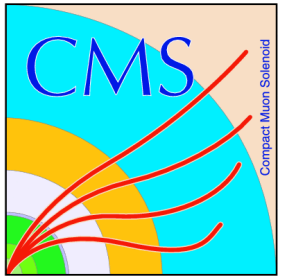
Overview of Recent Heavy-Ion Results from CMS



Byungsik Hong
(Korea University)

for the CMS Collaboration

Quark Matter Conference, Kobe, Japan
27 September - 3 October, 2015

Outline of CMS in QM2015

Physics	Topics	Talks/Posters
Global observable, collectivity and fluctuation	Transverse-energy flow in pPb	M. Murray
	Multi-particle correlation in pPb	Q. Wang
	Long-range correlation in high-multiplicity pp events	Z. Chen
	Ridges in pp, pPb and PbPb	S. Padula (Poster)
	K_S^0, Λ, and Ξ in pp, pPb and PbPb	H. Ni
	Multiplicity dependence of Ξ in pp, pPb and PbPb	Z. Tu (Poster)
	Longitudinal fluctuation in PbPb and pPb	M. Guilbaud
	PCA of two-particle correlations in PbPb and pPb	J. Milosevic
Production mechanism and initial state effect (nPDF)	Jet fragmentation in pPb	A. A. Baty
	J/ψ in pPb and PbPb	Y. Kim
	B in pPb	K. Lee (Poster)
	W and Z productions in pp, pPb and PbPb	E. Chapon

Outline of CMS in QM2015

Physics	Topics	Talks/Posters
Final state effect (Energy loss and melting)	Missing p_T analysis in PbPb	C. McGinn
	Energy balance of the quenched jets in PbPb	O. Evdokimov
	Nuclear modification of jets in PbPb and pPb	R. K. Elayavalli (Poster)
	Υ in PbPb and pPb	M. Jo
	Open heavy flavors in PbPb and pPb	J. Sun
	D in PbPb	Y.-J. Lee (Poster)
	Heavy-flavored jets in PbPb and pPb	K. E. Jung (Poster)

- Since QM2014,
  - New results on the LR correlation in pp, E_T-flow, c-jet, D, Ξ, etc.
  - Better understanding on collectivity, fluctuation and jet with more sophisticated analyses
  - Improved Υ and Z data with more statistics and refined analyses
  - More information on the cold nuclear matter effect using quarkonia and electroweak probes in pPb

New release or update in QM2015

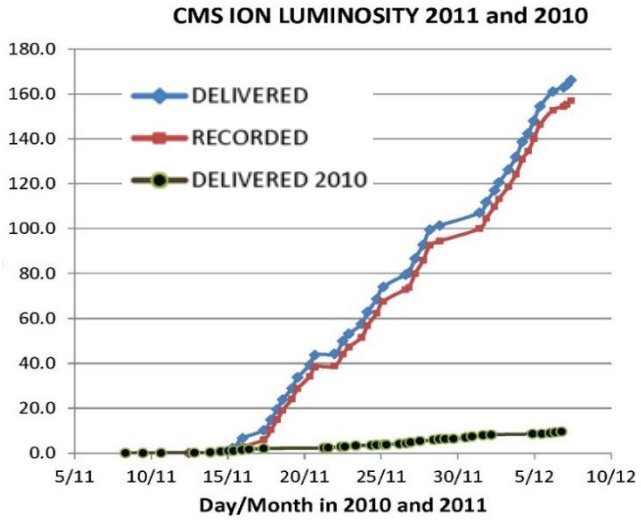
List of CMS Physics Analysis Summary

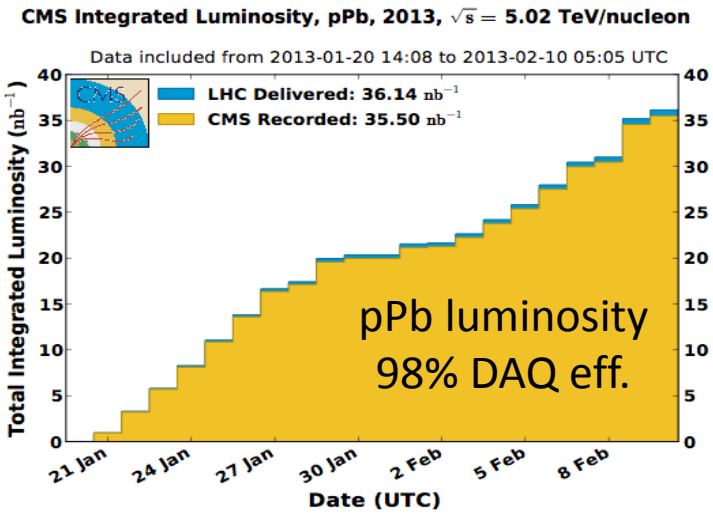
- HIN-14-004: B in pPb
- HIN-14-009: J/ψ in pPb
- HIN-14-010: Missing p_T
- HIN-14-012: Longitudinal fluctuation in PbPb and pPb
- HIN-14-014: Energy flow in pPb
- HIN-14-016: Jet-track correlations
- FSQ-15-001: $dN/d\eta$ in pp @ 13 TeV
- FSQ-15-002: Ridge in pp @ 13 TeV
- HIN-15-001: $\Upsilon(nS)$ in PbPb
- HIN-15-002: Z in pPb
- HIN-15-004: Frag. function in pPb
- HIN-15-005: D in PbPb
- HIN-15-006: Strangeness in pPb
- HIN-15-008: Differential v_n
- HIN-15-009: v_2 and v_3 in pp
- HIN-15-010: PCA for v_2 and v_3
- HIN-15-011: Jet energy balance
- HIN-15-012: c-jet in pPb

Public CMS HI results are available at
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

Heavy-ion oriented data samples

Period	System	Energy (TeV)	Rec. Lumi.	Comments
2010	p+p	7	6.2 nb^{-1}	Low pile-up
2010	Pb+Pb	2.76	7 μb^{-1}	Similar N_{coll}-scaled luminosities for pp, pPb, and PbPb: As many Z's and W's for each collision system
2011	Pb+Pb	2.76	150 μb^{-1}	
2011	p+p	2.76	230 nb^{-1}	
2013	p+Pb	5.02	35 nb^{-1}	
2013	p+p	2.76	5.4 pb^{-1}	
2015	p+p	13	270 nb^{-1}	Low pile-up

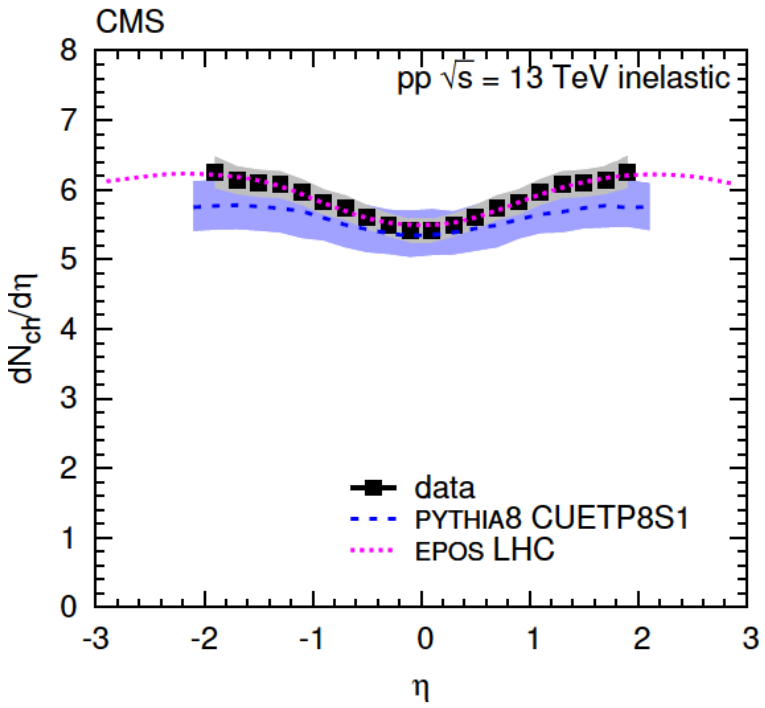


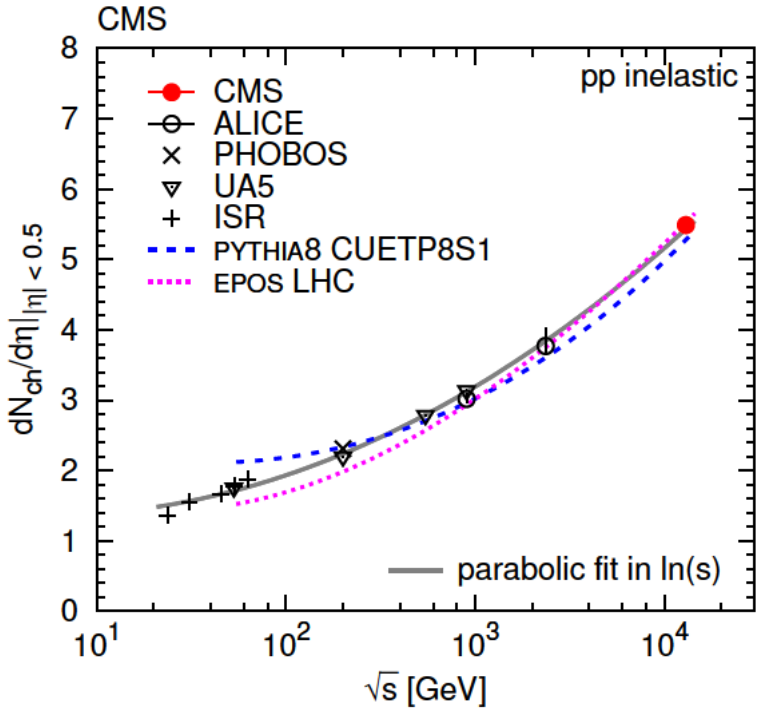


I. Global observables, collectivity in small systems and fluctuations

Charged hadron multiplicity in pp @ 13 TeV

CMS-FSQ-15-001, arXiv:1507.05915





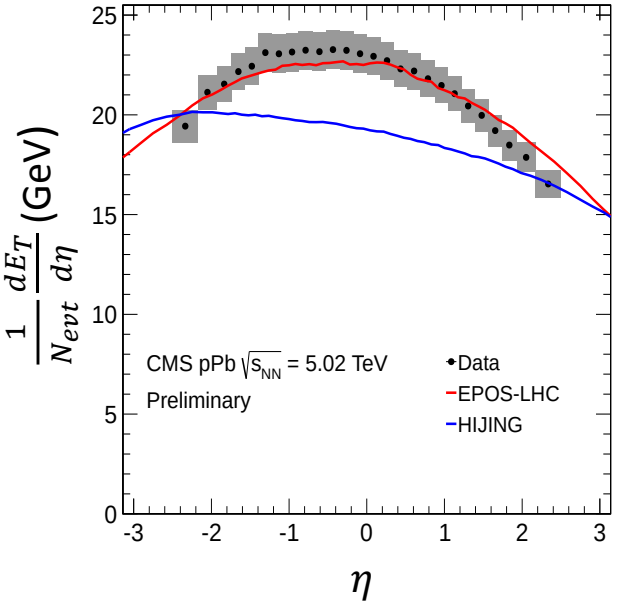
- First LHC RUN II paper on hadron production in pp collisions at 13 TeV
- $\left[\frac{dN_{ch}}{d\eta}\right]_{|\eta|<0.5} = 5.49 \pm 0.01(\text{stat}) + 0.17(\text{syst})$ for inelastic events
- Energy dependence well described by a second-order polynomial in $\ln(s)$
- New constraints for various event generators

