Probing the Quark Gluon Plasma with Jets

Yi (Luna) Chen, Vanderbilt University

APS GHP, Mar 15 2025

Jets and the QGP

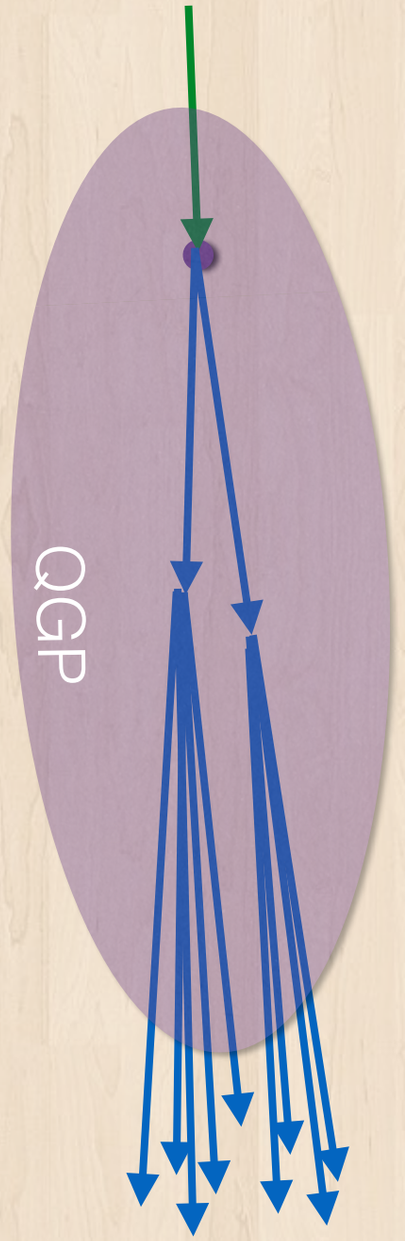
Submerge jet into the QGP

Different mechanisms at play, e.g.

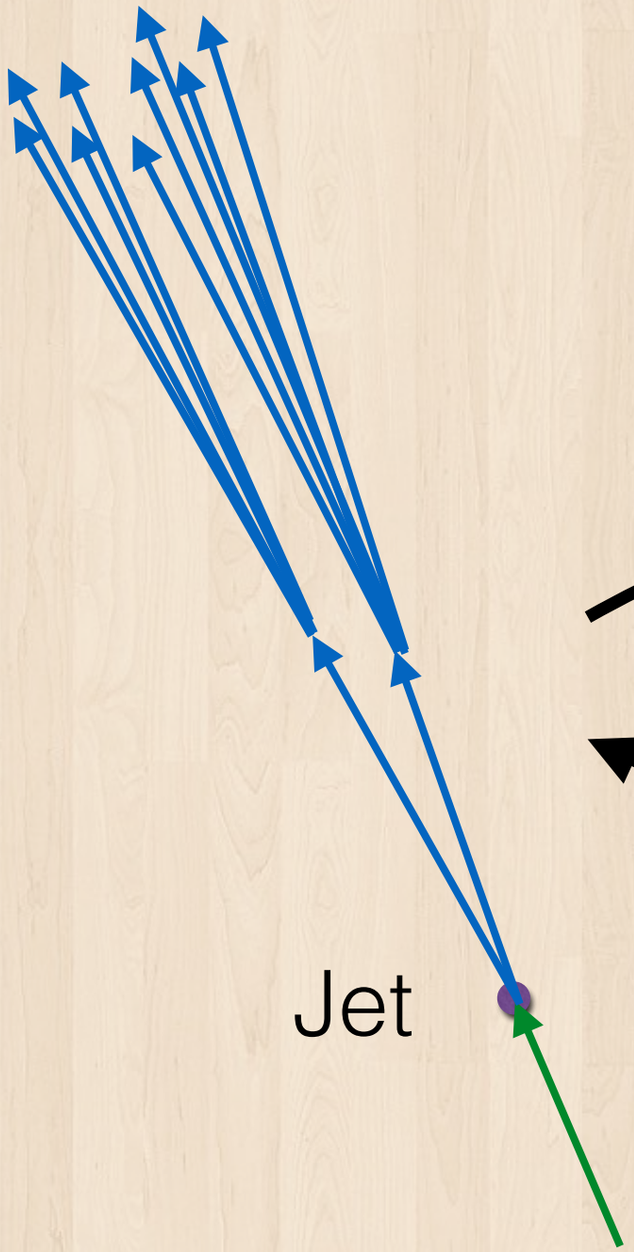
- collisional vs. radiative energy loss?

And many questions we can ask

- Can QGP **resolve** the shower?
- How does energy **dissipate** in QGP?
  - **Wake** effect?
- Is QGP “smooth” or “lumpy”?
- **Color charge** dependence?
- **Space-time** picture of parton shower?
- …



Two sides of jet quenching



Jet

Energy deposit
Medium response

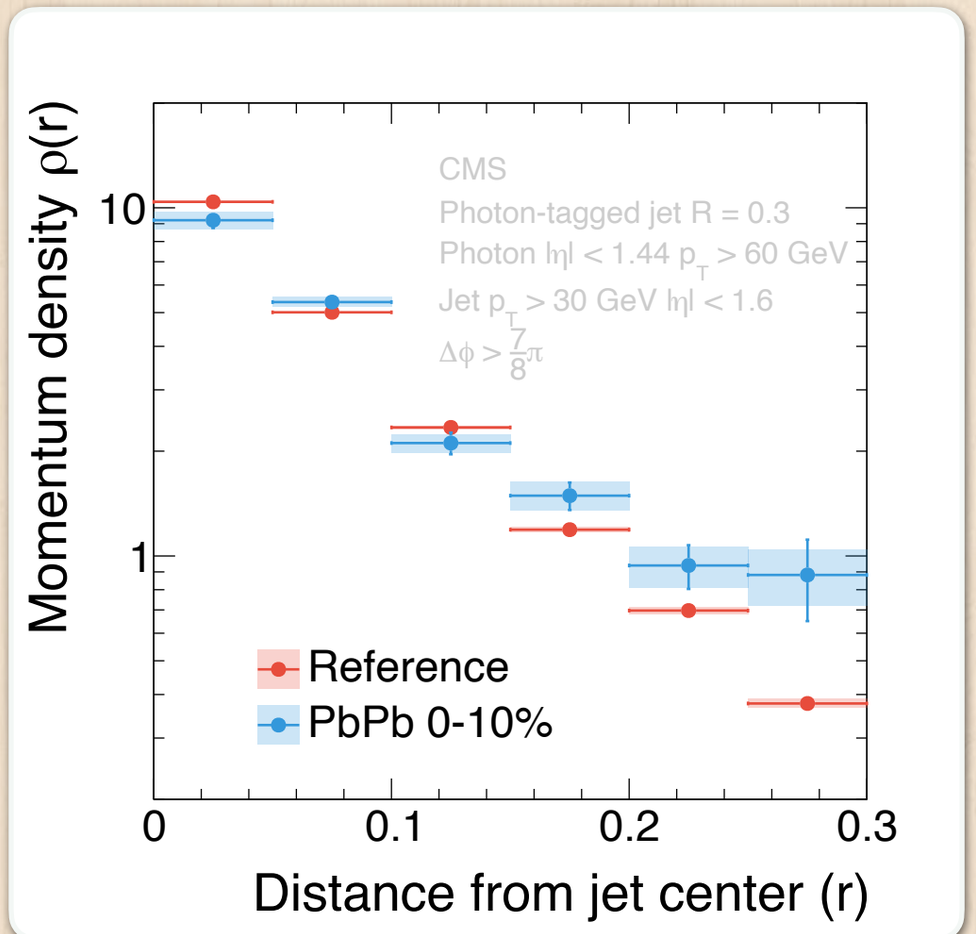
Modification
Energy loss

QGP

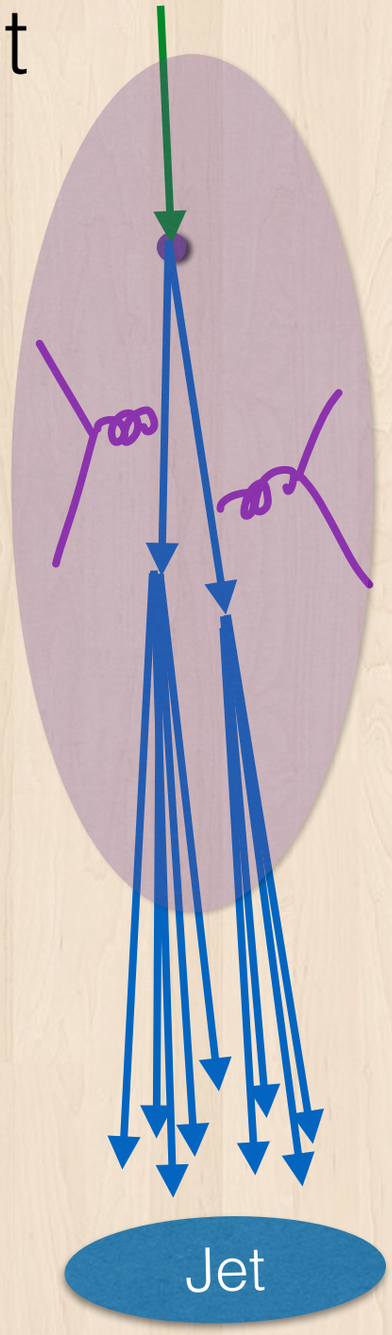
early on

What do we know so far?

Energy gets transported away from the jet



Energy distribute farther from jet



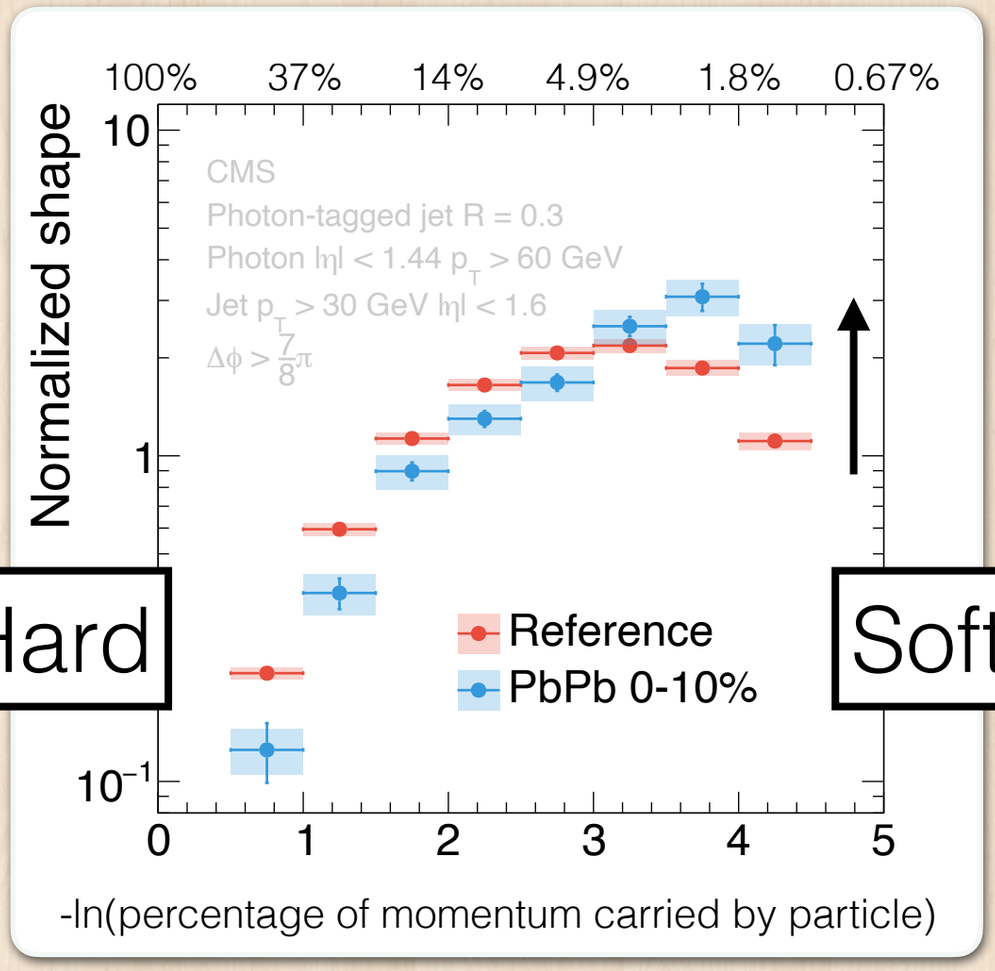
This energy extends very far

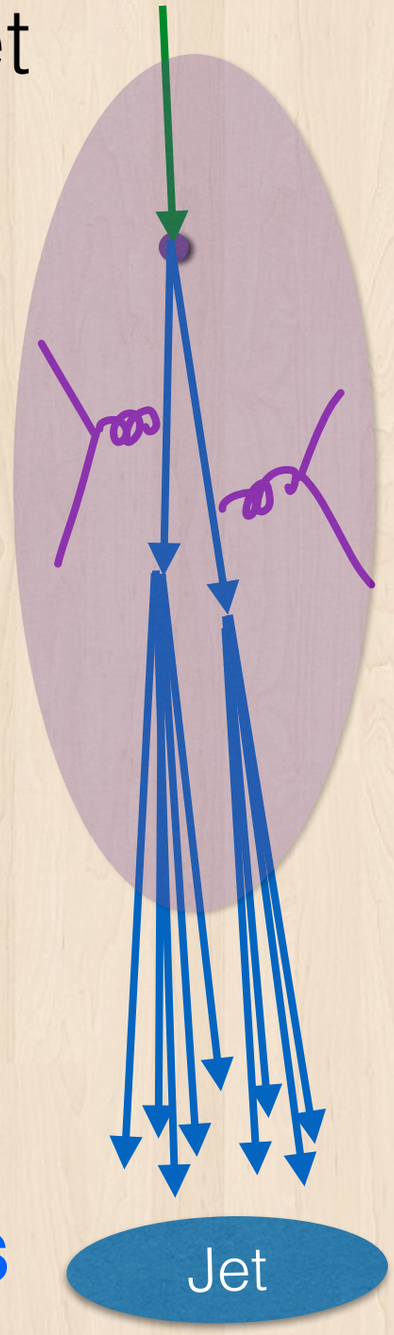
PRL 122 (2019) 152001

early on

What do we know so far?

Energy gets transported away from the jet





Fragmentation function: a lot of **soft particles**

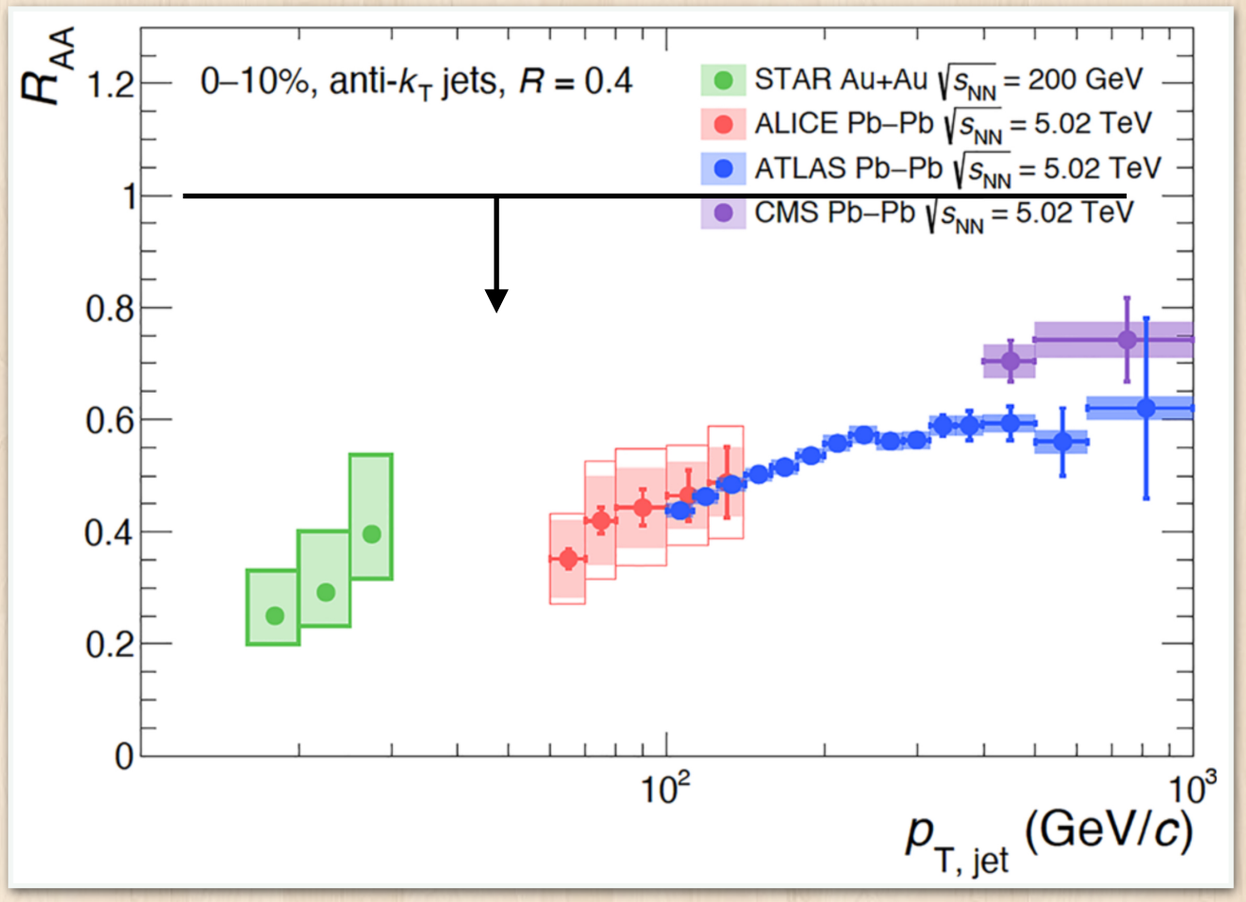
PLB 785 (2018) 14

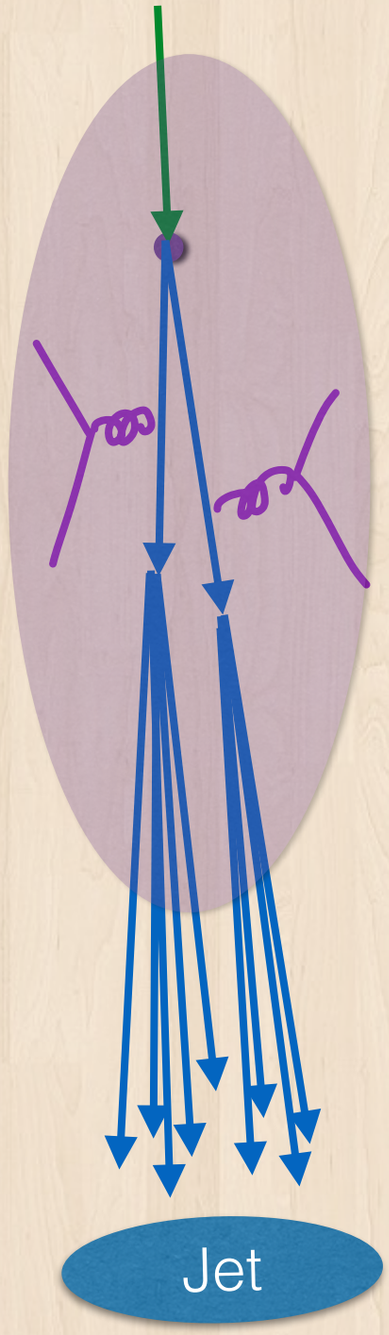
early on

What do we know so far?

Energy gets transported away from the jet

More suppressed





Cross section reduced since jet area catches smaller amount of energy

A lot of excitement in recent years

- **Pushing boundaries**: phase spaces (momentum scale and jet size) and types of jets
- **Hunting specific effects**: wake effect and (refilled) dead cone as examples
- **Jet (sub)structure** studies with ever greater detail
- The rise of **global analysis** for parameter extraction and model studies
- …and many more

Goal today: give some examples on recent studies

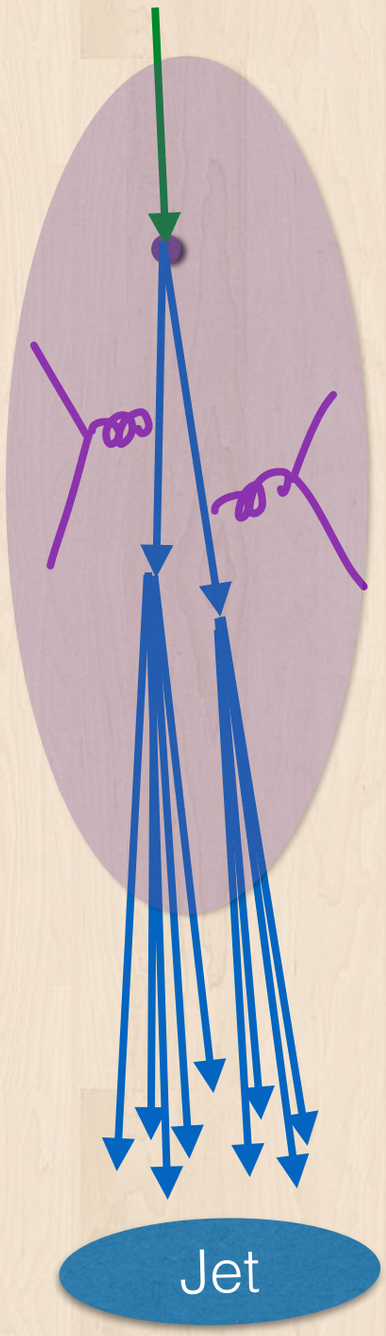
Pushing boundaries

Large size jets

- Jet quenching effect
  = energy gets spread out

  - Enlarge jet size to collect back those energy

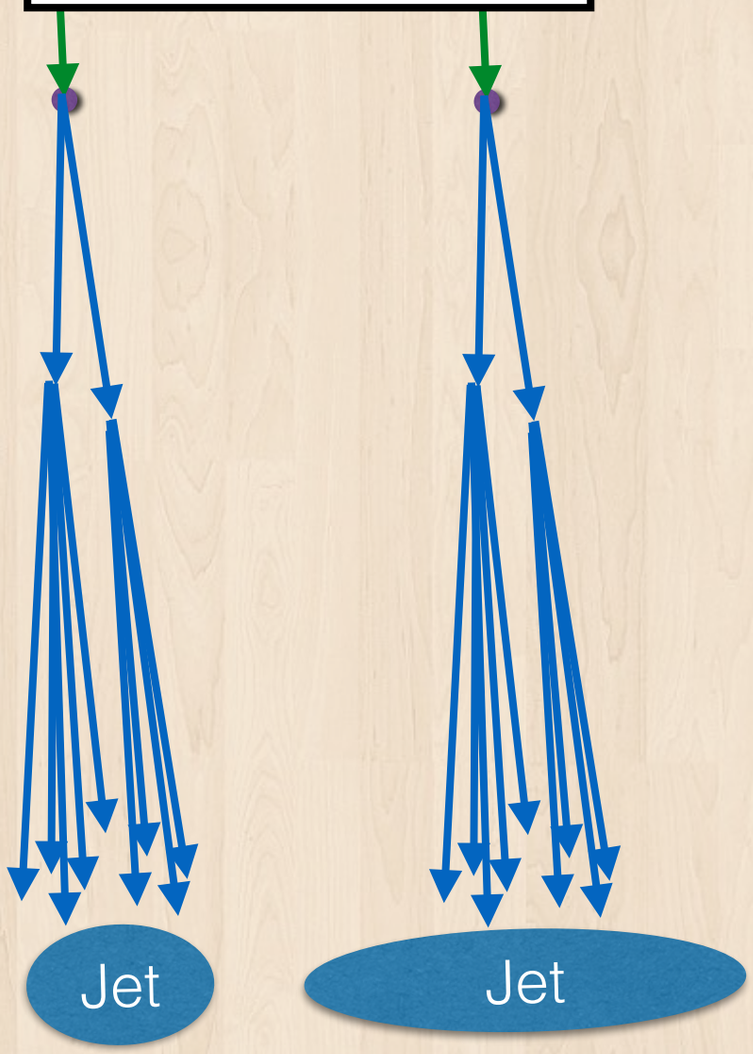
- Interplay between energy recovery and suppression of wide jets

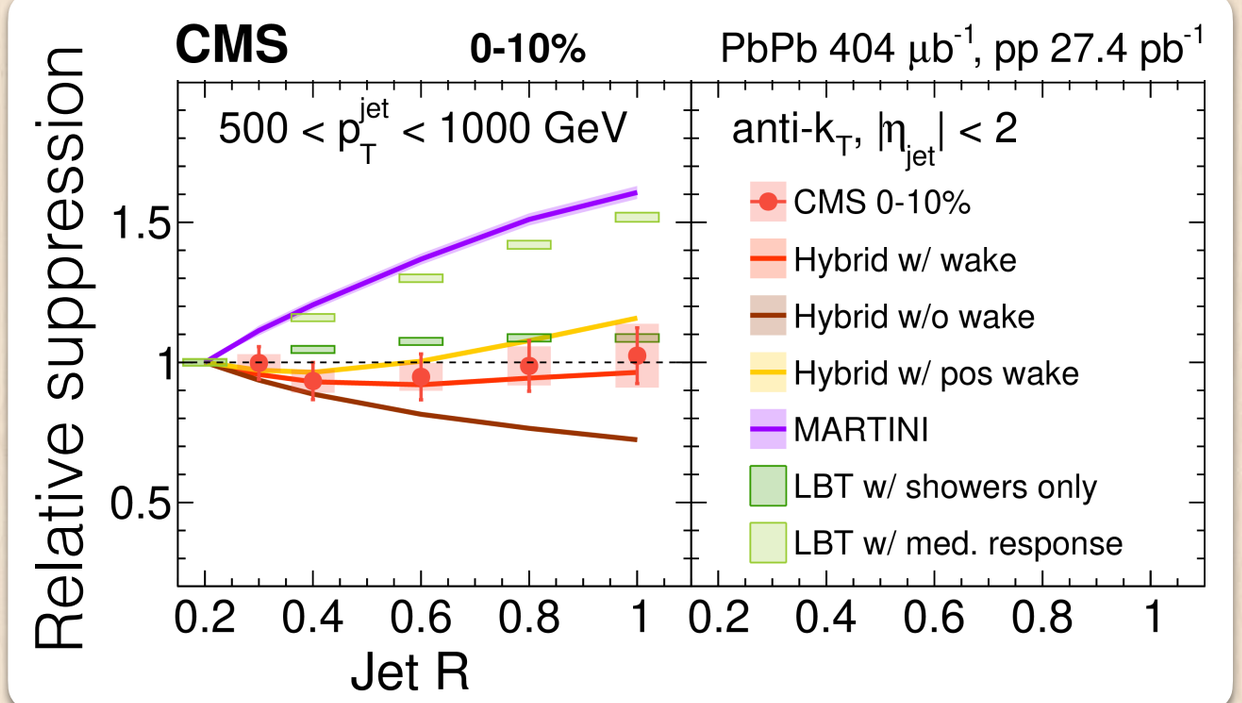


Jet size dependence

Change jet size
(~energy capture area)

R = 0.2 - 1.0!





