Jet results in heavy ion collisions from CMS

Yen-Jie Lee (MIT)

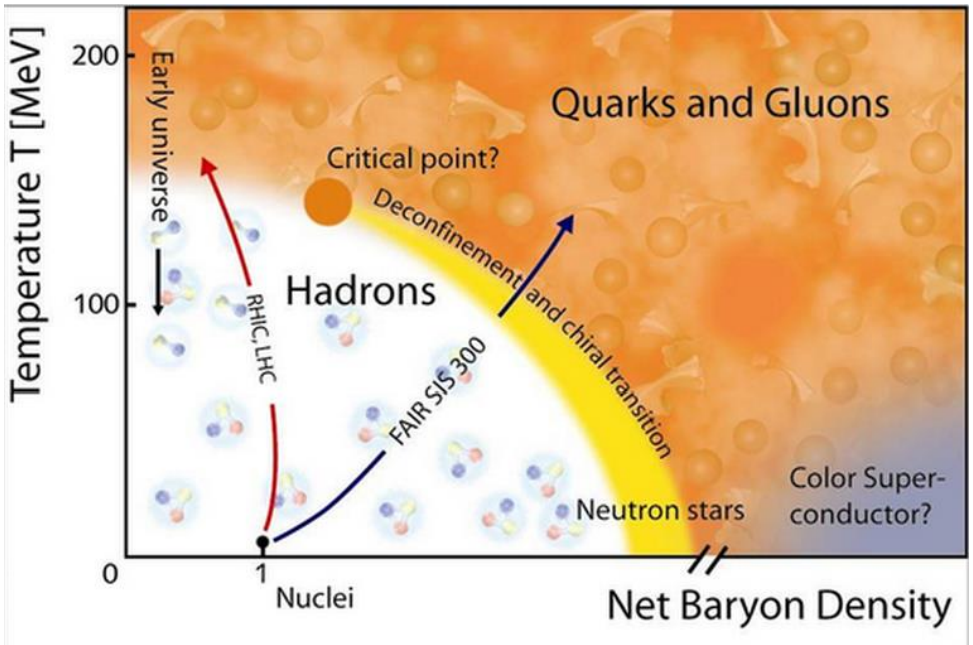
For the CMS collaboration

2nd Conference on Heavy Ion Collisions in the LHC era and beyond

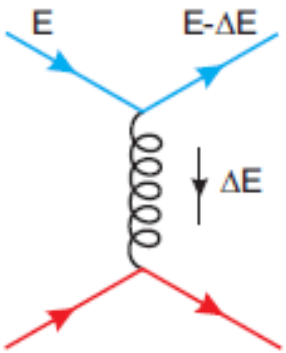
Quy Nhon, Vietnam

26-31 July, 2015

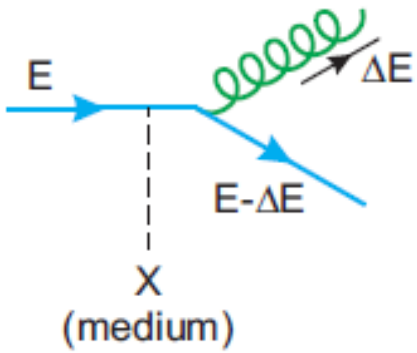
Probing the properties of the medium



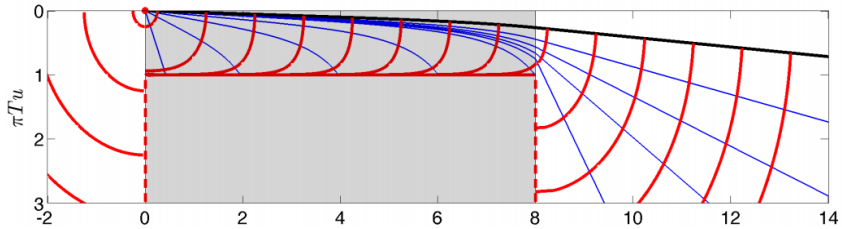
Collisional energy loss

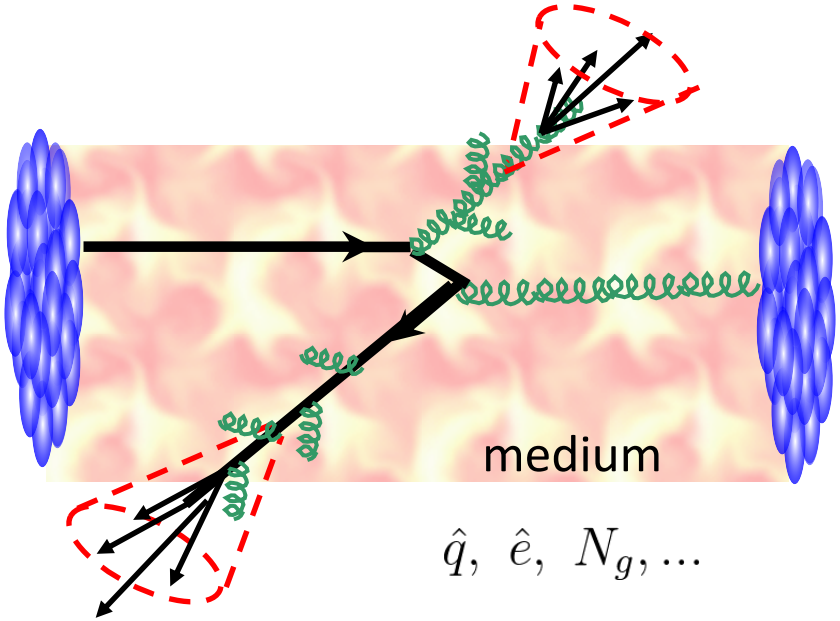


Radiative energy loss



Strong coupling: “AdS drag force”

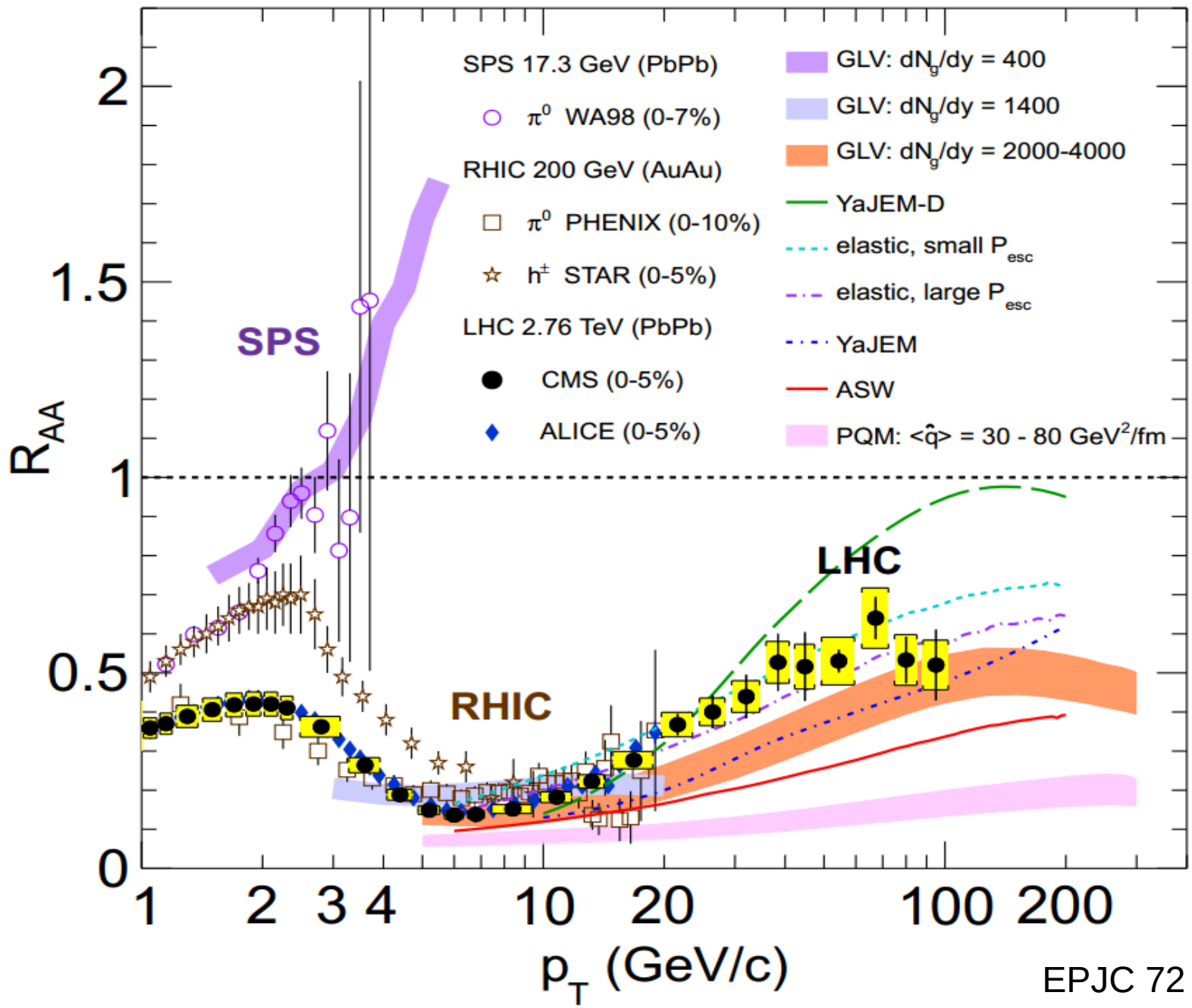




Goal: understand the properties of the produced medium

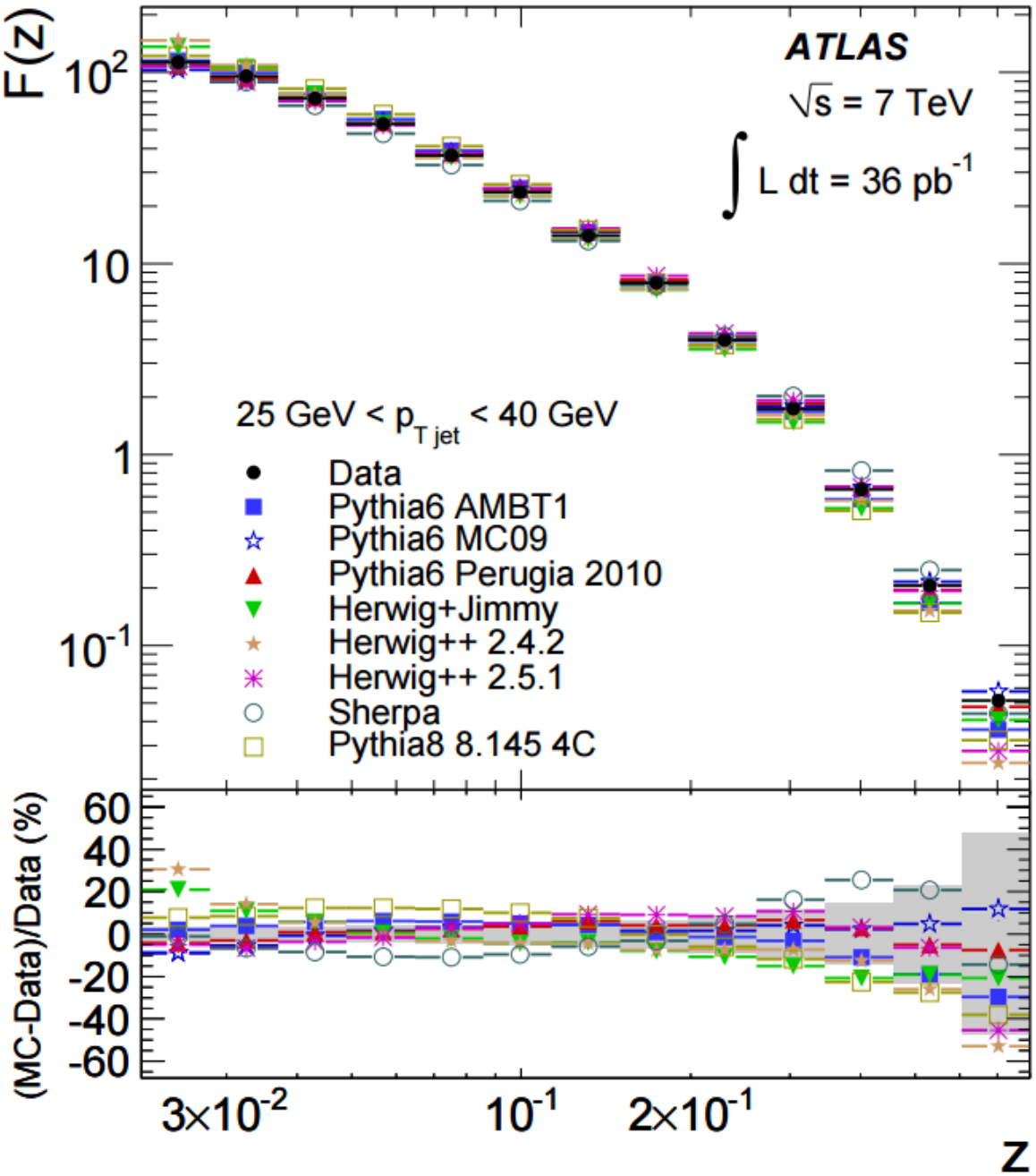
Status: validating the theoretical understanding of jet quenching

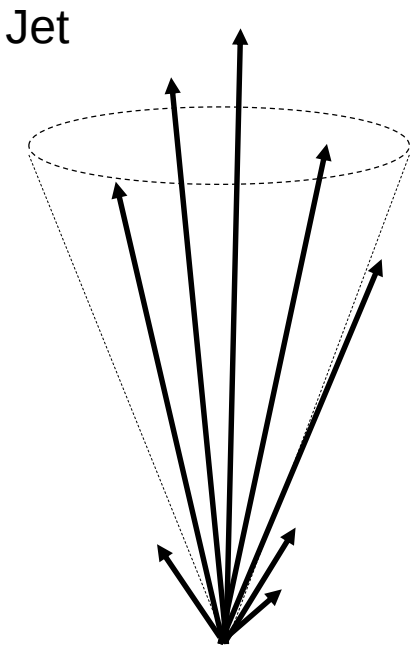
Jet quenching without jets



EPJC 72 (2012) 1945

Why do we study jet quenching with jets?



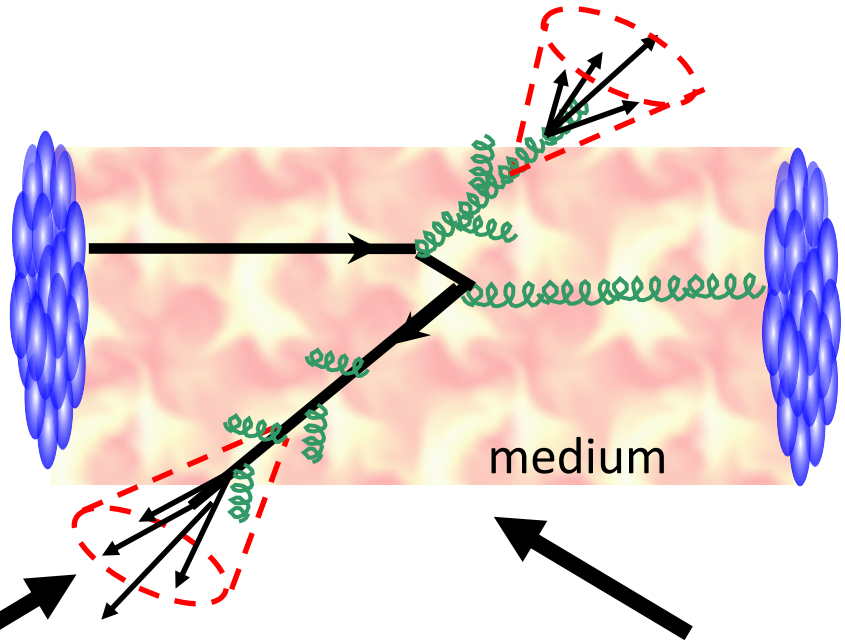


$$z = \frac{\boldsymbol{p}_{\mathrm{jet}} \cdot \boldsymbol{p}_{ch}}{|\boldsymbol{p}_{\mathrm{jet}}|^2}$$

EPJC 71 (2011) 1795

Jet as a versatile probe

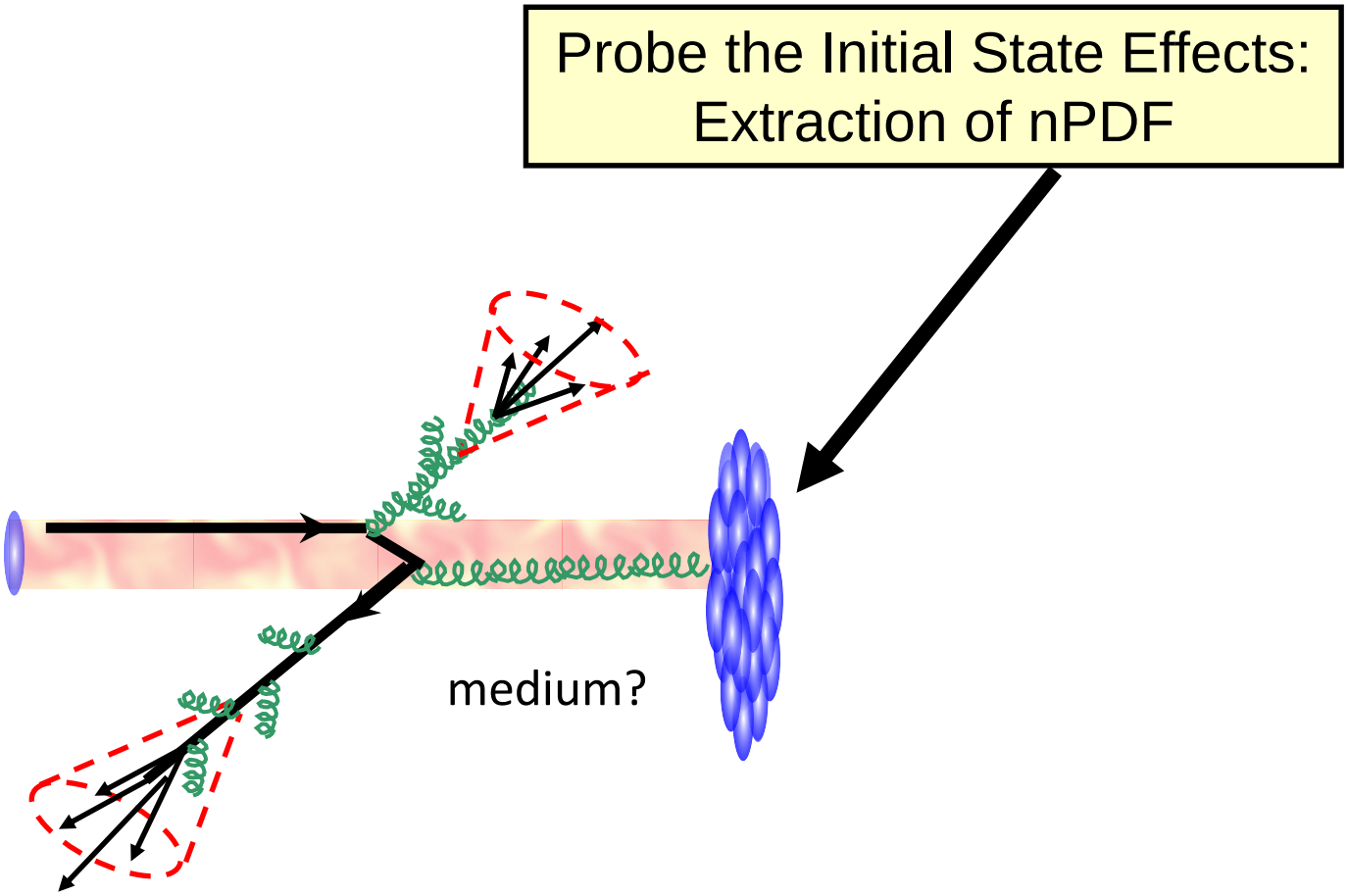
Probe the Initial State Effects:
Extraction of nPDF



Probe the Final State
Modification of Jets

Search for medium response
Where does the quenched energy go?

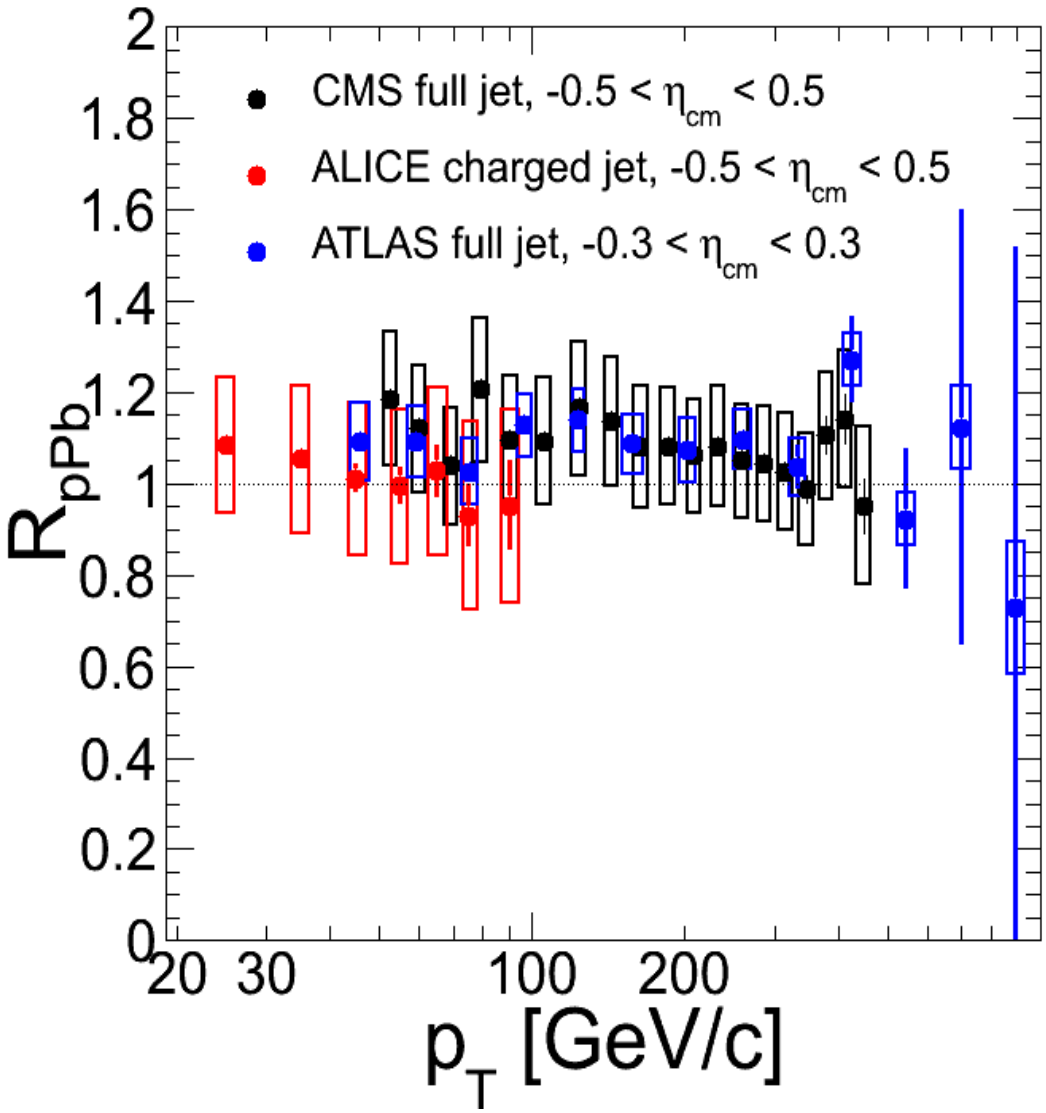
Jet as a versatile probe



→ p(d)A collisions

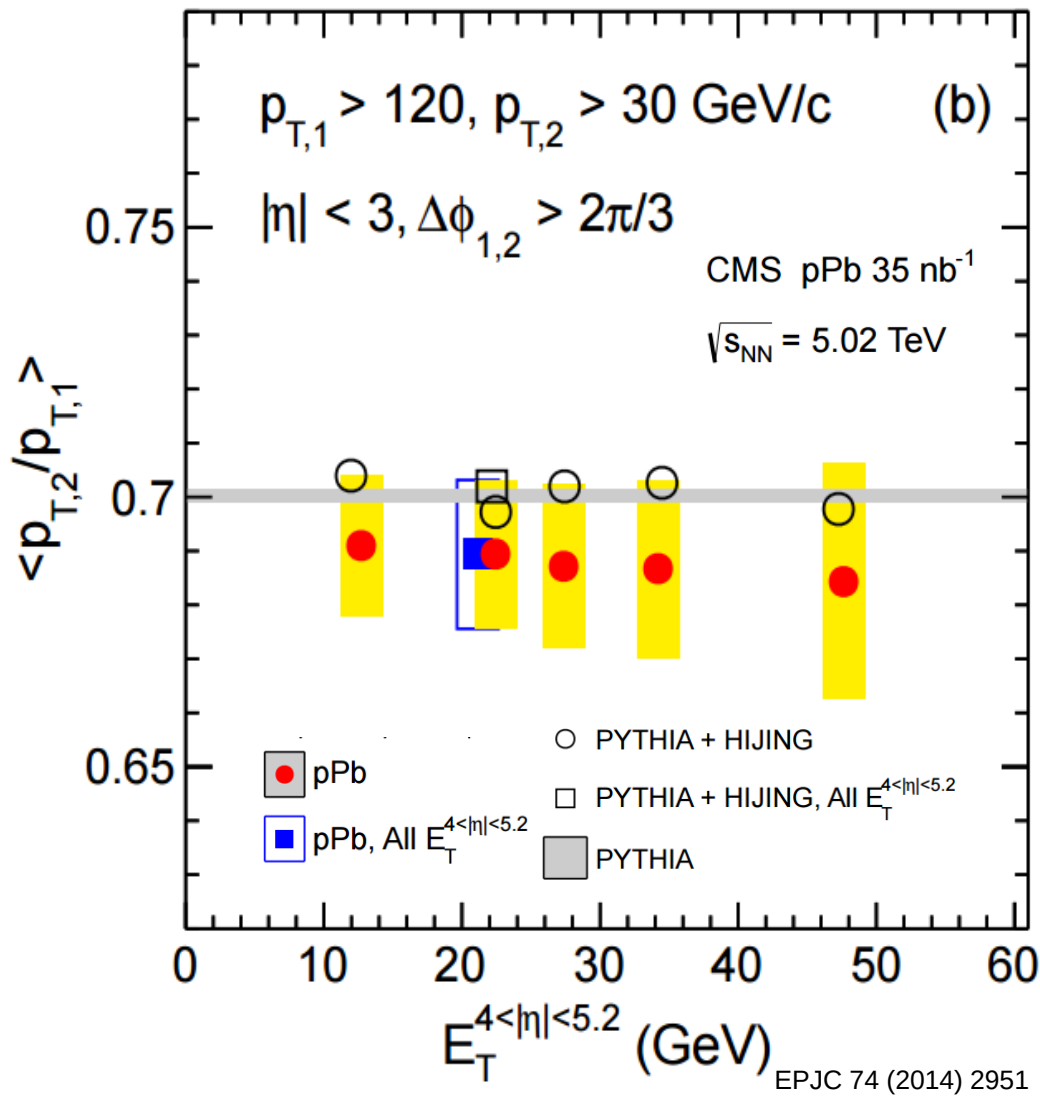
(Di-)Jet production in pPb collisions at 5.02 TeV

