Measuring energy-energy correlators at the CMS experiment

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For the CMS Collaboration

Goal: Understanding the details of QCD dynamics

What gets me excited: studying the detailed dynamics of high-energy QCD

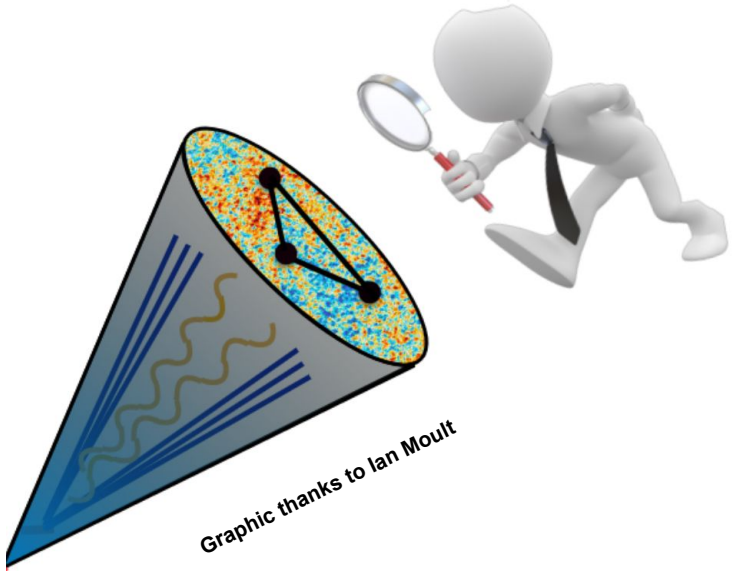
As we know, high-energy partons shower into columanted sprays of hadrons: **jets**

Emergent QCD dynamics play key role in jet formation→imprinted directly in energy pattern within jets

In HI collisions, impact of QGP should be encoded in modifications to this structure

Conclusion: **study jet substructure!**

(yes this is an instruction)



Enter: energy-energy correlators

Thought experiment: **pretend you are a conformal field theorist**

Maybe you don't have to pretend!

Energy patterns inside jets encoded in energy flow operator

$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt n^i T_{0i}(t, r\vec{n})$$

The study of jet substructure **is*** the study of correlators of this operator!

- Can employ many powerful theoretical tools (lightray OPE, …)
- NP corrections relatively straightforward
- …

So this is what we should measure!

* *other formalisms are available*

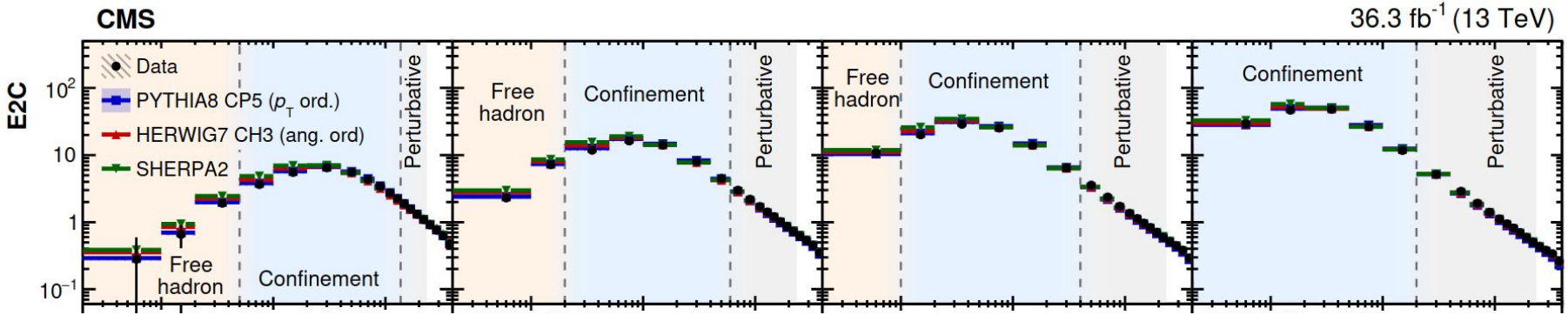
Understanding energy-energy correlators

x_L ~ splitting p_T
~ $1/t_{formation}$

Small angle
E2C ~ R_L -> uniform distribution
-> free particles

Intermediate angle
Crossover between two regimes
Confinement transition

Large angle
E2C ~ $R_L^{\text{anomalous dimension}}$
~ asymptotically free partons



CMS-SMP-22-015

Confinement transition ~ Λ_{QCD} / p_T

Energy-energy correlator measurements at CMS

Talk about three analyses today:

1. Second- and third-order EECs at 13 TeV, with measurement of α_S (CMS-SMP-22-015)

2. Modification of inclusive-jets EECs in in PbPb collisions (CMS-HIN-23-004)

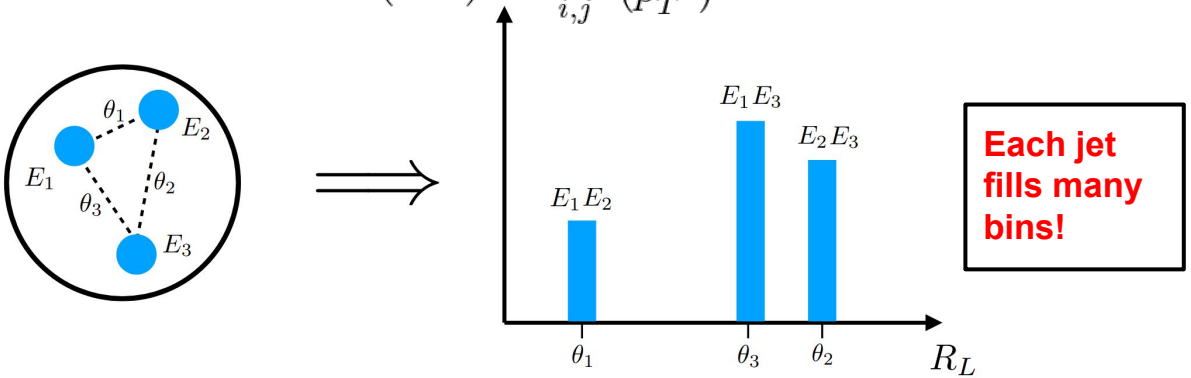
3. Modification of full-event EECs in Z+Jets PbPb events (CMS-HIN-24-019)

Common experimental challenges

Measuring EECs

- N-point correlator measured as energy-weighted N-way correlation between configurations of particles
- **Each jet contributes a distribution in configuration space**
  - Configuration space can be projected onto longest axis for single scaling variable
- Ex: 2-point correlator depends only on angular separation between pair

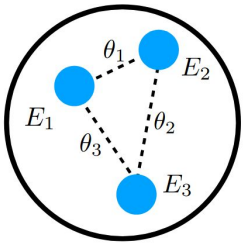
$$\frac{d\Sigma}{d(\Delta R)} = \sum_{i,j} \frac{p_T^i p_T^j}{(p_T^{jet})^2} \delta(\Delta R_{ij} - \Delta R)$$

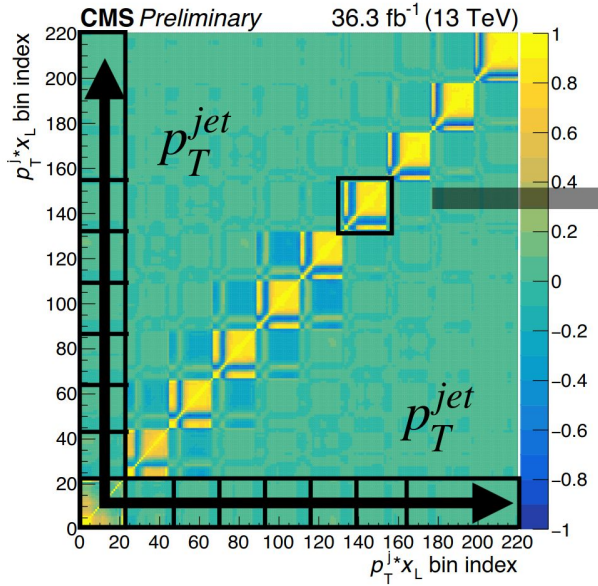


Statistical correlations

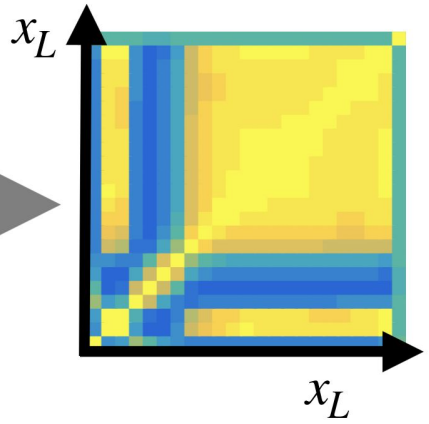
Every bin of every observable is statistically related to every other bin of every other observable

