Probing bottom quark mass effects in jet substructure with CMS

using a novel technique to cluster the b hadron decays

CMS-PAS-HIN-24-005

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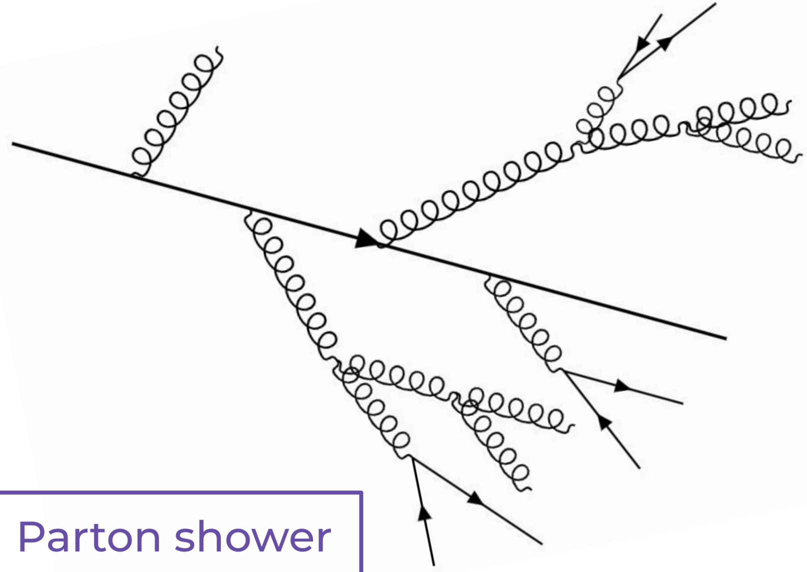
on behalf of the CMS collaboration
LLR, École Polytechnique

EPS-HEP 2025, Marseille, 7 July 2025

Jet evolution

quark or gluon
(parton)

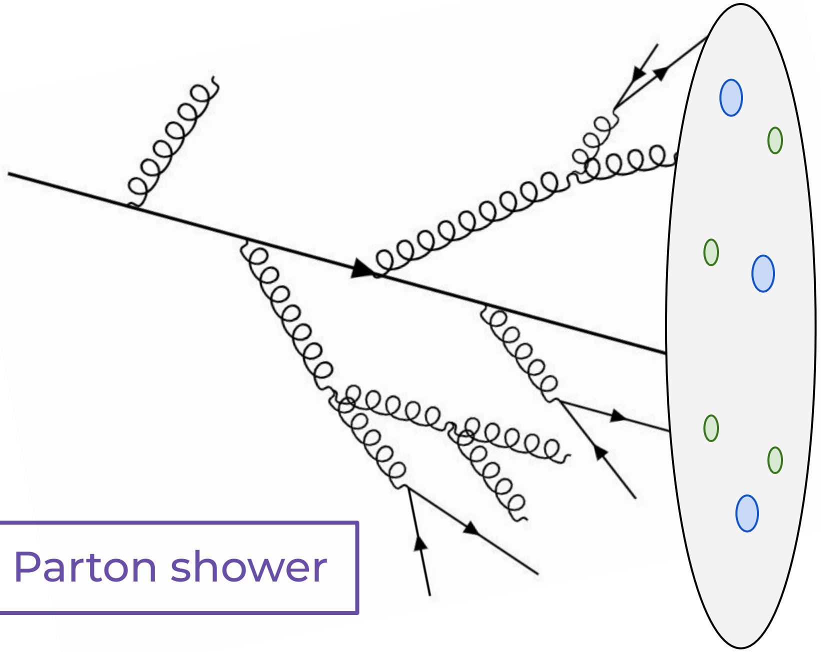


Parton shower

Jet evolution

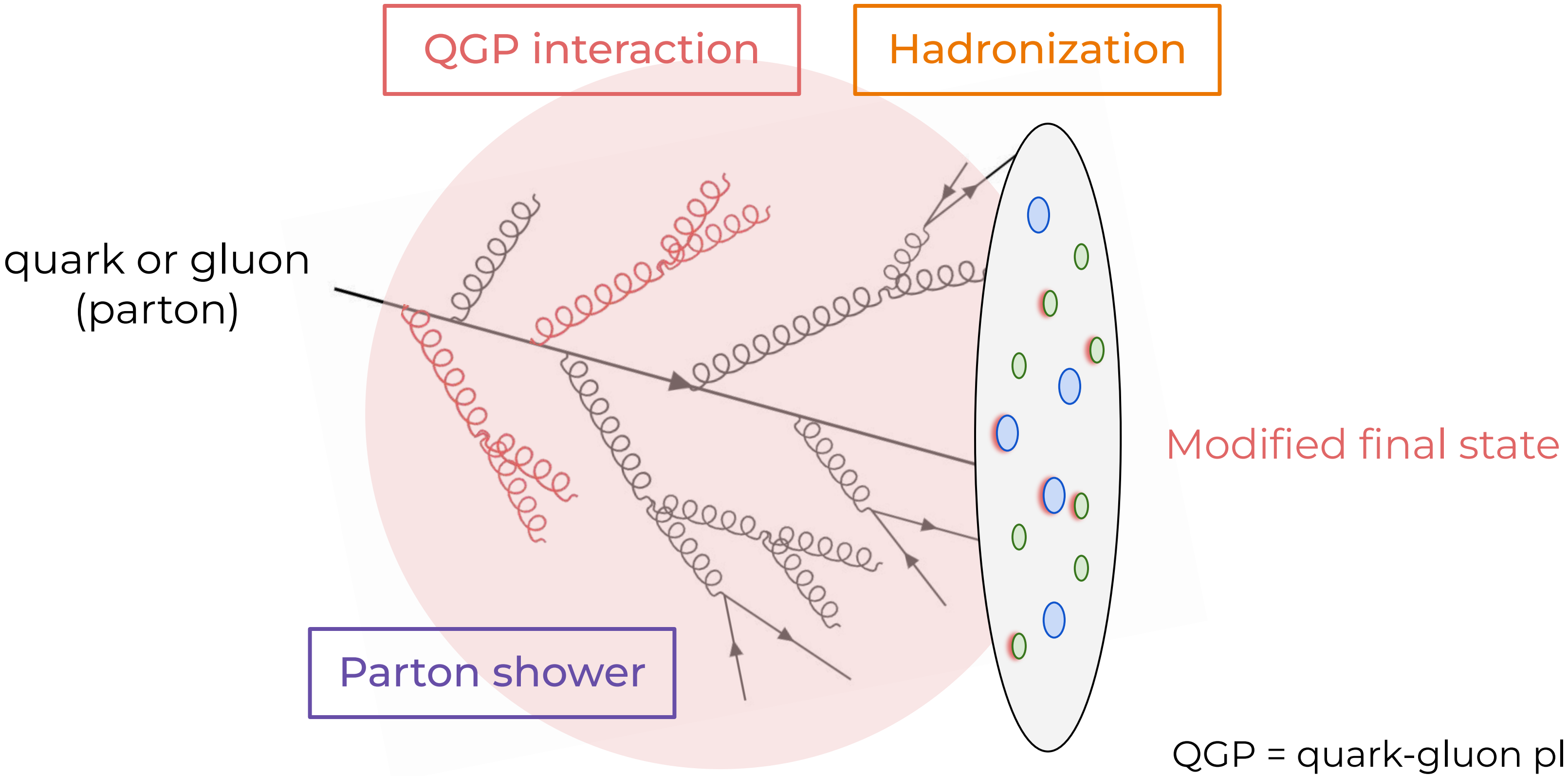
Hadronization

quark or gluon
(parton)



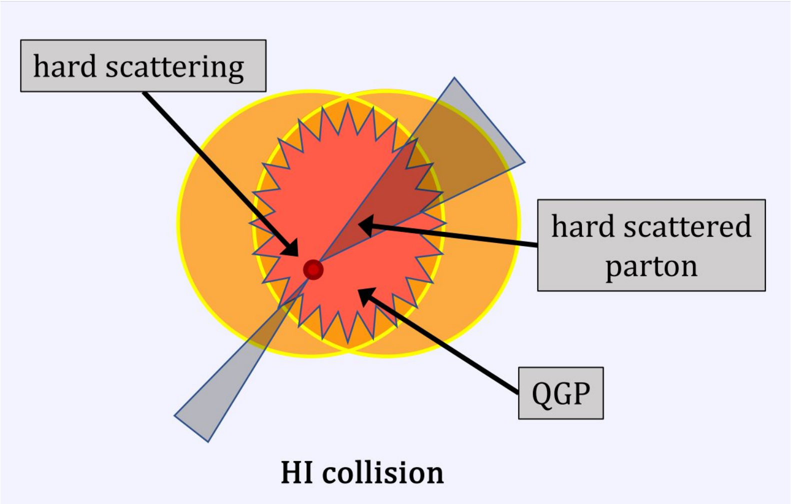
Parton shower

Jet evolution in medium



QGP = quark-gluon plasma

Jet quenching

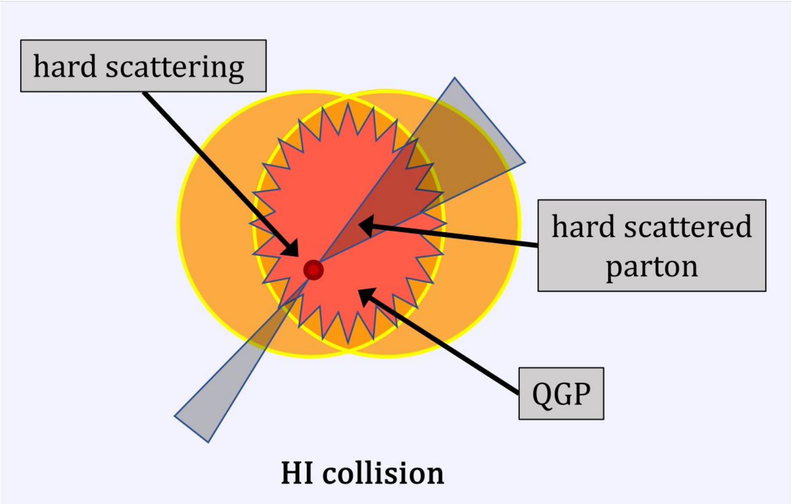


Centrality (nuclear overlap)

