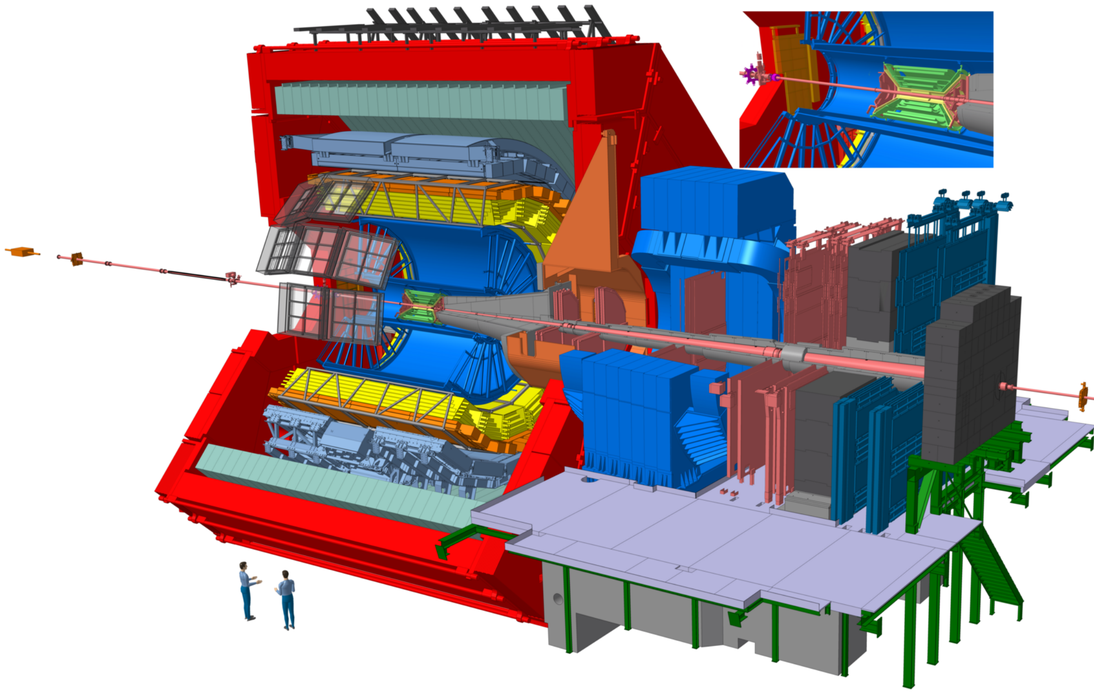
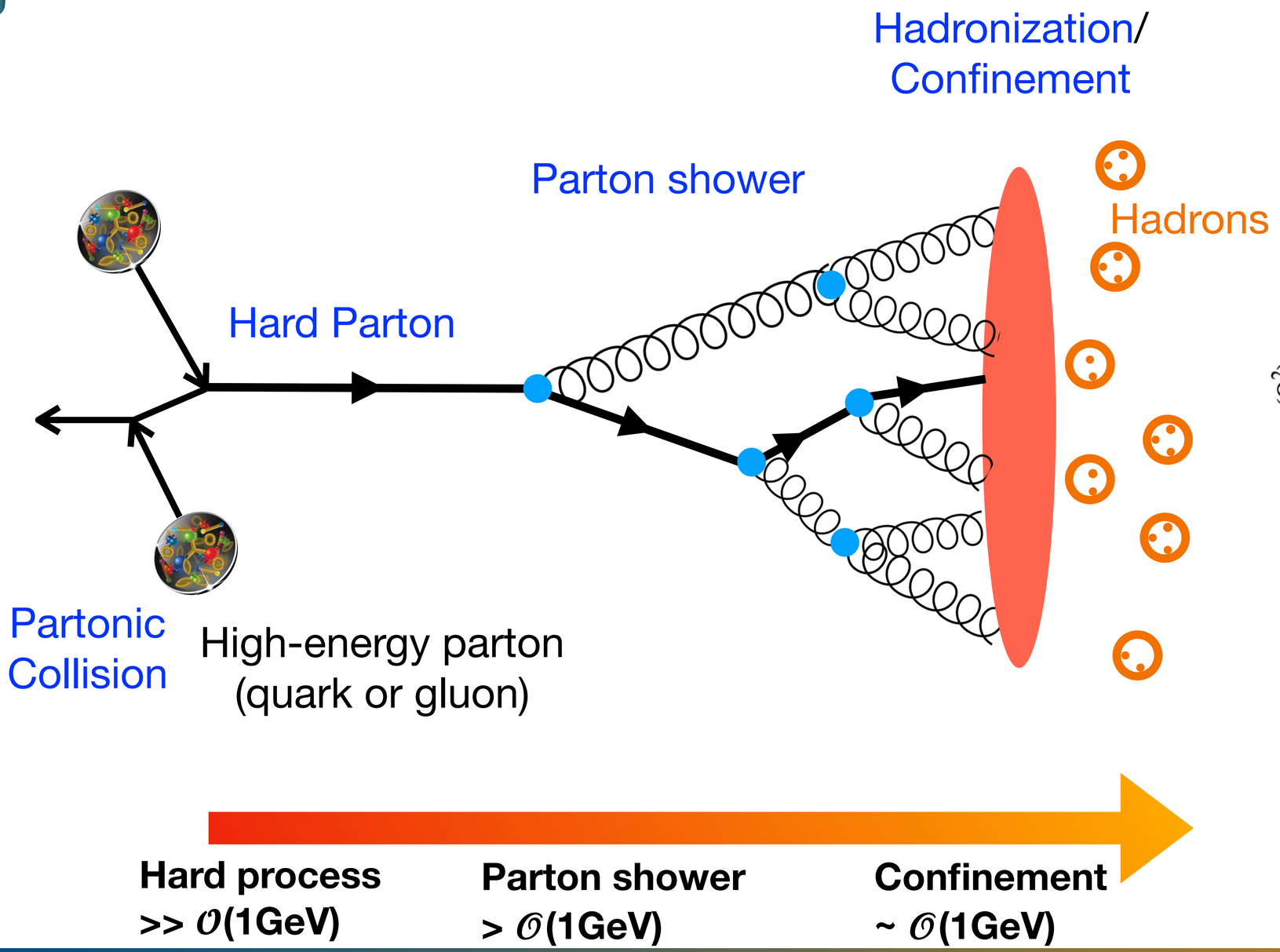
Exploring QCD dynamics with charm-tagged jet substructure studies with ALICE

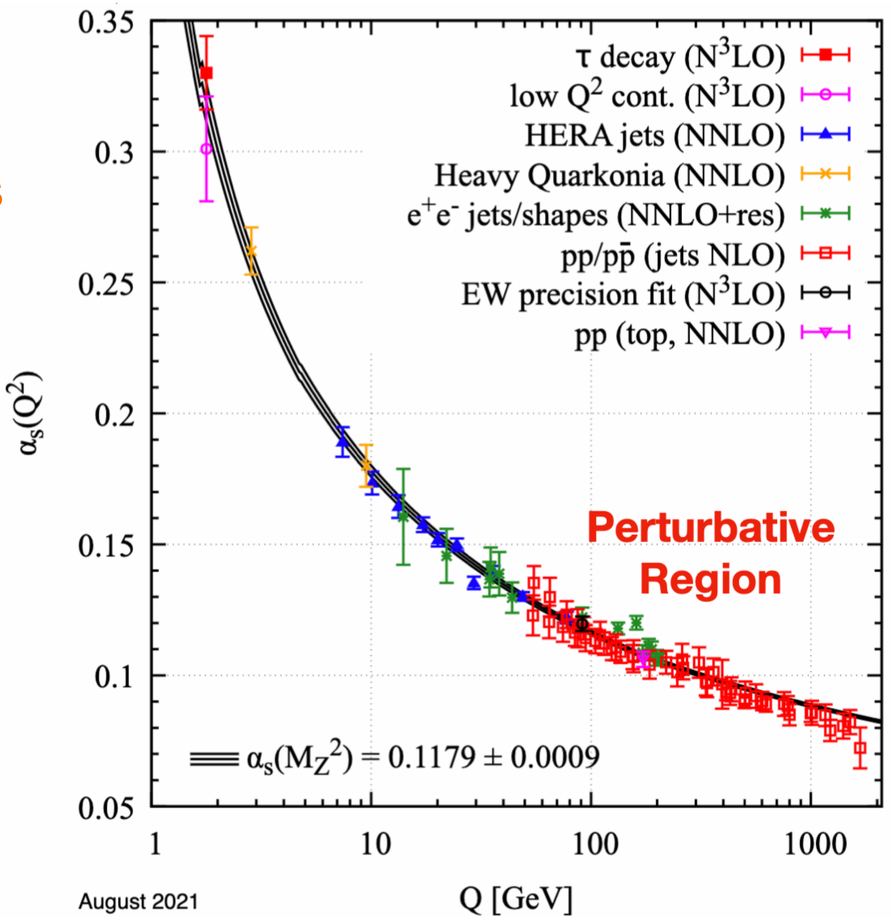
Preeti Dhankher
UCB/LBNL
on behalf of ALICE Collaboration

Hot Jets Workshop
UIUC
08 Jan 2025



Jets probe a wide range of Q^2



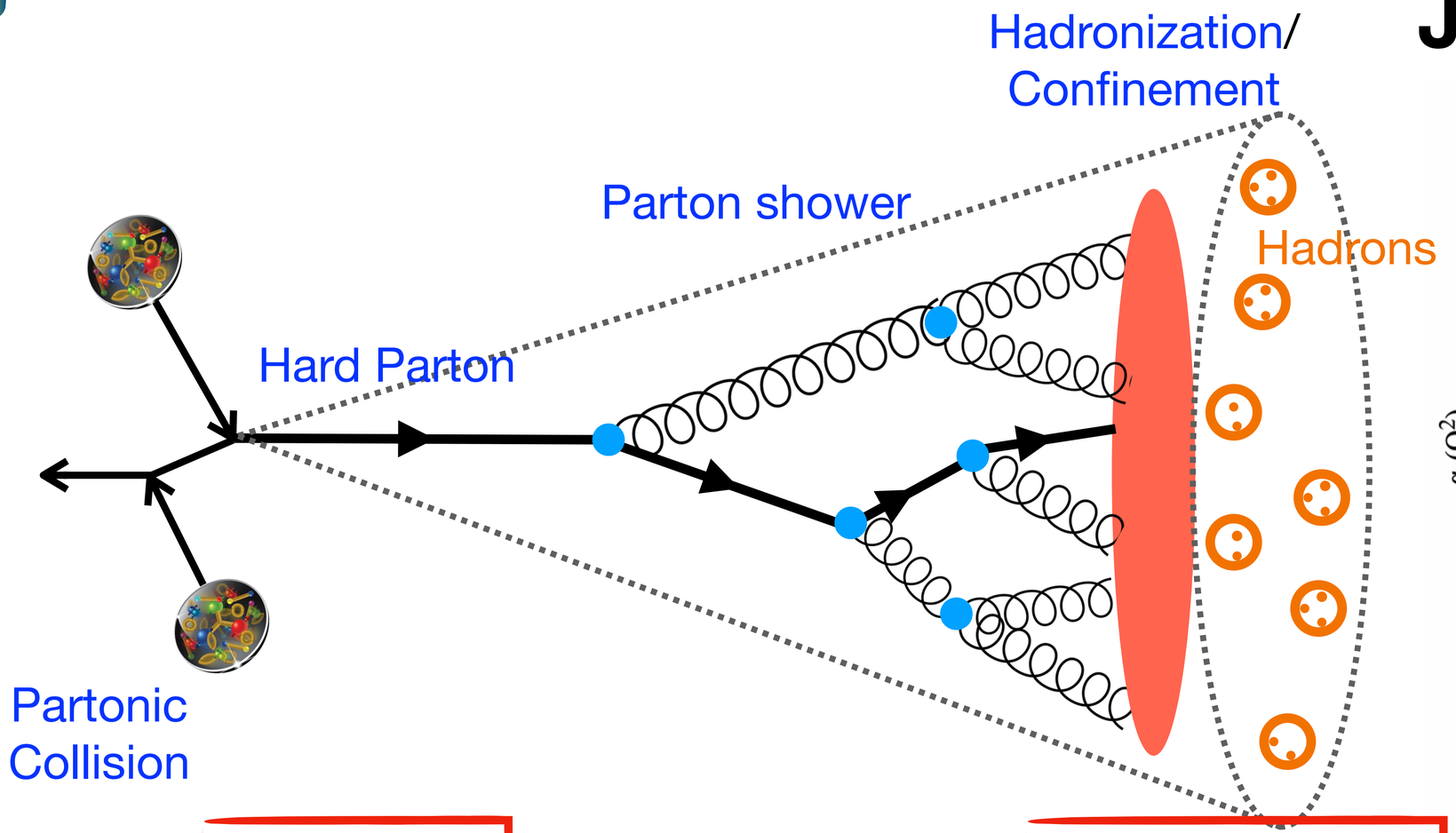


Hard process
>> $\mathcal{O}$(1GeV)

Parton shower
> $\mathcal{O}$(1GeV)

Confinement
~ $\mathcal{O}$(1GeV)

Jets probe a wide range of Q^2



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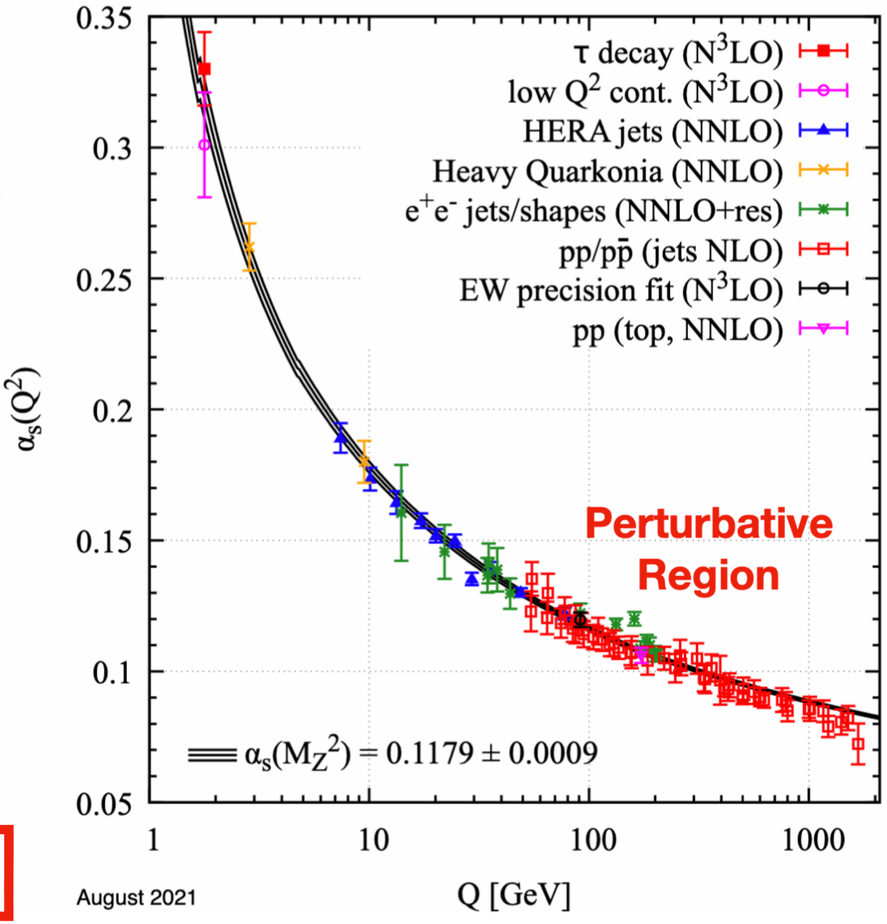
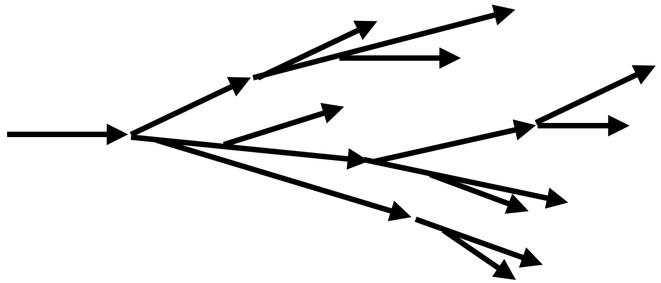
Jets!

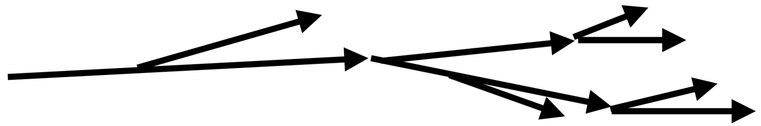


Flavor dependence in QCD showers

Gluon-initiated shower



Quark-initiated shower



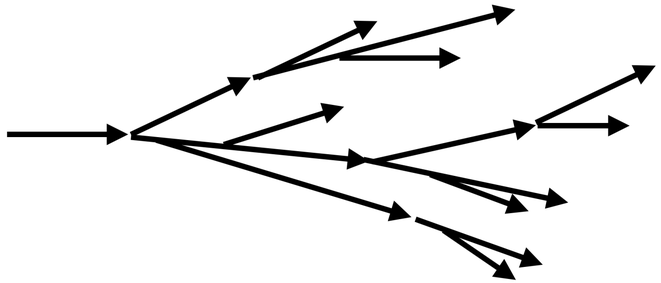
$$\frac{C_A}{C_F} = \frac{9}{4}$$

Casimir color factors

Gluon-initiated showers are expected to have a broader and softer fragmentation profile than quark-initiated showers

Flavor dependence in QCD showers

Gluon-initiated shower



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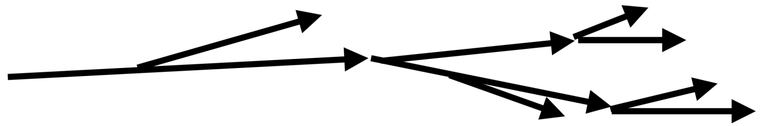
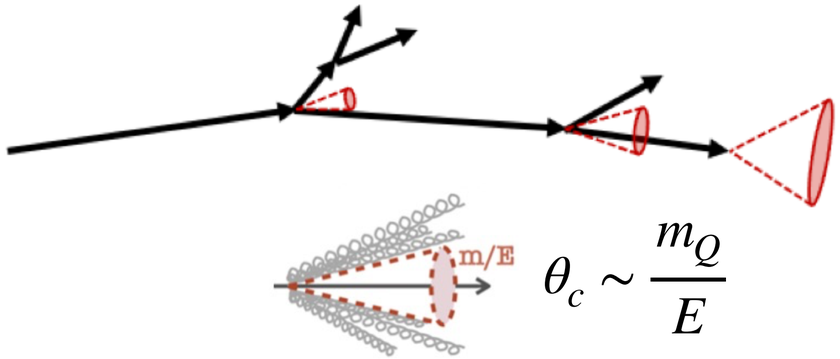


$$\frac{C_A}{C_F} = \frac{9}{4}$$

Heavy-quark-initiated shower



$$\theta_c \sim \frac{m_Q}{E}$$

Casimir color factors

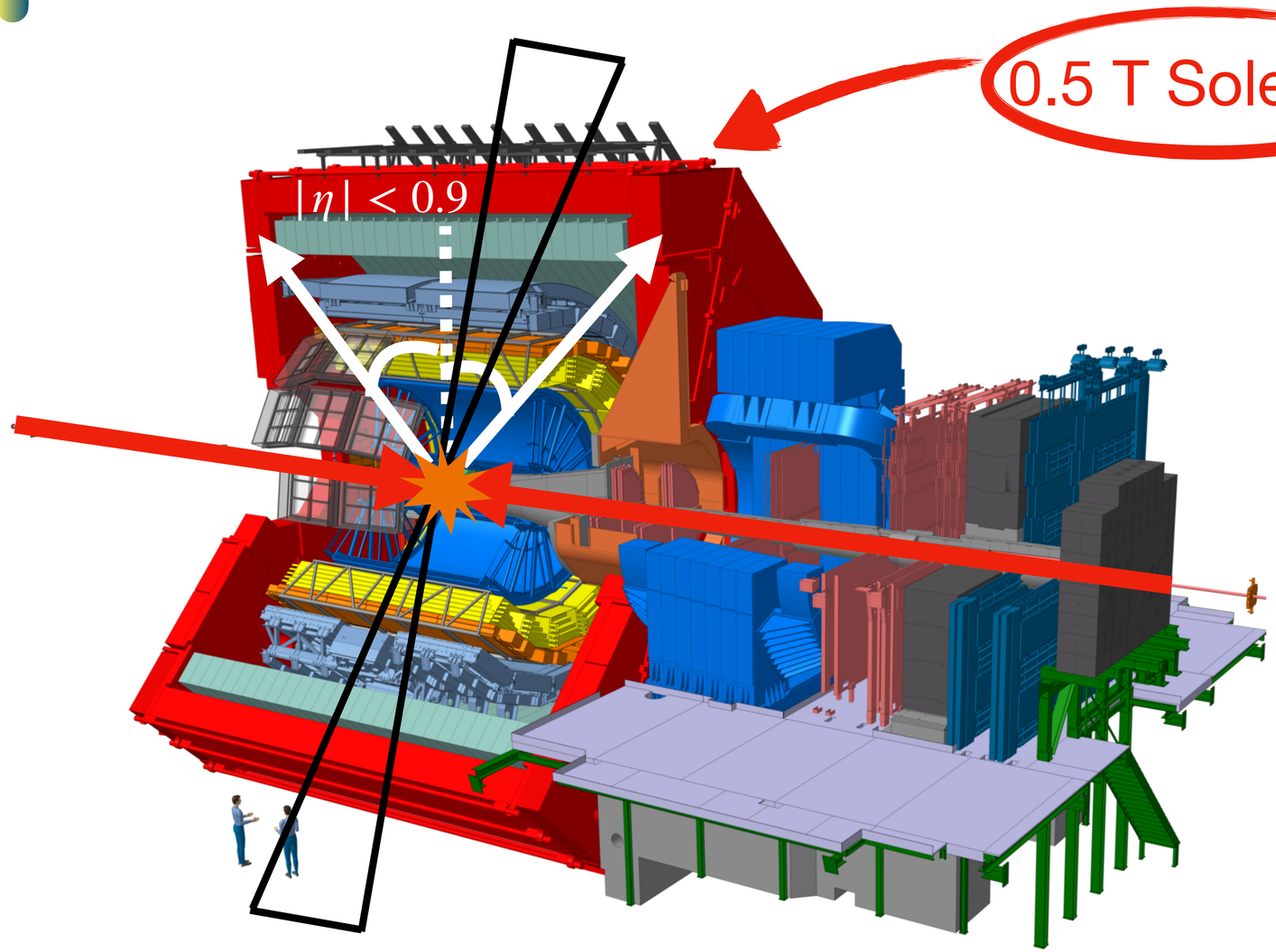
Gluon-initiated showers are expected to have a broader and softer fragmentation profile than quark-initiated showers

Mass effects

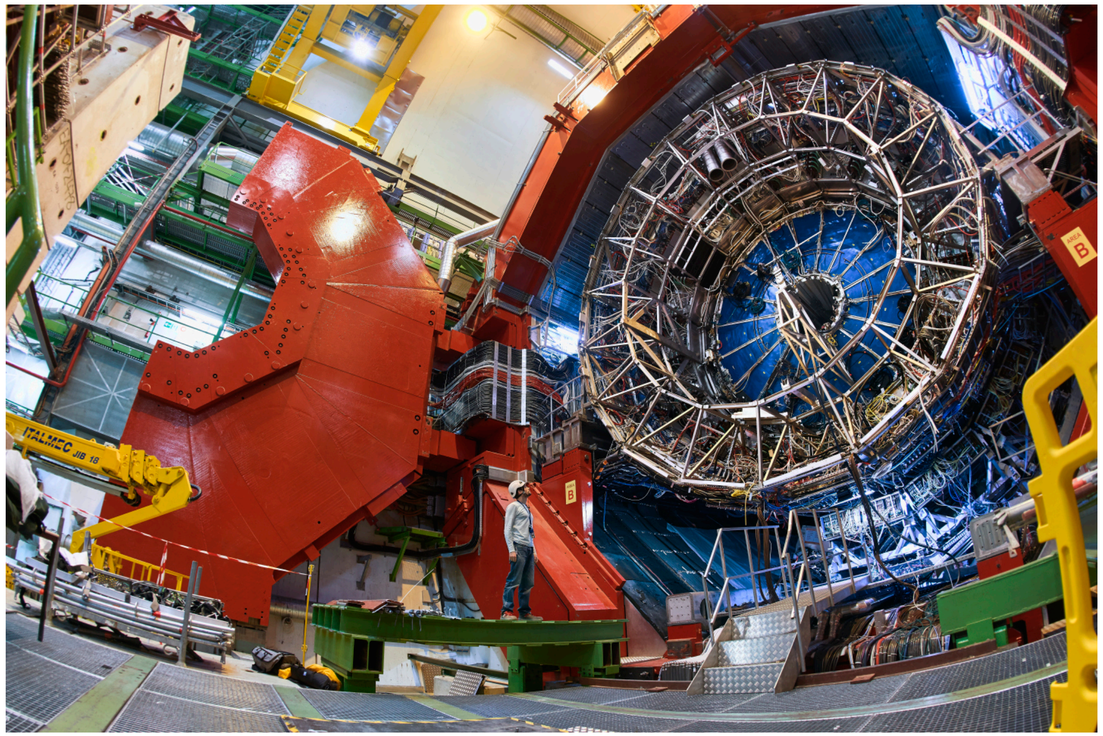
A harder fragmentation is expected in low energy heavy-quark initiated showers due to the presence of the dead-cone effect

Mass effects are dominant at low p_T

A Large Ion Collider Experiment



Jet of particles



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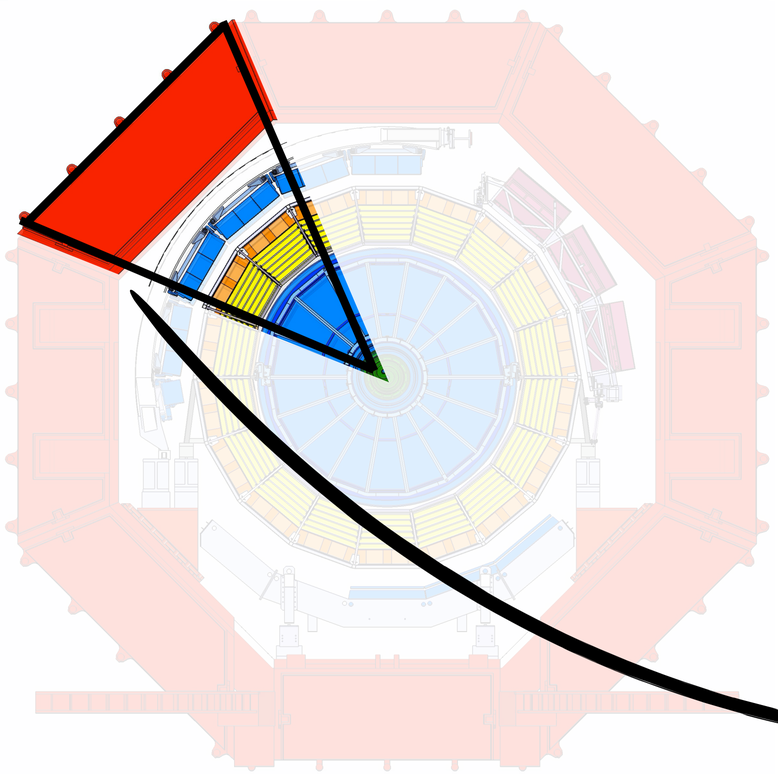
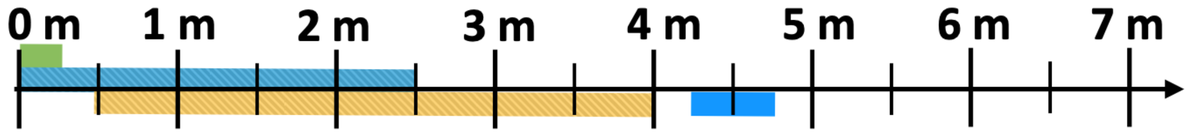




EMCal

TOF

TRD

Tracking: Momentum

Vertexing: Origin point

TPC

ITS

π^+

K^-

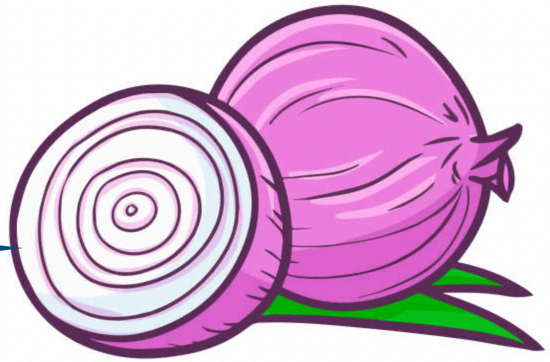
γ

Particle identification(PID)

Calorimeter: energy

Solenoid magnet

We both have layers!



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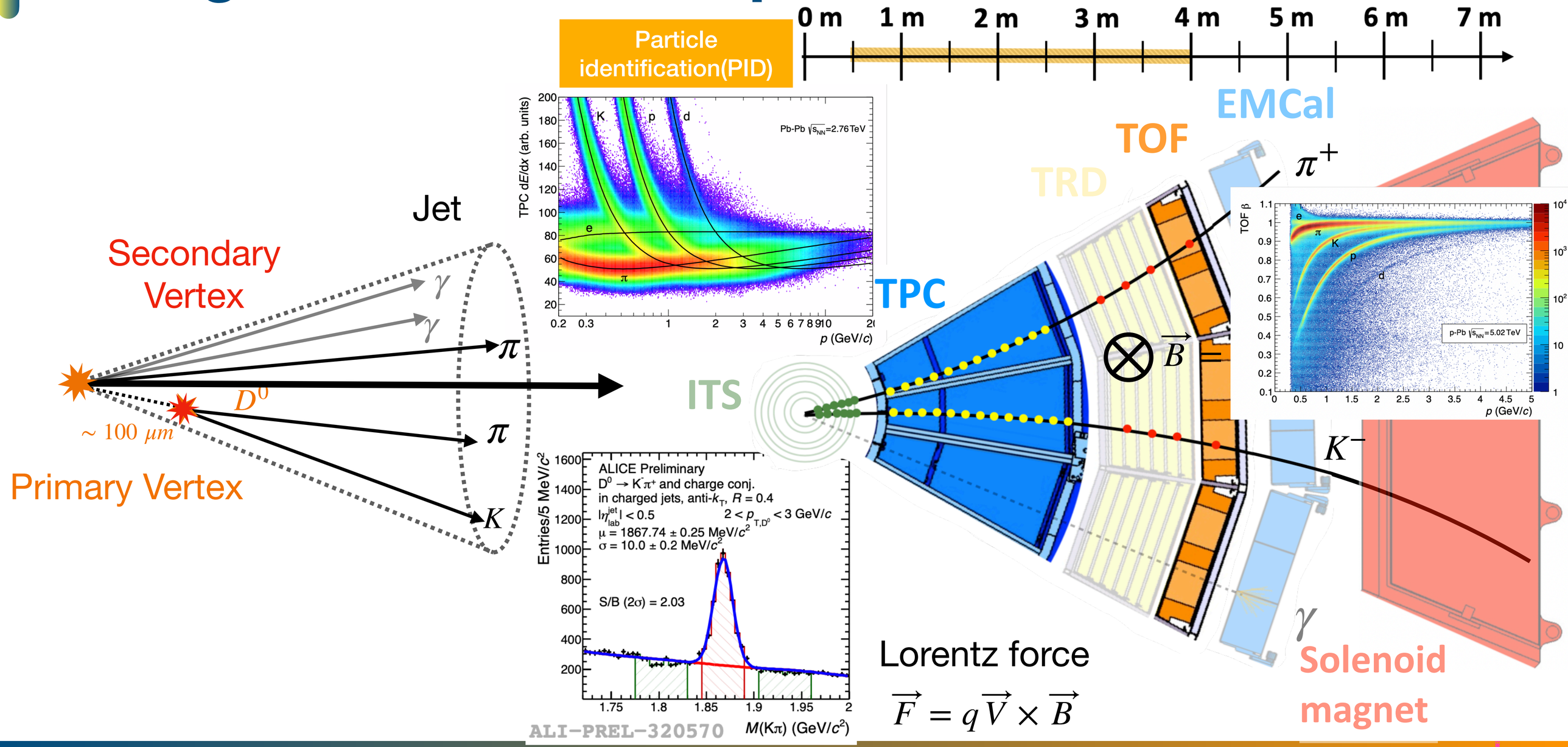

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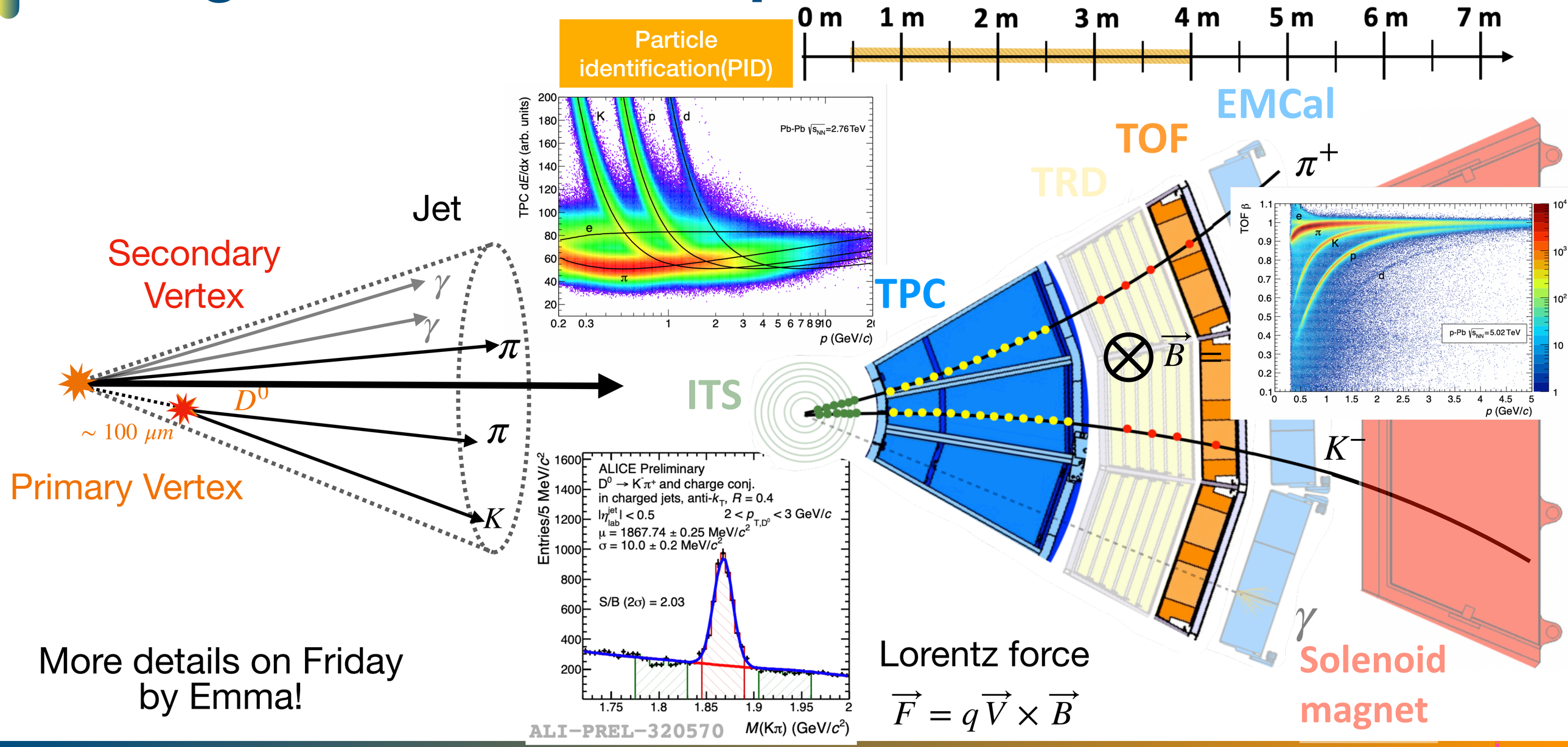


More details on Friday by Emma!