Transverse-energy flow in pPb

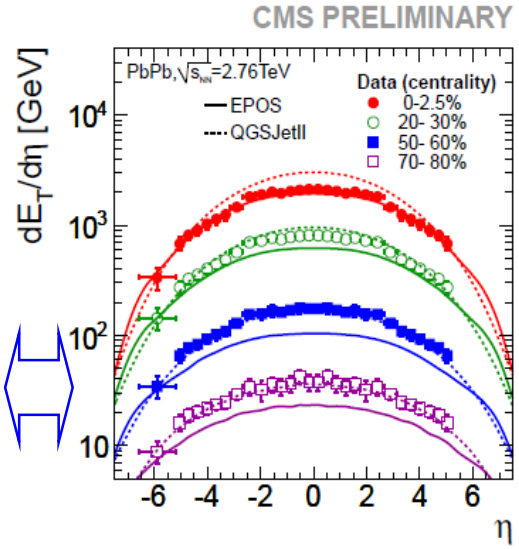
M. Murray

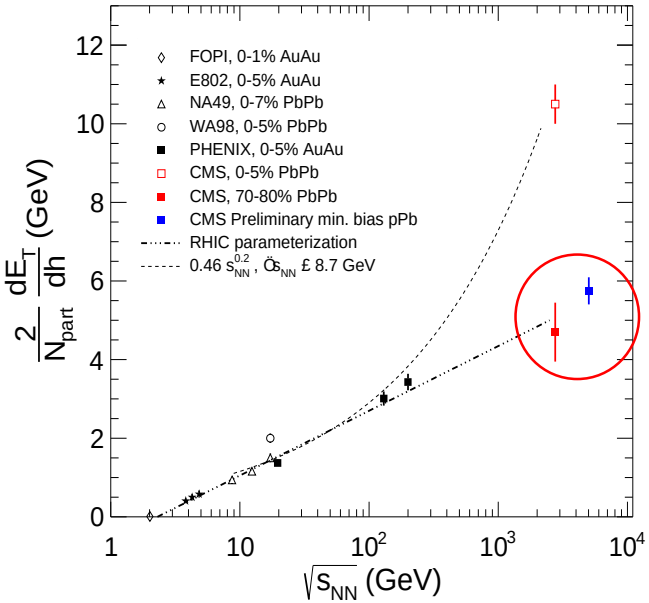
CMS-HIN-14-014

Min. bias pPb @ 5.02 TeV



CMS-HIN-12-006
PbPb @ 2.76 TeV





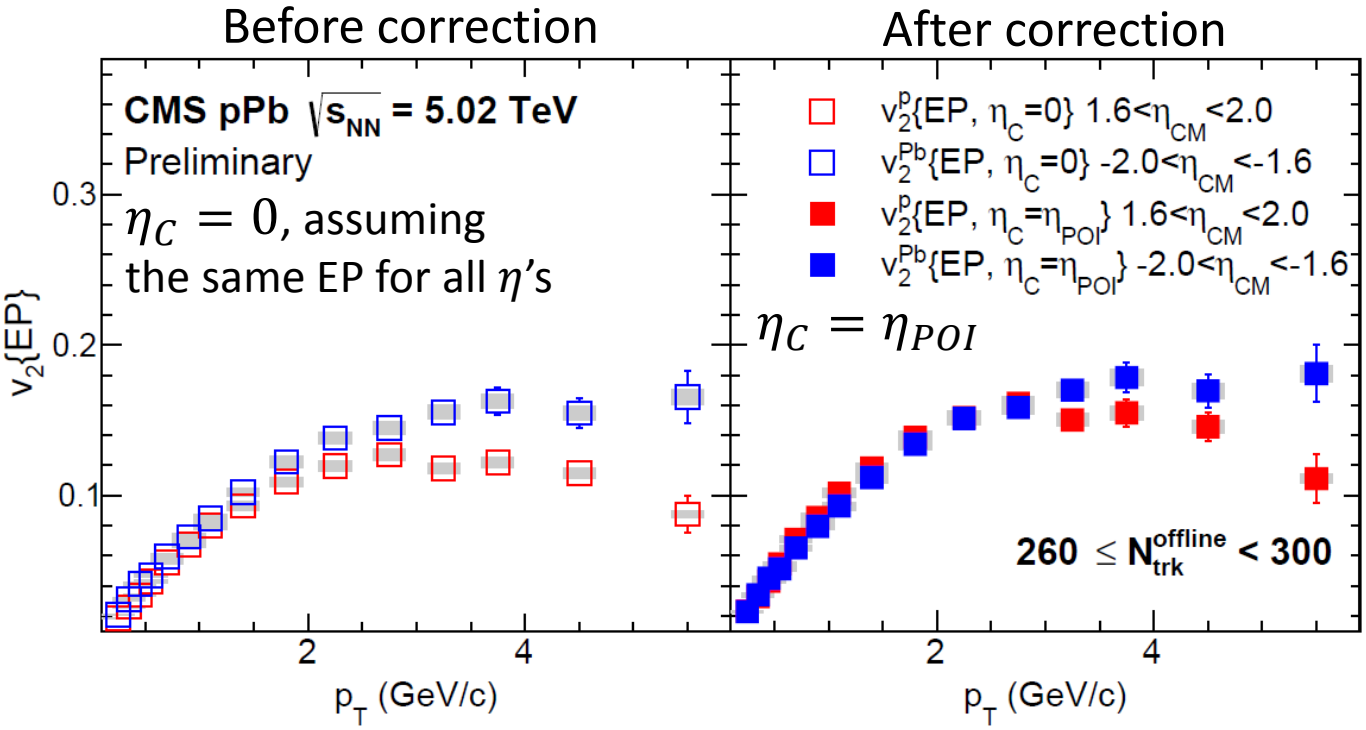
- $\frac{1}{N_{evt}}\left[\frac{dE_T}{d\eta}\right]_{\eta=0} \approx$ 23 GeV for Min. bias pPb ~1/90 of 0-2.5% PbPb
- Geometrical cross-sectional area in pPb ~1/50 of central PbPb
  - Local energy density in Min. bias pPb is about 5/9 of that in 0-2.5% PbPb.
- $\left(\frac{dE_T}{d\eta}\right) / \left(\frac{N_{part}}{2}\right) \sim$ 5.8 GeV: Min. bias pPb@5.02 TeV > 70% PbPb@2.76 TeV

Flow harmonics v_n in pPb

- η-dependence of v_2 taking into account the event plane (EP) decorrelation effect
- $v_2\{EP\}$ analysis extended from 3 to 6 GeV/c in p_T

CMS-HIN-15-008

Q. Wang



POI: Particle Of Interest

Pb-going side

p-going side

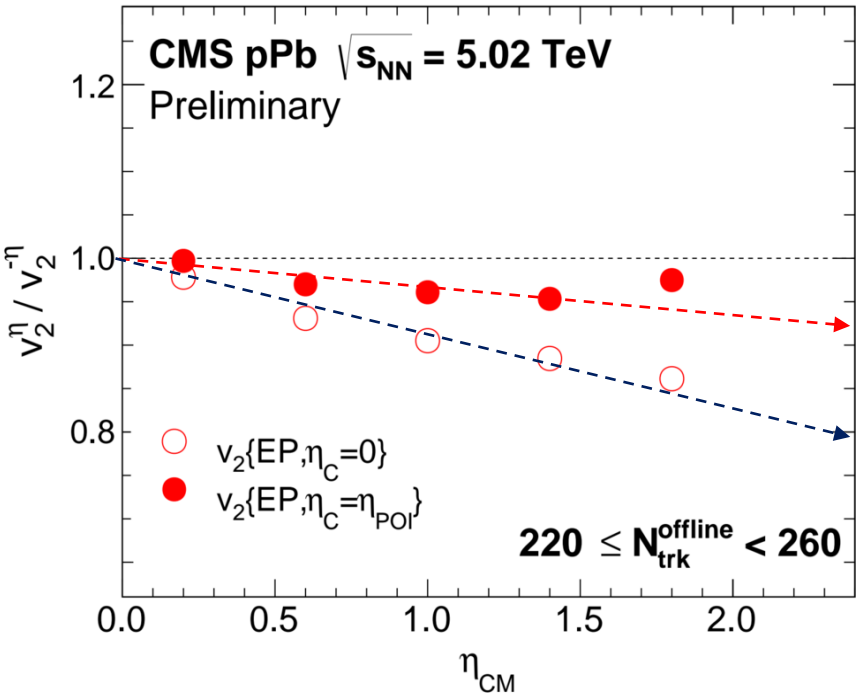
- Considering the event-plane (EP) decorrelation effect, the difference of v_2 between Pb-going side and p-going side is reduced.
- $v_2\{EP\}$ in Pb-going side $\approx v_2\{EP\}$ in p-going side for $p_T \lesssim 3$ GeV/c

Flow harmonics v_n in pPb & PbPb

$v_2(\mathrm{p}-\mathrm{going})/v_2(\mathrm{Pb}-\mathrm{going})$

Q. Wang

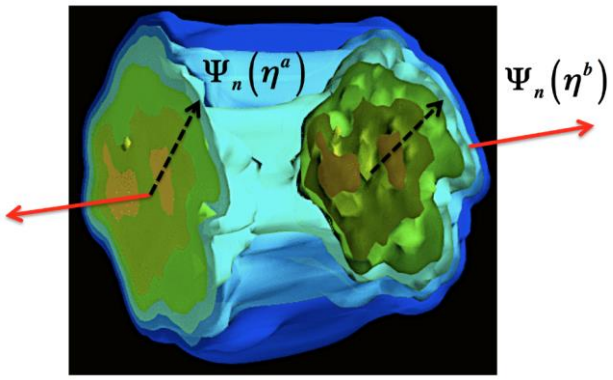
CMS-HIN-15-008

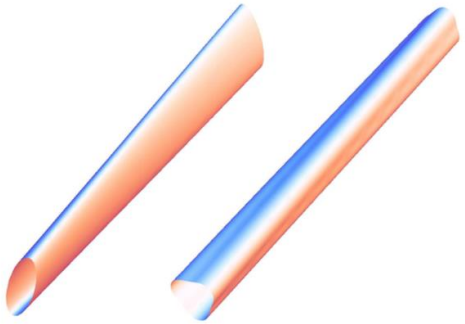


After correcting EP decorrelation

Before correcting EP decorrelation

- Correcting the EP decorrelation effect significantly reduces the η asymmetry of $v_2\{EP\}$ in pPb.





Bozek et al, PRC83, 034911 (2011)

- η-dependent EP fluctuation analysis

M. Guilbaud

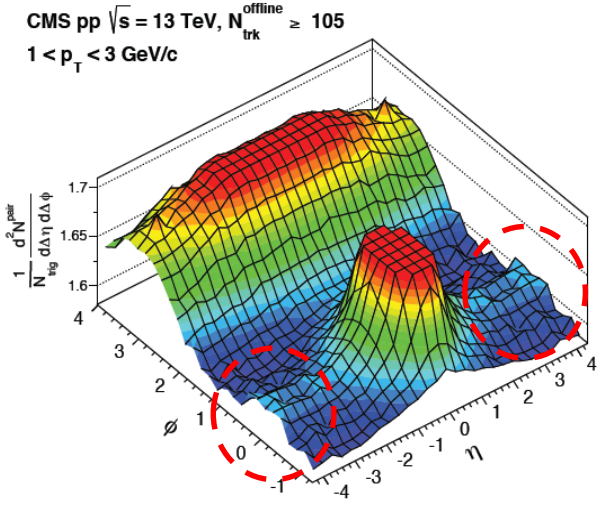
CMS-HIN-14-012

arXiv:1503.01692

2-D correlations in high-mult. pp

CMS-FSQ-15-002

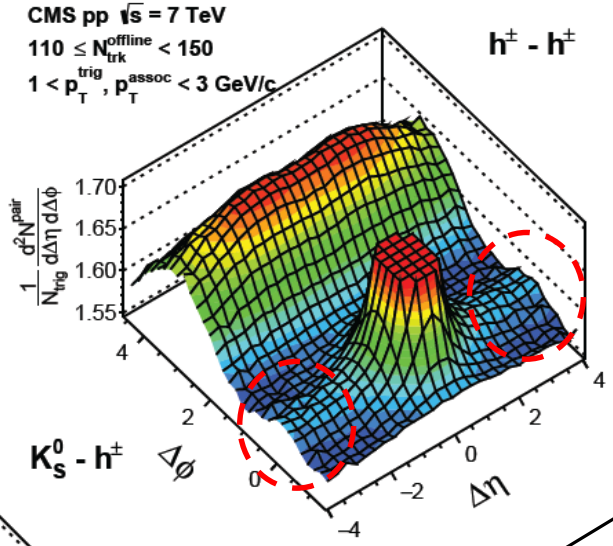
pp @ $\sqrt{s}$ = 13 TeV ($105 \leq N_{trk}^{offline}$)

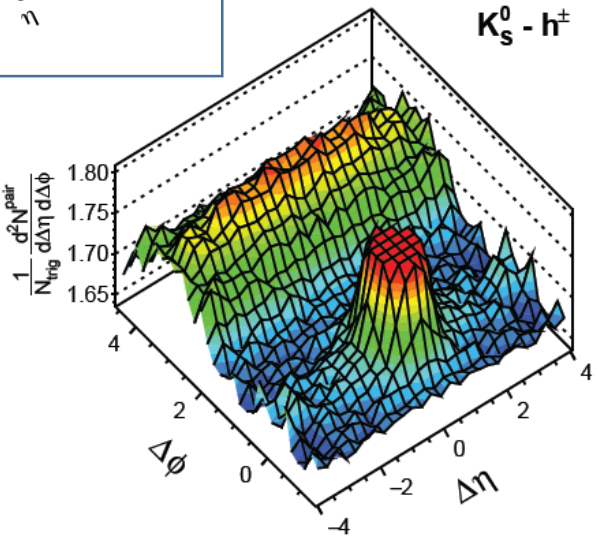


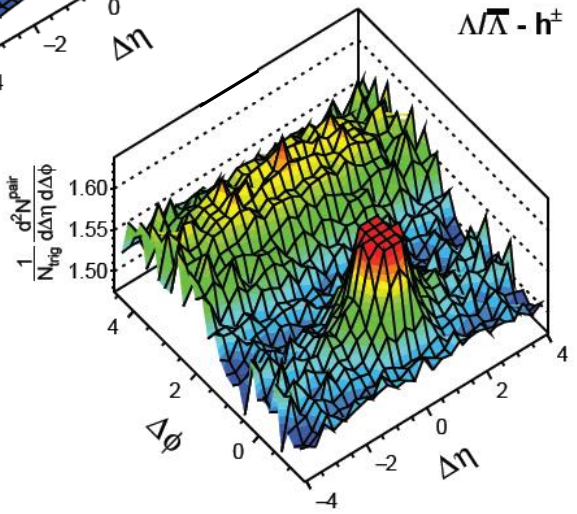
Z. Chen

CMS-HIN-15-009

pp @ $\sqrt{s}$ = 7 TeV ($110 \leq N_{trk}^{offline} < 150$)





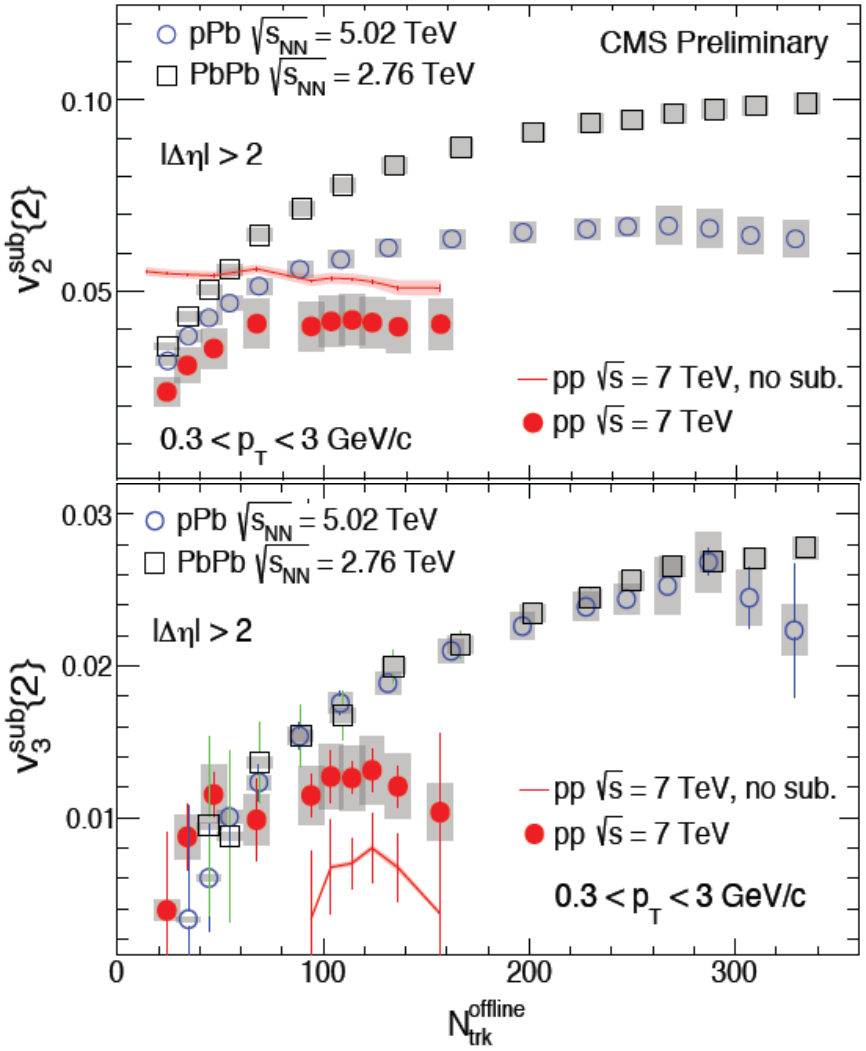


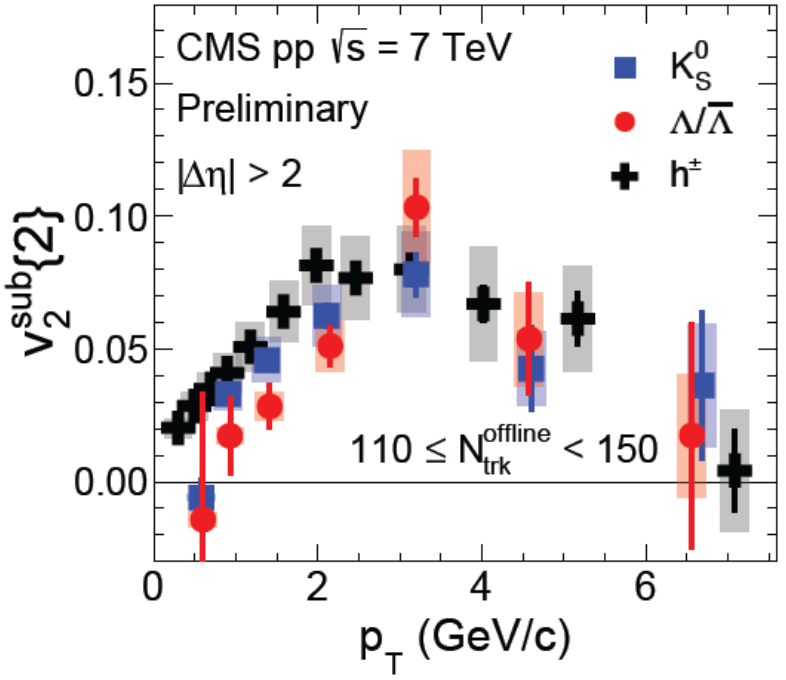
Long-range correlations in high-mult. pp

