Jet Quenching Studies in CMS

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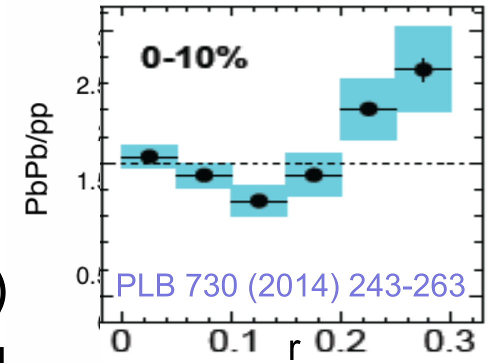
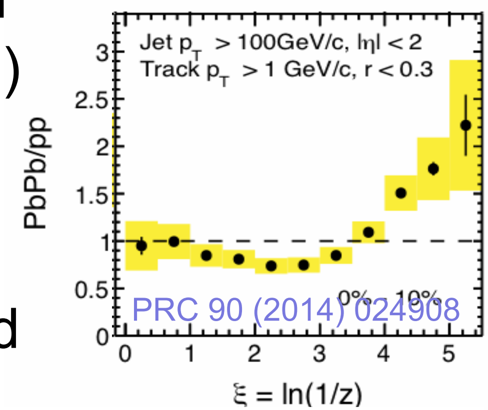
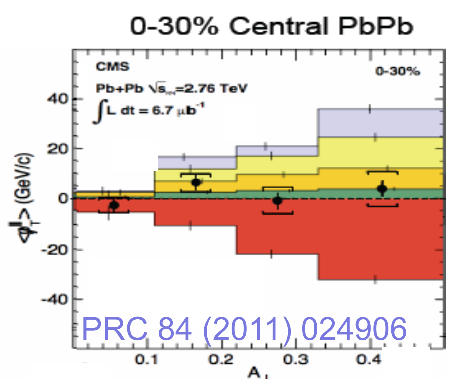
Motivation

- Jet quenching effect has been firmly established at RHIC and LHC
- Full jet reconstruction better connects to the initial parton (compared to high-p_T hadron measurements)
- Jet studies have shown modifications of shapes and fragmentation functions inside the jet cone ($\Delta R < 0.3$)
- Increase of dijet asymmetry with collision centrality has been reported
- Missing (quenched?) transverse momentum is found on subleading jet side far from the jet cone

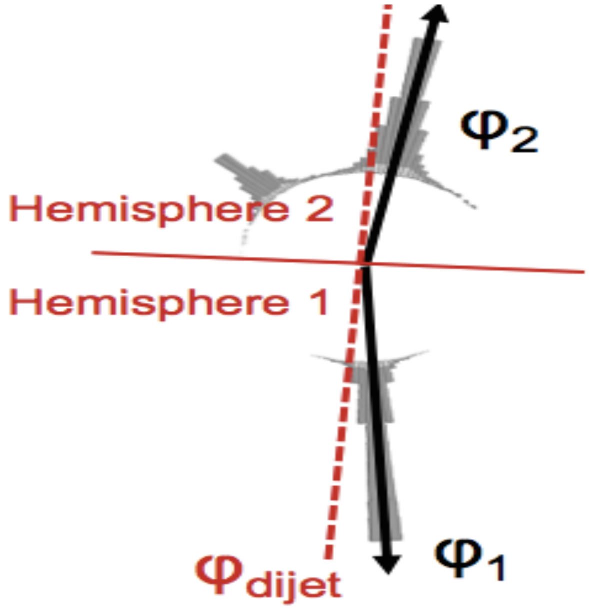
New results extend all the measurements above to large angles, and provide a differential look at the jet-energy flow



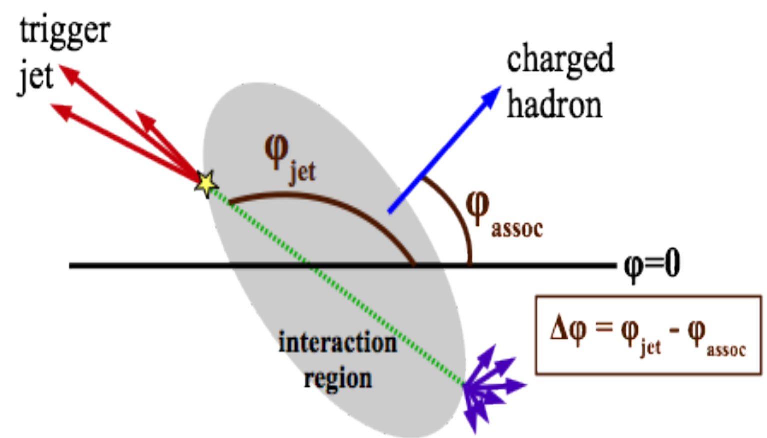




Jet Energy Flow Characterization



- **Missing p_T measurements:**
  - Determine dijet axis and divide event into hemispheres
  - Compare multiplicity and track p_T excess subleading - leading



- **Jet-track 2D correlations:**
  - Measure distribution of all charged tracks about the jet axis in $\Delta\eta - \Delta\phi$
  - Study jet energy flow on each side of the dijet individually

Datasets & Event Selection

- Data Samples at 2.76 TeV
  - PbPb data: 166 μb^{-1}
  - pp data: 5.3 pb^{-1}
  - Trigger threshold: one jet with p_T>80 GeV/c (PbPb and pp)

- Monte Carlo Samples
  - Used to determine tracking corrections, correction for background fluctuation bias in jet reconstruction, and systematic uncertainties
  - PYTHIA simulation of pp reference
  - PYTHIA+HYDJET simulation (embedding PYTHIA hard processes in HYDJET background modeling as hydro+"minijets")

Jet Selections

- Jet Reconstruction
  - **PbPb:** anti-kT, CaloJets, R=0.3, Voronoi UE subtraction
  - **pp:** anti-kT, CaloJets, R=0.3, no underlying event subtraction
- Inclusive Jet Selection
  - $|\eta_{jet}| < 1.6$
  - $p_T > 120$ GeV/c (may select more than one jet in an event)
- Dijet Selection
  - Highest and second highest-p_T jets in $|\eta| < 2$ are first selected, and termed leading (jet1) and subleading (jet2), respectively
  - Final kinematic selection:

    $|\eta_{jet}| < 1.6$ (jet-track correlations), $|\eta_{jet}| < 0.5$ (missing p_T)

    $p_{T,jet1} > 120$ GeV/c, $p_{T,jet2} > 50$ GeV/c, $\Delta\phi_{12} > 5\pi/6$

Track Reconstruction & Selection

- Track reconstruction
  - **PbPb:** Heavy Ion reconstruction, $p_T > 0.4$ GeV/c
  - **pp:** pp reconstruction, $p_T > 0.2$ GeV/c

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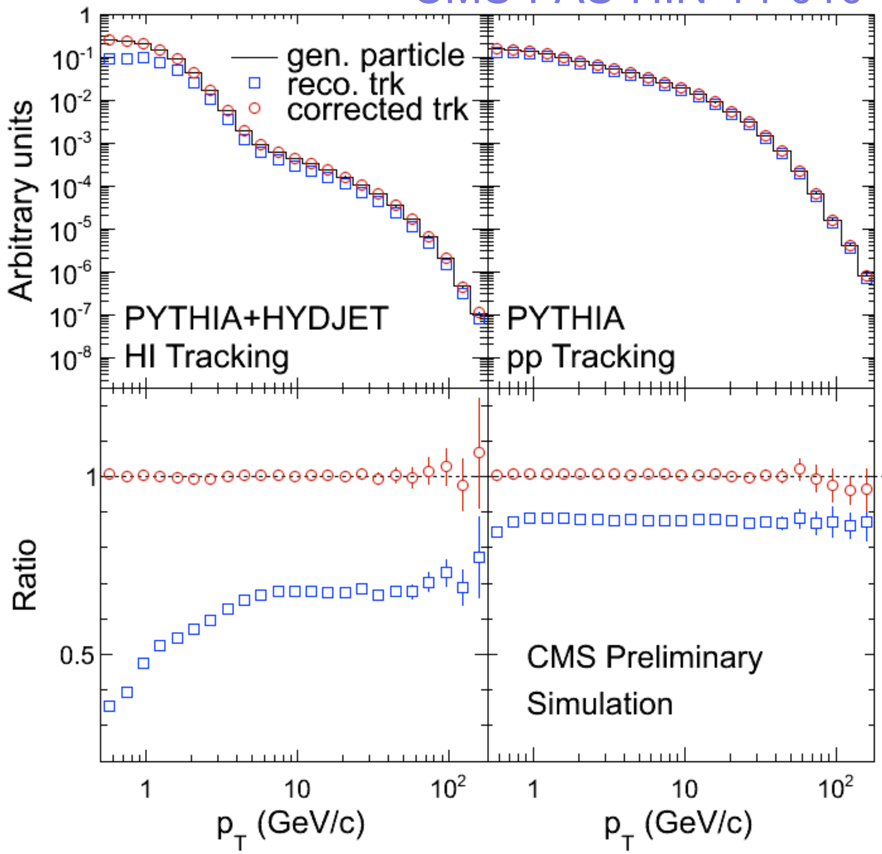
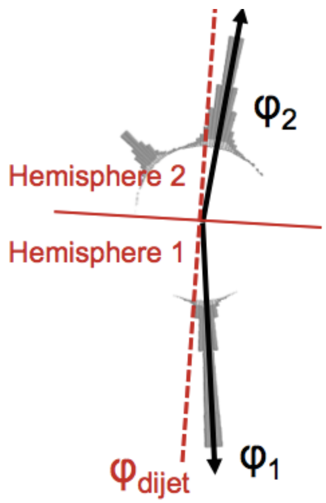
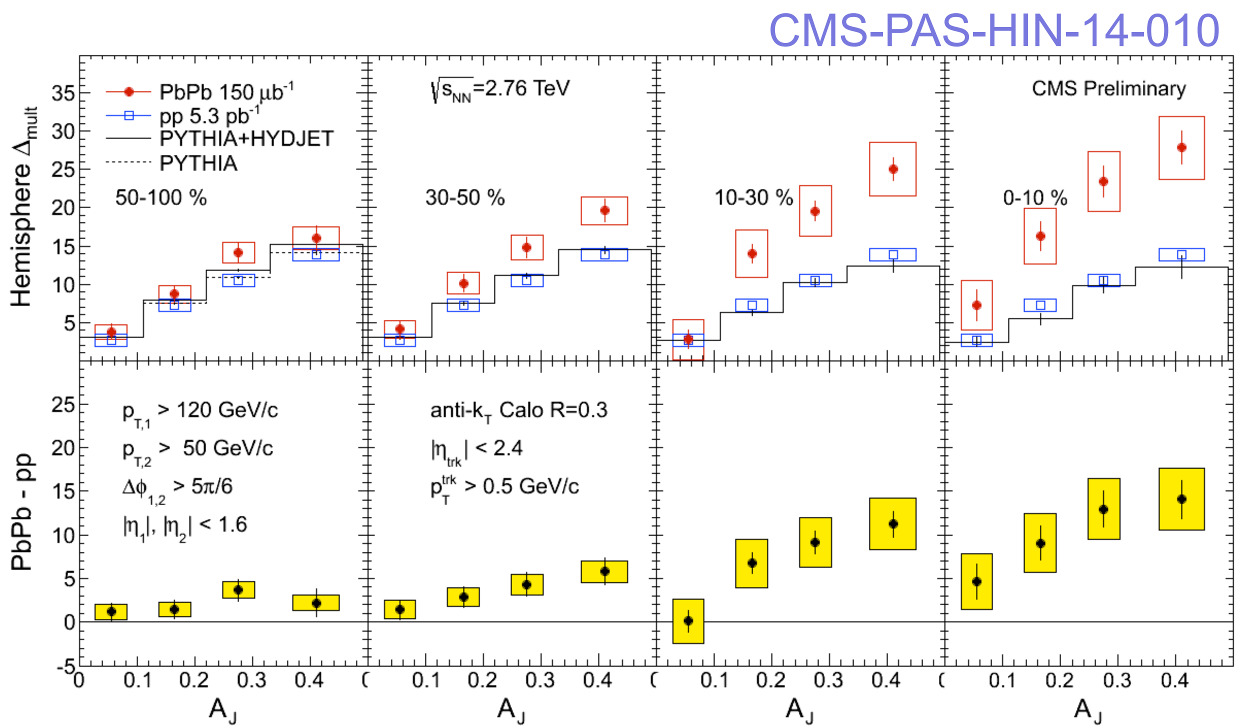


