b jet substructure via the aggregation of the b hadron decay daughters with CMS

CMS-PAS-HIN-24-005

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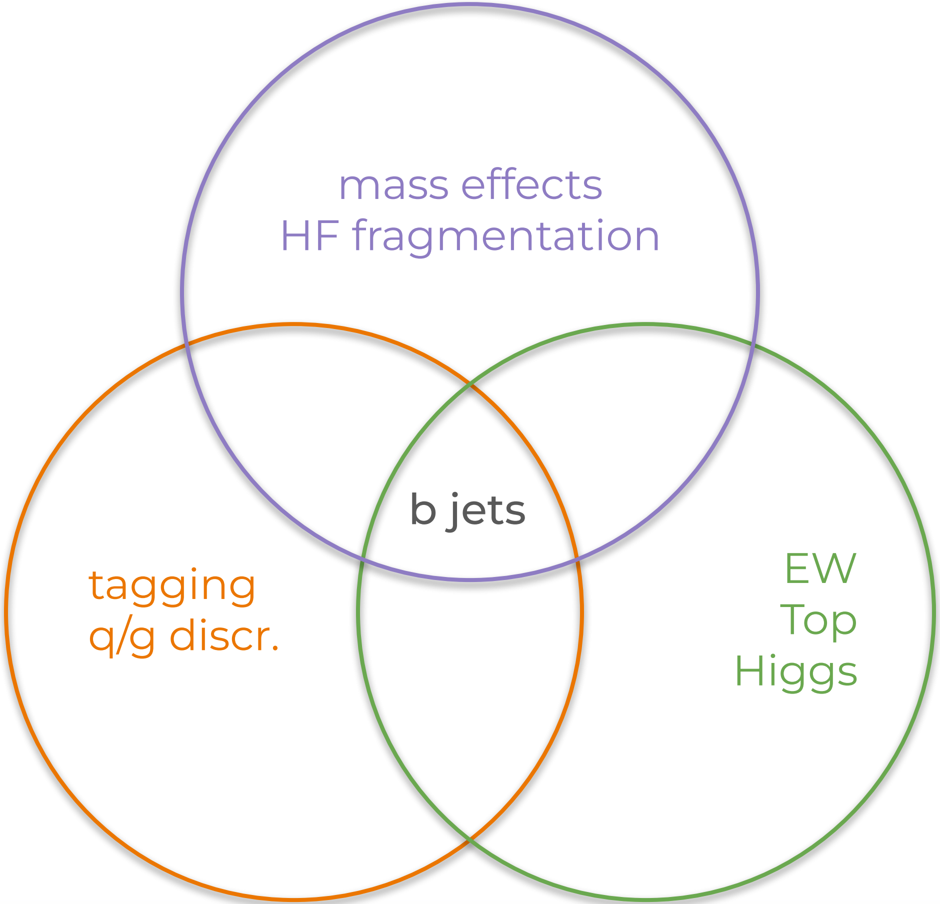
LLR, École Polytechnique

LHC-EW Jets and Bosons
13 November 2024

Heavy flavor jets



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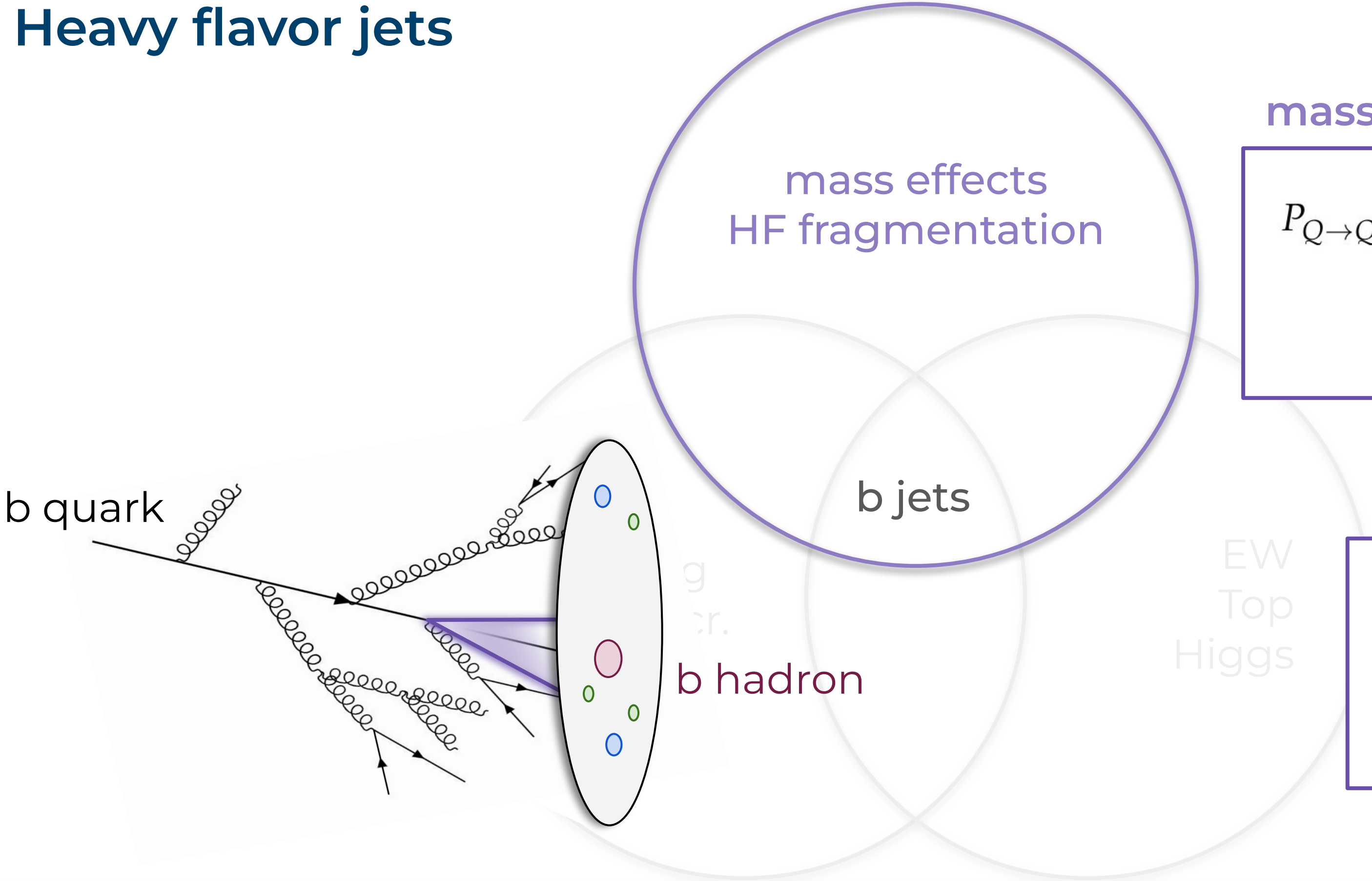


mass dependent shower

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

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

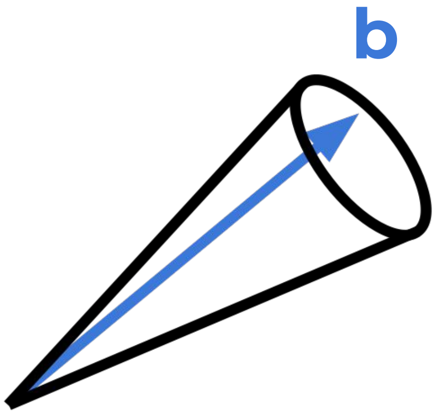
dead cone

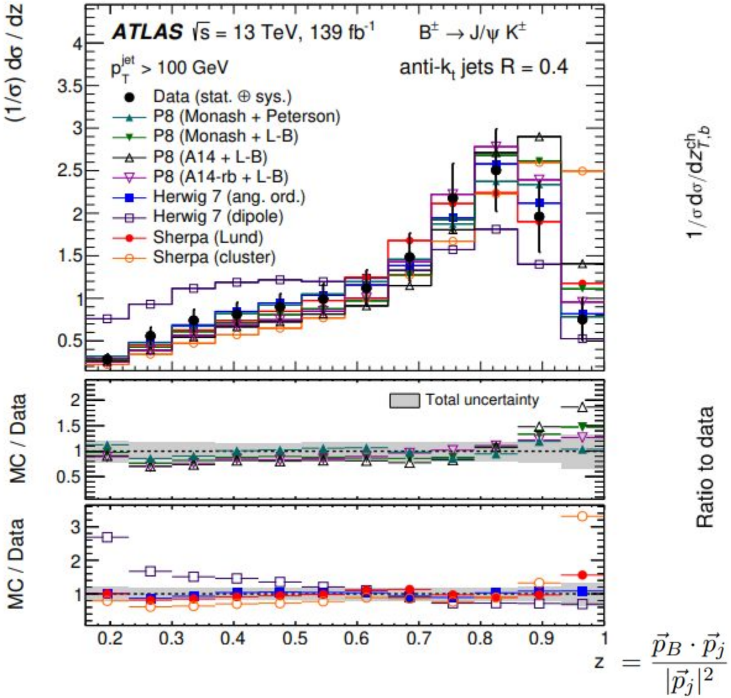
$$d\mathcal{P}(\theta) \propto \frac{d\theta^2}{(\theta^2 + \theta_0^2)^2}$$