0-10% 10-30% 30-50% 50-90%

Jet quenching

$$R_{AA} = 1/\langle N_{coll}\rangle \times N_{jet}^{PbPb} / N_{jet}^{pp}$$



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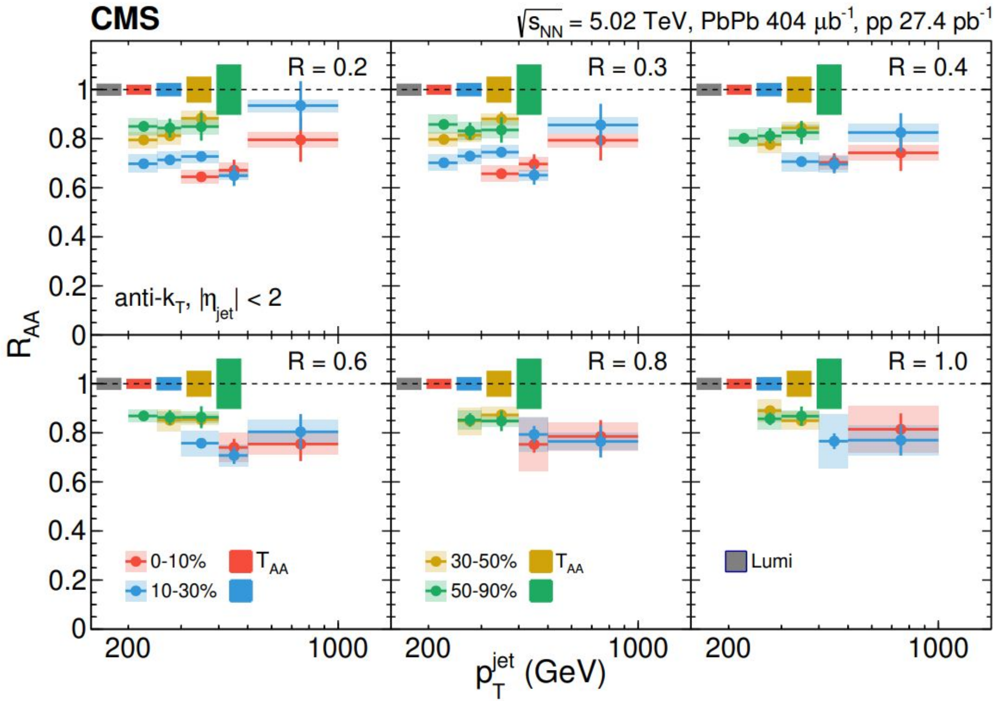

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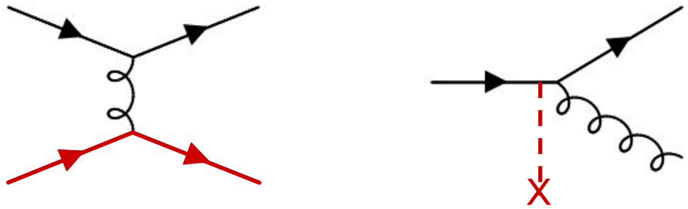
Energy loss mechanisms

Elastic vs Radiative



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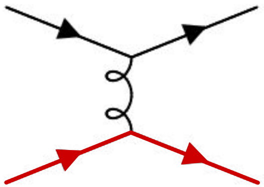
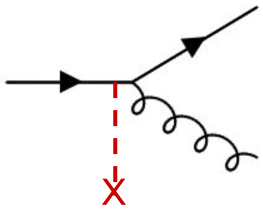
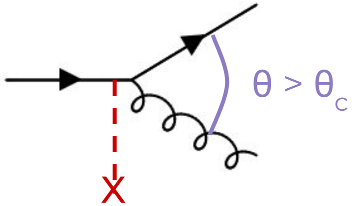
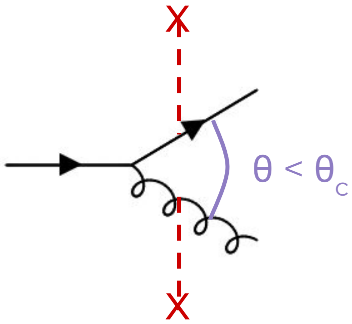




Coherent aka unresolved color charges vs Incoherent aka resolved color charges





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JHEP 2011 (2011) 15
PLB 707 (2012) 156

Energy loss mechanisms

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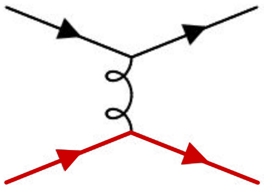
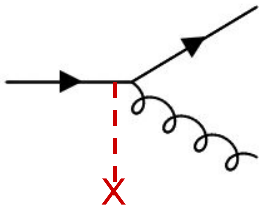
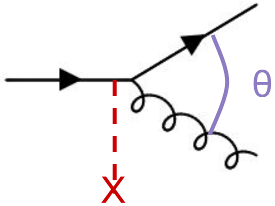
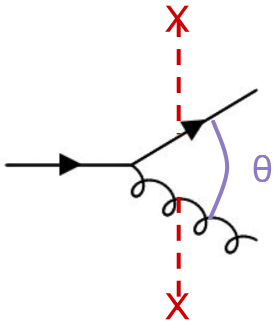




Coherent vs **Incoherent**

aka unresolved color charges | aka resolved color charges





How to disentangle these mechanisms?

Look at the jet substructure !

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Heavy flavor jets

Mass dependent shower

$$P_{Q\to Qg}(z) = \frac{1-z}{z} + \frac{z}{2} - 2\mu^2_{Qg}$$

$$\mu^2_{\mathrm{Qg}} = \frac{m^2_{\mathrm{Q}}}{m^2_{\mathrm{Qg}} - m^2_{\mathrm{Q}}}$$

Suppression of collinear radiation (dead cone)

$$\mathrm{d}\mathcal{P}(\theta) \propto \frac{\mathrm{d}\theta^2}{(\theta^2 + \theta_0^2)^2}$$

$$\theta_0 = m_{\mathrm{Q}}/E_{\mathrm{Q}}$$

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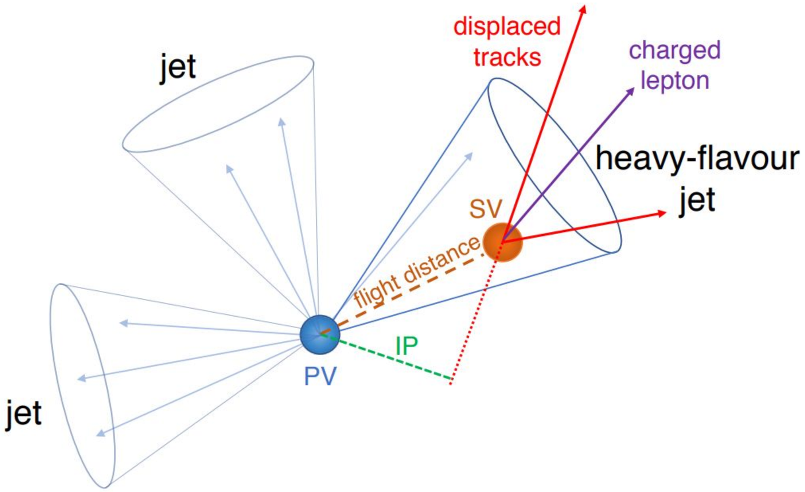
Large datasets via b tagging