Lorentz force

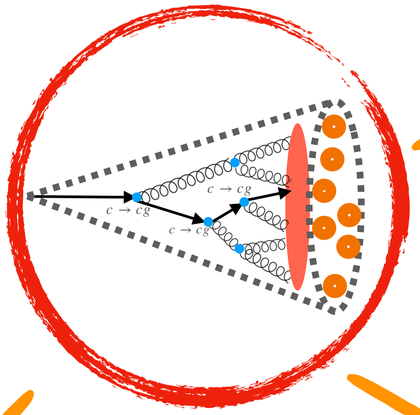
$$\vec{F} = q\vec{V} \times \vec{B}$$

Charm jet measurements with ALICE

Jet axes differences

Jet angularities

Energy-energy correlator



Dead cone

Fragmentation function $z_{\parallel}$

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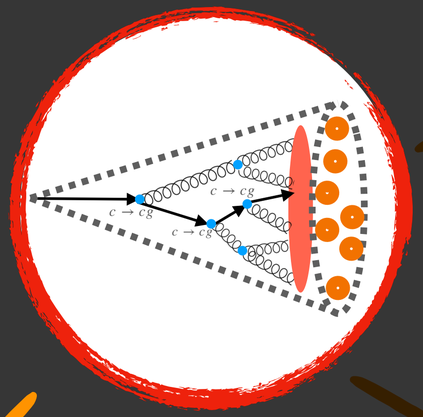


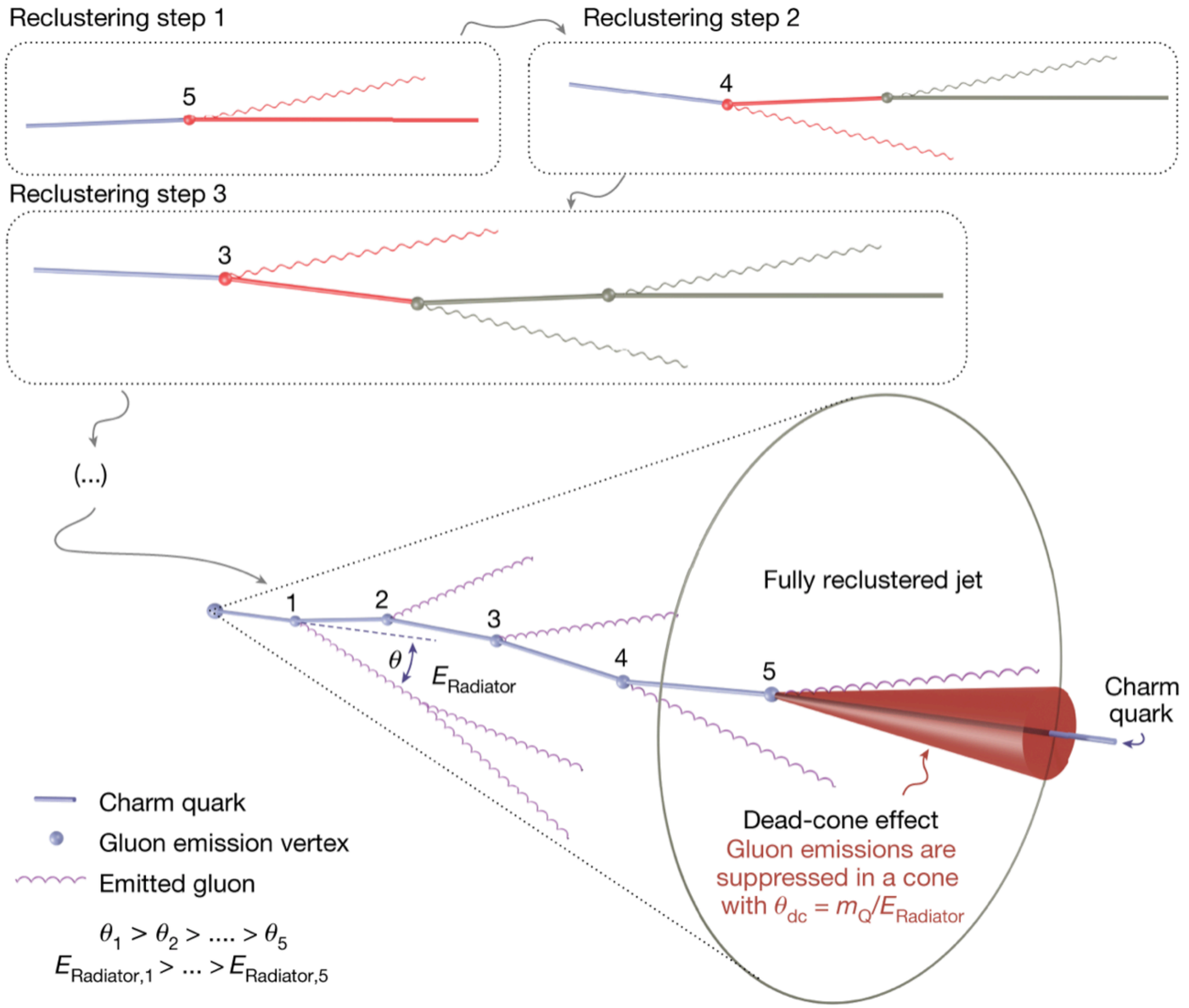
Dead cone

Fragmentation function $z_{\parallel}$

First direct observation of the dead-cone effect

Challenges of Measurement:

- Determining the dynamic direction of the heavy quark throughout the shower



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Challenges of Measurement:

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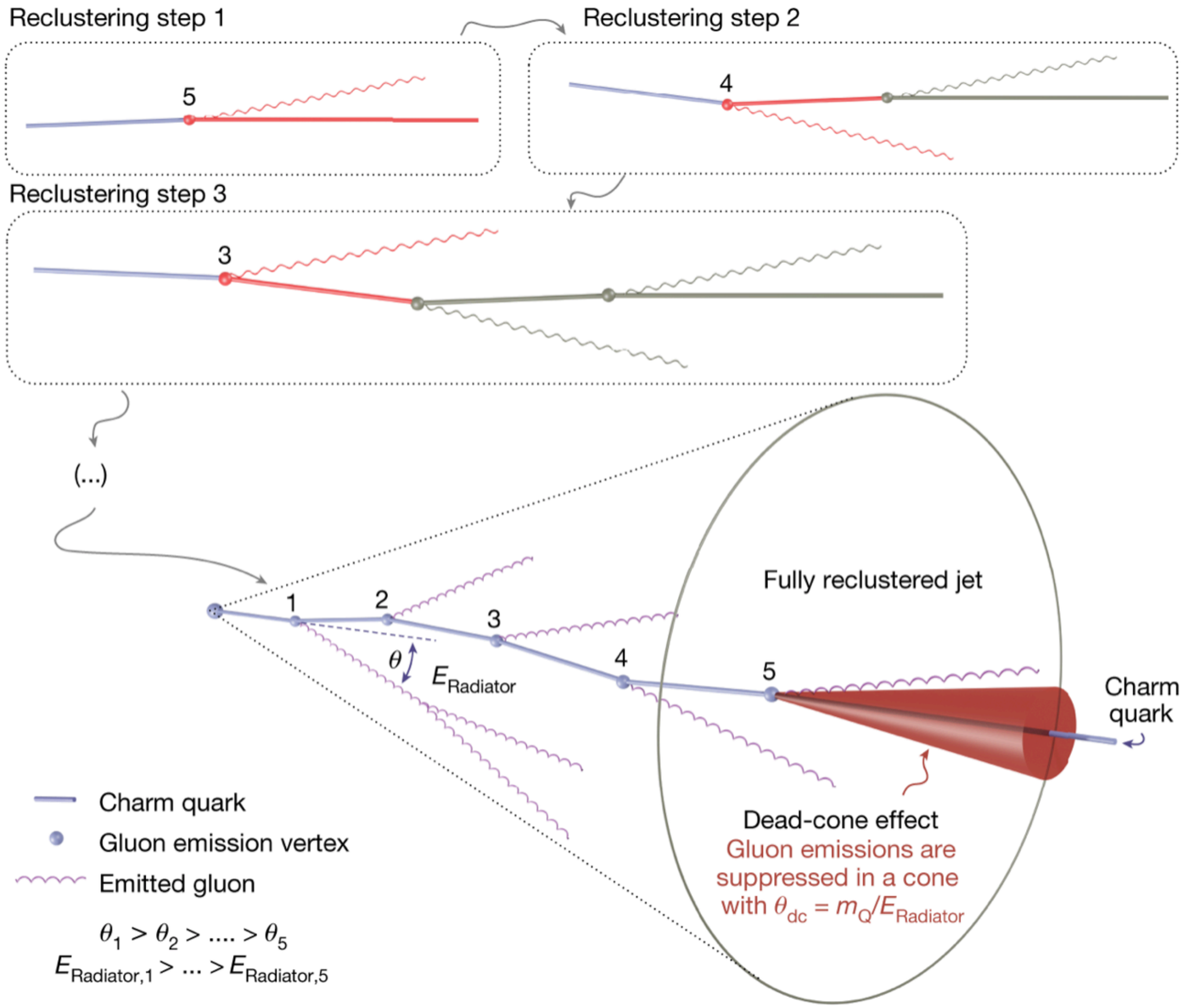
Solution:

- use declustering procedure with Cambridge/Aachen algorithm



First direct observation of the dead-cone effect

Challenges of Measurement:

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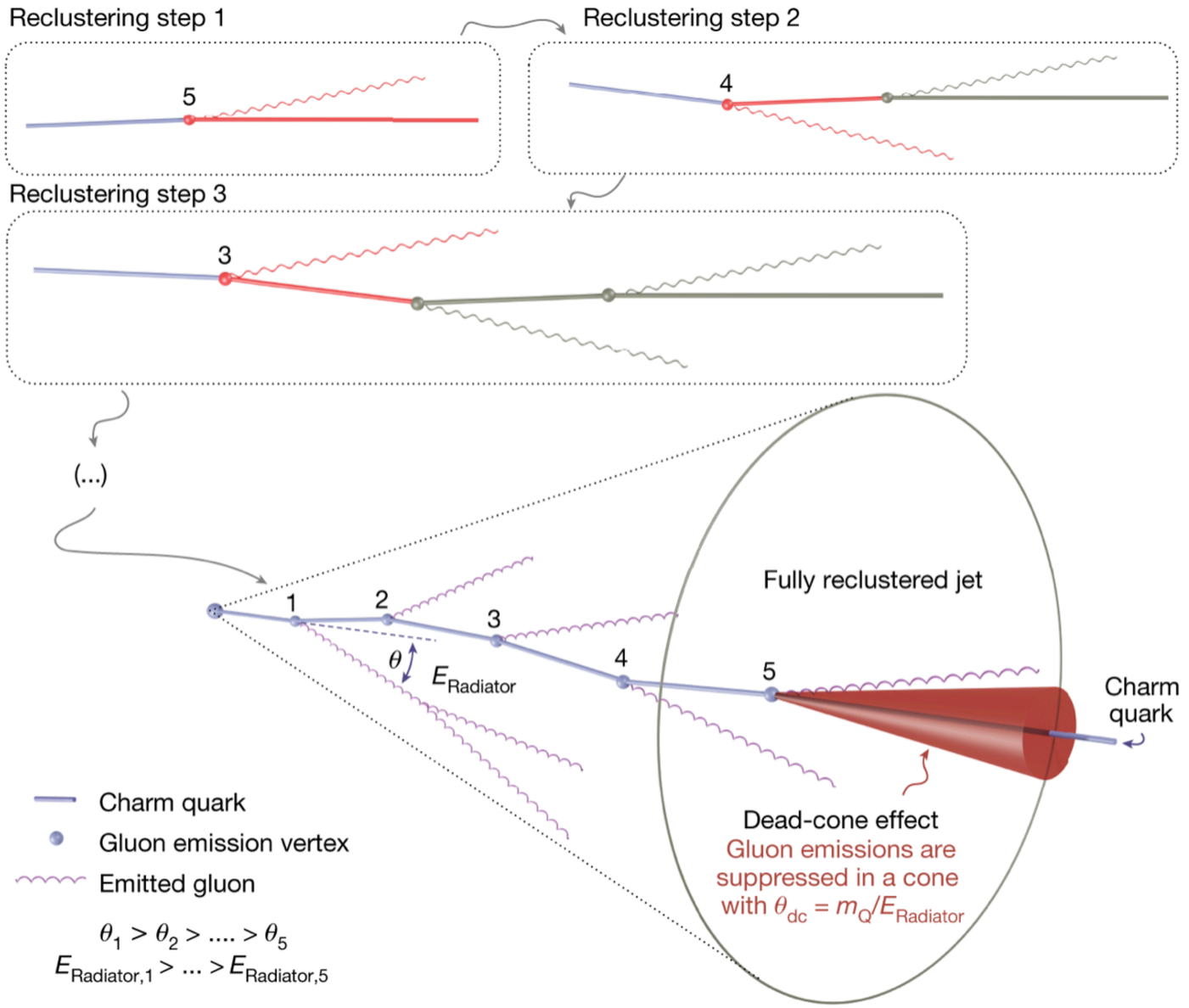
Solution:

- use declustering procedure with Cambridge/Aachen algorithm

Cambridge/Aachen clusters constituents based solely on their angular distance from one another

→ well motivated by QCD



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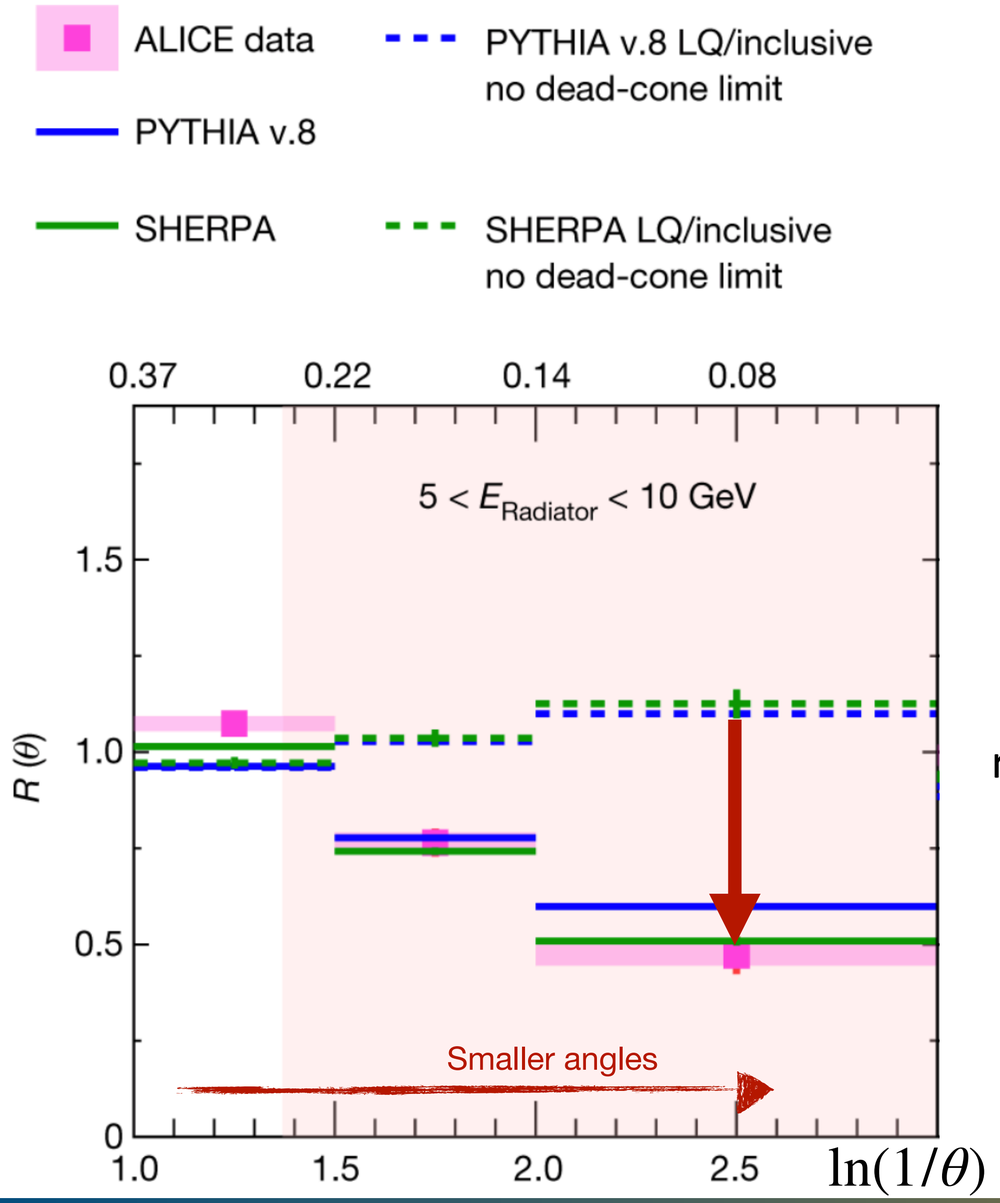
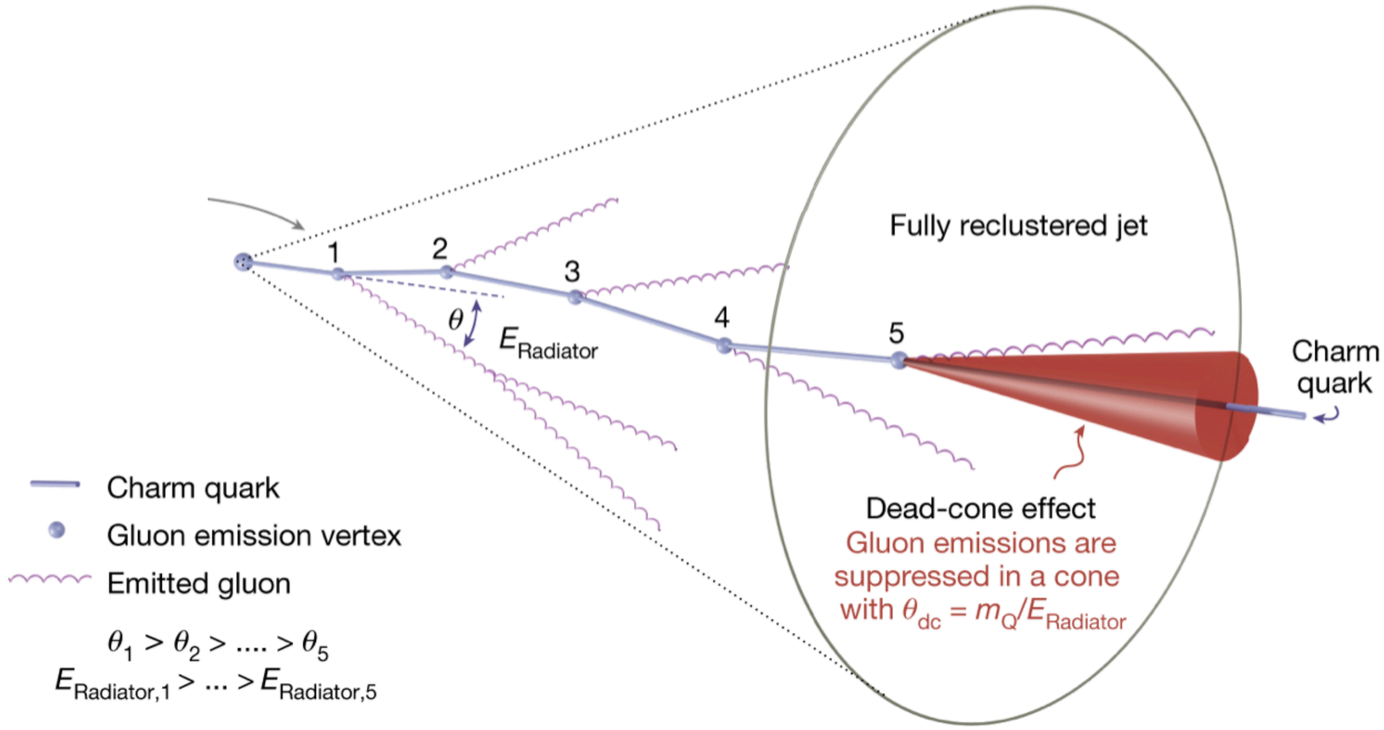




ratio of the splitting angle (θ) for D^0-tagged vs. inclusive jets, vs. E_{Radiator}

$$R(\theta) = \frac{1}{N^{\mathrm{D^0jets}}} \frac{\mathrm{d}n^{\mathrm{D^0jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\mathrm{inclusive\ jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\ jets}}}{\mathrm{d}\ln(1/\theta)} \Big|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

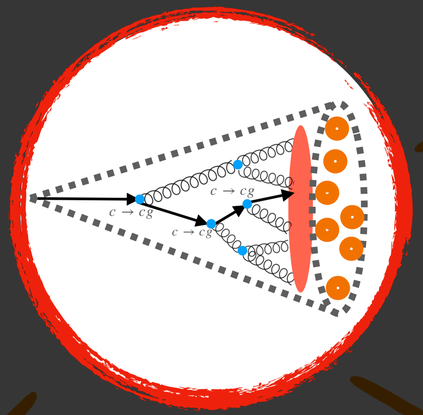
significant suppression of small-angle emissions

Charm jet measurements with ALICE

Jet axes differences

Jet angularities

Energy-energy correlator



Follow Emma's talk!

Dead-cone

Fragmentation function $z_{\parallel}$

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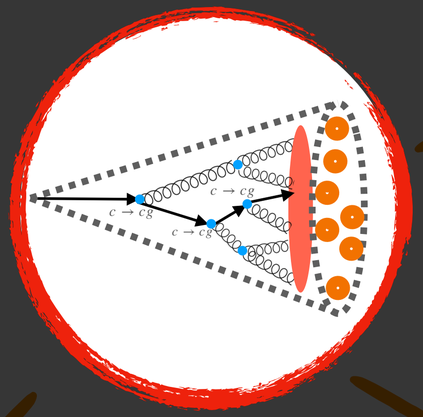


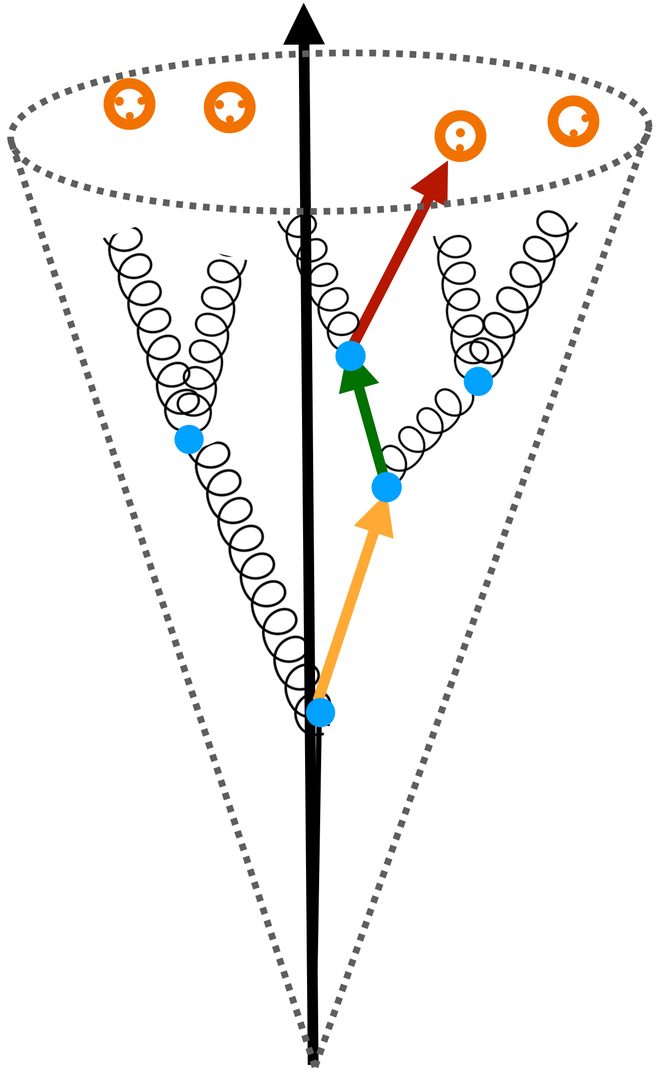
Dead-cone

Fragmentation function $z_{\parallel}$

Probe mass and color effects with heavy-flavor jets

Jet Angularities :

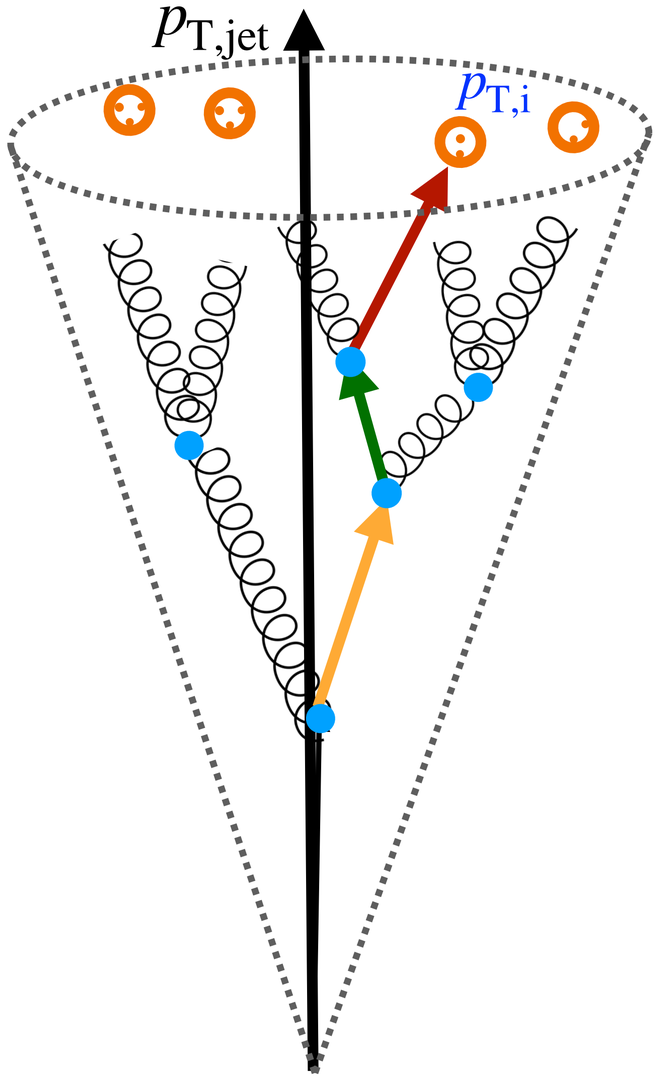
$$\lambda_\alpha = \sum_{i \in \text{jet}} \dots$$



Probe mass and color effects with heavy-flavor jets

Jet Angularities :

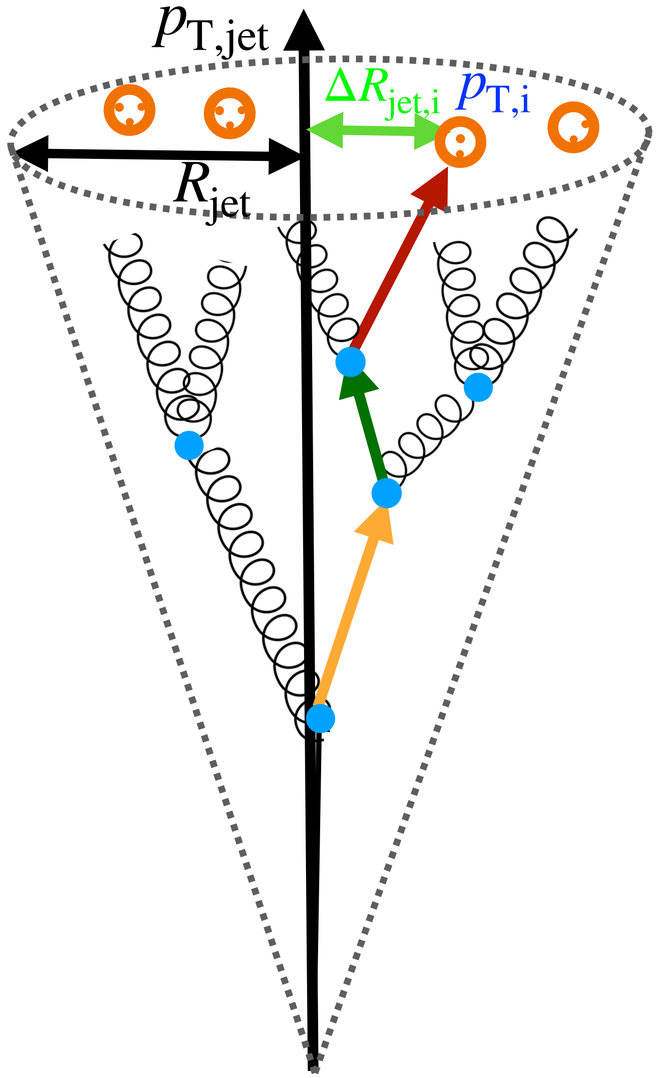
$$\lambda_\alpha = \sum_{i \in jet} \left(\frac{p_{T,i}}{p_{T,jet}} \right)^\kappa \dots$$



Probe mass and color effects with heavy-flavor jets

Jet Angularities : Where is the p_T in the jet?

$$\lambda_\alpha = \sum_{i \in jet} \left(\frac{p_{T,i}}{p_{T,jet}} \right)^\kappa \left(\frac{\Delta R_{jet,i}}{R_{jet}} \right)^\alpha$$



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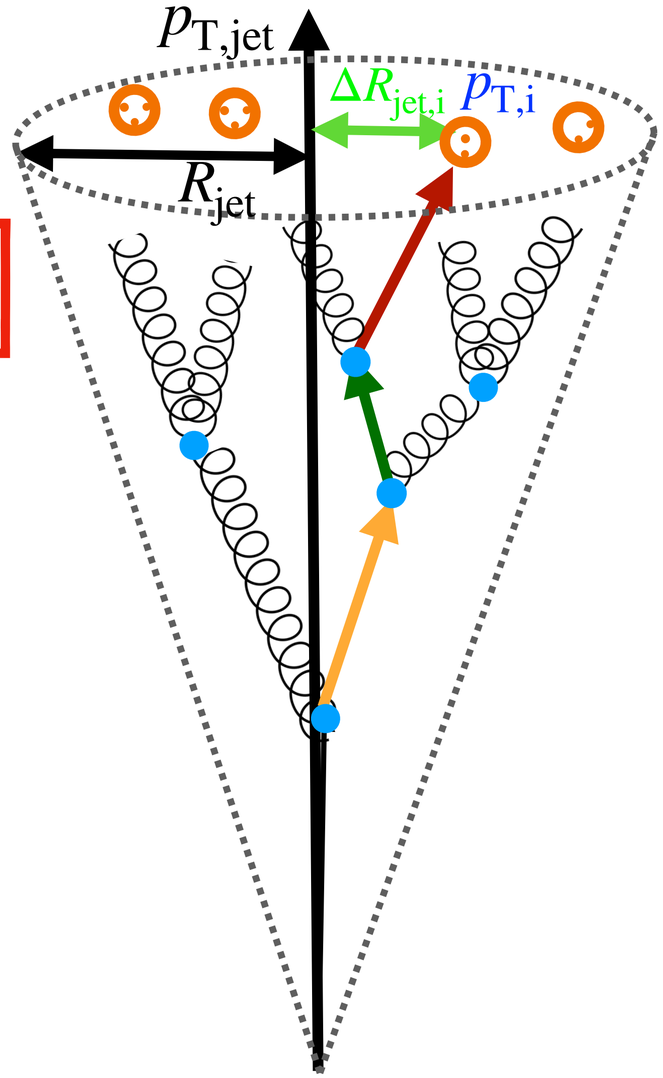
κ & α tunable parameter!

κ =1 & $\alpha > 0$
IRC safe observable!



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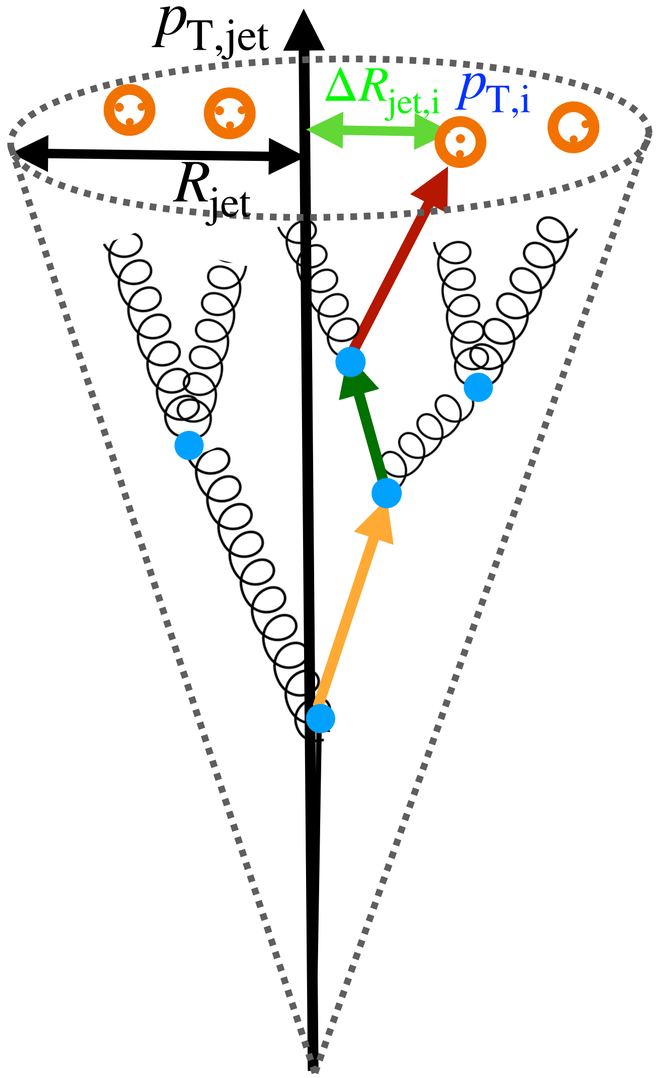
$$\lambda_\alpha = \sum_{i \in jet} z_i \theta_i^\alpha$$

α tunable parameter!



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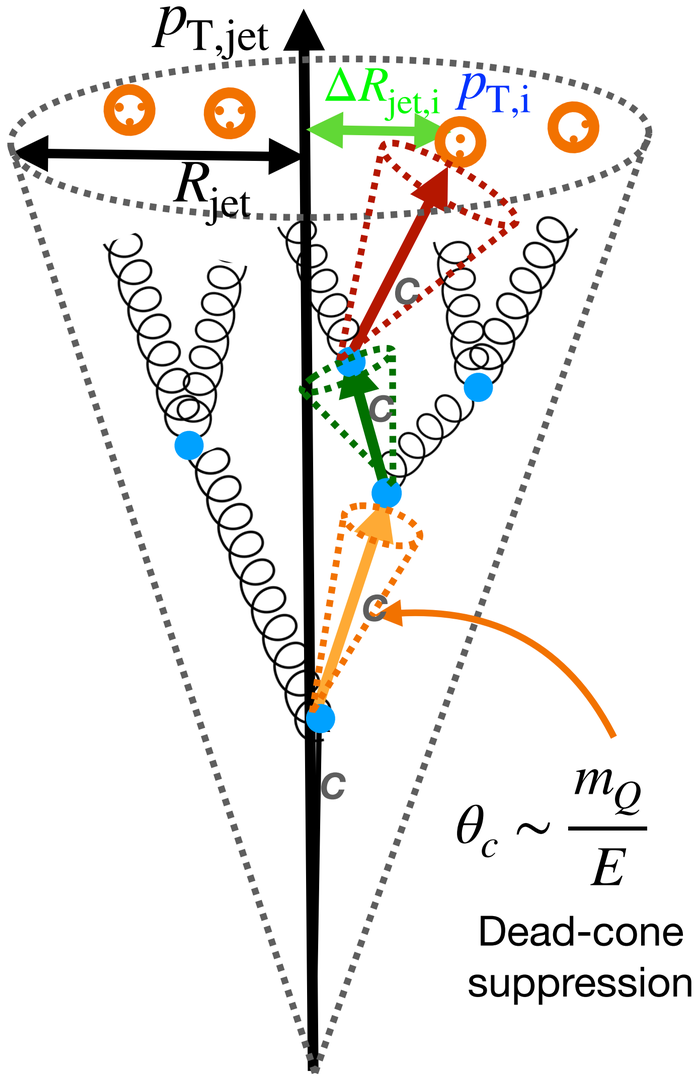

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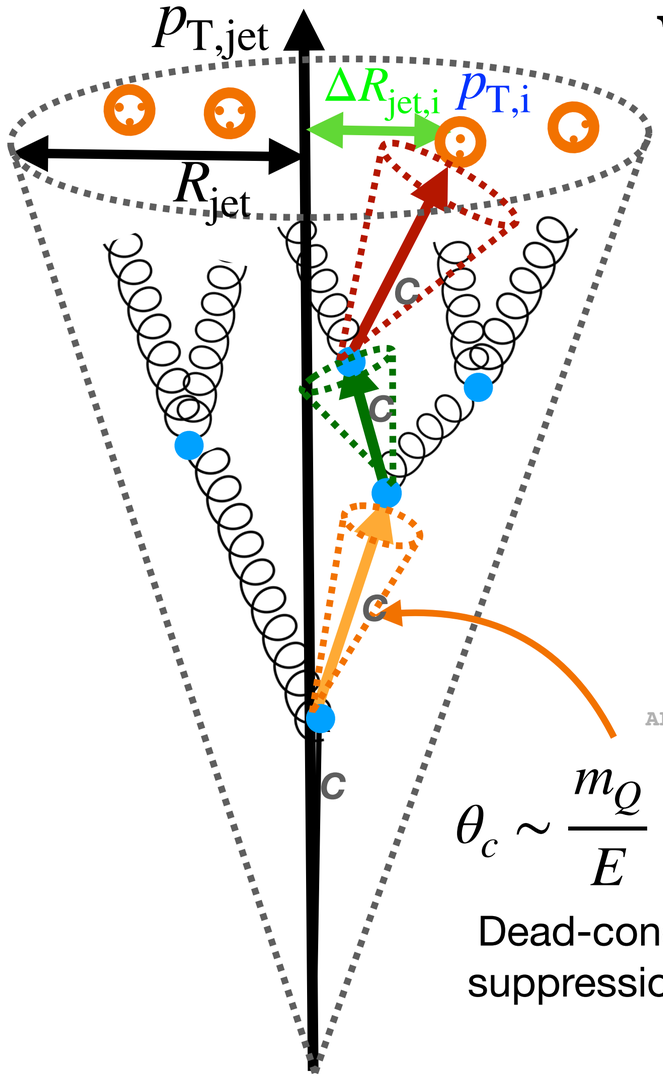
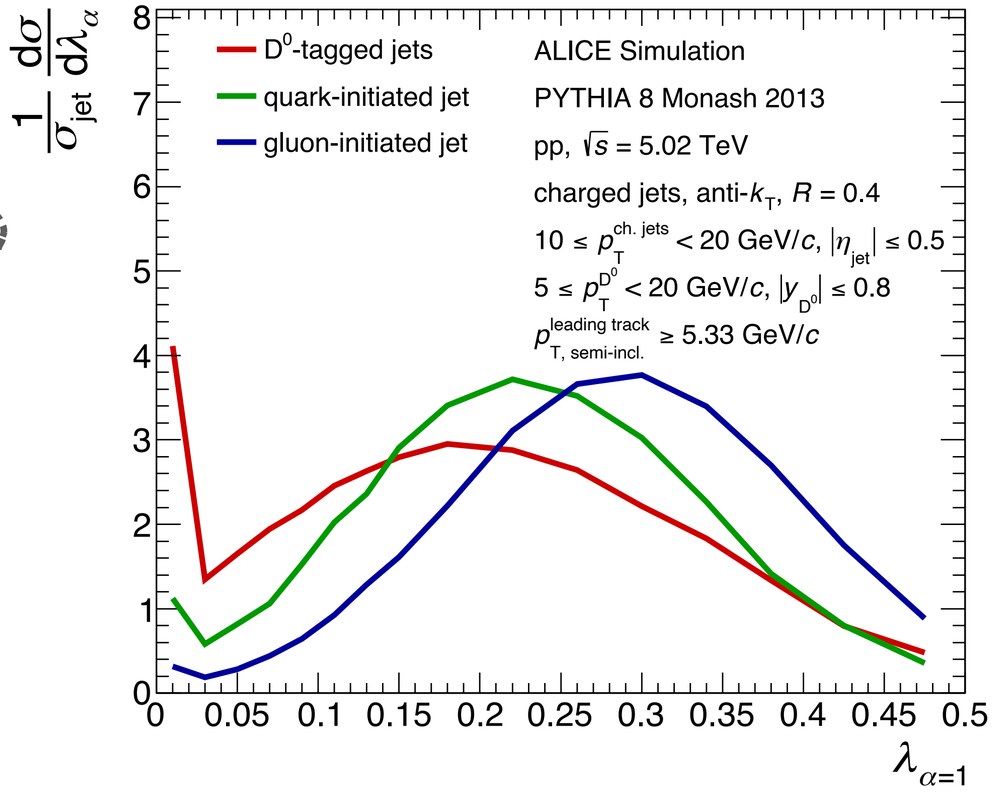
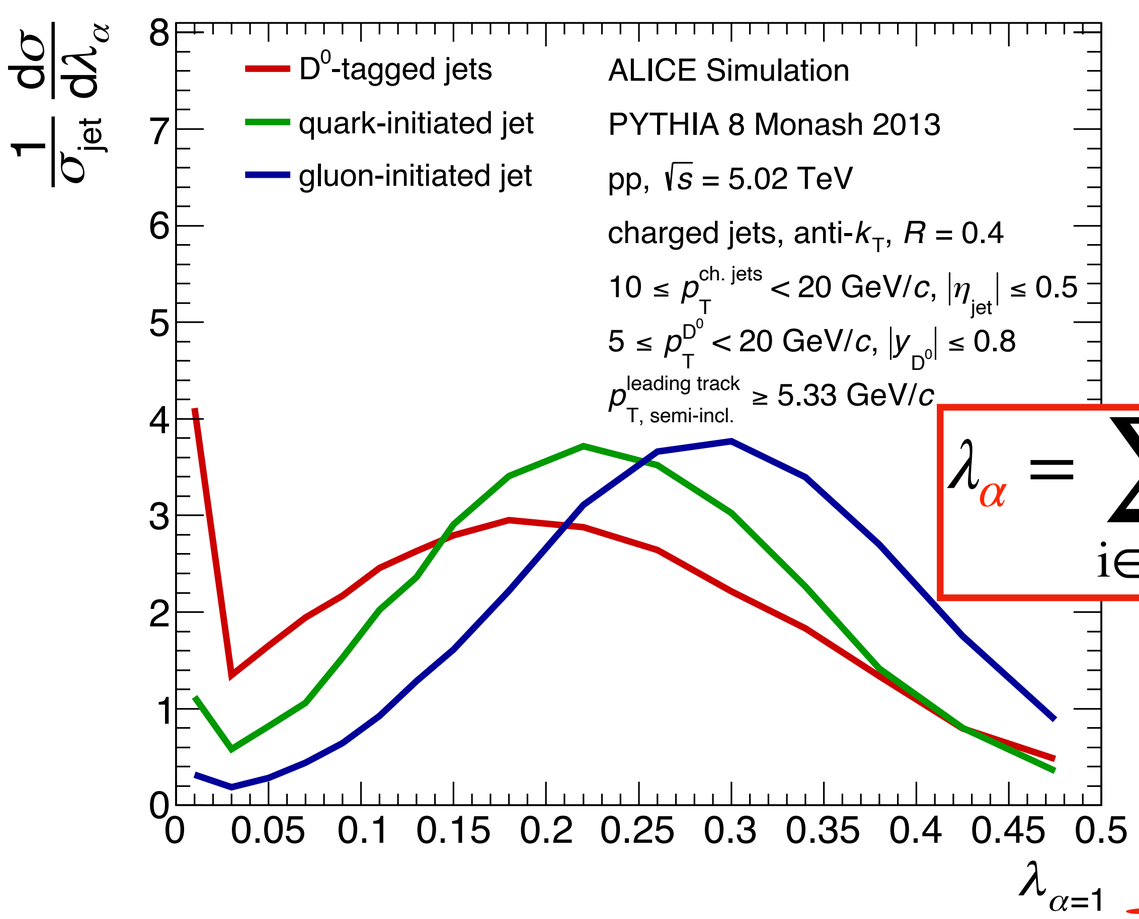




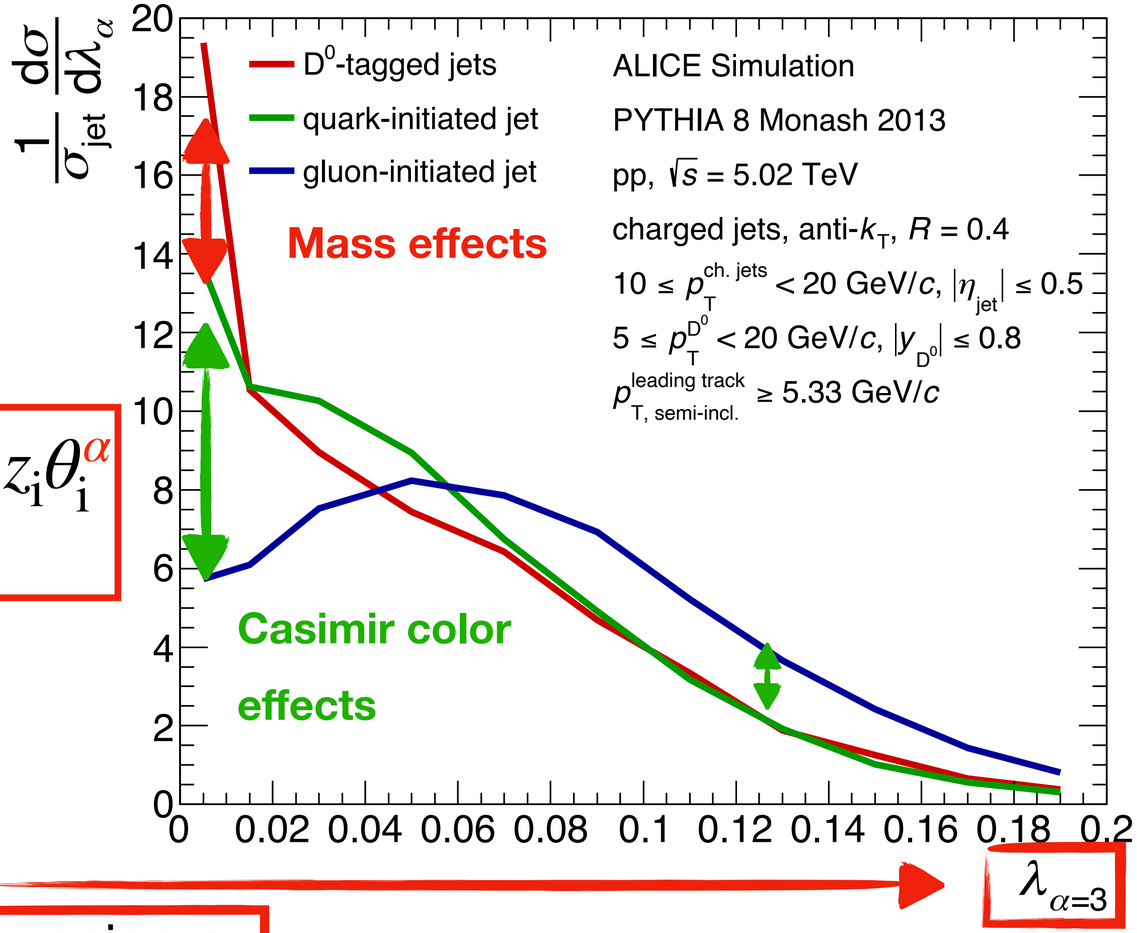
ALI-SIMUL-540830

The jet angularities are sensitive to flavor dependences in shower

Results: Probing flavor effects with angularity



$$\lambda_\alpha = \sum_{i \in jet} z_i \theta_i^\alpha$$



ALI-SIMUL-540830

increasing α

Charm distribution shifted to lower values of $\lambda_{\alpha=1}$ →**Dead-cone effect**