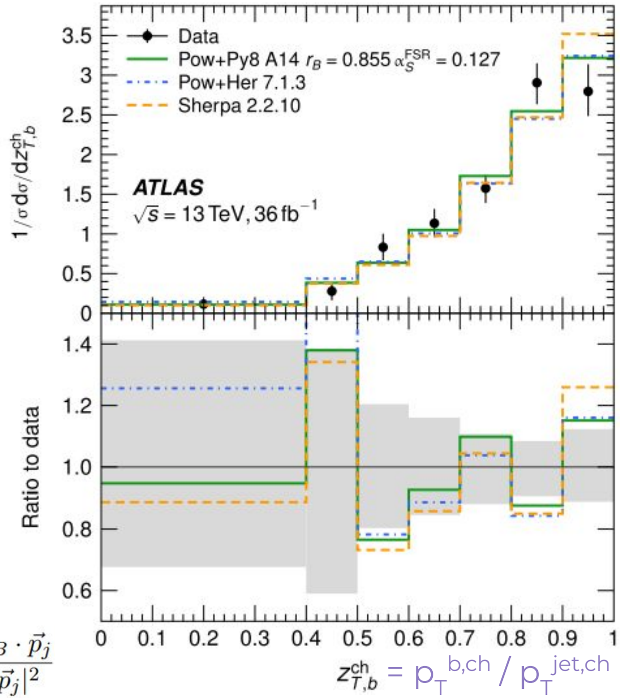
$$\theta_0 = m_Q / E_Q$$

b hadron fragmentation

b hadron momentum
relative to the jet







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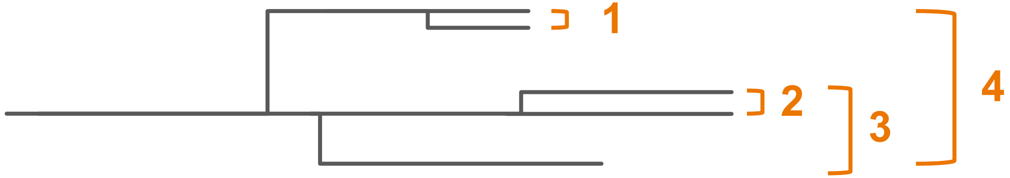
Jet declustering

1) Recluster jet constituents from smaller to larger angles



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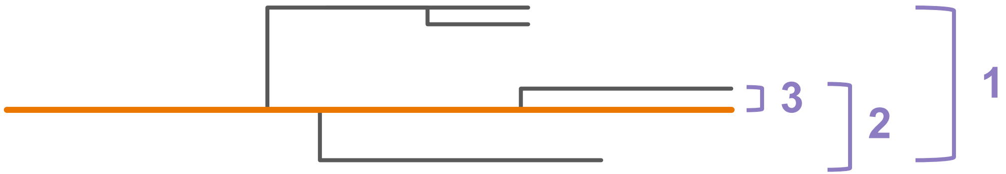
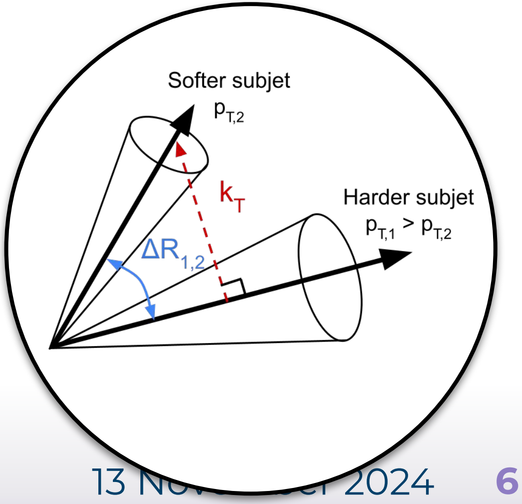


2) Decluster from larger to smaller angles following the hardest prong

$\Delta R_{1,2}^{2} = \Delta y_{1,2}^{2} + \Delta \phi_{1,2}^{2}$ $k_T = p_{T,2} \cdot \Delta R_{1,2}$ $z = p_{T,2} / (p_{T,1} + p_{T,2})$



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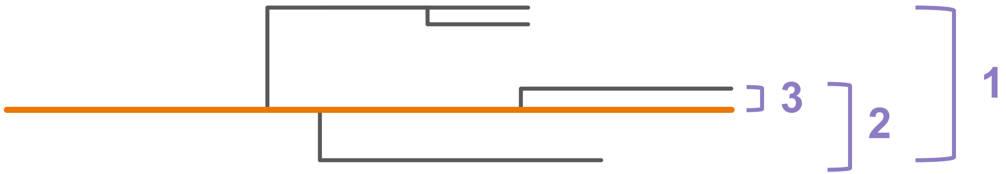

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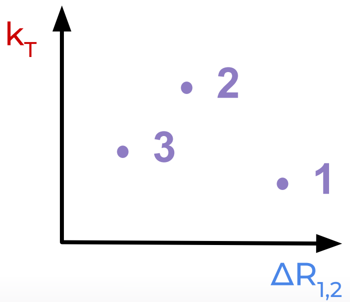
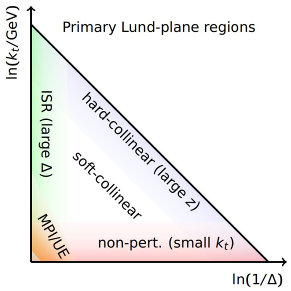
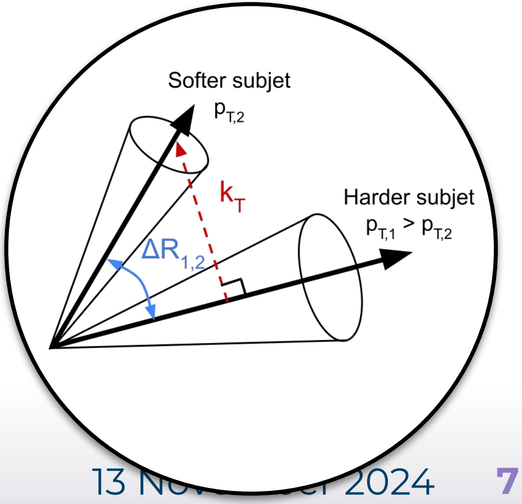
2a) The primary Lund jet plane







Jet declustering

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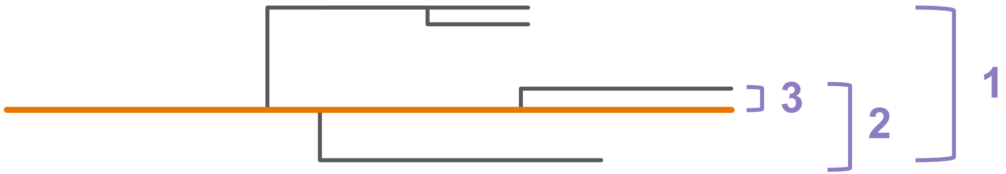

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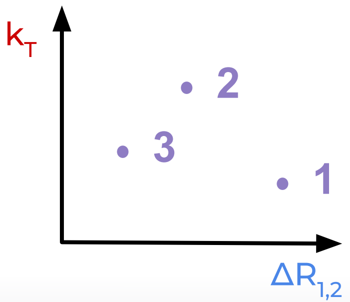
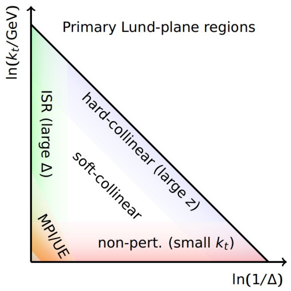