Heavy flavor jets in medium

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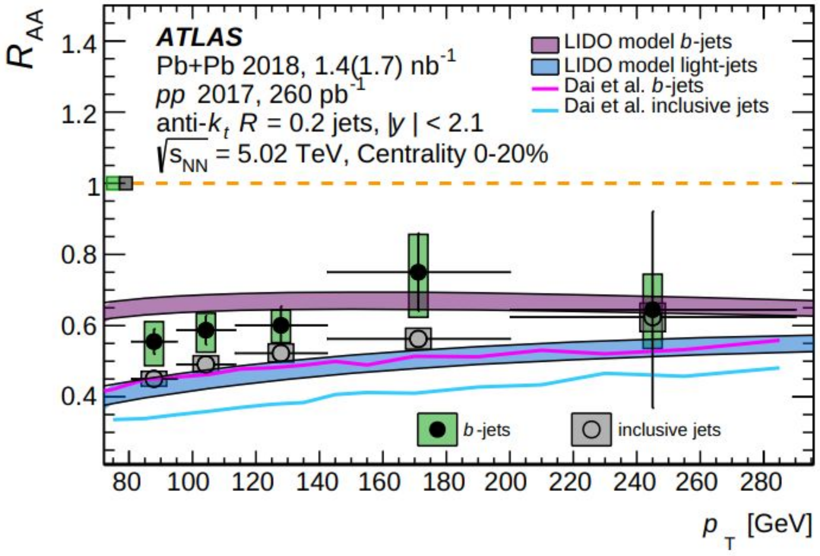

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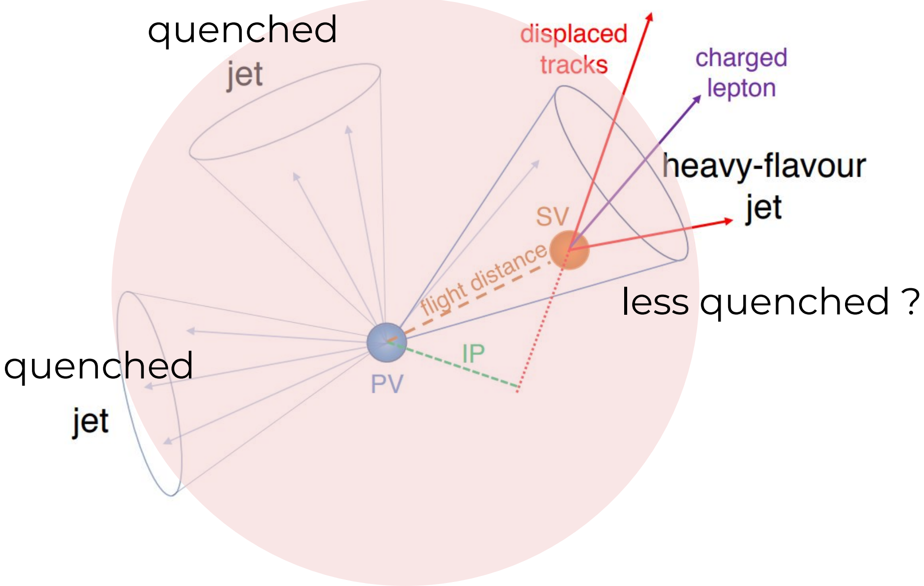
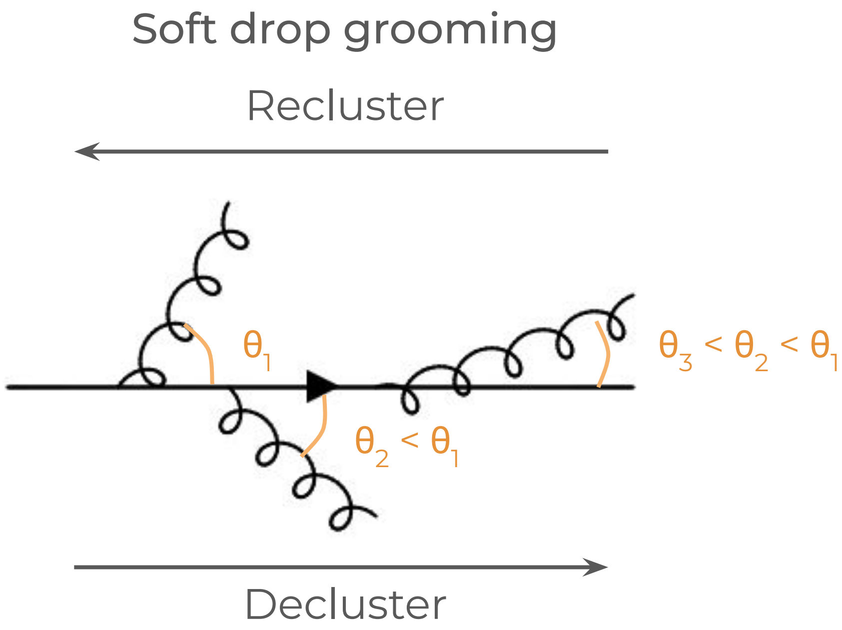


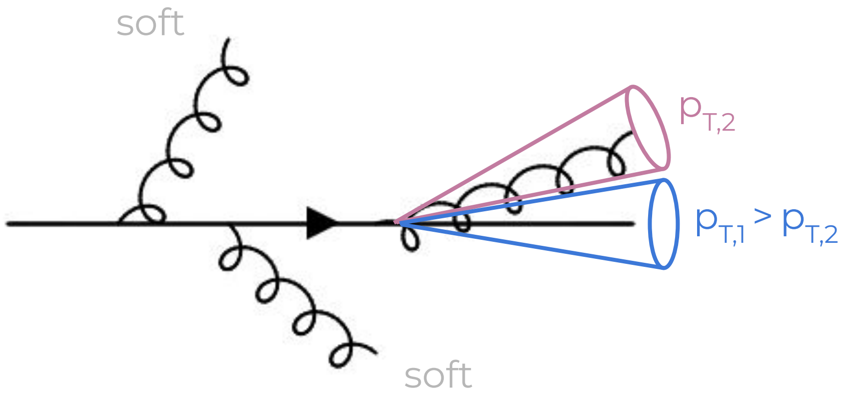
Penetrating probe of the QGP

Observable definition



Observable definition

Soft drop grooming



Remove soft, wide-angle radiation to access hard two-prong structure

Groomed jet radius

$$R_g^{\,2} = \Delta y_{1,2}^{\,2} + \Delta\phi_{1,2}^{\,2}$$

Momentum balance

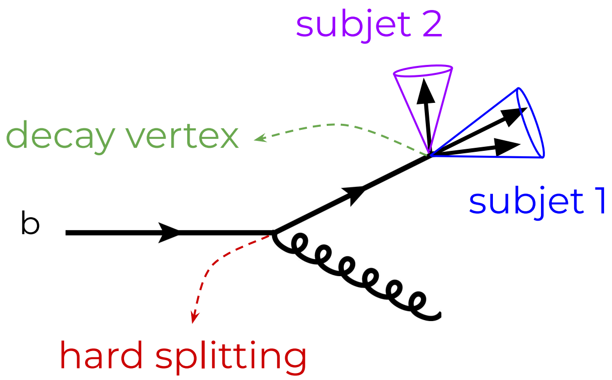
$$p_{T,2} \,/\, (p_{T,1}+p_{T,2})$$

Relative transverse momentum

$$k_T = p_{T,2} R_g$$

Heavy flavor decay effects

Decay daughters do not follow angular ordering



Heavy flavor decay effects

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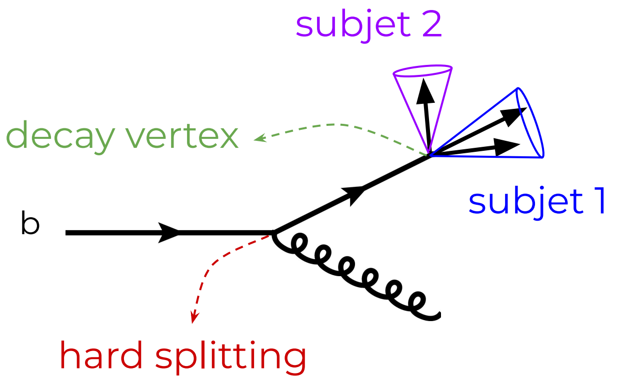
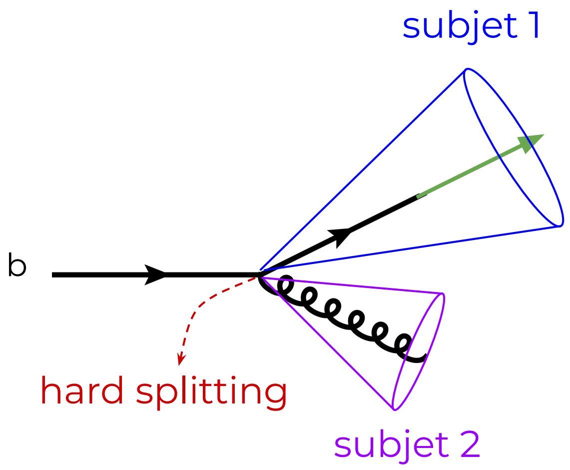