Z. Chen

CMS-HIN-15-009

Flow parameter analysis





- $v_2(\mathrm{pp}) < v_2(\mathrm{pPb}) < v_2(\mathrm{PbPb})$
- $v_3(\mathrm{pp}) \approx v_3(\mathrm{pPb}) \approx v_3(\mathrm{PbPb})$, but $v_3(\mathrm{pp})$ deviates for $N_{trk}^{offline} \gtrsim 90$
- Mass ordering for $v_2^{sub}\{2\}$ at low p_T

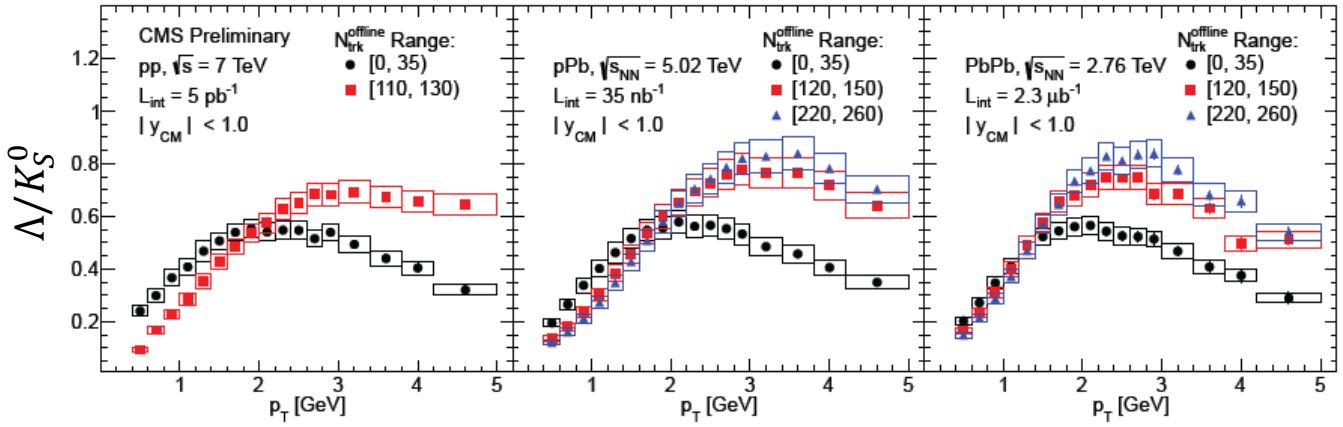
Strangeness production in pp, pPb & PbPb

Highest Mult.
High Mult.
Low Mult.

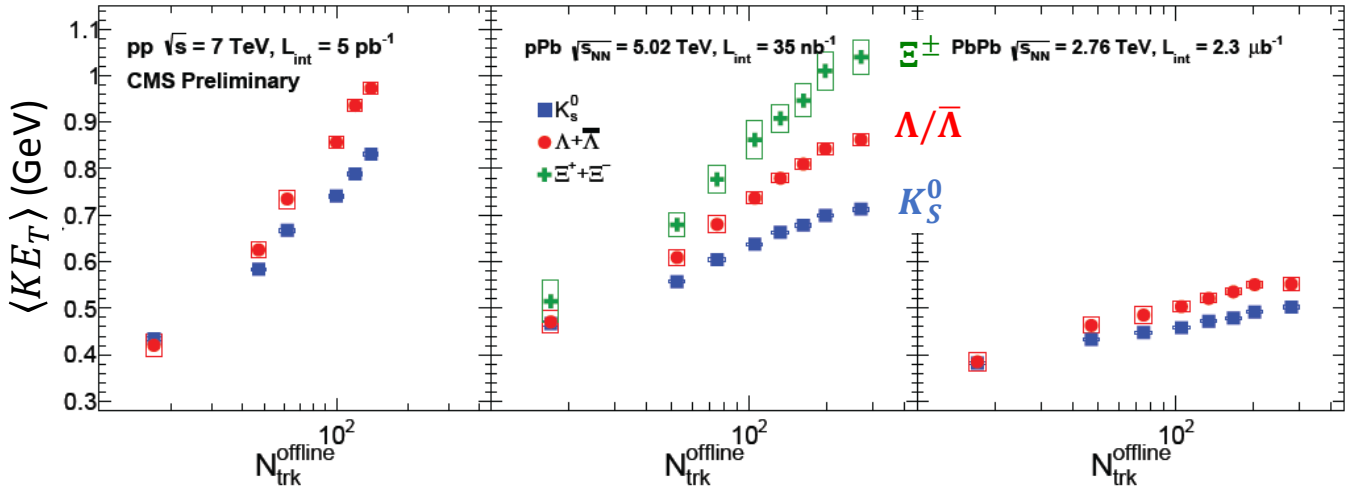
H. Ni (Oral), Z. Tu (Poster)

CMS-HIN-15-006

pp pPb PbPb



$$KE_T = \sqrt{p_T^2 + m^2} - m$$



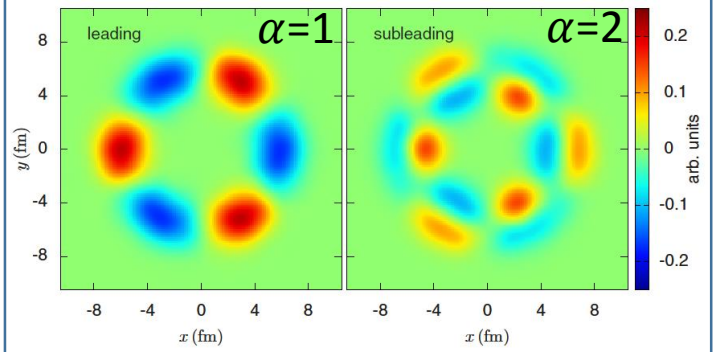
- Λ/K_S^0 ratio shows larger difference between high & low multiplicity events in smaller system at low p_T.
- Heavier particle increases faster with track multiplicity, especially, for smaller collision system: Stronger radial flow velocity.

PCA for factorization breakdown

PCA: Principal Component Analysis

J. Milosevic CMS-HIN-15-010

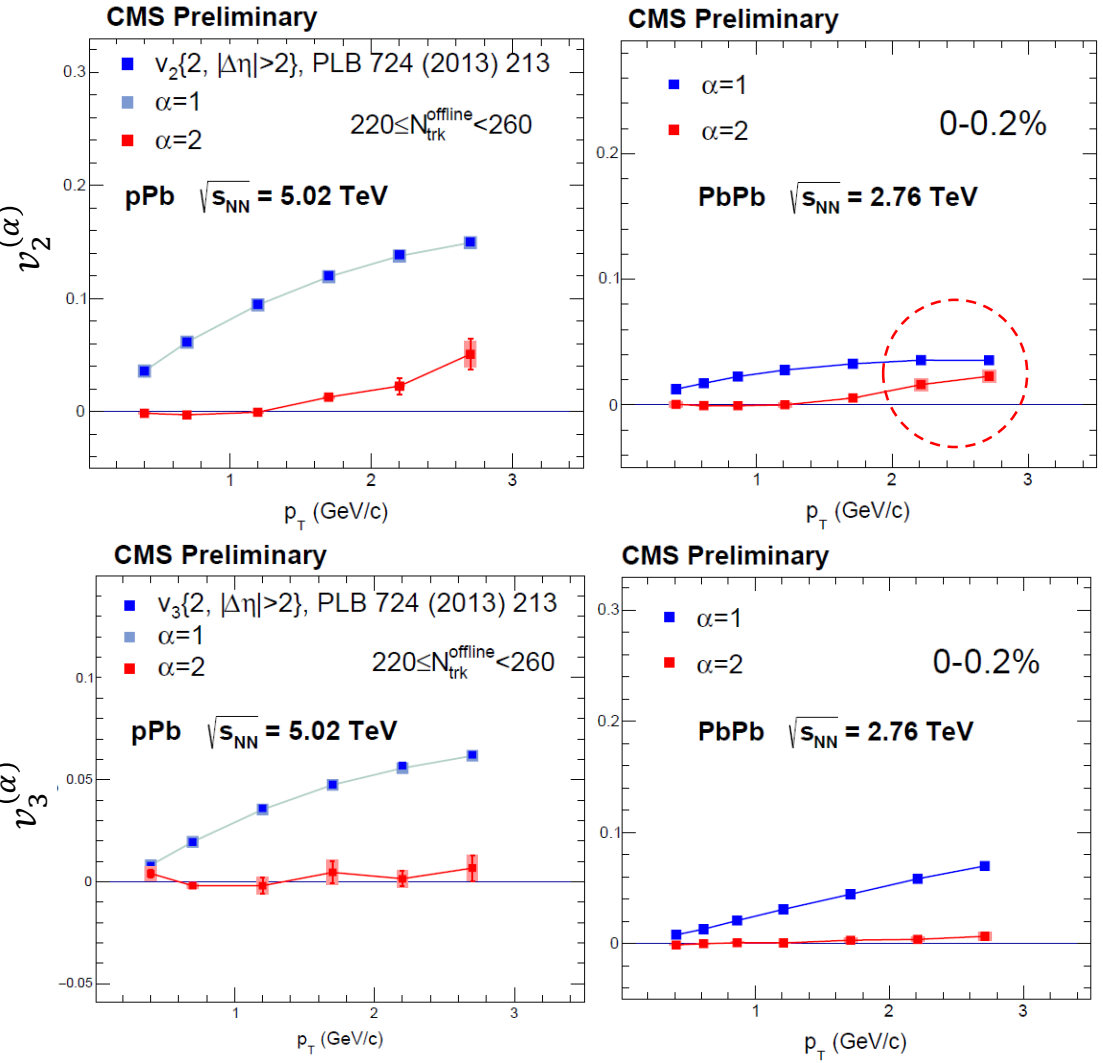
Hydro simulation for $v_3^{(\alpha)}$



Ref) A. Mazeliauskas and D. Teaney, PRC 91, 044902 (2015)

- $v_{2,3}^{(\alpha=1)} \approx v_{2,3}^{Standard}$
- $v_2^{(\alpha=2)}$ rises for $p_T \gtrsim 2$ GeV/c.
  $\Rightarrow v_2^{(\alpha=2)}$ significant relative to $v_2^{(\alpha=1)}$ only for UCC in PbPb
- $v_3^{(\alpha=2)}$ fluctuation around zero

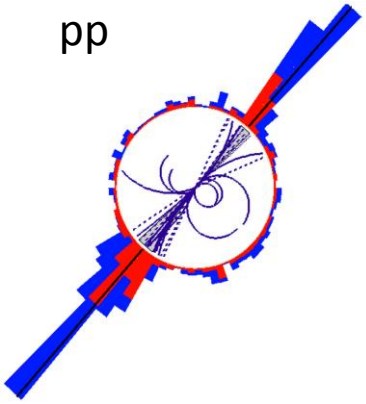
$v_2^{Standard}$: CMS, PLB 724, 213 (2013) for pPb
ALICE, PLB 708, 249 (2012) for PbPb



II. Modification of jets

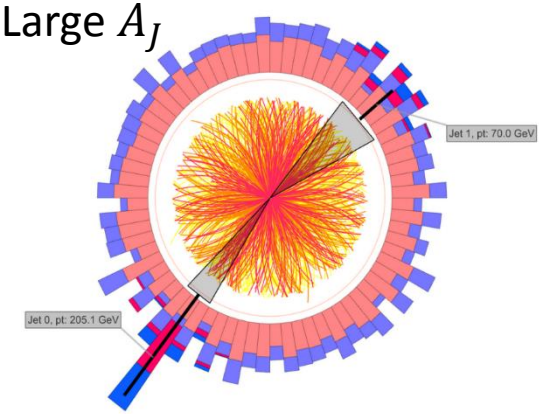
Momentum flow in dijet events in PbPb

pp



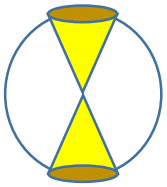
PRC 84, 024906 (2011)
PLB 712, 176 (2012)

Large A_J

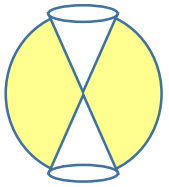


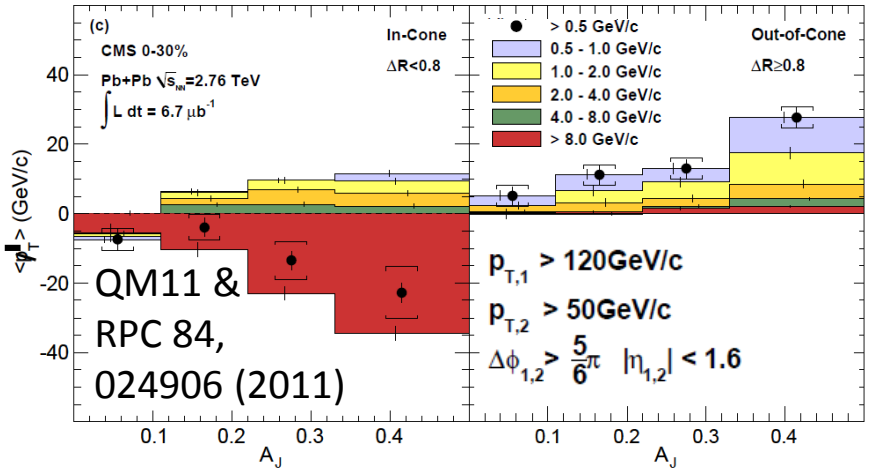
Larger fraction of asymmetric dijet events in central PbPb

