Jetting through the Quark Soup

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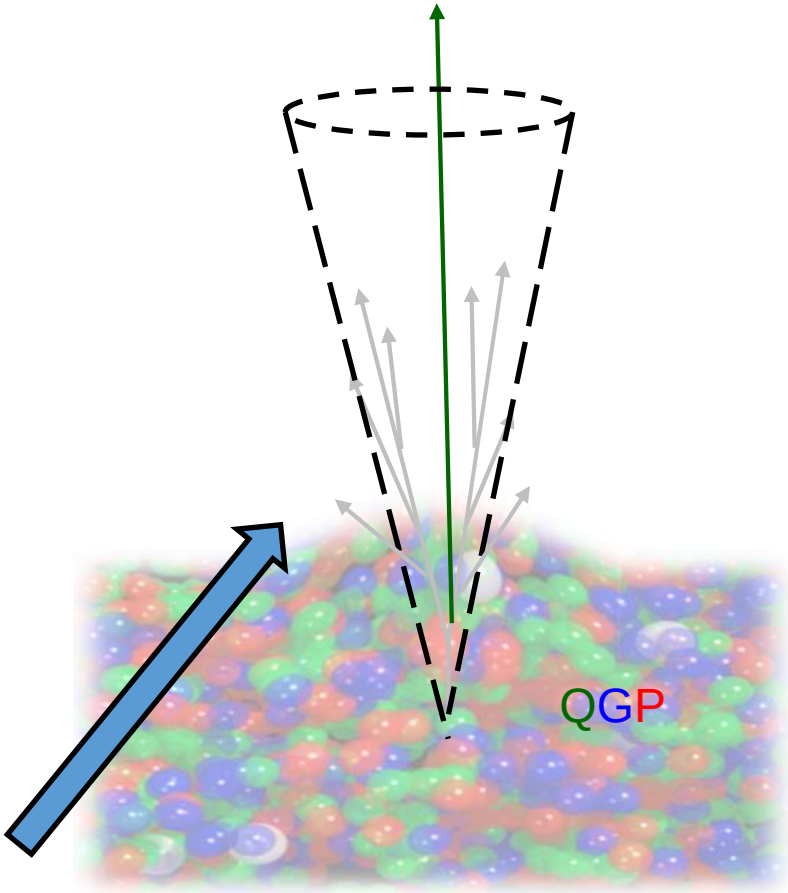
Lecture 4
Modification of jet substructure and medium response

Outline

- Lecture 1
  Why do we study relativistic heavy ion collisions?
- Lecture 2
  How do we measure jets in heavy ion collisions?
- Lecture 3
  Parton energy loss and its parton flavor dependence
- Lecture 4
  ⇒ Modification of jet substructure and medium response
- Lecture 5
  Open questions and future direction

Jet Quenching



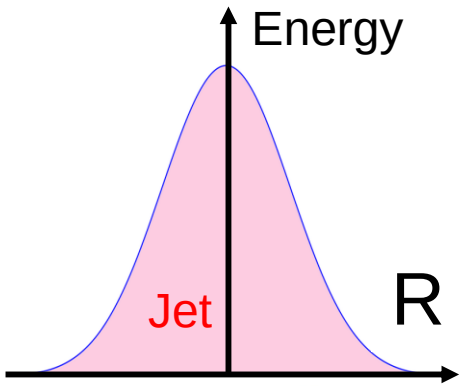
Is the jet substructure modified?

Inclusive Jet Shape and Longitudinal Structure

Jet shape **PbPb / pp**

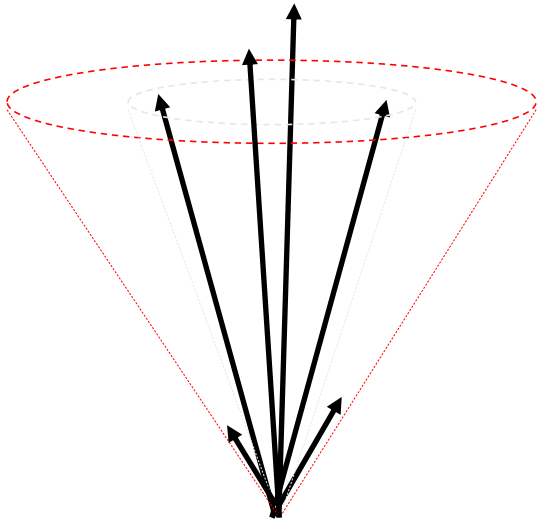
Charged particle in cone PbPb / pp

Jet shape:
"the jet energy distribution" as a function of R



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

Jet Fragmentation function:
how transverse momentum is distributed inside the jet cone



$$\xi^{\text{jet}} = \ln\frac{|\mathbf{p}^{\text{jet}}|^2}{\mathbf{p}^{\text{trk}}\cdot\mathbf{p}^{\text{jet}}}$$

Inclusive Jet Shape and Longitudinal Structure

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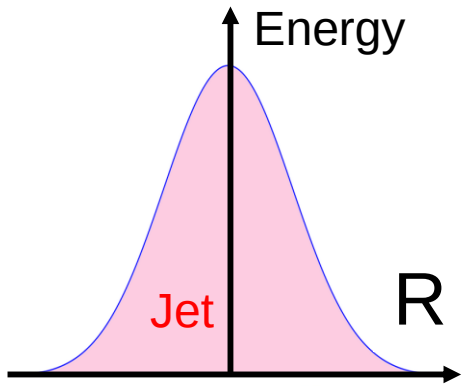

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Inclusive Jet Shape

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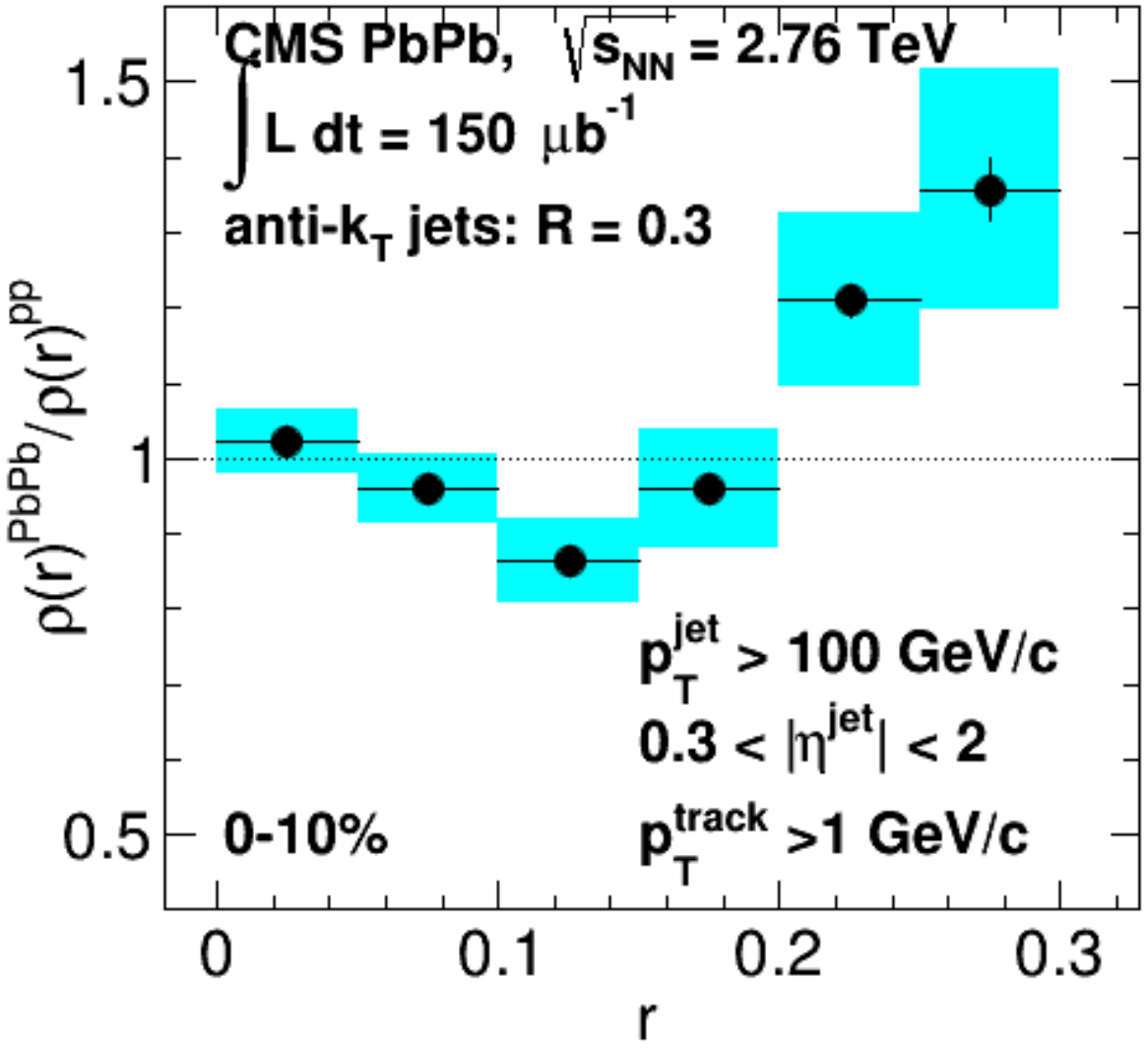

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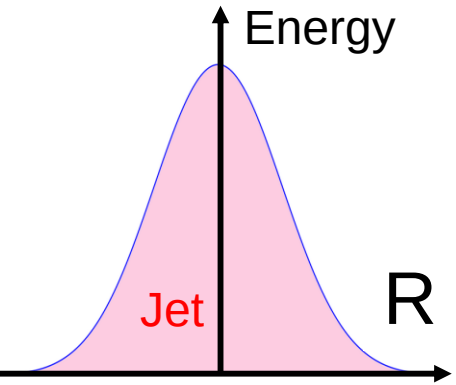
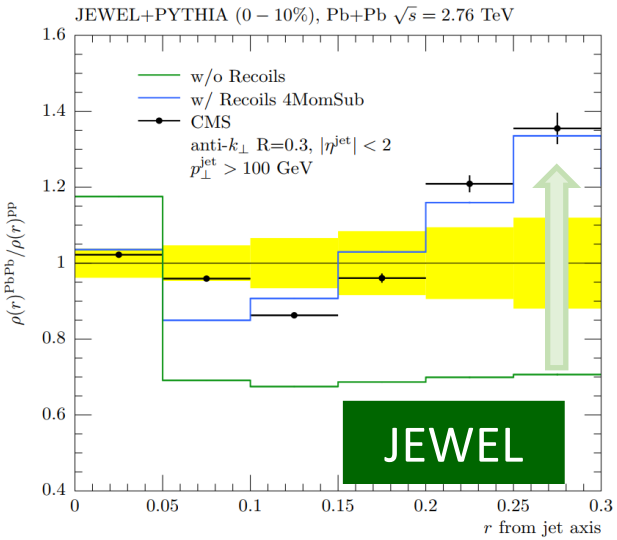


Observation of energy redistribution inside the jet cone

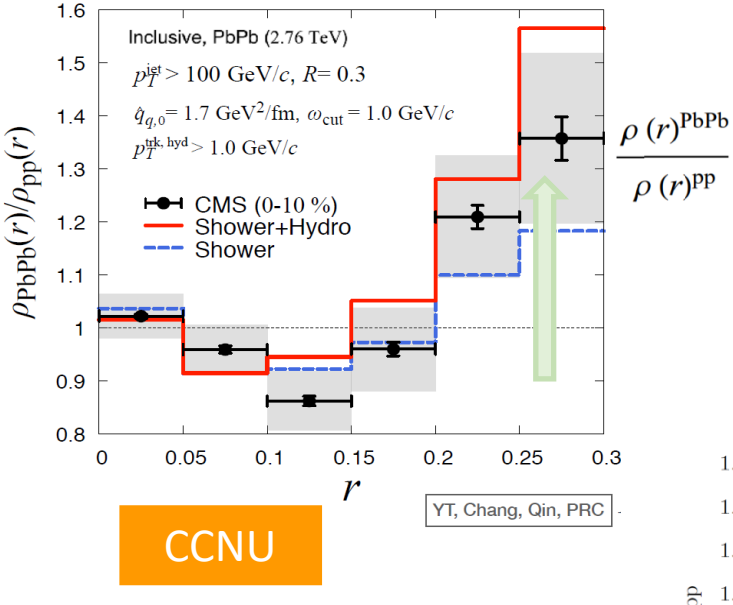
(Some modification at large R; ~ one more low track p_T)

The bulk of the jet structure is actually **pretty similar** to that in pp

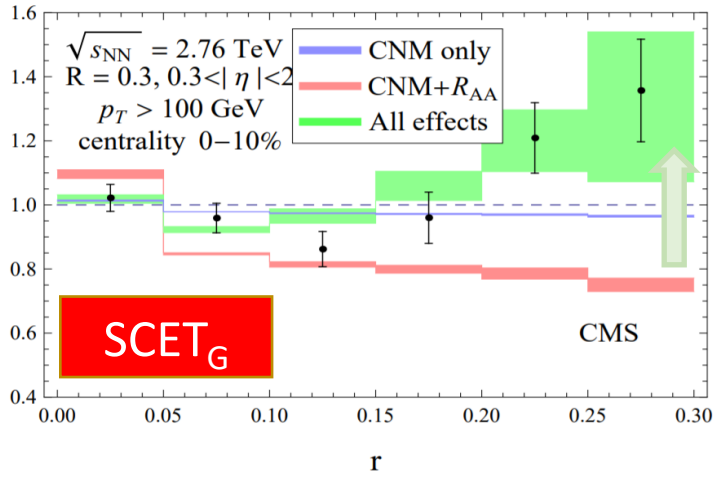
Theoretical Interpretation of the Excess

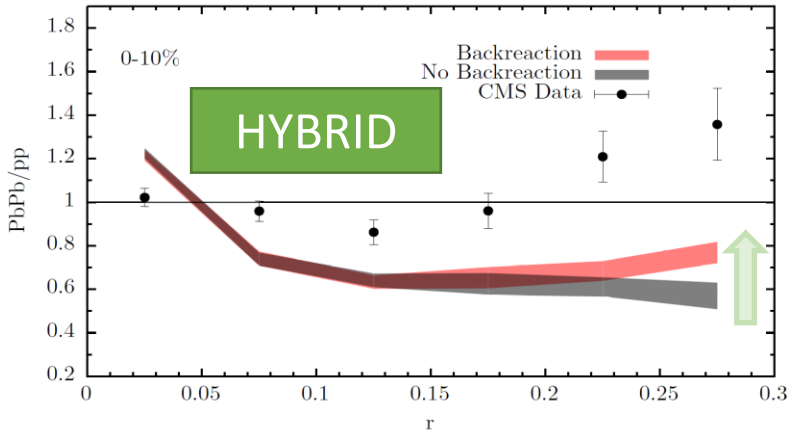


arXiv:1707.01539



$$\frac{\rho\,(r)^{PbPb}}{\rho\,(r)^{pp}}$$

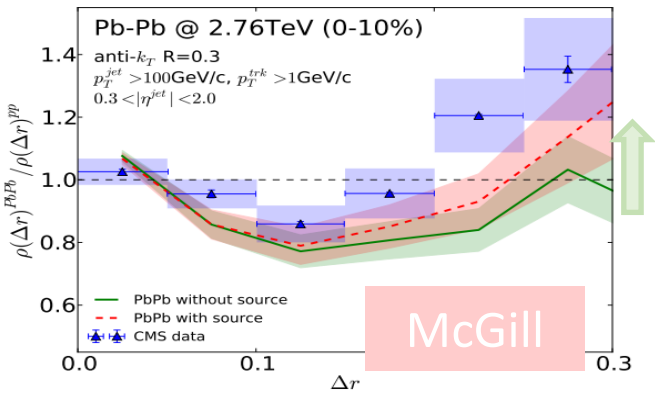




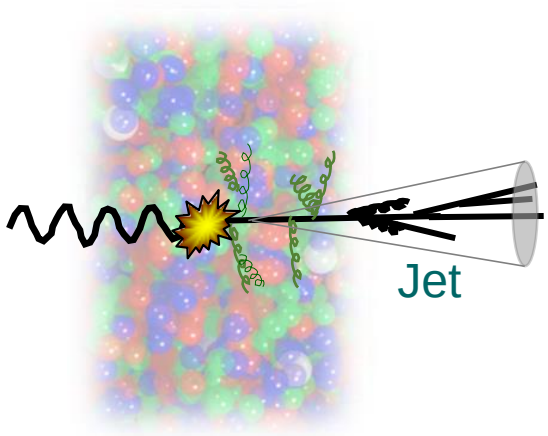
Different explanation of the large angle enhancement in jet shape measurement

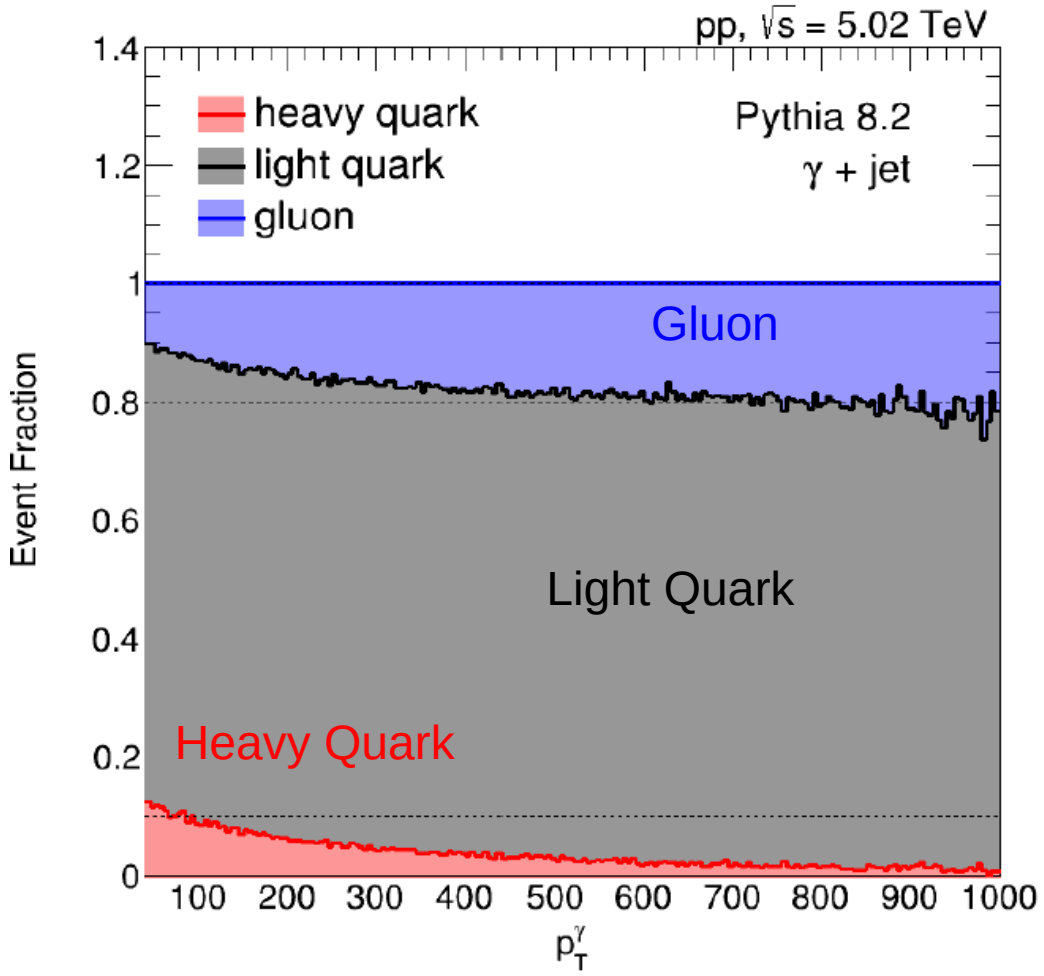
- SCET$_G$: Splitting function (large angle radiation)
- JEWEL & JETSCAPE: medium recoil parton
- CCNU: recoil parton + hydro dynamical evolution
- HYBRID: fully thermalized medium response
- McGill: medium response + shower

Can we test our understanding of small r region by varying the jet flavor?



Photon-Tagged Jet



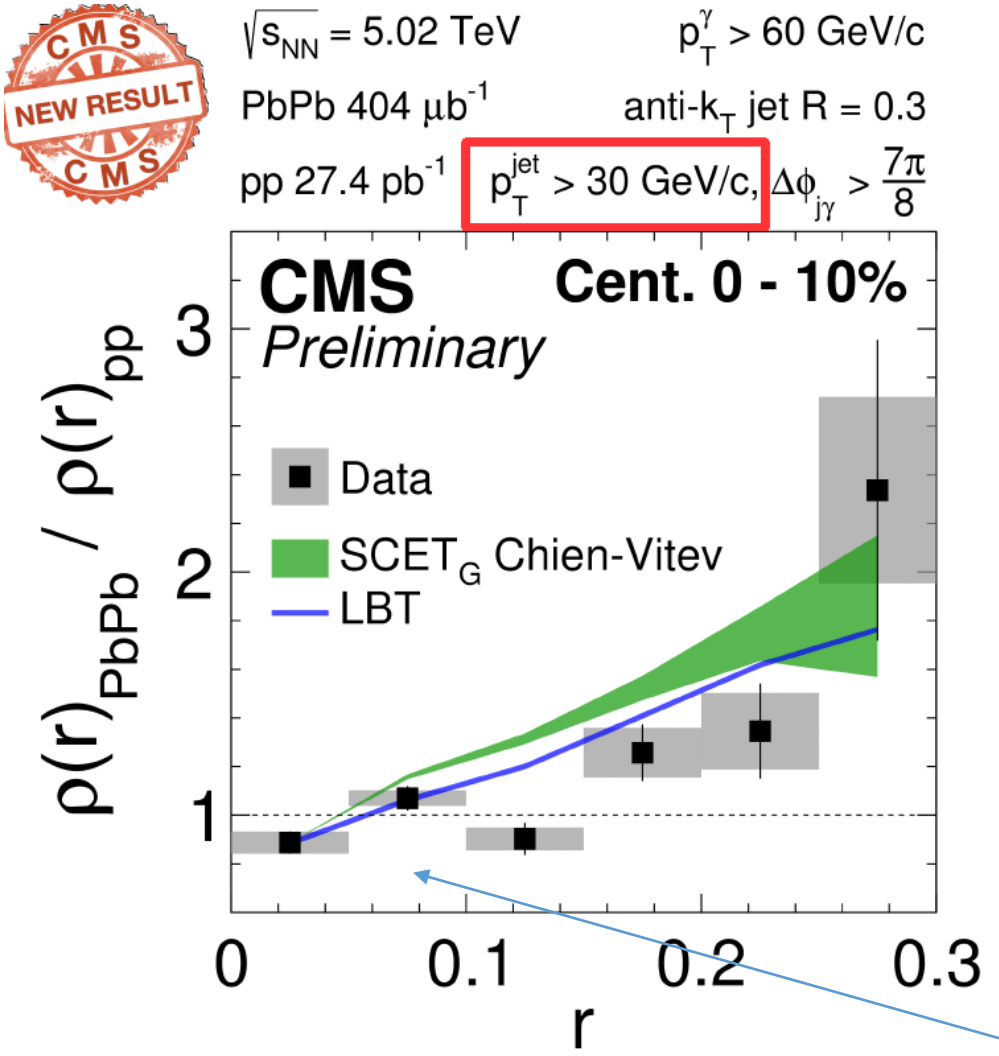


From Kaya Tatar (MIT)

- Decrease the population of gluon jets:
  >70% of the tagged jets are quark jets

Inclusive Jet Shape

Photon-tagged Jet shape **PbPb / pp**



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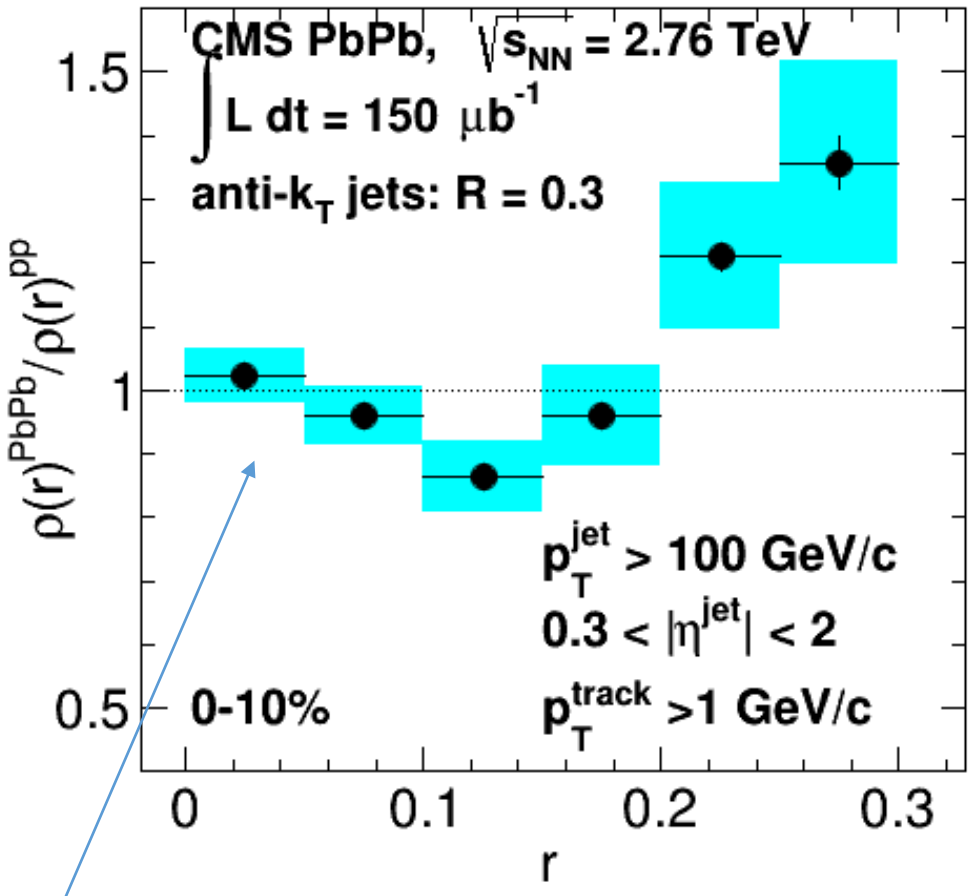