Need to reconstruct the b hadron to restore angular ordering



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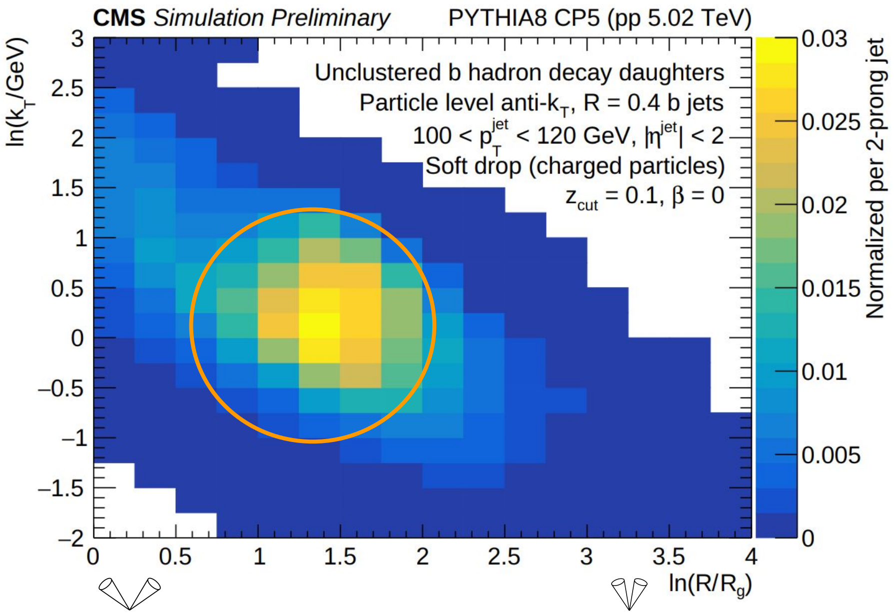
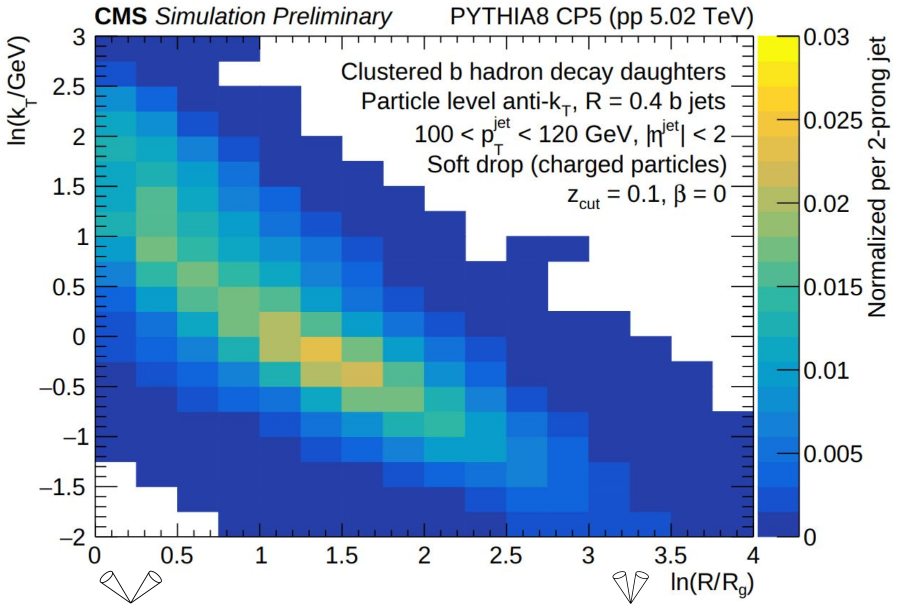


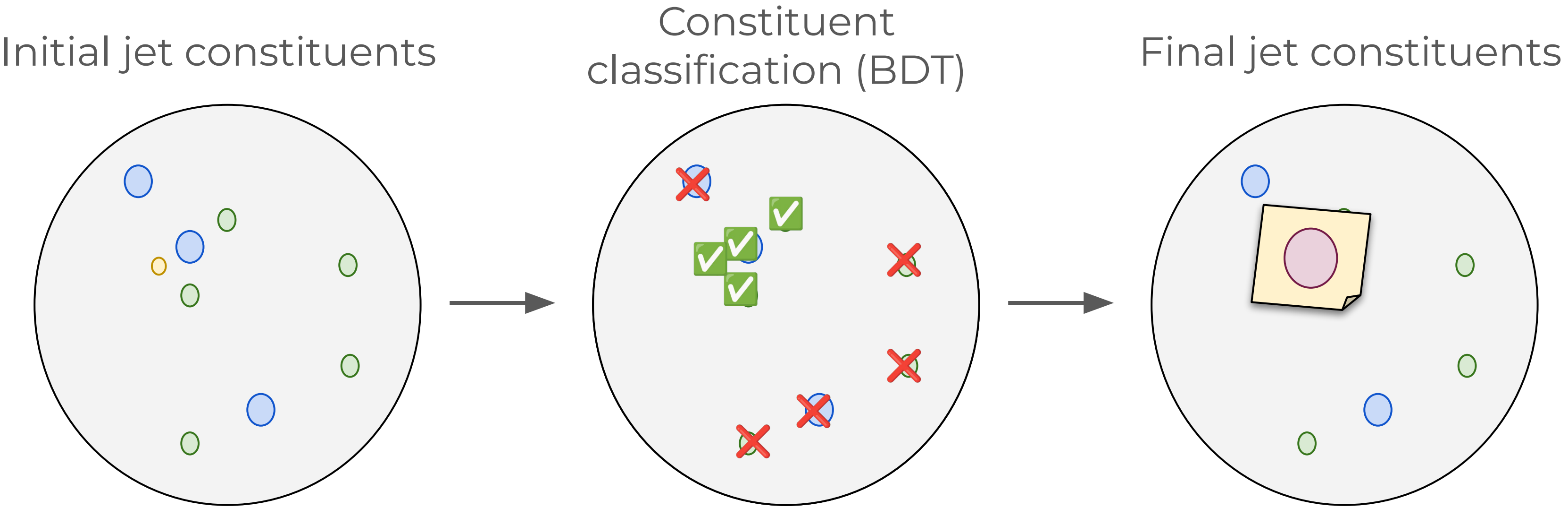
b decay daughters individually present



b decay daughters clustered into single particle

Partial b hadron reconstruction

Identify the decay daughters in the jet and sum their four-momenta



Signal (✅) = from b hadron decay
Background (❌) = from primary interaction

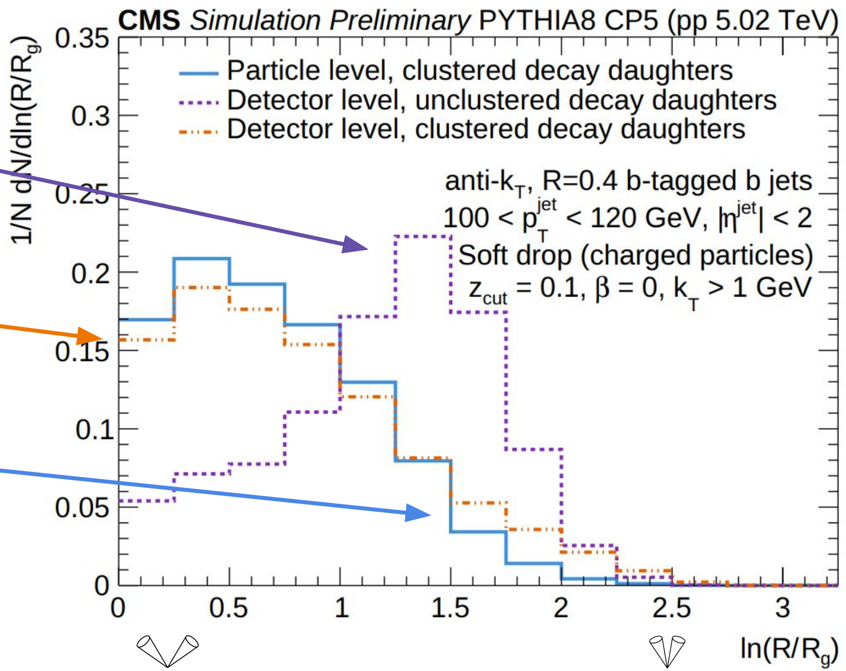
Partial b hadron reconstruction

Identify the decay daughters in the jet and sum their four-momenta

detector level with decays

detector level without decays

particle level without decays



Jet selection and corrections

b tagging

b jets selected with ParticleNet
at very high purity working point

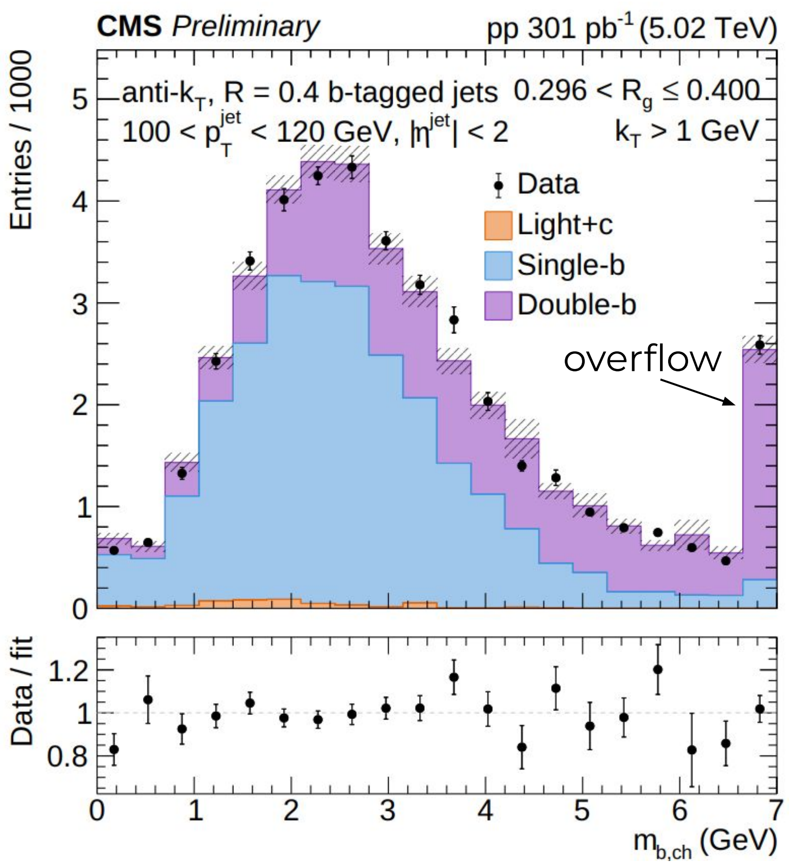
But...

