# Direct observation of the dead-cone effect in b quark-initiated jets from $t\bar{t}$ decays at CMS

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*on behalf of the CMS collaboration*

Based on CMS PAS SMP-25-008

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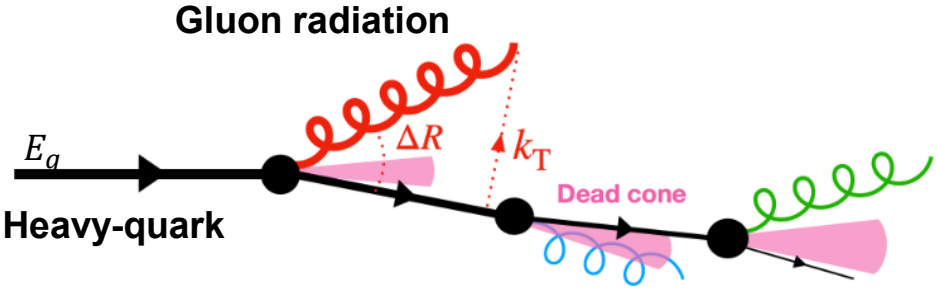
# Intro: the dead cone effect

J. Phys. G: *Nucl. Part. Phys* 17 (1991) 1602

- At small $\theta$ and leading order of perturbative QCD, **emission probability**

$$\frac{\mathrm{d}P}{\mathrm{d}\theta^2} \sim \frac{\theta^2}{\left[\theta^2+\left(m_q/E_q\right)^2\right]^2}$$




- The **dead-cone effect**: the **suppression of collinear gluon emissions** around a massive quark at $\boldsymbol{\theta < \frac{m_q}{E_q} = \theta_0}$
- Consequence: harder fragmentation of b and c quarks
- Important benchmark to QCD resummation and parton shower developments
- Can help reduce theoretical and modeling uncertainties in measurements with b final state

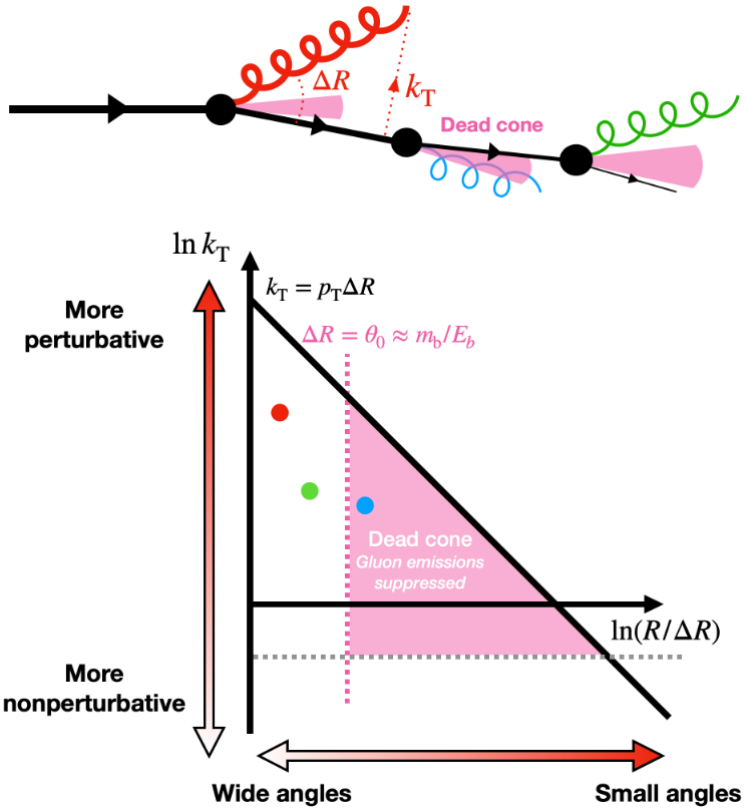
$\theta$: emission angle
$m_q, E_q$: mass, energy of the radiating quark
$k_T$: relative transverse momentum between partons
$\theta \approx \Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$: angular separation

# Intro: Lund jet plane

- For a **direct measurement of Dead cone**, reconstruction of the **showering history of partons** is required
- Use Lund Jet plane (LJP):
  1. Jets are re-clustered with the Cambridge/Aachen algorithm (angular ordered)
  2. Each jet is de-clustered, registering $\Delta R$ and $k_T$
  3. Follow along the hardest prong
- The LJP is often measured as emission density normalised per-jet:

$$\frac{1}{N_{\text{jets}}} \frac{d^2 N_{\text{emission}}}{d \ln(k_T) \ln(R/\Delta R)}$$

- In LJP splittings are separated in regions




$\Delta R = \sqrt{\Delta y^2 + \Delta \phi^2}$: angular separation
$k_T$: relative transverse momentum between partons

