Jet measurements with ALICE: substructure, dead cone, charm jets

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ALICE

MAGYAR TUDOMÁNYOS AKADÉMIA 1825

WIGNER

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ALICE jets in pp collisions

This talk: a selection of pp results

- Groomed jet substructure
- Measurement of the dead-cone
- D-mesons in jets: production
- D-meson and Λ_c-baryon: fragmentation

Data samples:

$\sqrt{s_{NN}}$ (TeV)	Years	L_{int}
5.02 TeV	2016-2017	~1.3 pb^{-1}
7 TeV	2009-2013	~1.5 pb^{-1}
13 TeV	2016-2017	~59 pb^{-1}

→ Test of pQCD and hadronization models

→ Flavor-dependent production and fragmentation

→ Baseline for measurements in heavy-ions

Not covered: Jets in heavy ion collisions

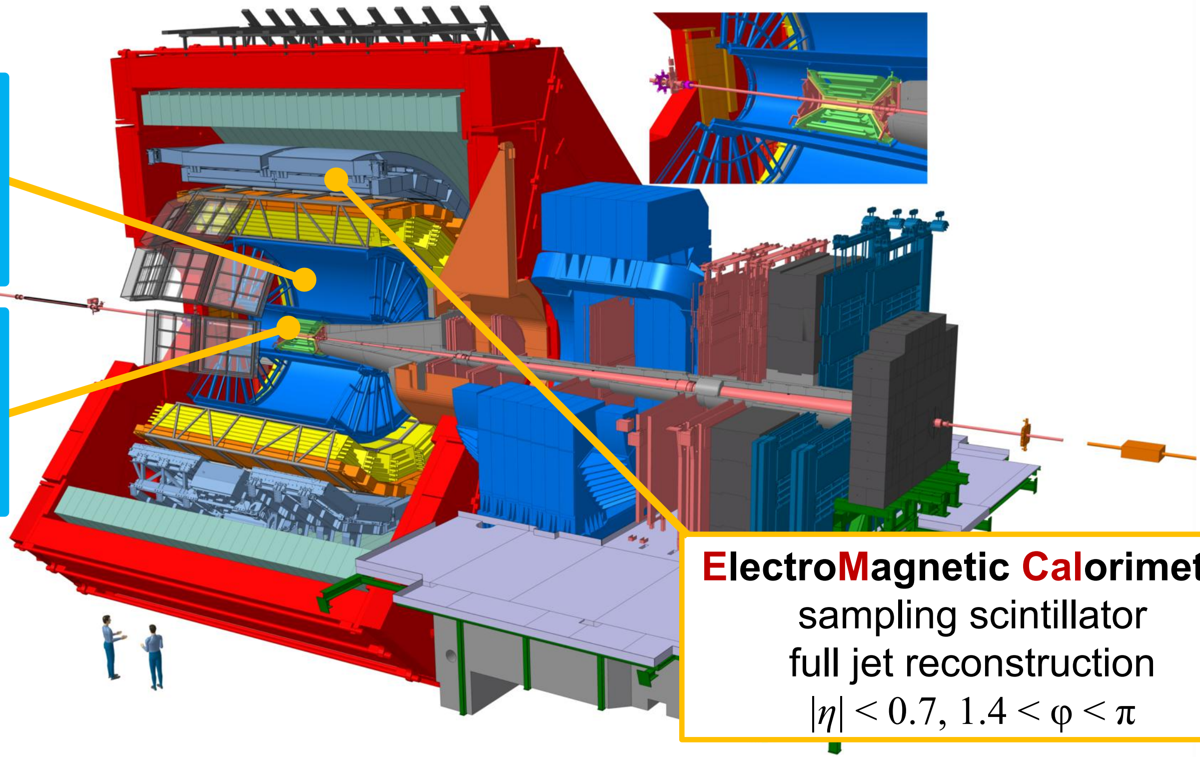
- Modification of substructures by jet-medium interactions
- Flavor-dependent energy loss mechanisms

Jet measurements with ALICE

central barrel: $|\eta|<0.9$

Time Projection Chamber:
gas detector
charged-particle tracking
and identification

Inner Tracking System
silicon detectors
charged-particle tracking,
secondary vertex



ElectroMagnetic Calorimeter
sampling scintillator
full jet reconstruction
$|\eta| < 0.7,\ 1.4 < \varphi < \pi$

Charged-particle jets

- Full azimuth coverage
- Experimentally easier

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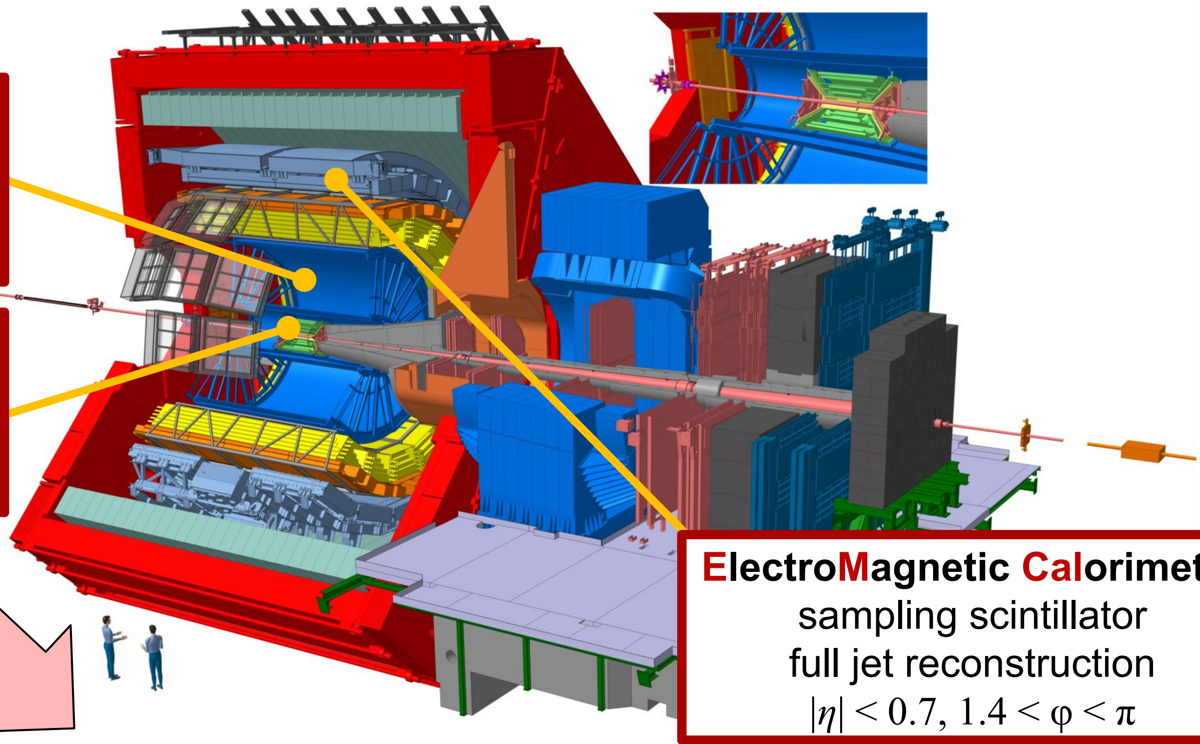

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Charged-particle jets

- Full azimuth coverage
- Experimentally easier

Full jets

- Direct theory comparison
- Limited acceptance, technically more challenging

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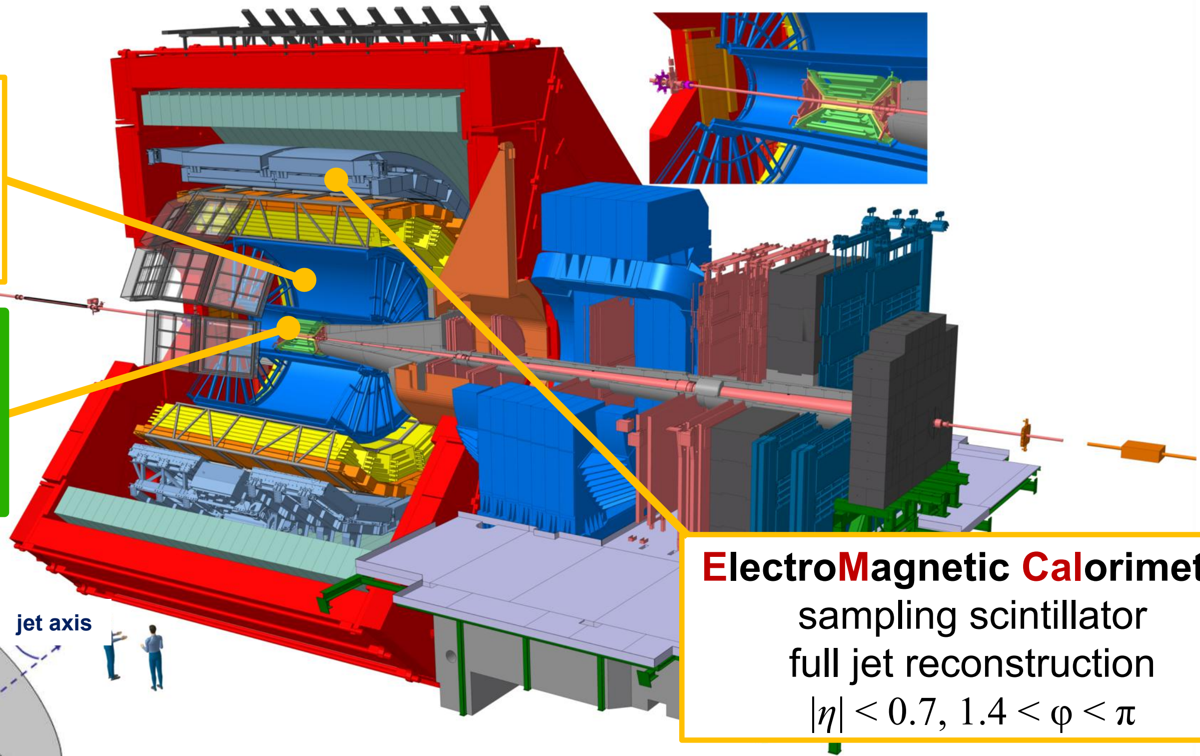