$$N = \sum_i w_i \pm \sqrt{\sum_i w_i^2}$$





E2C correlation matrix



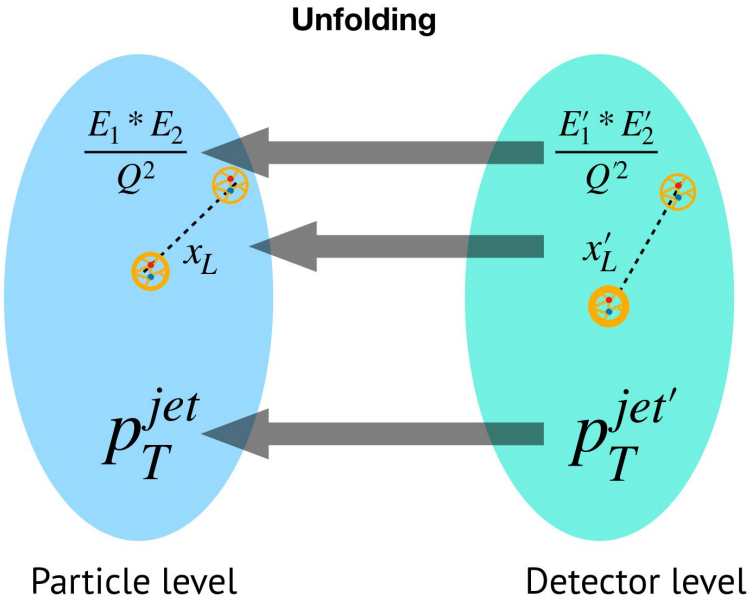
x_L bins in a p_T^{jet} region

Correlation: 80%

Figures from Meng Xiao's alphas workshop talk

Unfolding complications

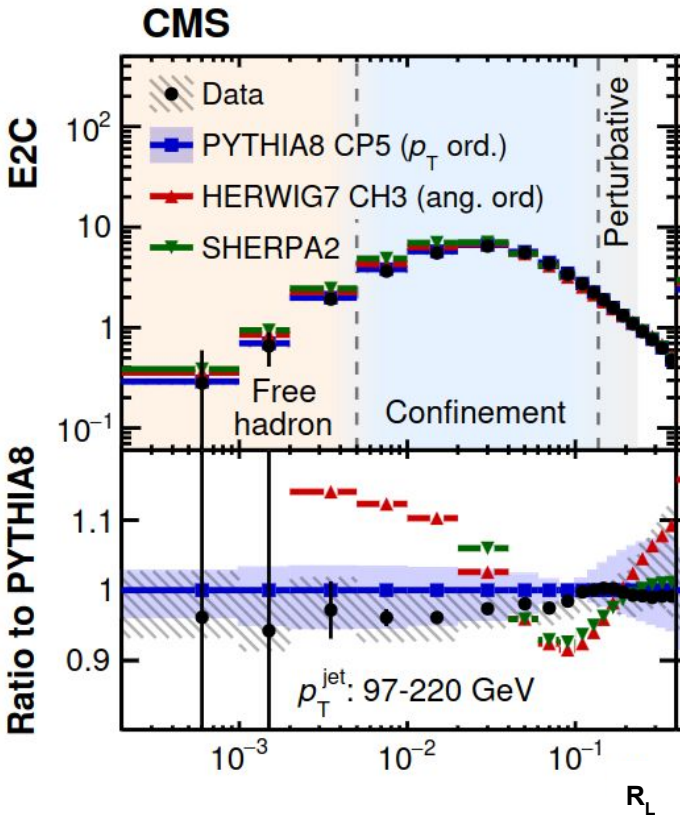
- Each jet contributes distribution, rather than single number
  - Not sufficient to simply match jets from particle to detector level
  - **Must account for reconstruction of individual final-state particles**
- Most complicated for neutrals, where particle-level to detector-level mapping can be many-to-many



Second- and Third-Order EECs in 13 TeV pp collisions

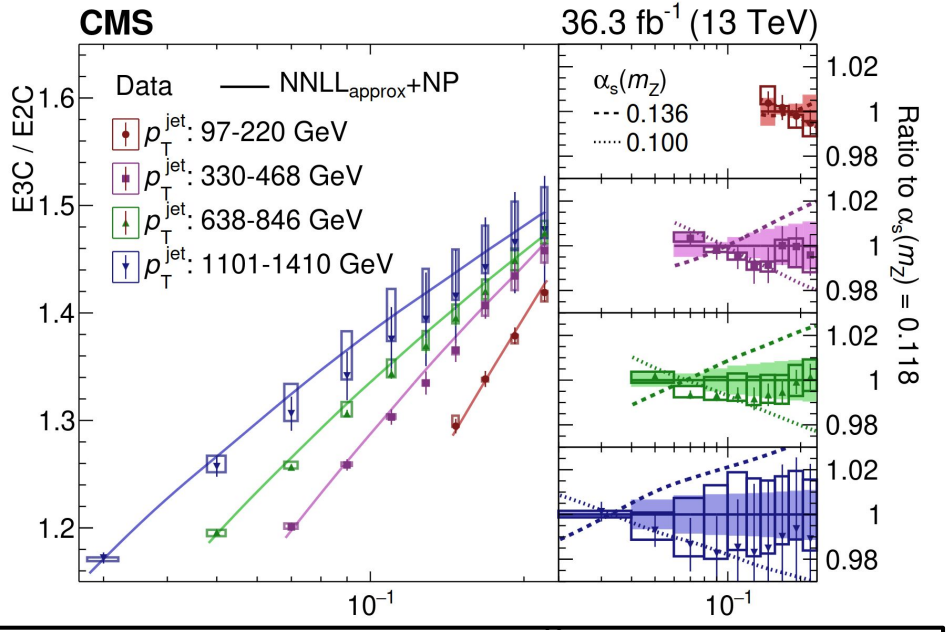
EECs in 13 TeV proton-proton collisions

- Measurement is fully-unfolded in three dimensions: jet pT, ΔR, EEC weight
- Make direct comparison with parton shower models
- Agreement with Pythia8 predictions remarkably good
- Herwig, Sherpa agreement worse



Slopes and the strong coupling

- EEC slope (in log-log) in perturbative regime is anomalous dimension
- Higher-order EECs probe higher-order anomalous dimensions
- Ratio of third-order to second-order cancels systematics and isolates strong coupling
- Comparison with NNLL calculation allows extraction of strong coupling



Result: $\alpha_S = 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$

Slopes and the strong coupling

Most precise α_s to date from pp jet substructure!

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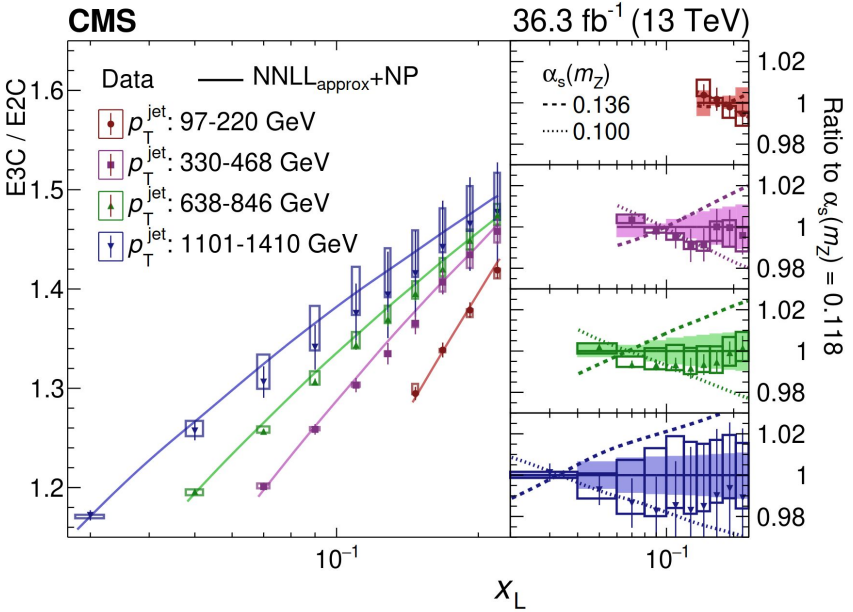

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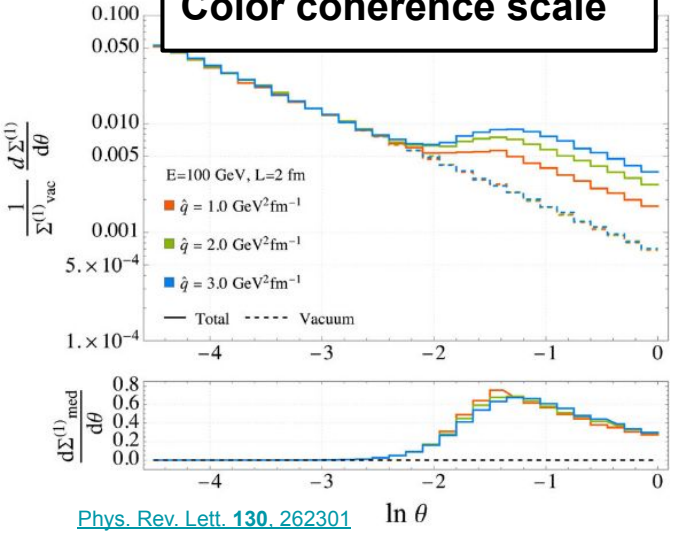
Inclusive-jets EECs in PbPb collisions

Modification of EECs in medium

- Natural next question: how are EECs modified in medium?

