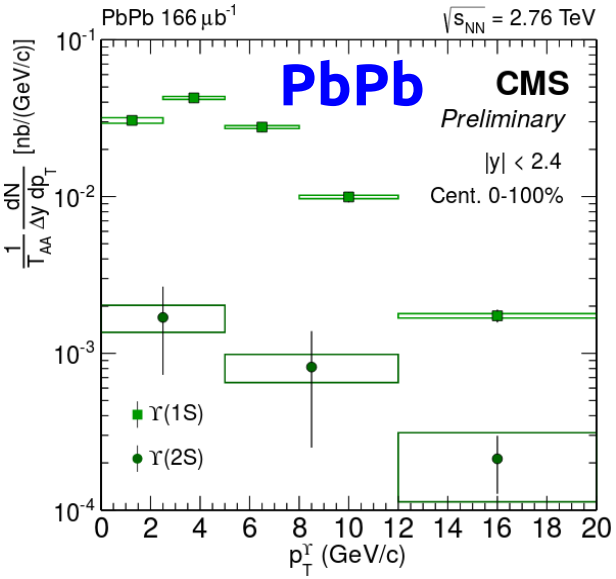
- Run 1 data:
  → Y(1S) suppression independent of kinematics!
  → First Y(2S) spectrum in PbPb!
  → R_{AA} Y(3S) < 0.14 @ 95% confidence!

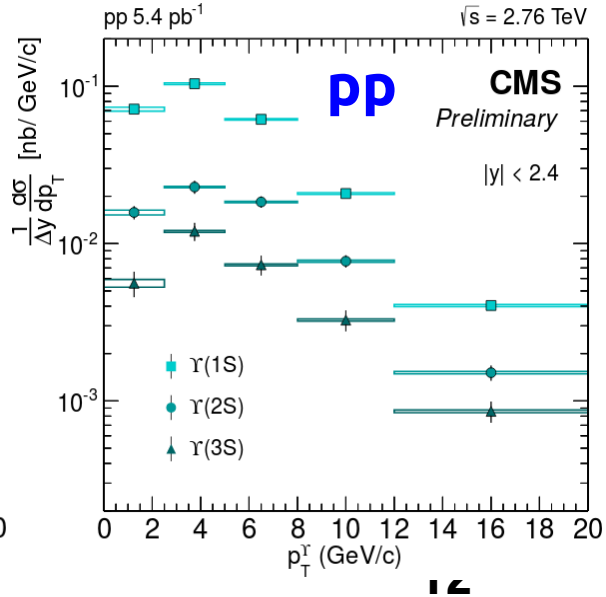
- Run 2 data: any Y(3S) surviving in peripheral collisions?

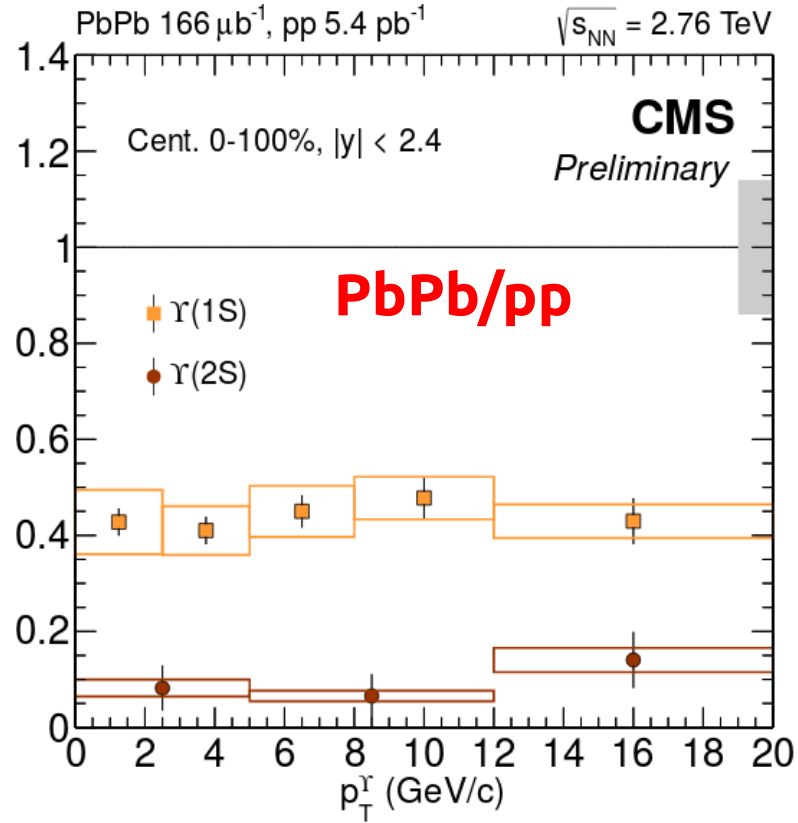
CMS-PAS-HIN-15-001



$$\frac{1}{T_{AA}}\frac{d^2N}{dy\,dp_T} \Big/ \frac{d^2\sigma}{dy\,dp_T} = R_{AA}$$








JADROLINIJA
MARJAN

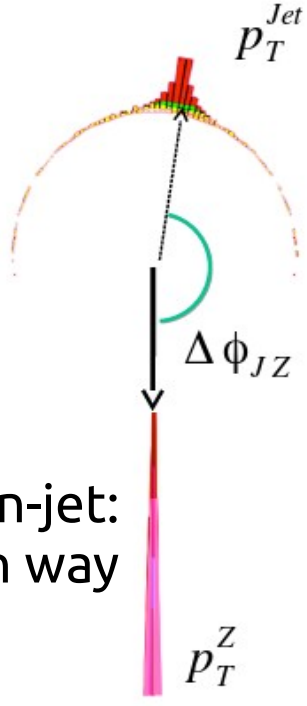
Primer

CMS-PAS-HIN-15-013

Jet quenching: jet goes through the medium and loses energy...

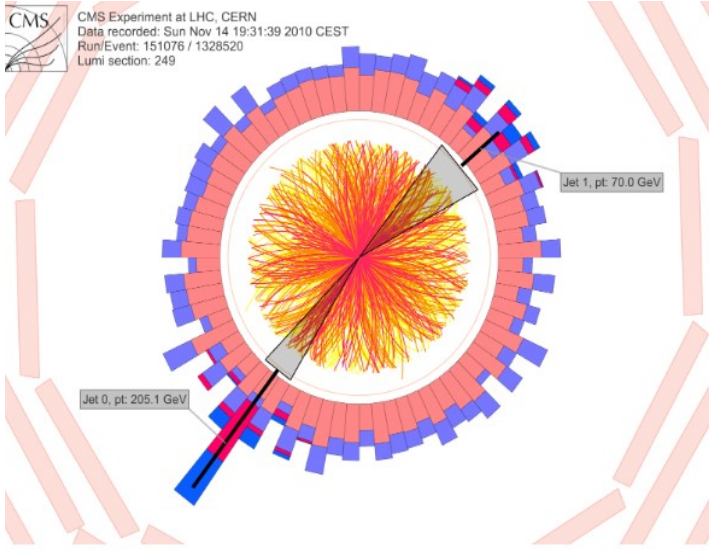
- What happens to the jet in a dense medium?
  → Energy loss at the parton level
  → Modification of fragmentation function
  → Flavour/mass dependence of parton energy loss?

Boson-jet:
The clean way

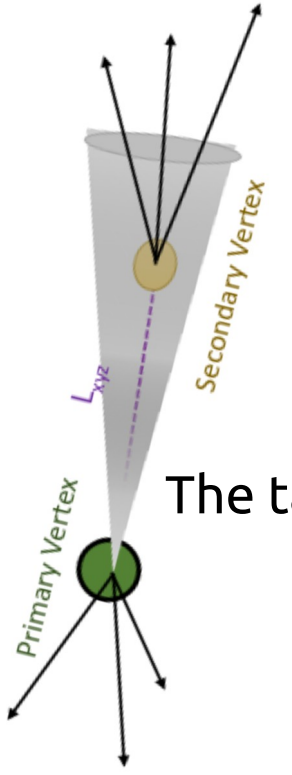


$$x_{JZ} = \frac{p_{\mathrm{T}}^{\mathrm{Jet}}}{p_{\mathrm{T}}^{Z}}$$

Di-jets: the hard way



- Δϕ,Δη
- ρ(r)
- Splitting function ...



