CMS Experiment at the LHC, CERN

Overview of Experimental Medium Response Signal and Insights from Theoretical Models

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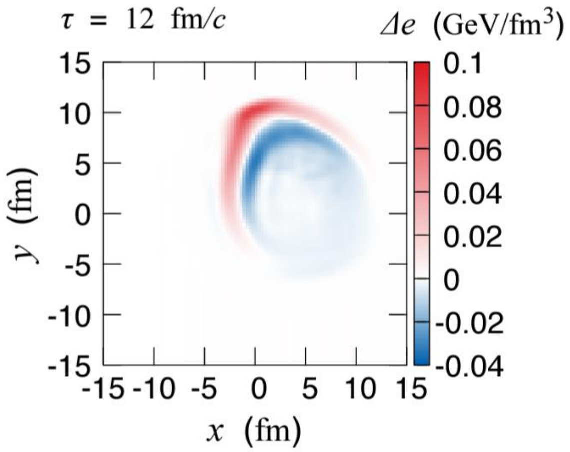
Jet Modification and Hard-Soft Correlations (SoftJet 2024)
University of Tokyo, Tokyo, Japan

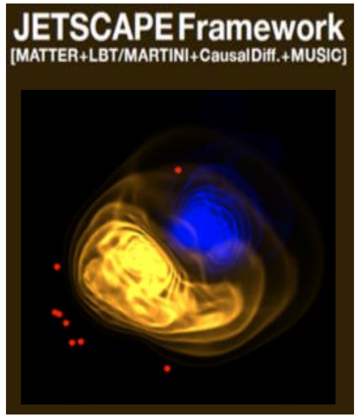
MIT HIG group's work was supported by US DOE-NP

Medium Response to Hard Probes in QGP

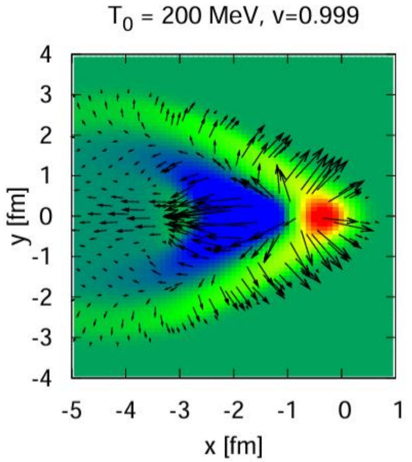
Quark plowing through the QGP



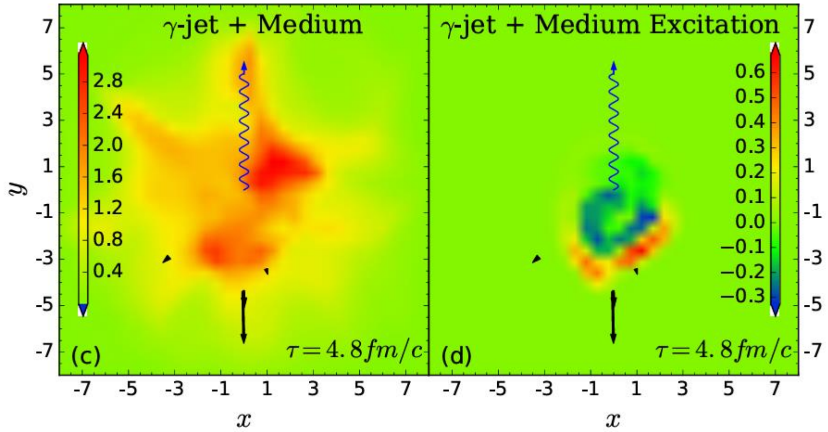
Jet-Fluid Yasuki, Chang, Qin
PRC 95 (2017) 4, 044909



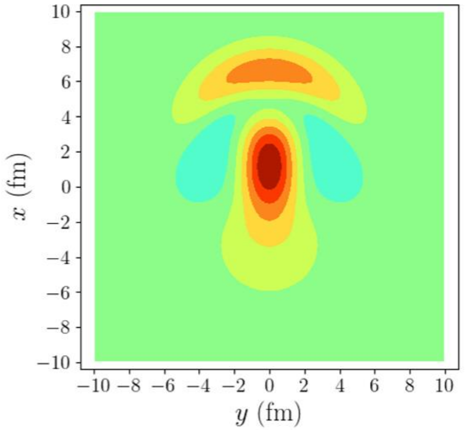
JETSCAPE framework
Tachibana, Shen, Majumder
PRC 106 (2022), L021902



Betz, Noronha, Torrieri, Gyulassy, Mishustin, Rischke
PRC 79 (2009) 034902



CoLBT Chen, Cao, Luo, Pang, Wang
PLB 777 (2018) 86-90



Casalderrey-Solana, Milhano, Pablos, Rajagopal Yao
JHEP 05 (2021) 230

More QGP going in the jet direction

Duck swimming through water

More water going in the duck direction

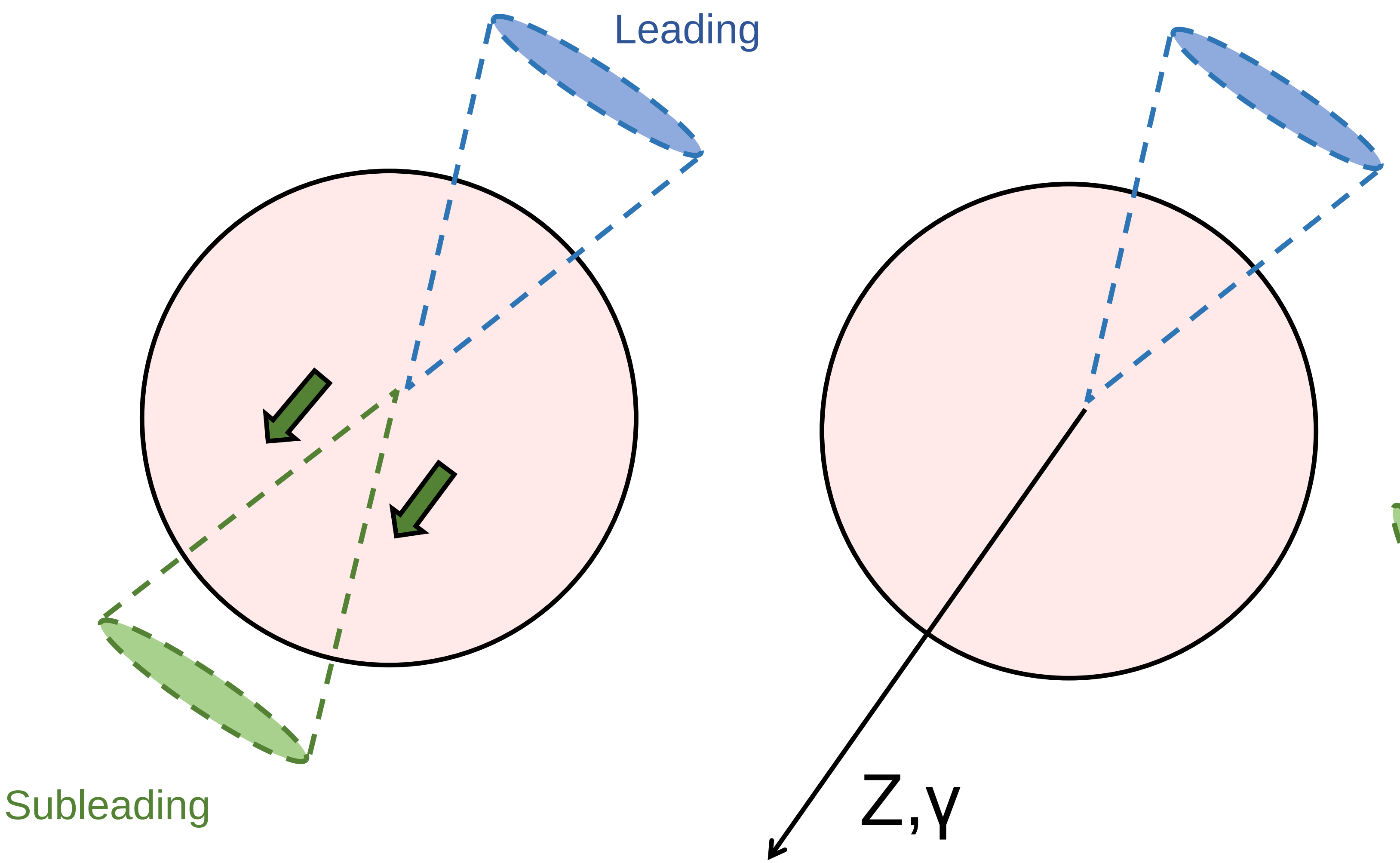
In Position Space

Medium Response in Different Jet Configurations

Receive back reaction effect from the **away side jet**

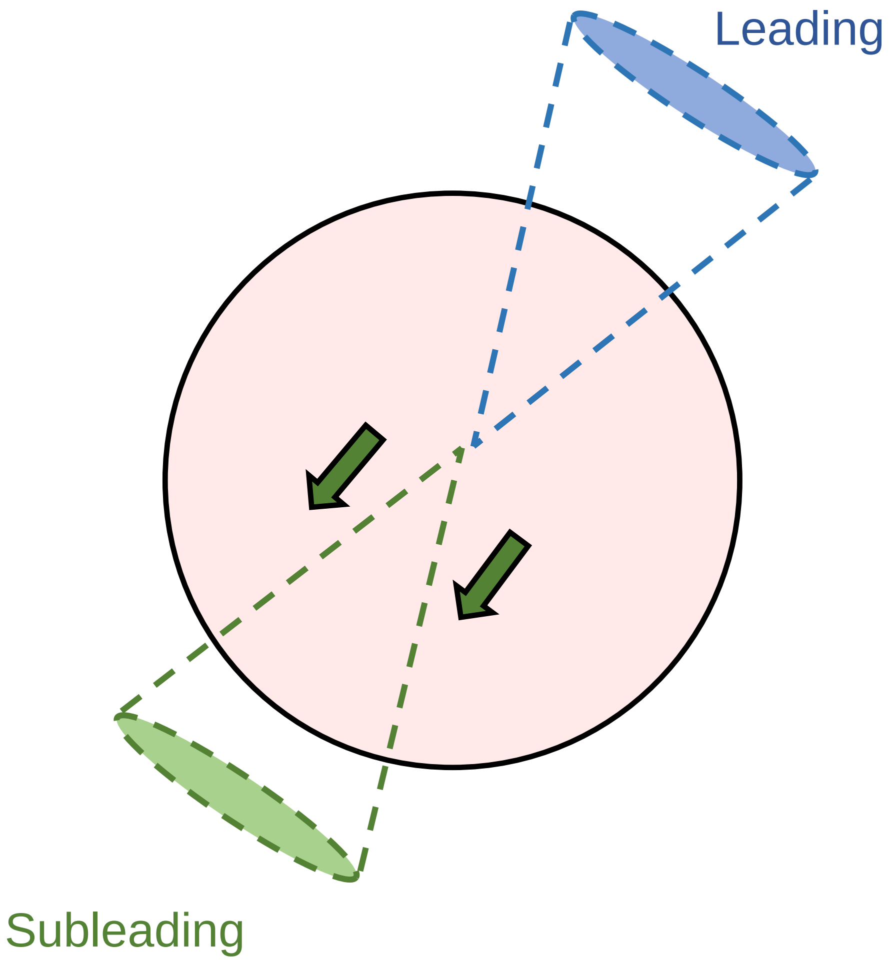
No back reaction from the electroweak boson

Receive **some** back reaction from the away side jet



Medium Response in Different Jet Configurations

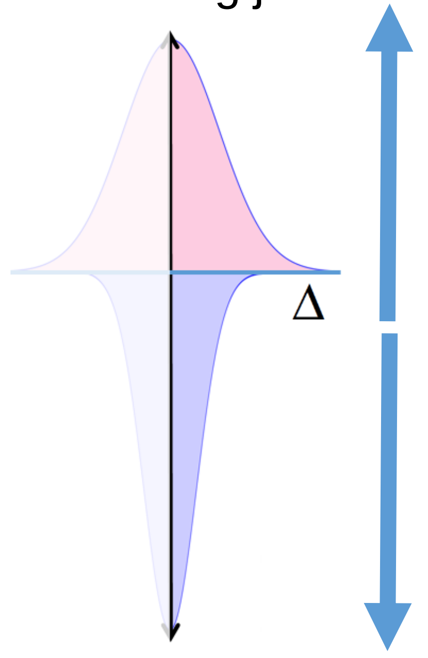
Receive back reaction effect from the **away side jet**

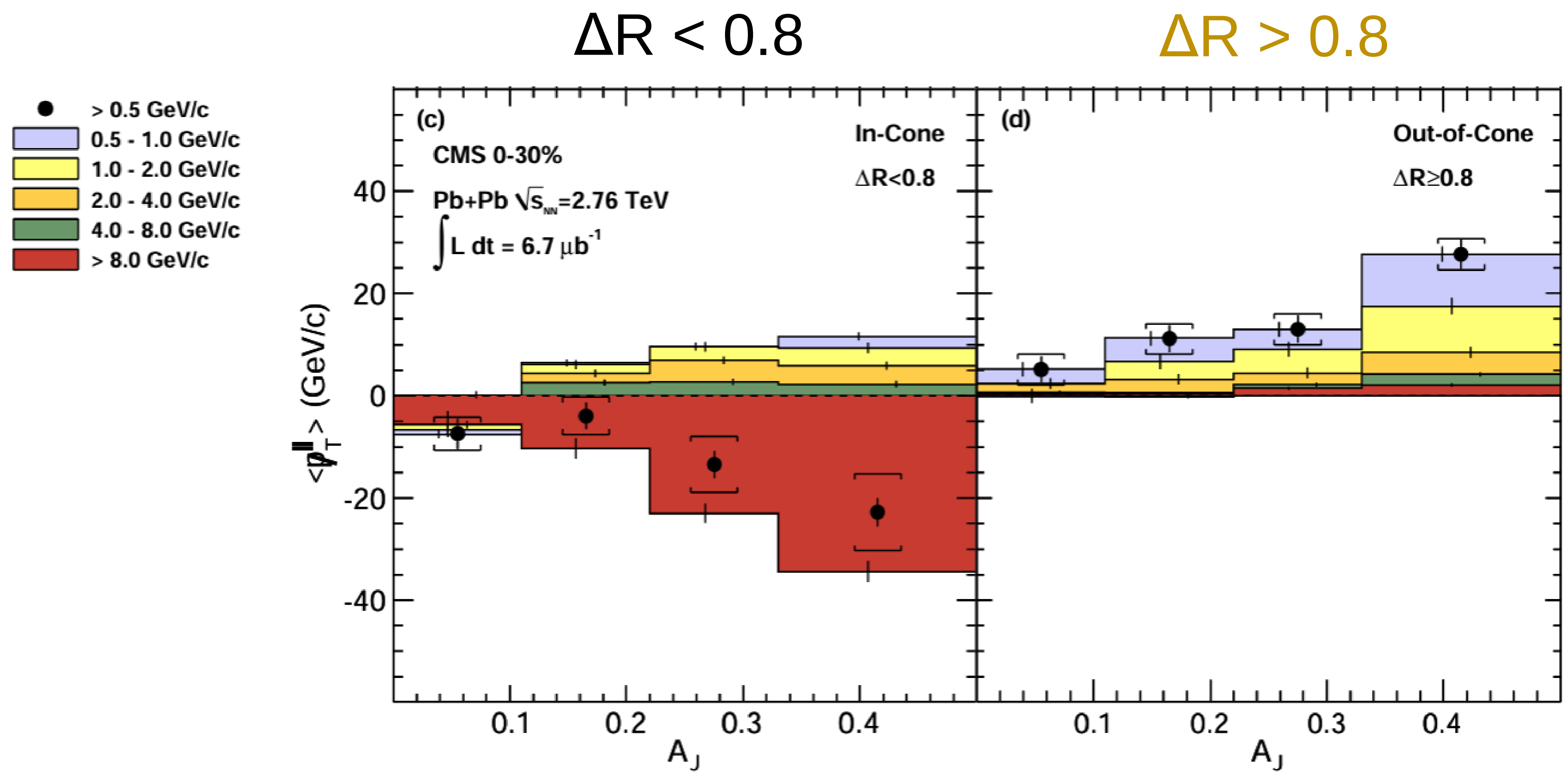


No back reaction from the electroweak boson

Receive **some** back reaction from the away side jet

The First Indication of Medium Response at LHC: Missing $p_T^{||}$

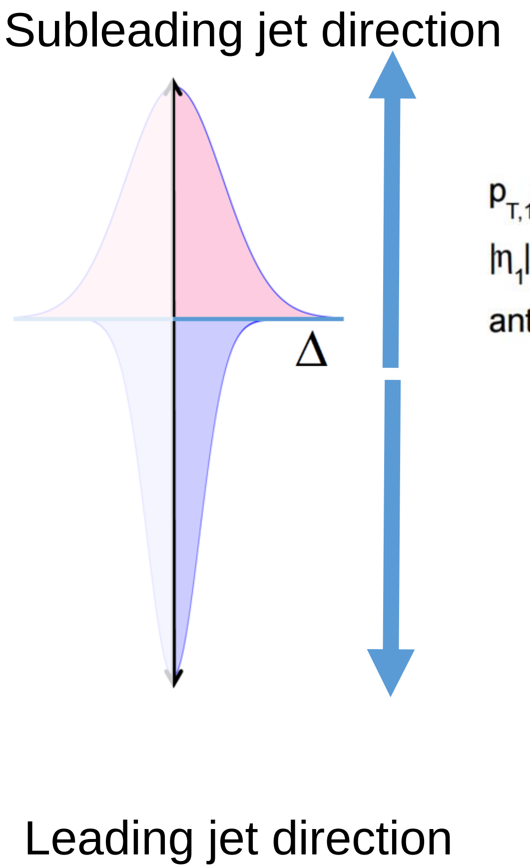


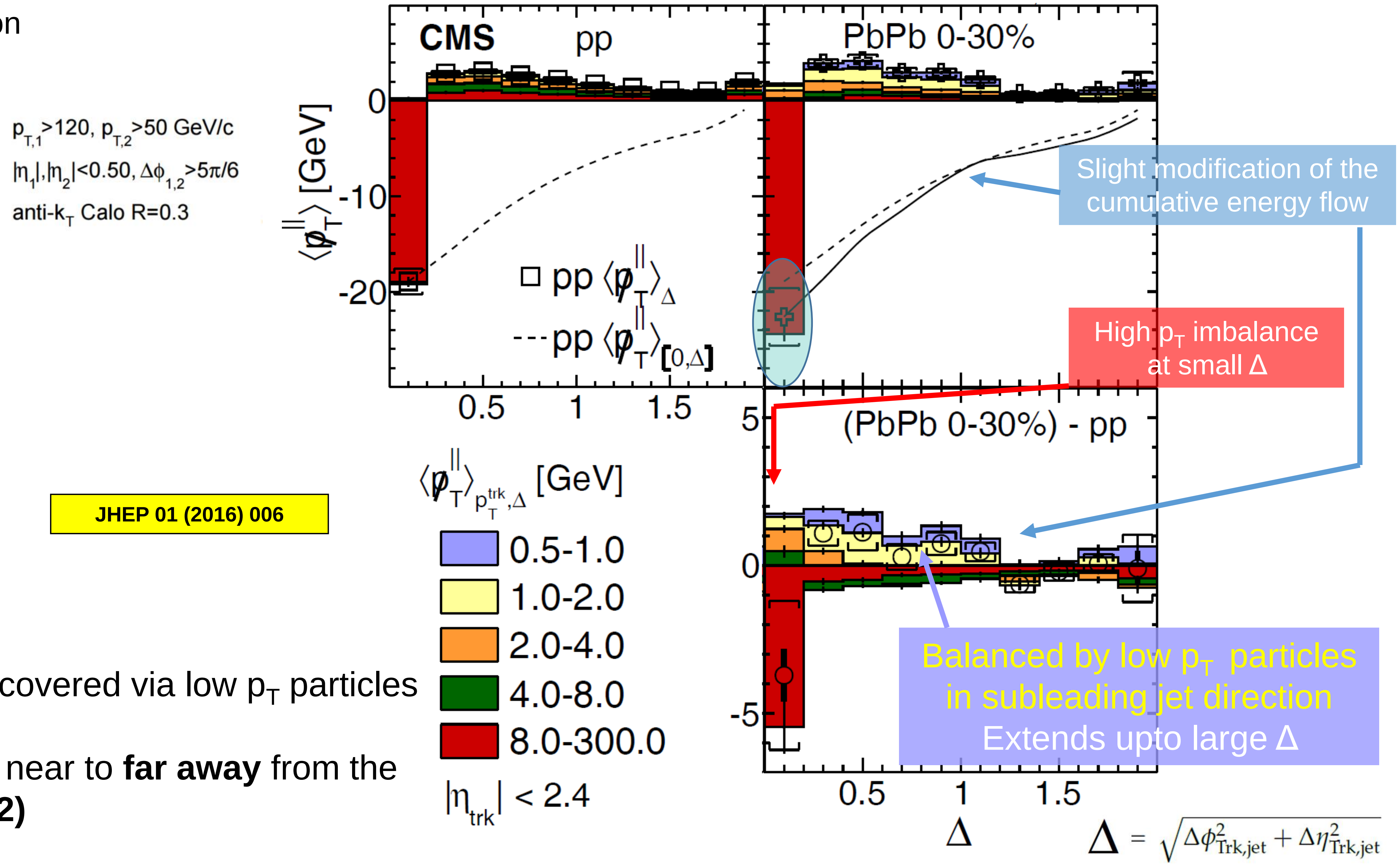


- Quenched energy fully recovered via low p_T particles $p_T < 2$ GeV
- They are distributed from near to **far away** from the (di)-jet axis ($\Delta R > 0.8$)

PRC 84 (2011) 024906

The First Indication of Medium Response at LHC: Missing $p_T^{||}$



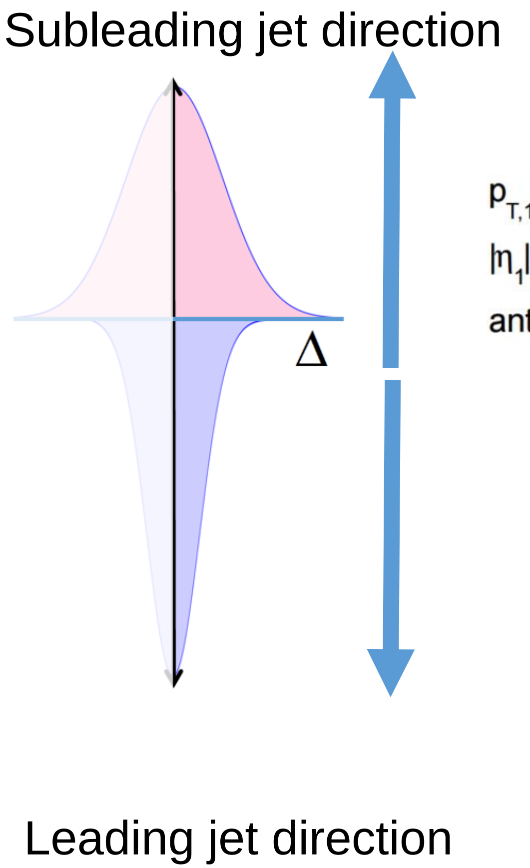


JHEP 01 (2016) 006

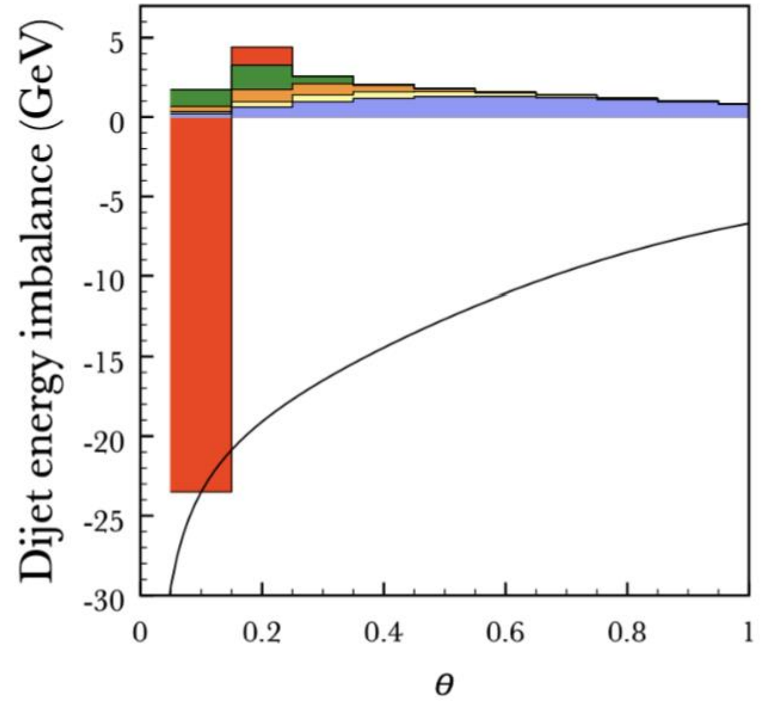
- Quenched energy fully recovered via low p_T particles $p_T < 2$ GeV
- They are distributed from near to **far away** from the (di)-jet axis **(up to ΔR~1-2)**

Interpretation of Missing $p_T^{||}$

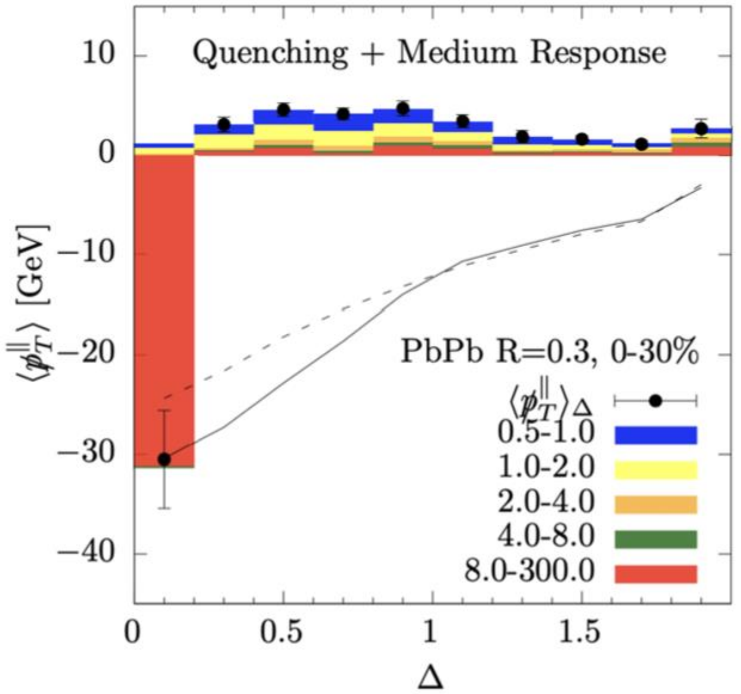
Compiled by Dani Pablos



$p_{T,1}$>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



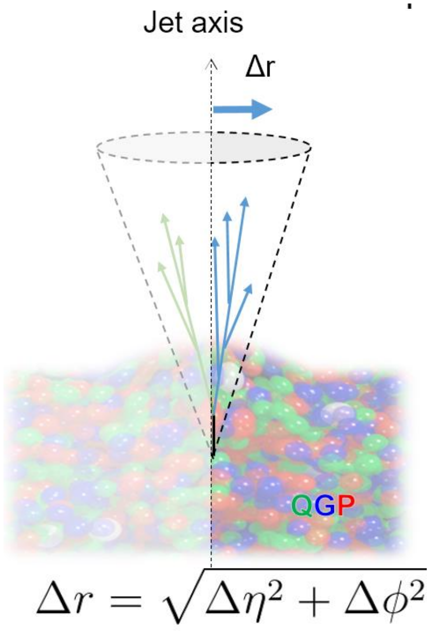
Medium-induced Parton Cascade
Blaizot & Mehtar-Tani
Int.J.Mod.Phys.E 24 (2015) 11, 1530012

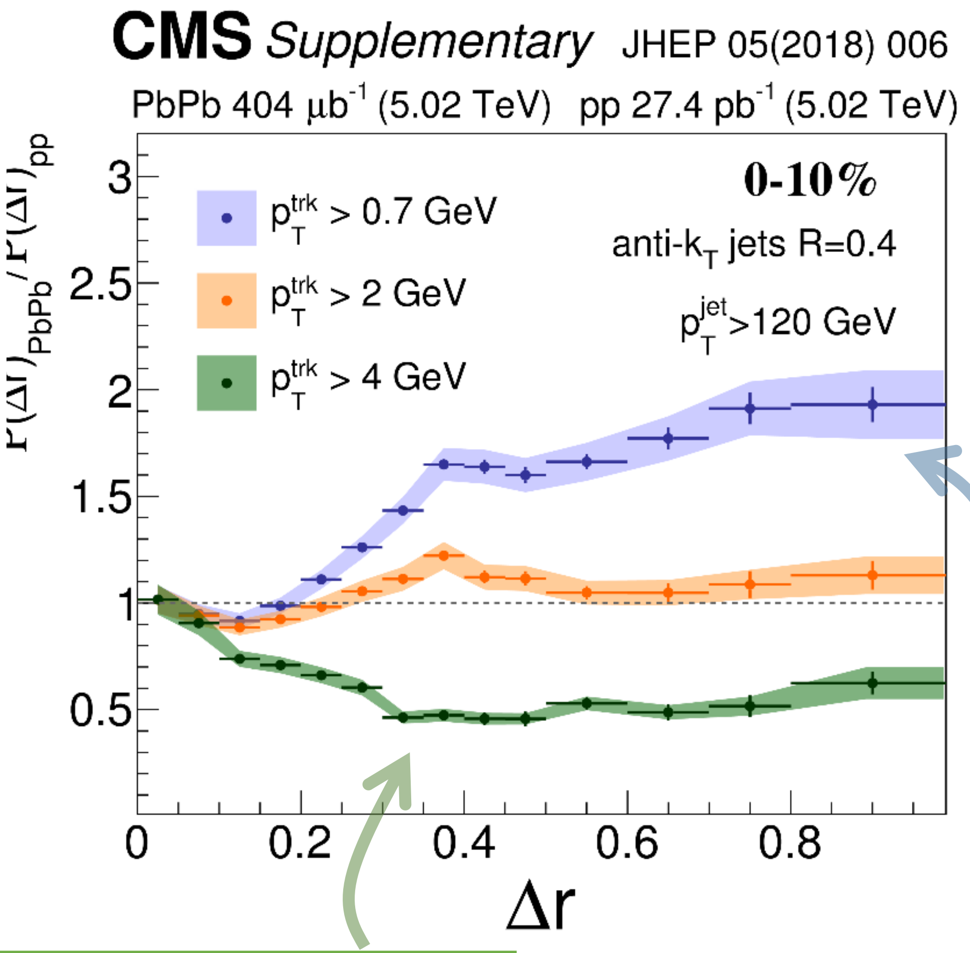


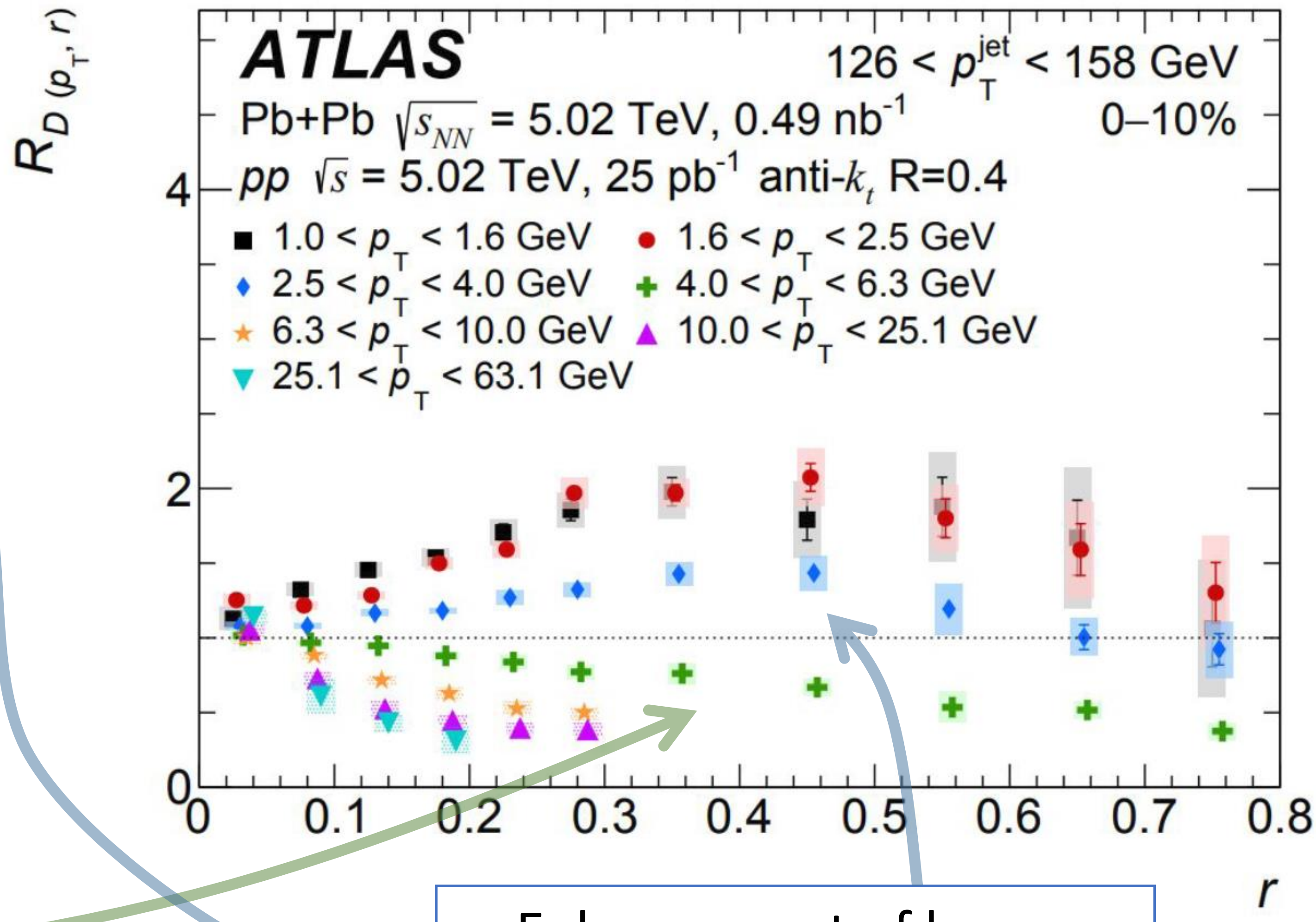
Hydrodynamic wake
Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal
JHEP 03 (2017) 135