Inclusive (charged) jet R_{pPb}



Jet R_{pPb} ~ 1.1 ± 0.2, Consistent with pQCD calculation with EPS09 nPDF

Subleading Jet p_T / leading jet p_T



EPJC 74 (2014) 2951

Dijet p_T ratio compared to PYTHIA from CMS. No significant reduction of dijet p_T ratio (<2%)

Dijet dN/dη in pPb collisions at 5.02 TeV

CMS pPb 35 nb^{-1}

$\sqrt{s_{NN}}$ = 5.02 TeV

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

$p_{T,2}$ > 30 GeV/c

$\Delta\phi_{1,2} > 2\pi/3$

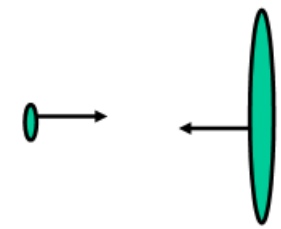
All $E_T^{|\eta|>4}$

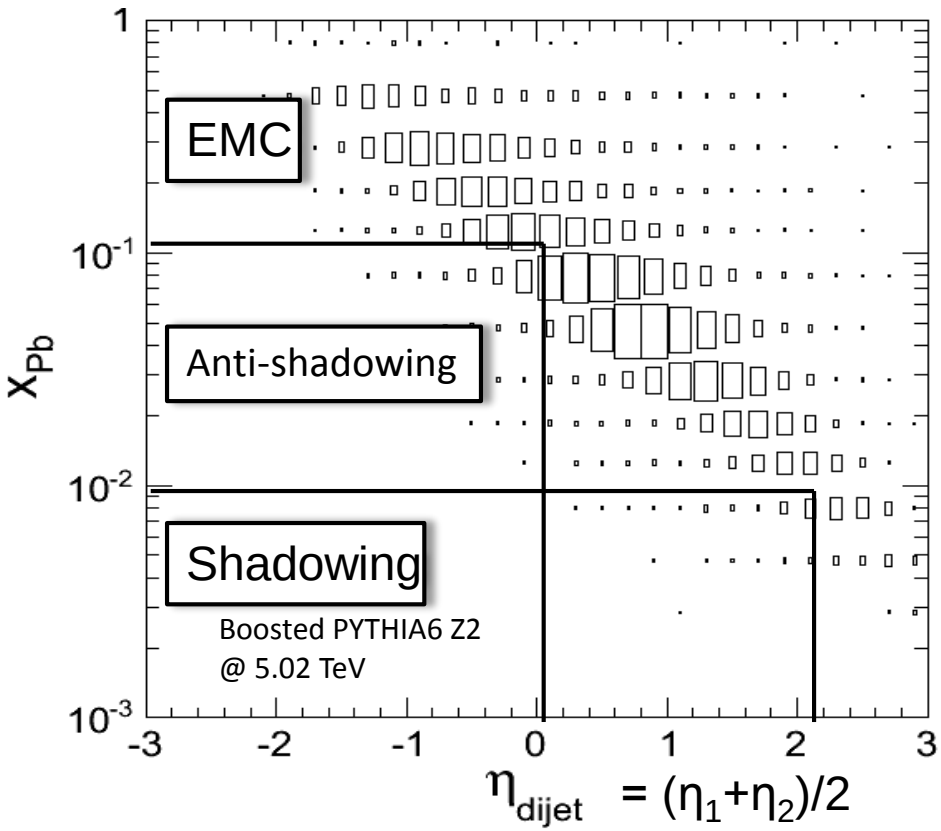
Jet quenching from dijet analysis in pPb:

Dijet asymmetry <2%

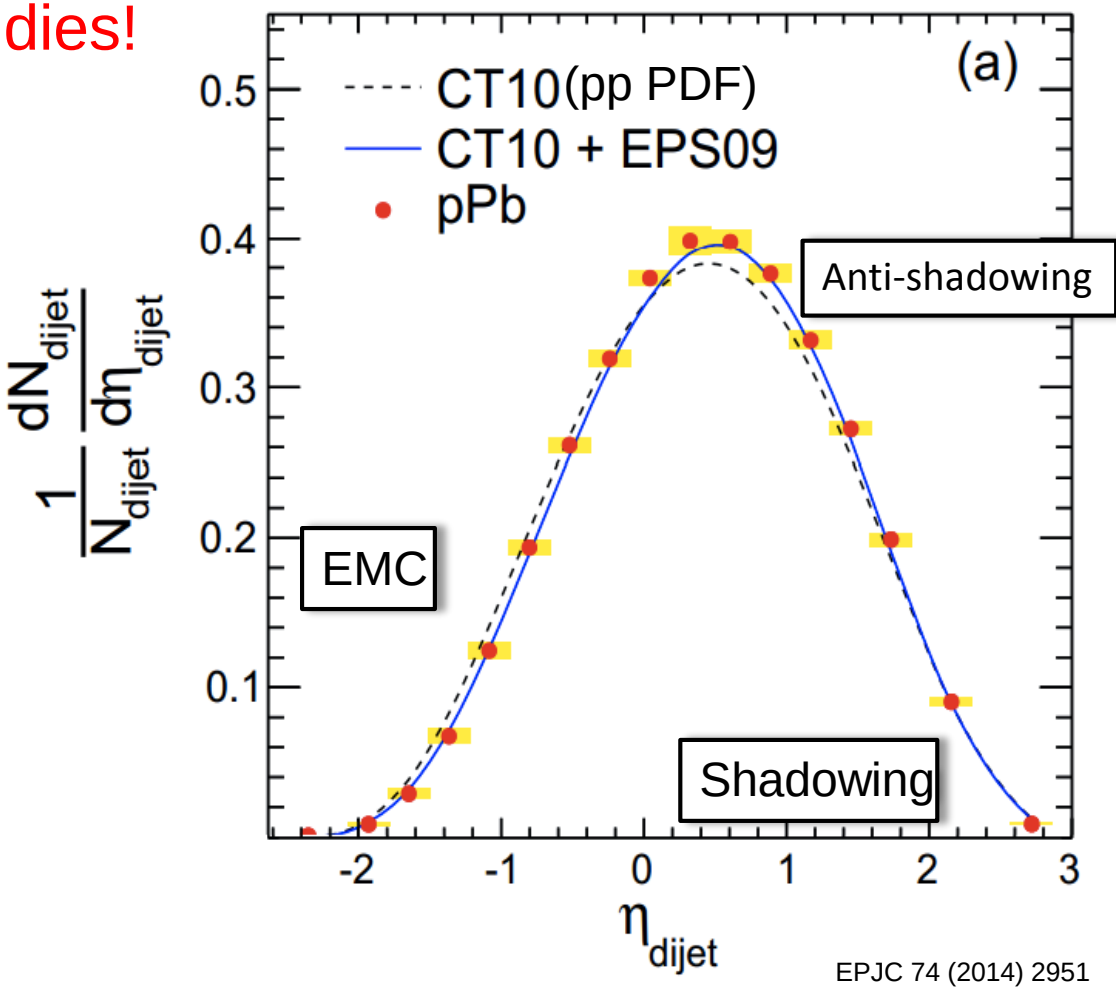
No sizable deviation from unity found in jet R_{pPb}

→ Jets for nPDF studies!





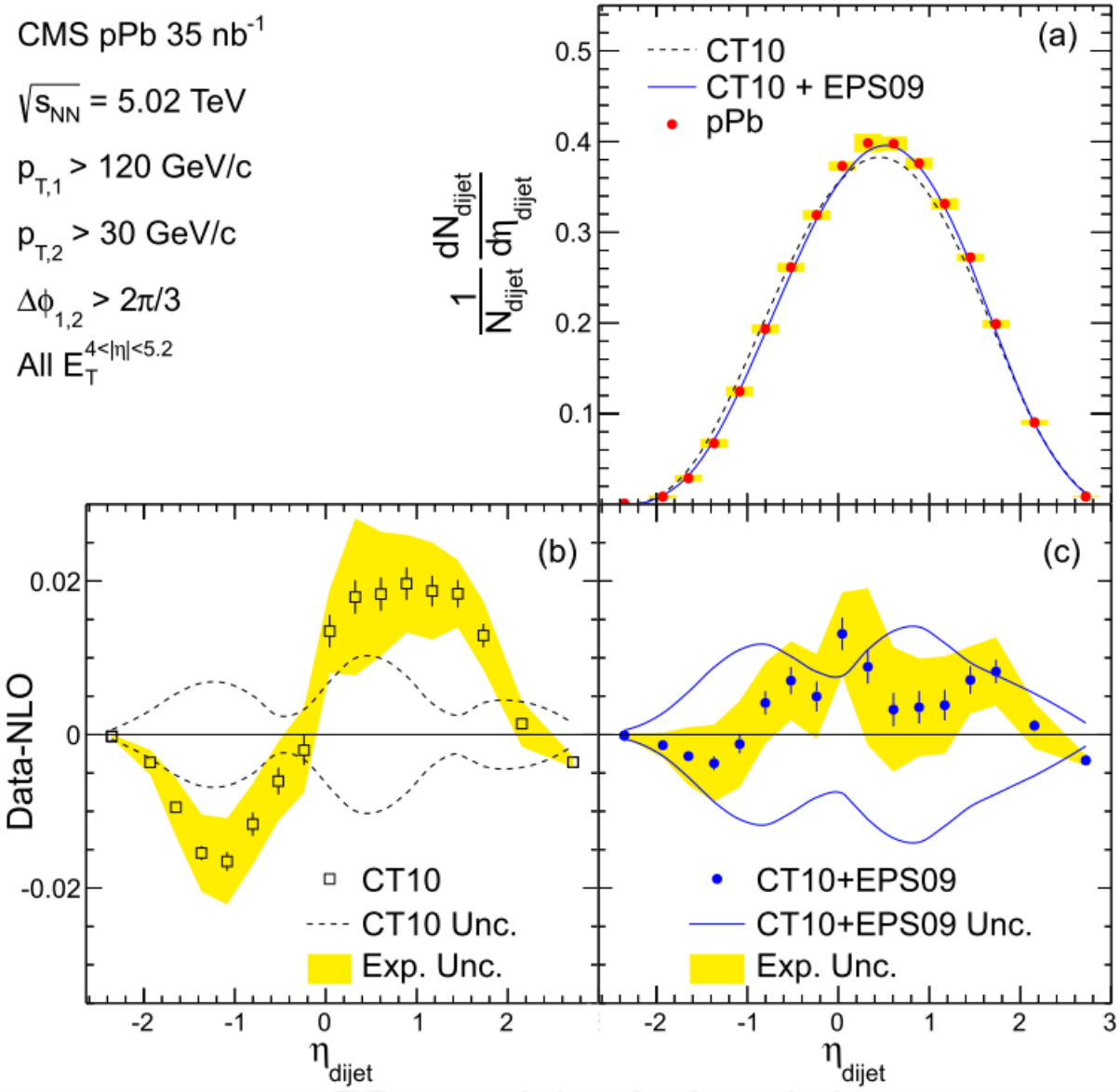
(In the lab frame)

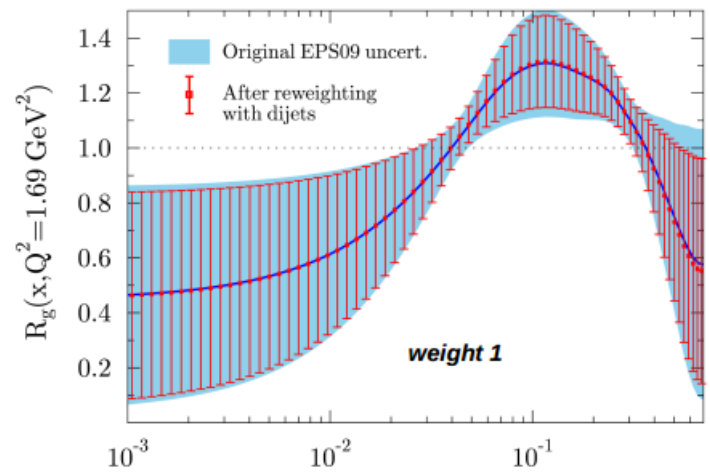


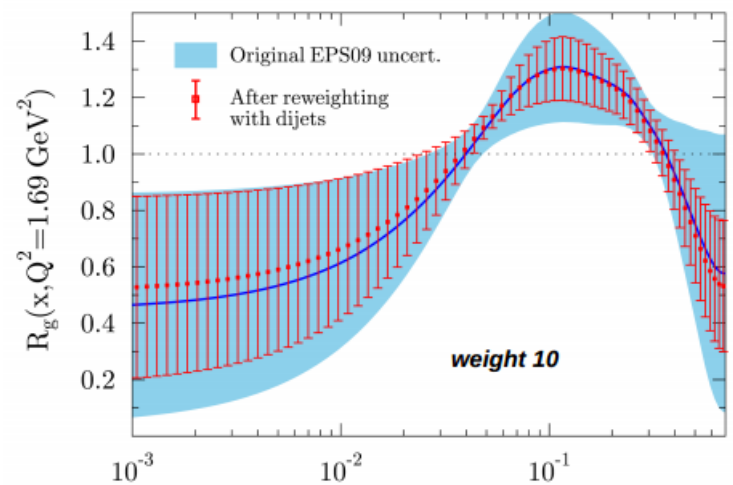
EPJC 74 (2014) 2951

Compare to CT10 and CT10+EPS09

EPJC 74 (2014) 2951



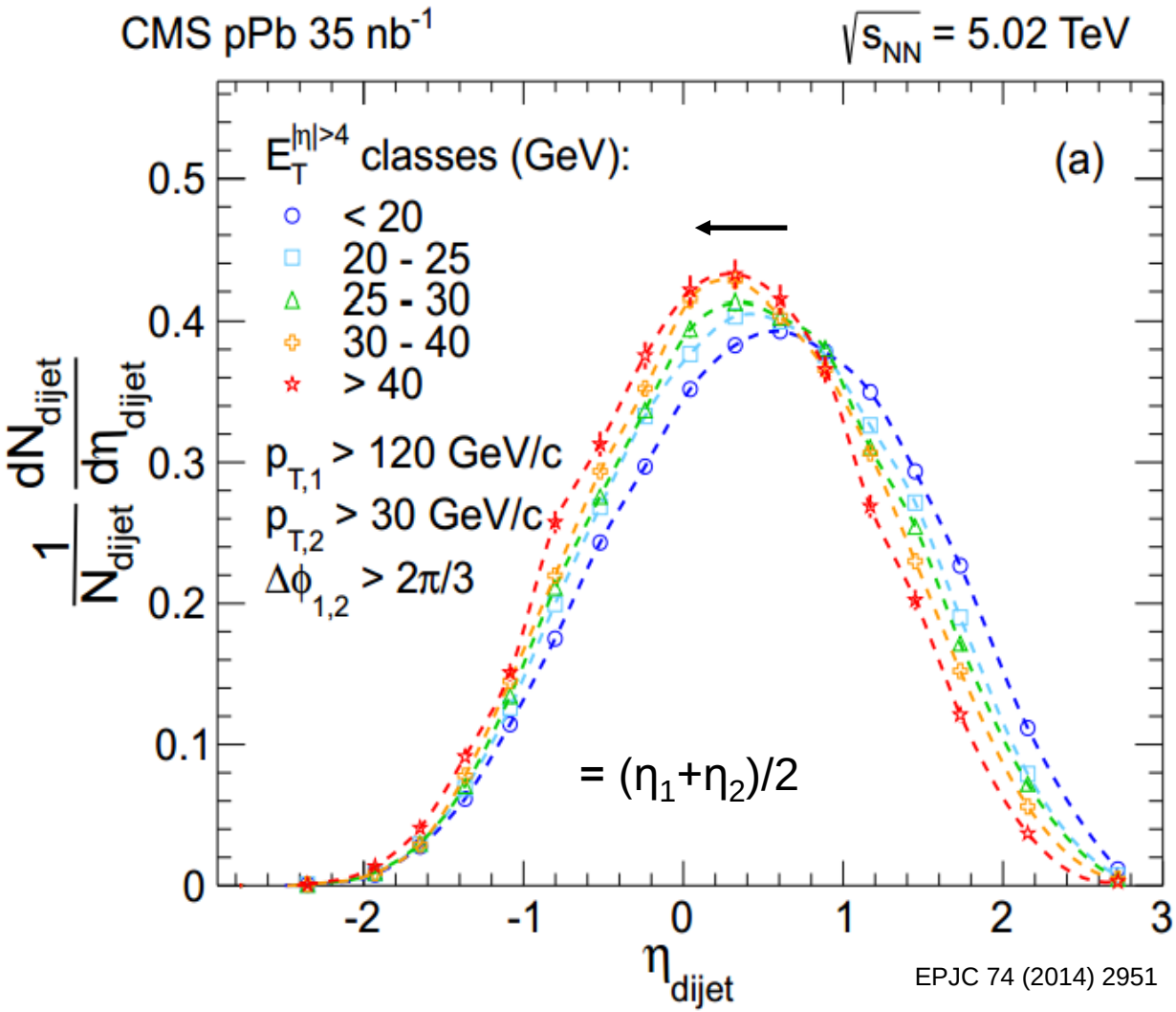




Hannu's QM14 talk

Dijet dN/dη vs. event activity

Red: event with **large** forward energy
Blue: event with **small** forward energy



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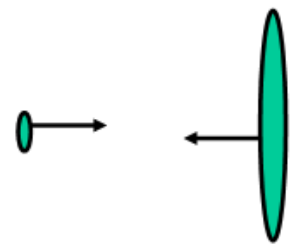
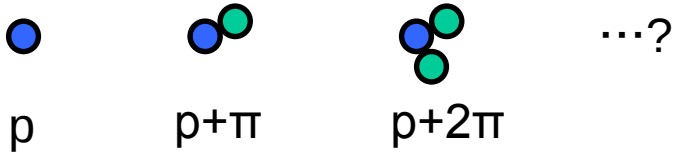




Stringy proton from quantum fluctuations caughter by a nucleus?

PRD 89, 025019 (2014)

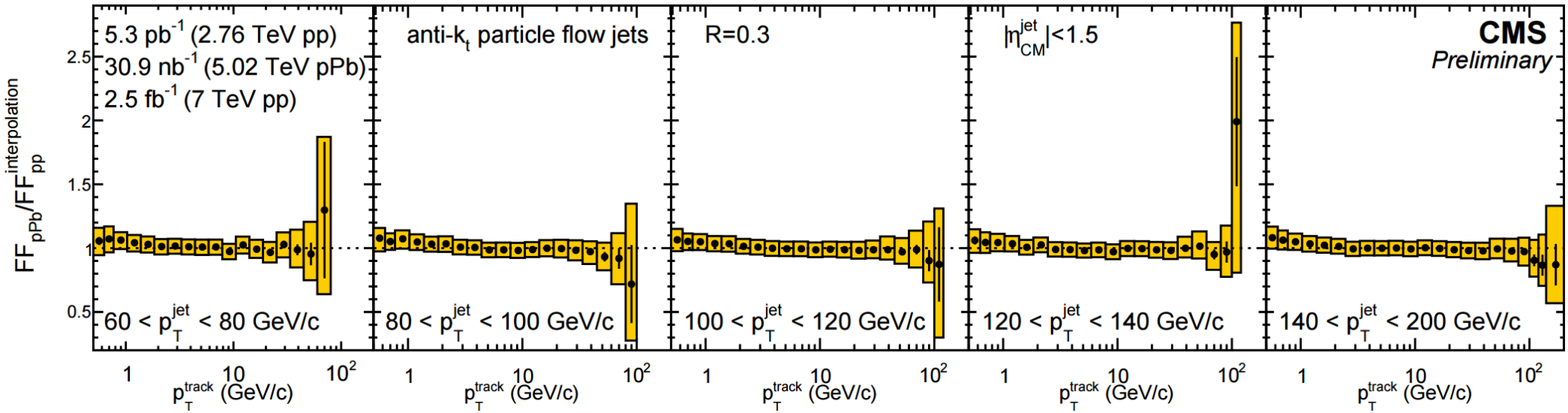
(Too) large modification vs. event activity.

