CWR

Exploring small-angle emissions in charm jets in pp collisions

@ 5.02 TeV

-

17.12.2024

Purpose

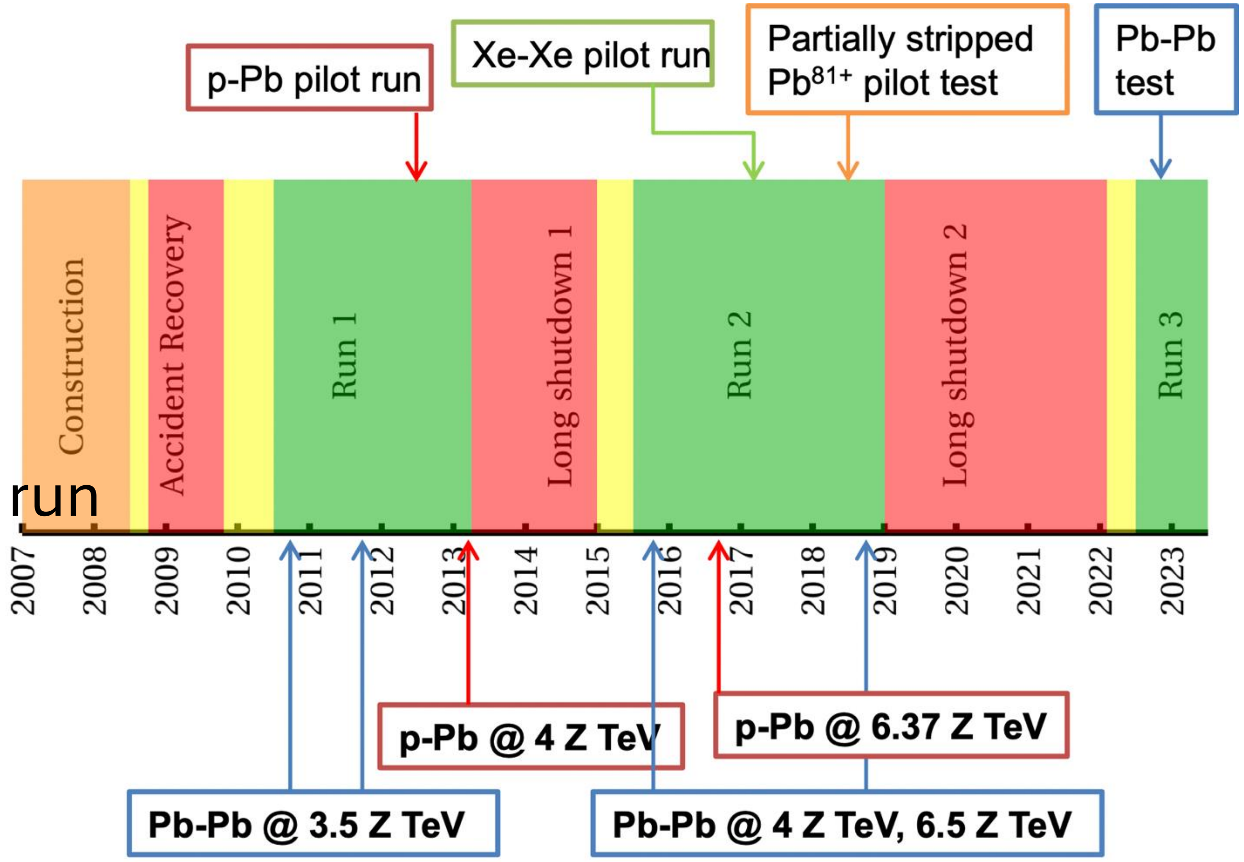
- angular structure of charm jets
  - compare incl. jets & jets with prompt D^0 meson
  - dead cone effect (p. 5)

- Explore hard collinear emissions
  - w/o hadronization effects

- 301 /pb p-p data @ 5.02 TeV in 2017 (next page)

LHC physics (Run-II)

- pp collisions @ 13 TeV
- Pb-Pb, p-Pb, Xe-Xe ... collisions
  - (1 mon/yr normally)
  - $^{208}Pb^{82}$
  - Run-3 has O runs as well
- VdM, High-beta run (450 GeV/p), Low PU run



2017 run: https://cds.cern.ch/record/2646066/files/mopmf051.pdf

Run-2 HIN: https://inspirehep.net/files/b943dba3d8cc874849196e53056ac2f6

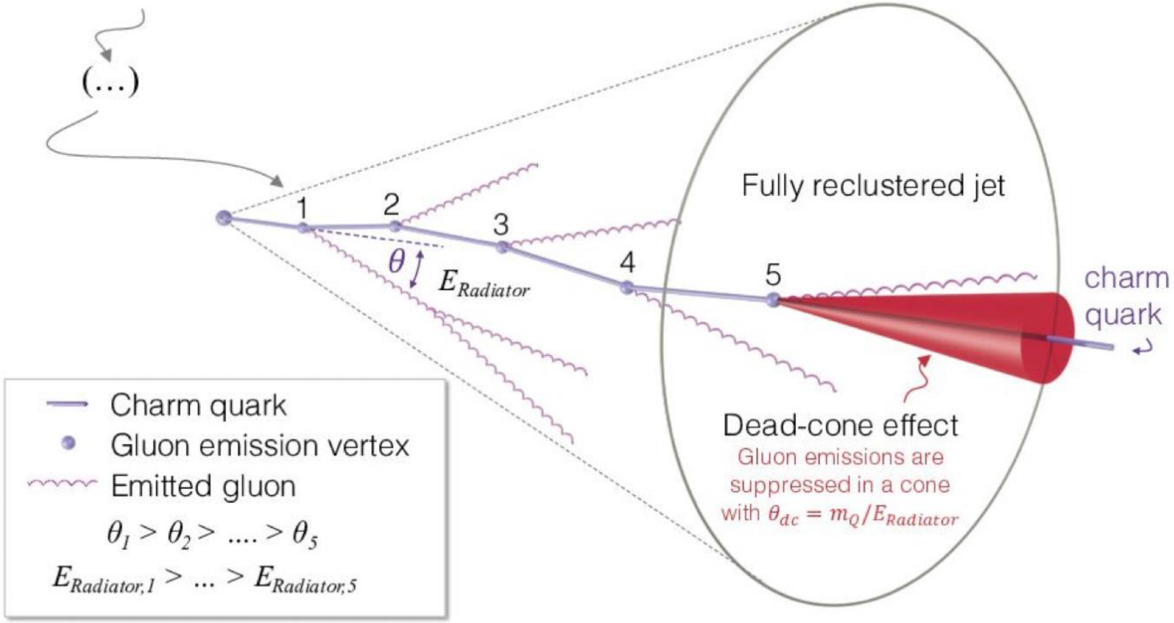
Why is 5.02 TeV special?