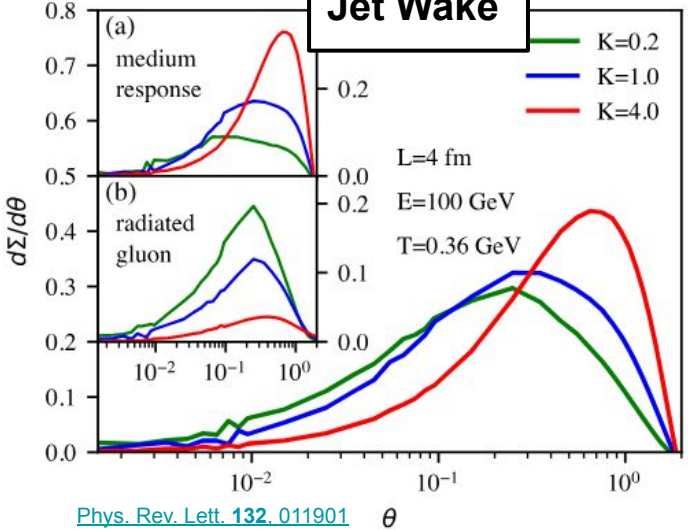
- Theory indicates that EECs are powerful probe of medium effects

Color coherence scale



Phys. Rev. Lett. **130**, 262301

Jet Wake



Phys. Rev. Lett. **132**, 011901

Measuring EECs in PbPb

Analyze jets with momenta between 120-200 GeV from inclusive-jets trigger

Main challenge: large, uncorrelated underlying event background

Mitigation strategies:

1. Apply minimum track pT cut of either 1 GeV or 2 GeV
   a. Higher cut eliminates more background
   b. Lower cut keeps more signal from soft emissions and medium-induced radiation
2. Modify EEC definition to further suppress soft background and reduce sensitivity to uncertainty in jet momentum response
3. Careful background subtraction (see next slides)

Modified EEC definition

Recall the definition of the second-order EECs|

$$\frac{d\Sigma}{d(\Delta R)} = \sum_{i,j} \frac{p_T^i p_T^j}{(p_T^{jet})^2} \delta(\Delta R_{ij} - \Delta R)$$

Modified EEC definition

Recall the definition of the second-order EECs|

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We make two modifications:

1. **Replace jet pT in denominator with a simple normalization factor**
   a. Uncertainty in jet pT >> uncertainty in track momenta
   b. This avoids having to unfold in the EEC weight
   c. Equiv to assumption that pT bins are delta-function thin

Modified EEC definition

Recall the definition of the second-order EECs|

$$\frac{d\Sigma}{d(\Delta R)} = \sum_{i,j} \left(\frac{p_T^i p_T^j}{(\ \mathbf{N}\ )^2} \right)^{\mathbf{n}} \delta(\Delta R_{ij} - \Delta R)$$

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1. **Replace jet pT in denominator with a simple normalization factor**
   a. Uncertainty in jet pT >> uncertainty in track momenta
   b. This avoids having to unfold in the EEC weight
   c. Equiv to assumption that pT bins are delta-function thin
2. **Consider extended EECs with larger powers of particle momenta (n=**
   a. Breaks IRC safety of the observable, but in a well-controlled manner that is still amenable to theoretical interpretation
   b. Adds additional suppression of low-momentum backgrounds

Background subtraction

- Each jet constituent can be consider to be either **S**ignal or **B**ackground
  - Signal is from fragmentation of initial hard parton, plus particles from jet-medium interactions
  - Background is everything else
- EECs consist of **S**+**S**, **S**+**B**, and **B**+**B** components
- **S**+**B**, and **B**+**B** are **background**, and **need to be subtracted**

- Strategy: mix in two DATA minimum-bias events with each event
  - Selected to have the same global characteristics as the main event
  - Need two matched events in order to capture both correlated **B**+**B** and uncorrelated **S**+**B**

- The background is modeled as

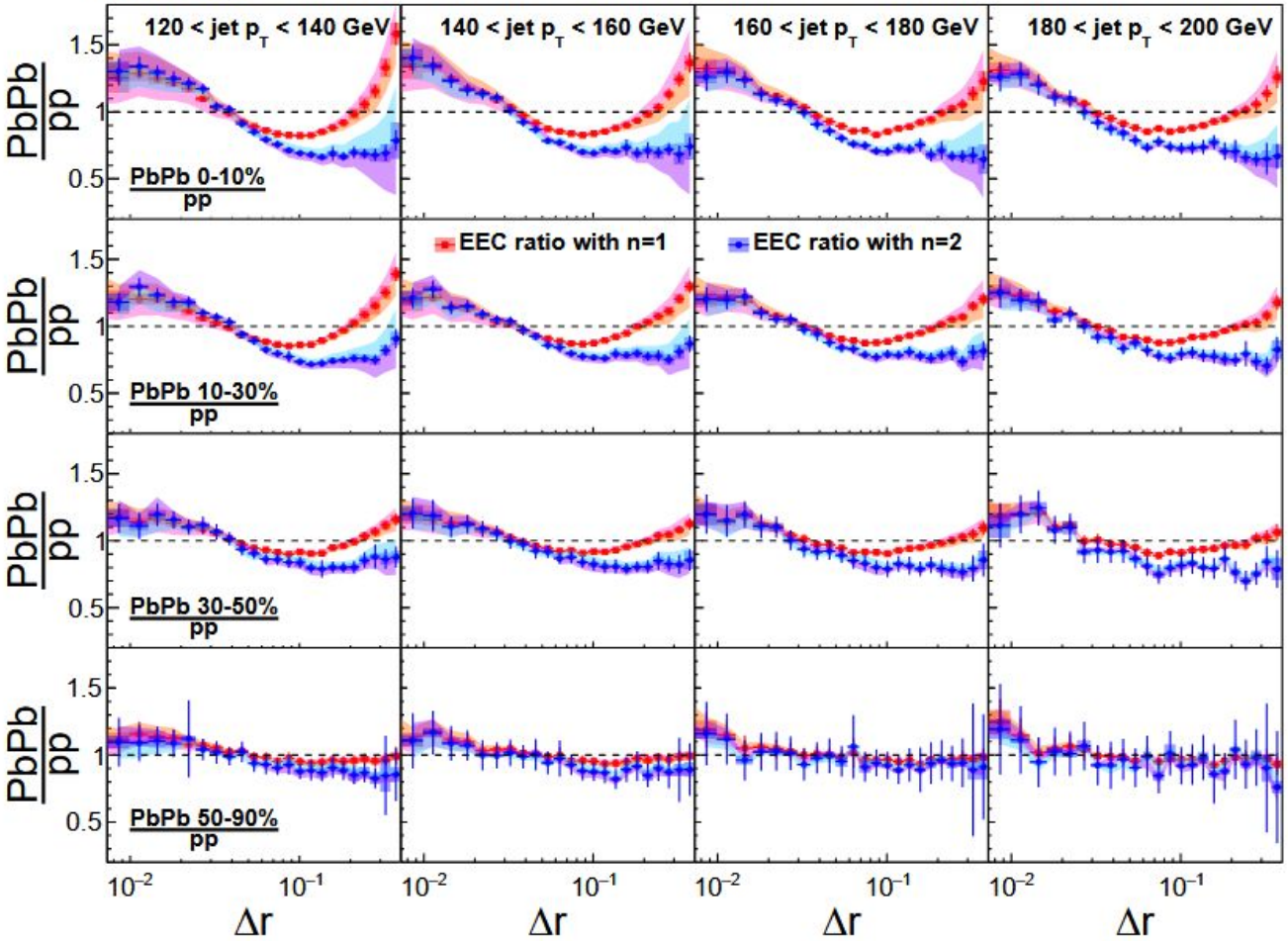
$$\mathrm{BG_{mixed}} = (\mathrm{S} + \mathrm{M1}) + (\mathrm{M1} + \mathrm{M1}) - (\mathrm{M1} + \mathrm{M2}).$$

Unfolded results

CMS *Preliminary*

$p_T^{ch} > 1$ GeV

track pT threshold 1 GeV

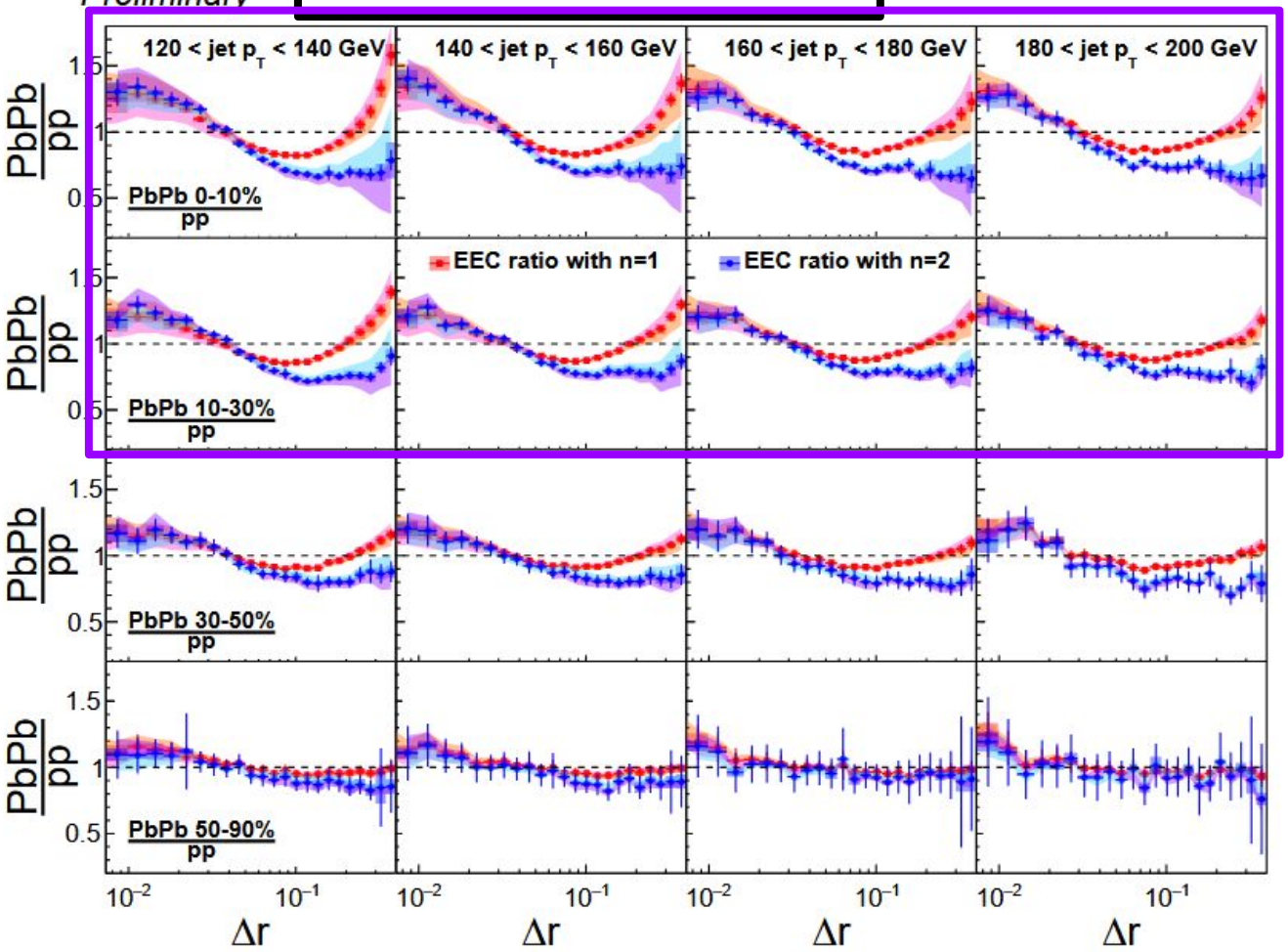


Red: standard EECs with exponent n=1

Blue: modified EECs with exponent n=2

Track threshold 2 GeV in backup

Unfolded results



track pT threshold 1 GeV

Large modification at low centrality -> more QGP, particularly at low pT -> more quenching

