Scanning the Lund plane of D-tagged jets to expose charm quark mass effects

CMS-HIN-24-007, soon on CDS

Jelena Mijušković

on behalf of the CMS collaboration

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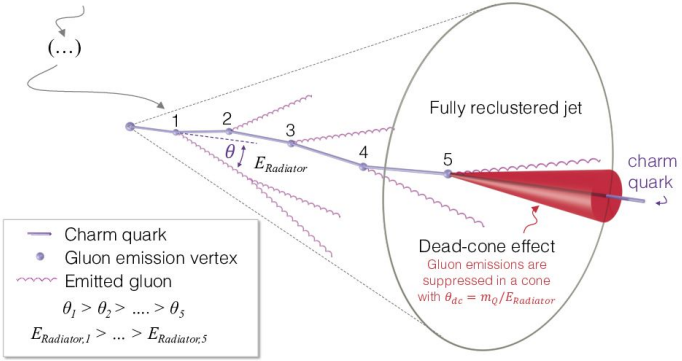
The dead-cone effect in QCD

- Gluon radiation by a particle of mass ***m*** and energy ***E*** is suppressed within a cone of angular size ***m/E*** around the emitter



[Nature 605, 440-446 (2022)]

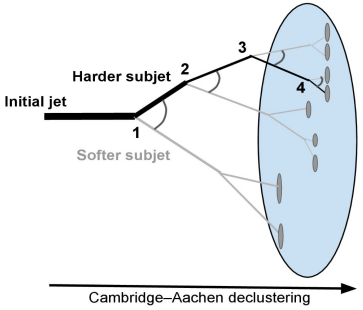
- Sizeable implications of the dead-cone effect is expected for **charm** and **beauty** quarks
- Experimental measurement of the dead-cone effect very challenging
- The development of **declustering techniques** - reconstructing the evolution of the jet shower, access to the the splittings at the smallest angles

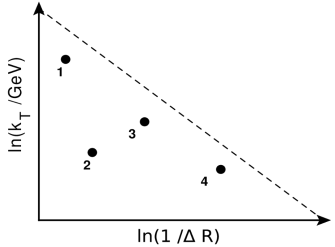
- Measurements sensitive to the heavy-quark mass and how it affects the jet shower - inputs to improve the description of heavy-flavor jet showers
- Dead-cone can potentially be used to understand medium-induced radiation in head-on heavy ion collisions

Lund plane of D jets in CMS

➢ Declustering using Cambridge-Achen algorithm:

→ the branch containing the heavy flavour is followed at each step
→ kinematics of the complementary untagged prong is registered
→ kinematics of all the emissions can be studied **(Lund plane)**



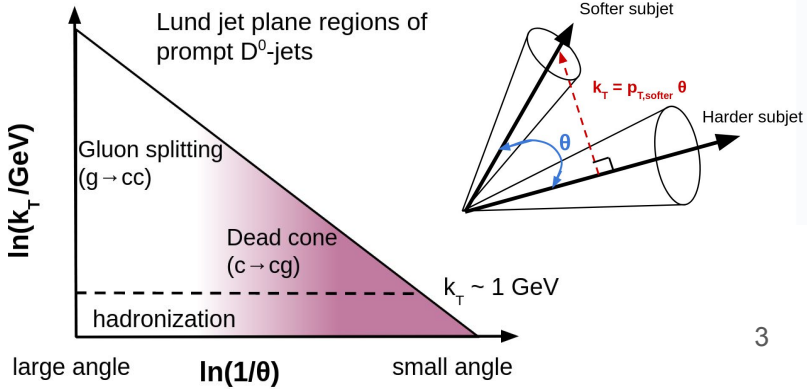


JHEP12(2018)064
Phys. Rev. Lett. 124, 222002 (2020)
JHEP 05 (2024) 116

➢ Measurement of the angular structure of jets containing a **prompt D^0 meson** and of **inclusive jets** in **pp collisions** at the LHC at a center-of-mass energy of 5.02 TeV