- p-Pb run @ 2013
  - beam energy: \sqrt{s} = 4 Z TeV
  - \sqrt{s_{NN}} ~ 5.02 TeV
  - 11-20.Nov.2017

- pp @ 5.02 TeV = p-Pb @ 4 Z TeV = Pb-Pb @ 6.37 Z TeV
  - have same \sqrt{s_{NN}} = 5.02 TeV
  - give good reference for heavy ion runs

Dead cone effect

gluon radiation from heavy flavour (HF) quarks
should have larger angular separation
due to its mass scale ~ m/E



Nature 605, 440-446 (2022)

[Herwig BSM]

$$P_{f\to f'V}(z,\tilde{q}) = (|g_R|^2\rho_+ + |g_L|^2\rho_-)\left(\frac{1+z^2}{1-z}(1+m_{0,t}^2) - \frac{1+z}{1-z}m_{1,t}^2 - m_{2,t}^2\right) + (|g_R|^2\rho_- + |g_L|^2\rho_+)zm_{0,t}^2 - 2\Re(g_L g_R^*)(\rho_+ + \rho_-)m_{0,t}m_{1,t}.$$

Light quark

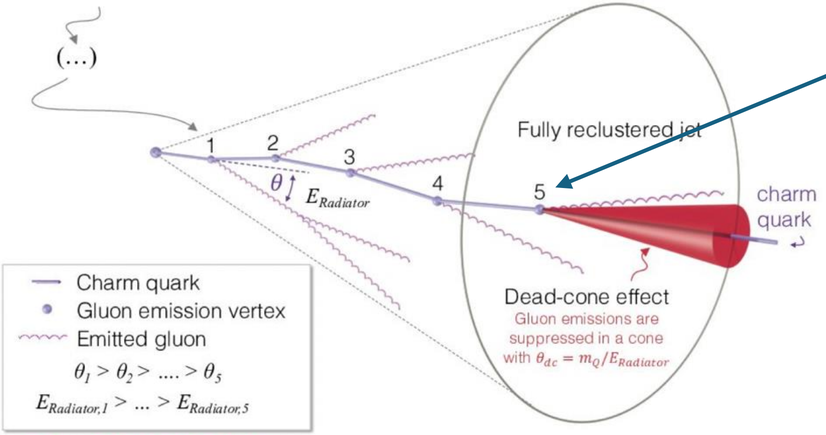
$$P_{q\to qZ'}(z,\tilde{q}) = \frac{|g_R|^2 + |g_L|^2}{2}\left(\frac{1+z^2}{1-z} - m_{Z',t}^2\right)$$

Heavy flavour

$$P_{b\to bZ'}(z,\tilde{q}) = \frac{|g_R|^2 + |g_L|^2}{2}\left(\frac{1+z^2}{1-z} - m_{Z',t}^2\right) \underbrace{- 2\mathrm{Re}(g_L \cdot g_R^*)\, m_{b,t}^2}_{\text{heavy flavour effect}}$$

How to measure the dead cone?

- Properly pick up a splitting representing the dead cone effect



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PICK THIS SPLITTING!

→ gromming algorithms, e.g. soft-drop (SD) & late-kT

- Difficulties when measuring the dead cone effect
  - Decays of the HF hadrons fill the dead-cone → require one fully reconstructed HF hadron (D^0 meson)
  - Hadronization effects → impose a kT cut > 1 GeV
  - Detector effect → unfolding

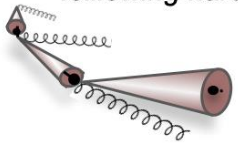
Analysis workflow

Inclusive jets

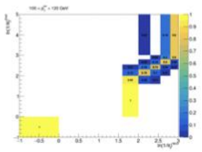
Compare iincl. jets & jets w/ D^0 meson

Jet selection

Select splitting
folllowing hardest prong

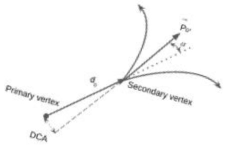


Unfolding



D-tagged jets

D candidate and D-jet selection



Select splitting
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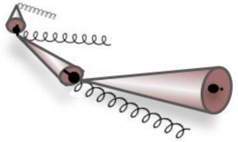

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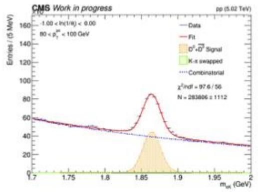

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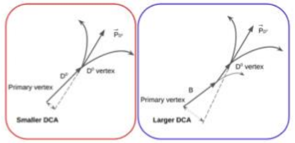

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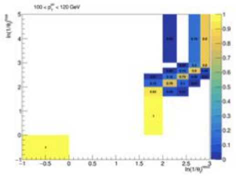

Analysis workflow

Datasets & event selection

Inclusive jets

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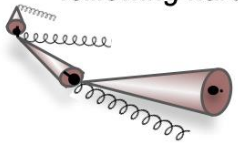

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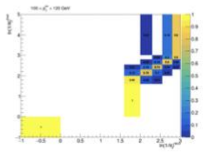

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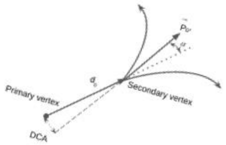

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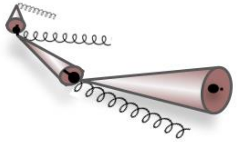

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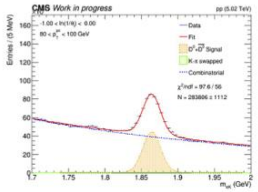

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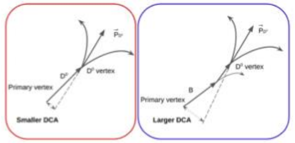

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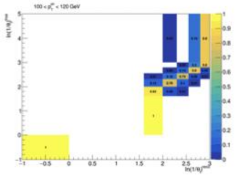


Datasets and triggers

Data samples:

✓ */LowEGJet/Run2017G-17Nov2017-v1/AOD*
✓ */HighEGJet/Run2017G-17Nov2017-v1/AOD*

Simulation:

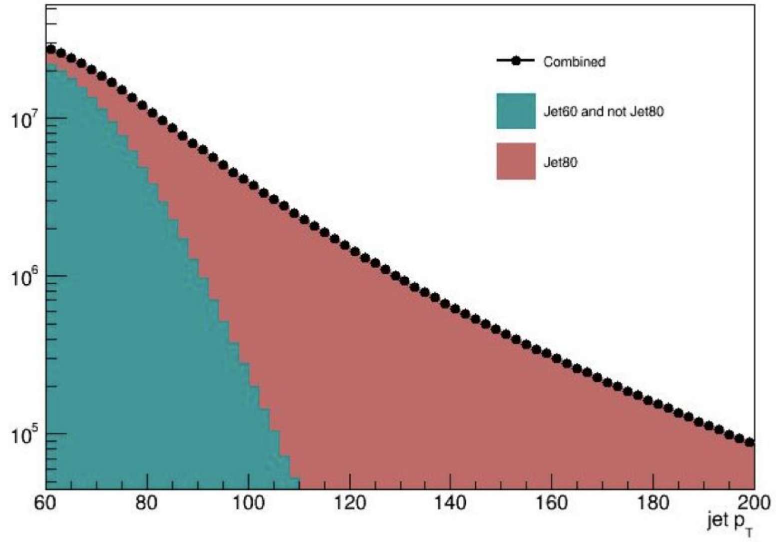
✓ */QCD_pThat-15_Dijet_TuneCP5_5p02TeV_pythia8/RunIIpp5Spring18DR-94X_mc2017_realistic_forppRef5TeV_v1-v1/AODSIM*
✓ */eos/cms/store/group/phys_heavyions/ec/lcunquei/Run2_Herwig_inclusive reco/*
✓ */Pythia8_D0pt2p0_Pthat0_TuneCUETP8M1_5020GeV_evtgen130_cff/*
✓ */eos/cms/store/group/phys_heavyions/ec/lcunquei/Run2_Herwig_D0_reco*