- However, the interpretation includes both Medium-induce Parton Cascade and Hydrodynamic Wake.
- The attention was turned to individual jet shower

Excess in Jet-Hadron Correlation





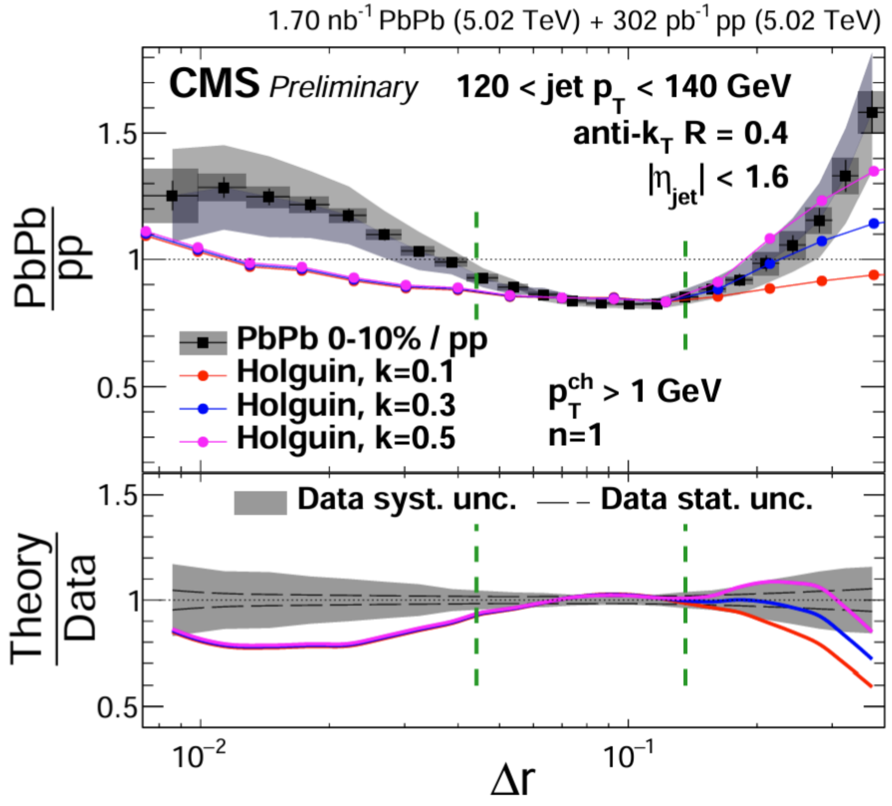


Depletion of high p_T charged particles at large Δr

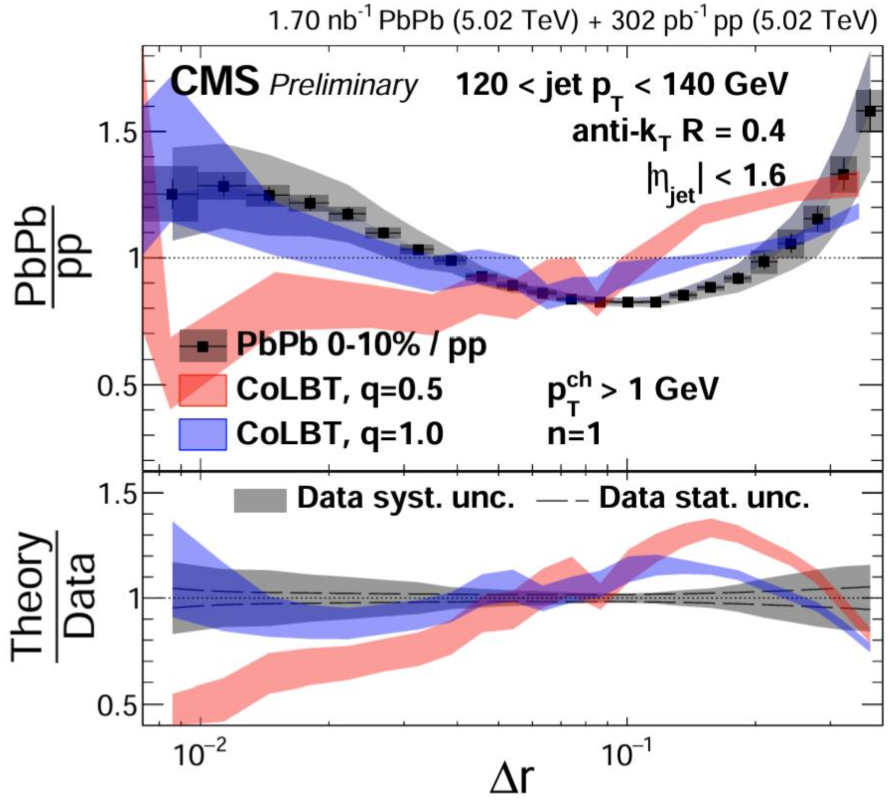
Enhancement of low p_T charged particles at large Δr

Interpretations of the low p_T enhancement at large ΔR include **medium response**, **medium induce radiation / splitting**, and **vacuum-like emissions out of the medium**

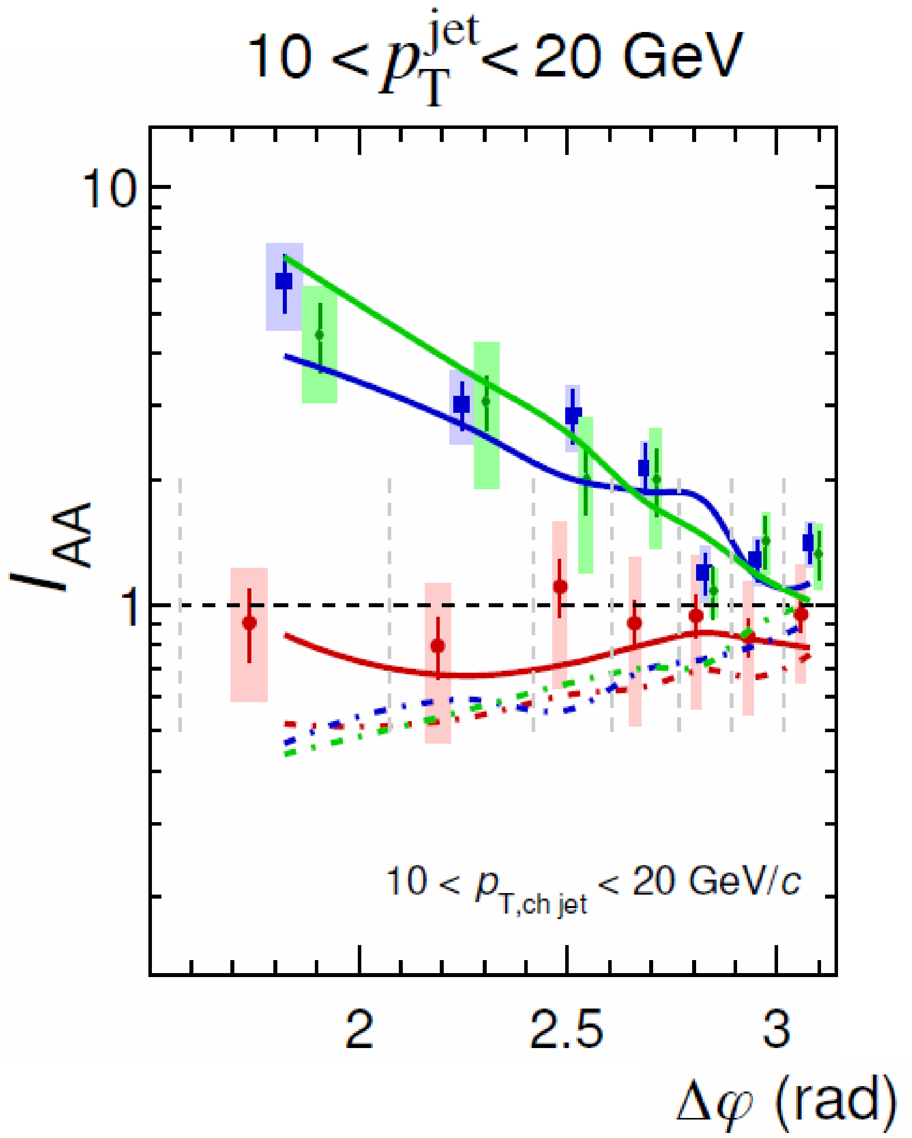
Inclusive Jet EEC and h±-Jet



Holguin, Andrés, Dominguez, Marquet, Moult



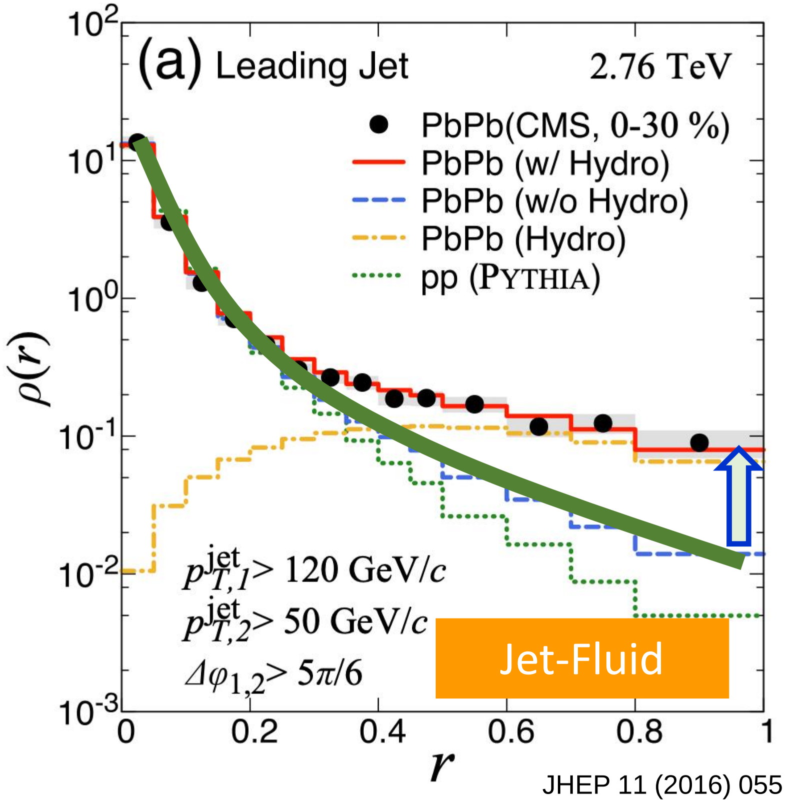
Yang, He, Wang



EEC in PbPb
Jussi Viinikainen

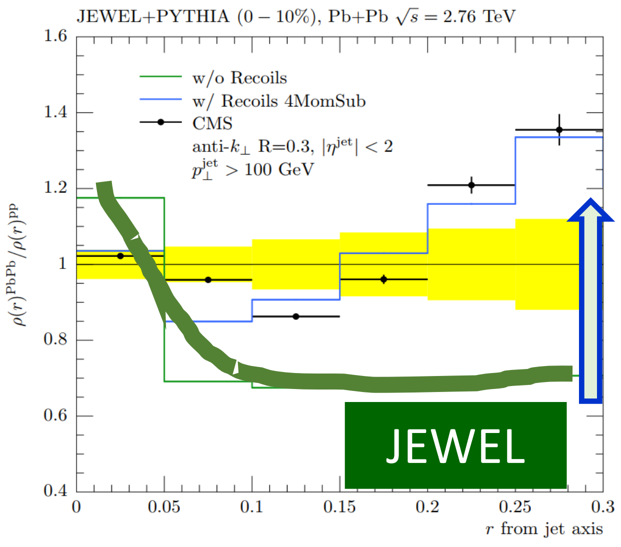
h±-Jet
Peter Jacobs

Interpretation of the CMS Jet Shape

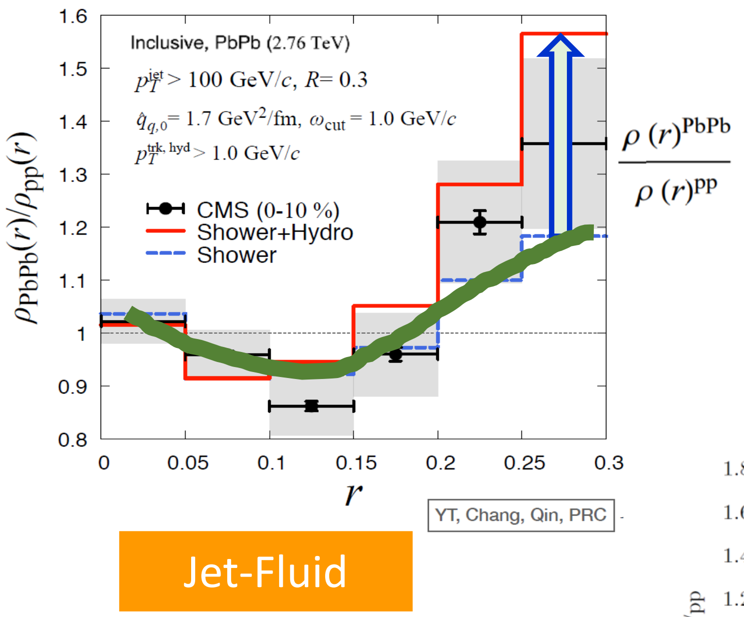


JHEP 11 (2016) 055
PRC 95 (2017) 4, 044909

Medium Response

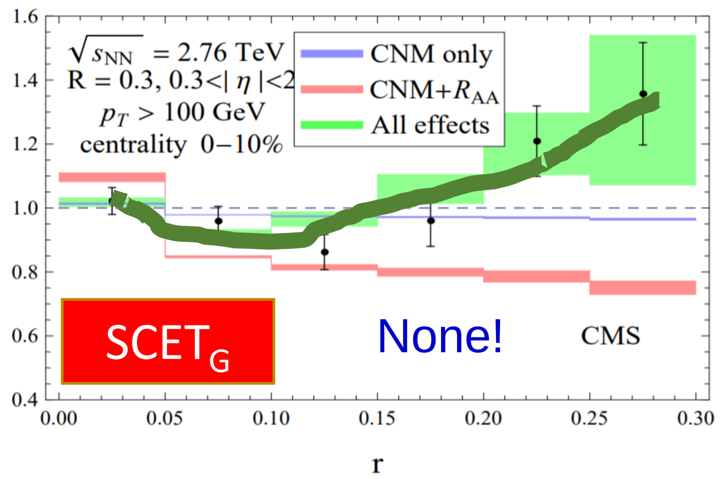


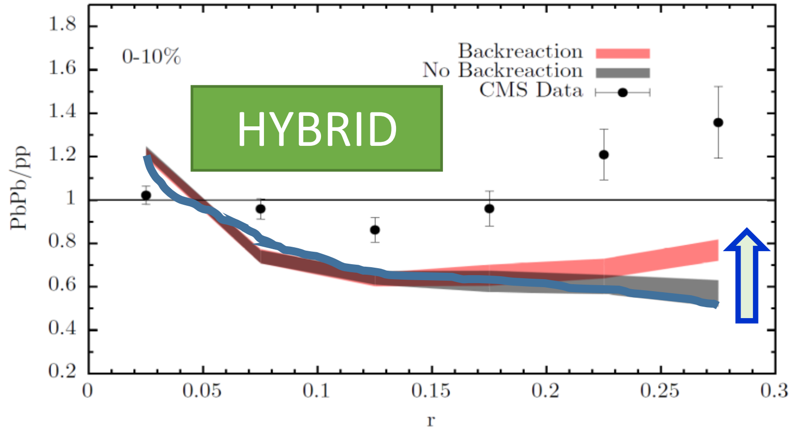
JHEP 07 (2017) 141

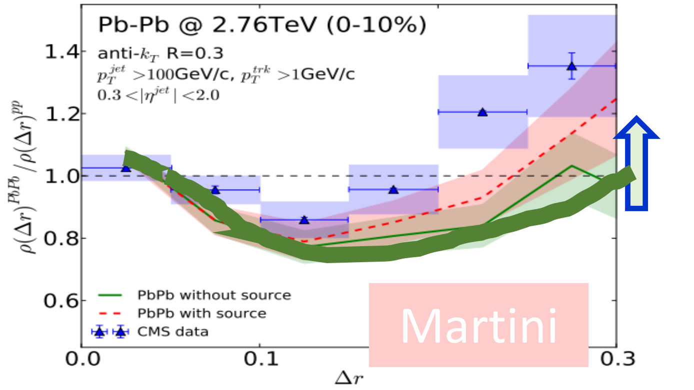


Modifications of the shower

Medium Recoil and Response







Lessons learned so far:

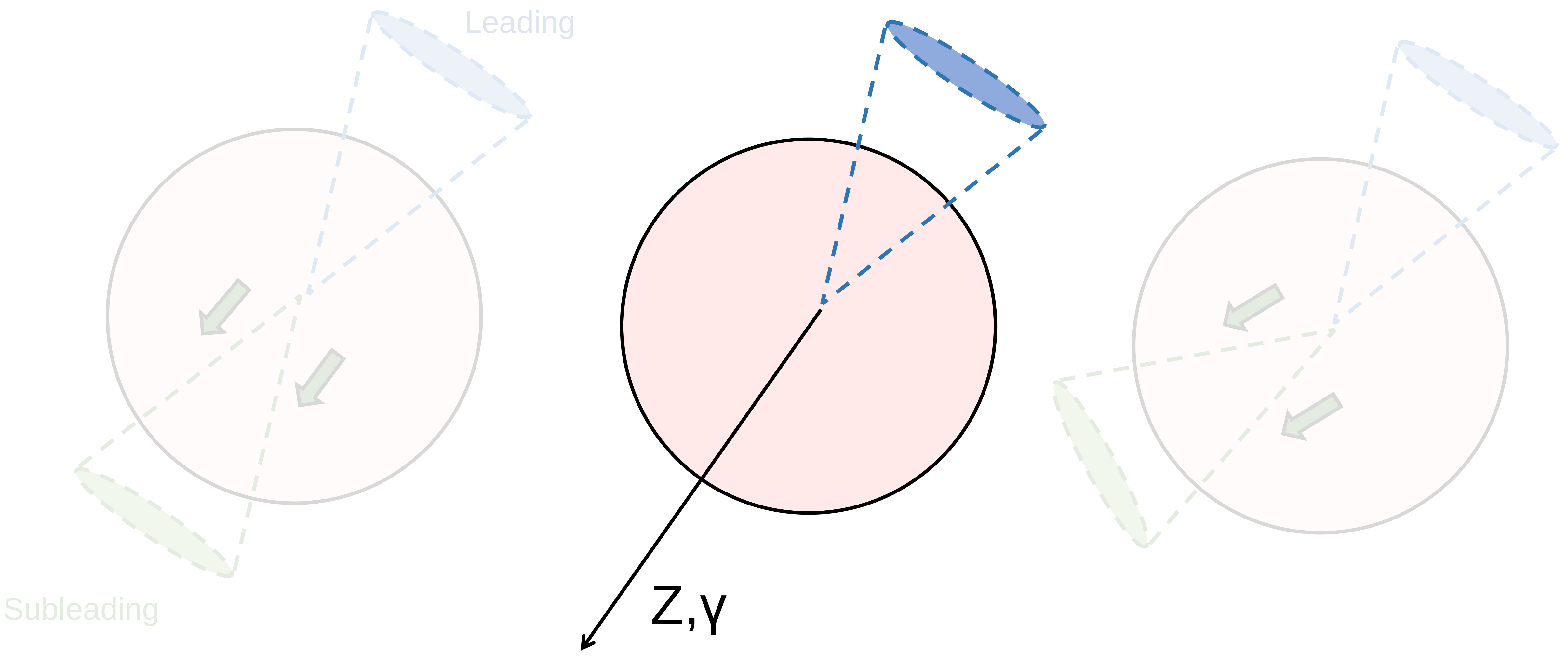
- Models suggest: Medium response dominates the jet shape at **large r**
- Medium response or induced radiation carried by **low p_T particles**; they **could form low p_T charged jet**
- Models with very different mechanisms give reasonable description of the inclusive jet shape and many other observables

Medium Response in Different Jet Configurations

Receive back reaction effect from the **away side jet**

No back reaction from the electroweak boson

Receive **some** back reaction from the away side jet



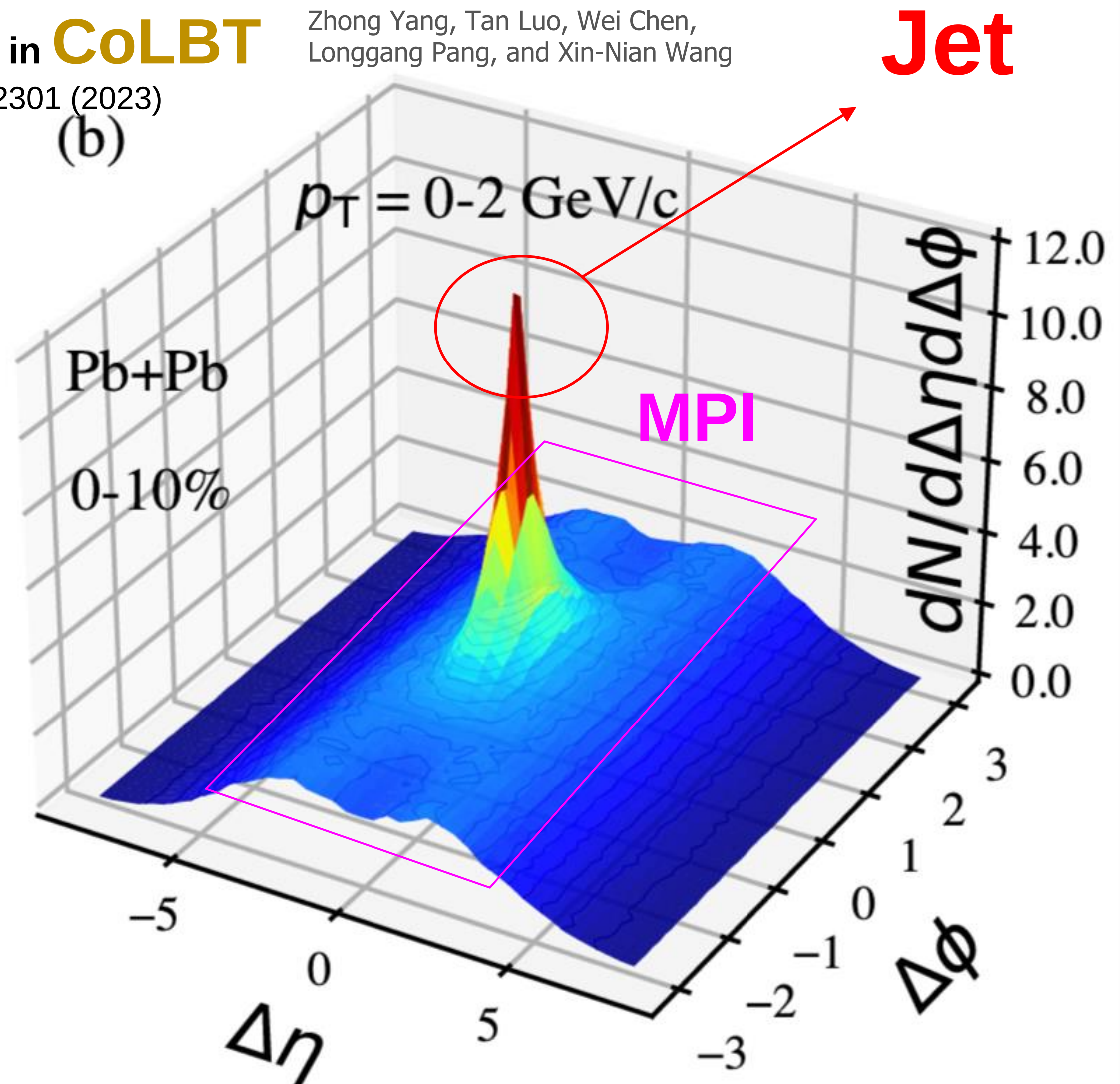
Medium Response to Hard Probes in **Momentum Space**

Jet and **Hadron** correlation in **Photon-Jet event**

QGP wake in CoLBT

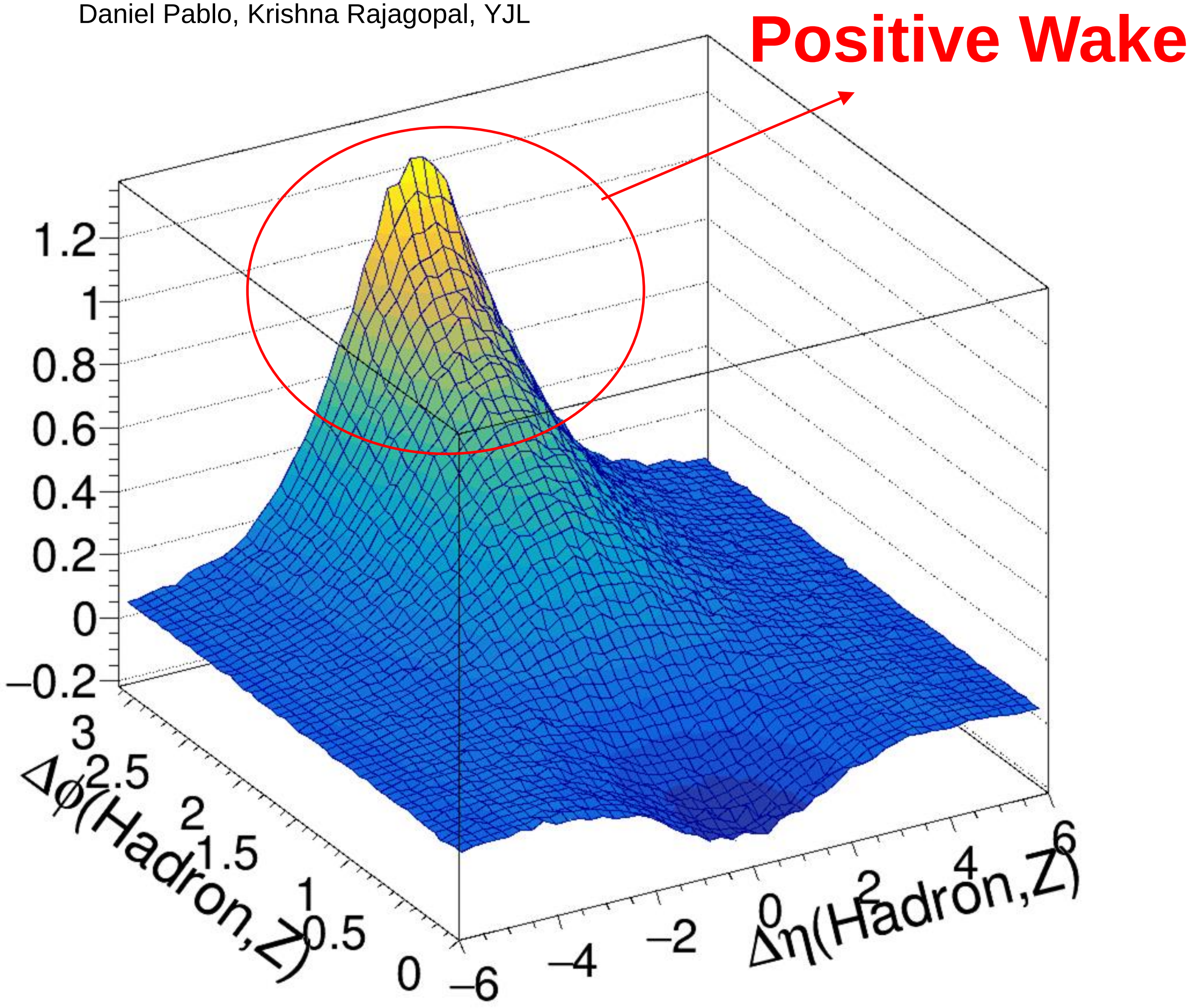
Zhong Yang, Tan Luo, Wei Chen, Longgang Pang, and Xin-Nian Wang

PRL 130, 052301 (2023)



Z^0 and **Wake Hadron** correlation in **Hybrid** model

Daniel Pablo, Krishna Rajagopal, YJL



More QGP going in the jet direction, however, with complication from induced radiation

