Recent jet substructure measurements in heavy-ion collisions with the CMS experiment

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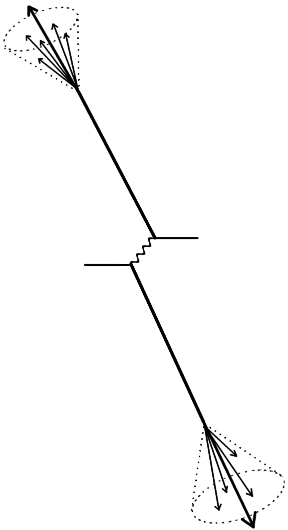
Vanderbilt University

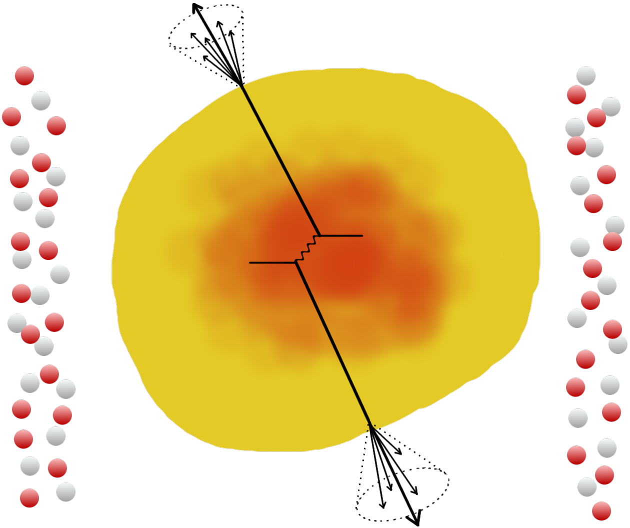
for the CMS collaboration

BOOST 2022

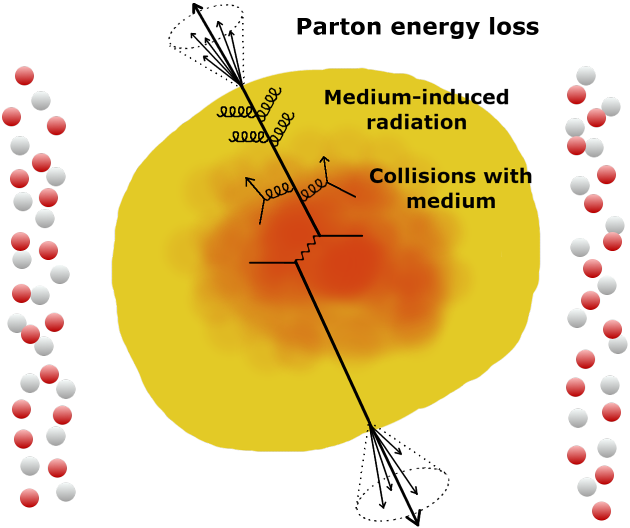
Introduction

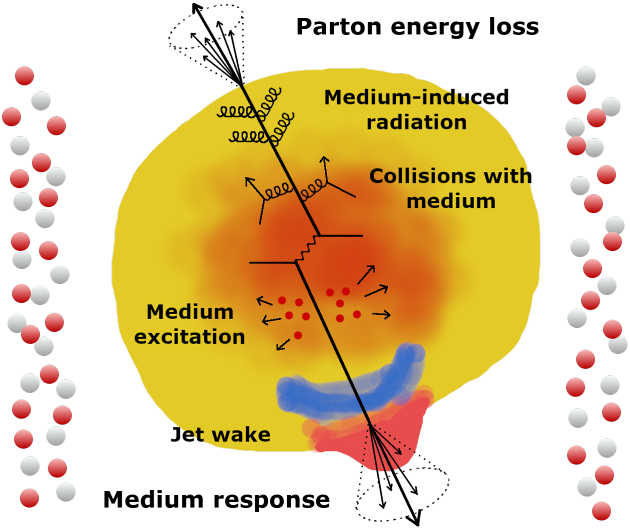


Introduction

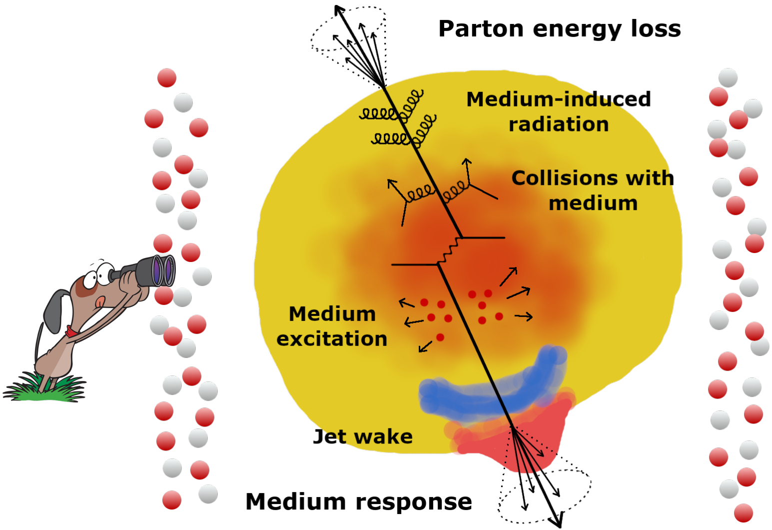


Introduction




Parton energy loss
Medium-induced radiation
Collisions with medium
Medium excitation
Jet wake
Medium response

Integrated observables

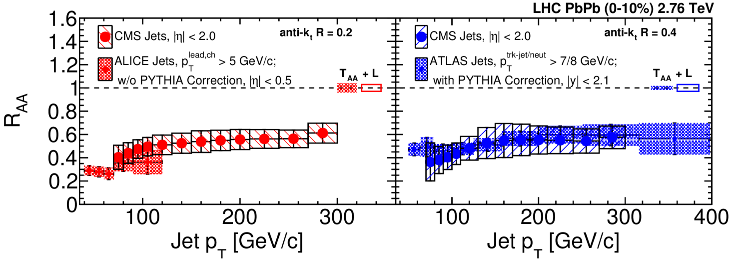


Nuclear modification factor R_{AA}

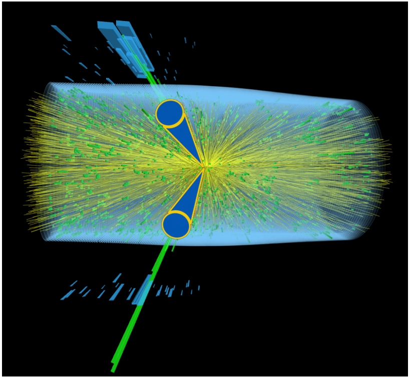
- Traditional measure of jet energy loss

$$R_{\mathrm{AA}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

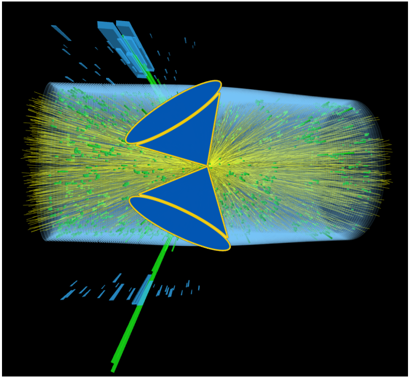
CMS: PRC 96 (2017) 015202
ATLAS: PRL 114 (2015) 072302
ALICE: PLB 746 (2015) 1



New twist to R_{AA} measurements: increase jet radius



VS



R-dependence of the jet energy loss

- Effects decreasing the energy loss (larger R_{AA}) with R
  - Recovery of wide angle radiation
  - Medium response adds energy to jet cone
- Effects increasing the energy loss (smaller R_{AA}) with R
  - More incoherent energy loss sources compared to coherent ones
  - Increase of gluon jet fraction

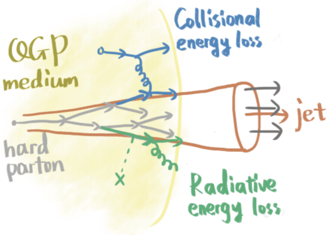
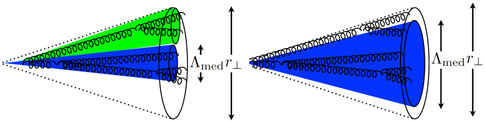
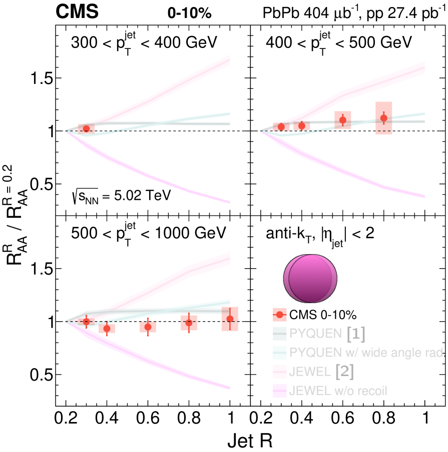
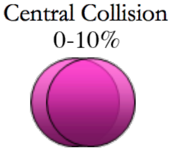


