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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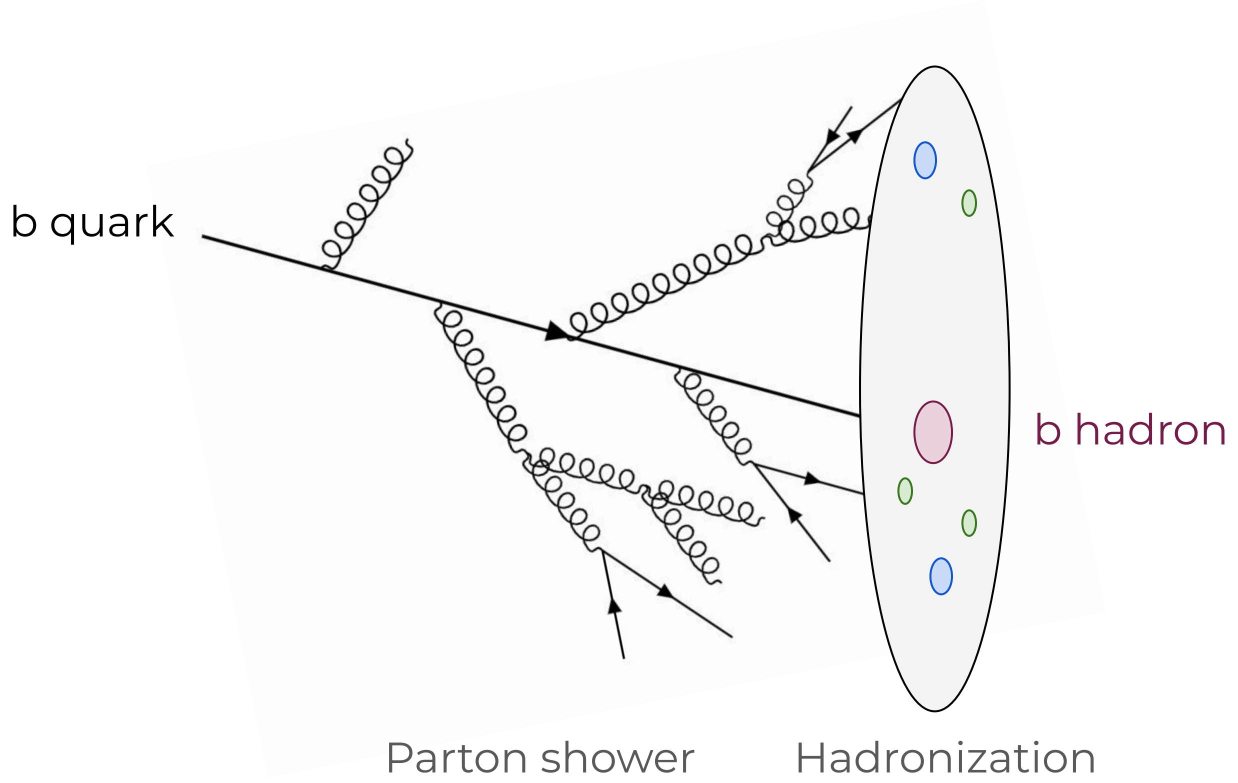
on behalf of the CMS collaboration
LLR, École Polytechnique

HARD PROBES 2024, 25 September 2024

Heavy flavor jets

In theory



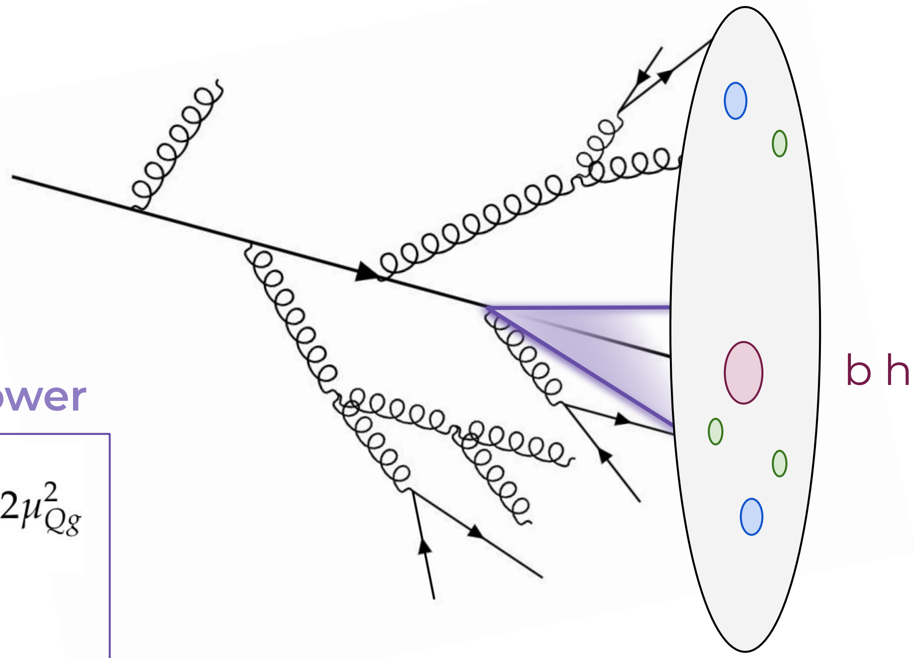
Heavy flavor jets

In theory

dead cone

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

$$\theta_0 = m_Q / E_Q$$



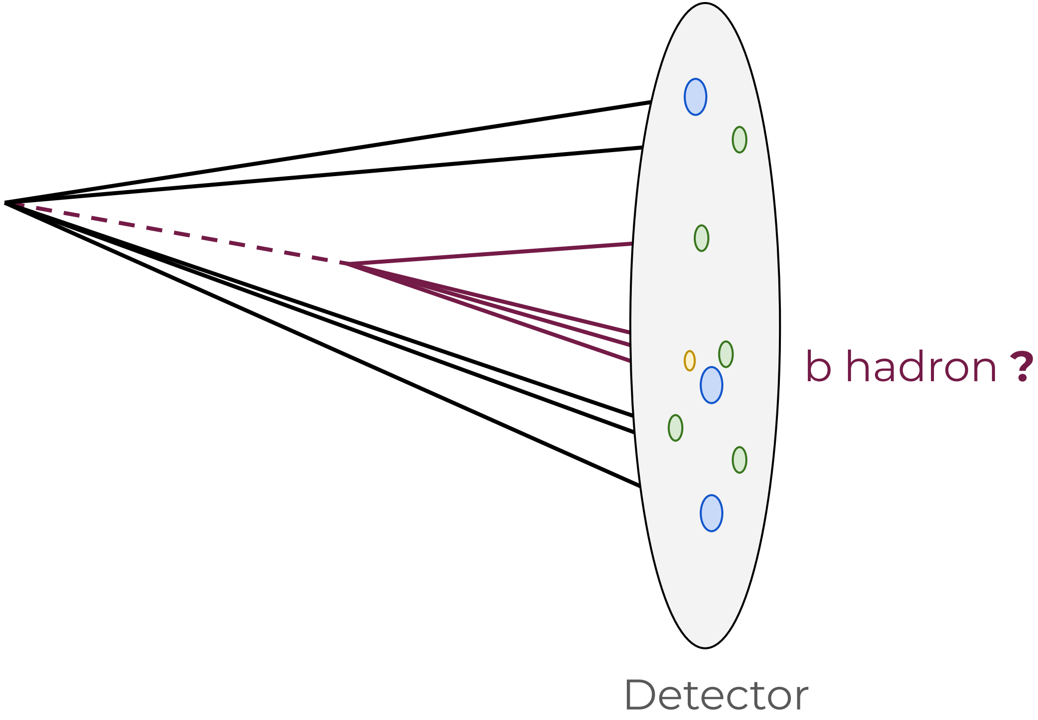
mass dependent shower

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

$$\mu_{Qg}^2 = \frac{m_Q^2}{m_{Qg}^2 - m_Q^2}$$

Heavy flavor jets

In practice



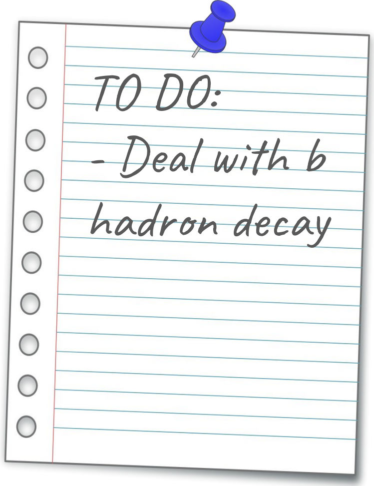
Jet substructure

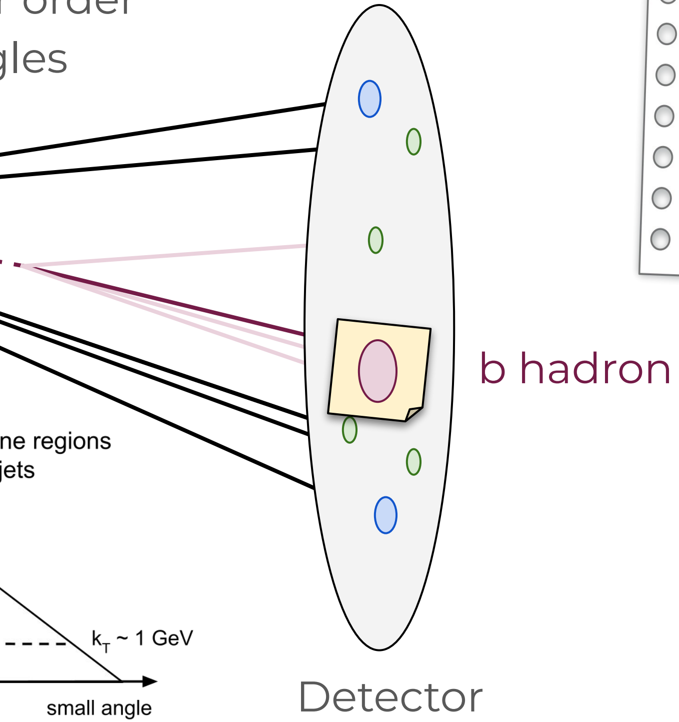
The primary Lund jet plane

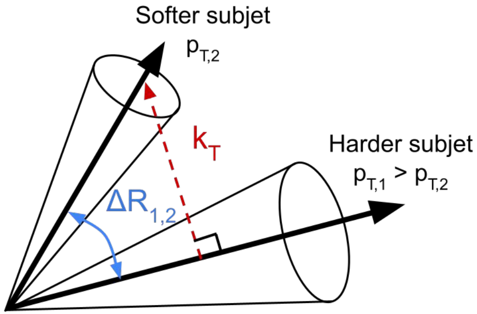
- Recluster jet constituents in angular order
- Decluster from larger to smaller angles following the harder subjet
- Register