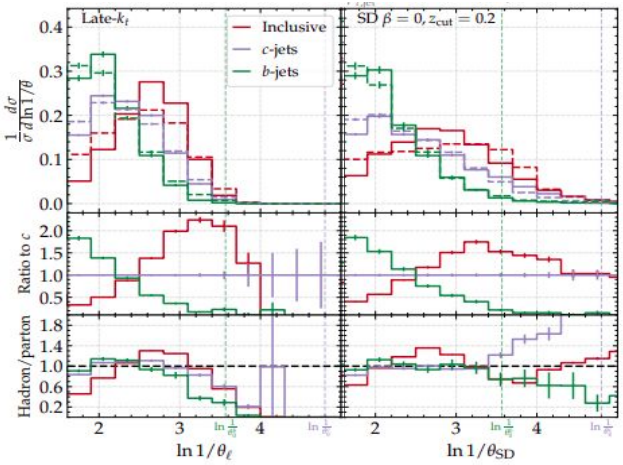
➢ High-p_T jet in range **100-120 GeV**
- description in the framework of perturbation theory
- visualization of a sizeable impact of the dead cone effect

➢ Measurement in range doable in PbPb too (**R=0.2**, high jet p_T)

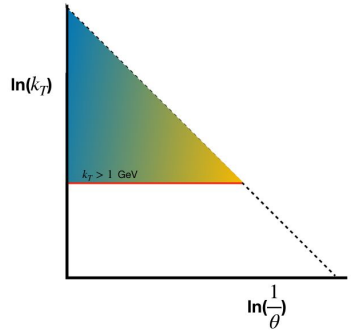


Lund plane of D jets in CMS

Phys.Rev.D 107 (2023) 9, 094008

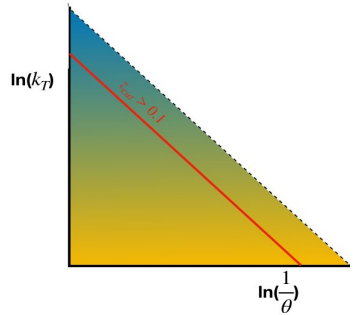


➢ Selecting one emission per jet by applying **grooming algorithms:**



Late-k_t groomer (θ_l)

- most collinear among the perturbative splittings in the jet tree
- the latest splitting that satisfies a hard k_T cut ($k_T > 1$ GeV)



Modified SoftDrop groomer (θ_{SD})

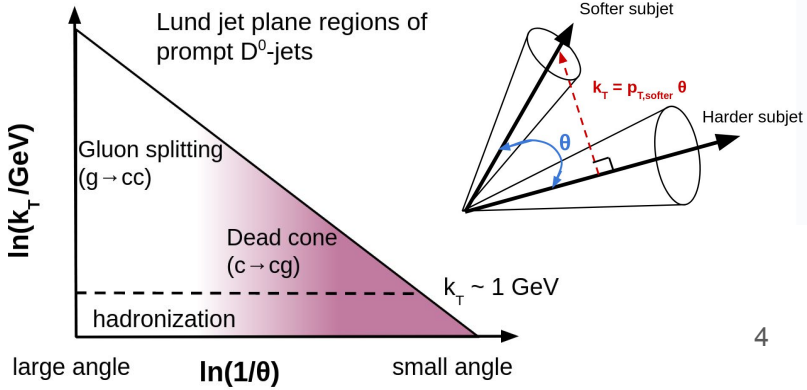
- first splitting that satisfy:

  $z_{cut} = 0.1$

  $\beta = 0$

  $k_T > 1$ GeV

z - momentum fraction between the two prongs
k_T - relative transverse momentum of the pair



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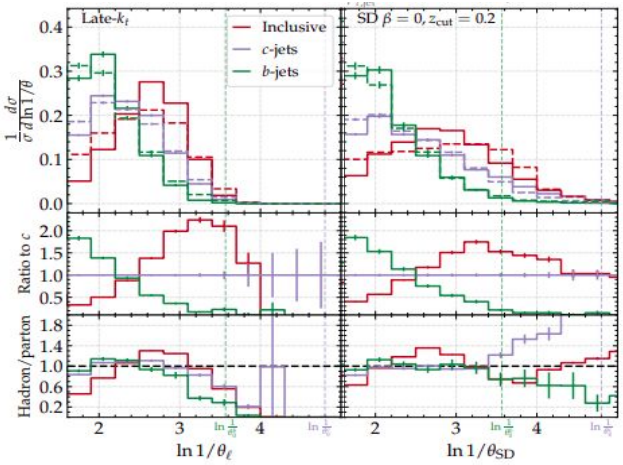

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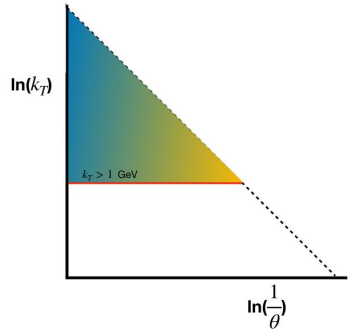

