Recent highlights on QCD and QED studies with heavy ion collisions at CMS

Chris McGinn on behalf of the CMS collaboration

ICHEP, Prague

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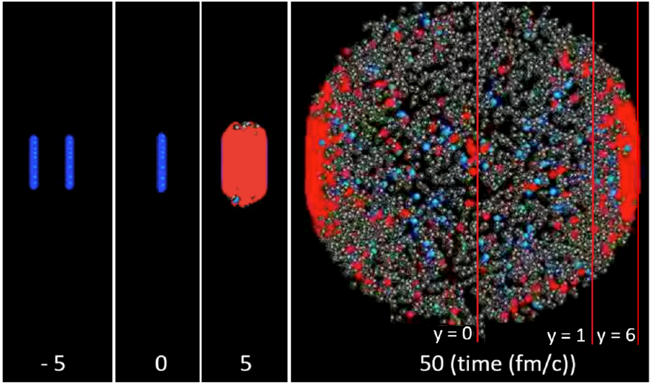
The Quark Gluon Plasma



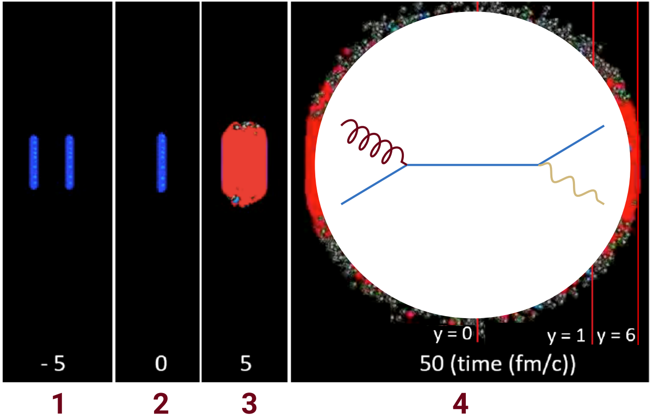
1 2 3 4

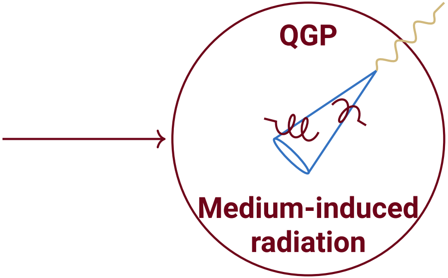
Still via Ann.Rev.Nucl.68 (2018)

Full video via Yen-jie Lee, Wit Busza, and Andre Yoon

1. Lorentz-contracted nuclei inbound
2. Initial collision; Hard-probes formed here
3. After some formation time, Quark Gluon Plasma (QGP)
4. After some longer time, freezeout and hadronization

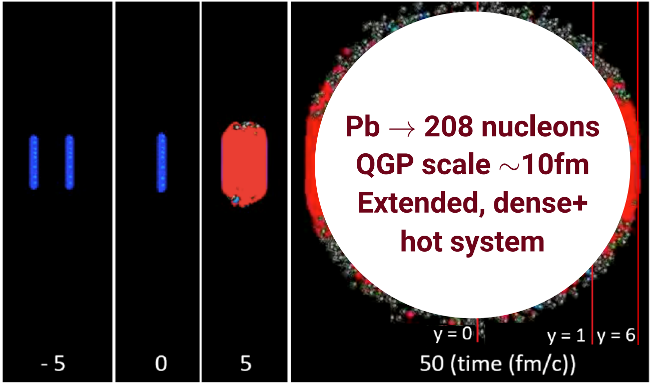
The Quark Gluon Plasma





- Deconfined quarks and gluons form a dense medium (3)
  - Strong interactions make it opaque to color charge
- Early time (2) hard scatterings produce jets as probes!
- Today: 2 new results probing jet-medium interactions in PbPb

Quark Gluon Plasma... in Small Systems?