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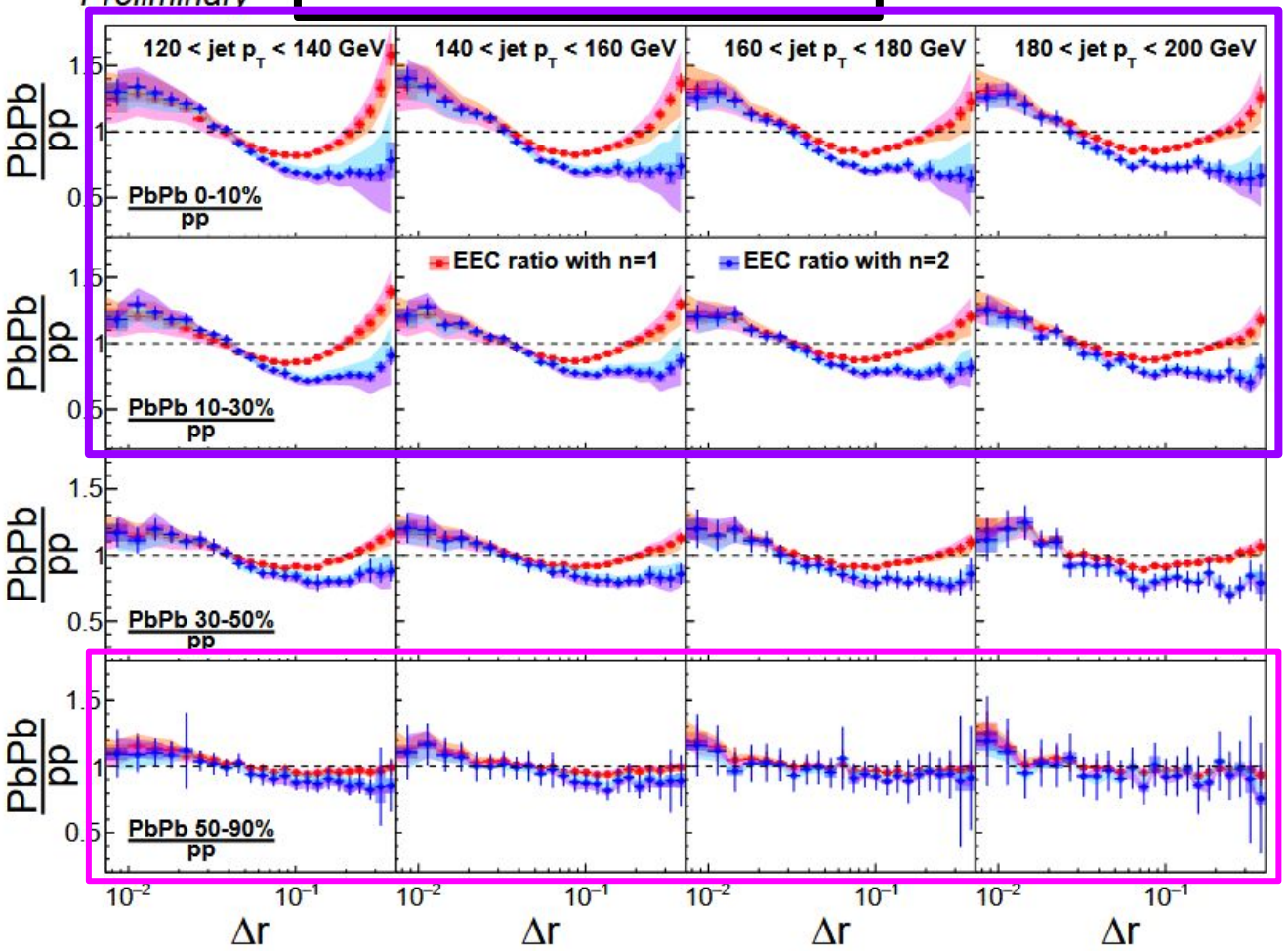
Unfolded results



track pT threshold 1 GeV

Large modification at low centrality -> more QGP, particularly at low pT -> more quenching

Red: standard EECs with exponent n=1

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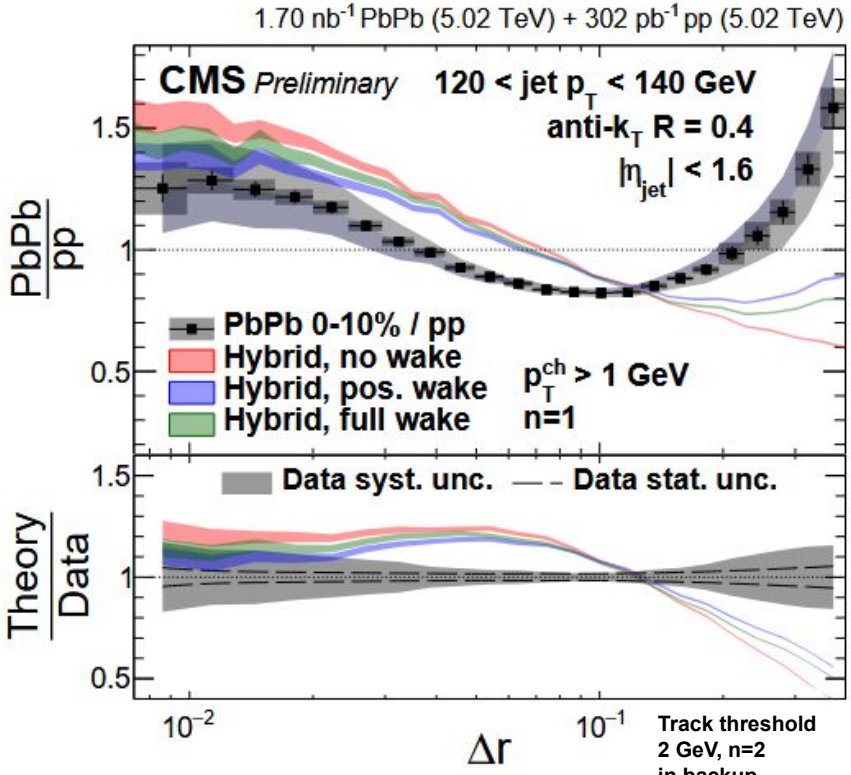
Less modification at high centrality -> less QGP

Track threshold 2 GeV in backup

What is this modification?

- Enhancement at small angle -> jet shape is **narrower** in PbPb
  - This has been seen before in other observables by ATLAS, ALICE
- Recent CMS gamma+jets result suggests cause: **wider jets more likely to be quenched**
- Enhancement at large angle not modeled well in MC, but **qualitative behavior can only be reproduced with full wake**



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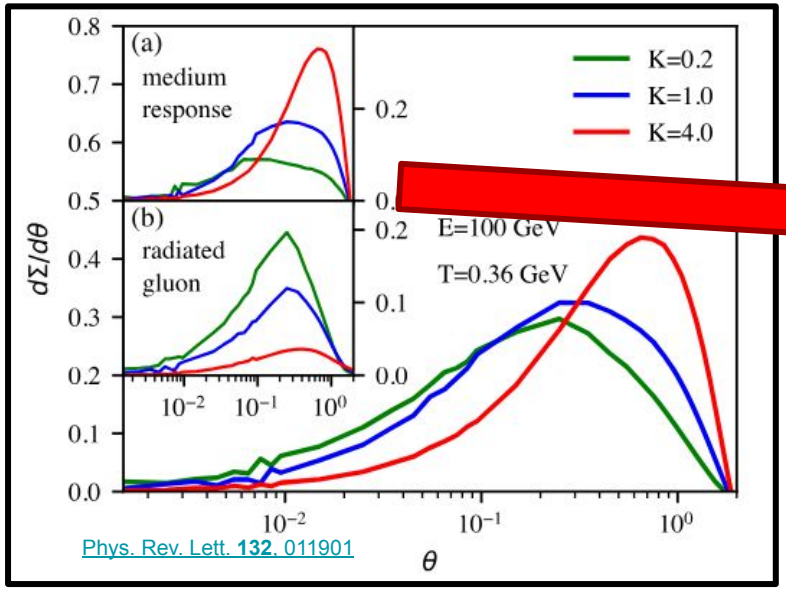