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{jets}}\Sigma_{jets}\frac{\Sigma_{tracks\in(r_a,r_b)}p_T^{trk}}{\Sigma_{tracks}p_T^{trk}}$$

- Varying the jet flavor!
- Consistent with the expectation due to the changed quark vs gluon ratio

Inclusive Jet Shape and Longitudinal Structure

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Charged particle in cone PbPb / pp

Jet shape:
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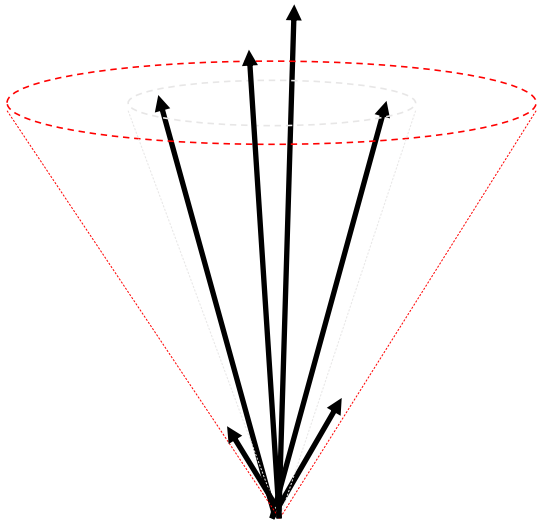
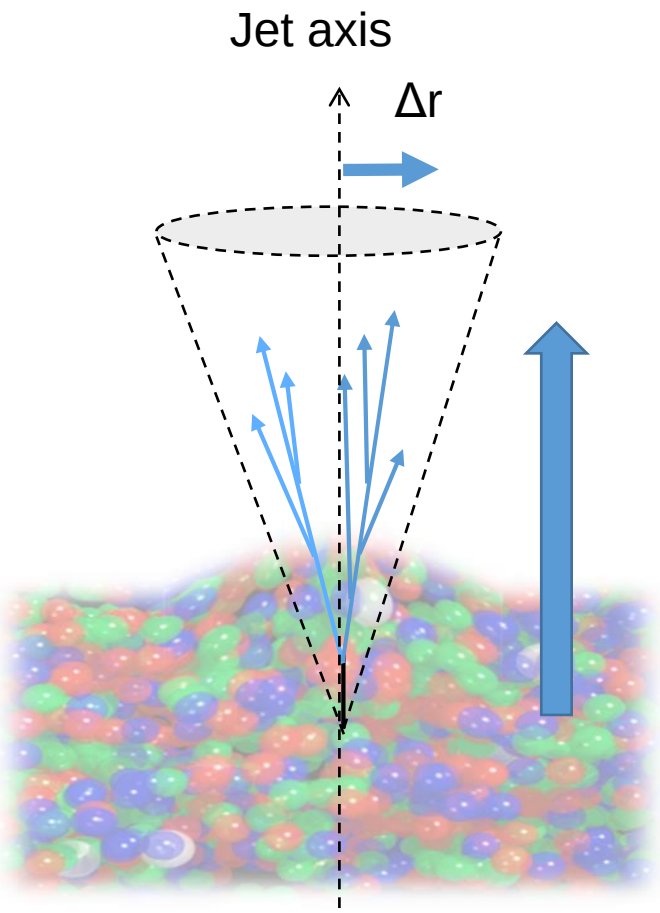
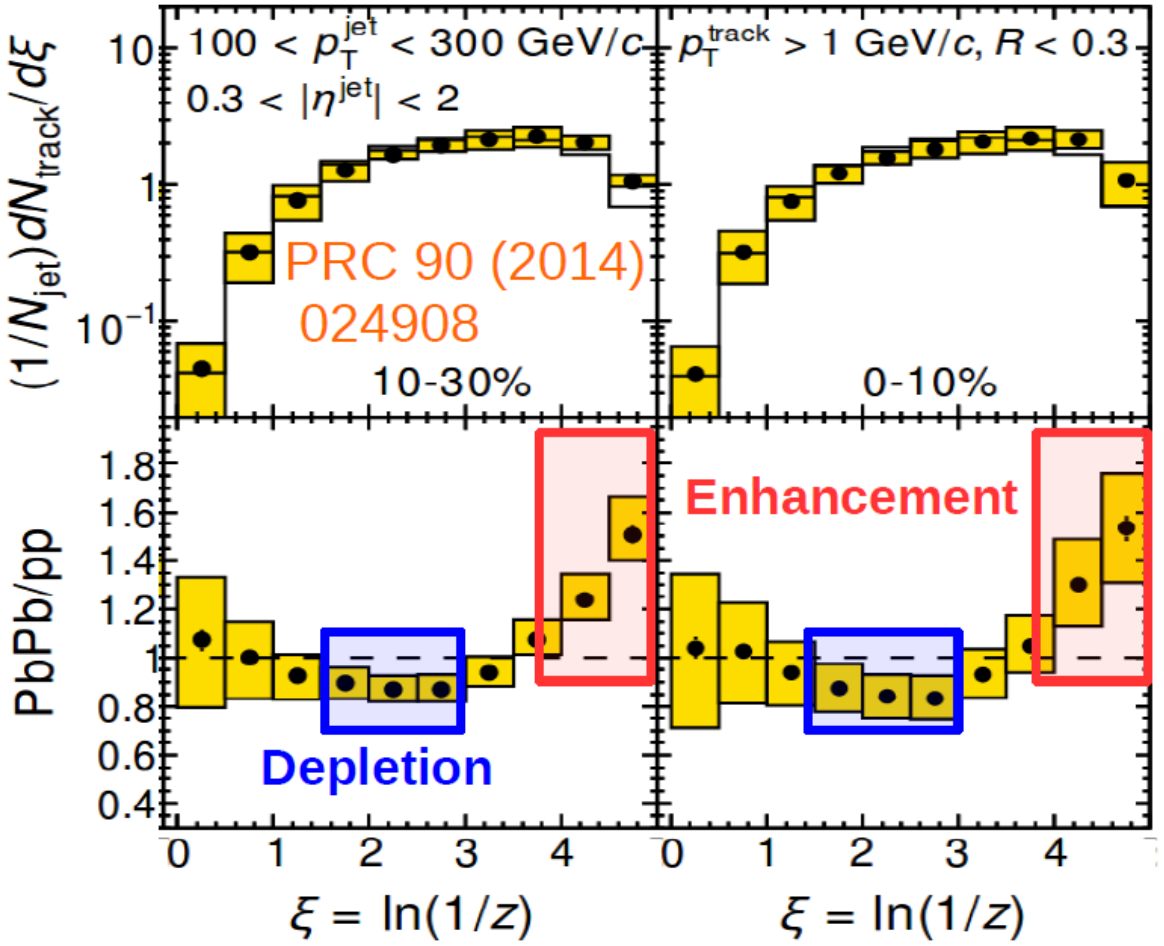


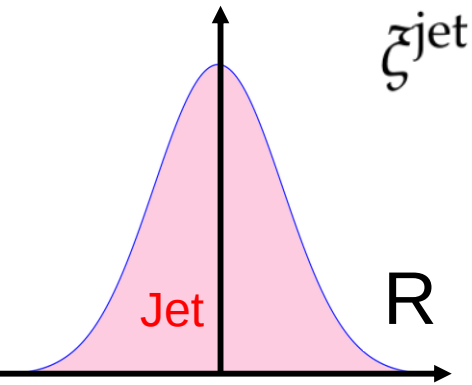
$$\xi^{\text{jet}} = \ln\frac{|\mathbf{p}^{\text{jet}}|^2}{\mathbf{p}^{\text{trk}}\cdot\mathbf{p}^{\text{jet}}}$$ = -ln Z

Inclusive Jet Longitudinal Structure





$$\xi^{jet} = \ln \frac{|\mathbf{p}^{jet}|^2}{\mathbf{p}^{trk} \cdot \mathbf{p}^{jet}}$$

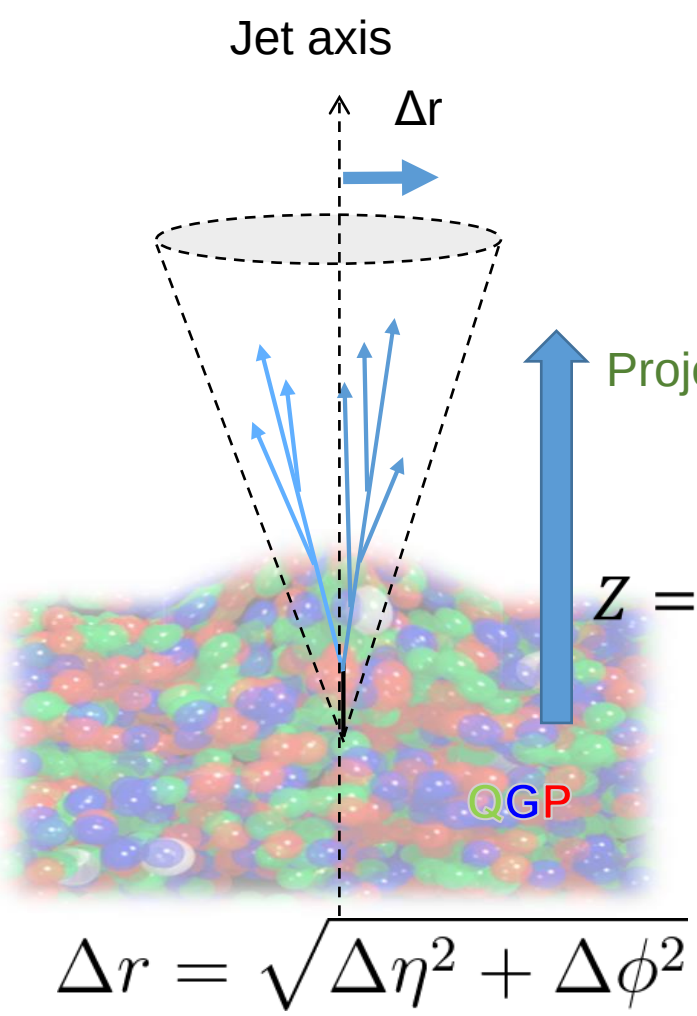


Observation of energy redistribution inside the jet cone

(Some modification at large R; ~ one more low track p_T)

The bulk of the jet structure is actually **pretty similar** to that in pp

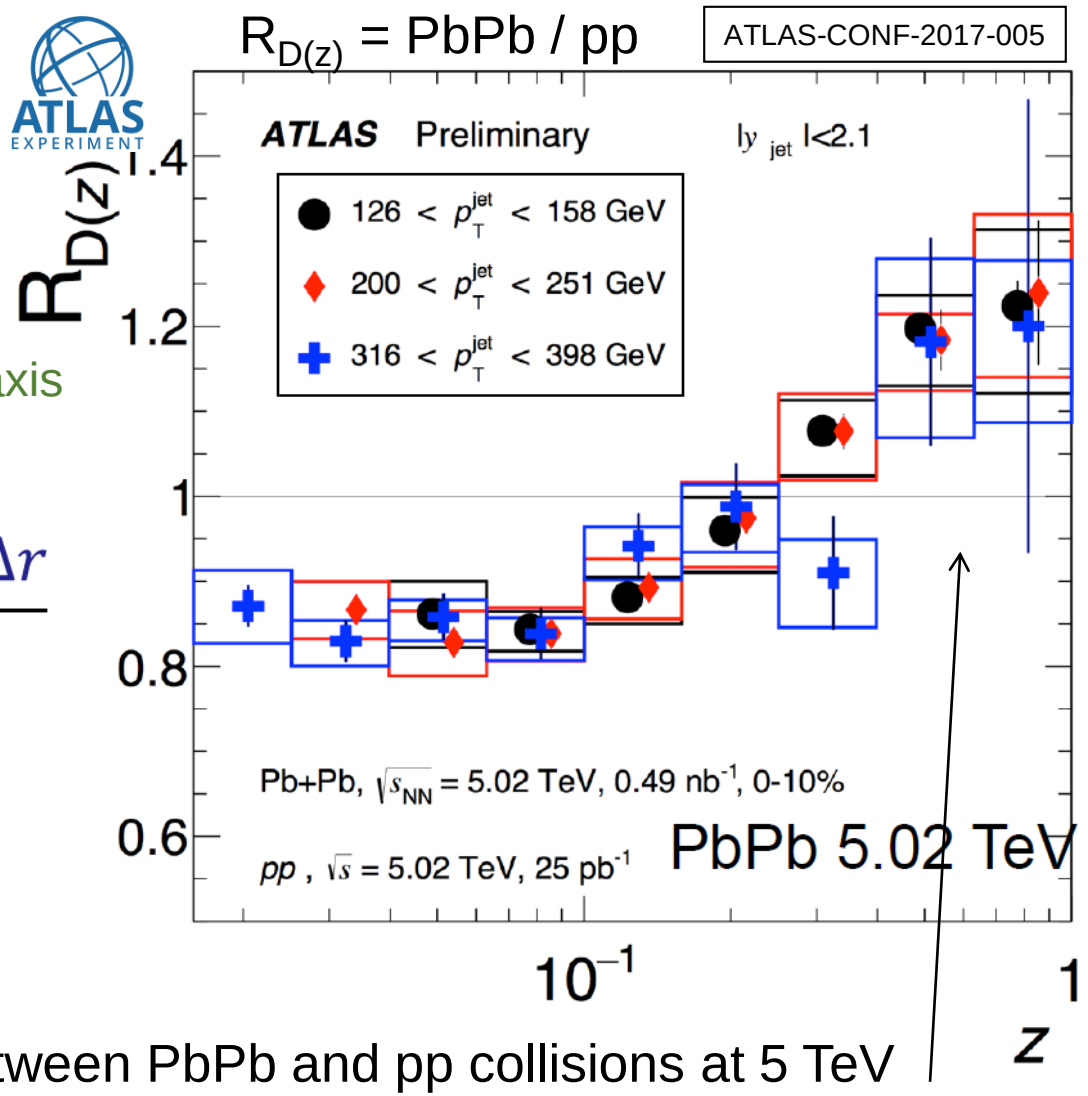
Jet Longitudinal Structure



Projection to jet axis

$$z = \frac{p_T^{Trk} \cos \Delta r}{p_T^{Jet}}$$

$$\Delta r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



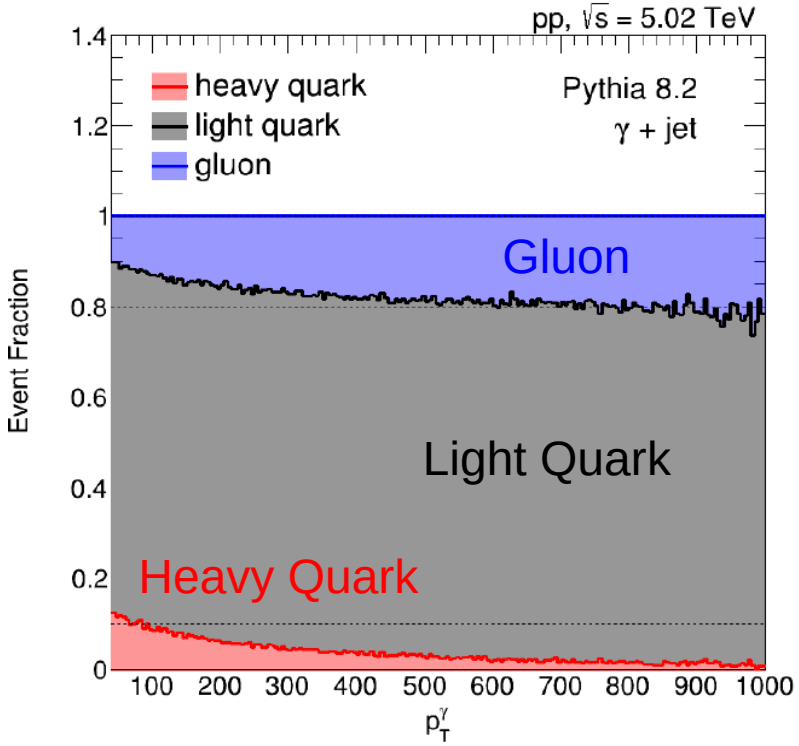
- Fragmentation functions Ratio $R_{D(z)}$ between PbPb and pp collisions at 5 TeV
- Enhancement at large z (high p_T particles in jet): **smaller gluon/quark ratio** in PbPb
- Weak or no dependence on the jet p_T

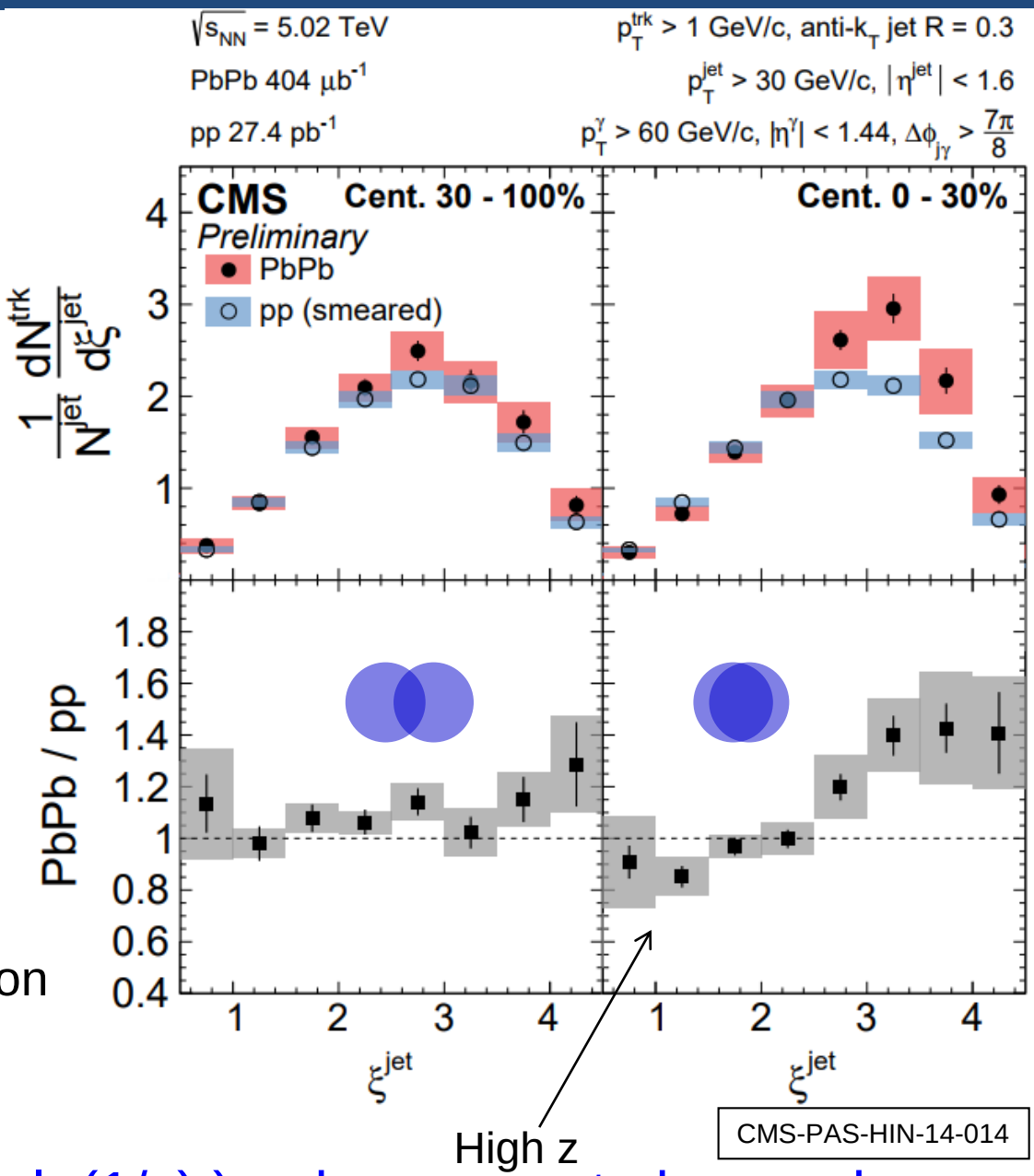
See discussions in Frank Ma, thesis (2013)
arXiv:1504.05169 Martin Spousta, Brian Cole

→ **If switch to γ-tagged jet (mainly quarks), will this enhancement go away?**

Photon-Tagged Fragmentation Function

From Kaya Tatar



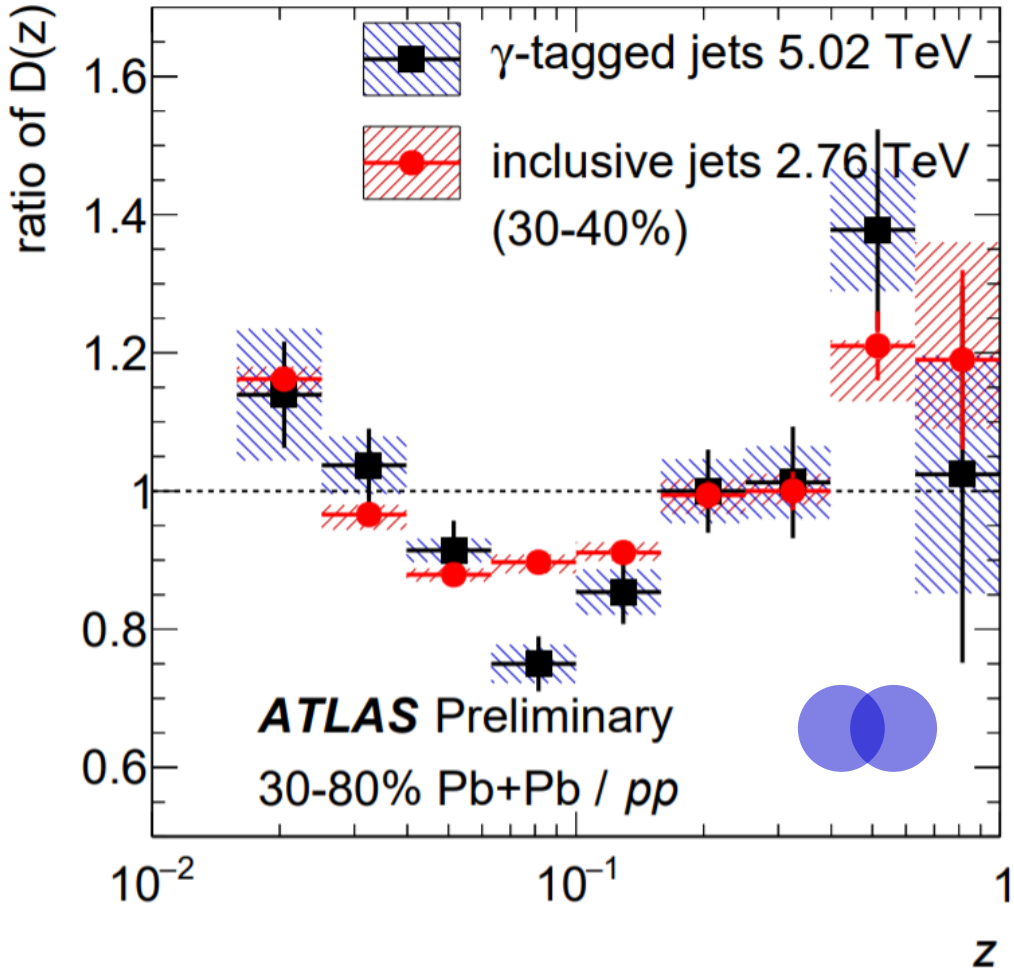


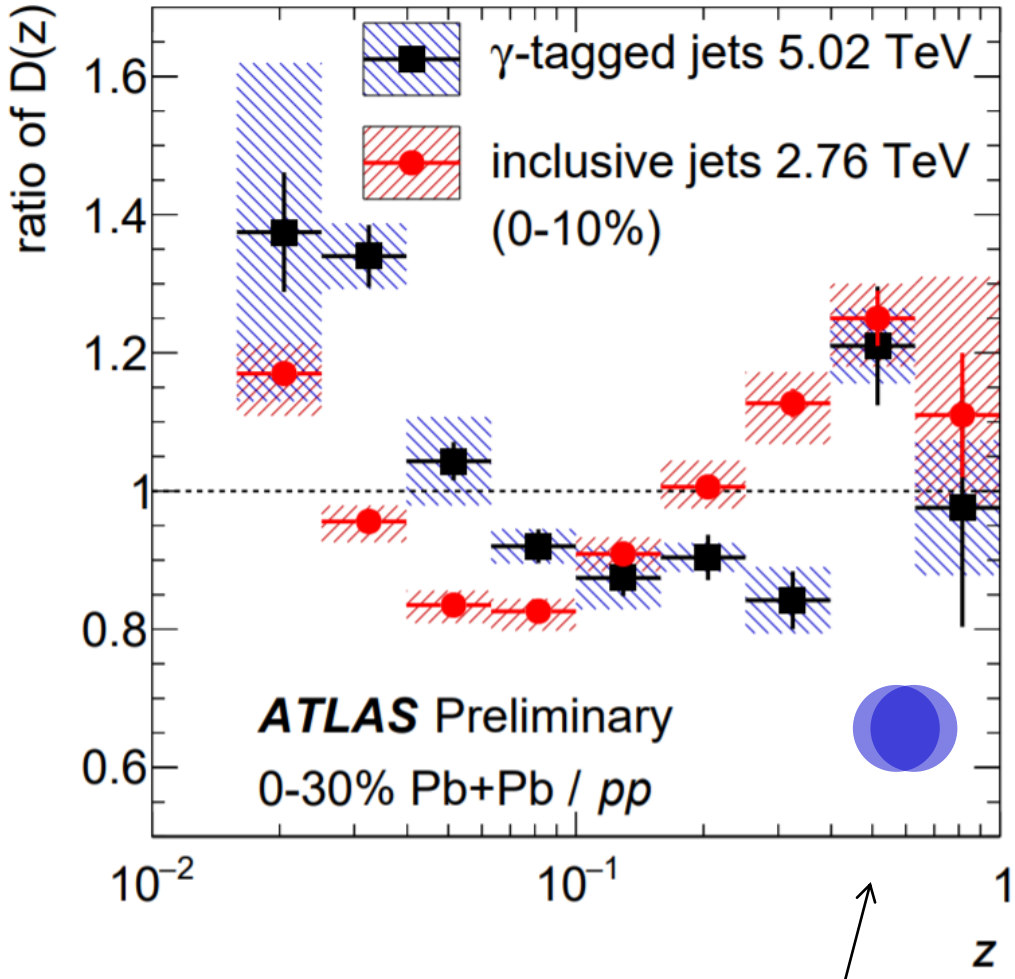
- Decrease the population of gluon jets: **>70%** of the tagged jets are quark jets
- Observation of modified jet fragmentation function in **PbPb** with respect to **pp**