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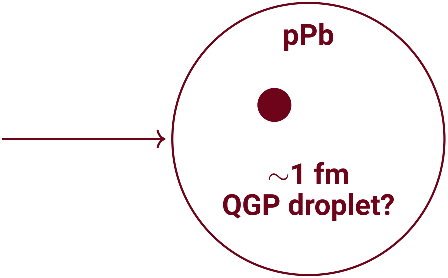
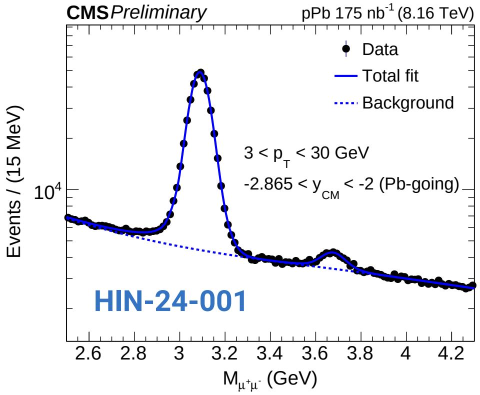


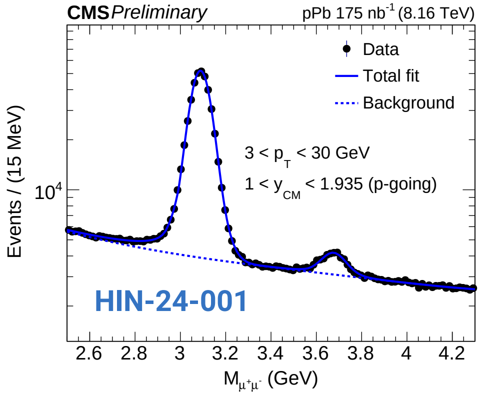
- Have observed QGP-like behavior in small systems many years now
  - True droplet of QGP? Something else?
- Signatures like flow, strangeness enhancement, etc.
- Today: Three new pPb results exploring QGP signatures

Recent Results exploring QPG-like effects in pPb

$\sigma(\psi(2S))/\sigma(J/\psi)$ in pPb (I)



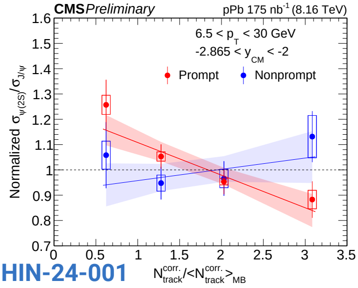
Backward, Pb-going

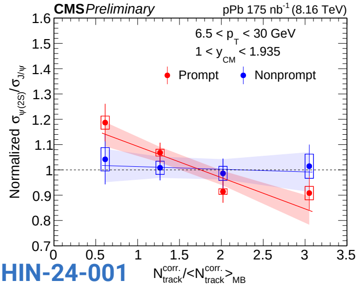


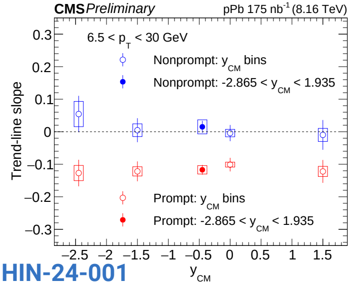
Forward, p-going

- **Measured in bins of p_T, y, and charged particle multiplicity, for prompt and non-prompt**
- **Above mass peaks in two rapidity binnings**
  - **Relative peak size implies statistical limitations in ψ(2S) measurement**

$\sigma(\psi(2S))/\sigma(J/\psi)$ in pPb (II)





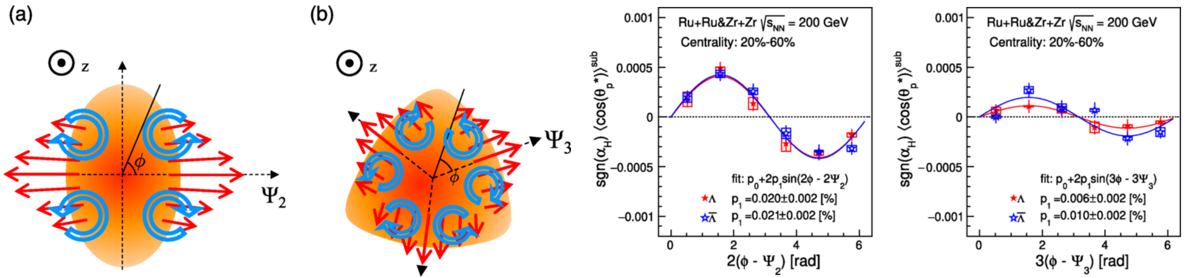


Backward, Pb-going **Forward, p-going** **Slope (y-averaged)**

- **Consistently observe negative slope in prompt, across all y**
  - **No slope observed in nonprompt**
- **Qualitatively consistent with expected final-state effects on hadronization**
  - **Prompt experience full evolution of the system**
  - **b-hadron produces non-prompt post-system evolution**