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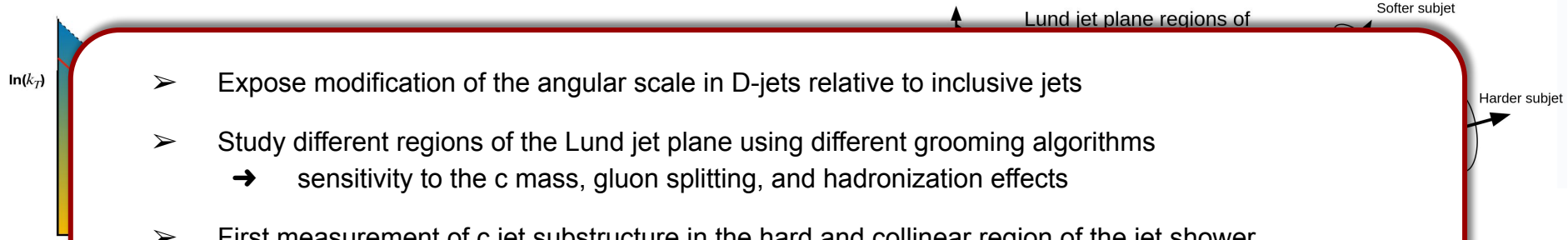


➢ Expose modification of the angular scale in D-jets relative to inclusive jets

➢ Study different regions of the Lund jet plane using different grooming algorithms
➜ sensitivity to the c mass, gluon splitting, and hadronization effects

➢ First measurement of c jet substructure in the hard and collinear region of the jet shower (contribution from hadronization effects reduced, parton-level picture is more direct)

z - momen
k_T - relative

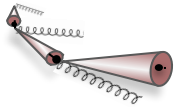
Analysis workflow

Inclusive jets

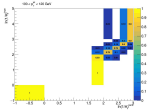
Jet selection:

$100 < p_T^{jet} < 120$ GeV
$R=0.2$
$|\eta| < 1.6$

Select splitting
folllowing hardest prong

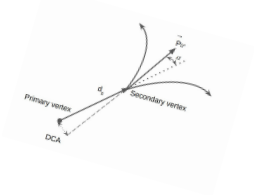


Unfolding

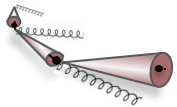


D-tagged jets

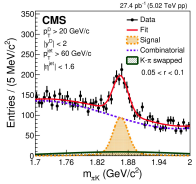
D candidate and D-jet selection



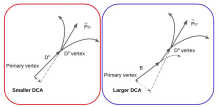
Select splitting
folllowing hardest prong + contains D



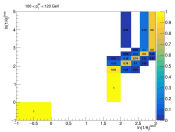
Combinatorial background reduction



Non-prompt reduction



Unfolding

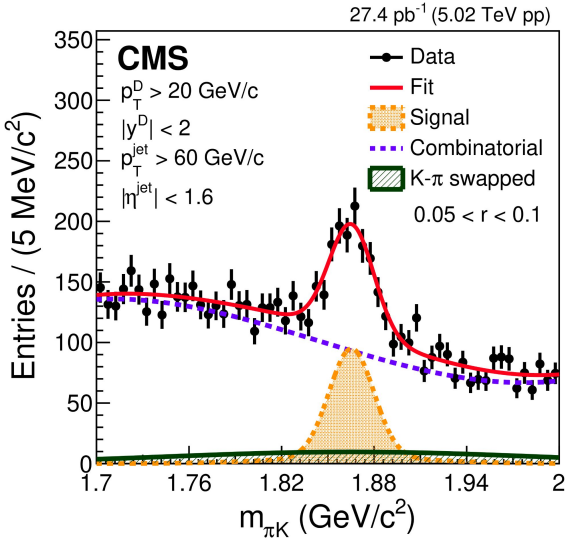


For declustering - D meson aggregated and it's daughters removed from procedure

D-tagged jets

- D^0 candidates are reconstructed through the decay $D^0 \rightarrow K\pi$
- D^0 meson candidate is selected with a $p_T > 4$ GeV and $|y| < 1.2$.
- The D^0 meson yield in each p_T and θ_l (θ_{sd}) interval is extracted with a fit to the invariant mass distributions in the range $1.7 < m_{\pi K} < 2.0$ GeV