JHEP12 (2018) 064 arXiv 1807.04758

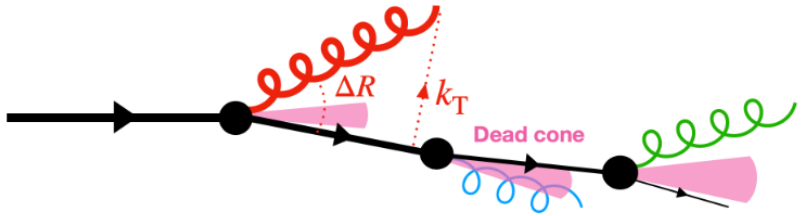
# Probing the dead-cone

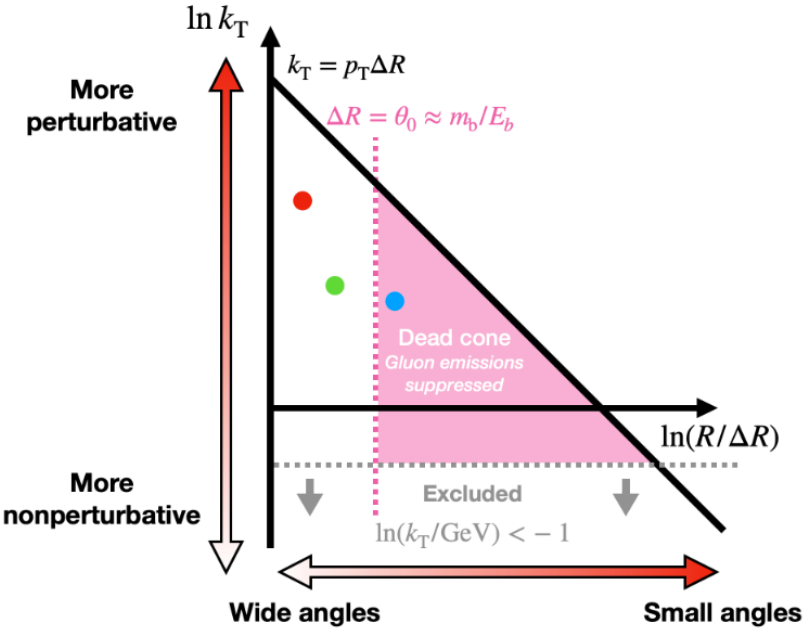
- Dead cone probed using the **LJP projection on $\Delta R$**

$$\frac{1}{N_{\text{jets}}}\frac{dN_{\text{emission}}}{\ln(R/\Delta R)}$$

- A cut on the soft emissions $\ln(k_T/\text{GeV}) > 1 \Rightarrow k_T \gtrsim 368$ MeV helps to suppress **non-perturbative effects**

- In this measurement, LJP projection measured for **b jets with $40 < p_T/\text{GeV} < 200$ in dileptonic $t\bar{t}$** events



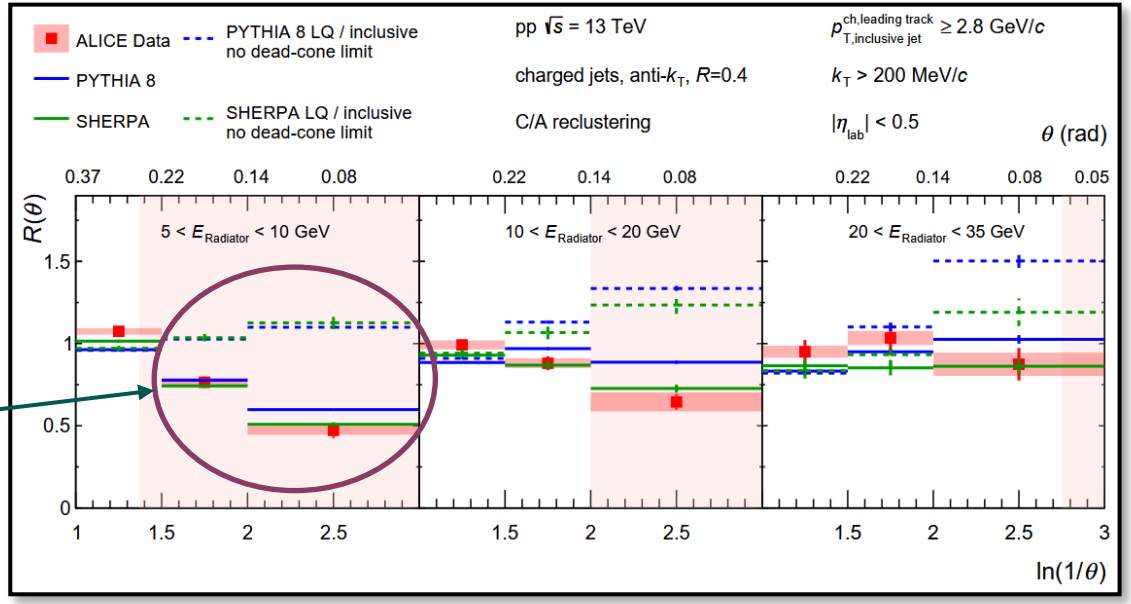
# Previous measurements

# Previous measurements (ALICE)

- The **first direct observation** of the dead-cone: by ALICE in **charm quark** using similar techniques
- Measuring $R(\theta)$: the **ratio of the emission** density between **c jets and inclusive jets** for splittings with > 200 MeV
- c jets tagged via $D_0 \to K^+\pi^-$ (and charge conjugate)

$$R(\theta) = \frac{1}{N^{D^0\,\text{jets}}} \frac{\mathrm{d}n^{D^0\text{jets}}}{\mathrm{d}\ln\left(\frac{1}{\theta}\right)} \Big/ \frac{1}{N^{\text{incl. jets}}} \frac{\mathrm{d}n^{\text{incl. jets}}}{\mathrm{d}\ln\left(\frac{1}{\theta}\right)} \Bigg|_{k_T, E_\text{Radiatior}}$$

Data prefer a model with the dead cone effect included.
Suppression at large $\ln\left(\frac{1}{\theta}\right) \Rightarrow$ small $\theta$ is seen