At very high momentum, not much size dependence

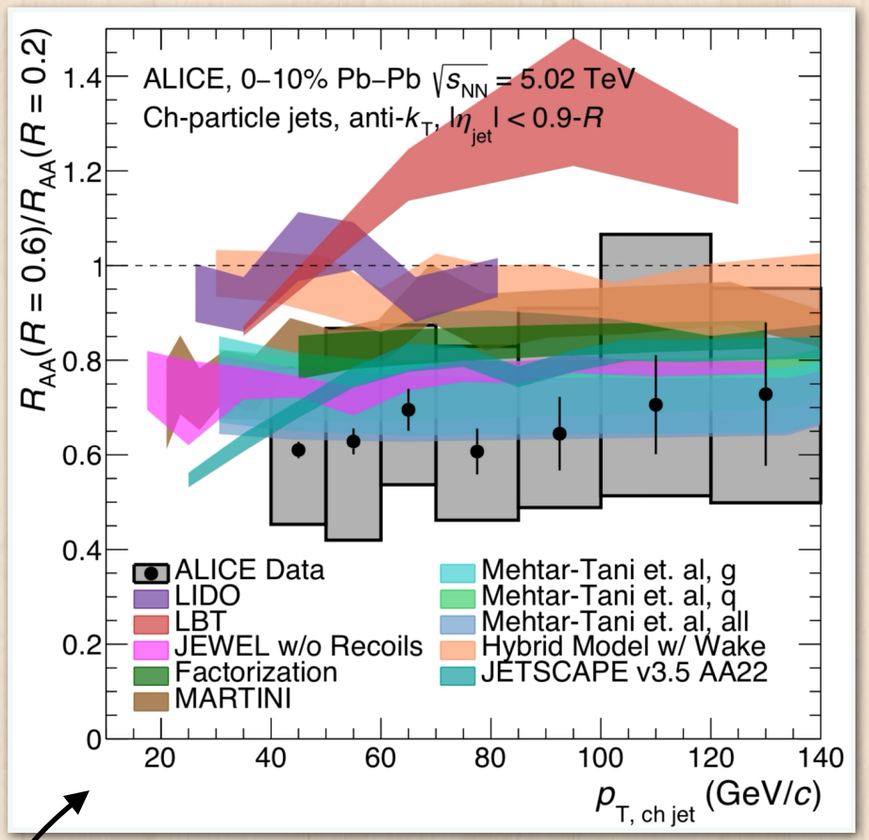
Balance between energy recovery and large jet suppression

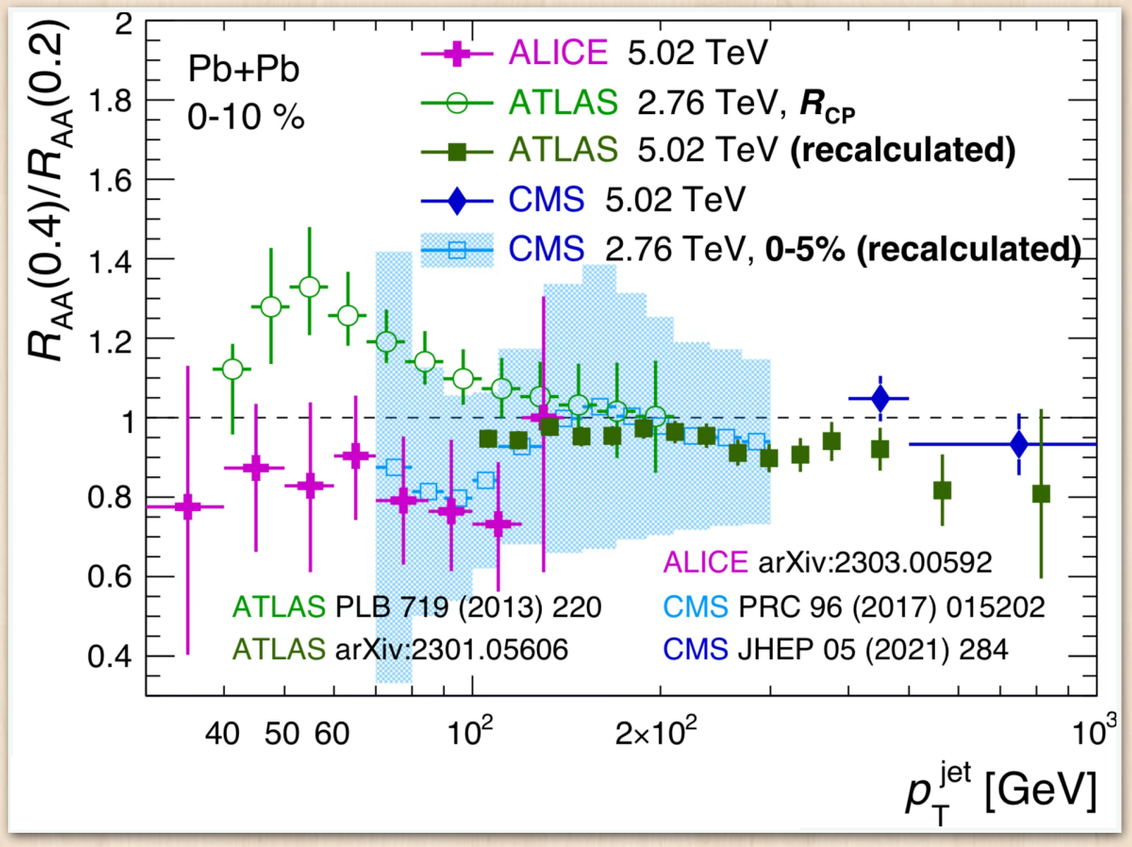
JHEP 05 (2021) 284

Jet size dependence

Going lower in momentum → larger medium effect

Large jet more suppressed





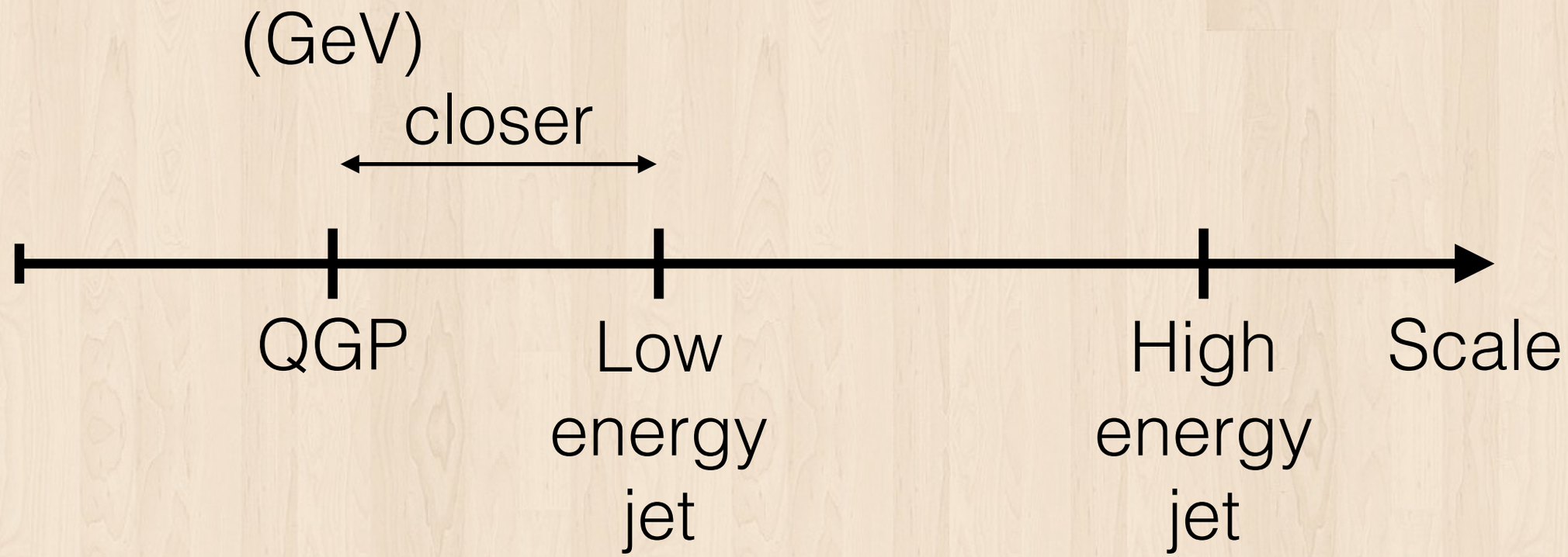
Large radius jet slightly more suppressed

Covering large range of phase space

PLB 849 (2024) 138412

Plot from Yeonju Go talk in LHCP2024

Pushing to even lower scale



Medium effect more dominant at low jet energy

See e.g. 2308.16131, 2308.16128, …

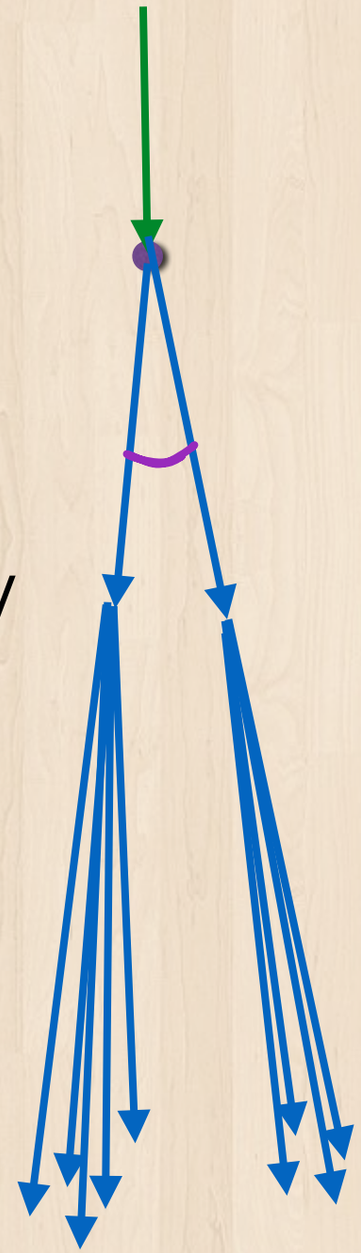
RHIC program is very valuable in the low energy range

What can substructure tell us? — example

Looking at the angle

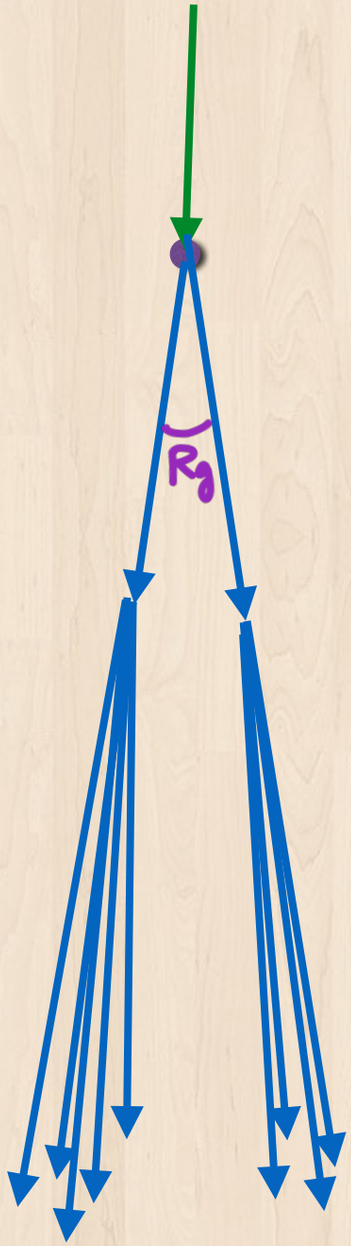
small

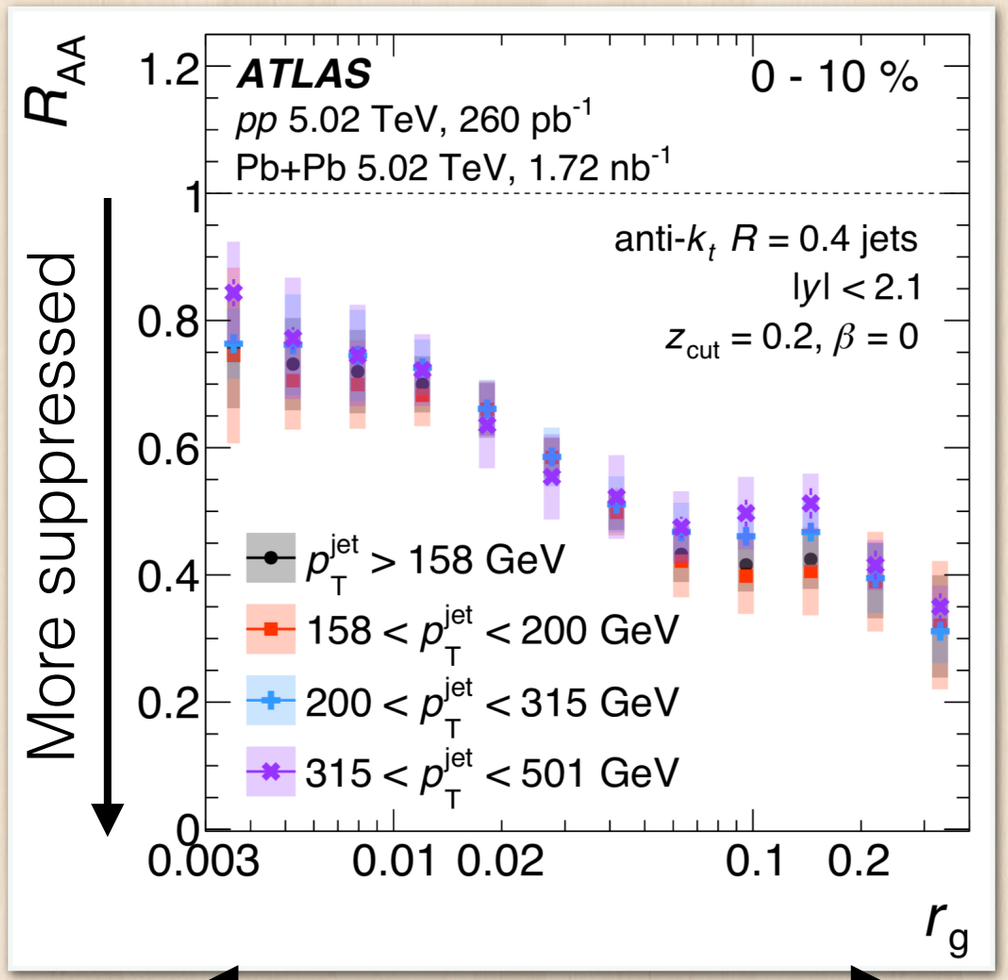
large



If QGP can see into jet shower,
wider ones should interact differently

Looking at the angle





narrow ⟷ wide

Larger suppression for large angle jets

Jets get narrower!

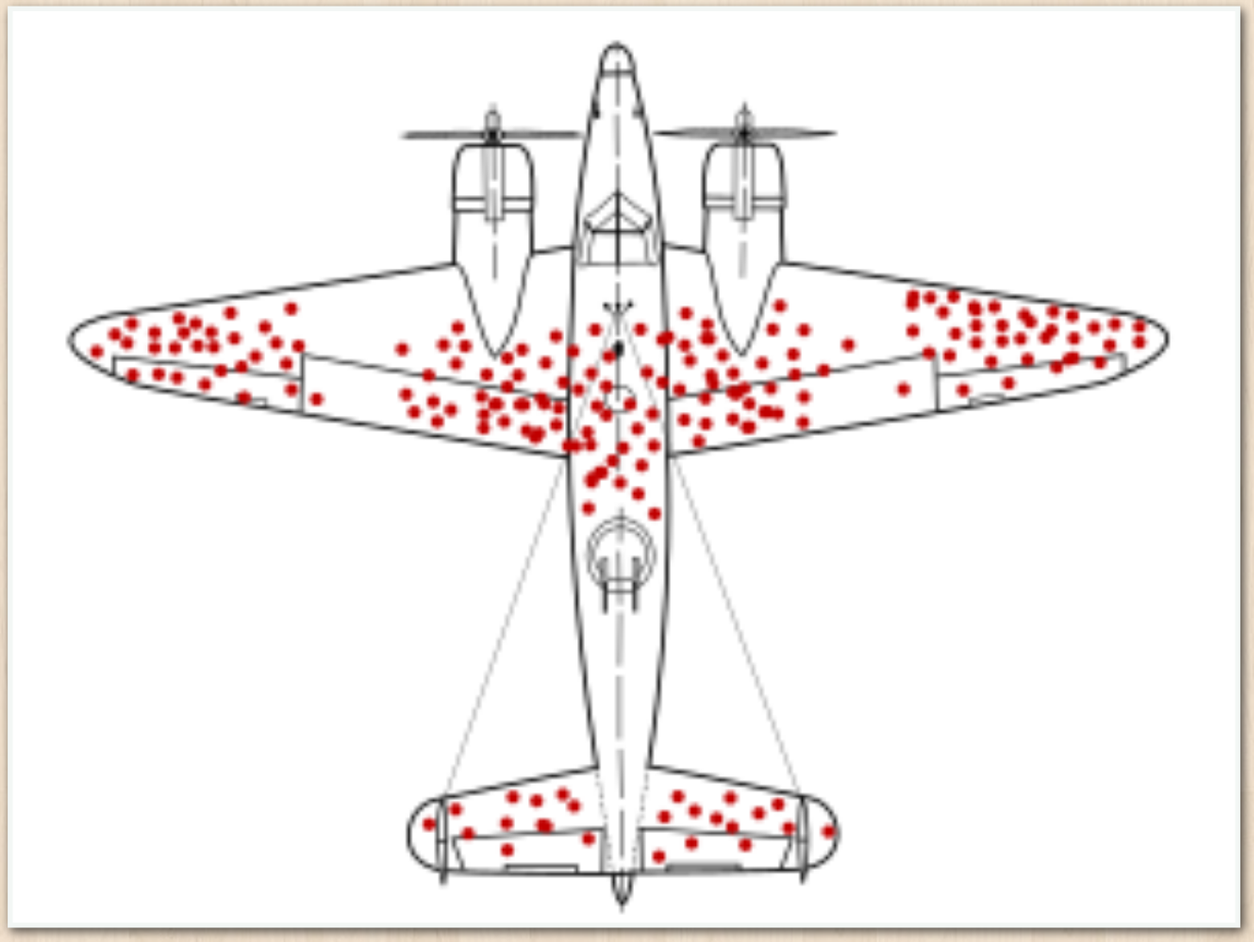
So…can QGP resolve jet internal structure?

PRC 107 (2023) 054909

See also PRL 128 (2022) 102001

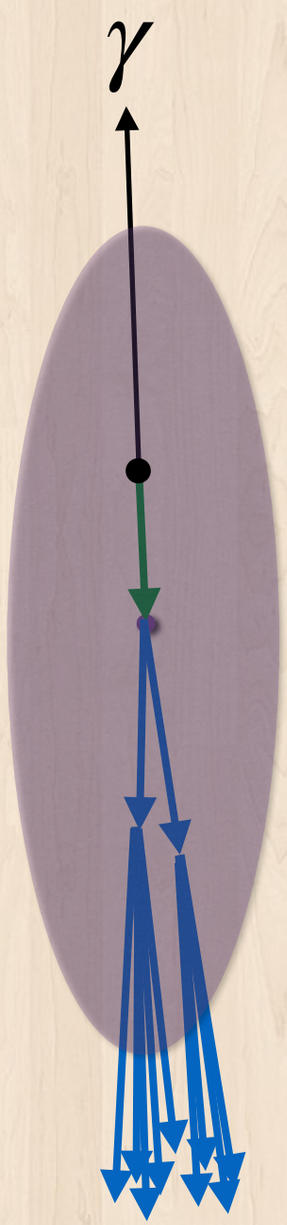
Survivor bias?

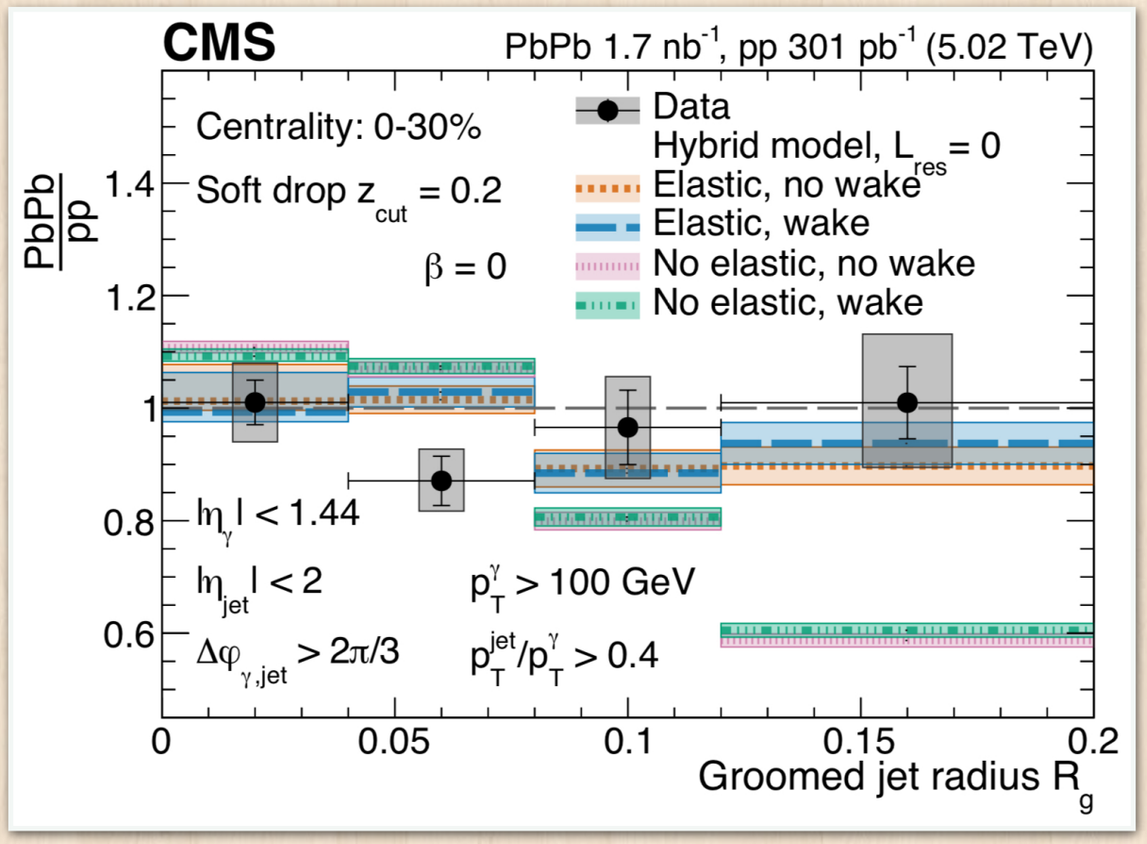
Are jets becoming narrower?
Or only narrow jets survive?



