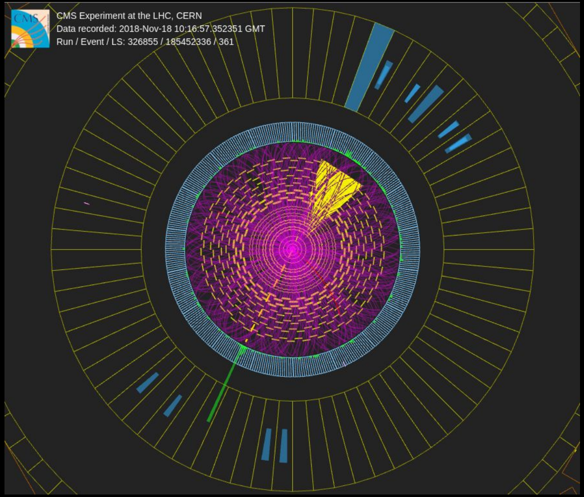
# Detection of jet shower width and survival bias effect with photon-tagged jet substructure in CMS

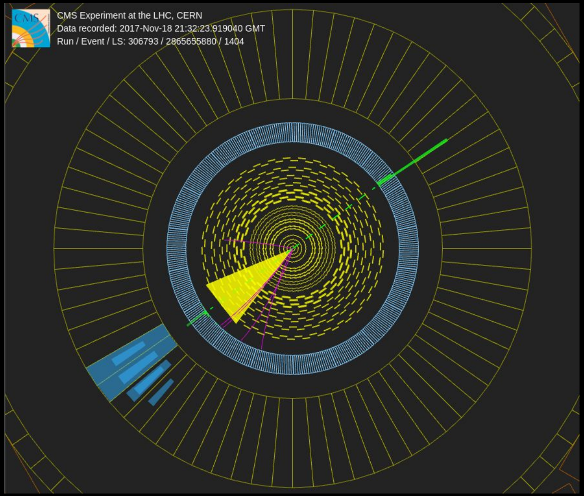
*Bharadwaj Harikrishnan* (**Laboratoire Leprince-Ringuet**)
on behalf of the CMS Collaboration

**BOOST 2024 @ Genova, Italy**
**August 1, 2024**

**CMS, arXiv:2405.0273**
**Submitted to PLB**

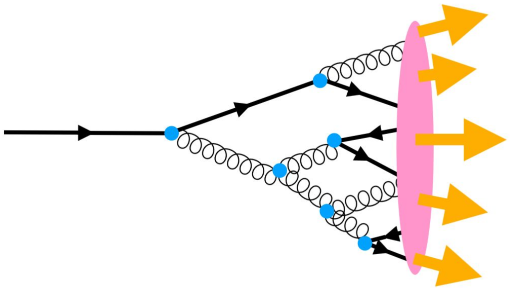
European Research Council



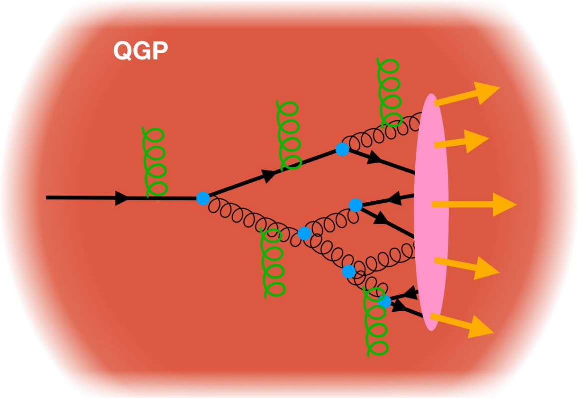


# Probing QCD at high densities and temperature

**pp (“vacuum”)**



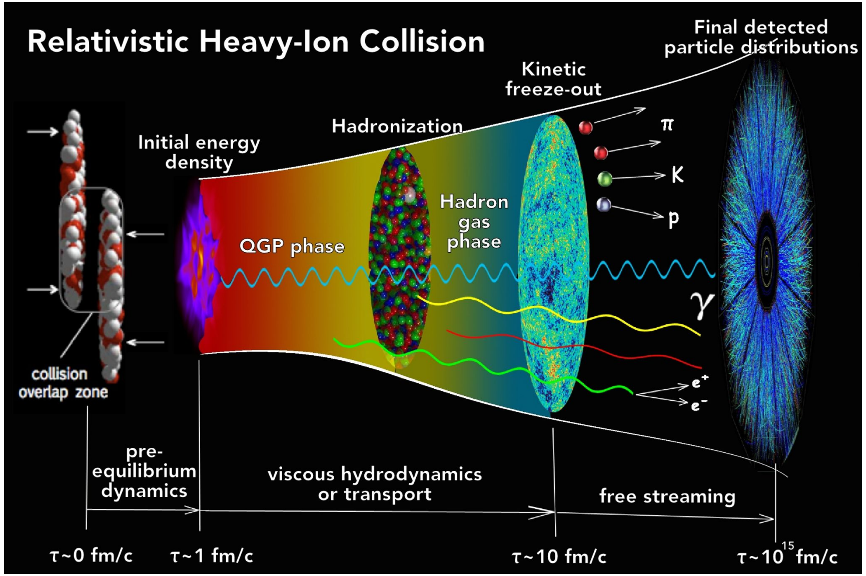
**PbPb (in medium)**



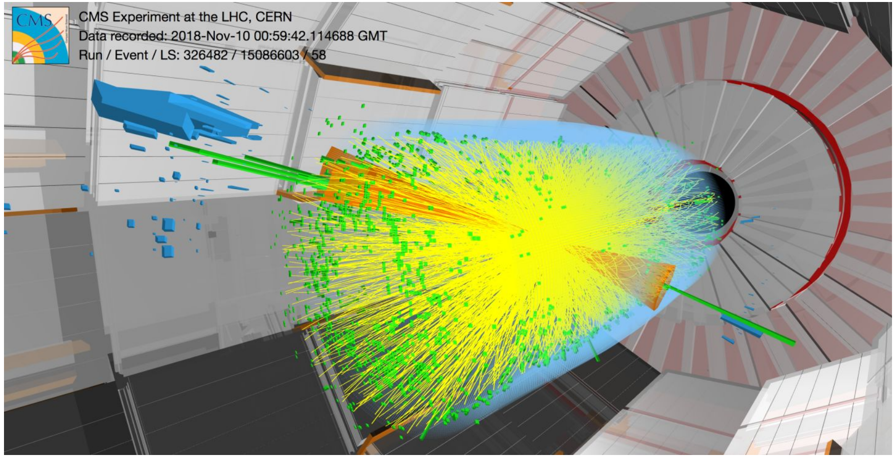
*sketches from Rey Cruz*

- Jets are used to study QCD at short distance scales
- QCD in vacuum is studied extensively in proton-proton collisions
- Deviations from vacuum behavior can be studied in heavy ion collisions

# Probing QCD at high densities and temperature



**What we see**

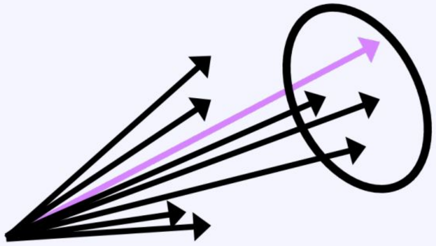


- QGP is formed when heavy ions collide
- Hard scattered partons interact with the QGP and lose energy
- Jet quenching => Modification of the jet radiation pattern

# Jet substructure

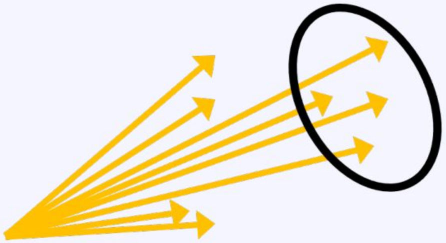
- Jet quenching involves modification of the jet radiation pattern
- Jet substructure observables map 4-momenta of jet constituents to physically meaningful observables

**Fragmentation functions**



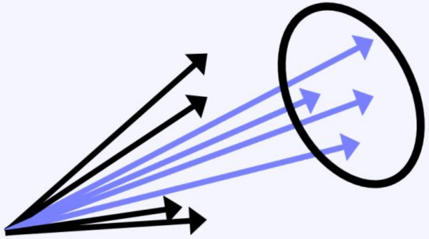
*Single hadron*

**Classic jet shapes**



*All hadrons*

**Groomed observables**



*Subset of hadrons*

# Photon-jet substructure

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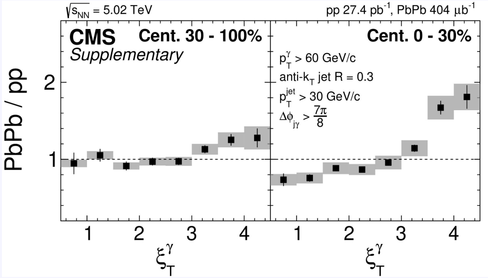

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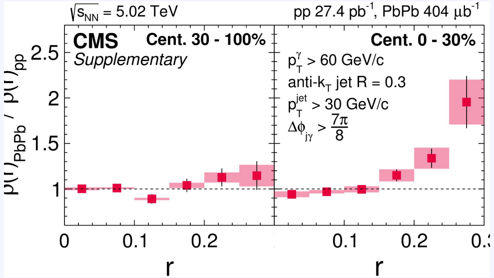


