CMS results on EEC

Yi Chen (Vanderbilt)

May 12, 2025. C3NT EEC Workshop

The Vanderbilt HENP group's work is supported by DOE-NP

What I will talk about today

EEC in jet: 13 TeV pp

EEC in jet:
5 TeV pp & PbPb

Z-tagged EEC:
5 TeV pp & PbPb

How does it look like in vacuum?

link to document

How does QGP modify it?

link to document

Can we go beyond jet R?

link to document

What I will talk about today

EEC in jet: 13 TeV pp

How does it look like in vacuum?

EEC in jet:
5 TeV pp & PbPb

How does QGP modify it?

Z-tagged EEC:
5 TeV pp & PbPb

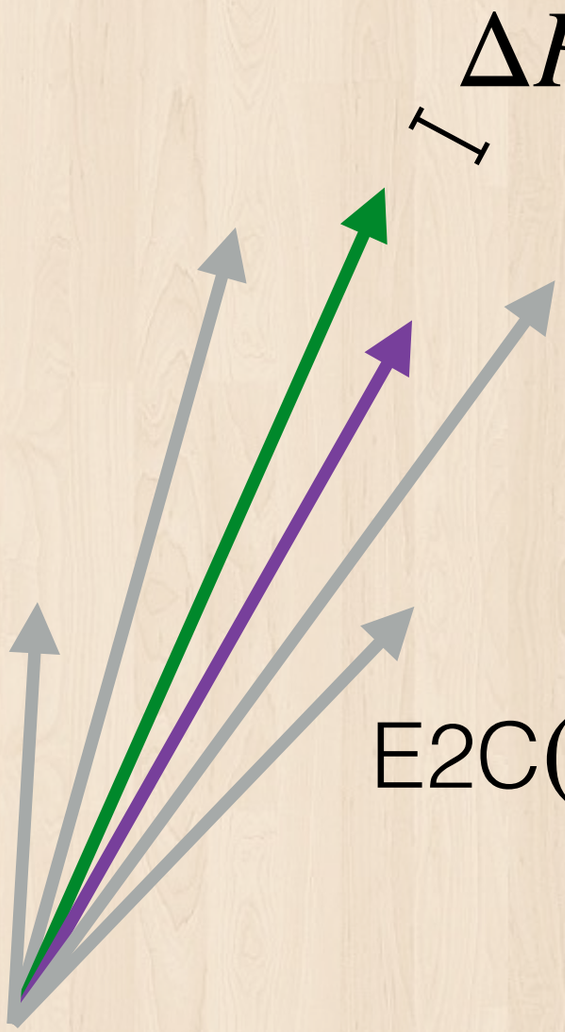
Can we go beyond jet R?

New! Focus on this more

EEC in jets:

pp 13 TeV (vacuum)

Energy-energy correlator

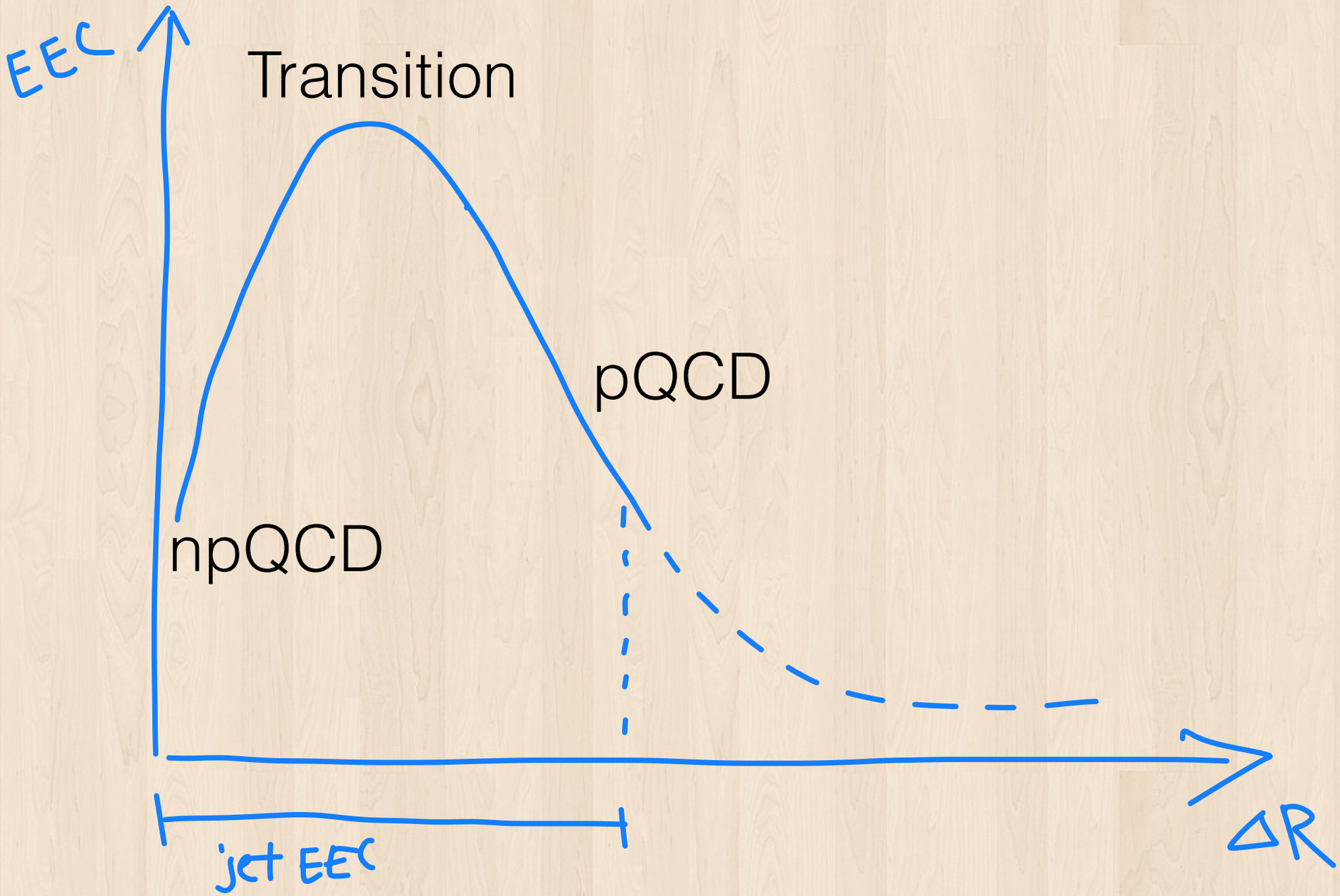


Renewed interest in recent years

$$\mathrm{E2C}(\Delta R) = \frac{1}{N}\sum_{i,j}\frac{p_{T,i}\,p_{T,j}}{Q^2}\,\delta(\Delta R_{ij} - \Delta R)$$

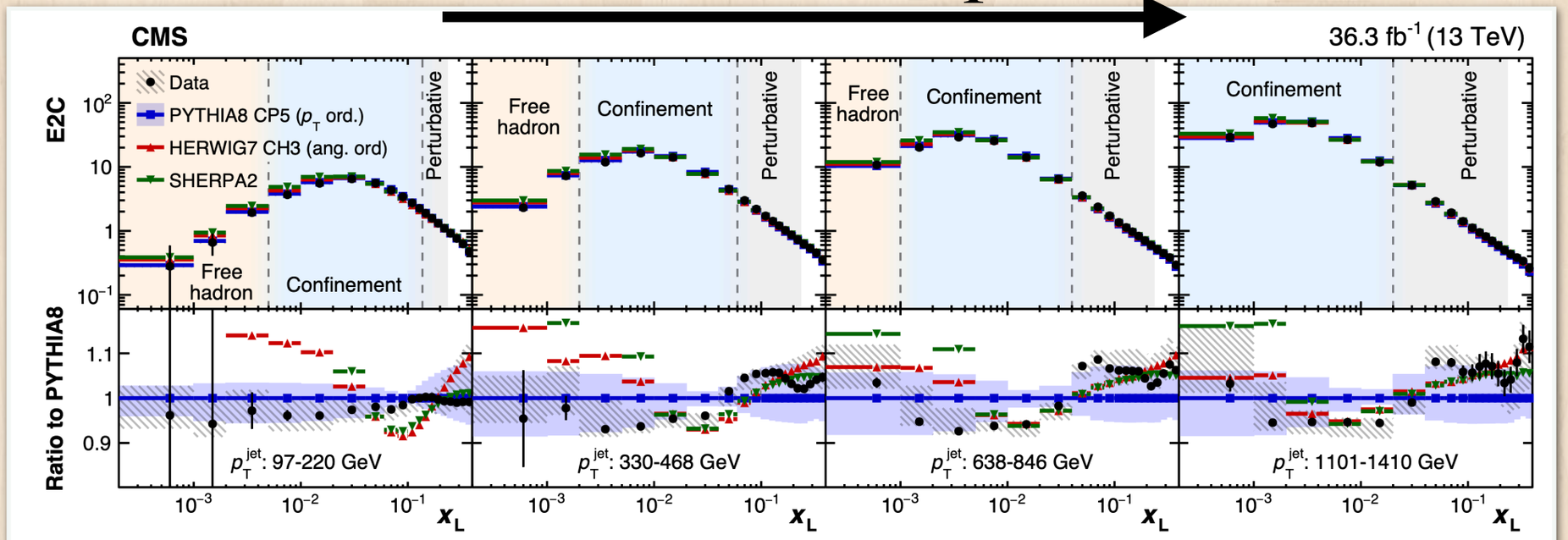
Two-point correlator:
Loop over all pairs
and tally them up

General features



E2C Result

Larger jet p_T



Transition region scales as $x_L \propto 1/p_T$

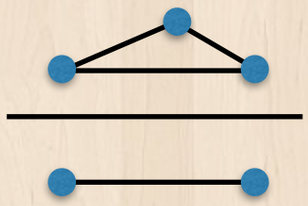
Large angle: pQCD, generally described by MC
Up to 10% across generators

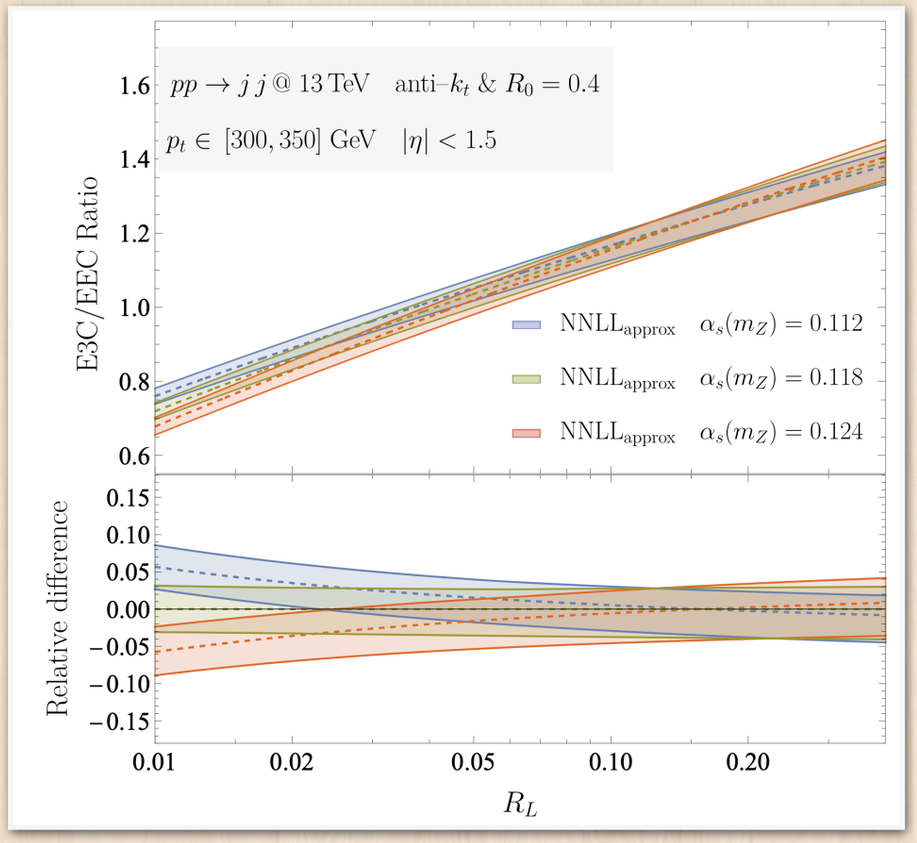
Small angle: npQCD effect important, MC spreads out

PRL 133 (2024) 071903

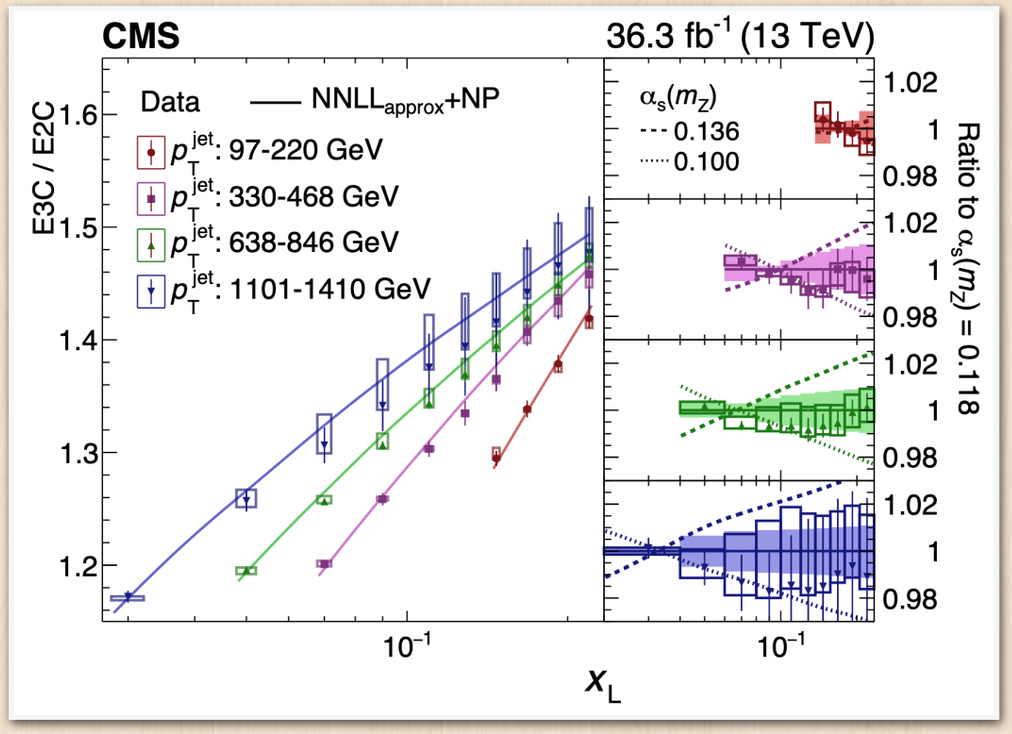
E3C/E2C ratio in pQCD region

Ratio sensitive to α_s



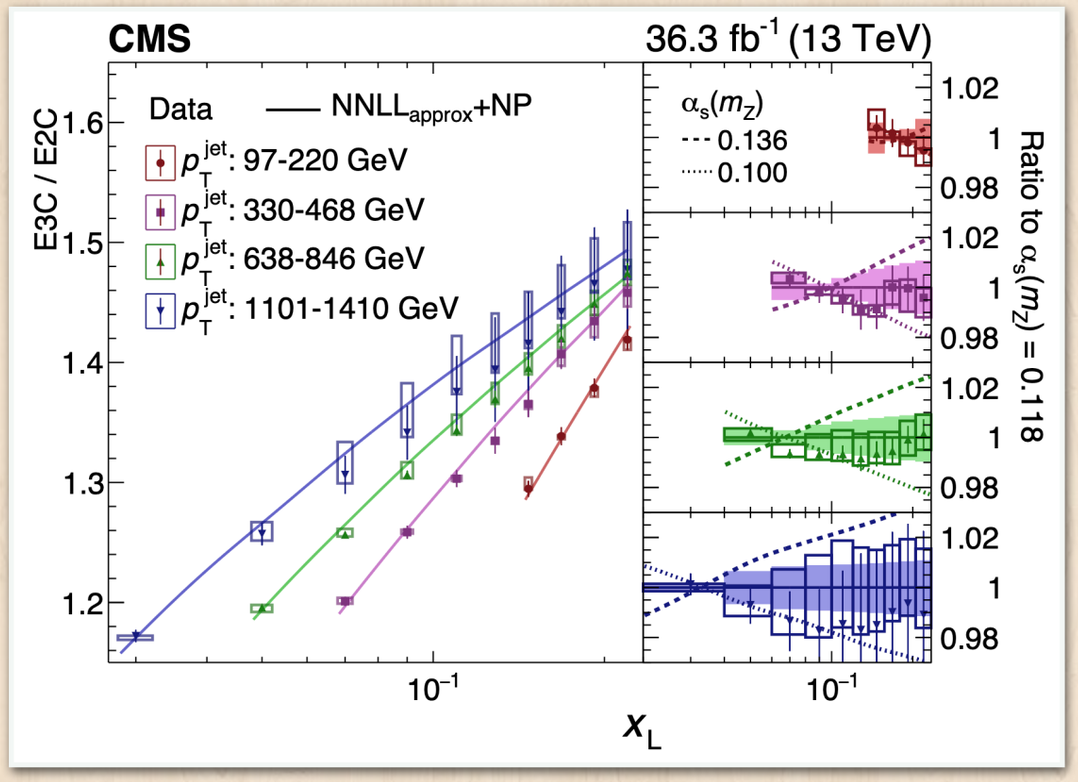


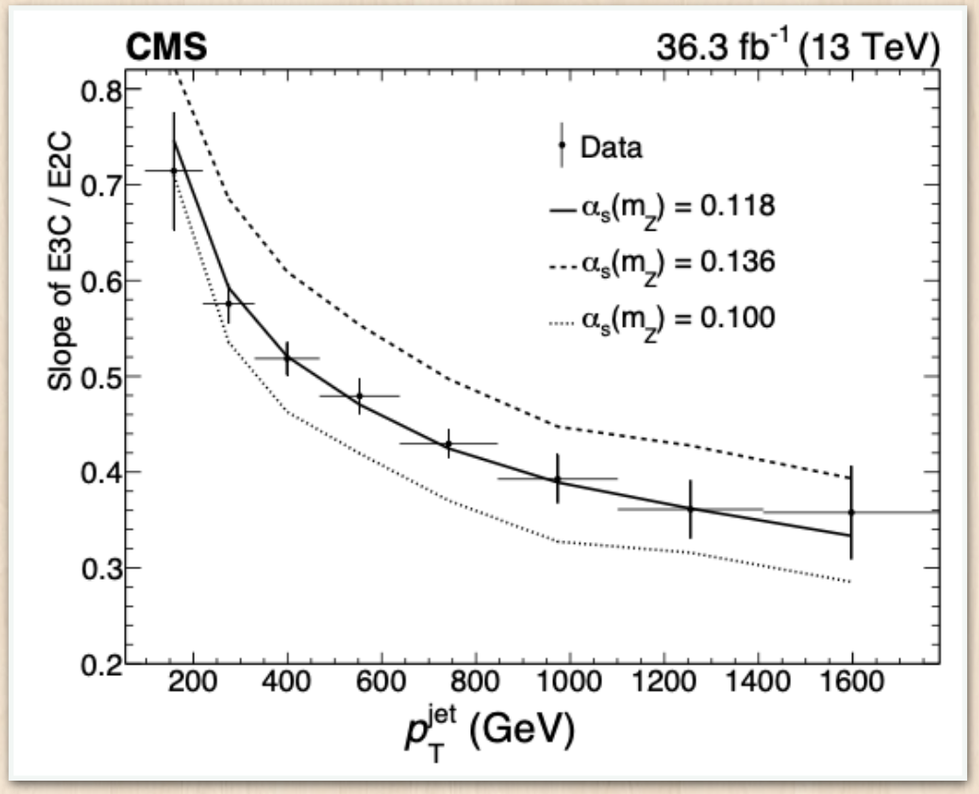
Expect flatter E3C, or steeper E3C/E2C for larger α_s



Calculation compatible with data in pQCD region

Sensitivity to α_s





Characterize the slope → running of α_s

Quantify effect of different $\alpha_s(m_Z)$ by calculating χ^2 between prediction and data

PRL 133 (2024) 071903

Sensitivity to α_s

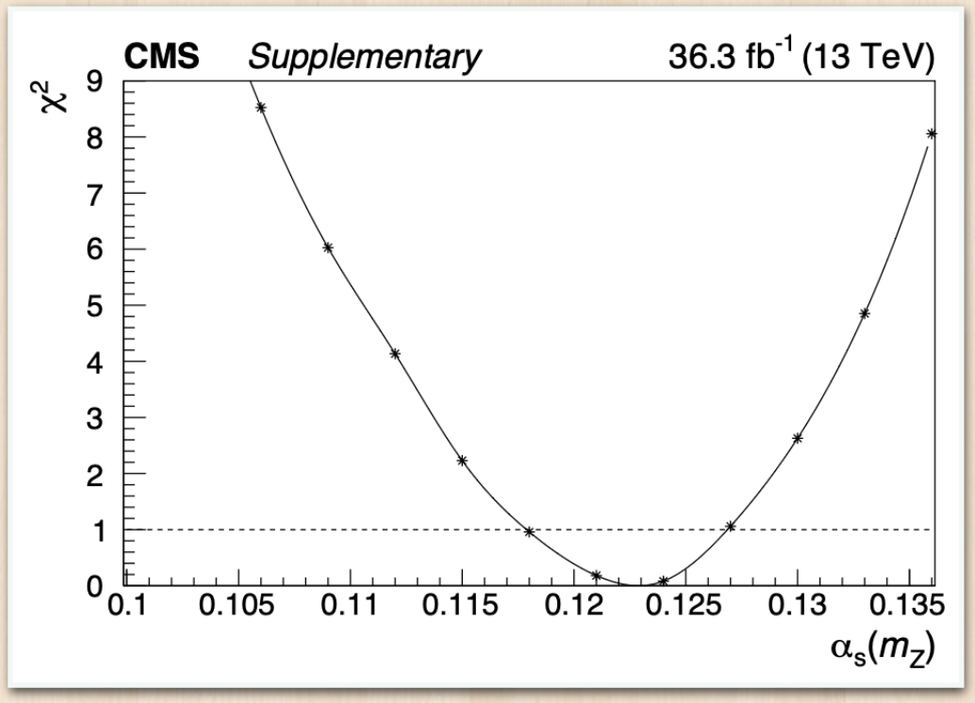
$$\chi^2 = [\vec{v}_{\mathrm{m}}(\vec{\theta}) - \vec{v}_{\mathrm{th}}(\alpha_{\mathrm{S}}, \vec{\theta})]^{\mathsf{T}} V_{\mathrm{m}}^{-1} [\vec{v}_{\mathrm{m}}(\vec{\theta}) - \vec{v}_{\mathrm{th}}(\alpha_{\mathrm{S}}, \vec{\theta})] + \sum_j \theta_j^2,$$

Measured Predicted Unfolding unc. matrix

$\vec{\theta}$: nuisance parameters for uncertainty sources

Consider only shape effect in the variations

$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0030}$$



α_s from substructure!

Jet EEC in heavy ions:

PbPb 5.02 TeV

See more in prof RKE talk

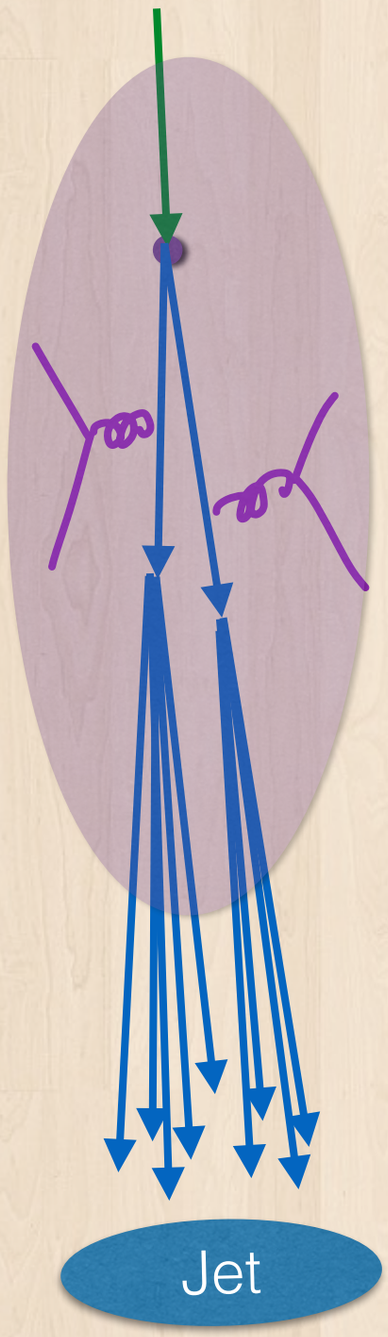
Jets through the QGP

High energy partons fragment through QGP and interact

Energy spreads out
→ cross section drops

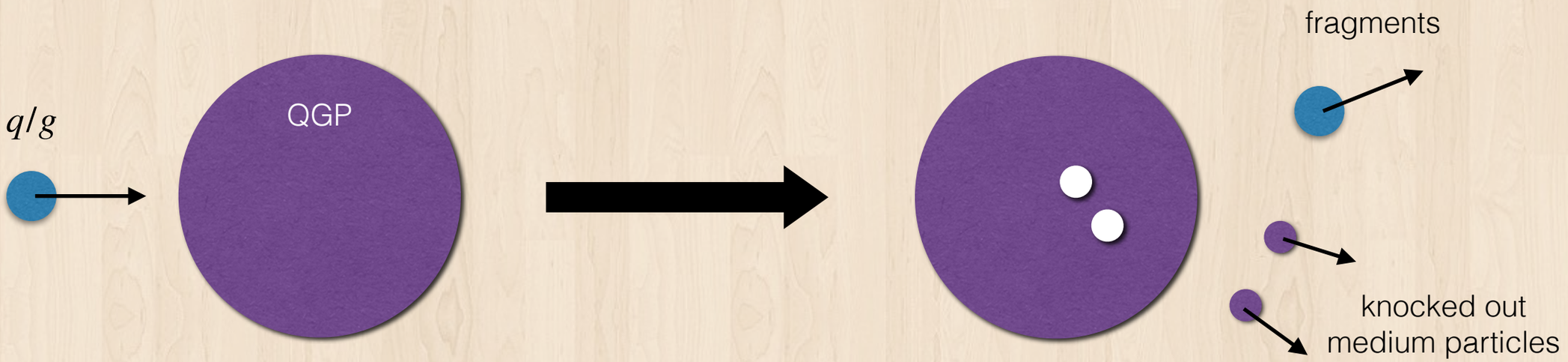
Some general things to keep in mind:

1. **Fragmentation** change of the jet
2. **Energy propagation** through the QGP



How can we try to understand it?