Sample includes jets with
more than one b hadron

Residual background subtraction

Fit the mass of the reconstructed b hadron
with MC templates

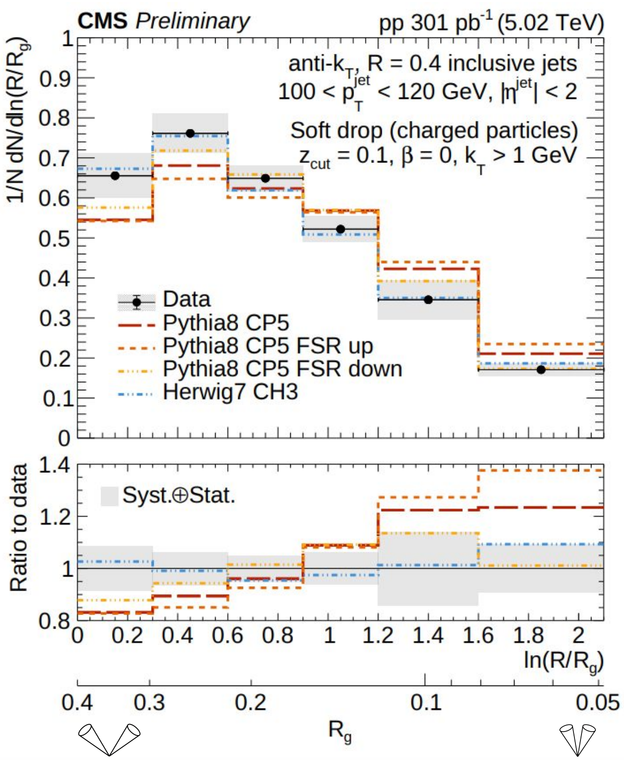
Unfolding to the charged-particle level b jet
+ Tagging efficiency correction



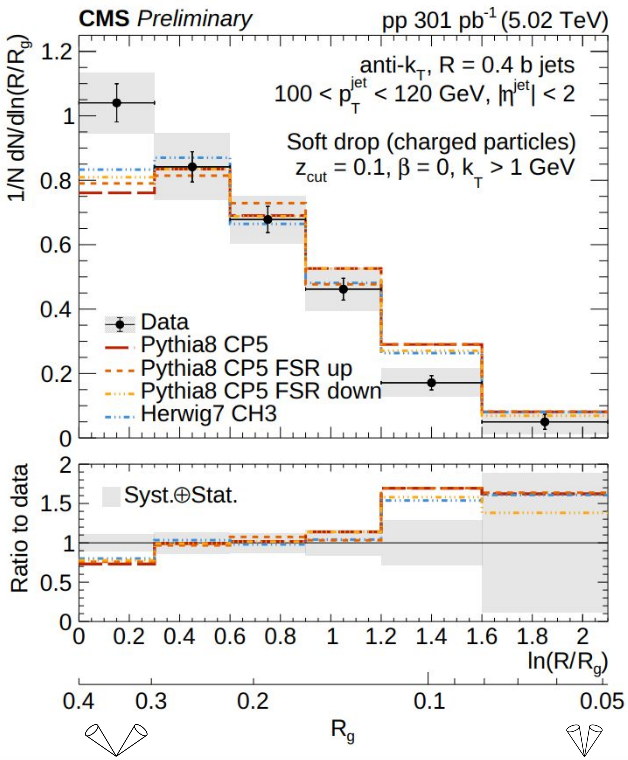
reconstructed b hadron mass

The groomed jet radius results

Inclusive jets



b jets

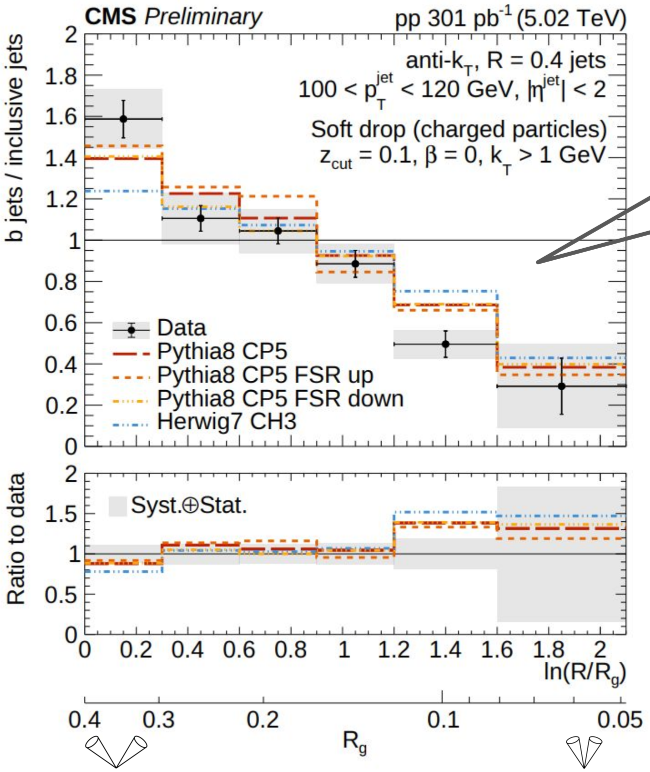


Model comparison

	Pythia	Herwig
Inclusive	❌	✅
b jets	❌	❌

The groomed jet radius results

b to inclusive jet ratio



Suppression of small-angle radiation

Dead cone manifestation !

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ratio	✅	❌

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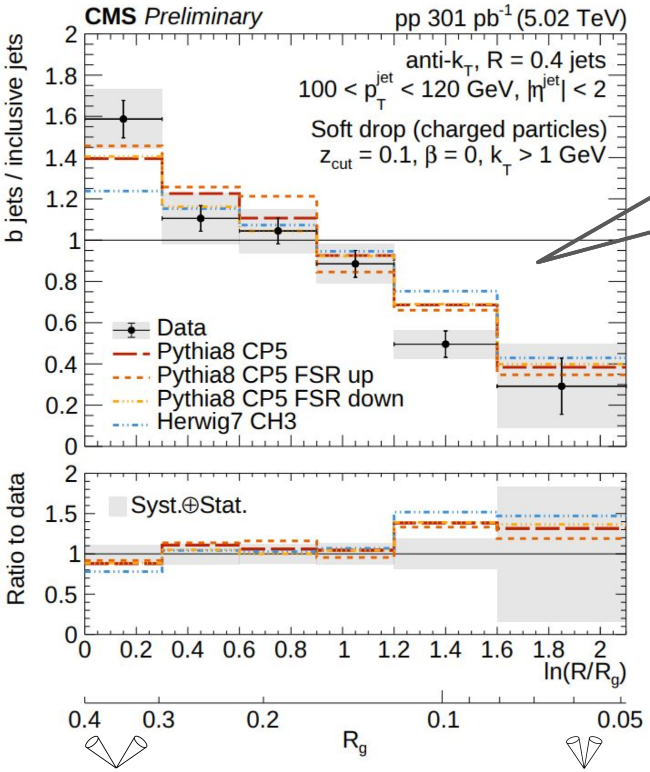

Suppression of small-angle radiation

Dead cone manifestation !