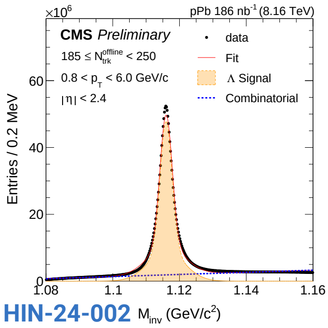
Lambda Polarization in pPb (I)

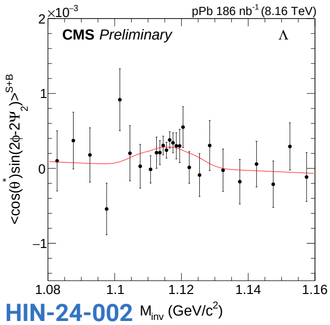
Via STAR, PRL 131 202301

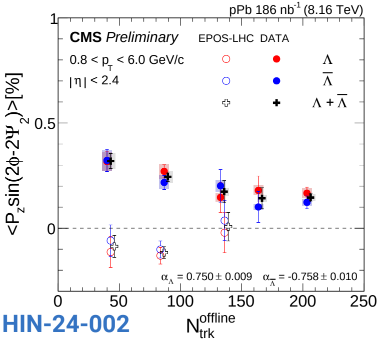


- **Pressure gradient induces vorticity fields; can result in local polarization of hyperons**
  - **Extract as $P_z\sin(2(\phi - \Psi_2))$**
- **Star has observed the local polarization in AA collisions!**
- **We also observe signatures of flow in small systems...**
  - **Similar to our history w/ the ridge, search for this effect in small systems**

Lambda Polarization in pPb (II)



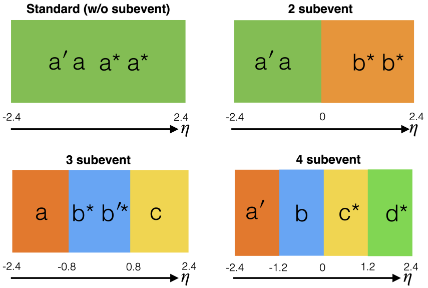


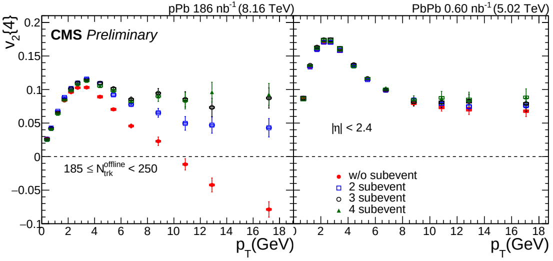


- **Left and middle: Simultaneous fit in mass and $\cos\theta^*\sin(2(\phi - \Psi_2))$**
- **Right: Extracted $P_z\sin(2(\phi - \Psi_2))$ in pPb multiplicity classes**
- **EPOS-LHC does not capture this behavior (negative values)**
- **Analysis also performed for K_S^0 - result 0, consistent with 0 spin**

High-p_T v_2 in pPb (I)