Photon-tagged jet angle

Use color-neutral tag (γ) to reduce survivor bias

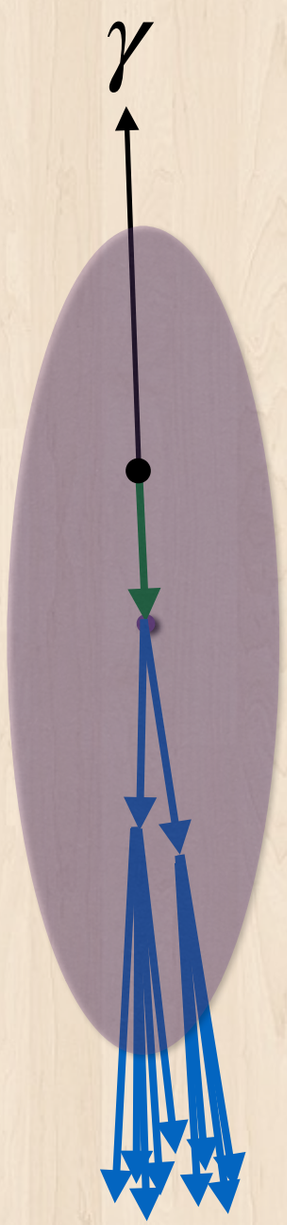


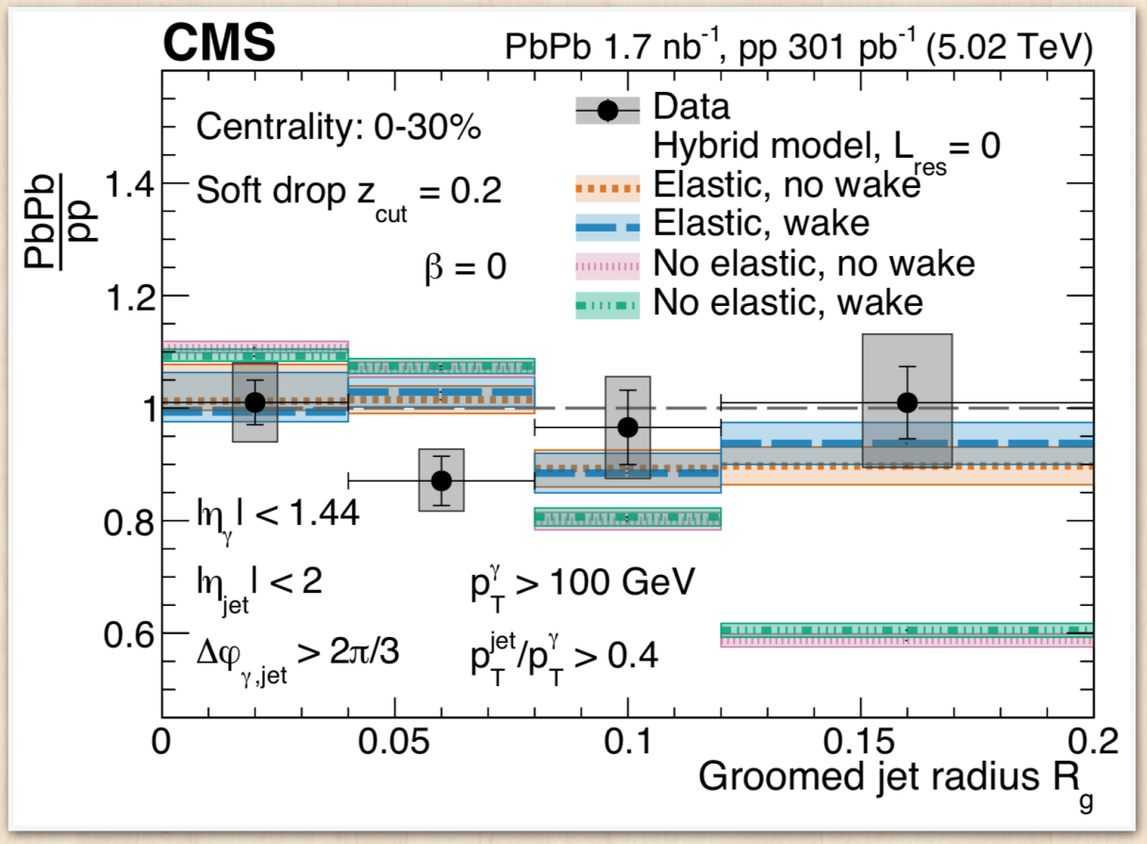


A different trend is seen!

Photon-tagged jet angle

Use color-neutral tag (γ) to reduce survivor bias



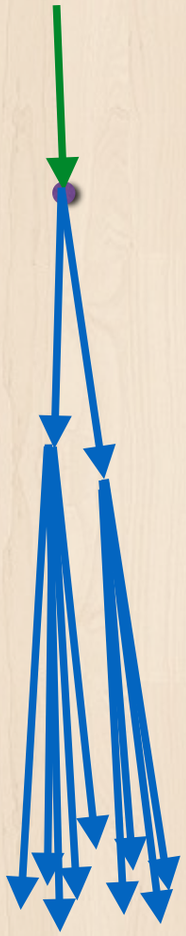


Importance of **elastic scattering** in this model

Opportunity to disentangle medium effects

Study further: differential

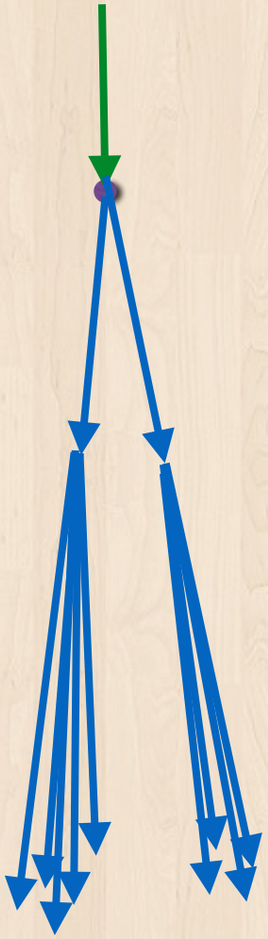
Narrow ⟷ Wide



Within each type of jets,
how do things look?

Study how balanced things are

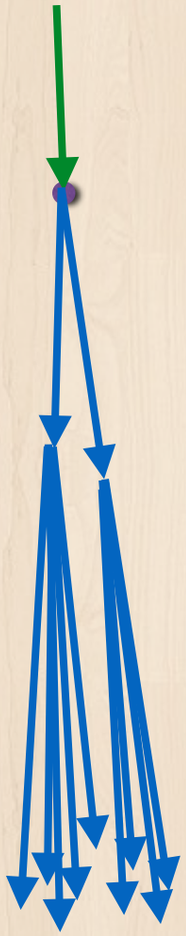
If QGP can resolve jet internal structure,
things should get more imbalanced

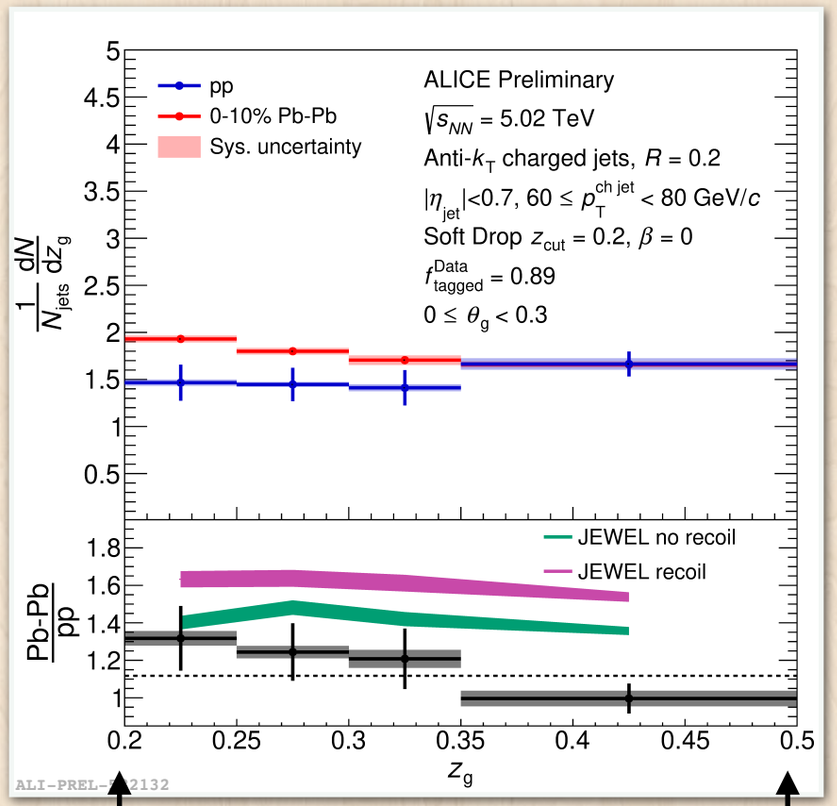


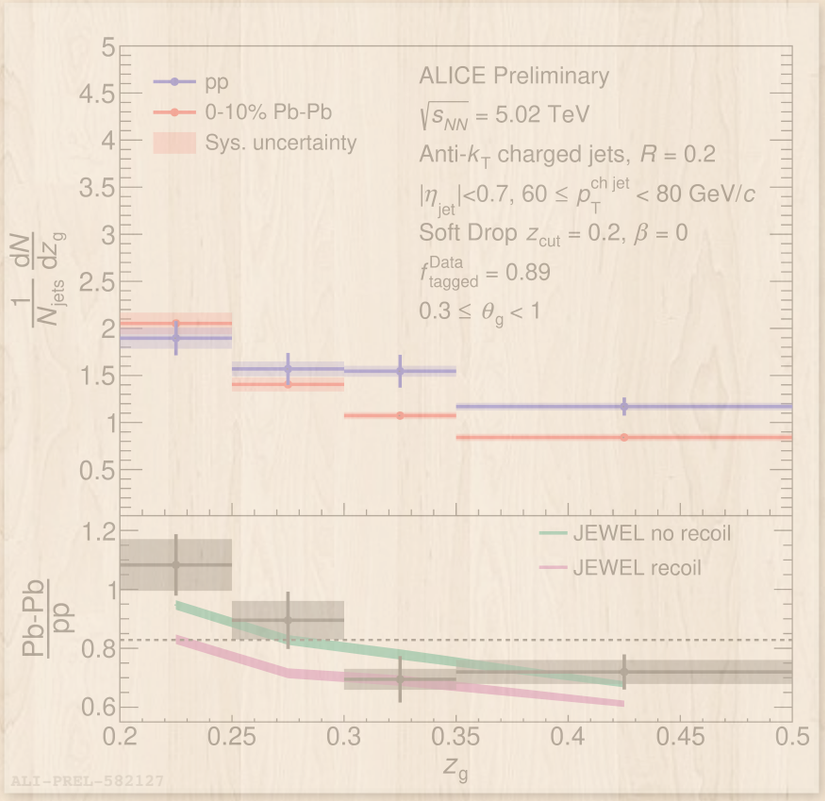
Study further: differential

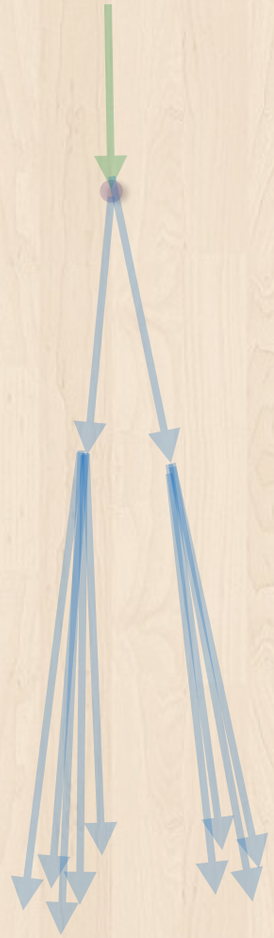
Narrow

pp **PbPb**





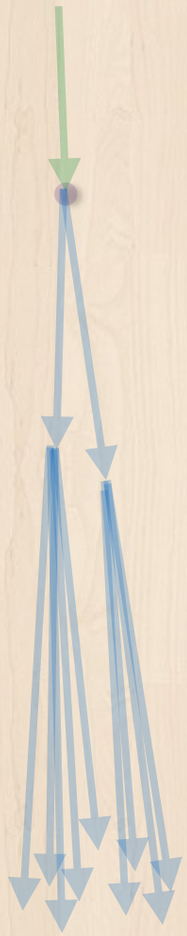


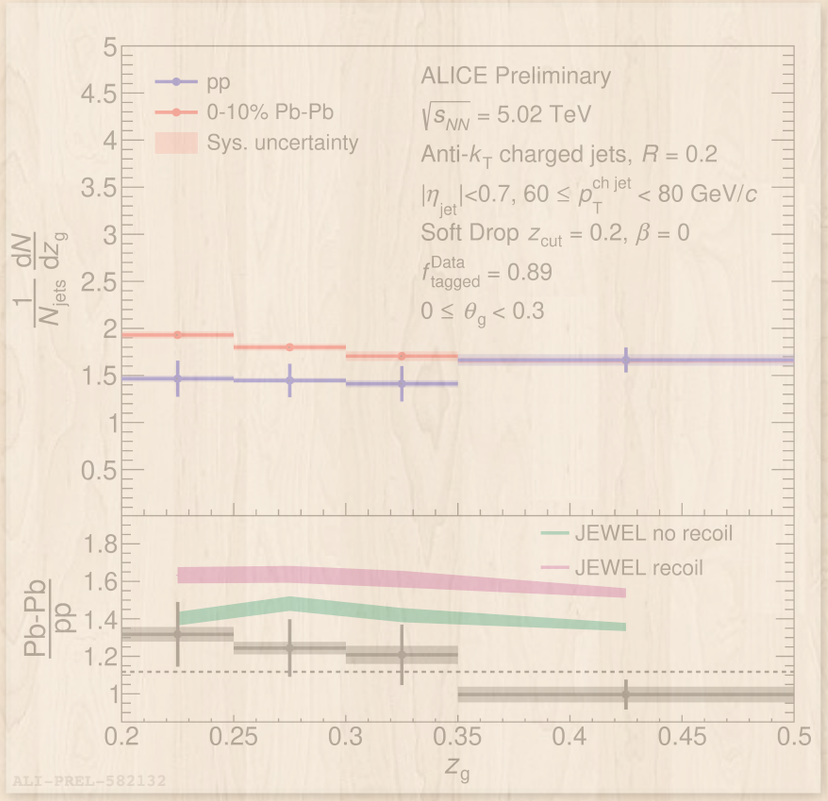


Imbalanced configuration

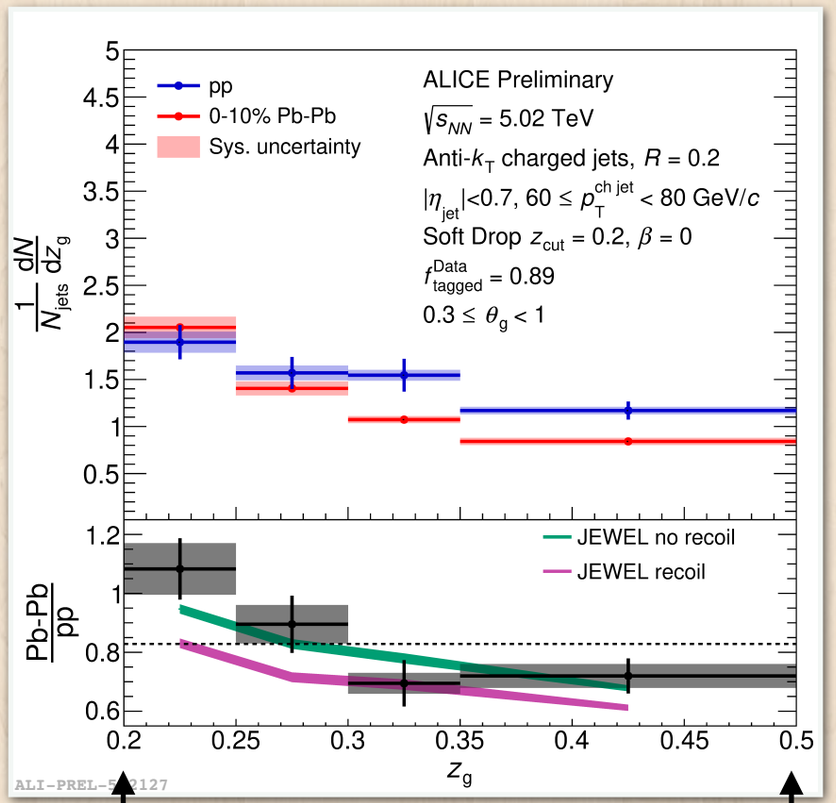
Balanced configuration

Study further: differential

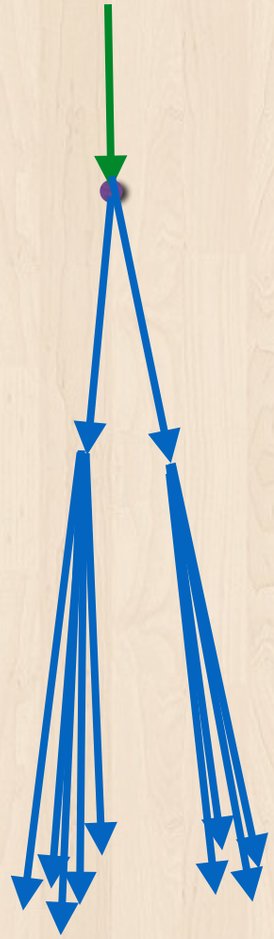




pp **PbPb**



Wide

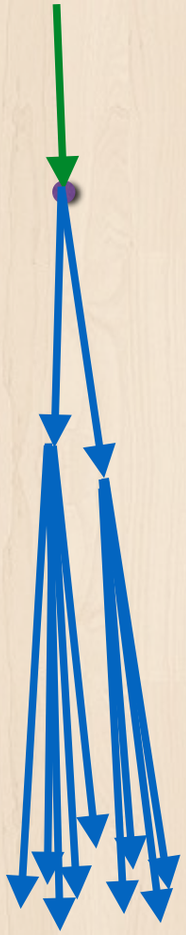


Imbalanced configuration

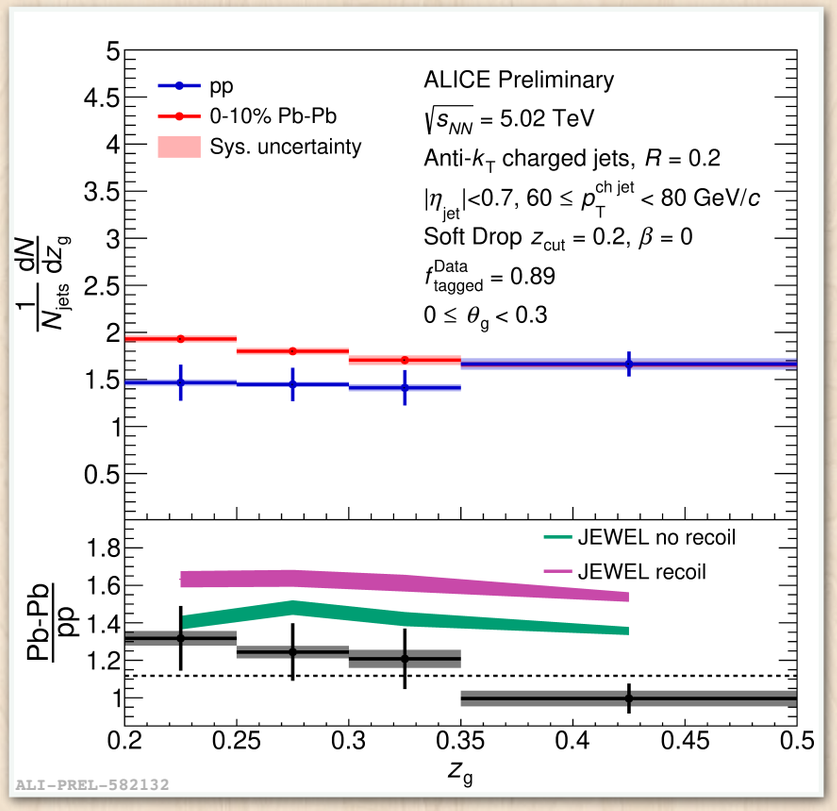
Balanced configuration

Study further: differential

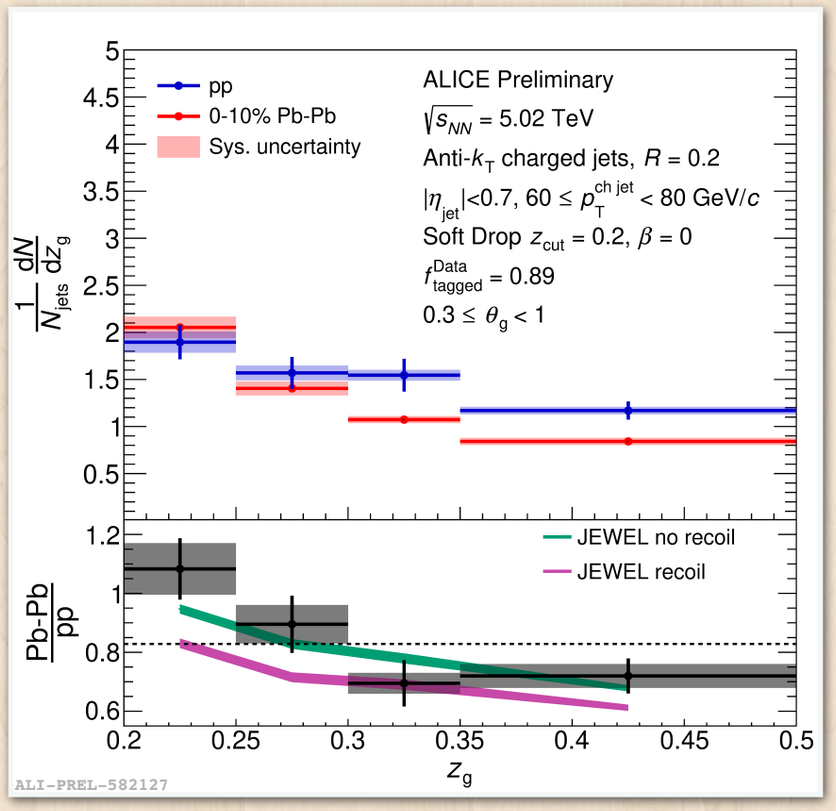
Narrow



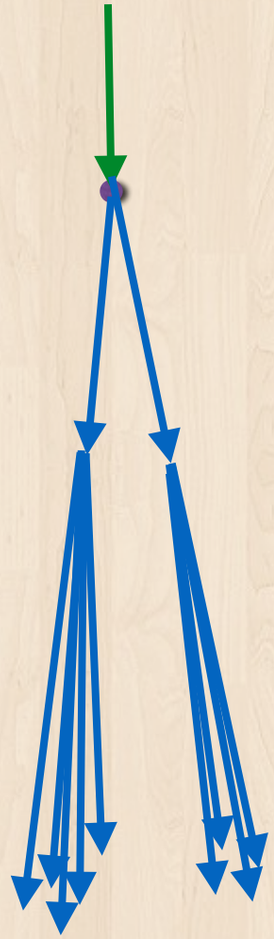
pp **PbPb**



pp **PbPb**



Wide

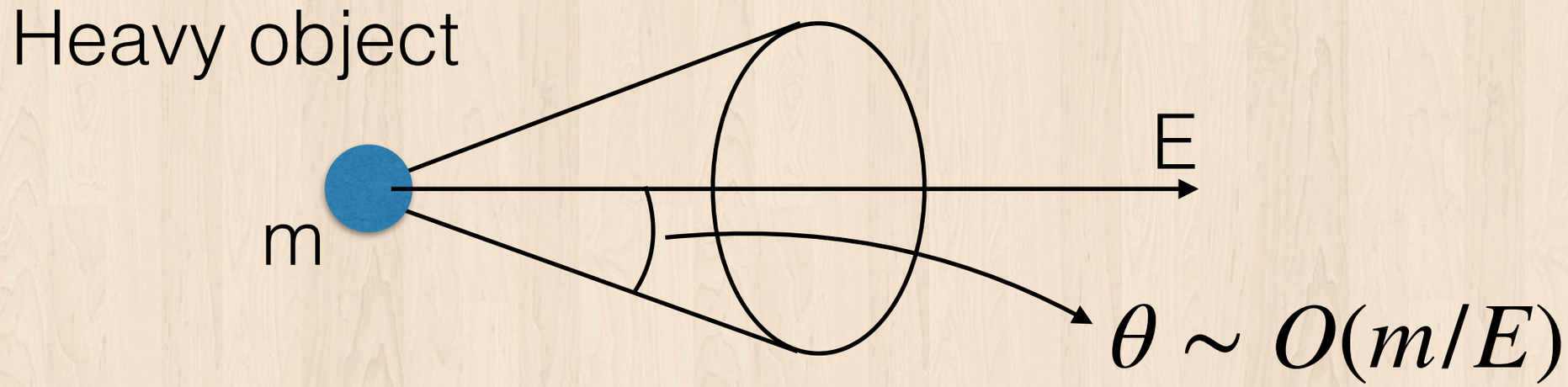


Wide jets are becoming more imbalanced

Different parts of hard structure act independently?