- Track selection
  - $p_T > 0.5$ GeV/c (dijet p_T study)
  - $p_T > 1$ GeV/c (correlation study)
  - $|\eta| < 2.4$

- Track corrections
  - Corrections for tracks are calculated as a function η, φ, p_T, centrality, and local charged particle density

Results: Dijet Multiplicity Difference



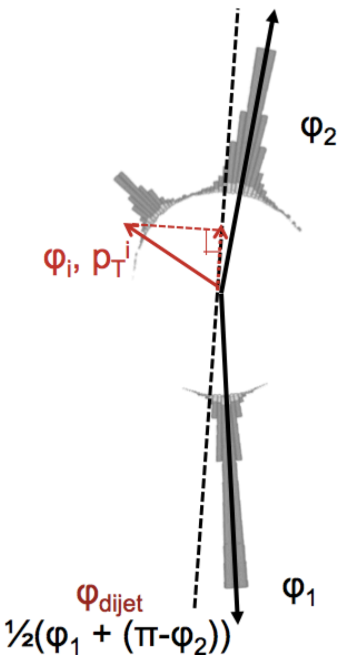


Asymmetry parameter

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

- Hemisphere particle multiplicity difference rises with A_J in both pp and PbPb data
- PbPb subleading-to-leading difference:
  - Centrality dependent
  - In peripheral events – similar to pp reference data
  - In central events – exceeds pp reference by ~15 particles for A_J>0.22

Results: Dijet Missing p_T



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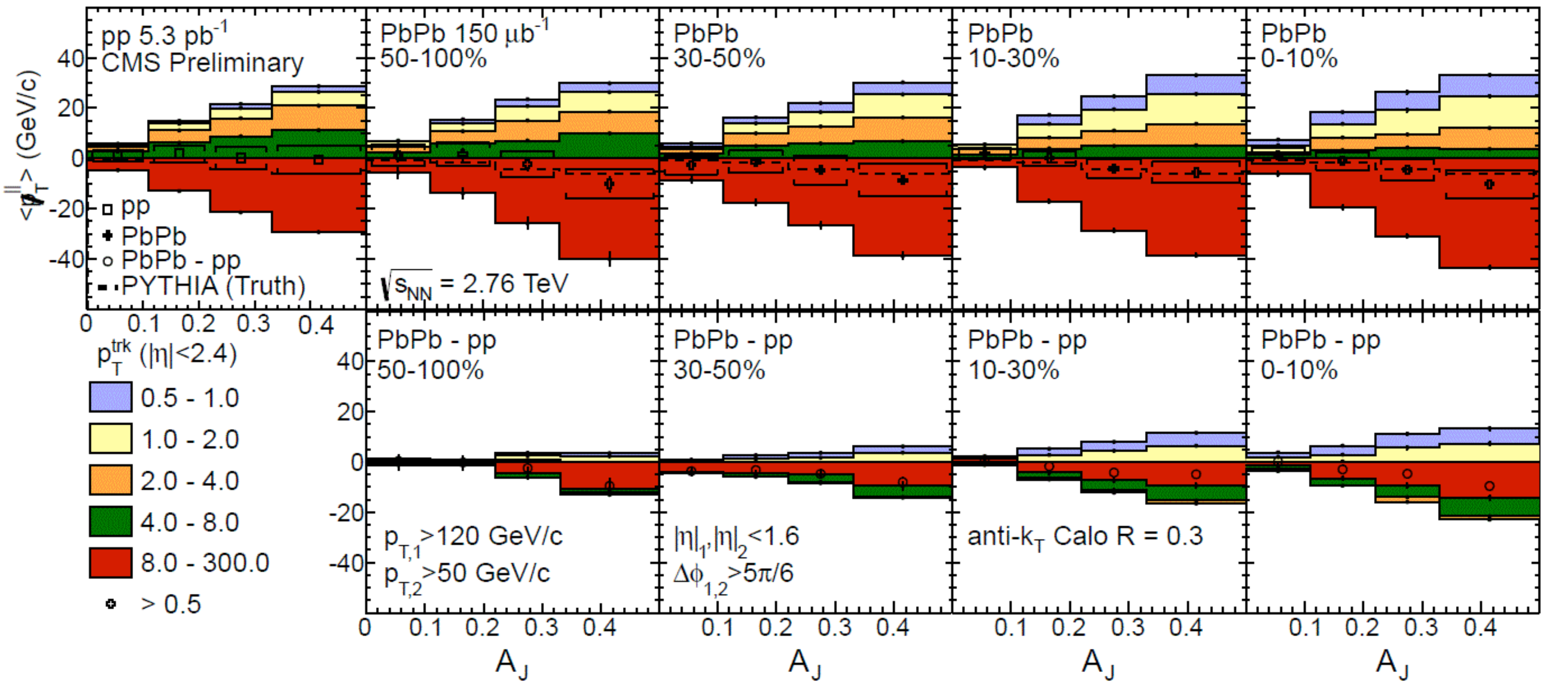

- Look at hemisphere difference in transverse momentum projected onto the dijet access:

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

  - Shows p_T spectrum of particles balancing dijet energy
  - In pp excess is composed of more 2-8 GeV/c particles
  - In PbPb excess is primarily low-p_T (p_T<2 GeV/c) particles

Results: Dijet Missing-p_T by ΔR

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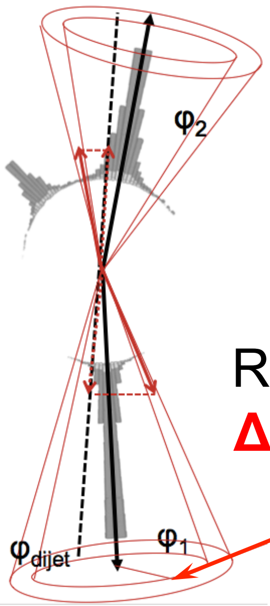
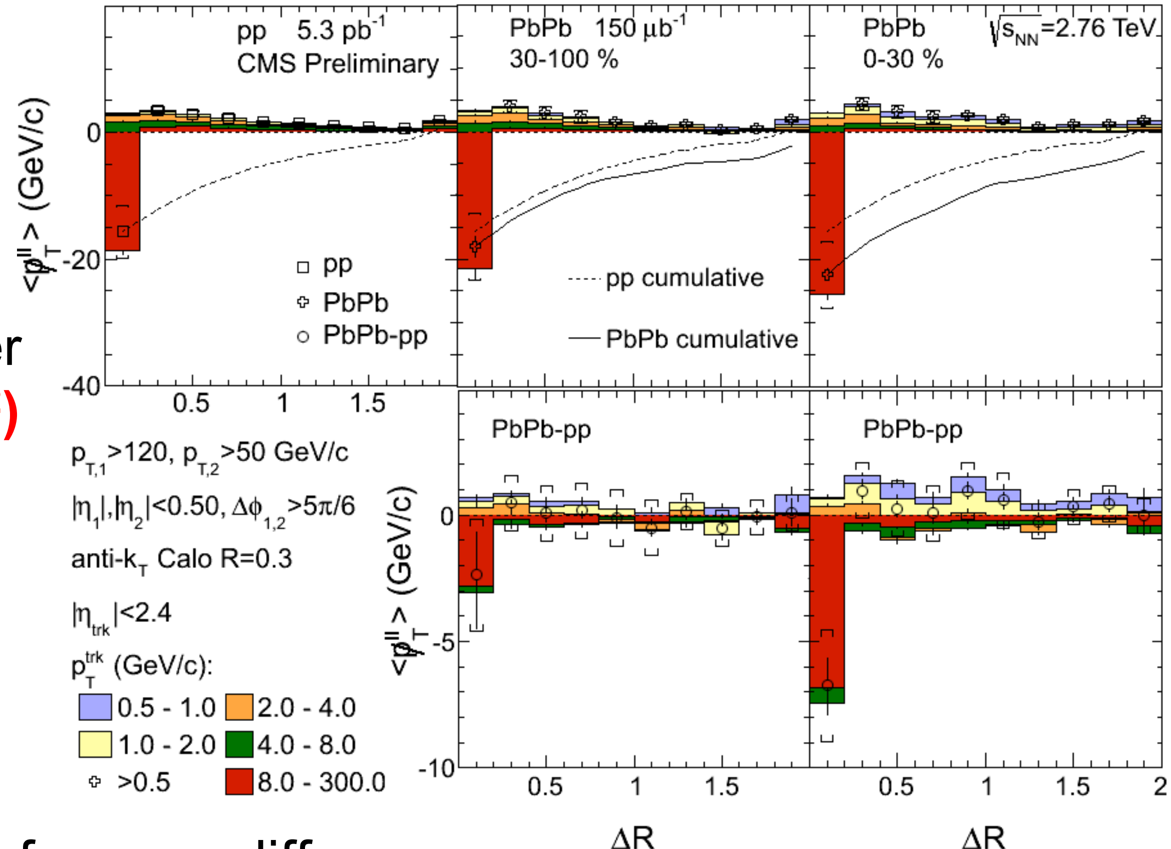


