Heavy-flavor jets in heavy ion collisions

The 20th International Conference on Strangeness in Quark Matter

Busan, Republic of Korea – June 15, 2022

Saehanseul Oh (Sejong University, LBL)

SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

BERKELEY LAB

- Strangeness 2000 (5th SQM)
  - Strangeness Production in Heavy Ion Collision
  - Strangeness and the Quark Gluon Plasma
  - Strange Matter and Astrophysical Aspects
  - Future Developments

- SQM 2022 (20th SQM)
  - Strangeness and heavy-quark production in nuclear collisions and hadronic interactions
  - Hadron resonances in the strongly-coupled partonic and hadronic medium
  - Bulk matter phenomena associated with strange and heavy quarks
  - QCD phase structure
  - Collectivity in small systems
  - Strangeness in astrophysics
  - Open questions and new developments

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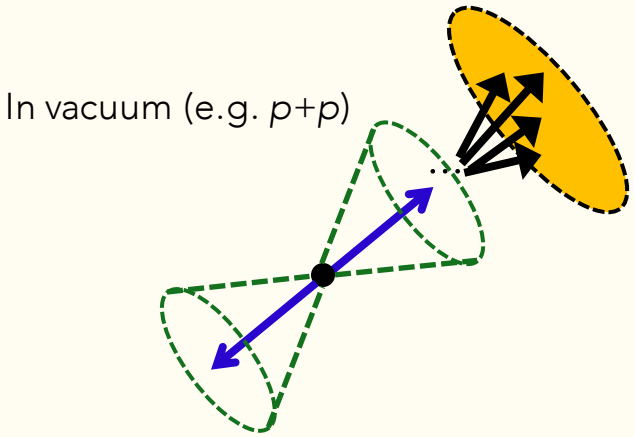
Heavy-flavor jets?

Why are we interested in heavy-flavor jets?

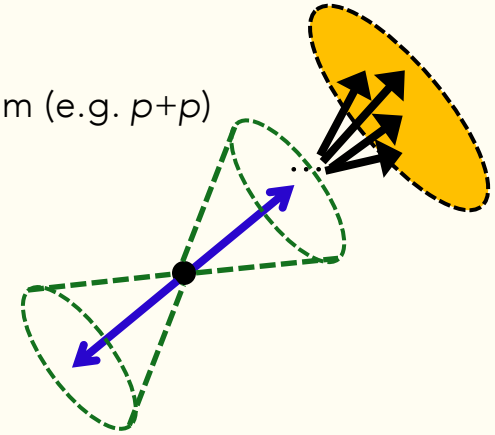
Jet



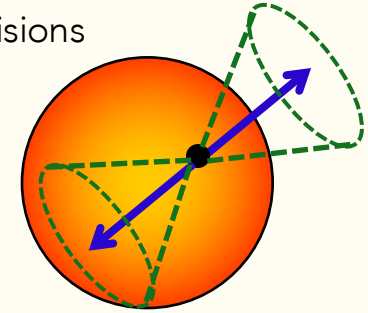
- Jets in vacuum
  - Hard-scattered parton fragments into final state particles → Algorithmic recombination into a **Jet**
  - Jets in vacuum are well understood in pQCD framework

Jet

In vacuum (e.g. p+p)



In A+A collisions



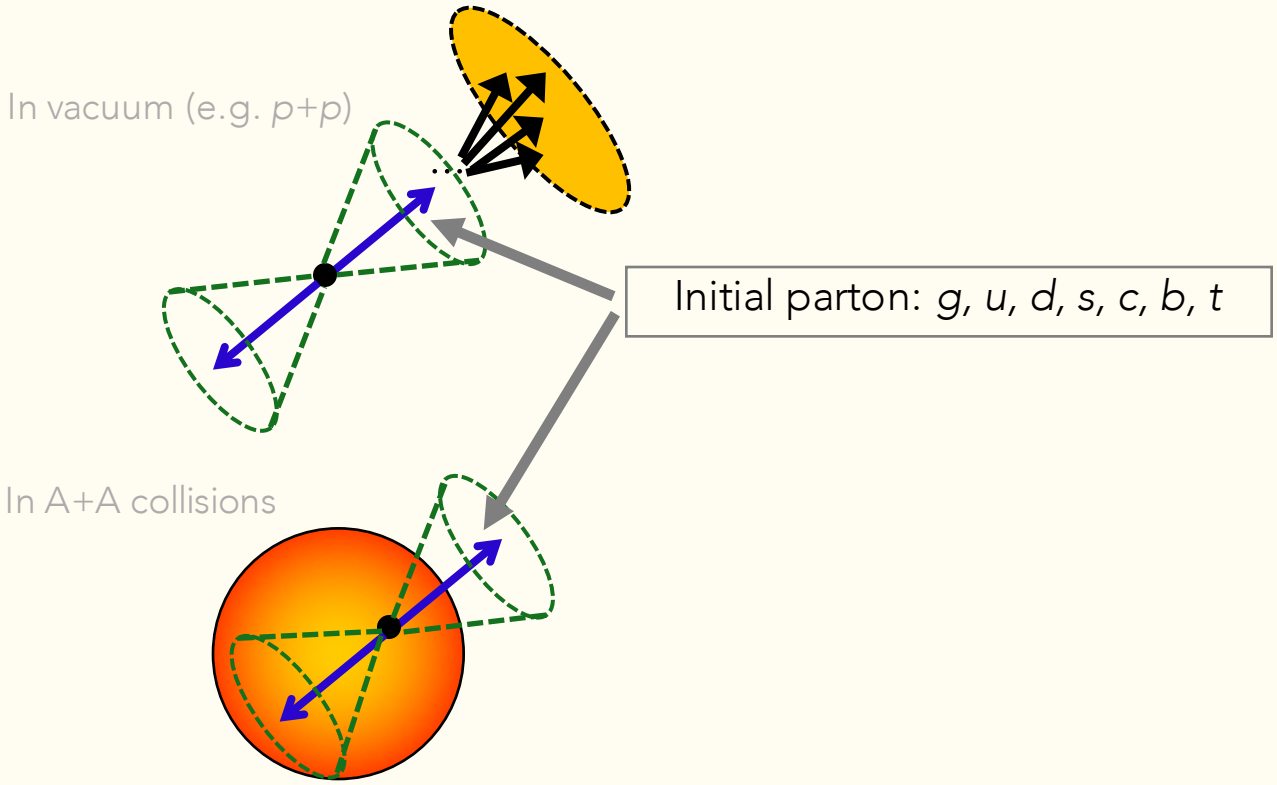
➢ **Jets in vacuum**

- Hard-scattered parton fragments into final state particles → Algorithmic recombination into a **Jet**
- Jets in vacuum are well understood in pQCD framework