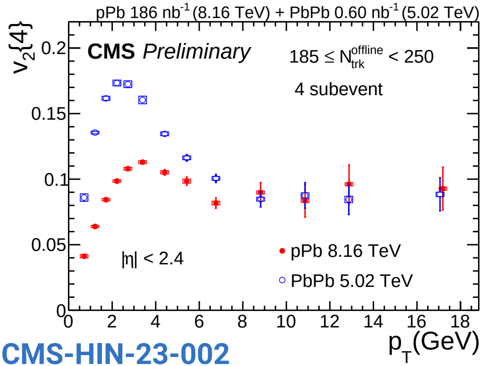
CMS-HIN-23-002



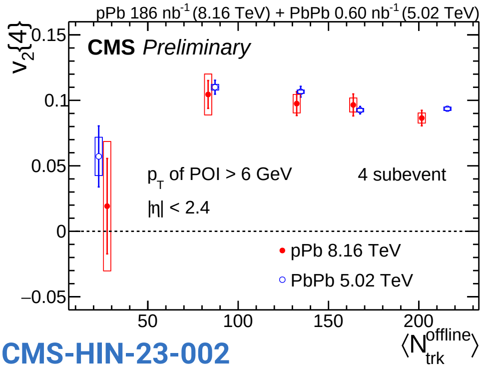


- v_2: Magnitude of correlations from elliptical anisotropy
- Left: Subevent categories, particles taken from each subevent region
- Right: Results with different subevent cumulant methods in pPb, PbPb
  - No subevent, negative sign, suggests significant confounders (nonflow)
  - 3 / 4 subevent self-consistent, suggest confounders removed

High-p_T v_2 in pPb (II)



CMS-HIN-23-002



CMS-HIN-23-002

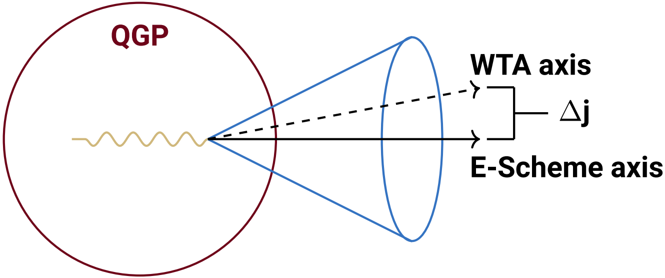
- **Result: Observe a consistent high-p_T v_2 in pPb**
- **Consistent with original observation by ATLAS using different method**
- **High-p_T v_2 is understood as signature of differential jet energy-loss**
  - **No observed jet energy loss in pPb**
  - **Does high-p_T v_2 in PbPb come from differential jet energy-loss alone?**

Jet axis decorrelation with γ+jet events

WTA and E-Scheme Jet Axes

Study of jet-axis decorrelation in photon-tagged jets through the observable Δj, defined as

$$\Delta j = \sqrt{(\phi_{\text{E-Scheme}} - \phi_{\text{WTA}})^2 + (\eta_{\text{E-Scheme}} - \eta_{\text{WTA}})^2}$$



E-Scheme

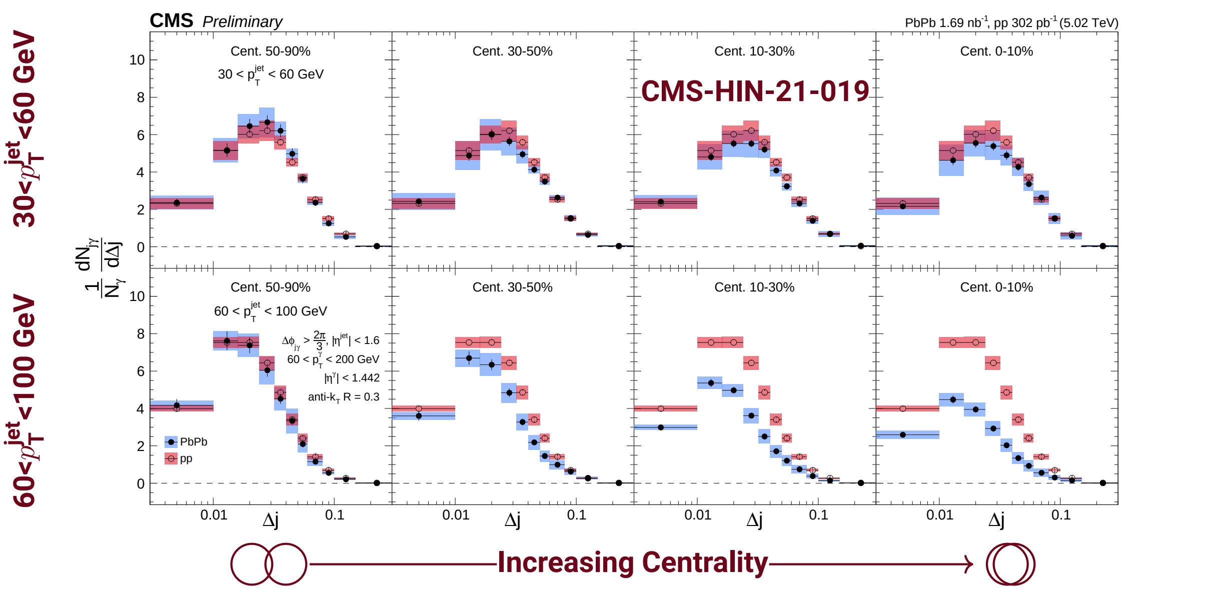
- Axis from 4-vector sum at each step of clustering
- "Average energy flow" of jet