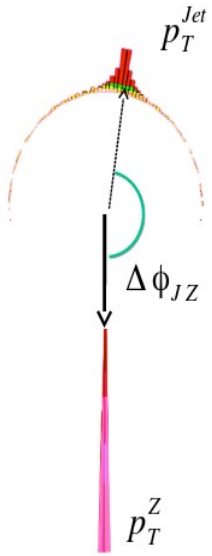
c/b-jet
The tasty way

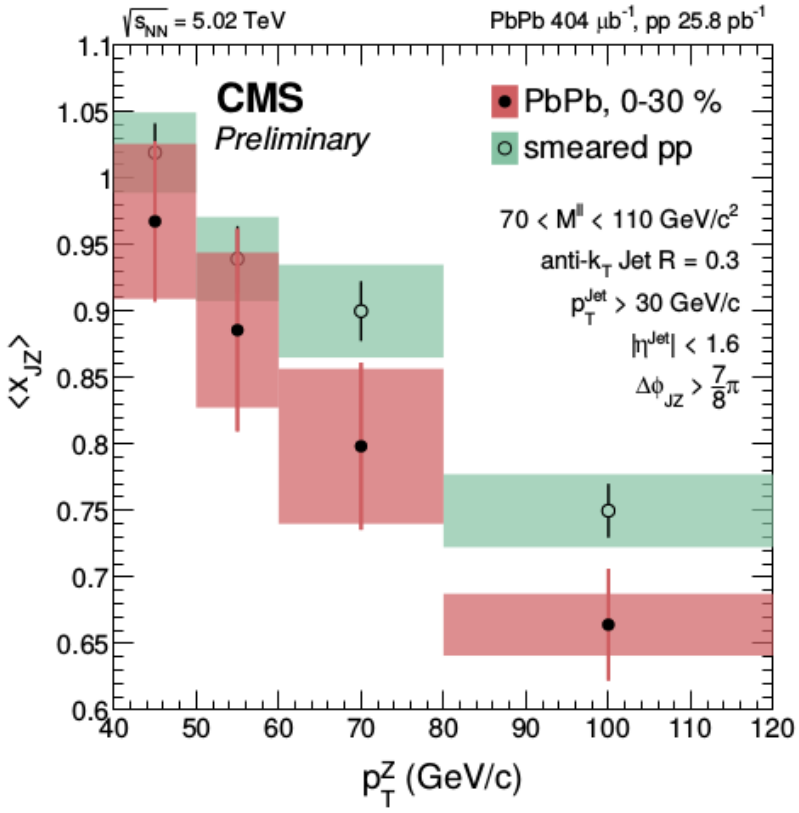
Boson-jet in PbPb @ 5 TeV

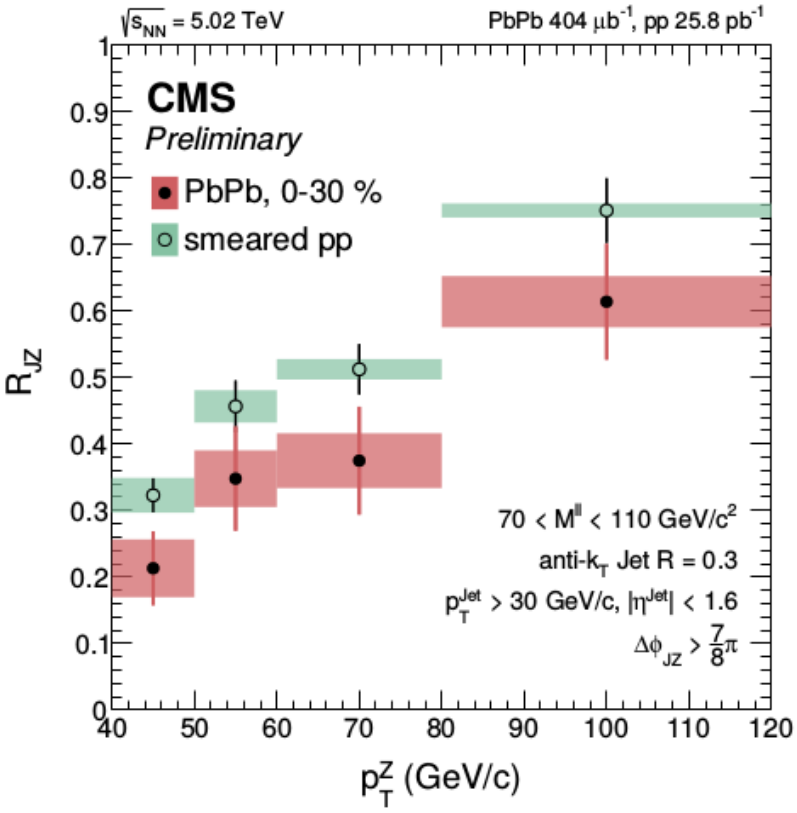
CMS-PAS-HIN-15-013

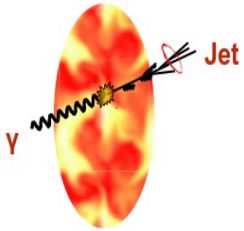
$$x_{JZ} = \frac{p_{\mathrm{T}}^{\mathrm{Jet}}}{p_{\mathrm{T}}^{Z}}$$

→ Z-jet p_T imbalance in PbPb:
energy loss of the initial parton + quenching
quark-jet dominated measurement









- Jet energy loss increases with the p_T(Z)

- Probability of jet associated to Z is lower in PbPb at all p_T(Z)
- Jets lose energy and fall under the selection threshold

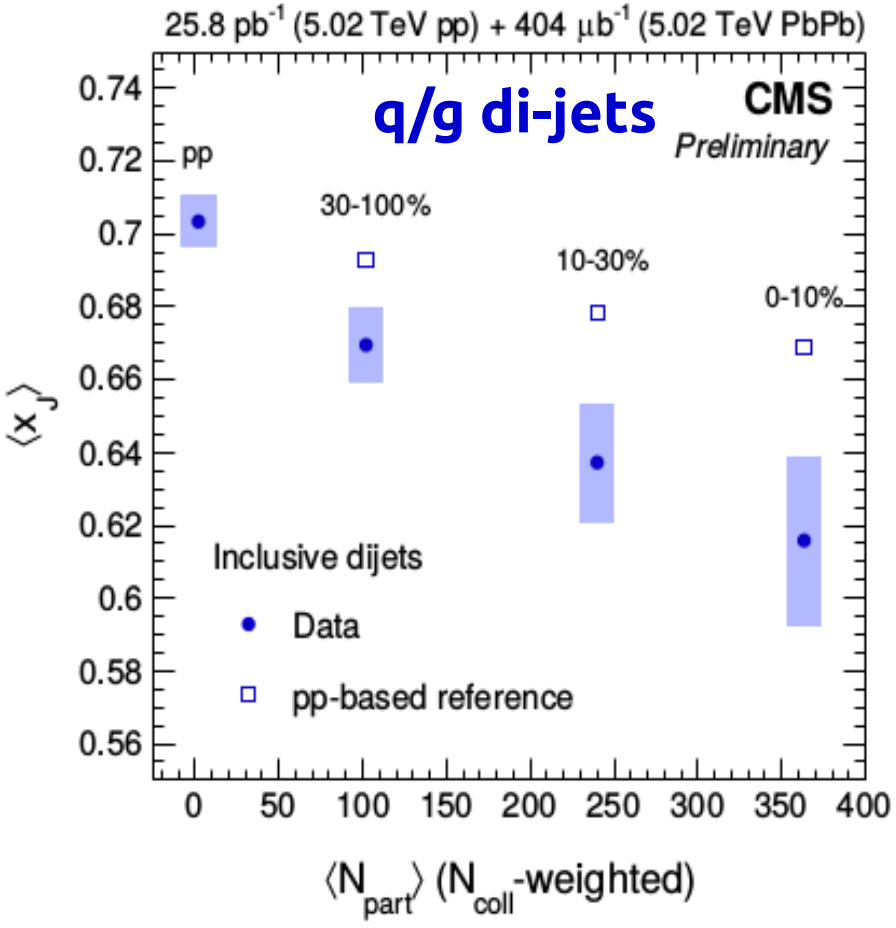
...Stay tuned for photon-jet studies!

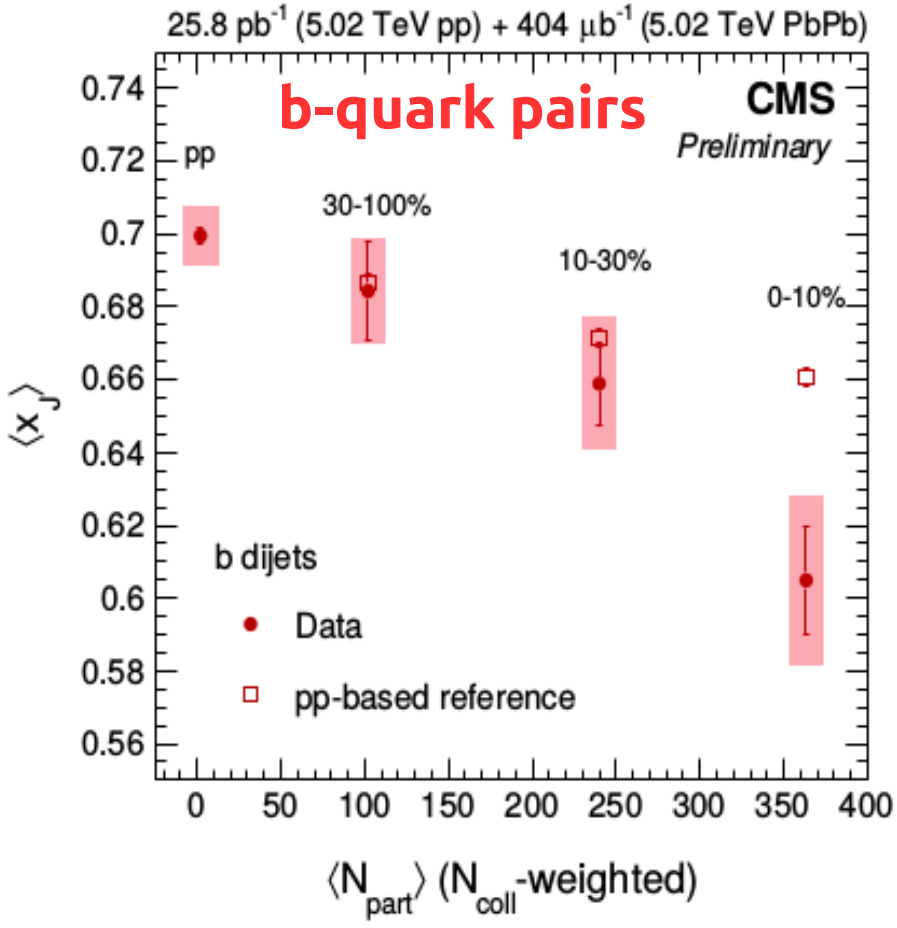
b-jet pairs in PbPb

CMS-PAS-HIN-16-005

→ *Flavour dependence* of jet energy loss

- Select b-tagged back-to-back jets: probe b-quark pair creation
- Compare to the p_T-imbalance of inclusive di-jet events