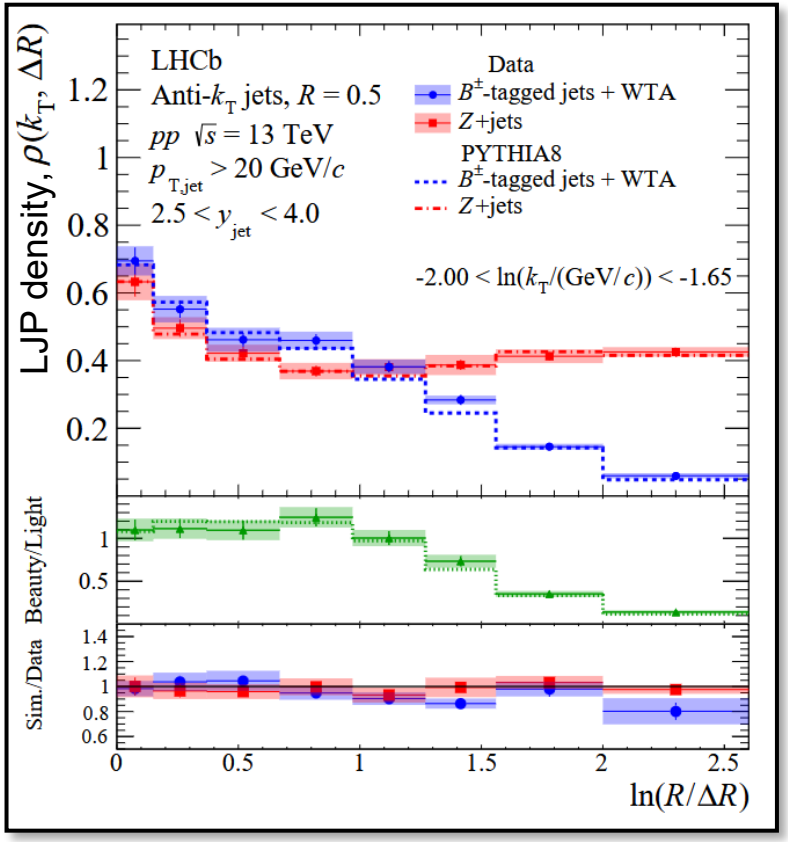



Nature 605 (2022) 440-446 | arXiv | 2106.05713

# Previous measurements (LHCb)

- Measurement of LJP for **b jets** (tagged via $B^{\pm} \to J/\Psi(\to \mu\mu)K^{\pm}$)) and **inclusive jets in Z+jets** events
- Suppression of radiation for $B^{\pm}$-tagged jets at small angles vs. inclusive jets

- Both shown measurements drew conclusions of the dead-cone observation by **comparing heavy and inclusive jets**
- The extent to which **non-perturbative effects** contribute to the differences in heavy/inclusive jets is unclear




Phys. Rev. D112 (2025) 072015 arXiv 2505.23530

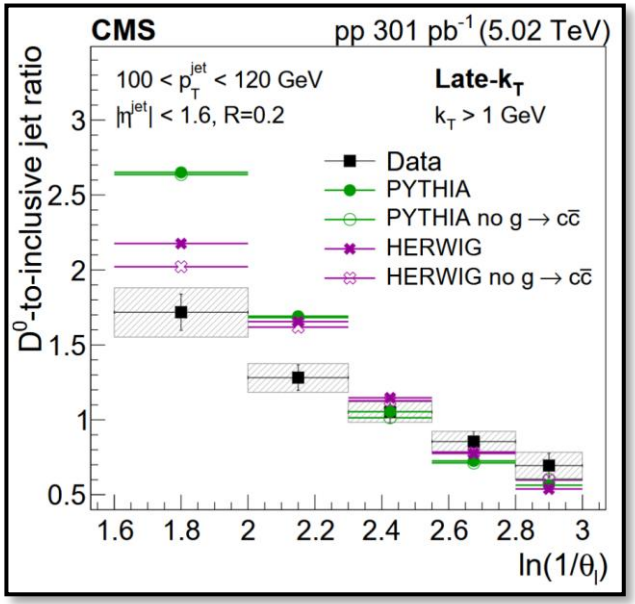
# Previous measurements: Small-angle emissions in charm jets

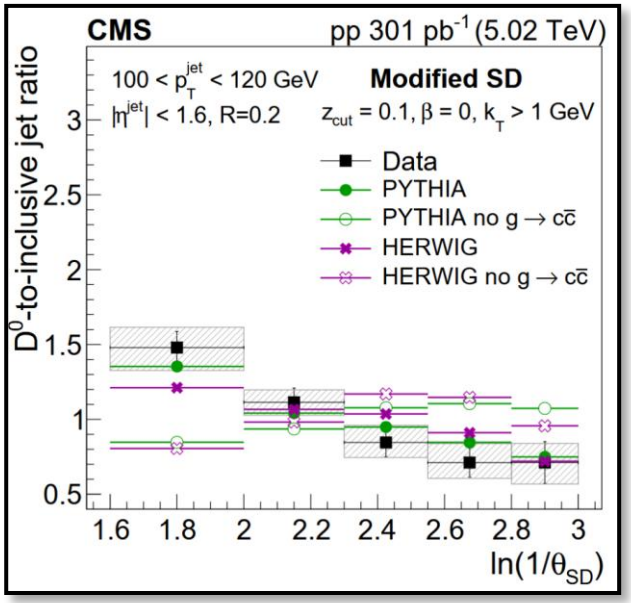
One hard emission per jet, selected using two grooming algorithms:

- late-$k_T$
- Soft drop (SD)

Useful benchmark for heavy ion measurements

- **Ratio** of the emission density for $D^0$**-tagged jets to inclusive jets** shows suppression for collinear emissions
- Disagreement with PYTHIA 8 and HERWIG 7 predictions



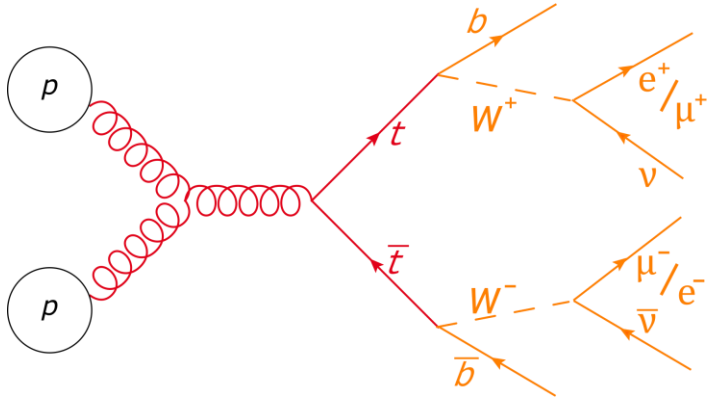

Accepted at JHEP arXiv 2507.13469

# Probing the dead cone of b quarks at CMS

SMP-25-008

# Event selection

- Data: 59.8 $\mathrm{fb}^{-1}$ collected at CMS in 2018, Run 2
- Targeting $\mathrm{t\bar{t}}$ events in the **dileptonic decay** channel
- Exactly one electron and one muon of opposite charge
- At least one of the two leading jets is identified as b jet (**)
- Purity of dileptonic $\mathrm{t\bar{t}}$: 96%