One example approach

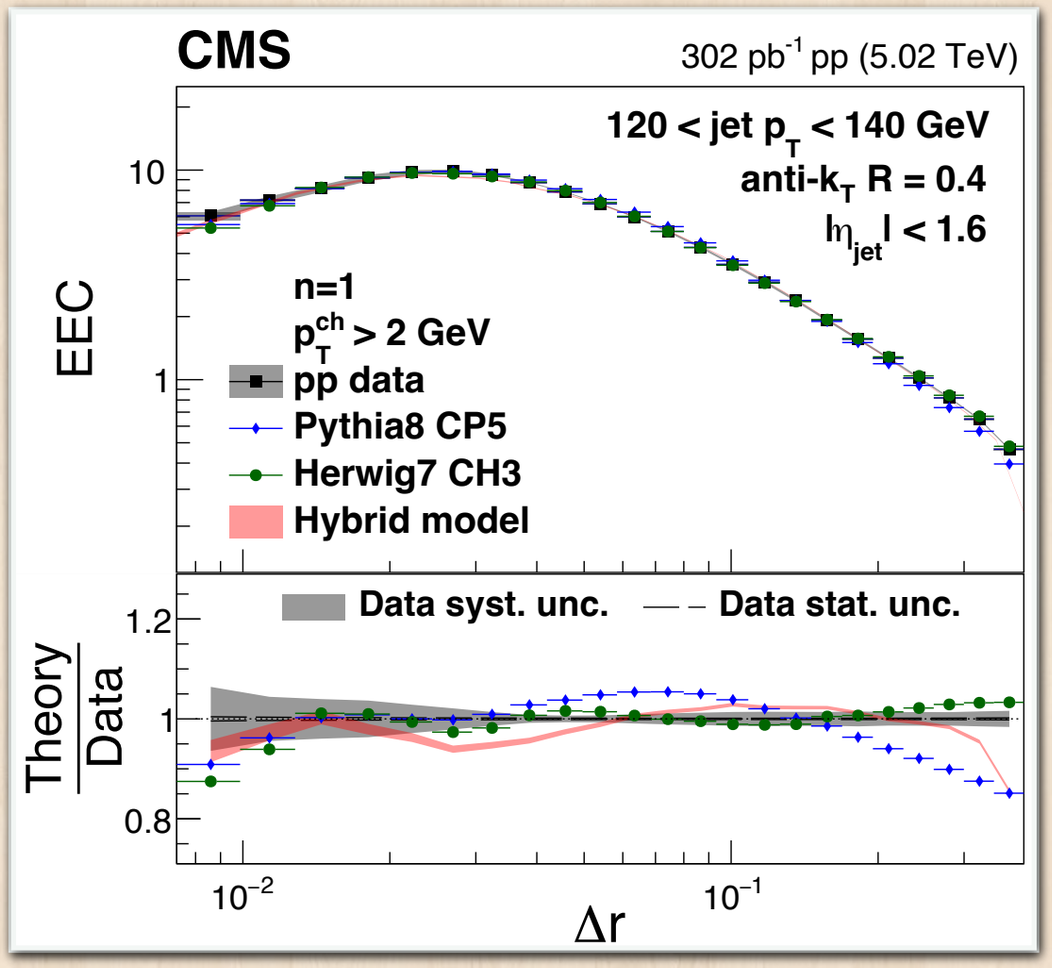


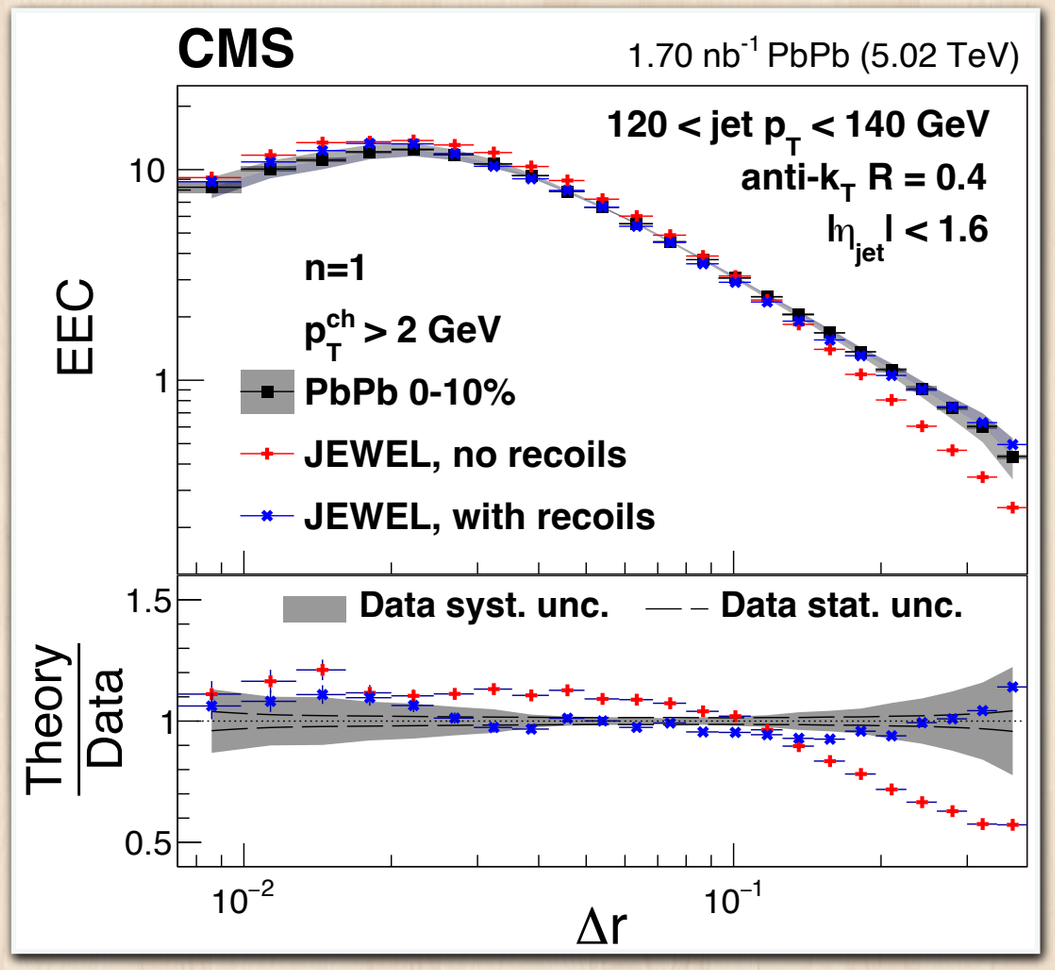
e.g. JEWEL model

"Recoil" = particles knocked out + holes

(Many other approaches not mentioned, e.g. CoLBT)

EEC in pp & PbPb





pp at 5.02 TeV
Similar to 13 TeV result

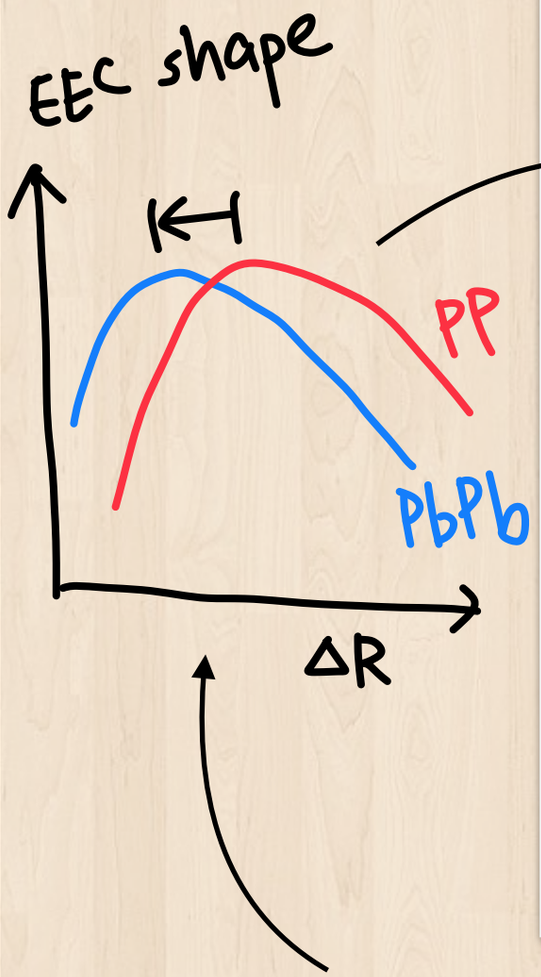
Similar gross feature

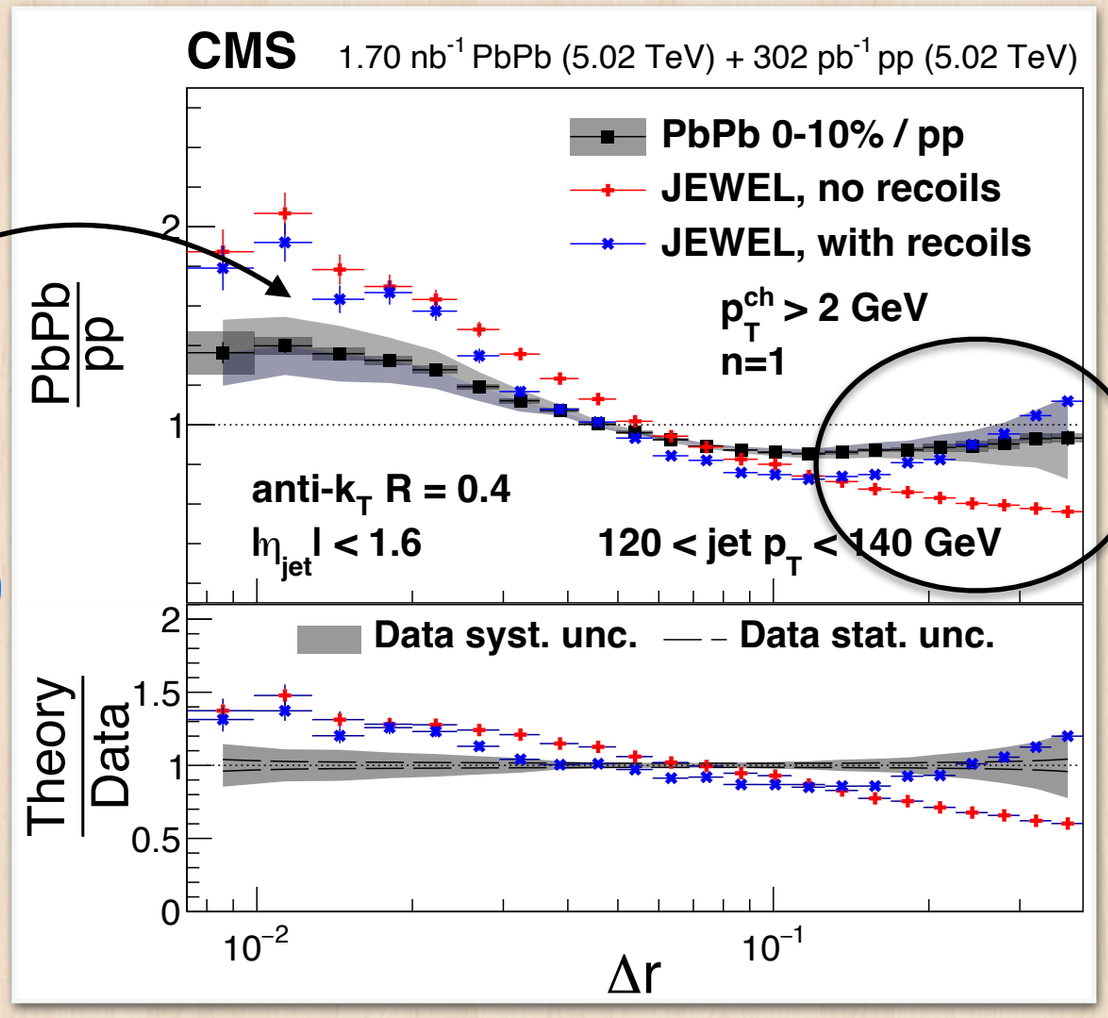
We take the ratio to isolate the effects

arXiv: 2503.19993 → PLB

EEC in PbPb within jets

Many regions of interest in PbPb





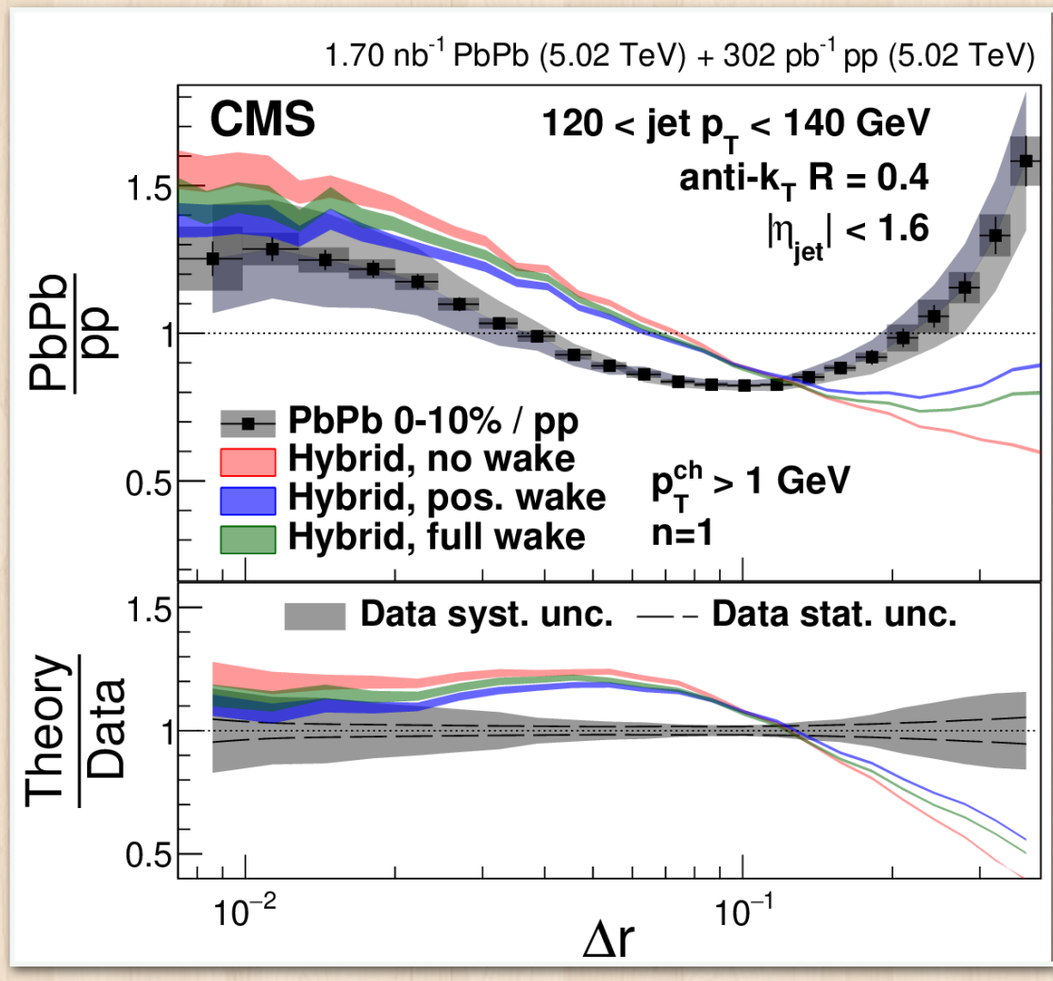
Larger angle medium effect (e.g. recoil) more important

Let's look in a bit more details

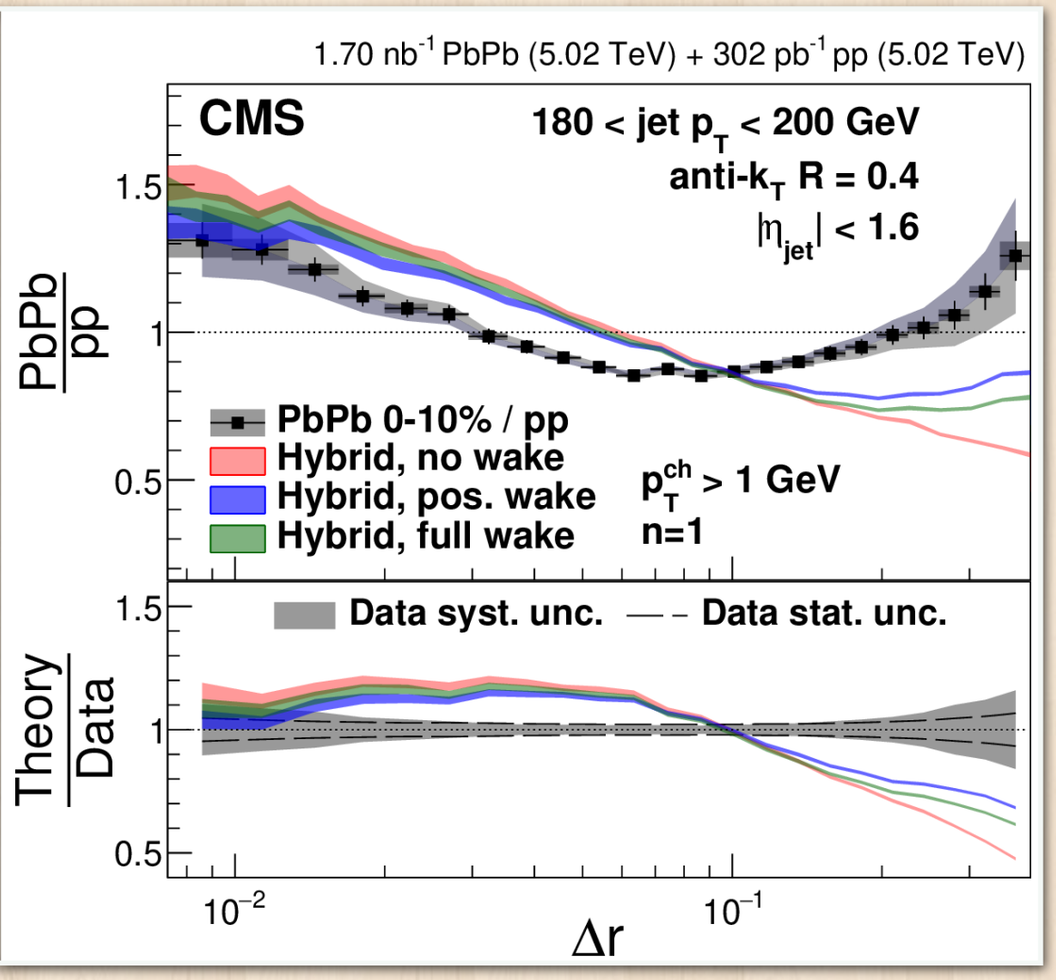
Jet energy loss → peak shift

Jet p_T dependence

Jet p_T = 120-140



Jet p_T = 180-200



Similar trend at small angle (jet energy loss)

Effect at large angle bigger for lower energy jets

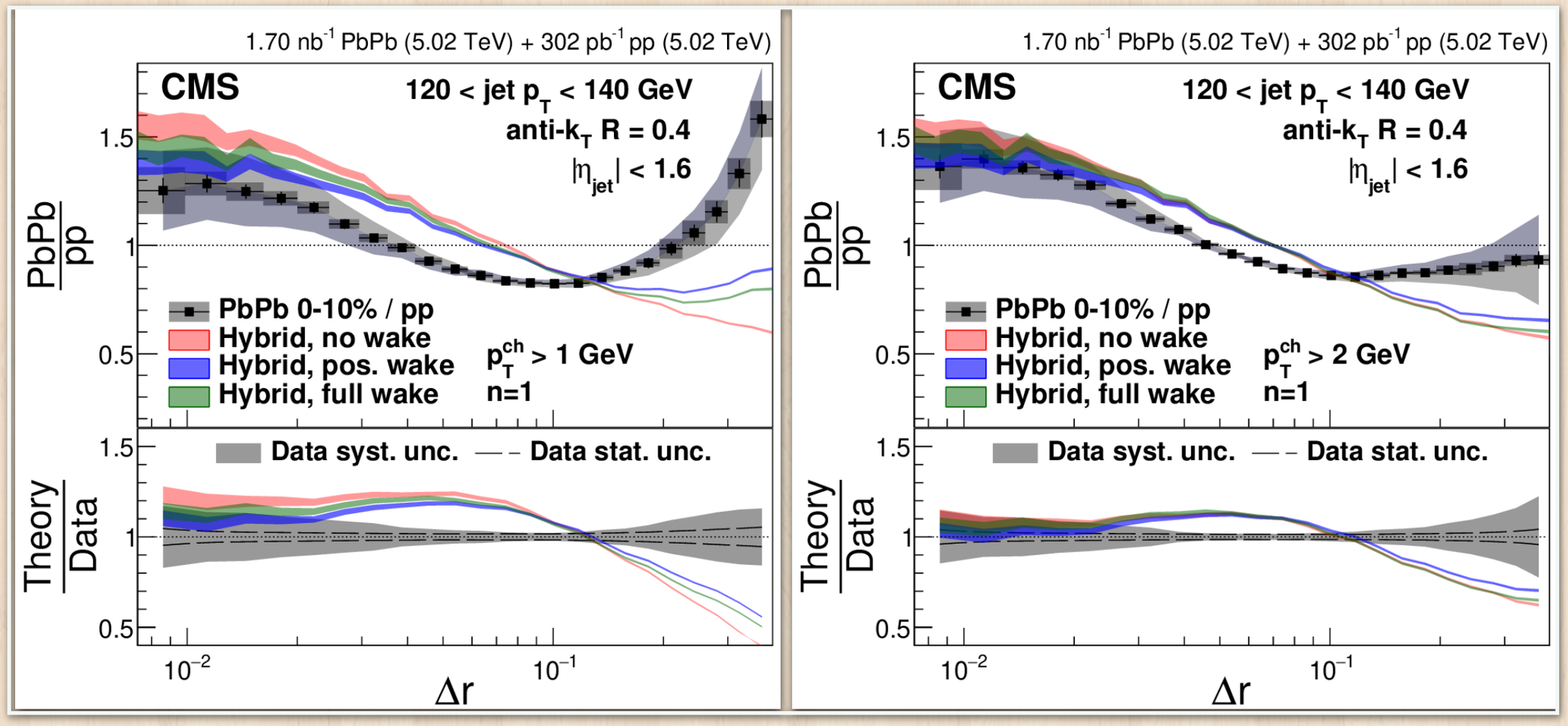
arXiv: 2503.19993 → PLB

See more in prof RKE talk

Particle p_T dependence

Particle p_T > 1 GeV

Particle p_T > 2 GeV

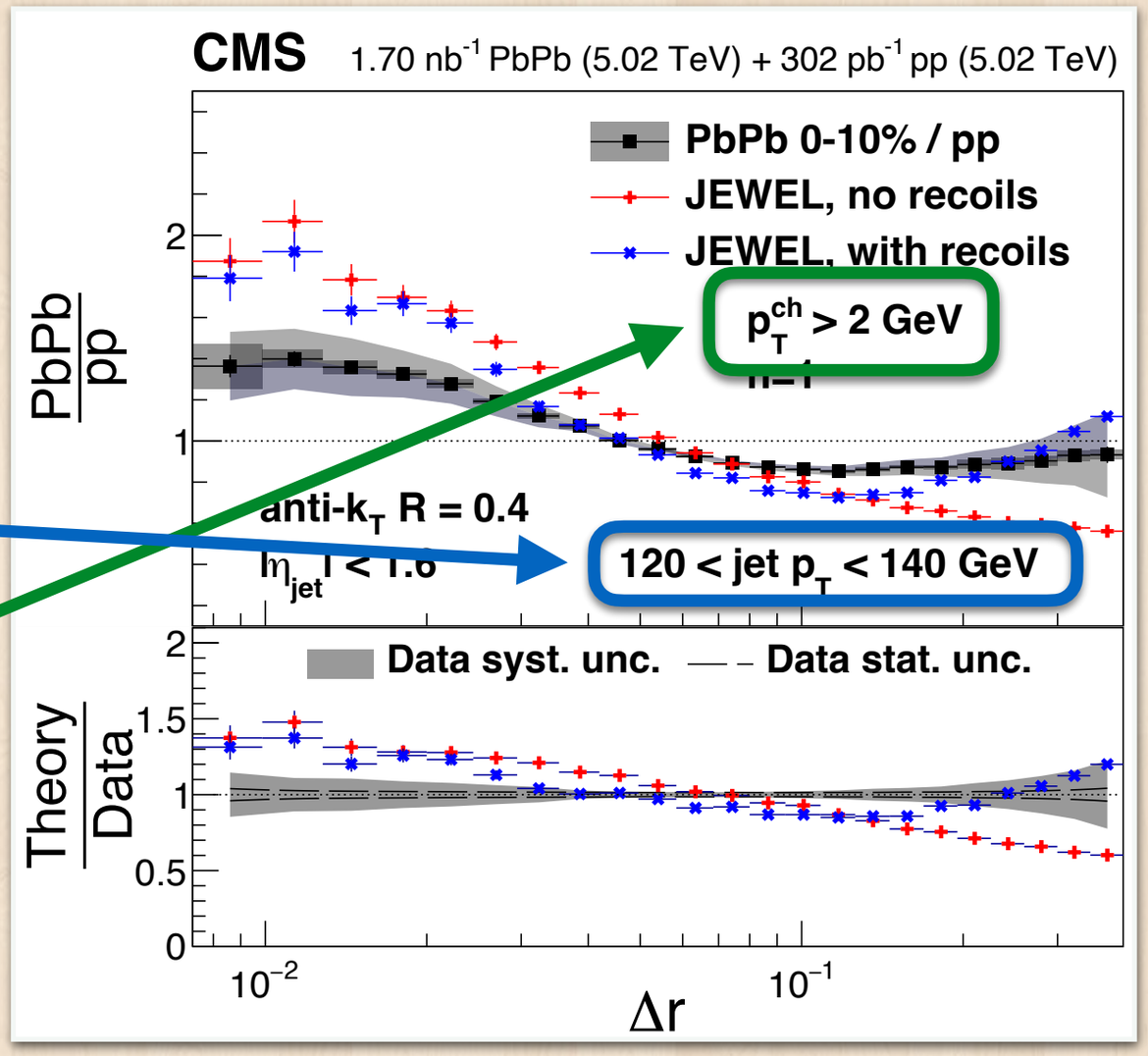


Small angle dominated by higher p_T particles in jet

Larger particle p_T diminishes effect

Where to look to isolate recoils?