Example fit from *Phy. Rev. Lett. 125 (2020) 102001*

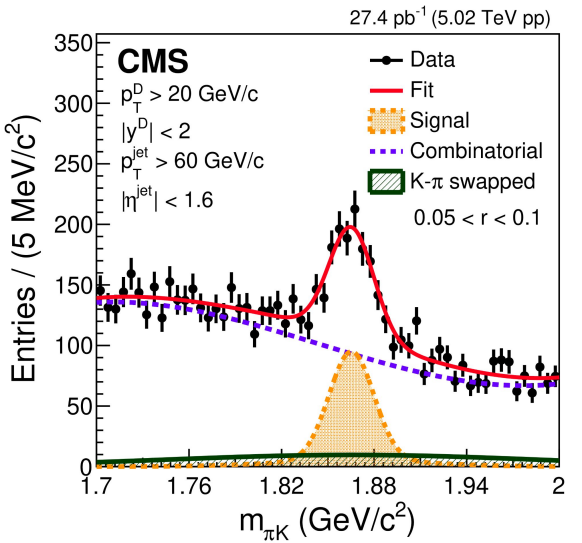


- Mass distribution fitted by:
  - → Double Gaussian to model the **signal**
  - → Gaussian to model the D^0 invariant mass shape of candidates with wrong mass assignment (**swap**)
  - → Powerlaw to model the **combinatorial background**
- The shape of signal and swapped components is fixed by MC

D-tagged jets

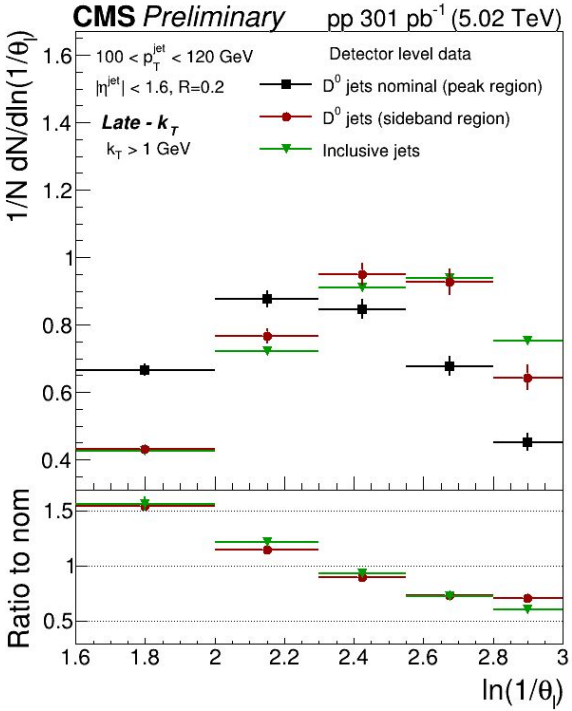
- D^0 candidates are reconstructed through the decay $D^0 \to K^- \pi^+$
- D^0 meson candidate is selected with a
- The D^0 meson yield in each p_T and θ_l (the range $1.7 < m_{\pi K} < 2.0$ GeV

Example fit from Phy. Rev. Lett. 125 (2020) 102001



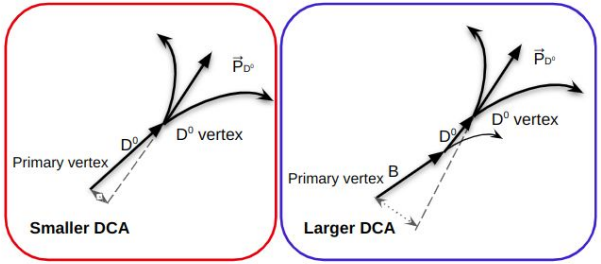
Sideband study

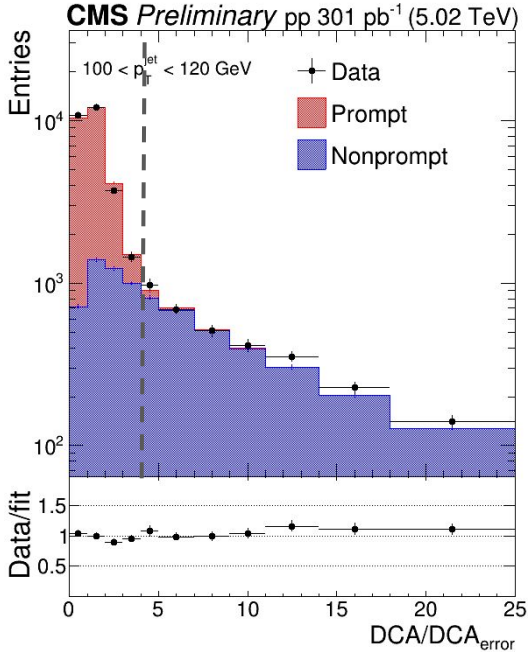
- Check for possible biases introduced with different procedure for D-jets compared to inclusive jet
- D-jets from sideband of invariant mass distribution are compared with inclusive distribution
- Sideband distribution is shown to be consistent with inclusive