Image: Jing Wang

PLB 725 (2013) 357



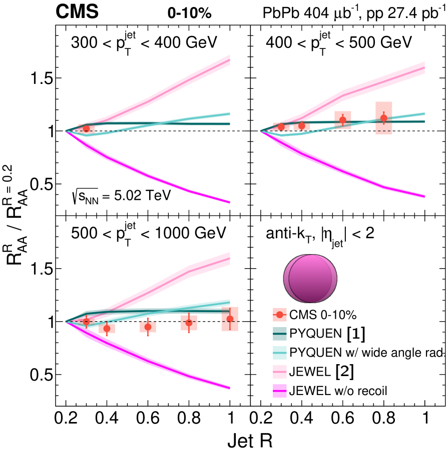


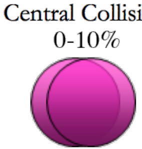


- No significant R-dependence for high-p_T jets observed

[1]EPJC 45 (2006) 211, [2]EPJC 74 (2014) 2762

R-dependence of R_{AA} – JHEP 05 (2021) 284





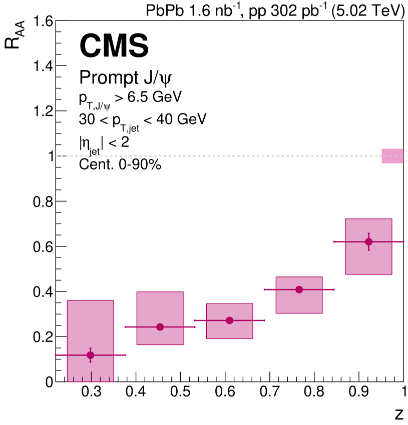
- No significant R-dependence for high-p_T jets observed

- Results are compared to PYQUEN[1] and JEWEL[2] event generators
- The observable has discriminating power between models

[1]EPJC 45 (2006) 211, [2]EPJC 74 (2014) 2762

J/Ψ in jets – PLB 825 (2021) 136842

- Add heavy flavor to R_{AA} measurements

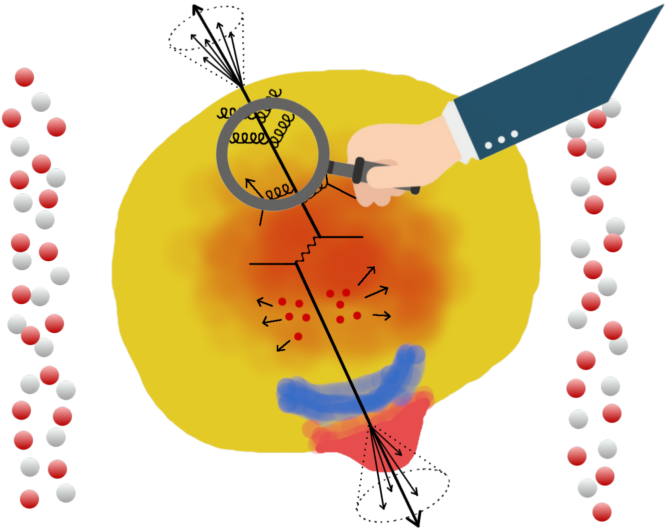


- Select jets containing J/Ψ ($c\bar{c}$)

$$z = \frac{p_{\mathrm{T}}^{J/\Psi}}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

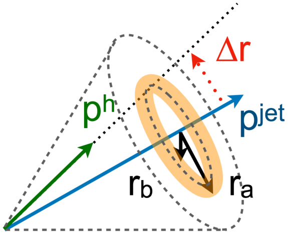
- Low $z \Rightarrow J/\Psi$ produced later in parton shower than at high z
  - More interaction with QGP
- Jet quenching important for modeling of J/Ψ suppression

Observables tailored for parton energy loss



Jet shapes introduction

- Jet shape = radial momentum density profile of the jet
- Study the momentum flow in and around jets



$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jets}}}\sum_{\mathrm{jets}}\frac{\sum_{\mathrm{track}\in(r_a,r_b)} p_{\mathrm{T}}^{\mathrm{track}}}{p_{\mathrm{T}}^{\mathrm{jets}}}$$

$$\Delta r = \sqrt{(\varphi_{\mathrm{jet}} - \varphi_{\mathrm{track}})^2 + (\eta_{\mathrm{jet}} - \eta_{\mathrm{track}})^2}$$

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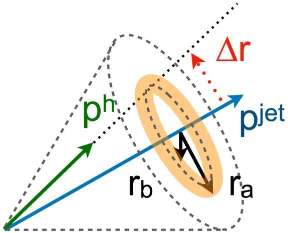
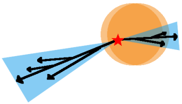


$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\sum_{\text{jets}}\frac{\sum_{\text{track}\in(r_a,r_b)} p_{\mathrm{T}}^{\text{track}}}{p_{\mathrm{T}}^{\text{jets}}}$$

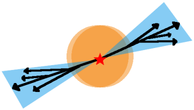
$$\Delta r = \sqrt{(\varphi_{\text{jet}} - \varphi_{\text{track}})^2 + (\eta_{\text{jet}} - \eta_{\text{track}})^2}$$

$$x_j = \frac{p_{\mathrm{T}}^{\text{subleading}}}{p_{\mathrm{T}}^{\text{leading}}}$$

Unbalanced dijet, low x_j



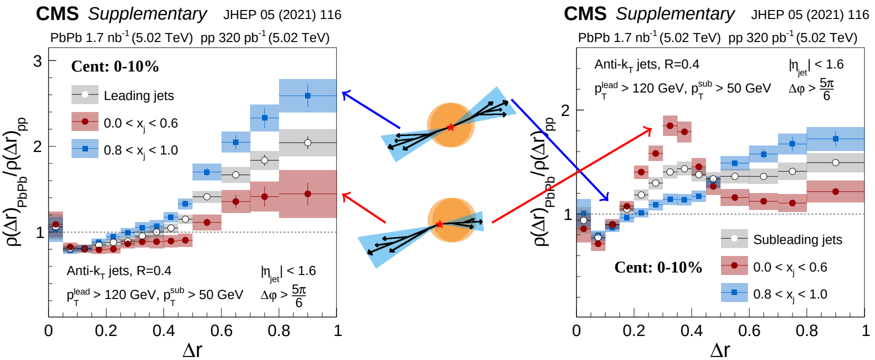
Balanced dijet, high x_j



Jet shape ratios in dijet events – JHEP 05 (2021) 116

Leading jets

Subleading jets

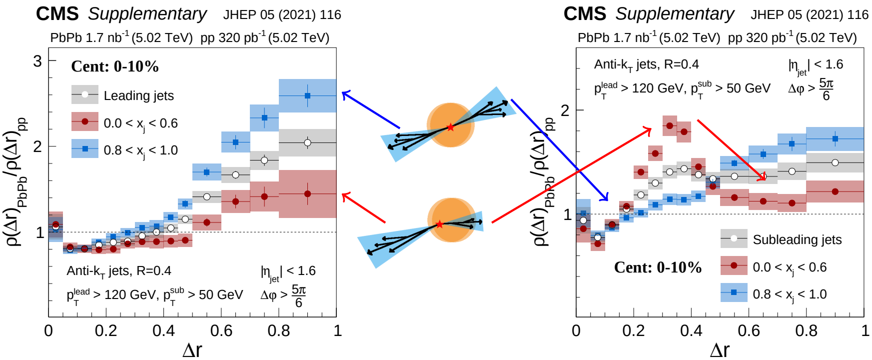


- Largest modifications in balanced events
- Largest modifications in unbalanced events

Jet shape ratios in dijet events – JHEP 05 (2021) 116

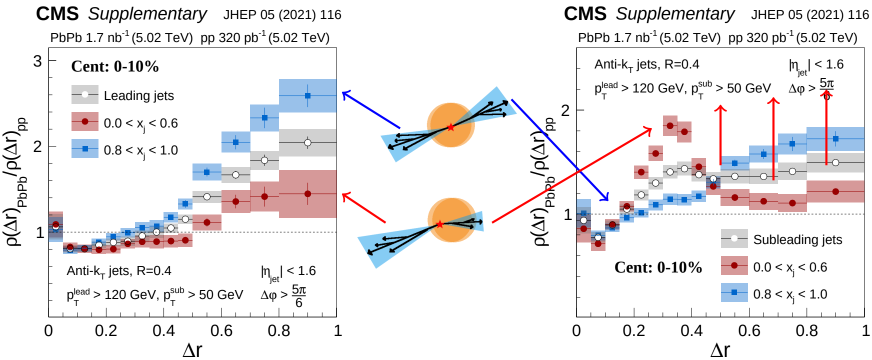
Leading jets

Subleading jets



- Largest modifications in balanced events
- Largest modifications in unbalanced events
- Dip in subleading unbalanced ratio due to 3-jet events in pp reference

Leading jets | Subleading jets



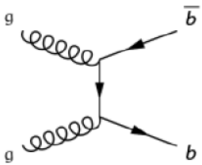
- Largest modifications in balanced events
- Largest modifications in unbalanced events

- Dip in subleading unbalanced ratio due to 3-jet events in pp reference
- With x_j integrated pp reference, the unbalanced ratio will stay high

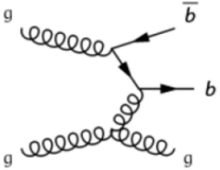
Jet shapes for b-jets – CMS-HIN-20-003

- Sensitive to b-quark production processes
- Sensitive to parton fragmentation and mass effects
  - Dead cone effect, b-hadron formation, ...

