CMS Experiment at the LHC, CERN

First Evidence of Medium Response to Hard Probes with Z^0-tagged Hadrons in Lead-Lead Collisions

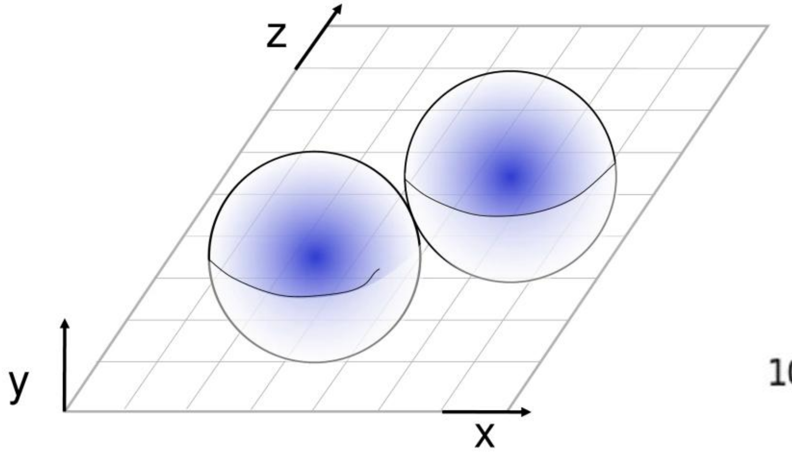
Yen-Jie Lee

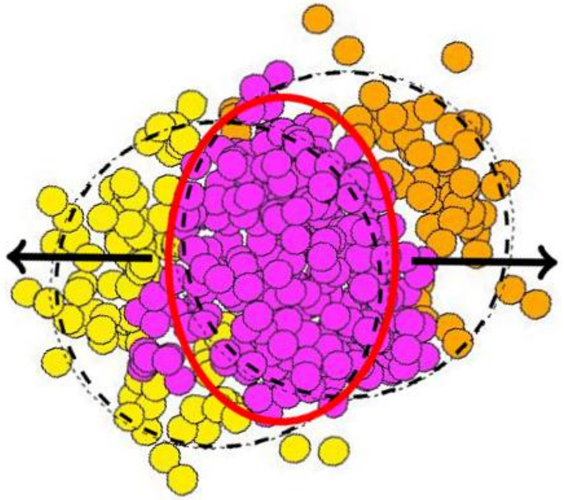
For the CMS Collaboration

The 11th Workshop of APS Topical Group on Hadronic Physics
March 14, 2025

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

Effect of Shear Viscosity in Simulation

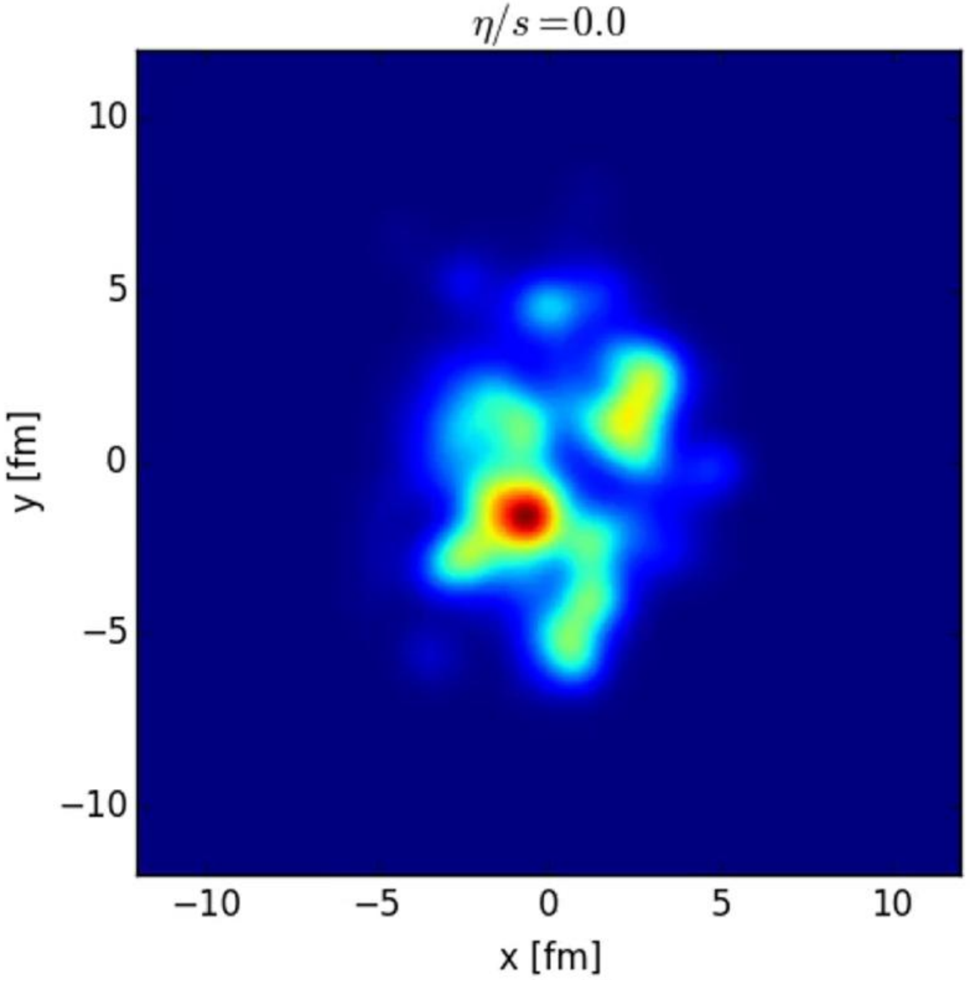




Alver and Roland (MITHIG)
“Collision geometry fluctuation”
PRC82 (2010) 039903

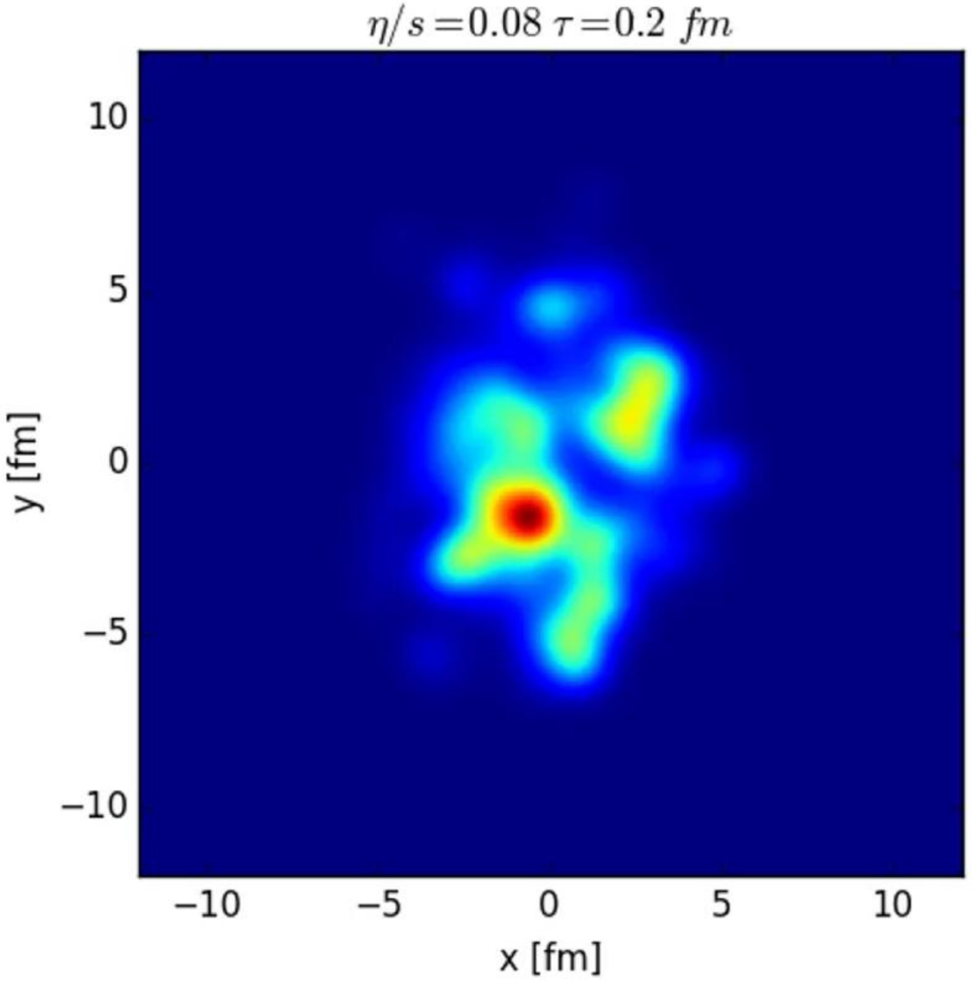
Ideal hydrodynamics

η/s = 0



Viscous hydrodynamics

η/s = 0.08



Animation from L. G. Peng

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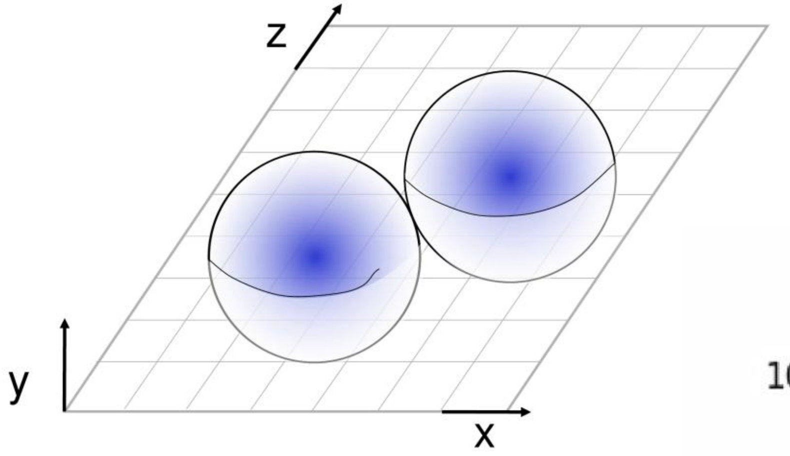

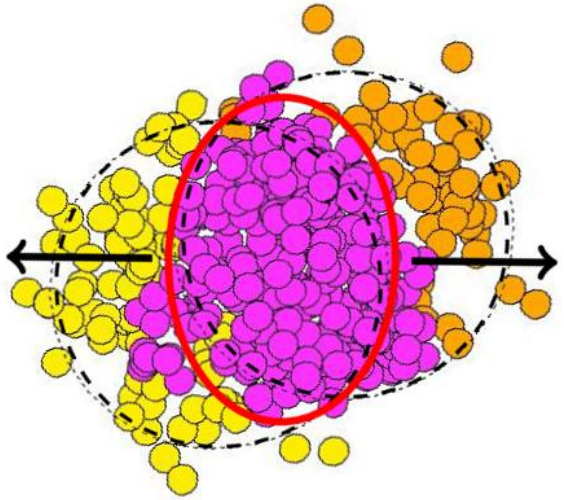

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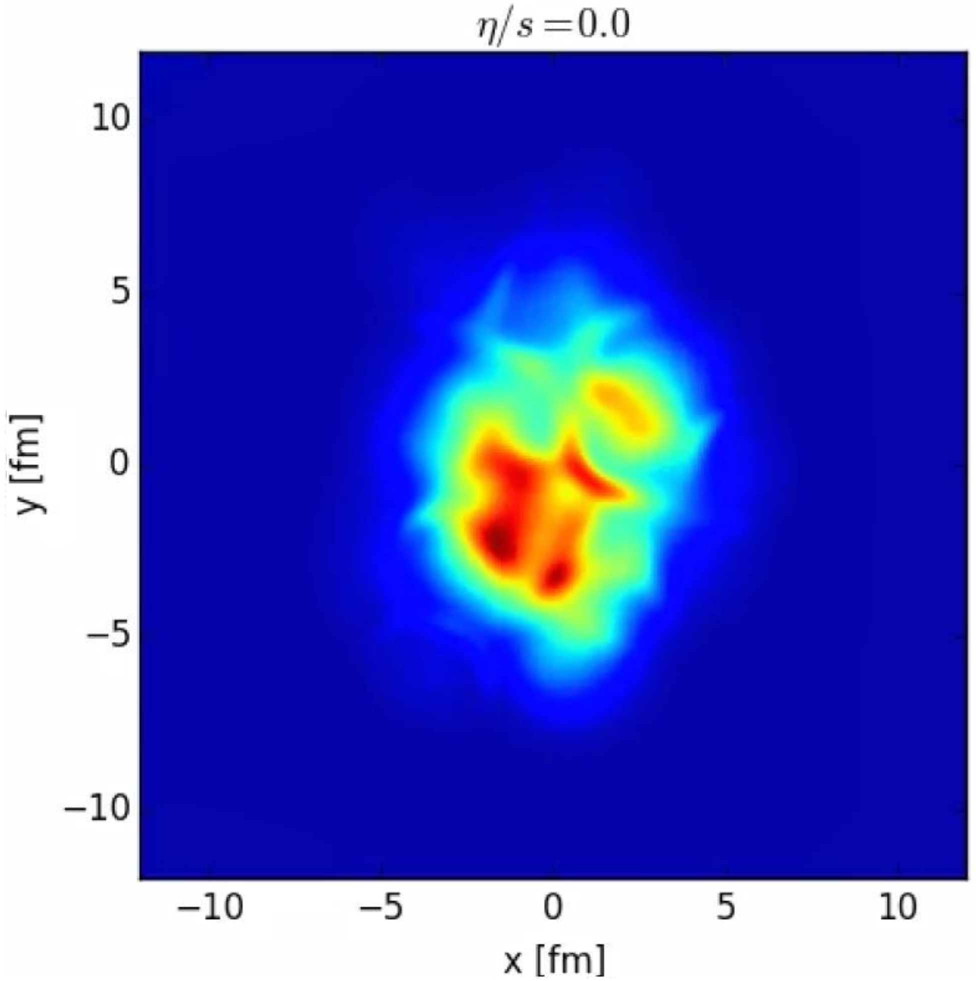

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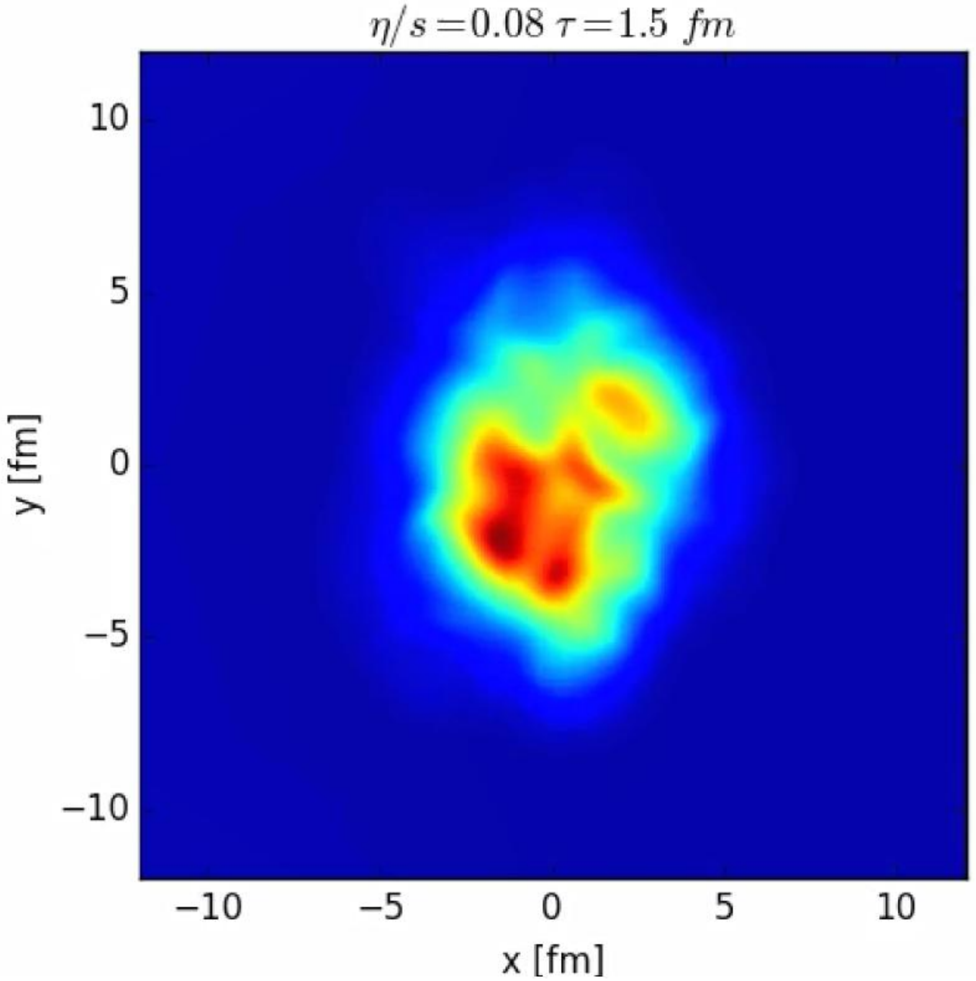

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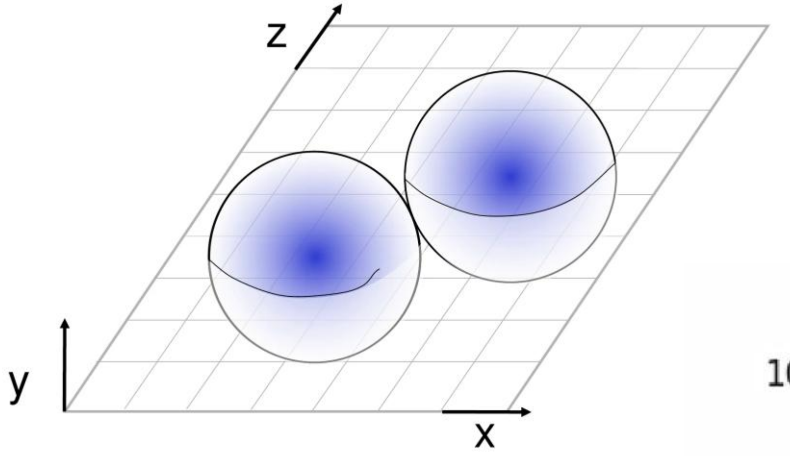

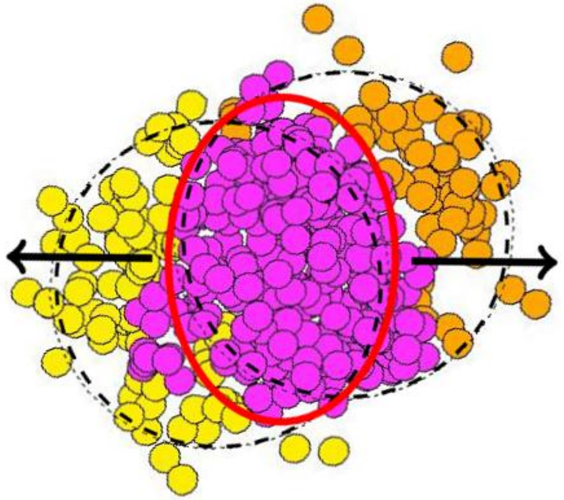

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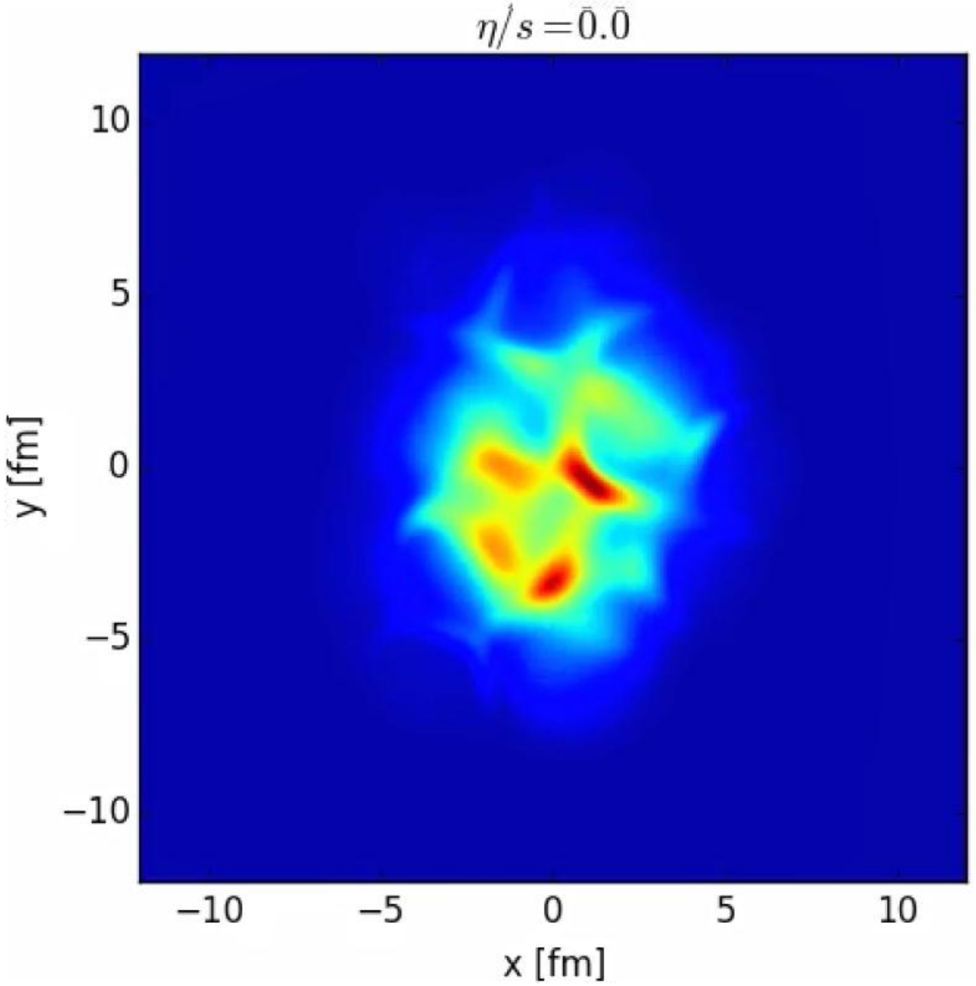

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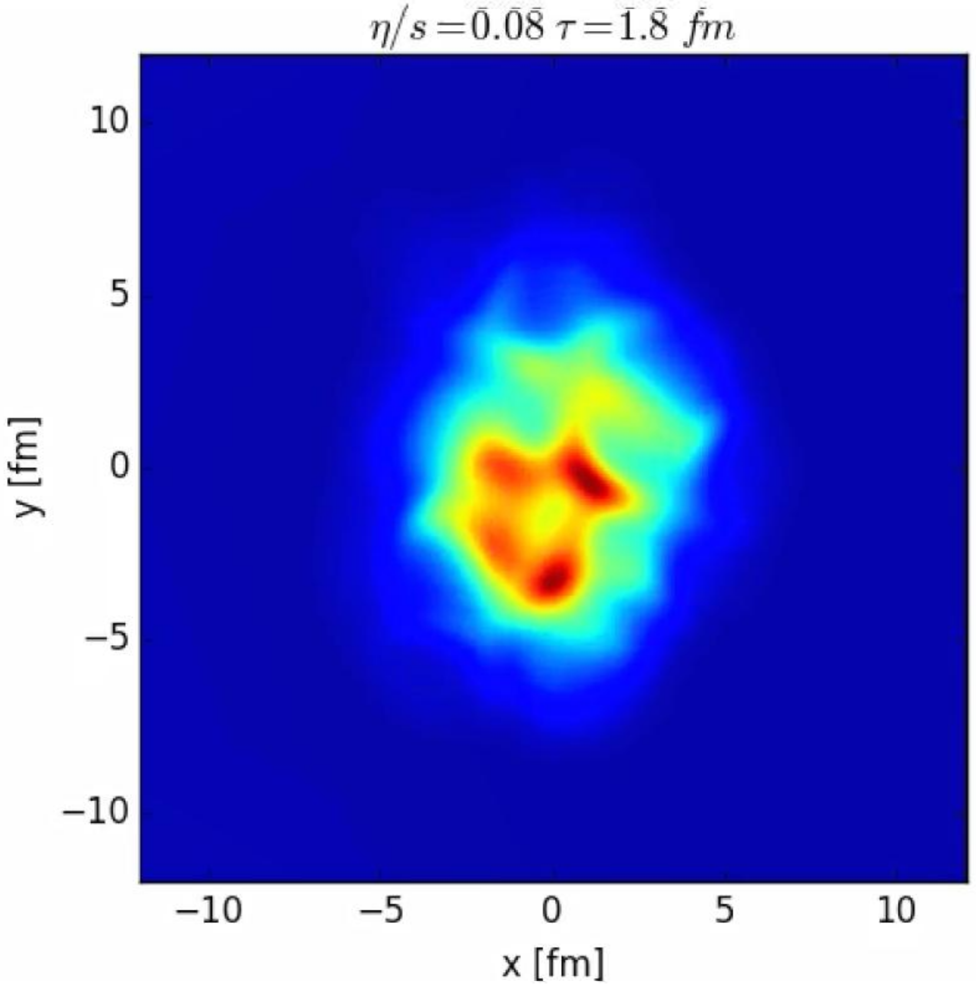

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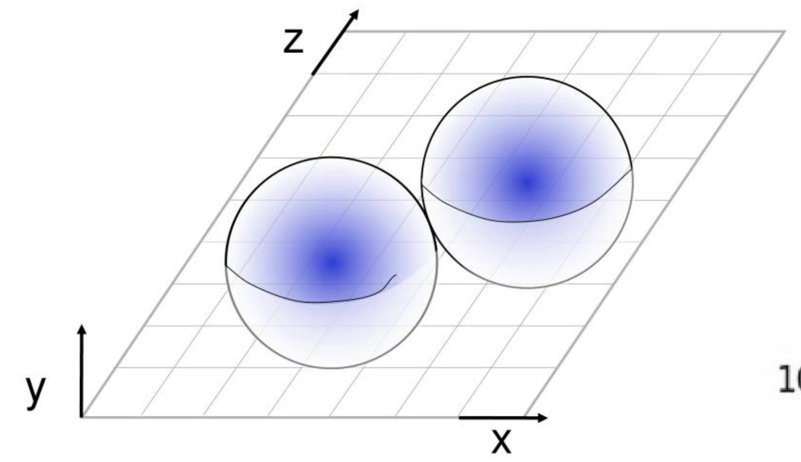

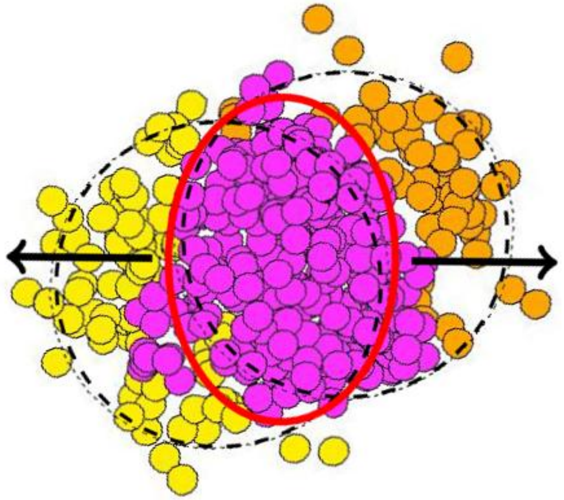

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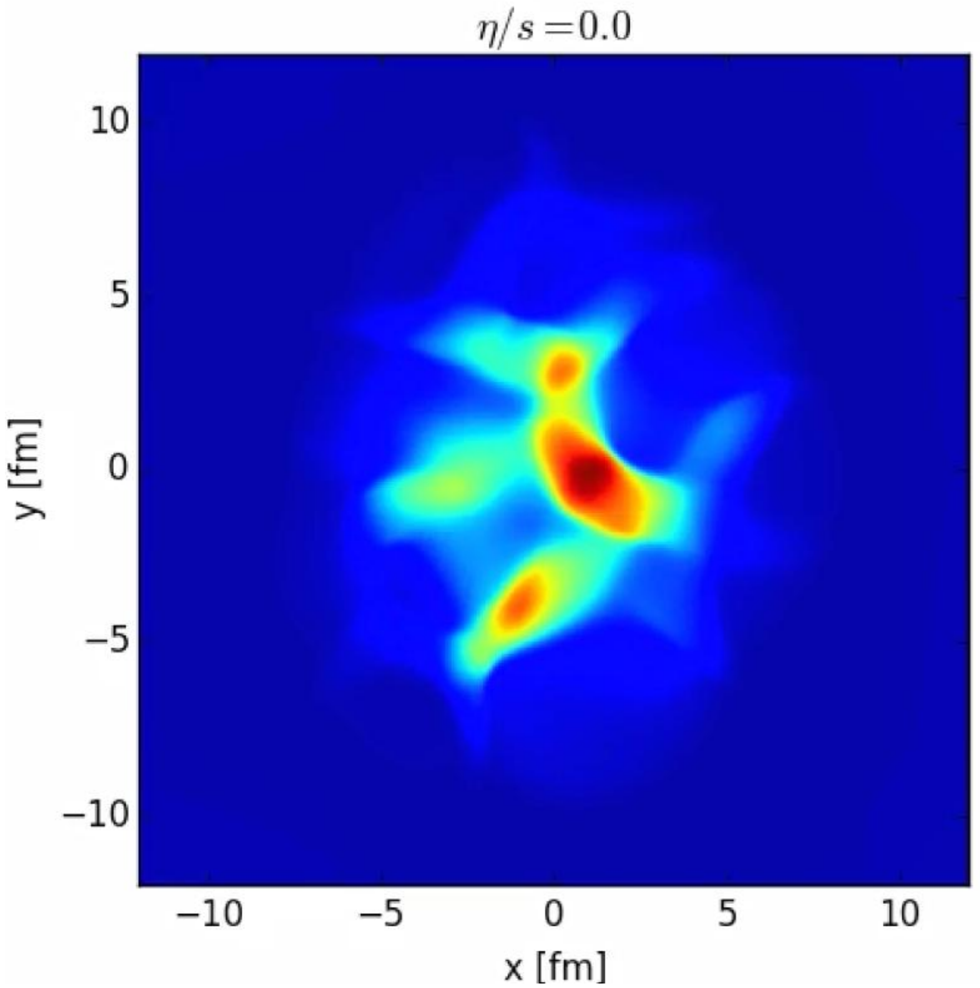

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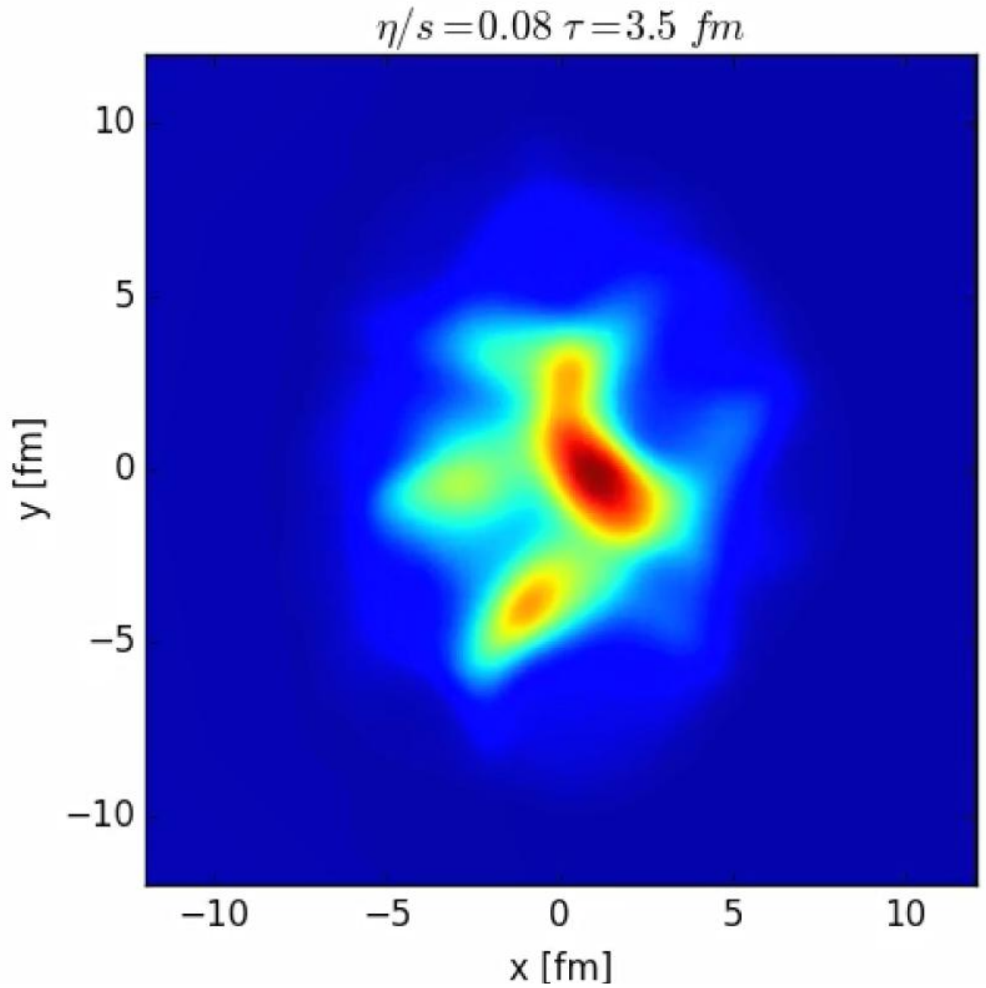
η/s = 0.08



Animation from L. G. Peng

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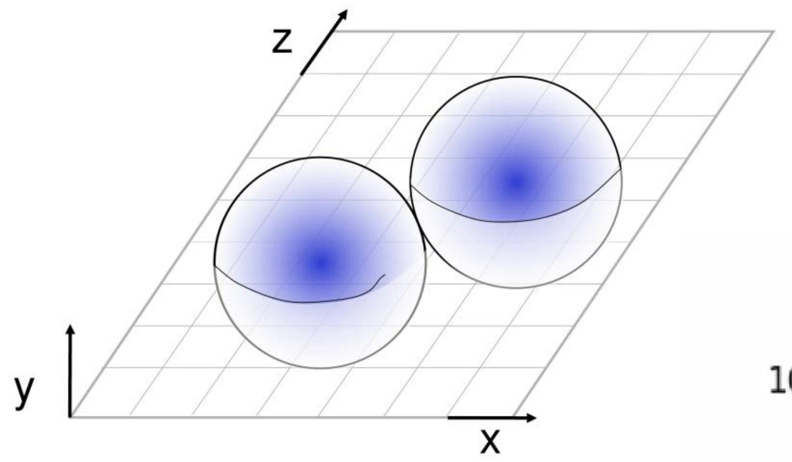

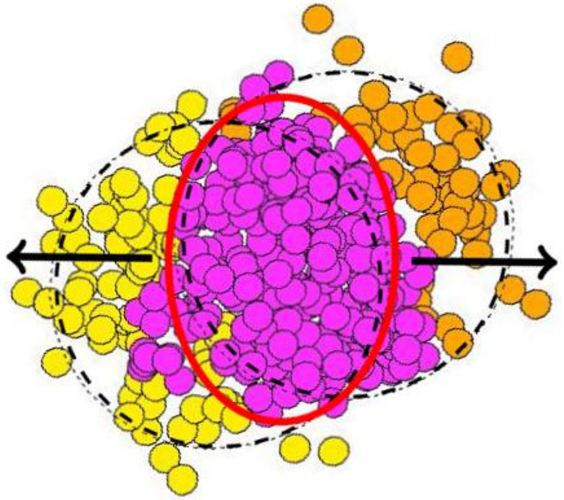

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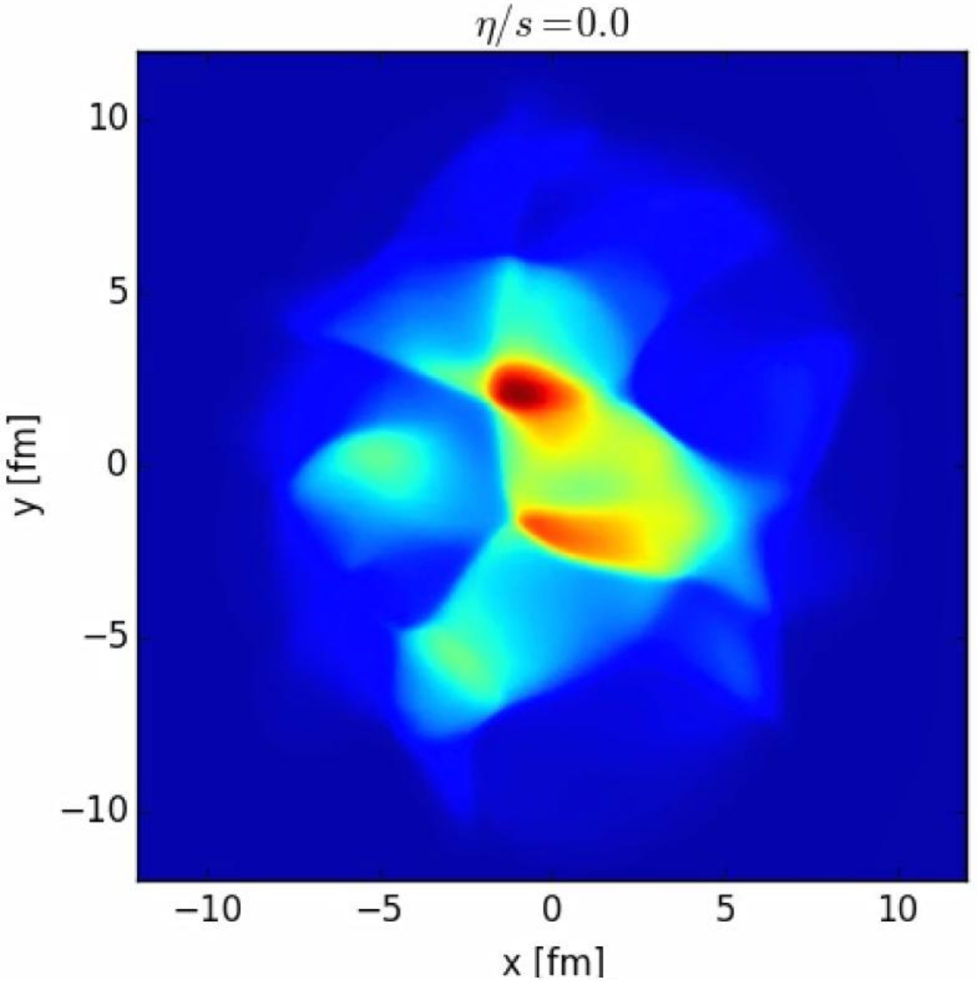

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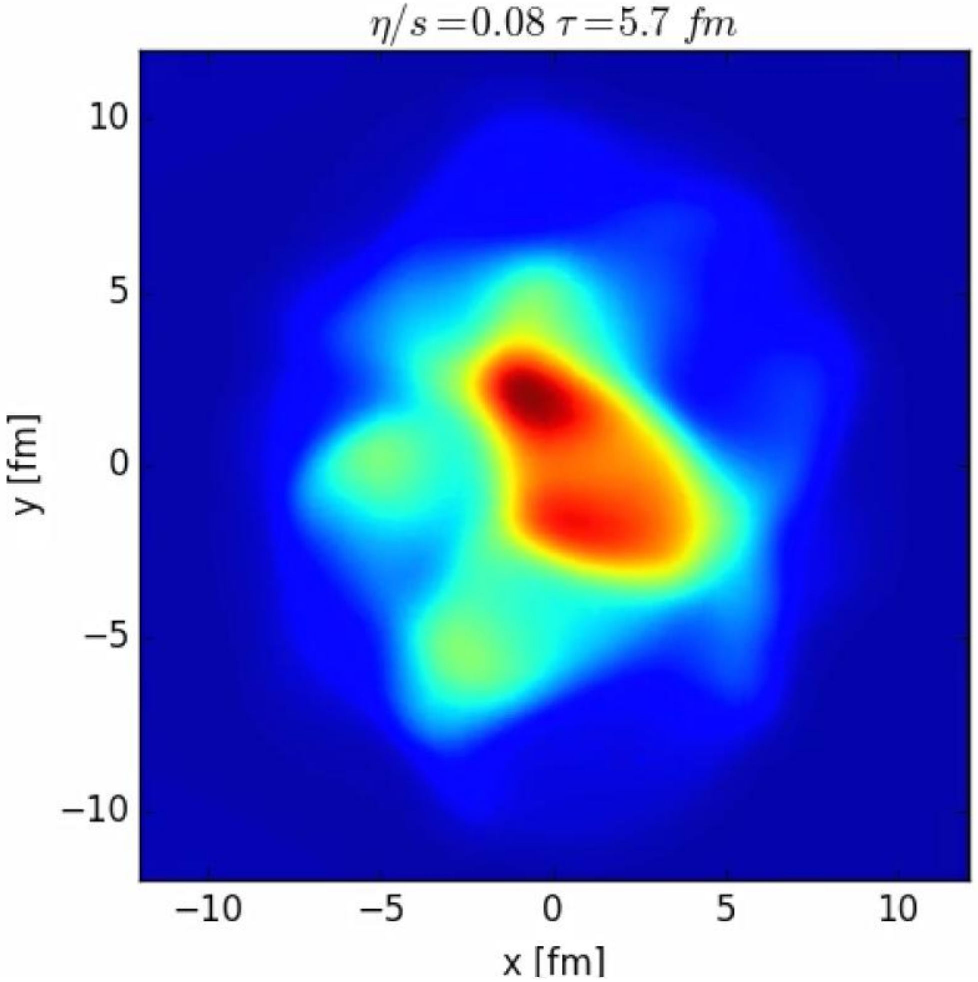

Animation from L. G. Peng

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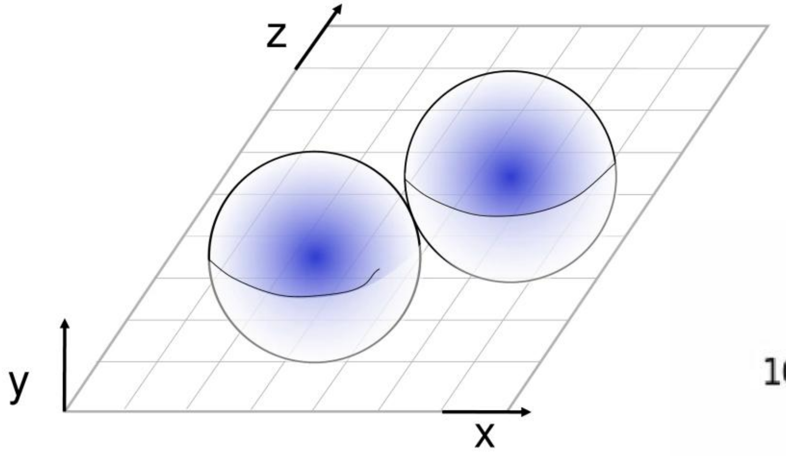

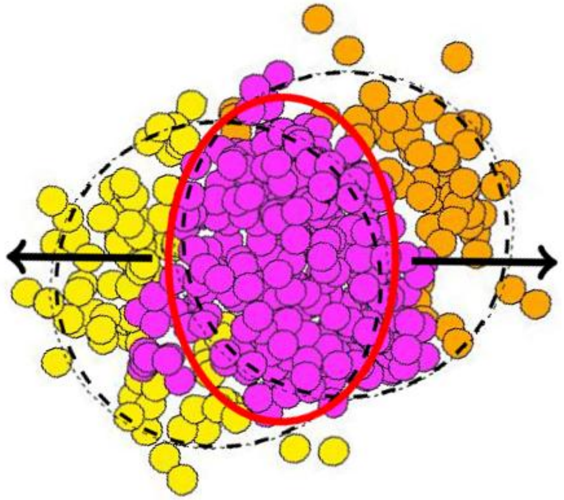

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PRC82 (2010) 039903

Ideal hydrodynamics

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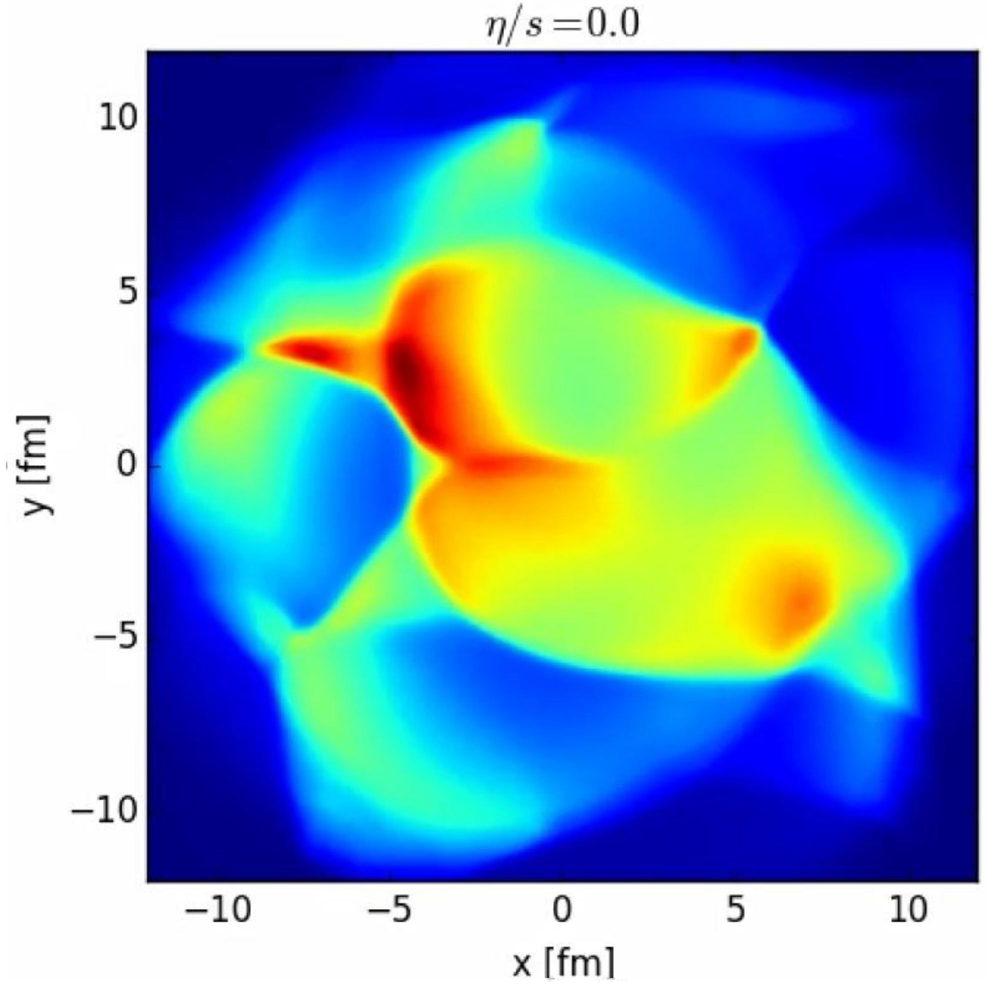

Viscous hydrodynamics

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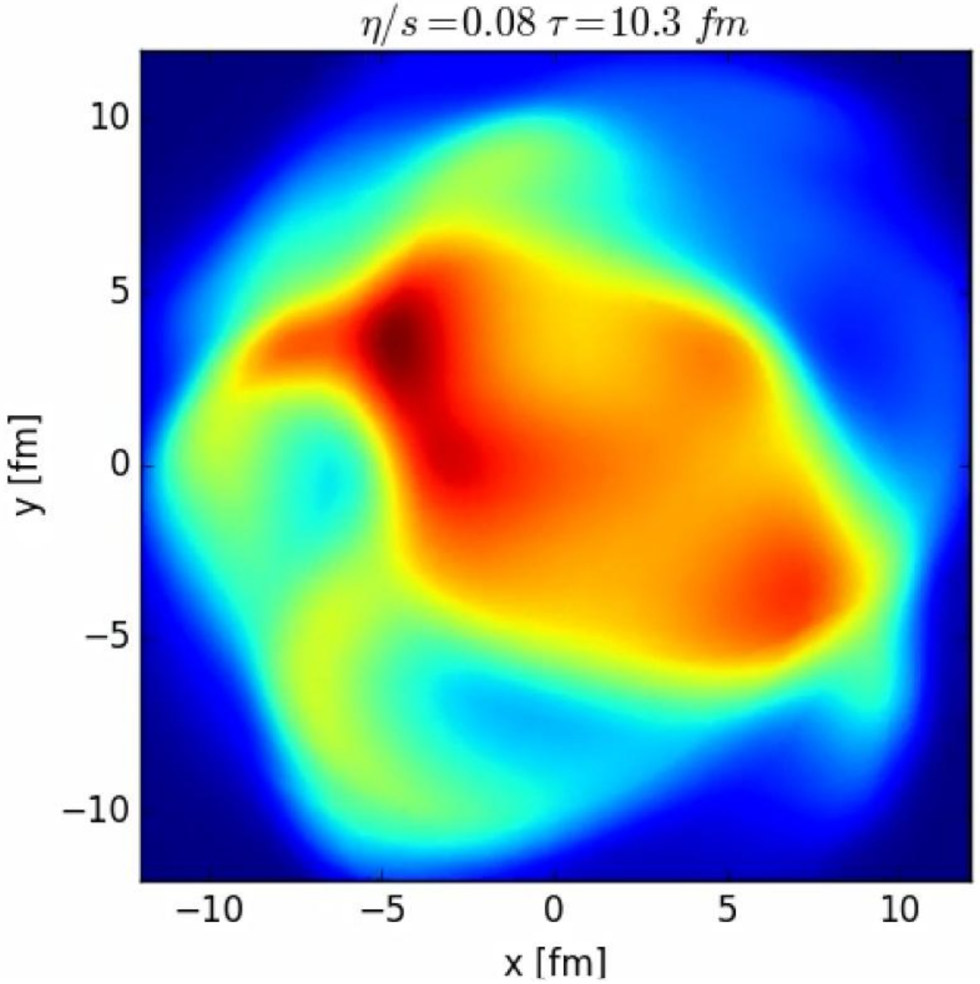
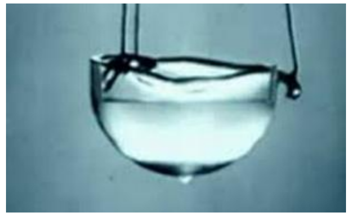
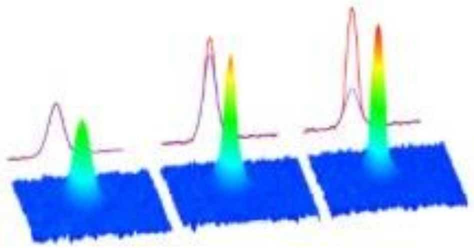
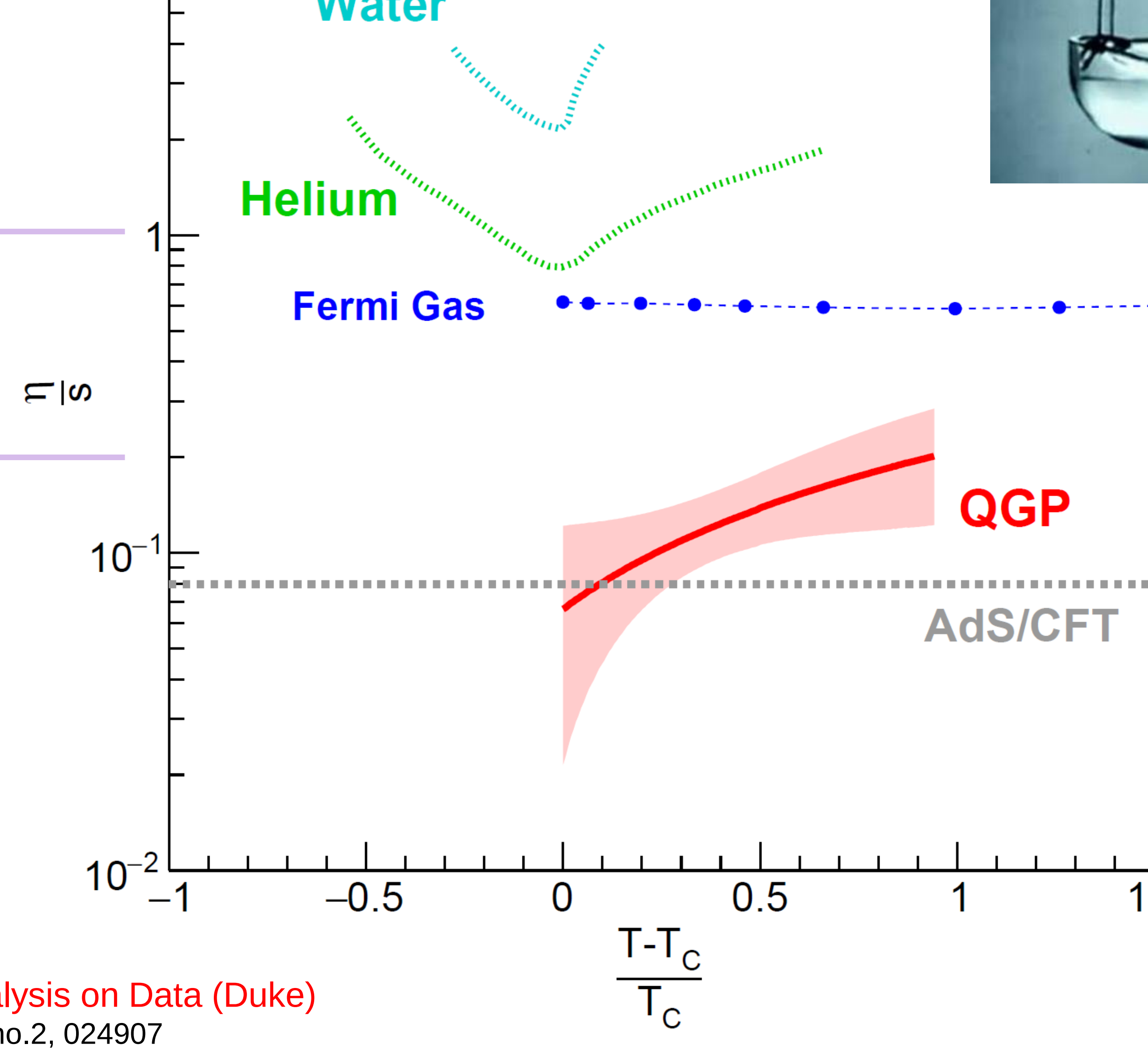


Animation from L. G. Peng

Near Perfect Fluid

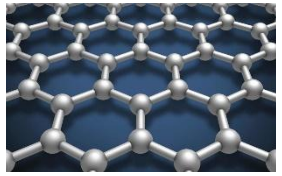
Specific Shear Viscosity

MIT cold atom group

Calculation from
Annals Phys.326:770-796,2011

Electron fluid in Graphene
PRL103,025301 (2019)



Bayesian Analysis on Data (Duke)
PRC94 (2016) no.2, 024907

QGP: extracted from **flow correlation** and **particle spectra** at **low p_T**

Extracted from hydrodynamics models

How can we cross-check this result?