Radius parameter
$\Delta R = \sqrt{(\Delta\eta^2+\Delta\varphi^2)}$

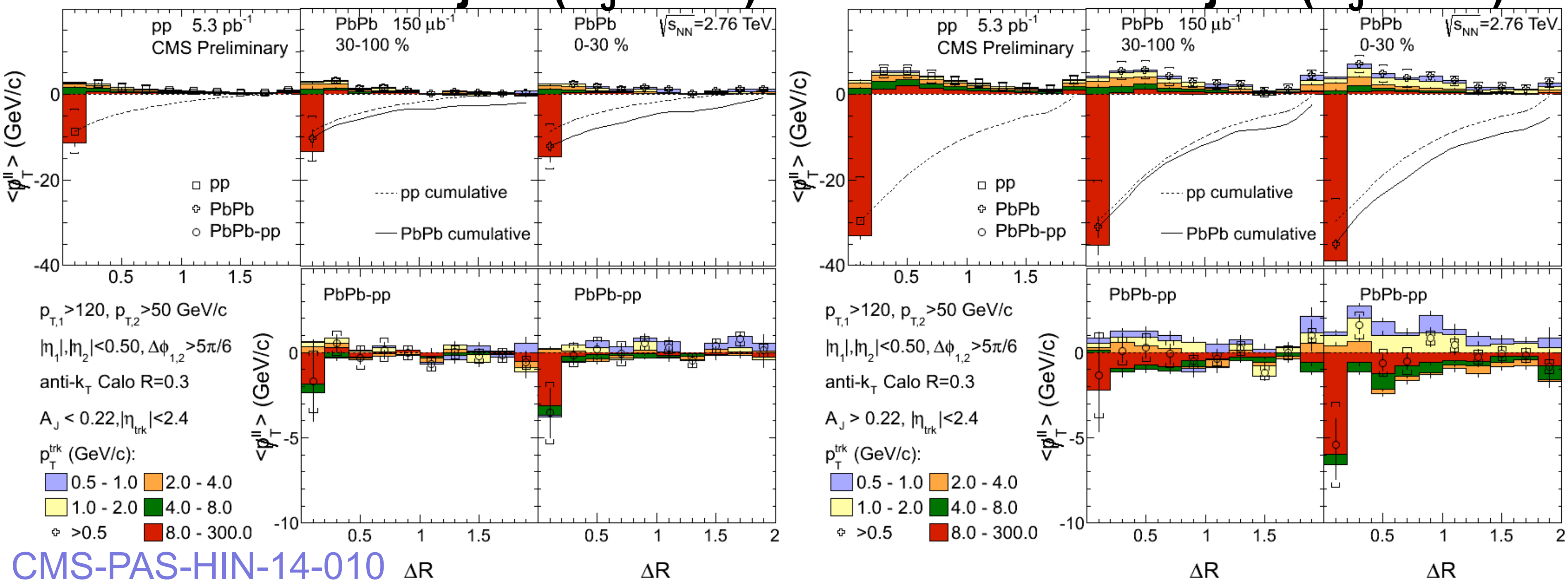


- Radial dependence of energy difference
  - Loss of high-p_T particles on subleading side at small angles is balanced by excess of low-p_T particles
  - Low-p_T excess on subleading side extends to large ΔR

Results: Dijet Missing-p_T by ΔR

- Separately consider more balanced and unbalanced dijets
  - Larger asymmetry ←→ larger subleading low-p_T excess
  - Shape of p_T-integrated distribution is similar in PbPb and pp, but p_T composition is different

More Balanced Dijets (A_J <0.22) vs. Unbalanced Dijets (A_J >0.22)



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Jet-Track Correlations

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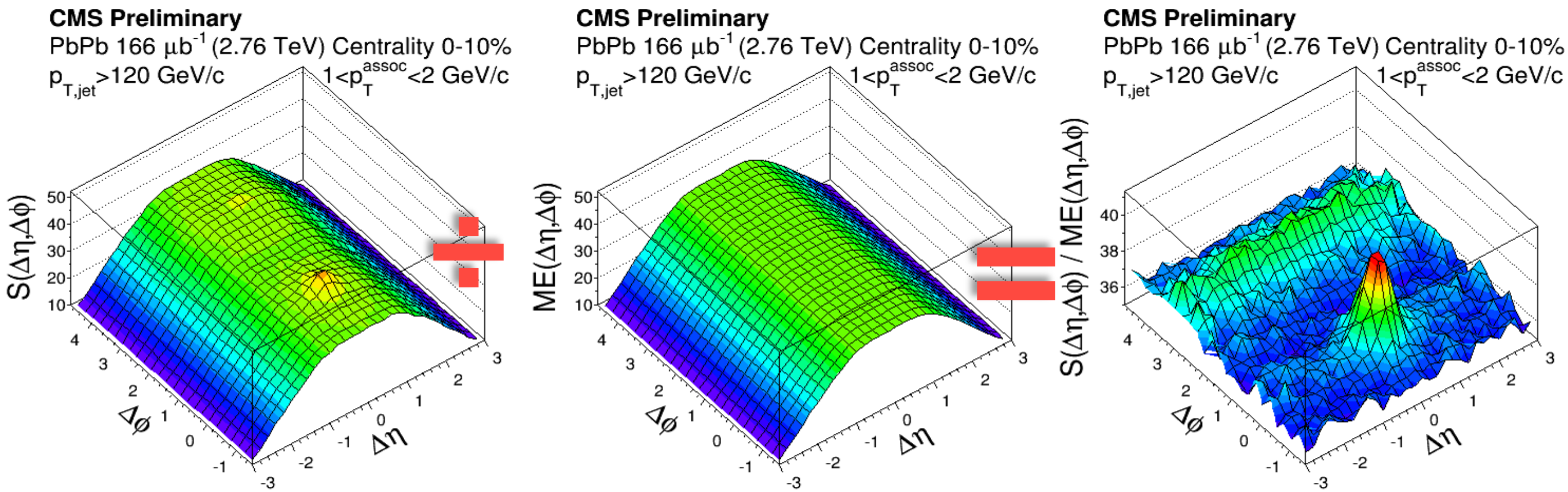

Raw Correlation

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

Mixed Event

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

Result

$$\frac{S(\Delta\eta,\Delta\phi)}{ME(\Delta\eta,\Delta\phi)} \times ME(0,0)$$

- Correlations are formed by measuring angular distances of all charged particles with respect to the jet axis direction
- Mixed Event corrects for pair acceptance effects
  - Mixed events are constructed by tight matching of vertex *z* and centrality
  - Efficiency corrections are applied per track to correlations

Jet-Track Correlations: Background Subtraction

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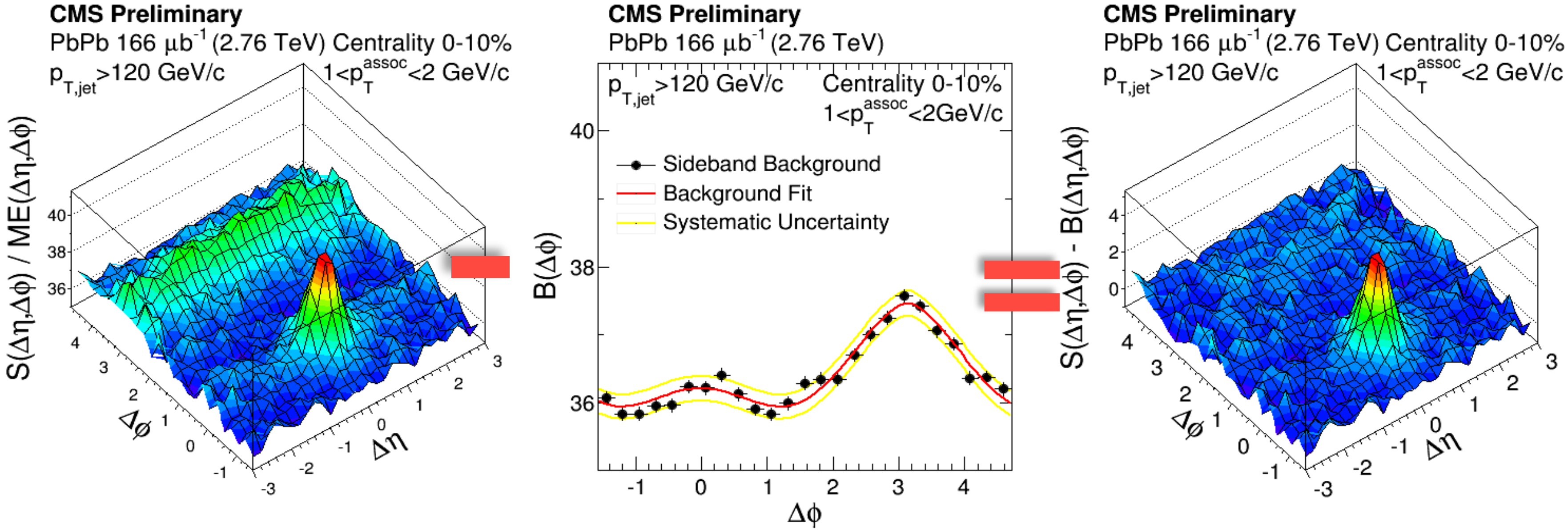


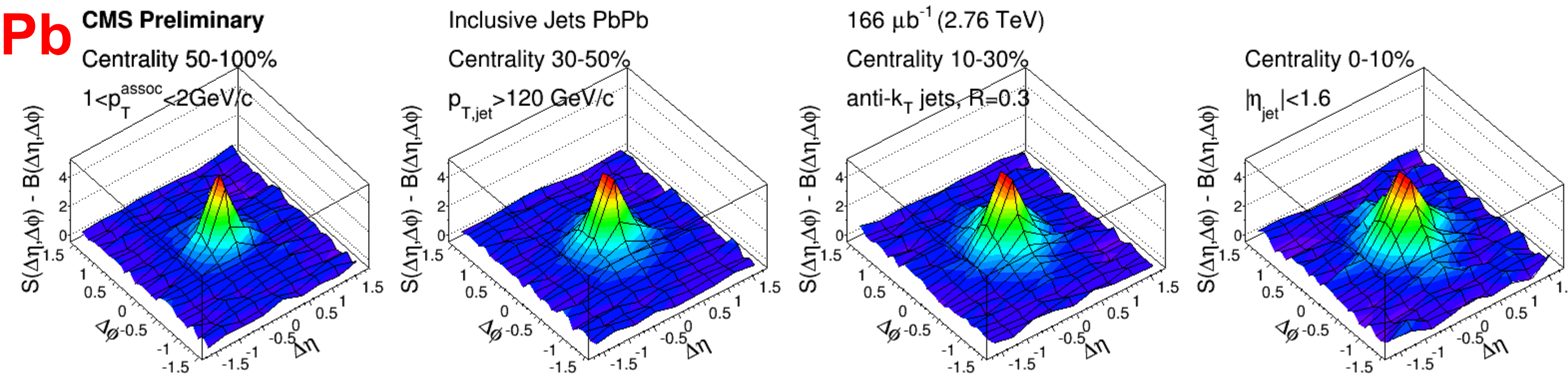
- Sideband method is used to subtract the correlated background, with sideband selection: $1.5<|\Delta\eta|<3$
- Fit function: two first Fourier terms + generalized Gaussian (away-side)

$$B(\Delta\phi) = B_0(1 + 2V_1 cos(\Delta\phi) + 2V_2 cos(2\Delta\phi)) + A_{AS} exp(-\left(\frac{|\Delta\phi|}{\alpha}\right)^{\beta})$$

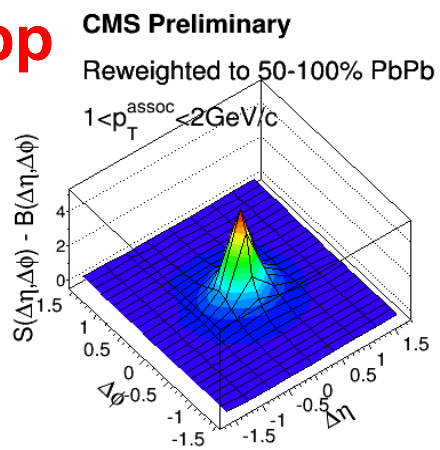
- Error estimation: sideband range variation, direct subtraction, etc.