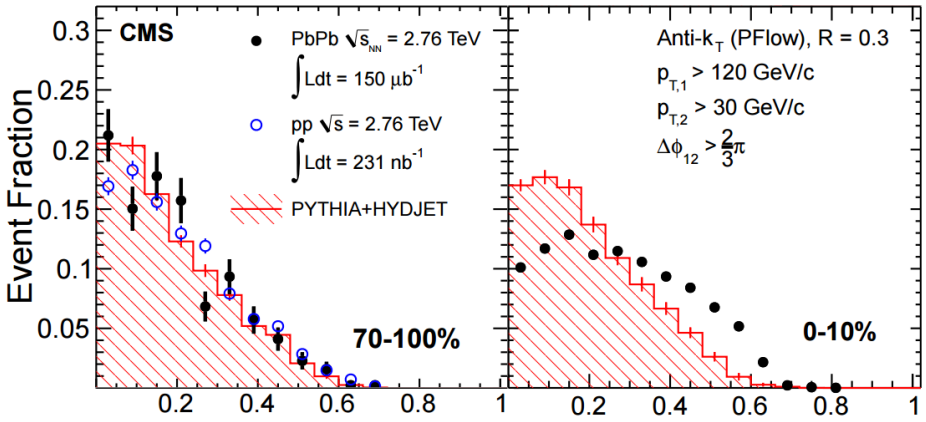
In-cone



Out-of-cone





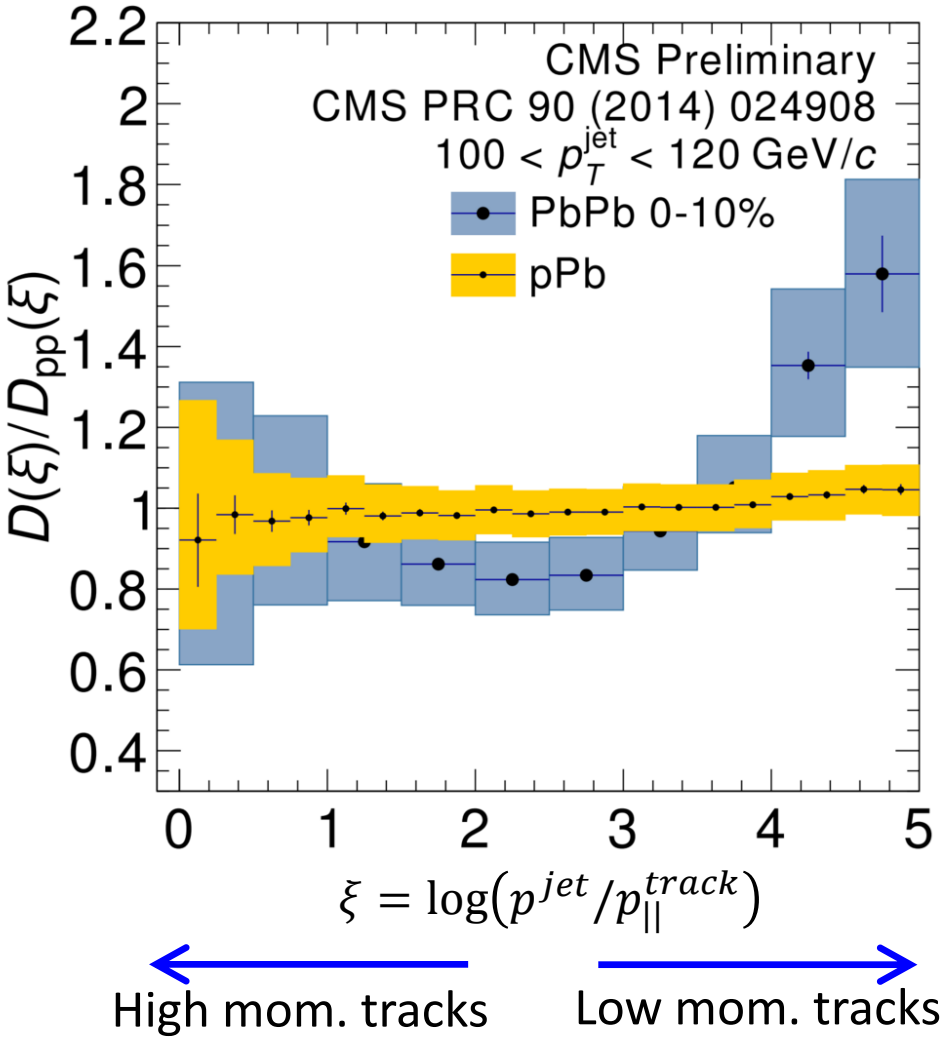


$$A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$$

- Many theoretical ideas such as
  - Jet collimation, decoherence, hydro, turbulence cascade, third jet, etc.
- Further development of jet analysis
  - Detailed angular distribution of the quenched energy flow and jet shape

Jet fragmentation function in pPb

A. Baty CMS-HIN-15-004



- No modification of jet fragmentation function in pPb with respect to the interpolated pp reference
- Without modification in R_{pPb} and D_{pPb}, the observed PbPb modification can be attributed to the final-state hot nuclear matter effect.

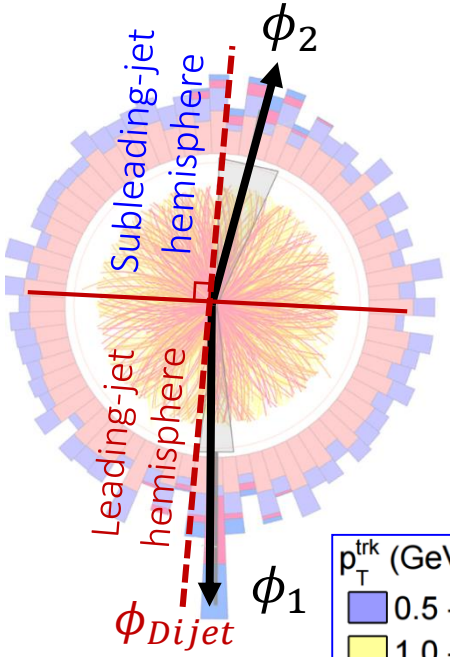
Momentum flow in dijet events in PbPb

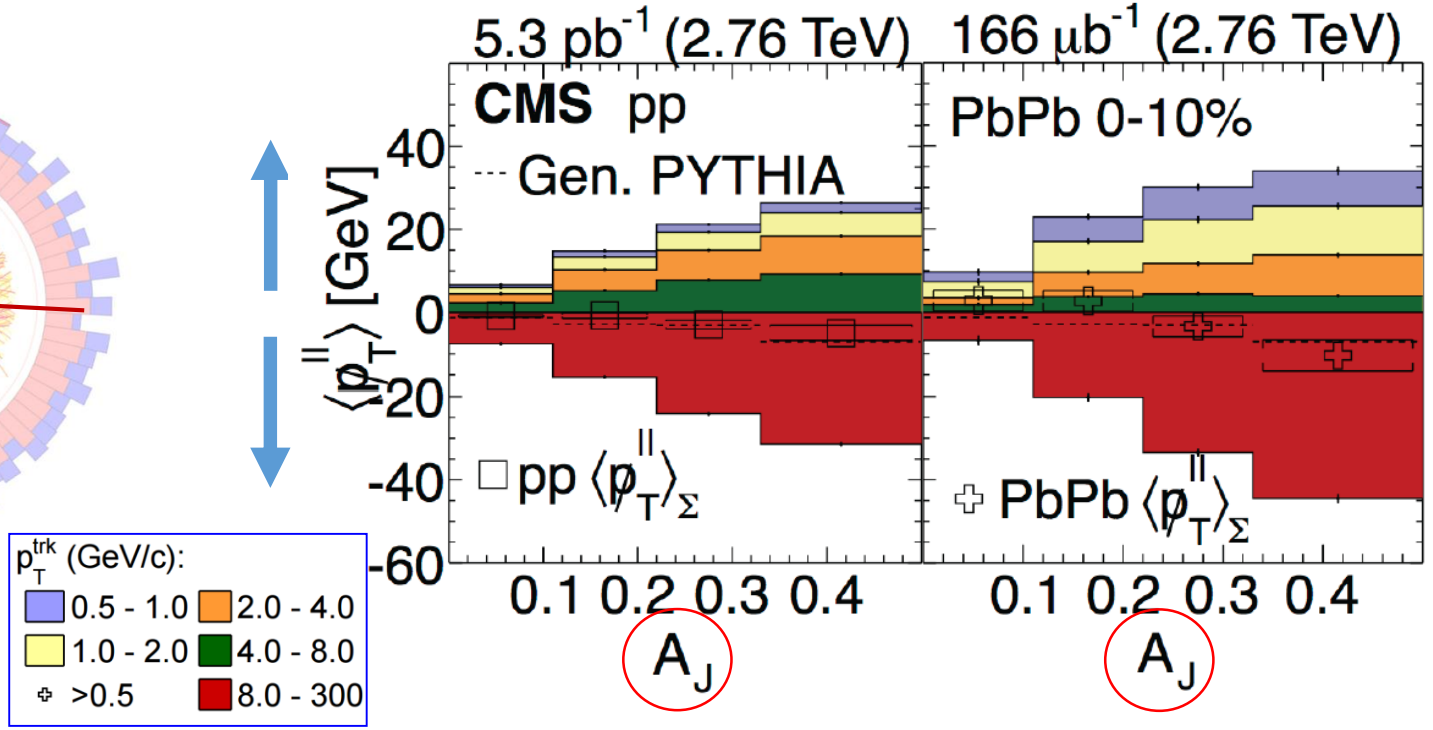
- Projection of p_T for reconstructed charged tracks onto ϕ_{Dijet}:

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\mathrm{Dijet}}\right)$$

CMS-HIN-14-010

C. McGinn

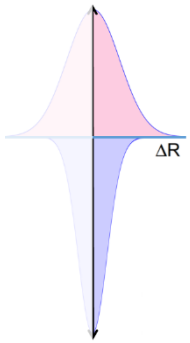




- $\left\langle \not{p}_T^{\parallel} \right\rangle$ from high-p_T particles increases with A_J in the leading-jet direction.
  - pp: balanced by 2-8 GeV/c particles in the sub-leading-jet direction
  - Central PbPb: balanced by softer particles with p_T < 2 GeV/c

Momentum flow in dijet events in PbPb

Subleading-jet direction



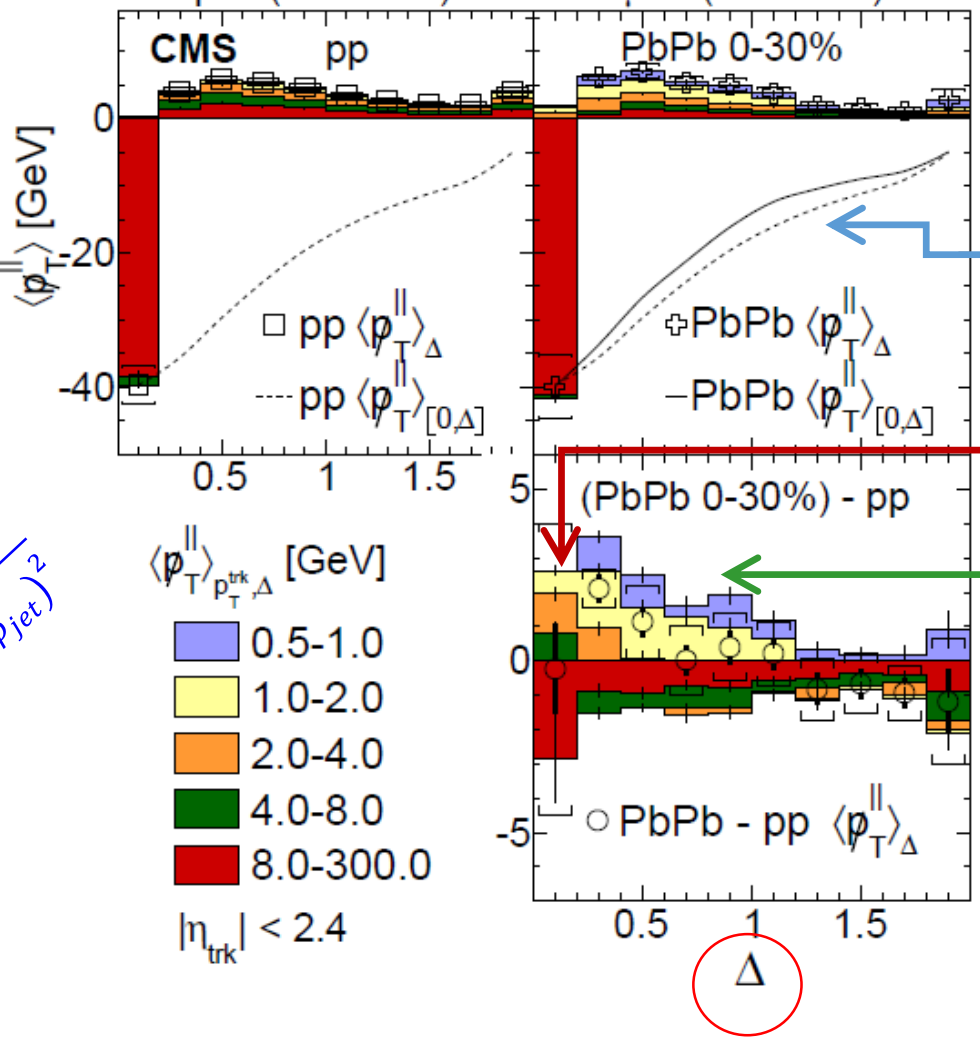
Leading-jet direction

$A_J > 0.22$ anti-k_t R = 0.3

5.3 pb^{-1} (2.76 TeV) 166 μb^{-1} (2.76 TeV)