Can not be explained by centrality dependent nPDF

Jet fragmentation pattern in pPb

Low p_T jet
60-80 GeV

High p_T jet
140-200 GeV

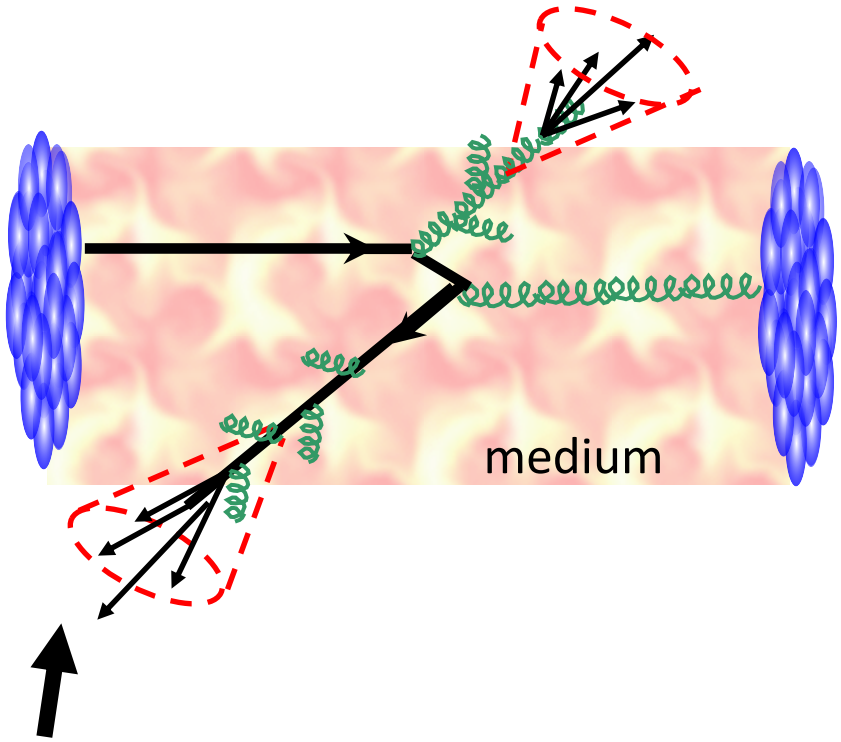


CMS-PAS-HIN-15-004

- Track p_T spectra inside the jet cone is measured in pPb collisions
- Ratio of pPb and the interpolated pp reference is consistent with unity

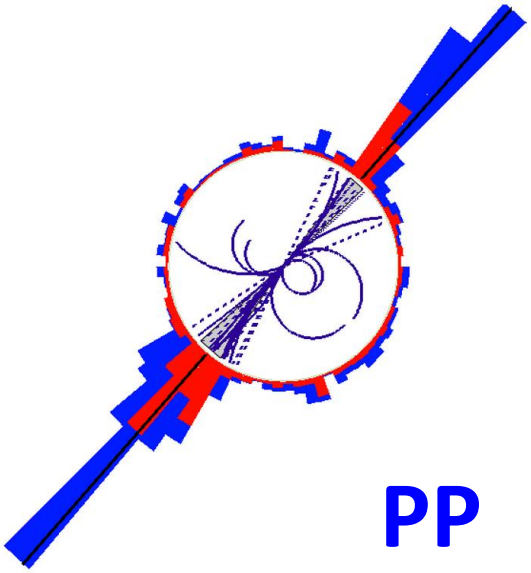
Jet as a versatile probe

Probe the Initial State Effects:
Extraction of nPDF

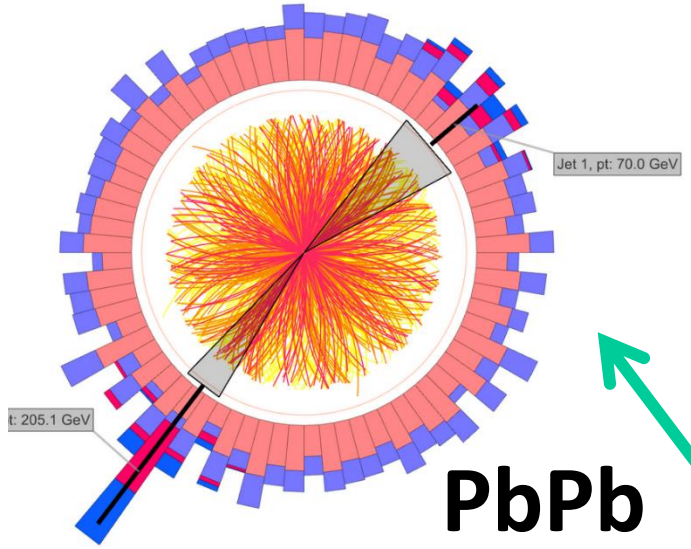


Probe the Final State
Modification of Jets

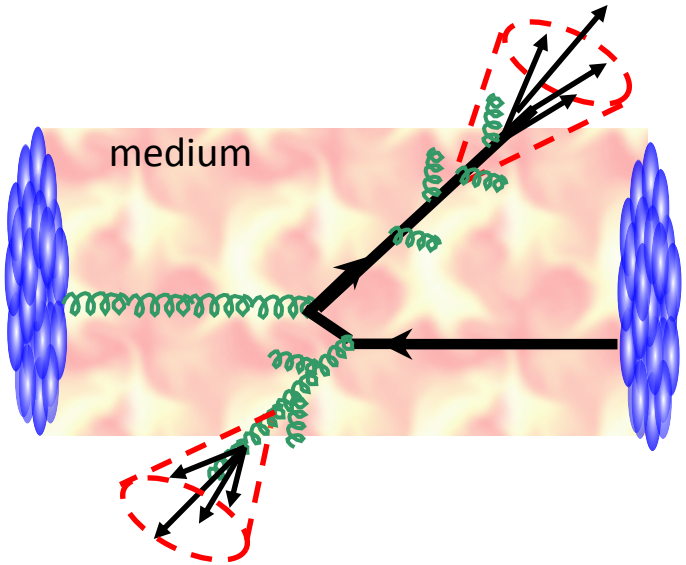
Probe the QGP with high energy quarks and gluons



PP



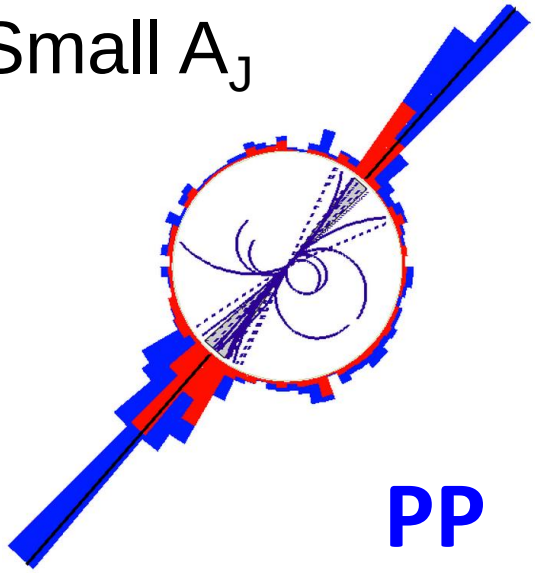
PbPb



Increased rate of
asymmetric dijets
in central PbPb collisions

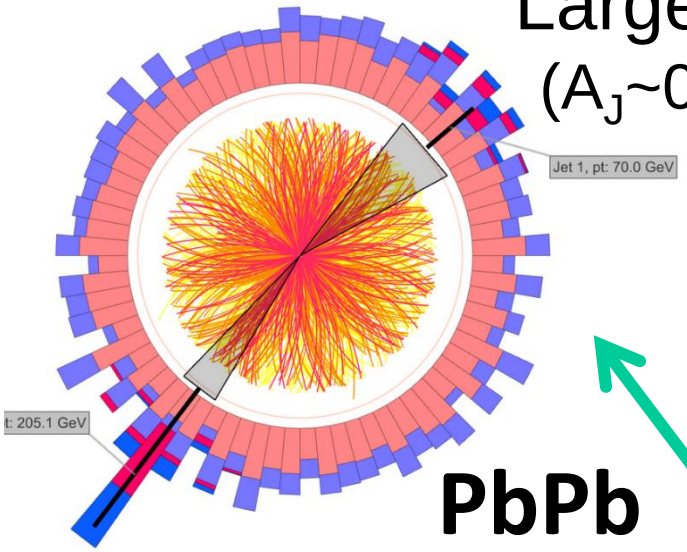
Probe the QGP with high energy quarks and gluons

Small A_J

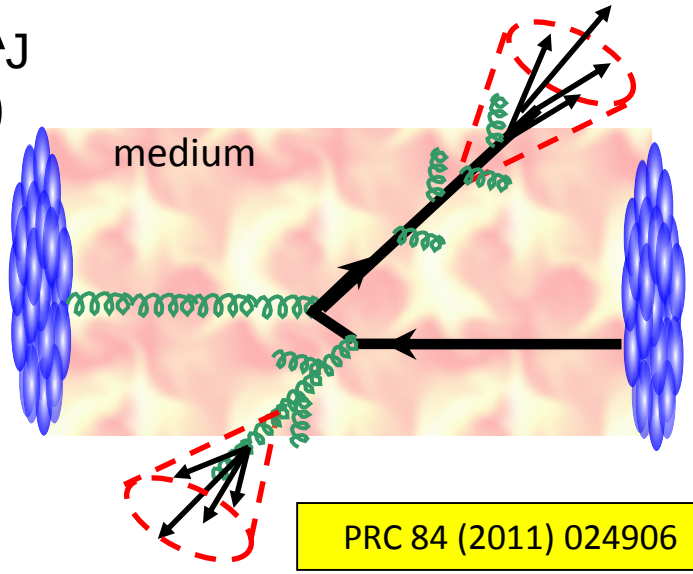


PP

Large A_J
(A_J~0.5)

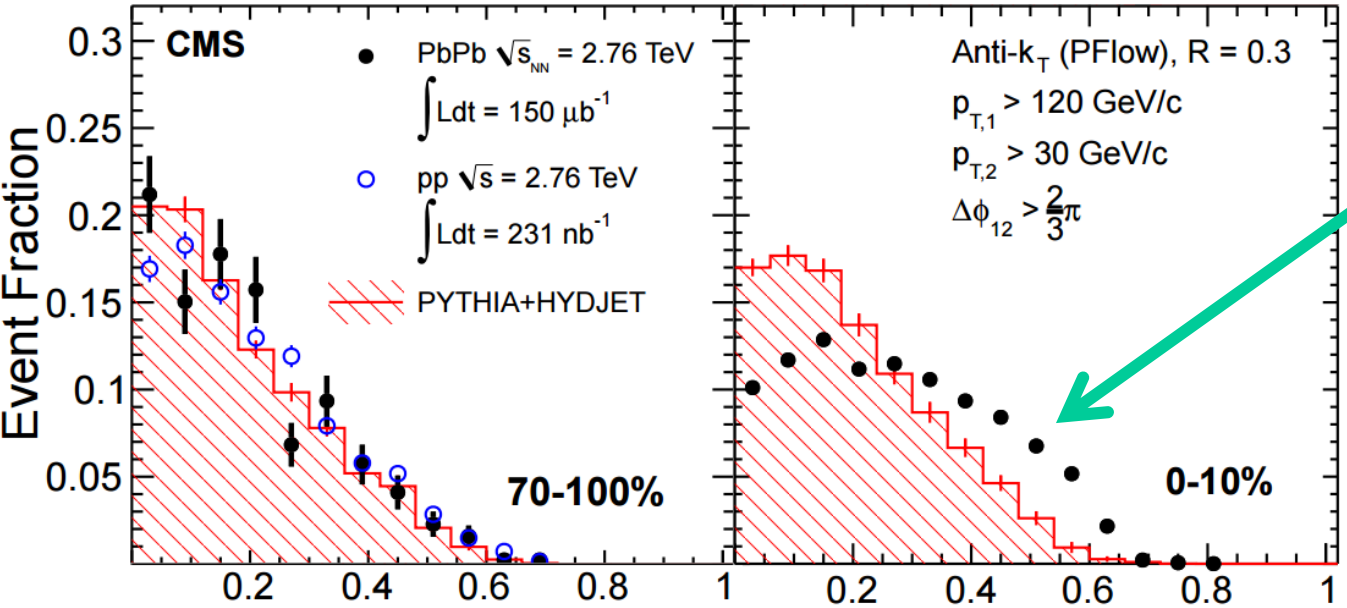


PbPb



PRC 84 (2011) 024906

PLB 712 (2012) 176



$$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$$

Increased rate of asymmetric dijets in central PbPb collisions

Jet Fragmentation at LHC

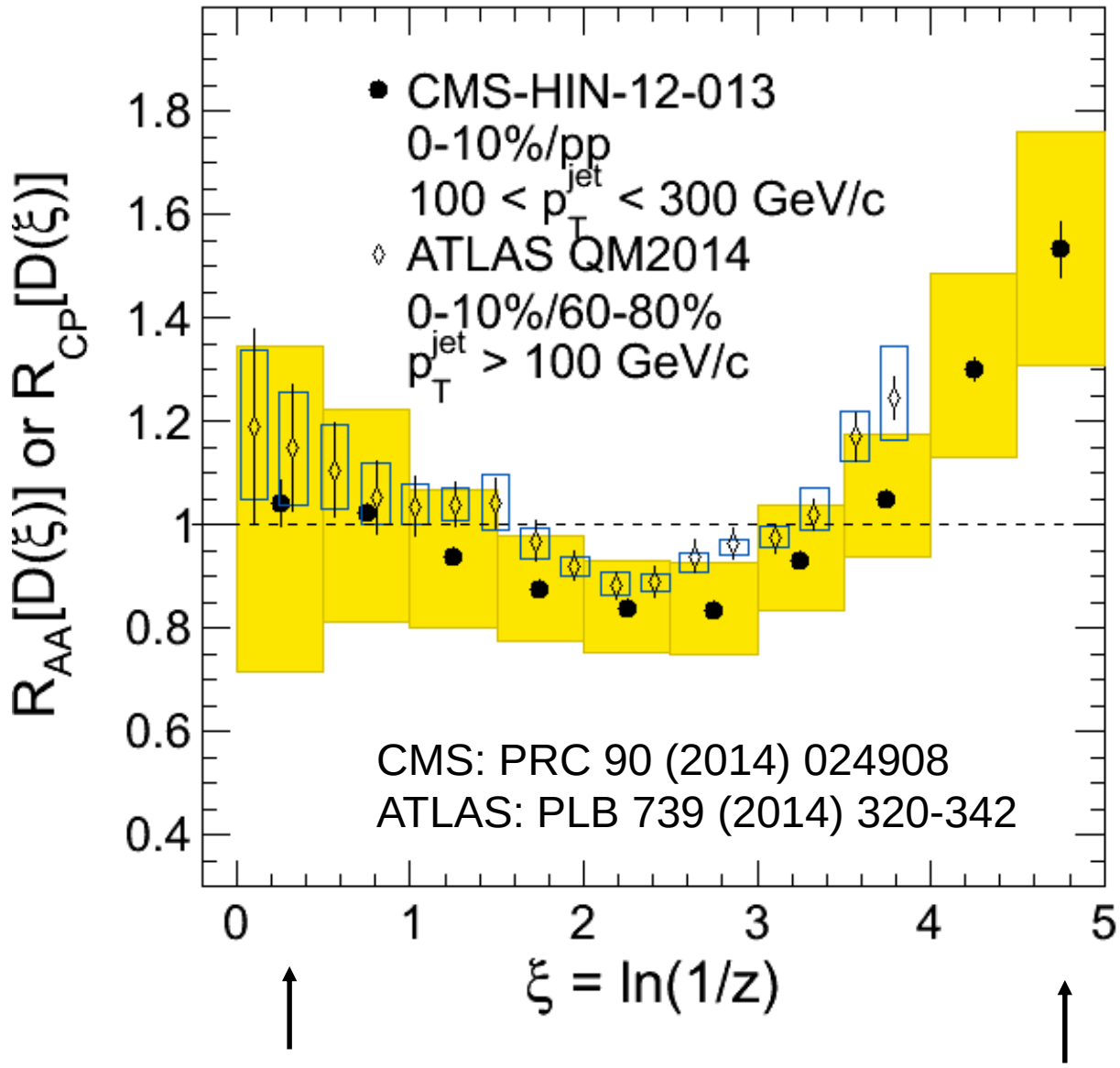
Using **Jet Energy** as a reference

CMS FF R_{AA} compared to ATLAS FF R_{CP}

$Z = p_{||}^{Trk} / p^{Jet}$

Qualitative consistent results between CMS and ATLAS

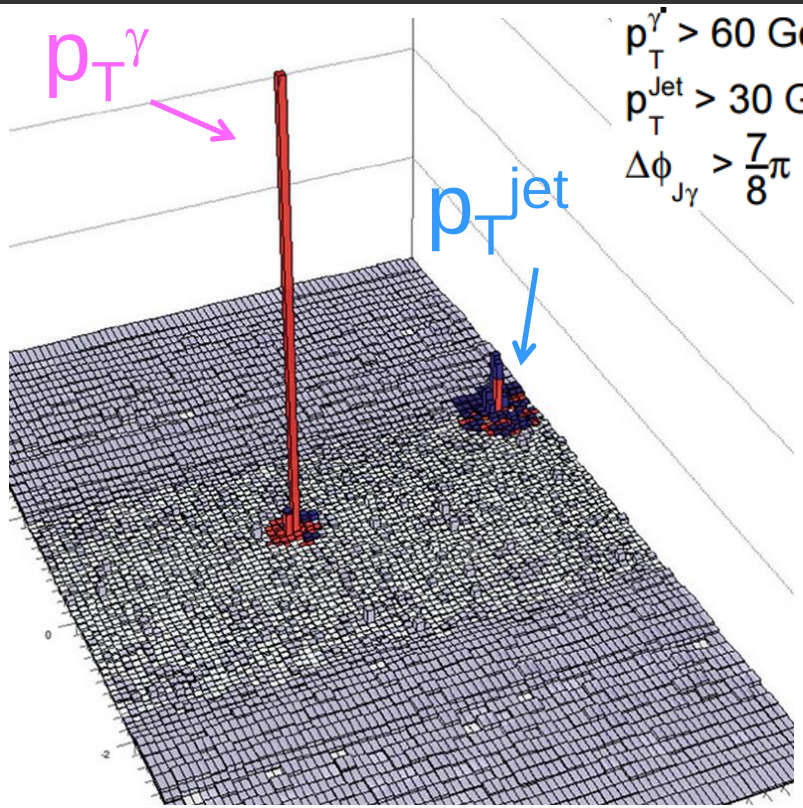
ATLAS : indication of enhancement of low ξ (high z) particles in the jet cone



High p_T particles

Low p_T particles

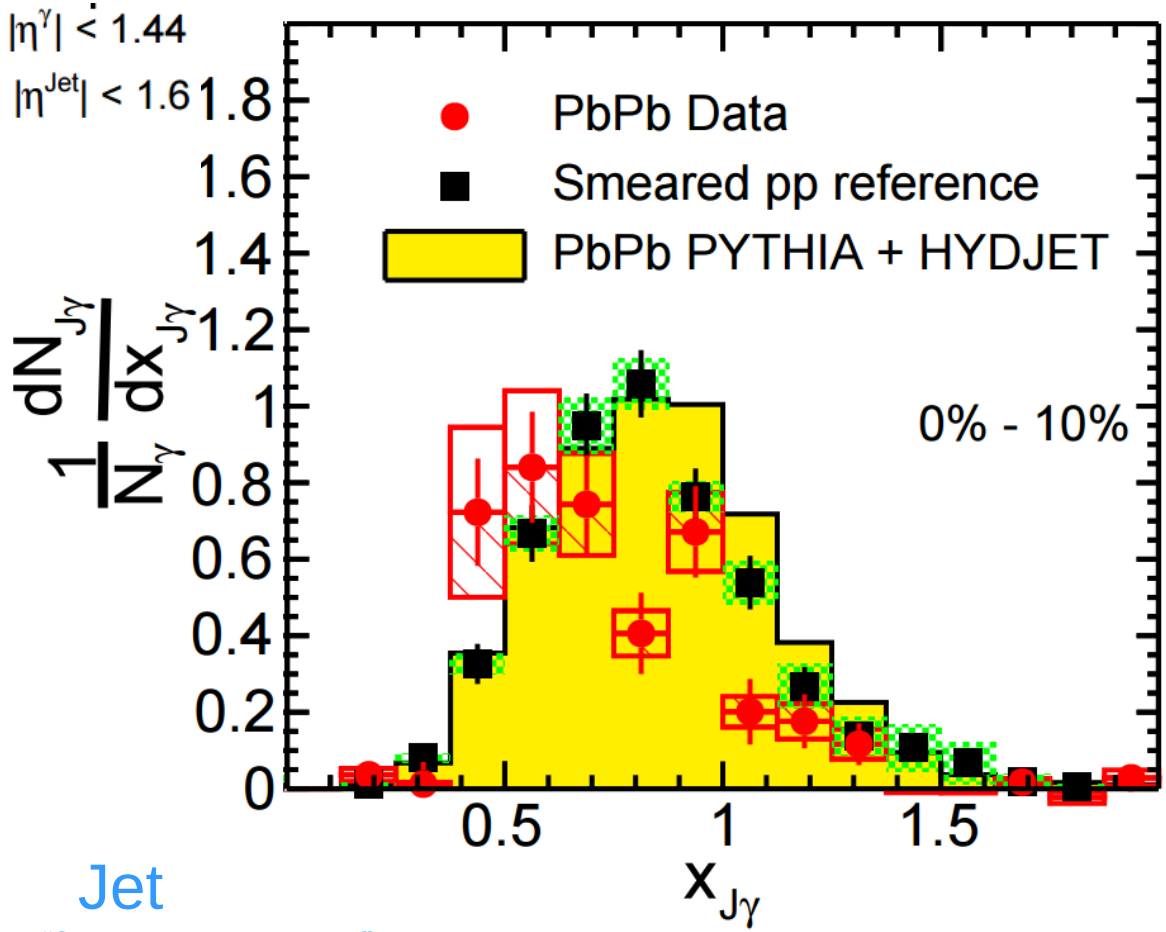
Photon-Jet correlation



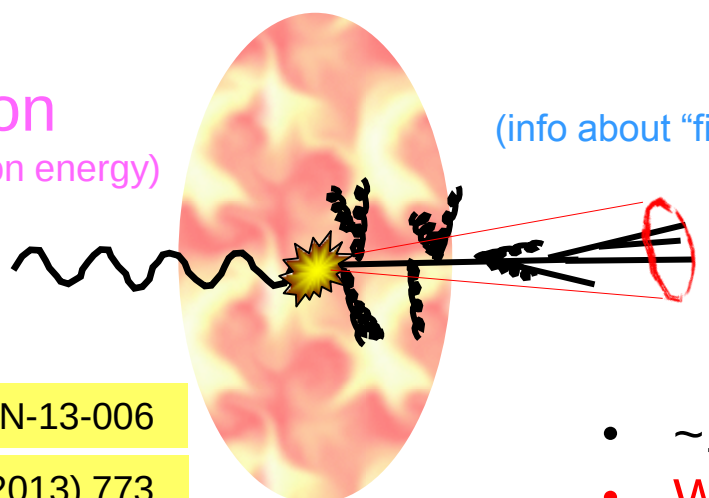
$p_T^{\gamma} > 60$ GeV/c $\quad |\eta^{\gamma}| < 1.44$

$p_T^{Jet} > 30$ GeV/c $\quad |\eta^{Jet}| < 1.6$

$\Delta\phi_{J\gamma} > \frac{7}{8}\pi$



Photon
(tag initial parton energy)



Jet
(info about "final parton energy")

$$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$$

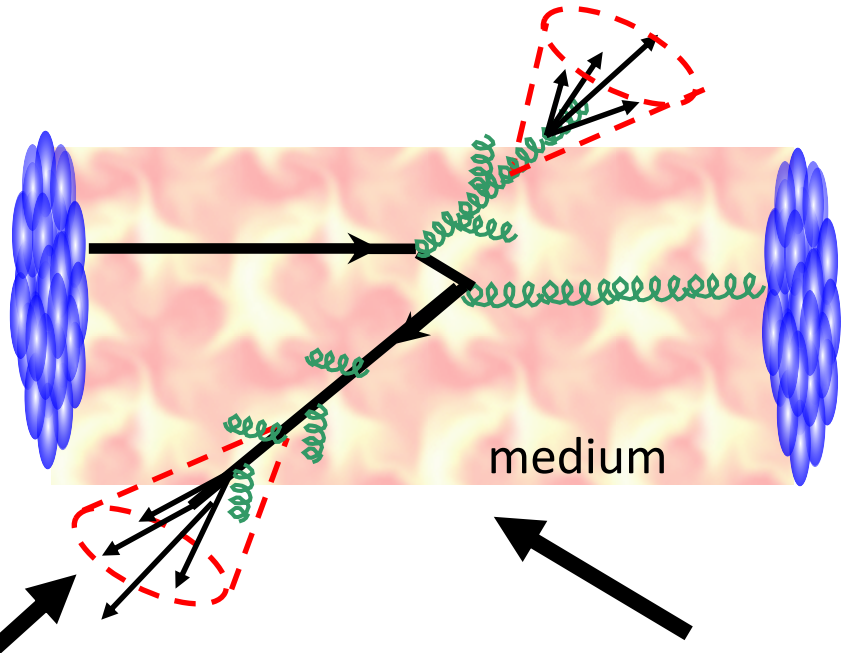
CMS-PAS-HIN-13-006

PLB 718 (2013) 773

- ~10% of the jet energy goes out of the jet cone
- Where does the quenched energy go?

Jet as a versatile probe

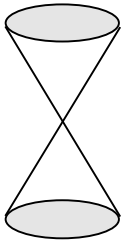
Probe the Initial State Effects:
Extraction of nPDF



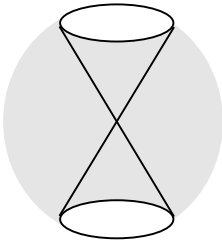
Probe the Final State
Modification of Jets

Search for medium response
Where does the quenched energy go?