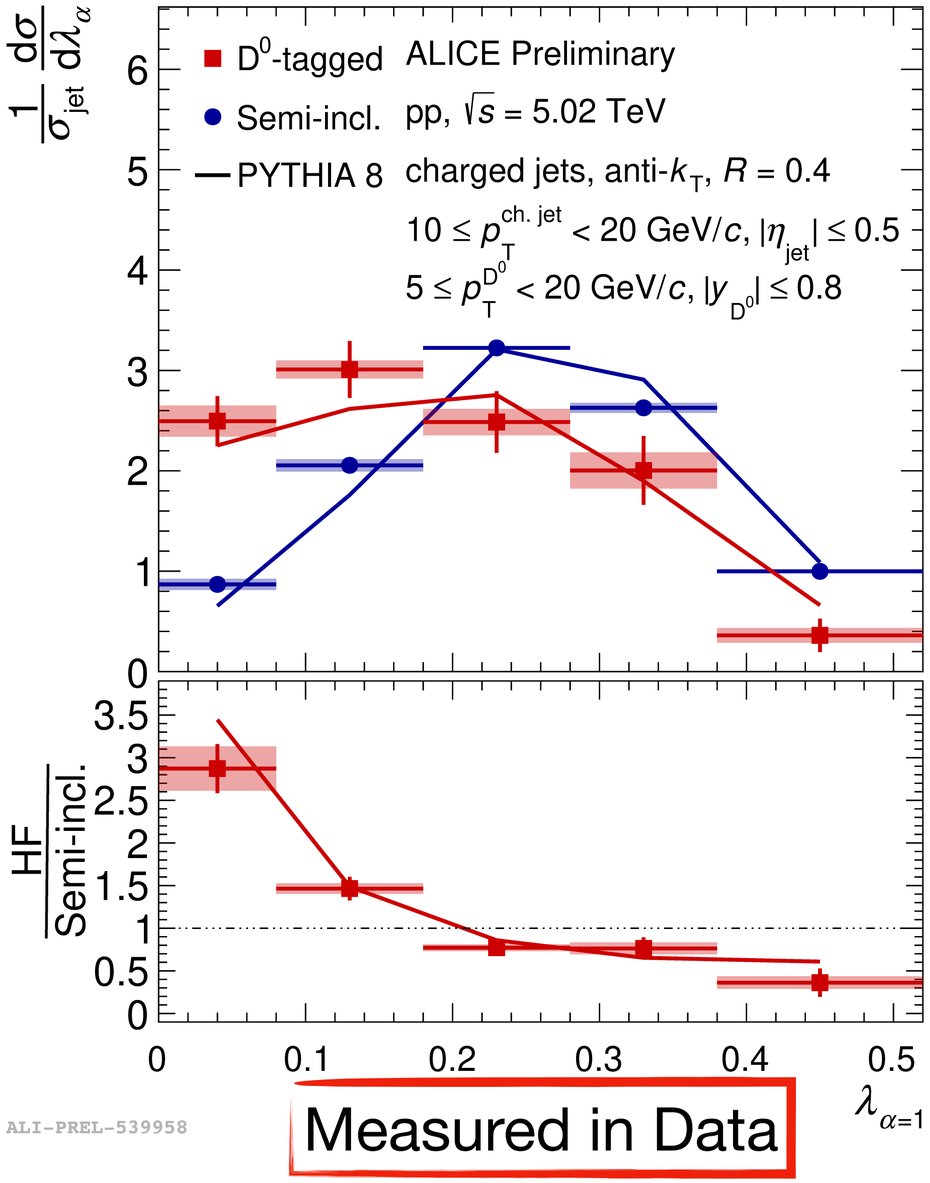
more weight on wide angle emissions→ Increased sensitivity to Casimir at wide angles

Results: Probing flavor effects with angularity

Jet Angularities :

$$\lambda_\alpha = \sum_{i \in jet} z_i \theta_i^\alpha$$

α tunable parameter



Measured in Data

Results: Probing flavor effects with angularity

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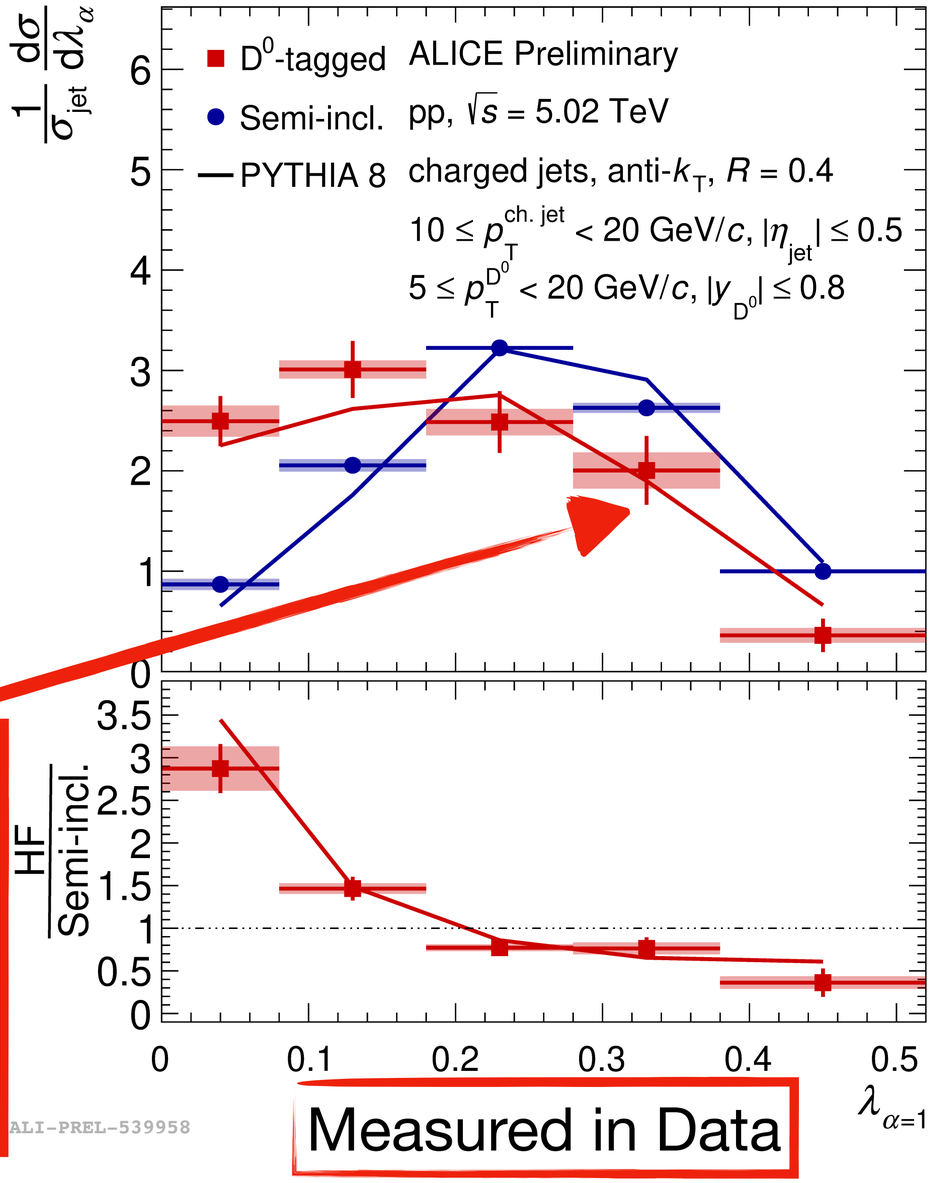
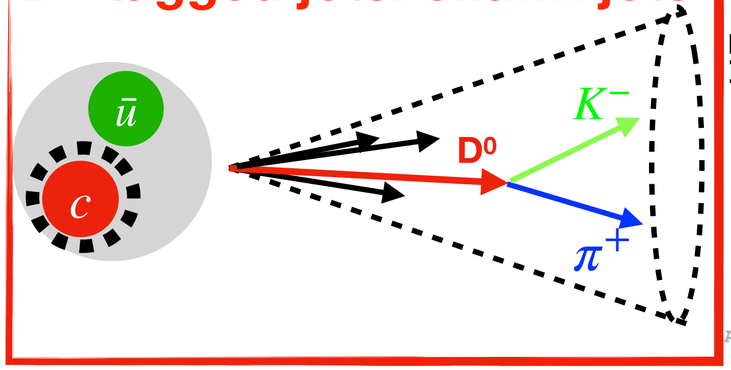


Measured in Data

D^0 tagged jets: charm jets



ALI-PREL-539958

Results: Probing flavor effects with angularity

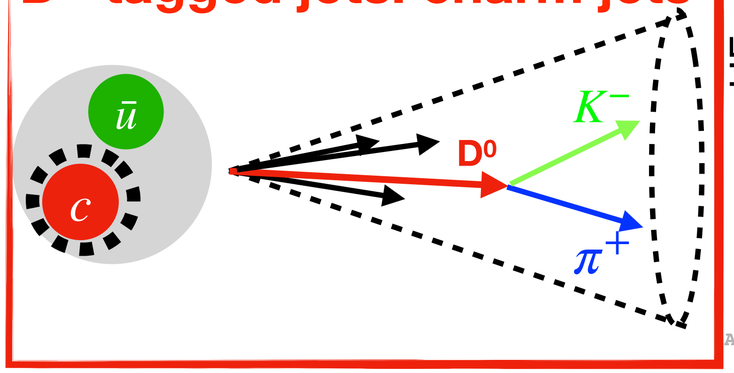
Jet Angularities :

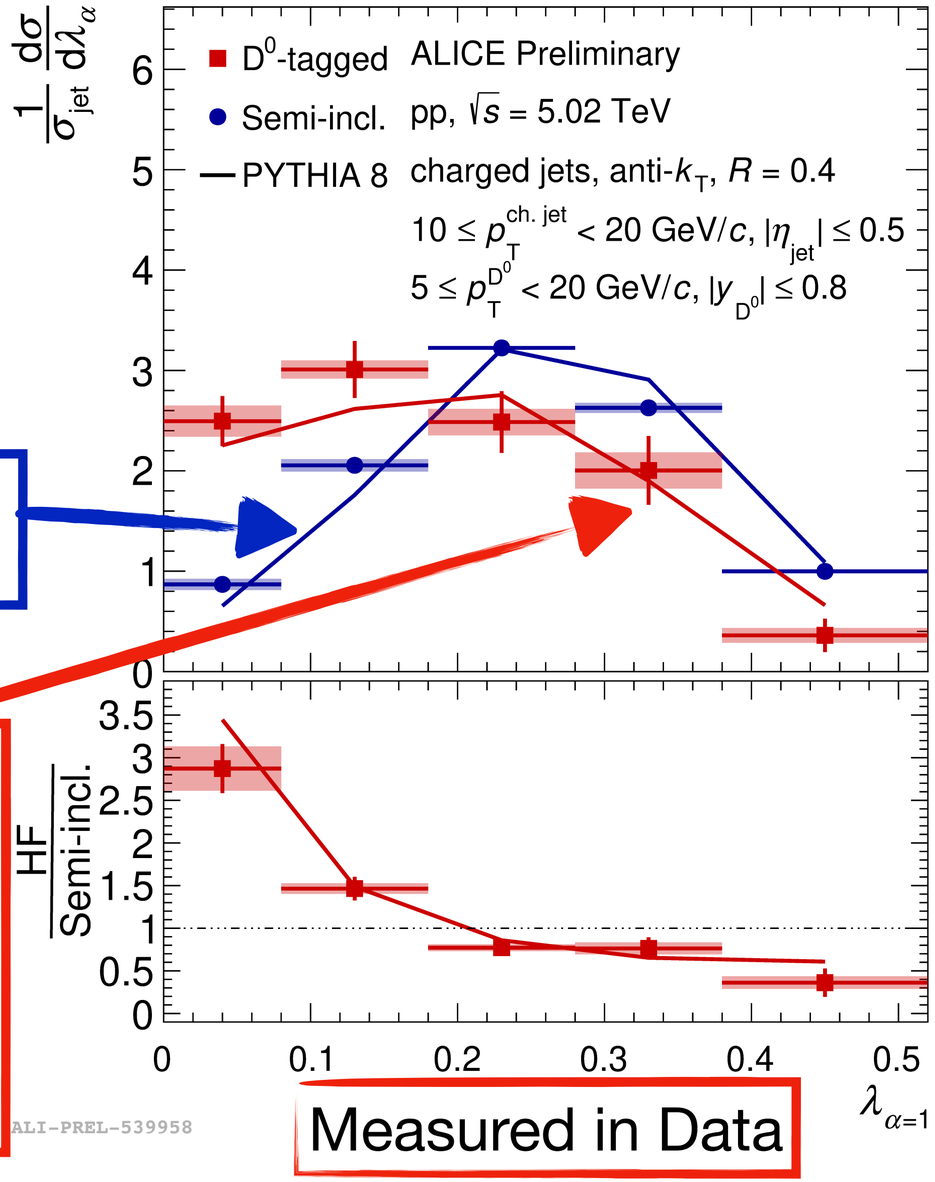
$$\lambda_\alpha = \sum_{i \in jet} z_i \theta_i^\alpha$$

α tunable parameter

Semi-inclusive jets: gluon and light-flavor jets

D^0 tagged jets: charm jets





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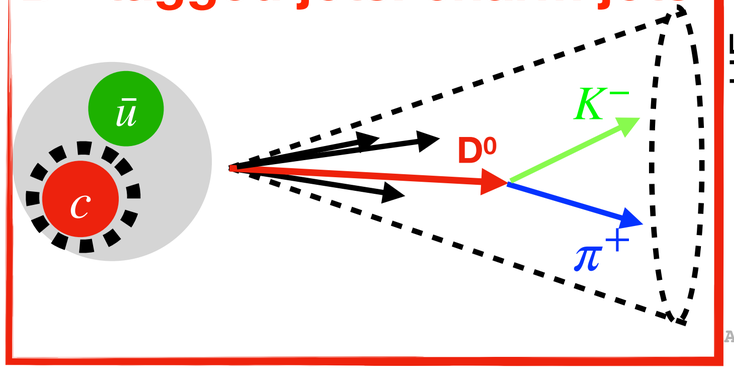

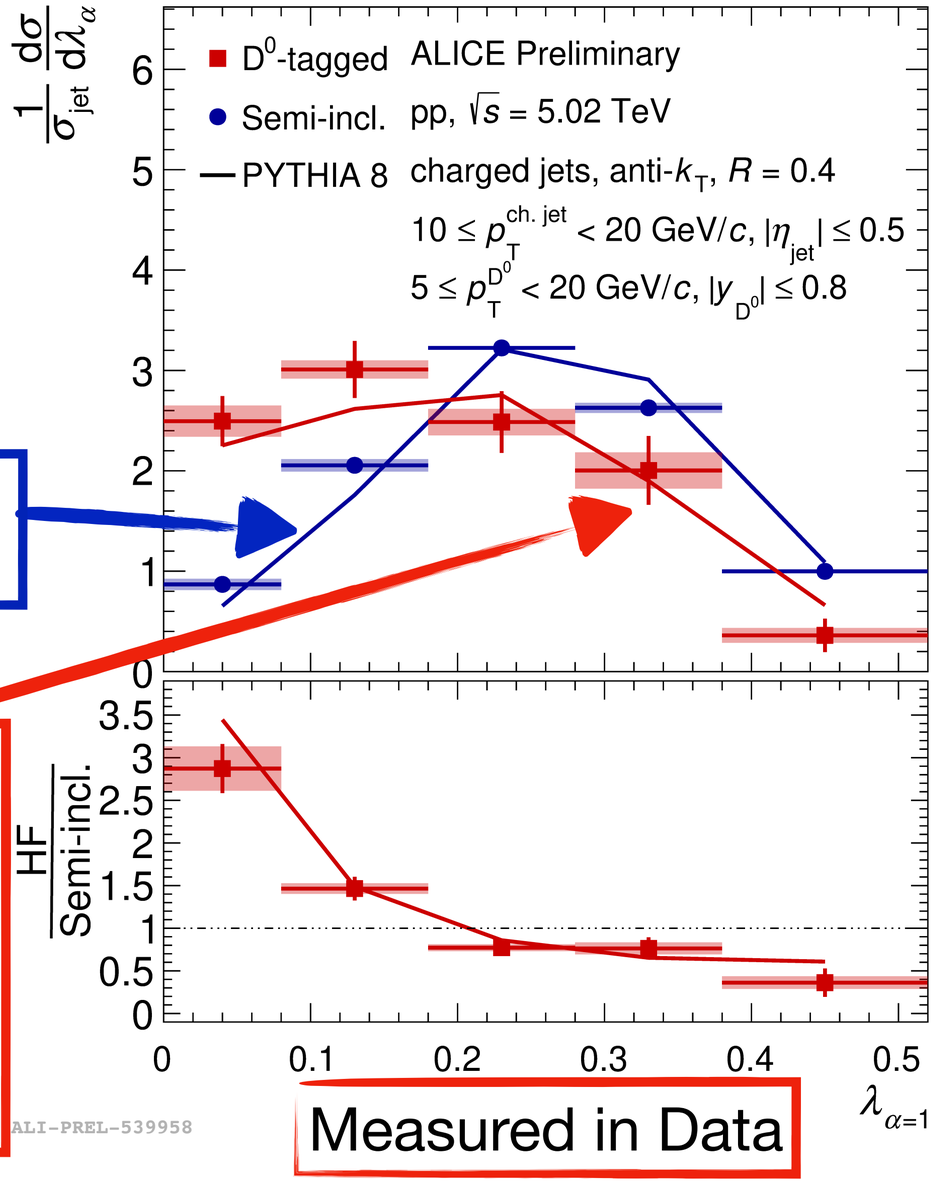

Measured in Data

Why enhanced?

Results: Probing flavor effects with angularity

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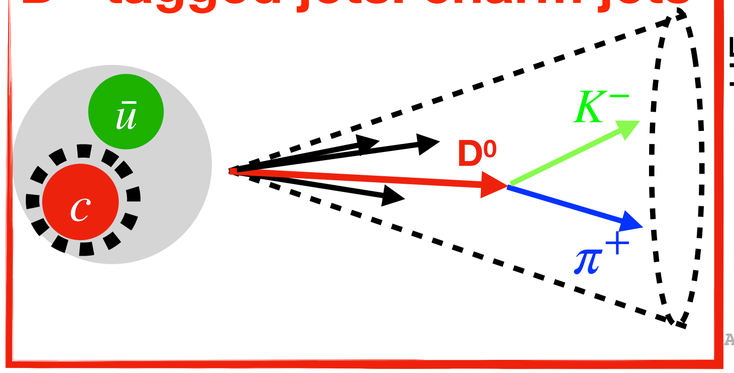

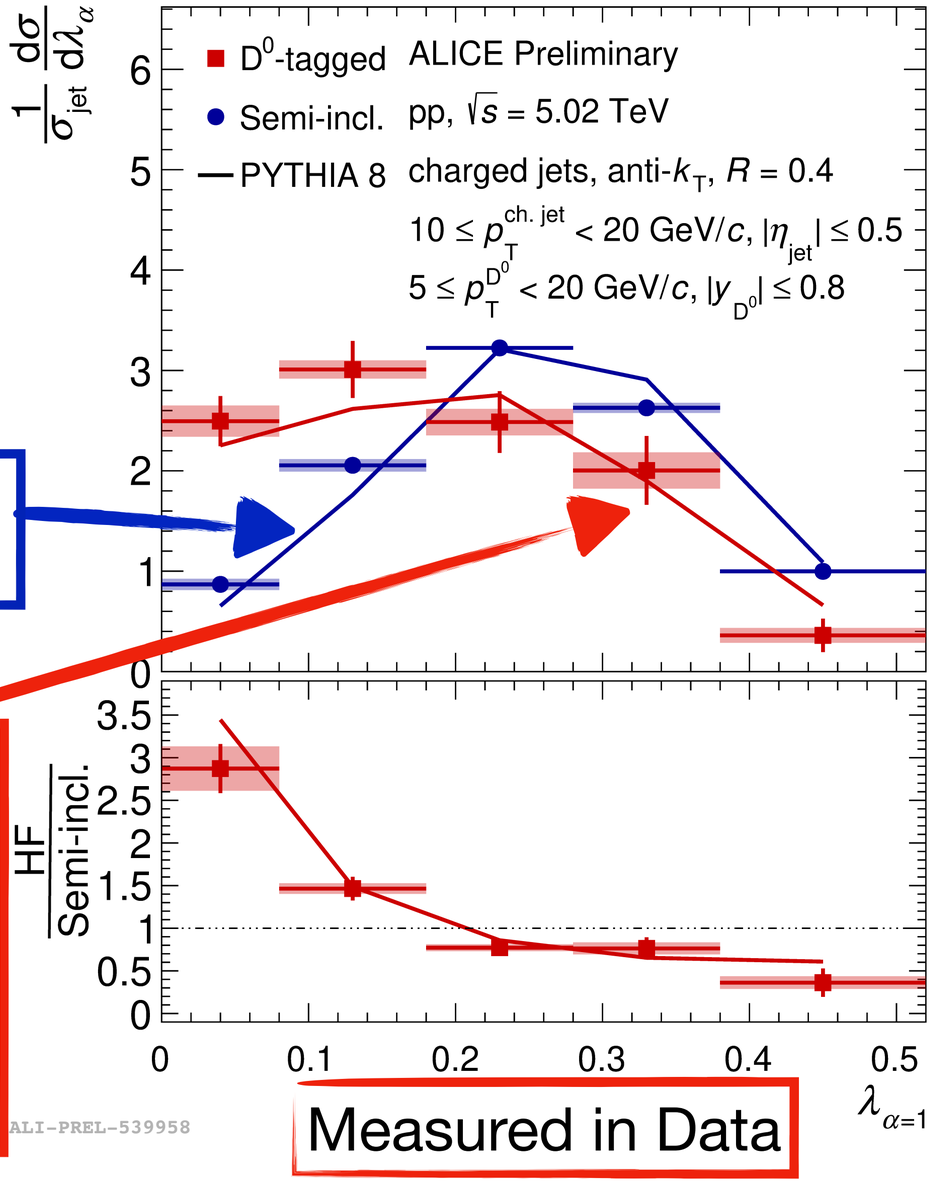

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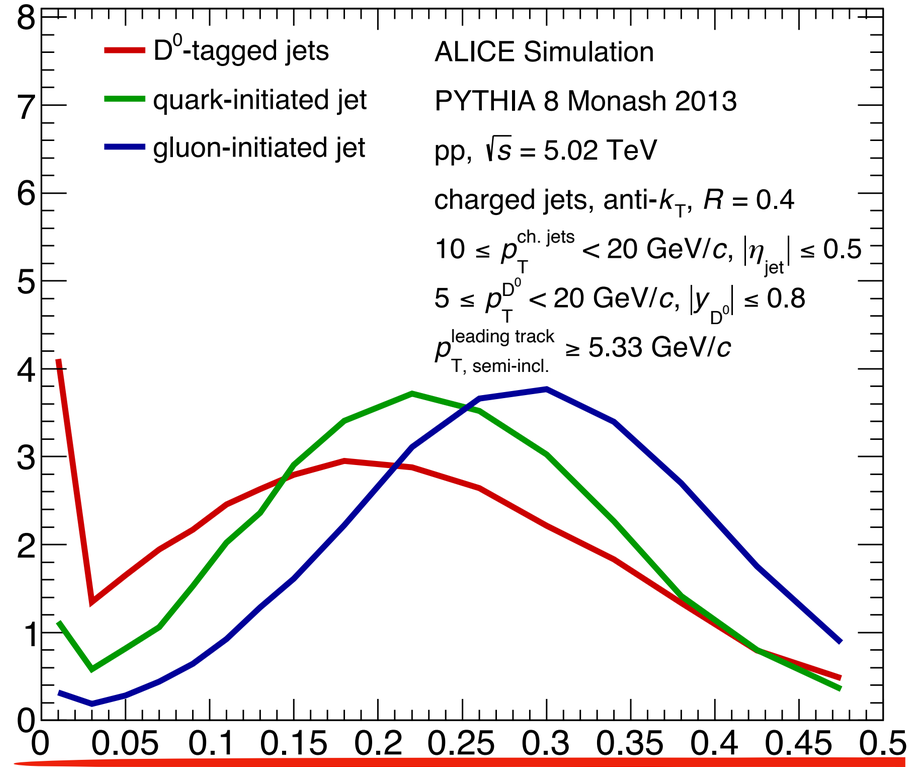

Why enhanced?

Pythia agrees with Data

Results: Probing flavor effects with angularity

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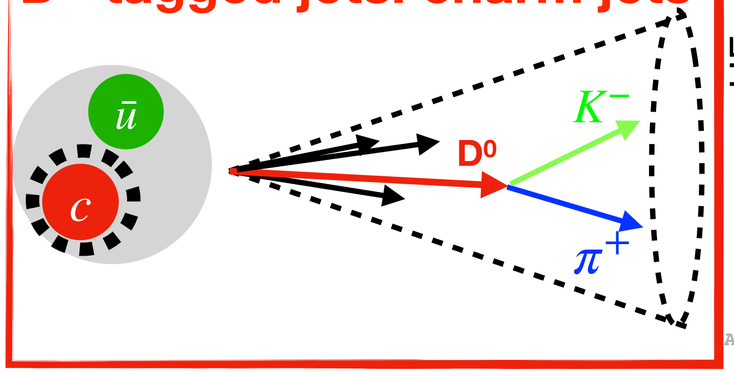
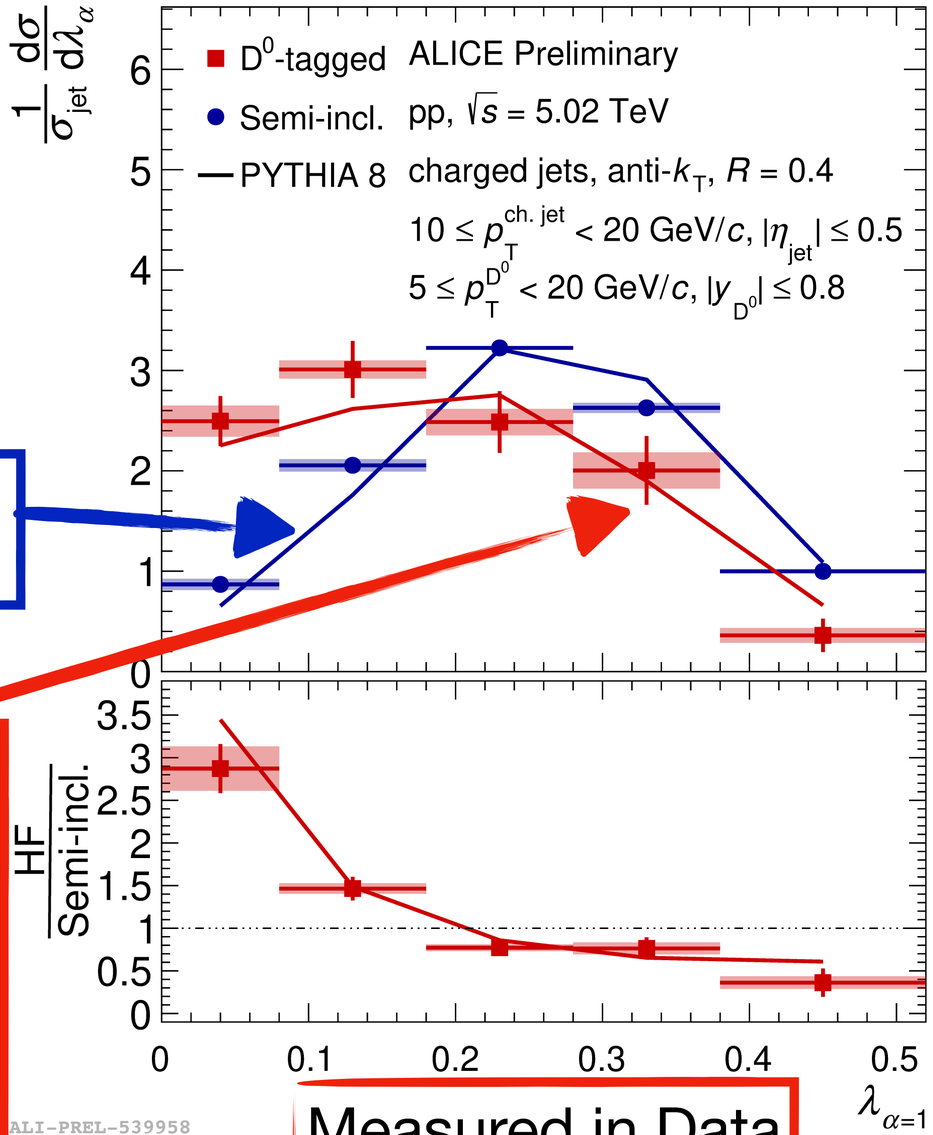
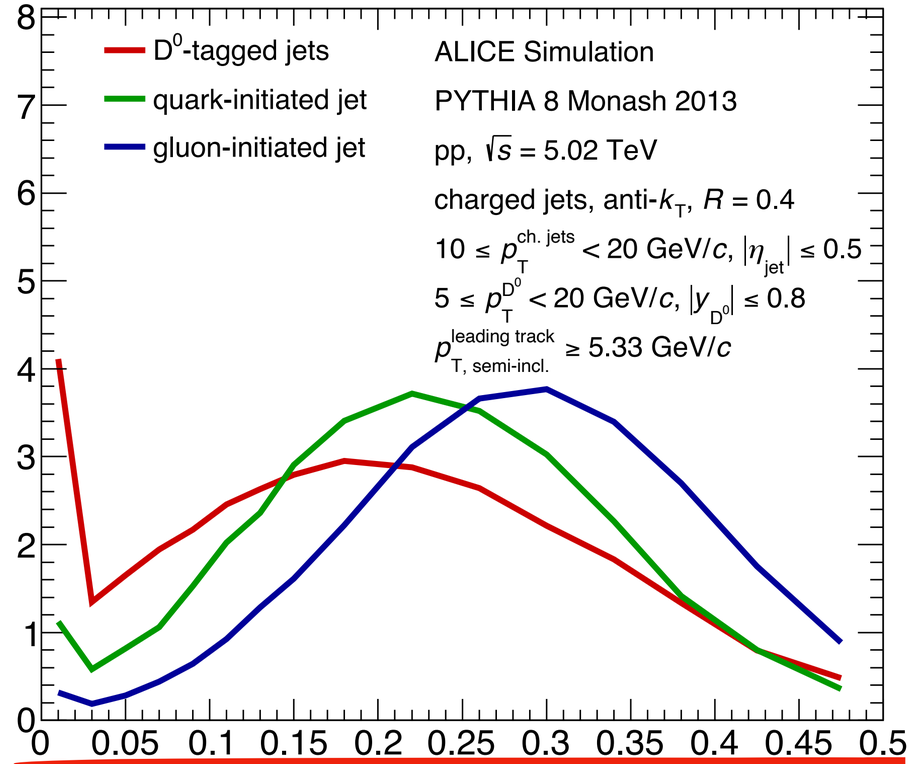
Semi-inclusive jets: gluon and light-flavor jets

D^0 tagged jets: charm jets





Measured in Data



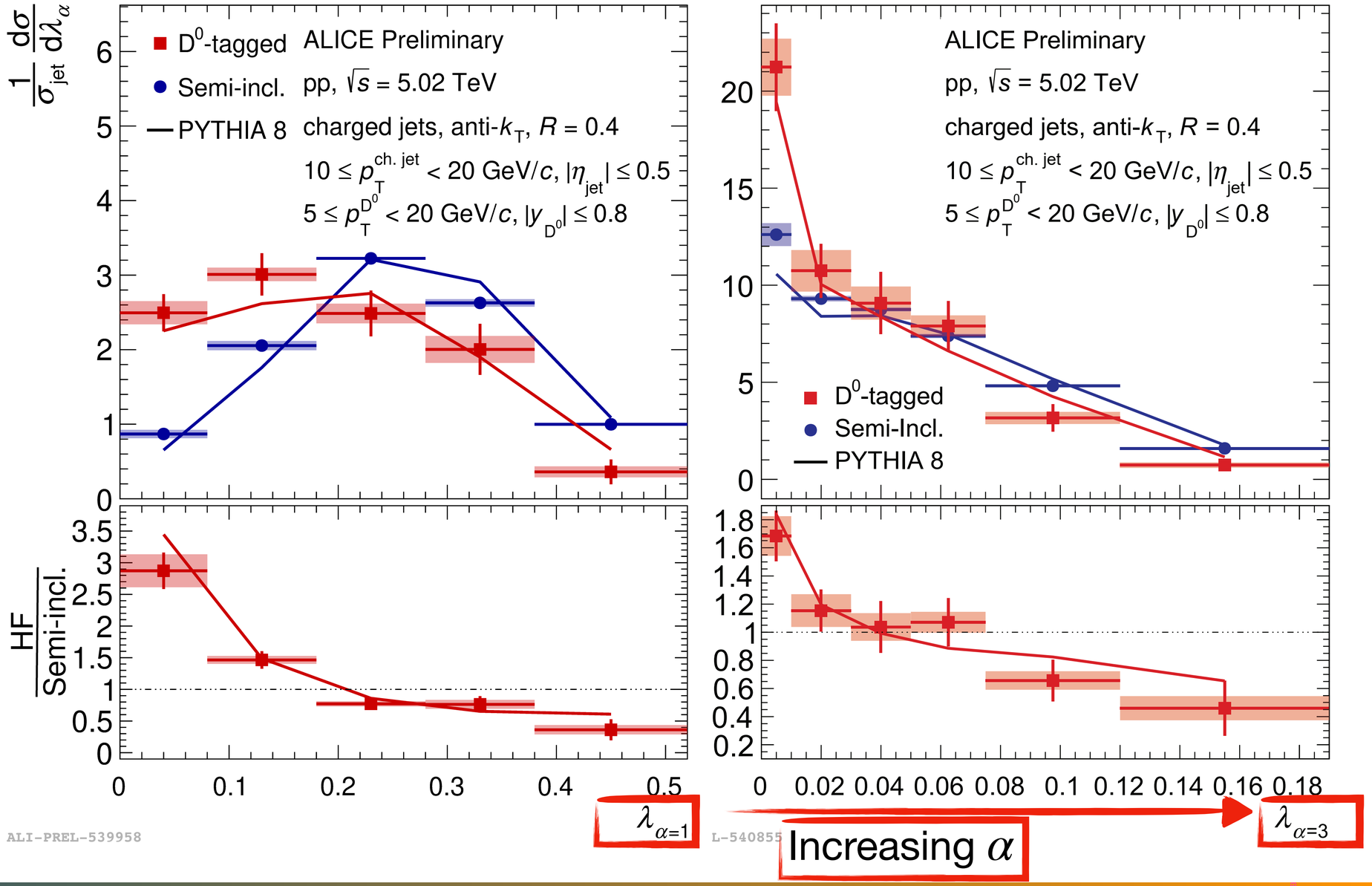
Why enhanced?
HF fragments harder, D^0 carries most of the momentum → **Dead-cone effect**

Pythia agrees with Data

Results: Probing flavor effects with angularity

Jet Angularities :

$$\lambda_\alpha = \sum_{i \in jet} z_i \theta_i^\alpha$$



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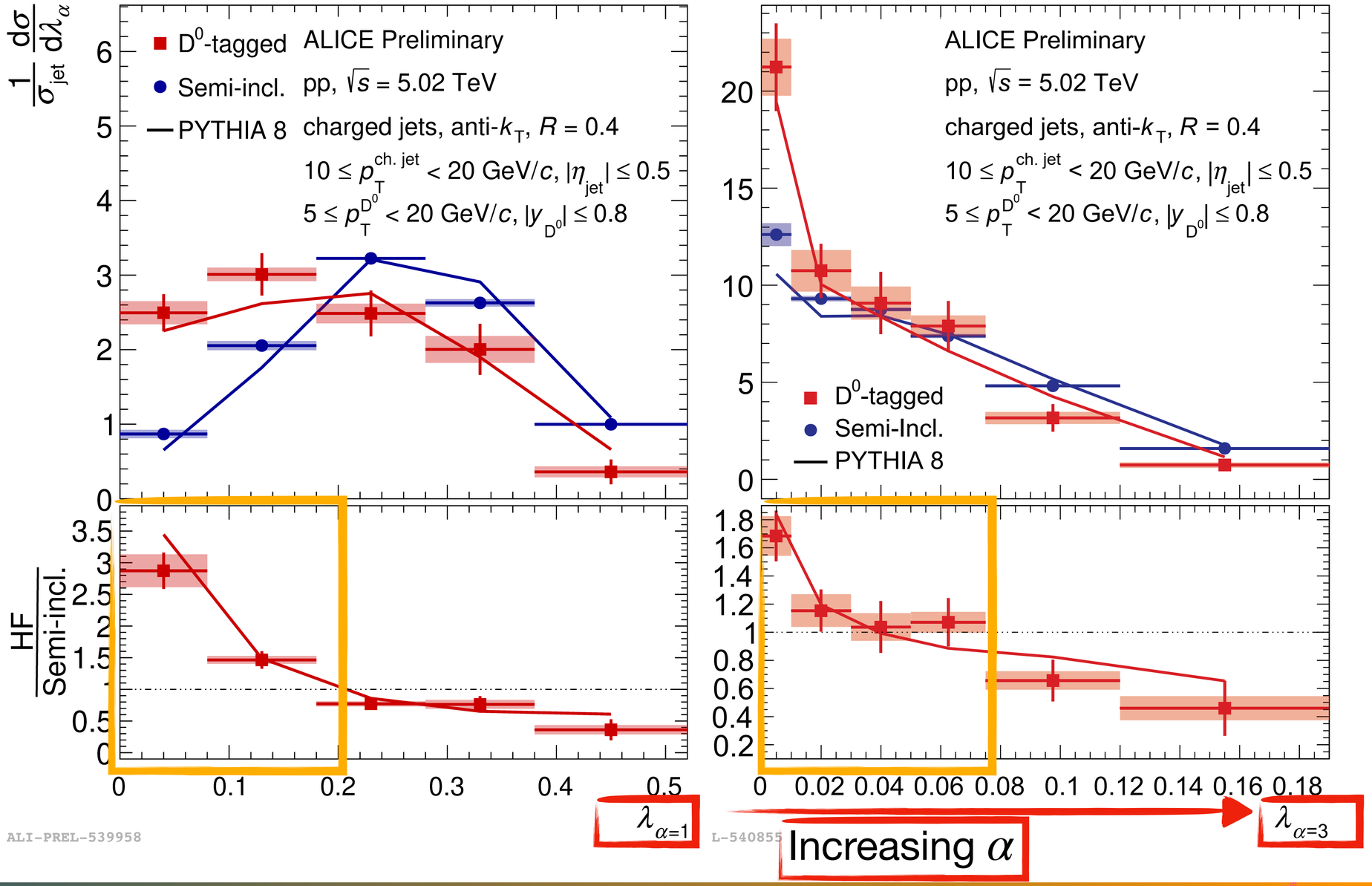

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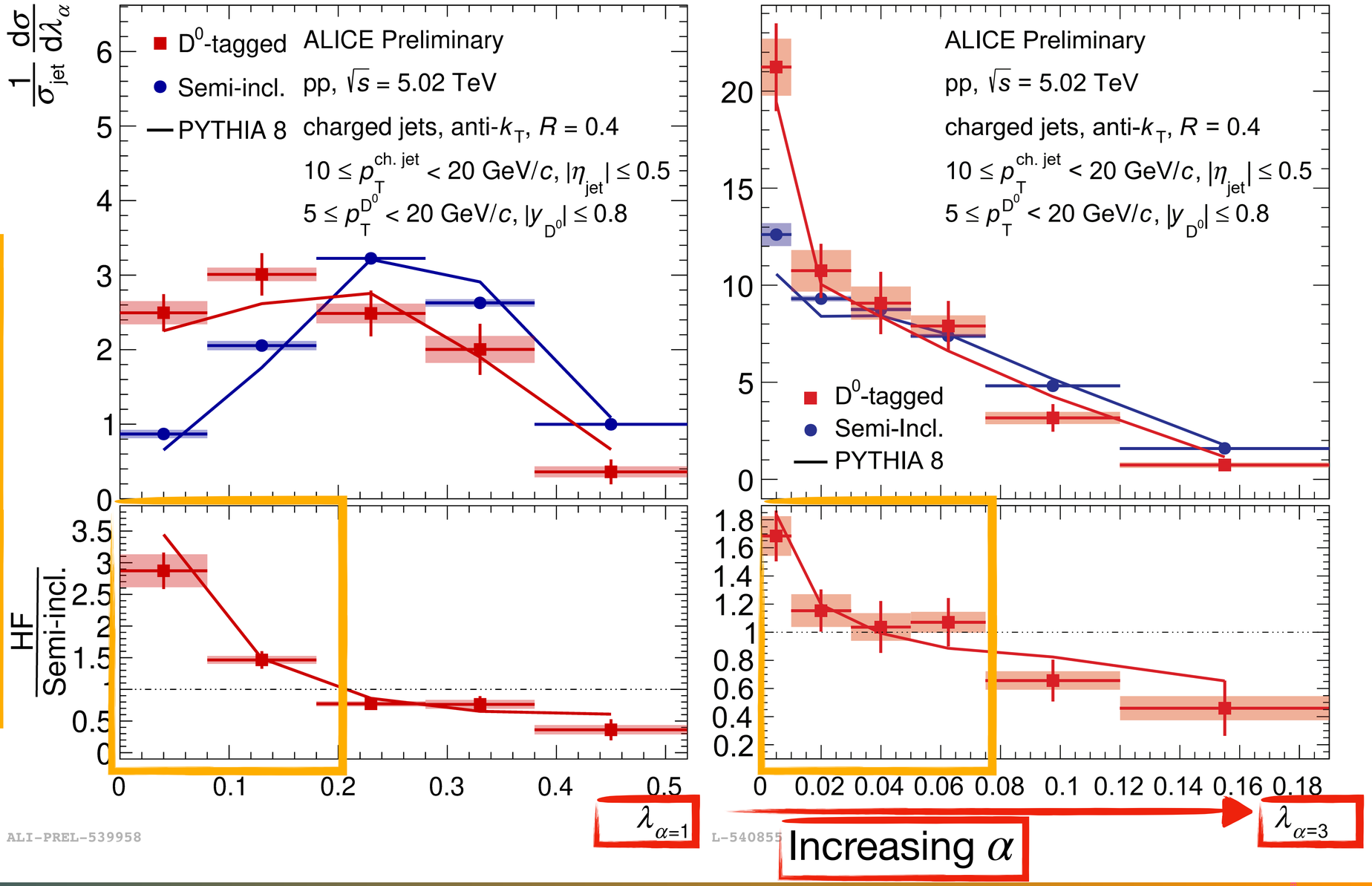