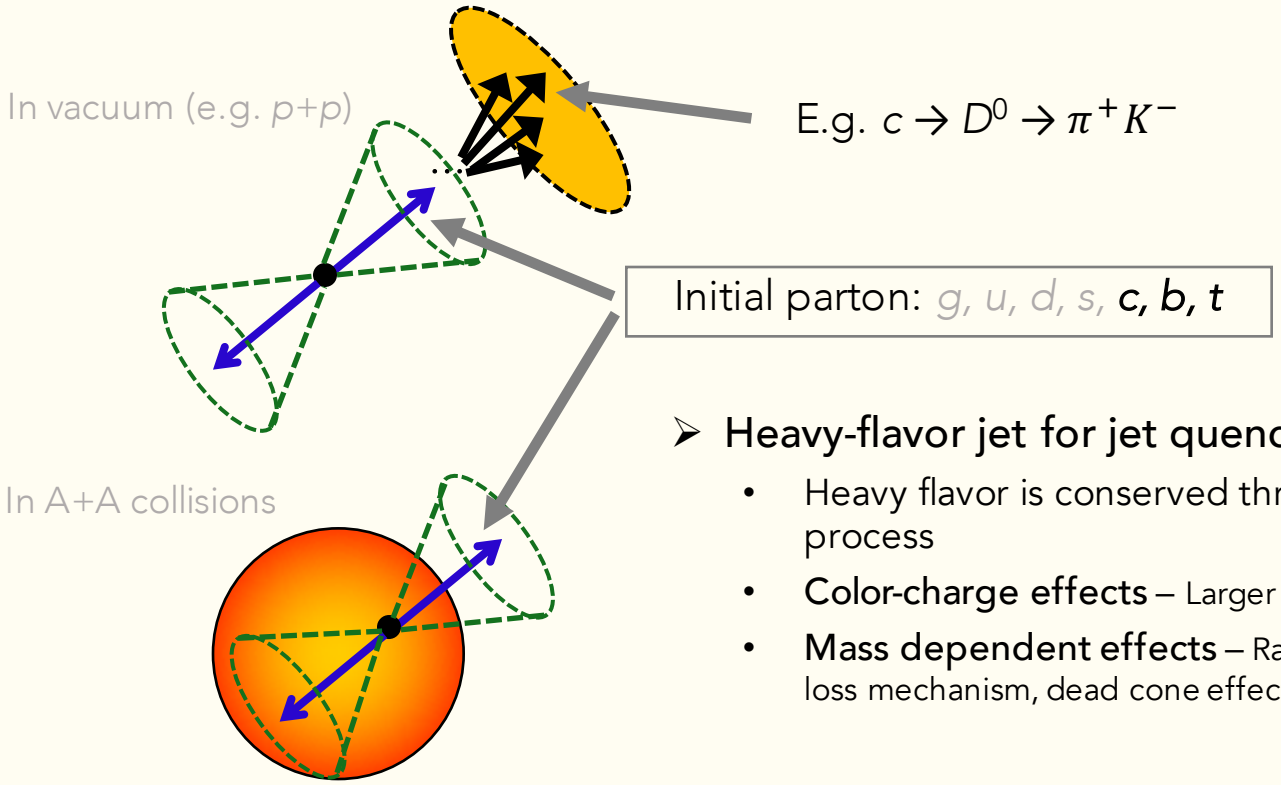
➢ **Jets in heavy-ion collisions**

- Hard-scattered partons are produced at the very early stages of collisions → Interact with QGP as they traverse it
- Any modifications to jet observables are due to the interaction with the QCD medium → Jet quenching

Heavy-flavor jet

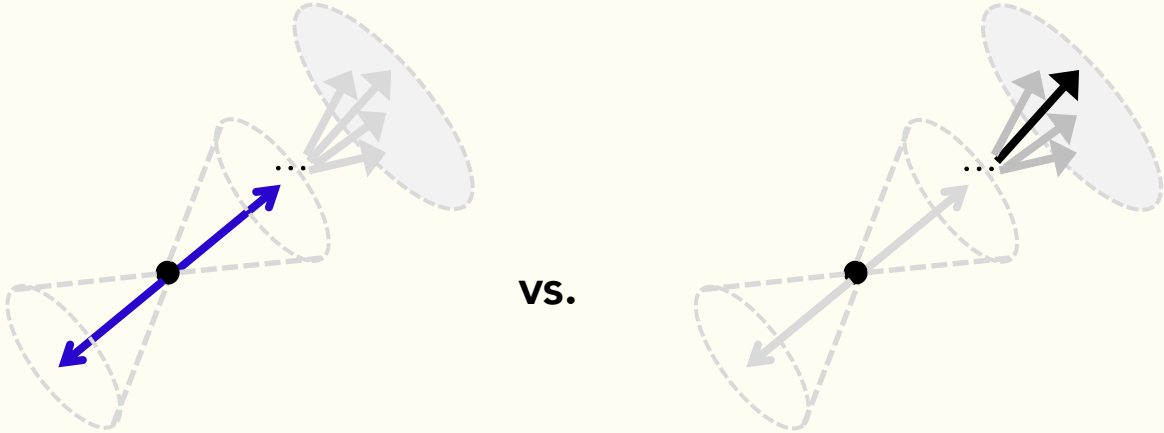


Heavy-flavor jet



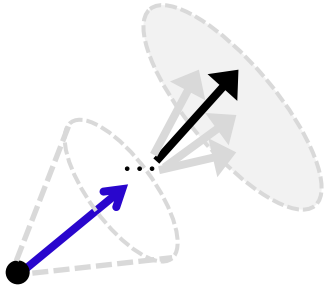
- **Heavy-flavor jet for jet quenching**
  - Heavy flavor is conserved throughout the showering process
  - **Color-charge effects** – Larger radiation from g-jet
  - **Mass dependent effects** – Radiative and collisional energy loss mechanism, dead cone effect

Heavy-flavor jet

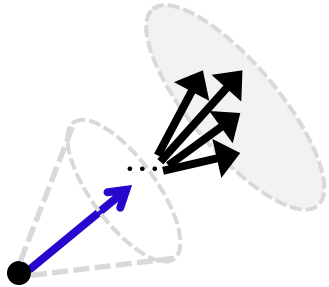


- HF jet vs. HF hadron or HF's semileptonic decay products
  - Direct access to the primary heavy-flavor parton kinematics
  - Production and fragmentation effects can be studied separately

How to identify HF jets?

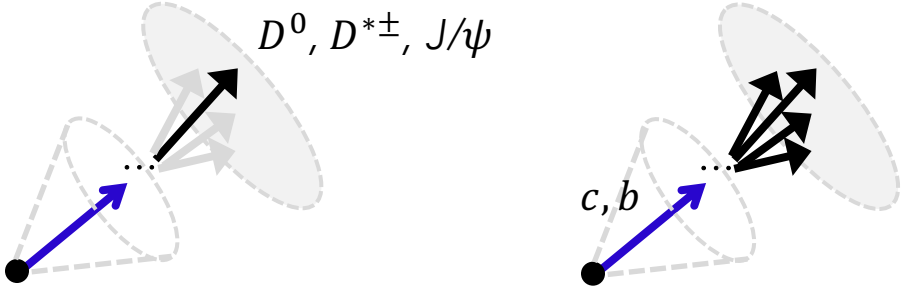


- Using a final-state HF hadron
  - Jets are matched to the HF particle or reconstructed with the HF particle
  - E.g. D^0-jet, J/ψ-jet

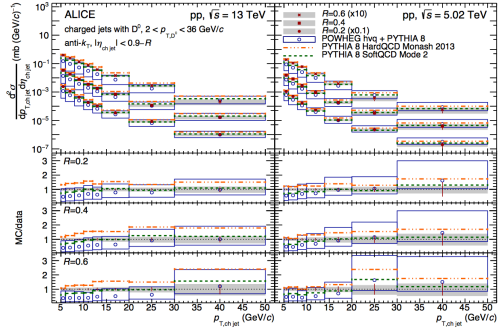


- Using final-state particles' (i.e. jet constituents) properties
  - Jet tagging based on constituents' secondary vertex displacement, impact parameter, …
  - E.g. *c*-jet, *b*-jet

HF jets in *p*+*p* collisions

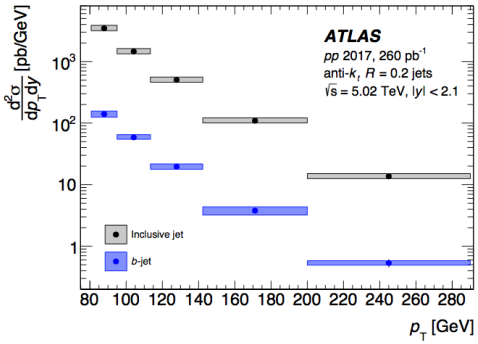


ALICE, arXiv:2204.10167



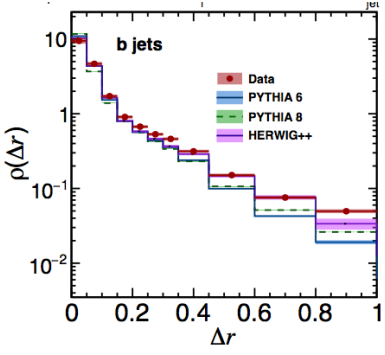
D^0-jet spectra, 5.02 TeV

ATLAS, arXiv:2204.13530



b-jet spectra, 5.02 TeV

CMS, JHEP 05 (2021) 054



b-jet shape, 5.02 TeV

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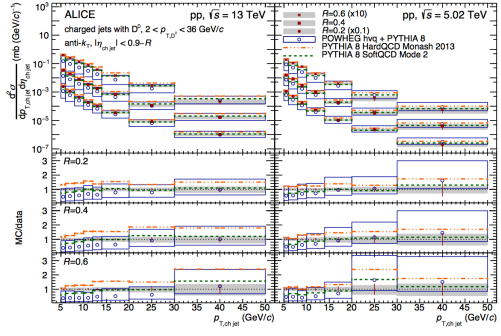
HF jets in *p*+*p* collisions

- Due to the large mass (m > Λ_{QCD}), they are well described with pQCD
- Different sensitivity on heavy-quark production processes → constraints on pQCD calculation
- Constraints on the gluon fragmentation function