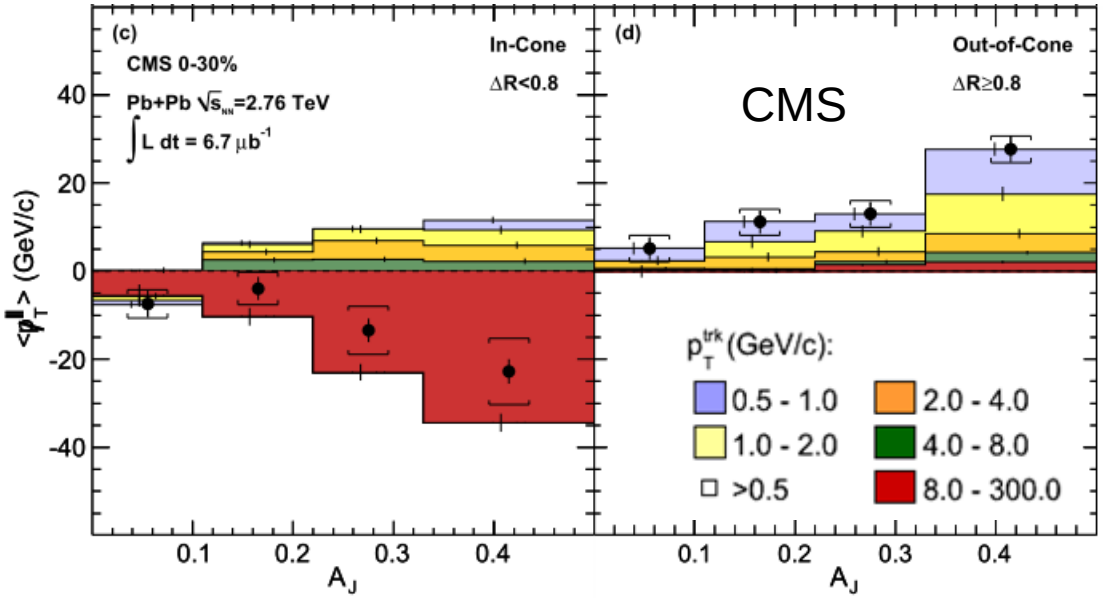
Significant energy flow out of the jet cone



Tracks in the jet cone $\Delta R<0.8$



Tracks out of the jet cone $\Delta R>0.8$



PRC 84 (2011) 024906

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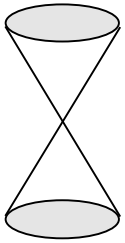

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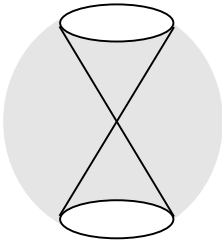

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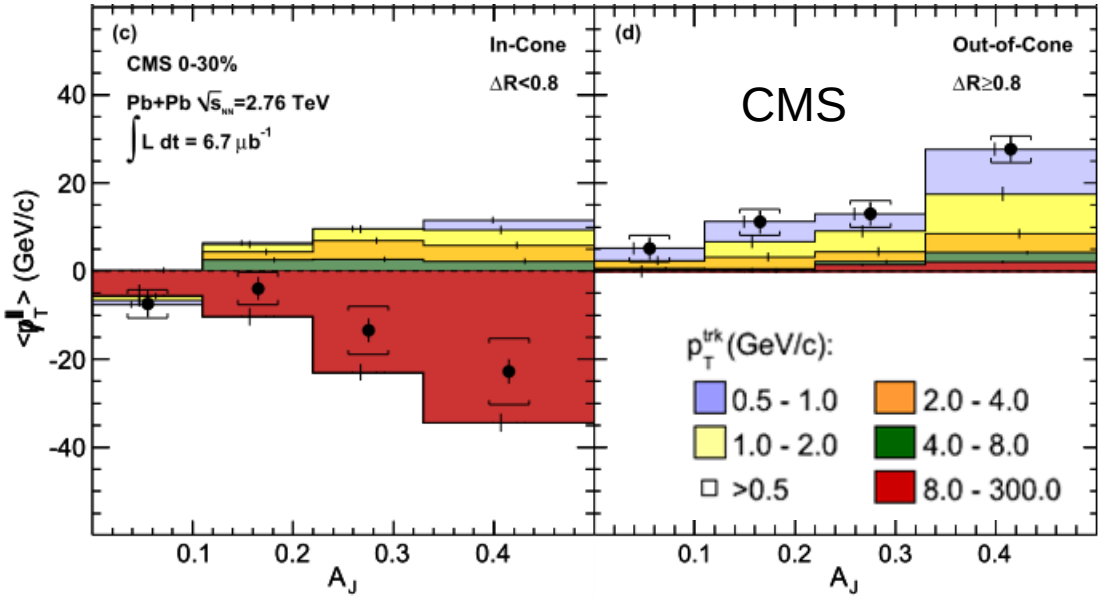

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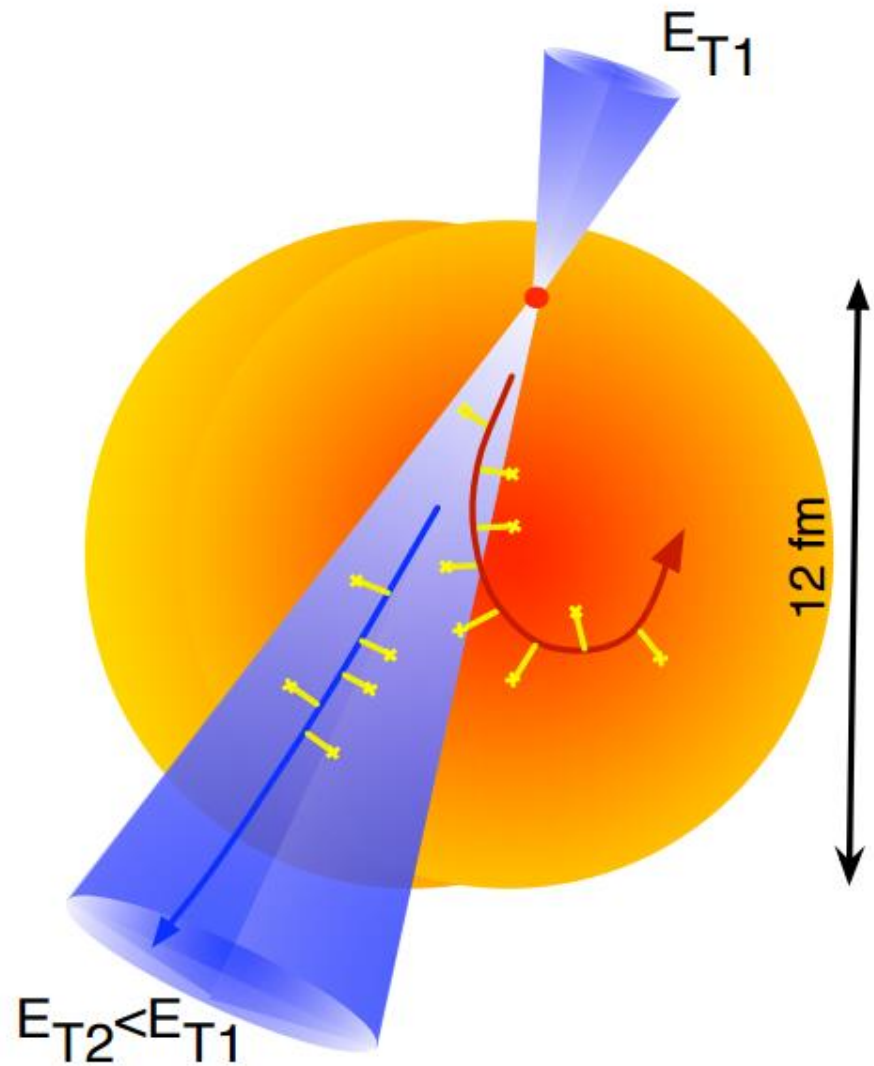
Jet collimation



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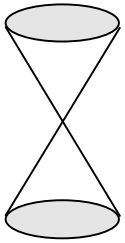

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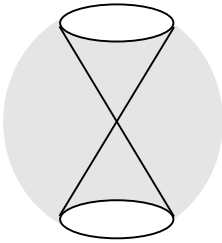

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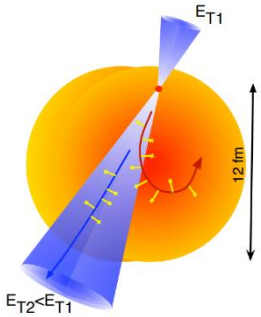
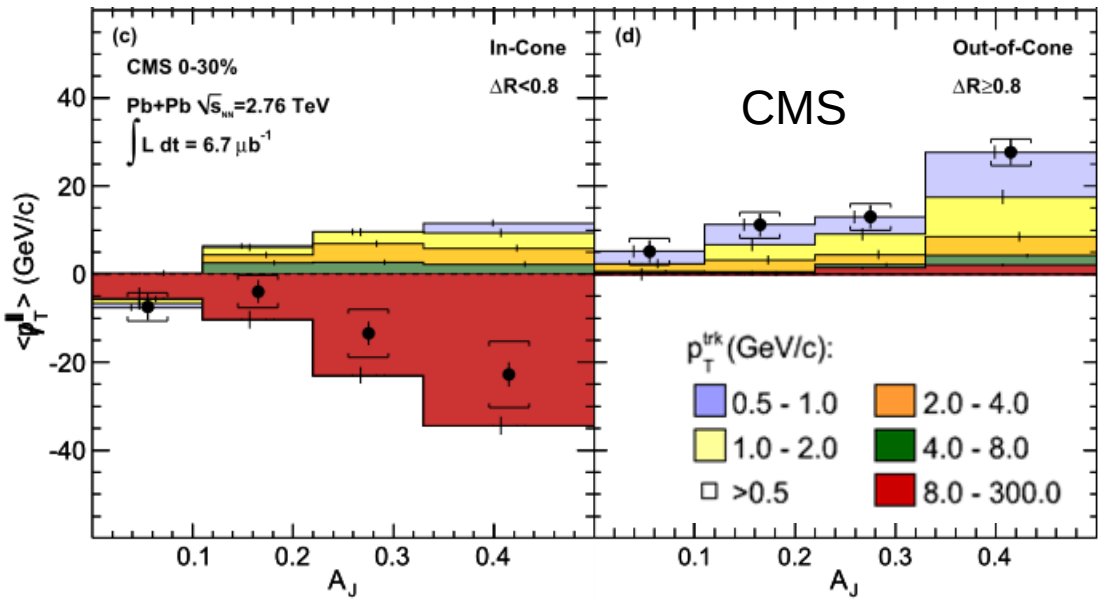
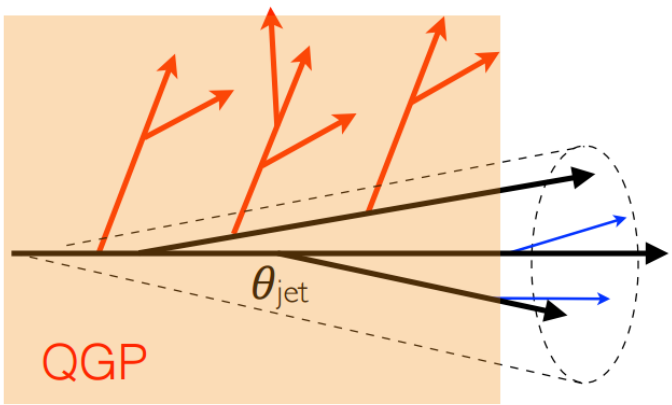
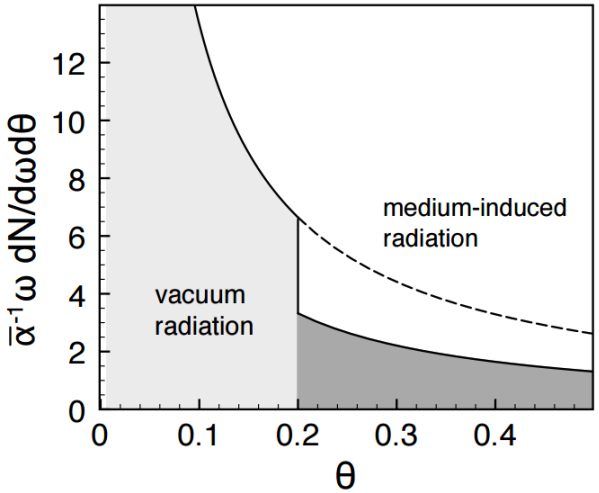


Decoherence



PRC 84 (2011) 024906





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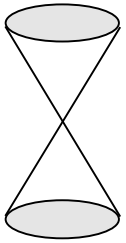

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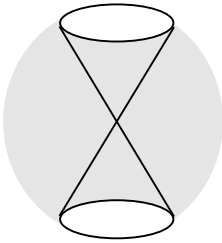

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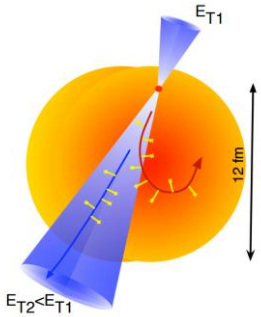
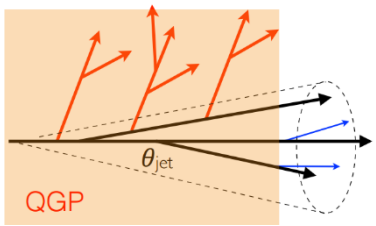
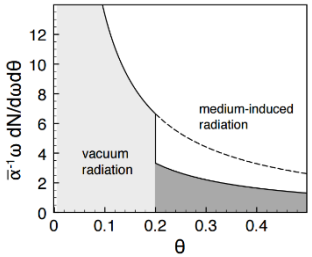
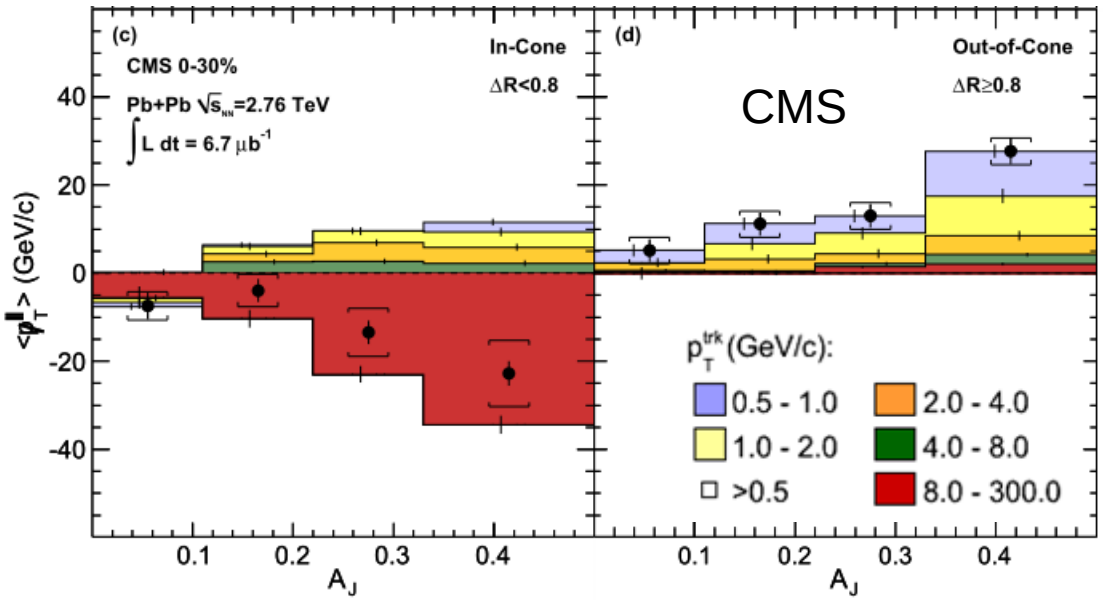


Decoherence

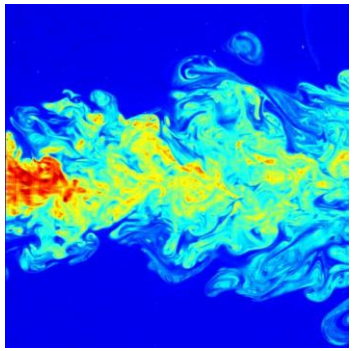


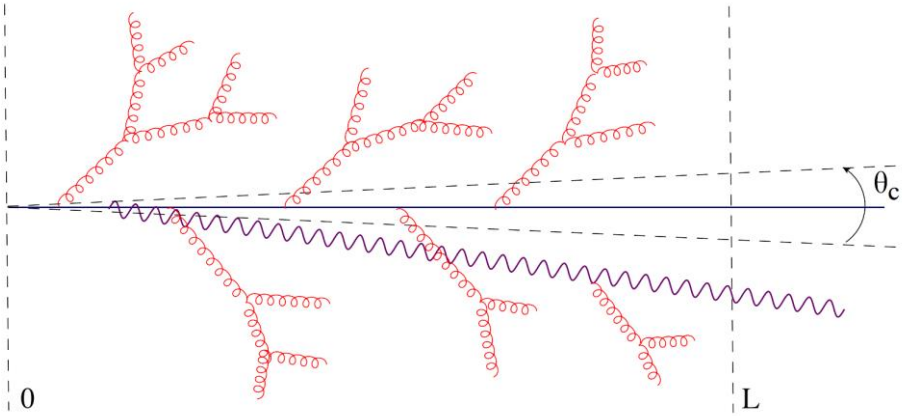




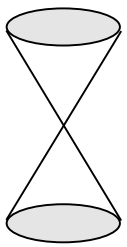
PRC 84 (2011) 024906

Turbulance cascade

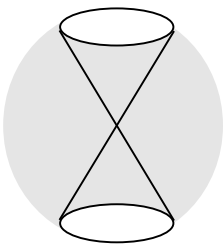




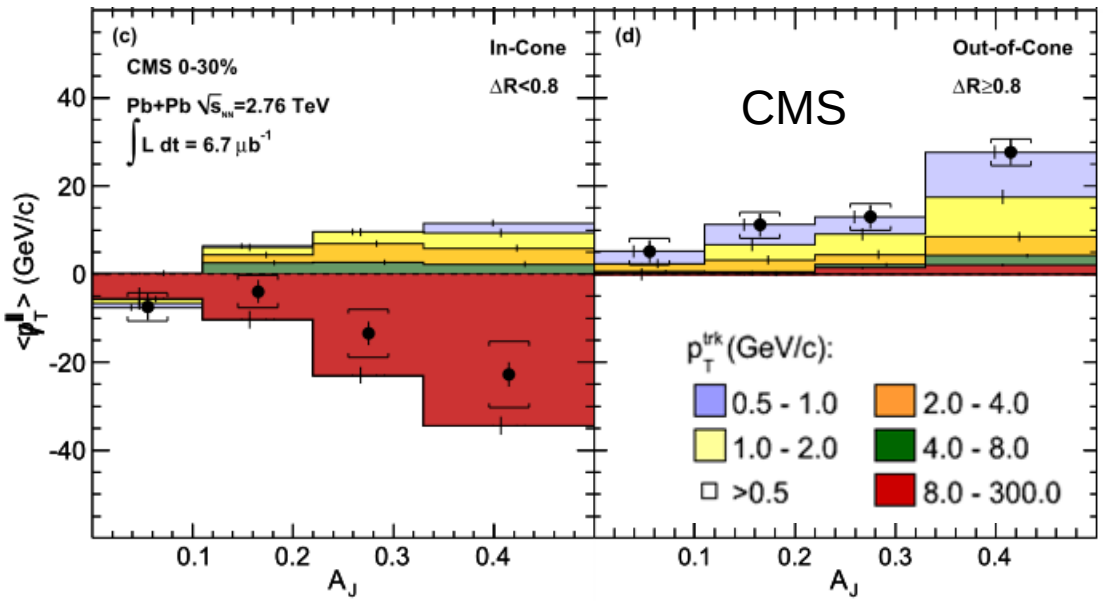
Significant energy flow out of the jet cone



Tracks in the jet cone ΔR<0.8

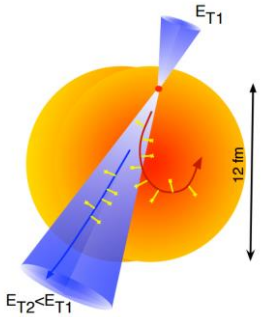


Tracks out of the jet cone ΔR>0.8

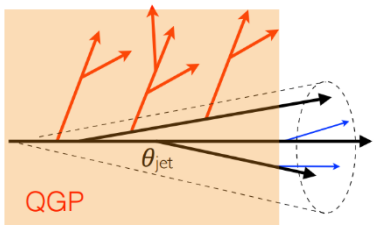


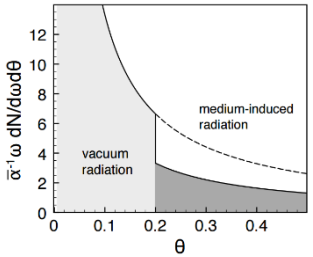
PRC 84 (2011) 024906

Jet collimation

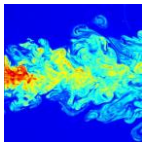


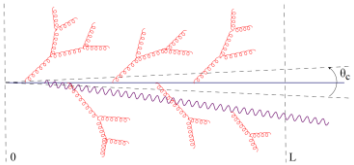
Decoherence



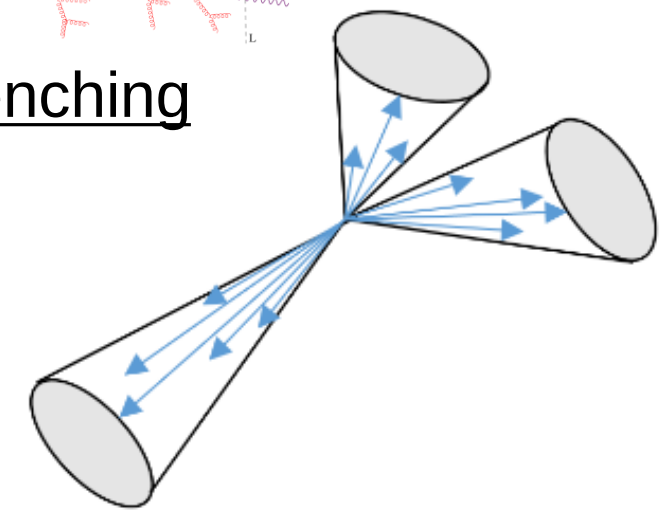


Turbulance cascade





Third jet quenching



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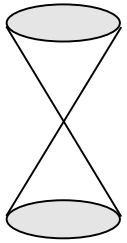
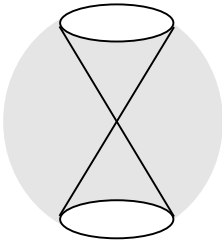
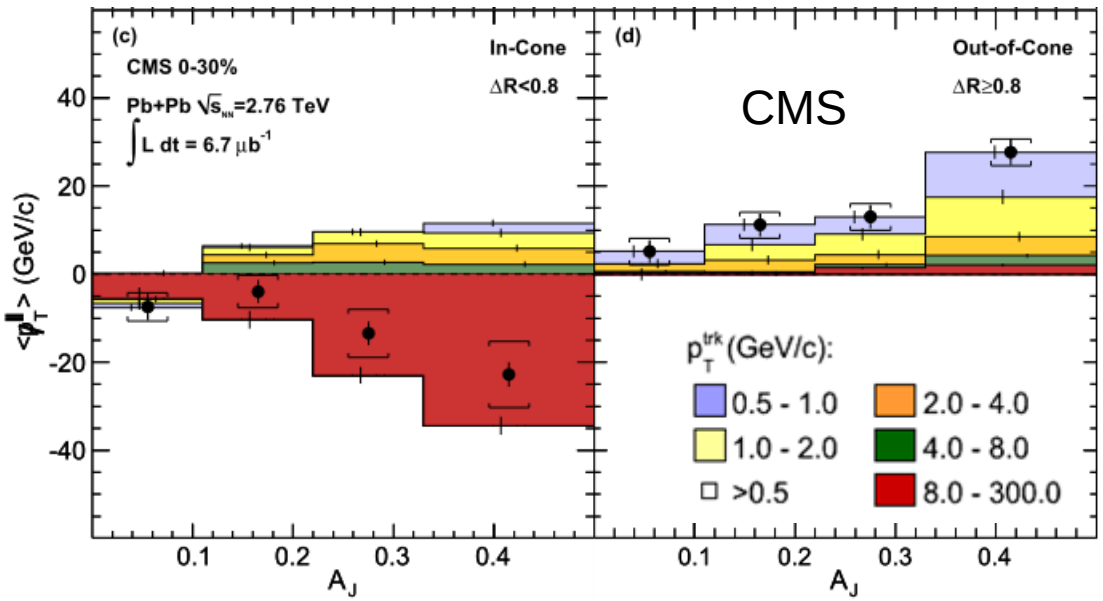


Tracks in the jet cone ΔR<0.8



Tracks out of the jet cone ΔR>0.8



PRC 84 (2011) 024906

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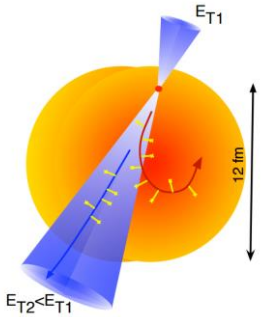
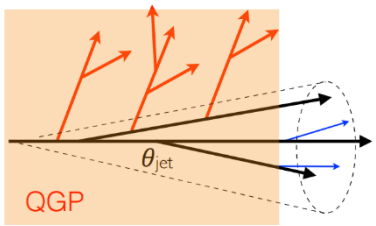
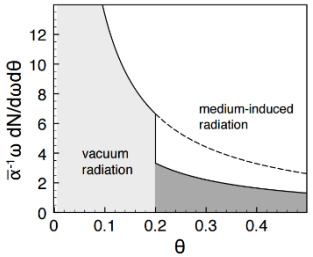
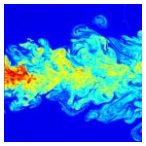