*All hadrons*

**Groomed observables**

CMS
FINAL RESULT
2024

*Subset of hadrons*

CMS, PRL 121 (2018) 242301

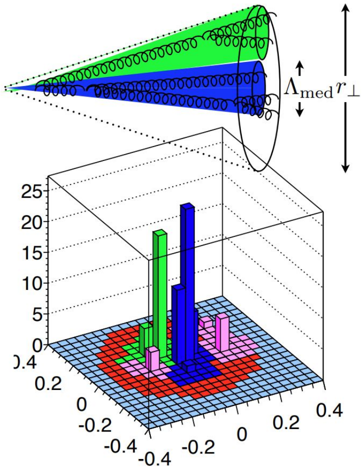
CMS, PRL 122 (2019) 152001

CMS, arXiv:2405.0273

# Medium resolution length and color coherence

- Depending on medium resolution length, resolve as single charge or multiple charges⟶**color coherence**
- Emergent property of the QGP due to quantum interference

***Resolved as two charges***
***→ more quenching***



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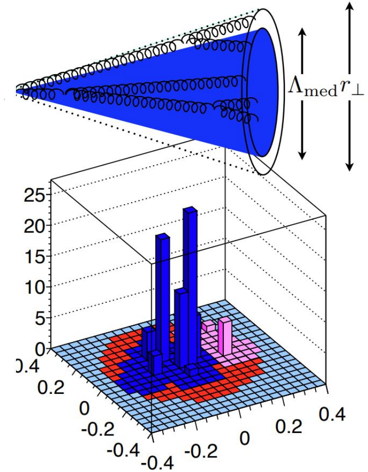

Diagrams from
J.Casalderrey-Solana,
Y. Mehtar-Tani,
C. A. Salgado,
K. Tywoniuk,
arXiv:1210.7765

# Soft drop (SD) grooming algorithm

- SD helps control large contribution from underlying event in PbPb
- Jet constituents are reclustered with Cambridge-Aachen (CA)
- The CA jet is declustered iteratively until we find **first** subjet pair that satisfies the **SD condition**

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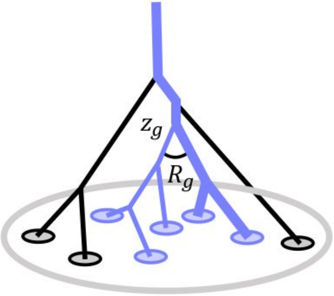
$$z_g \overset{\text{def}}{=} \frac{\min(p_T^1, p_T^2)}{p_T^1 + p_T^2} > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta_{SD}}$$

$$R_g \overset{\text{def}}{=} \Delta R_{12}$$



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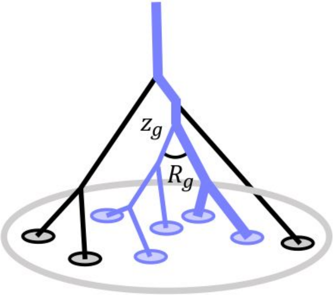


- $\beta_{\text{SD}}$ and $z_{cut}$ are free parameters, set to $\beta_{\text{SD}}$ = 0 and $z_{cut}$= 0.2 in heavy ion collisions
- SD subjets are proxy for the first hard 1⟶2 splitting in the jet shower
- $R_g$, the angular distance of this splitting, can be sensitive to the medium resolution length

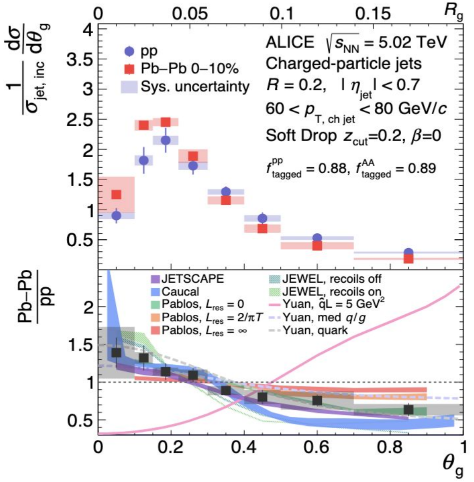
M. Dasgupta, A. Fregoso,
S. Marzani, G. P. Salam,
JHEP09 (2013) 029

A. J. Larkoski, S. Marzani,
G. Soyez, J. Thaler,
JHEP 1405 (2014) 146

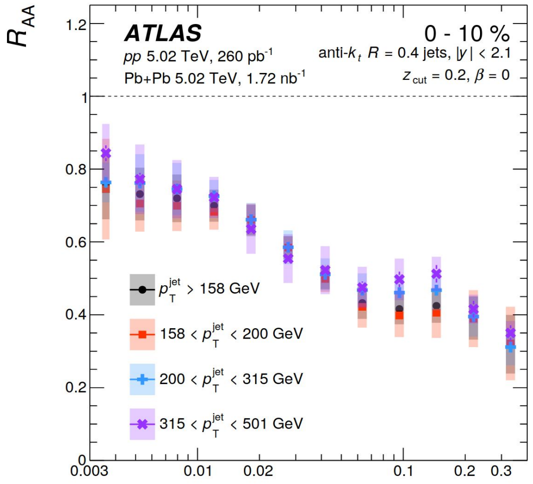
Y. Mehtar-Tani,
K. Tywoniuk,
JHEP04 (2017) 125

# Previous measurements in inclusive jet events

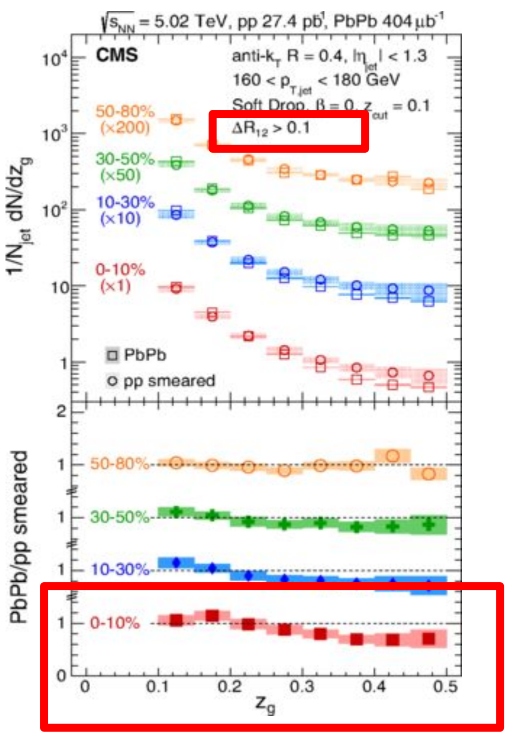
ALICE, PRL 128.102001(2022)



ATLAS, PRC 107, (2023) 054909



***Splitting function***

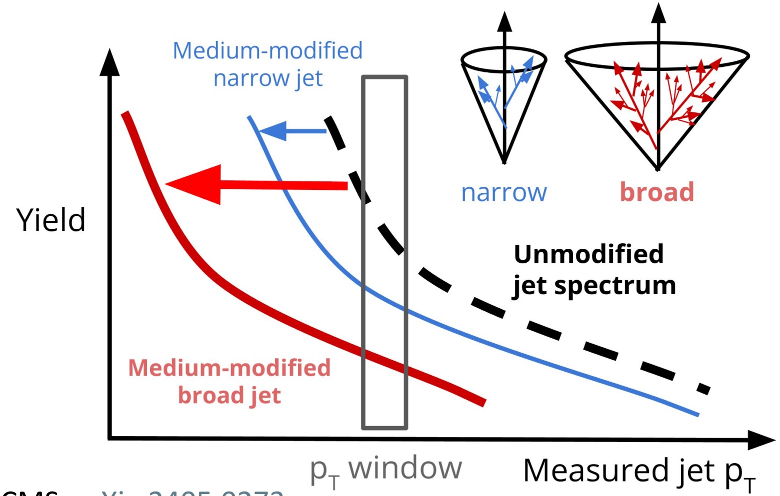


- Broad angular structures are more suppressed in PbPb collisions
- Splitting between branches also becomes increasingly unbalanced

***Is this a consequence of color decoherence?***

CMS, PRL 120, 142302 (2018)

# Jet quenching and the selection bias



CMS, arXiv:2405.0273

- **Quark jets** tend to be narrow, **gluon jets** tend to be broad
- Broader jets are expected to be more quenched than narrower jets
- Potential effect in a measured jet $p_T$ bin→higher population of narrow jets