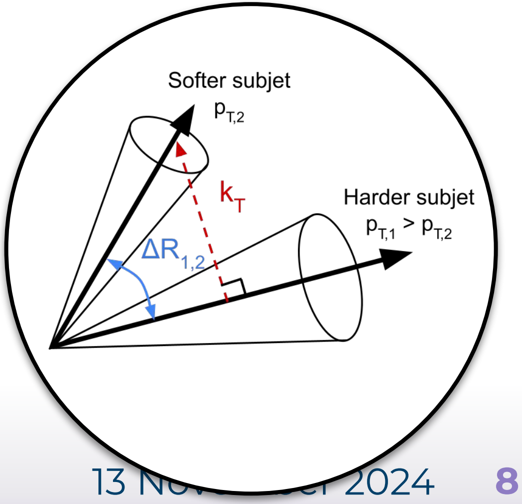


2b) Soft drop

stop when

$z > z_{cut} \cdot (\Delta R_{1,2} / R)^{\beta}$

⇒ 2 subjets



Groomed observables in ttbar

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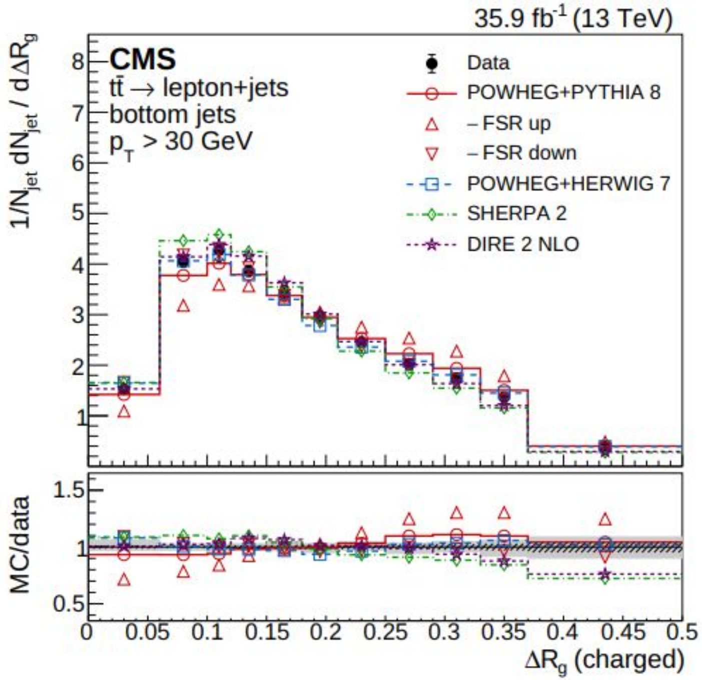
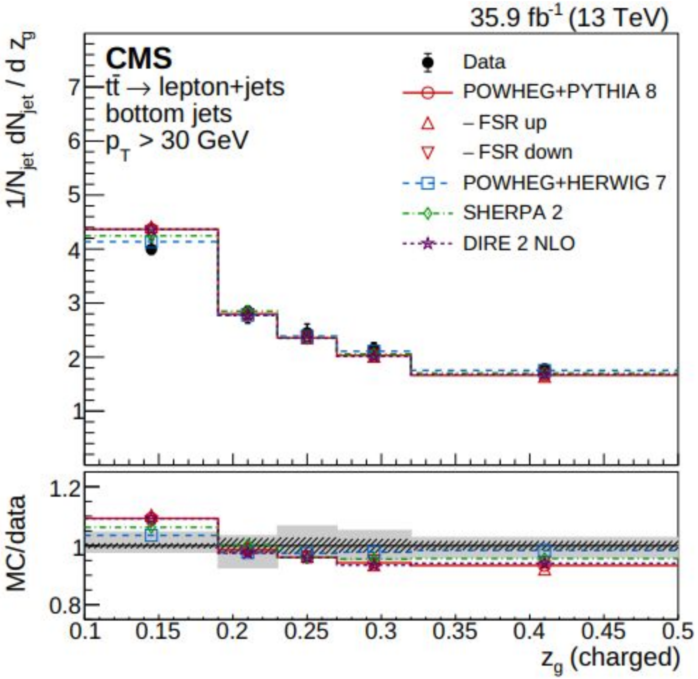
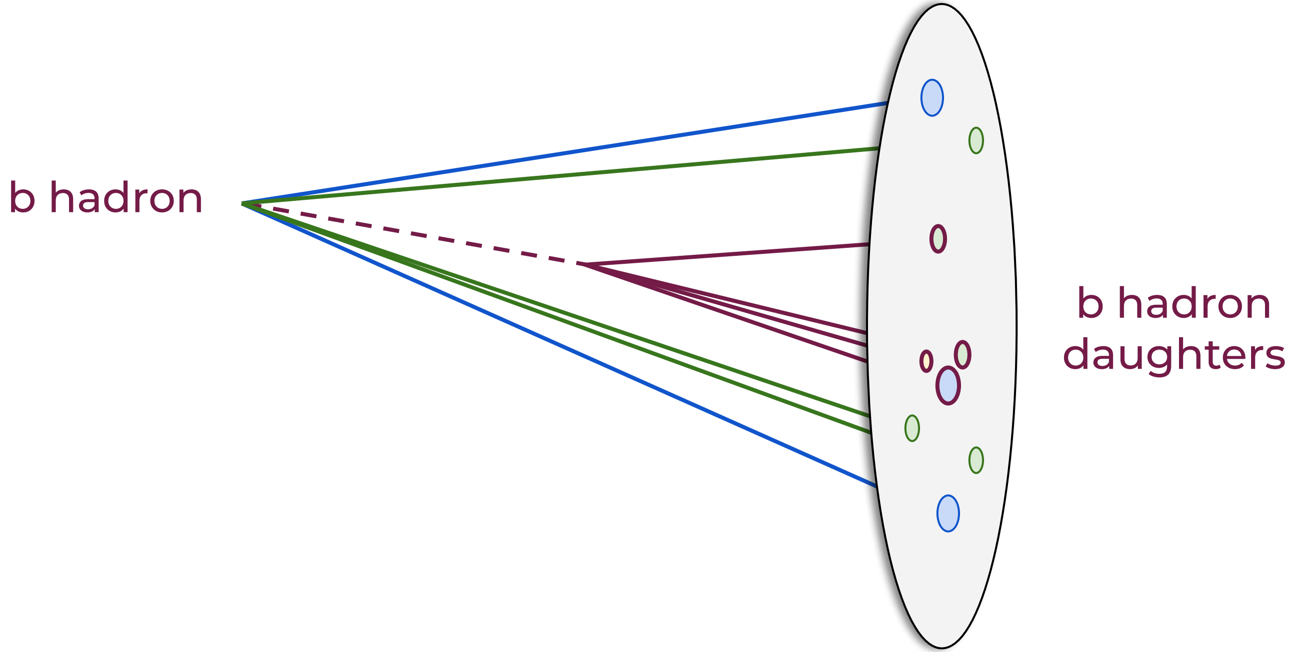
QCD cascade and decay kinematics intertwined