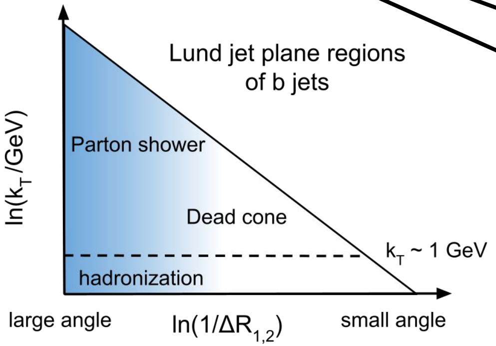
  $\Delta R^2 = \Delta y^2 + \Delta \phi^2$

  $k_T = p_{T,2} \cdot \Delta R$









Jet substructure

Soft drop grooming

- Same as before, but **stop** when

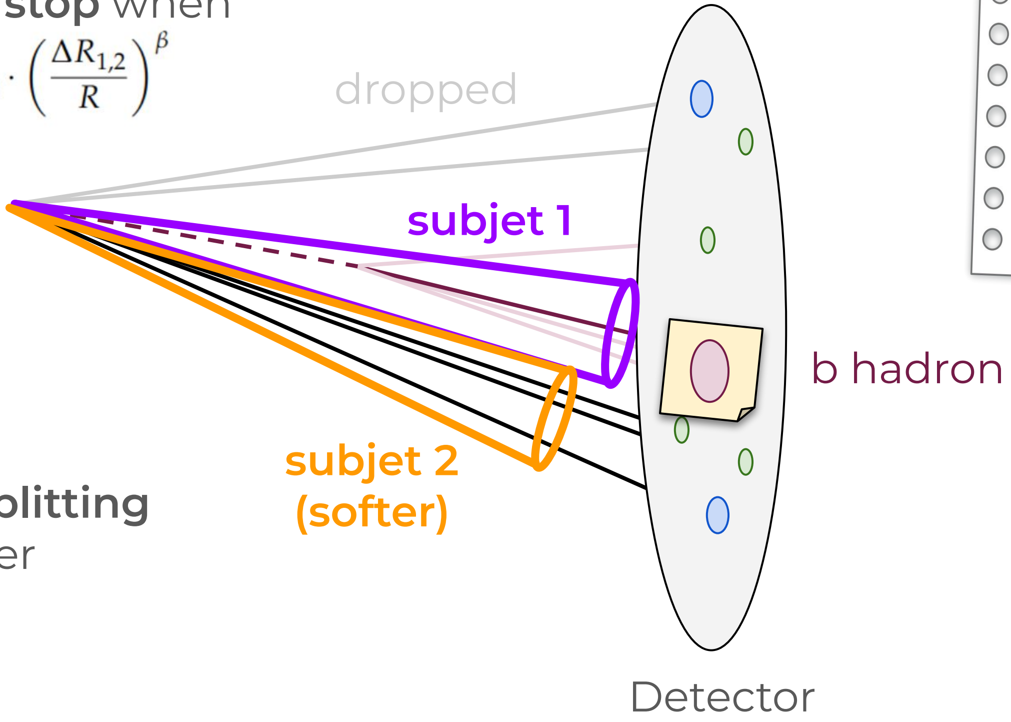
$$z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \cdot \left(\frac{\Delta R_{1,2}}{R}\right)^{\beta}$$