Mismodeling of substructure

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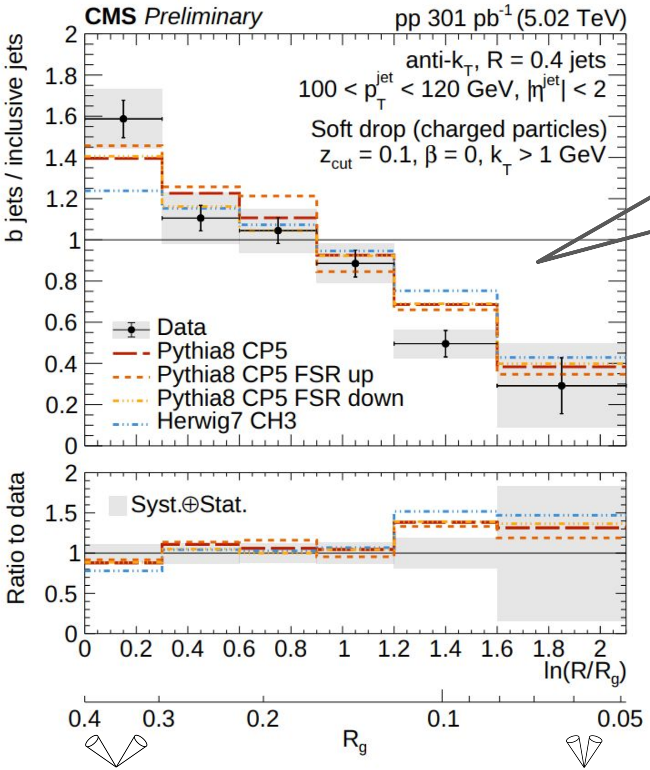


Suppression of
small-angle radiation

Dead cone manifestation !

Mismodeling of substructure

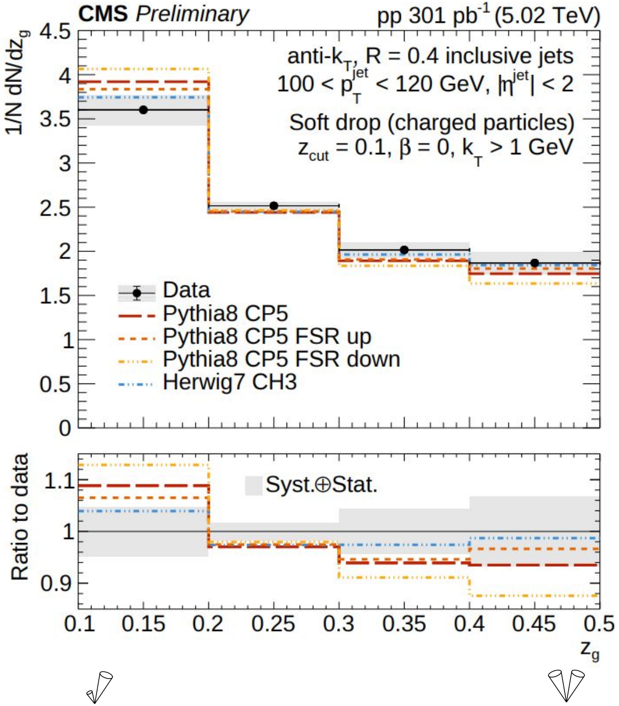
Mismodeling of mass effects

Model comparison

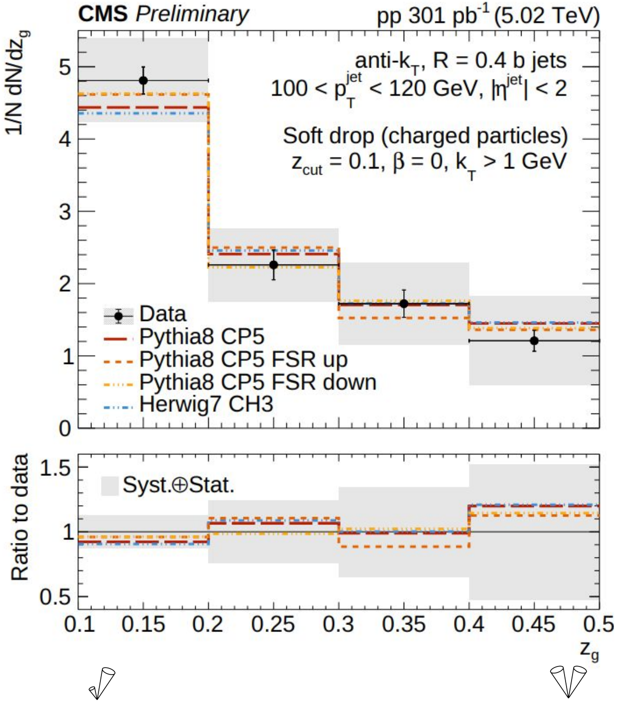
	Pythia	Herwig
Inclusive	❌	✅
b jets	❌	❌
ratio	✅	❌

The groomed momentum balance results

Inclusive jets



b jets



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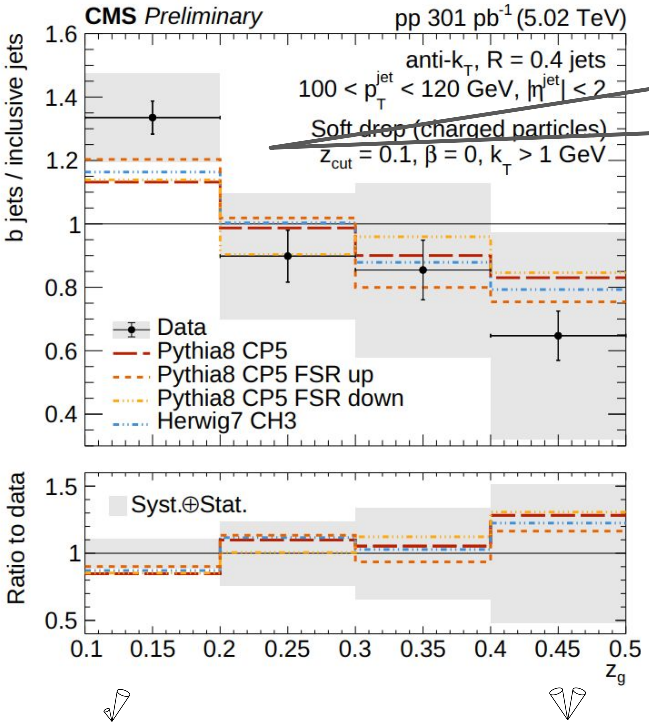
The groomed momentum balance results

b to inclusive jet ratio



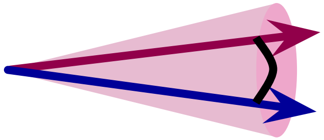
Hint of more imbalanced splittings for b jets

Model comparison

	Pythia	Herwig
Inclusive	❌	✅
b jets	✅	✅
ratio	✅	✅

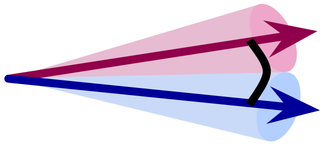
Prospects in heavy ion collisions

unresolved color charges



$\theta < \theta_c$

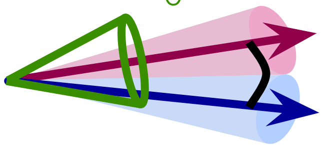
resolved color charges



$\theta > \theta_c$

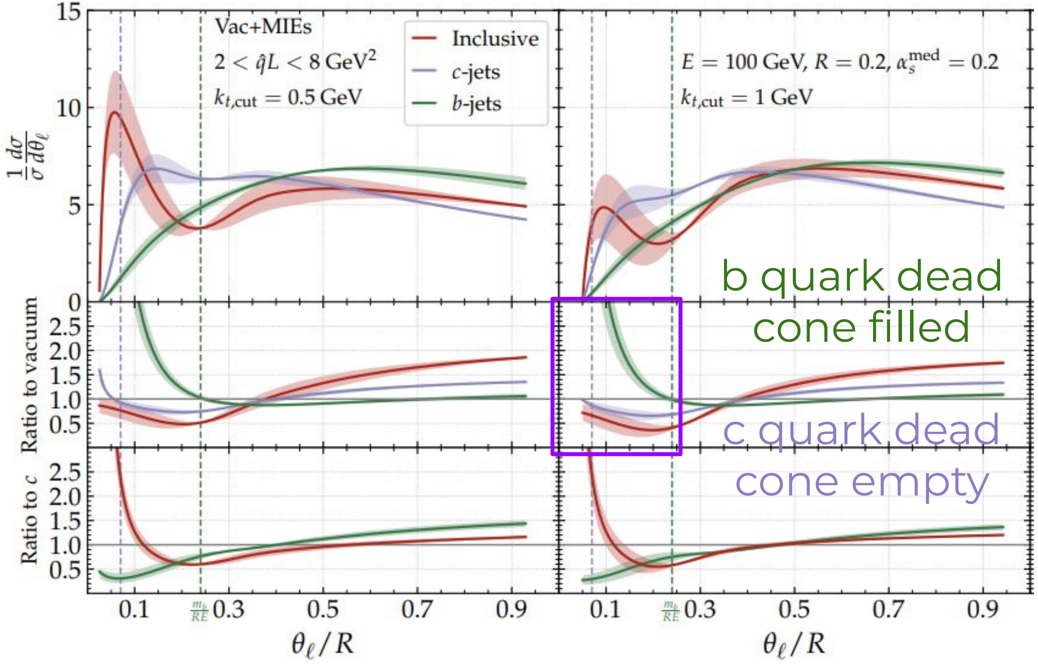
filled dead cone

$\theta_0 > \theta$



$\theta > \theta_c$

Isolate medium-induced radiation
in dead cone region



PRD 107 (2023) 094008

Conclusion

Aim to study jet energy loss mechanisms
via jet substructure

✅ Disentangle parton shower and decay kinematics

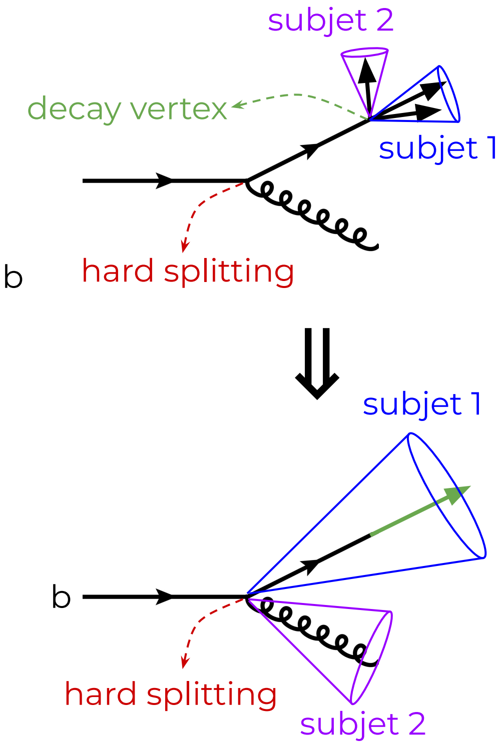
→ Partial reconstruction of the b hadron