Privately produced samples

Official samples ready - will update results after preapproval

- ➢ In order to increase statistics for the D-jets studies *LowEGJet* and *HighEGJet* data samples combined:
  LowEGJet* : events that passed trigger *CaloJet60* and not *CaloJet80
  HighEGJet* : events that passed trigger *CaloJet80

- ➢ Trigger ***HLT_HIAK4CaloJet60*** is prescaled - events weighted with the prescale factor (6.32)



Selections

➢ D^0 candidates are reconstructed through the decay $D^0 \to K\pi$

Jets w/ D^0 meson

Tracks

Incl. jet events

- HighPurity
- p_T > 1 GeV
- $|\eta|$ < 2.4
- p_T^{err}/p_T < 0.1
- NHits > 11
- χ /dof/nTrackerLayers < 0.18
- $|m_{\pi K} - m_{D0}^{PDG}|$ < 0.2 GeV

pT > 1 GeV & high quality tracks

Jets

- Anti-kt jets
- R = 0.2
- $|\eta|^{jet}$ < 1.6
- *JEC - *Spring18_ppRef5TeV_V4_DATA(MC)_AK2PF*
- JER - *Fall17_V3_MC_SF_AK4PF*

AK2PFJets w/ 80 < pT < 160 GeV

*Same used for Djets - studying possible biases

→ Djets response consistent with inclusive within JEC uncertainty

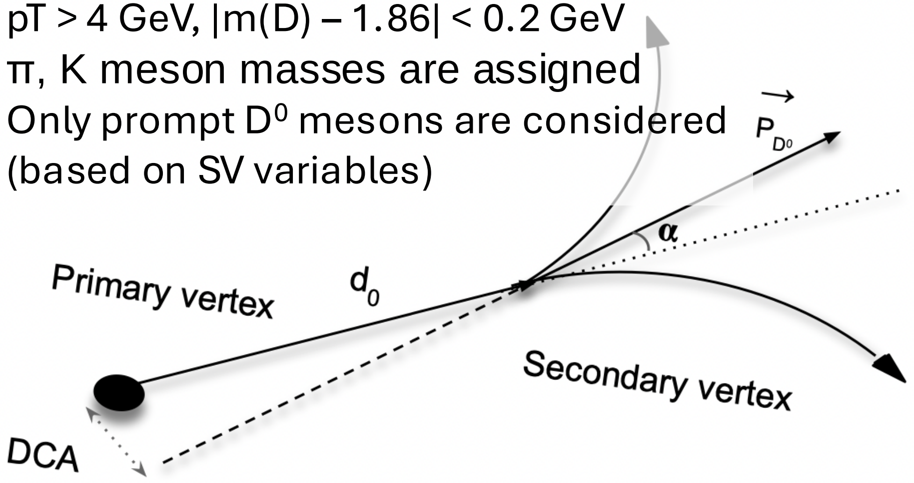
D candidate

- p_T^D> 4 GeV
- $|y|^D$ < 1.2
- secondary vertex probability > 0.05
- pointing angle α < 0.046
- $d_0/\sigma(d_0)$ > 2.86
- DCA/DCA_{error} < 4

SV cuts

**Selections adopted from previous D meson analysis - possible optimization*

- pT > 4 GeV, |m(D) – 1.86| < 0.2 GeV
- π, K meson masses are assigned
- Only prompt D^0 mesons are considered (based on SV variables)