- Large angle
- Lower scales
- Lower particle p_T



This motivates the Z-tagged EEC study

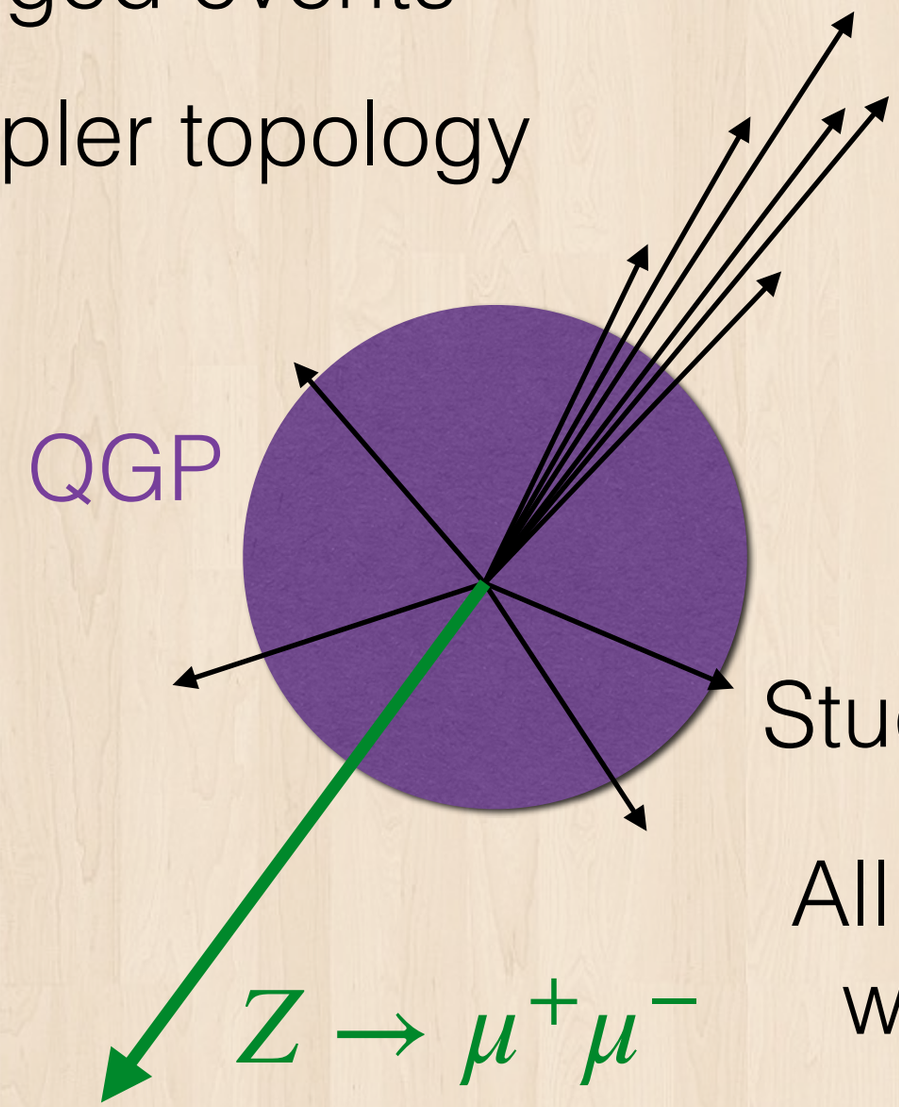
Z-tagged EEC:

pp & PbPb 5.02 TeV

Looking further

Look into Z-tagged events

One sided: simpler topology



Charged particles

Study **full event EEC**

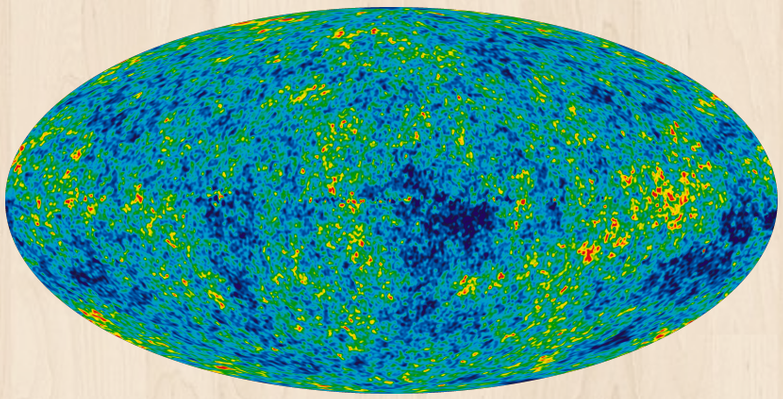
All charged particles within acceptance

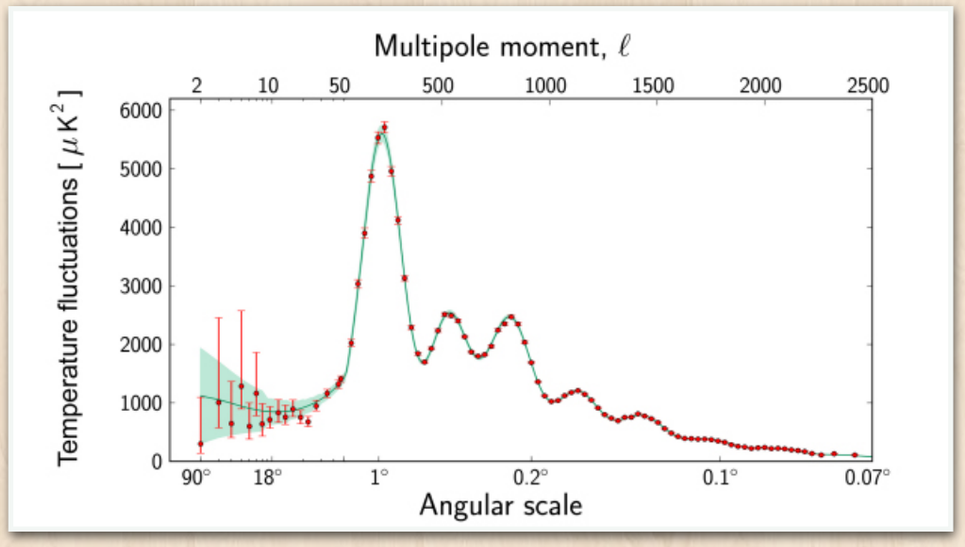
No explicit jet finding

$$\mathrm{EEC}(\Delta R) = \frac{1}{N_Z} \sum p_{T,i}\, p_{T,j}\, \delta(\Delta R_{ij} - \Delta R)$$

Mapping out angular scales

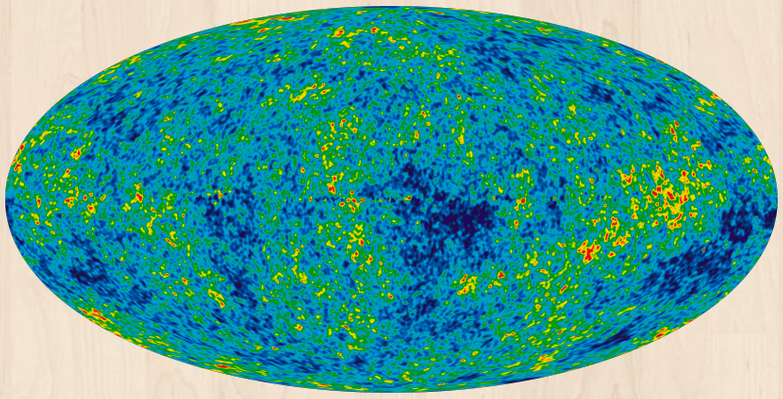
CMB Map

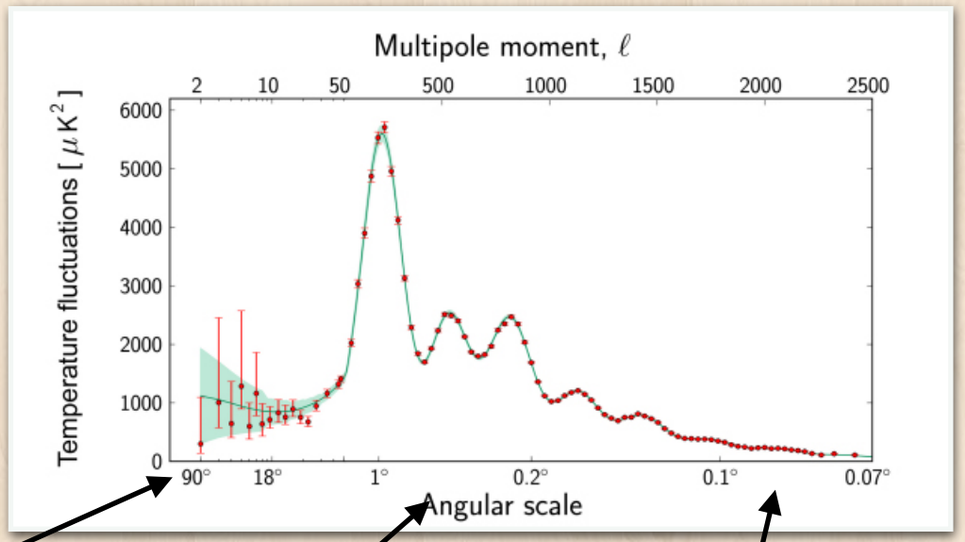




Mapping out angular scales

CMB Map





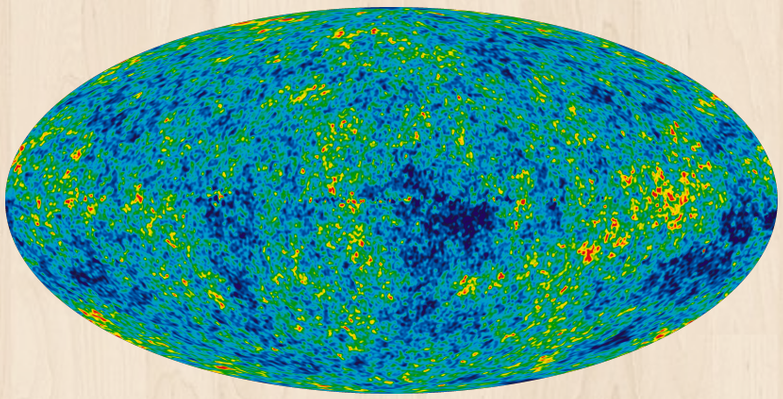
Large angle: inflation

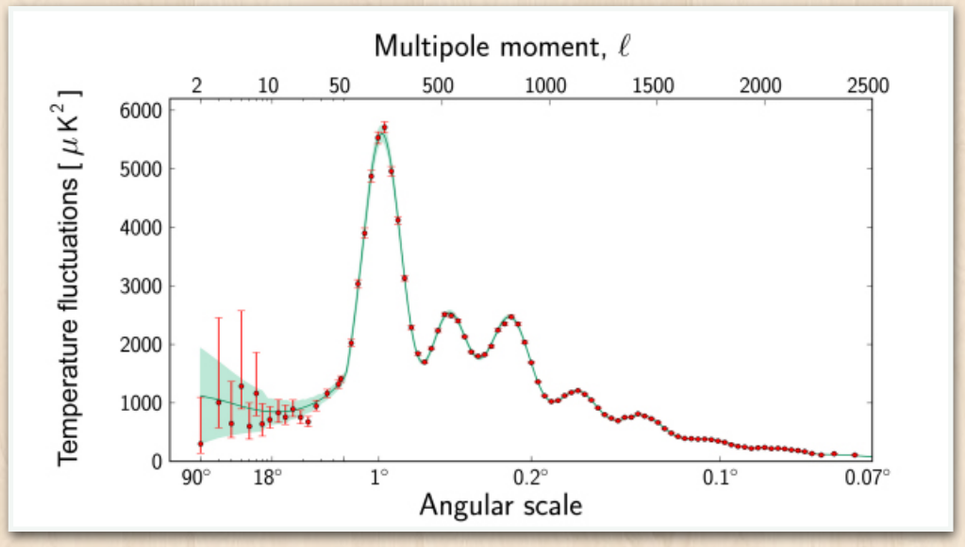
Small angle: diffusion

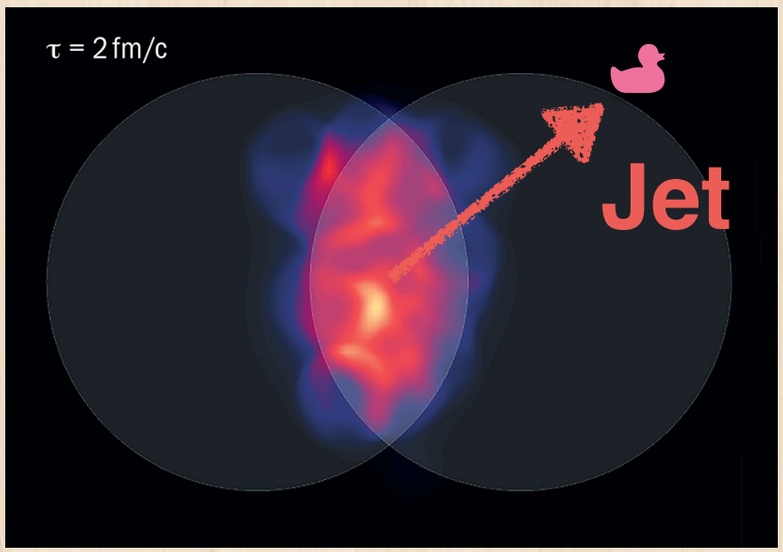
Intermediate: acoustics

Mapping out angular scales

CMB Map







????

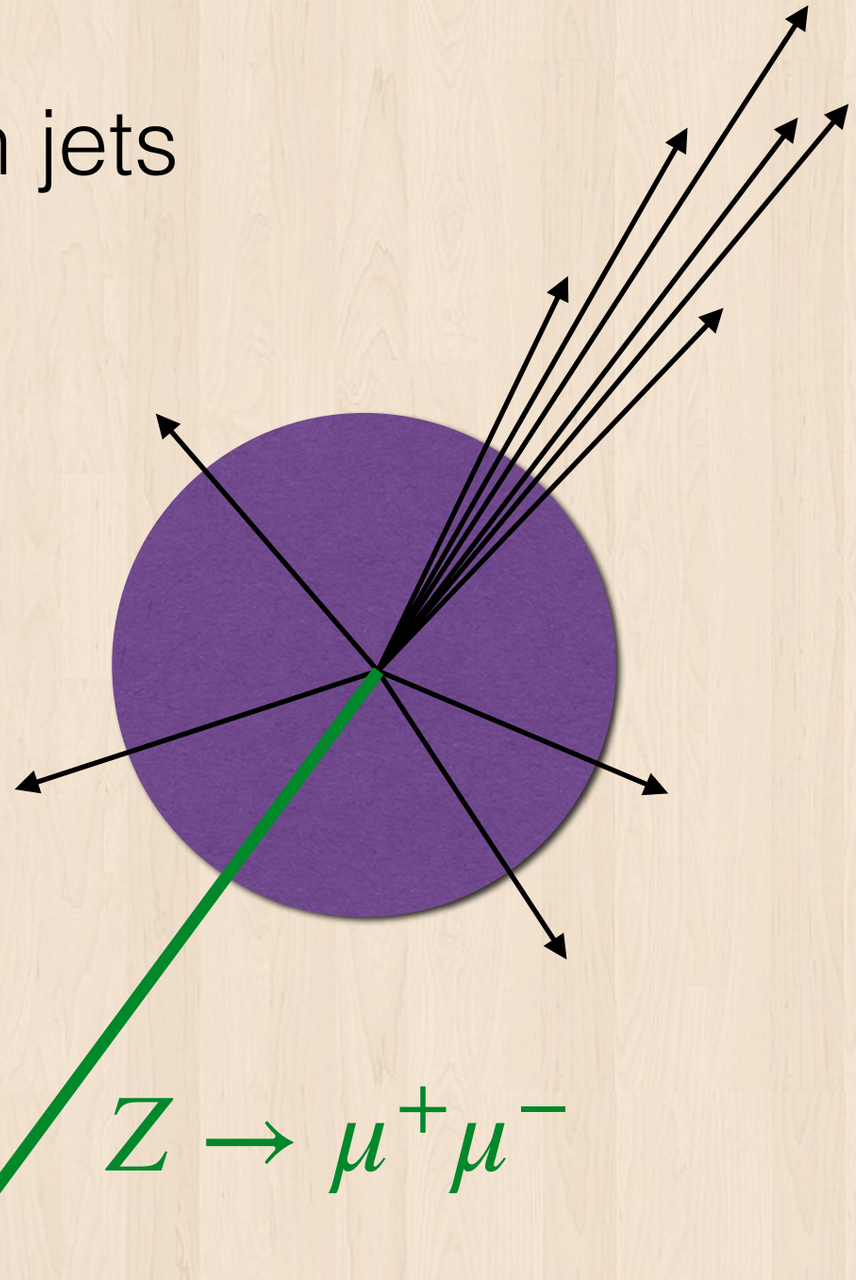
Selections

Lower scale than jets

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

$p_T^\mu > 20$ GeV
$|\eta^\mu| < 2.4$

$p_T^Z > 40$ GeV
$|y^Z| < 2.4$
$60 < m_Z < 120$ GeV



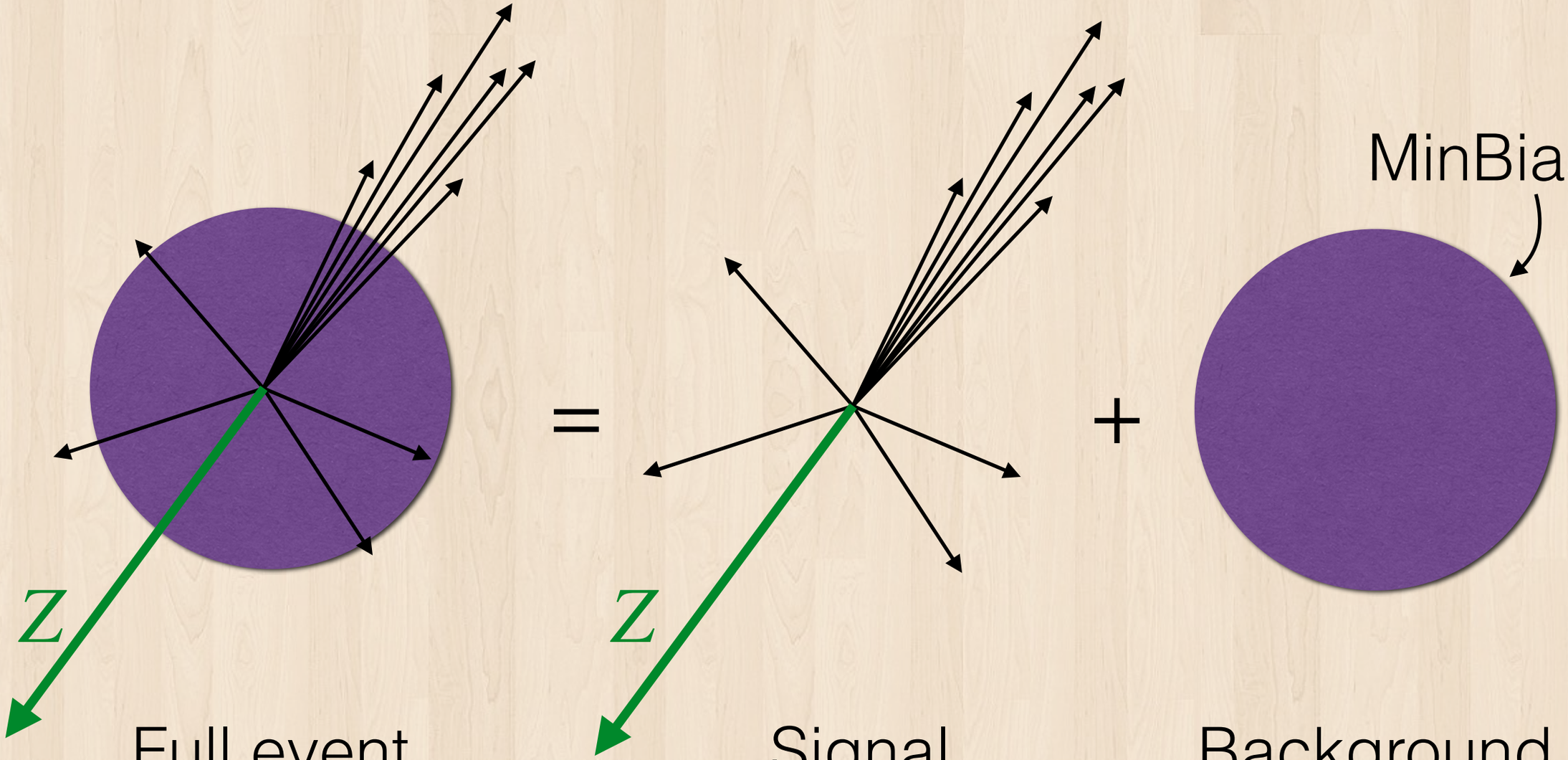
Charged hadron

$p_T > 2$ GeV
$|\eta| < 2.4$

Reject muon tracks

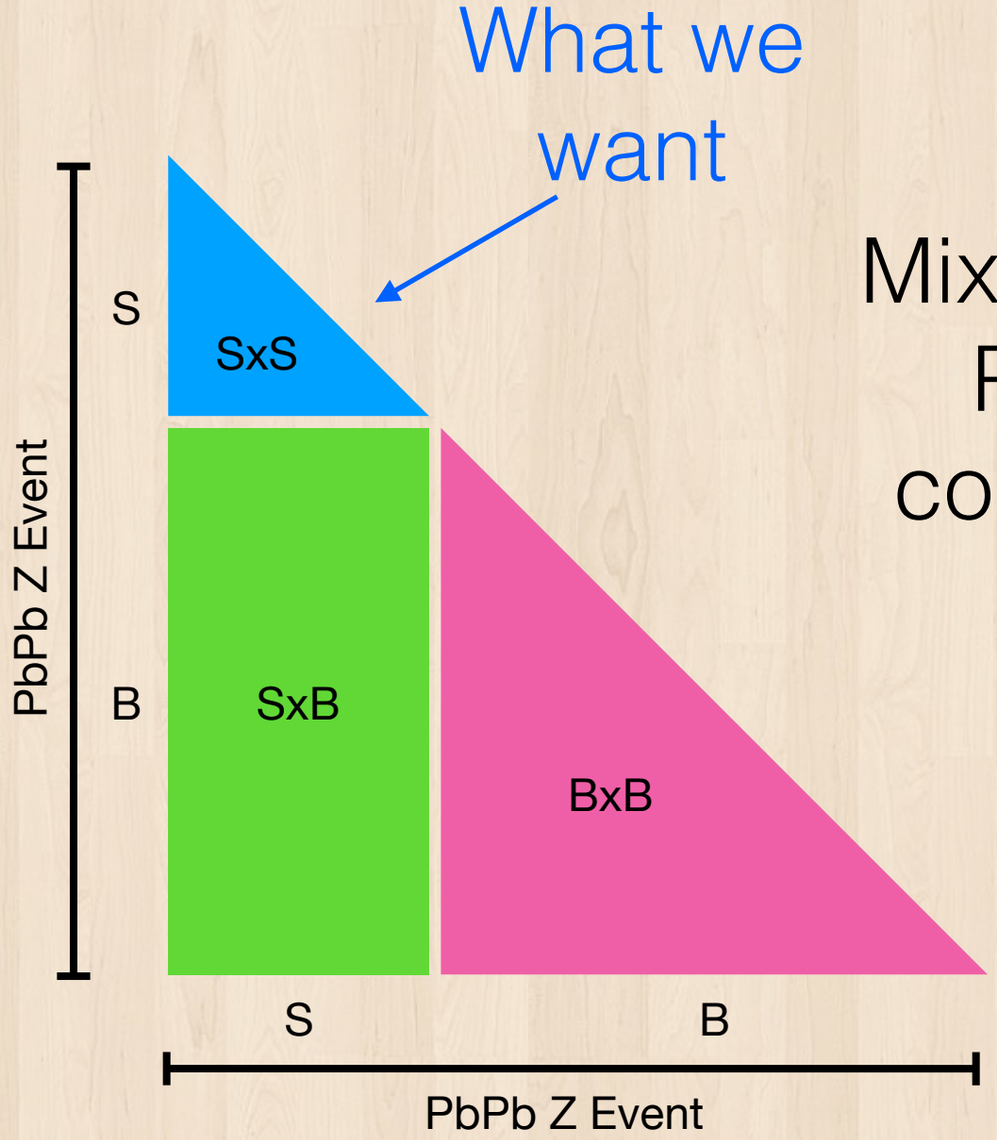
High-ish particle p_T

Definition of “signal”



Do event mixing to remove unwanted contributions

Event mixing scheme



Mixing particles from the same PbPb Z event gives three contributions: (S+B)x(S+B) =

SxS + **SxB** + **BxB**

See next page

Self-mixing in background events

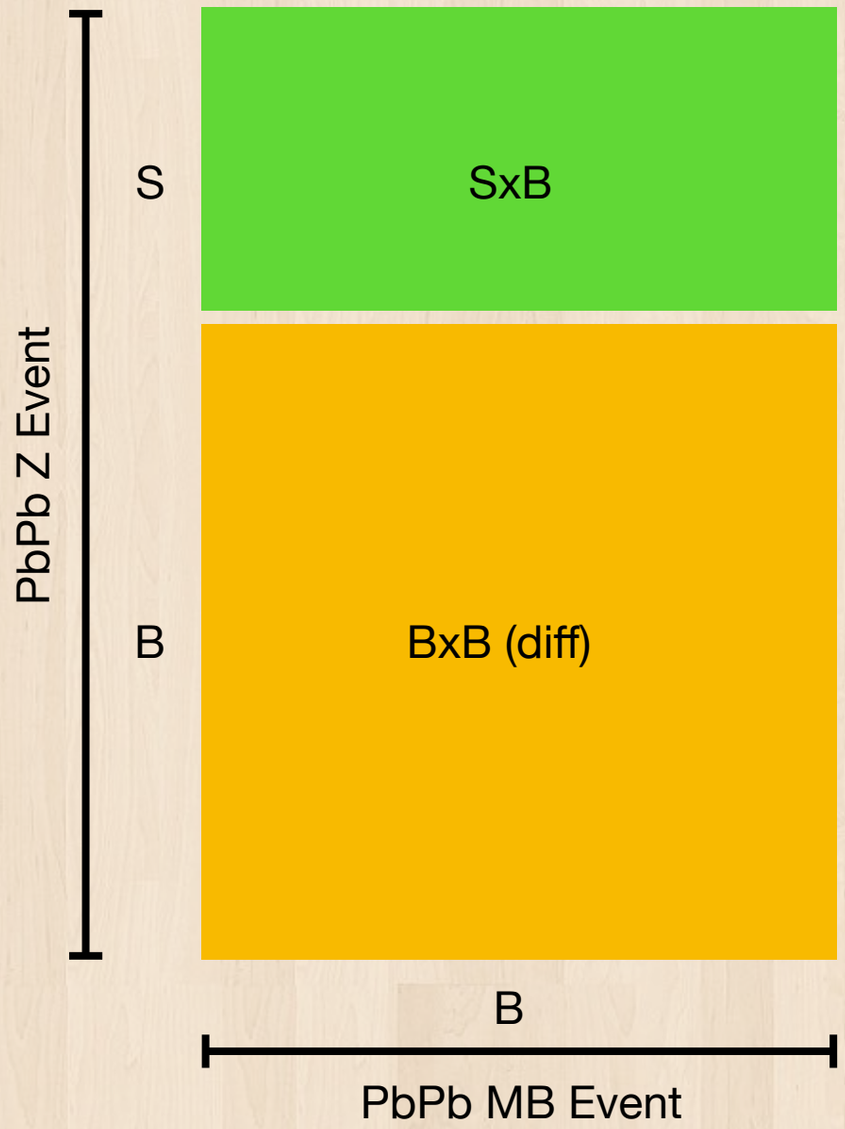
Notation: AxB = one particle from A, another from B

