



HP2024  
NAGASAKI



# Jets: Experimental Overview

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CENTRAL CHINA NORMAL UNIVERSITY



12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions



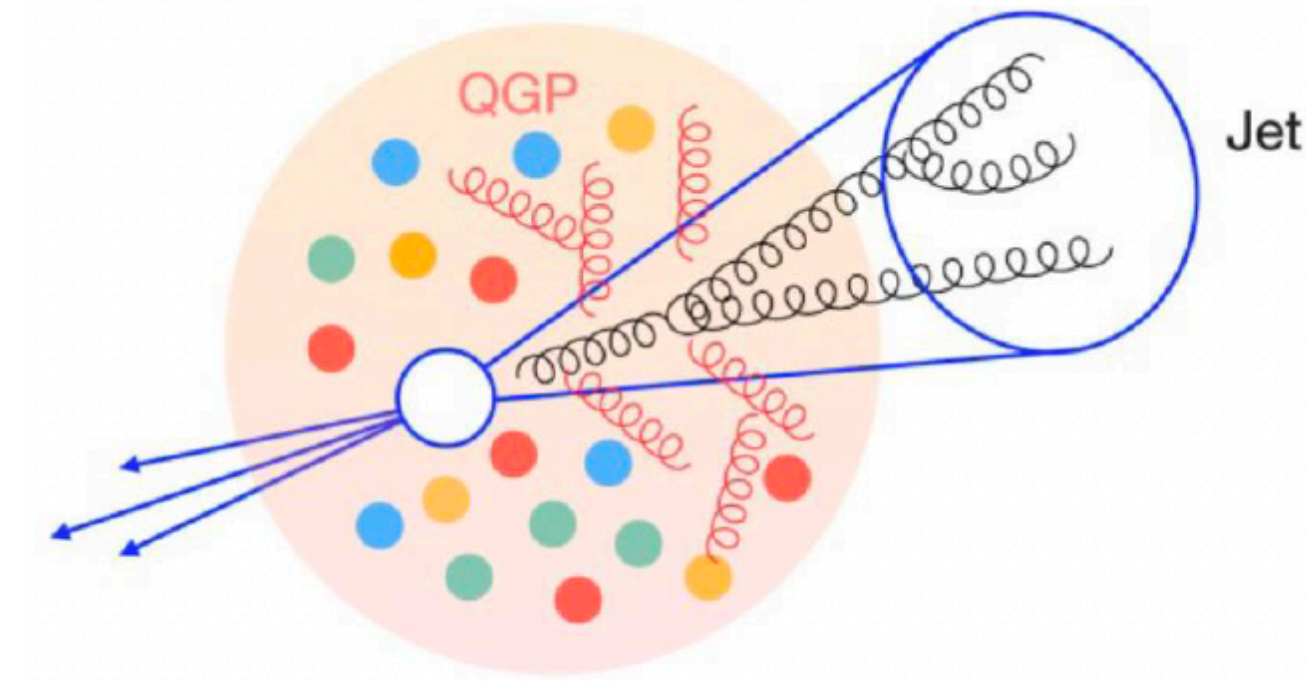
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HP2024, Nagasaki, 26/09/2024



# Jets as a probe of the quark-gluon plasma

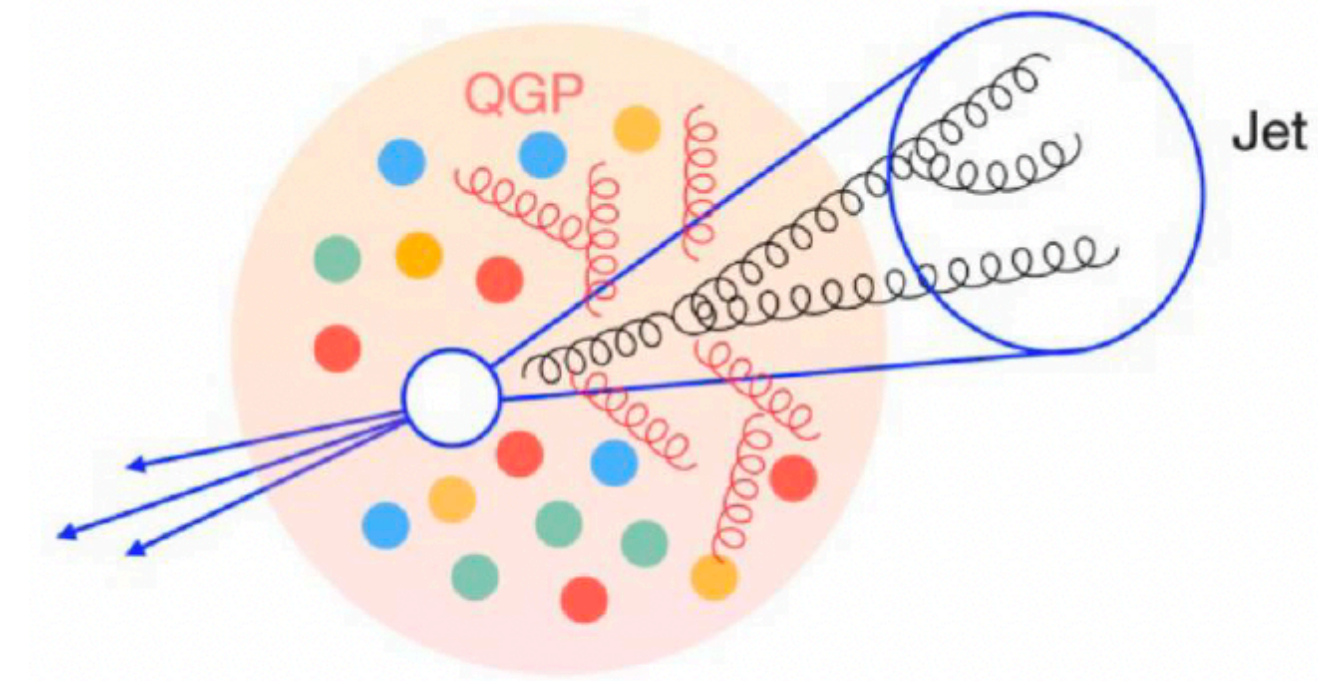
- Study structure of QGP by understanding jet modification from medium interaction (jet quenching)
- Several types of jet observables
  - Jet yields and constituents → suppression and energy redistribution
  - Jet reconstruction and declustering → jet substructure modification
  - Jet correlations and tagging → angular deflection and asymmetry



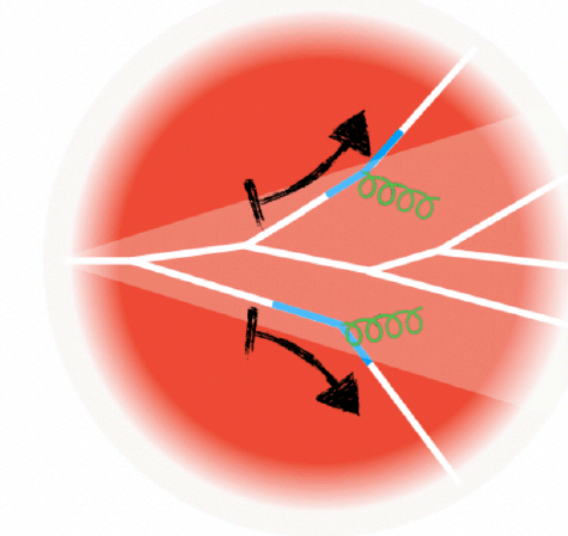
<https://www.int.washington.edu/node/776>

# Jets as a probe of the quark-gluon plasma

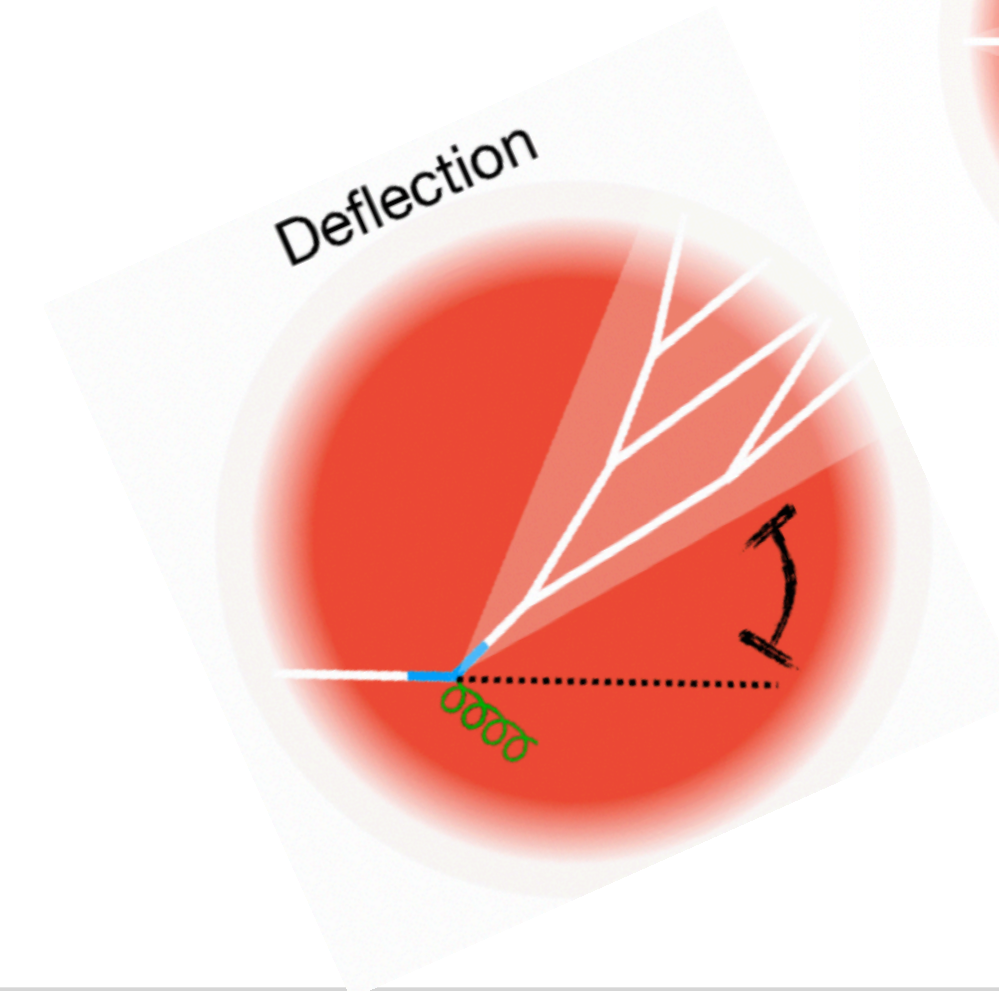
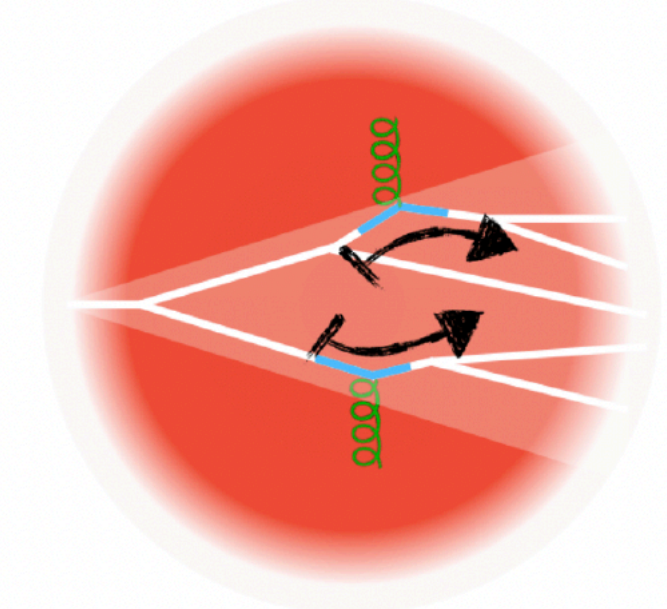
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Energy Redistribution ("loss") [://www.int.washington.edu/node/776](http://www.int.washington.edu/node/776)

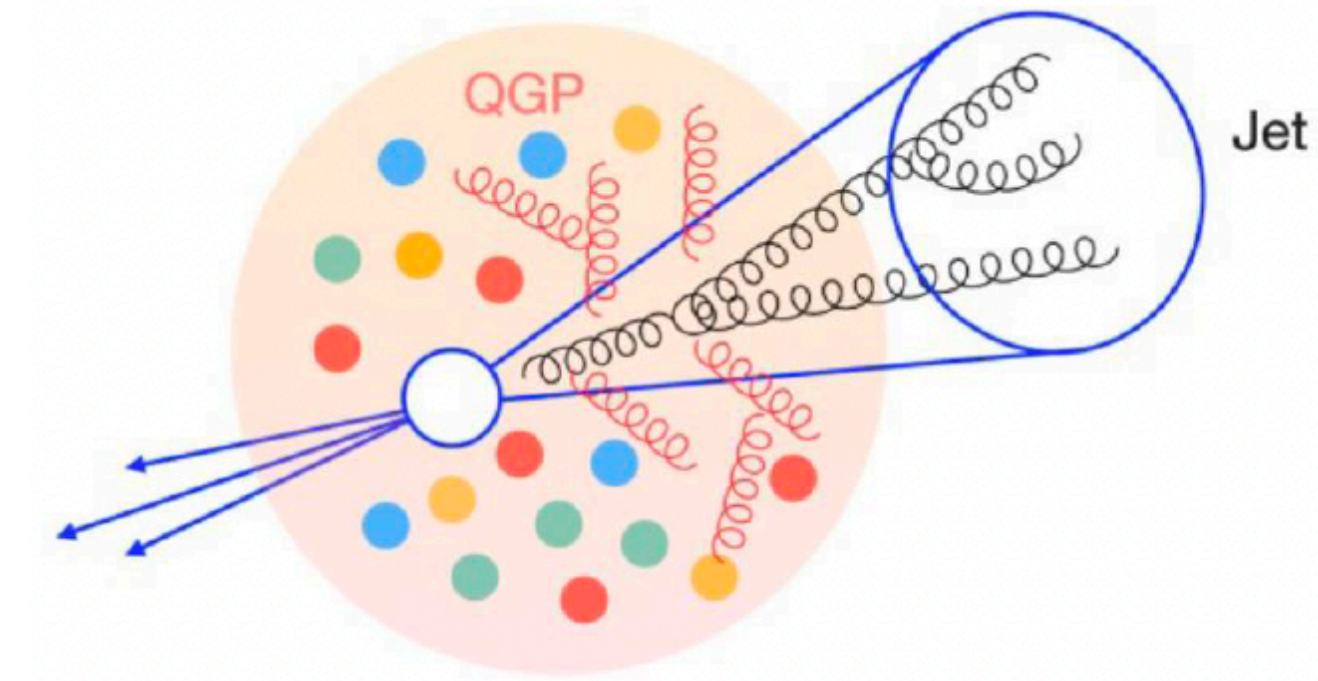


Substructure modification

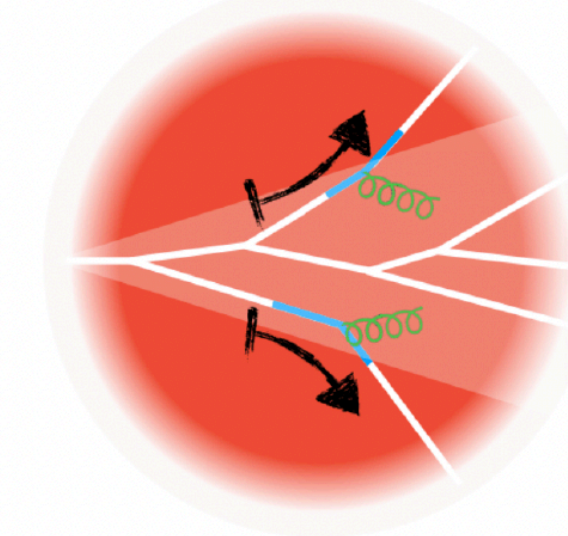


# Jets as a probe of the quark-gluon plasma

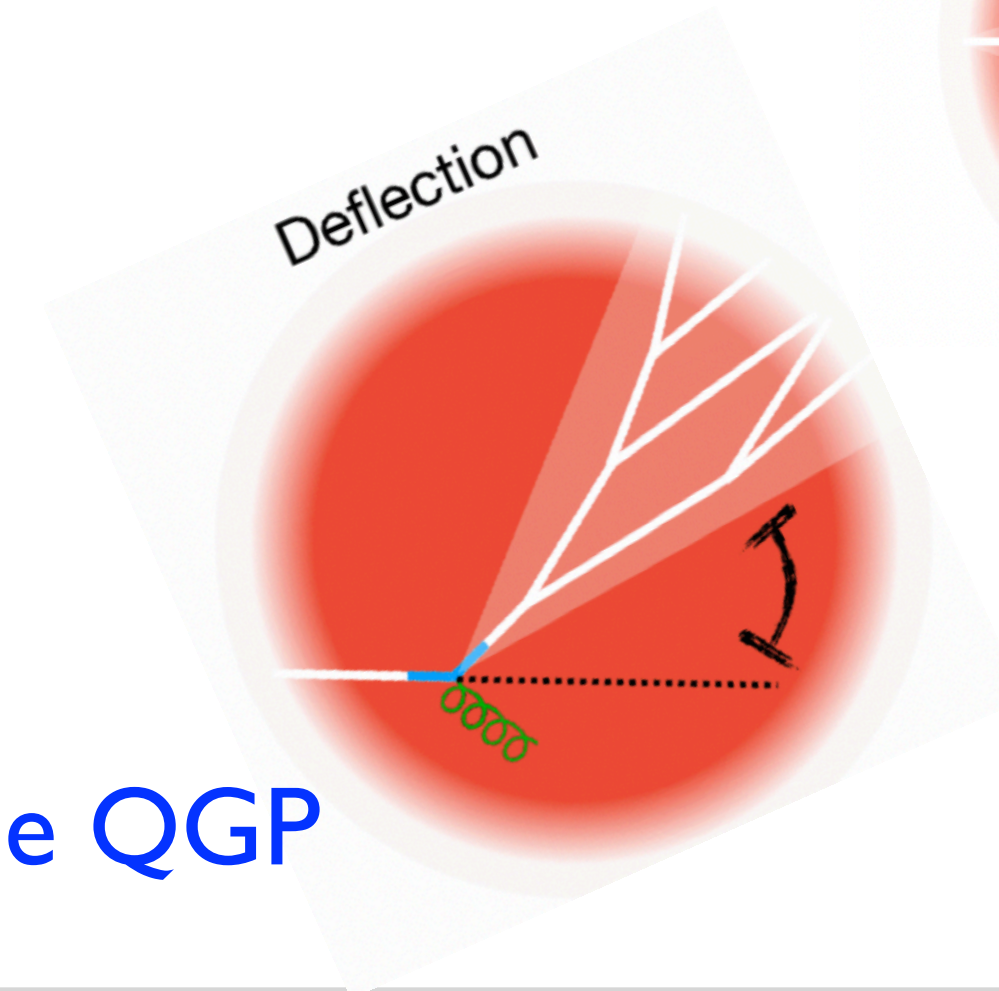
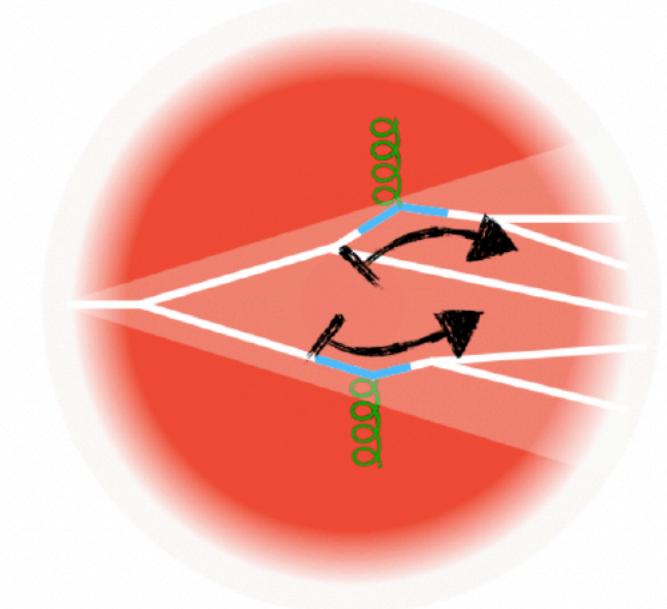
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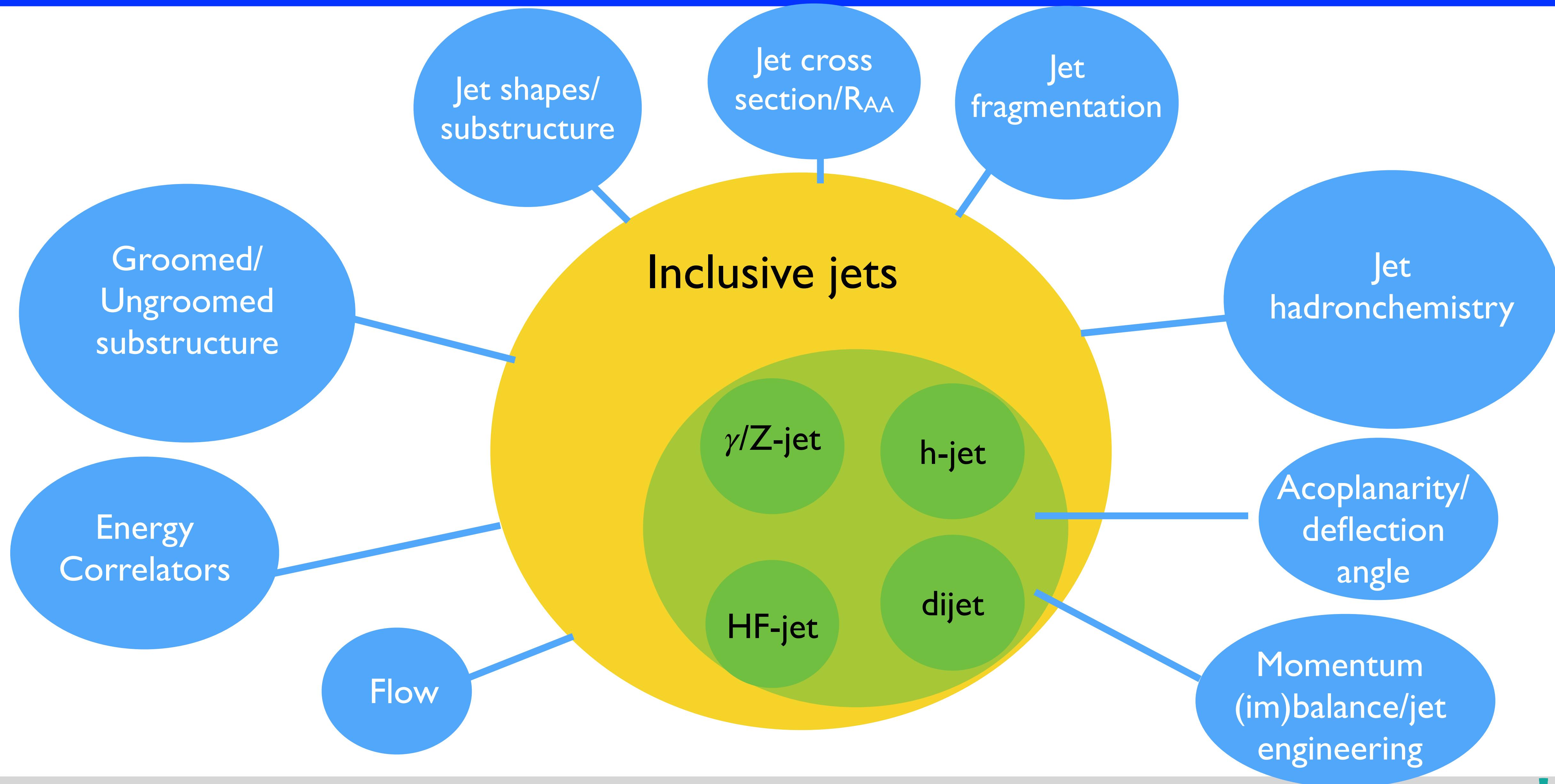


Substructure modification

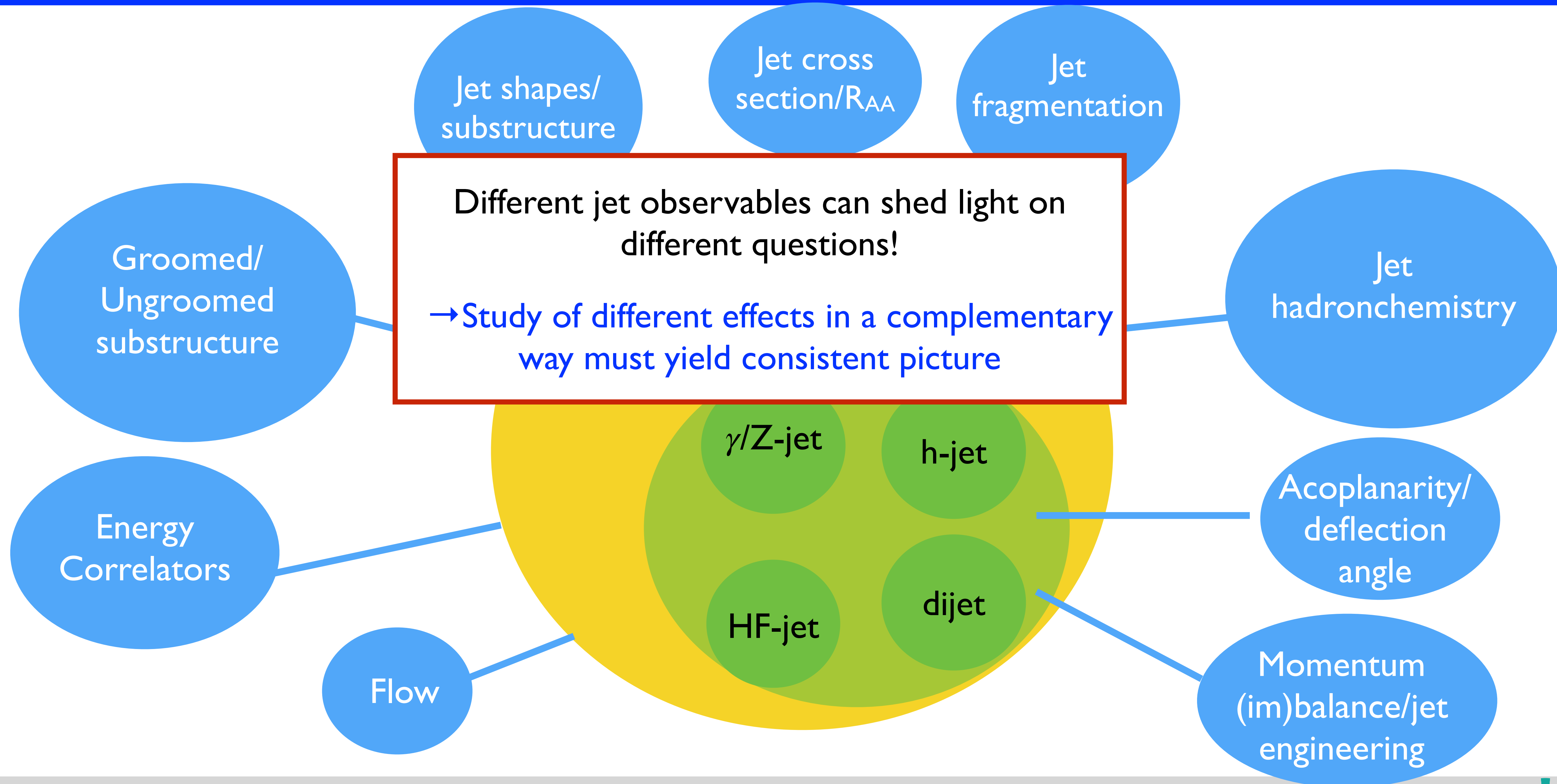


Goal: design observables to disentangle effects and extract properties of the QGP

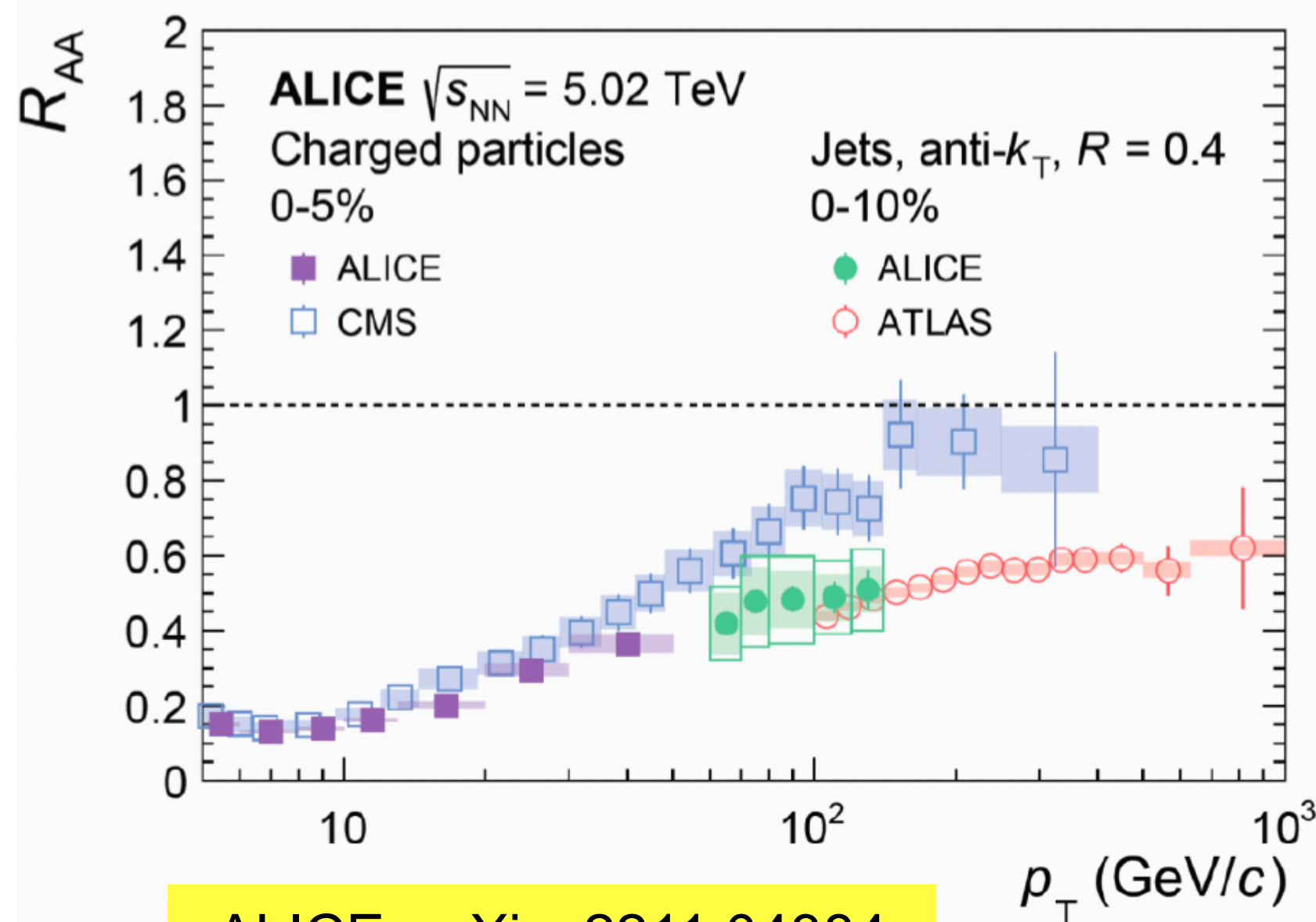
# A (incomplete) roadmap of jet measurements



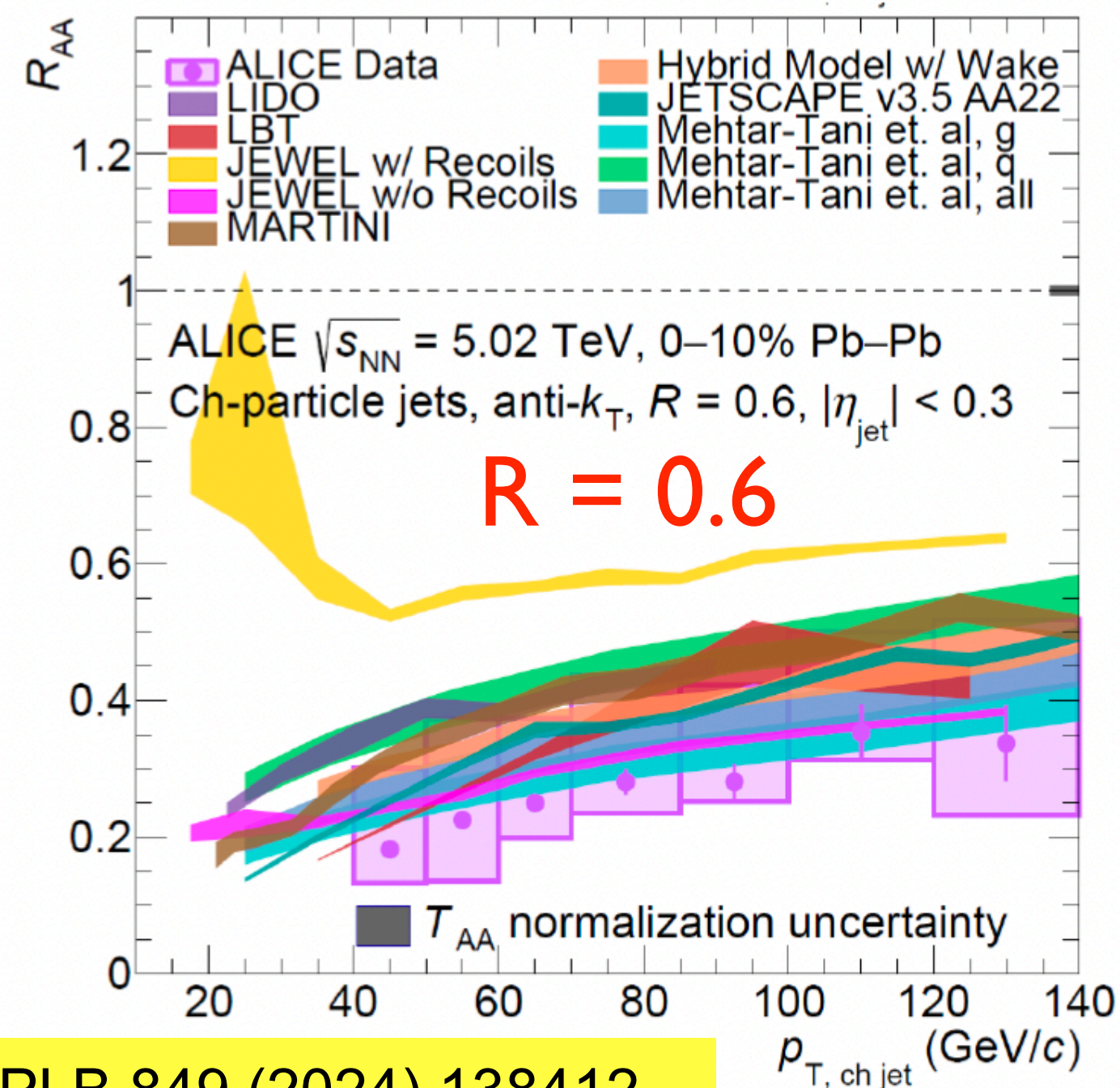
# A (incomplete) roadmap of jet measurements



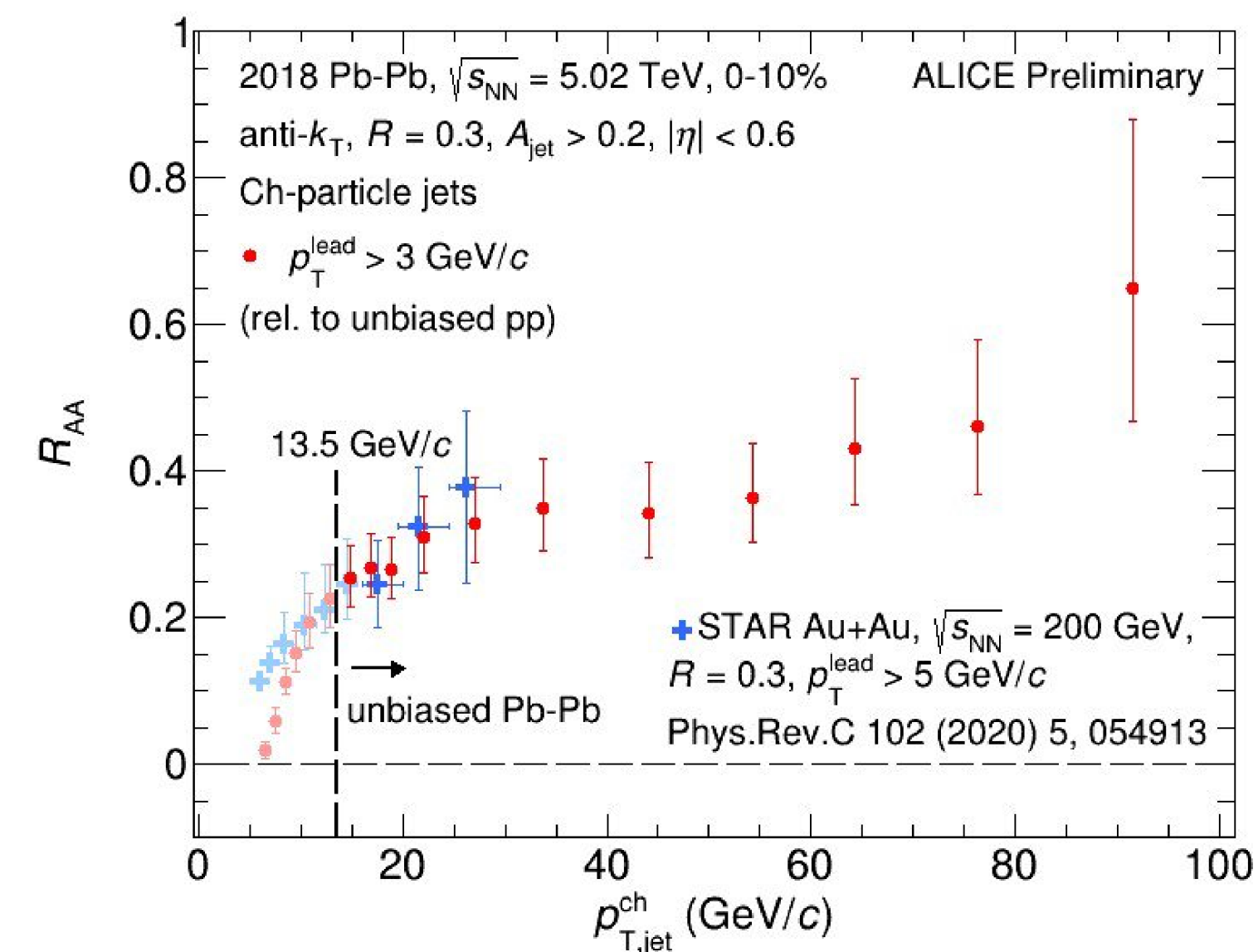
# Jet suppression and energy redistribution



ALICE, arXiv: 2211.04384



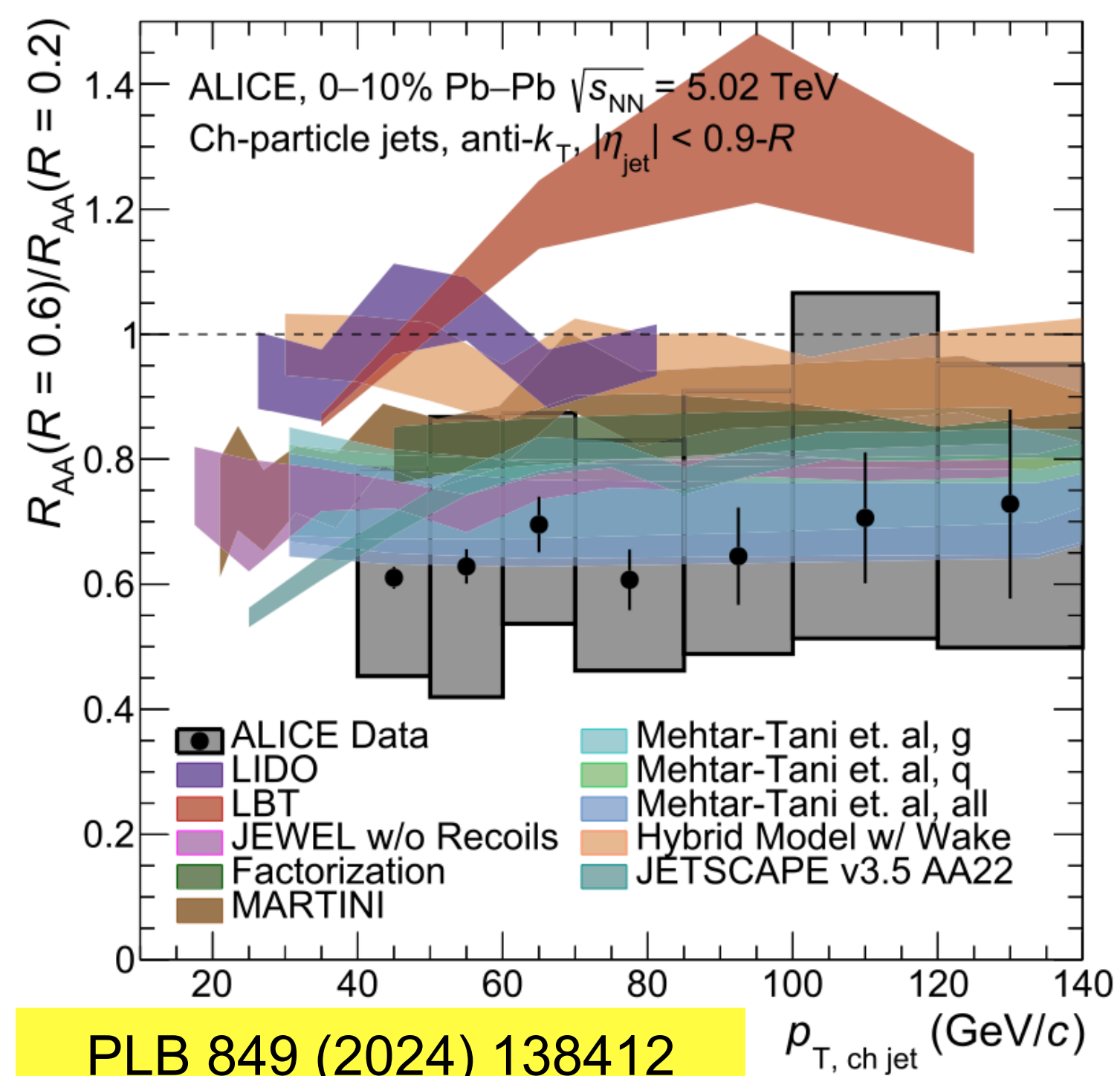
PLB 849 (2024) 138412



Talk by A. Landou, Sec. 17, Tue, 15:00

- Jet and high  $p_T$  hadron suppression observed over extensive range
  - Interplay between high  $p_T$  and jet results
- New ML&ME techniques allow for the extension to lower jet  $p_T$  and large  $R$ 
  - Allows for an overlapping regime between RHIC and LHC

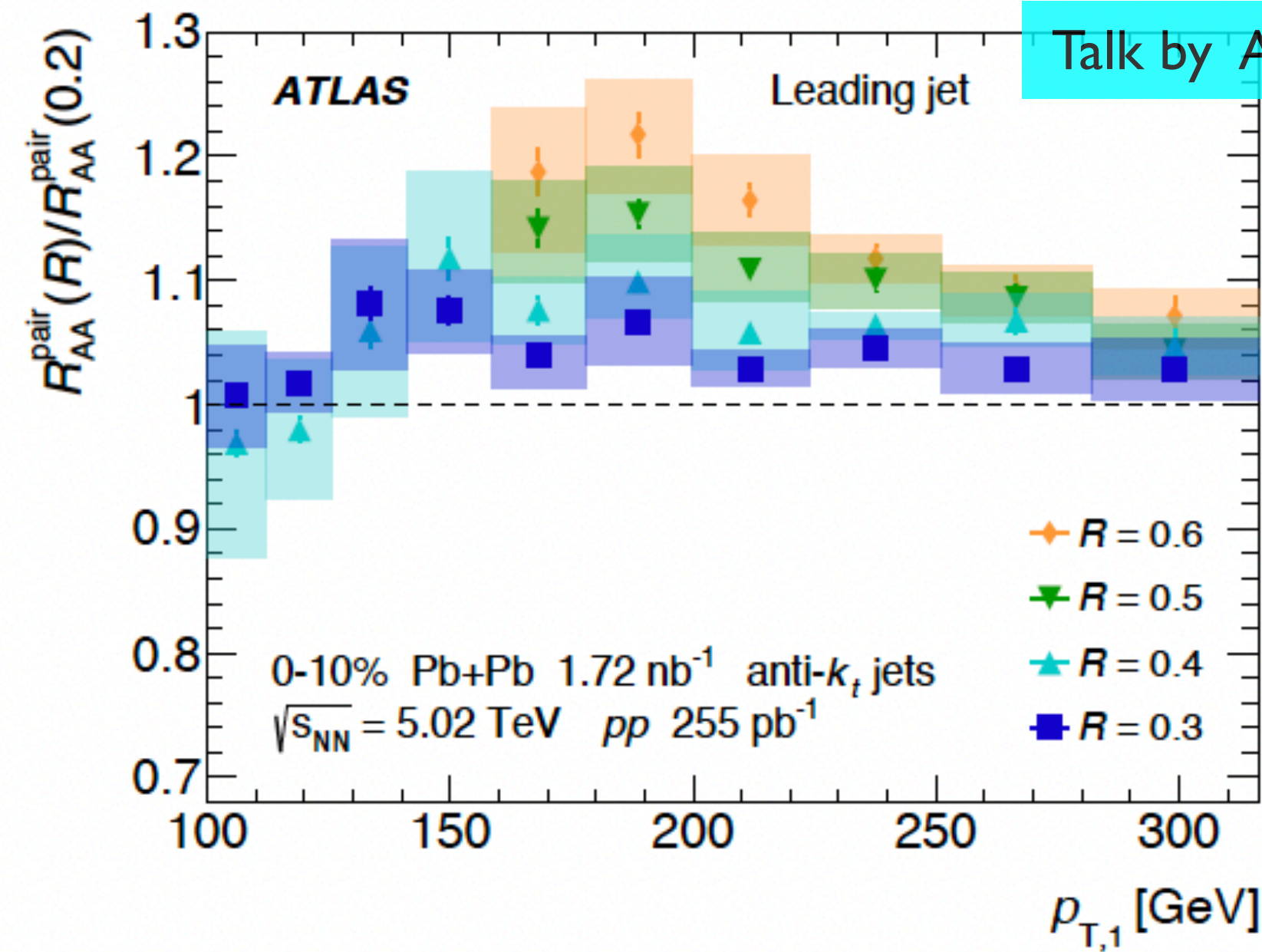
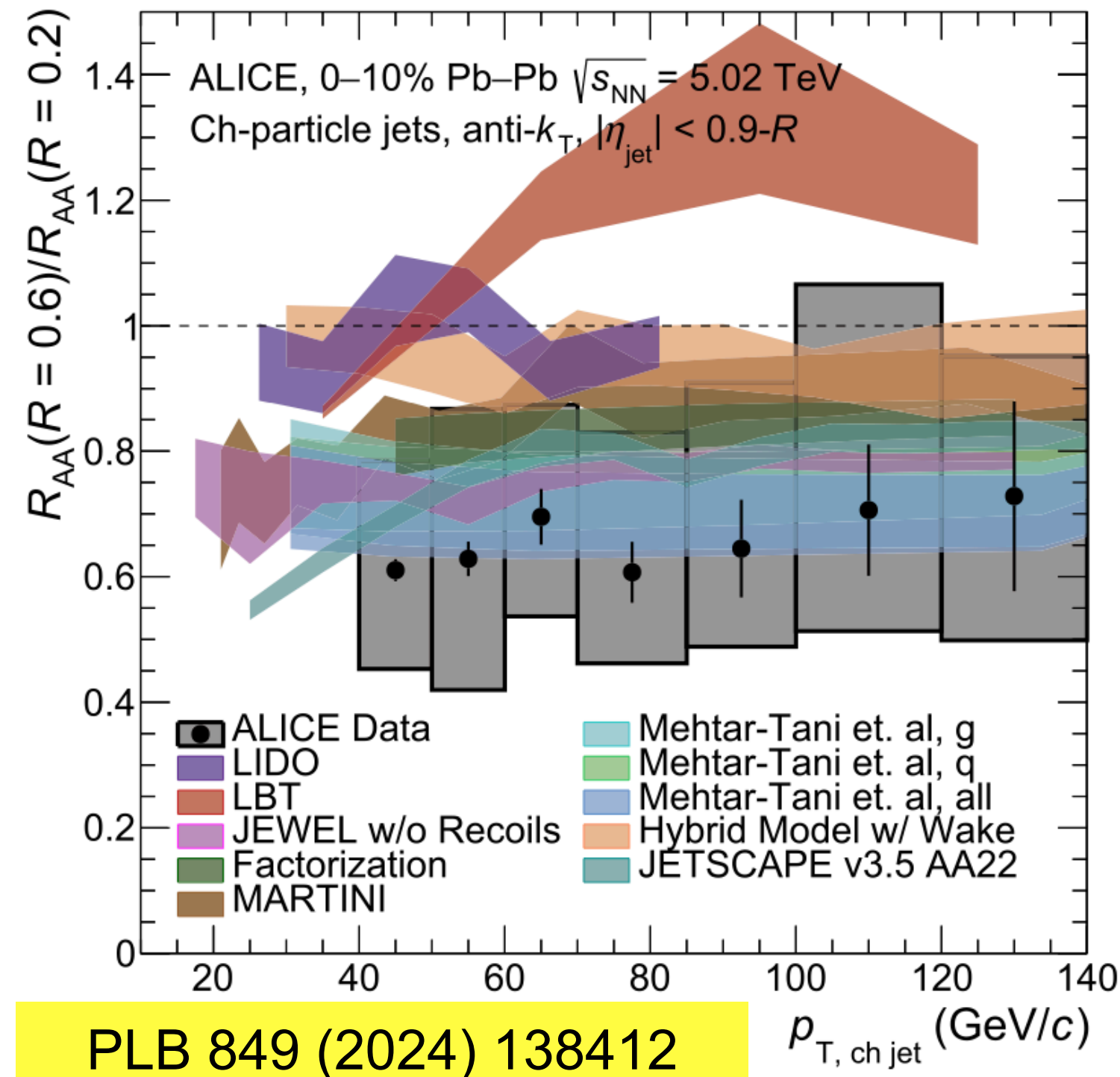
# R dependence of jet quenching