ALICE, arXiv:2204.10167



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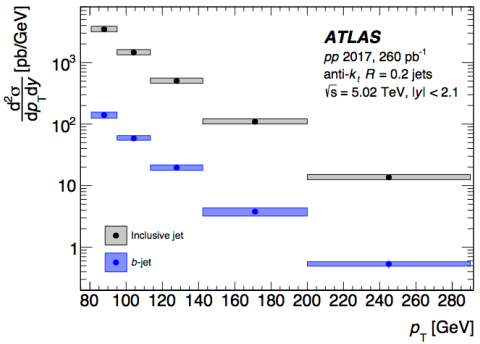
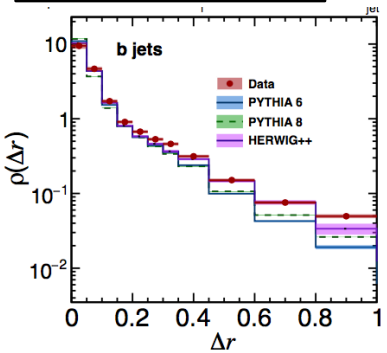


b-jet spectra, 5.02 TeV

CMS, JHEP 05 (2021) 054



b-jet shape, 5.02 TeV

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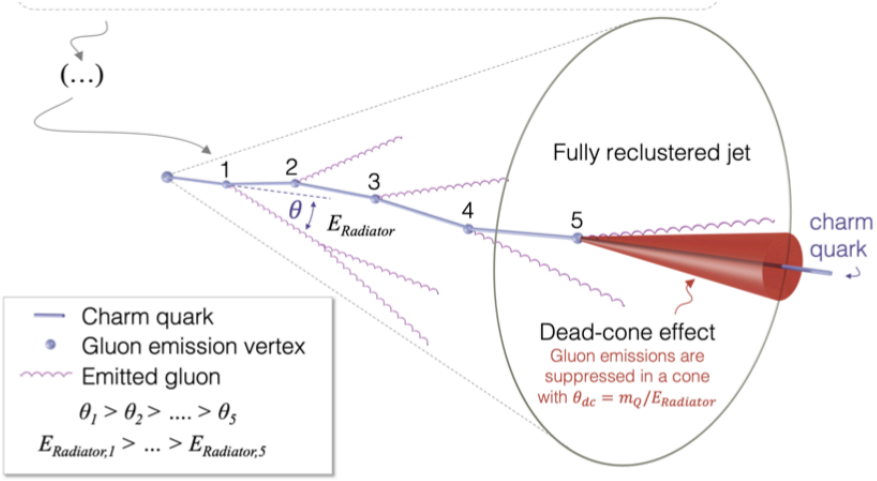
There exists a variety of results in *p*+*p*, but only few are discussed here (with apologies!)

HF jets in *p*+*p* collisions

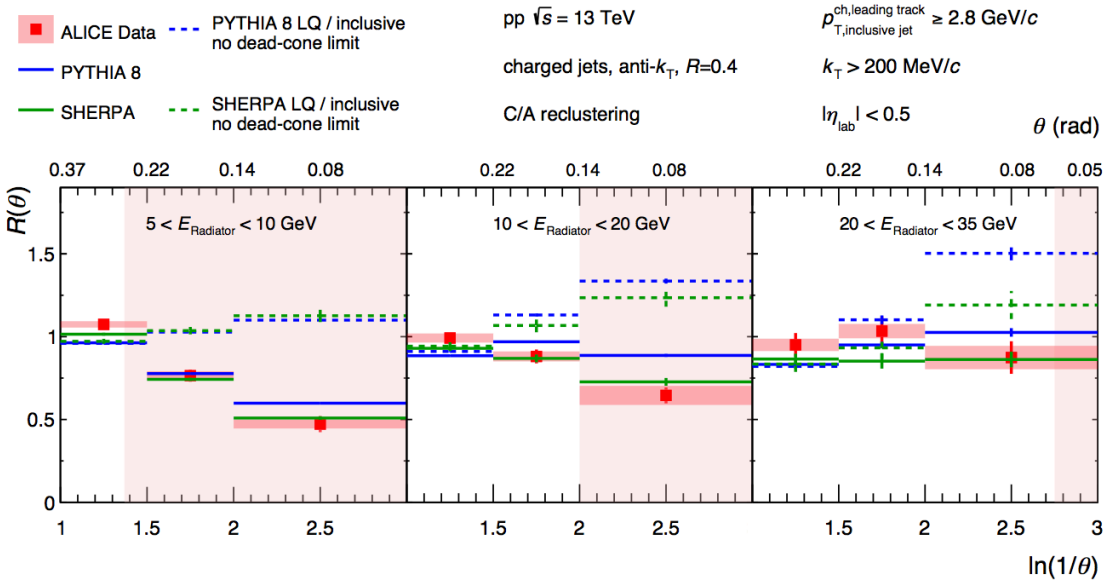
ALICE, Nature 605 (2022) 440-446

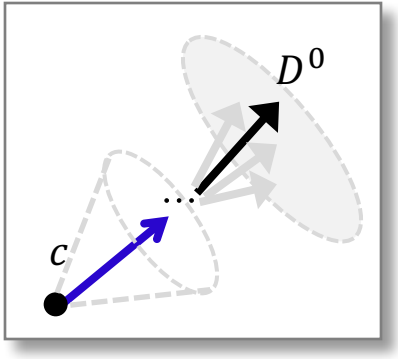


- **Dead cone effect** – Suppression of gluon emission within a cone of angular size $\theta < m_q/E_q$

HF jets in *p*+*p* collisions

ALICE, Nature 605 (2022) 440-446

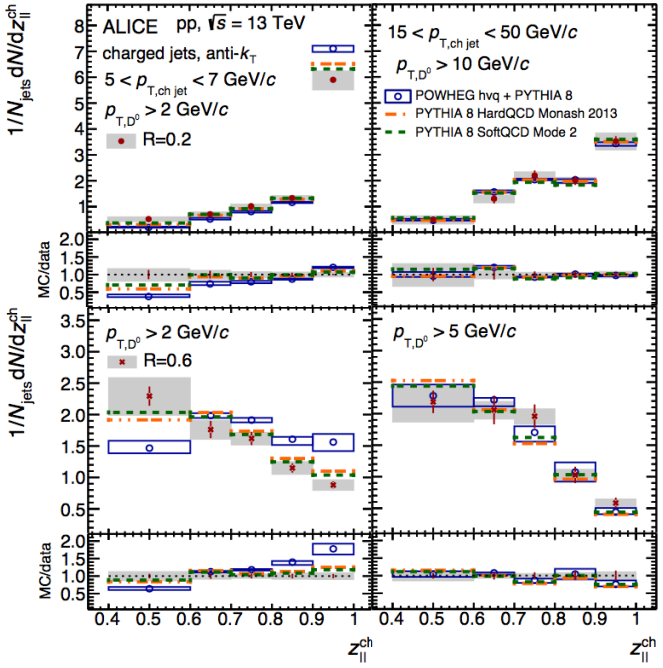




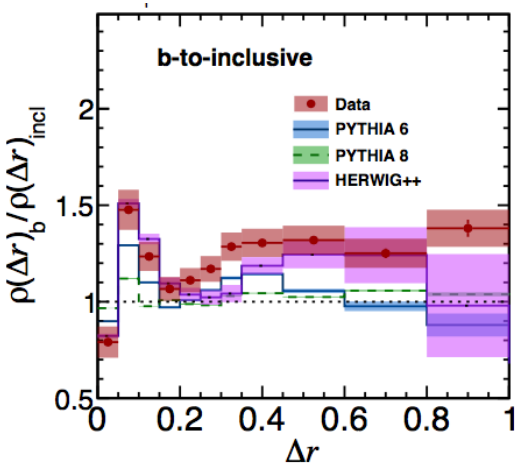
- **Dead cone effect** – Suppression of gluon emission within a cone of angular size $\theta < m_q/E_q$
- D^0-jet in 13 TeV *p*+*p* collisions
  - Ratio of emission angle distributions for D^0 jets with respect to inclusive jets
  - Significant suppression of small θ emission at low radiator energy