CMS-HIN-14-010

C. McGinn



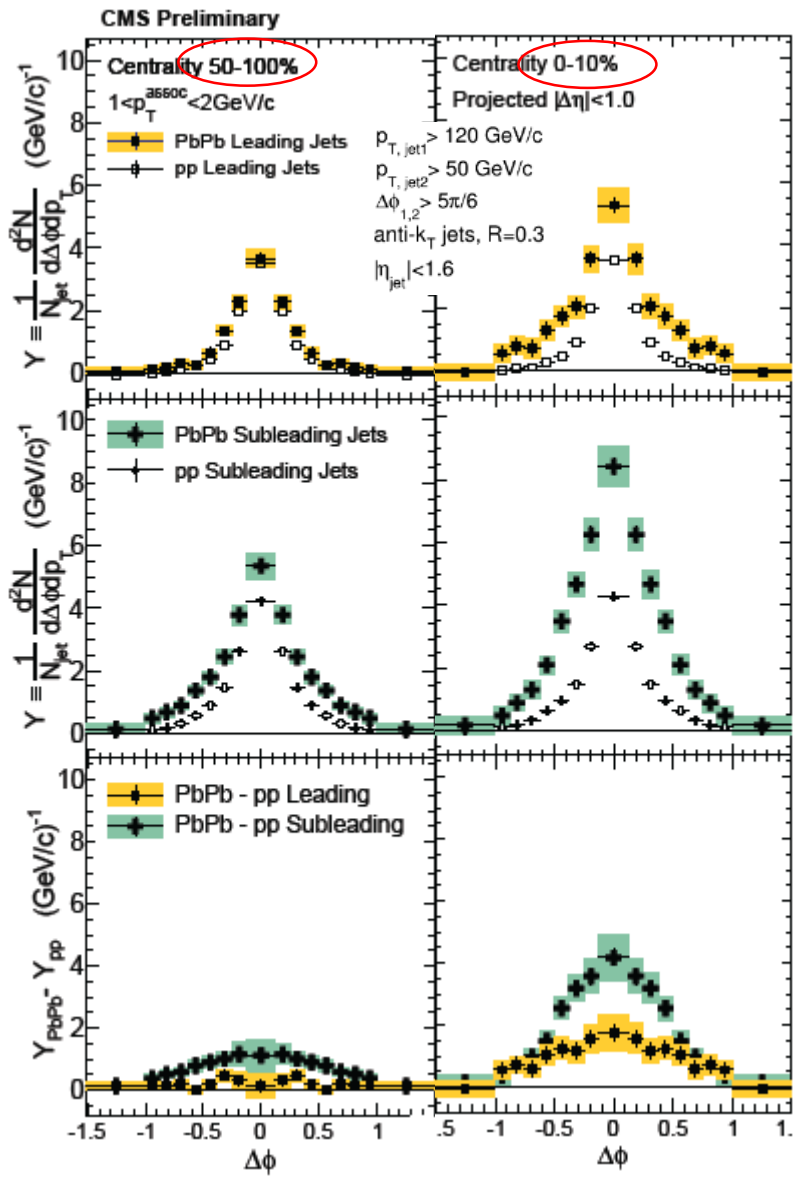
Similar cumulative energy flows

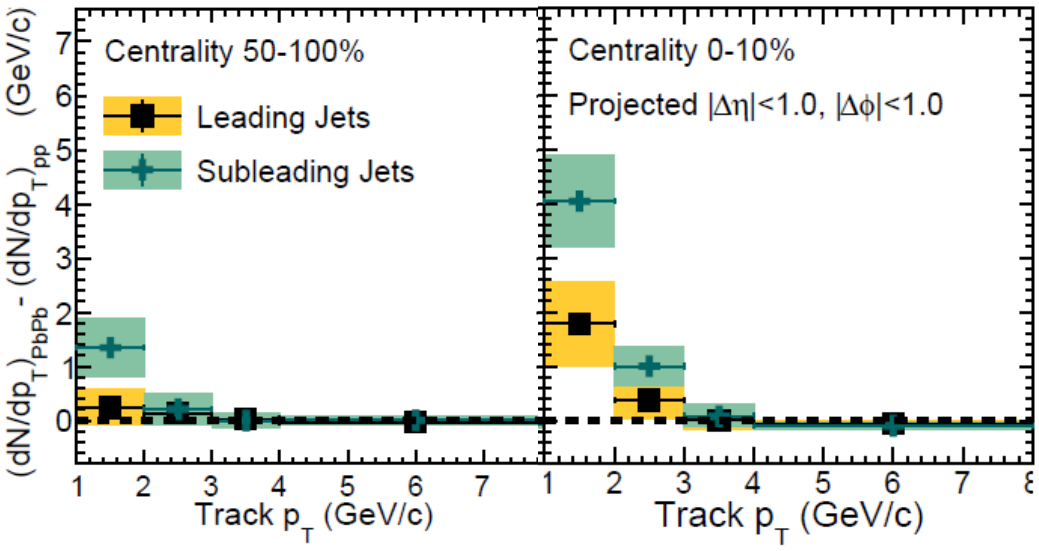
High-p_T imbalance at small ΔR

Balanced by low-p_T particles in the subleading-jet direction extended to large Δ

Relative angle: $\Delta = \sqrt{(\eta_{trk} - \eta_{jet})^2 + (\phi_{trk} - \phi_{jet})^2}$

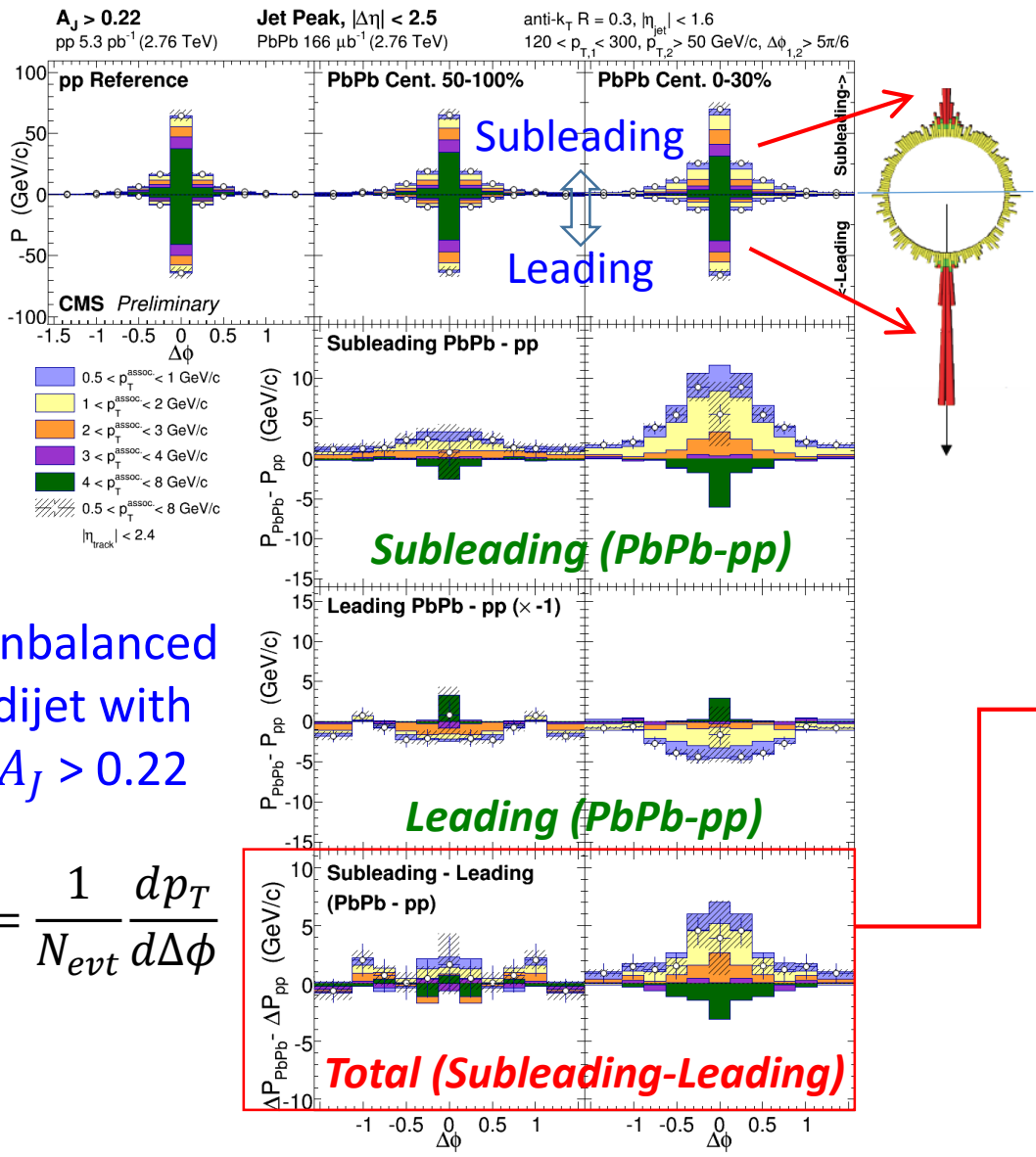
Jet-track # correlation function in PbPb





- Yield differences between PbPb and pp increase from peripheral to central collisions.
- The excess yield extends significantly to large $\Delta\phi$ (and also $\Delta\eta$).
- The excess yield exists for both peaks, but is more pronounced on the subleading-jet side at low p_T, and diminishes at high p_T.

Decomposing energy balance contribution



Unbalanced dijet with $A_J > 0.22$

$$P = \frac{1}{N_{evt}} \frac{dp_T}{d\Delta\phi}$$

O. Evdokimov CMS-HIN-15-011

Analysis for separate contributions by jet peaks and LR components

- Dijet p_T analysis
  - Low-p_T enhancement and high-p_T depletion for both sides
  - Larger effects for subleading jet in central events
  - Double difference recovers only part of total hemisphere momentum difference
- The rest of momentum difference comes from long-range asymmetry component.

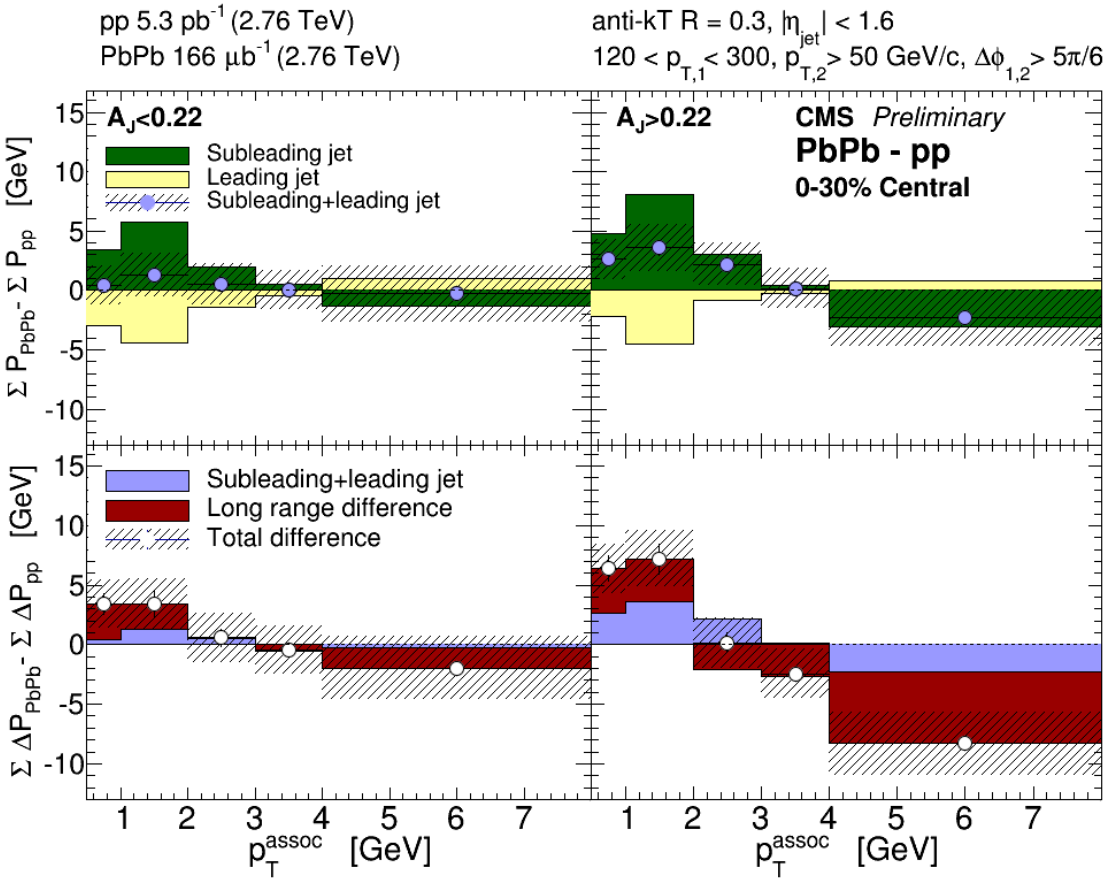
Decomposing energy balance contribution

O. Evdokimov

CMS-HIN-15-011

Jet-peak p_T difference (Central PbPb - pp)
Subleading and leading jet modifications

Total p_T difference (Central PbPb - pp)
Total jet and LR asymmetry contributions



- Jet peak modifications in $p_T < 3$ GeV/c for both leading and subleading jets
- Long-range asymmetry more enhanced at low p_T and more suppressed at high p_T in PbPb relative to pp