Contributions from nonprompt D

- The reconstructed D^0 signal in data includes both prompt D^0 and nonprompt D^0
- To suppress non-prompts selection applied on **Distance of Closest Approach (DCA)** normalized by its error

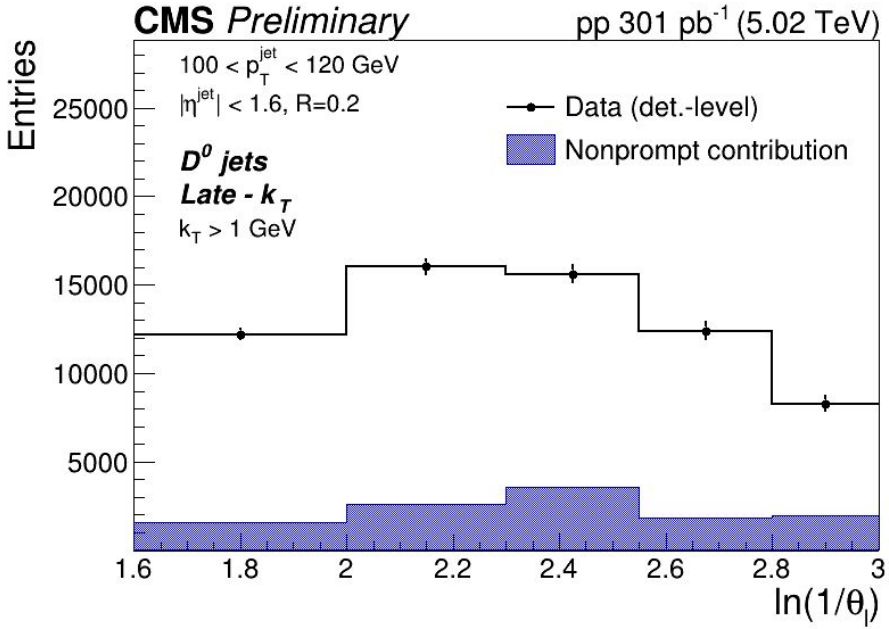




- Selection on DCA significance - DCA/DCA$_{err}$ < 4
- Contributions of non-prompts still present
- Fractions of prompt determined by performing template fit of DCA significance
- The shape of **prompts** and **non-prompts** distribution extracted from simulation

Nonprompt corrected yields

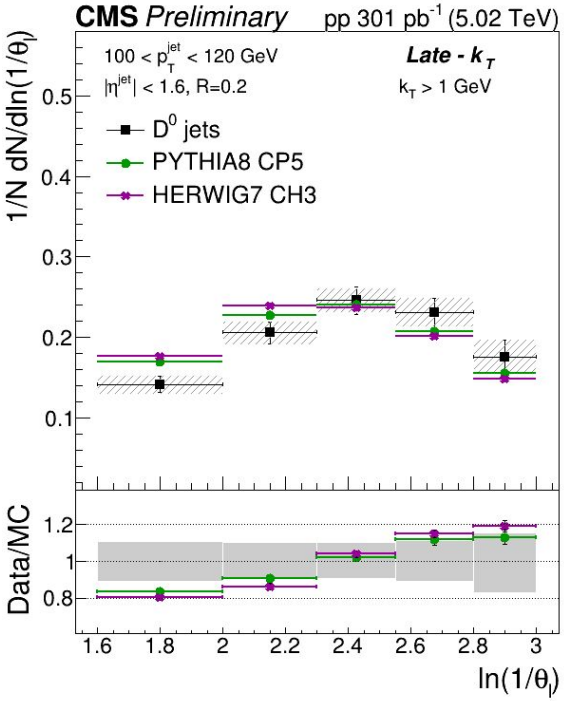
- The nonprompt D^0 subtraction causes a reduction of the uncorrected yield and a change in the shape of the substructure

