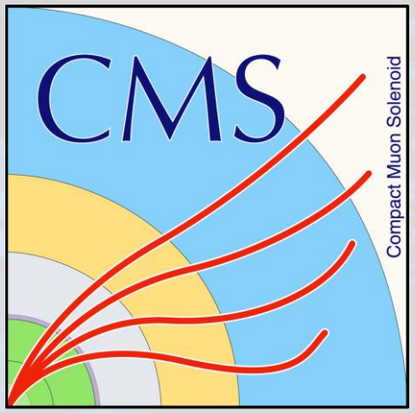
Evidence of Medium Response to Hard Probes with Z^0-tagged Hadrons in PbPb and pp at 5.02 TeV



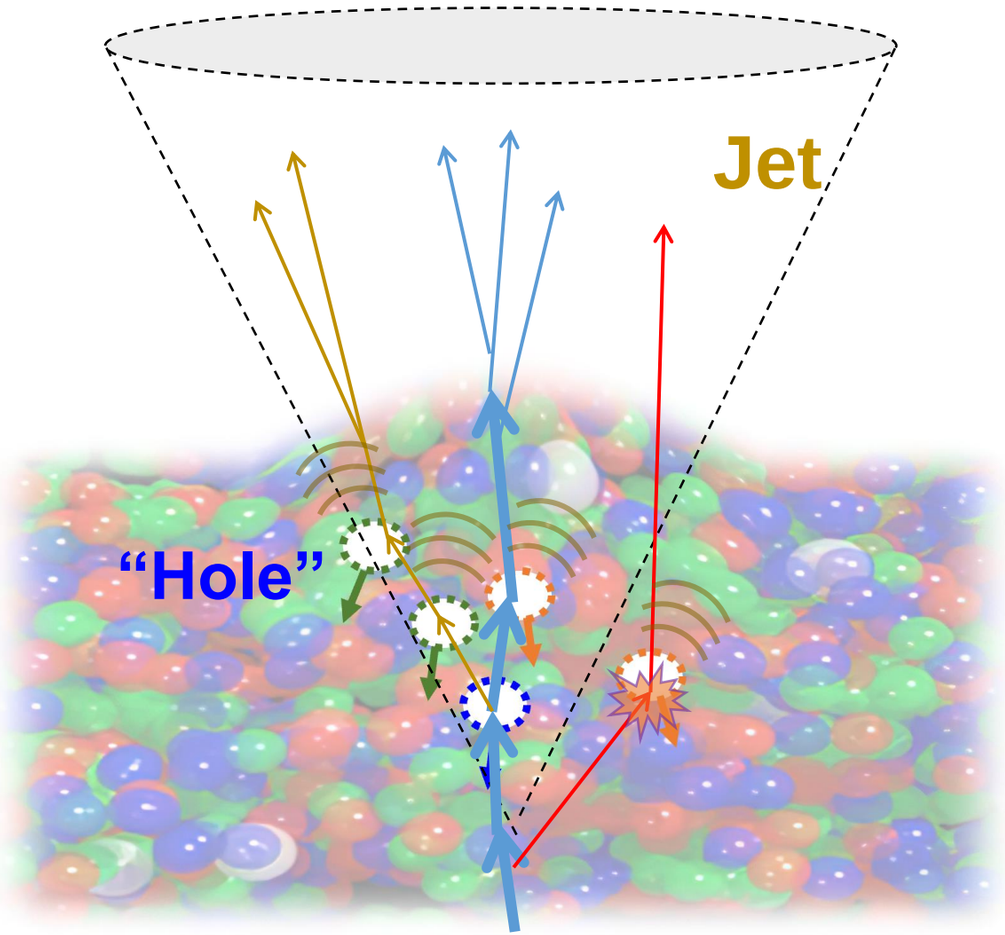
Yen-Jie Lee

For the CMS Collaboration

12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, Nagasaki, Japan

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

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

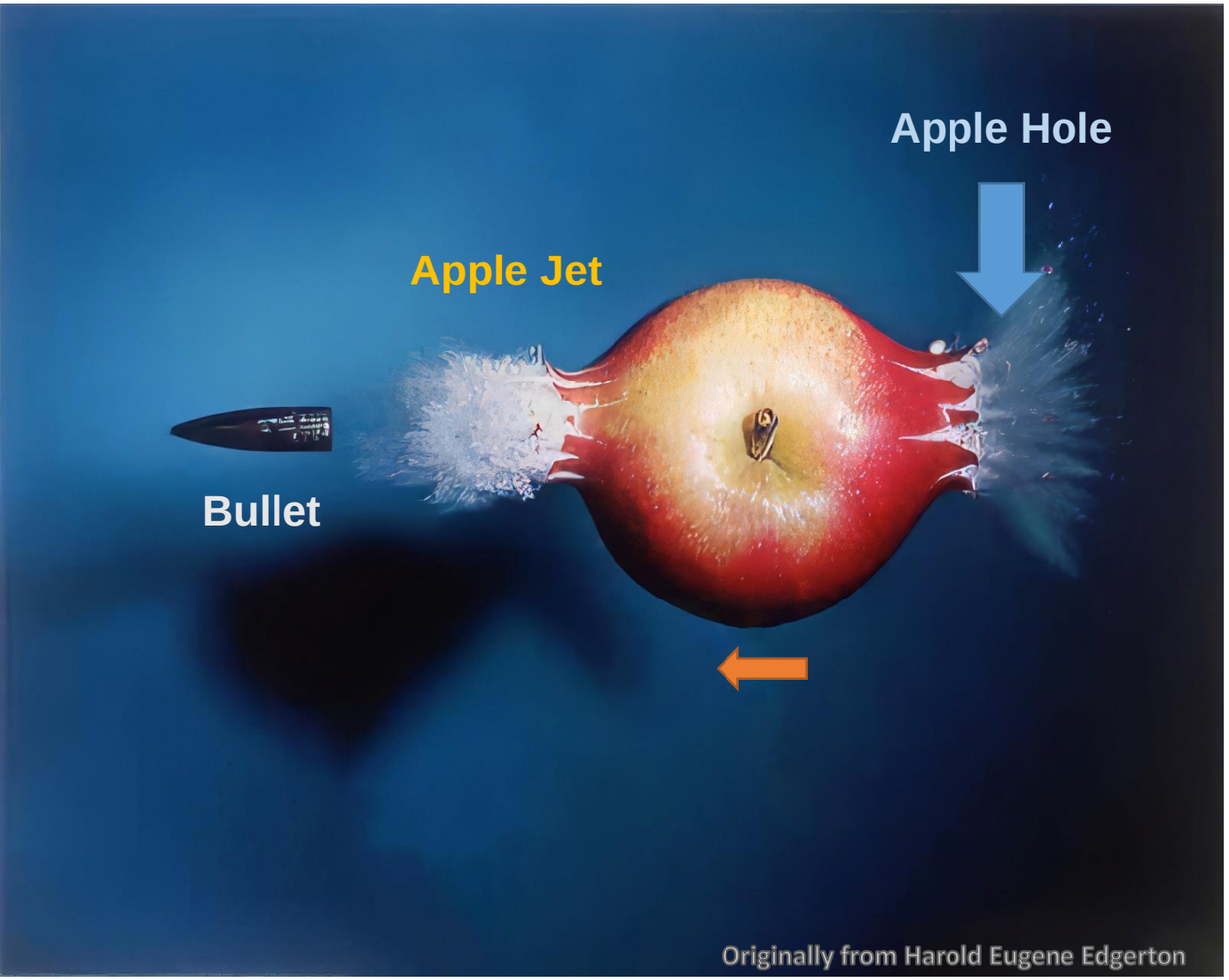
See also: *Molly Taylor: Photon-tagged Jet Δ_j in PbPb
*Matthew Nguyen: Photon-tagged Jet R_g and Girth in PbPb

*Raghunath Pradhan: inclusive Jet Δ_j in PbPb
*Yi Chen: Z-Tagged EEC in PbPb

*Jussi Viinikainen: inclusive jet EEC in PbPb
*Dener De Souza Lemos: Dijet in pPb

Medium Response to Hard Probes in QED

Bullet plowing through an **apple**



More **apple** going in the bullet direction

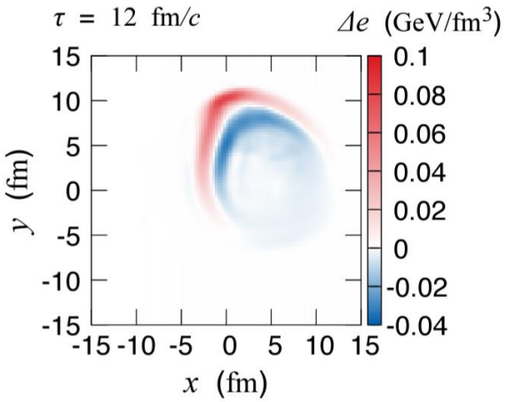
Duck swimming through **water**

More **water** going in the duck direction

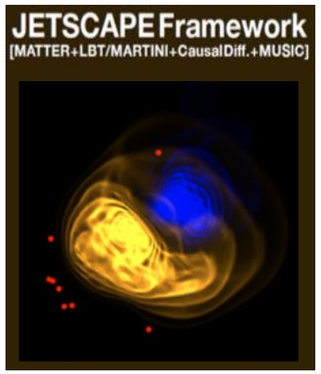
In Position Space

Medium Response to Hard Probes in QGP

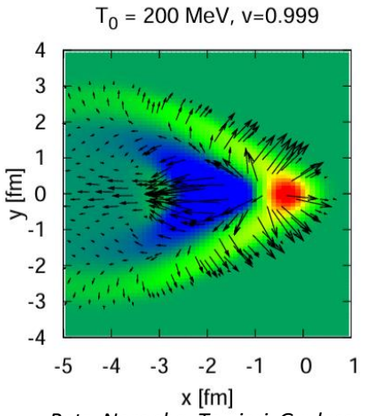
Quark plowing through the QGP



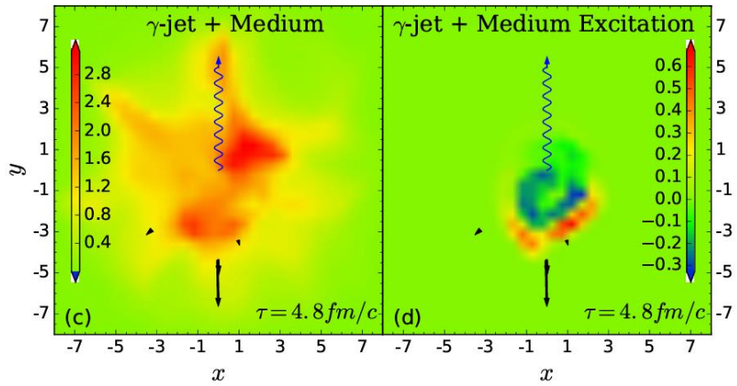
Jet-Fluid Yasuki, Chang, Qin
PRC 95 (2017) 4, 044909



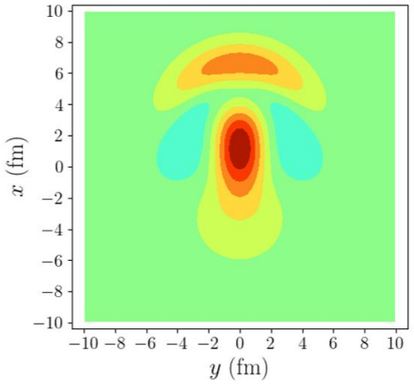
JETSCAPE framework
Tachibana, Shen, Majumder
PRC 106 (2022), L021902



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

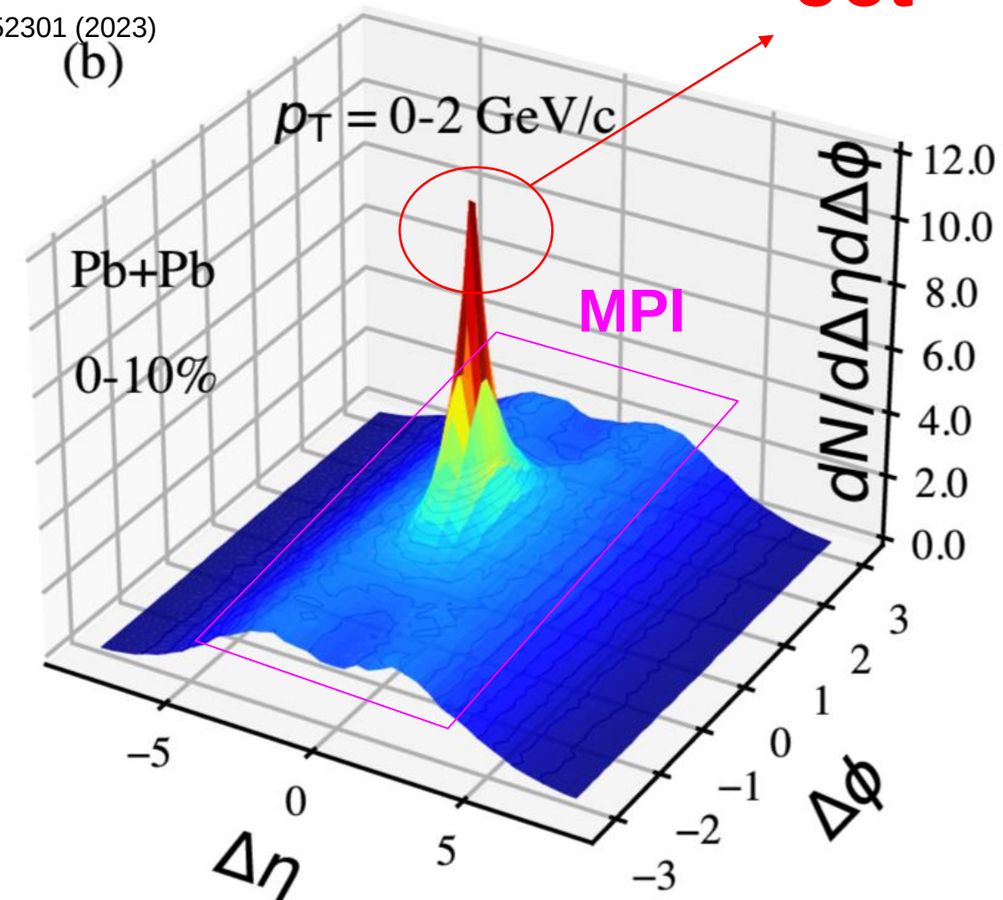
Medium Response to Hard Probes in **Momentum Space**

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

QGP wake in CoLBT

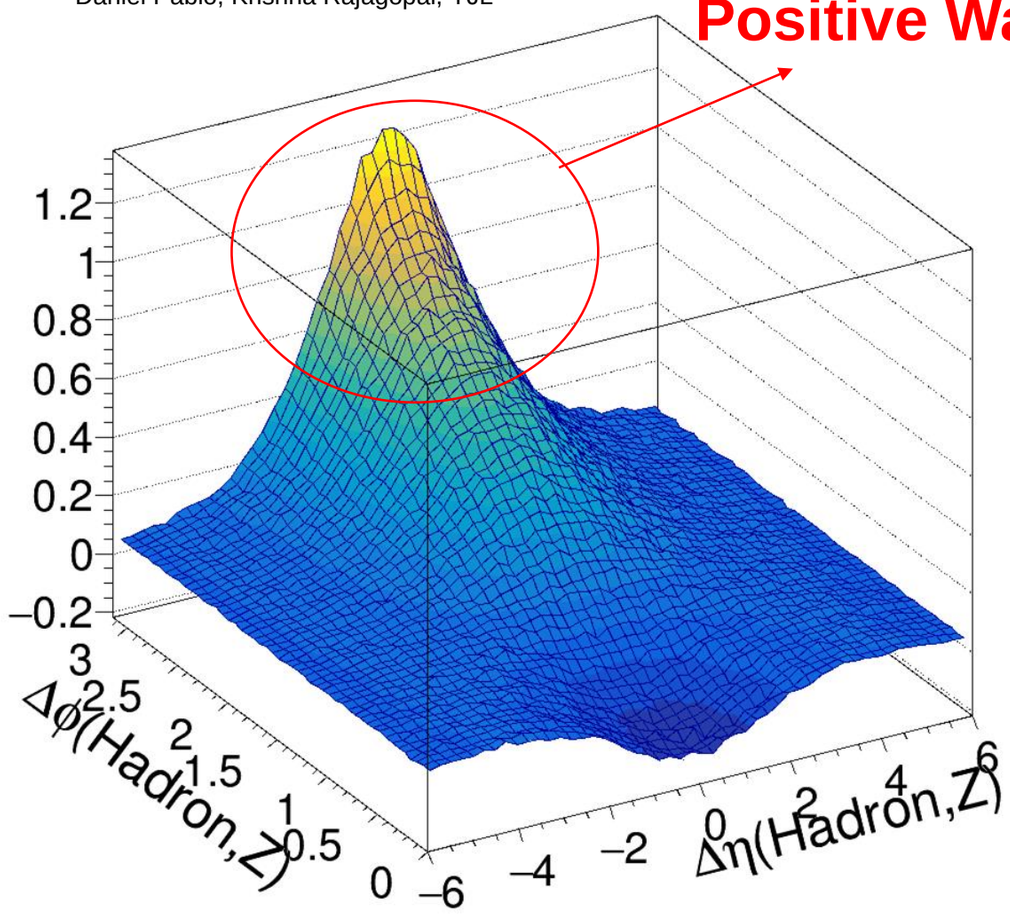
Zhong Yang, Tan Luo, Wei Chen, Longgang Pang, and Xin-Nian Wang

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

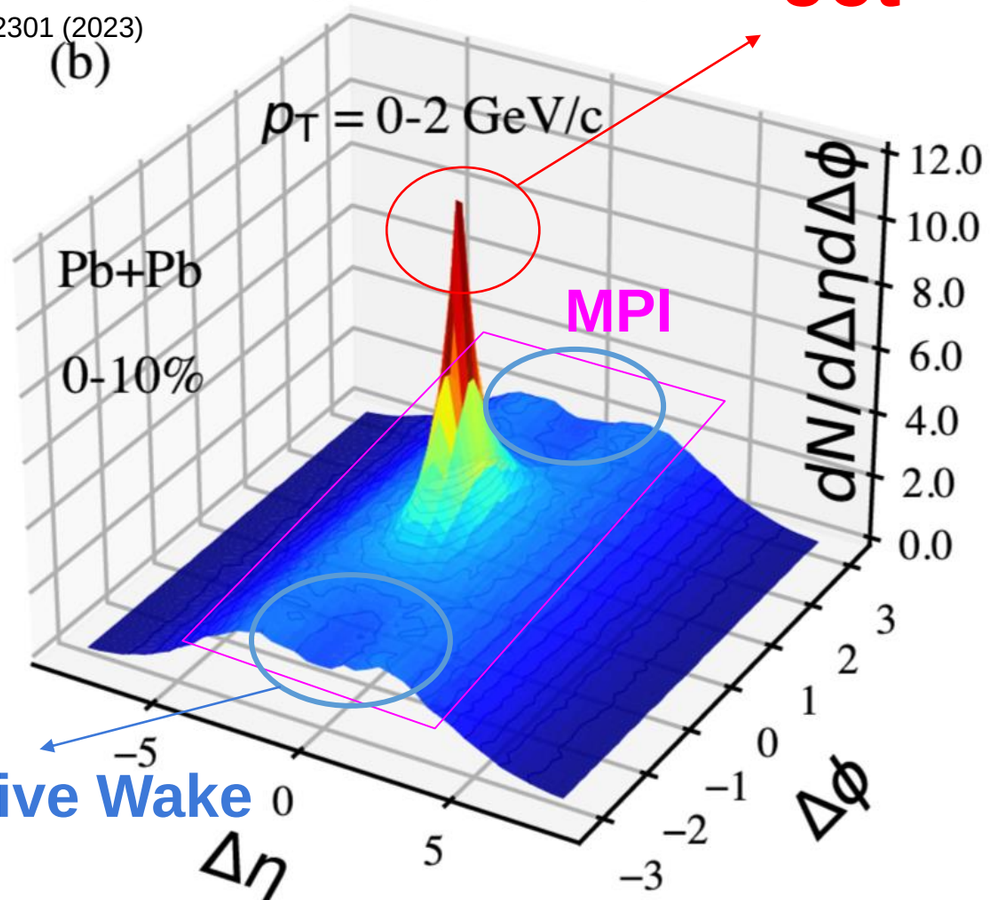
Measure the “Depletion” due to Medium Recoil