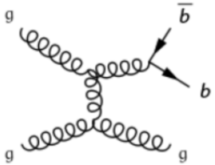
Flavor creation

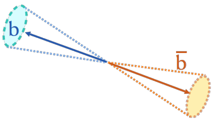


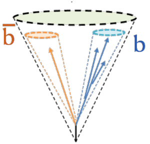
Flavor excitation



Gluon splitting

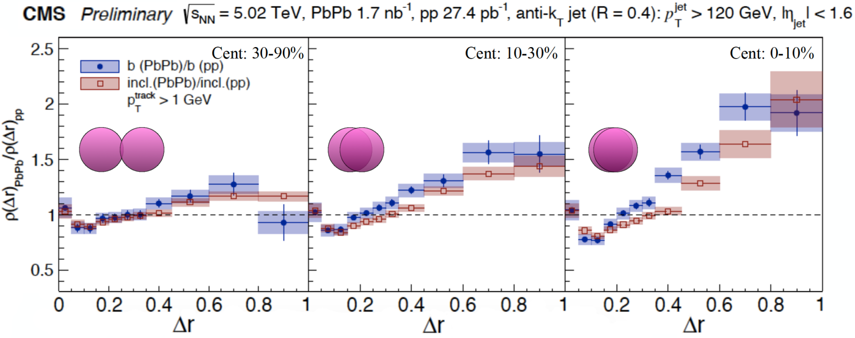






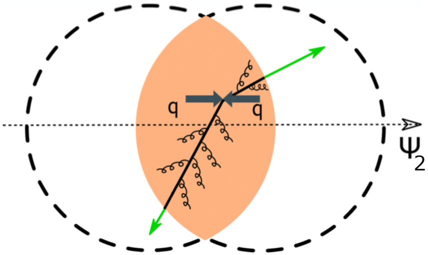
Jet shapes for b-jets – CMS-HIN-20-003

- Sensitive to b-quark production processes
- Sensitive to parton fragmentation and mass effects
  - Dead cone effect, b-hadron formation, . . .
- b-jets are more modified compared to inclusive jets



Jet azimuthal anisotropies

- The collision region for non-central heavy ion collisions is almond-like
- Path length within medium for partons shorter along short axis
  - ⇒ Less energy loss in average
  - ⇒ Produces azimuthal anisotropies of jet yields w.r.t. event plane Ψ_2



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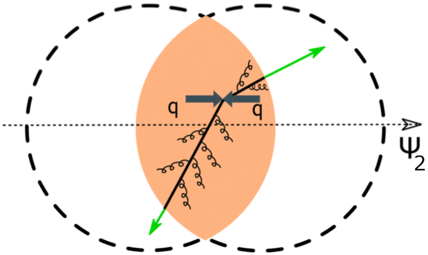
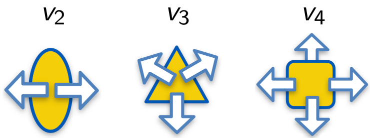


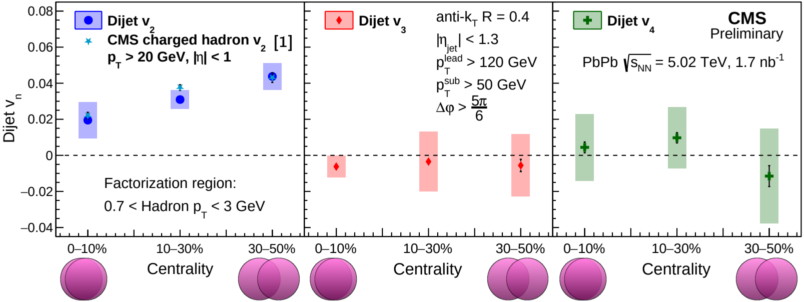
- Fourier expansion:

$$1 + 2\sum_n v_n \cos(n(\varphi - \Psi_n))$$



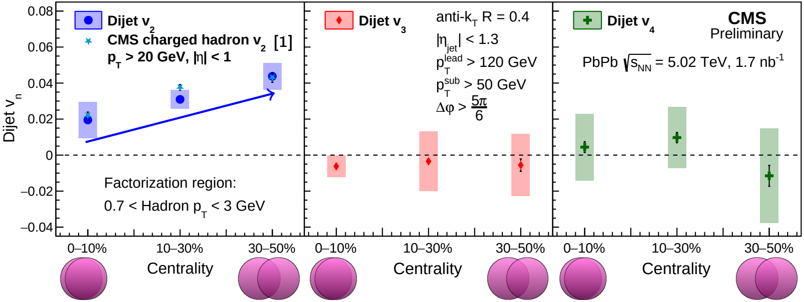
Dijet v_n as a function of centrality – CMS-HIN-21-002

- Fourier expansion coefficients v_n measured for dijet system



[1] PLB 776 (2018) 195

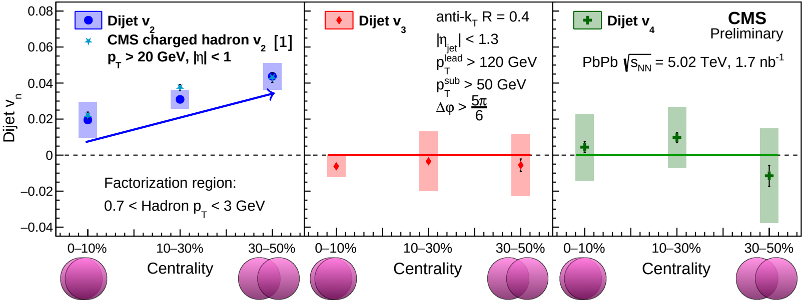
- Fourier expansion coefficients v_n measured for dijet system
- Positive dijet v_2, increasing towards more peripheral events
  - $\Rightarrow$ More different path-lengths for more almond-like initial geometry



[1] PLB 776 (2018) 195

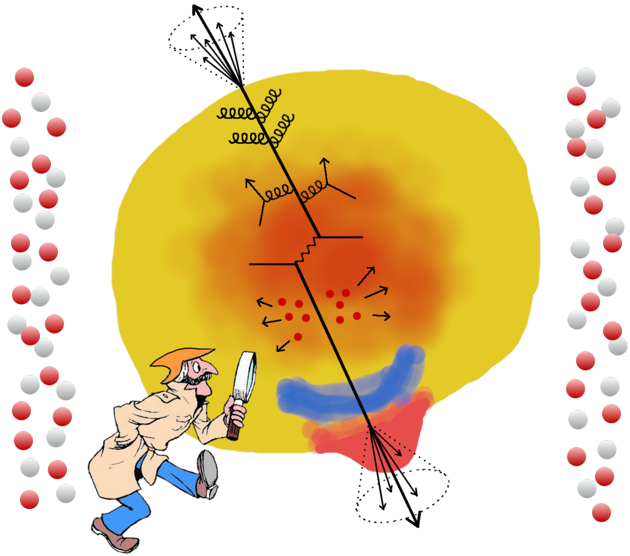
Dijet v_n as a function of centrality – CMS-HIN-21-002

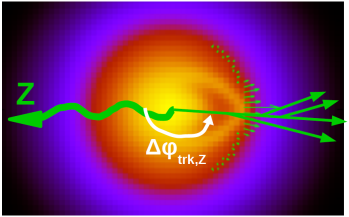
- Fourier expansion coefficients v_n measured for dijet system
- Positive dijet v_2, increasing towards more peripheral events
  - ⇒ More different path-lengths for more almond-like initial geometry
- Dijet v_3 and v_4 consistent with zero
  - ⇒ No measurable impact from medium density fluctuations