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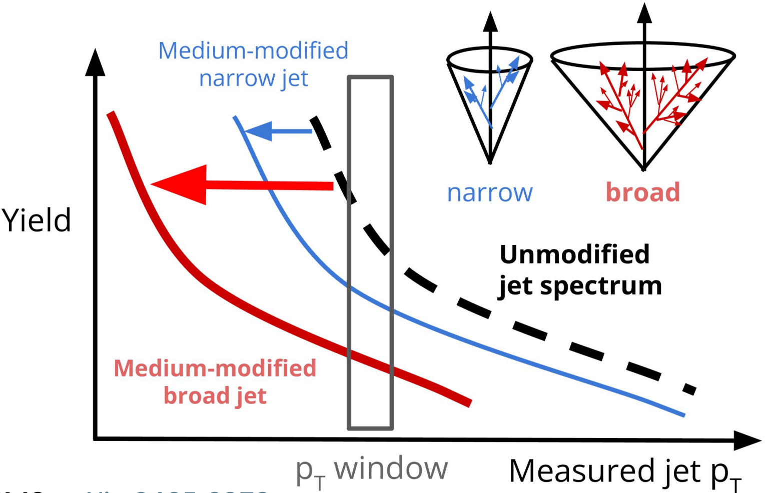
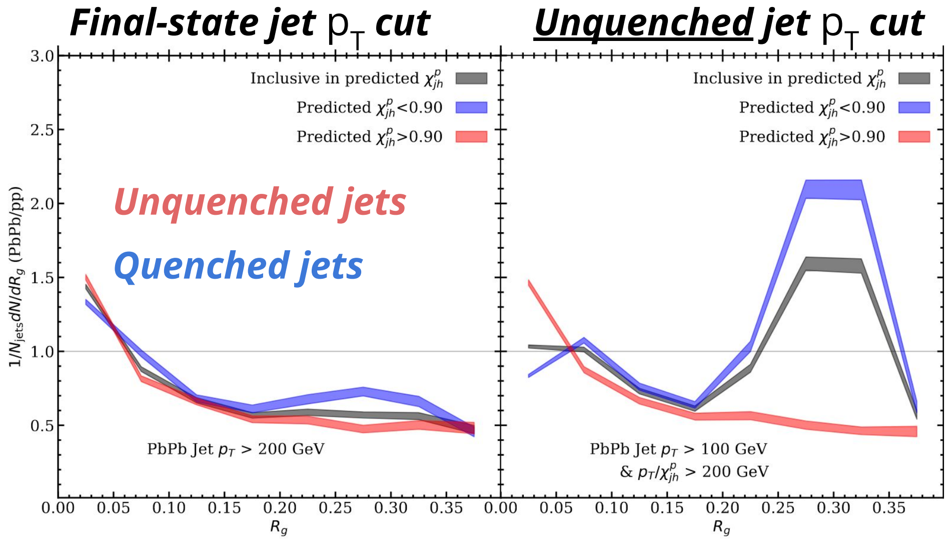


CMS, arXiv:2405.0273



Y.L. Du, D. Pablos, K. Tywoniuk, JHEP 21 (2021), 206

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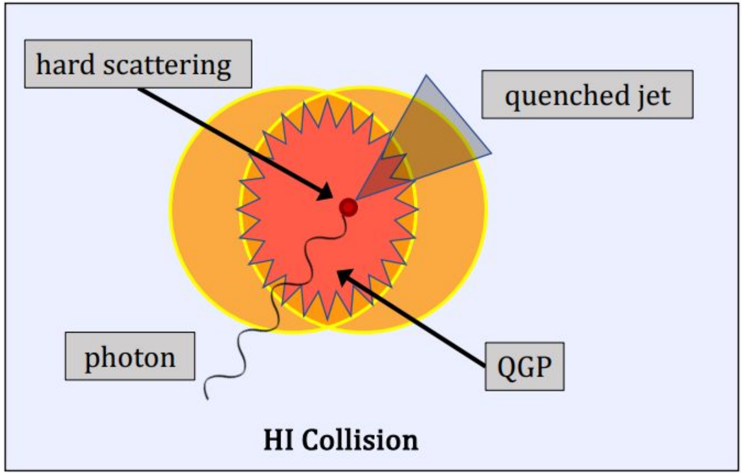
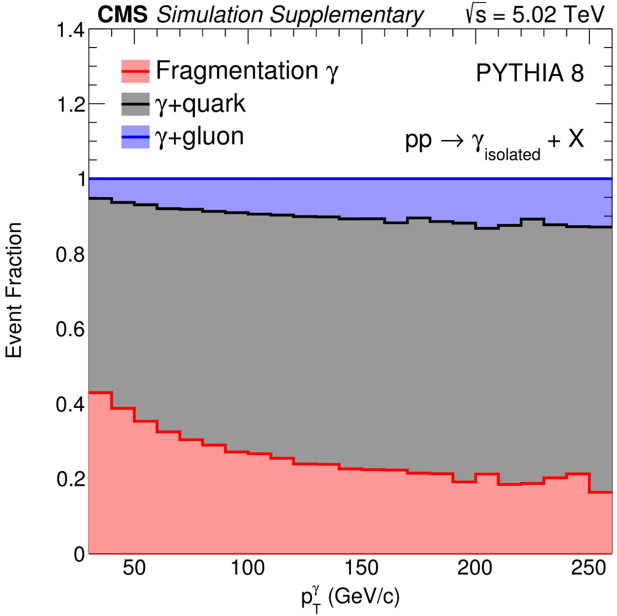
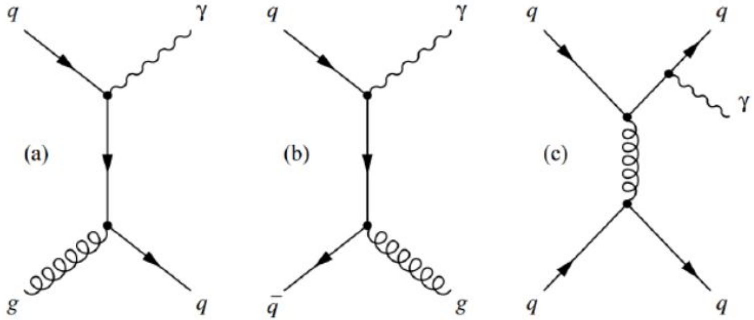
# Using photon-tagged jets





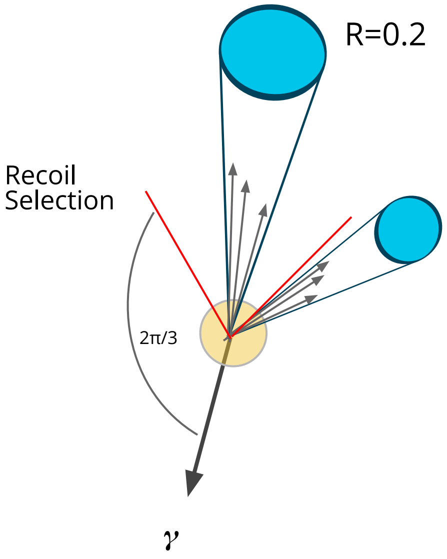
- Photon does not interact strongly with QGP →tags initial parton $p_T$
- Less bias from photon selection, compare PbPb/pp with same $p_T^\gamma$
- Good handle on q/g fraction of recoil parton
- Still some remaining bias from minimum jet $p_T$ requirement



CMS, PRL 122 (2019) 152001

# Measurement setup

- Isolated photons: $p_T^{\gamma} > 100$ GeV and $|\eta^{\gamma}| < 1.44$
- Associated anti-$k_T$ jets: R=0.2, $\Delta\phi_J^{\gamma} > 2\pi/3$ , $|\eta^{jet}| < 2$



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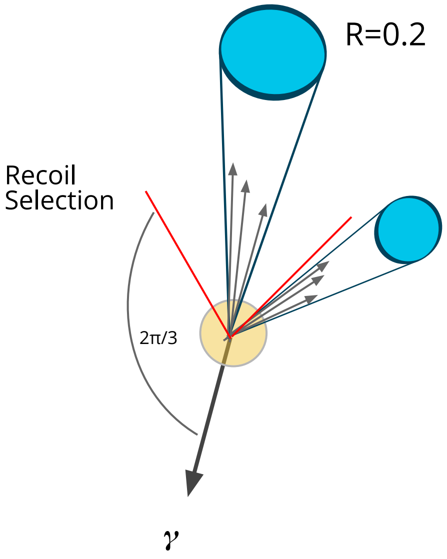
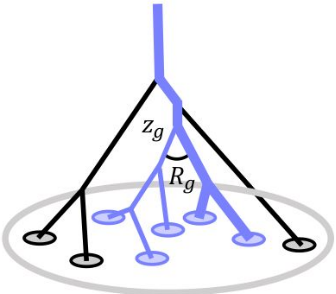
- Observables:
  - Groomed jet radius $R_g$ ($\beta_{SD} = 0$ and $z_{cut} = 0.2$)
  - Jet girth $g$
- Two categories for measurement
  - $p_T^{jet}/p_T^{\gamma} = x_{\gamma j} > 0.4$ (quenched and unquenched jets)
  - $p_T^{jet}/p_T^{\gamma} = x_{\gamma j} > 0.8$ (less quenched jets)



$$g = \sum_{i=0}^{i=N} \frac{p_T^i \Delta R_{i,jet}}{p_{T,jet}}$$



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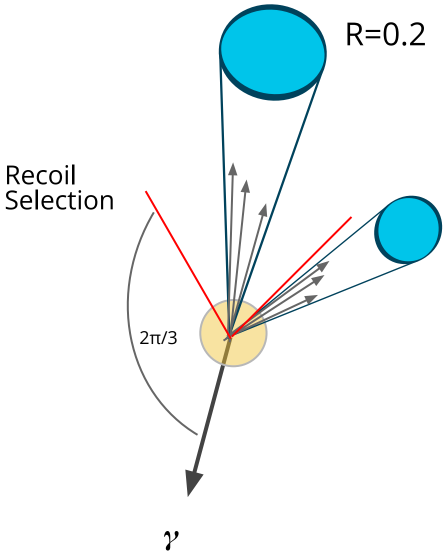
- Analysis method
  - Apply a purity correction for photons from neutral meson decays with template fits and ABCD method
  - Correct detector resolution effects, acceptance and efficiency with D'Agostini unfolding