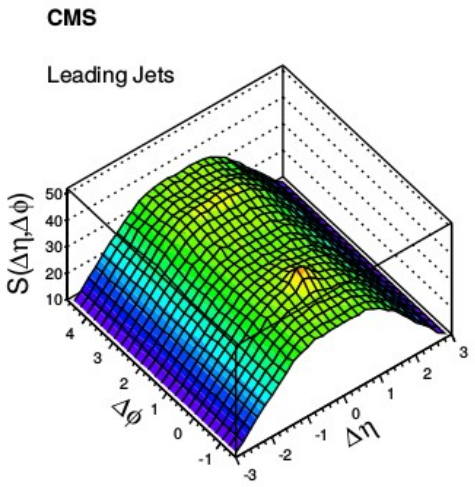
- More data will place more constraints on flavour and mass depedence
- CMS can also do c-jet tagging!

Jet-track correlations

CMS-PAS-HIN-14-016

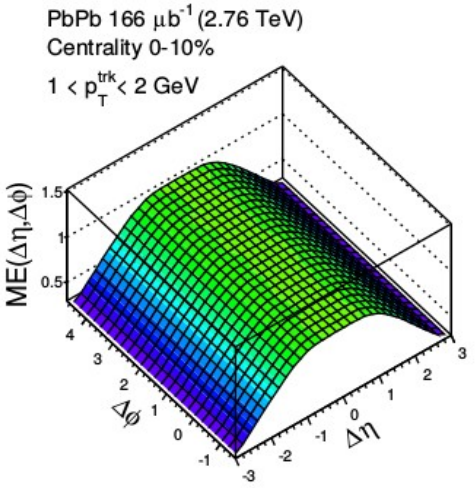
What is the QGP response to the hard parton process?

→ Compare: charged particle eta-distributions with respect to leading and subleading jet PbPb



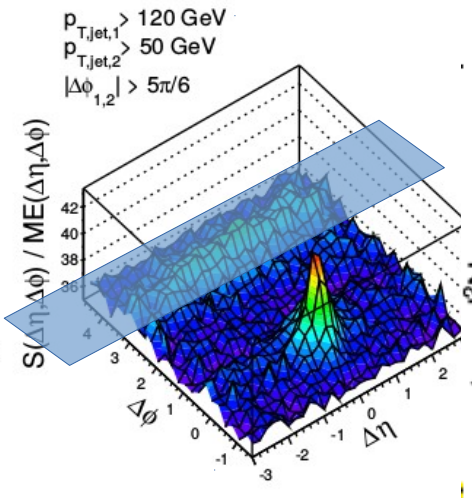
$S(\Delta\eta, \Delta\phi)$

1<pT(trk)<2



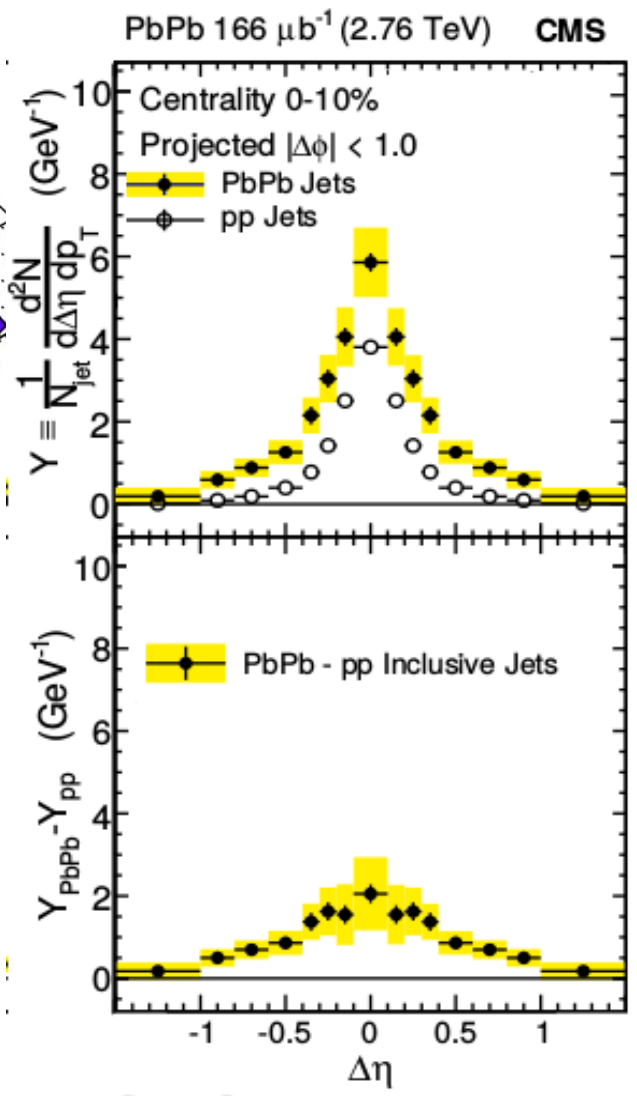
$ME(\Delta\eta, \Delta\phi)$

Removes U.E.



= Yield

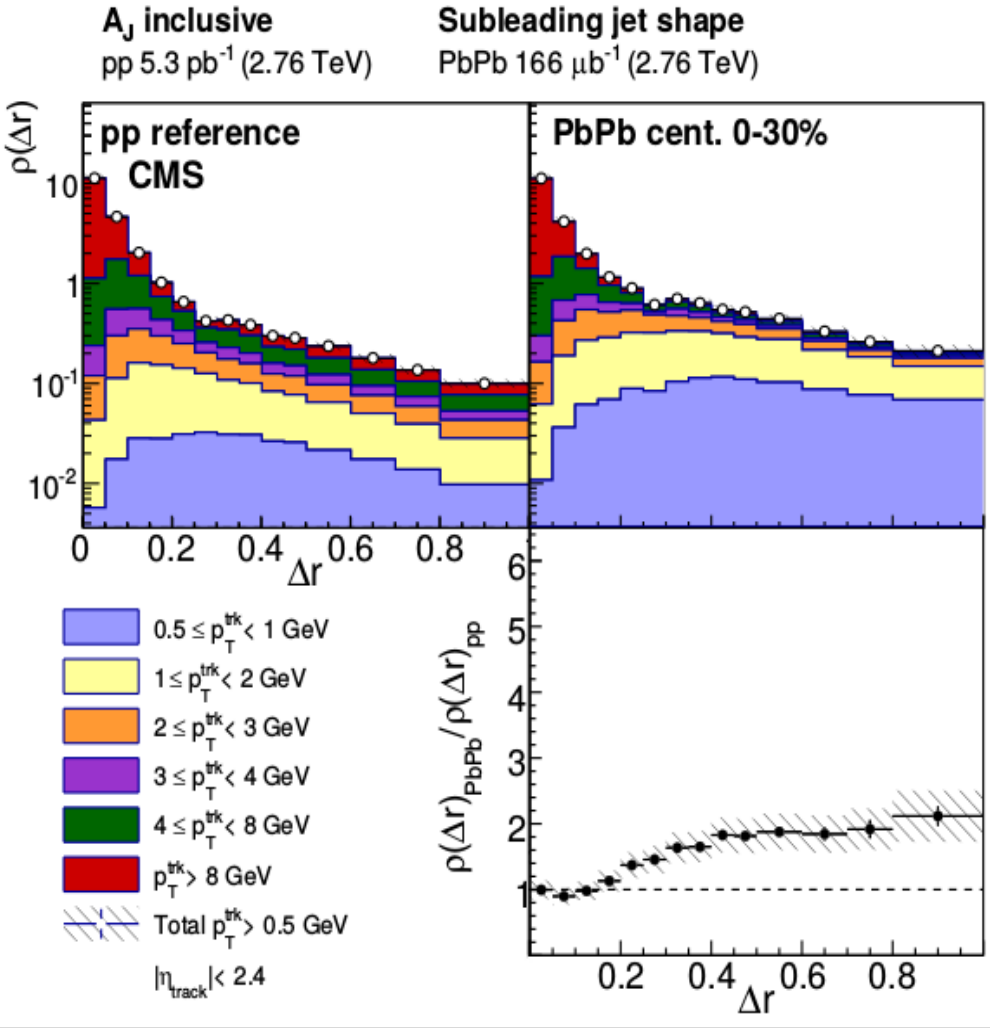
(Flow must be subtracted)



- Large fraction of jet energy radiated out of leading jet cone (large eta and phi)
- Further modification on sub-leading jet (see paper or backup)