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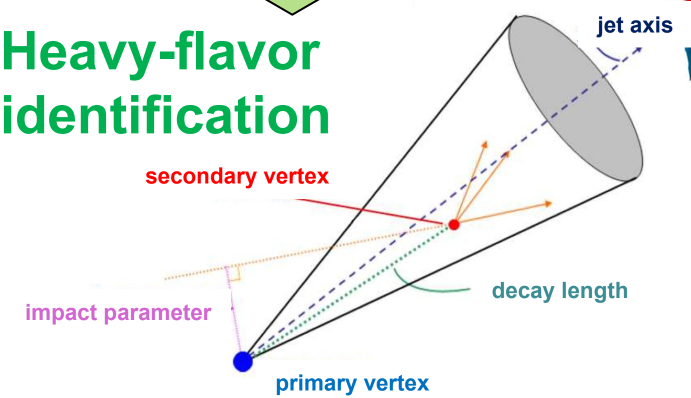
Heavy-flavor identification



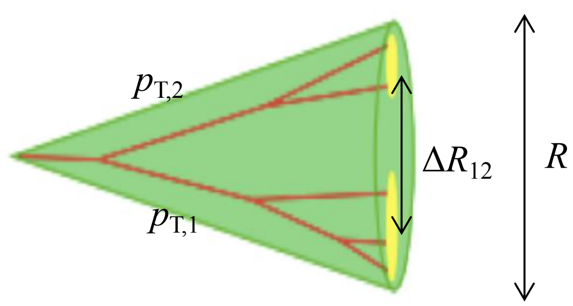
Lifetime of heavy flavor:	$c\tau$ (D) ~ 100-300 μm
	$c\tau$ (B) ~ 400-500 μm
Secondary vertex resolution:	< 100 μm

→**M. Faggin**
Performance
Monday 3pm

Groomed jet substructure

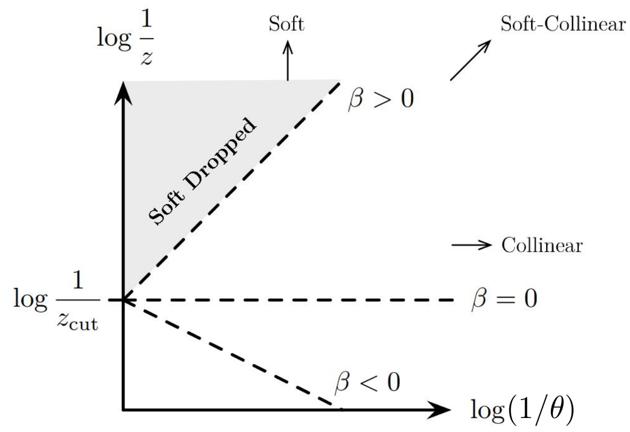
- Access to the hard parton structure of a jet
  - Mitigate influence from underlying event, hadronization
  - Direct interface with QCD calculations
- Soft-drop grooming: Remove large-angle soft radiation
  - Recluster a jet with Cambridge-Aachen algorithm (angular ordered)
  - Iteratively remove soft branches not fulfilling

$$z > z_{\mathrm{cut}}\theta^{\beta}$$



$$z = \frac{p_{\mathrm{T},2}}{p_{\mathrm{T},1} + p_{\mathrm{T},2}}$$

$$\theta = \frac{\Delta R_{12}}{R}$$



Larkoski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146

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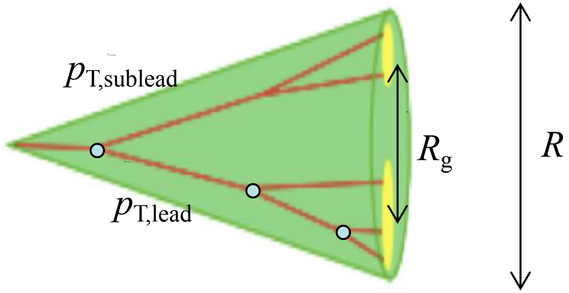