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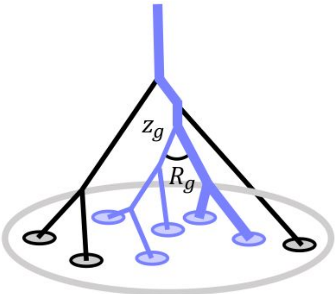
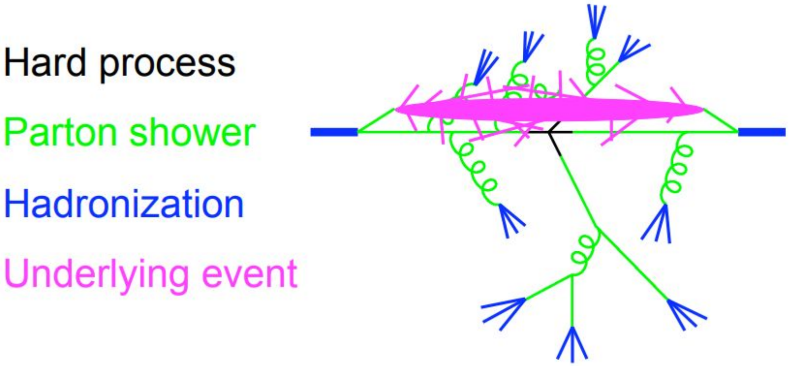


# Model comparison

- Monte-Carlo models for pp :
  - **Pythia8**: CP5, VINCIA, DIRE

Dipole parton shower with string hadronization



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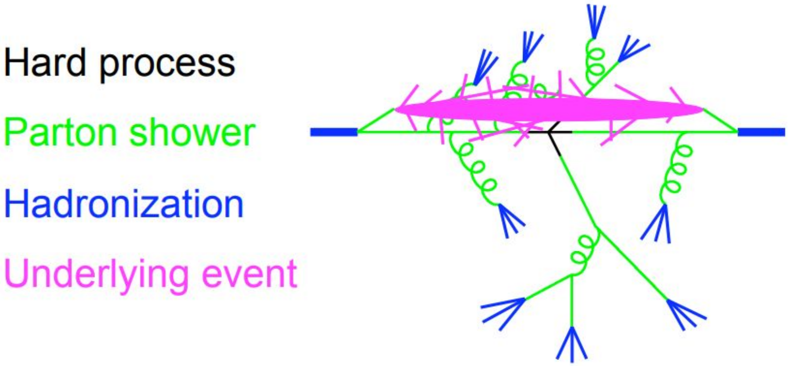
  - Herwig7 with dipole shower



# Models

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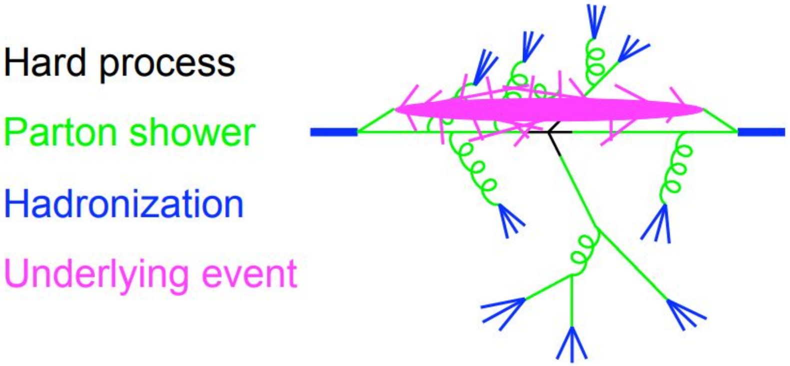
- Phenomenological model for PbPb: Hybrid
    - **Elastic** → Moliere scattering
    - **Wake** → Nonpertubative backreaction

Weak+strong coupling approach to jet quenching

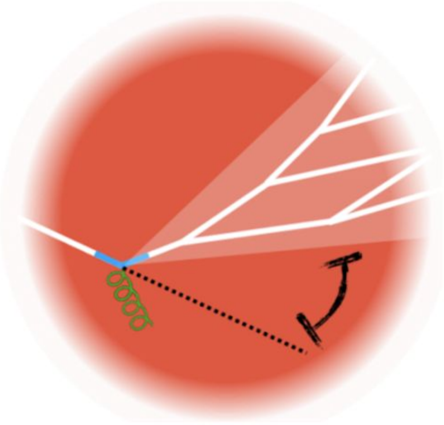

Hard process

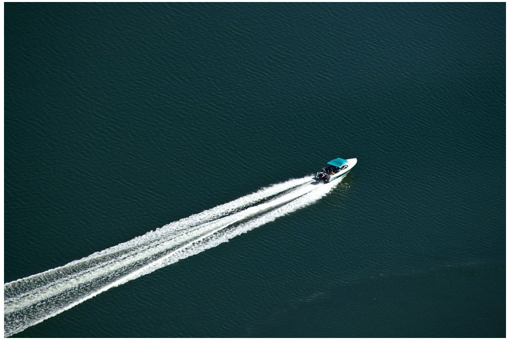
Parton shower

Hadronization

Underlying event

Point-like scatterers
in the QGP (Quasi-particles)