Jet-Track Correlations: Correlated Yield

PbPb



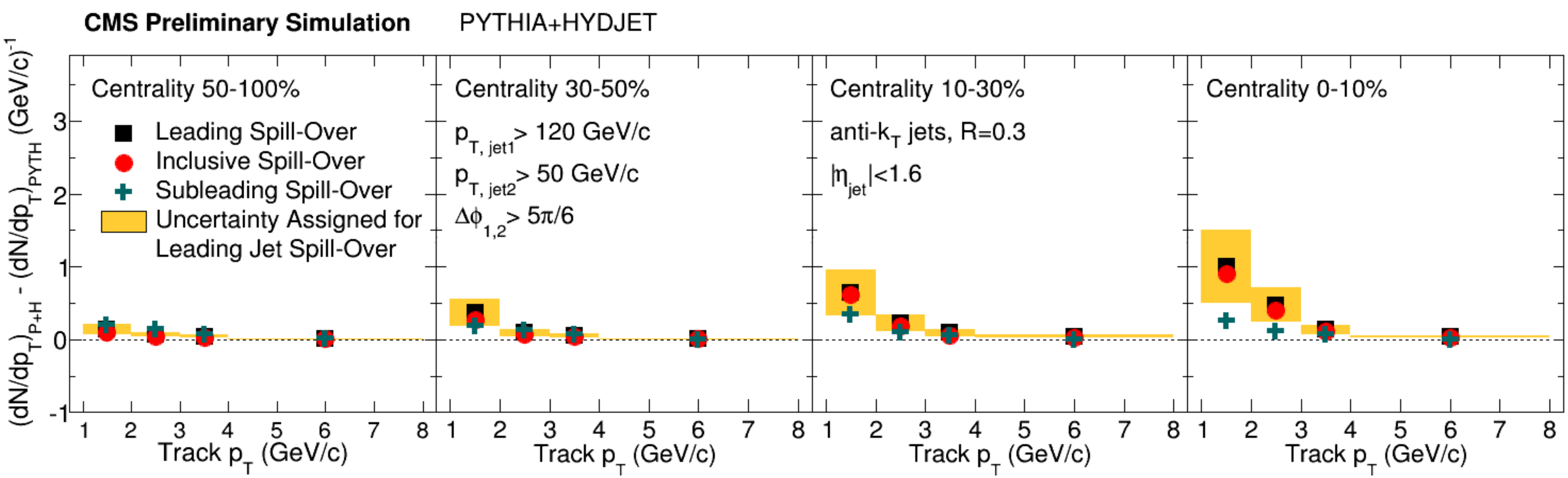
pp



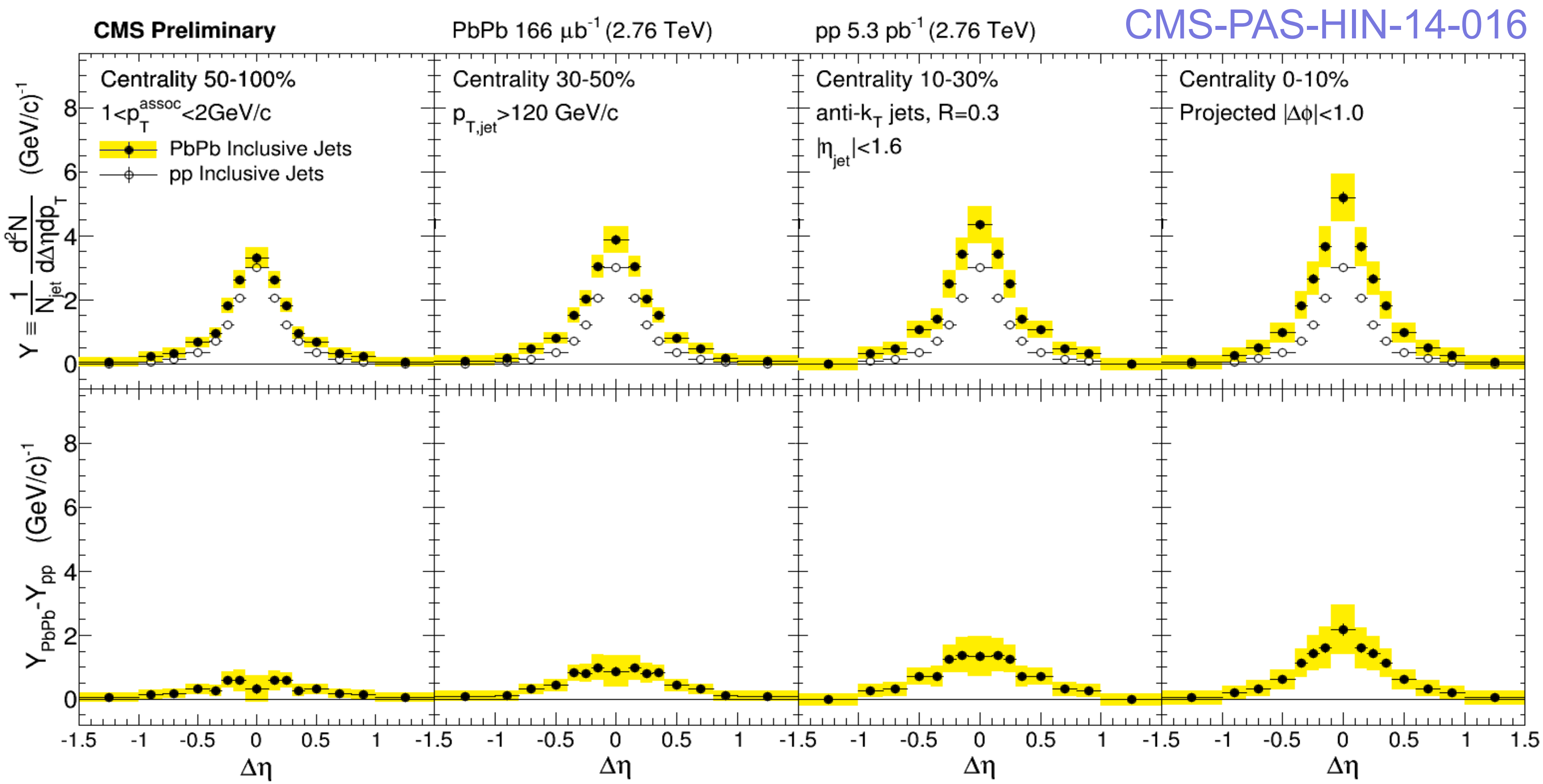
- Result: background-subtracted 2D correlations for PbPb and pp inclusive jets (shown for 1<p_T^{assoc}<2 GeV/c)
- Larger yield immediately evident in central collisions (right)
- Peripheral collisions (left) similar to pp reference
- One final correction is needed before quantifying the results…

Jet-Track Correlations: Spill-Over Correction

- Background fluctuations effects on jet reconstruction is the dominant source of systematic uncertainty
- Upward fluctuation+ steeply falling spectra → “spilled” jets
- Spill-over correction derived from MC and confirmed by data-driven cross-check