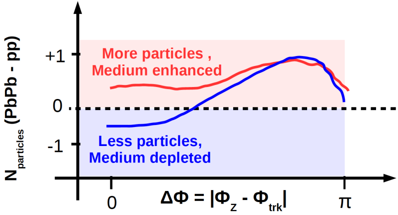


[1] PLB 776 (2018) 195

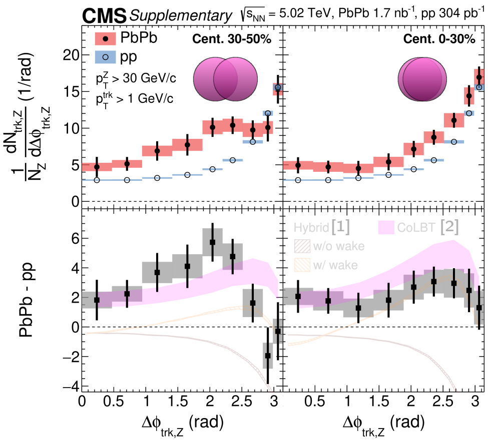
Observables tailored for medium response

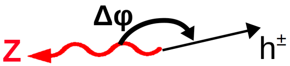






- Study particles associated with Z-bosons
  - Note: no jet reconstruction in this analysis
- Goal: study medium response to a jet in large angles

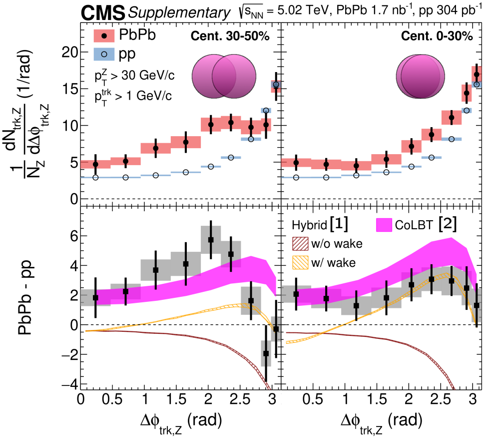


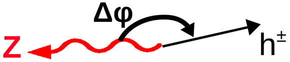


- Almost constant excess in $\Delta\varphi$ in HI collisions
  - Hint of medium excitation

[1] JHEP 10 (2014) 019, [2] PLB 810 (2020) 135783

Particle correlations with a Z-boson – PRL 128 (2022) 122301





- Almost constant excess in $\Delta\varphi$ in HI collisions
  - Hint of medium excitation

- Results compared to Hybrid[1] and CoLBT[2] models
- Models predictions with different medium response vary significantly

[1] JHEP 10 (2014) 019, [2] PLB 810 (2020) 135783

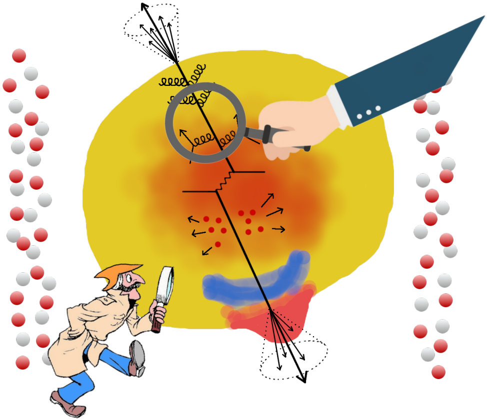
Summary

- CMS has several new and exciting results on jet substructure in heavy ion collisions!

Overall energy loss:

R-dependent R_{AA}

R_{AA} for jets with J/Ψ



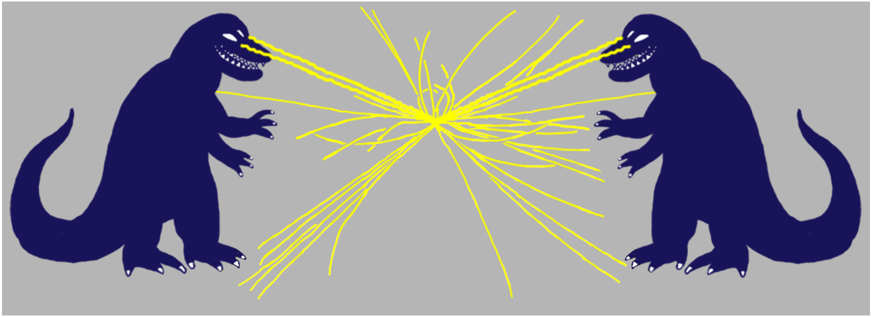
Momentum flow around dijets

Mass and flavor effects

Path-length dependent energy loss

Medium response

Back-up



Background subtraction algorithm for jet reconstruction[1]

- Particle flow candidate: a lepton, photon or a charged or neutral hadron reconstructed using various elements of the CMS detector

1. Calculate mean $\langle E_{\mathrm{PF}} \rangle$ and dispersion $\sigma(E_{\mathrm{PF}})$ of PF candidate transverse energies in η slices[2] $\Rightarrow \rho(\eta) = \langle E_{\mathrm{PF}}(\eta) \rangle + \sigma(E_{\mathrm{PF}}(\eta))$
2. Determine event plane angles Ψ_2 and Ψ_3 from hadronic forward calorimeters ($3 < |\eta| < 5$)
3. Fit the charged-hadron PF candidates with $0.3 < p_{\mathrm{T}} < 3\,\mathrm{GeV}$ and $|\eta| < 1$ to find event-by-event underlying event flow modulation:

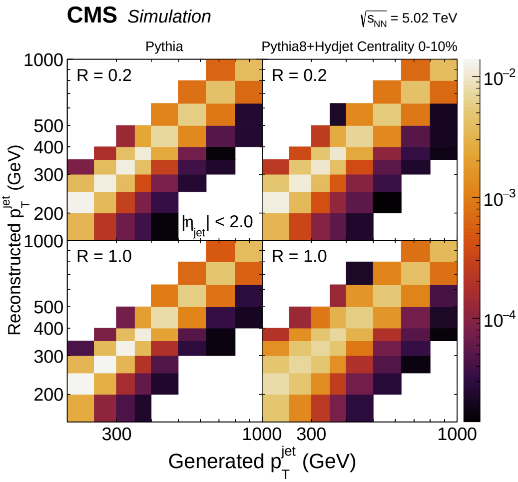
$$N(\varphi) = N_0(1 + 2v_2 \cos(2[\varphi - \Psi_2]) + 2v_3 \cos(3[\varphi - \Psi_3]))$$

4. Subtract underlying event contribution using constituent subtraction method[3] with local average underlying event density as

$$\rho(\eta, \varphi) = \rho(\eta)\,(1 + 2v_2 \cos(2[\varphi - \Psi_2]) + 2v_3 \cos(3[\varphi - \Psi_3])))$$

[1] JHEP 05 (2021) 284, [2] EPJC 50 (2007) 117, [3] JHEP 06 (2014) 092

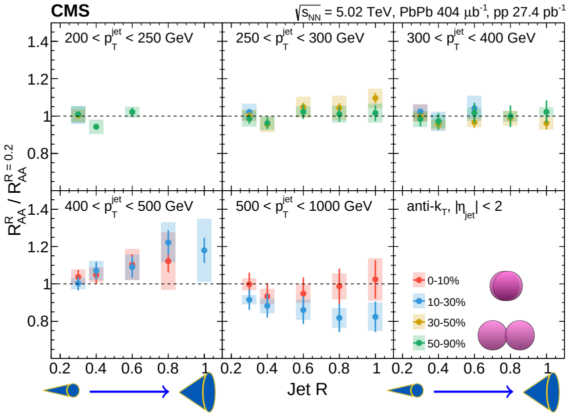
Jet p_T unfolding for R_{AA} analysis – JHEP 05 (2021) 284

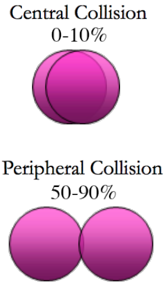


- Jet p_T is unfolded using d'Agostini method with early stopping[1]

[1] NIMA 362 (1995) 487

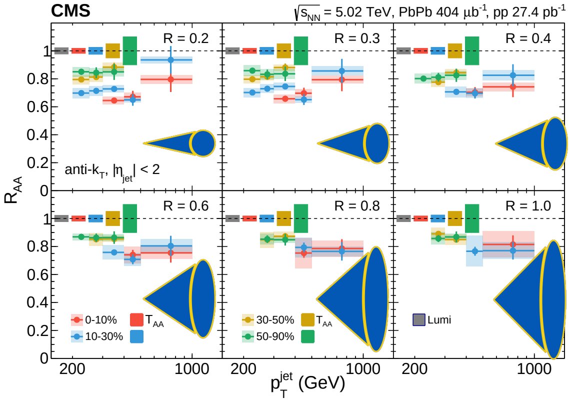
R-dependence of R_{AA} – JHEP 05 (2021) 284

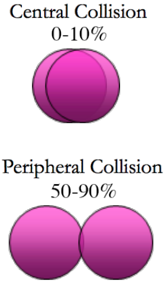




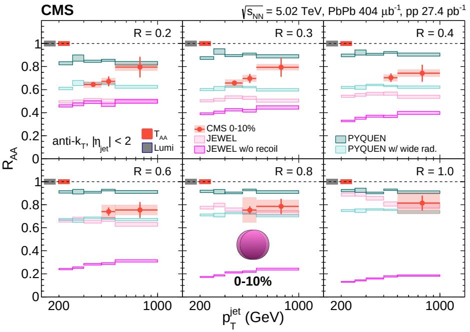
- No significant R-dependence for high-p_T jets observed

