CMS Experiment at the LHC, CERN

Probing the Trillion Degree Quark Soup

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GSI/FAIR Colloquium

GSI, Darmstadt, Germany

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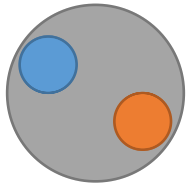
MIT HIG group's work was supported by US DOE-NP

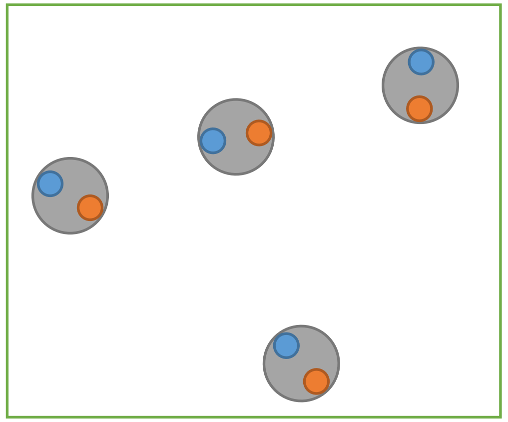
Ultra-dense QCD (Quarks and Gluons) Matter

Increase the Temperature (T)

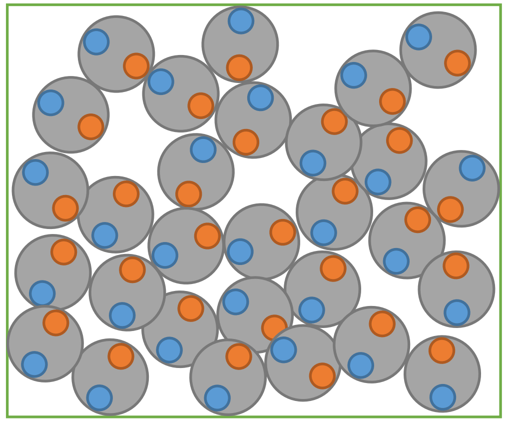
Quark
Anti-quark



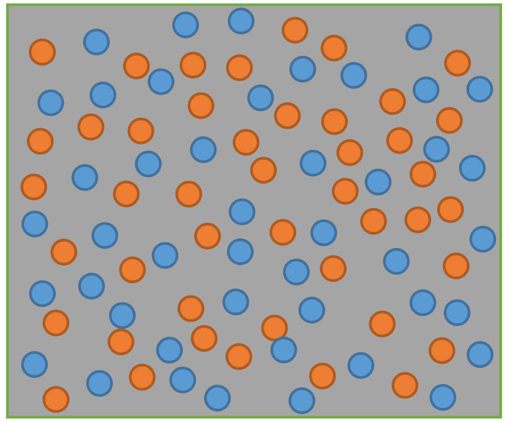
Mesons
(quark and anti-quark)



$T<T_C$

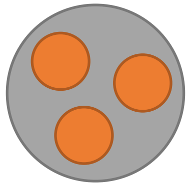


$T \sim T_C \sim$ 2 trillion degrees

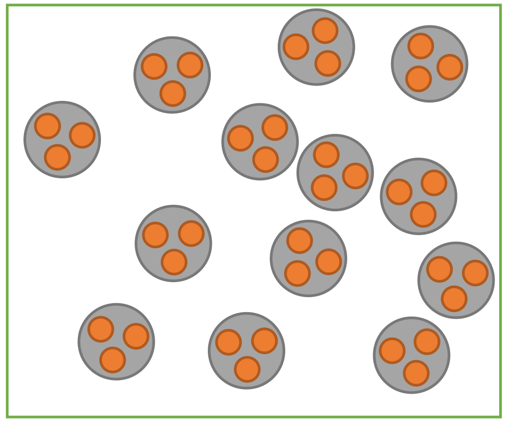


$T>T_C$

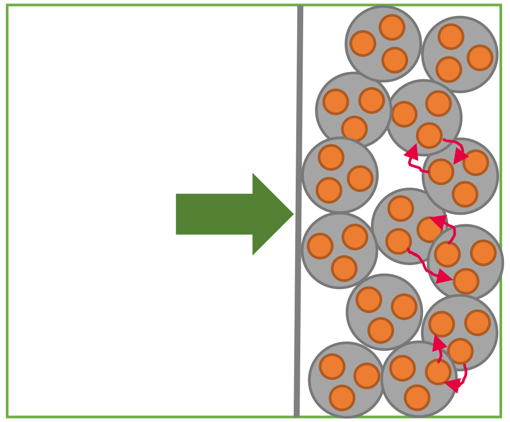
Increase the Density (ρ)



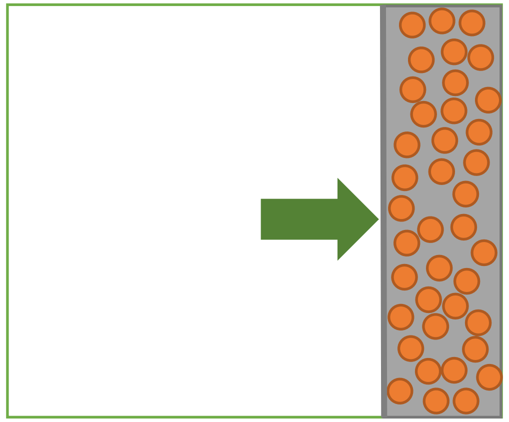
Baryons
(Three quarks)



Small ρ



ρ~ a few times of nuclei density



Large ρ

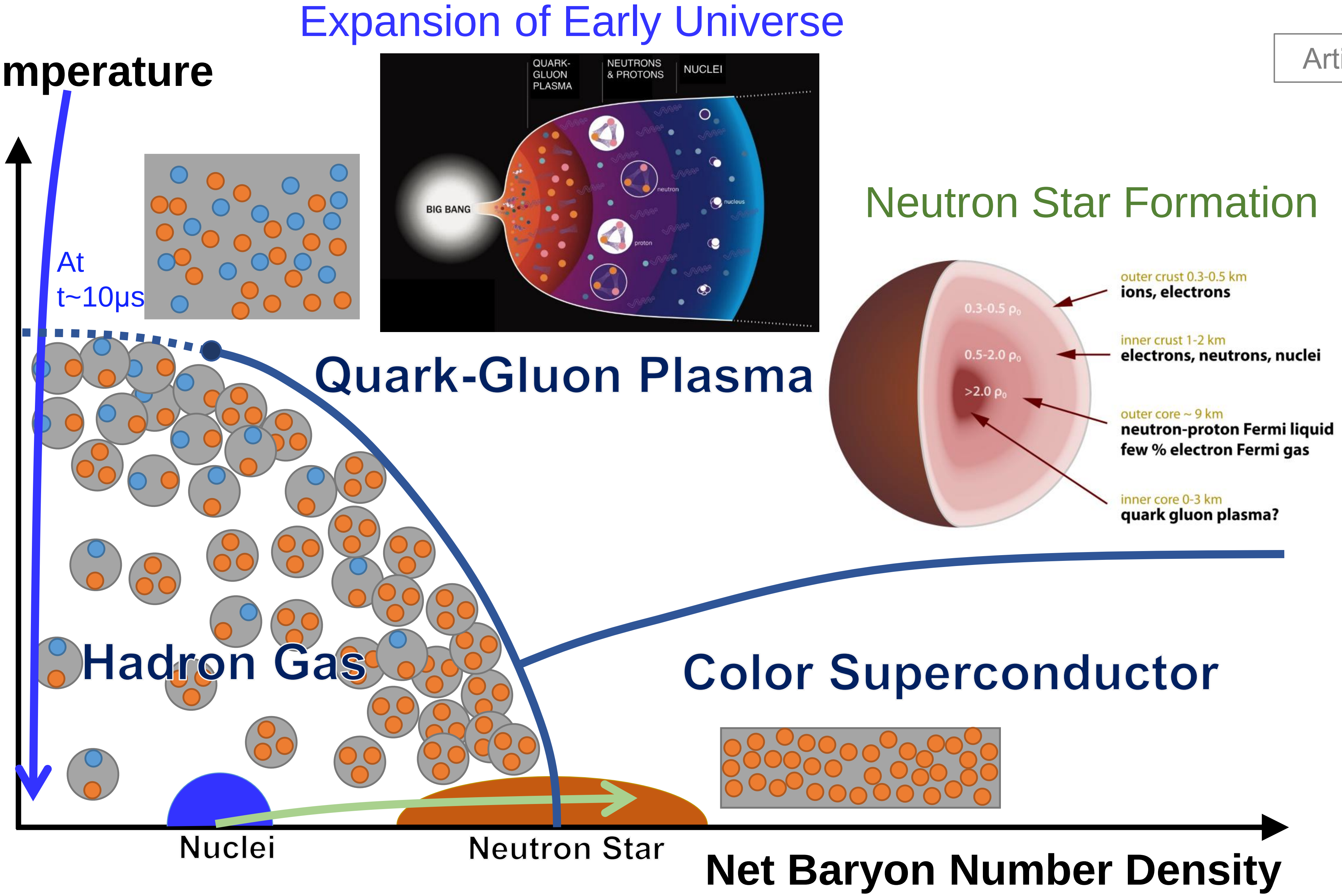
QCD Phase Diagram

Artist's Impression

Crossover from
Lattice QCD

156.5 ± 1.5 MeV

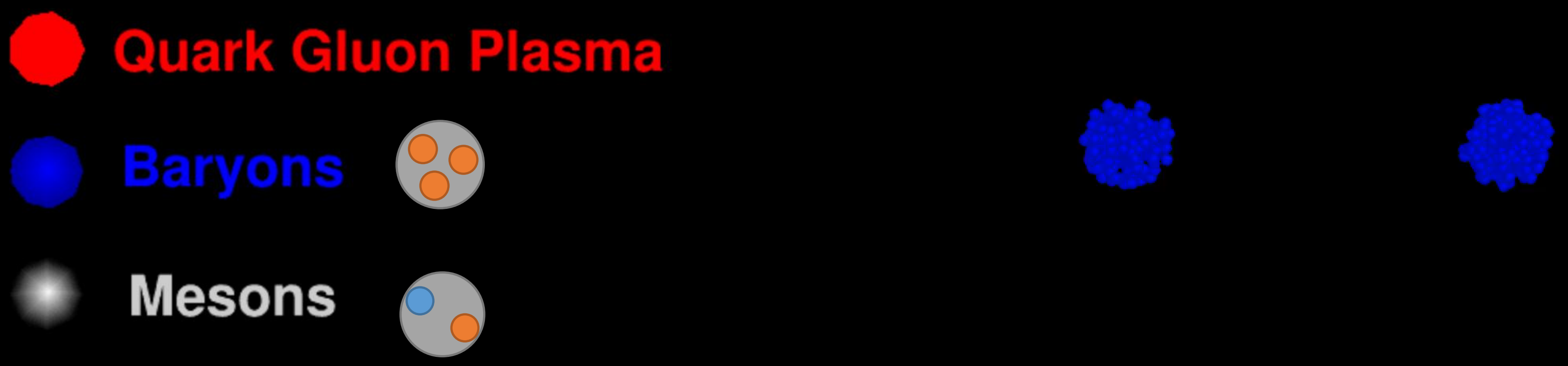
HotQCD
PLB 795, 15-21 (2019)



Making the Quark Soup

Relativistic Heavy Ion Collisions (Simulation)

MIT Heavy Ion Event Display: Pb+Pb 5.02 TeV

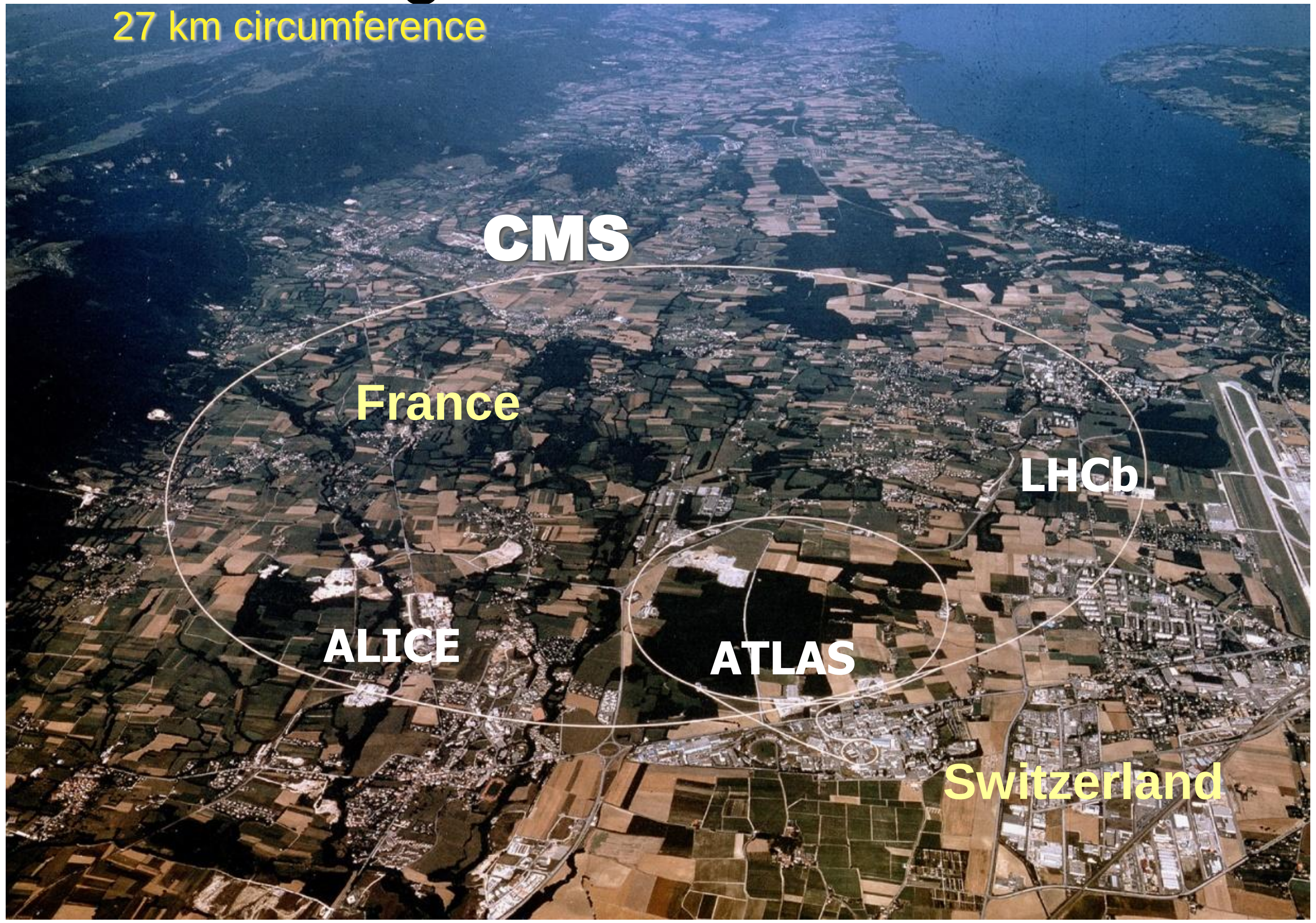


Yen-Jie Lee, Andre S. Yoon and Wit Busza

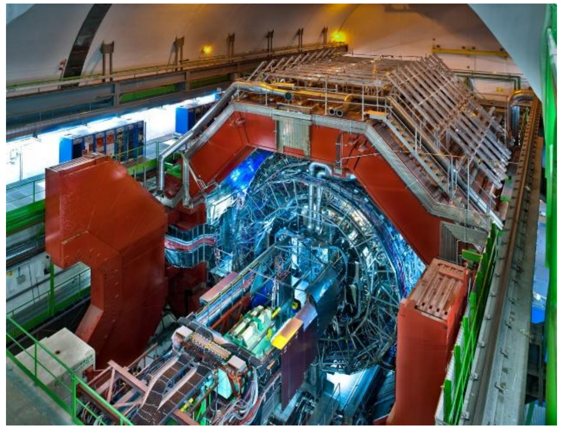
Acceleration

High Energy (Temperature) Frontier

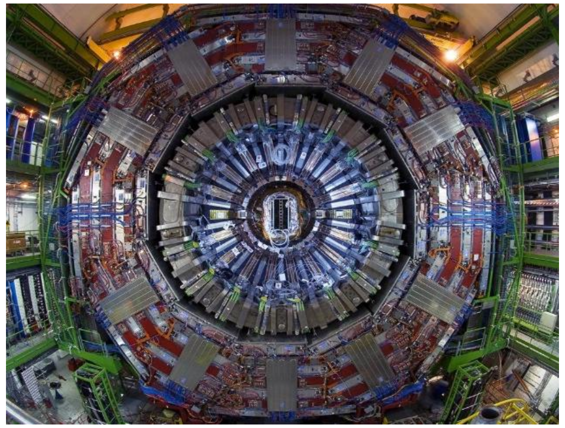
Large Hadron Collider



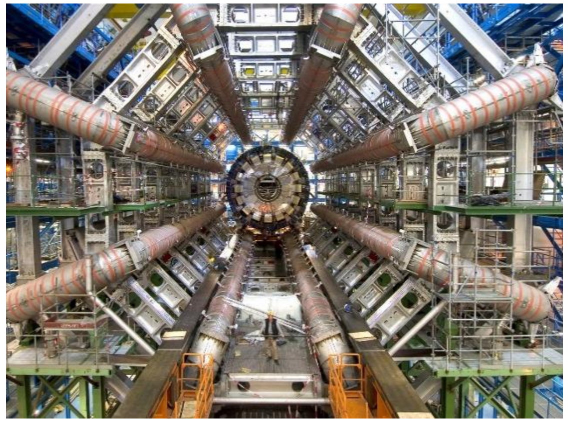
ALICE



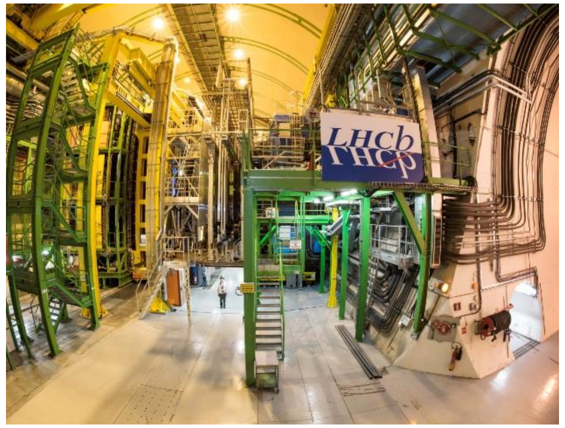
CMS



ATLAS



LHCb

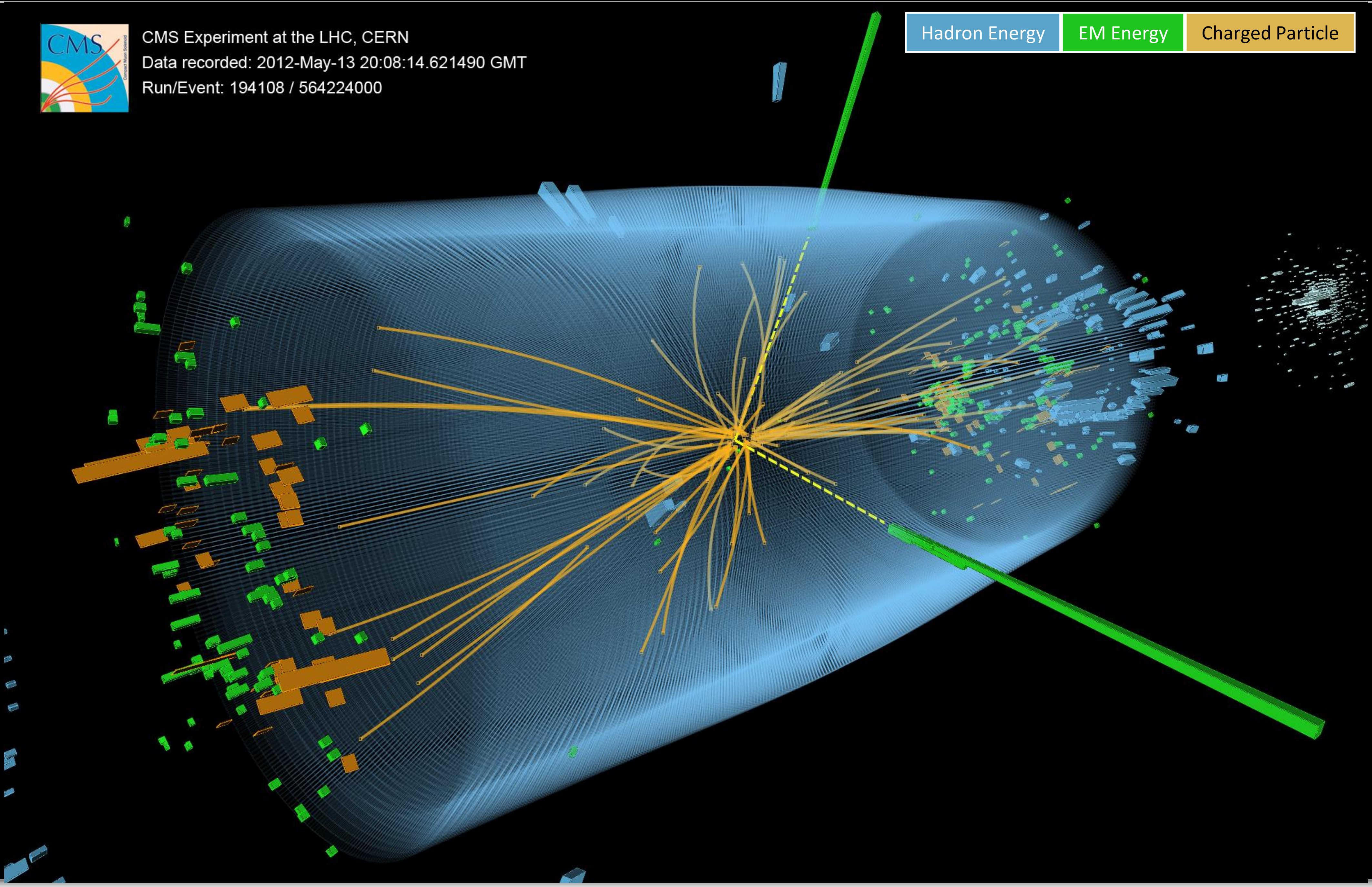


Lead-Lead (PbPb) collisions
2010-11: 2.76 TeV
2015-18: 5.02 TeV
2022-26: 5.36 TeV

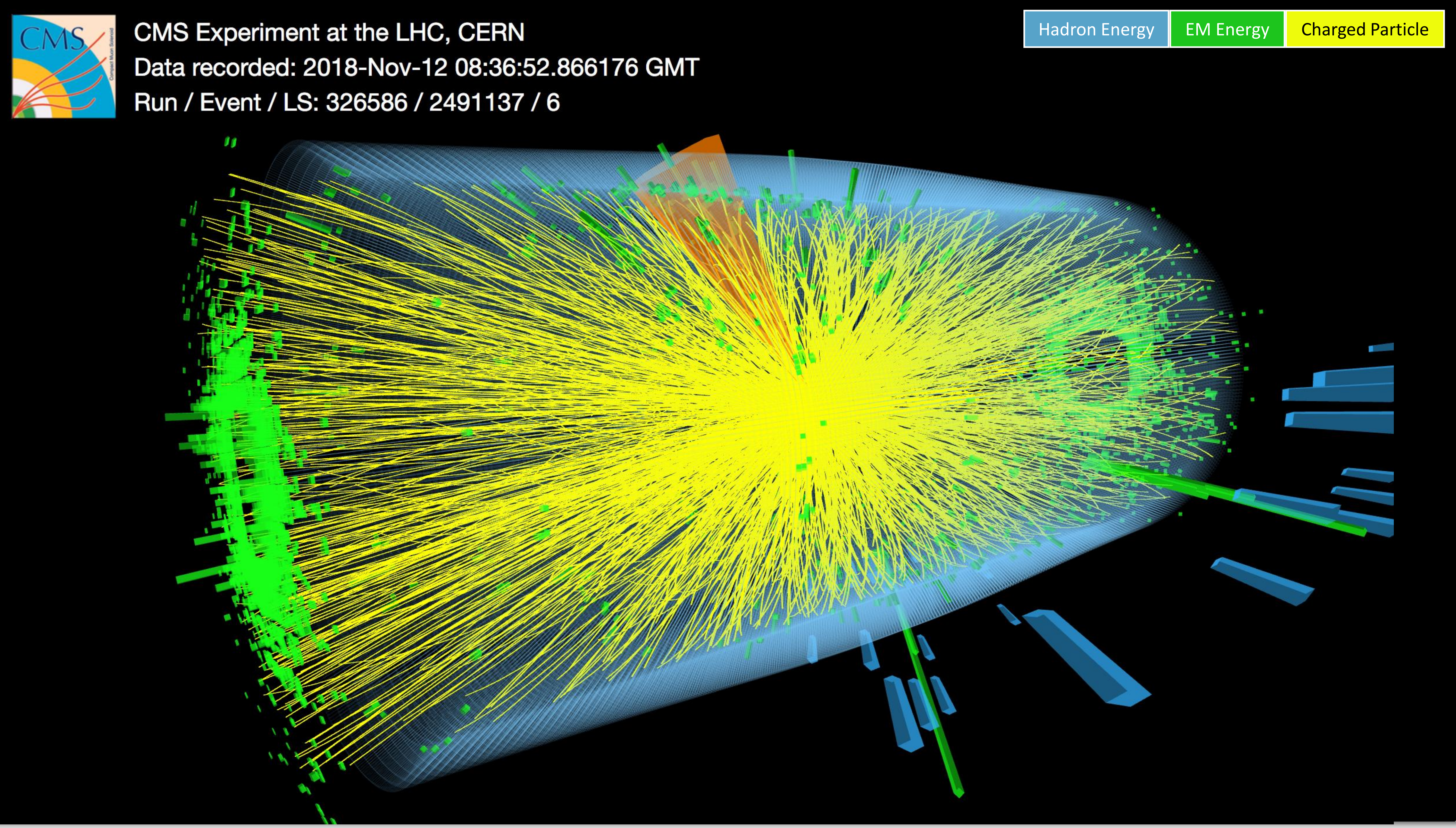
Also smaller system data:
Proton-lead at 5.02 & 8.16 TeV
Xenon-Xenon at 5.44 TeV
Oxygen-Oxygen and **Neon-Neon** at 5.36 TeV (2025!)