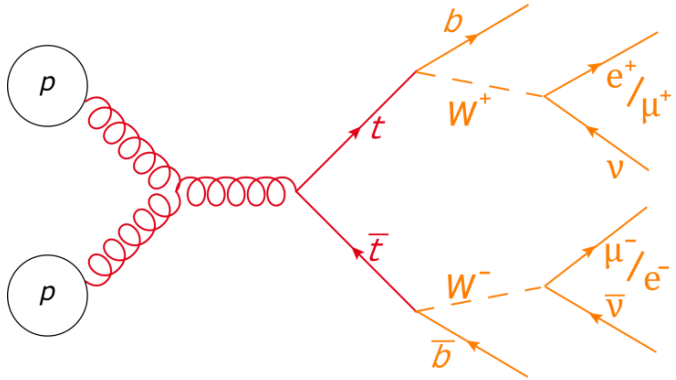

| Object | $p_T$ (GeV) | $\lvert\eta\rvert$ | Impact parameter | Others |
|---|---|---|---|---|
| AK4 jets * | $> 20$ | $< 2.5$ | | |
| Jet constituents | $> 1$ | – | $\lvert dxy\rvert < 0.2$ cm<br>$\lvert dz\rvert < 0.2$ cm | Charged-only |
| Electrons | $> 20$ | $< 2.5$ | $\lvert dxy\rvert < 0.5$ cm<br>$\lvert dz\rvert < 0.2$ cm | Isolated |
| Muons | $> 26$ | $< 2.4$ | | Isolated |

(*) Jets clustered with anti-$k_T$ algorithm with R=0.4, charged hadron subtraction (CHS) algorithm applied

(**) passes tight working point of the DeepJet b-tagging algorithm based on neural networks

# b-jet selection

- **Two leading AK4 jets** per event are considered as a **tag-and-probe (TnP)** pair *
  - **Tag:** identified as b-jet
  - **Probe:** within tracker acceptance ($|\eta| < 2$)
- If 2 b tagged jets in event: reverse the pair ⇒ 2 probe jets per event
- Purity improvements:
  - at least one secondary vertex (SV) associated to the jet
  - $m(l,j) < 150$ GeV **




Purity and efficiency of the b-jet selection

| Selection | Purity (%) | Efficiency (%) |
|---|---|---|
| None | 74 | 100 |
| $m(l,j) < 150$ GeV | 79 | 97 |
| $N_{SV} > 0$ | 86 | 86 |
| Both | 91 | 83 |

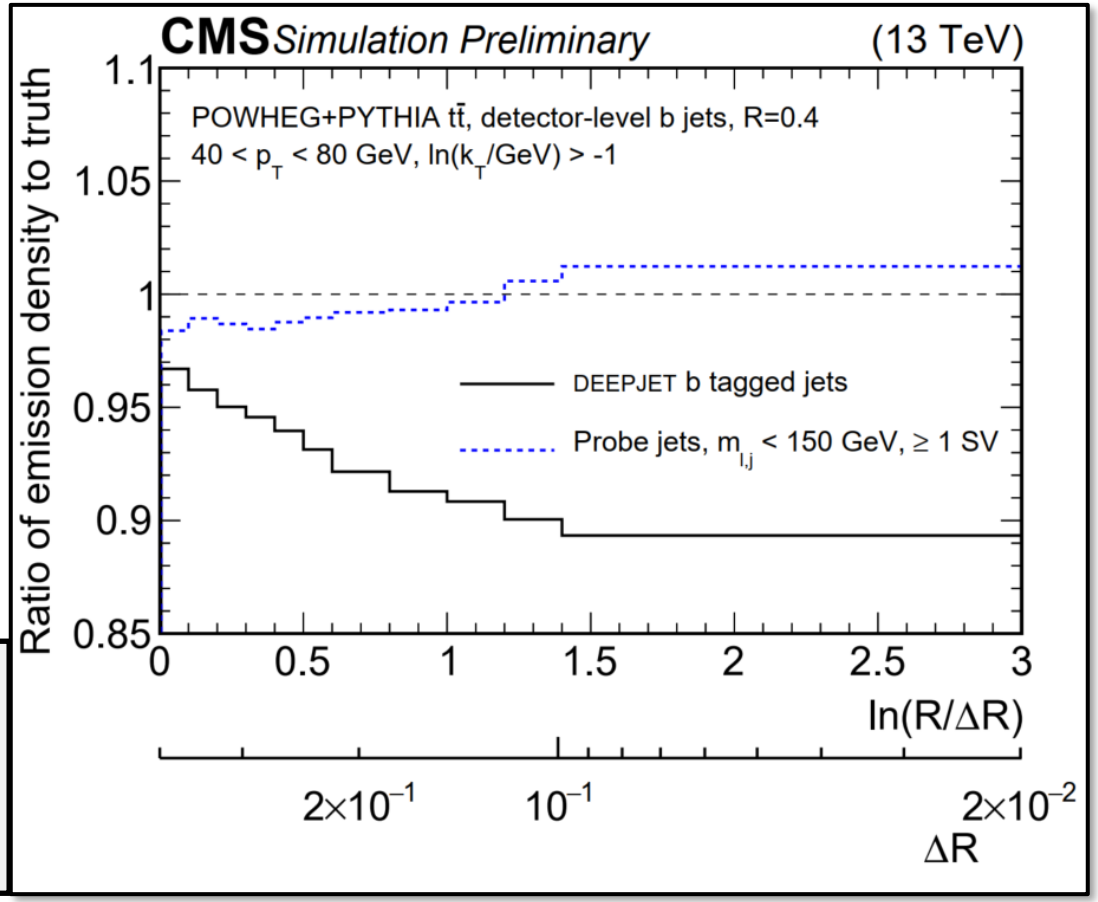
(*) A similar technique used for the ATLAS b-tagger calibration Eur. Phys. J. C 79 (2019) 970 arXiv 1907.05120

(**) calculated for the jet-lepton pair, that minimizes $m^2_{l_i,j_1} + m^2_{l_j,j_2}$

# b-jet selection

Jets selected with TnP avoid the direct use of b-taggers and **minimize any jet substructure bias**

**Ratio** of the b jets LJP density selected from the TnP approach or DeepJet at detector-level **relative** to the **unbiased selection from truth** info