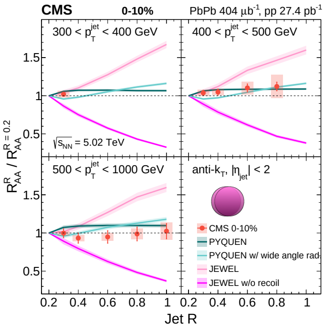
R-dependence of R_{AA} – JHEP 05 (2021) 284





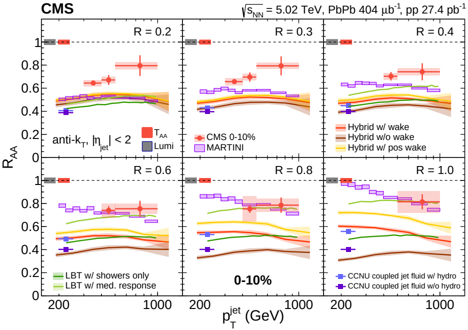
- Jets with all R lose energy in PbPb with respect to pp collisions
- Small R results show some p_{T} dependence

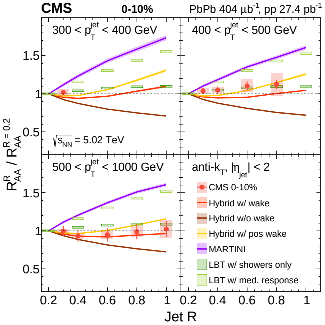




- JEWEL (EPJC 74 (2014) 2762): recoil = scattered medium particles on/off
- PYQUEN (EPJC 45 (2006) 211): medium-induced wide angle radiation on/off
- Different parameter tunes have big impact on predictions
  - The observable has discriminating power between models

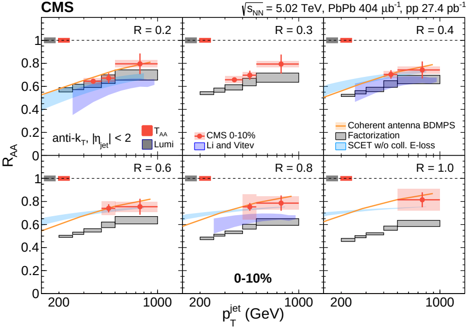
R-dependent R_{AA}, theory comparisons 2 – JHEP 05 (2021) 284

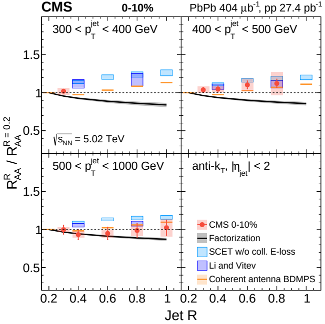




- Hybrid: combines weak (pQCD) and strong (gauge/gravity) coupling regimes. Wake includes medium response. (JHEP 10 (2014) 019)
- MARTINI event generator: (EPJC 45 (2006) 211)
- LBT: 3+1D viscous relativistic hydrodynamics (PRC 99 (2019) 054911)
- CCNU: Jet-coupled fluid model (PRC 95 (2017) 044909, PRC 94 (2016) 024902, PLB 801 (2020) 135181)

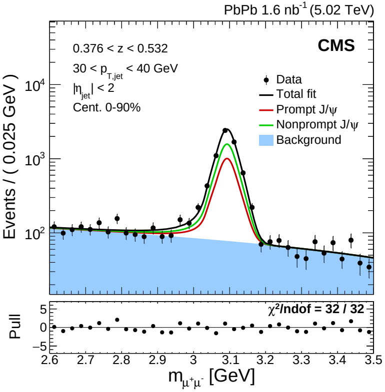
R-dependent R_{AA}, theory comparisons 3 – JHEP 05 (2021) 284

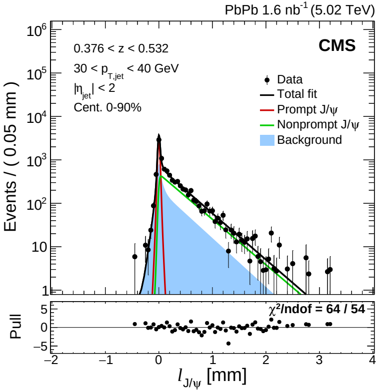




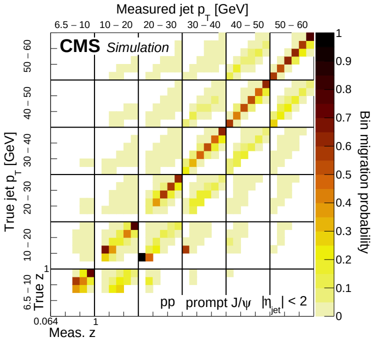
- Factorization: phenomenological jet cross sections (PRL 122 (2019) 252301)
- BDMPS: Analytical resum of multiple emissions (PLB 345 (1995) 277)
- SCET: Glauber gluons in soft-collinear effective theory (JHEP 05 (2016) 023)
- Li and Vitev: SCET with collisional energy loss (JHEP 07 (2019) 148, PLB 795 (2019) 502)

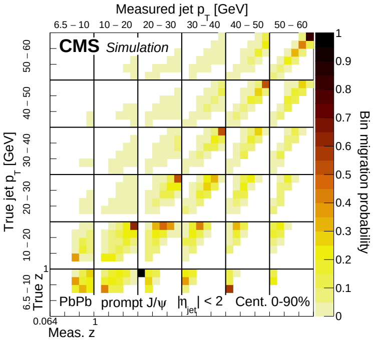
Identifying J/Ψ mesons – PLB 825 (2021) 136842





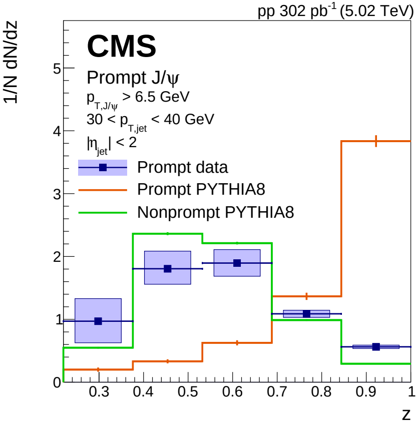
- J/Ψ candidates are identified by a two-dimensional fit to invariant mass and pseudo-proper decay length distribution





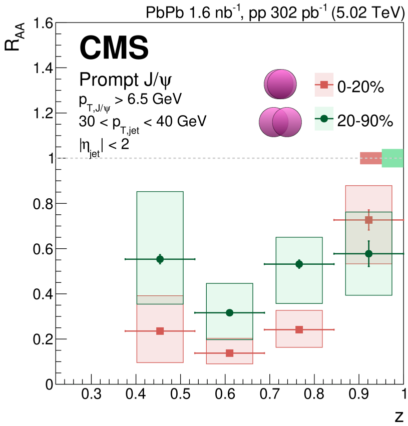
- Response matrices are constructed using
  - PYTHIA8 for pp
  - PYTHIA8+HYDJET for PbPb
- Jet p_{T} is unfolded using iterative d'Agostini method[1]

[1] NIMA 362 (1995) 487



- Non-prompt: J/Ψ produced in b-hadron decay
- Prompt: J/Ψ from all other sources
- PYTHIA8 doesn't do a good job in describing the data

J/Ψ in jets, centrality dependence – PLB 825 (2021) 136842



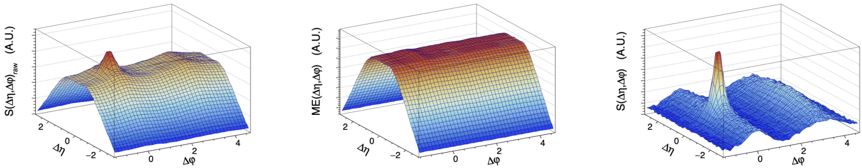
- Select jets containing J/Ψ ($c\bar{c}$)

$$z = \frac{p_{\mathrm{T}}^{J/\Psi}}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

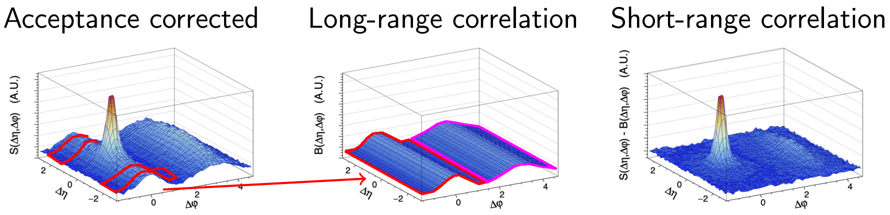
- Low $z \Rightarrow J/\Psi$ produced later in parton shower than at high z
  - More interaction with QGP
- More suppression in central events