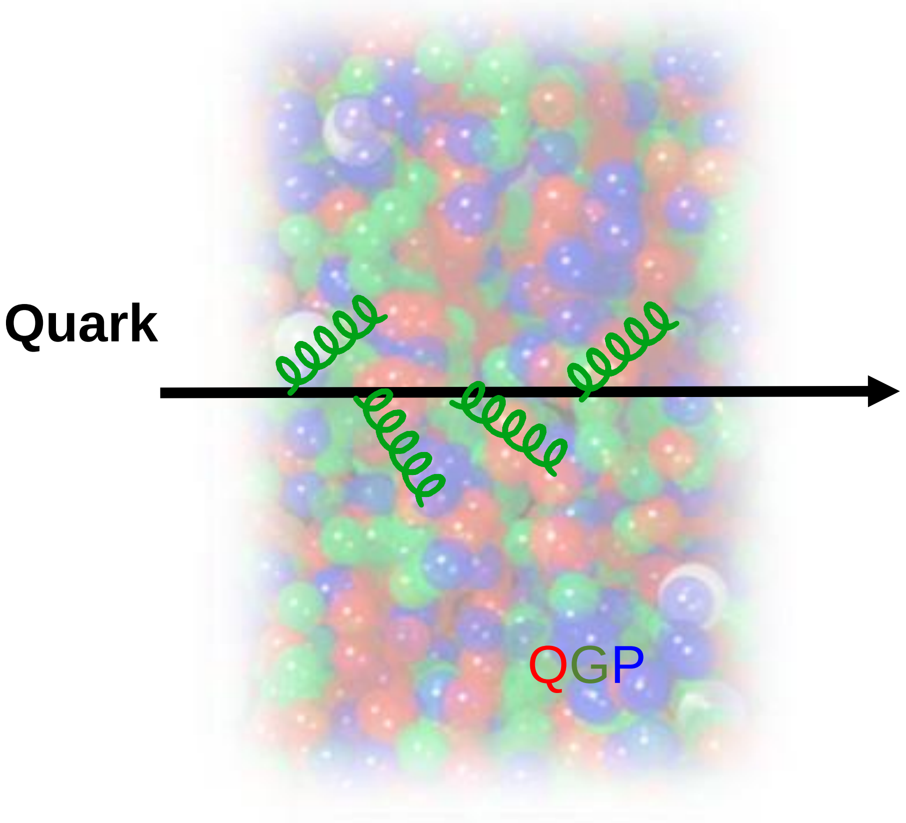
Hard Probes of Quark Gluon Plasma

James Bjorken (1982)

FERMILAB-PUB-82-059-T

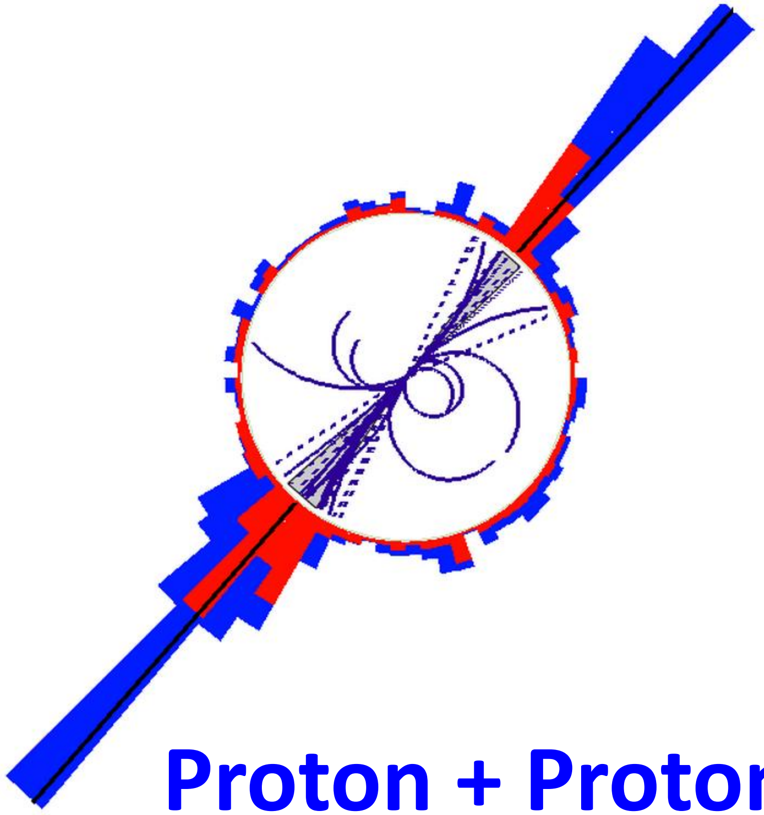
Jet Quenching

Lifetime O(10^{-24}s)

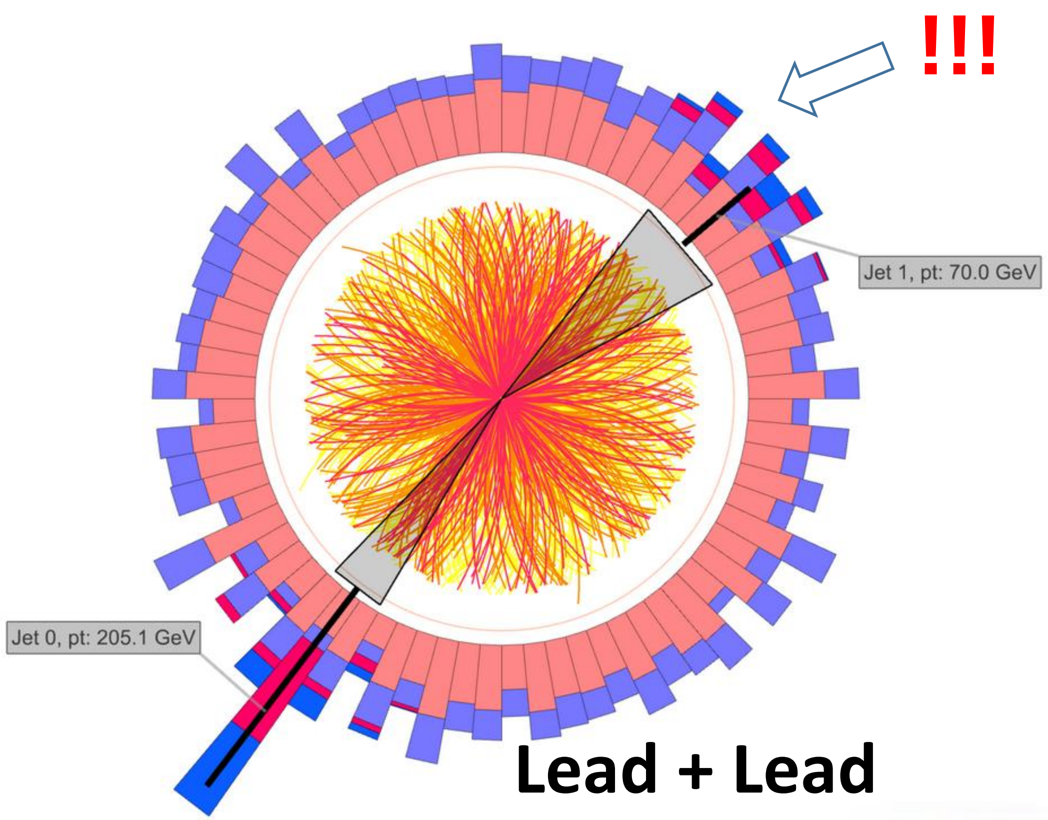


Use **Energetic Quarks** to reveal
QGP structure at various length scales

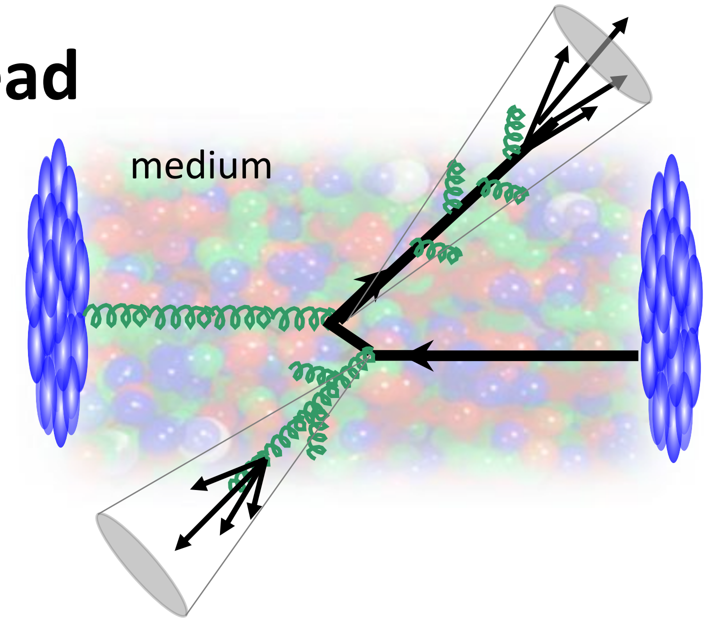
Probe the QGP with High Energy Quarks and Gluons



Proton + Proton



Lead + Lead



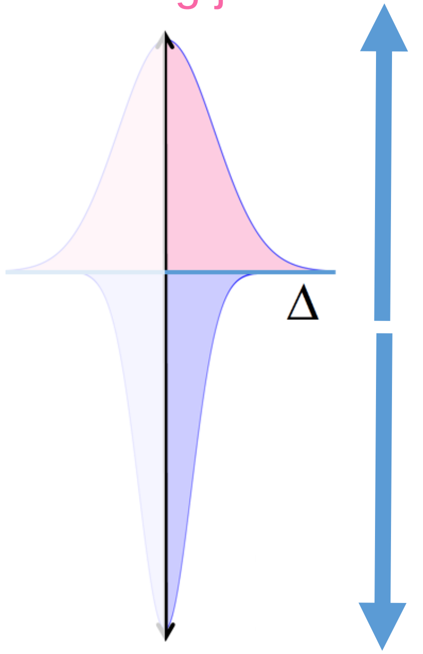
- **Direct observation of jet quenching:**
  Asymmetric dijets in Lead+Lead collisions
- The stopping power (dE/dx) of the QGP is **Strong**

PRC 84 (2011) 024906

PLB 712 (2012) 176

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

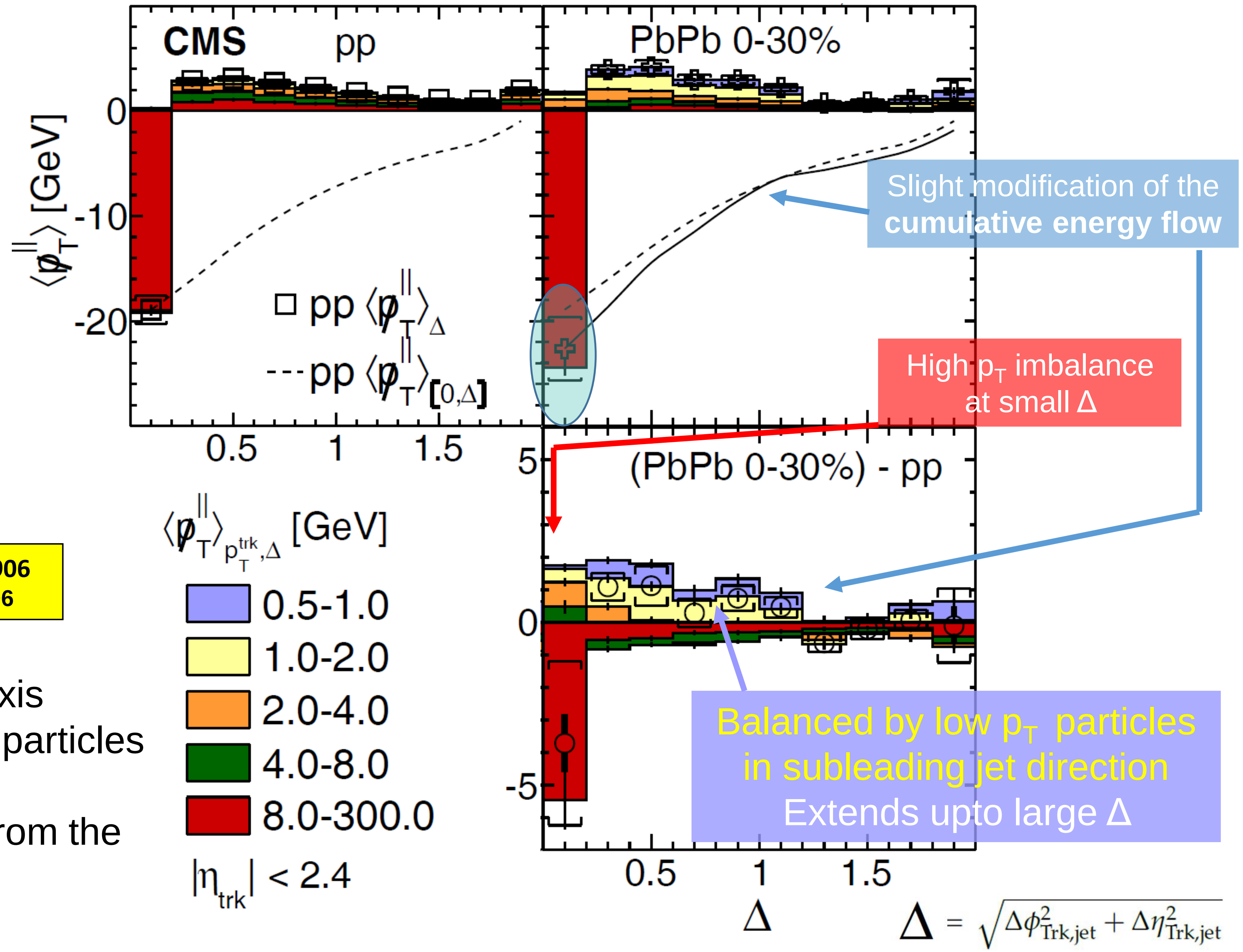
Subleading jet direction



Leading jet direction

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

PRC 84 (2011) 024906
JHEP 01 (2016) 006

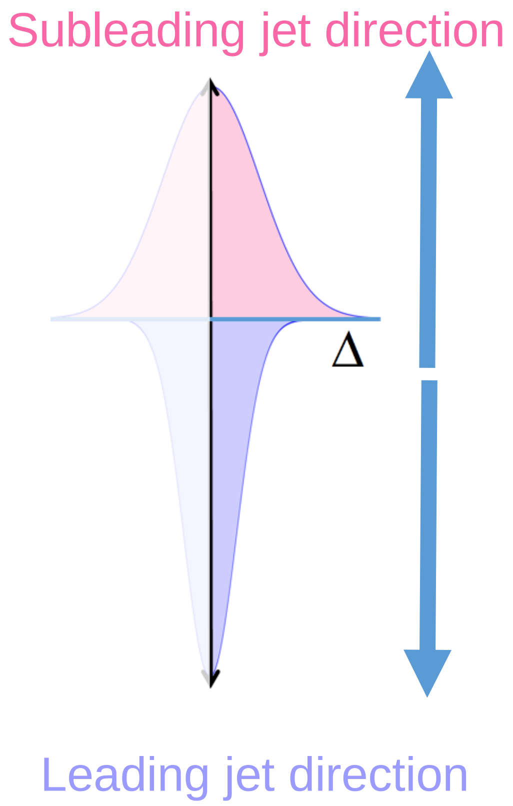


$$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

- Study momentum balance **parallel** to dijet axis
- 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
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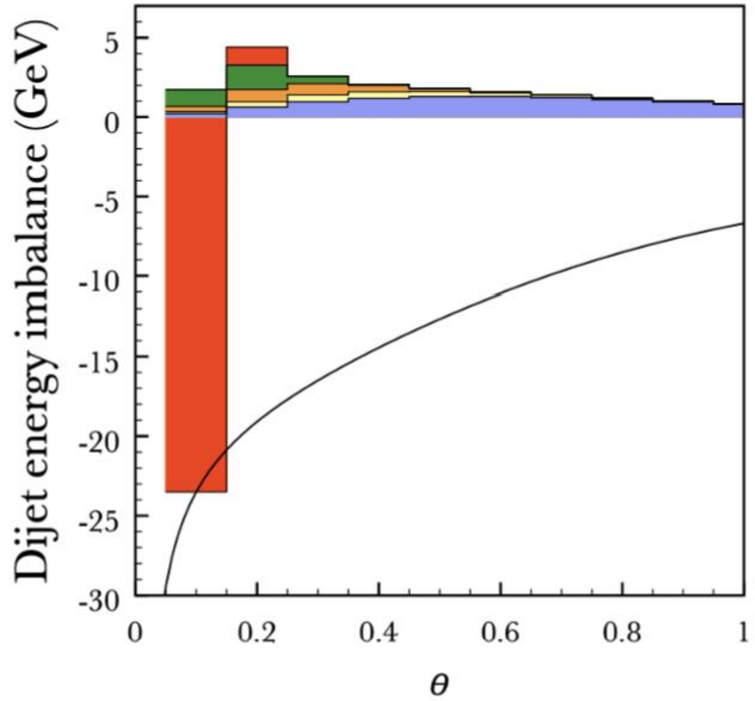
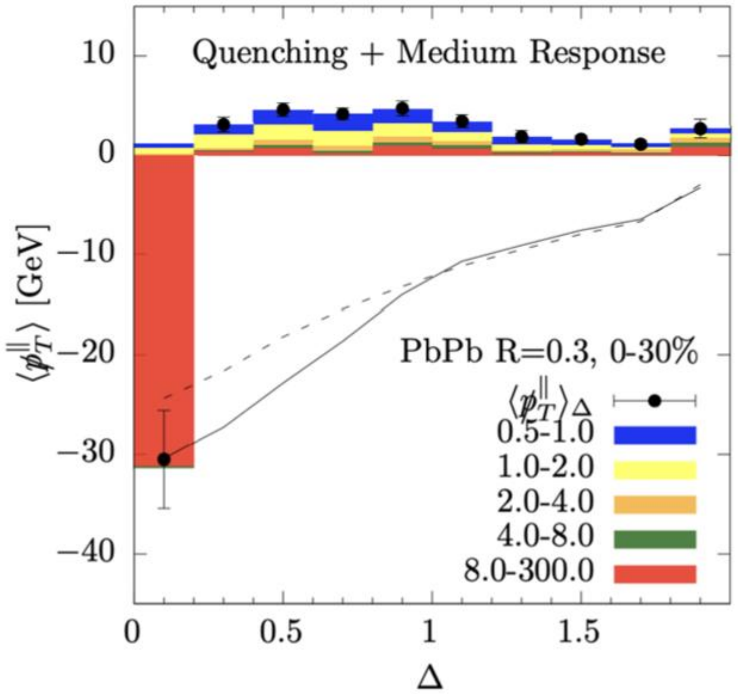


Medium-induced Parton Cascade
Blaizot & Mehtar-Tani
Int.J.Mod.Phys.E 24 (2015) 11, 1530012

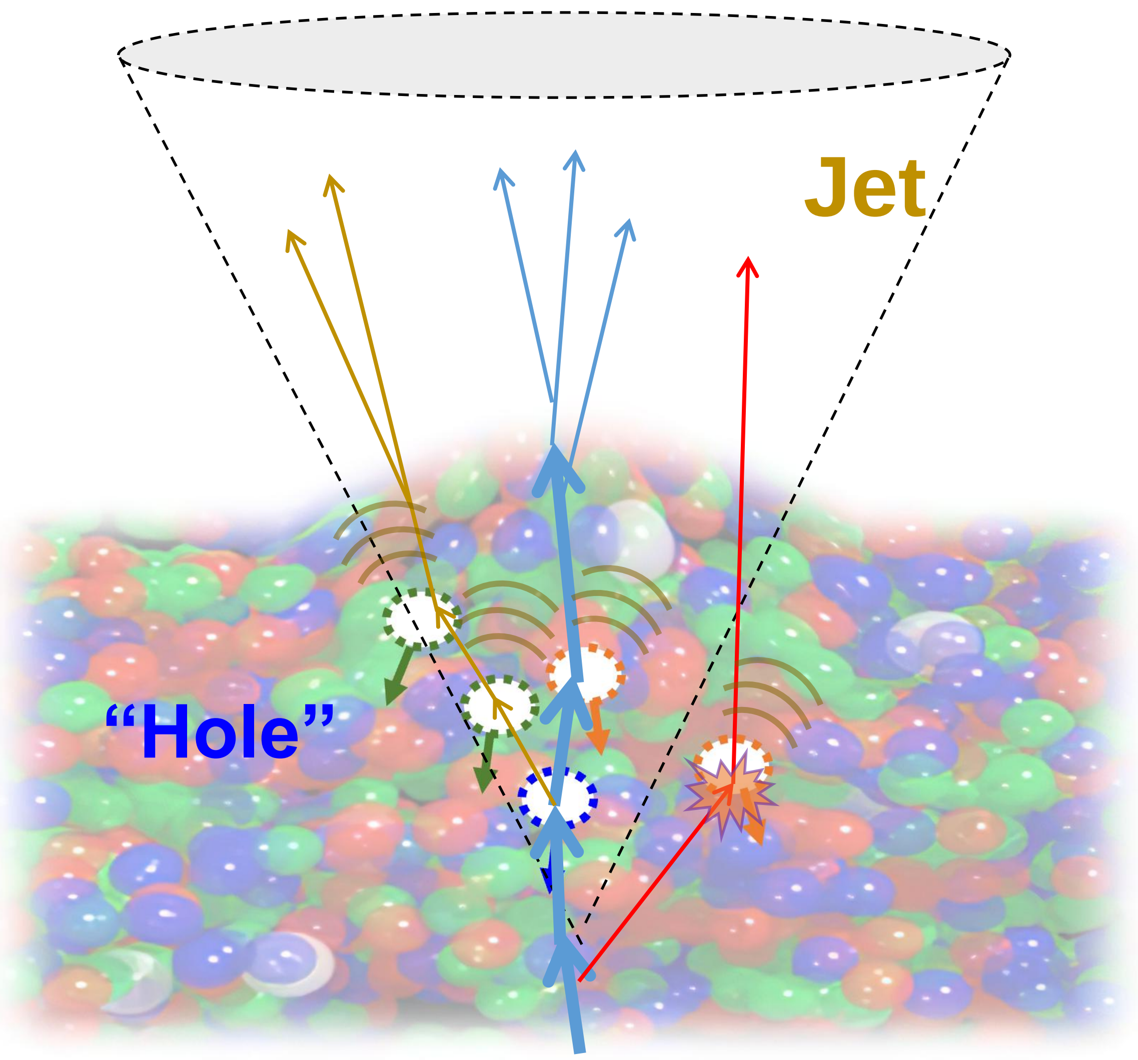


Hydrodynamic wake
Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal
JHEP 03 (2017) 135

- However, the interpretation includes both Medium-induce Parton Cascade and Hydrodynamic Wake.
- Since then, a lot of focus on the observables involving fully reconstructed jets (See Yi Chen's talk)

QGP Transport Properties and Structure with Jets

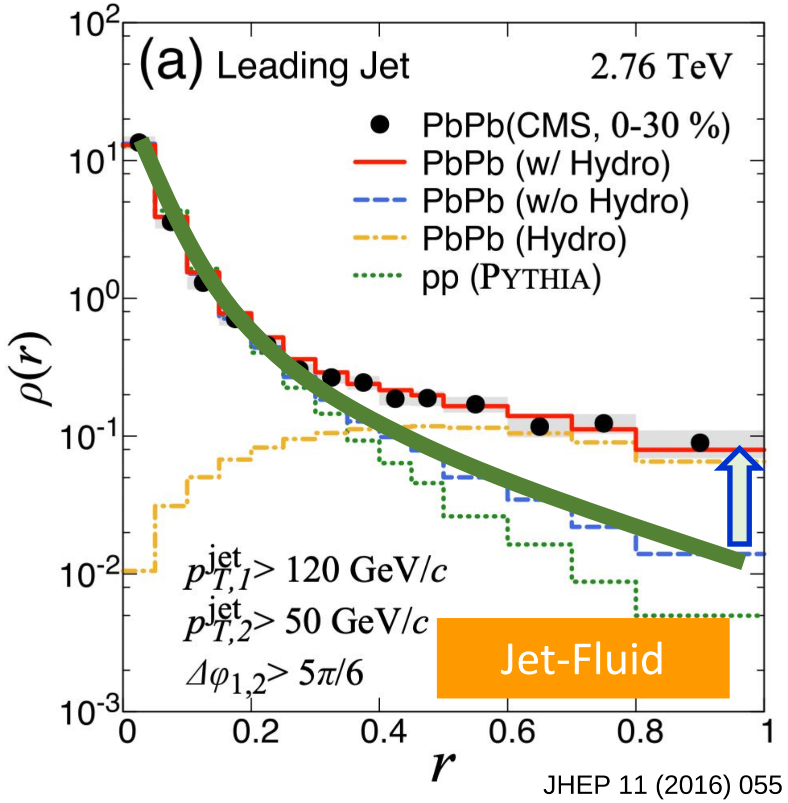
Artist's impression



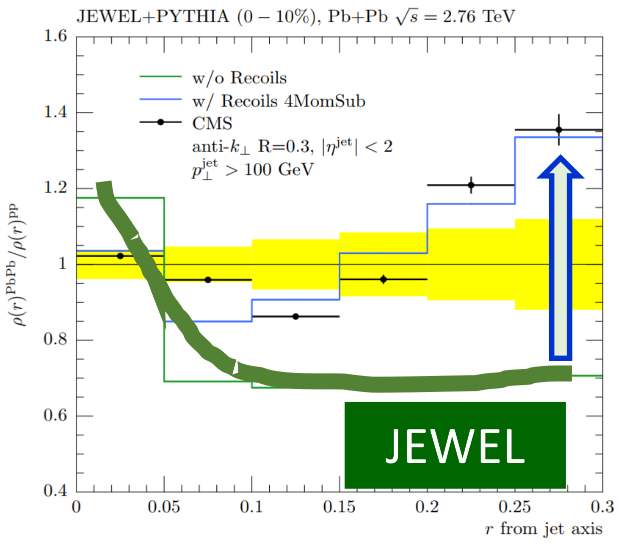
In pQCD-based calculations

- 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

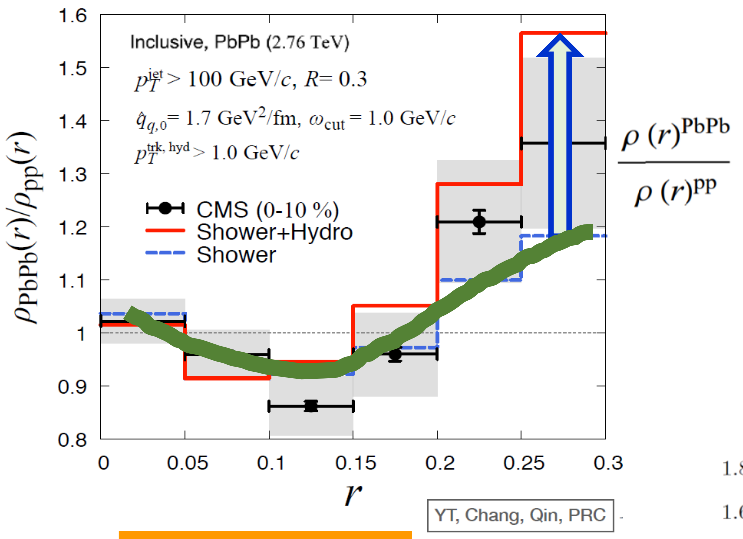
Interpretation of the CMS Jet Shape

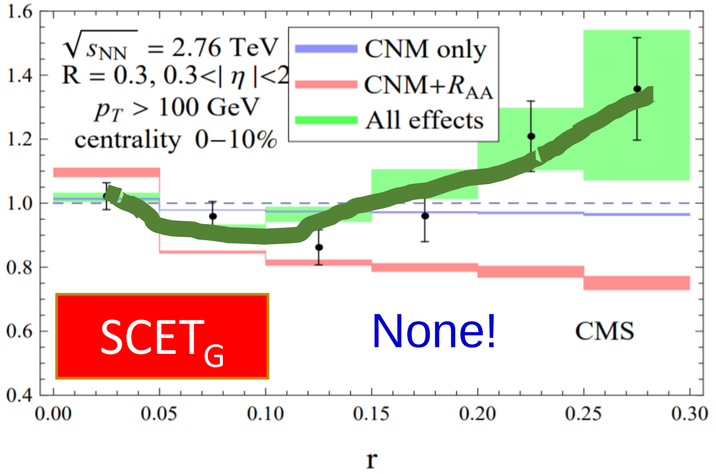


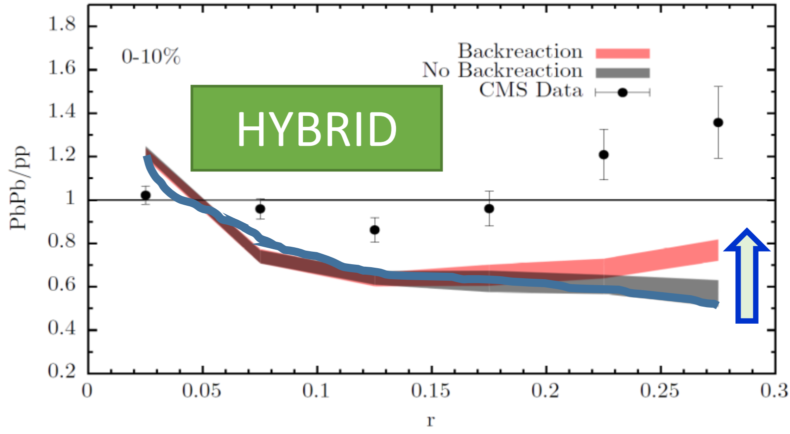
JHEP 11 (2016) 055
PRC 95 (2017) 4, 044909



JHEP 07 (2017) 141

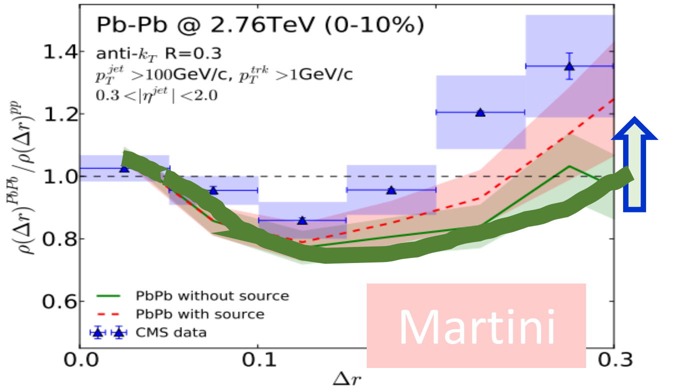






Modifications of the shower —

Medium Recoil and Response ⇧

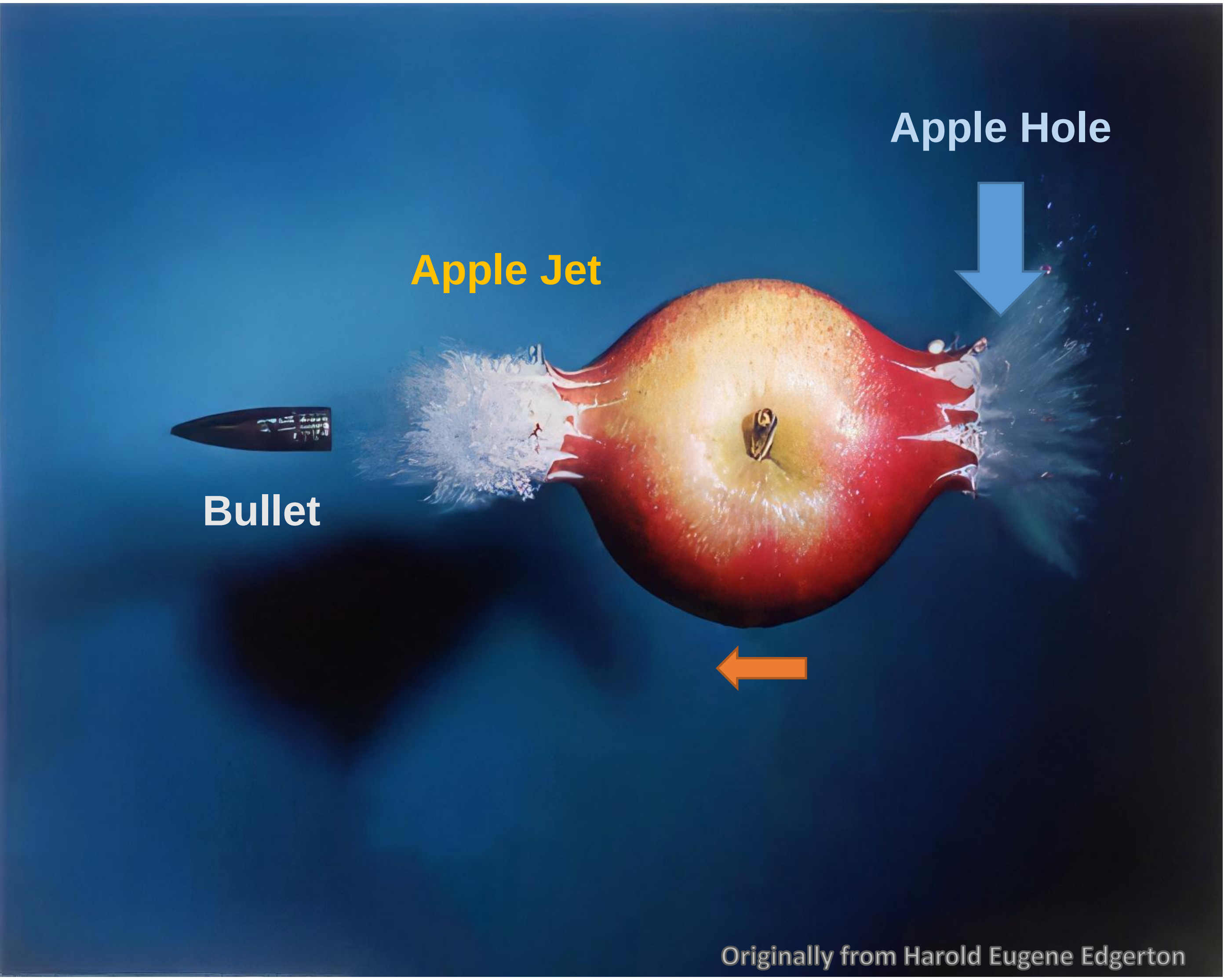


Models with **different mechanisms** give reasonable description of the inclusive jet shape and many other observables

How do we make more progress?

Inspiration: Medium Response to Hard Probes in **QED**

Bullet plowing through an **apple**



More **apple** going in the bullet direction

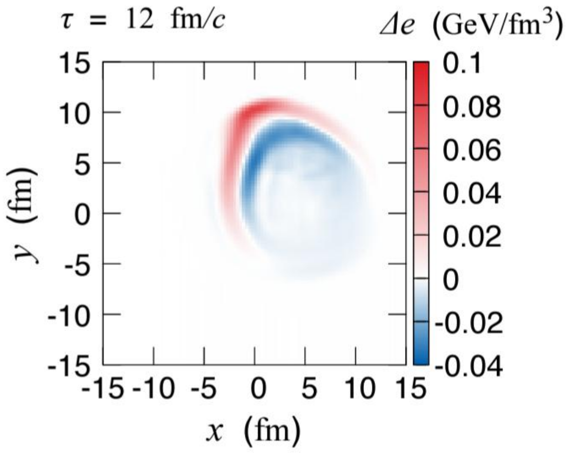
Duck swimming through **water**

More **water** going in the duck direction

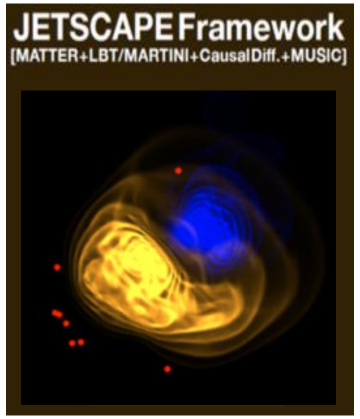
In Position Space

Medium Response to Hard Probes in QGP

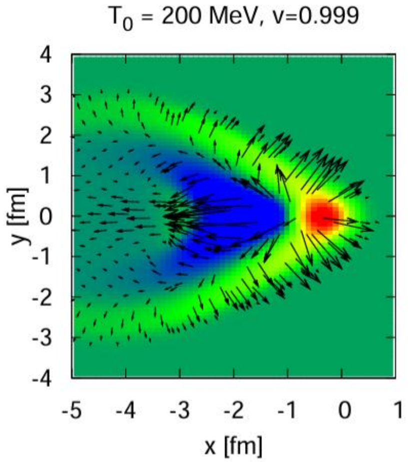
Quark plowing through the QGP



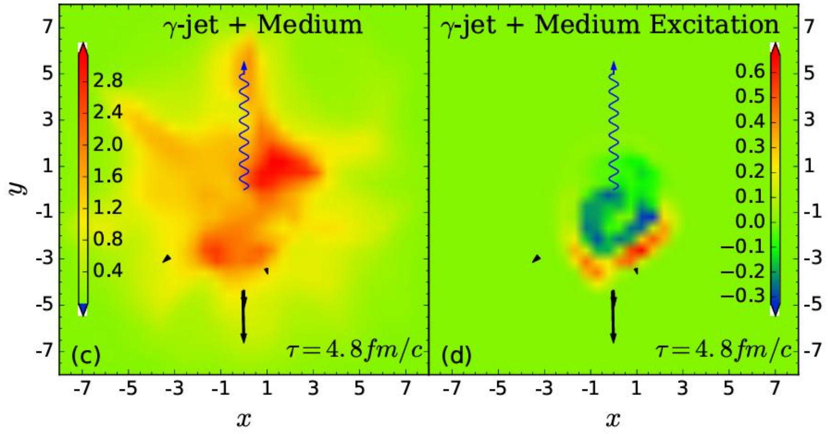
Jet-Fluid Yasuki, Chang, Qin
PRC 95 (2017) 4, 044909



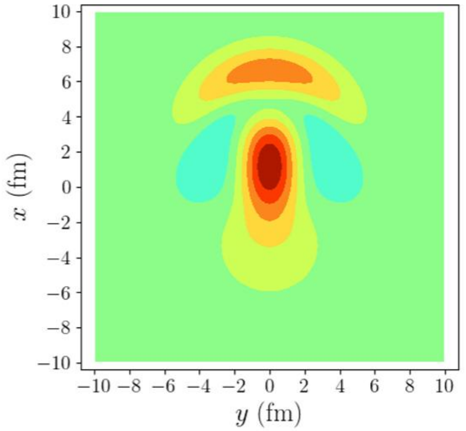
JETSCAPE framework
Tachibana, Shen, Majumder
PRC 106 (2022), L021902



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

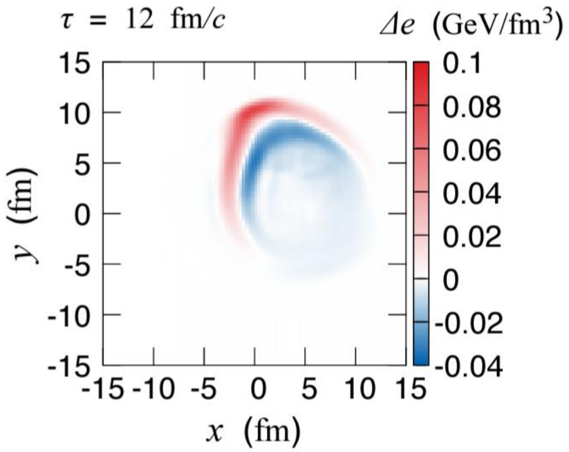
Duck swimming through water

More water going in the duck direction

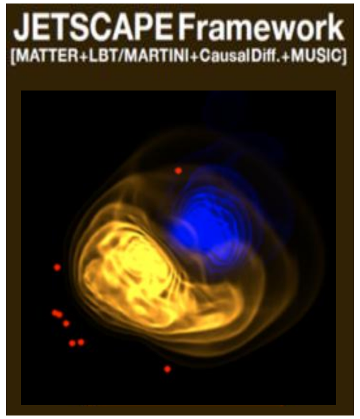
In Position Space

Medium Response to Hard Probes

Quark plowing through the **QGP**



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



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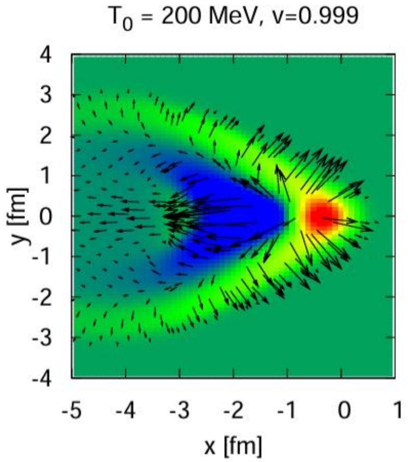
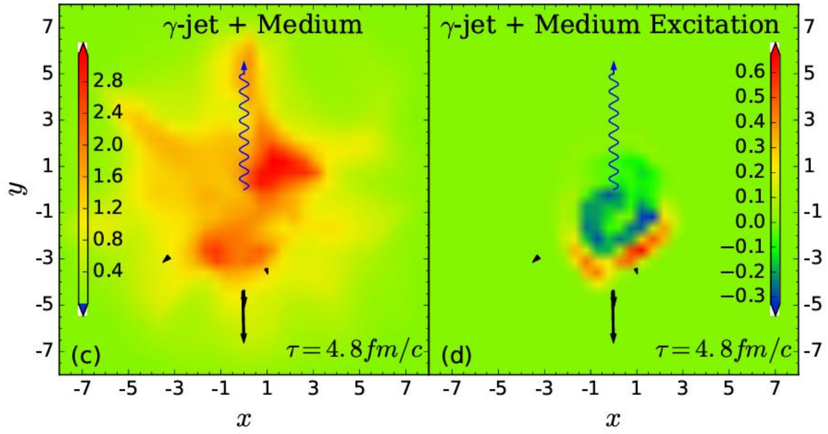
Tachibana, Shen, Majumder
PRC 106 (2022), L021902





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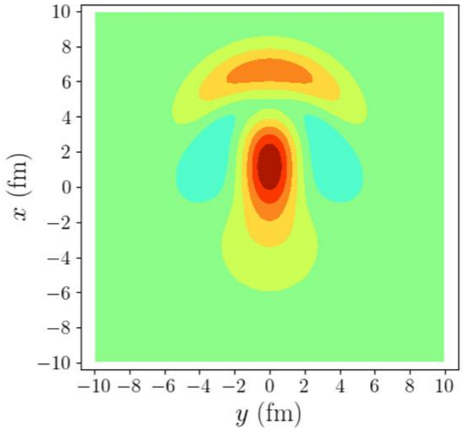
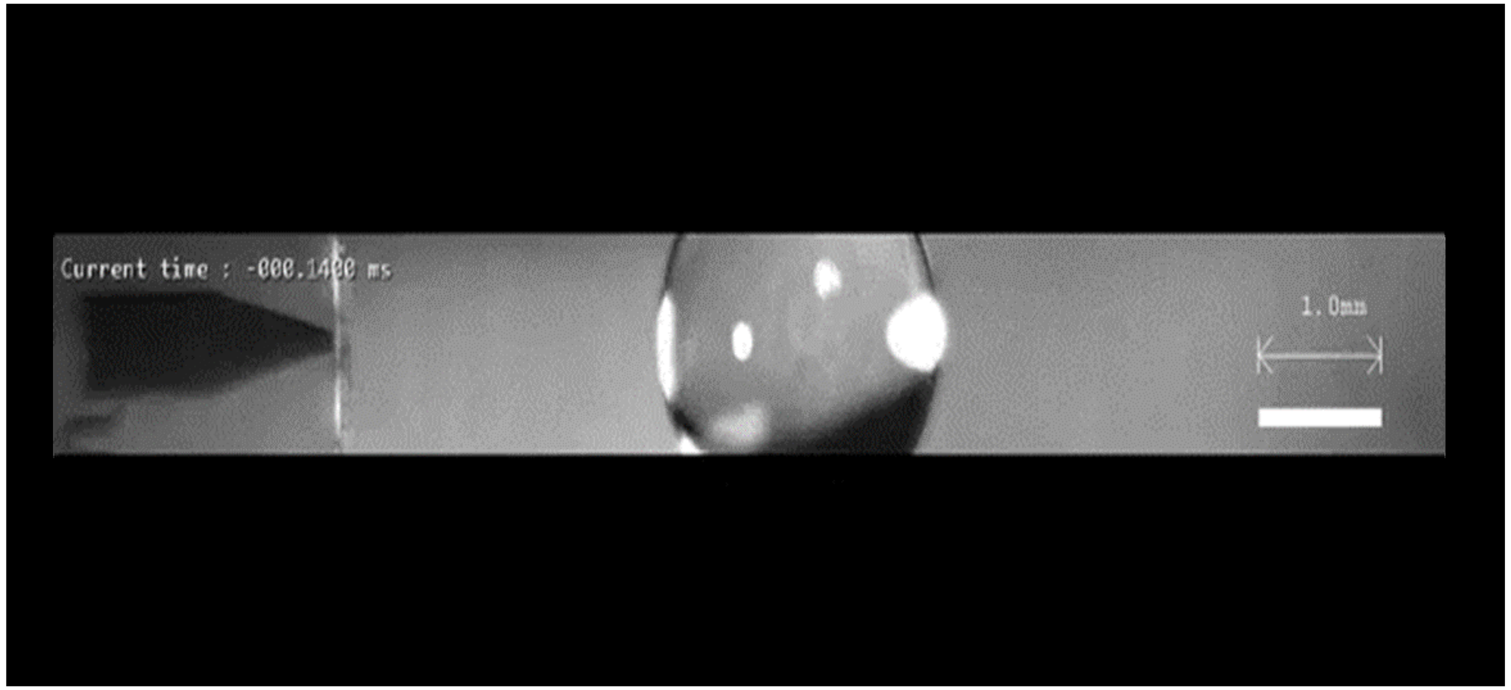