✅ Build a solid baseline in proton-proton collisions

→ Observation of the b quark dead cone

… Study medium-induced radiation inside dead cone

→ In progress

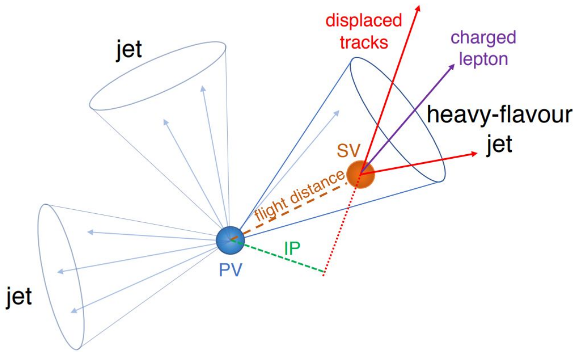


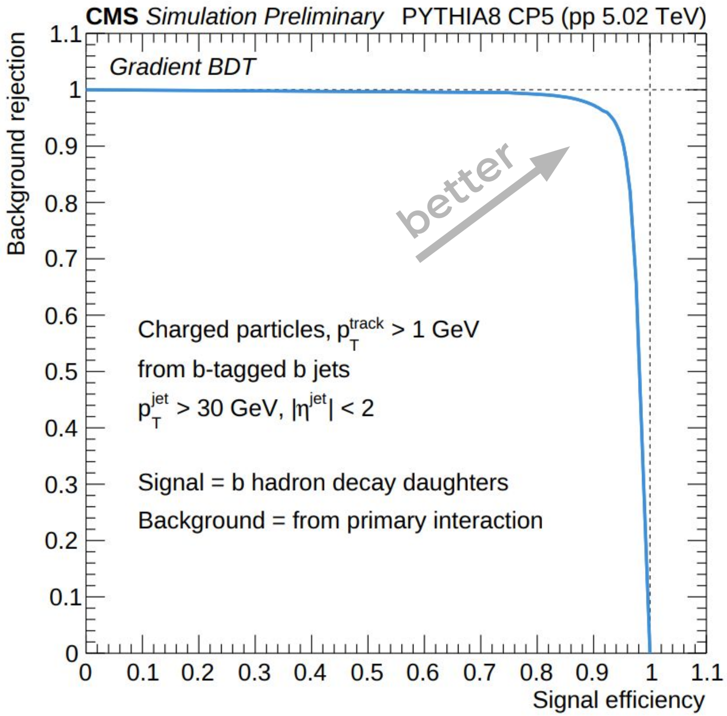
Backup

Decay product identification

Binary classifier

- Gradient boosted decision tree
  - Signal = charged decay products
  - Background = charged particles from PV
- Inputs
  - Track properties (eg. impact parameter)
  - Associated SV properties (eg. flight distance)





Analysis workflow

Inclusive jets	b-tagged jets	b-tagged single-b jets	Unfolded b-tagged single-b jets	Unfolded single-b jets
AK4Chs jets in kinematic region	Jets passing ParticleNet XXT working point	Single-b fraction extraction via template fit	Unfolding with matrix inversion	b tagging efficiency correction

Dataset and jet kinematics

5.02 TeV low PU pp collisions

$100 < p_T^{jet} < 120$ GeV, $|\eta^{jet}| < 2$

Soft drop parameters

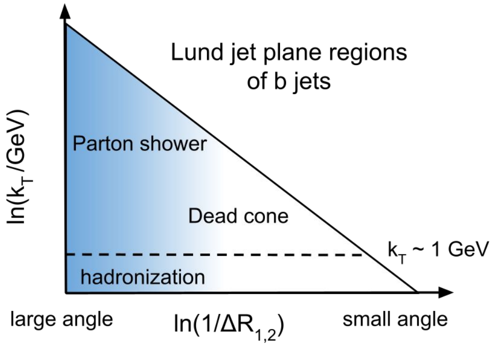
$z_{cut} = 0.1, \beta = 0$

$\Rightarrow p_{T,2} / (p_{T,1} + p_{T,2}) > 0.1$

Observables

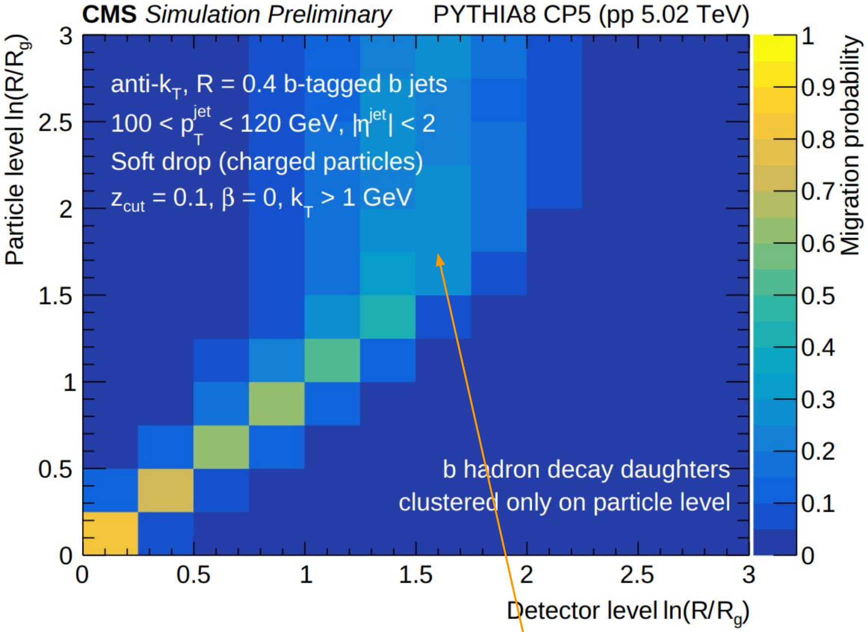
charged particle R_g, z_g

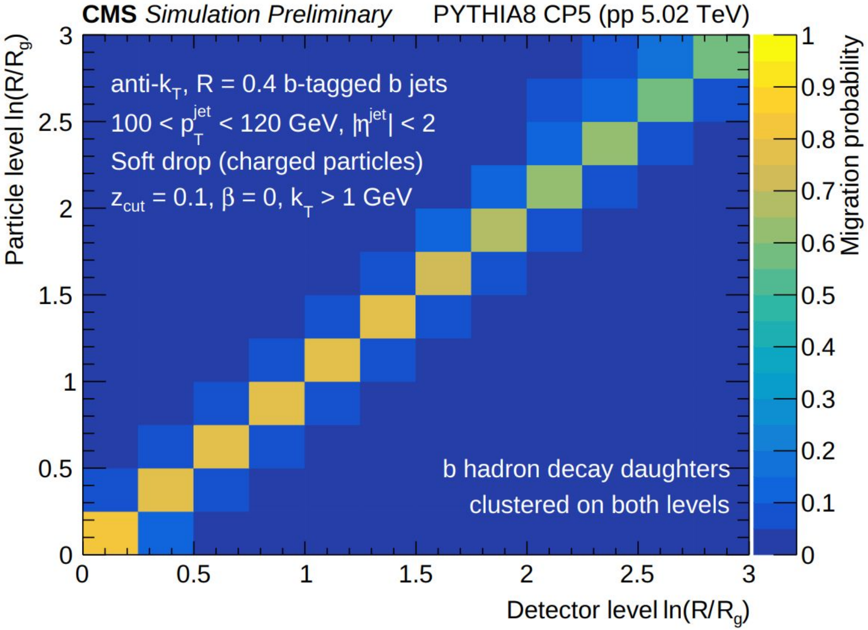
1-prong (fail soft drop) or **k_T < 1 GeV** (hadronization) in dedicated bin for unfolding