In Momentum Space

Measure the "Depletion" due to Medium Recoil

Jet and **Hadron** correlation in **Photon-Jet event**

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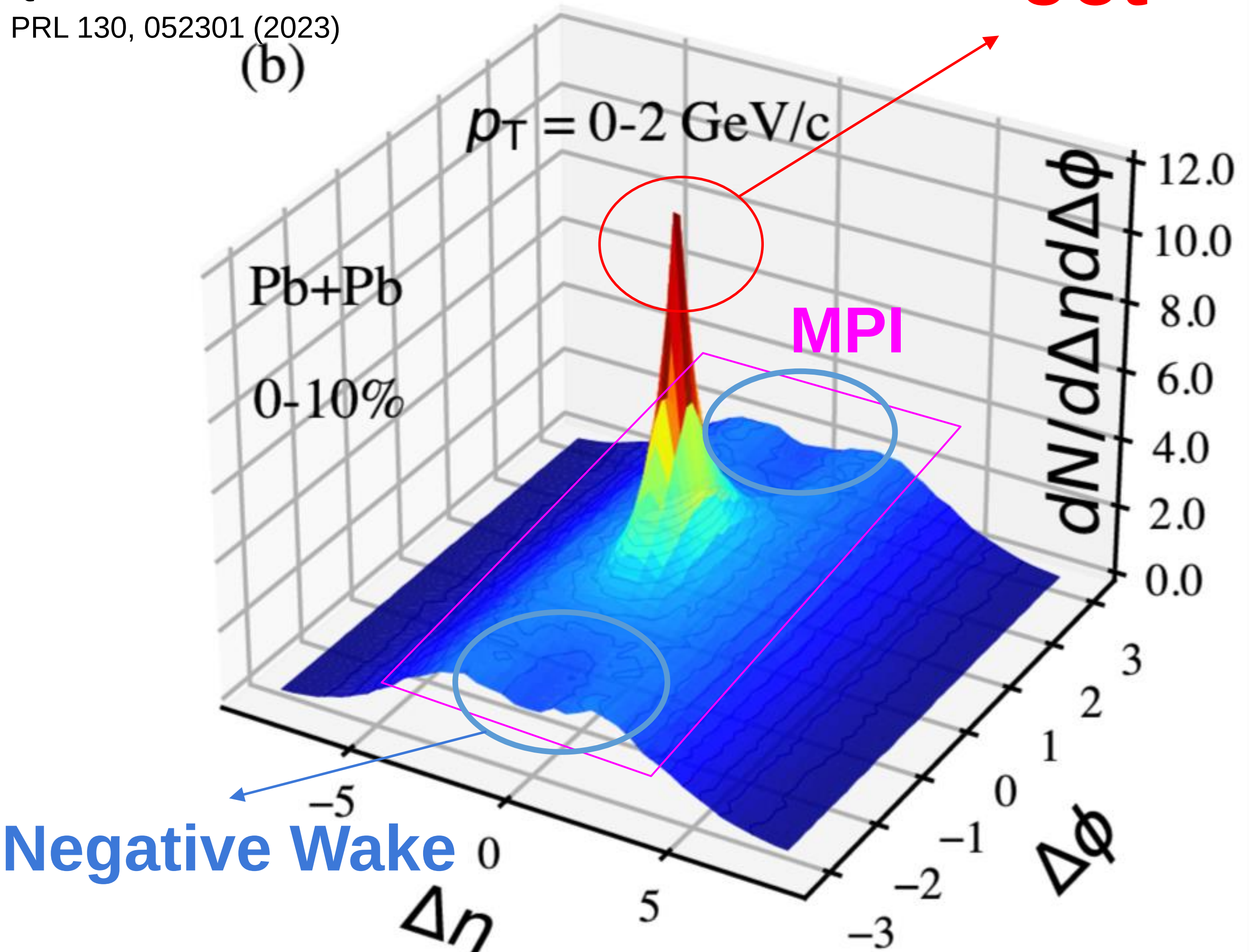
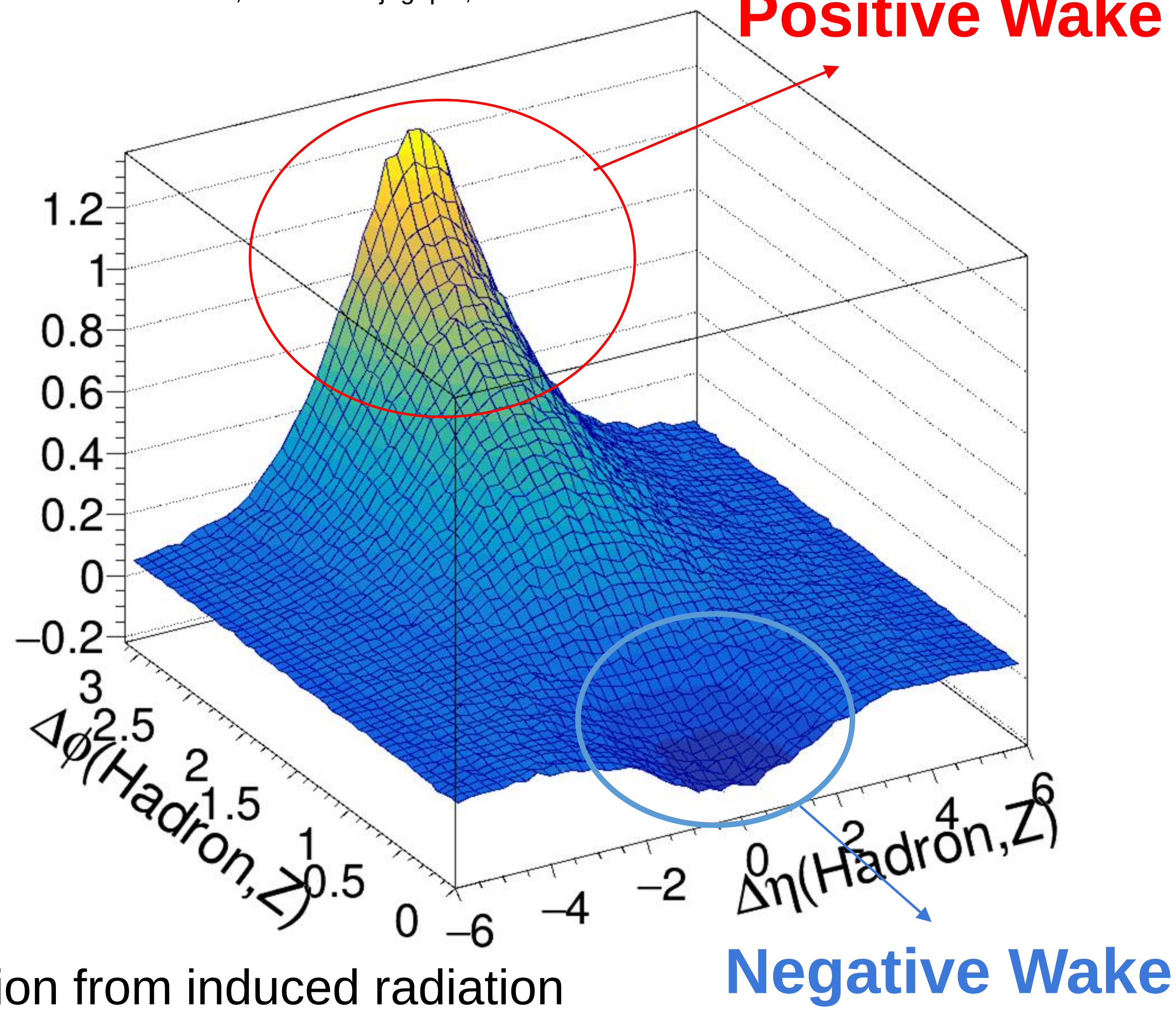
Zhong Yang, Tan Luo, Wei Chen, Longgang Pang, and Xin-Nian Wang

PRL 130, 052301 (2023)



Z^0 and **Wake Hadron** correlation in **Hybrid** model

Daniel Pablo, Krishna Rajagopal, YJL



More QGP going in the jet direction, however, with complication from induced radiation

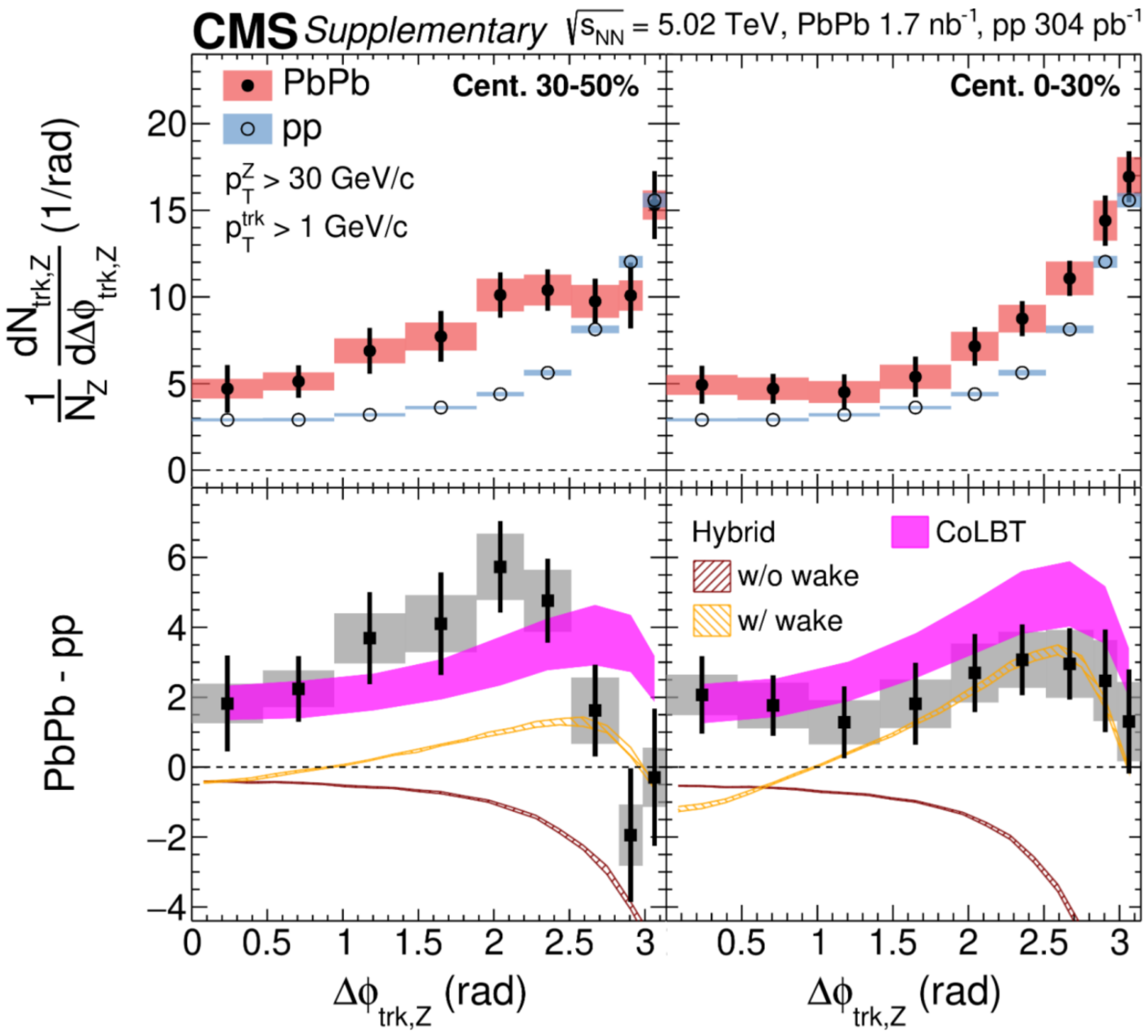
Less QGP left behind in the opposite direction of the jet!!!

→ Measure the **Boson-side associated yield** with **Z^0-Jet**

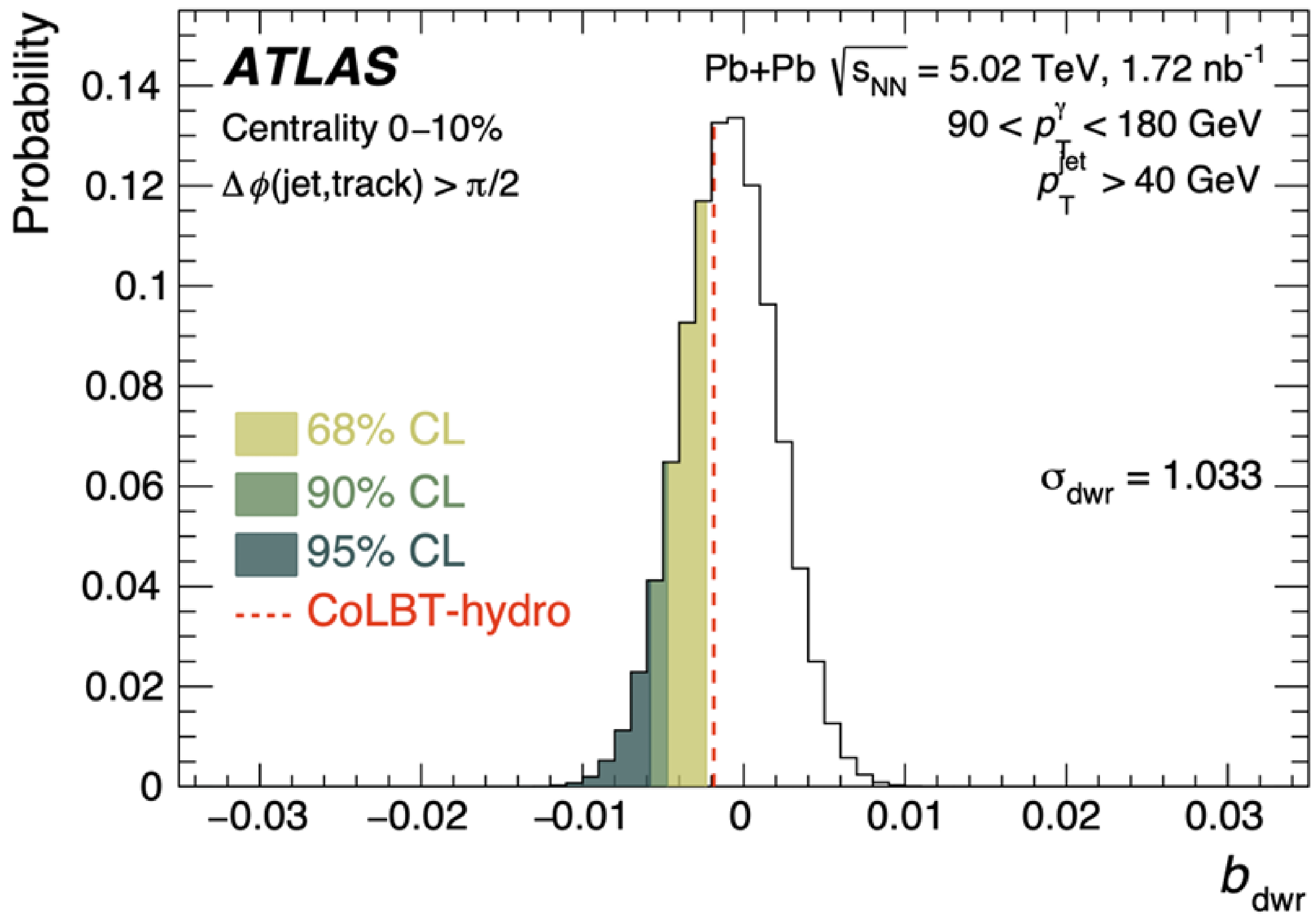
In Momentum Space

Recent Searches for Negative Wake

Z^0-Jet



Photon-Jet

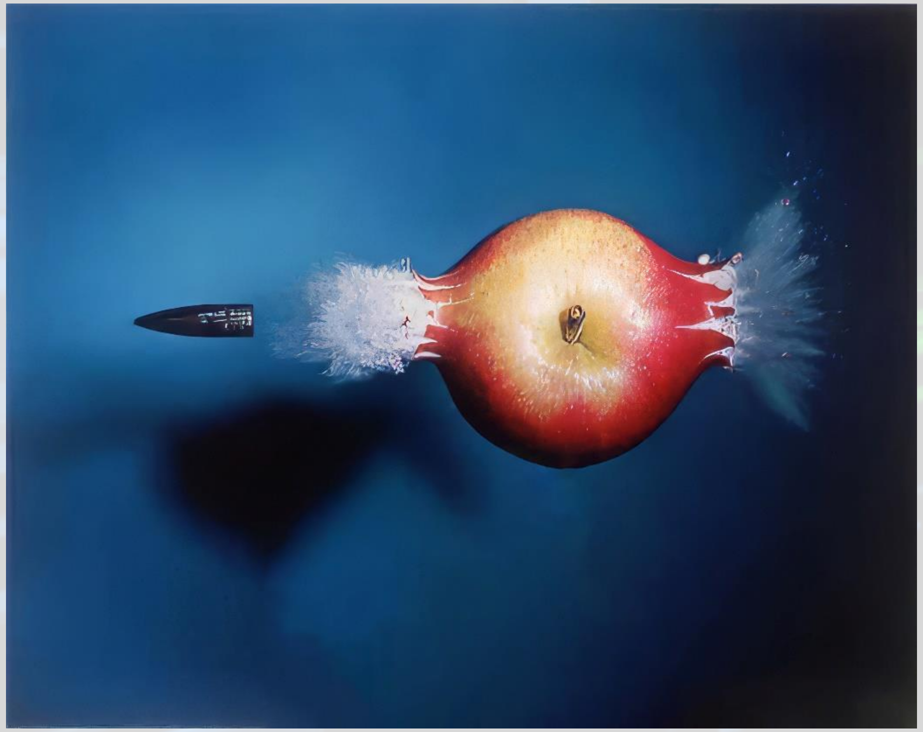


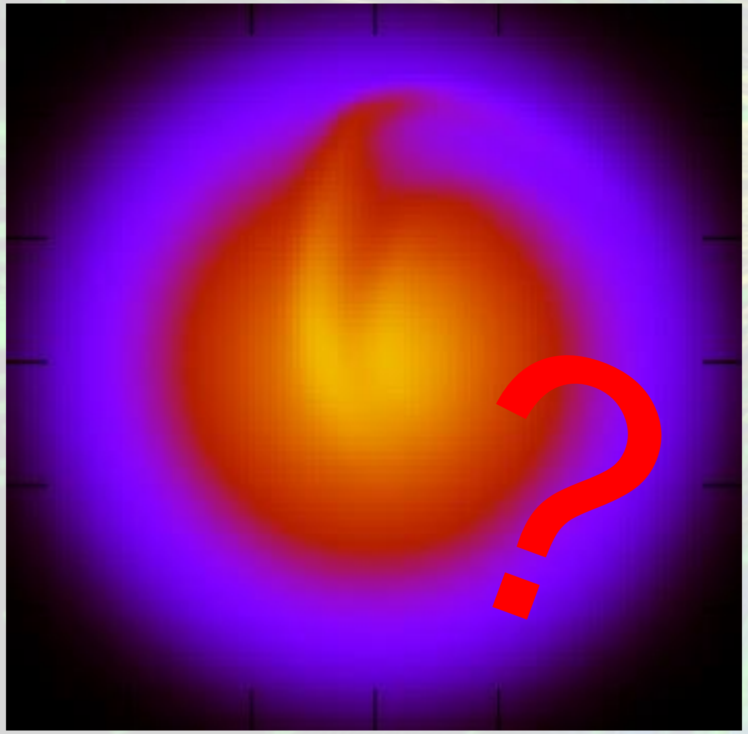
Yeonju Go “Search for the diffusion wake via measurements of jet-track correlations”

Yi Chen “Study of medium response and electroweak probes with the CMS collaboration”

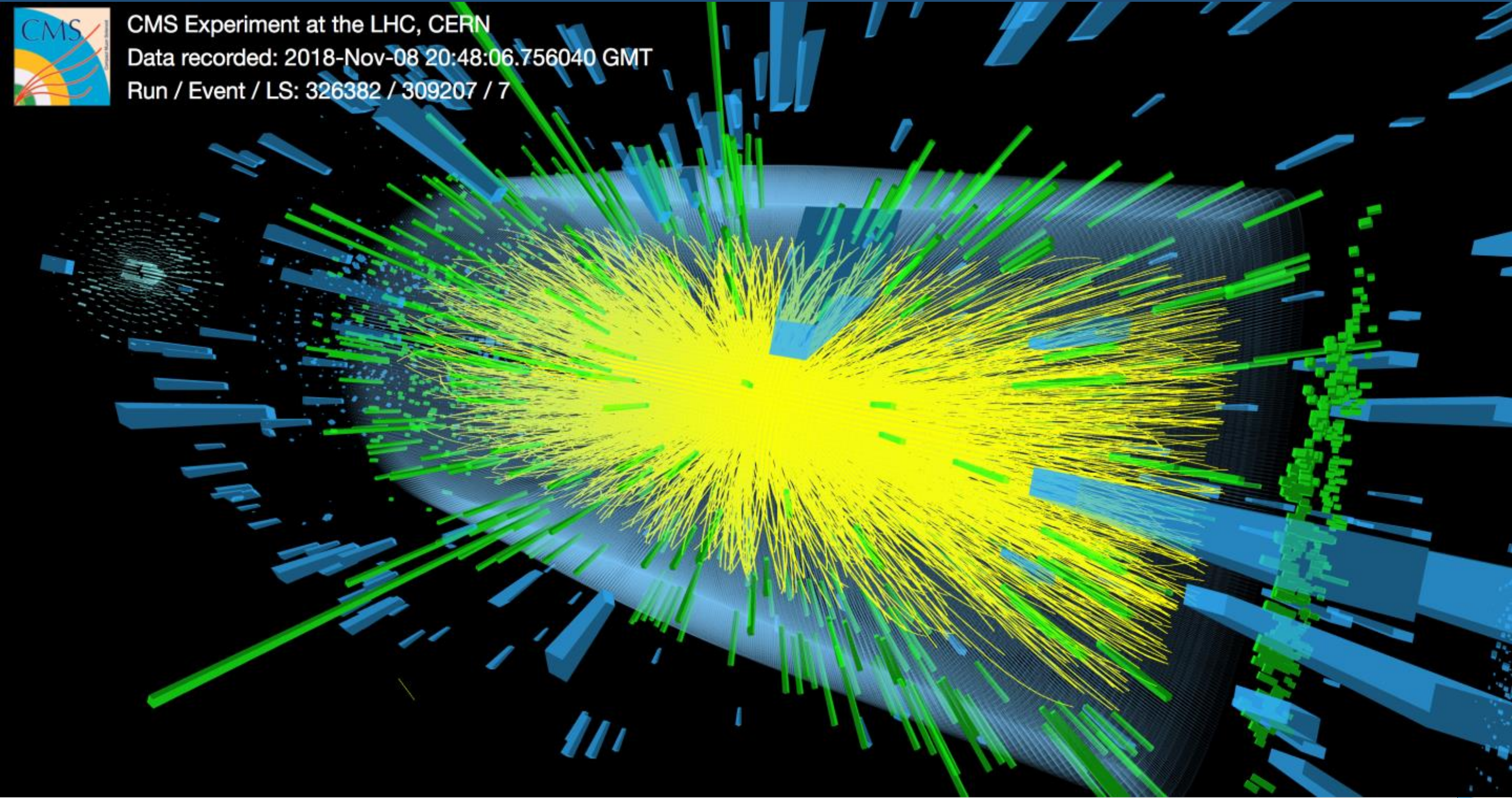
CMS Experiment at the LHC, CERN
Data recorded: 2011-Dec-01 14:35:39.907994 GMT
Run / Ev

Z-Hadron Correlation





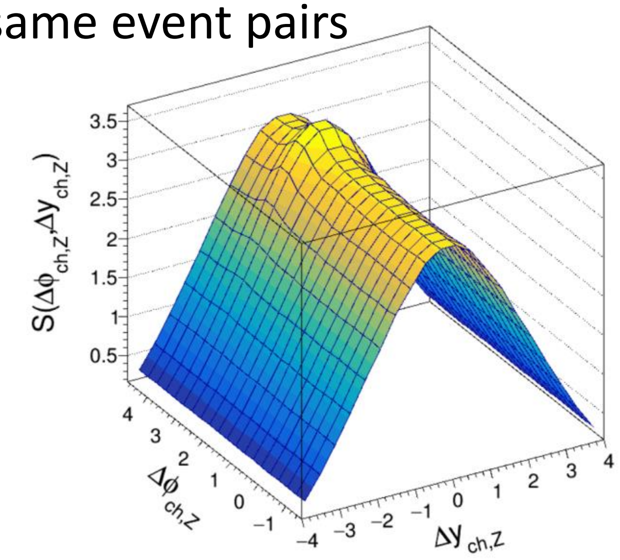
Can we see an unambiguous evidence of the QGP **wake** created by a fast moving quark?


CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-08 20:48:06.756040 GMT
Run / Event / LS: 326382 / 309207 / 7

Z^0-Hadron Correlation Function: Event Mixing

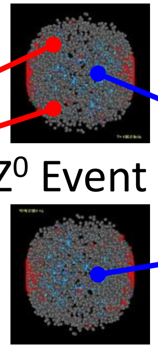
Average Signal pair distribution:

same event pairs



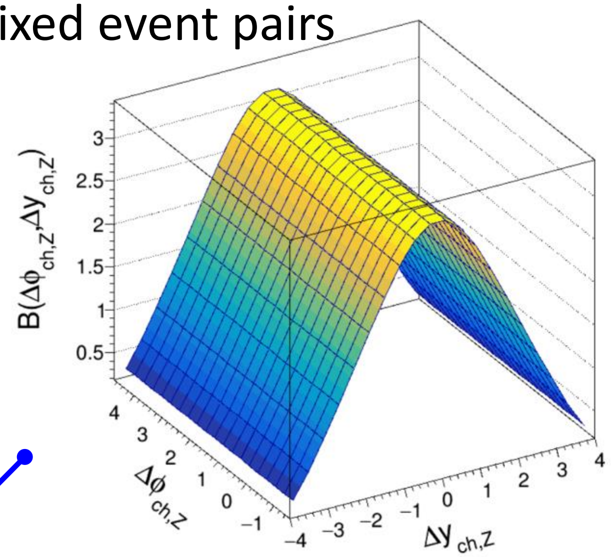
Z^0 Event 1

Z^0 Event 2



Average Background pair distribution:

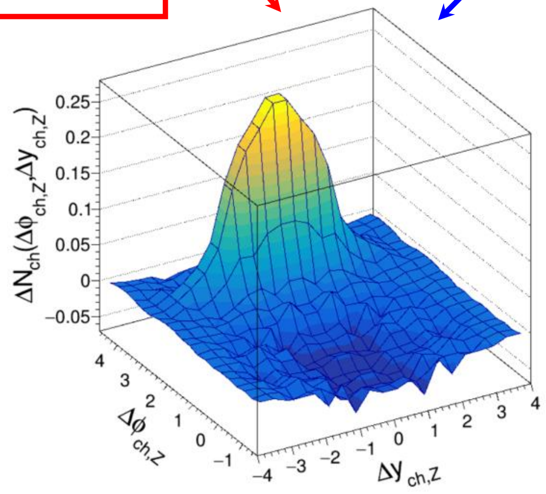
mixed event pairs



$$S(\Delta\phi_{\mathrm{ch,Z}}, \Delta y_{\mathrm{ch,Z}}) = \frac{1}{N_{\mathrm{z}}} \frac{d^2 N^{\mathrm{same}}}{d\Delta\phi_{\mathrm{ch,Z}} d\Delta y_{\mathrm{ch,Z}}}$$

$$B(\Delta\phi_{\mathrm{ch,Z}}, \Delta y_{\mathrm{ch,Z}}) = \frac{1}{N_{\mathrm{z}}} \frac{d^2 N^{\mathrm{mix}}}{d\Delta\phi_{\mathrm{ch,Z}} d\Delta y_{\mathrm{ch,Z}}}$$

$$\Delta N_{ch} = S - B$$



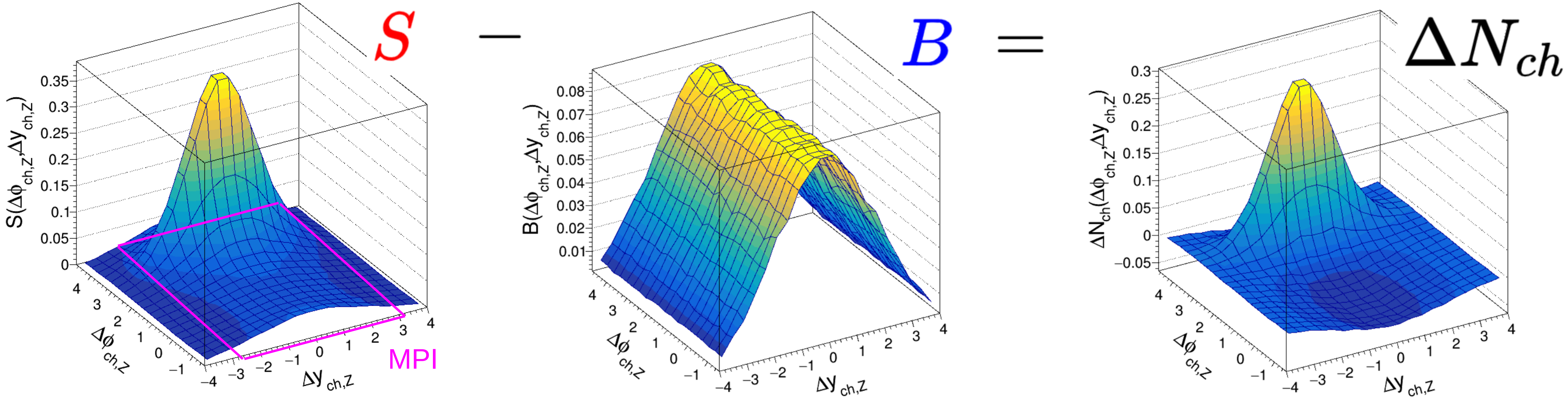
$\Delta y_{ch,Z} = y_z - \eta_{ch}$

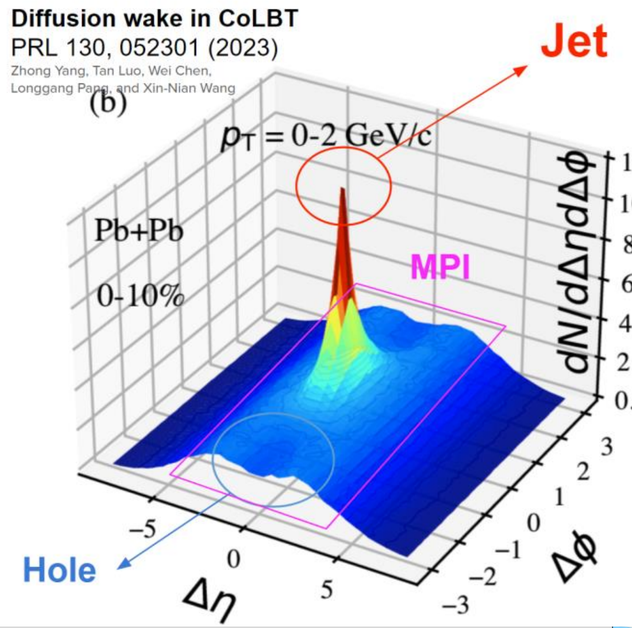
$\Delta\varphi_{ch,Z} = \varphi_z - \varphi_{ch}$

Demonstration with PYTHIA+HYDJET (Generator level events)

Integral of the ΔN_{ch} correlation function will be ~0

Mixed Event Subtraction in **PYTHIA8 pp** Events





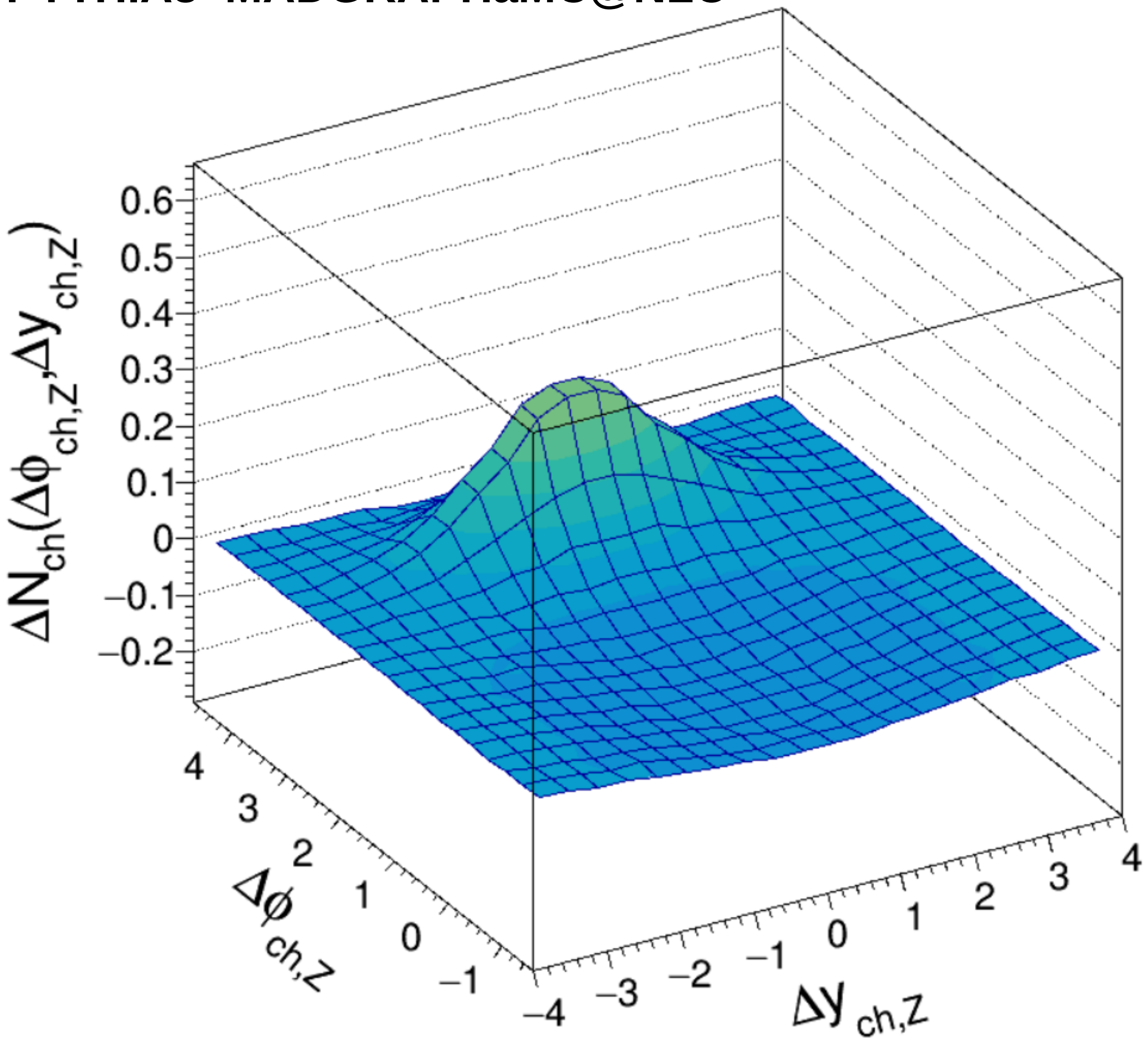
- Mixed event subtraction is also performed in **pp** analysis

- Tight correlation between charged hadron in jet and Z^0 not only in Δϕ **but also Δy** due to Z^0 p_T and rapidity selection