A flying mosquito has about 4 trillion electronvolts **(4TeV)** of energy

Proton-Proton Collision Recorded by CMS

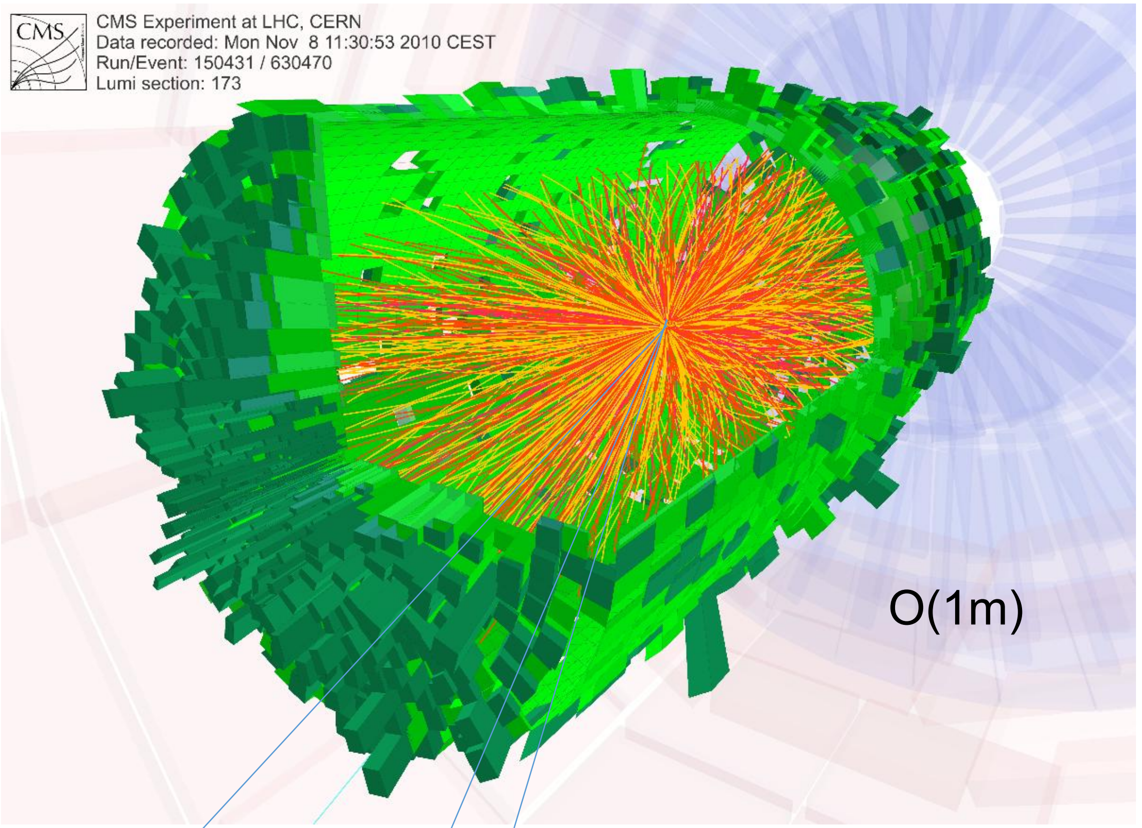


Lead-Lead Collision Recorded by CMS (2018)



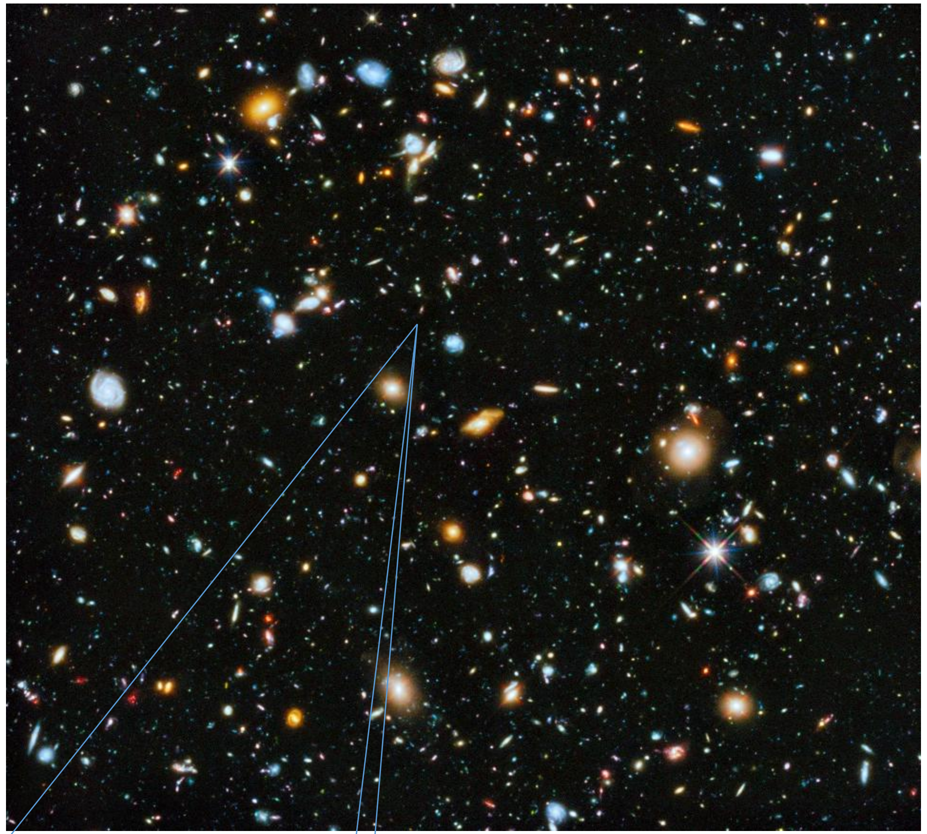
Reconstruct the Quark Soup with CMS

Size of the CMS detector

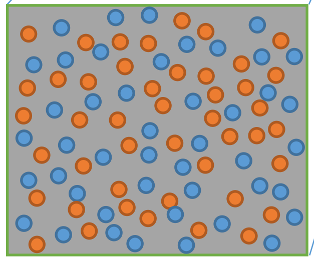


O(1m)

Size of the Observable Universe

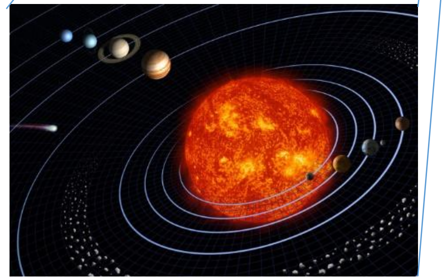


O(10^{27} m)



O(10^{-14} m)

Inner Structure of Quark Soup

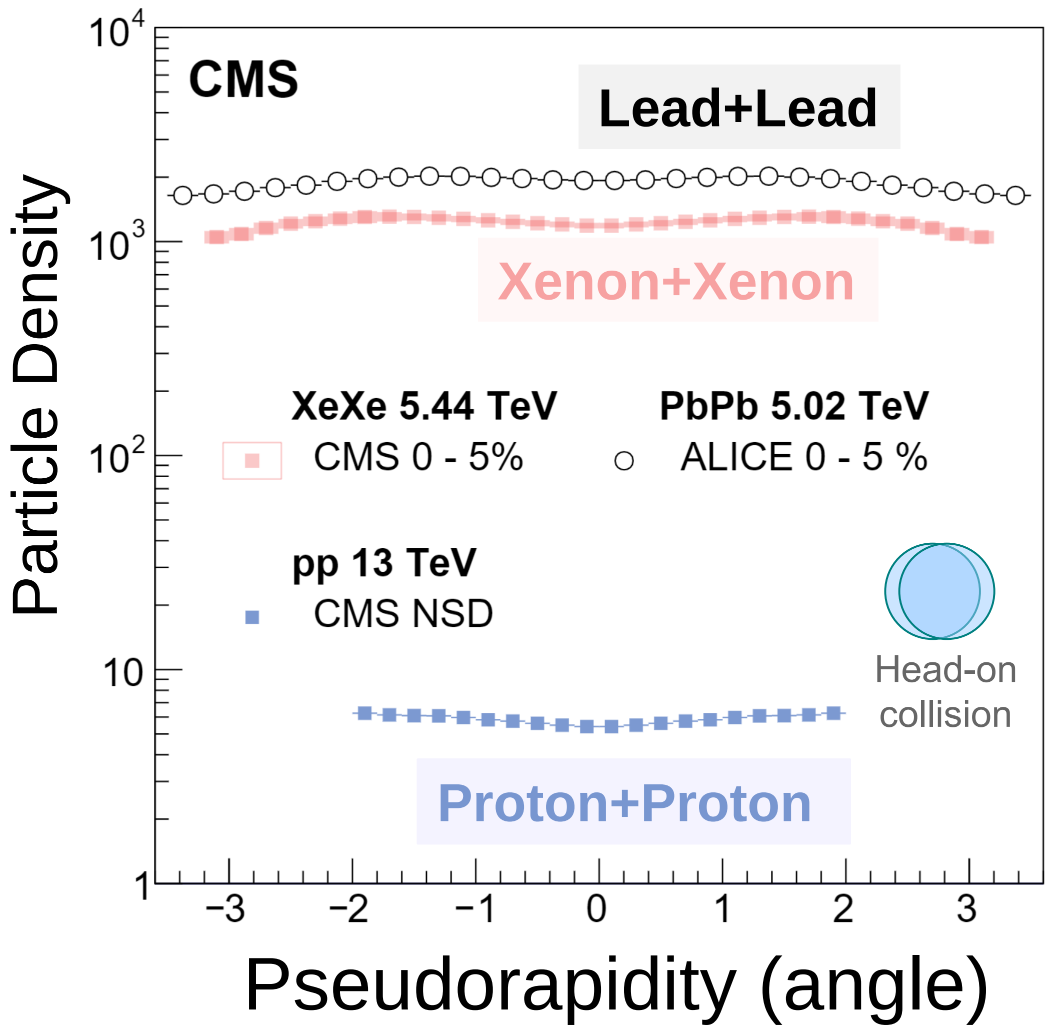


O(10^{13} m)

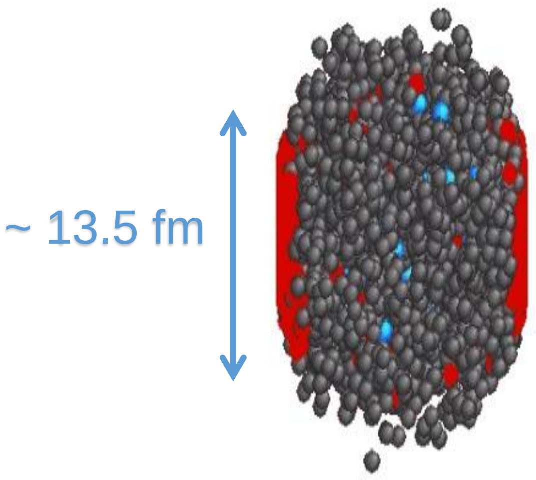
Inner Structure of Our Solar System

Density of the Quark Soup

Count the number of particles produced in **head-on** collisions.
Particle density in **Lead+Lead** ~ **400x** of that in **Proton+Proton**



At time ~ 1fm/c:

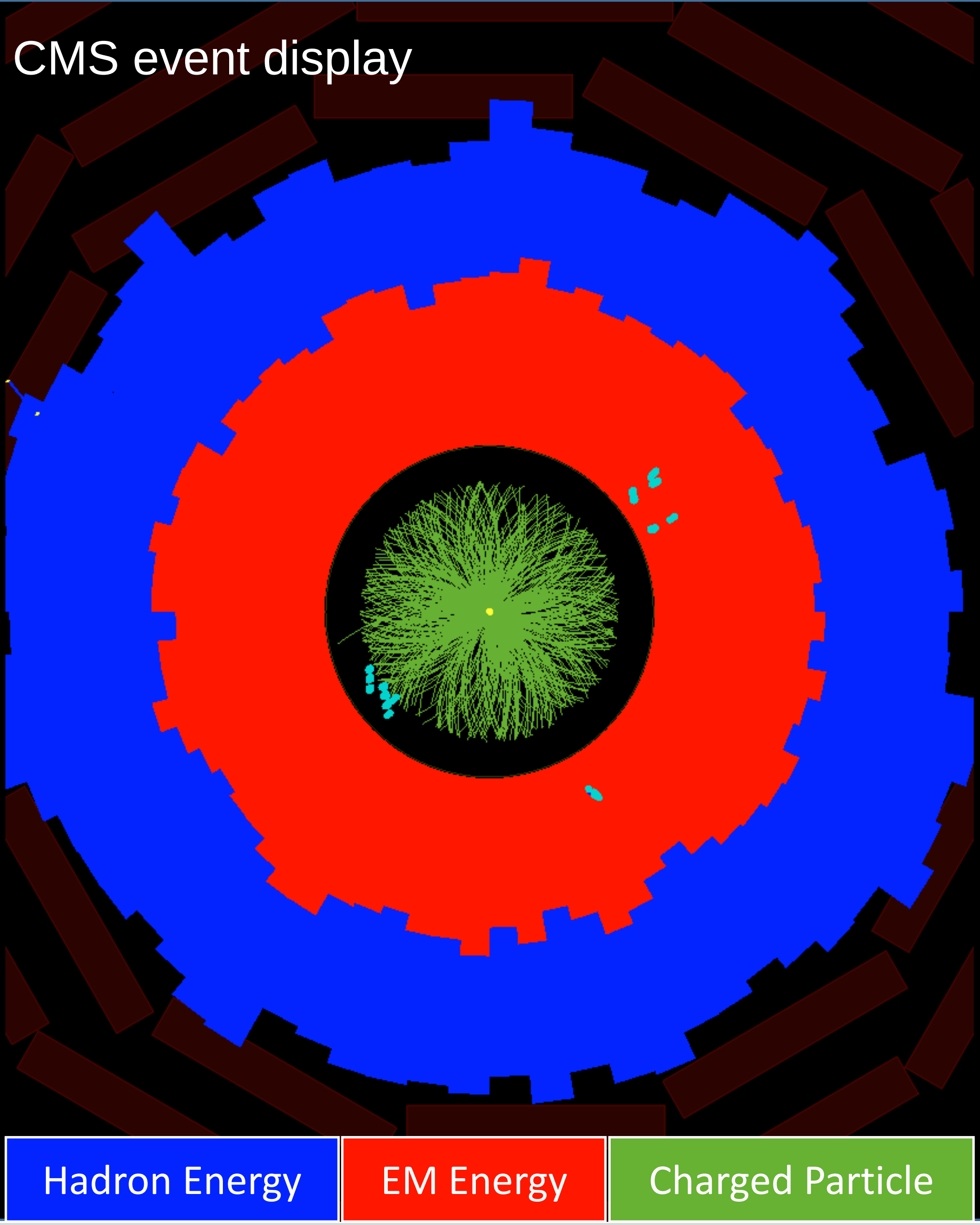


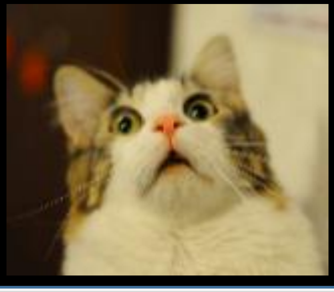
Energy density of the medium based on CMS measurement: ~14 GeV/fm^3 at $\tau_0 = 1\ \mathrm{fm/c}$

> 20x denser than the proton!

At **early time** of the collision, the system can not be described by hadrons

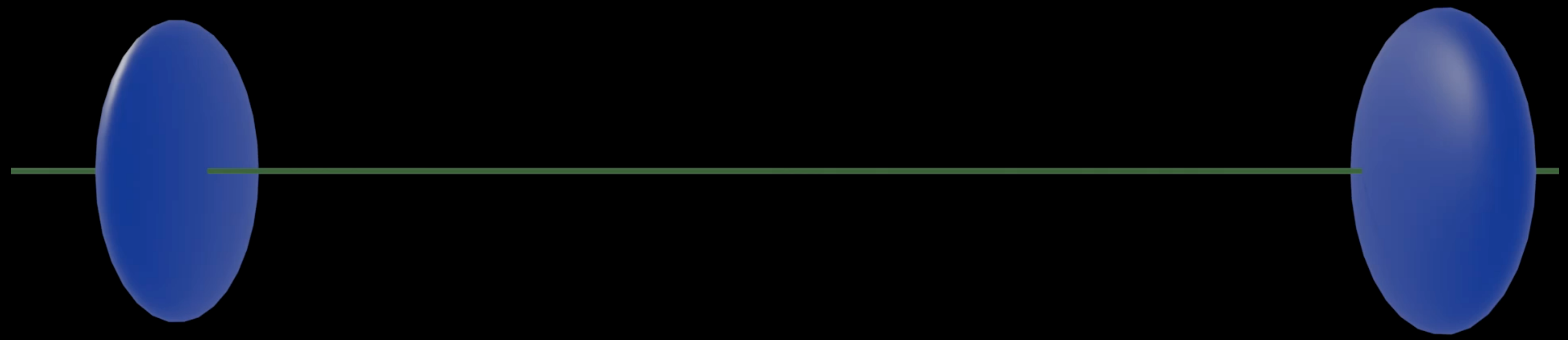
CMS Event Display





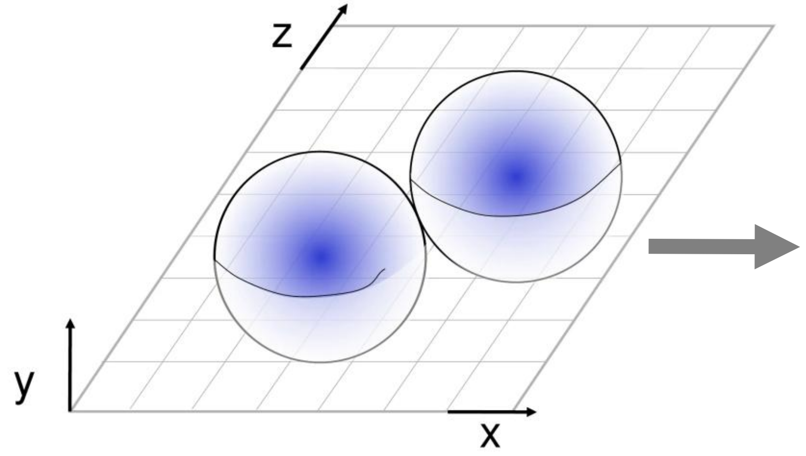
Initial Shape Before Expansion

Initial azimuthal anisotropic shape

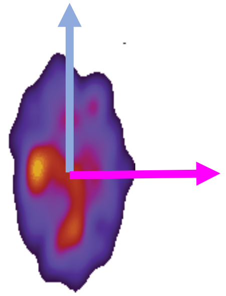


Animation from Jing Wang (MIT)

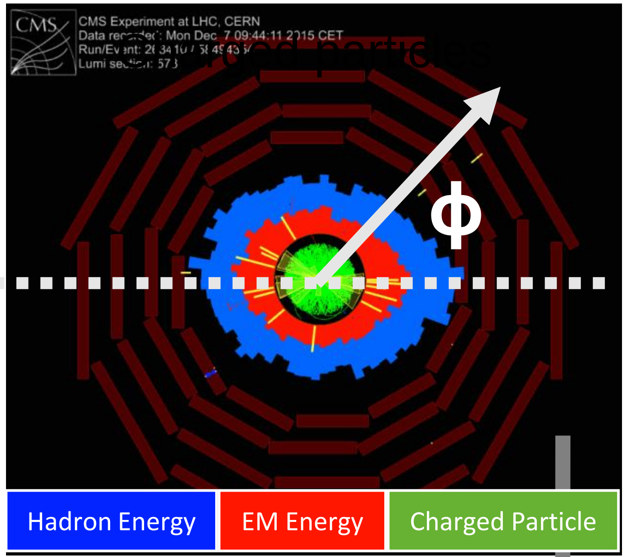
Pressure Driven Expansion of the Quark Soup



Small pressure gradient



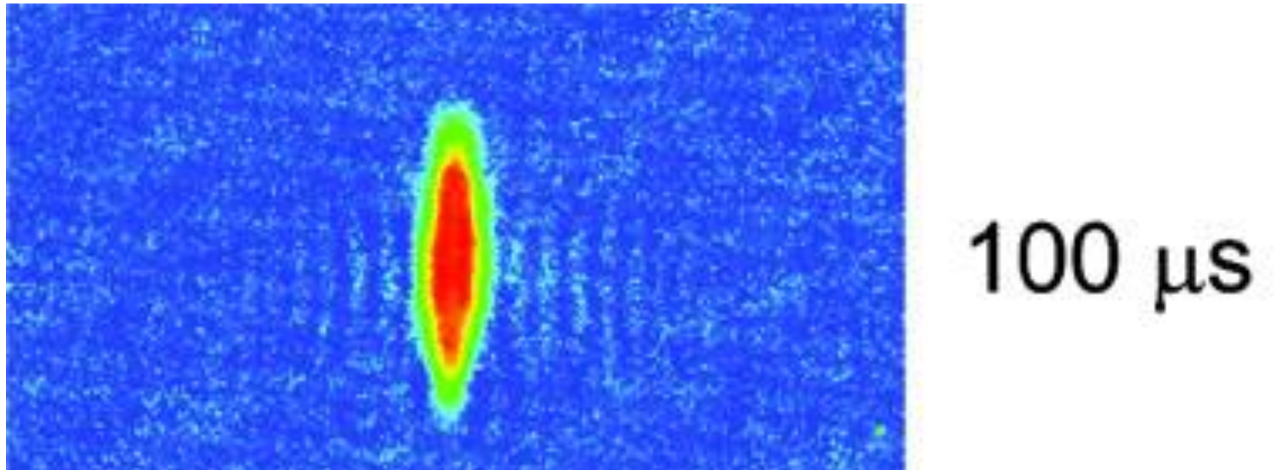
Large pressure gradient



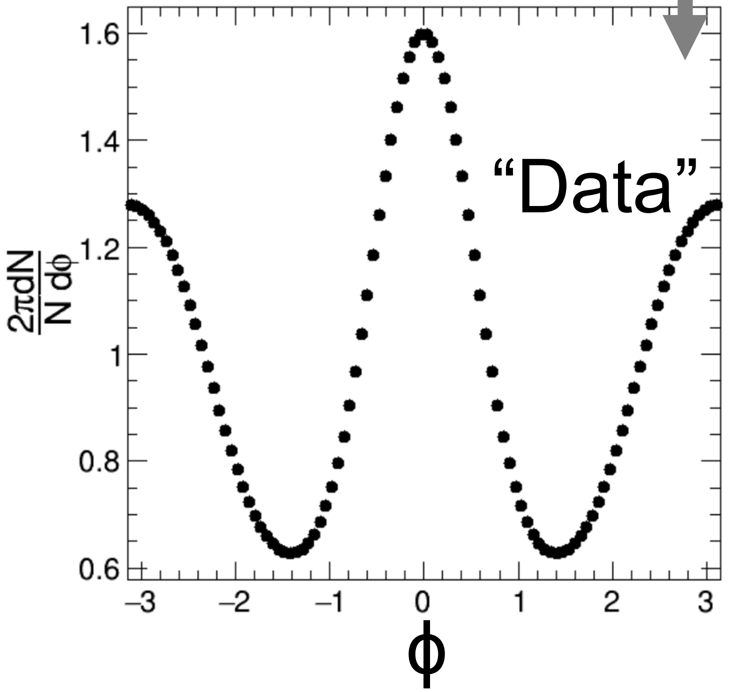
Event plane angle

Ψ_n

Expansion of **Ultra-cold atoms (Li-6)** released from laser trap



***Science*, 298**, pp. 2179-2182 (2002)



Particle Azimuth Angle Distribution

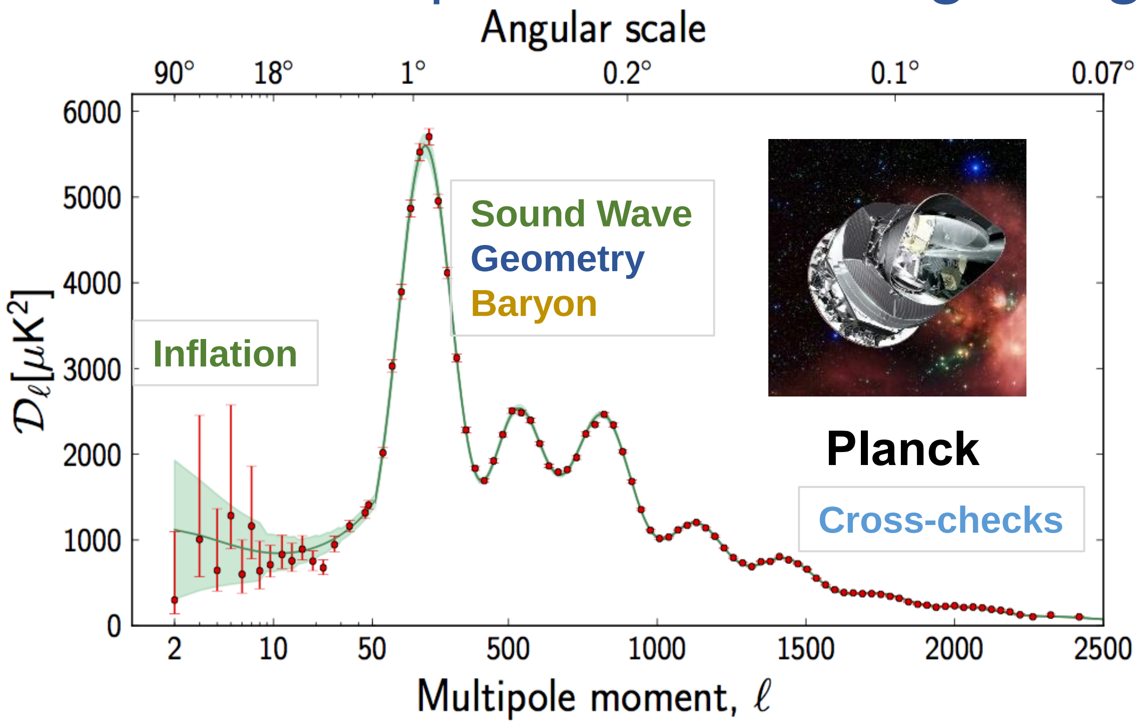
Hydrodynamics Simulations

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

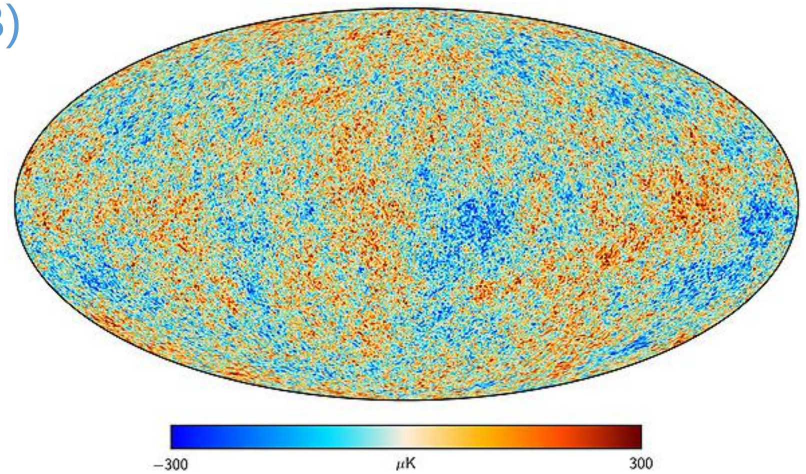
The successful hydrodynamics description implies rapid hydrodynamization!

Density Fluctuations

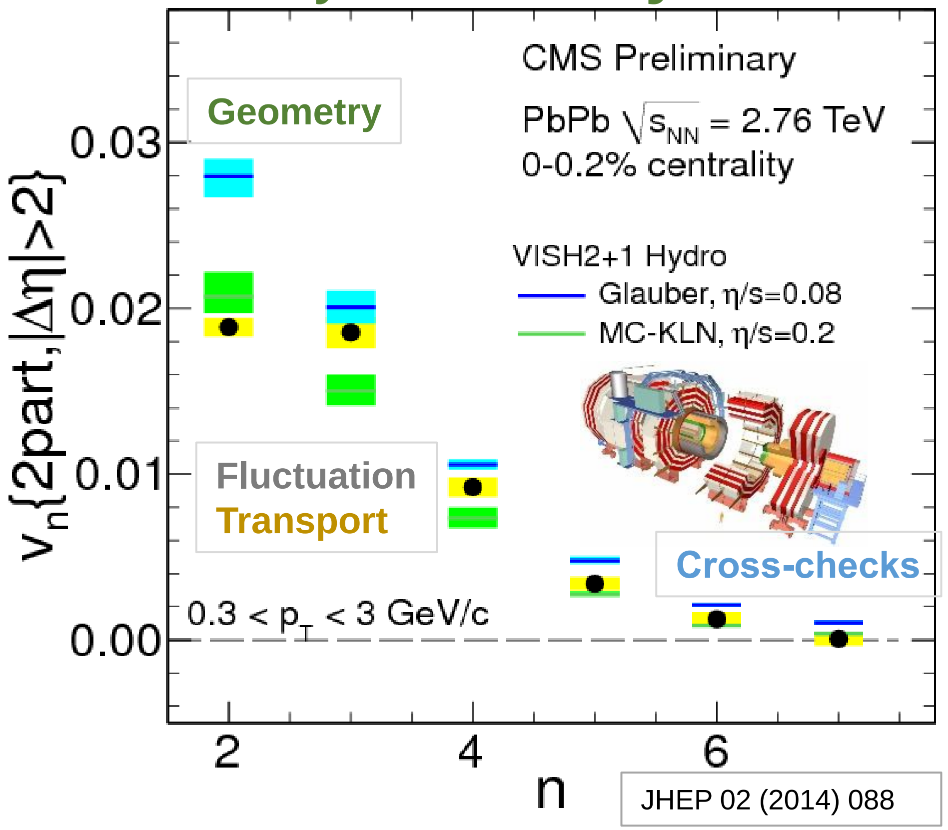
Power spectrum of **the Big Bang**

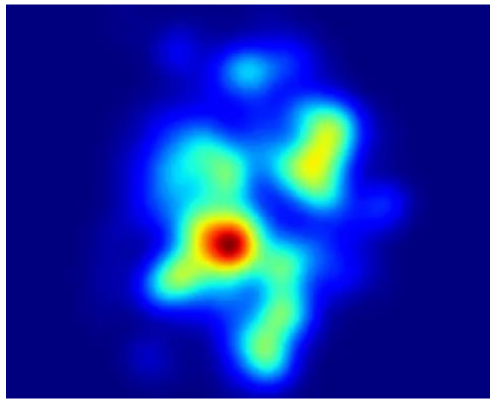


Cosmic Microwave Background (CMB)



Fourier analysis of **many little bangs**

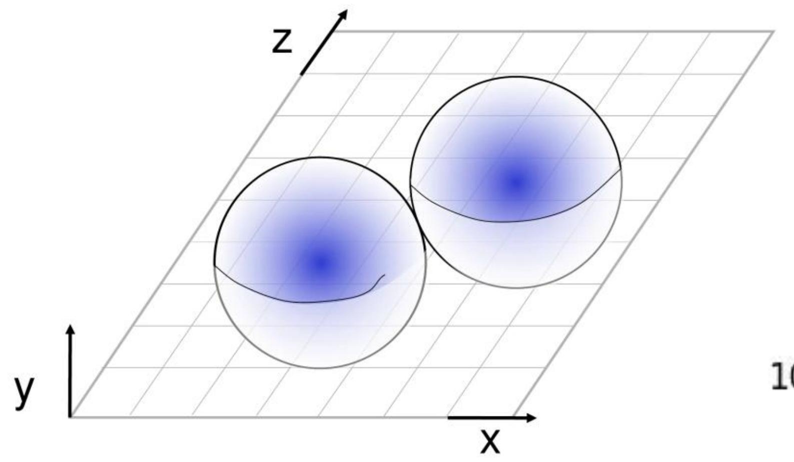


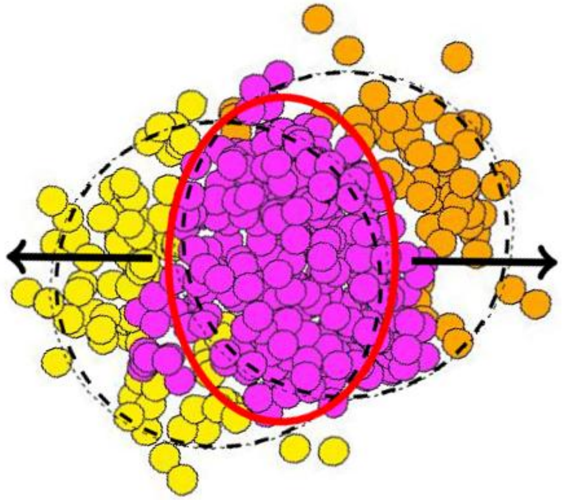


Quark Gluon Plasma (QGP)

(Hydro Simulation)