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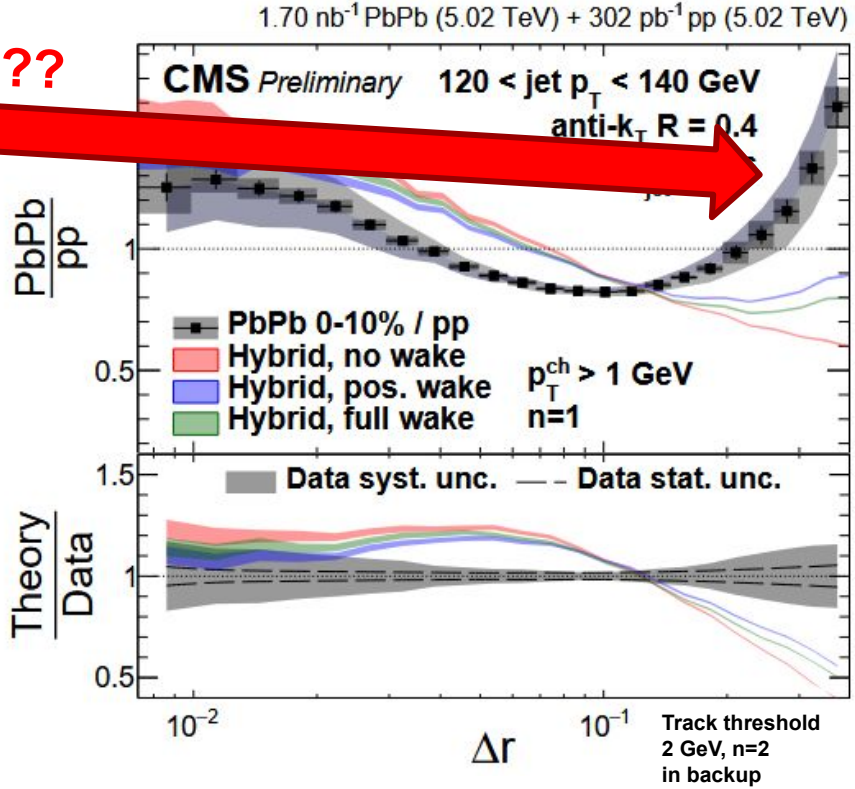

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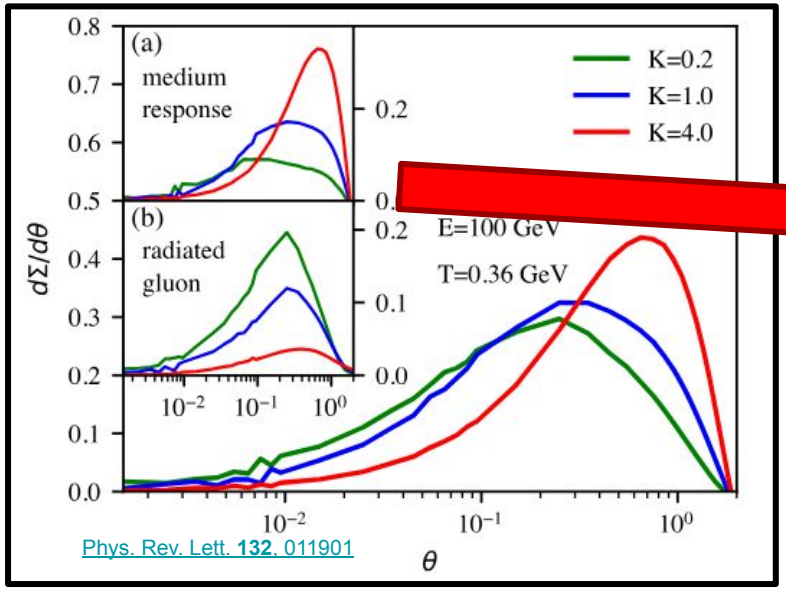
What is this modification?

Rithya will talk more about this next!!



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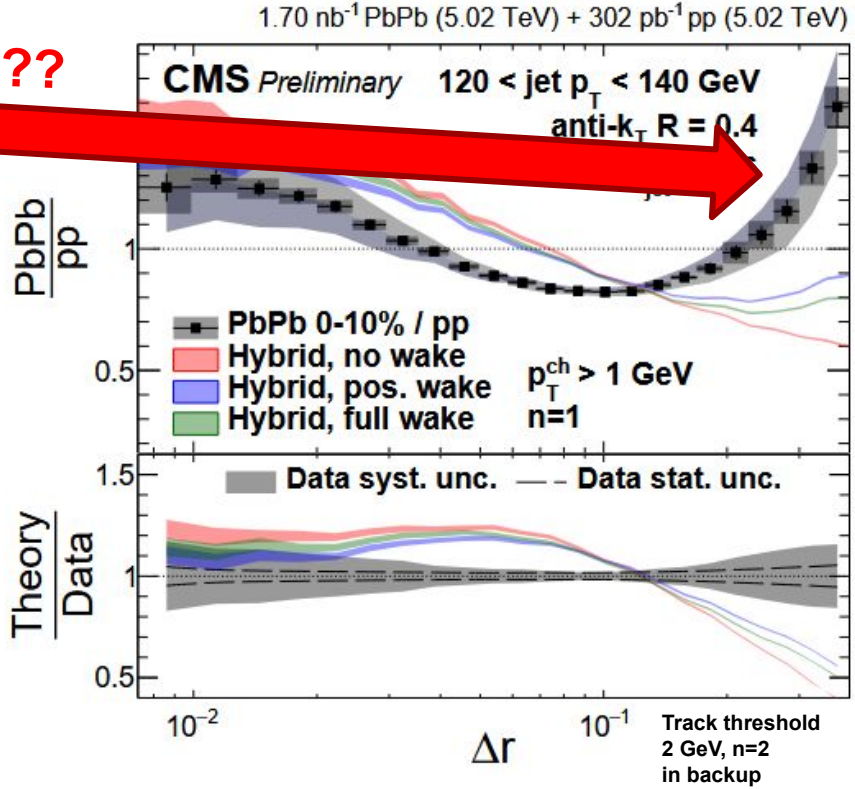


- Enhancement at large angle not modeled well in MC, but **qualitative behavior can only be reproduced with full wake**

Z+jets full-event EECs in PbPb collisions

EECs in Z+X

Complementary approach to inclusive-jets analysis:

- Tagging on Z boson allows extension to lower pT -> more quenching
- Z boson does not interact with QGP -> no selection biases
- Considering full event allows sensitivity to wide-angle radiation out to $\Delta R < 4$

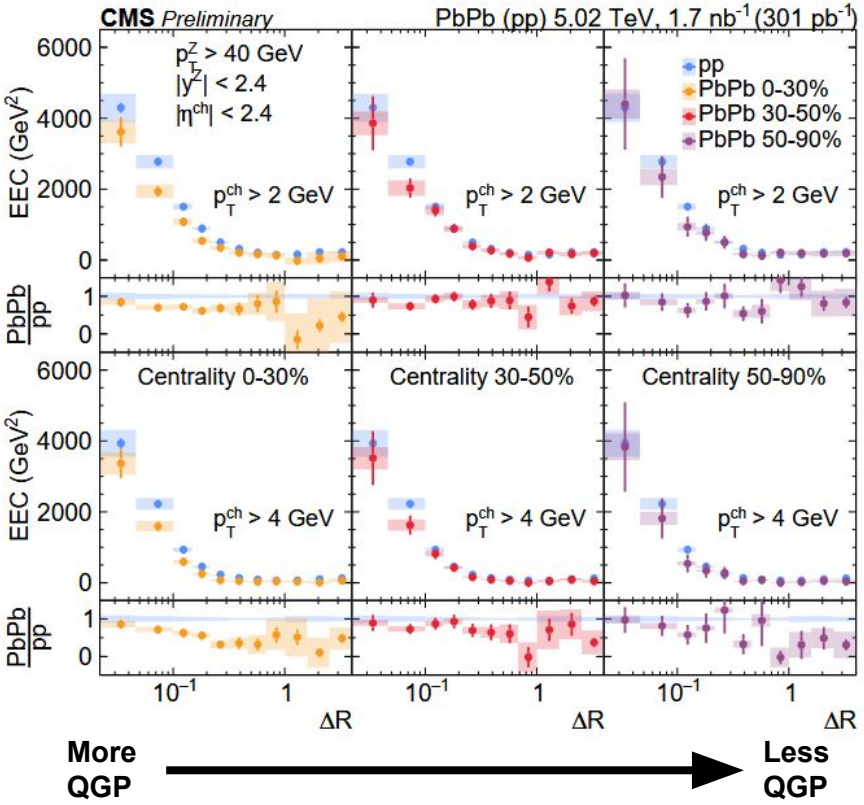
Same background strategy as inclusive-jets analysis, but only considering exponent n=1

This result is not unfolded

- Inclusive in Z pT > 40 GeV
- Don’t go to very small angles where detector smearing is important

Results

- Distributions dominated by collinear peak due to recoil jet
  - No back-to-back peak at R=pi as Z boson is color-neutral and decouples from the rest of the event