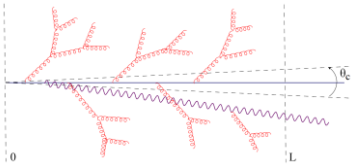
Decoherence





Turbulance cascade





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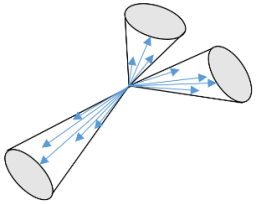
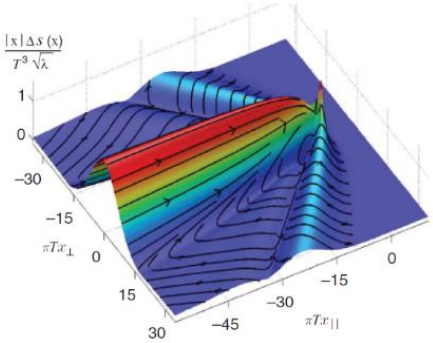
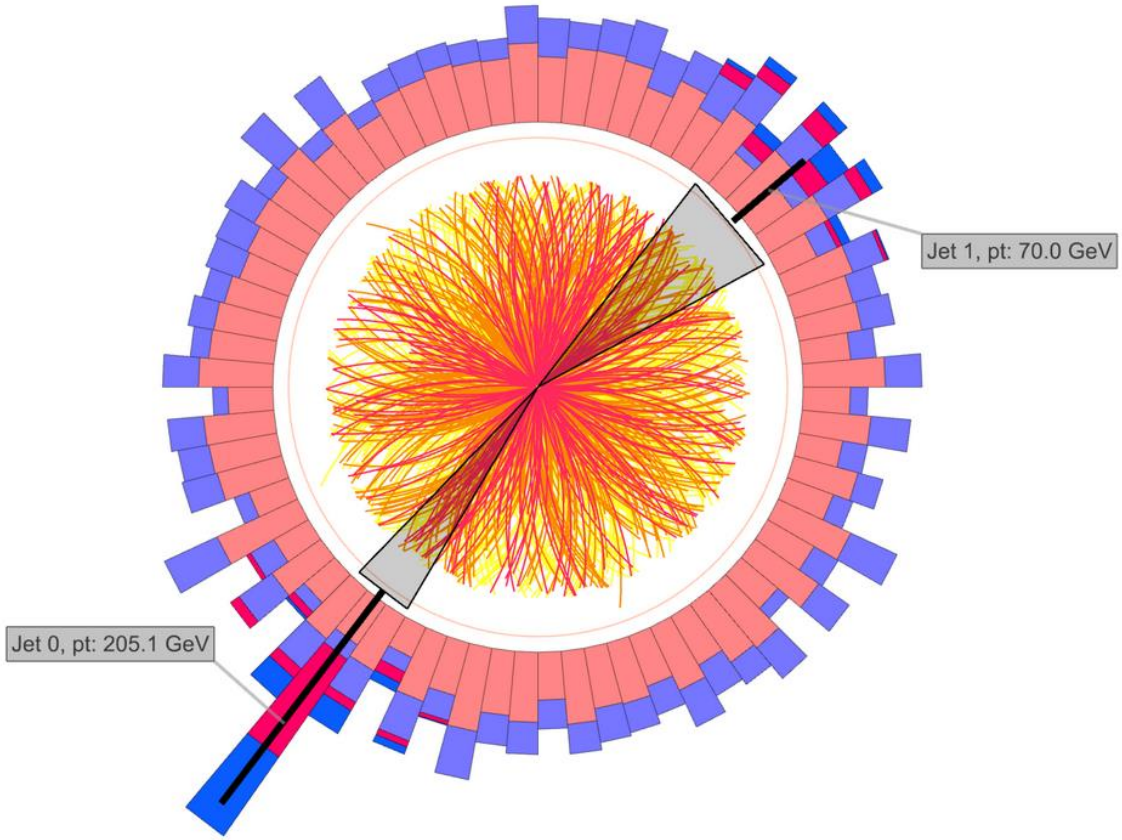


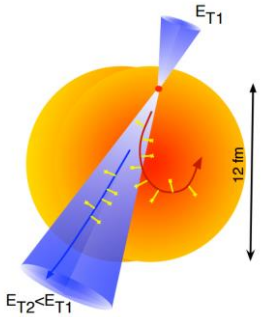


Strongly coupling approach, hydro

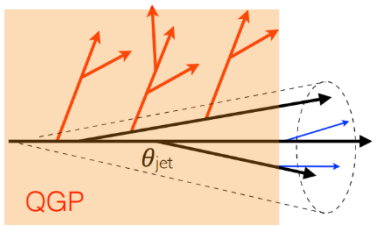
Significant energy flow out of the jet cone

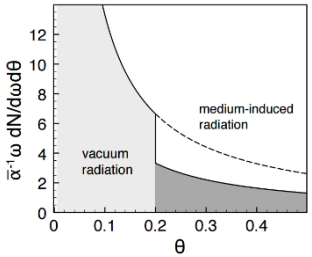


Jet collimation

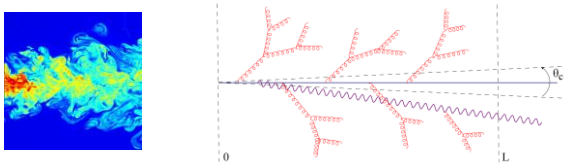


Decoherence

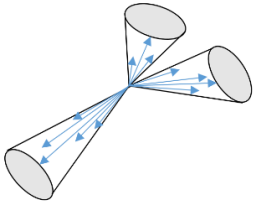




Turbulance cascade

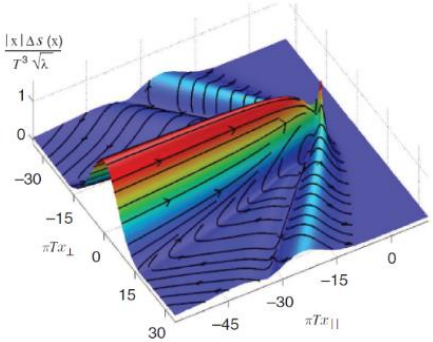


Third jet quenching



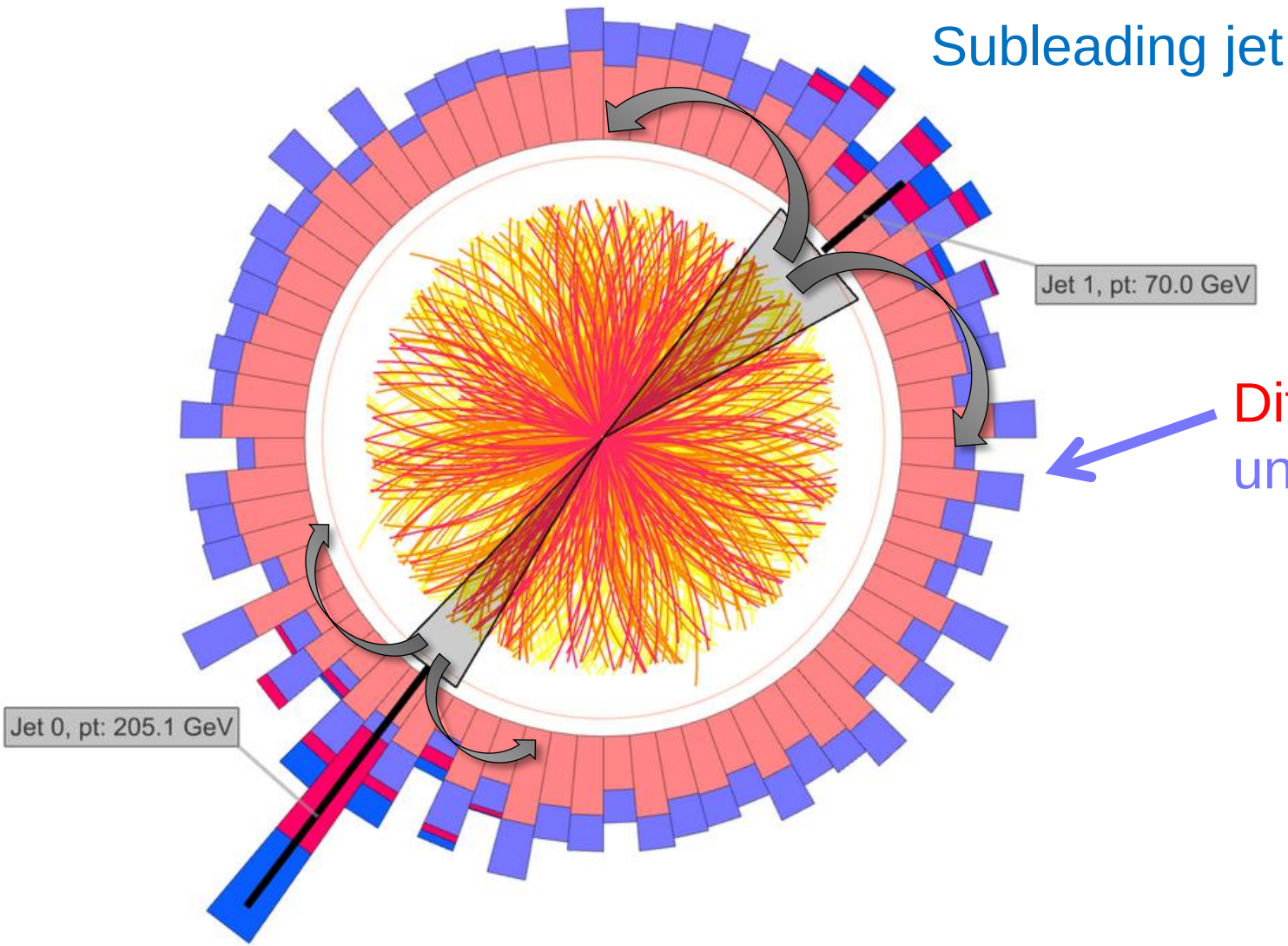
(1) How many particles are carrying the missing energy?

(2) What is the angular distribution of the quenched energy flow with respect to the dijet axis?



Strongly coupling approach, hydro

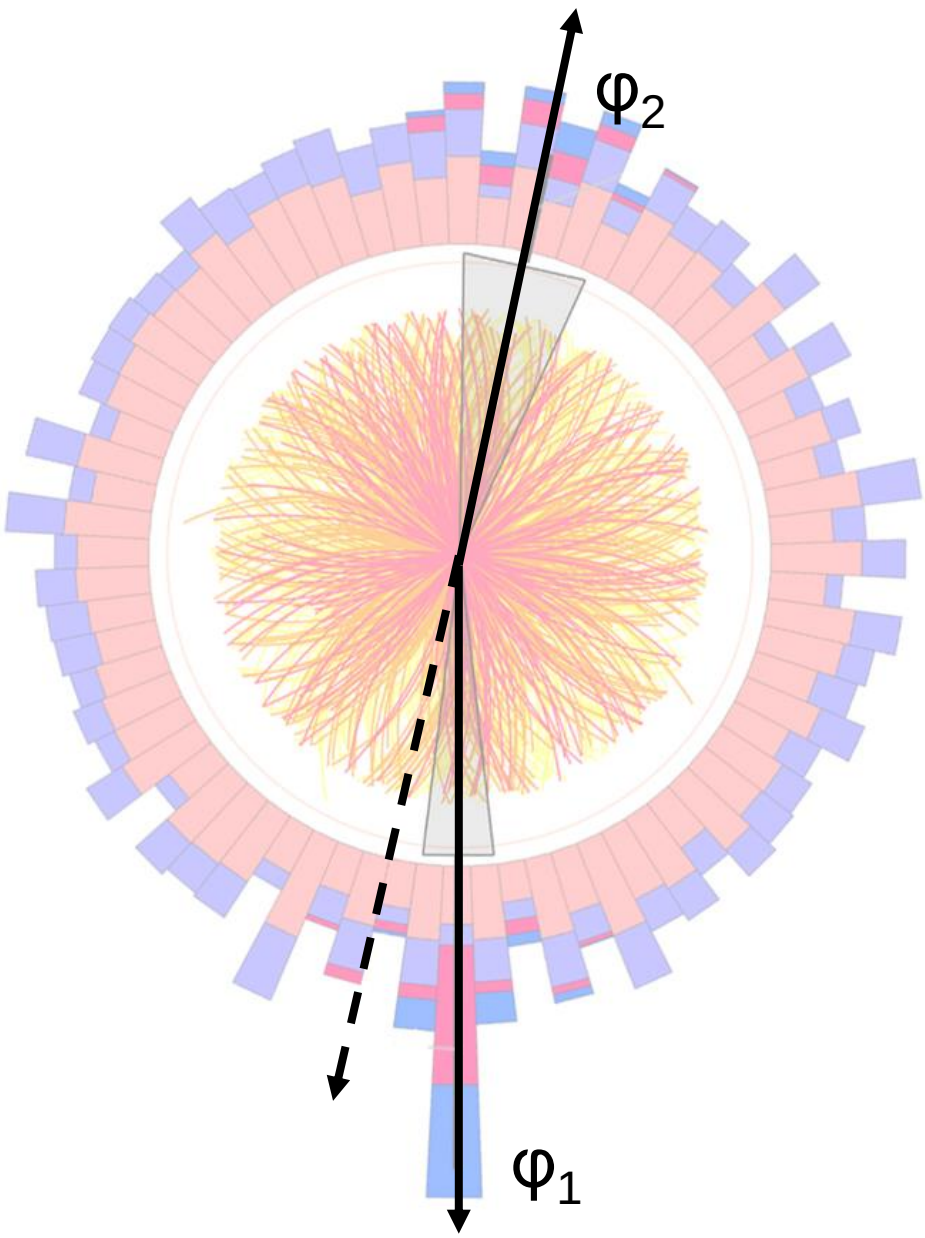
Measurement of quenched energy flow



Difficulty: Large PbPb underlying event (UE)

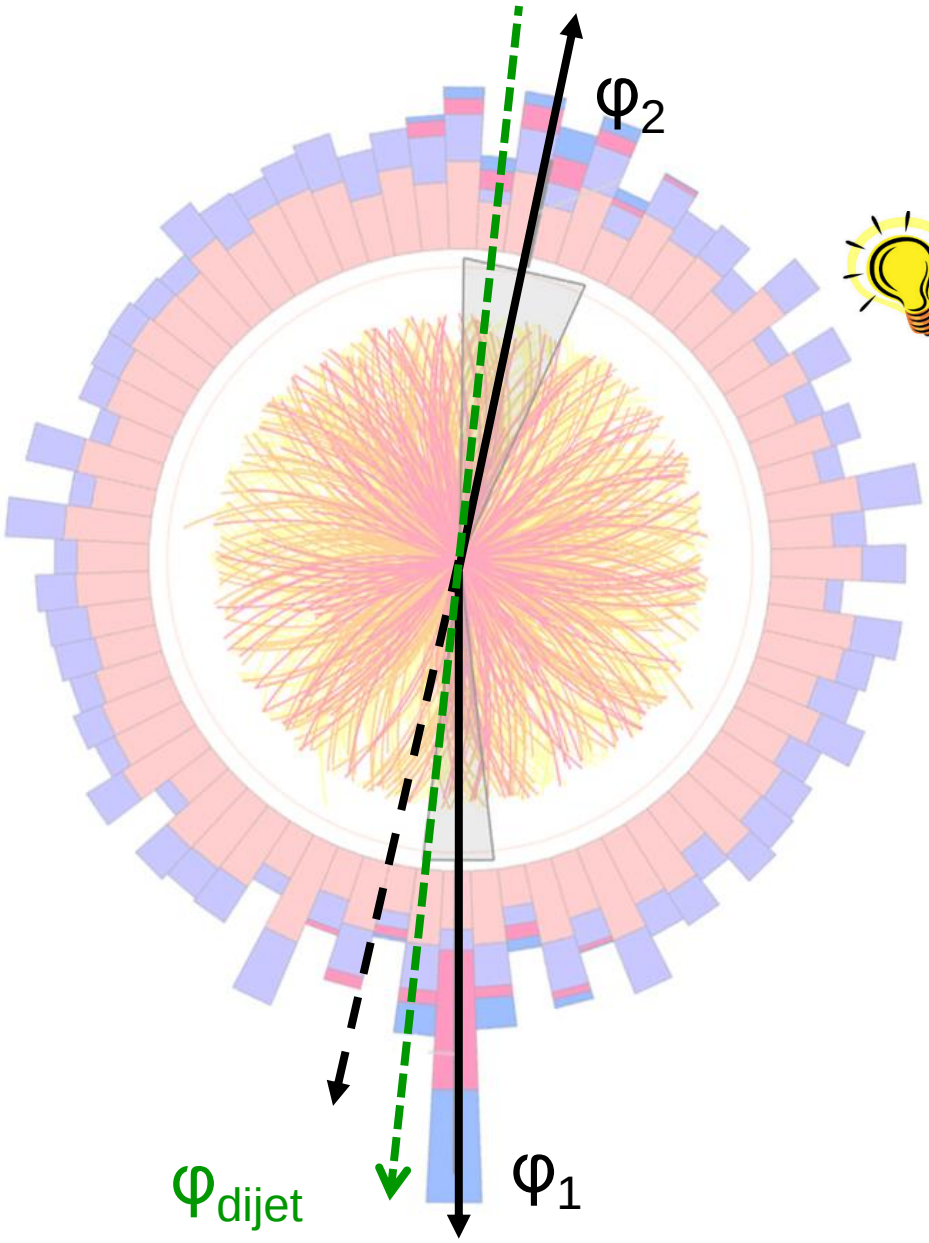
Idea: Use all charged particles (p_T>0.5 GeV/c)
Study the transverse momentum balance (uncorrelated UE cancels)

Multiplicity difference



What is the **multiplicity** of the particles that balance the “extra” lost p_T?

Multiplicity difference



What is the **multiplicity** of the particles that balance the "extra" lost p_T?

Compare the multiplicities in the leading and subleading jet hemispheres

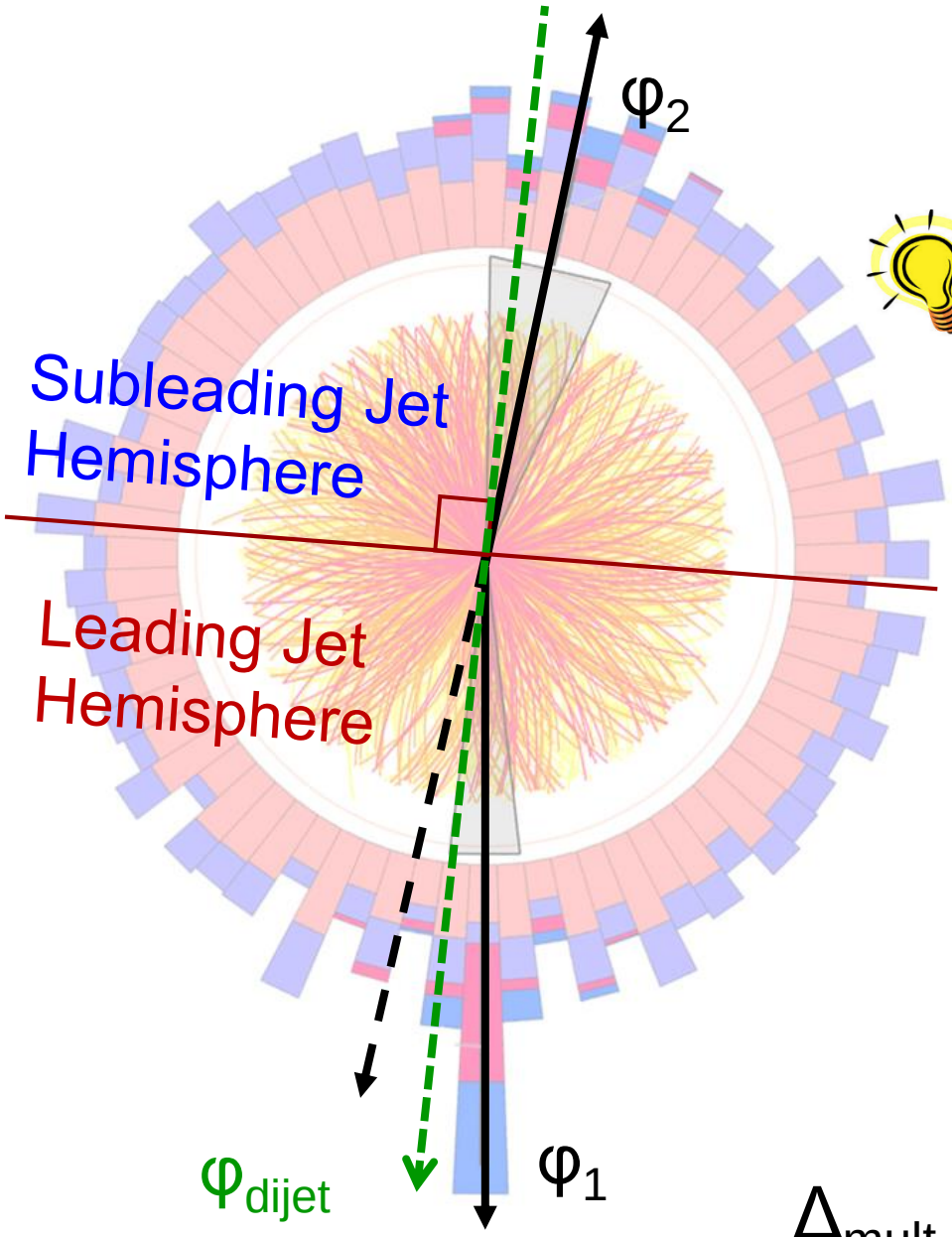
Direction of the dijet is defined as:

$$\varphi_{dijet} = \tfrac{1}{2}(\varphi_1 + (\pi - \varphi_2))$$

(In contrast to PRC 84 (2011) 024906, where the leading jet direction was used)

Provide UE cancellation differential in ΔR

Multiplicity difference (subleading – leading jet)



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(In contrast to PRC 84 (2011) 024906, where the leading jet direction was used)

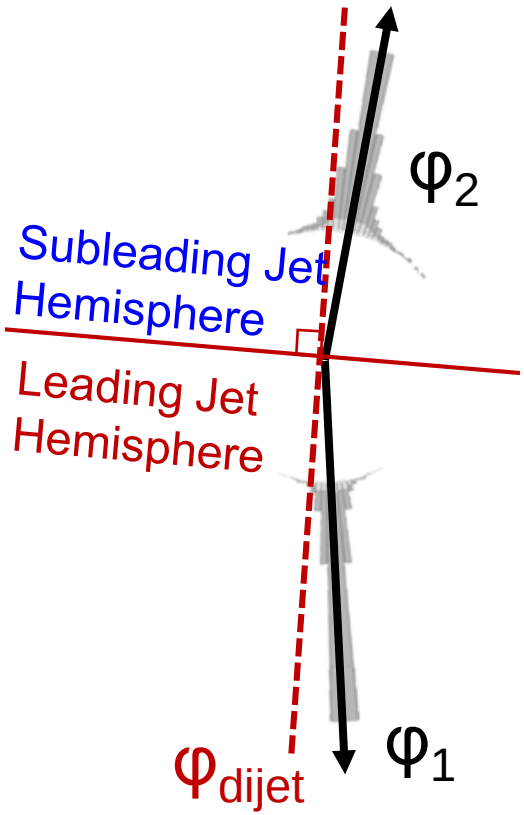
Provide UE cancellation differential in ΔR

Δ_{mult} = N_{ch} in **subleading** jet hemisphere - N_{ch} in **leading** jet hemisphere