- **Substructure variables**
  - **Groomed momentum fraction**

$$z_g = \frac{p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$

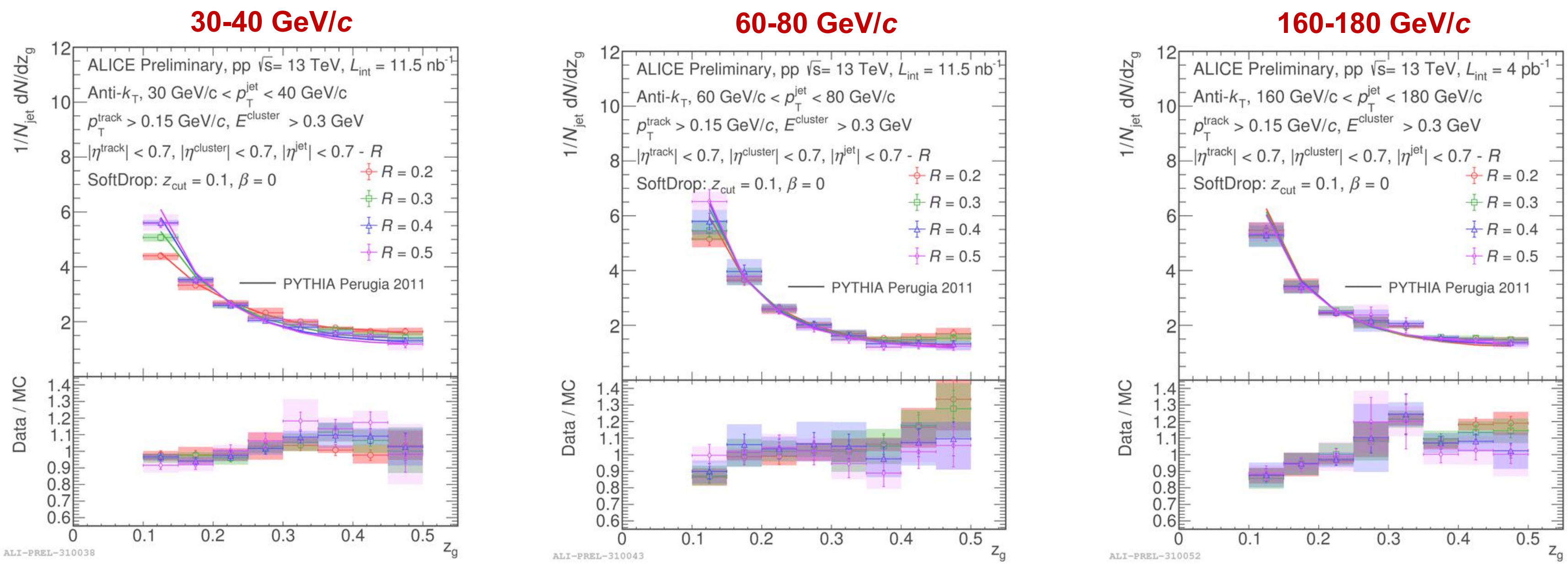
  - **Groomed radius**

$$\theta_g \equiv \frac{R_g}{R}$$

  - **Number of soft drop splittings**

$$n_{\mathrm{SD}}$$

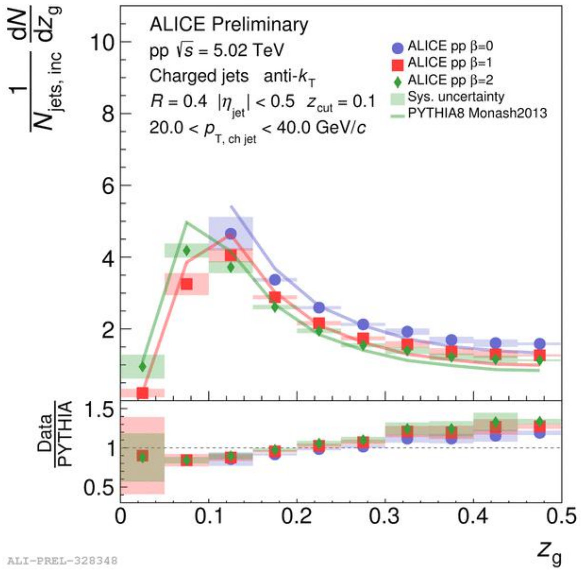
Soft Drop grooming: z_g vs. jet R



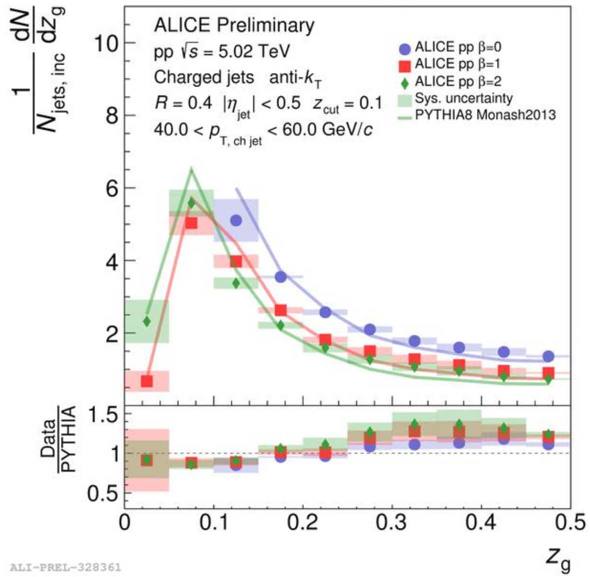
- **Full-jet groomed momentum fraction in pp collisions** at $\sqrt{s}$=13 TeV
  $z_{cut}=0.1$, $\beta=0$, absolute normalized, no background subtraction
- At low p_T: small radii jets tend to split more symmetrically
  larger radii: higher sensitivity to non-perturbative effects
- Slight p_T-dependence for small radii
- Trends reproduced well by PYTHIA

Soft Drop grooming: z_g vs. β

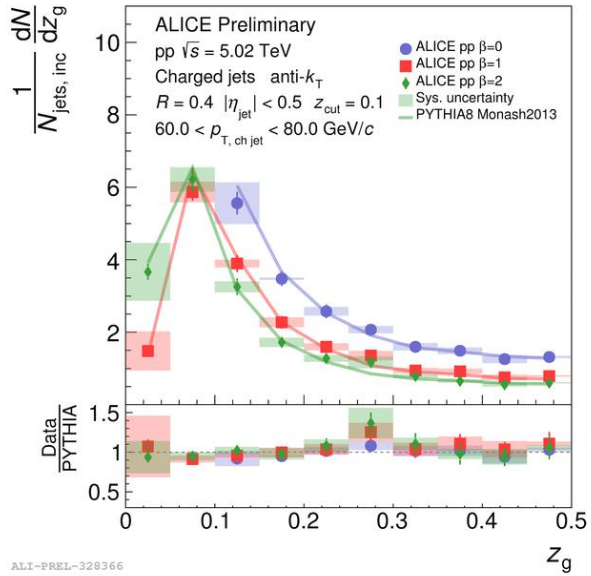
20-40 GeV/*c*



40-60 GeV/*c*

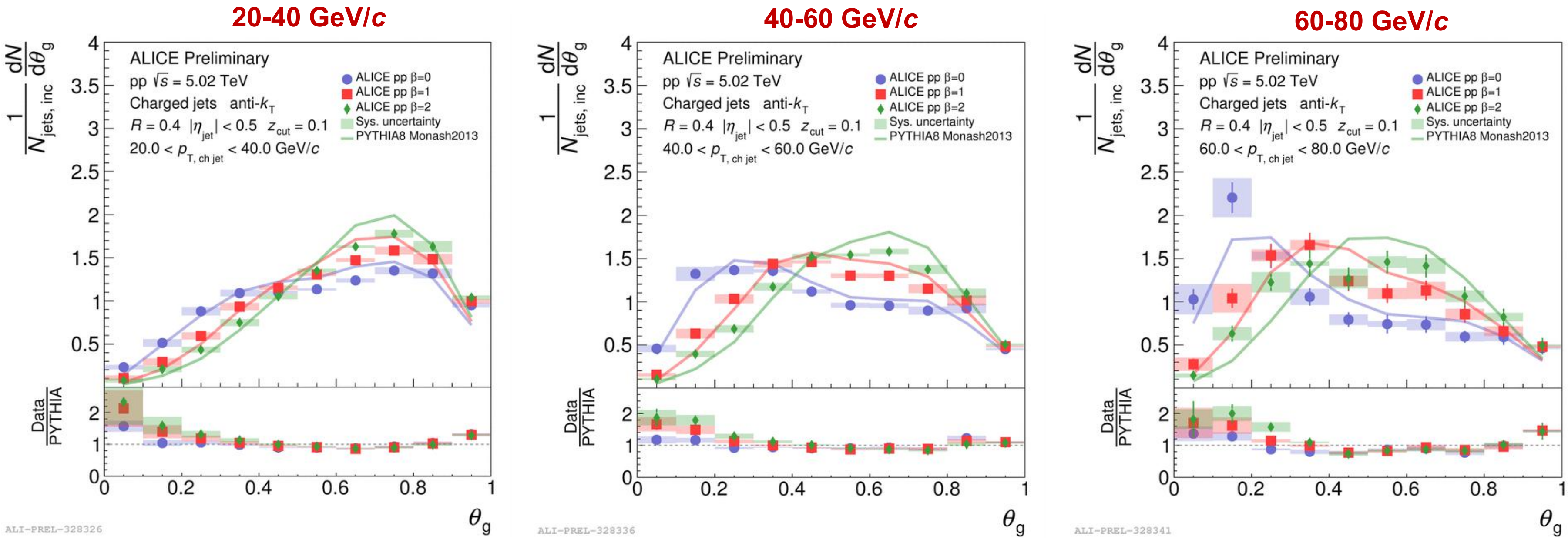


60-80 GeV/*c*



- **Charged-particle jet groomed momentum fraction in pp collisions** at $\sqrt{s}$=13 TeV
  z_{cut}=0.1, R=0.4, absolute normalized
- A weak p_T-dependence is present
- Trends reproduced relatively well by PYTHIA

Soft Drop grooming: θ_g vs. β



- **Charged-particle jet groomed radius in pp collisions** at $\sqrt{s}$=13 TeV
  z_{cut}=0.1, R=0.4, absolute normalized

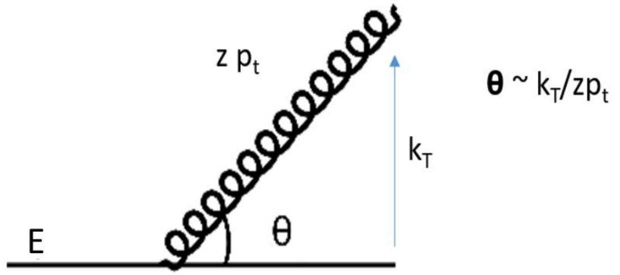
- Smaller β grooms soft splittings away → more collimated jets
- Trends reproduced relatively well by PYTHIA

→ *possibility to explore contributions from partonic and hadronic stages*

Heavy-Flavor fragmentation: The dead cone

- Dead cone:
  Forward emissions from radiators with large mass are suppressed

$$\theta < \frac{m_q}{E_q}$$



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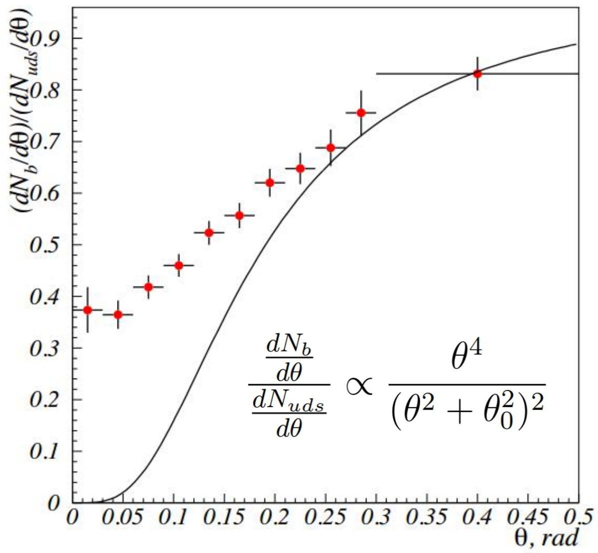
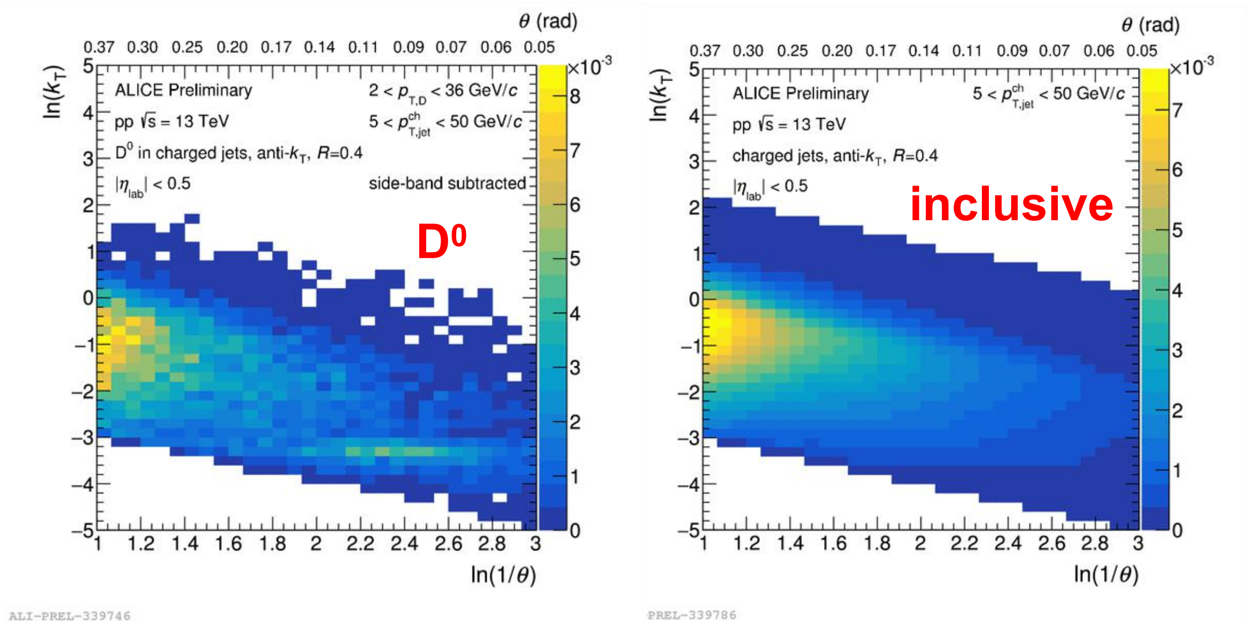
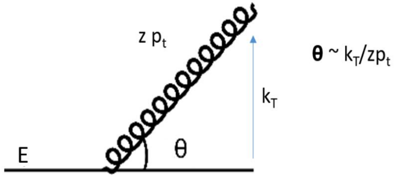