WTA (Winner-take-all)

- At every step of clustering, set axis to harder prong
- "Leading energy flow" of jet

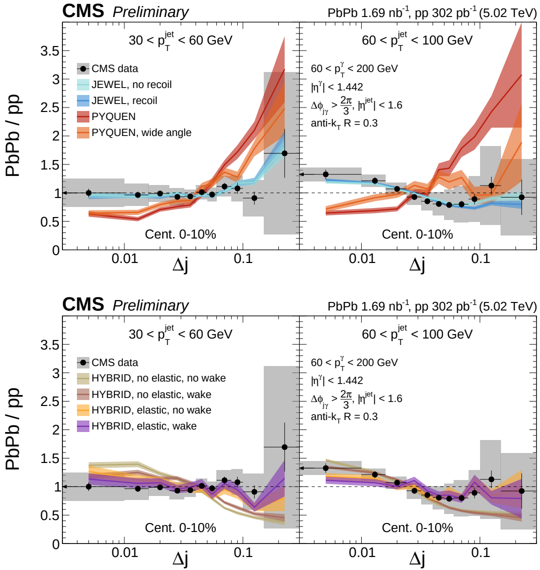
In QGP, jet quenching effects can modify E-Scheme-WTA correlation compared to pp!

New CMS Δj Result in γ-tagged Events (I)



New CMS Δj Result in γ-tagged Events (II)

Shape Ratios

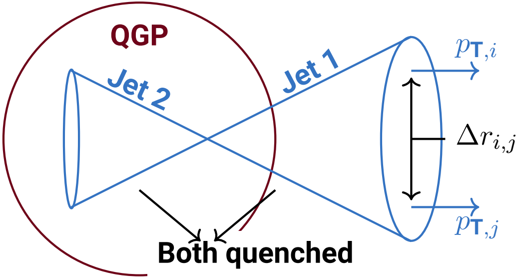


CMS-HIN-21-019: (hosted here soon!)

- **PbPb data agrees well with JEWEL independent of recoil handling**
- **PYQUEN overpredicts broadening observed in data**
- **PbPb data agrees well with Hybrid, with elastic effects closer to central values**
- **Observable appears insensitive to wake as implemented in Hybrid**

Energy-energy correlators in PbPb collisions

Motivating EEC's in Heavy Ions



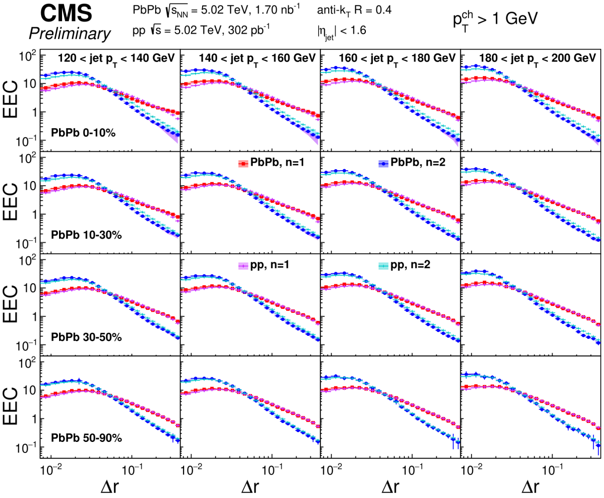
Experimental Definition:

$$\text{EEC}(\Delta r) = \frac{1}{W_{\text{pairs}}} \sum_{\text{jets} \in [p_{\mathrm{T},1}, p_{\mathrm{T},2}]} \sum_{\text{pairs} \in \Delta r_a, \Delta r_b} (p_{\mathrm{T},i} p_{\mathrm{T},j})^n$$