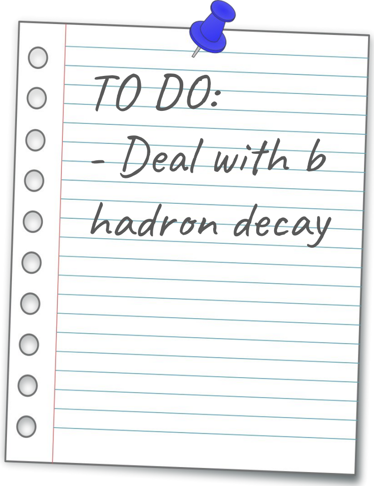
- Register

$R_g = \Delta R$

$z_g = z$

k_T

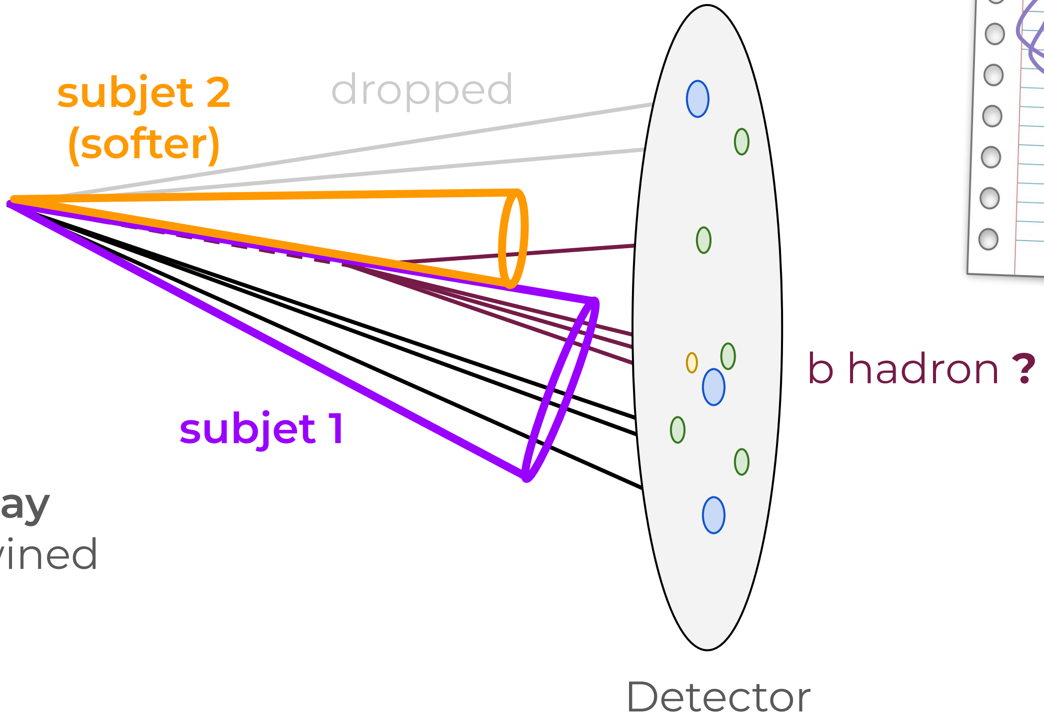


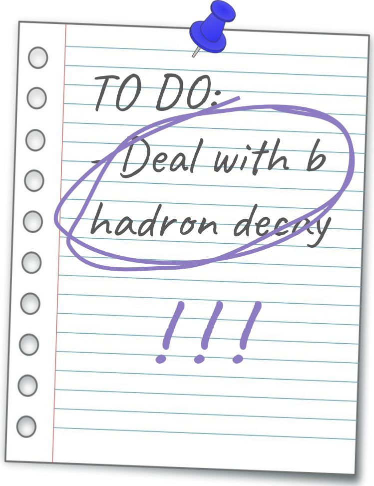


study first **hard splitting** in the shower

Heavy flavor decay impact

Heavy hadron decay daughters **do not** follow angular ordering

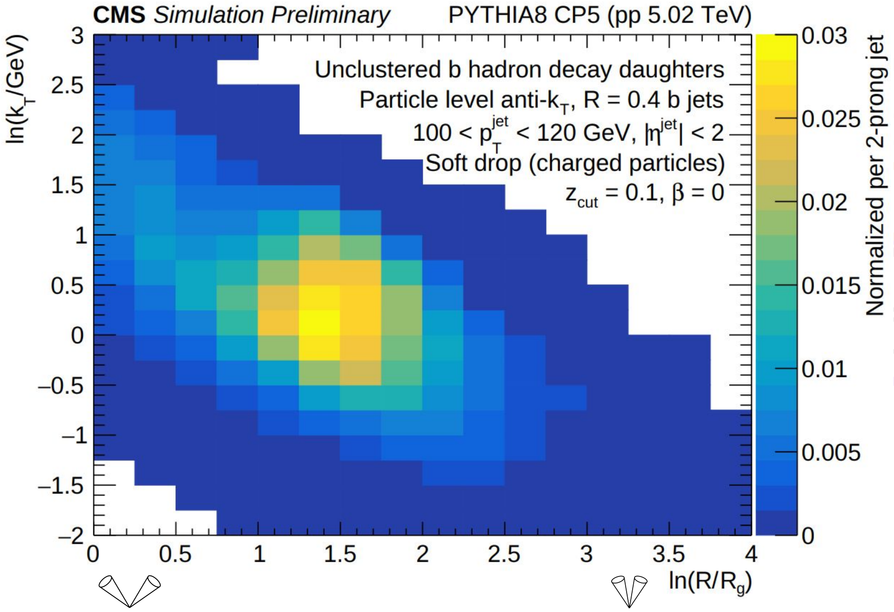


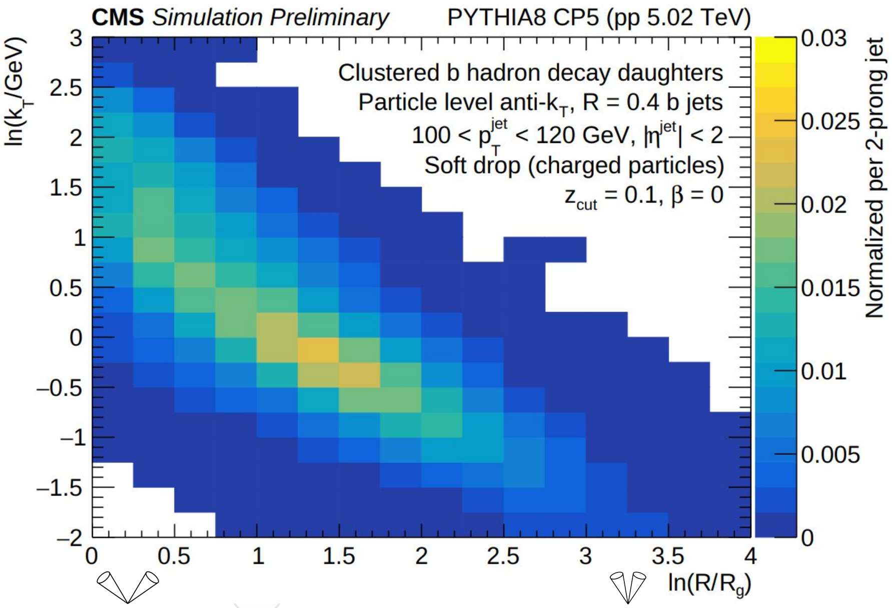


shower and **decay**
kinematics intertwined

Heavy flavor decay impact

Heavy hadron decay daughters **do not** follow angular ordering





Heavy flavor decay impact

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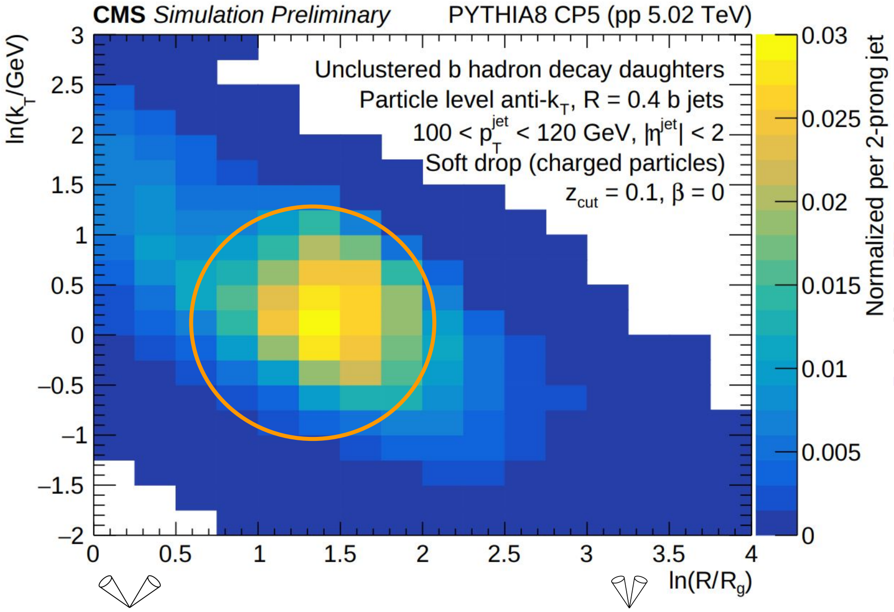
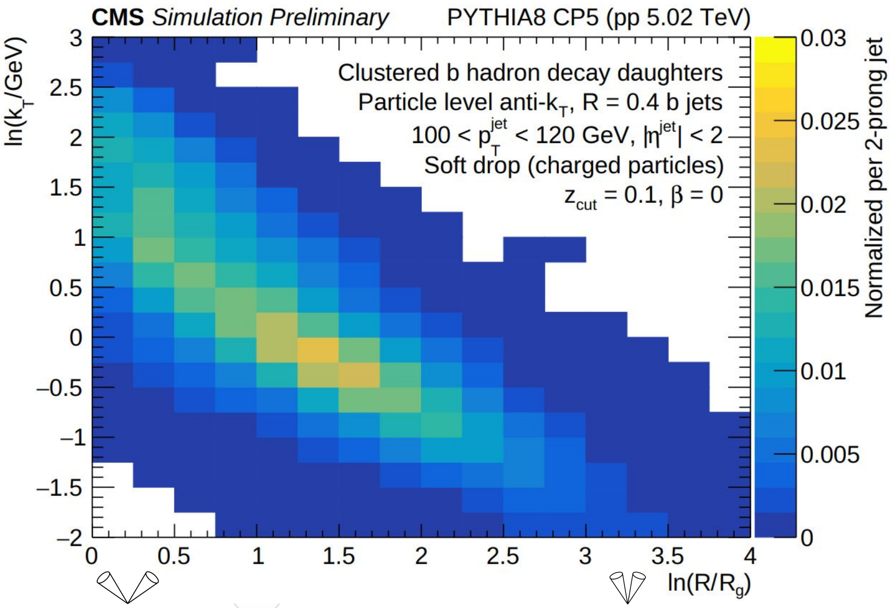


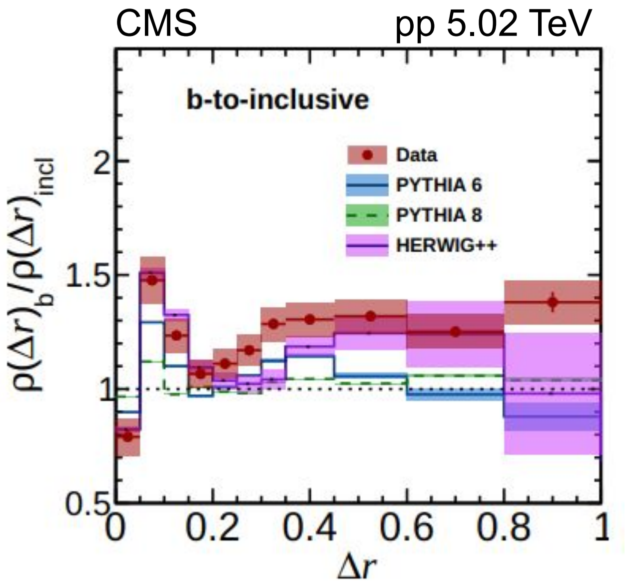
b decay daughters present



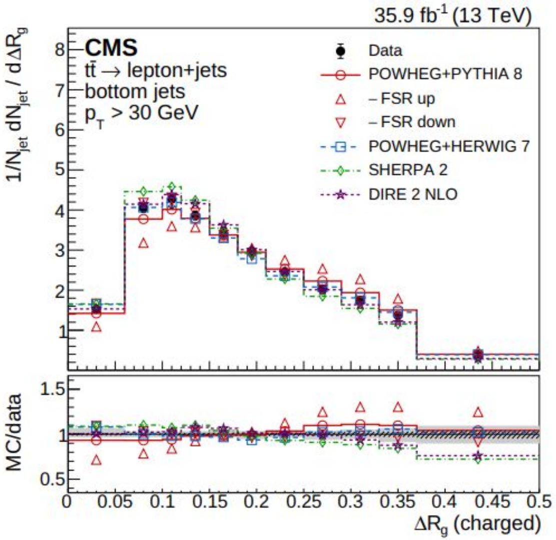
b decay daughters clustered

Previously on b jet substructure…

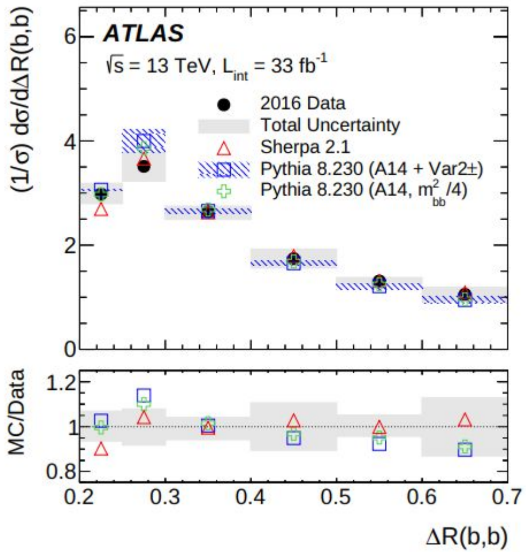
b jet shapes



b jet groomed observables



g to bbar



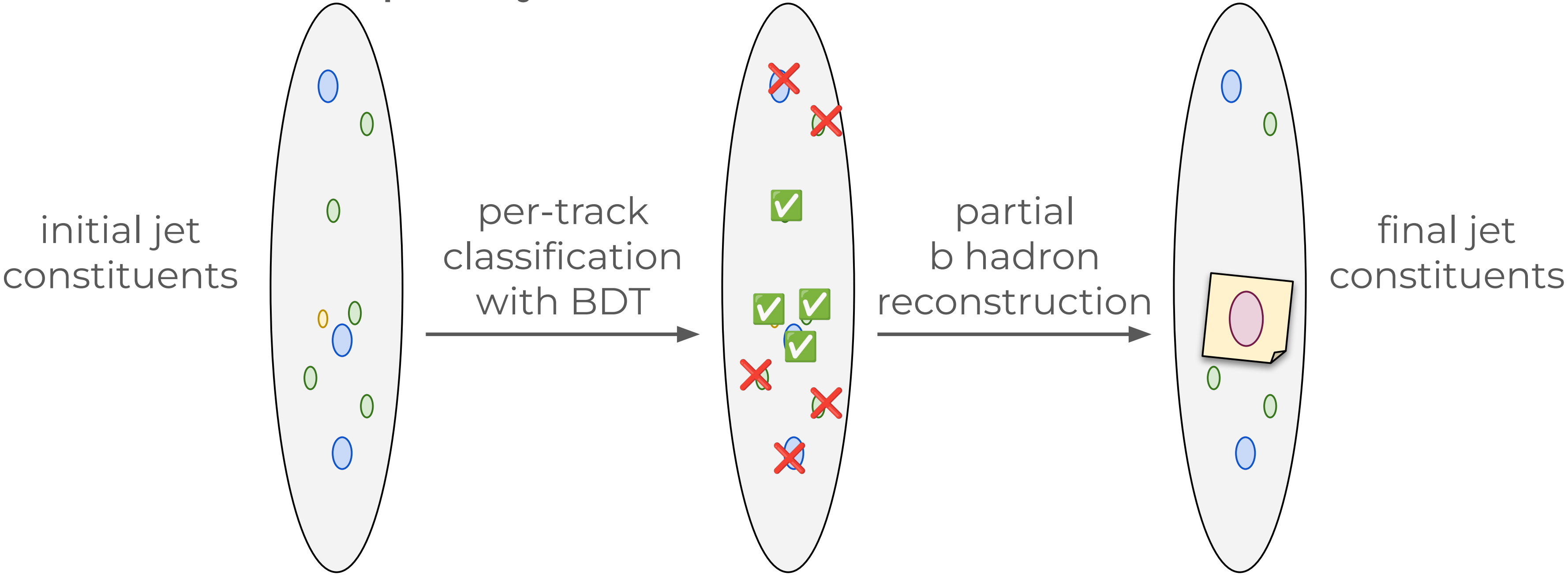
See also

Jelena's talk on D-tagged jets

Wed 25/09 09:20

Partial b hadron reconstruction

Treat b hadron decays by identifying the decay products in the jet and cluster them into **partially reconstructed b hadron**



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

Partial b hadron reconstruction

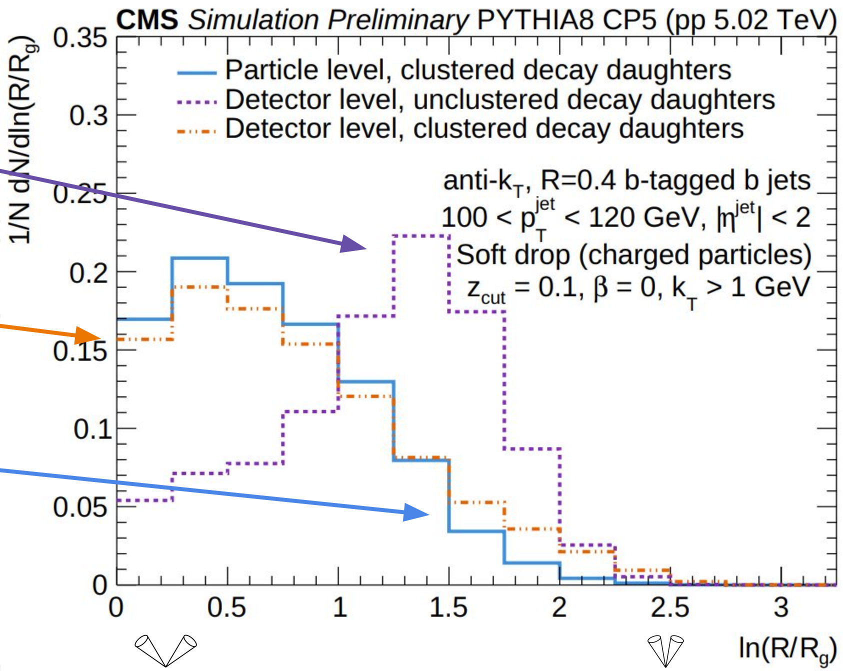
Treat b hadron decays by identifying the decay products in the jet and cluster them into **partially reconstructed b hadron**

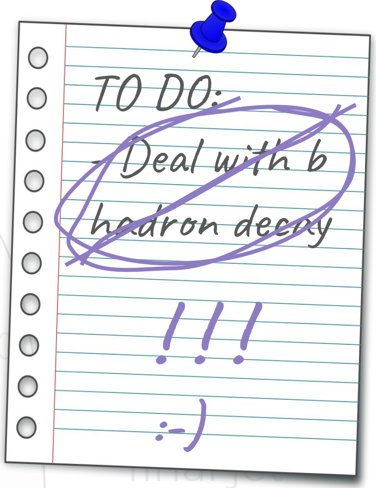
detector level with decays

detector level without decays

particle level without decays

it works!