- Measurements at LEP:
  Flavor-dependence of angles between jet fragments
  - Low-background e^+e^- environment
  - Indirect measurements w.r.t. jet axis

Dead cone: the Lund plane

- D^0 as well as inclusive jets: Reclustering with C/A
  L. Cunqueiro, M. Ploskon, PRD 99, 074027
- Lund plane populated with all splittings of the radiator's prong
  - D^0: depletion expected at low angles (~higher $\ln(1/\theta)$ values)
    Note: 10 to 15% feed-down contribution in D^0 from b





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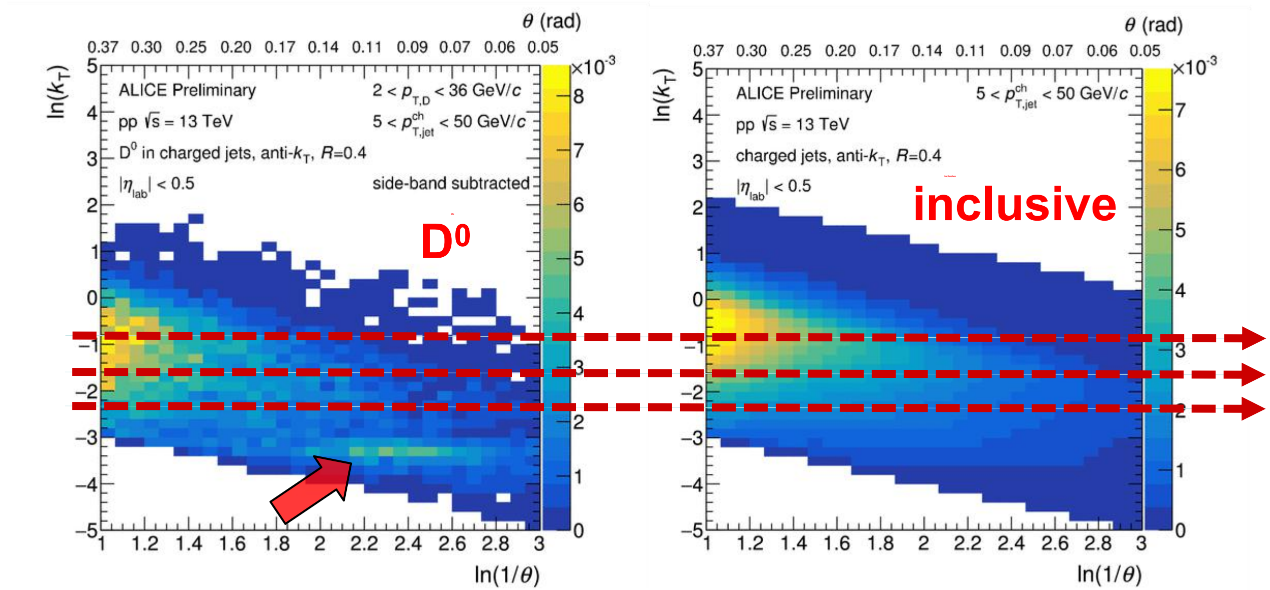
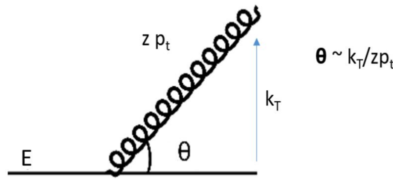


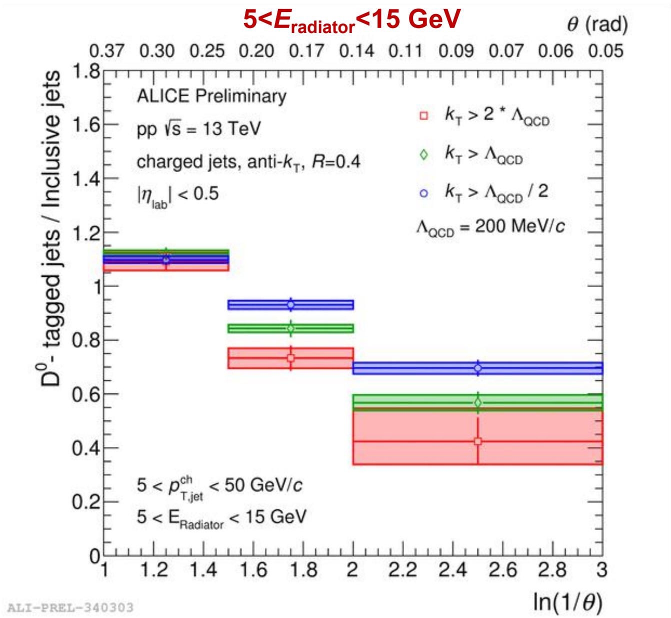


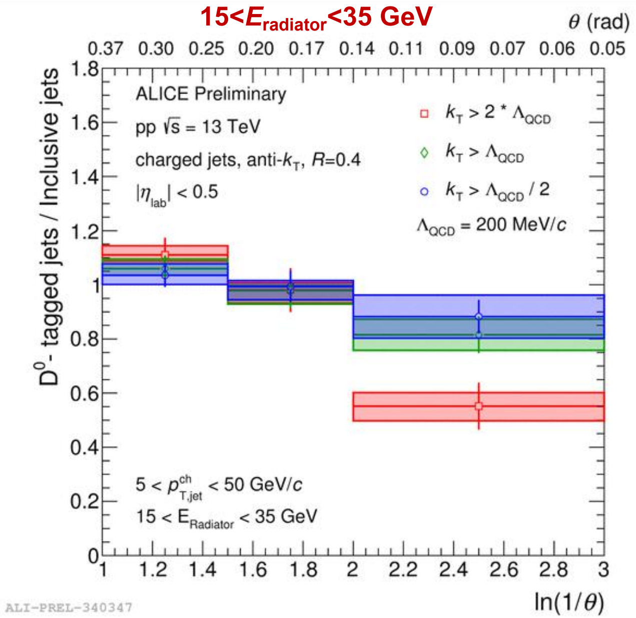
k_T=2 Λ_{QCD}
k_T=Λ_{QCD}
k_T=1/2 Λ_{QCD}

Λ_{QCD}=200 MeV

- k_T-cut to remove contamination from hadronization, decay and the underlying event