# Photon-tagged jets with $p_T^{jet}/p_T^{\gamma} > 0.4$ in pp collisions

CMS, arXiv:2405.0273

**Hybrid**

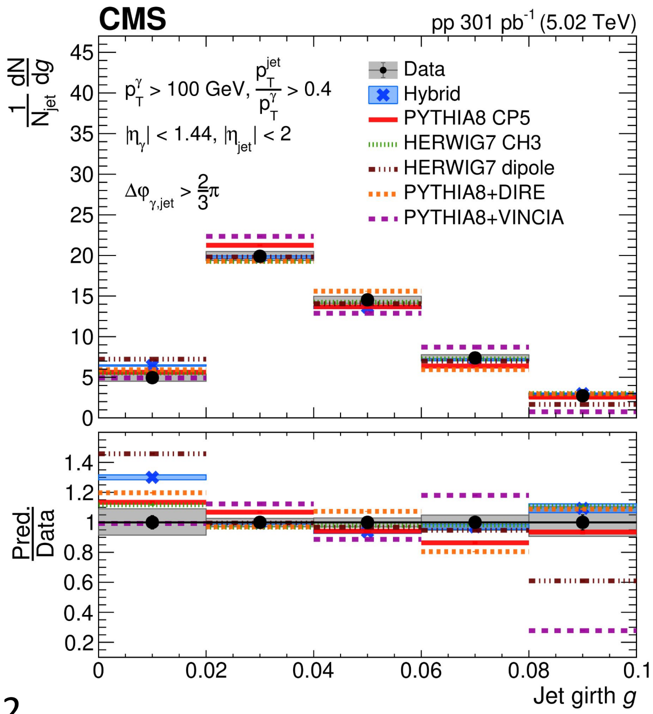
**PYTHIA8 CP5**

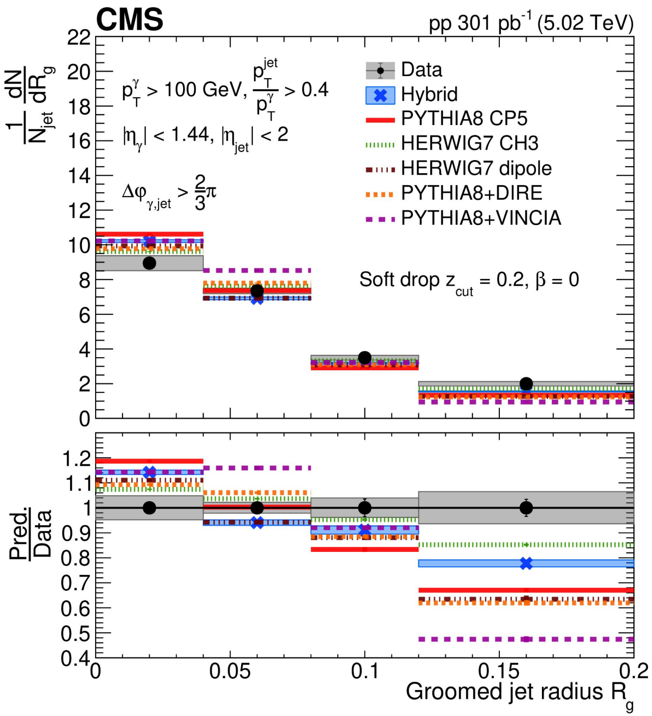
PYTHIA8 VINCIA

PYTHIA8 DIRE

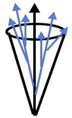
**HERWIG7 CH3**

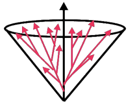
HERWIG7 dipole

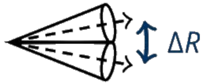


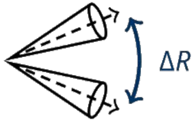


Data/MC simulation differences by factors upto 2









**Best global description by**

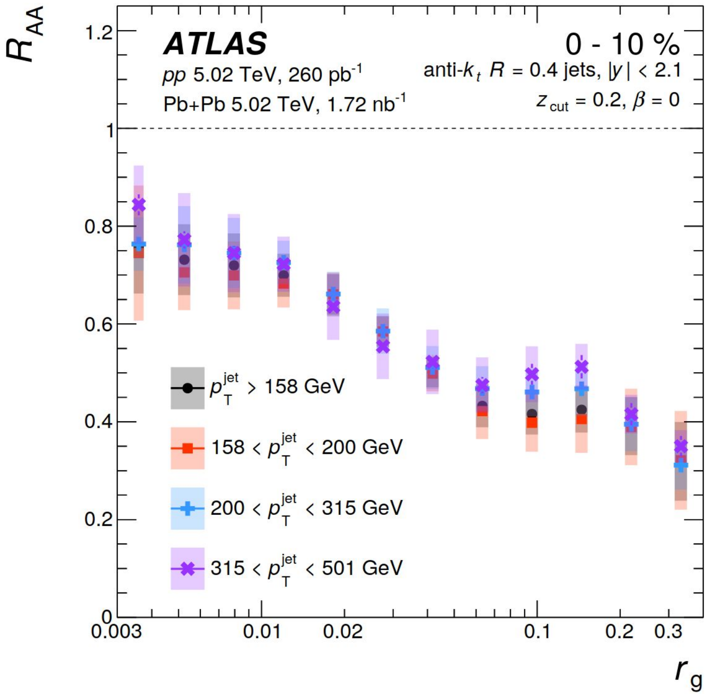
**HERWIG7 CH3 (angular ordered)**

# Comparison of $p_T^{jet}/p_T^{\gamma} > 0.4$ with ATLAS $R_g$ measurement

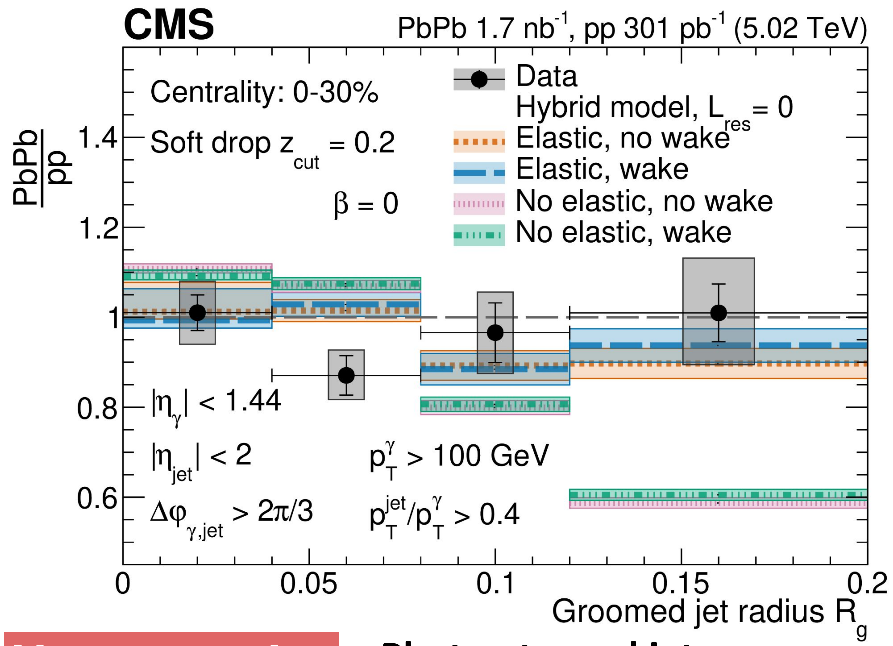
(**Selecting quenched and less quenched jets**)

ATLAS, PRC 107, (2023) 054909

CMS, arXiv:2405.0273



**Inclusive Jets**



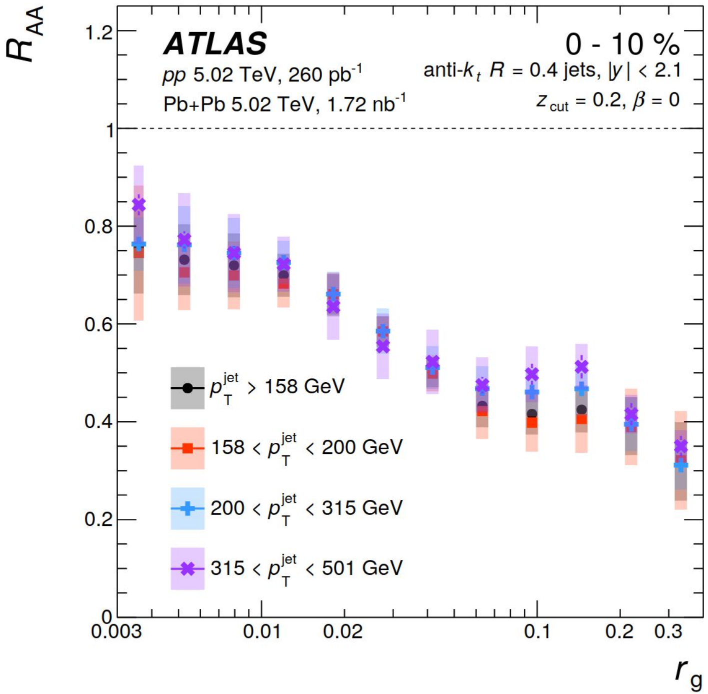
***No narrowing***

**Photon tagged jets**

Angular narrowing not observed in $\gamma$+jet events in contrast to inclusive jets

# Comparison of $p_T^{jet}/p_T^{\gamma} > 0.8$ with ATLAS $R_g$ measurement

**(Only less quenched jets)**



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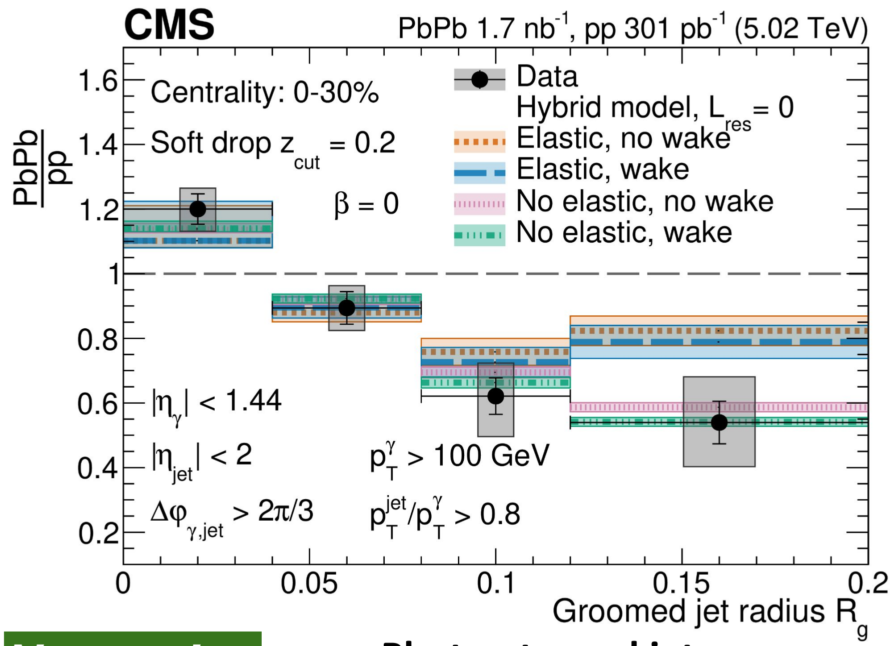
ATLAS, PRC 107, (2023) 054909

CMS, arXiv:2405.0273



***Narrowing***

**Photon tagged jets**

With stronger selection bias the narrowing trend is observed both in inclusive jet and $\gamma$+jet events

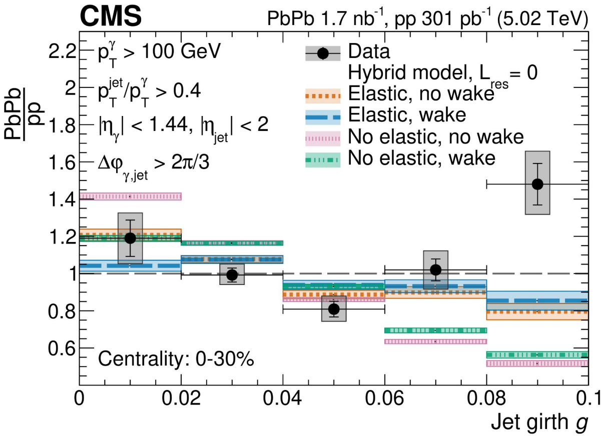
# Model comparison: $p_T^{jet}/p_T^{\gamma} > 0.4$