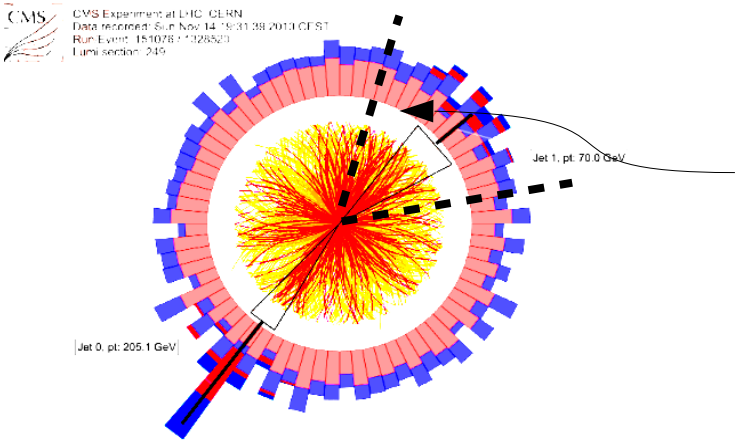
Dijet energy imbalance decomposition

- Jet substructure and large angle radiation:
  Where did the energy go ?



anti-k_T R = 0.3, $|\eta_{jet}| < 1.6$
$p_{T,1} > 120$ GeV, $p_{T,2} > 50$ GeV, $\Delta\phi_{1,2} > 5\pi/6$

CMS-HIN-15-011
Sub to JHEP & arXiv



ρ(r)

Jet momentum density profile:

- Excess of low p_T particles out of jet 'cone', in both leading and subleading hemispheres
- Higher imbalance due to quenching → higher excess on the subleading jet side
- Low-p_T tracks in jet peaks seem to only account for partial redistribution of energy

Summary

- Healthy and wealthy heavy ion program running in CMS!
  Not a full review of PbPb 2015 run (results coming out soon)

- Some hot questions hanging:
  → small systems (pp, pPb): why do particles seem to flow?
  → light vs heavy flavour: flavour and/or path dependence of energy loss?
  Or else?
  → quarkonia: interplay between suppression, regeneration, nuclear effects …?
  → jets, di-jets: fragmentation, jet substructure, what have we learned?

- CMS recorded pp and PbPb data in Dec 2015 at 5 TeV to address these questions!

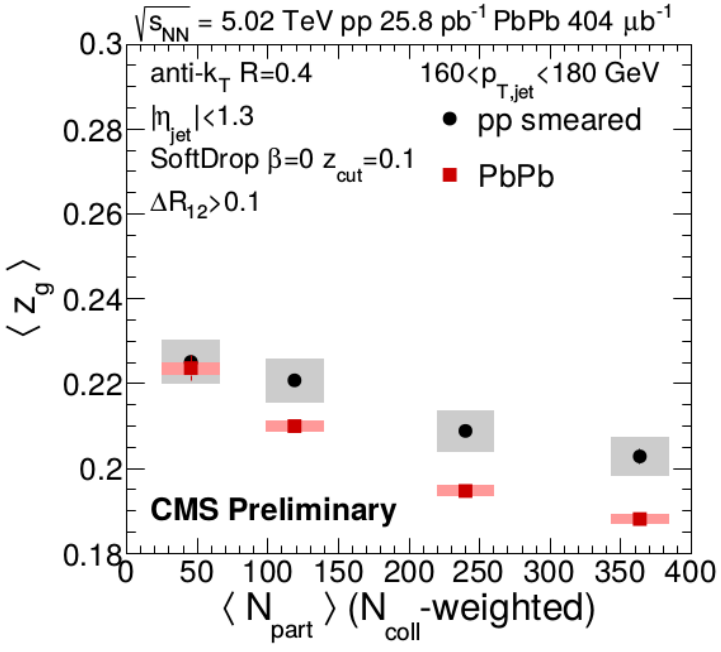
- Will take 5 and 8 TeV pPb data this November

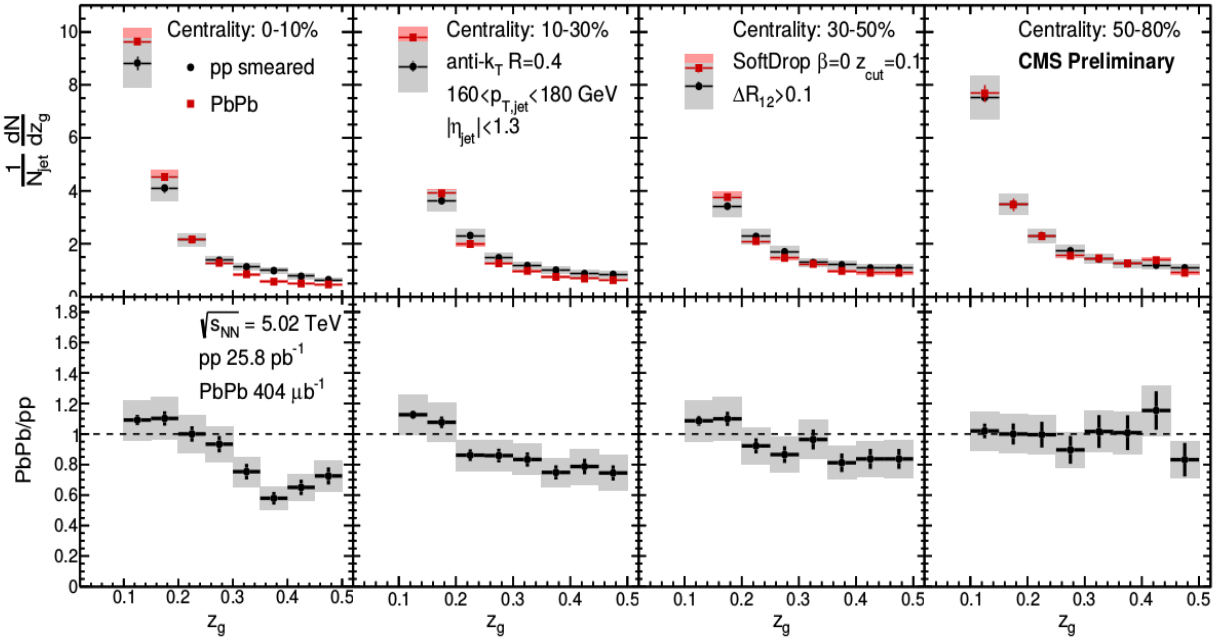
  … a recurring thought: stay tuned!

Thanks for your attention!

Backup

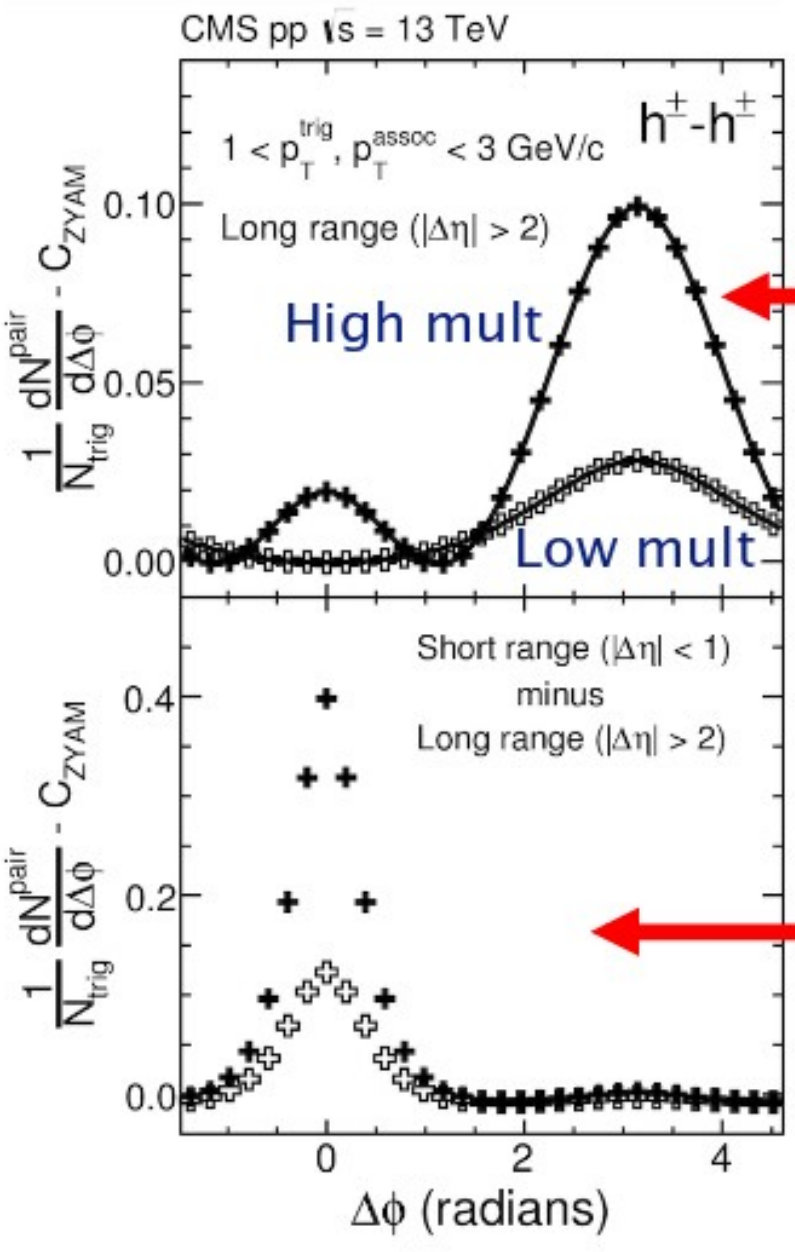
Splitting functions in PbPb and pp (5 TeV)