Dead cone effect in ALICE

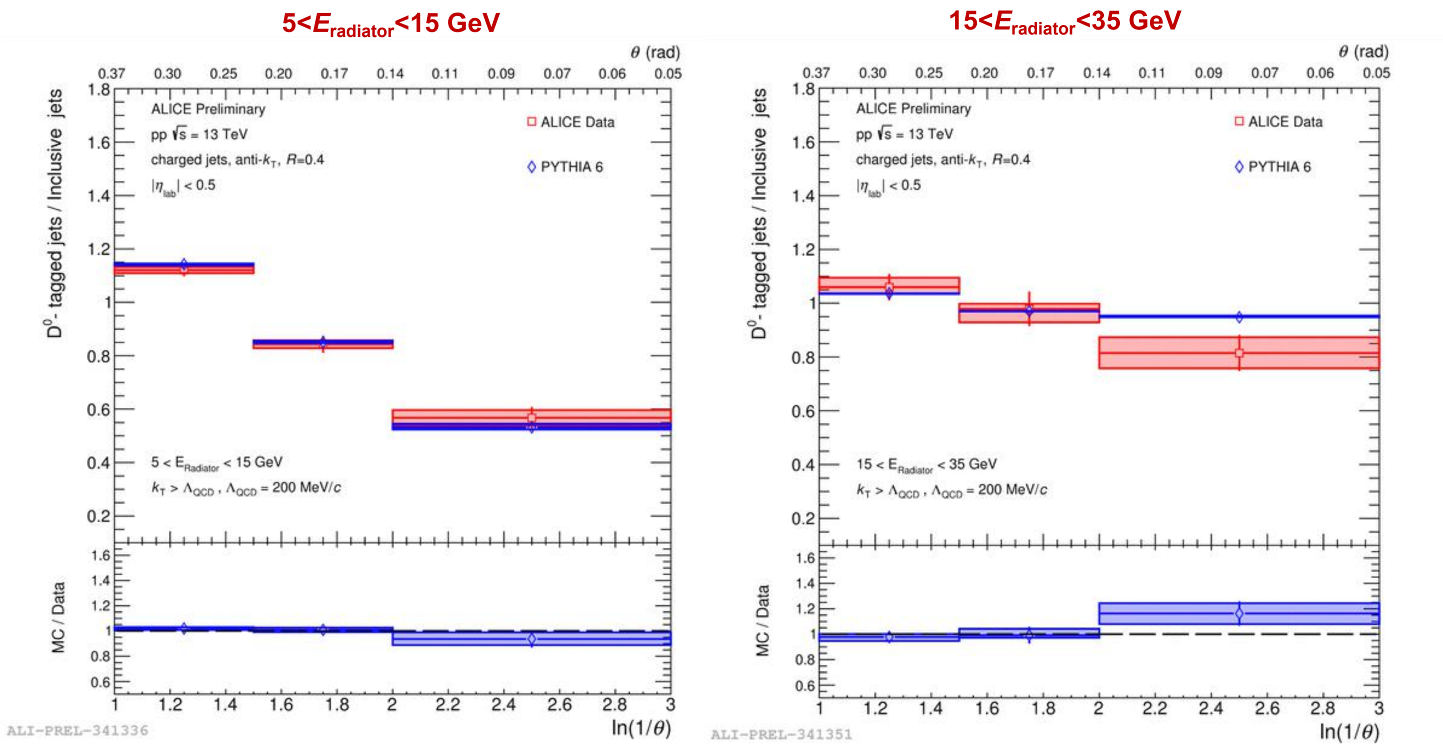




- **D-tagged to inclusive ratios vs. ln(1/θ) at $\sqrt{s}$=13 TeV**
- Significant suppression of radiation in D-tagged jets towards low angles
  - effect decreases toward higher energy of the radiator (→ $\theta > m_q/E_q$)
  - effect decreases towards lower k_T cut (→ more contamination)

First direct measurement of the dead cone effect in pp collisions

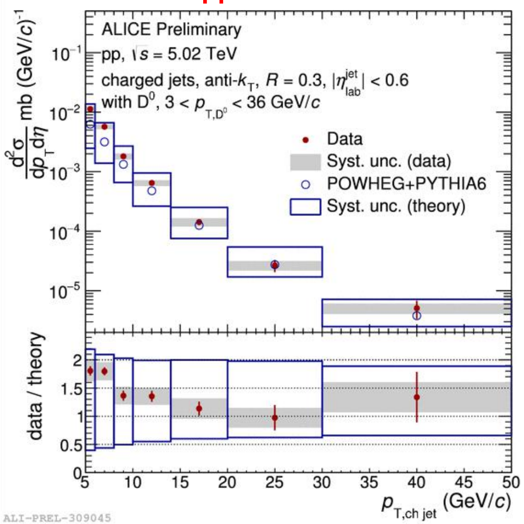
Dead cone: model comparison



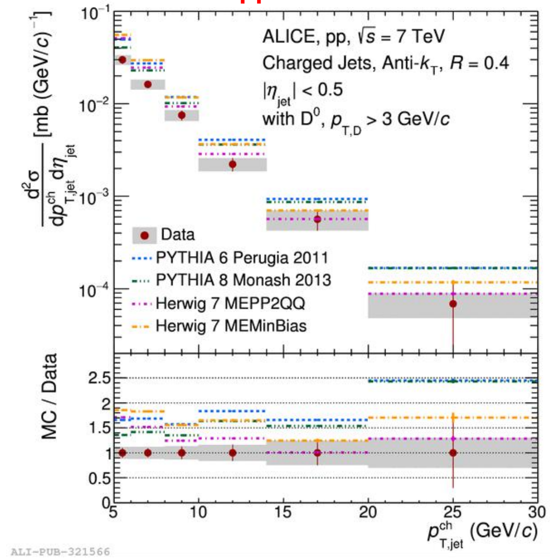
- **D-tagged to inclusive ratios vs. ln(1/θ) at $\sqrt{s}$=13 TeV**
- Simulations with PYTHIA6 describe ALICE data qualitatively

Charm production: D⁰-jet cross sections

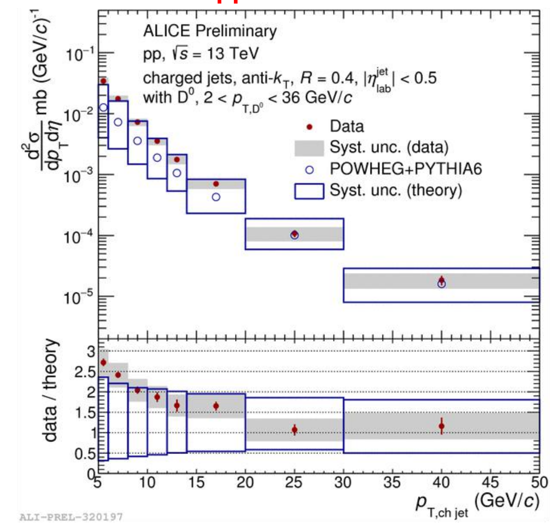
pp √s=5.02 TeV



pp √s=7 TeV

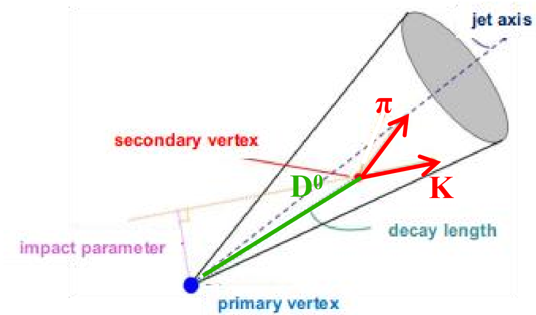


pp √s=13 TeV



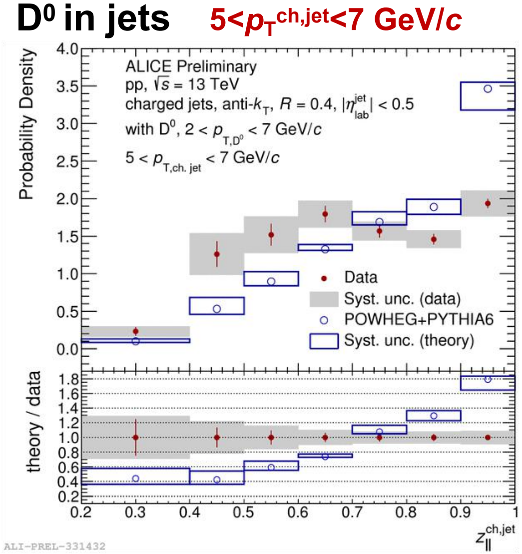
JHEP 1908 (2019) 133

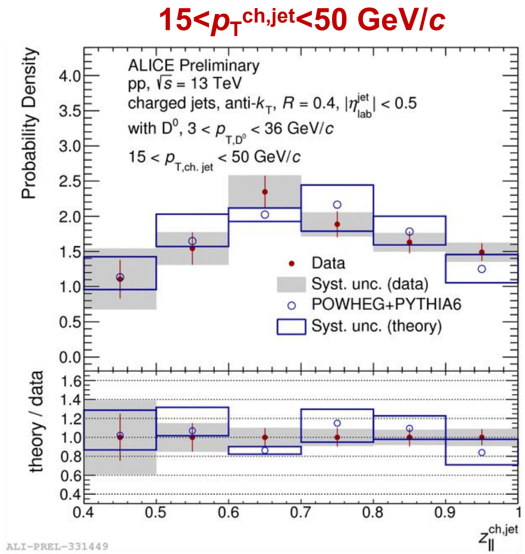
- Analysis technique
  - Identify D⁰ mesons via hadronic decays
  - Replace decay products with D⁰ in jet
- Comparison with models
  - NLO POWHEG+PYTHIA (hvq) calculations consistent with data (only marginally at low-p_T)
  - Neither LO PYTHIA 6 and 8, nor NLO HERWIG 7 describe the cross-section