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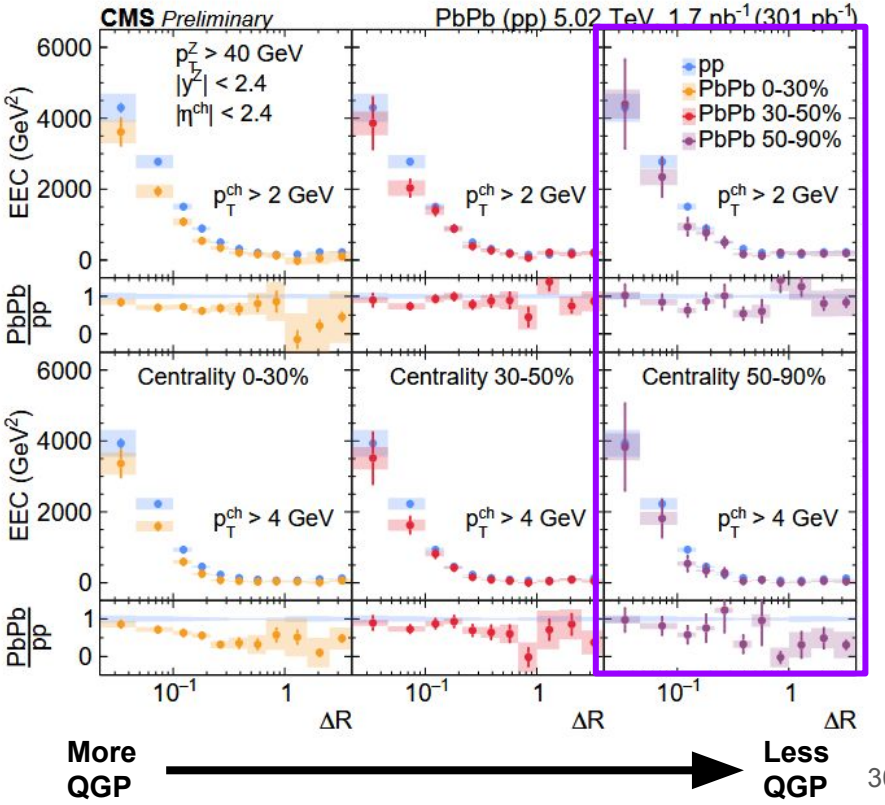

Results

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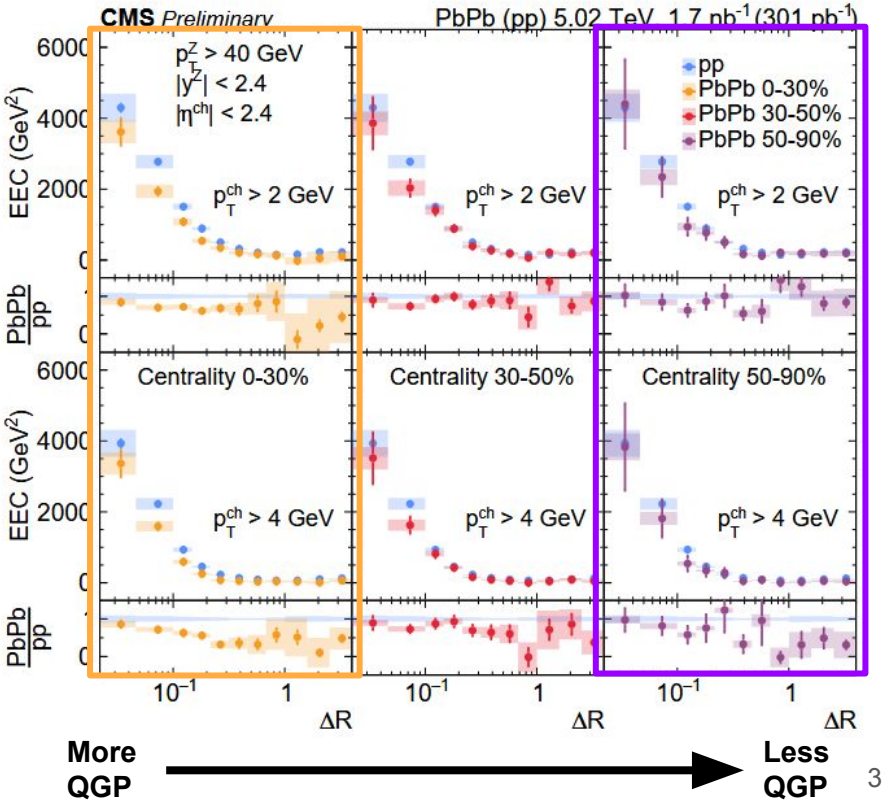
  - No back-to-back peak at R=pi as Z boson is color-neutral and decouples from the rest of the event
- **High-centrality (-> less QGP) consistent with no modification**
- **Low centrality (-> more QGP) sees modification across wide angular scales**



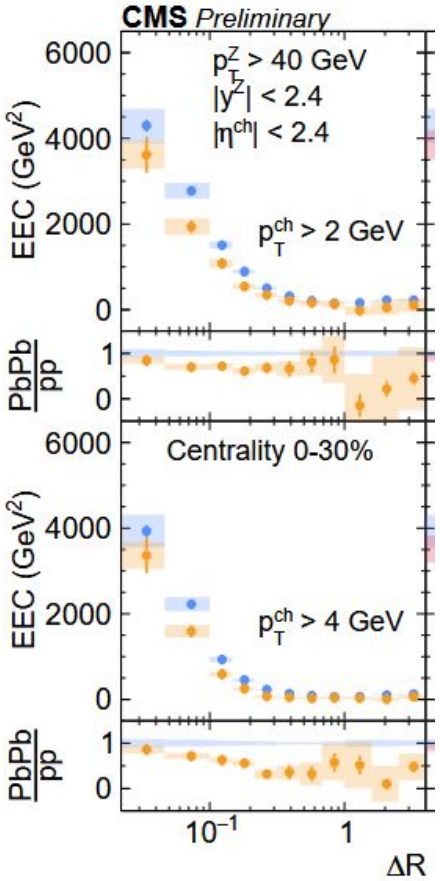
Understanding the modification

Medium effects are strongly dependent on the track pT cut

It is clear that the medium modification effects extent to very large angular separations

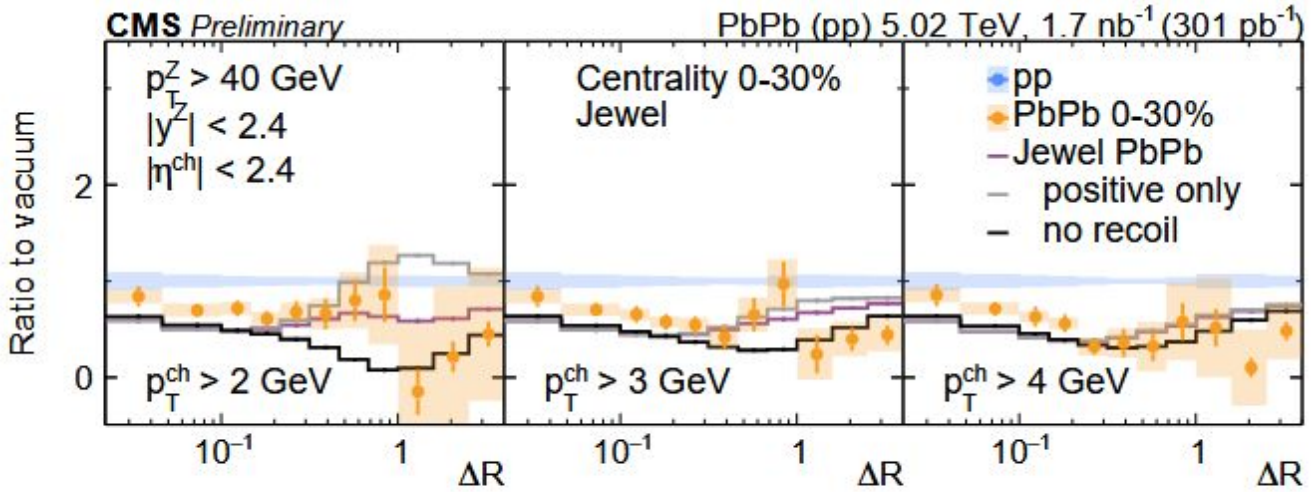
For **track pT > 2 GeV**, the EEC flux is **partially recovered** by soft hadron production in the QGP

For **track pT > 4 GeV**, the EEC flux is **suppressed** due to jet quenching



Data/MC comparison

Focus on lowest centrality bin



Jewel models the data well

More MC models in backup

Recoil is needed to capture the shape of the data for soft tracks

Conclusions

- Energy-energy correlators provide a powerful window into QCD dynamics
- The CMS collaboration is actively working to measure these observables all across the phase space, including in both pp and HI collisions
  - We're not done by a long shot - watch this space!
- Measurement of the second- and third-order EECs at 13 TeV has allowed for the most-precise extraction of the strong coupling from jet substructure
- Measurements in heavy ions cast light on medium modification to jet showering, including potential signals of wide-angle effects (the "jet wake")