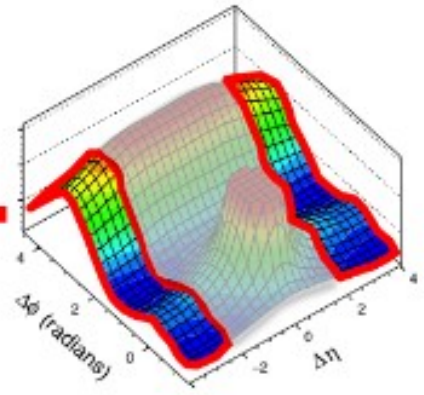




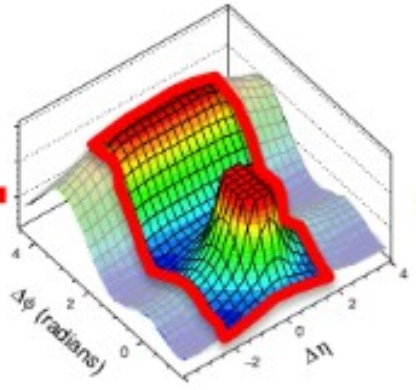
Jet-removal technique in pp ridge

- In pp, the away-side is dominated by jets (fragment and thus contribute to the particle yield)

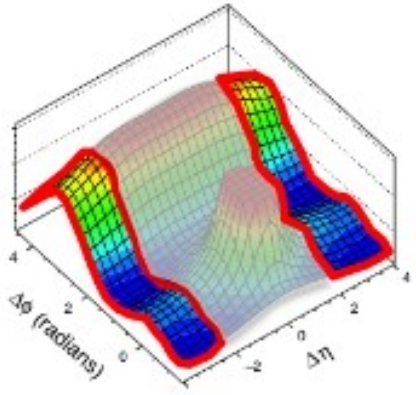




Project long range (above) and short minus long range (below)