- No significant high z (or small ξ=ln(1/z)) enhancement observed

Photon-Tagged Fragmentation Function

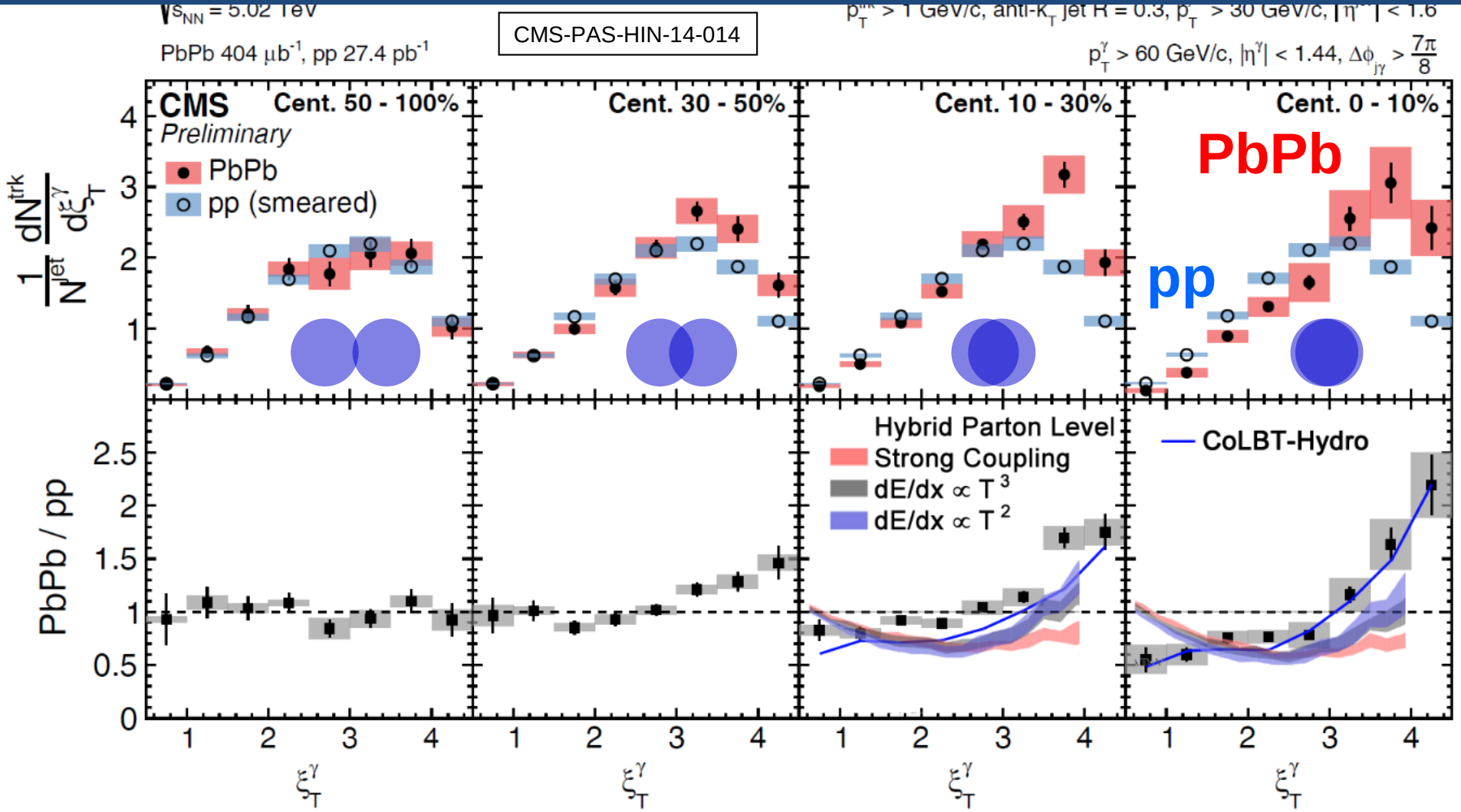
ATLAS: Select on jet p_T > ½ Photon p_T





- Strong modification of **photon-tagged jet FF** in both centrality intervals.
- Larger modification in the central collisions than that in **inclusive jets**
- Corrected for jet resolution smearing
- Hint of enhancement in PbPb/pp ratio at the **high z region**

Jet FF with photon p_T as reference



- Almost no modification in 50-100%, significant modification in central events
- Strong modification in central events, compared to **HYBRID** ("Parton level") and **CoLBT**

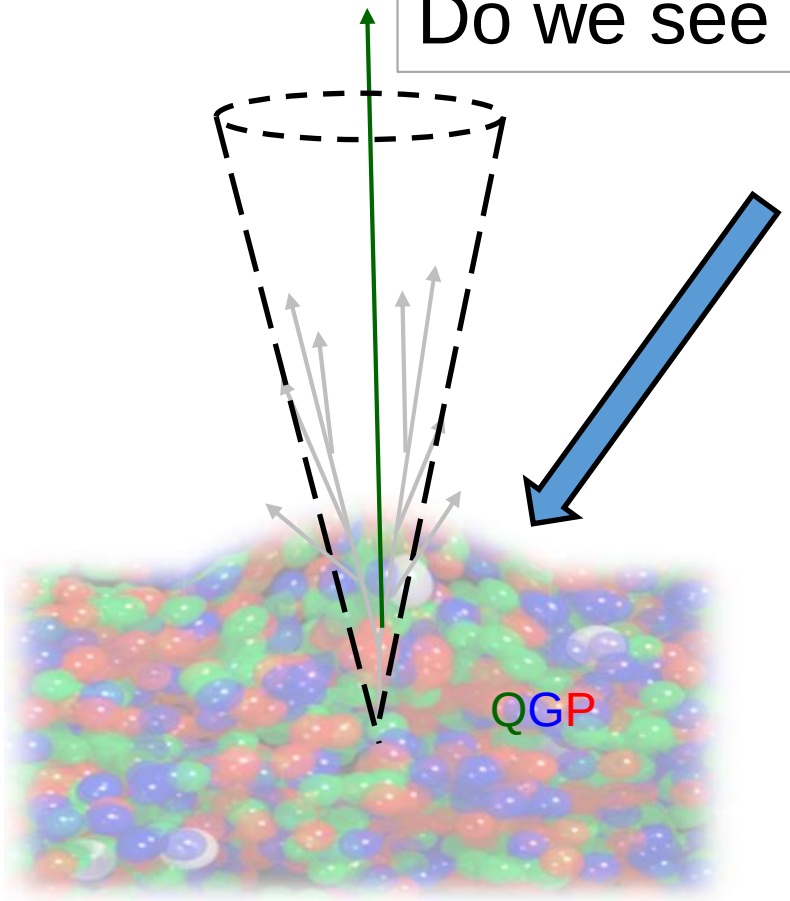
$$\xi_T^\gamma = \ln \frac{-|\mathbf{p}_T^\gamma|^2}{\mathbf{p}_T^{trk} \cdot \mathbf{p}_T^\gamma}$$

HYBRID Parton Level
J. Casalderrey-Solana *et al.*
JHEP 1603 (2016) 053

CoLBT-Hydro calculation
W. Chen, S. Cao, T. Luo, L.-G. Pang, X.-N. Wang
arXiv:1704.03648

Jet Quenching

Where does the quenched energy go?
Do we see medium response?



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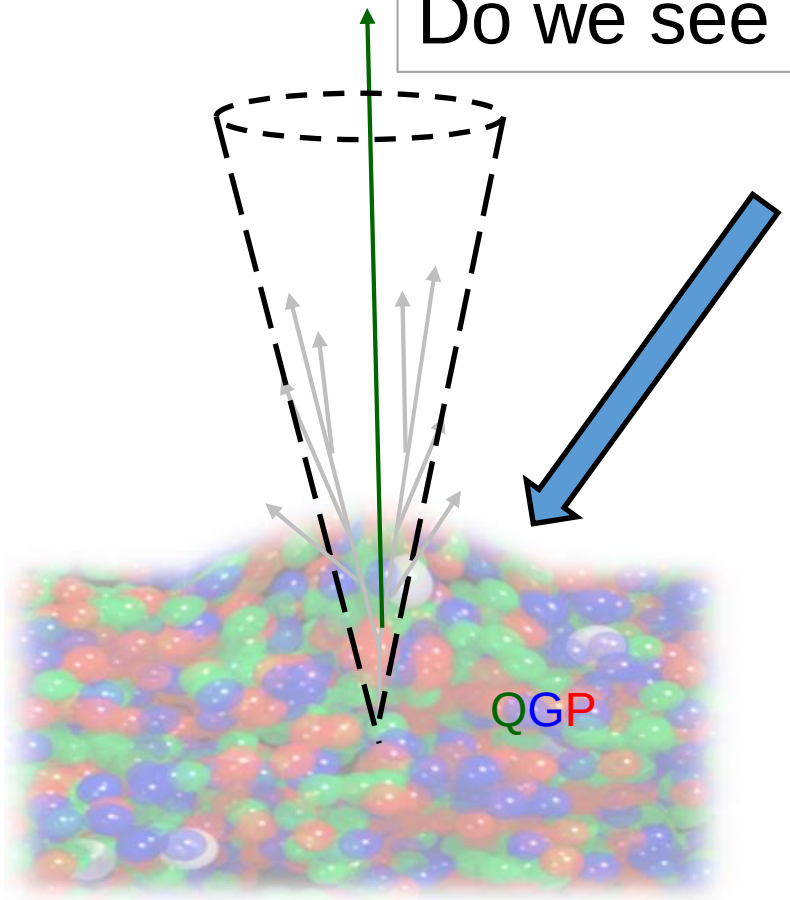
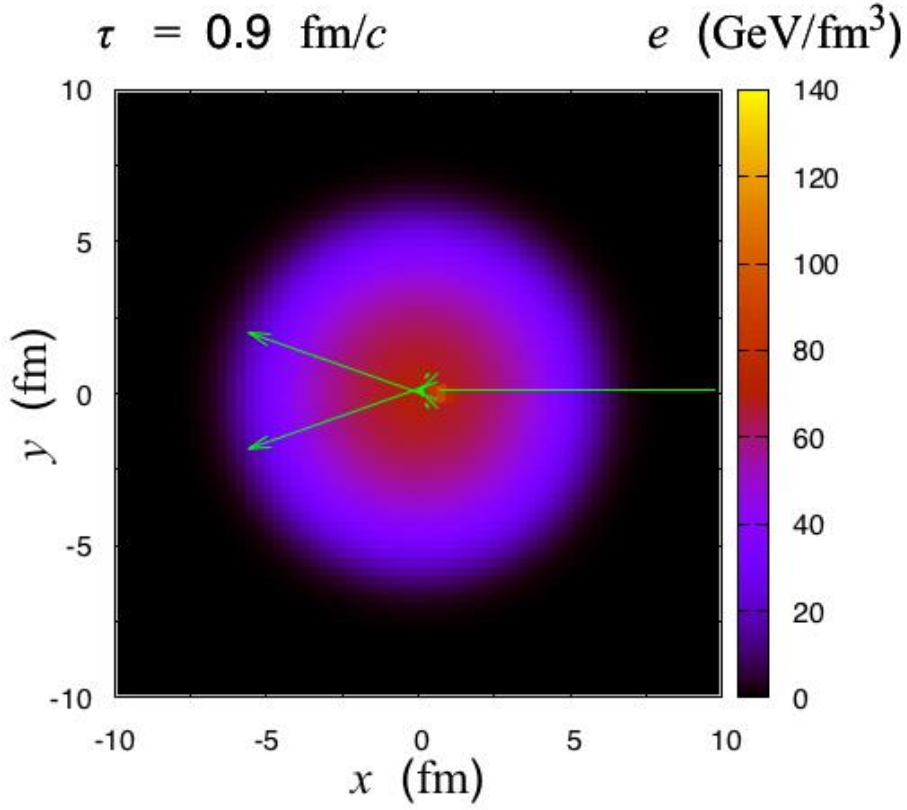
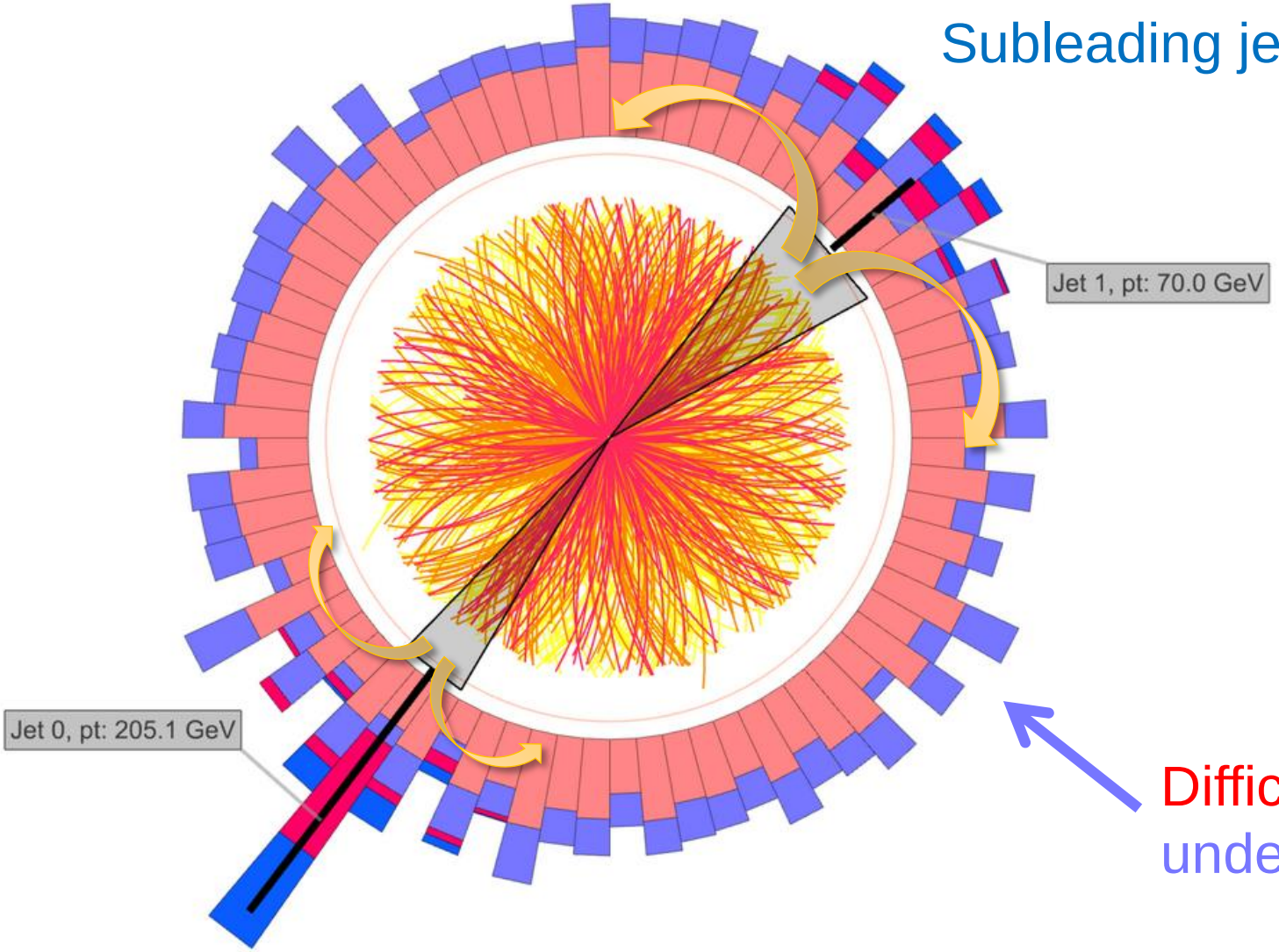




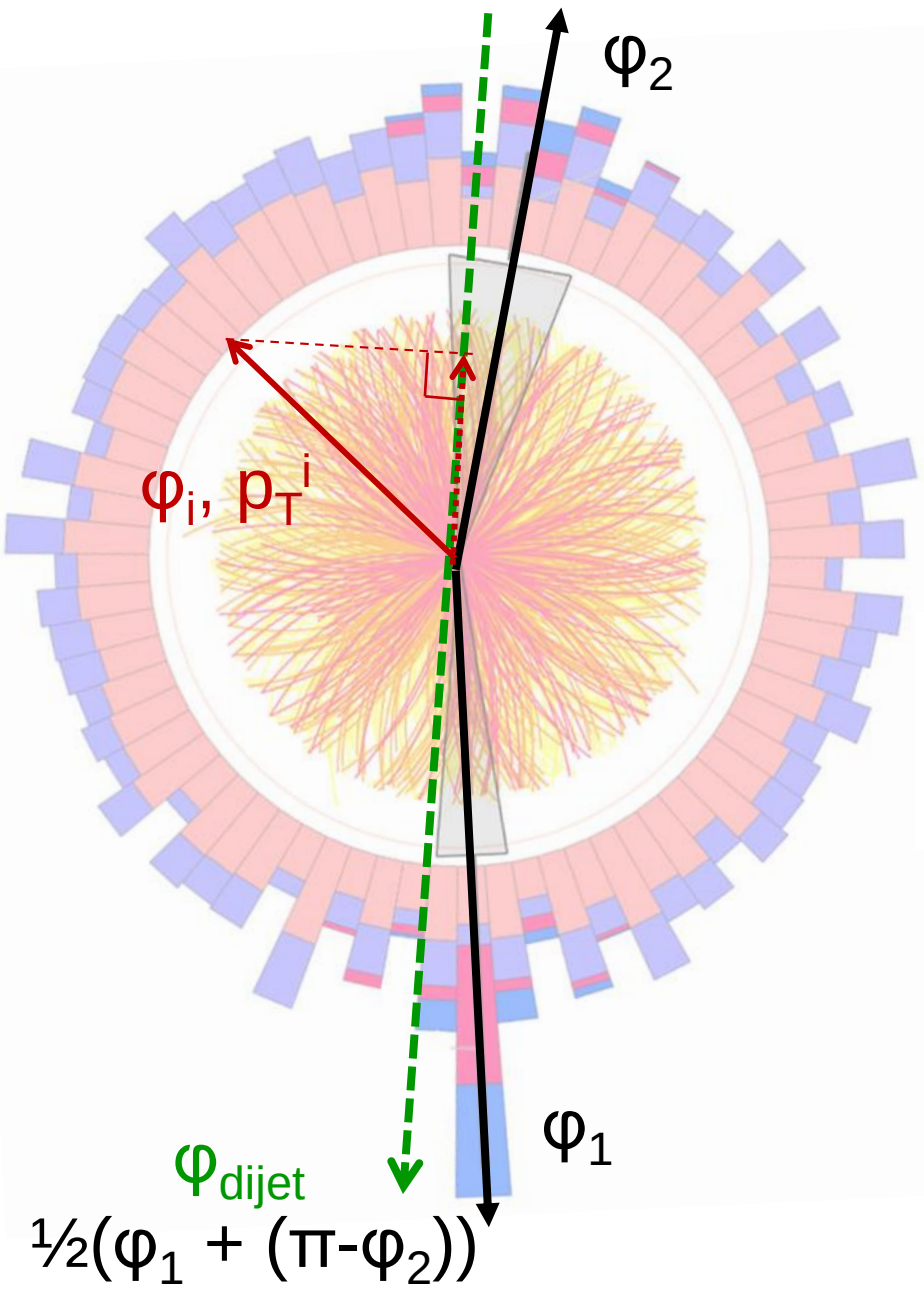
Measurement of the Quenched Energy Flow



Difficulty: Large PbPb underlying event (UE)

Idea: Use all charged particles (p_T>0.5 GeV/c)
Study the transverse momentum balance (uncorrelated UE cancels)

Missing $p_T^{||}$



What is the multiplicity and **p_T spectra** of the particles that balance the lost p_T?