New venues for quenching studies

The dead cone effect



Dead cone effect:
Suppression of emission in the forward direction of the heavy object

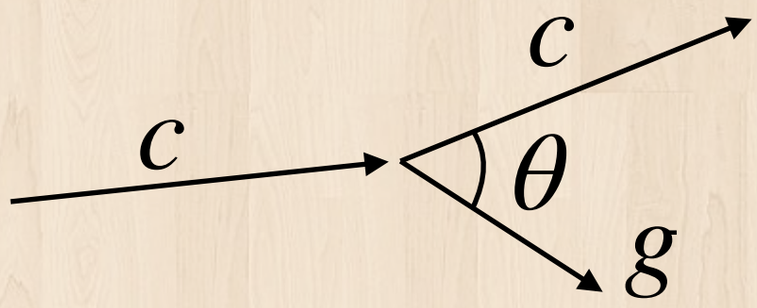
If we see something in HI, it is from QGP effect

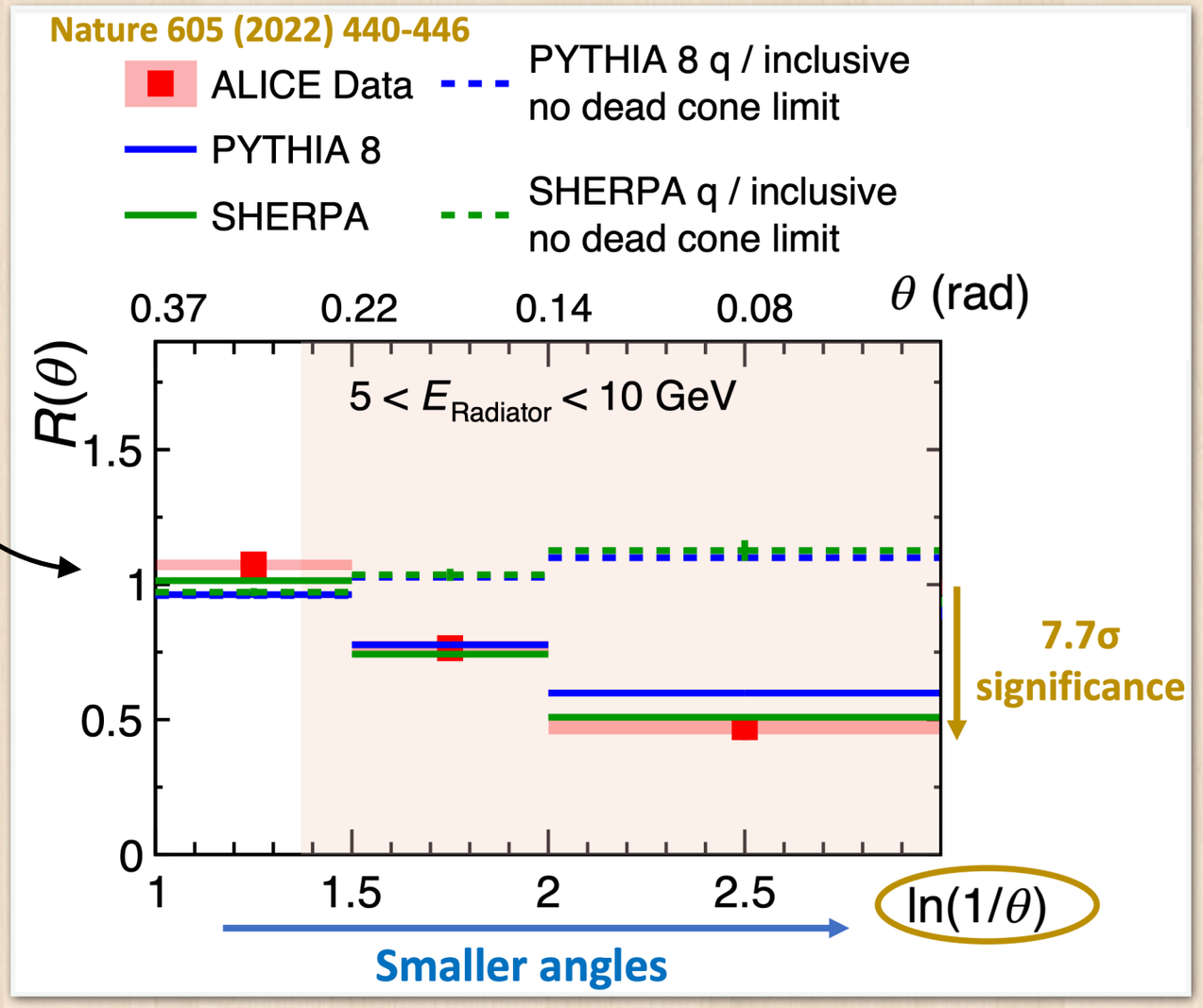
Dead-cone effect in pp

Use **jet substructure** techniques to extract **emission angle** θ of charm quark in a jet

$$\frac{D^0\text{-tagged jets}}{\text{light flavor jets}}$$

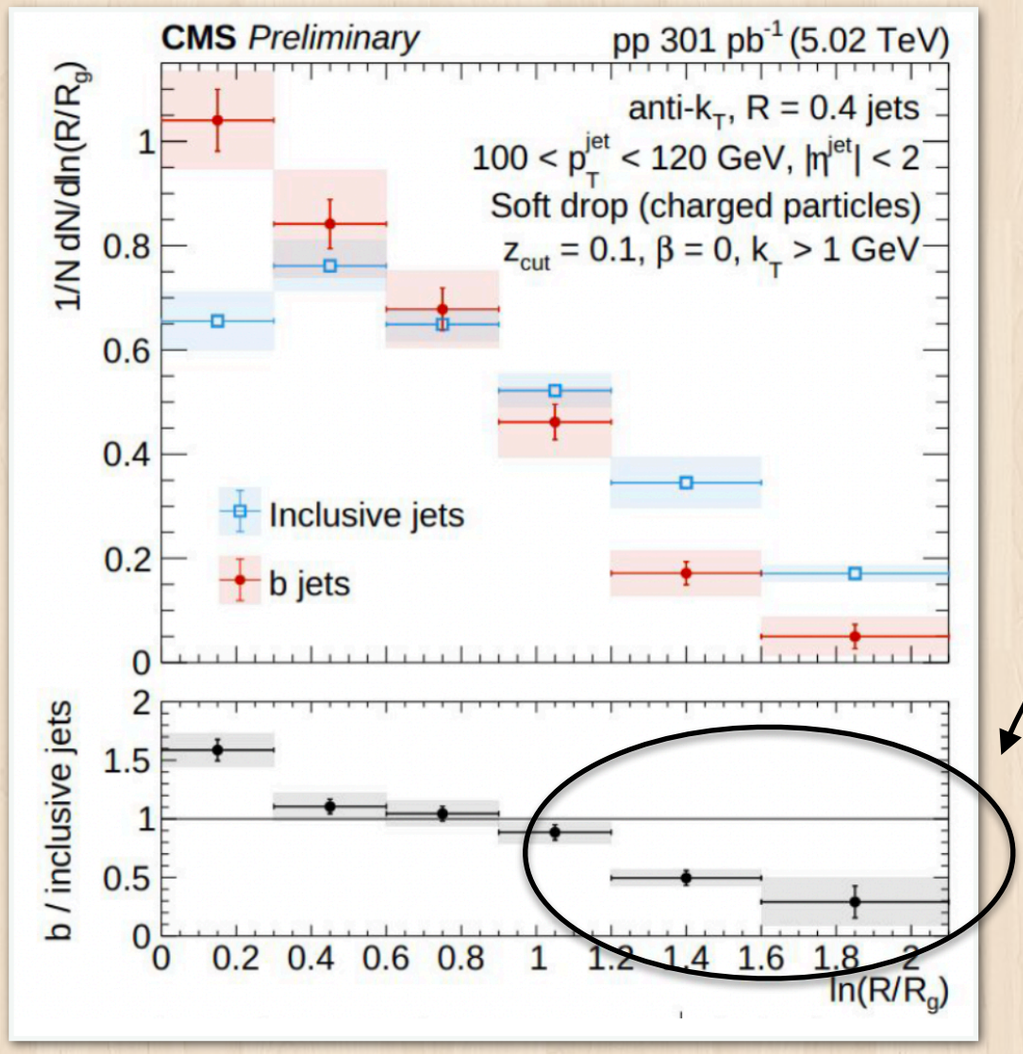
Clear suppression at small angle





Since then…

We see this in b-jet (pp) also!



Small angle

Also many detailed studies in pp (*)

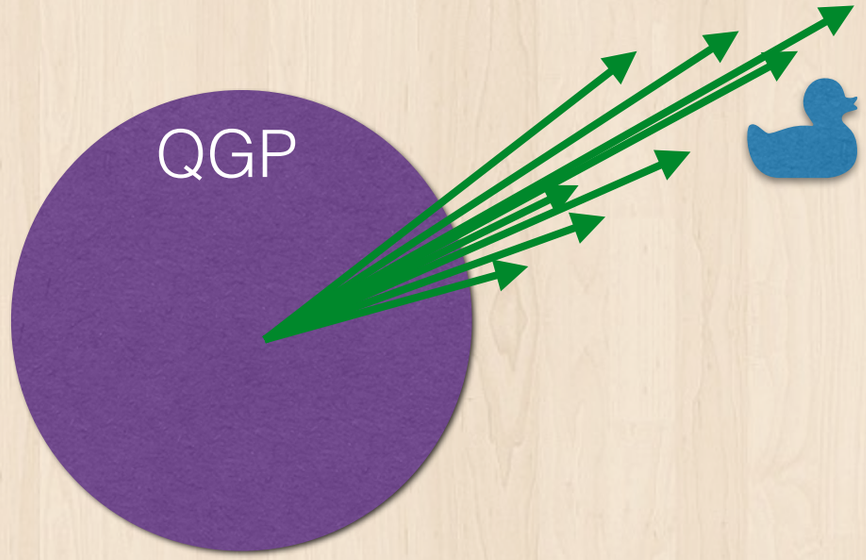
Depletion due to dead cone effect

Exciting to see if this gets filled up in heavy-ion

(*) See e.g. talk in HP2024

The wake effect

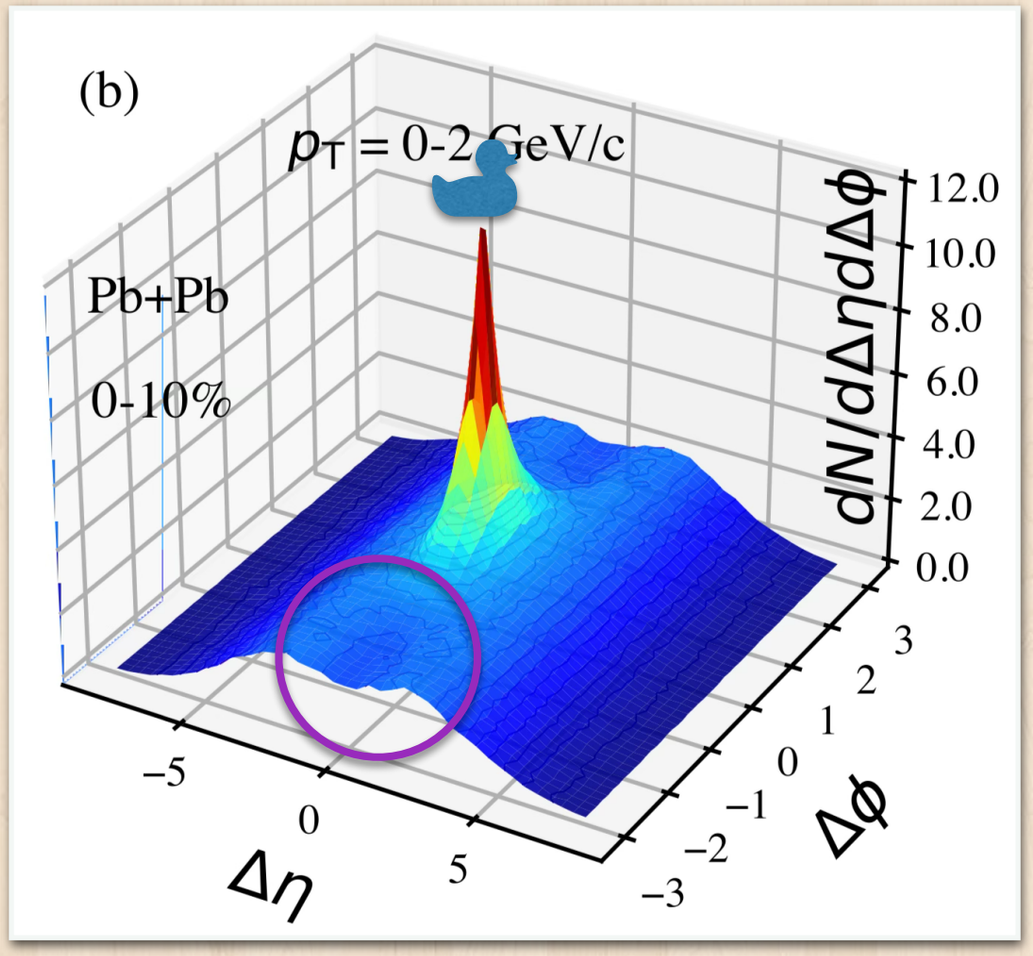
Ripples in water



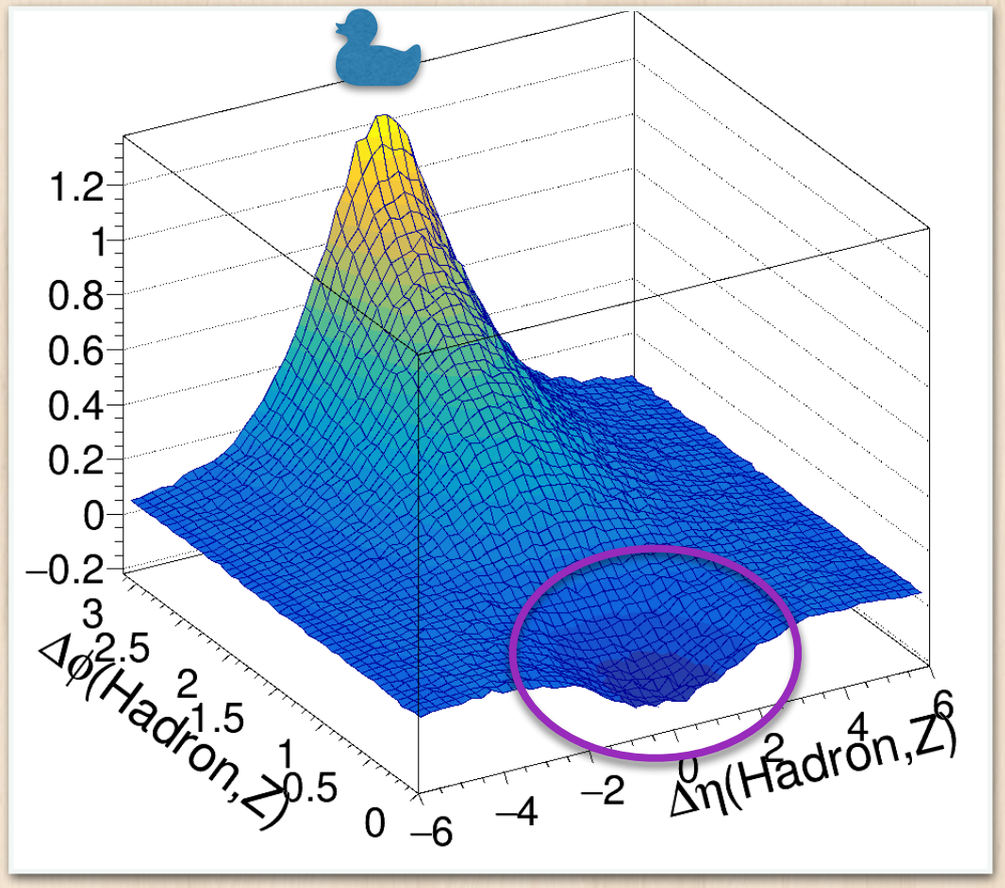
“Ripples” in QGP droplet

Wake effect in models

CoLBT



Hybrid (wake only)



Dominant: water pushed by duck (coincide with jet)

Negative wake comparatively smaller but far from jet

: Jet direction

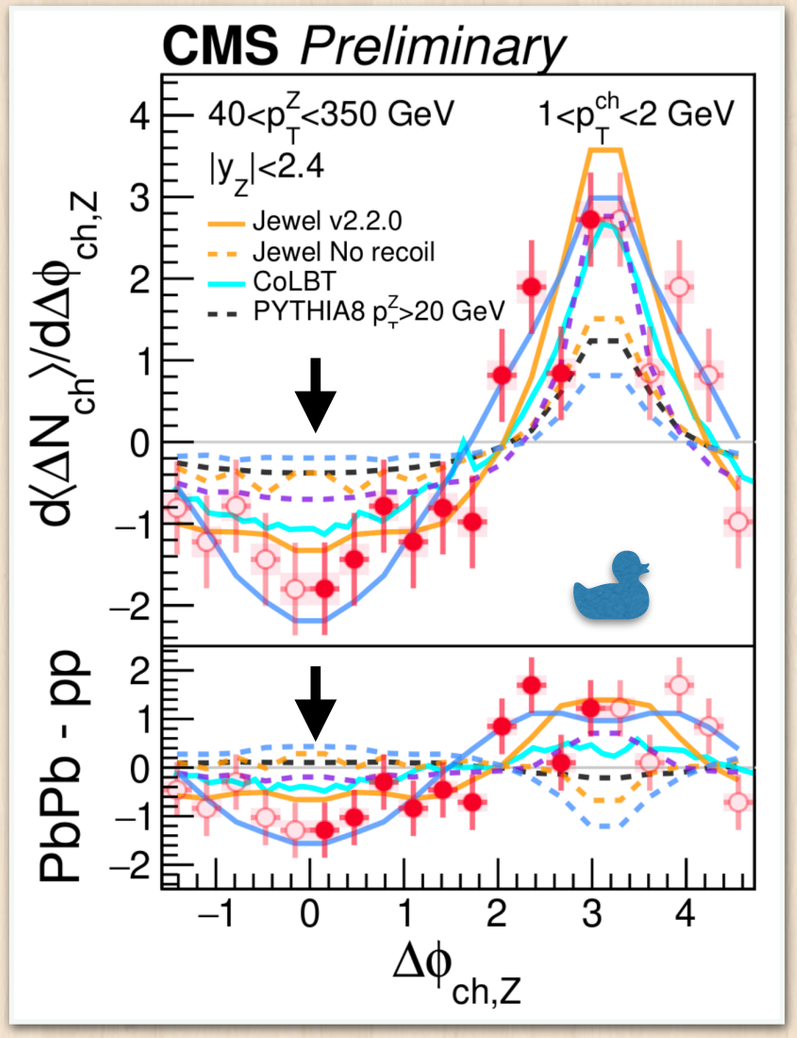
Why is negative wake interesting?

Around duck: possible that duck behaves differently in water?

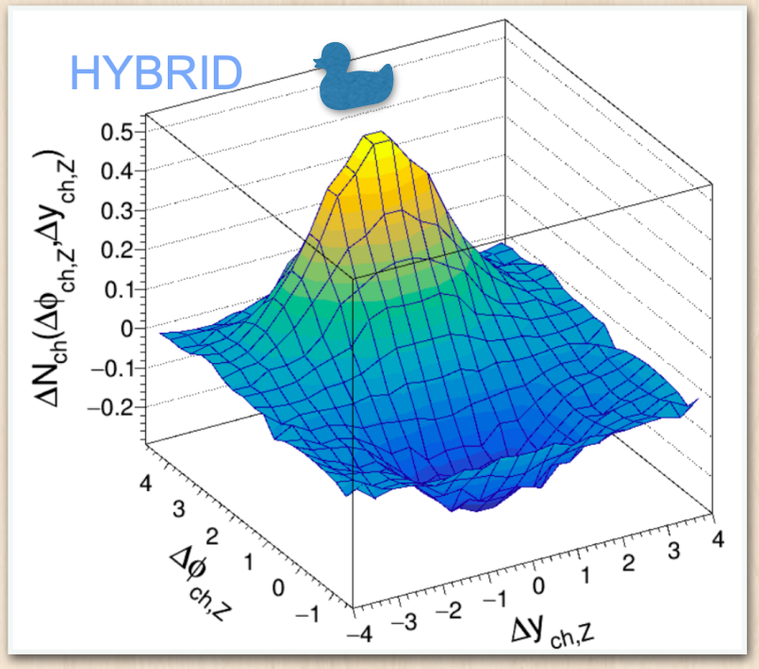
Behind duck: no water, no effect
Purely from energy propagation

Negative wake in Z-tagged collisions

Z+X events



Talk by Y-J Lee this afternoon



First evidence of the negative wake effect!

QGP effect extends very far from jet direction

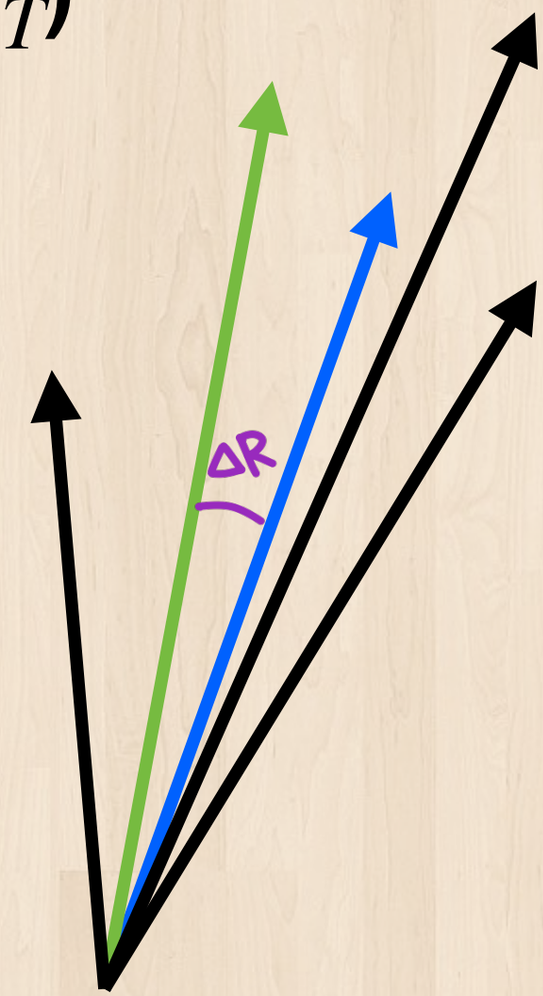
New venue for future differential studies

See also ATLAS γ-jet CONF 2023-054

CMS-PAS-HIN-23-006

Energy-energy correlator

Energy-energy correlator:
particle pair weighted by energy (or p_T)



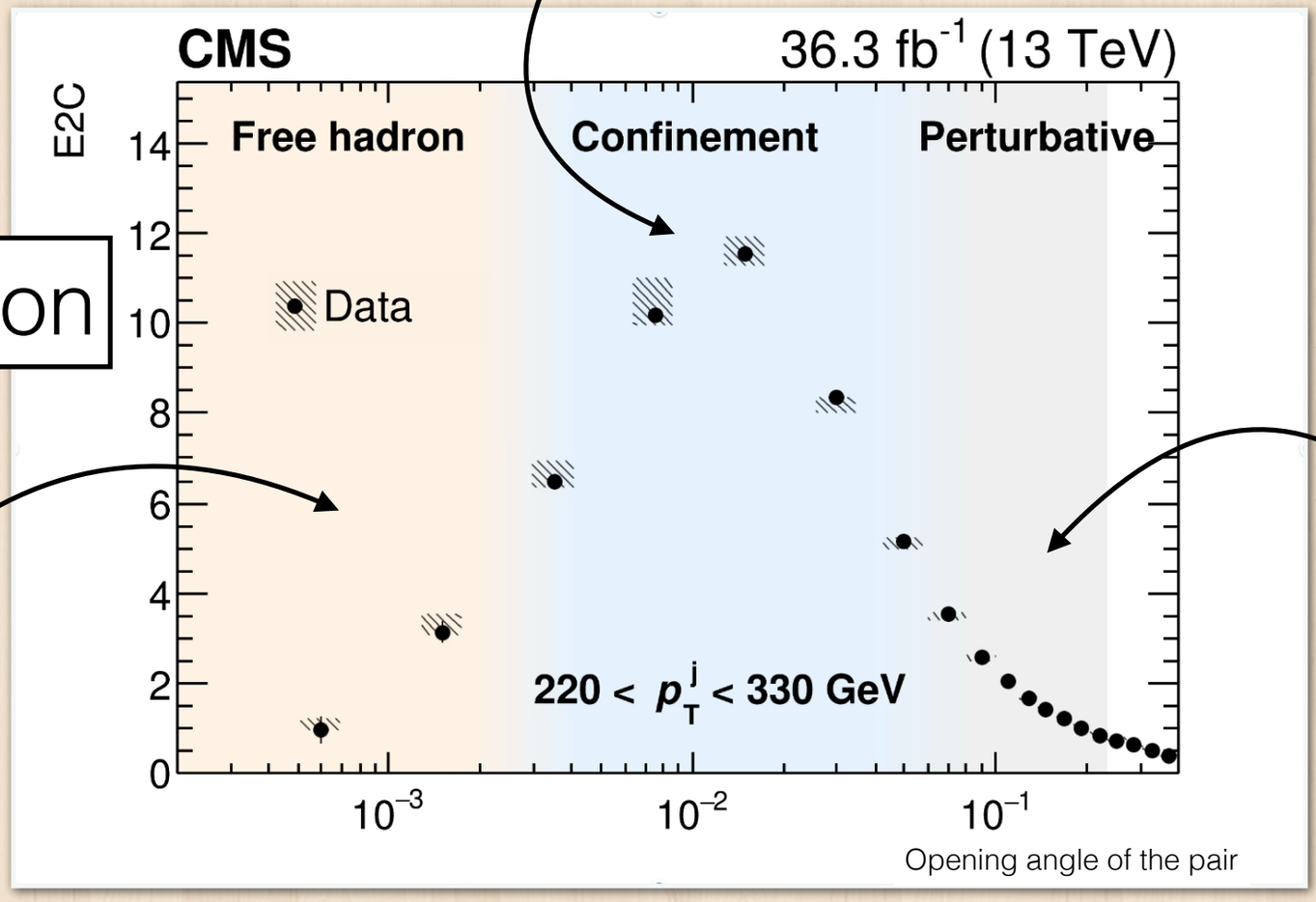
Why study EEC?