HF jets in *p*+*p* collisions

ALICE, arXiv:2204.10167

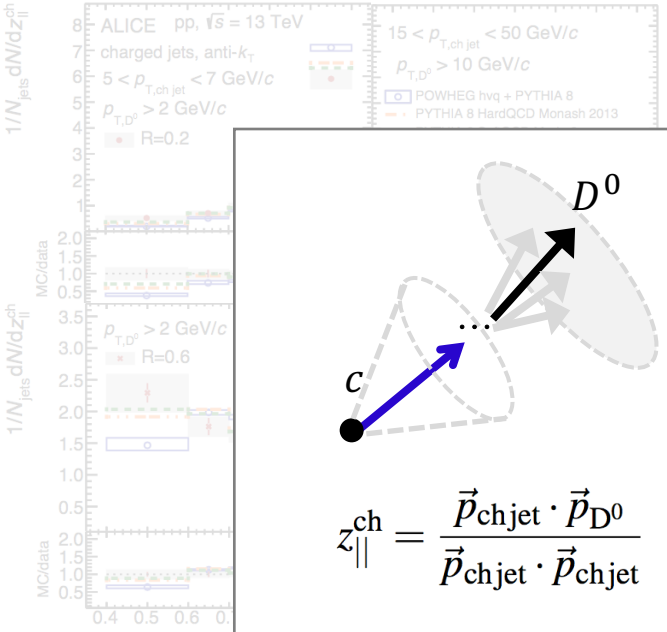


CMS, JHEP 05 (2021) 054



HF jets in *p*+*p* collisions

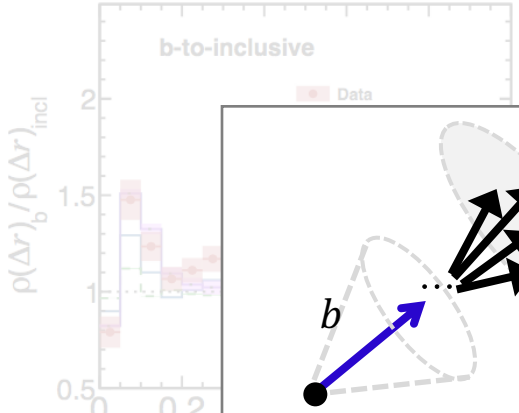
ALICE, arXiv:2204.10167



$$z_{||}^{ch} = \frac{\vec{p}_{ch\,jet} \cdot \vec{p}_{D^0}}{\vec{p}_{ch\,jet} \cdot \vec{p}_{ch\,jet}}$$

D^0 momentum fraction in the jet direction

CMS, JHEP 05 (2021) 054

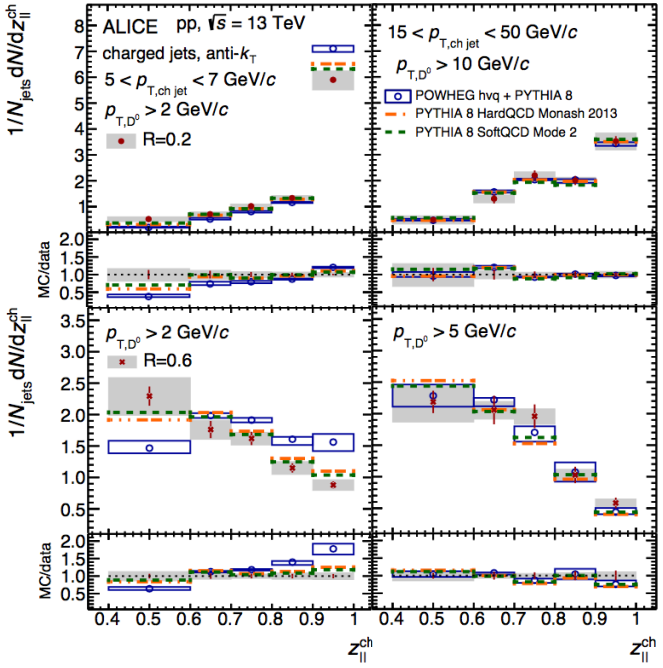


$$\rho(\Delta r) = \frac{1}{\delta r} \frac{\Sigma_{jets} \Sigma_{trk \in (\Delta r_a, \Delta r_b)} p_T^{trk}}{\Sigma_{jets} \Sigma_{trk} p_T^{trk}}$$

Jet shape for *b*-jet

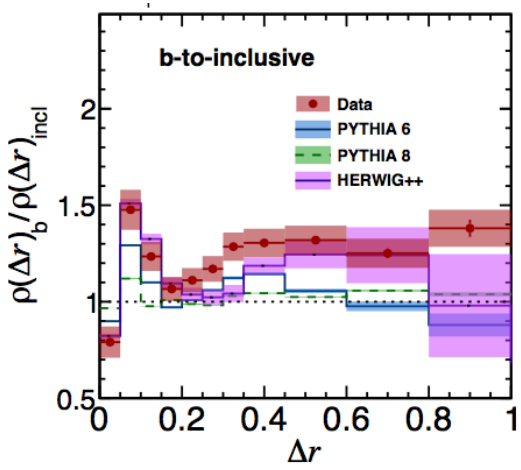
HF jets in *p*+*p* collisions

ALICE, arXiv:2204.10167



- Small R – Dominated by HF hadron, suppression of emission at low angle
- Large R – Emission recovered