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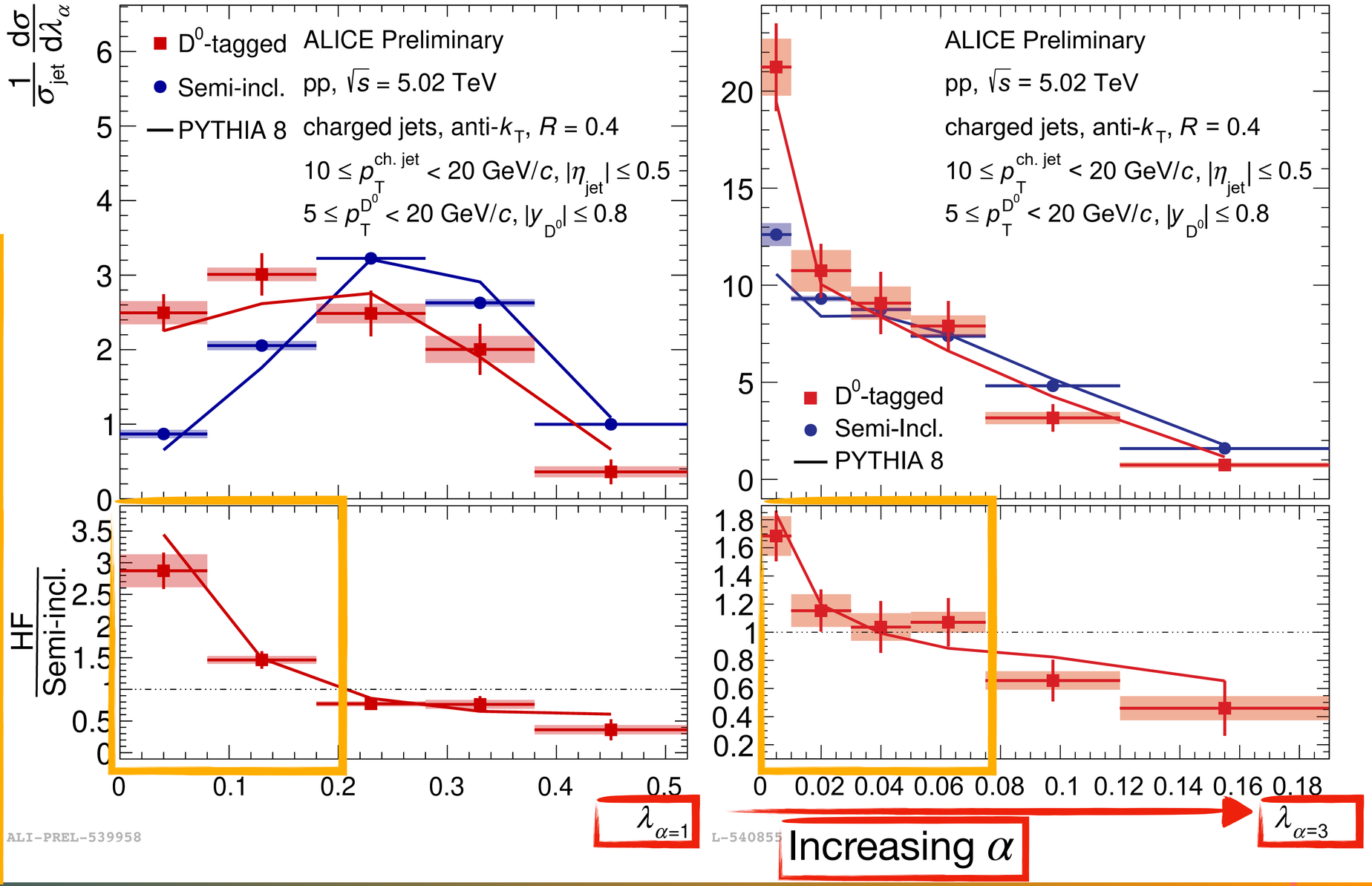
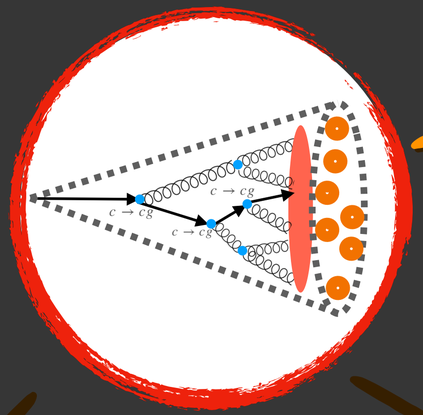


Charm jet measurements with ALICE

Jet axes differences

Jet angularities

Energy-energy correlator



Dead-cone

Fragmentation function $z_{\parallel}$

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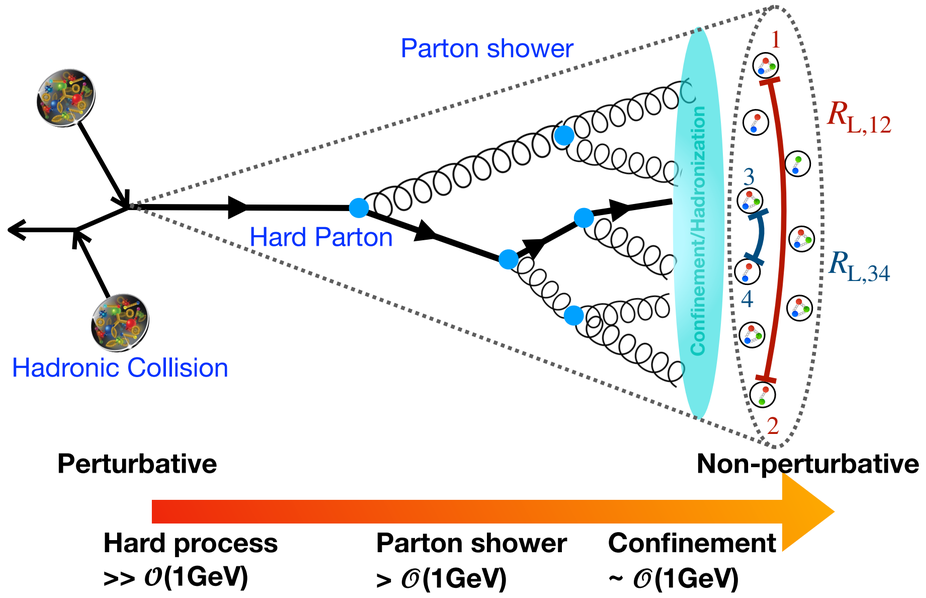
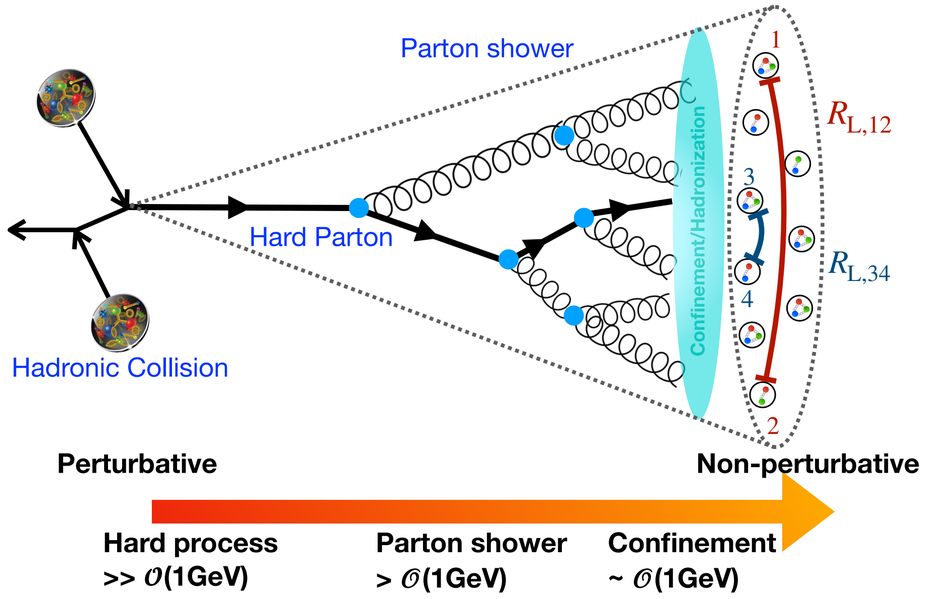


QCD emissions in parton showers are angular ordered.

early splittings (perturbative) →wider ($R_{L,12}$)

late splittings (non-perturbative) → narrower ($R_{L,34}$)

Energy-energy correlator



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Energy weight

Soft contribution (MPI, UE) power suppressed by energy weight

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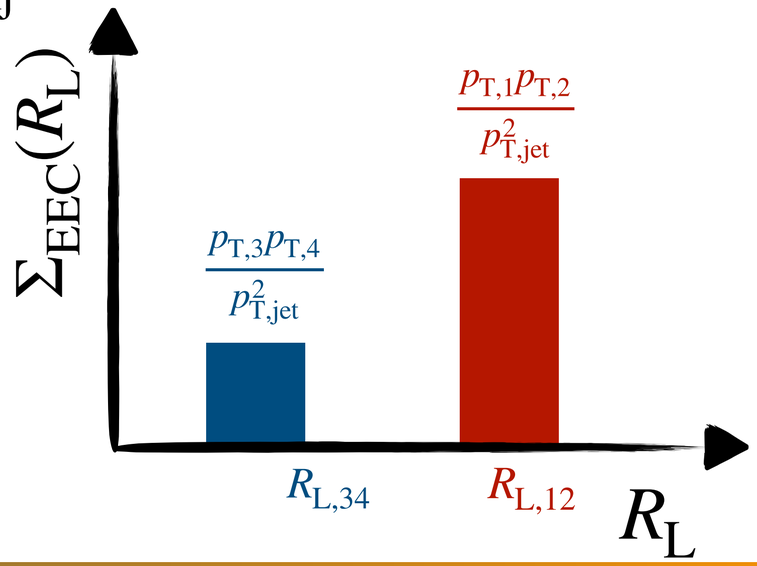
1. Energy weighted two particle correlation inside jet



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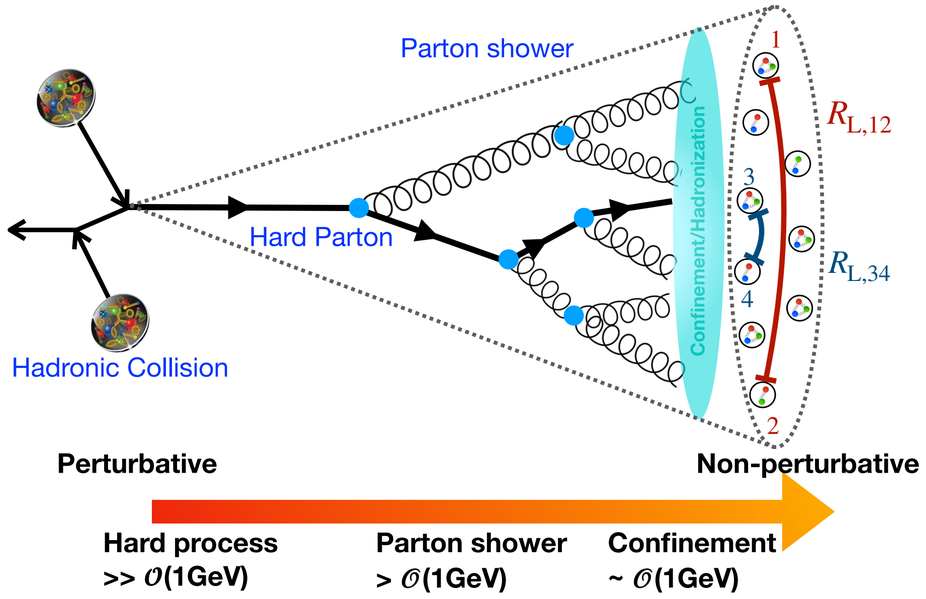

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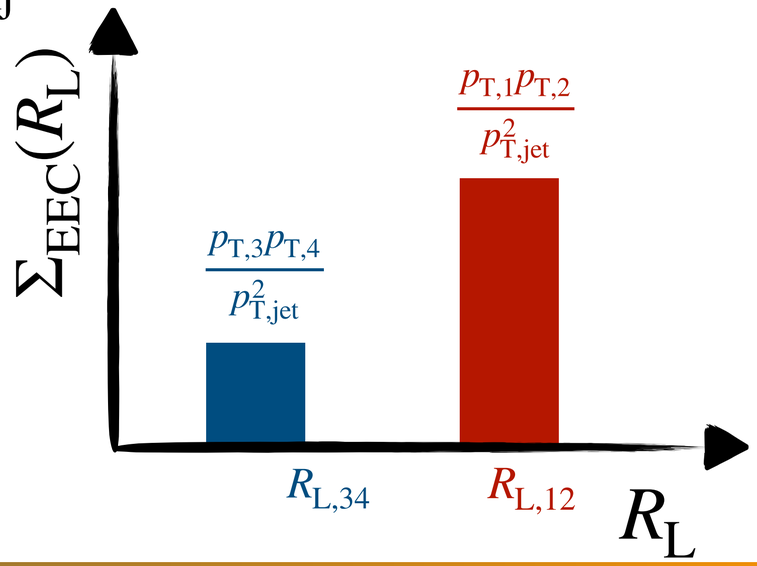

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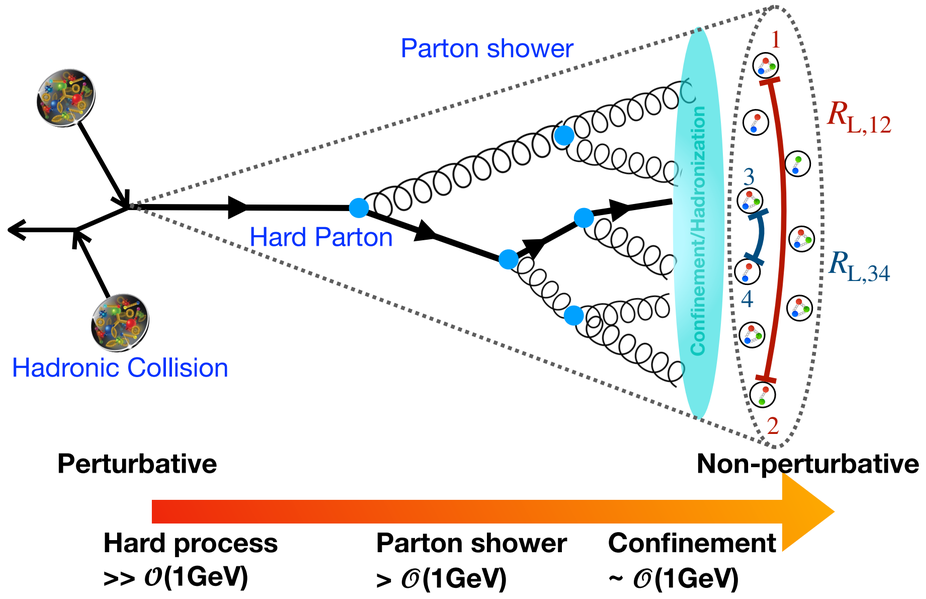

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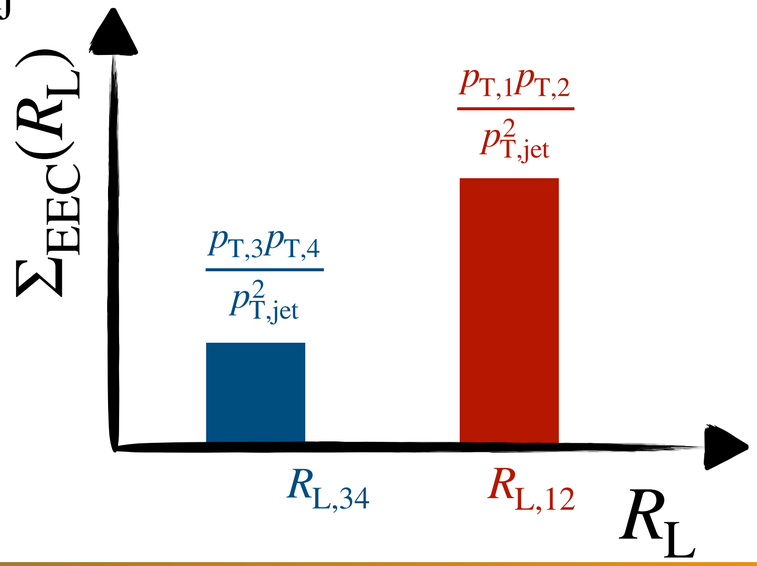
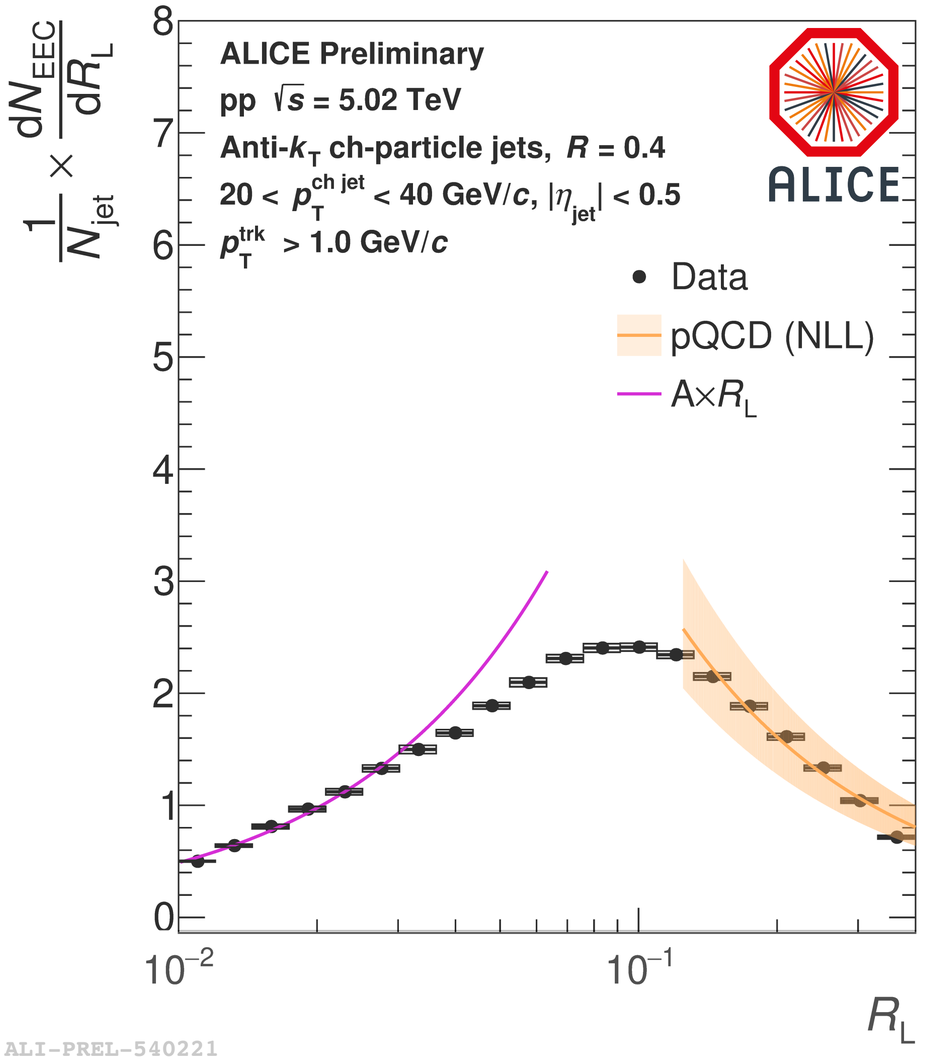


arXiv:2409.12687

Energy-energy correlator

Inclusive jets: gluon and light-flavor jets



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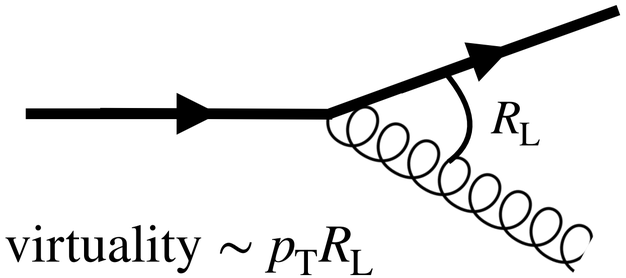

virtuality $\sim p_T R_L$

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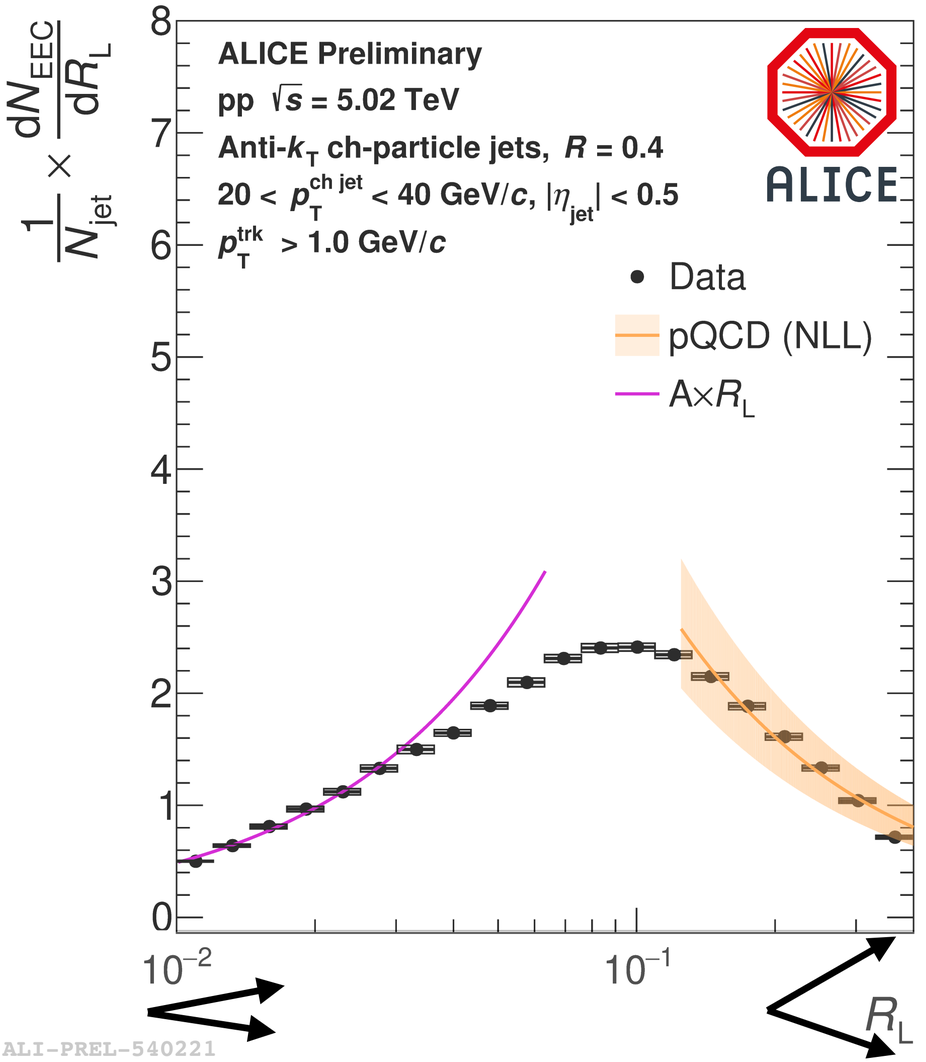

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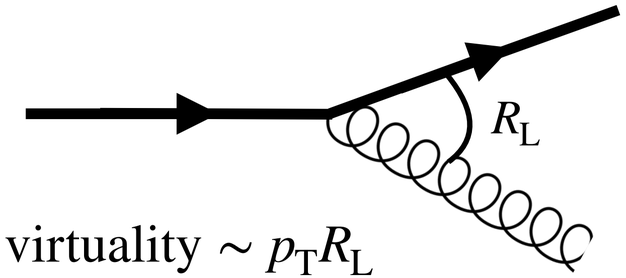

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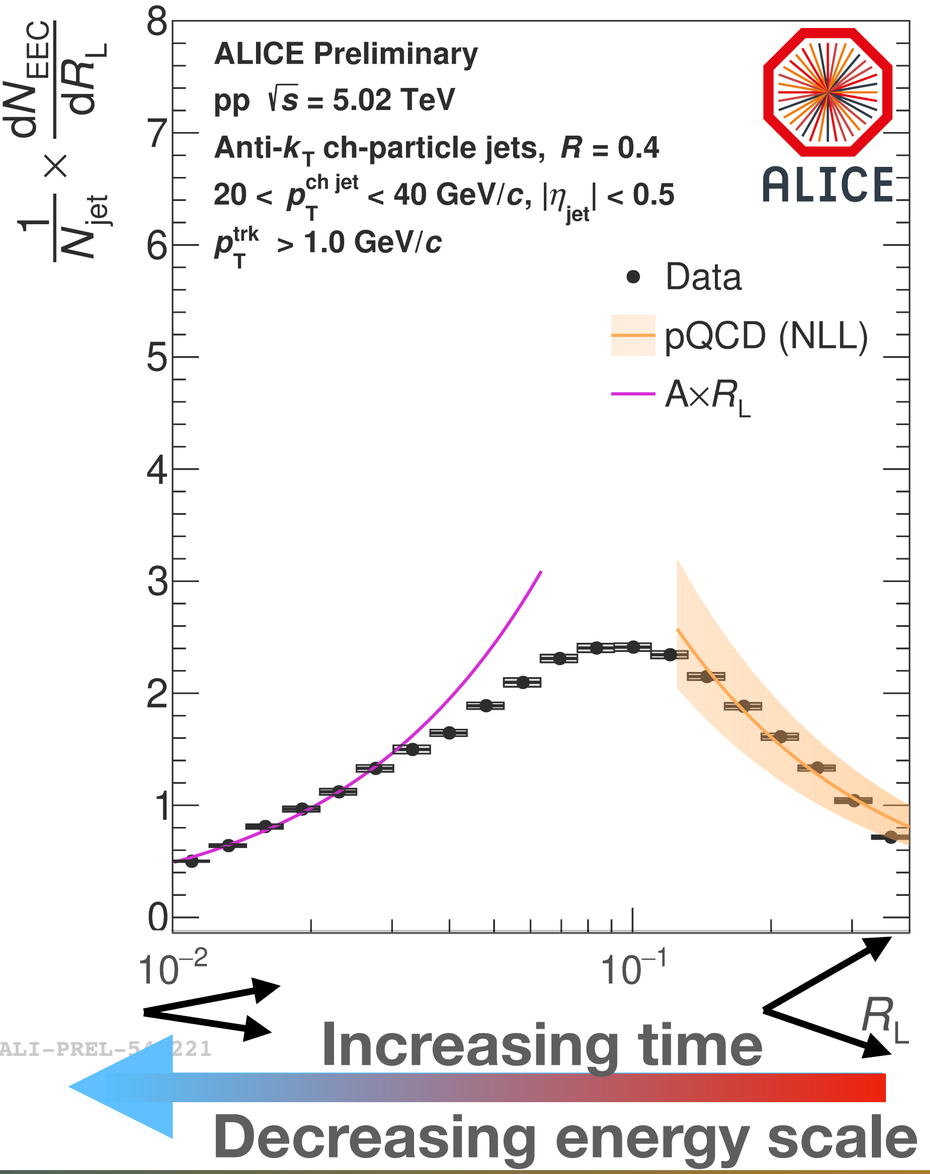

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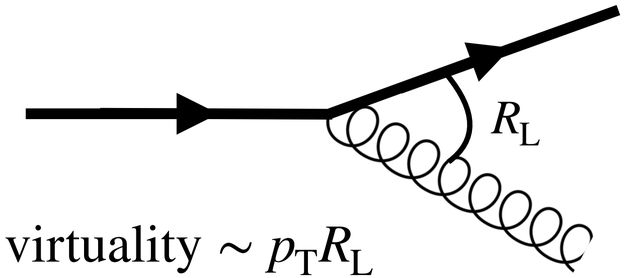

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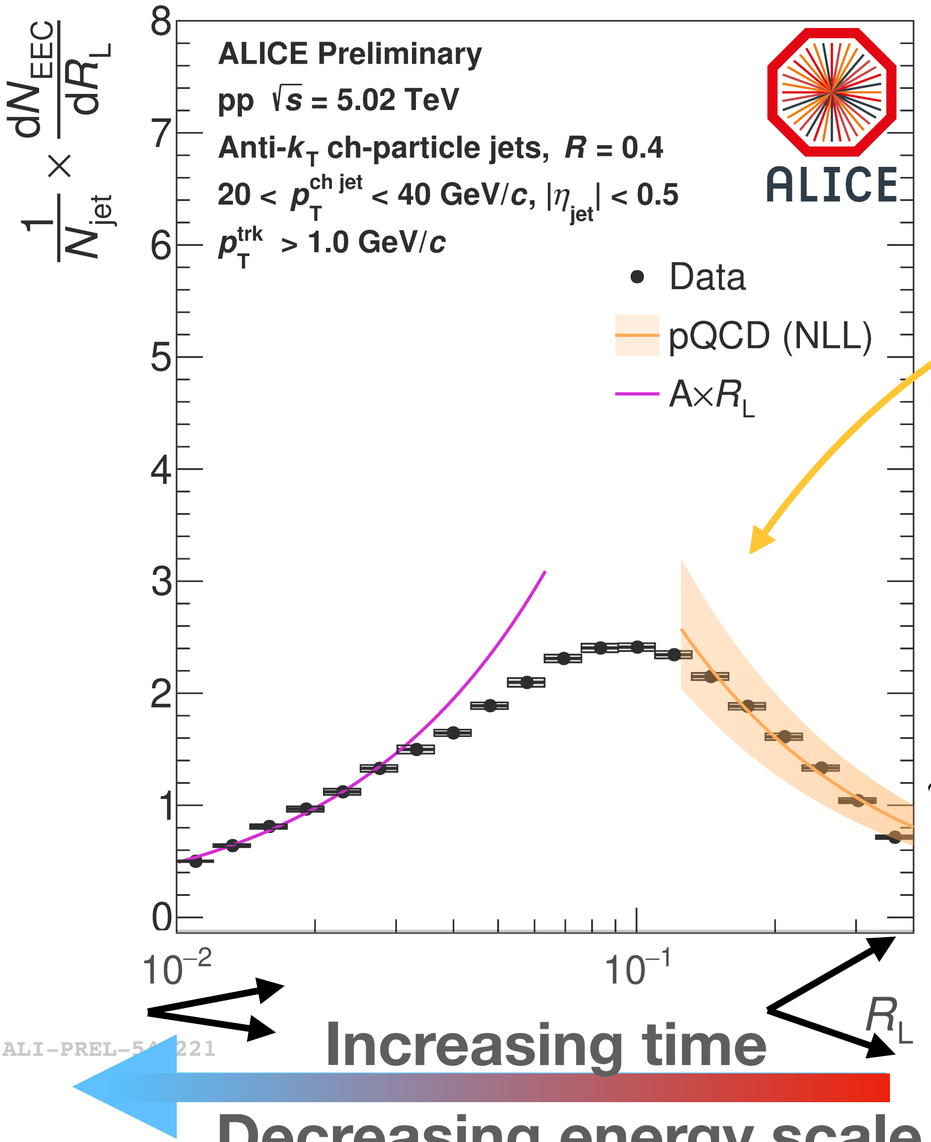
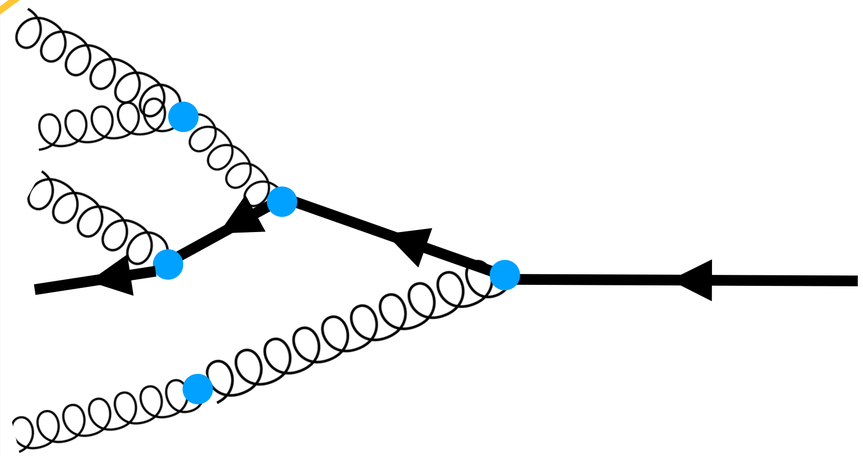


ALI-PREL-541221

Perturbative regime



Data agrees with pQCD calculation

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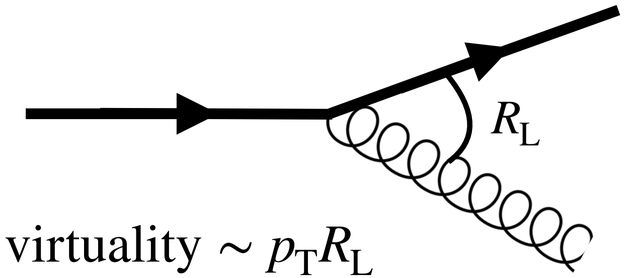

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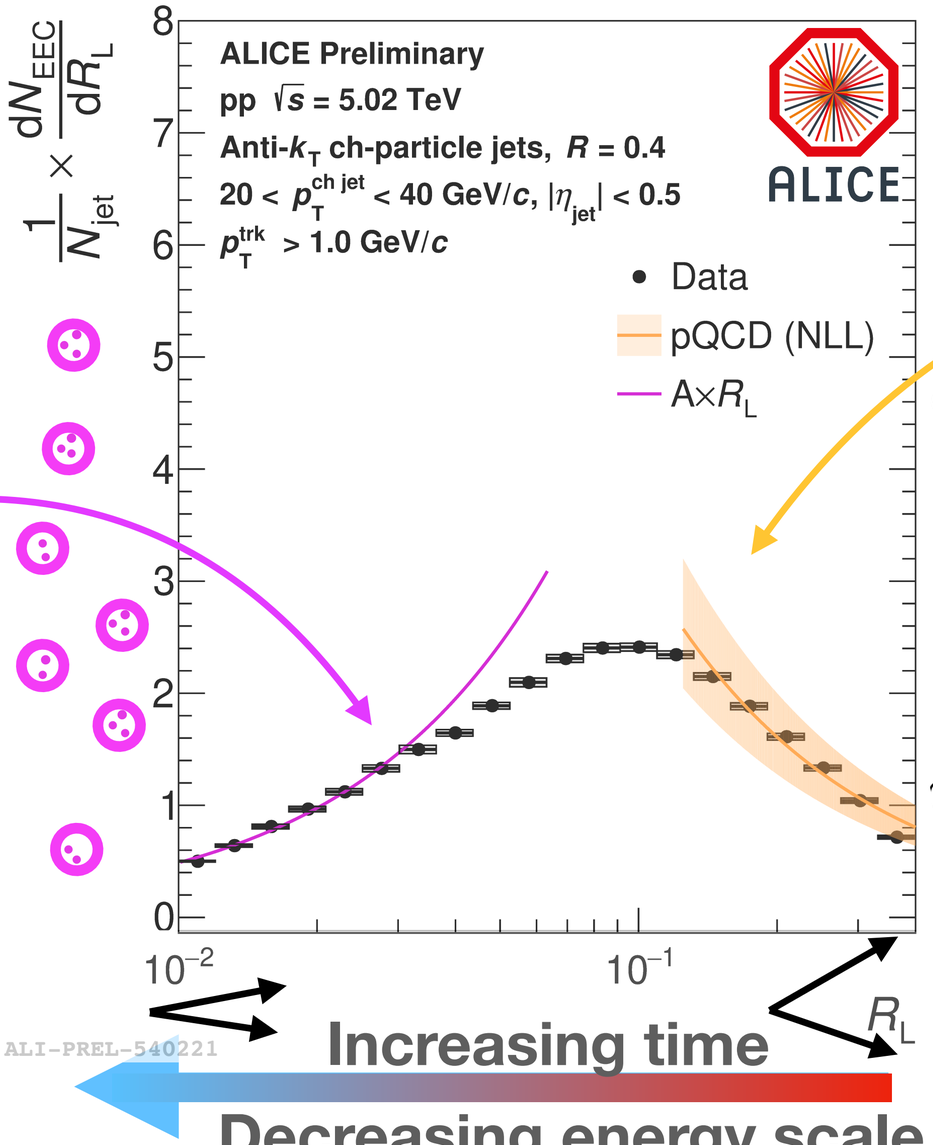

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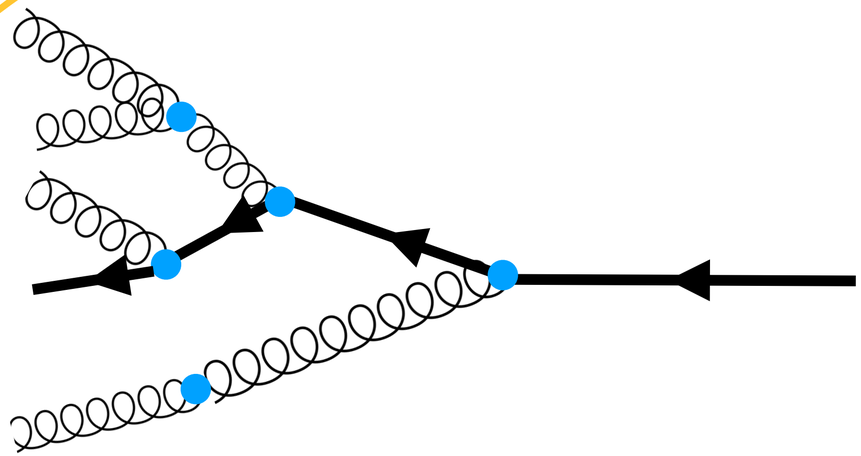

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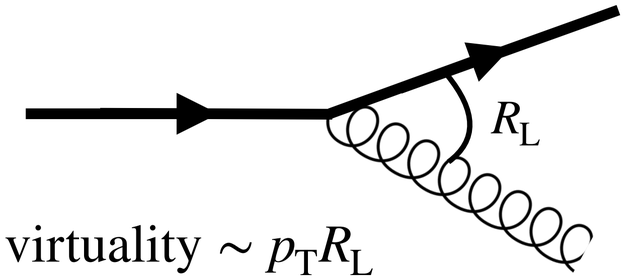

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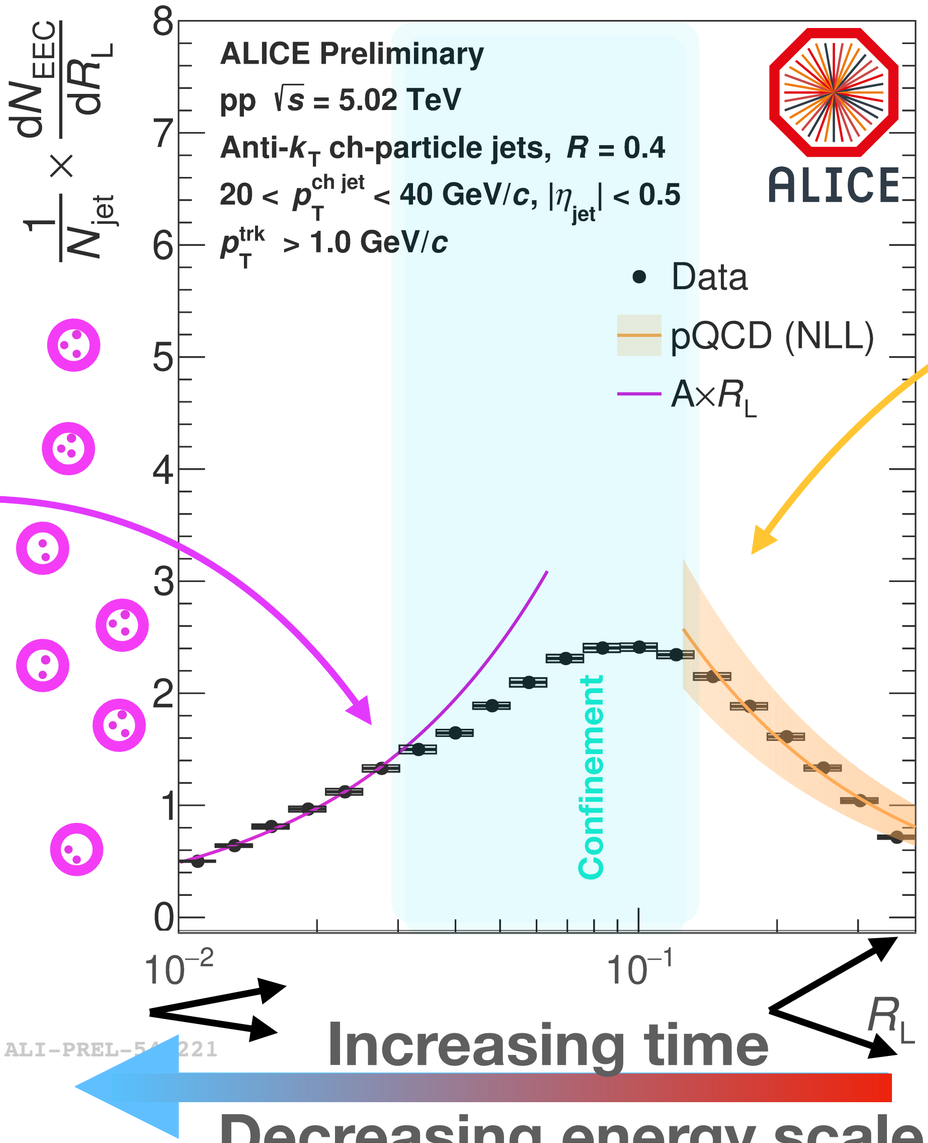