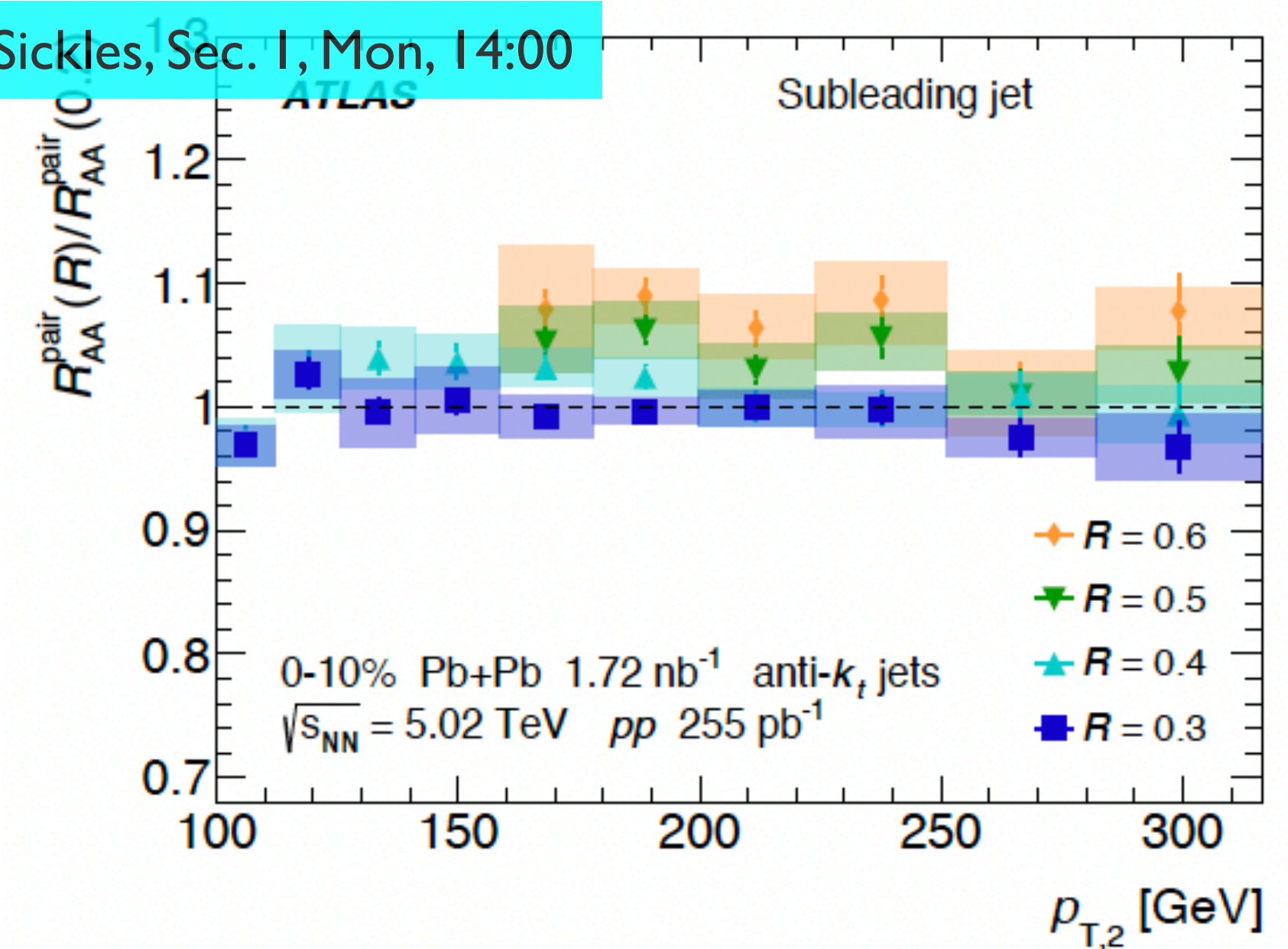
- Inclusive jets  $R_{AA}$  ratio from ALICE: larger radius jets more suppressed



# R dependence of jet quenching

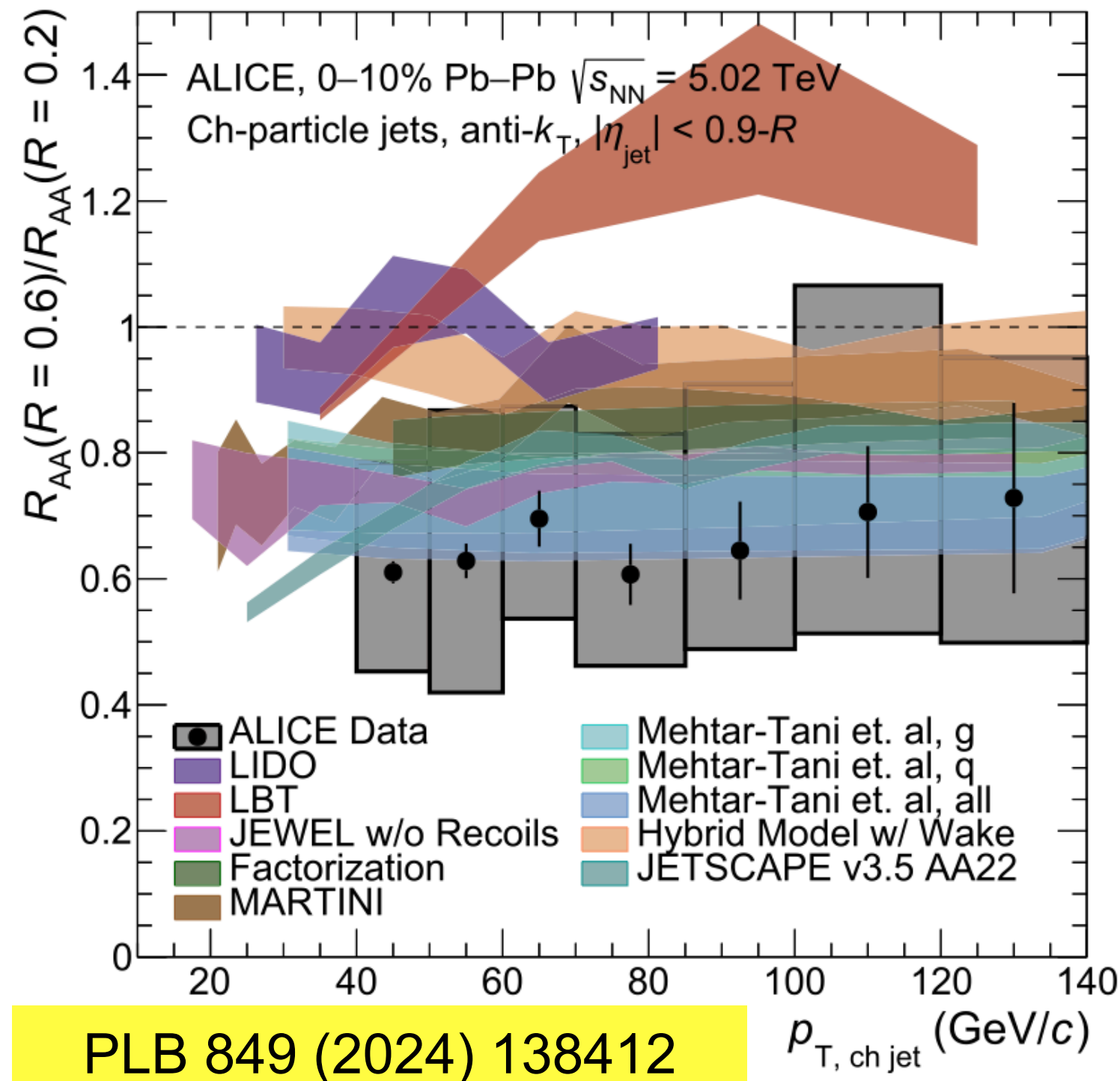


Talk by A. Sickles, Sec. I, Mon, 14:00

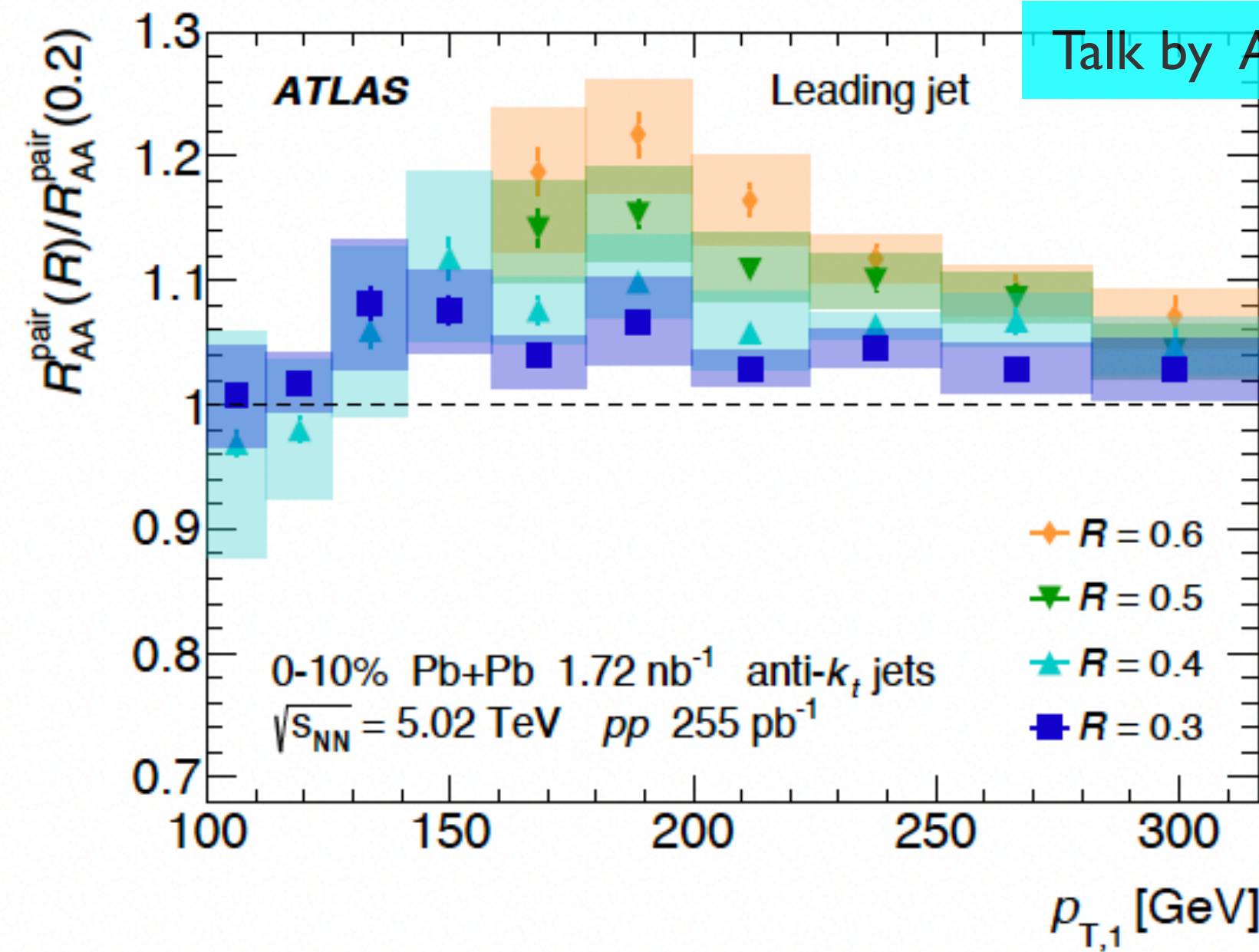


- Inclusive jets  $R_{AA}$  ratio from ALICE: larger radius jets more suppressed
- Dijet pair  $R_{AA}$  ratio from ATLAS: larger radius jets less suppressed

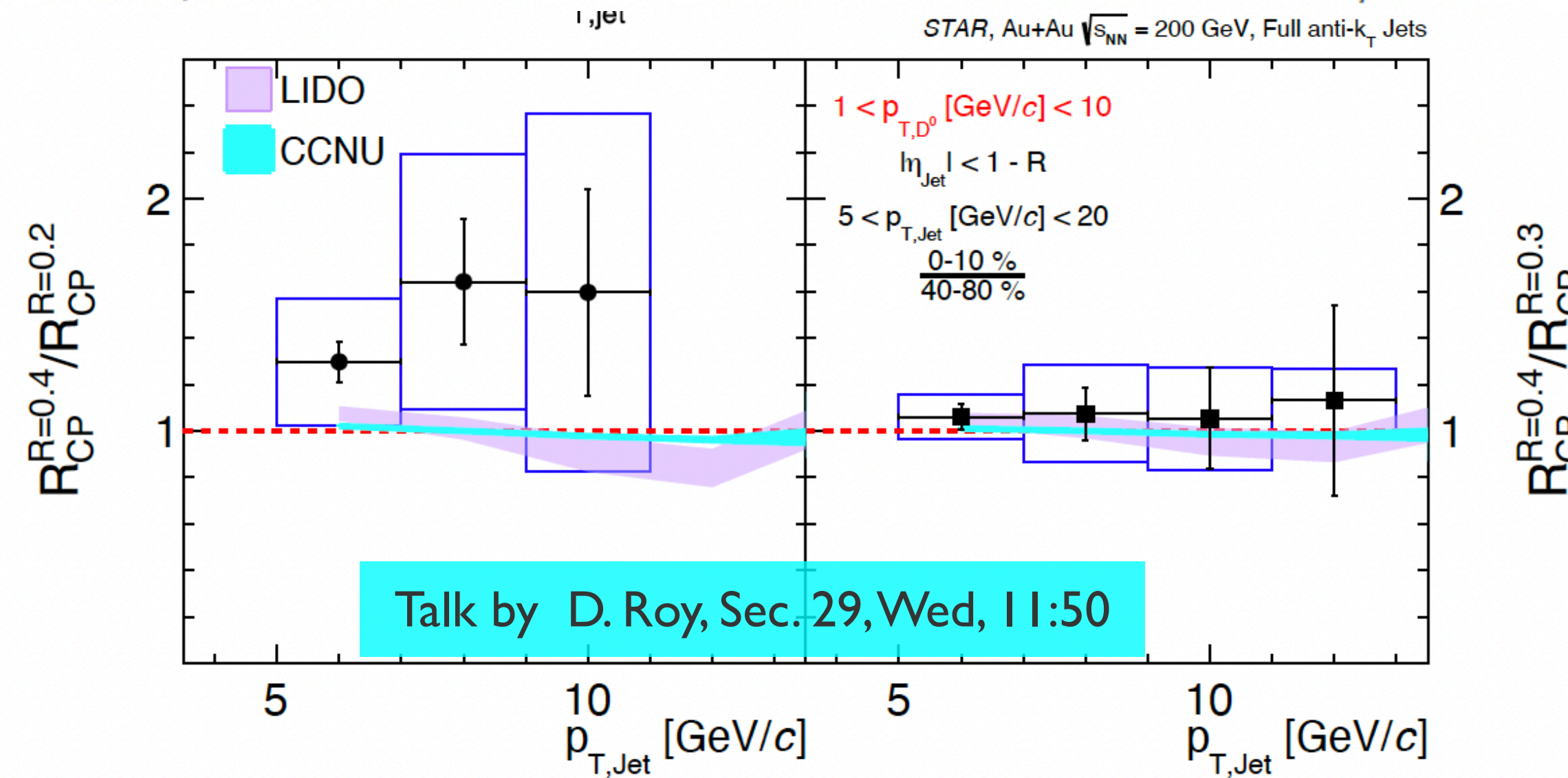
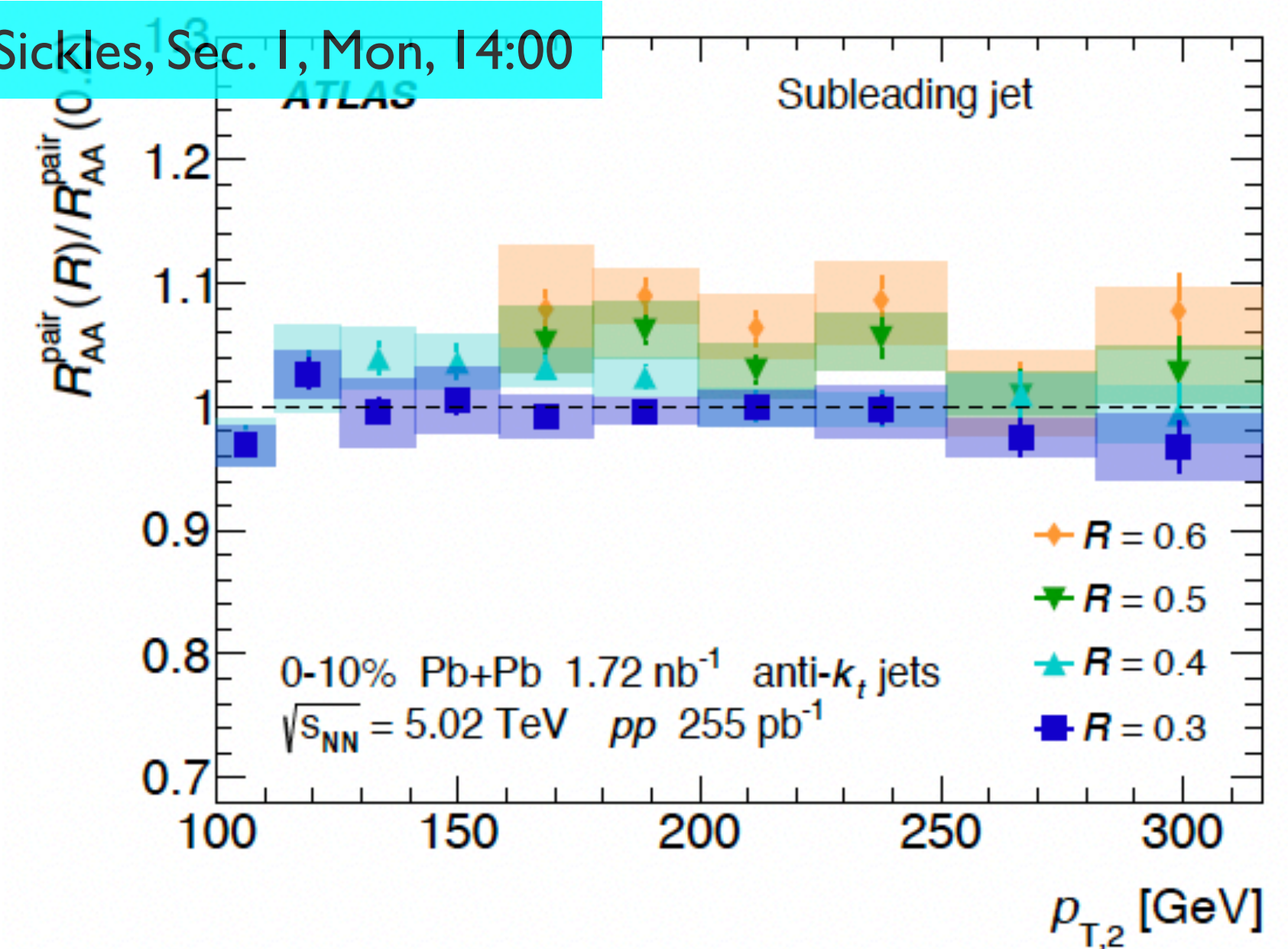
# R dependence of jet quenching



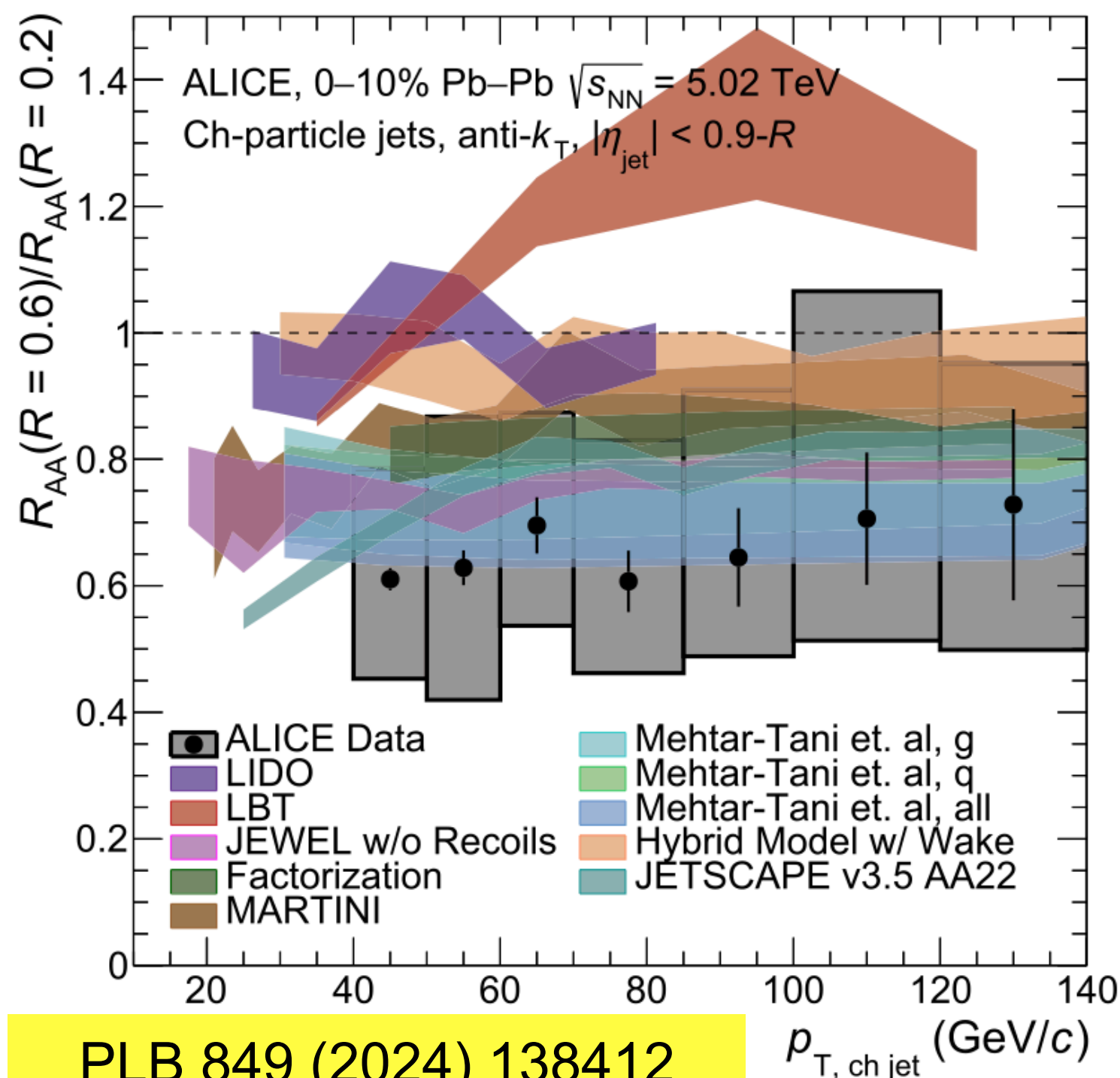
- Inclusive jets  $R_{AA}$  ratio from ALICE: larger radius jets more suppressed
- Dijet pair  $R_{AA}$  ratio from ATLAS: larger radius jets less suppressed
- B-jet  $R_{CP}$  ratio from STAR: no strong radius dependence



Talk by A. Sickles, Sec. I, Mon, 14:00

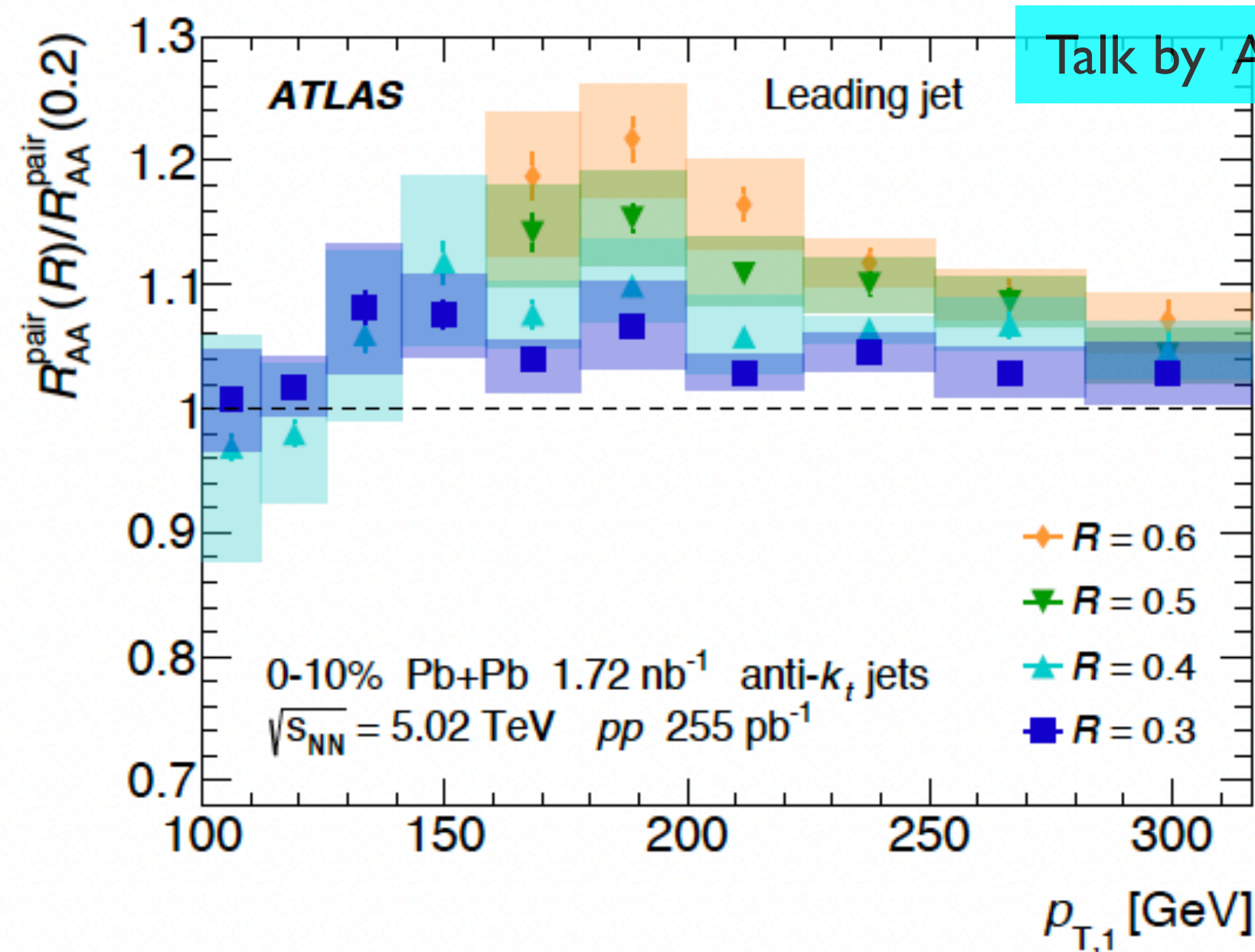


# R dependence of jet quenching

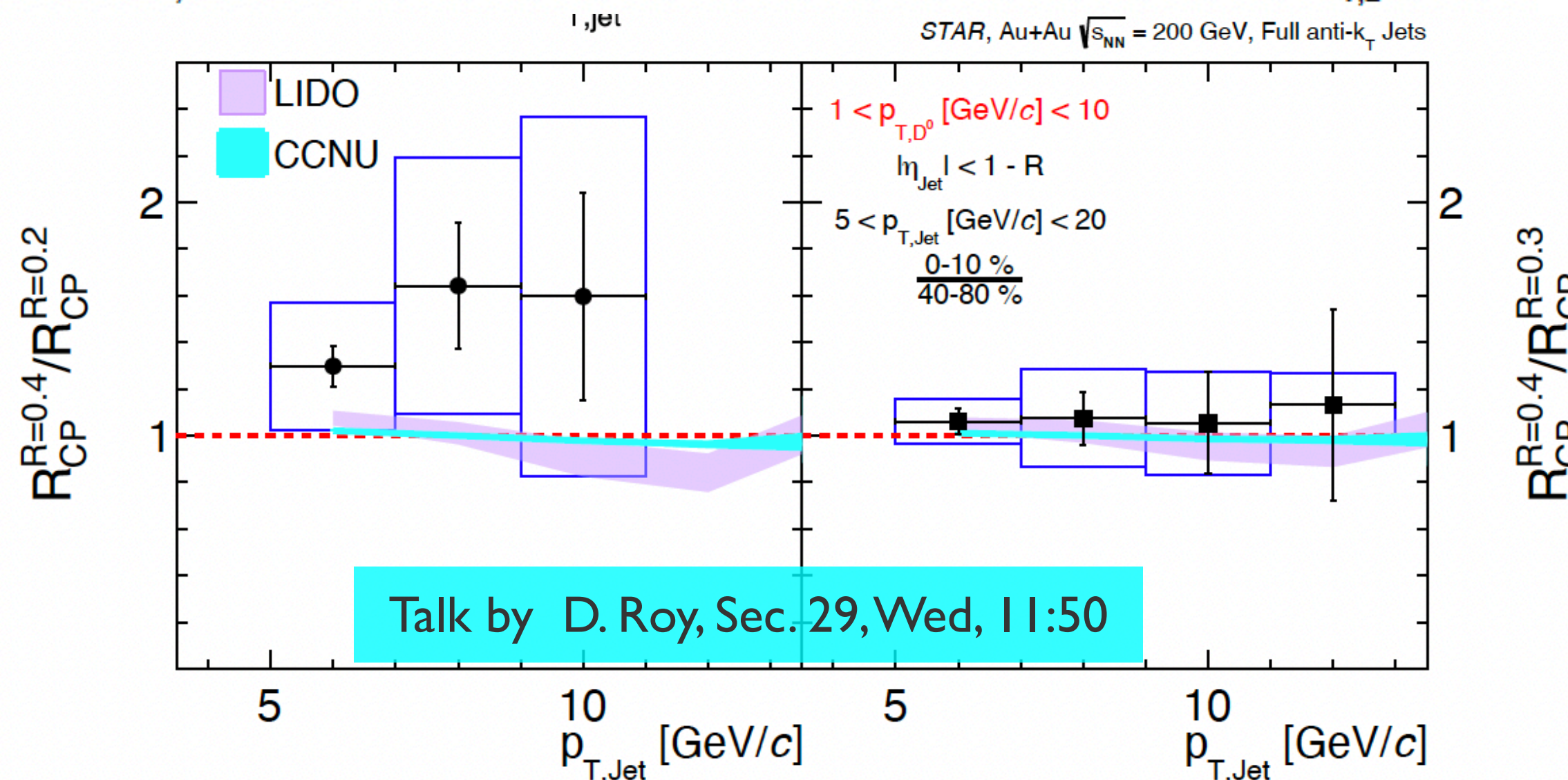
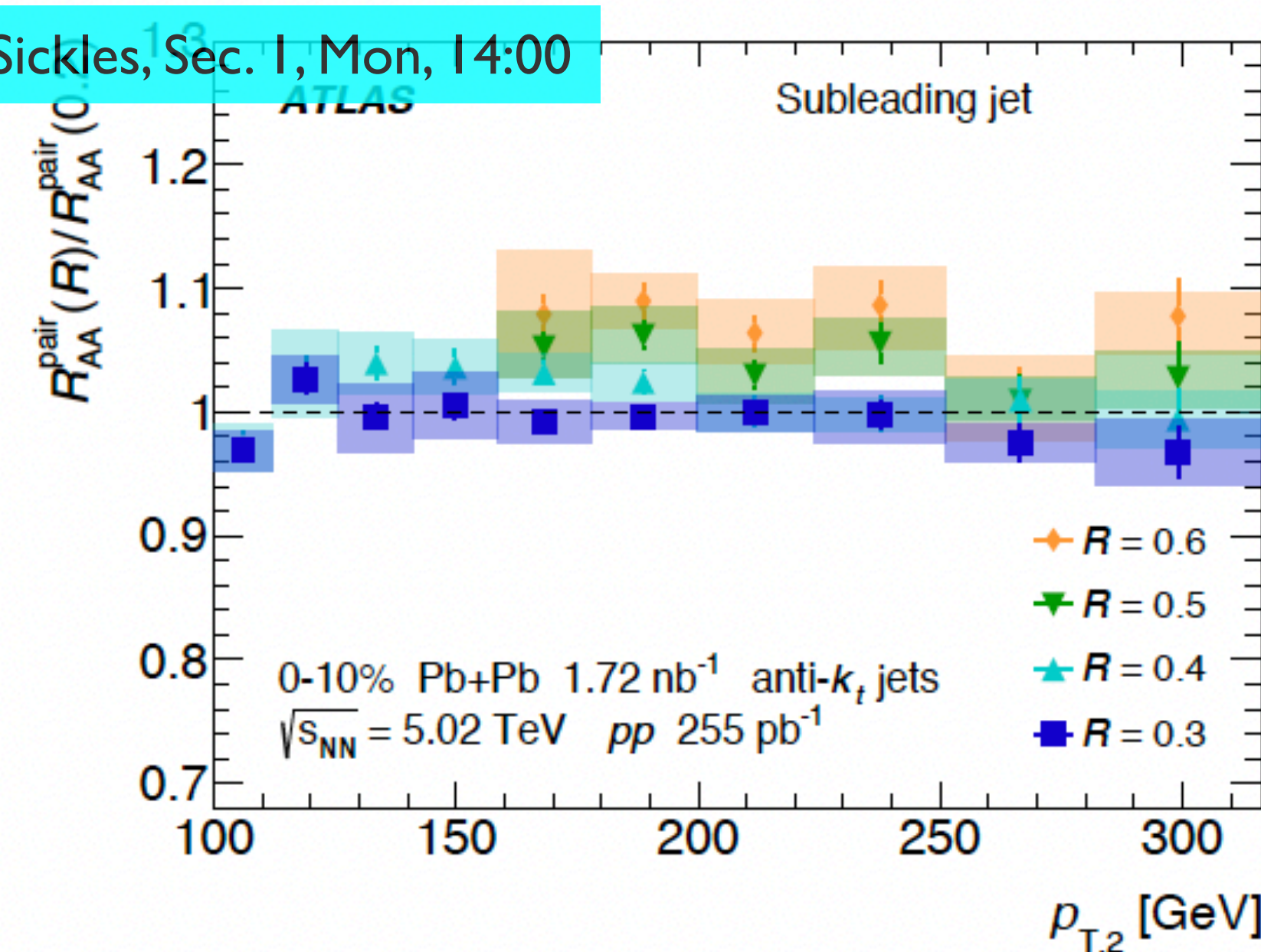


PLB 849 (2024) 138412

- Not the same jet type (inclusive vs. dijet vs. b-jet)
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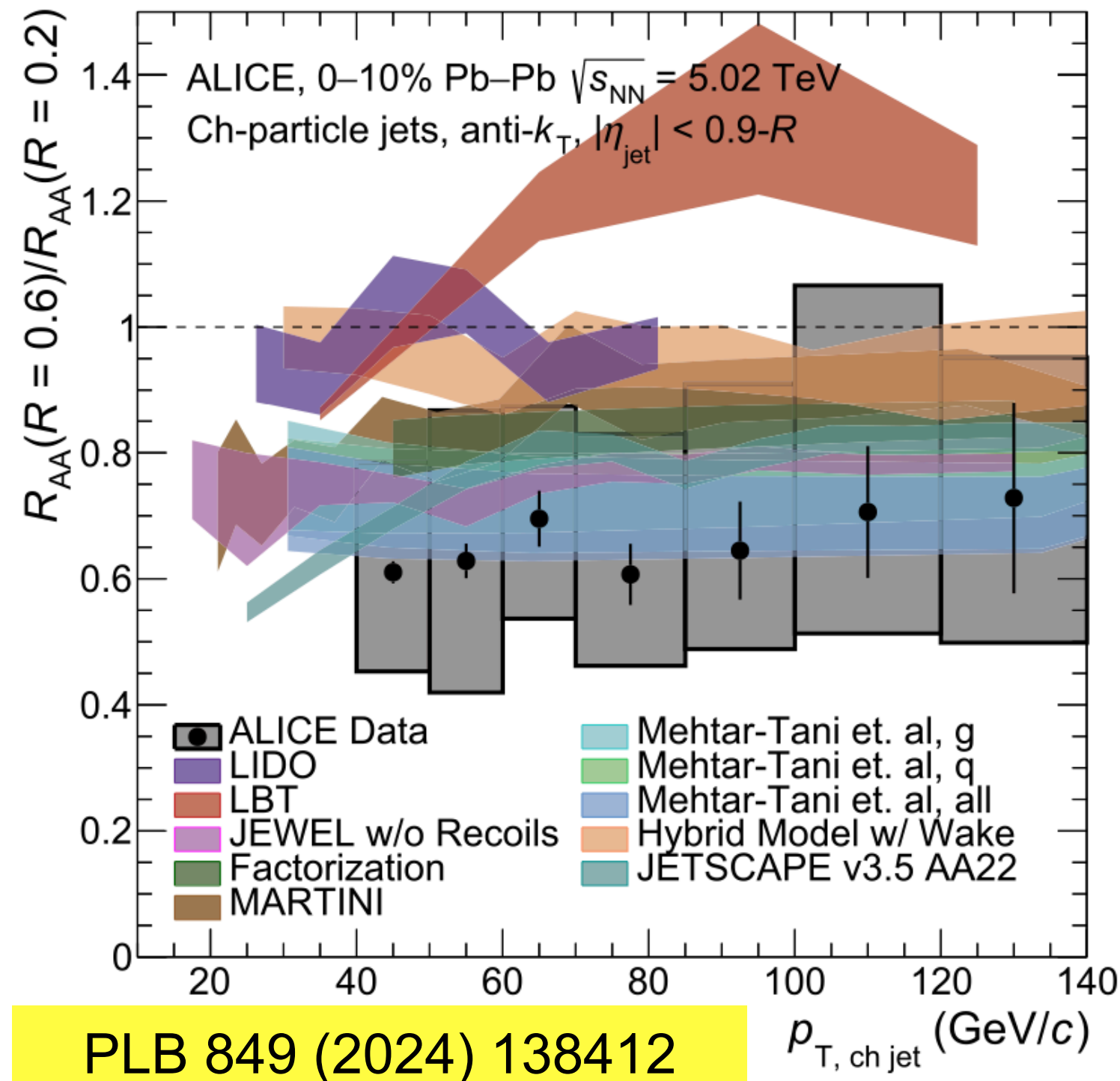


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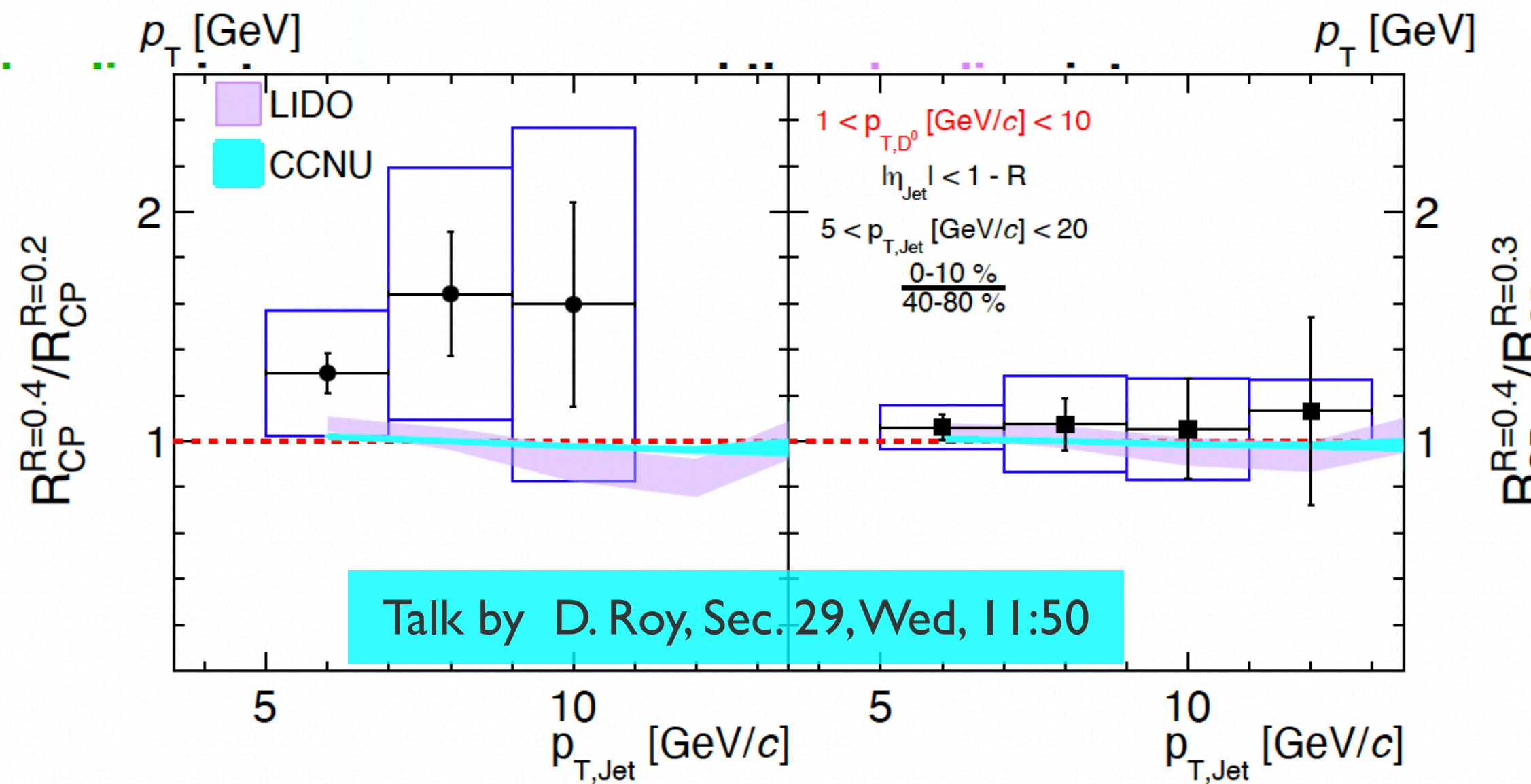
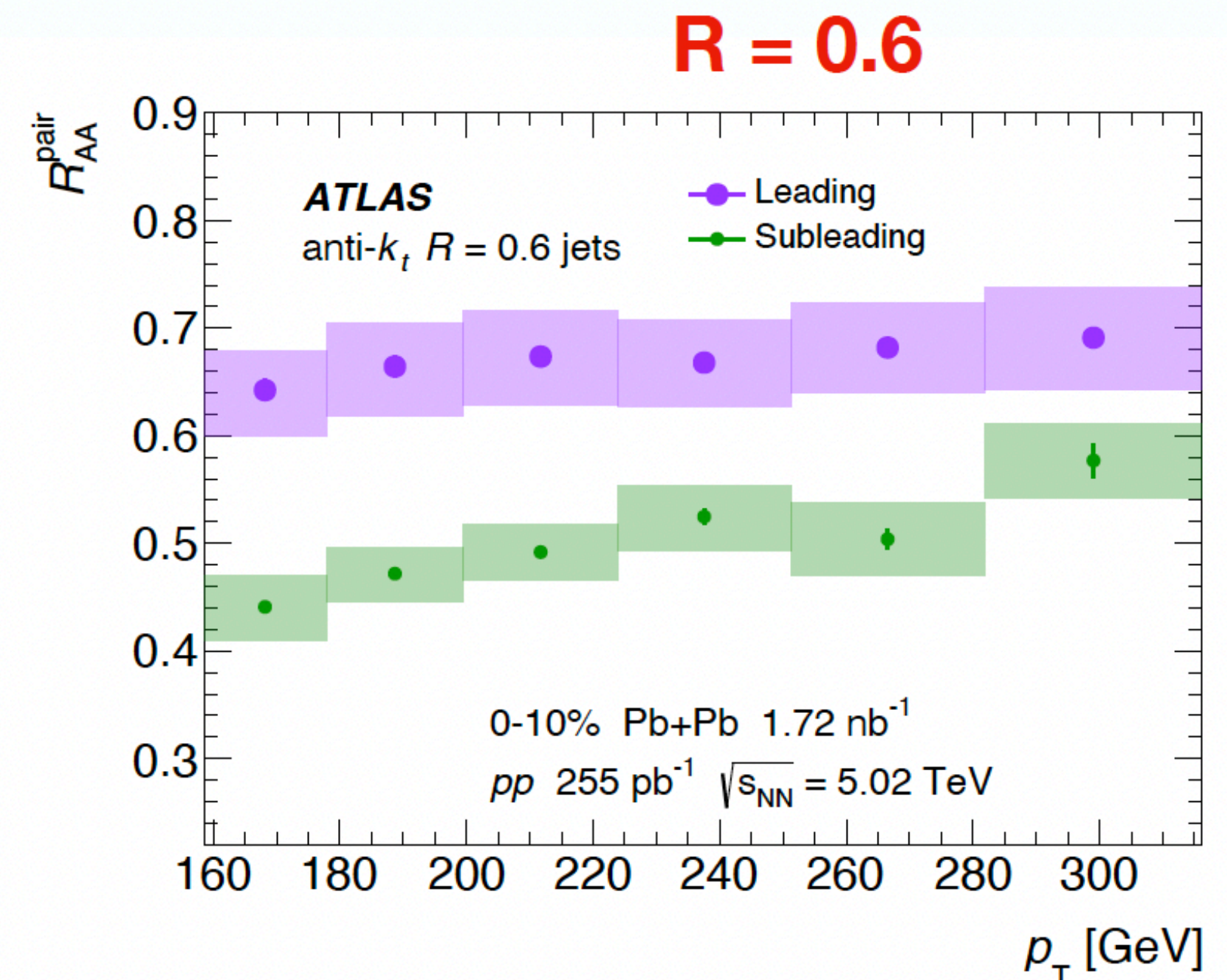
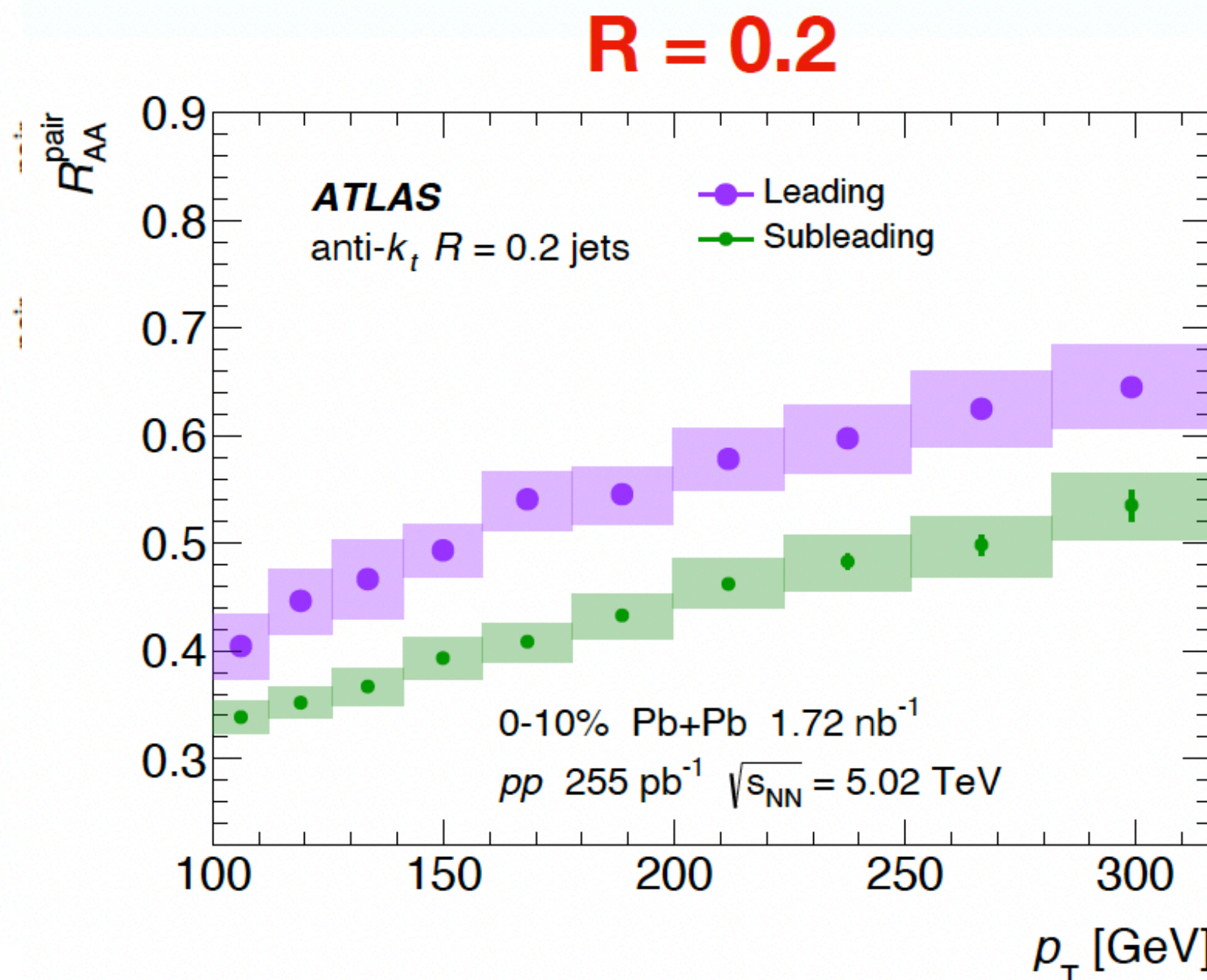
Talk by D. Roy, Sec. 29, Wed, 11:50