CMS, JHEP 05 (2021) 054

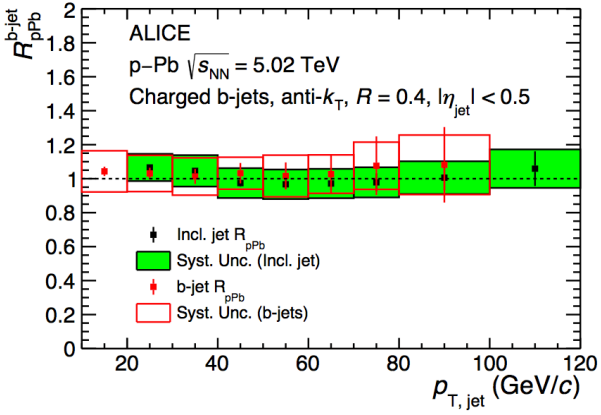


- Suppression near the jet core for b jets compared to inclusive jets

Dead cone effect

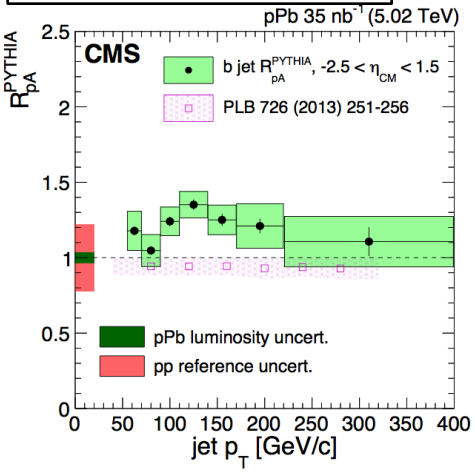
HF jets in *p*+Pb collisions

ALICE, JHEP 01 (2022) 178



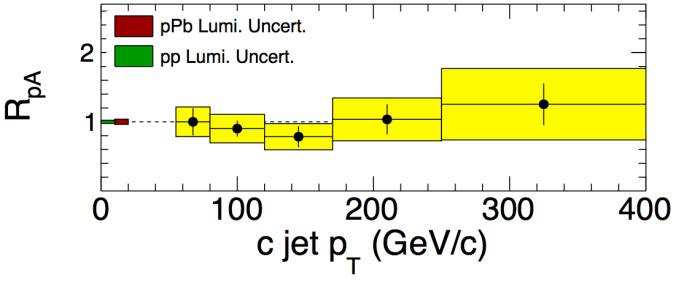
b-jet, 5.02 TeV

CMS, Phys. Lett. B 754 (2016) 59



b-jet, 5.02 TeV

CMS, Phys. Lett. B 772 (2017) 306



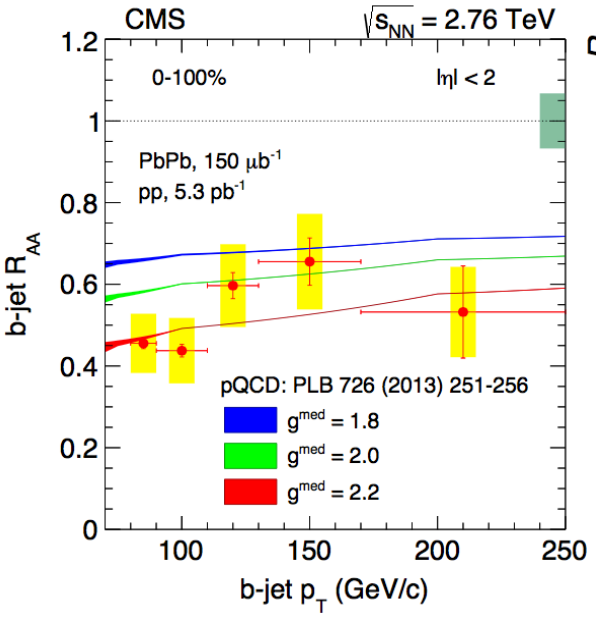
c-jet, 5.02 TeV

Cold nuclear matter effects do not play a major role

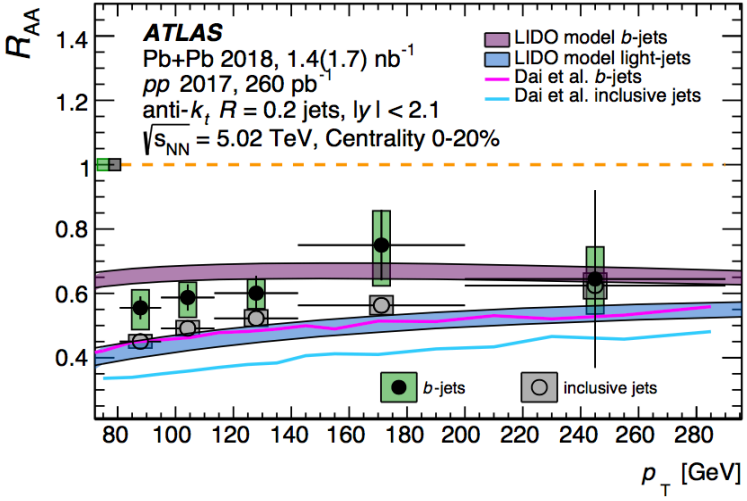
Heavy-flavor jets in heavy ion collisions

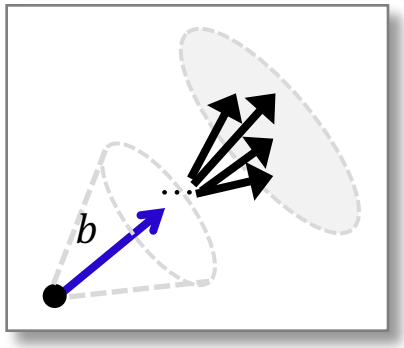
HF jets in AA - Spectra

CMS Phys. Rev. Lett. 113, 132301 (2014)



ATLAS, arXiv:2204.13530

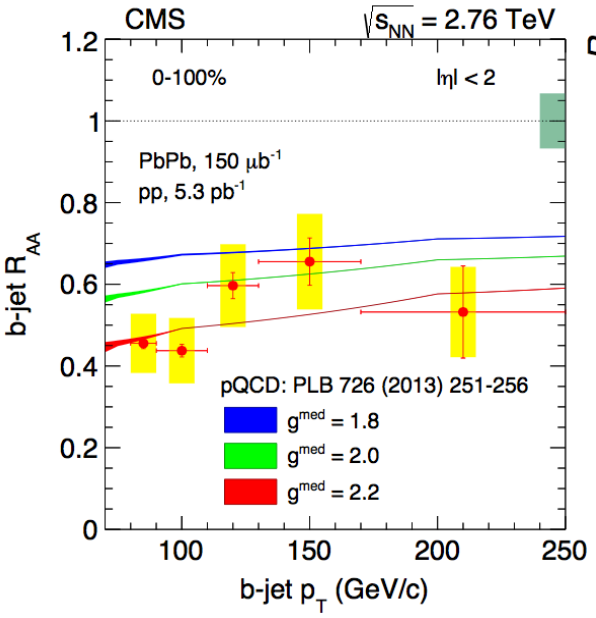




- *b*-jet with ***R* = 0.3** in 2.76 TeV, **0-100%** Pb+Pb collisions
- *b*-jet R_{AA} **consistent** with inclusive jet R_{AA} within uncertainties

HF jets in AA - Spectra

CMS Phys. Rev. Lett. 113, 132301 (2014)



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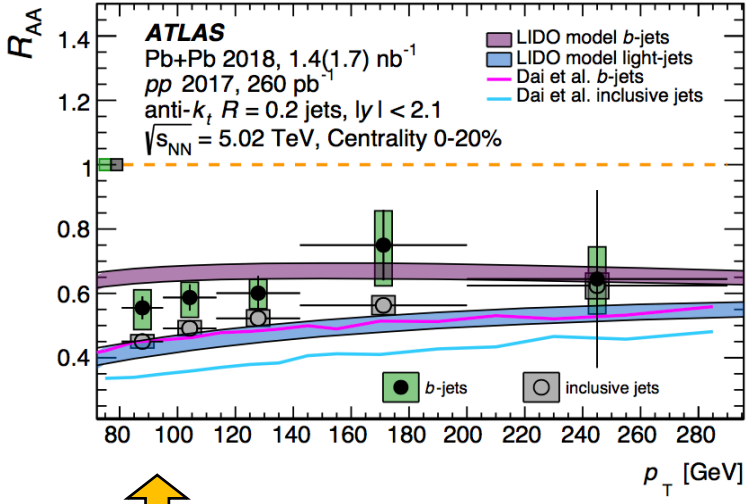

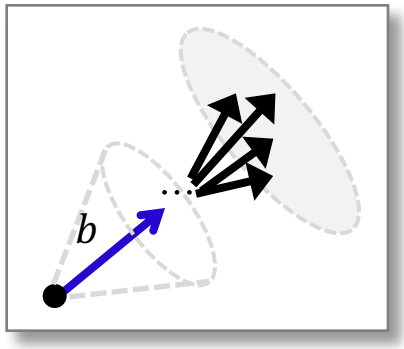

- *b*-jet with ***R* = 0.2** in 5.02 TeV, **0-20%** Pb+Pb collisions
- *b*-jets are **less suppressed** than inclusive jets

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HF jets in AA - Spectra

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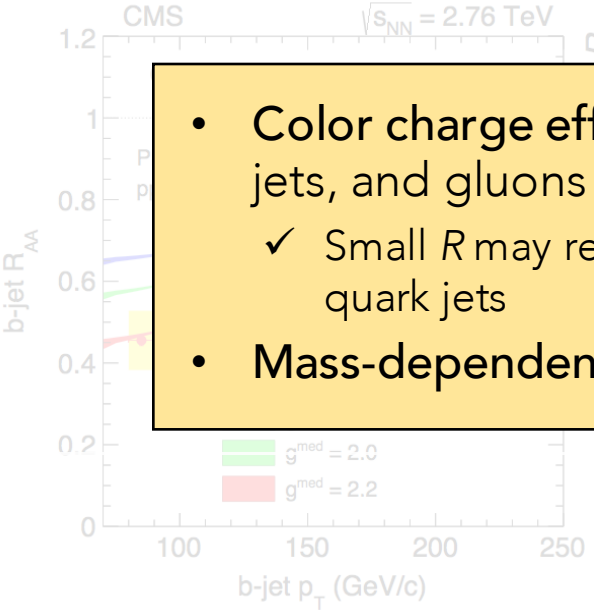

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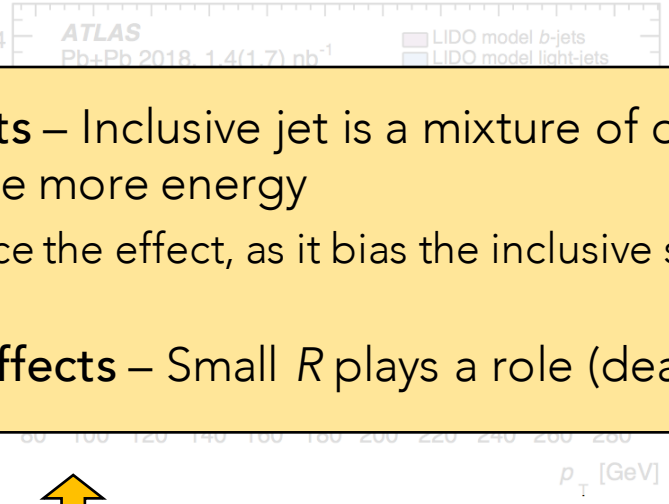

- **Color charge effects** – Inclusive jet is a mixture of quark and gluon jets, and gluons lose more energy
  - ✓ Small *R* may reduce the effect, as it bias the inclusive sample toward quark jets
- **Mass-dependent effects** – Small *R* plays a role (dead cone effect)?