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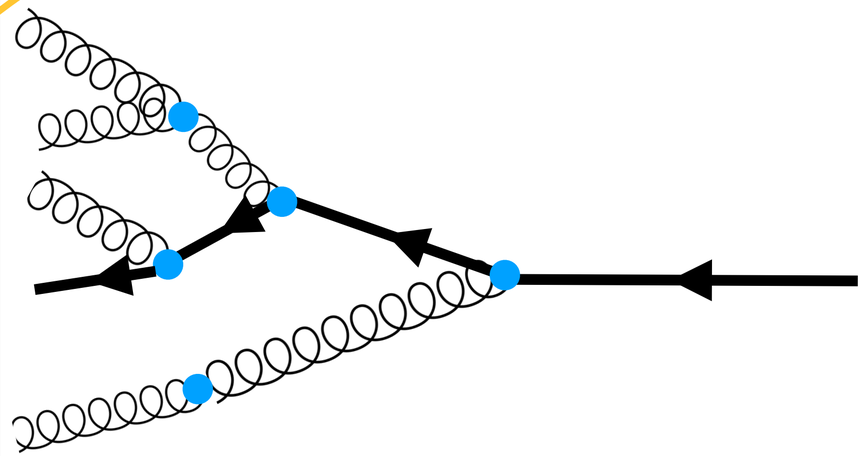

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arXiv:2210.09311

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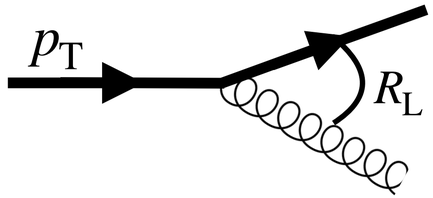

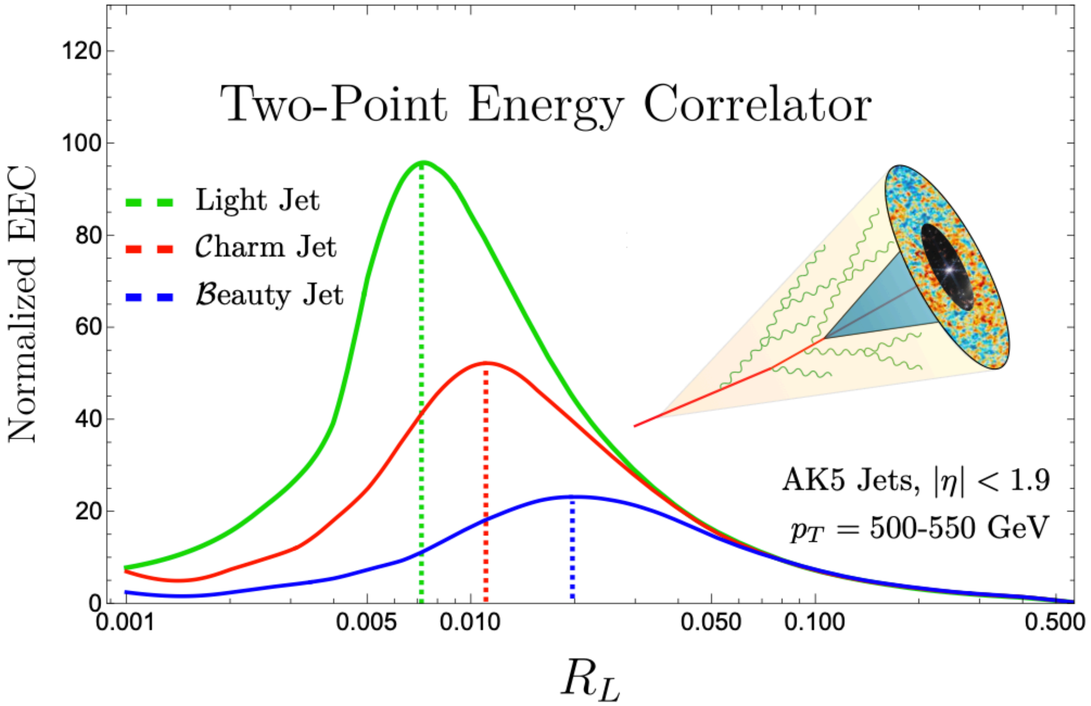

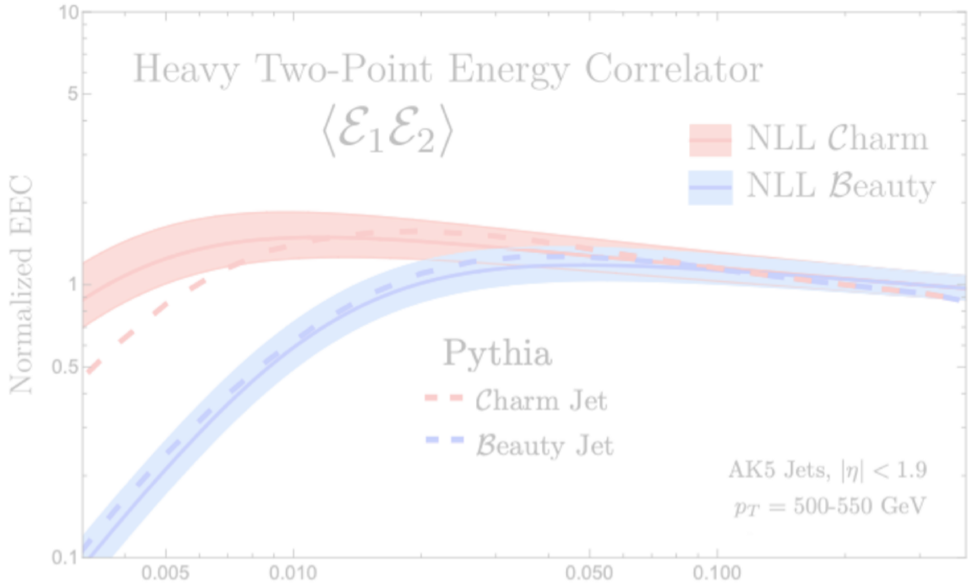

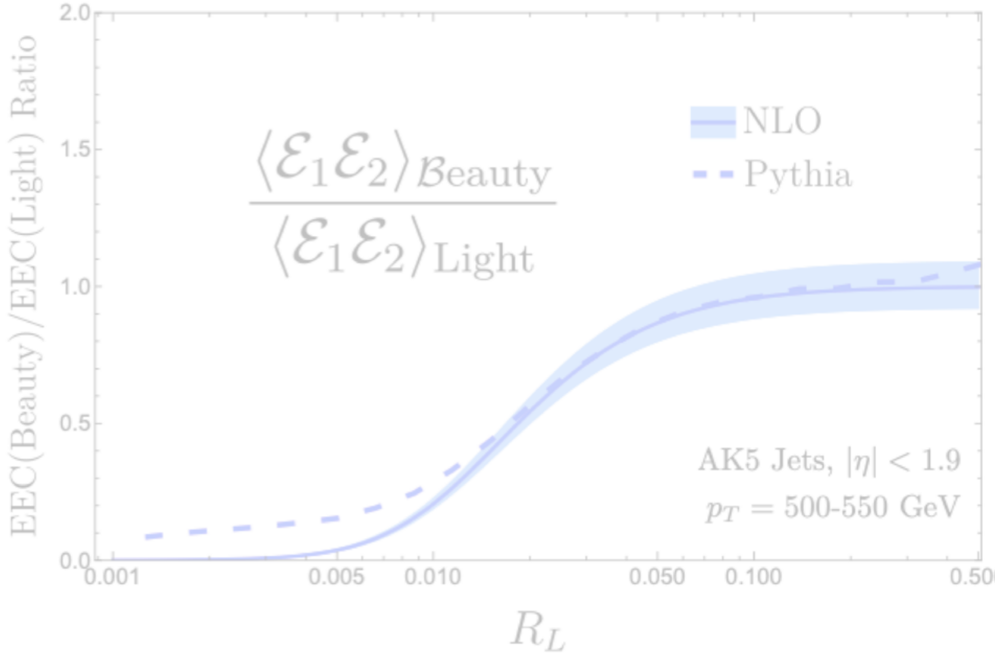

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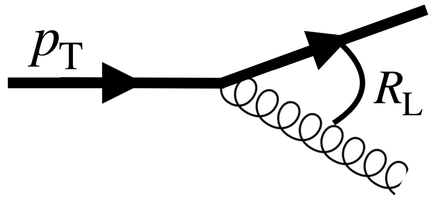

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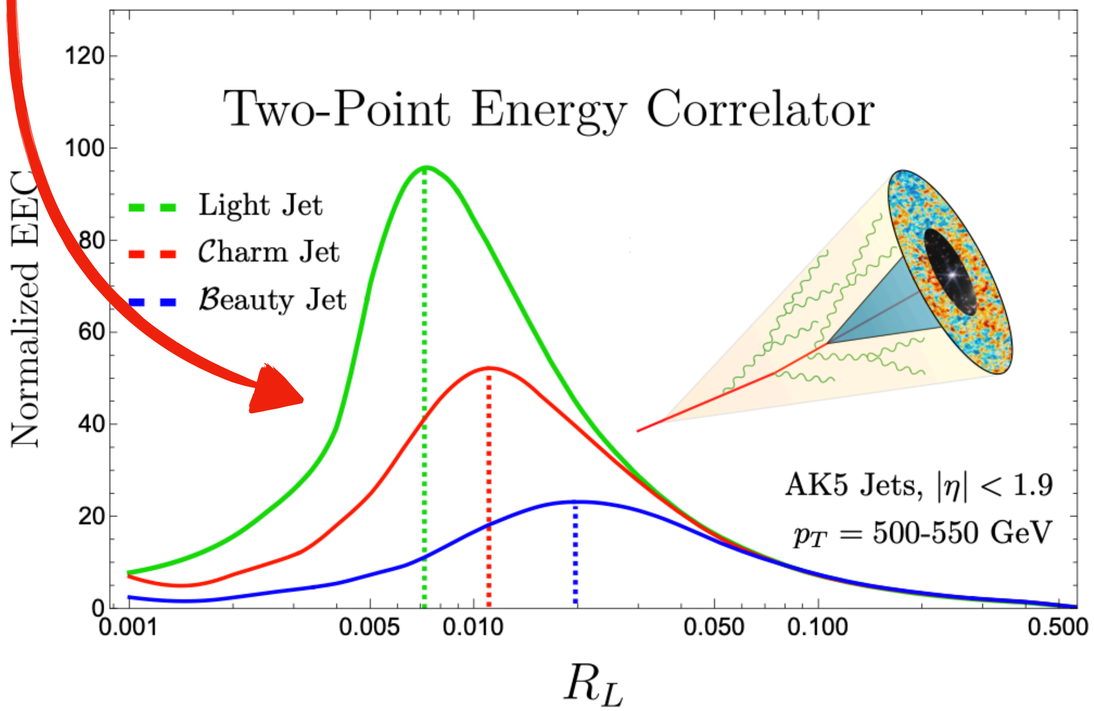

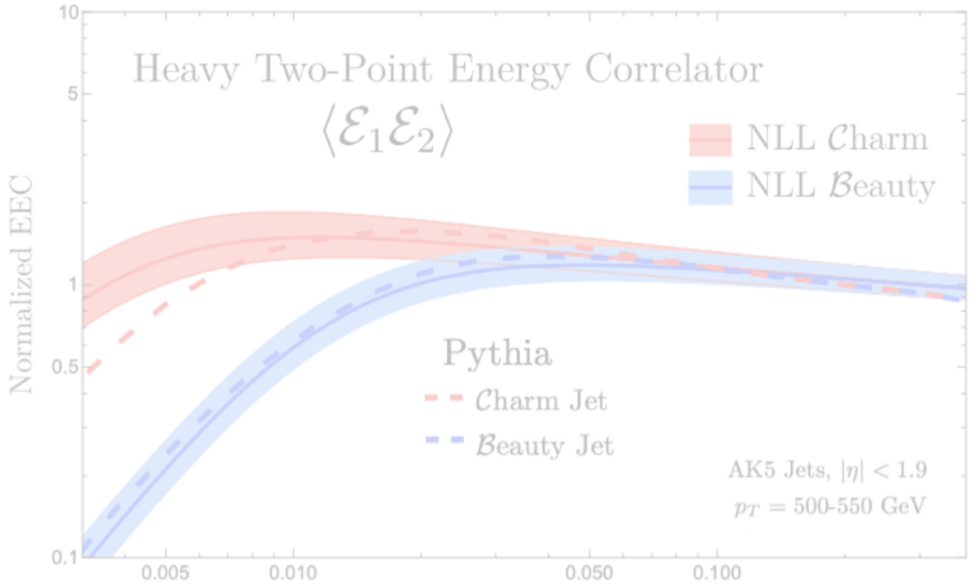

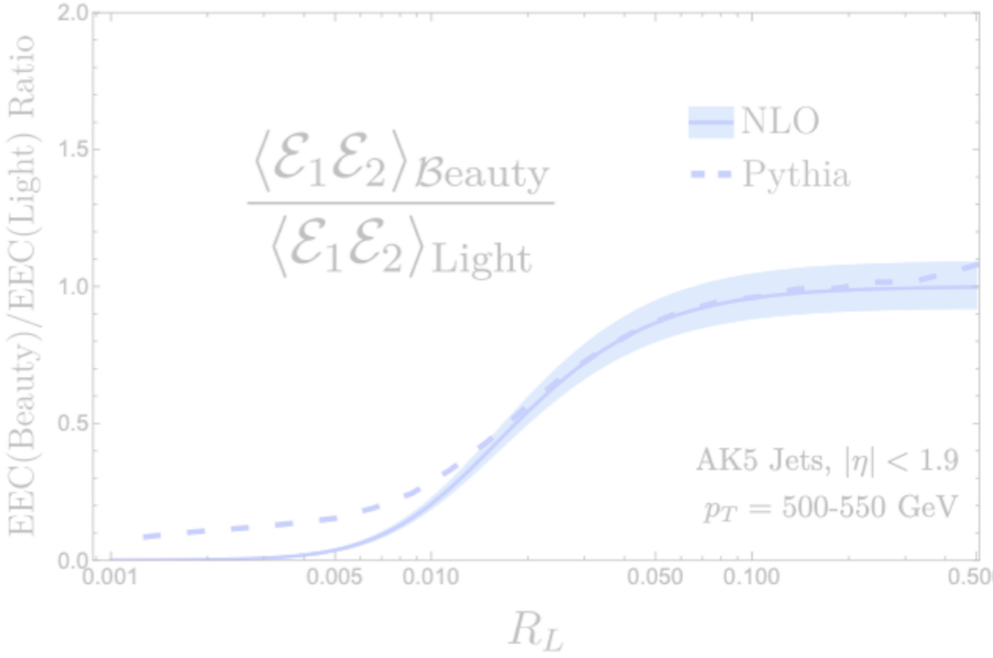

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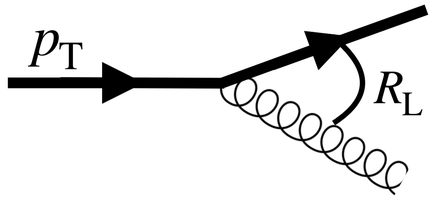

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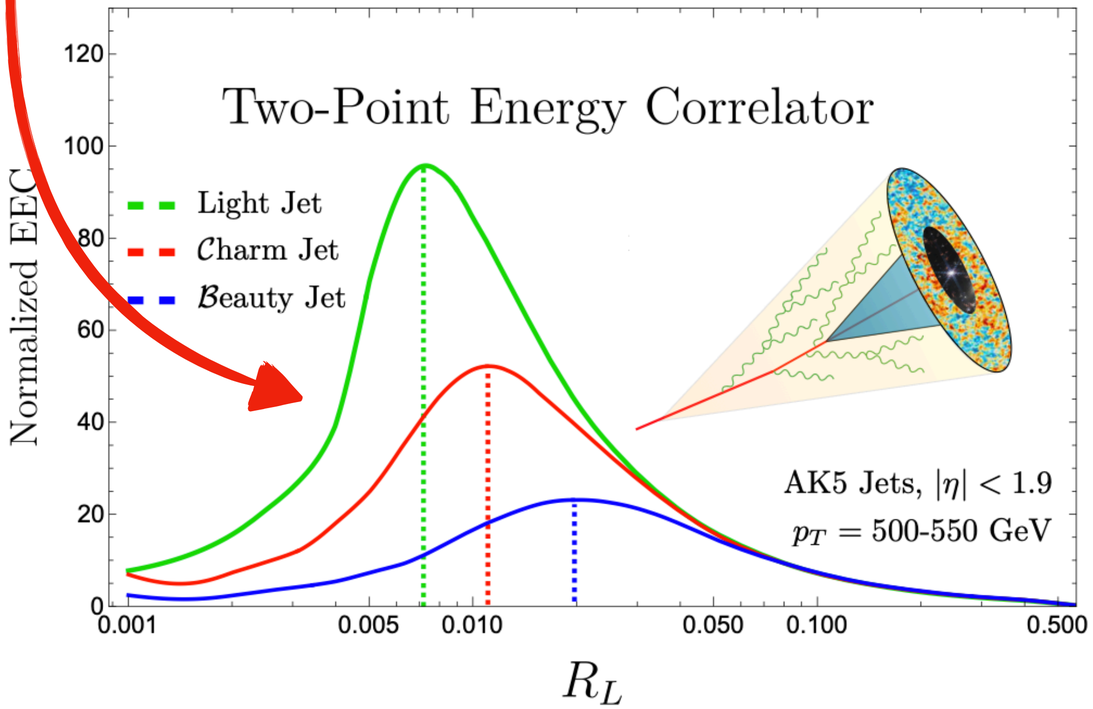

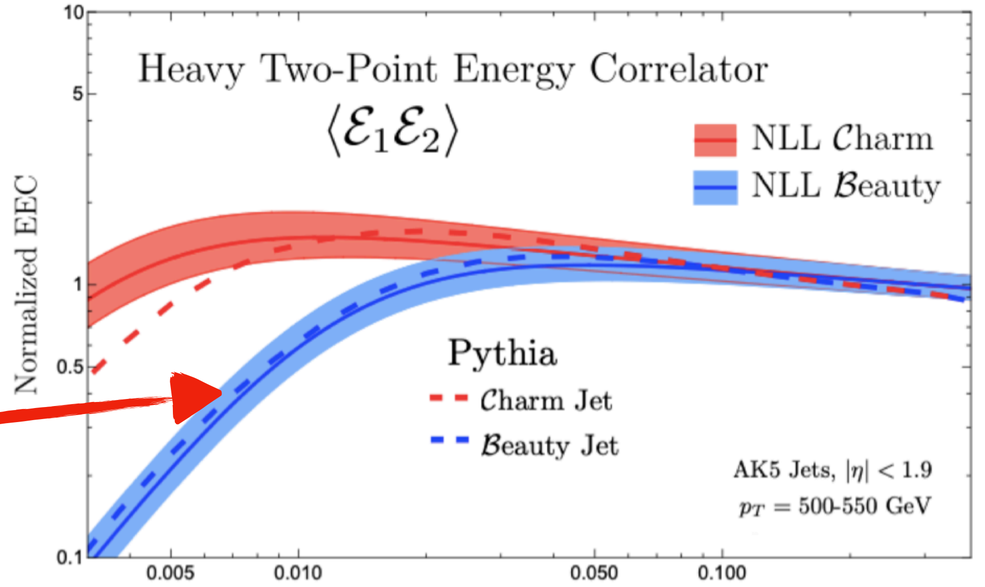

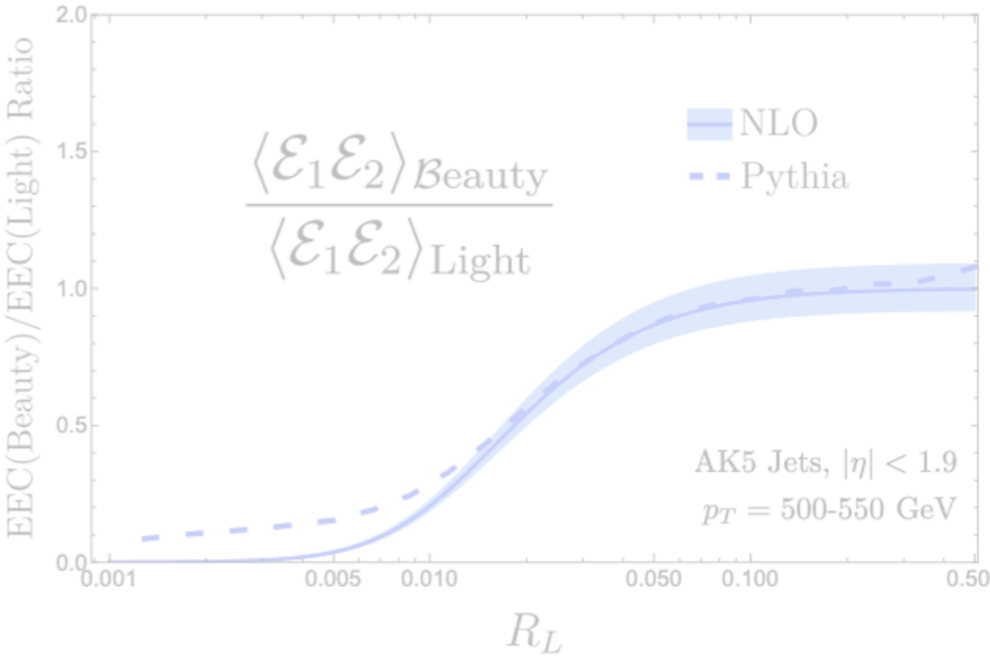

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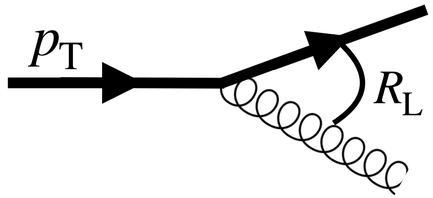

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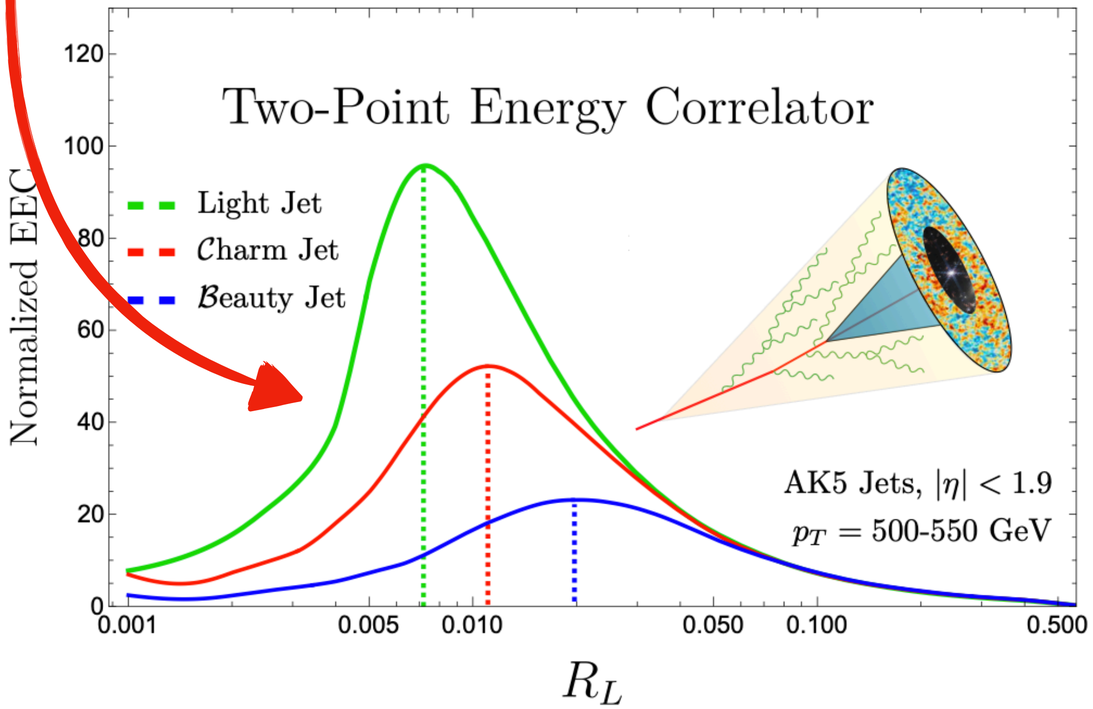
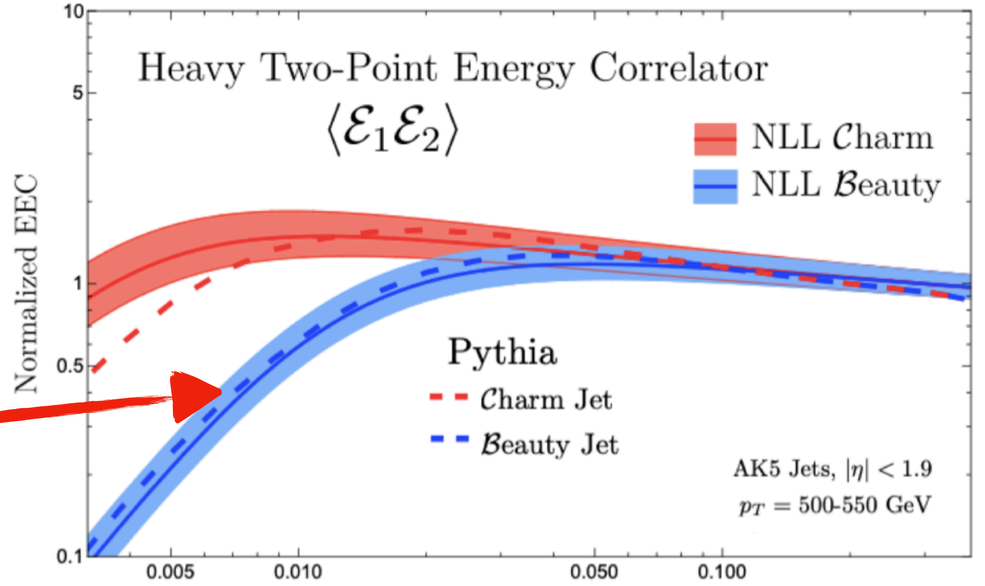
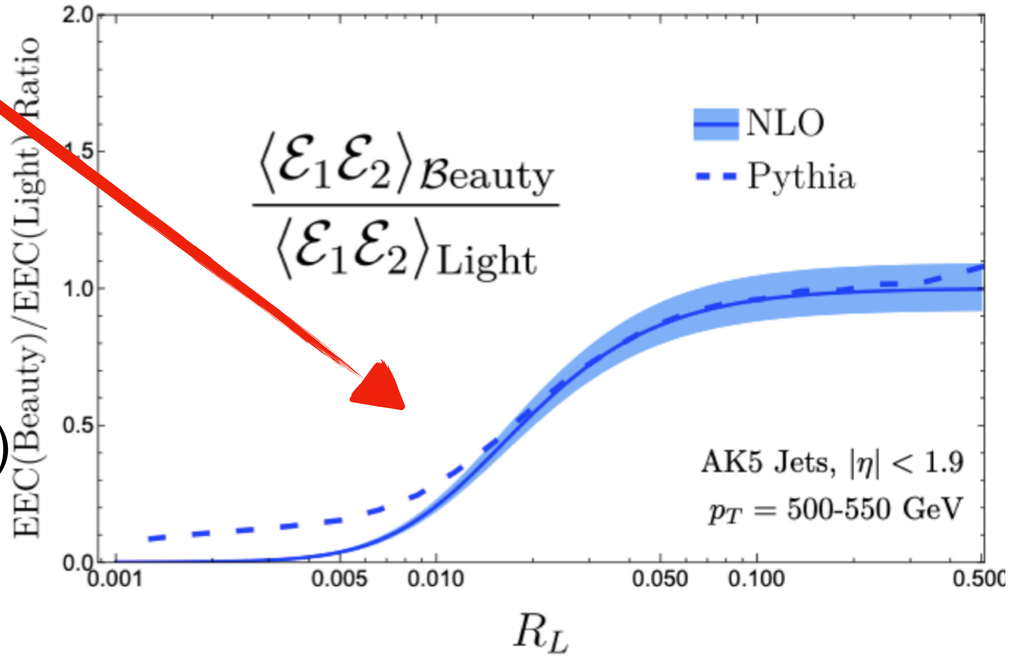


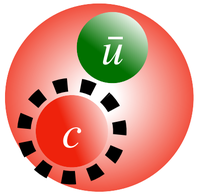
Ratios of the massive to light EECs isolate mass effects.

Small angle suppression (<*m*/*E*) →**"dead-cone" effect**

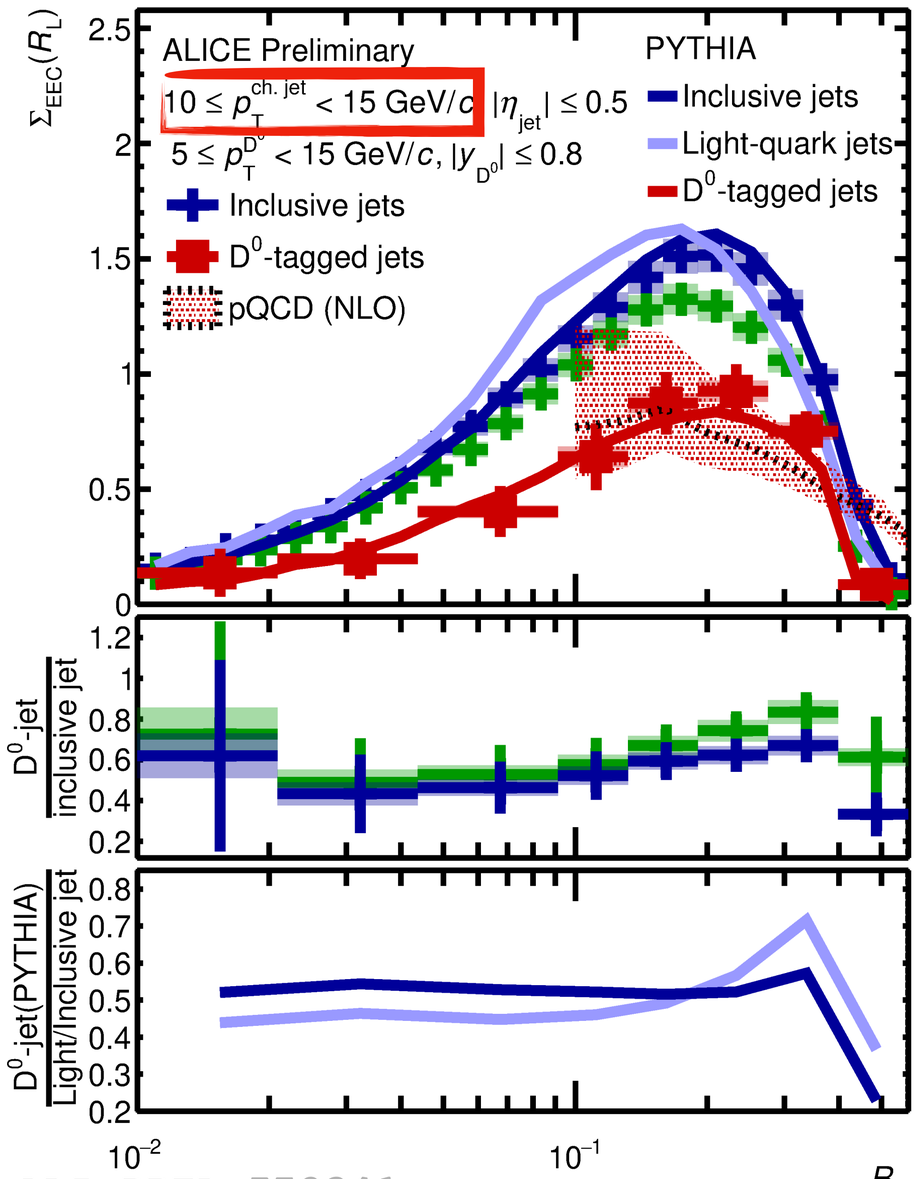




Charming energy-energy correlator



D^0



ALI-PREL-579241

*pQCD calculation by Kyle Lee and collaborators

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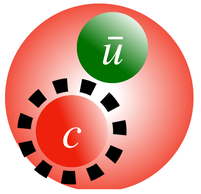
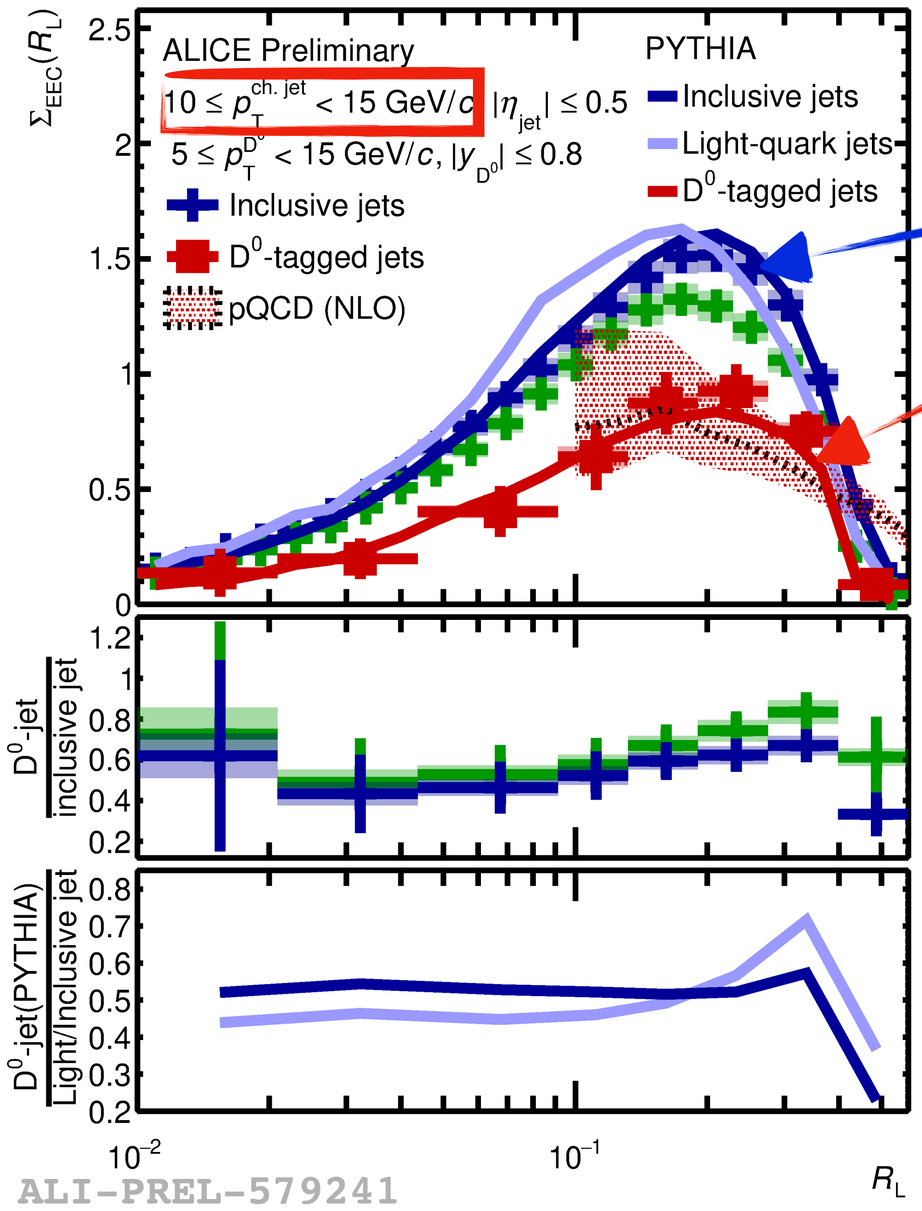


D^0



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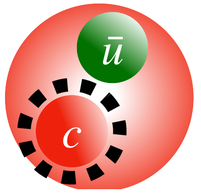
ALI-PREL-579241

Charming energy-energy correlator



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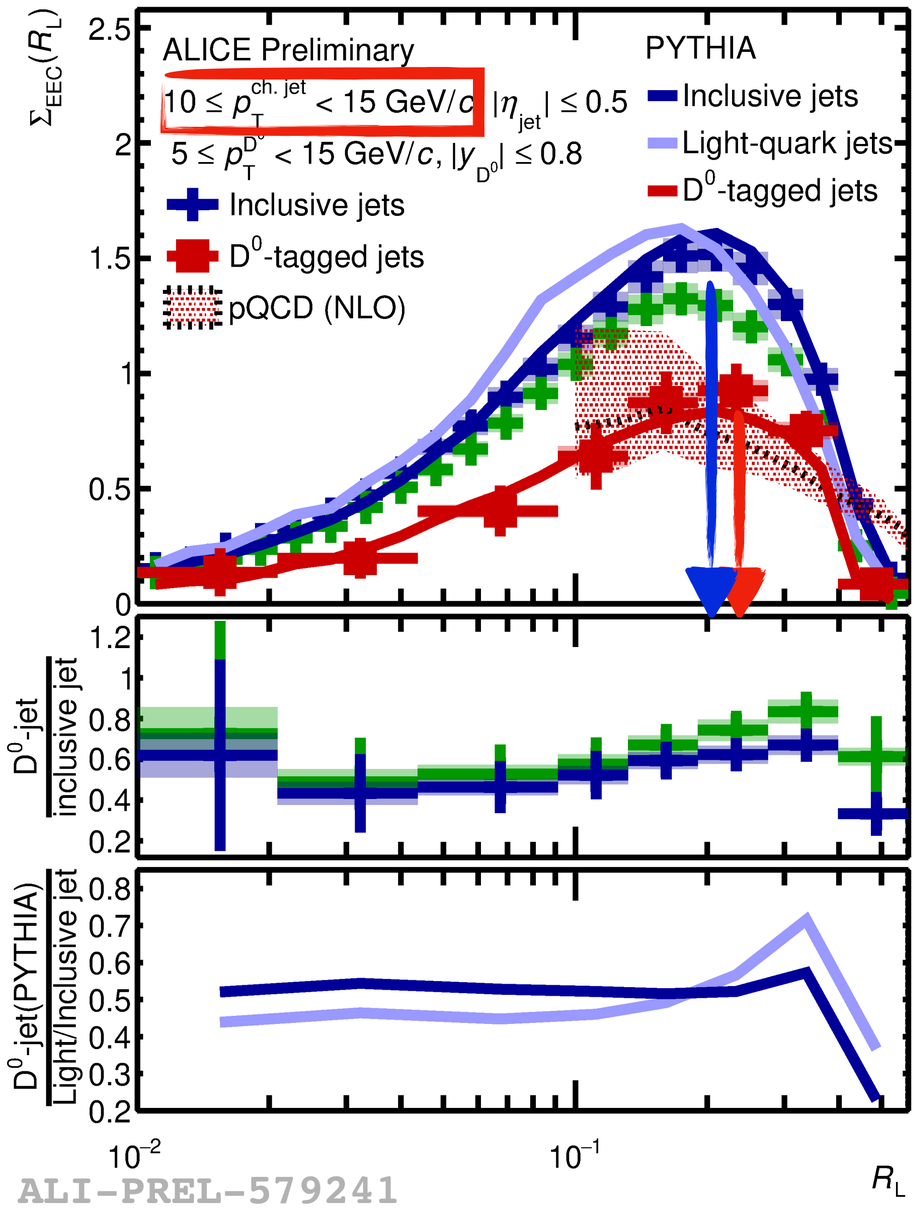

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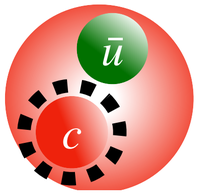