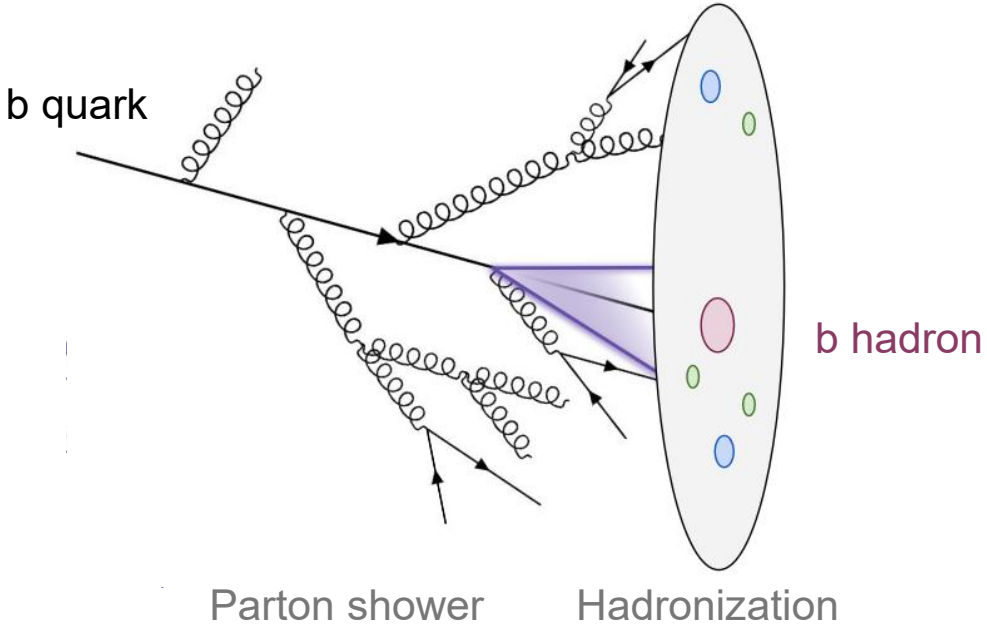
# B hadron reconstruction

- **B hadron decays** do **NOT** follow the rough **angular ordering** of QCD radiations
  ⇒ Soft emissions injected

- We develop a transformer encoder (TFE) to **identify charged B hadron decay products** in a jet *

- **21 kinematic features** are used, including jet, tracking, and SV info

- The **B hadrons** in jet are partially **reconstructed by summing the 4-momentum** of the identified charged decay products



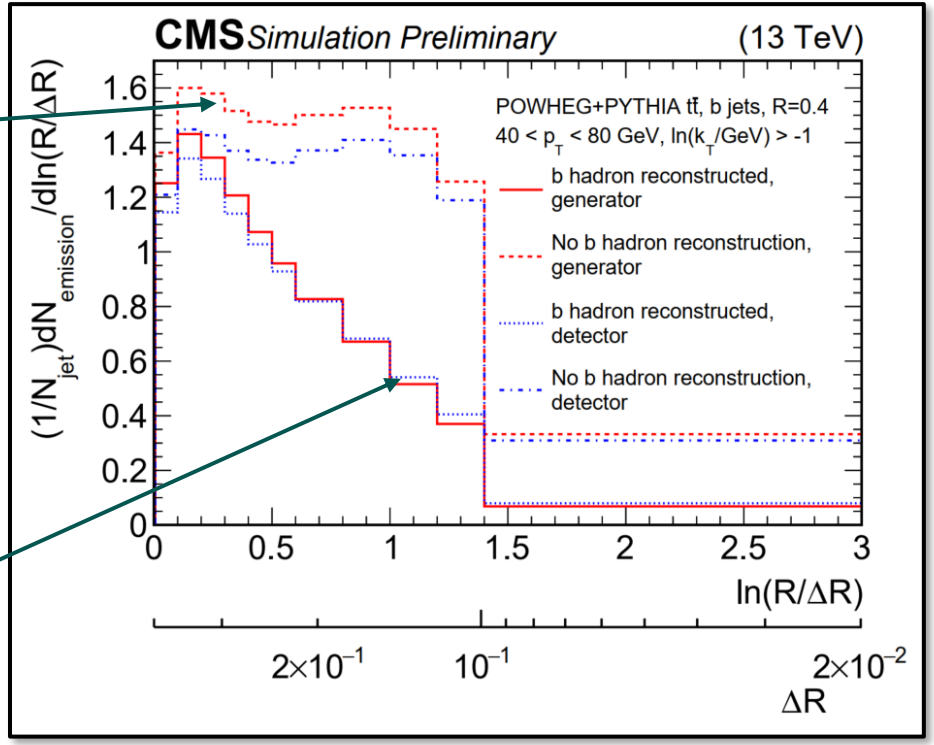

**Credits: Lida Kalipoliti, BOOST 2024 [link]**

(*) A similar technique introduced in CMS PAS: HIN-24-005

# B hadron reconstruction

**Before** the reconstruction of B hadron decay products, LJP is polluted with B hadron decay products

**After** B hadron reconstruction, the expected suppression of radiation at small $\Delta R$ is seen




The LJP density in simulation with or without the B hadron reconstruction at generator and reconstructed level for jets with $40 < p_T/\mathrm{GeV} < 80$

# Considered systematic uncertainties

Main uncertainty sources

- **MC model**, comparing PYTHIA 8 and HERWIG 7. Three uncorrelated sources:
  - Unfolding matrix
  - Prior (gen-level) distribution
  - Background composition
- **Tracker inefficiency** estimated by randomly killing 3% of charged jet constituents in MC

Theoretical/modelling

- Renormalization/factorization scale
- ISR/FSR renormalization scale
- PDF and $\alpha_s$ uncertainty
- Top $p_T$ correction

**Experimental**

- Jet energy scale, including flavour uncertainties
- Muon trigger, identification, isolation efficiencies
- Electron reconstruction, ID efficiencies
- DeepJet b-tagging efficiency
- Pre-firing rate
- Pileup jet ID efficiency
- PU reweighting

# Monte Carlo simulated datasets compared

- POWHEG+PYTHIA 8: used for unfolding for detector effects
- POWHEG+HERWIG 7

**Two types** of samples for the suppression effect:

- POWHEG+HERWIG 7 with Dead-cone effect switched off.
  1. set the **b quark mass to zero** ⇒ massless kernel **in the angular-ordered shower** ⇒ switch off the dead-cone effect
  2. **at the end of the showering** bring **b quarks on-shell** by momentum shuffling between their colour-connected partons