Selections

➢ D^0 candidates are reconstructed through the decay $D^0 \rightarrow K\,\pi$

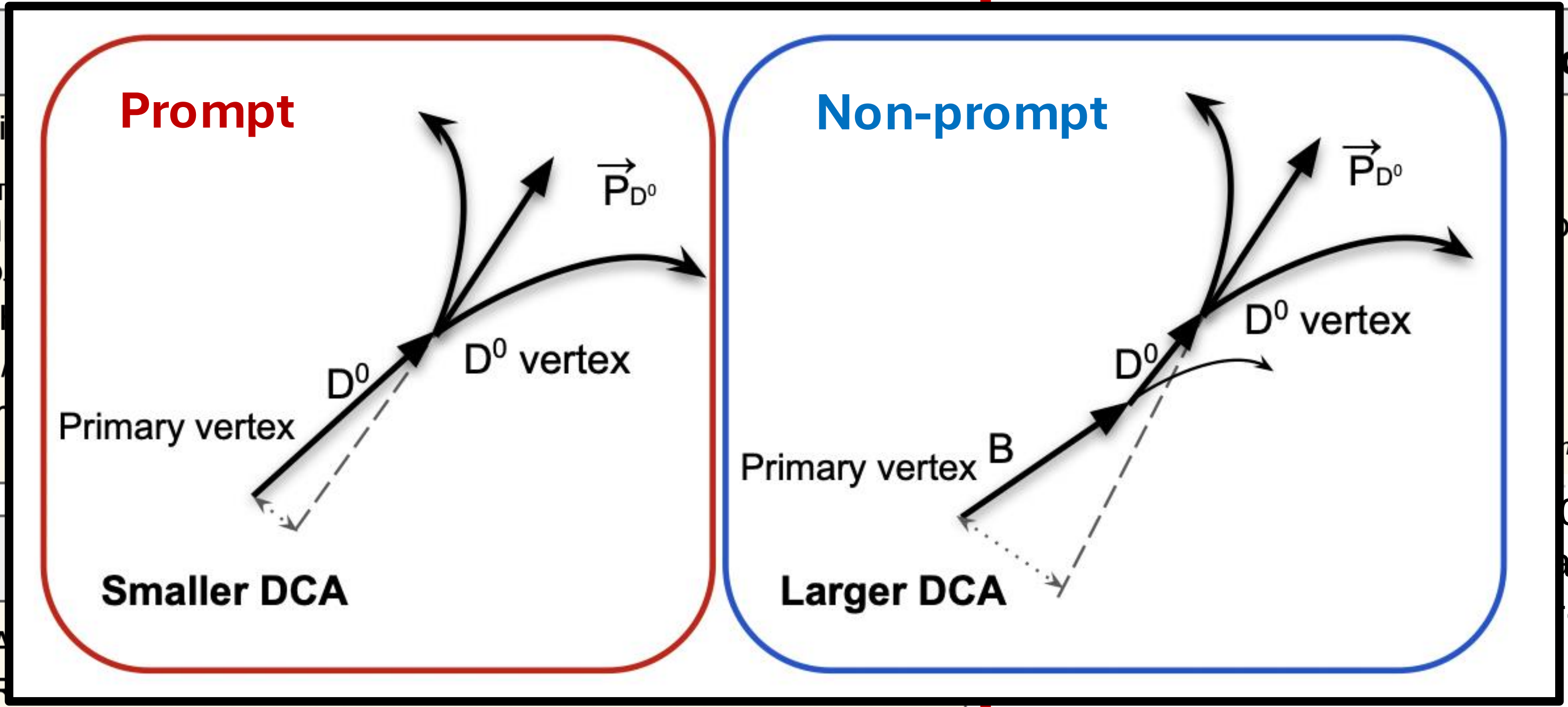
Jets w/ D^0 meson

- Hi
- p_T
- $|\eta|$
- p
- N
- χ
- $|m$

date

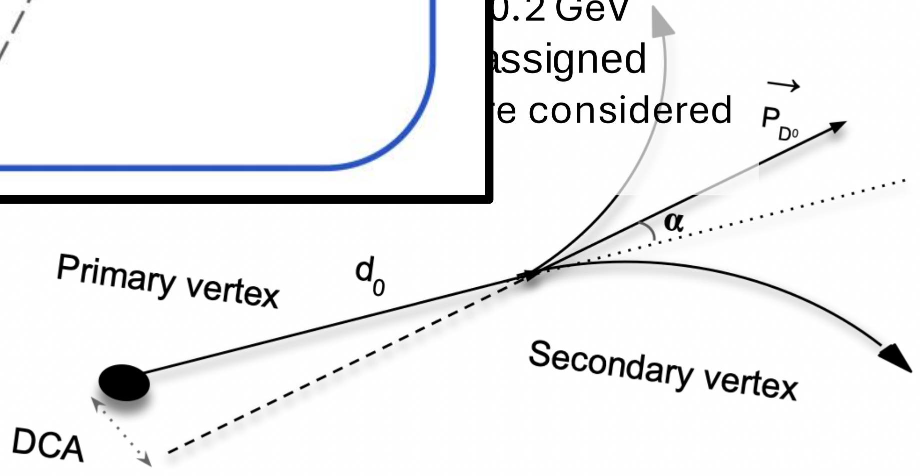
bility > 0.05

nalysis - possible optimization



- A
- F
- $|\eta|^{jet} < 1.6$
- *JEC - *Spring18_ppRef5TeV_V4_DATA(MC)_AK2PF*
- JER - *Fall17_V3_MC_SF_AK4PF*

0.2 GeV
assigned
e considered



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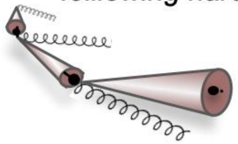

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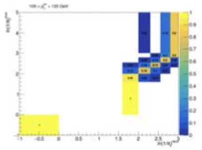

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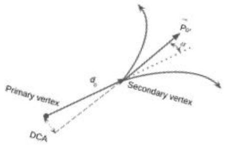

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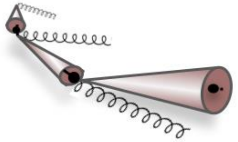

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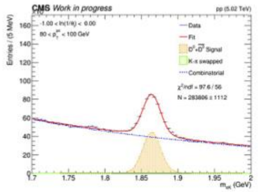

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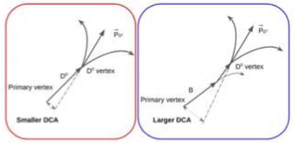

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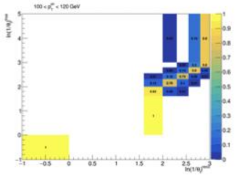


Grooming

- Purpose: Study jet substructure to discard soft & wide-angle components (from ISR/UE/PU)

- Recluster jet constituents w/ CA algorithm
  ~ particle history in MC

- From the original jet → particle-level components
  - check grooming variables

Soft drop

1. Recluster jet constituents with the CA cluster algorithm and undo the last CA clustering to form two subjets, $j = j_1 + j_2$, where j is an original jet and j_1 (j_2) is a harder (softer) subjet.

2. If two jets ... the discriminating equation,

$$z_{12} = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}, \tag{1.156}$$

   (In this case we set j_2 is a softer one, so when j_2 passes this cut, it guarantees that j_1 also passes.)

   - Pass: Stop the iteration and j is returned as a SD jet.
   - Fail: A softer subjet (j_2) is removed and j_1 replaces j. Step 1 is performed with this new j.

   This criteria mean even the subleading subjet (j_2) should occupy enough p_T of the parent jet (j).

3. If j has no further subjets, then

   - Tagging mode: The algorithm is terminated without returning a jet.
   - Grooming mode: Define j to be the SD jet.

late-kt

1. Same as the first step of the SD algorithm, i.e. undo the last CA clustering and make two subjets: $j = j_1 + j_2$.

2. If two jets ... the discriminating equation,

$$z_{12} = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}, \tag{1.158}$$

   - Pass: Keep both subjets.
   - Fail: A softer subjet (j_2) is removed and j_1 replaces j.

   The remaining subjets are added into a jet list and perform the step 1 again for each of them, i.e. redo the step 1 for $j_1 = j$ and $j_2 = j$, if both subjets survive.

3. The iteration is ceased when the discrimination criterion is satisfied N times, resulting in $(N+1)$-subjets, or the algorithm scans all CA branches.

Analysis workflow

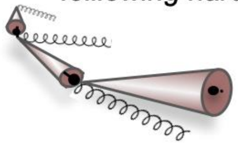
Datasets & event selection

Inclusive jets

Compare iincl. jets & jets w/ D^0 meson

Jet selection

Select splitting
folllowing hardest prong



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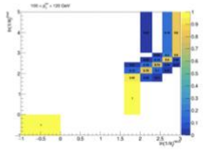
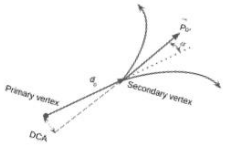


D-tagged jets

D candidate and D-jet selection



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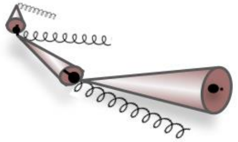
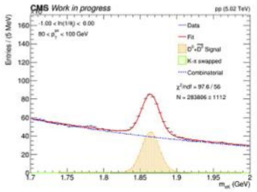


Yield extraction



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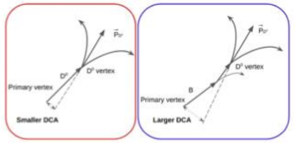