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

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

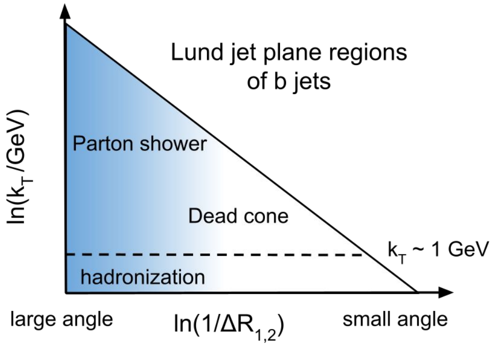
$\Rightarrow p_{T,2} / (p_{T,1} + p_{T,2}) > 0.1$

Observables

charged particle R_g, z_g

and $z_{b,ch} \equiv p_T^{b,ch} / p_T^{jet,ch}$

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



b jet selection and corrections

b tagging

b jets selected with ParticleNet
at very high purity working point

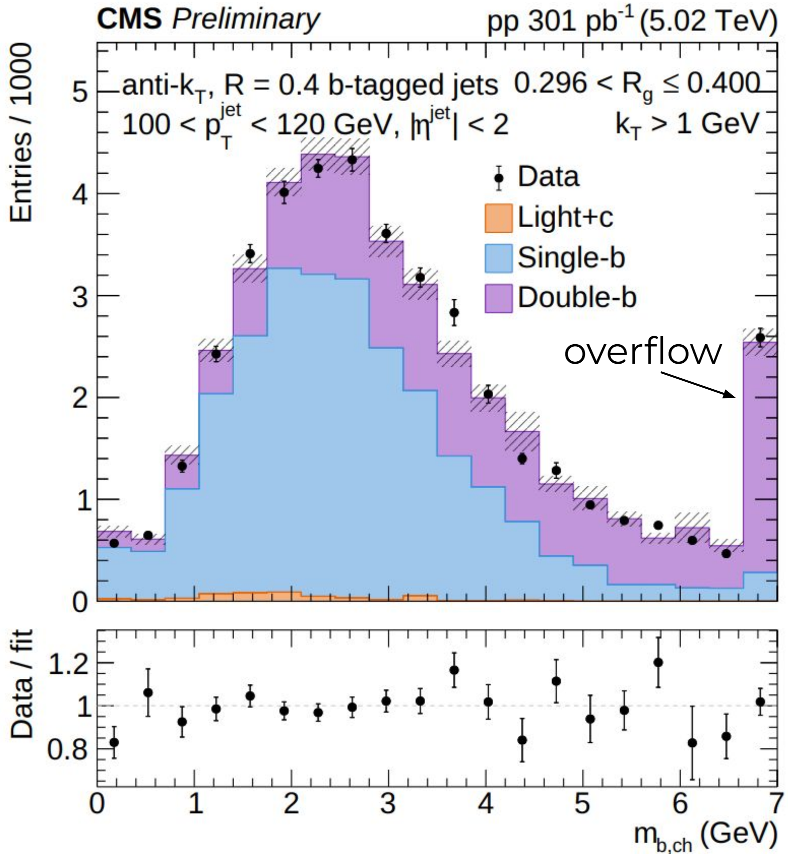
But...

Sample includes jets with
more than one b hadron

Residual background subtraction

Fit the mass of the reconstructed b hadron
with MC templates

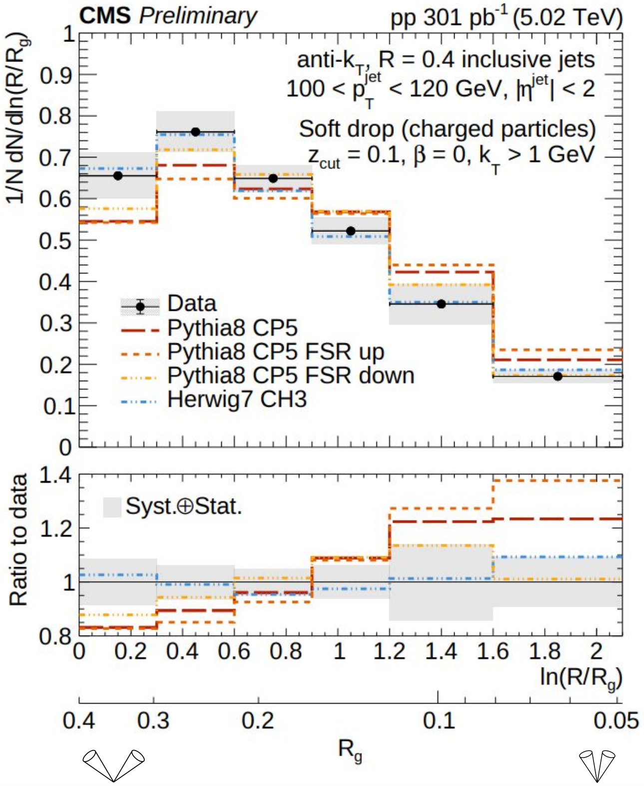
Unfolding to the charged-particle level b jet



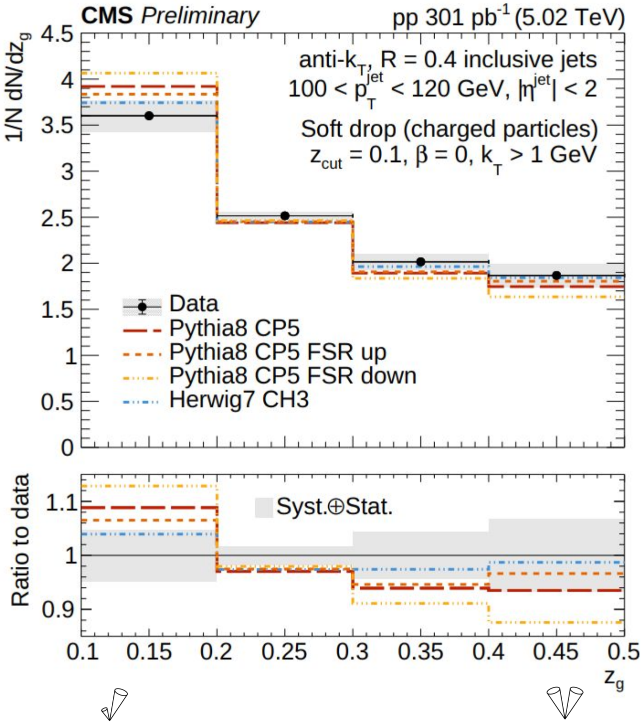
reconstructed b hadron mass

Inclusive jet results

Groomed jet radius



Groomed momentum balance



Inclusive jet results

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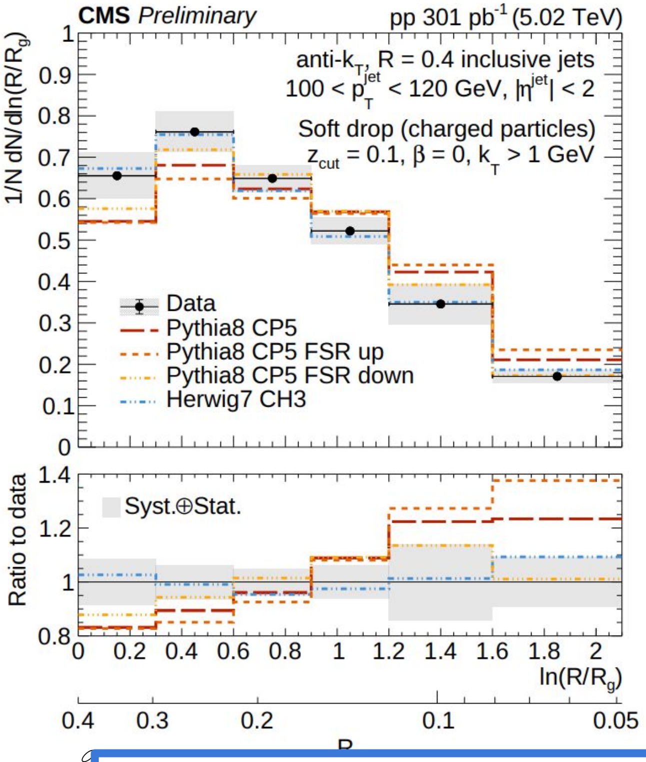