- All charged particle pairs with $p_{\mathrm{T}} > p_{\mathrm{T}}^{\text{ch}}$
  - Measured with $p_{\mathrm{T}}^{\text{ch}}$ 1 GeV and 2 GeV
- $\Delta r \equiv \Delta r_{i,j} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$
- Weighted by p_{T} product $(p_{\mathrm{T},i} p_{\mathrm{T},j})^n$ per pair
  - Measured for n = 1 and 2
- No jet p_{T} normalization
  - Instead restrict to tight jet p_{T} window
- Normalize by W_{pairs} such that integral is 1

In QGP, study proposed as probe of color coherence and jet wake effects

Spectra Results in pp, PbPb for p_T^{ch} > 1 GeV (I)



CMS-HIN-23-004: (hosted here soon!)

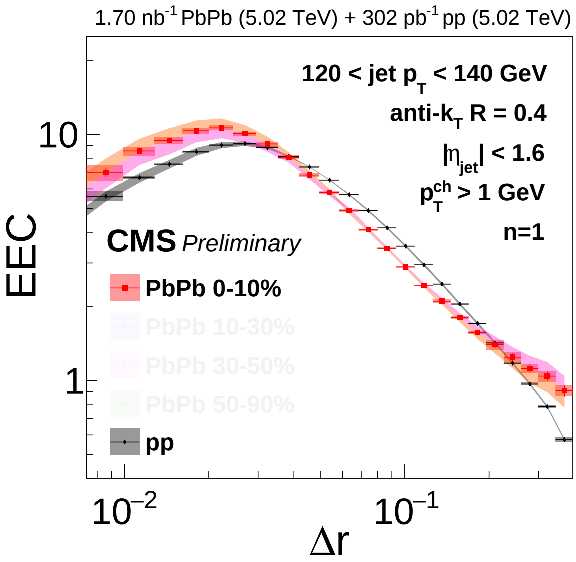
- **Panels in bins of jet p_T, centrality**
- **Shapes strongly depend on n**
  - **n=2 shifts distribution left relative n=1**
- **Let's zoom in on one selection**

Increasing Jet p_T →

Spectra Results in pp, PbPb for p_T^{ch} > 1 GeV (II)

CMS-HIN-23-004: (hosted here soon!)

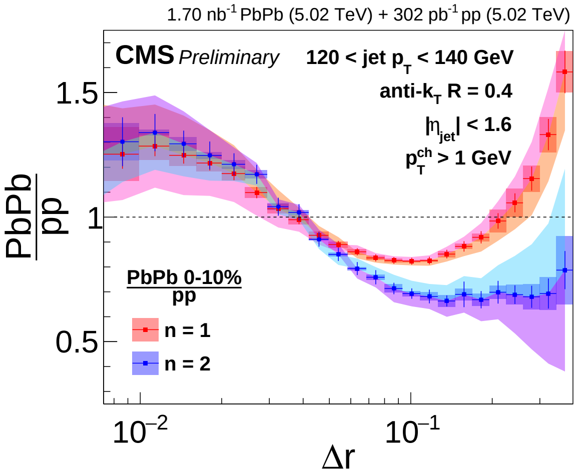
- Central 0-10% PbPb compared to pp
- n=1, p_T^{ch} > 1 GeV
  - Emphasizes soft particle contributions
- PbPb peak shifted to left $\rightarrow$ jet E-loss
- To quantify difference between PbPb and pp, check ratios!