Predictions with Moliere scattering (**Elastic**)-> the best global description

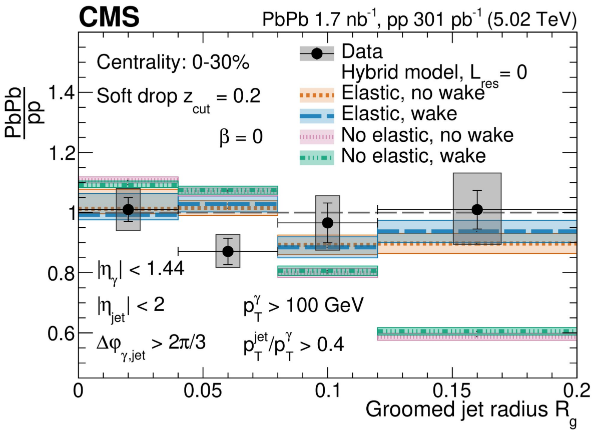
No sensitivity to wake effect

**Jet girth**

CMS, arXiv:2405.0273



**Groomed jet radius**



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**Jet girth** CMS, arXiv:2405.0273 **Groomed jet radius**

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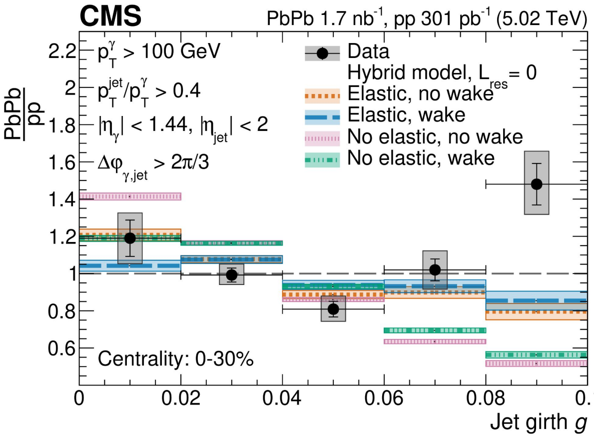
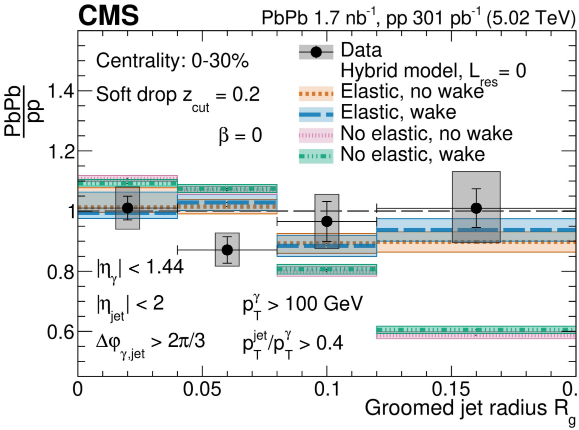
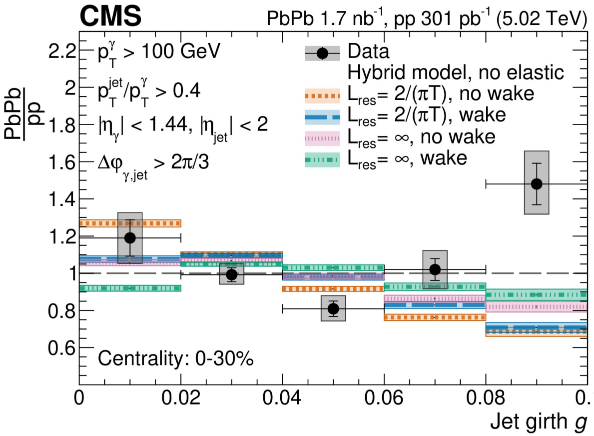


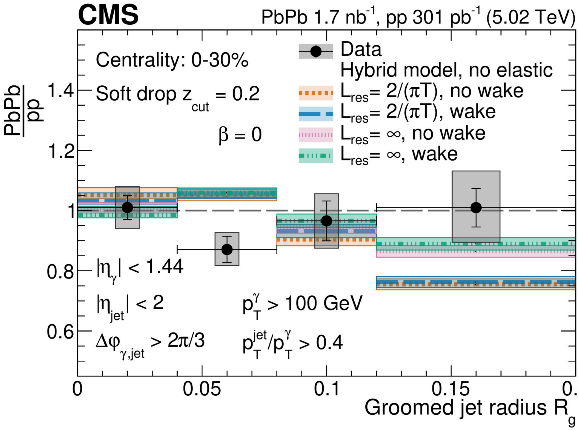


$L_{res} = 0 \rightarrow$ incoherent limit

$L_{res} = 2/(\pi T) \rightarrow$ intermediate state

$L_{res} = \infty \rightarrow$ coherent limit





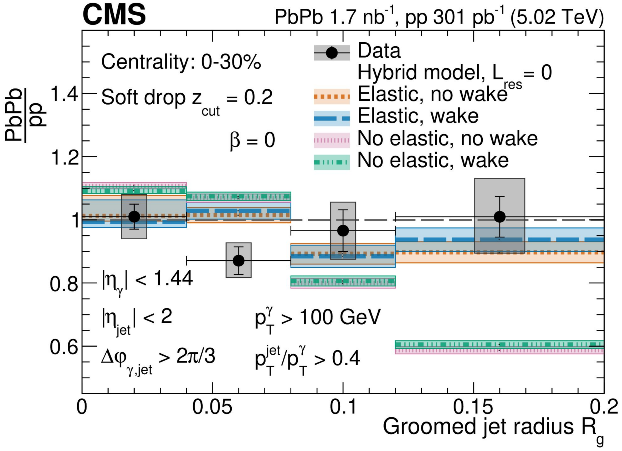
Slide 6: Medium resolution length

# Summary

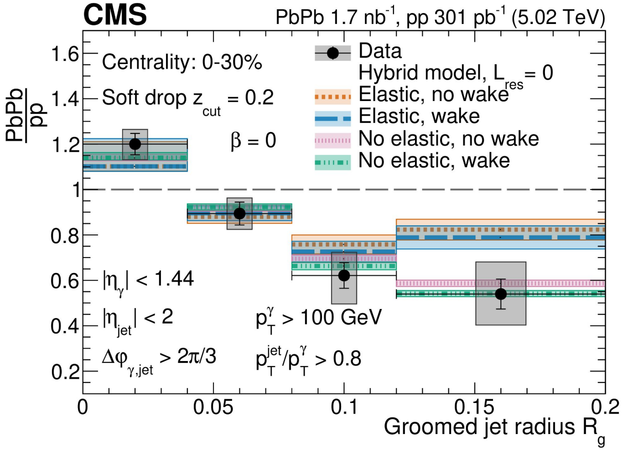
- Measured groomed jet radius and jet girth in $\gamma$+jet events in PbPb and pp collisions
- Looked at $\gamma$+jet events with $p_T^{\gamma} > 100$ GeV and two different setups:
    - $x_{\gamma j} > 0.4$ (quenched and unquenched jets) : **no narrowing is observed**
    - $x_{\gamma j} > 0.8$ (less quenched jets) : **narrowing is observed**
- No single consistent choice of model parameters describe the data in both setups