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

QGP wake in CoLBT

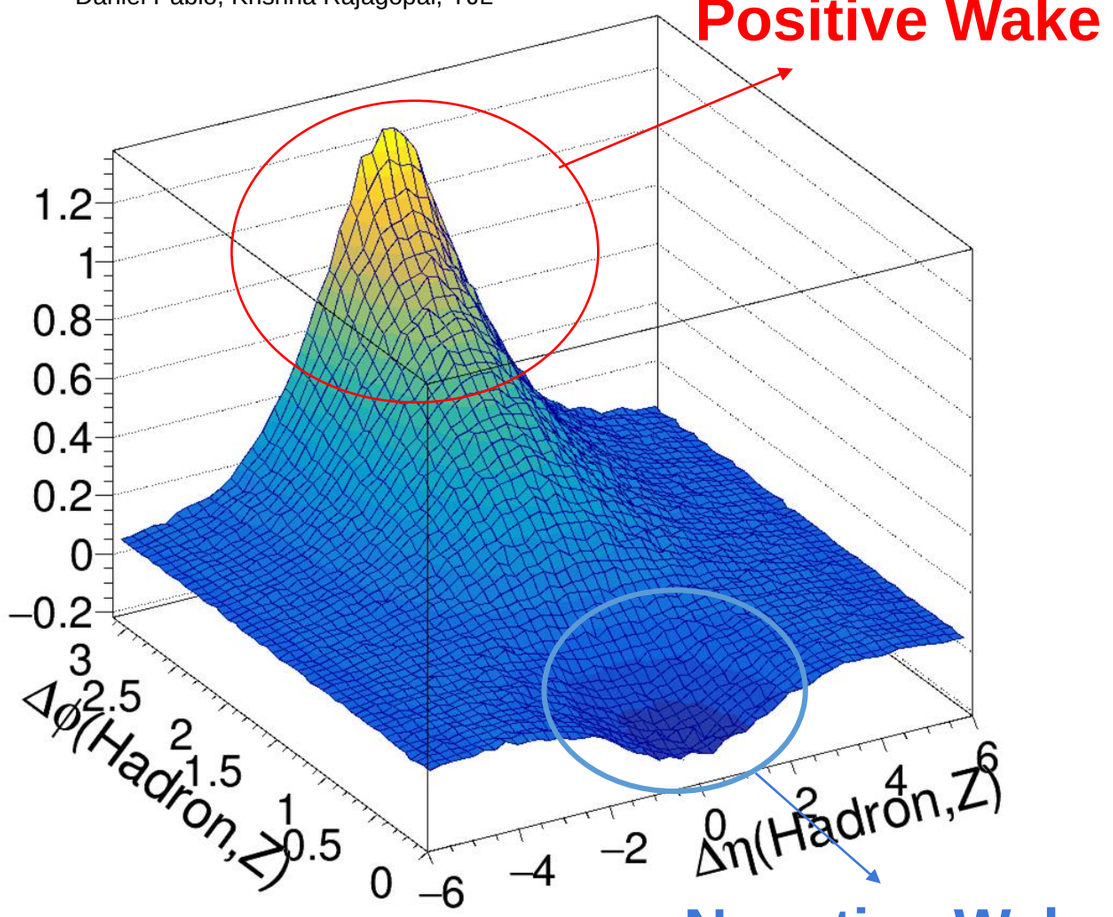
Zhong Yang, Tan Luo, Wei Chen, Longgang Pang, and Xin-Nian Wang

PRL 130, 052301 (2023)



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

Daniel Pablo, Krishna Rajagopal, YJL



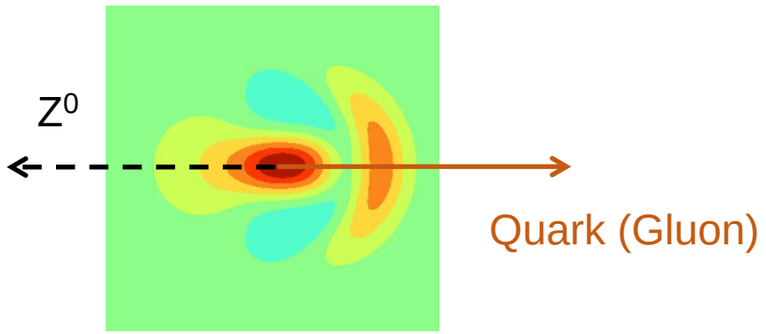
More QGP going in the jet direction, however, with complication from induced radiation

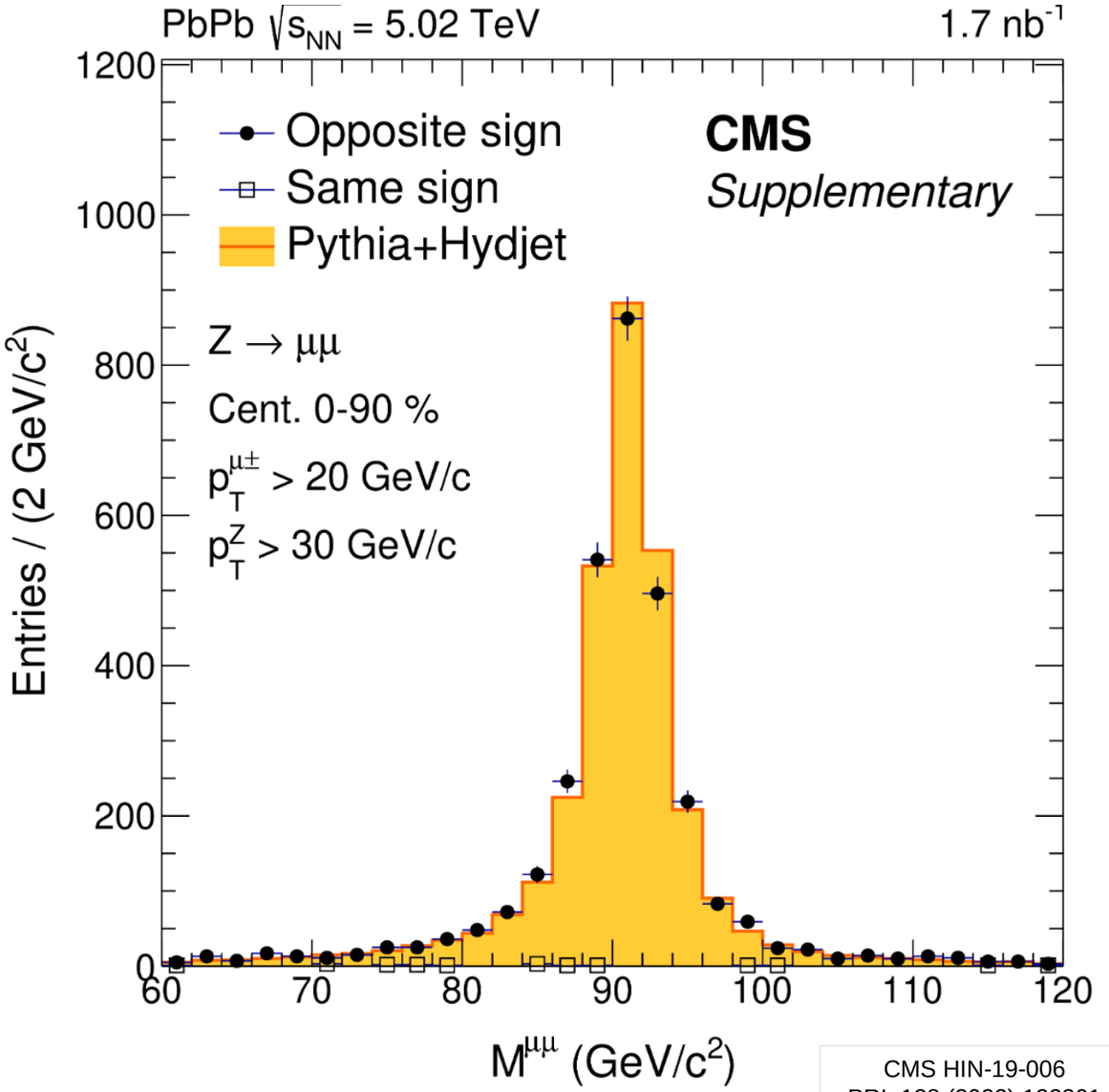
Less QGP left behind in the opposite direction of the jet!!!

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

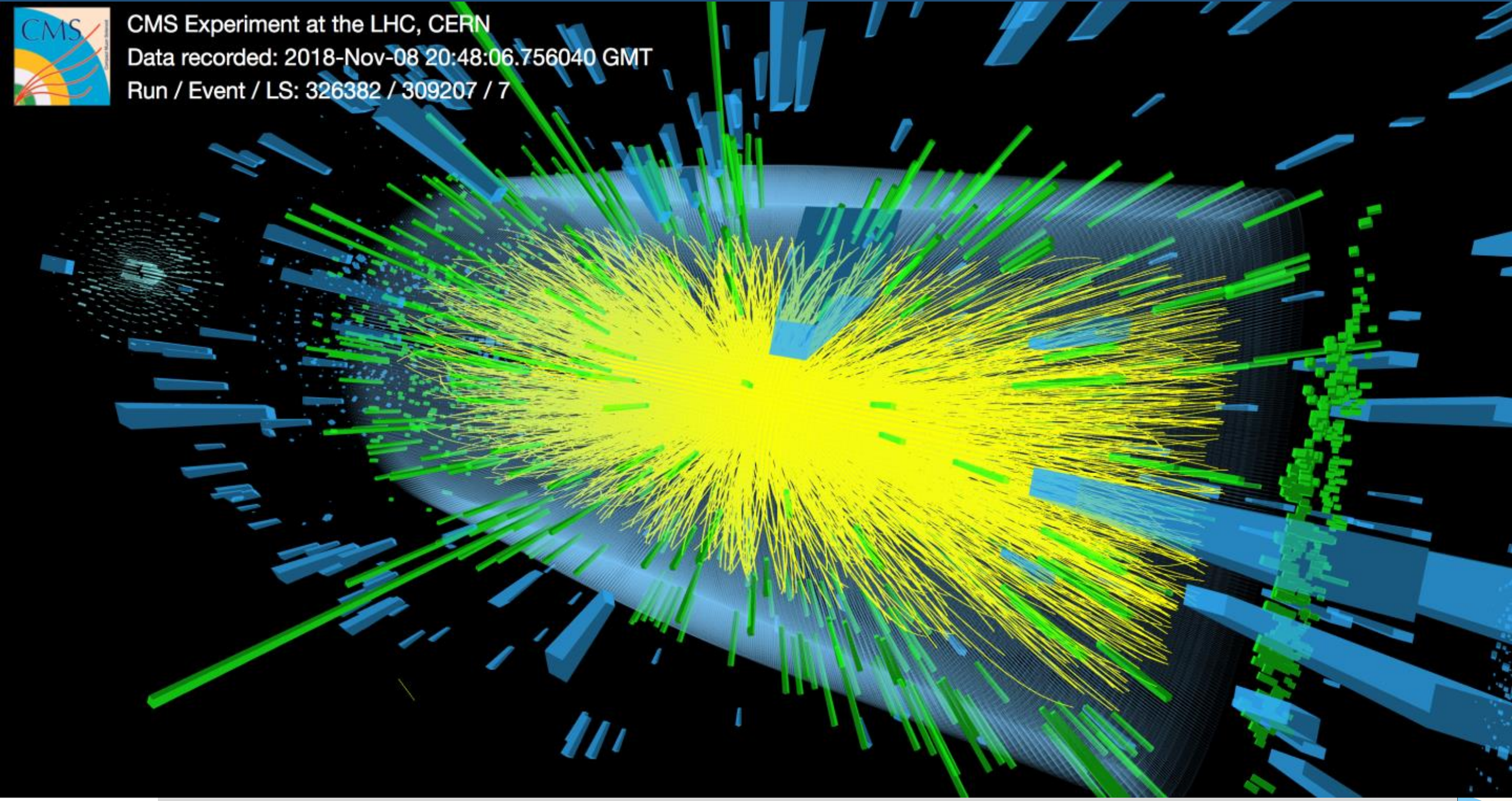
Z^0 Boson and Charged Hadron Track Selection

- $Z^0 \rightarrow \mu^+\mu^-$ 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





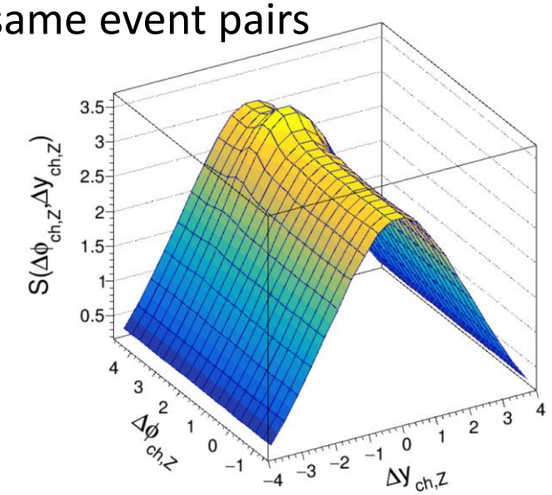
CMS HIN-19-006
PRL 128 (2022) 122301


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

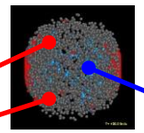
Z^0-Hadron Correlation Function: Event Mixing

Average **Signal pair** distribution:

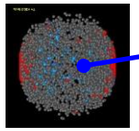
same event pairs



Z^0 Event 1

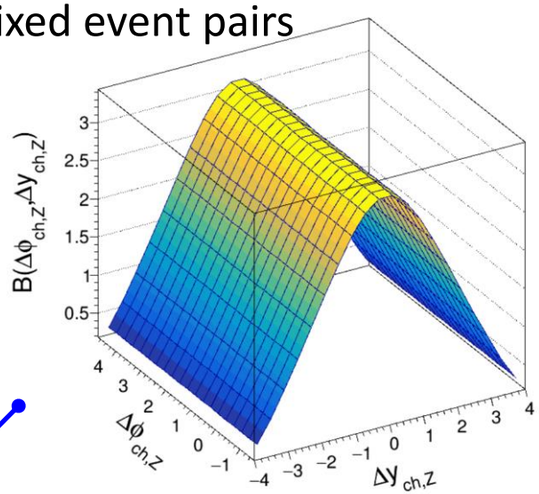


Z^0 Event 2



Average **Background pair** distribution:

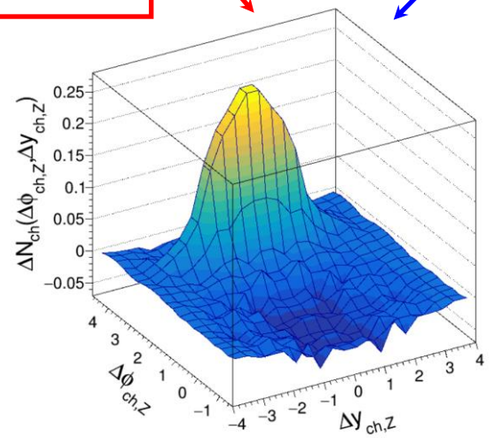
mixed event pairs



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

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

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



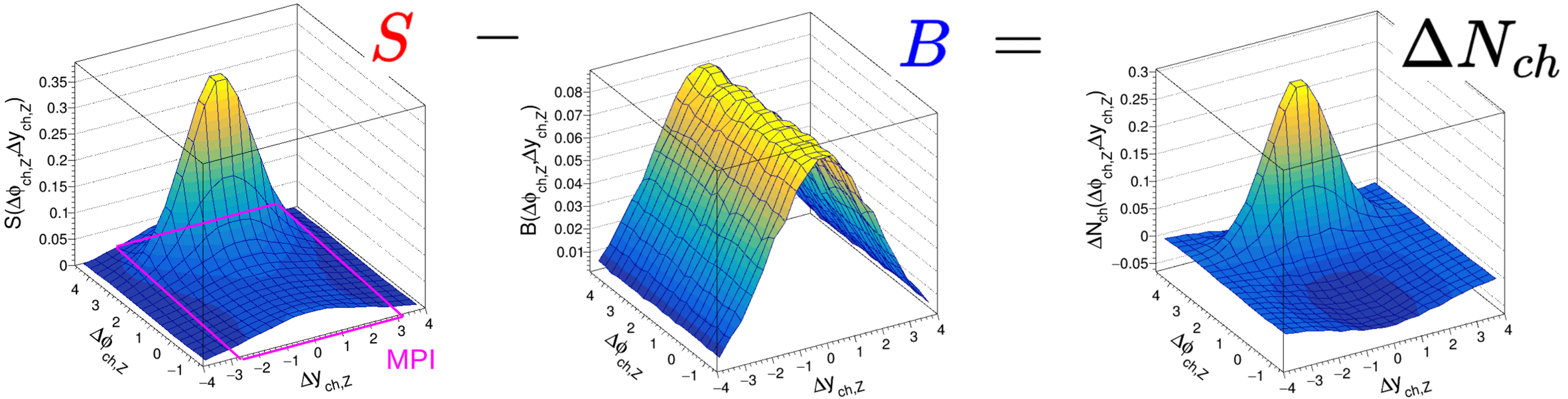
$\Delta y_{ch,Z} = y_z - \eta_{ch}$

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

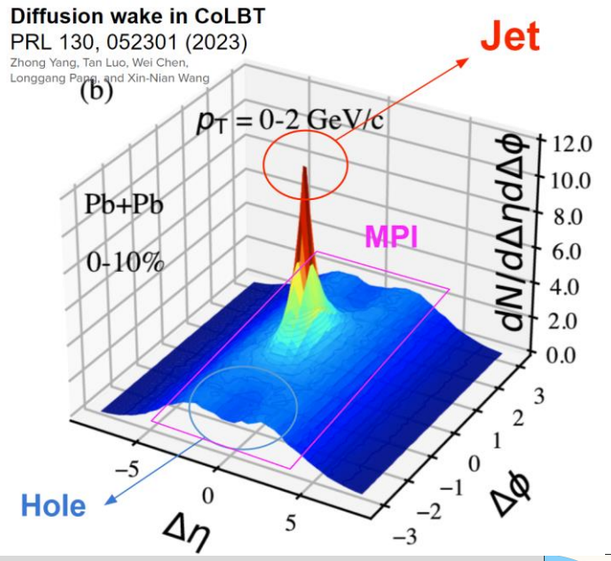
Demonstration with PYTHIA+HYDJET (Generator level events)