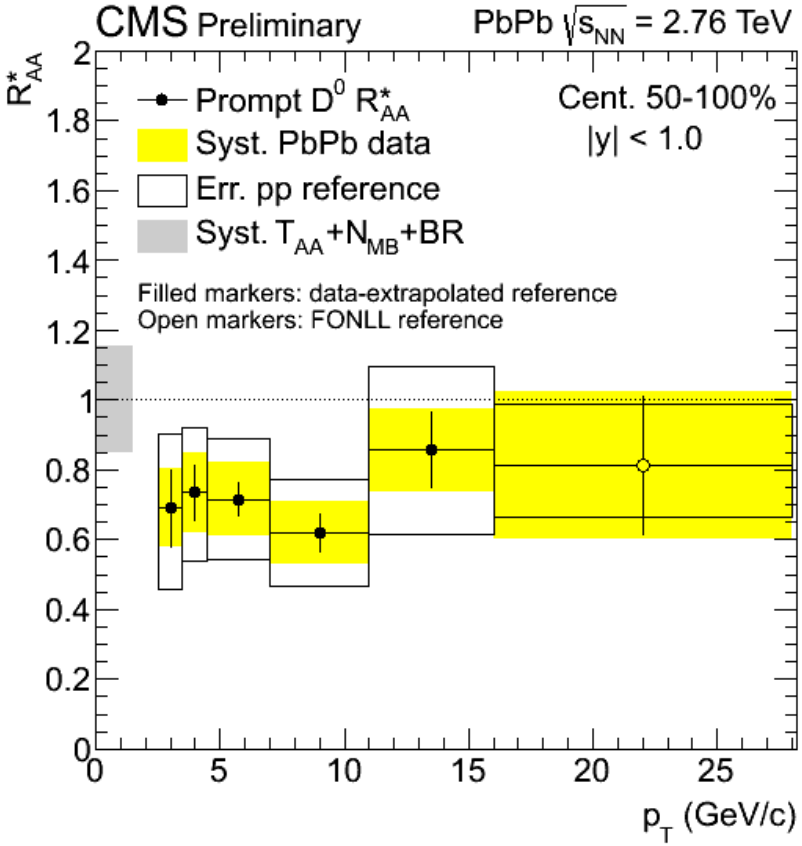
III. Open heavy flavors

Prompt D^0 production in PbPb

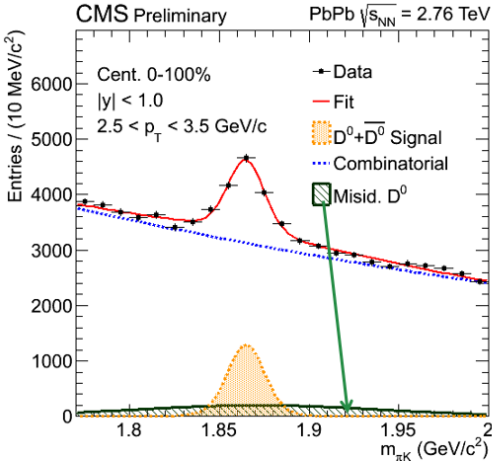
B feed-down subtracted

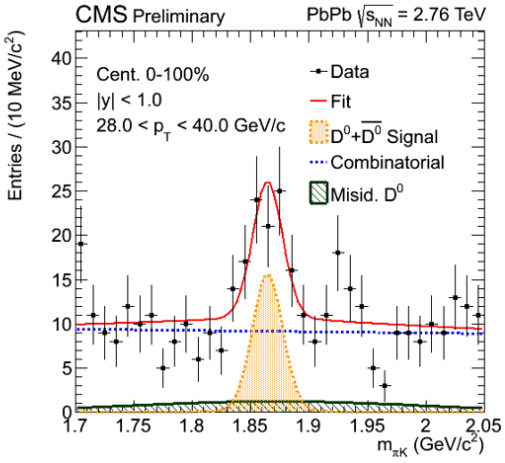
J. Sun, Y.-J. Lee (Poster)

CMS-HIN-15-005



- Clear D^0 signals in $2.5 < p_T < 40$ GeV/c



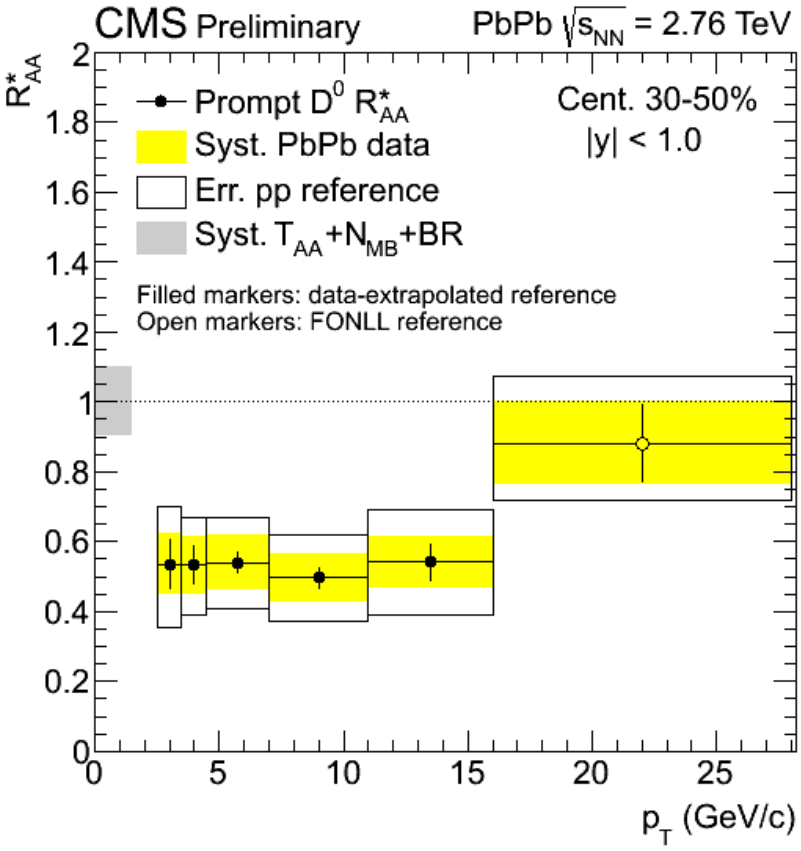


Prompt D^0 production in PbPb

B feed-down subtracted

J. Sun

CMS-HIN-15-005

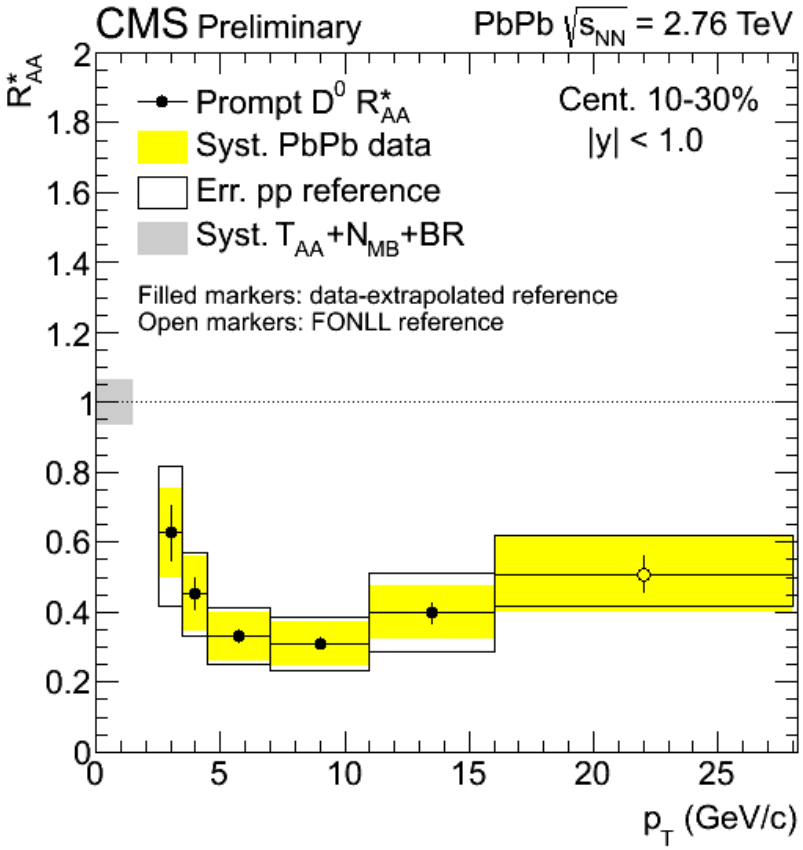


Prompt D^0 production in PbPb

B feed-down subtracted

J. Sun

CMS-HIN-15-005

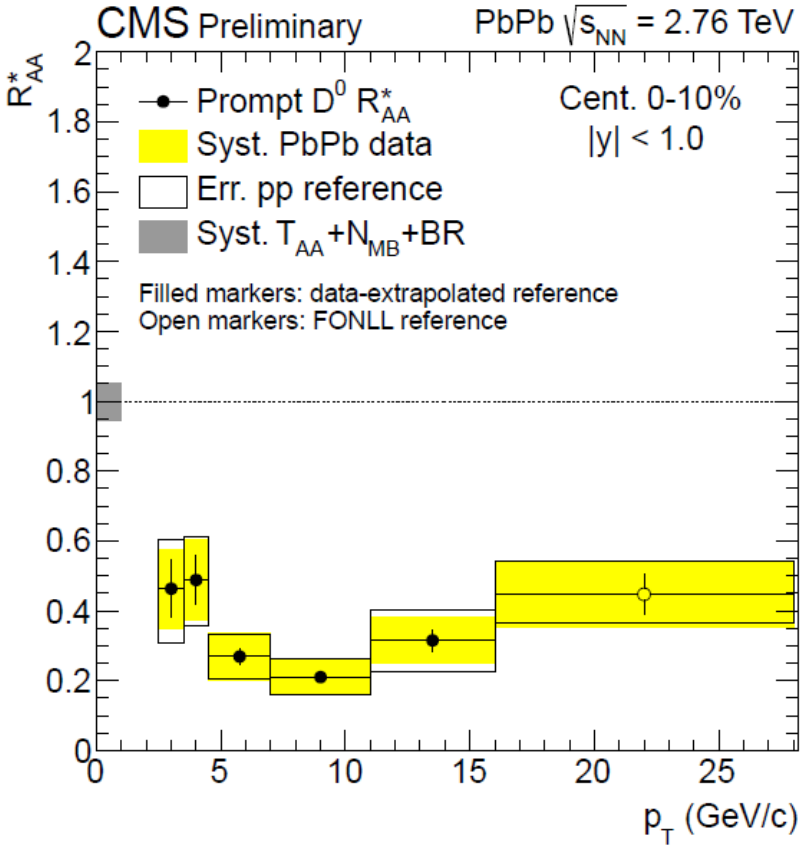


Prompt D^0 production in PbPb

B feed-down subtracted

J. Sun

CMS-HIN-15-005

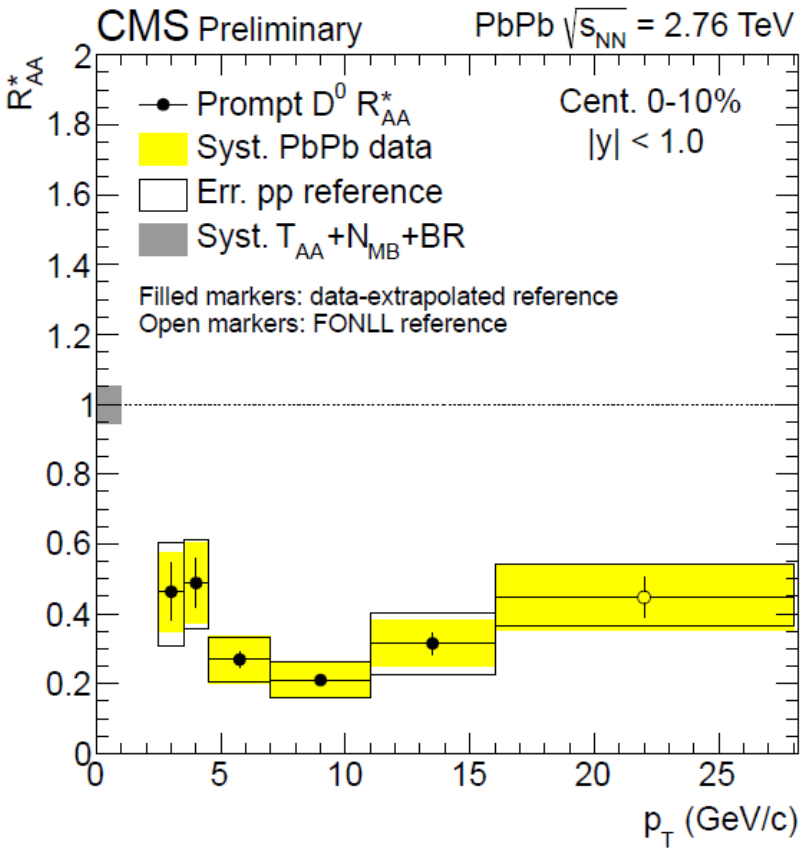


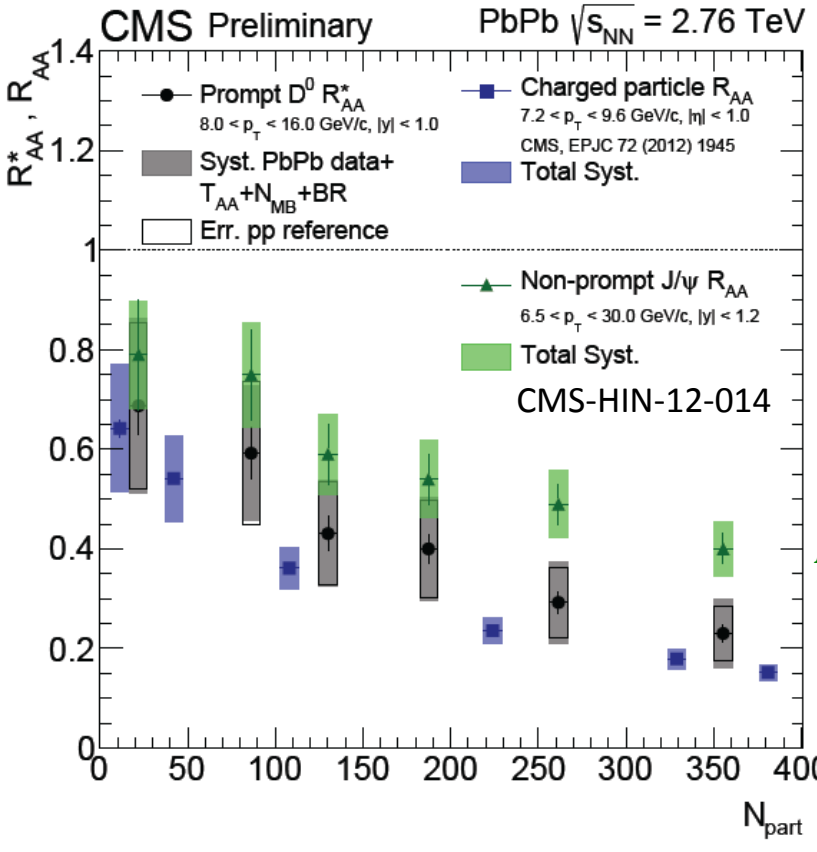
- Prompt D^0 in PbPb suppressed relative to FONLL based extrapolation
- Tendency to smaller suppression for increasing p_T in $p_T \gtrsim 11$ GeV/c