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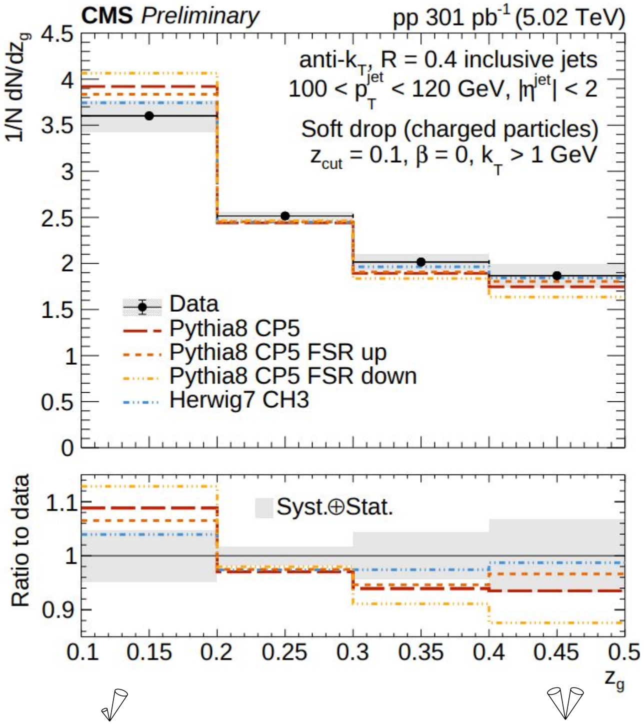
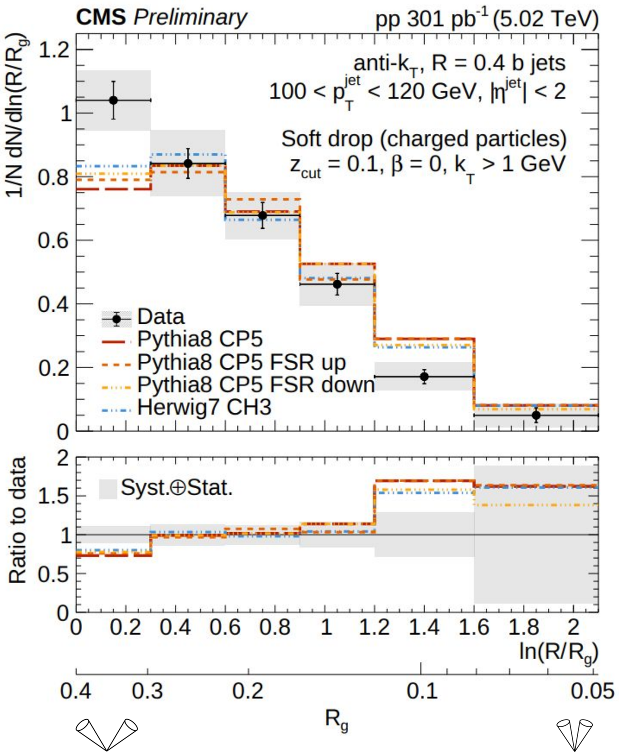


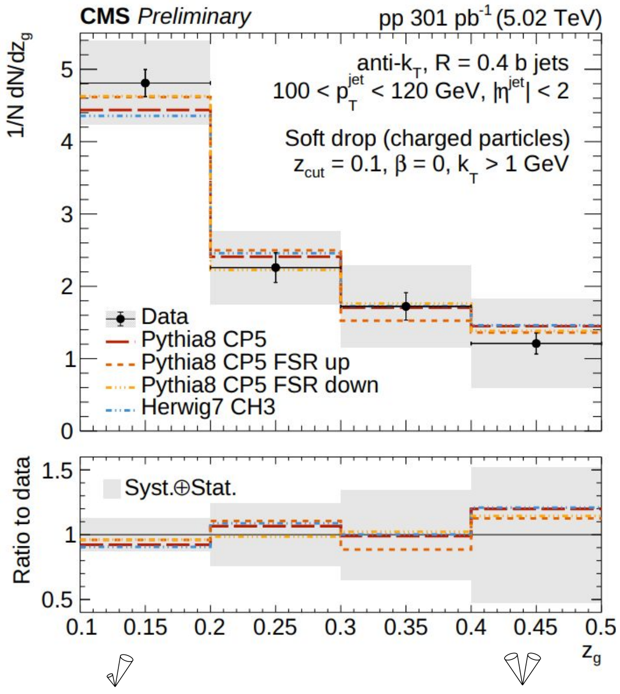
Dominated by physics modeling systematics
Good agreement with HERWIG7 but not with PYTHIA8