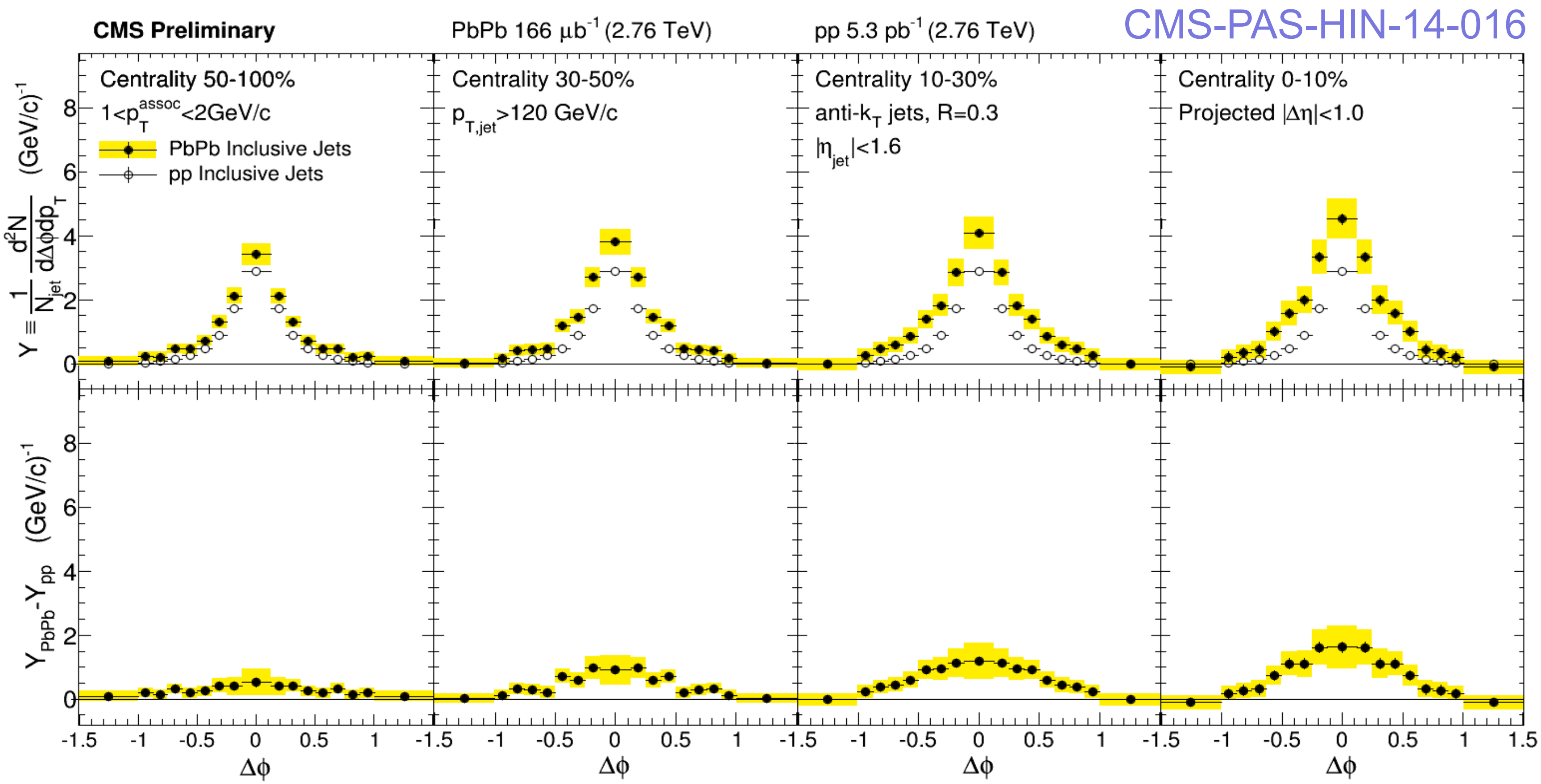


Results: Inclusive Jet Δη Correlations



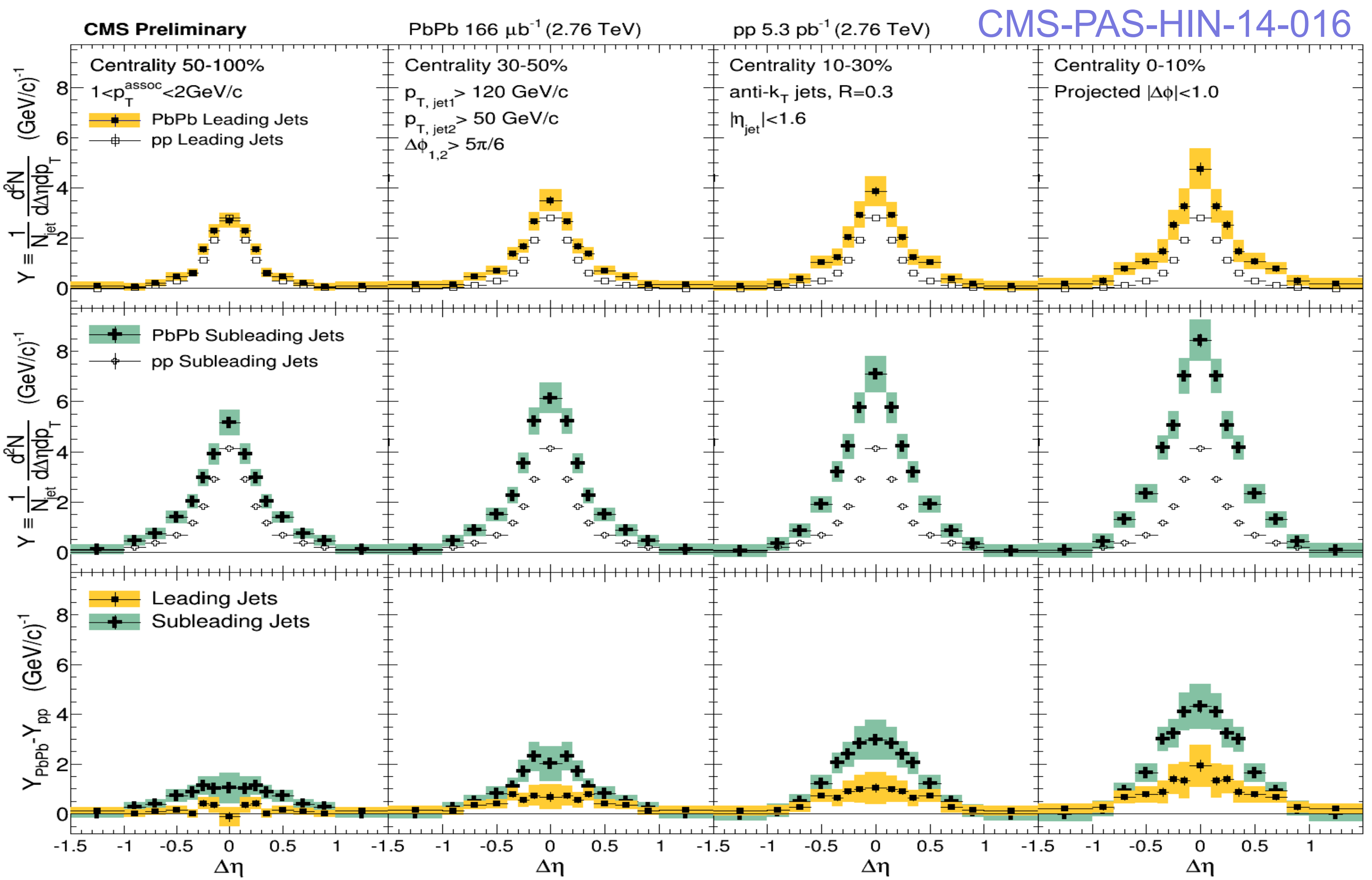
- Peripheral events: similar to pp reference
- Low-p_T excess yield develops with increasing centrality; extends to large angles
- Excess yield is consistent with published CMS Jet Fragmentation Function measurements *(doi:10.1103/PhysRevC.90.024908)*

Results: Inclusive Jet Δϕ Correlations



- Similar trends between Δη and Δϕ projections
- Low-p_T excess is centrality dependent, remains correlated with jet direction extending to large angles

Results: Dijet Δη Correlations



- Similarly to inclusive jet trends: low-p_T enhancement disappears at high-p_T
- Larger effects for subleading jets

Results: Dijet Δϕ Correlations

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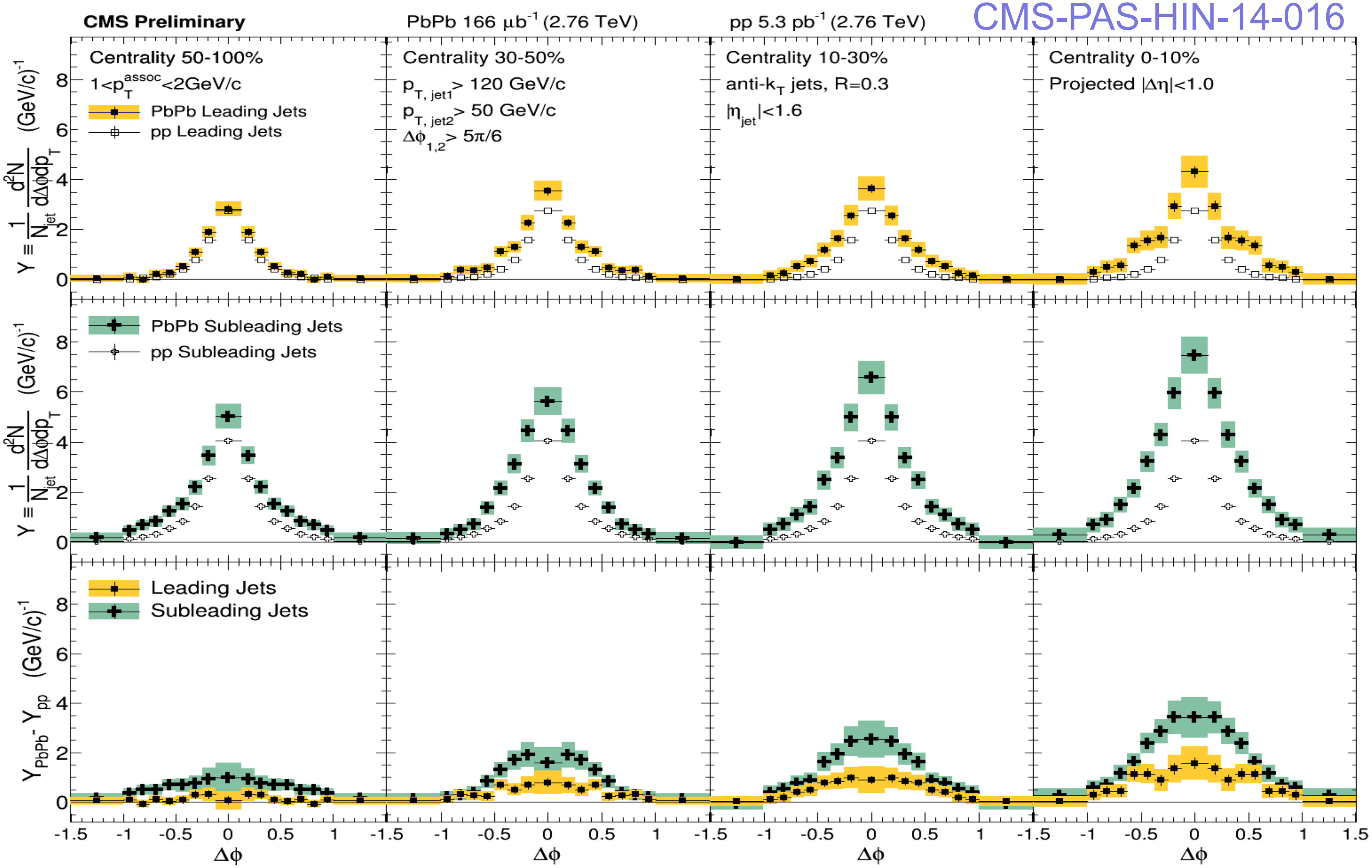
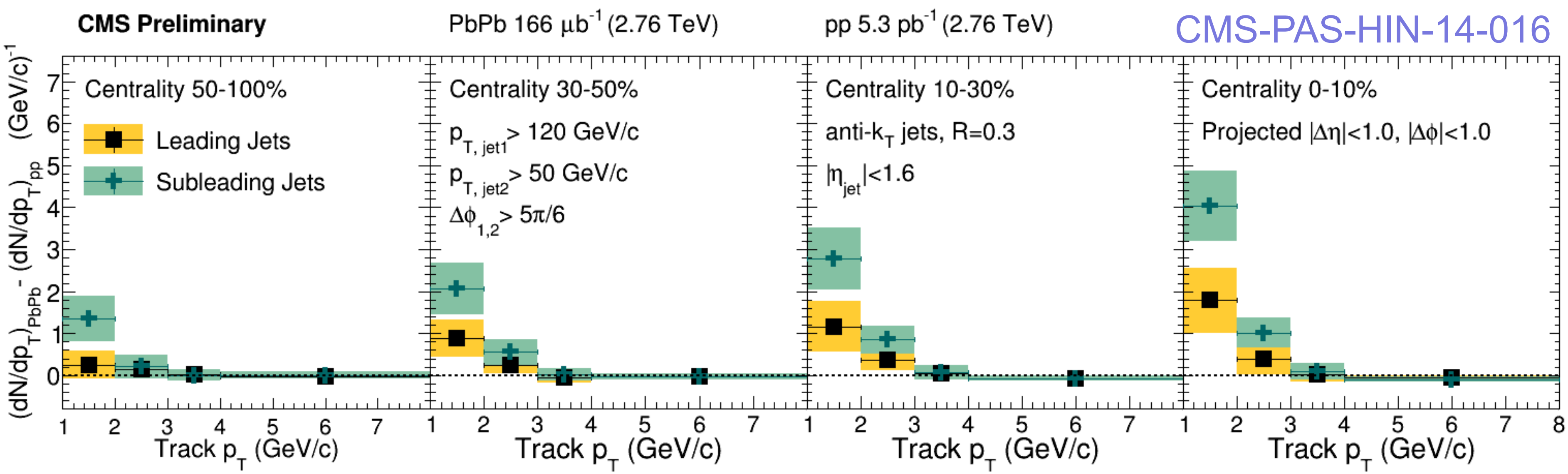


- No significant differences in trends in Δη and Δϕ dimensions

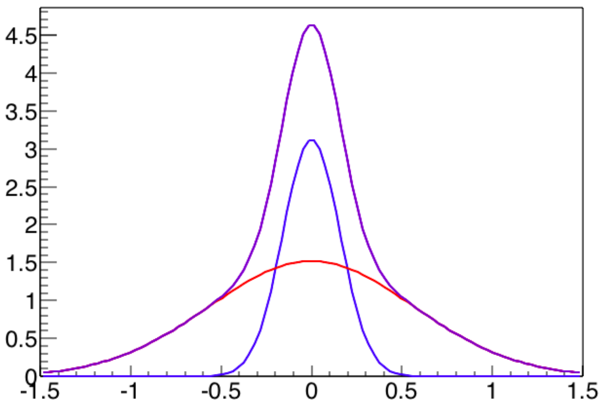
Results: Integrated Excess Yield



- Some energy redistribution begins in peripheral events
- Additional yield is most pronounced at the lowest track p_T
- Excess decreases with increasing track p_T,
- At highest p_T studied (4-8 GeV/c) yields are similar to pp reference
- Excess is more pronounced for subleading jets, but is evident for both near- and away-sides of the dijet.