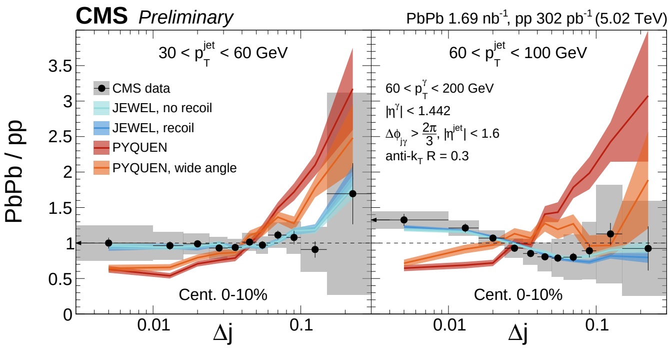
Ratio of PbPb/pp for p_T^{ch} > 1 GeV

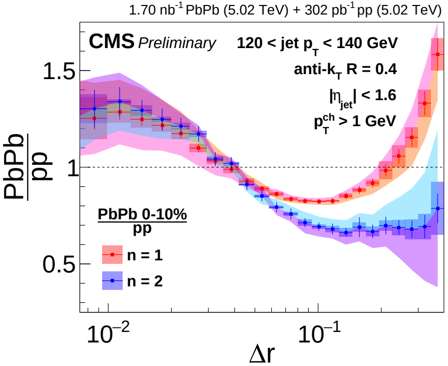
CMS-HIN-23-004: (hosted here soon!)

- As QGP effects increase, observe signficant modification in PbPb
  - Maximal in 0-10% selection (right)
- Enhancement in small ΔR (Free hadron regime)
  - Expected from jet energy loss in QGP
- Enhancement at large ΔR (Quark/Gluon perturbative regime)
  - Not modeled by simple energy loss
  - Also not explained by q/g fraction
  - Soft particles key to observation



Conclusions

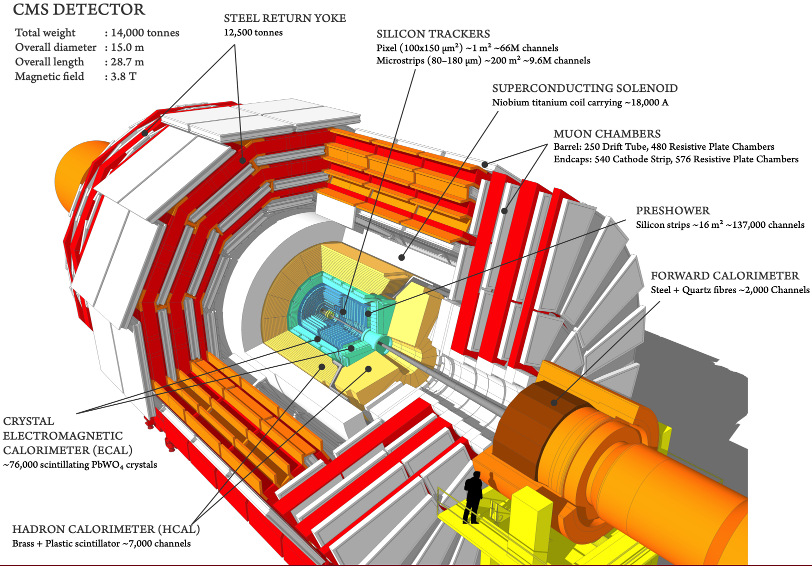




- **Three new CMS measurements probing QGP-like behaviors in pPb**
- **Two new-for-ICHEP CMS measurements of jet-medium interactions**
  - **First measurement of jet-axis decorrelation with photon-tag in PbPb data**
  - **First measurement of EEC modifications in PbPb compared to pp**
- **For a global perspective on the CMS HI program, see our overview publication!**

Backup

The CMS Detector



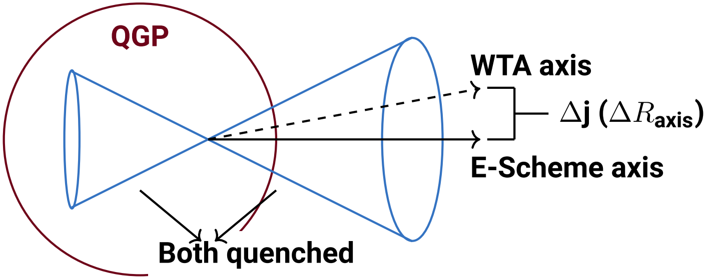
Study of QGP enabled by The CMS Detector