# R dependence of jet quenching

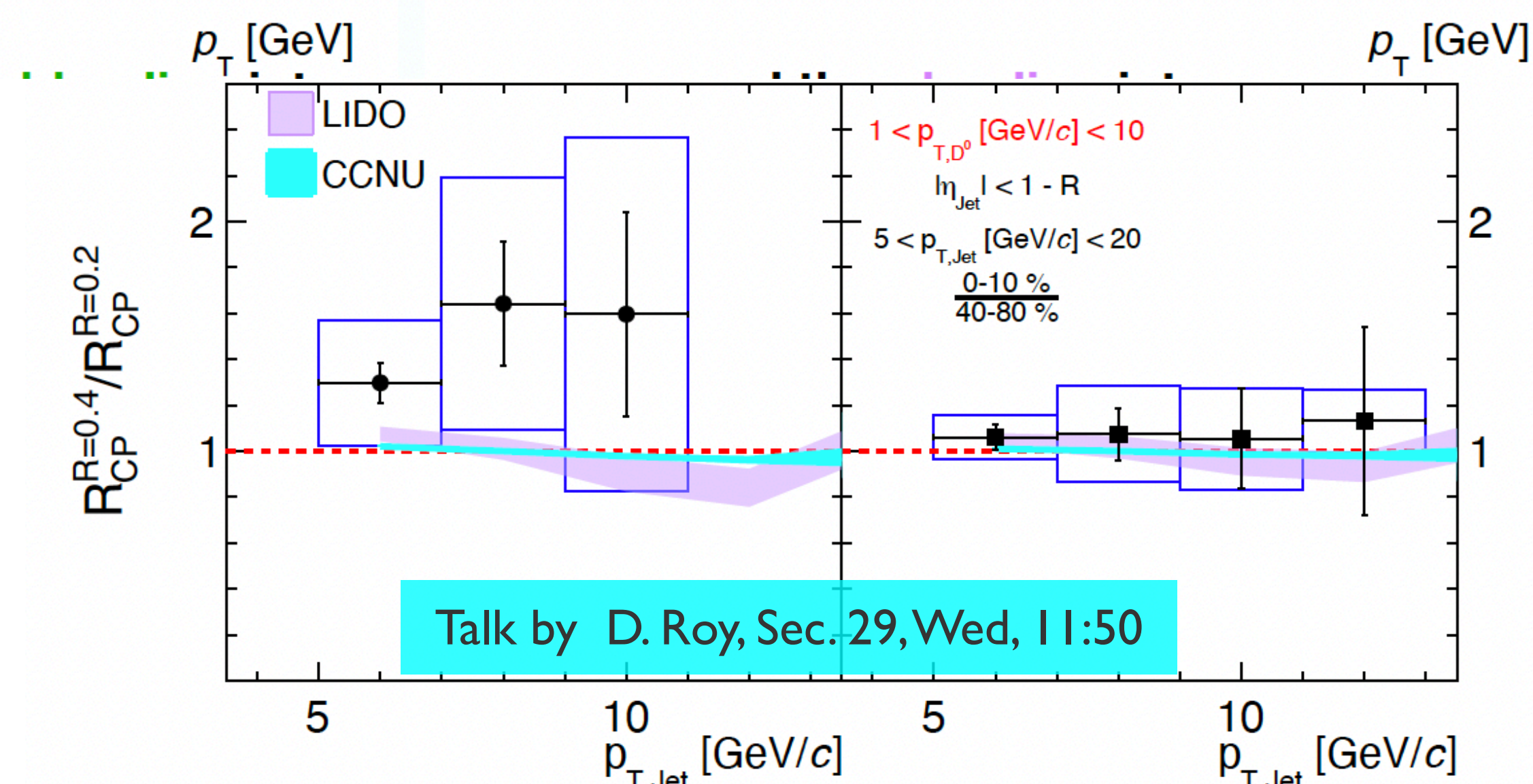
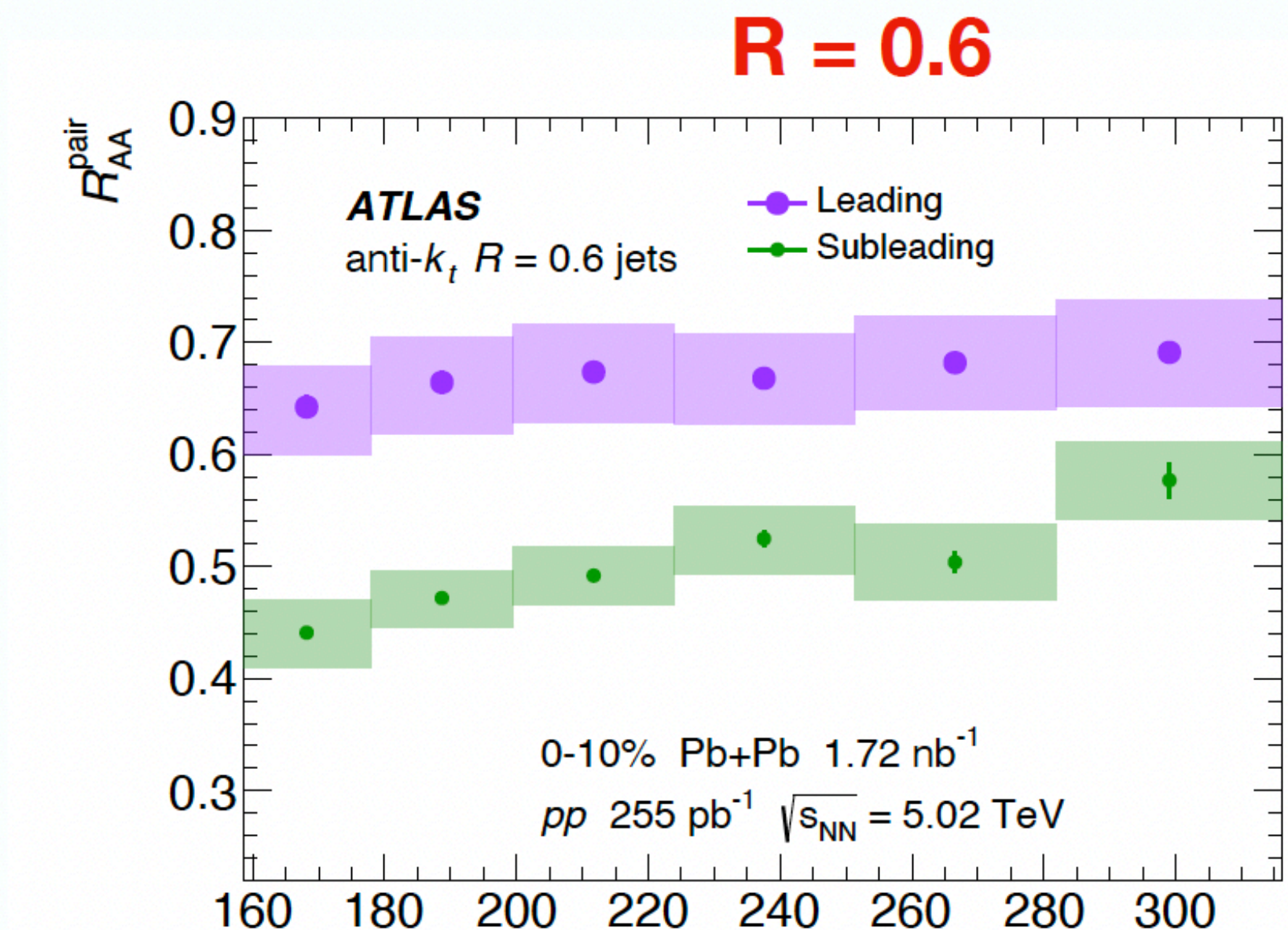
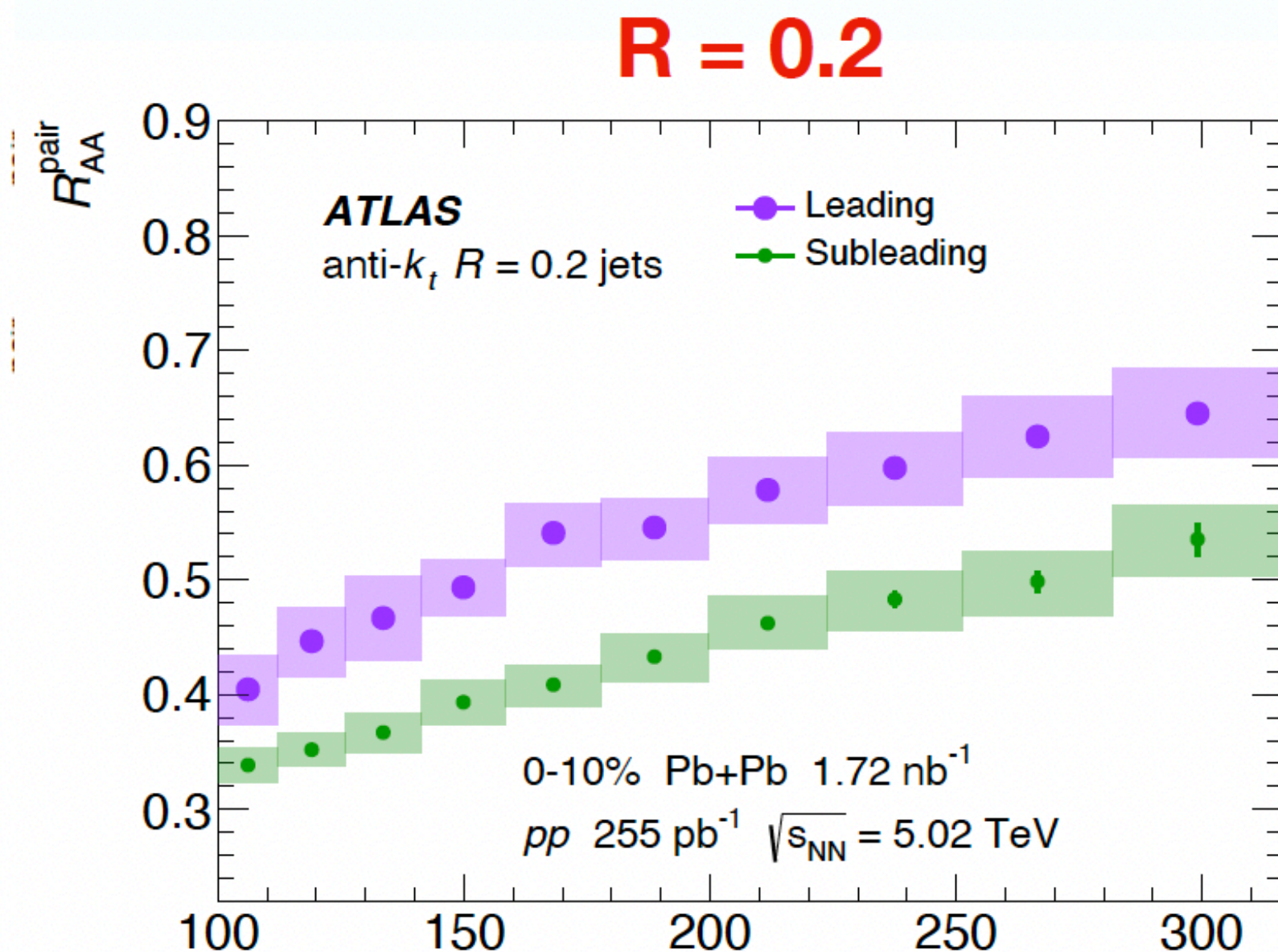
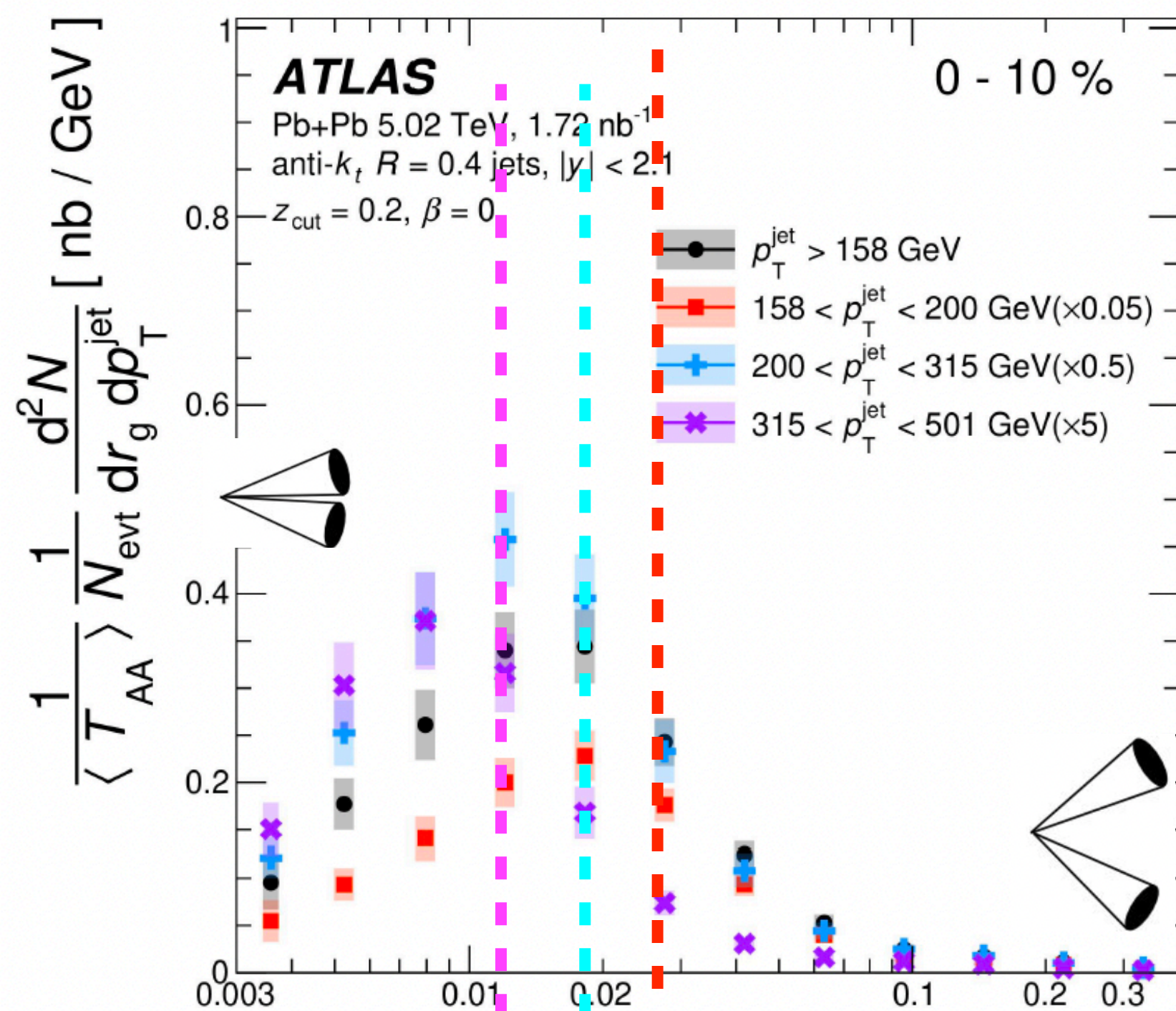


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- Not the same jet type (inclusive vs. dijet vs. b-jet)
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# R dependence of jet quenching

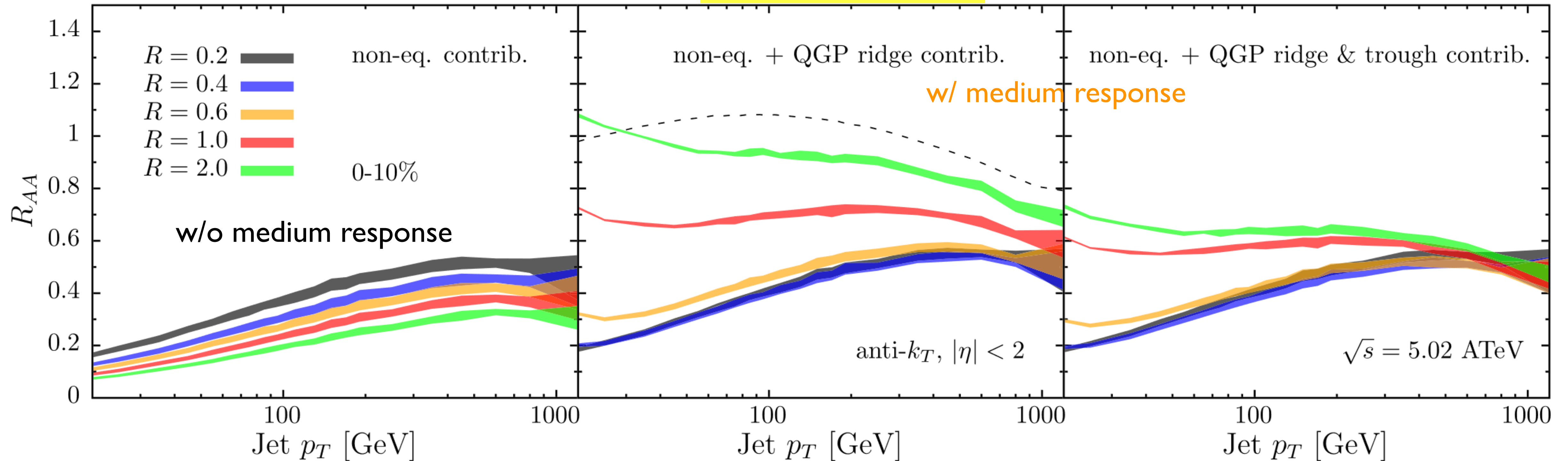


- Not the same jet type (inclusive vs. dijet vs. b-jet)
- Not the same kinematics (q/g fraction and jet structure can be different)
- p<sub>T</sub> dependence of energy loss are quite different (no matching for different R jets)

# Theory input: R dependence of jet quenching

- R dependence of jet  $R_{AA}$  can be sensitive to medium response effect and help to disentangle energy loss mechanisms
  - competing effect between the **amount/how energy redistributed** and **ability to recover it**

PRL 124 (2020) 052301

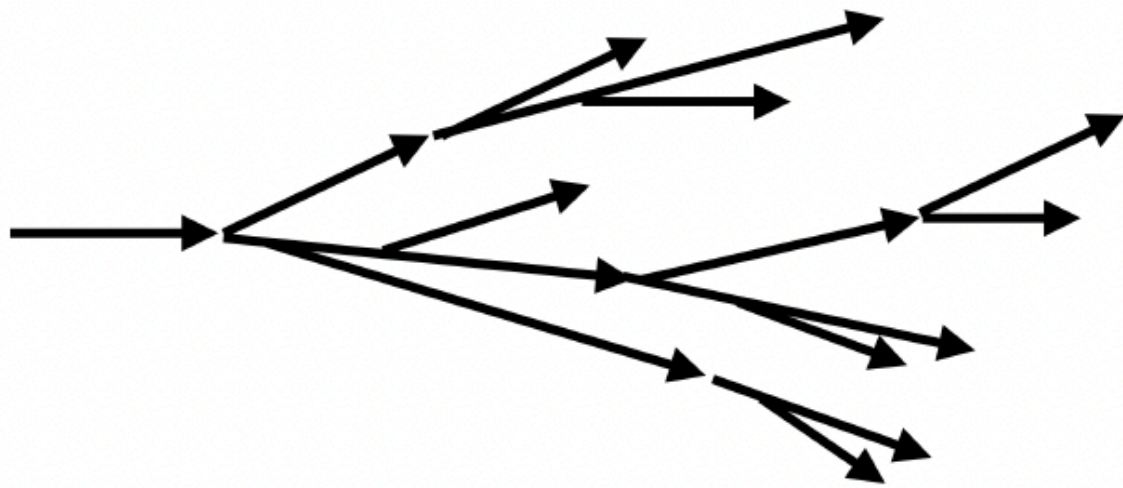


- Hybrid model predicts different (even reversed) R-dependence of jet  $R_{AA}$  due to medium response

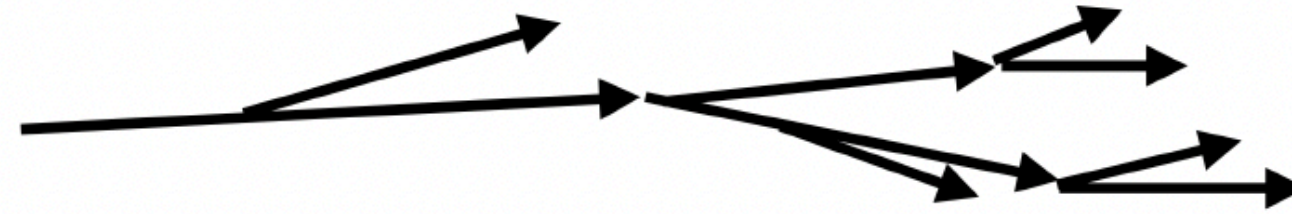
→ More differential and consistent analyses needed!

# Energy loss dependence on parton flavor/mass

## Gluon-initiated shower



## Quark-initiated shower



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

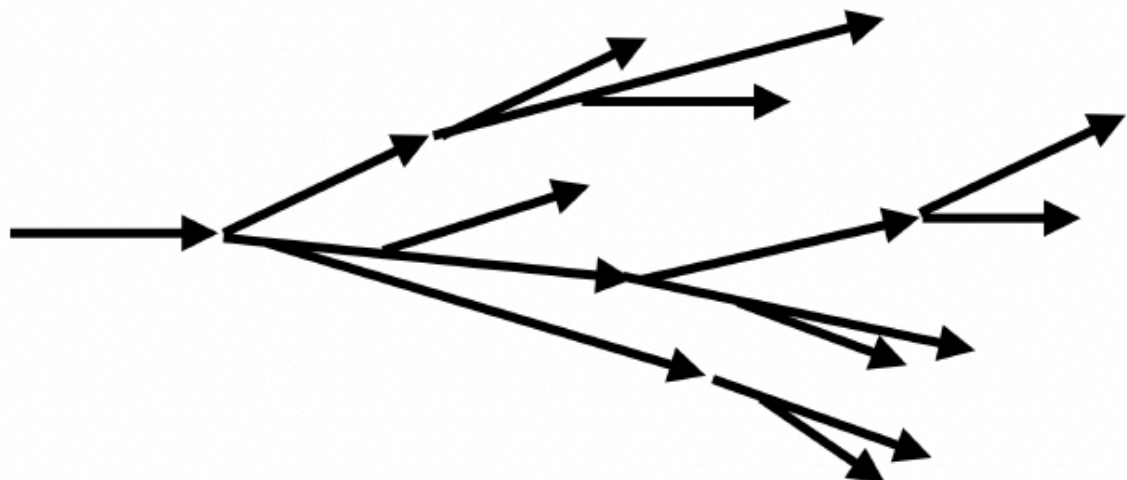
## Casimir color factors

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

- Color charge dependence of energy loss:  $E_{\text{loss}}^{\text{gluon}} > E_{\text{loss}}^{\text{quark}}$

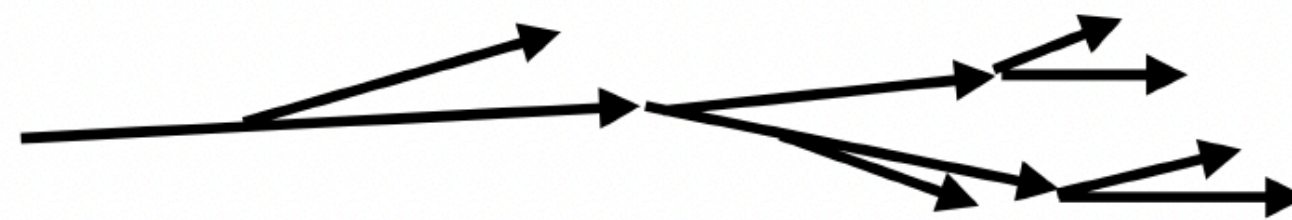
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## Gluon-initiated shower



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

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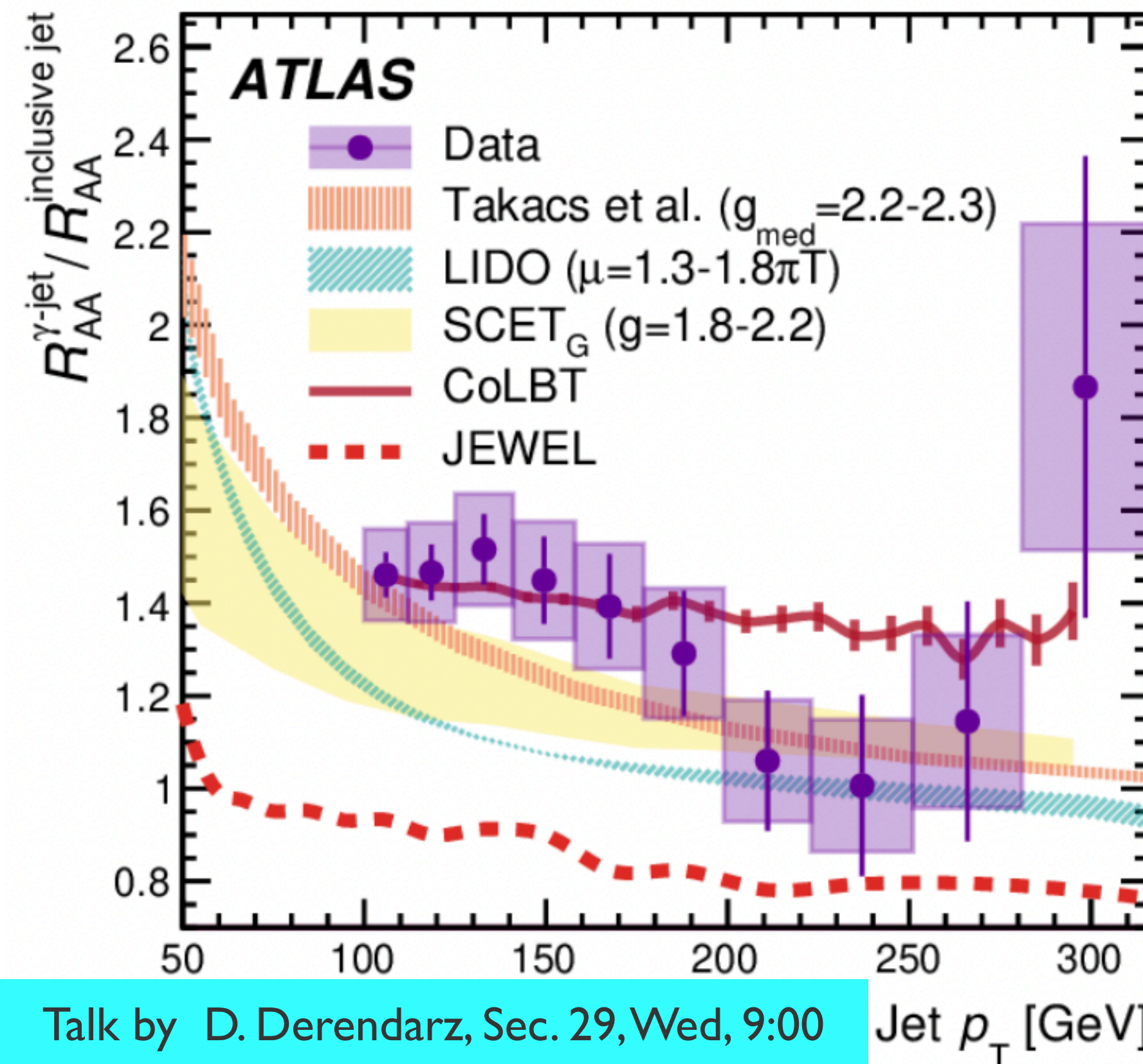


## Casimir color factors

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

- Color charge dependence of energy loss:  $E_{\text{loss}}^{\text{gluon}} > E_{\text{loss}}^{\text{quark}}$
- $\gamma$ -tagged (quark enriched) jets are less suppressed than inclusive (gluon dominated) jets

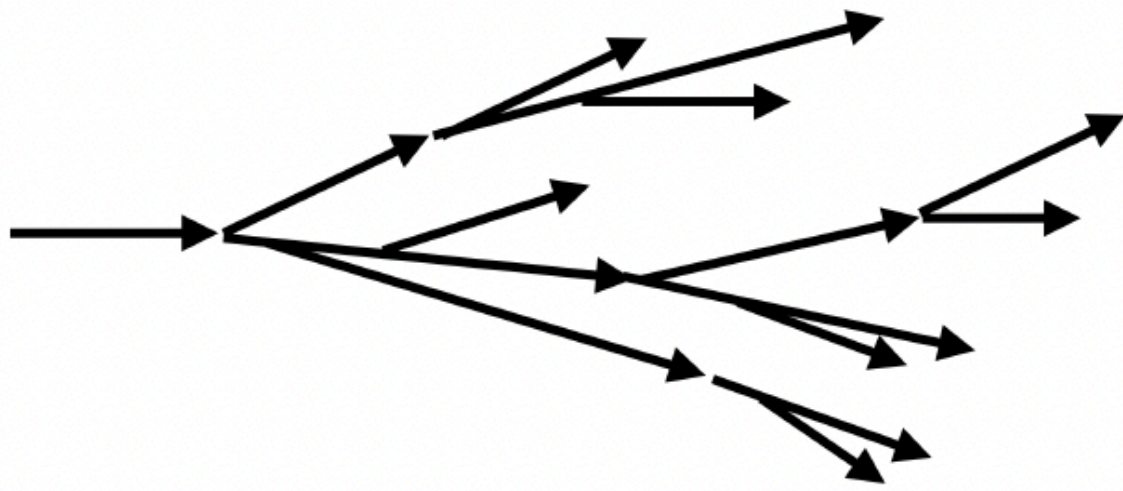
Phys. Lett. B 846 (2023) 138154





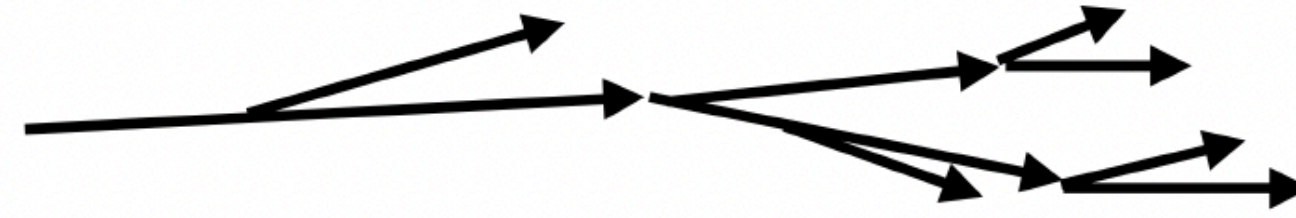
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## Gluon-initiated shower

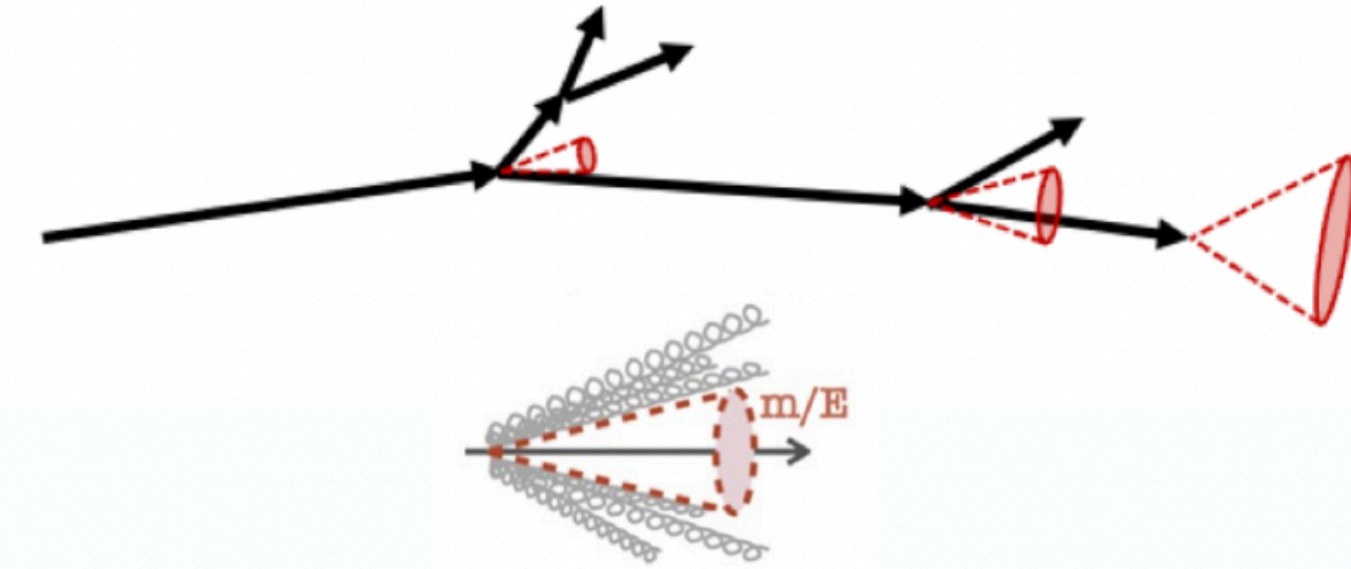


$$\frac{C_A}{C_F} = \frac{9}{4}$$

## Quark-initiated shower



## Heavy-quark-initiated shower



### 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 a dead cone which suppresses radiation close to the heavy-quark**

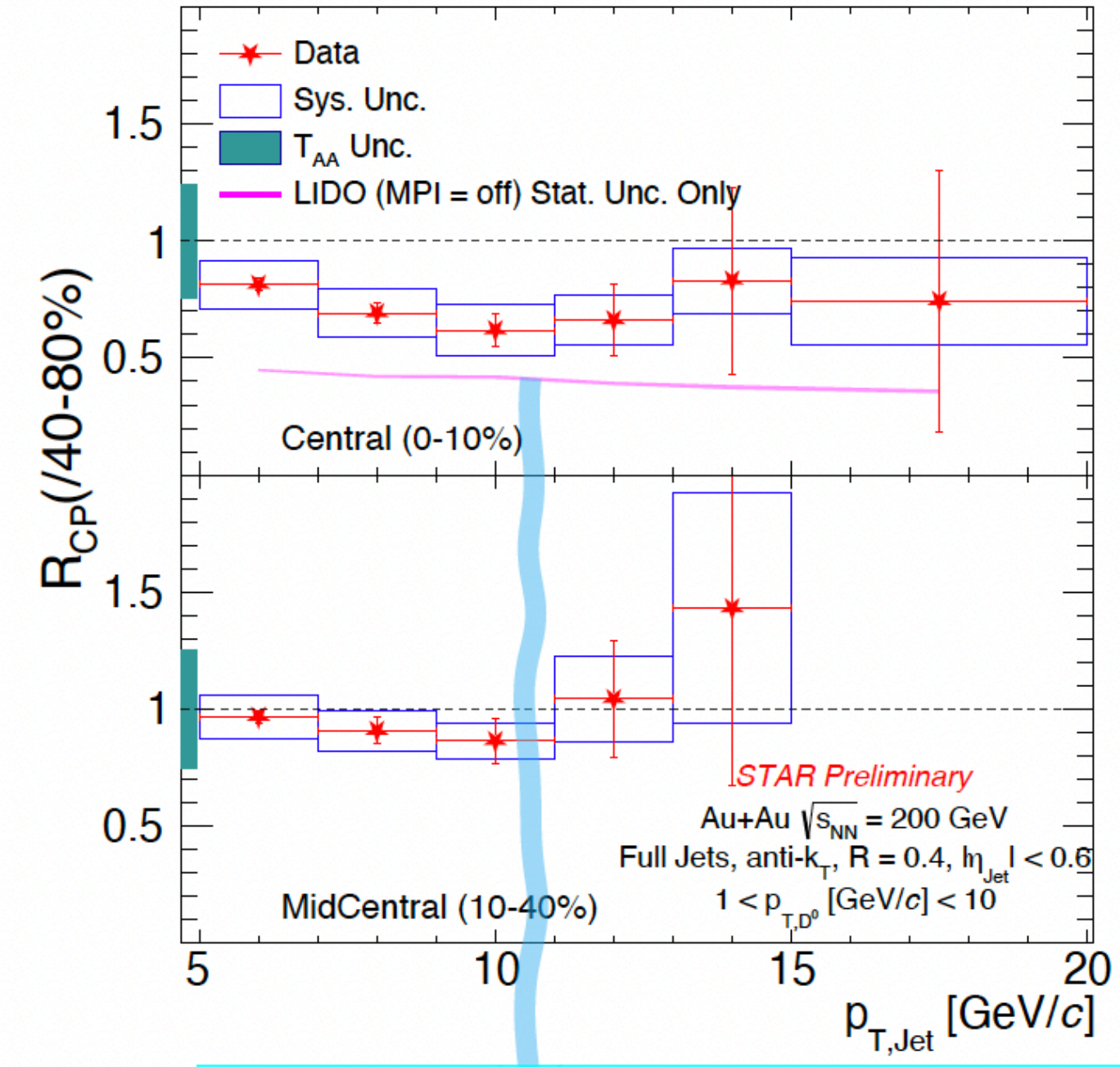
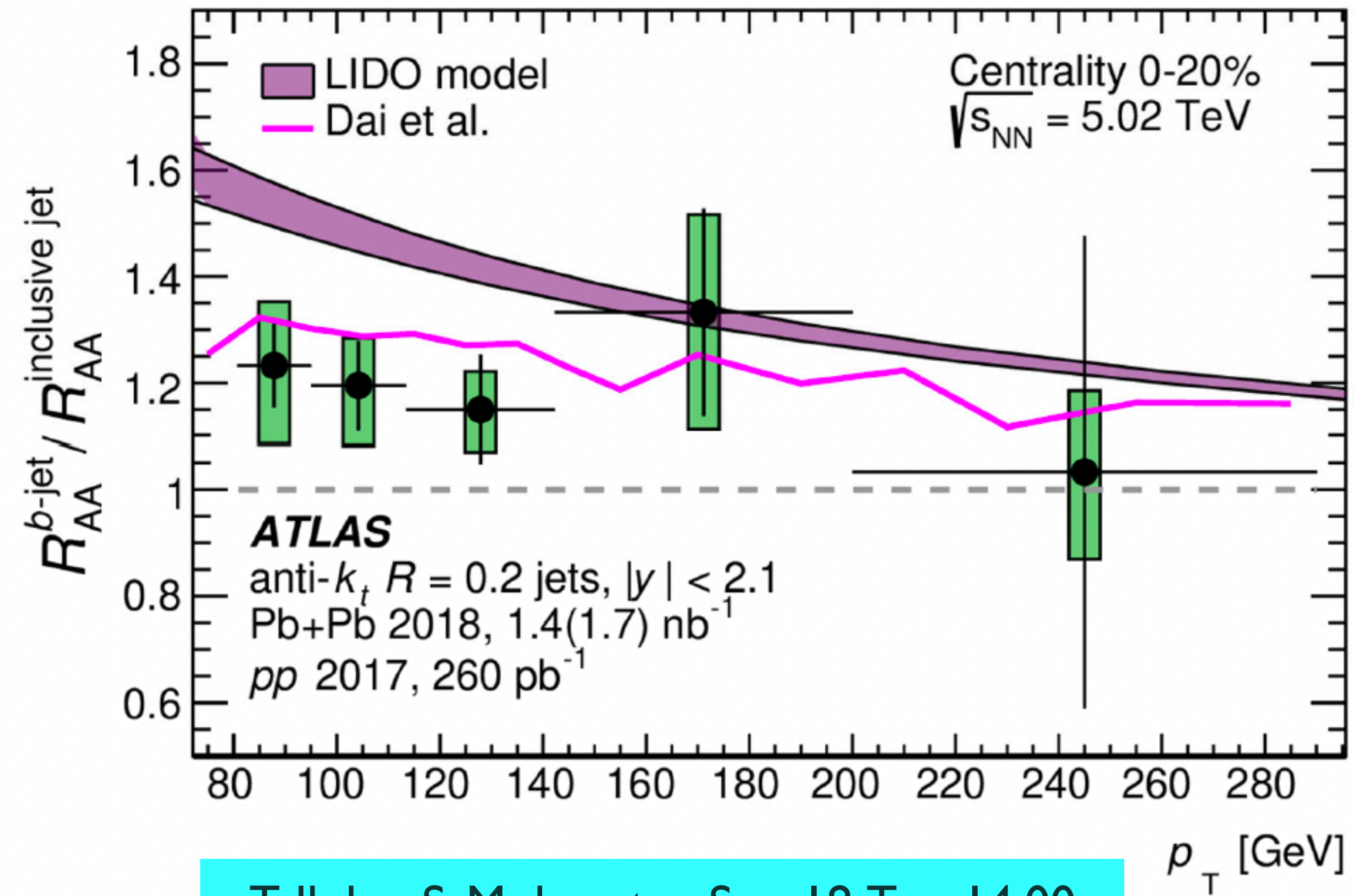
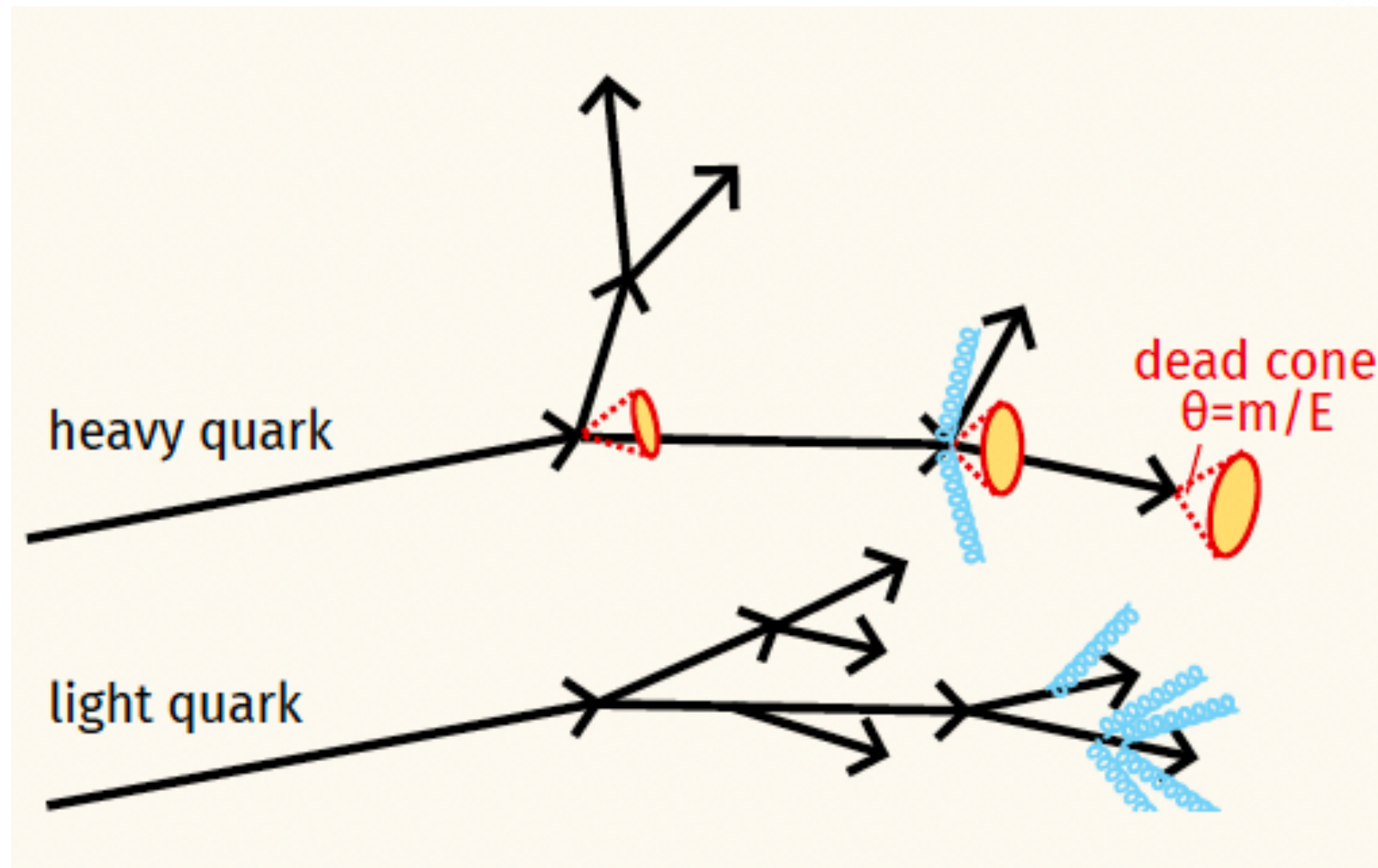
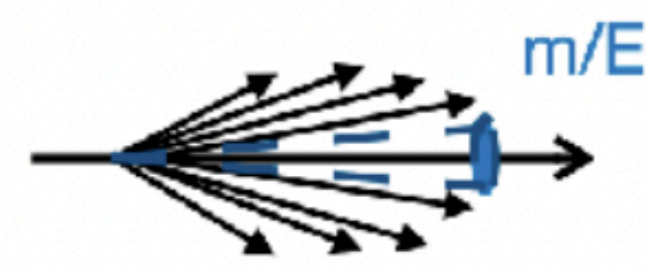
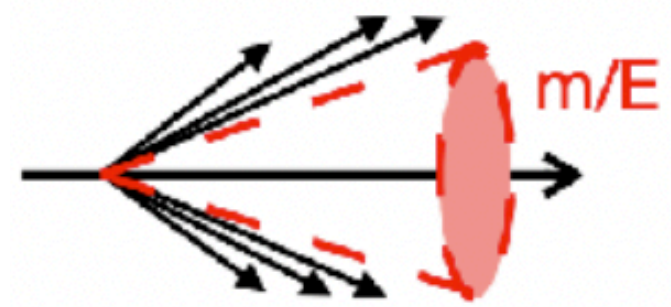
- Energy loss predicted to depend also on quark mass: reduction of gluon radiation from heavy quarks at small angles — “**Dead Cone**” effect
- Flavor dependence of energy loss:  $E_{\text{loss}}^{\text{gluon}} > E_{\text{loss}}^{\text{light-quark}} > E_{\text{loss}}^c > E_{\text{loss}}^b$

# Mass/flavor dependence of energy loss

## Dead-cone effect

Large parton mass

Small parton mass

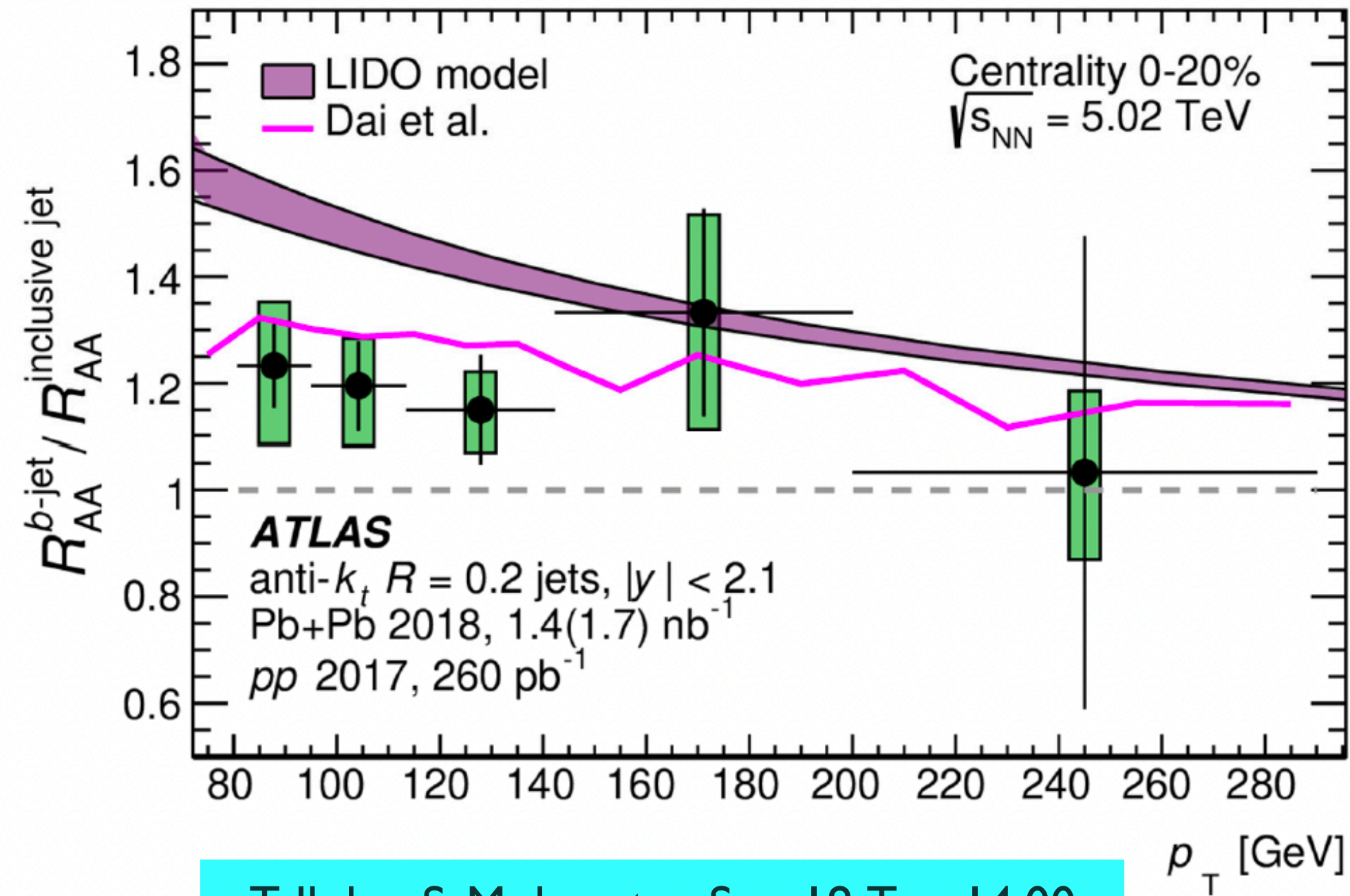
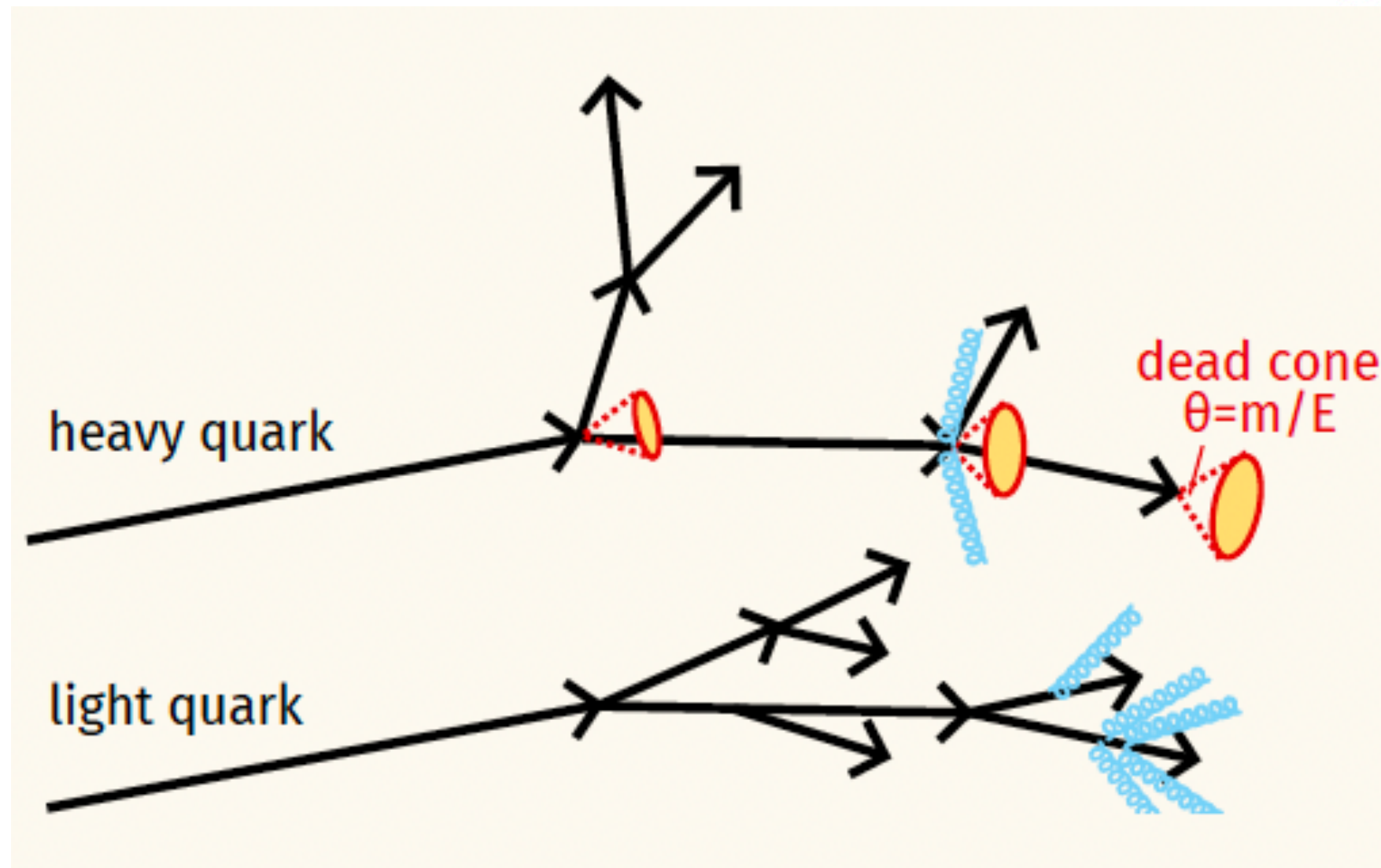
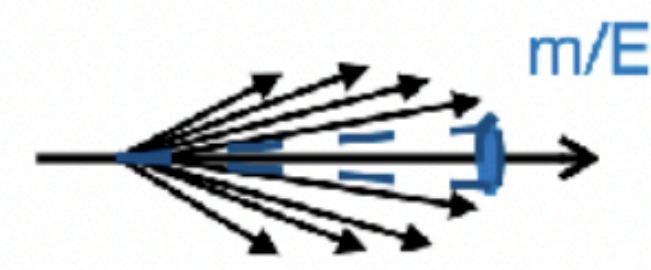
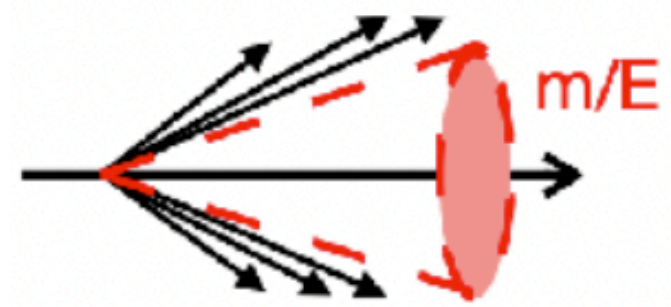


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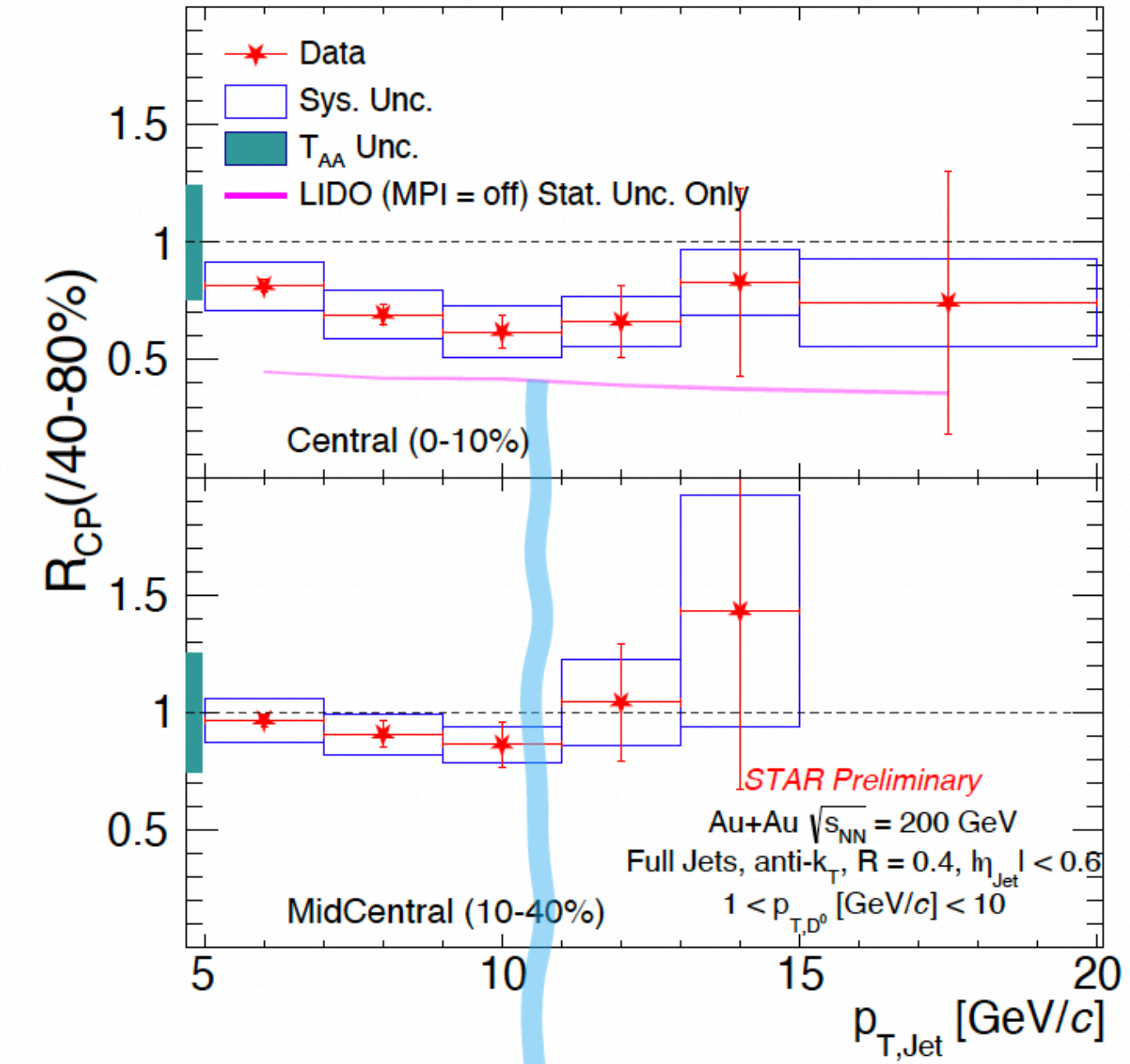
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Talk by S. Mohapatra, Sec. 18, Tue, 14:00