More **QGP** going in the jet direction

Microfluidic Jet against **viscoelastic droplet**



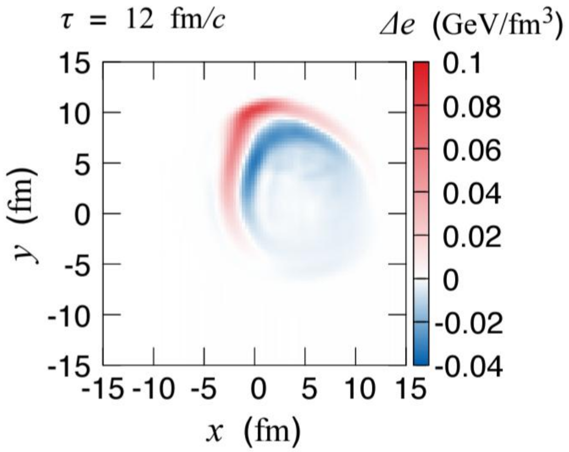
David Fernandez
https://www.youtube.com/watch?v=TPRur72FGyk

More **water** going in the jet direction

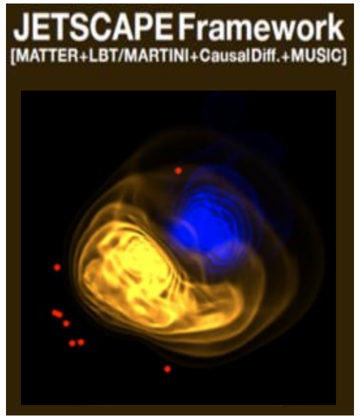
In Position Space

Medium Response to Hard Probes

Quark plowing through the **QGP**



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



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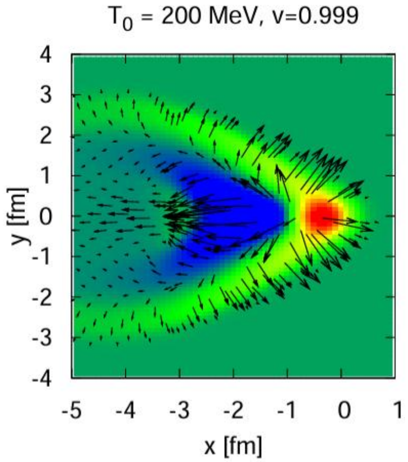
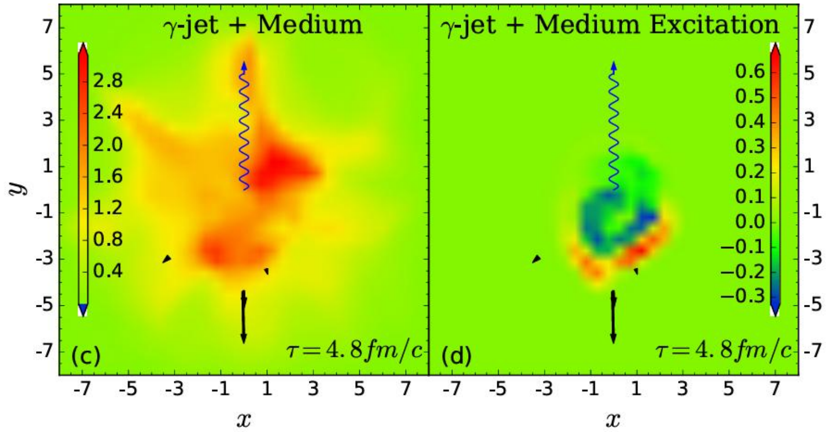
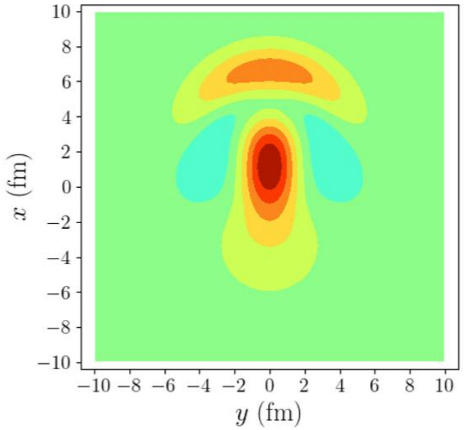
PRC 106 (2022), L021902



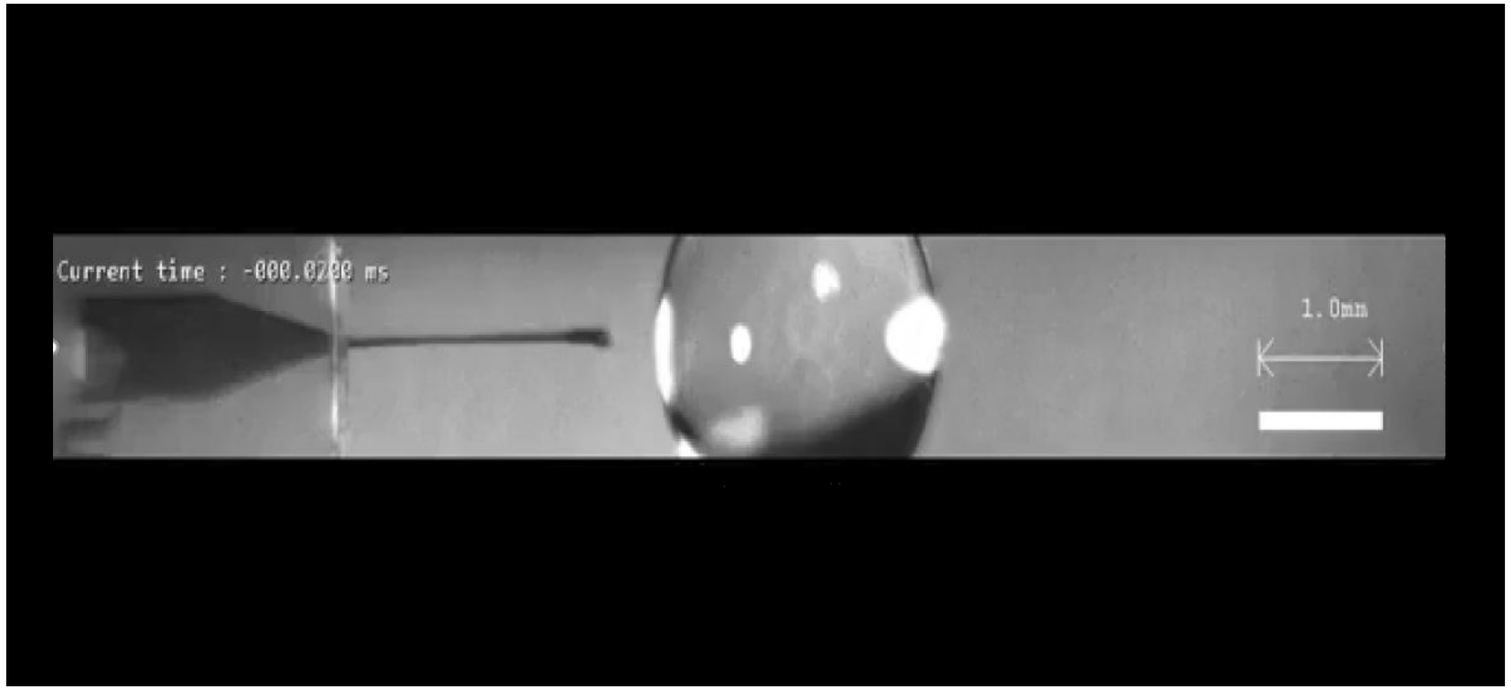


CoLBT Chen, Cao, Luo, Pang, Wang
PLB 777 (2018) 86-90



More **QGP** going in the jet direction

Microfluidic Jet against **viscoelastic droplet**



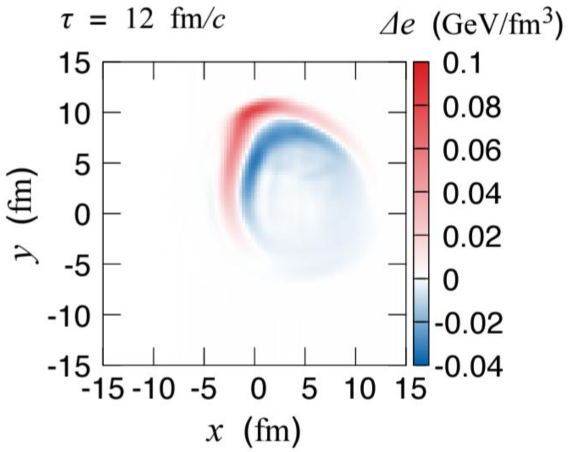
David Fernandez
https://www.youtube.com/watch?v=TPRur72FGyk

More **water** going in the jet direction

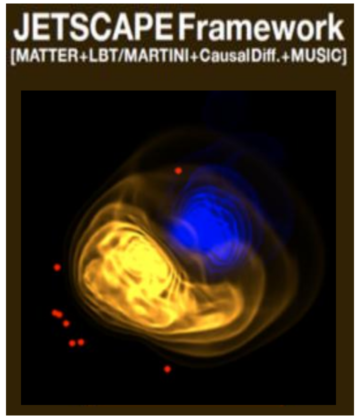
In Position Space

Medium Response to Hard Probes

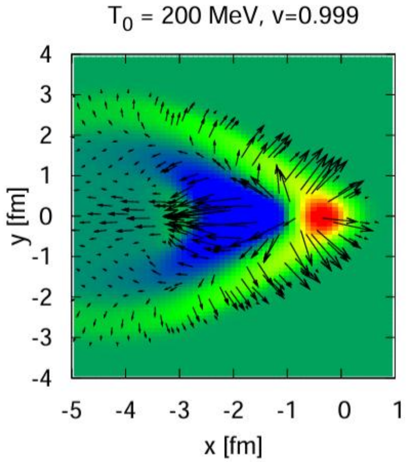
Quark plowing through the **QGP**

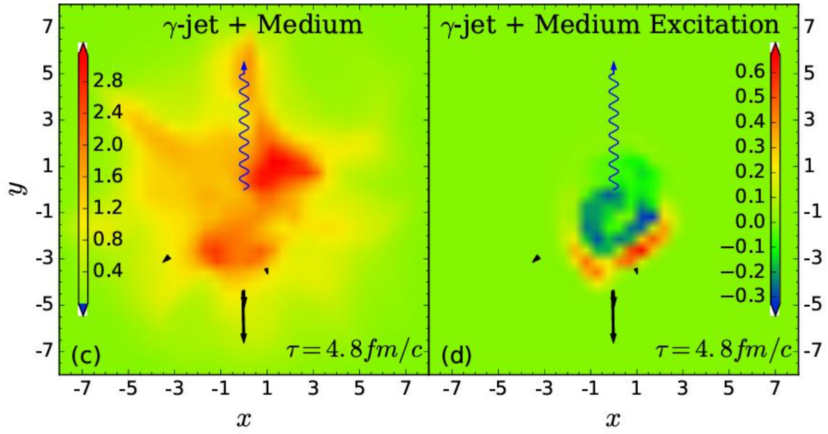


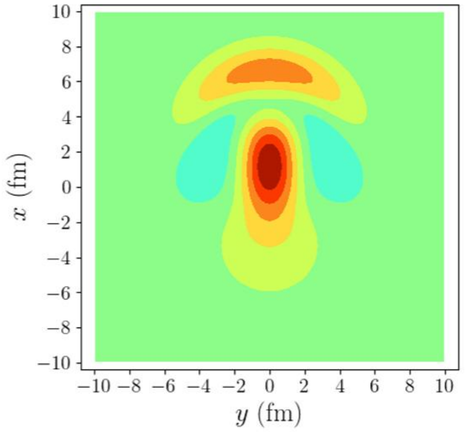
Jet-Fluid Yasuki, Chang, Qin
PRC 95 (2017) 4, 044909



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







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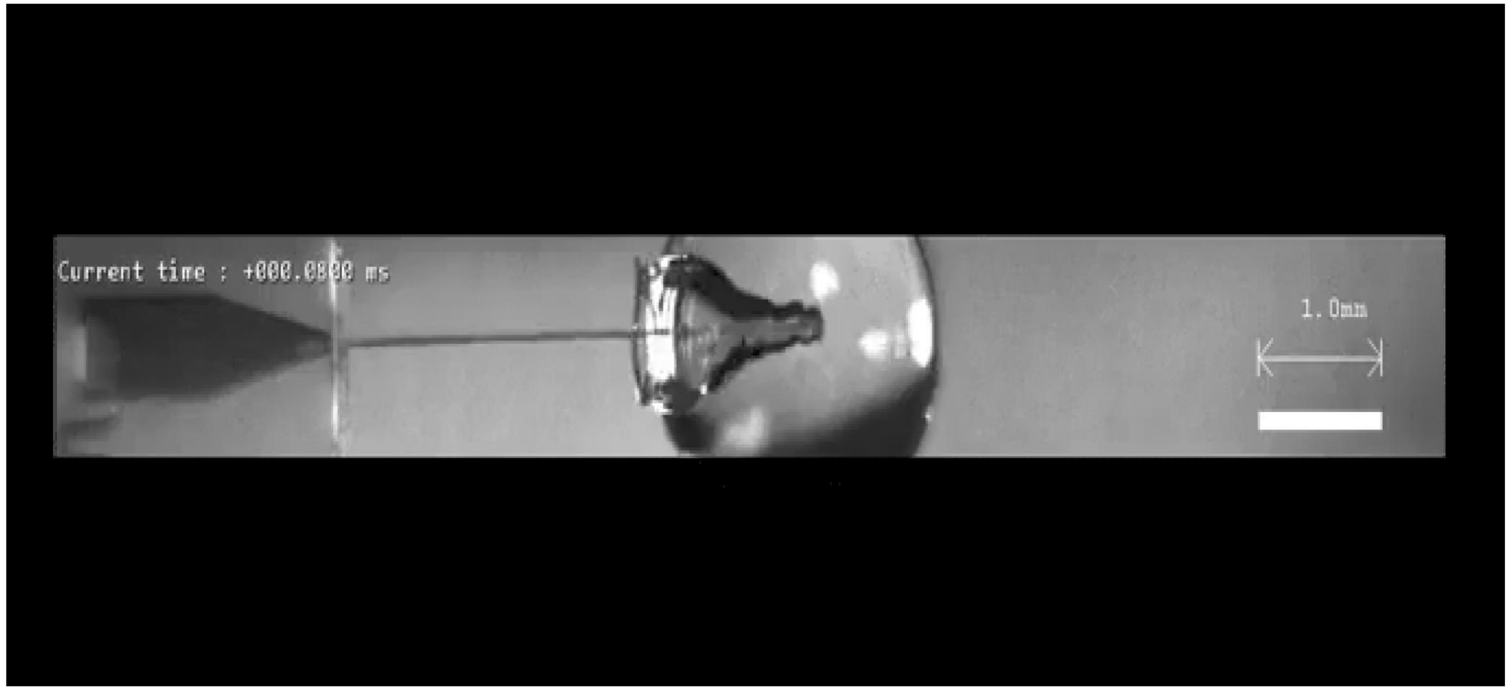

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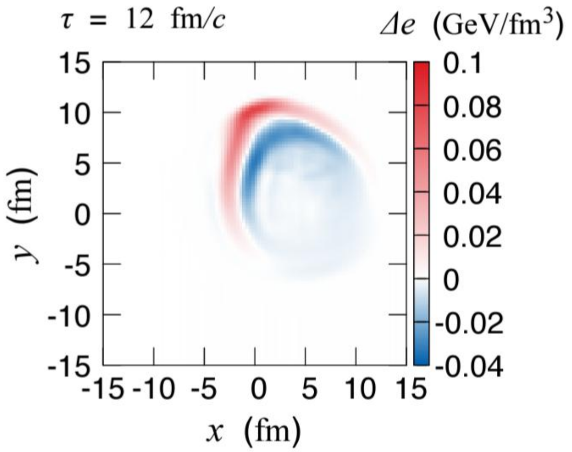

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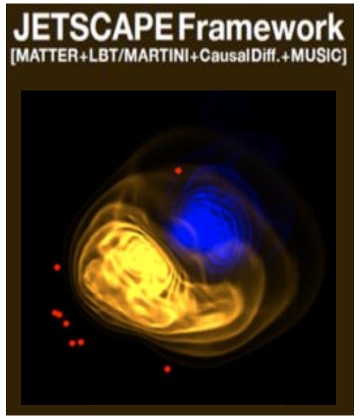

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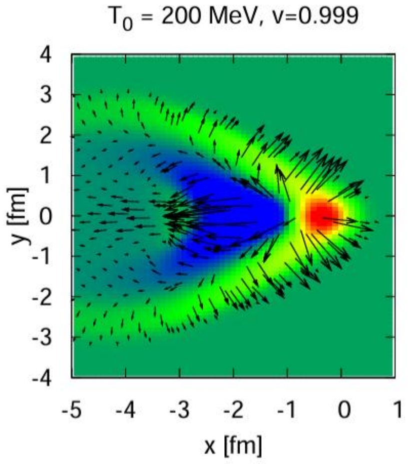

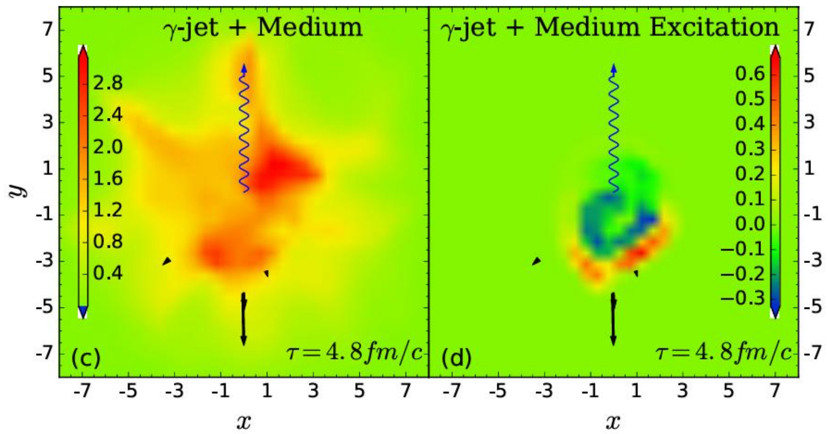

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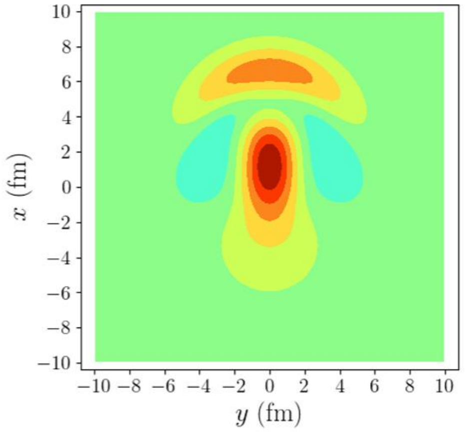

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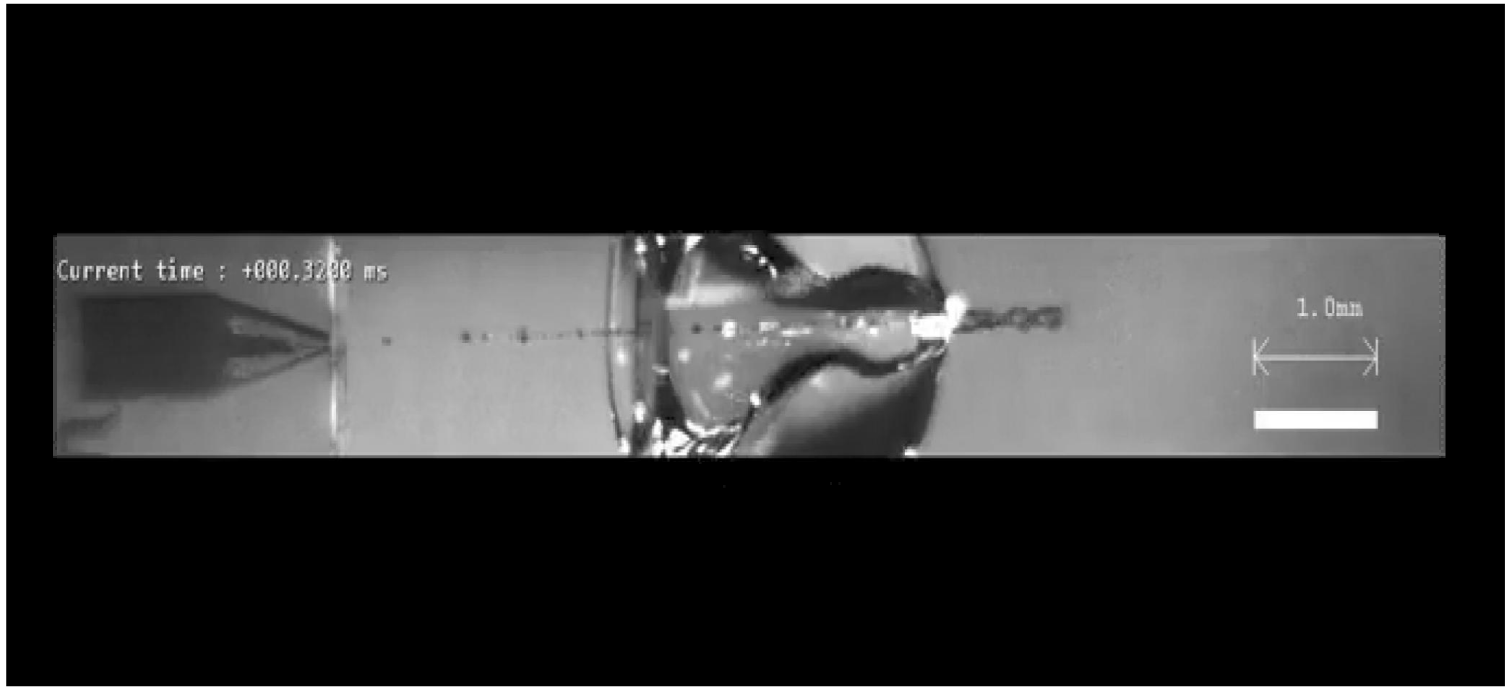

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More **QGP** going in the jet direction

More **water** going in the jet direction

In Position Space

Medium Response to Hard Probes

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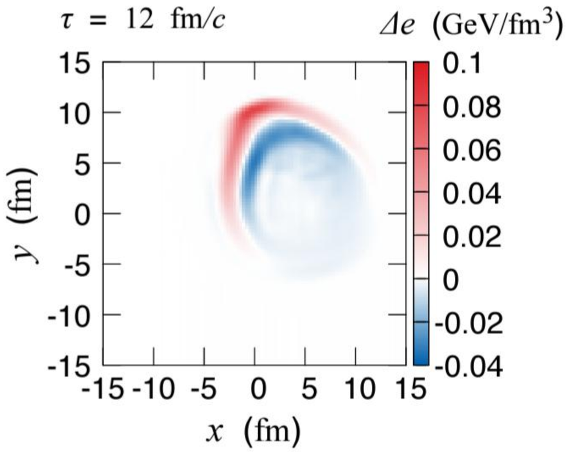

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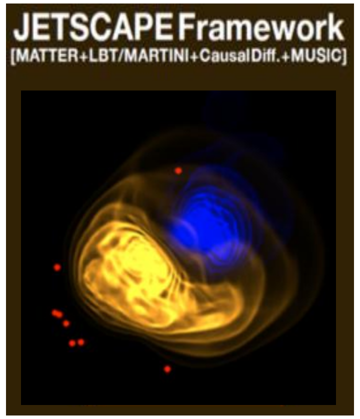

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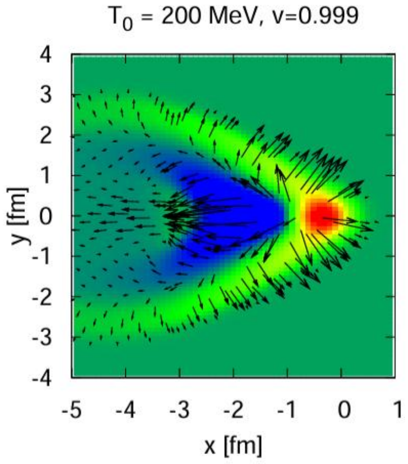

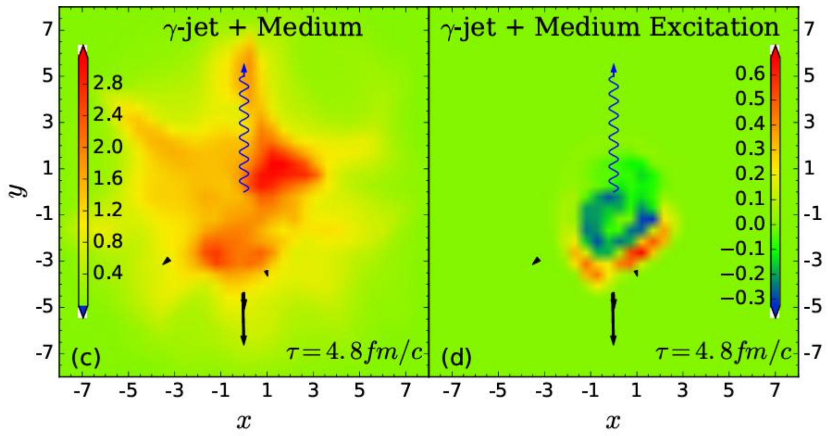

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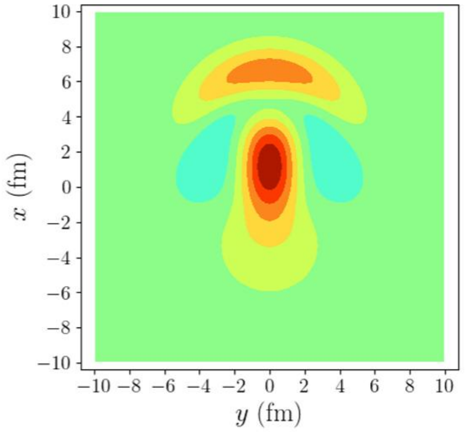

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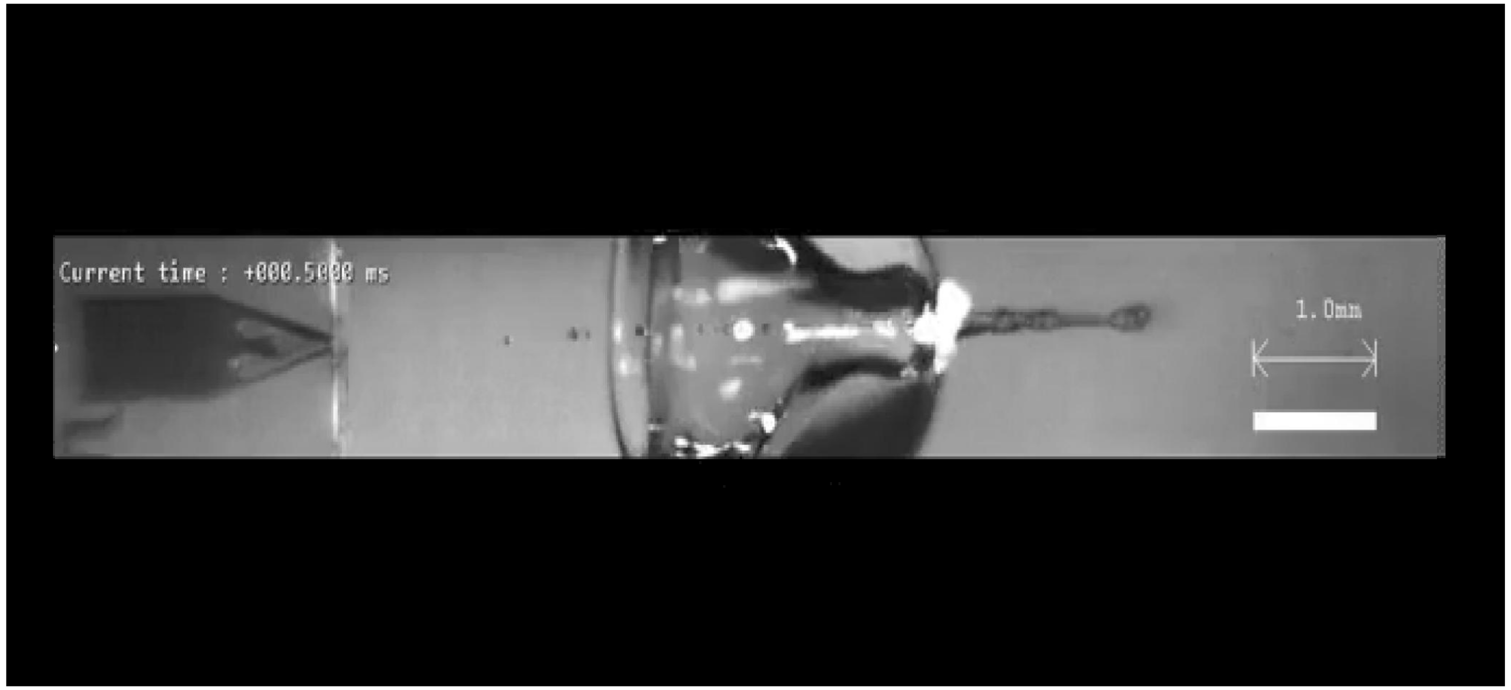

David Fernandez
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More **water** going in the jet direction

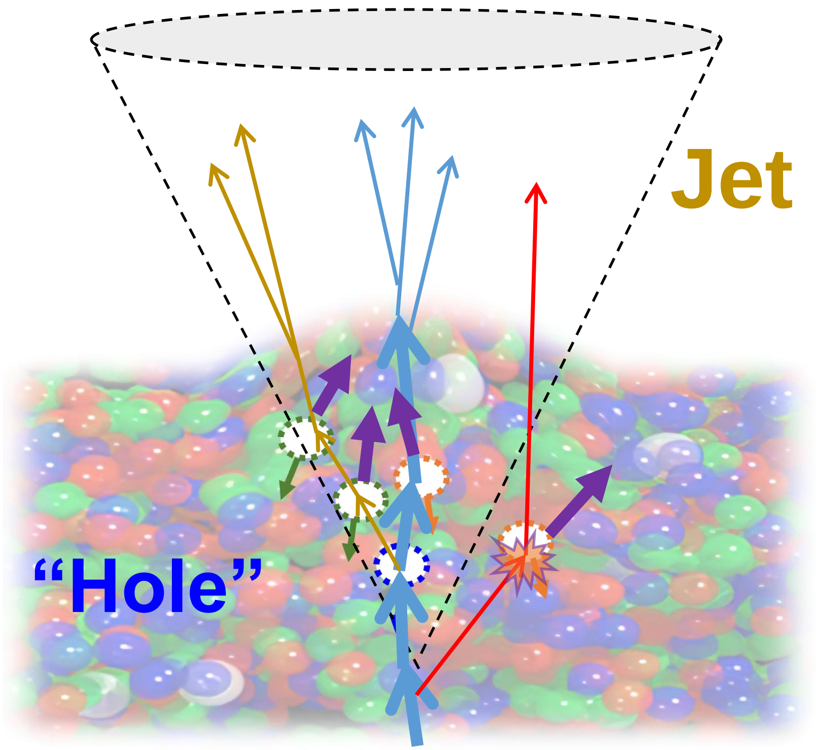
In Position Space

Theoretical Models

Jewel Model

(Jet Evolution with Energy Loss)

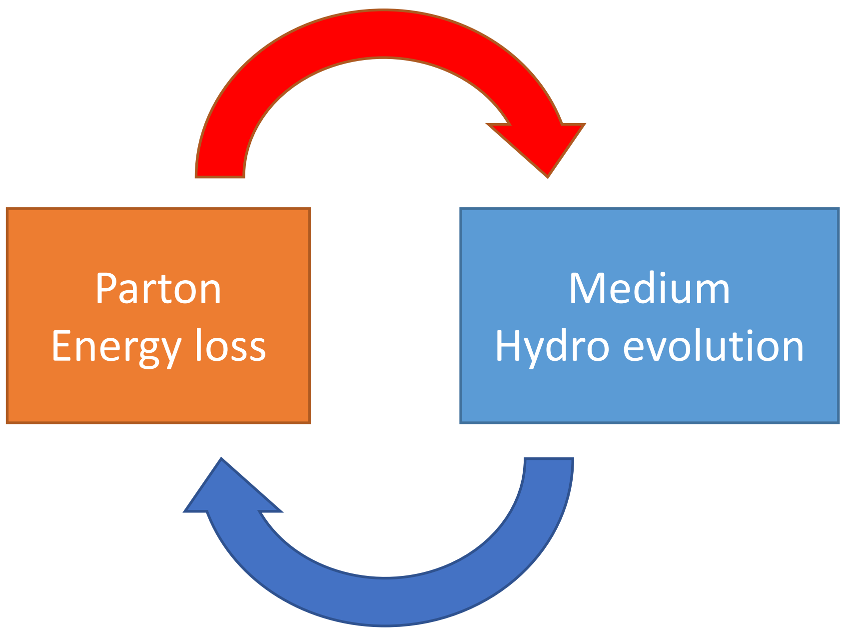
• **pQCD**-based energy loss model
• High-energy partons scatter with medium particles; **Recoiled partons** and holes **do not re-scatter** with **QGP** constituents.



CoLBT Hydro Model

(Coupled Linear Boltzmann Transport and Hydrodynamics)

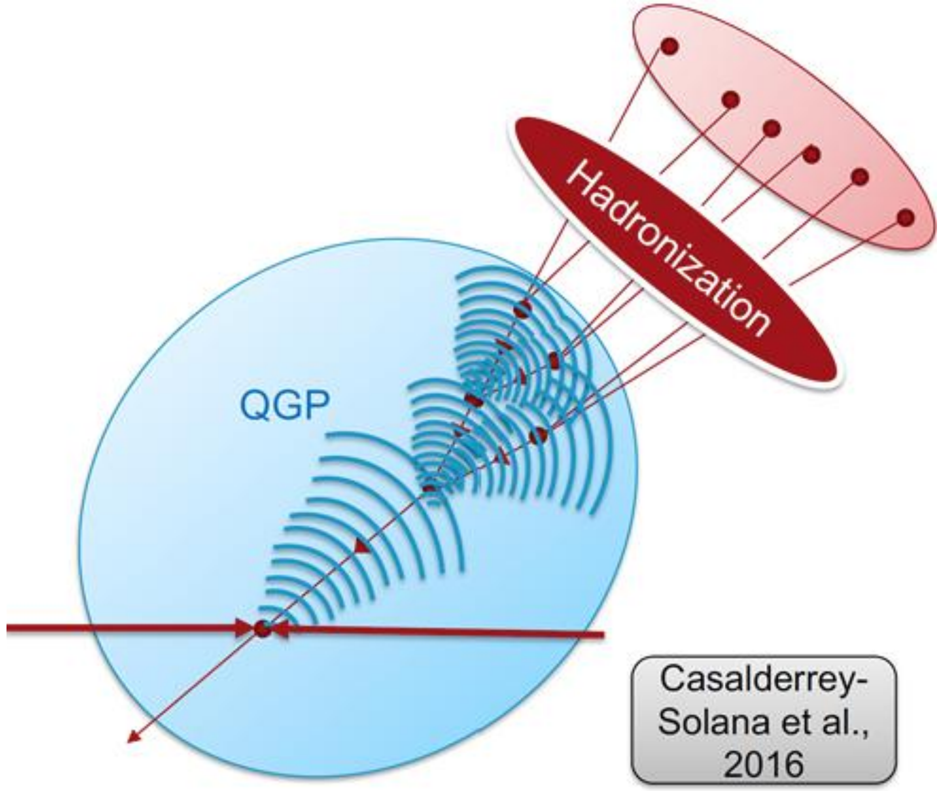
• Based on **pQCD**. Integrates the **Boltzmann transport equation** with **QGP** hydrodynamic simulations.
• Introduces **reheating**, where parton energy loss could heat and modifies the **QGP**.



Hybrid Model

(Hybrid Strong/Weak Coupling Approach)

• Based on the **AdS/CFT**, combining pQCD shower and strong-coupling dynamics.
• Lost energy deposits a **hydrodynamic wake** in the **QGP** via 4-momentum conservation.

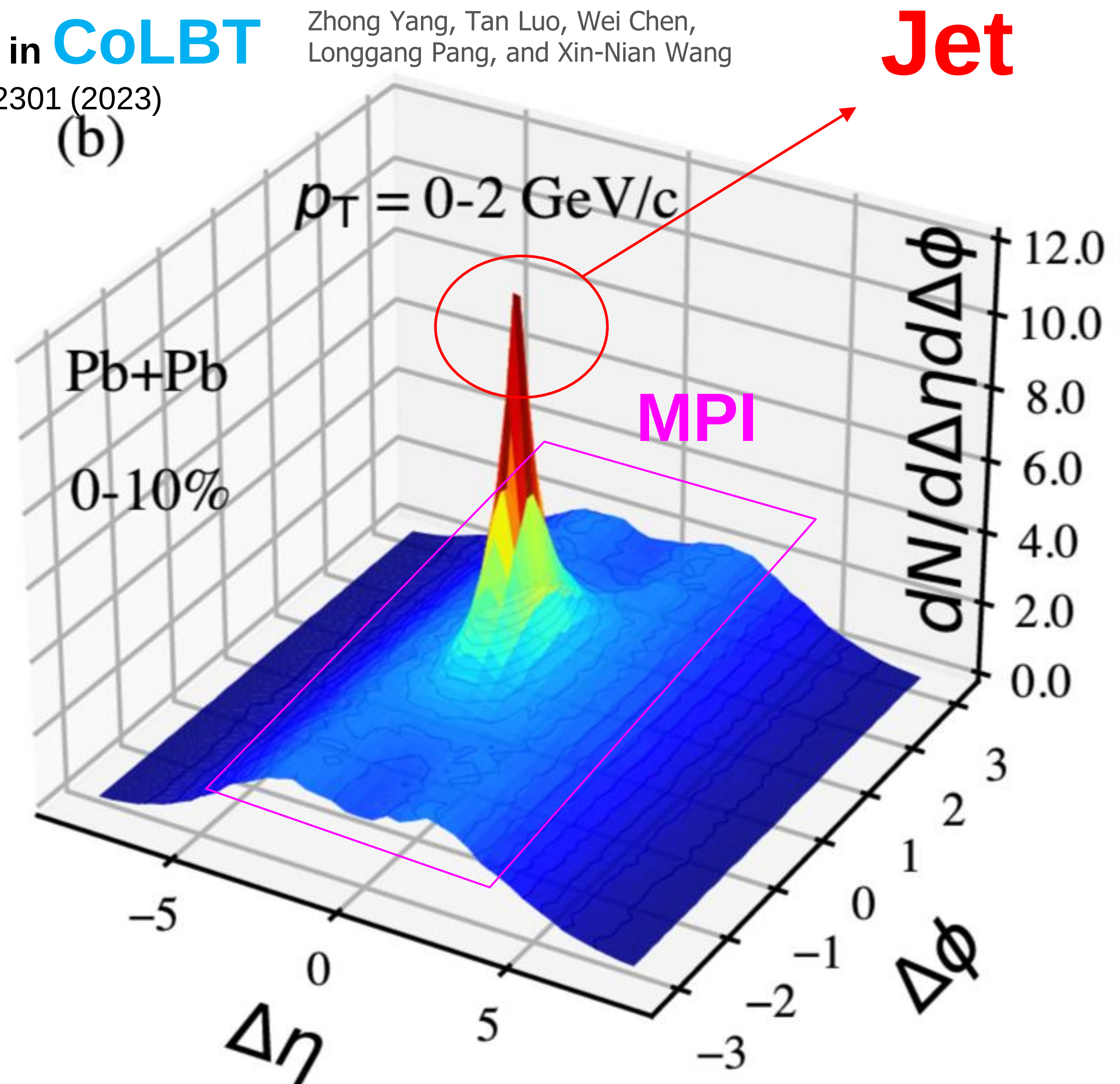


Medium Response to Hard Probes in **Momentum Space**

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

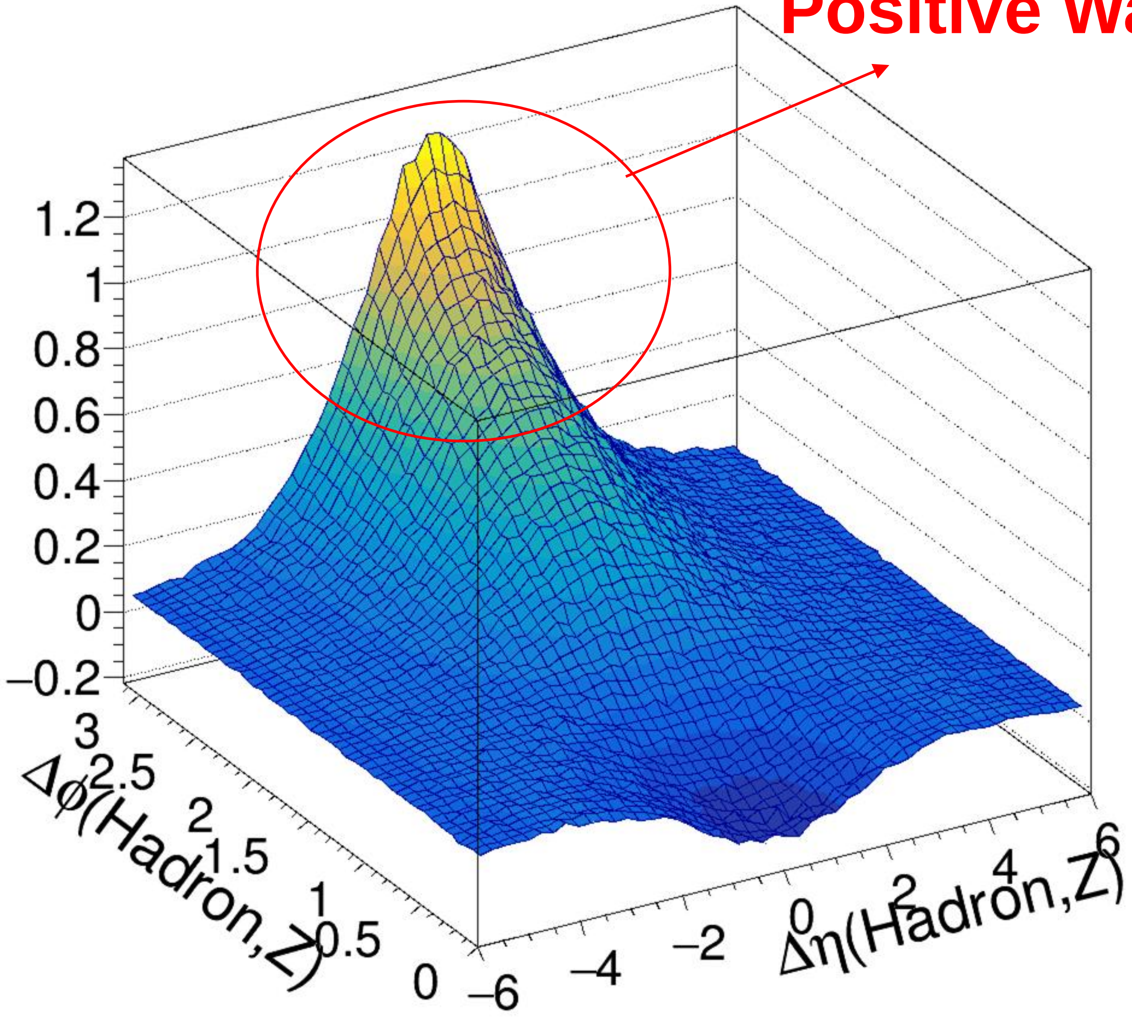
QGP wake in CoLBT Zhong Yang, Tan Luo, Wei Chen, Longgang Pang, and Xin-Nian Wang

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

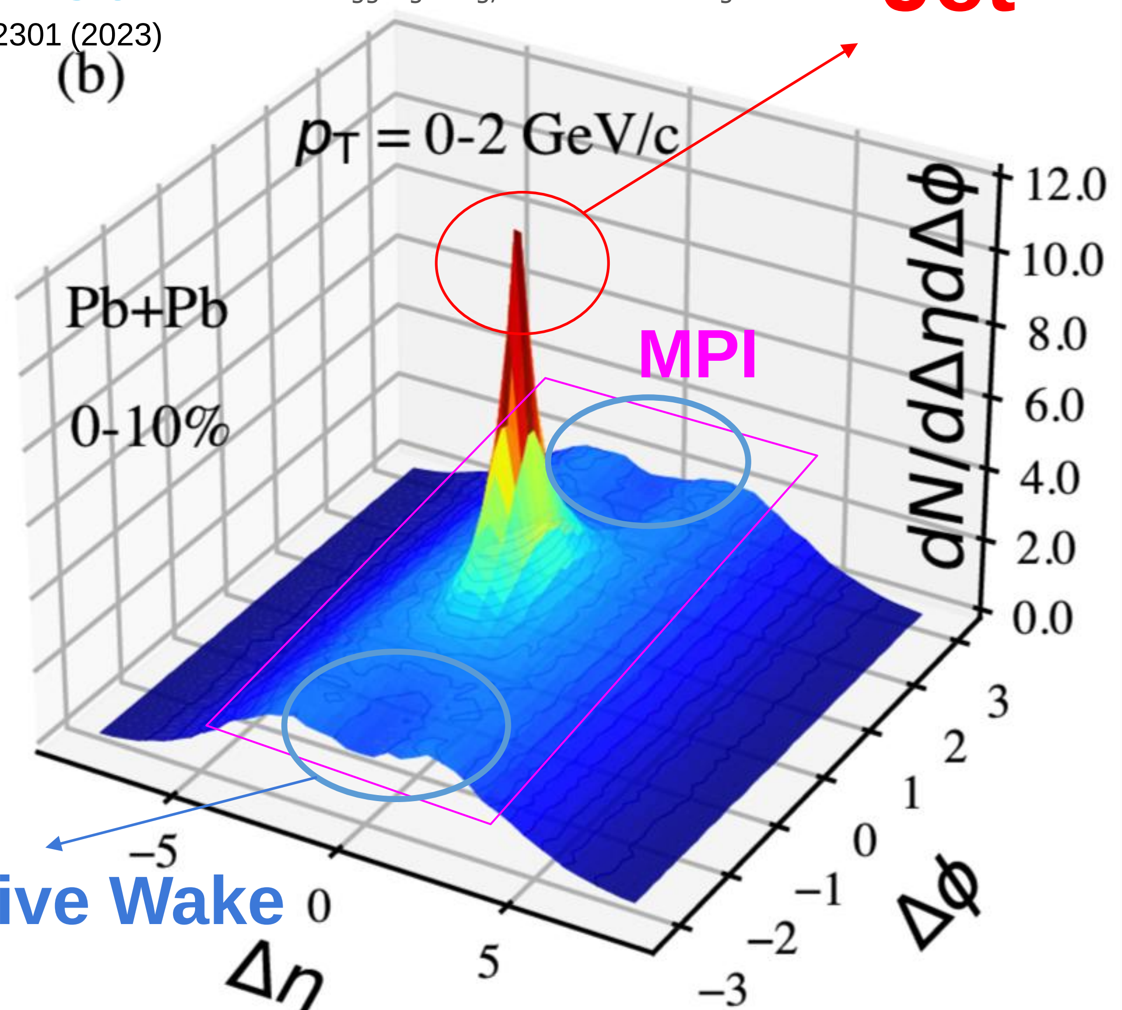
In Momentum Space

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)



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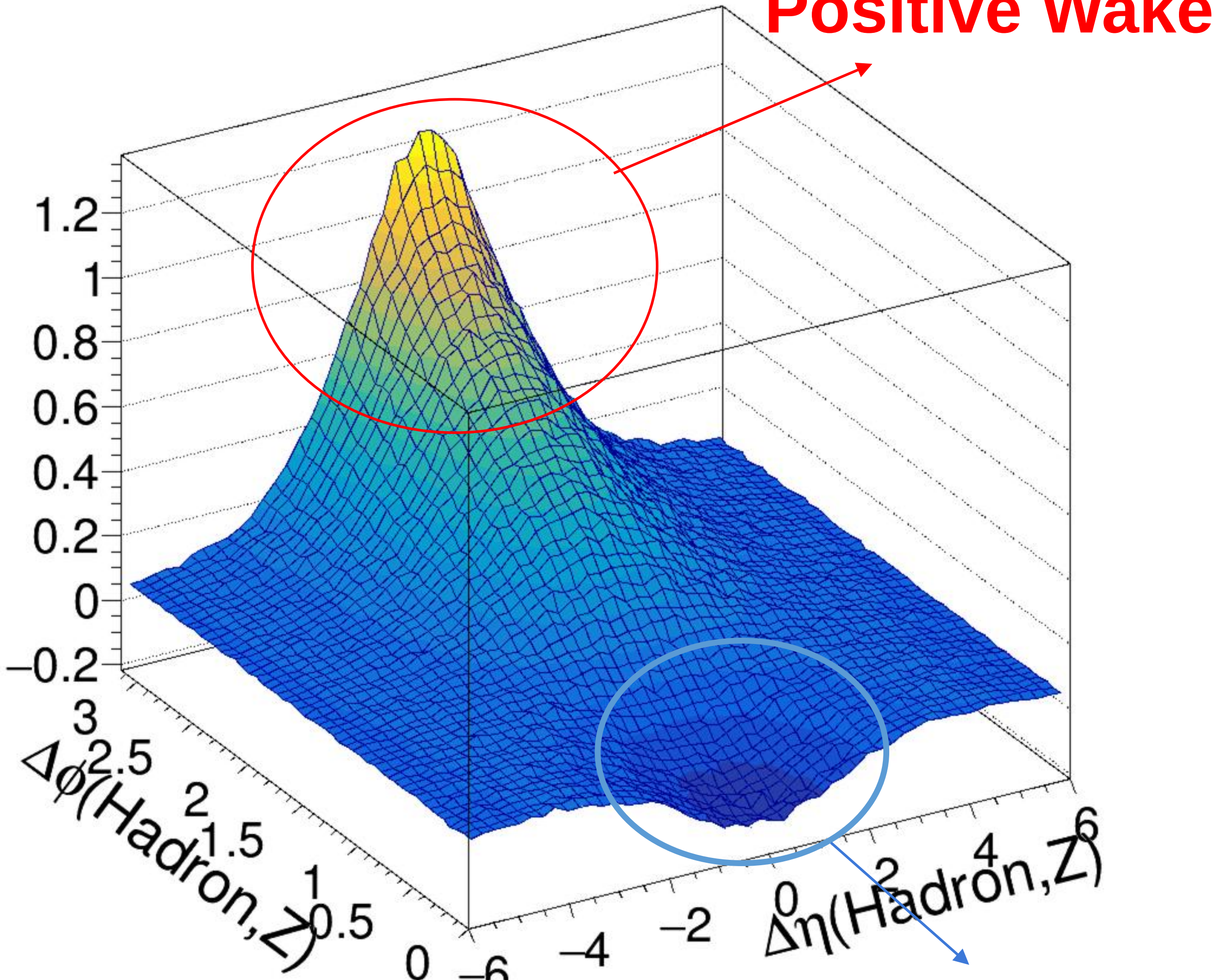