Charged particle azimuthal angle

$$\not{p}_{\mathrm{T}}^{||} = \sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\mathrm{Dijet}}\right)$$

Dijet axis

Projection to dijet axis

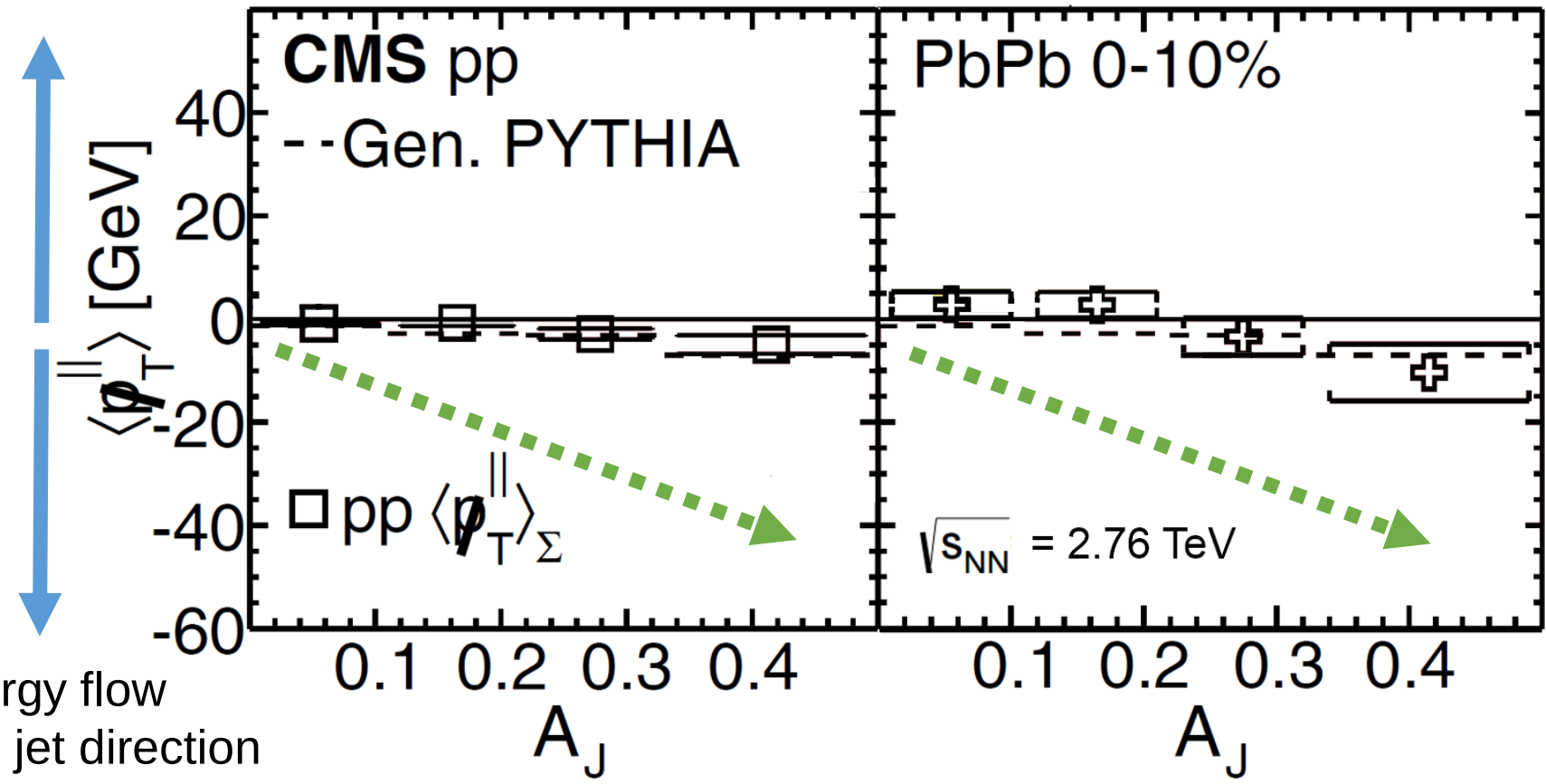
Missing $p_T^{||}$ vs. A_J

arXiv 1509.09029

More energy flow
in the **subleading** jet direction

PP

0-10% PbPb



More energy flow
in the **leading** jet direction

The momentum imbalance inside the jet cone is restored
if we consider all particles in the event
(in both pp and PbPb collisions)

$p_{T,1}$>120, $p_{T,2}$>50 GeV/c
$|\eta_1|,|\eta_2|$<0.50, $\Delta\phi_{1,2}$>5π/6
anti-k_T Calo R=0.3

Missing $p_T^{||}$ vs. A_J

arXiv 1509.09029

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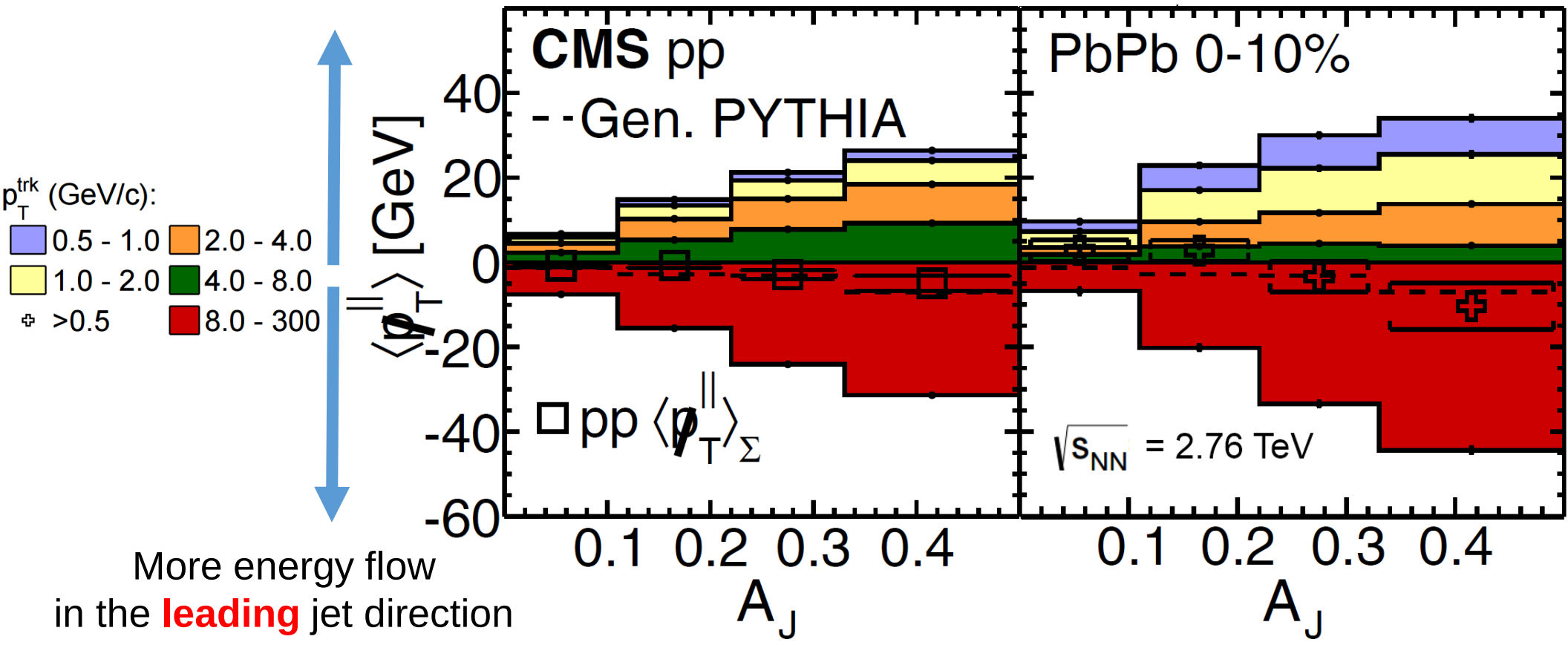
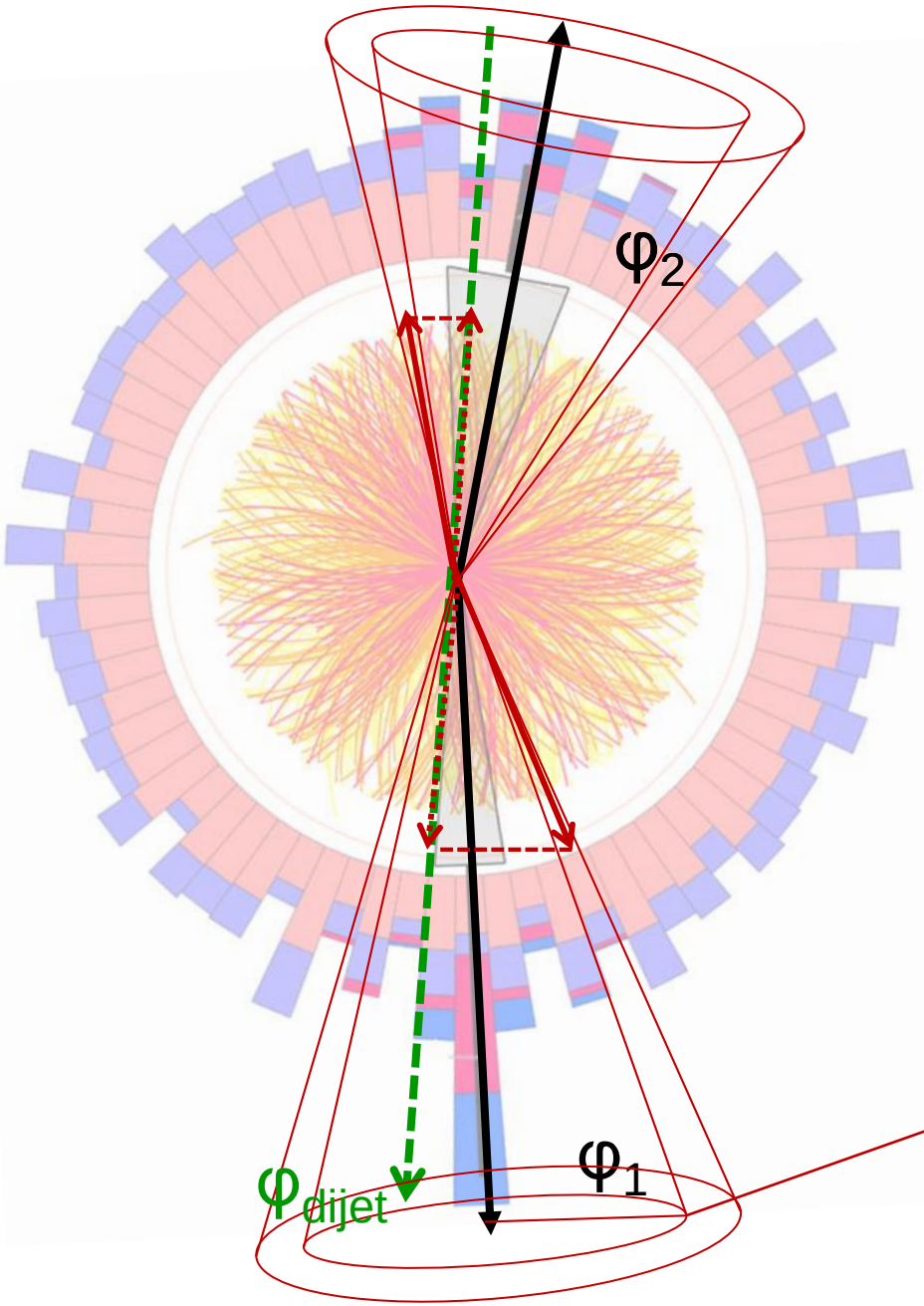


More energy flow
in the **leading** jet direction

- Missing p_T from high p_T particles increases as a function of A_J
- In pp ⟶ Balanced by 2-8 GeV/c particles
- In 0-10% PbPb ⟶ Balanced by particles with p_T < 4 GeV/c

Missing $p_T^{||}$ vs. Δ



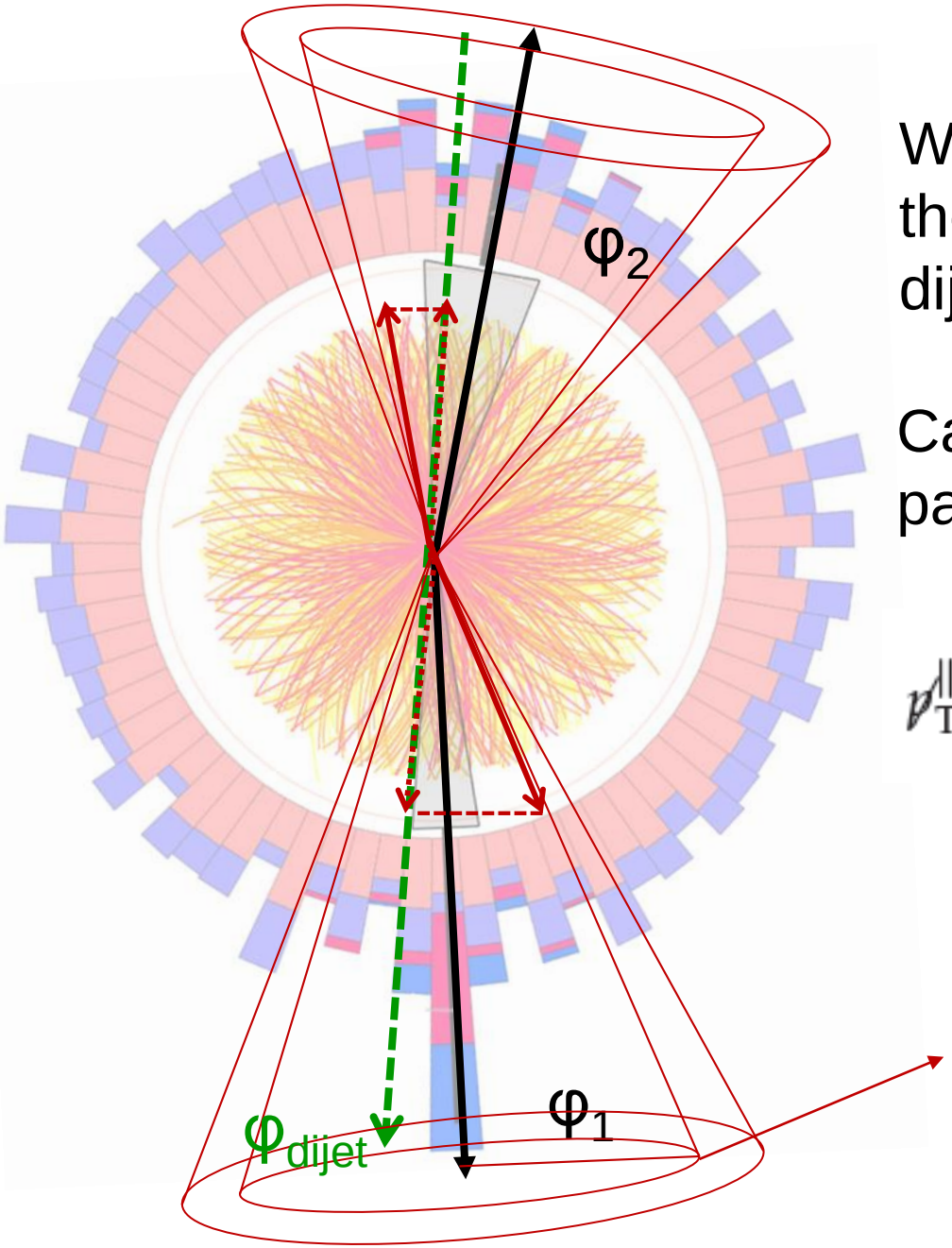
What is the angular distribution of these particles with respect to the dijet system?

Calculate the missing p_T for charged particles that fall in slices of Δ

$$\not{p}_{\mathrm{T}}^{\parallel} = \left(\sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\mathrm{dijet}}\right) \right) \Big|_{R_{\mathrm{down}} < \Delta < R_{\mathrm{up}}}$$

$$\Delta = \sqrt{\Delta\phi_{\mathrm{Trk,jet}}^2 + \Delta\eta_{\mathrm{Trk,jet}}^2}$$

Missing $p_T^{||}$ vs. Δ



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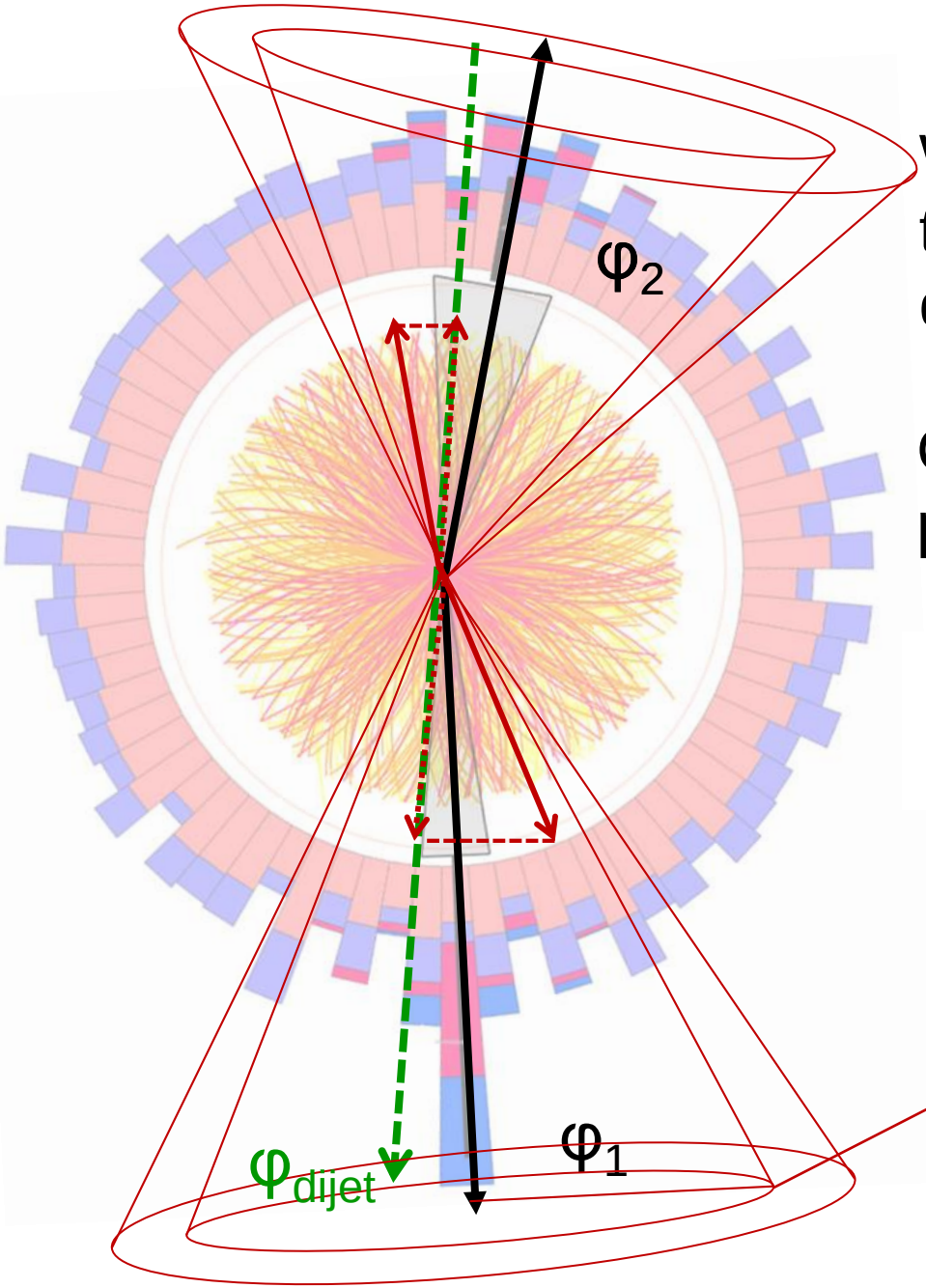

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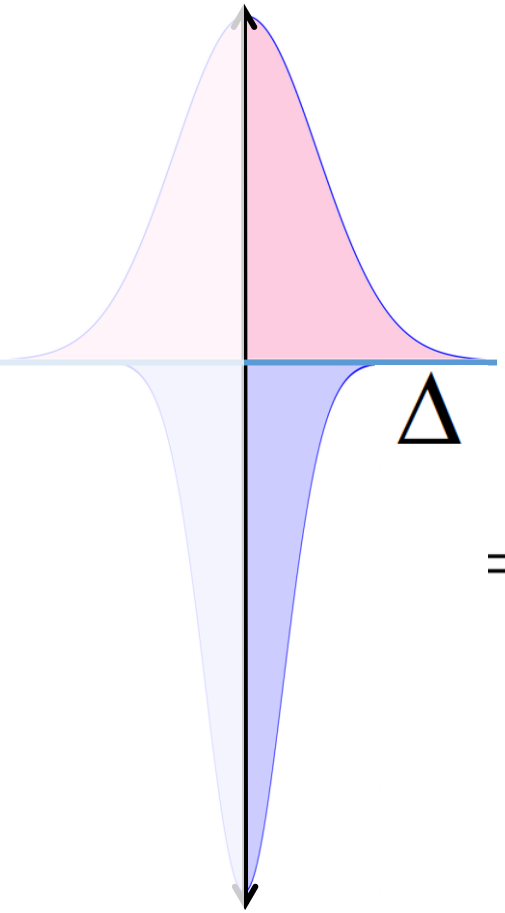
$$\Delta = \sqrt{\Delta\phi_{\mathrm{Trk,jet}}^2 + \Delta\eta_{\mathrm{Trk,jet}}^2}$$

Missing $p_T^{||}$ vs. Δ in pp

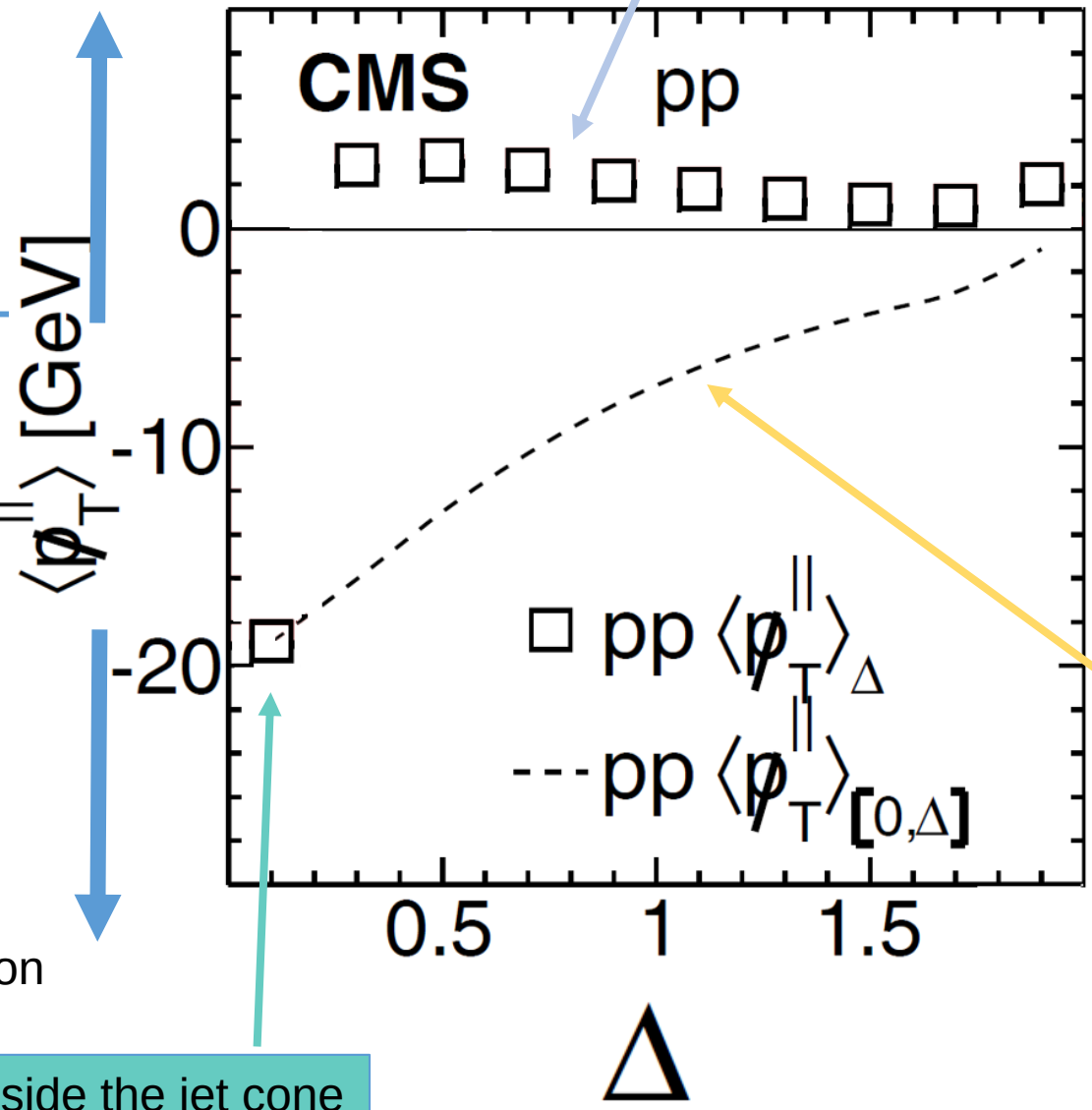
Subleading jet direction



Δ

Leading jet direction

Contribution from third jet



$p_{T,1}$>120, $p_{T,2}$>50 GeV/c

$|\eta_1|,|\eta_2|$<0.50, $\Delta\phi_{1,2}$>5π/6

anti-k_T Calo R=0.3

$|\eta_{trk}|$<2.4

p_T^{trk} (GeV/c):

- 0.5-300 GeV/c

Integrated curve from 0-ΔR

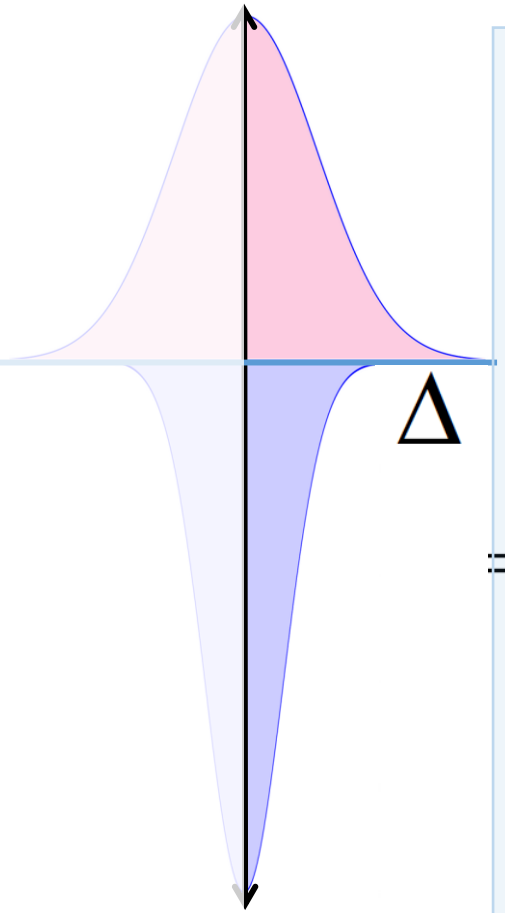
Asymmetry inside the jet cone

$$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

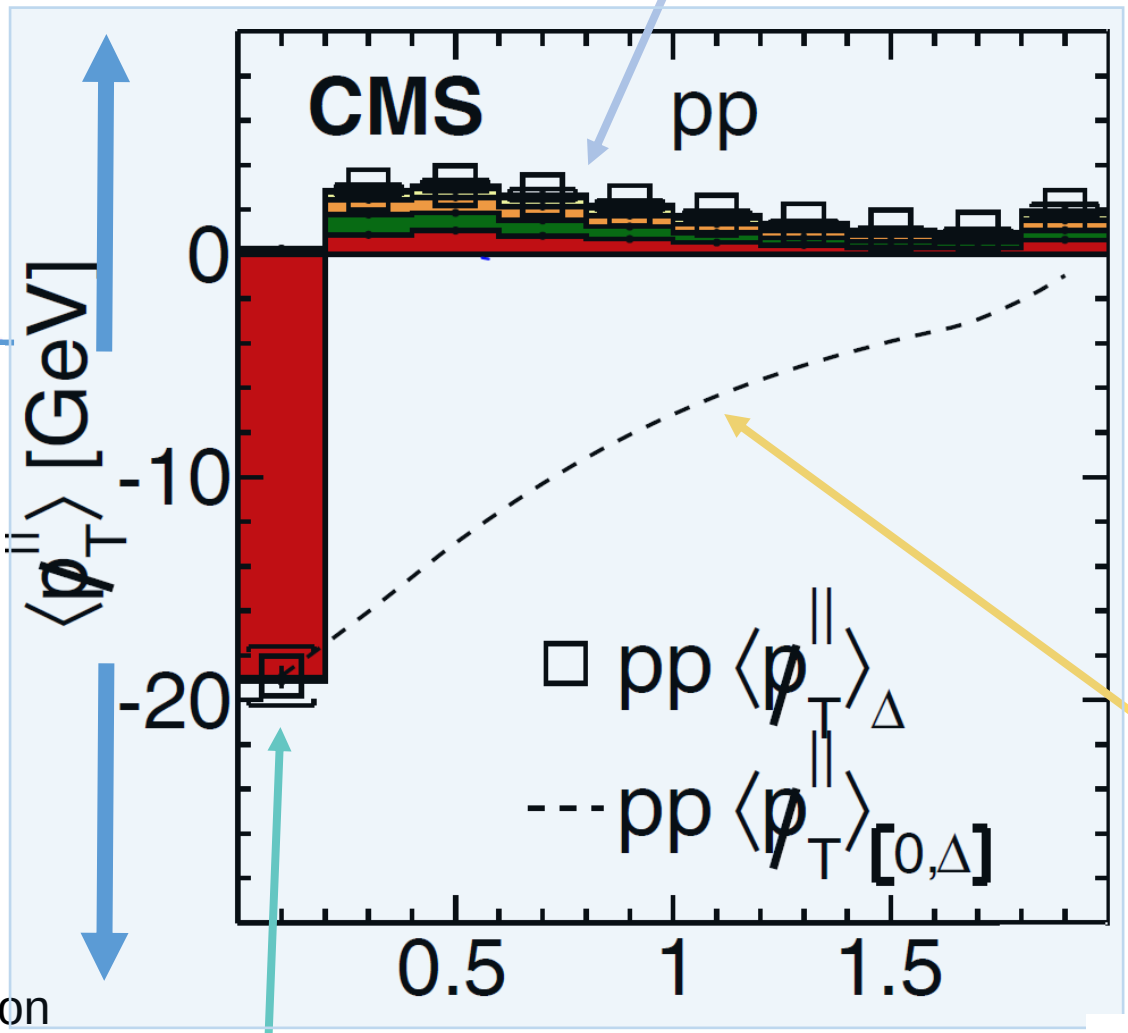
arXiv 1509.09029

Missing $p_T^{||}$ vs. Δ in pp

Subleading jet direction



Contribution from third jet



$p_{T,1}$>120, $p_{T,2}$>50 GeV/c

$|\eta_1|, |\eta_2|$<0.50, $\Delta\phi_{1,2}$>5π/6

anti-k_T Calo R=0.3

$|\eta_{trk}|$<2.4

p_T^{trk} (GeV/c):