Prompt D^0 production in PbPb

B feed-down subtracted

J. Sun CMS-HIN-15-005





$B \to J/\psi$

D^0

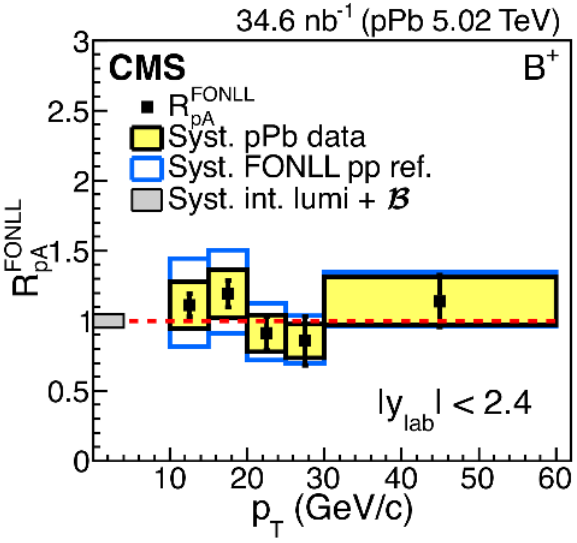
Charged hadrons

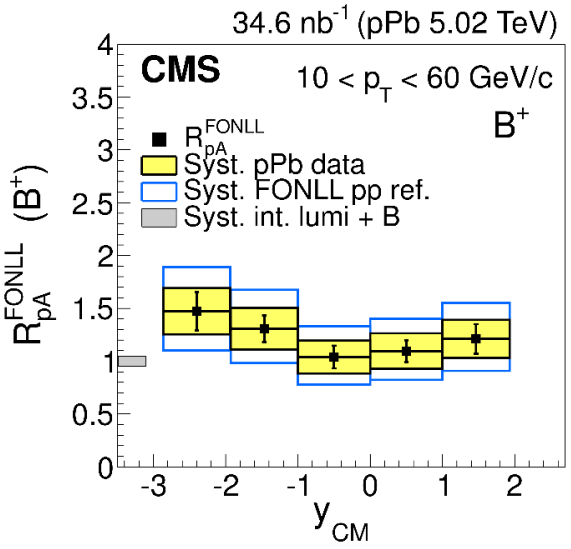
- Prompt D^0 in PbPb suppressed relative to FONLL based extrapolation
- Tendency to smaller suppression for increasing p_T in $p_T \gtrsim 11$ GeV/c
- Prompt D^0 suppressed more than non-prompt J/ψ from B

B production in pPb

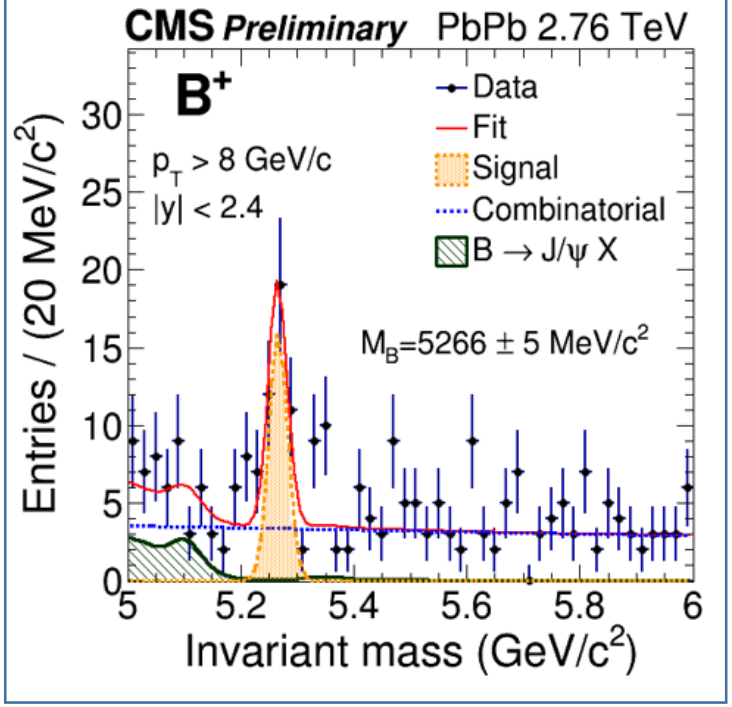
K. Lee (Poster)

CMS-HIN-14-004, arXiv:1508.06678





CMS detector performance plot
(2011 PbPb data at 2.76 TeV)

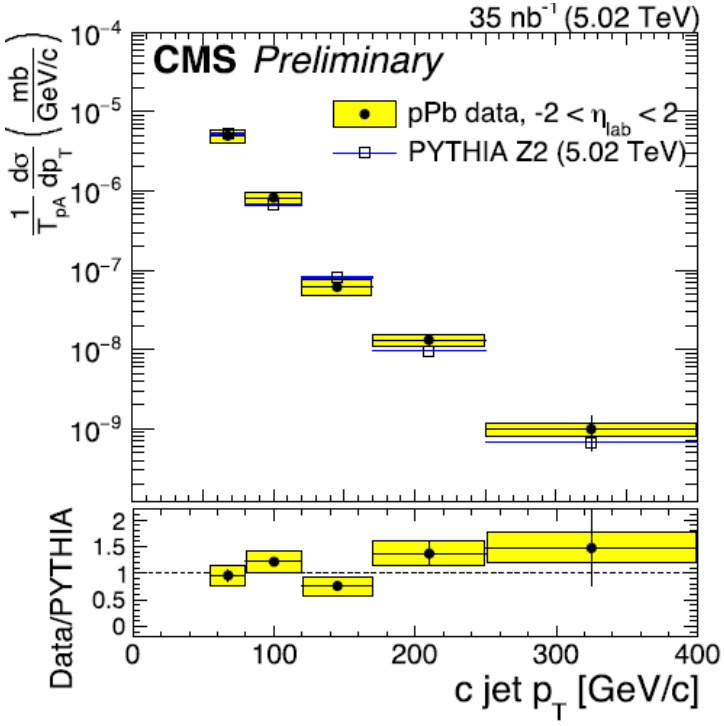


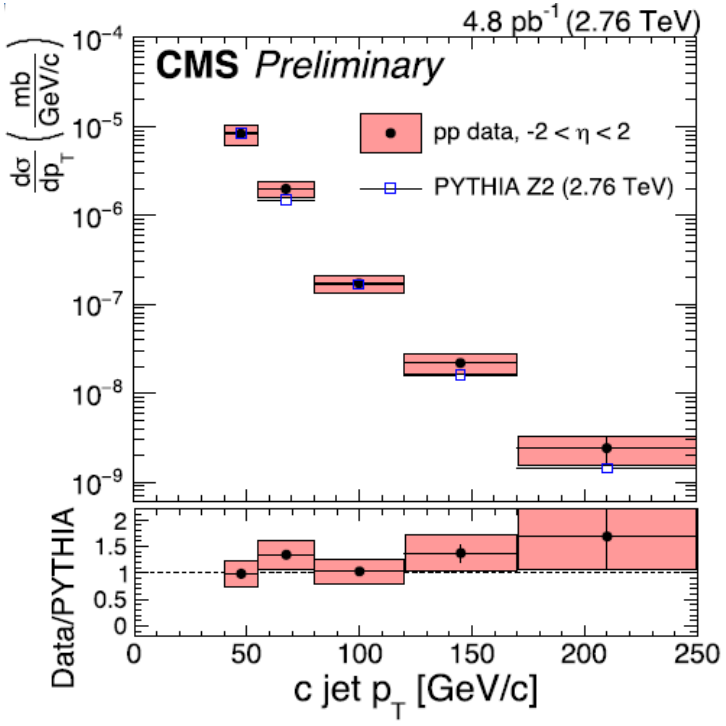
- B analysis in pPb
  - No modification for $B^{\pm}$, B^0, B_S^0 within uncertainties
  - Baseline for PbPb
- CMS capability to reconstruct B in PbPb
  - First fully reconstructed B in PbPb environment
  - Expect ~20 times more statistics in RUN II due to higher luminosity and energy increase

c-jet in pp and pPb

K. E. Jung (Poster)

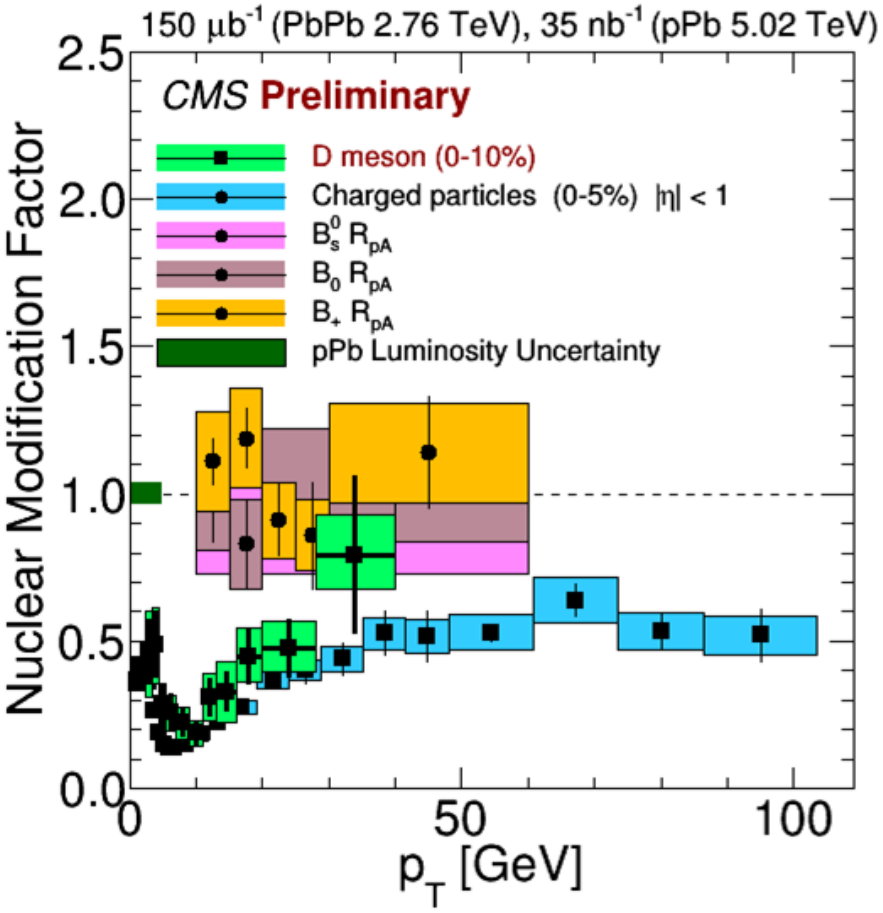
CMS-HIN-15-012

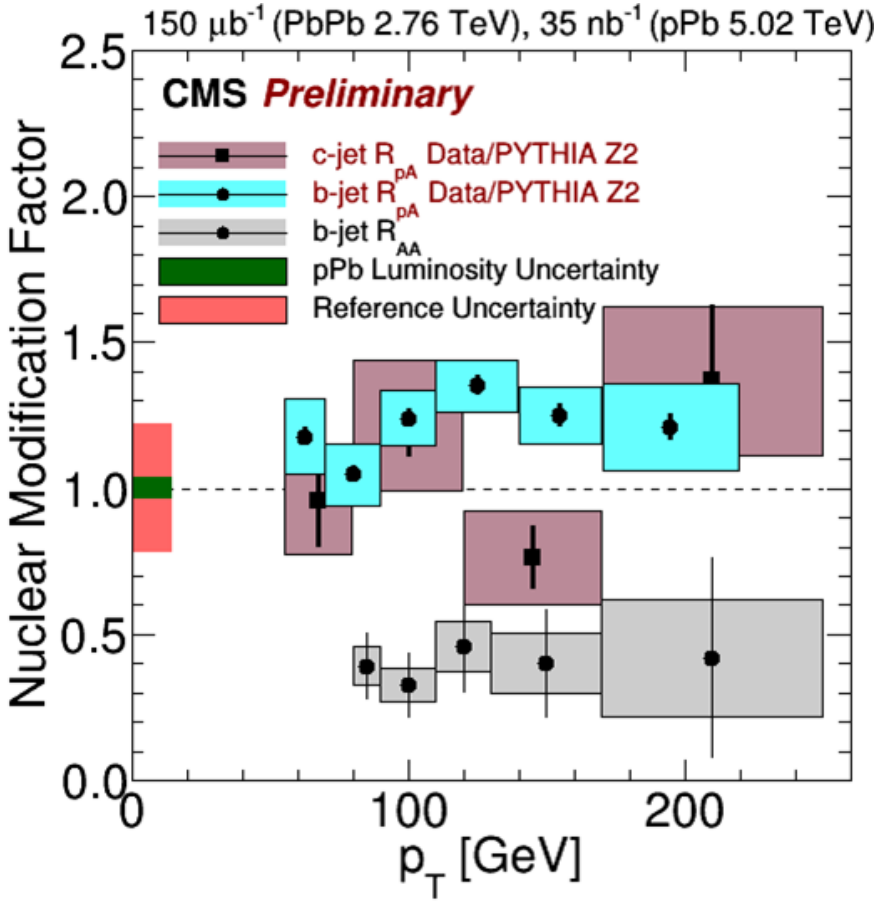




- First measurement of c-tagged jets in heavy-ion environment
- c-jet p_T spectra are consistent with PYTHIA in pp and pPb
  - (pPb) 1.00 ± 0.19, (pp) 1.15 ± 0.27
  - No significant modification in pPb relative to PYTHIA

Summary of heavy-flavor production





B in pPb: arXiv 1508.06678

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

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

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

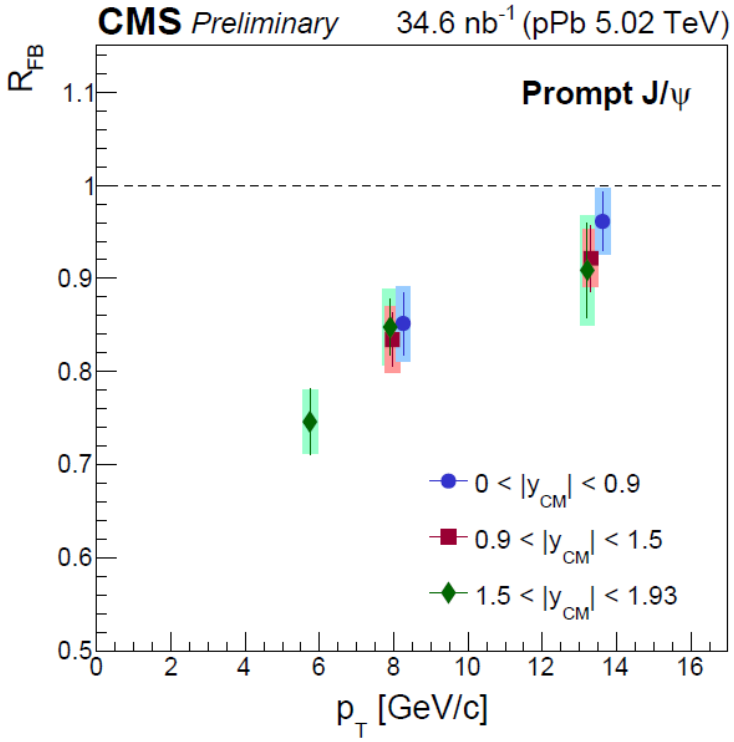
b-jet in PbPb: PRL 113, 132301 (2014)