⇒ Allows to probe heavy quark effect only in the **perturbative phase**

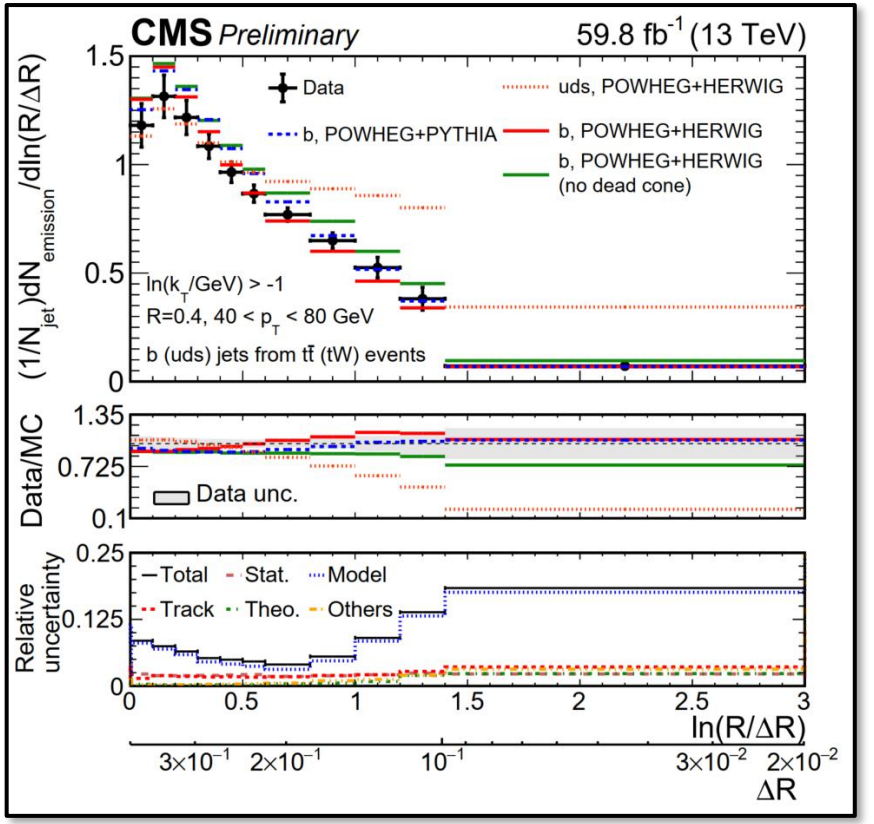
- uds (light) jets: obtained from HERWIG 7 **tW** sample. Light jets selected with $|\eta| < 2$. Jet $p_T$ reweighted to match that of b jets

⇒ Allows to probe heavy quark effect in the **perturbative and non-perturbative phase**

# Results ($40 < p_T/\mathrm{GeV} < 80$ bin )

- POWHEG+HERWIG 7: slightly underestimates the intermediate region $0.8 < \ln R/\Delta R < 1.2$
- POWHEG+PYTHIA 8: slightly overestimates the region $0.4 < \ln R/\Delta R < 0.8$
- Both: agreement at small angles
- **Light jets: higher number of collinear emissions** compared to data
- **Massless b-jet showering:** same as light jets but less prominent ⇒ hadronization effects for heavy quarks play a role.

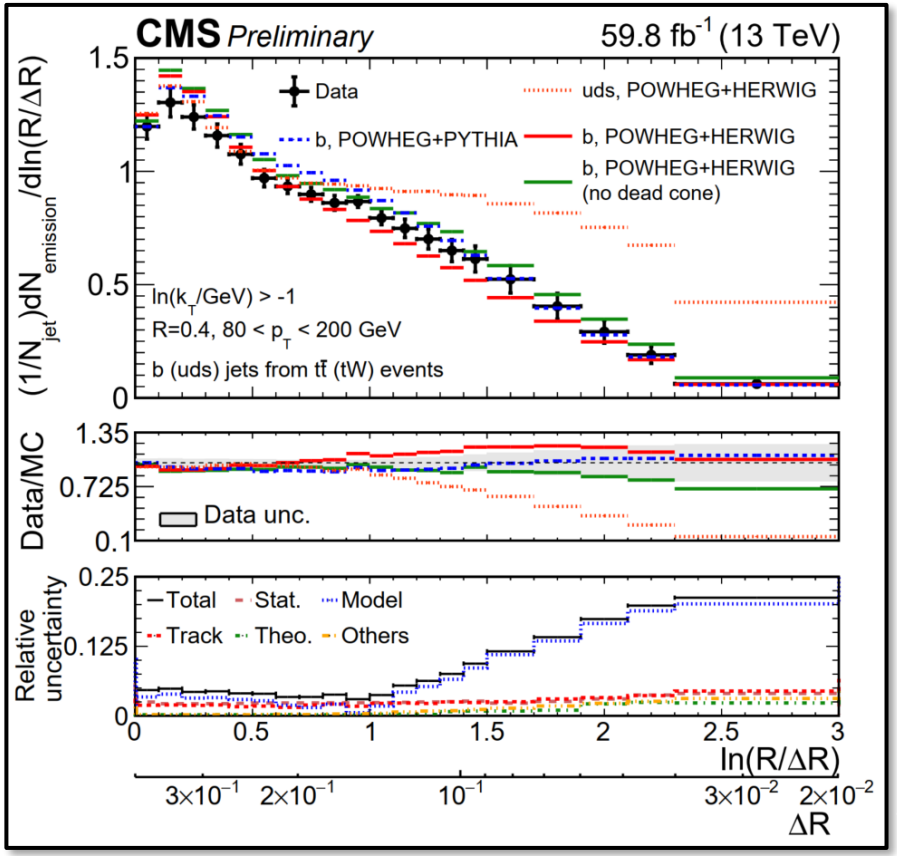
- $\chi^2$ estimate: HERWIG model with massless b-jet shower **strongly disfavoured** ($4.3\,\sigma$ deviation). Nominal one in a better agreement (p-value: 0.57)