Agreement between the detector and the particle level

Impossible to “unfold” the decay effects

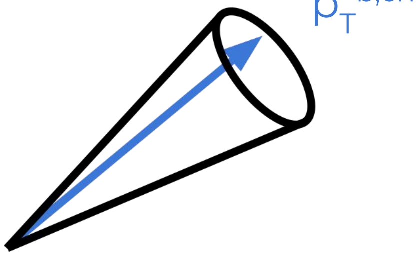




Multiple bin migrations to “decay angle”

The jet fragmentation function results

$z_{b,ch} = p_T^{b,ch}/p_T^{jet,ch}$



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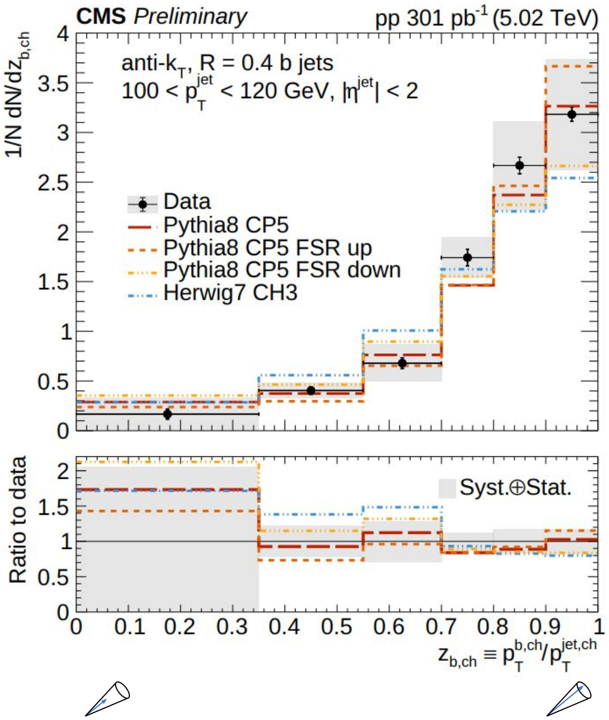


Systematic uncertainties

Both for inclusive and b jets

- **Statistical uncertainty**
- **Matrix response statistical uncertainty** (jackknife resampling)
- **Shower and hadronization** (unfolding with HERWIG7 CH3 vs PYTHIA8 CP5)
- **FSR and ISR scale** (x2 or x1/2 independently in PYTHIA8 CP5)
- **Jet energy resolution** (vary JER scale factors)
- **Jet energy scale** (vary JEC per source)
- **Tracking efficiency** (randomly discard 3% of reconstructed tracks in PYTHIA8 CP5)

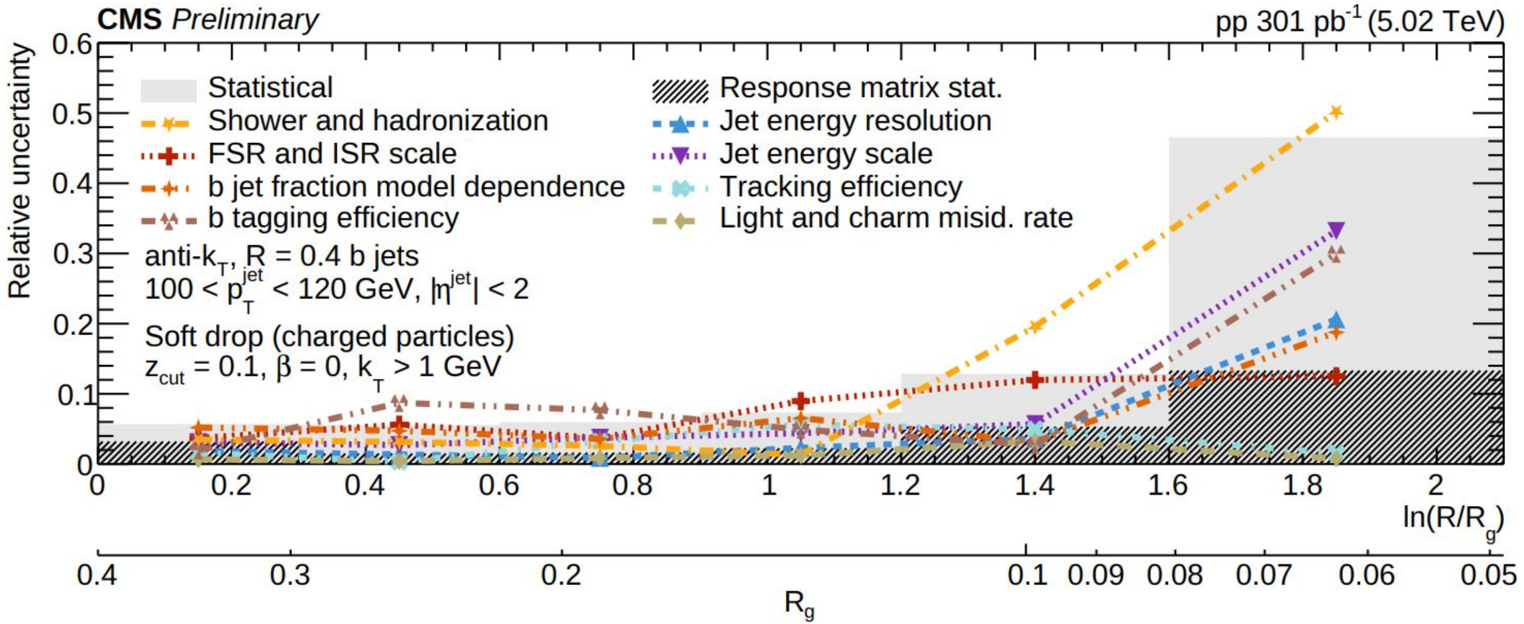
Only for b jets

- **b jet fraction model dependence** (template fit with HERWIG7 CH3 vs PYTHIA8 CP5)
- **Light and charm misidentification rate** (vary light+c fraction in template fit)
- **b tagging efficiency** (vary b tagging efficiency scale factors)

Systematic uncertainties

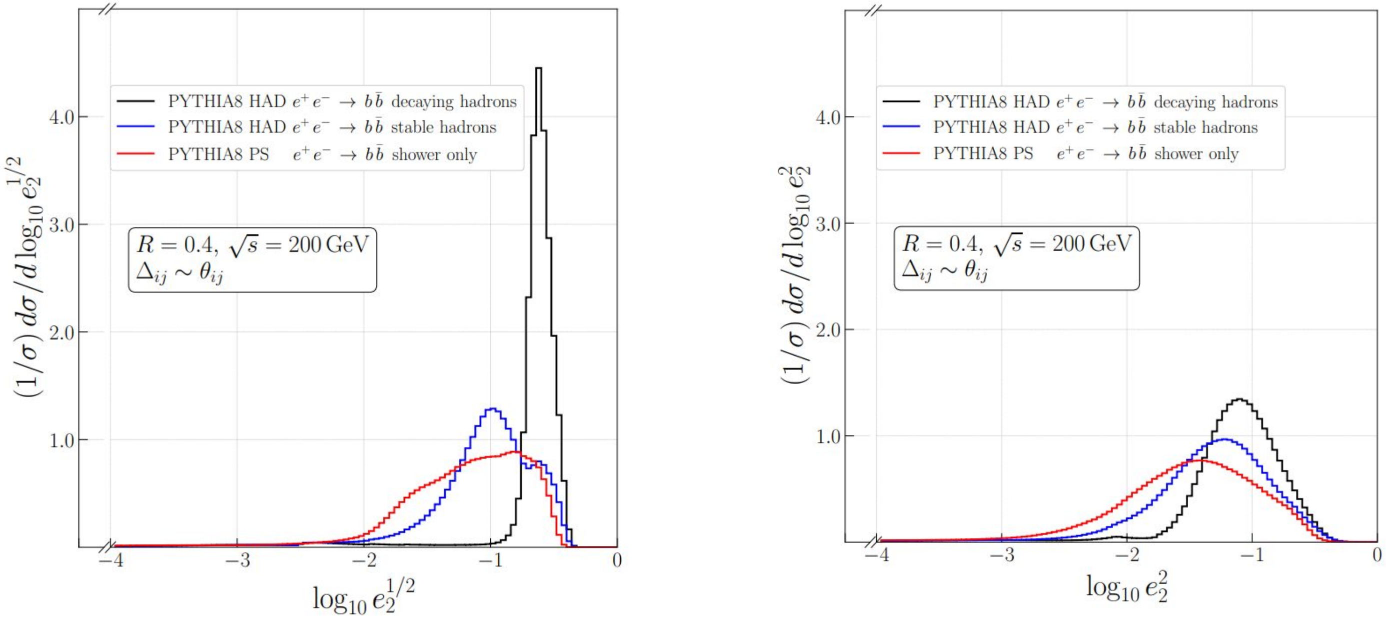
Leading sources related to physics model and b tagging

- **Shower and hadronization** (unfolding with HERWIG7 CH3 vs PYTHIA8 CP5)
- **FSR and ISR scale** (x2 or x1/2 independently in PYTHIA8 CP5)
- **b tagging efficiency** (vary b tagging efficiency scale factors)



Other substructure observables

b hadron decay effect in energy-energy correlators



Oleh Fedkevych, BOOST 2023