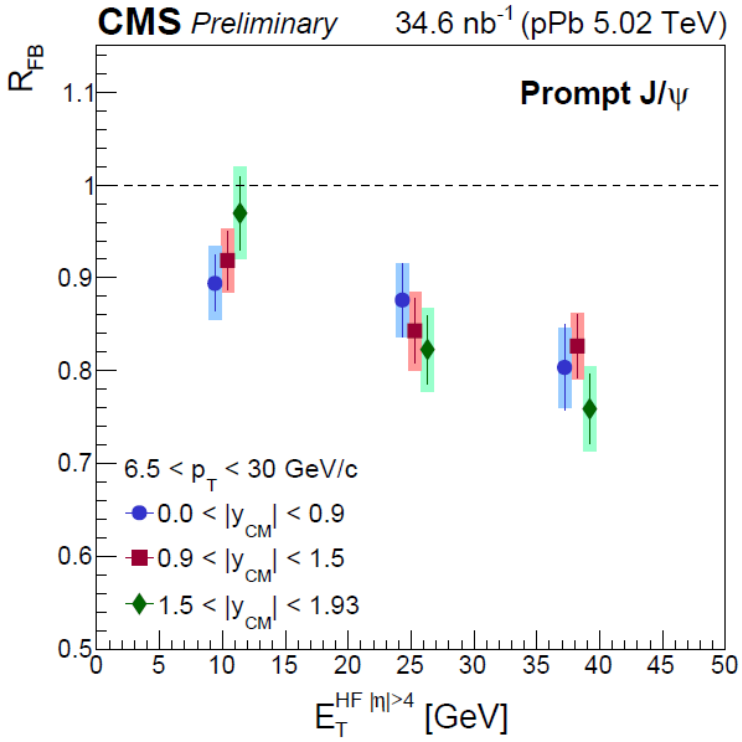
IV. Quarkonia & electroweak bosons

Prompt J/ψ production in pPb

$$R_{FB}(p_T, y) = \frac{d^2\sigma(p_T, y > 0)/dp_T dy}{d^2\sigma(p_T, y < 0)/dp_T dy}$$

Y. Kim CMS-HIN-14-009



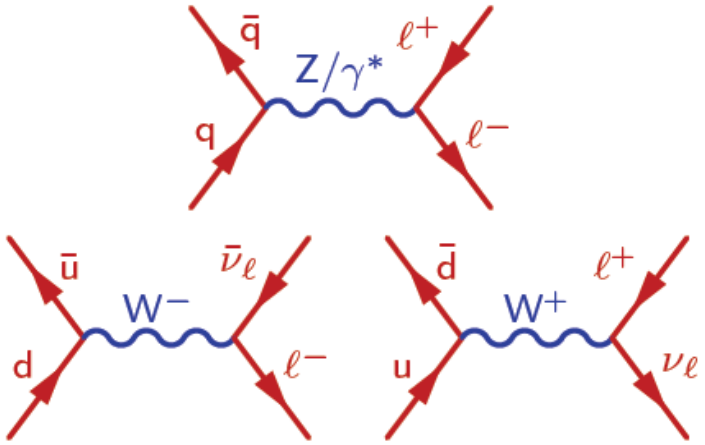


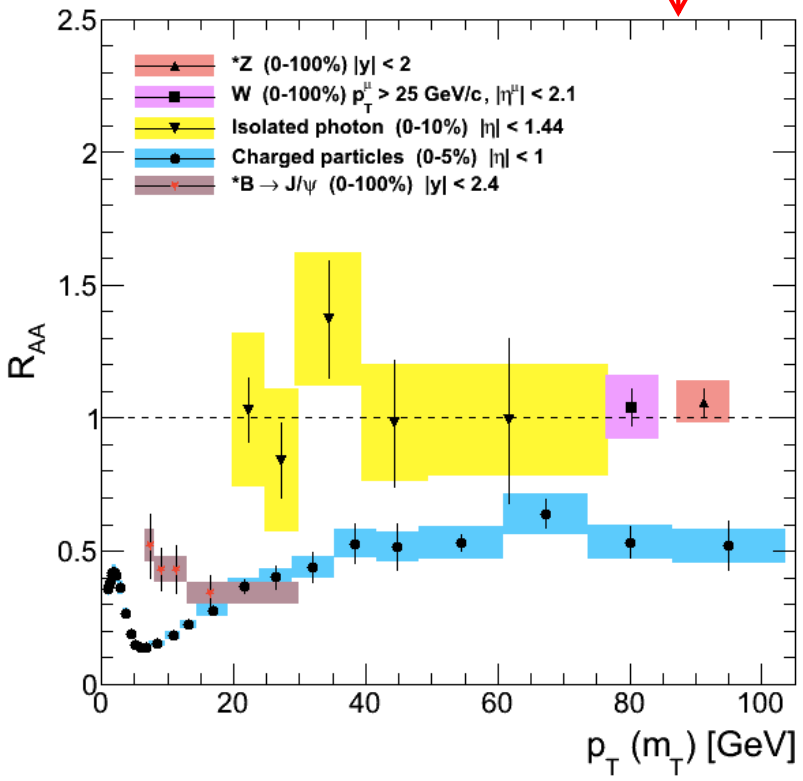
- $R_{FB}(\text{prompt } J/\psi) < 1$ at low p_T with little rapidity dependence
- $R_{FB}(\text{prompt } J/\psi)$ decreases with event activity
  - $E_T^{HF\ |\eta|>4}$: Transverse energy measured in forward ($4 < |\eta| < 5.2$)

W and Z productions

E. Chapon CMS-HIN-15-002

- Electroweak bosons are well calibrated particles in pp.
- Standard candle: No final-state modification in PbPb
- Probing nPDF for q and $\bar{q}$ in pPb:



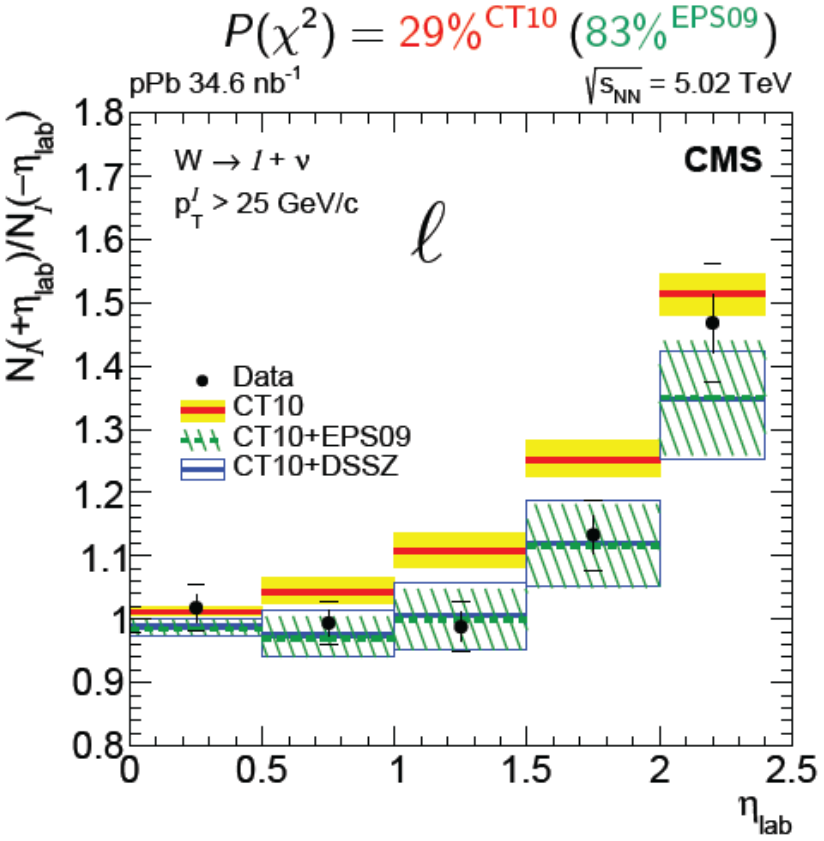


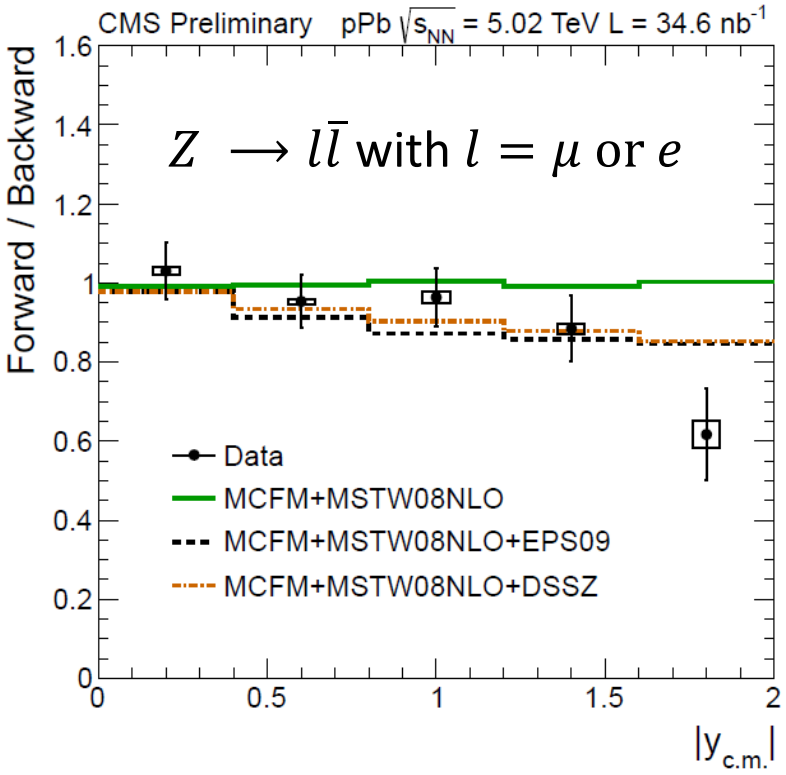
W and Z production in pPb

arXiv:1503.05825

E. Chapon

CMS-HIN-15-002





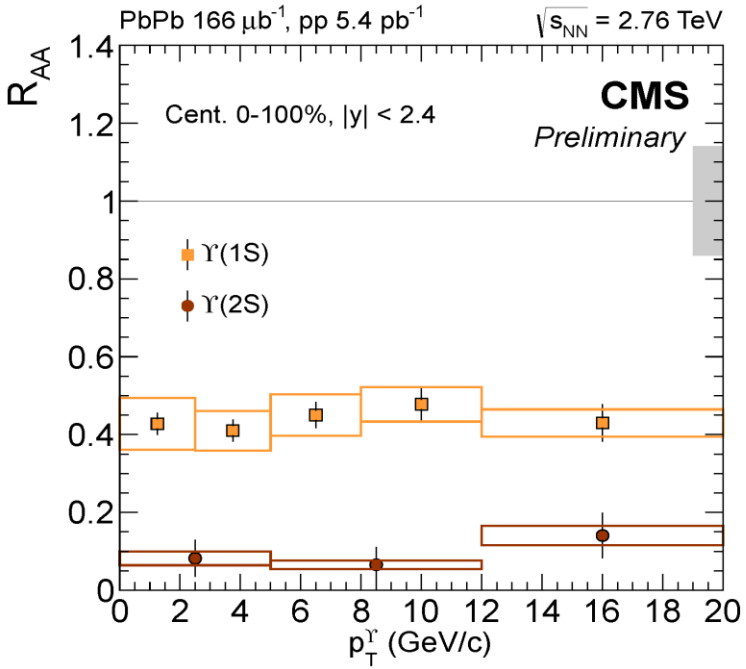
- Electroweak bosons favor the nuclear modification of PDF.
- Large statistical uncertainties yet prevent distinction among different nPDFs.

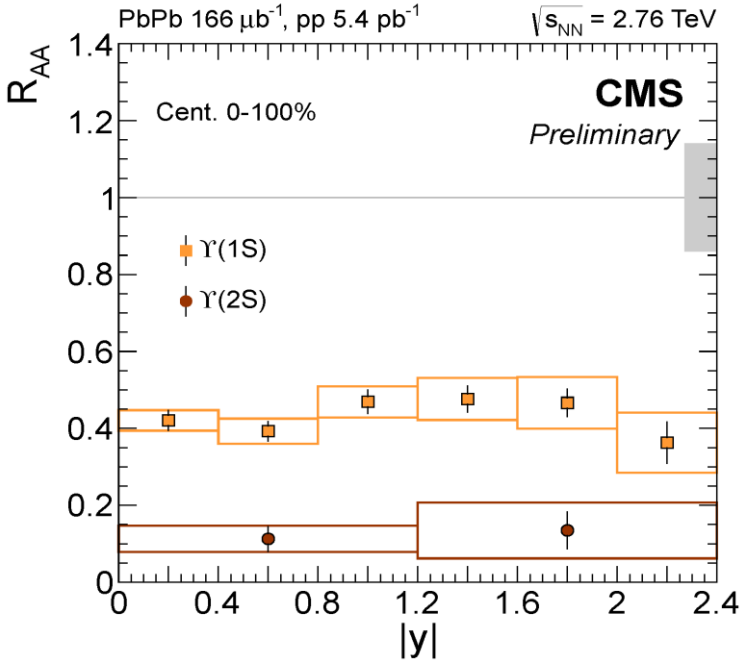
Υ production in PbPb

New data with 20 times more pp data

M. Jo

CMS-HIN-15-001





- Centrality integrated results: Υ states suppressed sequentially (0-100%)

$$R_{AA}[\Upsilon(1S)] = 0.425 \pm 0.029 \pm 0.070$$
$$R_{AA}[\Upsilon(2S)] = 0.116 \pm 0.028 \pm 0.022$$
$$R_{AA}[\Upsilon(3S)] < 0.14 \text{ at } 95\% \text{ CL}$$

- Υ suppression does not strongly depend on kinematics.

Conclusions

- Energy flow
  - Energy density is compatible in pPb and PbPb
- Collective flow
  - Finite v_2 and v_3 in high-multiplicity pp events
  - Stronger radial flow in smaller system
  - PCA quantifies the factorization breakdown for fluctuations in PbPb and pPb.
- Jet and energy loss
  - No modification in the jet fragmentation function in pPb
  - Low-p_T excess of jet tracks in subleading jet side extended to large angles
  - Suppression of prompt D^0 is larger than that for non-prompt J/ψ from B
- Quarkonia & EW probes
  - Forward-backward ratio of J/ψ decreases at low p_T.
  - Z's (and W's) in pPb support modification of nPDF
  - Υ suppression does not strongly depend on kinematics.
- CMS will be ready to take ×10 more heavy-ion events in RUN II.
  - Critical to increase the statistics particularly for the rarest QGP probes