minus

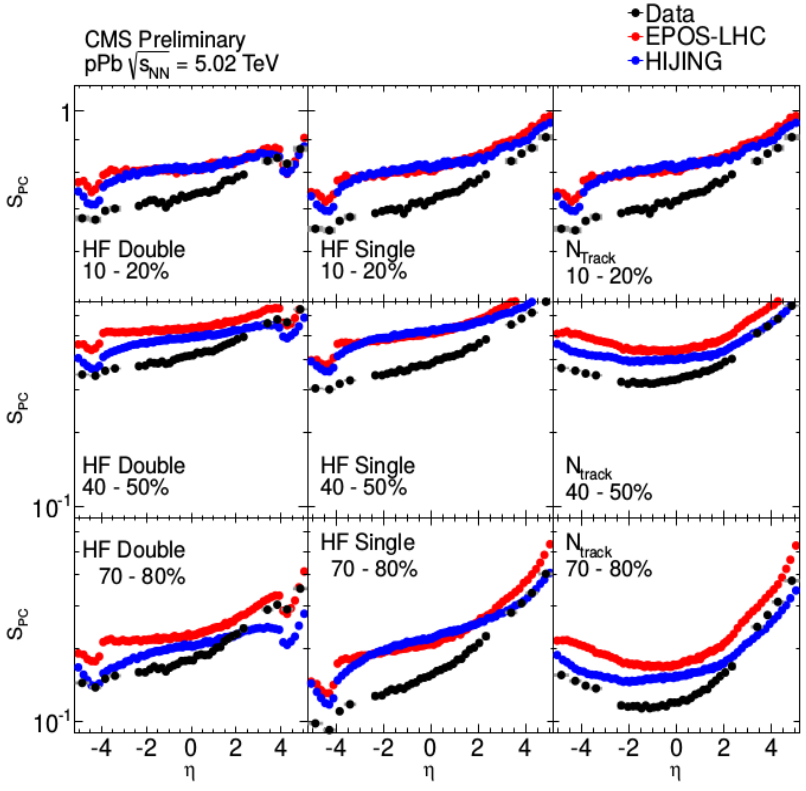


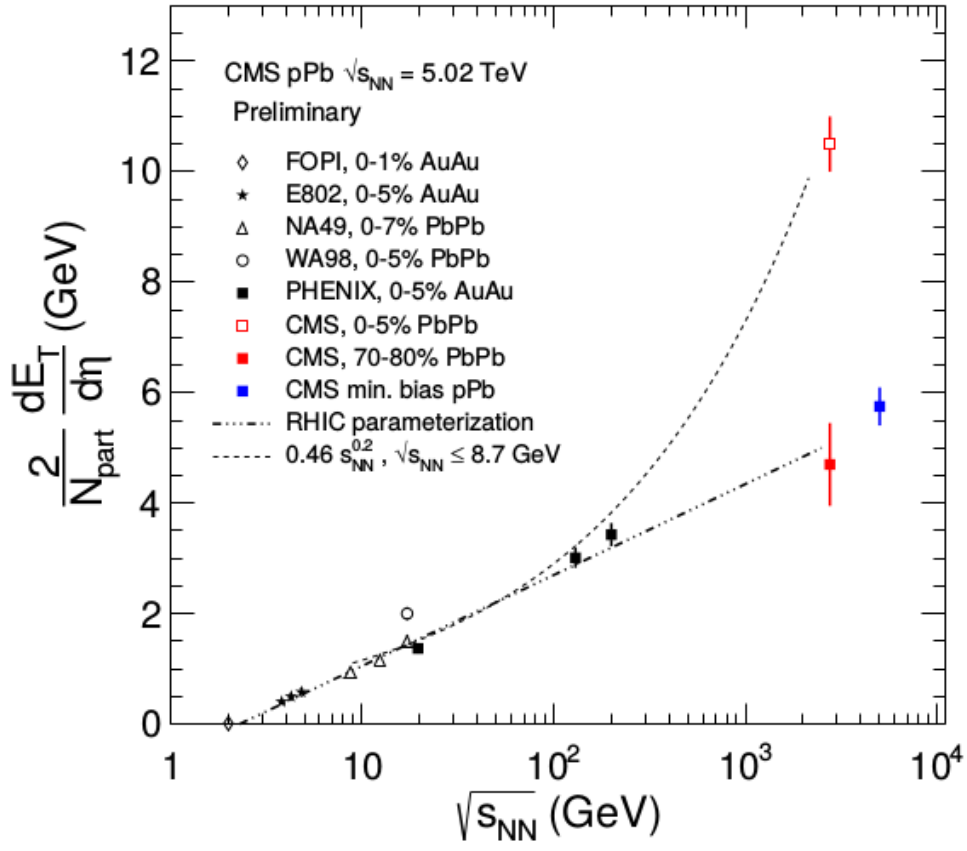
CMS HIN-16-010

Energy flow in pPb

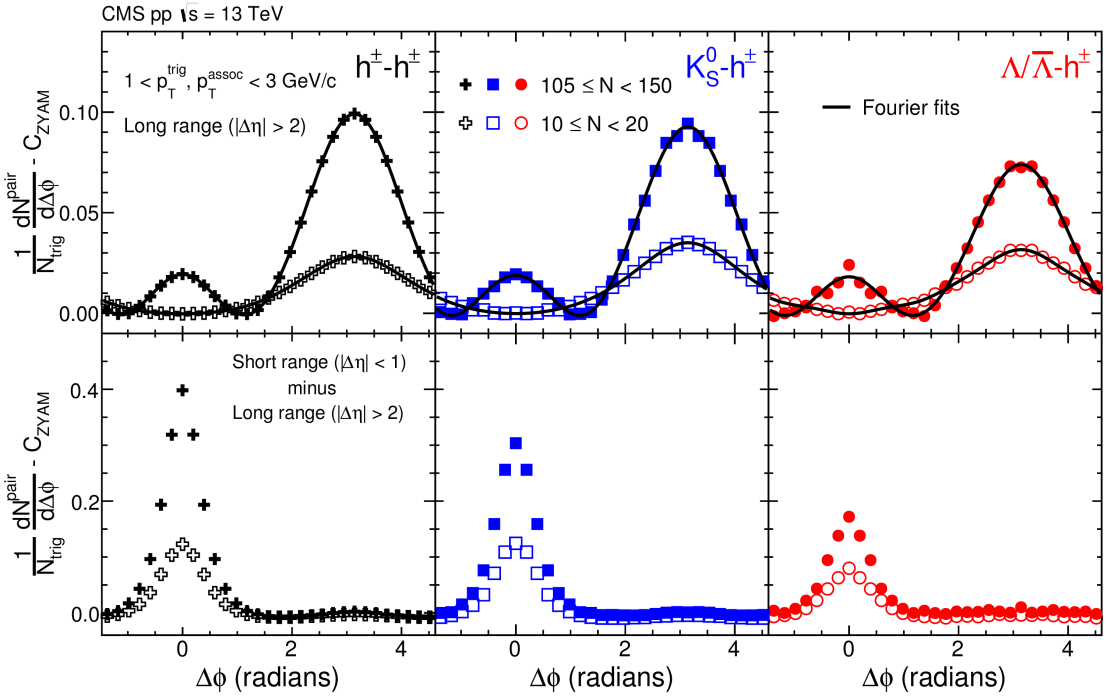
CMS-PAS-HIN-14-014

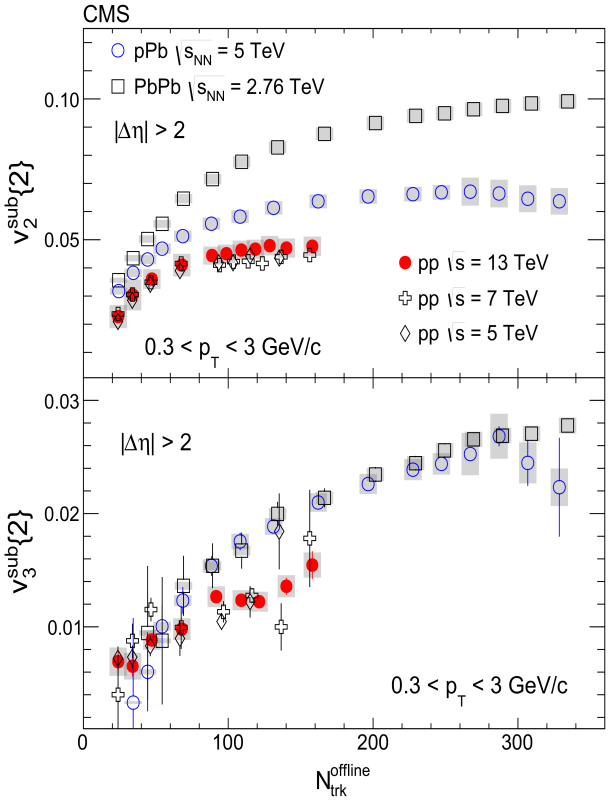
- Large Et produced in pPb collisions at 5.02 TeV
- ~ peripheral PbPb collisions at 2.76 TeV
- Eta shifted to the Pb side
- Centrality dependence different than generators and stronger on the Pb-going side