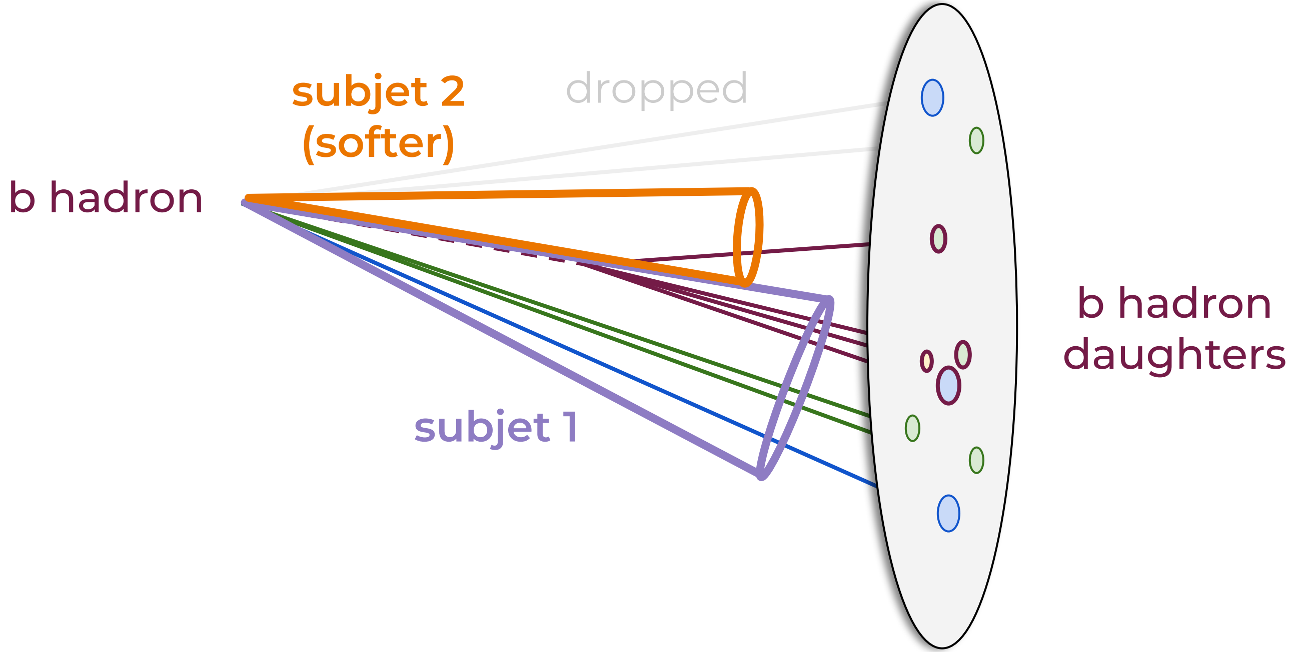
The b hadron decay problem

b hadron decays inside the detector



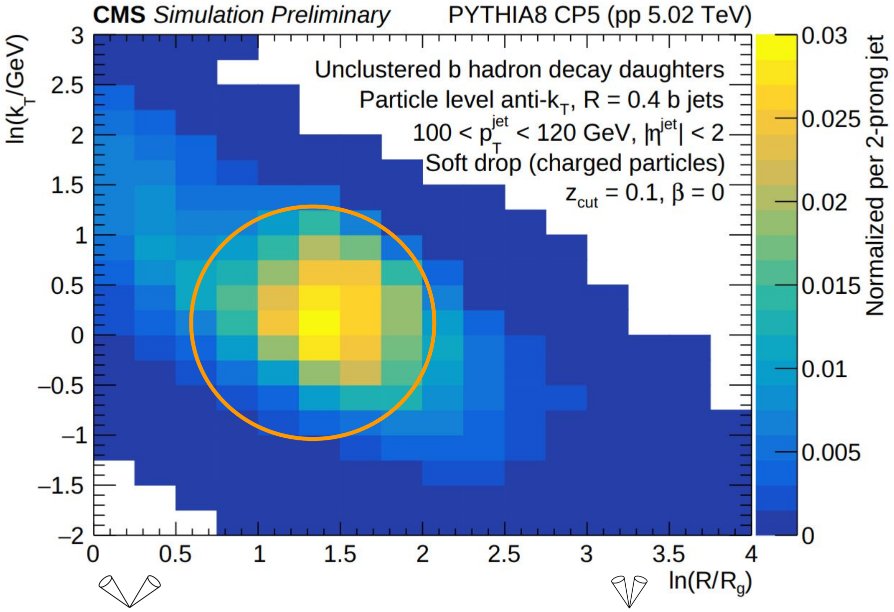
The b hadron decay problem

Soft drop gets caught in the decay daughters

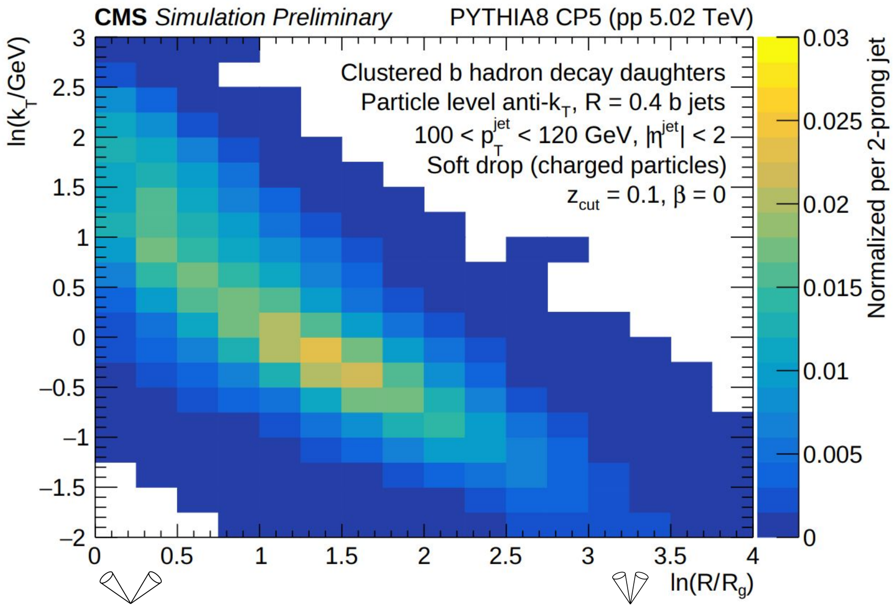


The b hadron decay problem

Charged-particle level simulation



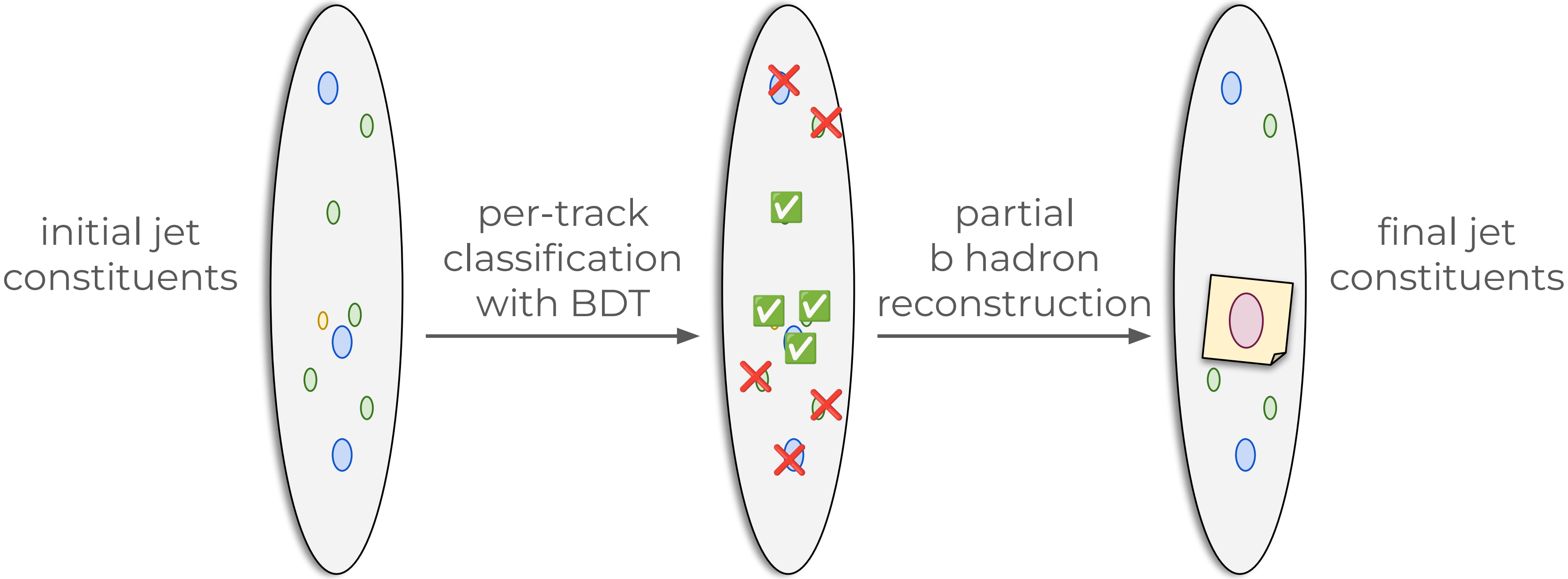
b decay daughters present



b decay daughters clustered

Partial b hadron reconstruction

Identify the b hadron daughters and cluster into a single particle



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

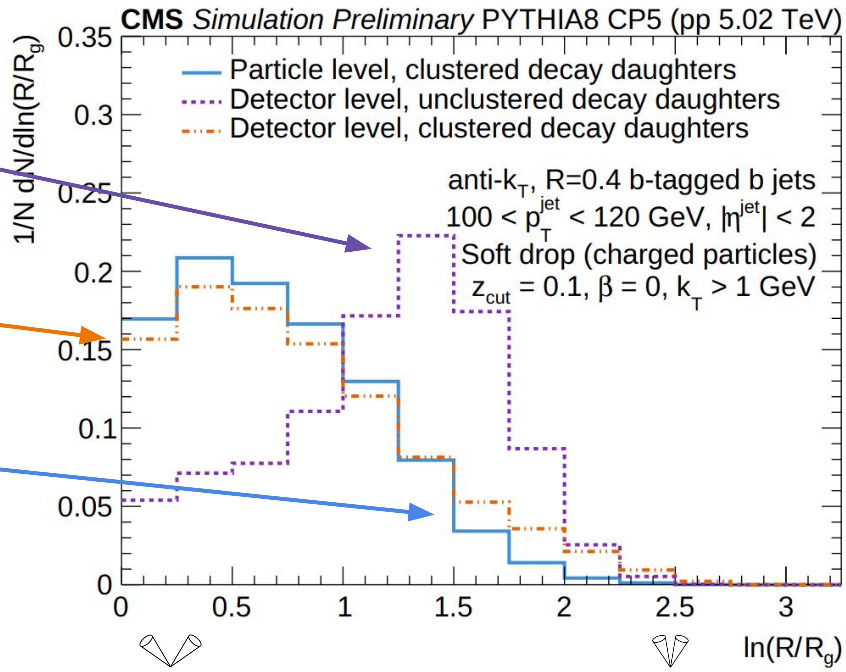
Partial b hadron reconstruction

Identify the b hadron daughters and **cluster** into a single particle

detector level with decays

detector level without decays

particle level without decays



Analysis workflow

"pp reference" run of 2017 @ 5.02 Tev, CMS <PU> = 3