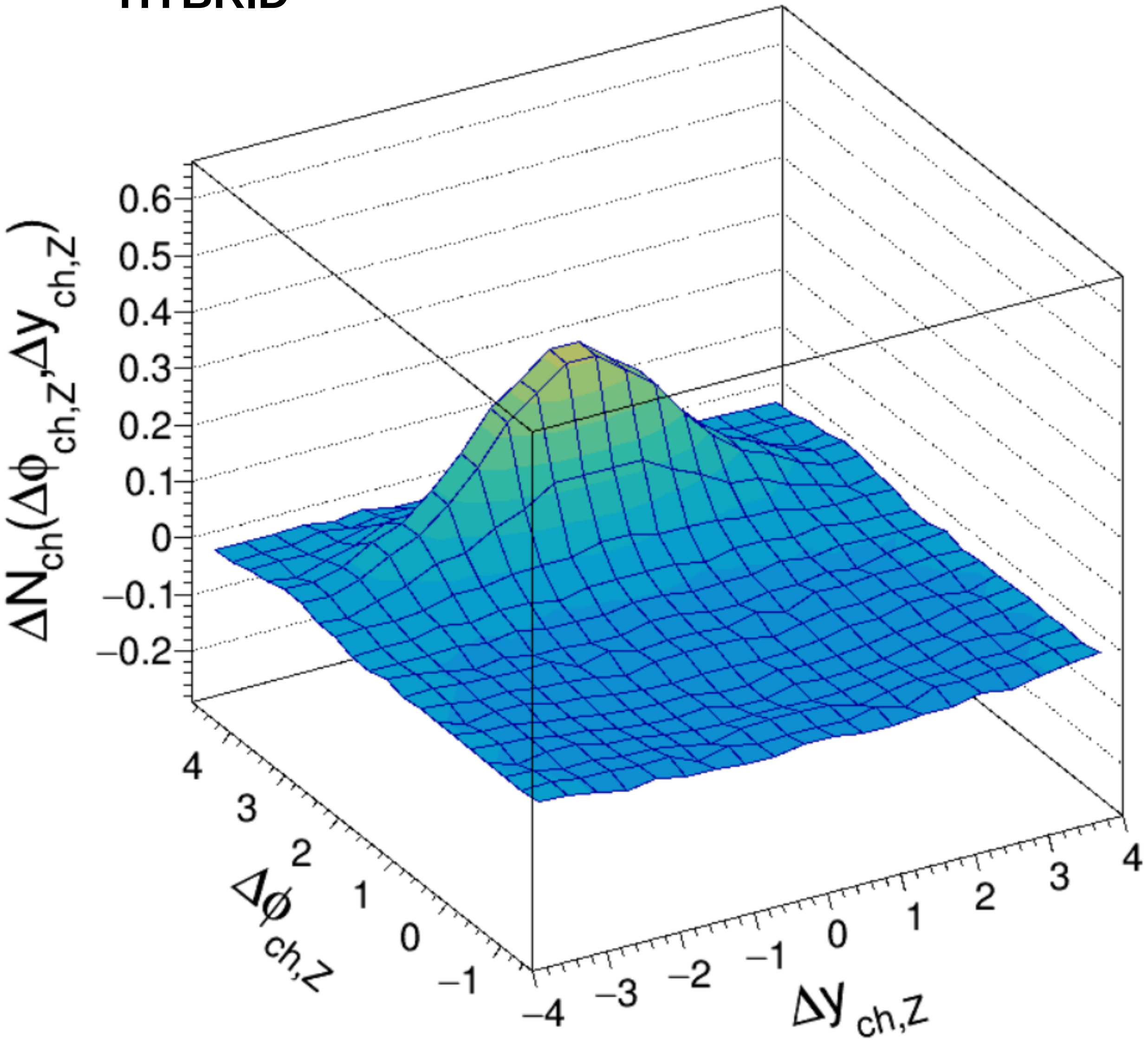
- The procedure suppresses the uncorrelated “MPI ridge” at fixed Δη (Δy)

Predictions from Models in pp for Charged Hadron p_T 1-2 GeV

PYTHIA8+MADGRAPHaMC@NLO

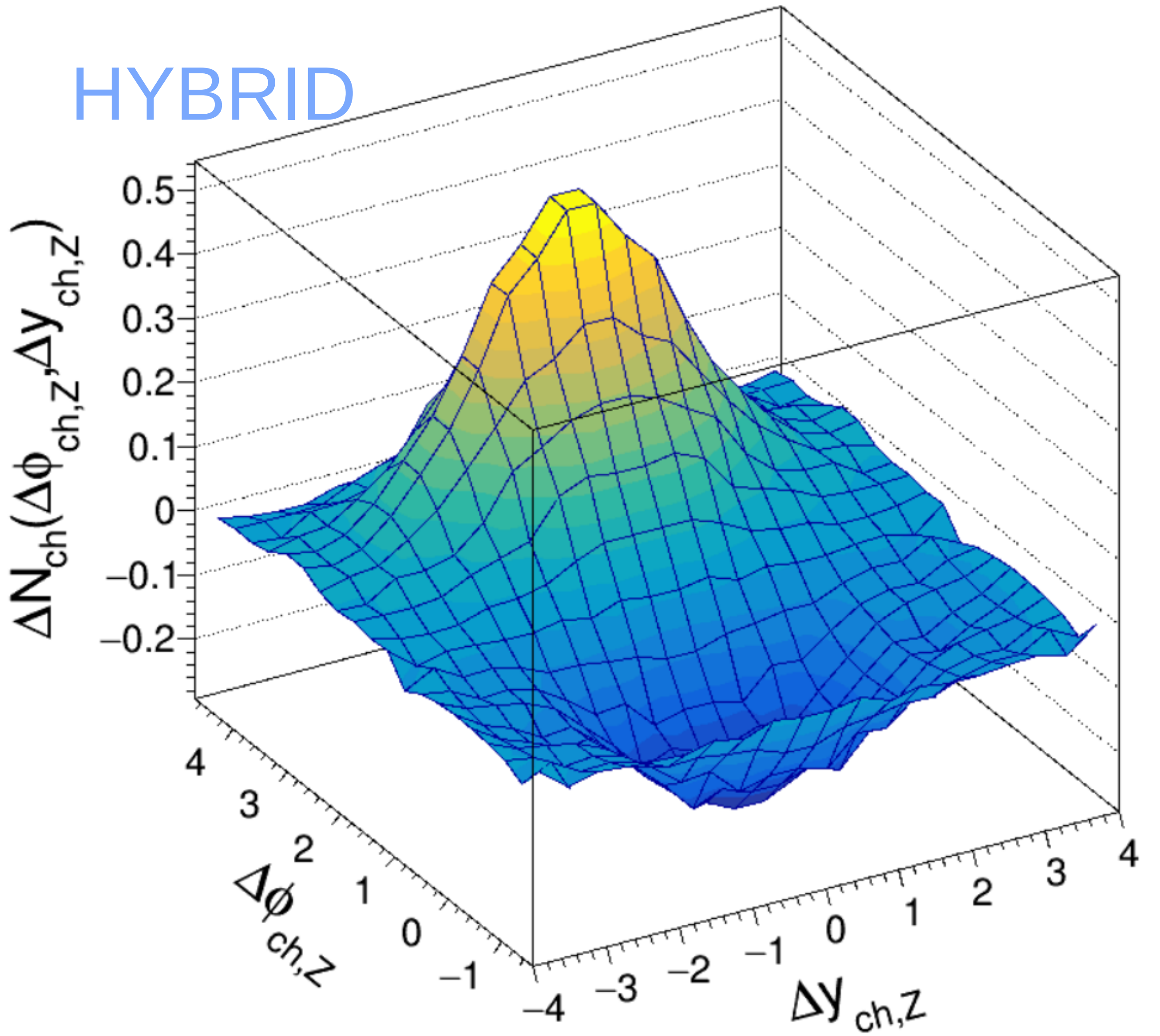


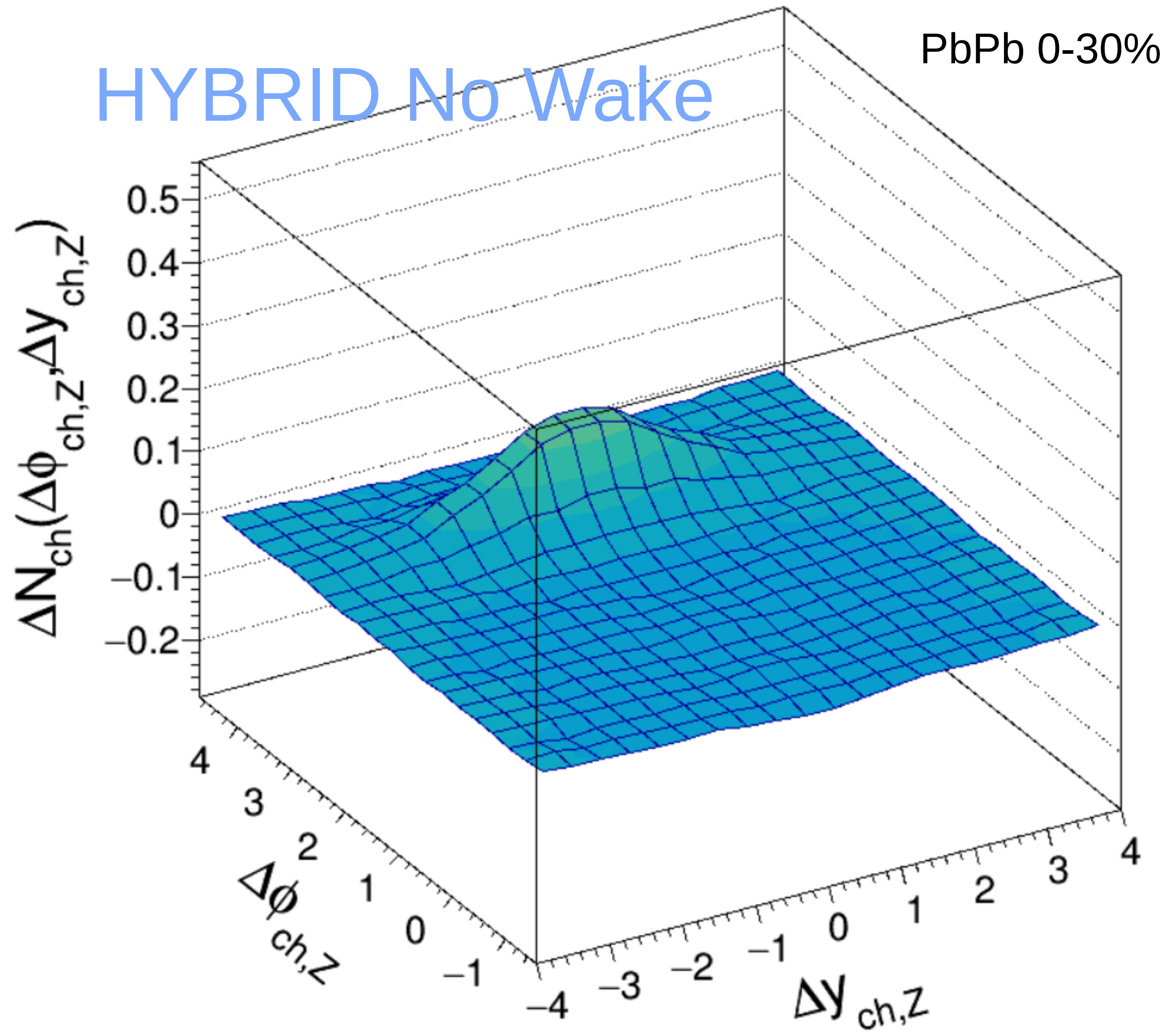
HYBRID



- NLO event generator gives a broader jet peak than PYTHIA8
- Identical subtraction procedure between MC model results and data analysis

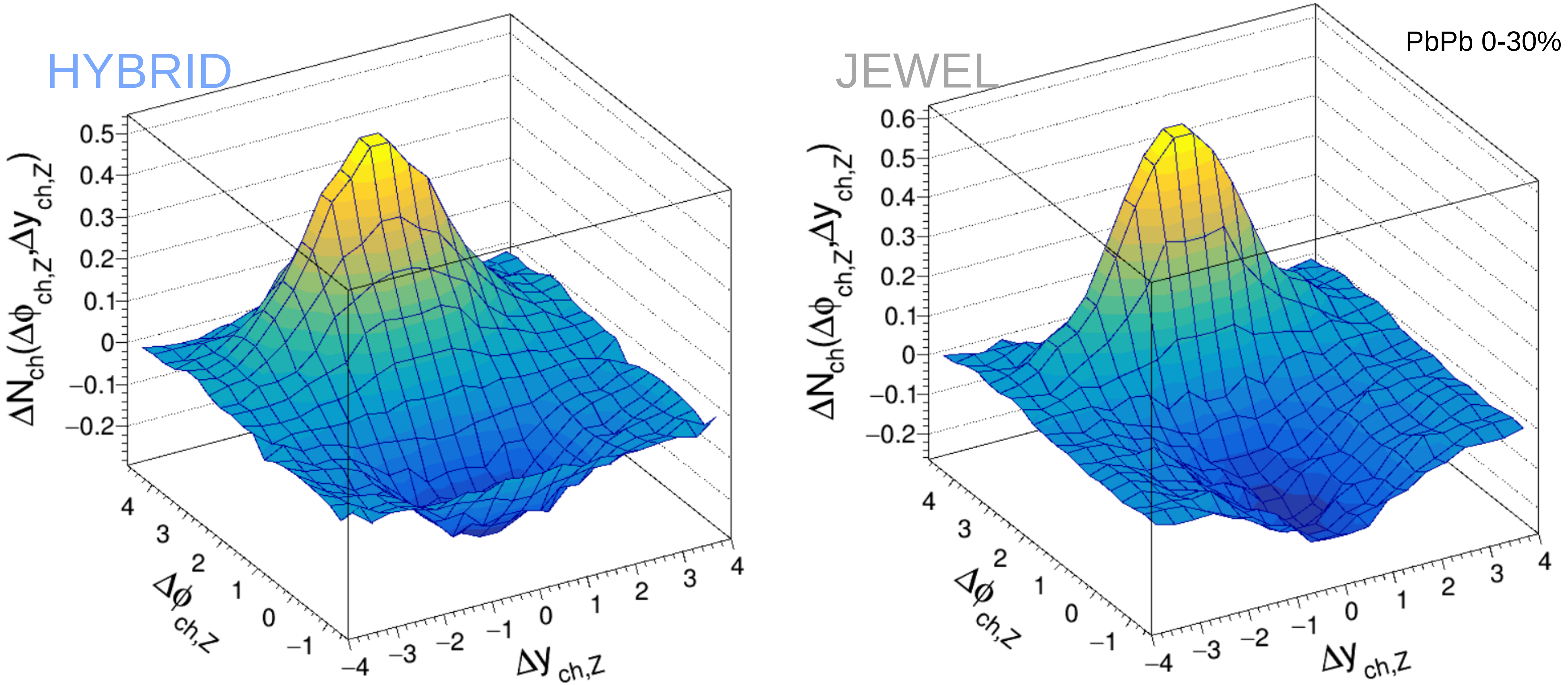
Predictions from Models for Charged Hadron p_T 1-2 GeV





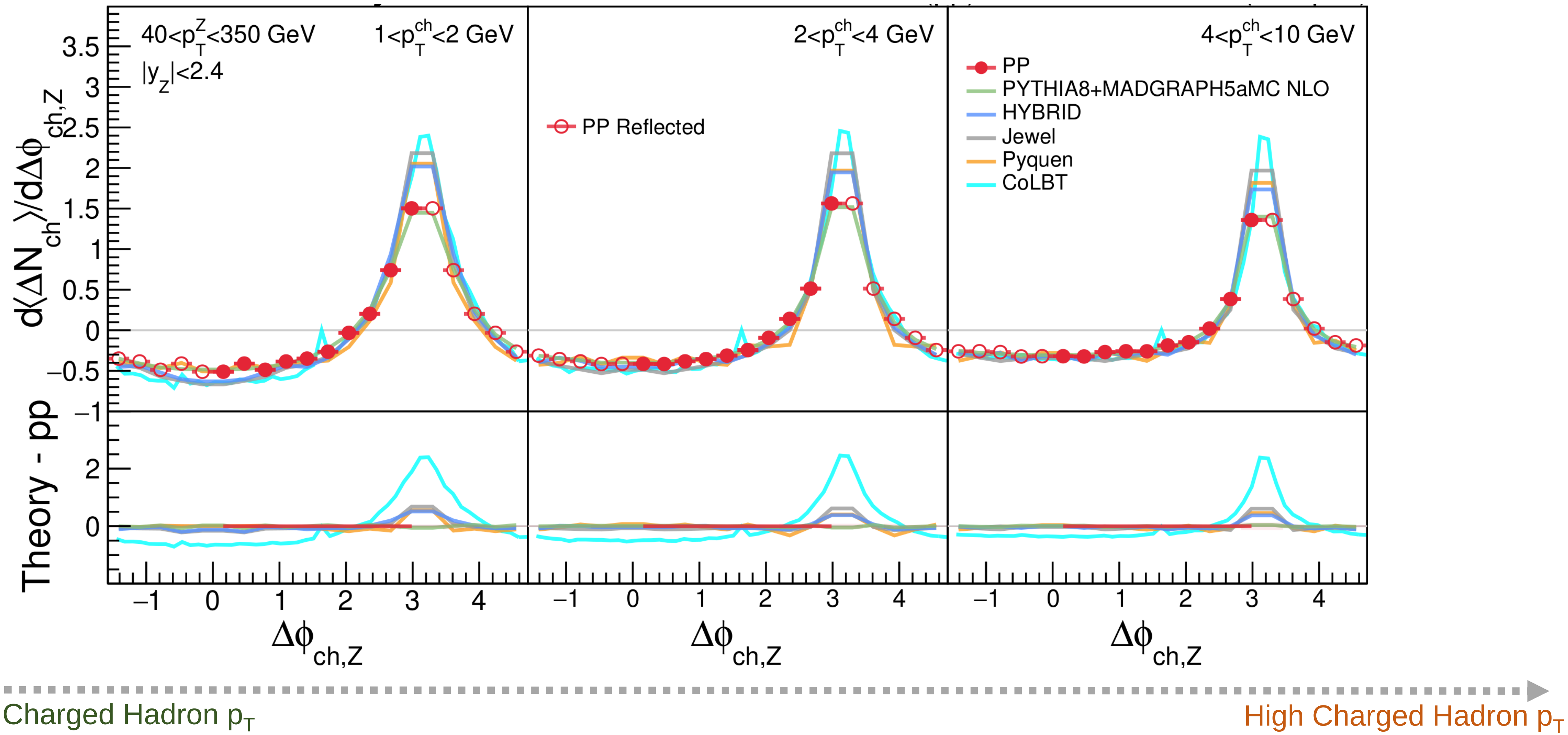
- HYBRID: QGP wake creates a Z-side dip structure and significantly enhance the jet peak

Predictions from Models for Charged Hadron p_T 1-2 GeV



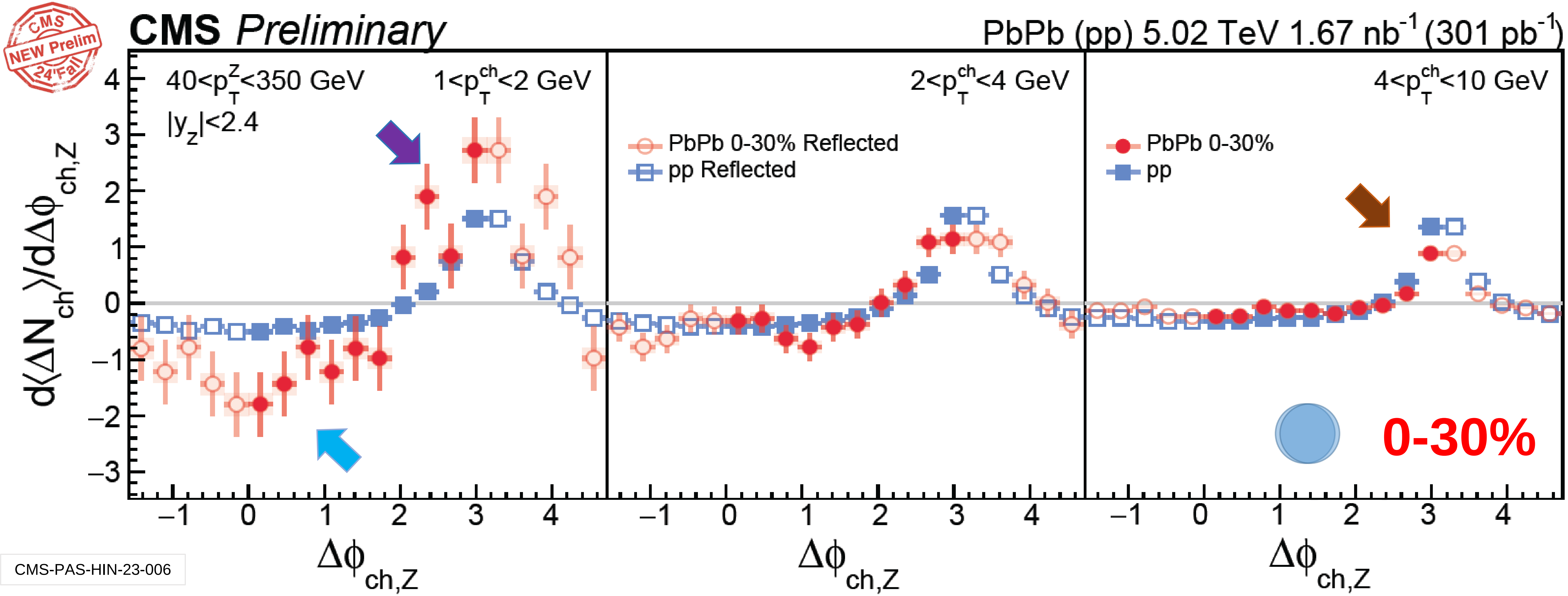
- HYBRID: QGP wake creates a Z-side dip structure and significantly enhance the jet peak
- JEWEL: recoil partons are responsible for the effects

Azimuthal Angle Distributions in pp vs. Theory



- **PYTHIA8+MADGRAPH5aMC@NLO** gives the best description of the data
- **PYTHIA6** **(8)** based calculations predicts a **sharper** jet peak

Azimuthal Angle Distributions in pp and 0-30% PbPb



CMS-PAS-HIN-23-006

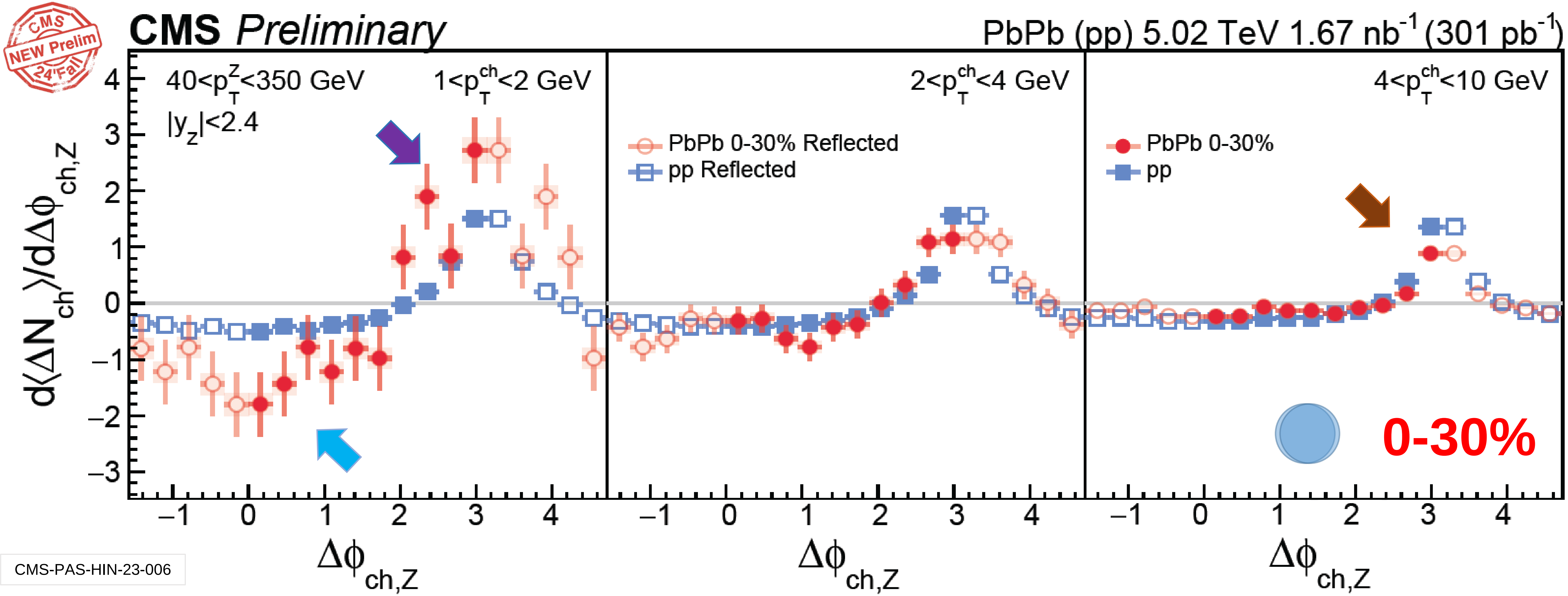
Low Charged Hadron p_T → High Charged Hadron p_T

PbPb: Clear depletion in Z^0 side ($\Delta\phi=0$) and enhancement in jet side ($\Delta\phi=\pi$)

PbPb: Effect reduced in the intermediate p_T region (2-4 GeV)

PbPb: **Jet side peak** ($\Delta\phi=\pi$) reduced due to jet quenching at high hadron p_T

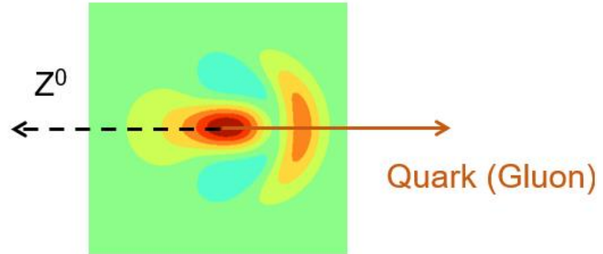
Azimuthal Angle Distributions in pp and 0-30% PbPb



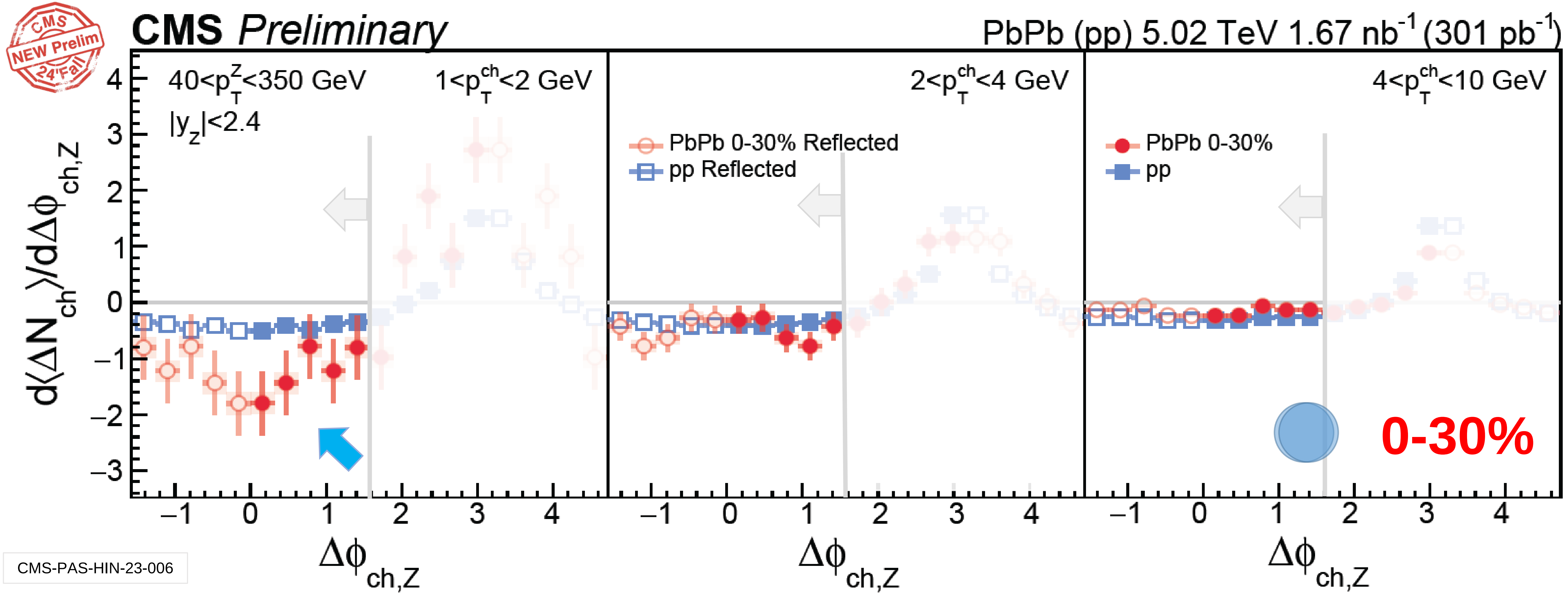
CMS-PAS-HIN-23-006

Now we have seen a deeper dip structure at $\Delta\phi$~0 in data

How about rapidity distributions?



Azimuthal Angle Distributions in pp and 0-30% PbPb

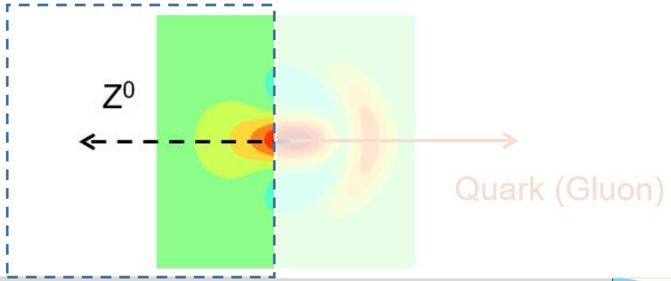


CMS-PAS-HIN-23-006

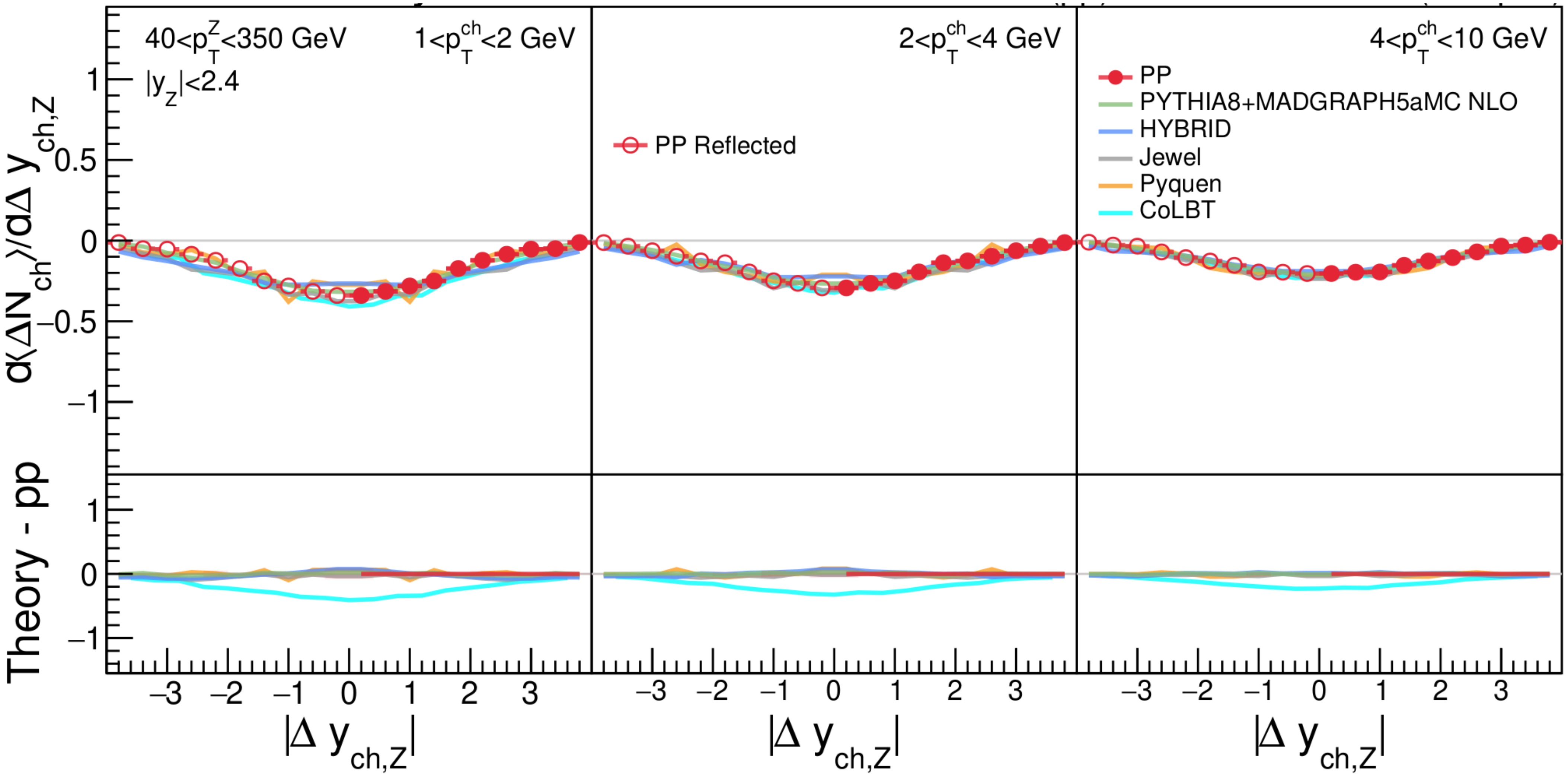
Now we have seen a deeper dip structure at $\Delta\phi\sim0$

How about rapidity distributions?