Results: Correlation Width

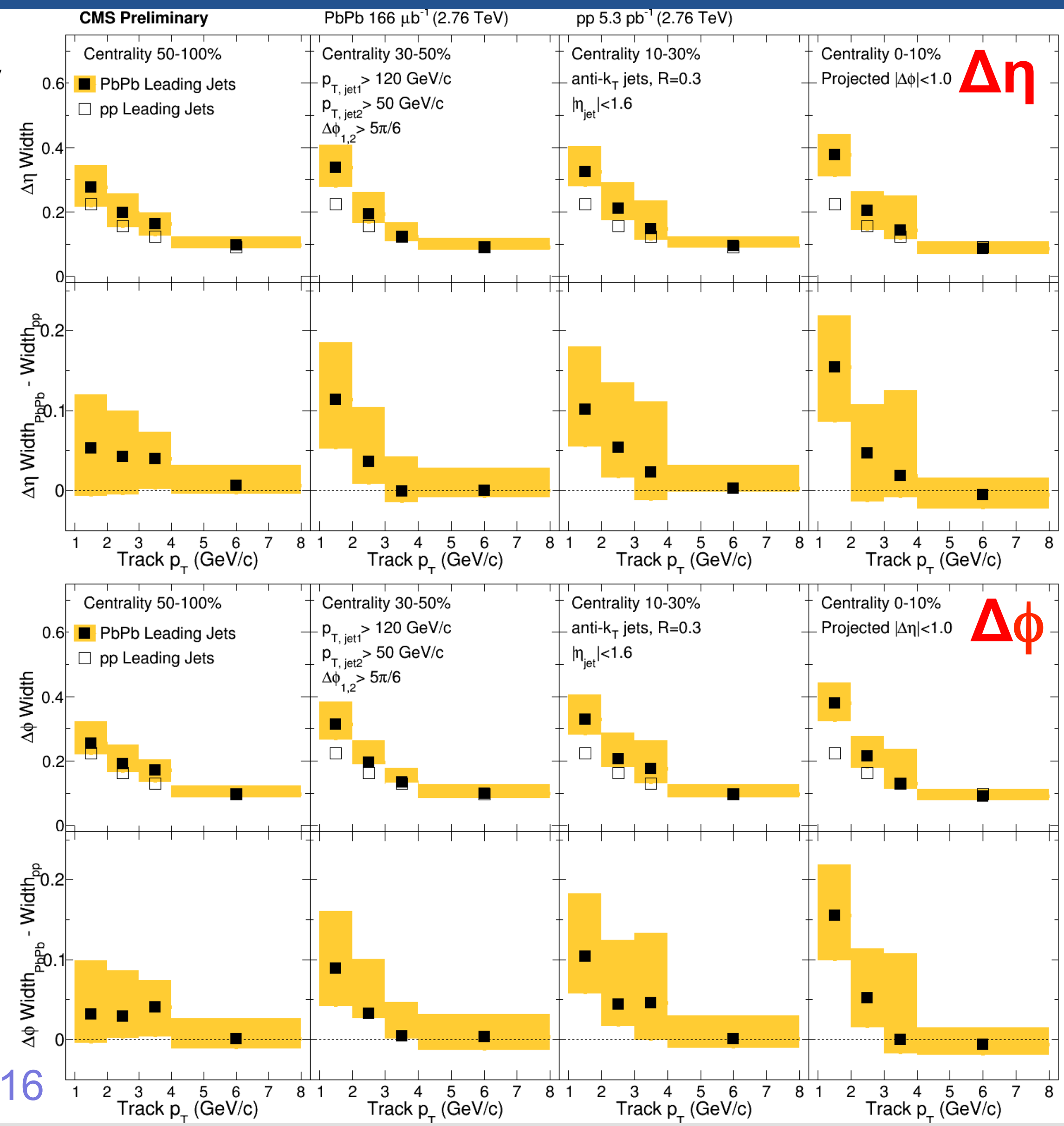
- Extract correlations widths by fitting with double Gaussian:



$$\sigma_{tot} = \sqrt{(\sigma_1^2 + \sigma_2^2)}$$

- Bottom panels show (PbPb width) – (pp width)

- Similar widths in $\Delta\eta$ and $\Delta\phi$
- Signs of low-p_T broadening?



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Summary

- Centrality-dependent energy redistribution for dijets is measured as a function of radial distance from dijet axis
- Subleading to leading energy balance shows redistribution of "missing p_T" into low-p_T particles extending to large ΔR
- Centrality-dependent excess correlated yield in PbPb collisions with respect to pp reference is measured for all types of jets: inclusive, leading, subleading
- Excess yield (PbPb – pp) grows with centrality, decreases with transverse momentum
- Excess yield is correlated with jet axis extending to large angles for all three jet samples studied.

Extra Slides

Systematic Uncertainties (Multiplicity Differences)

Multiplicity difference by A_J

Table 1: Summary of systematic uncertainties for the multiplicity difference analysis, given in number of tracks

	pp	PbPb 50 – 100%	PbPb 30 – 50%	PbPb 10 – 30%	PbPb 0 – 10%
Jet reco and selection	0.8	0.8	1.0	2.5	3.0
Track reco.	0.5	0.5 – 1.0	0.5 – 1.0	1.0	1.0
Residual JES	0.5	0.5	0.5	0.8	1.0
Residual track corr.	0.2 – 0.7	0.1 – 0.7	0.1 – 1.0	0.1 – 1.2	0.1 – 1.5
Event selection	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
HCAL noise	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Pile-up	<0.2	-	-	-	-
Total Systematics	1.1 – 1.5	1.1 – 1.3	1.2 – 1.7	2.8 – 3.0	3.3 – 3.5

Multiplicity difference by p_T

Table 2: Summary of systematic uncertainties for missing p_T versus asymmetry

	pp (GeV/c)	PbPb 50 – 100% (GeV/c)	PbPb 30 – 50% (GeV/c)	PbPb 10 – 30% (GeV/c)	PbPb 0 – 10% (GeV/c)
Jet reco.	2 – 5	3 – 4	3 – 5	2 – 3	2 – 4
Track reco.	0.5 – 2	1 – 4	2 – 4	1 – 3	1 – 3
Total reco.	2.1 – 5.4	4.1 – 5.7	3.6 – 6.4	2.2 – 4.2	2.2 – 5.0
Residual JES	0.5	1.0	0.5	0.5	0.5
Residual tracking corr.	0.2	0.5	0.5	0.4	0.6
Total Systematics	2.2 – 5.5	4.3 – 5.8	3.7 – 6.5	2.4 – 4.3	2.4 – 5.1

Systematic Uncertainties (Missing p_T by ΔR)

Table 3: Summary of systematic uncertainties for missing p_T versus ΔR for pp

	pp (GeV/c)								
ΔR	<0.2			0.2 – 0.8(1.2)			>0.8(1.2)		
A_J	All	< 0.22	> 0.22	All	< 0.22	> 0.22	All	< 0.22	> 0.22
Jet reco.	4	5	10	0.5	1	1.5	0.3	0.5	1
Track reco.	1	1	1	0	0	0	0	0	0
Residual JES	0.5	1	2.5	0.1	<0.1	0.2	0	0	0.1
Residual track corr.	0.5	0.5	1.5	0.2	0.1	0.2	0	0	<0.1
Pile-up	0.1	0.2	0.5	0	0.1	0.2	0	0	0
Total	4.1	5.2	10.4	0.5	1.0	1.5	0.2	0.5	1.0

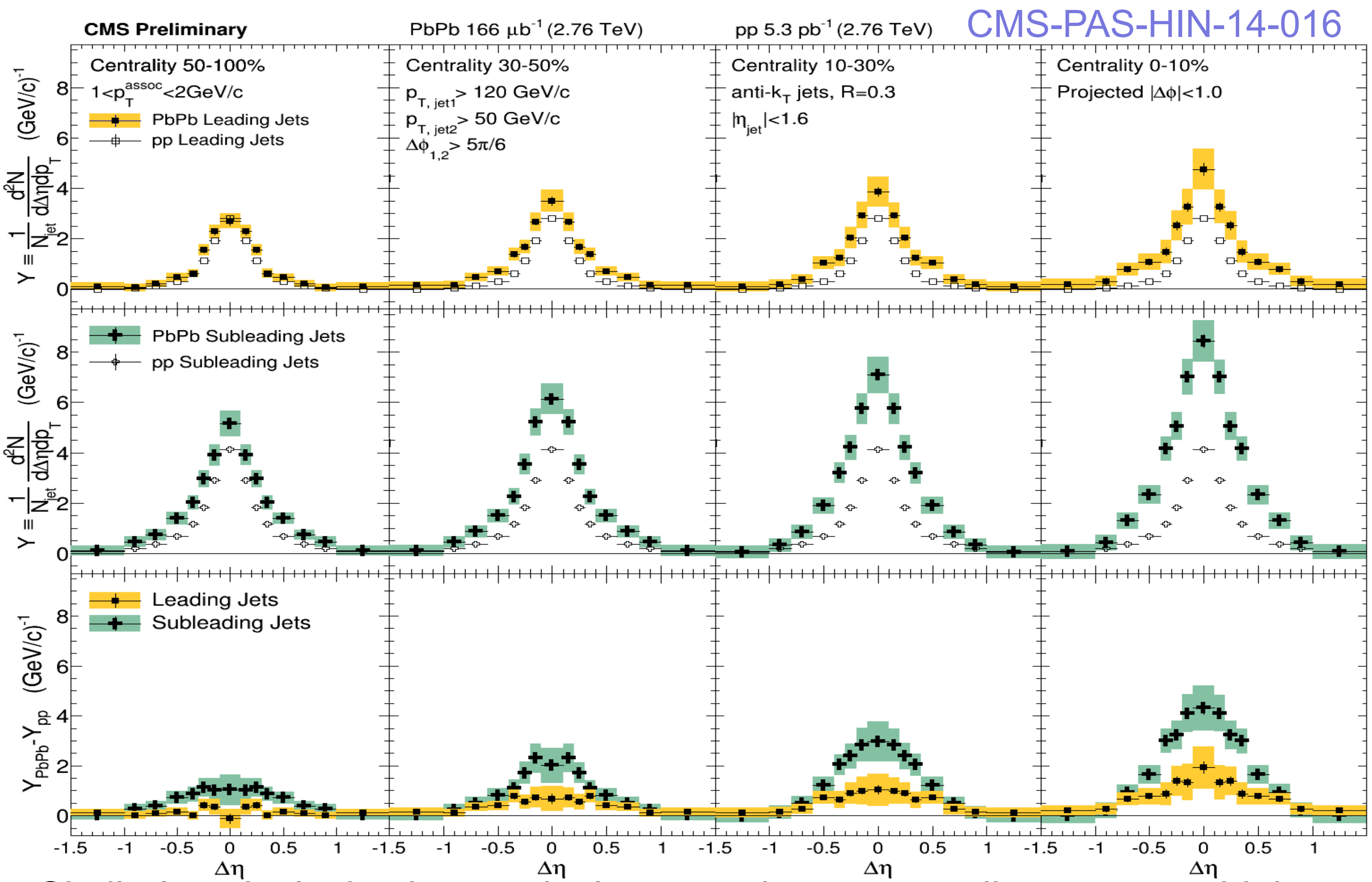
Table 4: Summary of systematic uncertainties for missing p_T versus ΔR for PbPb