- *b*-jet with ***R* = 0.2** in 5.02 TeV, **0-20%** Pb+Pb collisions
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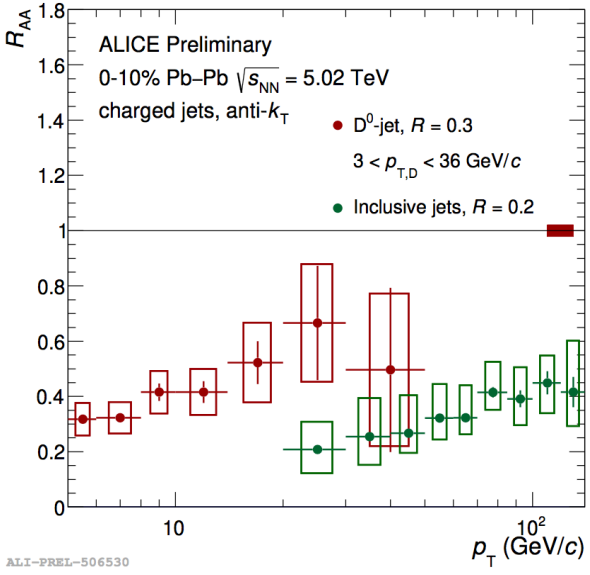
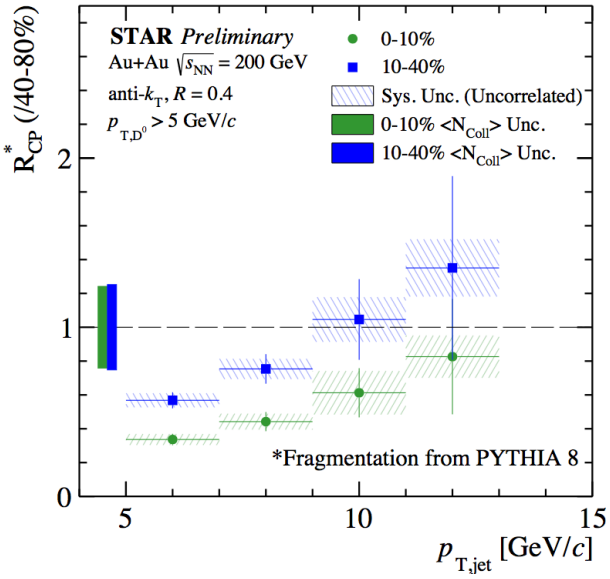
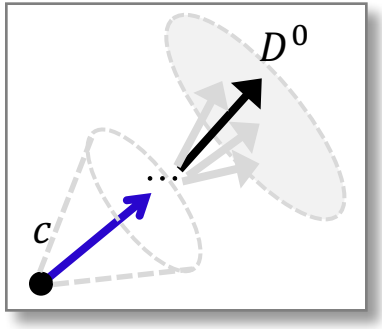
HF jets in AA - Spectra

ALICE, Preliminary



STAR, Preliminary



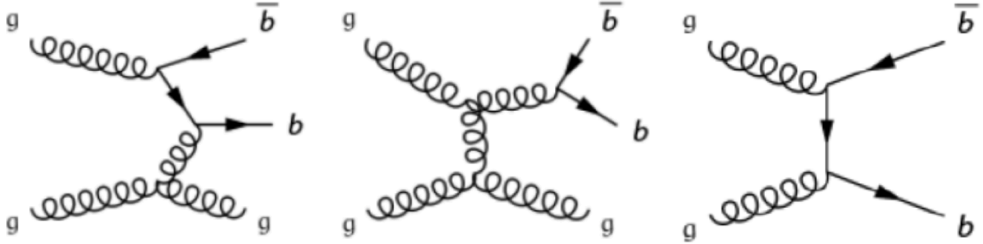


- D^0-jet in 5.02 TeV Pb+Pb & 200 GeV Au+Au collisions

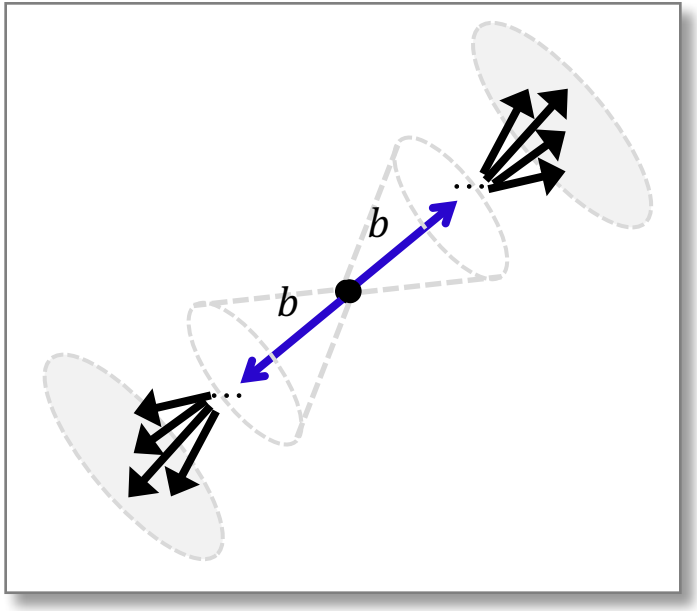
- Mass-dependent effects are more important at low p_T
- How to isolate mass-dependent effects or color charge effects?

HF jets in AA - x_J

- In *b*-jet measurements at the LHC, significant fraction of b-jets are from gluon splitting or flavor excitation

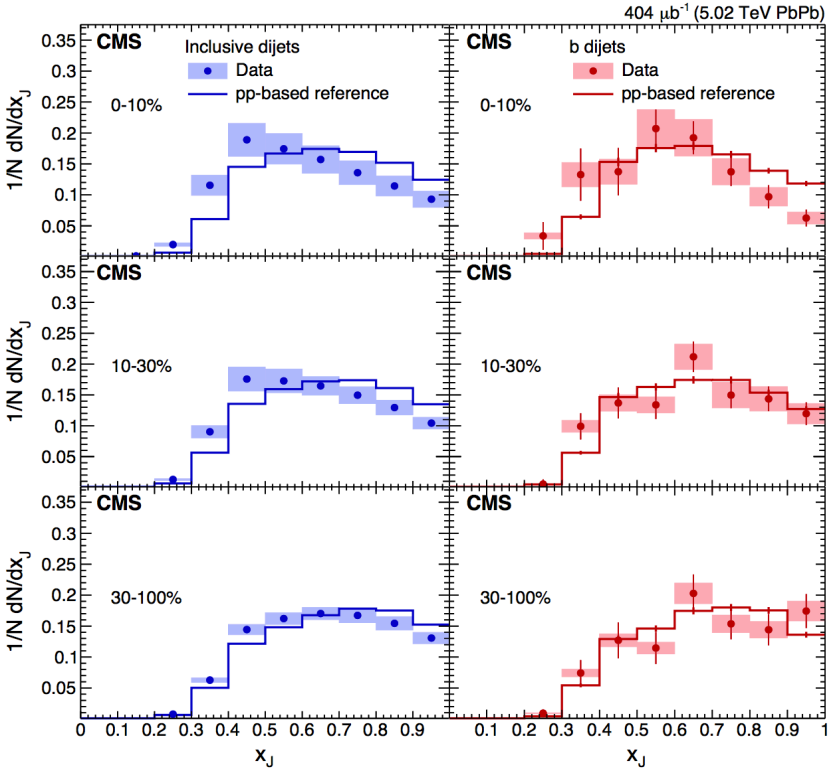


- Selecting back-to-back b-jets (di-b-jet) emphasizes flavor creation process, $gg \rightarrow b\bar{b}$, $q\bar{q} \rightarrow b\bar{b}$ with still sizable contributions from high-order contributions