Jet kinematics

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

CHS for PU mitigation

Observables

charged particle R_g, z_g

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

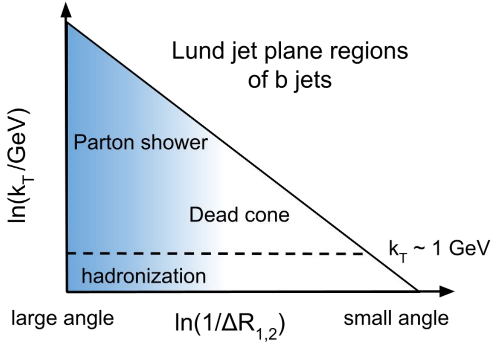
Soft drop parameters

Stop condition

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

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

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



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

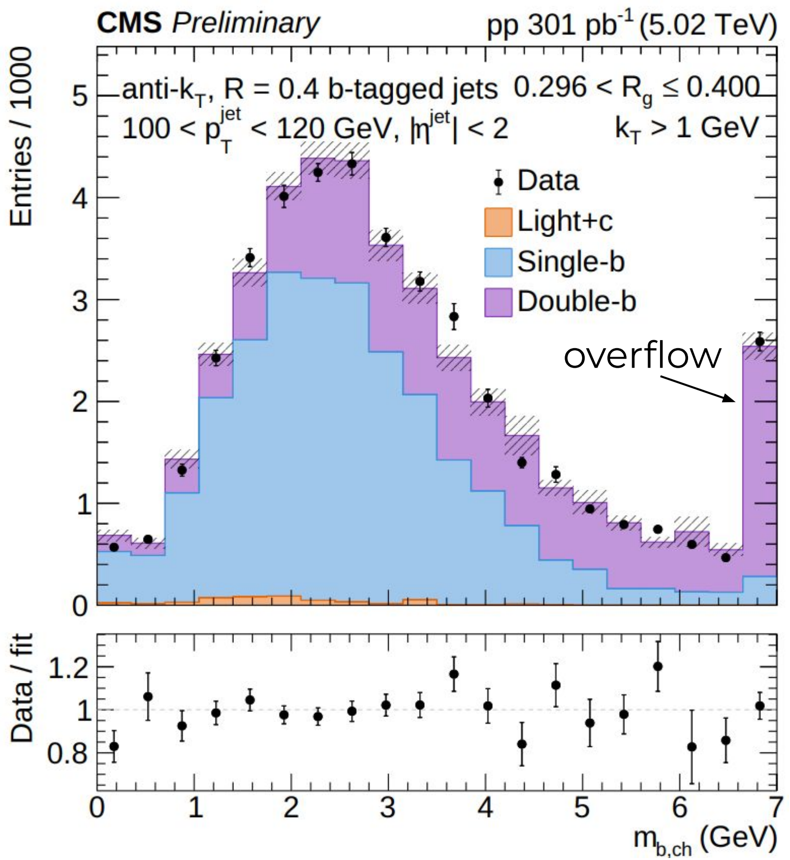
b jet selection and corrections

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



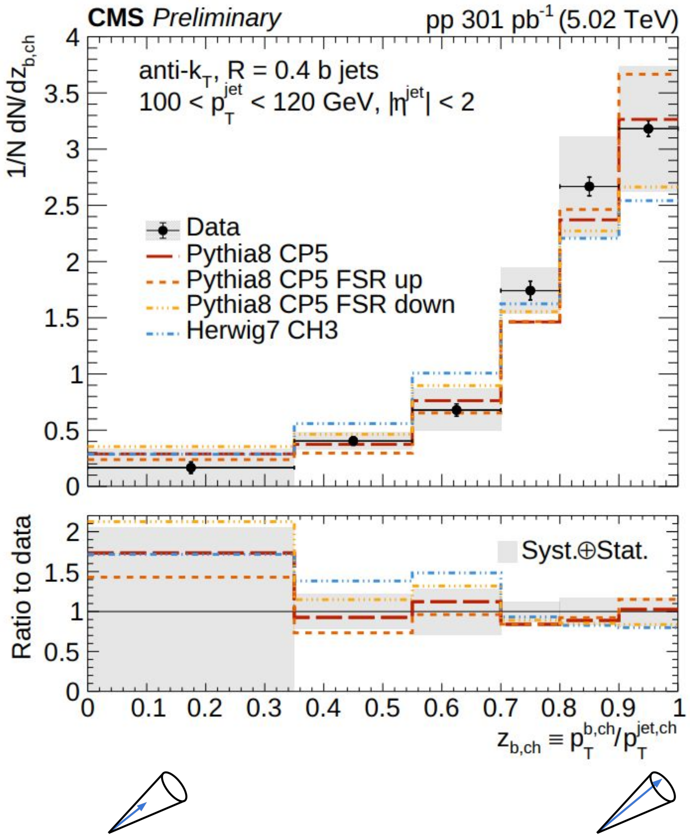
reconstructed b hadron mass

Fragmentation function

Peak at high z

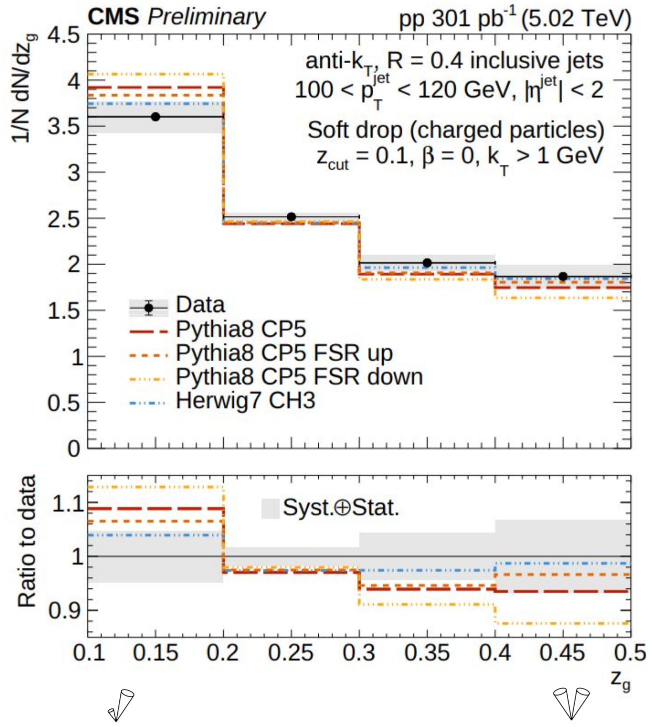
Large systematic uncertainties dominated by the physics modelling:
unfolding
template shape
b tagging efficiency