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)

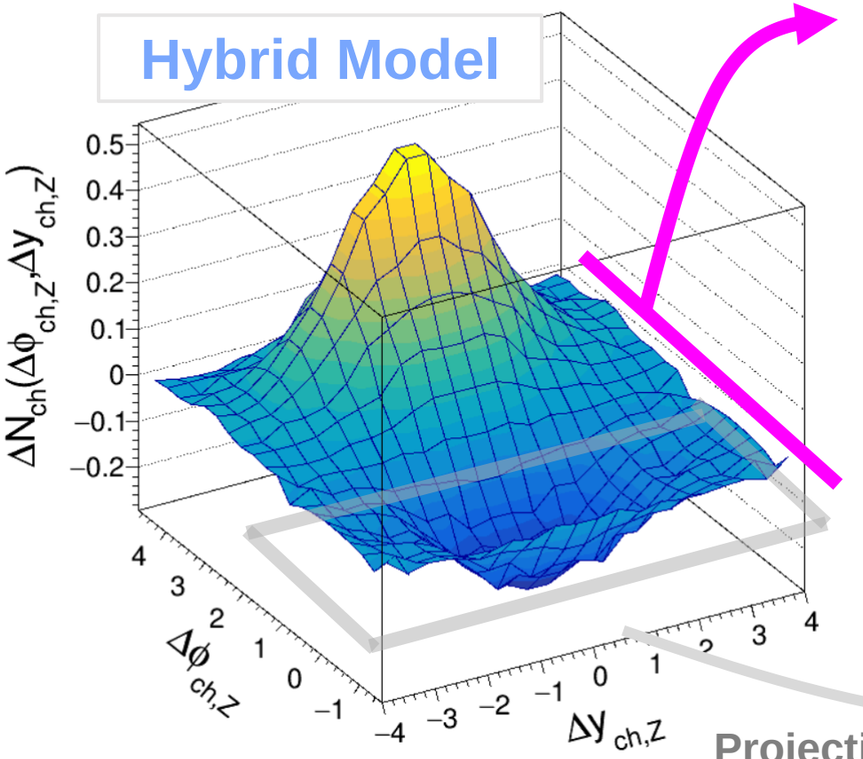


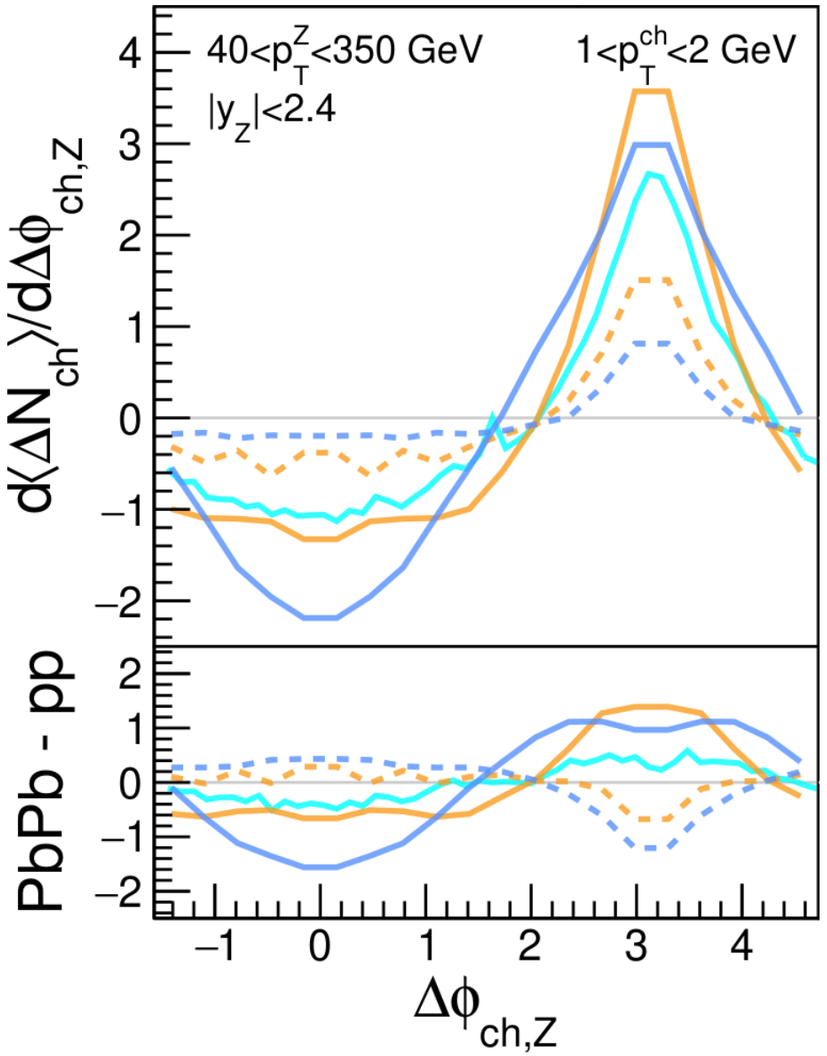
Theoretical Predictions

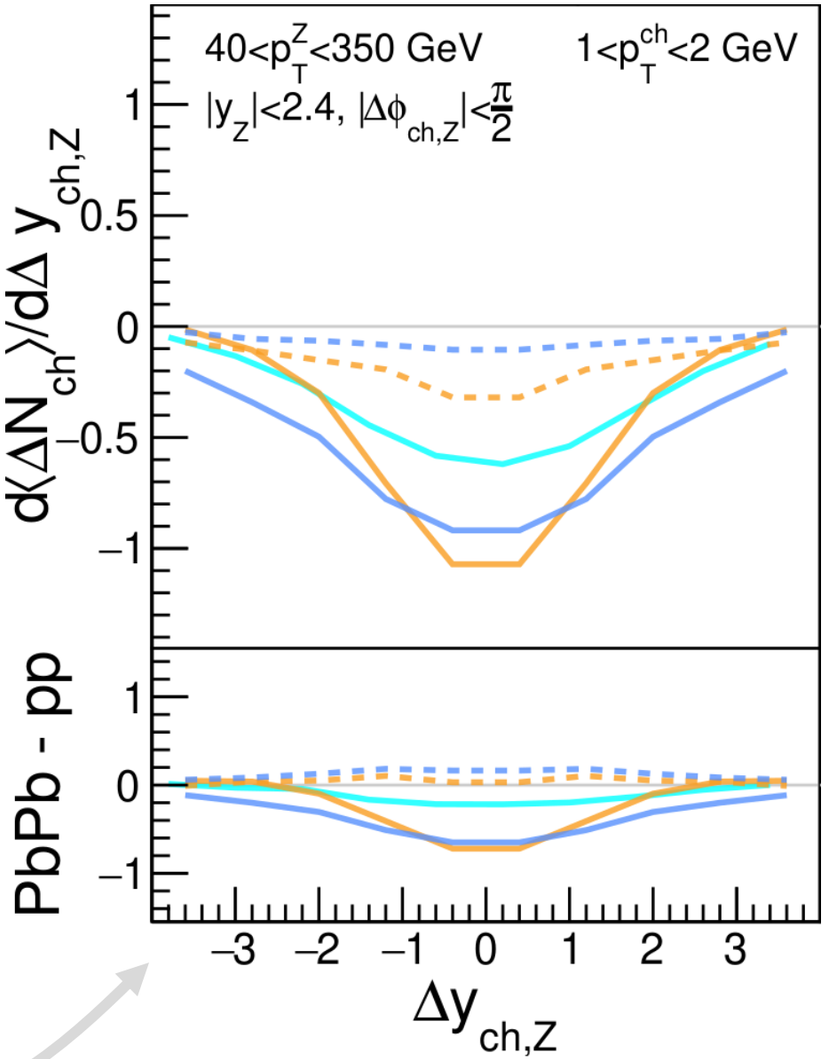
Hybrid
Hybrid No wake
Jewel v2.2.0
Jewel No recoil
CoLBT

Projection onto Δϕ axis

Hybrid Model

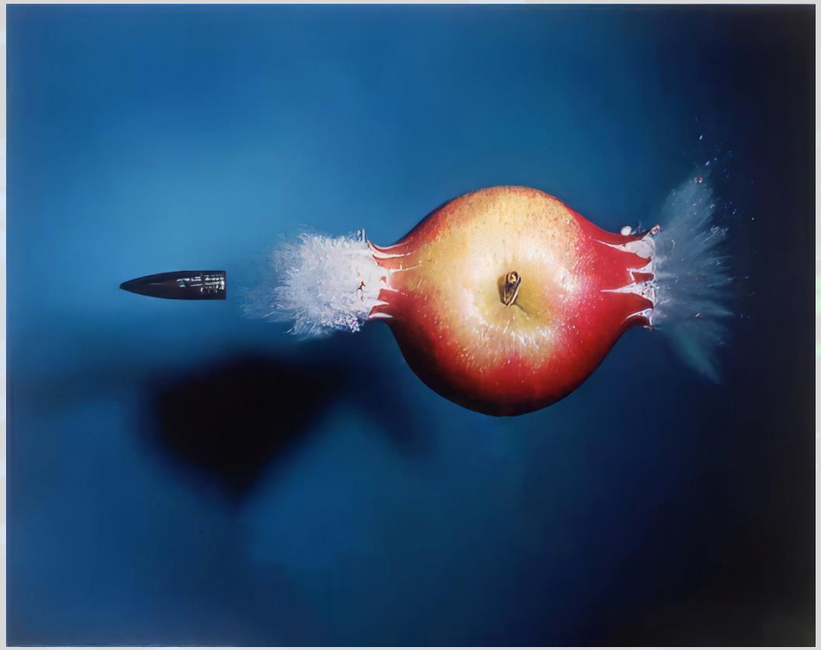


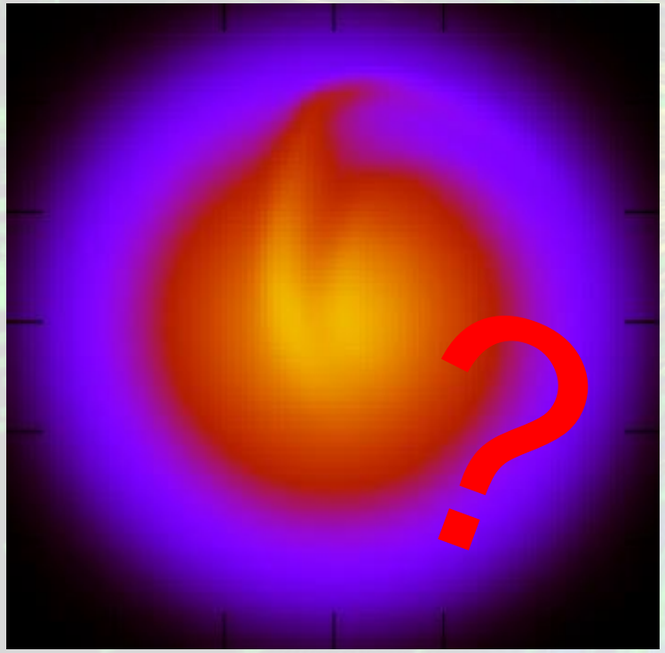




Projection on Δy axis

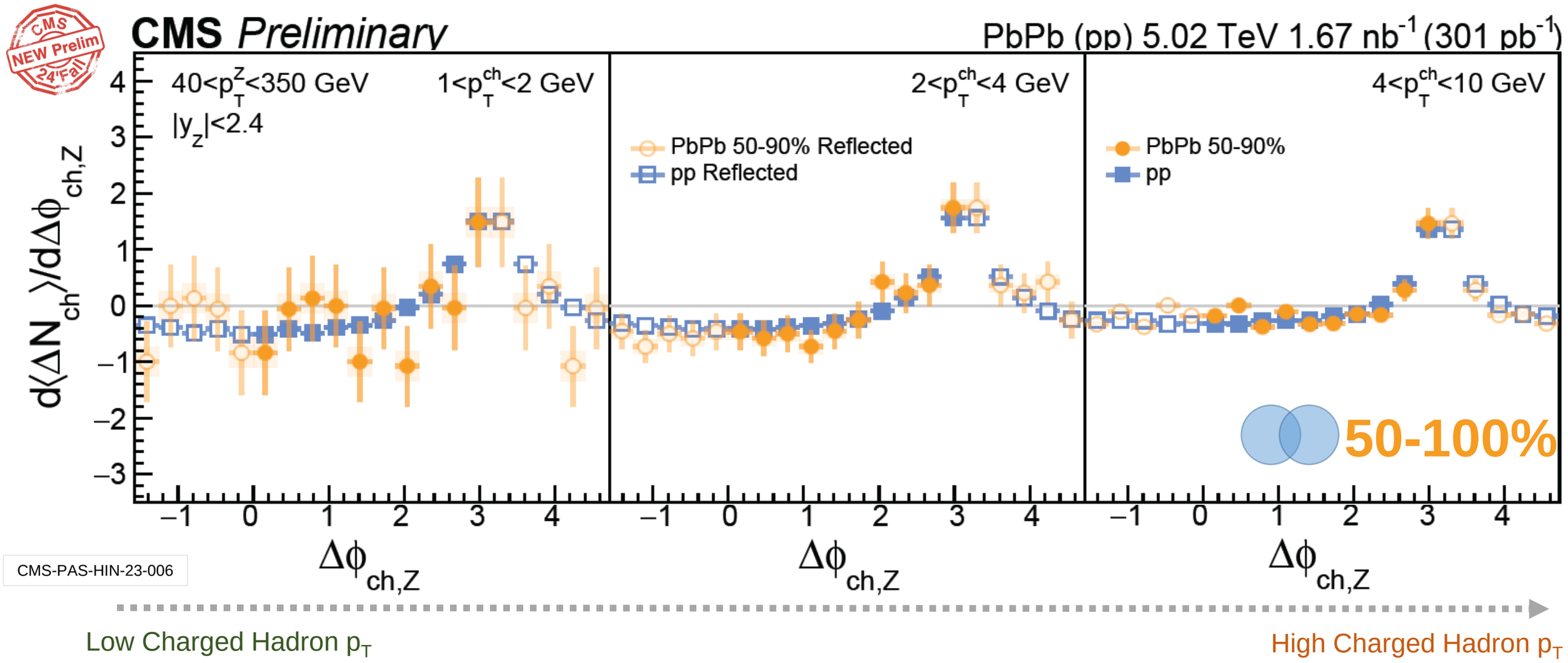
Results





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

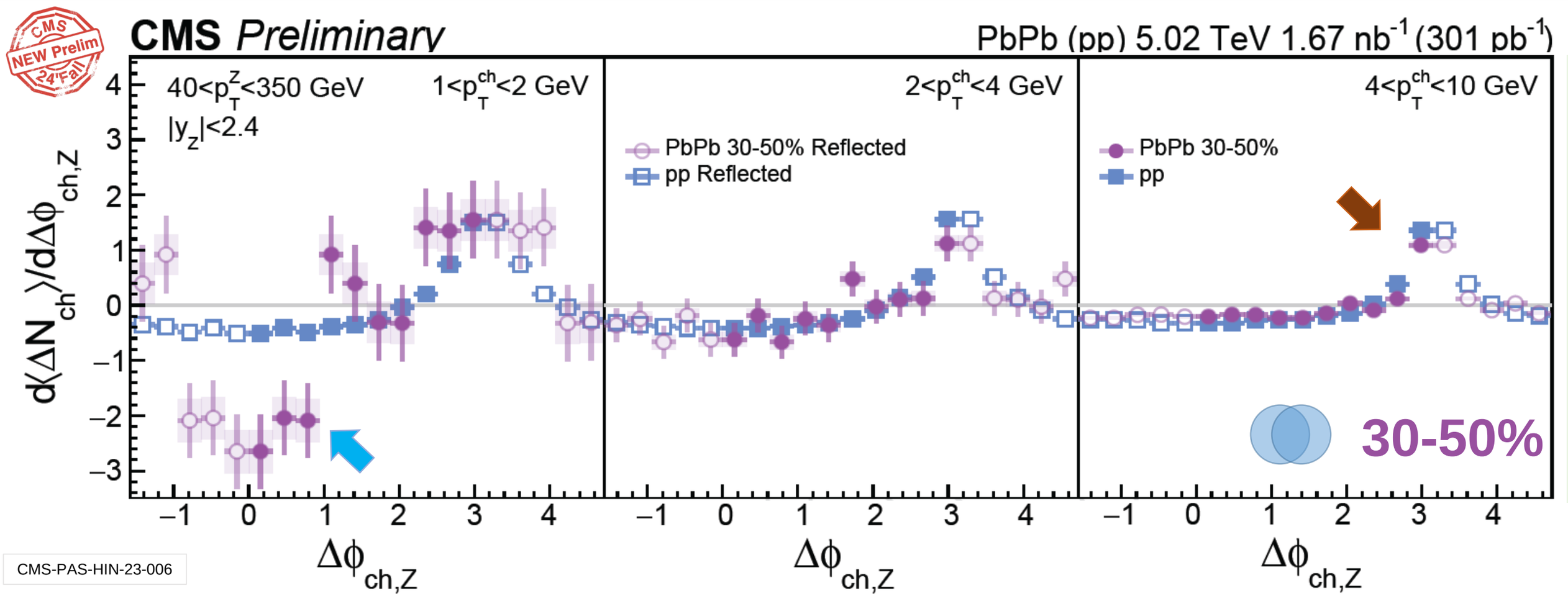
Azimuthal Angle Distributions in pp and 50-100% PbPb