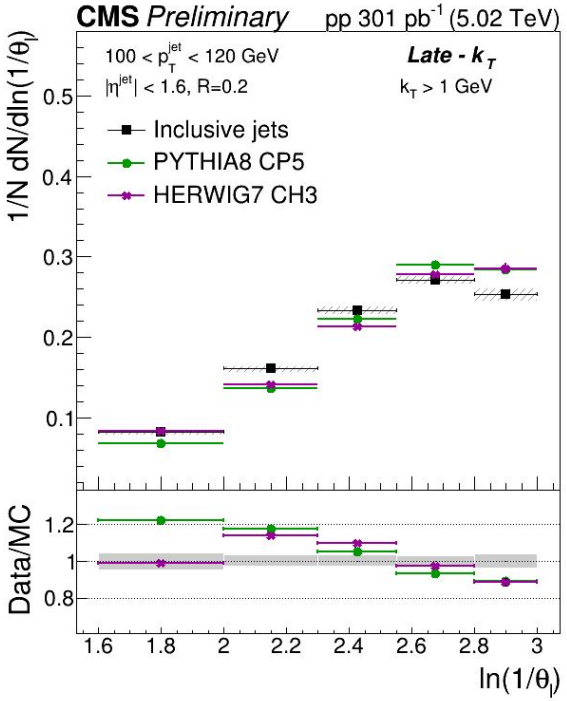


- The nonprompt D^0 meson contribution is found to be around **15%**
- The nonprompt and prompt D^0 templates derived using PYTHIA8 CP5
  - Nonptompt fraction from HERWIG7 compatible in shape with the derived from PYTHIA8 ones

Results: late-k_T selected splitting angle

- The measured detector-level distributions are corrected to the stable particle level using corrections derived from simulation
- Bin-to-bin migrations due to detector effects - two-dimensional unfolding of the **jet p_T** and **θ_l (θ_{SD})**





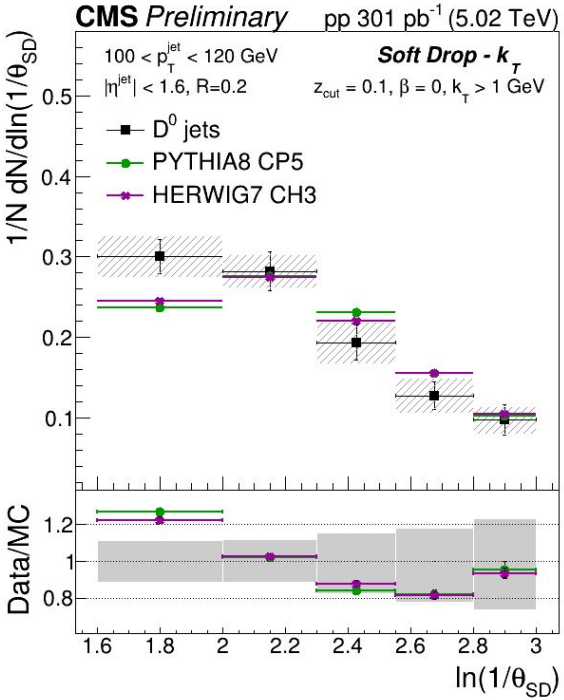
➢ Distributions are compared to **PYTHIA8** and **HERWIG7**

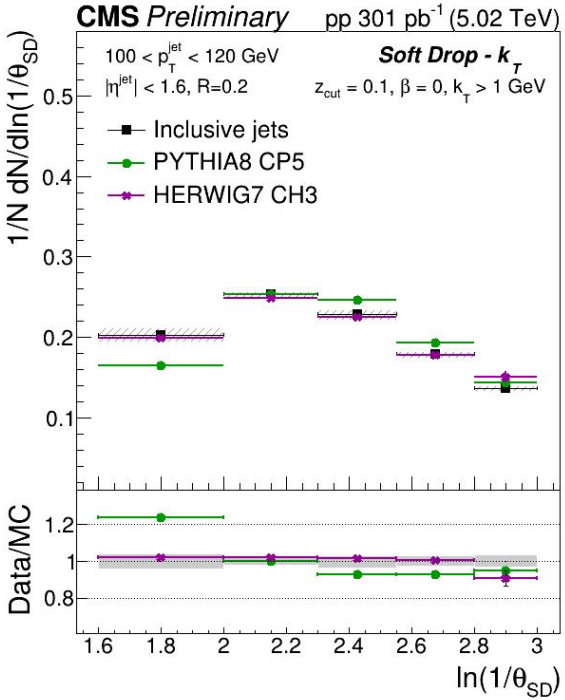
⇒ Agreement with D^0 jets within experimental uncertainties