Models agree with the data within the uncertainties

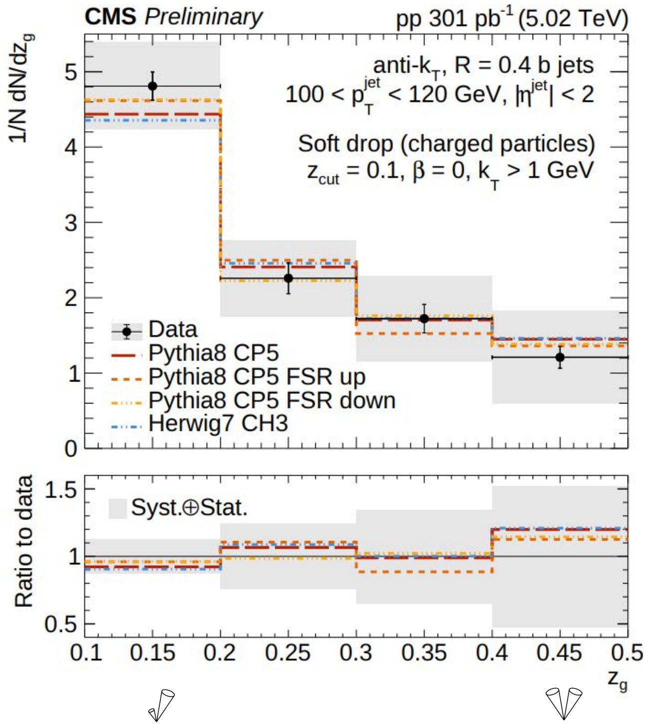


Groomed momentum balance

inclusive jets

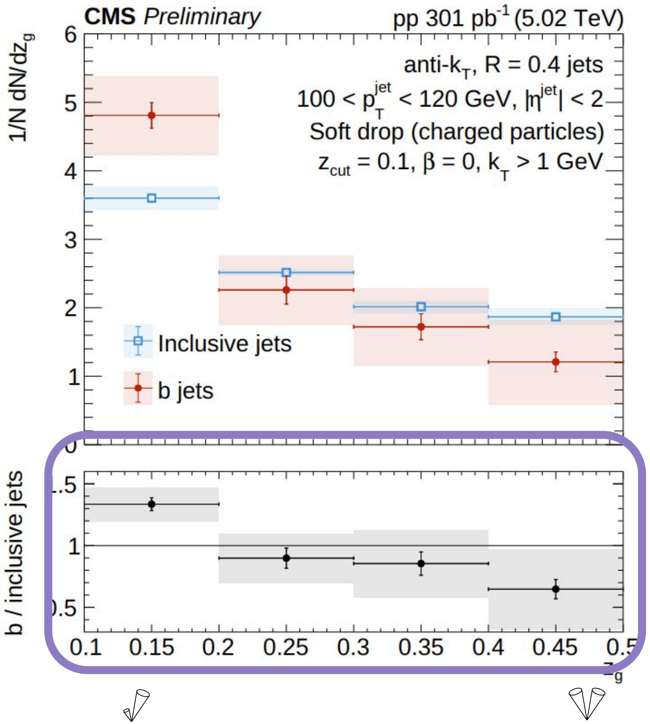


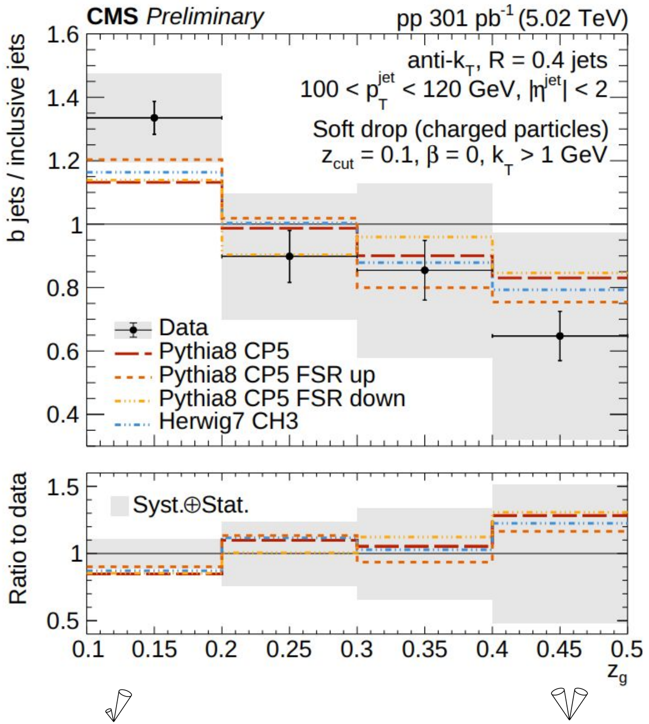
b jets



Groomed momentum balance

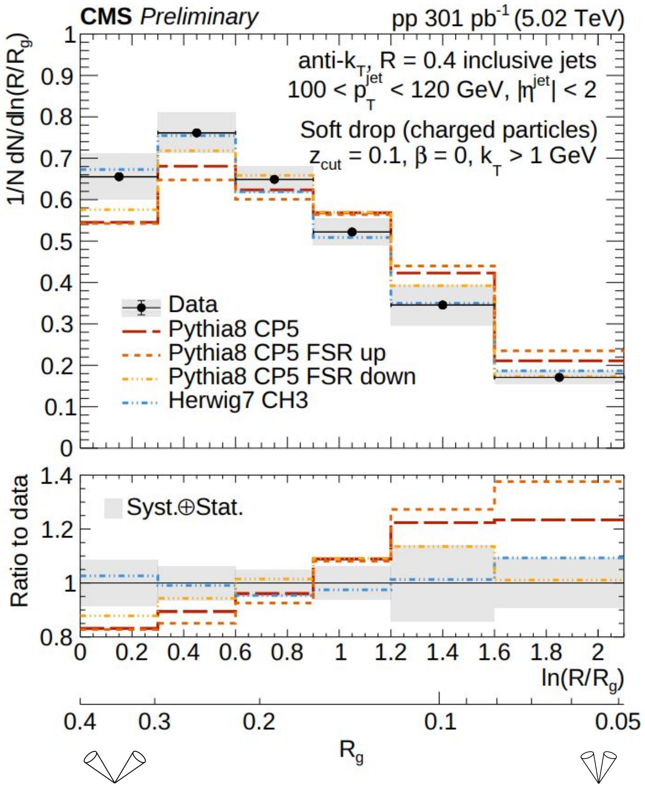
More imbalanced splittings for b jets



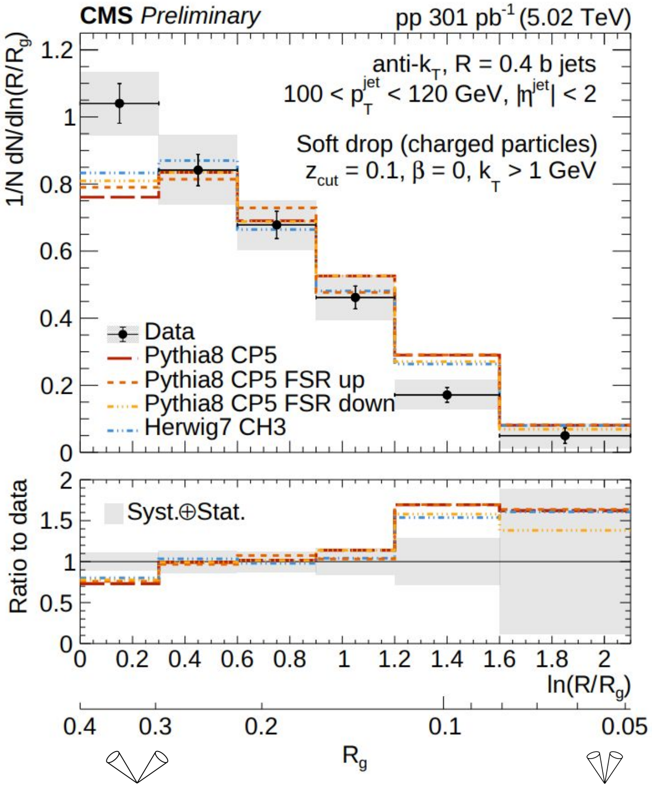


Groomed jet radius

inclusive jets

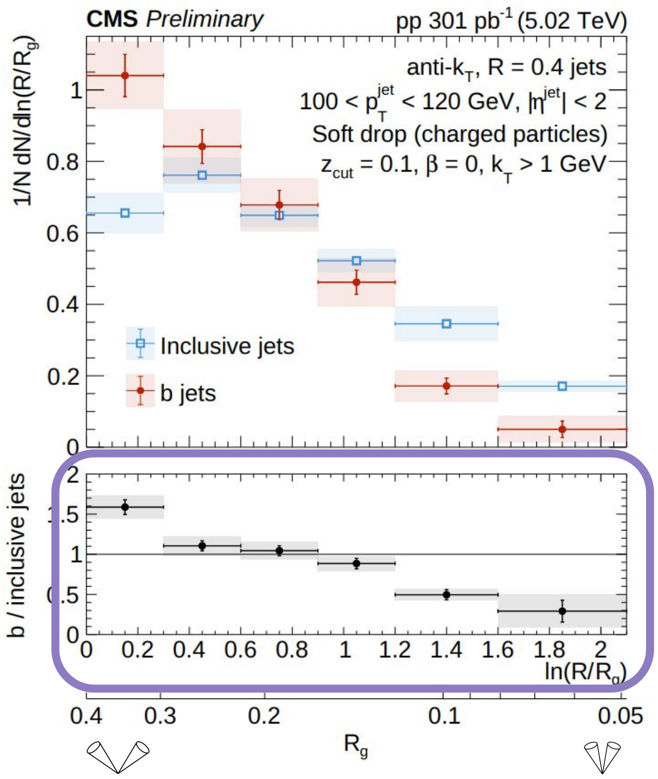


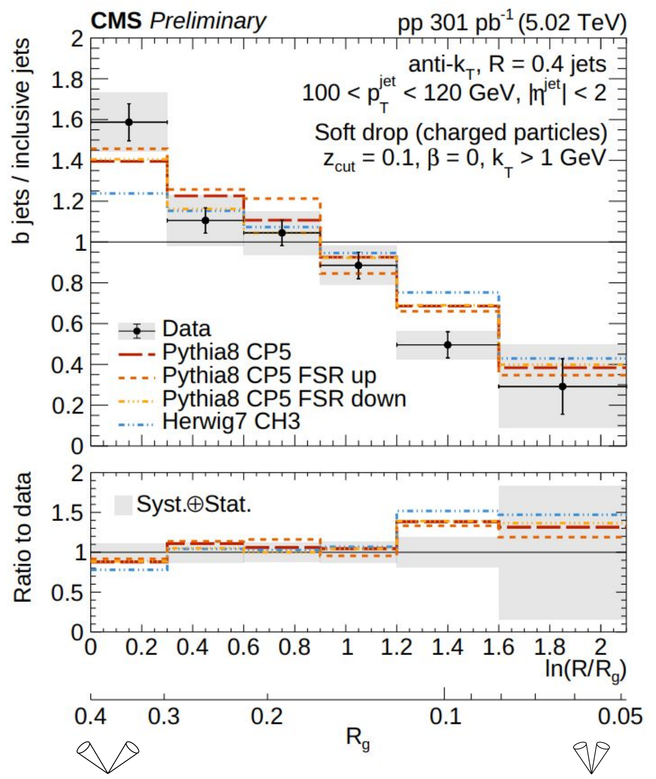
b jets