- Tool for α_s **extraction**
- Study of **pQCD** and **hadronization**
- Probe **QGP effects** on jets
- …

Jet energy correlator in pp

Transition location: encodes initial jet scale

Hadronization

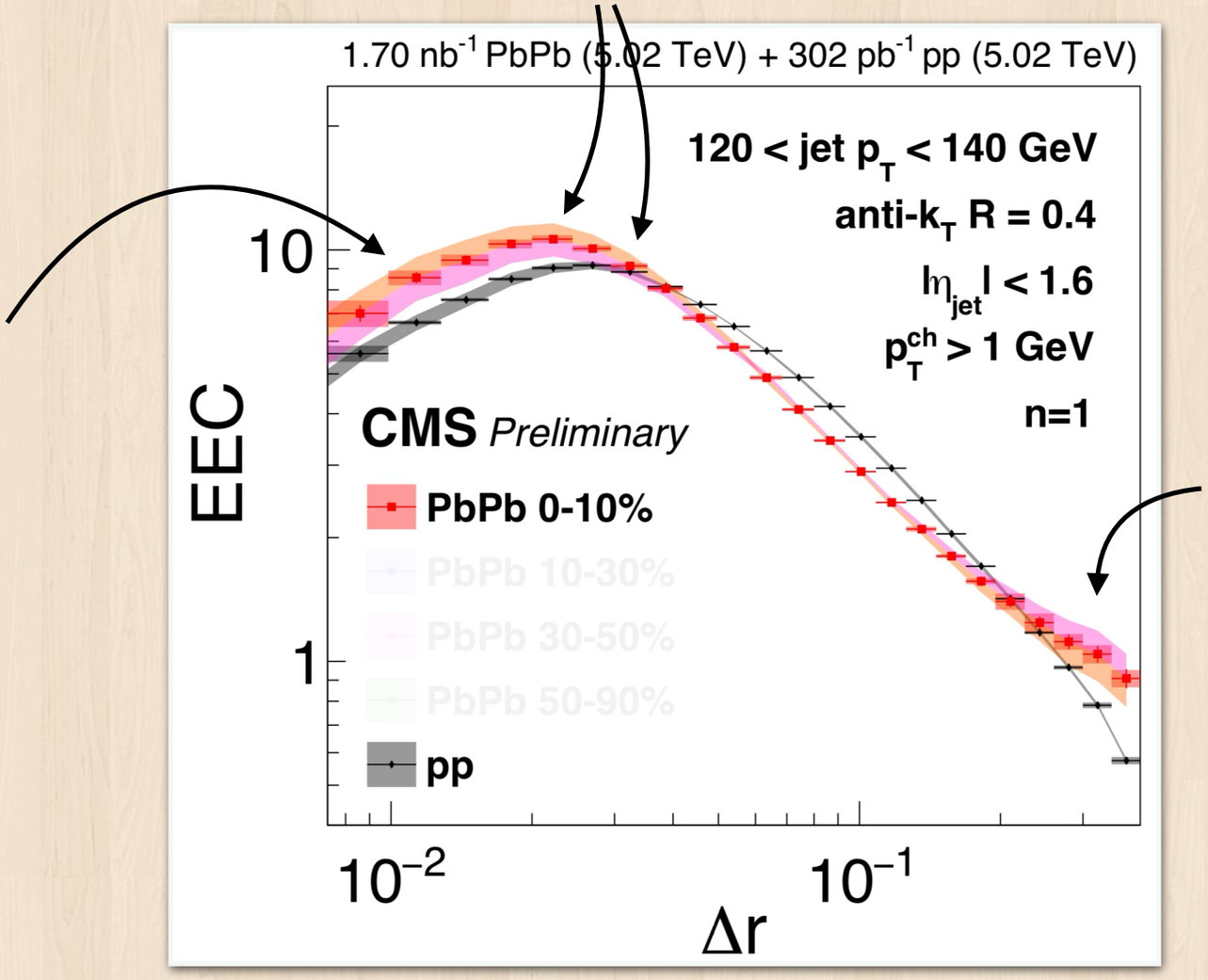


pQCD

Different region encodes different physics

arXiv 2402.13864, see also ALICE prelim. See also PoS HardProbes 2023 (2024)

Jet energy correlator in QGP



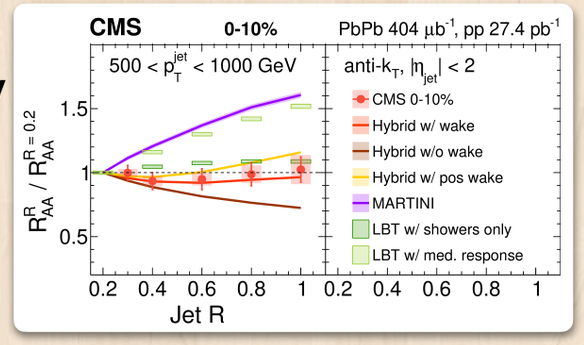
Rich physics encoded in the shape

CMS PAS HIN-23-004

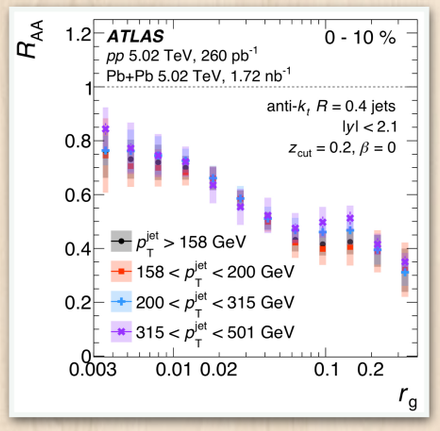
Concluding remarks

What have we seen?

- **Large size jets**: balance between energy recovery and wide jet suppression



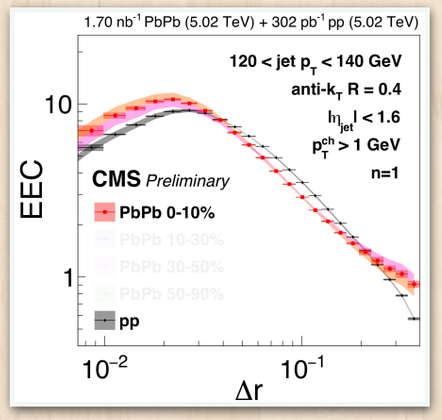
- **Jets become more narrow in QGP**: control survivor bias with color-neutral tag and differential studies



  - Opportunity to disentangle medium effects (e.g. elastic scattering)

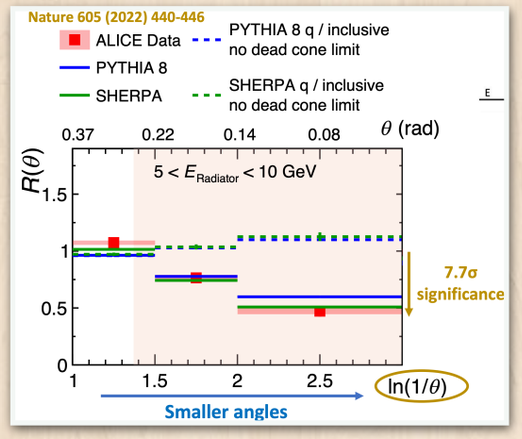
  - Hint that **QGP can see inside wide jets**

- **Energy-energy correlator**: organize physic of different angular scales



Looking into the future

- **New venues for isolating QGP effects**: dead cone effect, negative wake effect, …



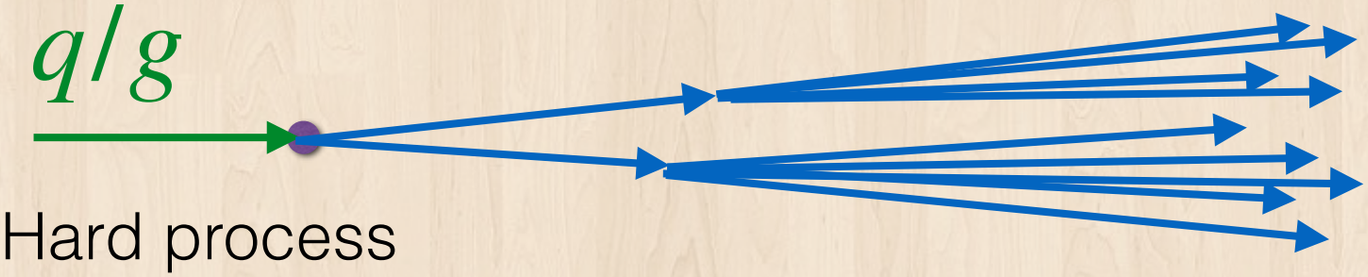
- **Lower energy jets** & **RHIC program** will be very valuable

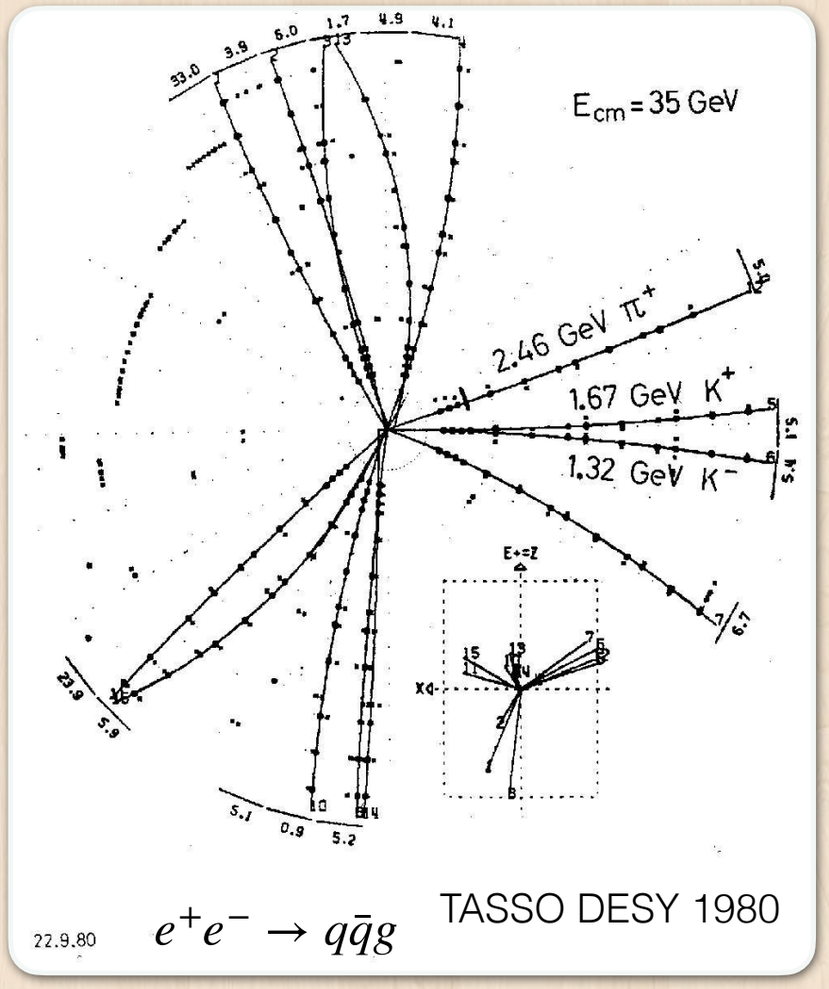
- Due to time many exciting results are not covered
- Looking forward to new discoveries!

Backup Slides Ahead

Jet: spray of collimated particles

It's like a shotgun





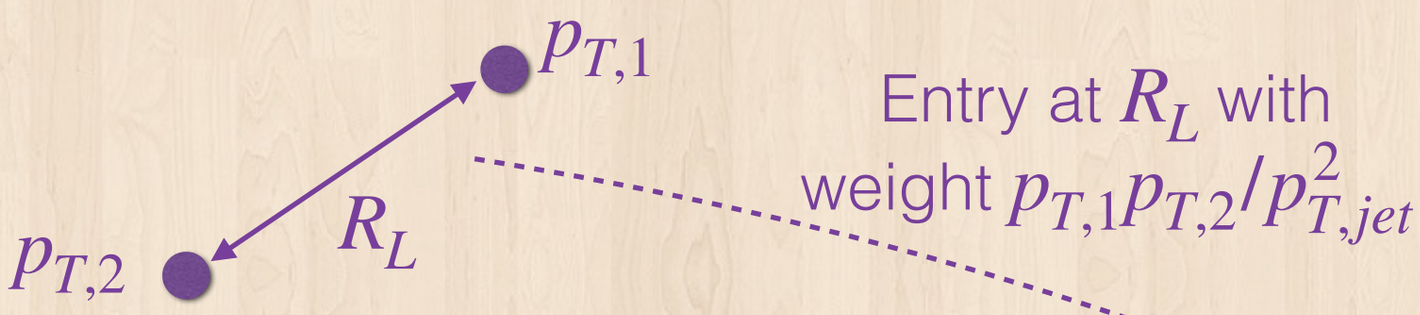
Each g/q evolve into a spray of final particles (= jets)

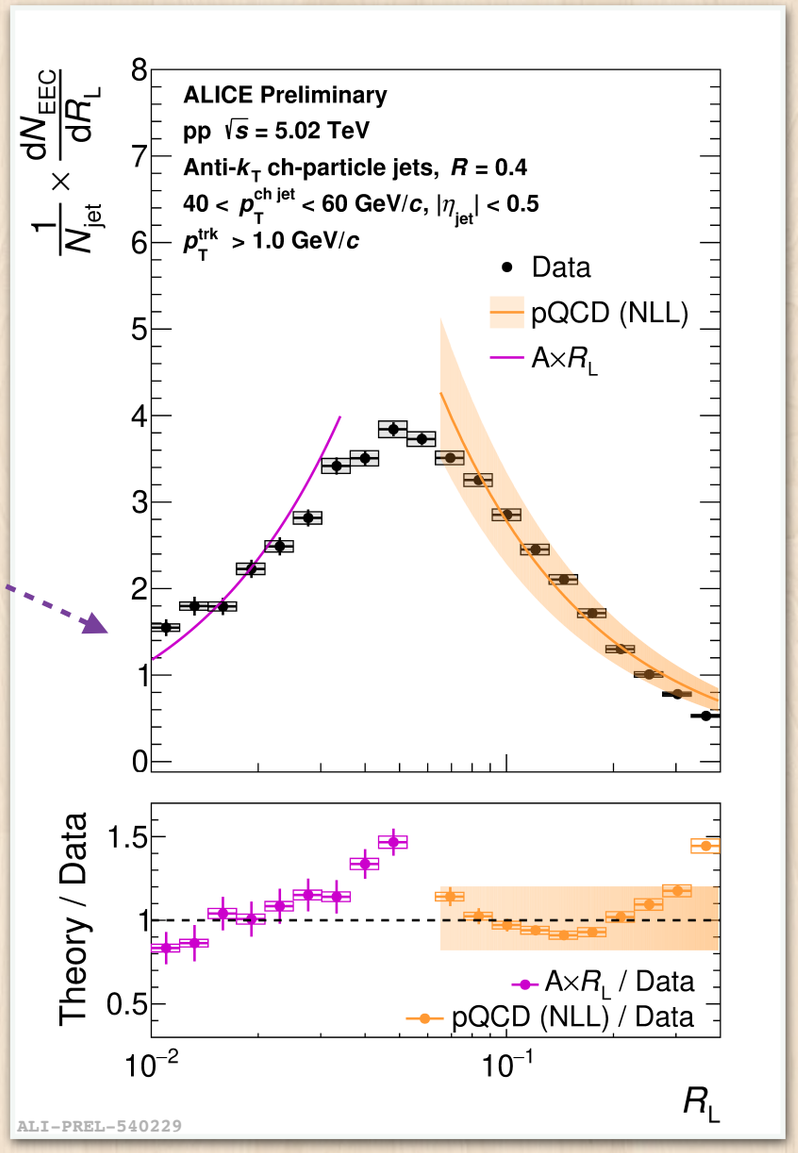
Jets = proxy for initial g/q

Relatively well-studied in proton-proton collisions

Energy-energy correlator

- 2-point correlator (“E2C”): weighted number of particle pairs as a function of opening angle

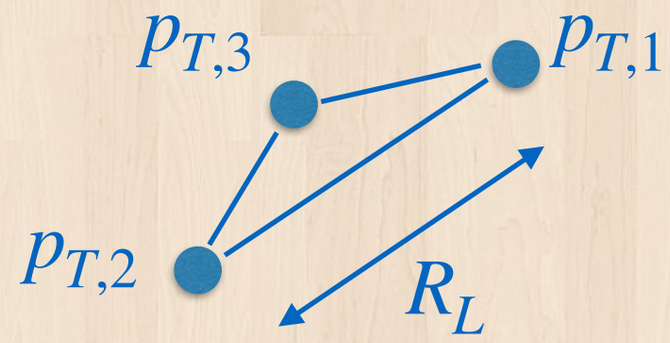


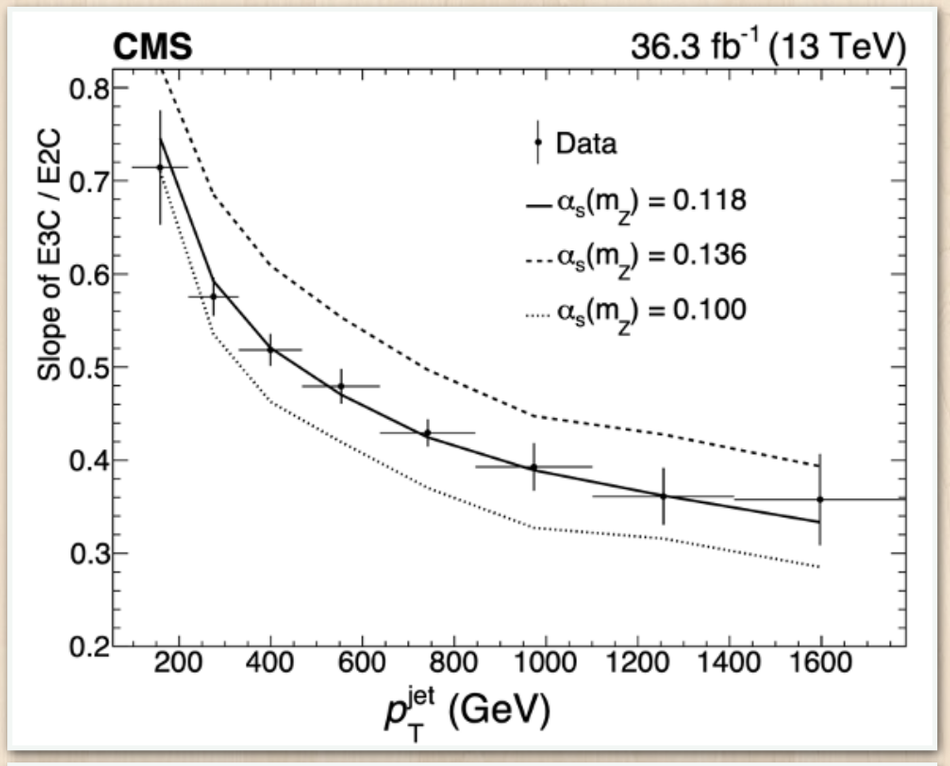


- IRC-safe
- Soft contribution suppressed
- Physics of different scales & R_L

Energy-energy correlator

- 3-point correlator (“E3C”): weighted number of triplets
- Slope of 3-point to 2-point sensitive to α_s
- Running coupling in action
  - Large jet p_T → large Q → smaller α_s → slope
- A lot more can be explored

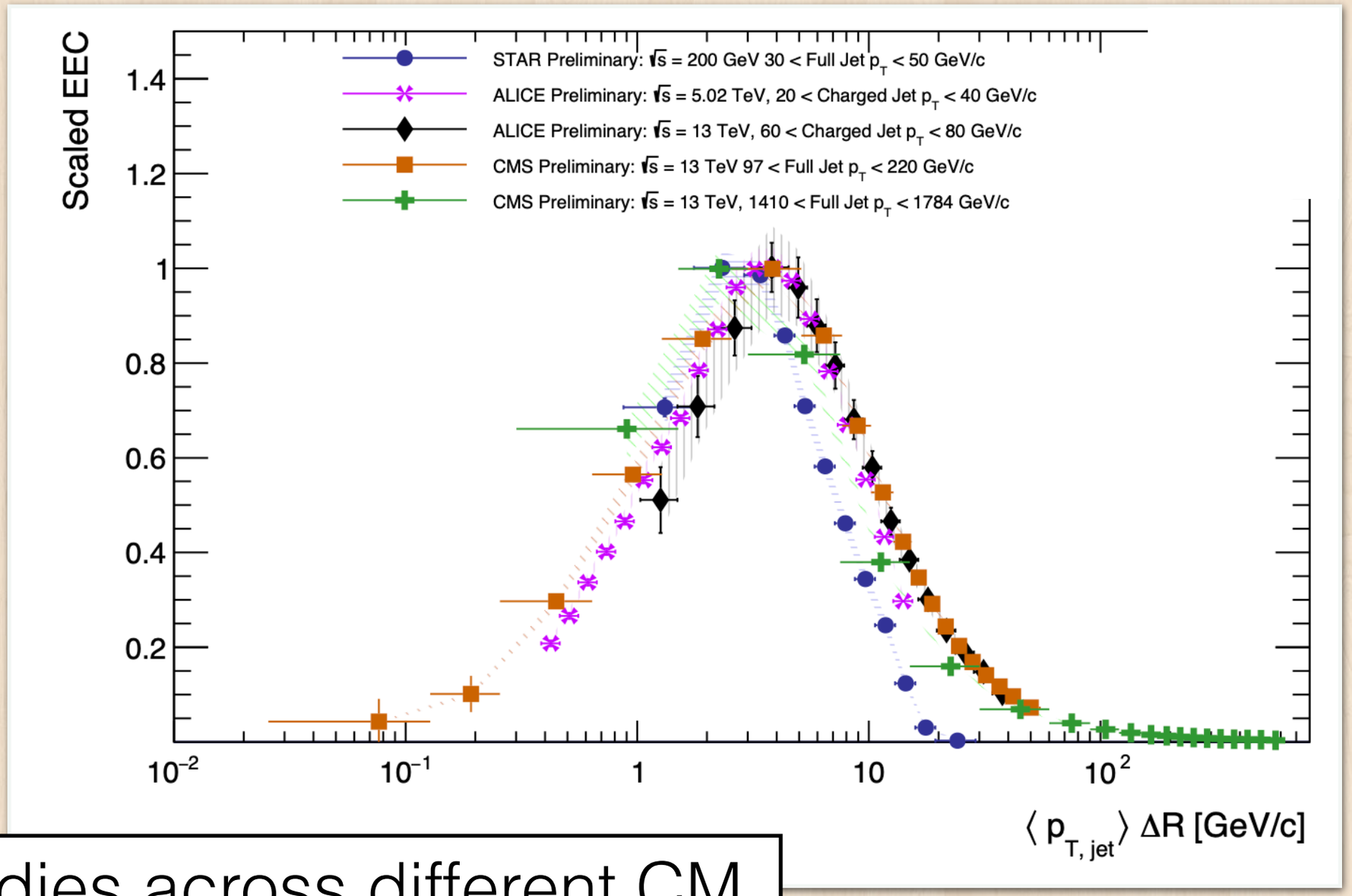




$$\alpha_S(m_Z) = 0.1229^{+0.0014}_{-0.0012}\,(\text{stat})^{+0.0030}_{-0.0033}\,(\text{theo})^{+0.0023}_{-0.0036}\,(\text{exp})$$

CMS SMP-22-015

Energy-energy correlator in pp



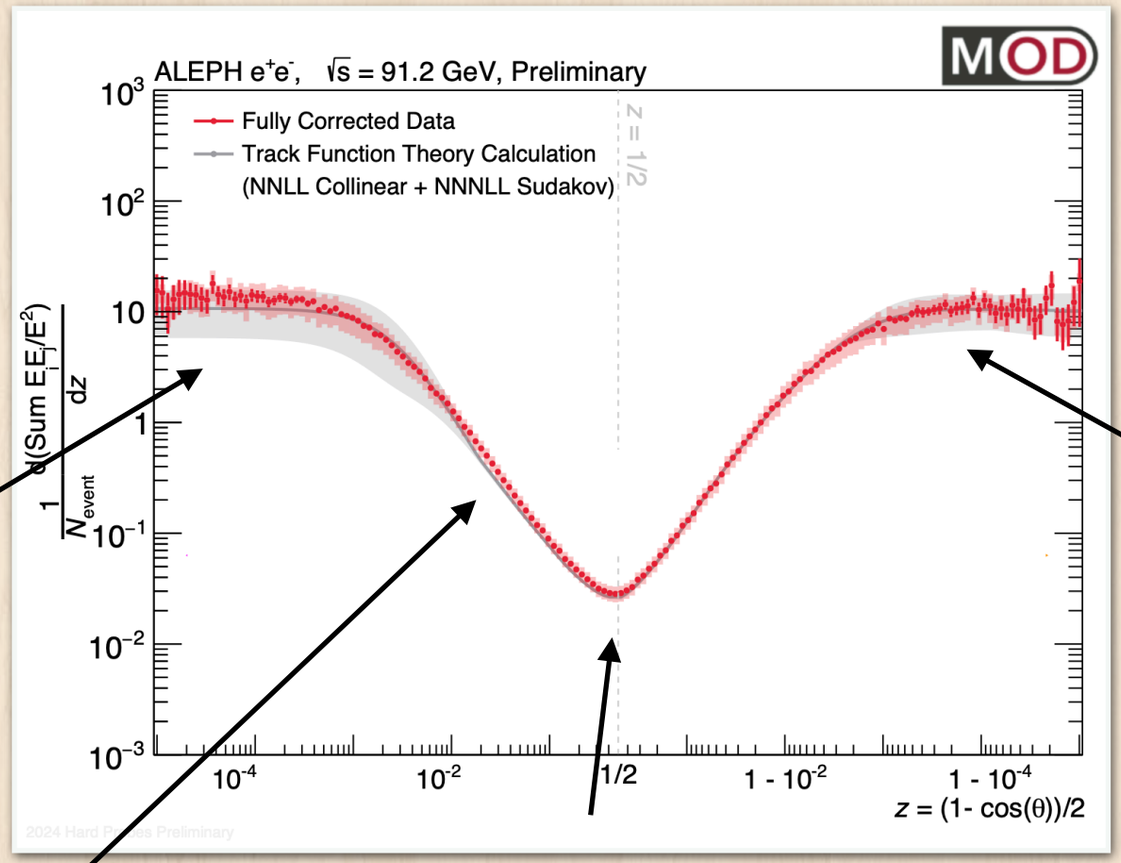
Many studies across different CM energy and jet energy scales

Preliminary result 🔥

Energy-energy correlator

Same-jet correlation

(Three-jet shoulder)



Opposite-jet correlation

Hadronization

pQCD

Non-perturbative effect

Non-perturbative, soft emissions

$$z = \frac{1 - \cos\theta_L}{2}$$

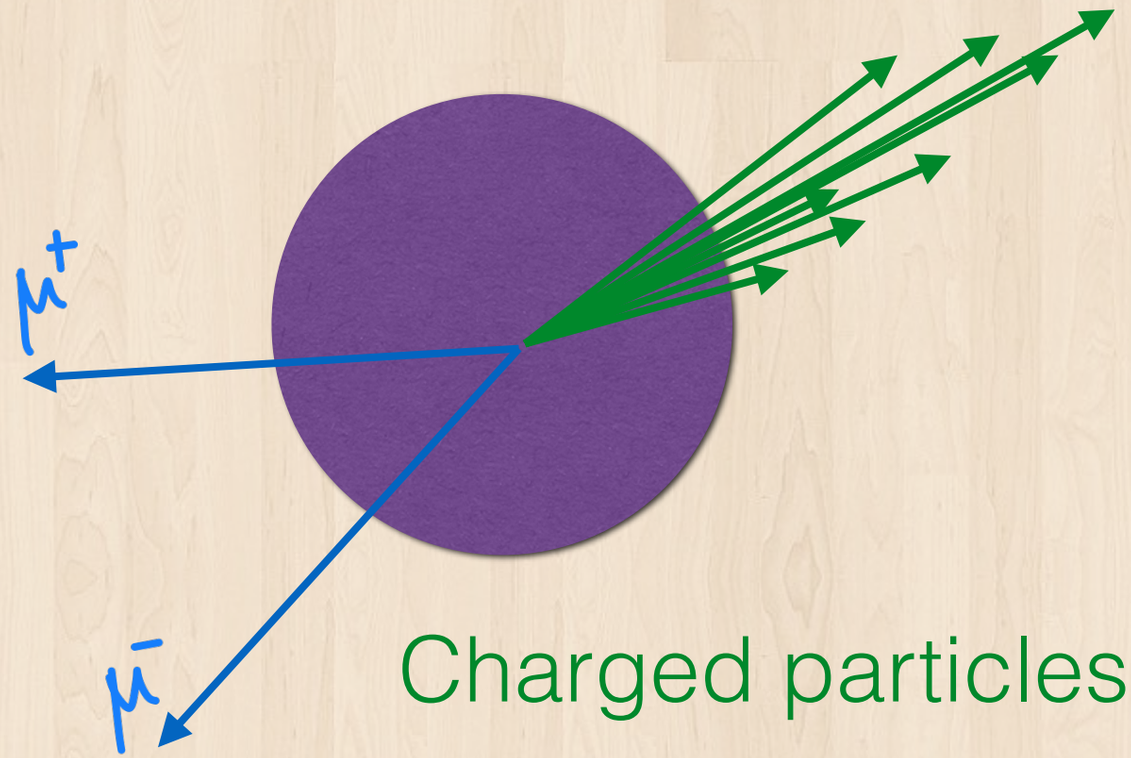
To be submitted soon!