More QGP going in the jet direction, however, with complication from induced radiation

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

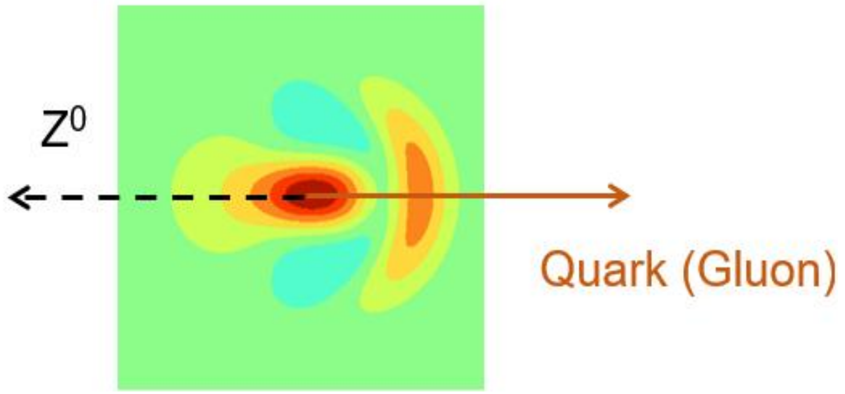
→ Measure the **Boson-side associated yield** with **Z^0-Jet**

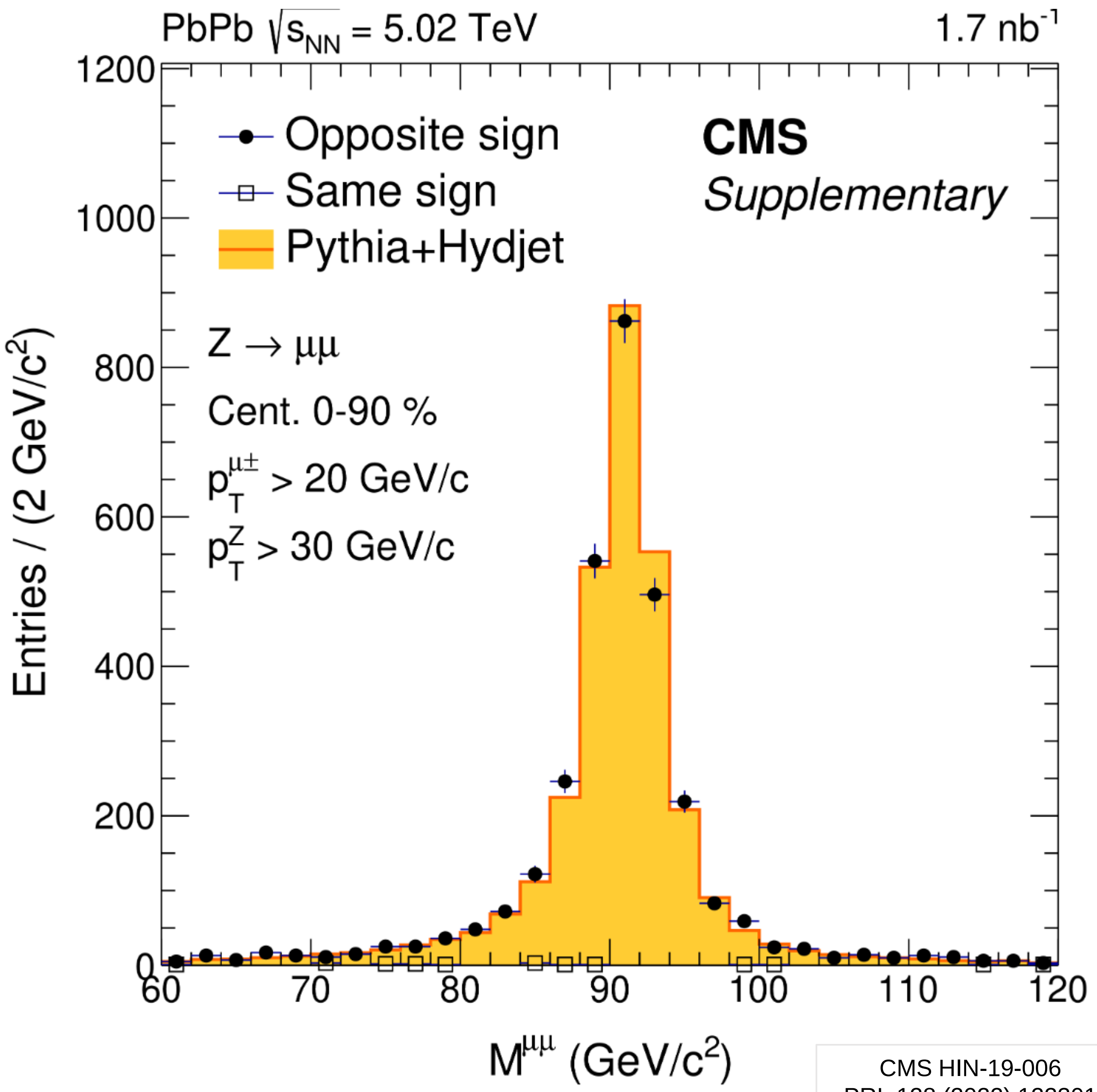
In Momentum Space

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





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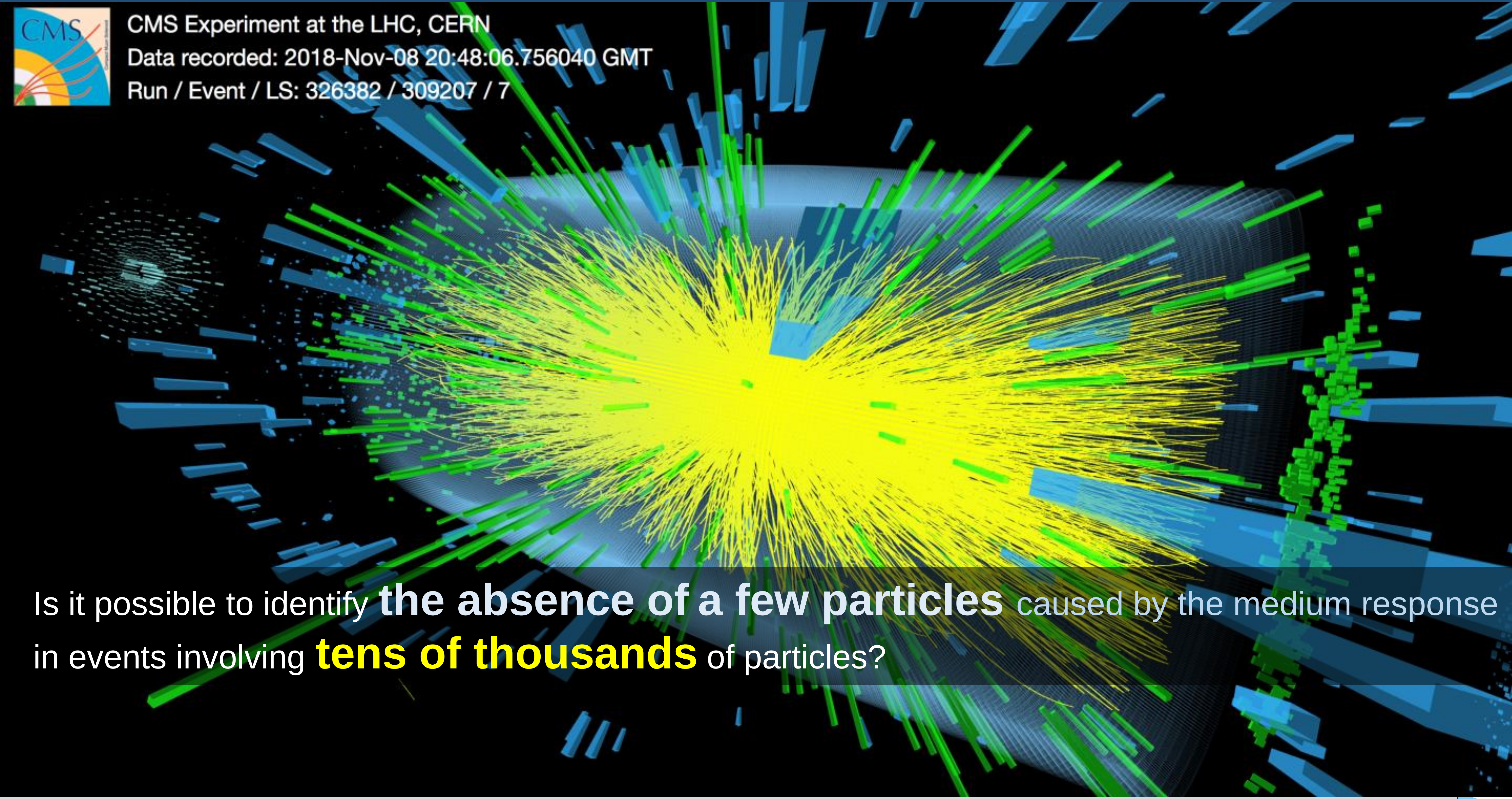
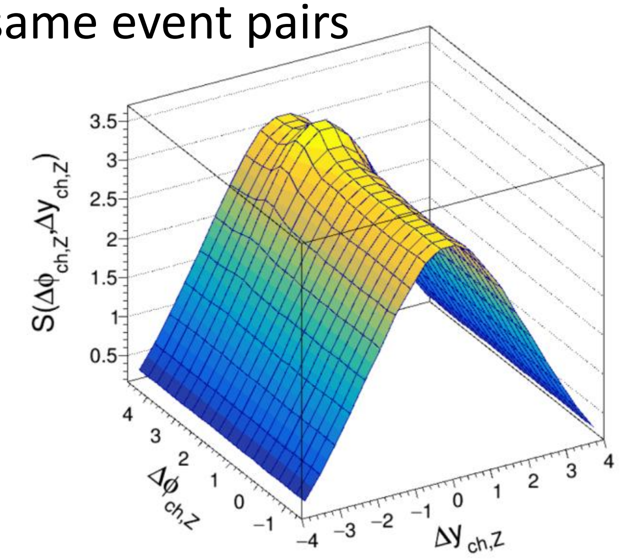


Is it possible to identify **the absence of a few particles** caused by the medium response in events involving **tens of thousands** of particles?

Z^0-Hadron Correlation Function: Event Mixing

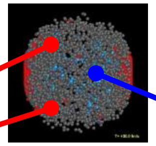
Average Signal pair distribution:

same event pairs

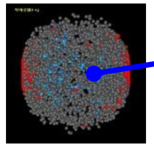


$$S(\Delta\phi_{\mathrm{ch,Z}}, \Delta y_{\mathrm{ch,Z}}) = \frac{1}{N_{\mathrm{z}}} \frac{d^2 N^{\mathrm{same}}}{d\Delta\phi_{\mathrm{ch,Z}} d\Delta y_{\mathrm{ch,Z}}}$$

Z^0 Event 1

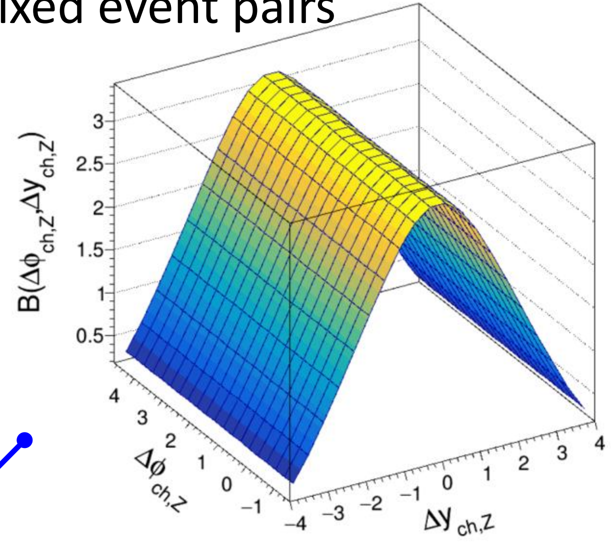


Z^0 Event 2



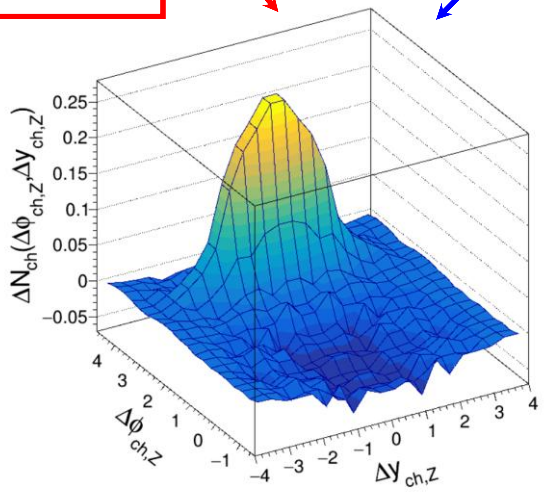
Average Background pair distribution:

mixed event pairs



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

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



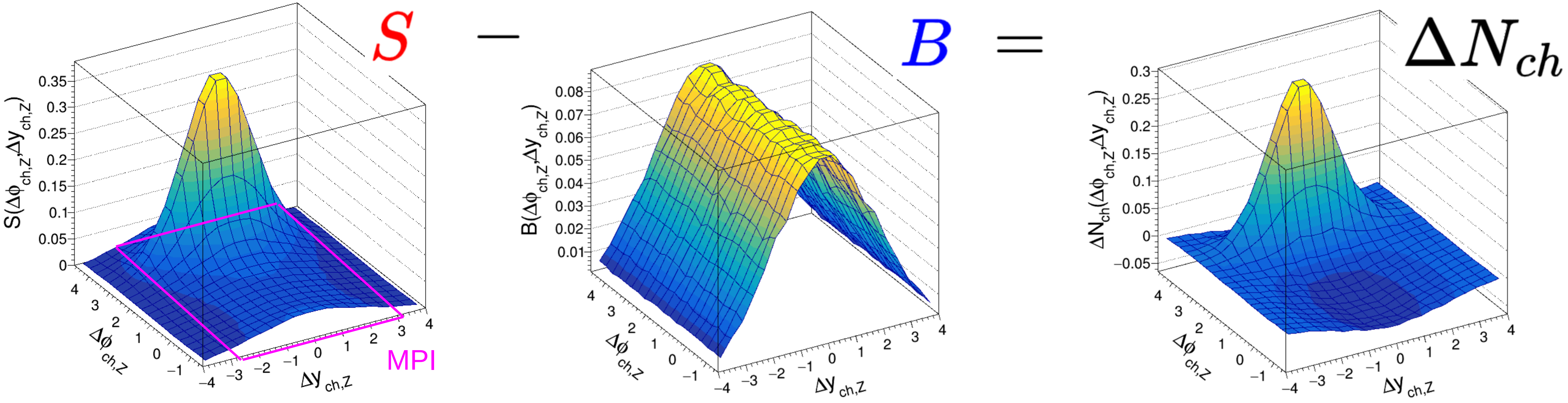
$\Delta y_{ch,Z} = y_z - \eta_{ch}$

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

Demonstration with PYTHIA+HYDJET (Generator level events)

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

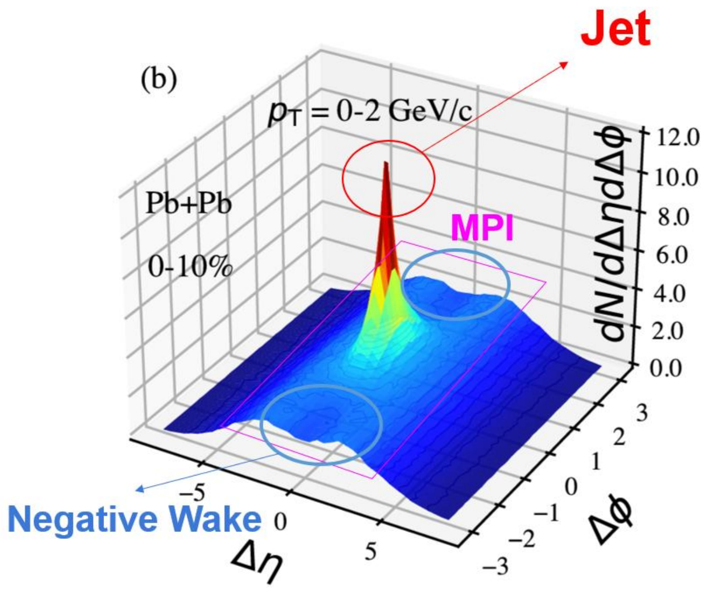
Mixed Event Subtraction in **PYTHIA8 pp** Events



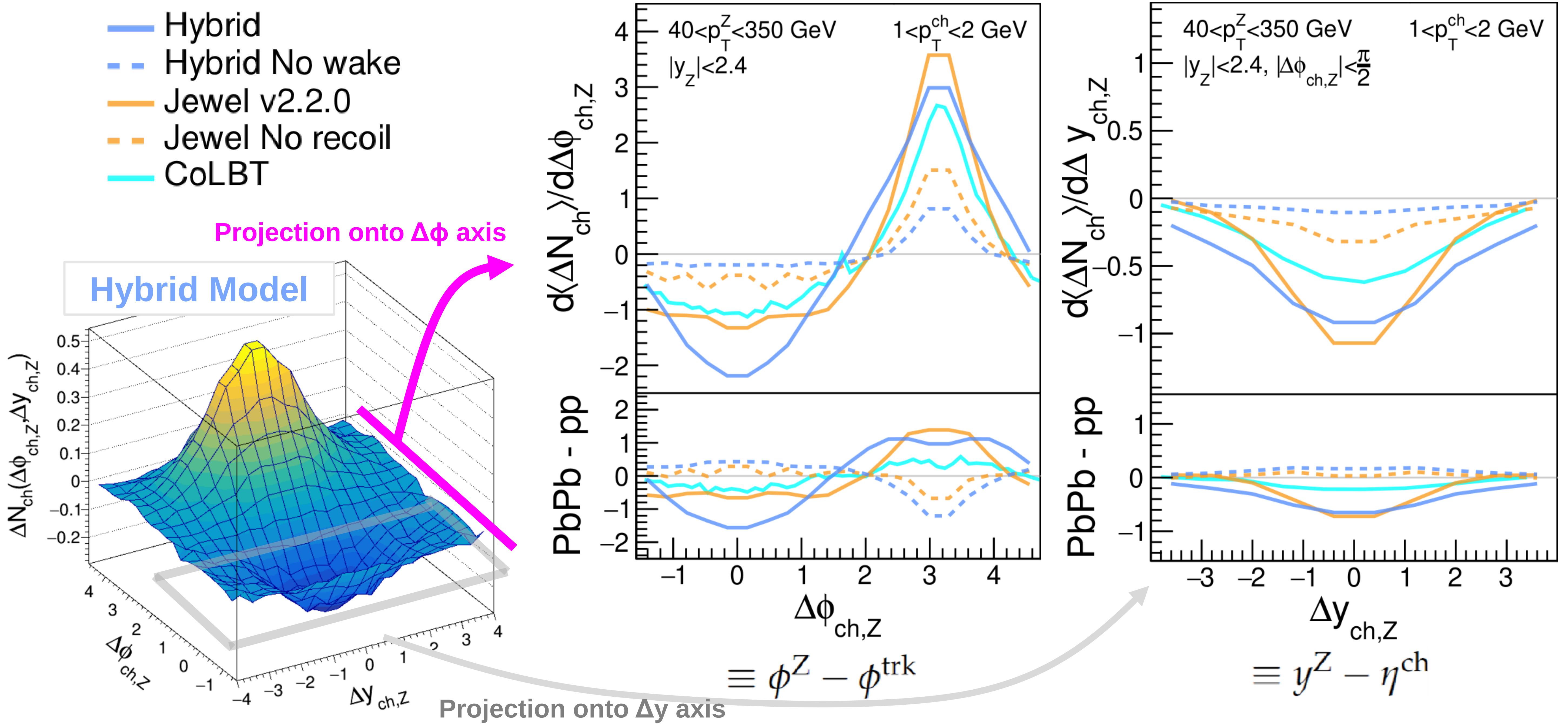
- Mixed event subtraction is also performed in **pp** analysis

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

- The procedure suppresses the uncorrelated "Multi-Parton Interaction (MPI) ridge" at fixed $\Delta\eta$ (Δy)



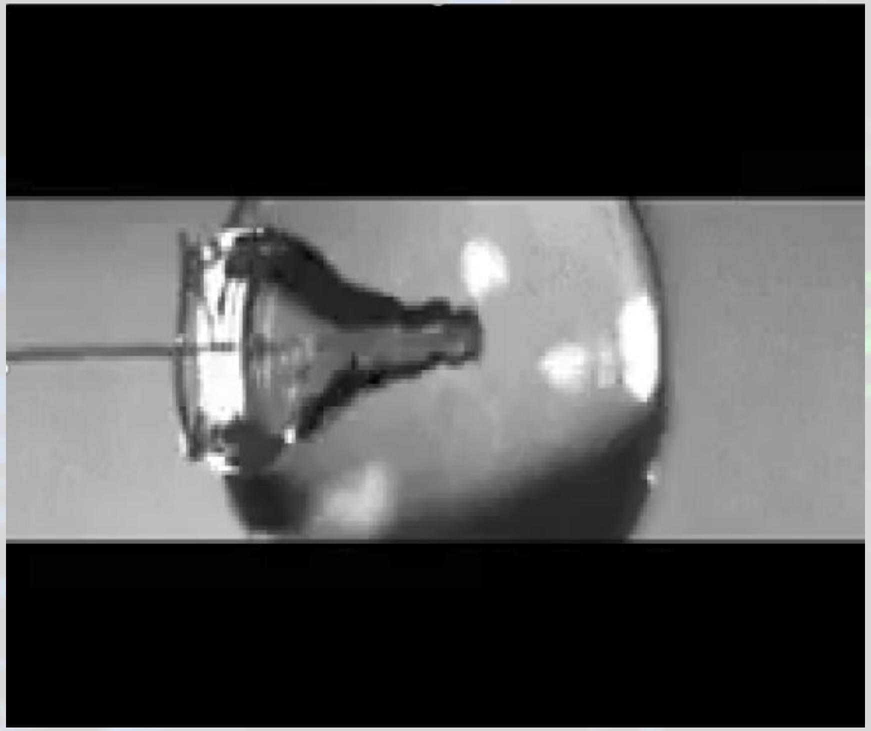
1D Projections of the Theoretical Predictions

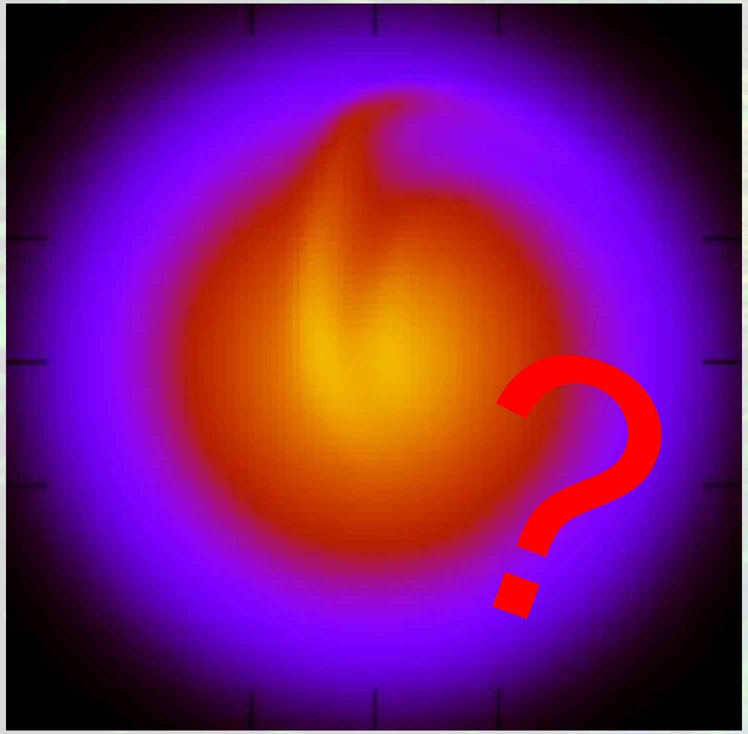


$\equiv \phi^Z - \phi^{trk}$

$\equiv y^Z - \eta^{ch}$

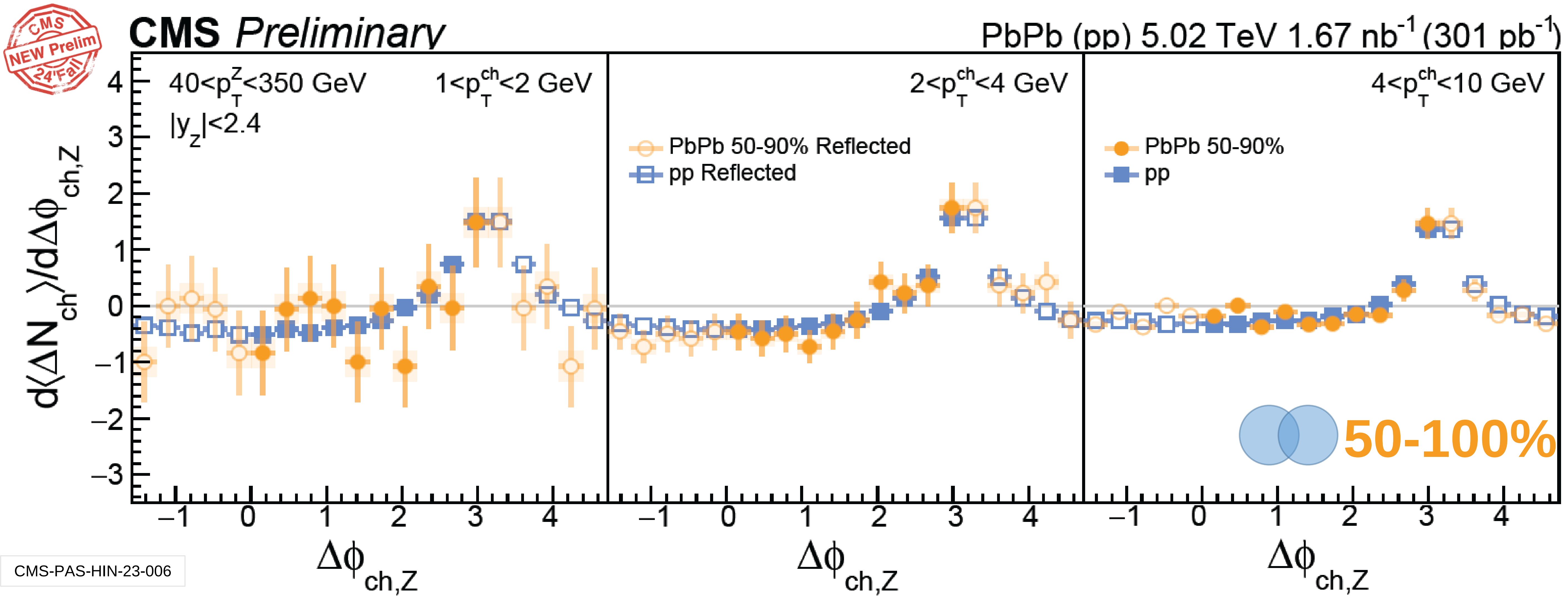
Results





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



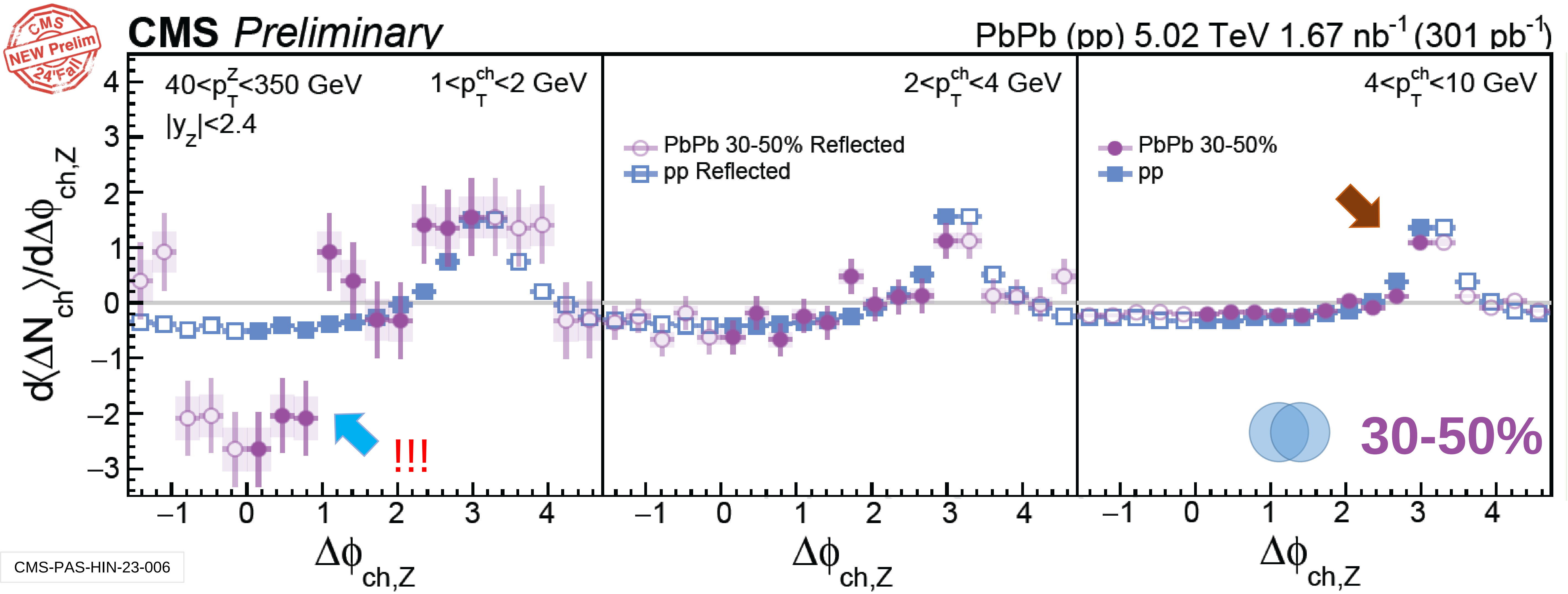
CMS-PAS-HIN-23-006

Low Charged Hadron p_T → High Charged Hadron p_T

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

The **QGP** is relatively small, resulting in a less pronounced jet quenching effect

Azimuthal Angle Distributions in pp and 30-50% PbPb



CMS-PAS-HIN-23-006

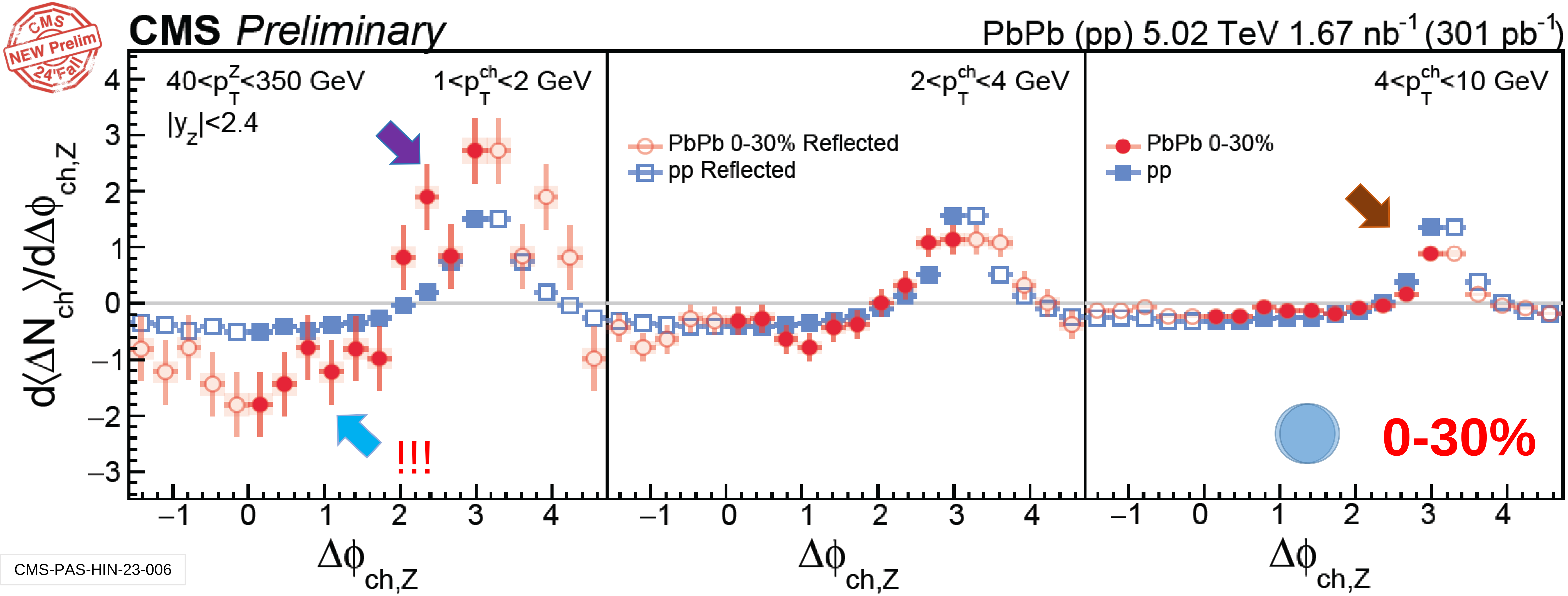
Low Charged Hadron p_T

High Charged Hadron p_T

PbPb: Clear relative depletion in Z^0 side (Δϕ=0)

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



CMS-PAS-HIN-23-006

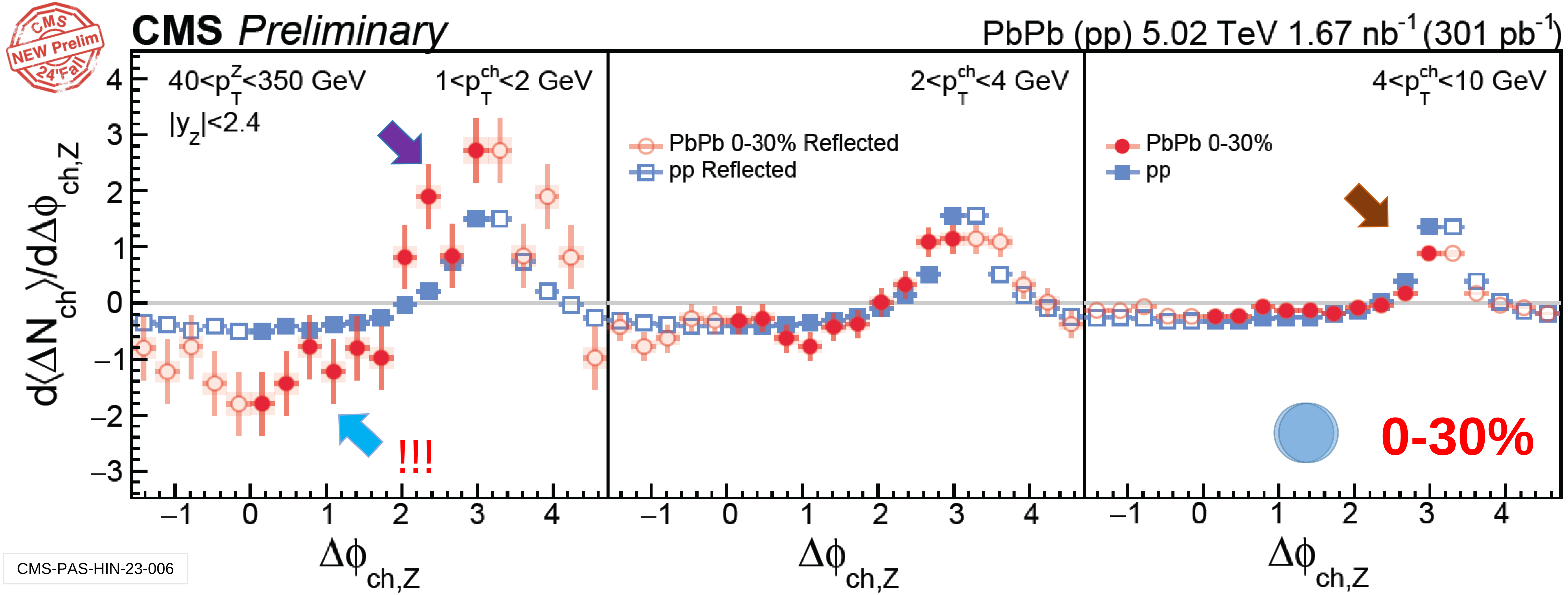
Low Charged Hadron p_T — High Charged Hadron p_T

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

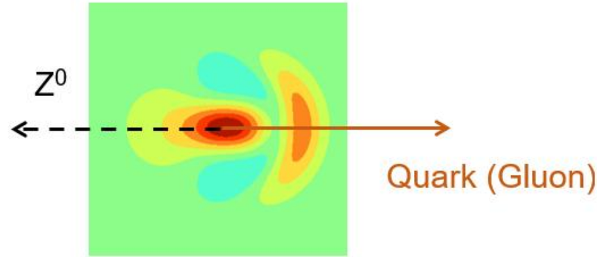
Azimuthal Angle Distributions in pp and 0-30% PbPb



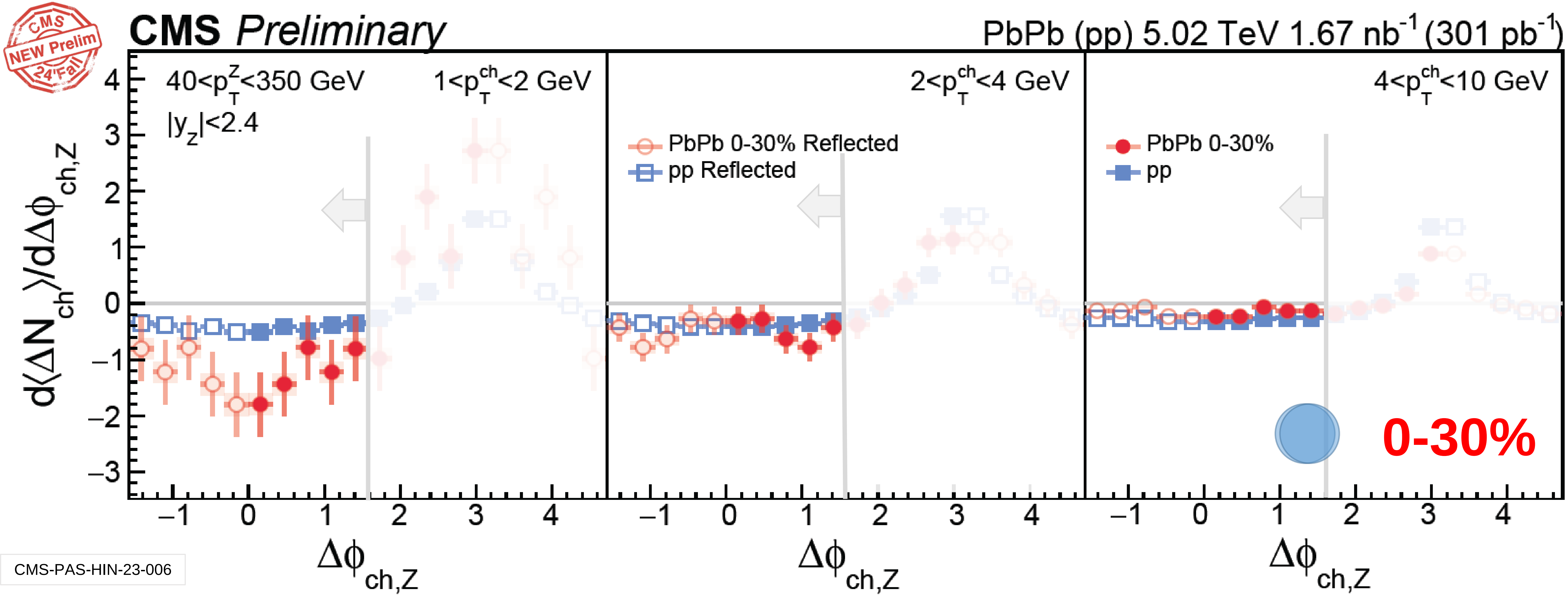
CMS-PAS-HIN-23-006

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

How about rapidity distributions?



Azimuthal Angle Distributions in pp and 0-30% PbPb

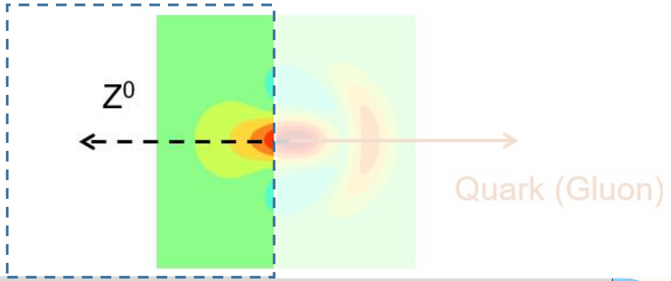


CMS-PAS-HIN-23-006

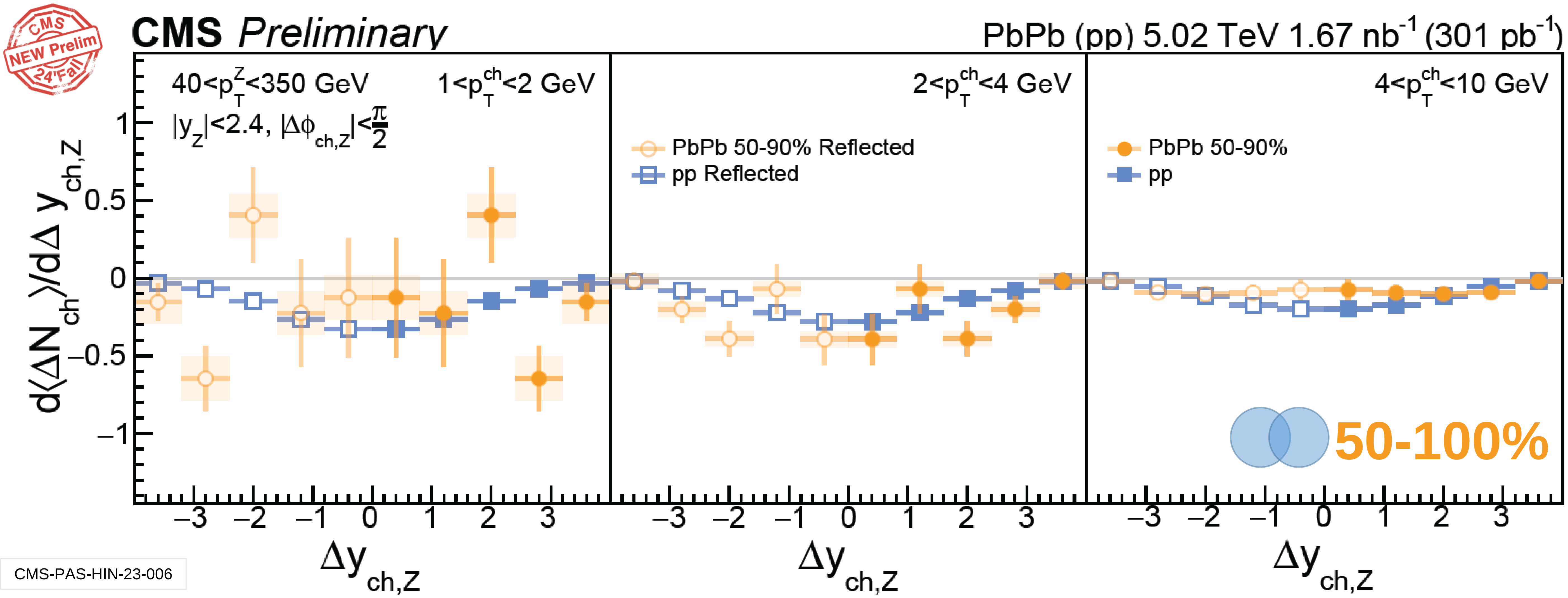
Now we have seen a deeper dip structure at Δϕ~0

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 50-100% PbPb

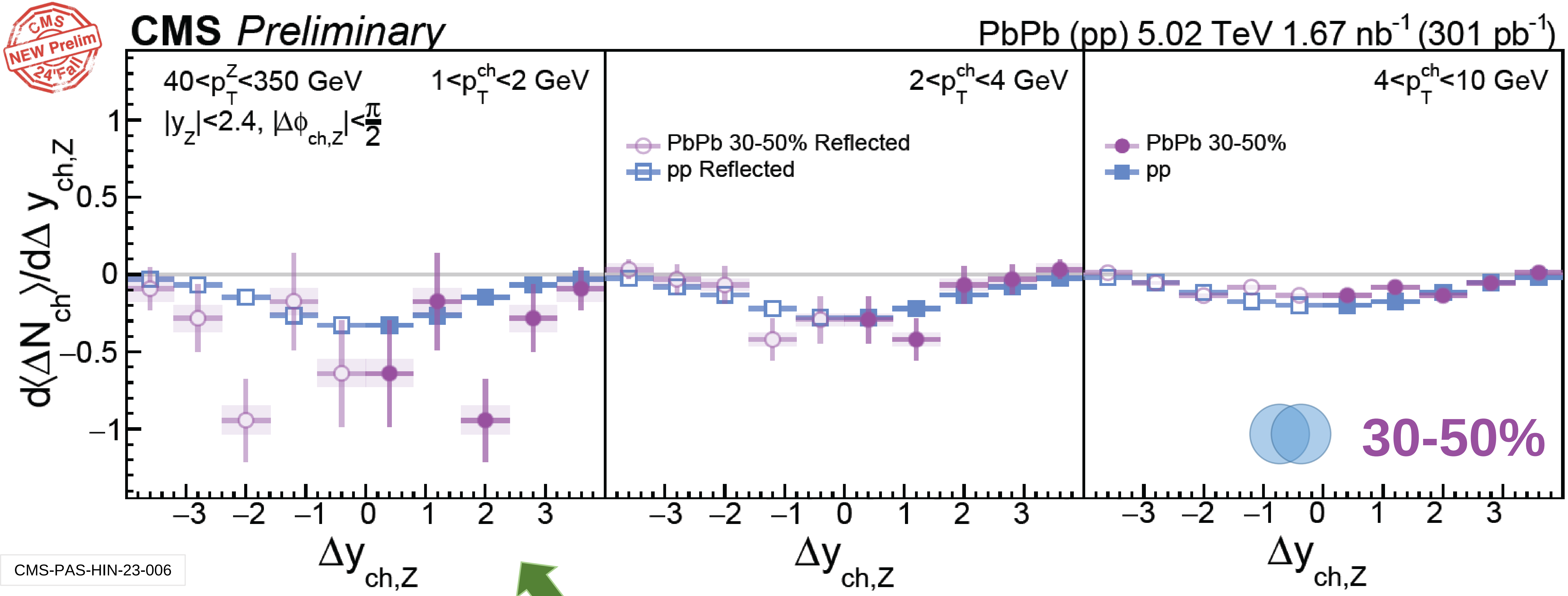


CMS-PAS-HIN-23-006

Low Charged Hadron p_T

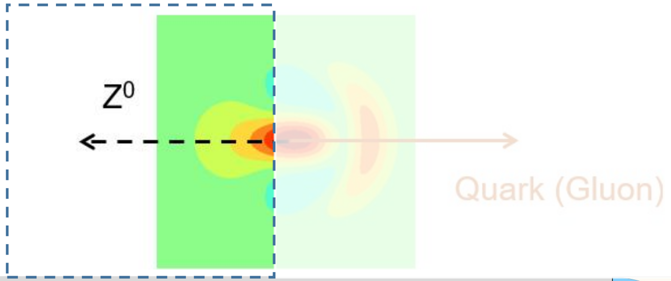
High Charged Hadron p_T

Rapidity Distributions in pp and 30-50% PbPb

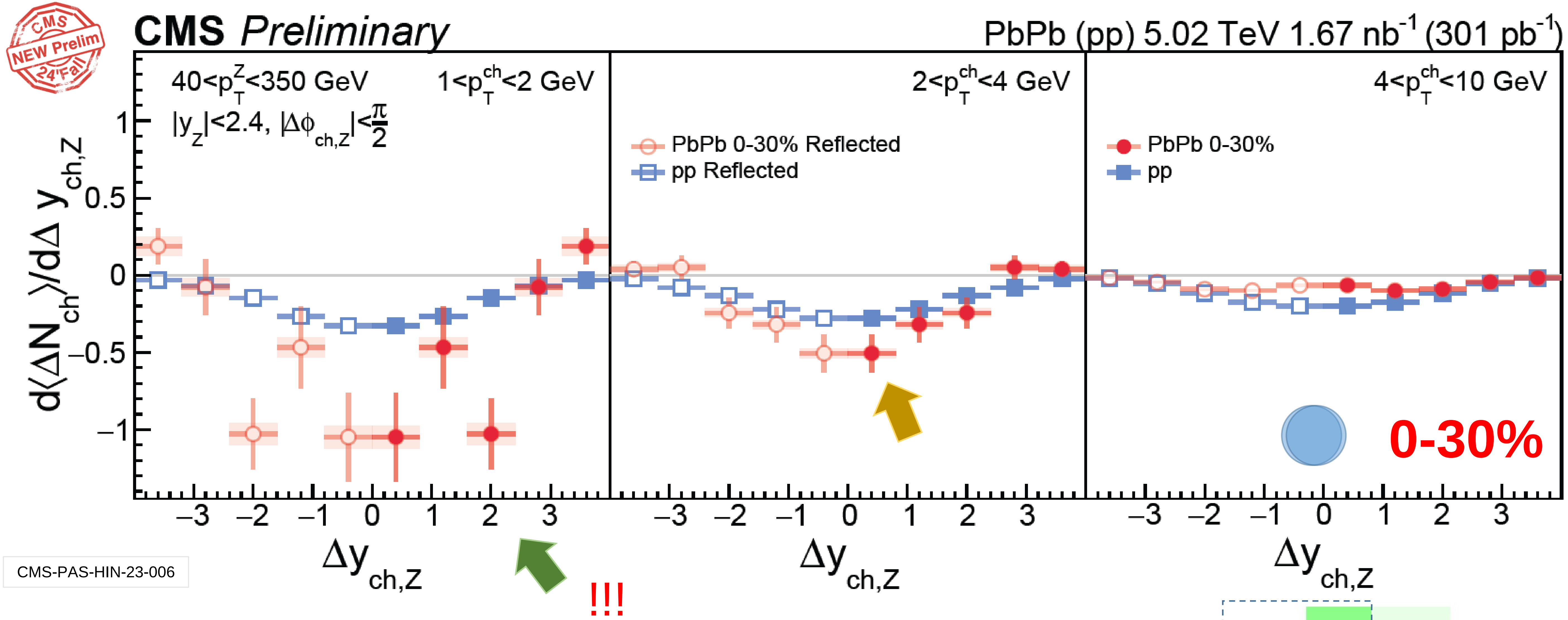


CMS-PAS-HIN-23-006

PbPb: Indication of depletion around the Z ($\Delta y=0$)



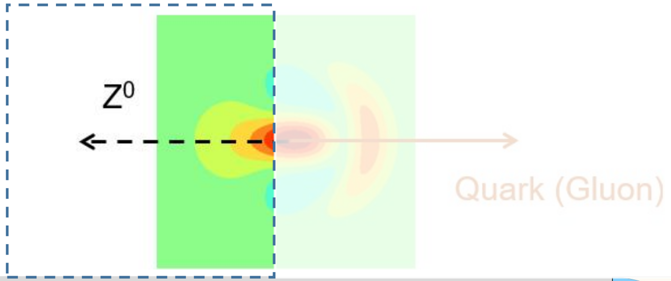
Rapidity Distributions in pp and 0-30% PbPb



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)



Comparison with Theoretical Models: Reminder

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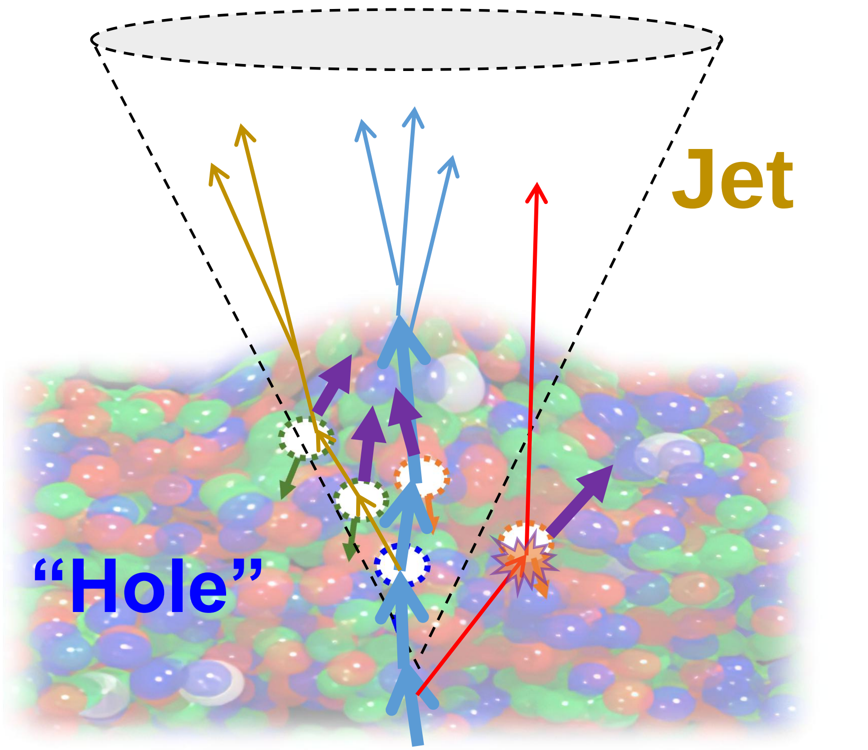
(Jet Evolution with Energy Loss)

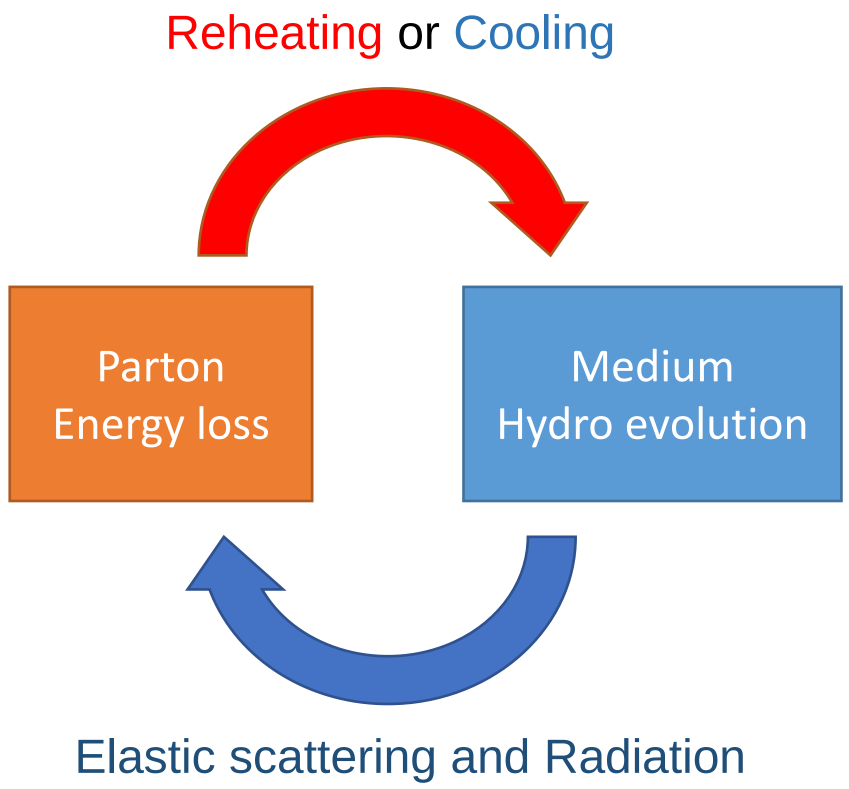
• **pQCD**-based energy loss model
• High-energy partons scatter with medium particles; **Recoiled partons** and holes **do not re-scatter** with **QGP** constituents.