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



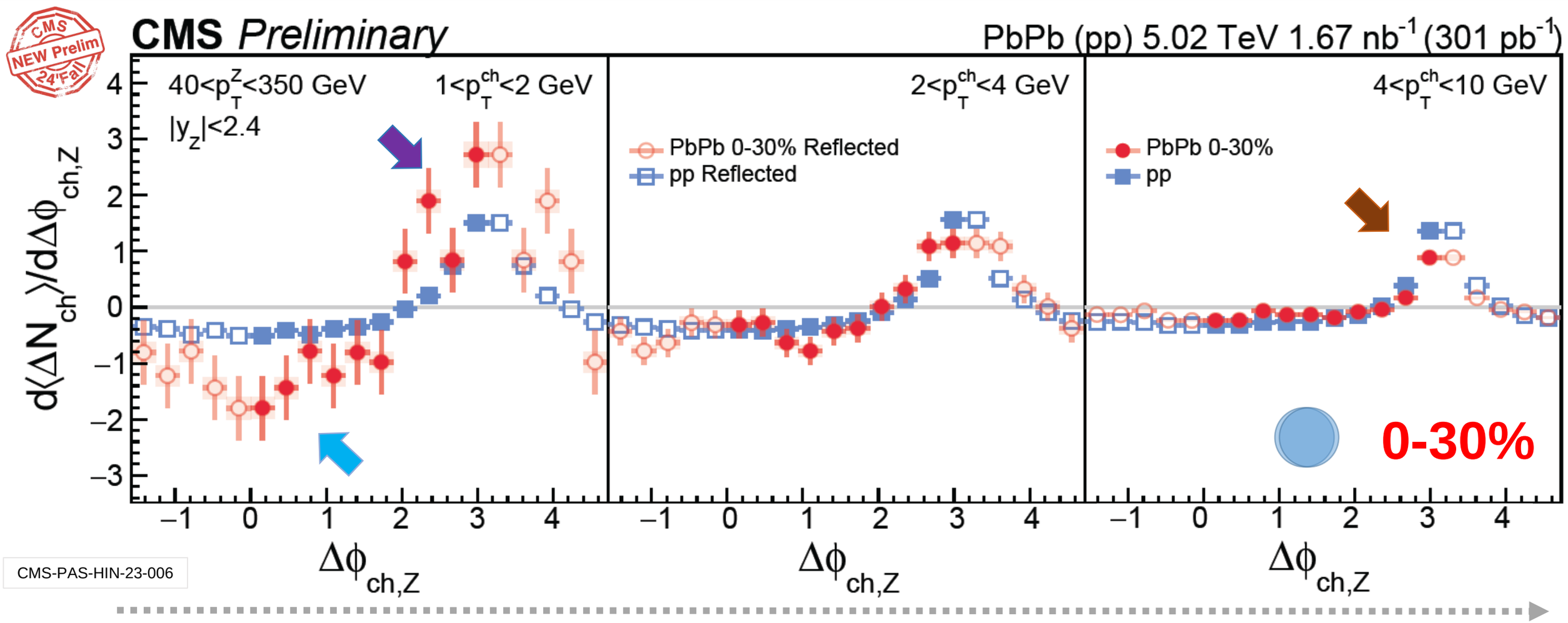
Low Charged Hadron p_T

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

Azimuthal Angle Distributions in pp and 0-30% PbPb



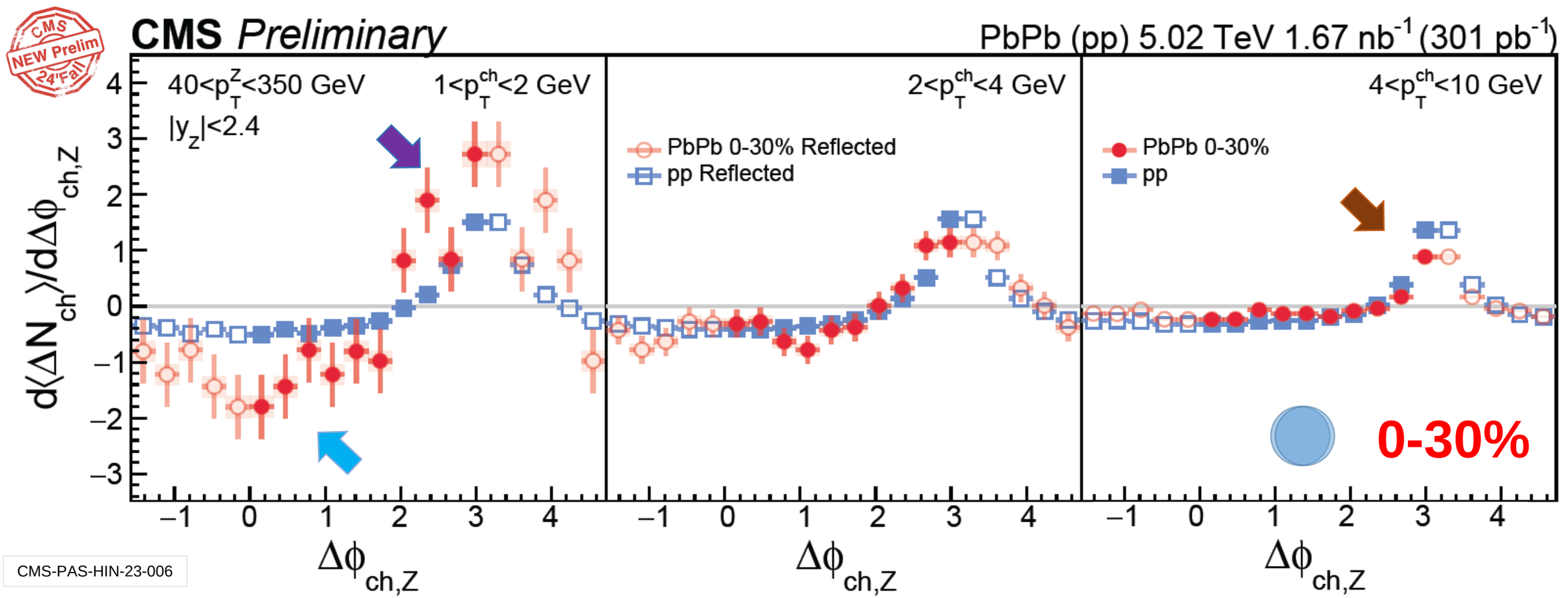
Low Charged Hadron p_T → High Charged Hadron p_T

PbPb: Clear depletion in **Z^0 side (Δφ=0)** and enhancement in **jet side (Δφ=π)**

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

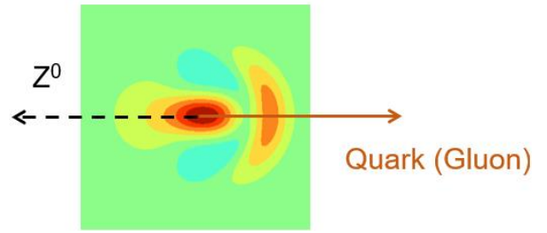
PbPb: **Jet side peak** (Δφ=π) reduced due to jet quenching at high hadron p_T

Azimuthal Angle Distributions in pp and 0-30% PbPb

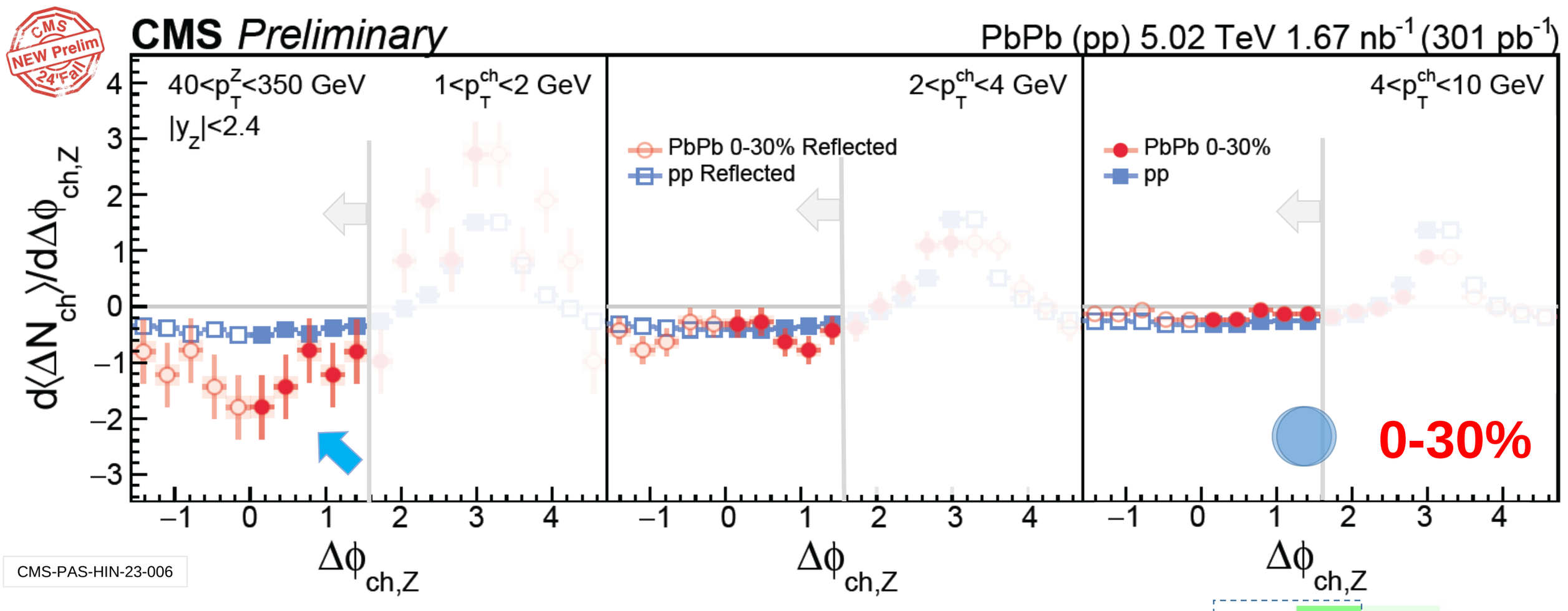


Now we have seen a deeper dip structure at Δϕ~0

How about rapidity distributions?



Azimuthal Angle Distributions in pp and 0-30% PbPb

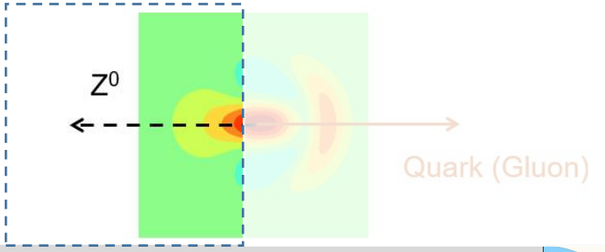


CMS-PAS-HIN-23-006

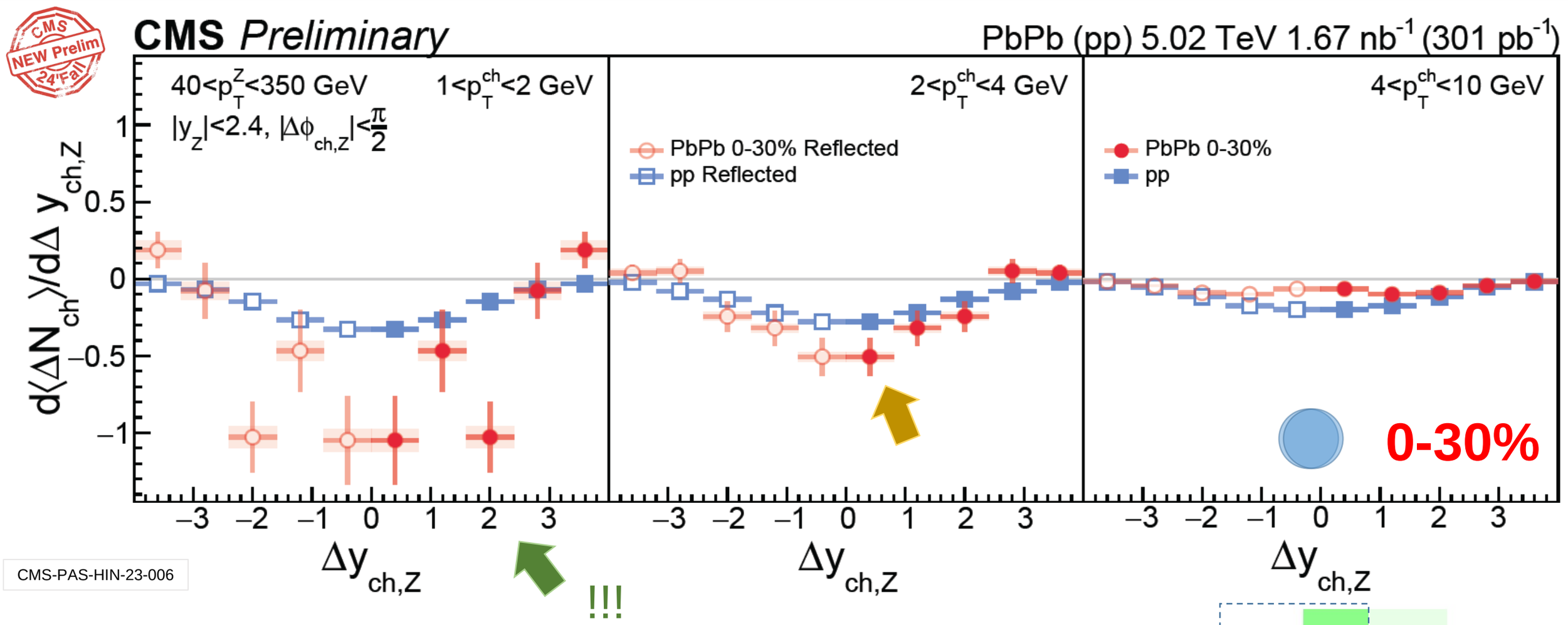
Now we have seen a deeper dip structure at Δϕ~0

How about rapidity distributions?

Let's focus on the **Z^0 side (Δϕ< π/2)** and then look at the Δy spectra



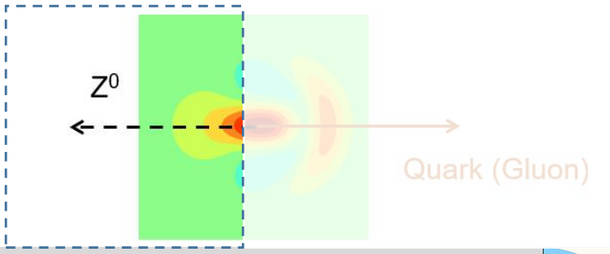
Rapidity Distributions in pp and 0-30% PbPb



CMS-PAS-HIN-23-006

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)

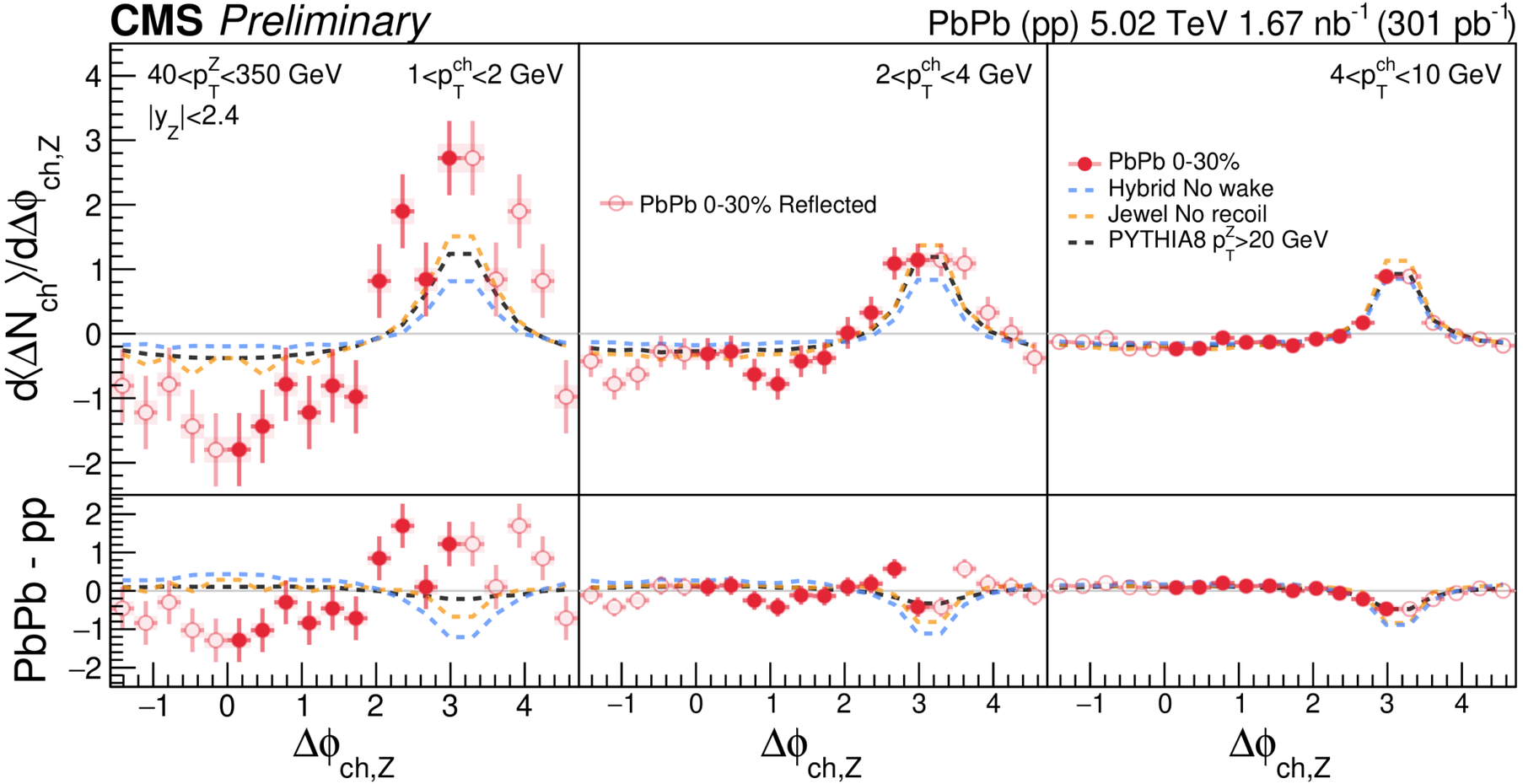


Azimuthal Angle Distribution in 0-30% PbPb vs. Theory **w/o** Medium Response

- **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.