Event mixing scheme

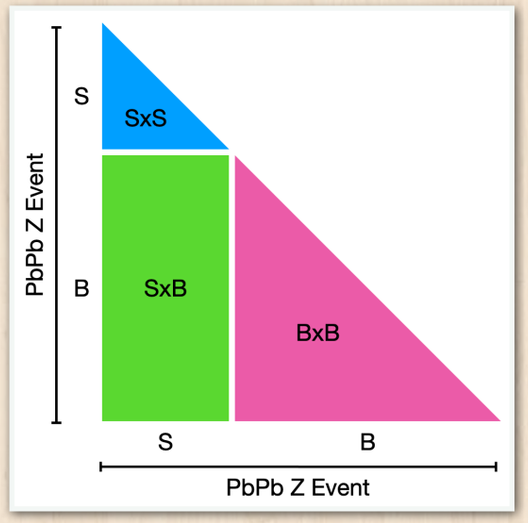
Mixing PbPb Z event with background event gives two contributions:

(S+B)xB = **SxB** + **BxB (diff)**

Mixing with different background events

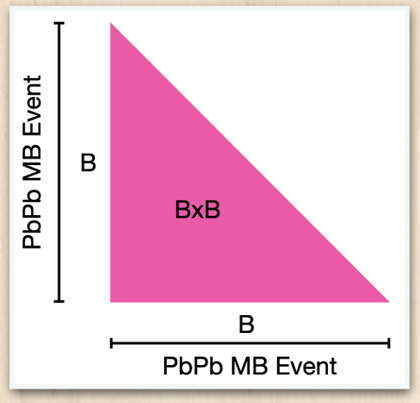


Essentially…



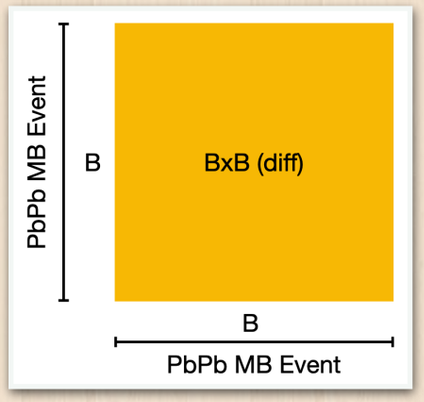
Z self-mixing

\-



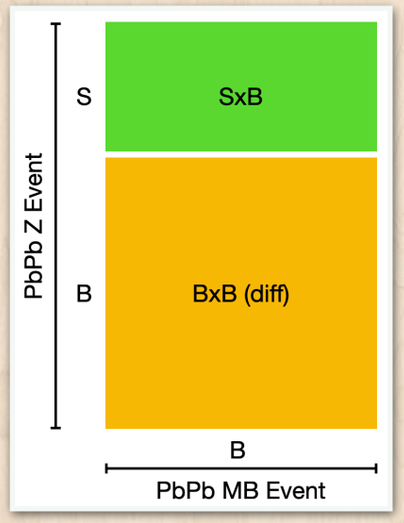
MB self-mixing

\+



MB with MB

\-



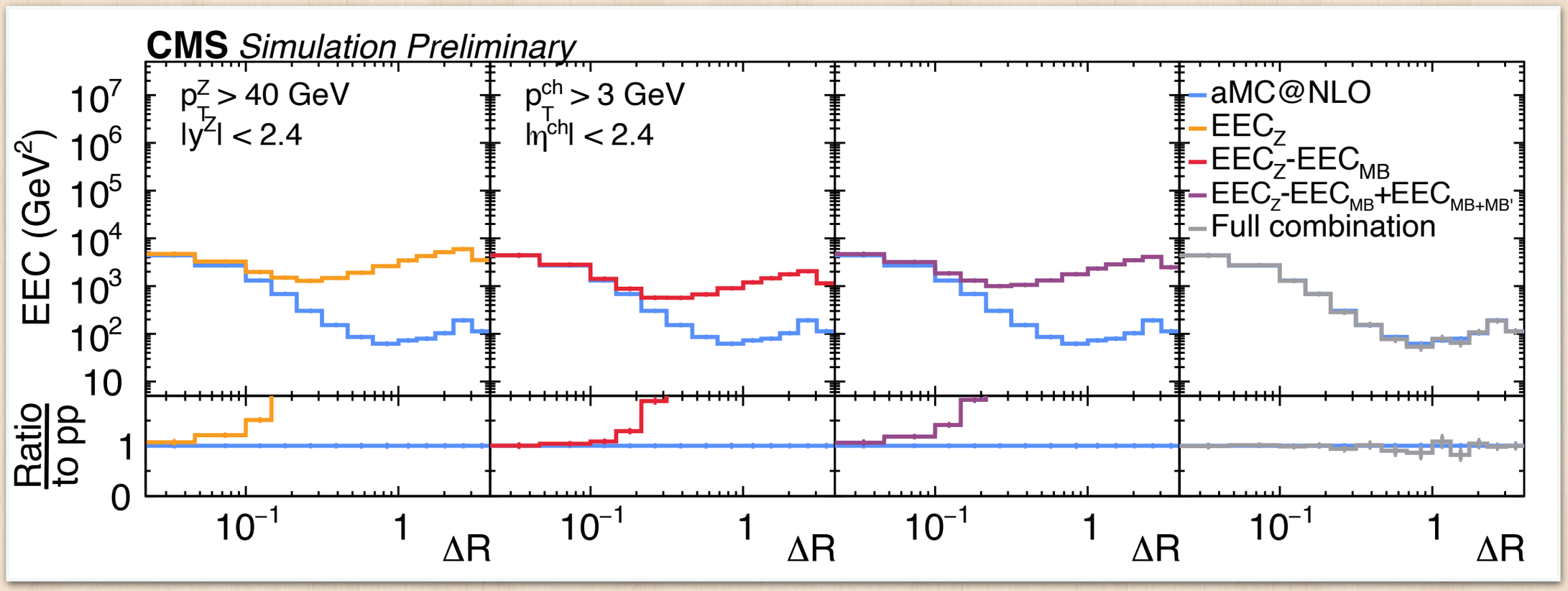
Z with MB

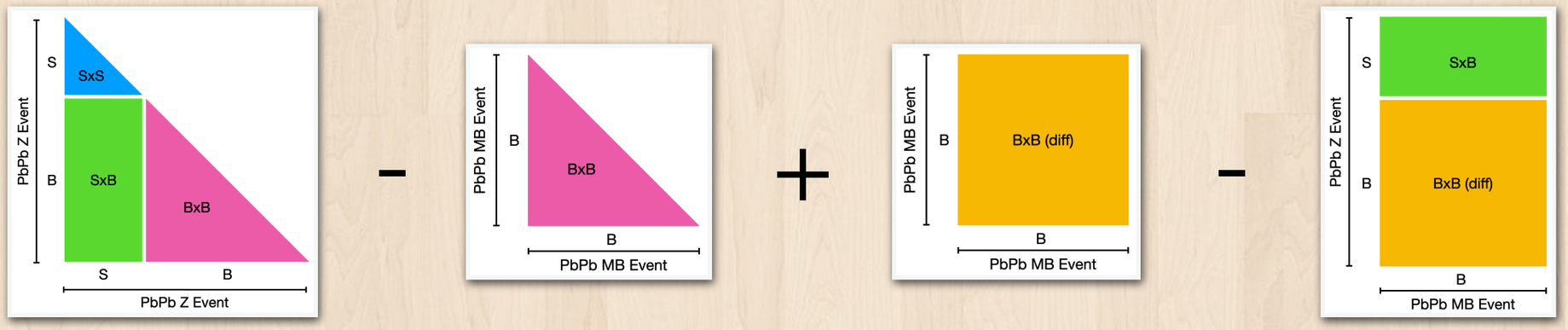
=

What we want

Event mixing demonstration

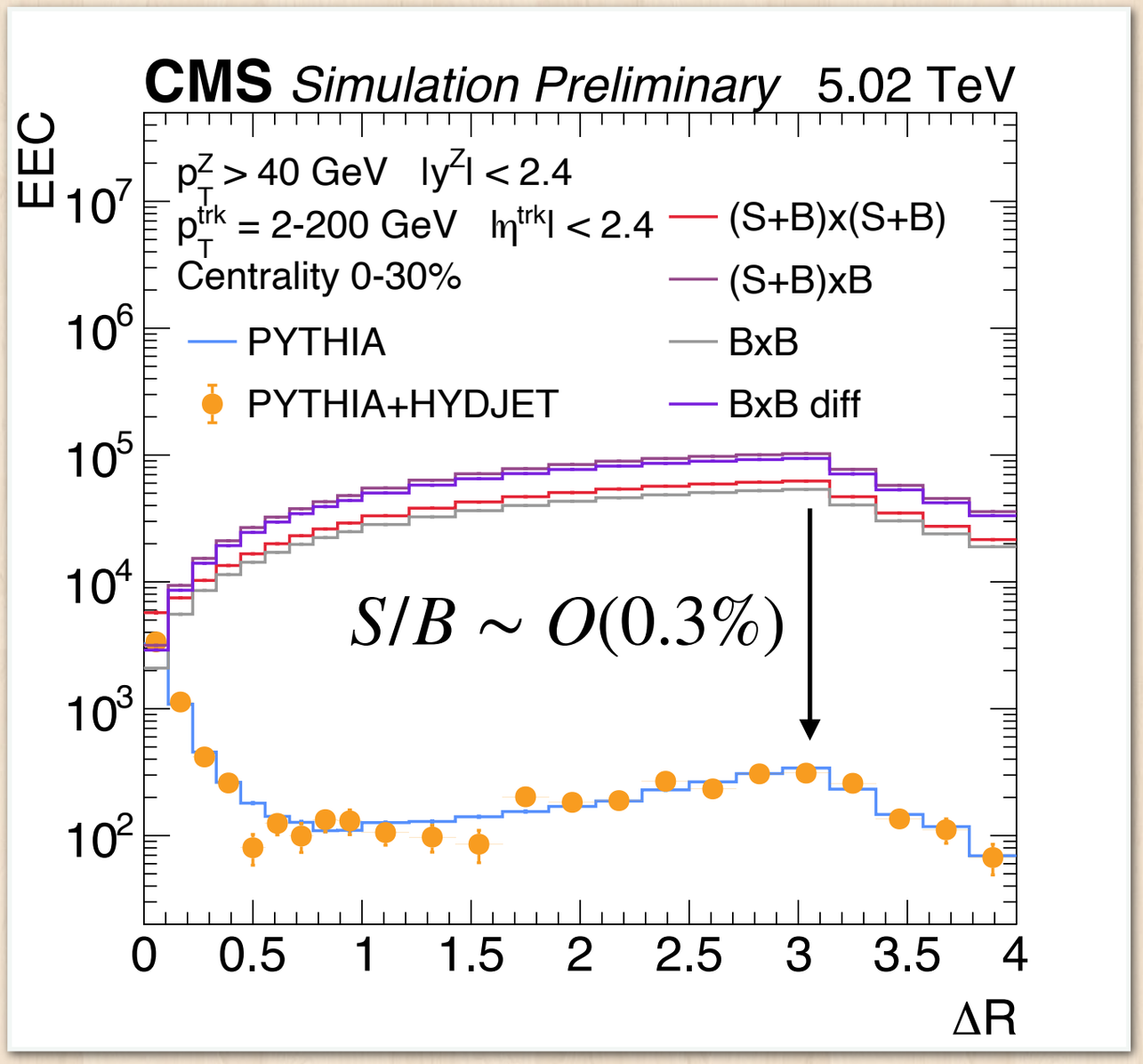
These are fully gen-level for demonstration





Analysis closure: 0-30%

Simulation: reproduce pythia from embedded pythia

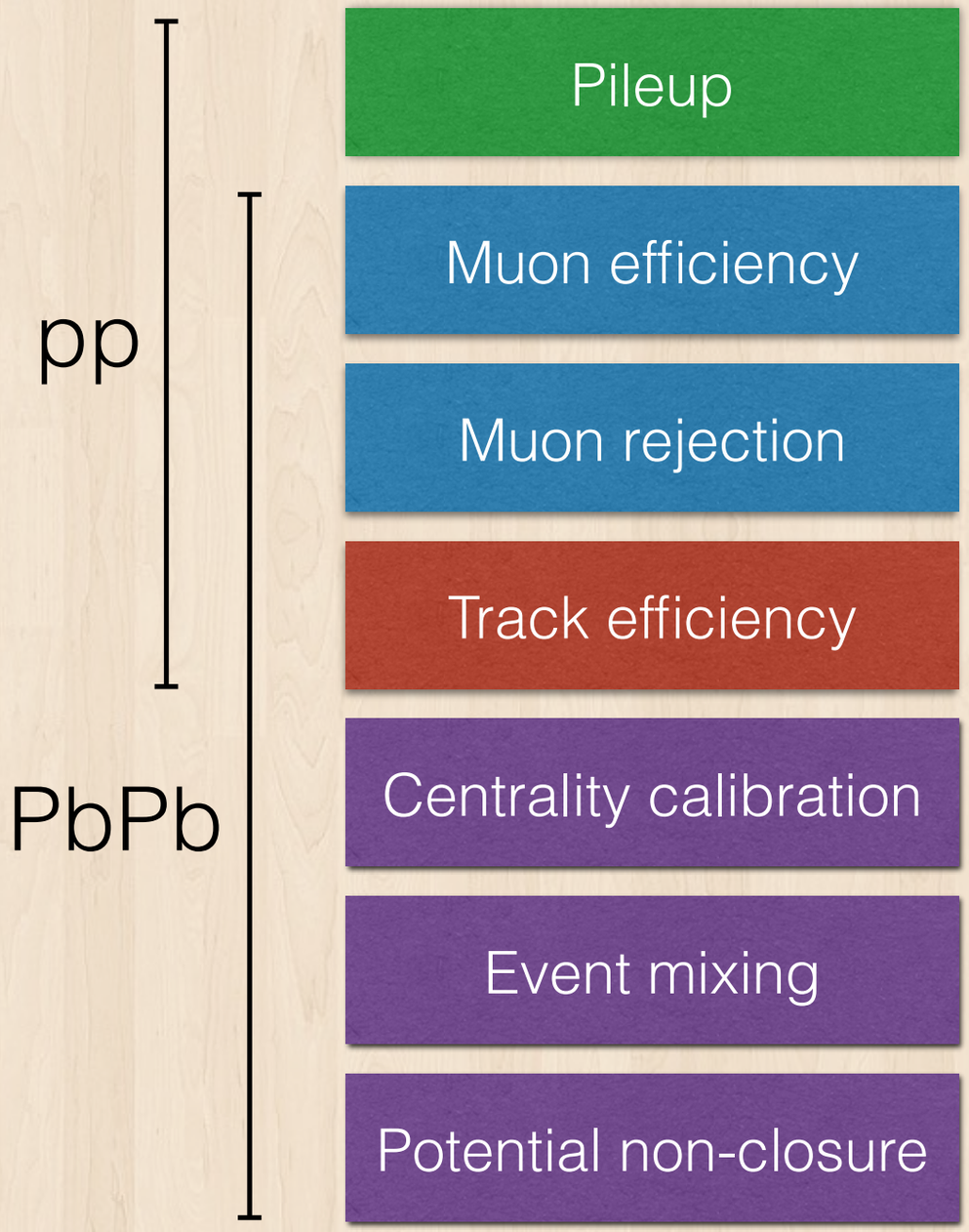


Blue:
Generator-level pp

Orange:
Starting from detector-level, run through analysis

Good analysis closure!

Systematic uncertainties

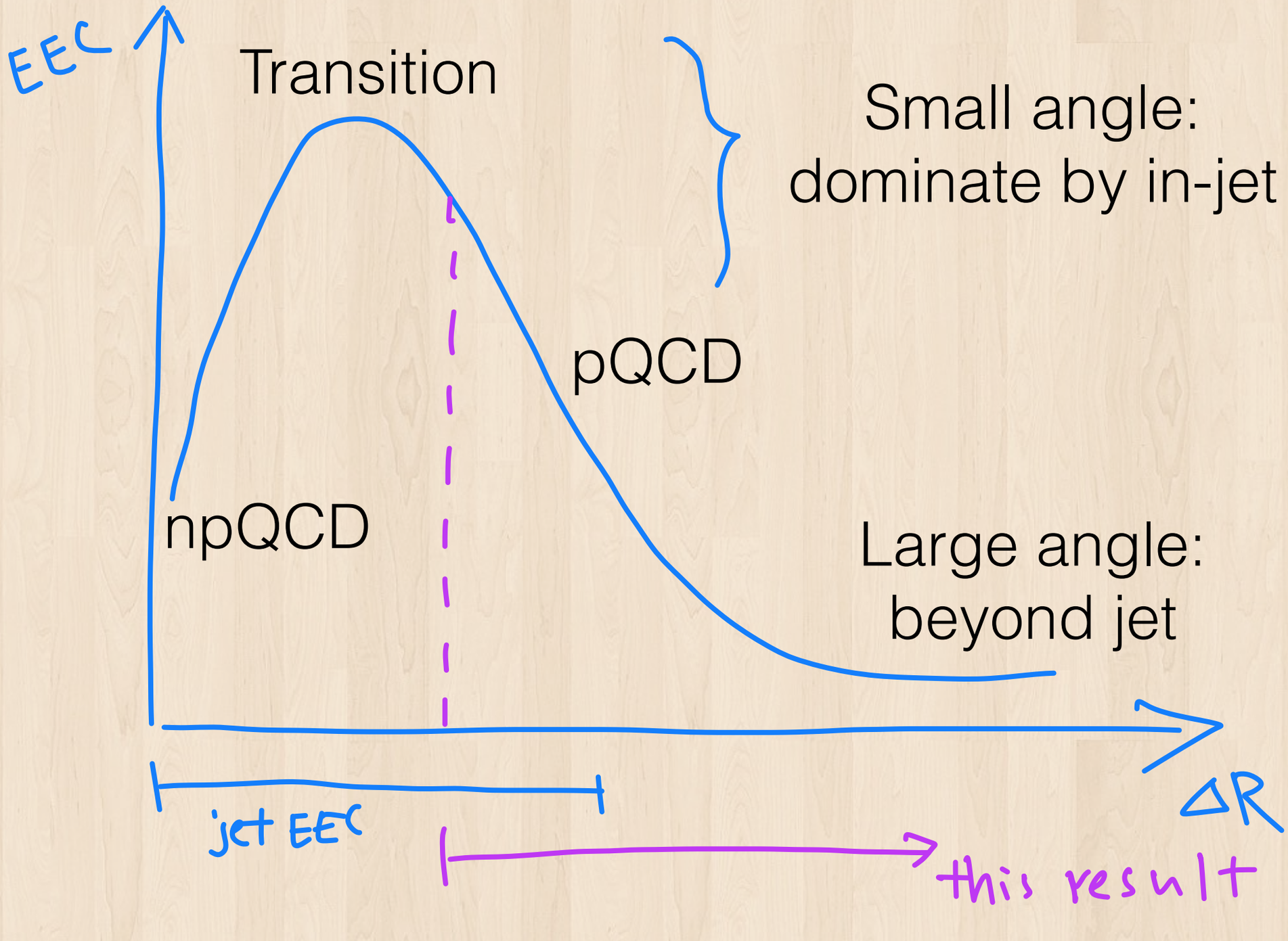


Dominant at small angles

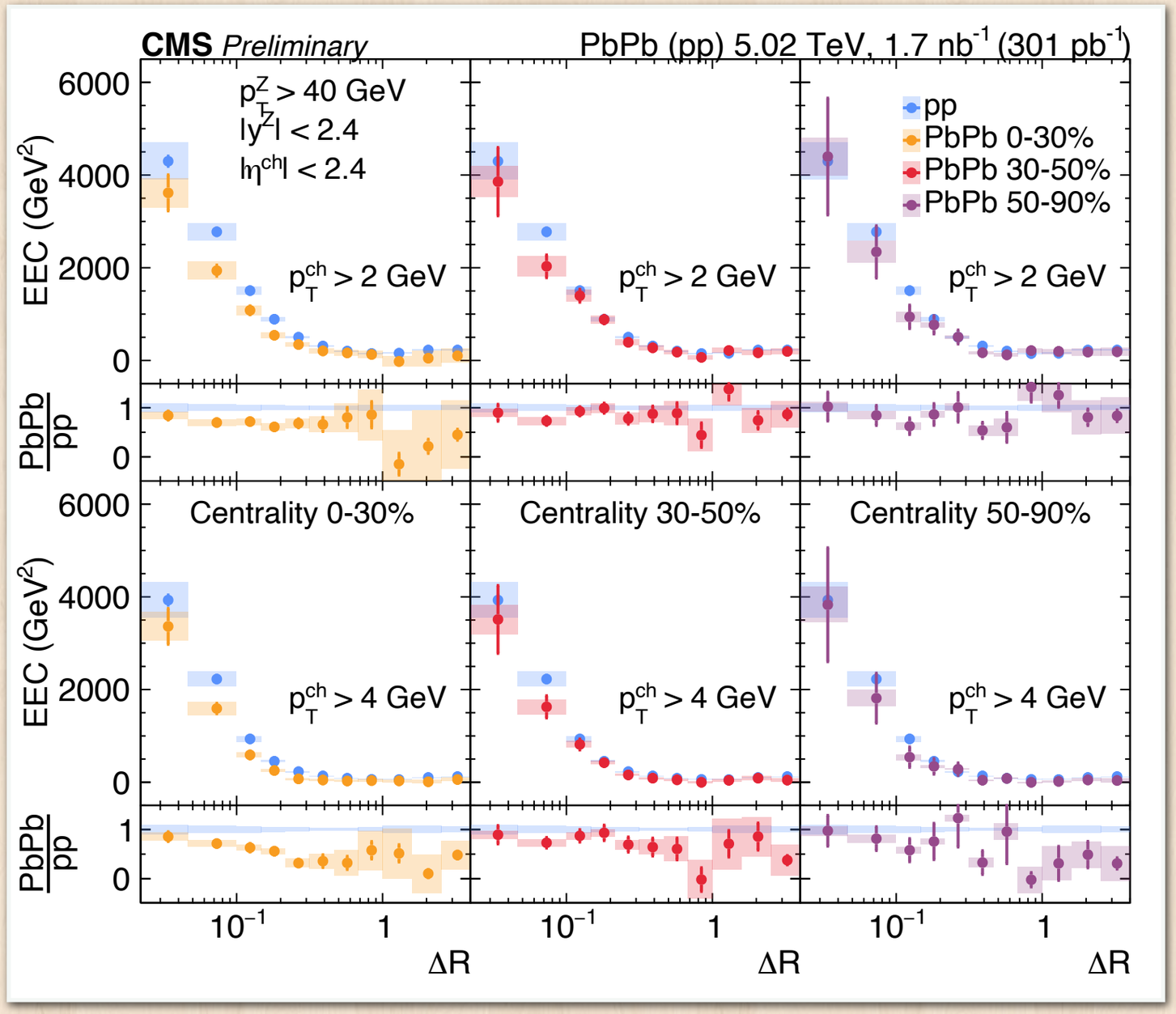
Dominant for PbPb

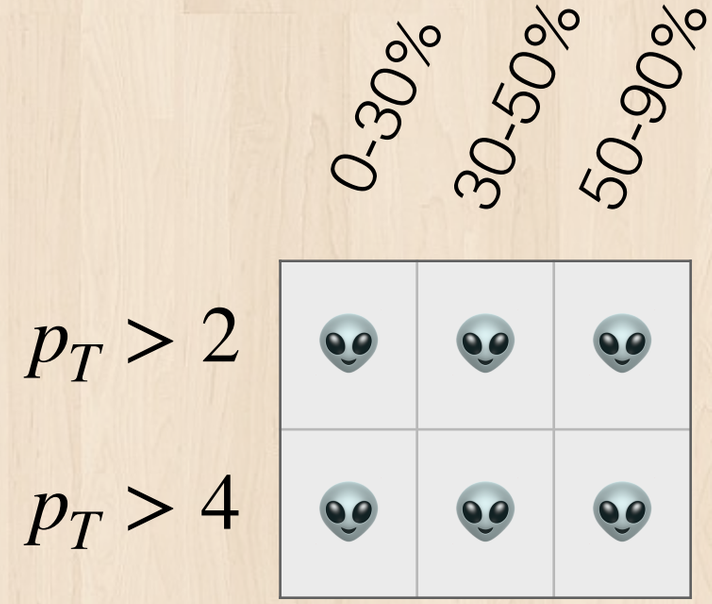
Z-tagged EEC Results

Overall shape (in pp)