CMS, arXiv:2405.0273
Submitted to PLB

**$x_{\gamma j} > 0.4$**



**$x_{\gamma j} > 0.8$**



# Backup

# Model references

**Hybrid :** Z. Hulcher, D. Pablos, K. Rajagopal, arXiv:1405.3864

**PYTHIA8 CP5 :** CMS, arXiv:1903.12179

PYTHIA8 VINCIA : W. Giele, D. Kosower, P. Skands, arXiv:0707.3652

PYTHIA8 DIRE : S. Höche, S. Prestel, arXiv:1506.05057

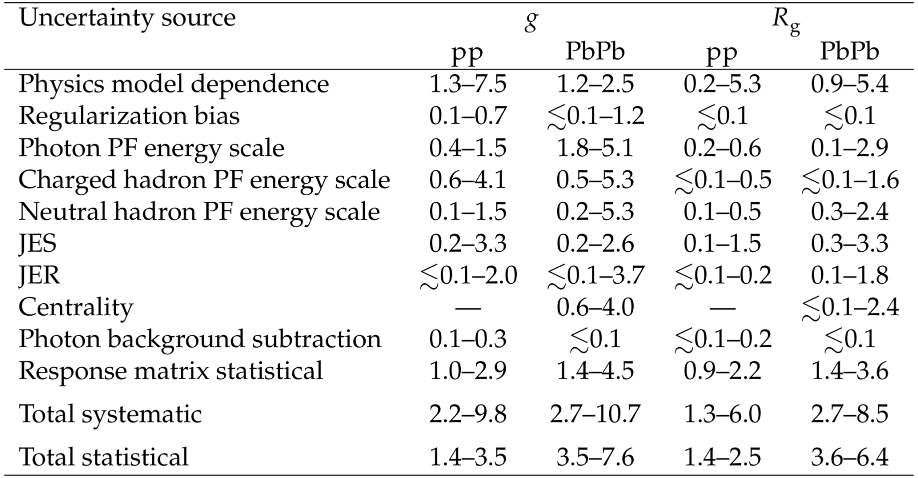
**HERWIG7 CH3 :** CMS, arXiv:2011.03422

HERWIG7 dipole : J. Bellm, S. Gieseke, D. Grellscheid, et al, arXiv:1512.01178

# Systematic uncertainties

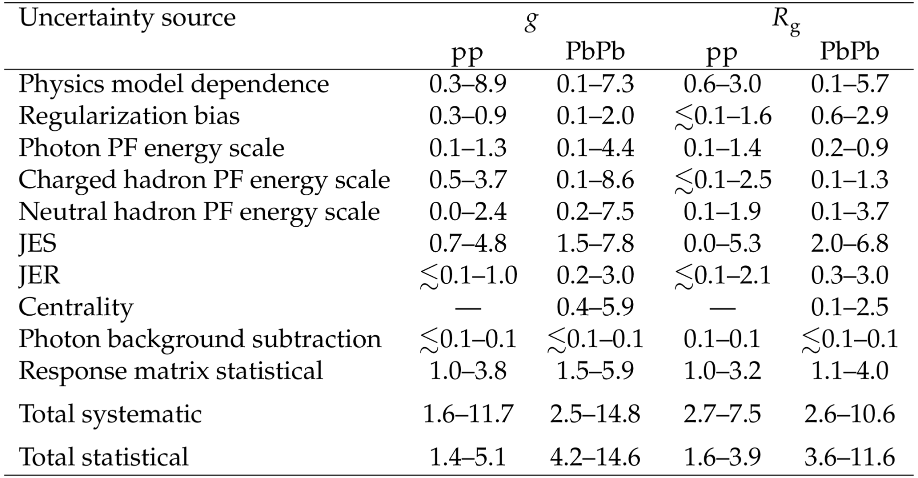
- **MC modelling (dominant) -** Quantifies uncertainty in modelling of UE, parton shower and hadronization model. Estimated by comparing PYTHIA8 embedded with a quark/gluon fraction reweighted PYTHIA8 embedded in PbPb. For pp collisions, we do PYTHIA8 vs HERWIG7.
- **Jet constituent energy scale (dominant)-** 4-momenta of PF candidates for a given anti-$k_T$ jet are varied by shifting the energy of photon and charged hadron species by 1% and neutral hadron species by 3% (similar to CMS-SMP-20-010, JHEP 01 (2022) 188)
- Jet energy corrections (JEC)
- Jet energy resolution (JER)
- Regularization bias
- Response matrix stats
- Photon purity
- Centrality

**$x_{\gamma j} > 0.4$**



| Uncertainty source | $g$ |  | $R_g$ |  |
|---|---|---|---|---|
|  | pp | PbPb | pp | PbPb |
| Physics model dependence | 1.3–7.5 | 1.2–2.5 | 0.2–5.3 | 0.9–5.4 |
| Regularization bias | 0.1–0.7 | $\lesssim$0.1–1.2 | $\lesssim$0.1 | $\lesssim$0.1 |
| Photon PF energy scale | 0.4–1.5 | 1.8–5.1 | 0.2–0.6 | 0.1–2.9 |
| Charged hadron PF energy scale | 0.6–4.1 | 0.5–5.3 | $\lesssim$0.1–0.5 | $\lesssim$0.1–1.6 |
| Neutral hadron PF energy scale | 0.1–1.5 | 0.2–5.3 | 0.1–0.5 | 0.3–2.4 |
| JES | 0.2–3.3 | 0.2–2.6 | 0.1–1.5 | 0.3–3.3 |
| JER | $\lesssim$0.1–2.0 | $\lesssim$0.1–3.7 | $\lesssim$0.1–0.2 | 0.1–1.8 |
| Centrality | — | 0.6–4.0 | — | $\lesssim$0.1–2.4 |
| Photon background subtraction | 0.1–0.3 | $\lesssim$0.1 | $\lesssim$0.1–0.2 | $\lesssim$0.1 |
| Response matrix statistical | 1.0–2.9 | 1.4–4.5 | 0.9–2.2 | 1.4–3.6 |
| Total systematic | 2.2–9.8 | 2.7–10.7 | 1.3–6.0 | 2.7–8.5 |
| Total statistical | 1.4–3.5 | 3.5–7.6 | 1.4–2.5 | 3.6–6.4 |

**$x_{\gamma j} > 0.8$**



| Uncertainty source | $g$ |  | $R_g$ |  |
|---|---|---|---|---|
|  | pp | PbPb | pp | PbPb |
| Physics model dependence | 0.3–8.9 | 0.1–7.3 | 0.6–3.0 | 0.1–5.7 |
| Regularization bias | 0.3–0.9 | 0.1–2.0 | $\lesssim$0.1–1.6 | 0.6–2.9 |
| Photon PF energy scale | 0.1–1.3 | 0.1–4.4 | 0.1–1.4 | 0.2–0.9 |
| Charged hadron PF energy scale | 0.5–3.7 | 0.1–8.6 | $\lesssim$0.1–2.5 | 0.1–1.3 |
| Neutral hadron PF energy scale | 0.0–2.4 | 0.2–7.5 | 0.1–1.9 | 0.1–3.7 |
| JES | 0.7–4.8 | 1.5–7.8 | 0.0–5.3 | 2.0–6.8 |
| JER | $\lesssim$0.1–1.0 | 0.2–3.0 | $\lesssim$0.1–2.1 | 0.3–3.0 |
| Centrality | — | 0.4–5.9 | — | 0.1–2.5 |
| Photon background subtraction | $\lesssim$0.1–0.1 | $\lesssim$0.1–0.1 | 0.1–0.1 | $\lesssim$0.1–0.1 |
| Response matrix statistical | 1.0–3.8 | 1.5–5.9 | 1.0–3.2 | 1.1–4.0 |
| Total systematic | 1.6–11.7 | 2.5–14.8 | 2.7–7.5 | 2.6–10.6 |
| Total statistical | 1.4–5.1 | 4.2–14.6 | 1.6–3.9 | 3.6–11.6 |