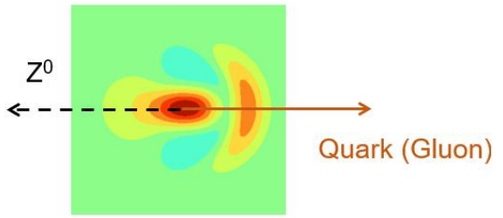
CMS-PAS-HIN-23-006



(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~~

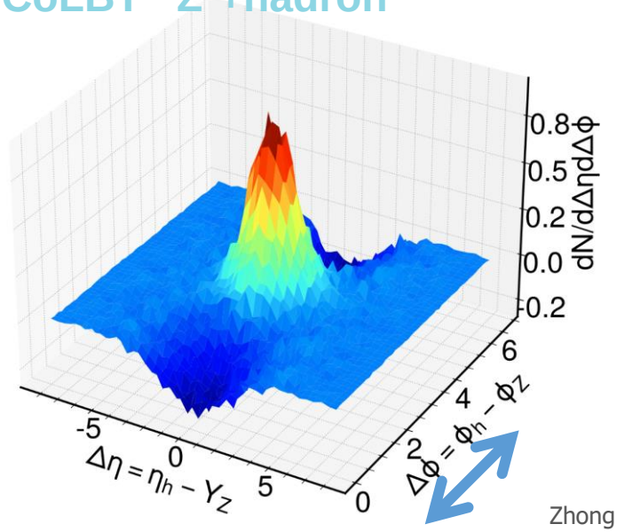


Azimuthal Angle Distribution in 0-30% PbPb vs. Theory

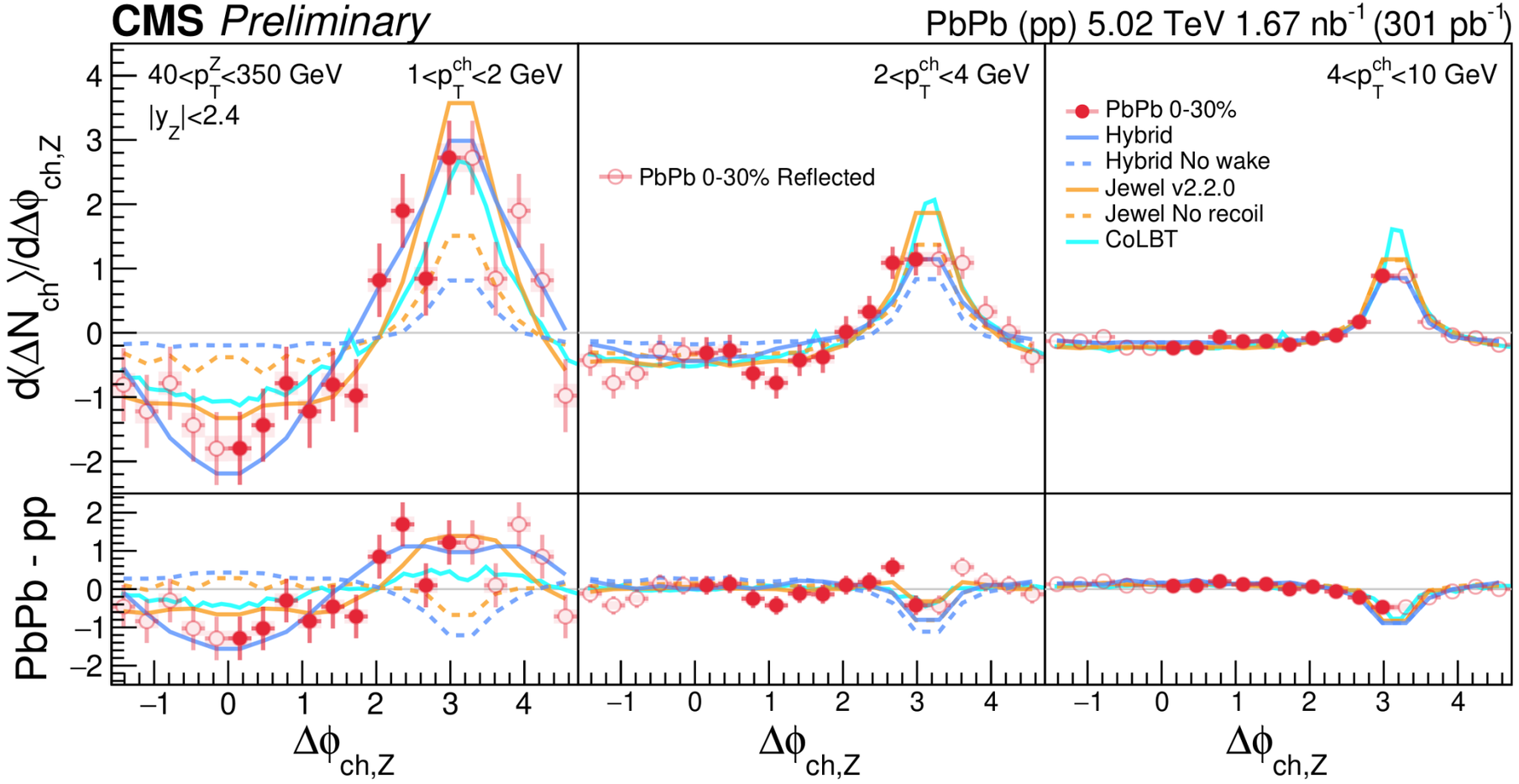
- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T

- **Hybrid with wake**, **Jewel with recoil** and **CoLBT with wake** (solid lines) agree better with the data with hadron $p_T < 4$ GeV

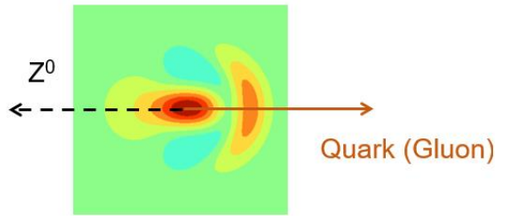
CoLBT Z⁰+hadron



Zhong Yang, Xin-Nian Wang



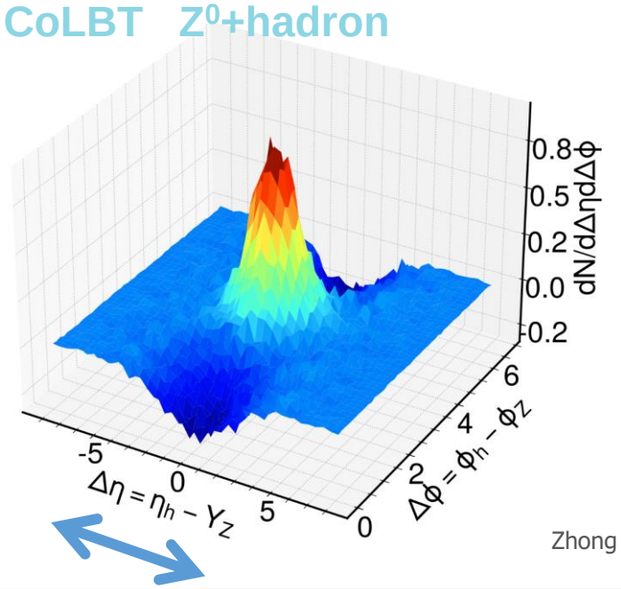
CMS-PAS-HIN-23-006



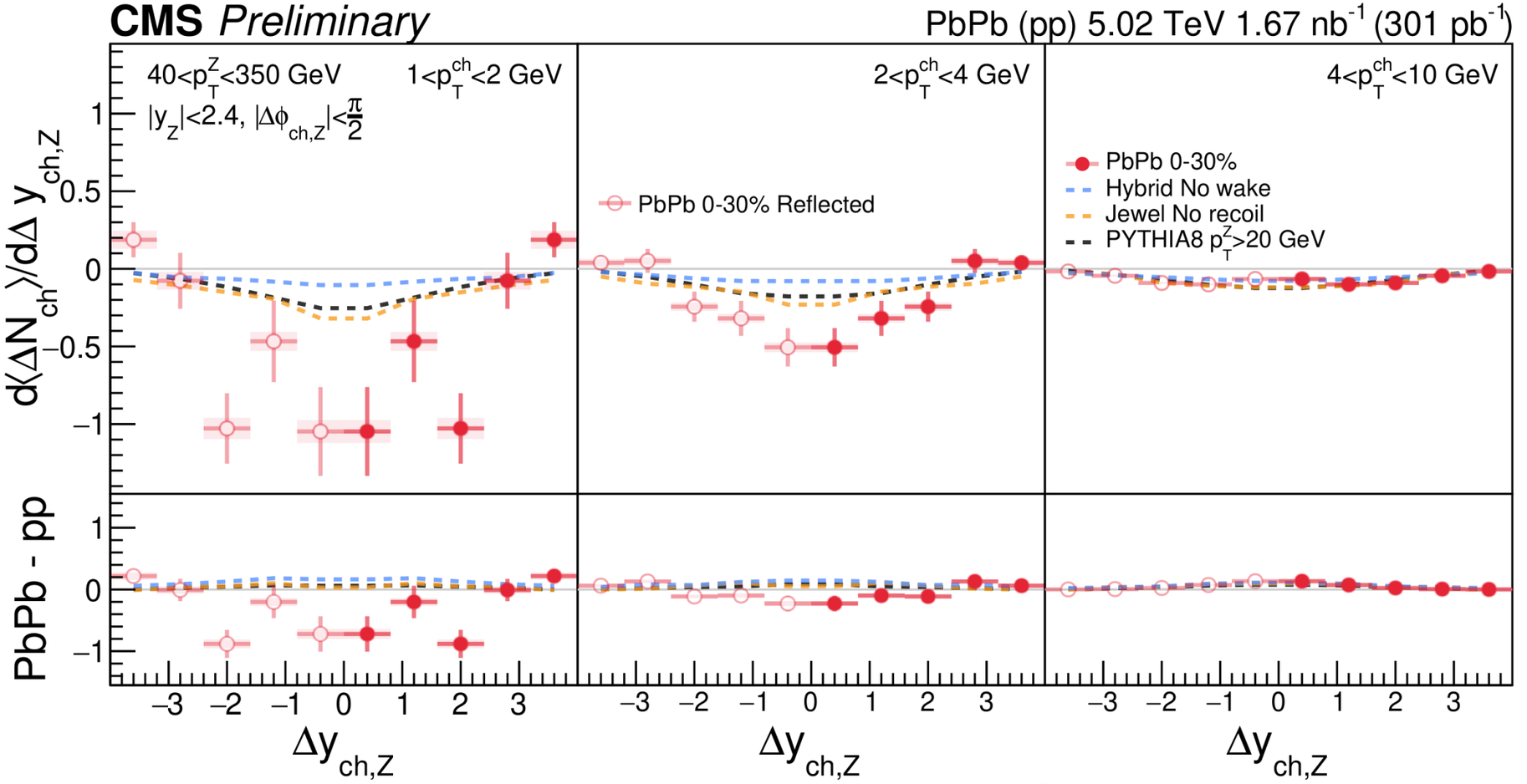
Rapidity Distribution in 0-30% PbPb vs. Theory without Medium Response

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

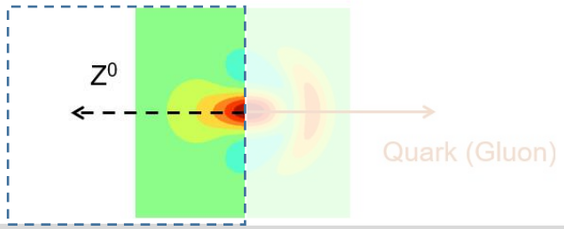
- **Lower p_T Z^0 tagged PYTHIA8 events** also fails to describe data with hadron p_T< 4 GeV.



Zhong Yang, Xin-Nian Wang



CMS-PAS-HIN-23-006



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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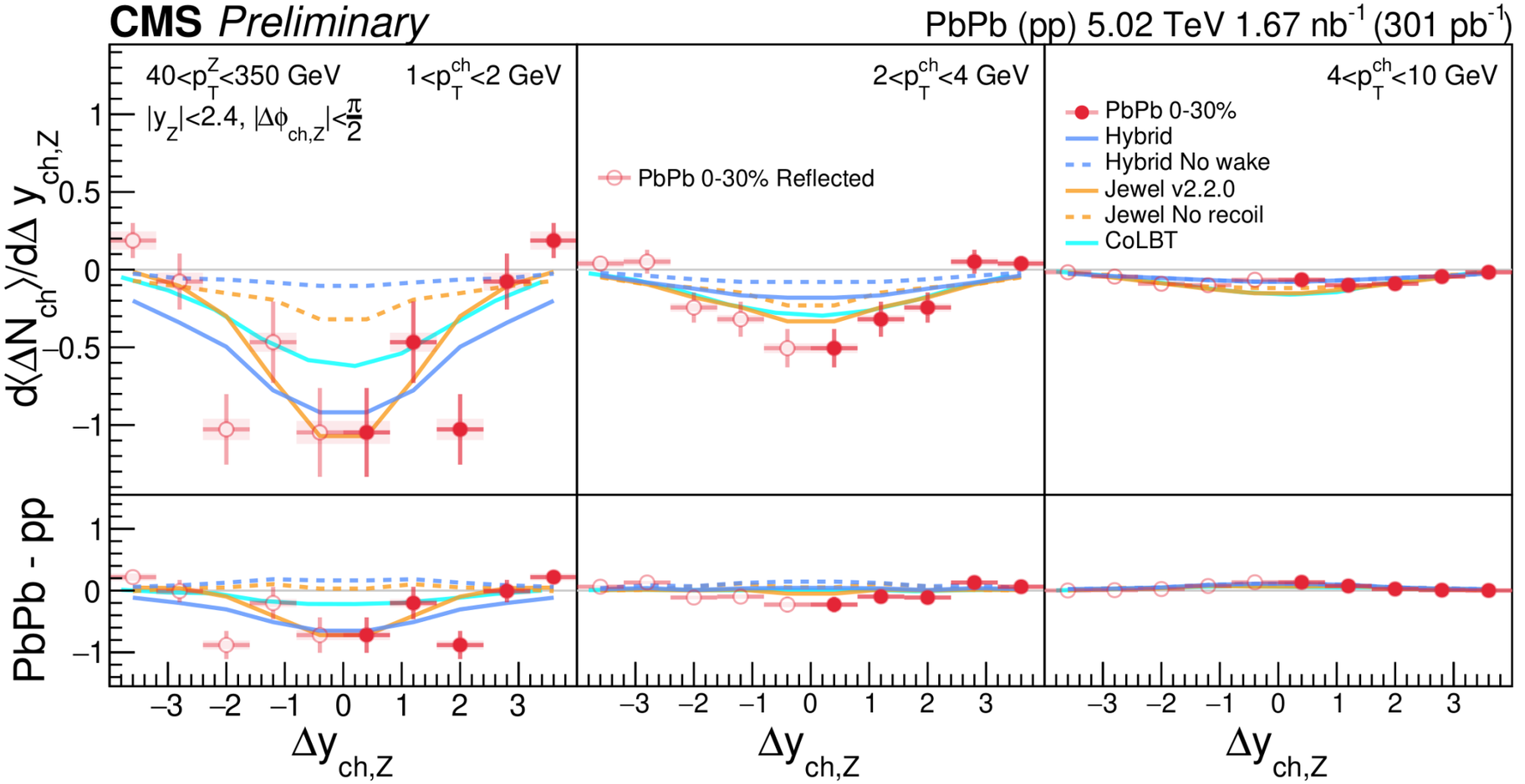
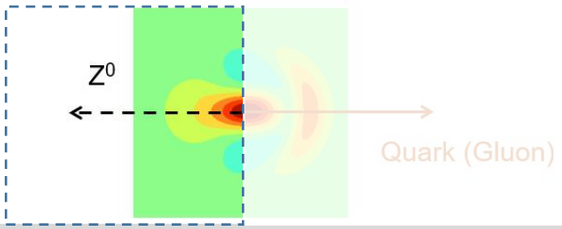


HP 2024
RIDING THE WAKE

With Δy and Δϕ spectra at low charged hadron p_T:

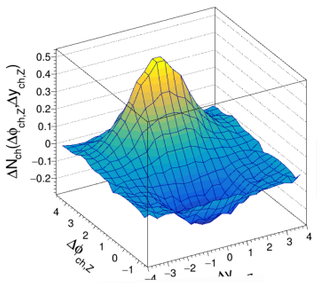
The first evidence of negative **QGP** wake!



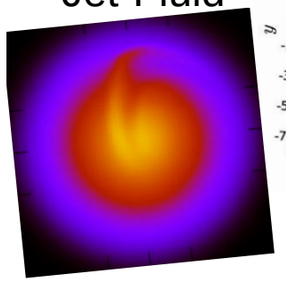
Summary and Outlook

- 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

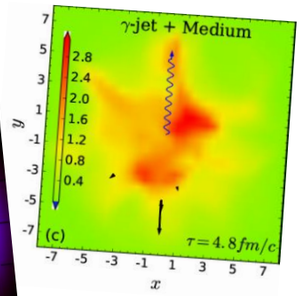
Hybrid Model

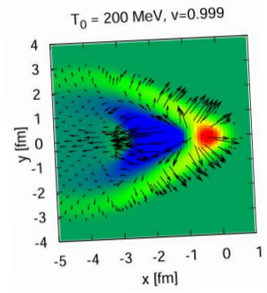


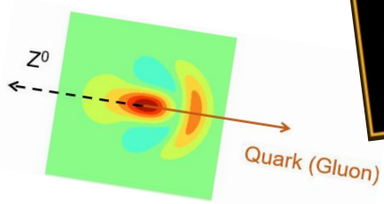
Jet-Fluid

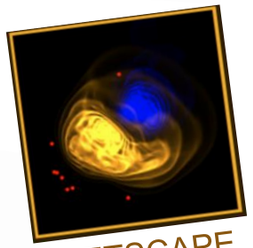


Co-LBT

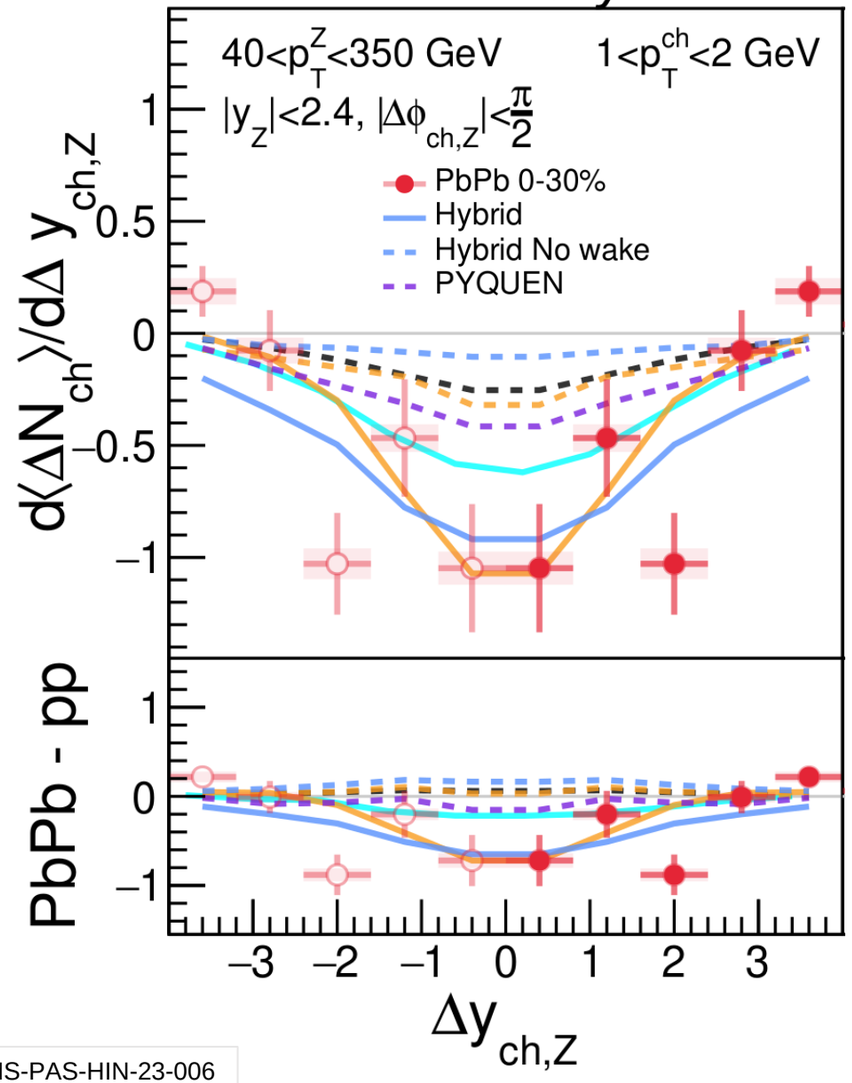








JETSCAPE



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Acknowledgement

Thank You!