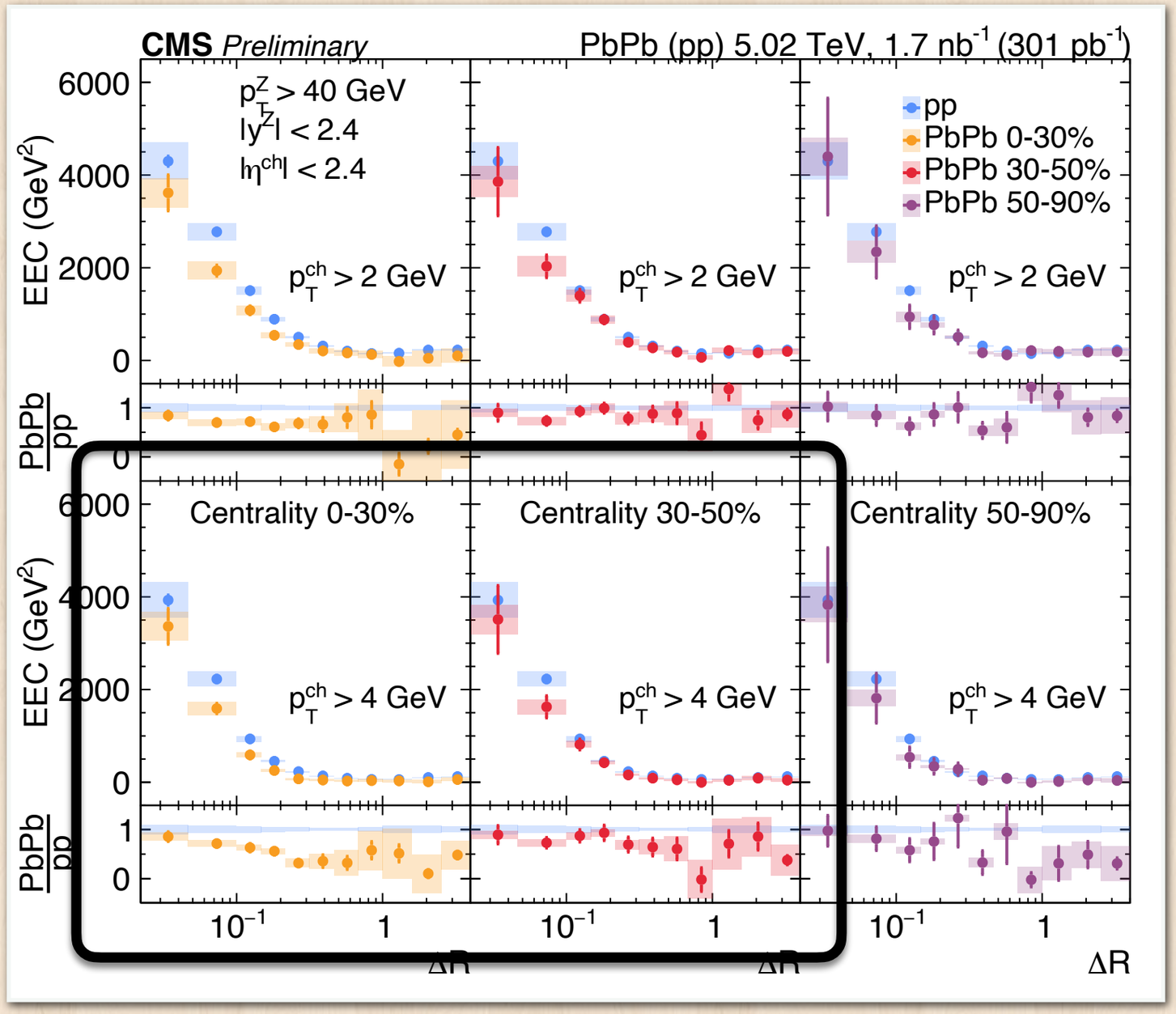
Result

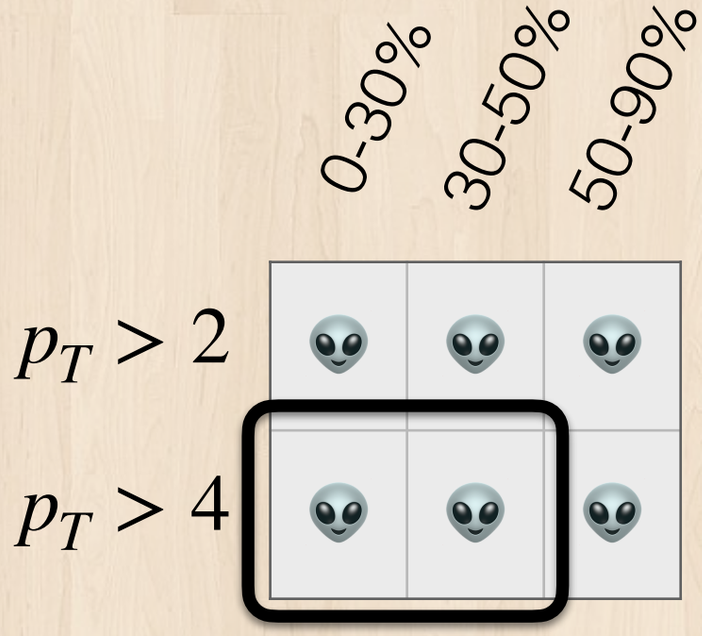




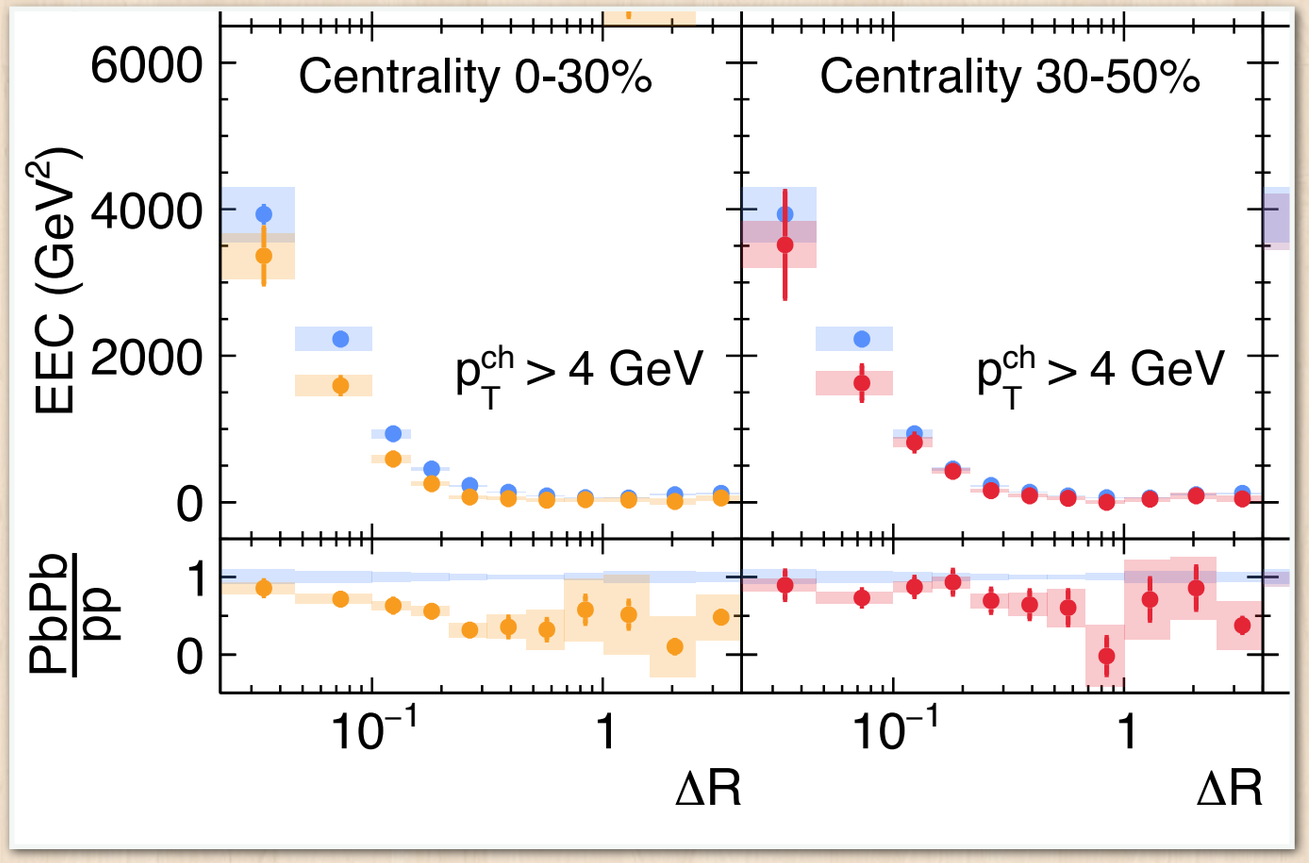
Now we zoom in to different parts

High p_T result





High p_T result

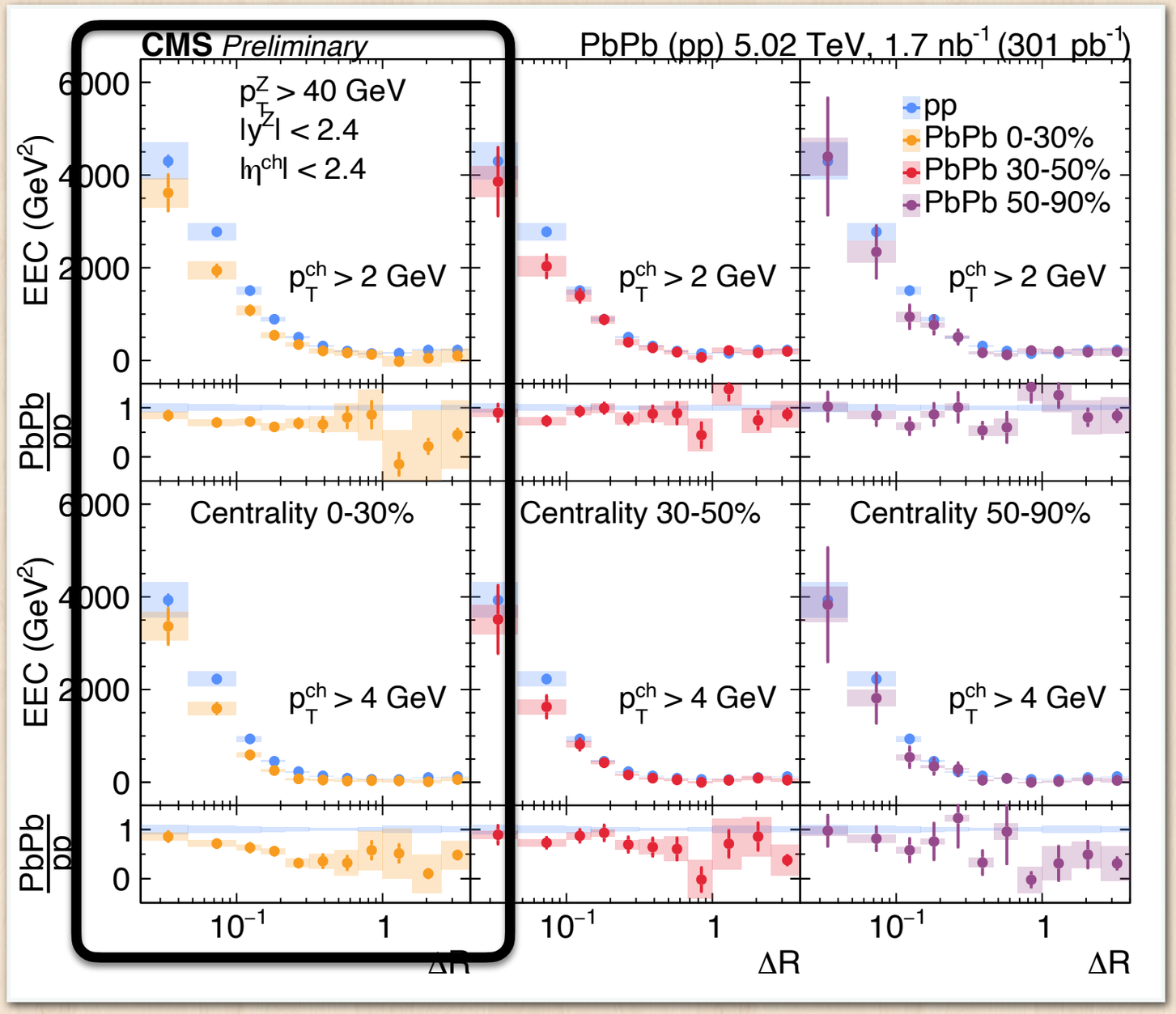


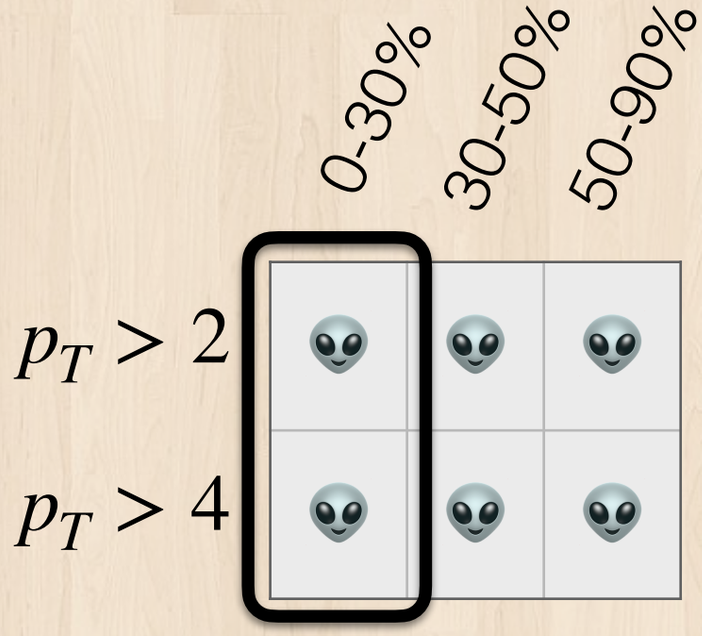
Stronger effect in central 0-30% collisions

Suppression in the whole range

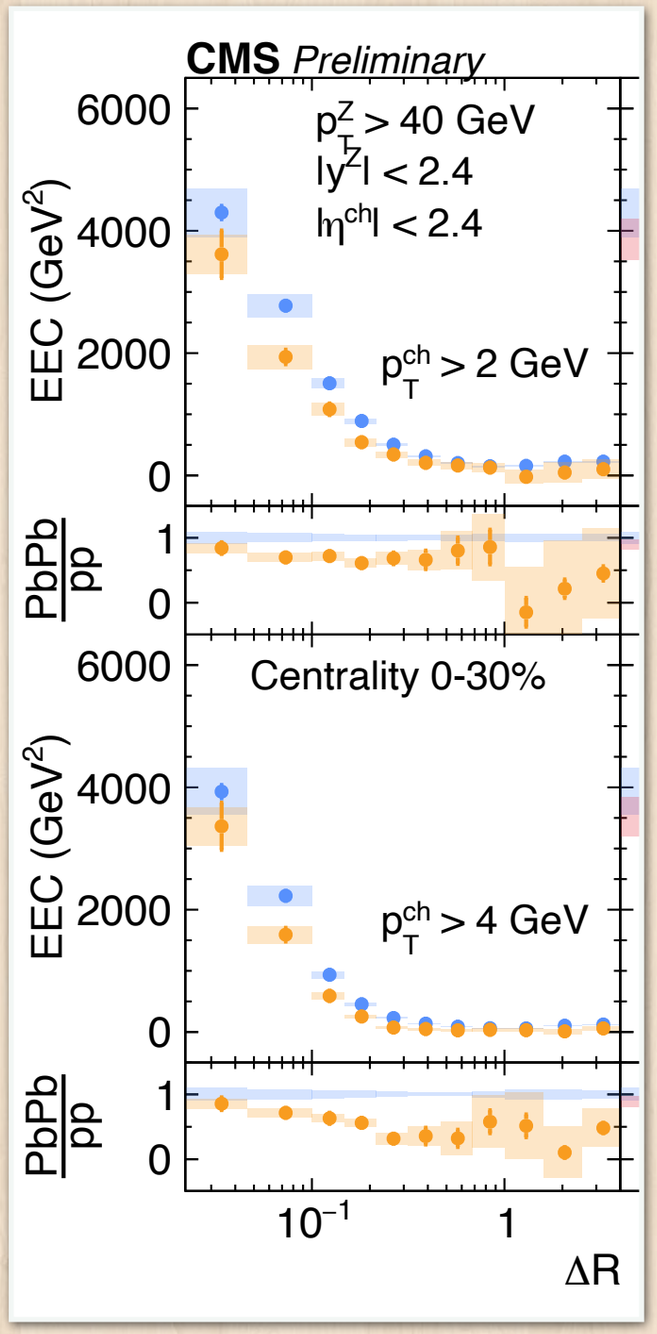
Consequence of the jet quenching effect

Central result





Central result: large angle



Much smaller amount of suppression for $p_T > 2$ GeV

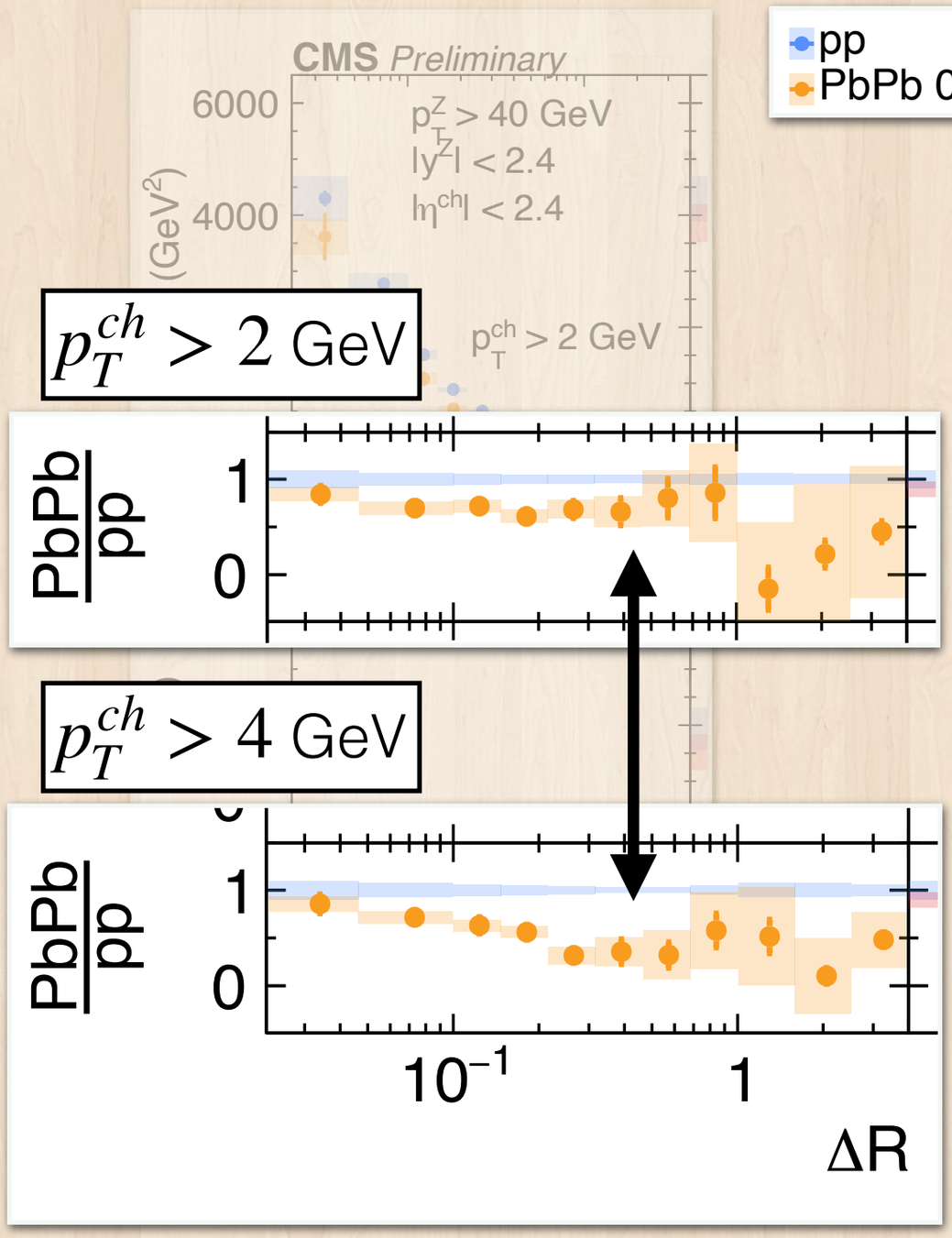
Doesn't rise forever

Medium effect much stronger at lower p_T

Extends to large angles

CMS HIN-24-019

Central result: large angle



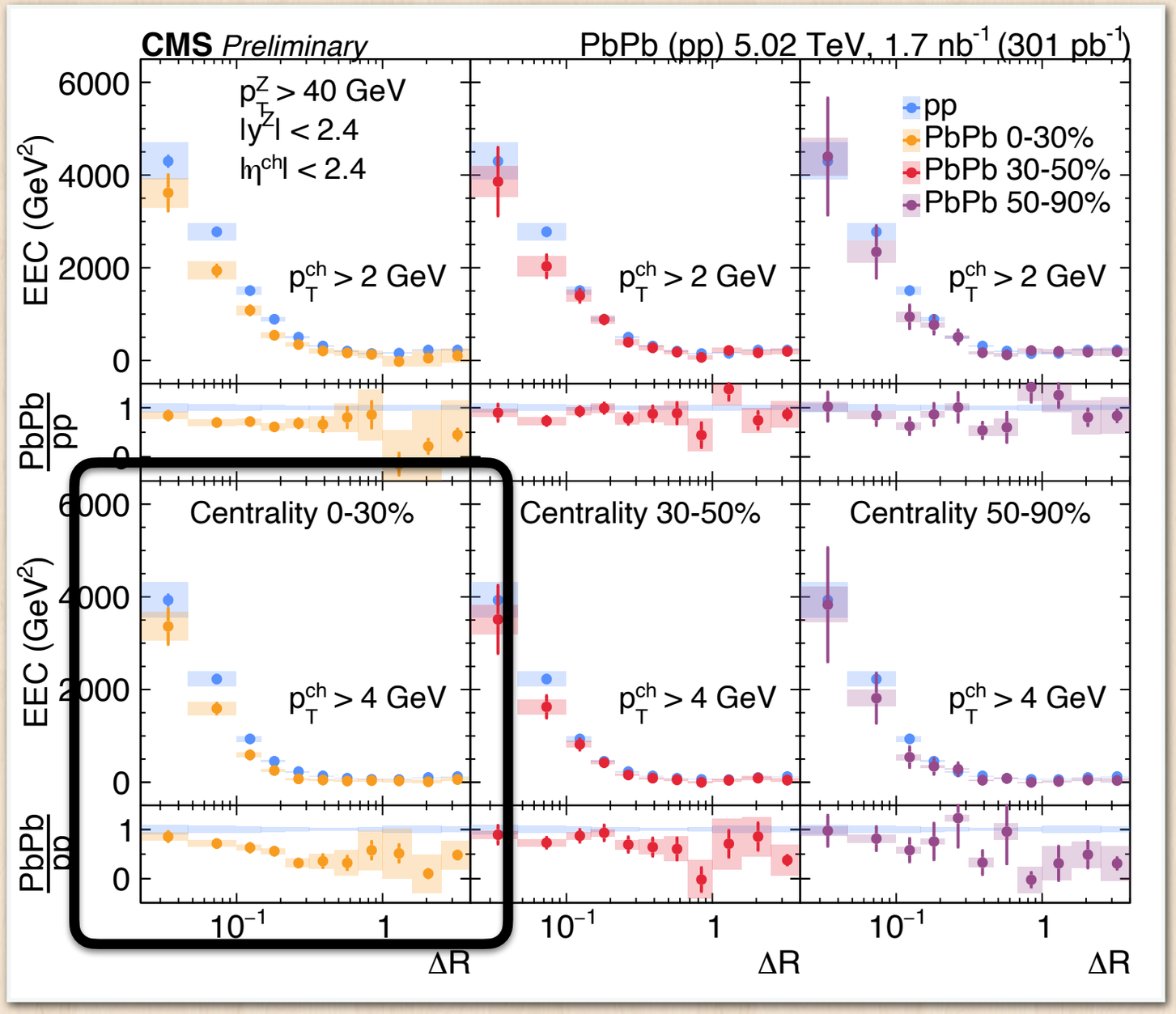
Much smaller amount of suppression for $p_T > 2$ GeV

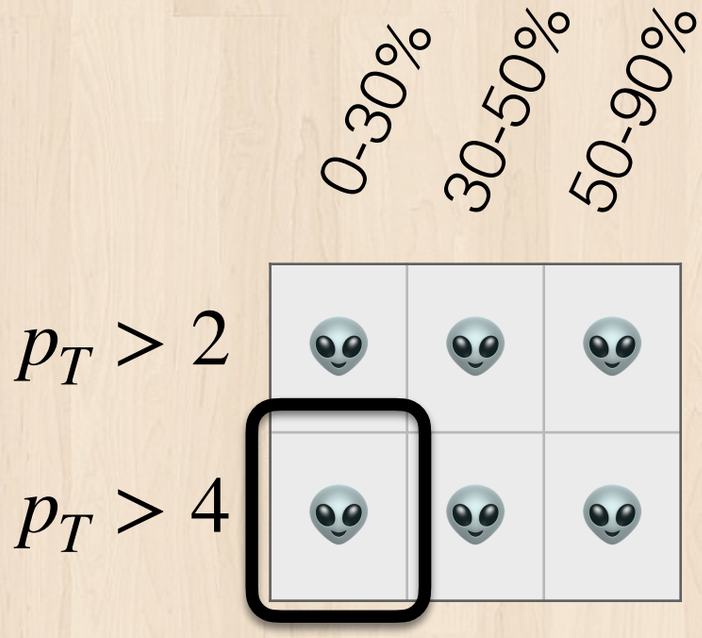
Doesn't rise forever

Medium effect much stronger at lower p_T

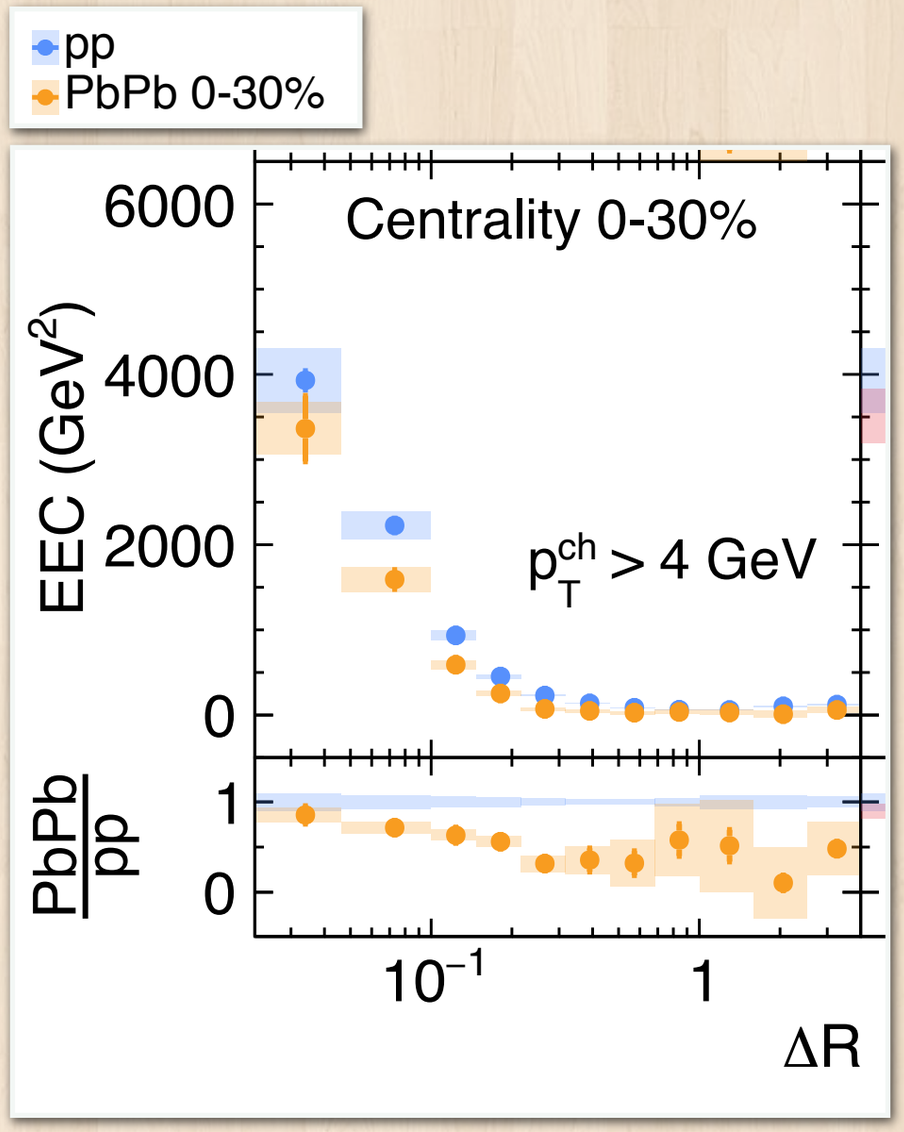
Extends to large angles

Zoom-in: small angle





Zoom-in: small angle



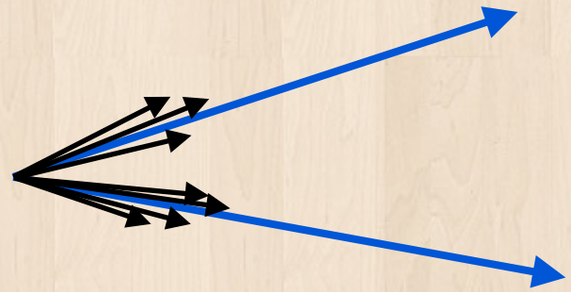
$p_T > 4$ GeV

Downward trend small angles

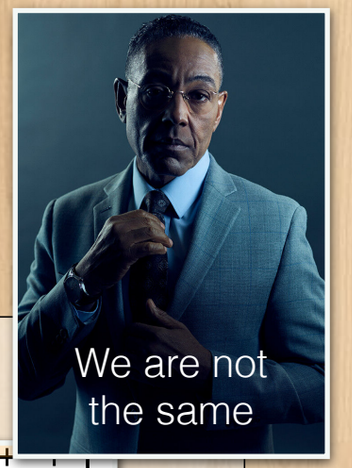
Dominated by in-jet

Note: no jet selection effect

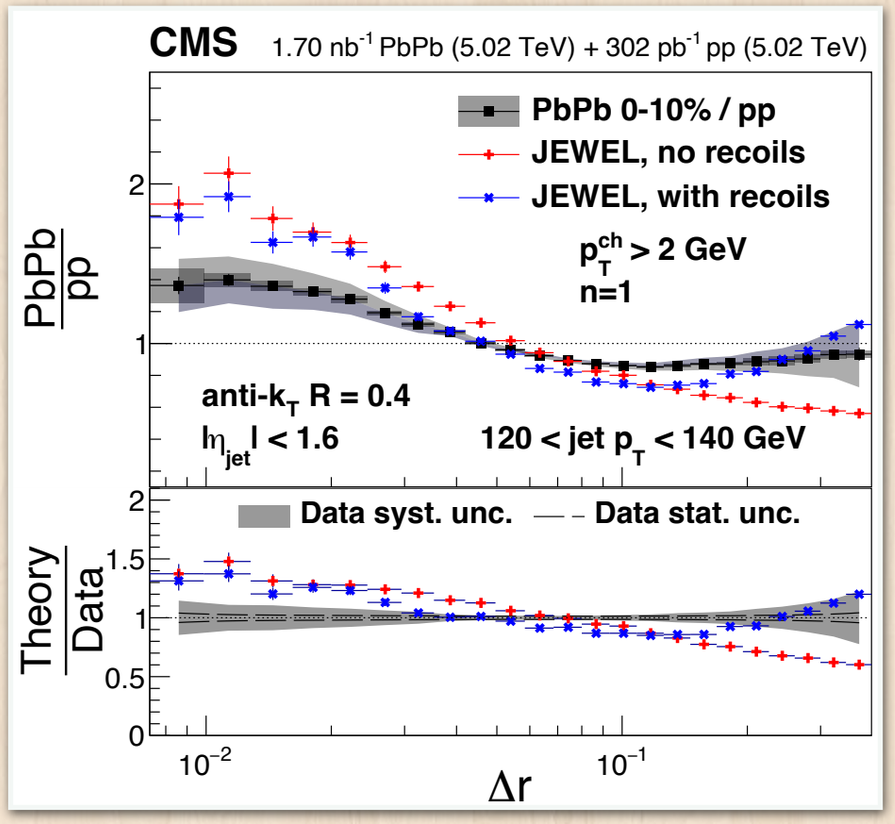
By selecting high p_T we isolate hard cores of jet shower