# Results ($80 < p_T/\mathrm{GeV} < 200$ bin )

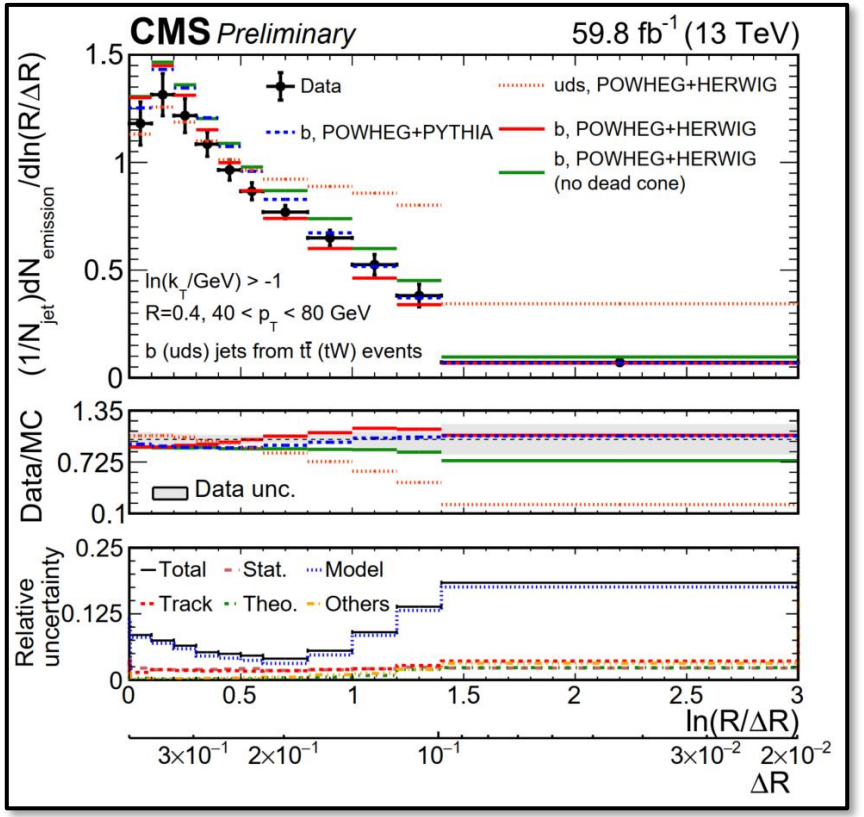
Similar trend:

- POWHEG+PYTHIA 8: overestimates in the region $\ln R/\Delta R < 1.2$, improvement towards collinear region
- POWHEG+HERWIG 7: underestimates the intermediate region $\ln R/\Delta R < 1.7$, agrees the most collinear region
- No significant deviation from data in terms of $\chi^2$. Nominal (massless) HERWIG prediction yields a p-value of 0.03 (0.01)



# Summary

- A **direct measurement of the dead-cone effect** in **b quark-initiated jets** from $t\bar{t}$ decays in pp collisions at $\sqrt{s} = 13$ TeV with the CMS detector
- **Novel experimental techniques**:
  - A tag-and-probe method, instead of replying on b-taggers, to minimize bias on the measurement
  - A transformer encoder to identify charged B hadron decay products inclusively
- **The measurement strongly disfavors the parton shower model without the dead-cone effect** and is in **better agreement** with the **nominal massive parton shower**.



# Extra slides

# Unfolding to correct for residual detector effects

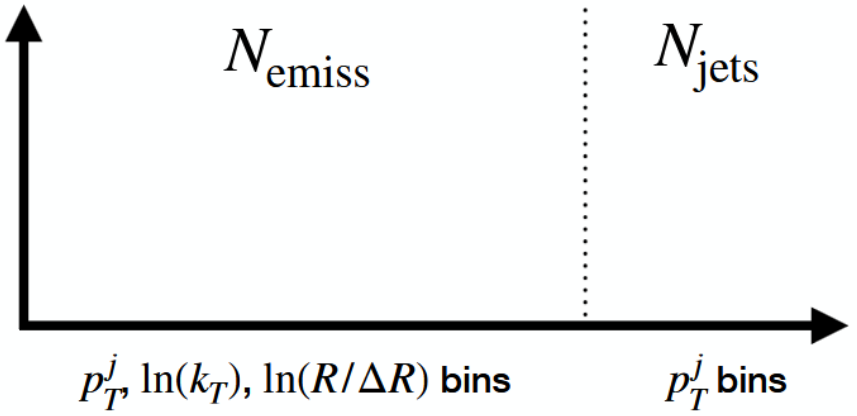
- Reco jets/emissions are **geometrically matched to gen-level** jets/emissions requiring $\Delta R < 0.2$ / $\Delta R < 0.1$
- The unfolding is carried out simultaneously for the $N_{\text{jet}}$ and $N_{\text{emiss}}$ by stitching the histograms together
- POWHEG+PYTHIA 8 sample used
- Binning used:
  - $p_T$/GeV: [20, 40], **[40,80]**, [80,200], [200,1000]
  - $\ln(k_T/\text{GeV})$: [-4,1], **[-1, ∞]**