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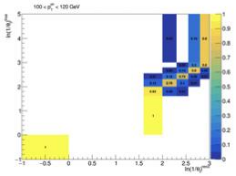
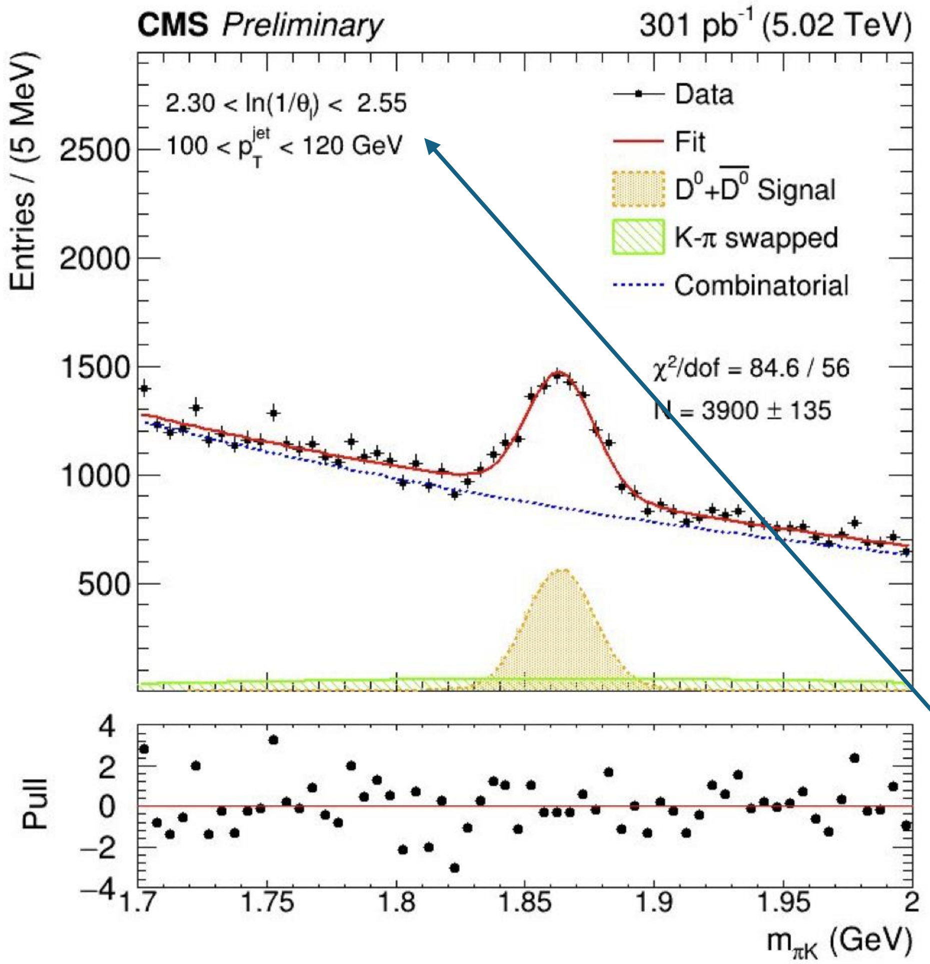


D meson yield extraction

- ➢ 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



- ➢ Mass distribution fitted by:
  - → sum of 2 Gaussians 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

θ & jet pT binnings (θ, final observable, will be explained later)

Analysis workflow

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Compare iincl. jets & jets w/ D^0 meson

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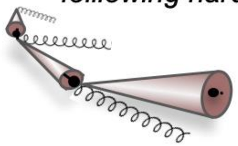

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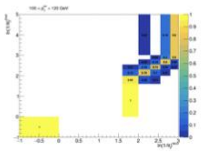

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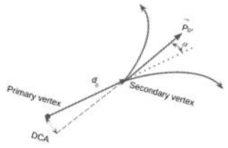

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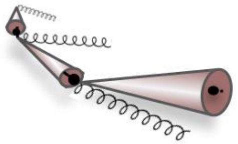

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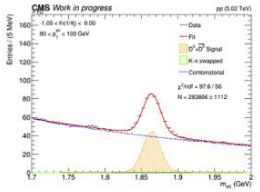

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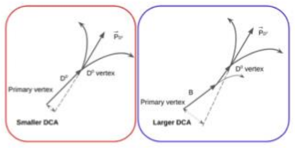

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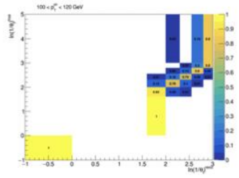
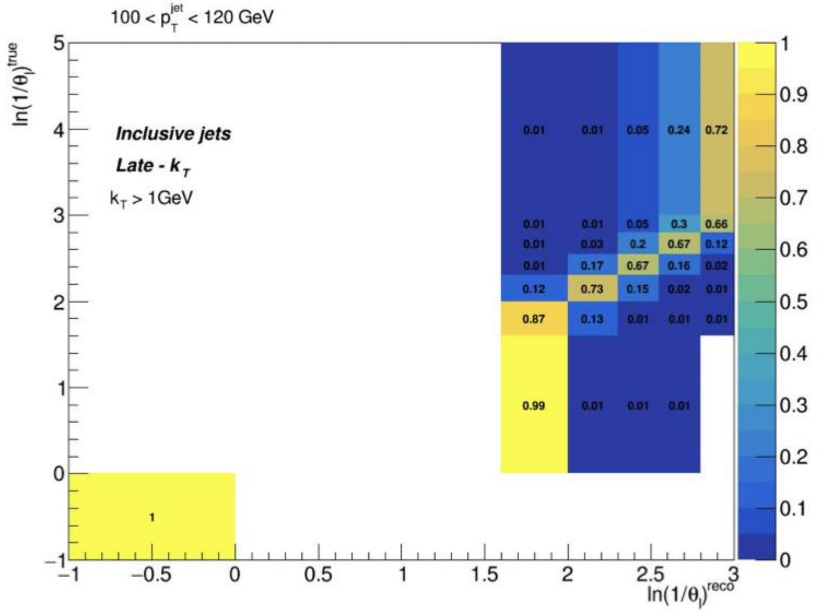
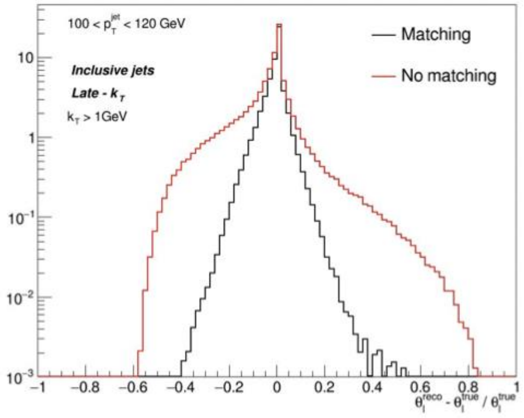


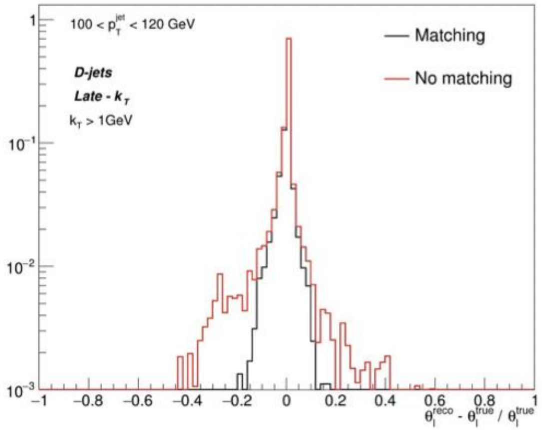
Unfolding

- Kinematic properties of each event are measured with a finite precision due to the detector resolution limits
- Observed distributions have to be corrected for detector effects (**unfolding procedure**)
- **D'Agostini** unfolding (**RooUnfold** package)
- **2D Unfolding** is performed in $\mathbf{p_T^{jet}}$ and $\boldsymbol{\theta_l}$ $(\boldsymbol{\theta_{SD}})$
- To fill response matrix - correspondence between true-level and det-level quantities:
  - → geometrical matching of true and det-level jets (closest in η,ϕ space)
  - → geometrical matching of true and det-level splittings (closest in η,ϕ space)
- Raw input multiplied with the matching purity and the unfolded solution is divided by the matching efficiency *(matching efficiency and purity ~ **50%**)*