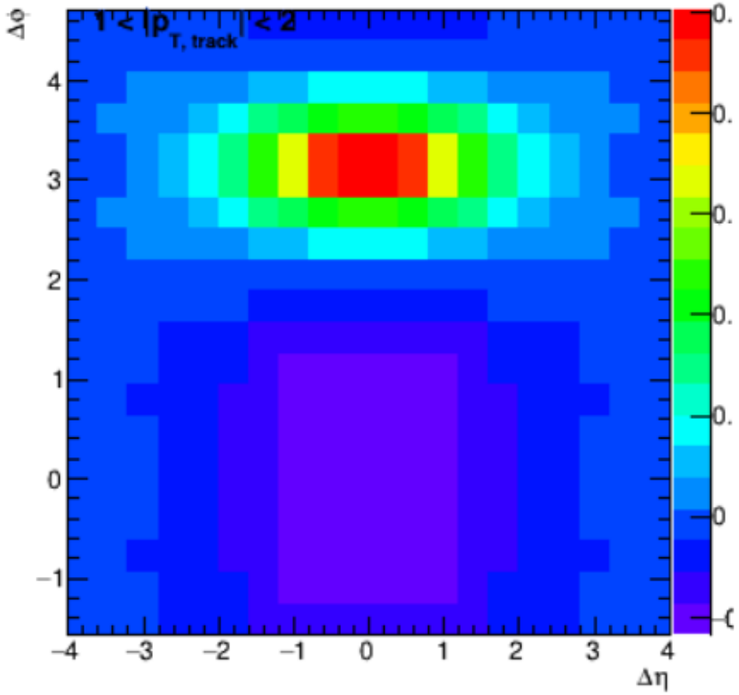
Backup Slides

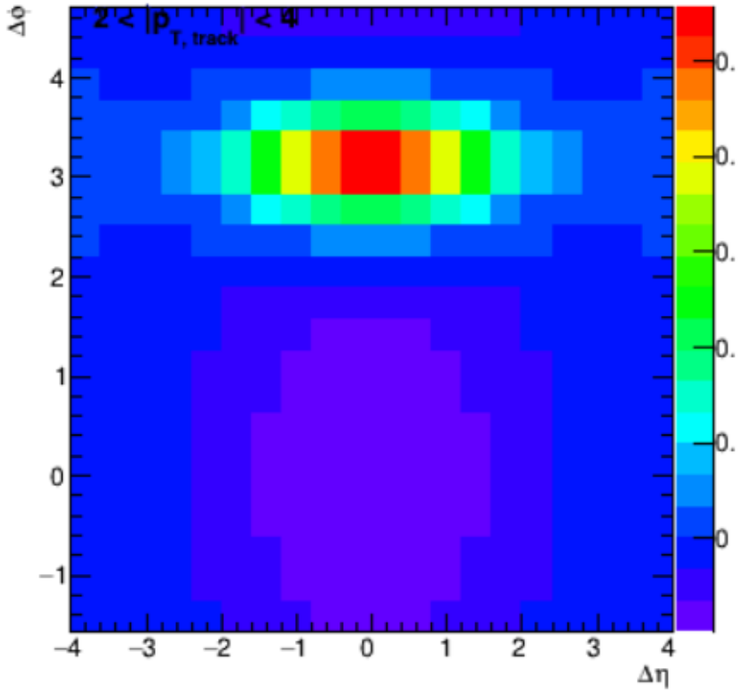
2D Distribution (pp PYTHIA)

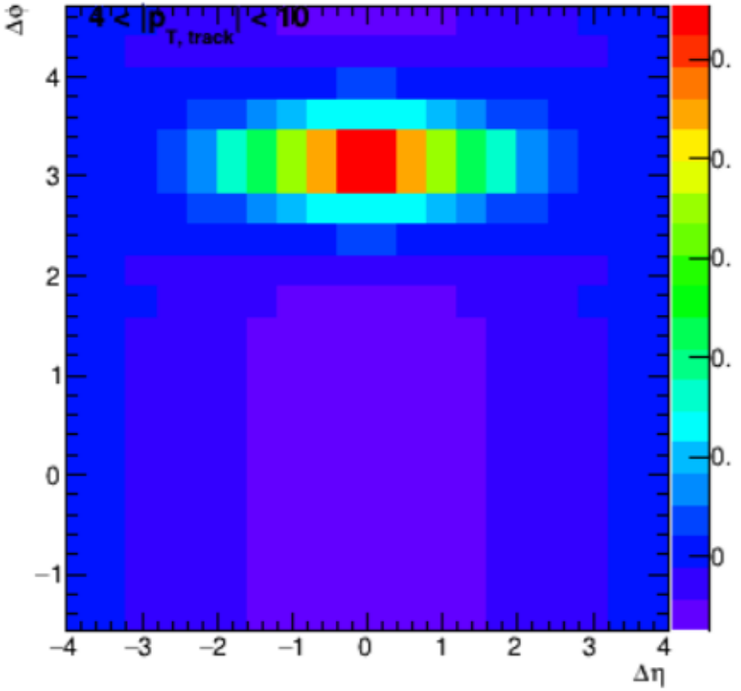
Track = 1-2 GeV

2-4 GeV

4-10 GeV







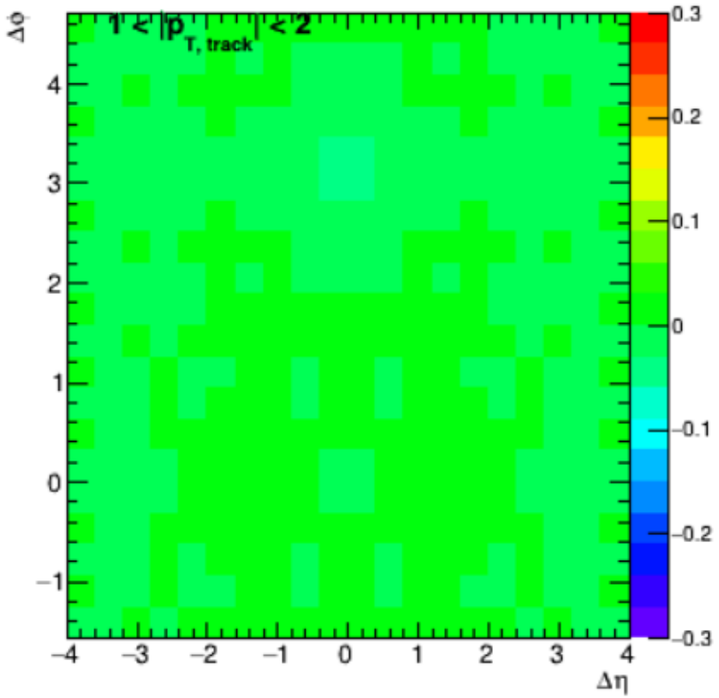
Delta eta = eta_ch - y_Z

Low Track p_T

High Track p_T

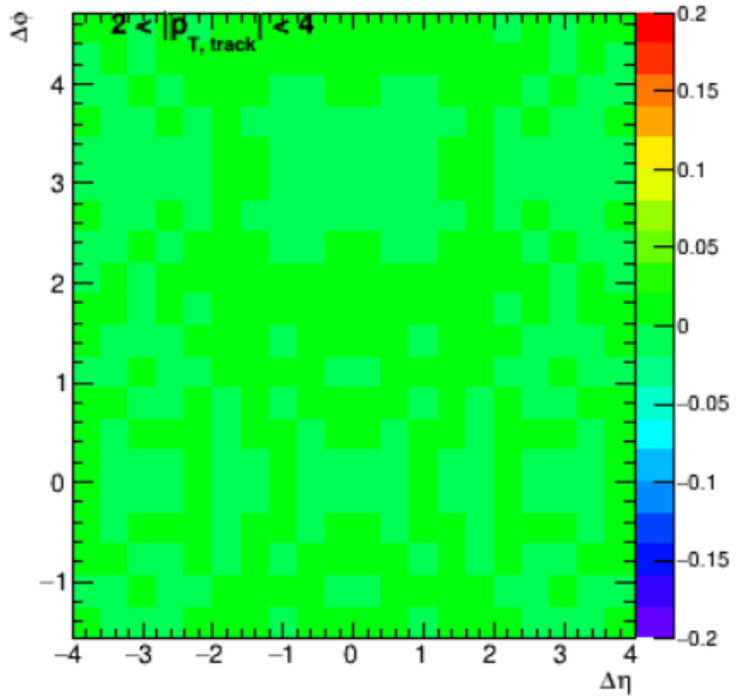
2D Results (PYTHIA+HYDJET 0-90% - PYTHIA)

Track = 1-2 GeV



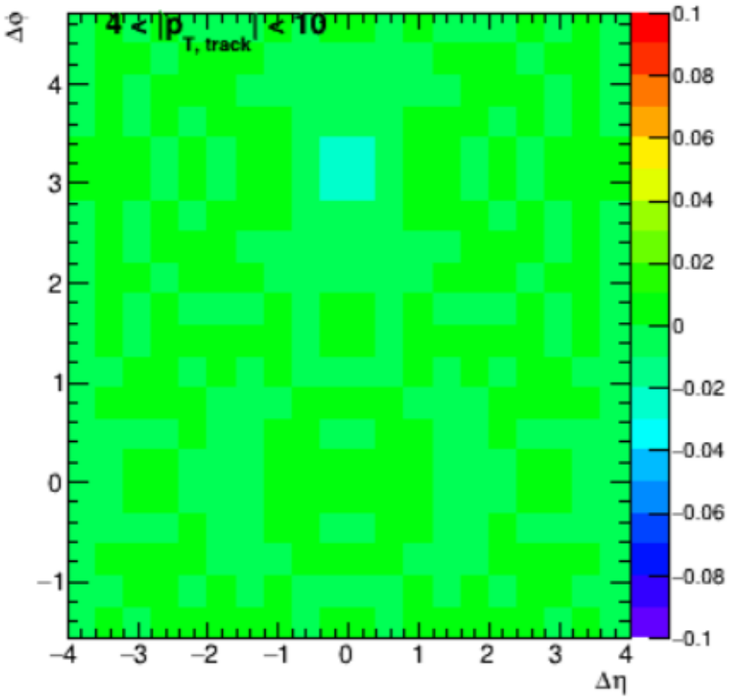
= y_z - η_{track}

2-4 GeV



= y_z - η_{track}

4-10 GeV

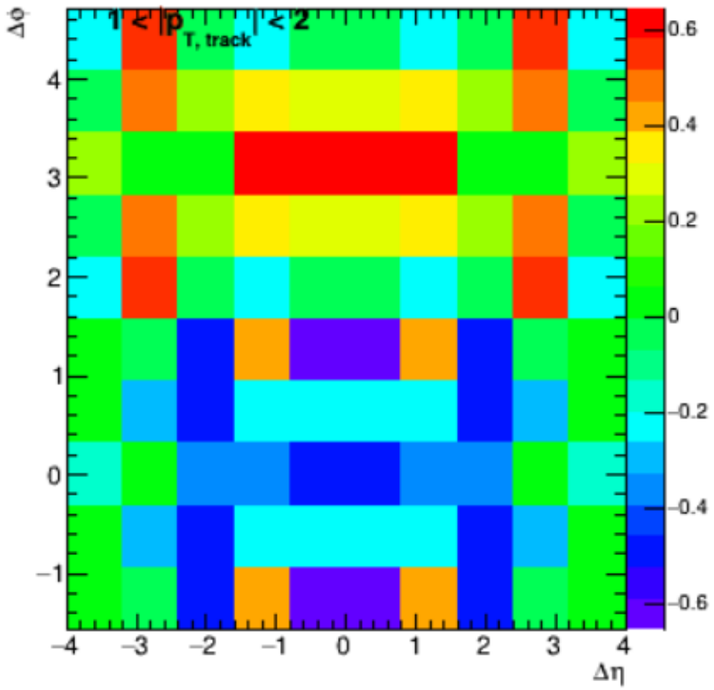


= y_z - η_{track}

Closure test for the 2D plots: Good closure achieved

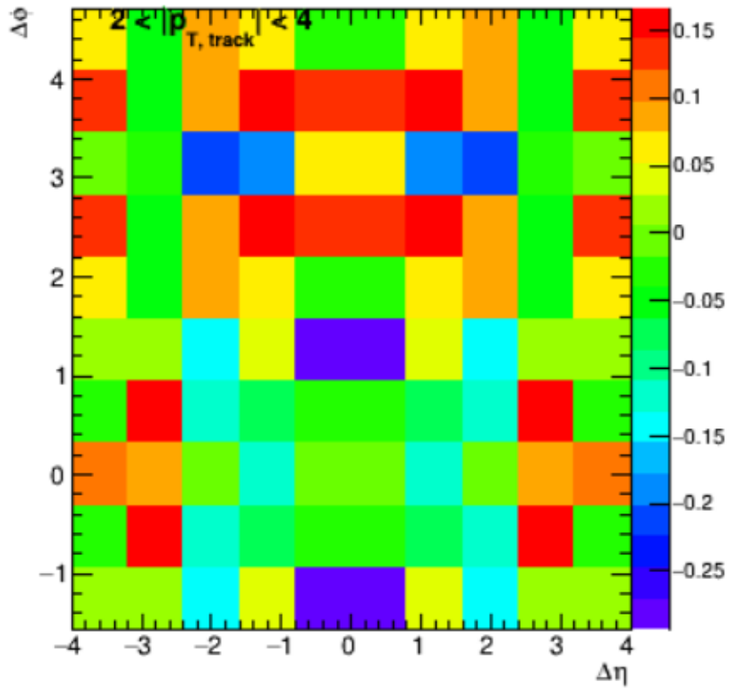
2D Results (PbPb 0-90% - pp rebin)

Track = 1-2 GeV



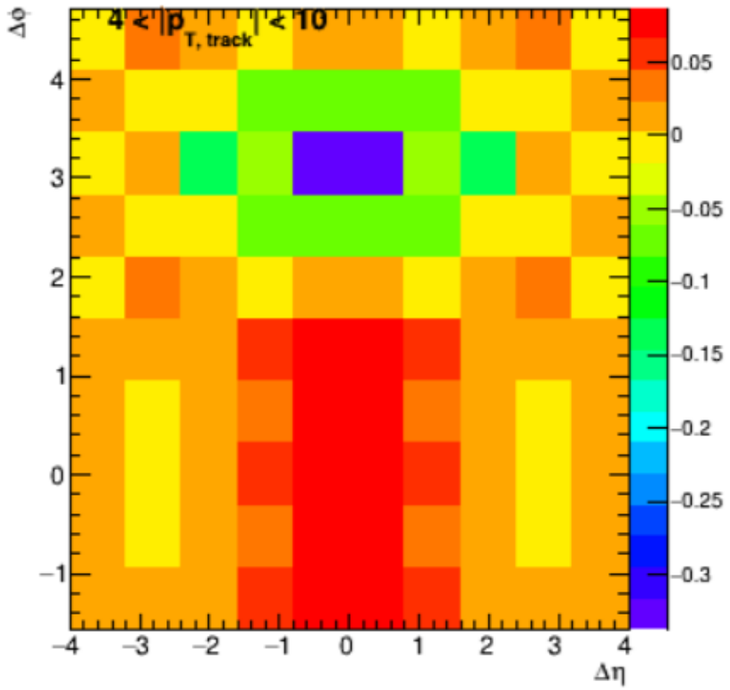
= y_z - η_{track}

2-4 GeV



= y_z - η_{track}

4-10 GeV



= y_z - η_{track}

It is fun to see the "color inversion" in the 3 panel plot
Different behavior between low and high p_T tracks

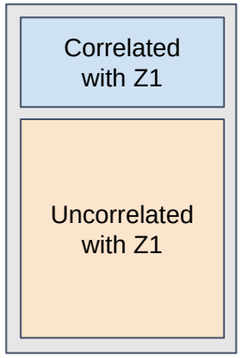
Systematics

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

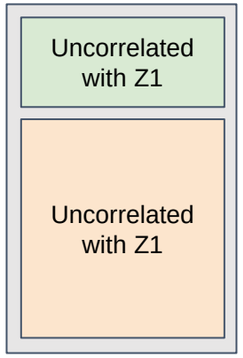
MC: embedded
Data: PbPb



Event 1

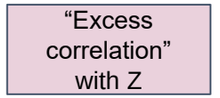
–

MC: embedded
Data: PbPb



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

=

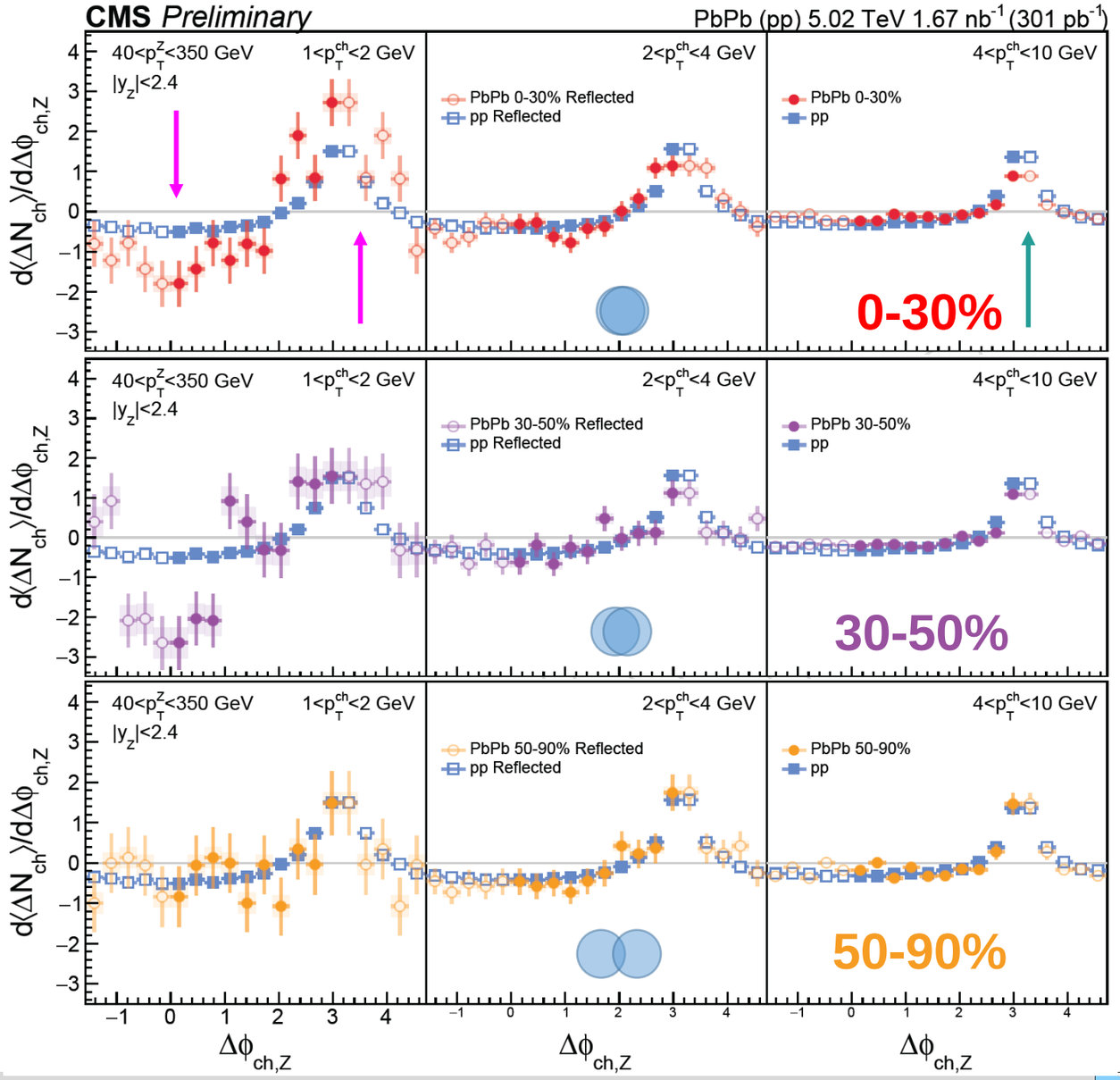


Same population of events

- 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

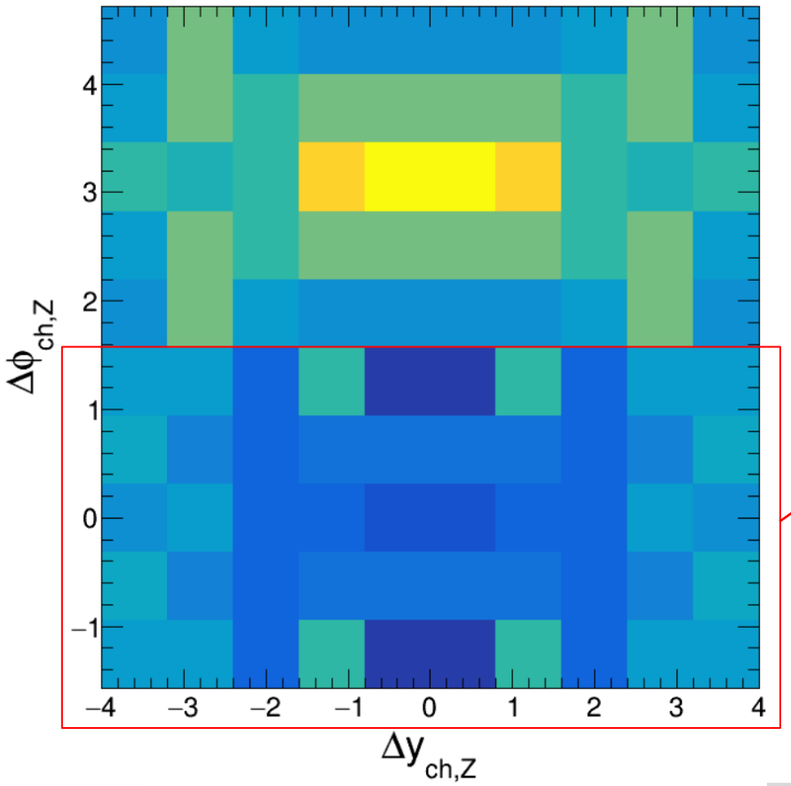
- Open markers are the same as filled data points but reflected to show the full range
- Low track P_T: clear relative depletion in Z side and enhancement in jet side
- High track P_T: jet quenching effect suppresses jet peak
- Effect disappears in **50-90%**