Effect of Shear Viscosity in Simulation

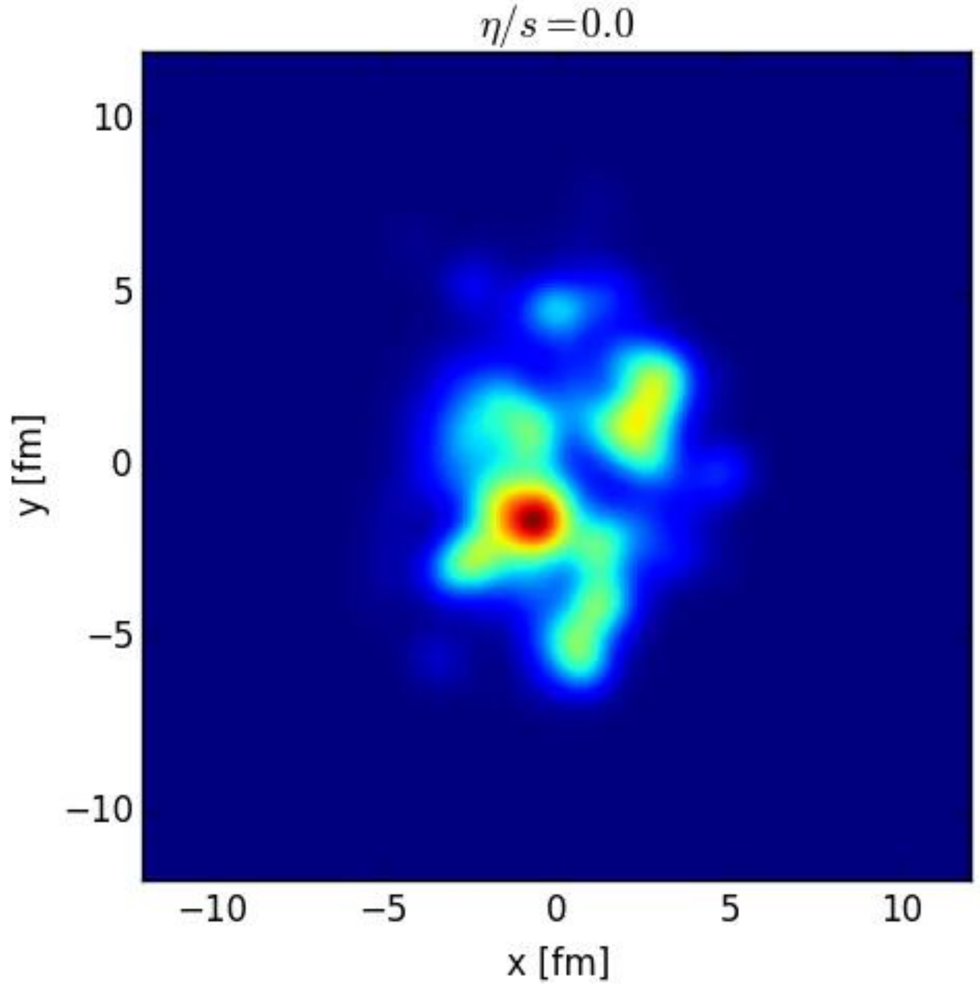




Alver and Roland (MIT)
"Collision geometry fluctuation"
PRC82 (2010) 039903

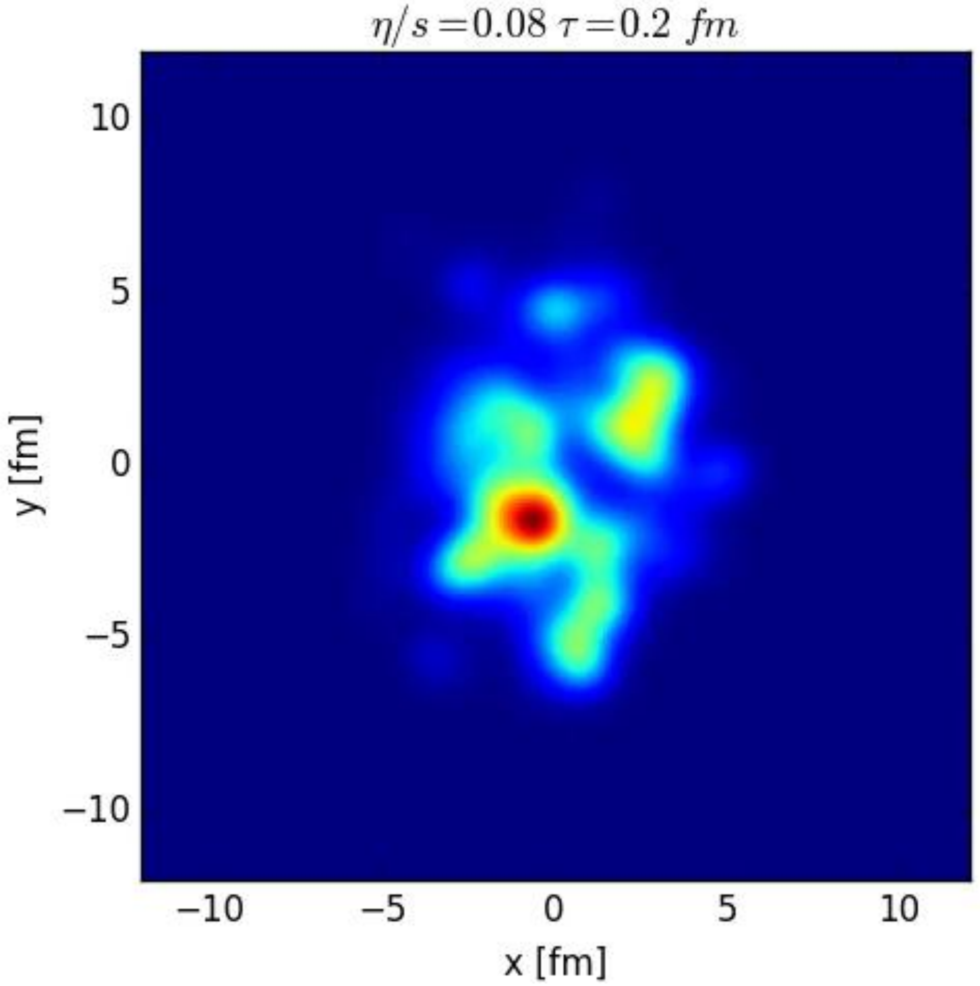
Ideal hydrodynamics

η/s = 0



Viscous hydrodynamics

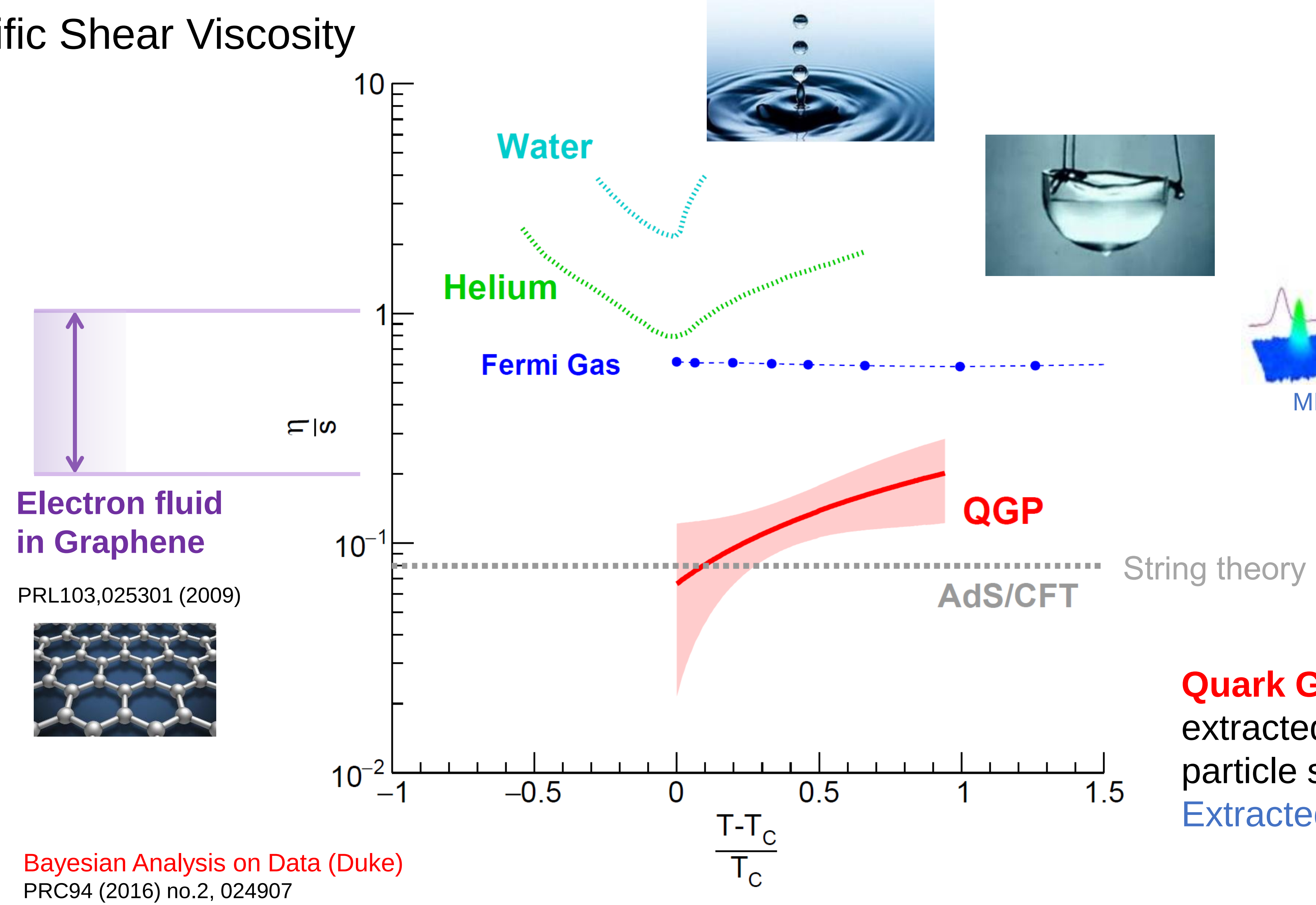
η/s = 0.08

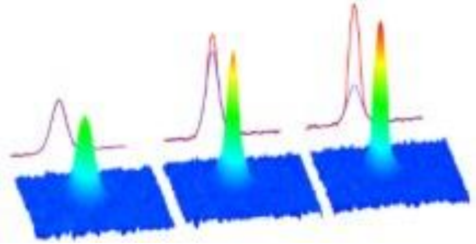


Animation from L. G. Peng

Near Perfect Fluid

Specific Shear Viscosity





MIT cold atom group

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

Quark Gluon Plasma (QGP):
extracted from flow correlation and particle spectra at low p_T
Extracted from hydrodynamics models

Open Questions

- What is the smallest collision that can still create Quark-Gluon Plasma?
- Can a fast quark stir the soup and leave a wake?
- How does a nonthermal quark become part of the soup? How did the early Universe turn quark soup into ordinary matter?

Open Questions

- What is the smallest collision that can still create Quark-Gluon Plasma?

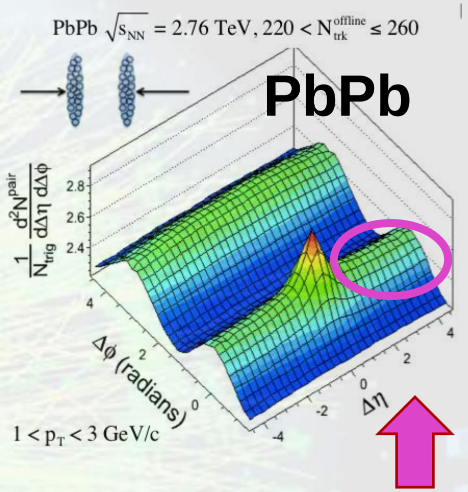
  Going to the smallest collision system

- Can a fast quark stir the soup and leave a wake?

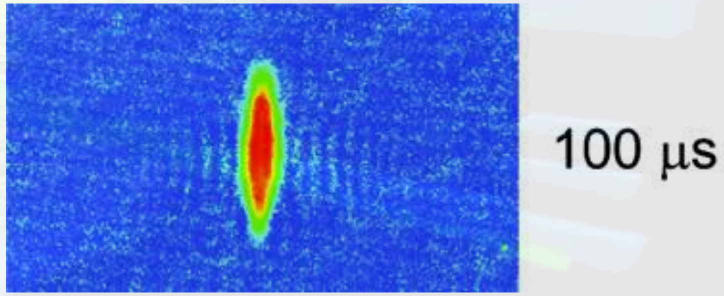
- How does a nonthermal quark become part of the soup? How did the early Universe turn quark soup into ordinary matter?

Making a Tiny Quark Soup

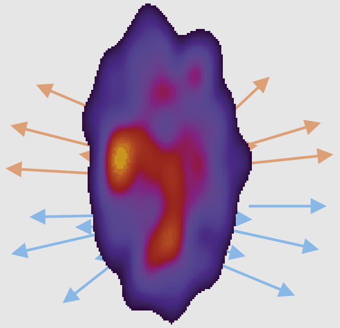
“Ridge-like Correlation” in Lead-Lead Collision



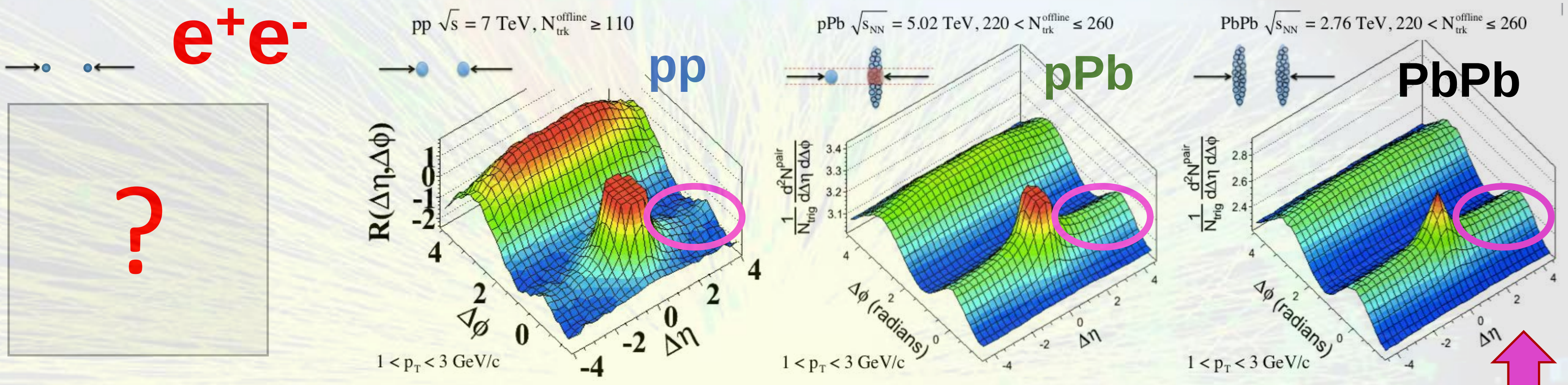
- “Ridge” in **Lead-Lead** collisions: Hydrodynamics Flow



Quark Gluon Plasma

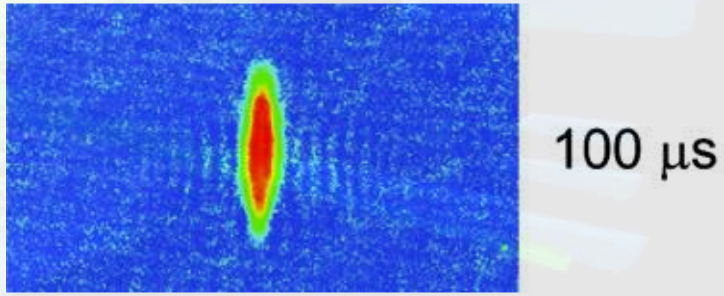


"Ridge-like Correlation" in Small Systems



JHEP 1009 (2010) 091

PLB 718 (2013) 795

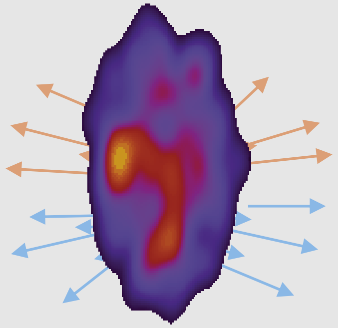


- "Ridge" in **Lead-Lead** collisions: Hydrodynamics Flow

- Observed in **high particle multiplicity**
  proton-proton (2010) and **proton-lead** (2013) collisions!!!

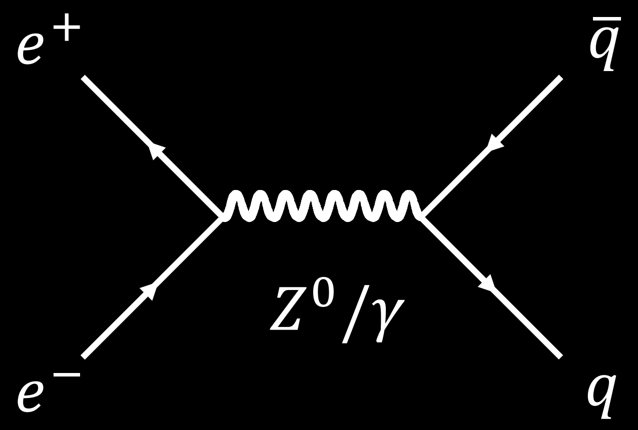
- What will happen to the smallest collision system:
  Electron-positron collision?

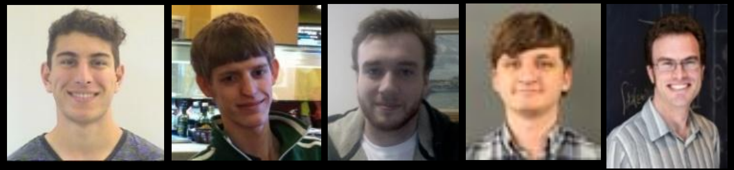
Quark Gluon Plasma



High Multiplicity Event in e^+e^- Collisions

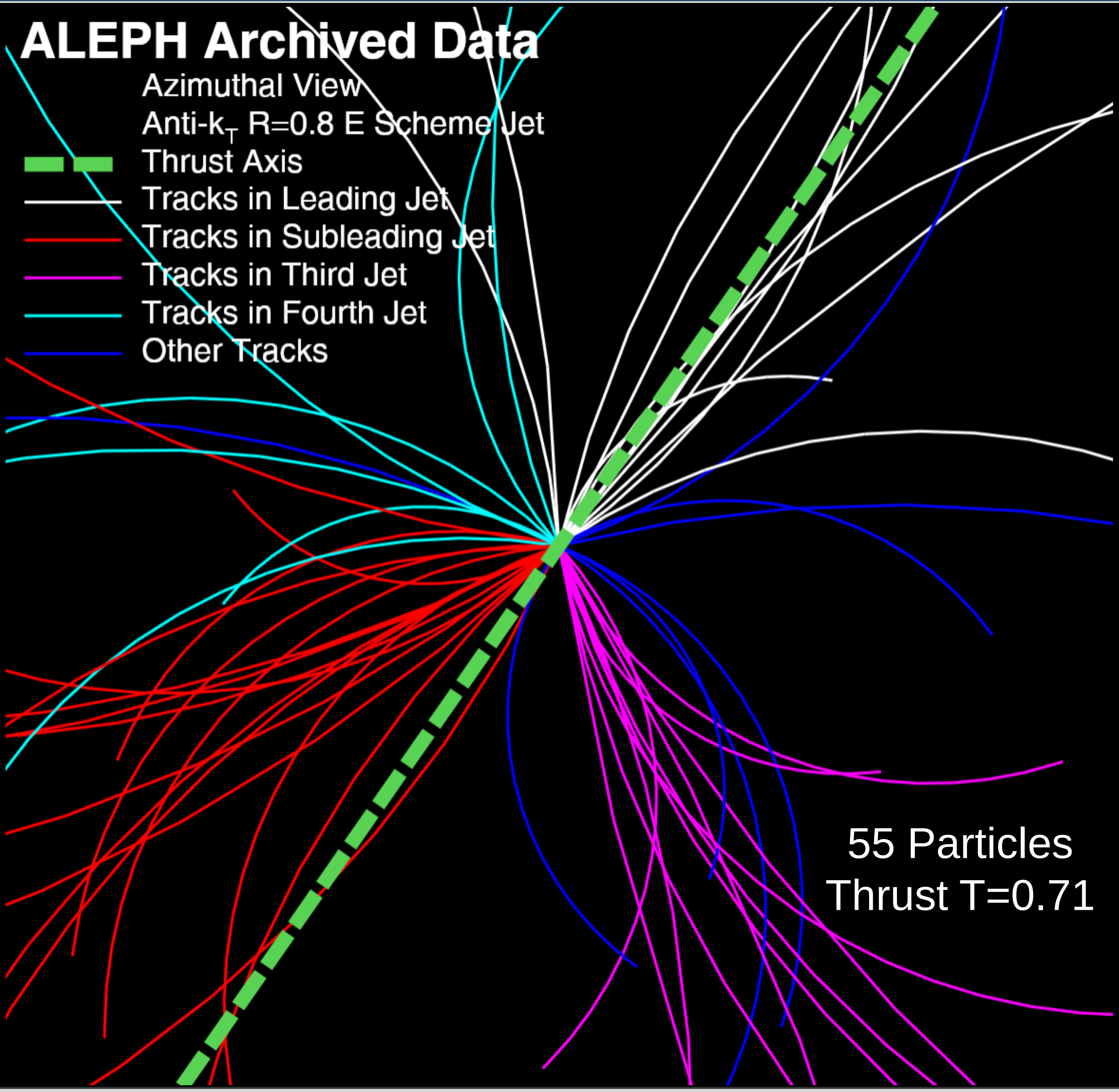
Large Electron Positron Collider 1 (LEP1): Sample from 1992-1995



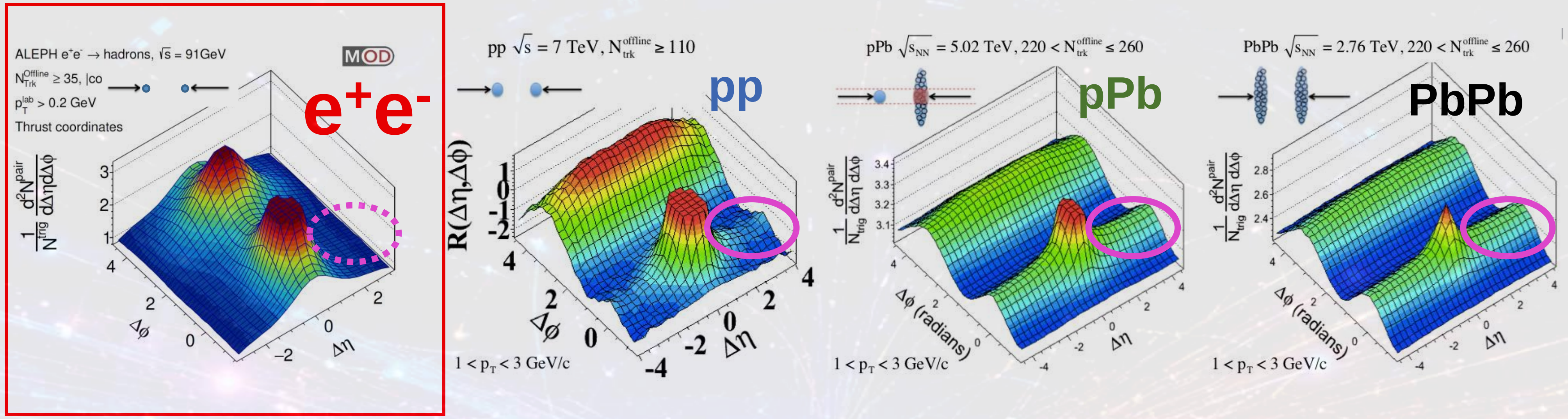


Anthony Badea Austin Baty Chris McGinn Michael Peters Jesse Thaler

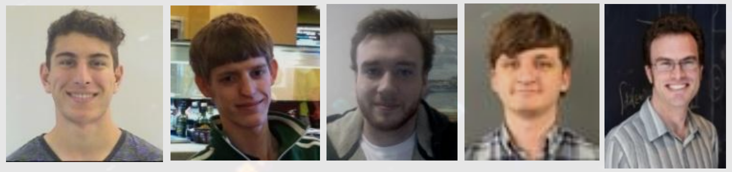
Highest multiplicity event
in ALEPH data at Z pole
Collision Energy = 91 GeV



Results from ALEPH e^+e^- at 91 GeV



- No sign of ridge signal in electron-positron collisions up to ~ 55 particles per event
- New reference to the collective behavior in small collision systems!



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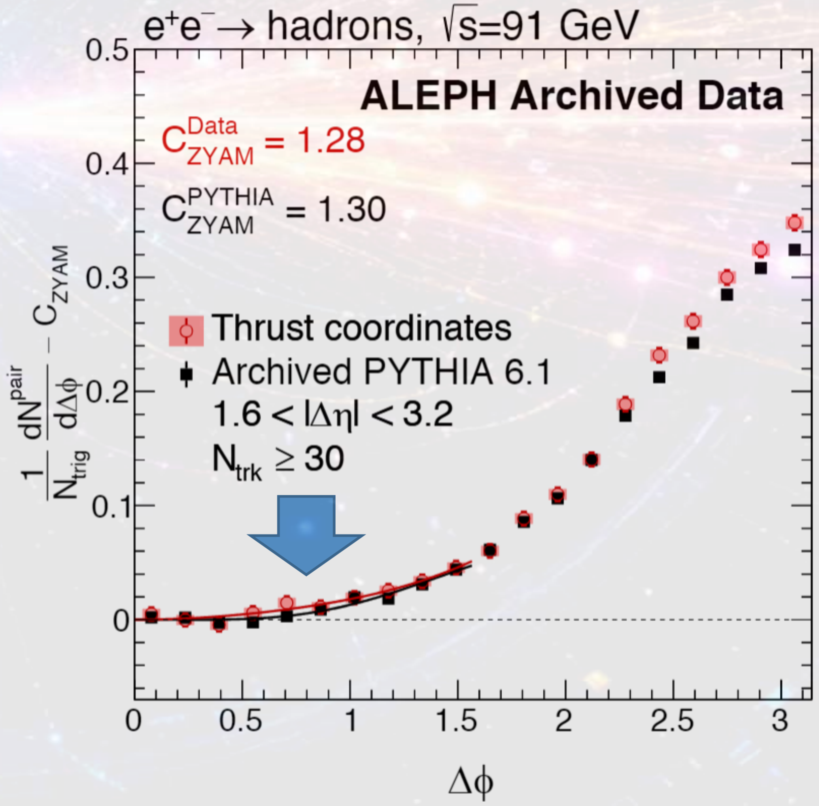
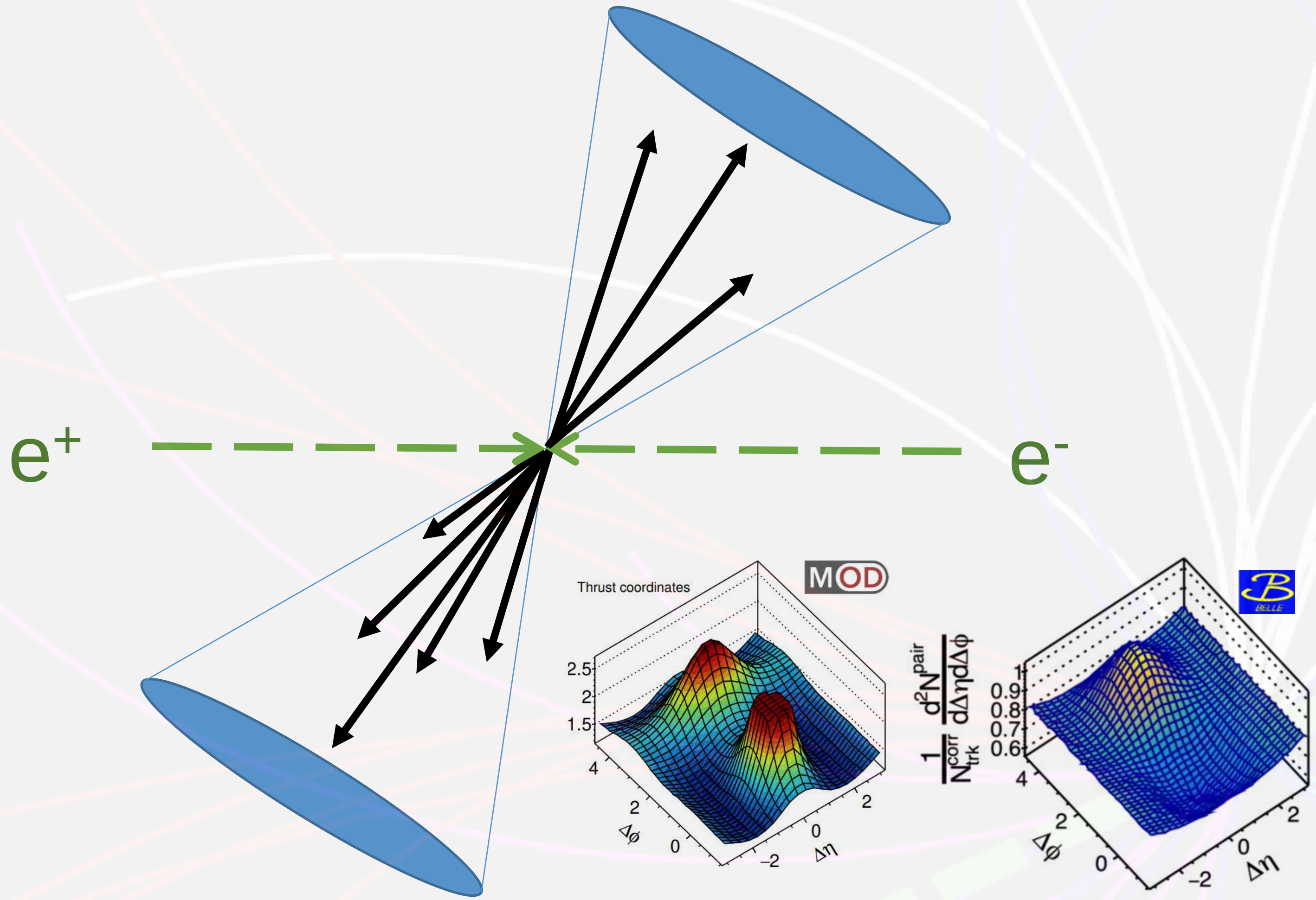
PRL 123, 212002 (2019)

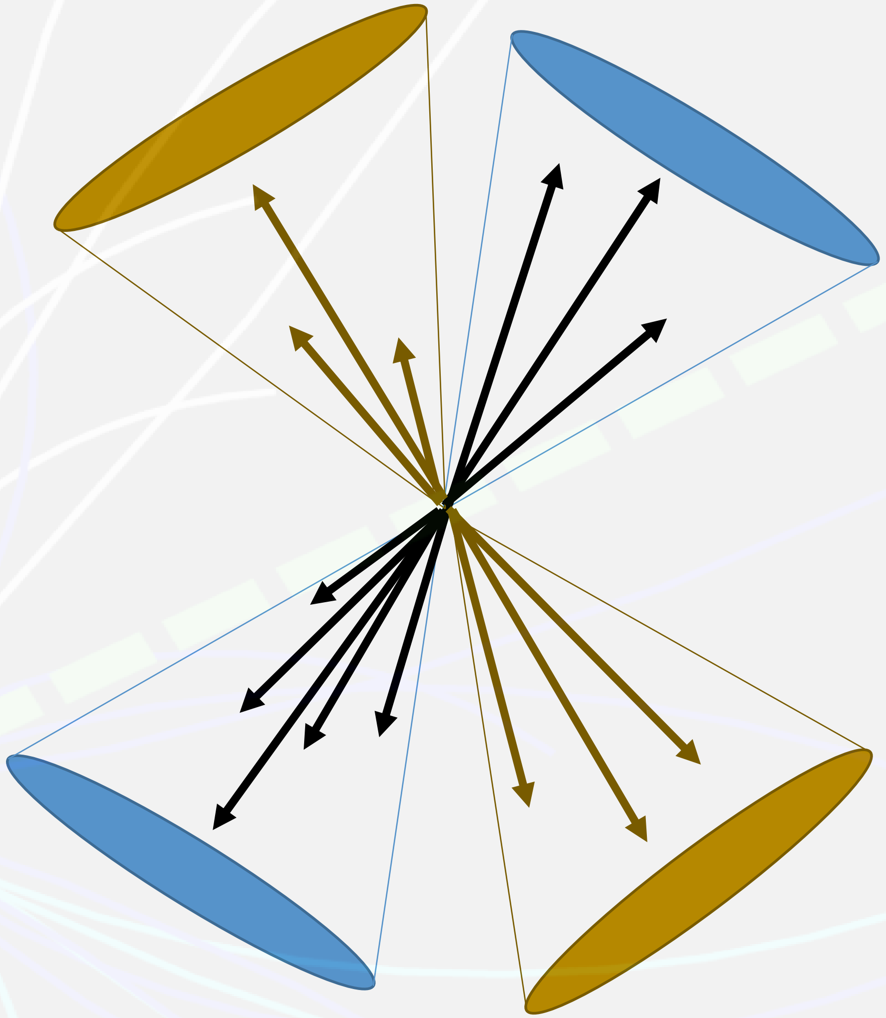


e^+e^- Alliance
http://ee-alliance.org/

Can We Overlap Two Color Strings?

$$e^+e^- \rightarrow q\bar{q}$$





?