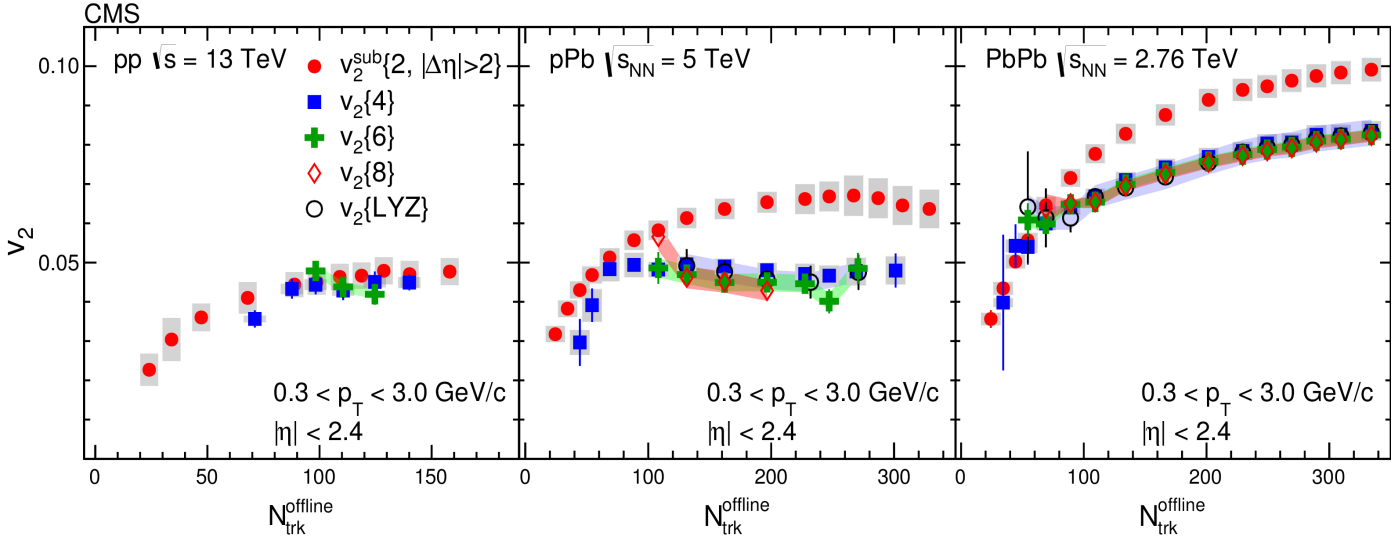




Collectivity in pp collisions







Inclusive-jet R_{AA}

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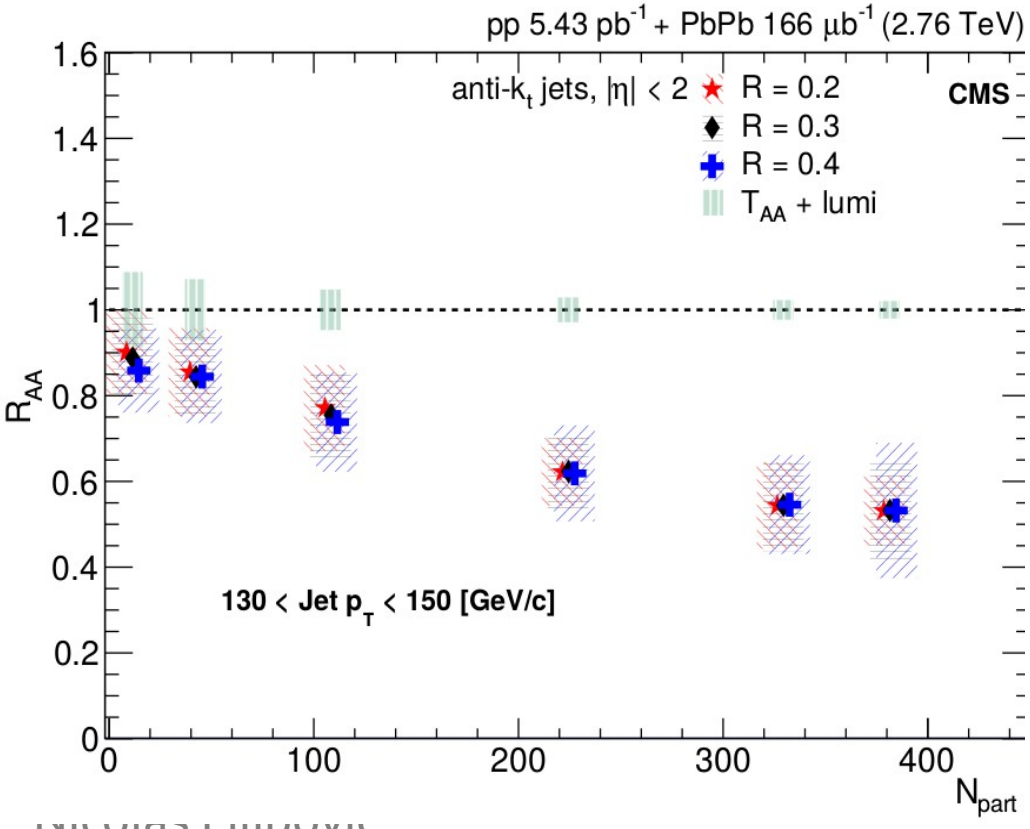
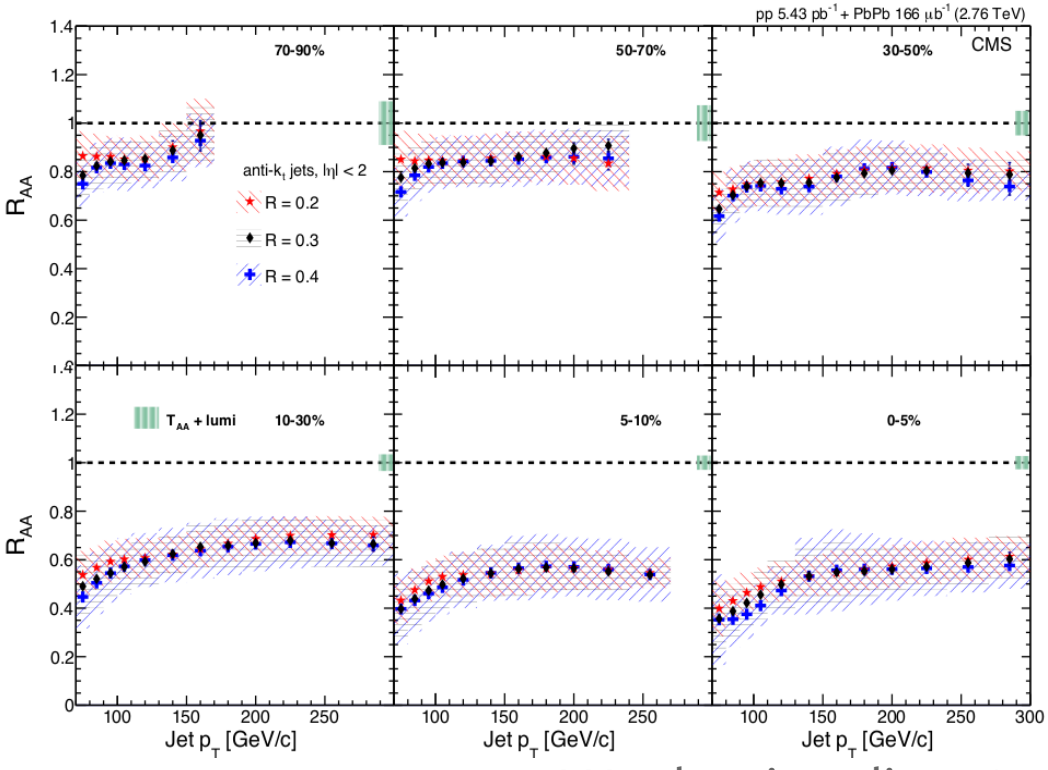
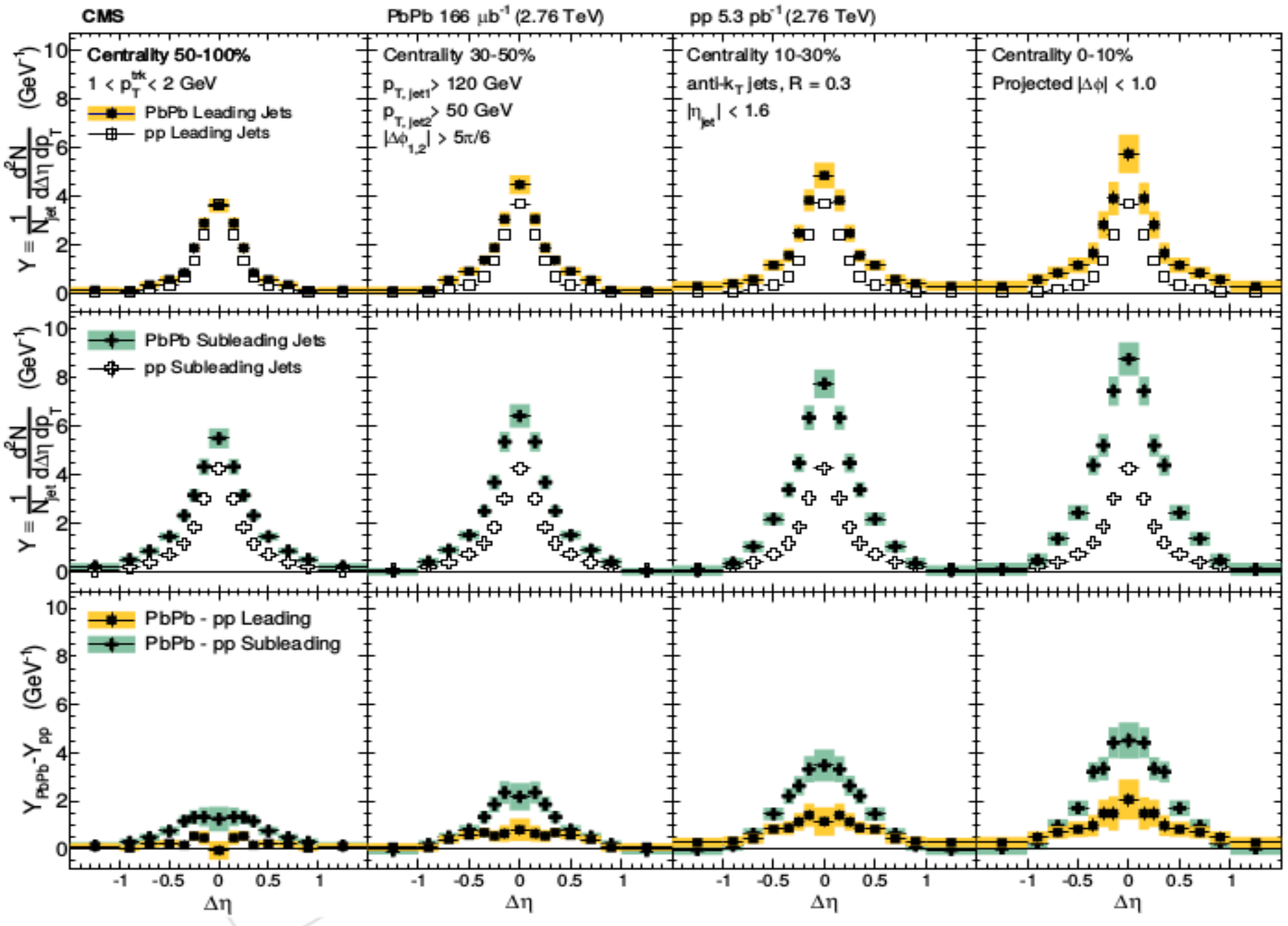
- Quantitative measure of jet quenching
  - Centrality-dependent, weakly pT-dependent
  - Independent of anti-kT jet distance parameter