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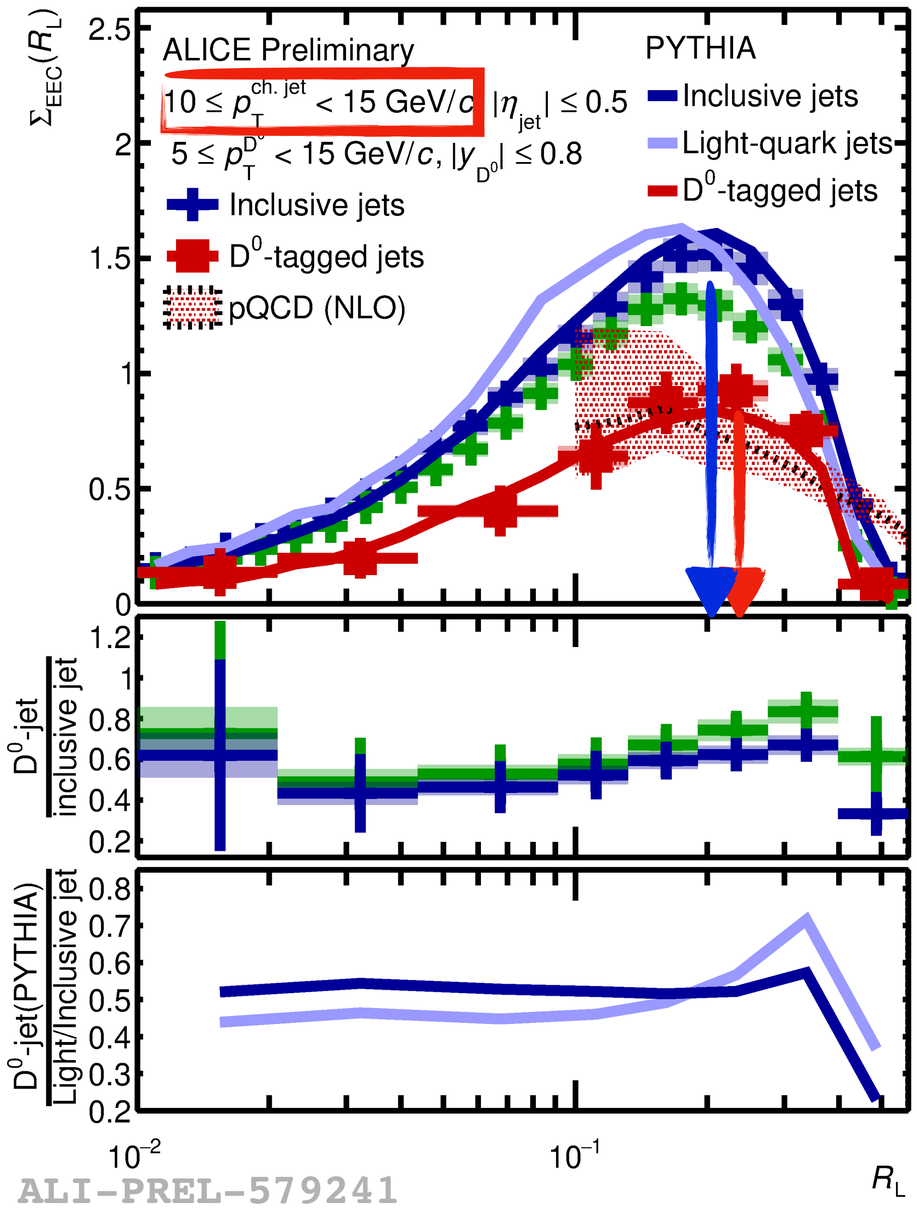

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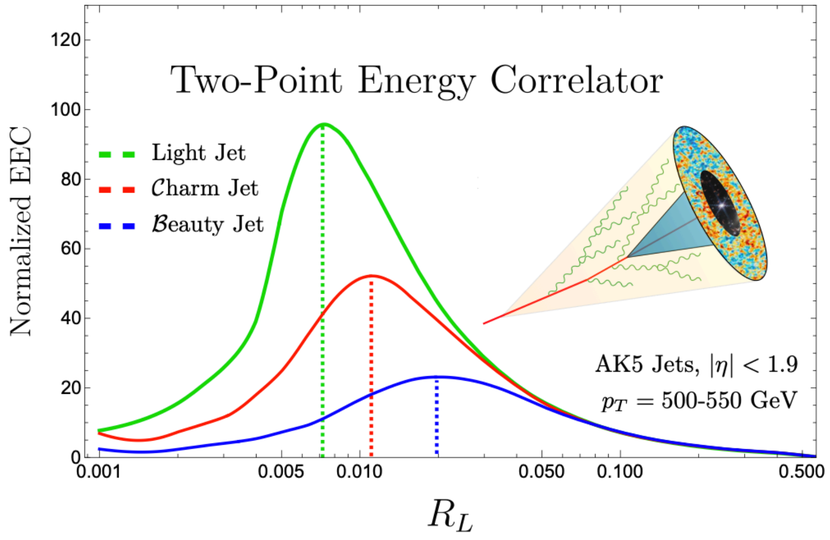

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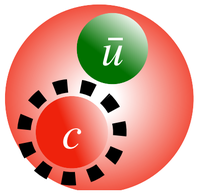

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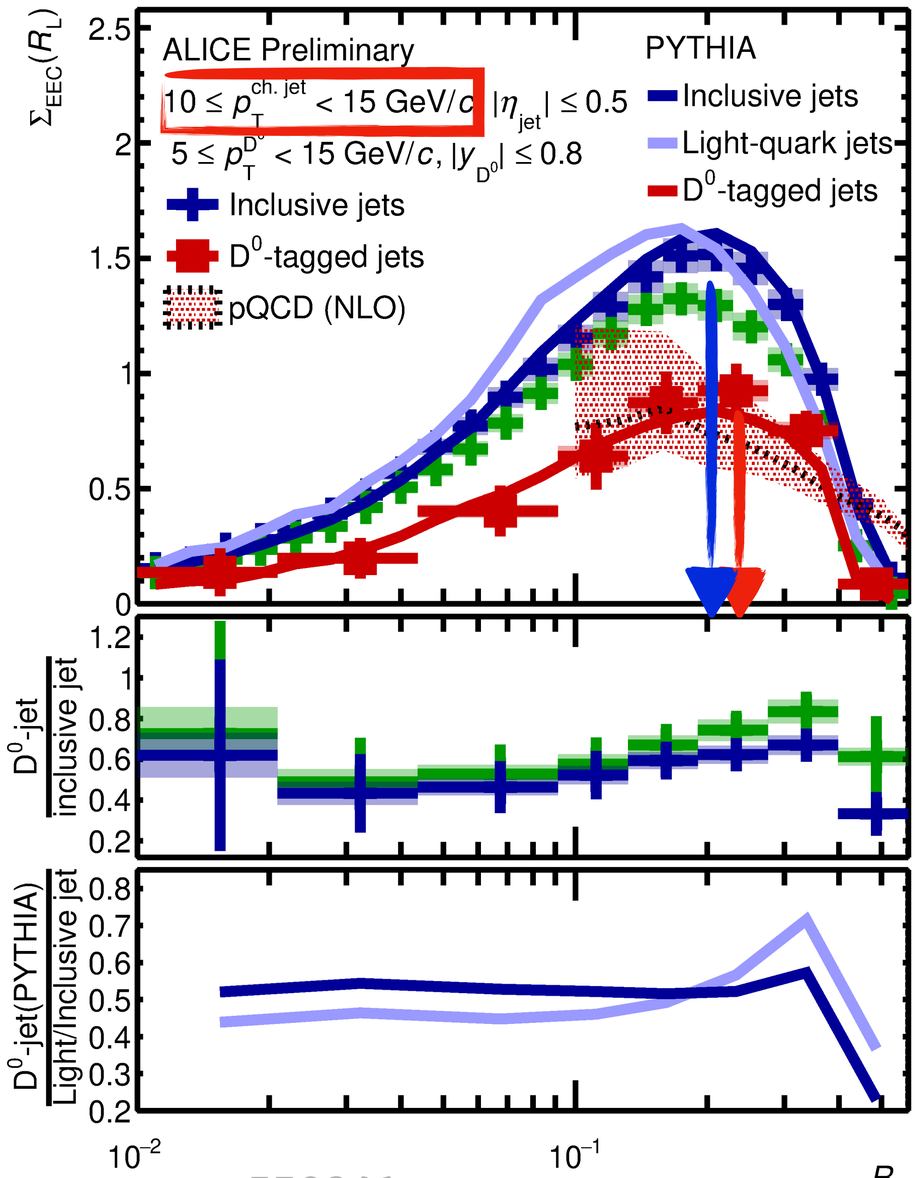

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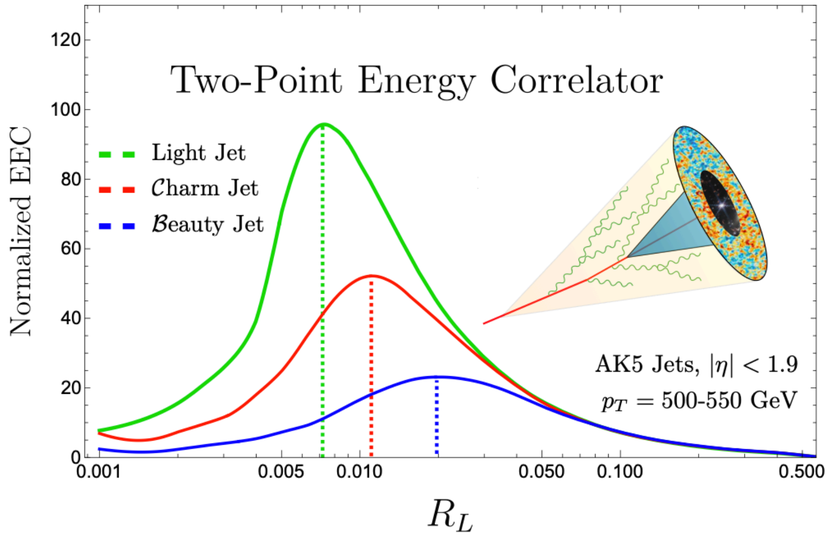

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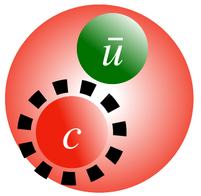

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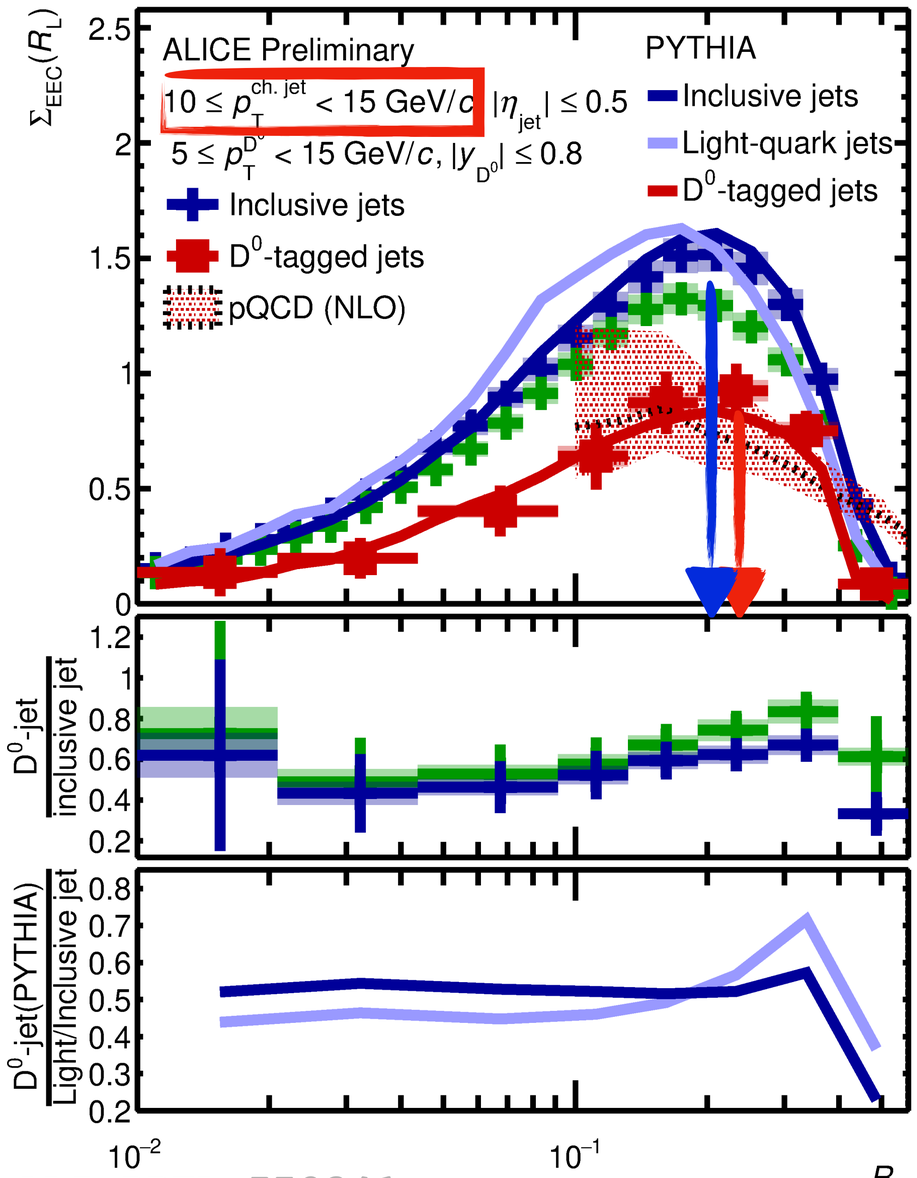

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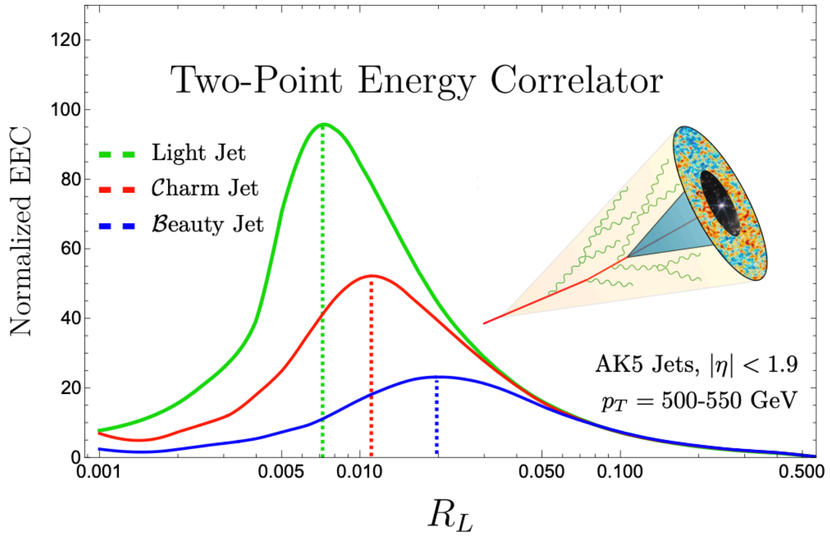

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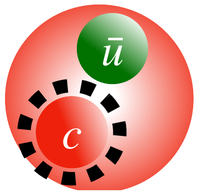

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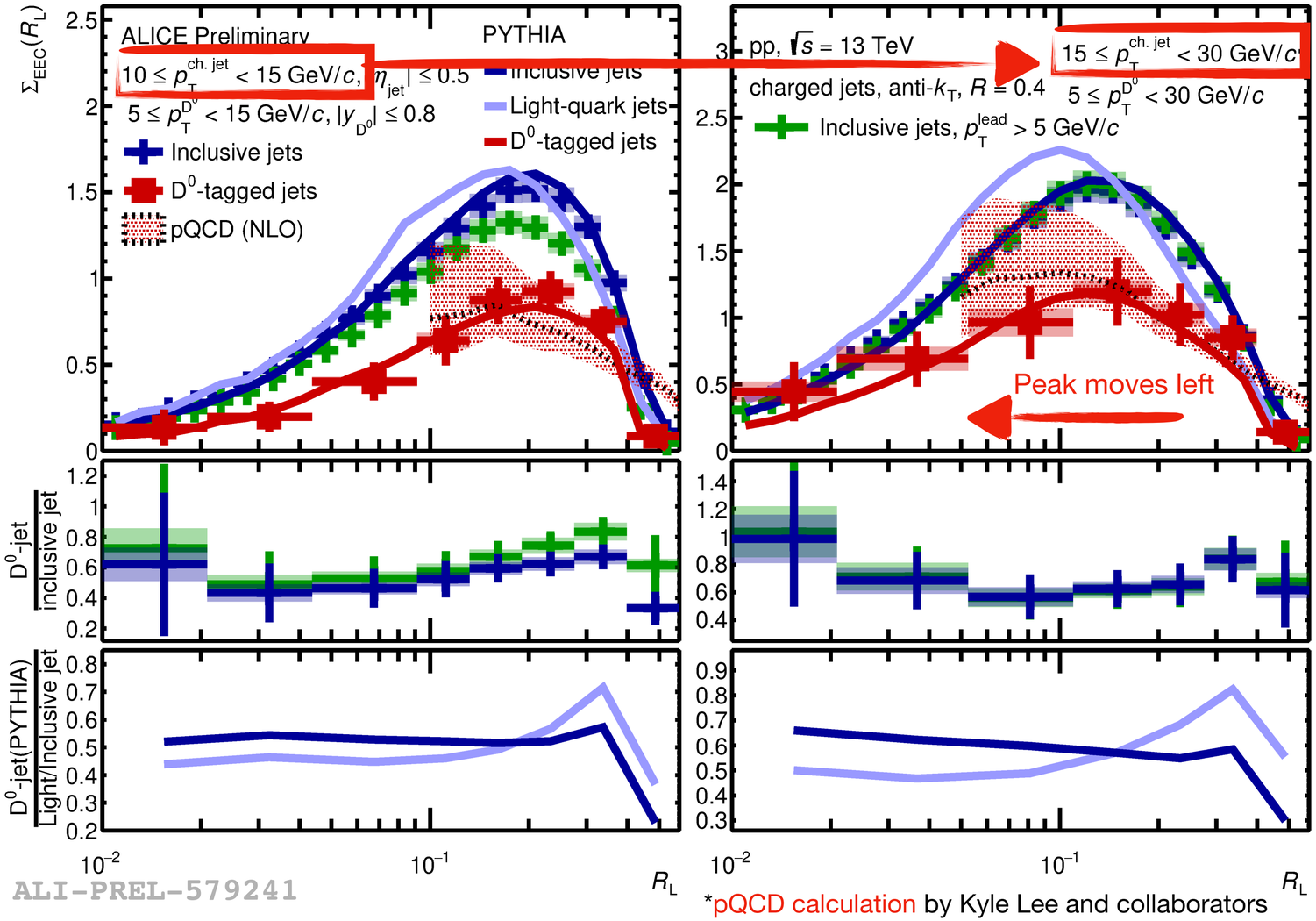

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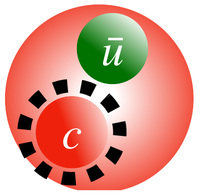

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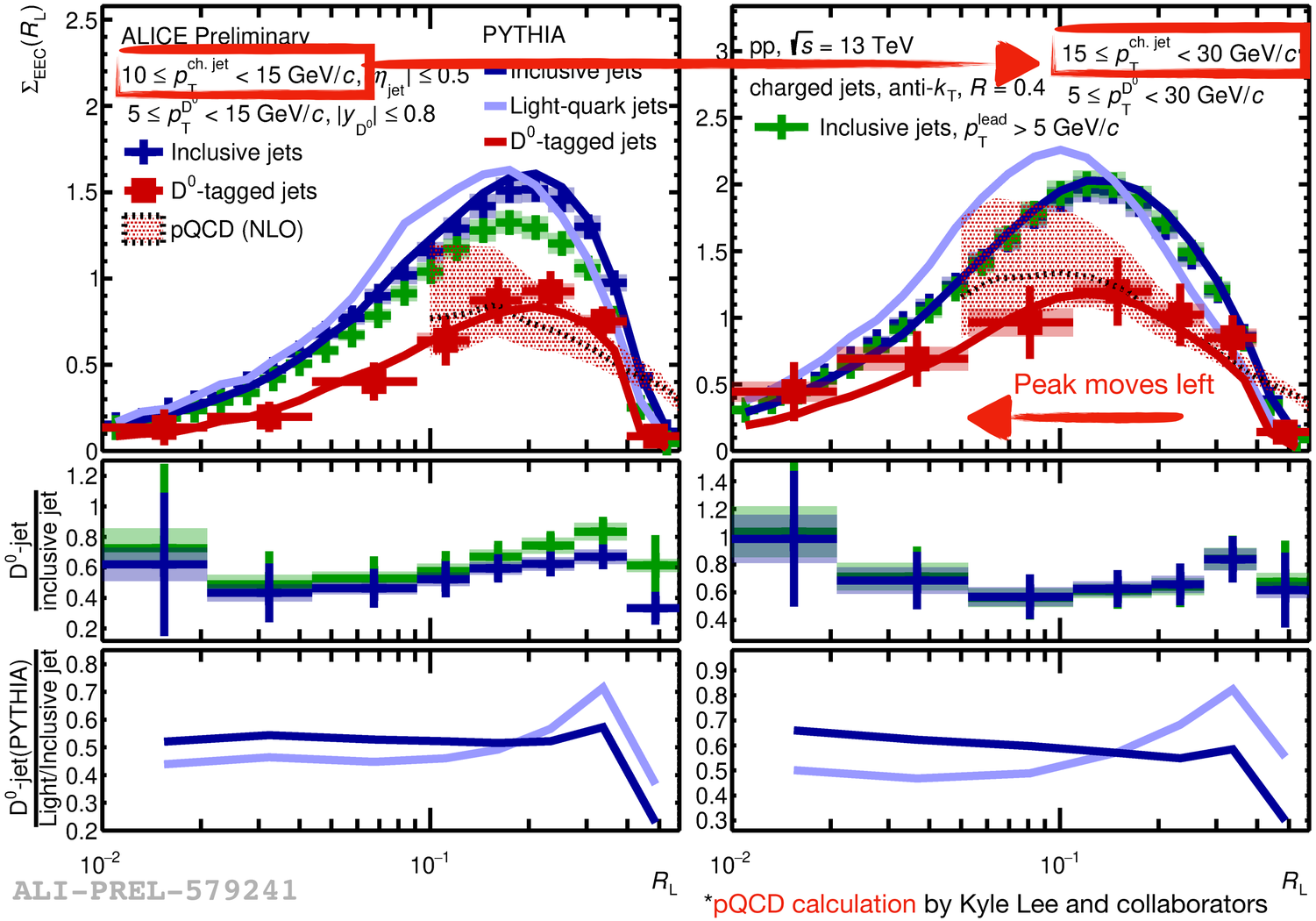

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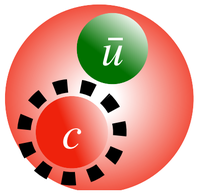

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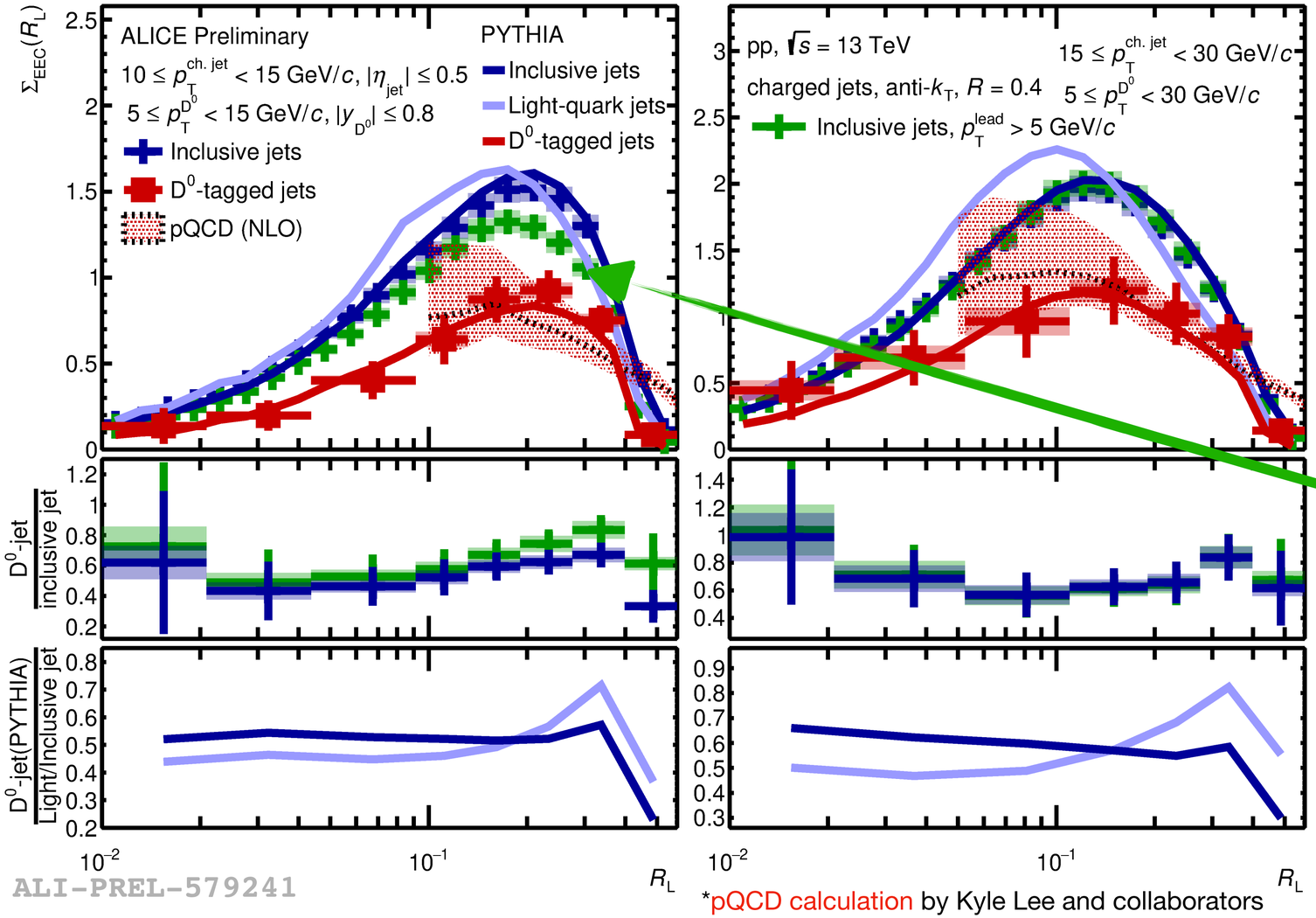

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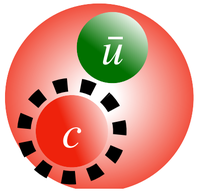

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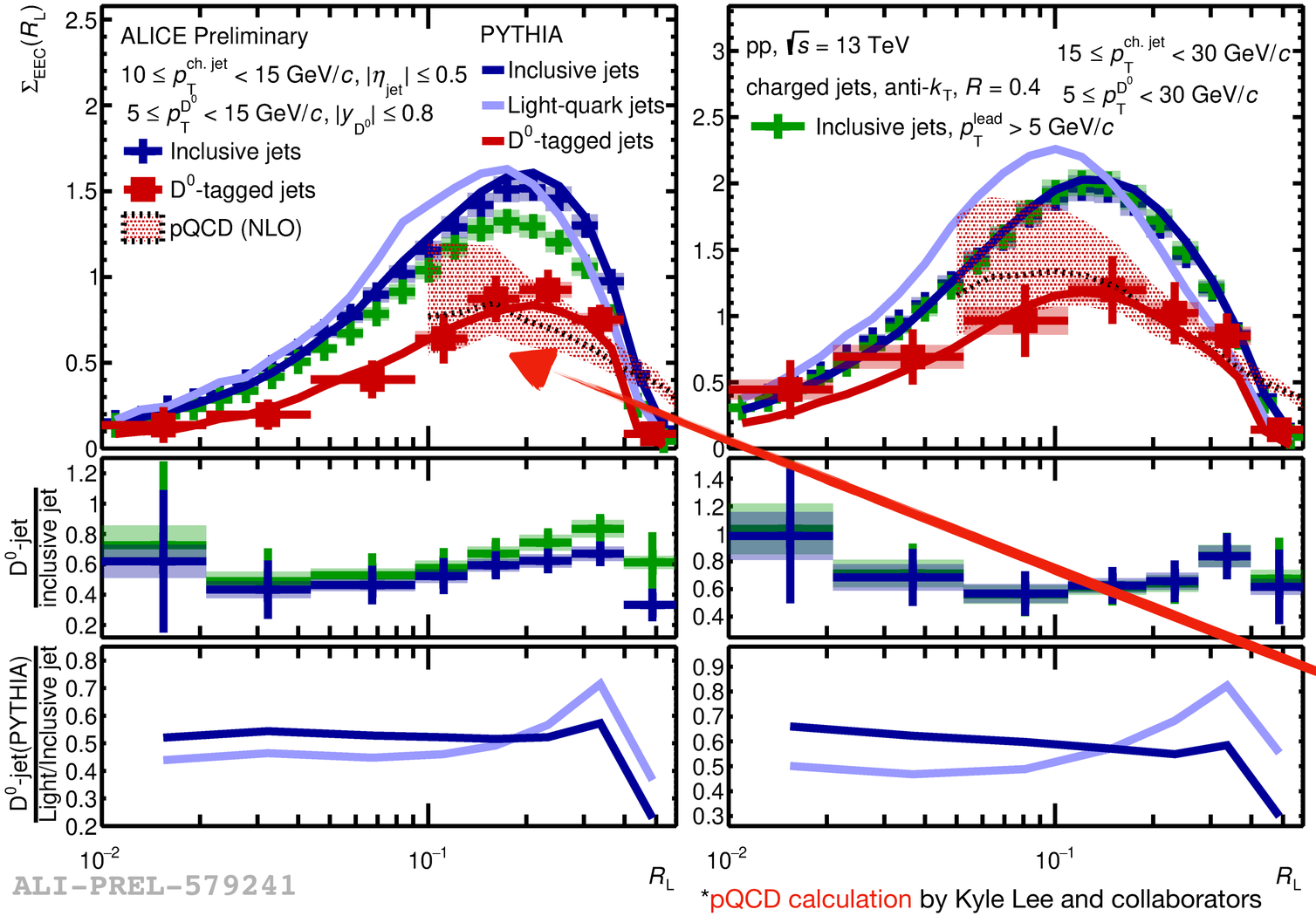

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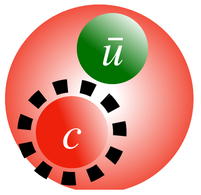

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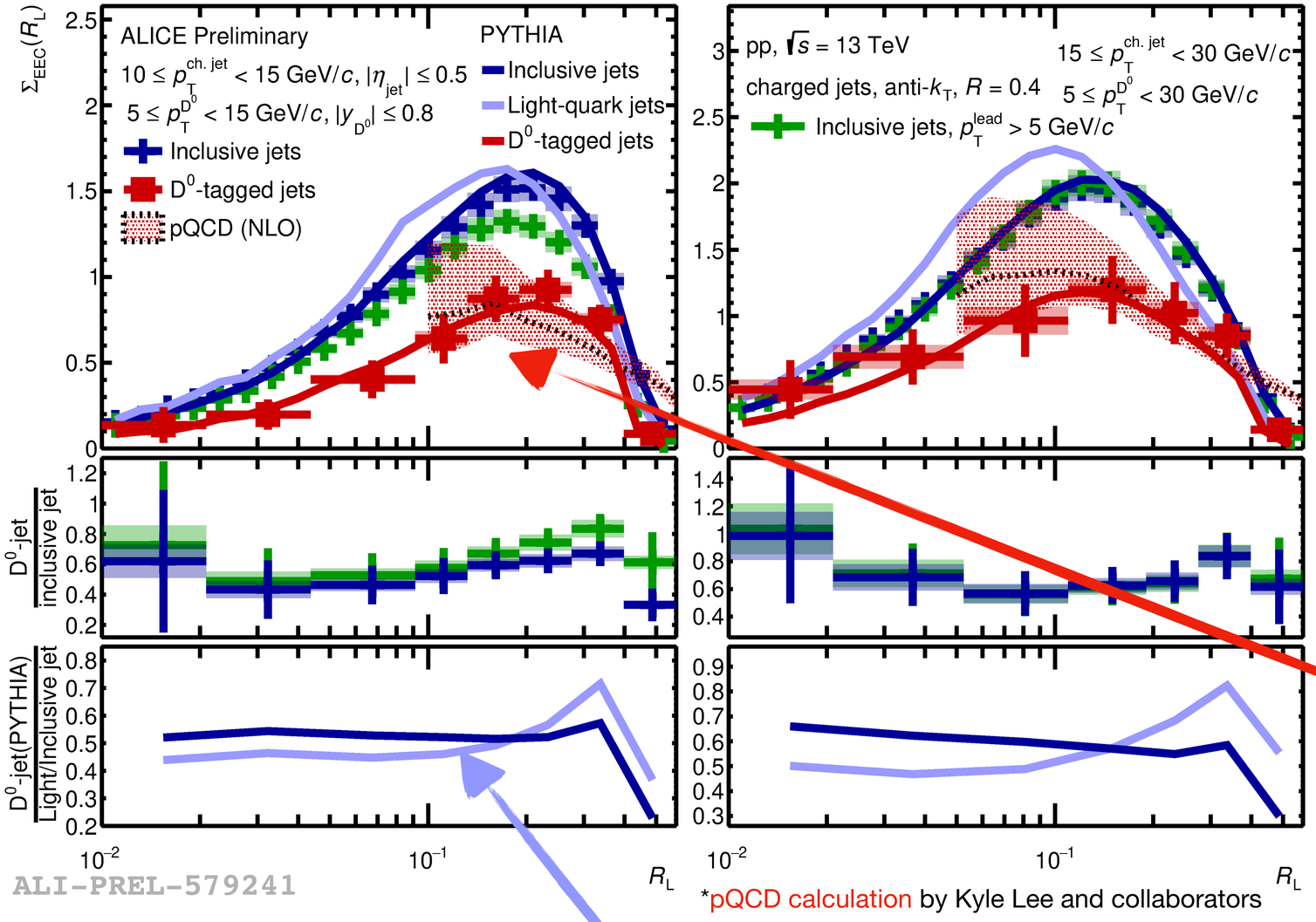

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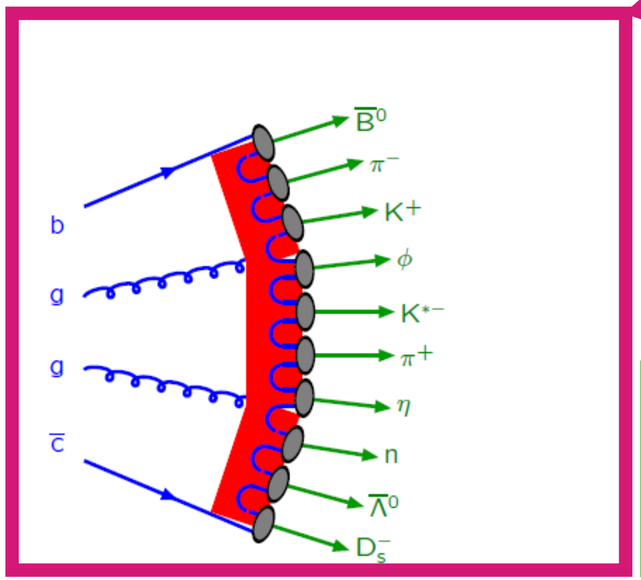
Sensitivity to Hadronization vs. Parton Shower



PYTHIA and
SHERPA LUND

HERWIG
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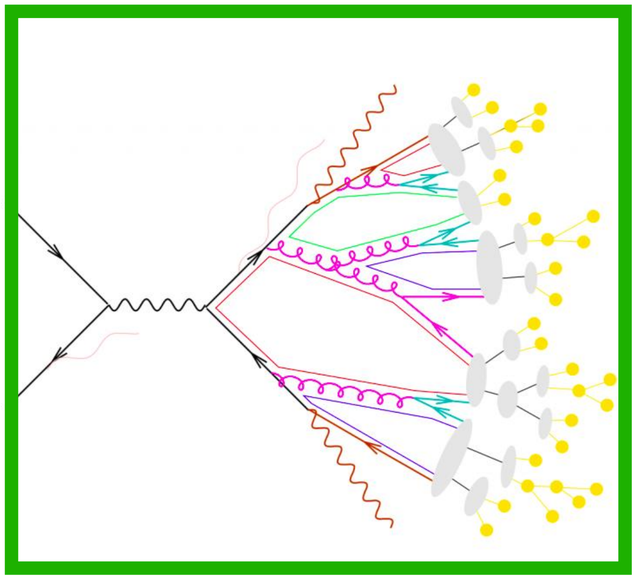

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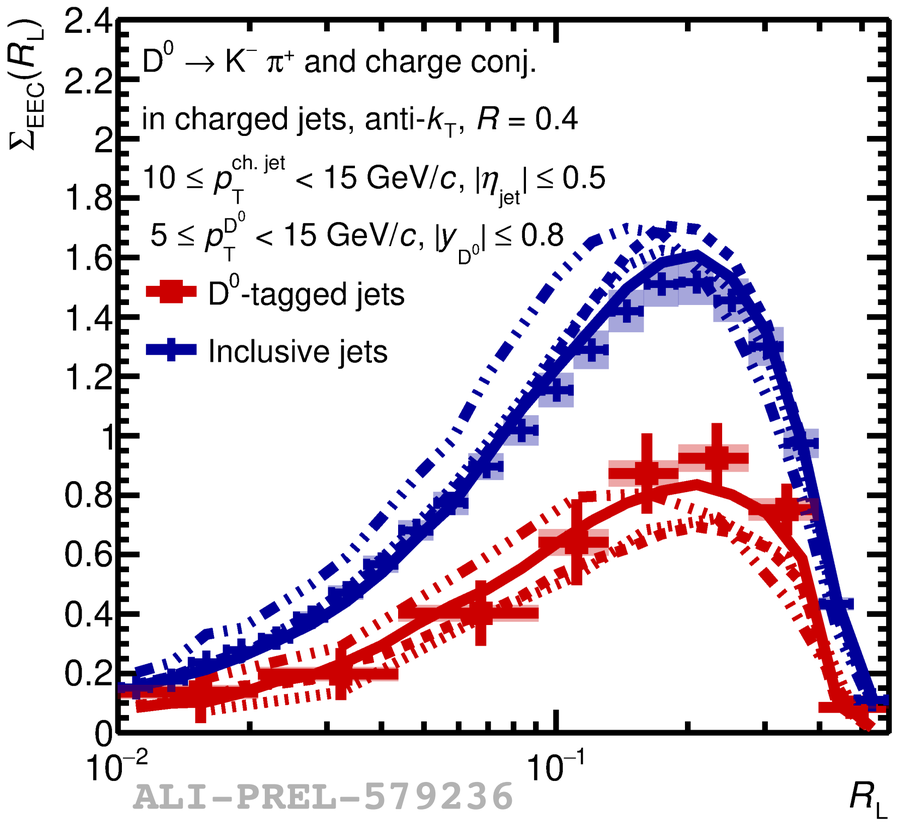

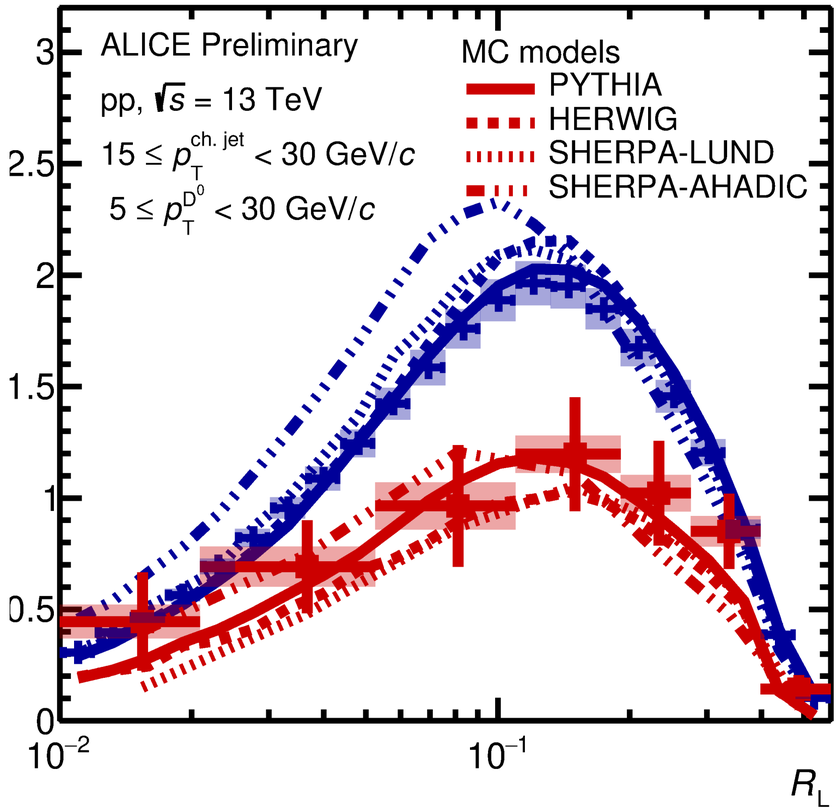

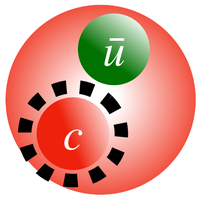

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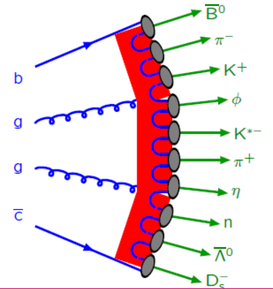
Lund string hadronization



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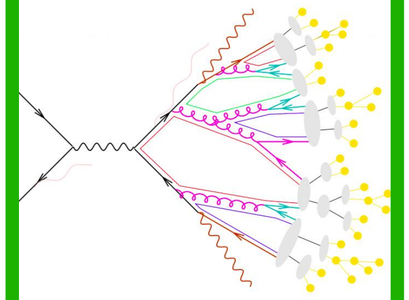
Cluster hadronization