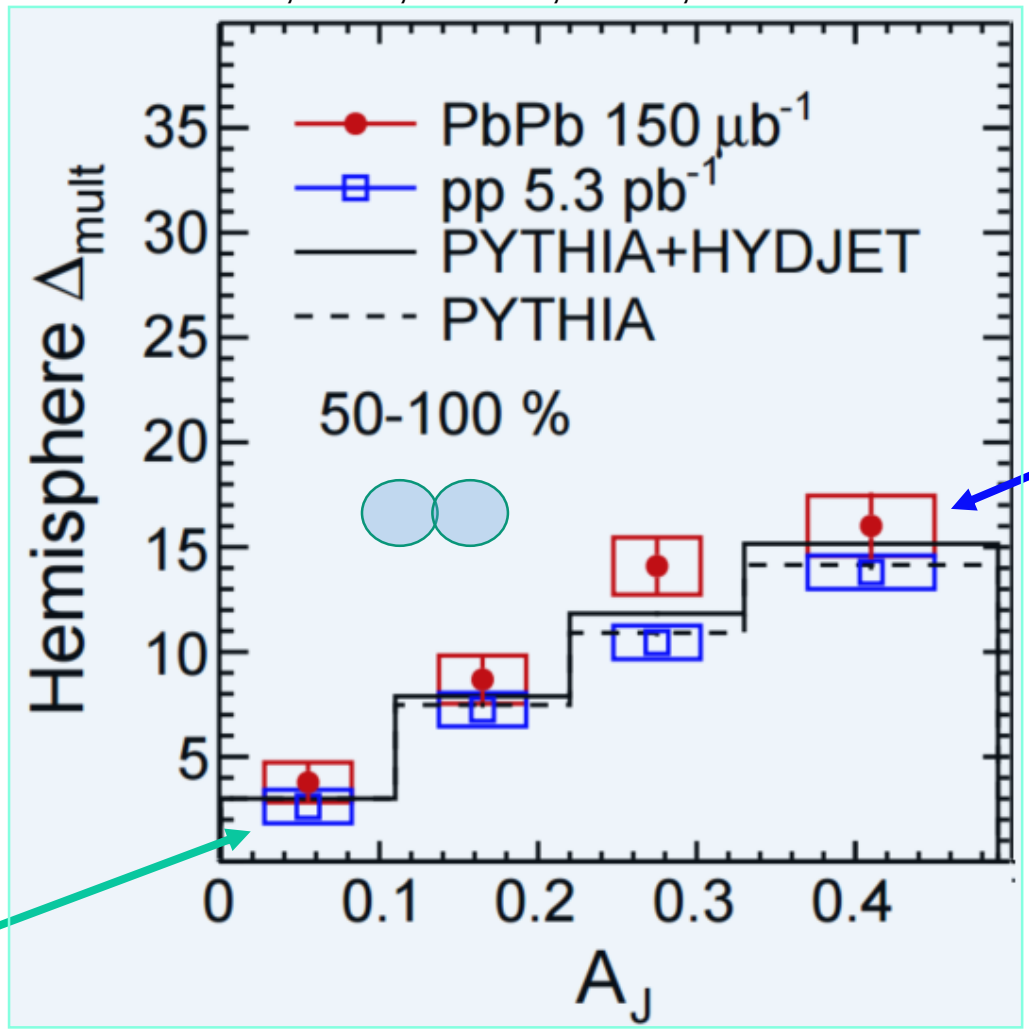
Multiplicity difference (subleading – leading jet)

CMS-PAS-HIN-14-010

$\sqrt{s_{NN}}$ = 2.76 TeV



$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$



Three / multi-jet events

$\sqrt{s_{NN}}$=2.76 TeV
anti-k_T Calo R=0.3
$|\eta_{trk}| < 2.4$
$p_T^{trk} > 0.5$ GeV/c

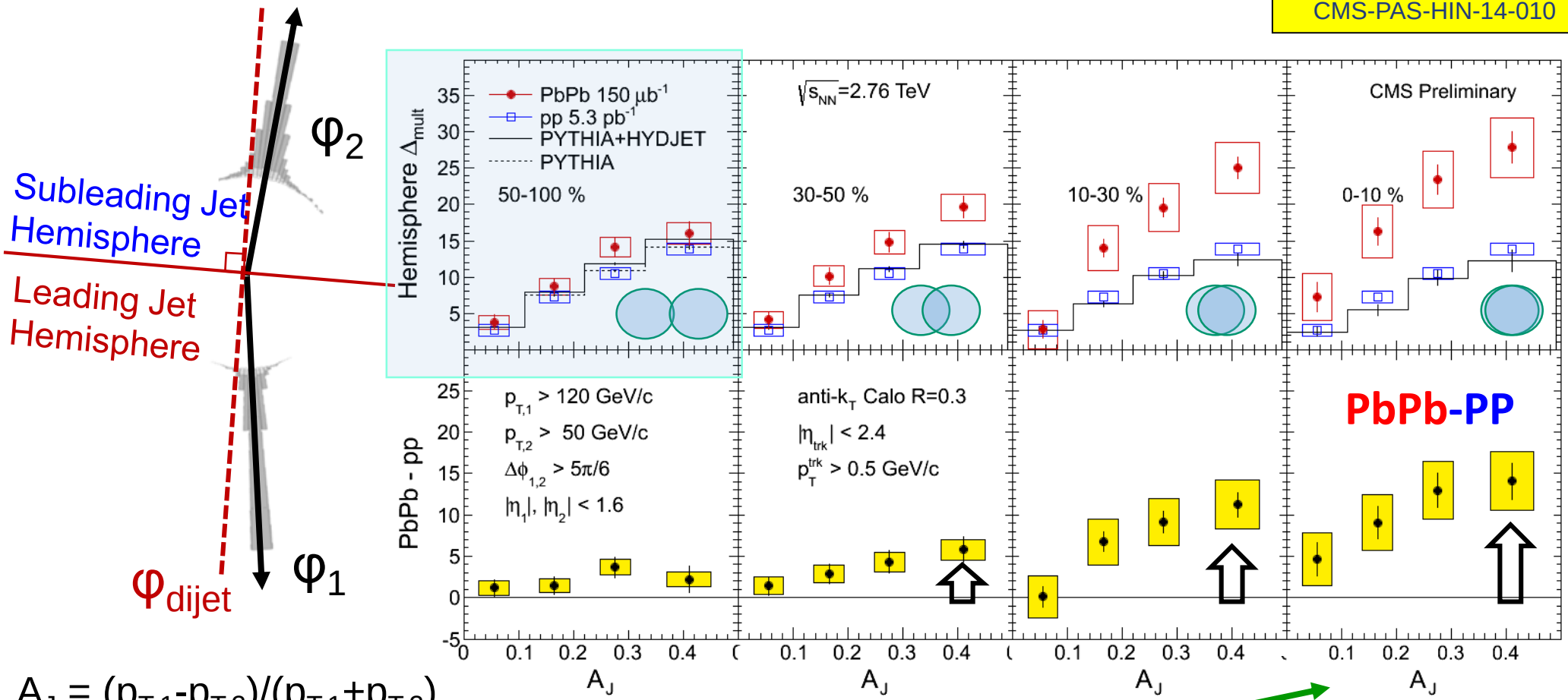
Symmetric Dijet Events

Multiplicity difference between the **subleading** and **leading** hemisphere is increasing vs. dijet asymmetry in pp and peripheral PbPb.

There are more charged particles in the **subleading** hemisphere

Multiplicity difference (subleading – leading jet)

CMS-PAS-HIN-14-010



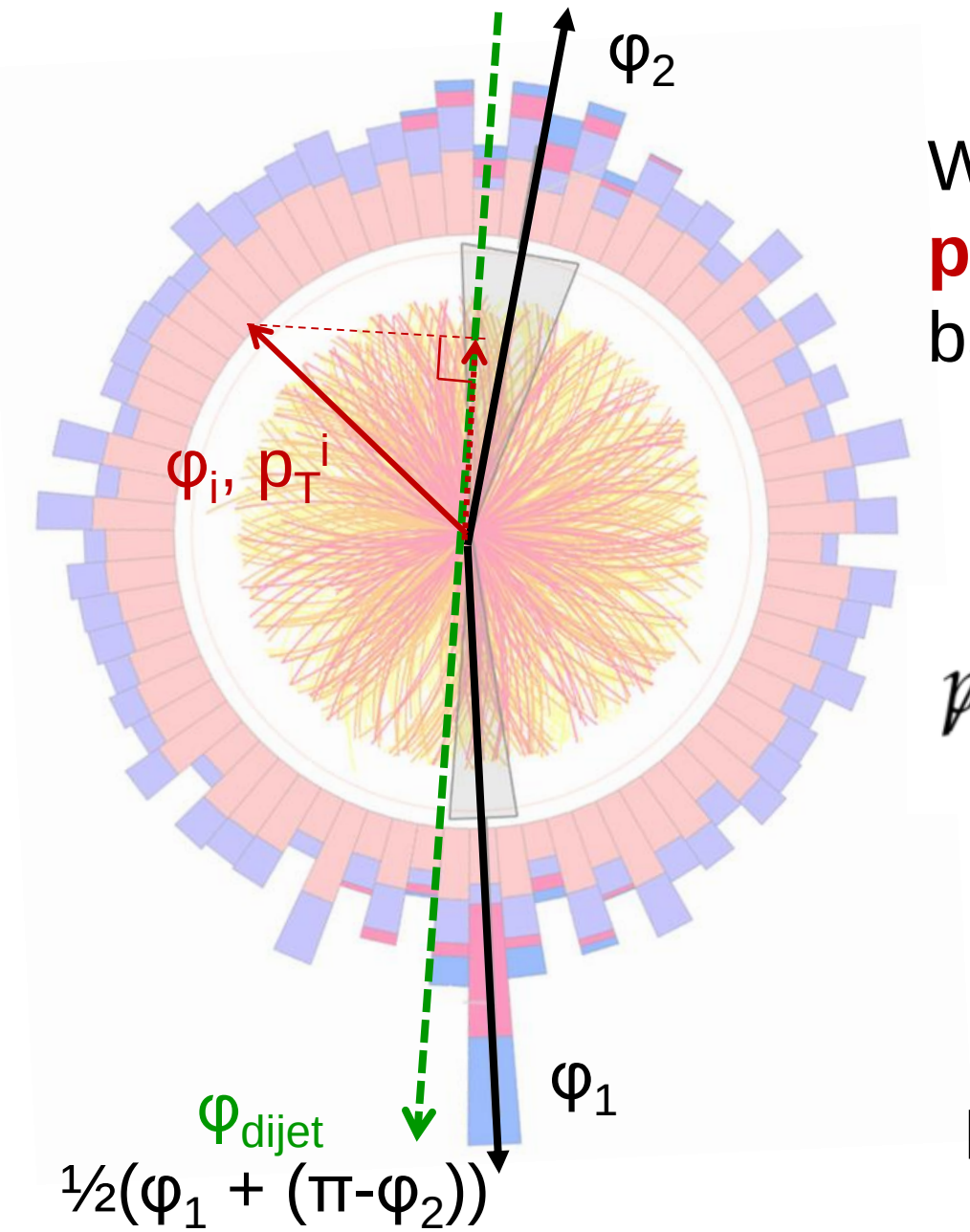
$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

This increase is larger in central PbPb

The enhancement in PbPb compared to pp increases with centrality

Large A_J, 0-10%: ~**14 extra particles (p_T>0.5 GeV)** in the subleading jet hemisphere

Missing $p_T^{||}$



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

Charged particle azimuthal angle

$$\not{p}_T^{||} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{Dijet}\right)$$

Dijet axis

Projection to dijet axis

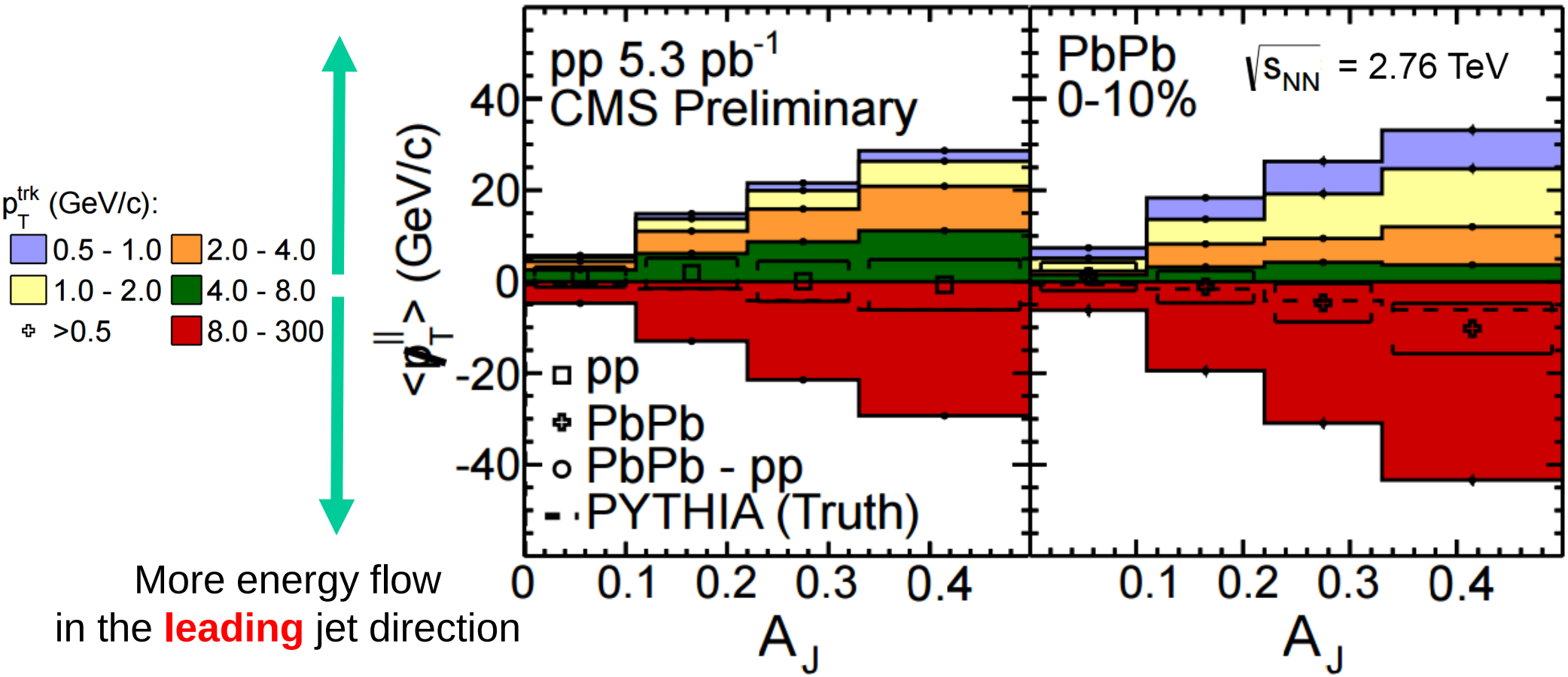
Missing $p_T^{||}$ vs. A_J

CMS-PAS-HIN-14-010

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

PP

0-10% PbPb



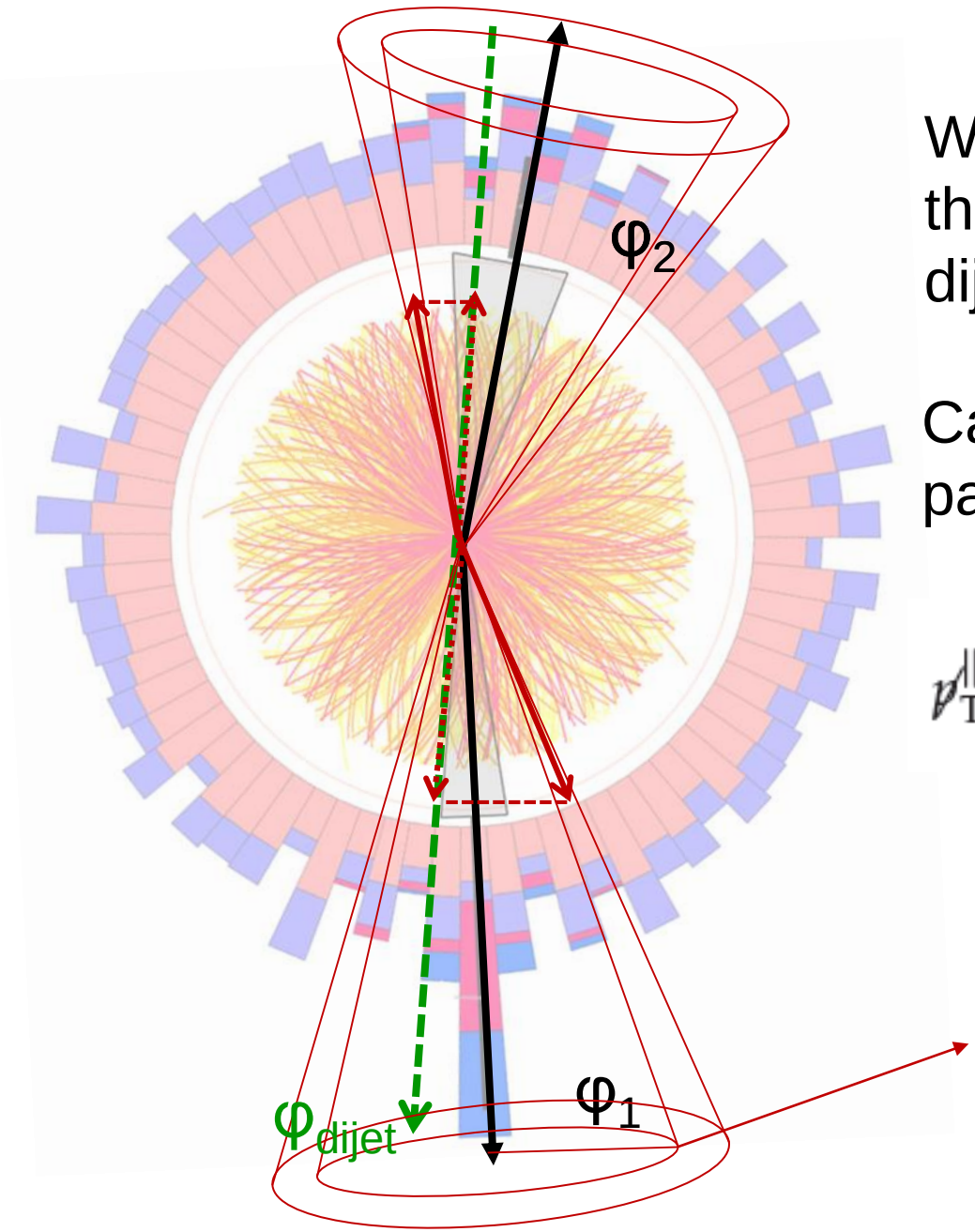
More energy flow
in the **leading** jet direction

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 < 2 GeV/c

Missing $p_T^{||}$ vs. ΔR



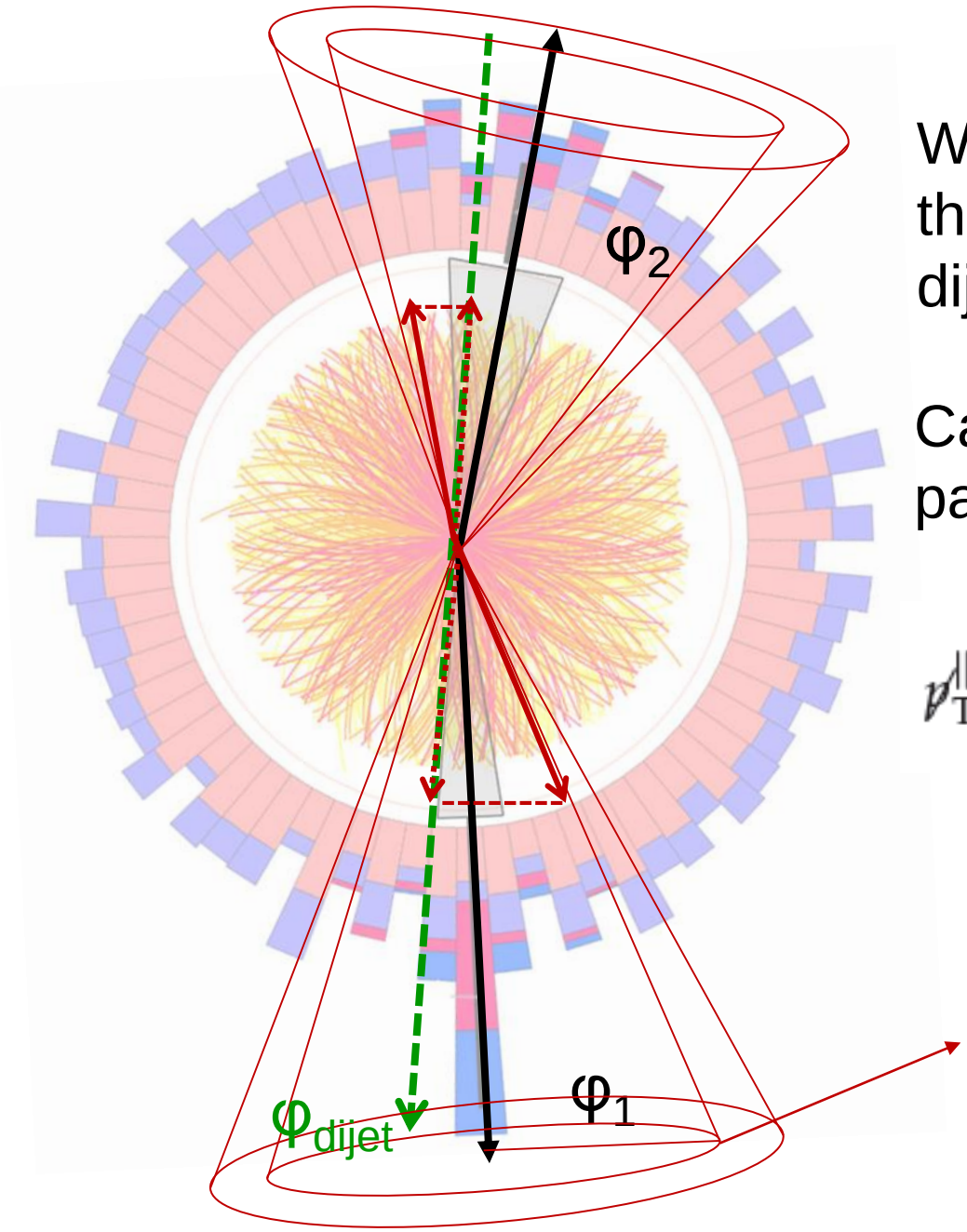
What is the angular distribution of these particles with respect to the dijet system?