Talk by D. Roy, Sec. 29, Wed, 11:50

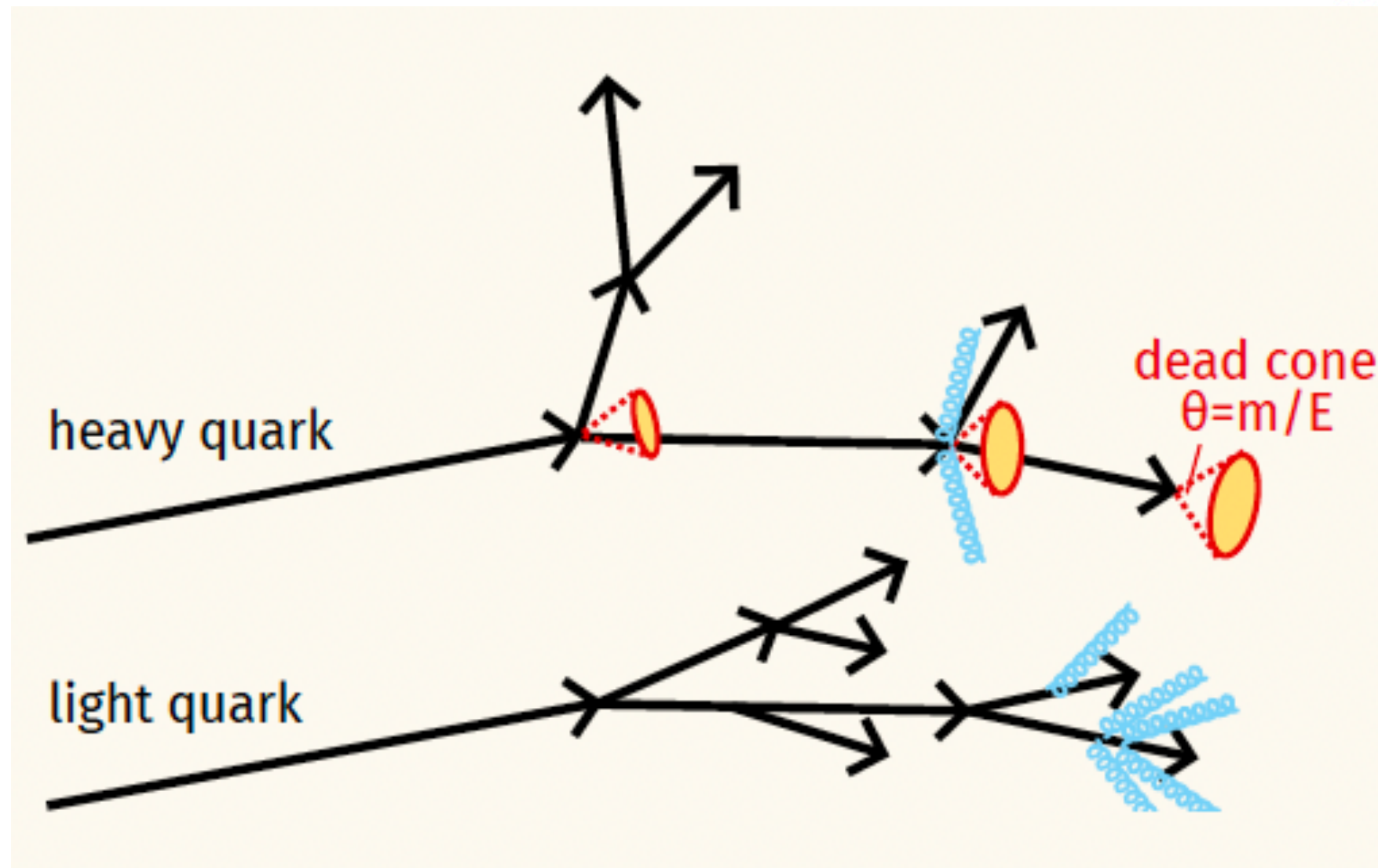
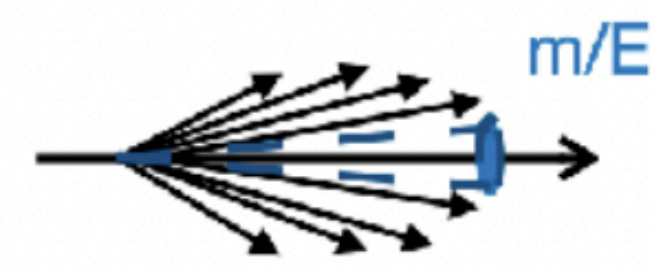
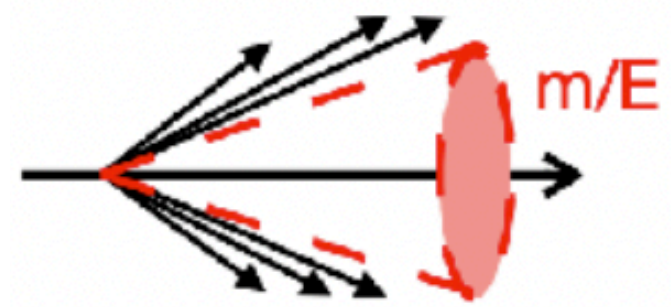
- Less suppression of b-jets than inclusive jets in most central collisions

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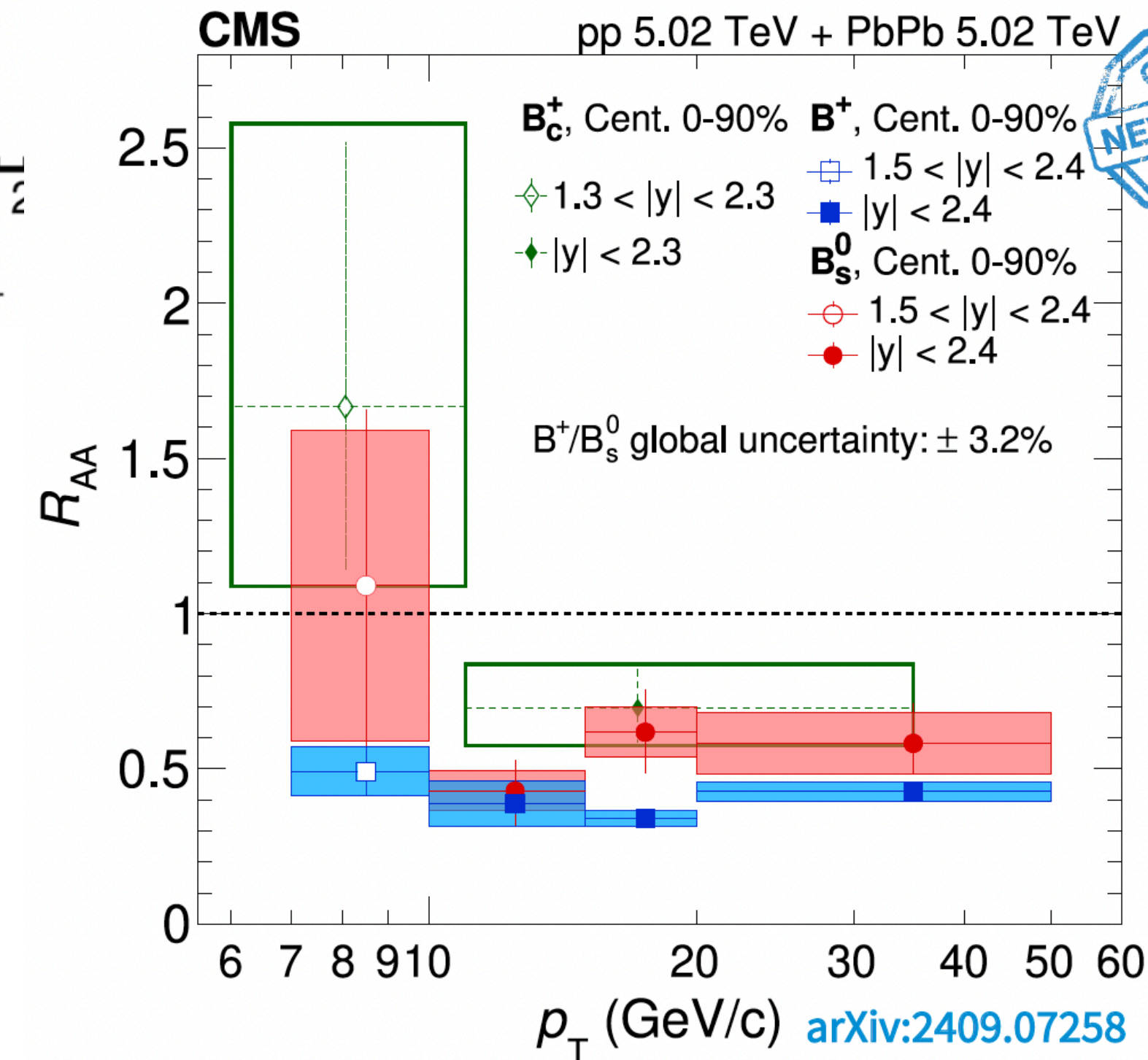
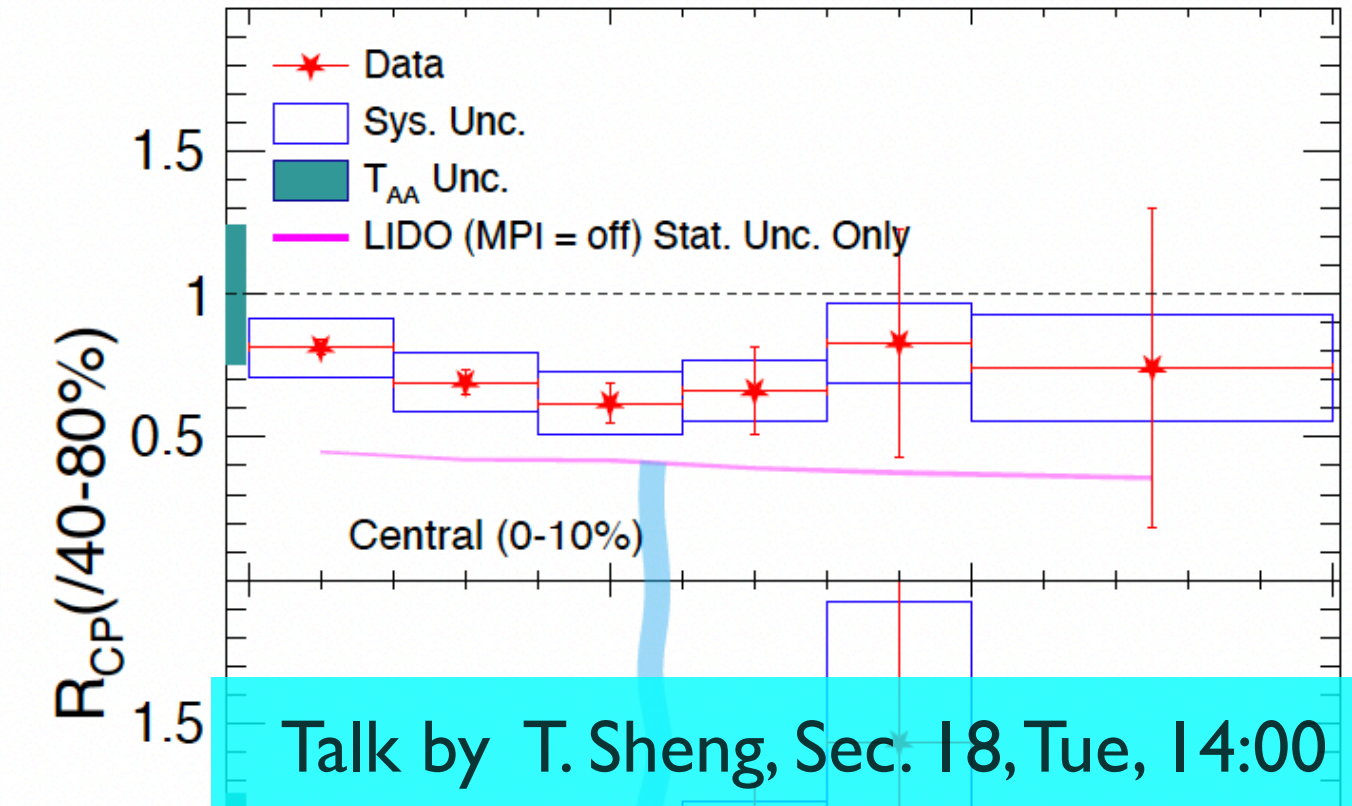
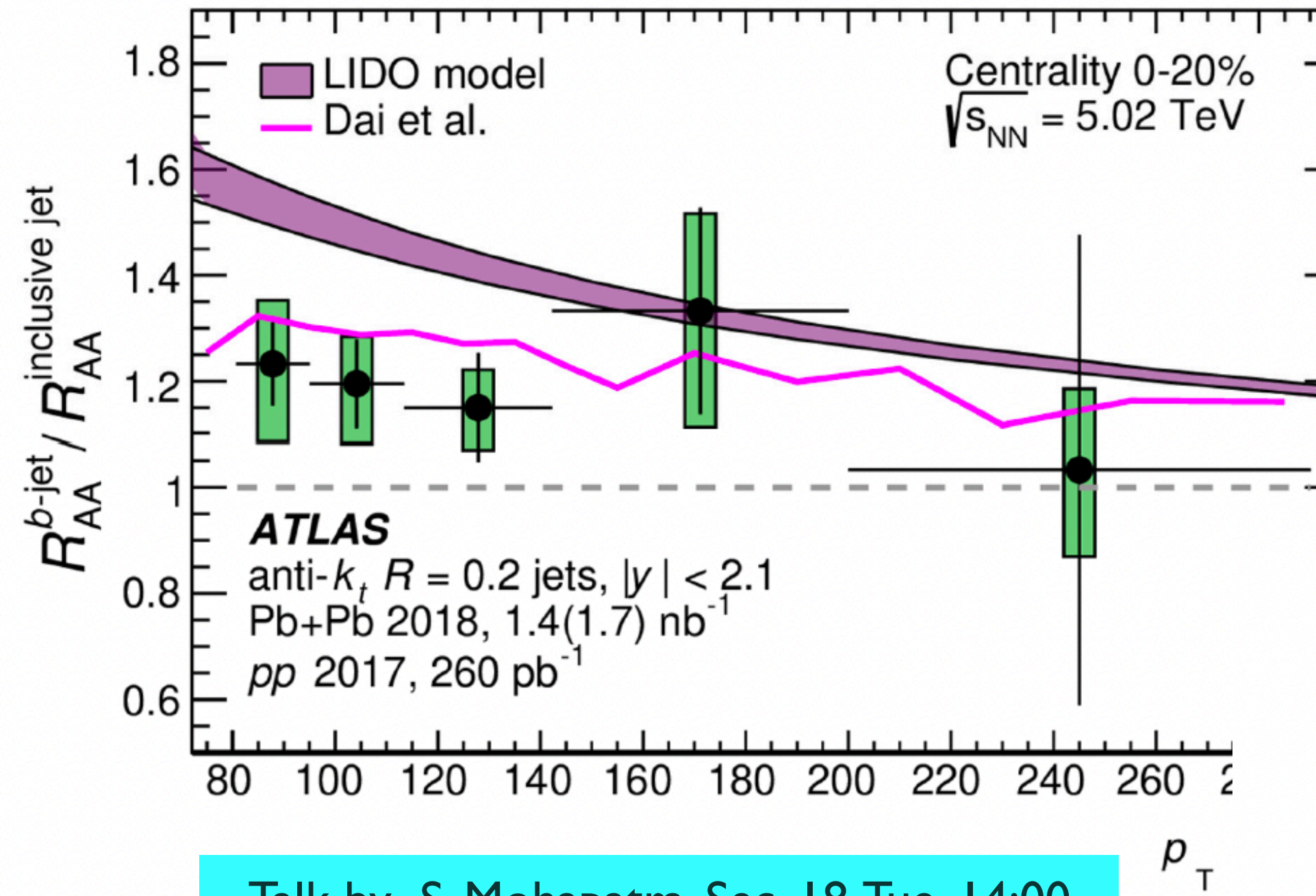
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Large parton mass

Small parton mass



- Less suppression of b-jets than inclusive jets in most central collisions
- Indication of mass ordering from HF hadrons at high  $p_T$

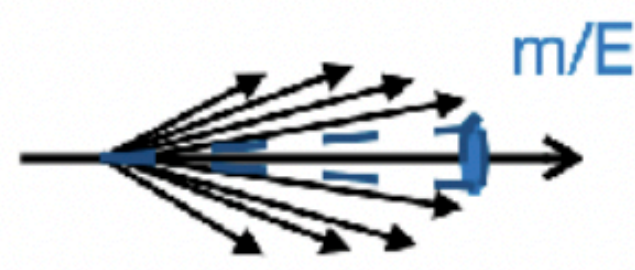
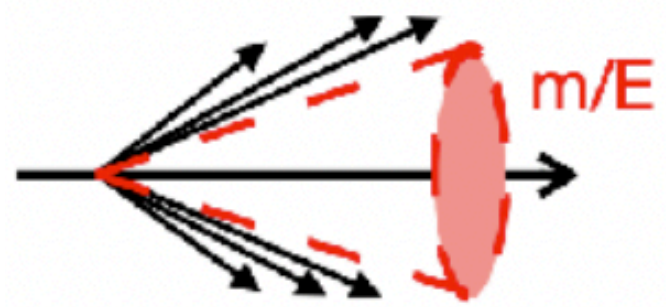


# Search for dead-cone effects in pp

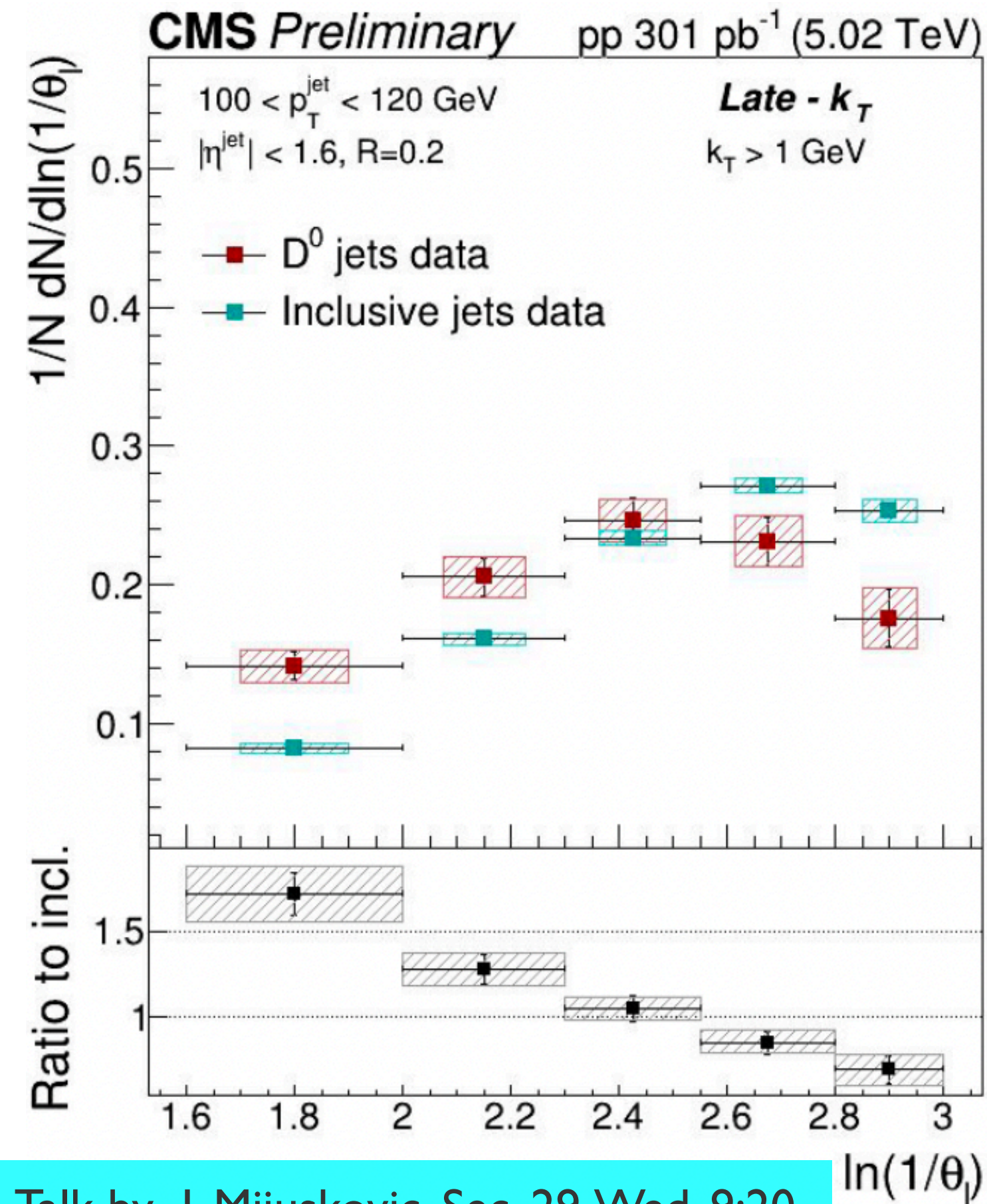
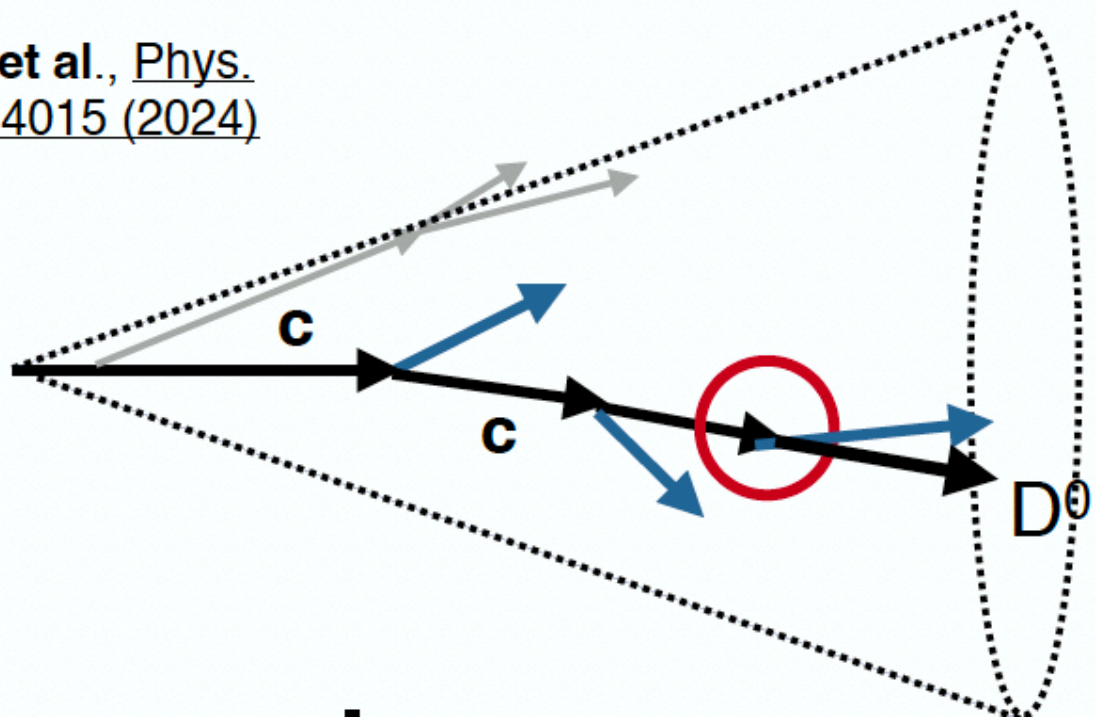
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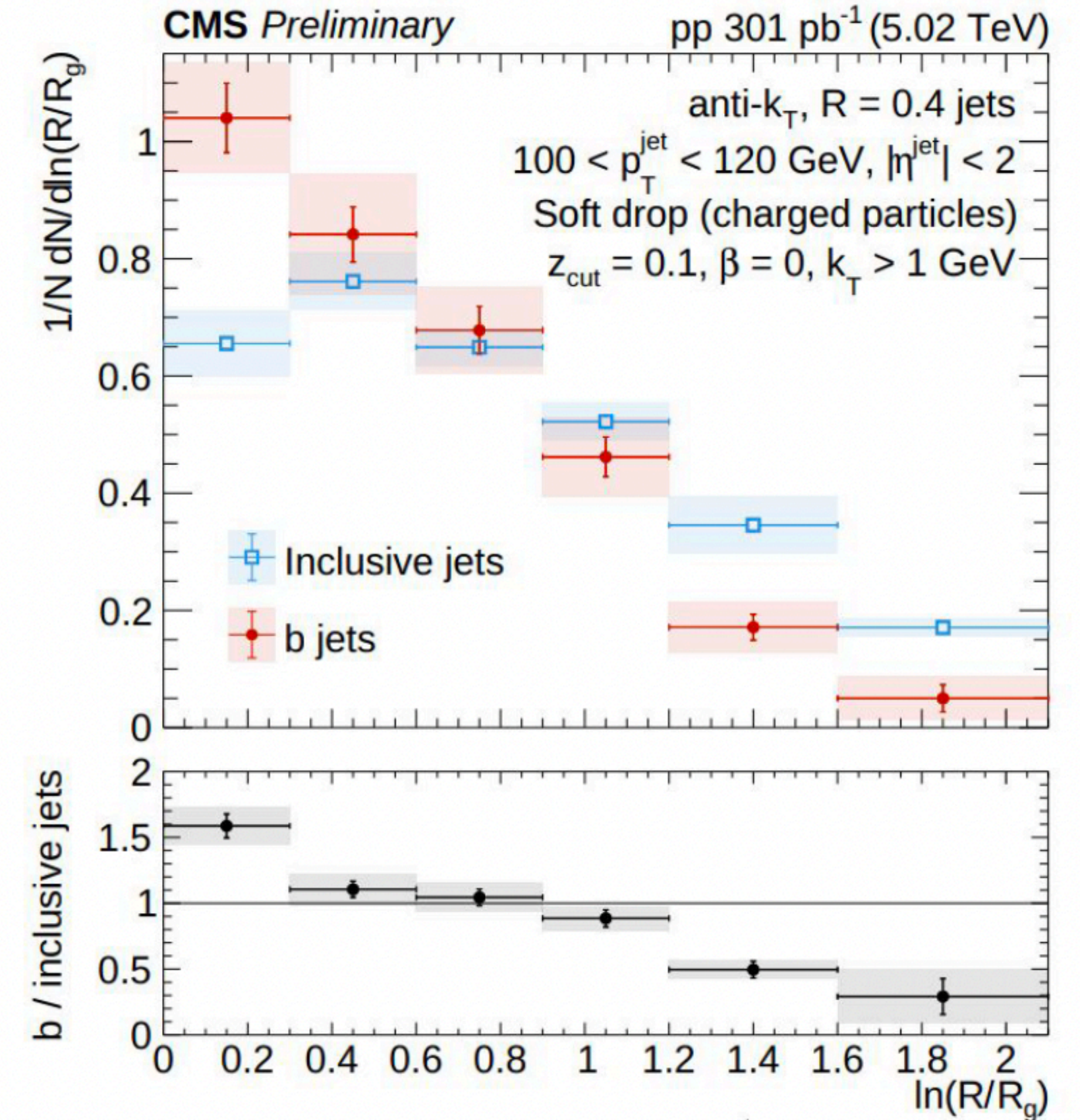
Small parton mass



L. Cunqueiro et al., Phys. Rev. D 110, 014015 (2024)



Talk by J. Mijuskovic, Sec. 29, Wed, 9:20



Talk by L. Kalipoliti, Sec. 29, Wed, 9:40

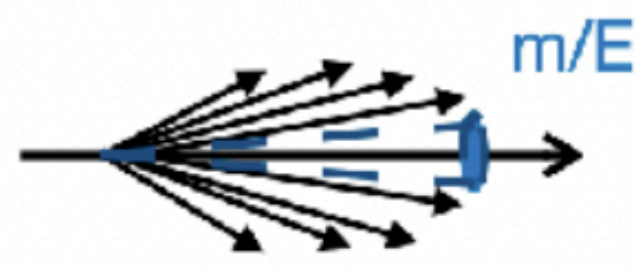
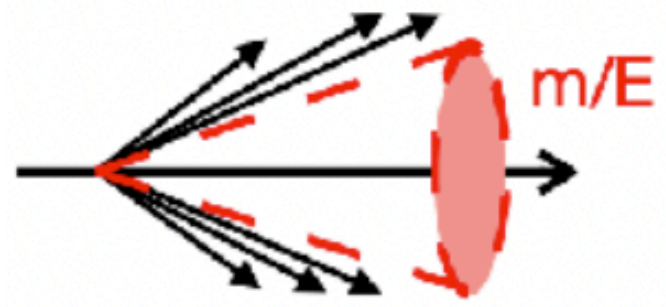
- Studying the hard collinear emissions by using CA declustering and late-k<sub>T</sub> grooming algorithm for k<sub>T</sub> > 1

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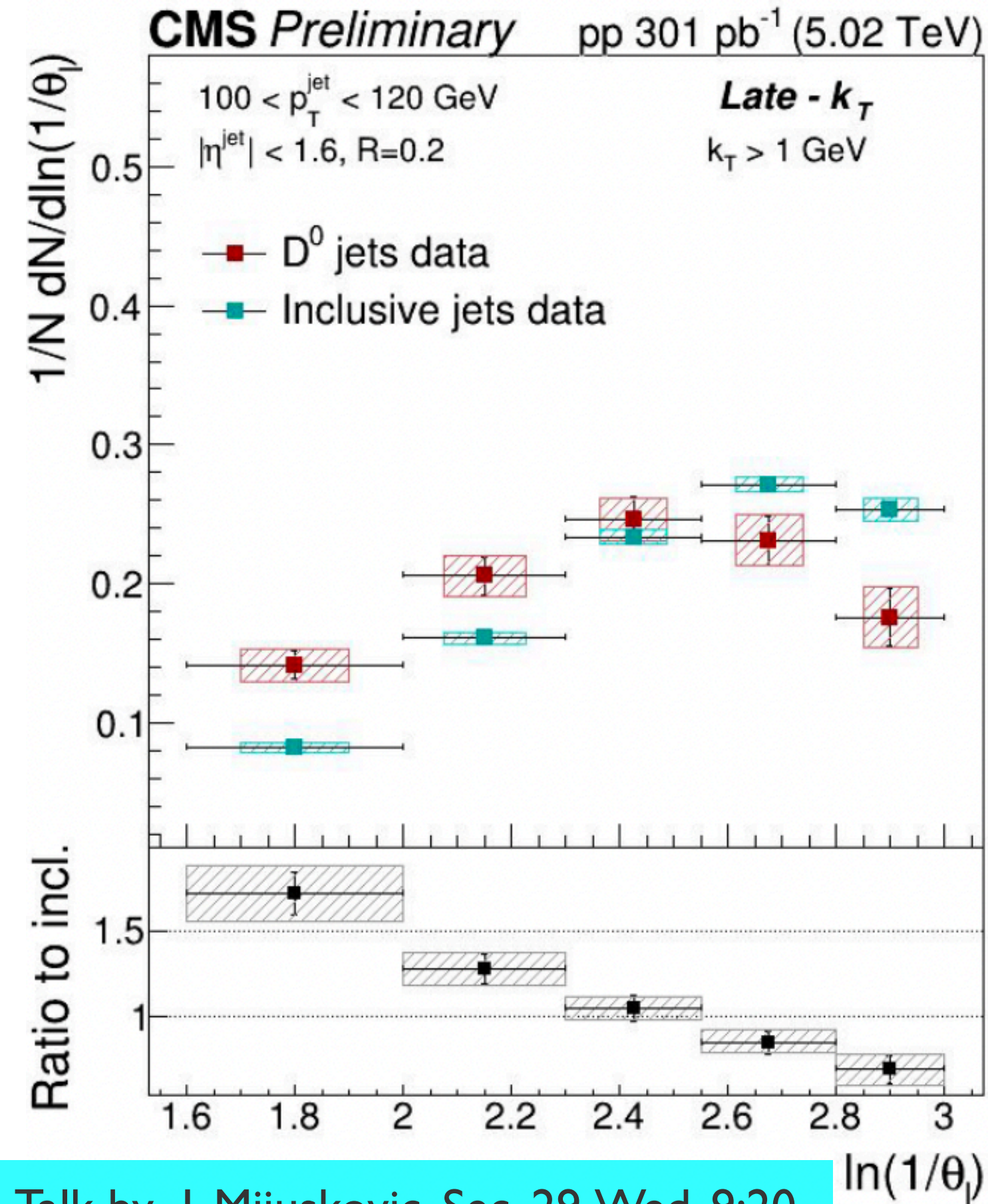
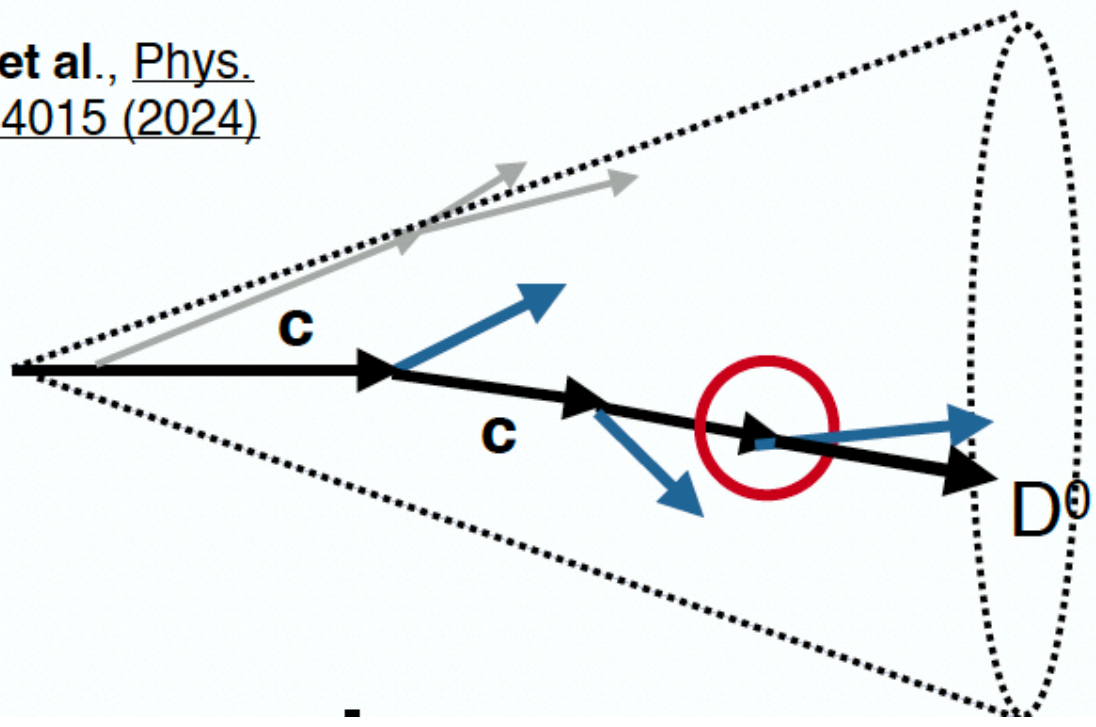
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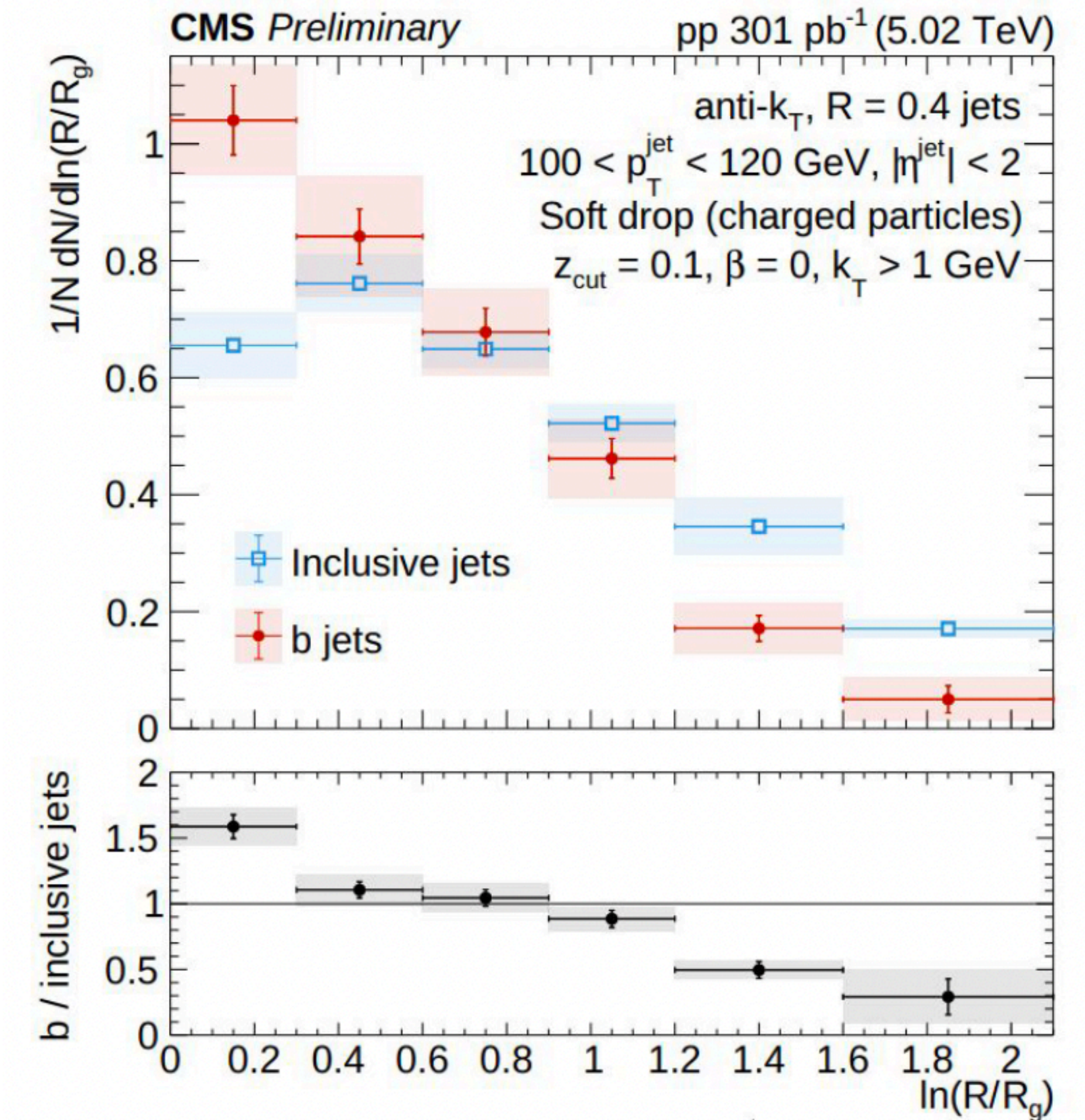
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L. Cunqueiro et al., Phys. Rev. D 110, 014015 (2024)



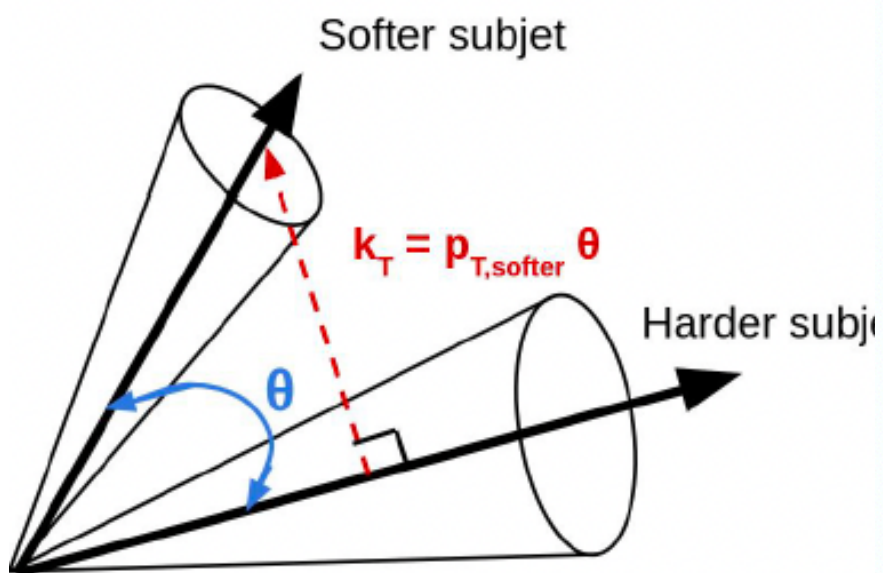
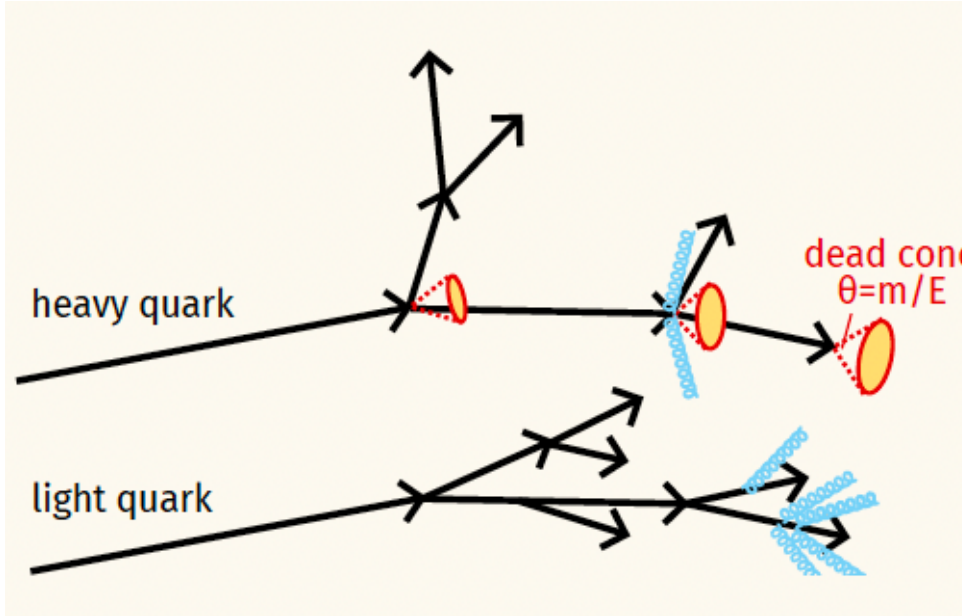
Talk by J. Mijuskovic, Sec. 29, Wed, 9:20



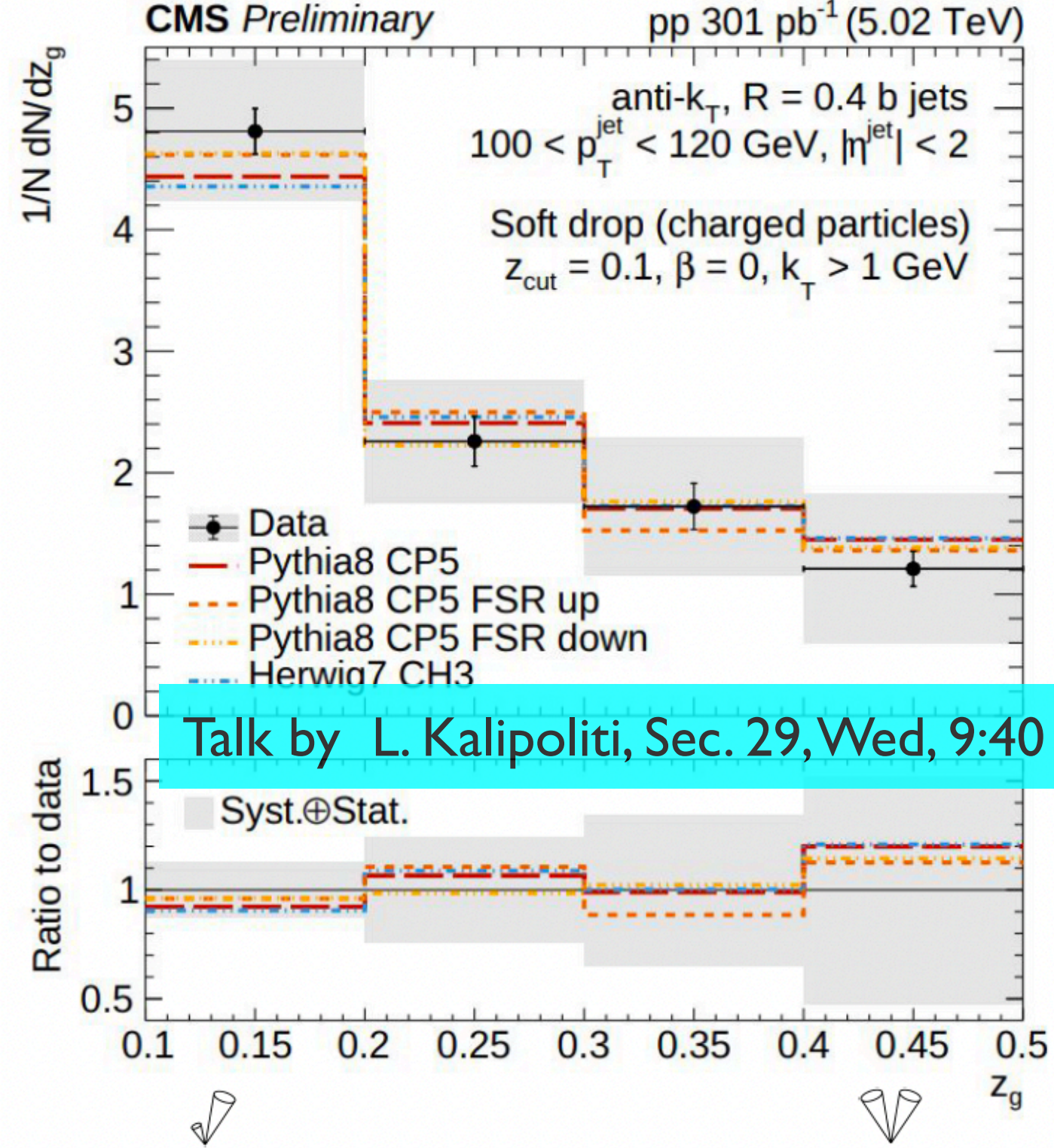
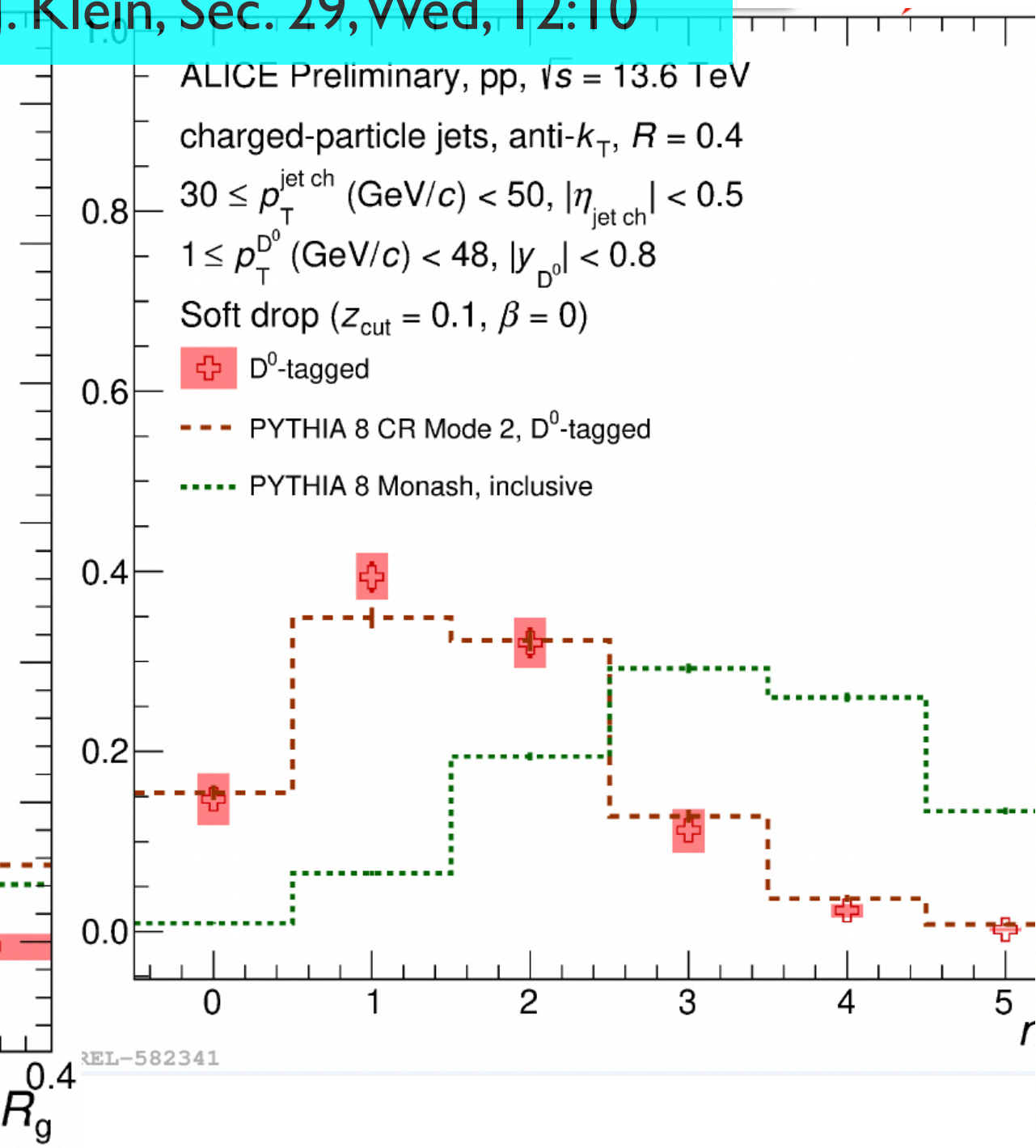
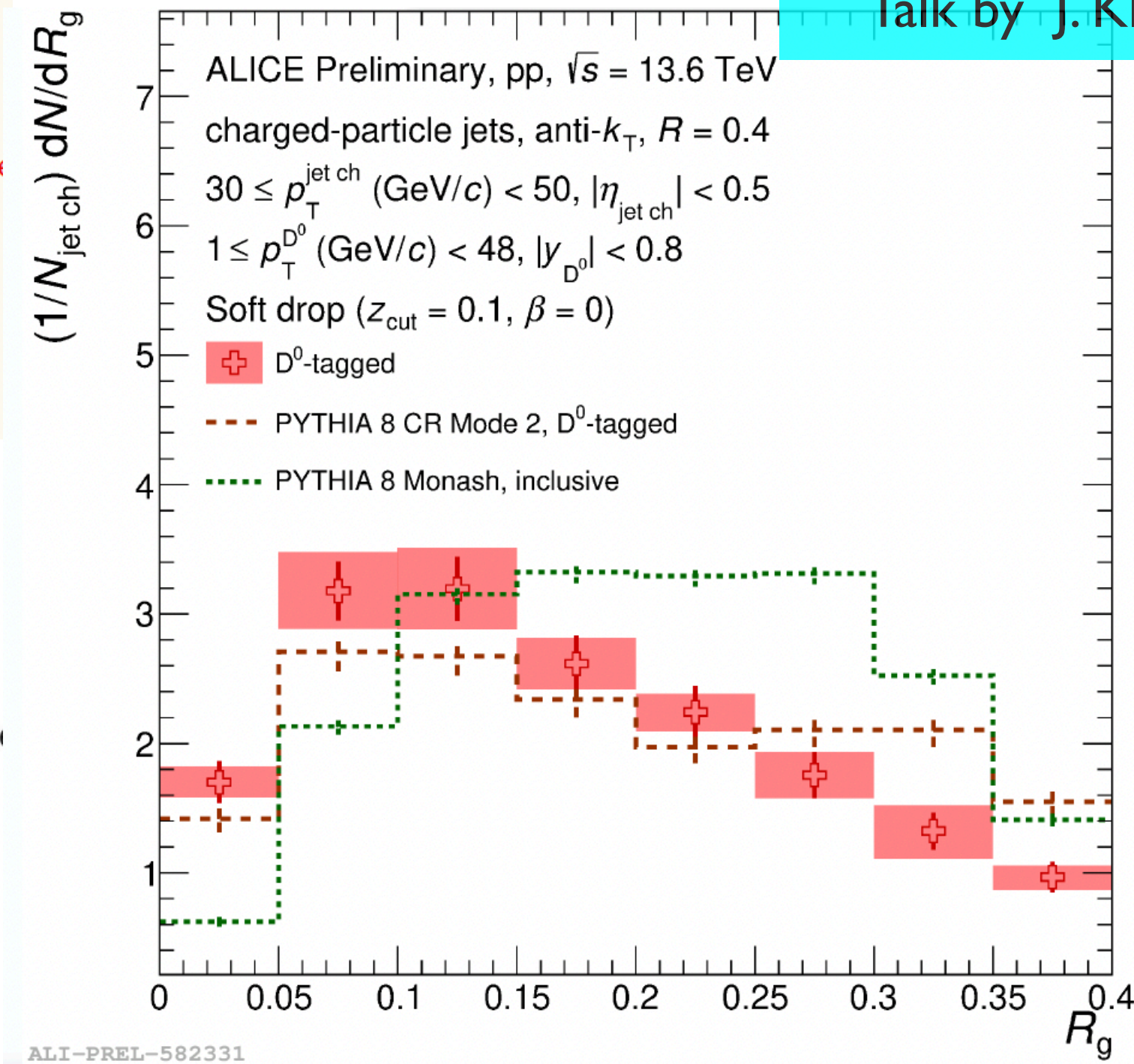
Talk by L. Kalipoliti, Sec. 29, Wed, 9:40