Groomed jet radius

Suppressed small angle radiation





Outlook

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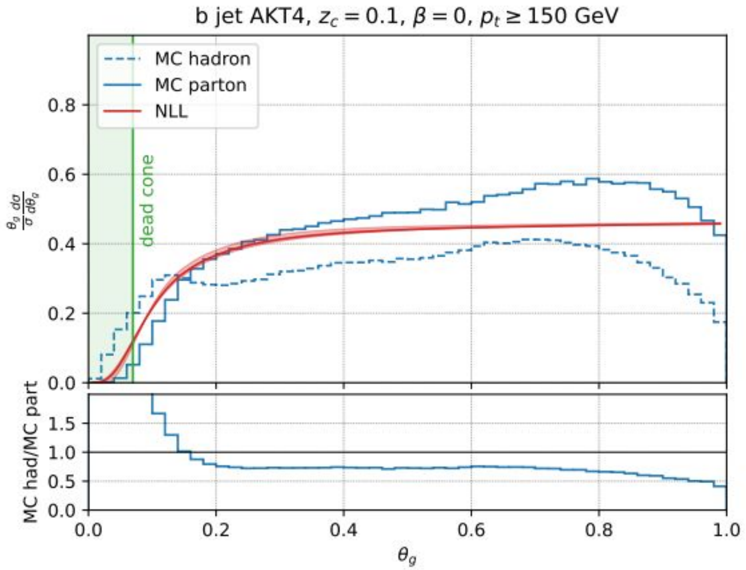
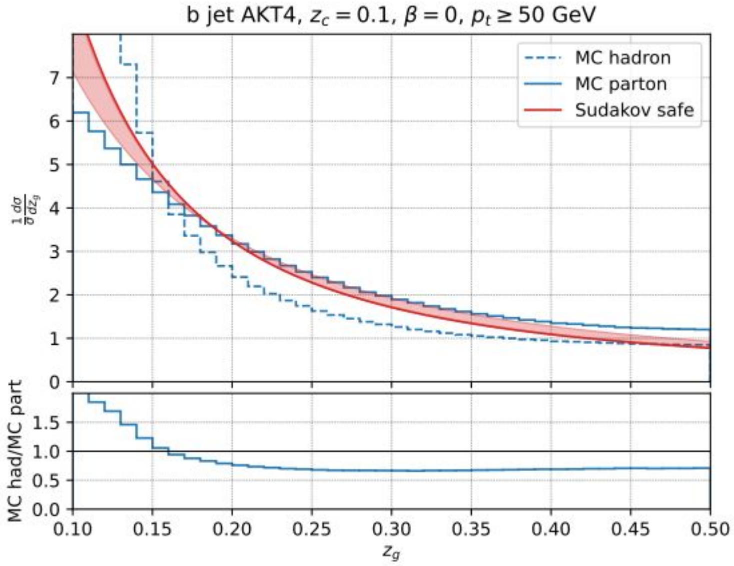
Theory comparison: NLL calculation exists with charged+neutral particles
possibility to compare in the future





Outlook

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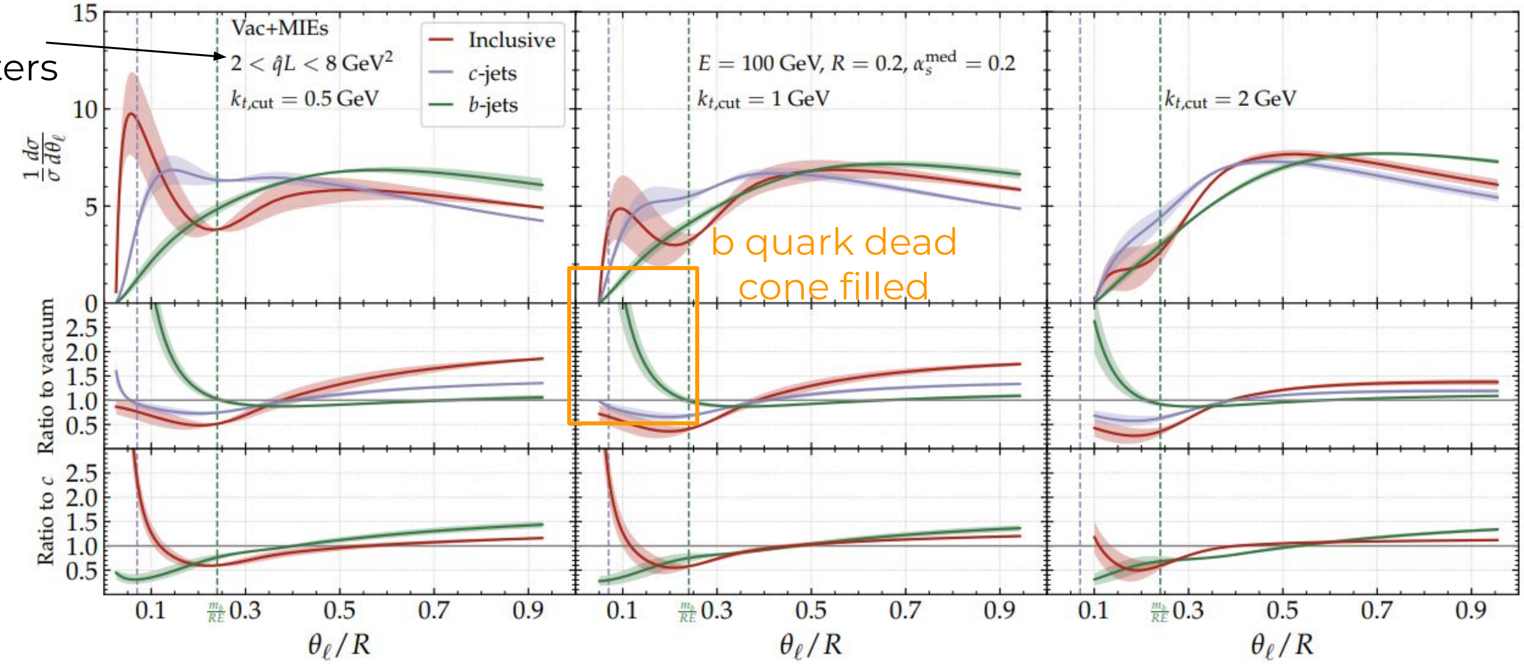
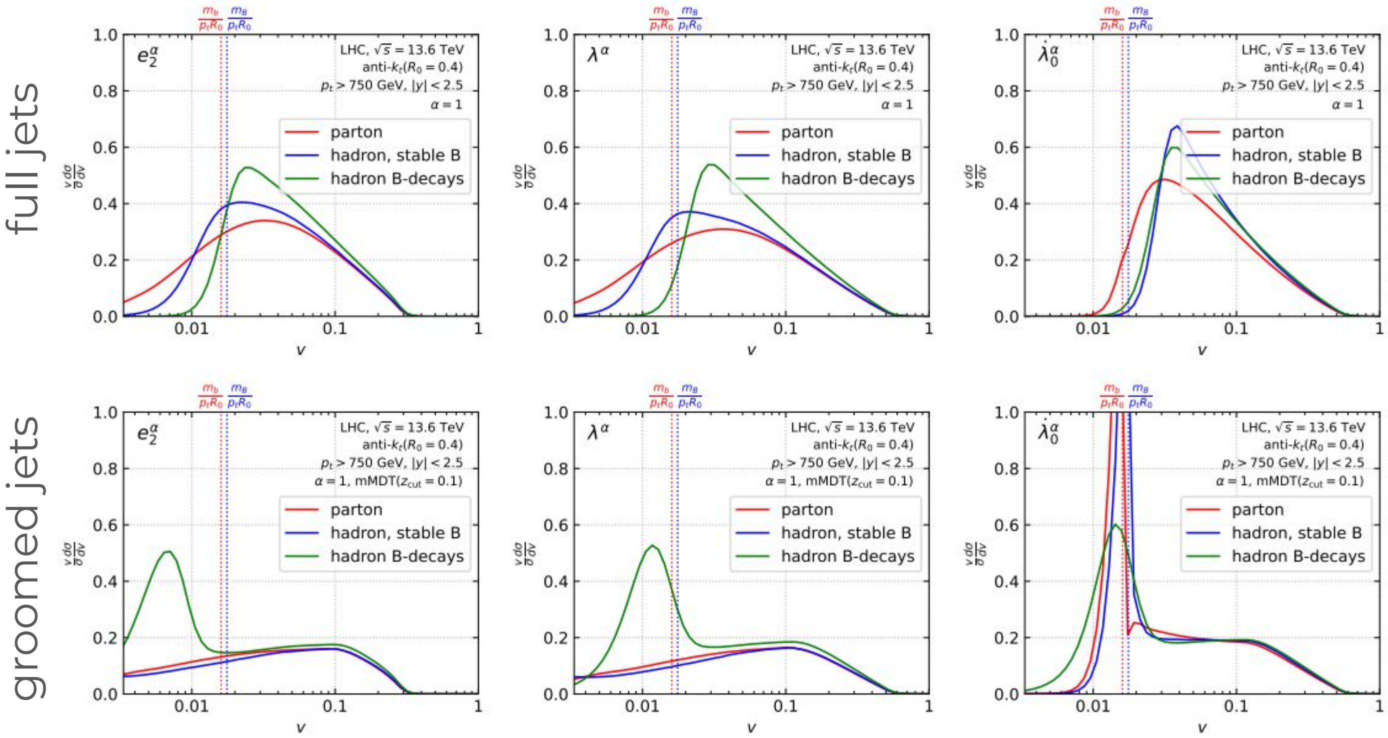
HI prospects: isolate medium induced radiation in dead cone region