0.5 - 1.0 | 2.0 - 4.0

1.0 - 2.0 | 4.0 - 8.0

>0.5 | 8.0 - 300.0

Integrated curve from 0 to Δ

Leading jet direction

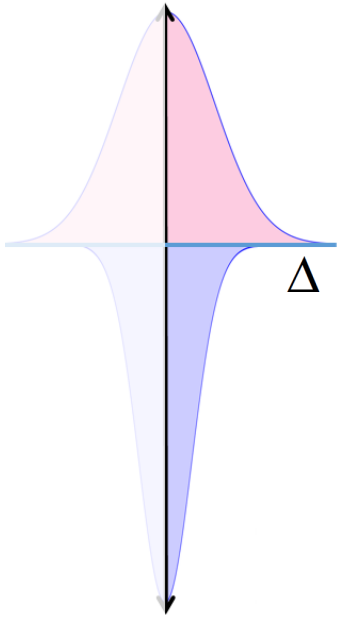
Asymmetry inside the jet cone

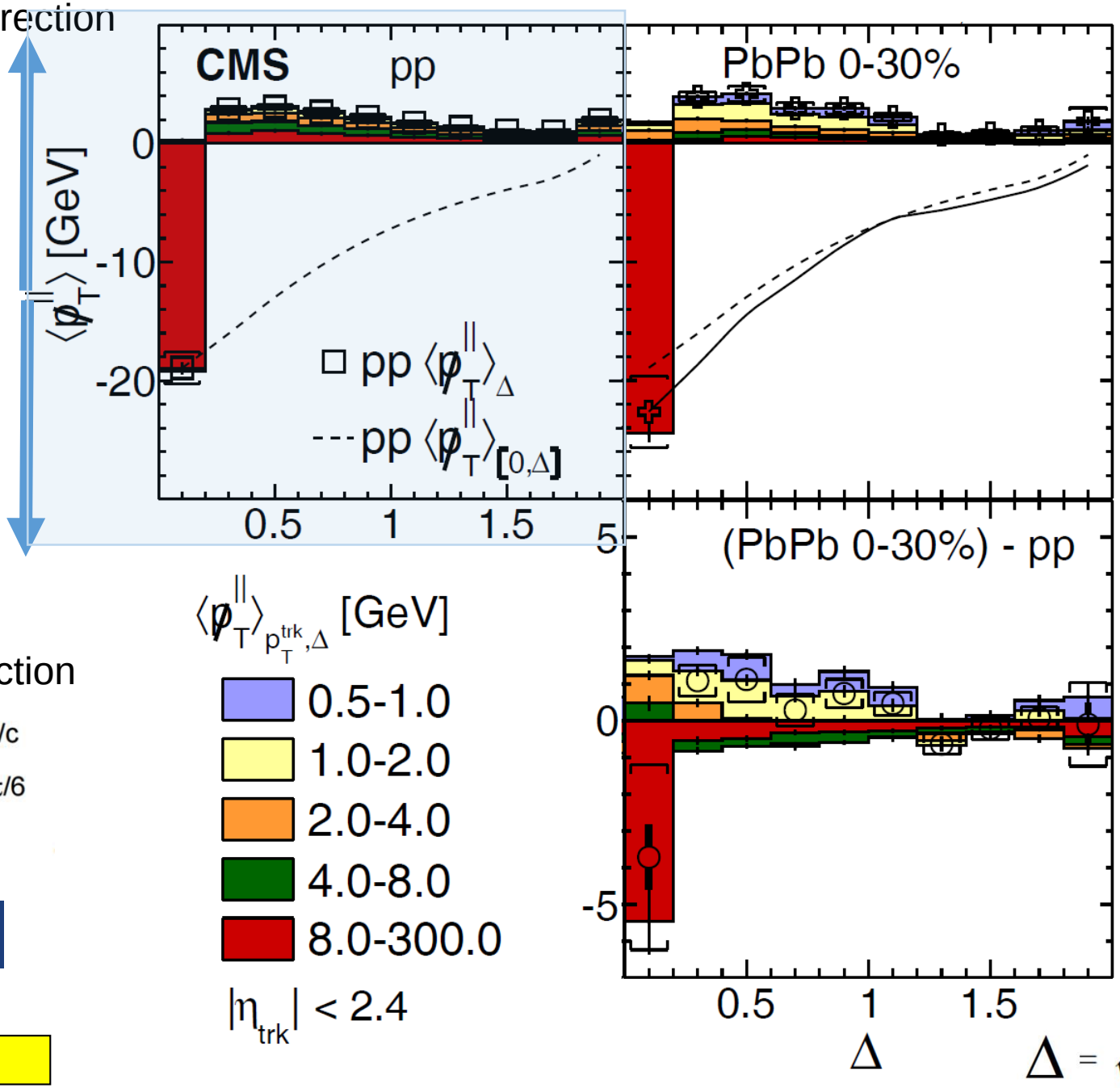
$$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

arXiv 1509.09029

Missing $p_T^{||}$ vs. Δ

Subleading jet direction





Leading jet direction

$p_{T,1}$>120, $p_{T,2}$>50 GeV/c

$|\eta_1|,|\eta_2|$<0.50, $\Delta\phi_{1,2}$>5π/6

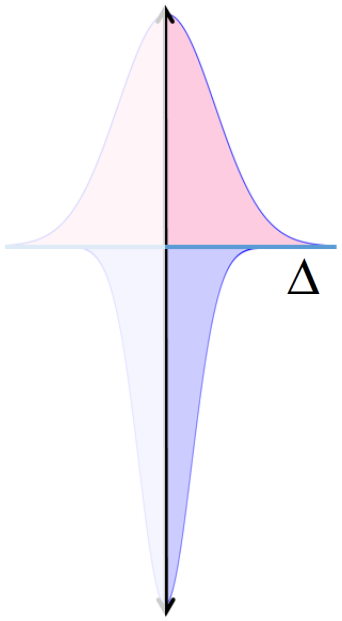
anti-k_T Calo R=0.3

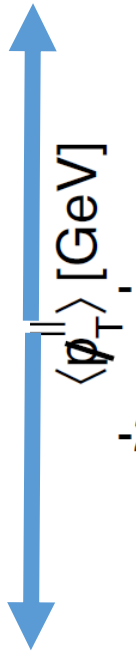
Inclusive A_J

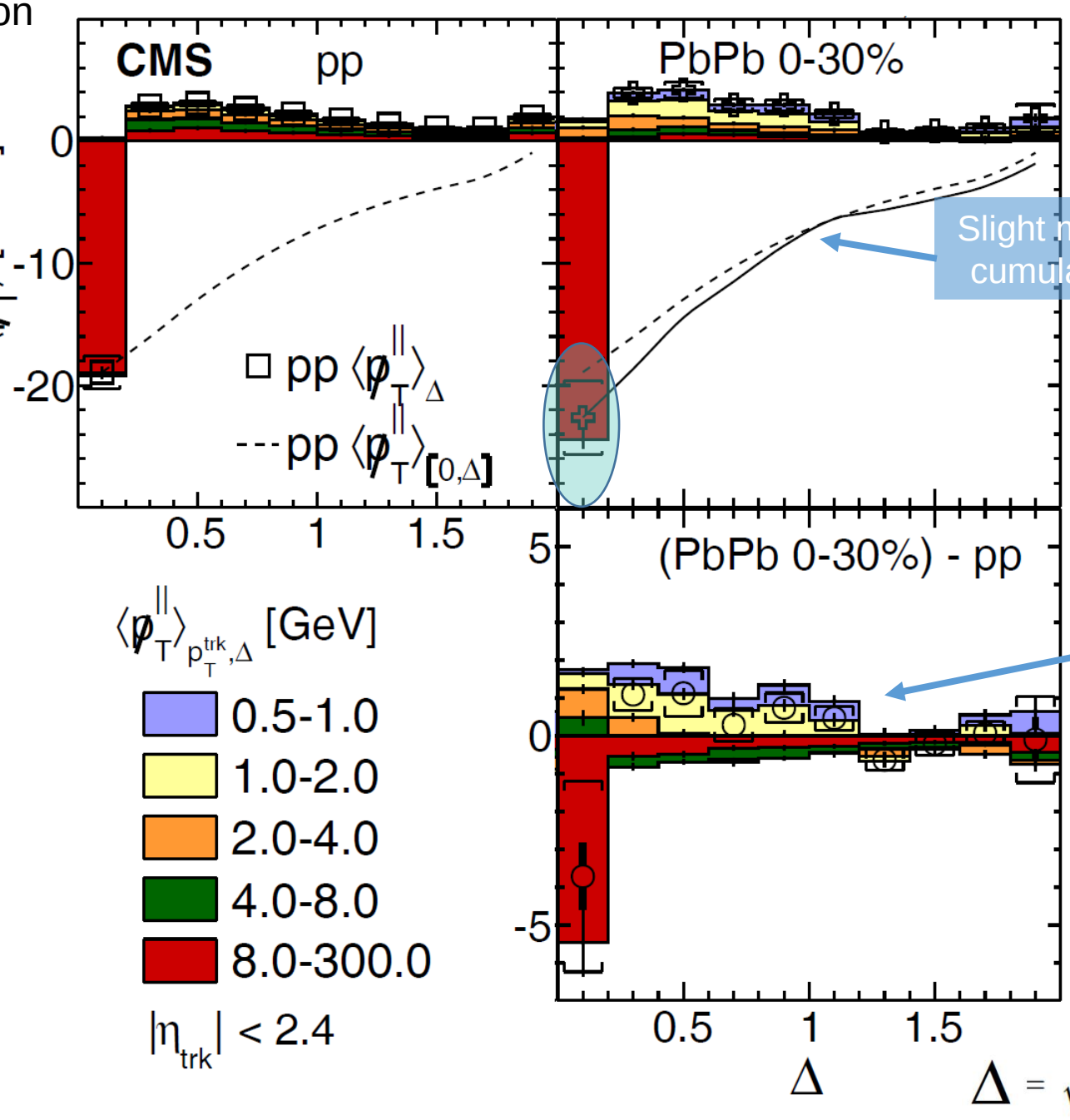
arXiv 1509.09029

Missing $p_T^{||}$ vs. Δ

Subleading jet direction







Slight modification of the cumulative energy flow

Open circles: Integrated over particle p_T

Leading jet direction

$p_{T,1}$>120, $p_{T,2}$>50 GeV/c

$|\eta_1|,|\eta_2|$<0.50, $\Delta\phi_{1,2}$>5π/6

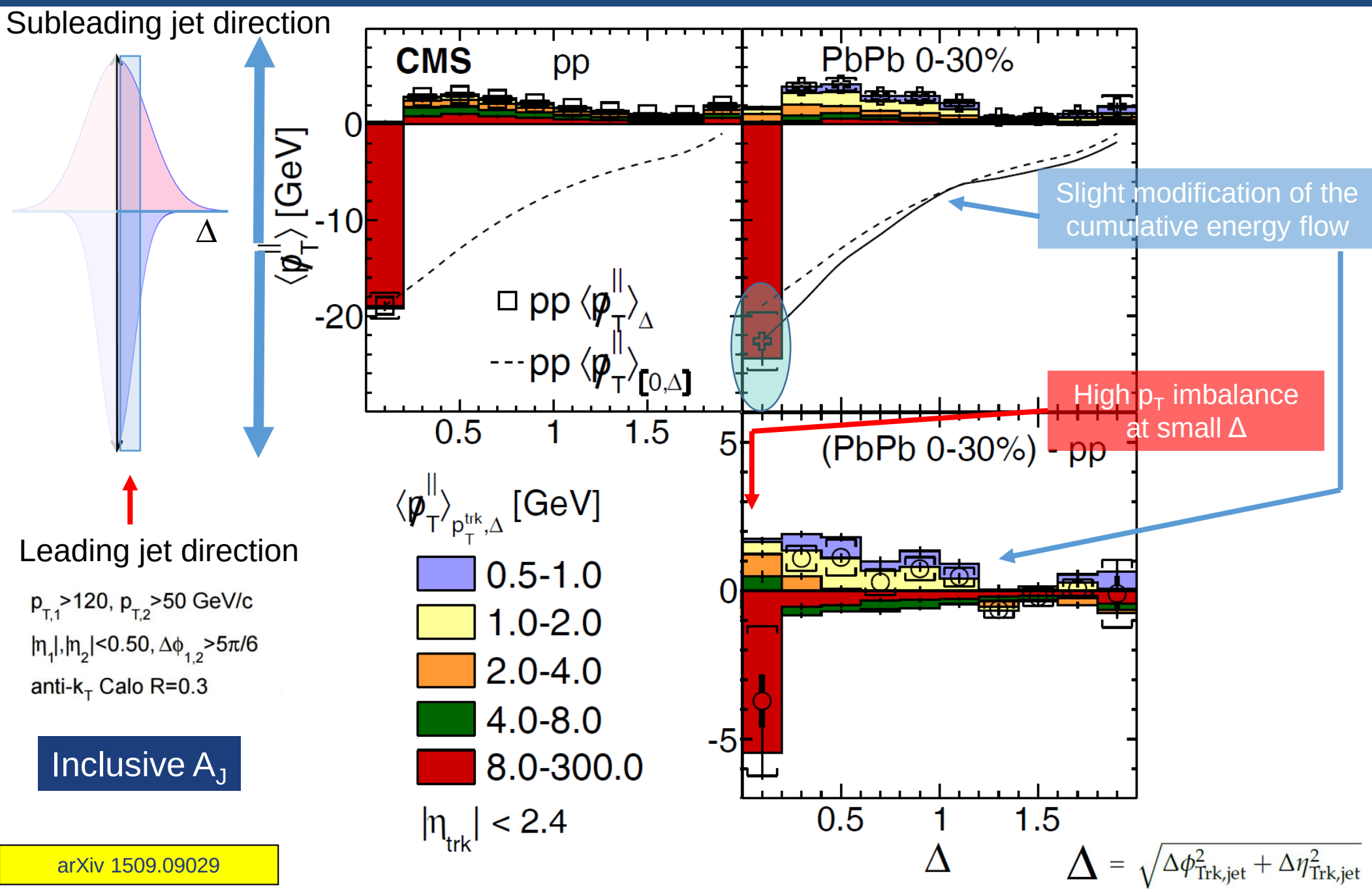
anti-k_T Calo R=0.3

Inclusive A_J

$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$

arXiv 1509.09029

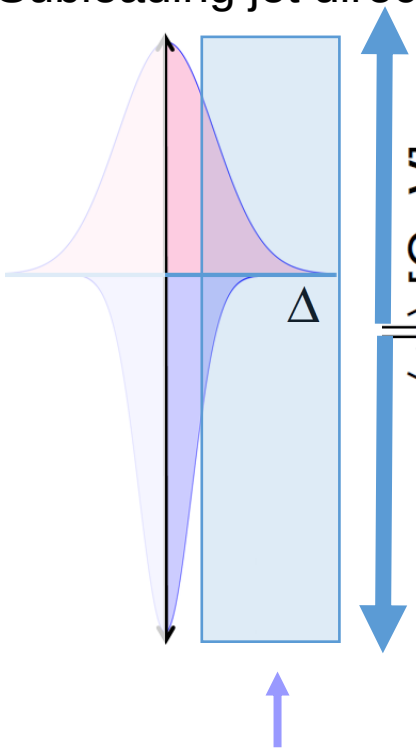
Missing $p_T^{||}$ vs. Δ



arXiv 1509.09029

Missing $p_T^{||}$ vs. Δ

Subleading jet direction



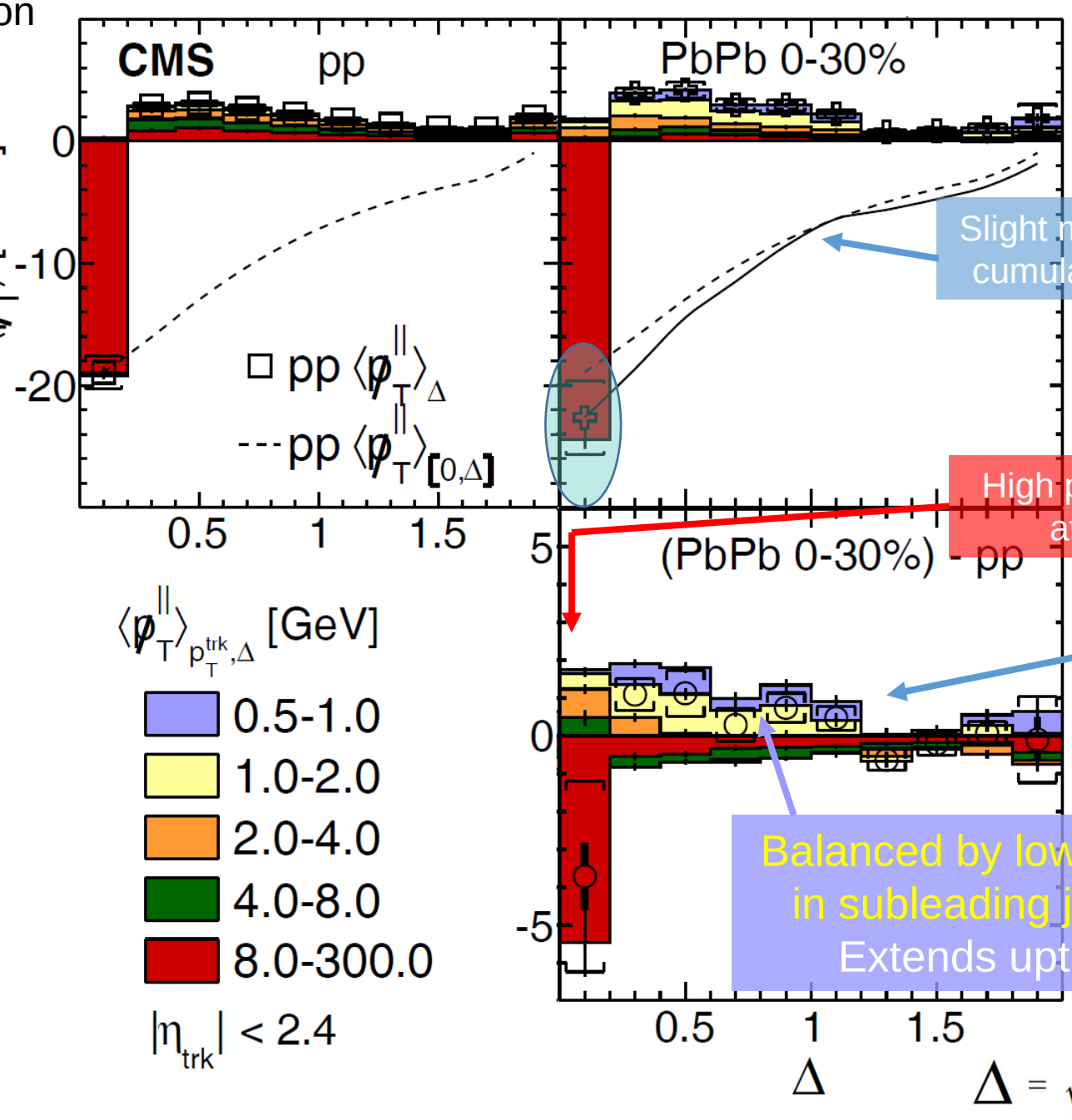
Leading jet direction

$p_{T,1}$>120, $p_{T,2}$>50 GeV/c

$|\eta_1|,|\eta_2|$<0.50, $\Delta\phi_{1,2}$>5π/6

anti-k_T Calo R=0.3

Inclusive A_J



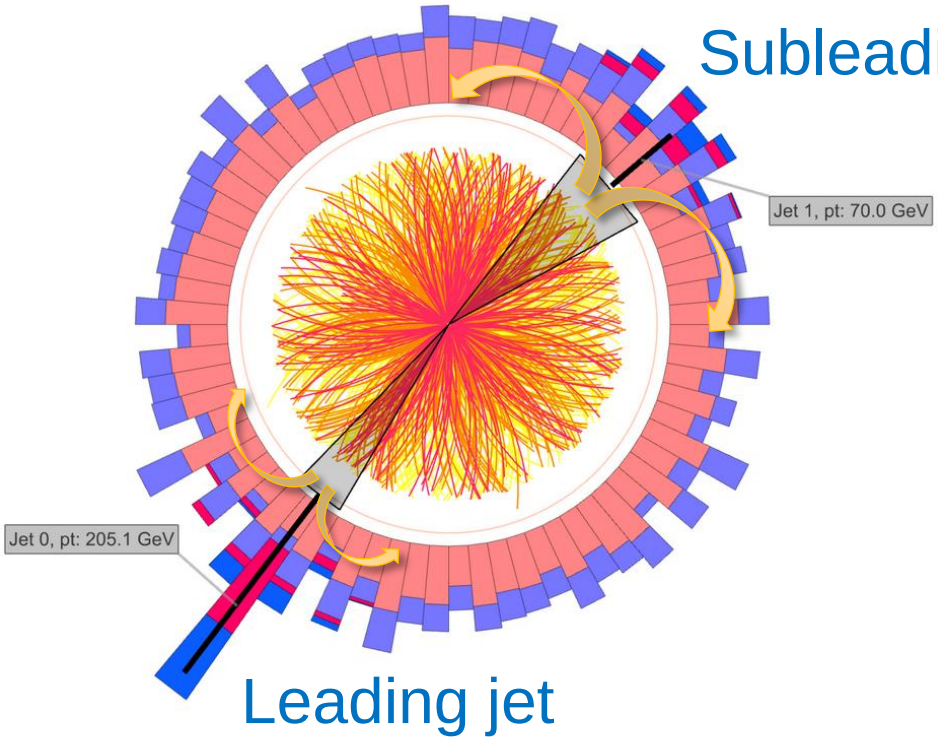
Slight modification of the cumulative energy flow

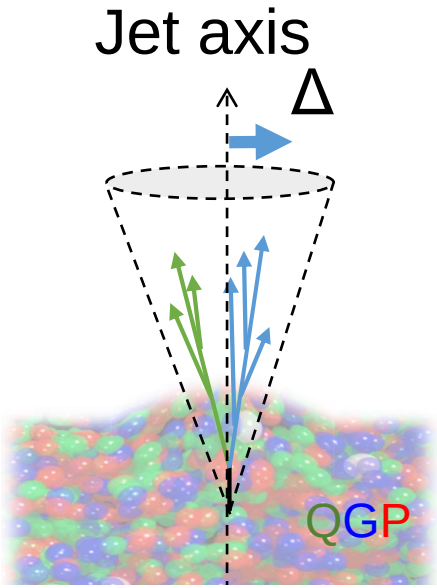
High p_T imbalance at small Δ

Balanced by low p_T particles in subleading jet direction Extends upto large Δ

arXiv 1509.09029

Where does the Quenched Energy Go?