- Studying the hard collinear emissions by using CA declustering and late-k<sub>T</sub> grooming algorithm for k<sub>T</sub> > 1
- A reduction of the collinear radiation for D/B-tagged jets with respect to inclusive one → dead cone effect

# Mass/Flavor dependent jet substructure

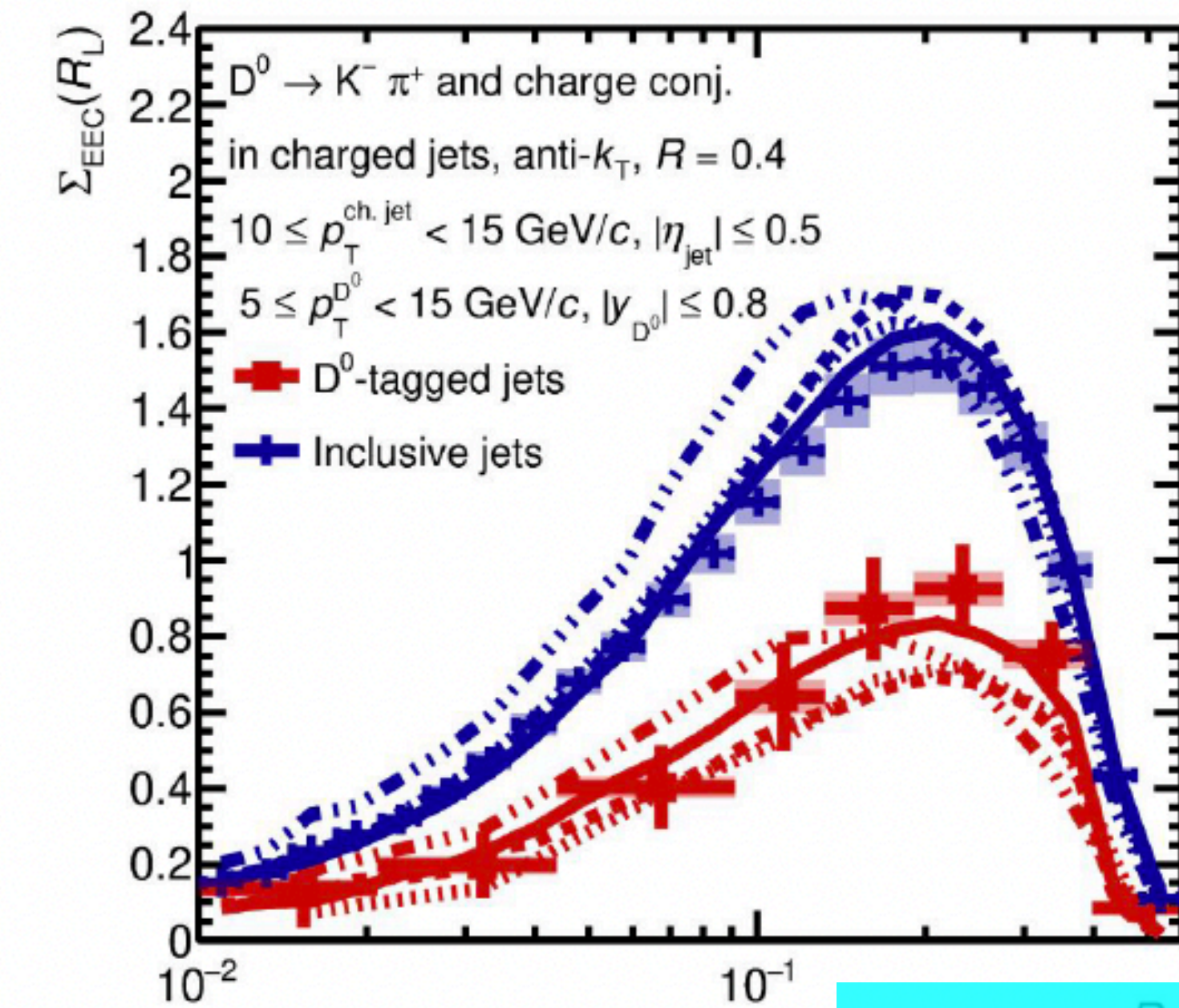


Talk by J. Klein, Sec. 29, Wed, 12:10

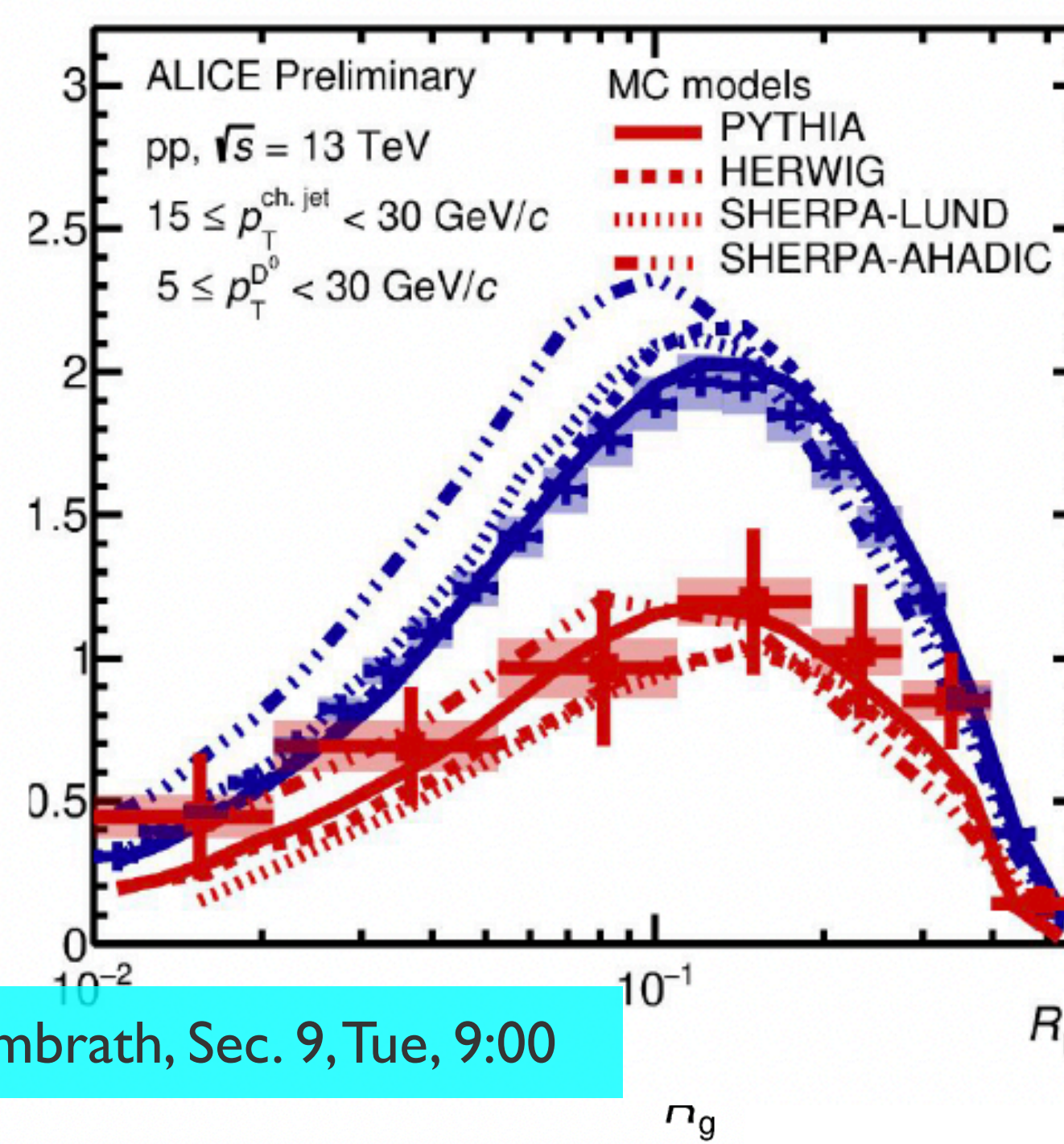


- More differential study on HF(c&b)-jet substructure, well reproduced by PYTHIA

# Mass/Flavor dependent jet substructure



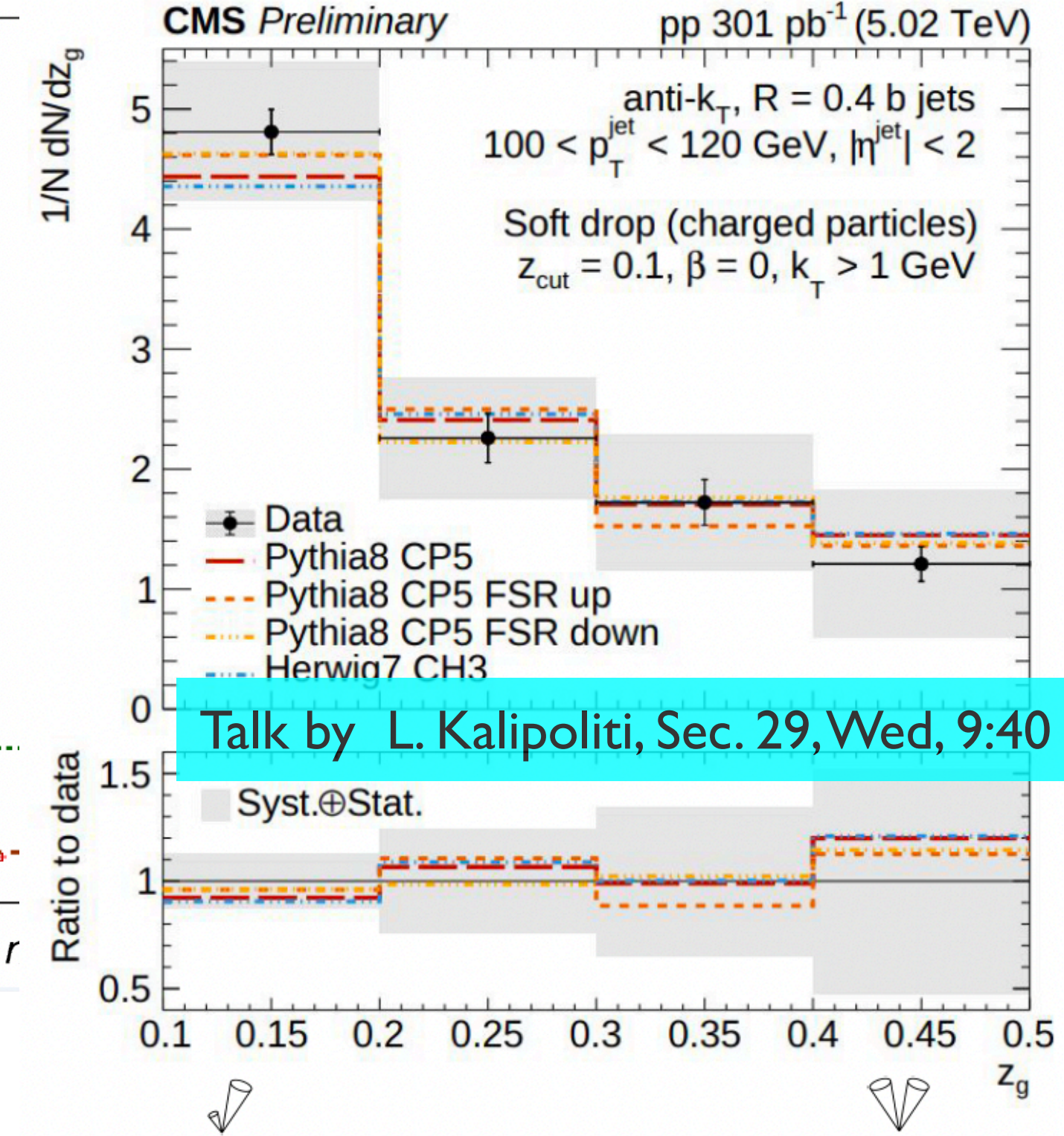
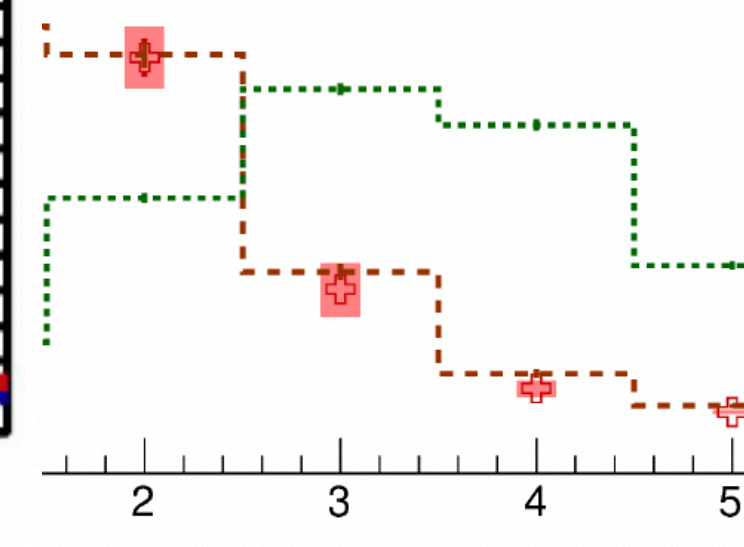
Talk by A. Nambrath, Sec. 9, Tue, 9:00



d, 12:10

y, pp, √s = 13.6 TeV  
 jets, anti-k<sub>T</sub>, R = 0.4  
 <math>|y| < 50, |\eta\_{jet\ ch}| < 0.5</math>  
 48, <math>|y\_{D^0}| < 0.8</math>  
 <math>|\eta| < 1, \beta = 0</math>

mode 2, D<sup>0</sup>-tagged  
 sh, inclusive

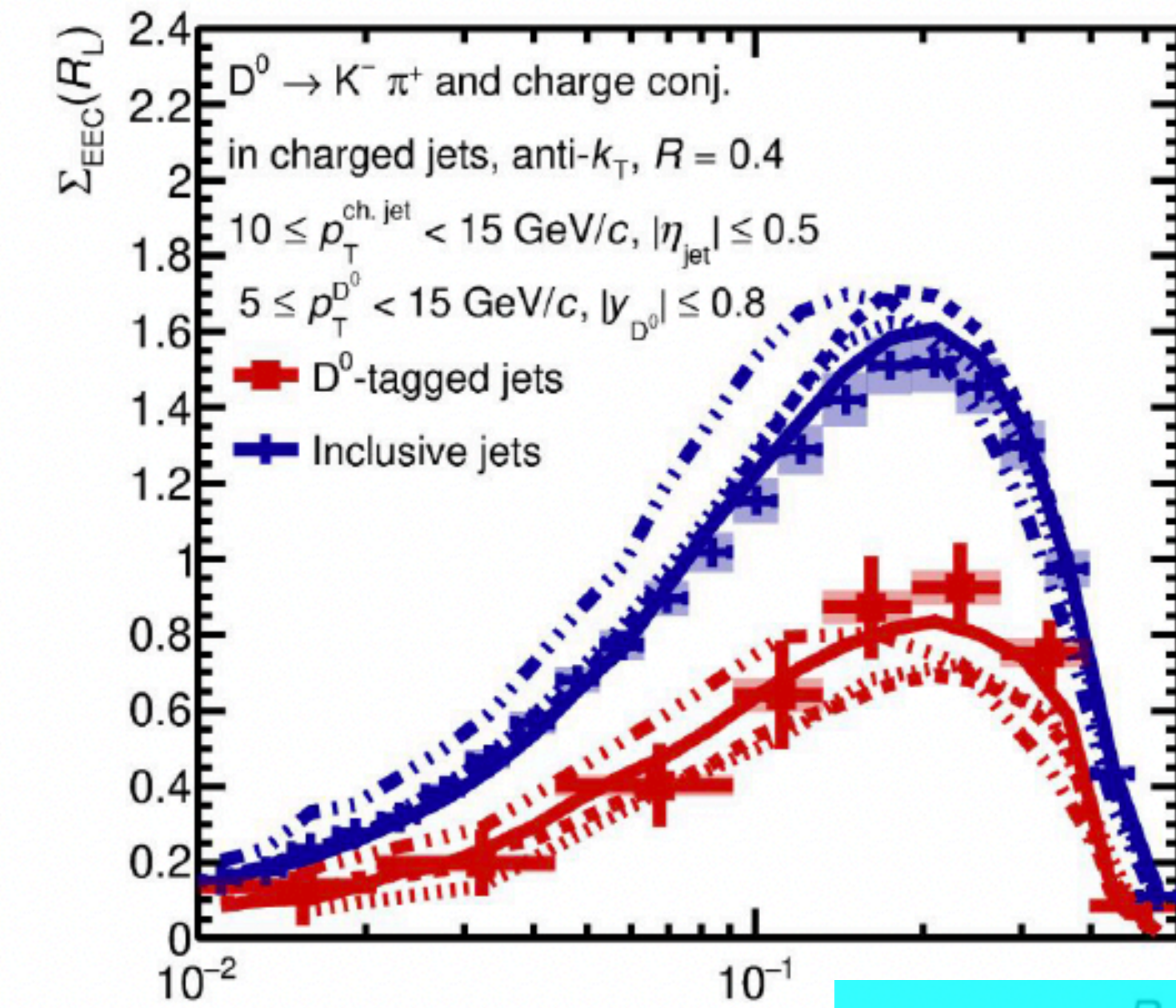


Talk by L. Kalipoliti, Sec. 29, Wed, 9:40

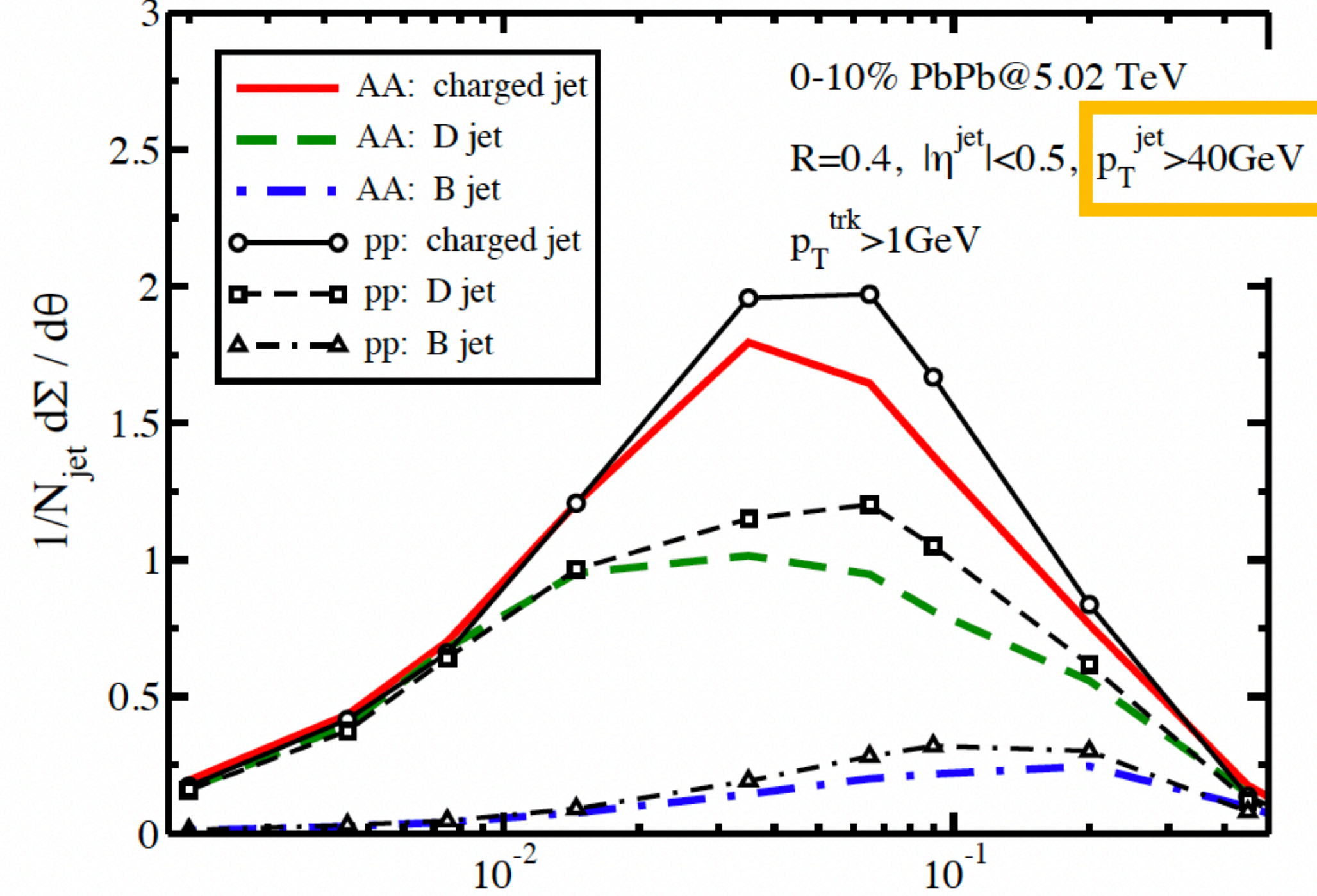
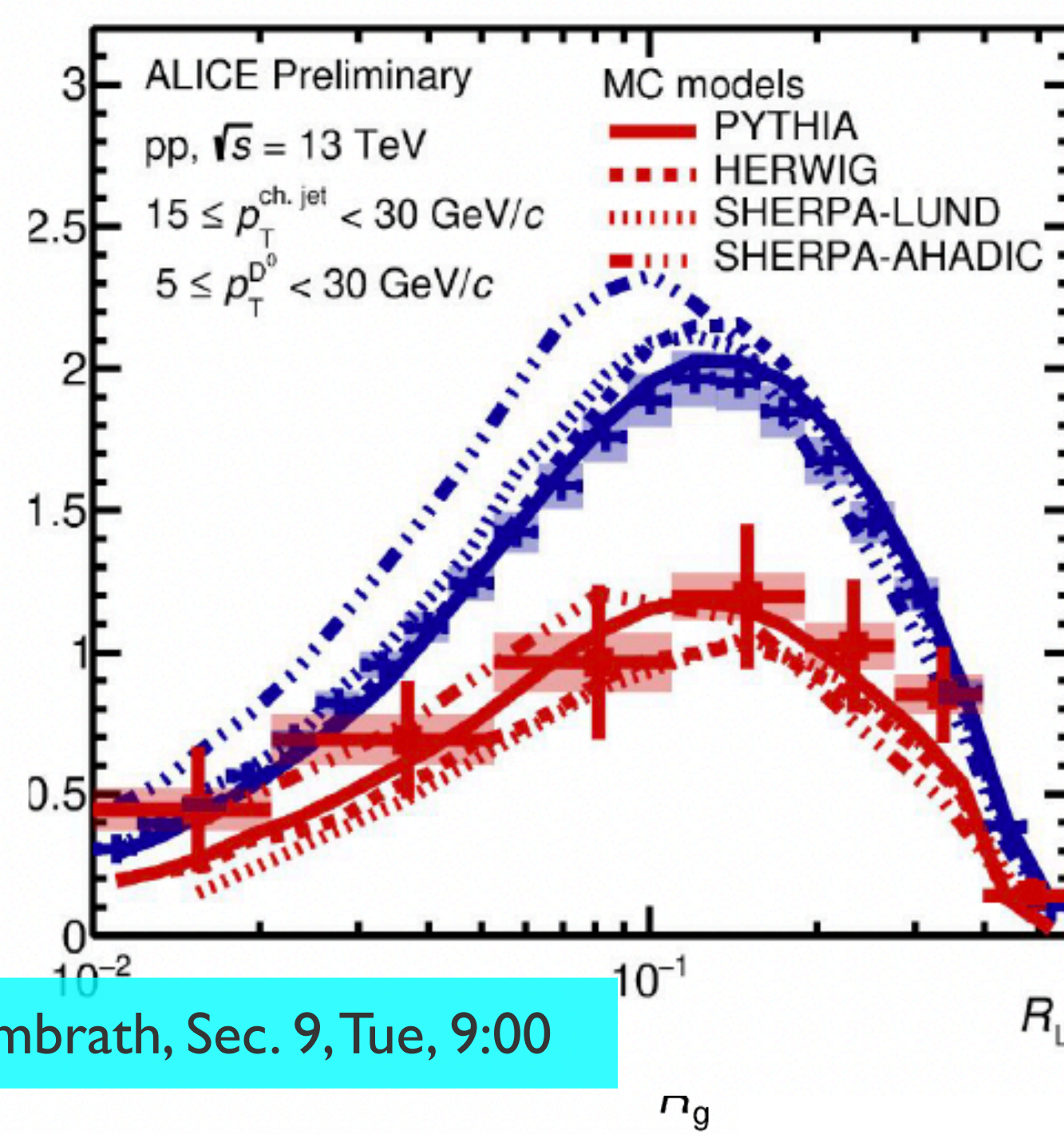
- More differential study on HF(c&b)-jet substructure, well reproduced by PYTHIA
- Clear flavor(mass) hierarchy observed in jet EEC measurements



# Mass/Flavor dependent jet substructure



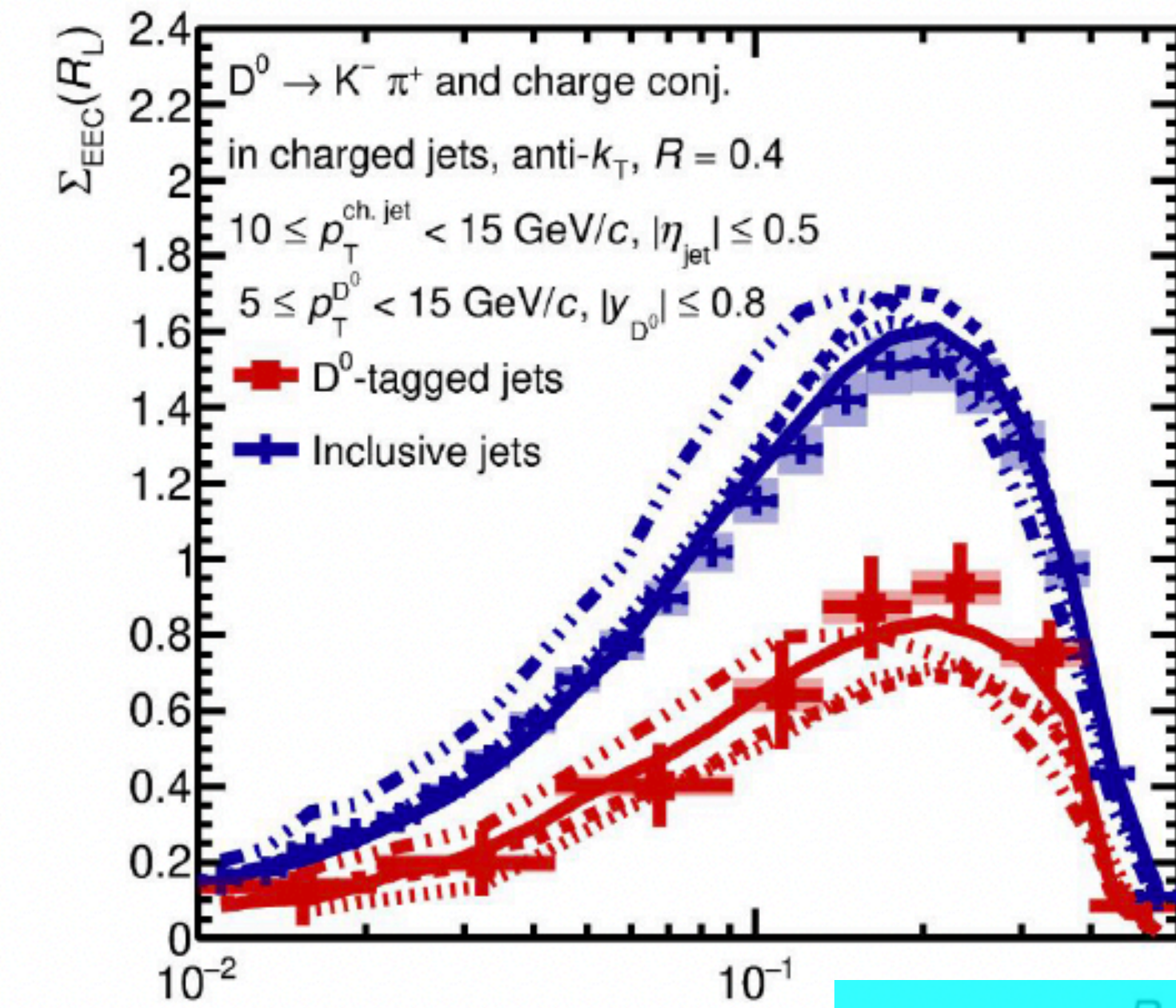
Talk by A. Nambrath, Sec. 9, Tue, 9:00



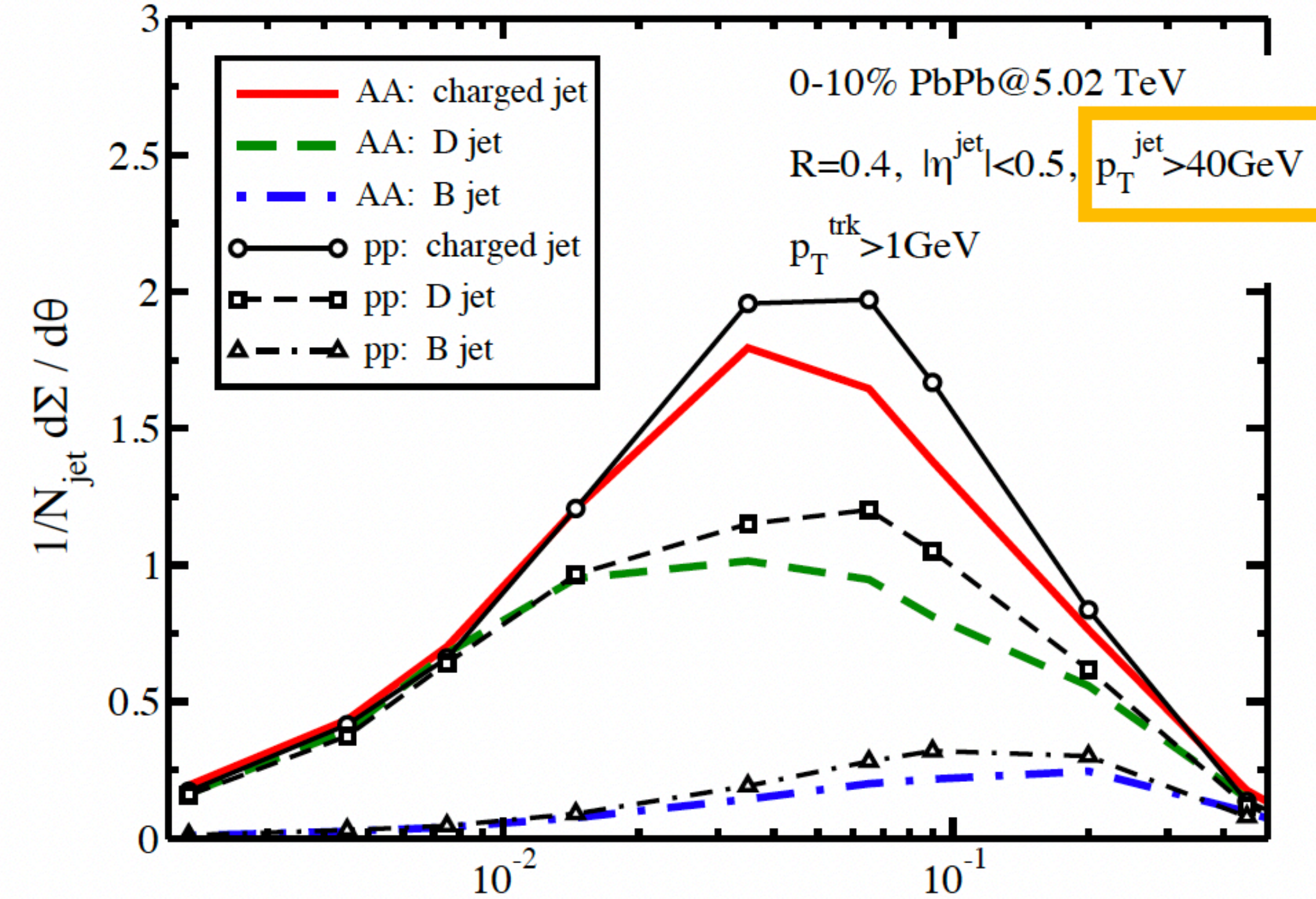
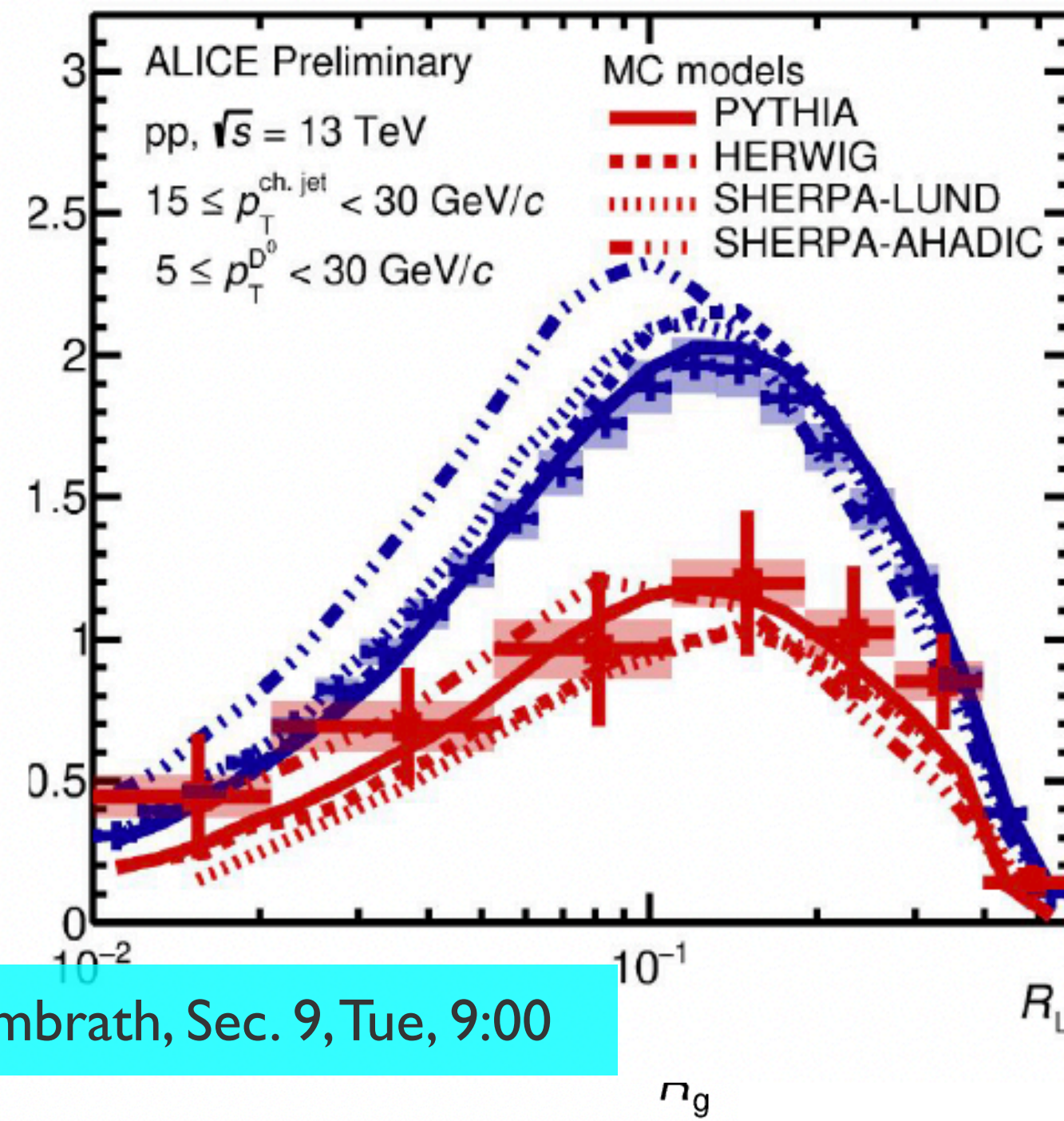
Talk by W. Xing, Sec. 22, Tue, 16:15

- More differential study on HF(c&b)-jet substructure, well reproduced by PYTHIA
- Clear flavor(mass) hierarchy observed in jet EEC measurements
- Theory already predicted the modifications in HI case → **experimental measurements ongoing**

# Mass/Flavor dependent jet substructure



Talk by A. Nambrath, Sec. 9, Tue, 9:00

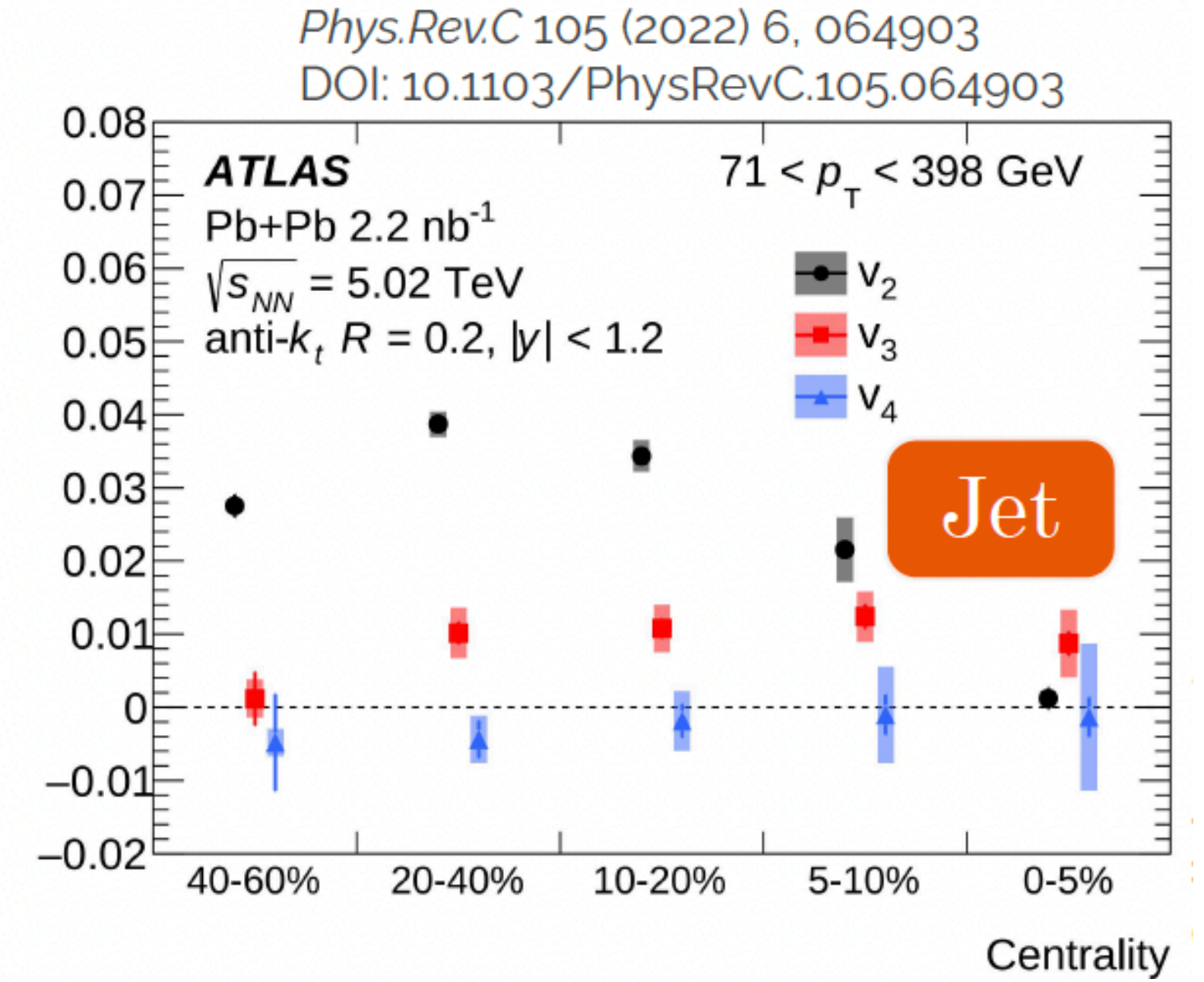
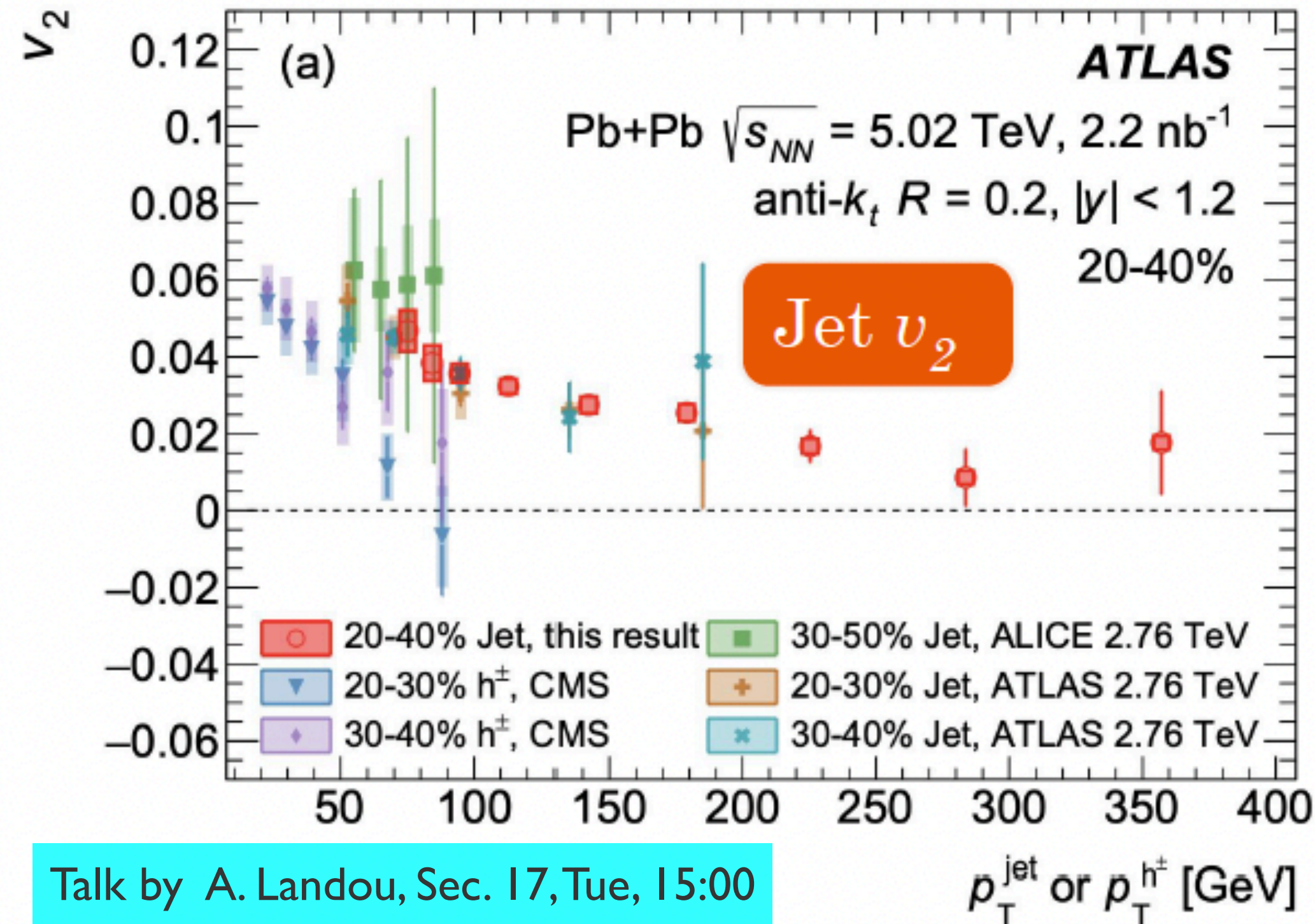
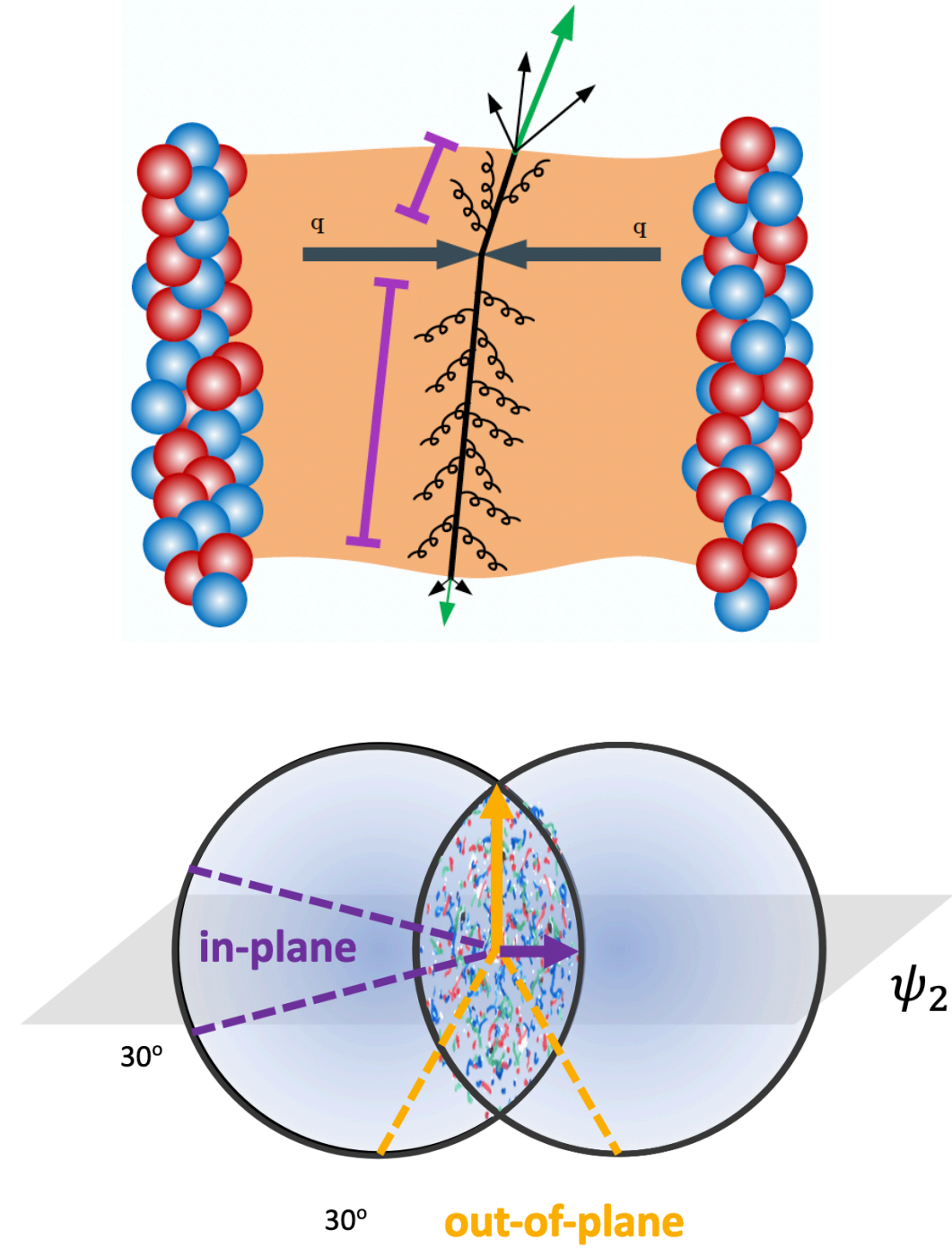