⇒ **PYTHIA8** and **HERWIG7** predictions consistent between each other for D^0 jets

Results: SD&k_T selected splitting angle

- The measured detector-level distributions are corrected to the stable particle level using corrections derived from simulation
- Bin-to-bin migrations due to detector effects - two-dimensional unfolding of the **jet p_T** and **θ_l (θ_{SD})**





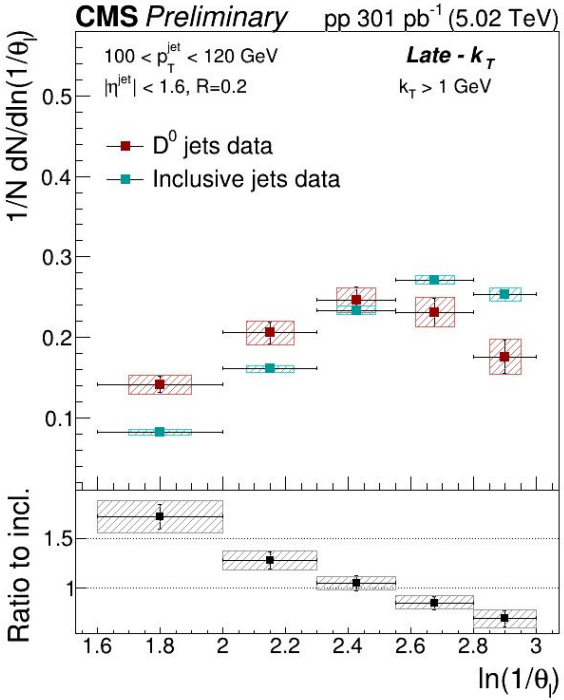
➢ Distributions are compared to **PYTHIA8** and **HERWIG7**

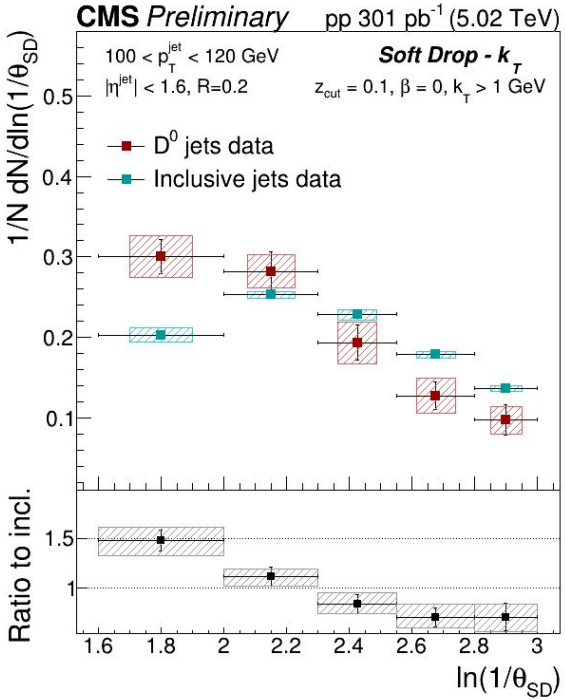
⇒ Agreement with D^0 jets within experimental uncertainties

⇒ In inclusive case **HERWIG7** describes the data better than **PYTHIA8**

Results: D^0 jets and inclusive jets

- Fully corrected θ_l and θ_{SD} distributions for D-tagged and inclusive jets and their ratios