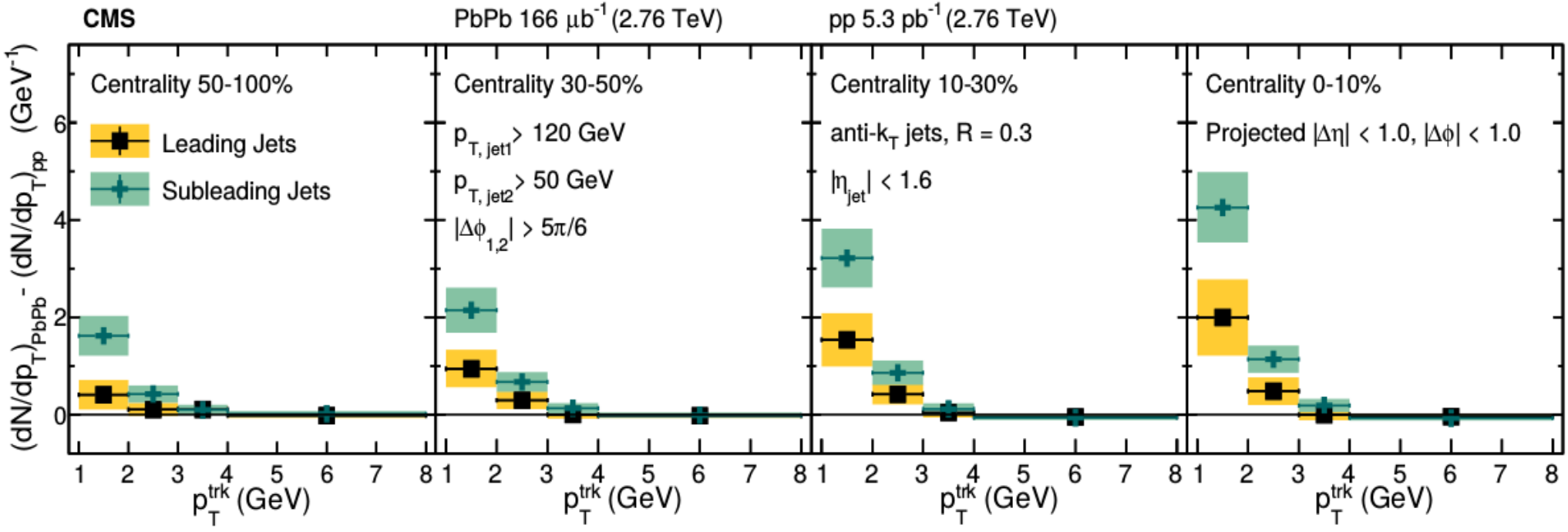


Jet-track correlations

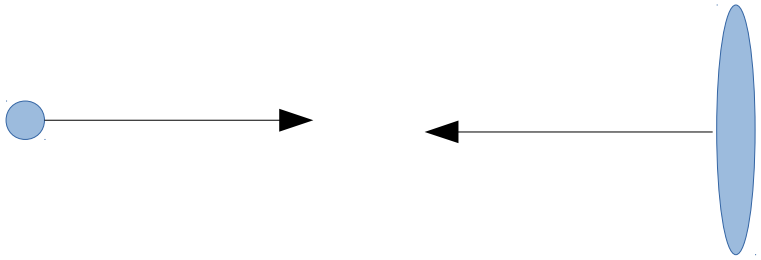


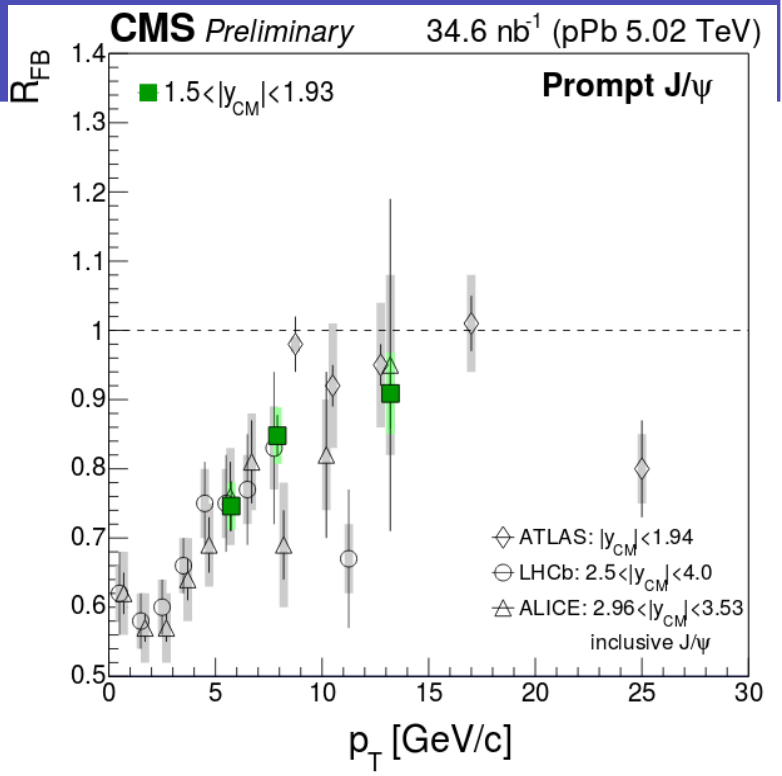
Jet-track correlations

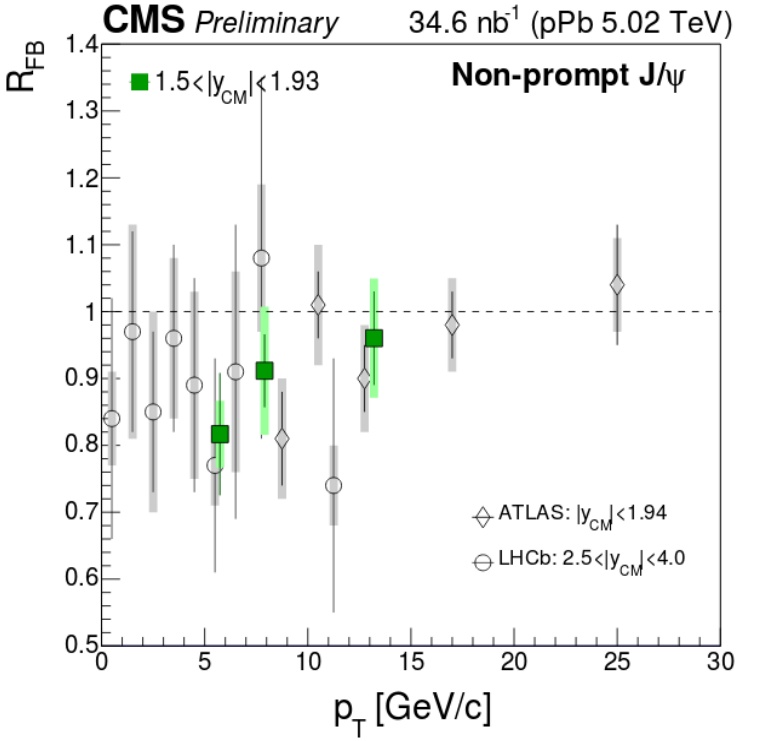
Subtracting pp jet shape



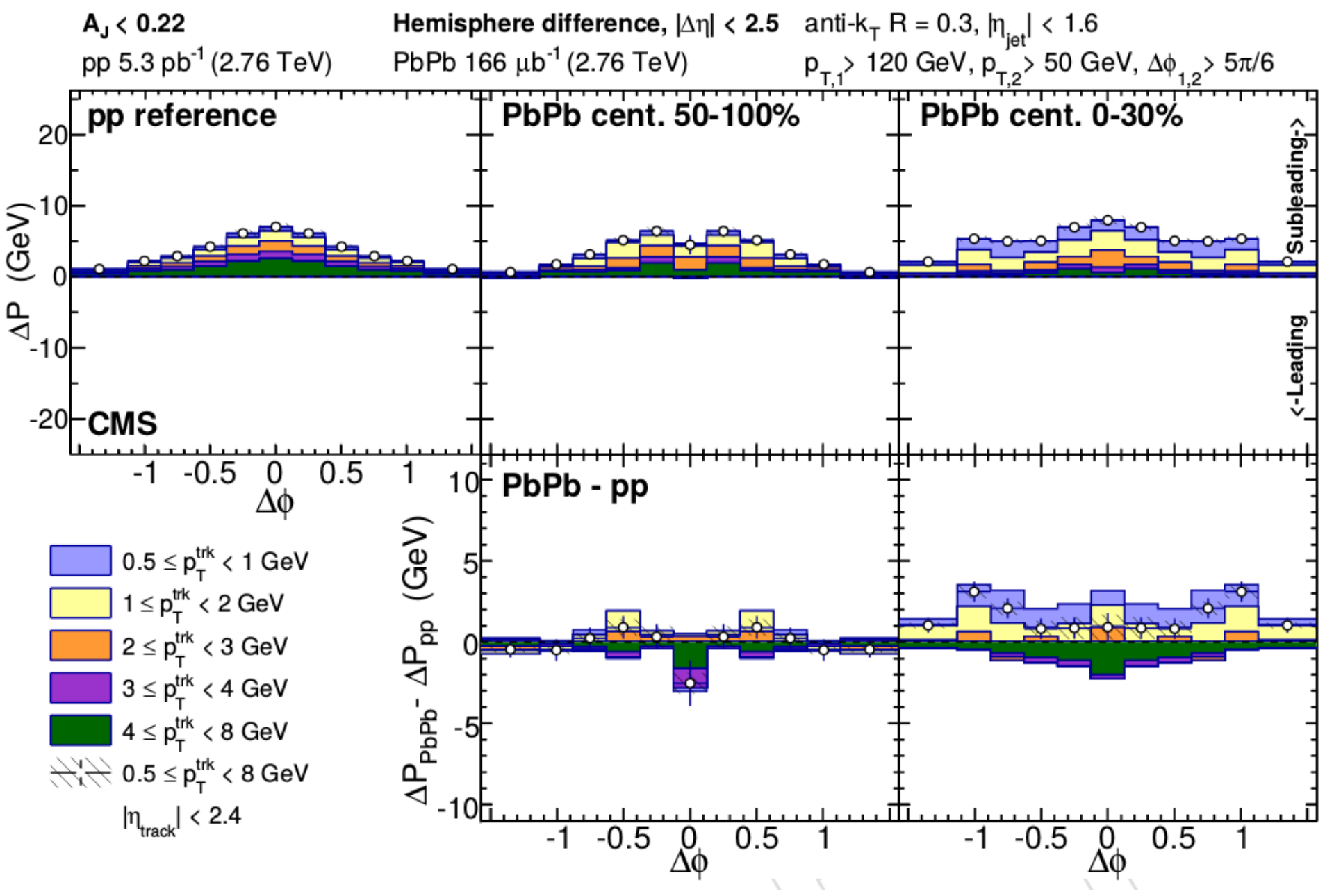
charmonia in pPb



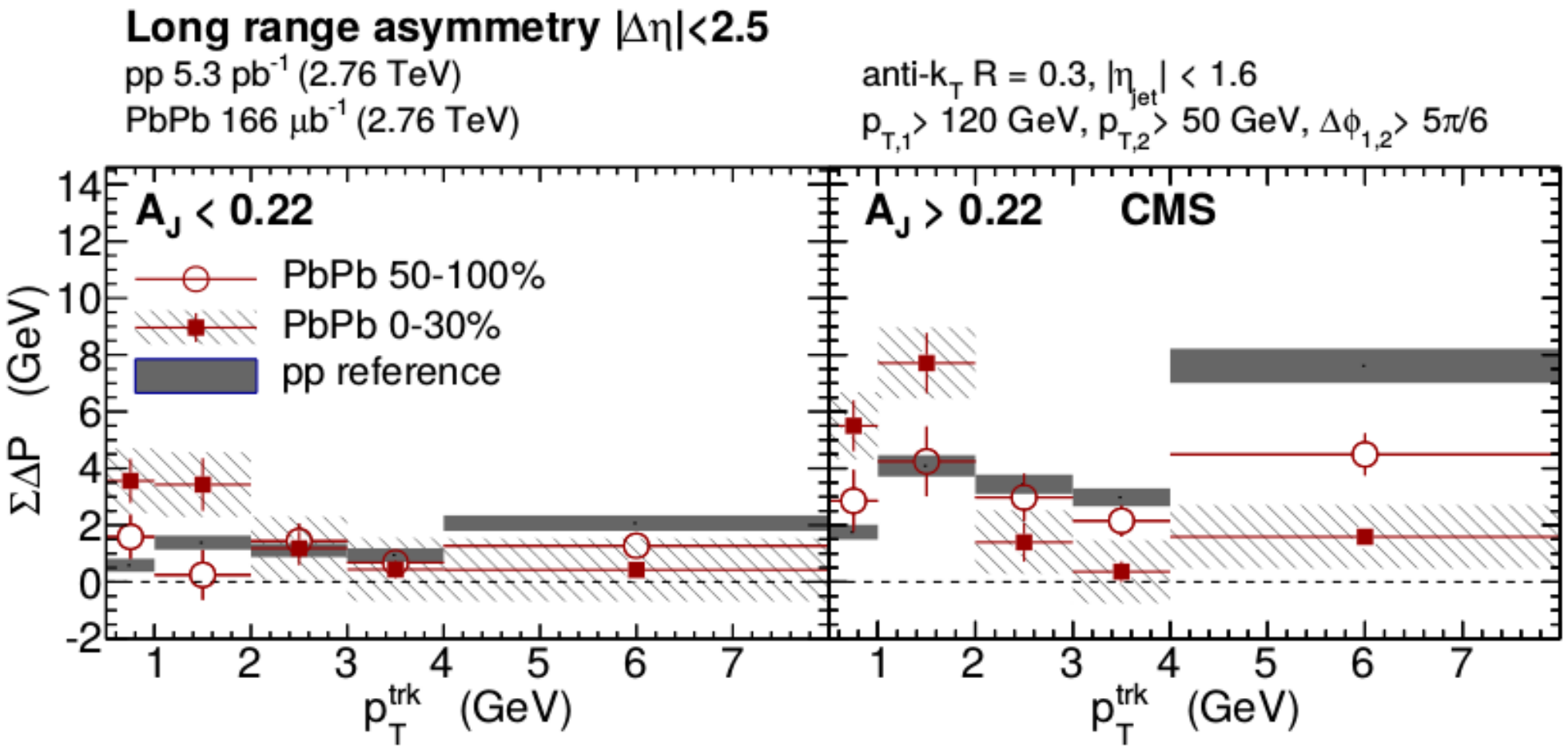




Energy loss contributions in balanced jets



Integrated momentum balance



(Sub)-leading jet-track p_T modifications in PbPb