Talk by W. Xing, Sec. 22, Tue, 16:15

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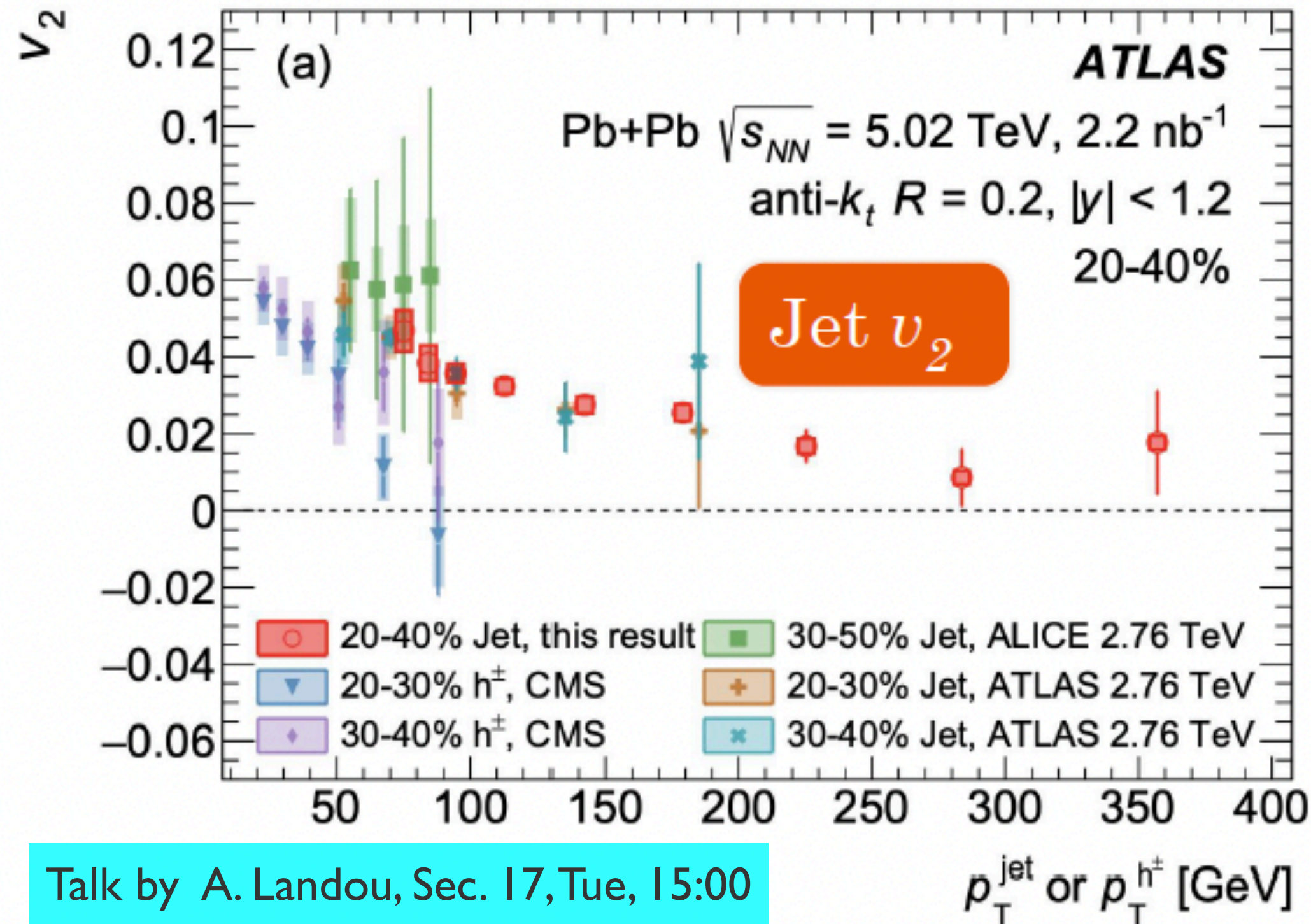
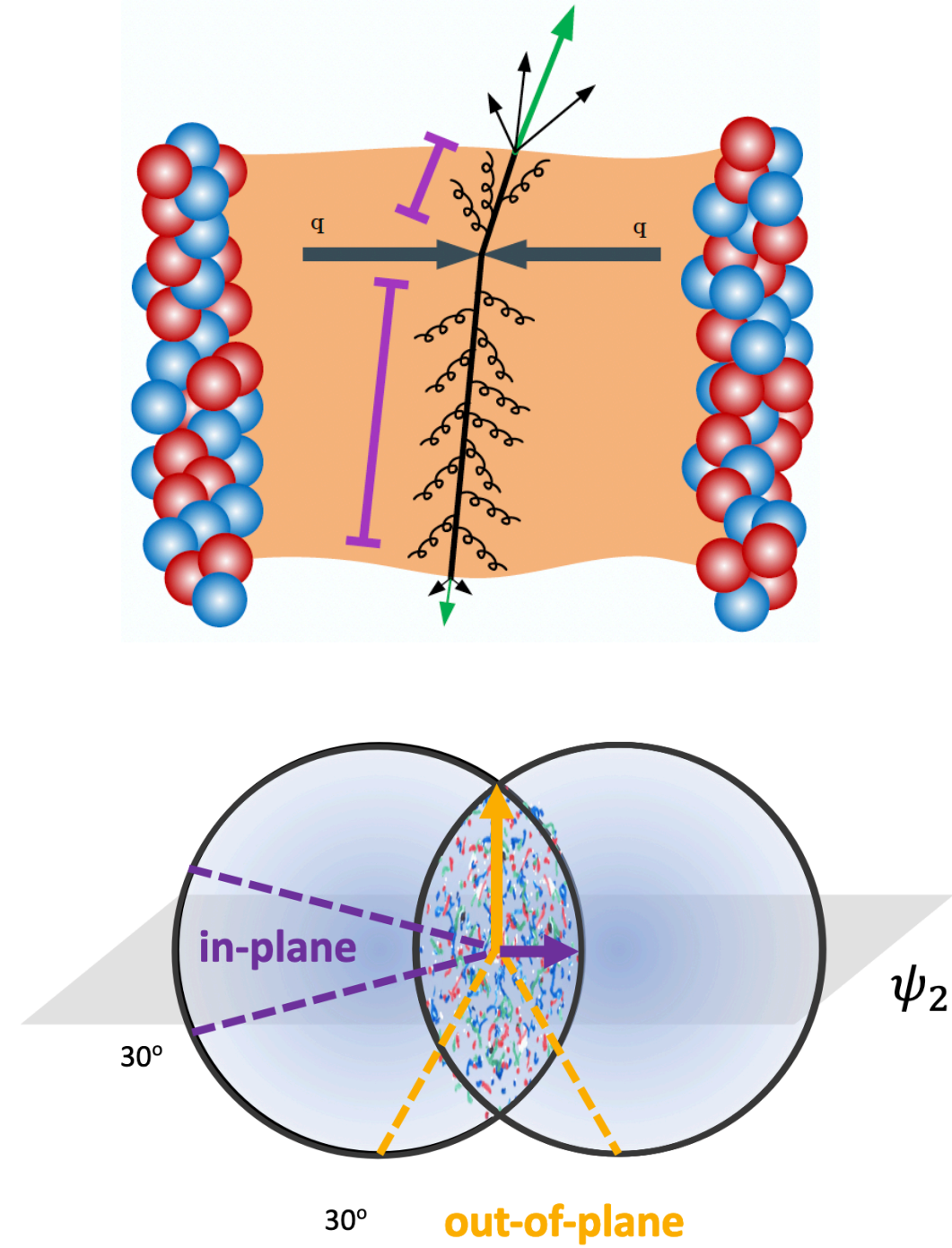
→ Next talk by R. K. Elayavali

# Path length dependence of jet energy loss

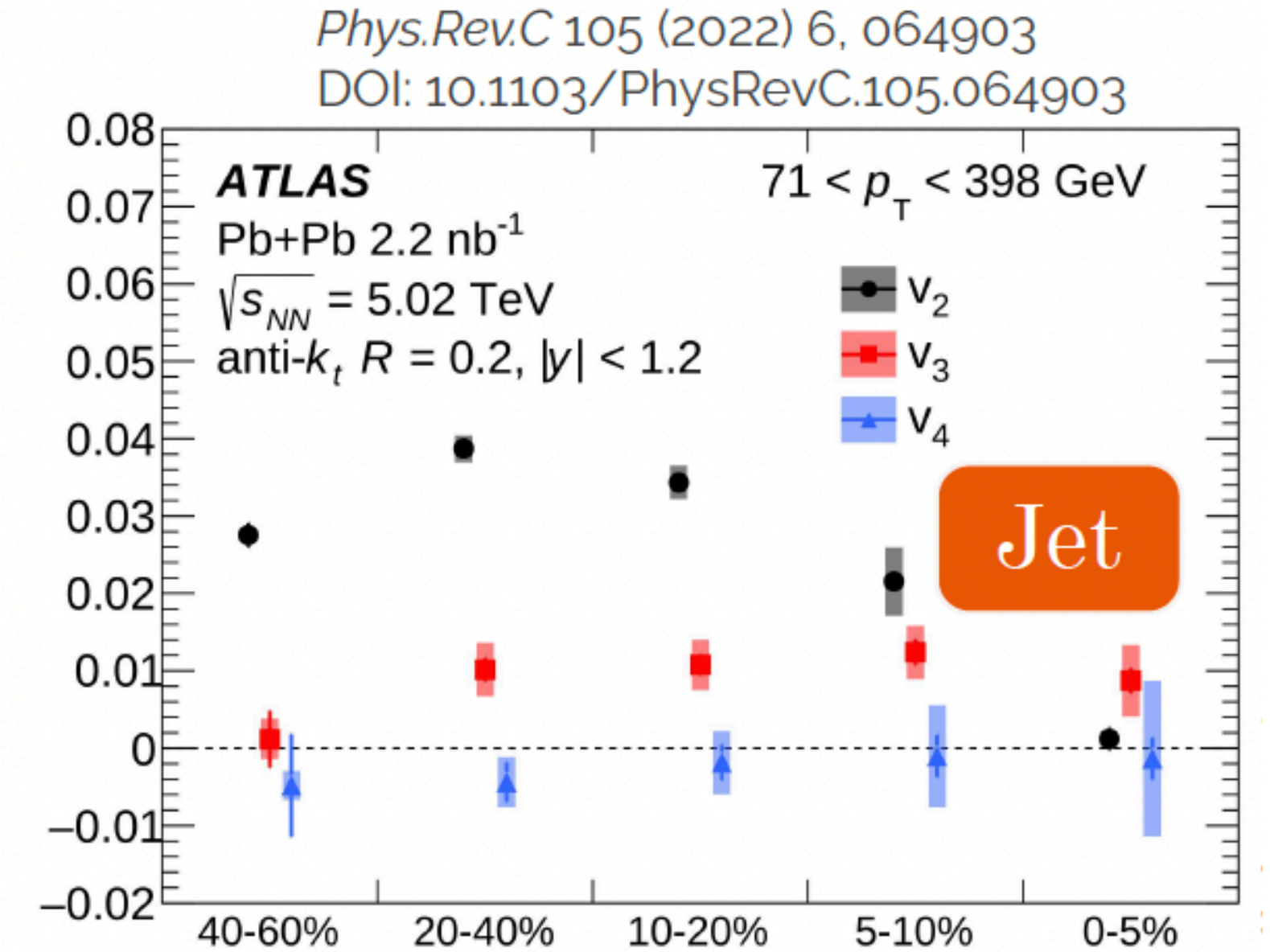


- In Pb+Pb collisions, jets have no-zero flow over a very large  $p_T$  range  $\rightarrow$  path length depends of energy loss

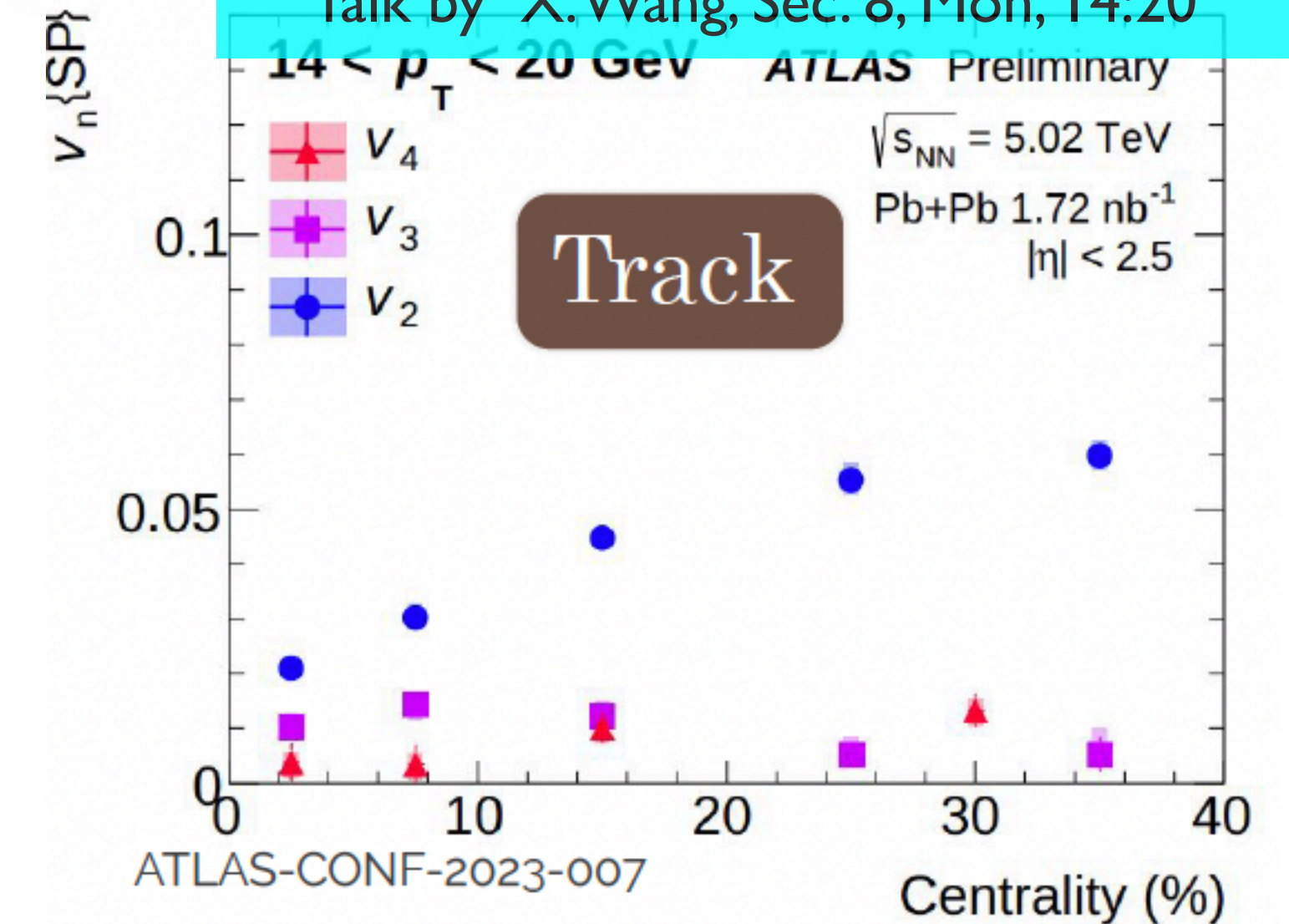
# Path length dependence of jet energy loss



Talk by A. Landou, Sec. 17, Tue, 15:00

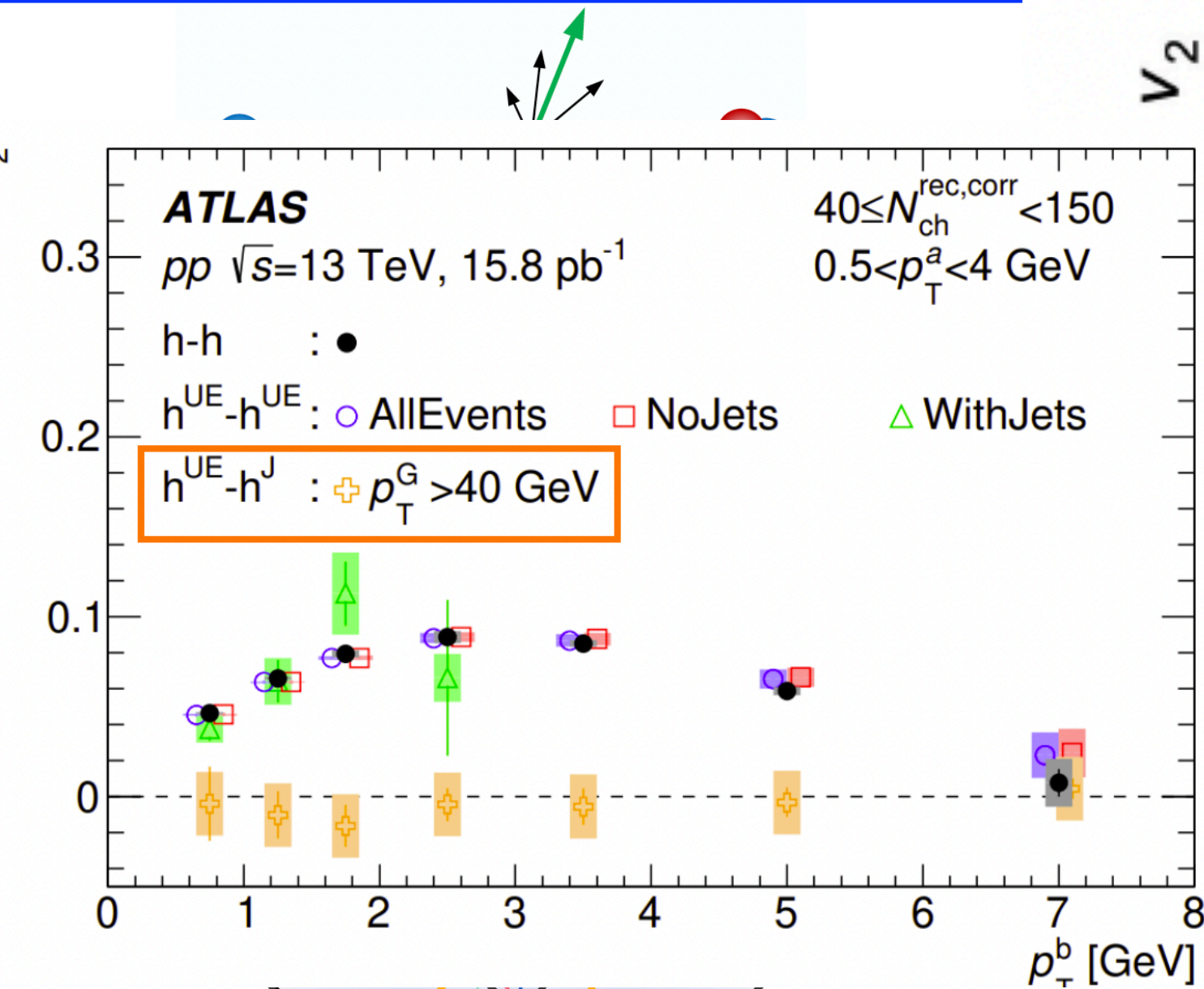


Talk by X. Wang, Sec. 8, Mon, 14:20



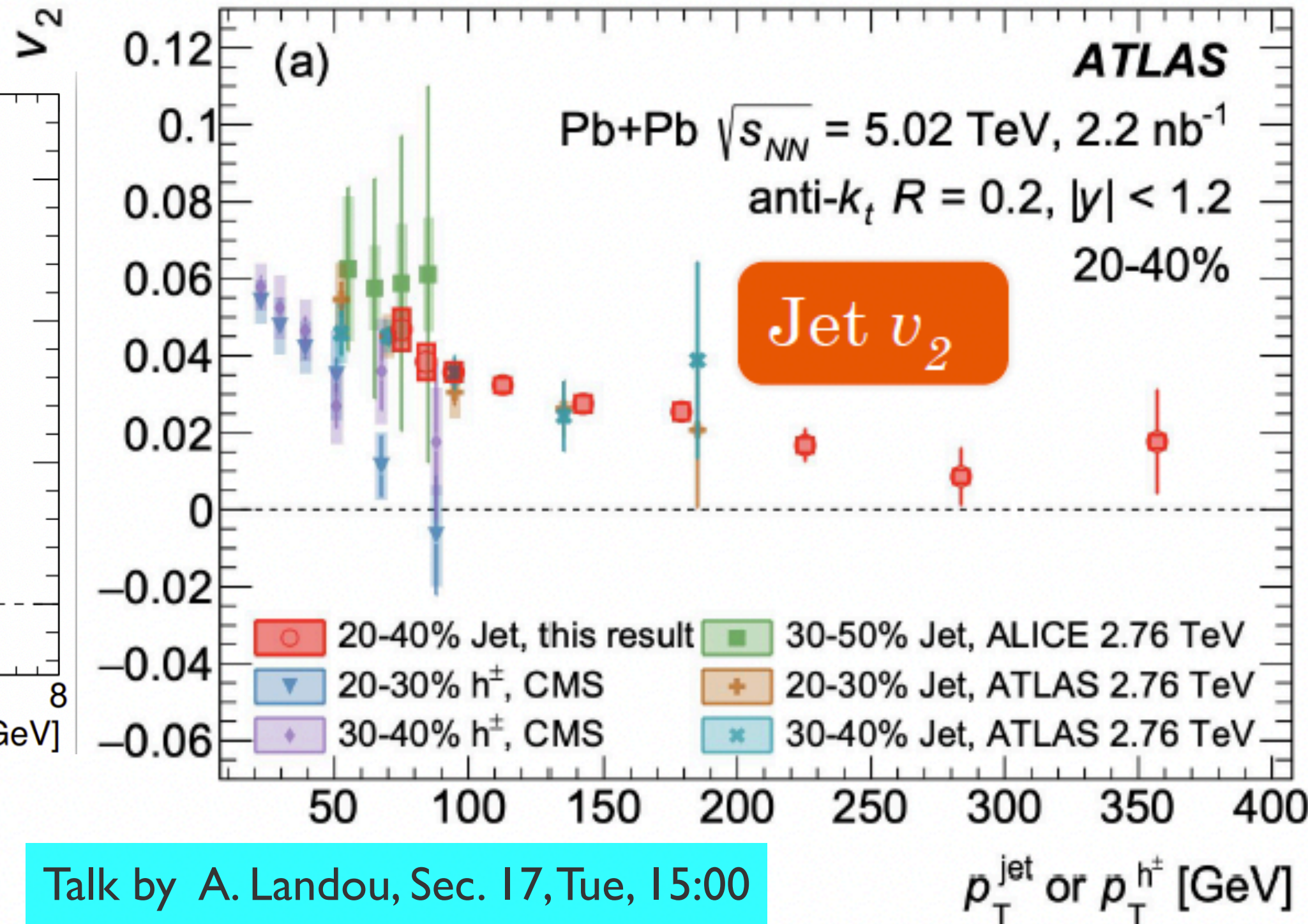
- In Pb+Pb collisions, jets have no-zero flow over a very large  $p_T$  range  $\rightarrow$  path length depends of energy loss
- Similar centrality dependence of  $v_n$  for very high  $p_T$  charged-particle and jets  $\rightarrow$  what could drive this?

# Path length dependence of jet energy loss

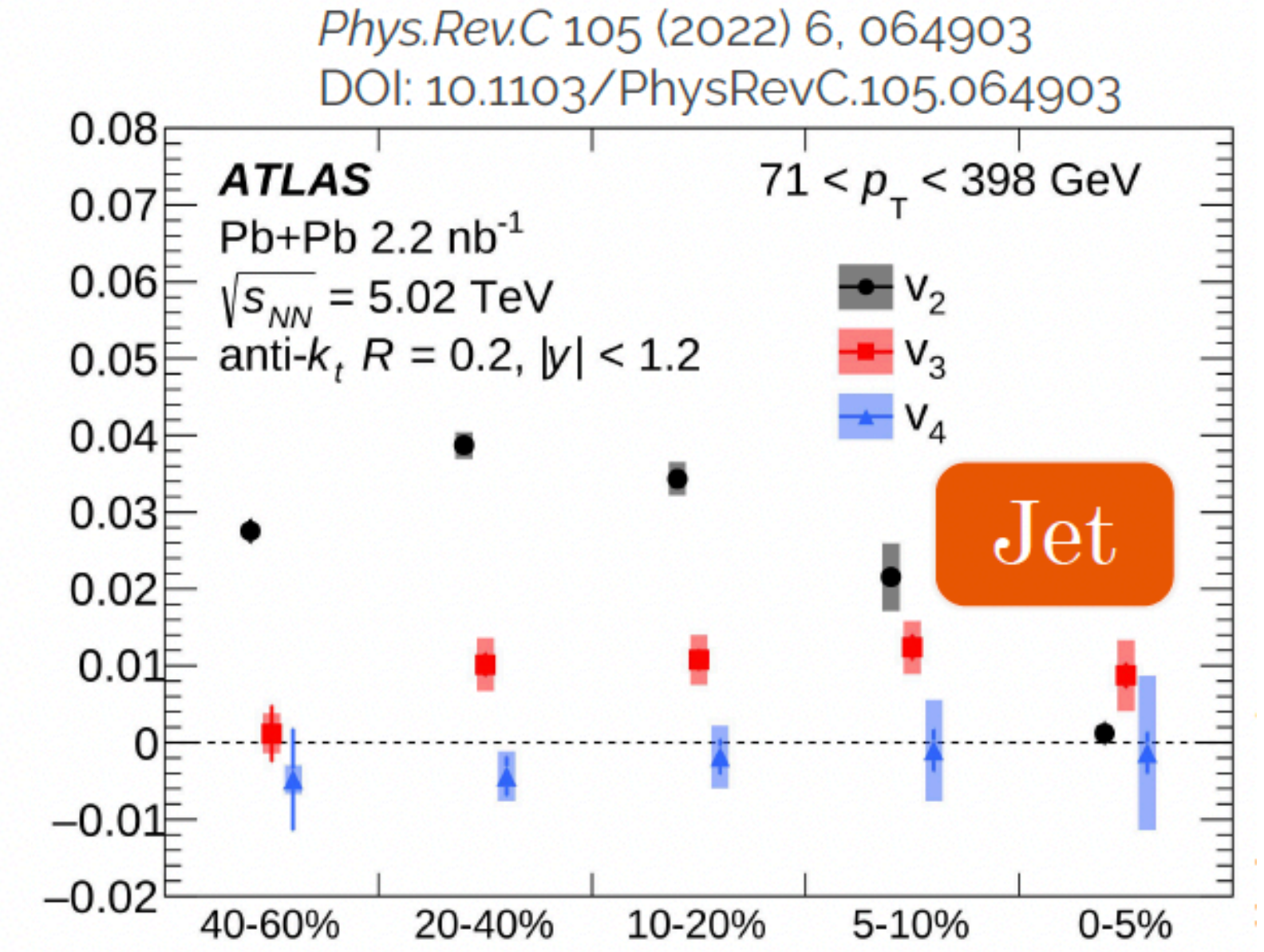


Talk by B. Seidlitz, Sec. 4, Mon, 14:20

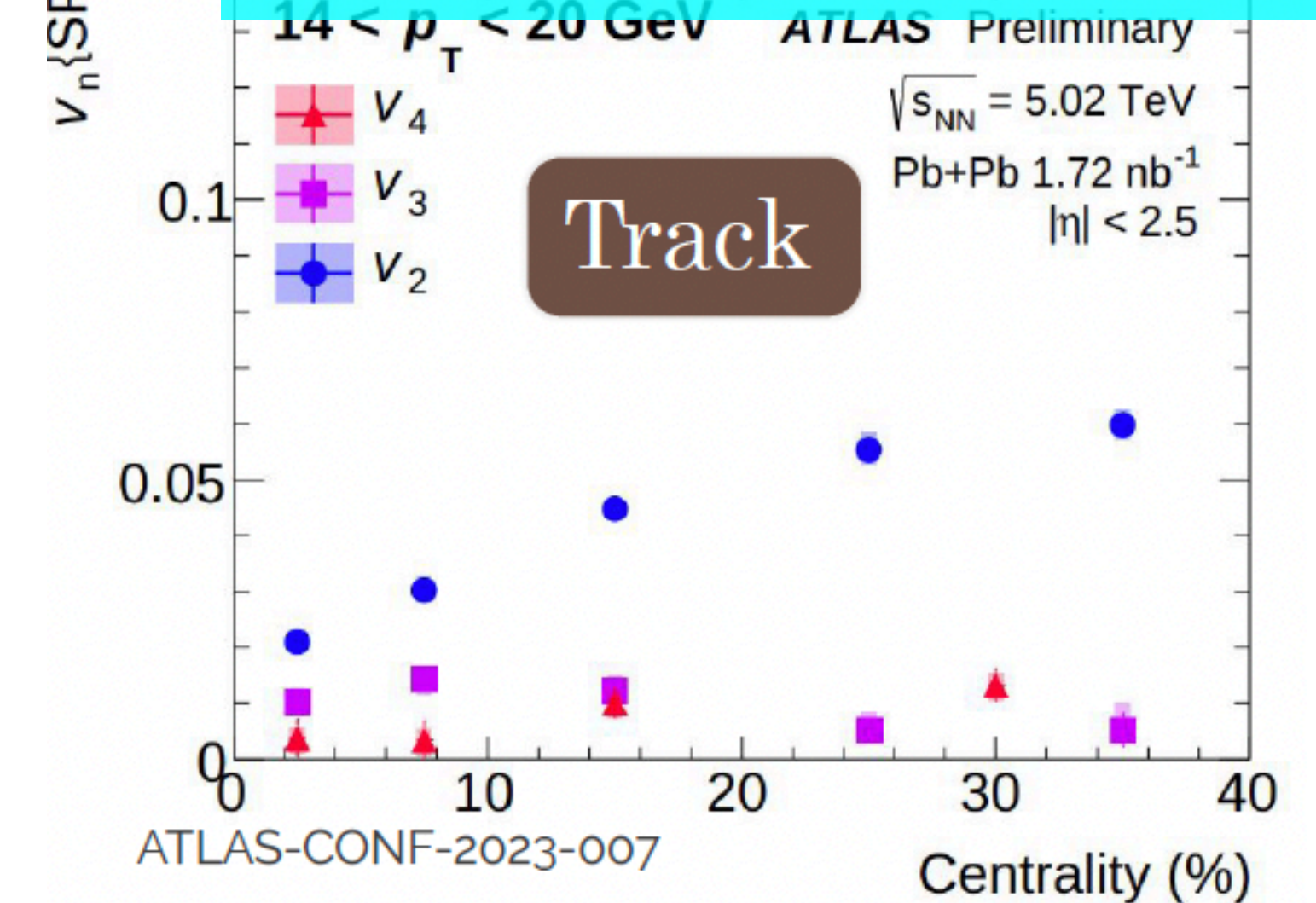
30° out-of-plane



Talk by A. Landou, Sec. 17, Tue, 15:00

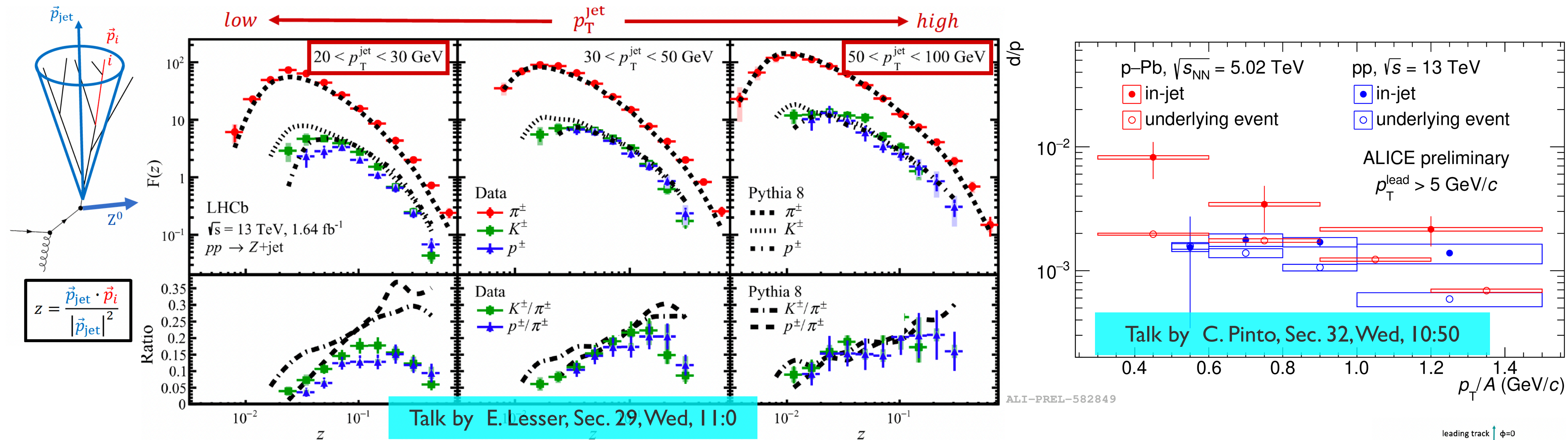


Talk by X. Wang, Sec. 8, Mon, 14:20

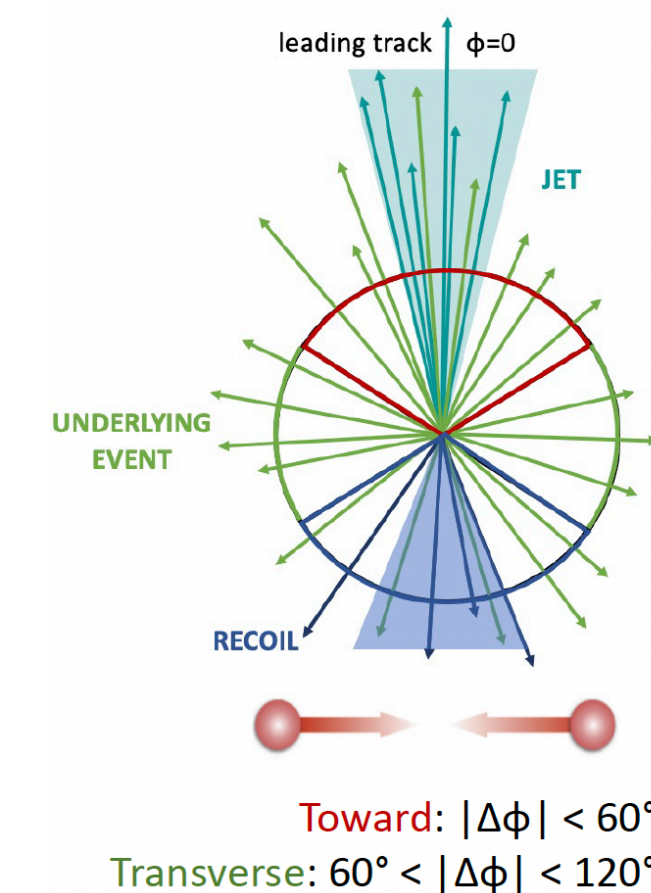


- In Pb+Pb collisions, jets have no-zero flow over a very large  $p_T$  range  $\rightarrow$  path length depends of energy loss
- Similar centrality dependence of  $v_n$  for very high  $p_T$  charged-particle and jets  $\rightarrow$  what could drive this?
- In pp collisions, jets does not affect UE collectivity

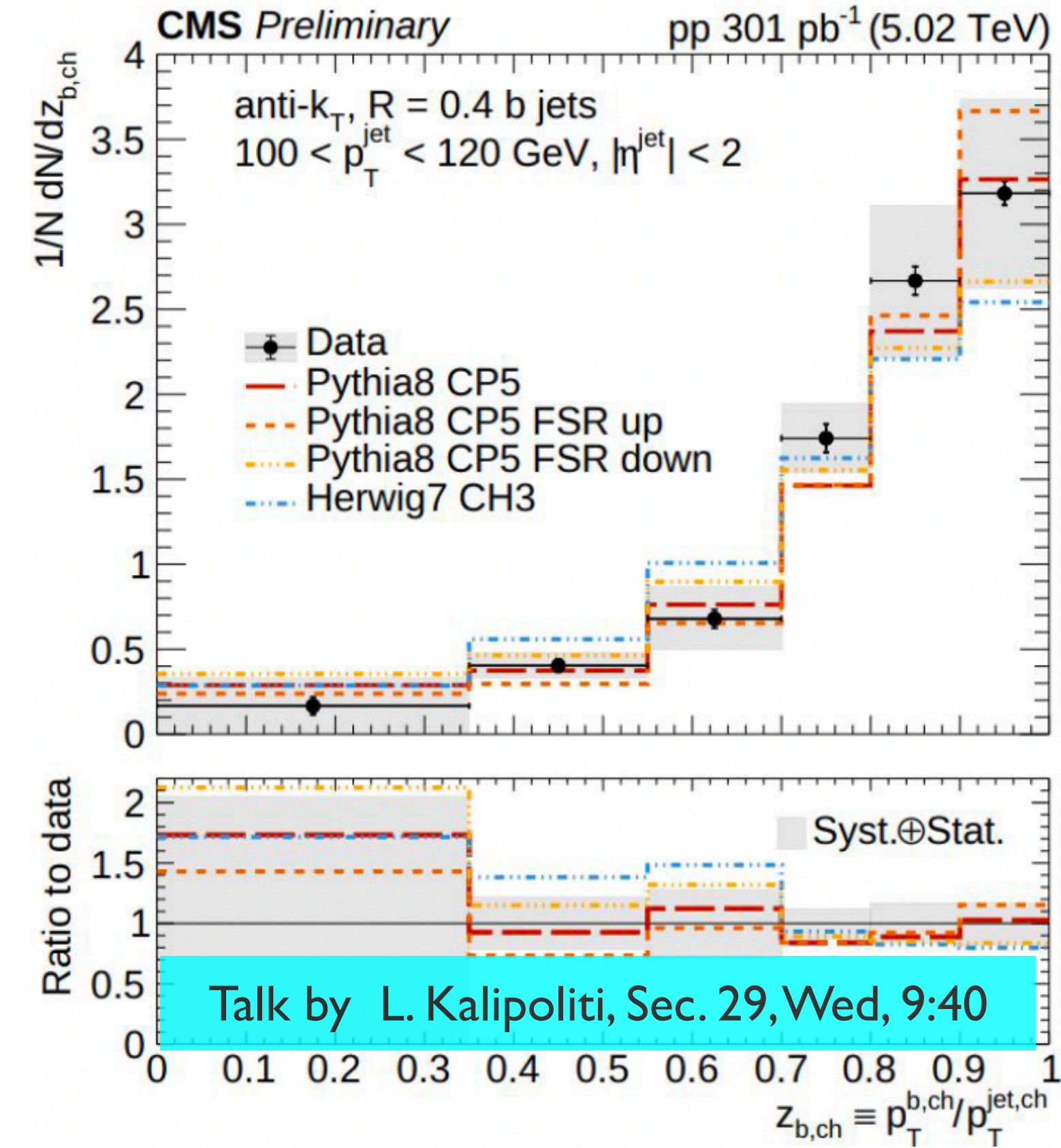
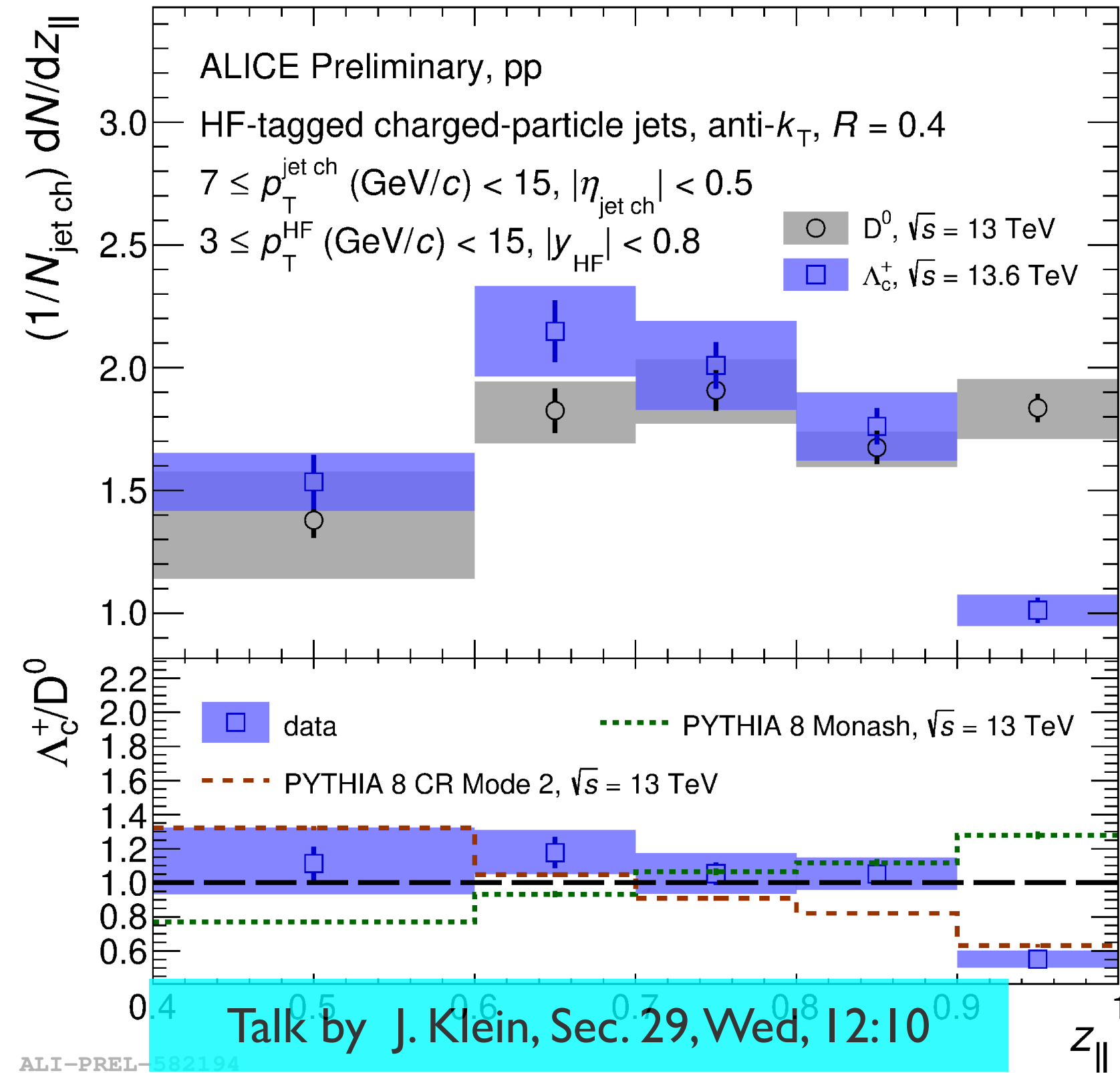
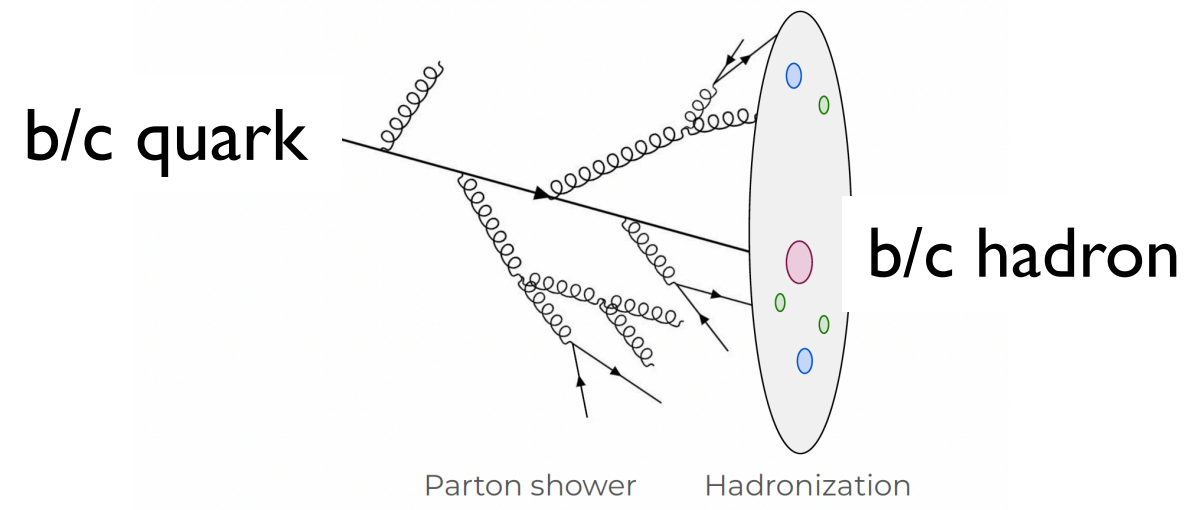
# Jet fragmentation into LF particles



- Using the Z-tagged jets to study jet fragmentation and identified particles → important for the understanding of hadronization mechanisms
- Deuteron/proton ratio in jets is higher in p-Pb than in pp, also higher in jets than in UE → hints of different particle composition in and out of jets

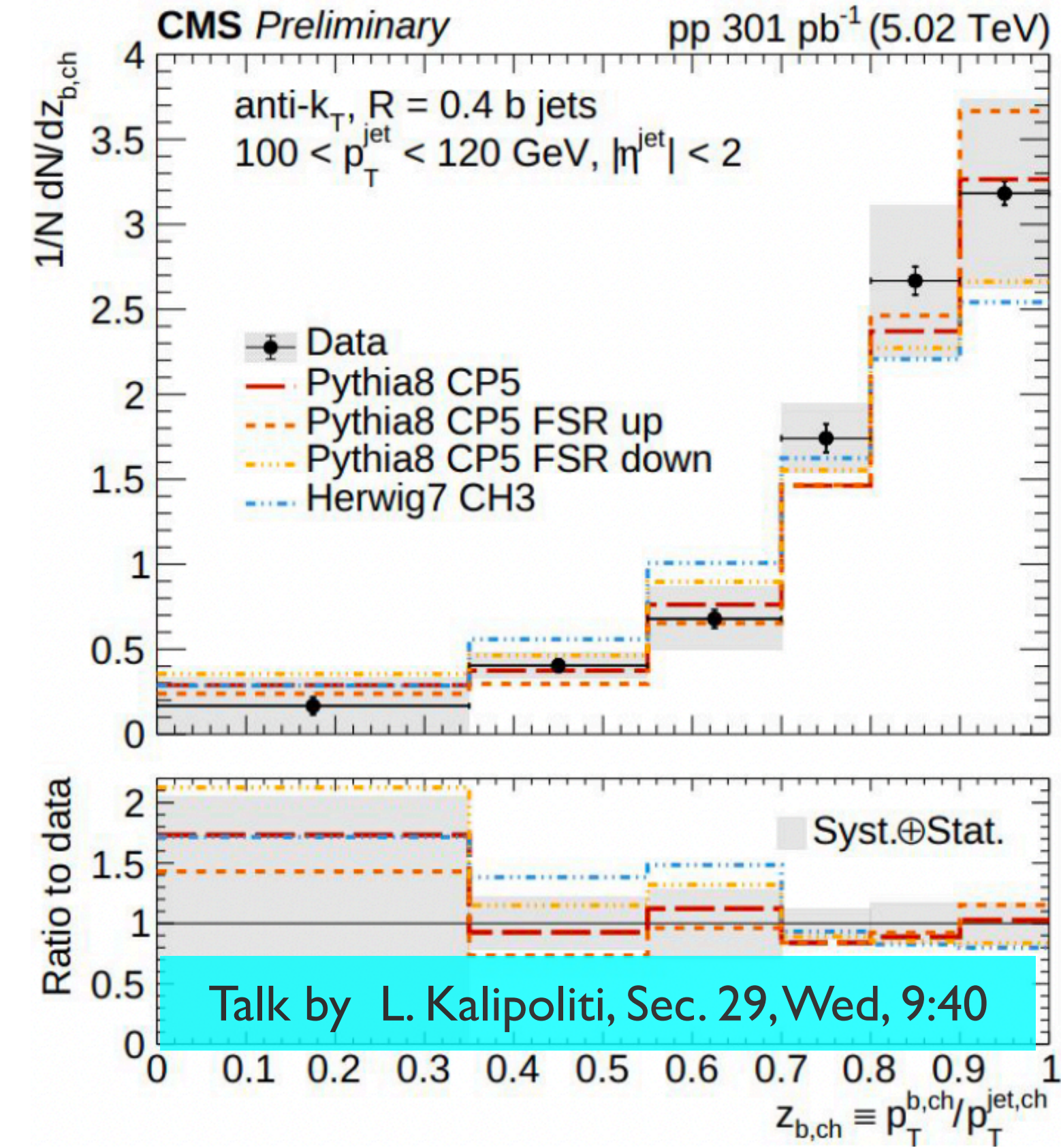
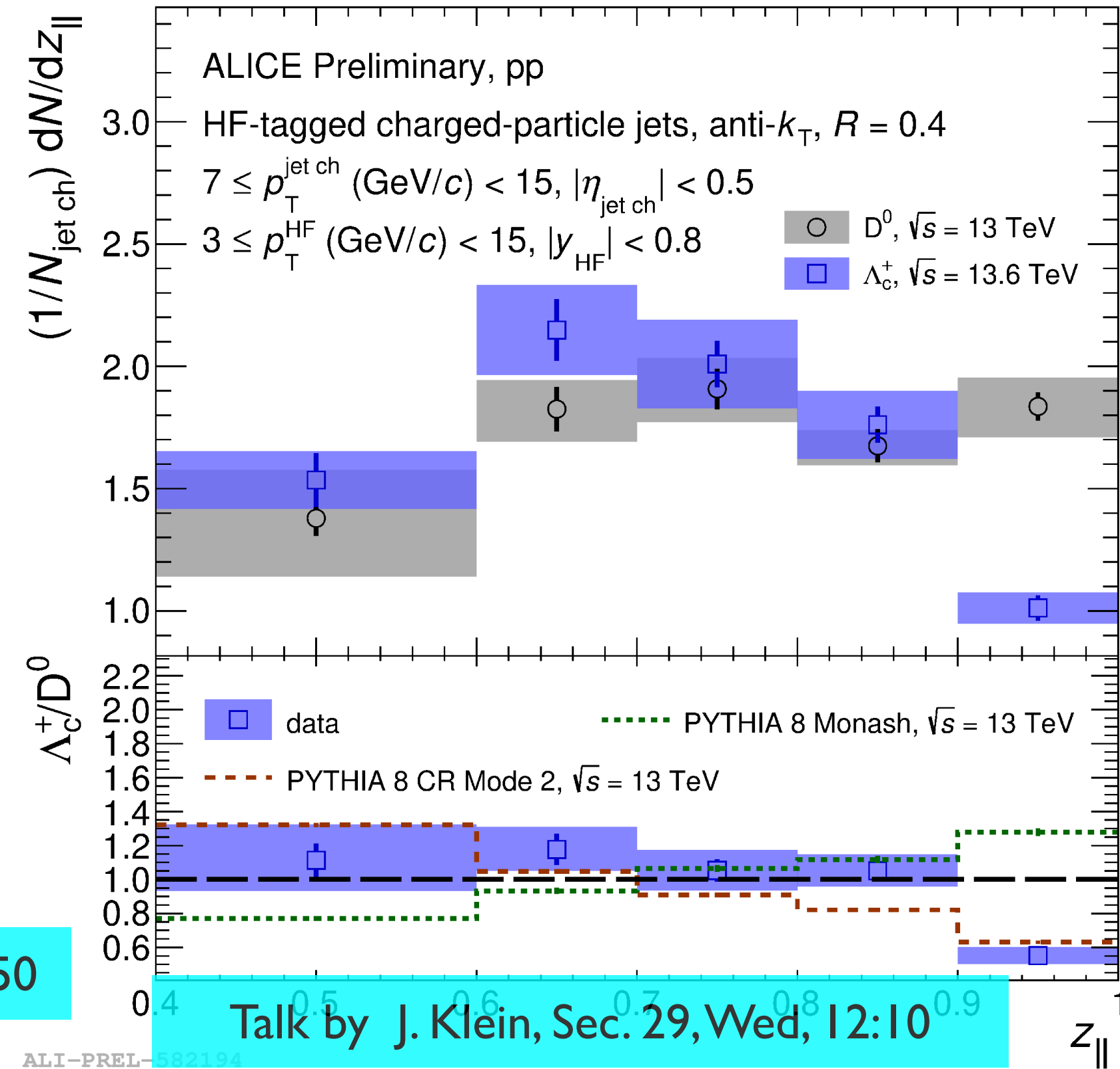
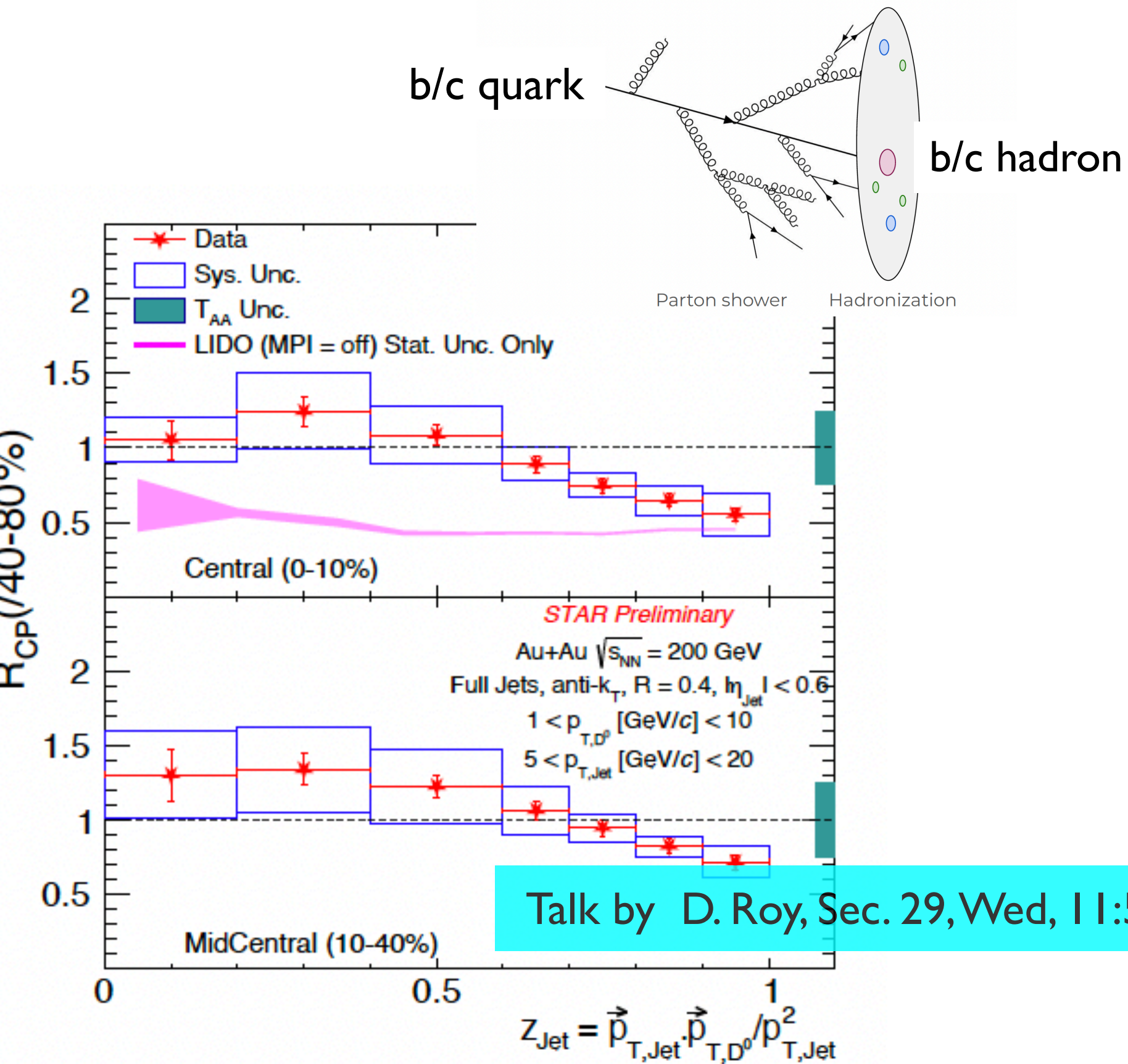