Charm fragmentation: D-jet $z_{||}$

D^0 in jets



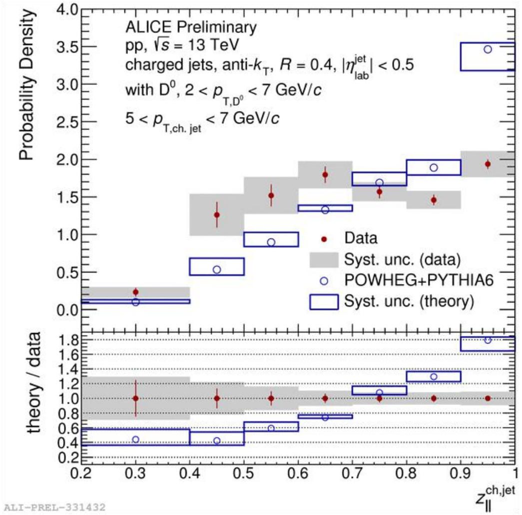


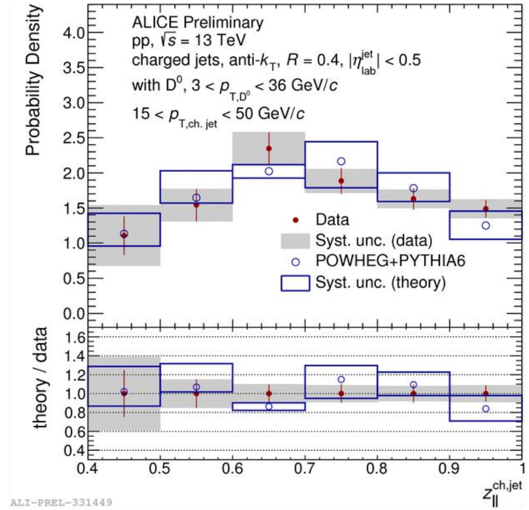
- **Parallel momentum fraction, pp $\sqrt{s}$=13 TeV**
  - Characteristic to heavy-flavor fragmentation
- **D-meson fragmentation** is softer at high p_T than at lower p_T
  - POWHEG+PYTHIA6 predicts a stronger change towards low p_T

$$z_{||}^{ch} = \frac{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{HF}}}{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{jet ch}}}$$

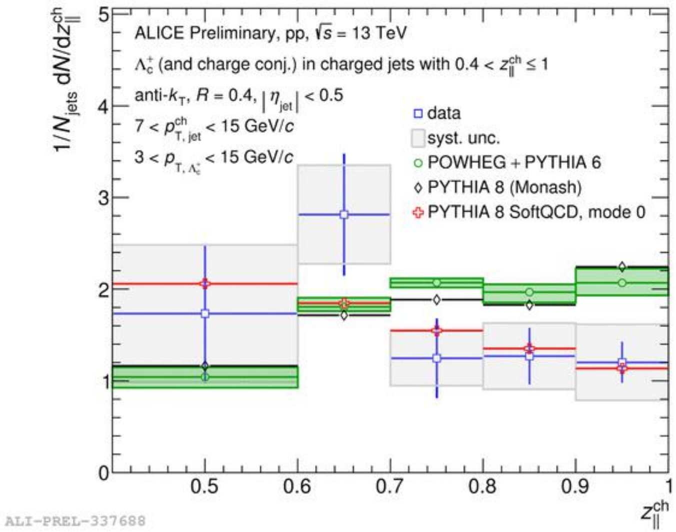
Charm fragmentation: Λ_c-jet and D-jet $z_{||}$

D⁰ in jets $5<p_T^{ch,jet}<7$ GeV/*c* | $15<p_T^{ch,jet}<50$ GeV/*c*





Λ_c in jets $7<p_T^{ch,jet}<15$ GeV/*c*



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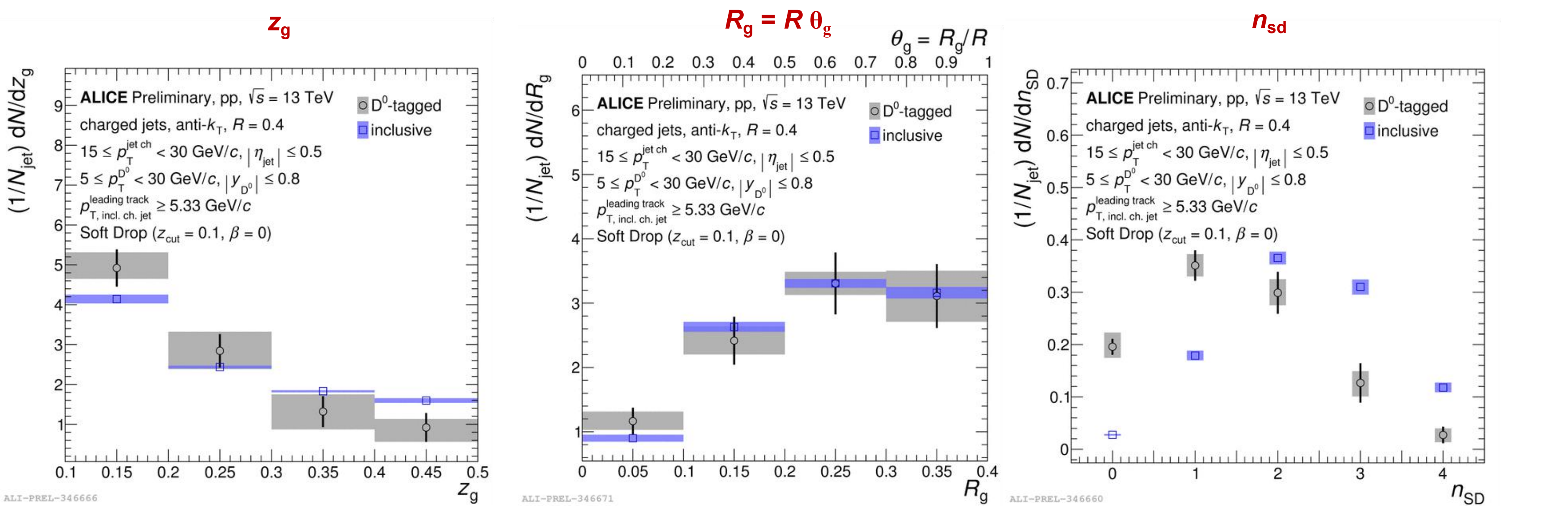
$$z_{||}^{ch} = \frac{\mathbf{p}^{\text{jet ch}} \cdot \mathbf{p}^{\text{HF}}}{\mathbf{p}^{\text{jet ch}} \cdot \mathbf{p}^{\text{jet ch}}}$$

- **D-meson fragmentation** is softer at high p_T than at lower p_T
  - POWHEG+PYTHIA6 predicts a stronger change towards low p_T
- **Λ_c fragmentation:** similar trends (different p_T range!)
  - PYTHIA8 with SoftQCD settings performs well with Λ_c
  - **Opportunity to compare baryon to meson fragmentation**

→A. Gromada
Heavy Ions
Monday 3:36pm

D-jet substructure: z_g, R_g, n_{SD}

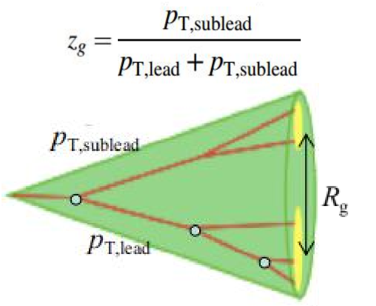
New!



ALICE-PUBLIC-2020-002

- **D^0-tagged charged-jet groomed substructuce**
  pp $\sqrt{s}$=13 TeV, z_{cut}=0.1, β=0
- n_{SD} : charm jets typically have less hard splitting than light jets

→ **Consistent with harder heavy-flavor fragmentation**
(mass and color charge effects)



Summary and outlook

- **Jet substructures with soft-drop grooming in pp collisions**
  - Full jets vs. R, charged jets vs. β in a broad p_T range

  → Opportunity to explore contributions of pQCD and hadronization

  → Baseline for measurements in heavy-ions

- **Charm-jet measurements in pp collisions**
  - Clear indication of the dead cone effect in first direct measurement
  - D-tagged jet cross sections, D and Λ_c parallel momentum fraction
  - D^0-jet substructure indicates harder fragmentation than light flavor

  → Test of pQCD models and flavor-dependent fragmentation

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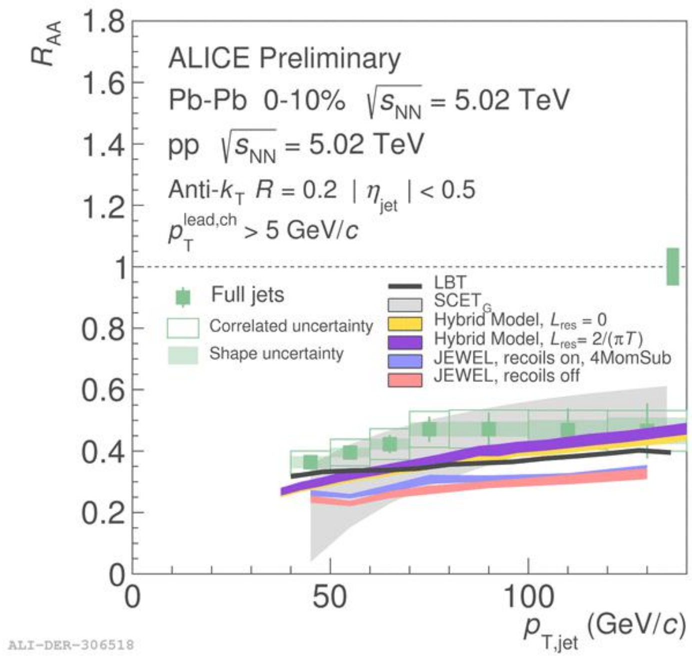
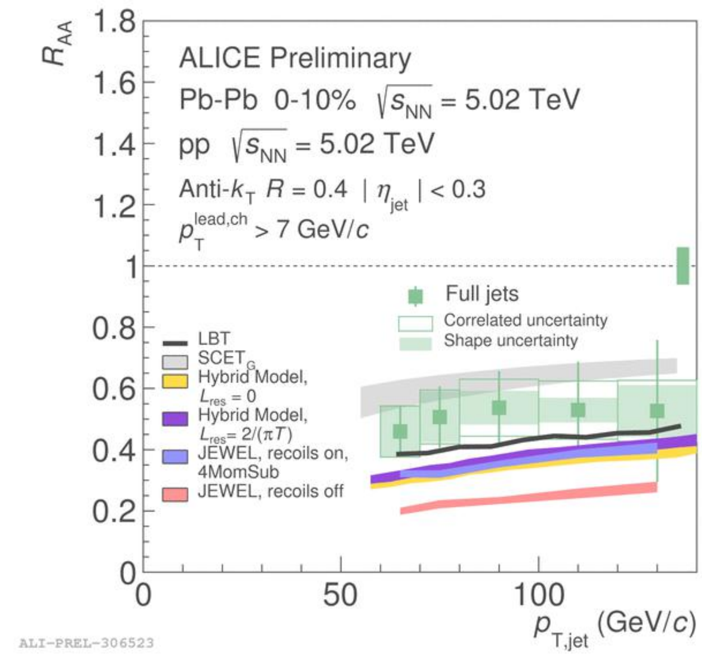
Stay tuned for new results soon