Backup

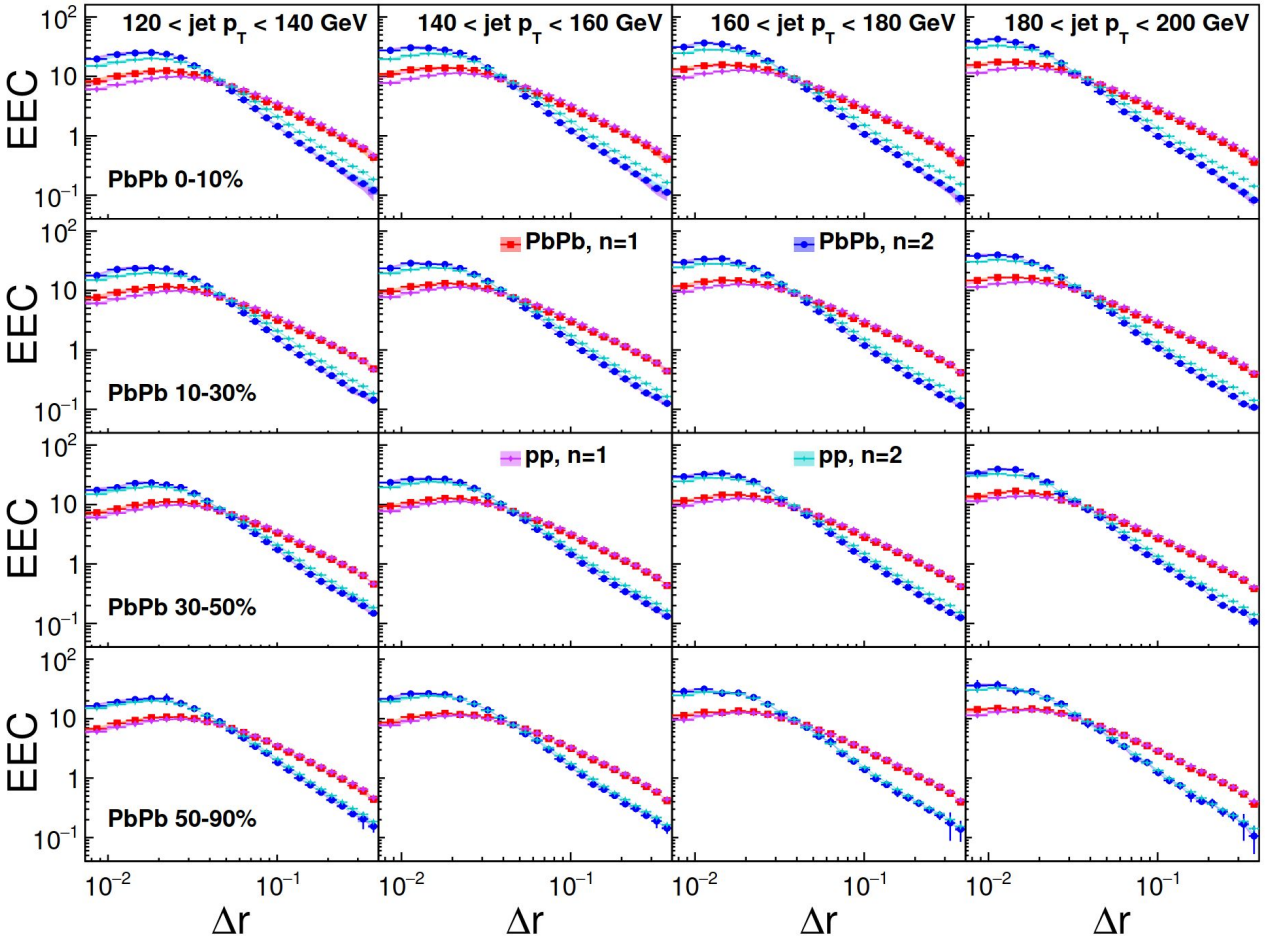
Inclusive-jets EECs in PbPb collisions

CMS *Preliminary*

Unfolded results

$p_T^{ch} > 2$ GeV

track pT threshold 1 GeV



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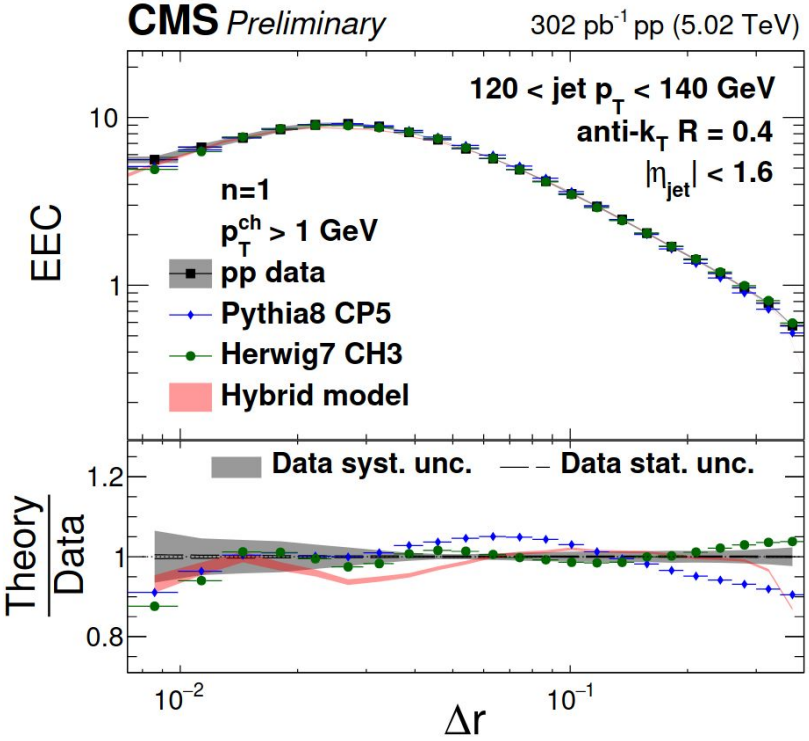
Vacuum EECs


CMS Preliminary
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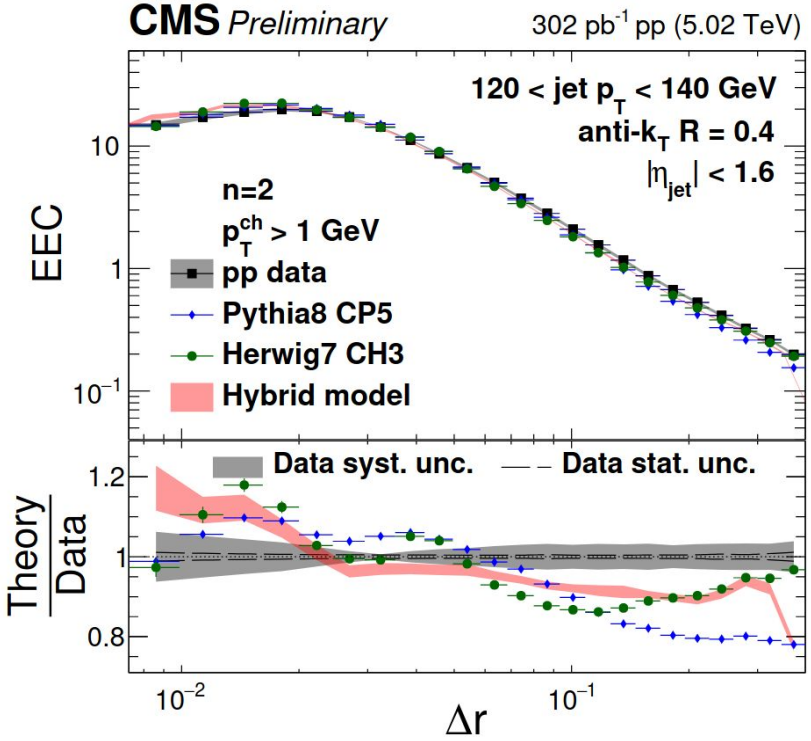
120 < jet pT < 140 GeV
anti-kT R = 0.4
|ηjet| < 1.6
n=1
pchT > 1 GeV
pp data
Pythia8 CP5
Herwig7 CH3
Hybrid model
EEC
Data syst. unc.
Data stat. unc.
Theory / Data
Δr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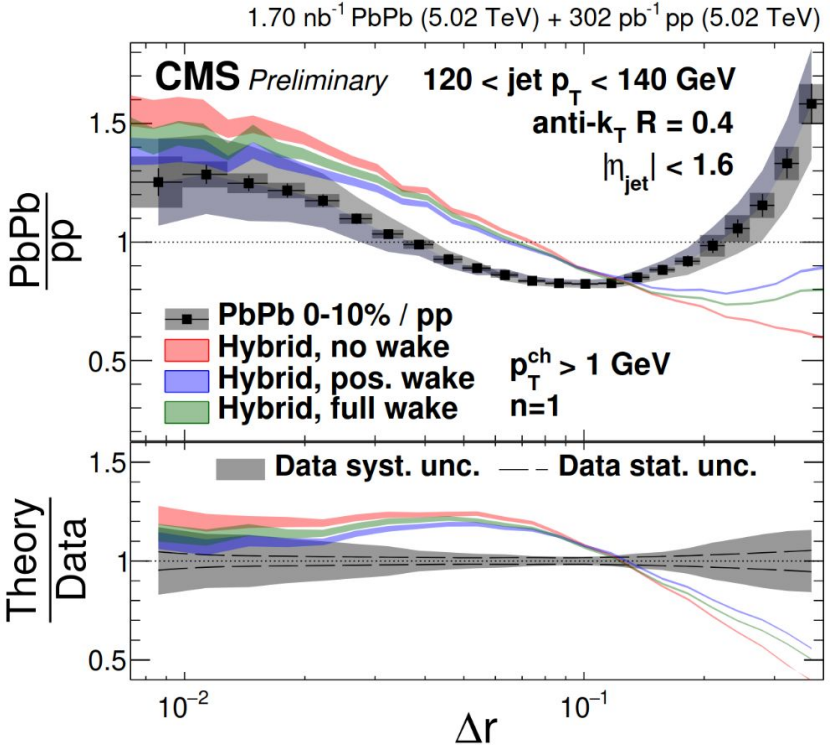
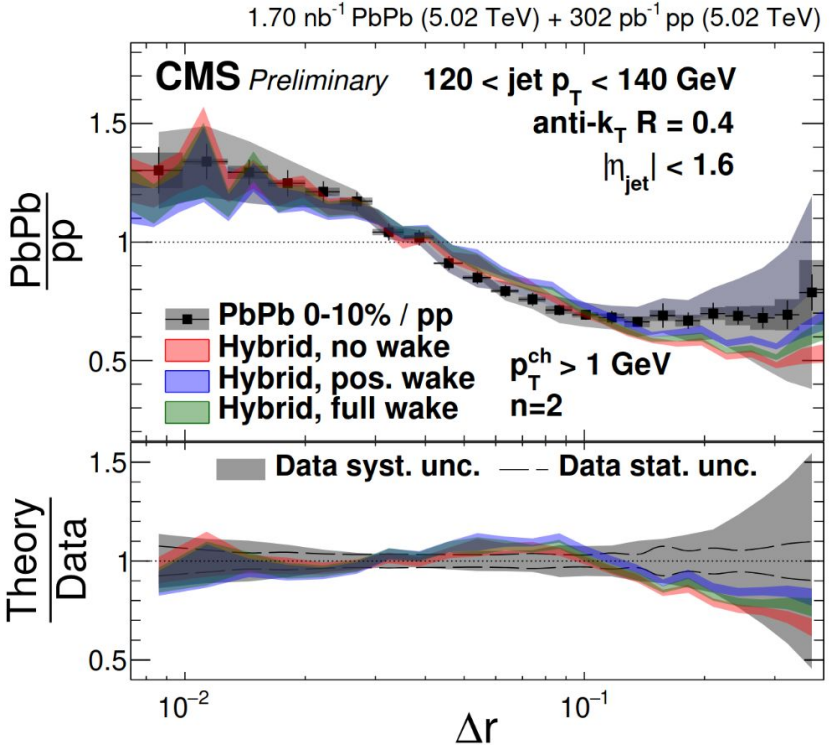
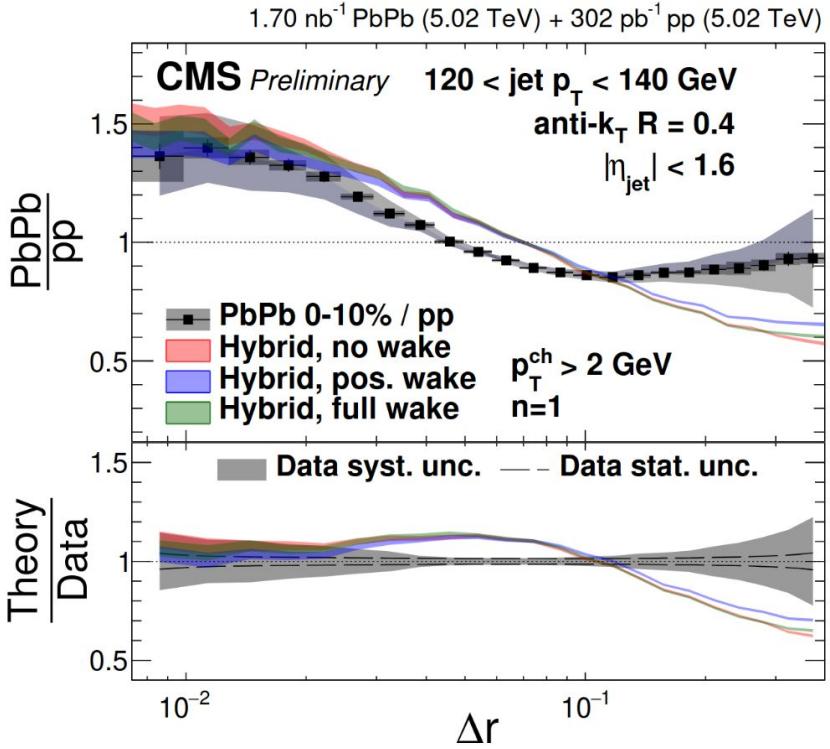
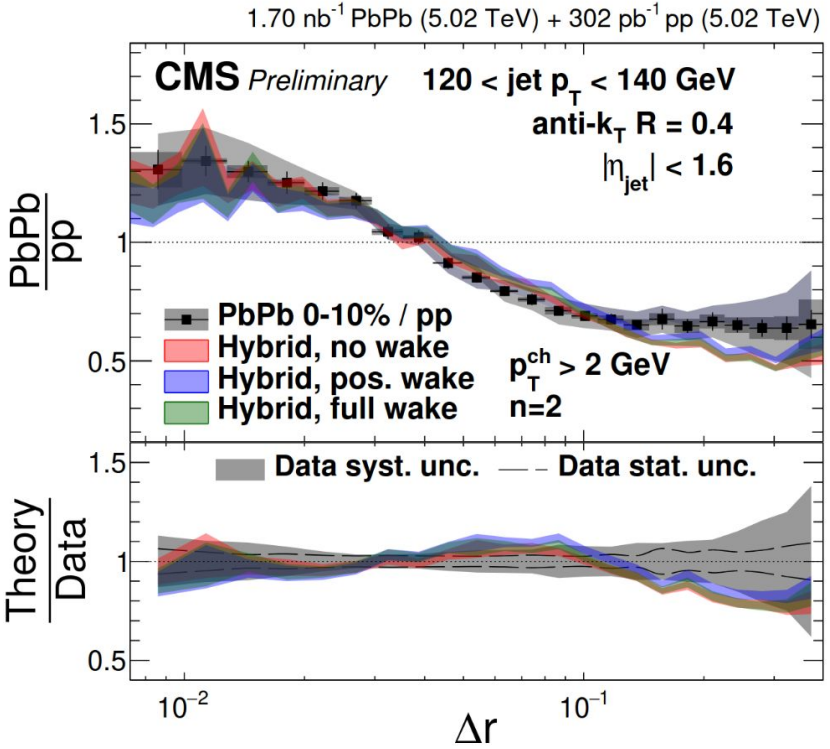
PbPb EECs - track pT > 1 GeV