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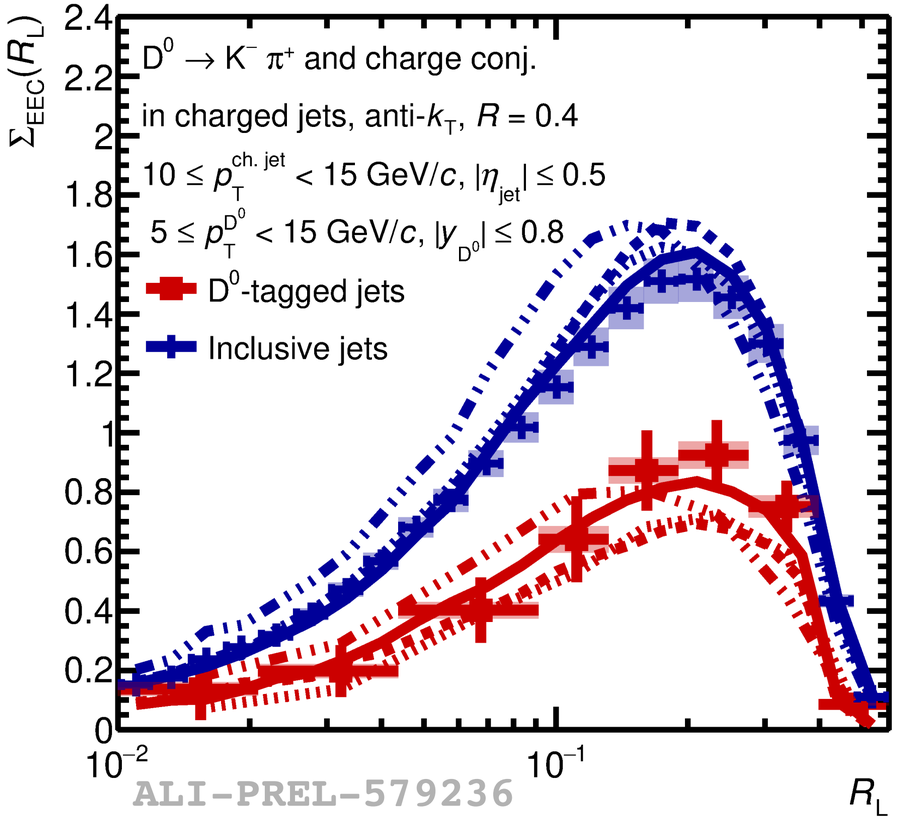

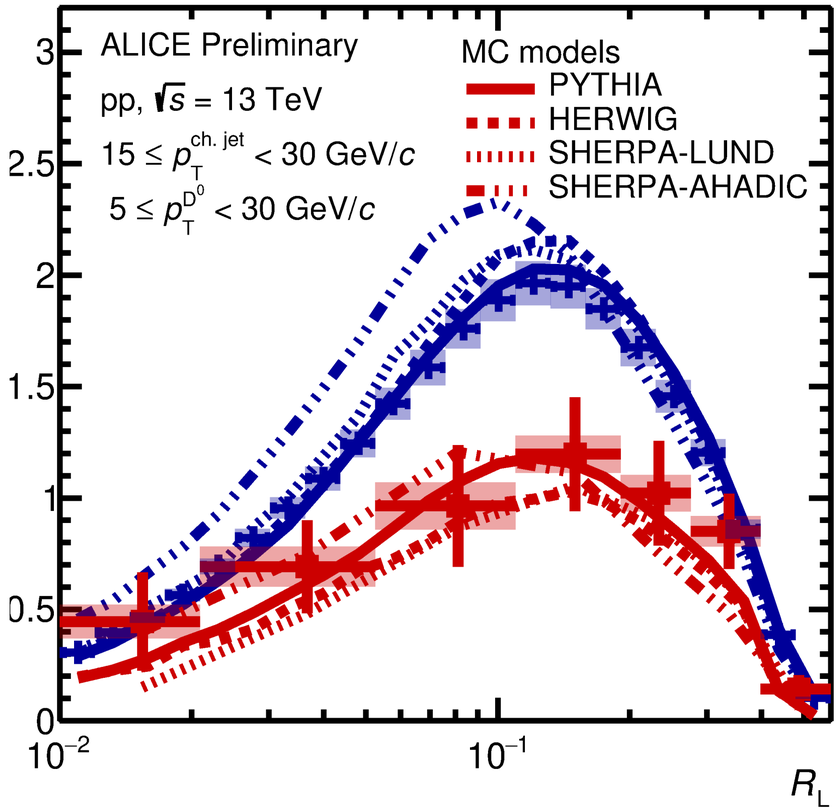

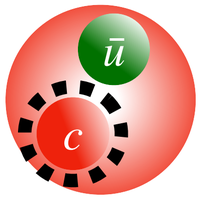

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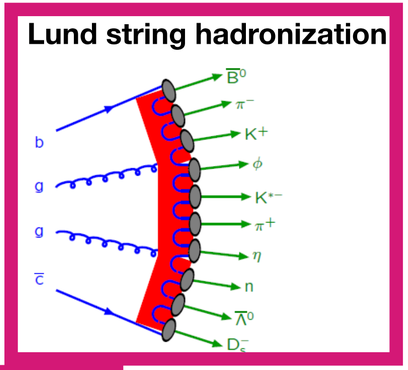

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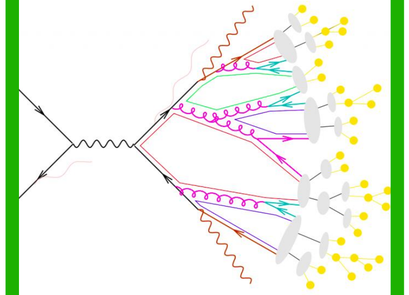

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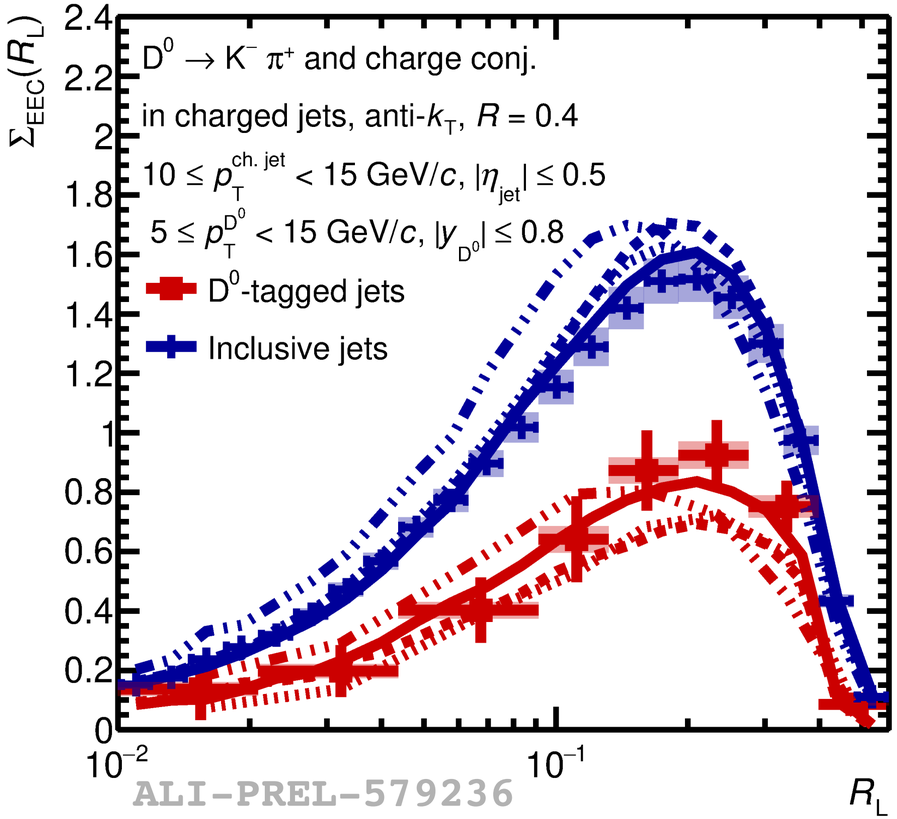

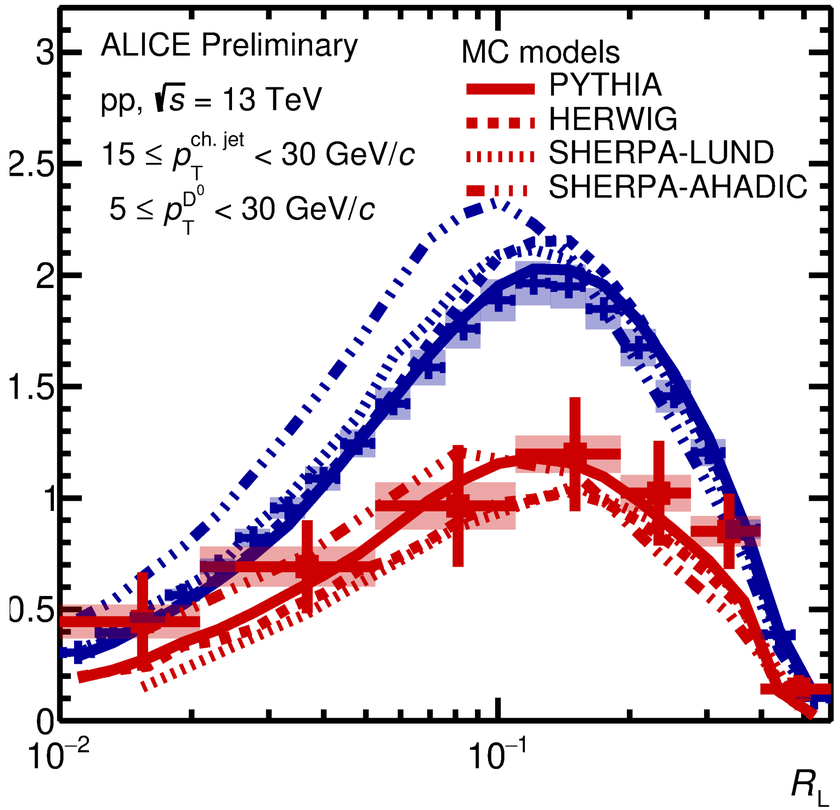

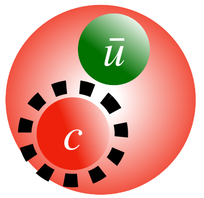

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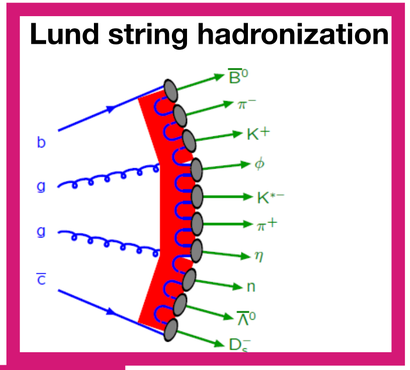

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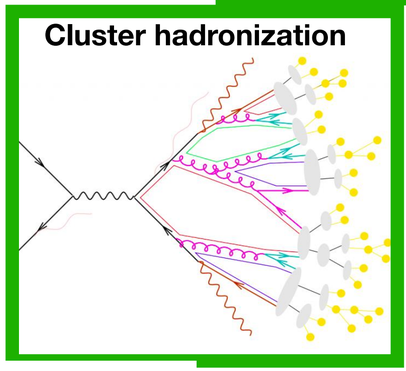

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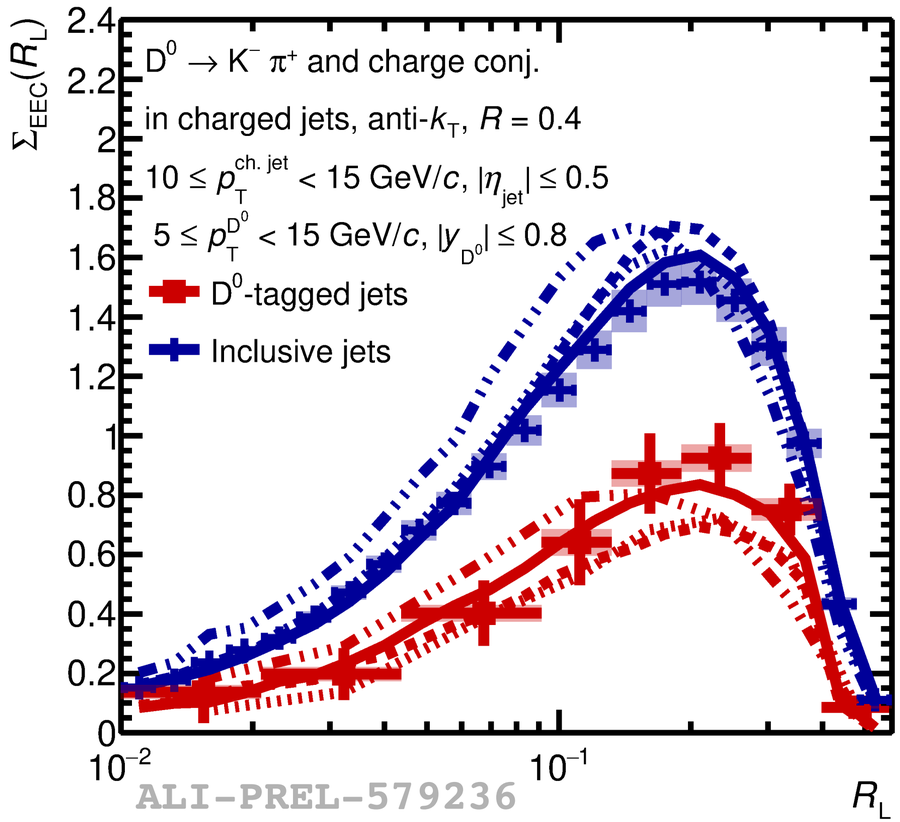

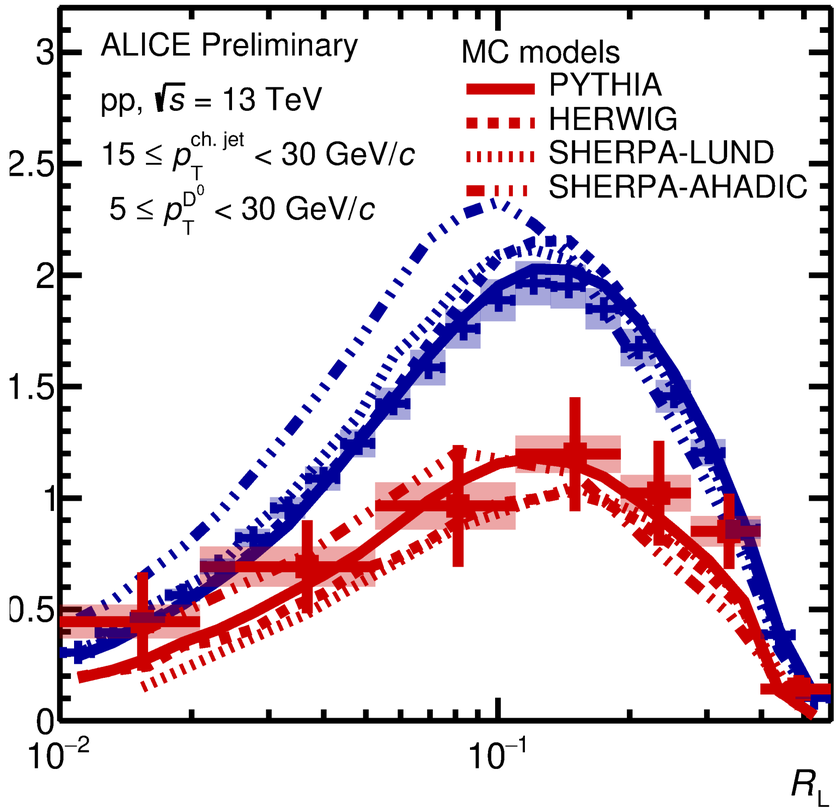

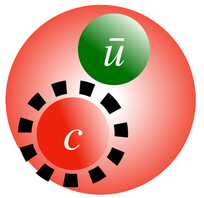

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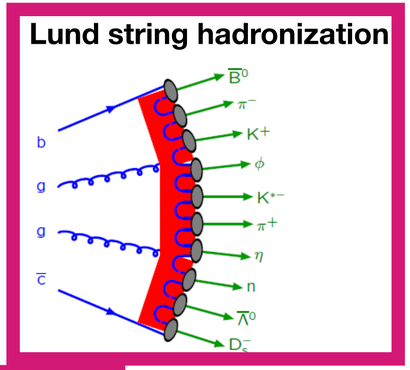

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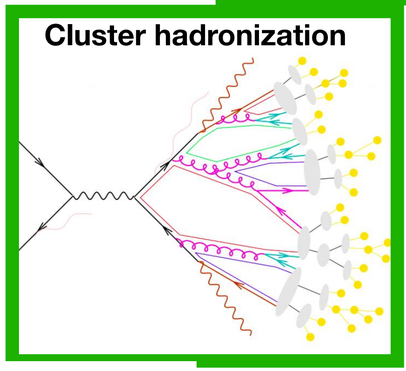

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What is next?

Largest challenge - Hadronization!

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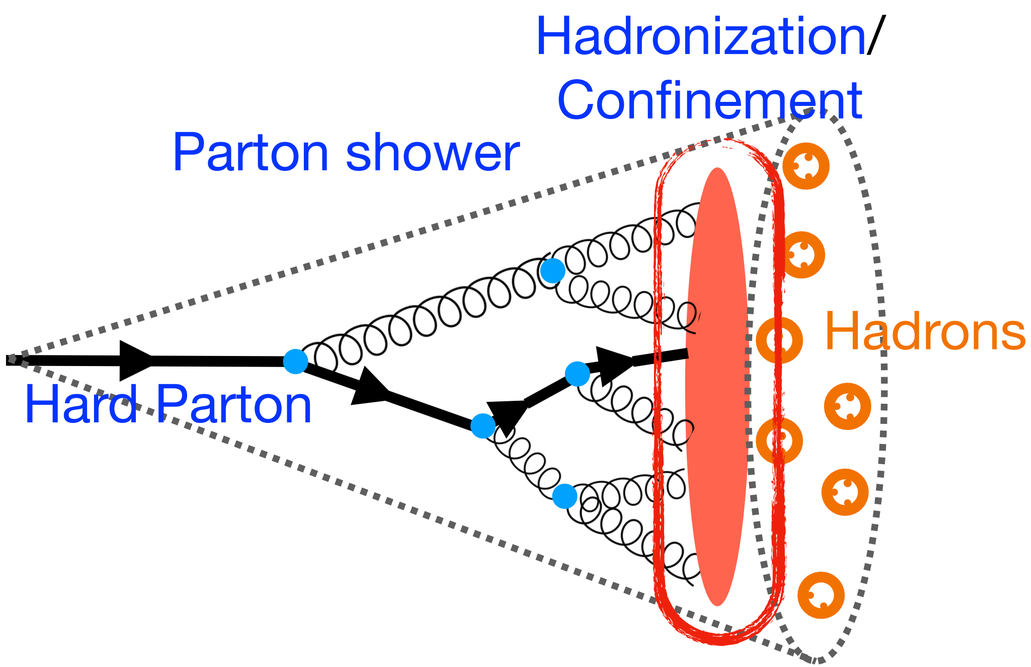
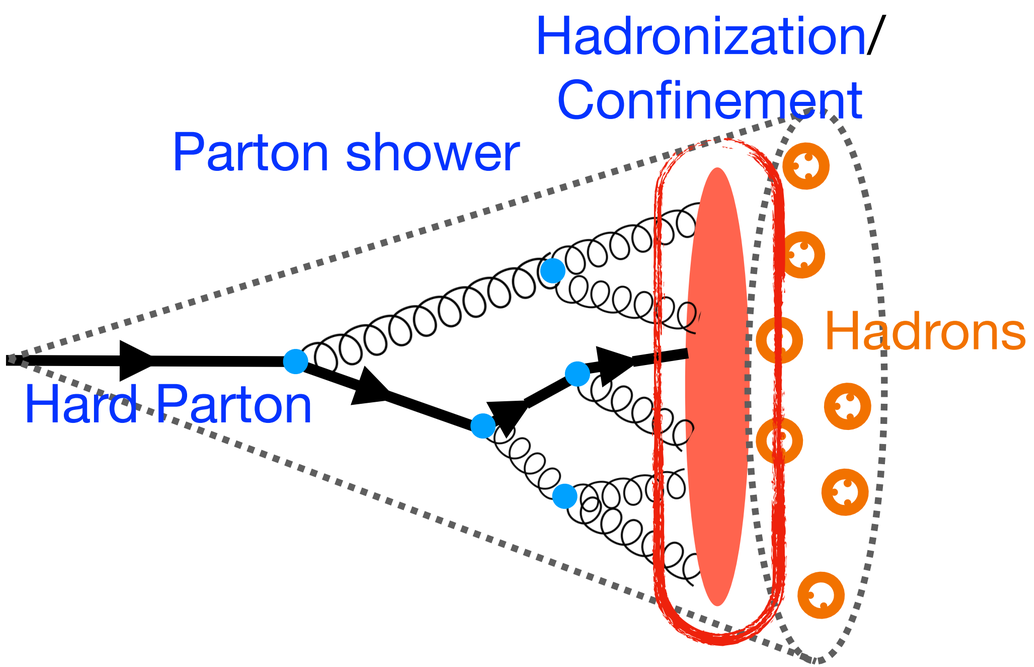
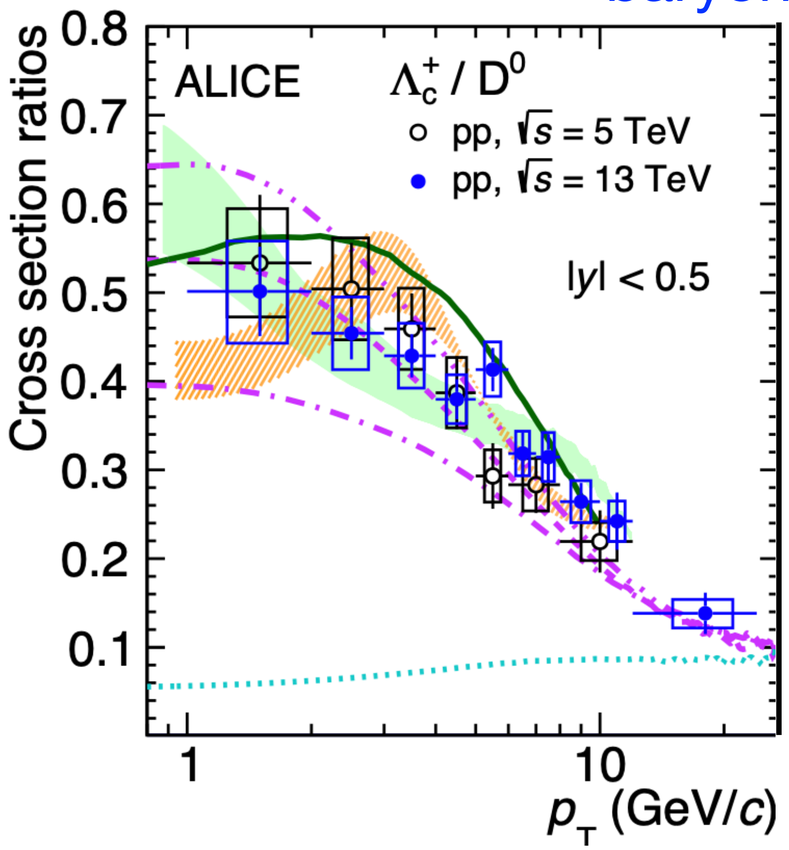
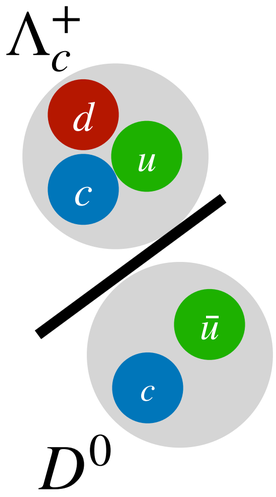


Largest challenge - Hadronization!

ALICE measured Charmed baryon to meson ratio







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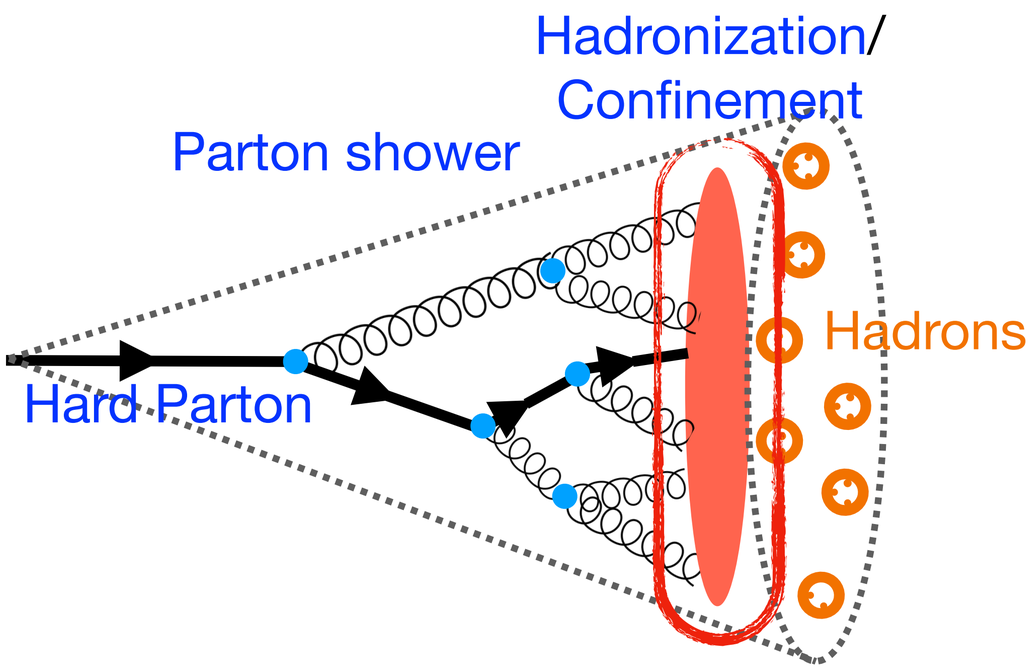

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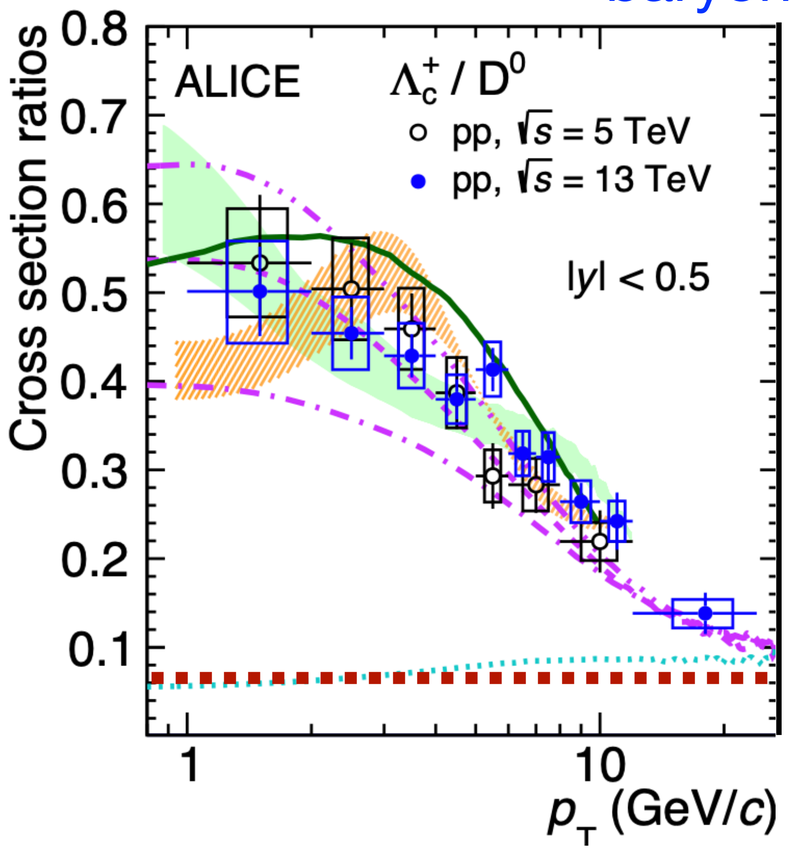
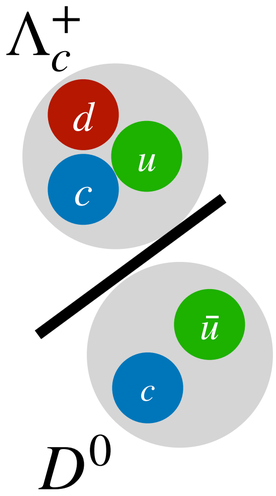
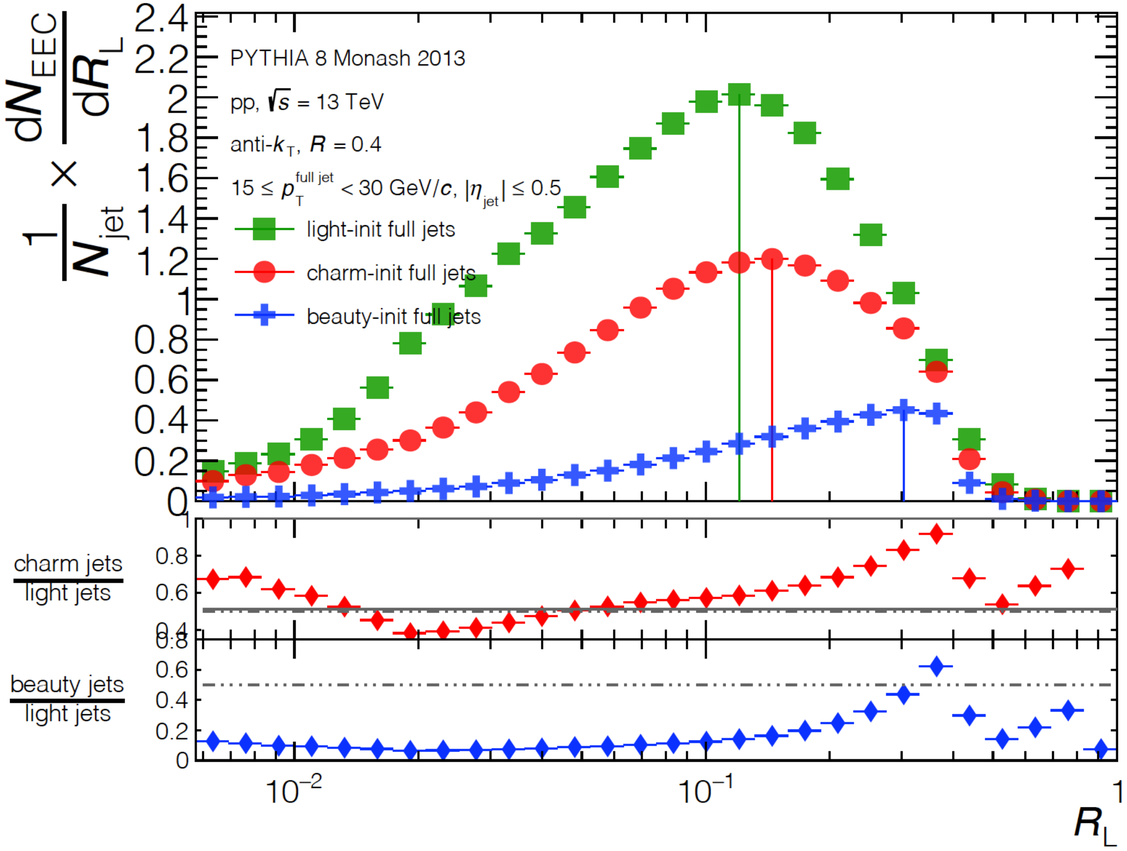




Enhanced production of baryon to meson ratio in hadronic collisions compared to e^+e^- collider

Universality broken!

Largest challenge - Hadronization!



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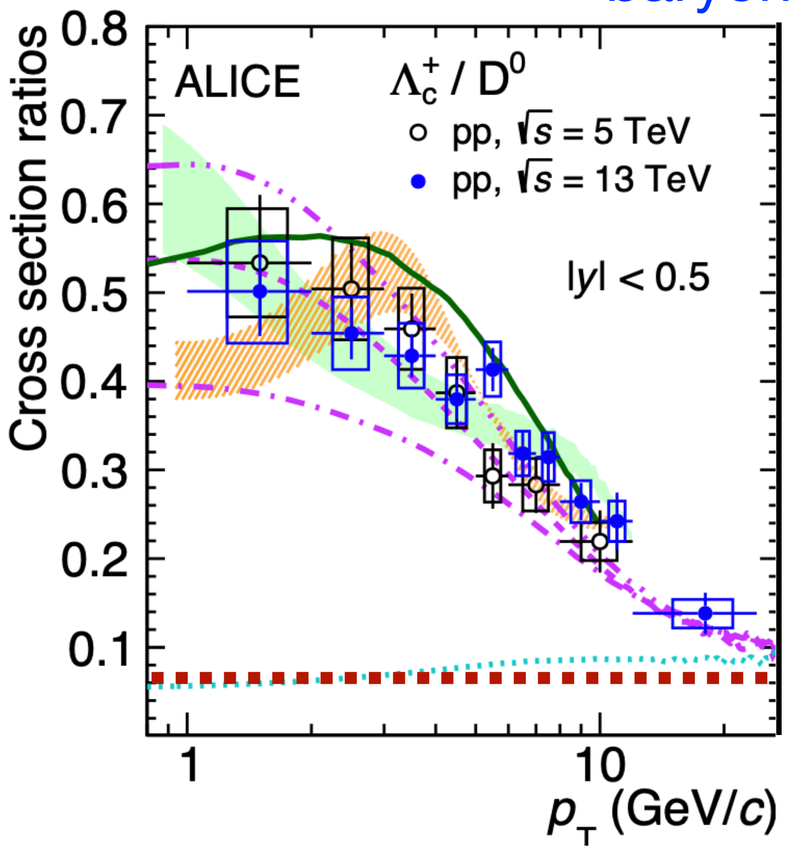

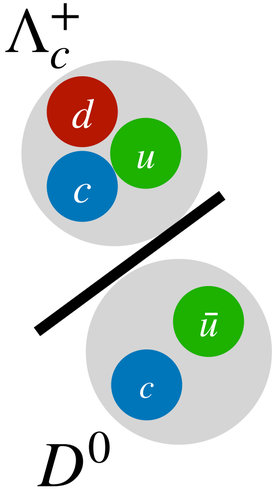

With Run3 high precision charm measurements and access to beauty measurement

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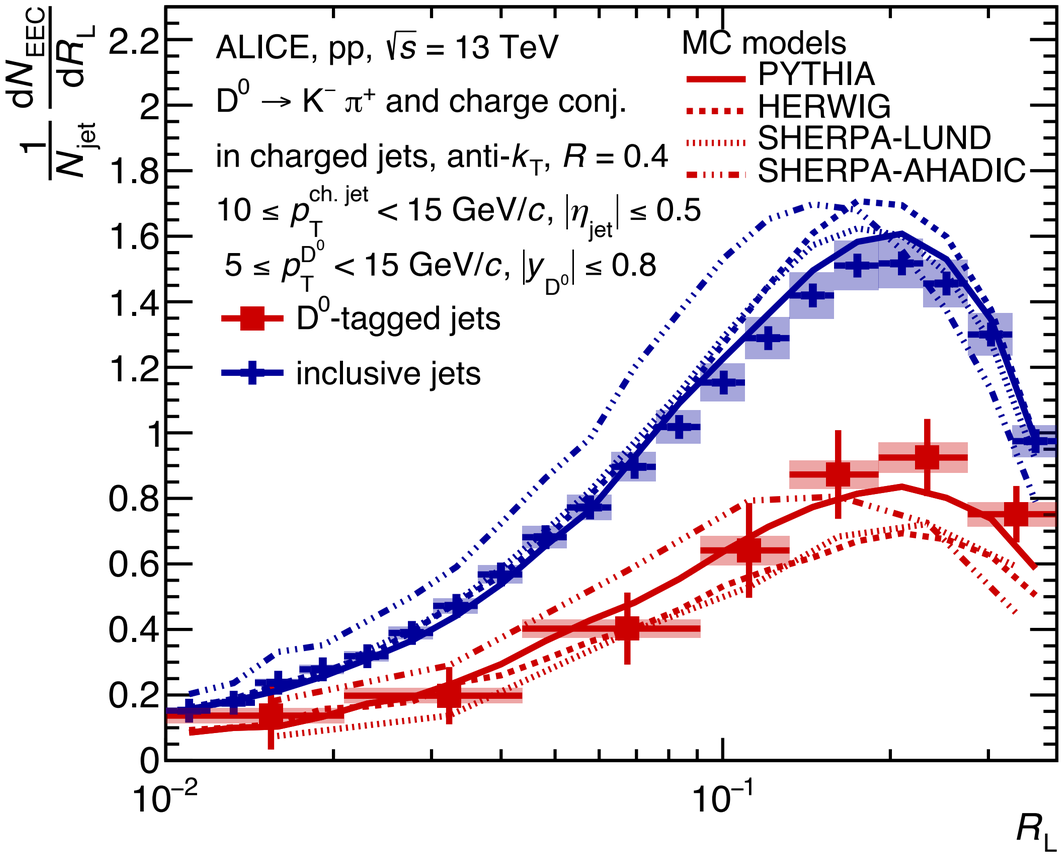
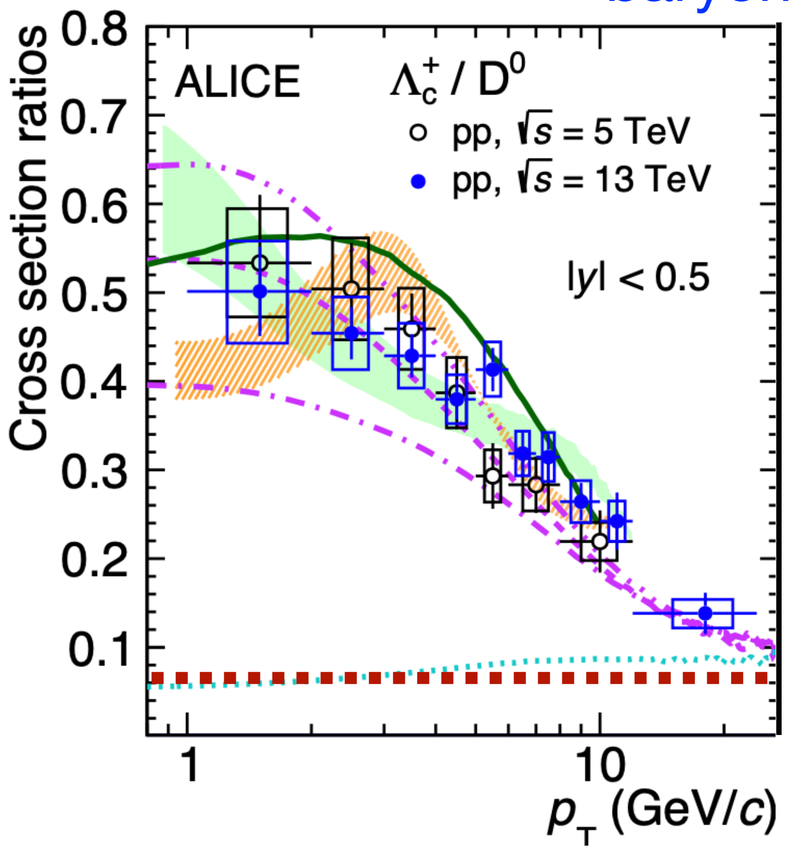
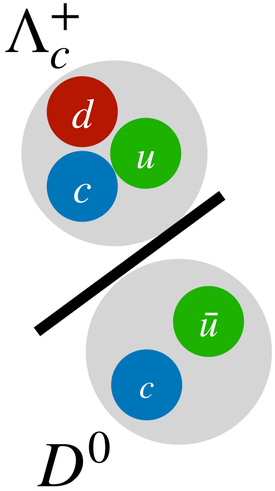


ALICE measured Charmed baryon to meson ratio





With Run3 high precision charm measurements and access to beauty measurement

Systematically **probe** **hadronization**

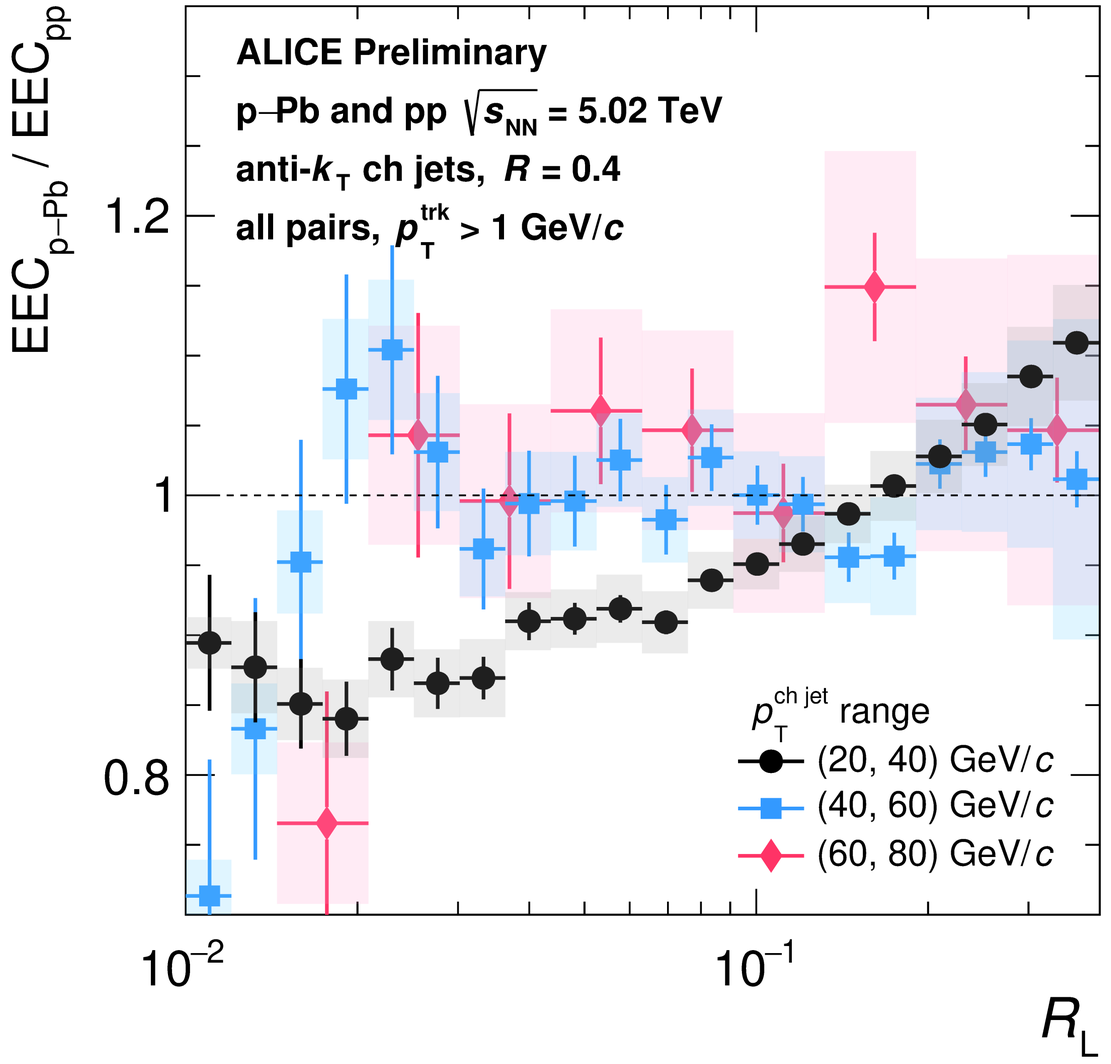
Enhanced production of baryon to meson ratio in hadronic collisions compared to e^+e^- collider

Universality broken!