Z and charged particles

$$Z \to \mu^- \mu^+$$

$$p_{T,\mu} > 20 \text{ GeV}$$
$$|\eta_\mu| < 2.4$$

$$60 < m_Z < 120 \text{ GeV}$$
$$40 < p_{T,Z} < 350 \text{ GeV}$$
$$|y_Z| < 2.4$$

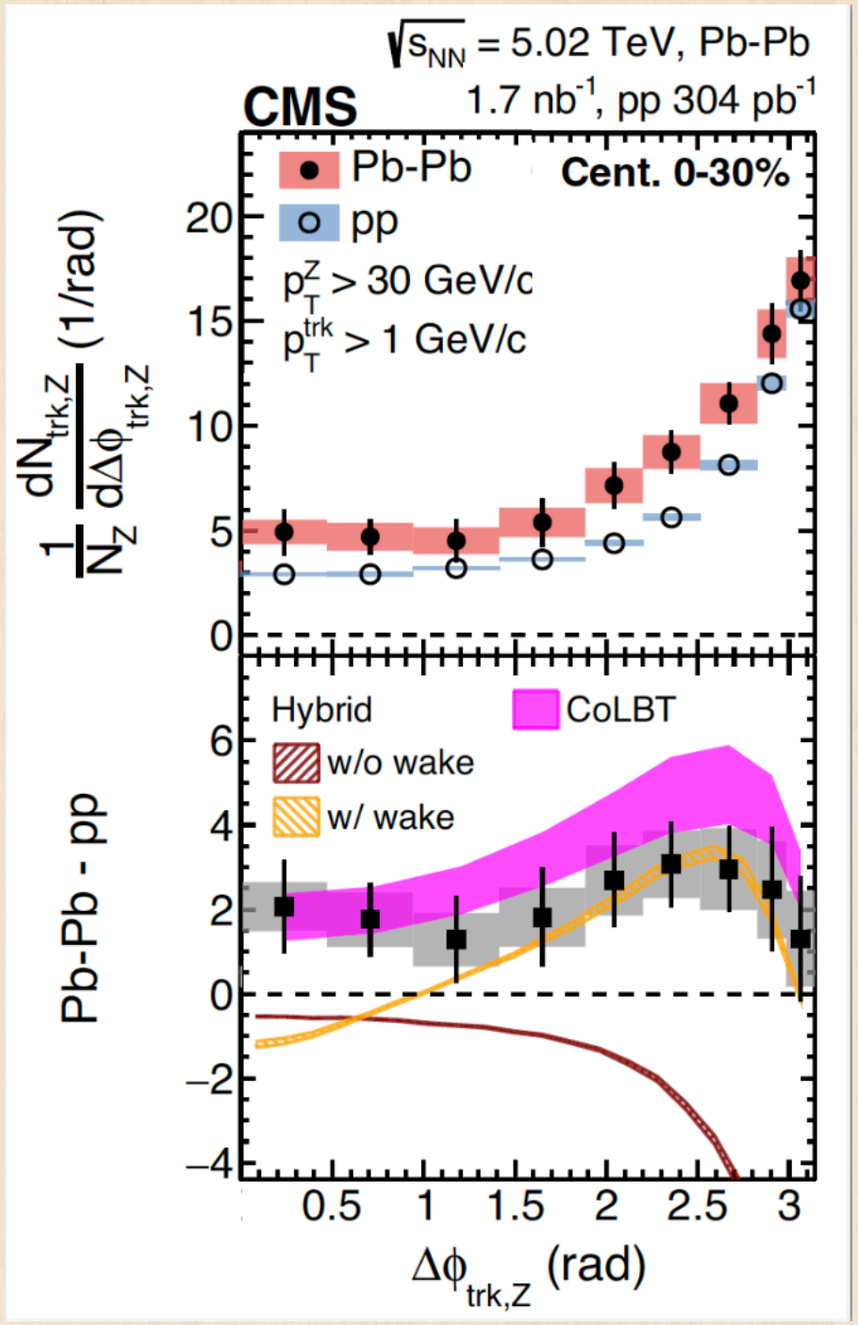


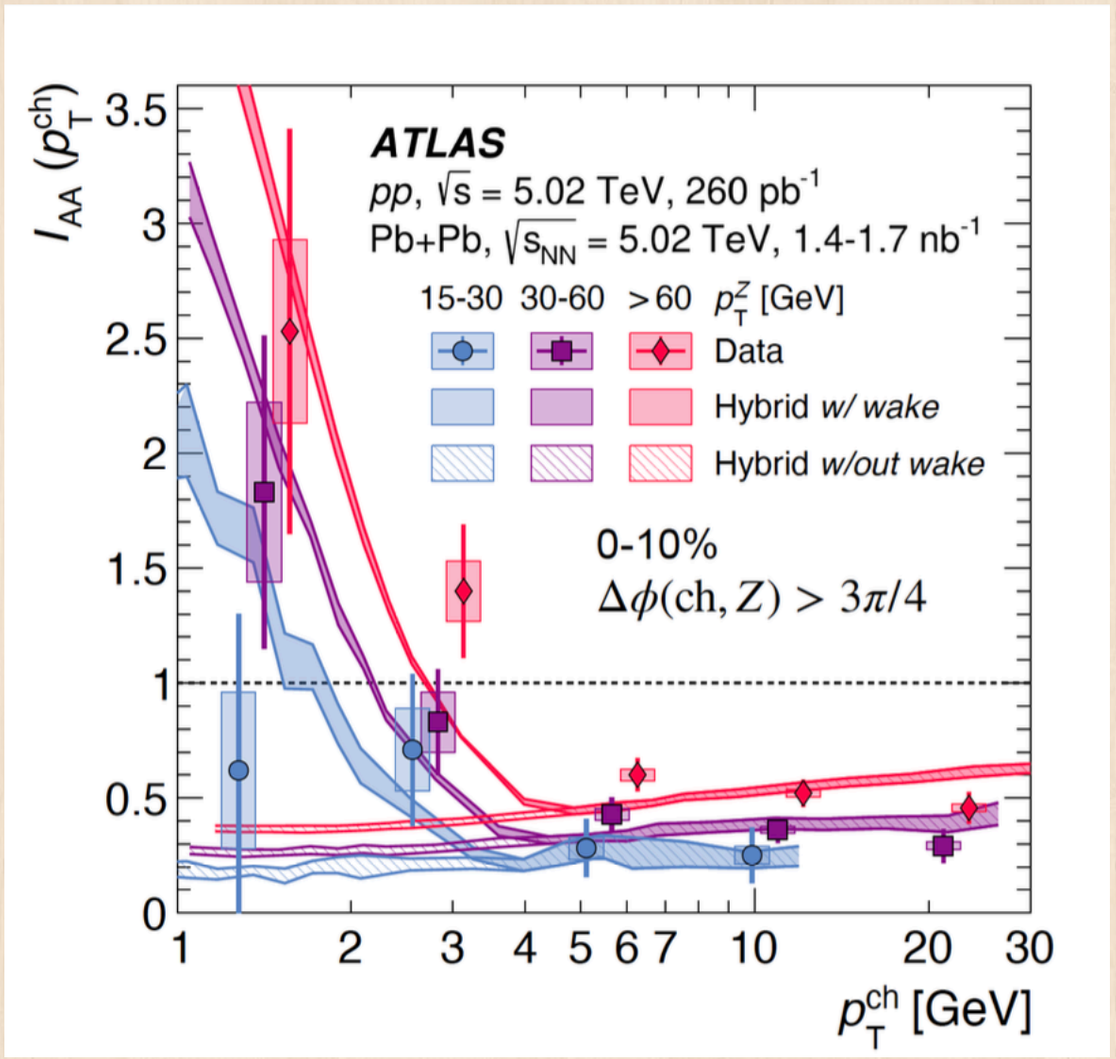
Charged particles

$$p_{T,ch} > 1 \text{ GeV}$$
$$|\eta_{ch}| < 2.4$$

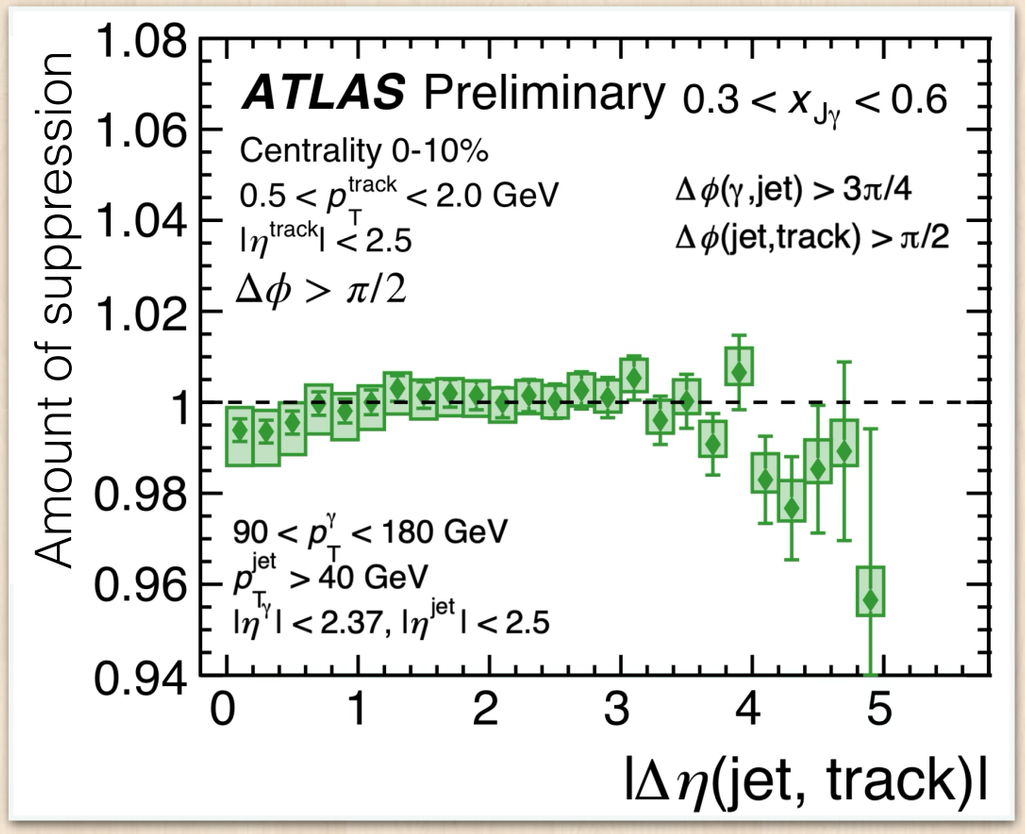
Measure $\Delta\phi_{ch,Z} = \phi_Z - \phi_{ch}$ and $\Delta y_{ch,Z} = y_Z - \eta_{ch}$

Z-hadron correlation



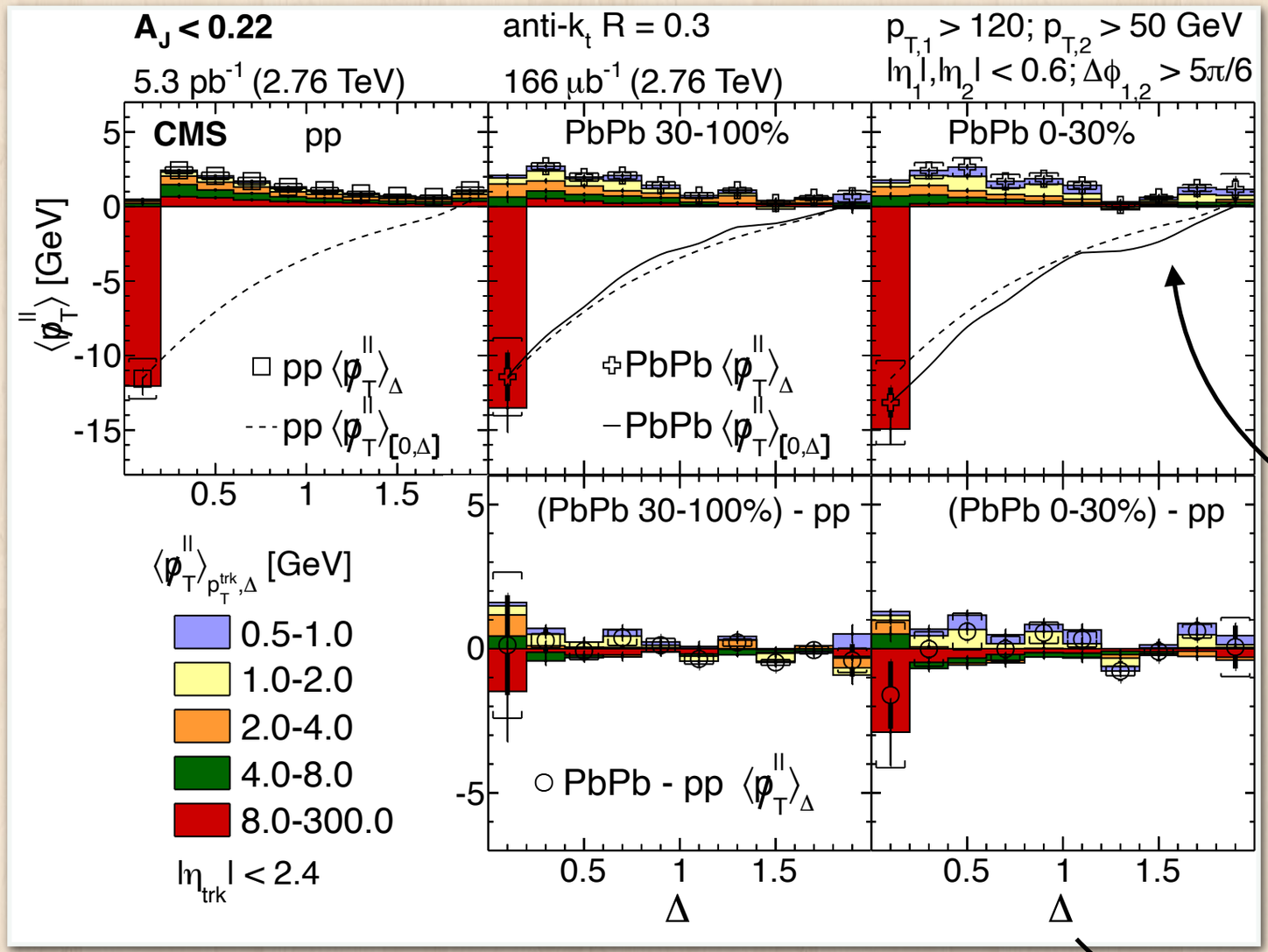


ATLAS photon jet



Effect extends very far

How far do we need to go to recover p_T balance?



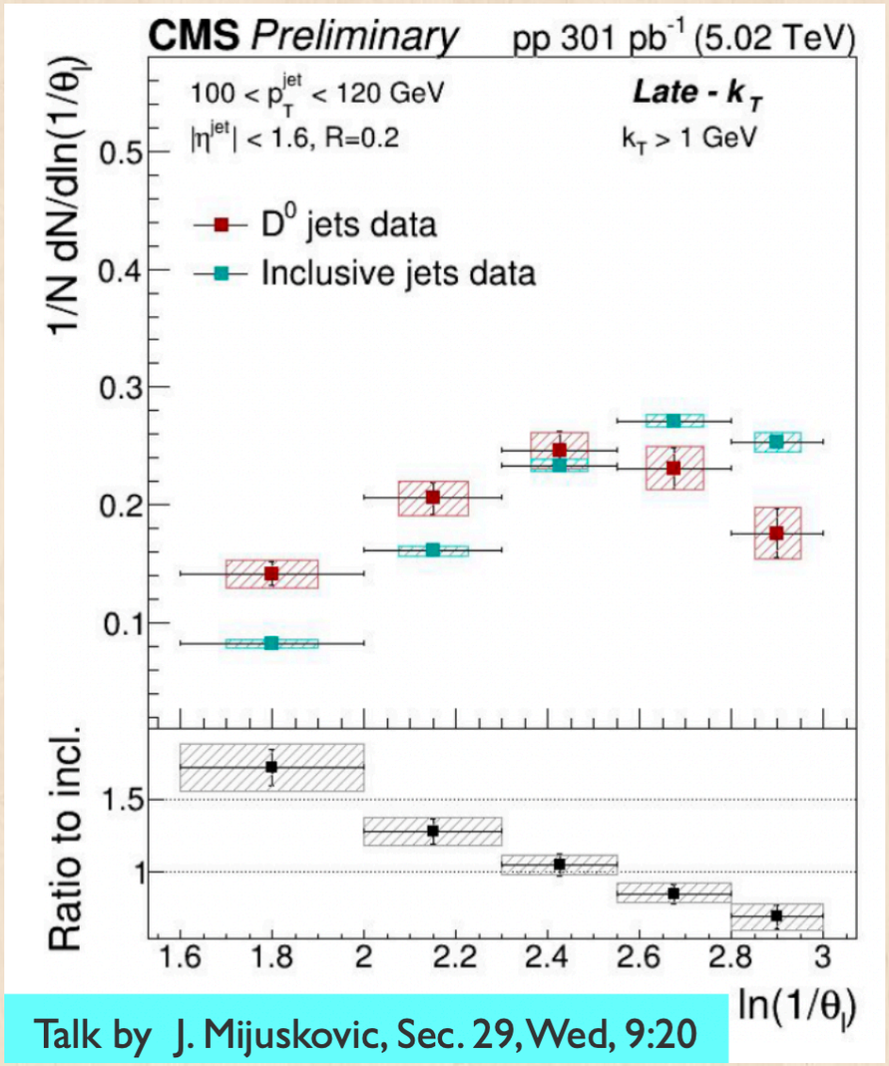
0 = balanced
non-zero = no balance

Effect seen very far away from the jets

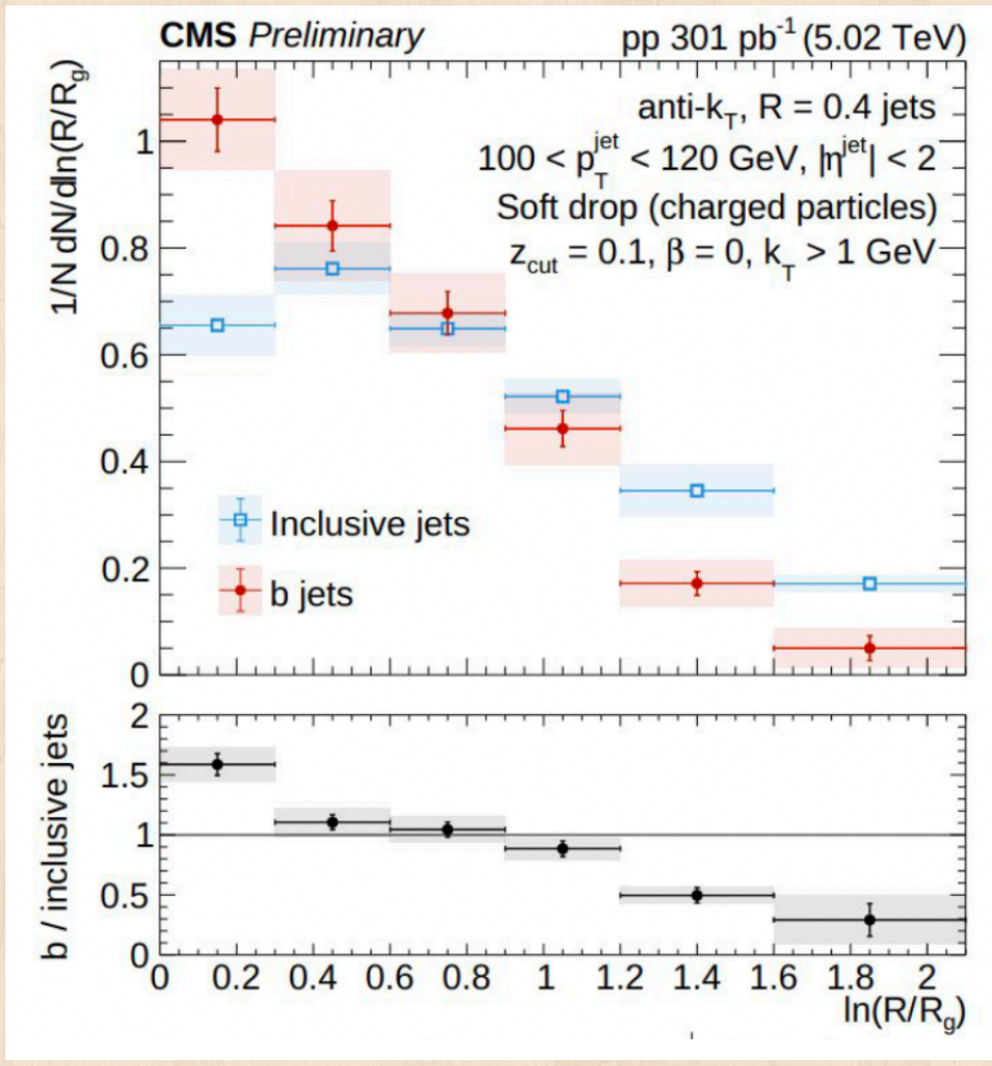
$$\sqrt{\Delta\phi_{ch,jet}^2 + \Delta\eta_{ch,jet}^2}$$