CoLBT hydro Model

(Coupled Linear Boltzmann Transport and Hydrodynamics)

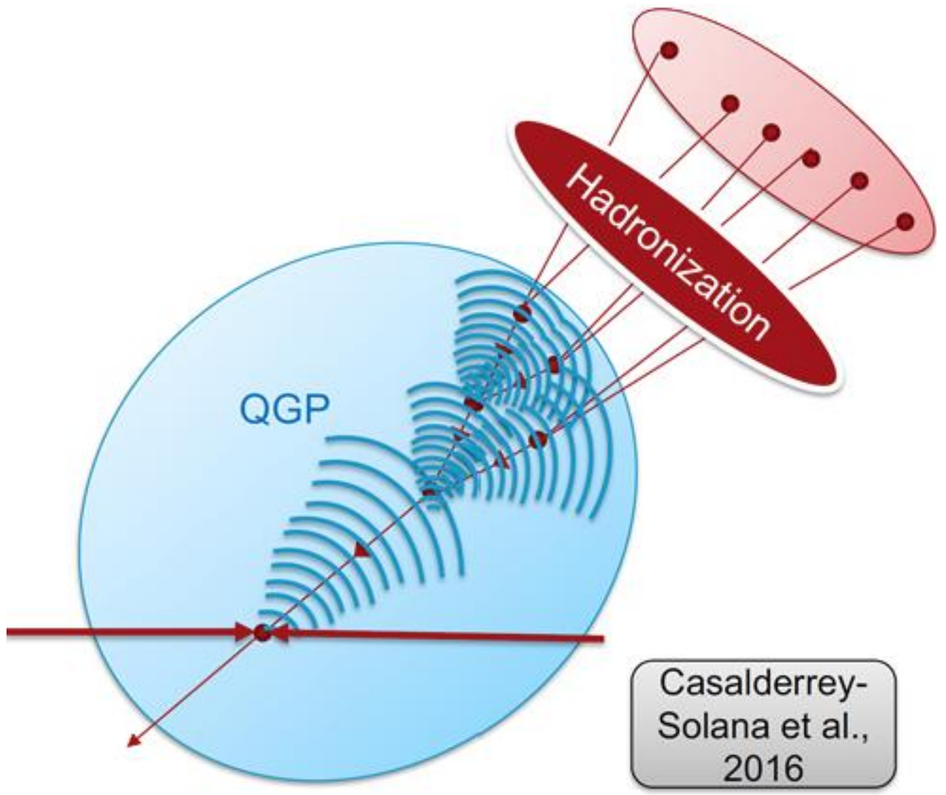
• Based on **pQCD**. Integrates the **Boltzmann transport equation** with QGP hydrodynamic simulations.
• Introduces **reheating**, where parton energy loss could heat and modifies the **QGP**.



Hybrid Model

(Hybrid Strong/Weak Coupling Approach)

• Based on the **AdS/CFT**, combining pQCD shower and strong-coupling dynamics.
• Lost energy deposits a **hydrodynamic wake** in the **QGP** via 4-momentum conservation.

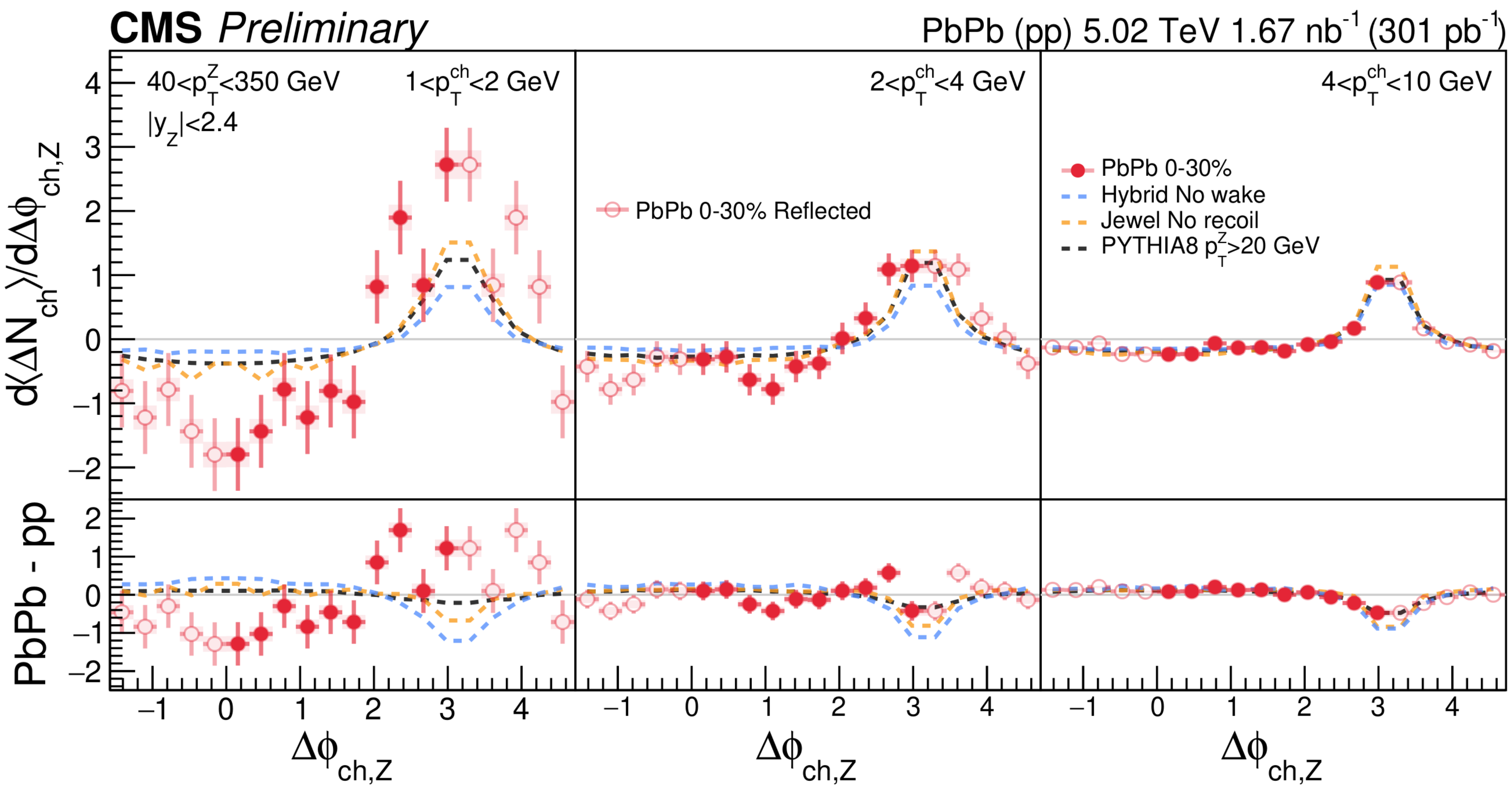


Azimuthal Angle Distribution in 0-30% PbPb vs. Theory **w/o** Medium Response

- **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

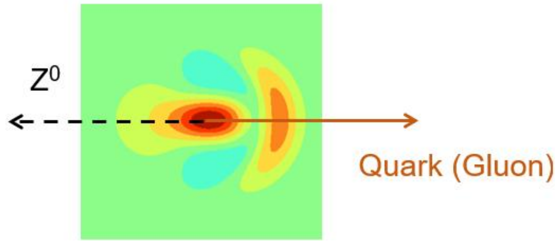


(Another test on magnitude of negative ΔN_{ch} near Z^0 without recoil/wake)

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

↕

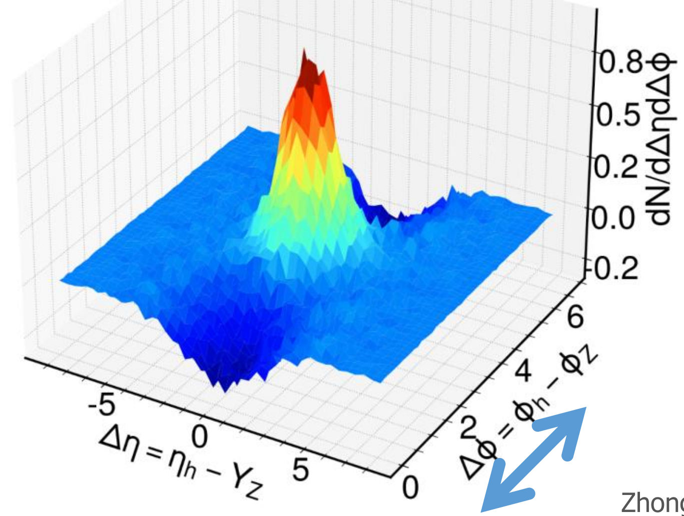
—Approx.→ 20 GeV Z + 20 GeV pythia jet ~~+ recoil/wake~~



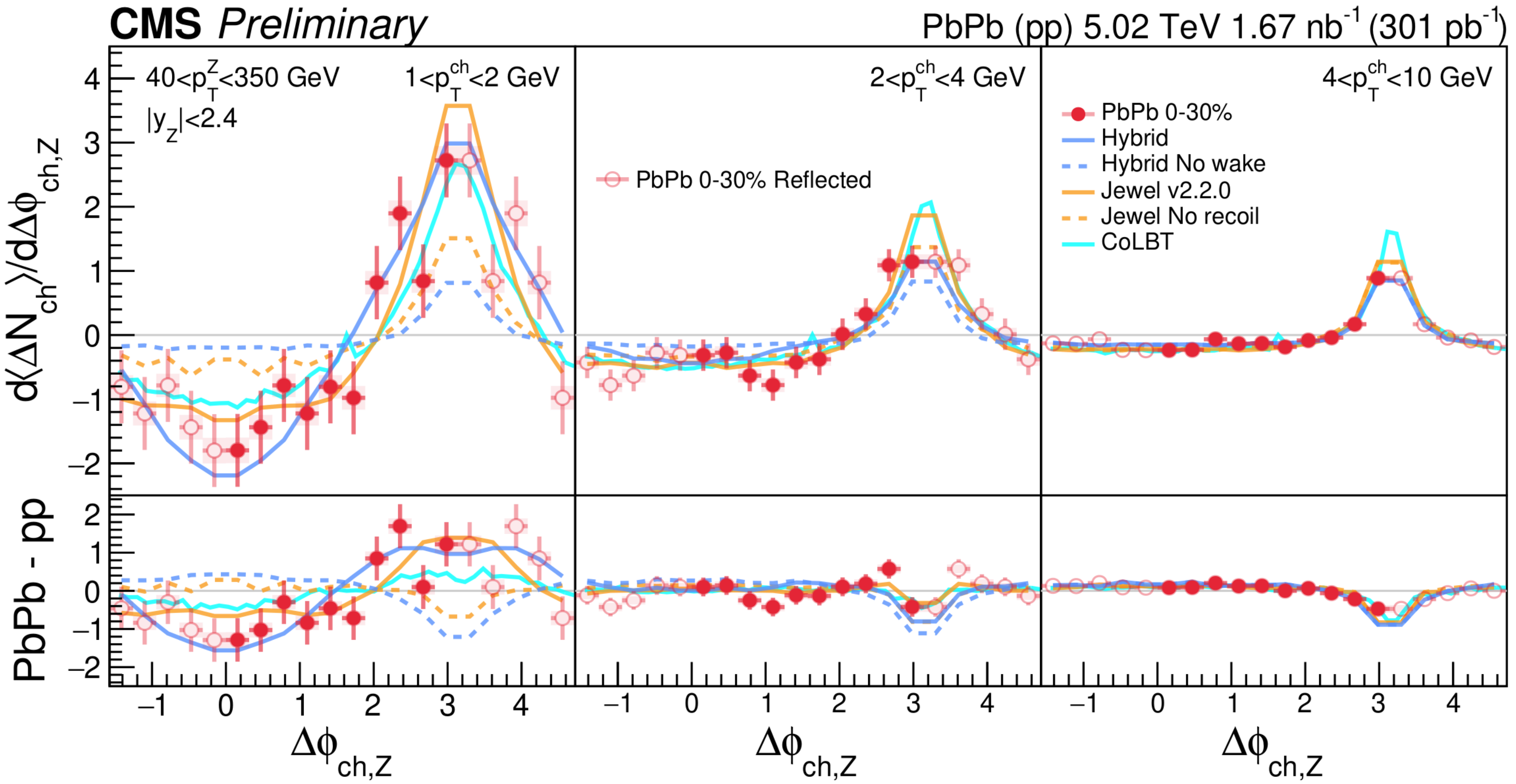
Azimuthal Angle Distribution in 0-30% PbPb vs. Theory

- **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



Zhong Yang, Xin-Nian Wang



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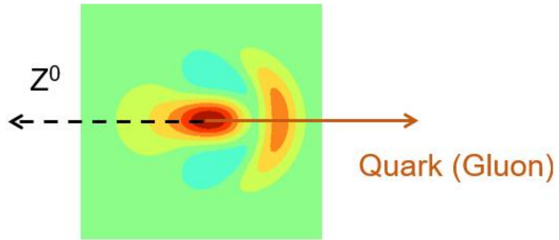
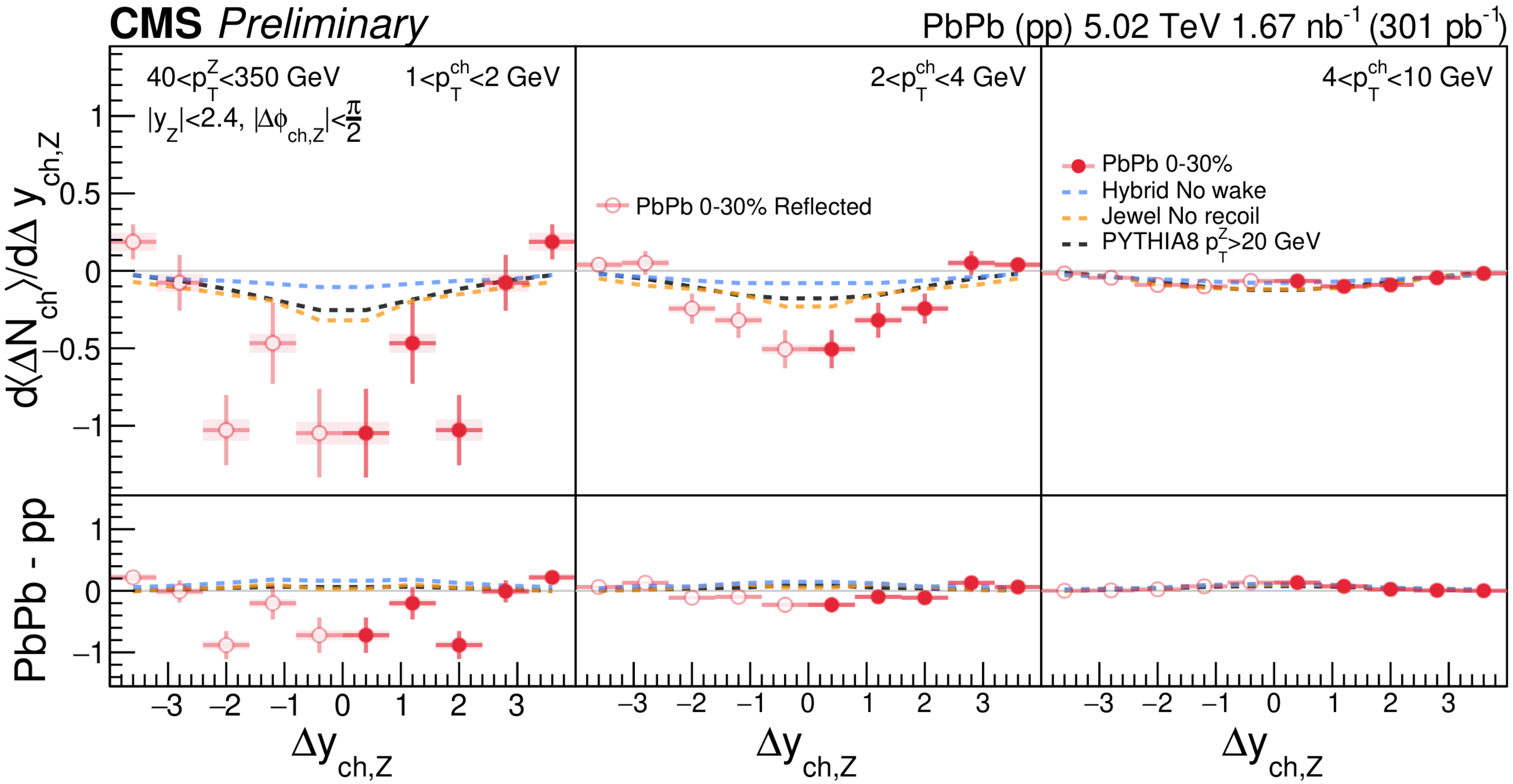


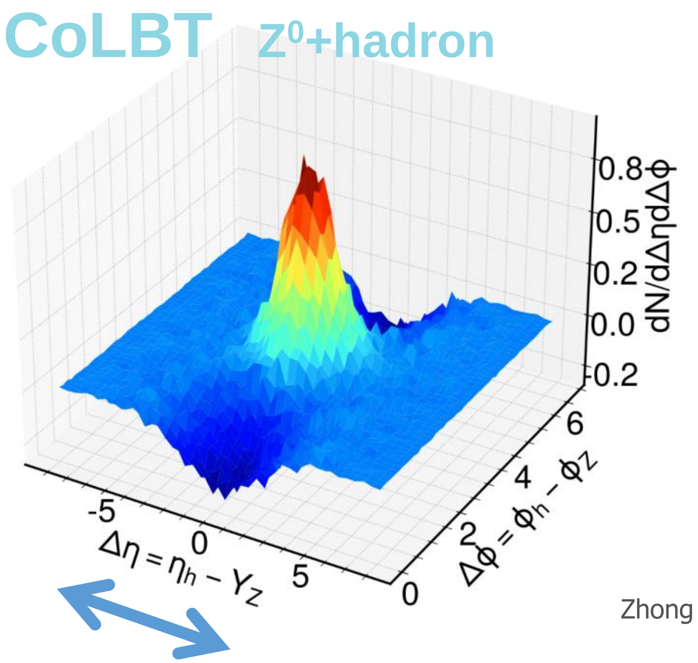
CMS NEW Prelim 24'Fall

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

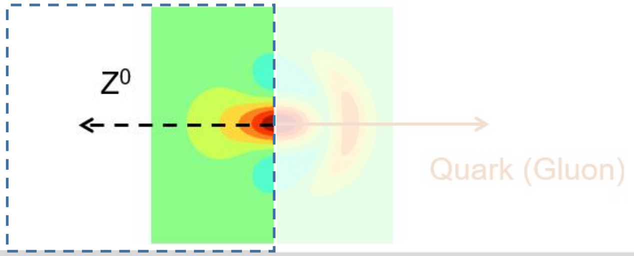
- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T
- **Lower p_T Z^0 tagged PYTHIA8 events** also fails to describe data with hadron p_T< 4 GeV.



CMS-PAS-HIN-23-006



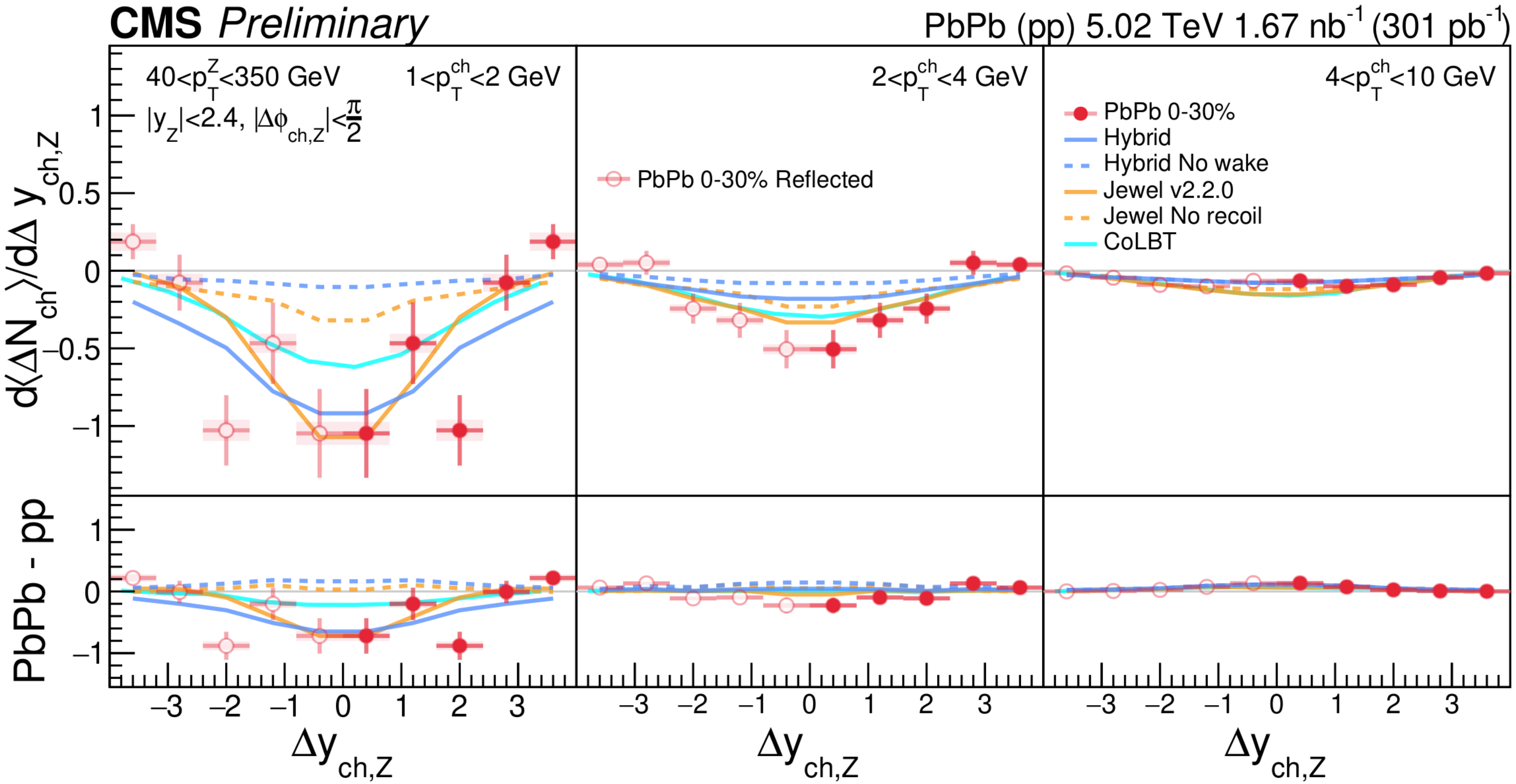
Zhong Yang, Xin-Nian Wang



CMS NEW Prelim 24'Fall

Rapidity Distribution in 0-30% PbPb vs. Theory

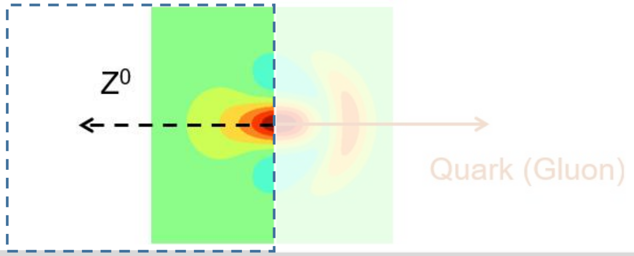
- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T
- **Hybrid with wake**, **Jewel with recoil** and **CoLBT** (solid lines) agree better with data



CMS-PAS-HIN-23-006

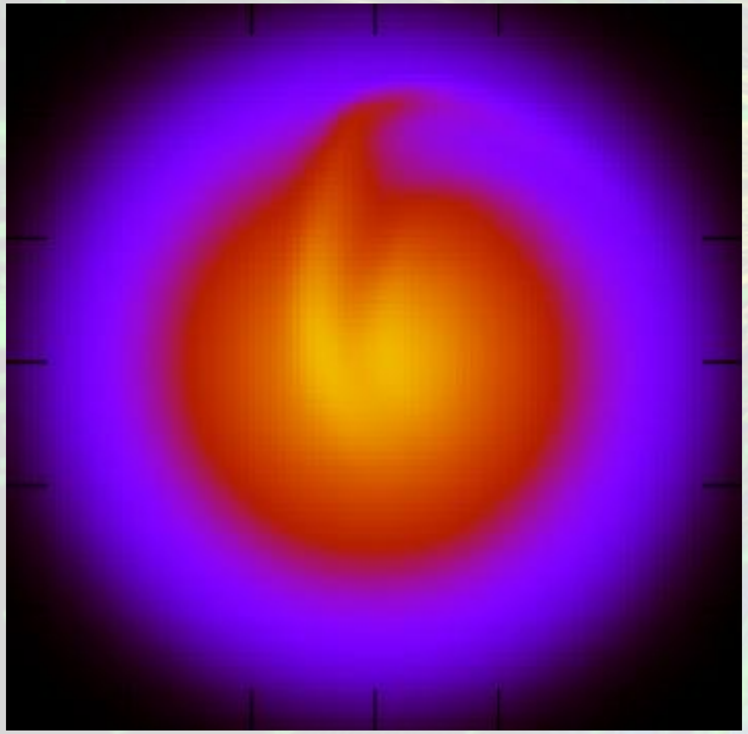
With Δy and Δϕ spectra at low charged hadron p_T:

The first evidence of negative QGP wake!



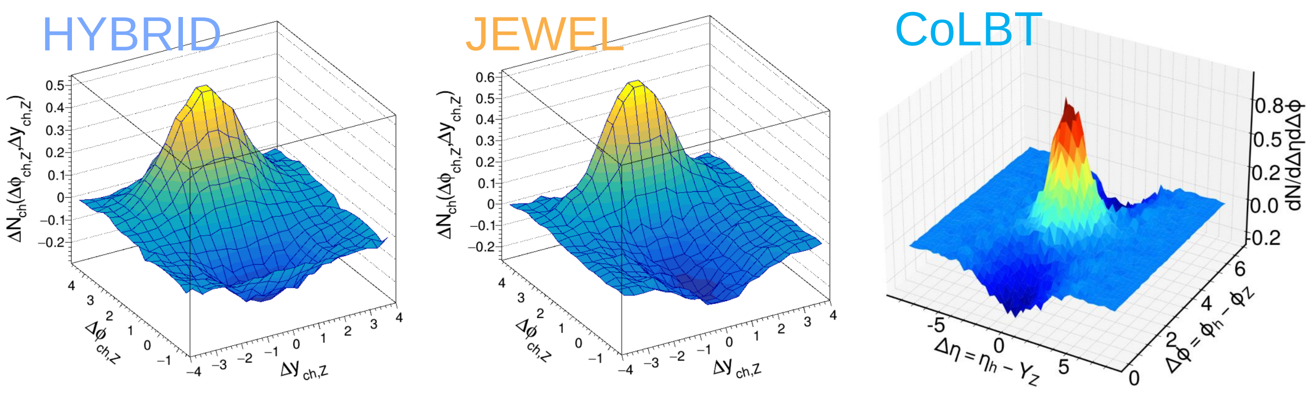
CMS Experiment at the LHC, CERN
Data recorded: 2011-Dec-01 14:35:39.907994 GMT
Run / E

Implication and Outlook



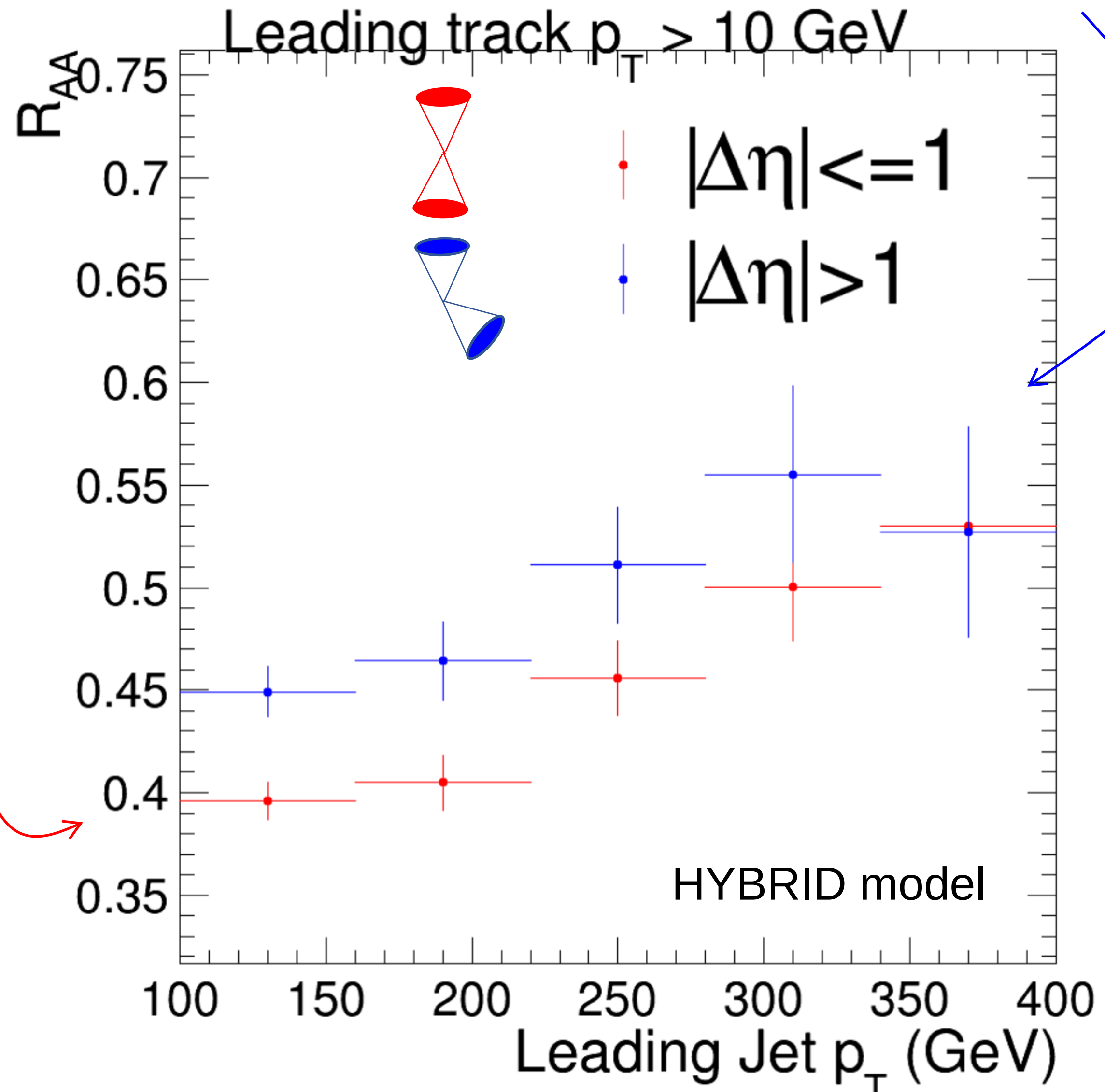
Unambiguous evidence of the **QGP wake** created by a fast moving quark

Implications from the Z-hadron Signal



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

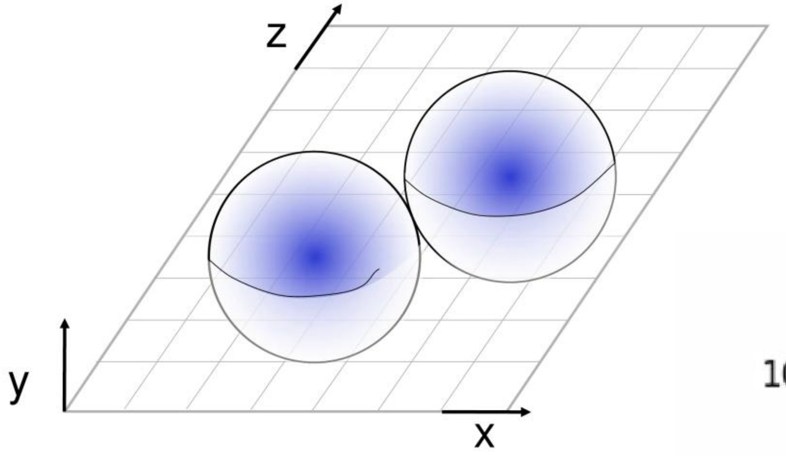
Receive **partial** back reaction from the away side jet

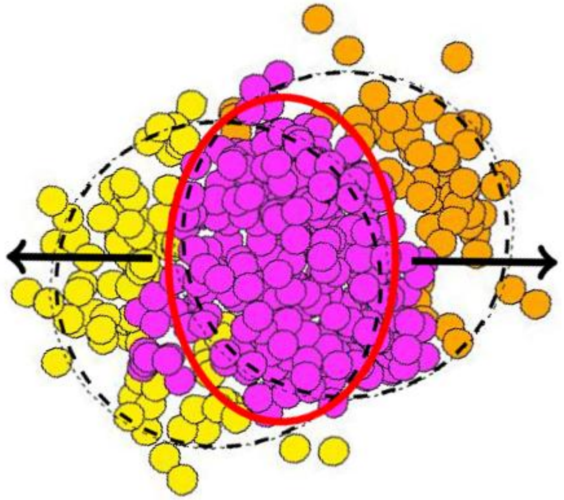


Daniel Pablo, Krishna Rajagopal, YJL

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

Effect of Shear Viscosity in Simulation





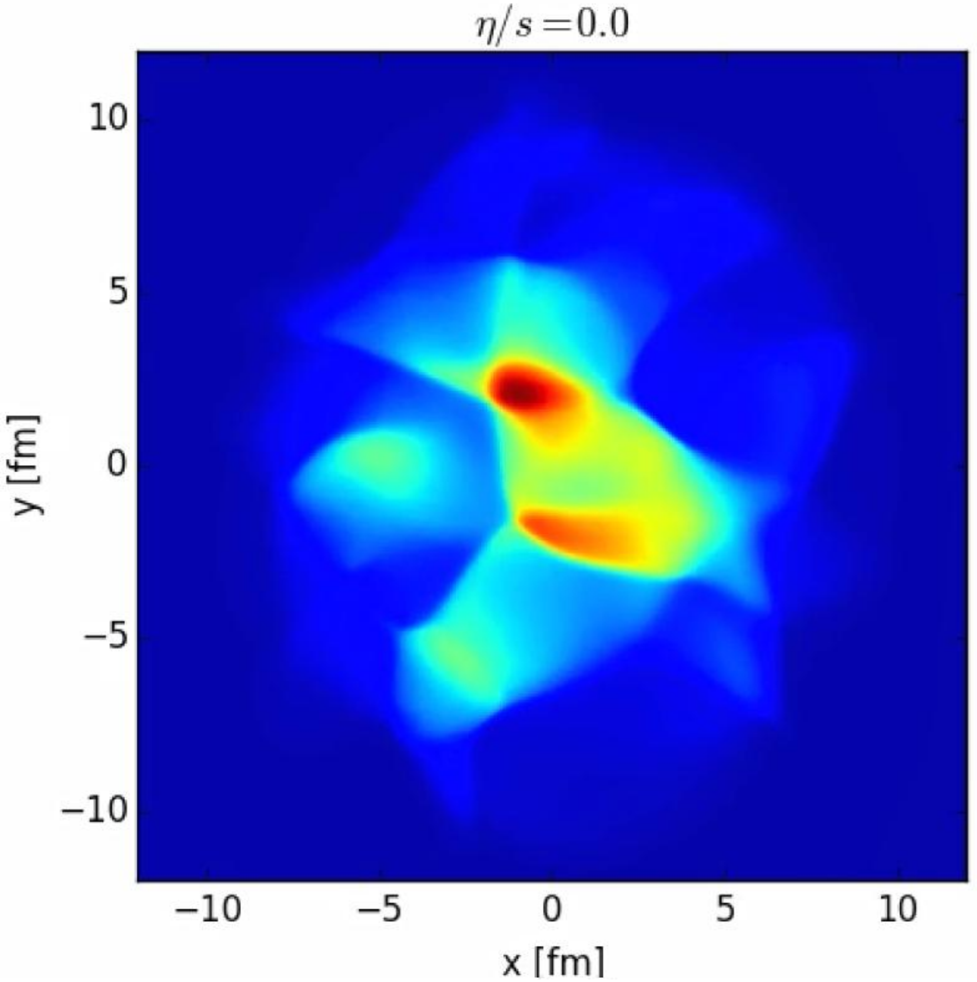
Alver and Roland (MITHIG)
“Collision geometry fluctuation”
PRC82 (2010) 039903

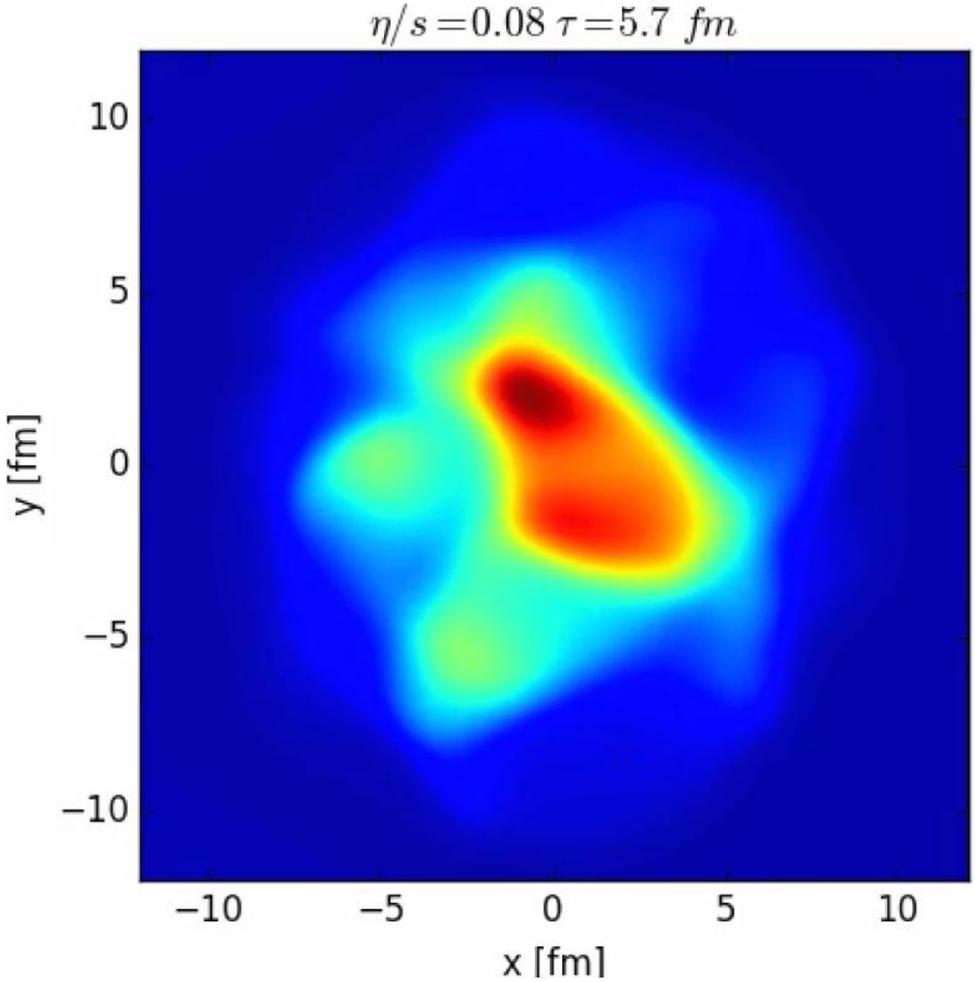
Ideal hydrodynamics

η/s = 0

Viscous hydrodynamics

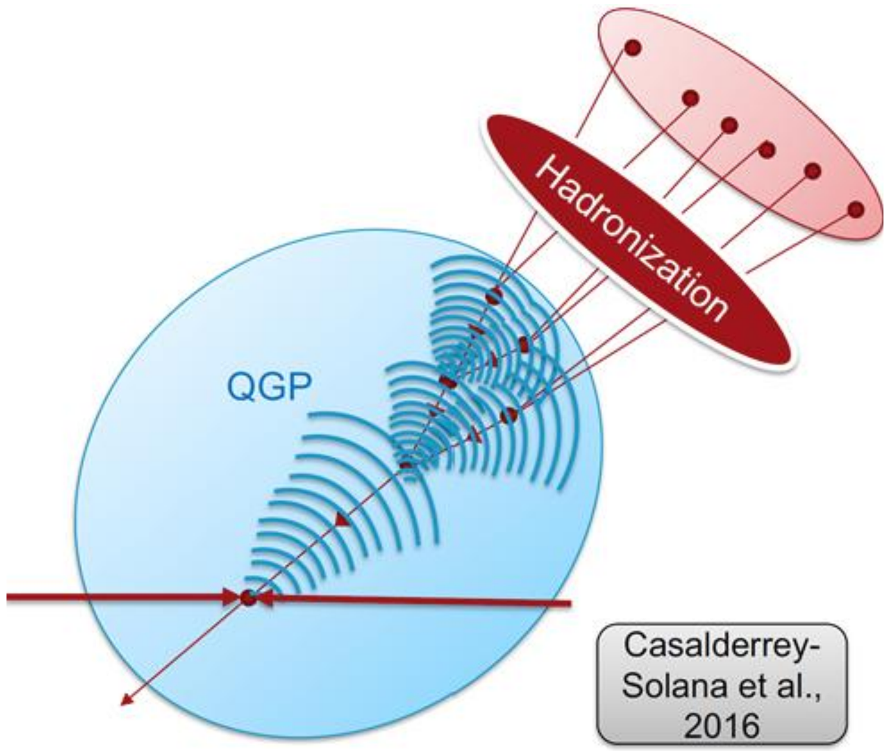
η/s = 0.08





Animation from L. G. Peng

Effect of Shear Viscosity in Medium Response

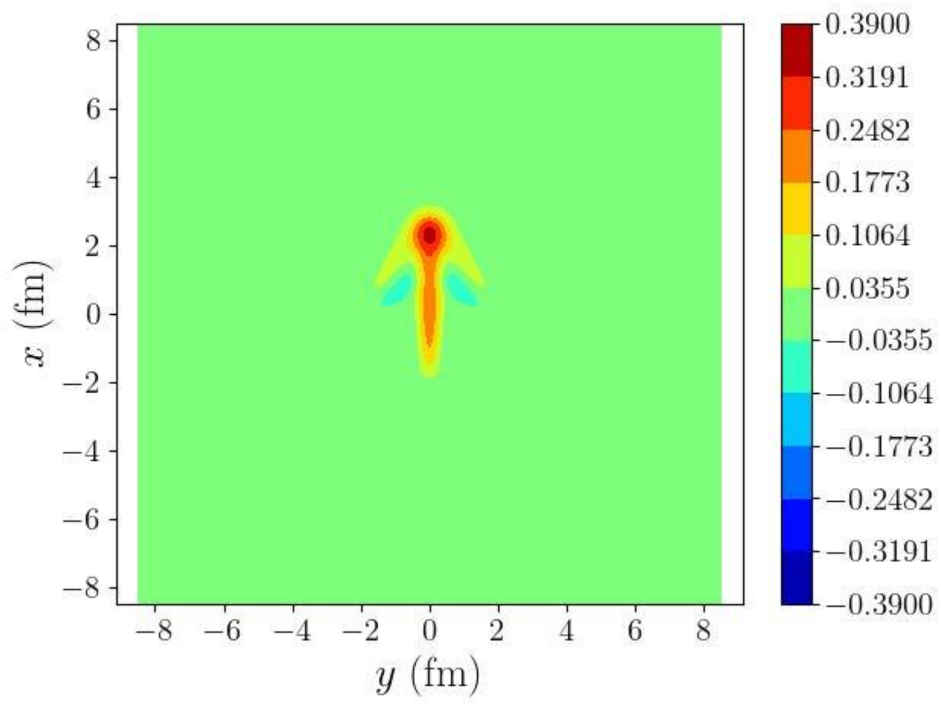


Krishna Rajagopal et al.