# Jet fragmentation into HF particles



- Tension with even softer HF-jet fragmentation into  $\Lambda_c^+$  baryons than D mesons

# Jet fragmentation into HF particles

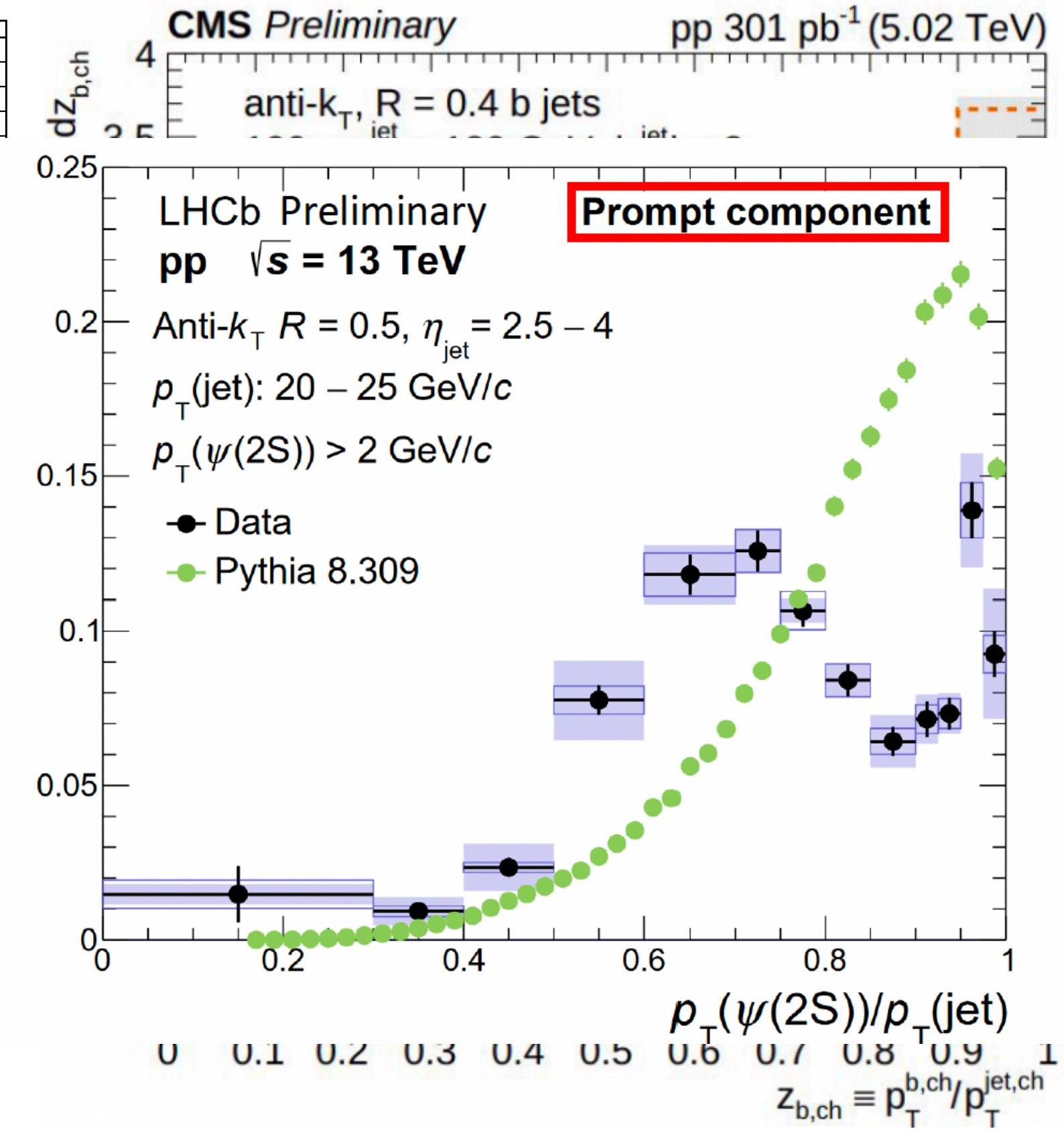
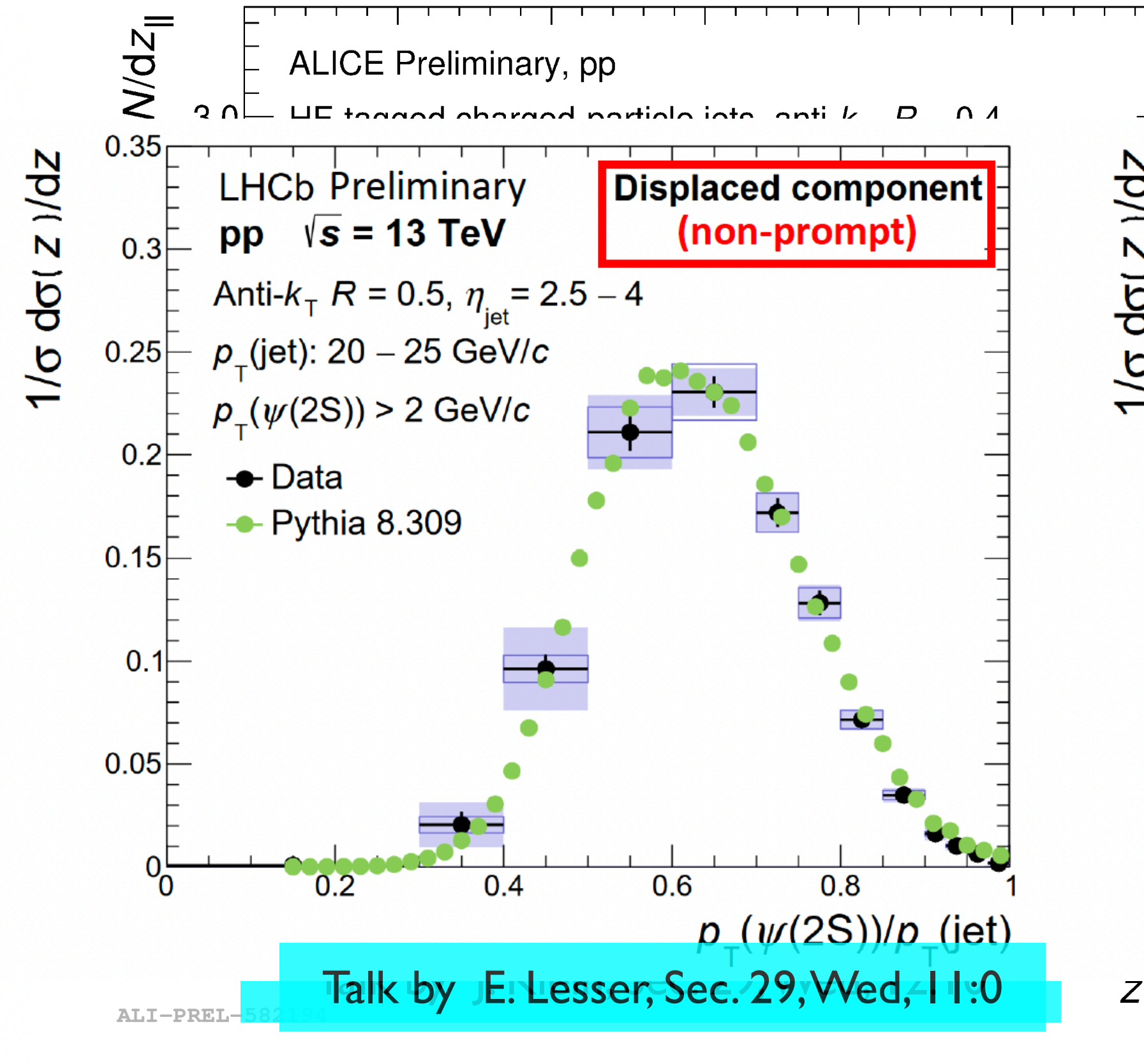
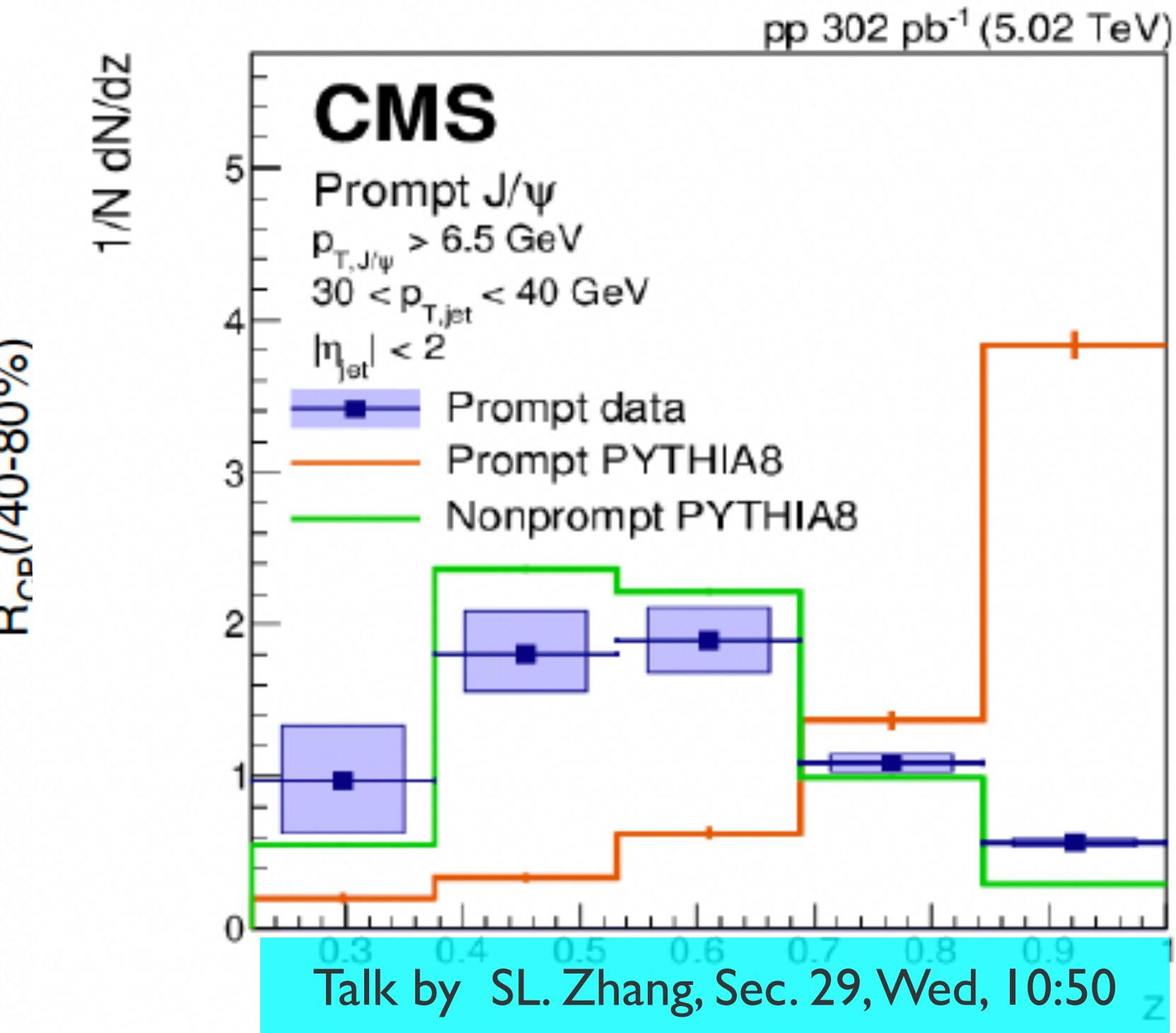


- Tension with even softer HF-jet fragmentation into  $\Lambda_c^+$  baryons than D mesons
- Hints of  $D^0$ -tagged jets fragmentation softer in most central Au+Au collisions



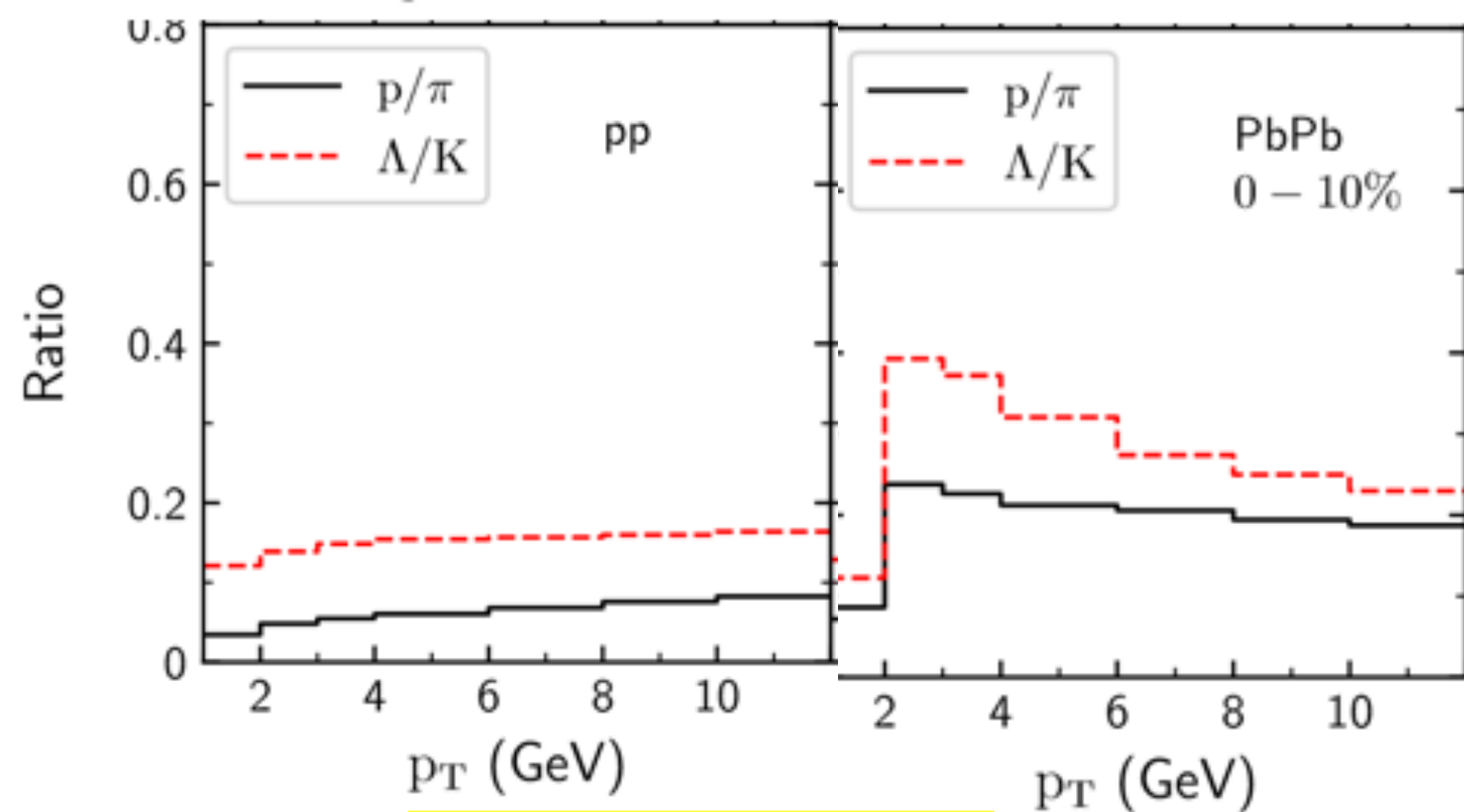
# Jet fragmentation into HF particles

PLB 825 (2022) 136842



- Tension with even softer HF-jet fragmentation into  $\Lambda_c^+$  baryons than D mesons
- Hints of  $D^0$ -tagged jets fragmentation softer in most central Au+Au collisions
- PYTHIA can't produce quarkonium jet fragmentation  $\psi(2S) \rightarrow$  further development of theoretical models are needed

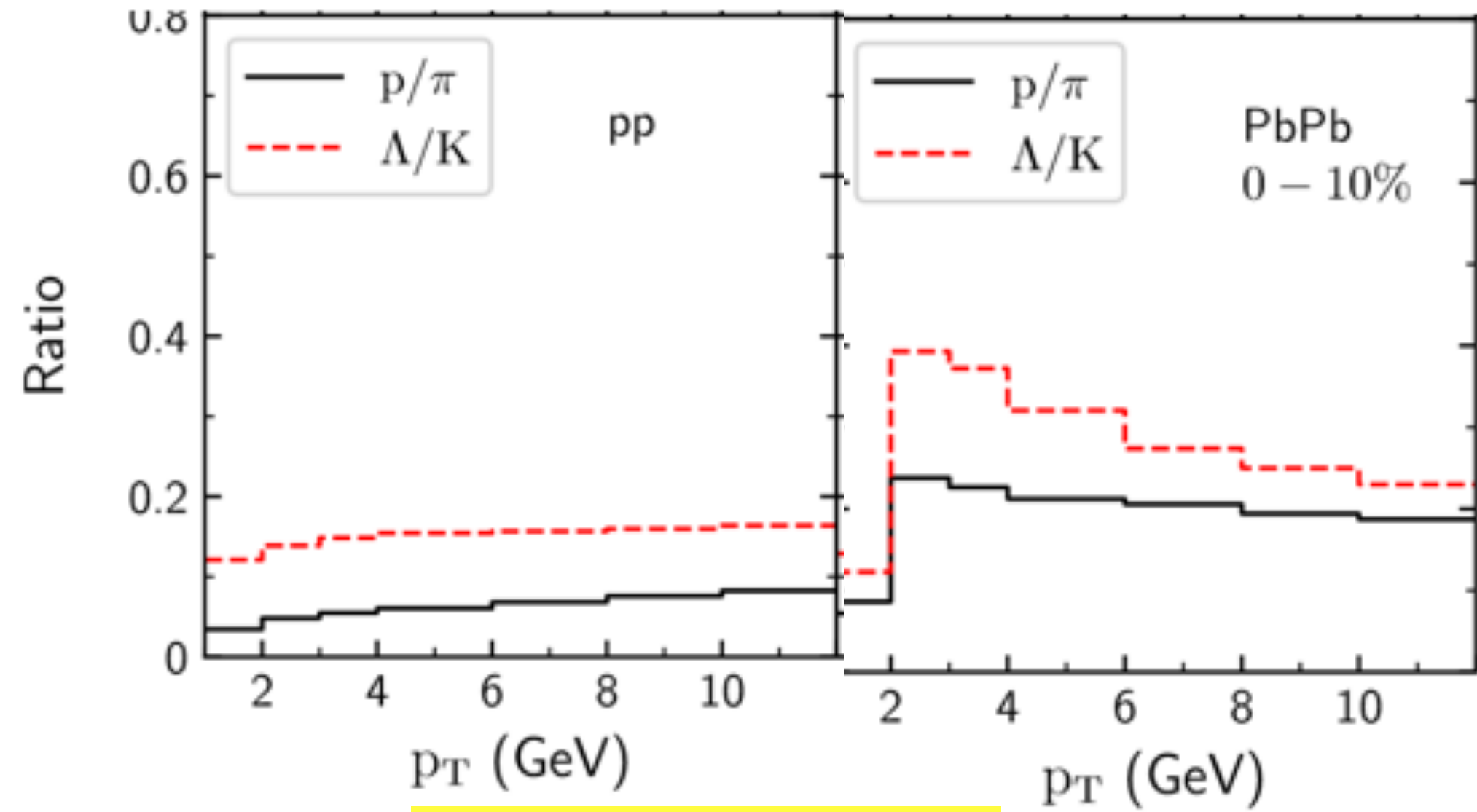
# Jet fragmentation and hadron chemistry



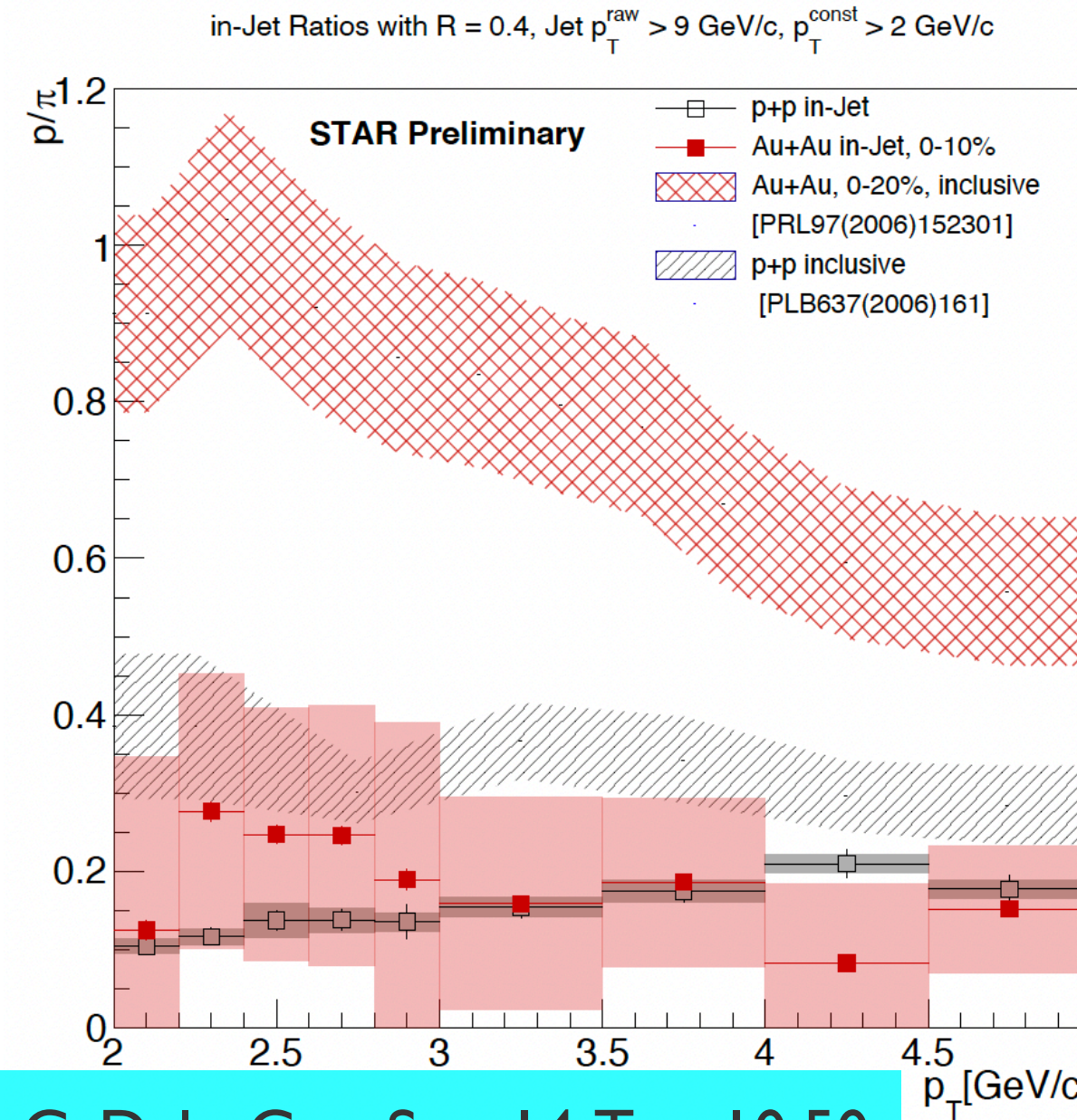
PLB 837 (2023) 137638

- Study jet hadron chemistry with identified particles to understand the hadronization and jet fragmentations

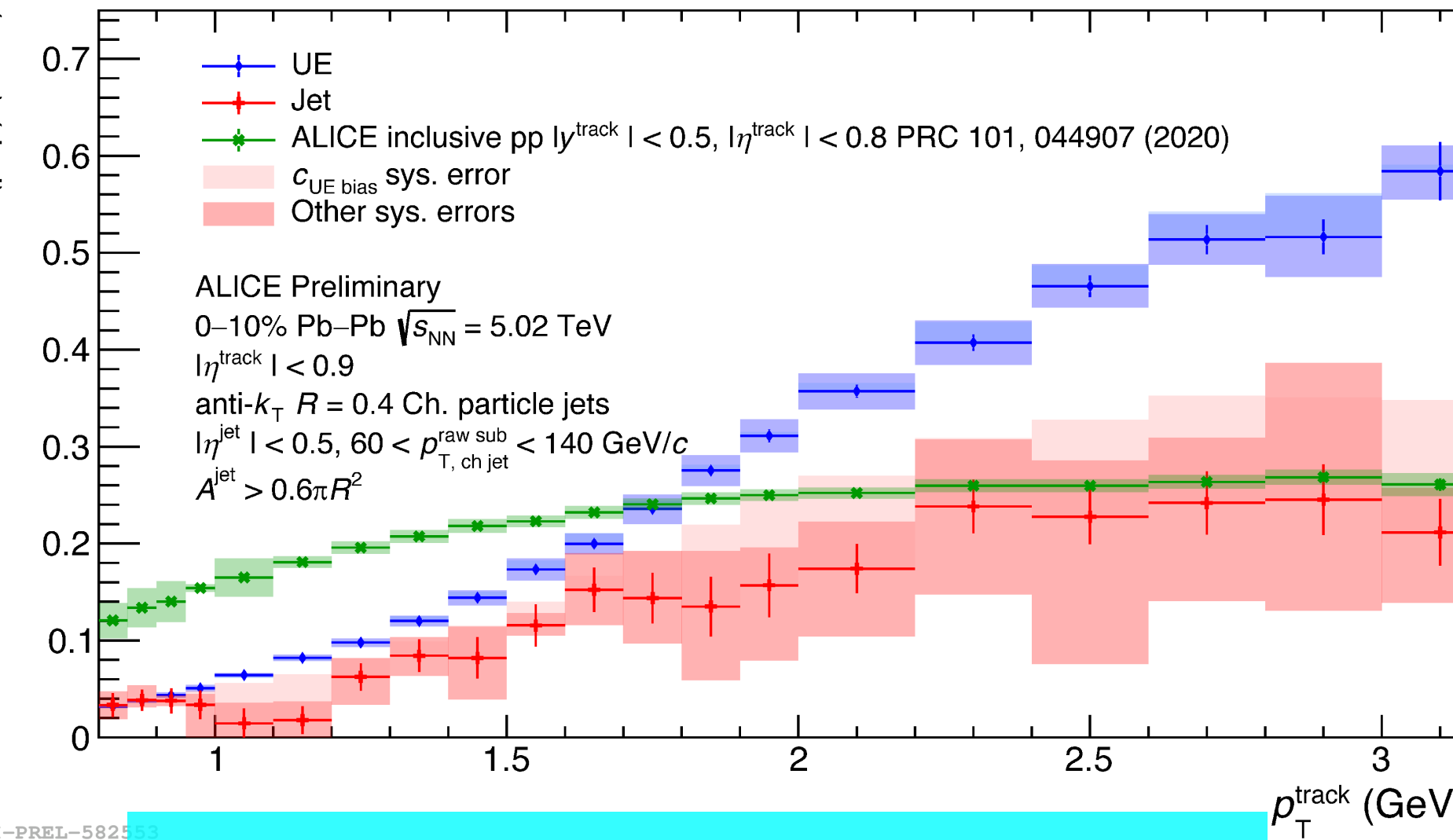
# Jet fragmentation and hadron chemistry



PLB 837 (2023) 137638



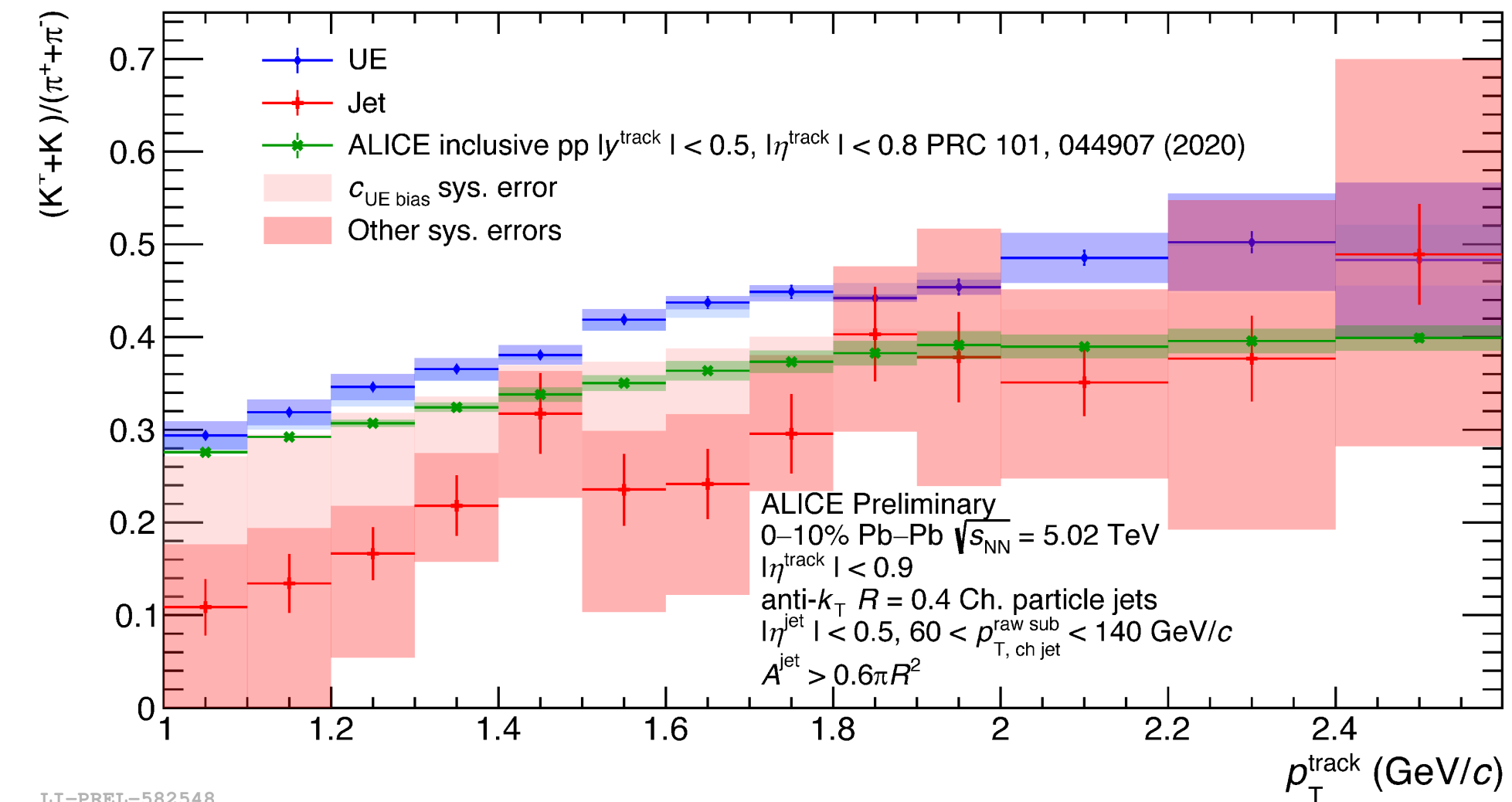
Talk by G. Dale-Gau, Sec. 14, Tue, 10:50



Talk by S. L. Weyhmiller, Sec. 14, Tue, 11:10

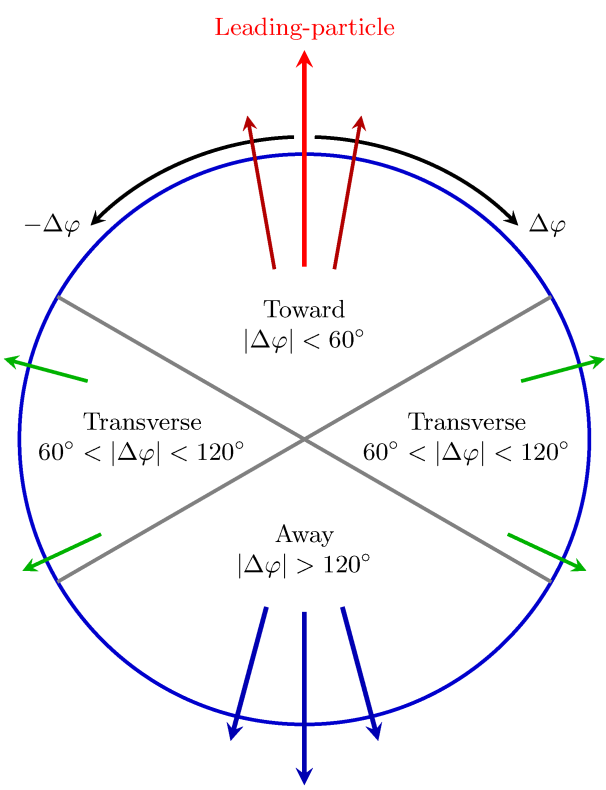
- Study jet hadron chemistry with identified particles to understand the hadronization and jet fragmentations
- Baryon to meson ratio measured by STAR and ALICE in AA collisions

→ uncertainty dominates! Precision measurements needed



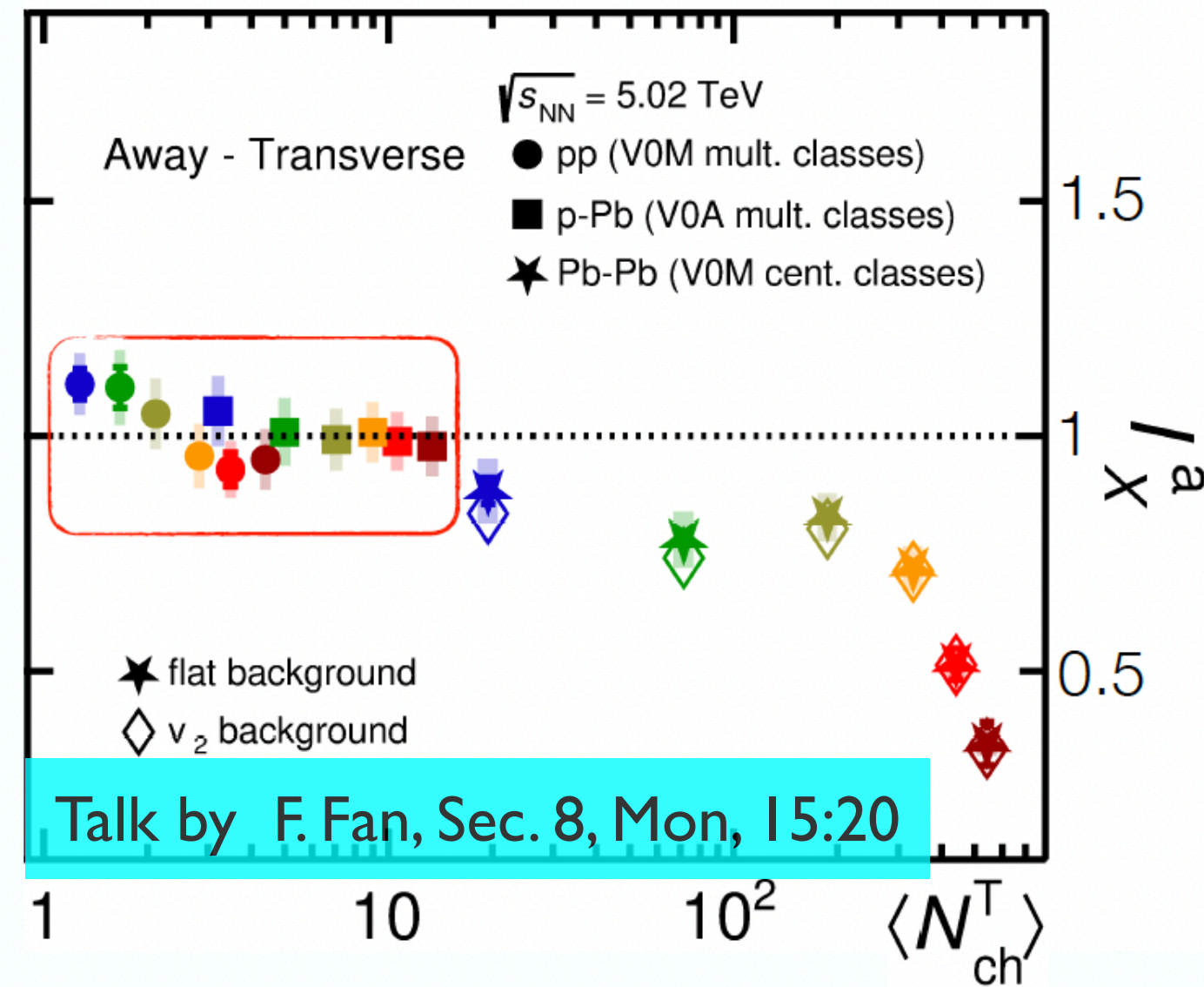
# Search for jet quenching in small systems

Talk by M.Virta, Sec. 8, Mon, 15:00



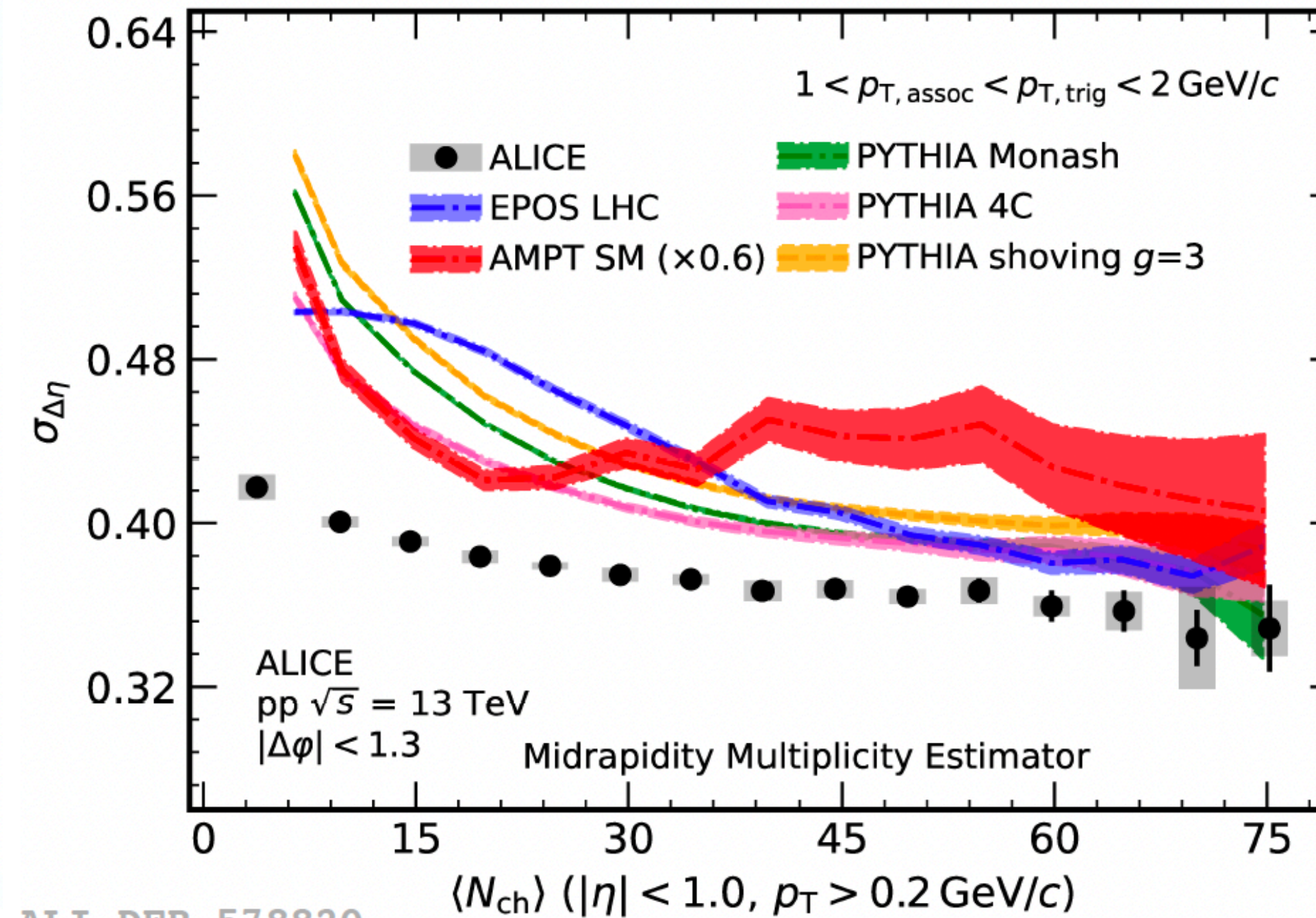
$$I_X^a = \frac{(dN_{ch}^{AS-TS}/dp_T)_{VOM}}{(dN_{ch}^{AS-TS}/dp_T)_{MB}}$$

ALICE, Phys. Lett. B 843 (2022) 137649



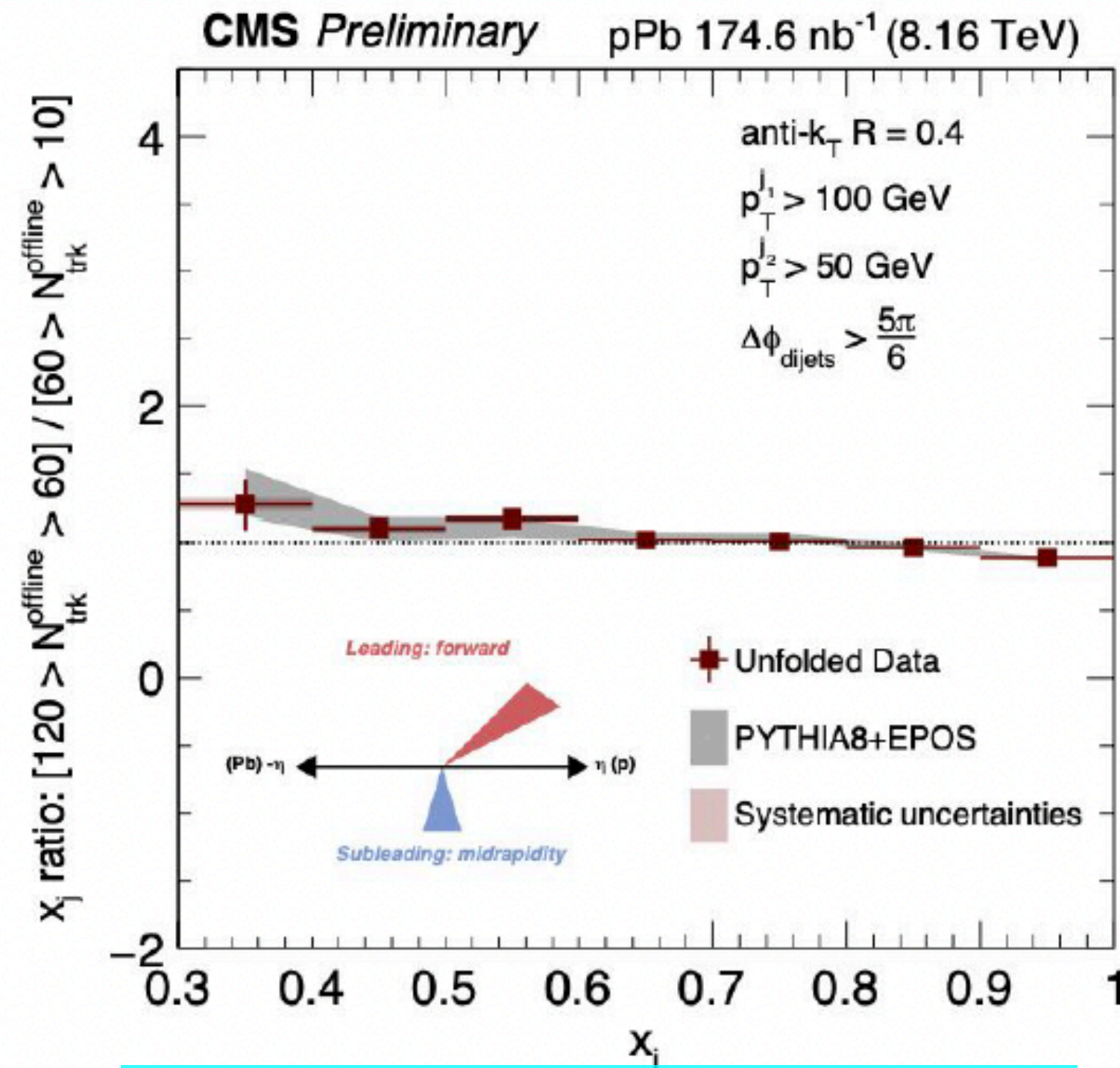
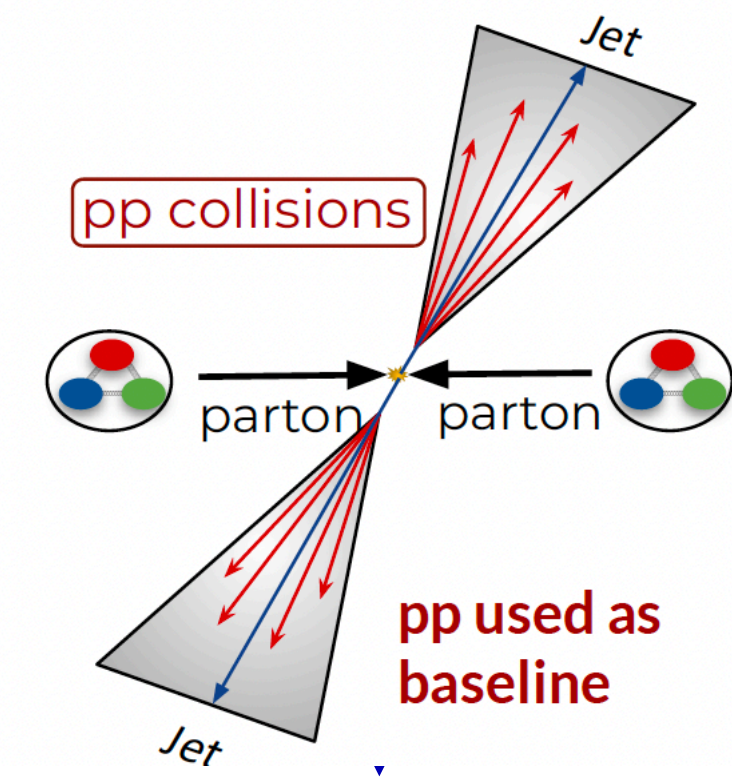
Talk by F. Fan, Sec. 8, Mon, 15:20

ALI-DER-578820



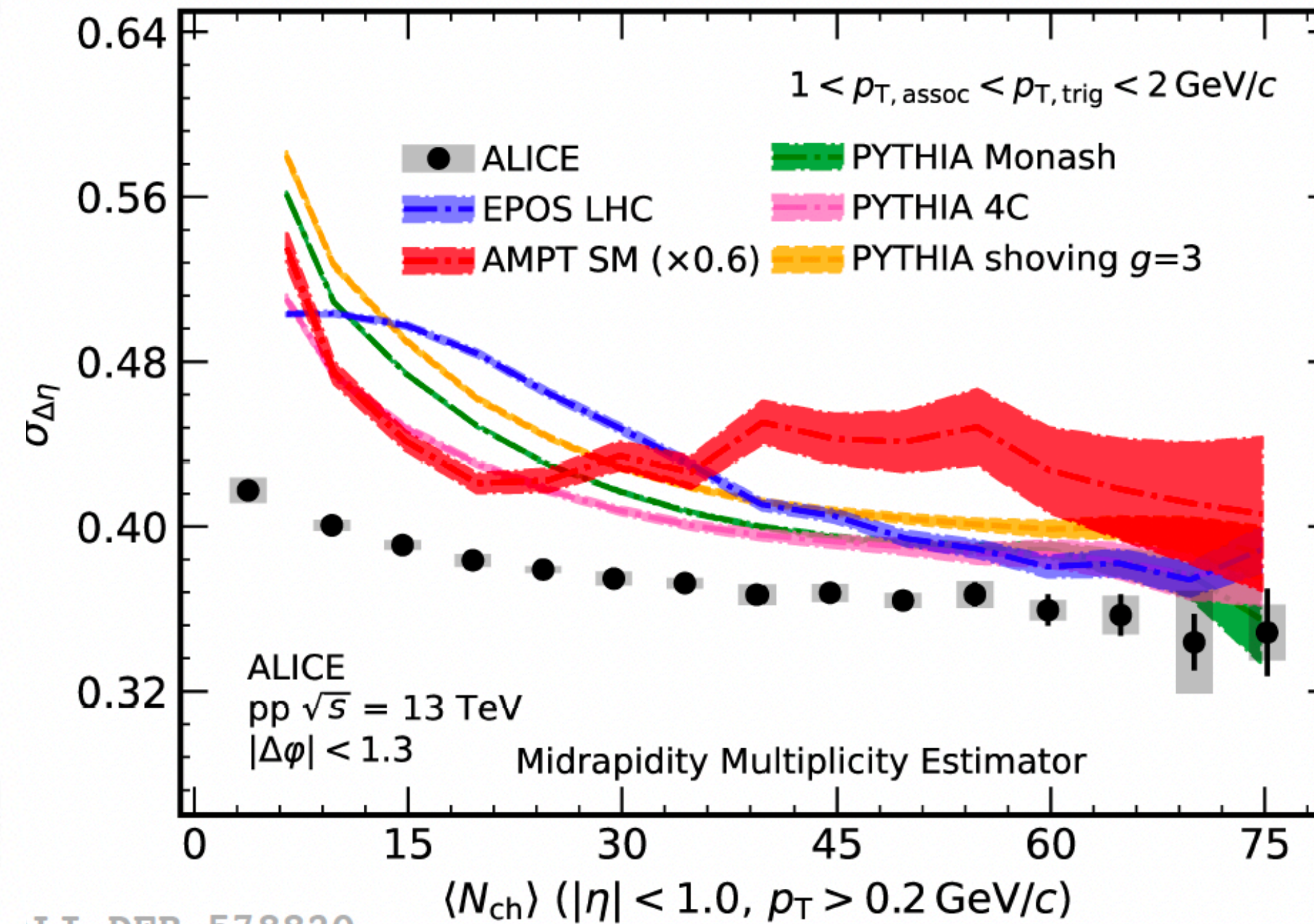
- Using particle correlation methods to study associated particles behavior as a function of (transverse) multiplicity
- No enhancement (suppression) observed for Near (Away) side in pp and p-Pb collisions
- Peak width become narrower in HM events for low  $p_T$  associated particles