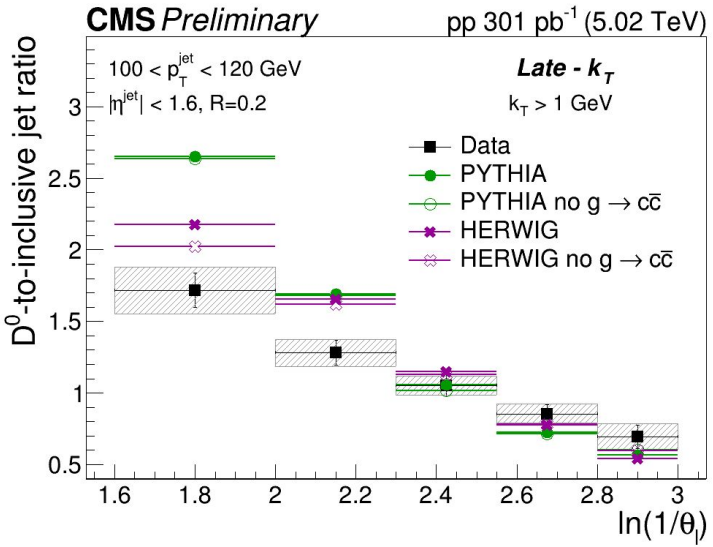


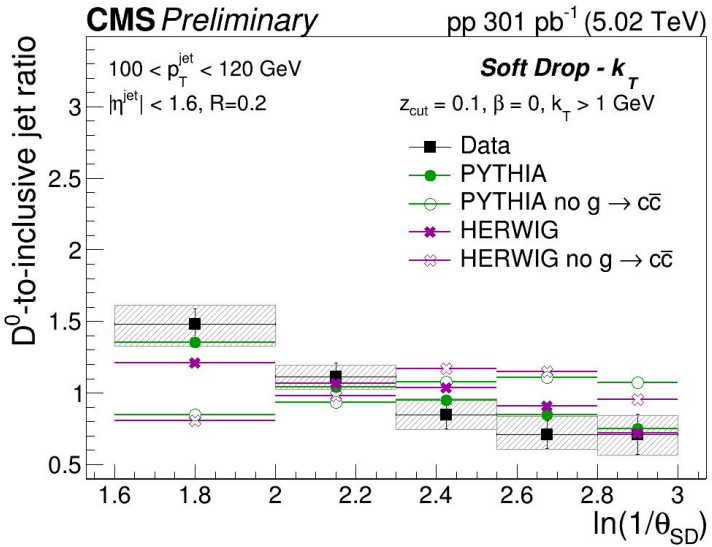


- **Shift observed towards bigger angles** with respect to the inclusive jets - expected from dead cone effect
- More prominent shift observed with late-k_T algorithm

Unfolded results late-k_T

- Study of contribution of the gluon splittings to the substructure of prompt D^0 jets
- Impact checked with **PYTHIA8** and **HERWIG7** generators for the ratio of the distributions of prompt D^0 jets to inclusive jets





Late-k_T: the gluon splitting contribution is negligible and has an effect mostly at large angles.

SD: the gluon splitting contribution stronger

- emissions at larger angles than the ones found by late-k_T

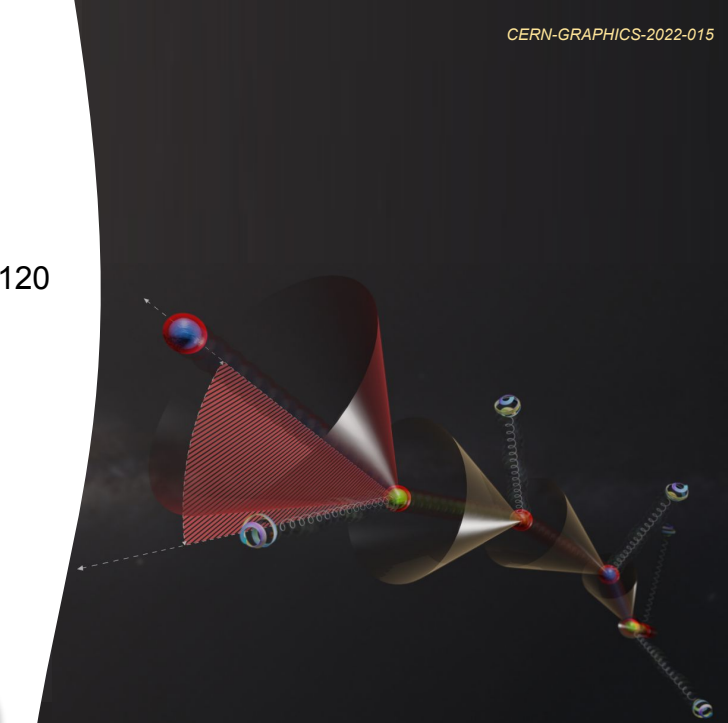
Summary

- Measurement of splitting angles using two different groomers, late kt and modified Soft Drop, for D^0-tagged and inclusive energetic jets of $100 < p_{T,jet} < 120$ GeV performed
- Measurement performed using 5.02 TeV pp data from 2017 collected by CMS experiment
- First measurement of charm quark jet substructure that probes the hard and collinear region of the jet shower

➢ The comparison of the angular distribution of late-k_T and Soft Drop splittings in prompt D^0 jet and inclusive jets shows a **shift toward larger angles for heavy-flavor splittings**

➢ The shift observed in late-k_T **- consistent with dead cone effect**

➢ Soft Drop selected splittings shown to be more sensitive to effects of gluon splitting



Thank you for your attention!