Let's focus on the **Z^0 side ($\Delta\phi< \pi/2$)** and then look at the Δy spectra



Rapidity Distributions in pp vs. Theory



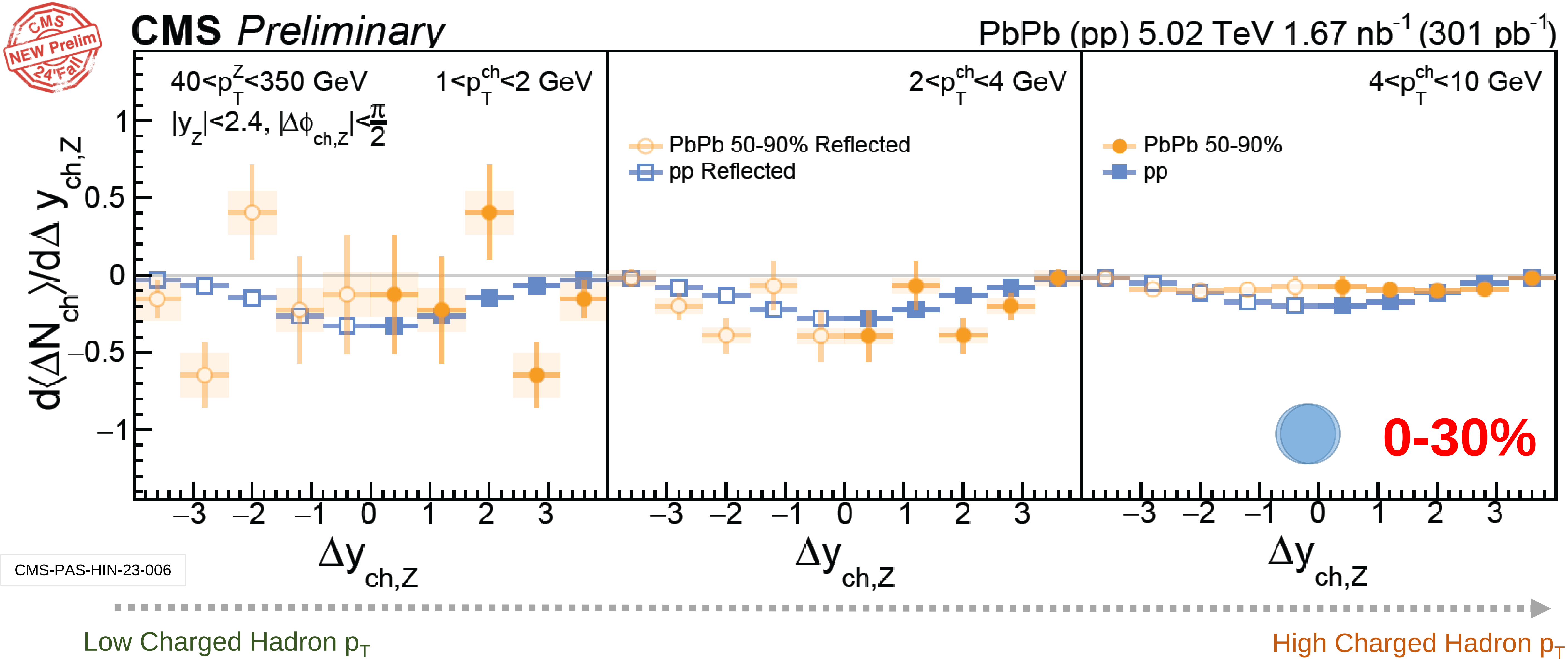
CMS-PAS-HIN-23-006

Low Charged Hadron p_T

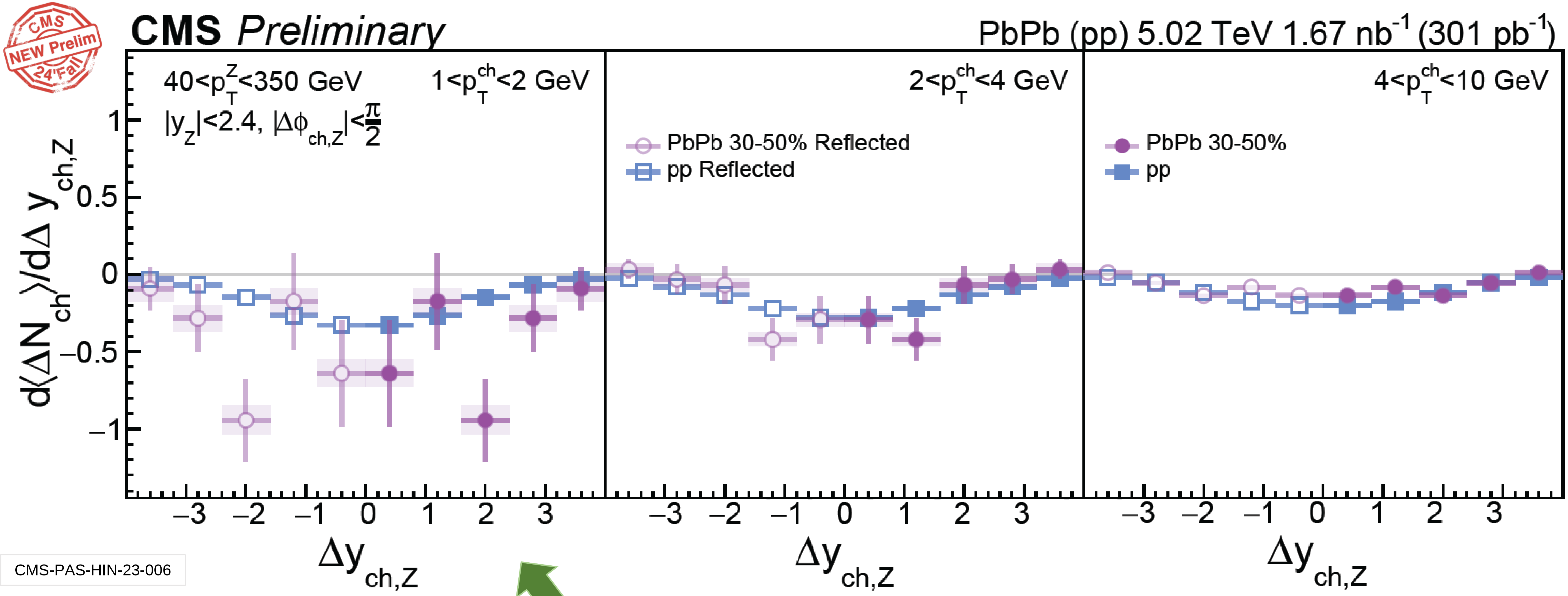
High Charged Hadron p_T

Generally, **PYTHIA6 (8)** and **PYTHIA8+MADGRAPH5aMC@NLO** describe the **pp data** very well.

Rapidity Distributions in pp and 50-100% PbPb



Rapidity Distributions in pp and 30-50% PbPb



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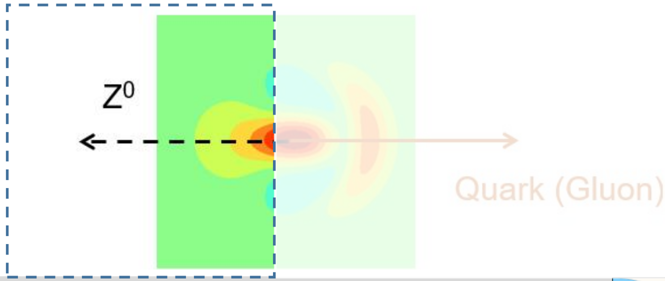
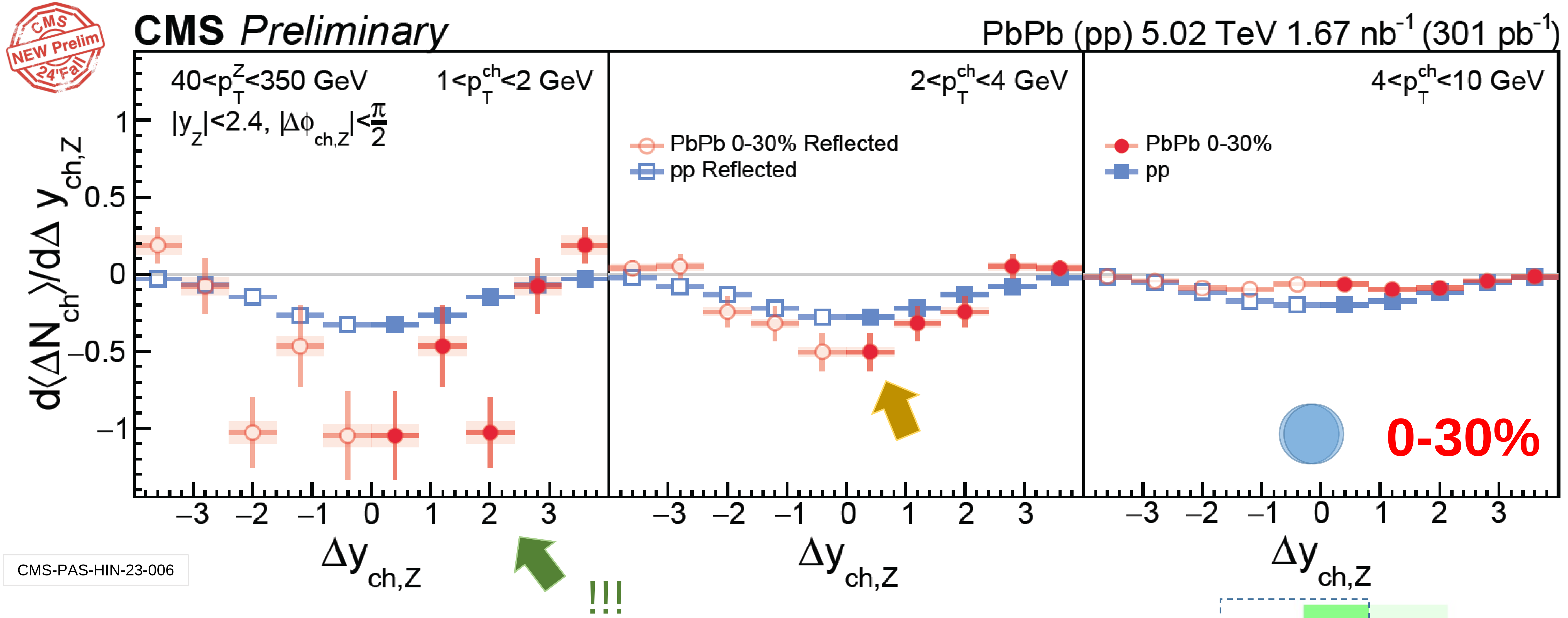
PbPb: Indication of depletion around the Z ($\Delta y=0$) and the effect reduces at higher Δy



Rapidity Distributions in pp and 0-30% PbPb



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PbPb: Clear depletion around the Z (Δy=0) and the effect reduces at higher Δy

PbPb: Effect reduced in the intermediate p_T region (2-4 GeV)

Azimuthal Angle Distribution in 0-30% PbPb vs. Theory **w/o** Medium Response

- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T

- **PYTHIA8 lower p_T Z^0 events:** can approximate jet quenching (similar to no-wake/recoil models with only the jet shower). It fails to describe data for hadron $p_T < 4$ GeV.

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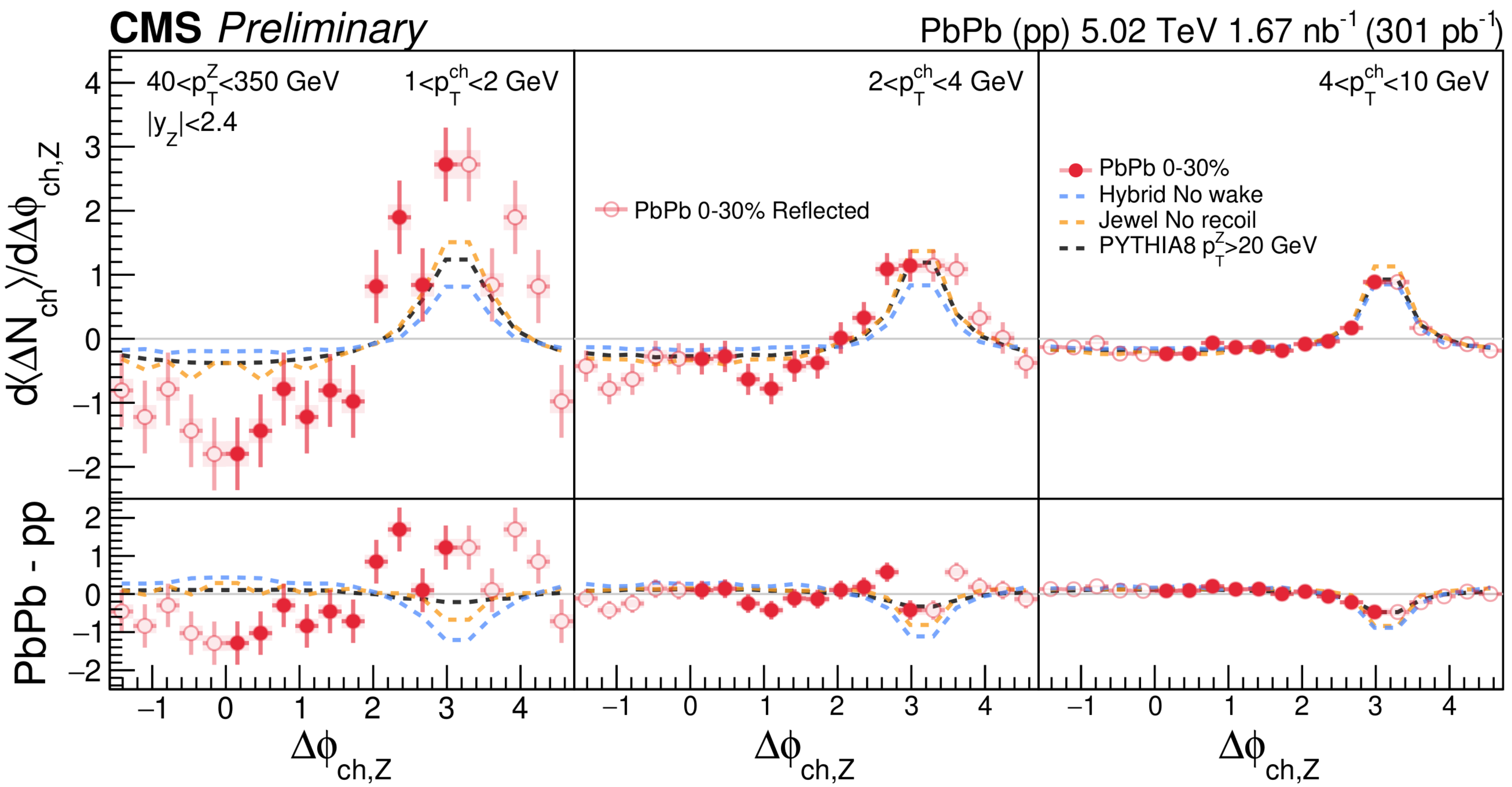
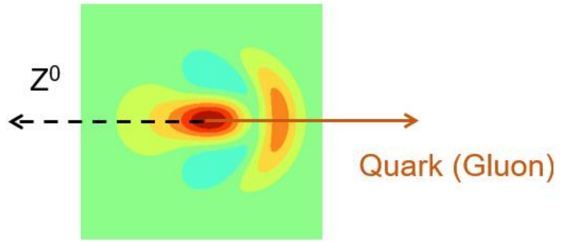


(Another test on magnitude of negative ΔN_{ch} near Z^0 without recoil/wake)

40 GeV Z + 40 GeV jet —Quench→ 40 GeV Z + quenched jet + recoil/wake

—Approx.→ 20 GeV Z + 20 GeV pythia jet ~~+ recoil/wake~~



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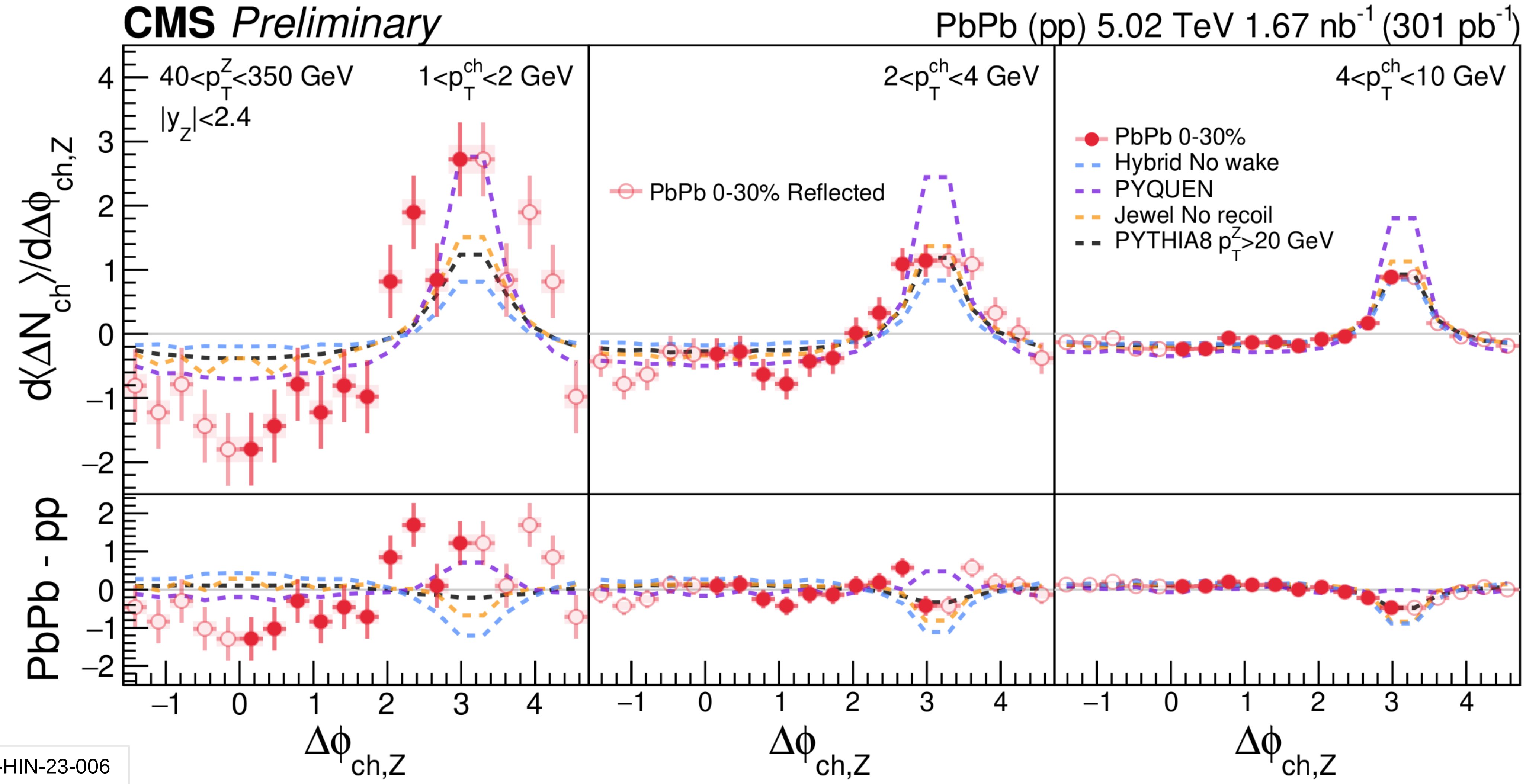
Theory Comparison: Azimuthal Angle Distribution in 0-30% PbPb

- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T

- **PYTHIA8 lower p_T Z^0 events**, can approximate jet quenching (similar to no-wake/recoil models with only the jet shower). It fails to describe data for hadron p_T < 4 GeV.

- **PYQUEN**, a model without 4-momentum conservation, fails to describe generally the data



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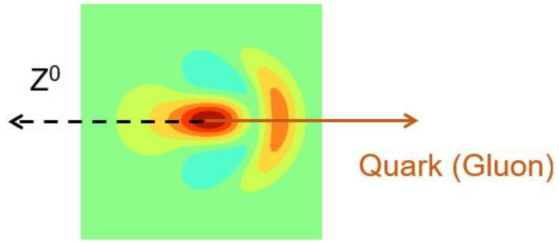
40 GeV Z + 40 GeV jet —Quench→ 40 GeV Z + quenched jet + recoil/wake

↕

—Approx.→ 20 GeV Z + 20 GeV pythia jet ~~+ recoil/wake~~



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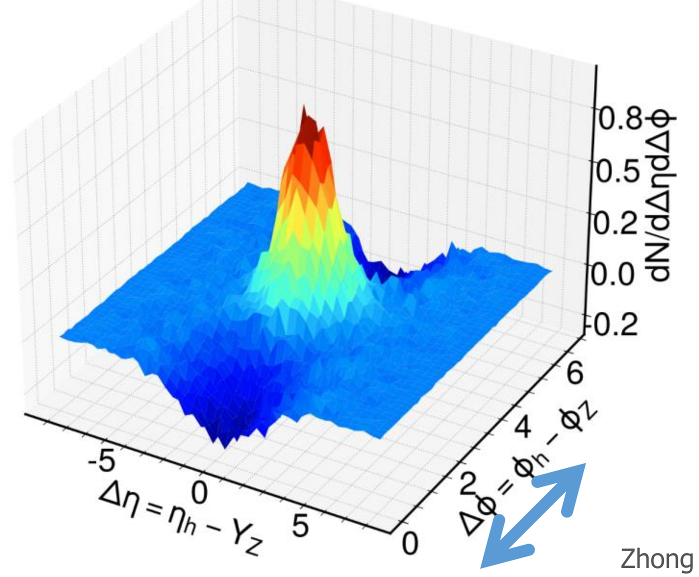
Azimuthal Angle Distribution in 0-30% PbPb vs. Theory

- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T
- **Hybrid with wake**, **Jewel with recoil** and **CoLBT with wake** (solid lines) agree better with the data with hadron p_T < 4 GeV

CoLBT **Z^0+hadron**



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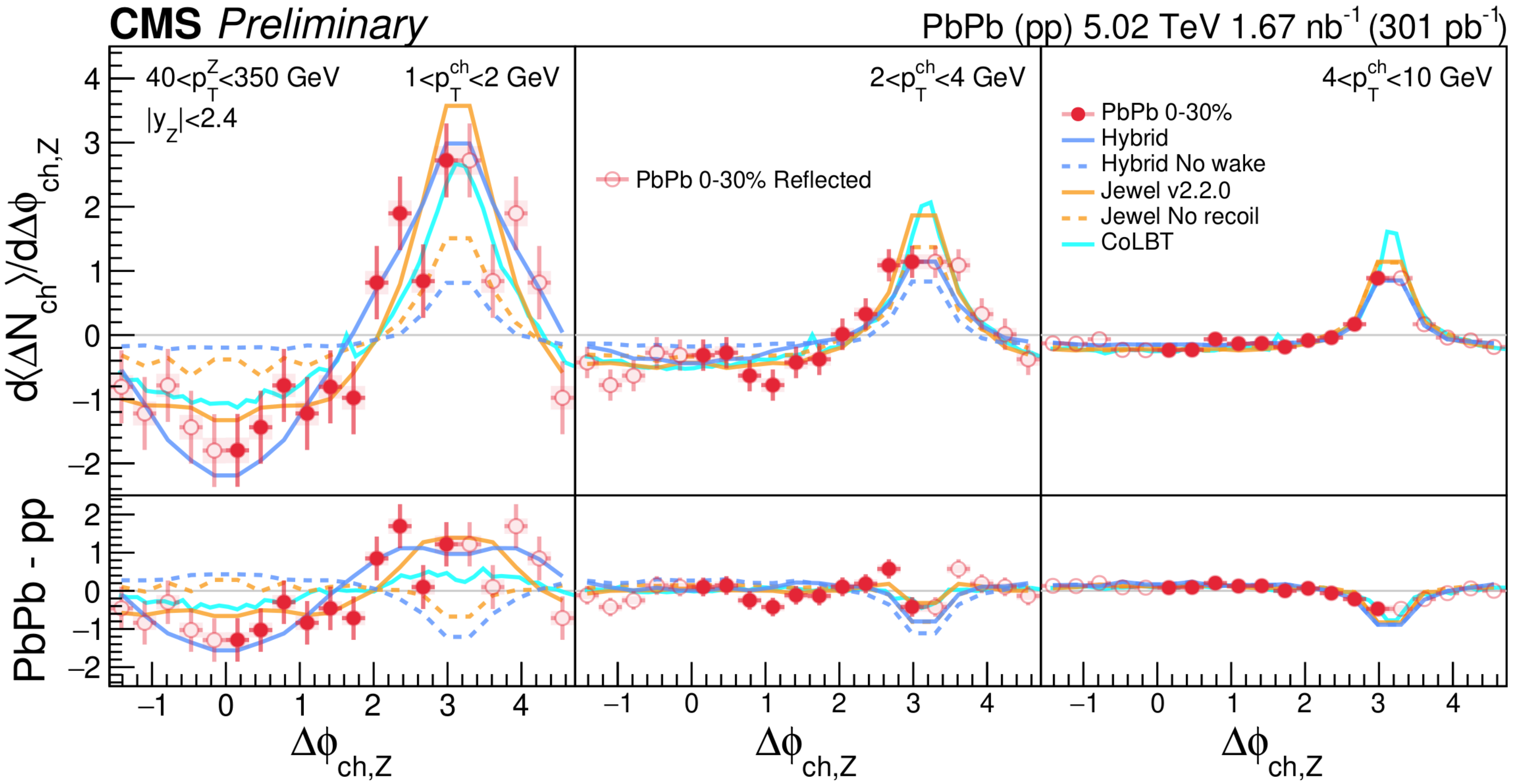

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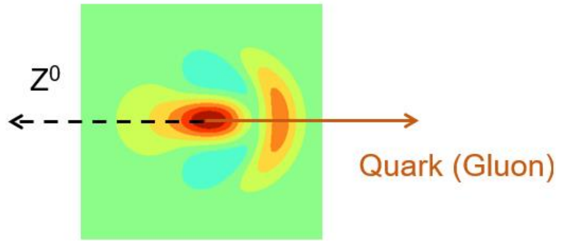

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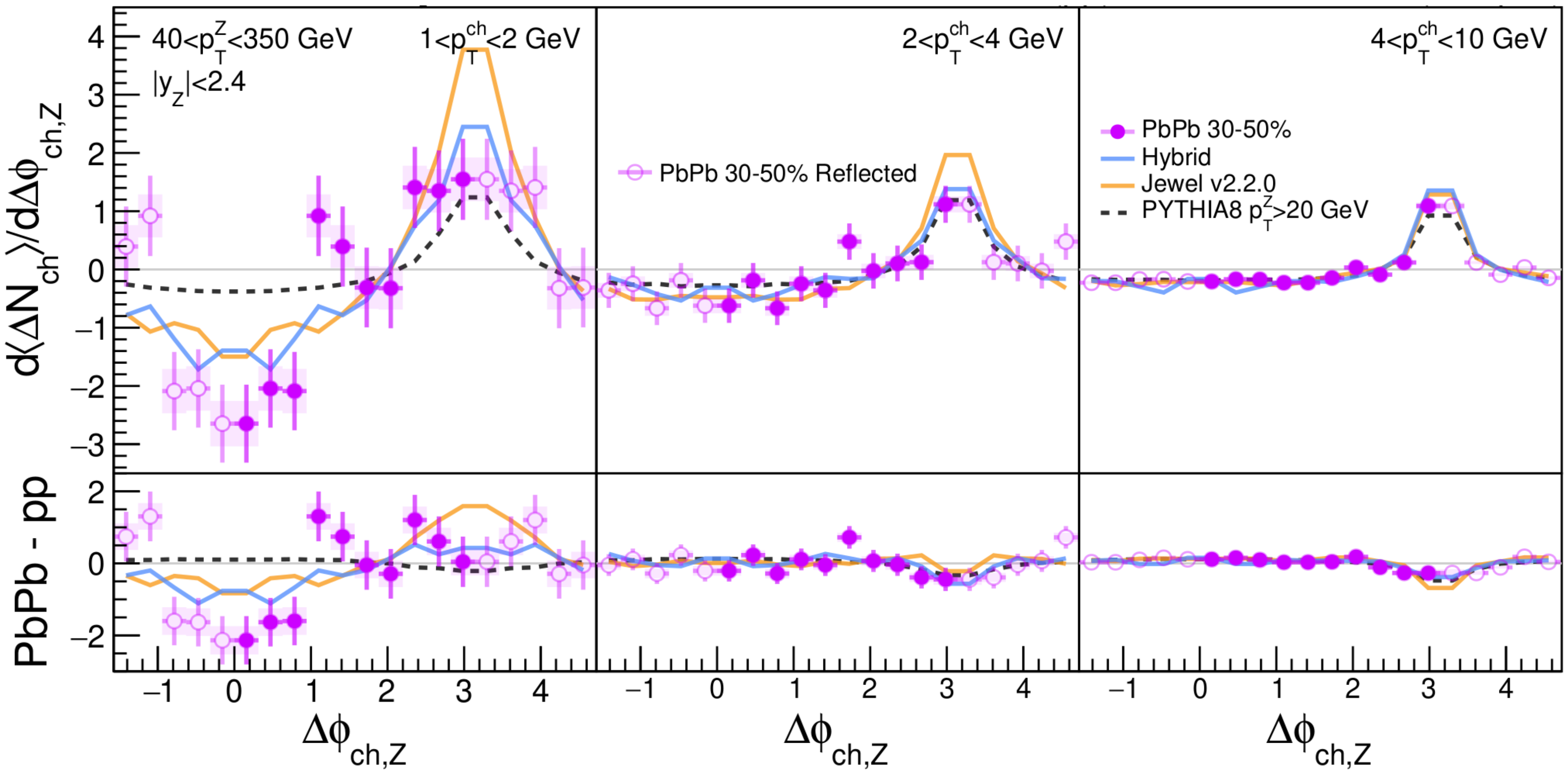
Azimuthal Angle Distribution in 30-50% PbPb vs. Theory

- The results are compared to low statistics **Jewel** and **Hybrid**
- In both models, we expect significantly larger modulation of low p_T spectra compared to pp
- **Hybrid with wake** (solid lines) agree better with the data with hadron p_T < 4 GeV



CAUTION: Jewel and Hybrid results are 2 days old

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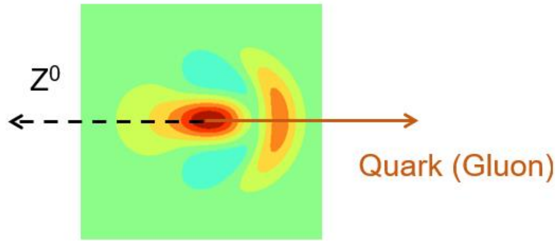

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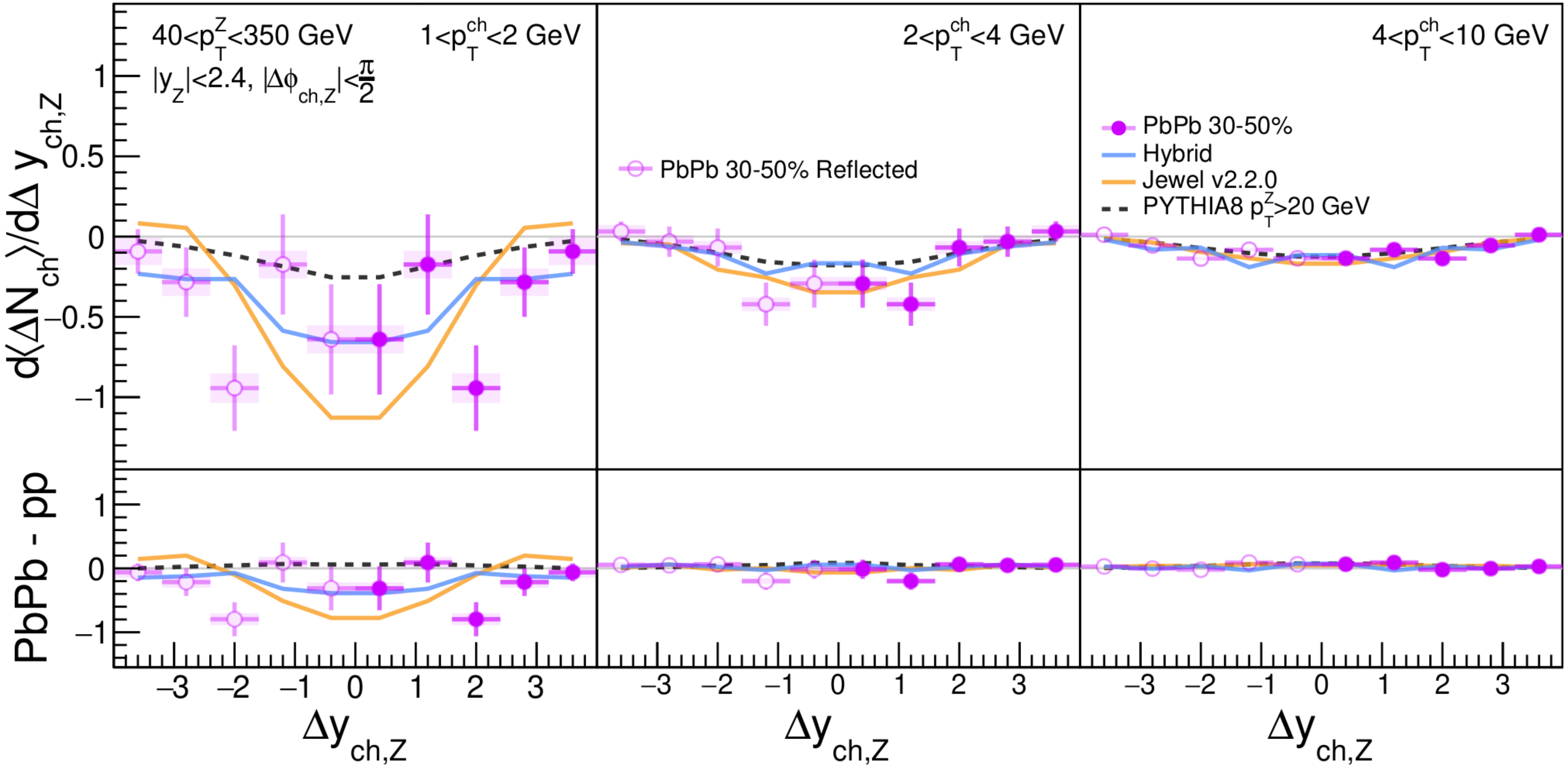
Rapidity Distribution in 30-50% PbPb vs. Theory

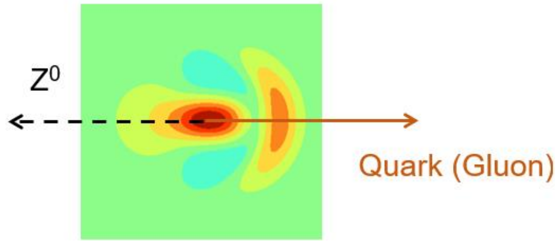
- The results are compared to low statistics **Jewel** and **Hybrid**

- **Hybrid with wake** (solid lines) and with **Jewel with recoil** give reasonable description of the data in all charged hadron p_T intervals

CAUTION: Jewel and Hybrid results are 2 days old



CMS-PAS-HIN-23-006



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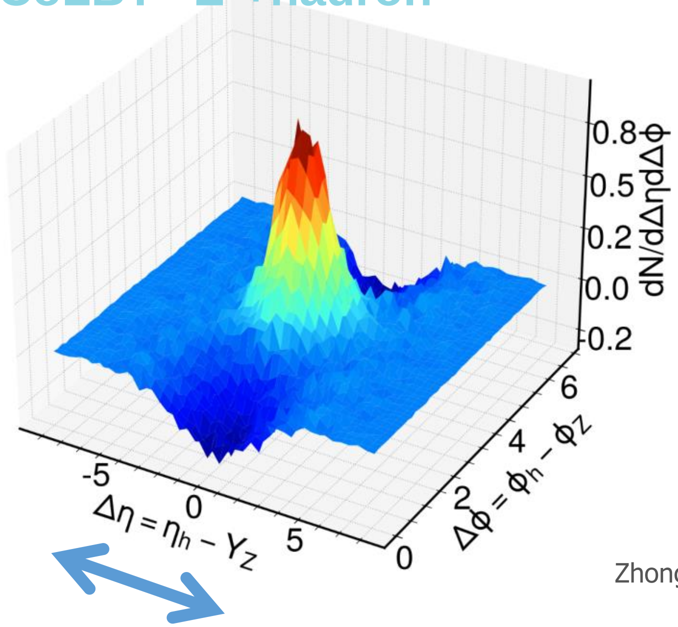
Rapidity Distribution in 0-30% PbPb vs. Theory without Medium Response

- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T

- **Lower p_T Z^0 tagged PYTHIA8 events** also fails to describe data with hadron p_T< 4 GeV.