Thank you for your attention!

EECs modified in p-Pb at low jet p_T bin

- **Significant difference between EECs in p-Pb compared to pp!**
  - jet structure appears to be altered only in the lowest jet p_T range
- Initial state effect?
  - some models lead to a qualitatively similar effect
- Final state effect?
  - modification is qualitatively consistent with ALICE measurement* of HM/MB z_{ch} in pp

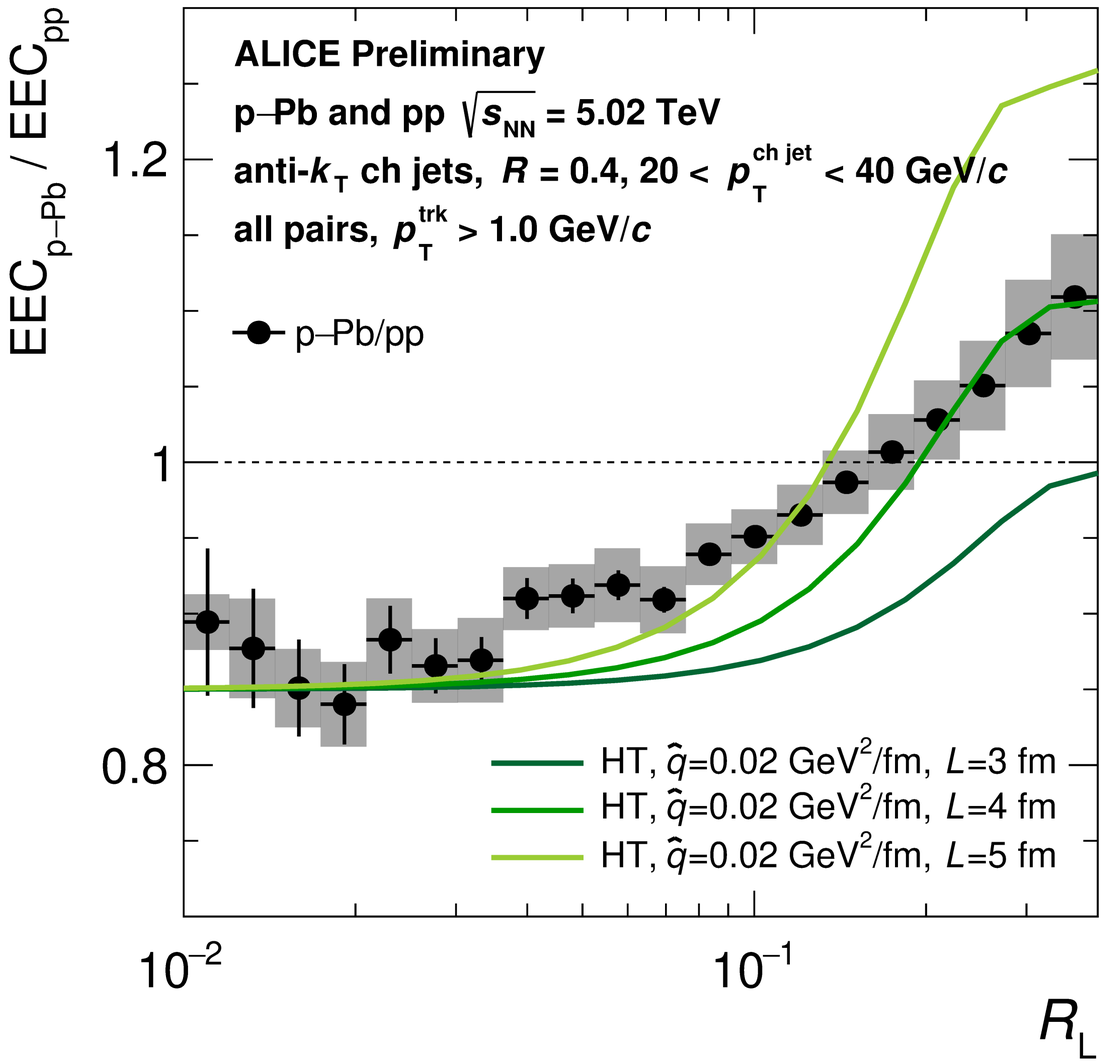


*arXiv:2311.13322

ALI-PREL-581947

Higher-twist formalism reproduces the data

- HT calculations* of final-state interactions from Yu Fu et al. show a stronger effect is possible
  - R_{pPb} (nuclear modification of nPDF) is chosen to be 0.85 (for x=0.01)
  - $\hat{q}$ is 0.02 GeV^2/fm (BDMPS 1997)
  - L is varied (R_{Pb} is 5.5 fm)
- Simulation (e.g. JETSCAPE) required for a more realistic estimate!



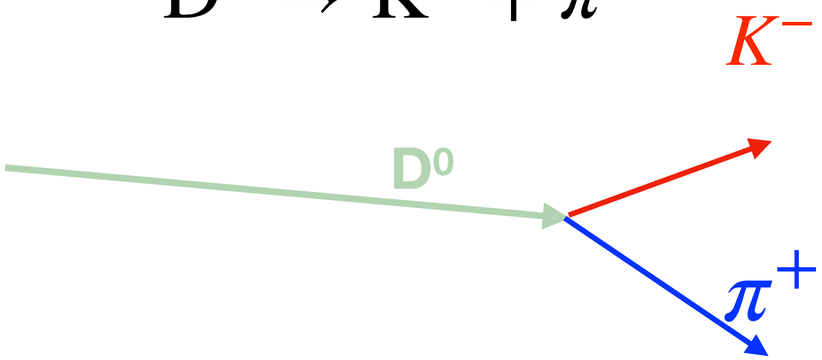
ALI-PREL-582290

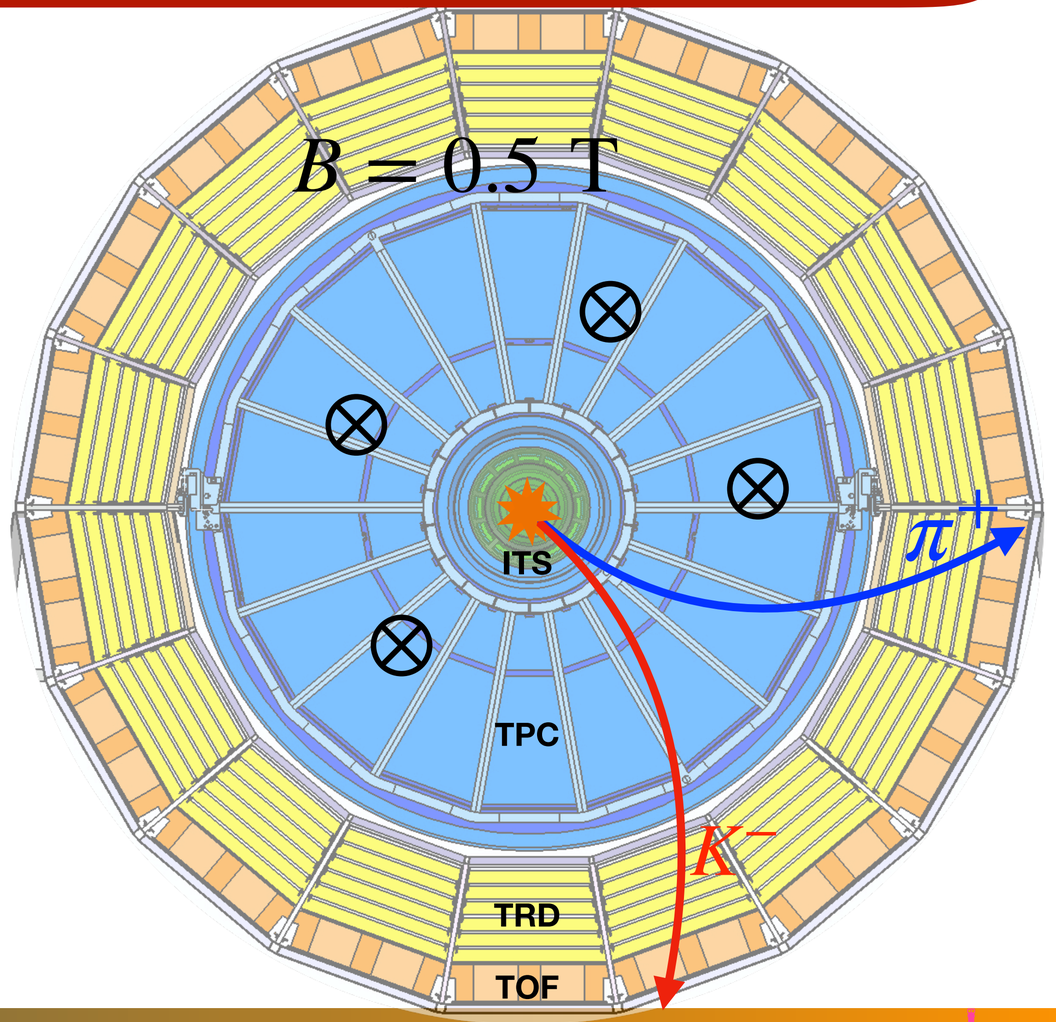
* models provided by Yu Fu, Berndt Mueller, and Chathuranga Sirimanna

HF tagging with ALICE

1. Charm meson(D^0)/baryon(Λ_c^+) reconstruction and selection by topological cuts and PID on decay daughters.

$$D^0 \rightarrow K^- + \pi^+$$





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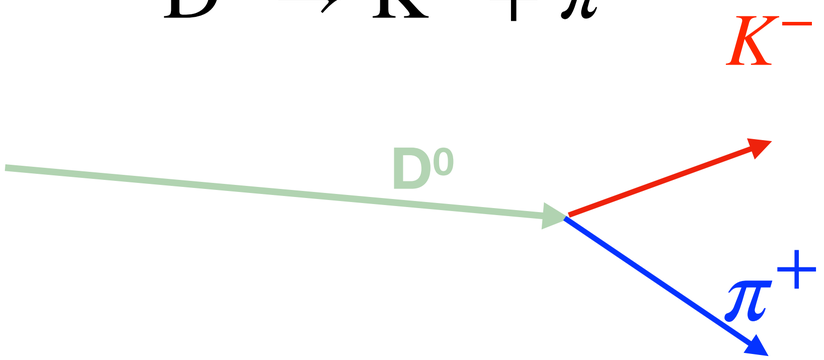
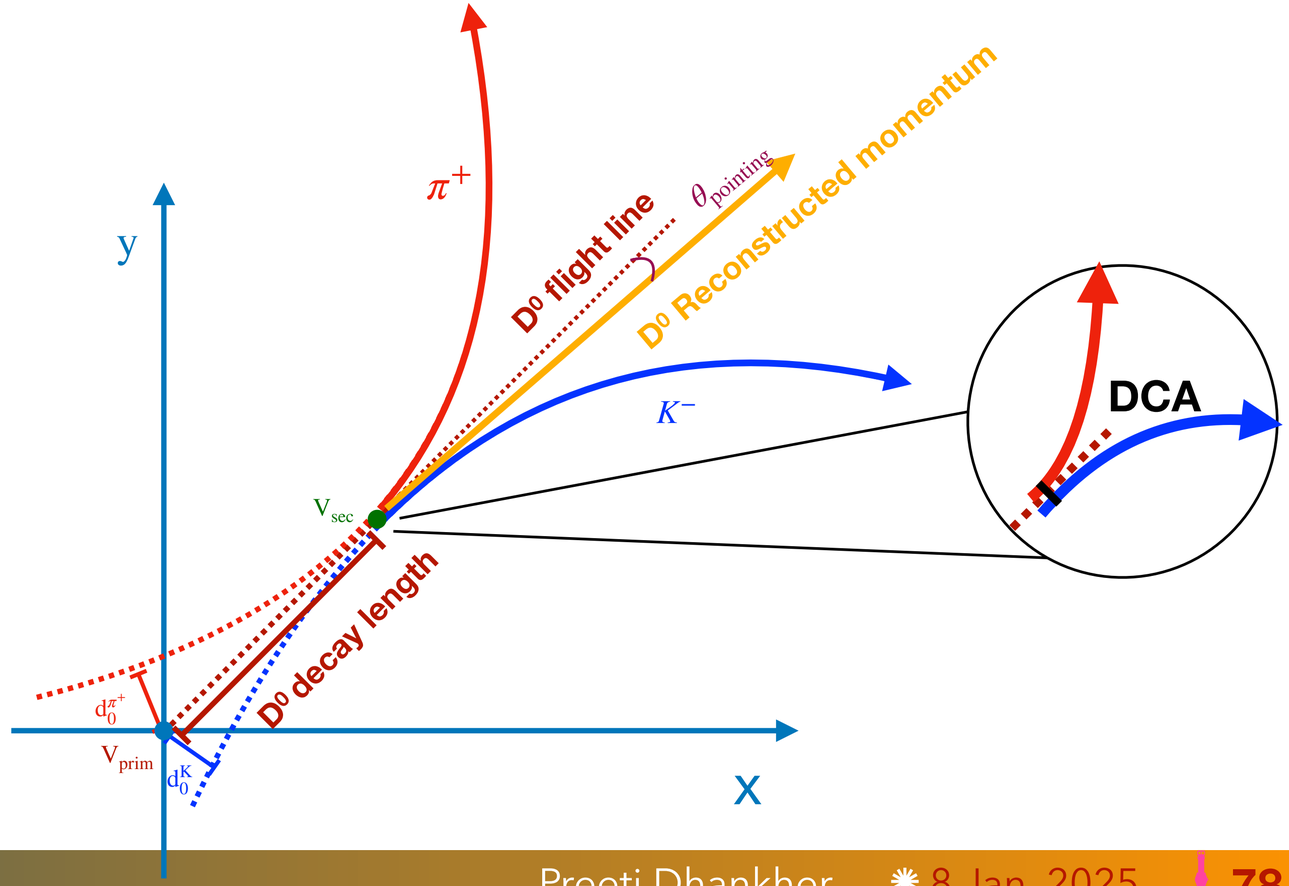


$2 \leq p_{T,D^0} \leq 36$ GeV/c



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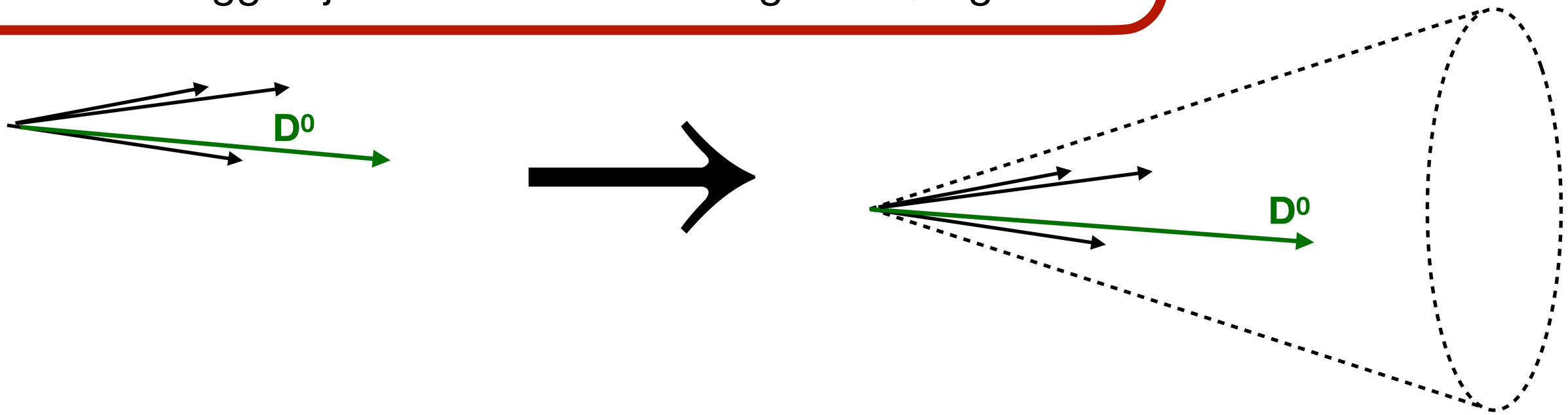

$2 \leq p_{T,D^0} \leq 36$ GeV/c

$5 \leq p_{T,\text{ch. jet}} \leq 50$ GeV/c

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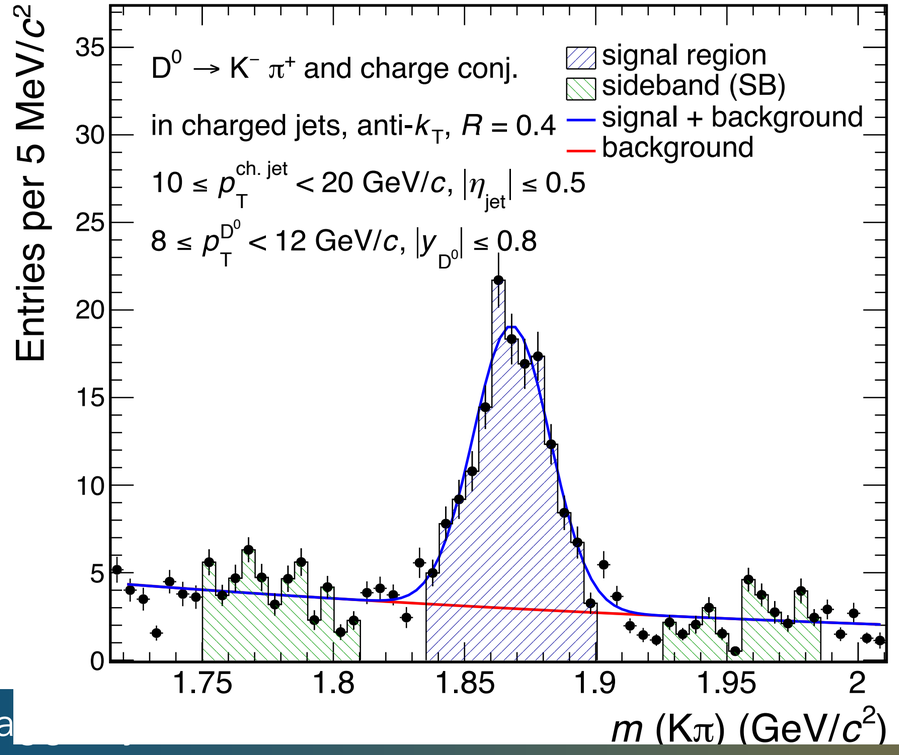

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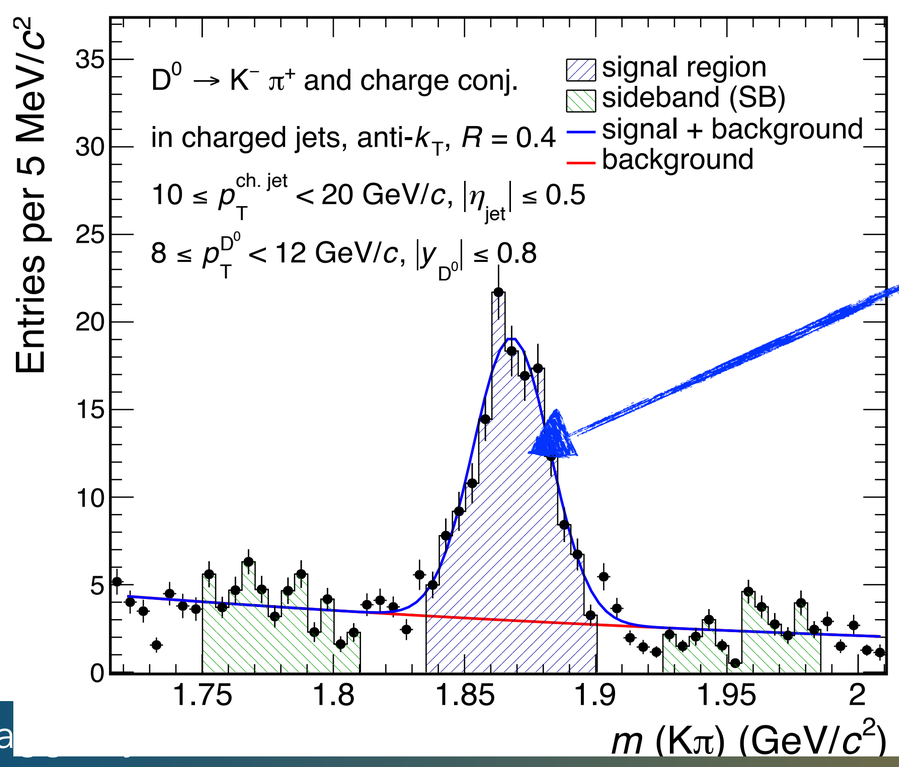
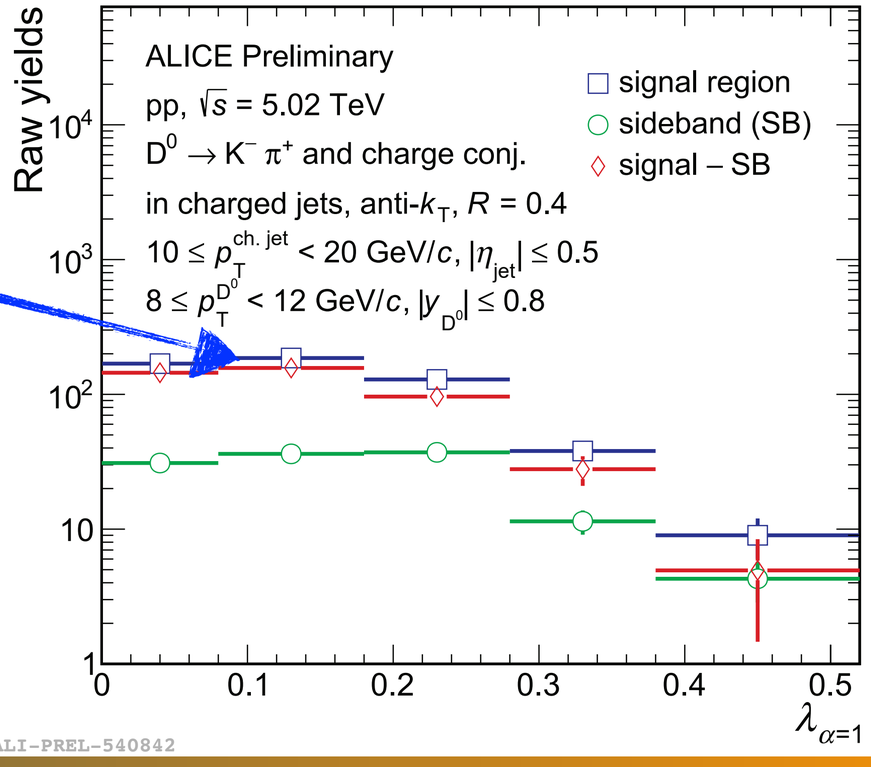


Signal region



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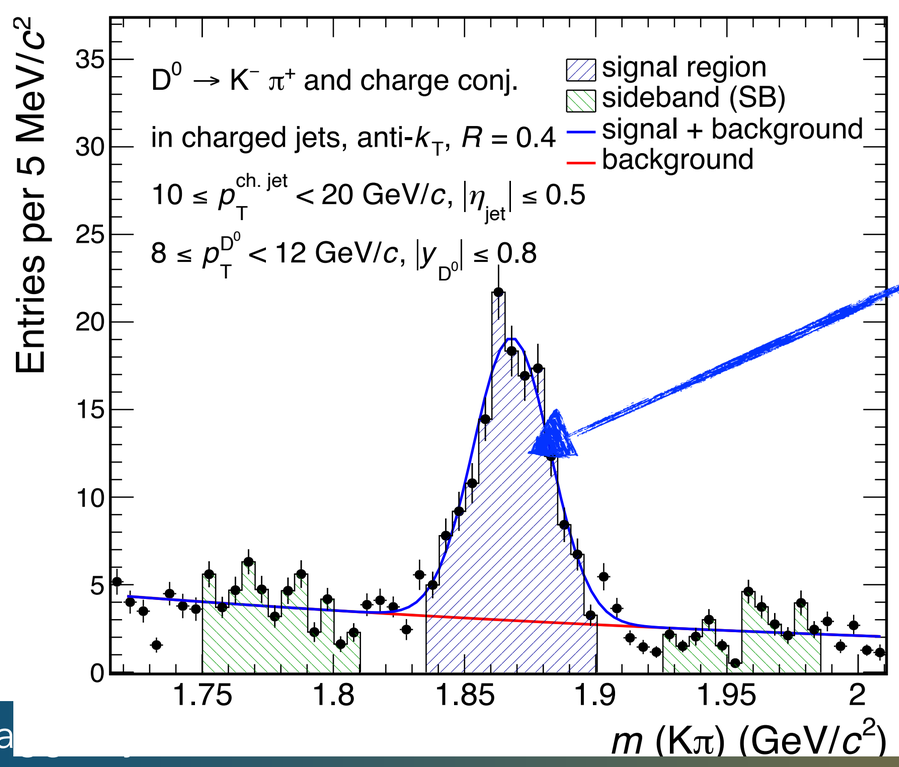
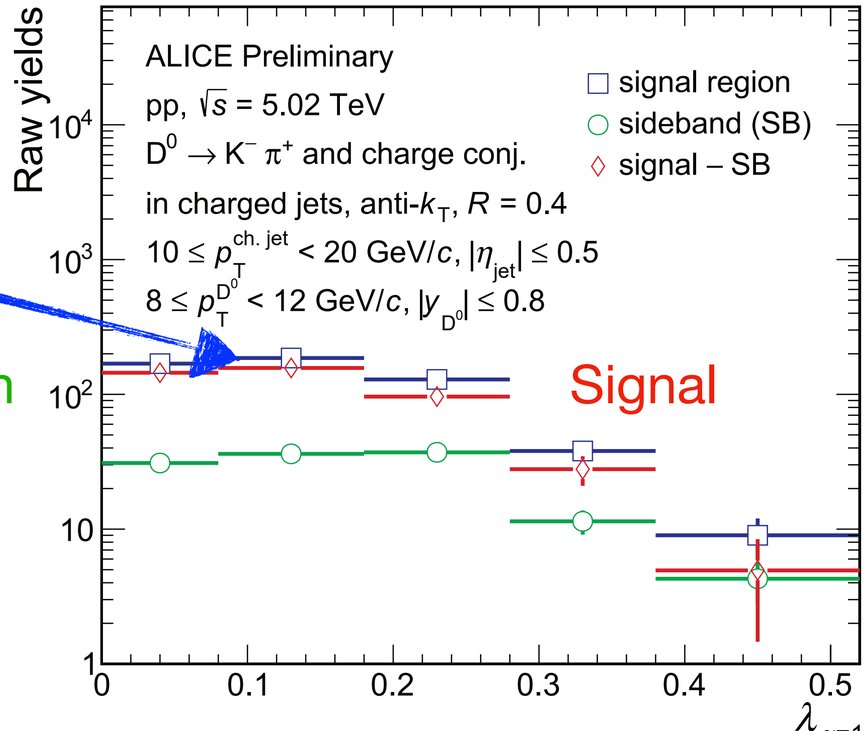


Signal region

Sideband region



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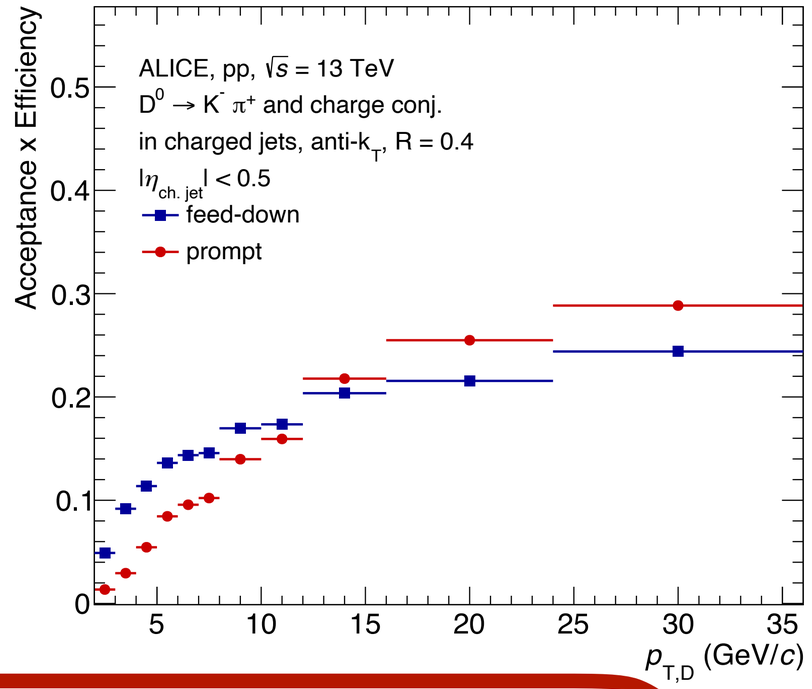

- Efficiency of the D^0 cut selections is strongly dependent on D^0-meson p_T
- sideband-subtracted distributions are corrected by the D^0 reconstruction and selection efficiency in narrow D^0 p_T intervals

HF tagging with ALICE

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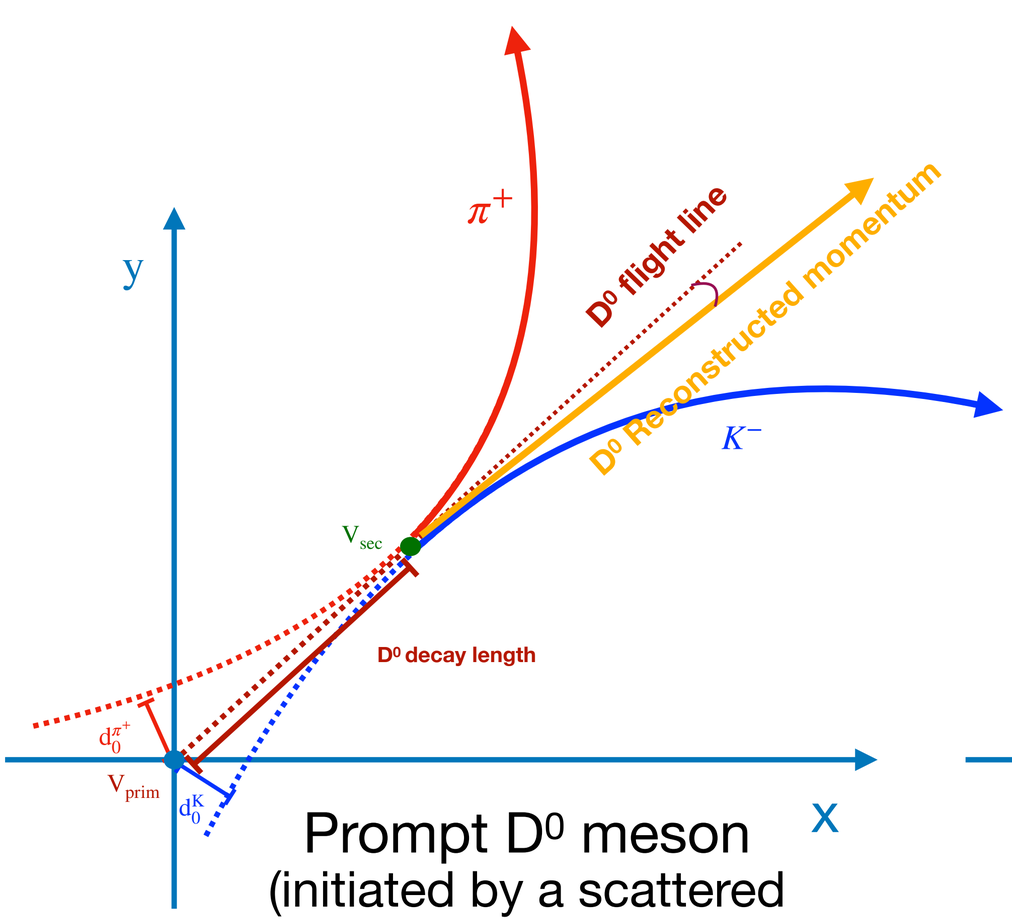
4. Efficiency correction: Charm(D^0/Λ_c^+)-tagged jet reconstruction efficiency correction
5. Estimating B $\rightarrow$ D^0/Λ_c^+ decays: Evaluate and subtract feed-down contribution using POWHEG + PYTHIA simulations

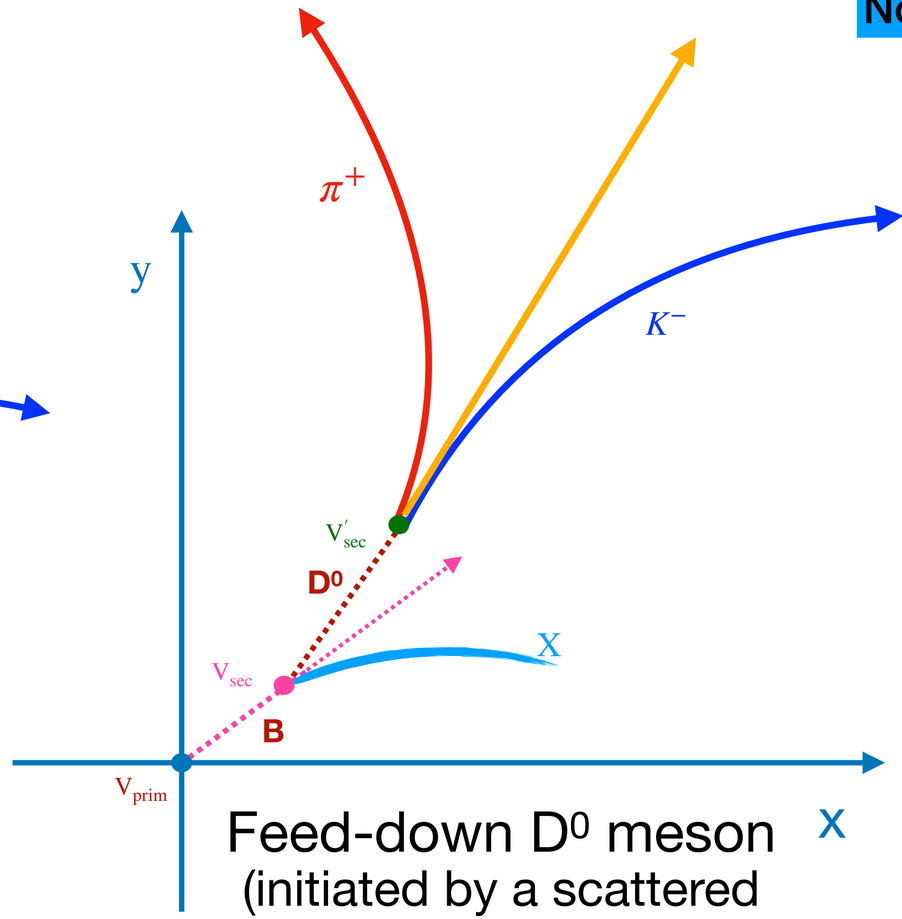
HF tagging with ALICE

$$N^{c\to D^0}(p_{T,ch\ jet}^{det}) = N_{raw}^{c}(p_{T,ch\ jet}^{det}) - N^{b\to D^0}(p_{T,ch\ jet}^{det})$$

Non-prompt D^0



Prompt D^0 meson
(initiated by a scattered charm quark)



Feed-down D^0 meson
(initiated by a scattered beauty quark)

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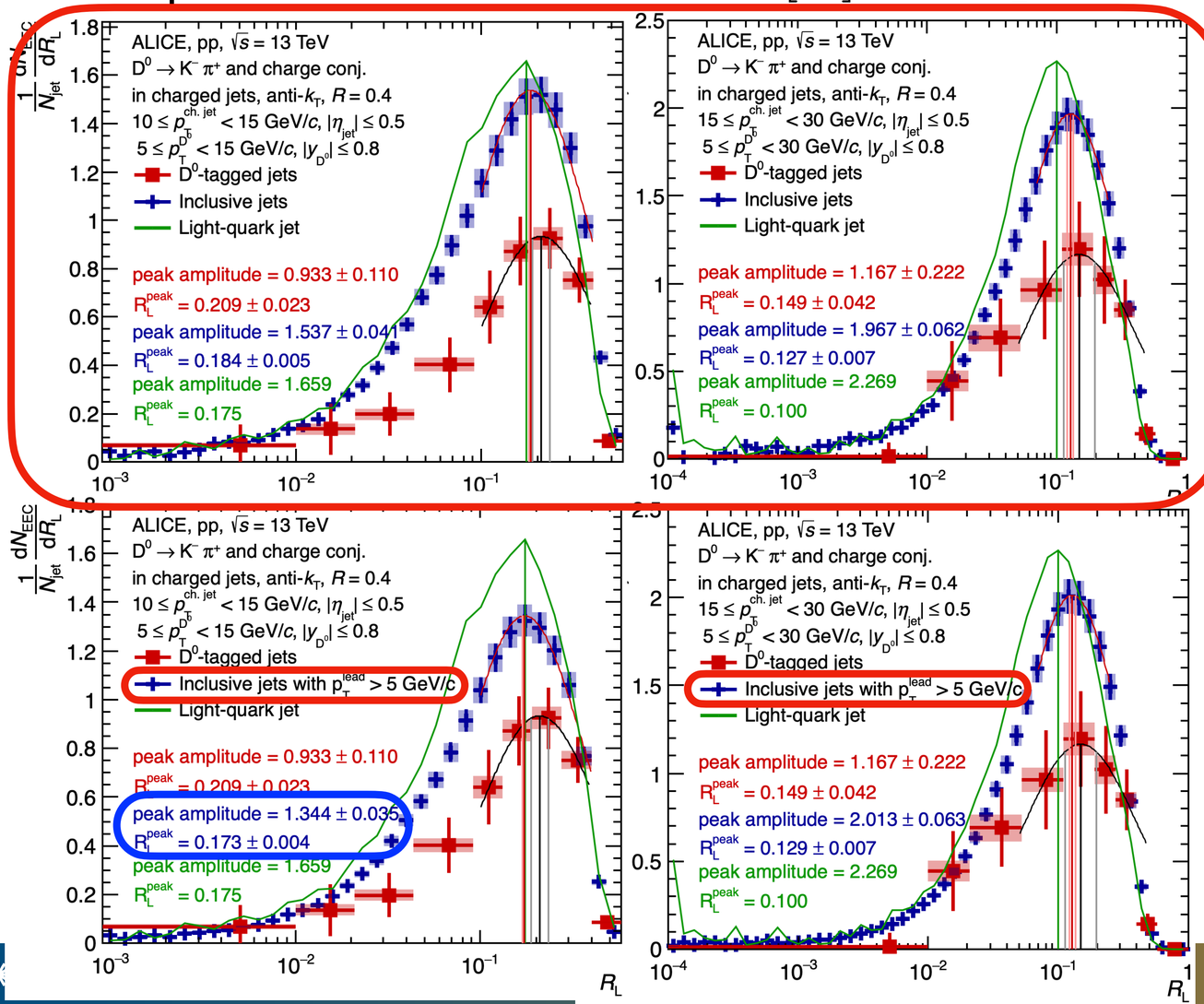
4. Efficiency correction: Charm(D^0/Λ_c^+)-tagged jet reconstruction efficiency correction
5. Estimating B $\rightarrow$ D^0/Λ_c^+ decays: Evaluate and subtract feed-down contribution using POWHEG + PYTHIA simulations
6. Detector effects correction: Correcting for detector effects using unfolding

Probe mass and color effects with heavy-flavor jets

The position of peak quantified by fitting with following function:

`[0]*exp(-0.5*pow((log(x)+[1])/[2], 2)` where

Amplitude of the fit function = `[0]` and R_L value corresponding to peak= $e^{-[1]}$



Fit includes statistical and systematic uncertainties.

Peak amplitude of HF jets is more than significance of 5σ(3.5σ) away from inclusive jets and 6.6σ(5σ) away from LF jets in 10-15(15-30) GeV/c p_T bin → Significant suppression → Mass effect (Dead-cone effect)

Most probable value (MPV) of peak position of HF jets is significance of 1σ(0.5σ) away from inclusive jets and 1.5σ(1.2σ) away from LF jets in 10-15(15-30) GeV/c p_T bin →Peak difference between HF and Inclusive jet are small. Consistent within 1σ significance.

MPV shift to lower RL with leading track p_T cut at low jet p_T.