Thank You!

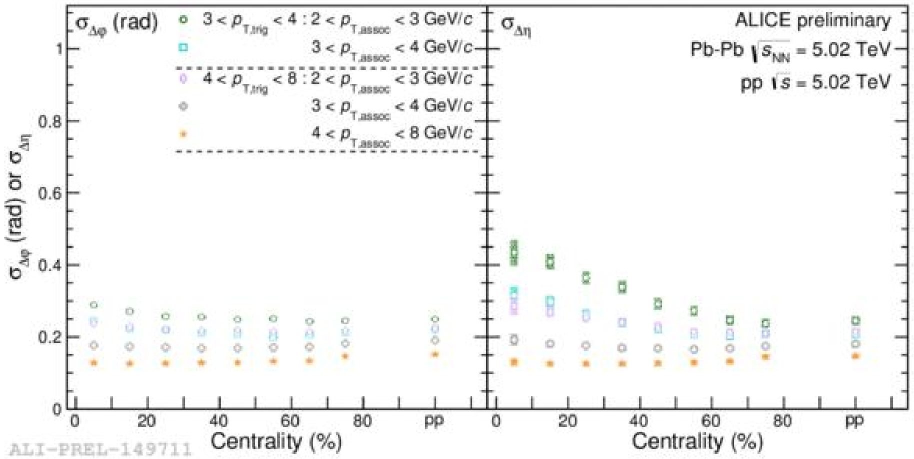
Jet suppression in Pb-Pb

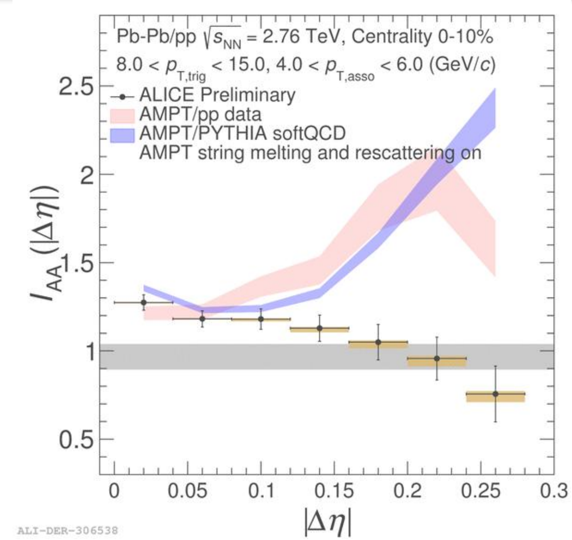




- Measurement down to p_T = 40 GeV/c => redistribution of energy
- Only weak dependence seen in data on jet resolution R
- Challenge to some models: stronger R dependence predicted than in data

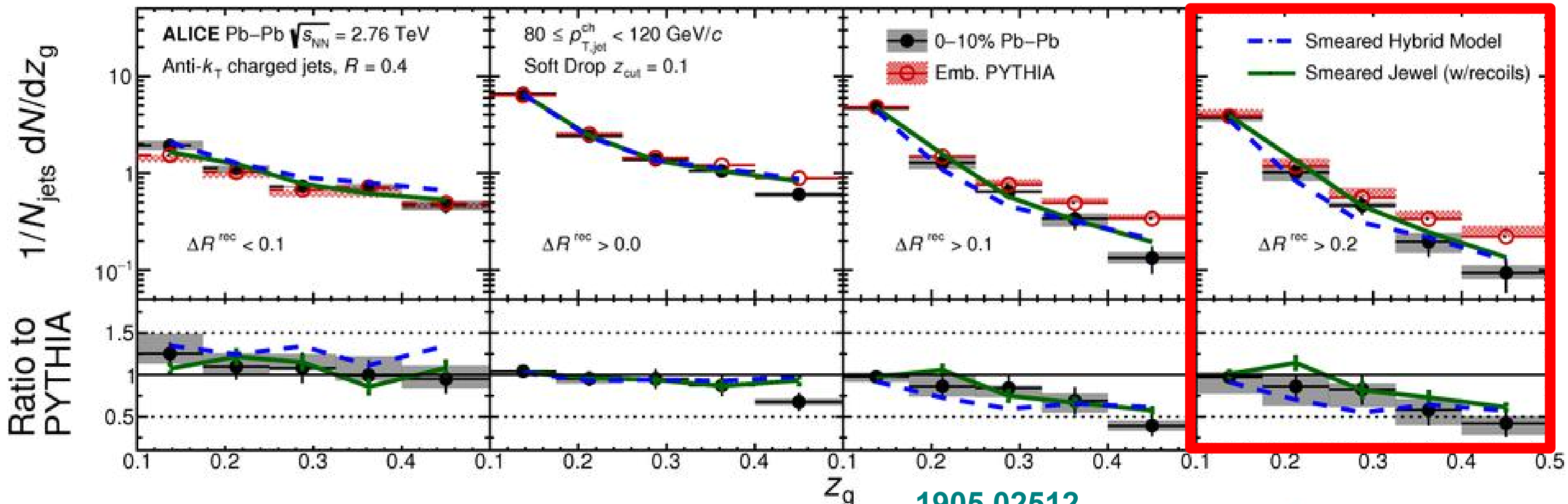
Jet-medium interactions





- **Low p_T**: Azimuthal h-h correlations, per-trigger normalized
  - **Broadening** of **central** angular correlation peaks in the **$\Delta\eta$** direction
  - Understanding: rescattering with radial flow (AMPT)
- **Higher p_T**: Azimuthal h-h correlations, $I_{AA} = Y_{AA}/Y_{pp}$
  - **Narrowing** of the peak in **central** events in the **$\Delta\eta$** direction
  - Jet structure modifications? No proper understanding by models.

Jet Substructure in Pb-Pb



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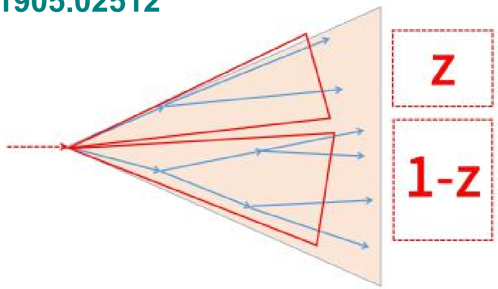
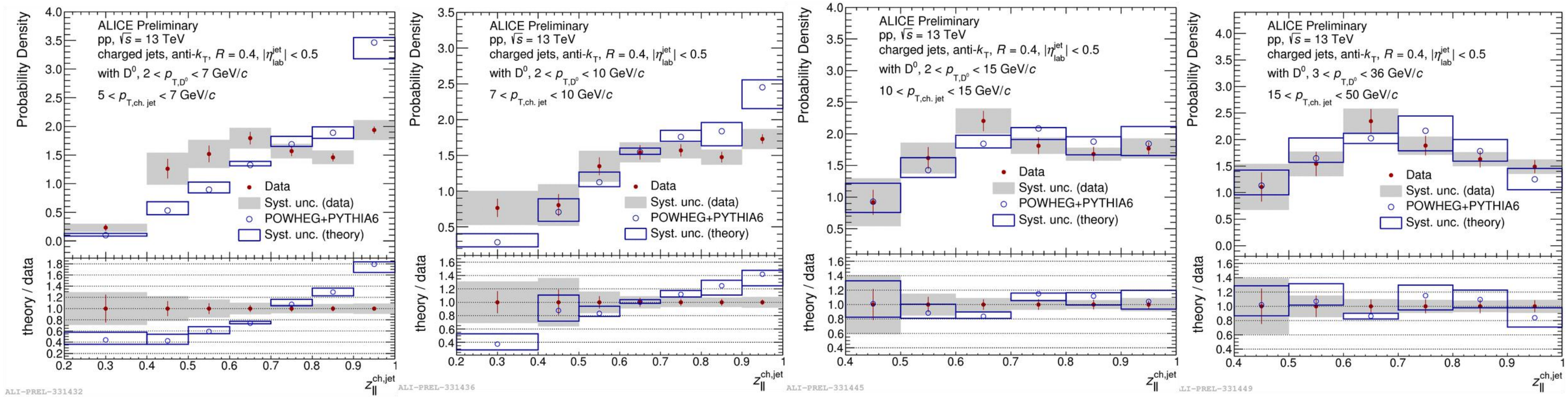


$$z = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

- First intra-jet splitting z_g
  - At small angles (ΔR < 0.1): consistent z_g distributions in Pb-Pb and vacuum
  - At large angles (ΔR > 0.2): z_g distributions are steeper in medium than in vacuum
- **Early jet development influenced by medium**