b jet results

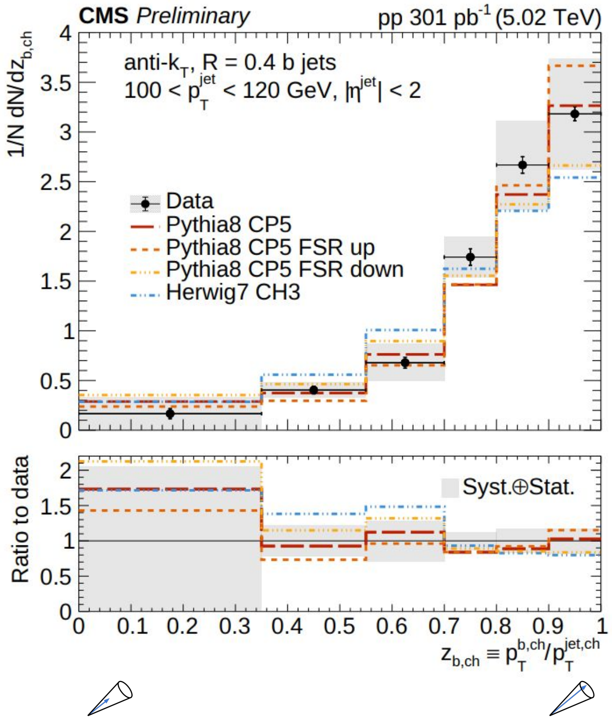
Groomed jet radius



Groomed momentum balance

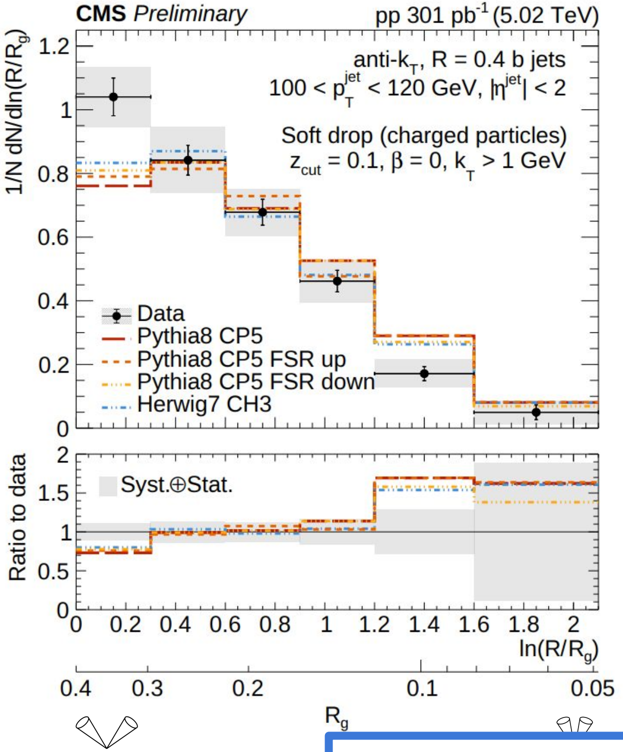


Fragmentation function

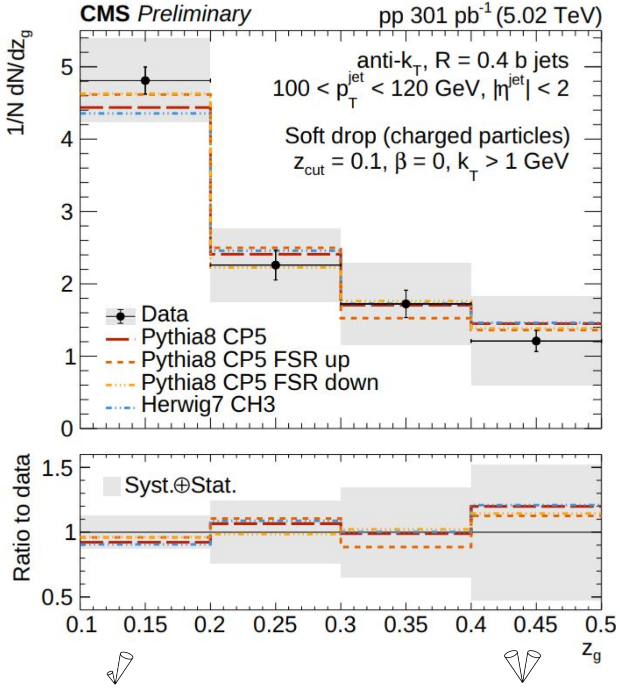


b jet results

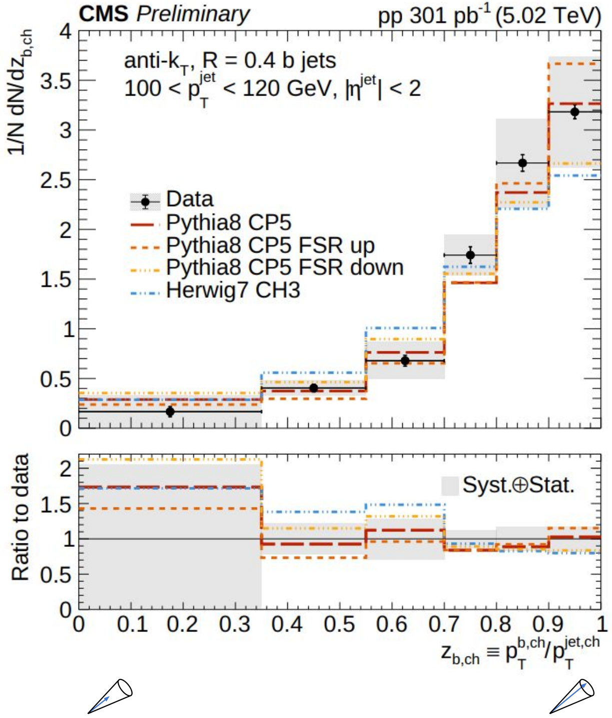
Groomed jet radius



Groomed momentum balance



Fragmentation function

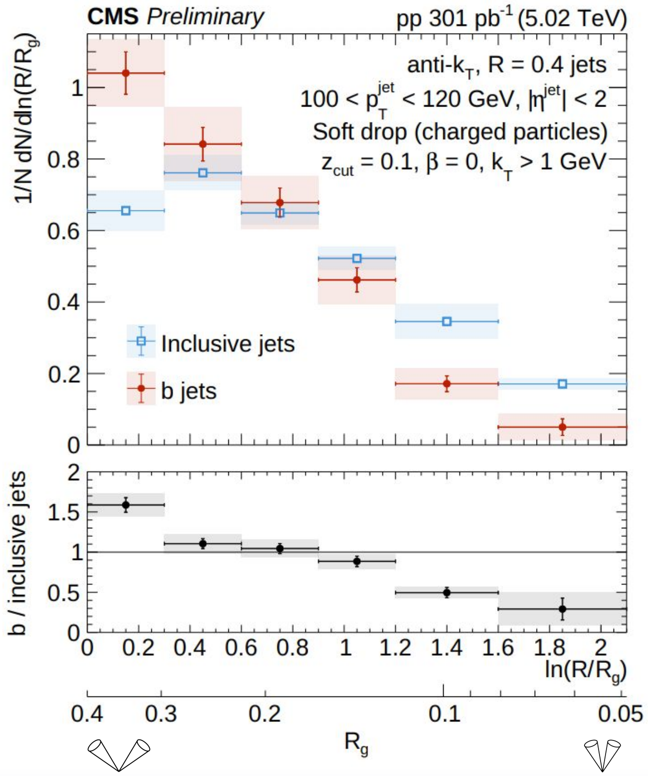


Dominated by physics modeling systematics

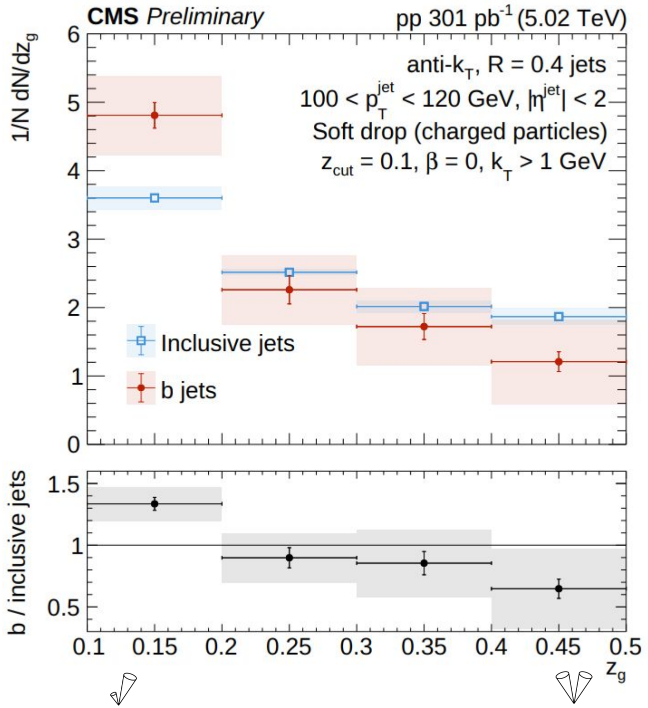
Models ~agree with z_g, $z_{b,ch}$ but **not** R_g

Ratio to inclusive

Groomed jet radius



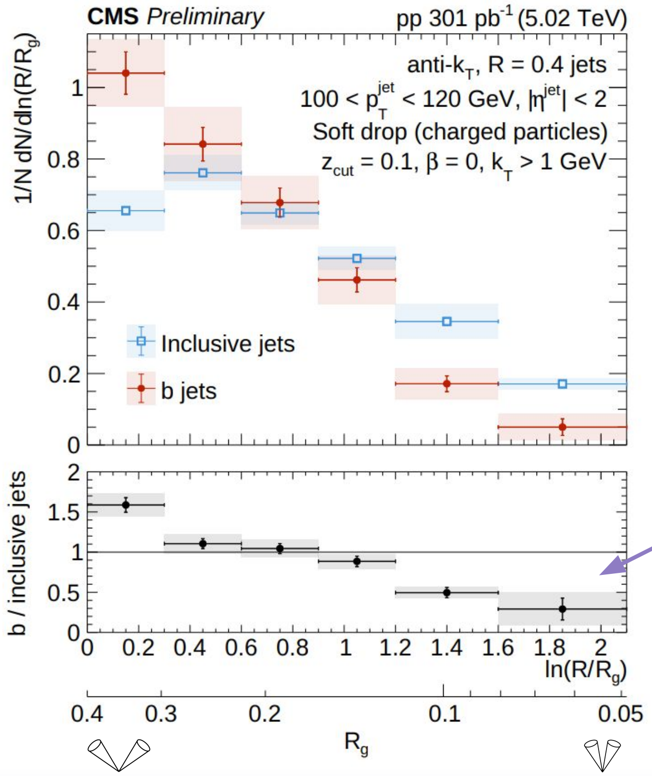
Groomed momentum balance



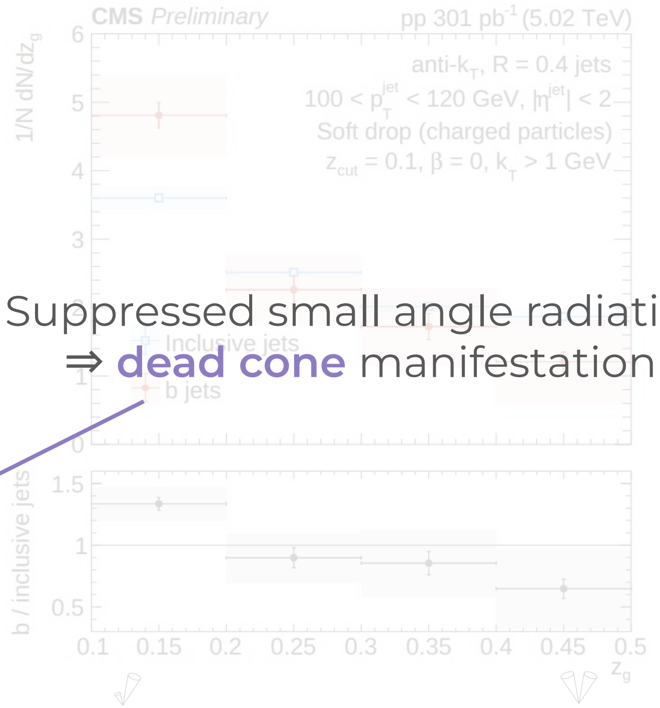
1-prong or low k_T ~38% for inclusive and ~68% for b jets

Ratio to inclusive

Groomed jet radius



Groomed momentum balance

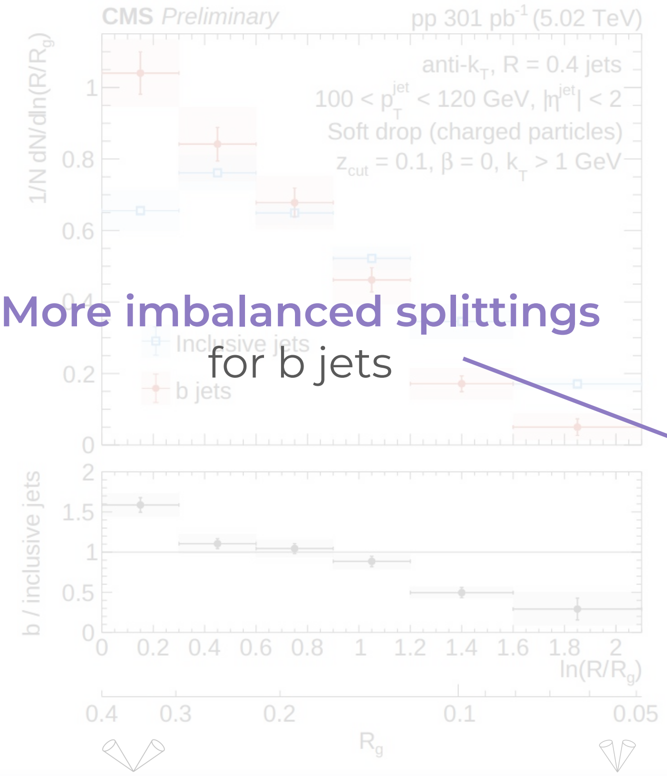


Suppressed small angle radiation
⇒ **dead cone** manifestation

1-prong or low k_T ~38% for inclusive and ~68% for b jets

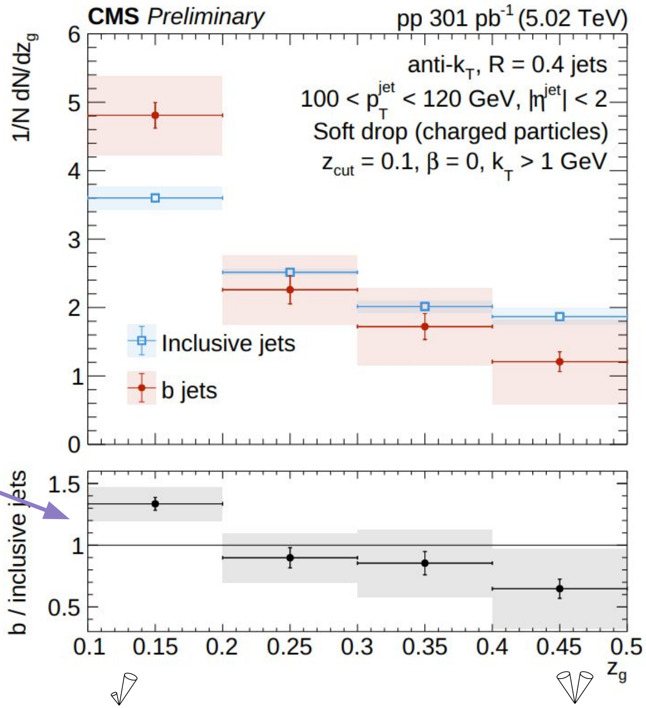
Ratio to inclusive

Groomed jet radius



More imbalanced splittings
for b jets

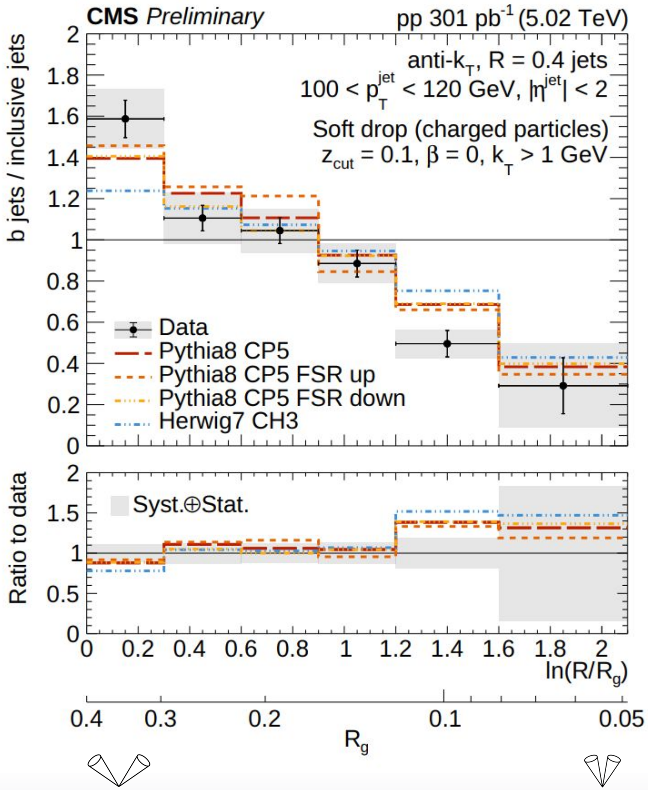
Groomed momentum balance



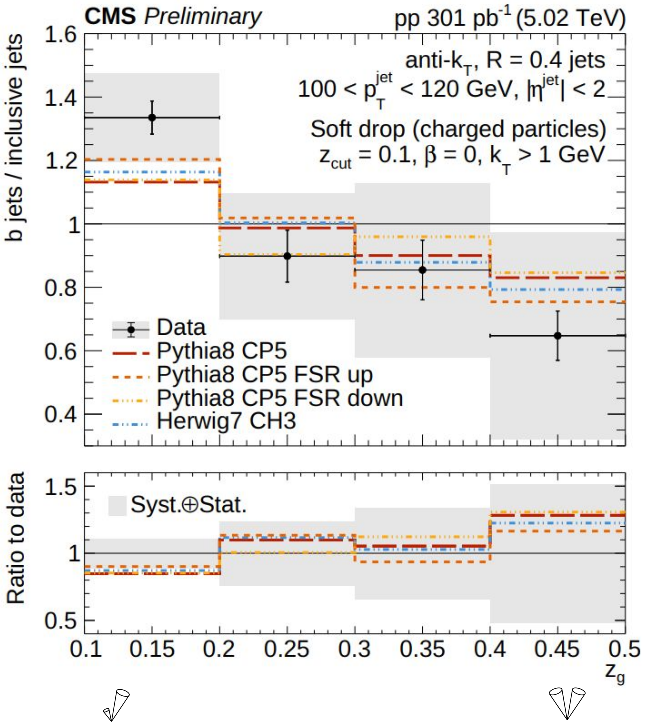
1-prong or low k_T ~38% for inclusive
and ~68% for b jets