	PbPb (GeV/c)								
ΔR	<0.8(1.2)			0.2 – 0.8(1.2)			>0.8(1.2)		
A_J	All	< 0.22	> 0.22	All	< 0.22	> 0.22	All	< 0.22	> 0.22
Jet reco.	5	5	10	1	0.5	2	0.3	0.3	1
Track reco.	1.5	1	3	0.2	0.2	0.5	0.2	0.2	0.5
Residual JES	0.5	1	2	<0.1	0.2	0.5	<0.1	0.2	0.2
Residual track corr.	0.8	0.5	1.5	0.2	0.1	0.2	0	0	<0.1
Total	5.3	5.2	10.8	1.0	0.6	2.1	0.4	0.4	1.1

Systematic Uncertainties (Correlations)

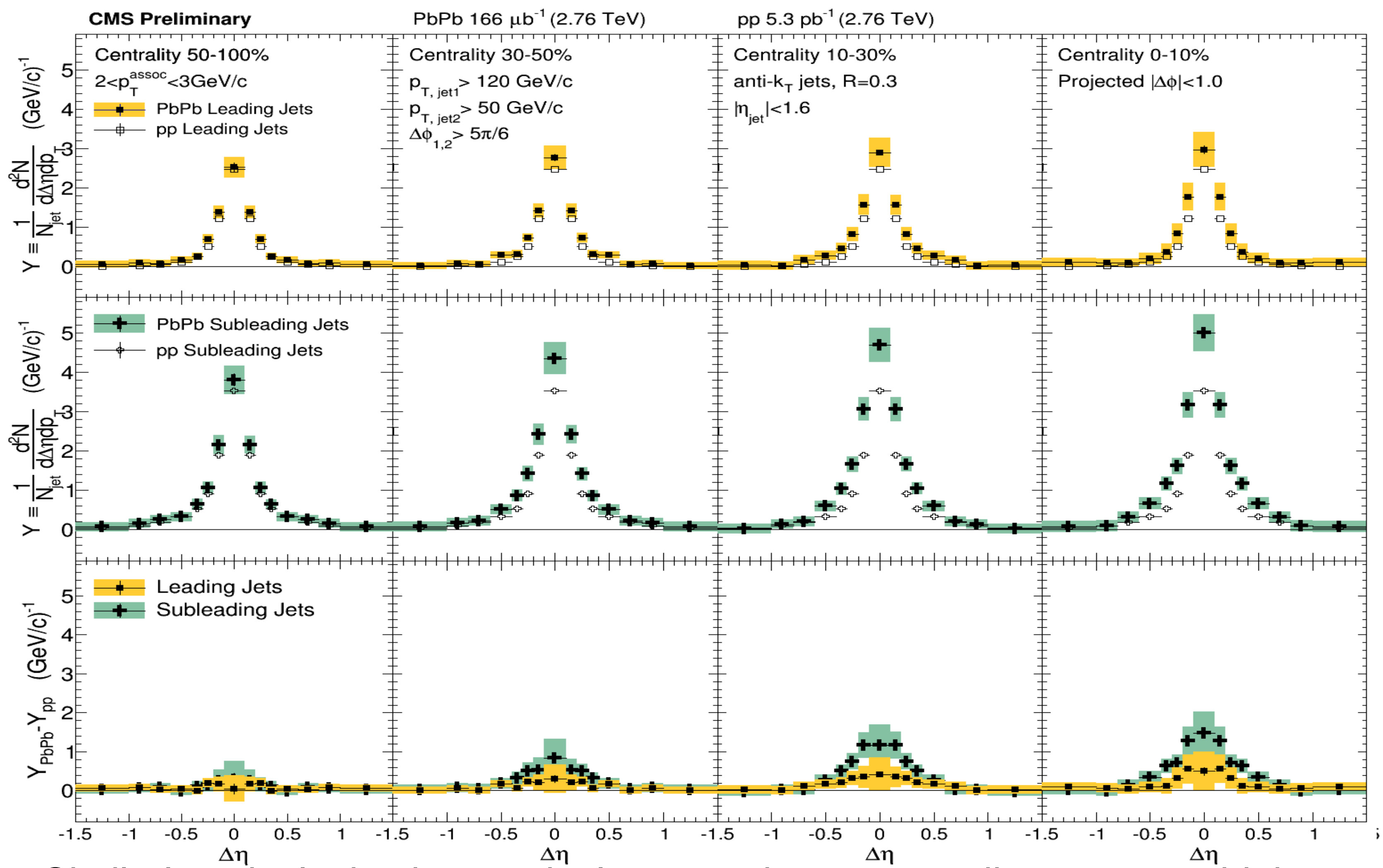
Source	0–10%	10–30%	30–50%	50–100%	ppRef
Background Fluctuation	4–15%	4–11%	2–6%	2–4%	–
Background Subtraction	3–6%	3–6%	3–5%	3–5%	2–5%
Tracking Efficiency Uncertainty	5%	5%	5%	5 %	3 %
Residual Track Efficiency Corr.	5%	5%	5%	5%	5%
Pair Acceptance Corrections	6–10%	6–9%	5–9%	5–9%	2–3%
Residual JES	5%	5 %	5%	5%	5%
Total	12–21%	12–18%	11–15%	11–14%	8–11%

Results: Dijet Δη Correlations ($1<p_T^{assoc}<2GeV/c$)



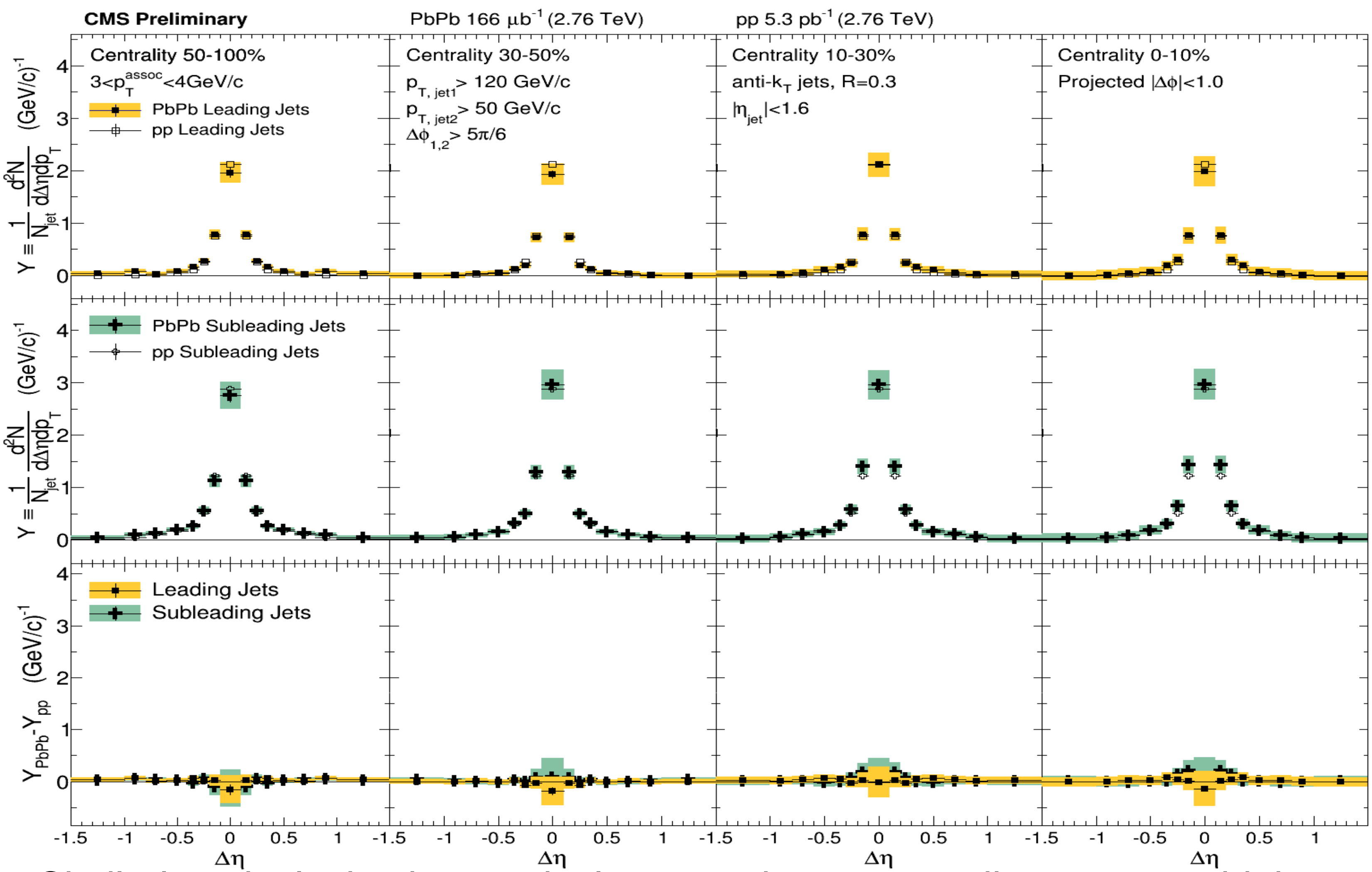
- Similarly to inclusive jet trends: low-p_T enhancement disappears at high-p_T
- Larger effects for subleading jets

Results: Dijet Δη Correlations ($2<p_T^{assoc}<3GeV/c$)