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

$$\not{p}_T^{||} = \left(\sum_i -p_T^i \cos\left(\phi_i - \phi_{\text{dijet}}\right) \right) \Big|_{R_{\text{down}} < \Delta R < R_{\text{up}}}$$

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

Missing $p_T^{||}$ vs. ΔR



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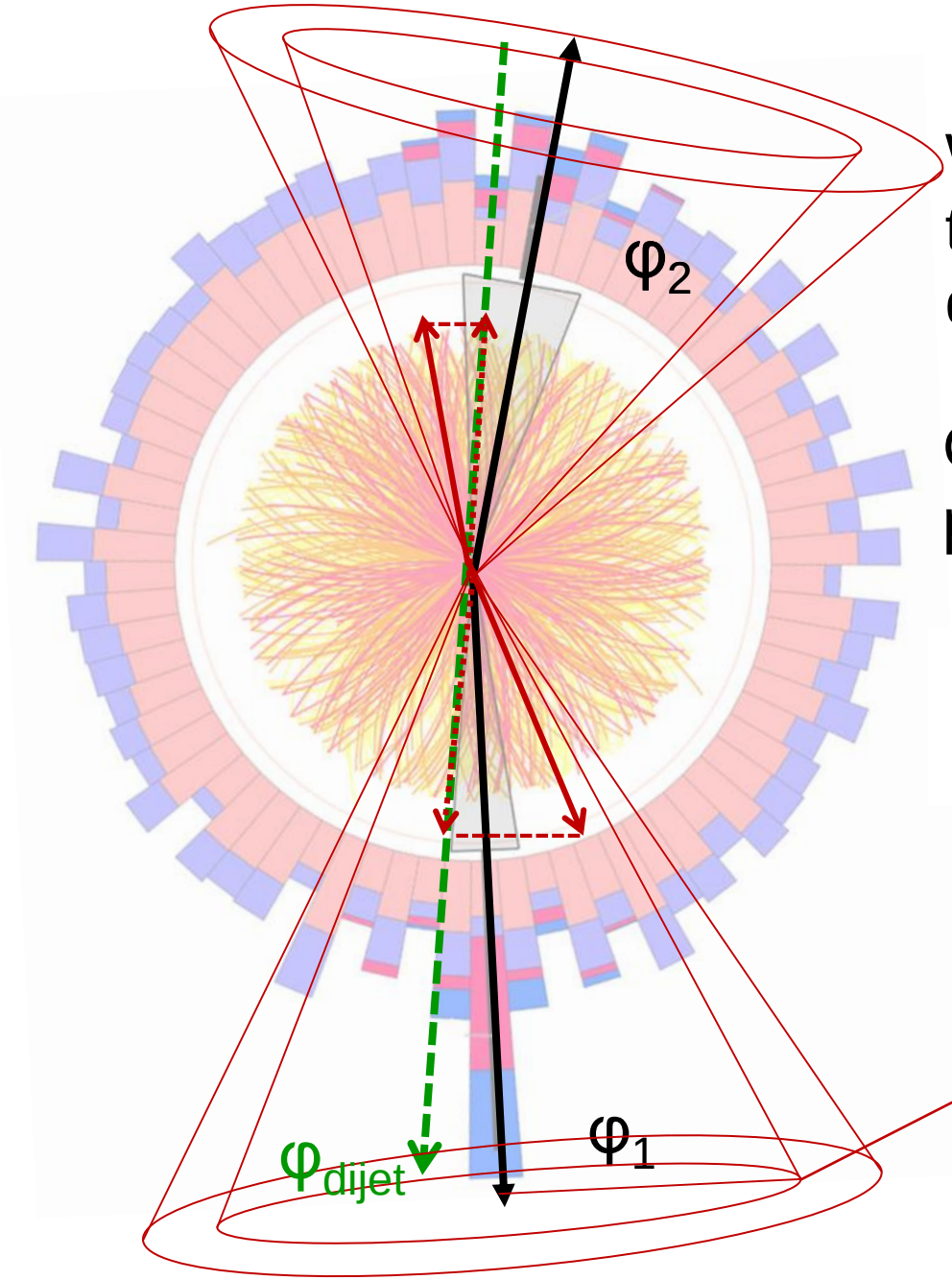
Missing $p_T^{||}$ vs. ΔR



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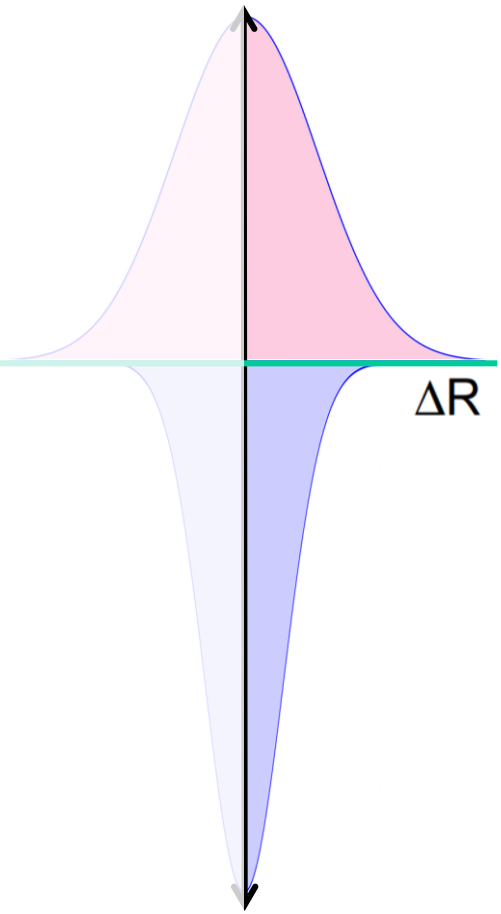
$$\Delta R = \sqrt{\Delta\phi^2_{\text{Trk,jet}} + \Delta\eta^2_{\text{Trk,jet}}}$$

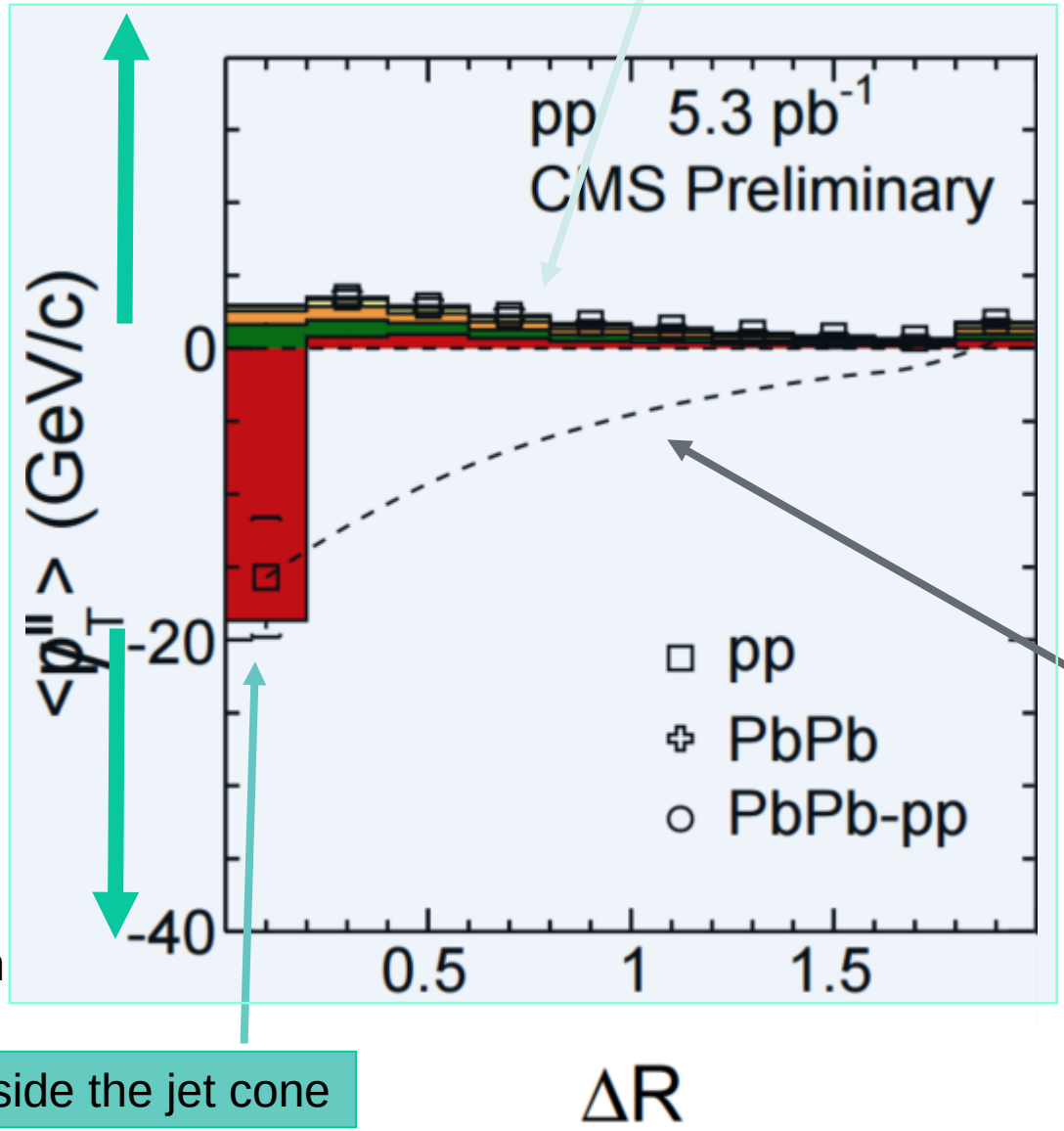
Missing $p_T^{||}$ vs. ΔR in pp

Subleading jet direction



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 - 1.0
2.0 - 4.0
1.0 - 2.0
4.0 - 8.0
>0.5
8.0 - 300.0

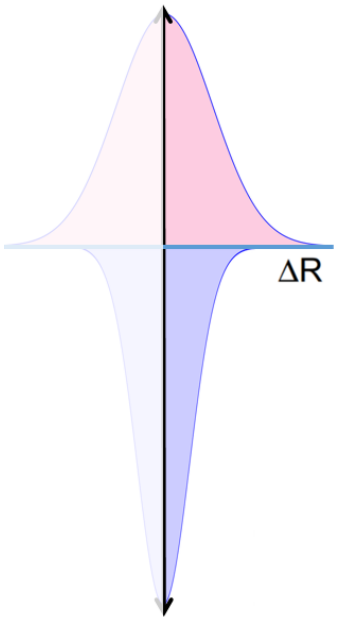
Integrated curve from 0-ΔR

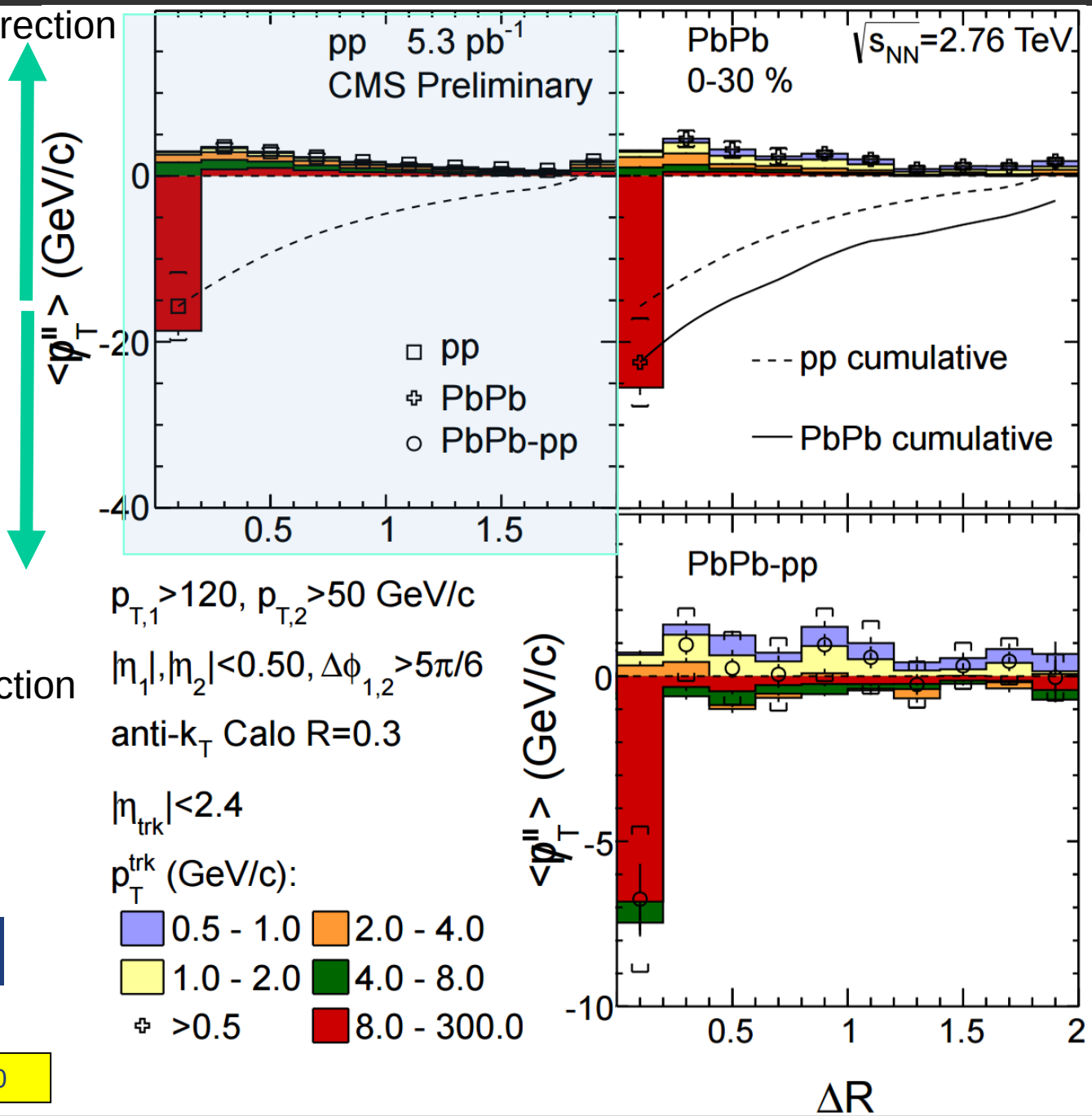
Asymmetry inside the jet cone

CMS-PAS-HIN-14-010

Missing $p_T^{||}$ vs. ΔR

Subleading jet direction





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$p_{T,1}$>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

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p_T^{trk} (GeV/c):

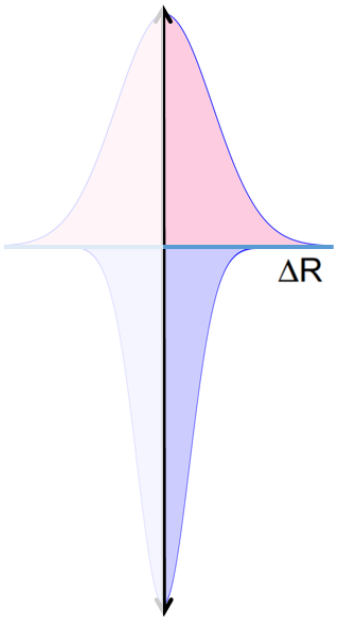
0.5 - 1.0 | 2.0 - 4.0
1.0 - 2.0 | 4.0 - 8.0
>0.5 | 8.0 - 300.0

Inclusive A_J

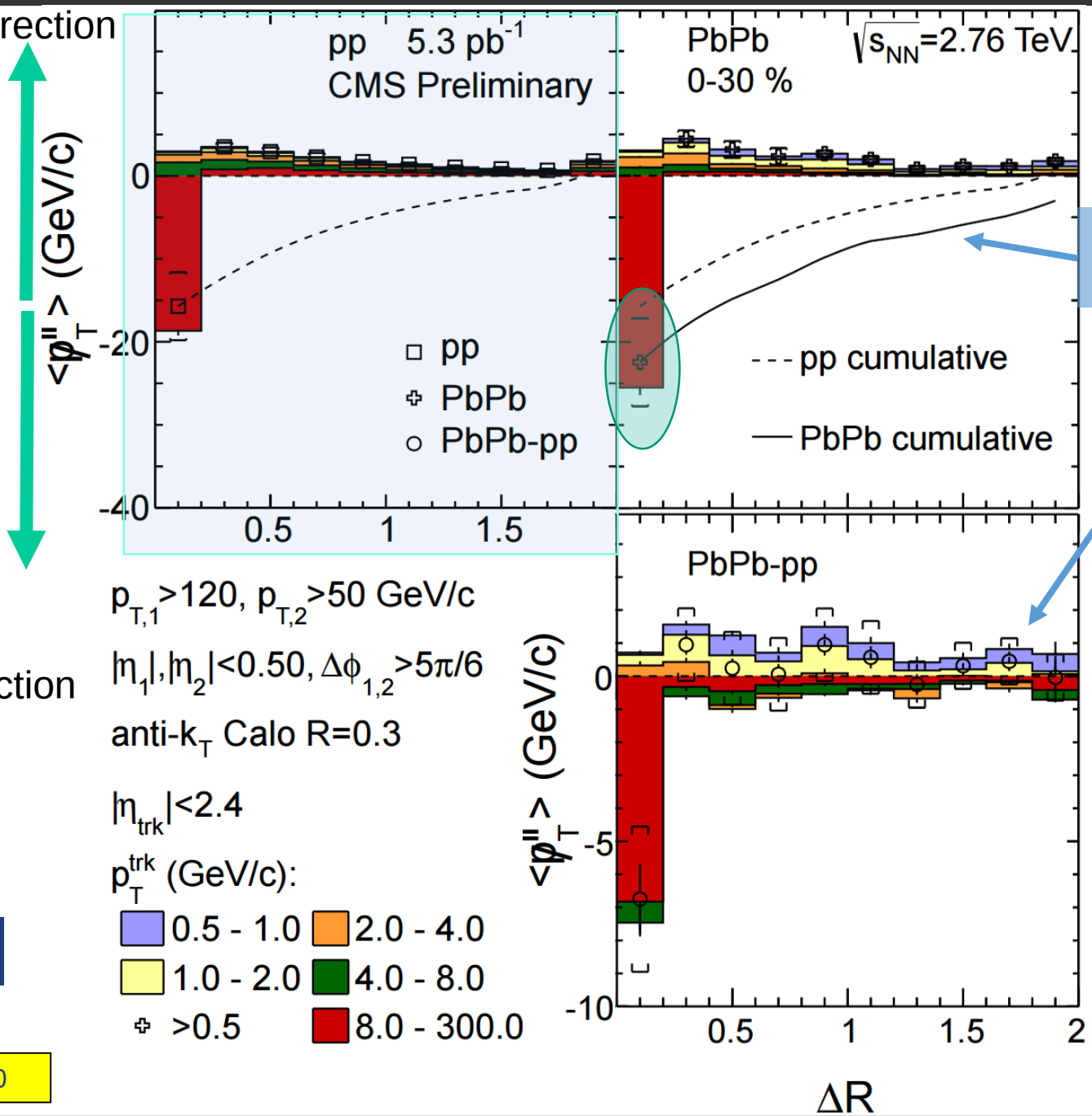
CMS-PAS-HIN-14-010

Missing $p_T^{||}$ vs. ΔR

Subleading jet direction



Leading jet direction



Cumulative energy flow are similar

Open circles: Integrated over particle p_T

$p_{T,1}$>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

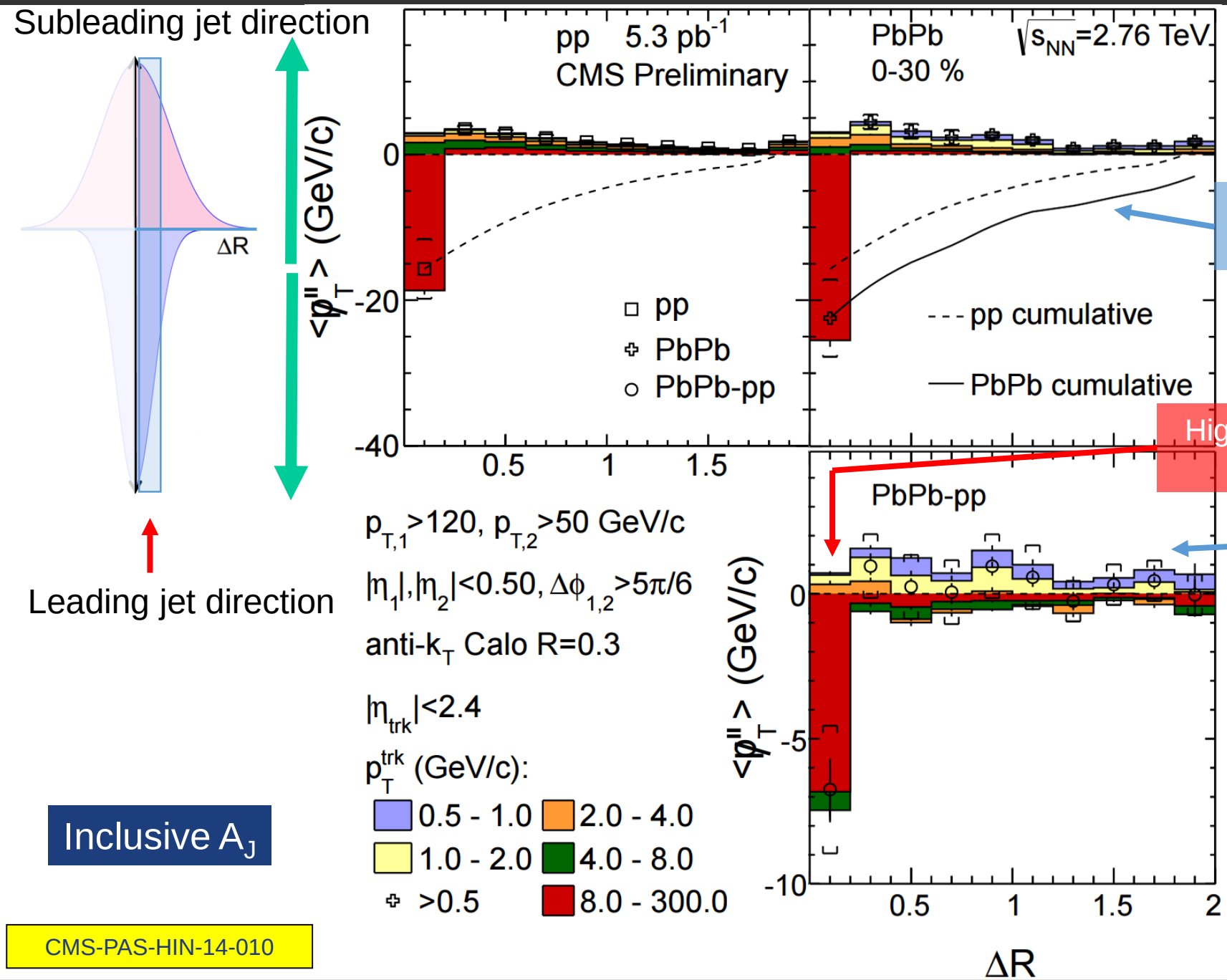
p_T^{trk} (GeV/c):

0.5 - 1.0, 2.0 - 4.0, 1.0 - 2.0, 4.0 - 8.0, >0.5, 8.0 - 300.0

Inclusive A_J

CMS-PAS-HIN-14-010

Missing $p_T^{||}$ vs. ΔR



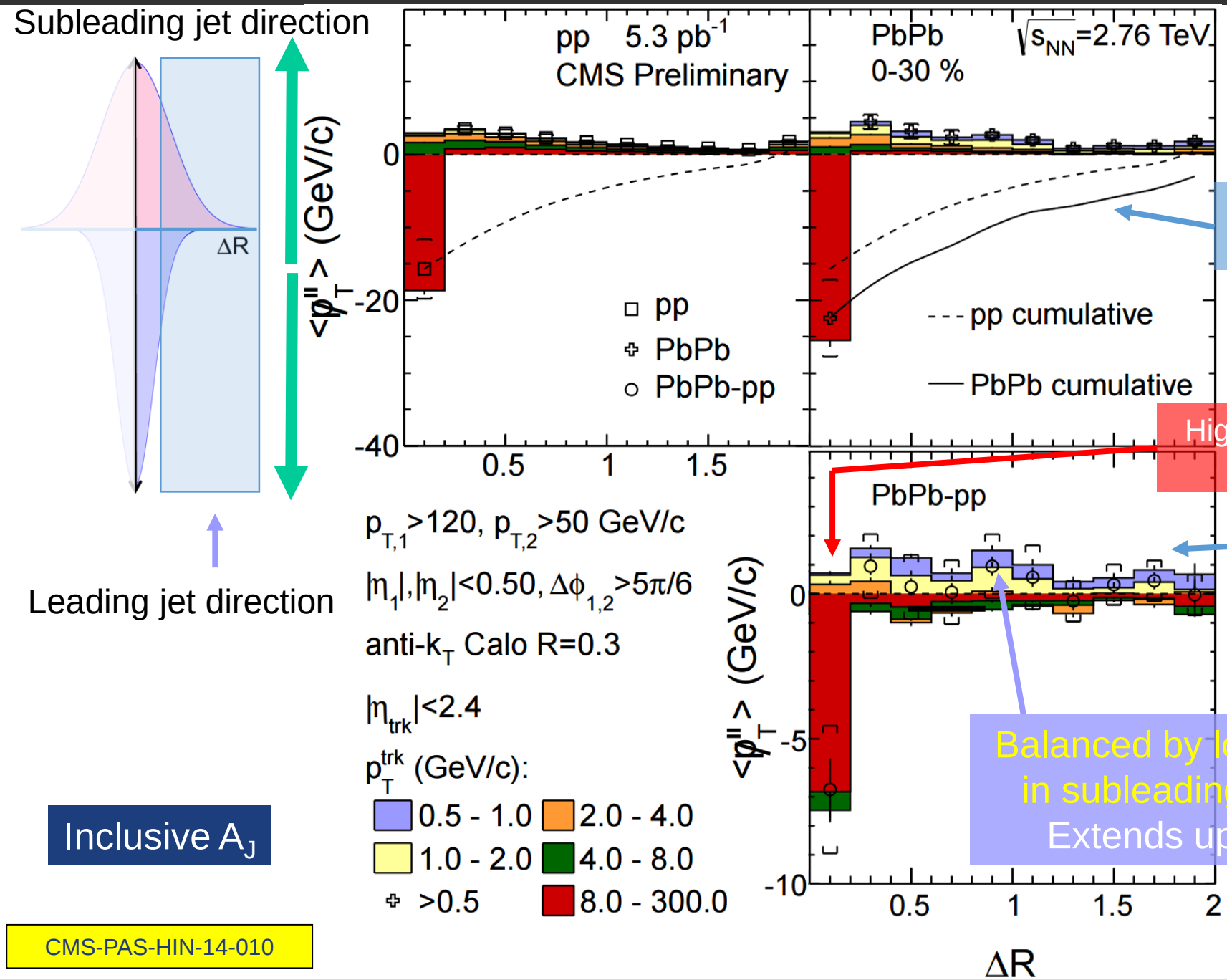
Cumulative energy flow are similar

High p_T imbalance at small ΔR

Inclusive A_J

CMS-PAS-HIN-14-010

Missing $p_T^{||}$ vs. ΔR



Cumulative energy flow are similar

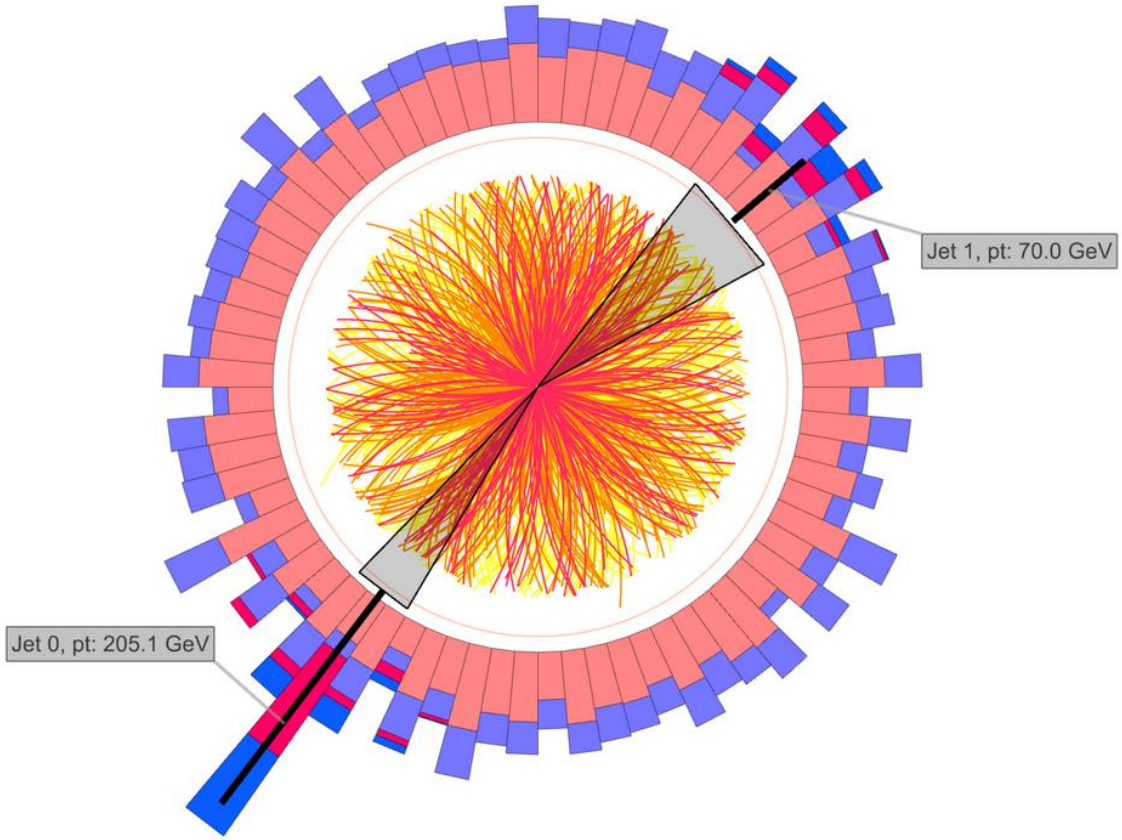
High p_T imbalance at small ΔR

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

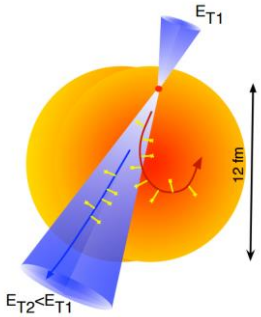
Inclusive A_J

CMS-PAS-HIN-14-010

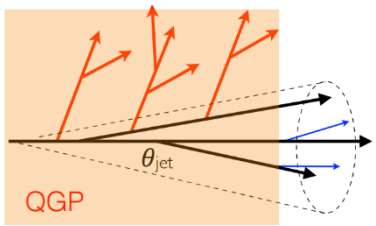
Significant energy flow out of the jet cone