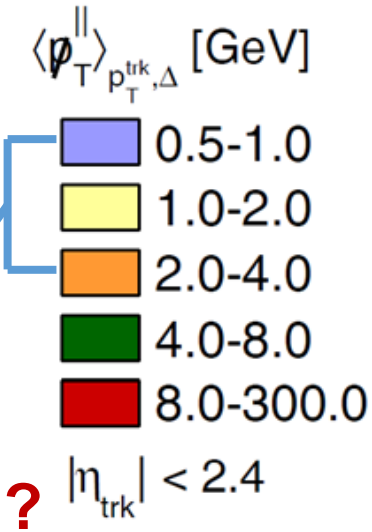


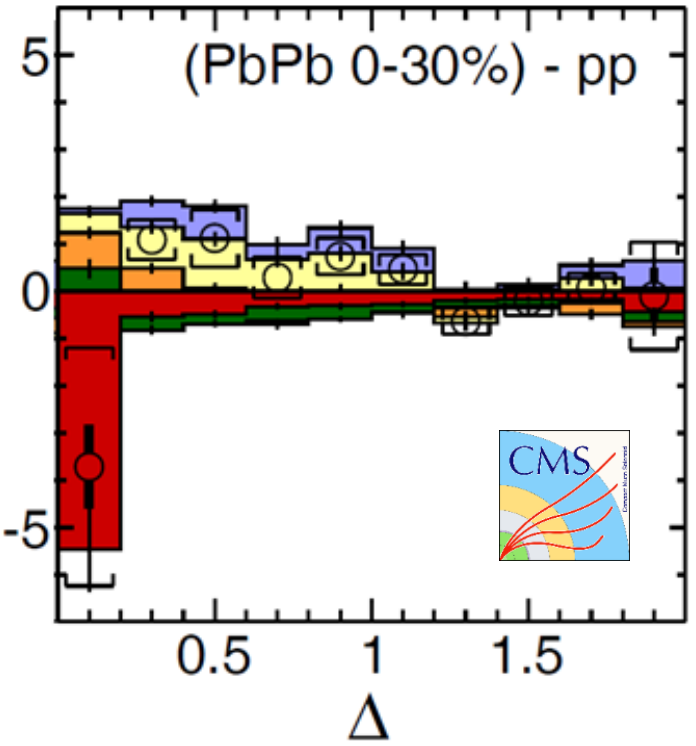


JHEP 01 (2016) 006

- Quenched energy carried by **low momentum particles!**
- Average momentum of those particles are **higher** than that from medium debris

→ **Not Completely Thermalized?**

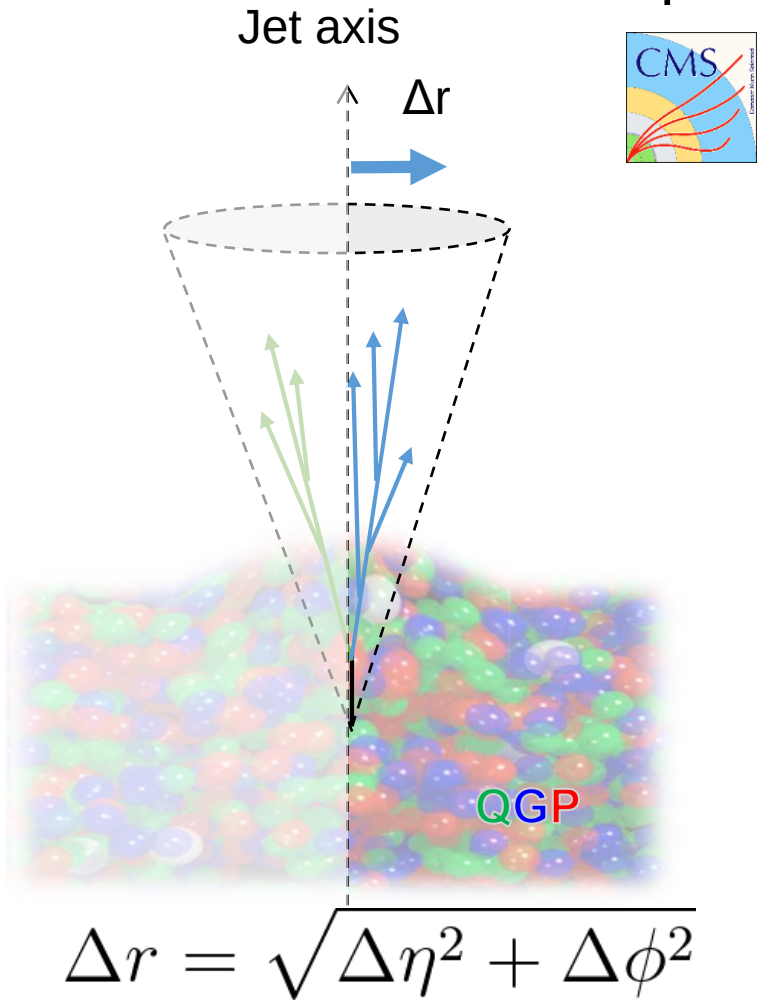


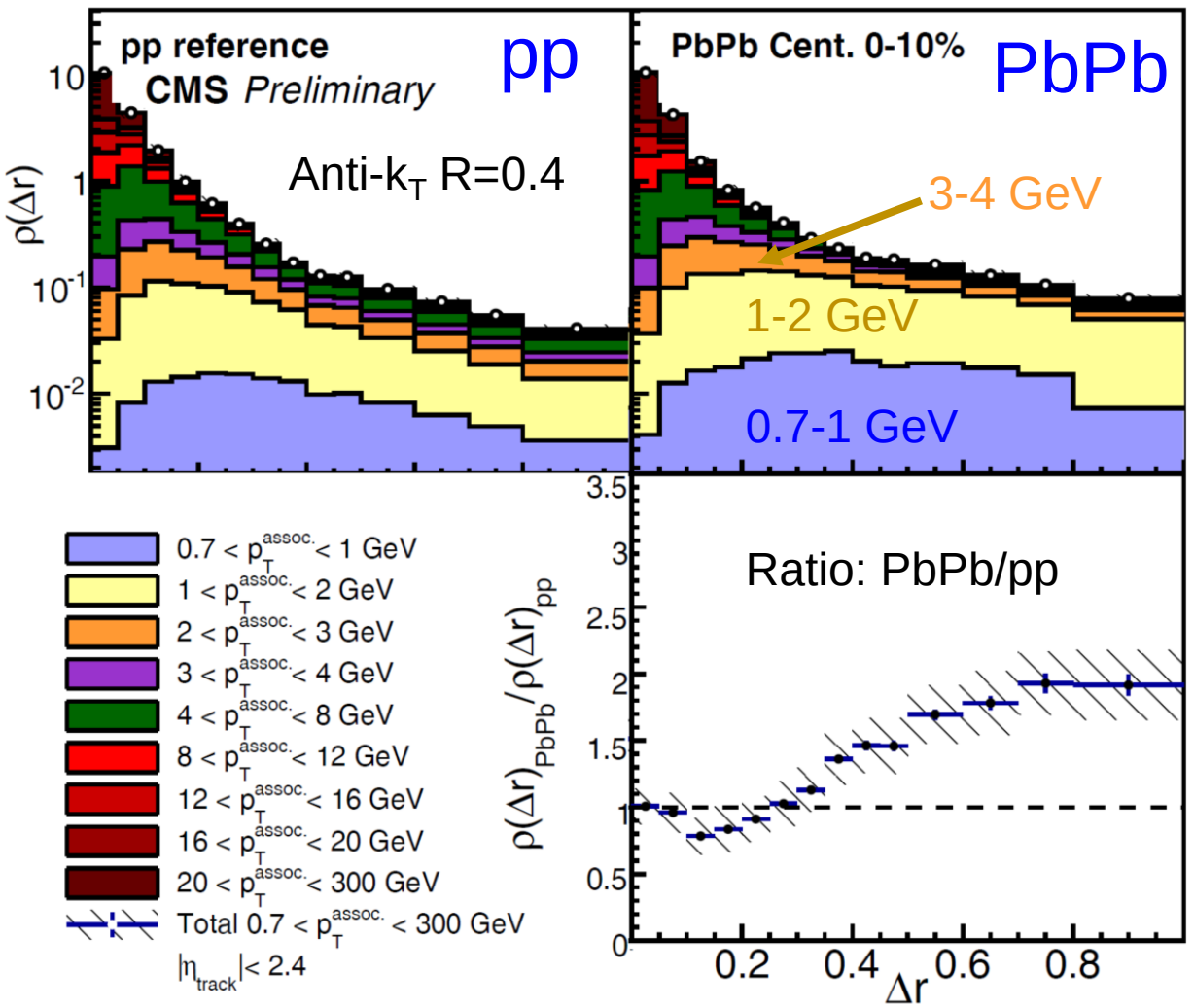


For instance the discussion in JHEP 1703 (2017) 135 from J. Casalderrey-Solana *et al.*

Jet Transverse Structure

Jet shapes in pp and PbPb at 5.02 TeV

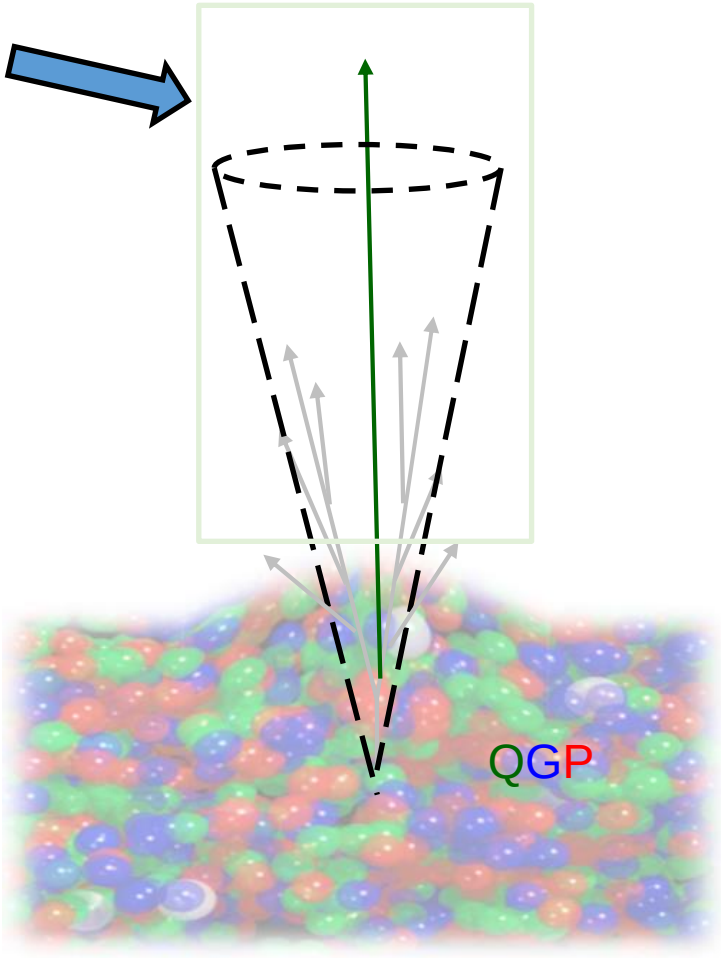




CMS-PAS-HIN-16-020

- Jet shapes and fragmentation functions in pp and PbPb collisions at 5 TeV
- Sensitive to the possible **medium response** to hard probes and **induced radiation**

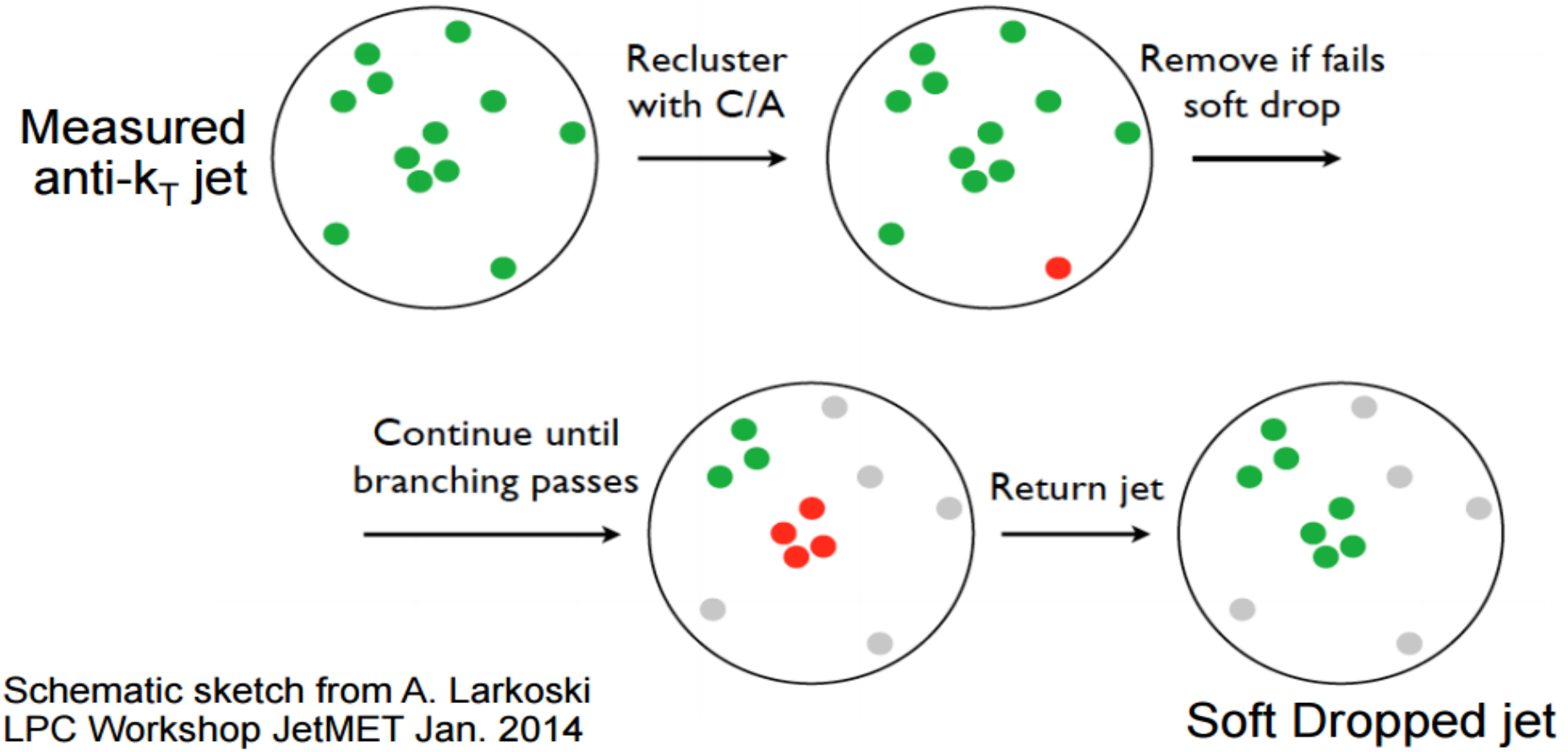
Focus on the hardest substructure



Does the magnitude of quenching depend on the structure of parton shower?
One could **remove the soft radiation** (isolate the hard jet core)

Groomed Jets

Jet grooming removes soft divergences and uncorrelated background
Common technique in HEP
This analysis is the first one using jet grooming in heavy ion collisions



Schematic sketch from A. Larkoski
LPC Workshop JetMET Jan. 2014

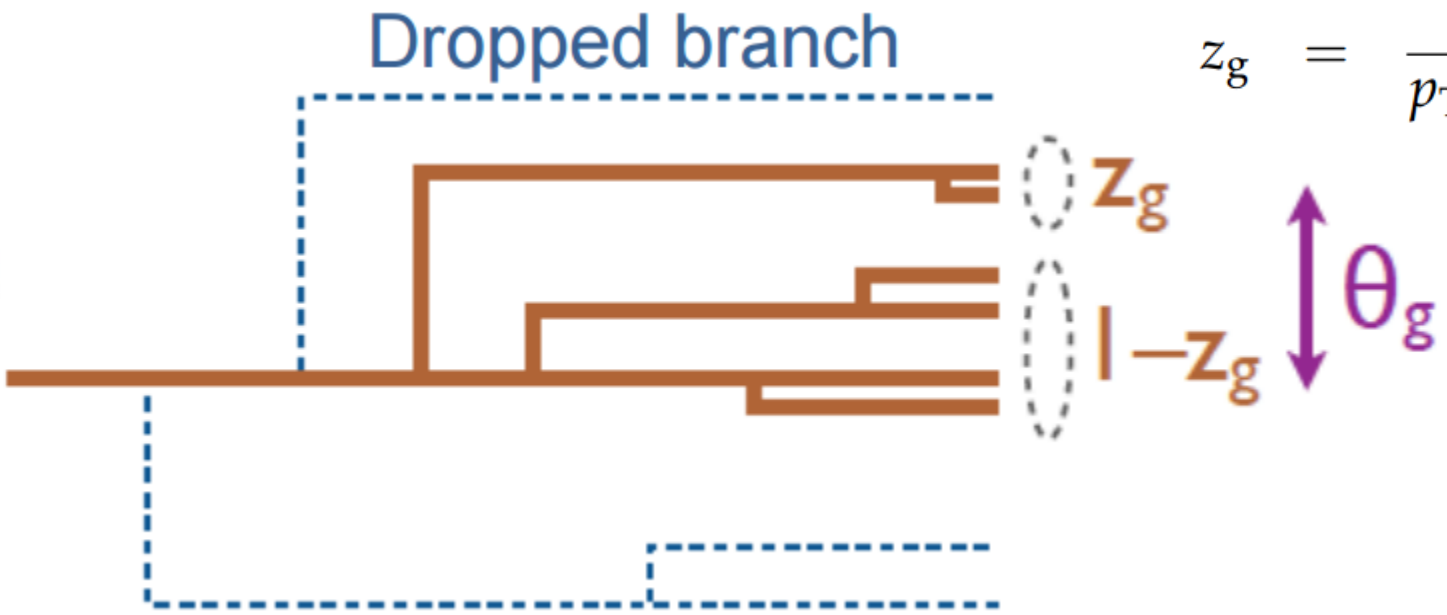
Soft drop condition in this analysis

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > 0.1$$

Andrew Larkoski, Jesse Thaler (CTP)
JHEP 1405 (2014) 1465

Jet grooming with Soft Drop

Anti-k_T jet is re-clustered with Cambridge/Aachen (CA)
Then decluster the angular-ordered CA tree
Drop soft branches



$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$

To minimize the smearing effect from PbPb underlying event, $\Delta R_{12} > 0.1$ is applied

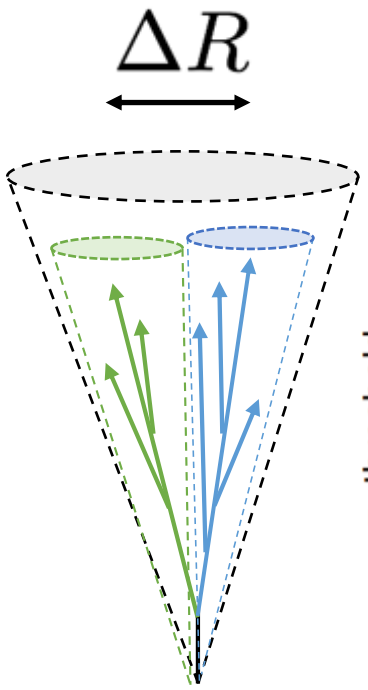
Measurement of **momentum sharing** between leading and subleading subjets

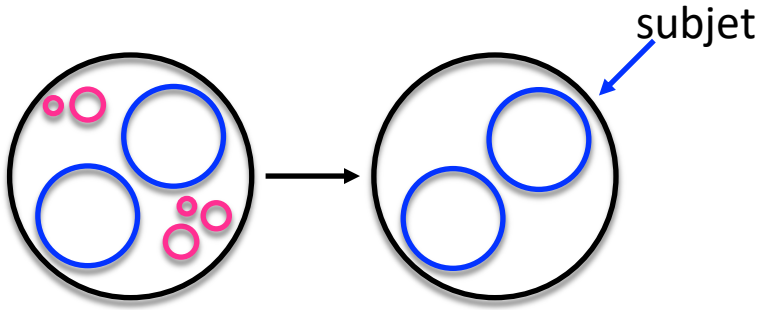
Andrew Larkoski, Jesse Thaler (CTP)
JHEP 1405 (2014) 1465

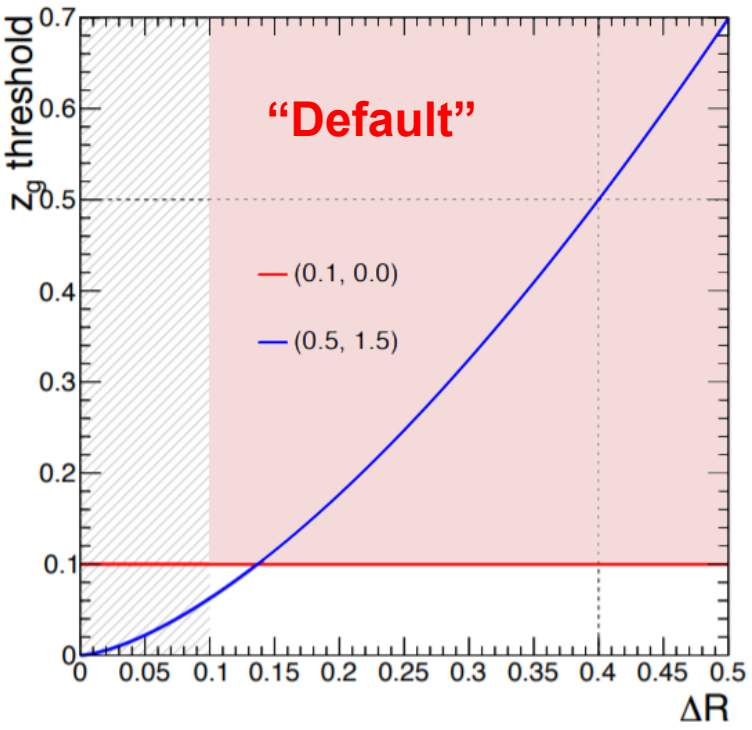
Groomed Jet Substructure with Soft Drop

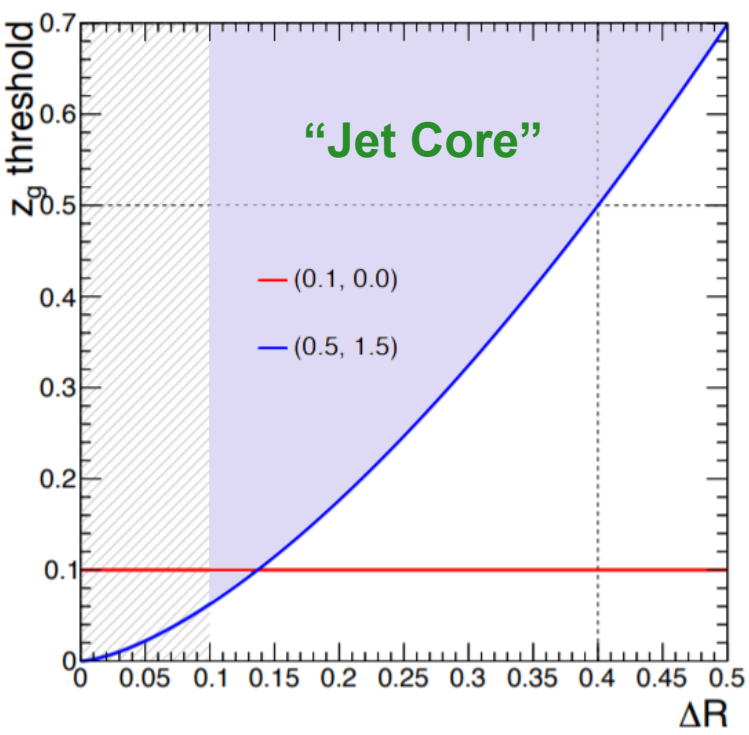
- CMS: used two grooming settings with ΔR>0.1 cut

$$z_g \equiv \frac{\min(p_1, p_2)}{p_1 + p_2} > z_{\text{cut}} \left(\frac{\Delta R}{R_0} \right)^{\beta}$$