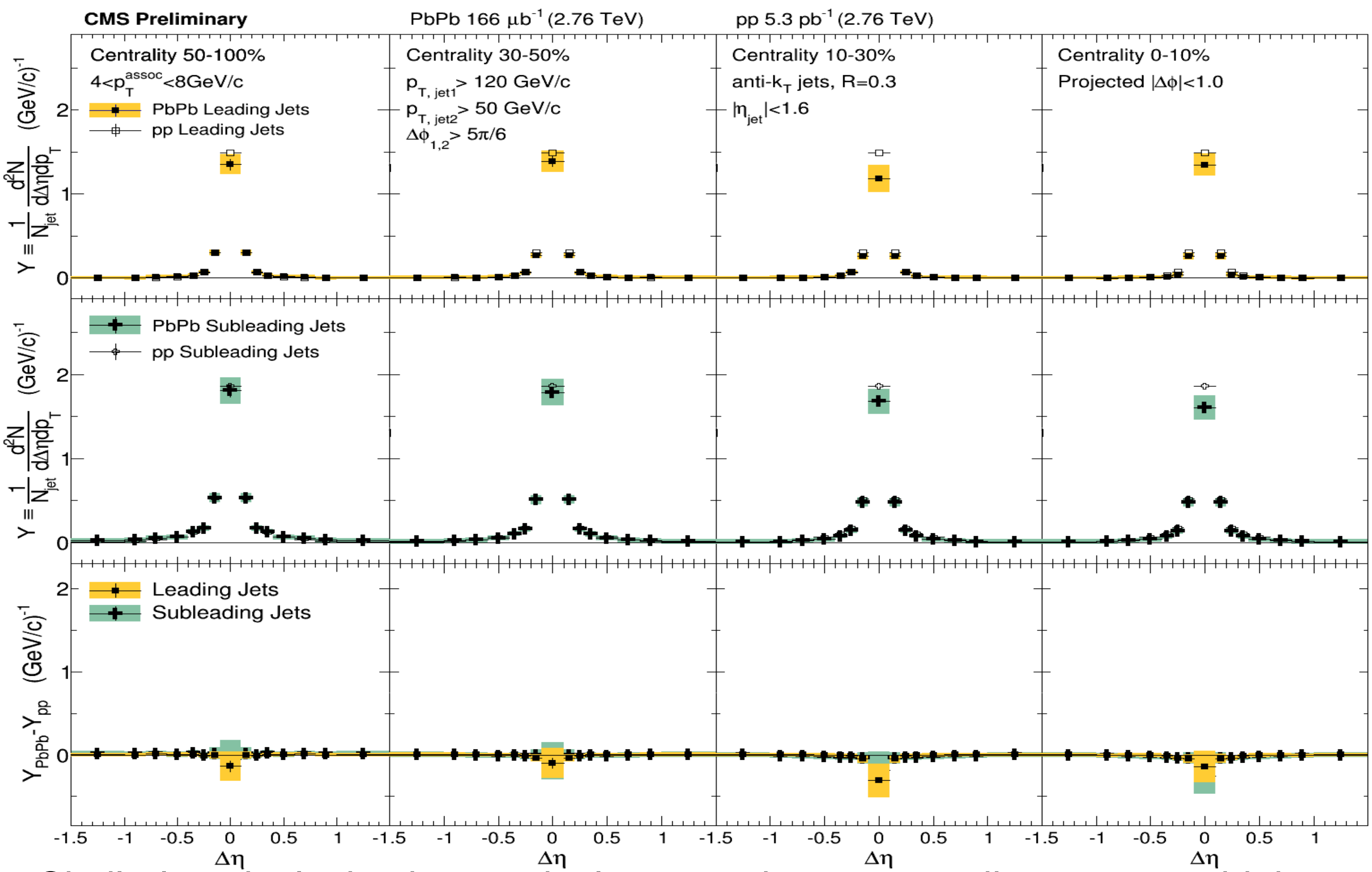
- Similarly to inclusive jet trends: low-p_T enhancement disappears at high-p_T
- Larger effects for subleading jets

Results: Dijet Δη Correlations ($3<p_T^{assoc}<4GeV/c$)



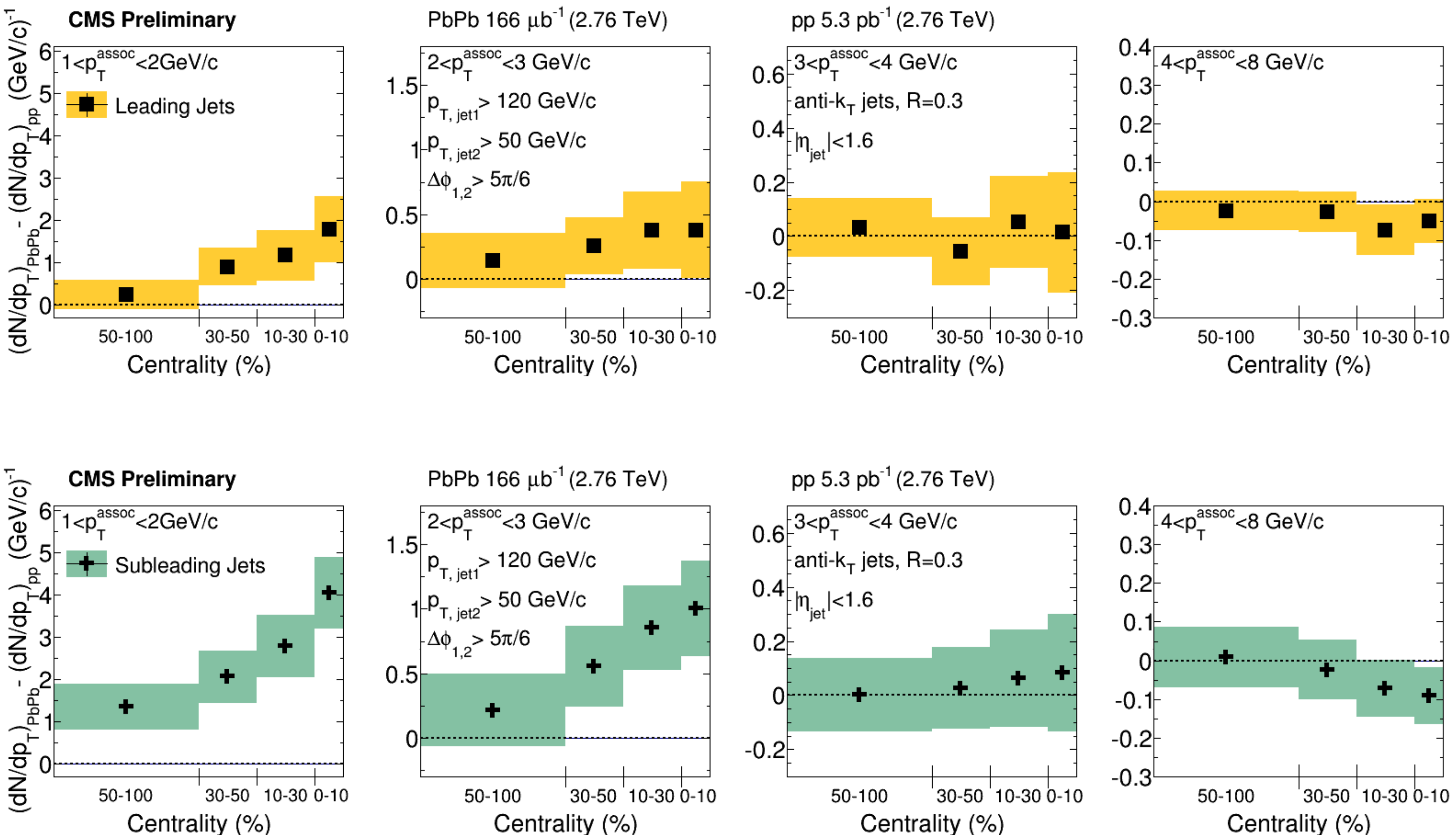
- Similarly to inclusive jet trends: low-p_T enhancement disappears at high-p_T
- Larger effects for subleading jets

Results: Dijet Δη Correlations ($4<p_T^{assoc}<8$GeV/c)



- Similarly to inclusive jet trends: low-p_T enhancement disappears at high-p_T
- Larger effects for subleading jets

Results: Integrated Yield by Centrality

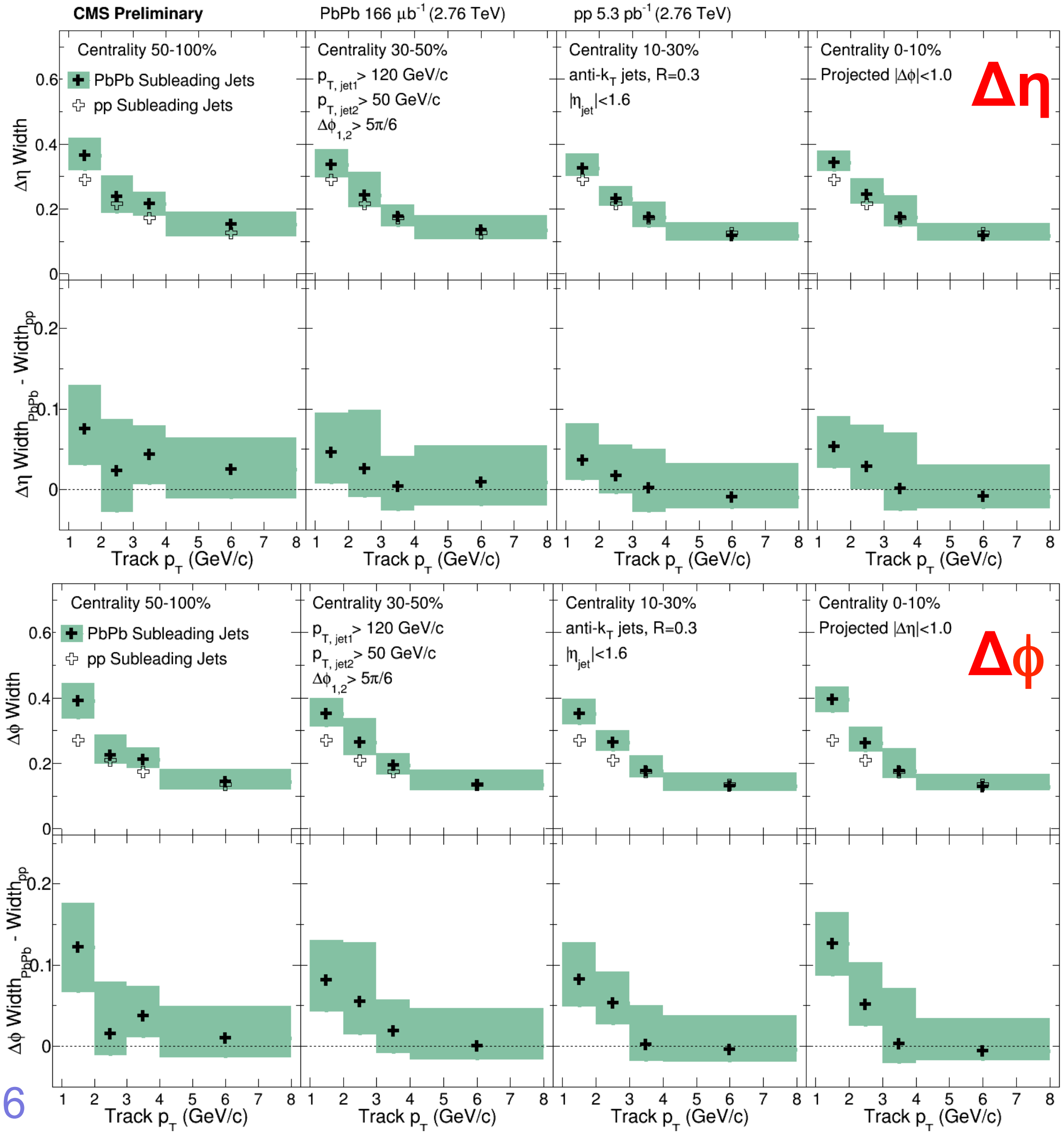


Results: Correlation Width (Subleading Jets)

- Extract correlations widths by fitting with double Gaussian

- Bottom panels show (PbPb width) – (pp width)

- Similar widths in $\Delta\eta$ and $\Delta\phi$
- Signs of broadening at low-p_T?



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Consistency Between Analyses

- Missing-pT analysis: projects all tracks onto average dijet axis, takes subleading minus leading hemispheres
- Jet-track analysis: could do the same from correlation—just weight by $p_T^{assoc}\cos(\Delta\phi)$
- **Cross-check shown perfect consistency between the two studies**
- Missing-p_T phase space:
  - $\Delta\eta$-$\Delta\phi$ area integrated into each Δr bin (cartoon for illustration)
  - Last Δr bin shown is catch-all for $\Delta r>1.8$