# Photon-tagged jets with $p_T^{jet}/p_T^{\gamma}$ › 0.8 in pp collisions

CMS, arXiv:2405.0273

**Hybrid**

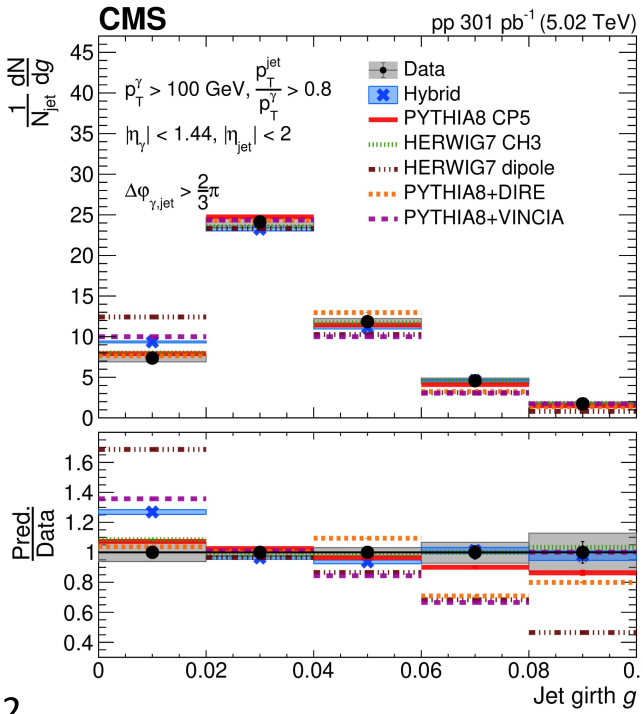
**PYTHIA8 CP5**

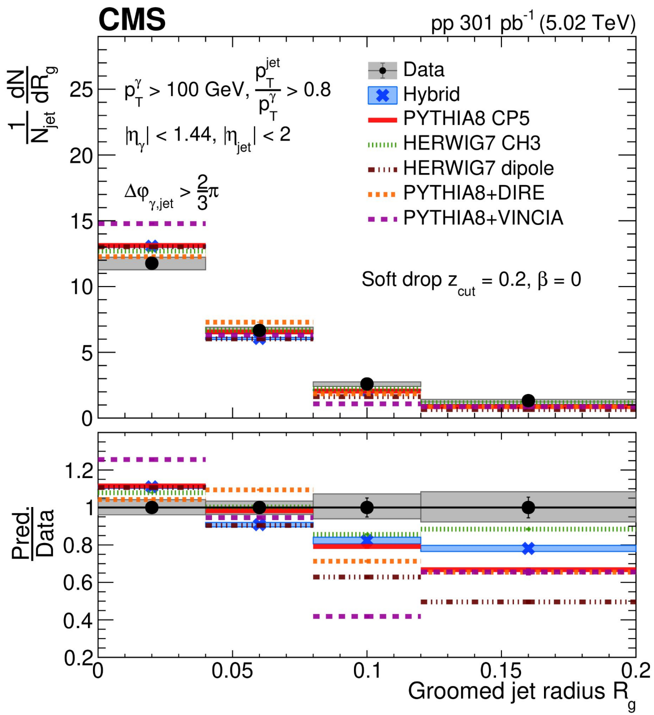
PYTHIA8 VINCIA

PYTHIA8 DIRE

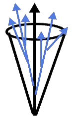
**HERWIG7 CH3**

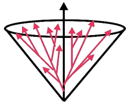
HERWIG7 dipole

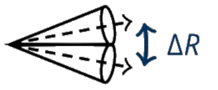


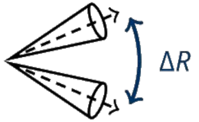


Data/MC simulation differences by factors upto 2





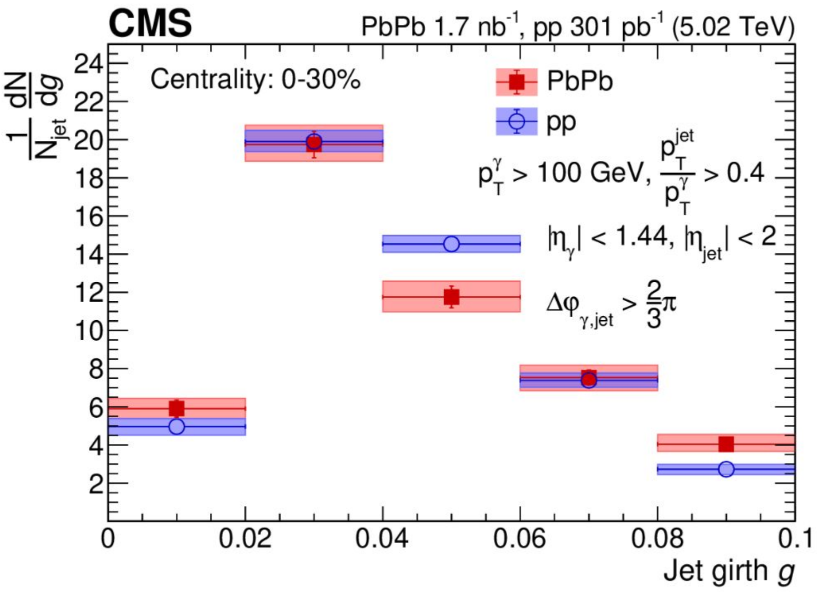


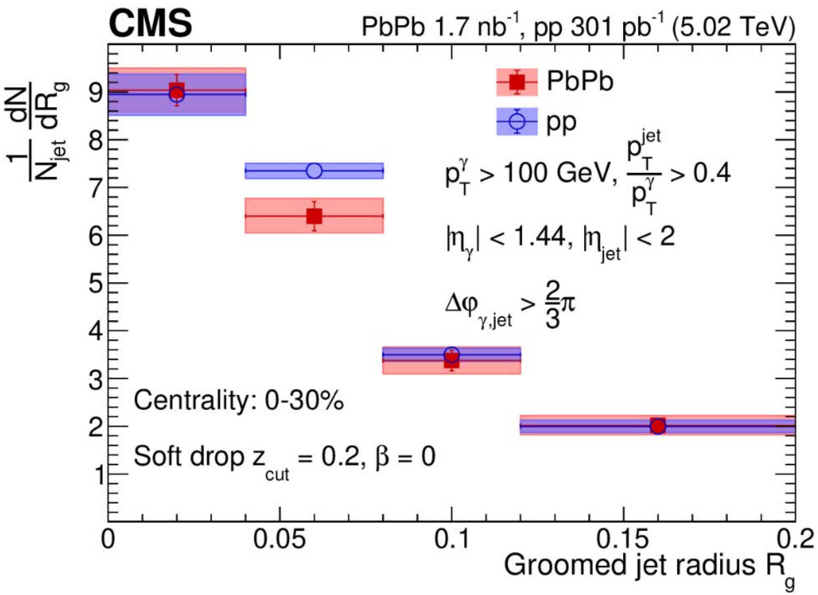


**Best global description by**

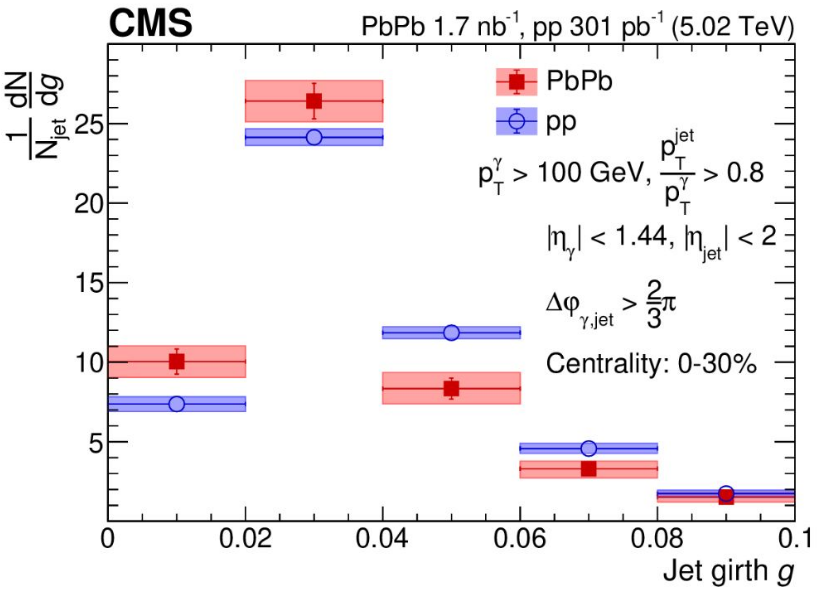
**HERWIG7 CH3 (angular ordered)**

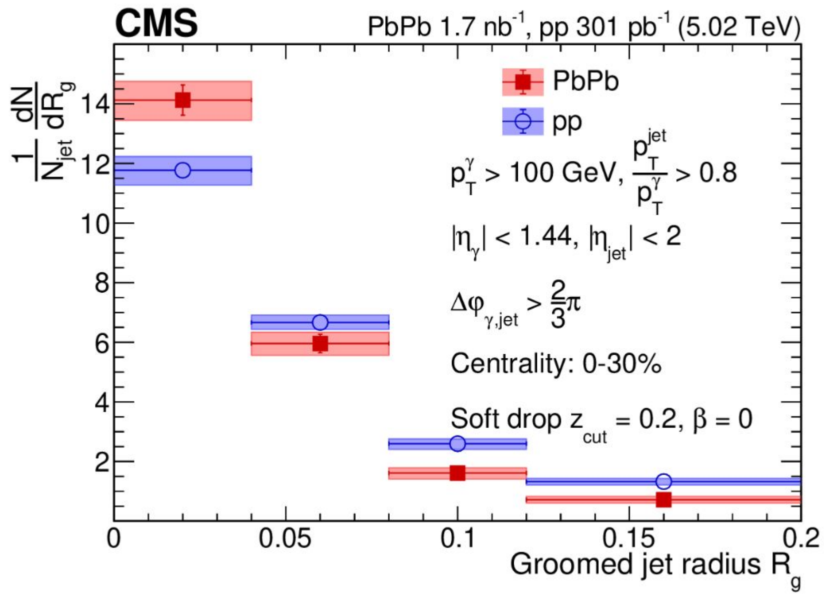
# Results (**pp** vs **PbPb**), $p_T^{jet}/p_T^{\gamma} > 0.4$





# Photon-tagged jets with energy-loss bias $p_T^{jet}/p_T^{\gamma} > 0.8$ (**pp** vs **PbPb**)





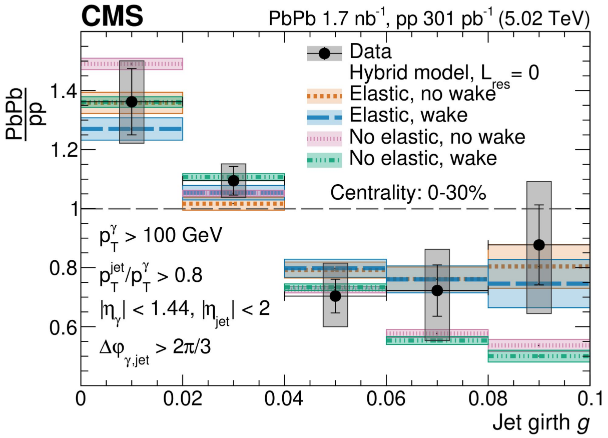
# Theory comparison:

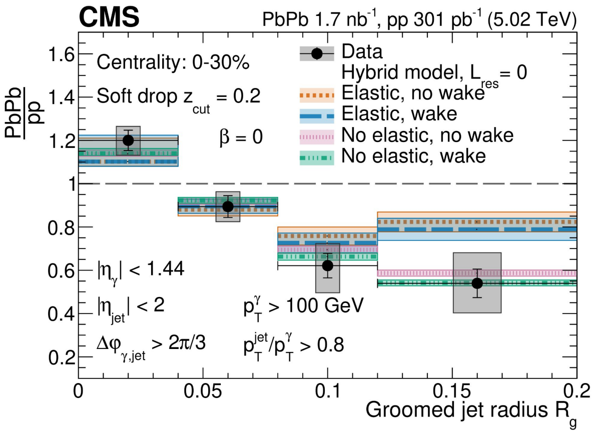
## $p_T^{jet}/p_T^{\gamma} > 0.8$

**Jet girth** CMS, arXiv:2405.0273 **Groomed jet radius**

Predictions with Moliere scattering (**Elastic**)-> the best global description

No sensitivity to wake effect





$L_{res} = 0 \rightarrow$ incoherent limit

$L_{res} = 2/(\pi T) \rightarrow$ intermediate state

$L_{res} = \infty \rightarrow$ coherent limit