Fluid velocity field

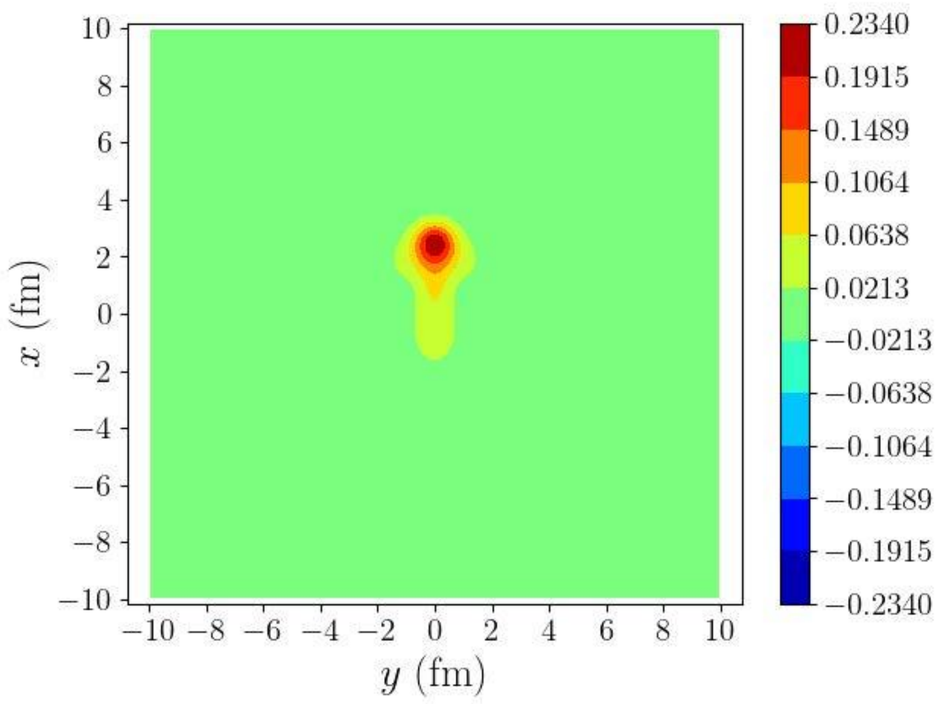
Ideal hydrodynamics

η/s = 0



Viscous hydrodynamics

η/s = 0.08



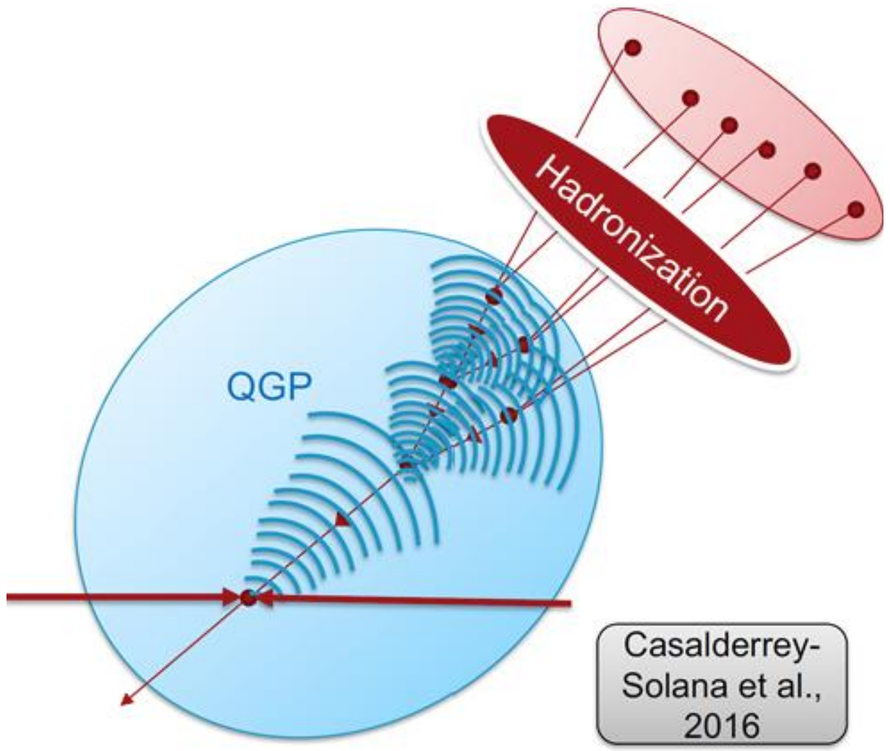
Effect of Shear Viscosity in Medium Response

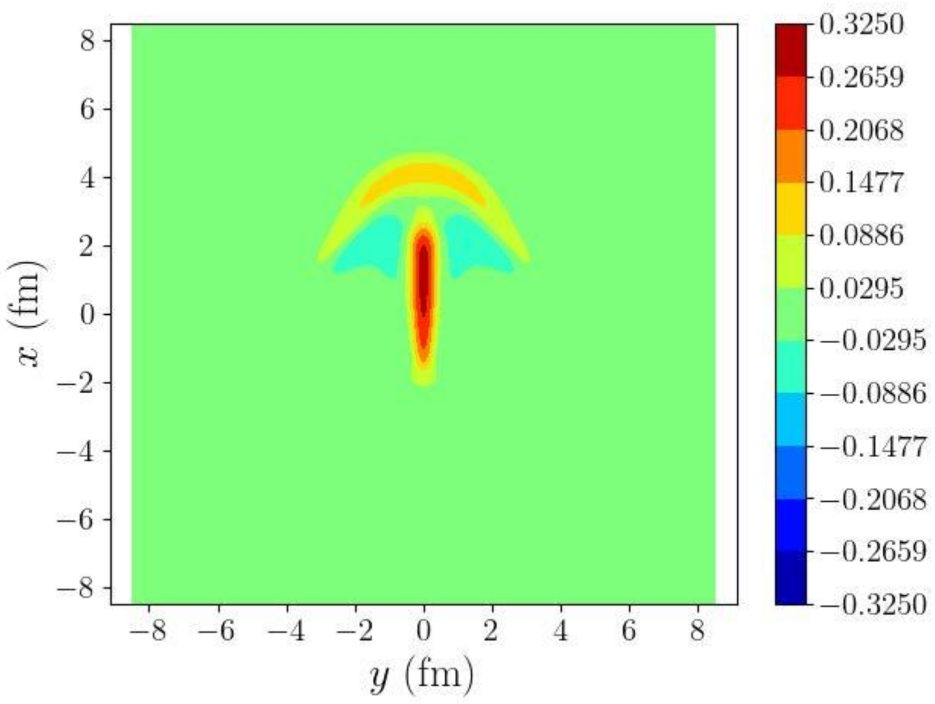
Ideal hydrodynamics

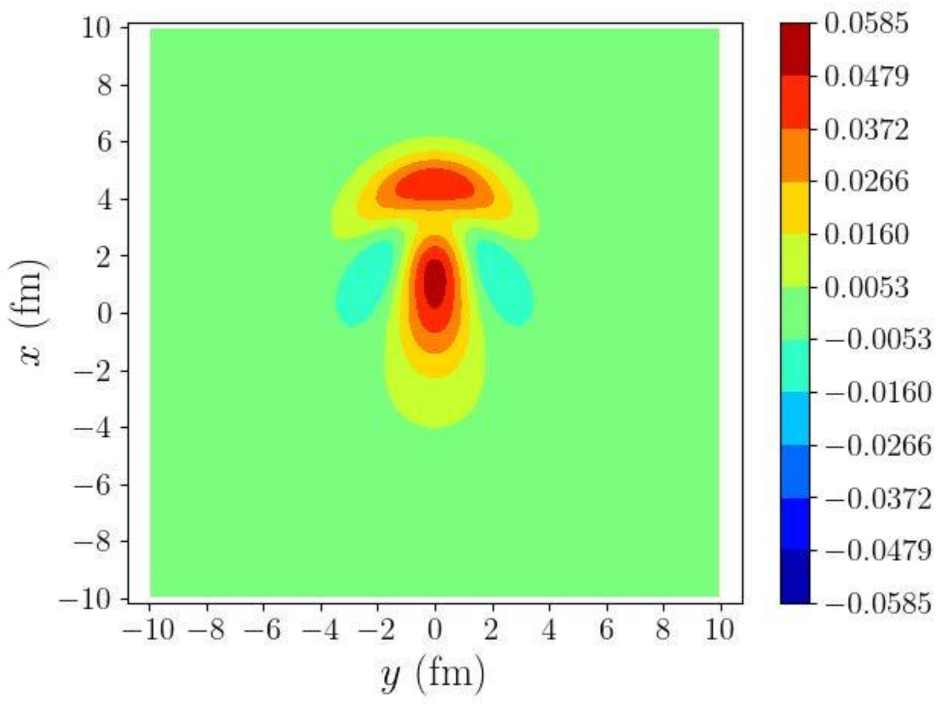
$\eta/s = 0$

Viscous hydrodynamics

$\eta/s = 0.08$



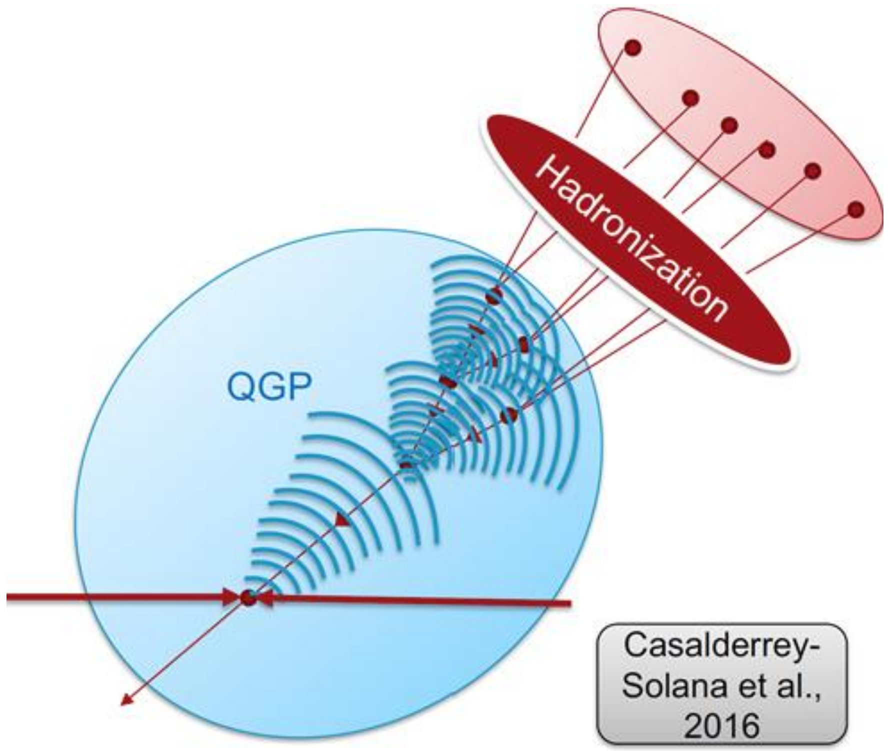




Krishna Rajagopal et al.

Fluid velocity field

Effect of Shear Viscosity in Medium Response

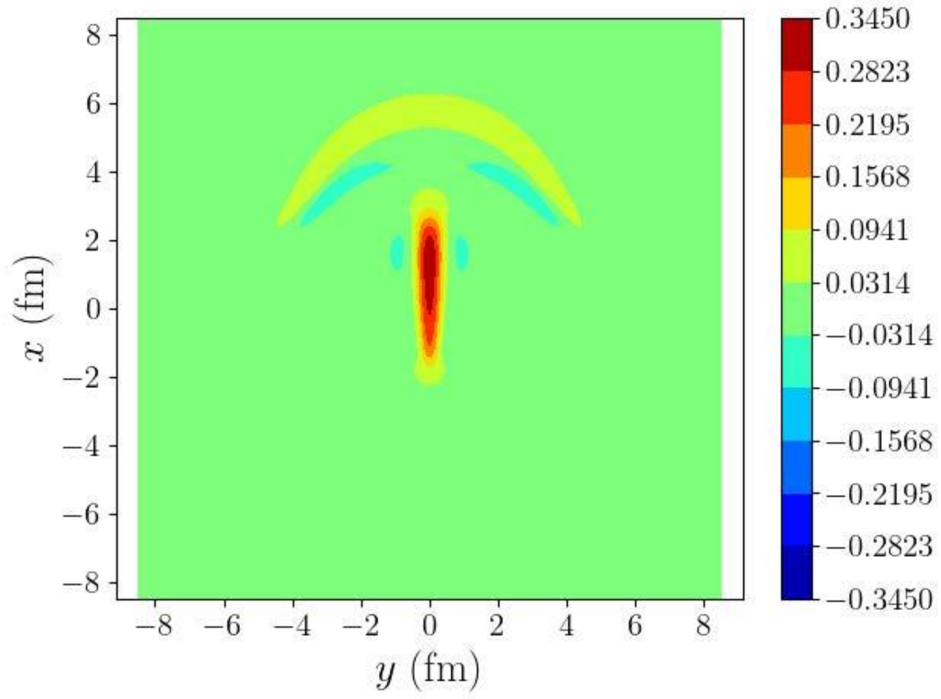


Krishna Rajagopal et al.

Fluid velocity field

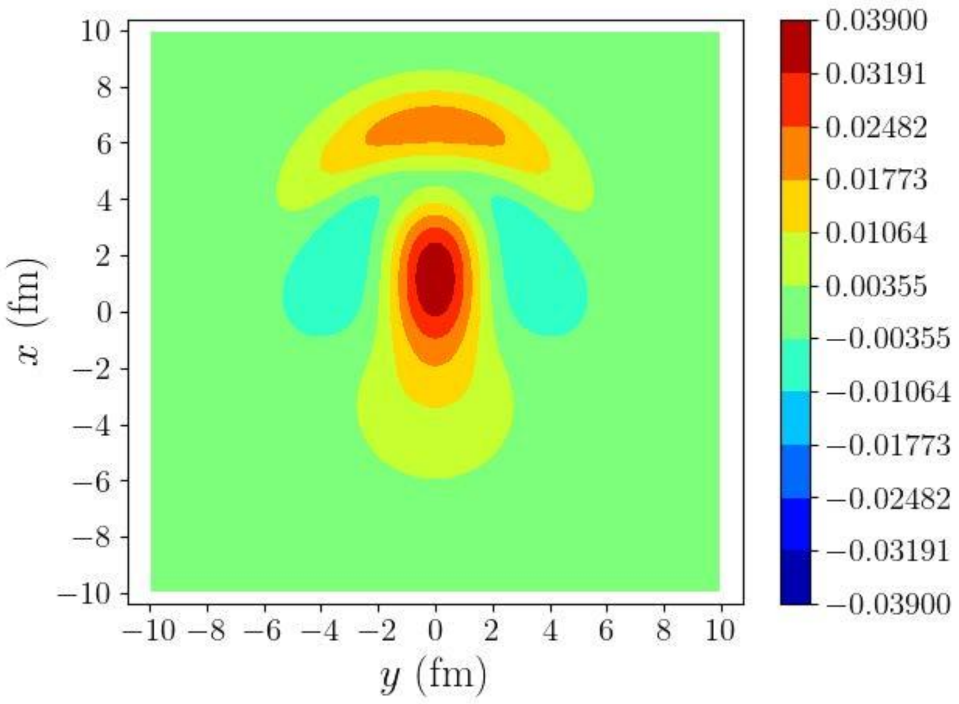
Ideal hydrodynamics

η/s = 0



Viscous hydrodynamics

η/s = 0.08



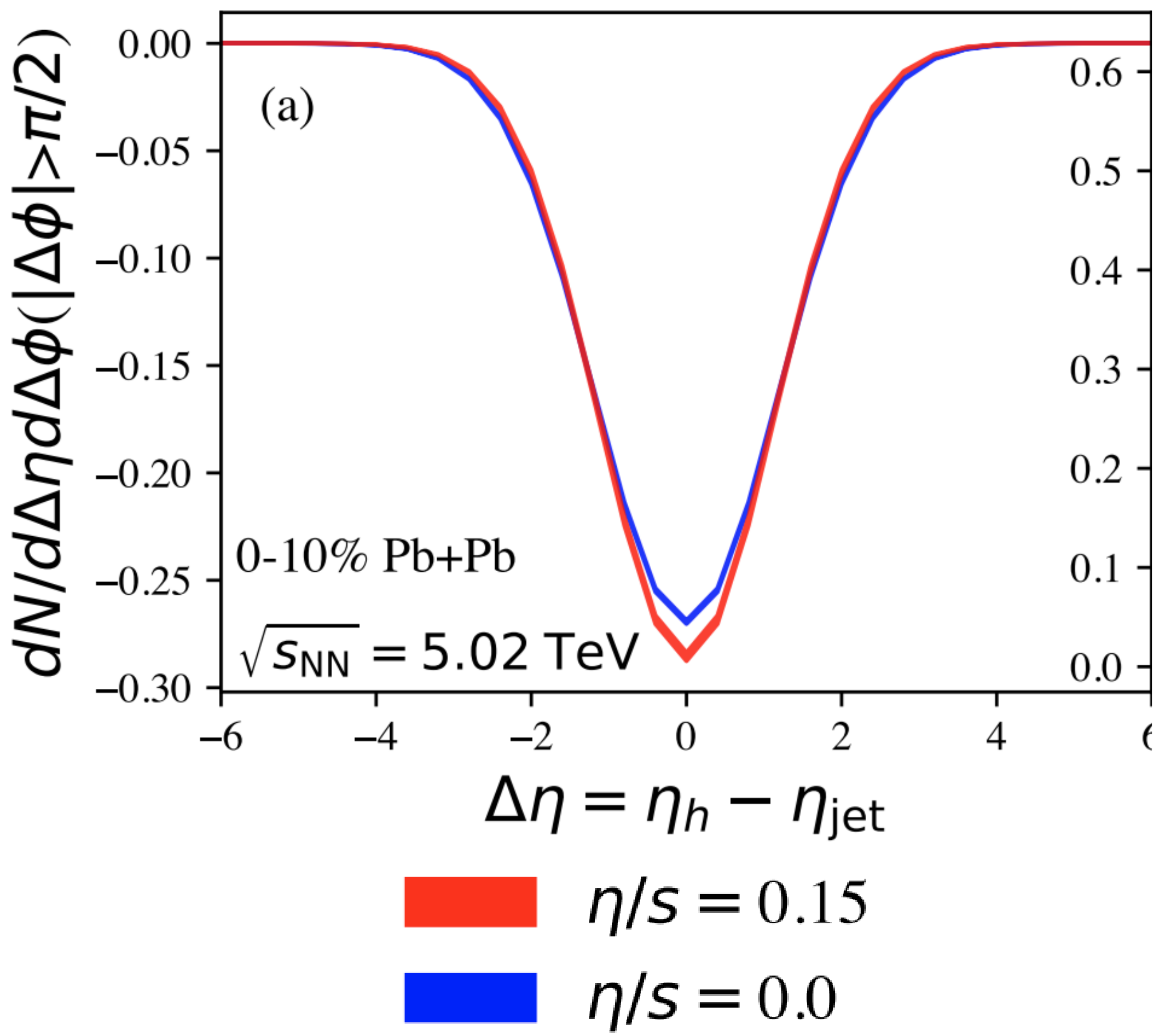
Sensitivity to Specific Shear Viscosity and EoS

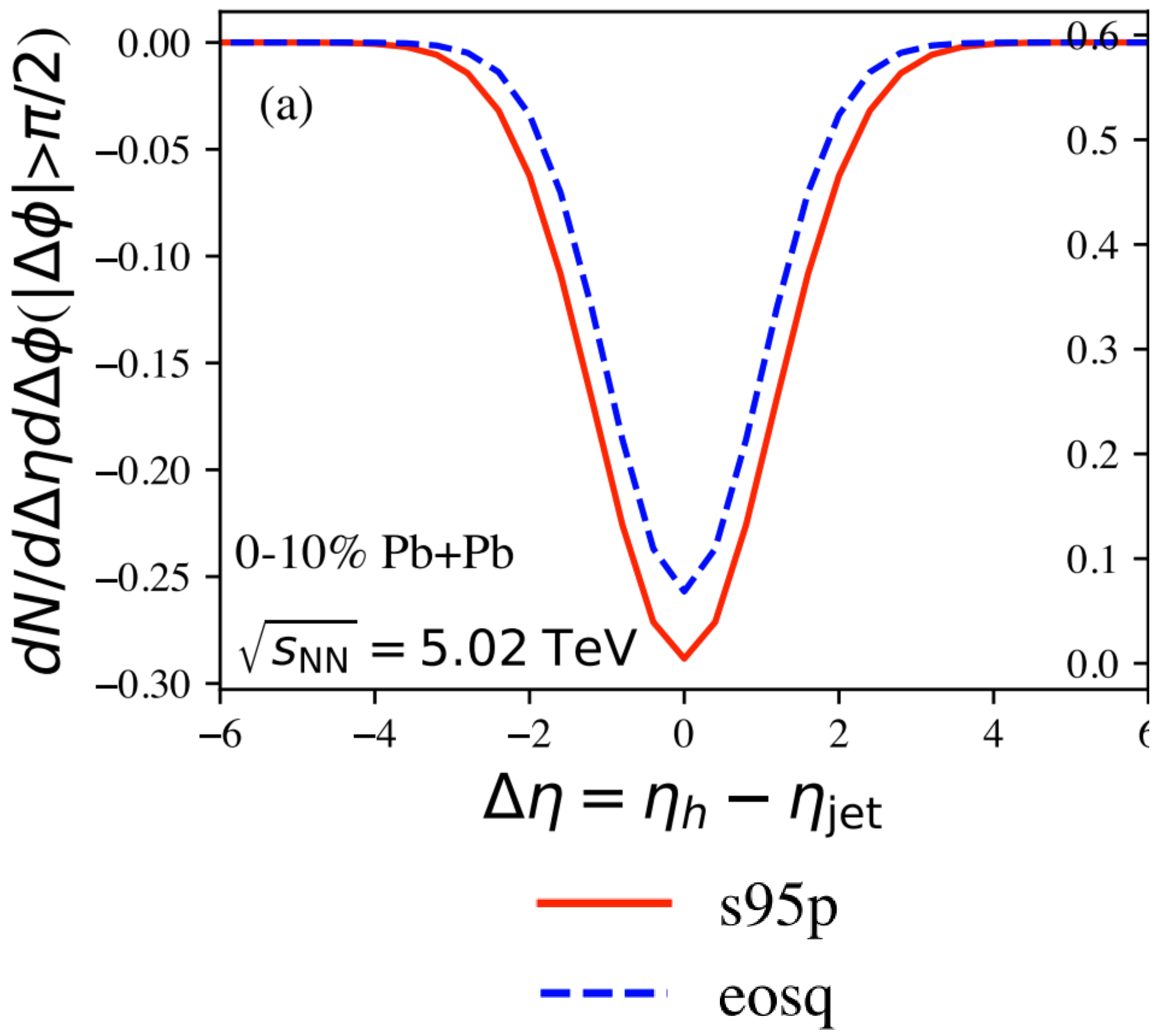
Jet and **Hadron** correlation in **Photon-Jet event**

QGP wake in CoLBT

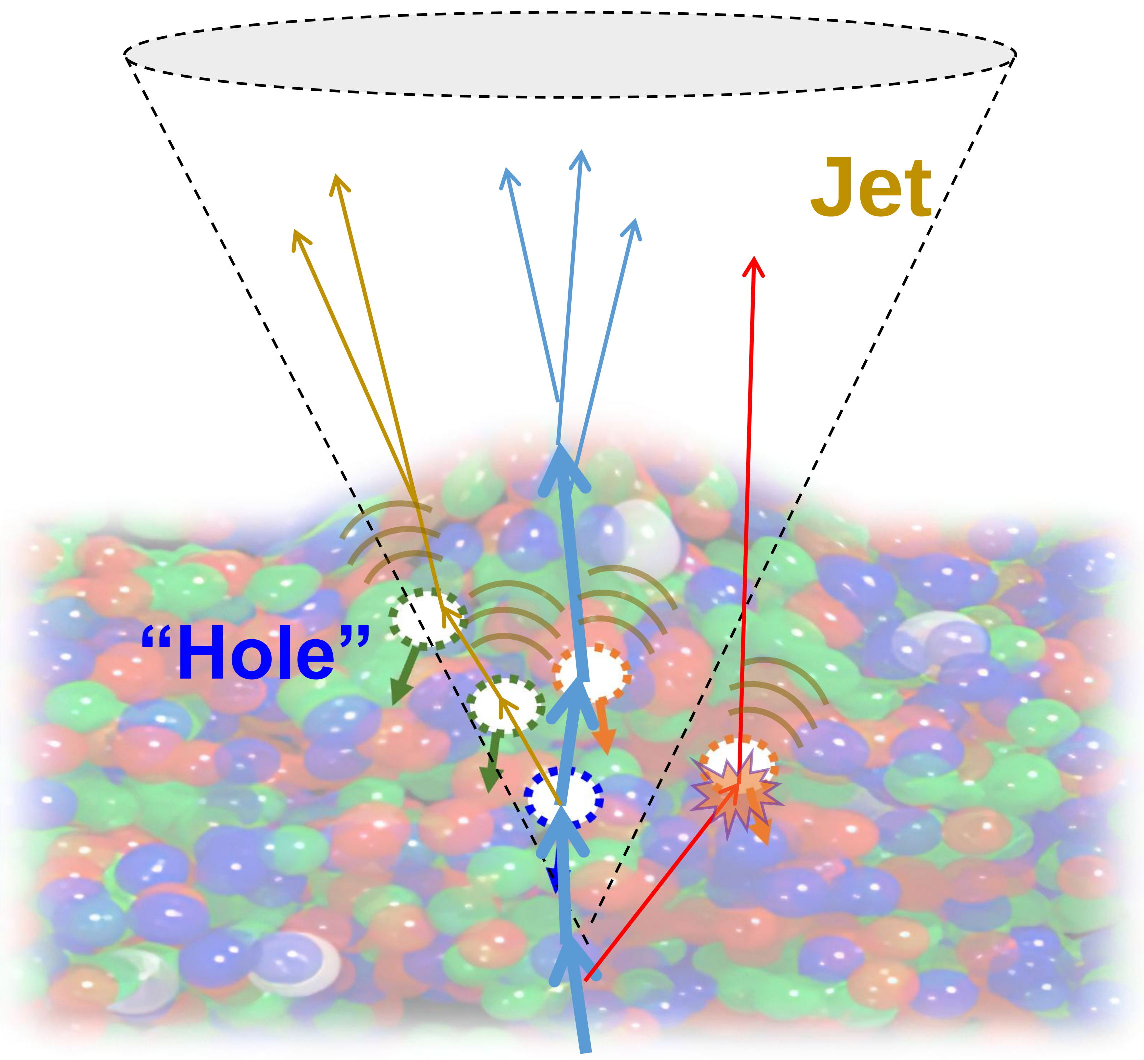
PRL 130, 052301 (2023)

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





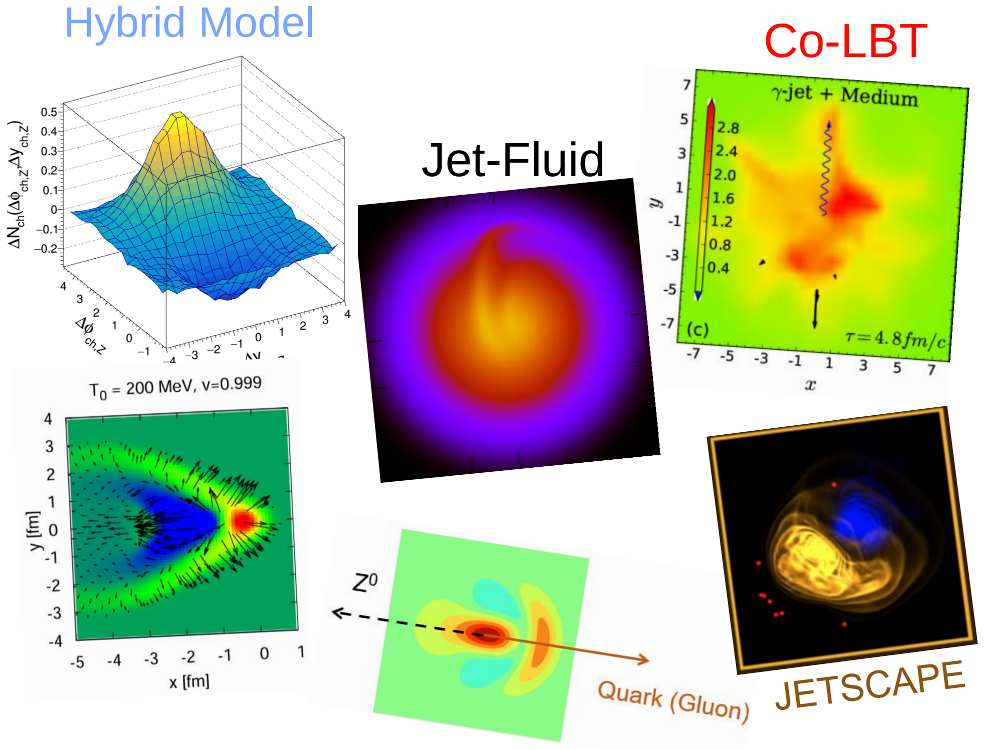
QGP Transport Properties and Structure with Jets

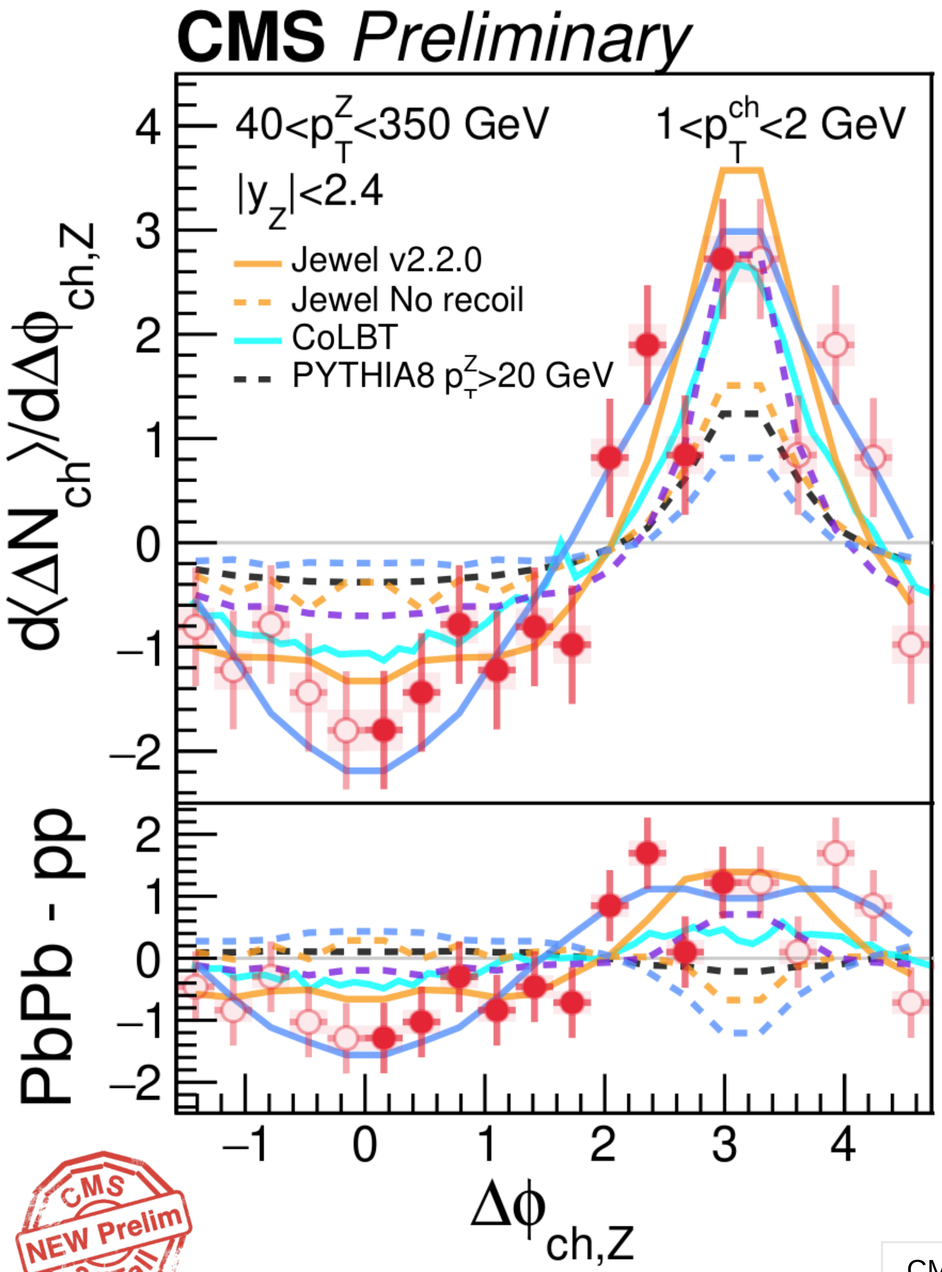


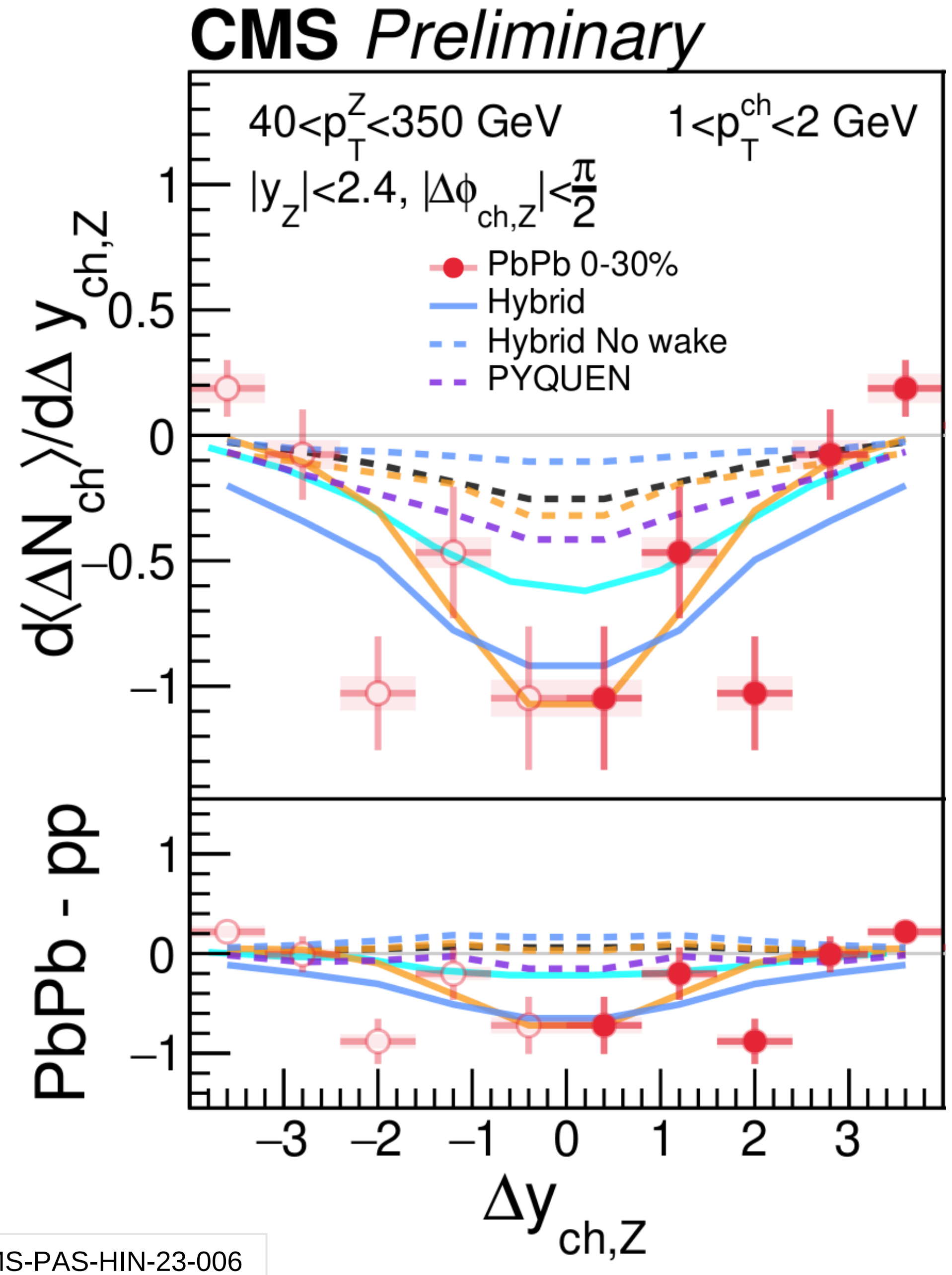
- Jet broadening effects from multiple soft scattering ($\hat{q}$) and medium induced radiation
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes / Negative wake)
- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere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

Summary

- **The first direct evidence of medium response in QGP**
- High statistics analysis with Run3+4 data in the near future
- This phenomenon marks the beginning of a new era in studying QGP properties using hard probes







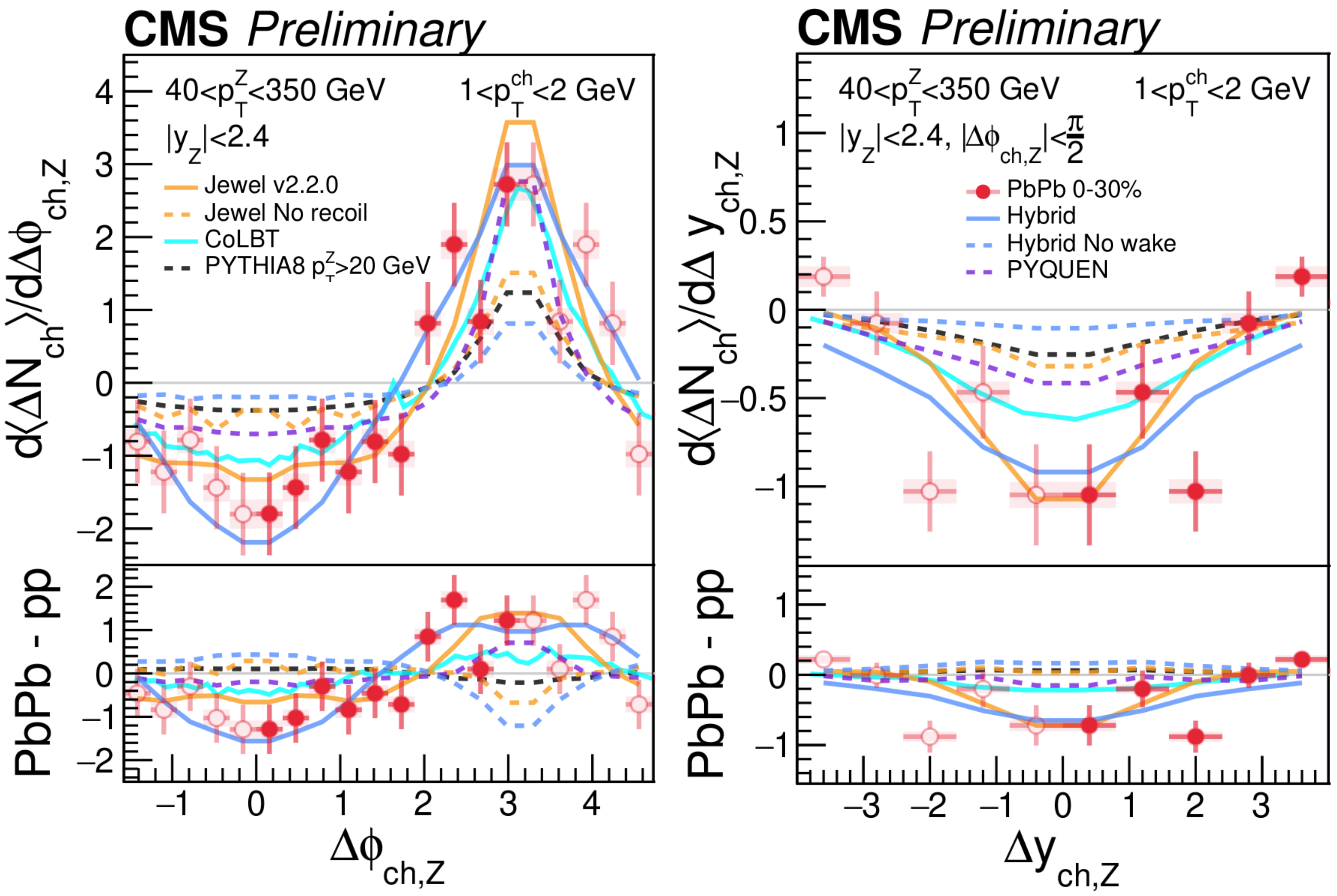
CMS-PAS-HIN-23-006

Thank You!

Backup Slides

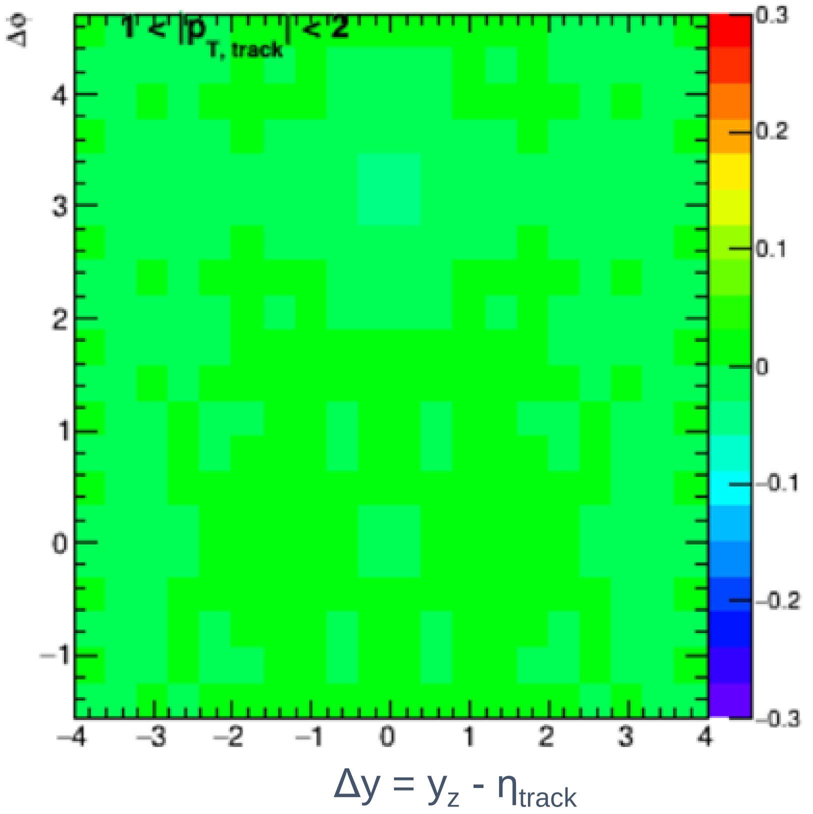
What We Still Want to Learn from Experimental Data

- 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?
- …

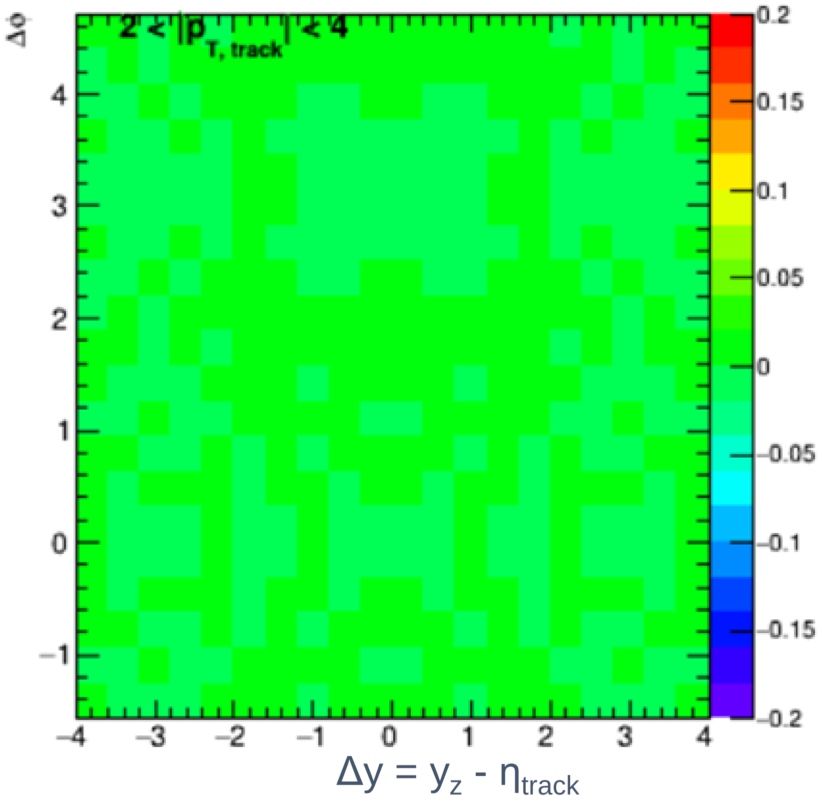


2D Results (PYTHIA+HYDJET 0-90% - PYTHIA)

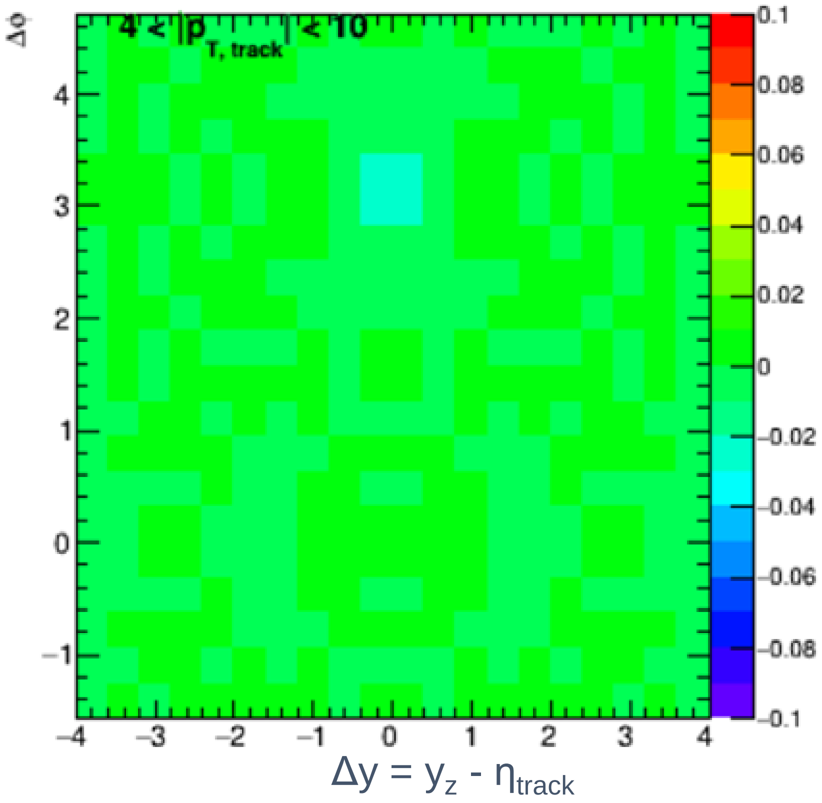
Charged Hadron p_T =1-2 GeV



2-4 GeV

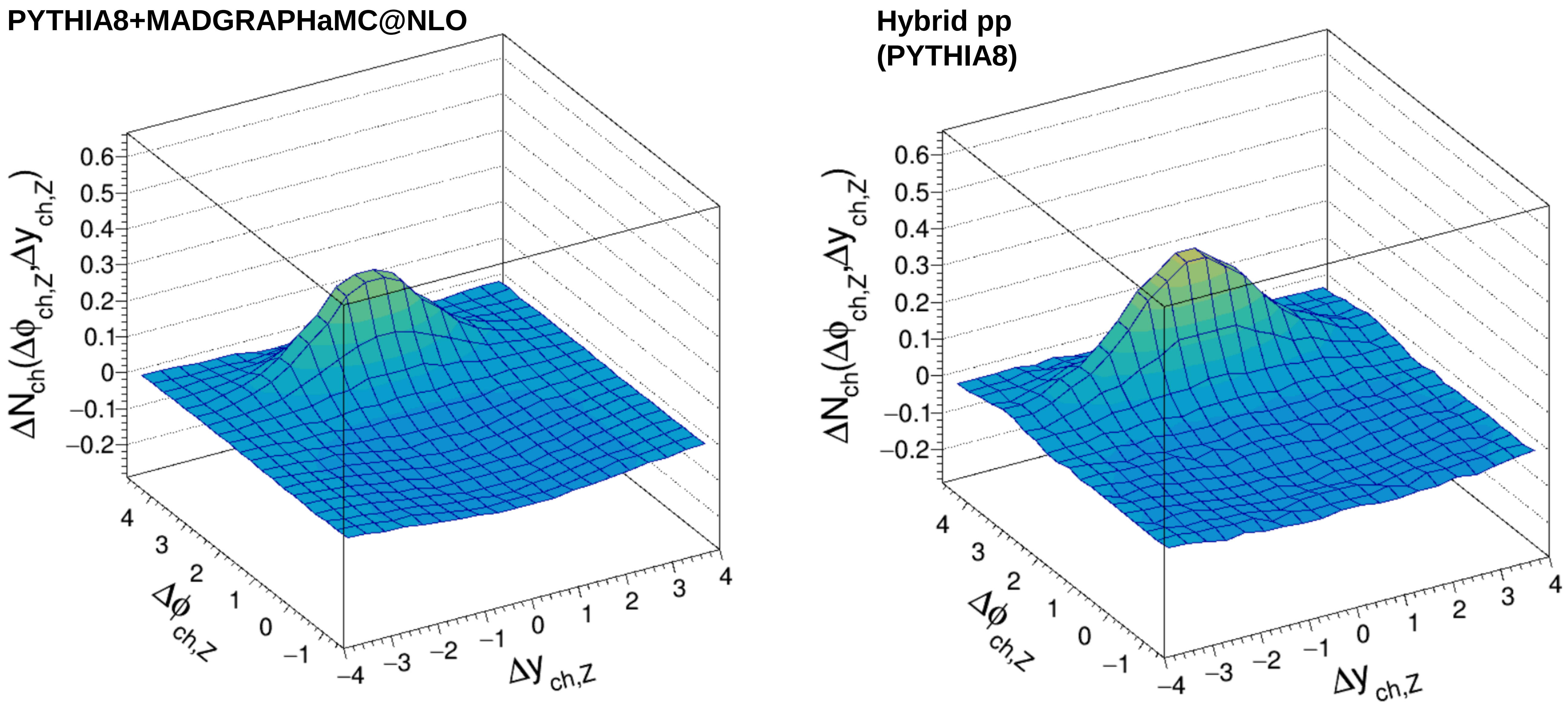


4-10 GeV



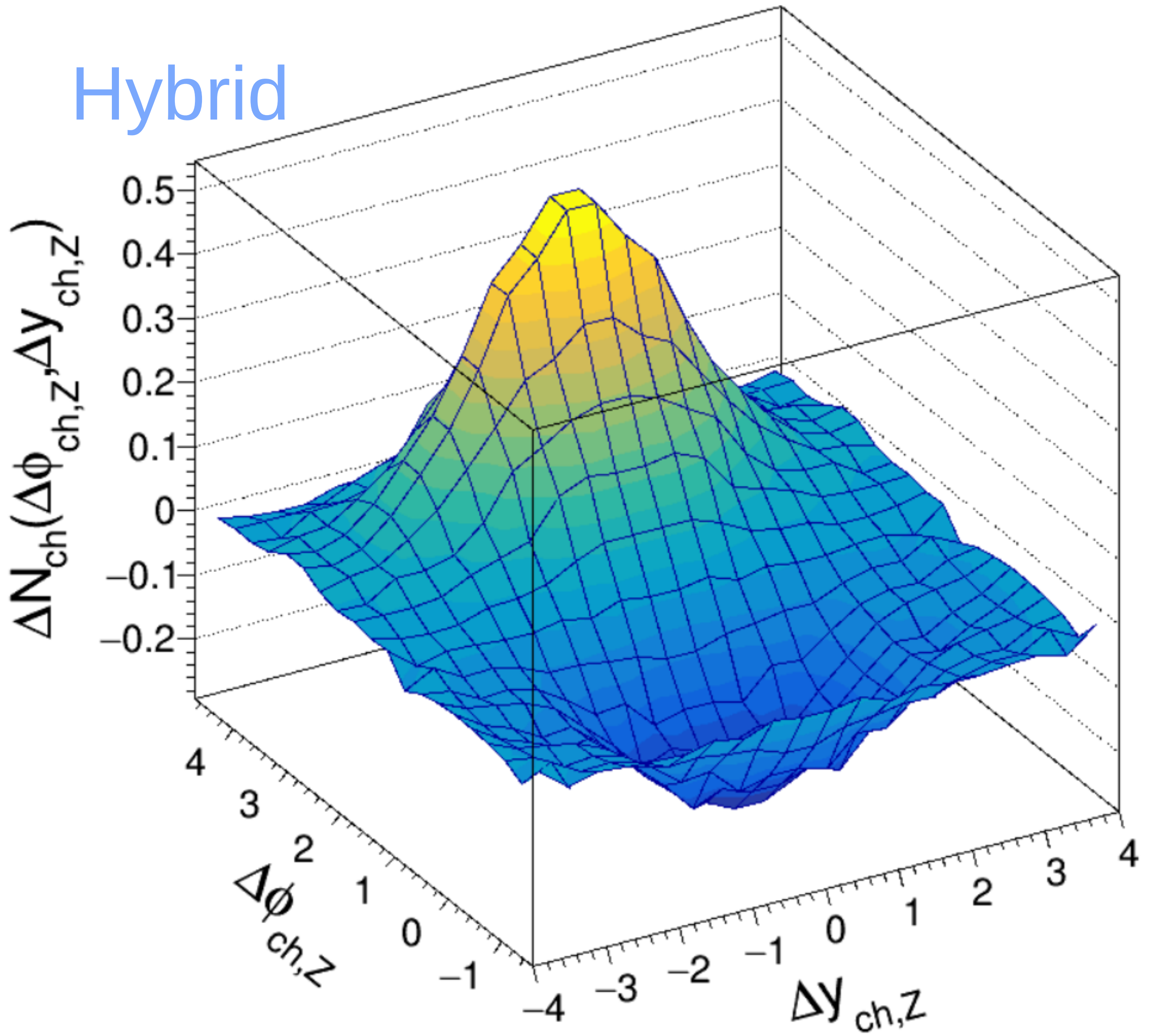
- Embed **PYTHIA8** in **HYDJET** event (model the underlying event in PbPb collisions at 5.02 TeV)
- The background subtracted results **with** and **without** PbPb underlying event agrees well:
  - →The subtraction method removes the uncorrelated UE.