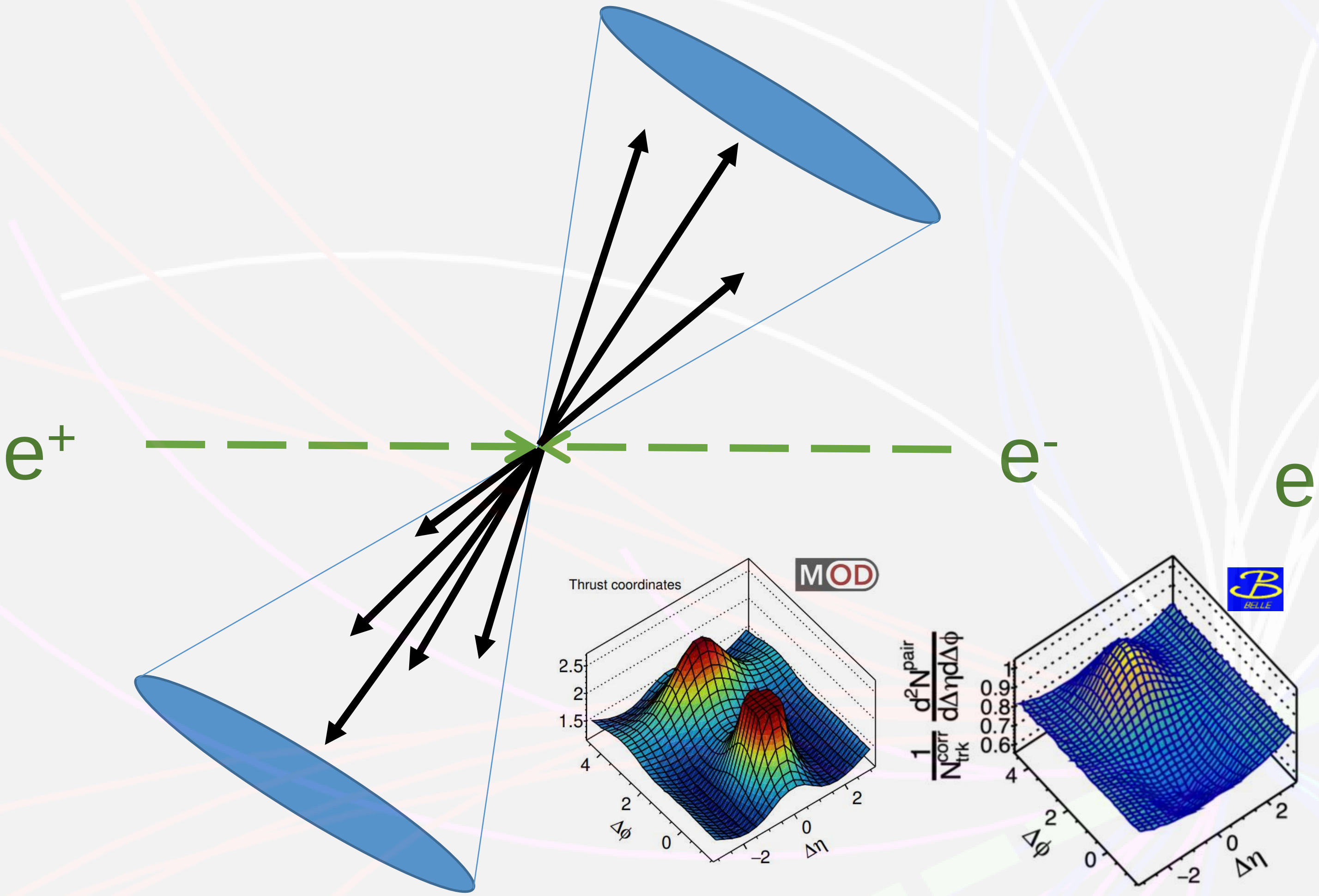
Belle PRL 128 (2022) 14, 142005
Belle JHEP 03 (2023) 171
Electron-Positron Alliance PRL 123, 212002 (2019)

No ridge-like structure

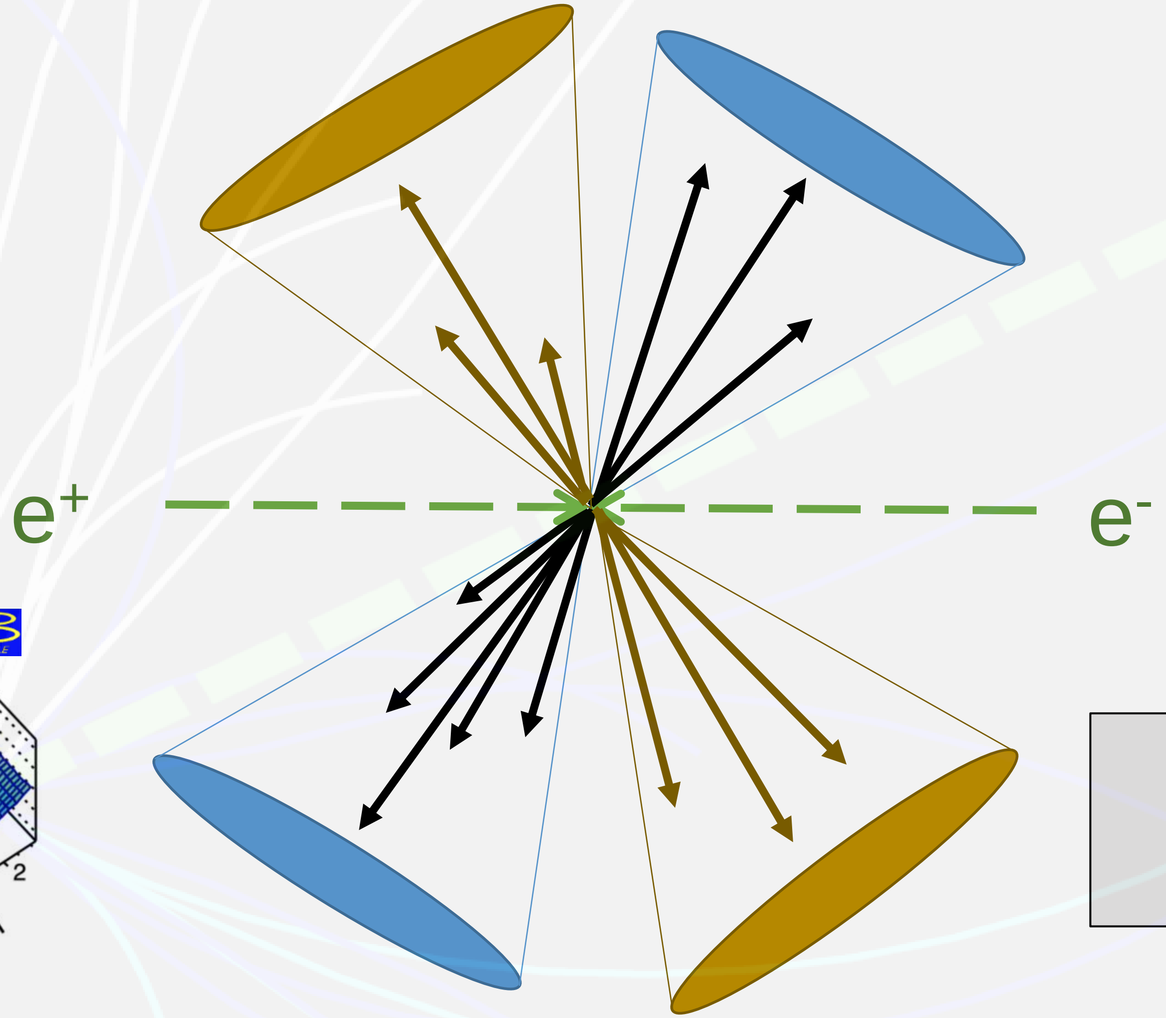
High Multiplicity e^+e^- Event at High Collision Energy !!

$$e^+e^- \rightarrow q\bar{q}$$

$$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$$



No ridge-like structure

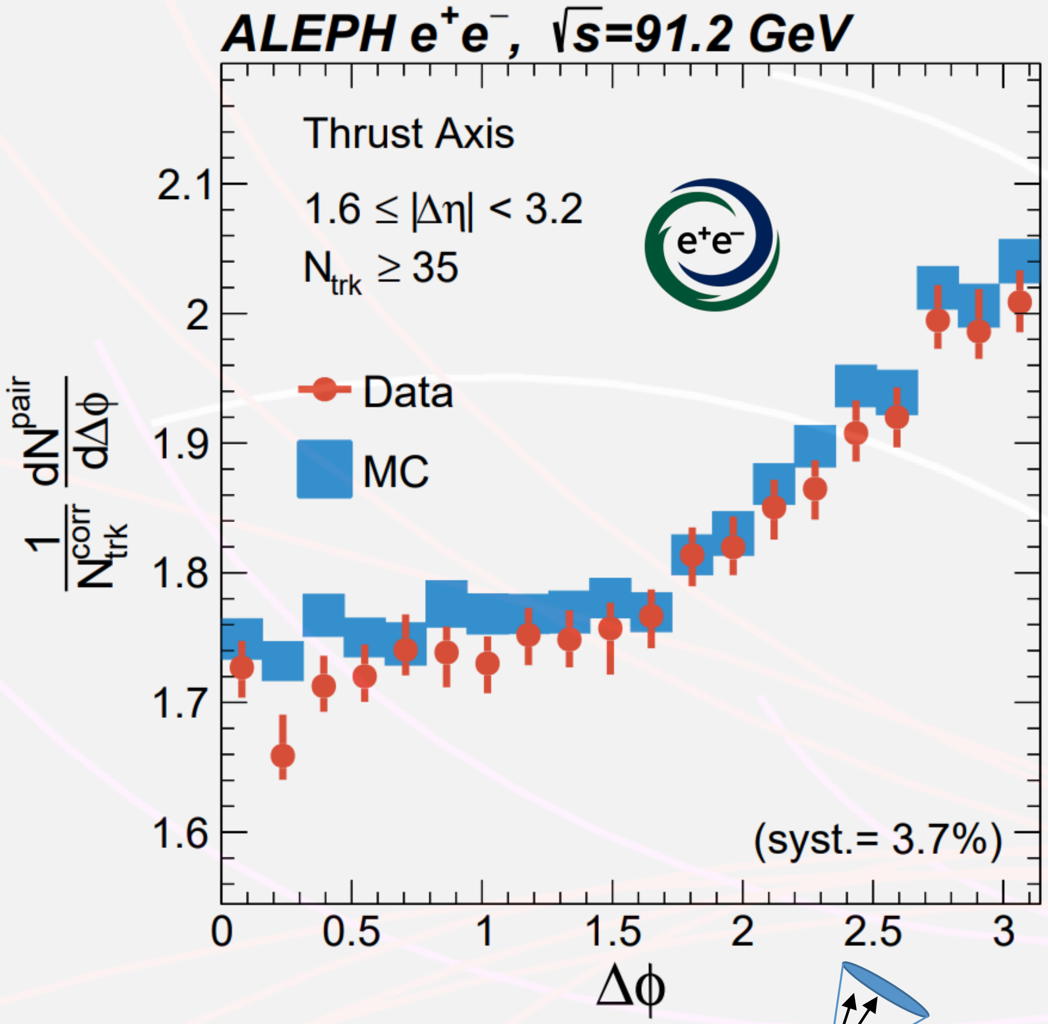


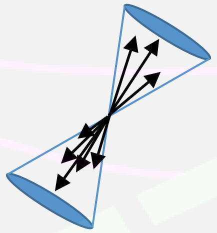
?

Belle PRL 128 (2022) 14, 142005
Belle JHEP 03 (2023) 171
Electron-Positron Alliance PRL 123, 212002 (2019)

High Multiplicity e^+e^- Events at LEP1 vs LEP 2

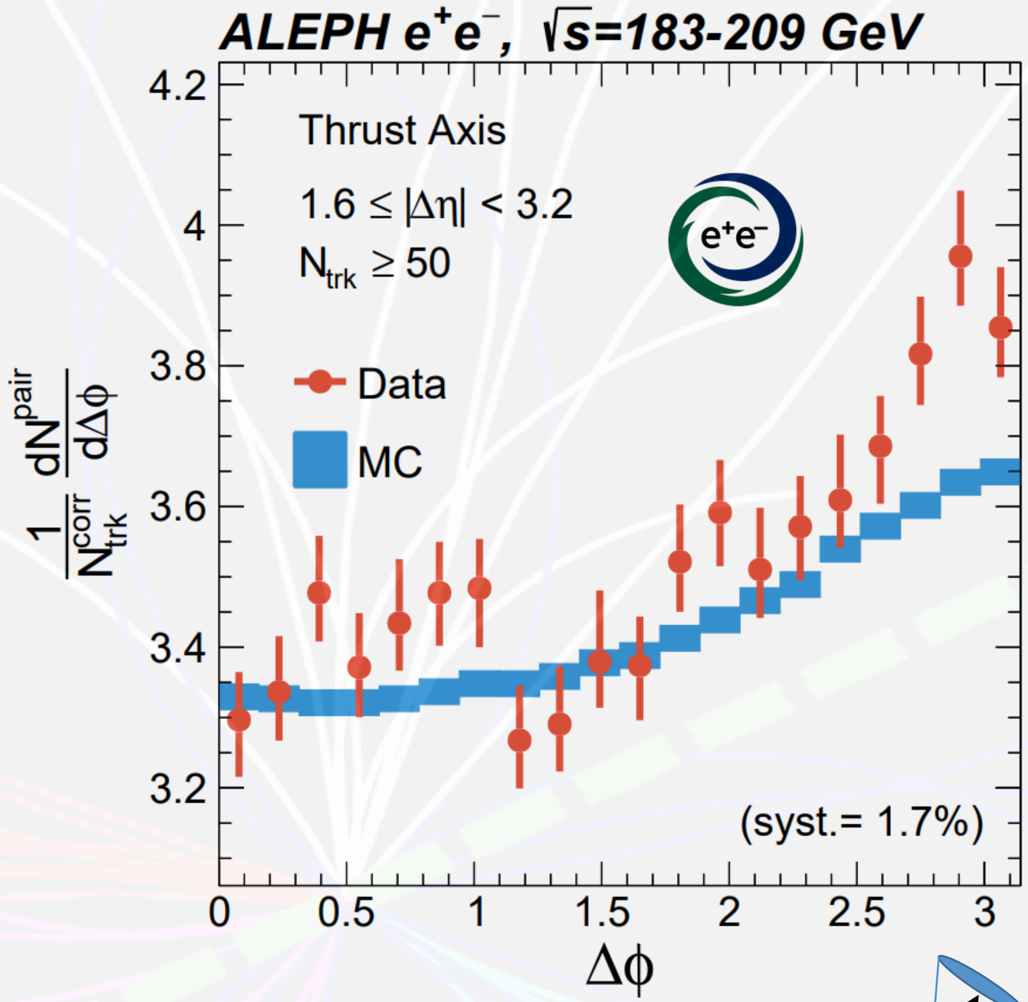
LEP1 N_{trk}>35



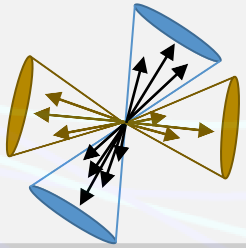


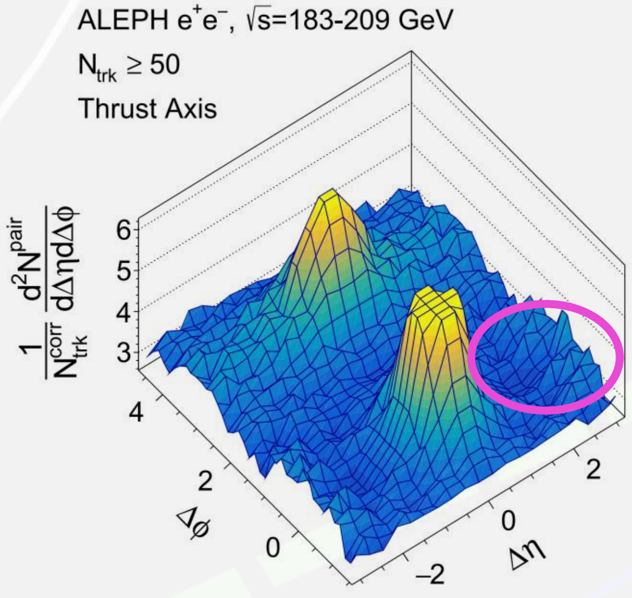
$e^+e^- \to q\bar{q}(\gamma)$

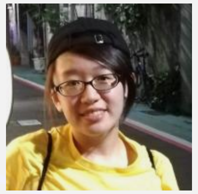
LEP2 N_{trk}>50



$e^+e^- \to W^+W^-$ enriched



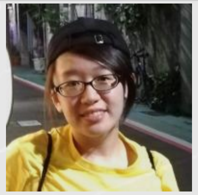




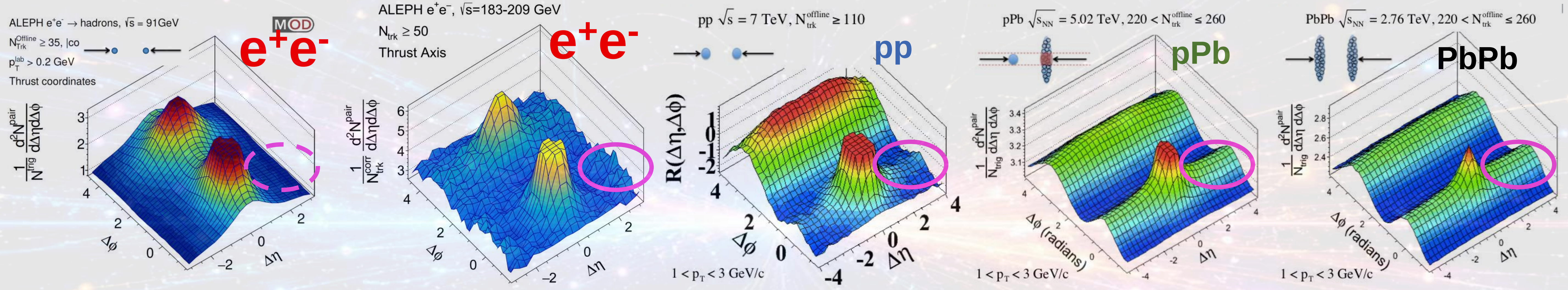
Yu-Chen “Janice” Chen (MIT)

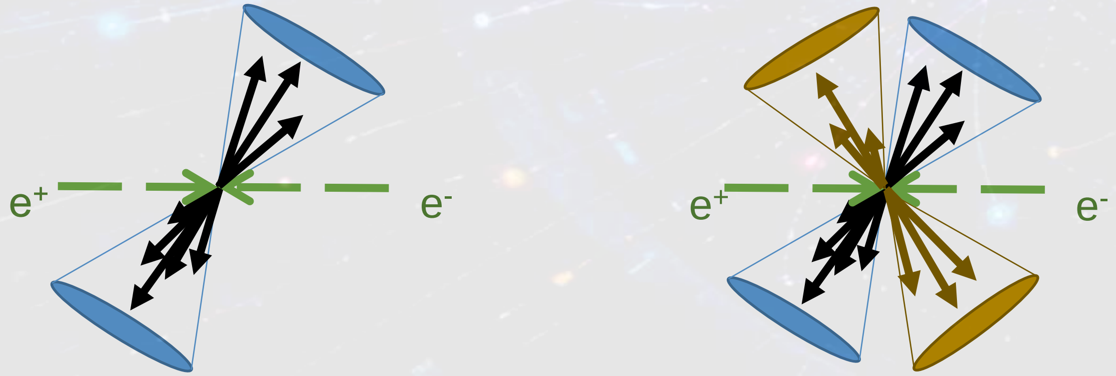
1. EPA PLB 856 (2024) 138957
2. EPA arXiv:2606.21094

Emerging Picture: Smallest Quark Soup?



Yu-Chen “Janice” Chen (MIT)





Are the two color strings beginning to talk?

A possible first inter-dipole rescattering:
the microscopic seed of collective QCD matter?

PRL 123, 212002 (2019)
PLB 856 (2024) 138957
arXiv:2606.21094

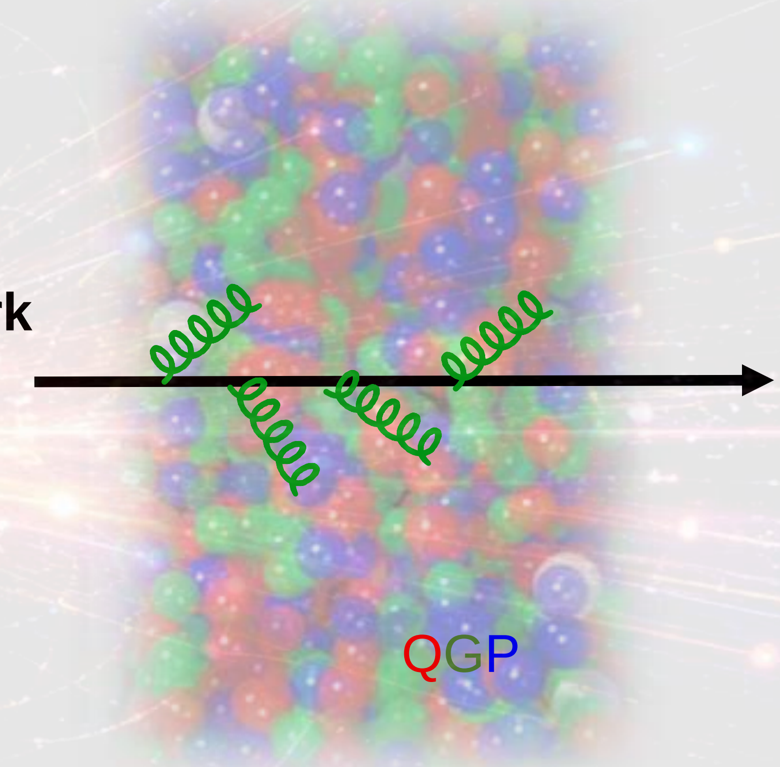
Hard Probes of Quark Gluon Plasma


James Bjorken (1982)

FERMILAB-PUB-82-059-T

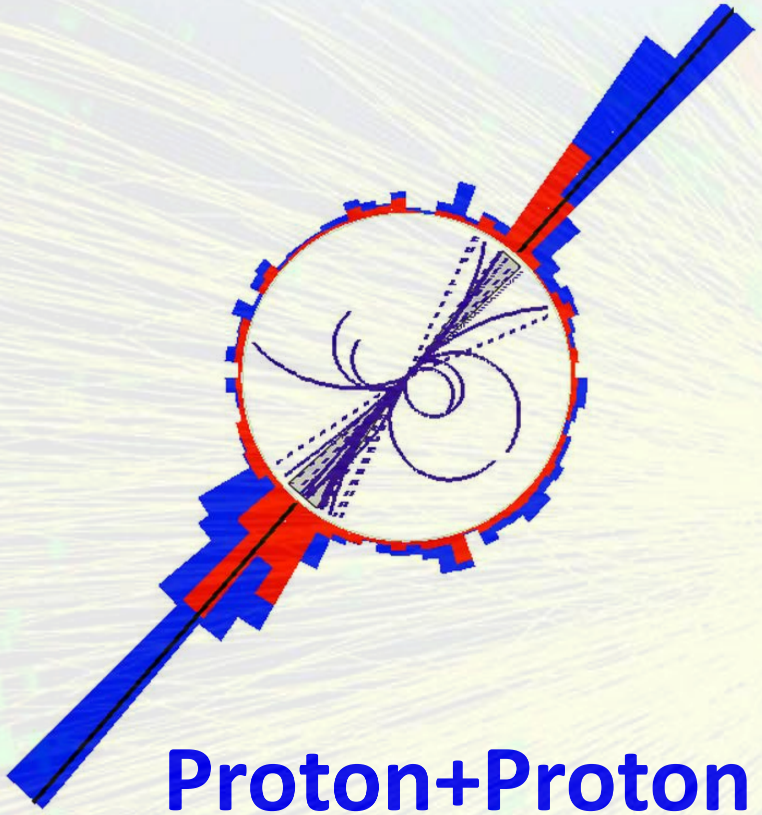
Jet Quenching

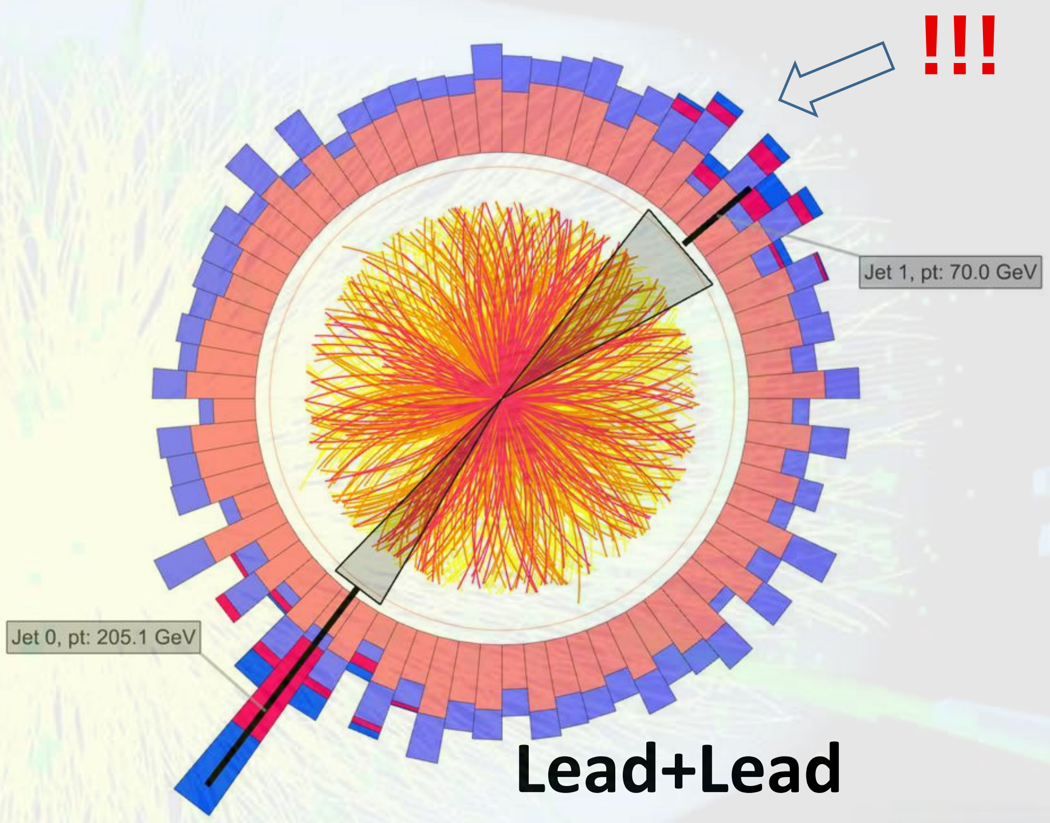
Lifetime O(10^{-23}s)

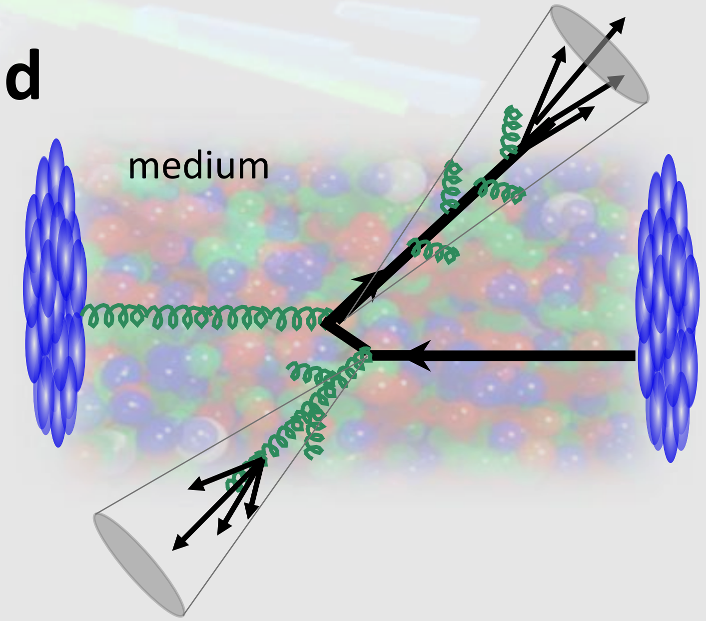


Use **Energetic Quarks** to reveal
QGP structure at various length scales

Probe the Quark Soup with High Energy Quarks and Gluons







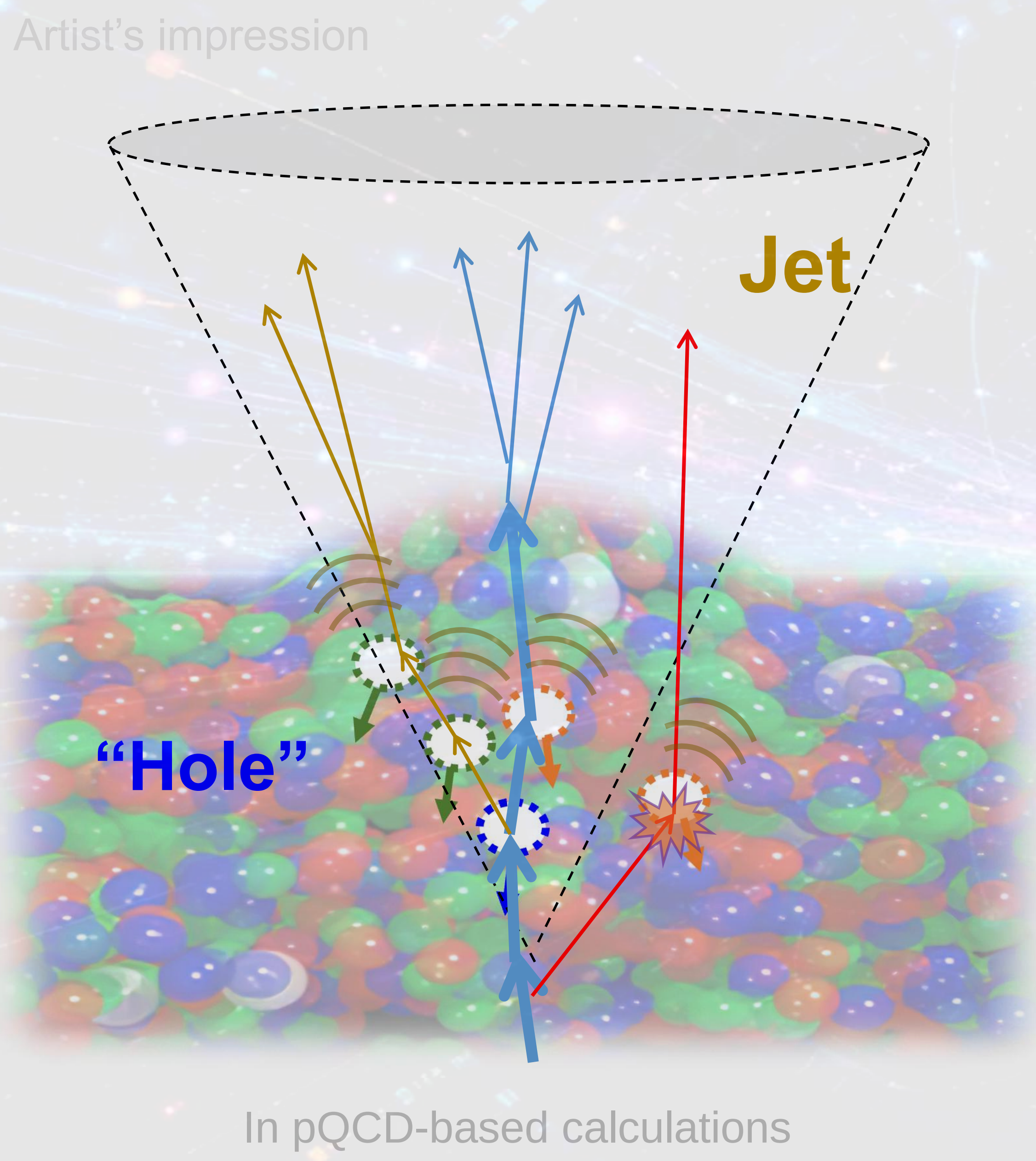
- **Direct observation of jet quenching: Asymmetric** dijets in Lead+Lead collisions
- The stopping power of the **QGP** is **Very Strong**

PRC 84 (2011) 024906

JHEP 01 (2016) 006

PLB 712 (2012) 176

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

Open Questions

- What is the smallest collision that can still create Quark-Gluon Plasma?