➜ Diagonal response matrix after matching



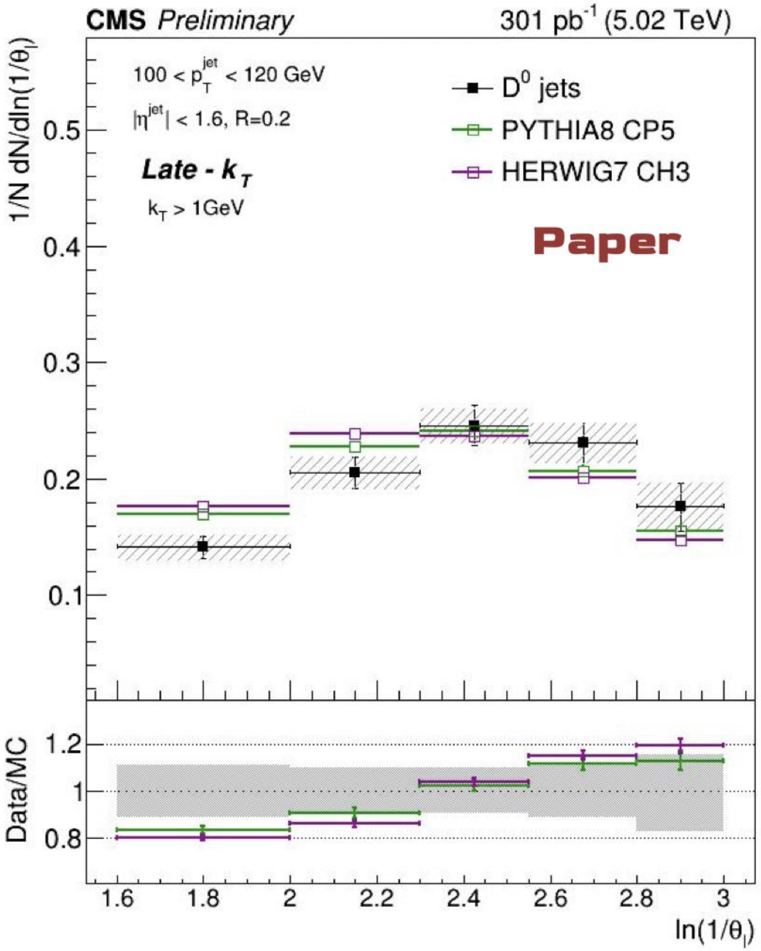


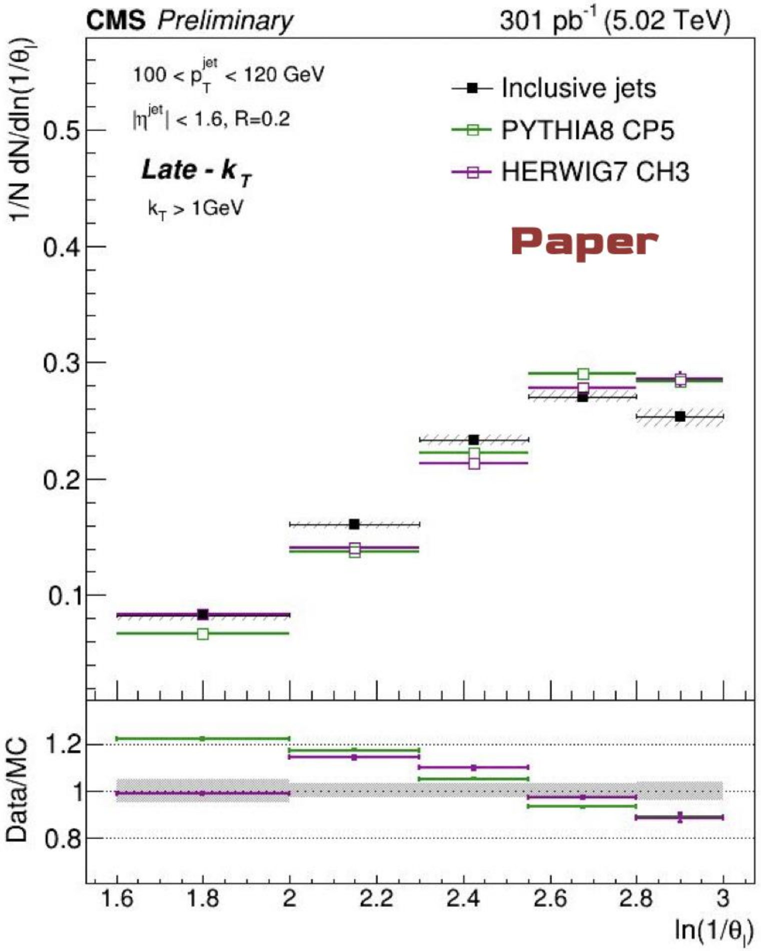
Uncertainties summary

Table 1: Summary of percentual relative uncertainties.

Uncertainty source	Late-k_T		Soft drop	
	Prompt D^0 jets	Inclusive jets	Prompt D^0 jets	Inclusive jets
Jet energy scale	1.5–5.8	0.3–2.6	0.7–4.6	0.2–2.4
Jet energy resolution	0.3–1.4	0.3–0.9	0.6–1.5	0.2–0.8
Charged hadron PF energy scale	0.2–0.6	0.7–1.4	0.2–0.8	0.4–0.8
Neutral hadron PF energy scale	1.3–2.8	0.3–1.3	1.4–5.3	0.1–1.5
Photon PF energy scale	0.3–1	0.5–6	0.2–1	0.1–0.8
Tracking efficiency	0.3–1.2	0.1–0.5	0.2–2.5	0.03–0.3
Physics model dependence	0.6–5.4	0.4–2.8	2.3–7.2	0.8–3
Response matrix statistical	5.5–9.6	0.9–1.5	5.2–14.9	0.6–1.2
Signal extraction	0.1–0.6	—	0.02 -0.2	—
Background modeling	0.5–2.8	—	2.3–7.6	—
Prompt D^0 fraction	0.7–3.8	—	2.4–12.8	—
Regularization bias	0.4–2.9	0.3-0.7	0.4–3.5	0.1–0.9
Trigger scale factor	≤ 0.02	≤ 0.02	≤ 0.03	≤ 0.02
Statistical	6.5–11.7	1.1–1.7	7.1–20	0.8–1.4