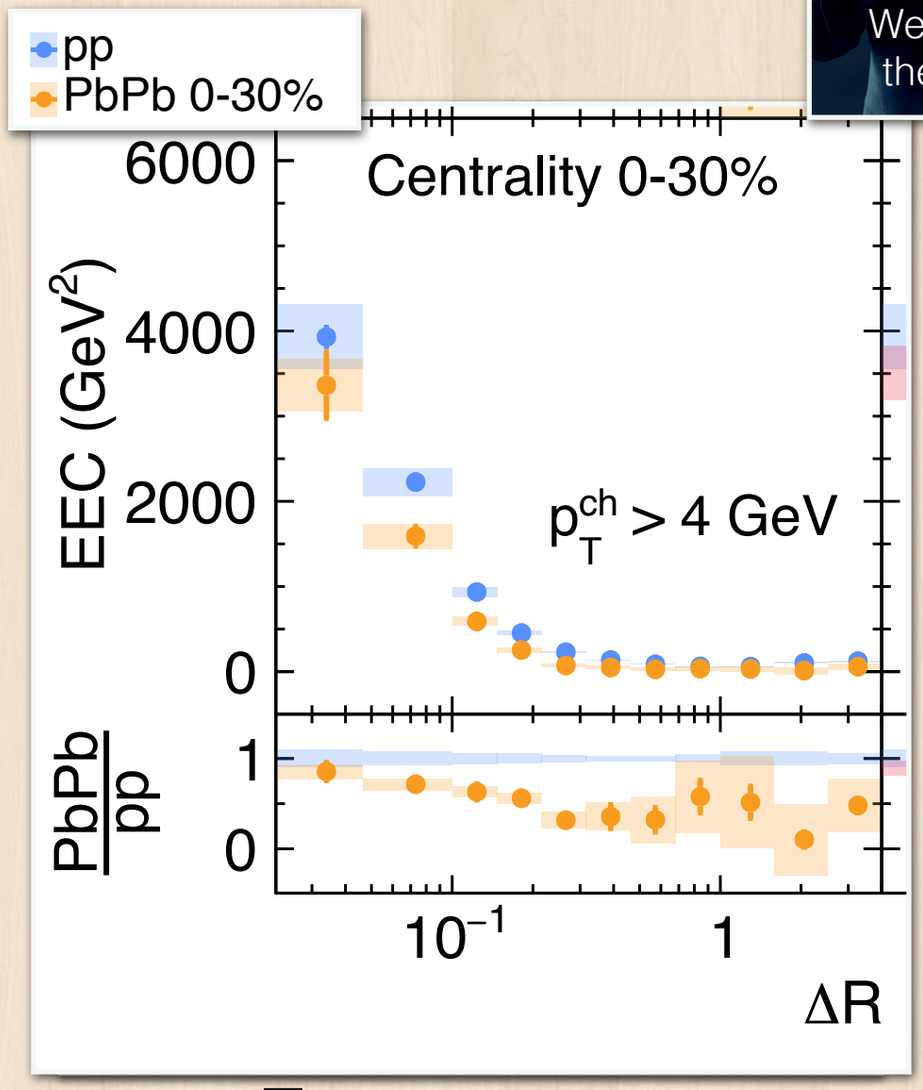


Zoom-in: small angle



EEC-in-jet





Jet $p_T = 120 - 140$ GeV

$p_T^Z \gtrsim 40$ GeV

Downward trend at small angles due to jet selection

Model comparisons

Hybrid

Jet quenching effect modeled as drag force on parton; the energy is then assumed to be thermalized and propagate as wakes

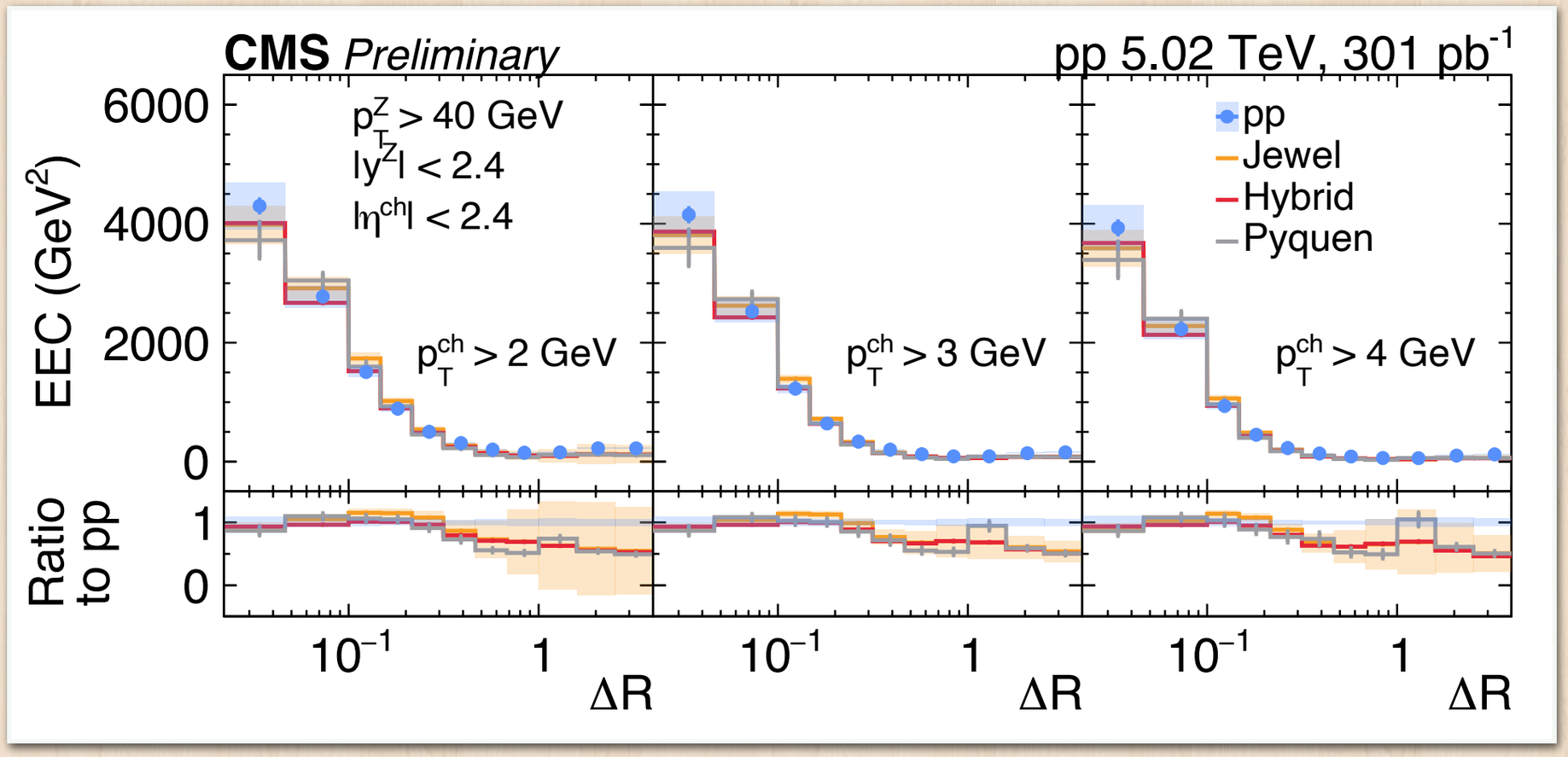
Jewel

Jet quenching effect modeled with collision with medium particles; scattered medium particles do not rescatter

See e.g. JHEP 10 (2014) 019

See e.g. EPJC 74 (2014) 2, 2762

Model comparisons: vacuum

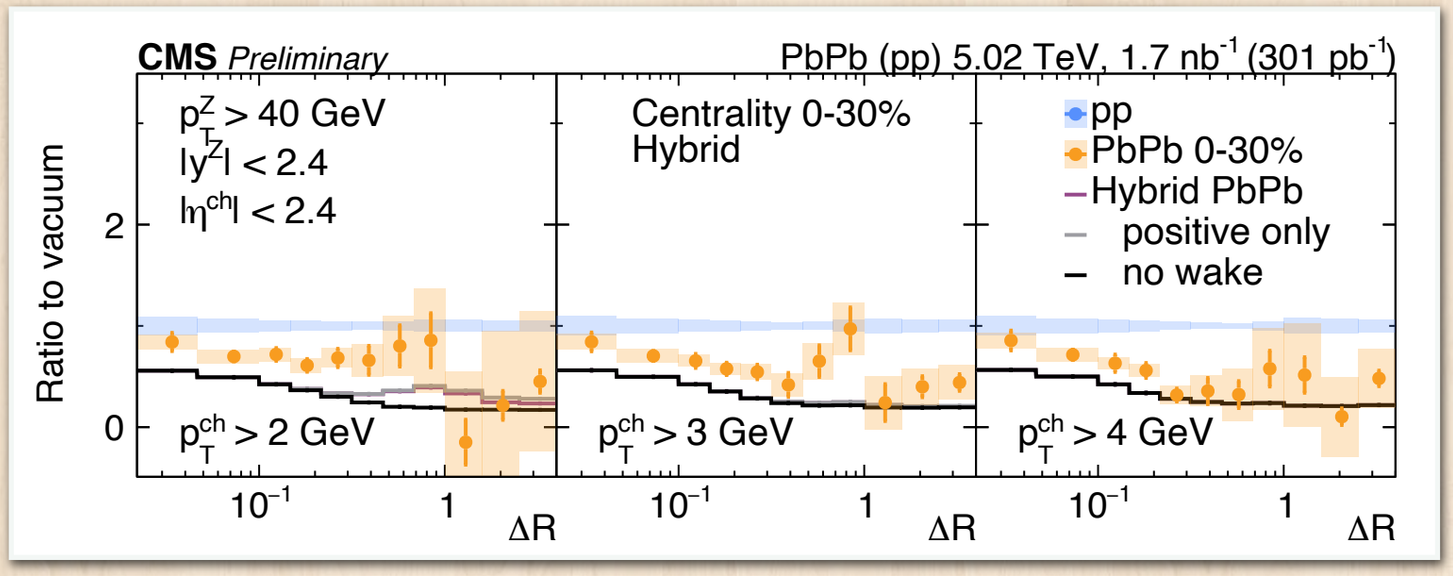


Comparison of vacuum modeling (Pythia-based)

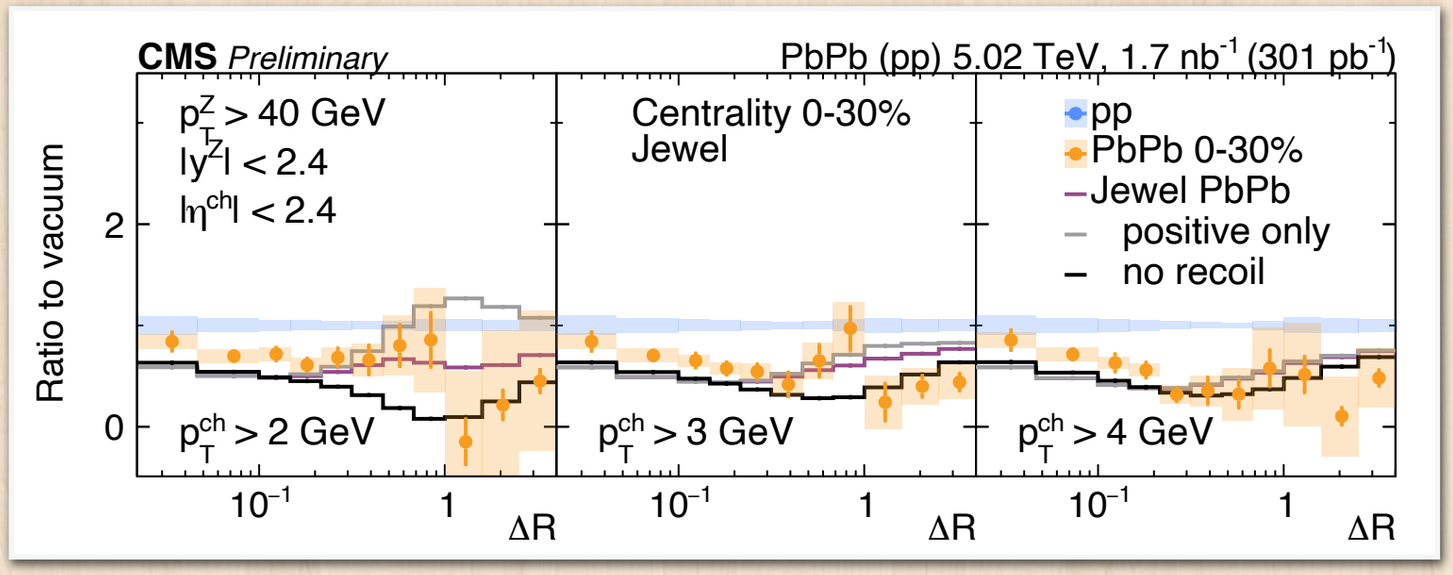
Opportunity to improve vacuum modeling at large ΔR