  Going to the smallest collision system

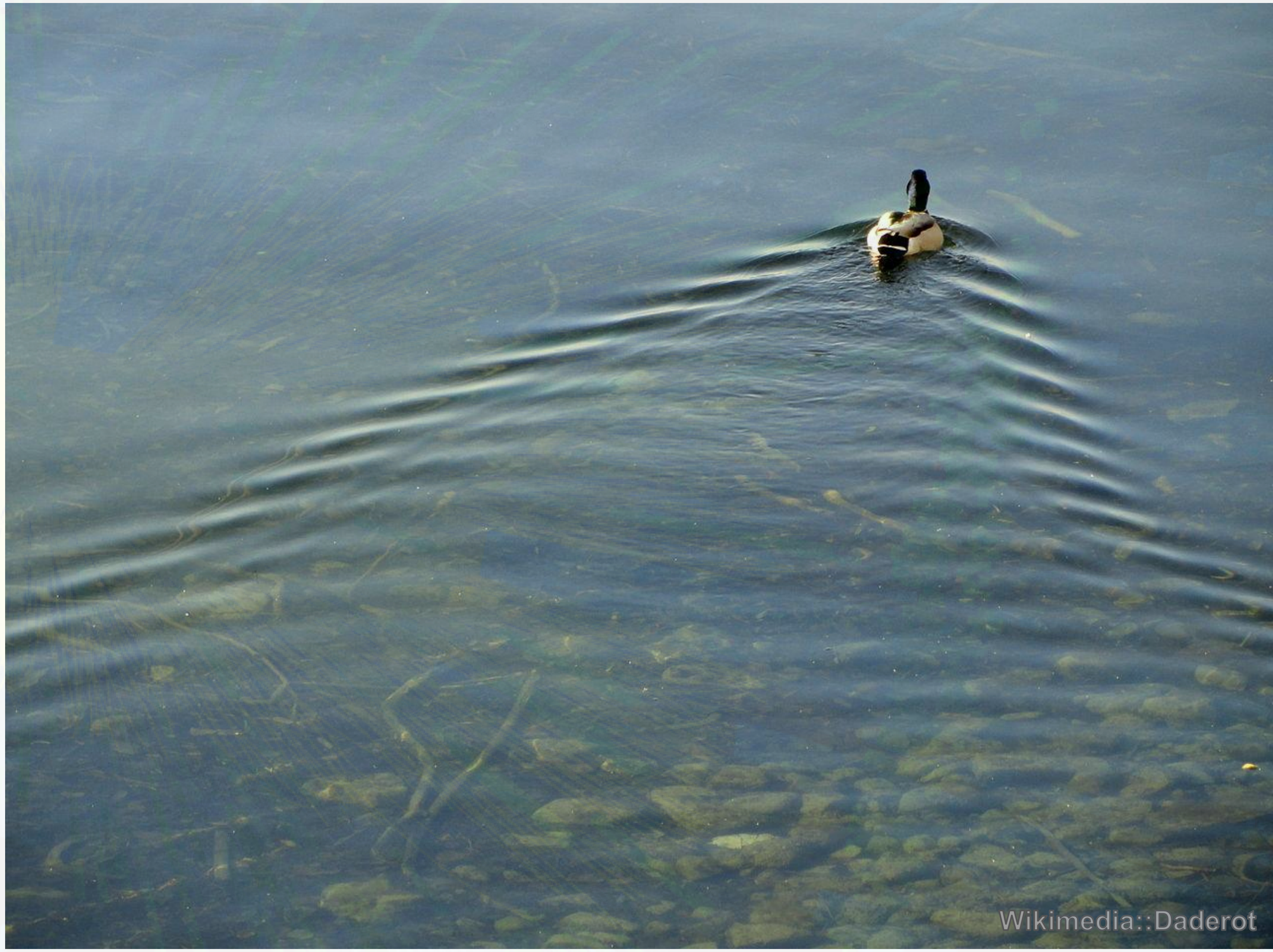
- **Can a fast quark stir the soup and leave a wake?**

  Follow a fast moving quark traversing the QGP closely

- How does a nonthermal quark become part of the soup? How did the early Universe turn quark soup into ordinary matter?

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

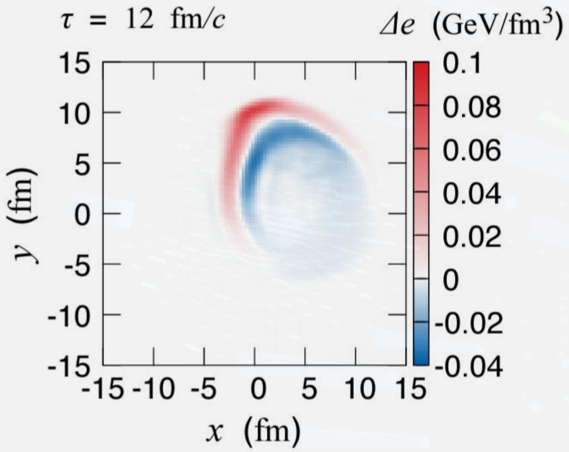
Duck swimming through **water**



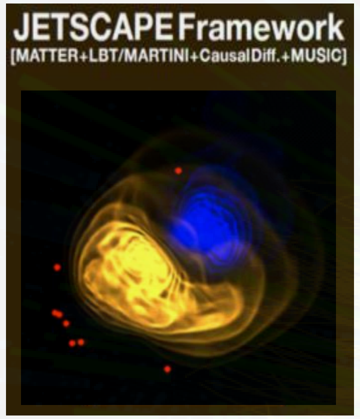
More **water** going in the duck direction

Medium Response to Hard Probes in Quark Gluon Plasma

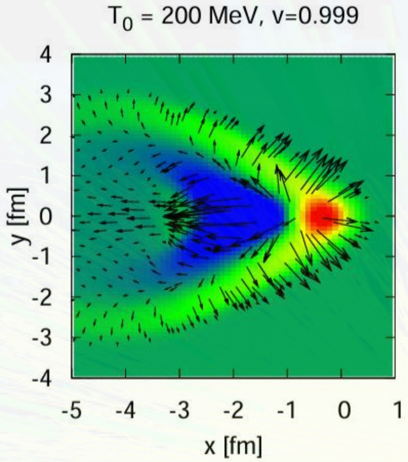
Quark plowing through the **Quark Soup**



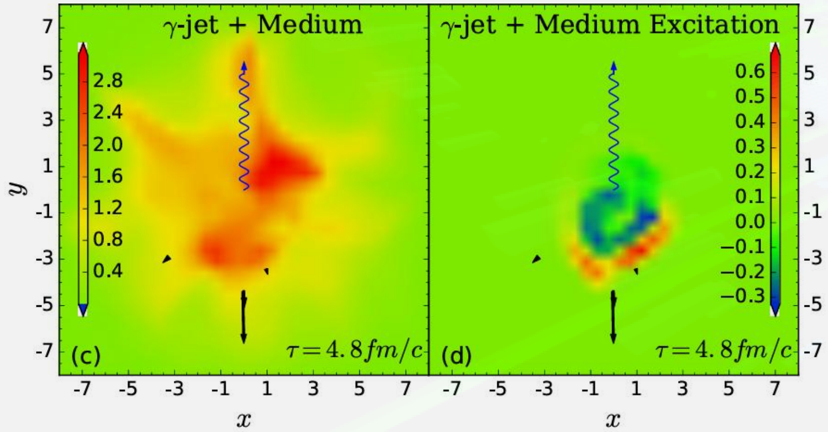
Jet-Fluid Yasuki, Chang, Qin
PRC 95 (2017) 4, 044909



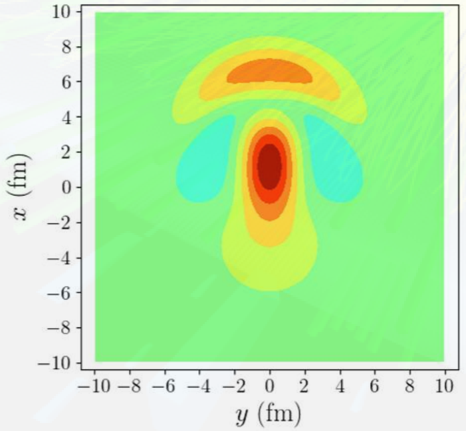
JETSCAPE framework
Tachibana, Shen, Majumder
PRC 106 (2022), L021902



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



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

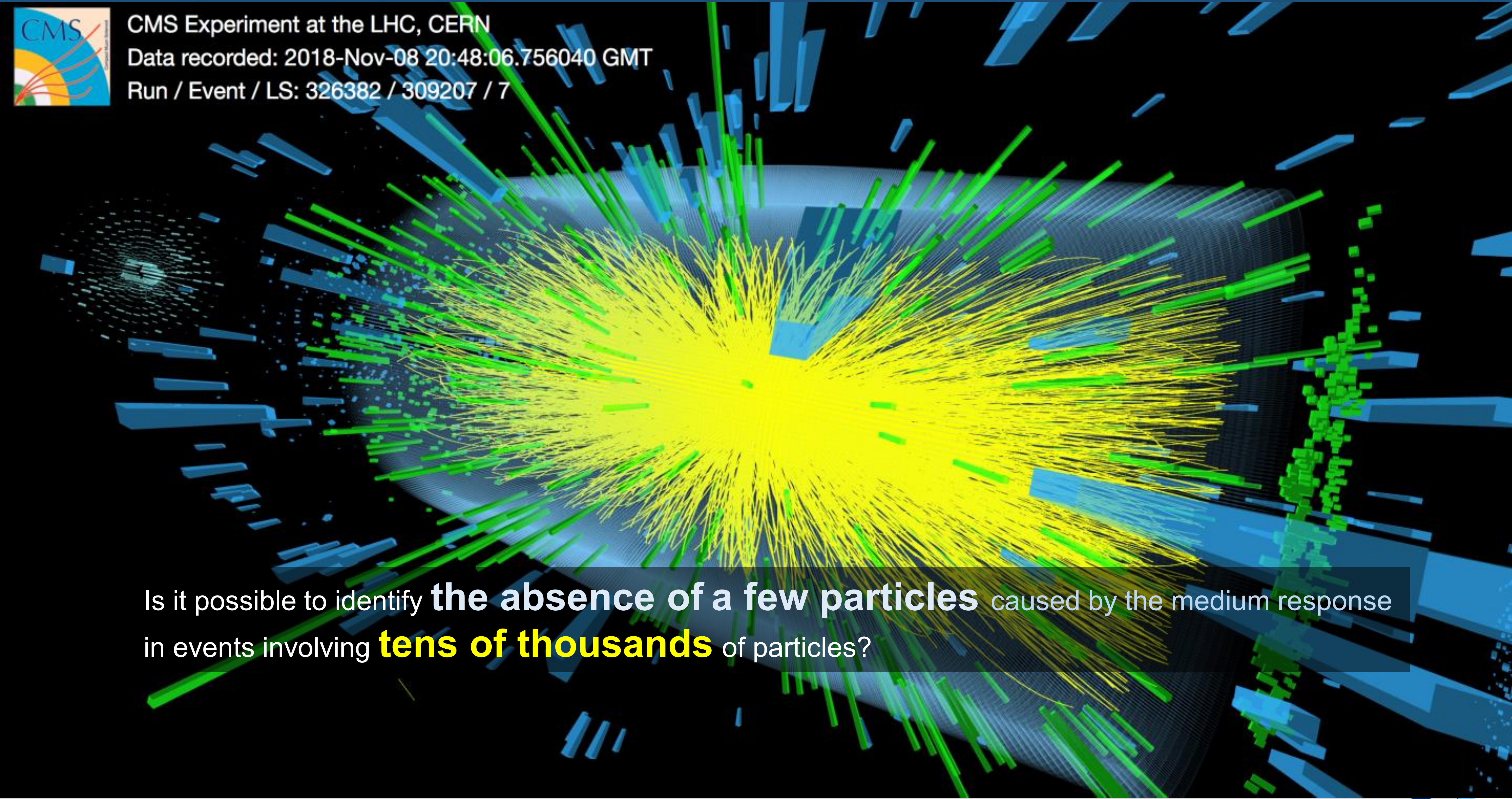


Casalderrey-Solana, Milhano,
Pablos, Rajagopal Yao
JHEP 05 (2021) 230

More **Quark Soup** going in the jet direction

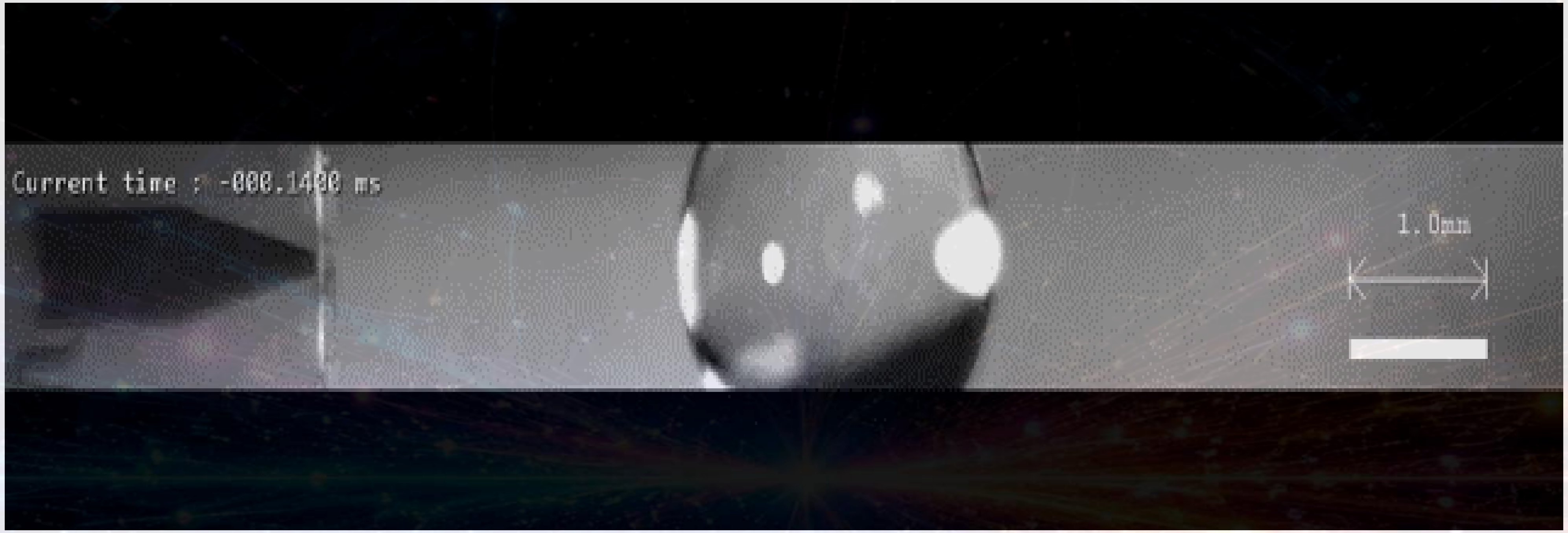
Duck swimming through **water**

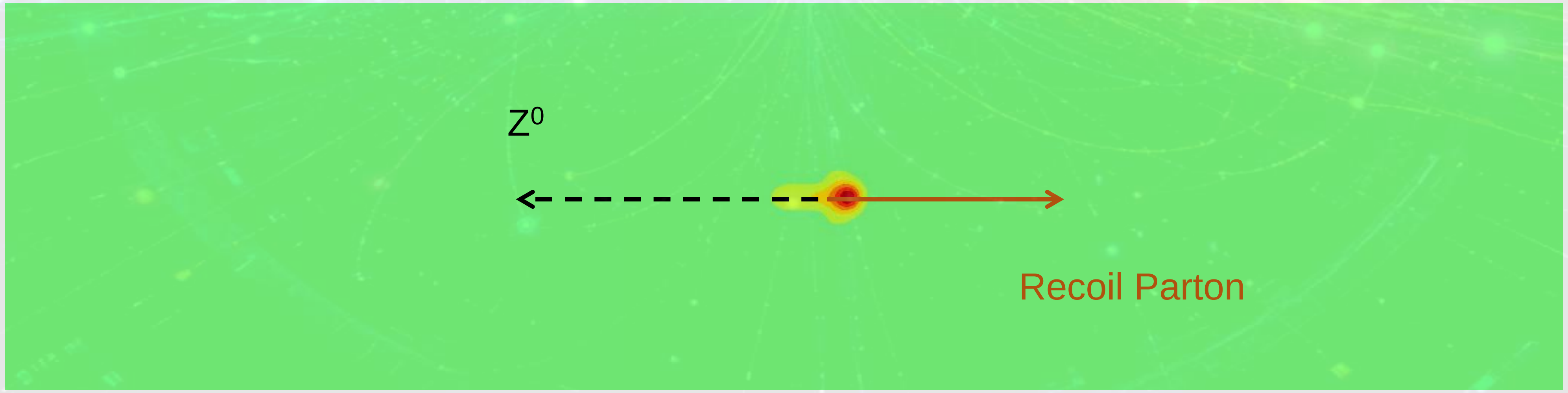
More **water** going in the duck direction



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 Boson as a tag of the Quark direction



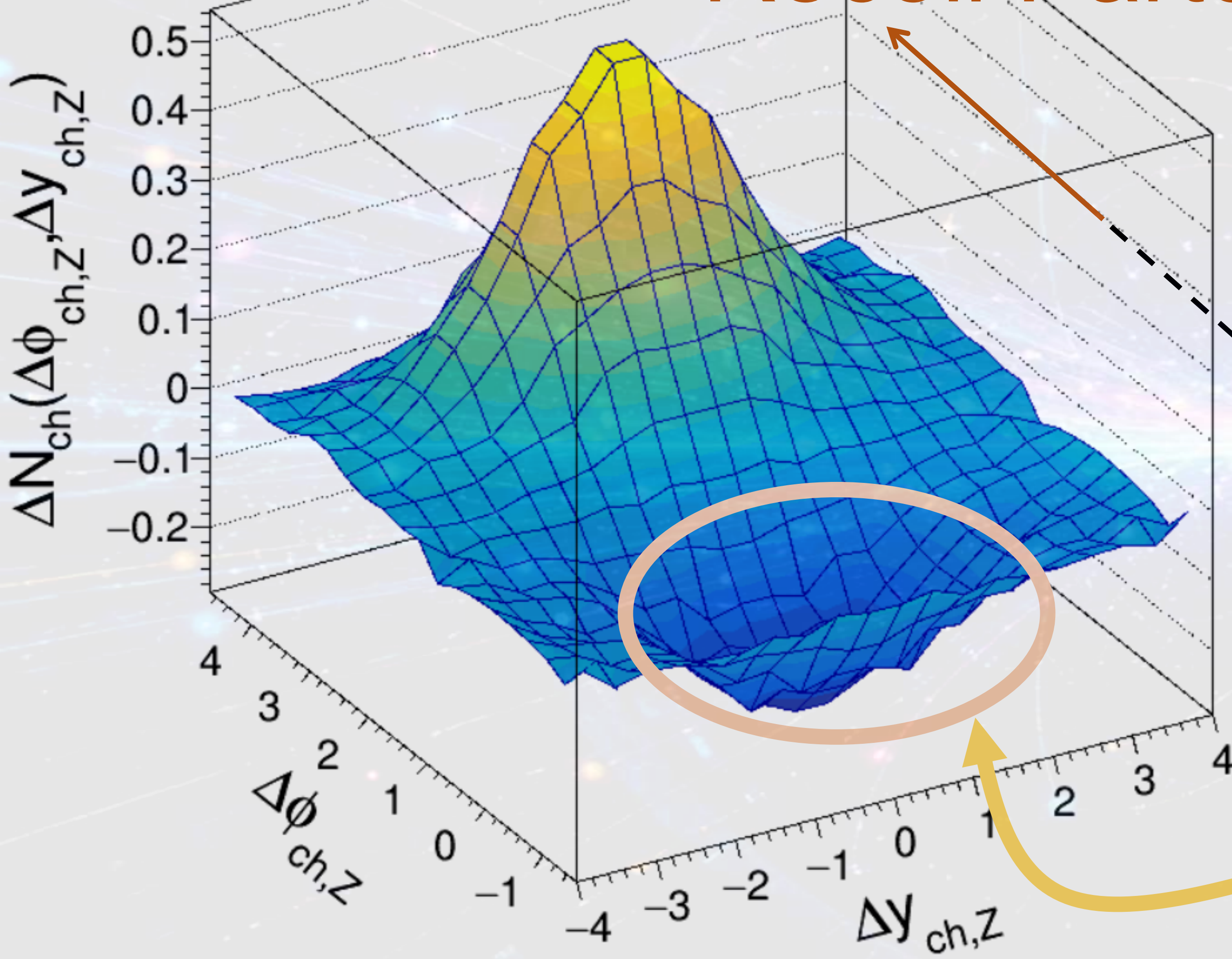


We use Z^0 bosons (**colorless** probe) to tag the recoil-parton direction:
Z^0 **escapes unaffected**; the jet plows through the quark soup

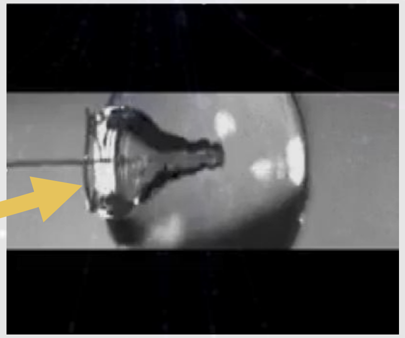
Z^0 Boson as a tag of the Quark direction

Simulation ***with*** **QGP wake**

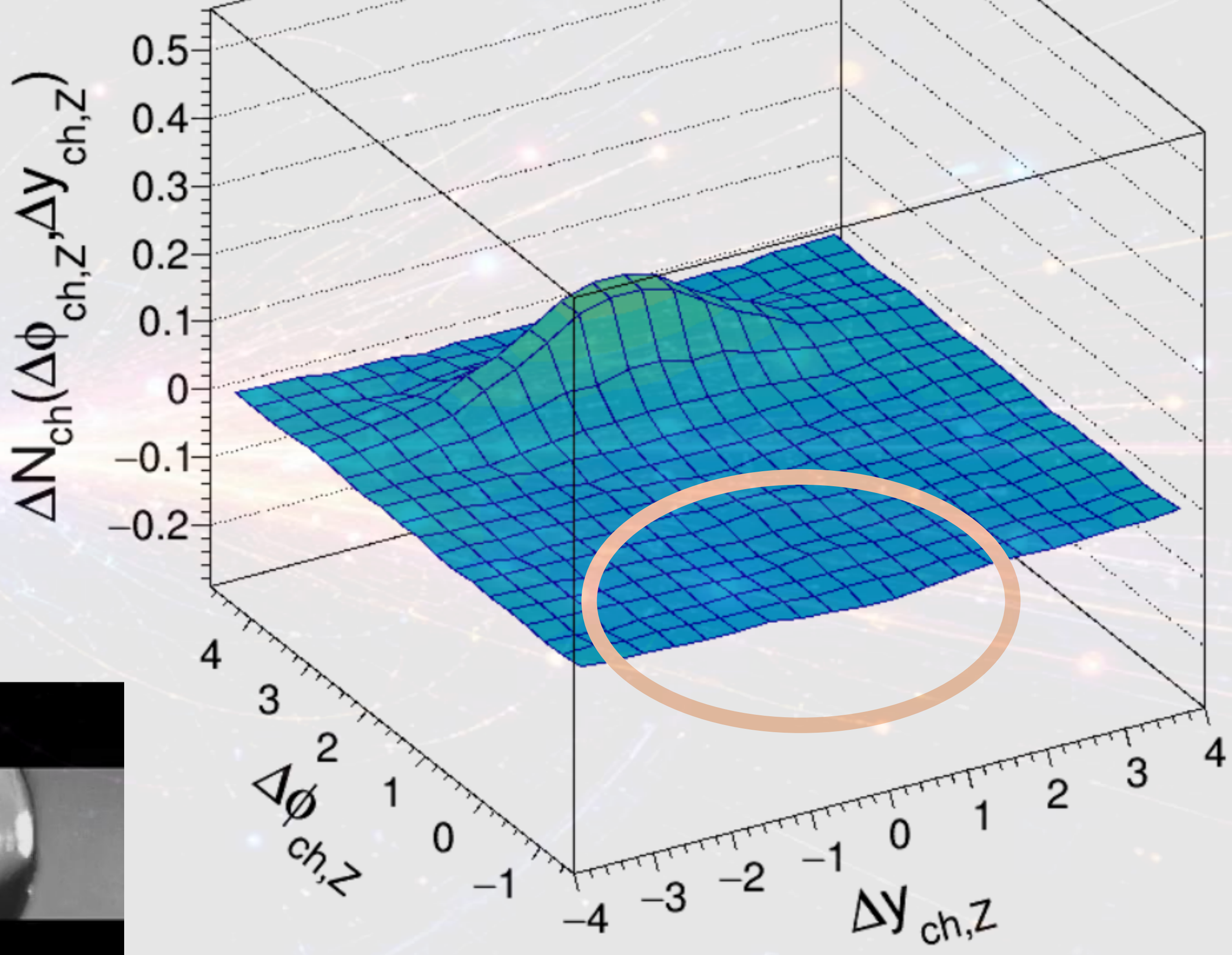
Recoil Parton



Z^0



Simulation ***without*** **QGP wake**

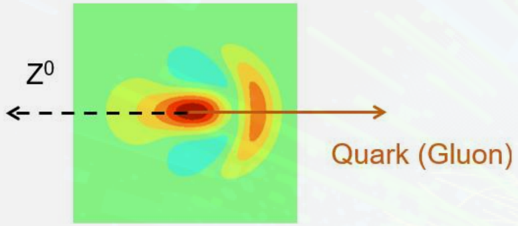


- Hybrid Model: QGP wake creates a **Z^0-side dip structure** and significantly enhance the jet peak

Direct Evidence of Medium Response

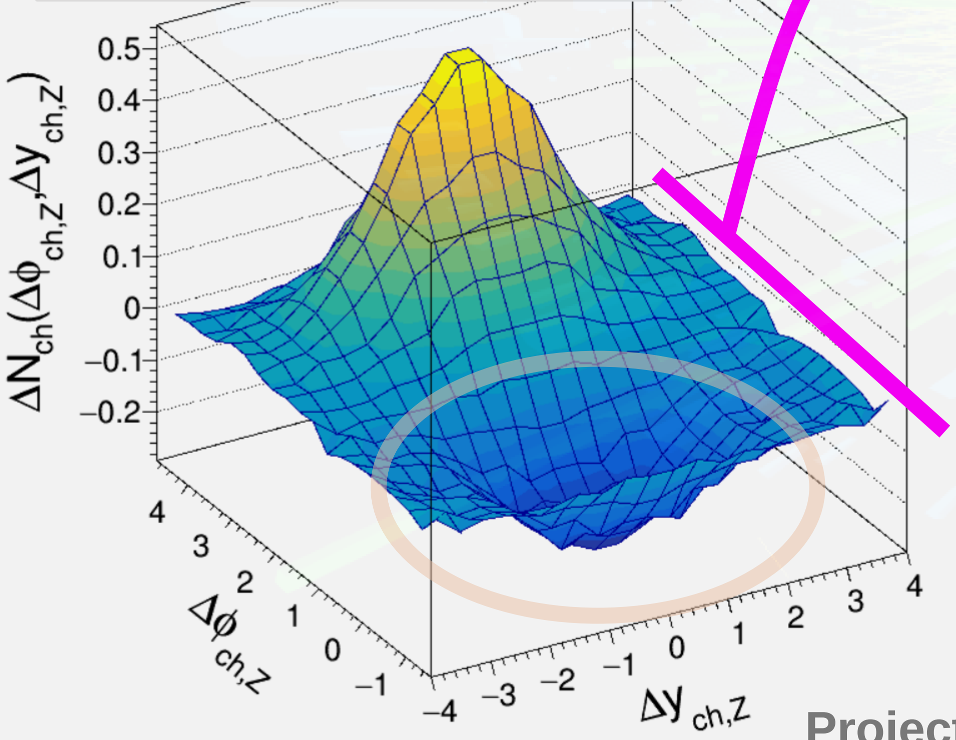
First direct evidence of medium response to hard probes in QGP