HF jets in AA - x_J

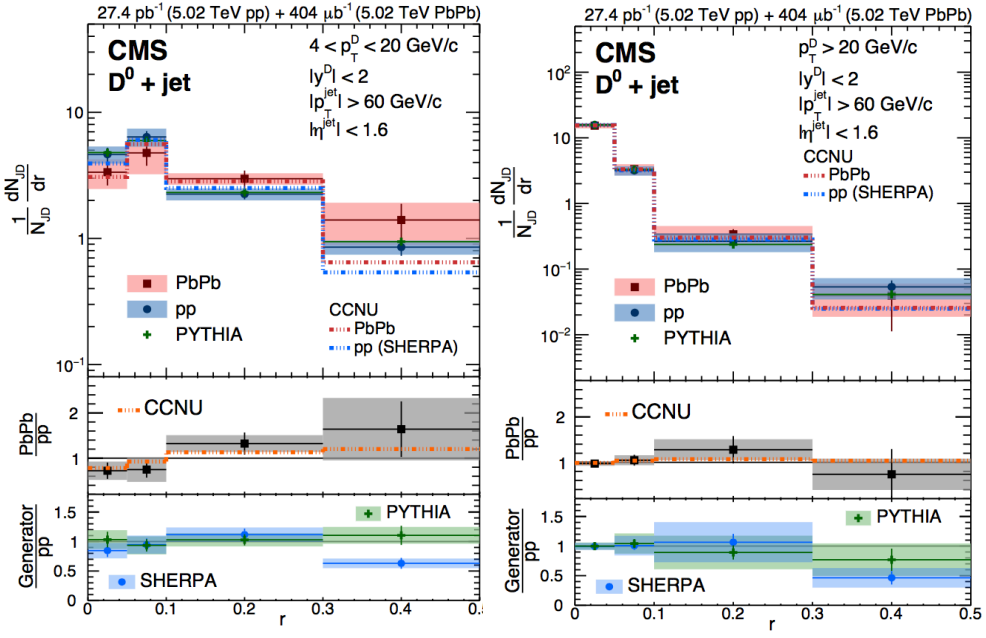
CMS, JHEP 03 (2018) 181

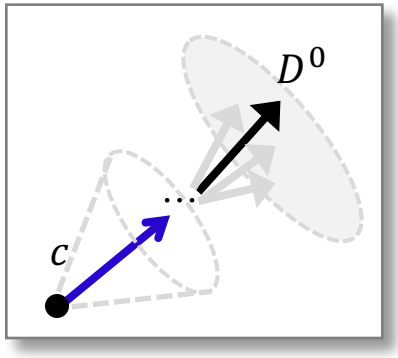


- Di-*b*-jet with ***R* = 0.4** in 5.02 TeV Pb+Pb collisions
- $x_J = p_{T,jet}^{sublead} / p_{T,jet}^{lead}$: ratio of the subleading to leading jet p_T
- Similar level of momentum imbalance observed in di-b-jets and inclusive di-jets

HF jets in AA – Radial distribution of HF hadron

CMS, Phys. Rev. Lett. 125, 102001 (2020)

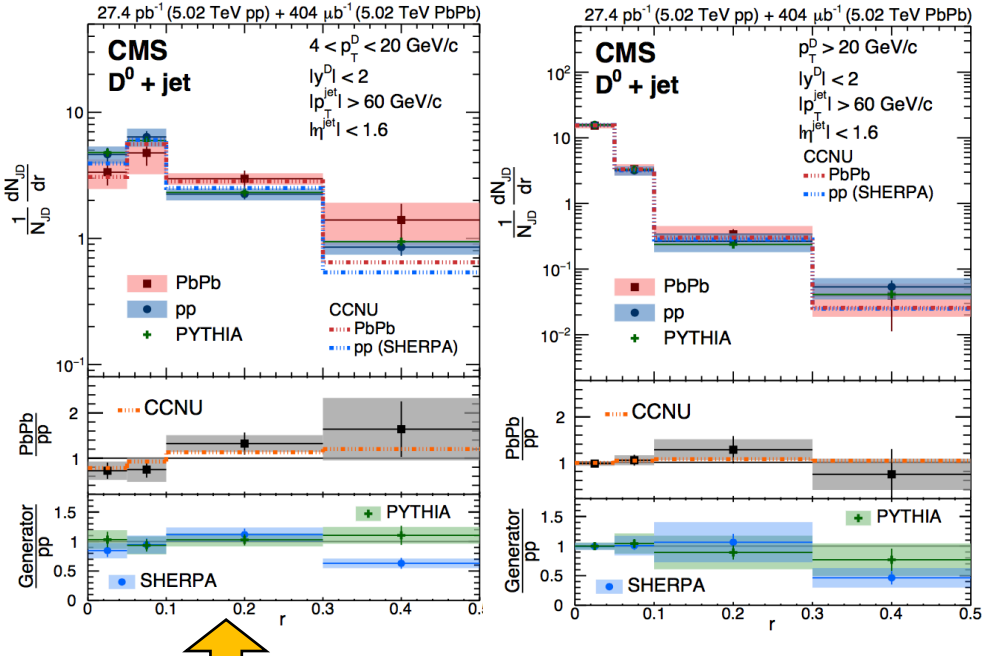


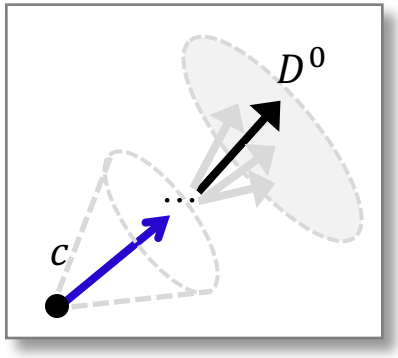


- D^0-jet with $R = 0.4$ in 5.02 TeV Pb+Pb
- Radial profile of D^0 with respect to the jet

HF jets in AA – Radial distribution of HF hadron

CMS, Phys. Rev. Lett. 125, 102001 (2020)



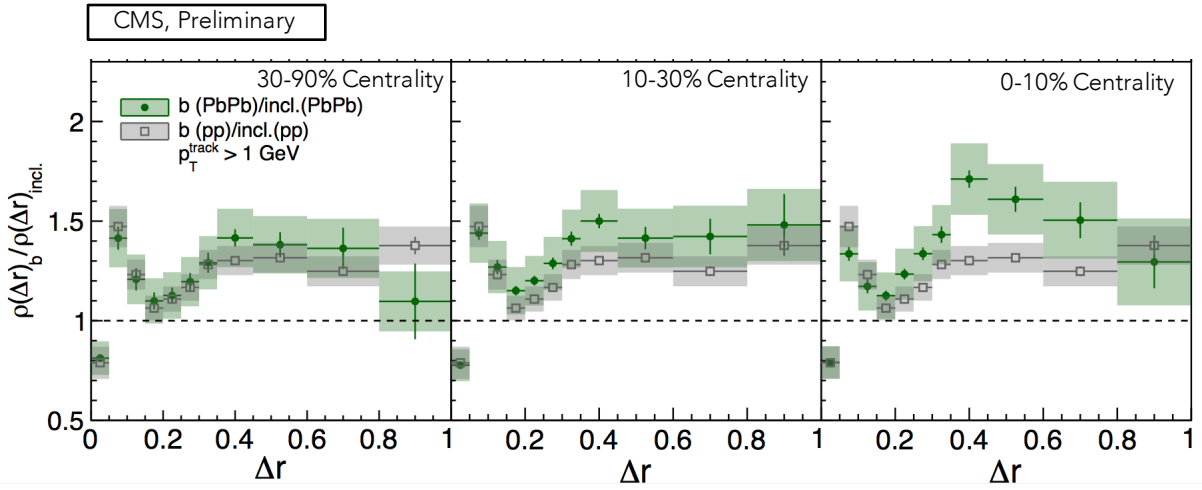


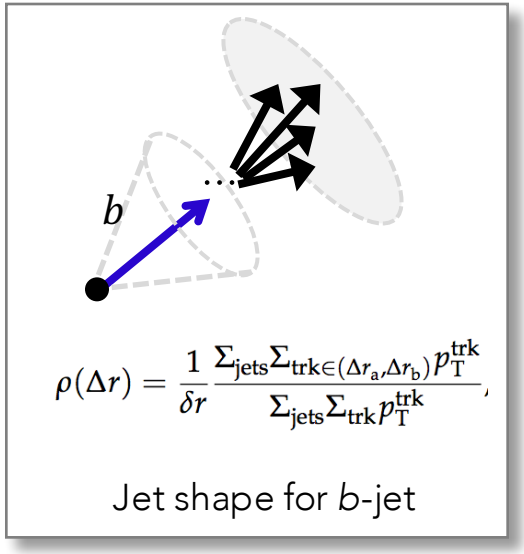
- D^0-jet with $R = 0.4$ in 5.02 TeV Pb+Pb
- Radial profile of D^0 with respect to the jet

Modification of D^0 meson radial profile at low p_{T,D^0}, which vanishes at high p_{T,D^0}