CoLBT Z^0+hadron



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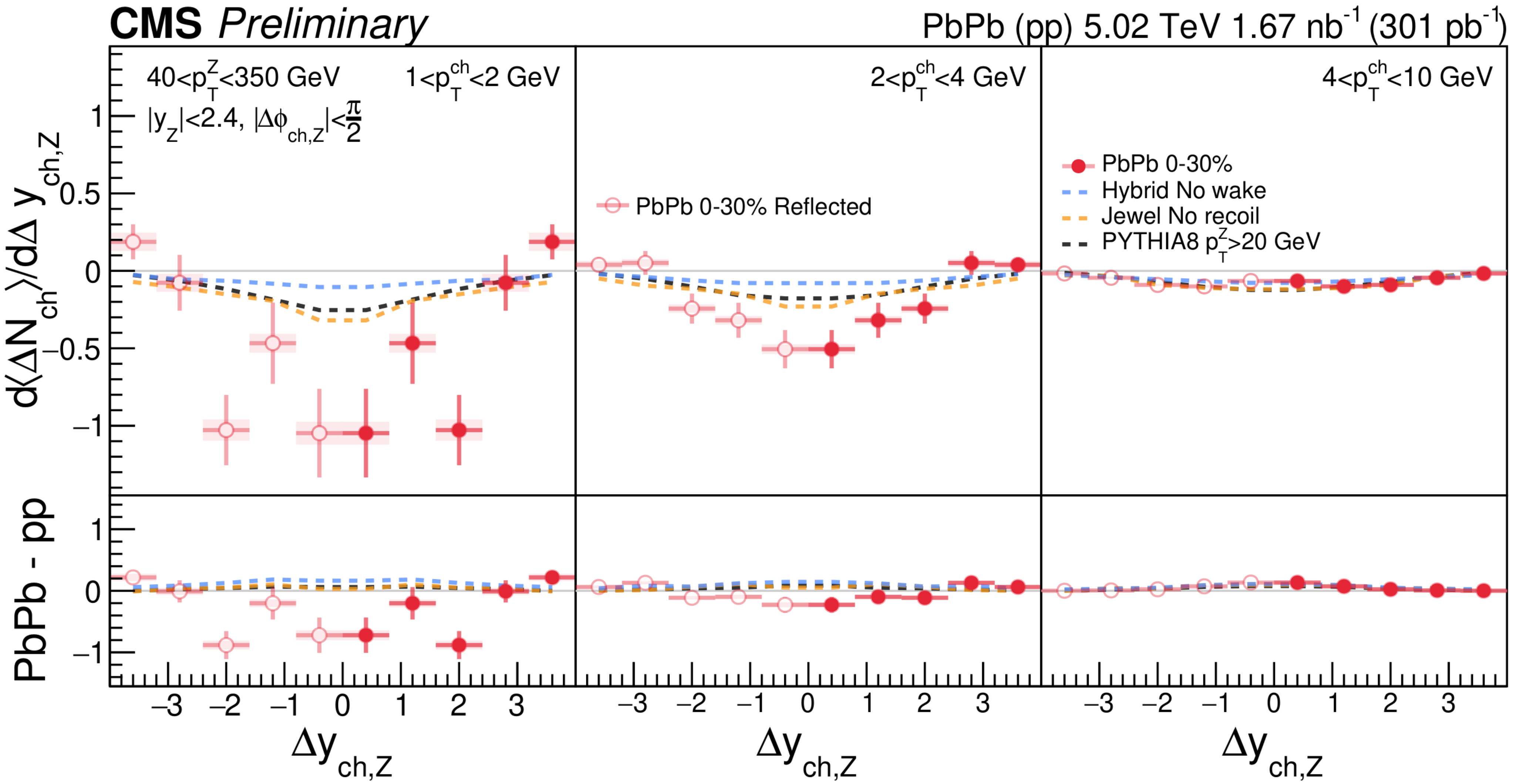
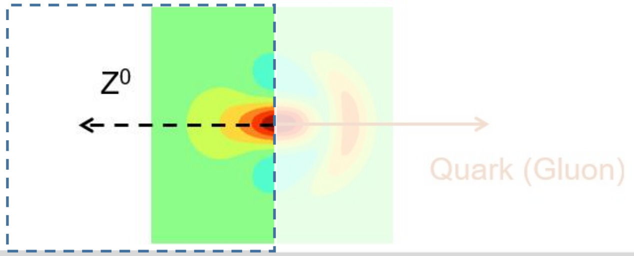


CMS-PAS-HIN-23-006

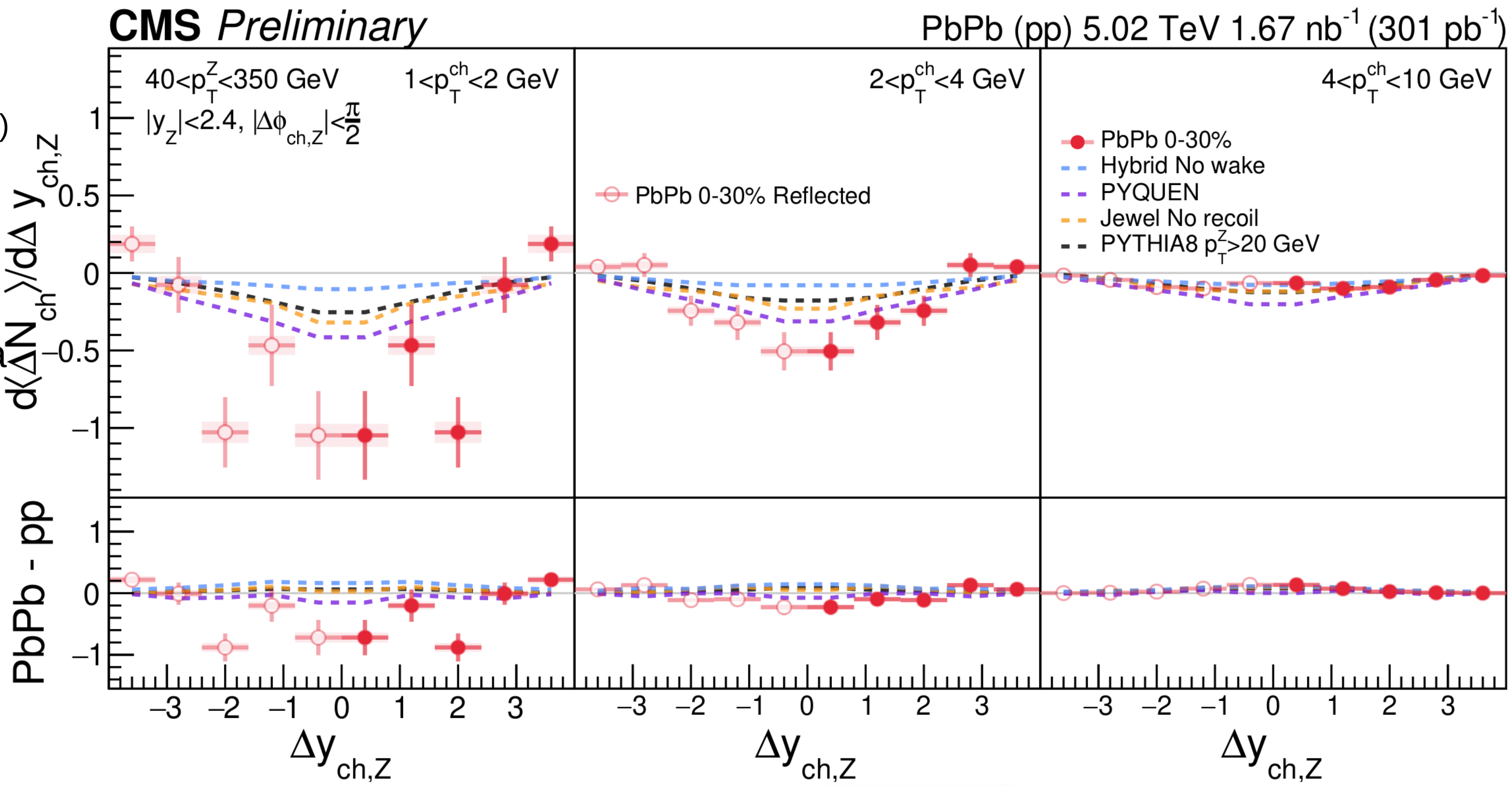


Theory Comparison: Rapidity Distribution in 0-30% PbPb

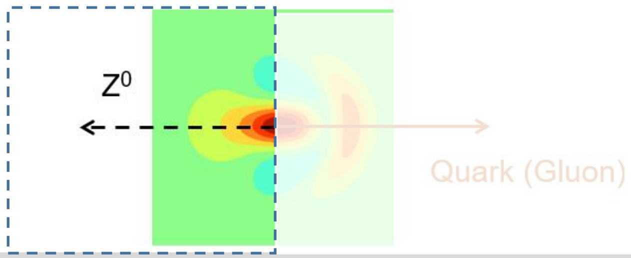
- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T

- **Lower p_T Z tagged PYTHIA8 events** also fails to describe data with hadron p_T< 4 GeV.

- **PYQUEN** fails to describe the data in all p_T intervals



CMS-PAS-HIN-23-006



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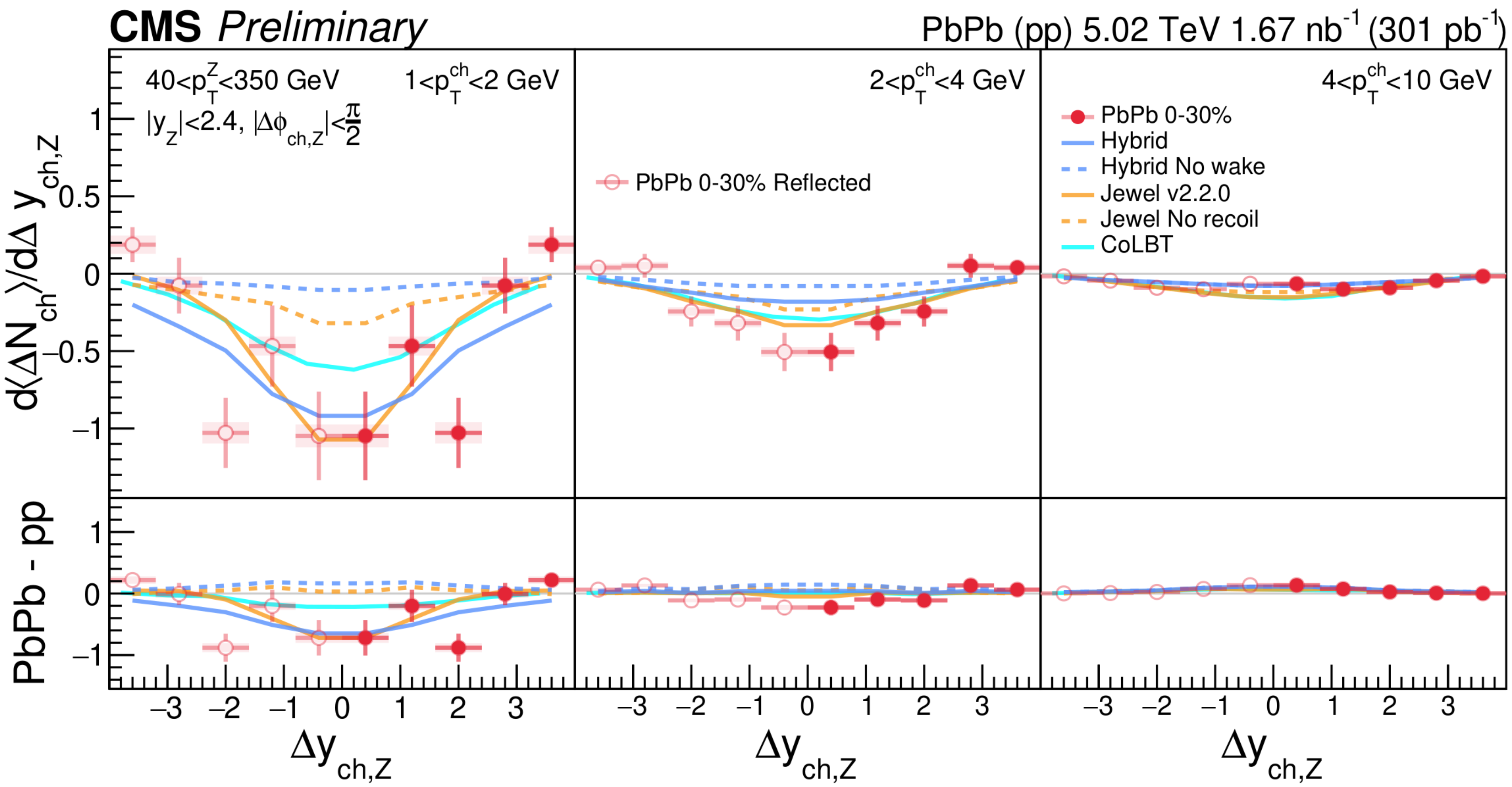
Rapidity Distribution in 0-30% PbPb vs. Theory

- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T

- **Hybrid with wake**, **Jewel with recoil** and **CoLBT** (solid lines) agree better with data



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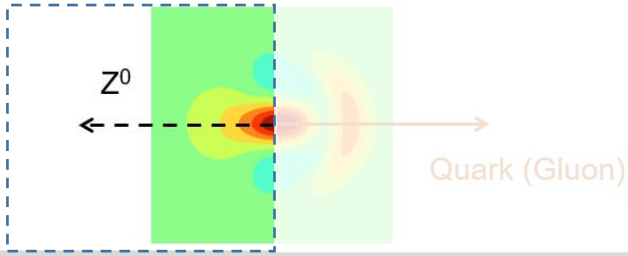
HP 2024 RIDING THE WAKE

With Δy and Δϕ spectra at low charged hadron p_T:

The first evidence of negative QGP wake!



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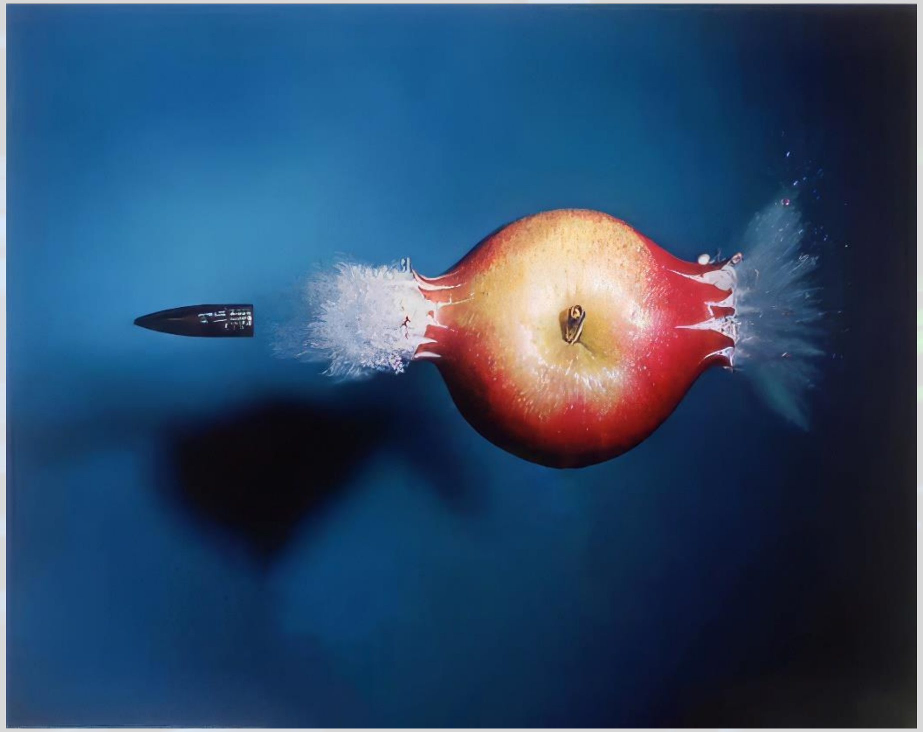
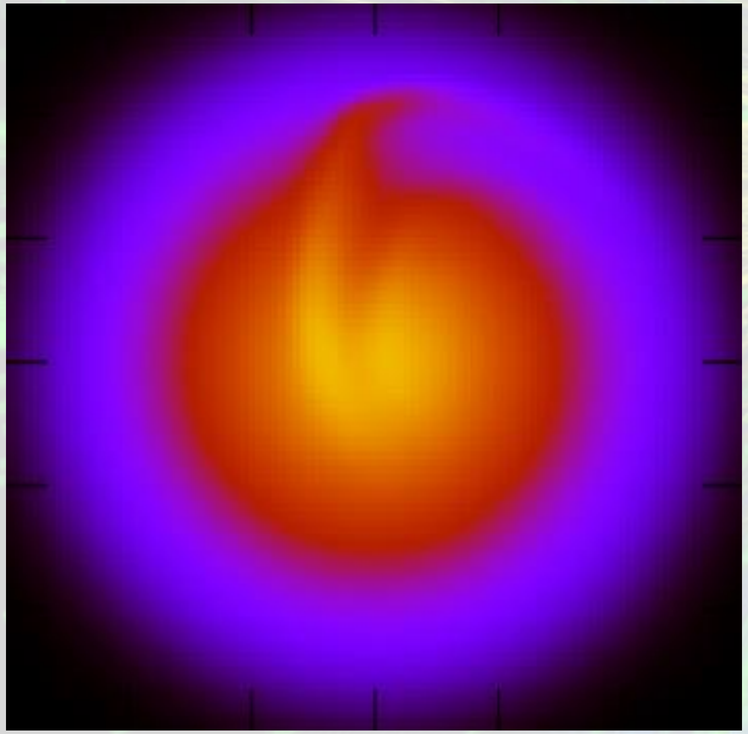
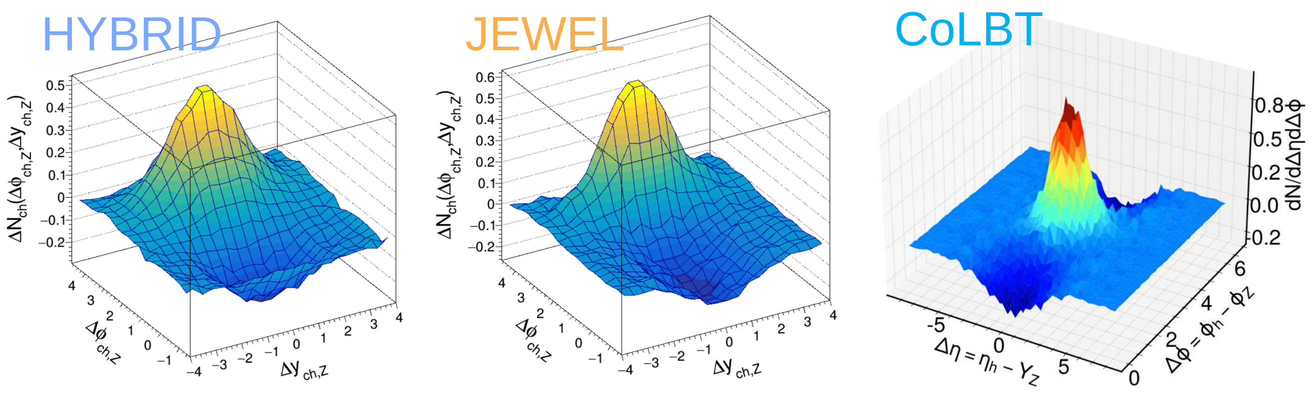
Implication and Outlook





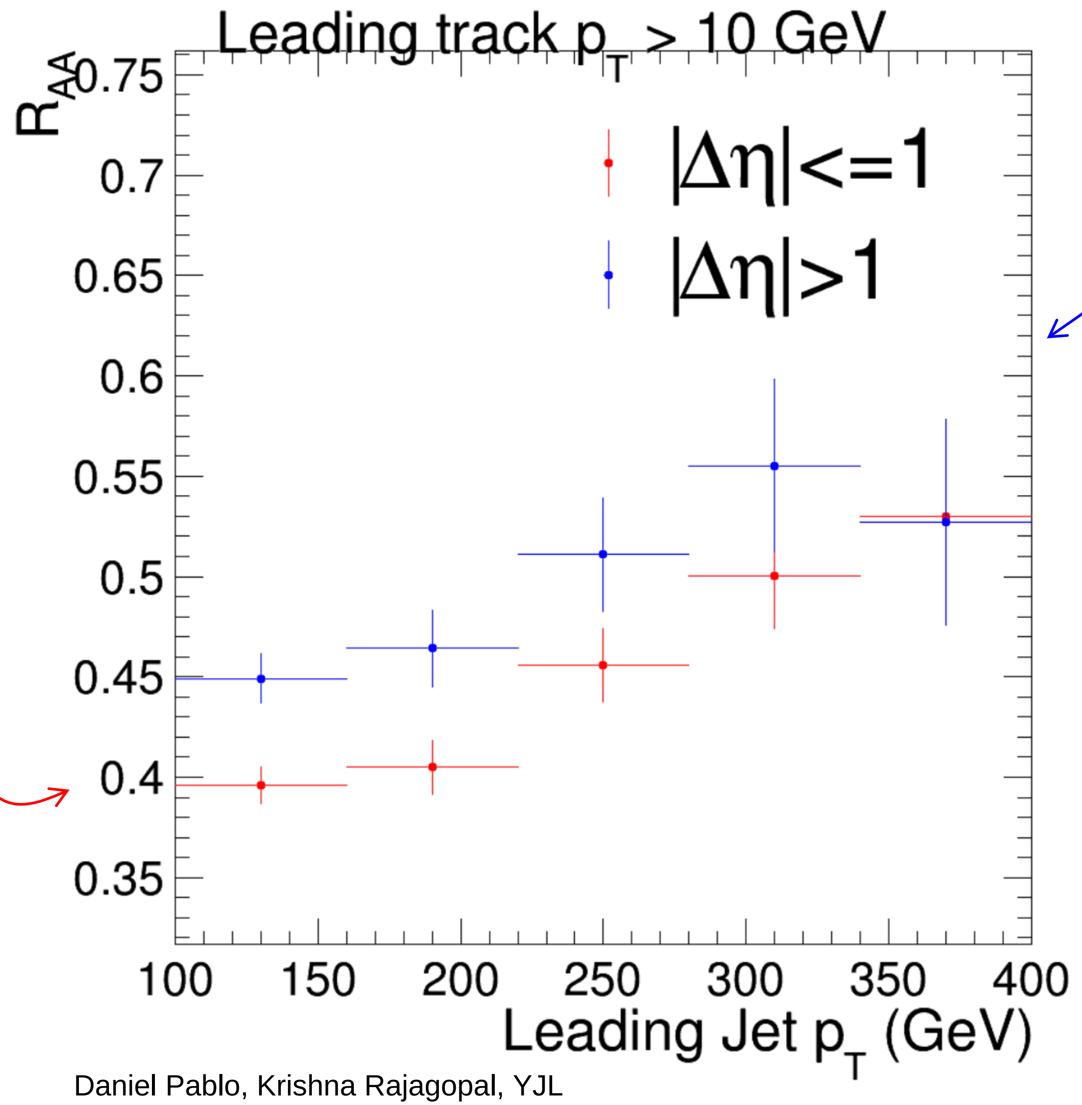
Unambiguous evidence of the QGP wake created by a fast moving quark

Implications from the Z-hadron Signal



Receive back reaction effect from the **away side jet**

Receive **partial** back reaction from the away side jet

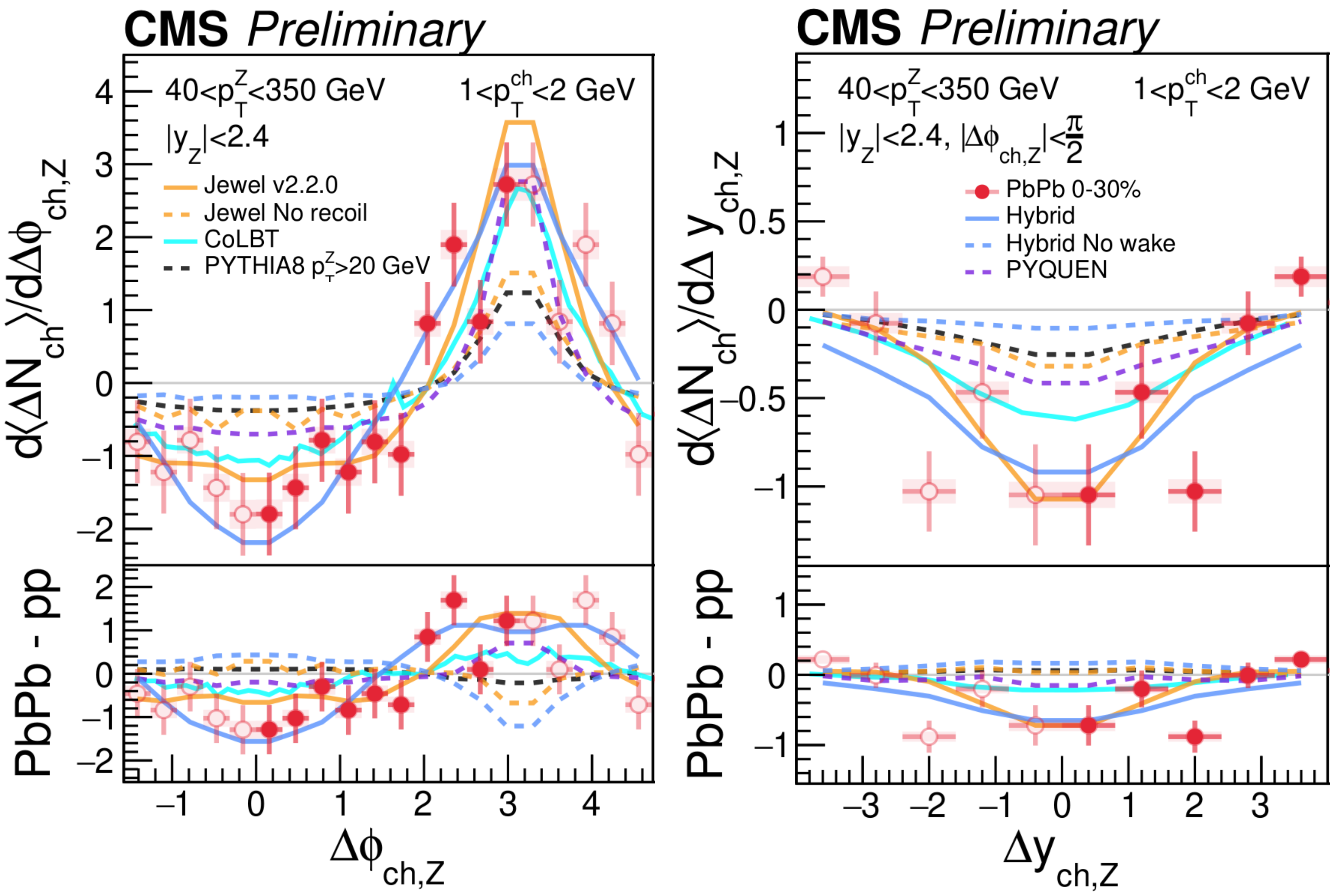


Daniel Pablo, Krishna Rajagopal, YJL

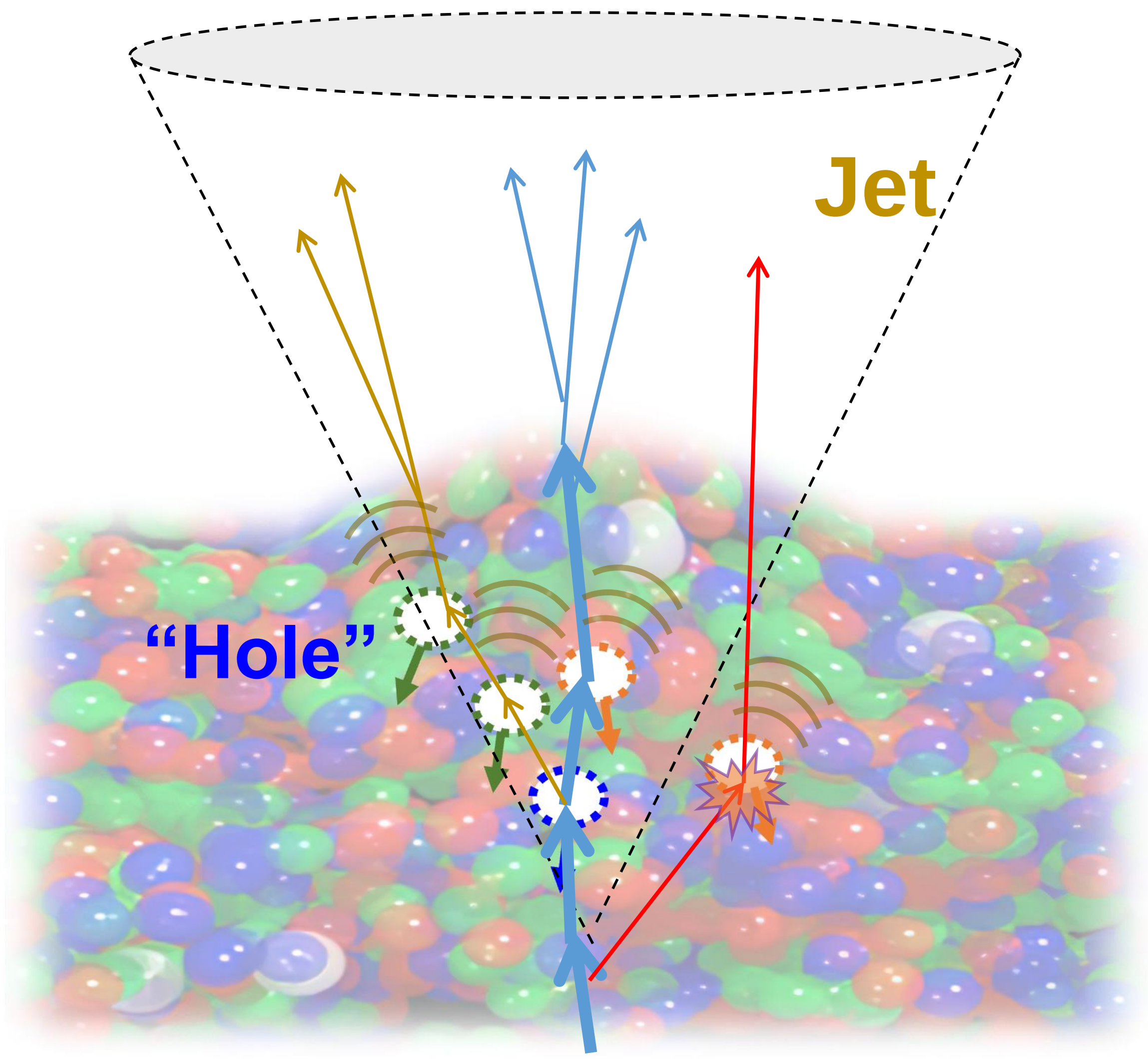
- Challenge the calculations / models based on independent jet shower
- Could change the way we compare **Photon / Z+jet** and **inclusive jet or h+jet** measurements
- Could impact the comparison of inclusive / dijet measurements with **different R** and **η acceptance**
- …

What We Still Want to Learn from Experimental Data

- How **correlated** is the negative wake with the **jet axis**?
- The **precise** angular and p_T spectra of medium recoil / negative wake hadrons
- How does the medium response **vary** with jet shower shape and the p_T of the hard probe?
- What is the **correlation** between medium response and hydrodynamic **flow**?
- What is the correlation between **negative** and **positive** wakes?
- …



QGP Transport Properties and Structure with Jets



- Jet broadening effects from multiple soft scattering $(\hat{q})$ and medium induced radiation
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes / Negative wake)
- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering

Possible Path Forward

- Jet broadening effects from multiple soft scattering ($\hat{q}$) and medium induced radiation
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes / Negative wake)
- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering

Extract from γ/Z+Jet and hadrons at low p_T +…

We have a clear path forward!