Model comparisons: PbPb

Hybrid

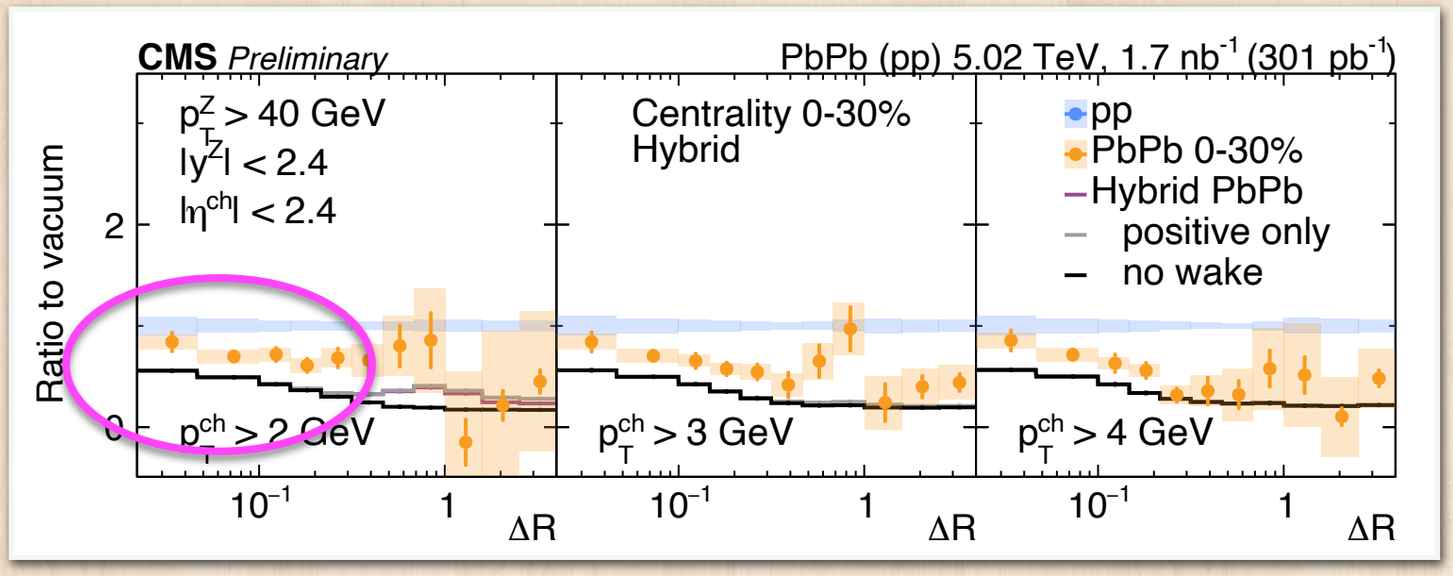


Jewel

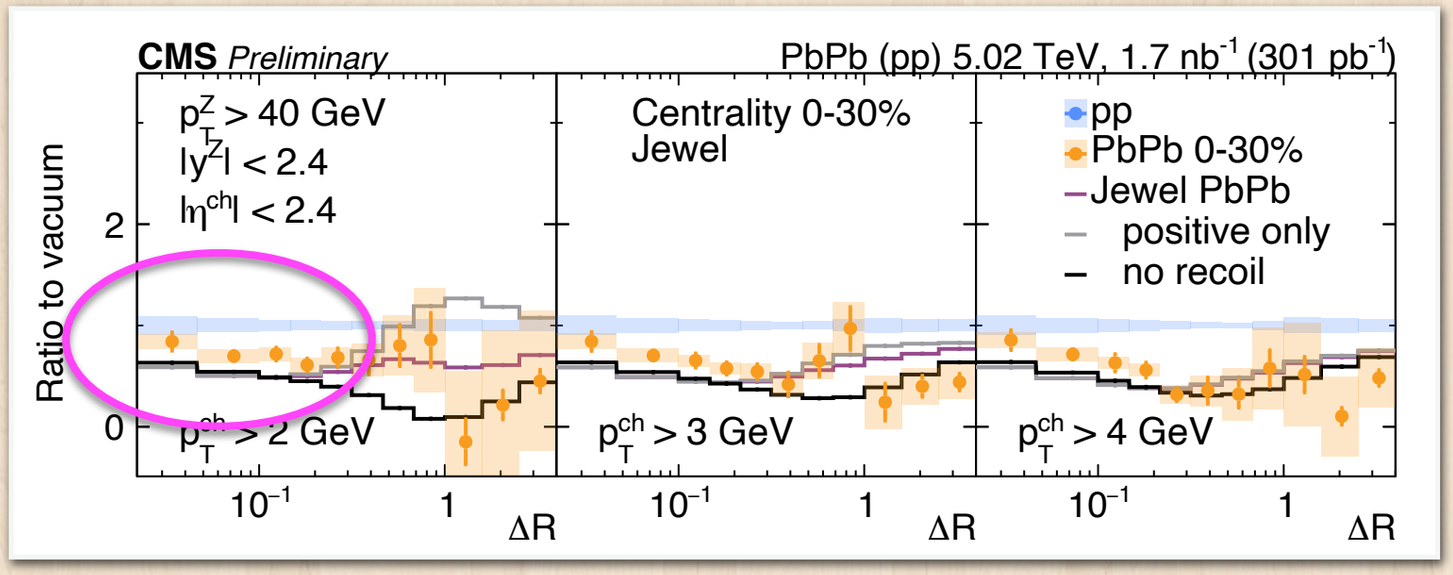


Model comparisons: PbPb

Models underpredicts EEC a little bit at small angle



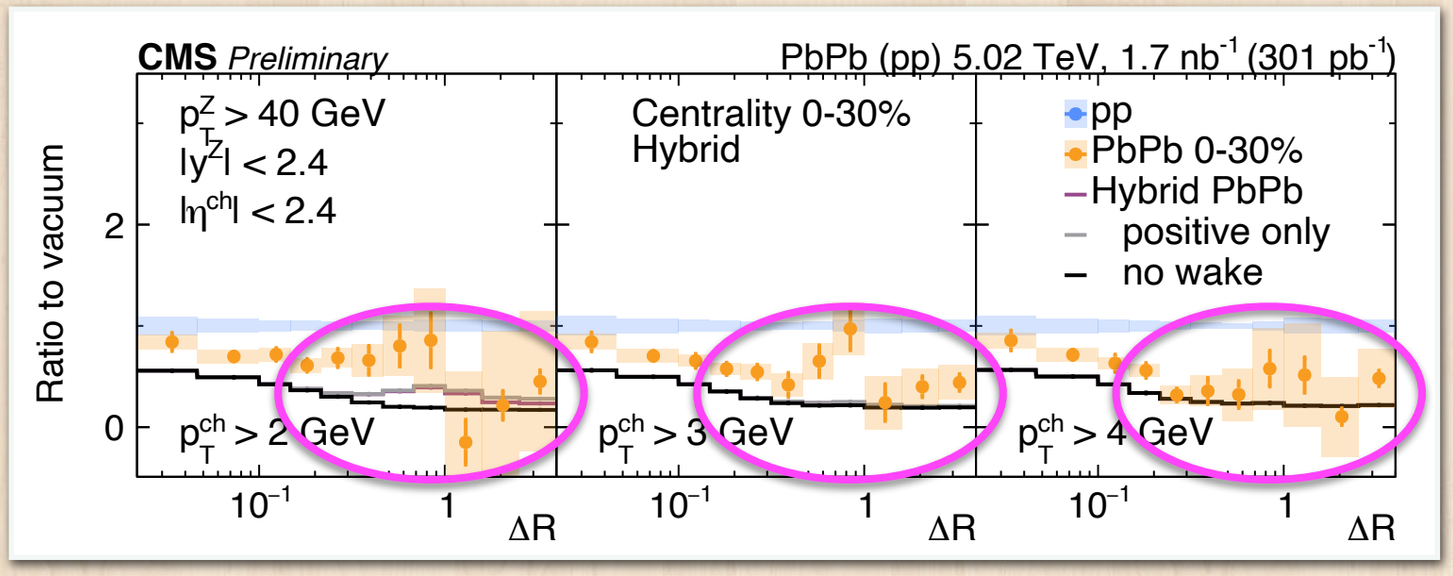
Hybrid



Jewel

Model comparisons: PbPb

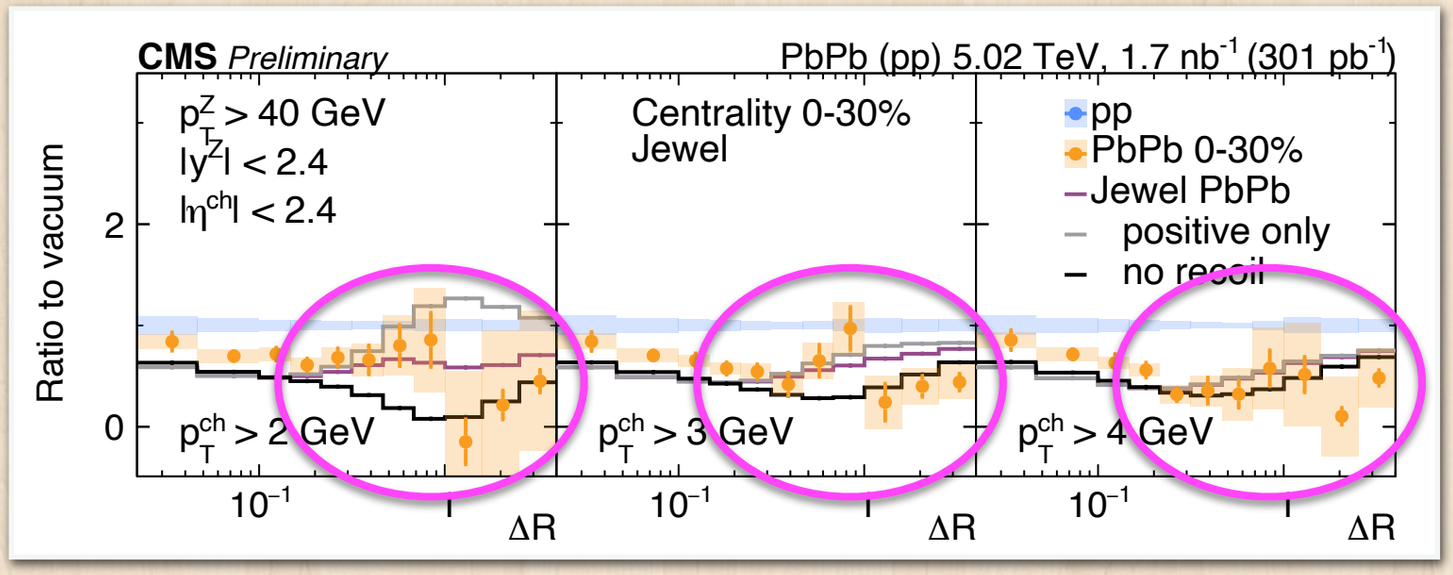
Hybrid wake spectra too soft



Hybrid

Recoils harder in JEWEL

Medium effect dominant at large angle

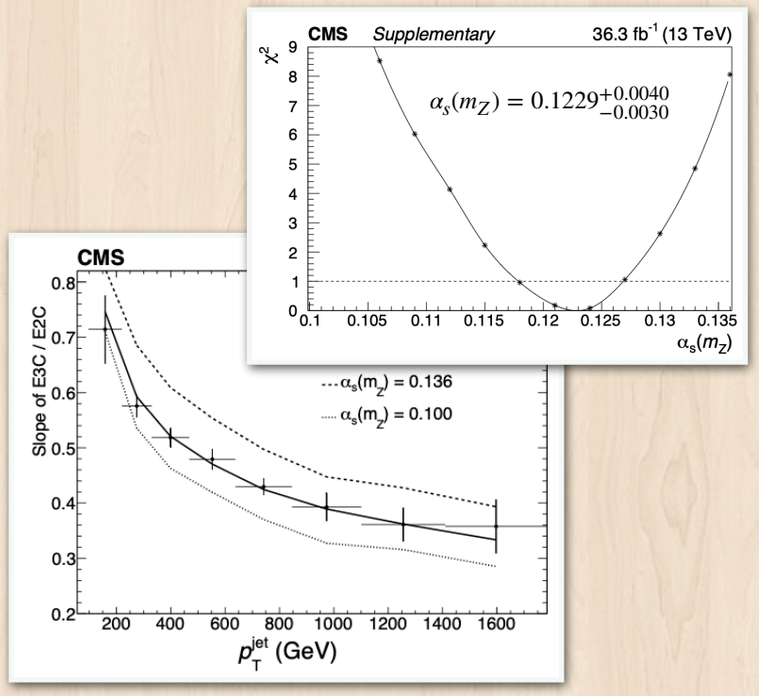


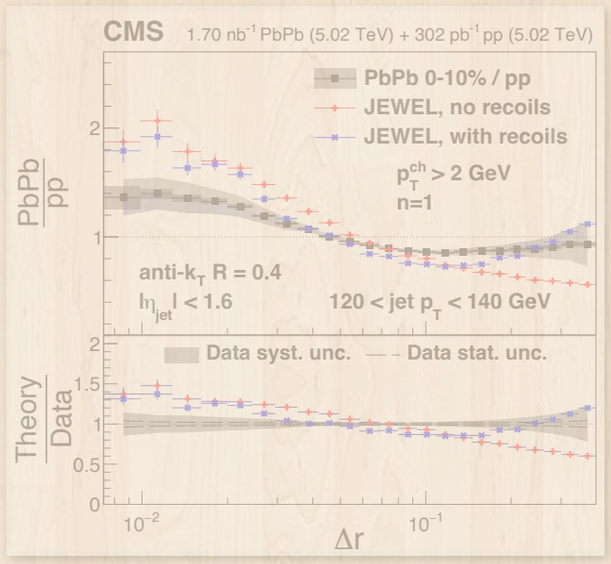
Jewel

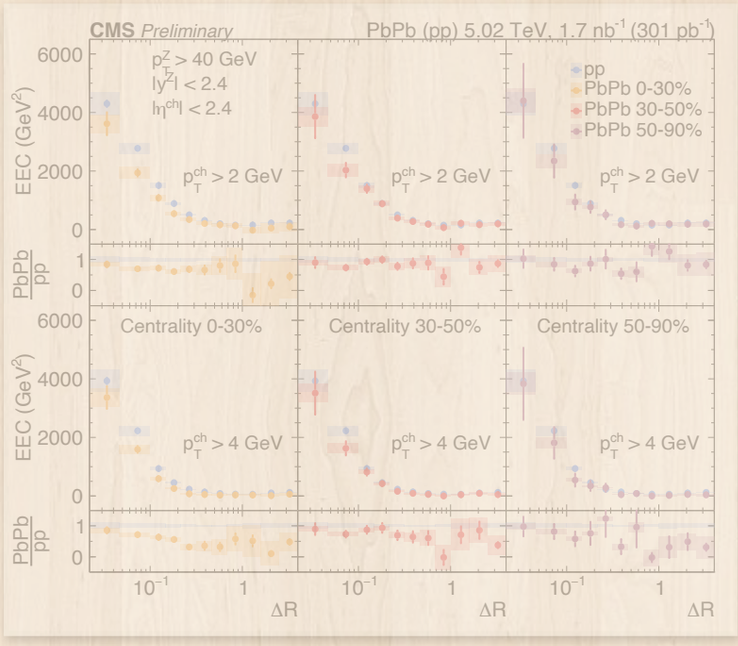
Concluding Remarks

Summary

pp jets







EEC: Separation of scales

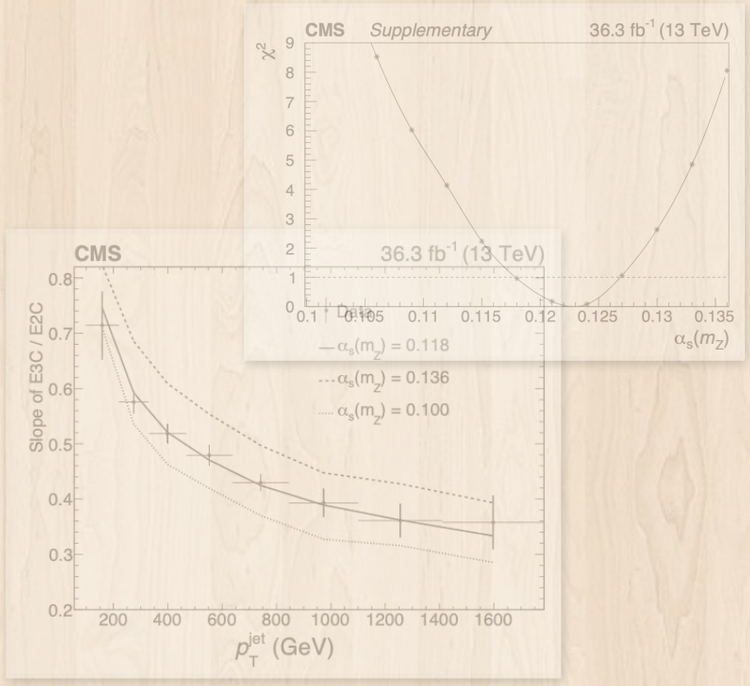
E2C & E3C in jet across wide kinematic range

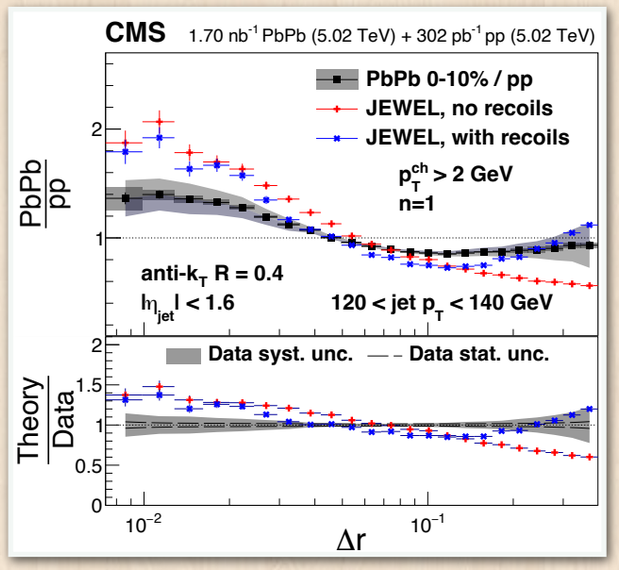
pQCD region: α_s extraction from substructure!

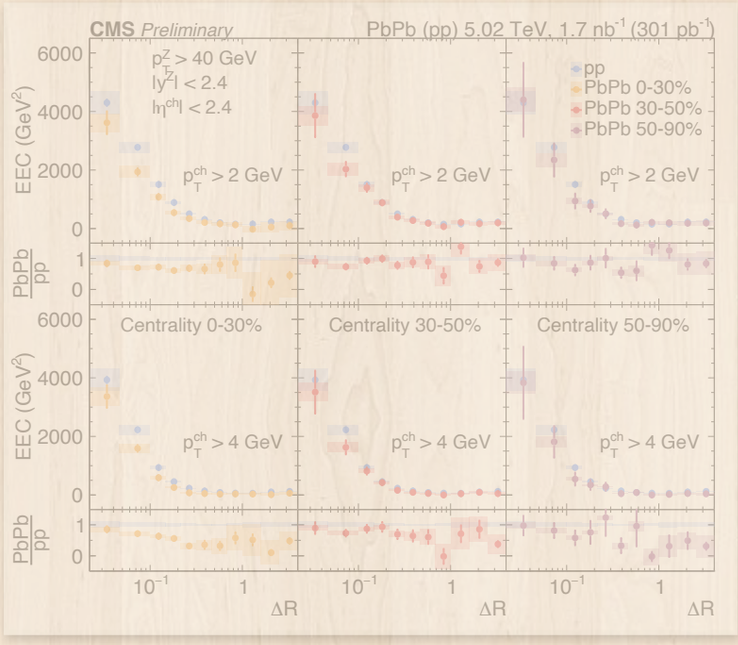
PRL 133 (2024) 071903

Summary

PbPb jets







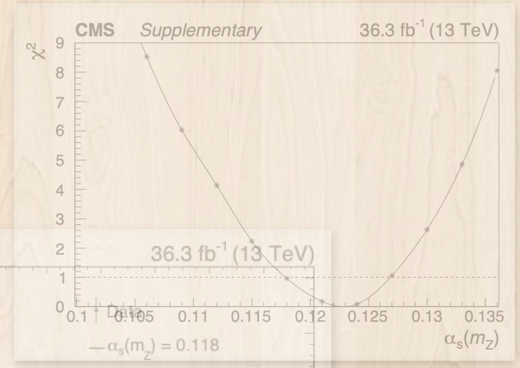
Lower angle: energy loss/jet selection effect

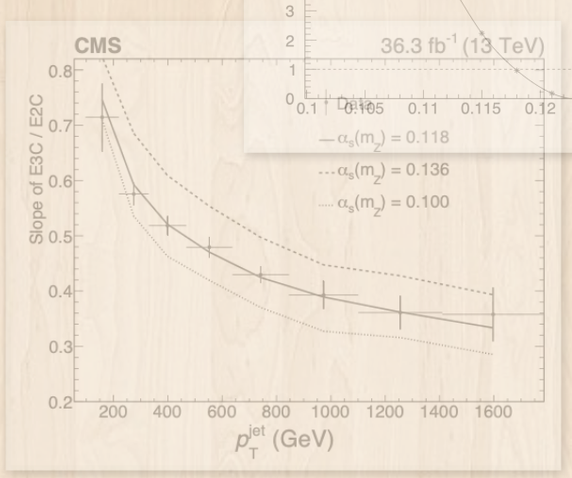
Recoil effects start to show up at large angle

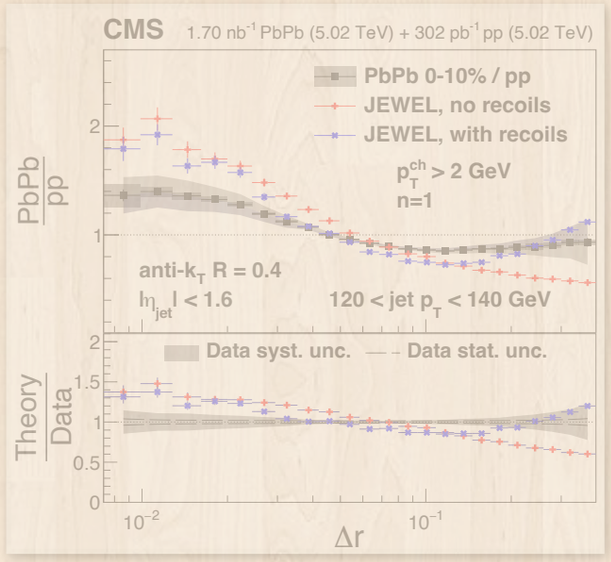
Systematic study of scale, particle p_T (and more)

arXiv: 2503.19993 → PLB

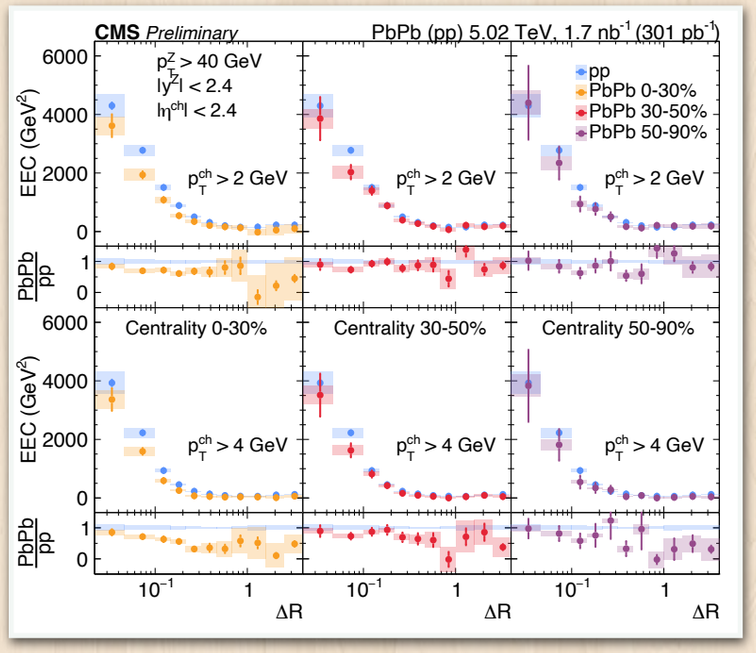
Summary







Z-tag, full event



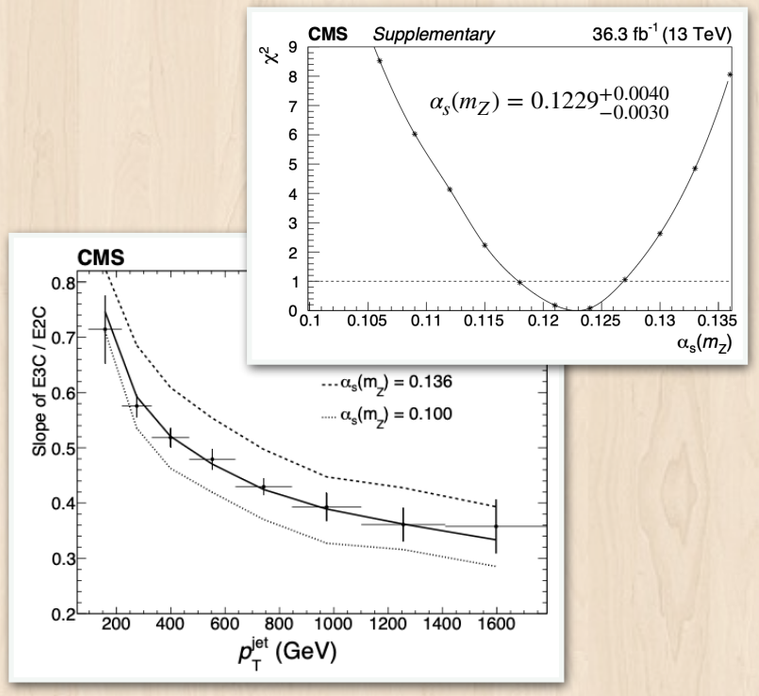
Map out the full phase space to $\Delta R = 4$

No jet selection effect: high p_T shape in jet core

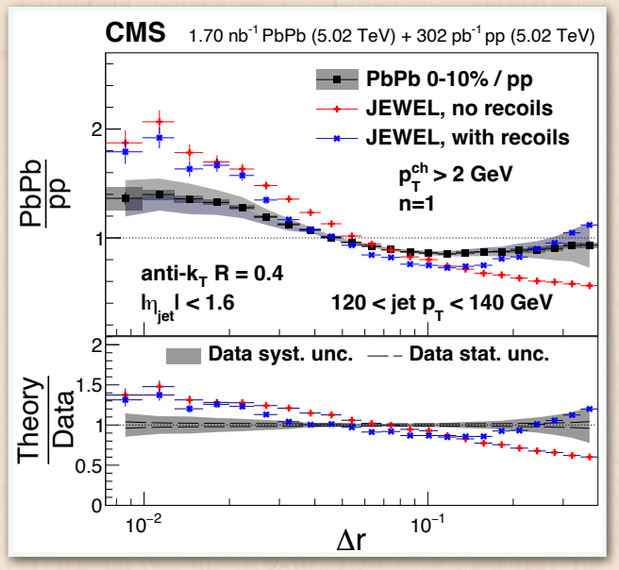
Interesting to push to lower particle p_T + more data

Summary

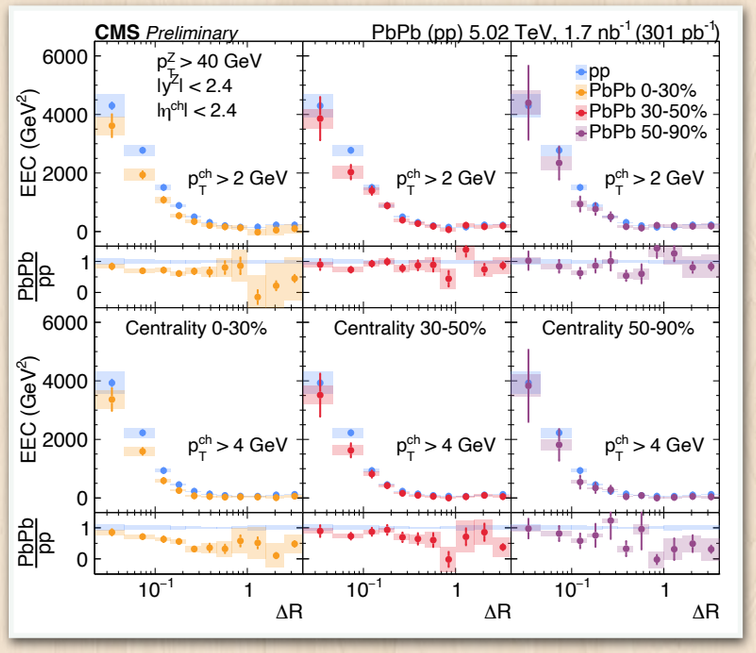
pp jets



PbPb jets



Z-tag, full event



link to document

link to document

link to document

Looking forward to new upcoming measurements!

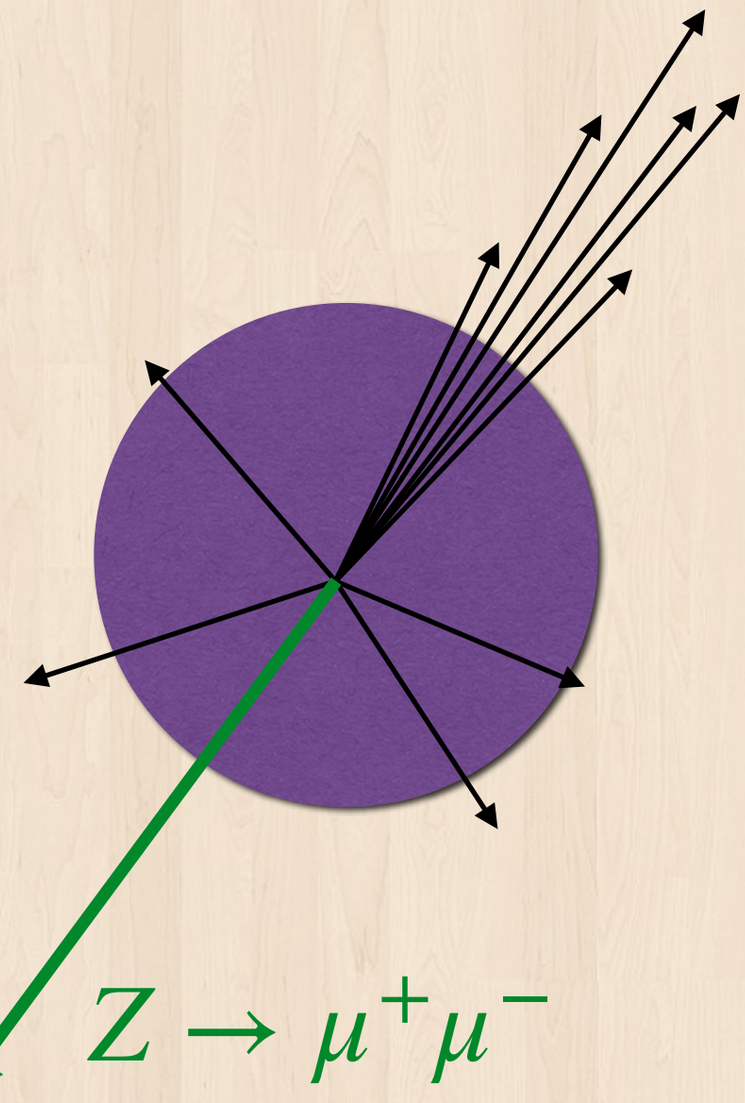
Back Slides Ahead

Difference to Z hadron

Z-hadron

Relative to Z

Effects at specific directions



EEC

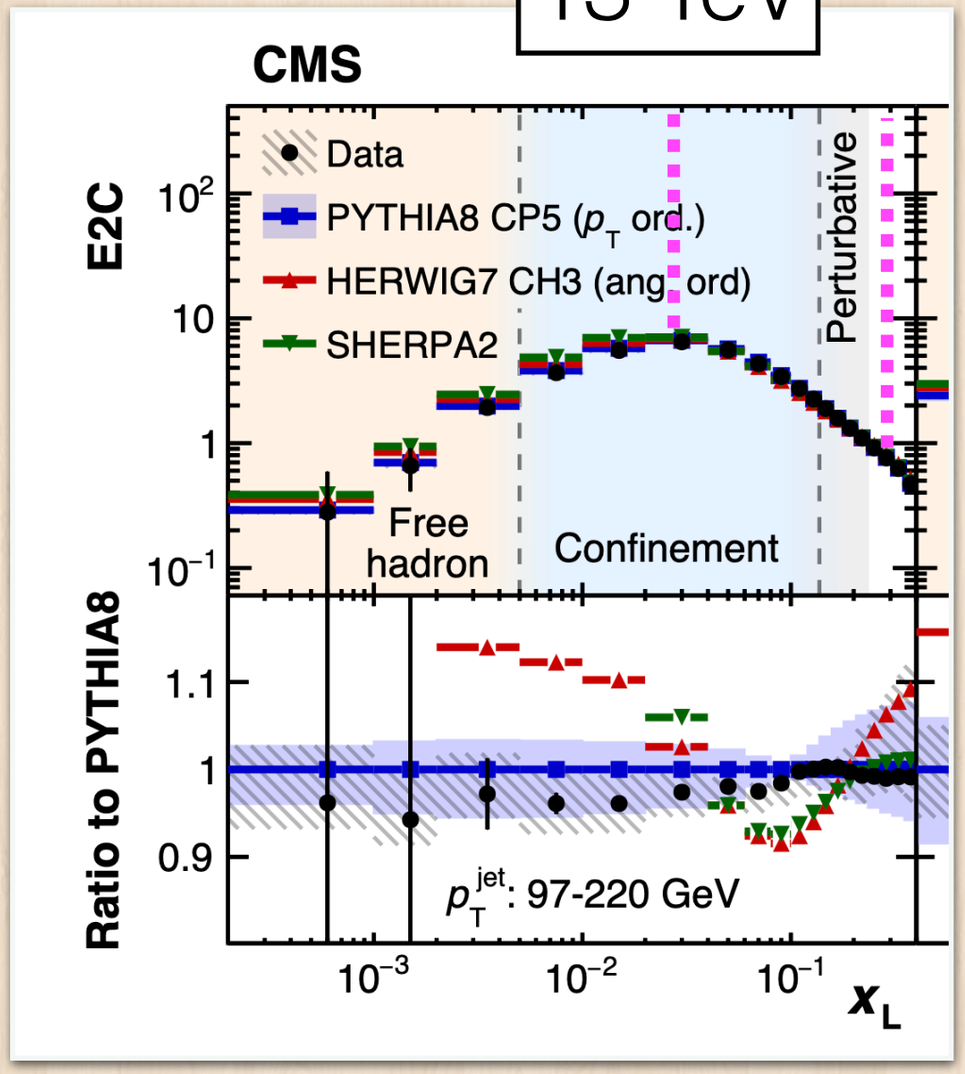
Hadrons relative to each other

Angular scale

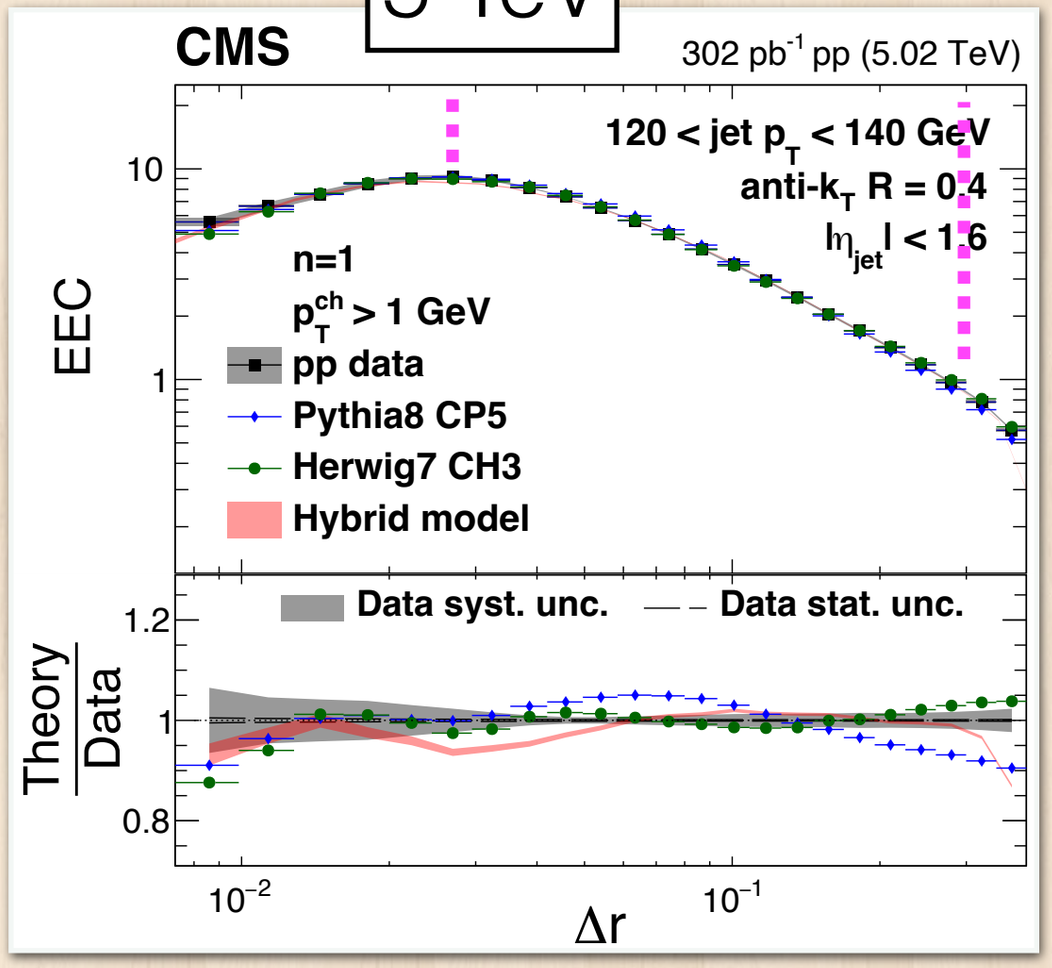
See talk by Y.-J. Lee next

EEC in pp across energy

13 TeV



5 TeV



Similar shape across collision energy

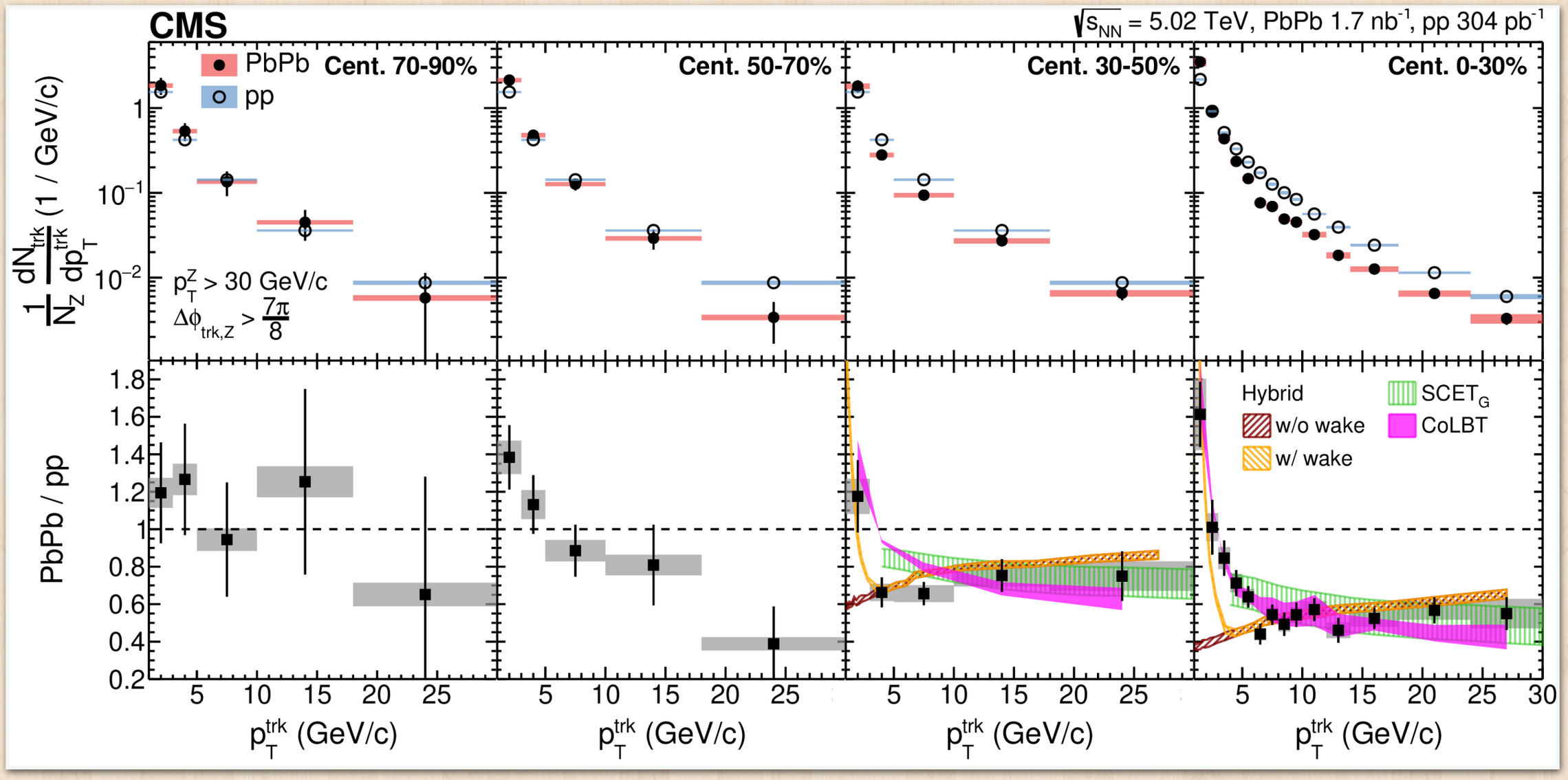
arXiv: 2503.19993 → PLB

See more in prof RKE talk

13 TeV jet measurement details

- 2016 pp data, 13 TeV, totaling $36.3\,fb^{-1}$
- Clustered with anti-k_T, R = 0.4
- Leading dijets, $|\eta| < 2.1$, p_T = 97-1784 GeV
- Both neutral and charged particles, $p_T > 1$ GeV
- Unfold for detector response
- E2C and E3C measured with statistically independent samples