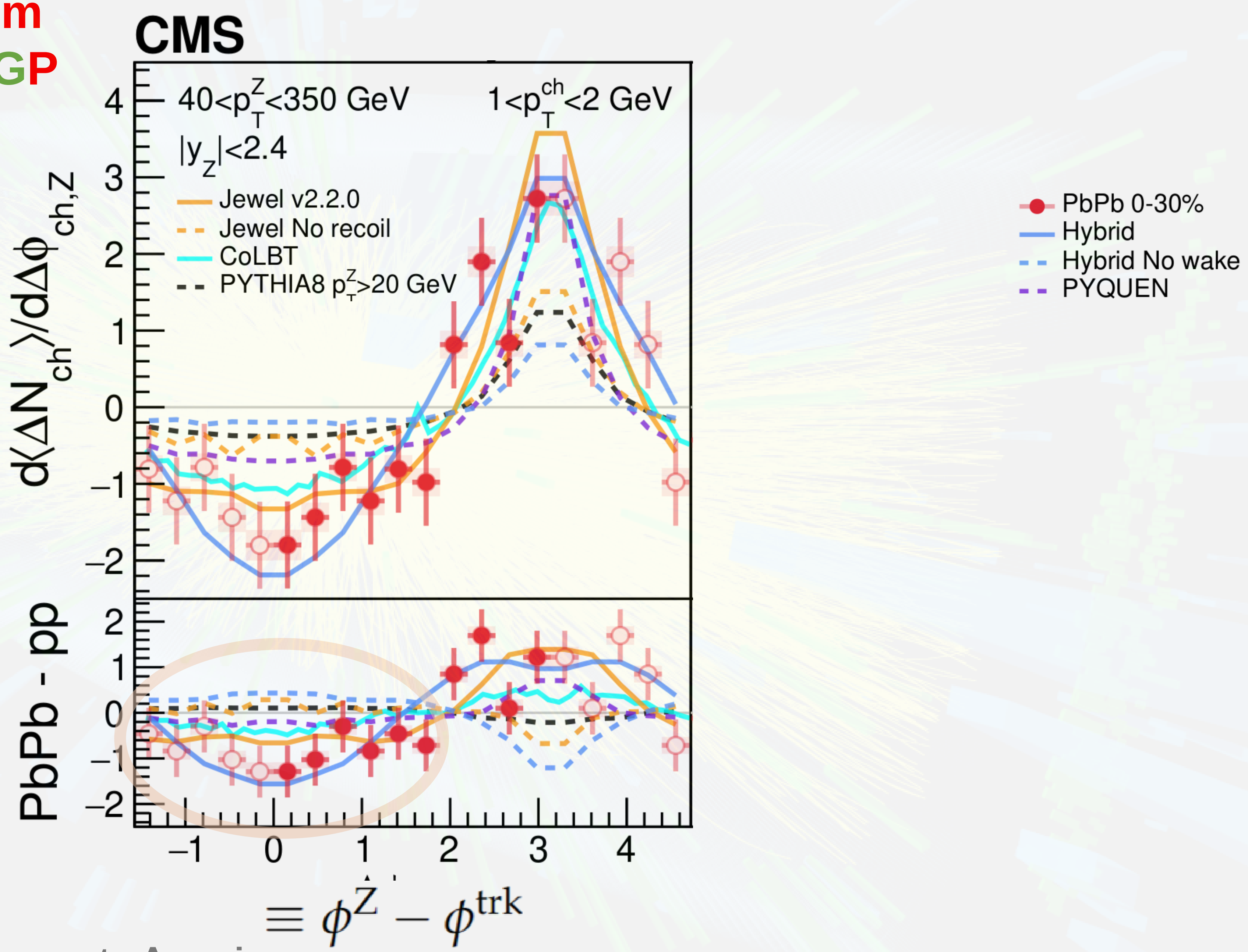

Luna Chen (Vanderbilt)   Pin-Chun Chou (MIT)



Projection onto Δϕ axis

Model Simulation





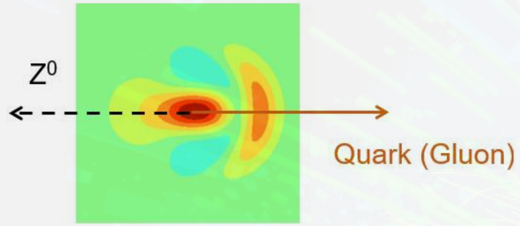
Projection onto Δy axis

Direct Evidence of Medium Response

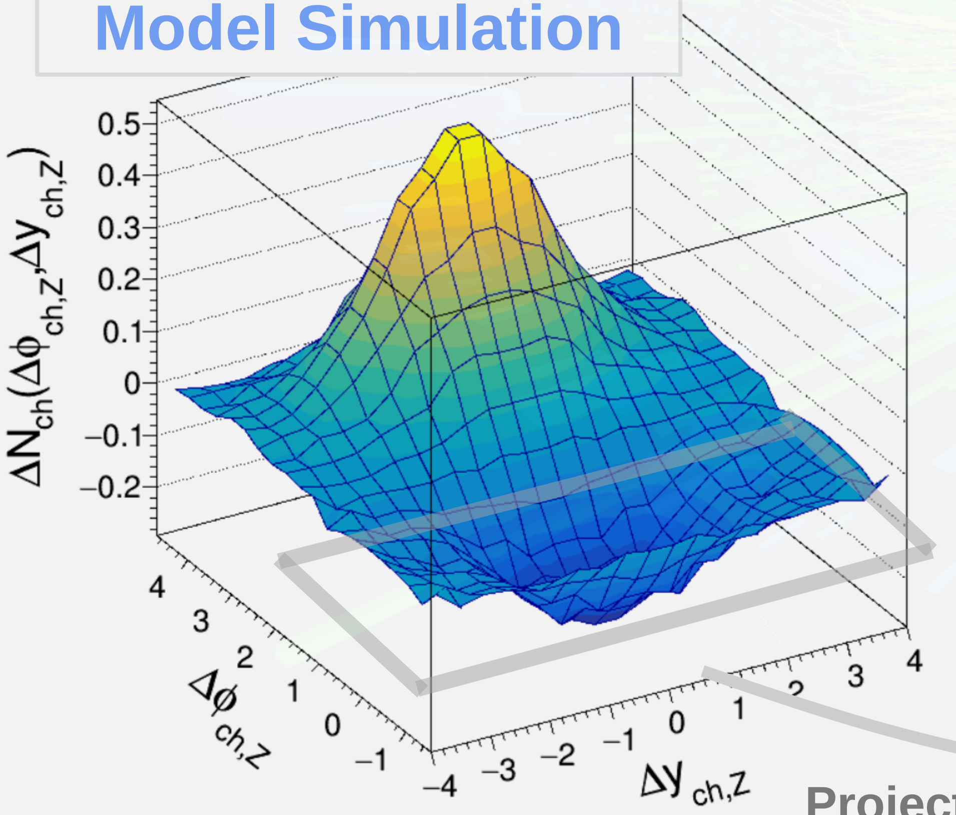
First direct evidence of medium response to hard probes in QGP

Luna Chen (Vanderbilt)

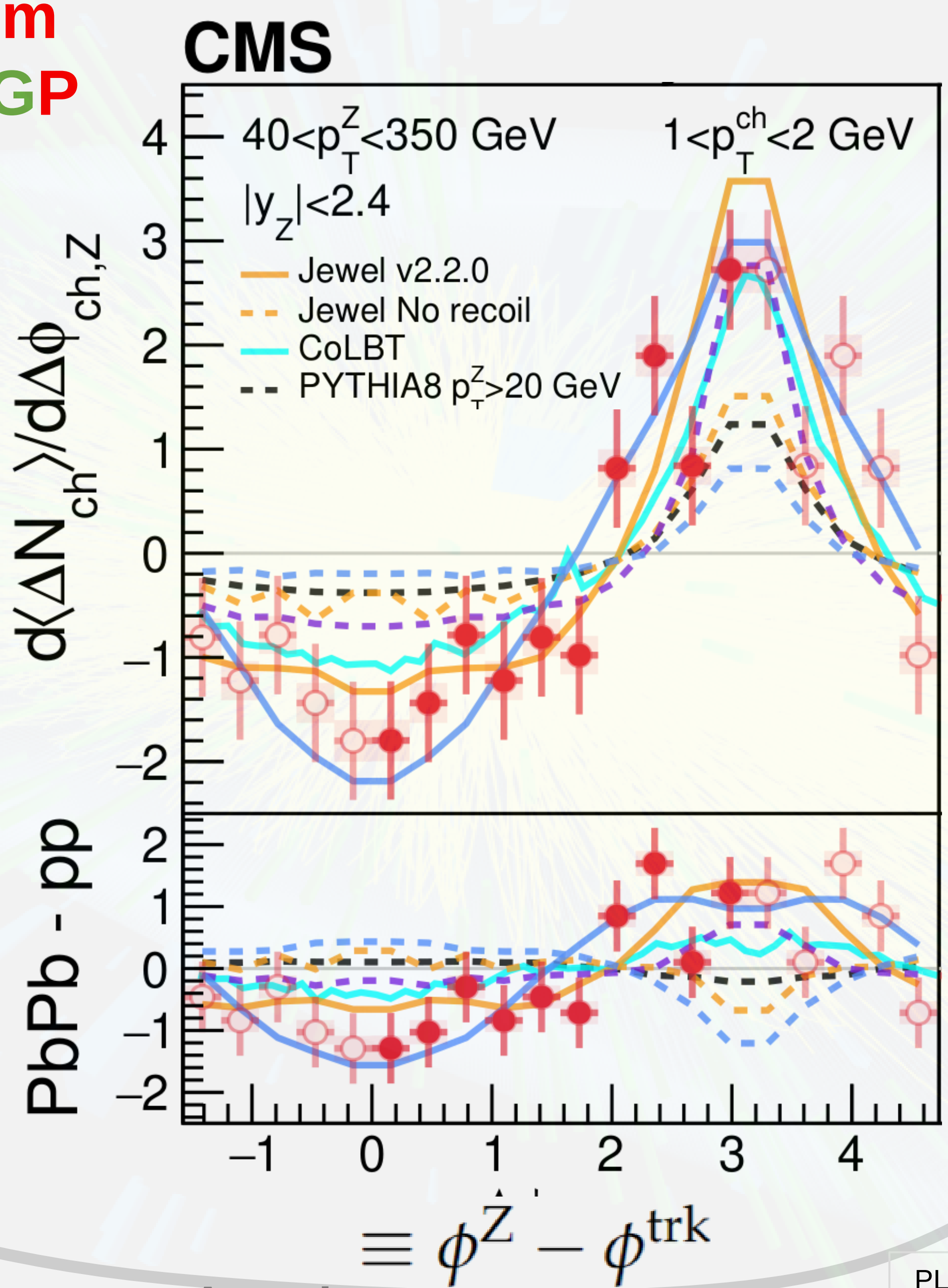
Pin-Chun Chou (MIT)

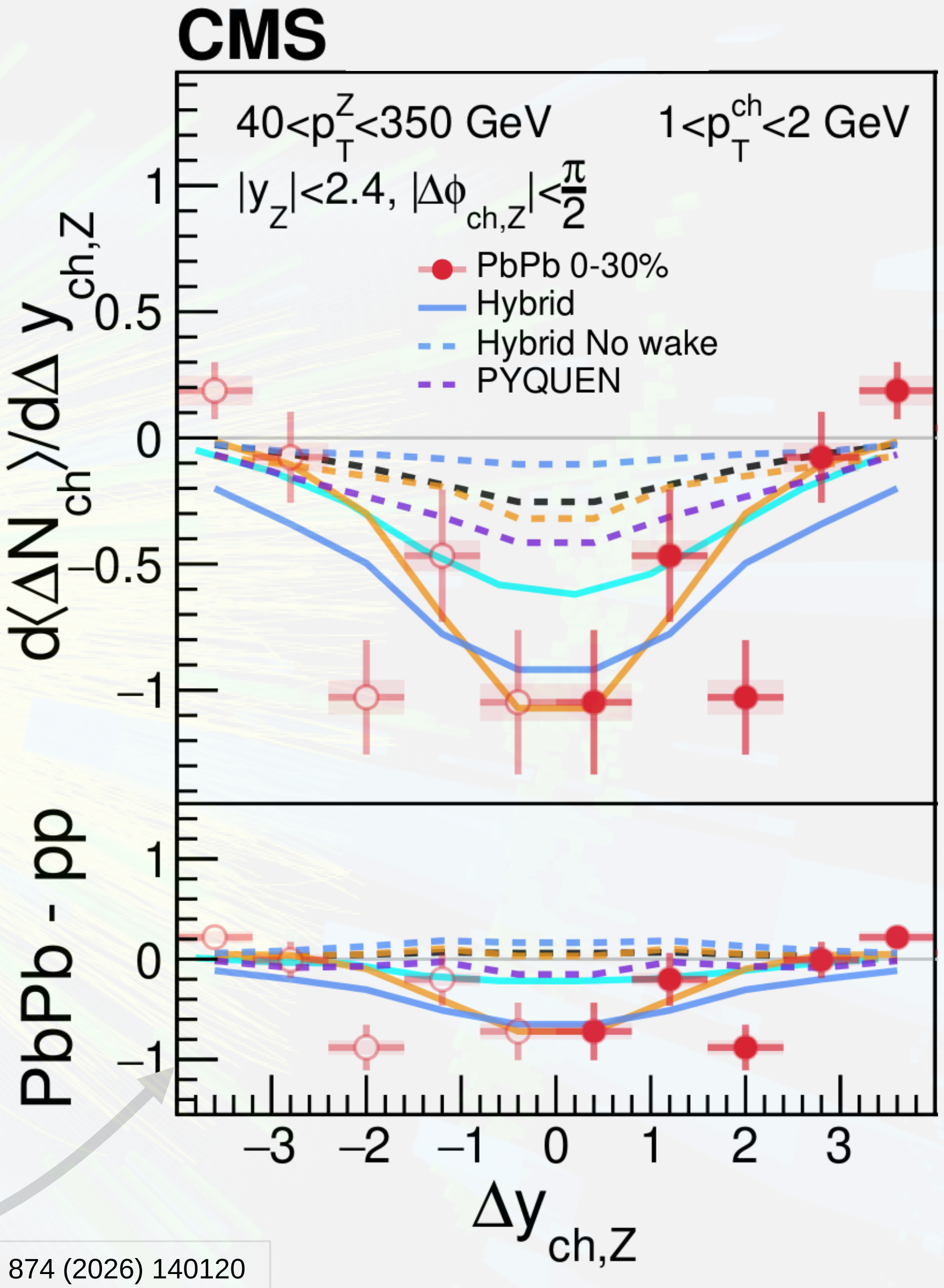


Model Simulation



Projection onto Δy axis





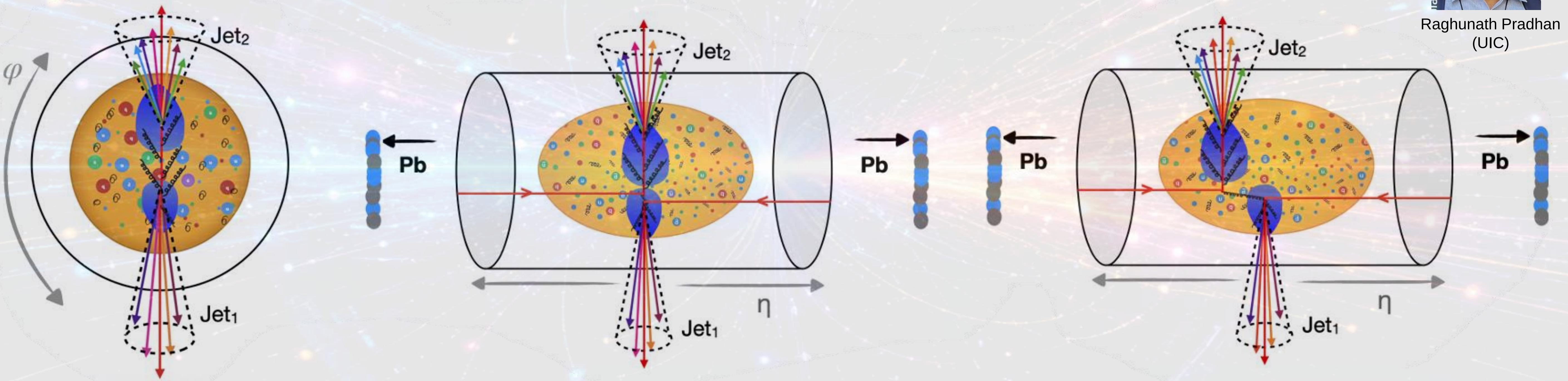
PLB 874 (2026) 140120

Search for Medium Response with Dijets

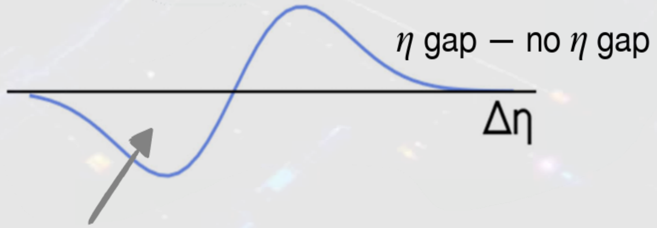
Problem: Dijets are usually back-to-back. Jets could overshadow the negative wake contribution!

Solution: separate two jets in pseudorapidity!

Raghunath Pradhan
(UIC)

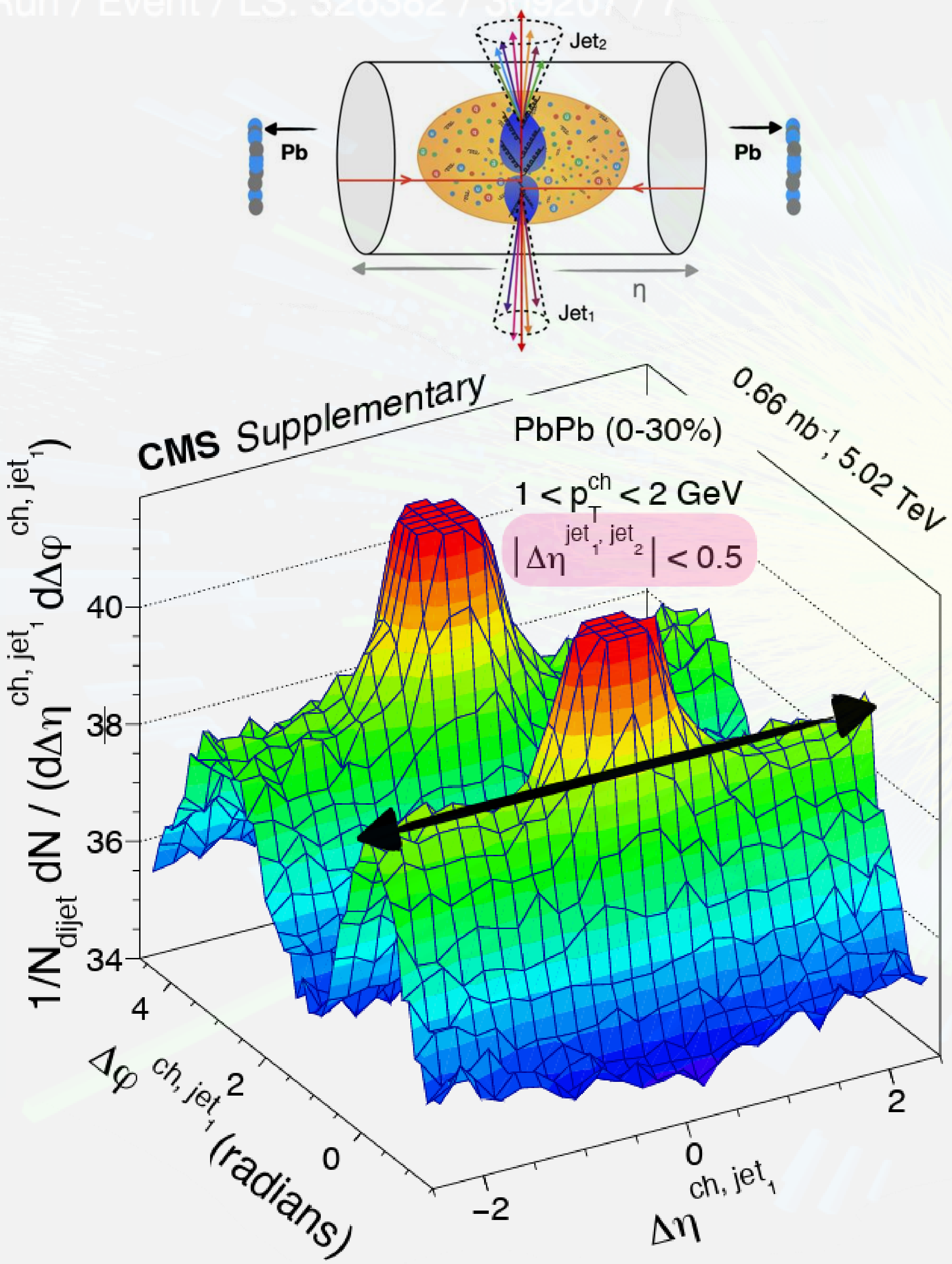


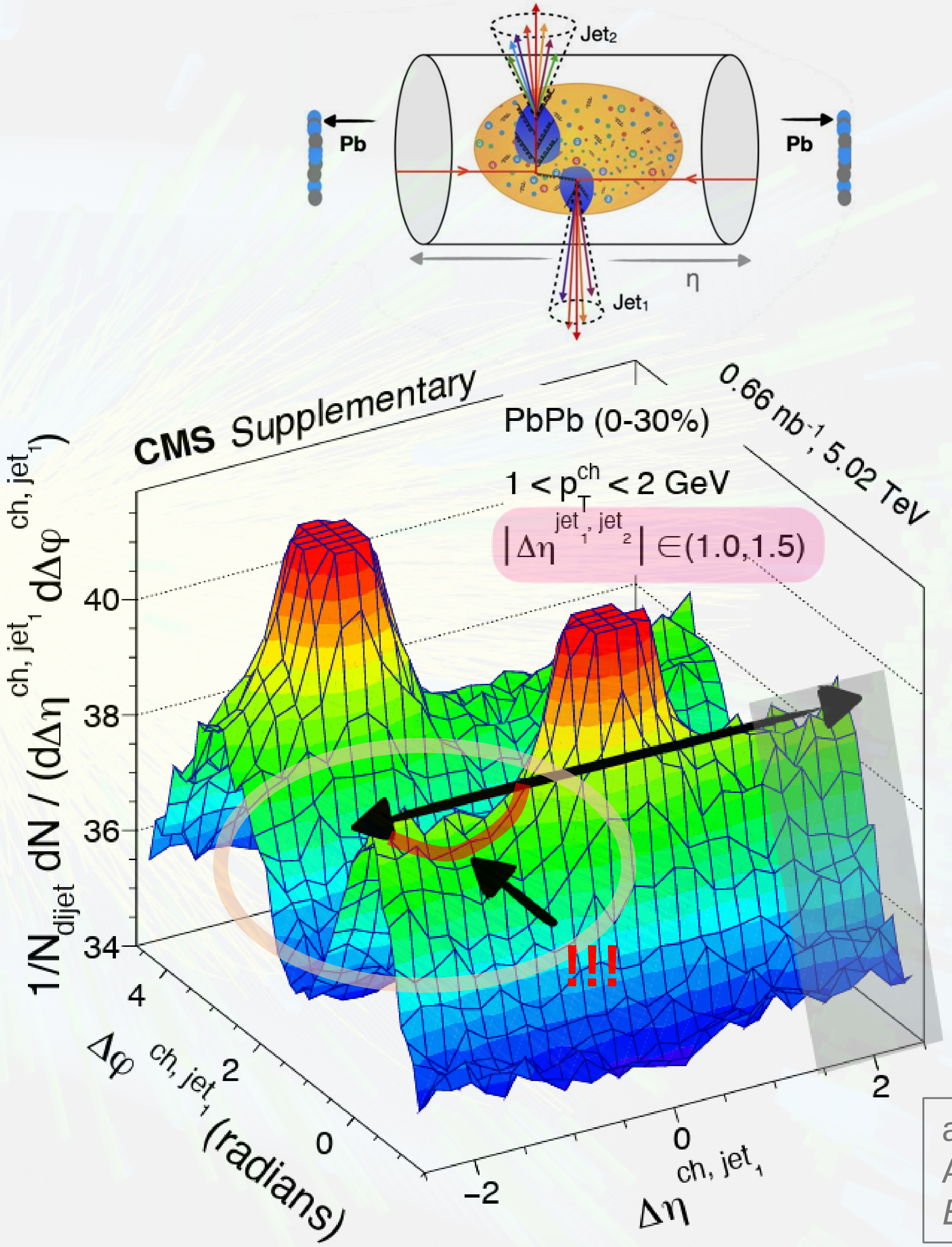
Drawing from Raghunath Pradhan (UIC)



Xin-Nian Wang and Zhong Yang
PRL 135, 072302

Observation of the Medium Response with Dijet

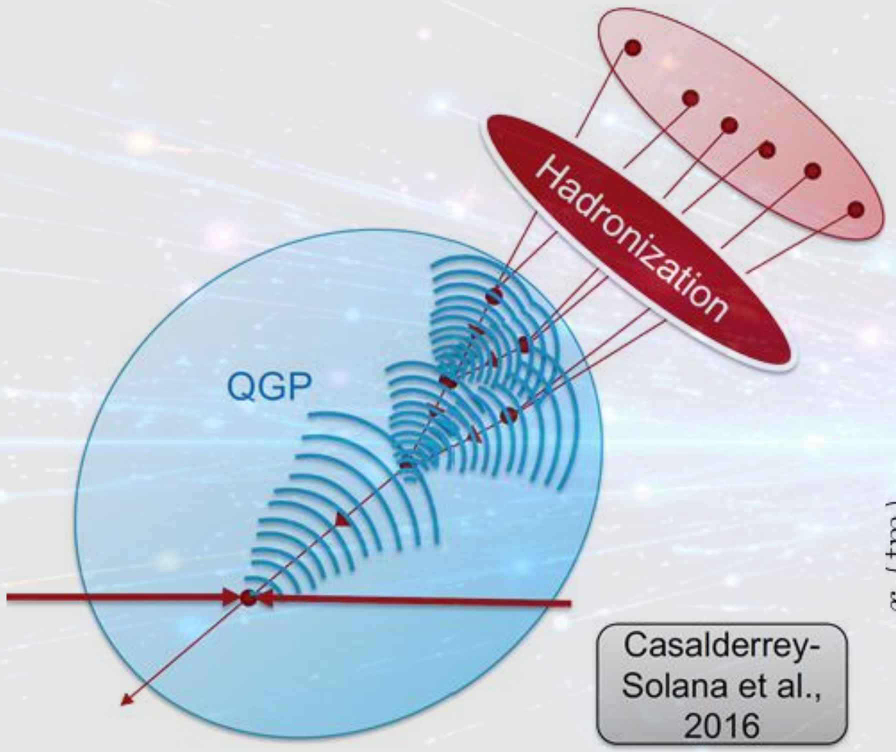




Raghunath Pradhan
(UIC)

arXiv 2602.19431
Accept by PRL
Editor's suggestion

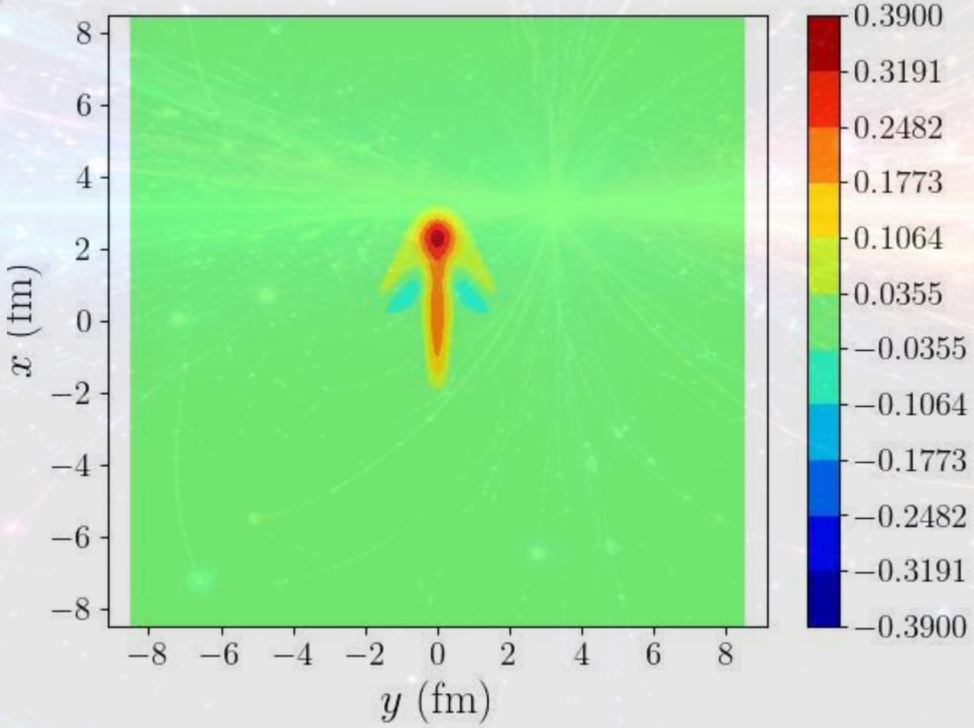
Effect of Shear Viscosity in Medium Response



Casalderrey-Solana et al., 2016

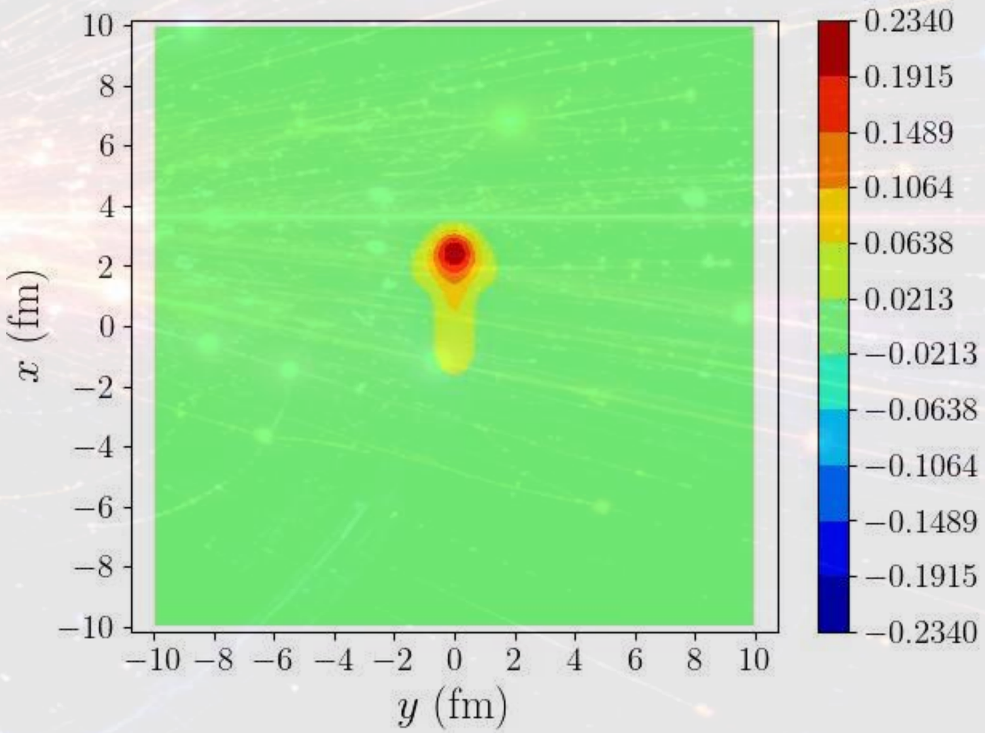
Ideal hydrodynamics

η/s = 0



Viscous hydrodynamics

η/s = 0.08



J. Casalderrey-Solana, J. G. Milhano, D. Pablos, K. Rajagopal and X. Yao, **"Jet Wake from Linearized Hydrodynamics,"** JHEP 05 (2021) 230

Open Questions

- What is the smallest collision that can still create Quark-Gluon Plasma?