PbPb EECs - track pT > 2 GeV

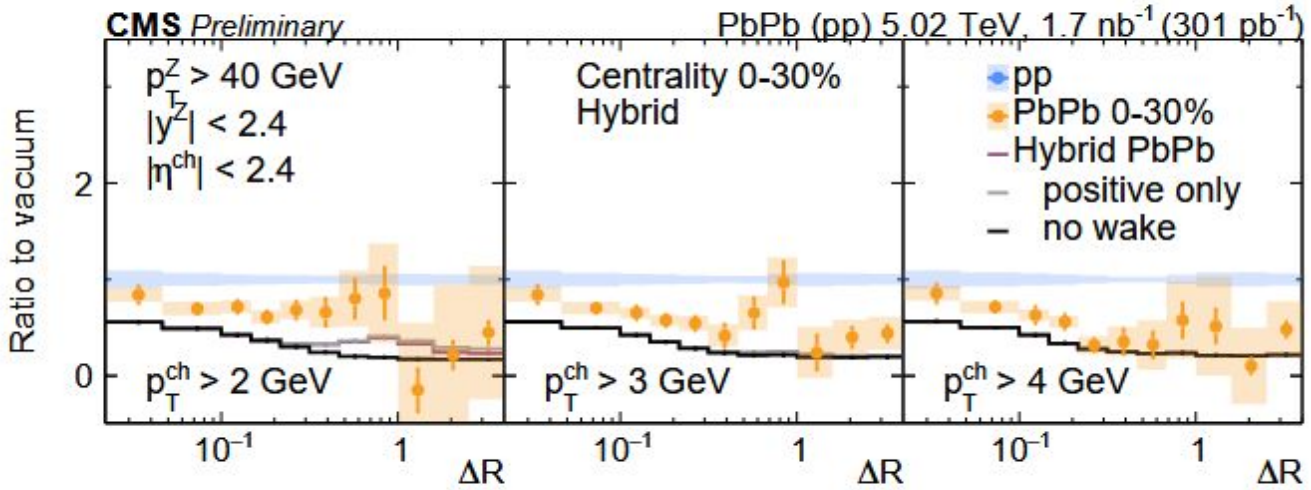




Z+jets full-event EECs in PbPb collisions

Data/MC comparisons

Focus on lowest centrality bin

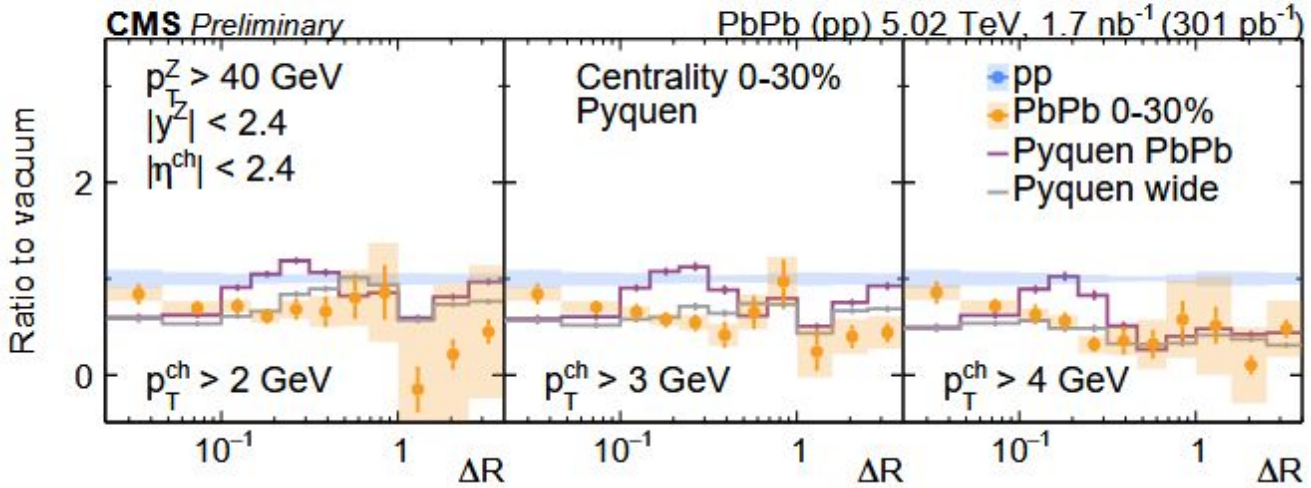


Hybrid model over-predicts suppression at small angle

Wake effects are predicted to be small

Data/MC comparisons

Focus on lowest centrality bin



Pyquen with wide-angle emissions models the data well

The model without wide-angle emissions over-predicts flux at intermediate angle