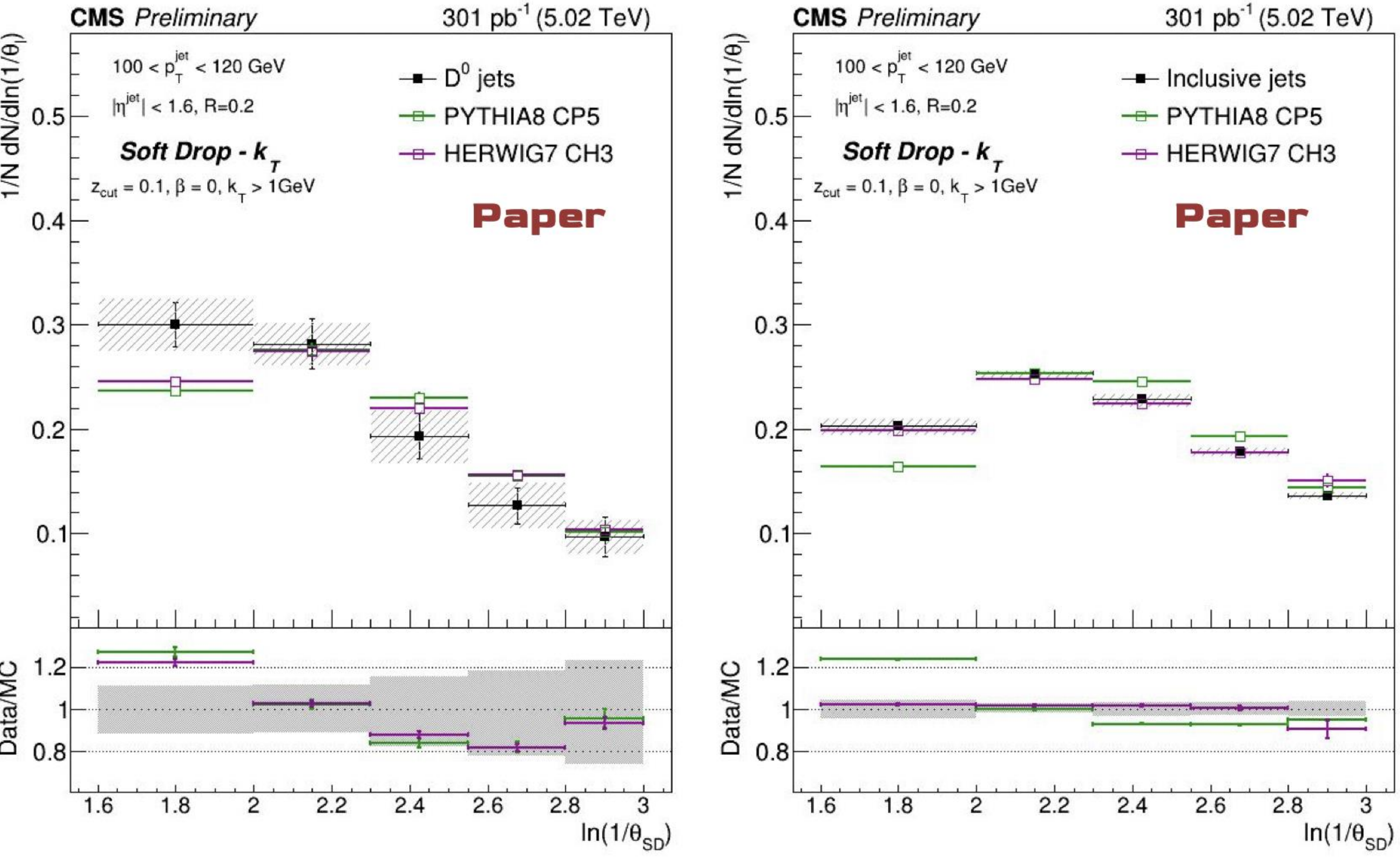
Unfolded results late-k_T





- ➢ Fully corrected θ_l distributions for D-tagged and inclusive jets
- ➢ 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

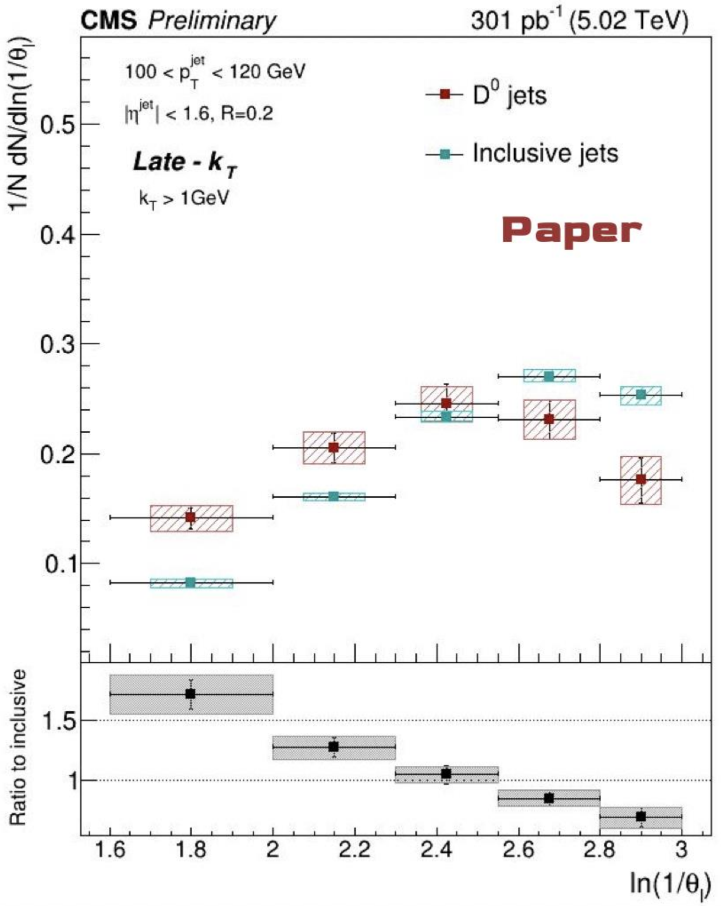
Unfolded results SD&k_T

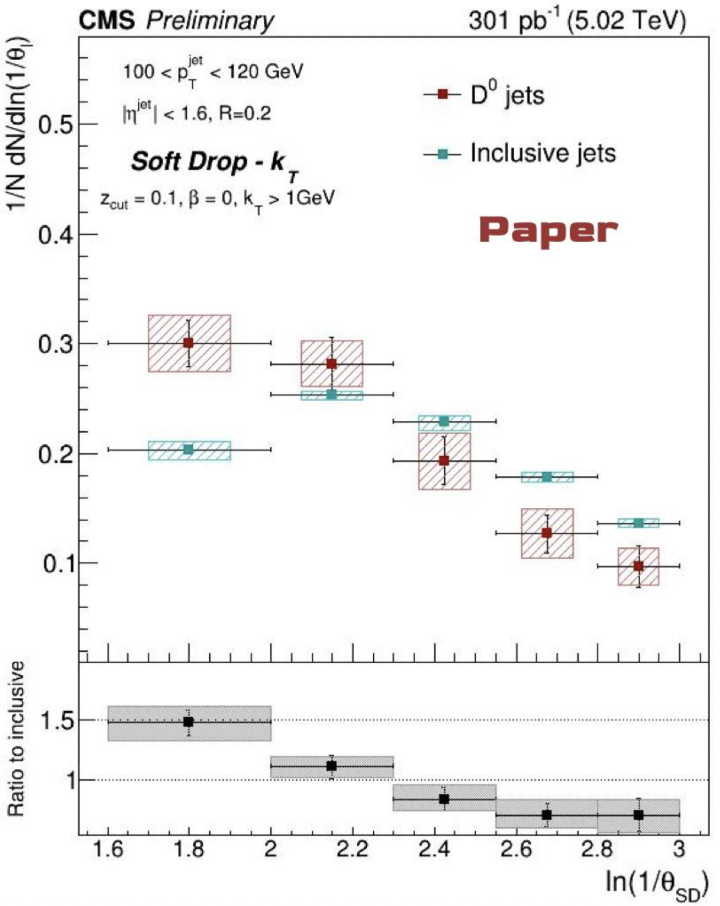


- ➢ Fully corrected θ_l distributions for D-tagged and inclusive jets
- ➢ Distributions are compared to **PYTHIA8** and **HERWIG7**
  - ⇒ Agreement with D^0 jets within experimental uncertainties
  - ⇒ In inclusive case **HERWIG7** describes the data better than **PYTHIA8**