JHEP 01 (2016) 006

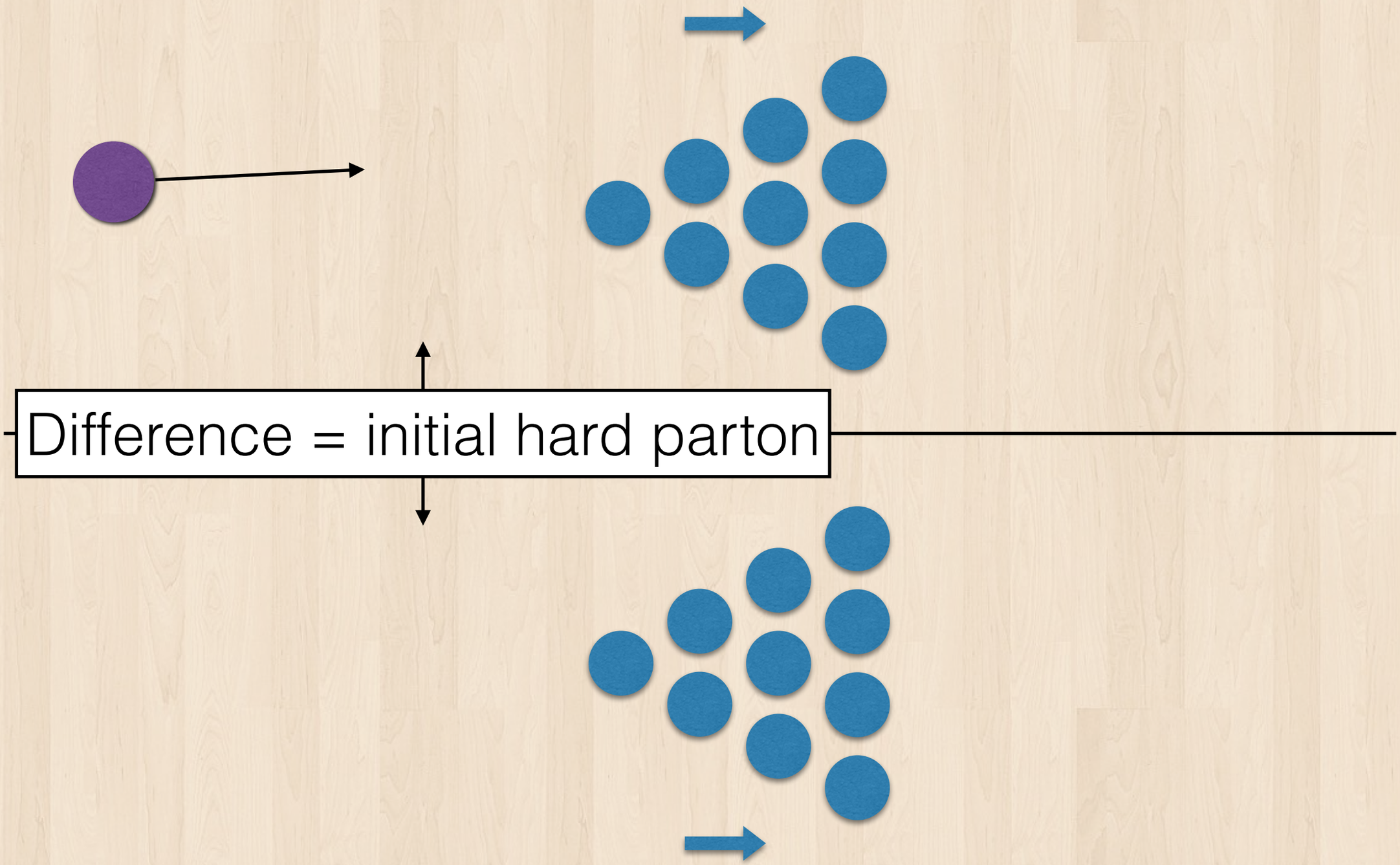
Dead cone effect



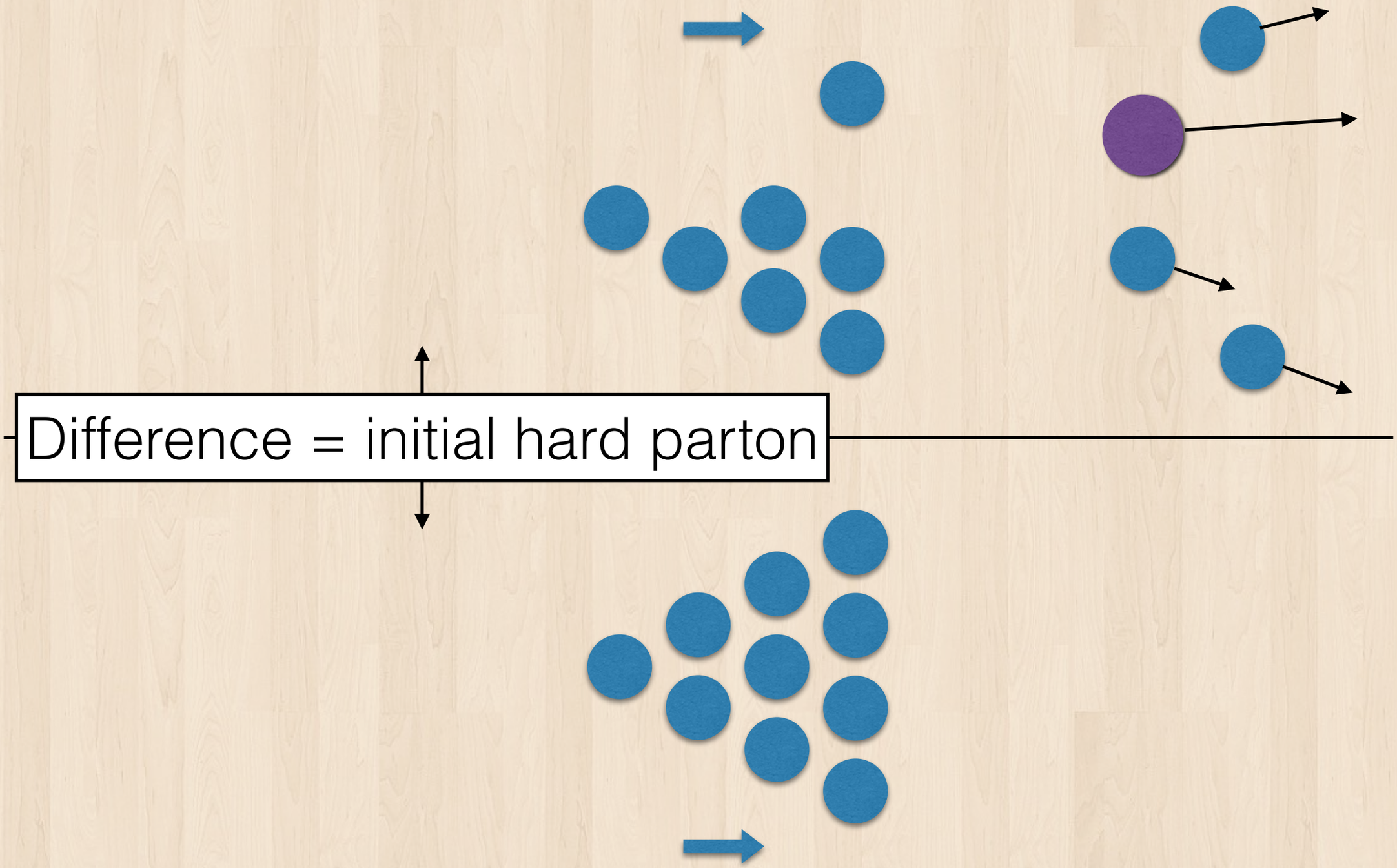
Talk by J. Mijuskovic, Sec. 29, Wed, 9:20



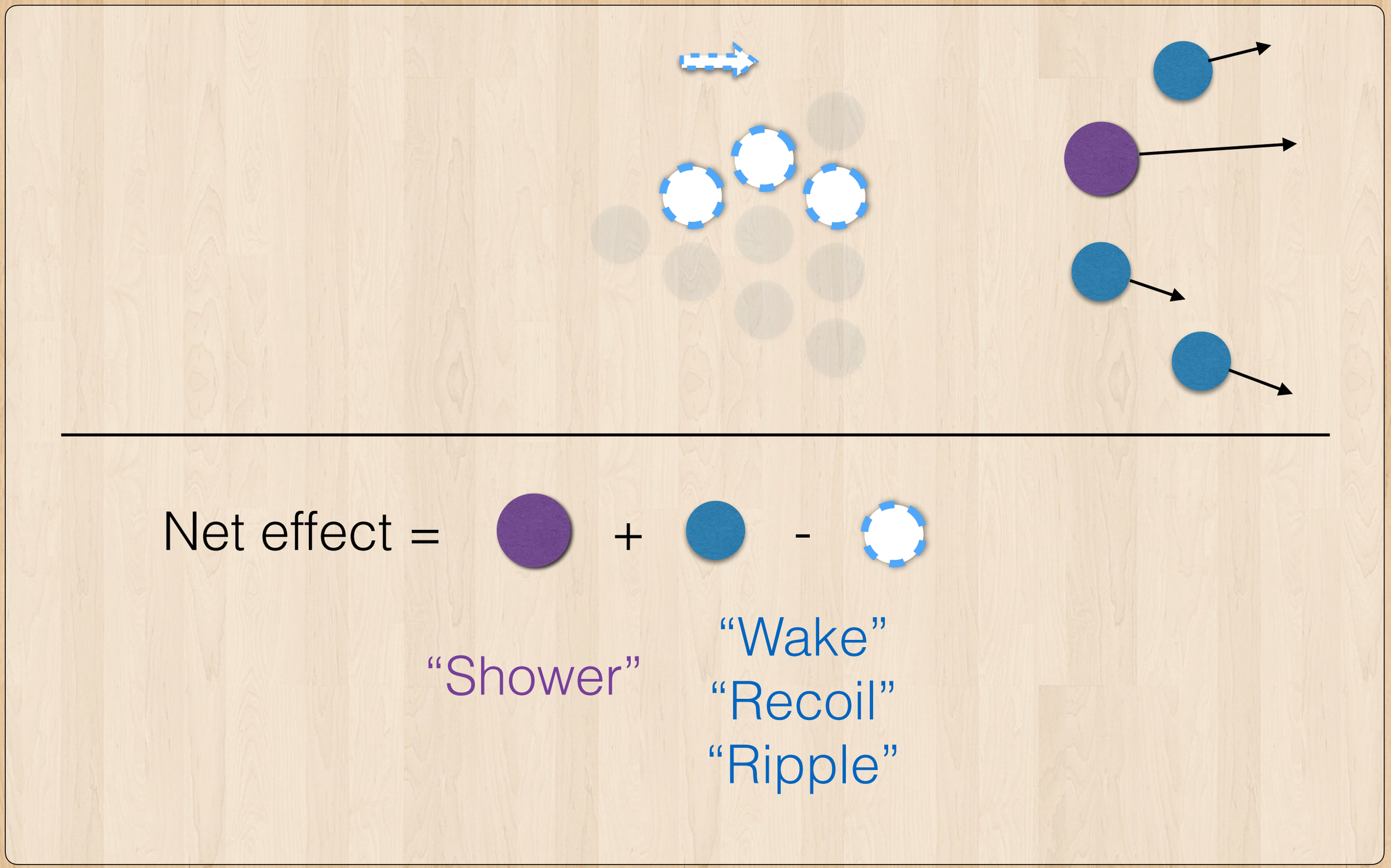
Bowling ball analogy



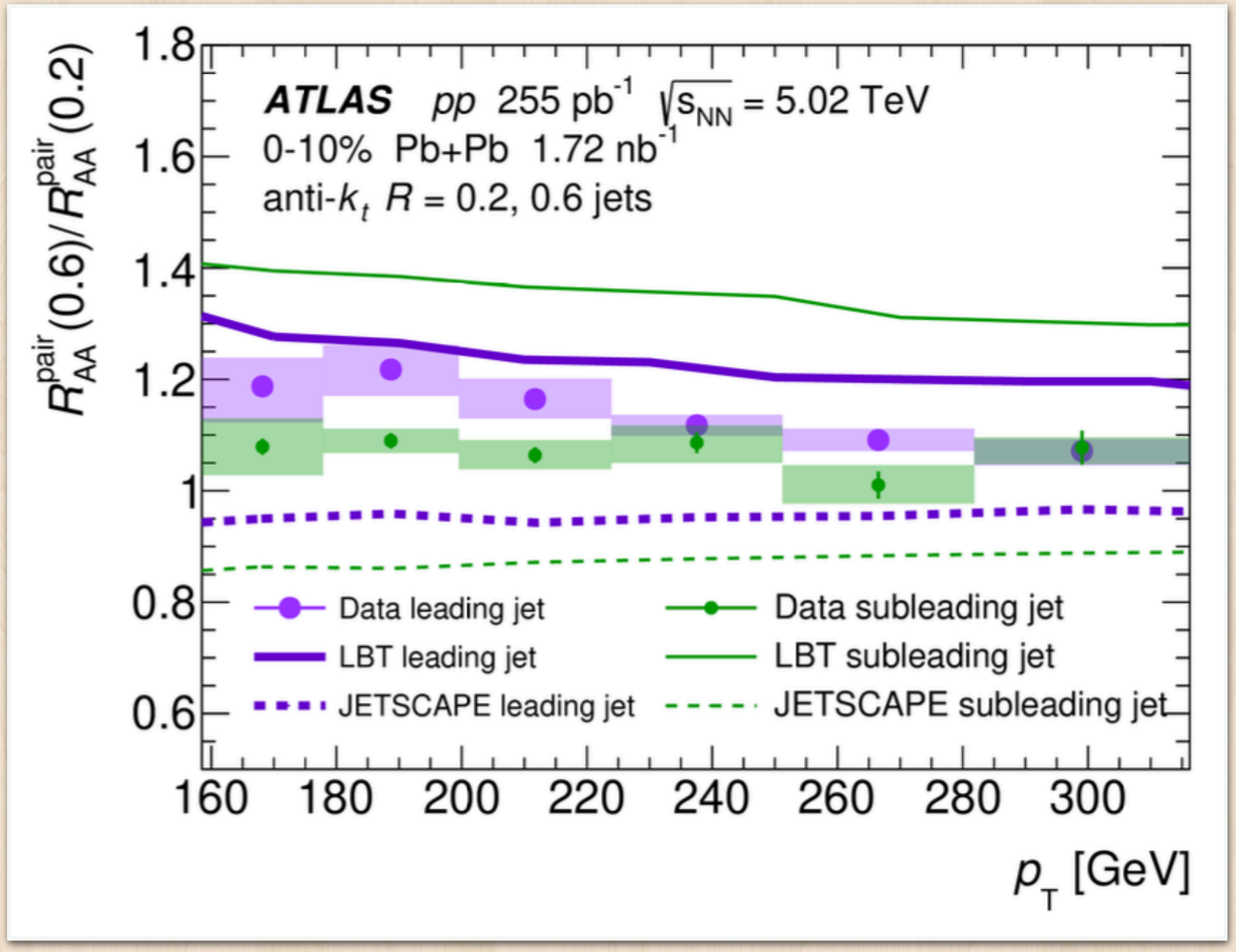
Bowling ball analogy



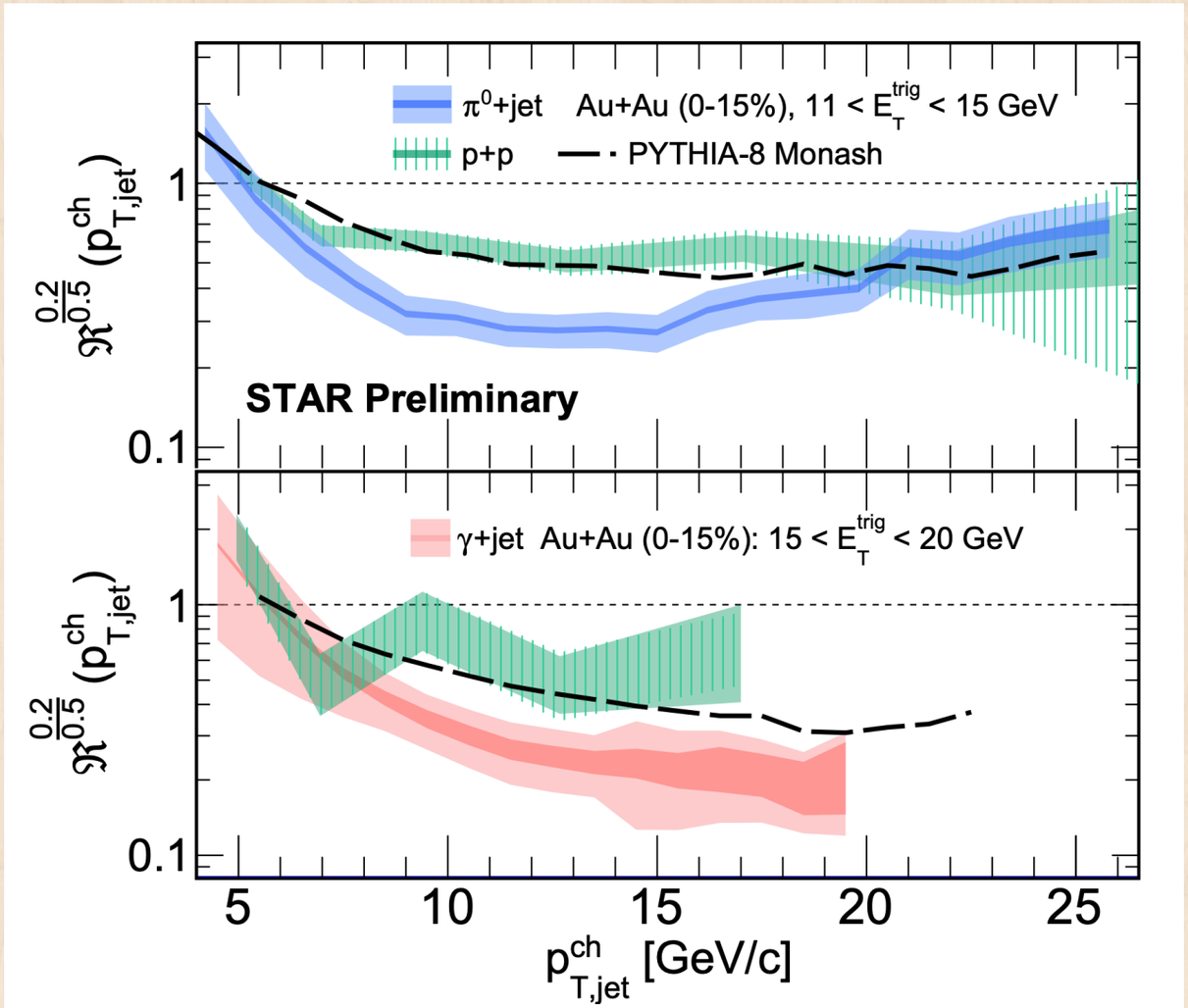
Net effect of bowling ball

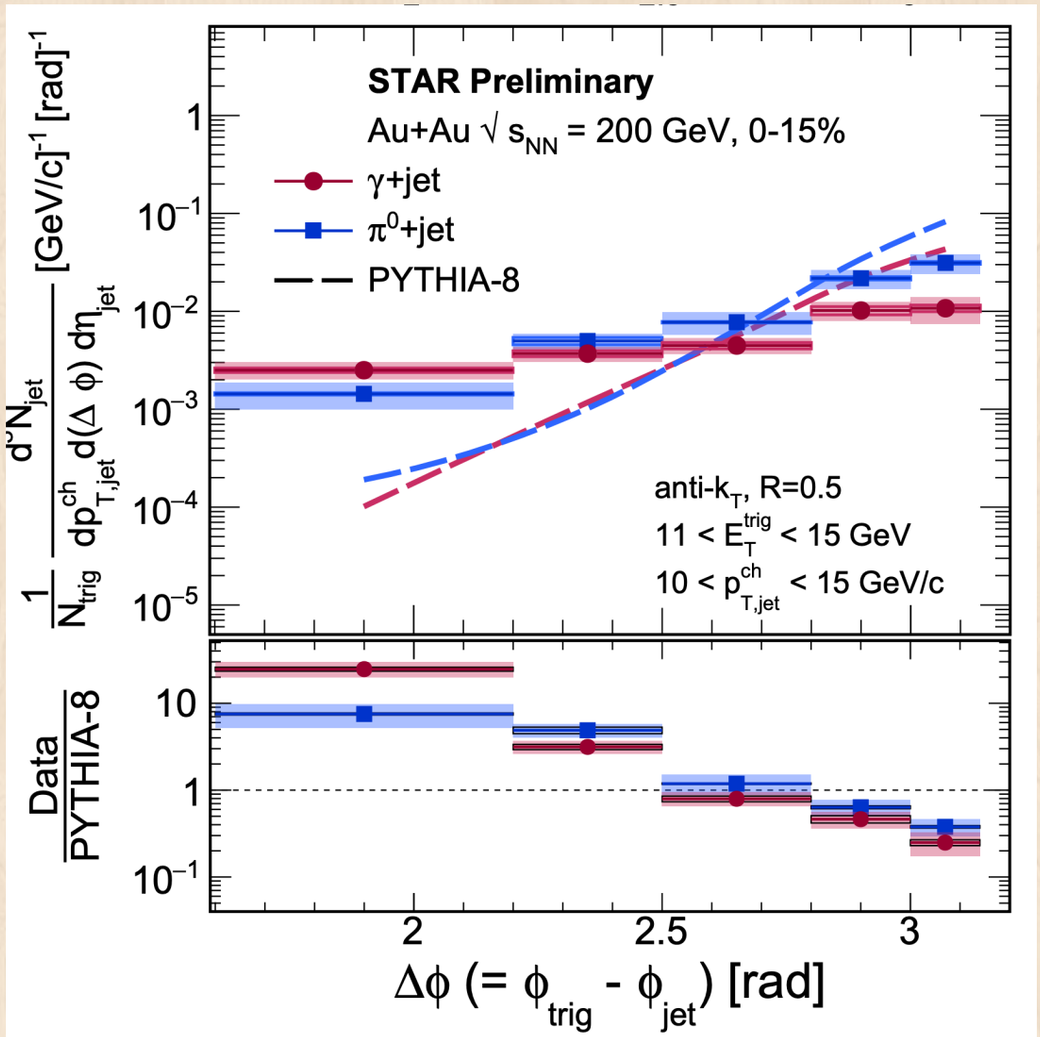


Pair RAA

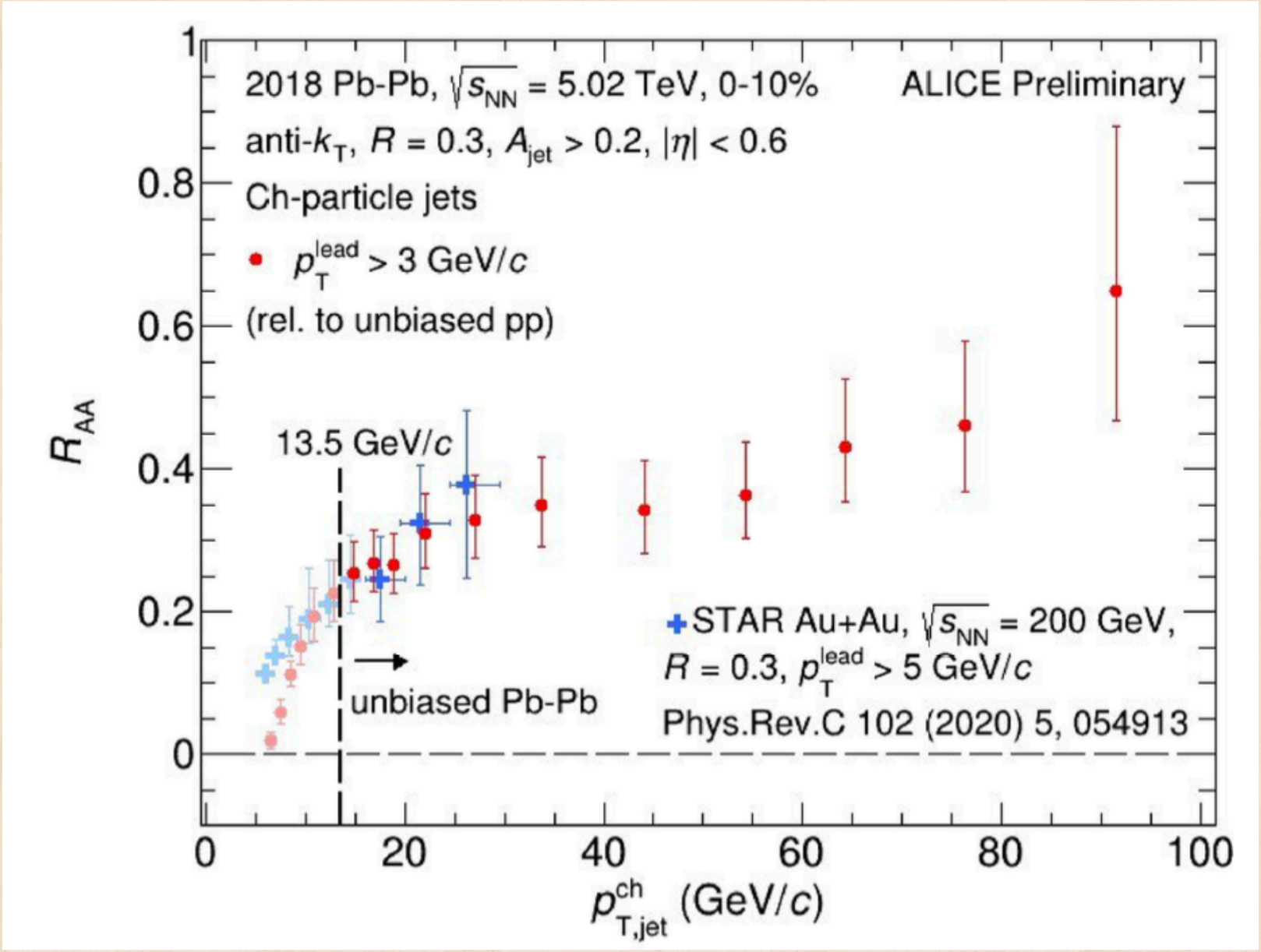

ATLAS pp 255 pb-1 √sNN = 5.02 TeV
0-10% Pb+Pb 1.72 nb-1
anti-kt R = 0.2, 0.6 jets
Data leading jet
LBT leading jet
JETSCAPE leading jet
Data subleading jet
LBT subleading jet
JETSCAPE subleading jet
RpairAA(0.6)/RpairAA(0.2)
pT [GeV]
1.8
1.6
1.4
1.2
1
0.8
0.6
160
180
200
220
240
260
280
300