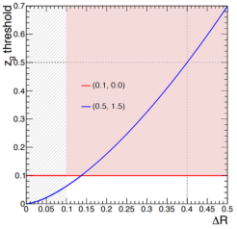




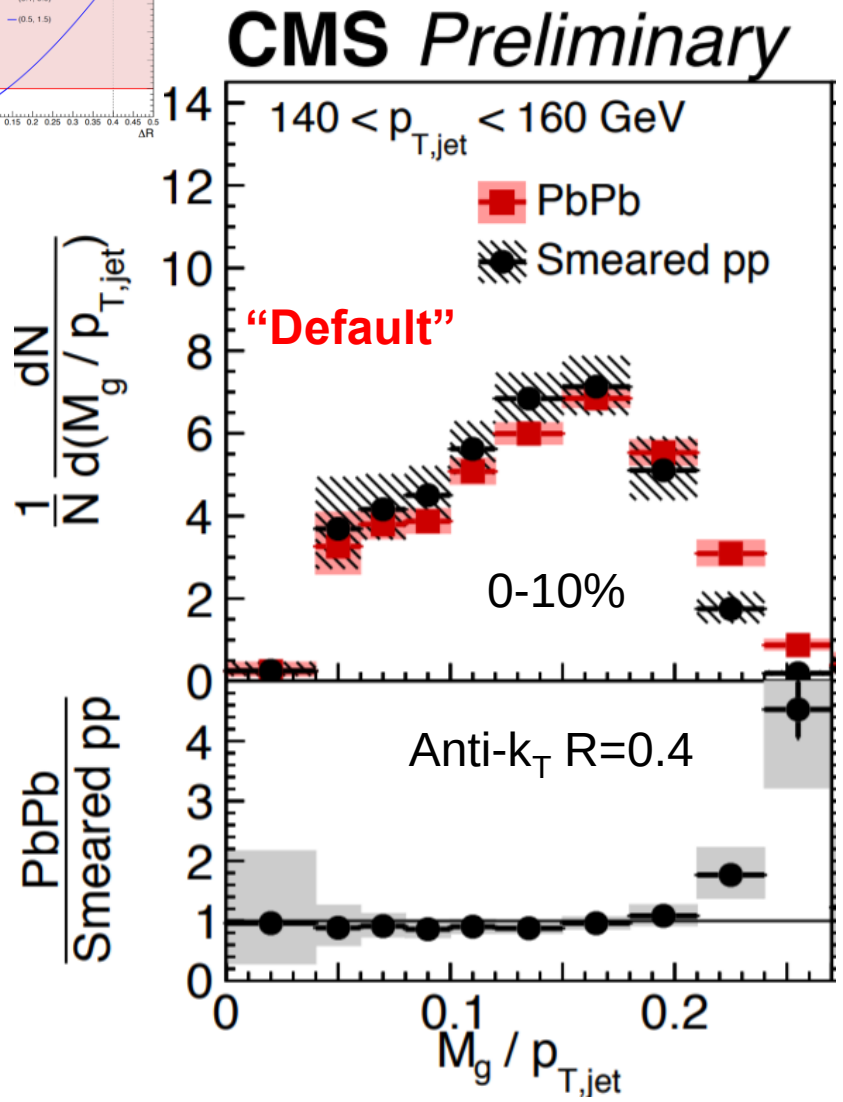


From Yi Chen

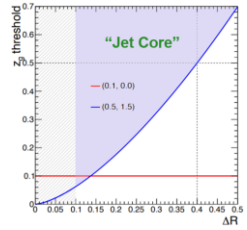
Groomed Jet Mass

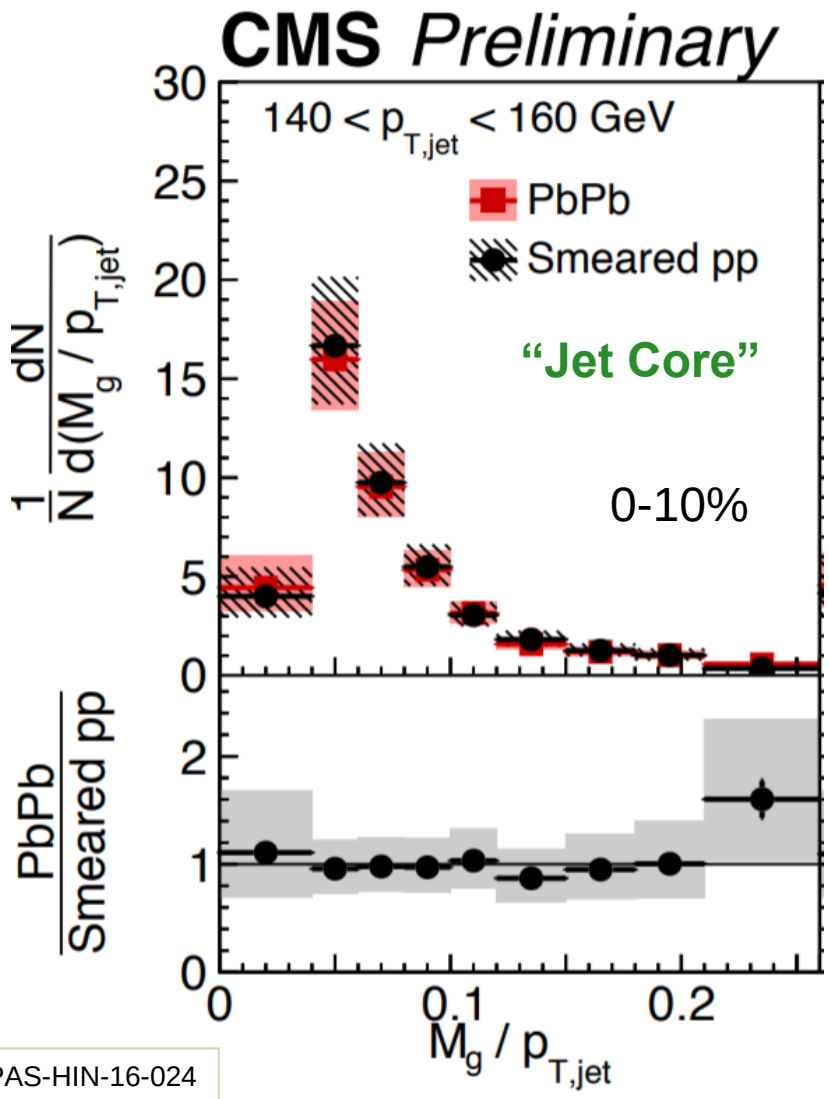


$(z_{cut},\beta) = (0.1,0.0)$ $\Delta R>0.1$



$(z_{cut},\beta) = (0.5,1.5)$ $\Delta R>0.1$

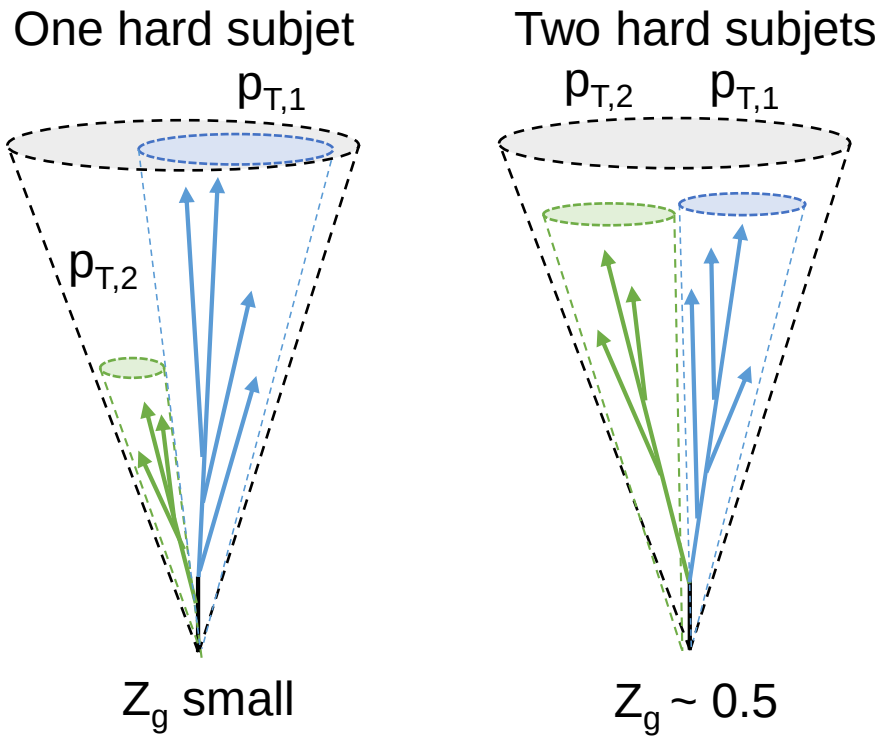




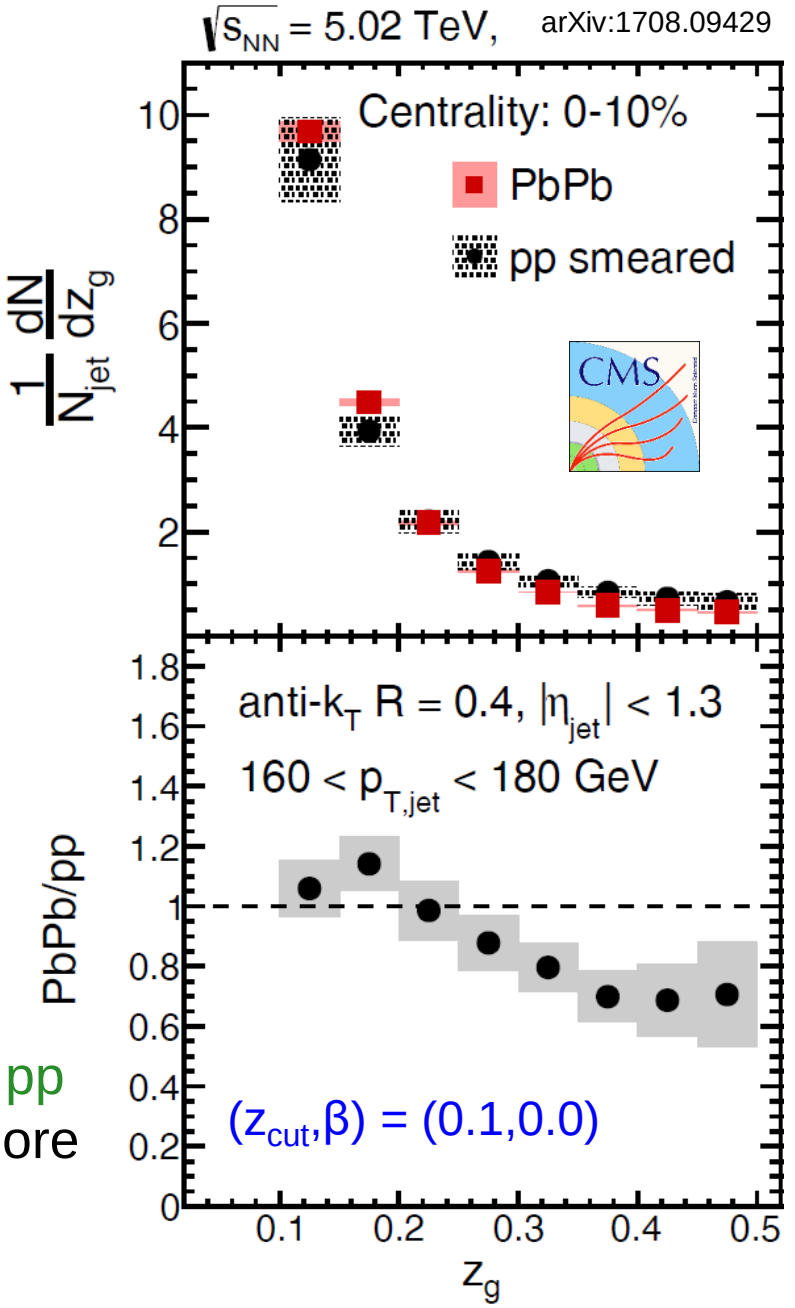
CMS-PAS-HIN-16-024

- Enhancement of large mass when looking at a less aggressive grooming setting
- Results with a "more aggressive grooming"
- No significant modification of the "jet core"

Momentum Sharing of Subjets



$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

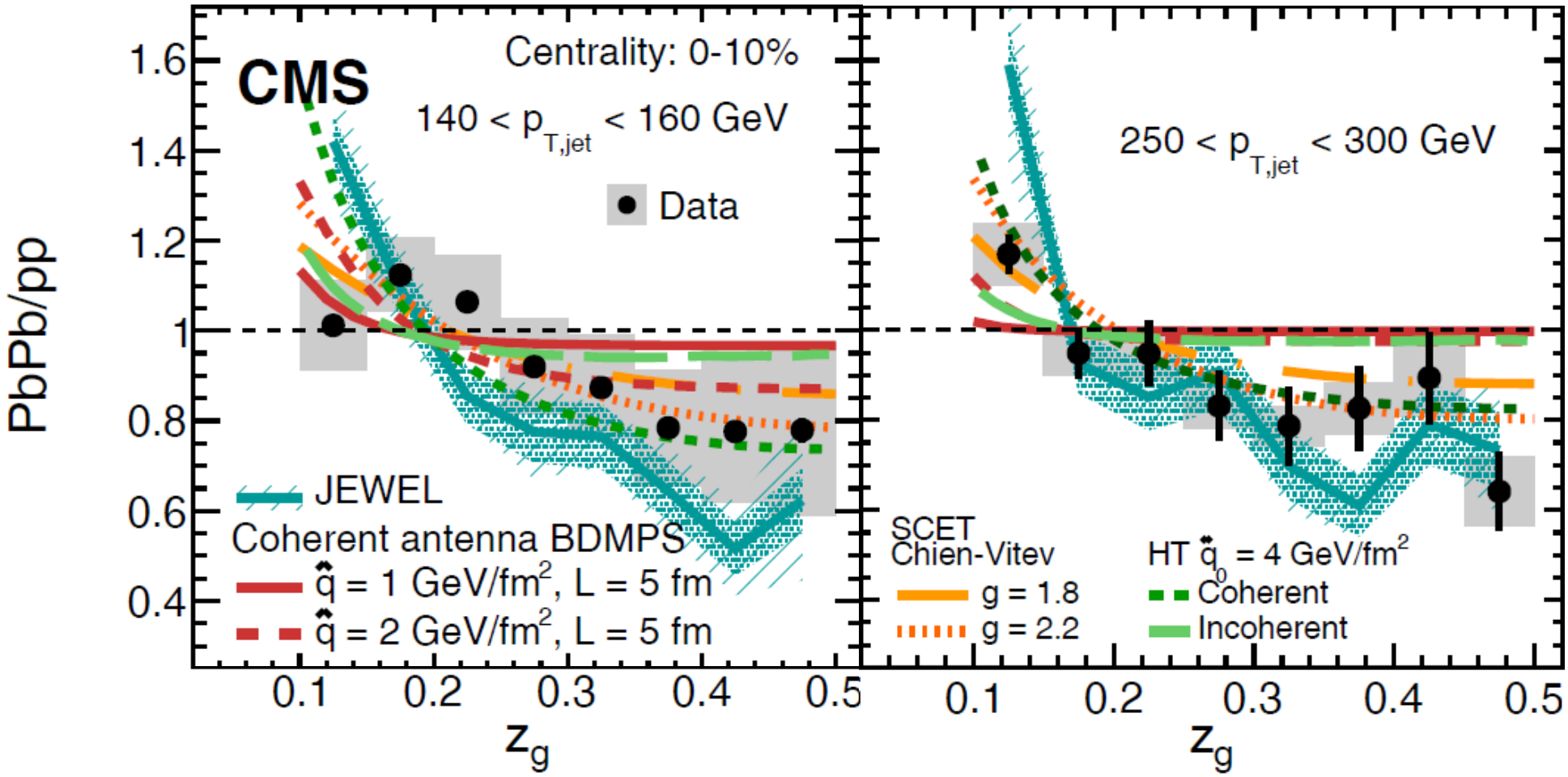


- Quark and gluon Z_g distributions are very similar in pp
- Jets with two hard subjets (large Z_g) **"relatively"** more suppressed than jets with a single core (small Z_g)

(Or small Z_g is enhanced)

CMS Groomed Jet Splitting Function

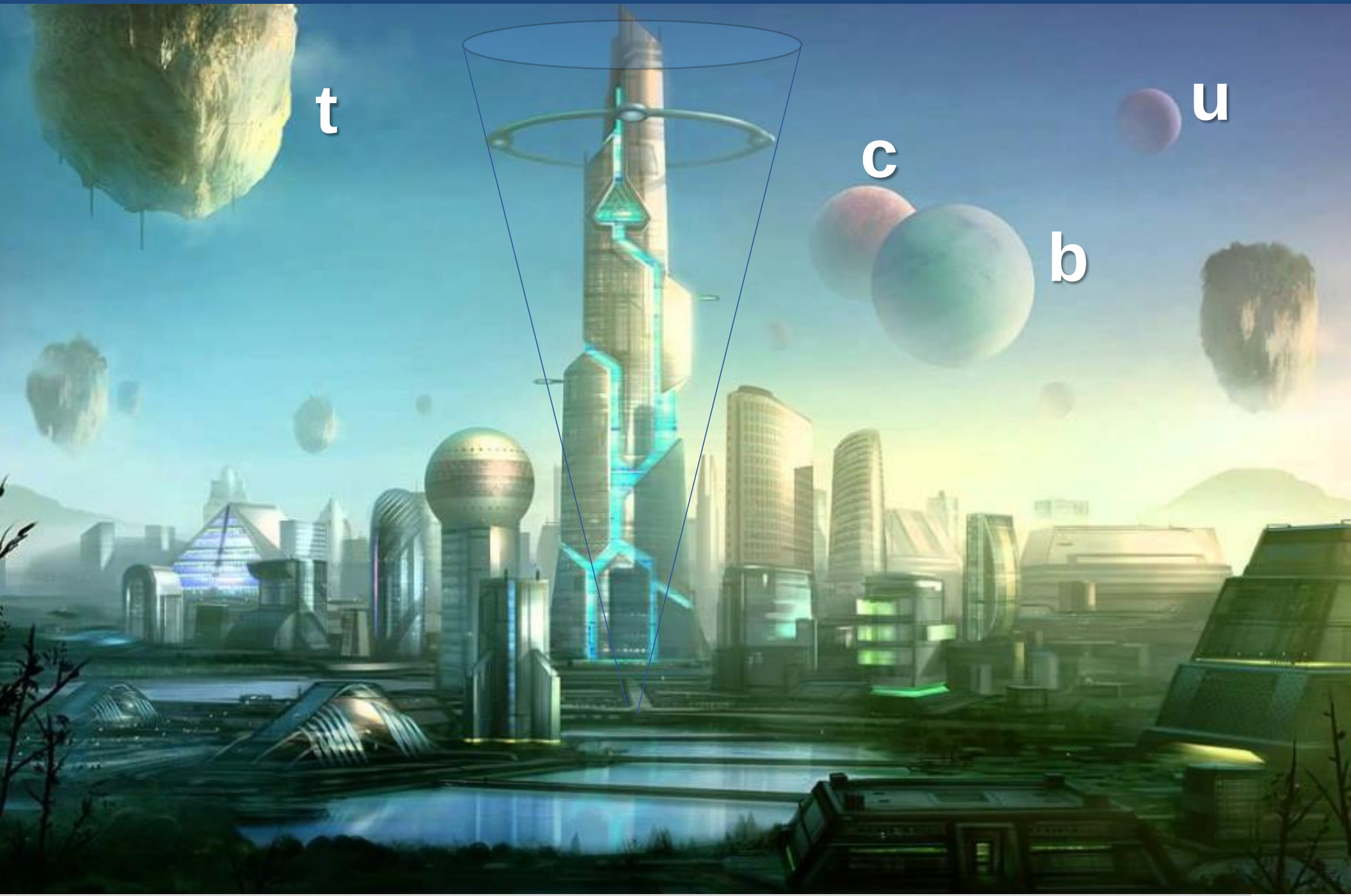
arXiv:1708.09429



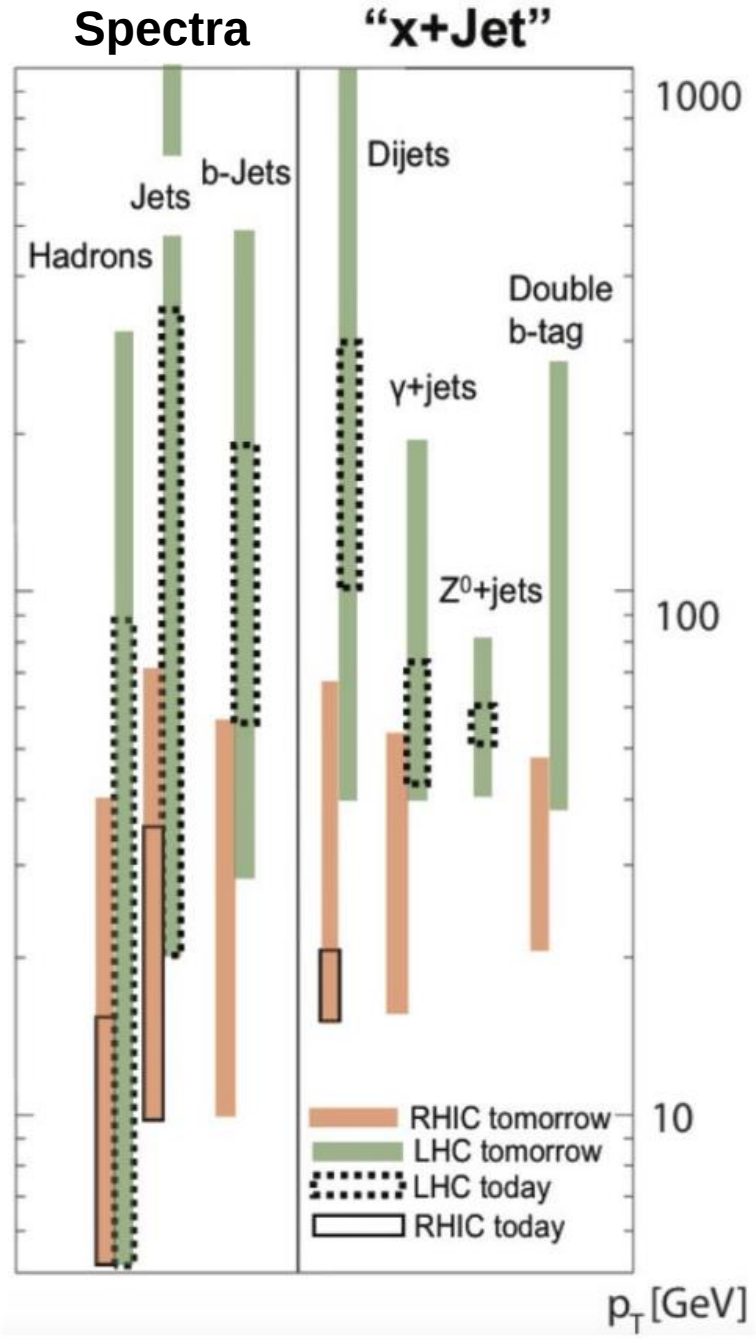
- **JEWEL**: enhancement of low Z_g jets (due to **medium recoil**)
- **SCET$_G$**: modification due to medium induced splitting function
- **HT** & Coherent antenna BDMPS: Data prefer coherent energy loss
- **Measurement of r_g and groomed R_{AA} would help to separate models**