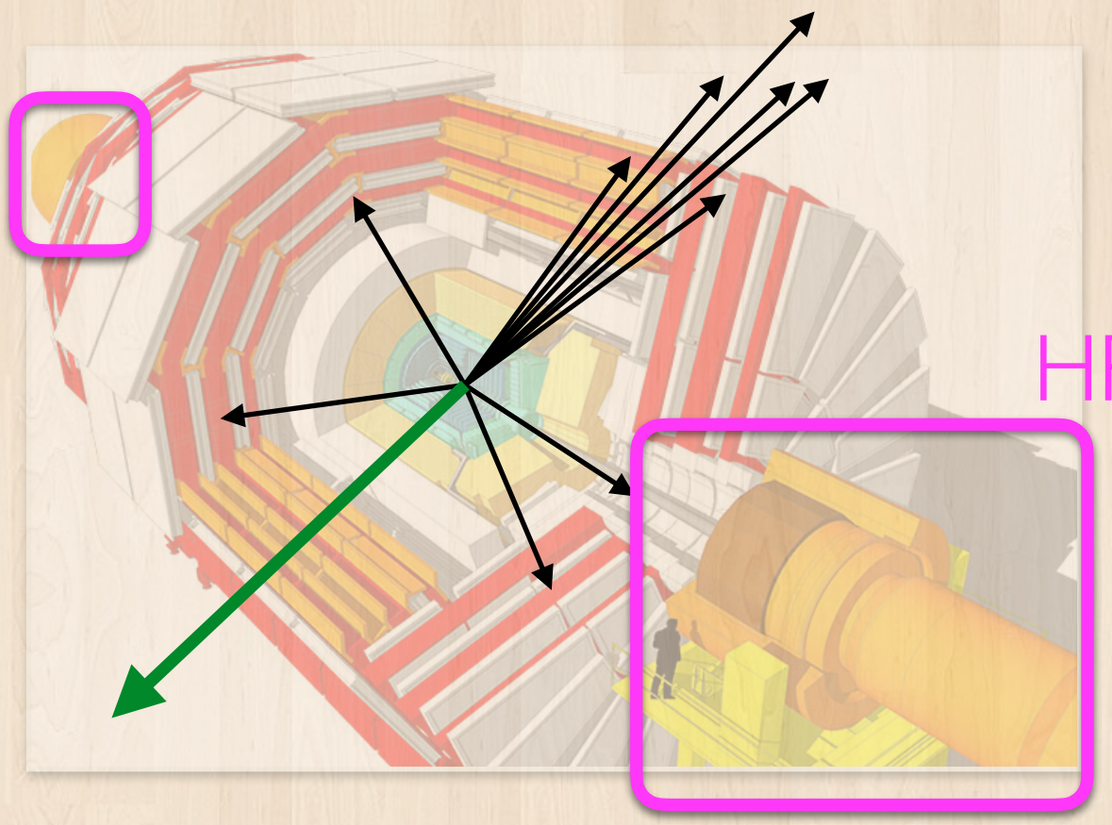
Z hadron track distribution



Note on Z EEC matching

- We use HF energy ($3 < |\eta| < 5$) as proxy of event activity

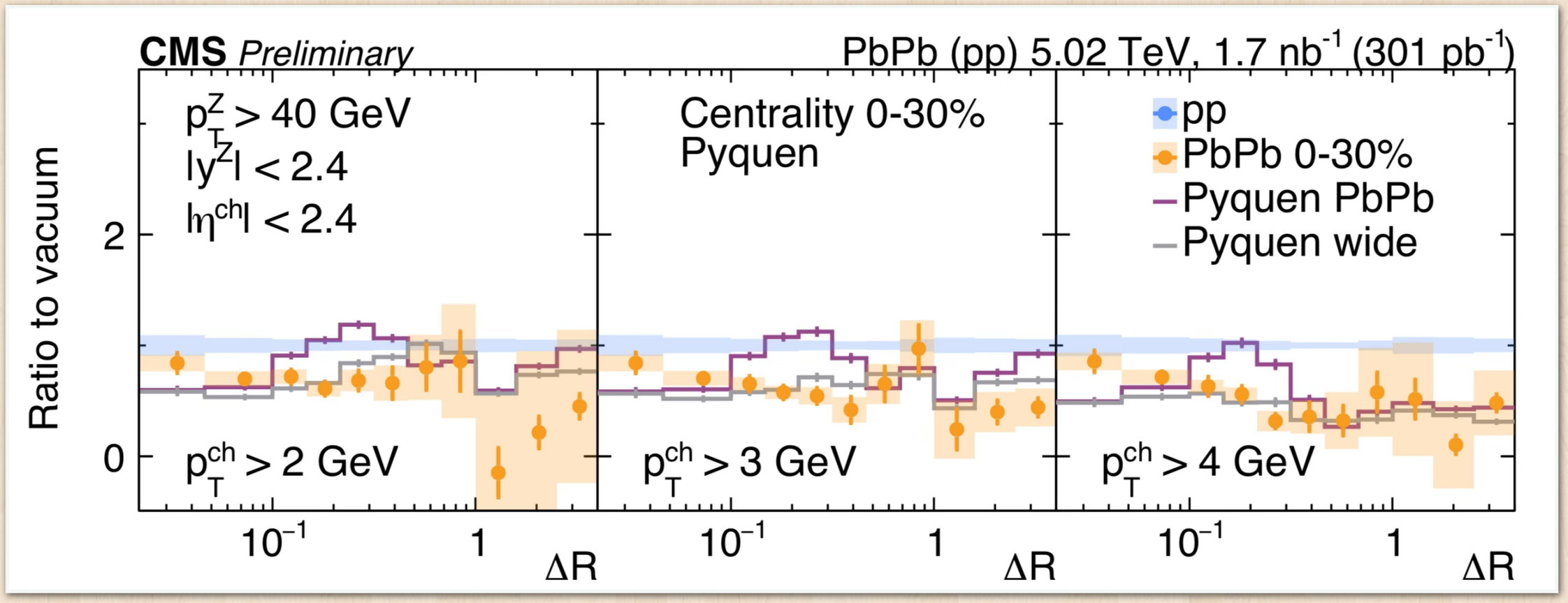
- Signal also deposits some energy in HF!



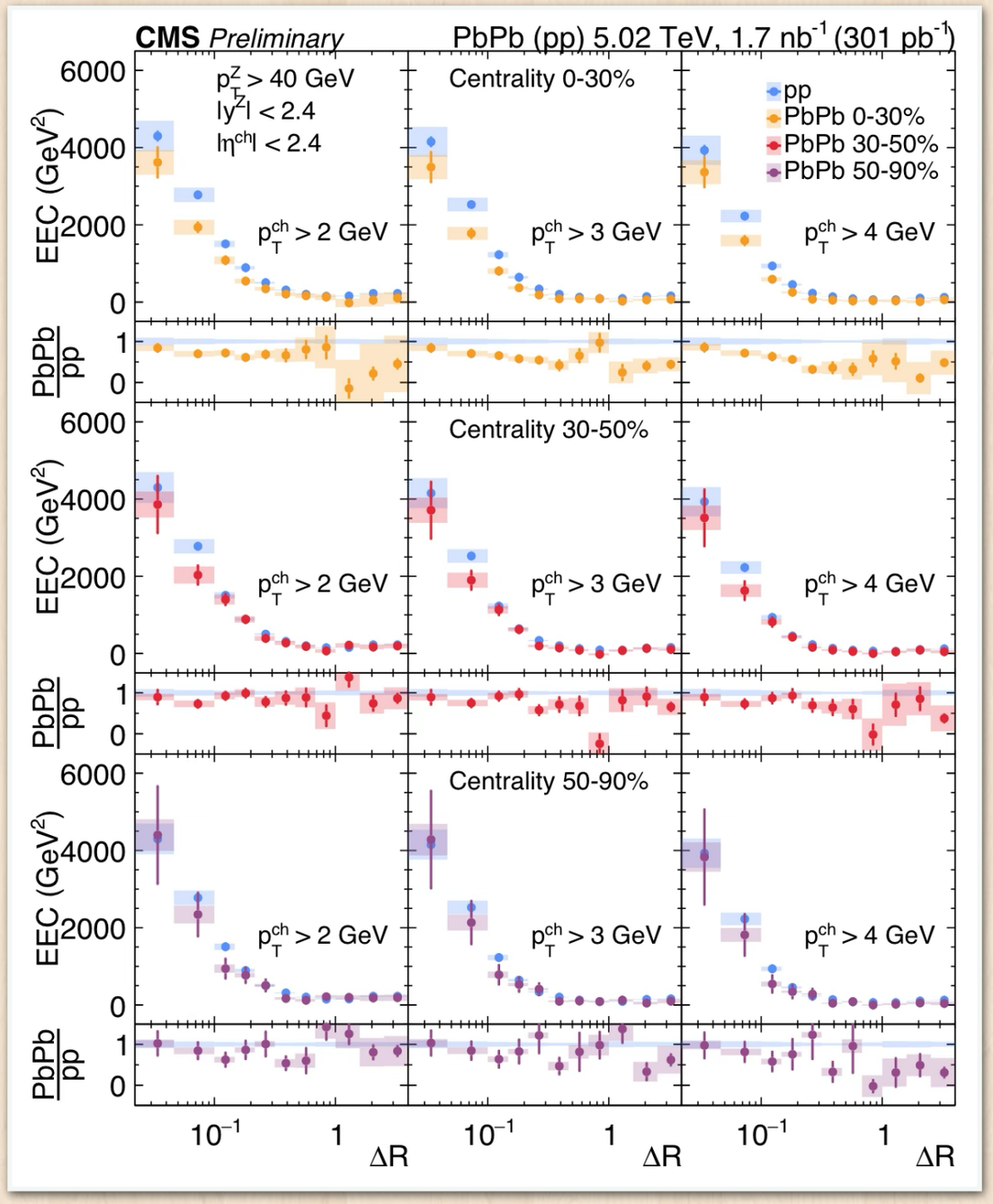
- Estimate with pp data with one reconstructed vertex

- This difference is then taken into account when matching events with Z and minimum bias events

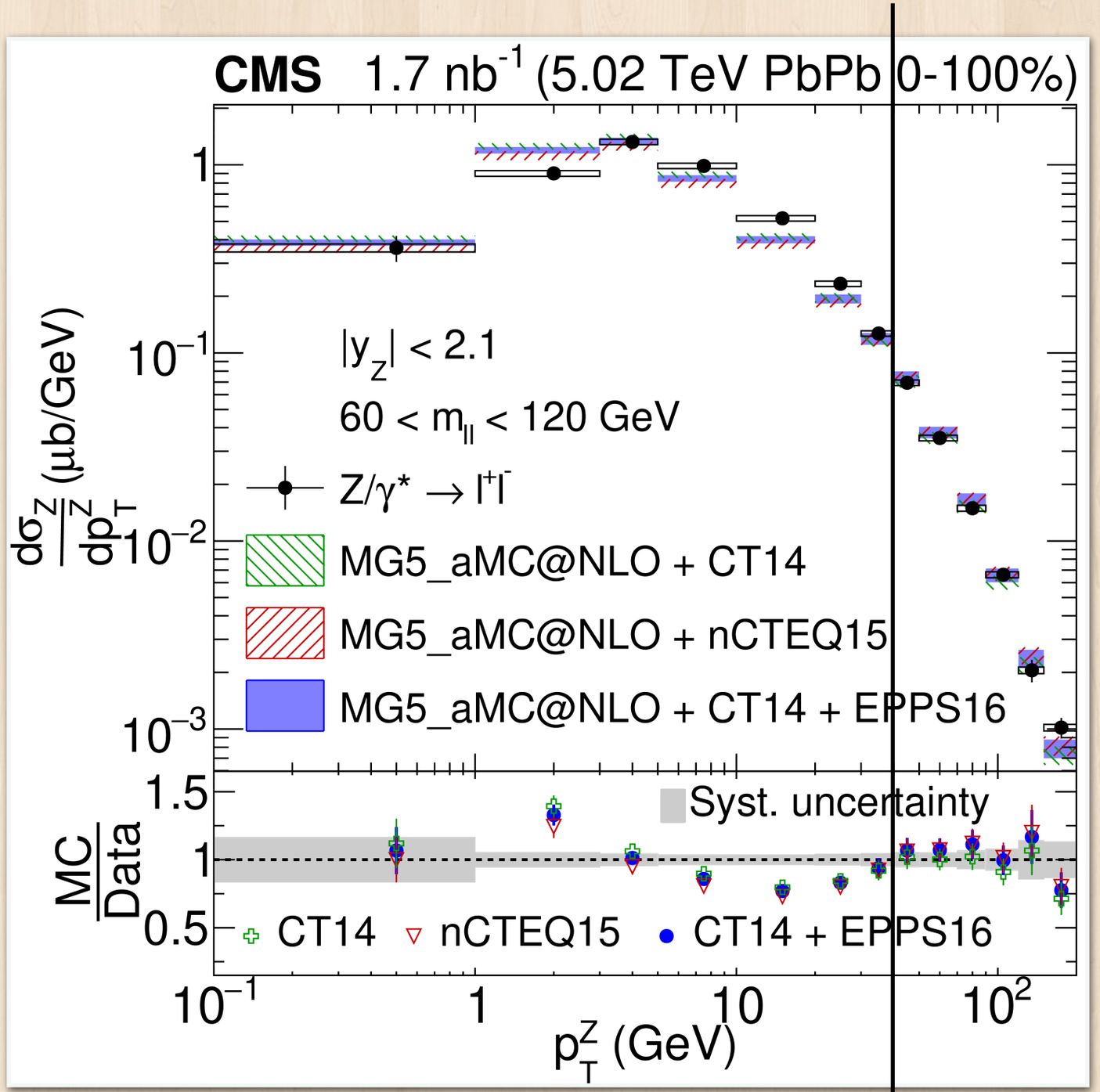
pyquen comparison



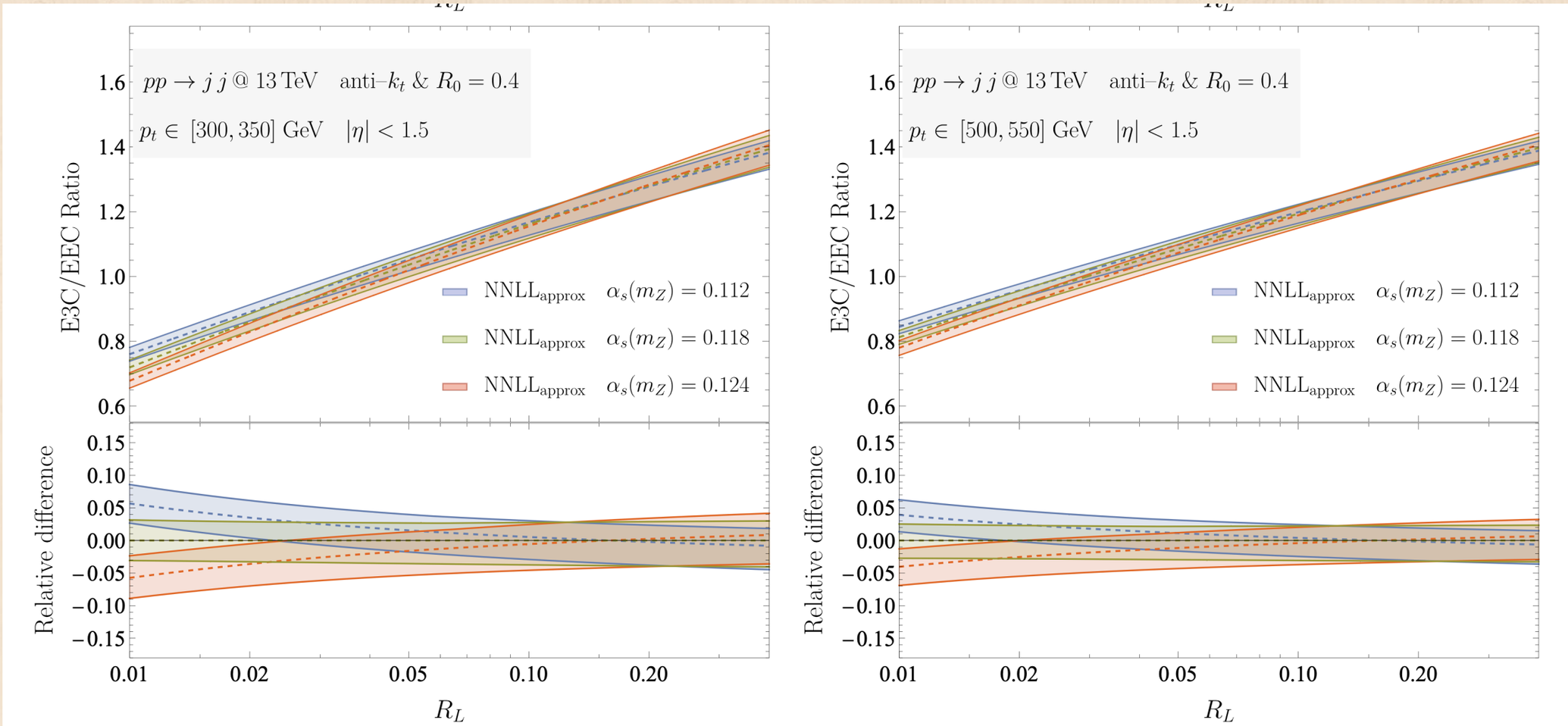
$p_T > 3$ GeV result



Z p_T spectrum



NNLL$_{\text{approx}}$ result



α_s details

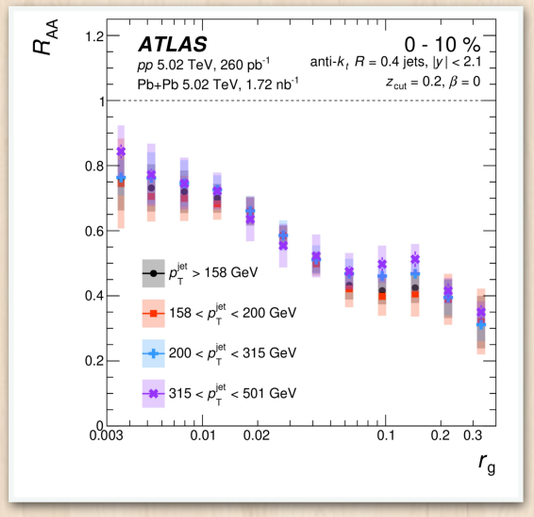
The best fit value of $\alpha_S(m_Z)$ is $0.1229^{+0.0014}_{-0.0012}\,(\text{stat})^{+0.0030}_{-0.0033}\,(\text{theo})^{+0.0023}_{-0.0036}(\text{exp})$, where theo and exp stand for theoretical and experimental systematic uncertainties, respectively. The central value is determined by minimizing the χ^2 with respect to the nuisance parameters, simultaneously varied, and the uncertainties are given by the $\alpha_S(m_Z)$ values that lead to χ^2 values exceeding the minimum by 1. The high precision stems from the cancelation of most E2C and E3C systematic uncertainties in their ratio. The largest sources of uncertainty are the renormalization scale in the theoretical calculation (2.4%) and the energy scales of the jet constituents (2.3%).

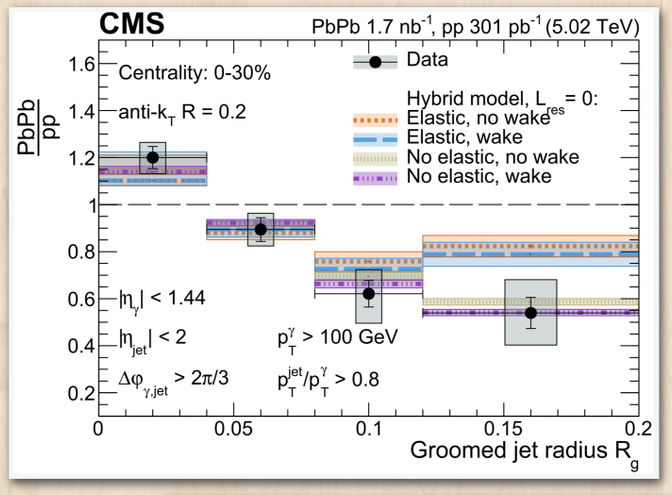
$$\chi^2 = [\vec{v}_{\mathrm{m}}(\vec{\theta}) - \vec{v}_{\mathrm{th}}(\alpha_S, \vec{\theta})]^{\intercal} V_{\mathrm{m}}^{-1} [\vec{v}_{\mathrm{m}}(\vec{\theta}) - \vec{v}_{\mathrm{th}}(\alpha_S, \vec{\theta})] + \sum_j \theta_j^2,$$

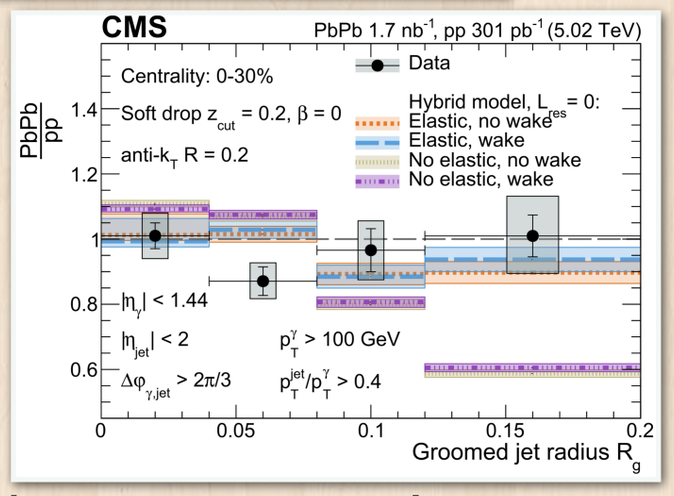
$$\alpha_s(m_Z) = 0.1229^{+0.0014}_{-0.0012}(\text{stat})^{+0.0030}_{-0.0033}(\text{theo})^{+0.023}_{-0.0036}(\text{exp})$$

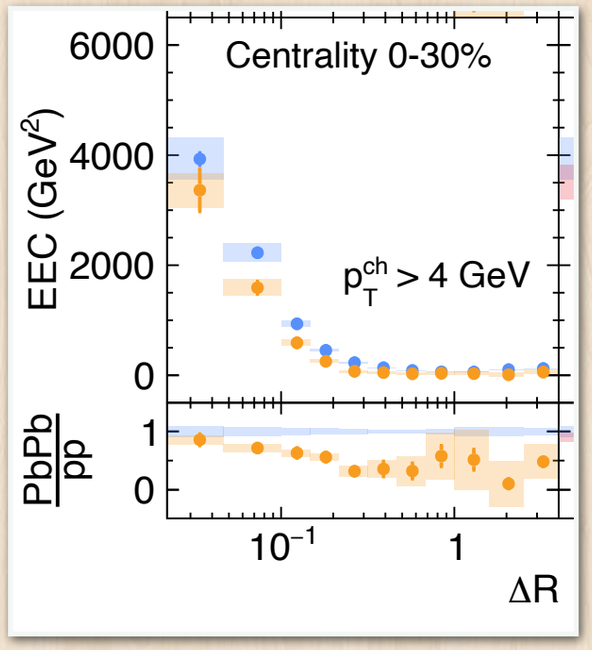
+ ⟵ Selection bias ⟶ −

Inclusive jet (EEC, r_g, etc)	Photon-tagged substructure (e.g. r_g)	Z-tagged & no jet
Jet narrowing	Tight: narrowing vs loose: recovery	High p_T core downward trend









Photon-tagged fragmentation