Ratio to inclusive

Groomed jet radius

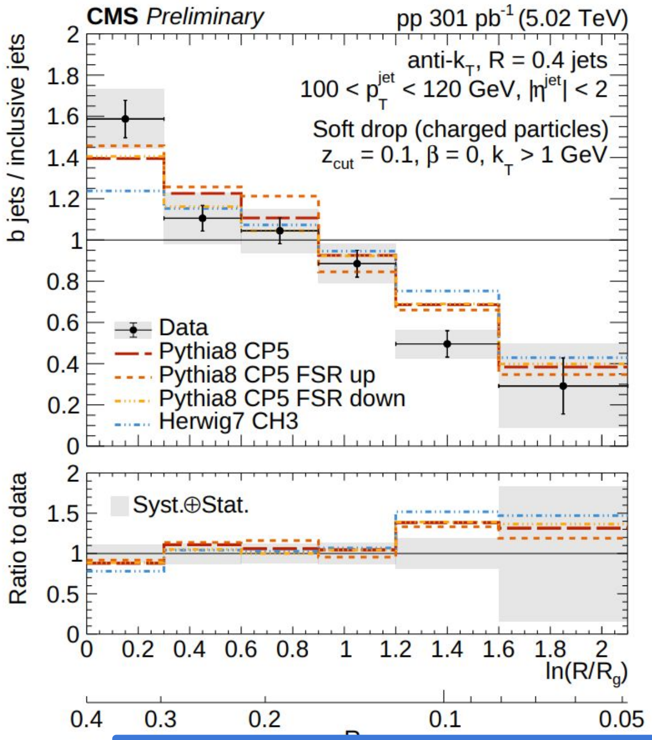


Groomed momentum balance

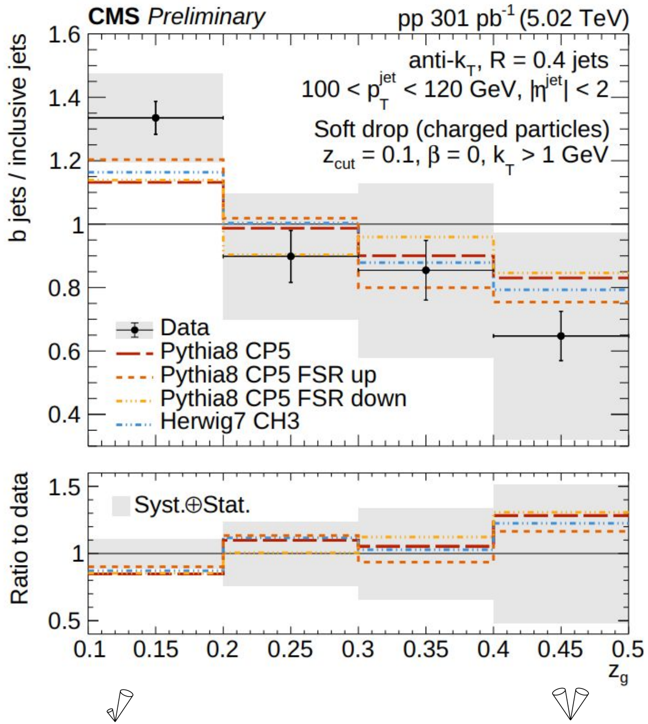


Ratio to inclusive

Groomed jet radius



Groomed momentum balance



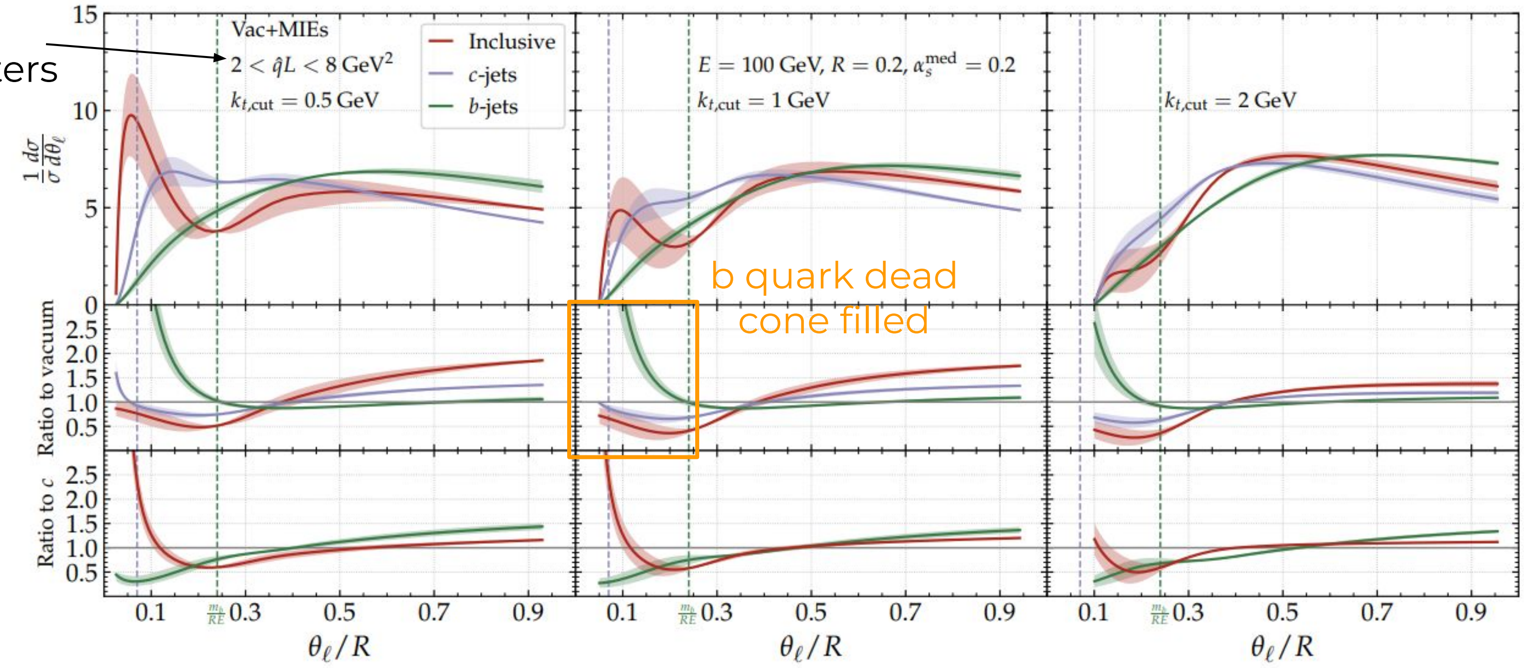
Models ~agree with z_g

PYTHIA8 in agreement with R_g but not HERWIG7

Prospects in HI collisions

Isolate medium induced radiation in dead cone region

QGP parameters



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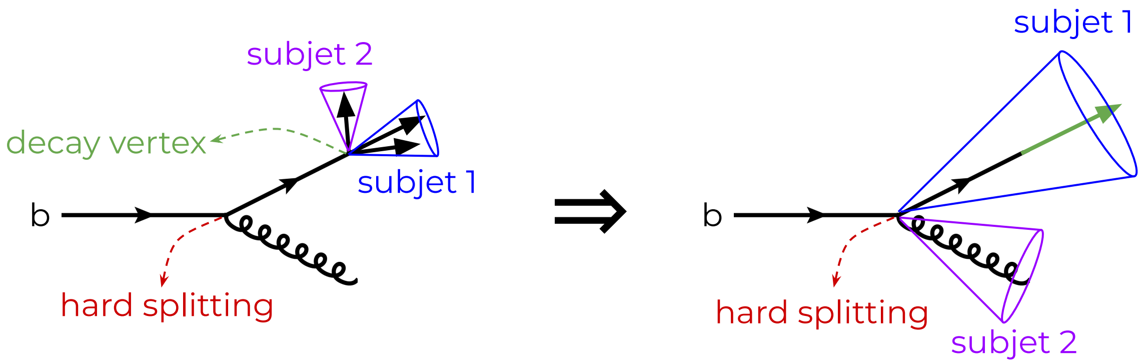
Conclusion

b hadron decays crucial for b jet substructure measurements
⇒ developed a tool to partially reconstruct the b hadron



First time we clearly observe the suppression of collinear emissions for b jets (**dead cone**)

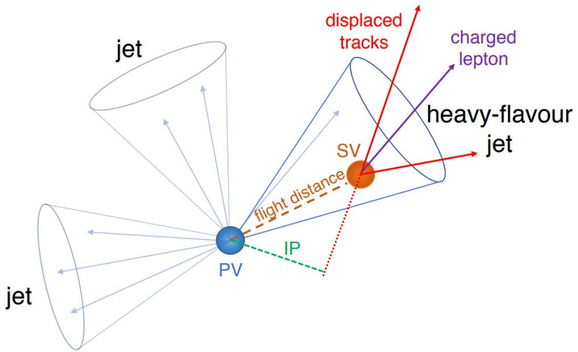
Separation of b hadron decay from QCD cascade can be used for other observables in the future (EECs, generalized angularities, masses)