Lecture 5
Future direction and open questions

Outlook

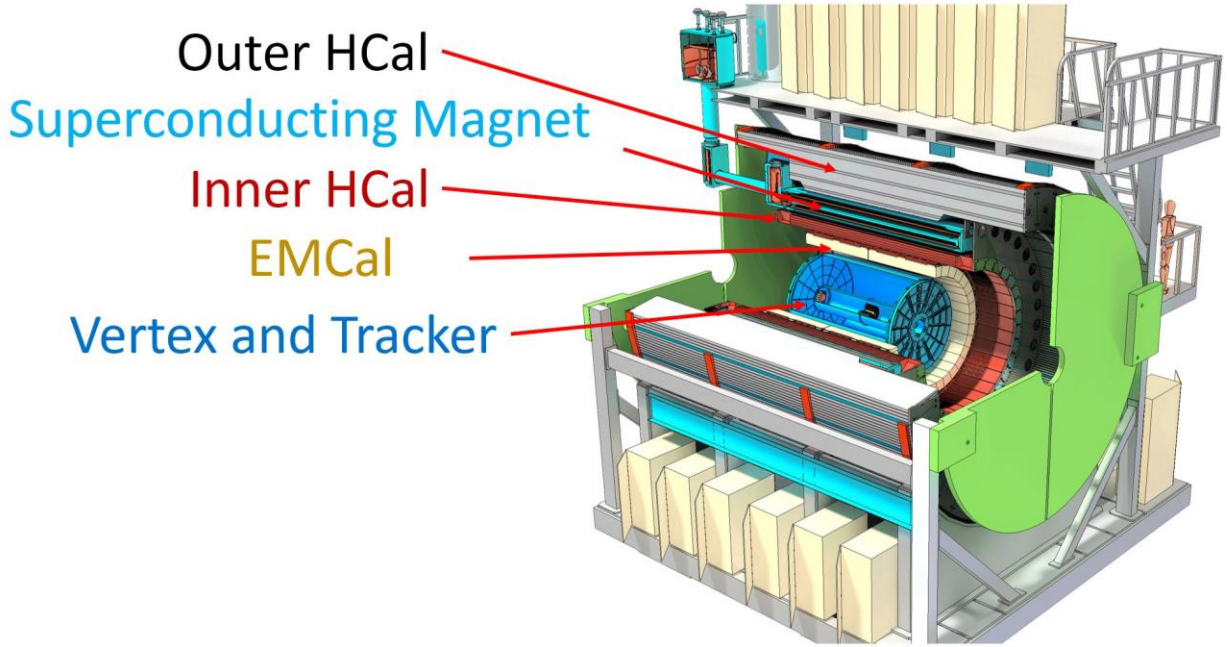


sPHENIX Physics at RHIC



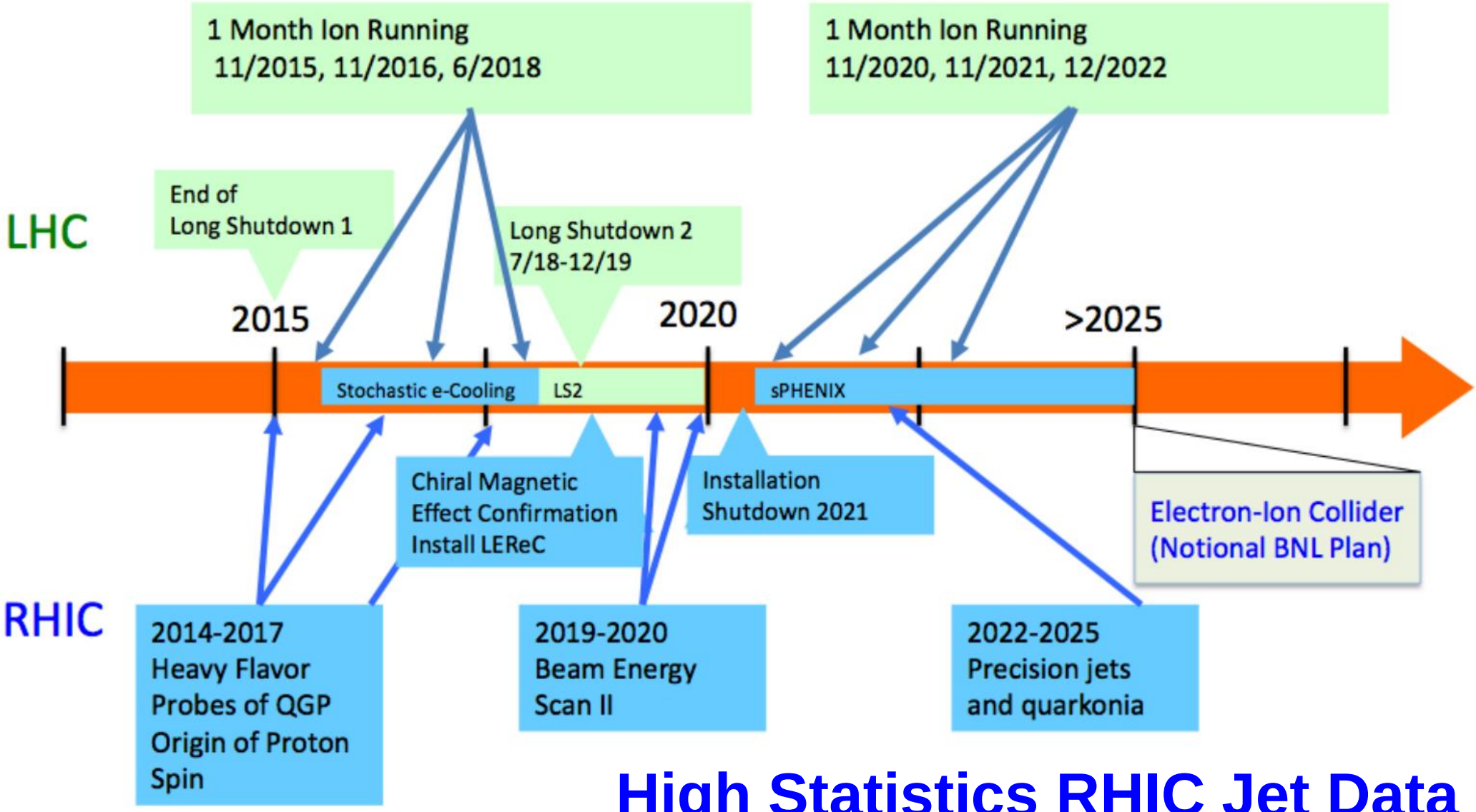
- Jetting through lower temperature Quark Soup from Gold+Gold collisions at 200 GeV
- Direct comparison with CMS data!

sPHENIX detector



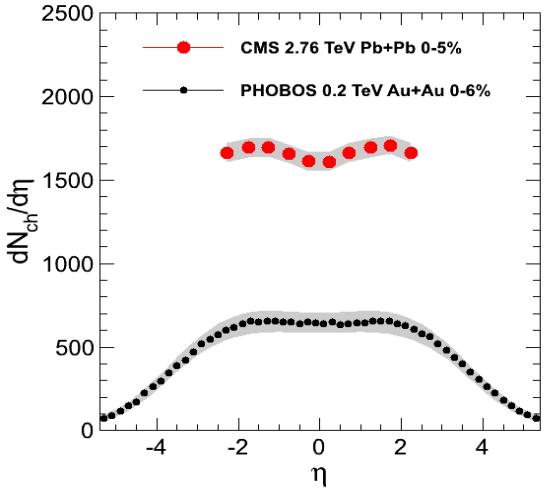
RHIC / LHC Timeline

High Statistics LHC Jet Data

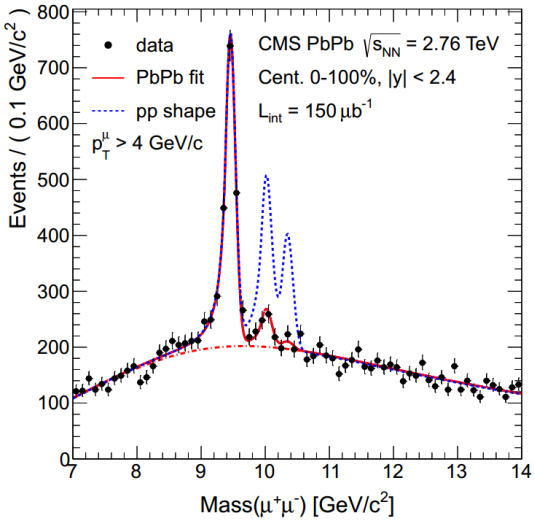


High Statistics RHIC Jet Data

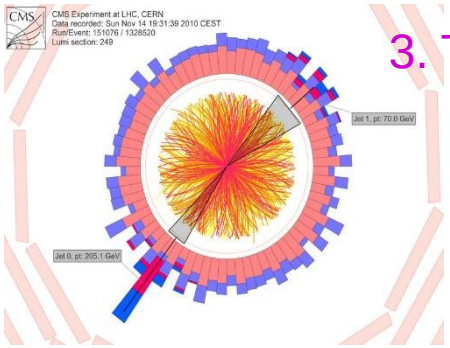
Summary: Quark Gluon Plasma at the LHC



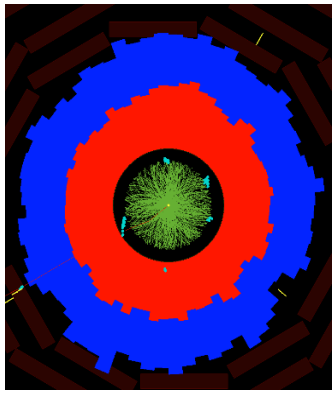
1. >10x denser than the proton or nuclei



2. 1 Trillion Degree!!!
= 1 million million
(1,000,000,000,000 ^oC)

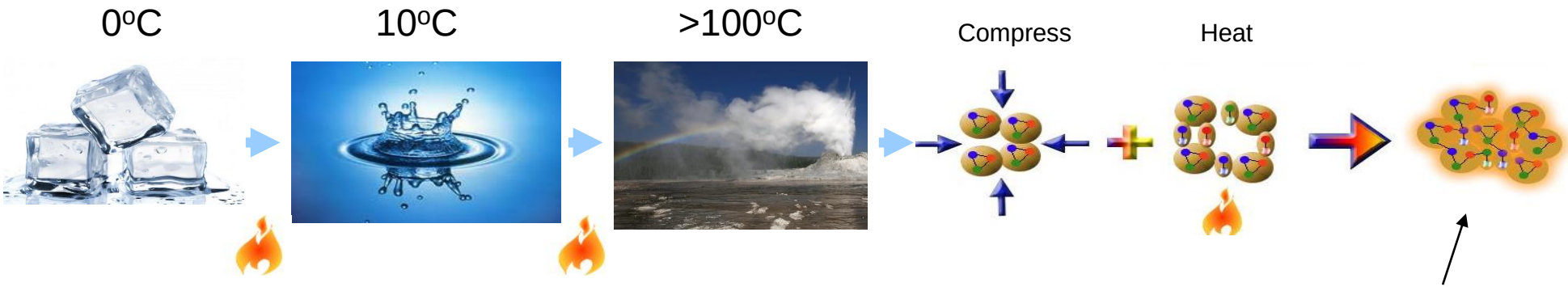


3. The stopping power is very strong O(10GeV/fm)



4. It flows like perfect fluid!

Signal in pPb collisions?



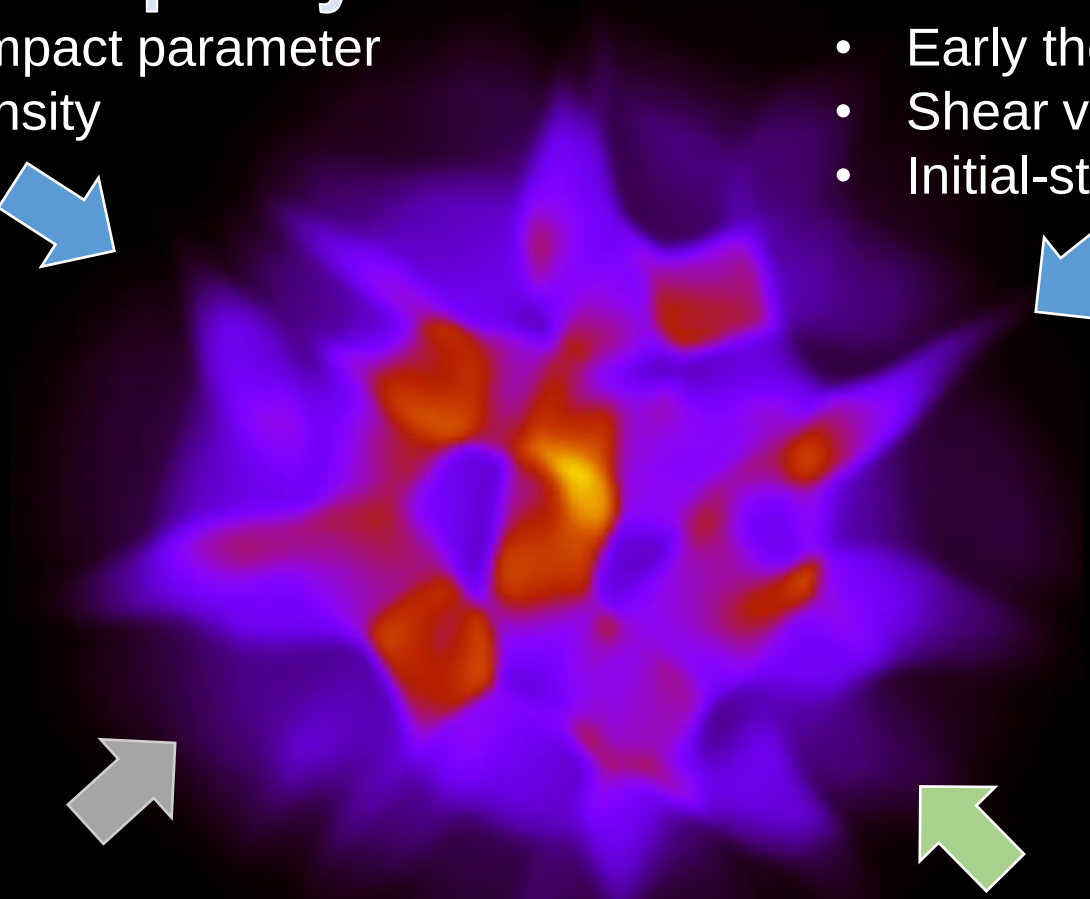
Jetting through the Quark Soup

Particle Multiplicity

- Collision impact parameter
- Energy density

Azimuthal Anisotropy

- Early thermalization <1 fm/c
- Shear viscosity
- Initial-state geometry fluctuation



Colorless Probes

- Initial state tagging
- Parton distributions
- Number of hard scatterings

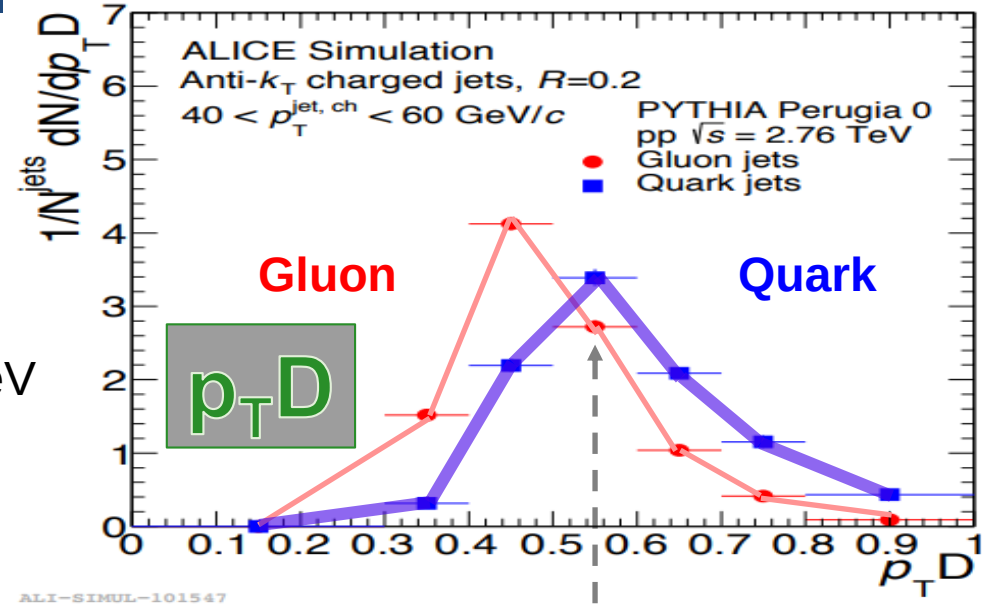
Jet Substructure and Hadrons

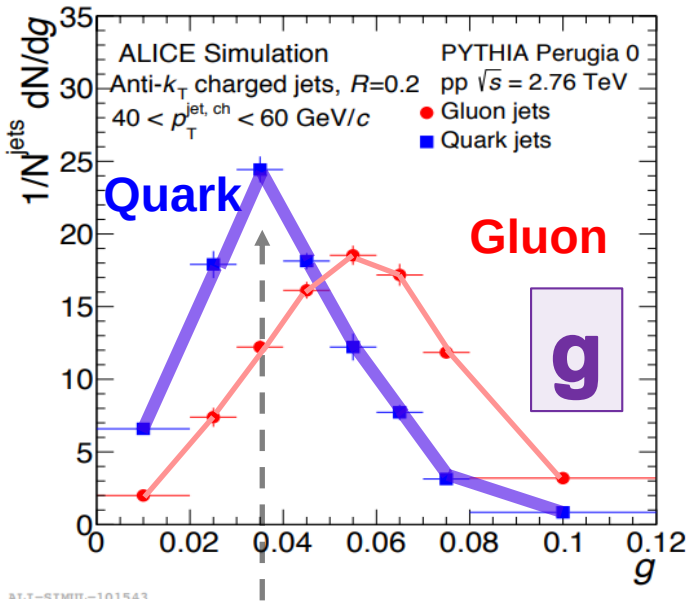
- Jet medium interaction
- Medium gluon density, structure
- Medium scattering power
- Temperature

Backup slides

Charged Jet $p_T D$ (Dispersion) and Jet Girth

Anti-k_T R=0.2
$40<p_T<60$ GeV

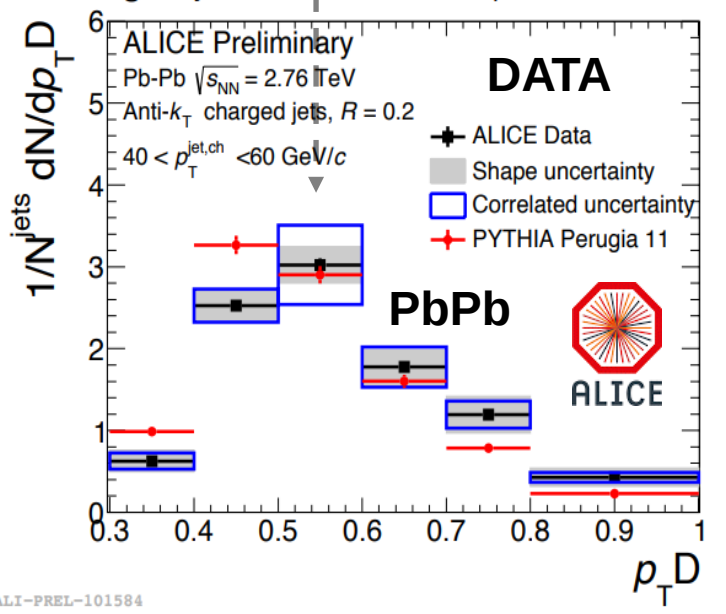


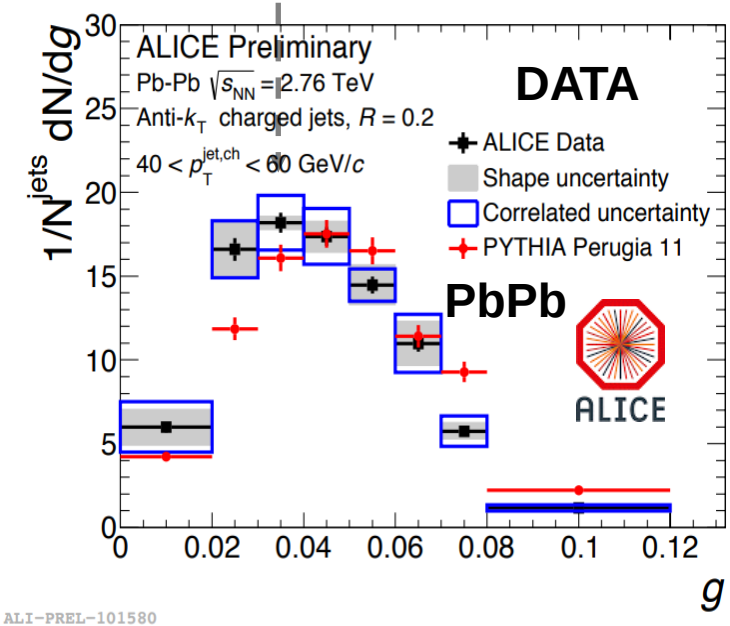


Charged jets, R = 0.2, $40 < p_T < 60$ GeV/c

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

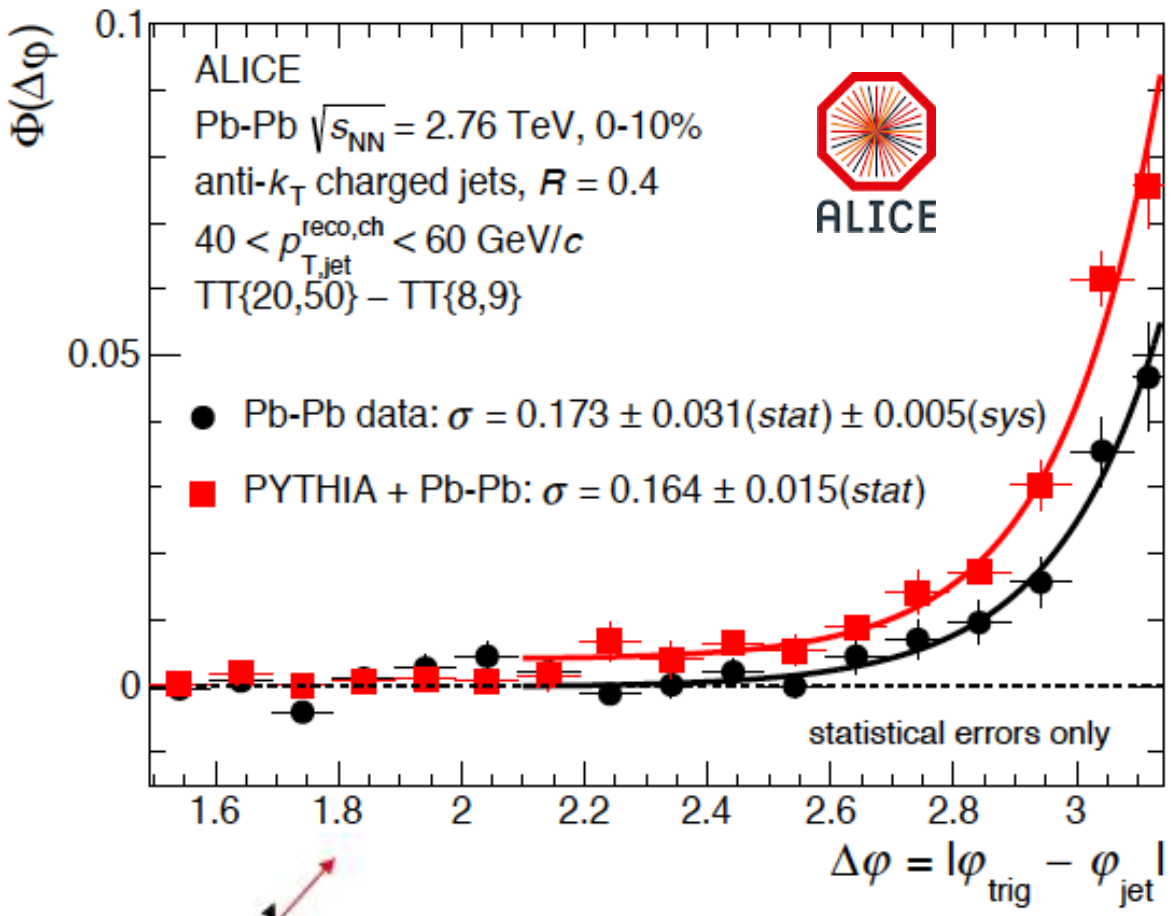
$$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{\text{jet}}} |r_i|$$

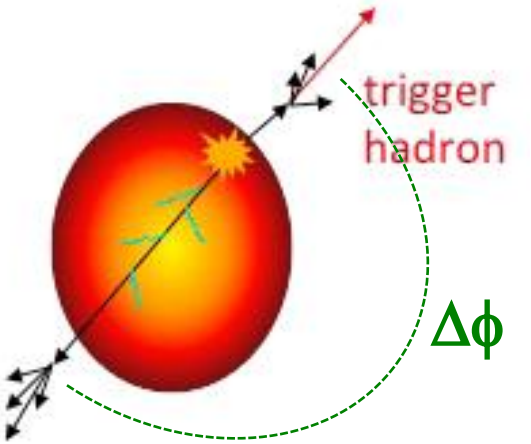


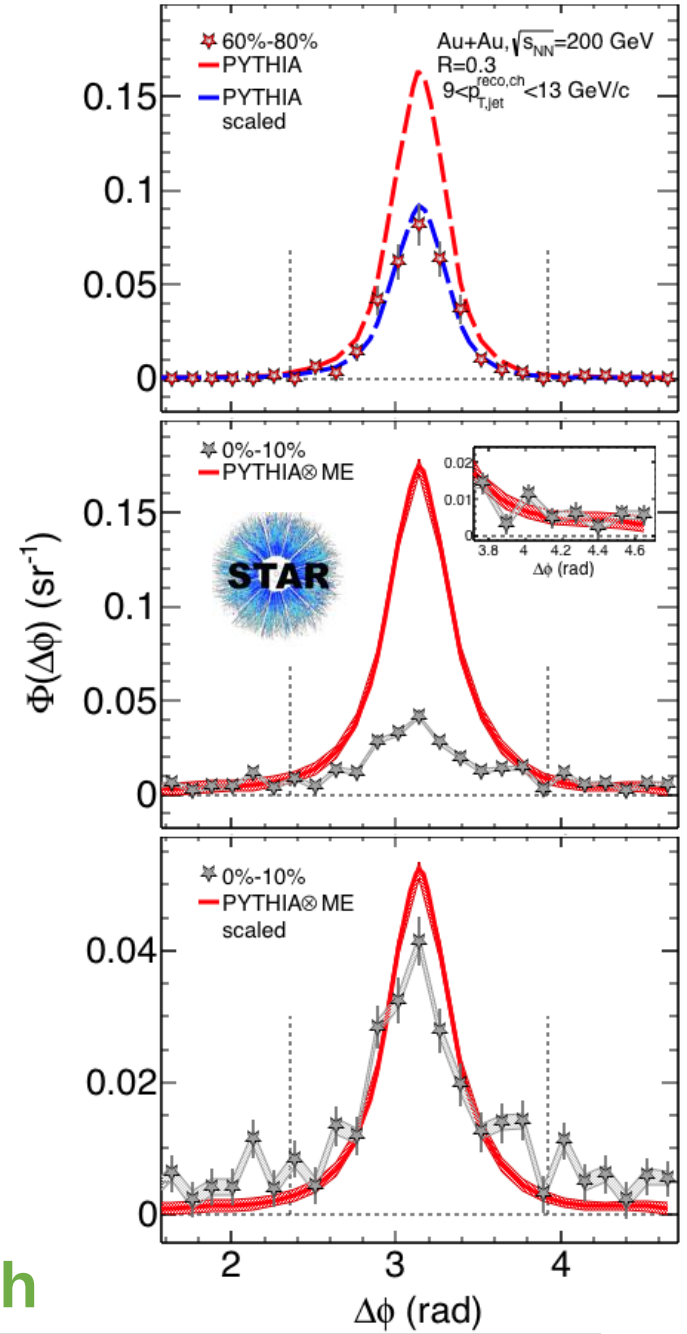


- Charged jets in PbPb are more **Quark-like**! (**Gluon jets** suppressed)

Hadron-Jet Angular Correlation







No significant broadening

QGP probed looks **smooth**