Jet-hadron correlation ($\Delta\varphi$, $\Delta\eta$) distribution

Same event Mixed event ME Corrected

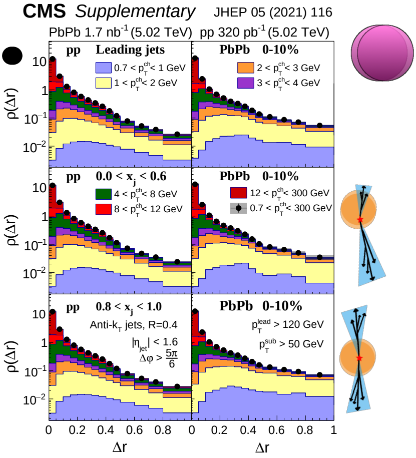


- Select dijet events with back-to-back leading and subleading jets
- Correlate charged particle tracks with leading and subleading jet axes
- Limited detector acceptance in beam direction ($\Delta\eta$)
  - $\Rightarrow$ More likely to see pairs with small $\Delta\eta$
- Mixed event: take jet from one event and particles from another
  - No correlations, only acceptance effects
- Divide same event with mixed event to correct for acceptance

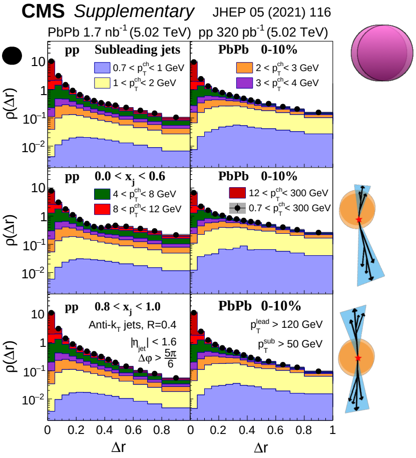


- Select dijet events with back-to-back leading and subleading jets
- Correlate charged particle tracks with leading and subleading jet axes
- Jet correlations are small-angle correlations
  - Estimate long-range correlations from $1.5 < |\Delta\eta| < 2.5$ "side band"
  - Avoid prolonged away-side peak
- Combine leading and subleading side bands to fill long-range correlation distribution in whole $(\Delta\eta, \Delta\varphi)$ region
- Subtract long-range correlation distribution from acceptance-corrected distribution to extract jet signal

Leading jets

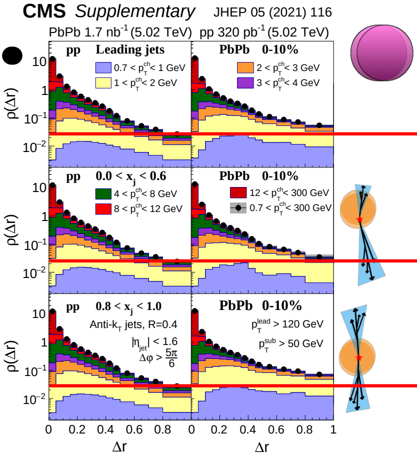


Subleading jets

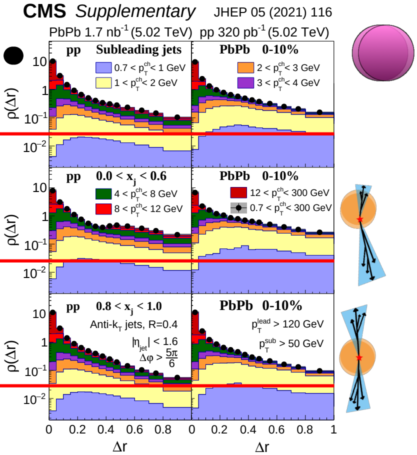


Jet shapes in dijet events – JHEP 05 (2021) 116

Leading jets



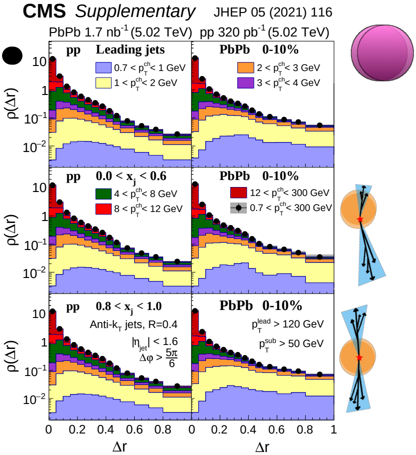
Subleading jets



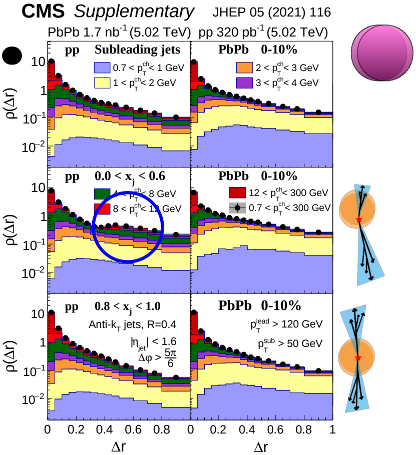
- PbPb shape wider than pp, subleading wider than leading

Jet shapes in dijet events – JHEP 05 (2021) 116

Leading jets



Subleading jets



- PbPb shape wider than pp, subleading wider than leading
- Large momentum imbalance in pp → third jet in the event

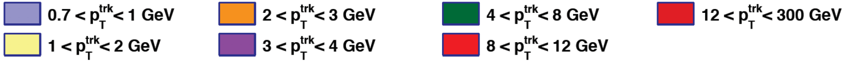
Extra studies for third jet in pp

- Make a cut based on the third highest jet p_{T} in the event
  - Three jet event = Third jet $p_{\mathrm{T}} > \frac{\text{Subleading jet } p_{\mathrm{T}}}{2}$
  - Two jet event = Third jet $p_{\mathrm{T}} < \frac{\text{Subleading jet } p_{\mathrm{T}}}{2}$
- The table below shows the numbers of dijets following this categorization in the used x_j bins for pp data

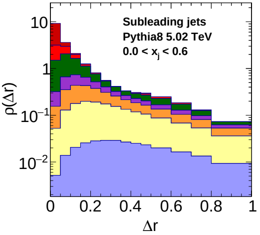
Event type	$0 < x_j < 0.6$	$0.6 < x_j < 0.8$	$0.8 < x_j < 1$
Three jet event	1391651 (52 %)	582004 (15 %)	131811 (3 %)
Two jet event	1298405 (48 %)	3331967 (85 %)	4259981 (97 %)
All events	2690056	3913971	4391792

- From the table it can be seen that unbalanced events are likely to have high p_{T} third jet, but balanced very unlikely

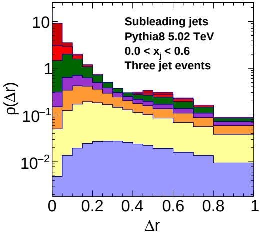
Jet shape in Pythia8 for $0 < x_j < 0.6$ bin for subleading jet



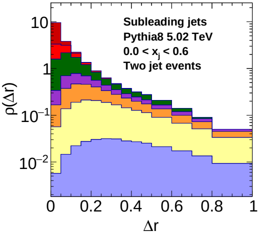
All dijets



Three jet events

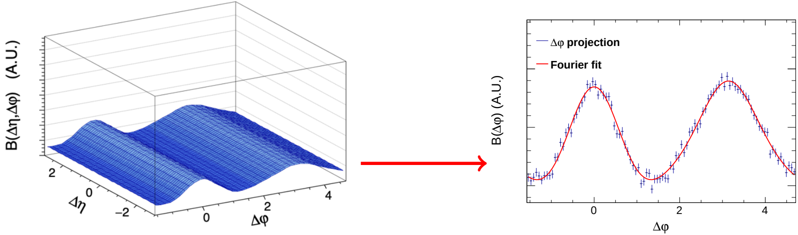


Two jet events



- Similar enhancement of high-p_{T} particles as in data
- Three jet events enhance the effect
- No effect visible in two jet events

Factorizing dijet v_n



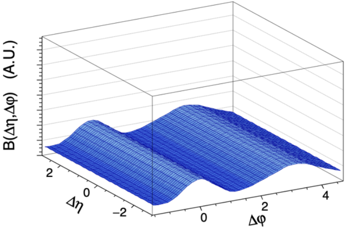
- Fit $\Delta\varphi$-projection of the long-range distribution with a Fourier fit:

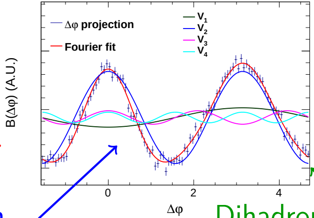
$$f_{\mathrm{Fourier}}(\Delta\varphi) = A \cdot \left(1 + \sum_{n=1}^{4} 2V_{n\Delta}\cos(n\Delta\varphi)\right)$$