Charm fragmentation: D-jet $z_{||}$ vs. p_T

$5<p_T^{\mathrm{ch,jet}}<7$ GeV/c | $7<p_T^{\mathrm{ch,jet}}<10$ GeV/c | $10<p_T^{\mathrm{ch,jet}}<15$ GeV/c | $15<p_T^{\mathrm{ch,jet}}<50$ GeV/c



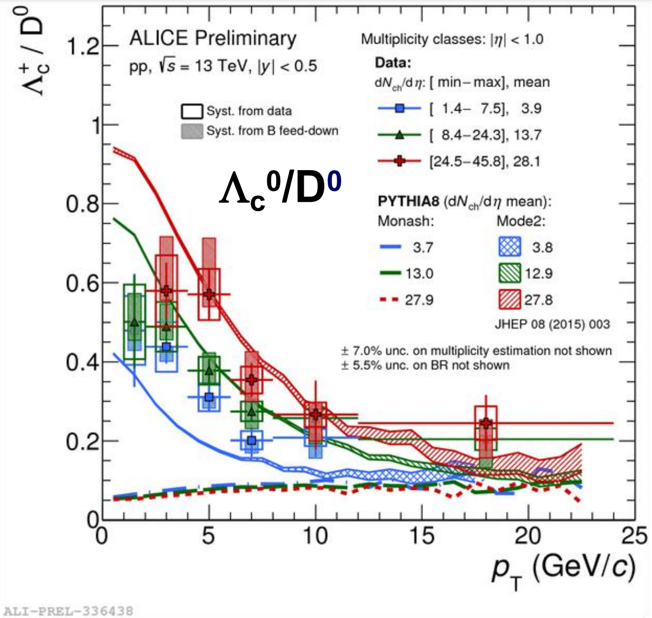
pp $\sqrt{s}$=13 TeV

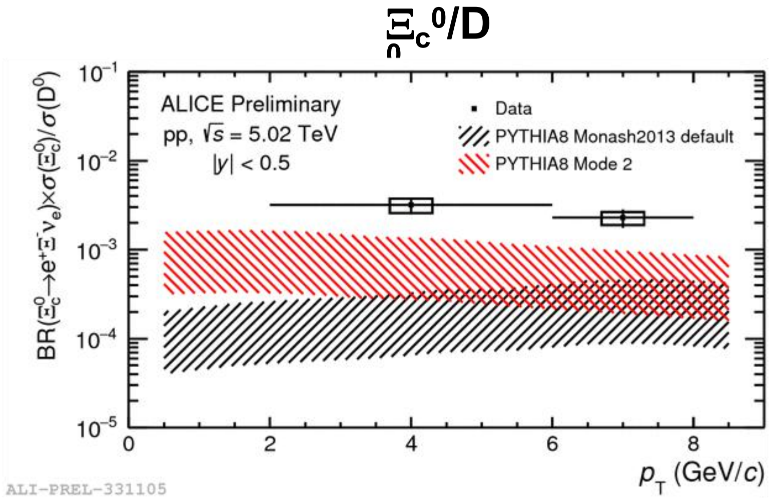
- **parallel momentum fraction**
  - Characteristic to heavy-flavor fragmentation

$$z_{||}^{\mathrm{ch}} = \frac{\boldsymbol{p}^{\mathrm{jet\ ch}} \cdot \boldsymbol{p}^{\mathrm{HF}}}{\boldsymbol{p}^{\mathrm{jet\ ch}} \cdot \boldsymbol{p}^{\mathrm{jet\ ch}}}$$

- D-meson fragmentation is softer at high p_T than at lower p_T
- POWHEG+PYTHIA6 predicts a stronger change towards low p_T

Baryon-to-meson ratio: Λ_c^+/D^0, Ξ_c^0/D^0

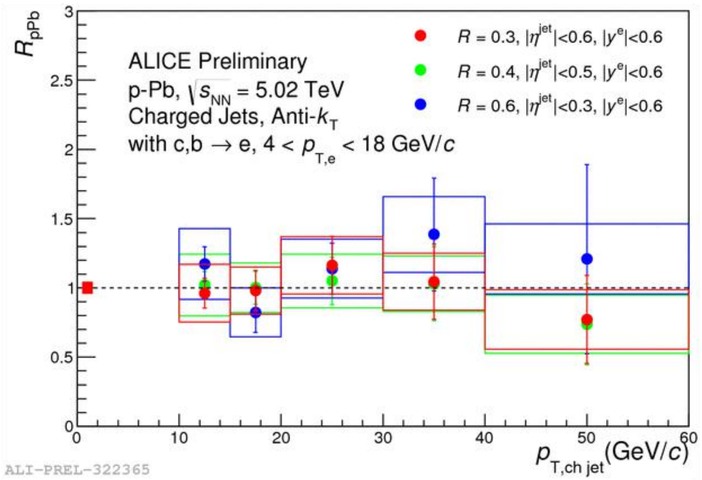


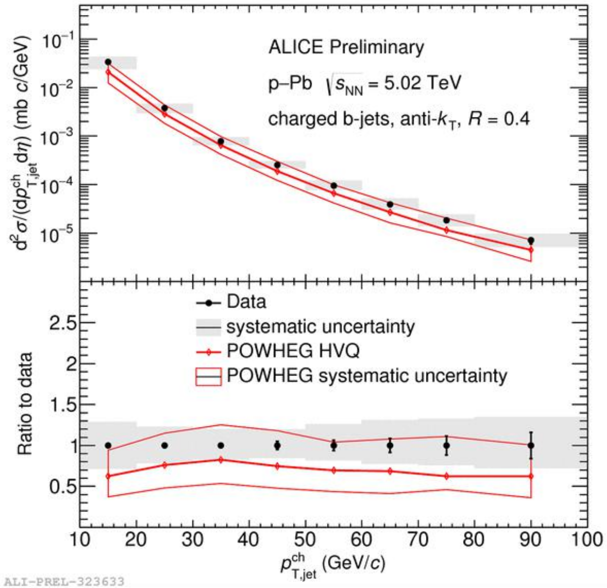


PYTHIA8: JHEP 05 (2006) 026
DIPSY: JHEP 1503 (2015) 148
HERWIG7: EPJ C76 (2016) no.4 196

- Ξ_c^0/D^0 as well as Λ_c^+/D^0 are underestimated by models based on ee collisions: Does charm hadronization depend on collision system?
  - PYTHIA8 with string formation beyond leading colour approximation?
    Christiansen, Skands, JHEP 1508 (2015) 003
  - Feed-down from augmented set of charm-baryon states?
    He, Rapp, 1902.08889
- Detailed measurements of charm baryons provide valuable input for theoretical understanding of HF fragmentation

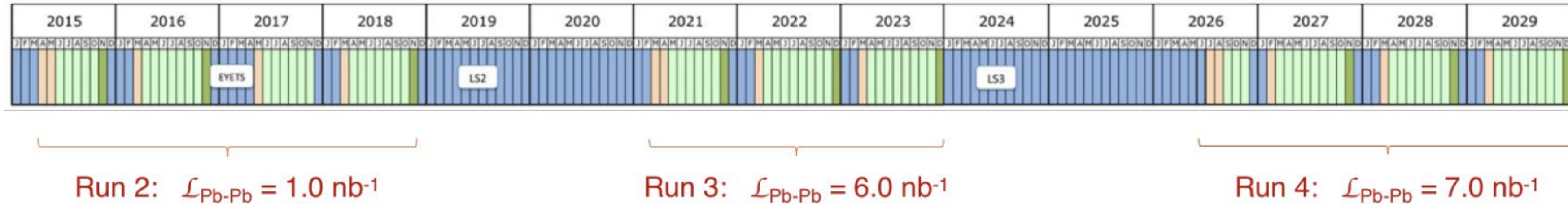
Heavy flavor jets in p-Pb





- Heavy-flavor jets measured down to p_T = 10 GeV/c
- **No mid-rapidity nuclear modification of HFE jets** visible
  - Regardless of chosen jet resolution parameter
- Cross section of **beauty jets** tagged with displaced vertices also **described by POWHEG HVQ x A (pp)** within uncertainty

ALICE Upgrade for Run-3 and Run-4



- Up to 50 kHz Pb-Pb interaction rate
- Requested Pb-Pb luminosity: 13 nb^{-1} (50-100x Run2 Pb-Pb)
- Improved tracking efficiency and resolution at low pT
- Detector upgrades: ITS, TPC, MFT, FIT
- Faster, continuous readout