Going to the smallest collision system

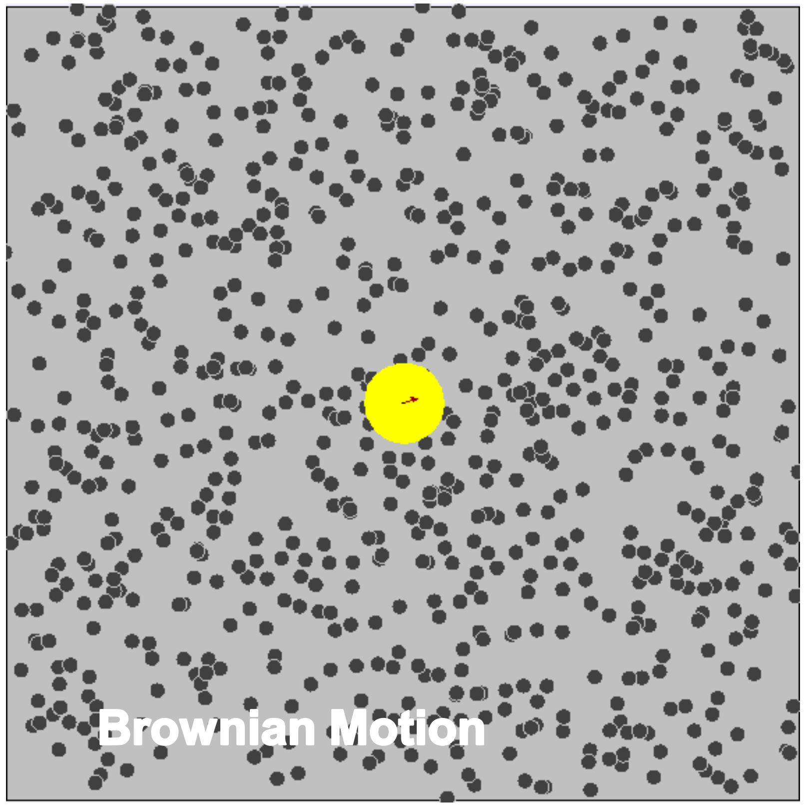
- Can a fast quark stir the soup and leave a wake?

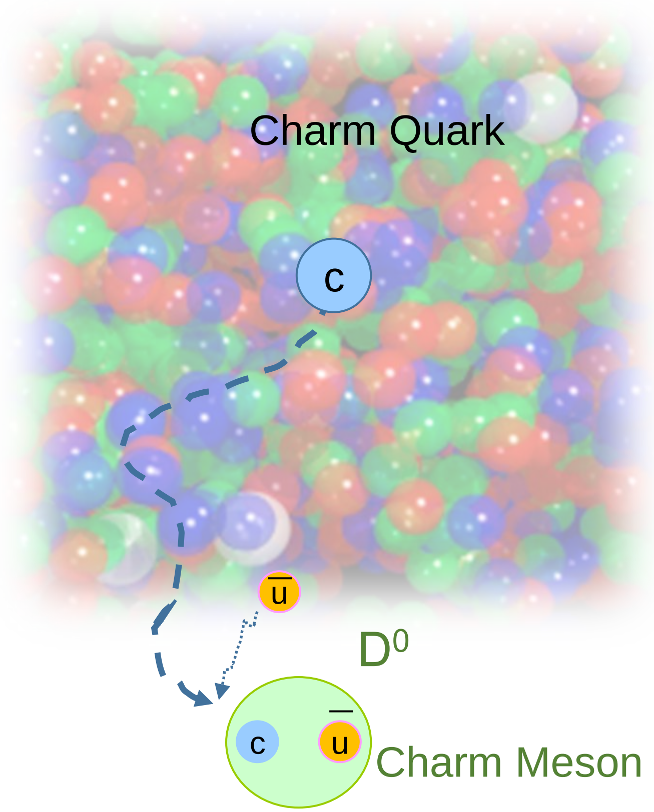
Follow a fast moving quark traversing the QGP closely

- **How does a nonthermal quark become part of the soup? How did the early Universe turn quark soup into ordinary matter?**

Heavy quarks let us watch this process in the laboratory

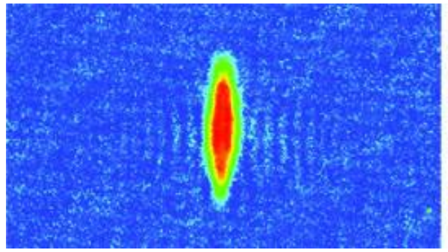
Heavy Quarks as Probes of the Quark Soup

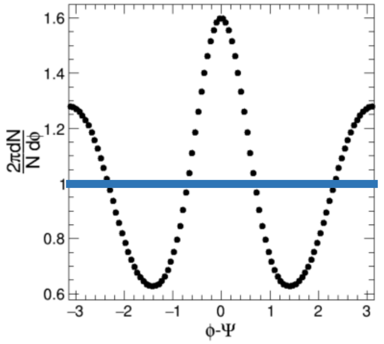




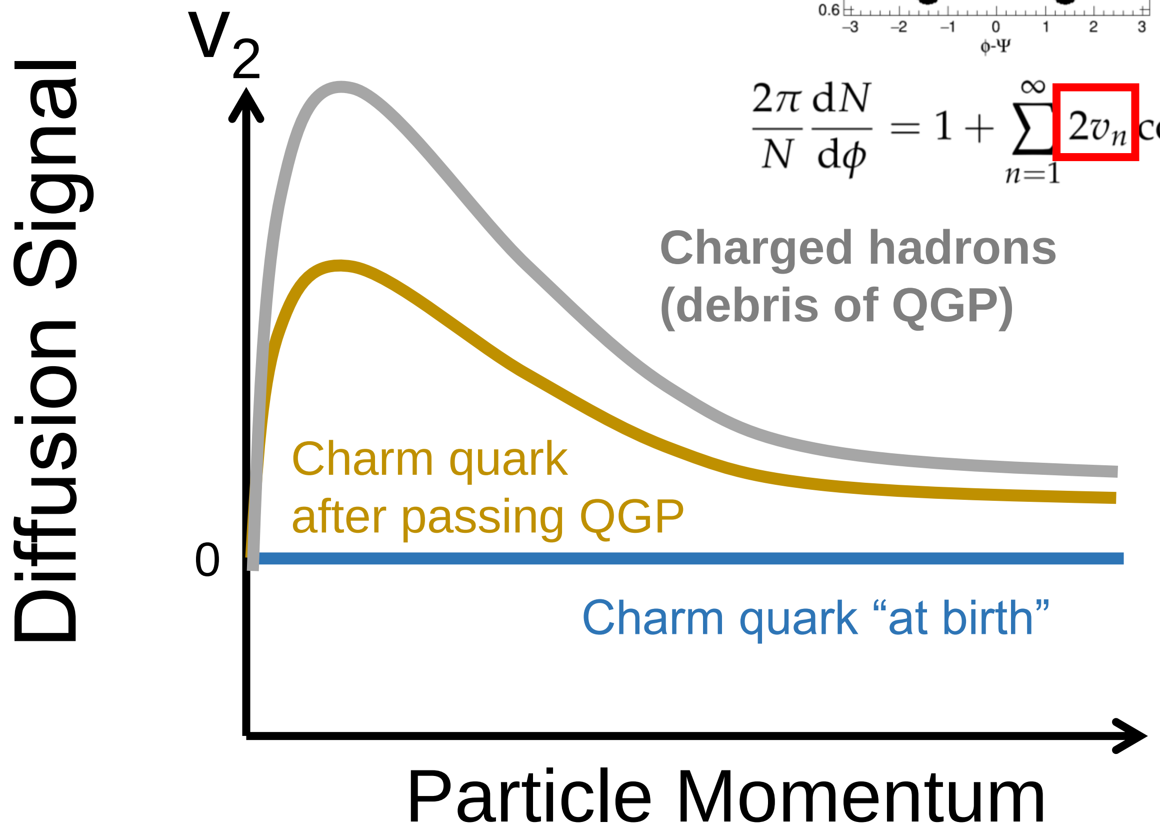
- **Charm** and **beauty** quarks ("heavy quarks") are produced before QGP formation (<0.2 fm/c)
- Low momentum heavy quarks are then "kicked around" by quasi-particles
- Once they are produced, the **total abundance is conserved**!
  - We can "**trace**" their hydrodynamization process!
- Heavy flavor hadron: insights into the hadronization process (from Quarks to Hadrons) with QGP

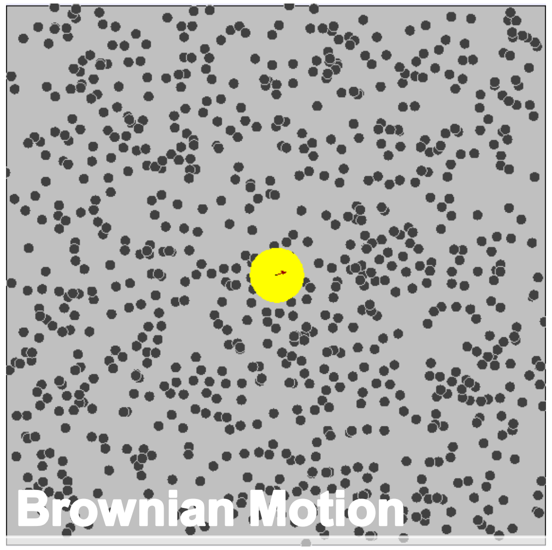
Heavy Quark (Charm and Beauty) Diffusion

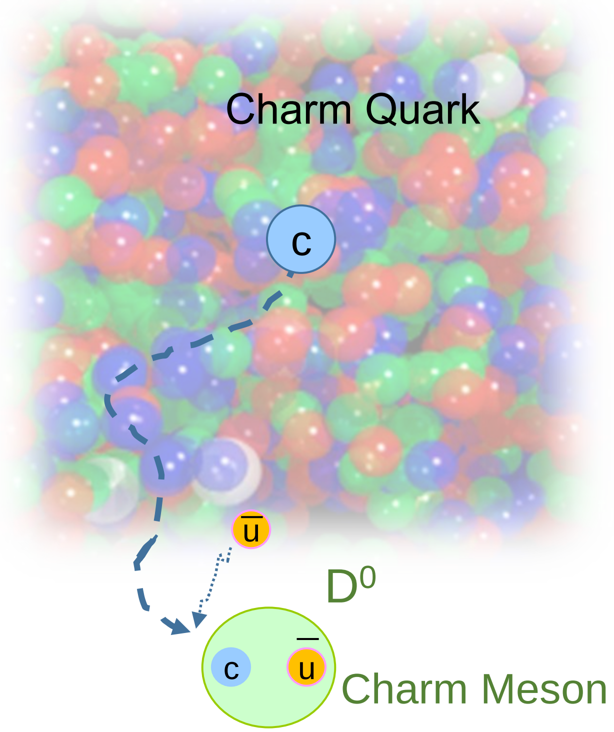




$$\frac{2\pi}{N}\frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + \sum_{n=1}^{\infty} \boxed{2v_n} \cos[n(\phi - \Psi_n)]$$

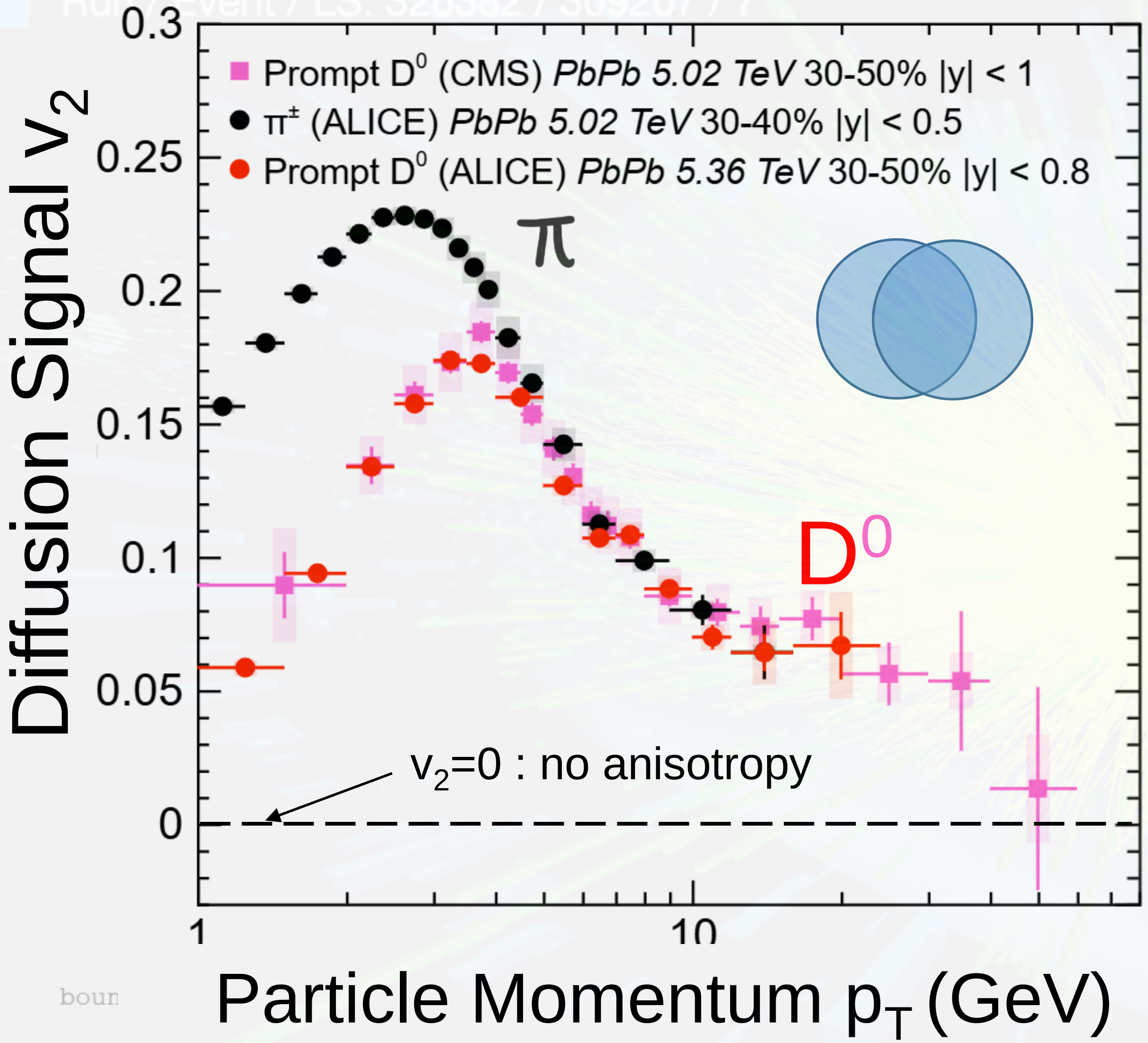


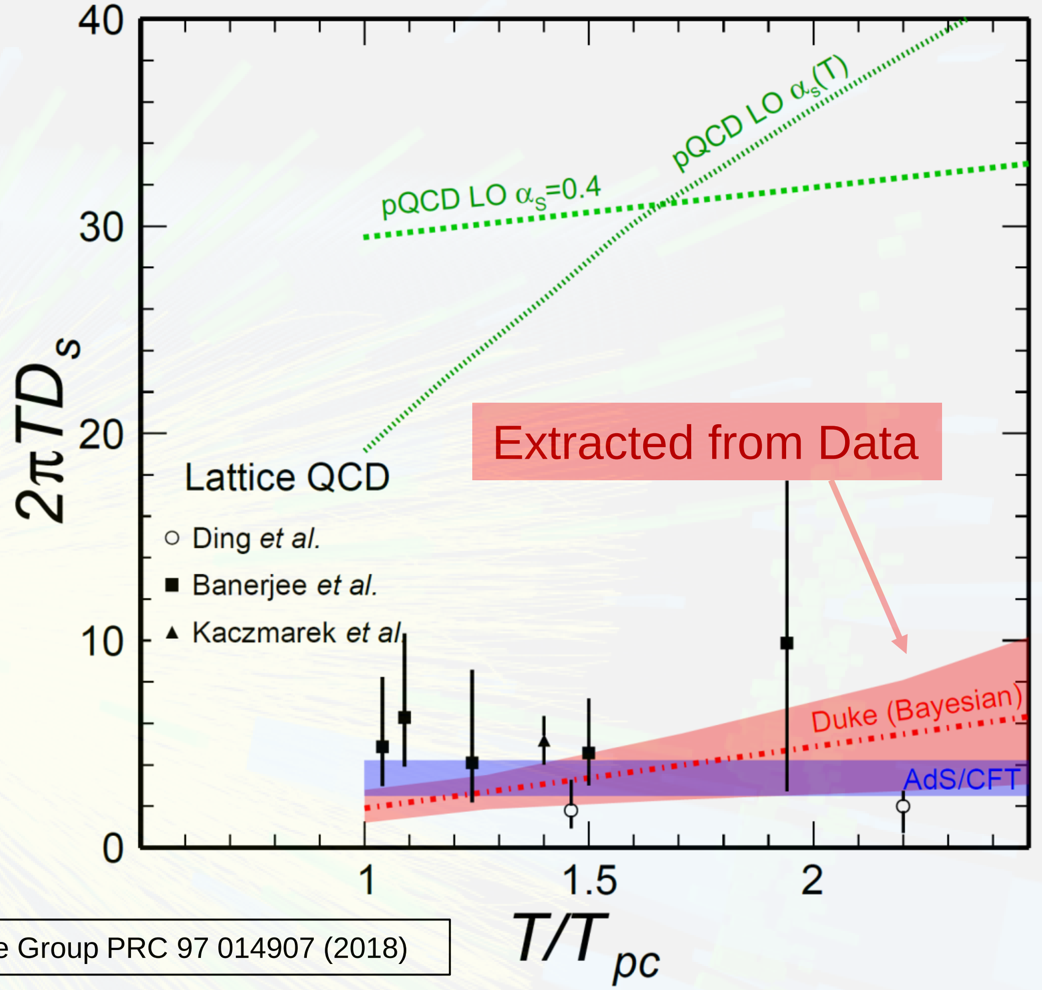




Since the **QGP is expanding radially**, QCD force (like '**wind**') increases the azimuthal anisotropy (v_2) of the charm quarks in the Quark Soup!!

Charm Meson Diffusion Signal





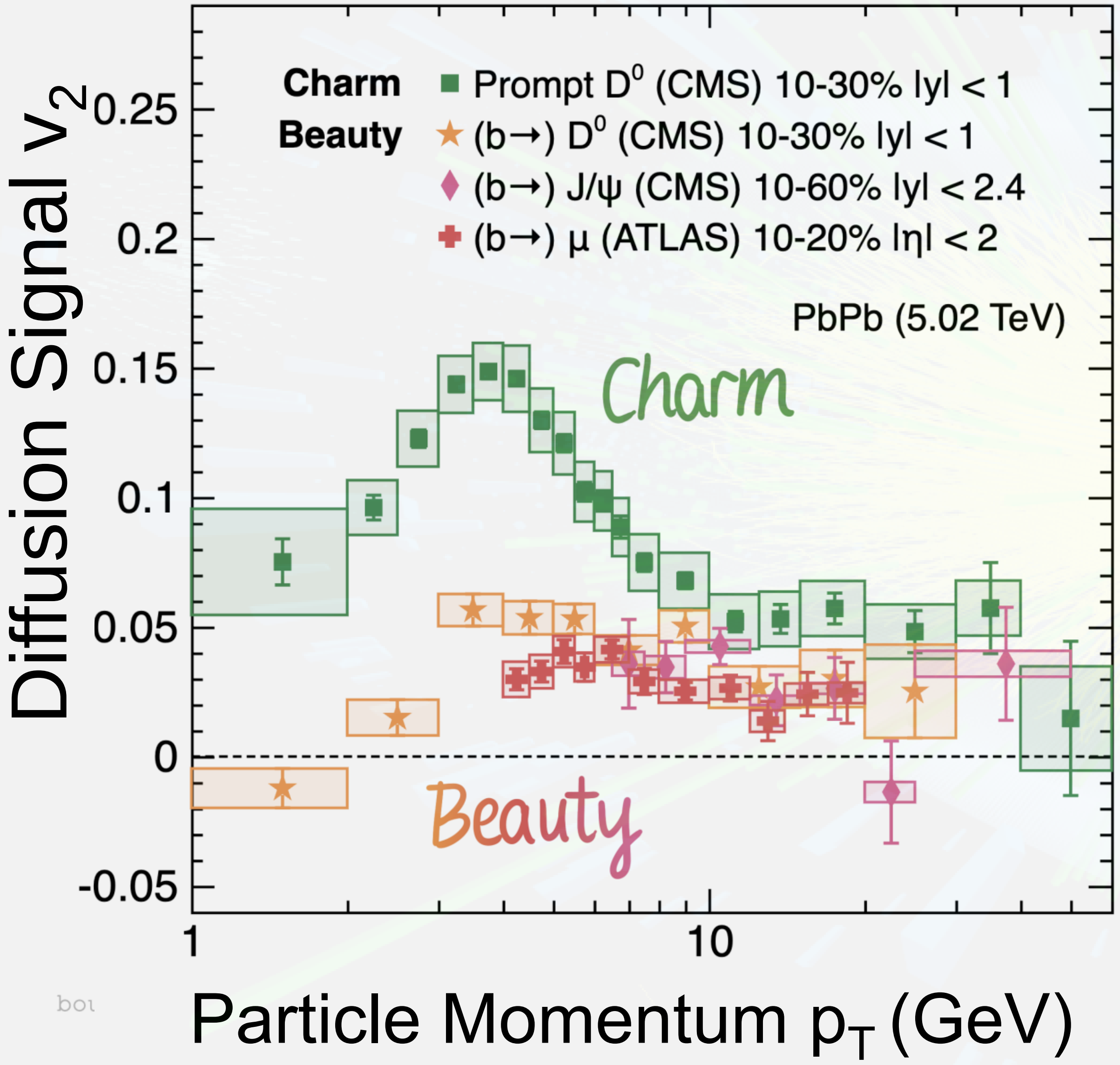
Duke Group PRC 97 014907 (2018)

Observation of charm meson elliptic flow (v_2)
→Charm quarks moving toward thermalization

arXiv:2603.18966 PLB 816 (2021) 136253 JHEP 09 (2018) 006

Heavy quark diffusion coefficient D_s is extracted from LHC data using a Bayesian analysis, comparable with **Lattice QCD** and **AdS/CFT** calculations

Collective Flow: Charm vs Beauty



- Significant **non-zero** open beauty flow signal from the LHC!
- Smaller beauty hadron v_2 than charm hadrons at low p_T

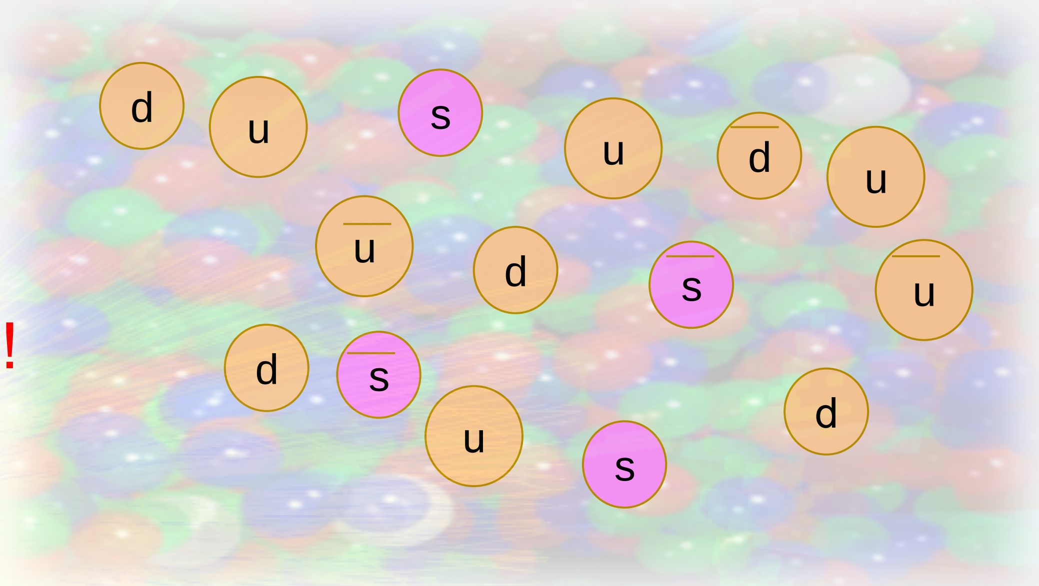
Weaker collective flow behavior than charm due to the larger mass!

PLB 850 (2024) 138389 JHEP 10 (2023) 115 PLB 807 (2020) 135595

Hadronization of Heavy Quarks in Quark Soup

Hadronization: from Quarks to Hadrons

Strange quark content is enhanced in Quark Soup
(Due to the high temperature)

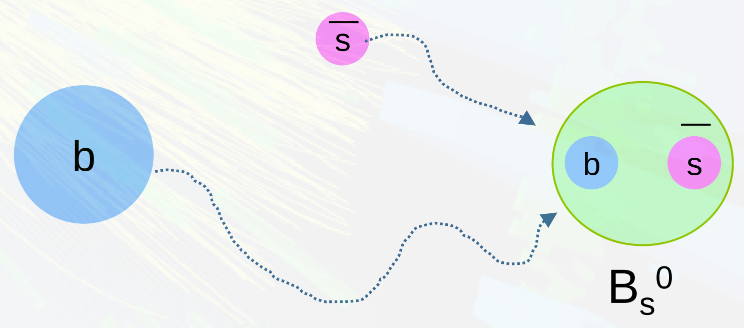


Idea: Probe ("Taste") the partonic Quark Soup by heavy quarks!