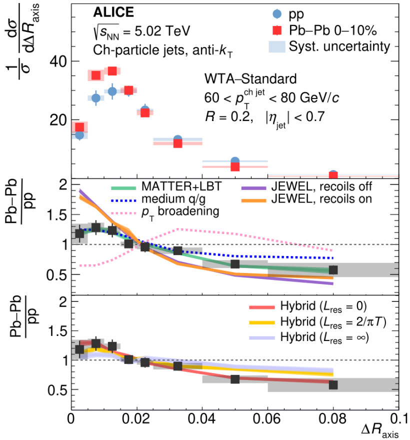
- Silicon trackers for charged hadrons
- ECAL for photons / π^0
- HCAL for neutrals
- Forward calorimeters for event activity / centrality
- All detectors in combination produce jets

ALICE Study in Inclusive Jets

Previous study by ALICE used inclusive jets (Submitted PRL)

- **Observed narrowing between axes in PbPb compared to pp reference**
- **Both jets are quenched → cannot tag initial hard-scattering p_T**

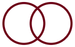


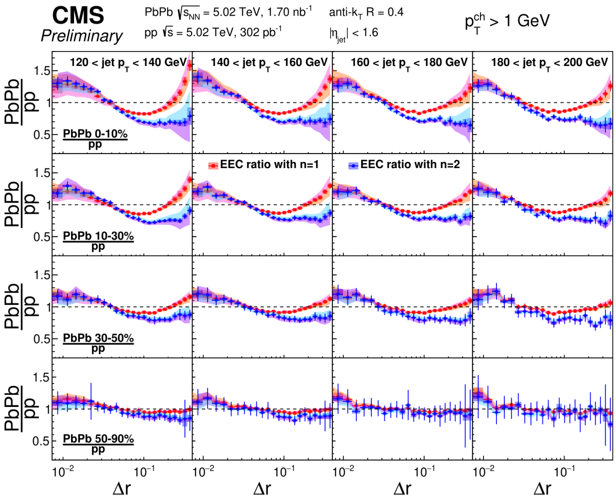


- **With γ tag, unquenched measure of initial p_T!**

Ratio of PbPb/pp for p_T^{ch} > 1 GeV

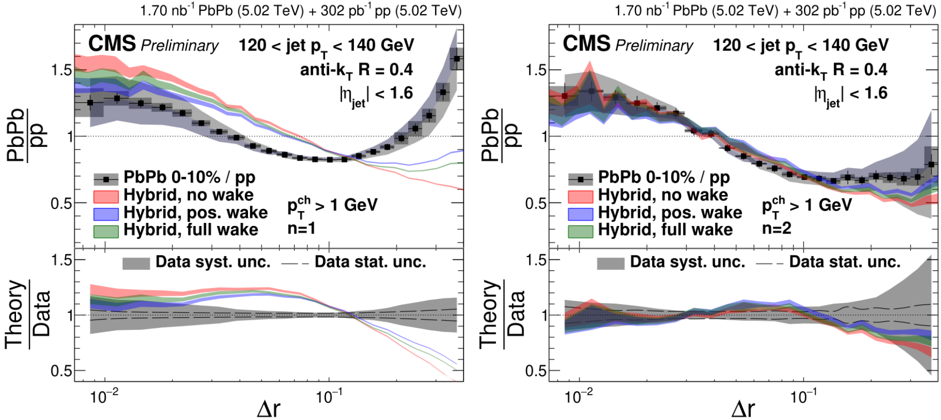
- Same panel by panel binning
- In peripheralmost (bottom), PbPb and pp agree within errors
- As QGP effects increase, observe signficant modification in PbPb
- p_T^{ch} > 2 GeV in backup





Increasing Jet p_T ⟶

Comparison to Theory for p_T^{ch} > 1 GeV



- **Hybrid fails to model the n=1 case (left)**
  - **n=1 choice is more sensitive to soft medium effects**
  - **Both n=2 and p_T^{ch}>2 GeV don't see the large ΔR enhancement**
- **Good agreement in n=2 case (right)**