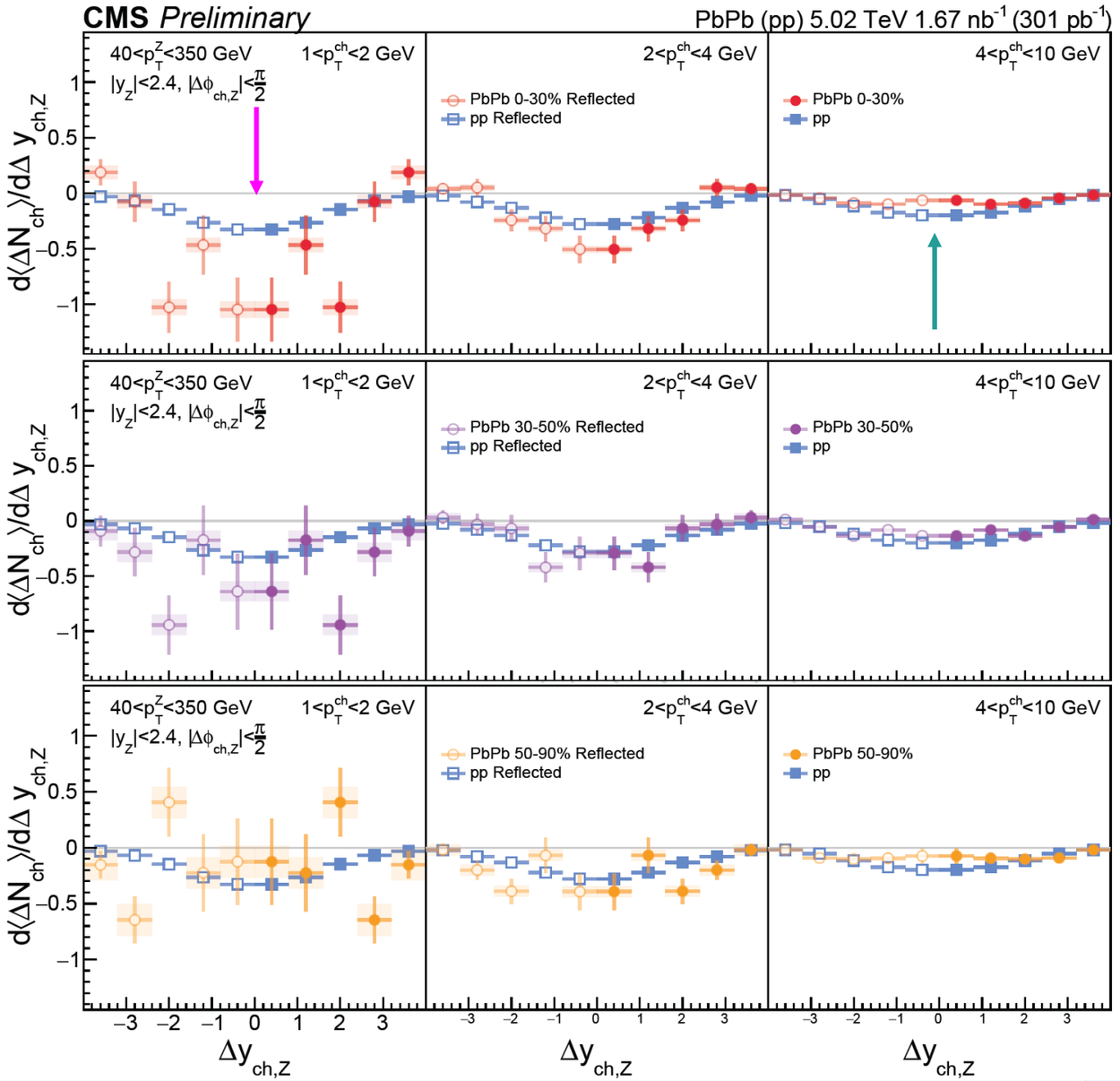


Results: Rapidity Distributions

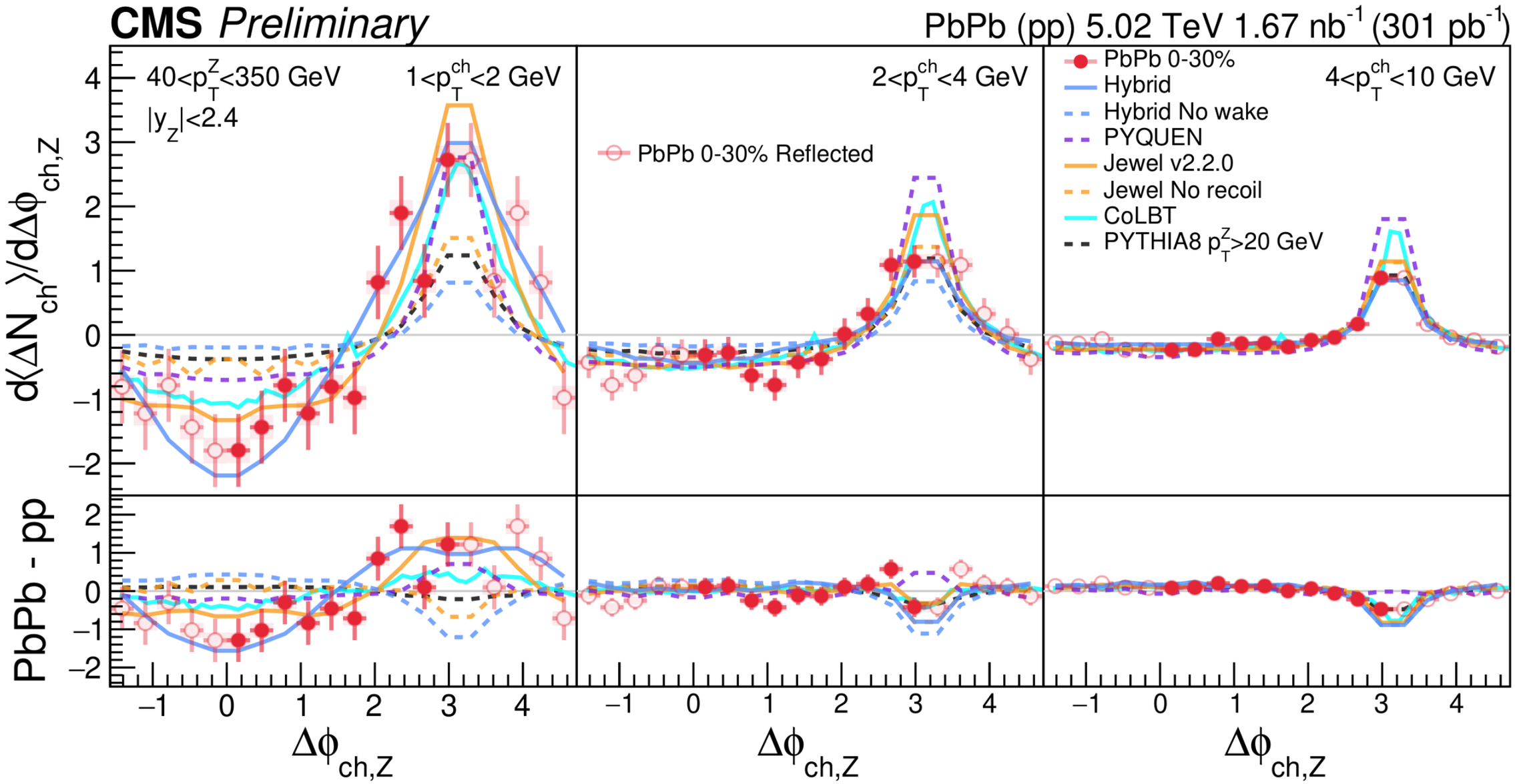
- Focus on the Z side: $|\Delta\Phi_{ch,Z}| < \pi/2$
- Integral **not zero** since this is not full range of $\Delta\Phi$

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

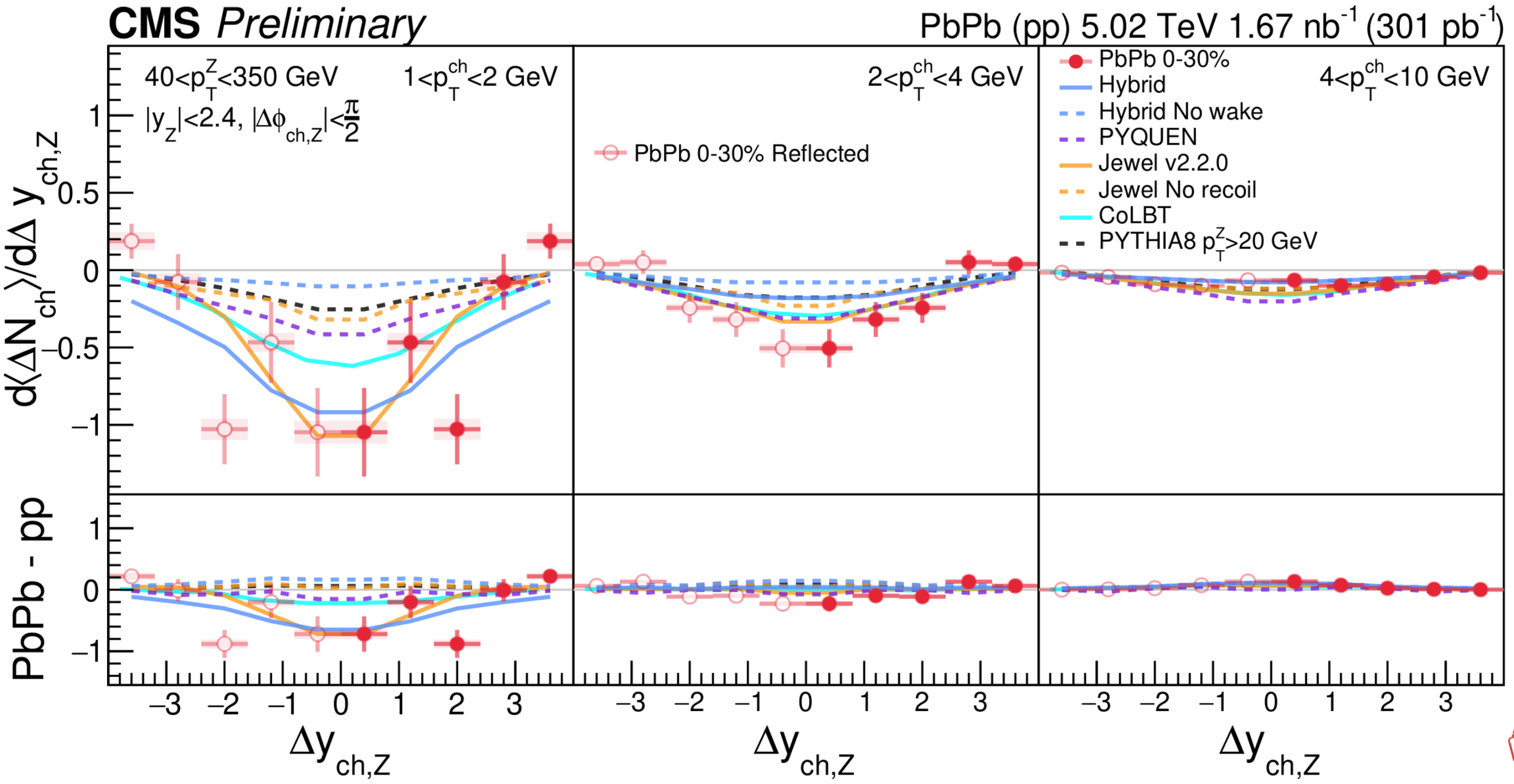




Theory Comparison on Δϕ Spectra



Theory Comparison on Δy Spectra

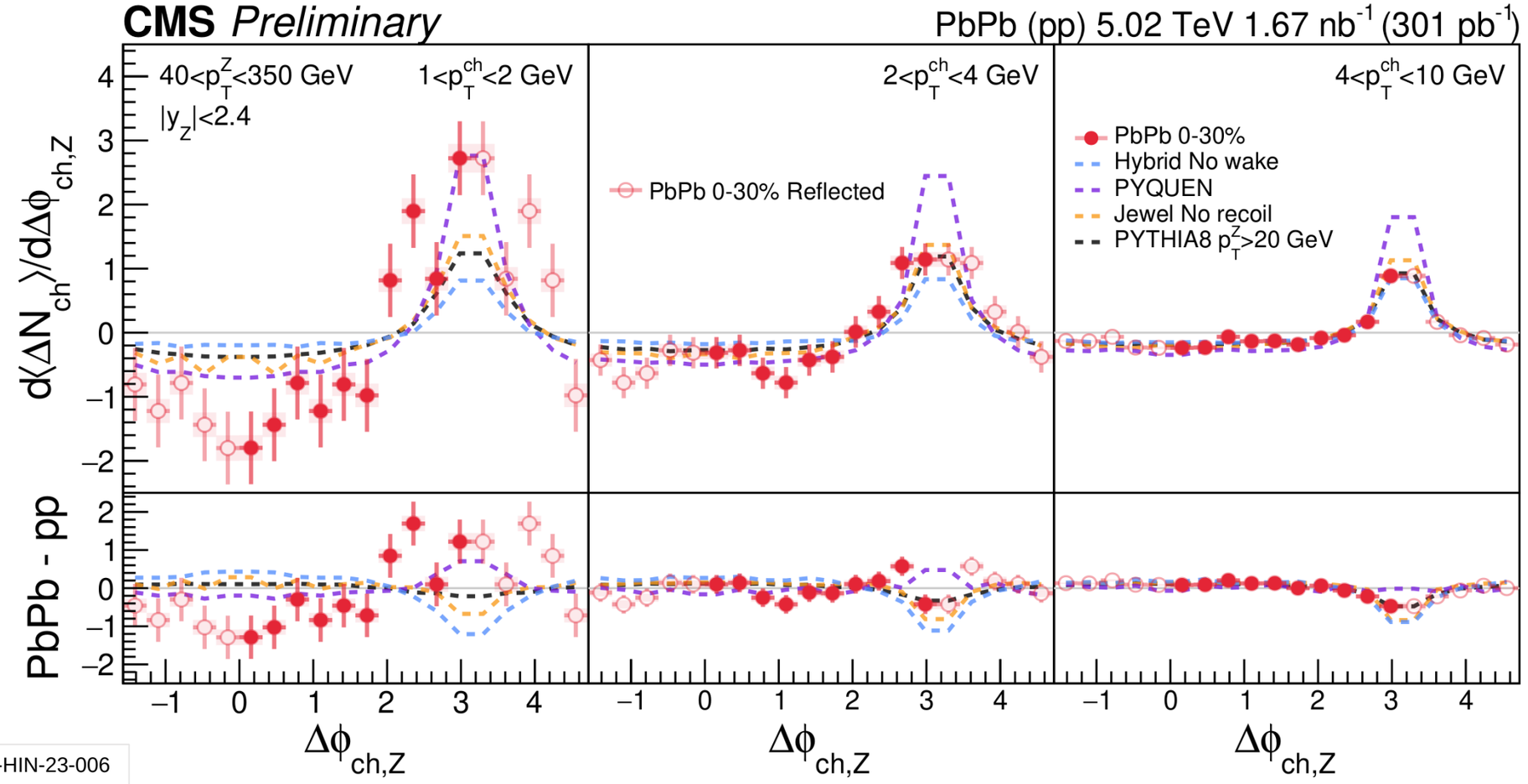


Theory Comparison: Azimuthal Angle Distribution in 0-30% PbPb

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

- **PYTHIA8 lower p_T Z-tagged 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**, (no 4-momentum conservation), fails to describe generally the data



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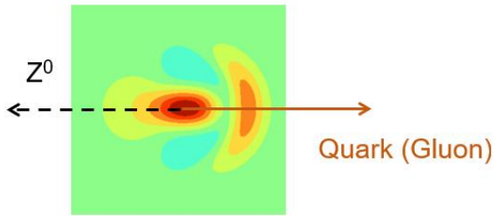
40 GeV Z + 40 GeV jet → (Quench) 40 GeV Z + quenched jet + recoil/wake