Lower scales

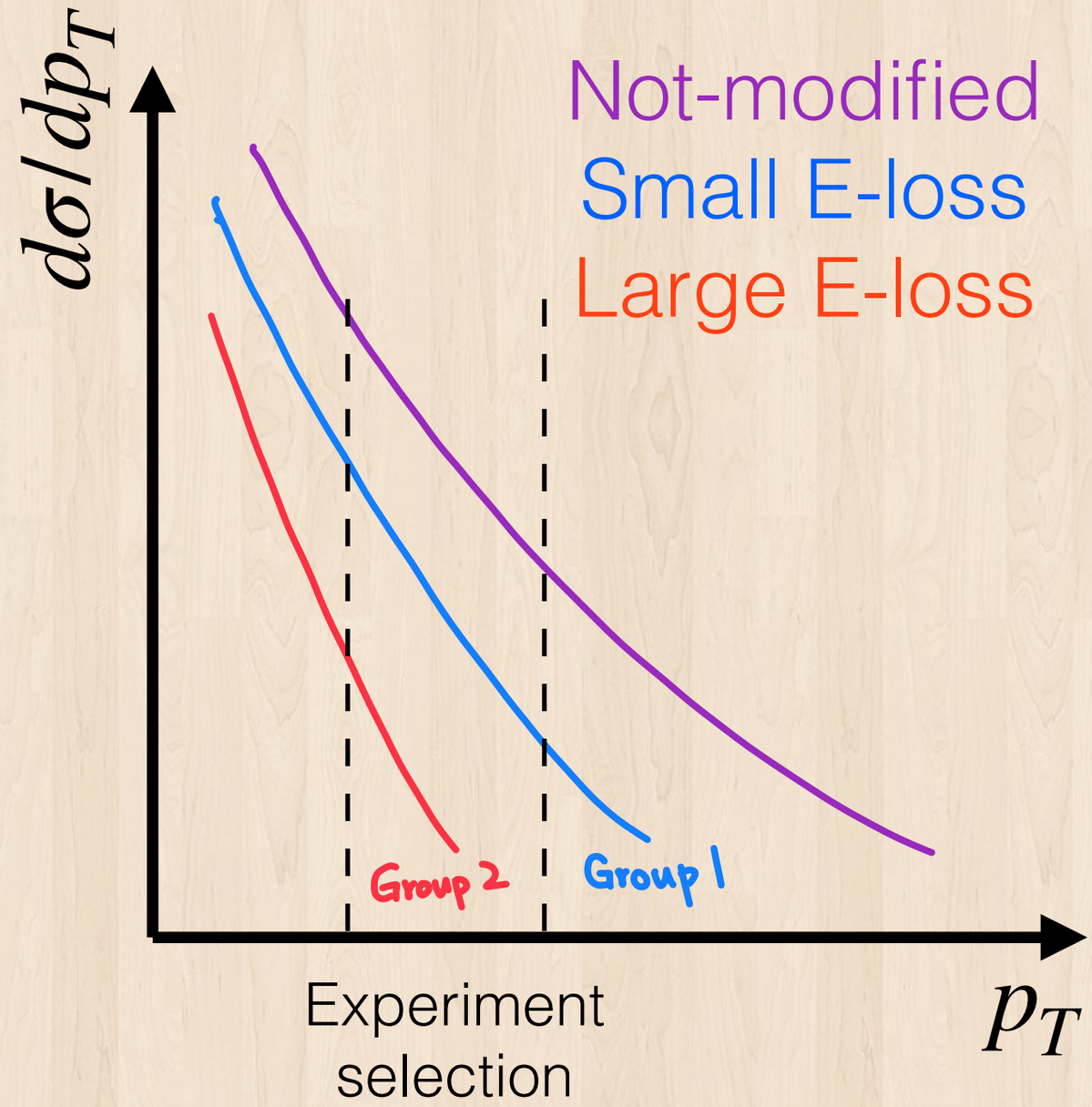




Lower scales



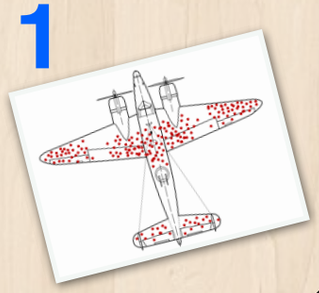
Complication: survival bias



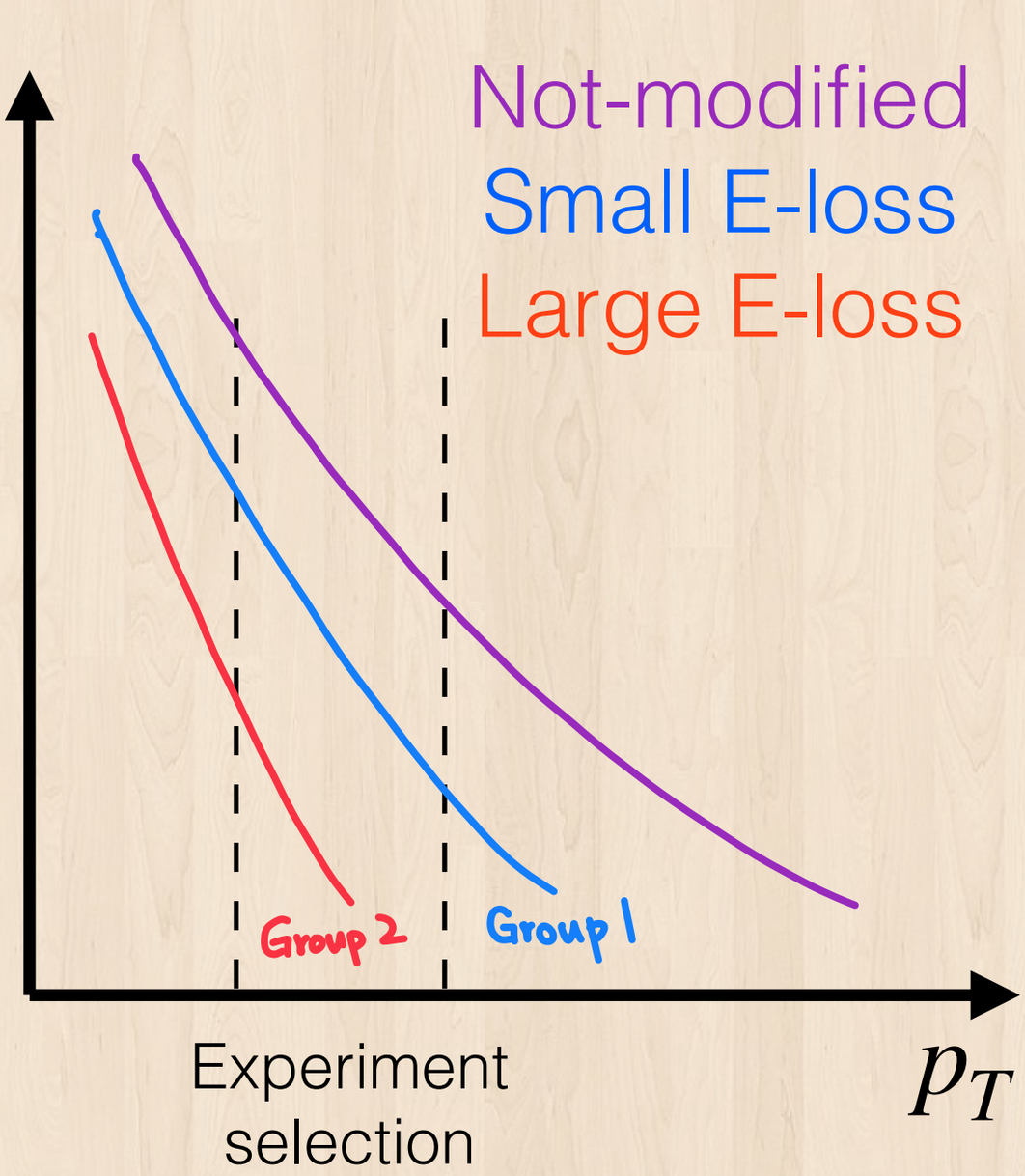
Suppose we have two groups of jets both start off with the **purple spectrum**

Group 1 lose less energy
Group 2 lose more

Experiments will see mostly **group 1**



Complication: survival bias



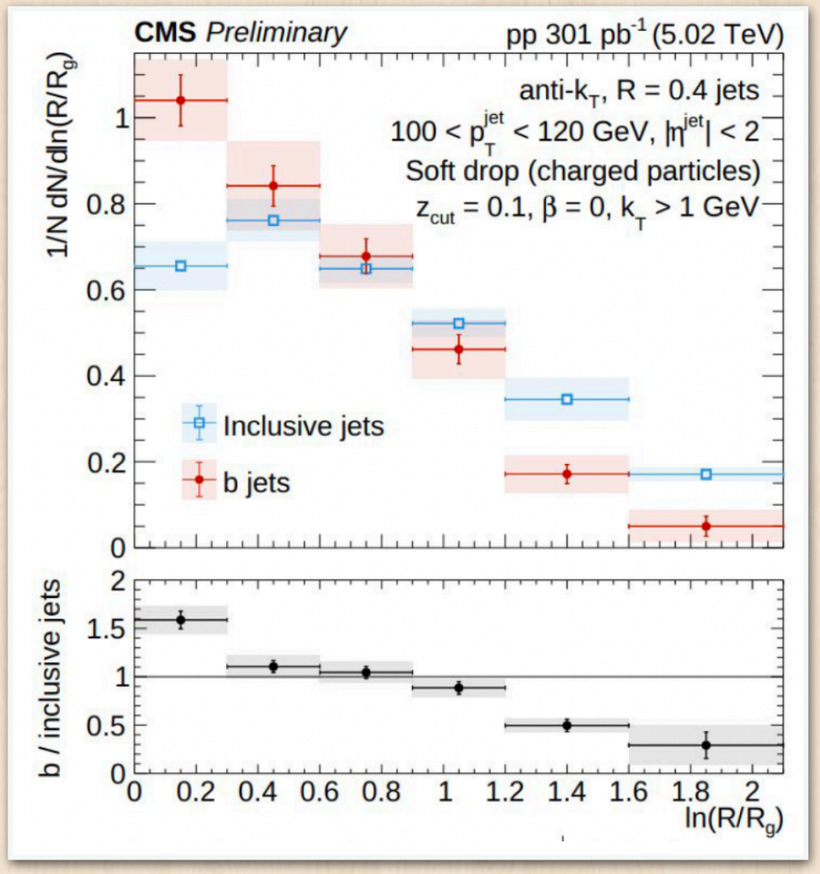
Experiment selection of p_T range naturally favors less modified jets

So… can QGP resolve internal structure? Or it's some other effects?

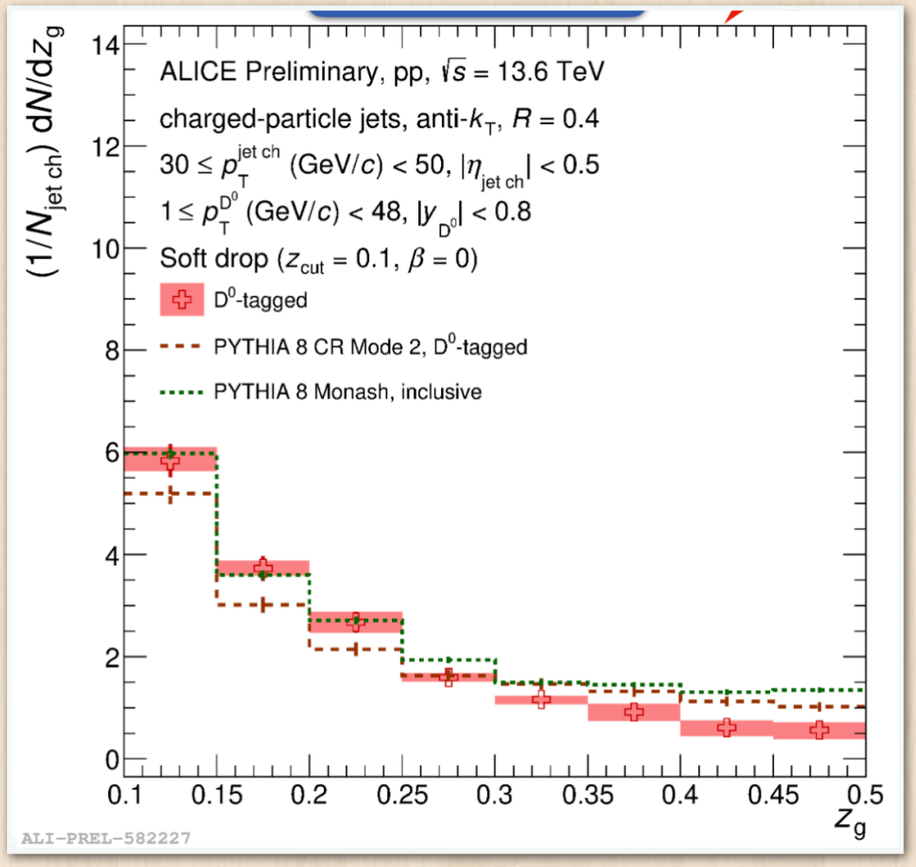
One way to reduce the effect: γ/Z + jet

Since then…

We see this in b-jet also!

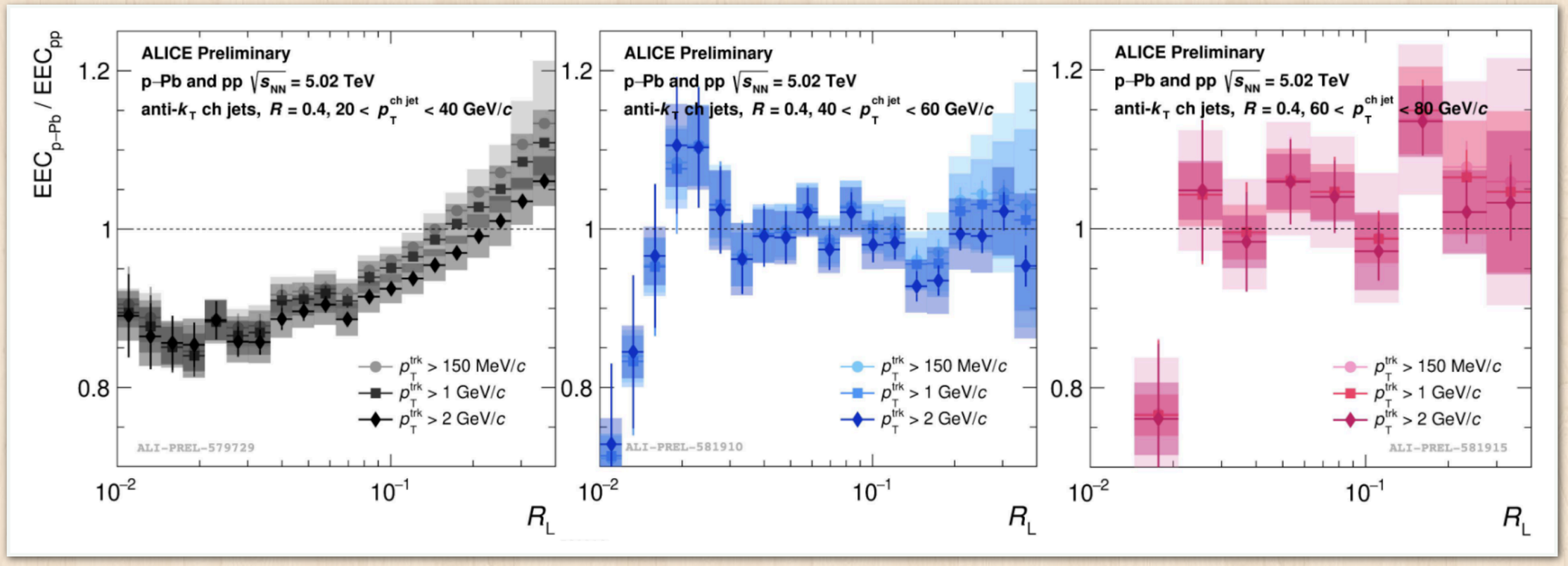


More detailed studies on HF jets



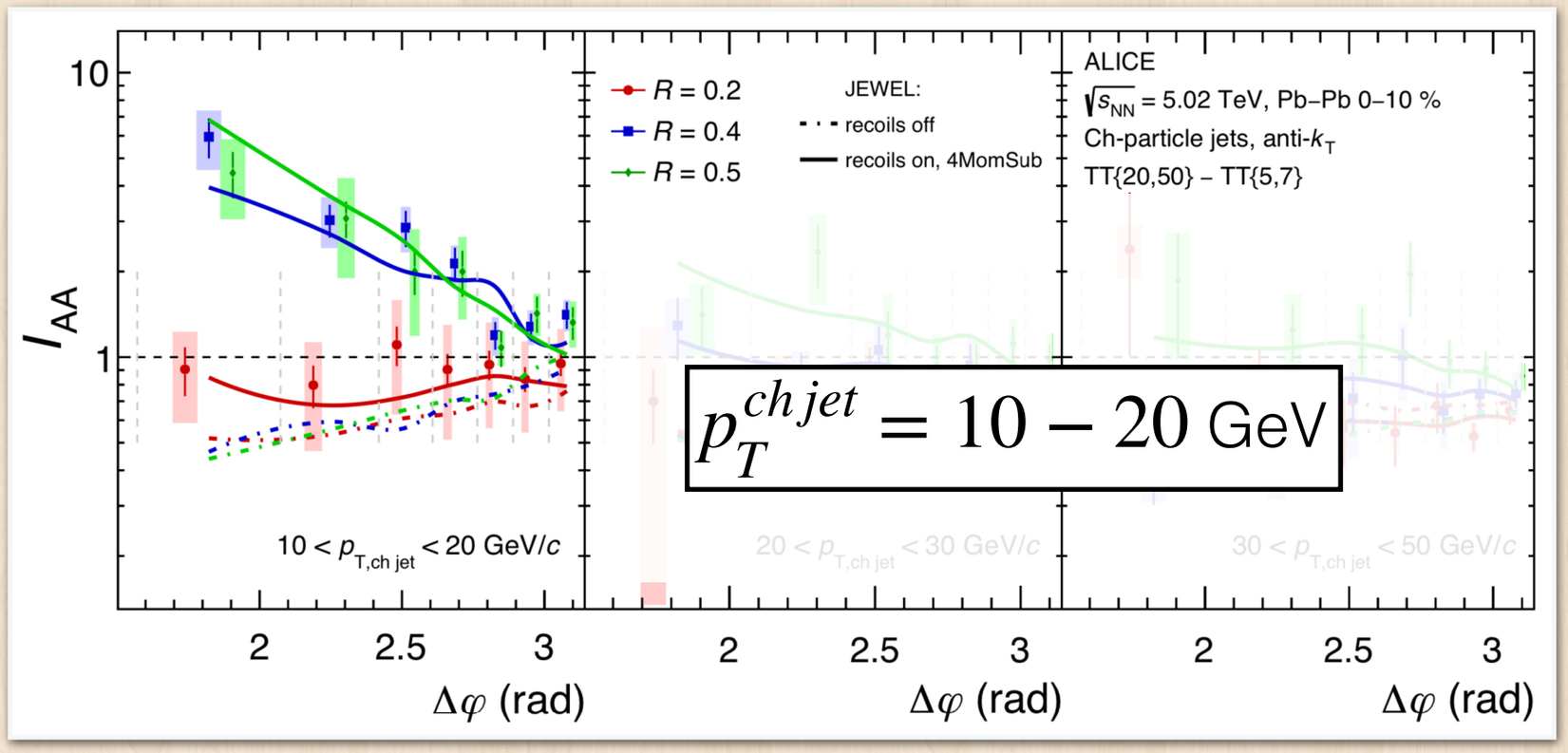
Many more studies ongoing, stay tuned!

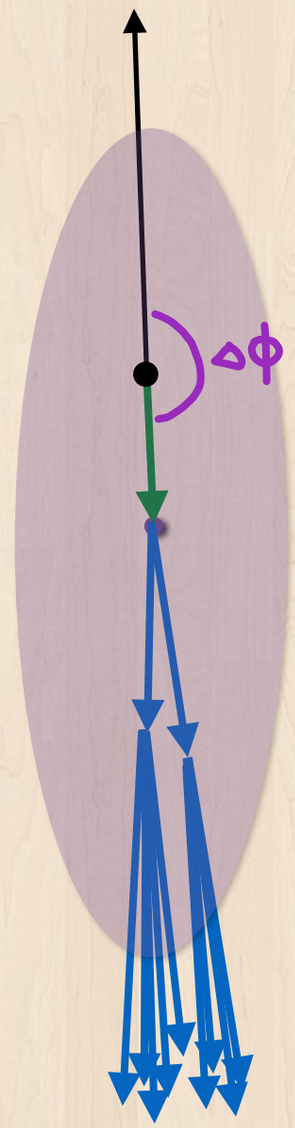
Energy-energy correlator in pA



Pushing to lower scale

Angle between jet and trigger hadron





Larger area jets

= capture more medium effect

= less back to back to the trigger hadron

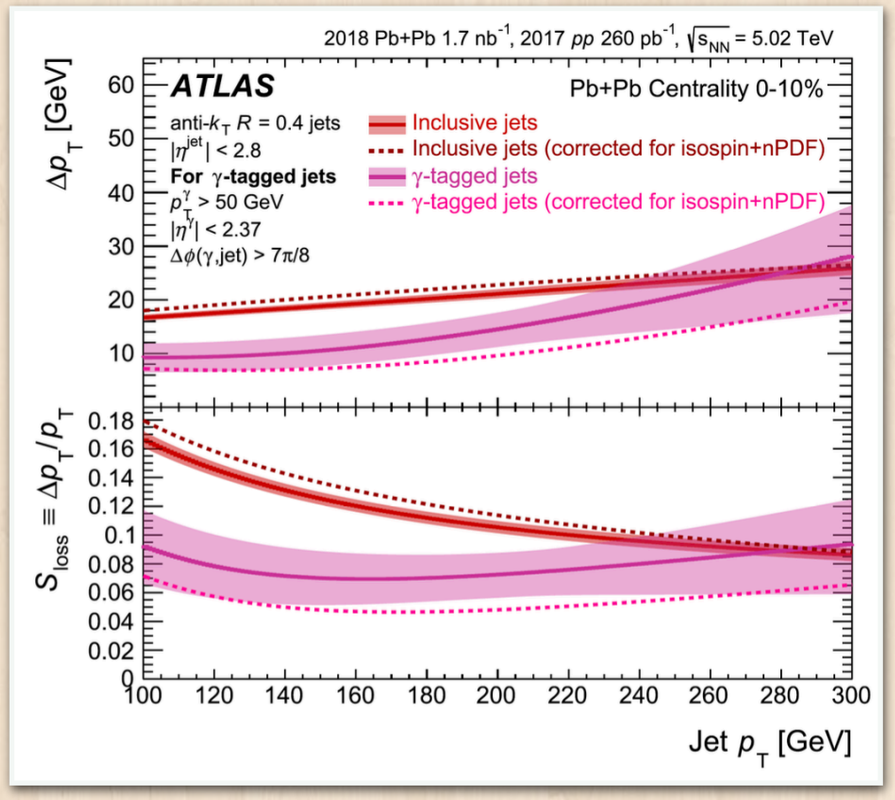
Medium effect dominant at low jet energy

arXiv 2308.16131

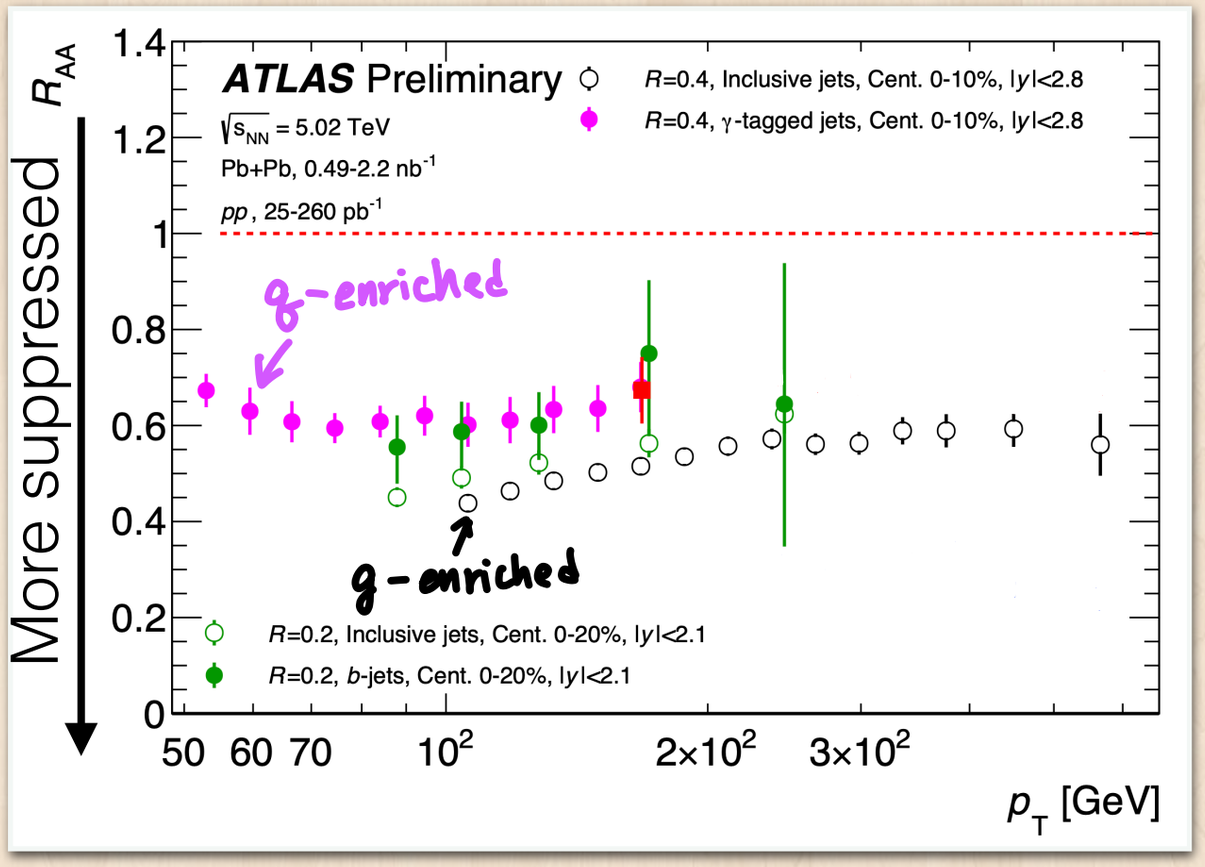
Different processes

Tag different types of jets

- q/g dependence
- mass effect



Amount of energy loss needed to match HI and pp spectra



example summary plot from ATLAS

Lower suppression for **quark-enriched** samples than **gluon-enriched**

Summary plot link + references within