- Here coefficients V_n are mixture of $v_{n,\mathrm{hadron}}$ and $v_{n,\mathrm{dijet}}$
- Based on [1], dijet v_n can be factorized: $V_n = v_{n,\mathrm{dijet}} \times v_{n,\mathrm{hadron}}$

[1] Eur. Phys. C 72 (2012) 10052

Factorizing dijet v_n





Jet-hadron

Dihadron

- Fit $\Delta\varphi$-projection of the long-range distribution with a Fourier fit:

$$f_{\mathrm{Fourier}}(\Delta\varphi) = A \cdot \left(1 + \sum_{n=1}^{4} 2 V_{n\Delta} \cos(n\Delta\varphi)\right) \quad p_{\mathrm{T}}^{\mathrm{trig}} = p_{\mathrm{T}}^{\mathrm{assoc}}$$

$$\sqrt{V_n^{\mathrm{dihadron}}}$$

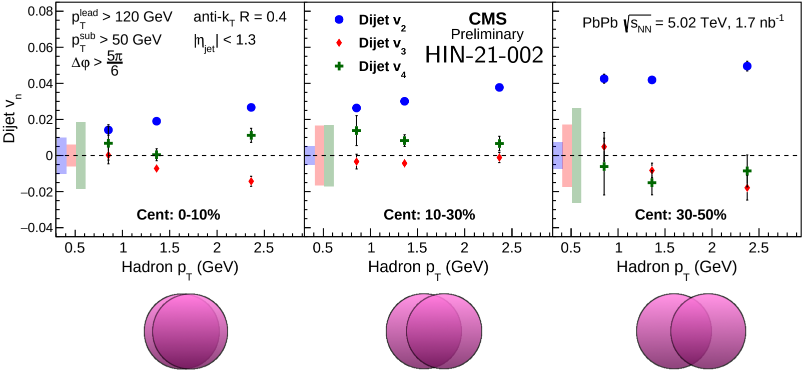
- Here coefficients V_n are mixture of $v_{n,\mathrm{hadron}}$ and $v_{n,\mathrm{dijet}}$
- Based on [1], dijet v_n can be factorized: $V_n = v_{n,\mathrm{dijet}} \times v_{n,\mathrm{hadron}}$

Calculate $\rightarrow \dfrac{V_n}{v_{n,\mathrm{hadron}}}$

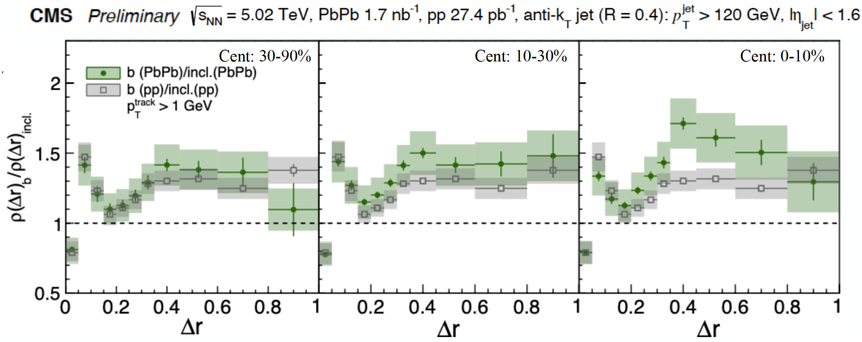
[1] Eur. Phys. C 72 (2012) 10052

Dijet v_n as a function of hadron p_{T}

- Jet-hadron correlations are free from away-side jet bias
- To mitigate the bias for dihadron correlations, analysis limited to region $0.7 < p_{\mathrm{T}} < 3\,\mathrm{GeV}$
- Dijet v_n values factorized from different hadron p_{T} bins shown below
  - $\Rightarrow$ No significant p_{T} dependence, can extract one value



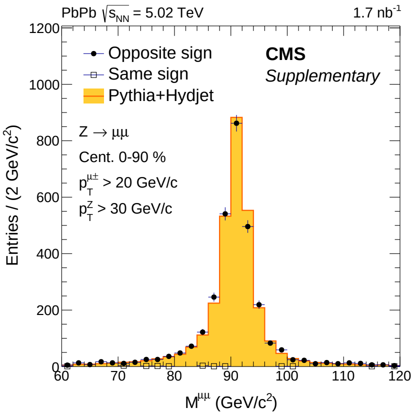
Jet shapes, b-to-inclusive comparison – CMS-HIN-20-003



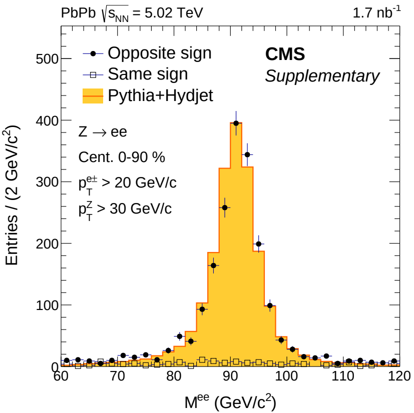
- b-jets are wider compared to inclusive jets
- The difference is larger in PbPb compared to pp collisions

Z-boson reconstruction – PRL 128 (2022) 122301

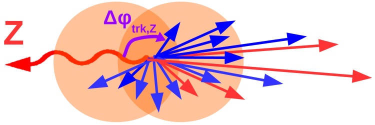
Muon pairs



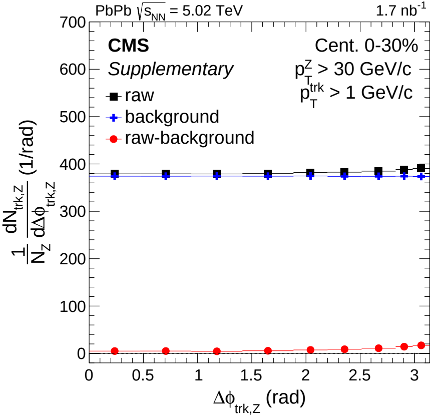
Electron pairs



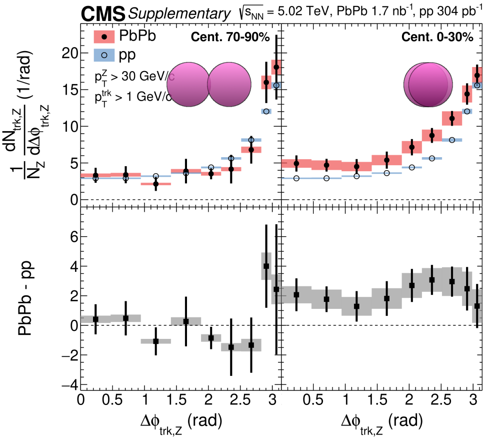
- $\sim$ 5000 events found in $Z \to \mu\mu$ and $Z \to ee$ channels



- Yield is composed of
  - Signal: hard scattering producing Z
  - Background: other sources
- Pair Z-boson with tracks from minimum bias events matched in forward energy to estimate background

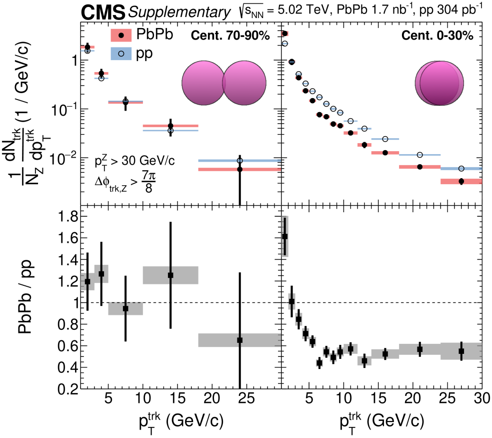


Particle correlations with a Z-boson – PRL 128 (2022) 122301

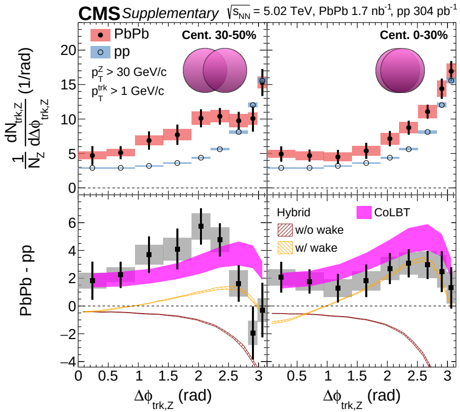


- Almost constant excess in $\Delta\varphi$ for central heavy ion collisions
    - Hint of medium excitation