Possible Path Forward

Extract from EEEC, h+jet +…

Extract from γ/Z+Jet and hadrons at low p_T +…

- Jet broadening effects from multiple soft scattering ($\hat{q}$) and medium induced radiation
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes / Negative wake)
- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering

Possible Path Forward

Jet substructure, jet and hadron R_{AA}
g→ccbar + …

- Jet broadening effects from multiple soft scattering ($\hat{q}$) and medium induced radiation

Extract from EEEC, h+jet
+…

- Contribution from medium response

Extract from γ/Z+Jet and hadrons at low p_T +…

- Reveal medium recoil (the propagation of QGP holes / Negative wake)

- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering

Possible Path Forward

Jet substructure, jet and hadron R_{AA}
g→ccbar + ...

- Jet broadening effects from multiple soft scattering ($\hat{q}$) and medium induced radiation

Extract from EEEC, h+jet
+...

- Contribution from medium response

Extract from γ/Z+Jet and hadrons at low p_T +...

- Reveal medium recoil (the propagation of QGP holes / Negative wake)

Sub-jet multiplicity, jet substructure
γ/Z+hadron at intermediate p_T
+...

- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering

We have a clear path forward!

Acknowledgement

I would like to thank Xin-Nian Wang, Zhong Yang, Krishna Rajagopal, Liliana Apolinario, Dani Pablos for the useful comments and discussions

Thank You!

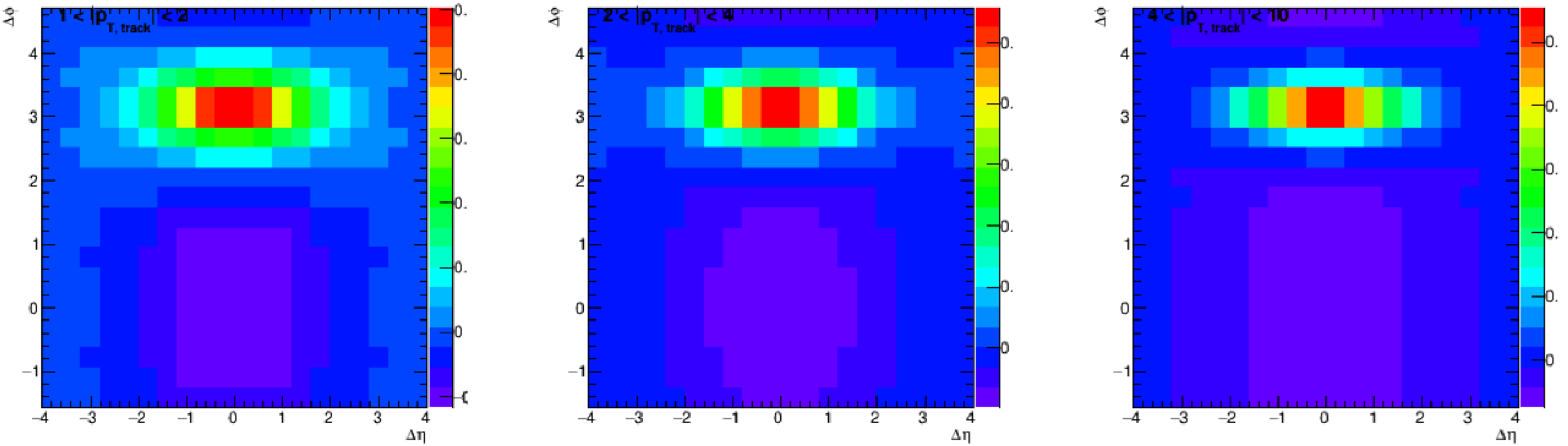
Backup Slides

2D Distribution (pp PYTHIA)

Track = 1-2 GeV

2-4 GeV

4-10 GeV



Delta eta = eta_ch - y_Z

Low Track p_T

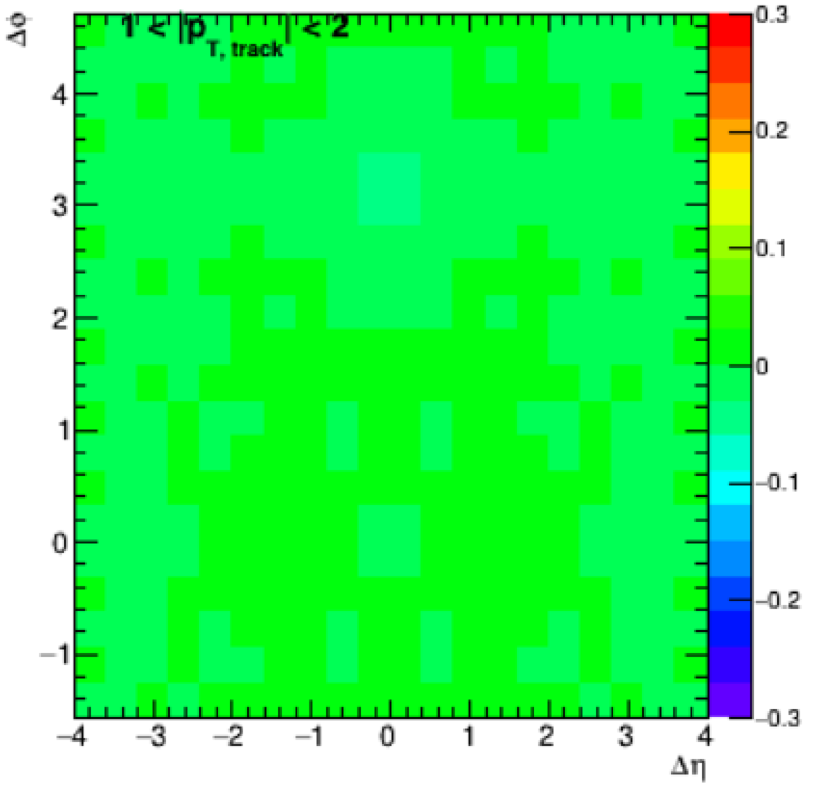
High Track p_T

2D Results (PYTHIA+HYDJET 0-90% - PYTHIA)

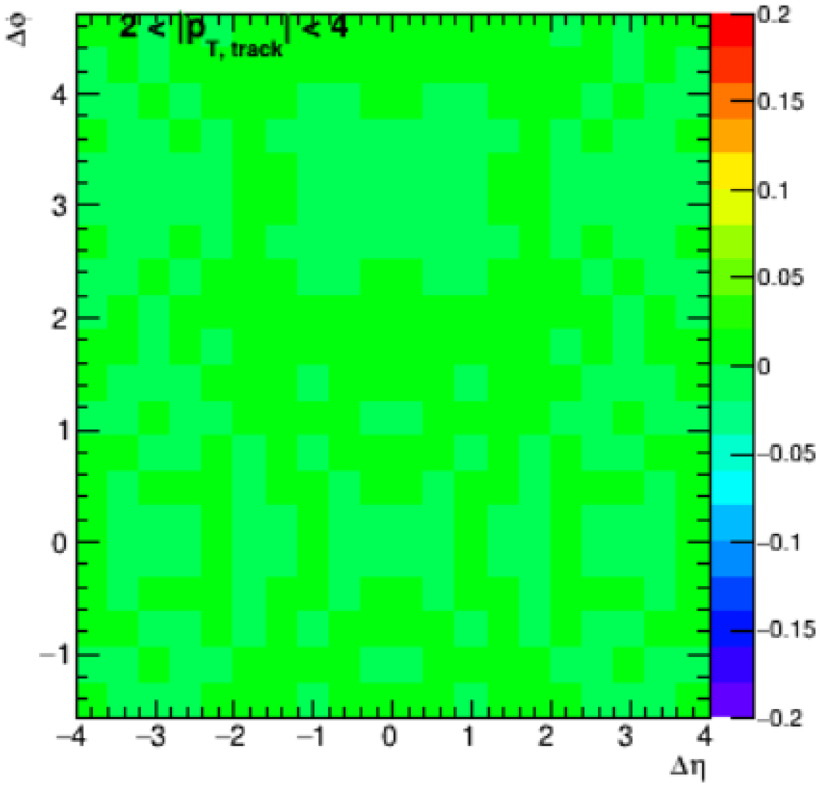
Track = 1-2 GeV

2-4 GeV

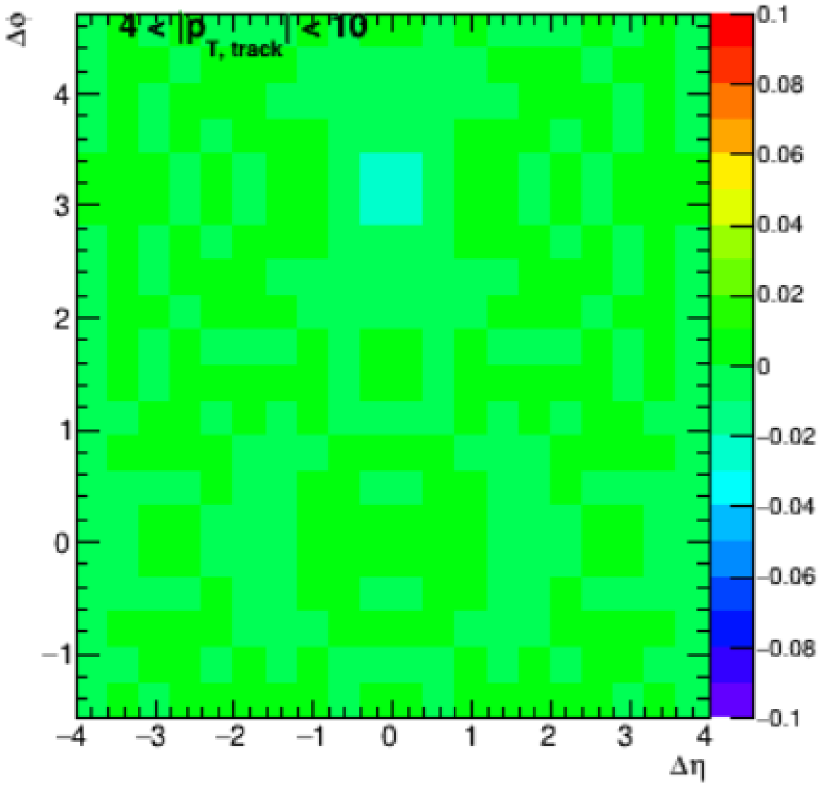
4-10 GeV



= y_z - η_{track}



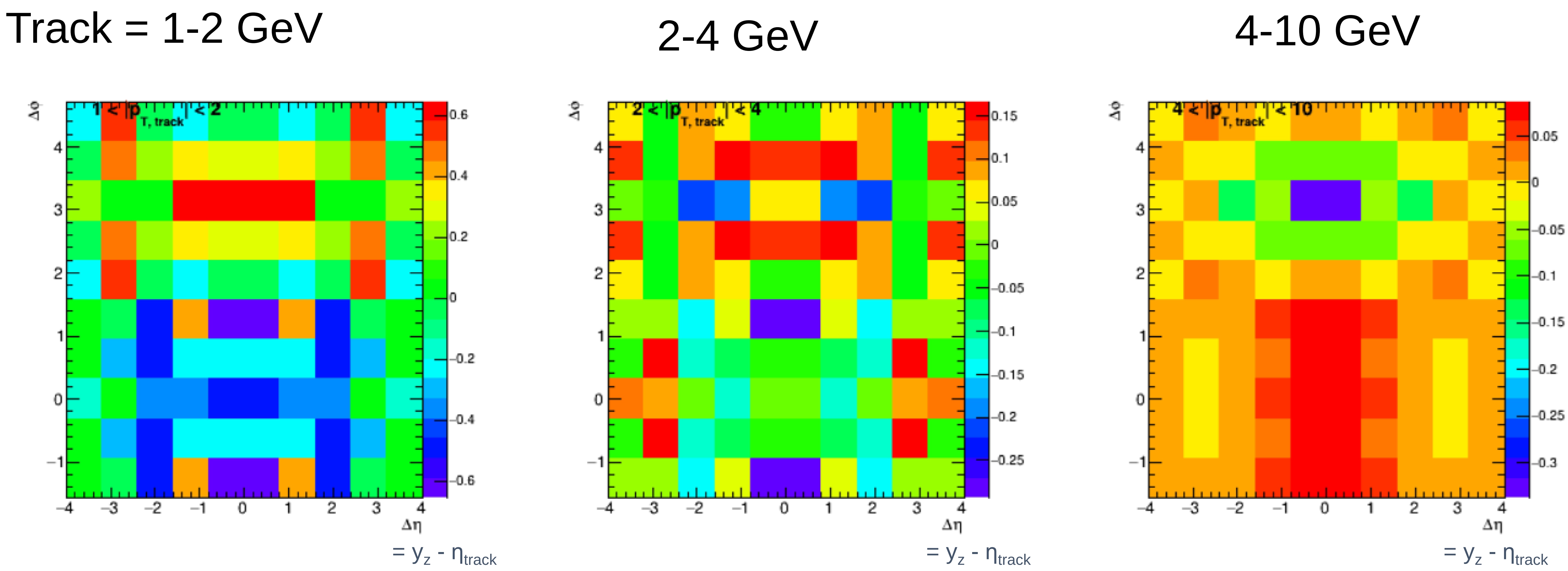
= y_z - η_{track}



= y_z - η_{track}

Closure test for the 2D plots: Good closure achieved

2D Results (PbPb 0-90% - pp rebin)



It is fun to see the "color inversion" in the 3 panel plot

Different behavior between low and high p_T tracks

Systematics

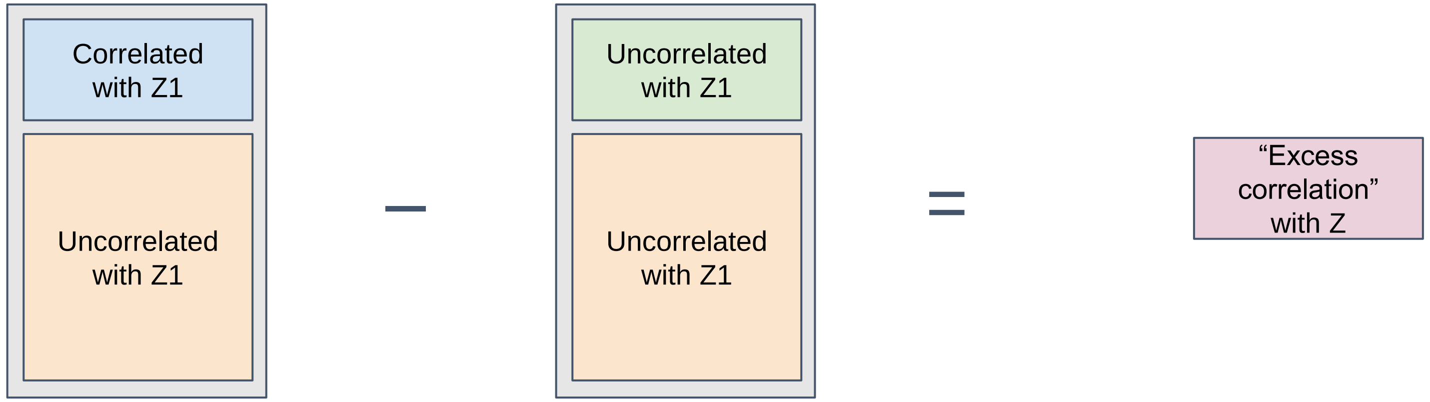
Systematics related to associated yield

- **Tracking efficiency**: 2.4% for pp and 5.0% for PbPb (of the associated yield)
- **PU (pp only)**: Difference between nPV = 1 and inclusive sample
- **Centrality (PbPb only)**: max absolute difference between nominal and varied (up and down) hiBin definition provided by global observable group
- **Muon efficiency:** vary the Z selection efficiency correction by 12 different variations in PbPb and 4 in pp, as defined by Dilepton / Muon mini-POG
- **Muon-track matching**: turn on or off the muon track - charged particle angular matching rejection (negligible)

Analysis Workflow: Event-Mixing

MC: embedded
Data: PbPb

MC: embedded
Data: PbPb



Event 1

Event 2
Correlated with Z in event 2, but not correlated with Z in event 1

Same population of events

- Normalize to 0 by construction
- Shape of correlation function across measurement range
  - e.g. small Δϕ vs large Δϕ
- Combining with expected number of particles reproduces event mixing result
- Apply same procedure on pp data to quantify effect from QGP

Results: Azimuthal Angle Distribution

- Open markers are the same as filled data points but reflected to show the full range
- Low track P_T: clear relative depletion in Z side and enhancement in jet side
- High track P_T: jet quenching effect suppresses jet peak
- Effect disappears in **50-90%**

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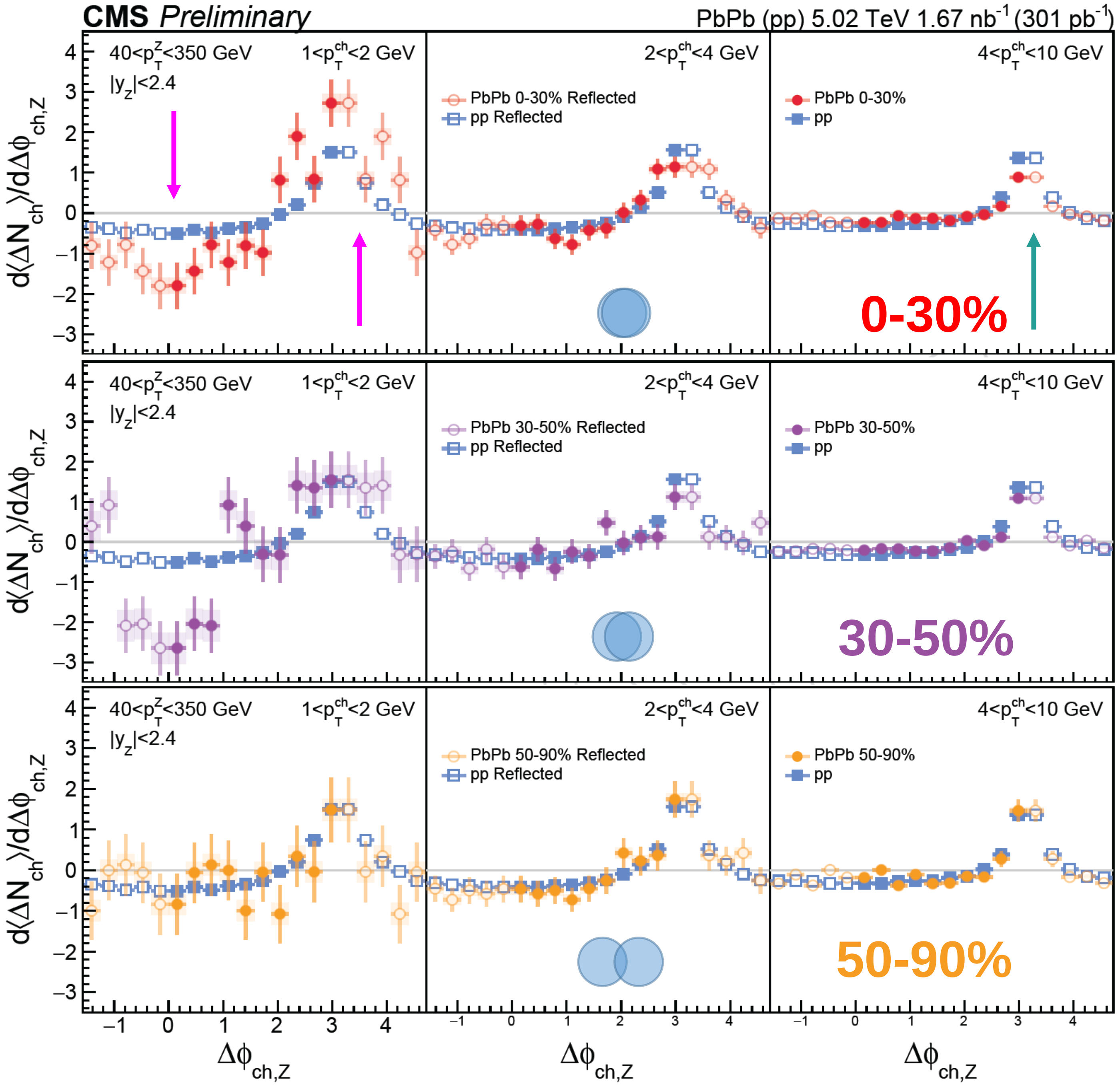
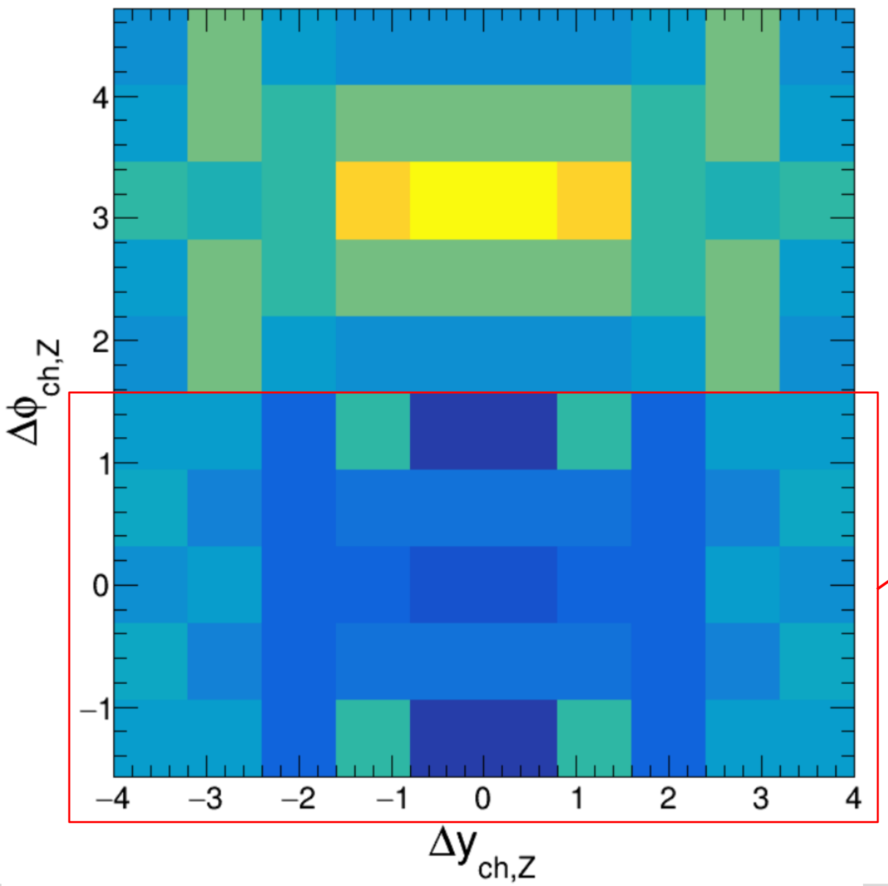
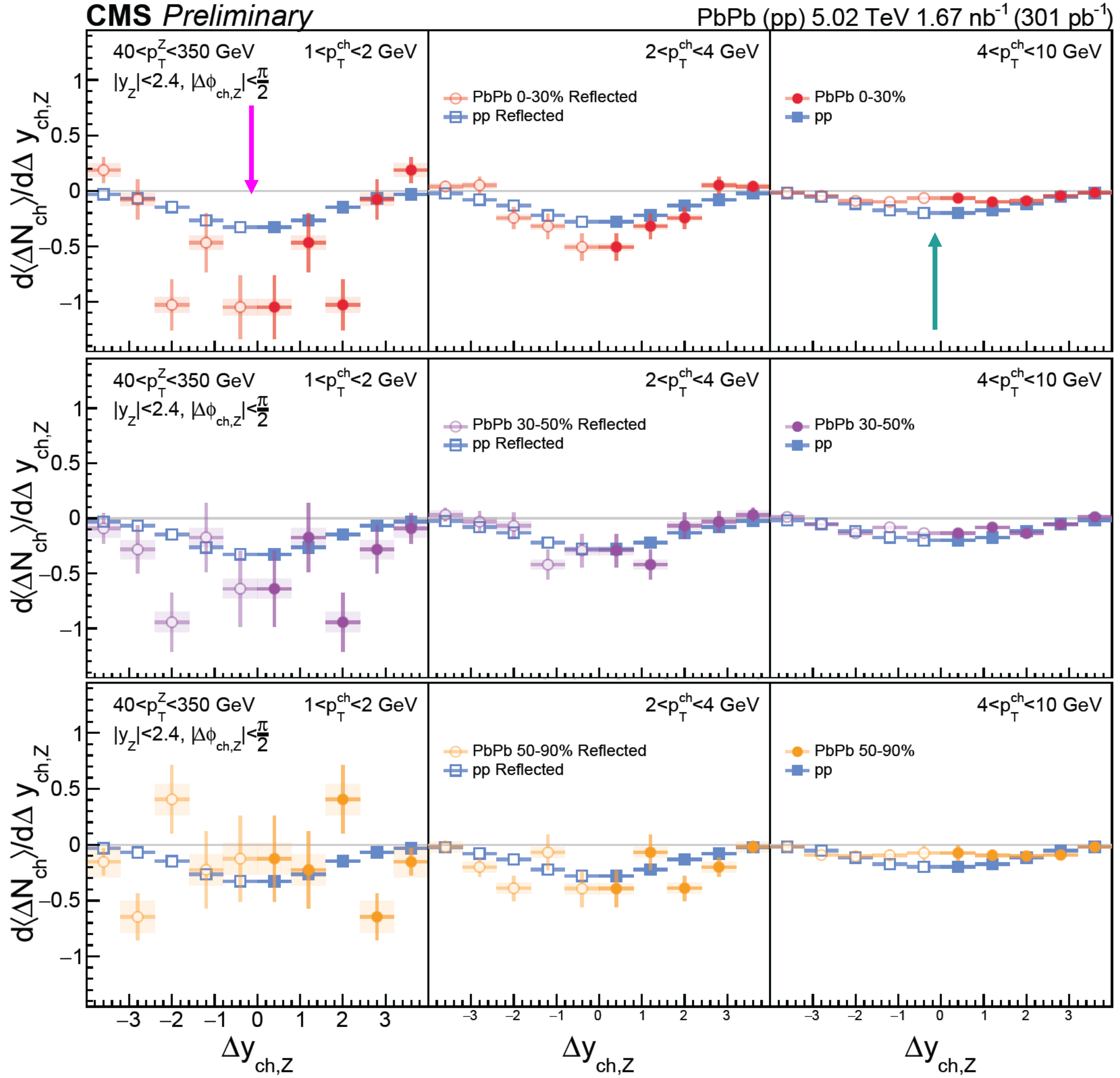


Results: Rapidity Distributions

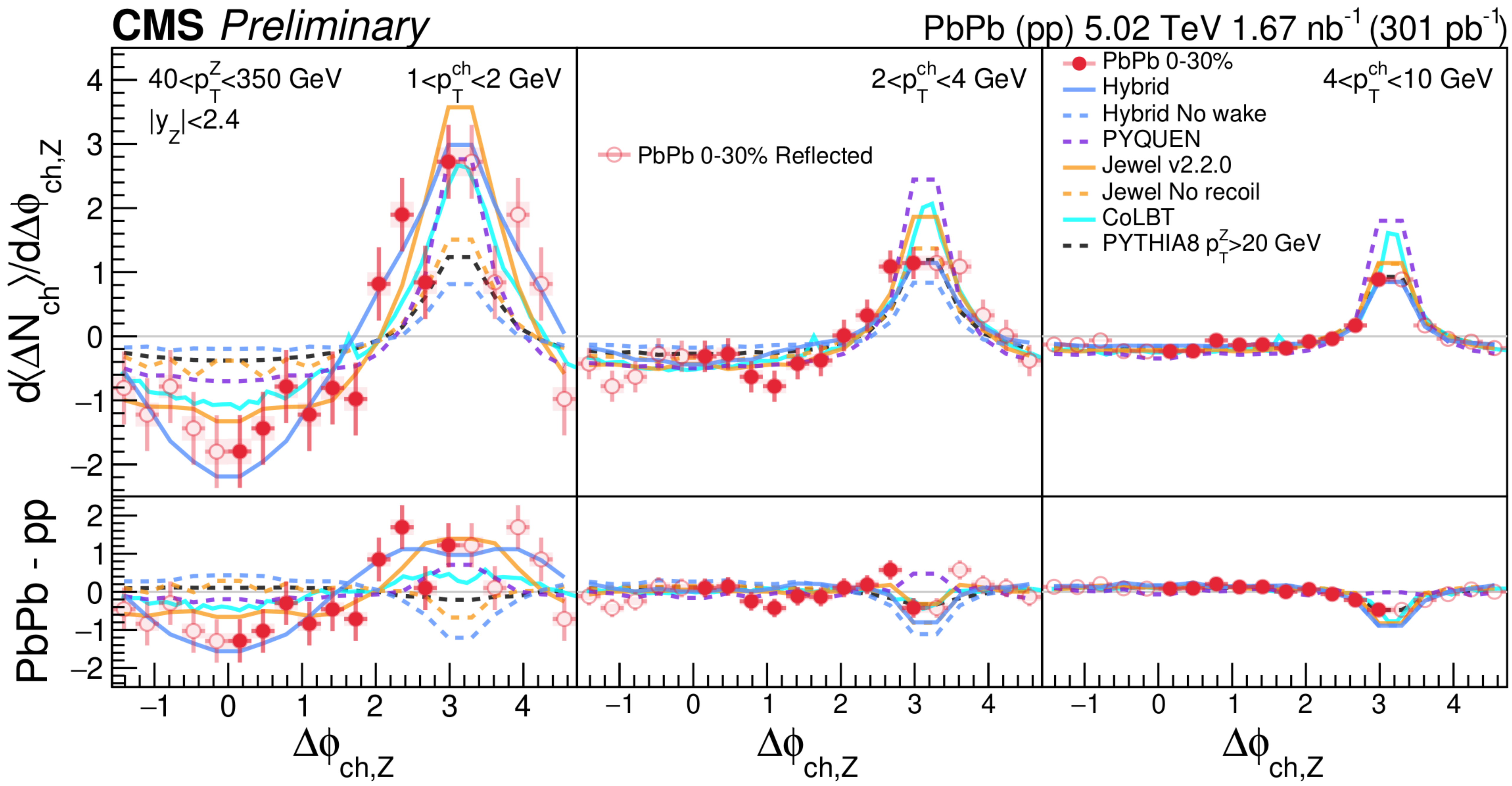
- Focus on the Z side: $|\Delta\Phi_{ch,Z}| < \pi/2$
- Integral **not zero** since this is not full range of $\Delta\Phi$