# Search for jet quenching in small systems



Talk by D. D. Lemos, Sec. 17, Tue, 14:20

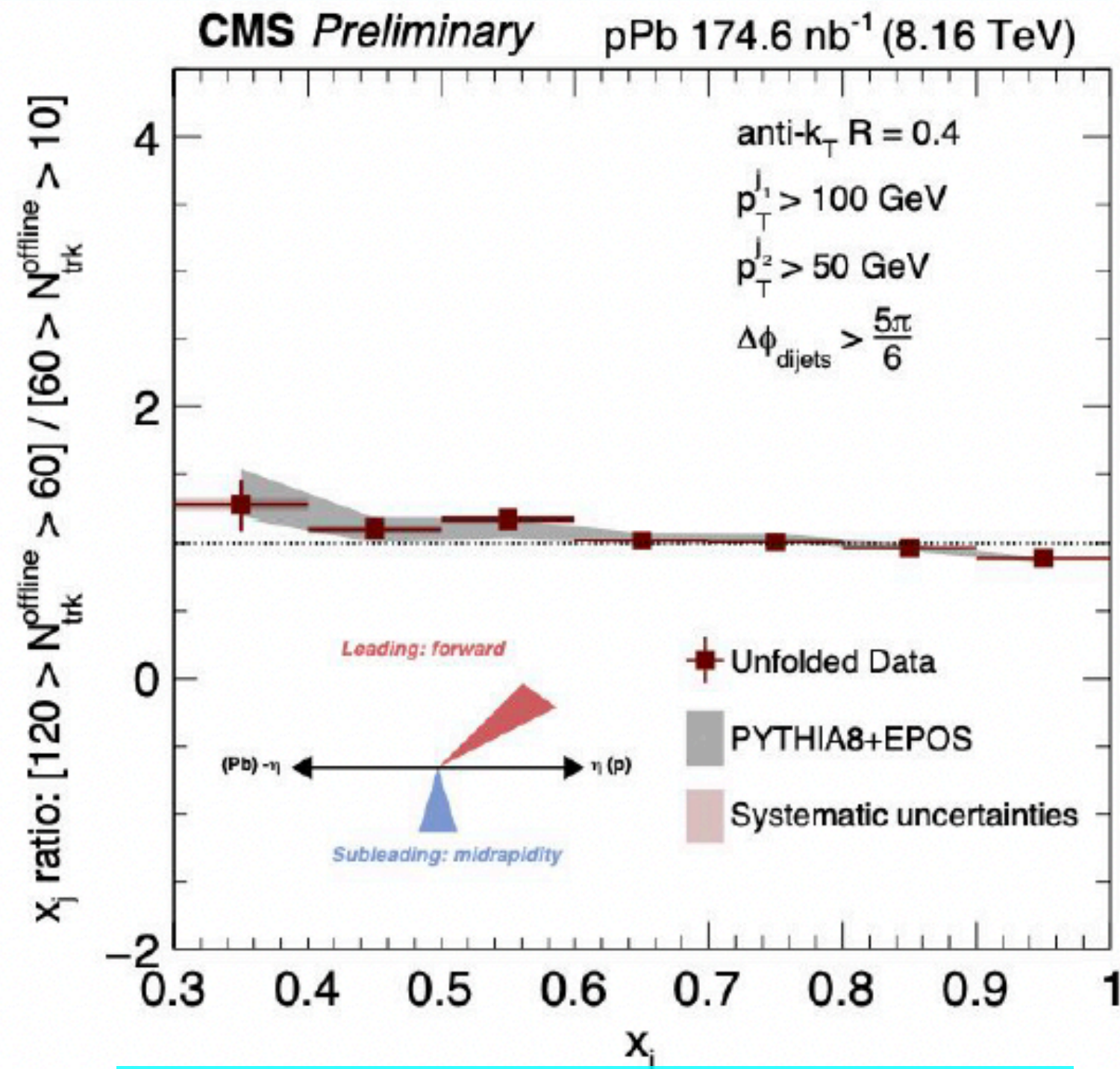
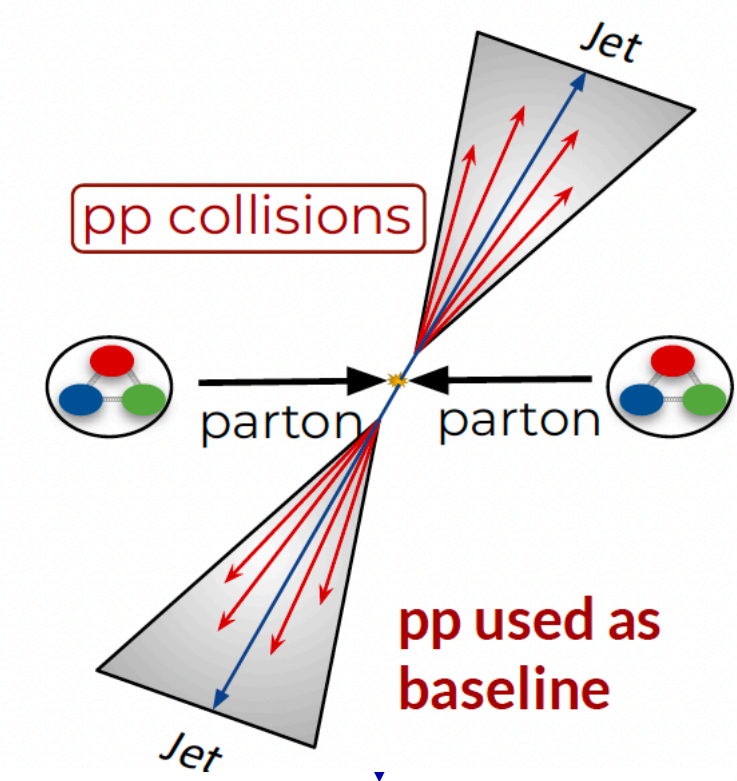
Talk by M. Virta, Sec. 8, Mon, 15:00



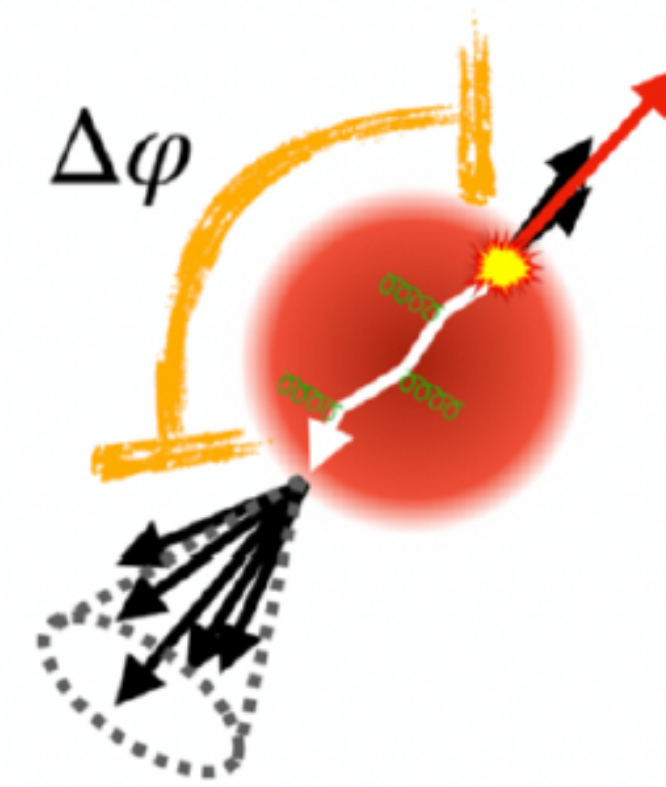
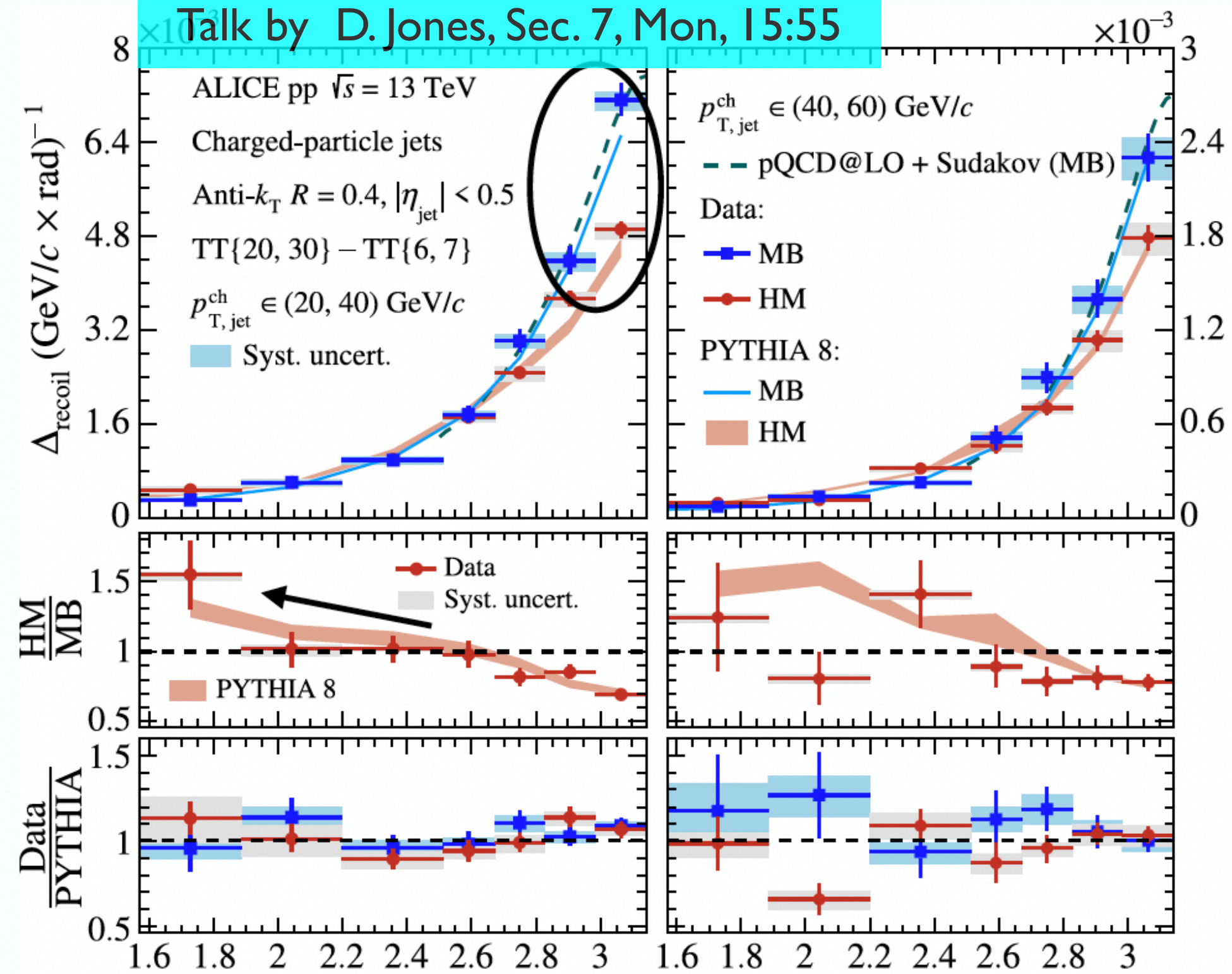
LI-DER-578820

- With full jet reconstruction, study the dijet balance or h-jet azimuthal correlations
- No modification observed at HM of jet-jet geometry

# Search for jet quenching in small systems



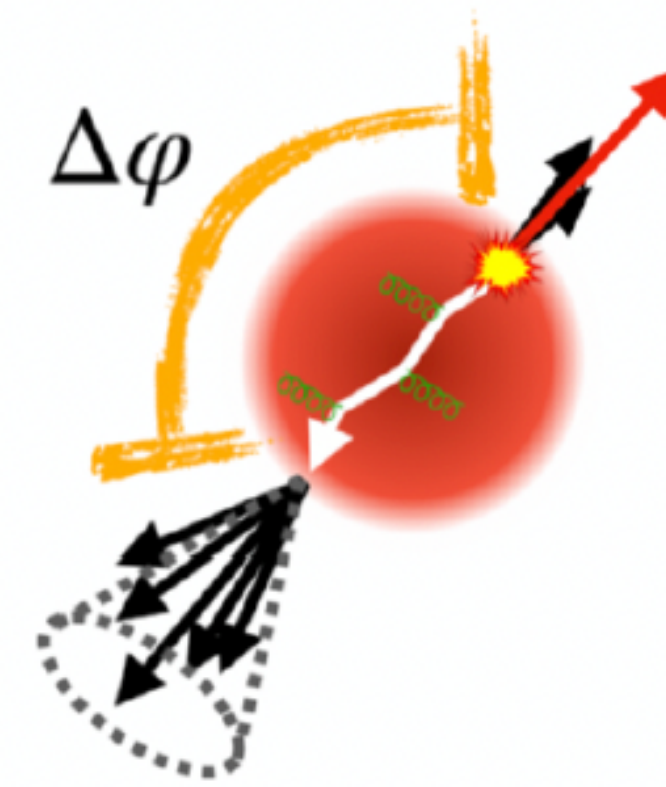
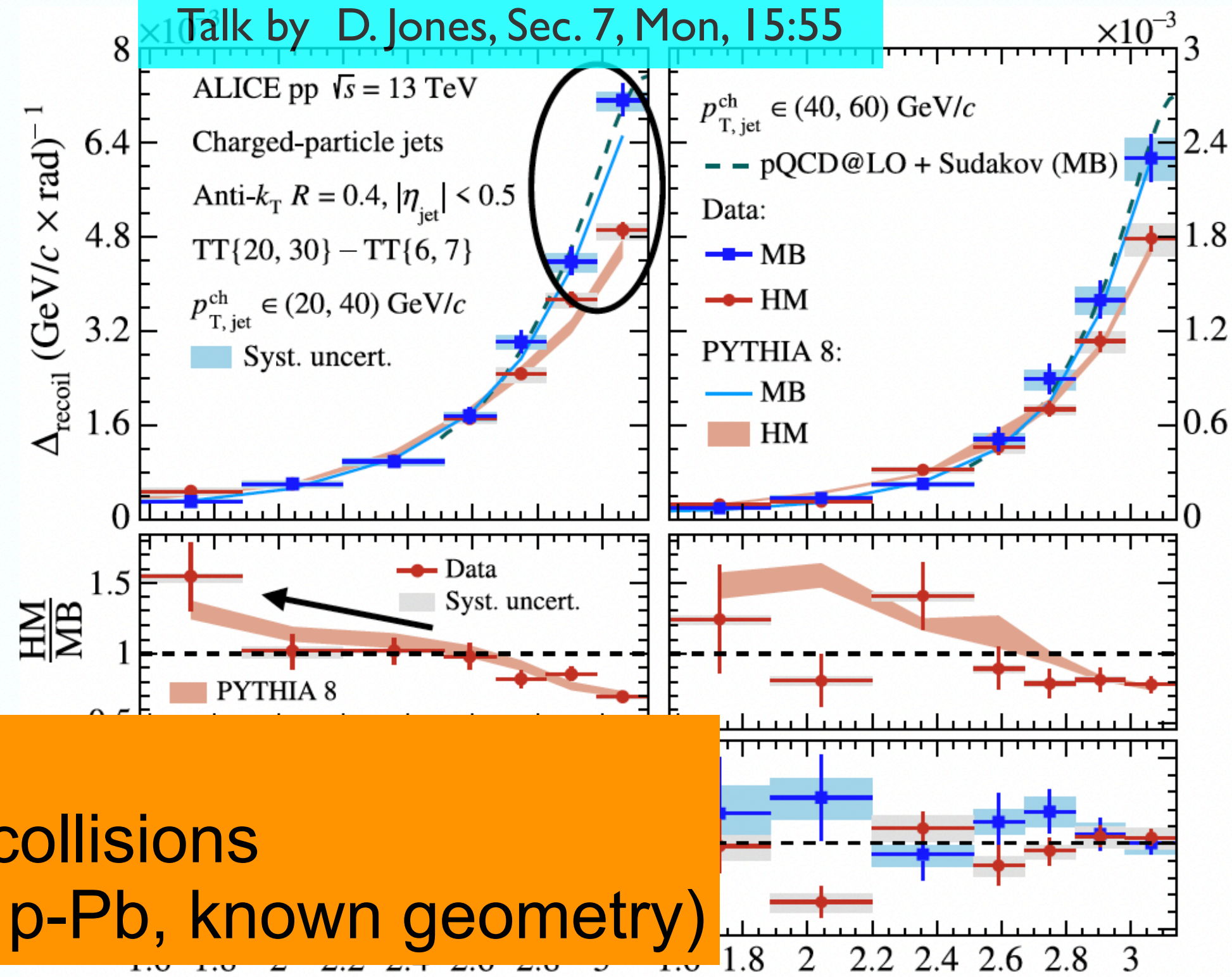
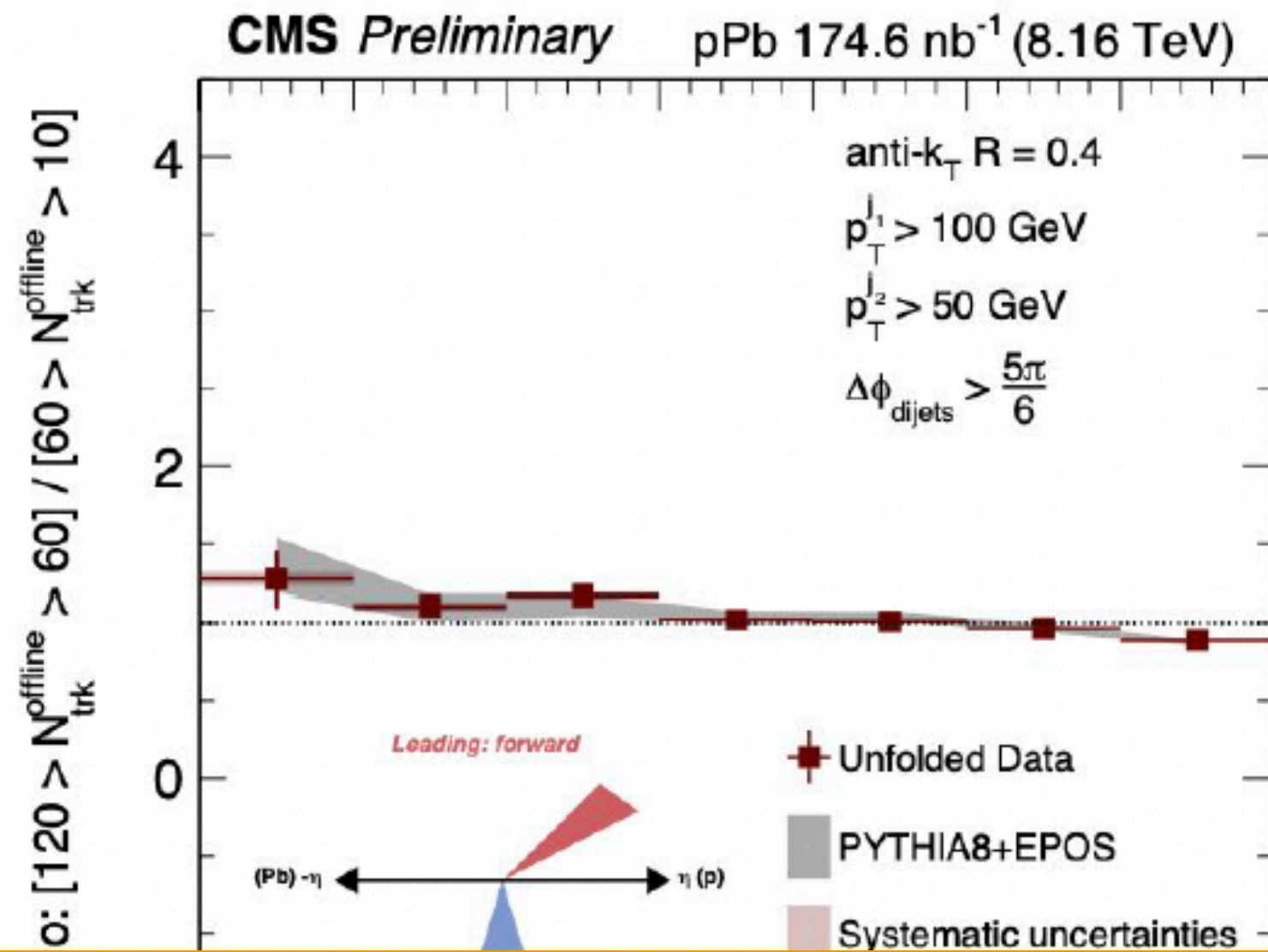
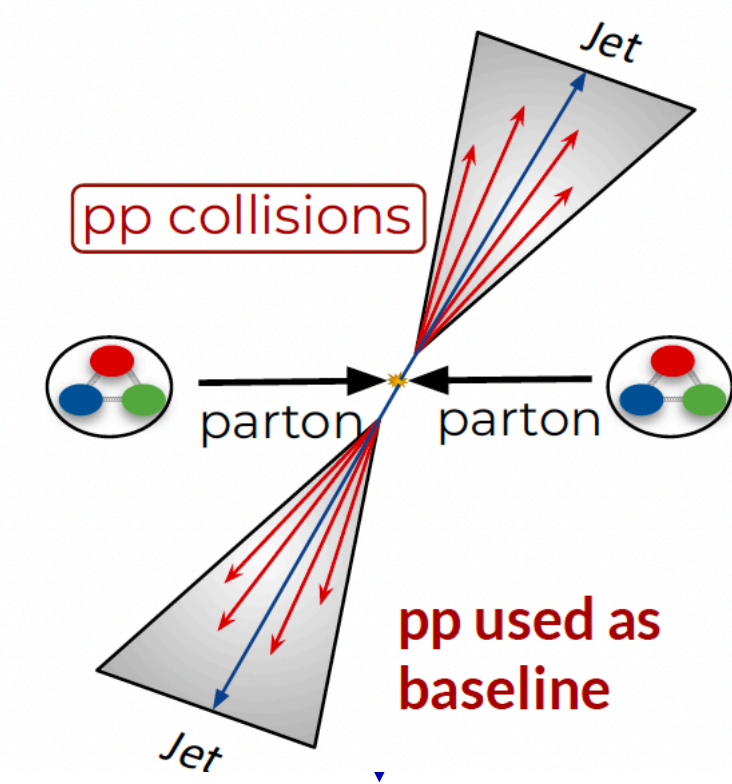
Talk by D. D. Lemos, Sec. 17, Tue, 14:20



→ Later talk by R. Longo

- With full jet reconstruction, study the dijet balance or h-jet azimuthal correlations
- No modification observed at HM of jet-jet geometry
- Azimuthal broadening in HM events observed for recoiling jets with high  $p_T$  trigger particles

# Search for jet quenching in small systems



Outlook to Run 3 and 4:

→ Search for energy loss effects with light ion collisions (e.g. O-O, Ar-Ar, low  $N_{\text{part}}$ , multiplicity similar to p-Pb, known geometry)

→ Later talk by R. Longo

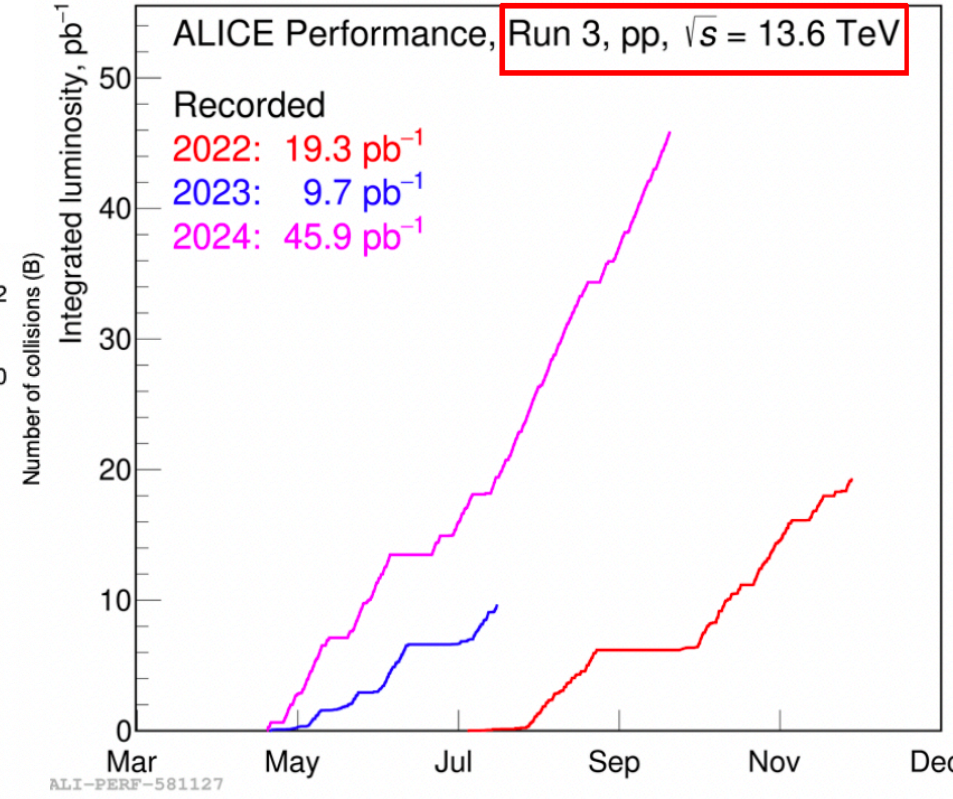
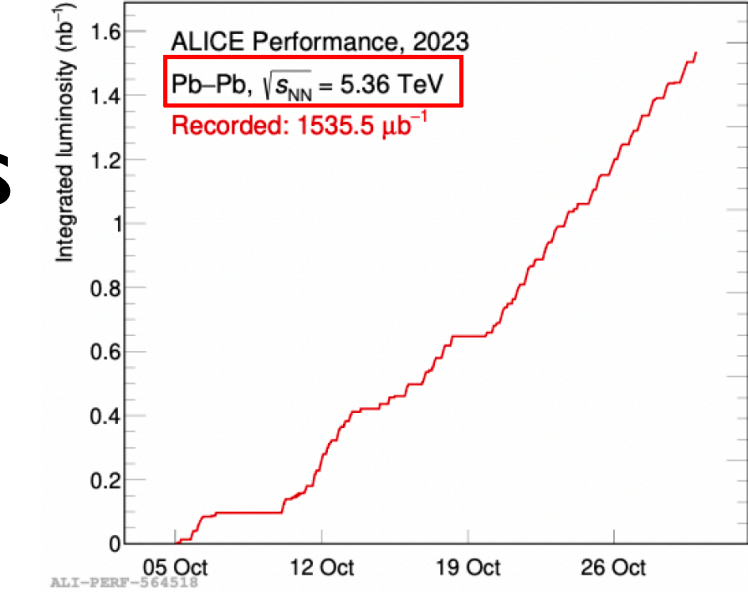
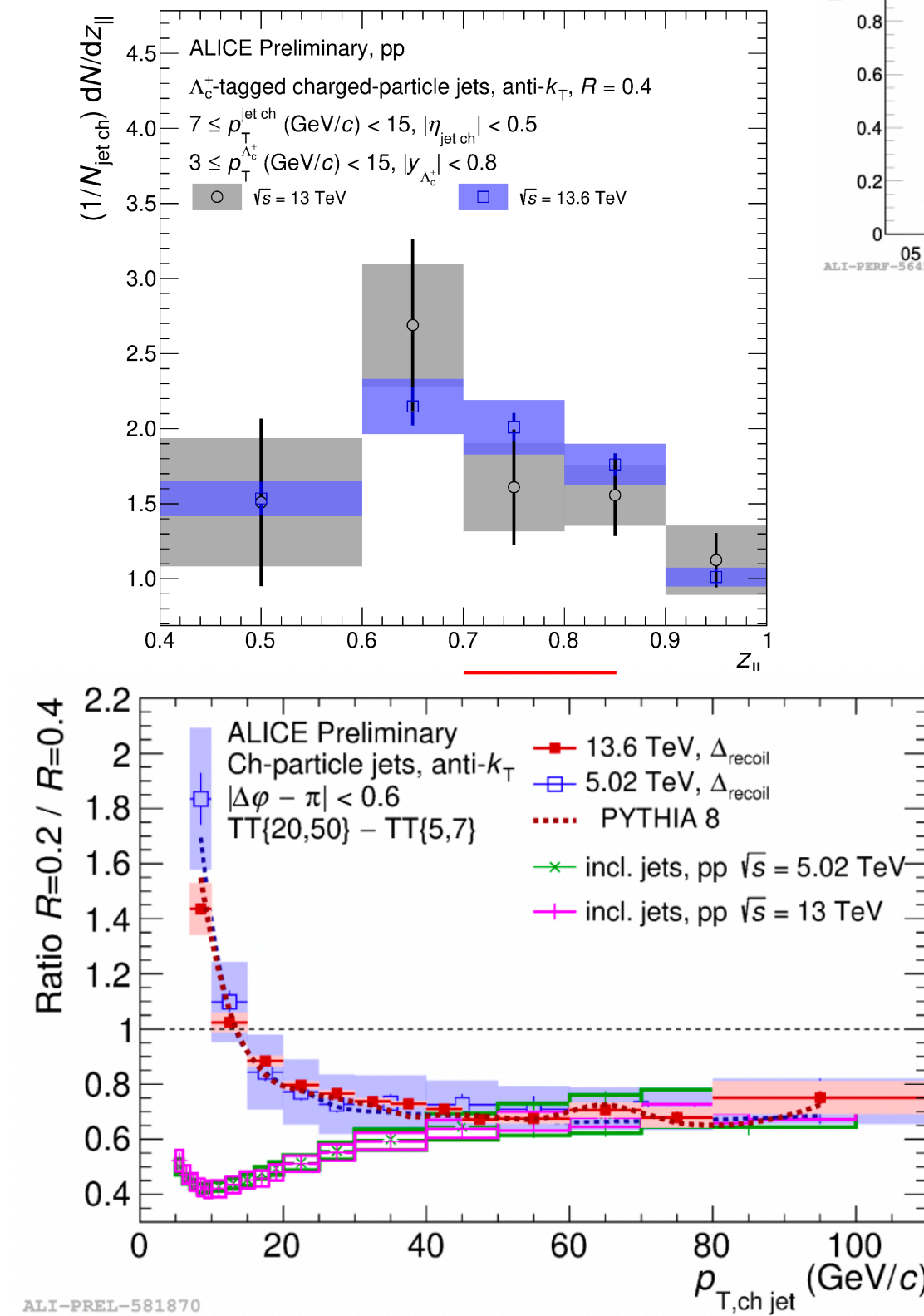
- With full jet reconstruction, study the dijet balance or h-jet azimuthal correlations
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→ Consistency study of between particle and jet correlations?

# Looking towards the future with jets

- Beautiful and exciting new results are shown and discussed at this conference!
- Precision and differential measurements allowed for rare hard probes measurements using LHC Run 3 high statistics data at highest energies

- R dependence
- Flavor/mass dependence
- Path length dependence
- Jet fragmentation and hadron chemistry
- Medium response
- ...



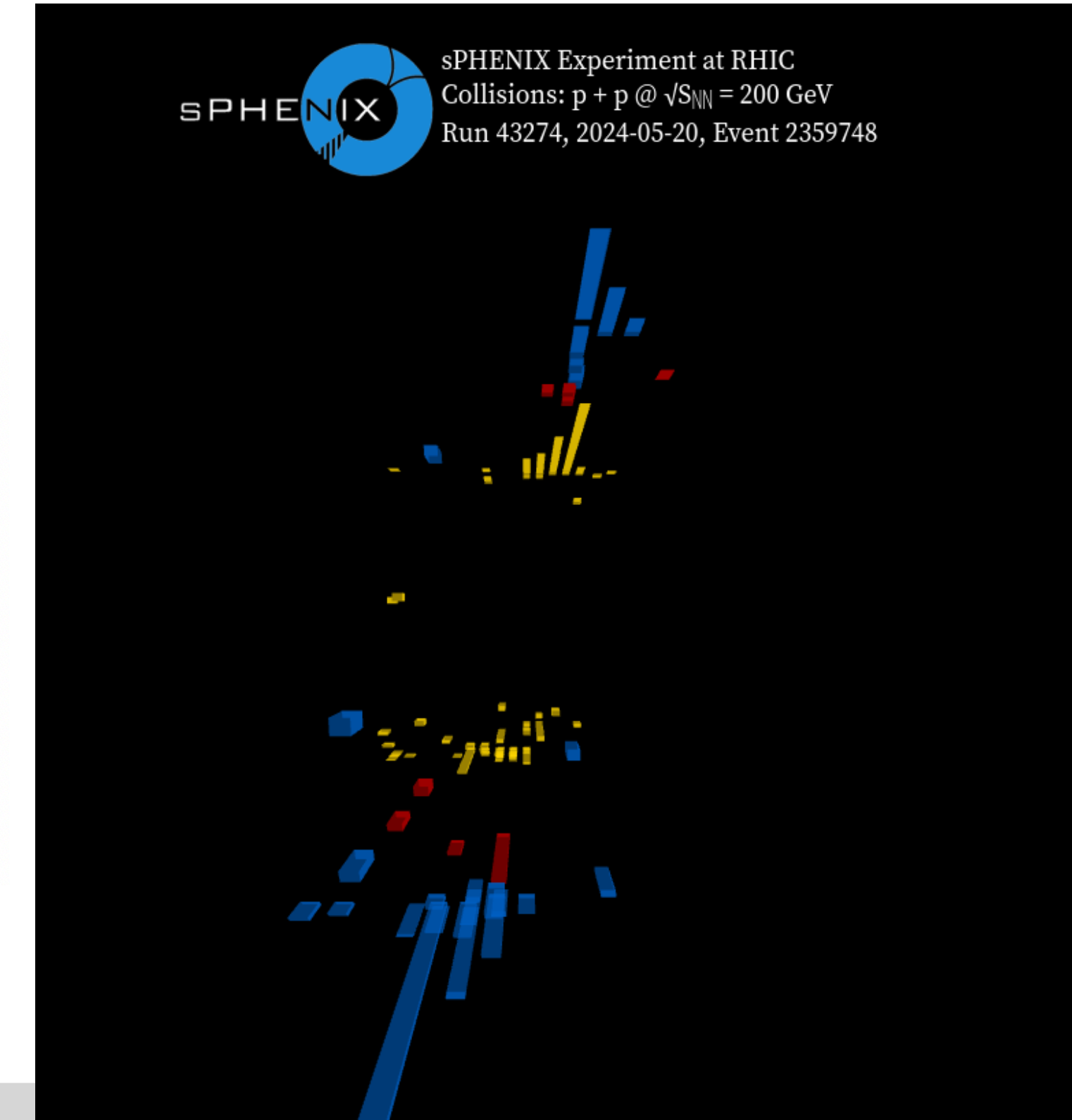
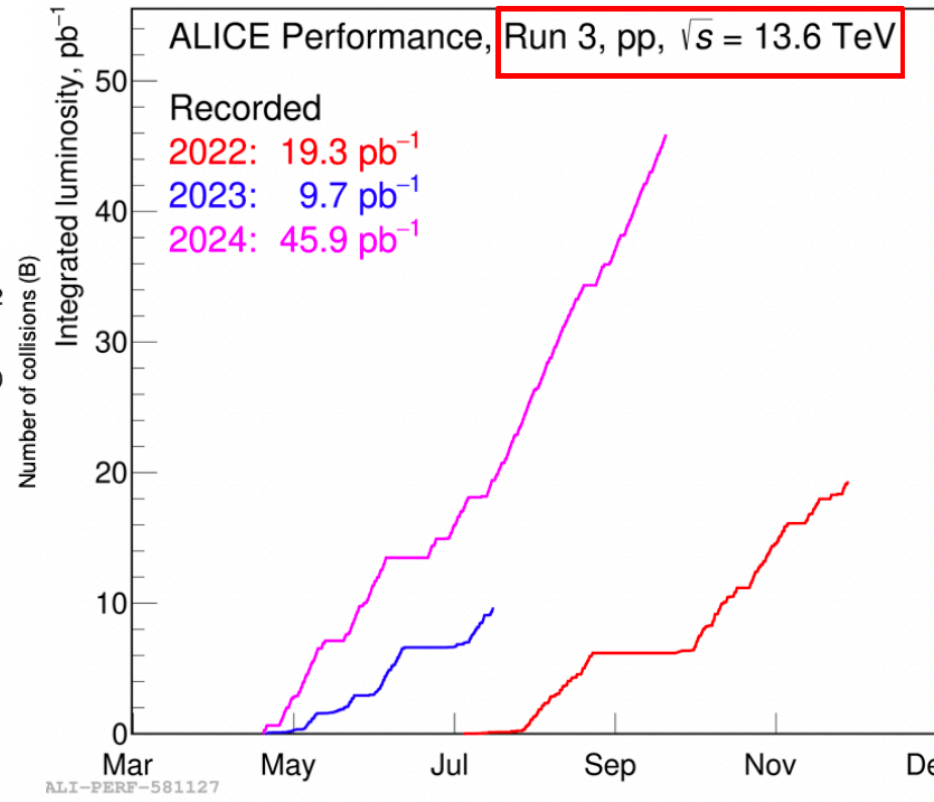
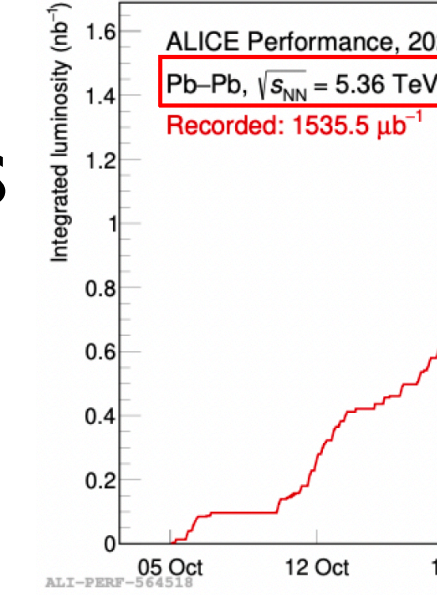
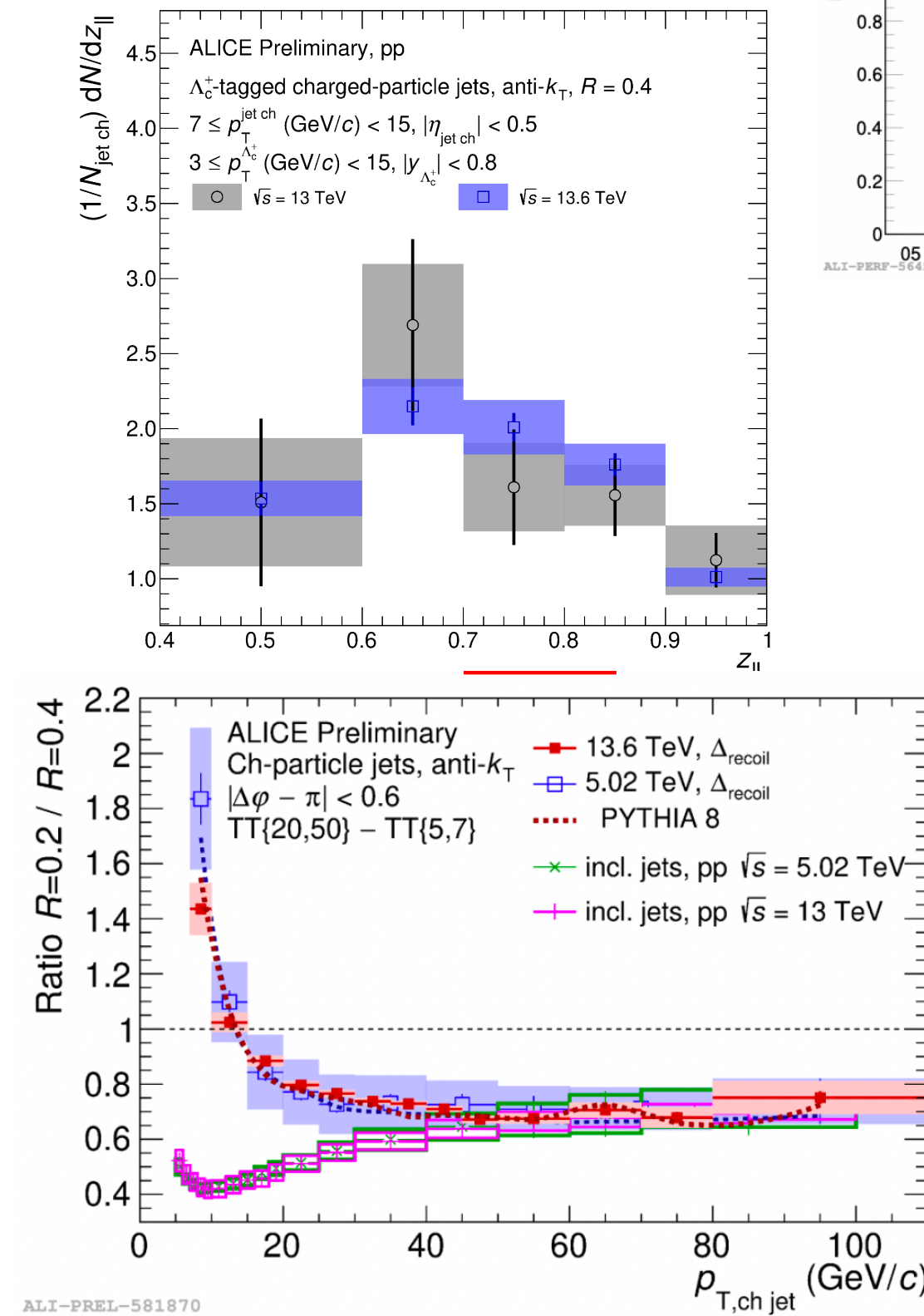


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- Flavor/mass dependence
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- Medium response
- ...

- sPHENIX jet physics will be started soon!



**Stay tuned! Thank you for your attention!**

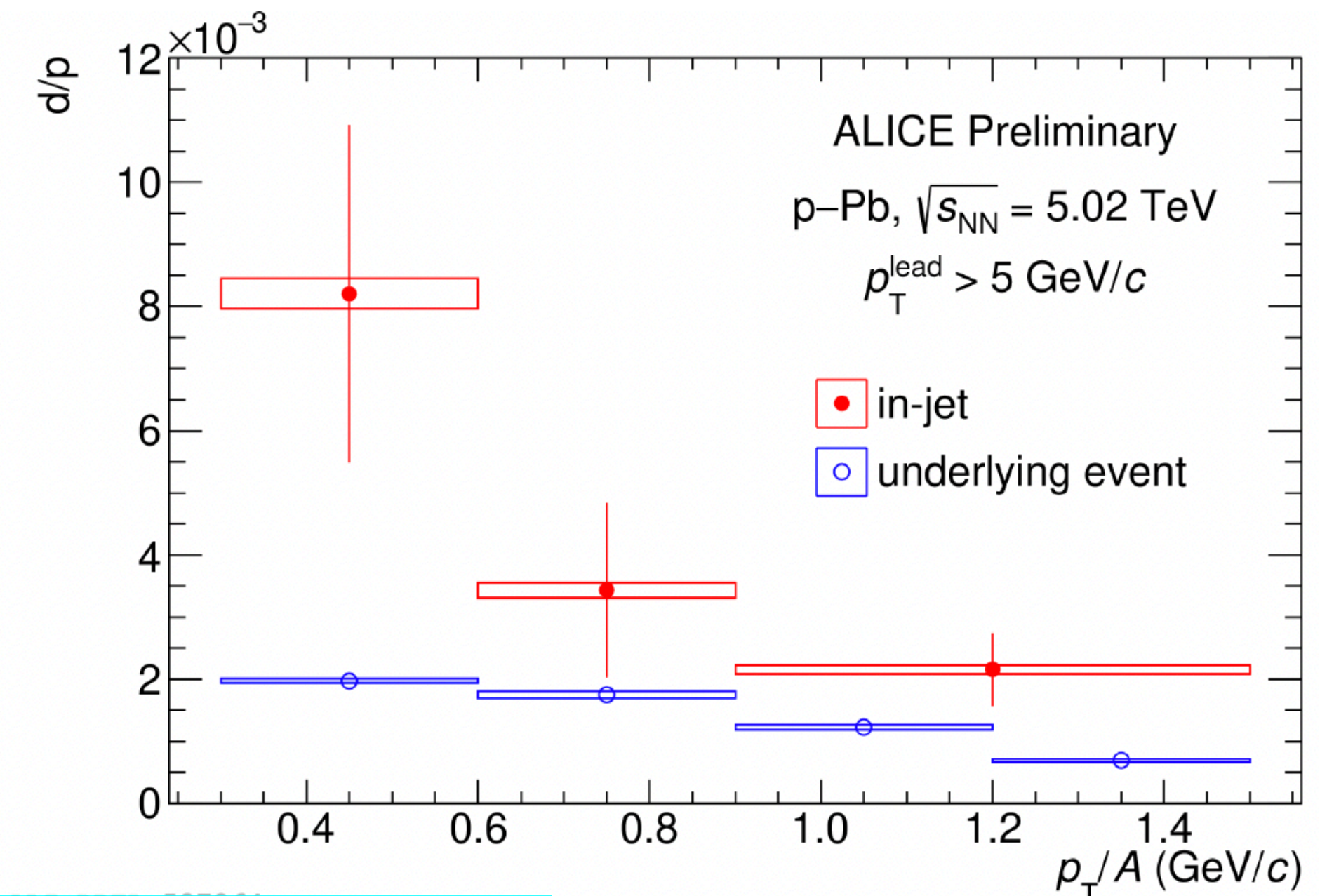
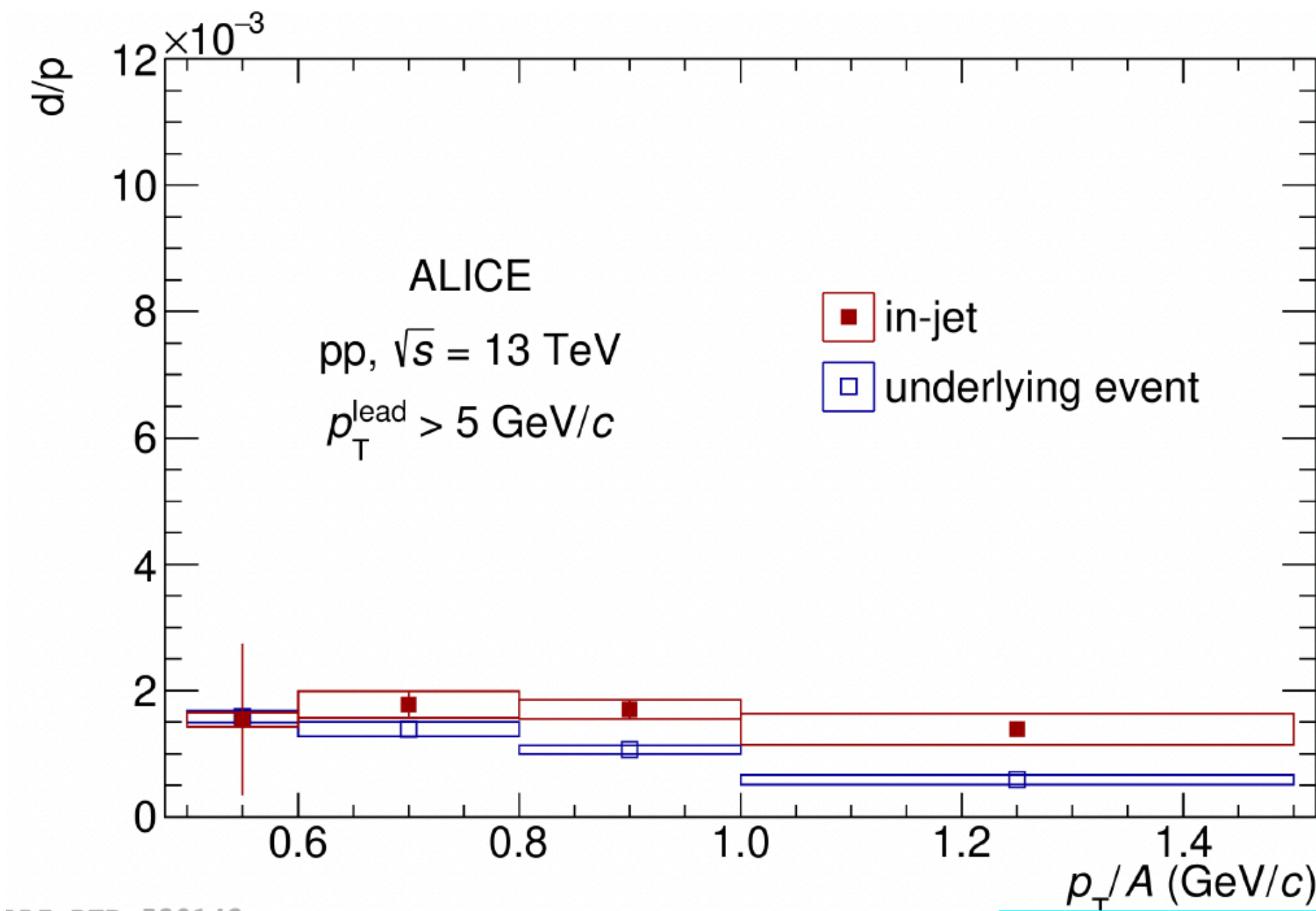
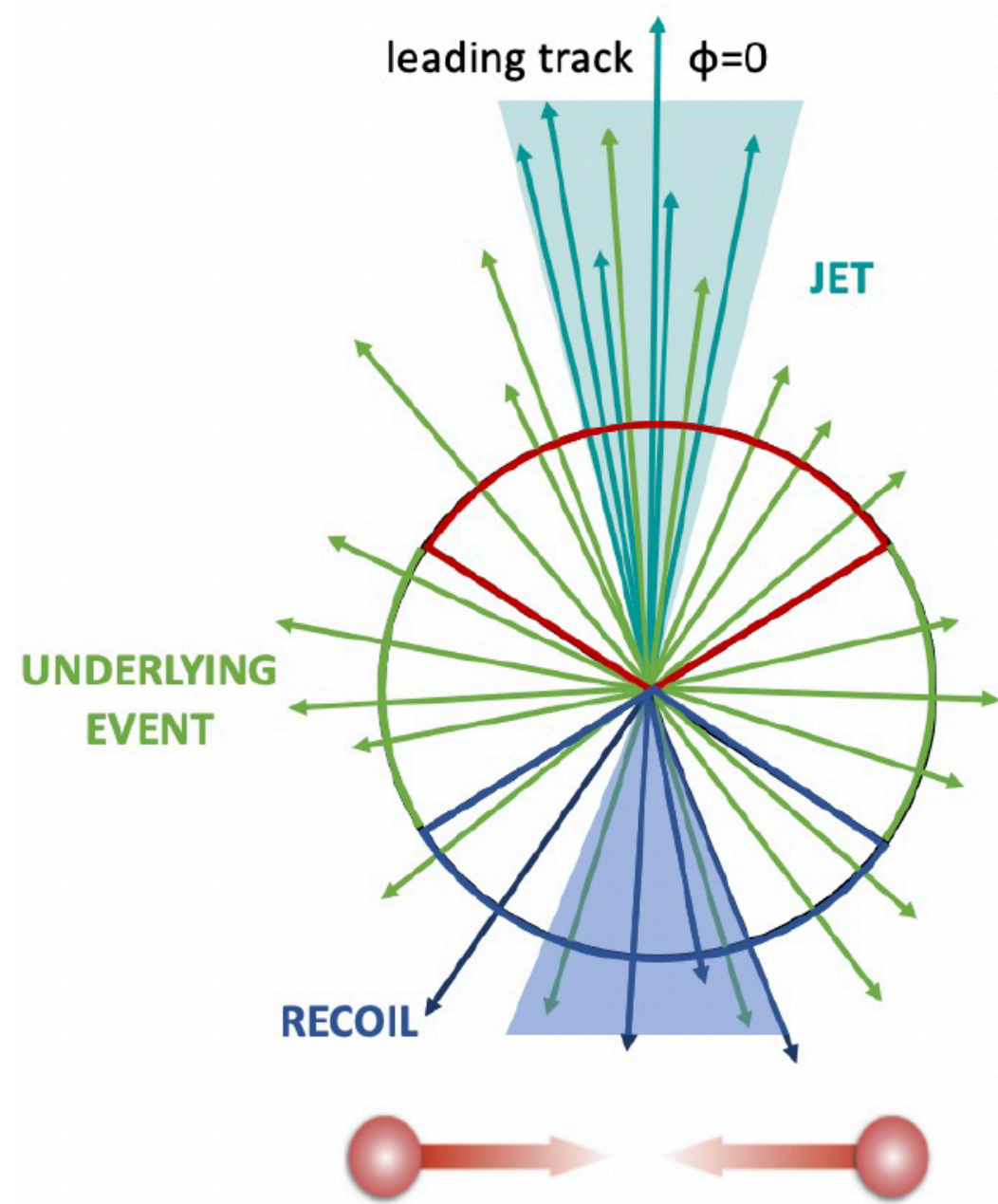
# Backup

## Workshop on “Advances, Innovations, and Future Perspectives in High-Energy Nuclear Physics”

“高能核物理进展、创新与展望”国际研讨会

October 19-24, 2024, *Science Hall, CCNU, No.152 Luoyu Road, Wuhan*  
<https://indico.cern.ch/event/1430136/>

# Light nuclei production in and out of jets

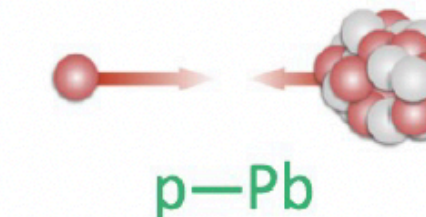


ALI-DER-538143

ALI-PREL-537264

Talk by C. Pinto, Sec. 32, Wed, 10:50

Toward:  $|\Delta\phi| < 60^\circ$   
Transverse:  $60^\circ < |\Delta\phi| < 120^\circ$



- Using the 2-particle correlations to study the nuclear particle production in jets and in Underlying Events (UE)
- D/p ratio in jets is increased with respect to in UE events
- Higher d/p ratio in jets in p-Pb collisions wrt in pp  $\rightarrow$  hints of different particle composition in and out of jets