QGP parameters



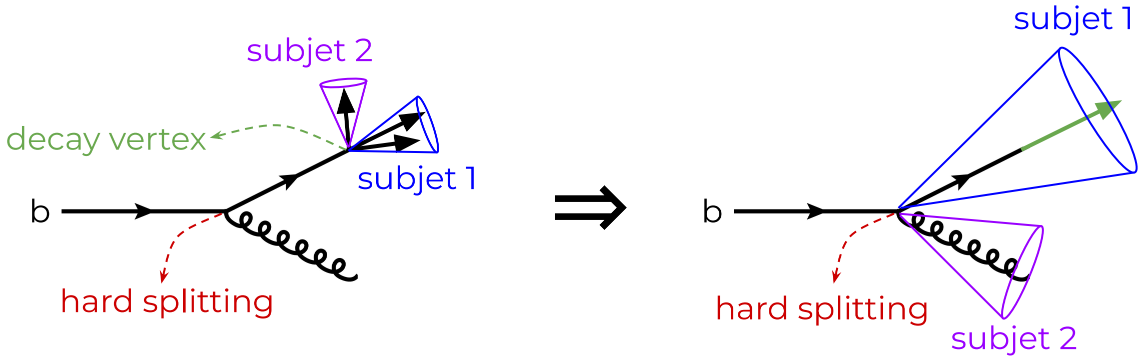
Outlook

Other substructure observables: b decay treatment necessary



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**)

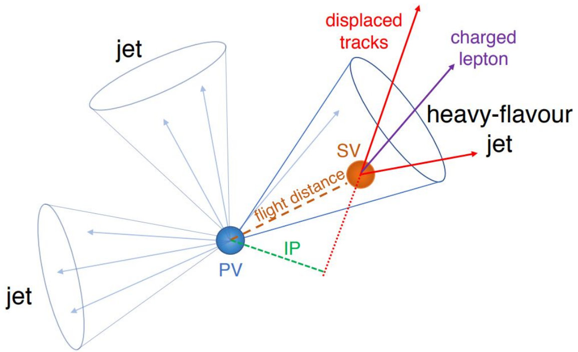
Separation of b hadron decay from QCD cascade can be used for other observables in the future (EECs, generalized angularities, masses)

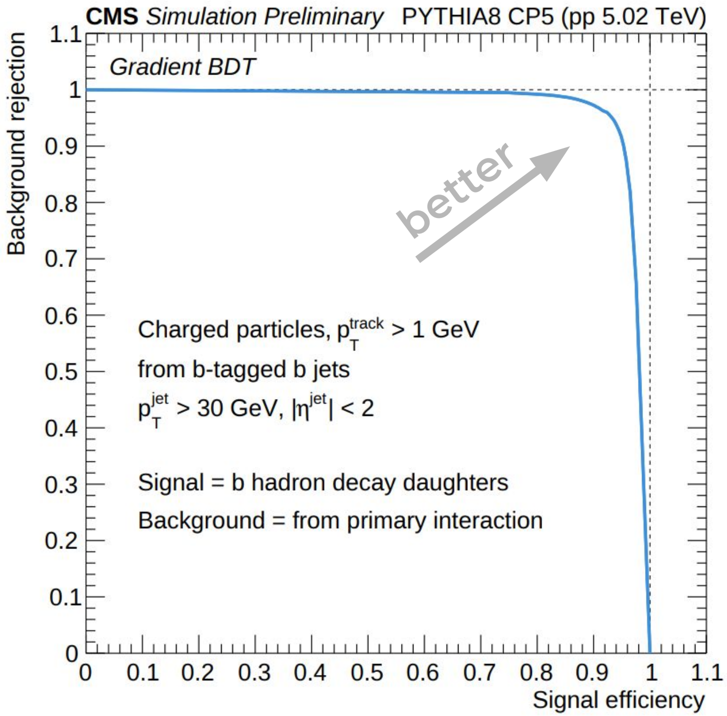
Backup

Decay product identification

Binary classifier

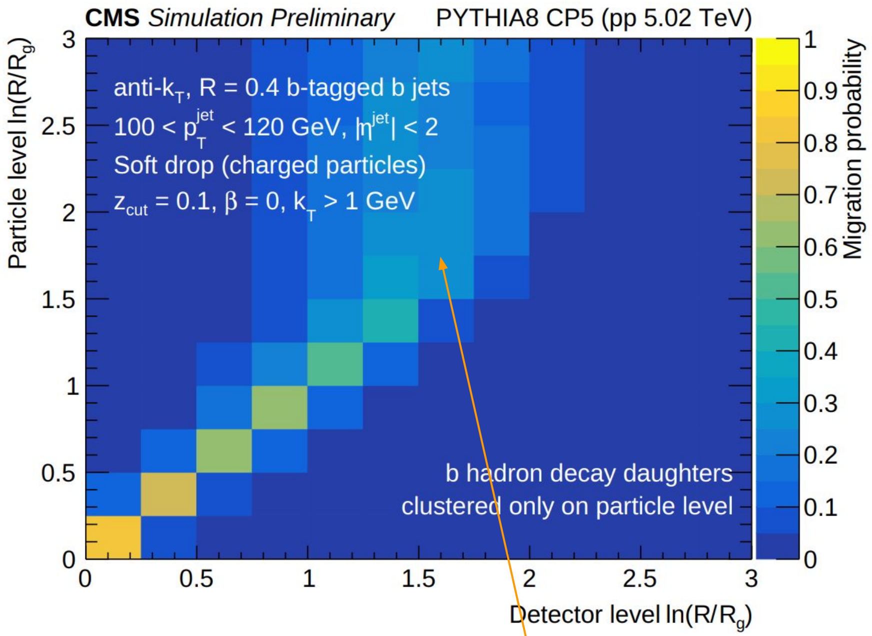
- Gradient boosted decision tree
  - Signal = charged decay products
  - Background = charged particles from PV
- Inputs
  - Track properties (eg. impact parameter)
  - Associated SV properties (eg. flight distance)

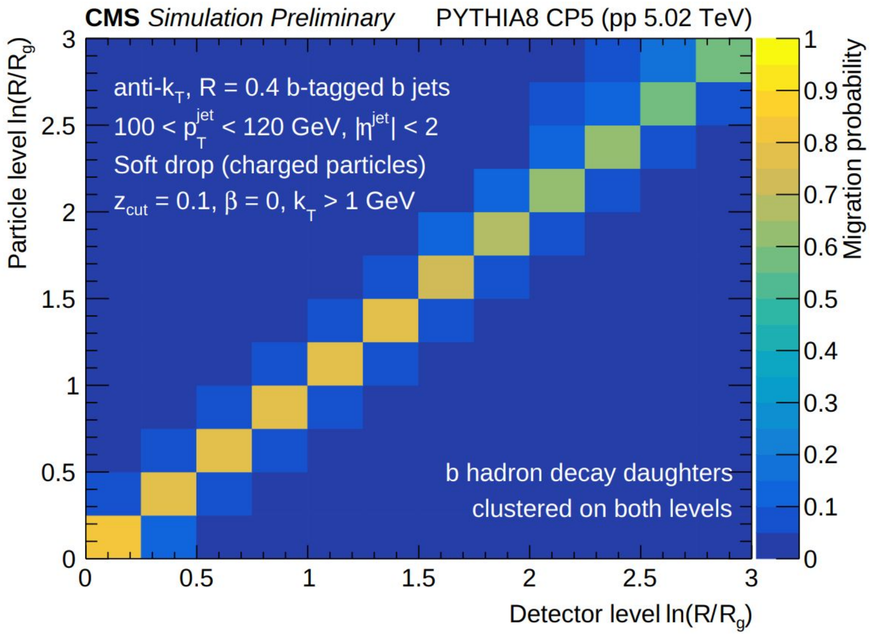




Agreement between the detector and the particle level

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)