→ Charm quark diffusion

HF jets in AA – Jet shape

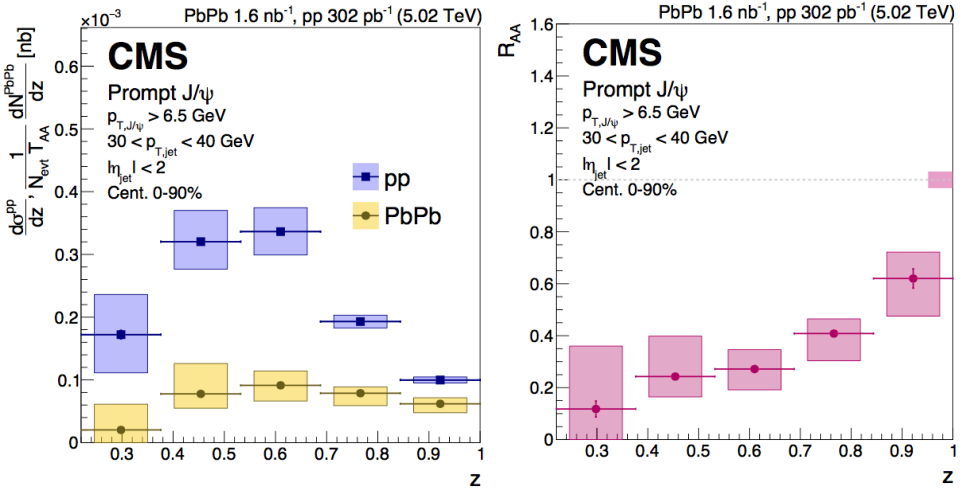


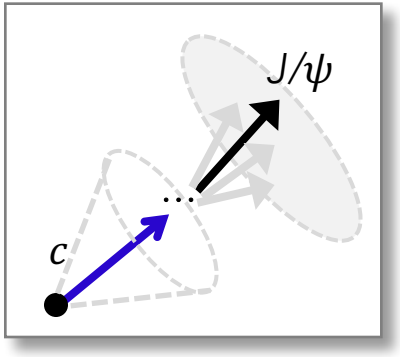


- *b*-jet with ***R* = 0.4** in 5.02 TeV Pb+Pb collisions
- Small angle depletion in b-jet shape with no centrality dependence ← Dead cone effect in AA

HF jets in AA – J/ψ fragmentation

CMS, Phys. Lett. B 825 (2021) 136842

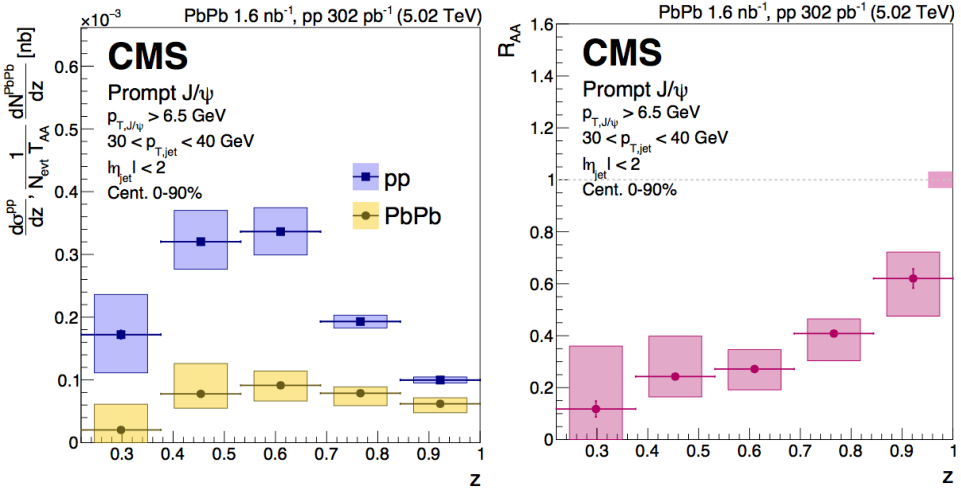


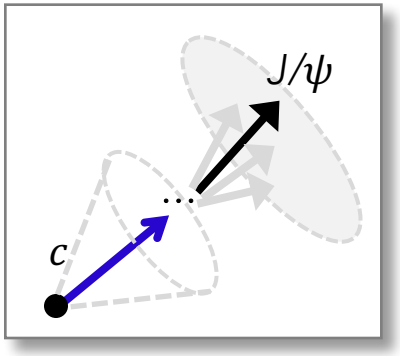


- J/ψ-jet with R = 0.3 in 5.02 TeV Pb+Pb
- Fragmentation variable $z = p_{T,J/\psi}/p_{T,jet}$

HF jets in AA – J/ψ fragmentation

CMS, Phys. Lett. B 825 (2021) 136842





- J/ψ-jet with $R = 0.3$ in 5.02 TeV Pb+Pb
- Fragmentation variable $z = p_{T,J/\psi}/p_{T,jet}$

➢ Larger suppression at low z – J/ψ produced with larger jet activity are more suppressed

Low z ← J/ψ produced late in the parton shower

⇨

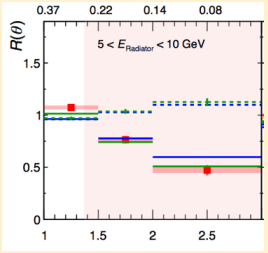
Such a parton cascade experiences larger degree of interaction with the QGP

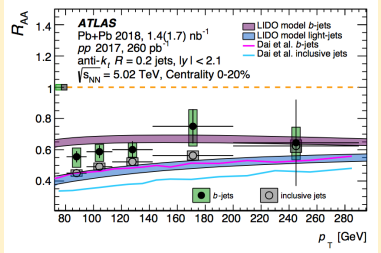
Jet quenching mechanism should be incorporated in J/ψ suppression models

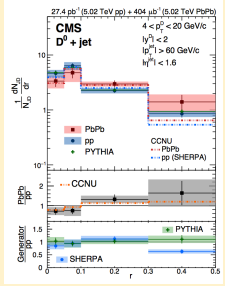
Summary

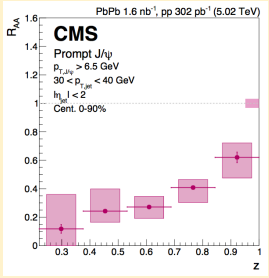
- Heavy-flavor jets allow
  - Direct access to the primary heavy-flavor parton kinematics
  - To investigate color effects and mass effects in vacuum and in medium

- Current results show
  - Direct measurement of the QCD dead cone
  - Less suppression from *b*-jet R_{AA}
  - Charm quark diffusion from D^0 radial profile at low p_{T,D^0}
  - Low *z* J/ψ is more suppressed – J/ψ production late in the parton shower





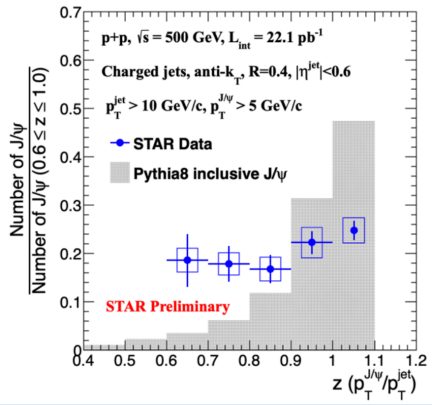




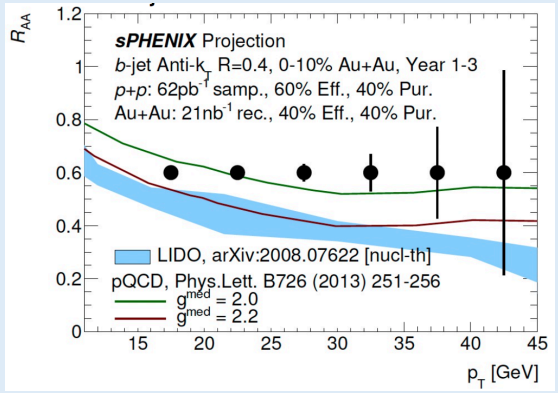
GBR2, 09:40 Tue, G. Bak
GBR2, 14:20 Tue, A. Silba
GBR2, 10:50 Wed, W. Zou

More is yet to come

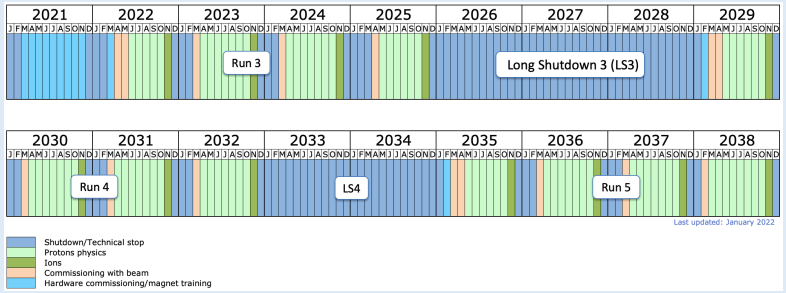
STAR, Preliminary



sPHENIX Projection



LHC Run 3 and 4



- sPHENIX and STAR in 2023-2025 – Lower p_T → Larger sensitivity to mass-dependent effects (with lower HI background)
- LHC Run 3 and 4 – Larger statistics (x100) and improved detectors

- How to disentangle color charge and mass effects?
- Comparability among observables and results from different collaborations?

감사합니다.