Particle correlations with a Z-boson – PRL 128 (2022) 122301

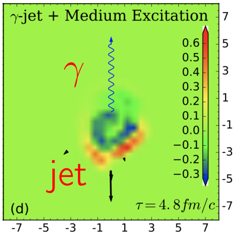


- Depletion of high p_T particles, excess of low p_T ones



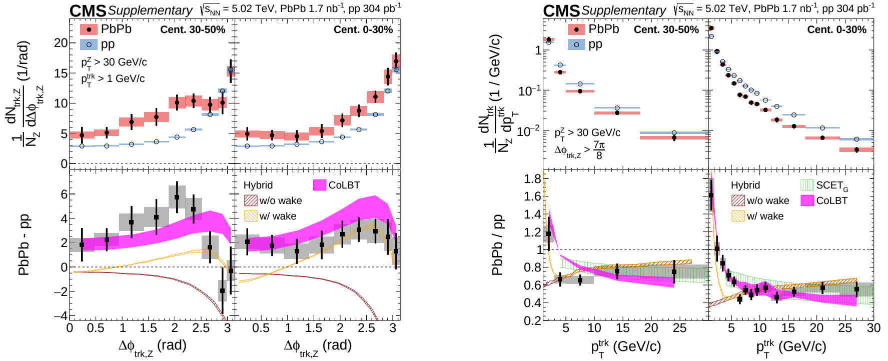
PLB 777 (2018) 86

Diffusion wake



- Hybrid: combines weak (pQCD) and strong (gauge/gravity) coupling regimes. Wake includes medium response. (JHEP 10 (2014) 019)
- CoLBT: evolves quenched jet energy with hydro. (PLB 810 (2020) 135783)
- Need good description of medium response to agree with data

Z-hadron correlation model predictions – PRL 128 (2022) 122301



- Hybrid: combines weak (pQCD) and strong (gauge/gravity) coupling regimes. Wake includes medium response. (JHEP 10 (2014) 019)
- $\mathrm{SCET_G}$: includes Glauber gluons into soft-collinear effective theory. (PRD 93 074030 (2016), PRD 101 076020 (2020))
- CoLBT: feeds quenched jet energy into hydrodynamics evolution. (PLB 810 (2020) 135783)

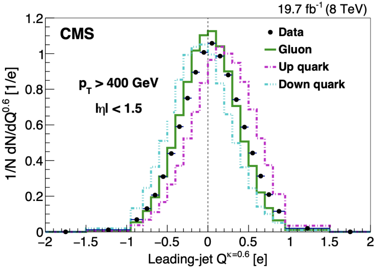
Jet charge definition

- Jet charge:

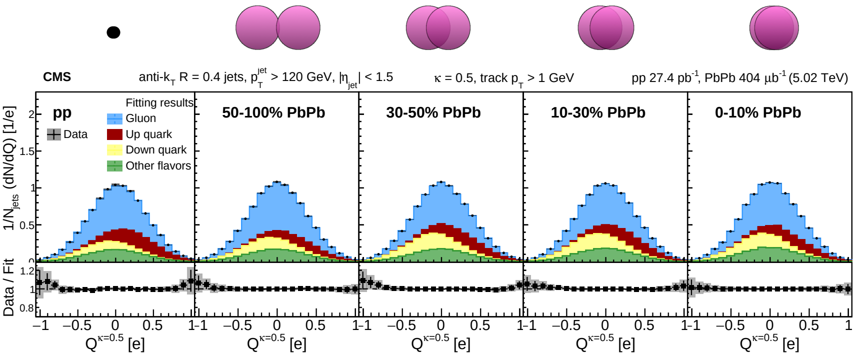
$$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}}^{\mathrm{jet}})^{\kappa}} \sum_i q_i (p_{\mathrm{T}}^i)^{\kappa}$$

- κ controls sensitivity to low and high p_{T} particles
- Can be used to study color charge effects of jet quenching

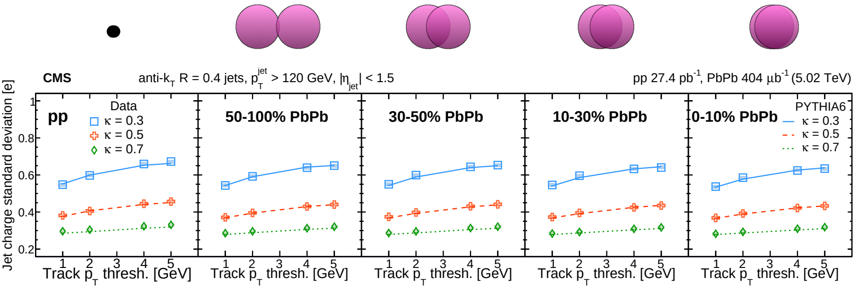
JHEP 10 (2017) 131



Jet charge measurement – JHEP 07 (2020) 115

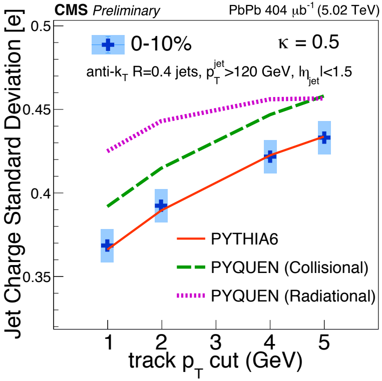


- Results fully unfolded for detector effects
- PYTHIA-based templates describe the data well



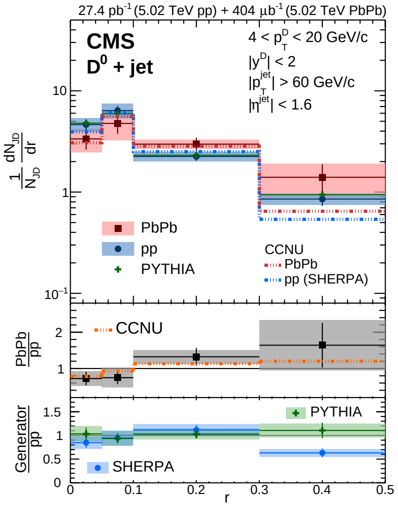
- No significant modifications in widths between PbPb and pp measurements
- Widths well described by PYTHIA 6 Z2 tune (unquenched)

  (JHEP05 (2006) 026, arXiv:1010.3558)

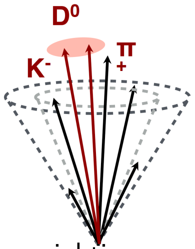


- PYTHIA 6 event generator (JHEP05 (2006) 026) without any jet quenching effects describes the data much better than PYQUEN (EPJC 45 (2006) 211) which includes these effects

D^0 ($c\bar{u}$) radial profile – PRL 125 (2020) 102001

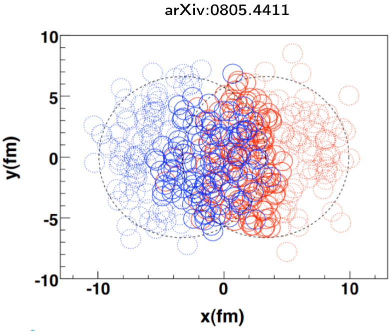


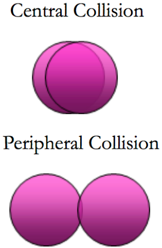
- Using D^0 allows to study production of charm in QGP and heavy-flavor energy loss



- No p_{T} weighting or centrality
- Hint of shape broadening
- More statistics needed for stronger conclusions

Geometry of heavy-ion collision

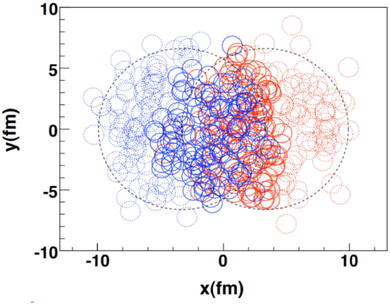




- $N_{\rm part}$ = Number of participants
- $N_{\rm coll}$ = Number of binary collisions

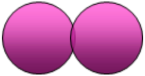
Geometry of heavy-ion collision

arXiv:0805.4411

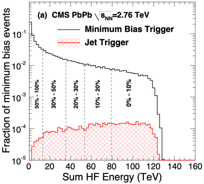


Central Collision

Peripheral Collision



PRC 84 (2011) 024906



HF: $3 < |\eta| < 5.2$

- N_{part} = Number of participants
- N_{coll} = Number of binary collisions
- Centrality = Degree of overlap of the nuclei
  - 0 % = central collision
  - 100 % = peripheral collision
- In CMS: energy sum from HF calorimeters

Anti-k_t jet algorithm - JHEP 04 (2008) 063

1. Define a distance measure for particles and pseudojets

$$d_{ij} = \min\left(p_{\mathrm{T}i}^{-2}, p_{\mathrm{T}j}^{-2}\right) \frac{(y_i - y_j)^2 + (\varphi_i - \varphi_j)^2}{R^2}$$
$$d_{iB} = p_{\mathrm{T}i}^{-2}$$

2. Find the smallest distance d_{min} of all the d_{ij} and d_{iB}.
3. If $d_{\mathrm{min}} = d_{ij}$, merge particles/pseudojets i and j to new pseudojet k
4. If $d_{\mathrm{min}} = d_{iB}$ we have found a jet. Remove d_{min} from the list of pseudojets.
5. Go back to step 1.

- In the end, apply minimum p_{T} cut for the list of jets.