Unfolded results Djets and inclusive

- Fully corrected θ_l and θ_{SD} distributions for D-tagged and inclusive jets and their ratios
- **Shift observed towards bigger angles** in case of D-jets - expected from dead cone effect
- More prominent shift observed with late-k_T algorithm

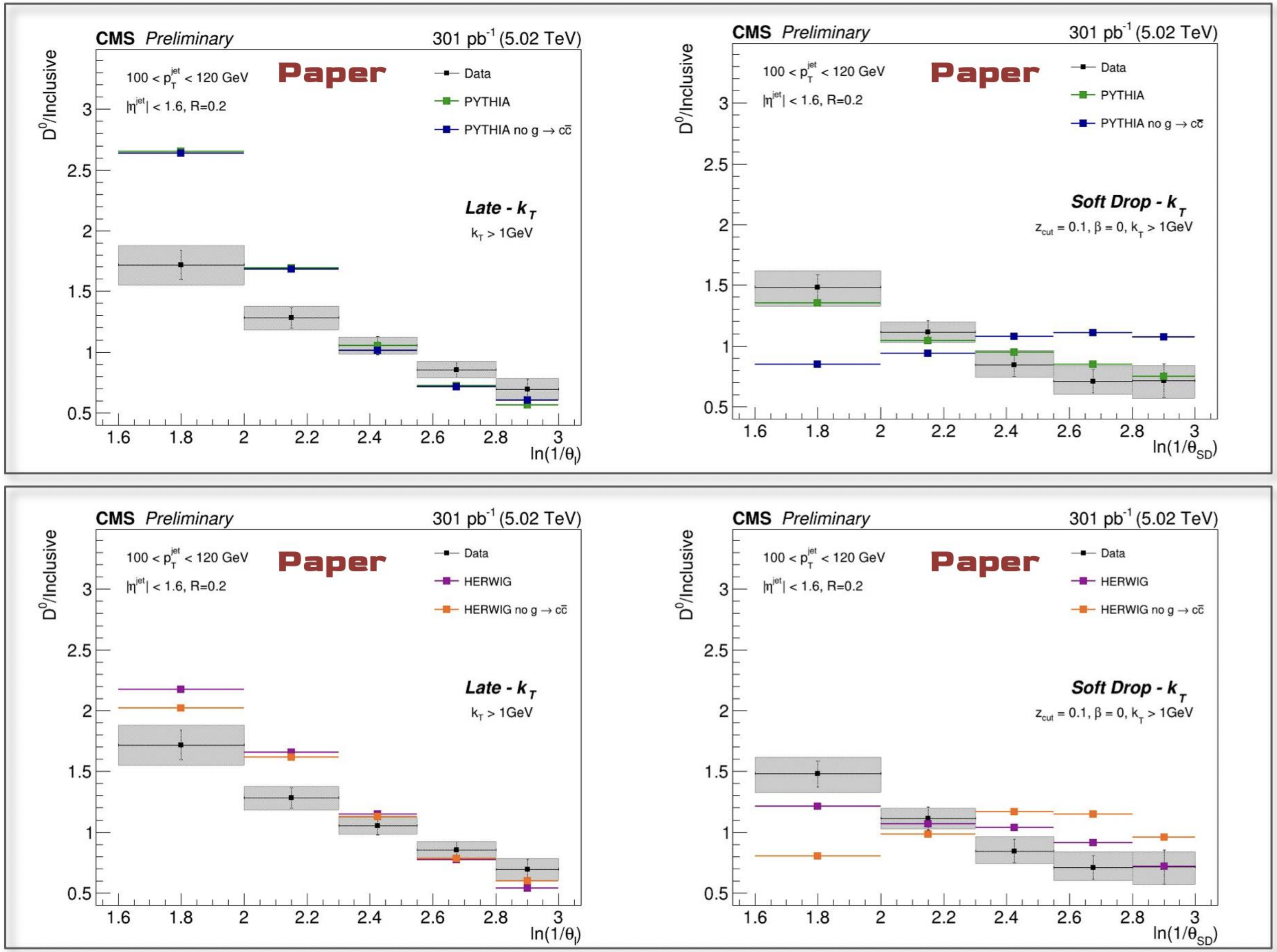




Some uncertainties propagated as fully correlated bin-by-bin for D^0-to-inclusive jet ratio:

- tracking efficiency
- PF candidate energy scale
- trigger fit modeling
- jet energy resolution

Model comparison



- ➢ Unfolded results compared with models to study different effects
- ➢ In both Pythia and Herwig shown that **late-k_T algorithm is less sensitive to gluon splittings** than Soft Drop

Comments

- 2011 data: 7 TeV w/ ~5/fb
  - 5.02 TeV w/ ~300/pb
- JER AK4?
- PV cut: dz = 24 cm, dz = 2 cm (vertex reco workbook)
  - 15 cm, 0.15 cm in paper
- Explanation for late-kt
- L133-134 & 233: I assume the kaon and pion assignment is done in combinatorics and choose the closest to D0 mass but from later line, seems not. how is it determined which is pion and which is kaon?
- L201-202: Do you remove the jets if D0 gets clustered into the softer jet?
- L209: Do you also require D0 in harder subjet?

- L199 & 204: Clarify the ordering of “first” and “last”. Is it in terms of decluttering order? or clustering order? The name “late-kT” could make the reader to assume clustering order.
- L226: Is the larger jet pT range used for the unfolding? This might confuse readers, as a range from 100 to 120 is used elsewhere.
- L148: A more detailed explanation of the optimization variables would improve clarity. Specifically, which distance is measured by the DCA?
- L200: k_T is defined as theta * p_T^sub, but it is referred to as the relative transverse momentum with respect to the harder subjet, which is confusing. Shouldn't it be theta * p^sub instead of theta * p_T^sub to correctly describe the relative transverse momentum?

- L232: It seems this part explains about the latter of the two Gaussian functions that model the signal shape, then I think it should change the order with the preceding sentence. L67-68: SD algorithm has tunable parameters that affect the final result, then what is the actual meaning of "emissions selected with SD algorithm are typically found at larger angles", does it apply only to parameters described in the paragraph starting with L204, or is it true in a more general senses
- L136 & L151: The explanation of the D0 Candidate pT cut is divided into two distant parts. It would be nice to at least tell that the description will come later.
- Fig 3. Do you have the same plot for the softdrop algorithms