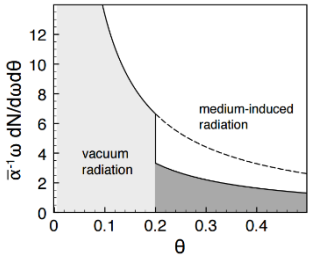


Jet collimation

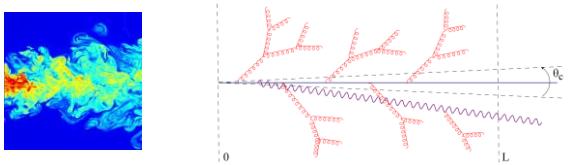


Decoherence

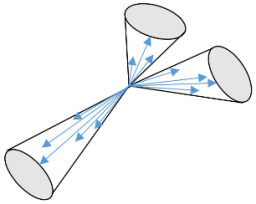




Turbulance cascade

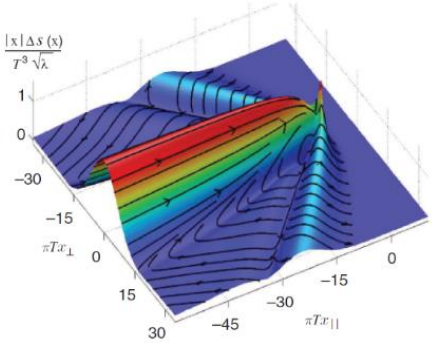


Third jet quenching



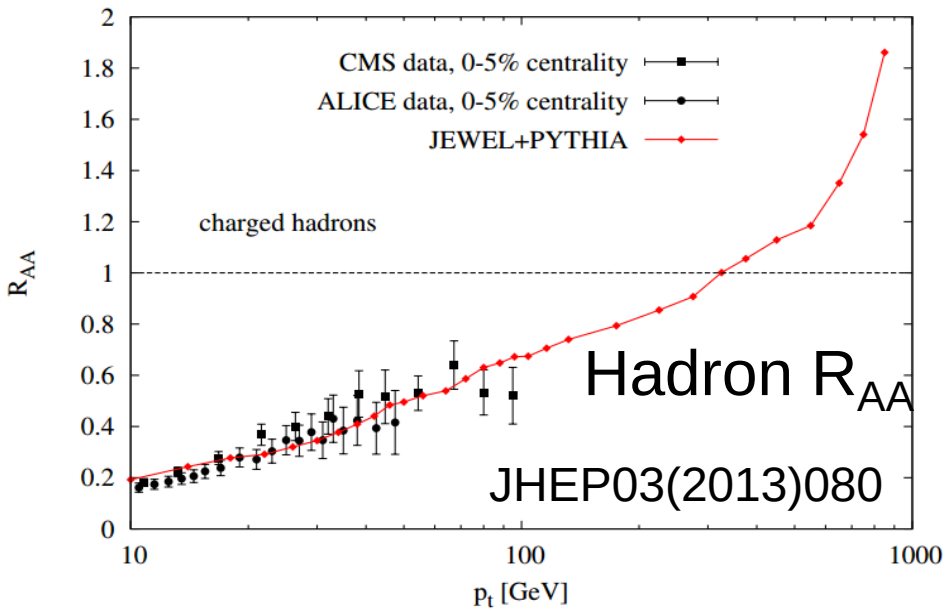
(1) How many particles are carrying the missing energy?

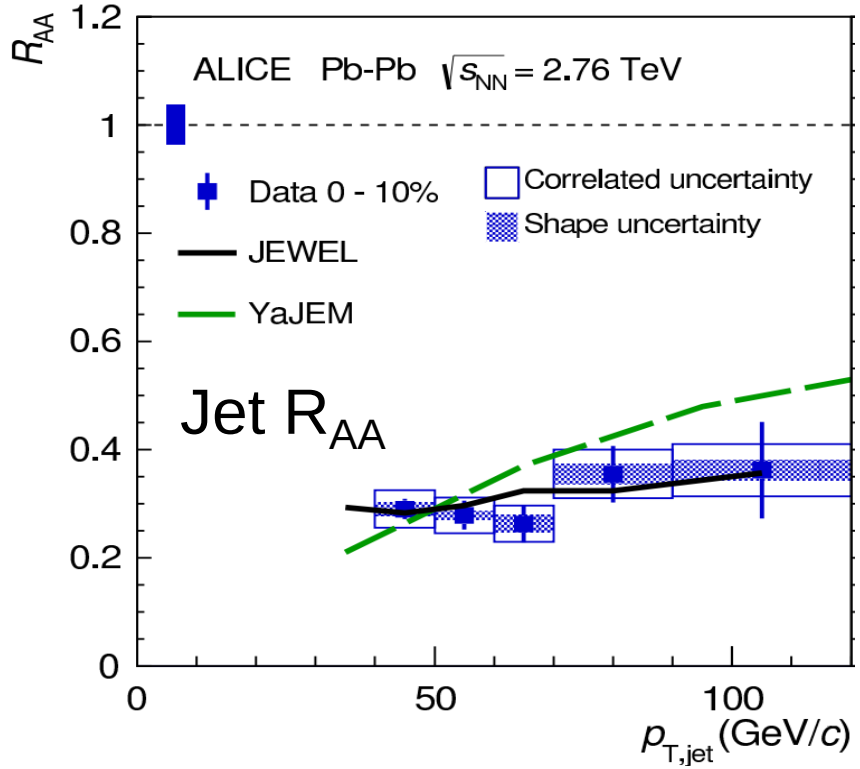
(2) What is the angular distribution of the quenched energy flow with respect to the dijet axis?

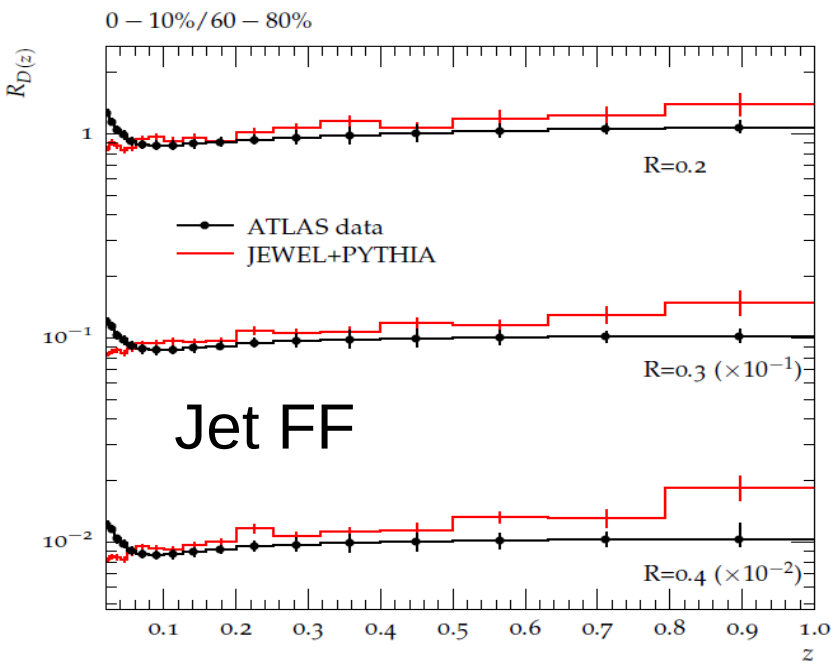


Strongly coupling approach, hydro

Jet data vs. JEWEL



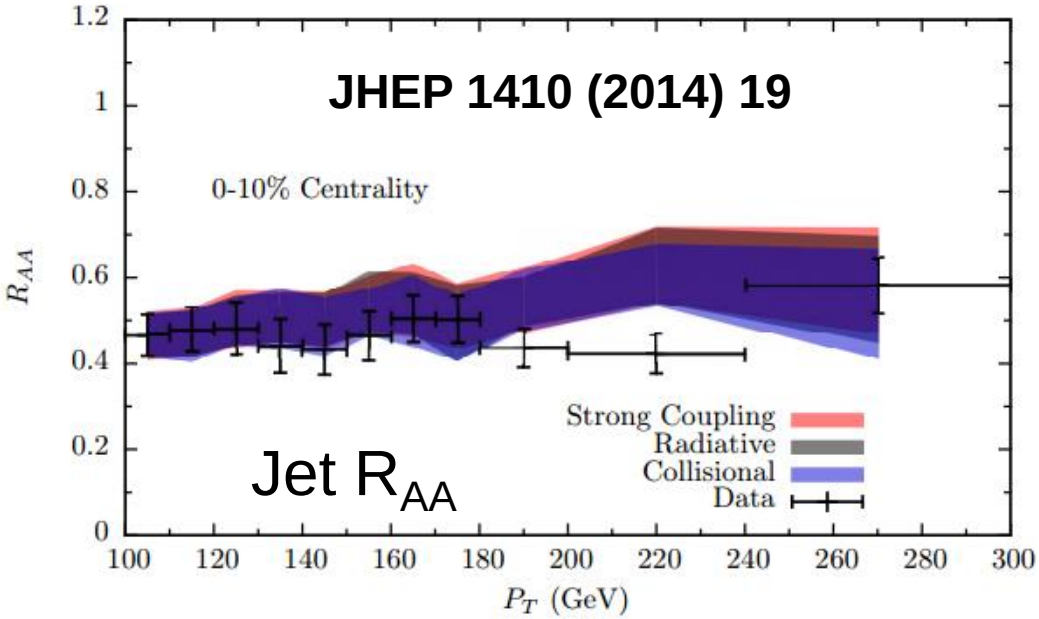


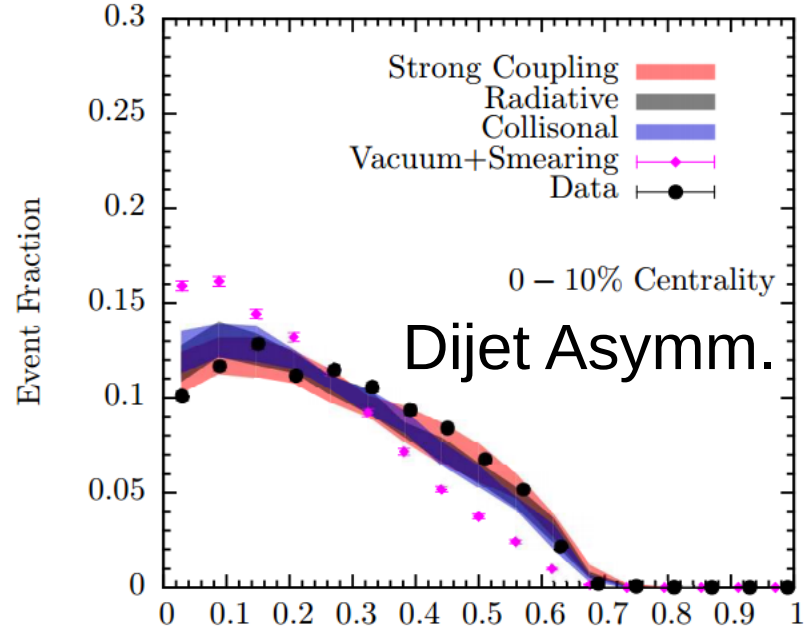


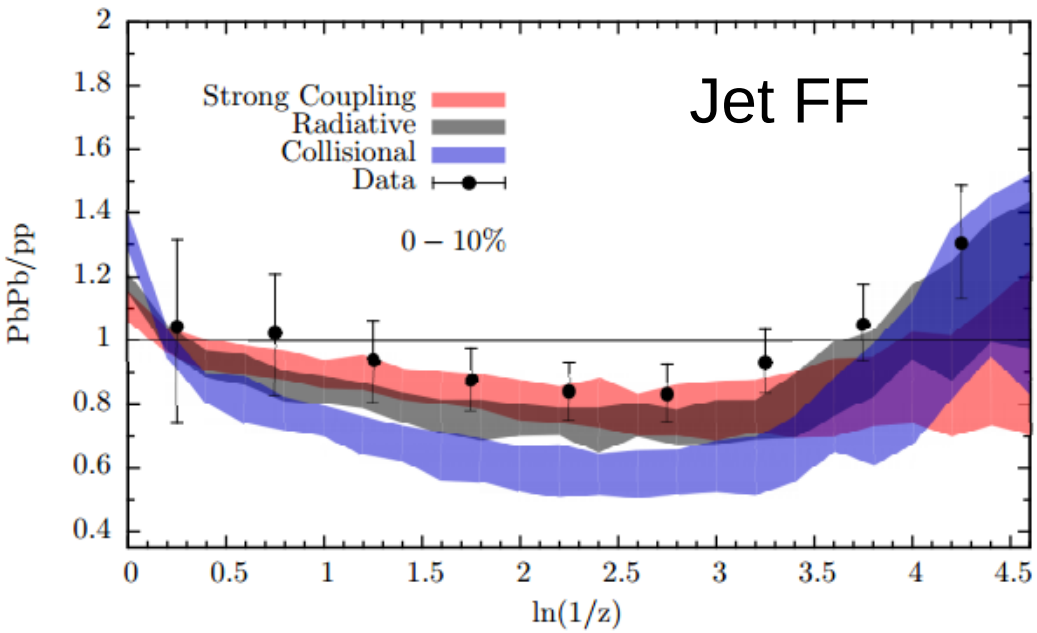
Jet Quenching Monte Carlo based on weak coupling approach:

Reasonable description of jet FF, jet R_{AA} and charged hadron R_{AA}

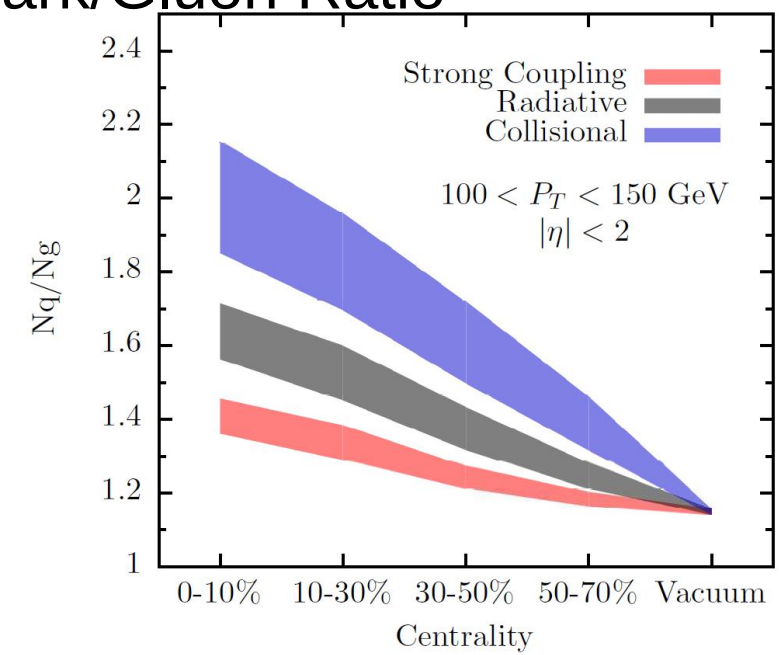
Description of the jet data with strong coupling approach







Quark/Gluon Ratio



Outlook

- LHC Run II: PbPb @ 5 TeV in 2015
  - High statistics photon-jet sample
  - Z-jet correlation
  - Multi-jet correlation
  - Flavor tagged jet

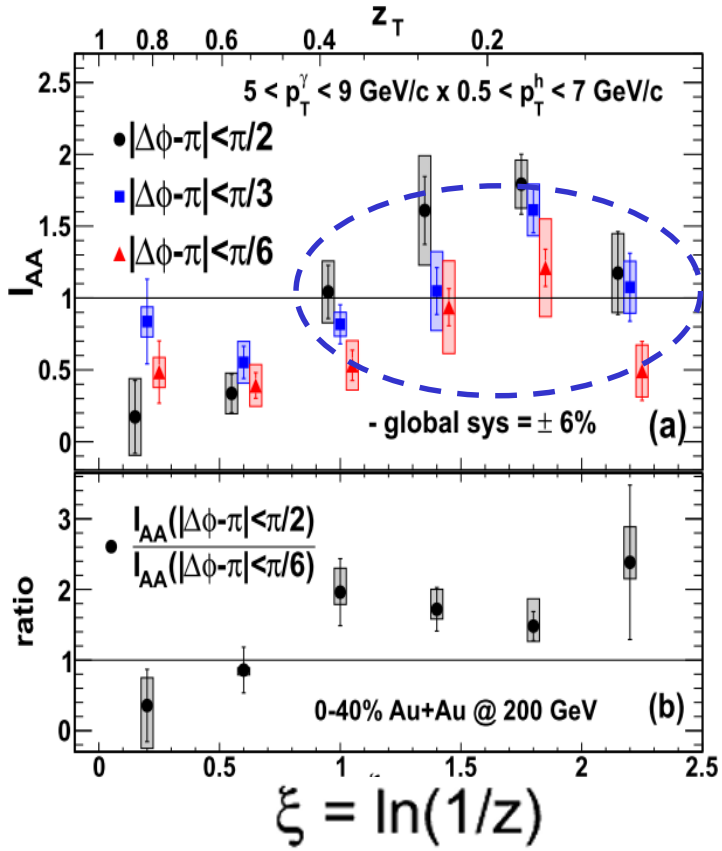
- Need an iterative feedback cycle between theory and experiment
  - Quenched jet event generator
  - Tell us your favorite analysis with Run II data!

Backup slides

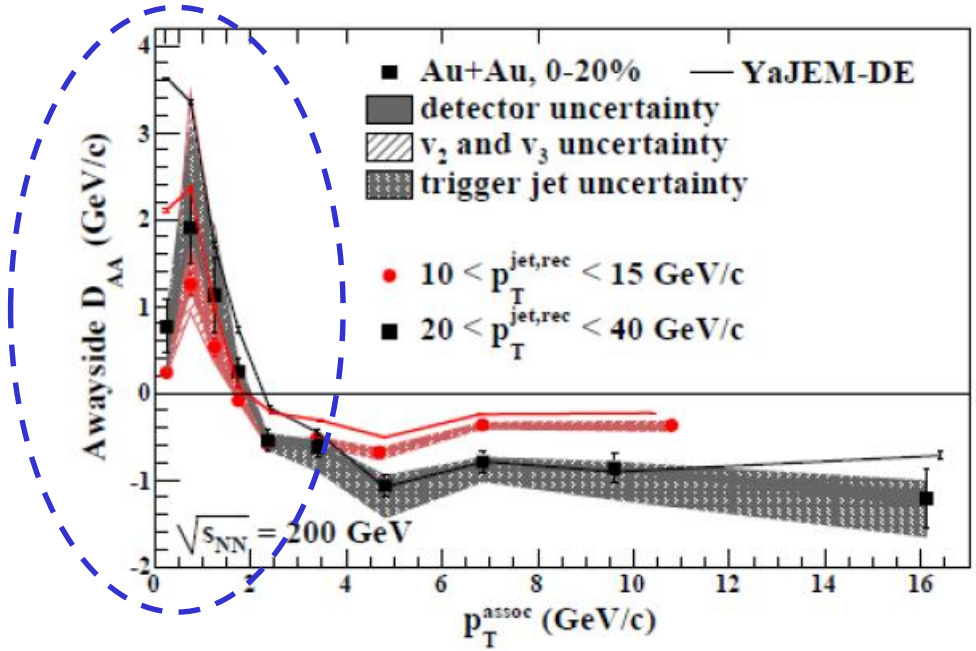
Consistent picture: excess of low p_T particle in the jet cone

PHENIX

Photon-tagged Hadron I_{AA}

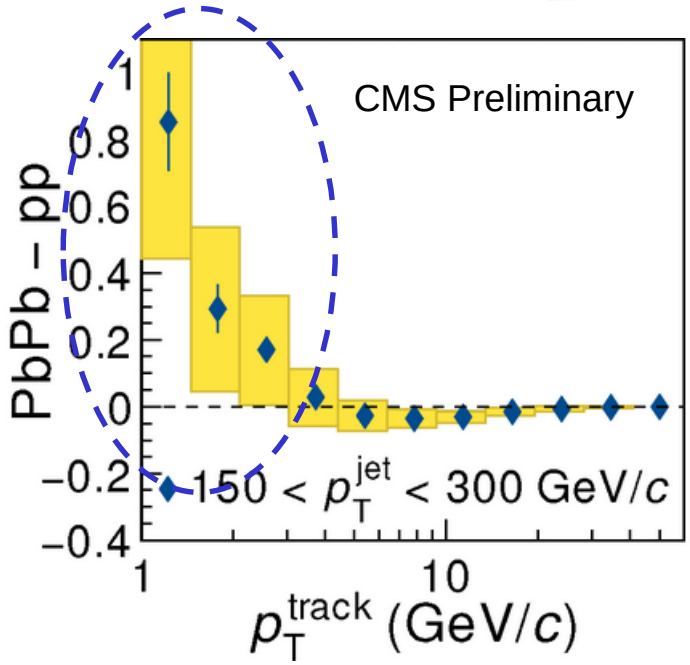


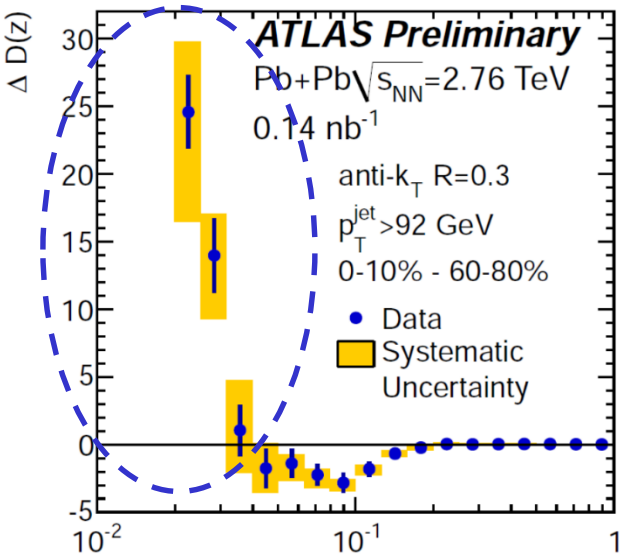
$Z = p_{||}^{Trk} / p^{Jet}$



STAR

Jet-Hadron





$Z = p_{||}^{Trk} / p^{Jet}$