with the **focused bin bolded**, and the under/overflow bins underlined

Unfold as a function of $p_T^j$, $\ln(k_T)$, and $\ln(R/\Delta R)$

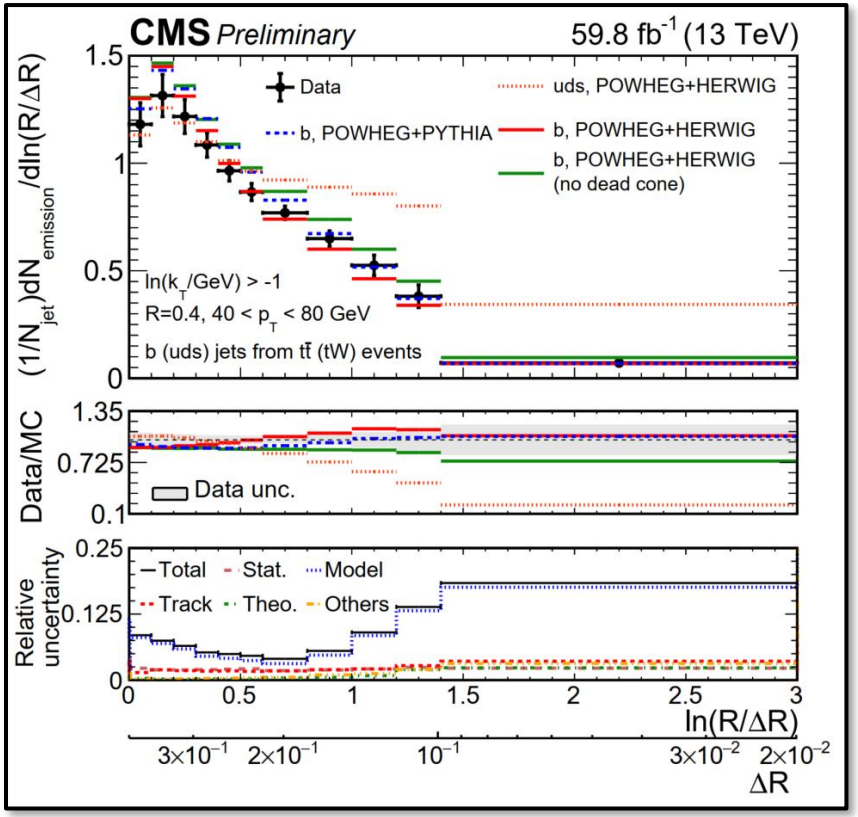
$$\frac{1}{N_{\text{jets}}} \frac{dN_{\text{emission}}}{\ln\left(\frac{R}{\Delta R}\right)}\Bigg|_{k_T > k_{T,\,\text{cut-off}}}$$

Unfold as a function of $p_T^j$



# Results ($40 < p_T/\mathrm{GeV} < 80$ bin )

- $\chi^2$ **value** computed to estimate **compatibility** of the unfolded data and predictions (nominal or massless kernel) by HERWIG
- Estimated in the $\ln(R/\Delta R) > 0.4$ to focus on the collinear region
- The **empirical distribution of the $\chi^2$** is constructed by **bootstrapping**
- A **4.3σ deviation is observed** between the unfolded data and the **massless kernel** prediction
- The nominal prediction is consistent with data (p-value of 0.57)



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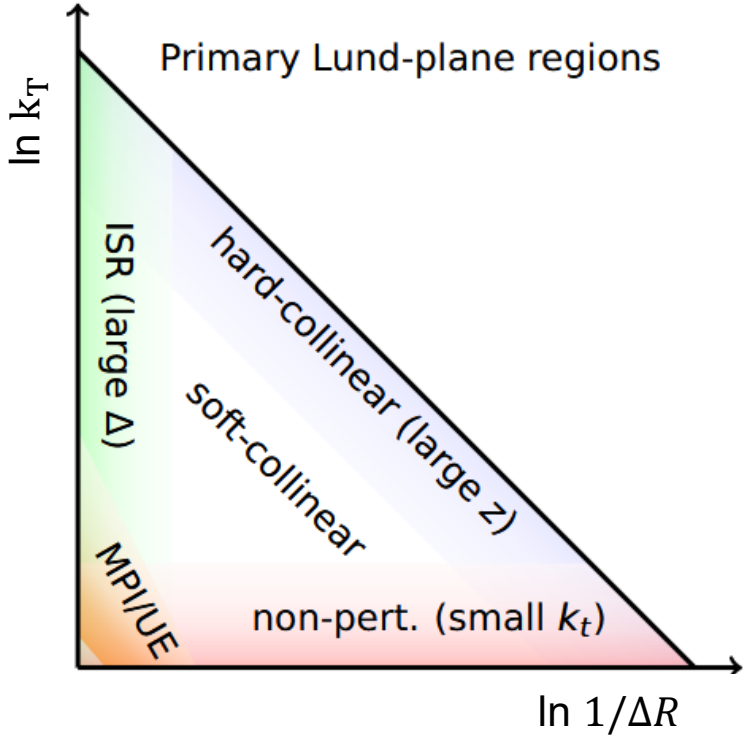


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R: distance parameter of the original anti-$k_T$ (AK) jets

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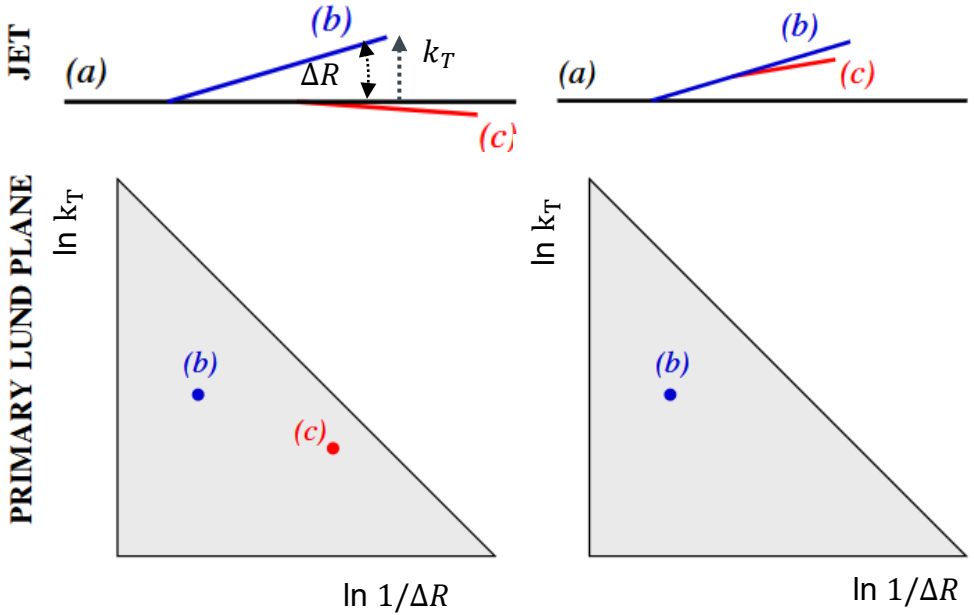


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$\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$: angular separation

$k_T$: relative transverse momentum between partons