(Approx.) 20 GeV Z + 20 GeV pythia jet ~~+ recoil/wake~~



Theory Comparison: Rapidity Distribution in 0-30% PbPb

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

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

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

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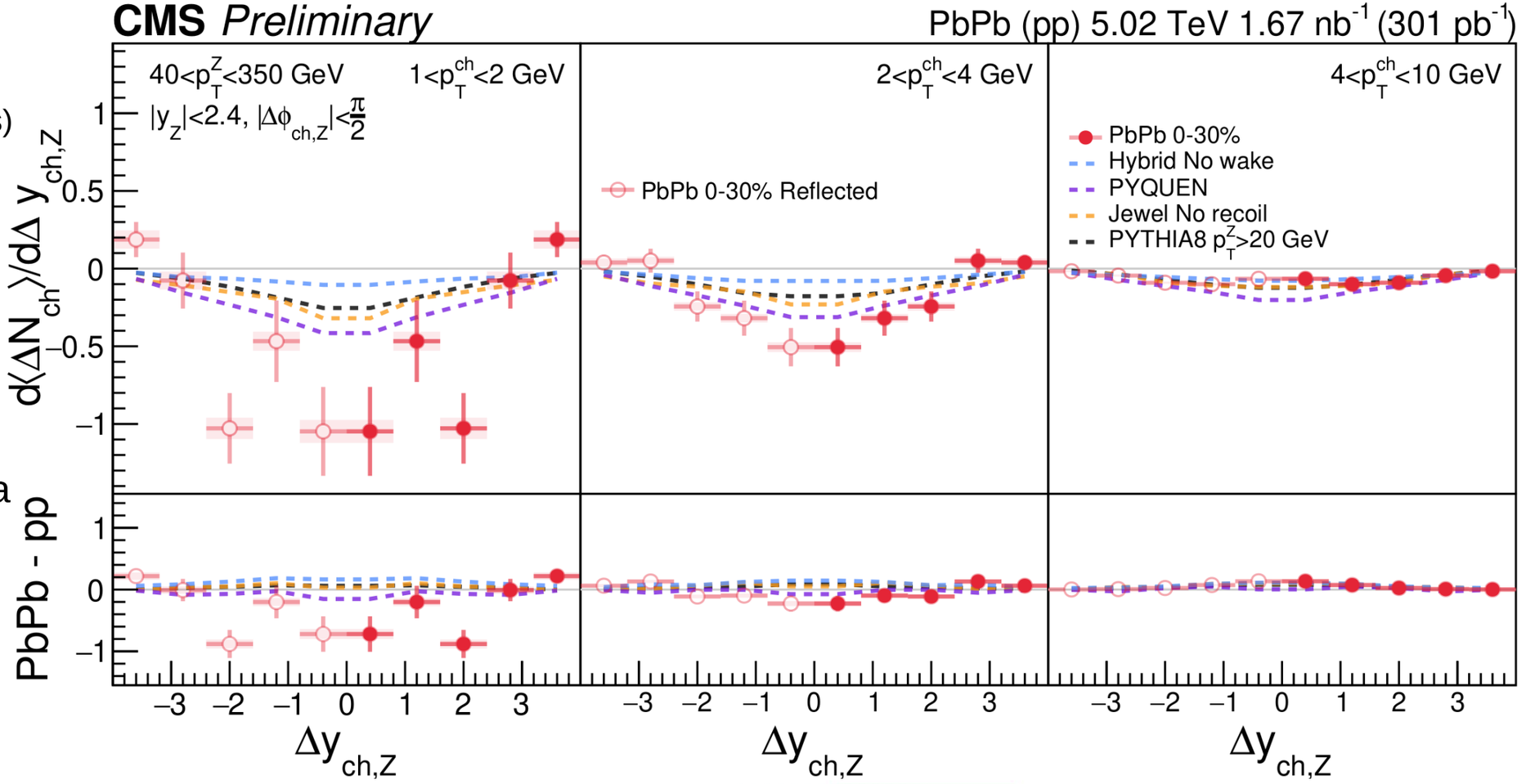
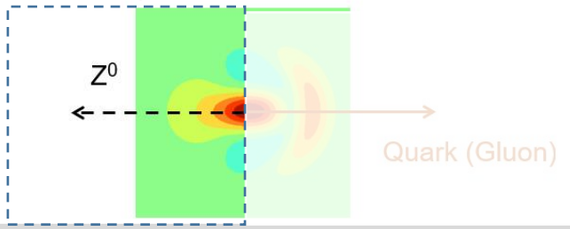
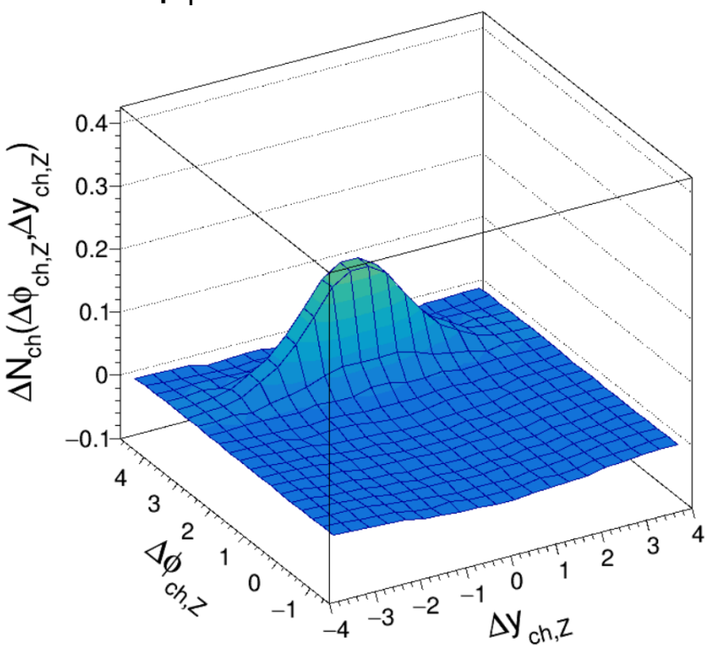




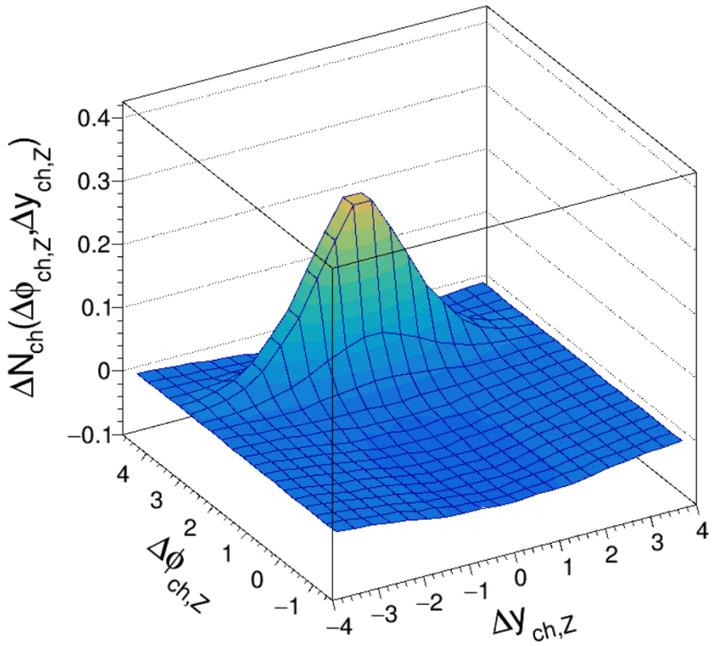
PYTHIA8 Z^0+Jet Event with Different Z^0 p_T Thresholds

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

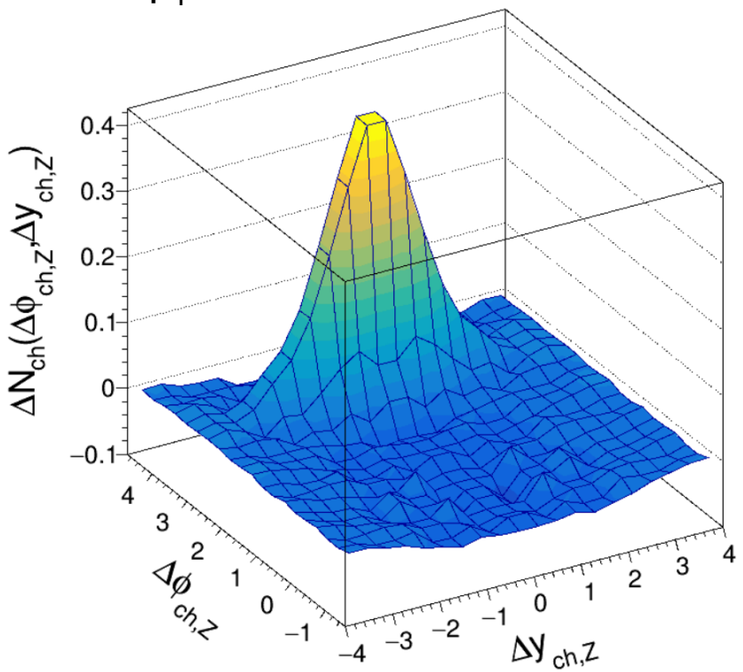
Z^0 p_T > 20 GeV



Z^0 p_T > 40 GeV

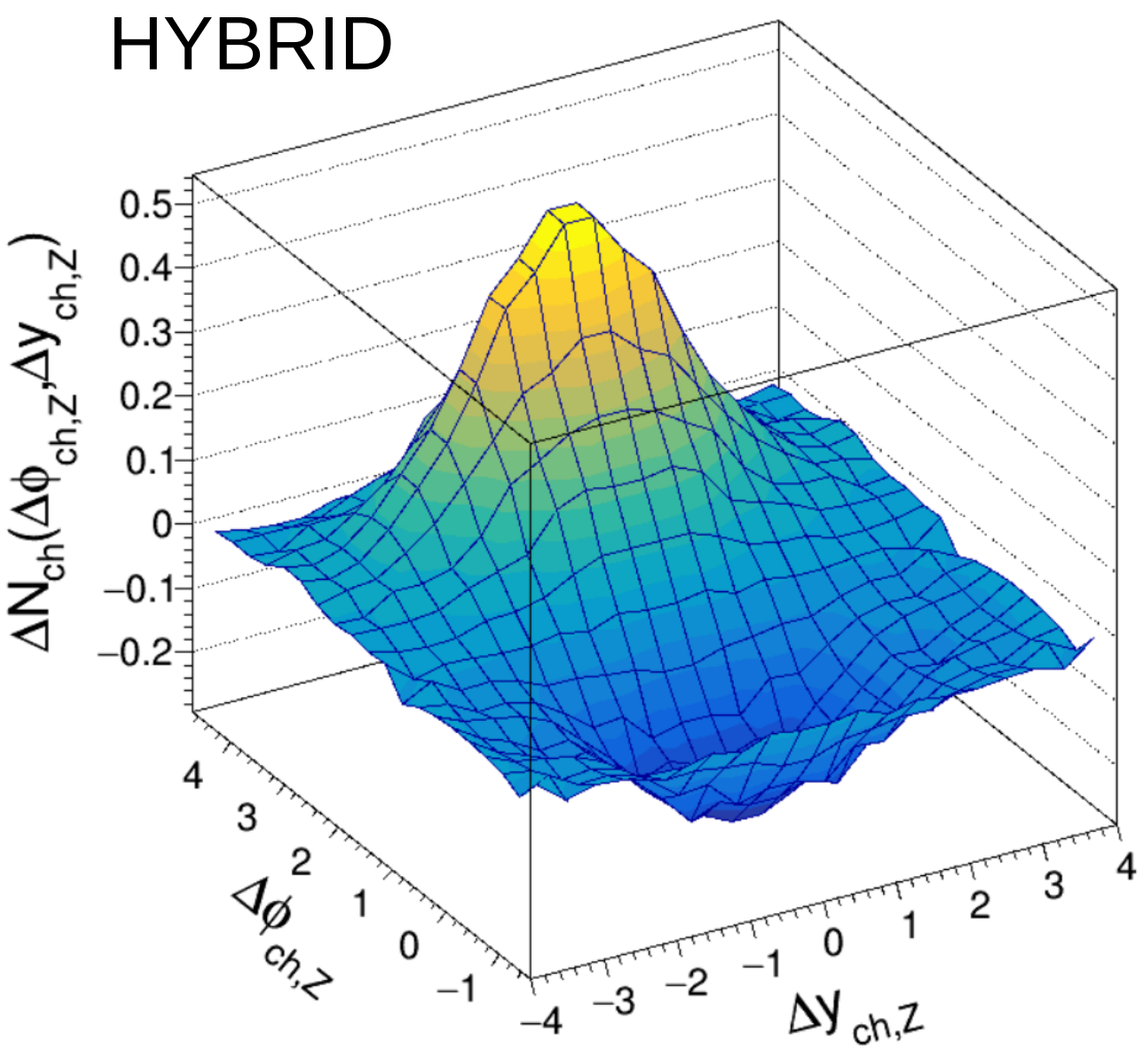


Z^0 p_T > 60 GeV

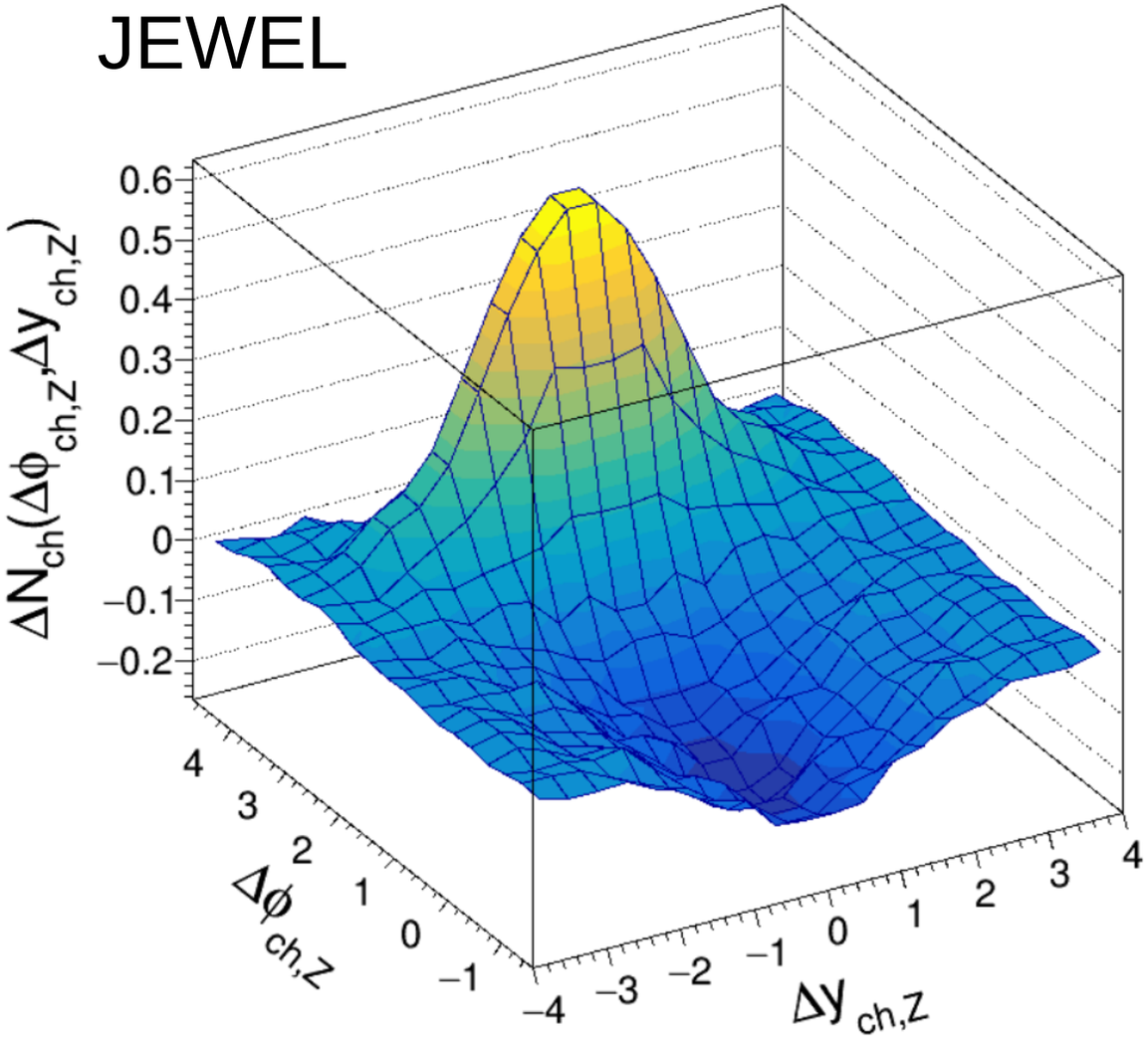


Predictions from Models for Charged Hadron p_T 1-2 GeV

HYBRID

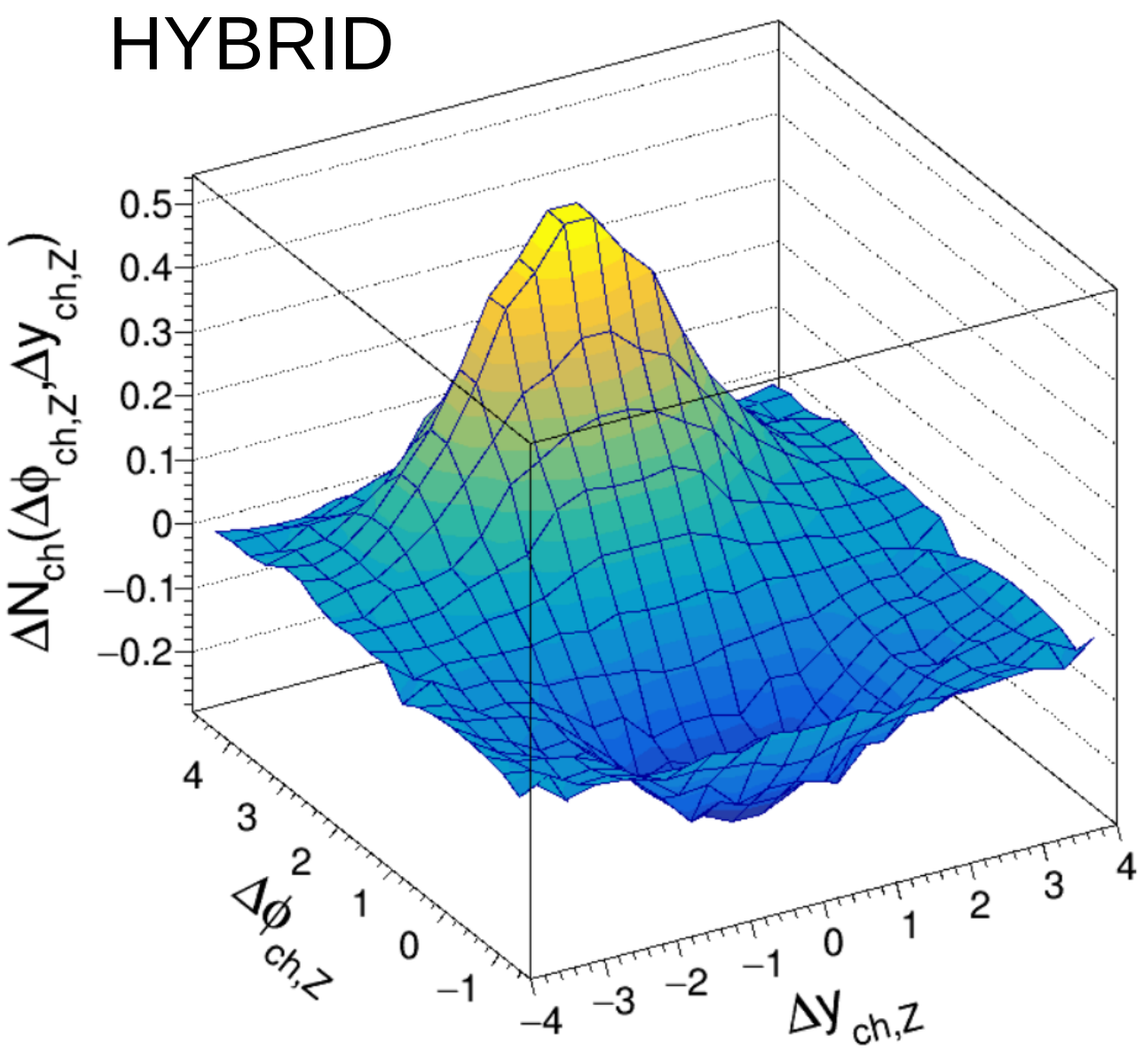


JEWEL



Predictions from Models for Charged Hadron p_T 1-2 GeV

HYBRID



HYBRID No Wake