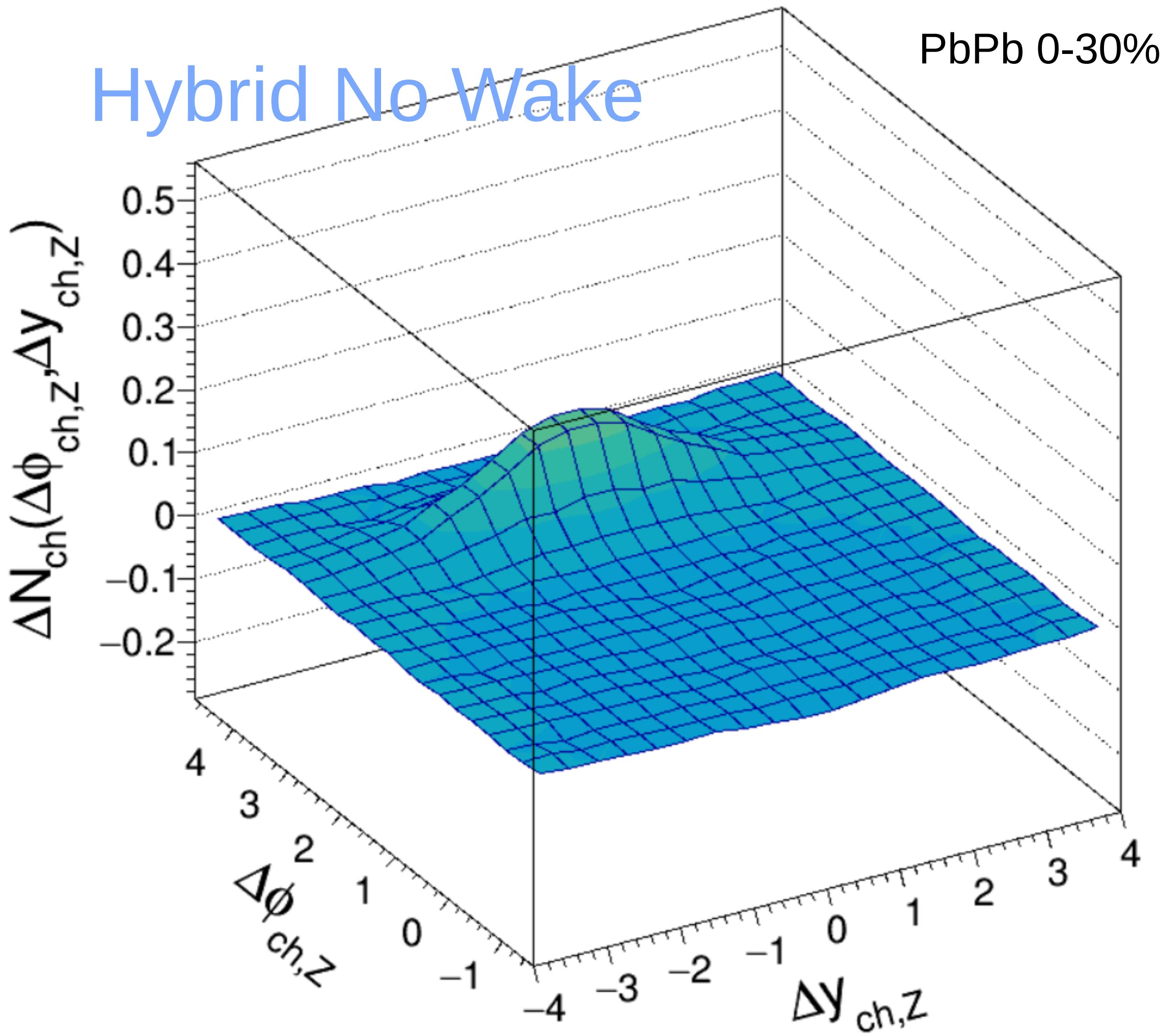
Predictions from Models in pp for Charged Hadron p_T 1-2 GeV



- NLO event generator gives a slightly **broader jet peak** than PYTHIA8
- Identical subtraction procedure applied to both MC model results and the data analysis

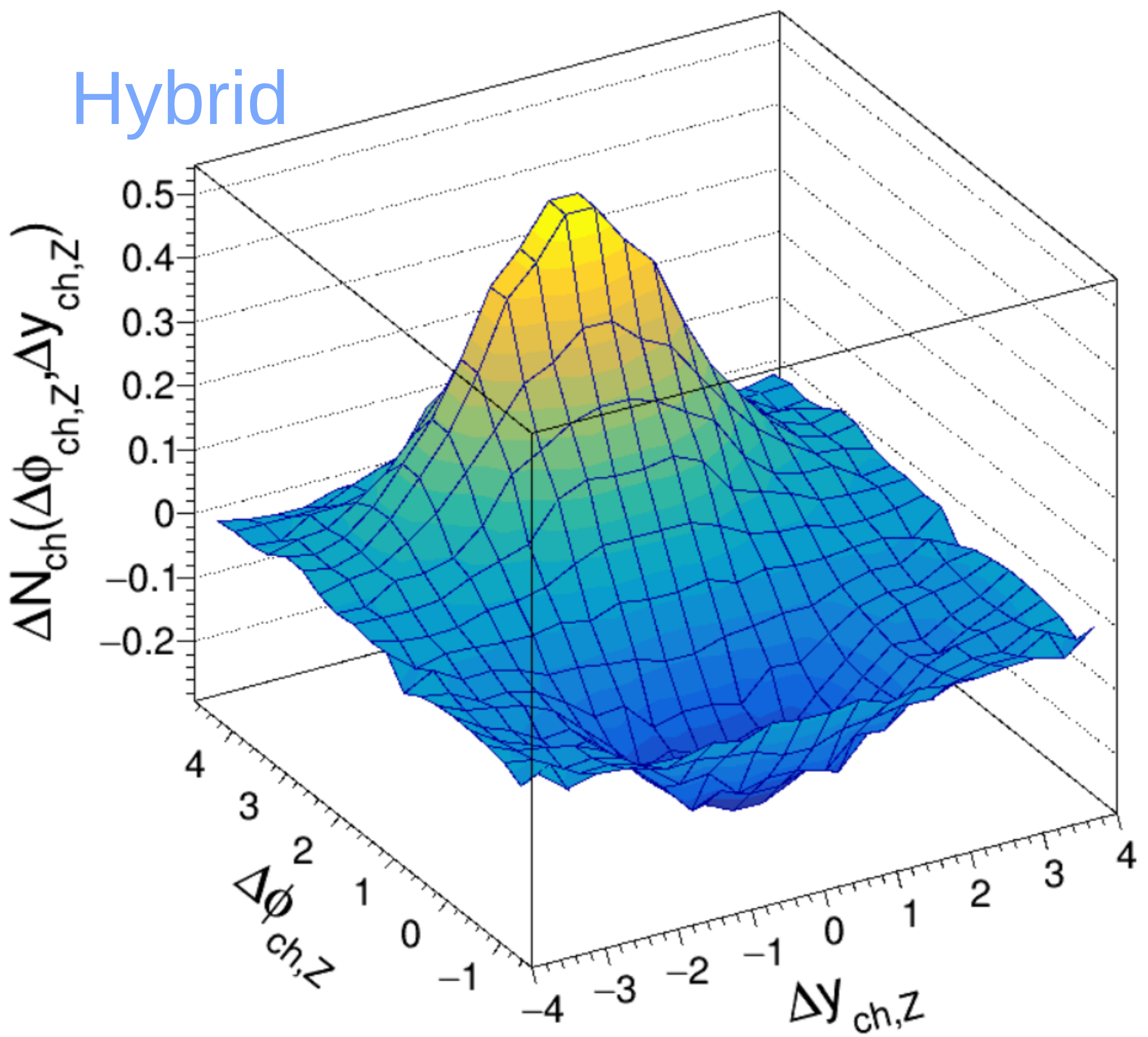
Predictions from Models for Charged Hadron p_T 1-2 GeV

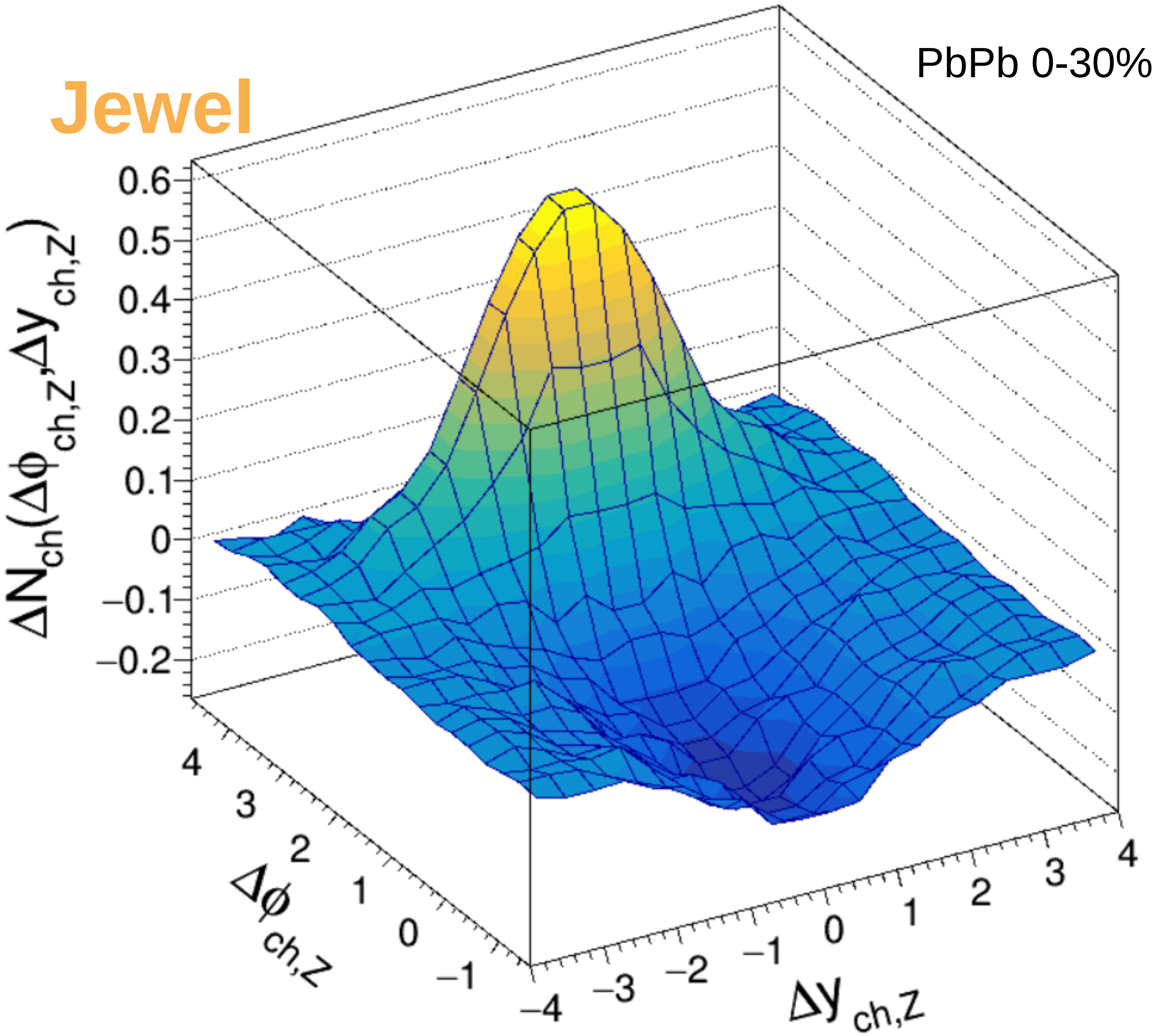




- **Hybrid**: **QGP** wake creates a **Z-side dip structure** and significantly enhance the jet peak (pQCD parton shower + AdS/CFT drag + hydro medium response)

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 (pQCD with **no re-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 +…

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)

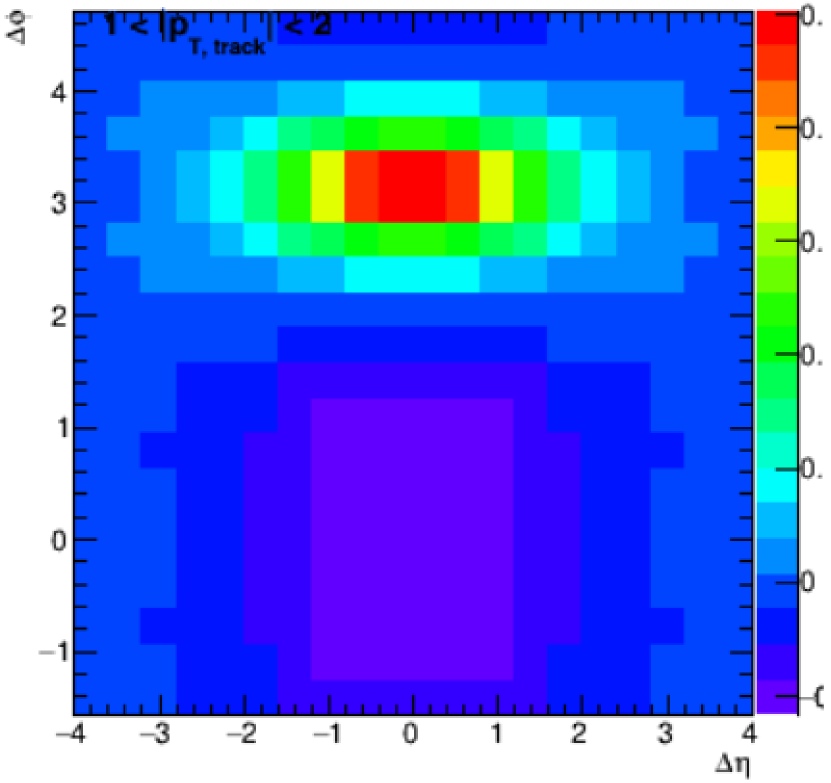
Sub-jet multiplicity, jet substructure
γ/Z+hadron at intermediate p_T
+…

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

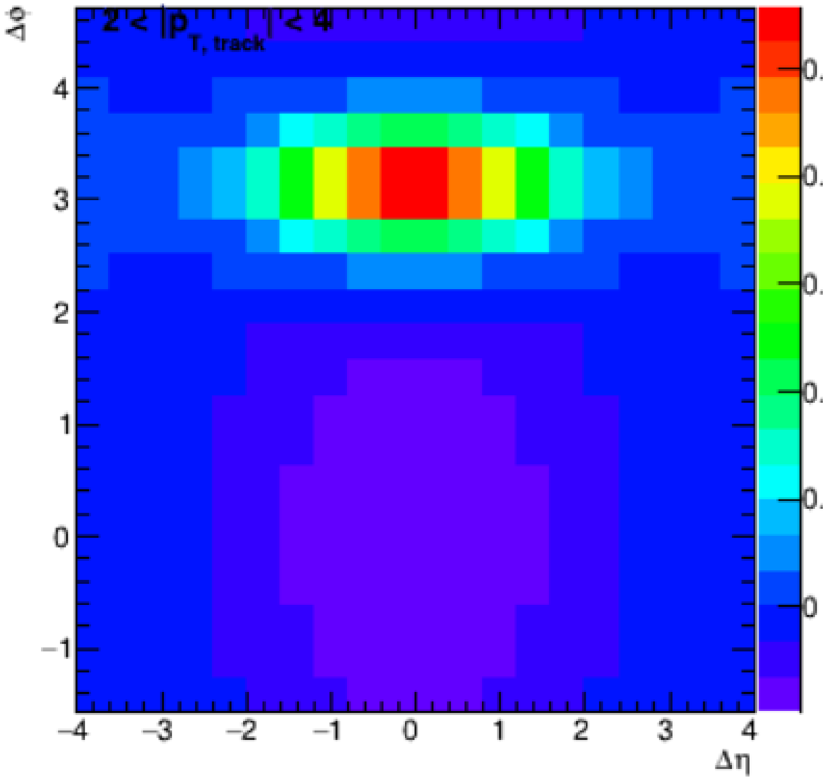
We have a clear path forward!

2D Distribution (pp PYTHIA)

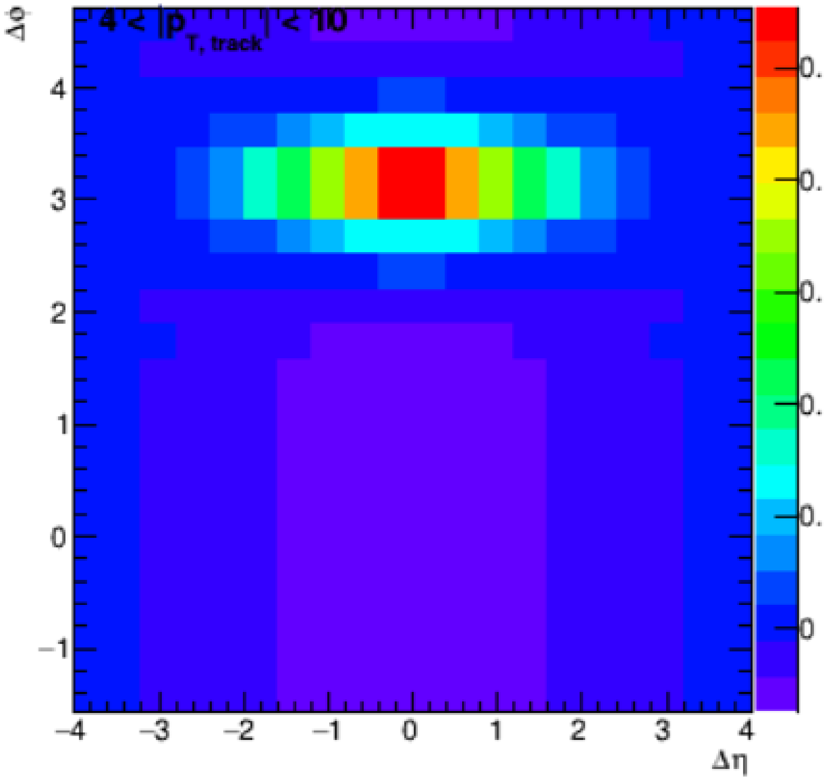
Track = 1-2 GeV



2-4 GeV



4-10 GeV



Delta eta = eta_ch - y_Z

Low Track p_T → High Track p_T

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

Correlated with Z1

Uncorrelated with Z1

−

Uncorrelated with Z1

Uncorrelated with Z1

=

"Excess correlation" with Z

Event 1

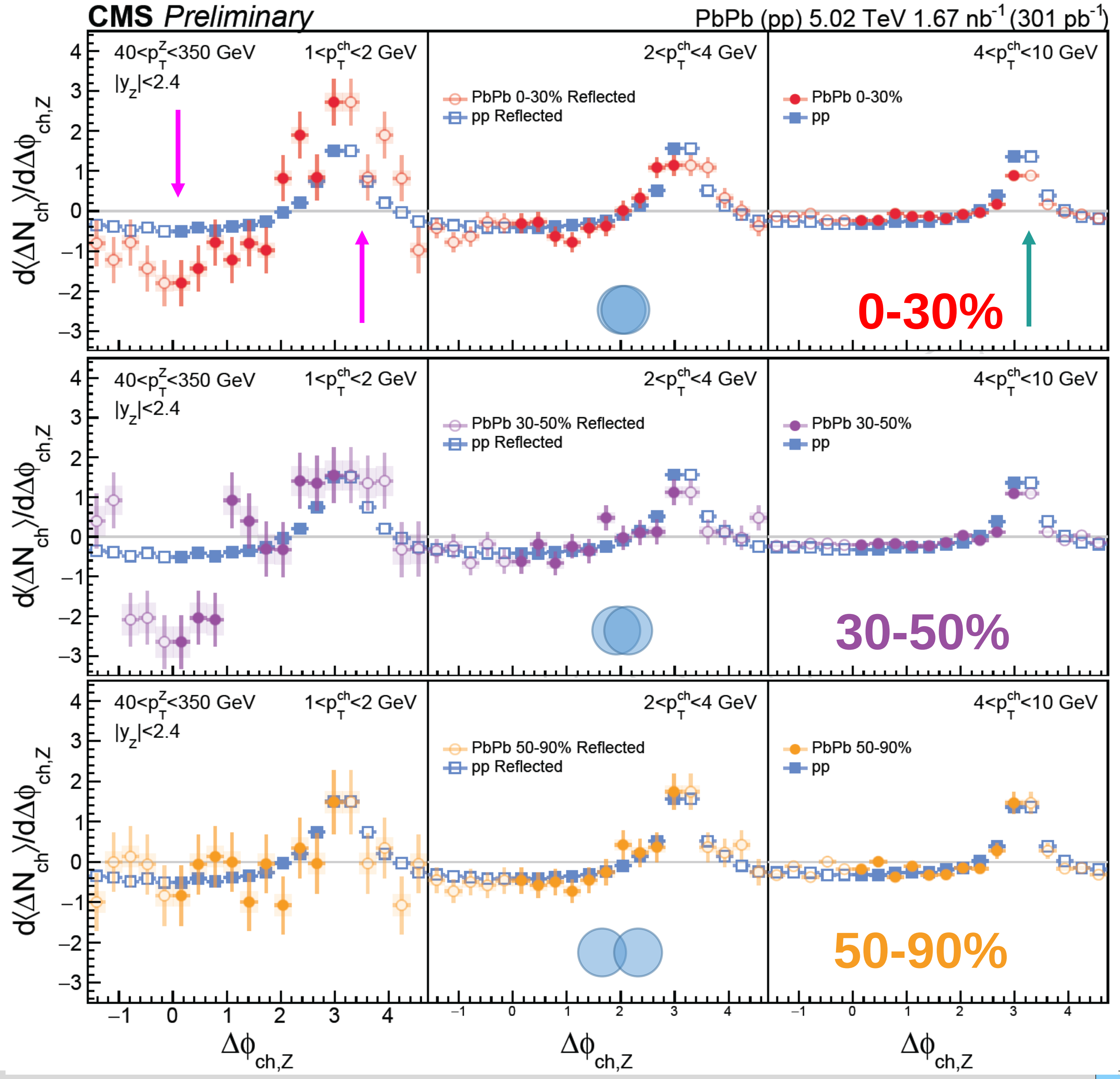
Event 2
Correlated with Z in event 2, but not correlated with Z in event 1

Same population of events

- Normalize to 0 by construction
- Shape of correlation function across measurement range
  - e.g. small $\Delta\phi$ vs large $\Delta\phi$
- 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

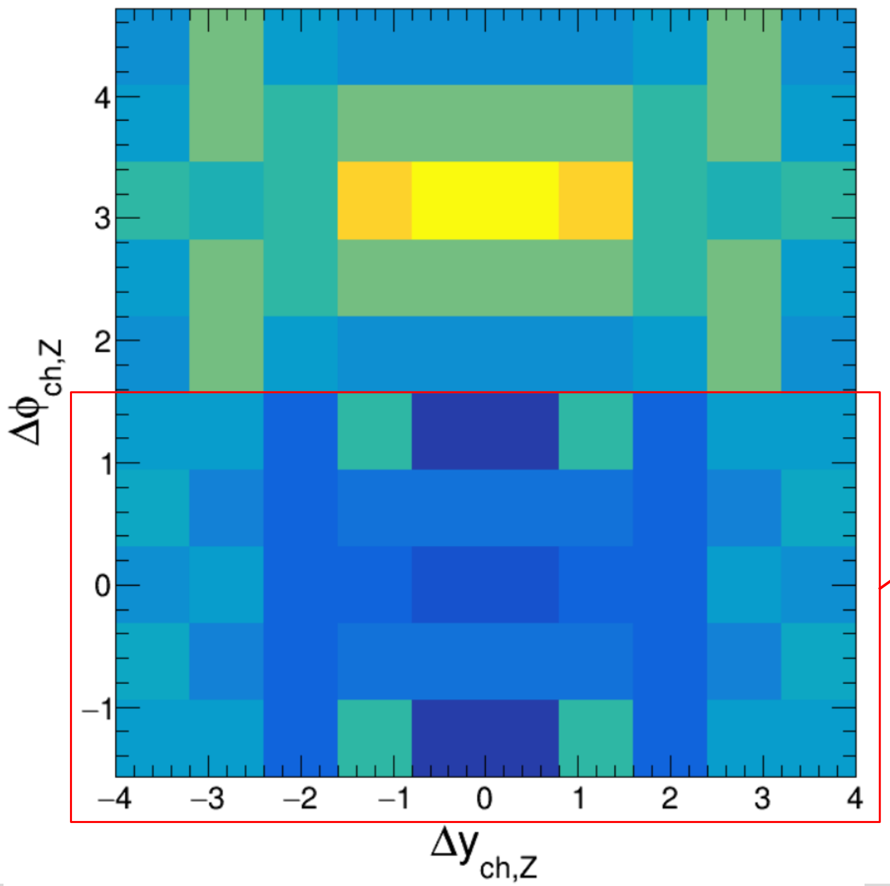
- Open markers are the same as filled data points but reflected to show the full range
- Low track P_T: clear relative depletion in Z side and enhancement in jet side
- High track P_T: jet quenching effect suppresses jet peak
- Effect disappears in **50-90%**

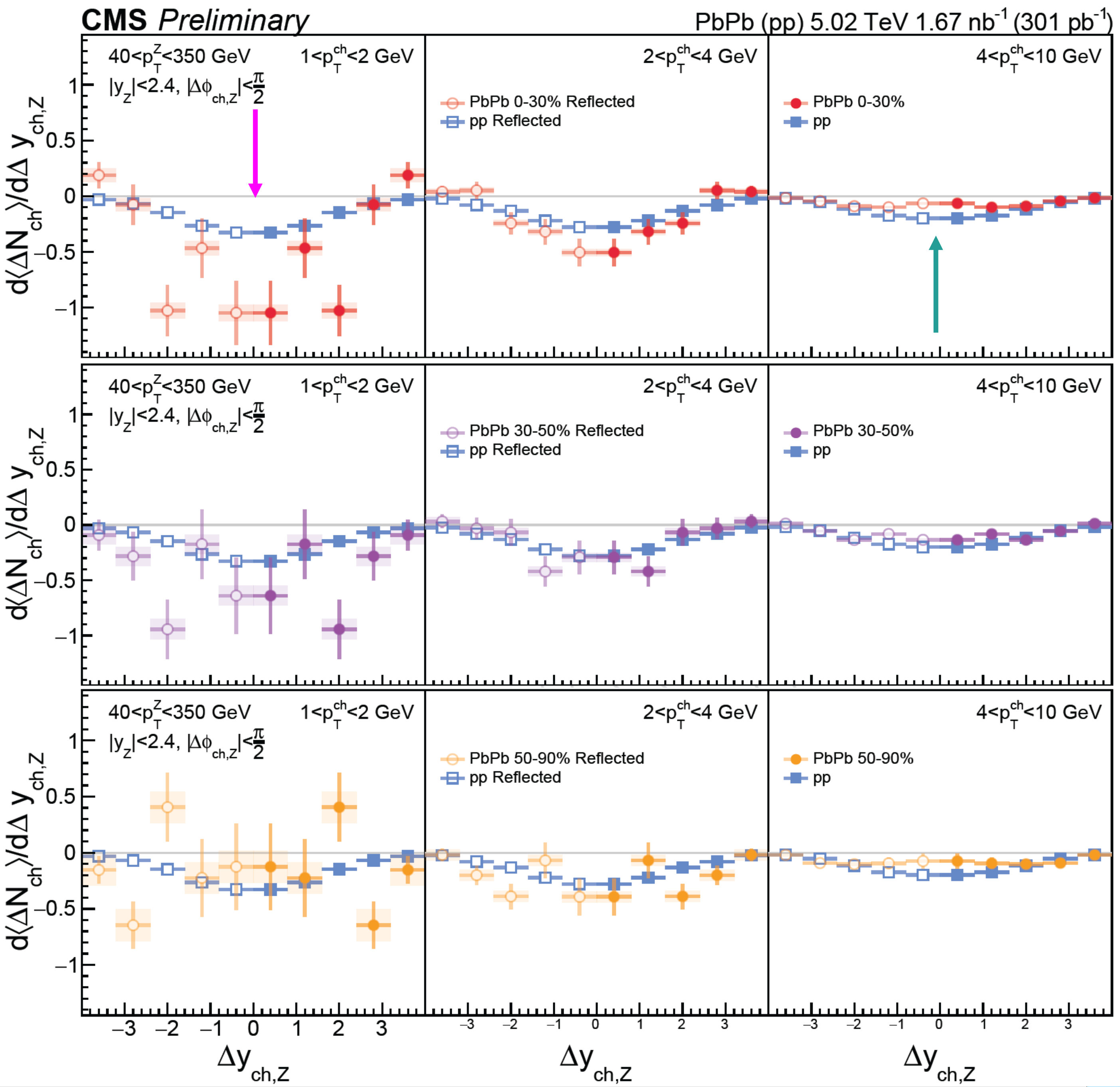


Results: Rapidity Distributions

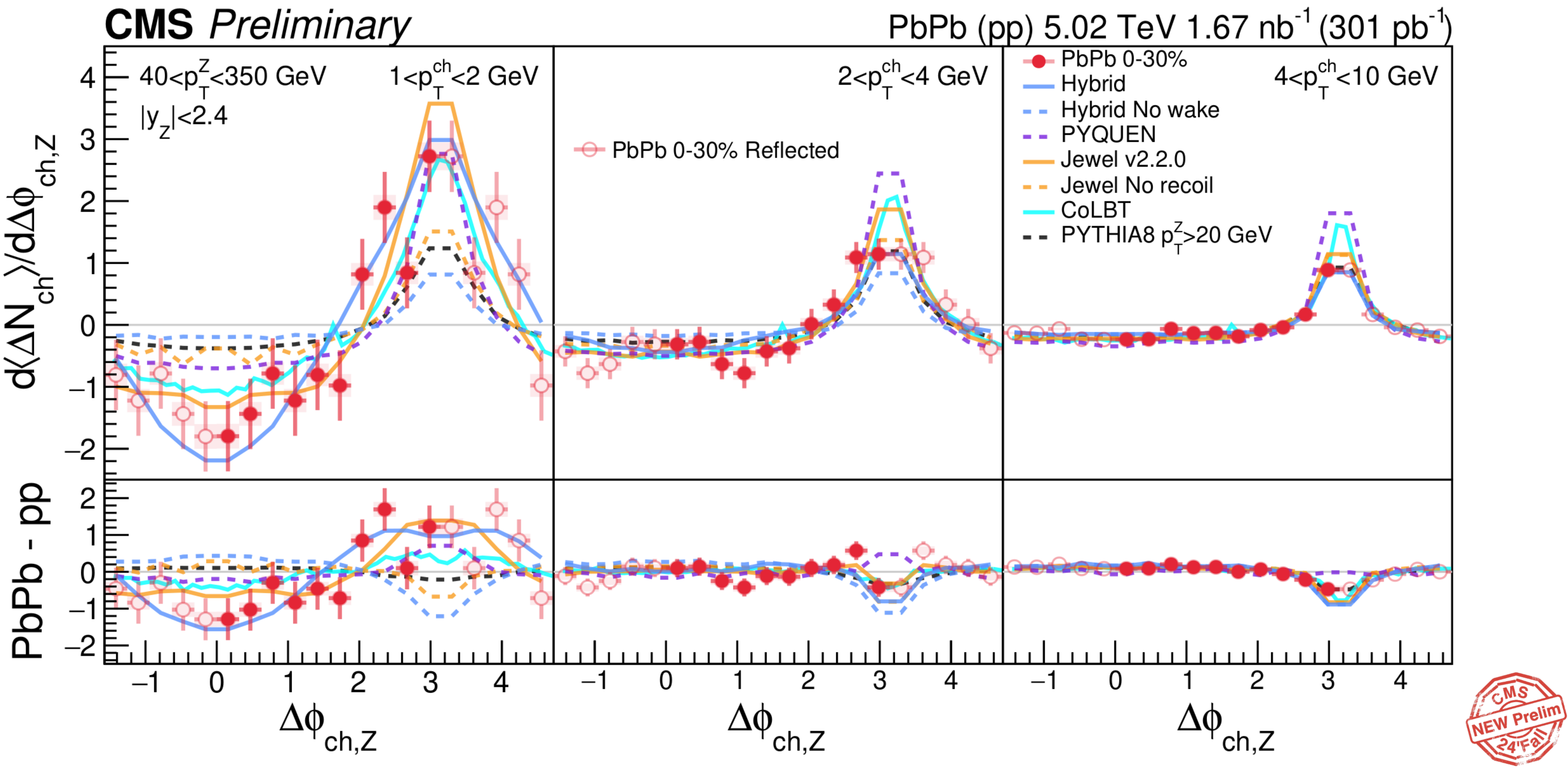
- Focus on the Z side: $|\Delta\Phi_{ch,Z}| < \pi/2$
- Integral **not zero** since this is not full range of $\Delta\Phi$

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

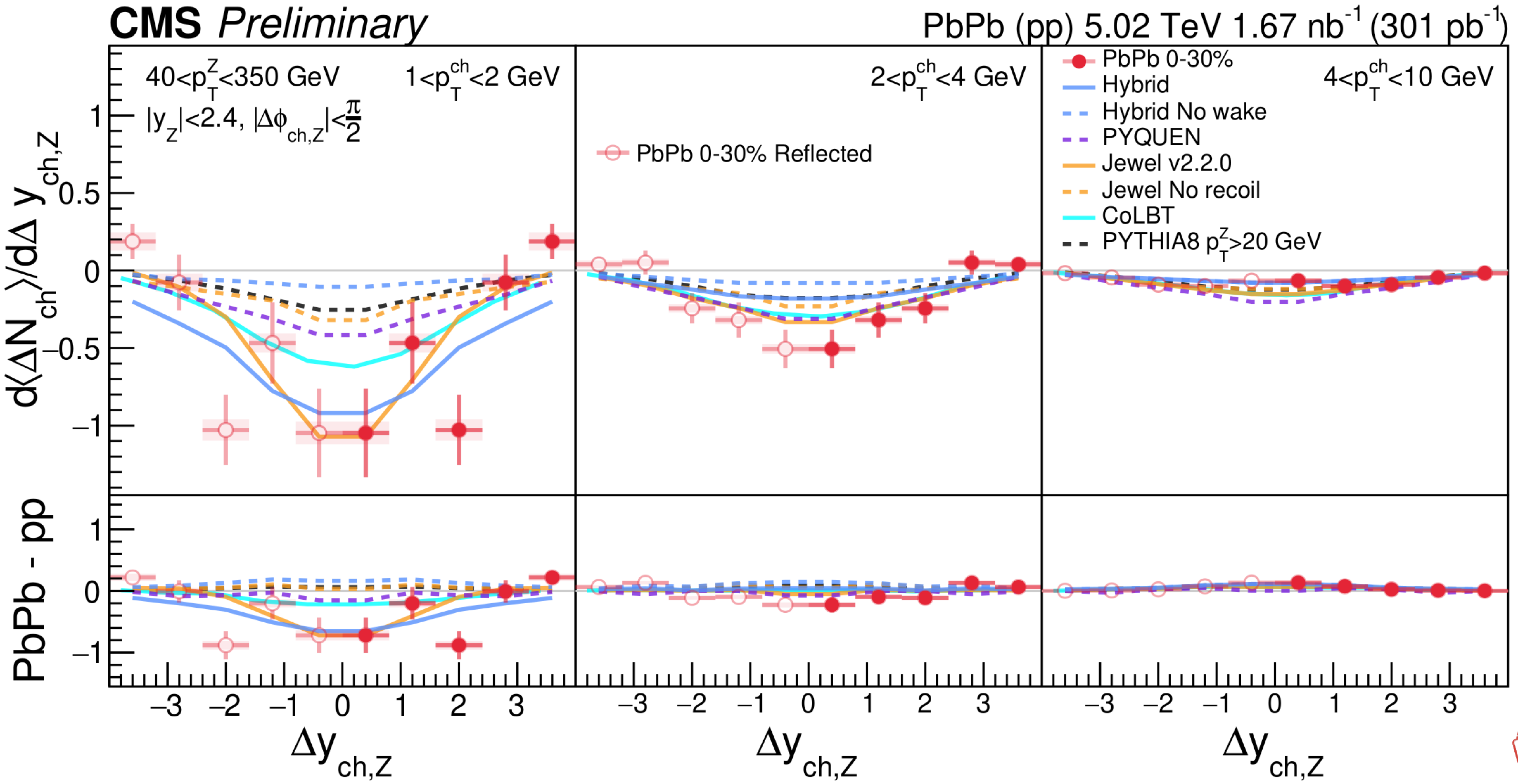




Theory Comparison on Δϕ Spectra



Theory Comparison on Δy Spectra

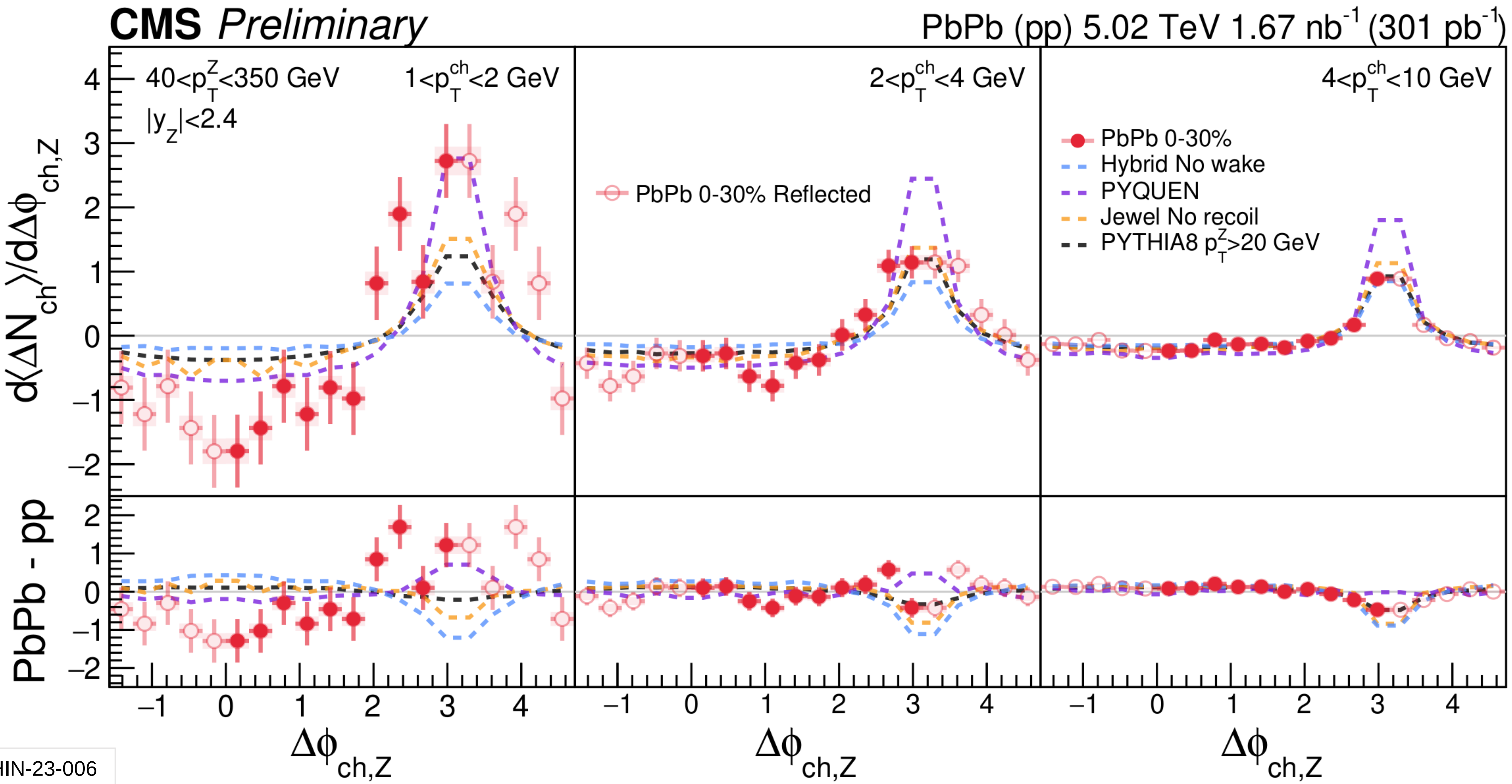


Theory Comparison: Azimuthal Angle Distribution in 0-30% PbPb

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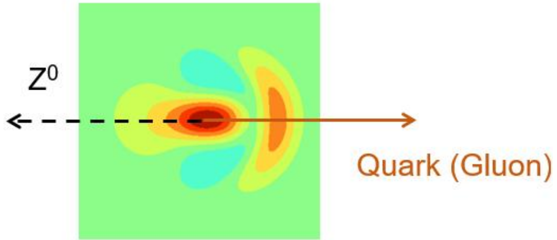
40 GeV Z + 40 GeV jet —Quench→ 40 GeV Z + quenched jet + recoil/wake

↕

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

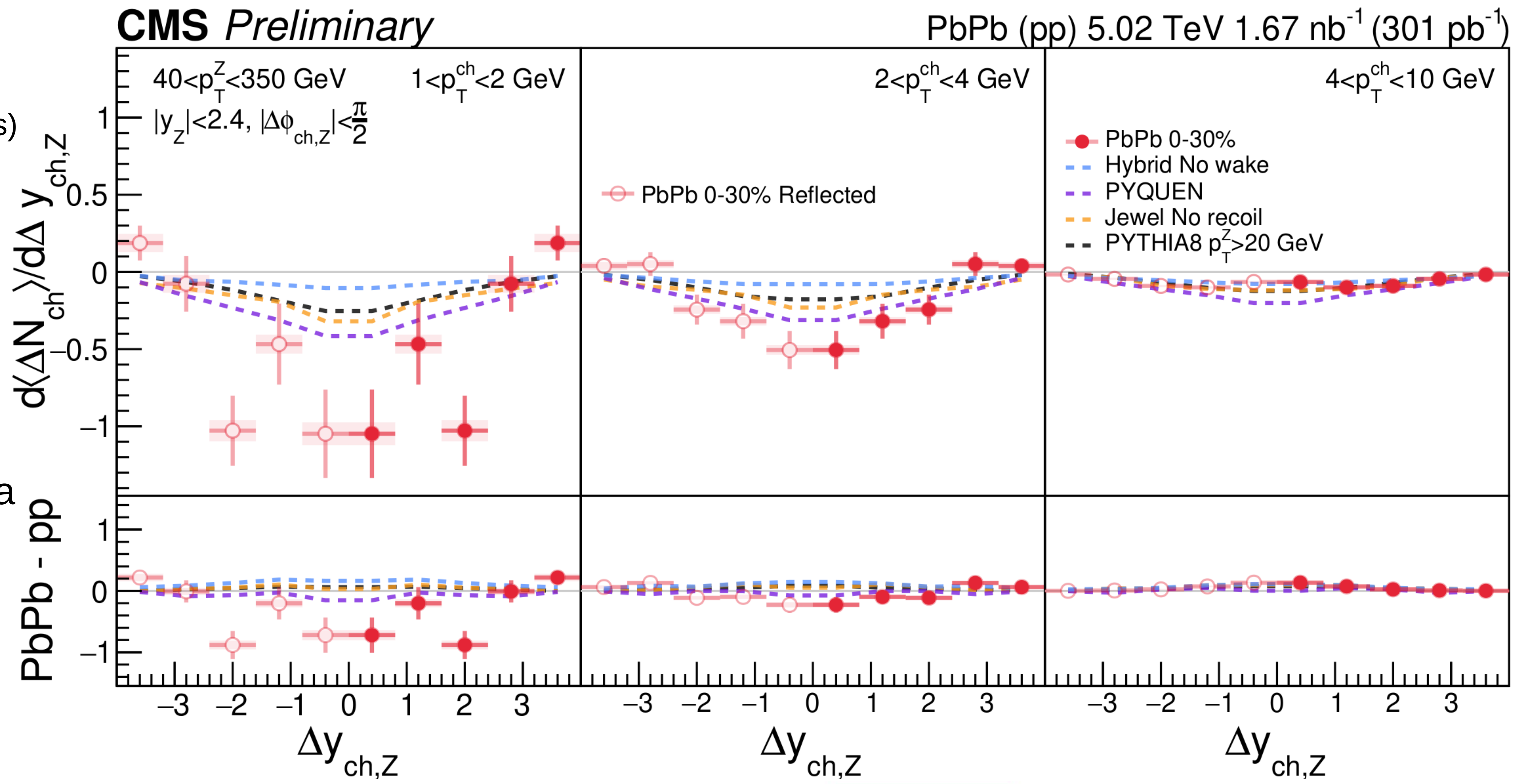


Theory Comparison: Rapidity Distribution in 0-30% PbPb

- **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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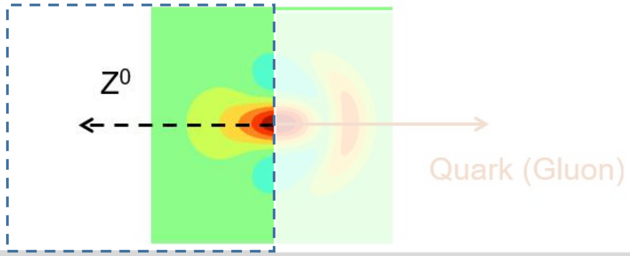
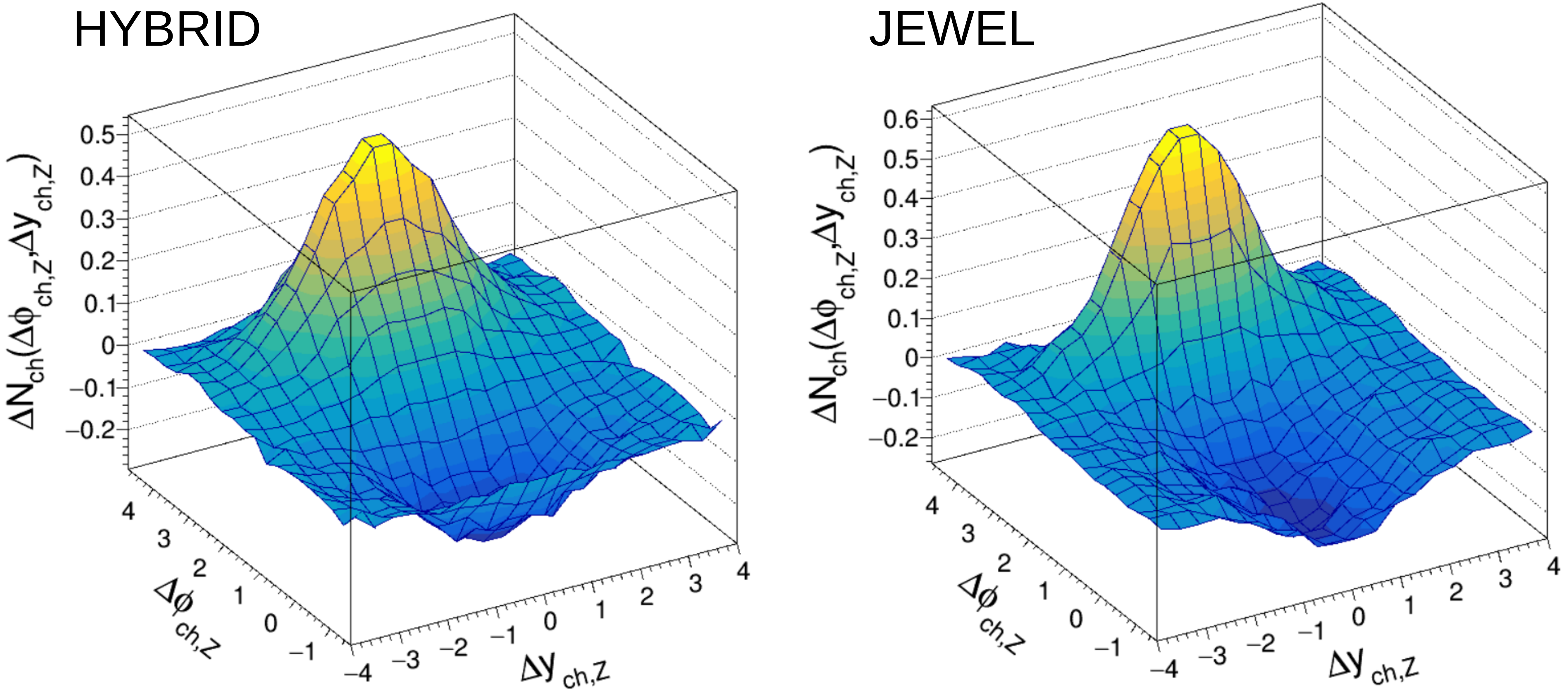
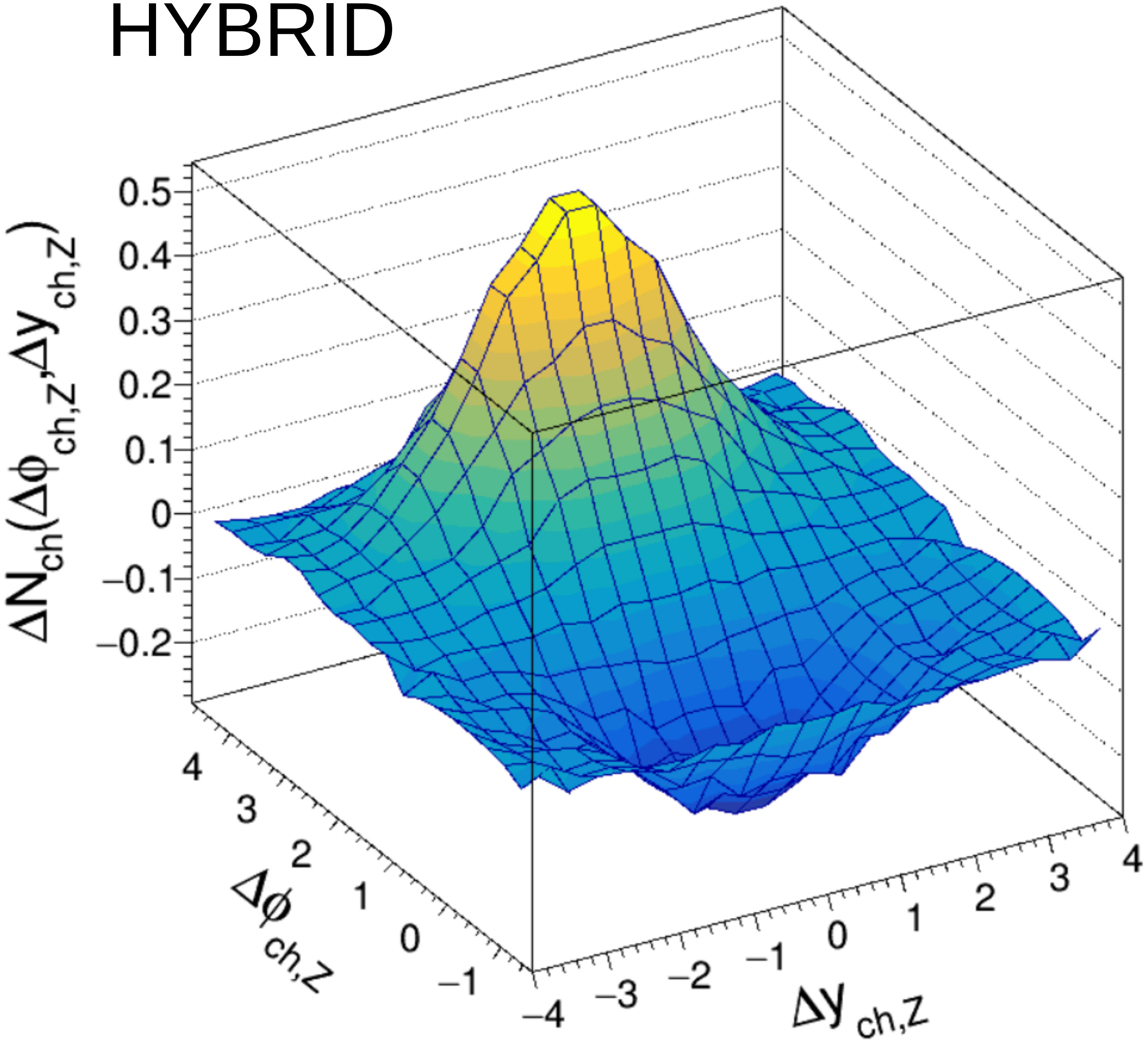