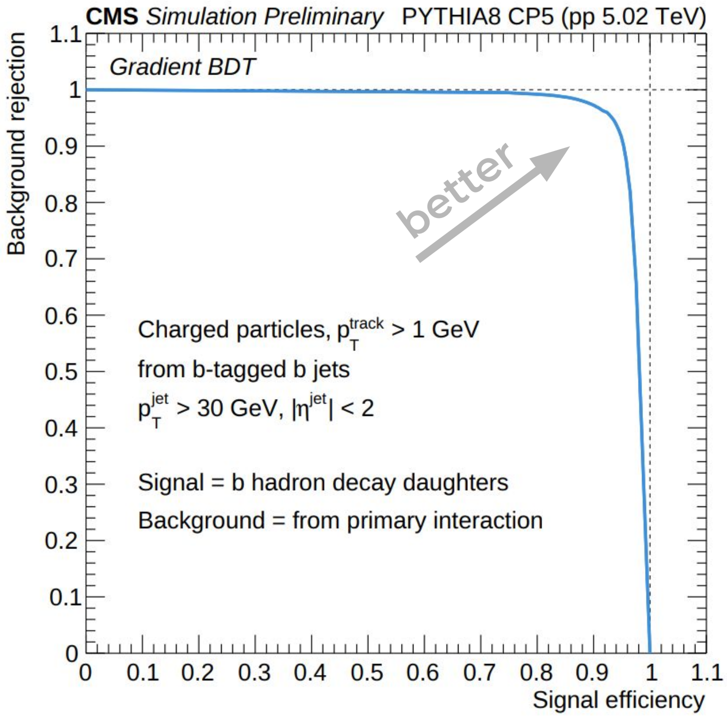
Backup

Decay product identification

Binary classifier

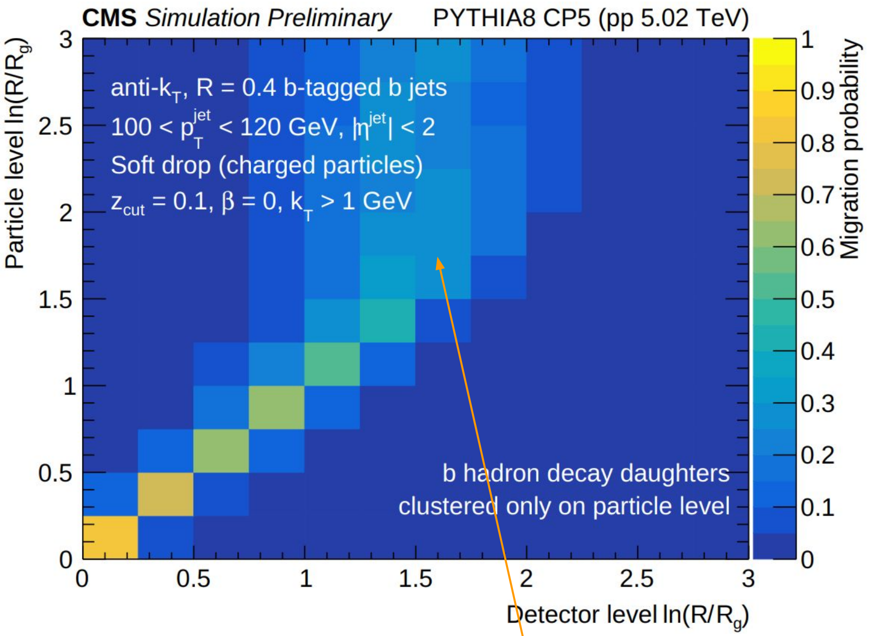
- Gradient boosted decision tree
  - Signal = charged decay products
  - Background = charged particles from PV
- Inputs
  - Track properties (eg. impact parameter)
  - Associated SV properties (eg. flight distance)

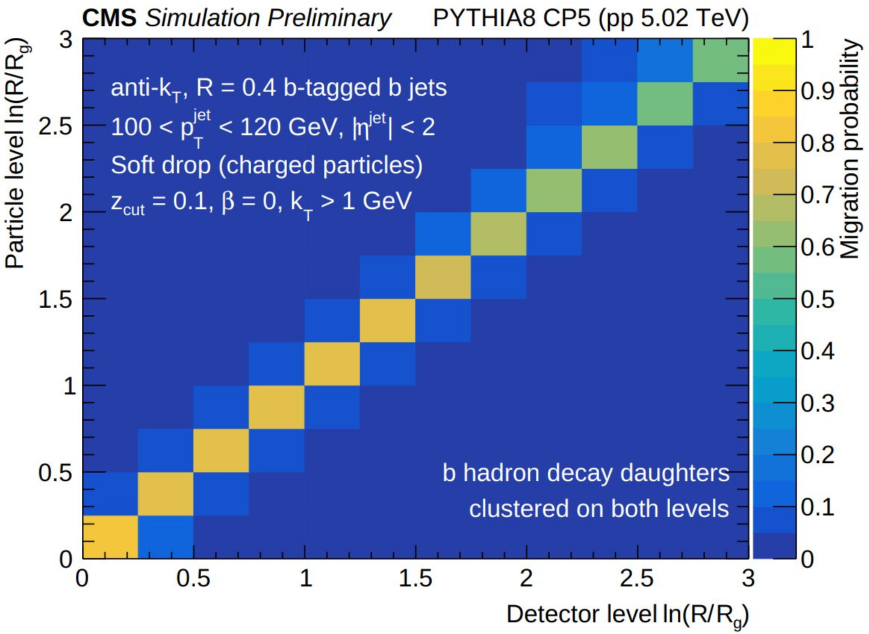




Agreement between the detector and the particle level

Impossible to “unfold” the decay effects





Multiple bin migrations to “decay angle”

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)

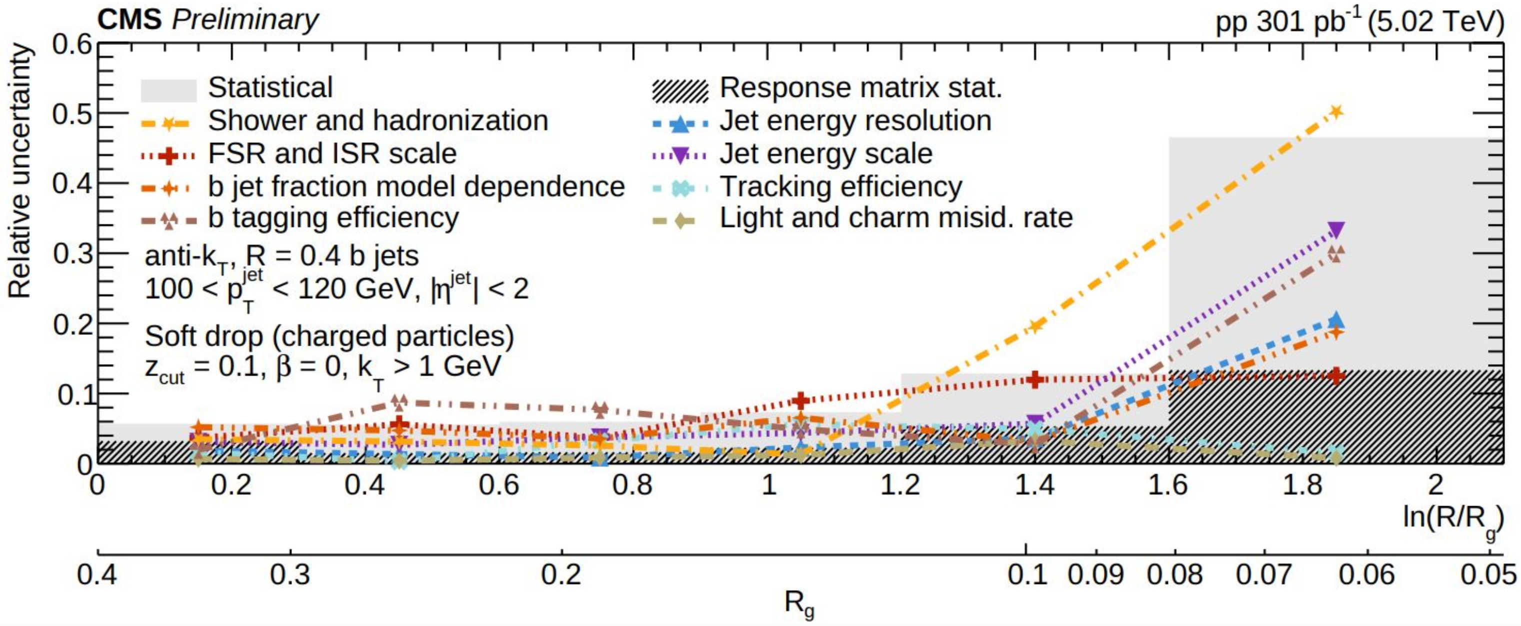
Only for b jets

- **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

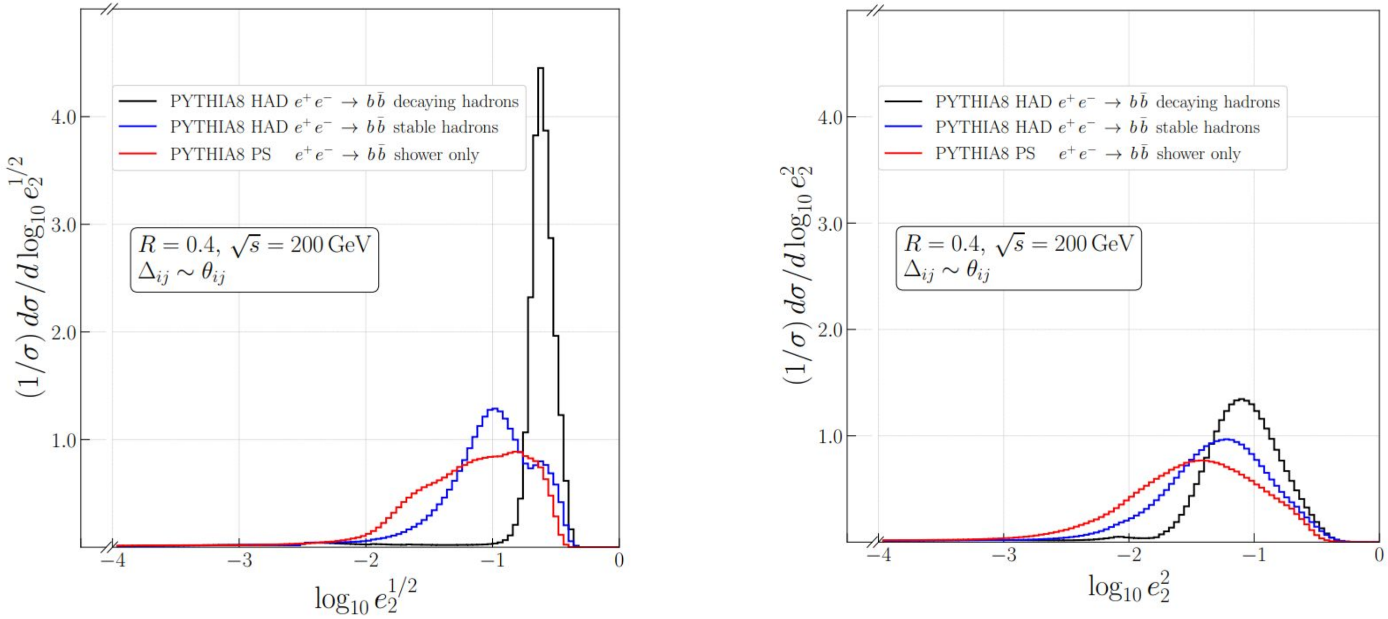
Leading sources related to physics model and b tagging

- **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