- Low track p_T: clear depletion observed
- High track p_T: PbPb shallower shape

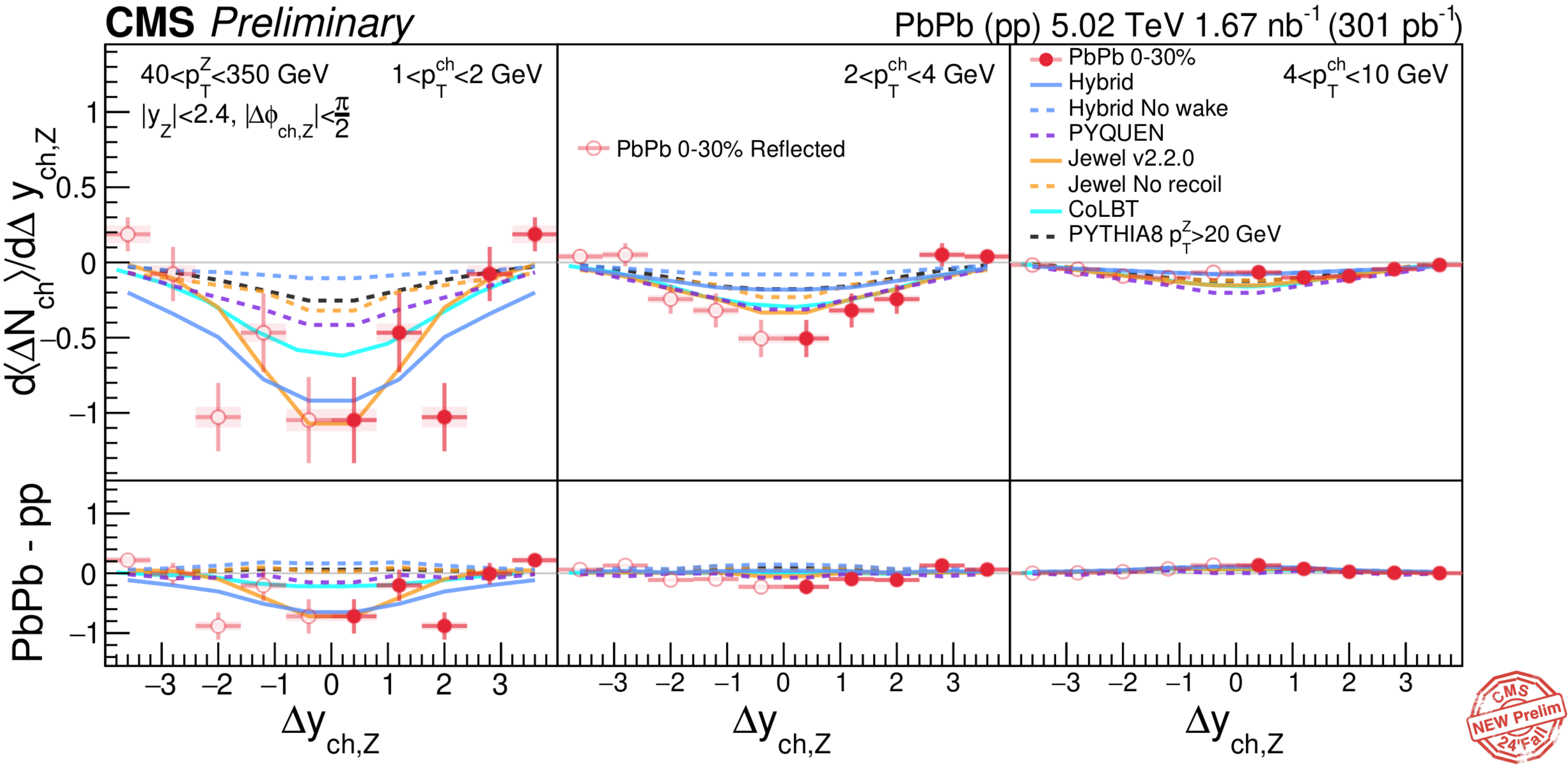




Theory Comparison on Δϕ Spectra



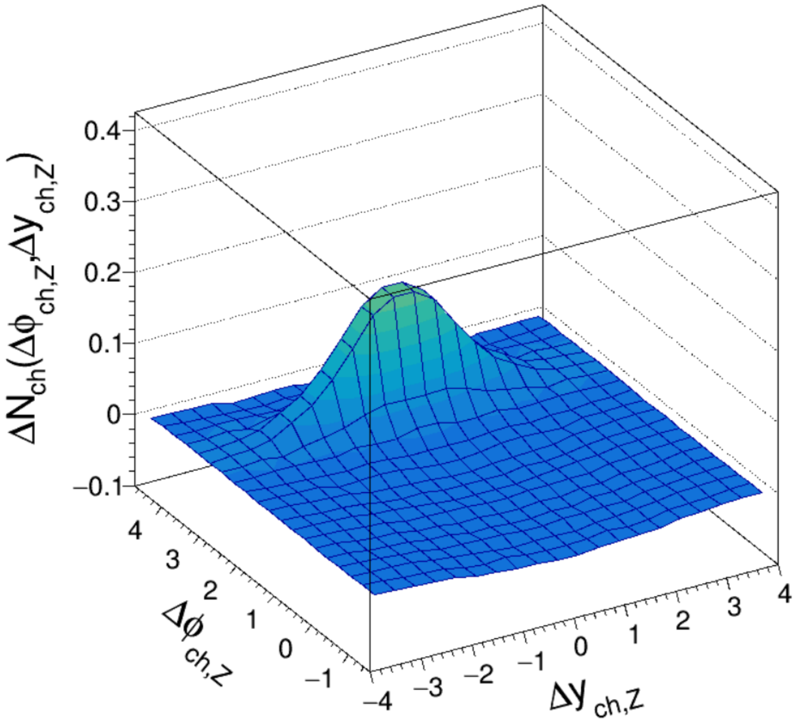
Theory Comparison on Δy Spectra



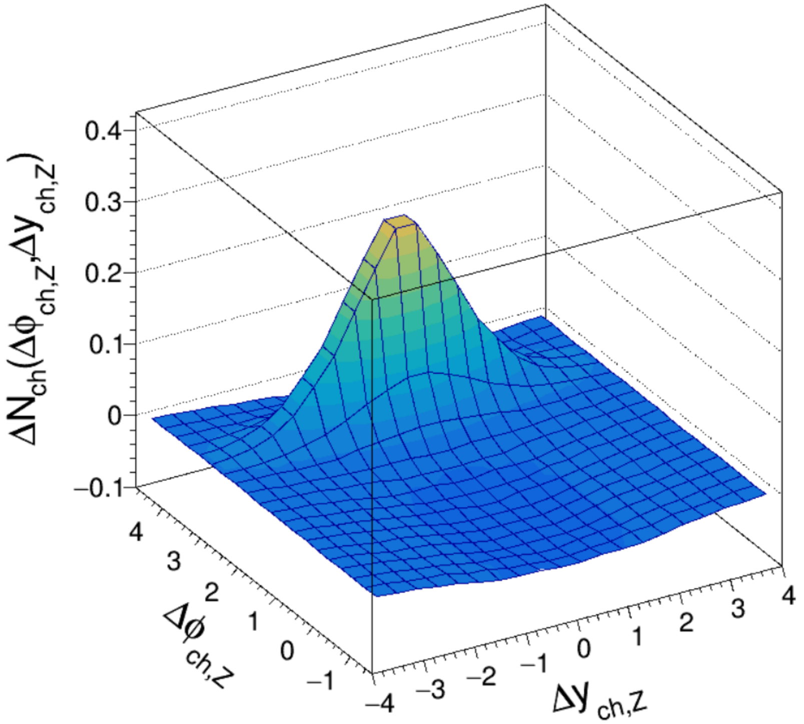
PYTHIA8 Z^0+Jet Event with Different Z^0 p_T Thresholds

ΔN_{ch} Spectra with Charged Hadron $4 < p_T < 10$ GeV

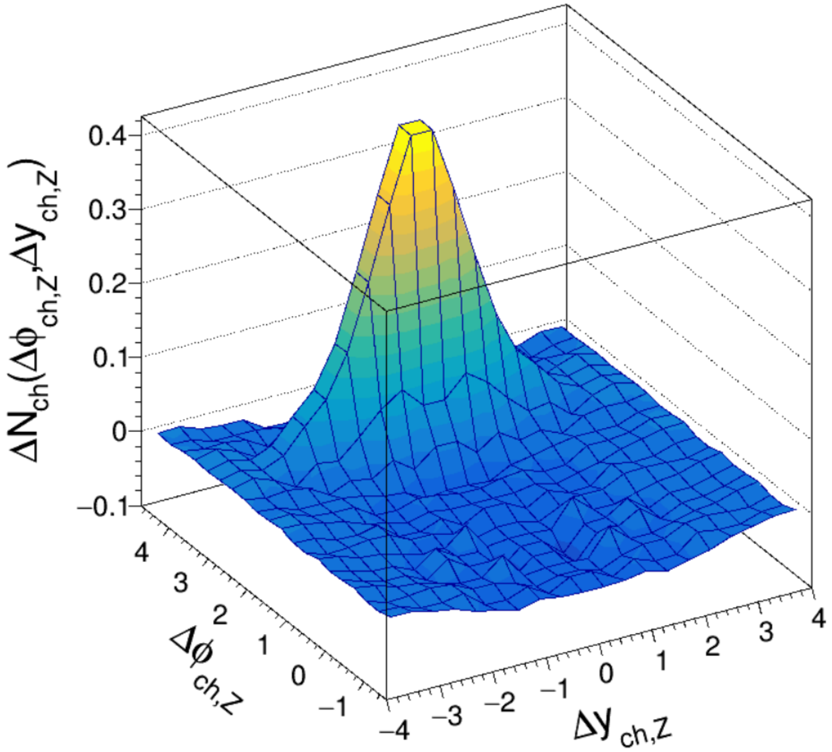
Z^0 $p_T > 20$ GeV



Z^0 $p_T > 40$ GeV



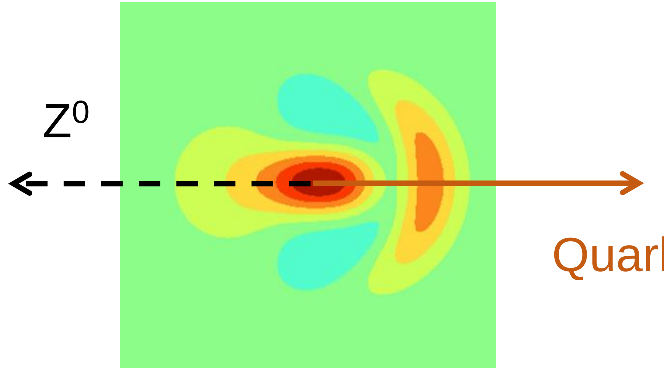
Z^0 $p_T > 60$ GeV

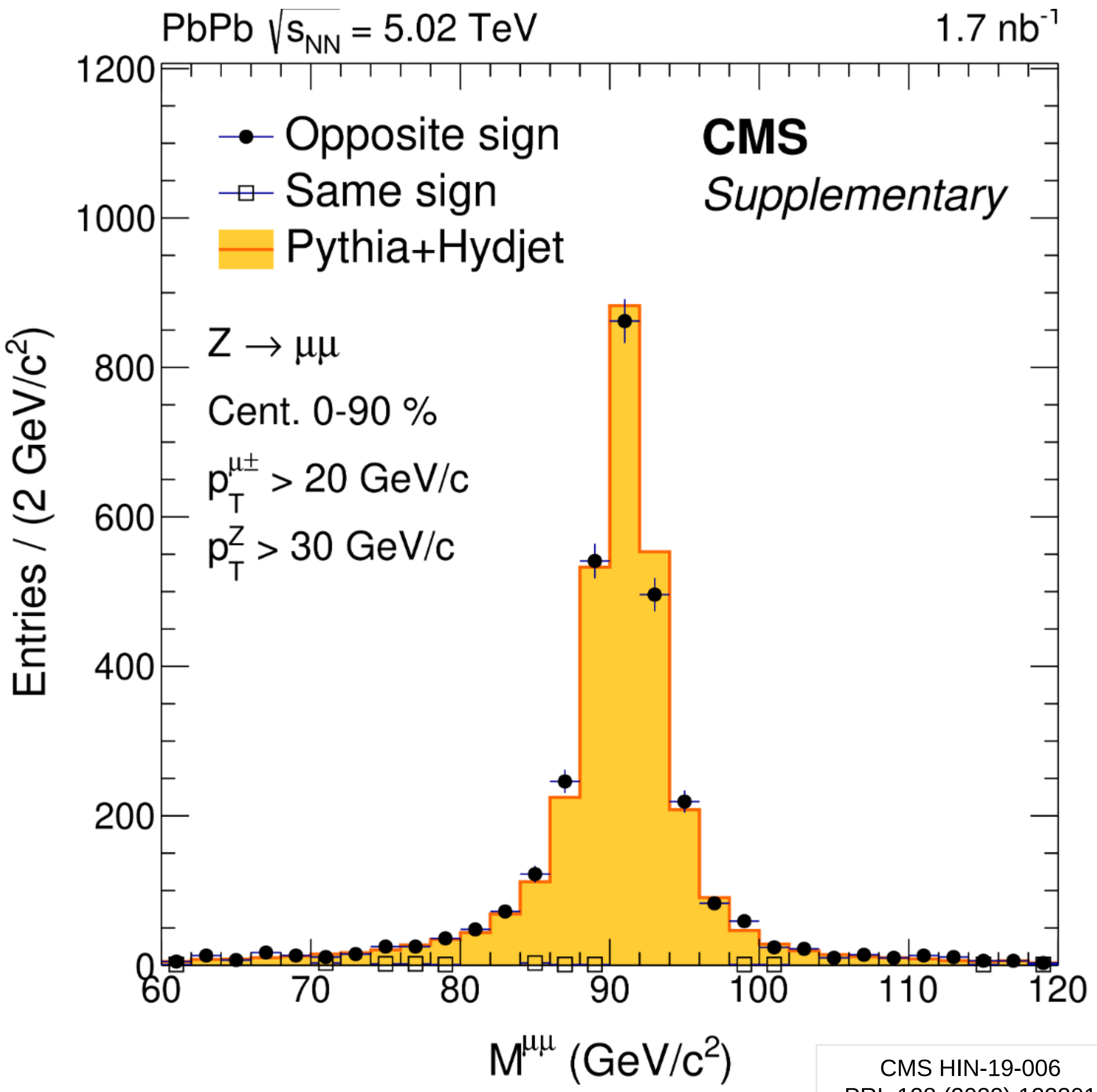


Z^0 Boson and Charged Hadron Track Selection

- $Z^0 \rightarrow \mu^+\mu^-$ selections:
  - Muons: $|\eta_\mu| < 2.4$, $|p_{T,\mu}| > 20$ GeV/c,
  - Z^0 Bosons:
    - 60 GeV/c^2 <$M_{\mu\mu}$< 120 GeV/c^2
    - **40 GeV/c <$|p_{T,Z}|$ < 350 GeV/c**
    - $|y_Z| < 2.4$

- Charged hadron selections:
  - $|\eta_{ch}| < 2.4$, $1 < p_{T,ch} < 10$ GeV/c.
  - Muon rejection: $\Delta R_{ch,\mu} > 0.0025$ between Muon candidates and charged hadron tracks

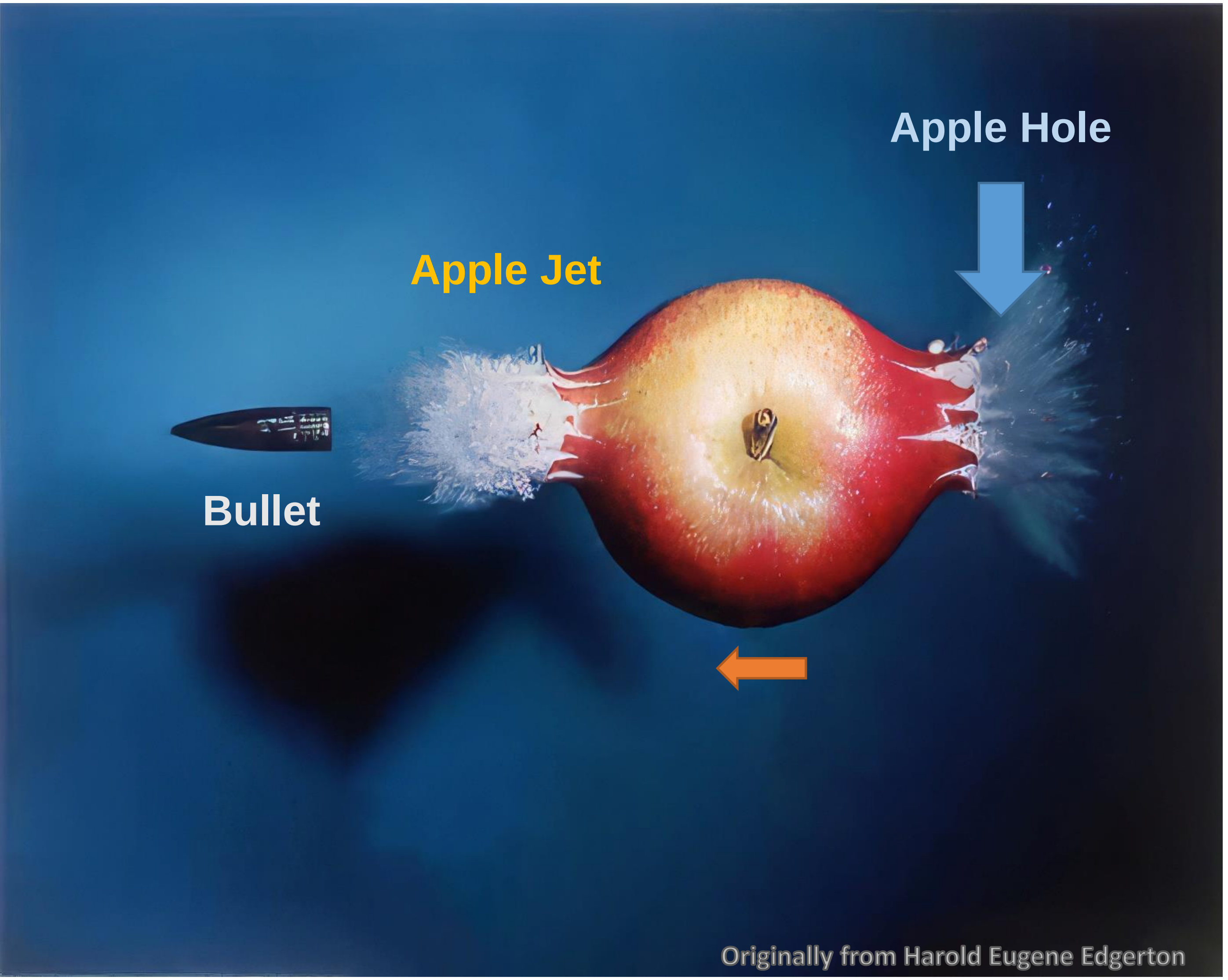




CMS HIN-19-006
PRL 128 (2022) 122301

Medium Response to Hard Probes in QED

Bullet plowing through an **apple**



More **apple** going in the bullet direction

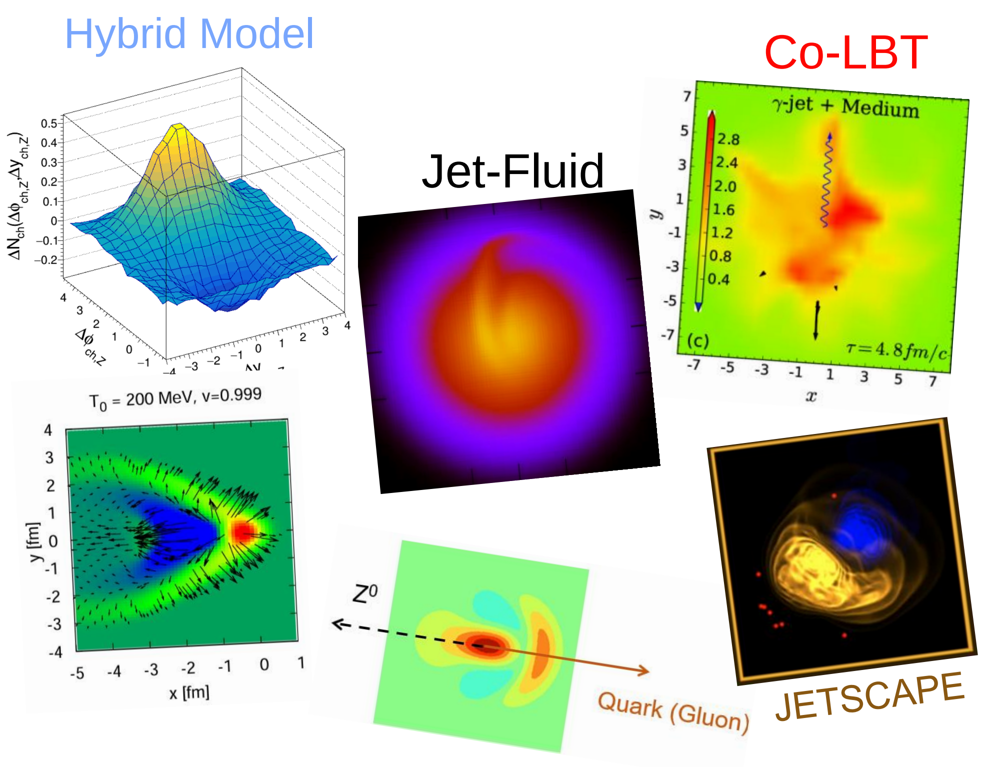
Duck swimming through **water**

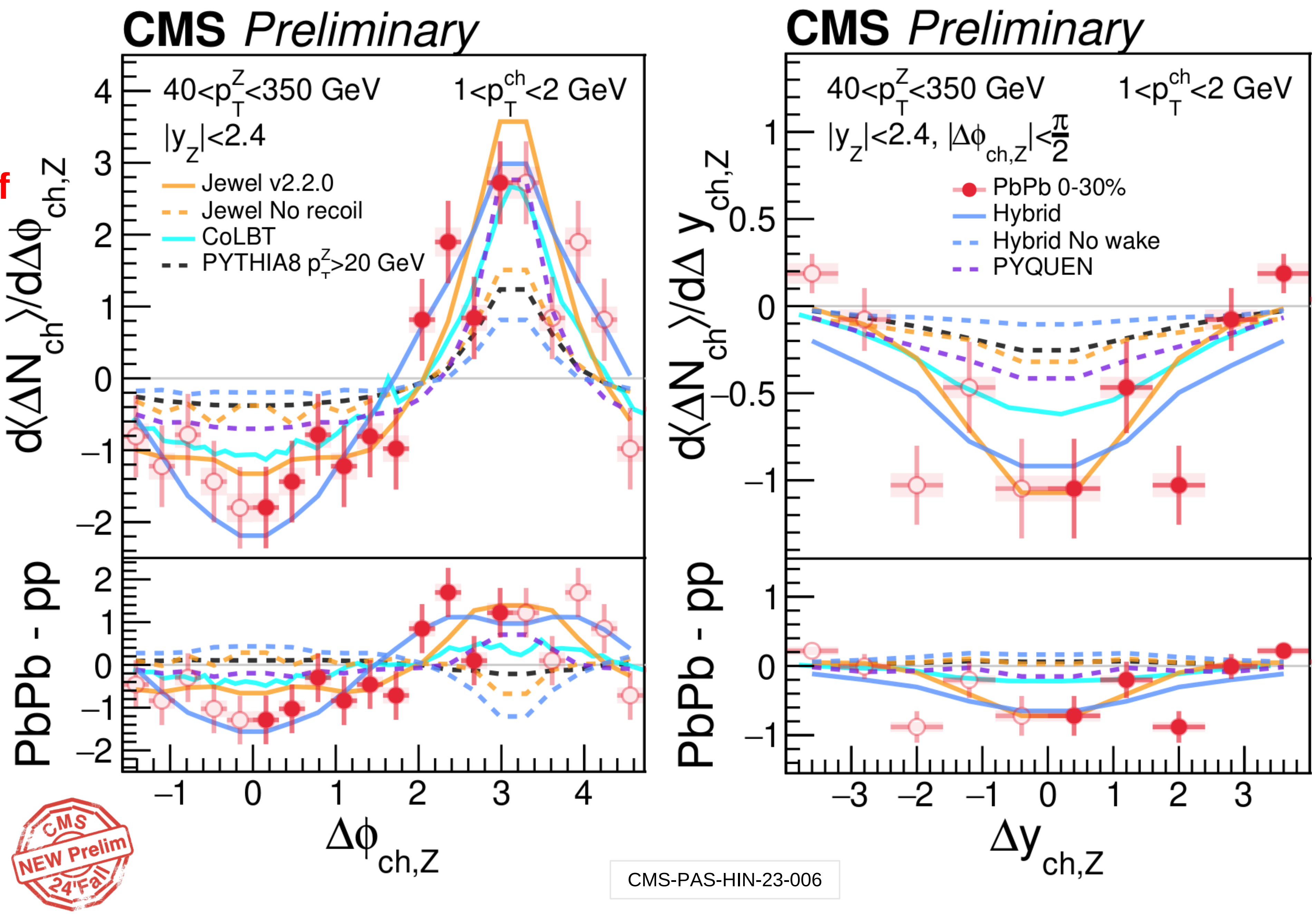
More **water** going in the duck direction

In Position Space

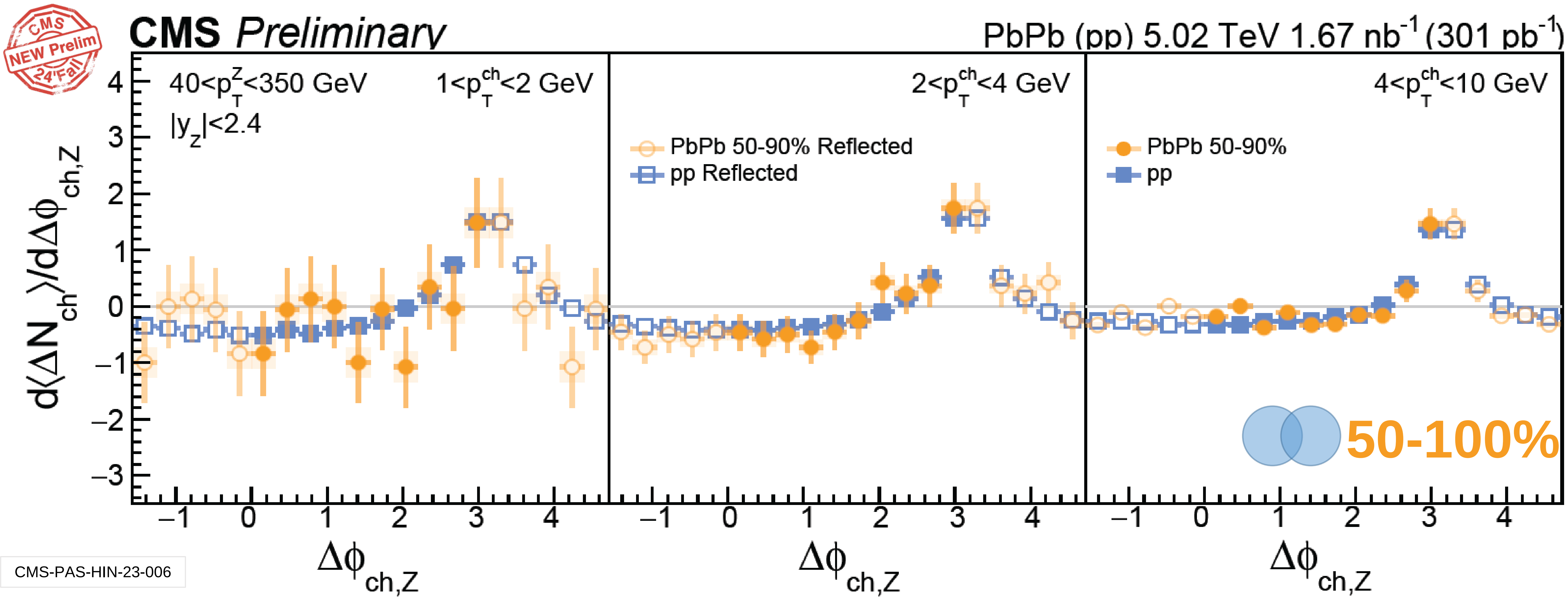
Summary and Outlook

- First p_T^{ch} differential measurement of Z^0-hadron correlation in azimuthal angle and rapidity
- We report the **first direct evidence of medium response in QGP**
- High statistics analysis with Run3+4 data in the near future





Azimuthal Angle Distributions in pp and 50-100% PbPb



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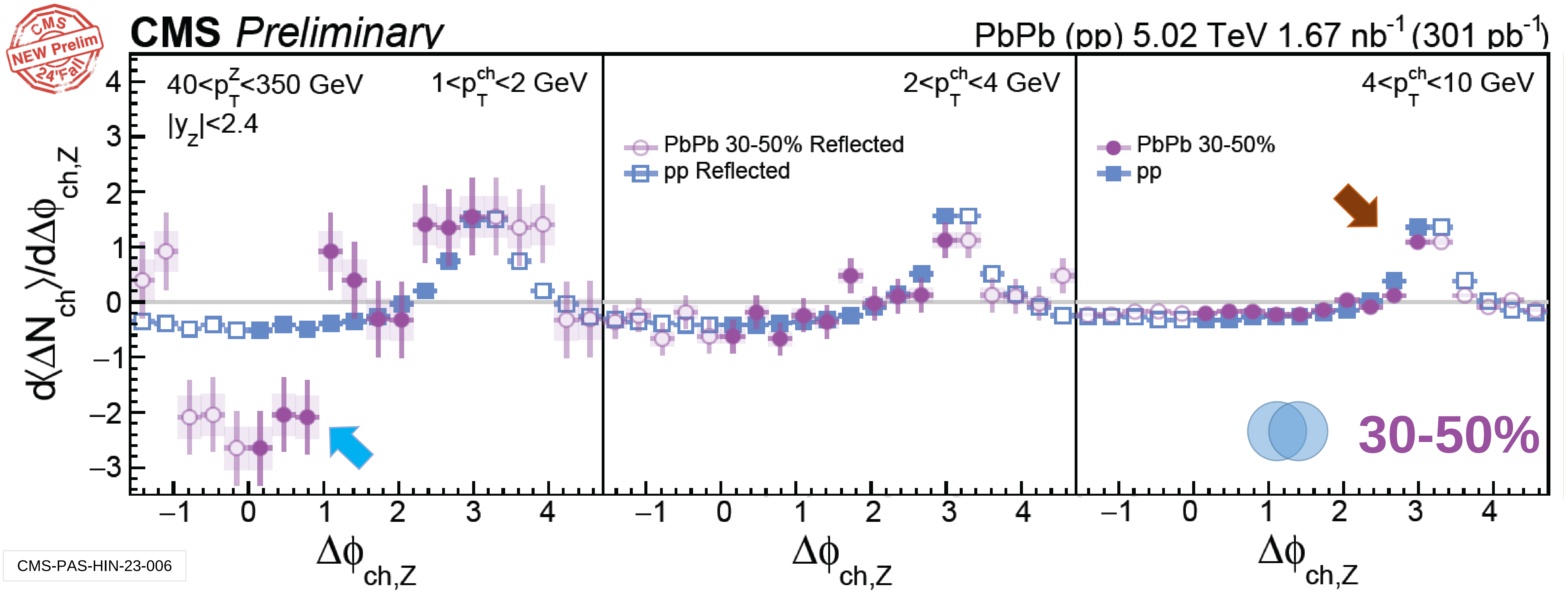
Low Charged Hadron p_T → High Charged Hadron p_T

50-100% PbPb and **pp reference** are consistent within experimental uncertainties

Azimuthal Angle Distributions in pp and 30-50% PbPb



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Low Charged Hadron p_T

High Charged Hadron p_T

PbPb: Clear relative depletion in Z^0 side ($\Delta\phi=0$)

PbPb: **Jet side peak** ($\Delta\phi=\pi$) reduced due to jet quenching at high hadron p_T

Theoretical Predictions