Predictions from Models for Charged Hadron p_T 1-2 GeV

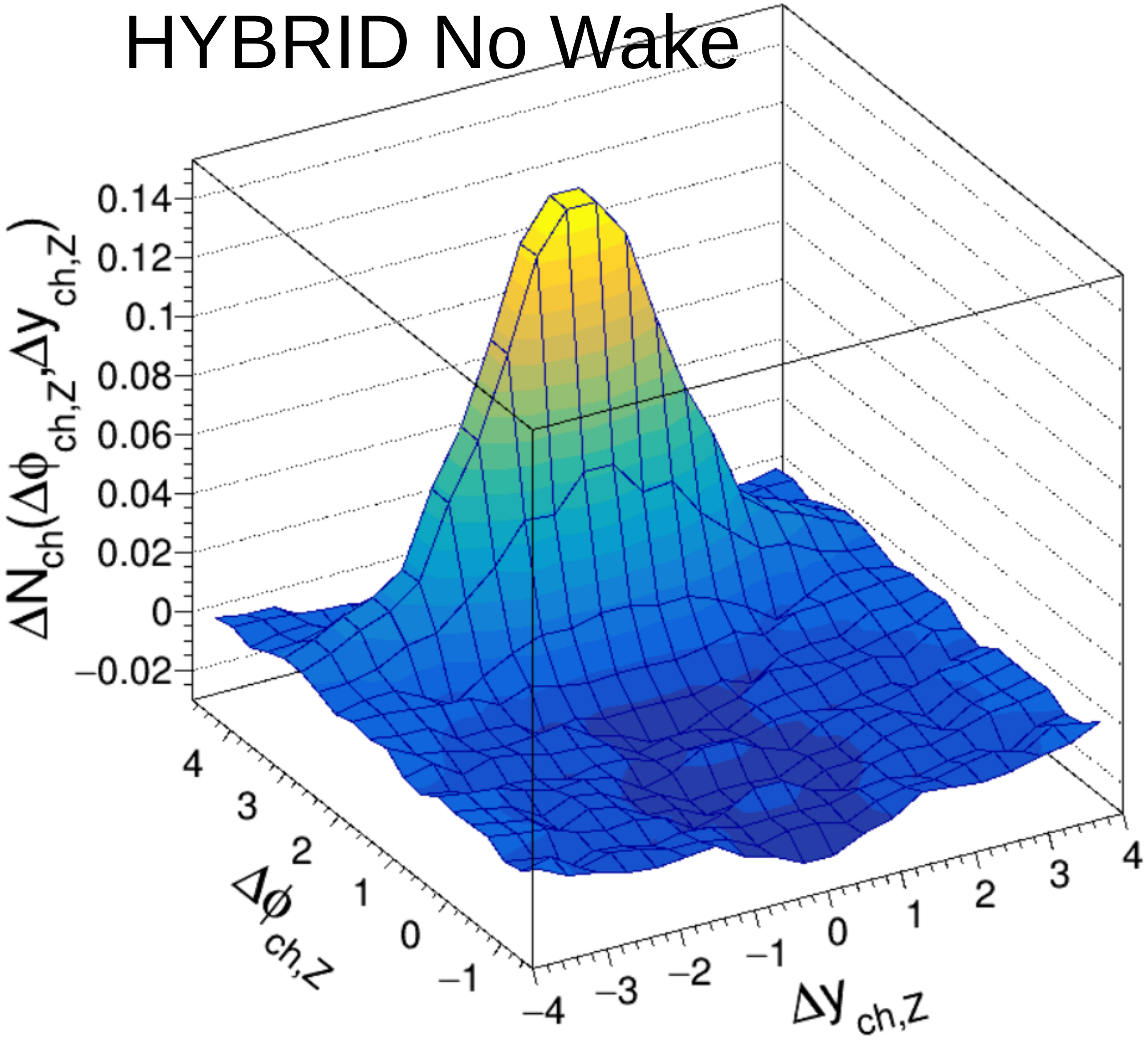


Predictions from Models for Charged Hadron p_T 1-2 GeV

HYBRID



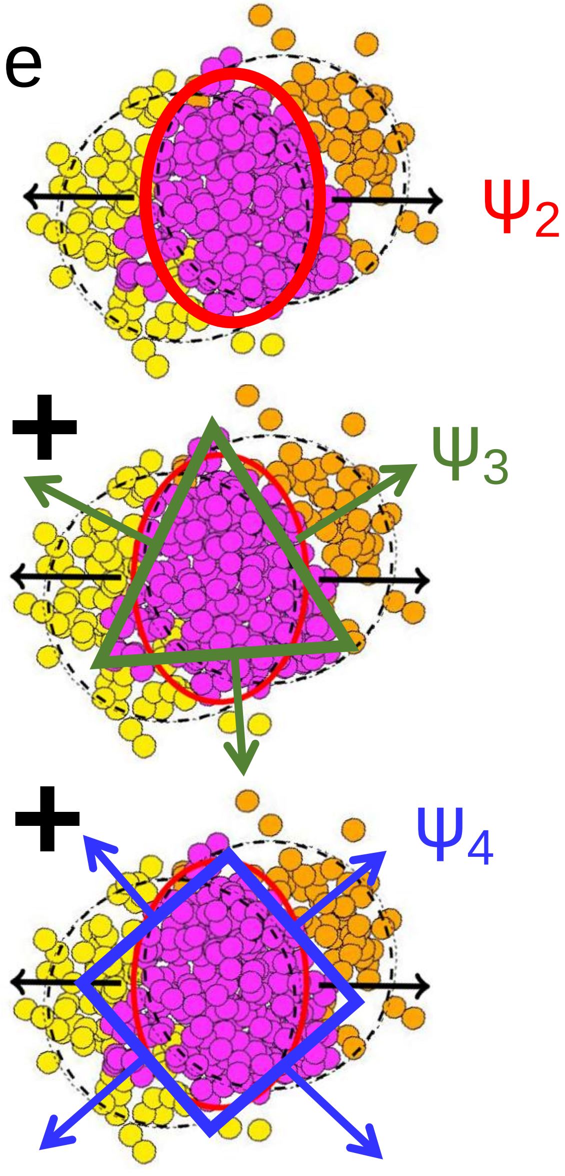
HYBRID No Wake



Particle Azimuthal Anisotropy

Magnitude

v_2



v_3

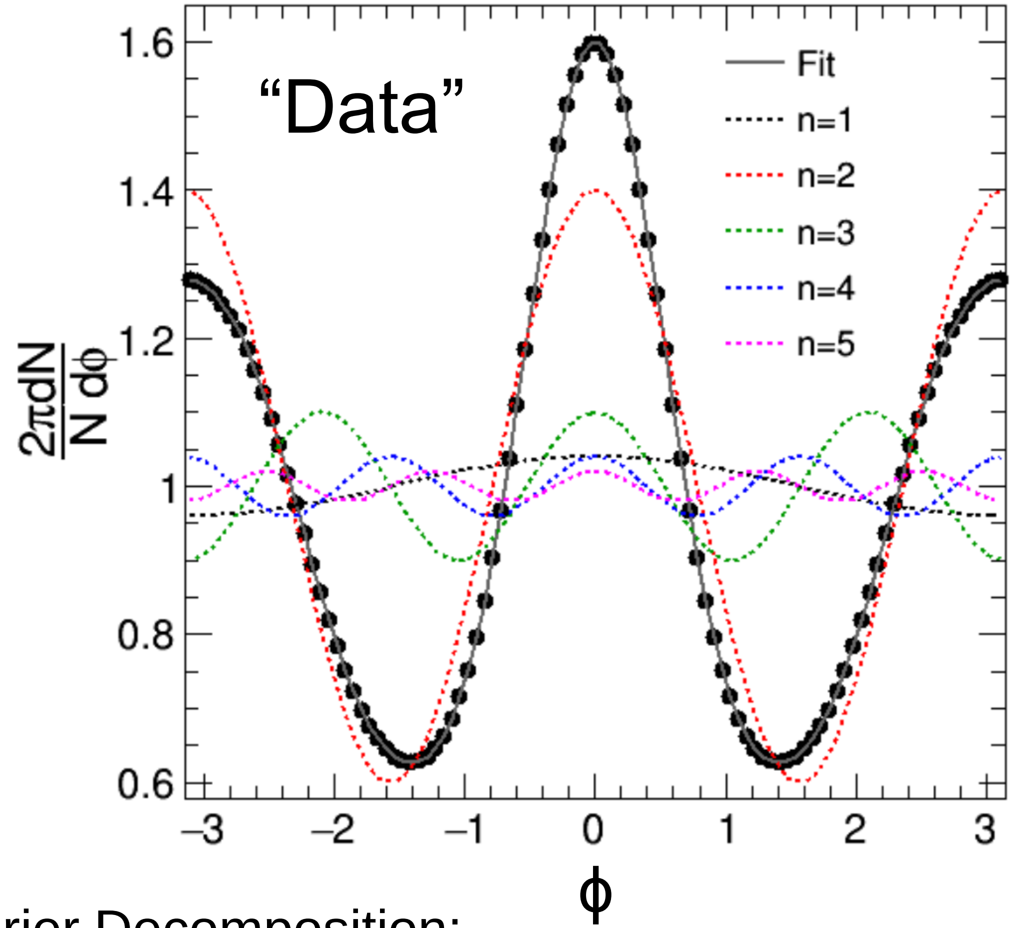
v_4

⋮

+

v_n

...

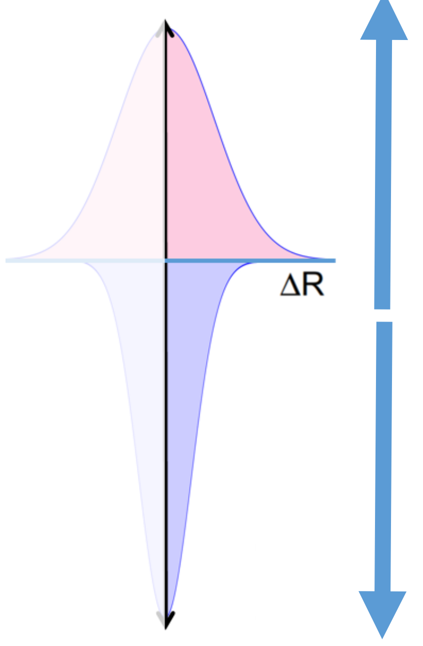


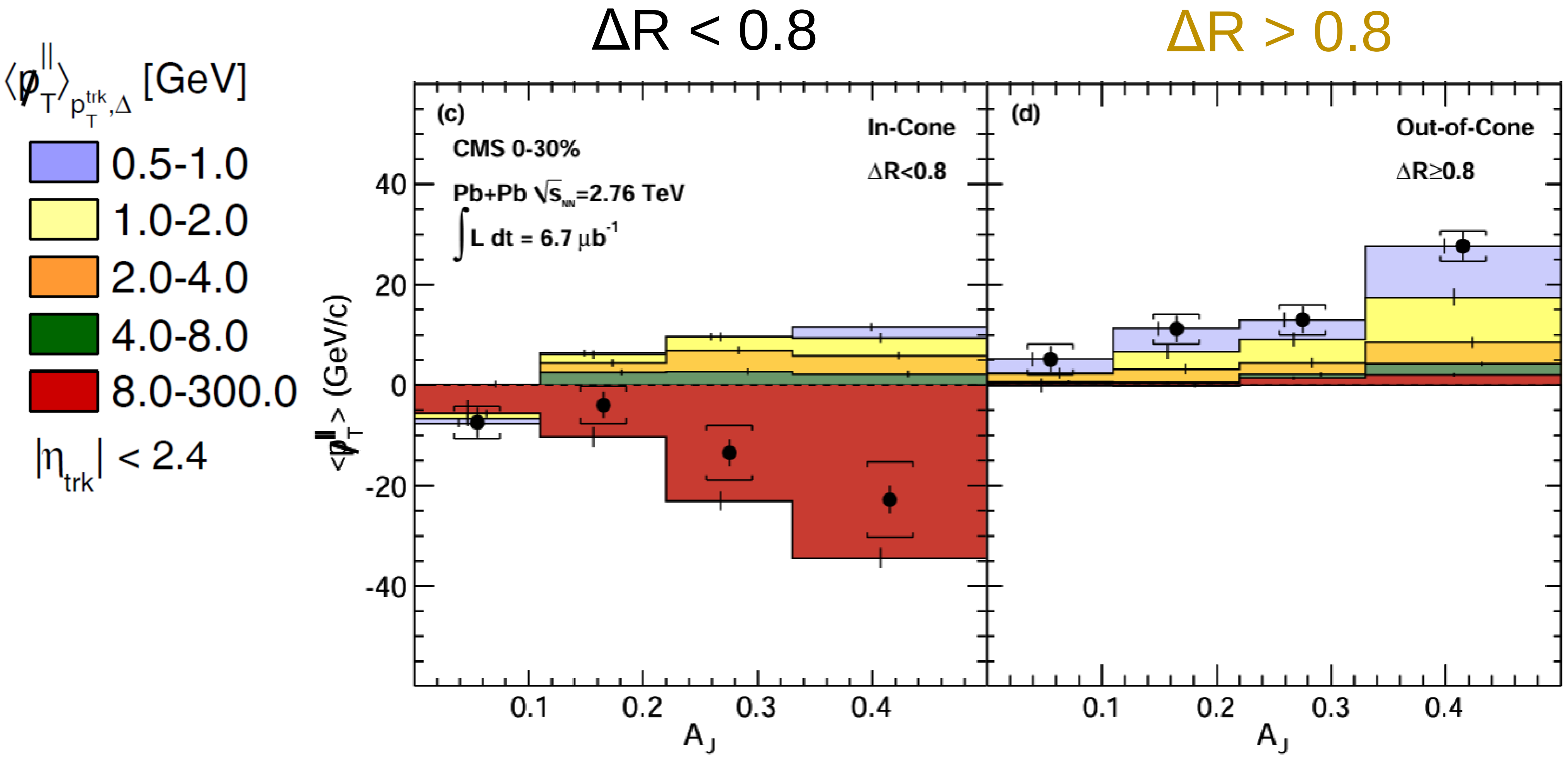
Fourier Decomposition:

$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$

Alver and Roland (MITHIG)
"Collision geometry fluctuation"
PRC82 (2010) 039903

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

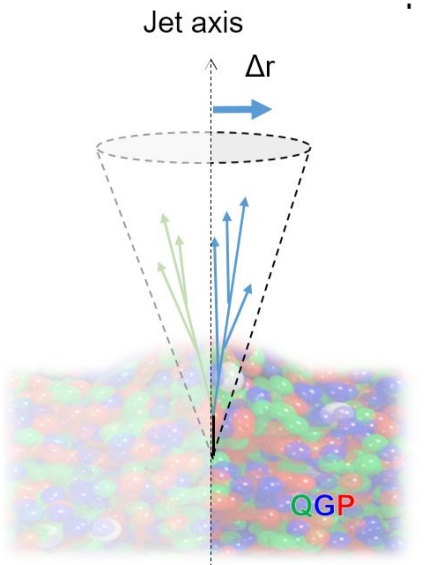




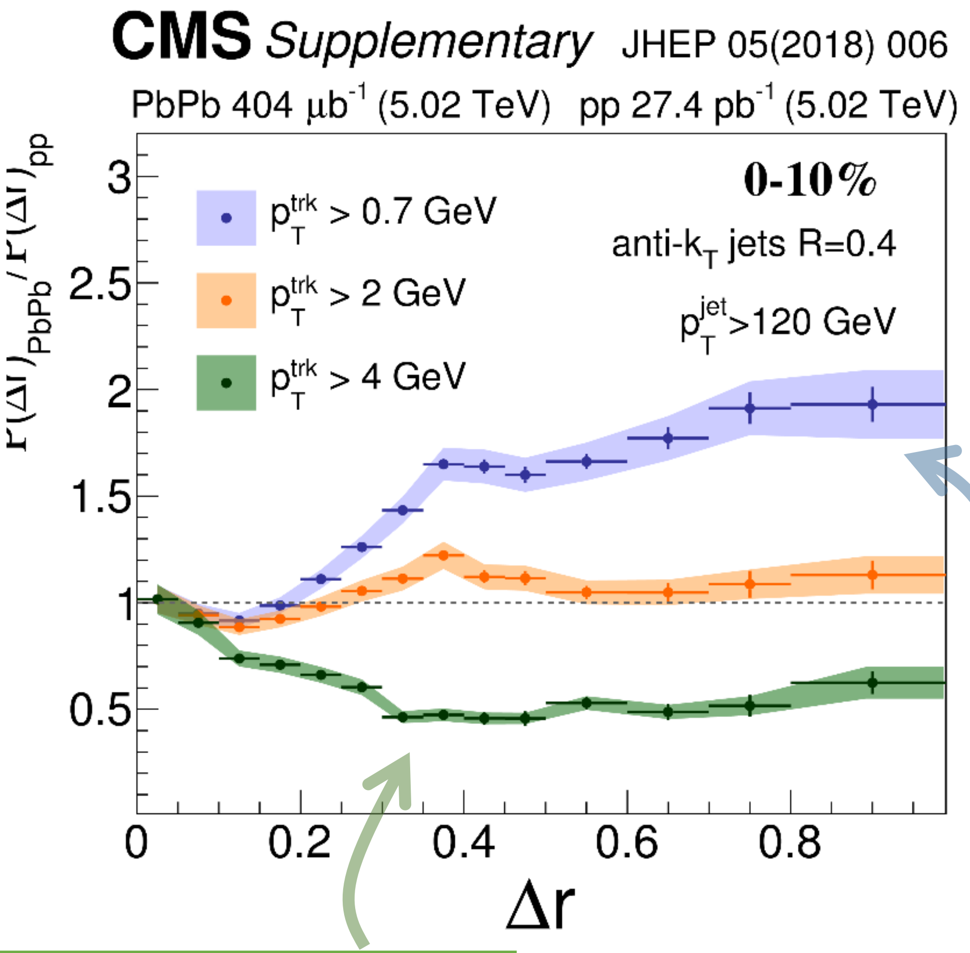
- Quenched energy fully recovered via low p_T particles **p_T< 2 GeV**
- They are distributed from near to **far away** from the (di)-jet axis (ΔR>0.8)

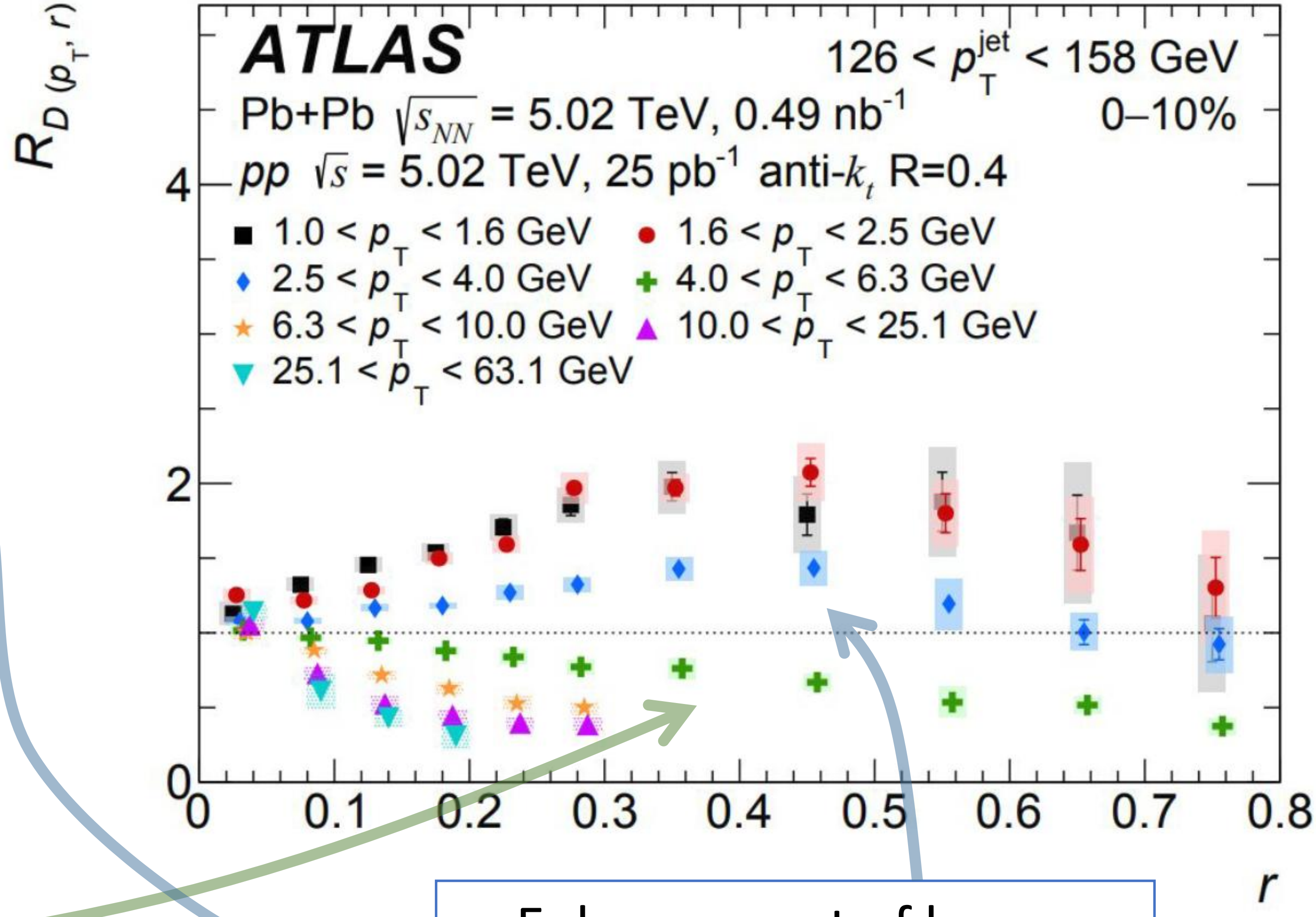
PRC 84 (2011) 024906

Excess in Jet-Hadron Correlation



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





Depletion of high p_T charged particles at large Δr

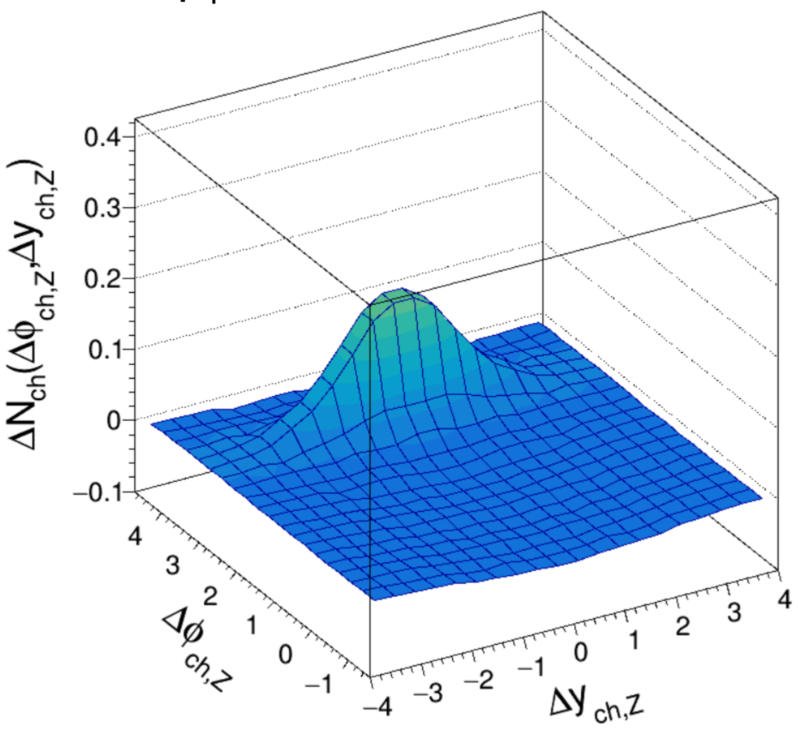
Enhancement of low p_T charged particles at large Δr

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**

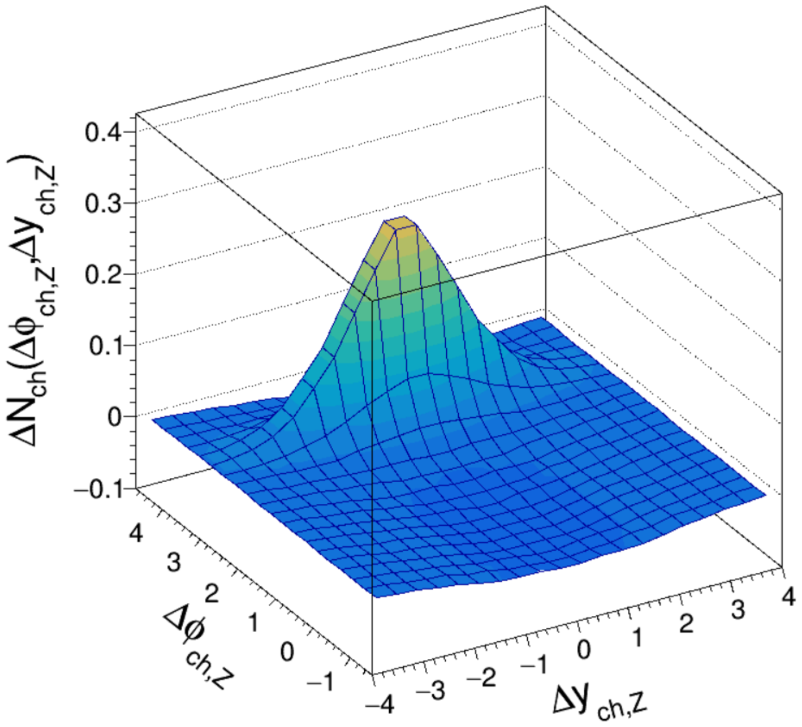
PYTHIA8 Z^0+Jet Event with Different Z^0 p_T Thresholds

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

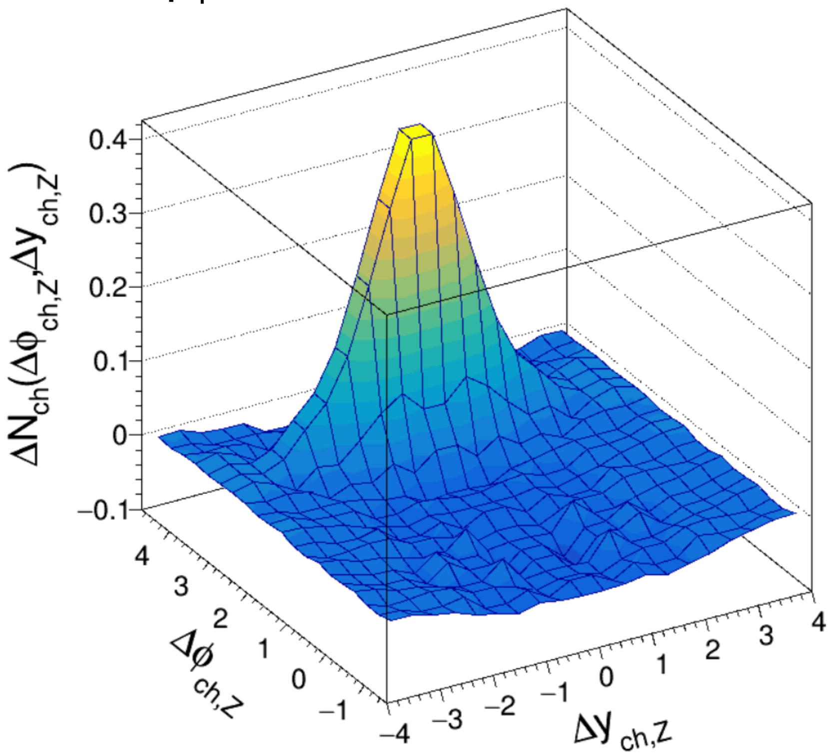
Z^0 p_T > 20 GeV



Z^0 p_T > 40 GeV

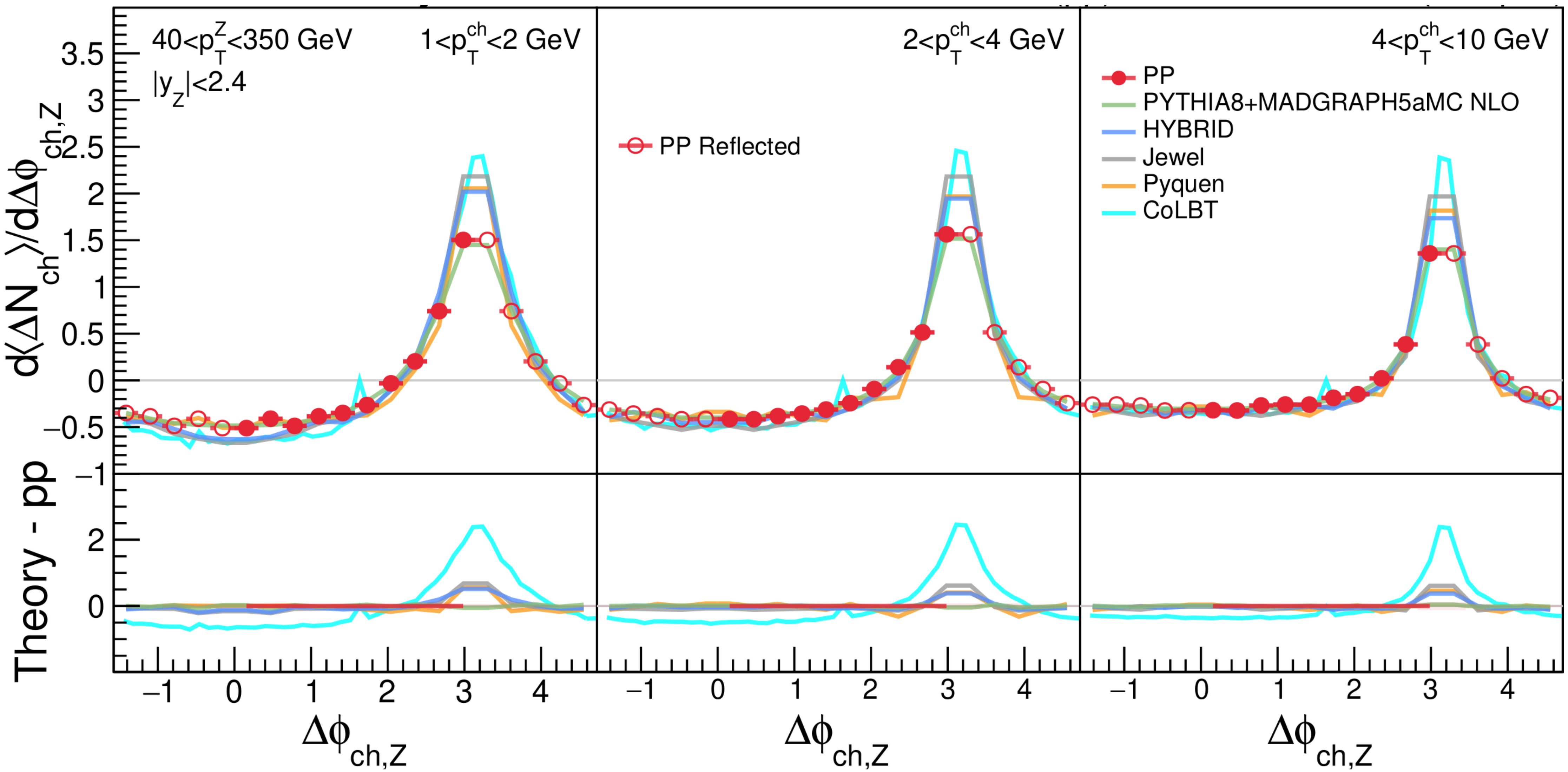


Z^0 p_T > 60 GeV



- Tighter correlation between charged hadron in jet and Z^0 not only in $\Delta\phi$ **but also Δy** with **higher** Z^0 p_T selection

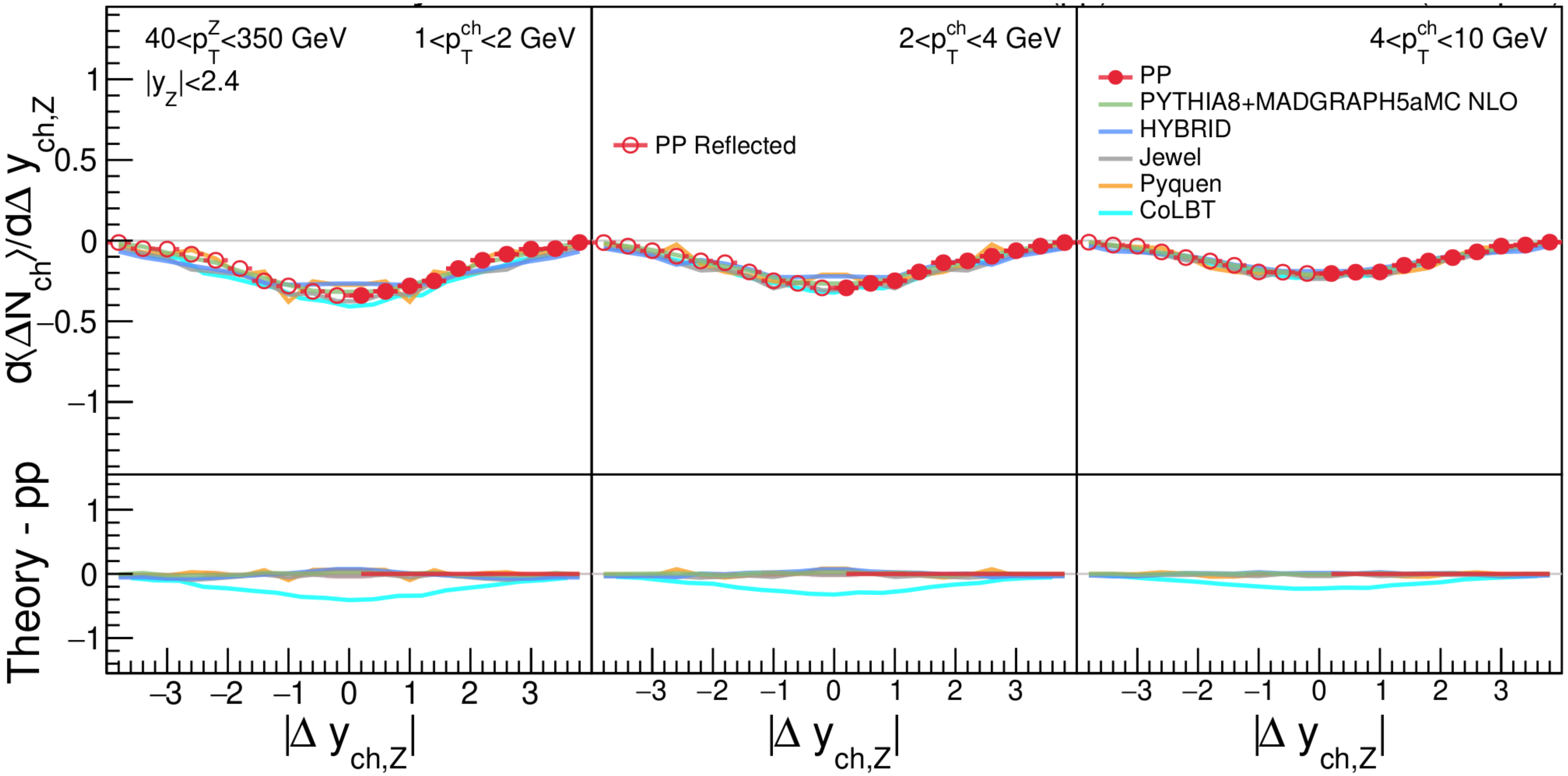
Azimuthal Angle Distributions in pp vs. Theory



Low Charged Hadron p_T → High Charged Hadron p_T

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

Rapidity Distributions in pp vs. Theory



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Low Charged Hadron p_T

High Charged Hadron p_T

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

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

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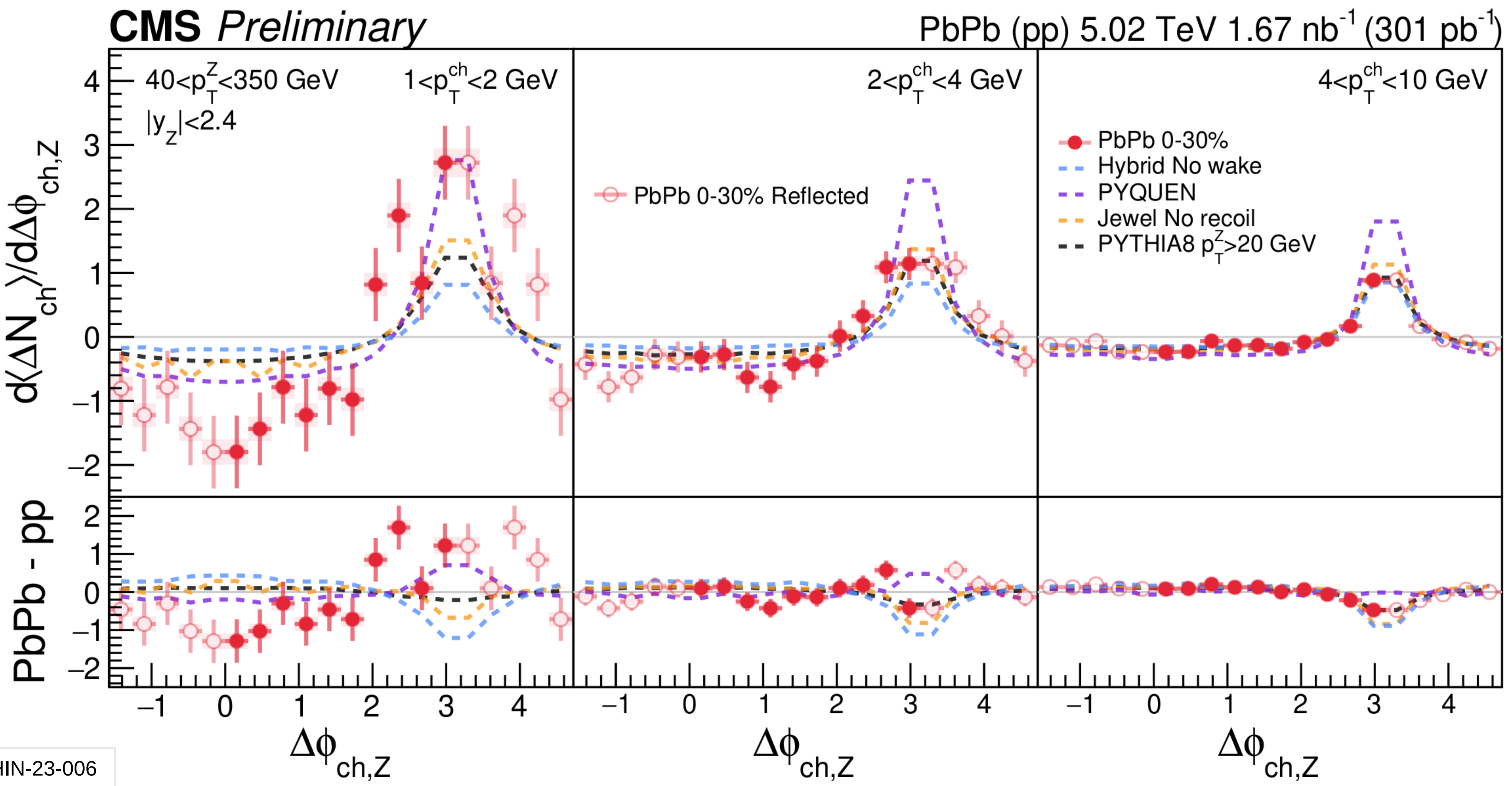

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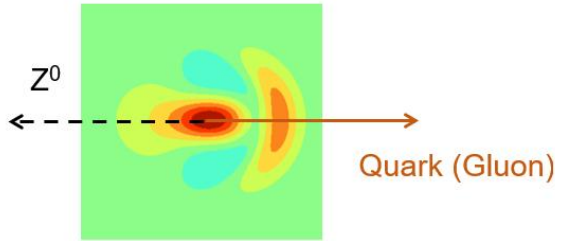

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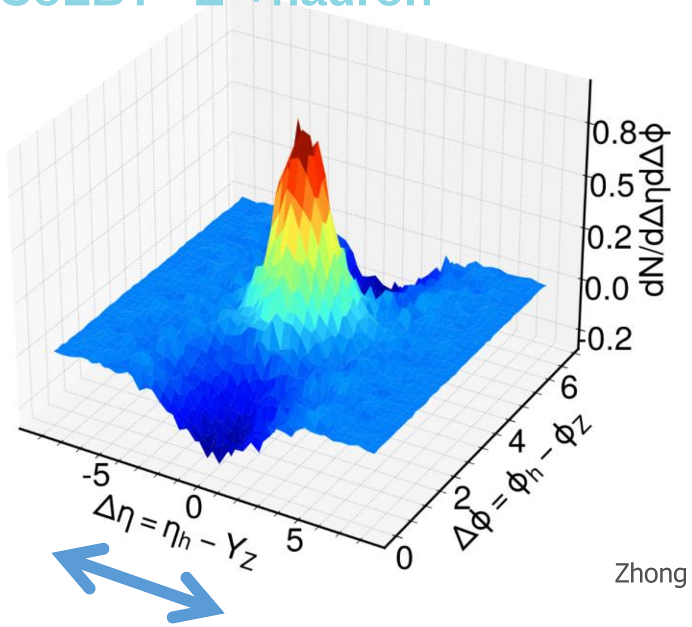
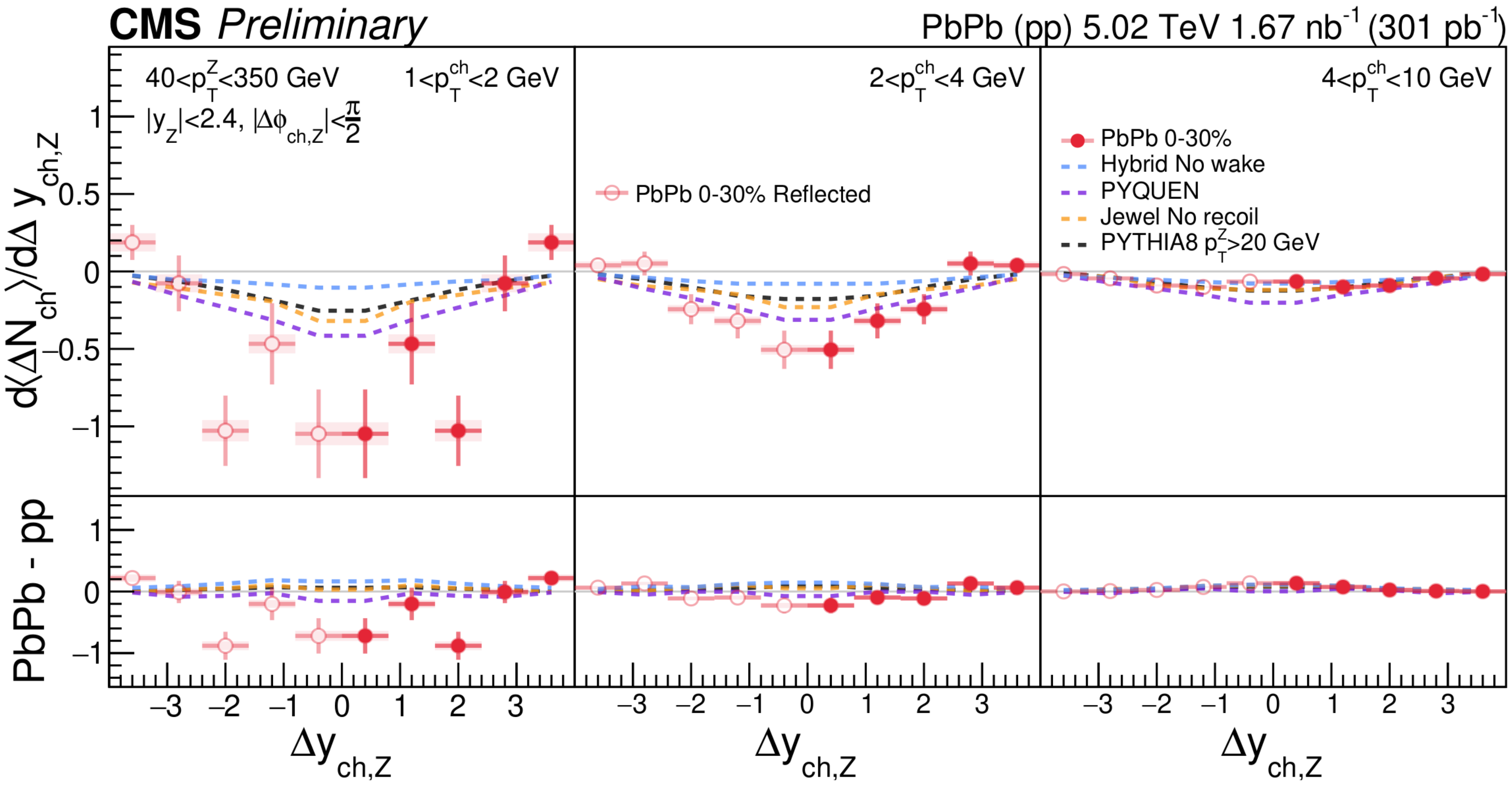
Theory Comparison: Rapidity Distribution in 0-30% PbPb

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

CoLBT Z^0+hadron



Zhong Yang, Xin-Nian Wang



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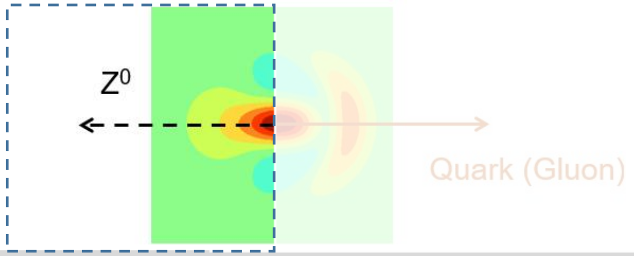

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