Example: in additional to parton shower,
B_s could be **enhanced via parton coalescence** in QGP

Parton shower

Parton Coalescence

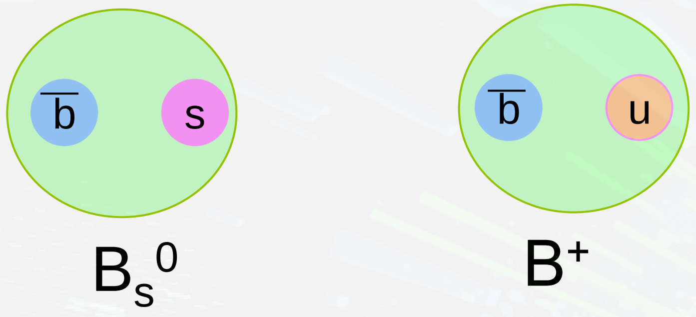


B_s^0 PLB 829 (2022) 137062

$B^{\pm}$ PRL 119 (2017) 152301

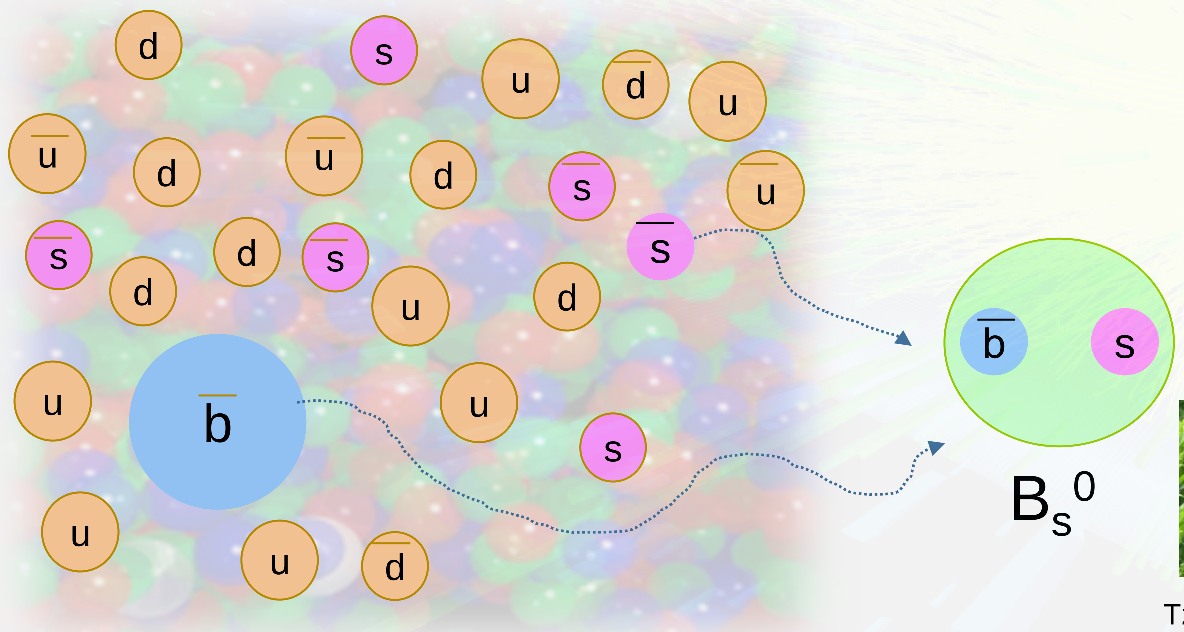
JHEP 02 (2025) 195

Beauty Quark Hadronization in Quark Soup



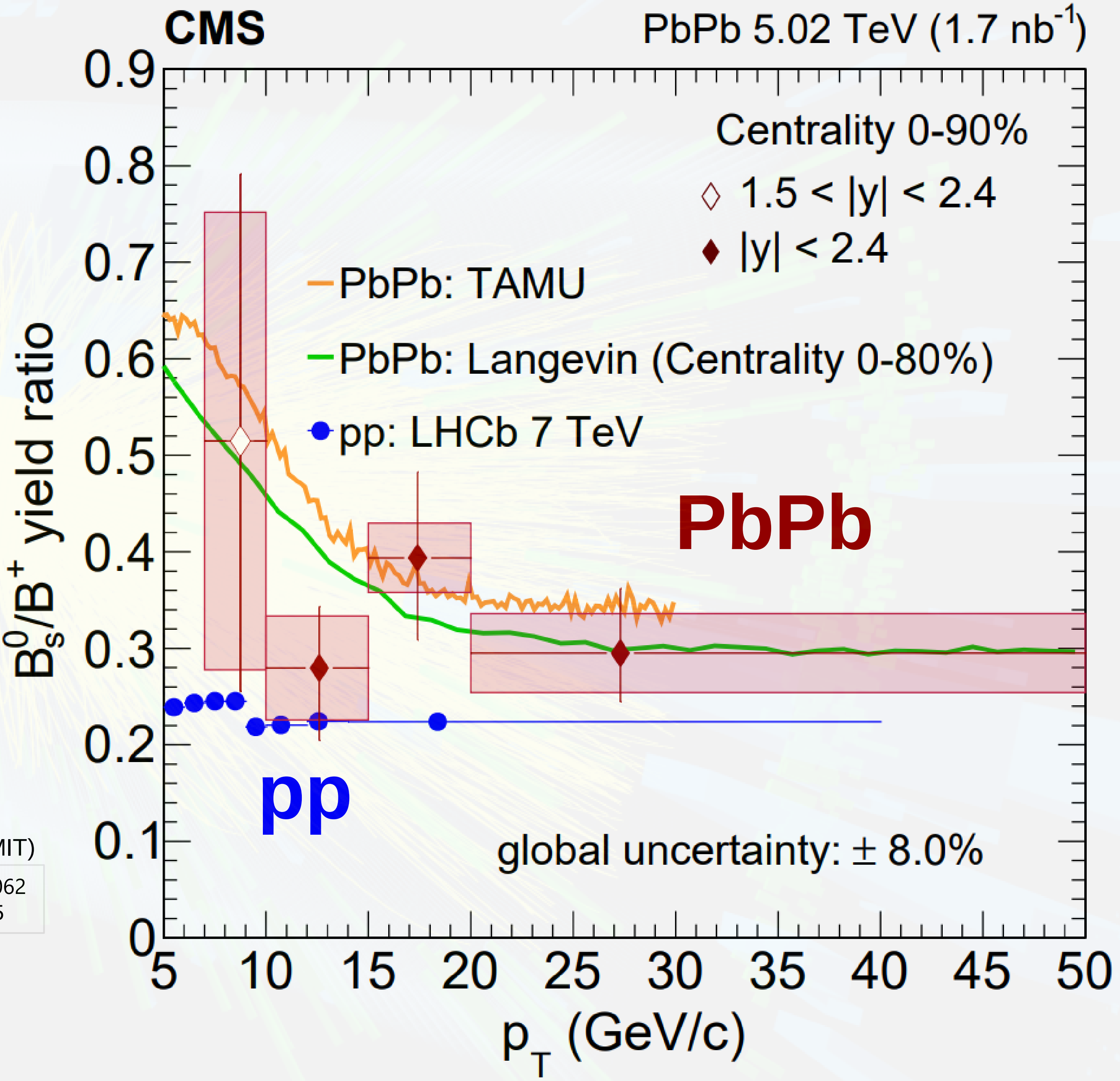
$$\frac{B_s}{B^+}$$

Parton Coalescence



Tzu-An Sheng (MIT)

PLB 829 (2022) 137062
JHEP 02 (2025) 195

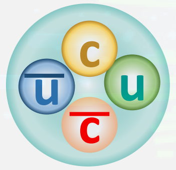


Hint of enhanced production of B_s^0!
→Consistent with flavor-dependent recombination in a **strange-rich soup**

Beyond Heavy Flavor Mesons: X(3872)

Tightly bound

Tetraquark (4q)

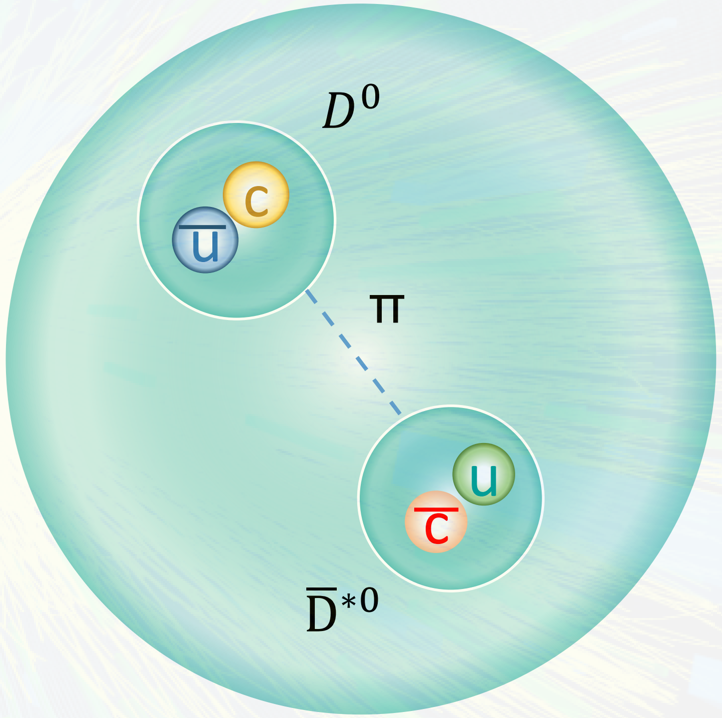


$r_{4q} \approx r_{c\bar{c}}$

≈ 0.3 fm

Loosely bound

$D^0 - \bar{D}^{*0}$ molecule



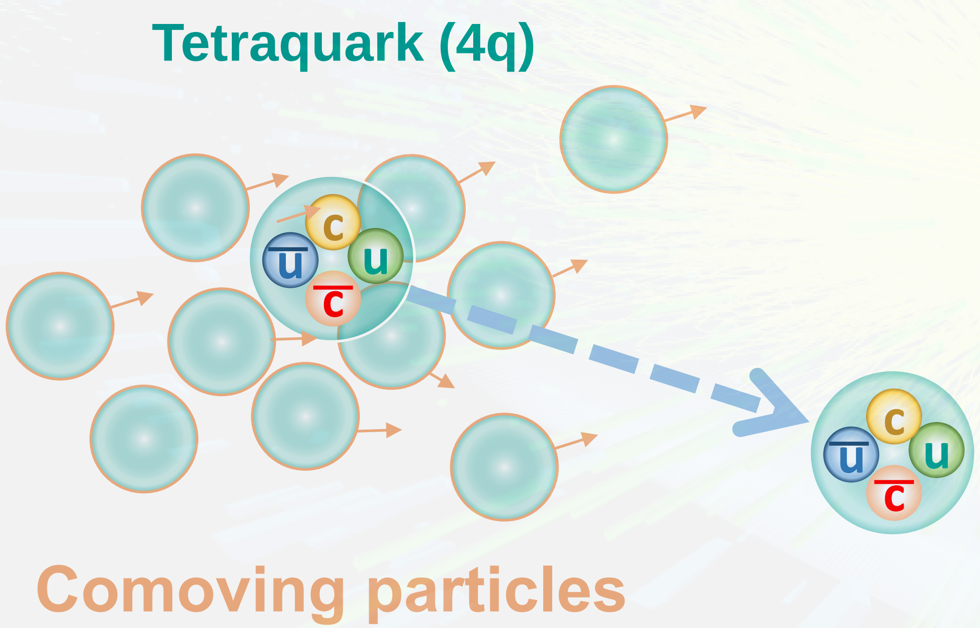
$r_{molecule}$

as large as 5 fm

(Model dependent)

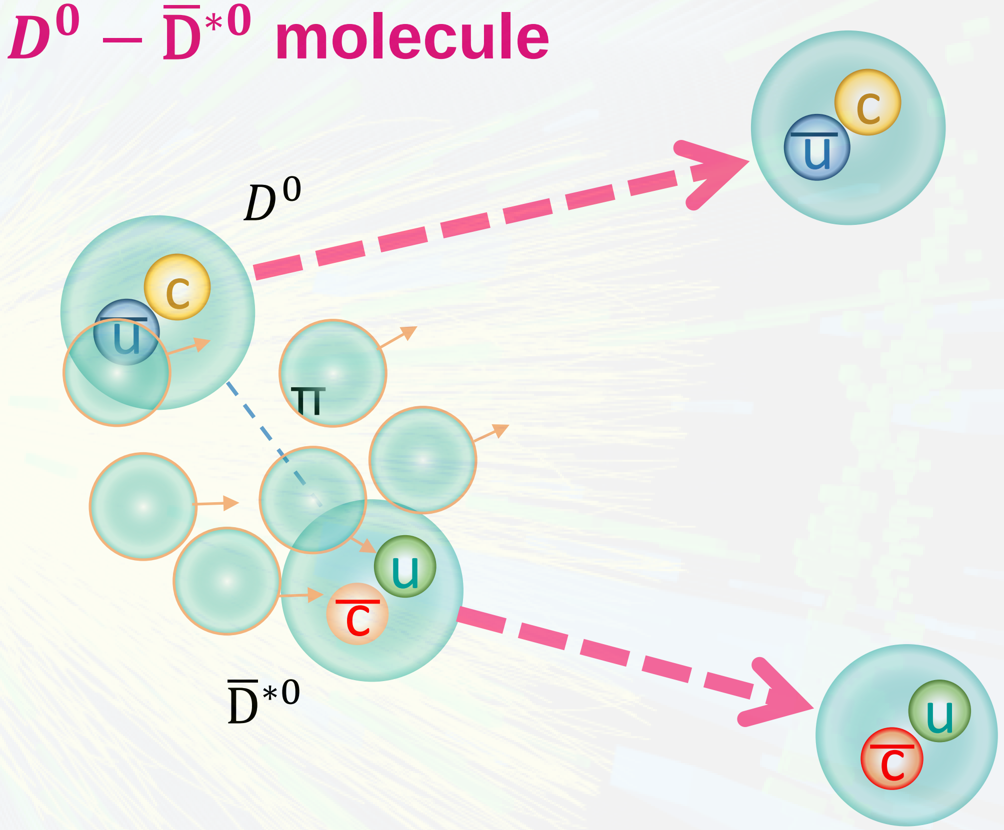
Probe the Nature of X(3872) with Comoving Particles

Tightly bound



Smaller dissociation probability

Loosely bound



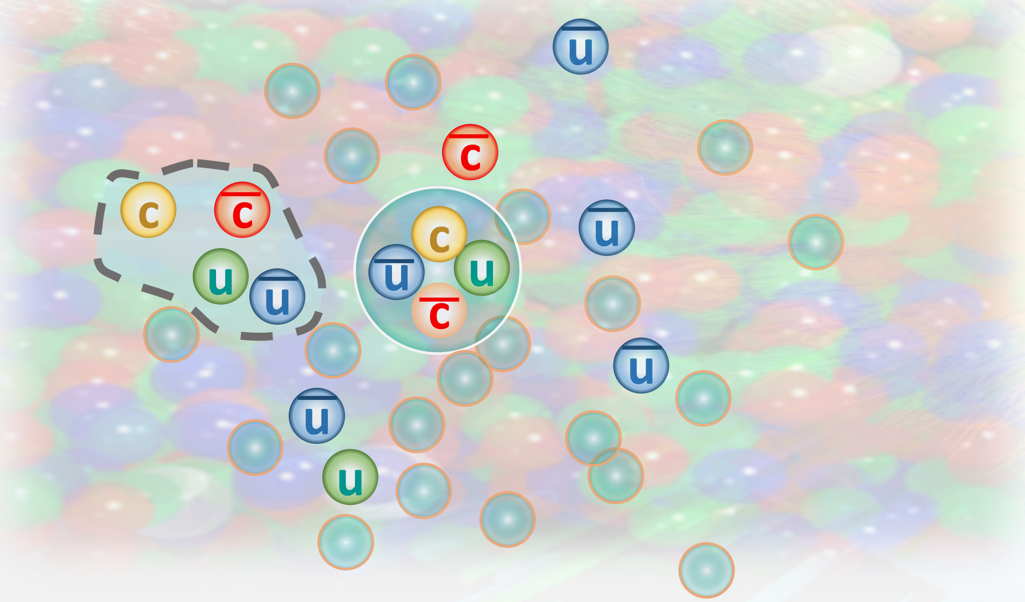
Larger dissociation probability

Esposito et al, arXiv: 2006.15044

Production of X(3872) in Heavy Ion Collisions

Tightly bound

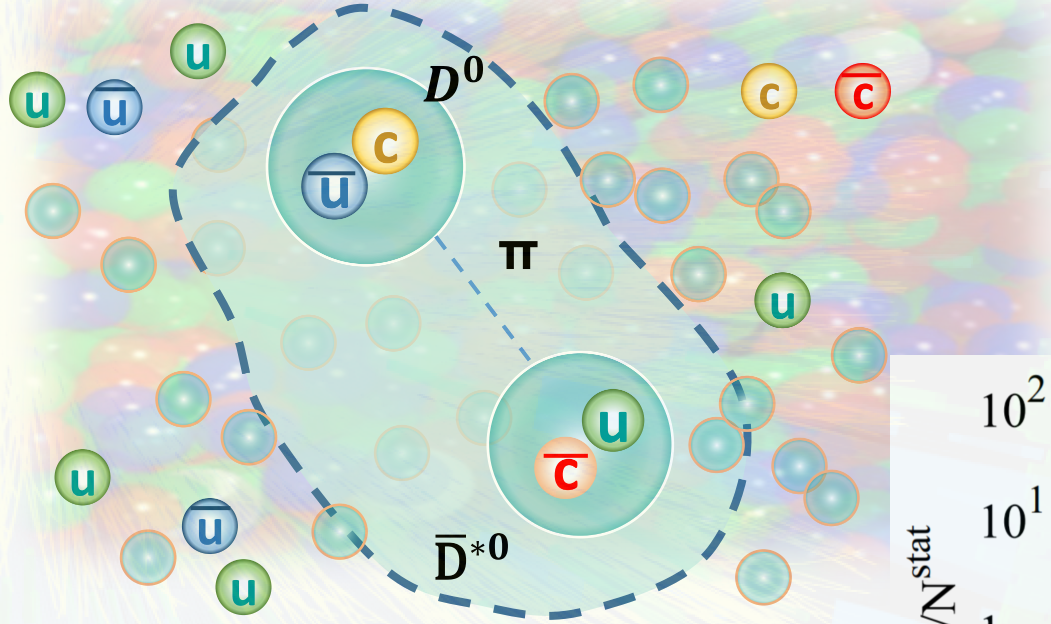
Tetraquark (4q)

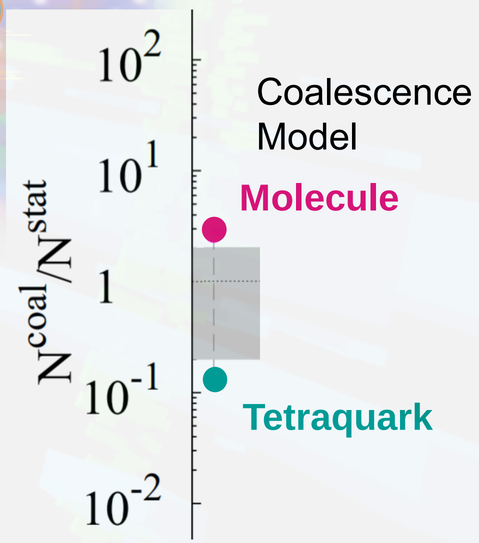


Loosely bound

Jinfeng Liao + collaborators
PRL 126 (2021) 1, 012301
Anton Andronic et al,
PLB 797 (2019) 134836

$D^0 - \overline{D}^{*0}$ molecule

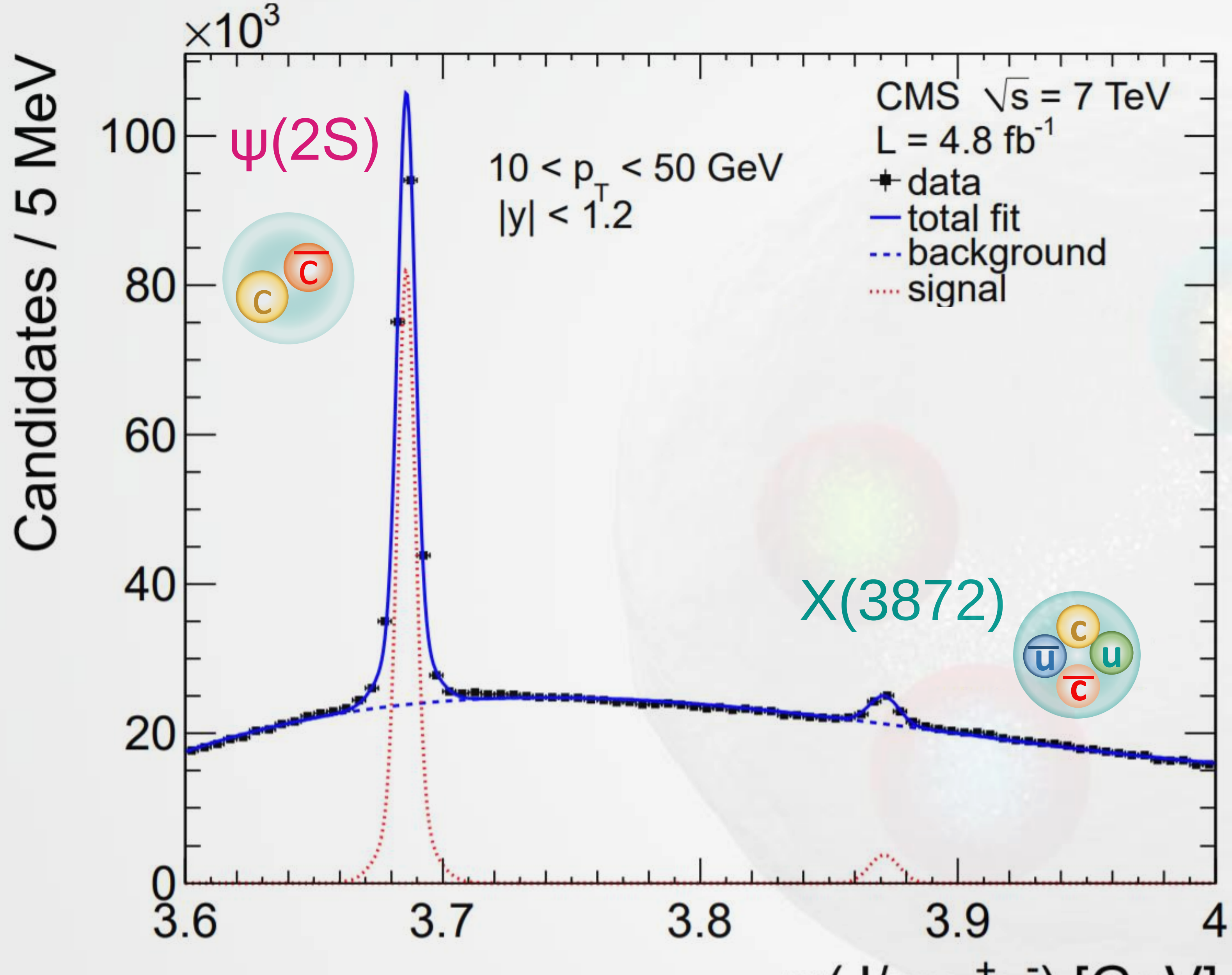




ExHIC Collaboration
PRL 106 (2011) 212001

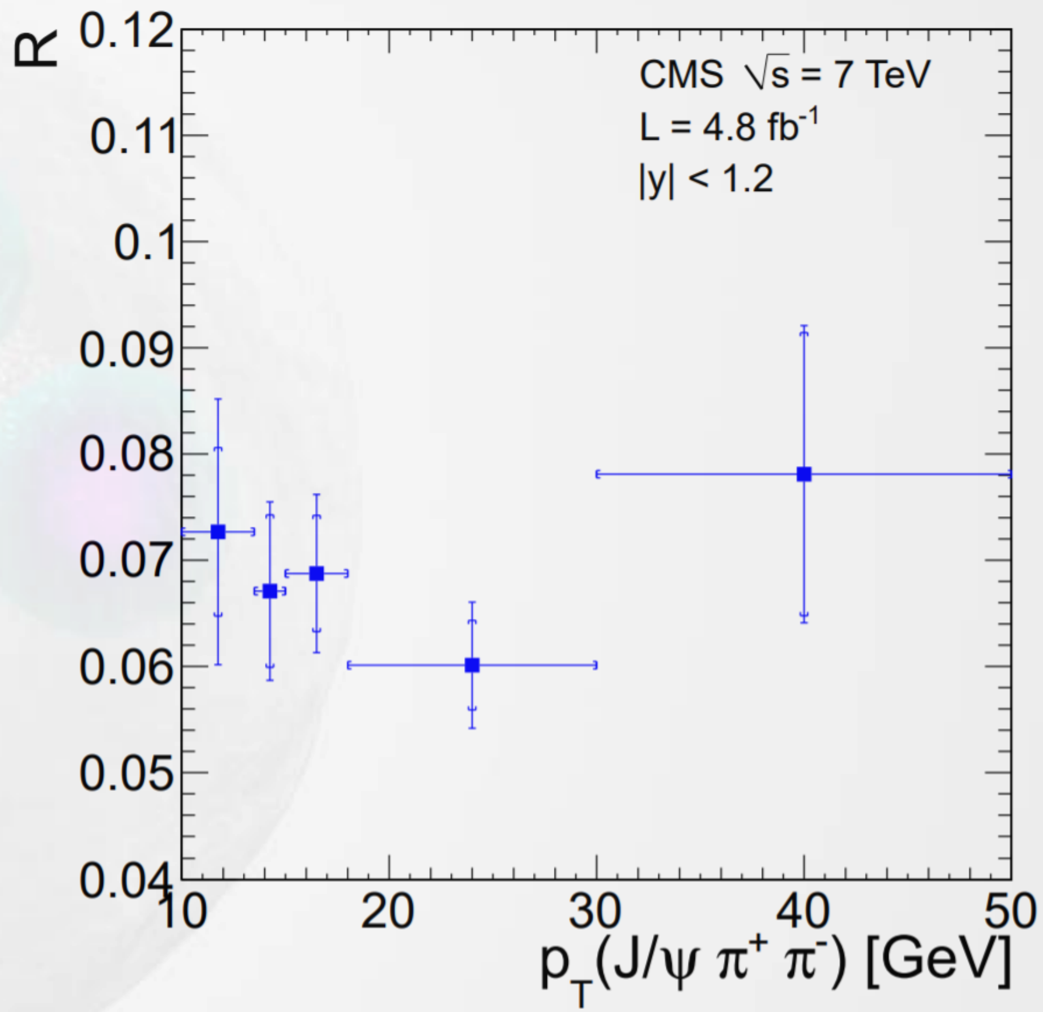
Production of X(3872) in **QGP** may depend on its inner structure

X(3872) to ψ(2S) Ratio in pp Collisions at 7 TeV



JHEP04 (2013) 154

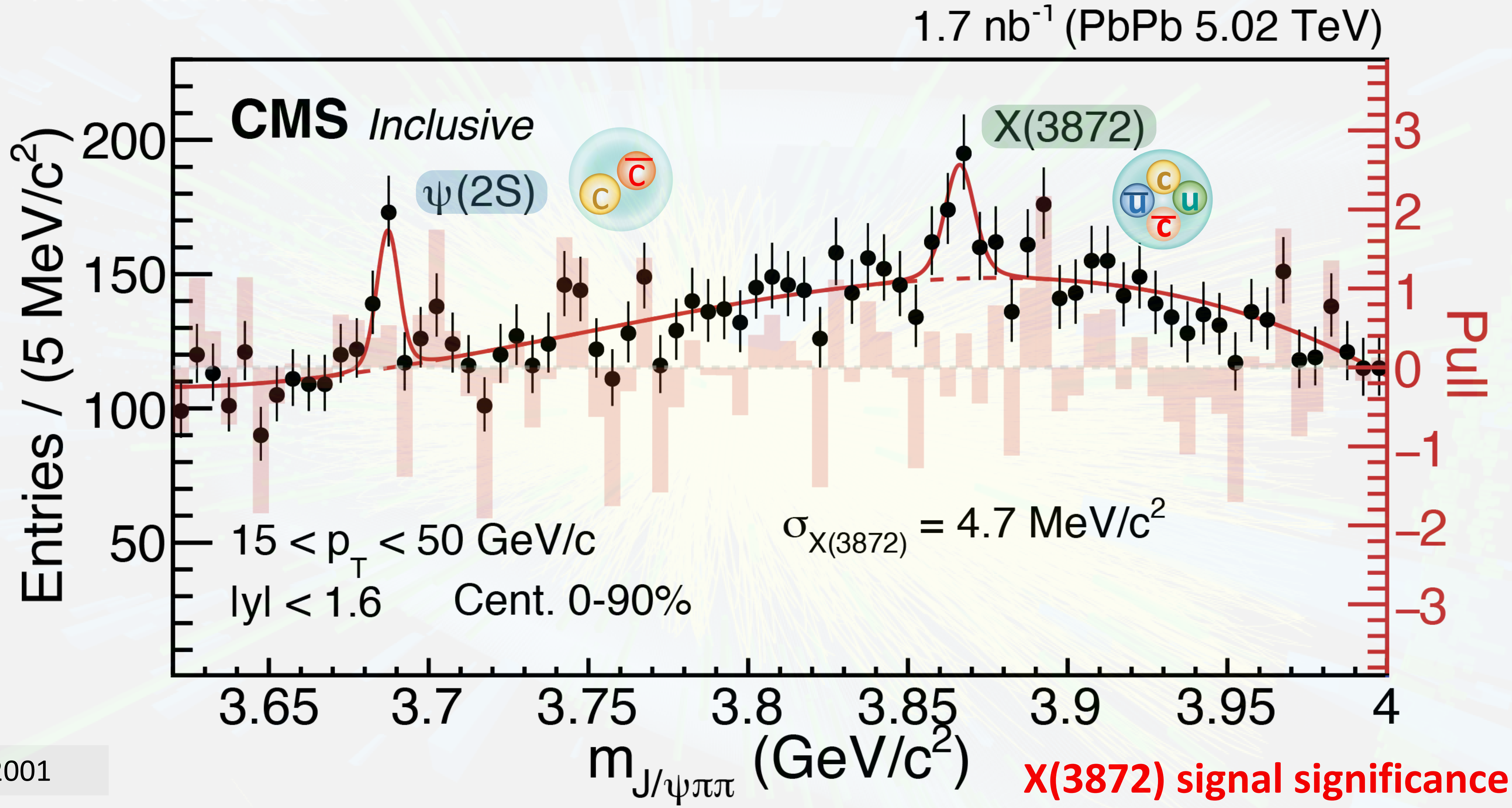
Inclusive X(3872) to ψ(2S) production ratio (include both prompt and nonprompt) **~7%**



$$R = N^{(\mathrm{Corr})}_{X(3872)} / N^{(\mathrm{Corr})}_{\psi(2S)}$$

First Evidence of X(3872) Production in Heavy Ion Collisions

Jing Wang (MIT)

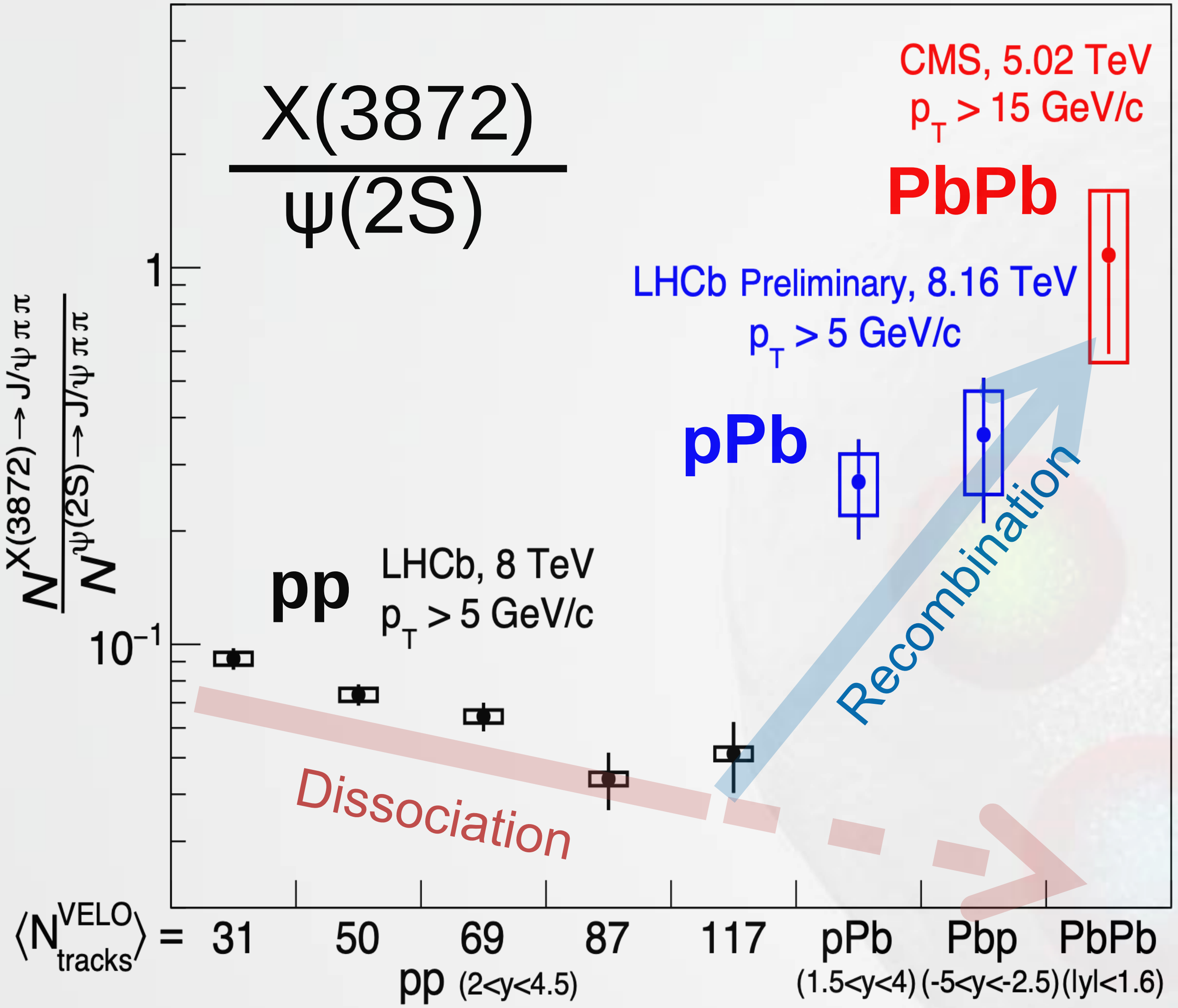


PRL 128 (2022) 032001

X(3872) signal significance ~ 4.2σ

Indication of **X(3872)** enhancement in Lead-Lead collisions with respect to **proton-proton collisions**

Dissociation-Recombination: Exotic Hadron X(3872)



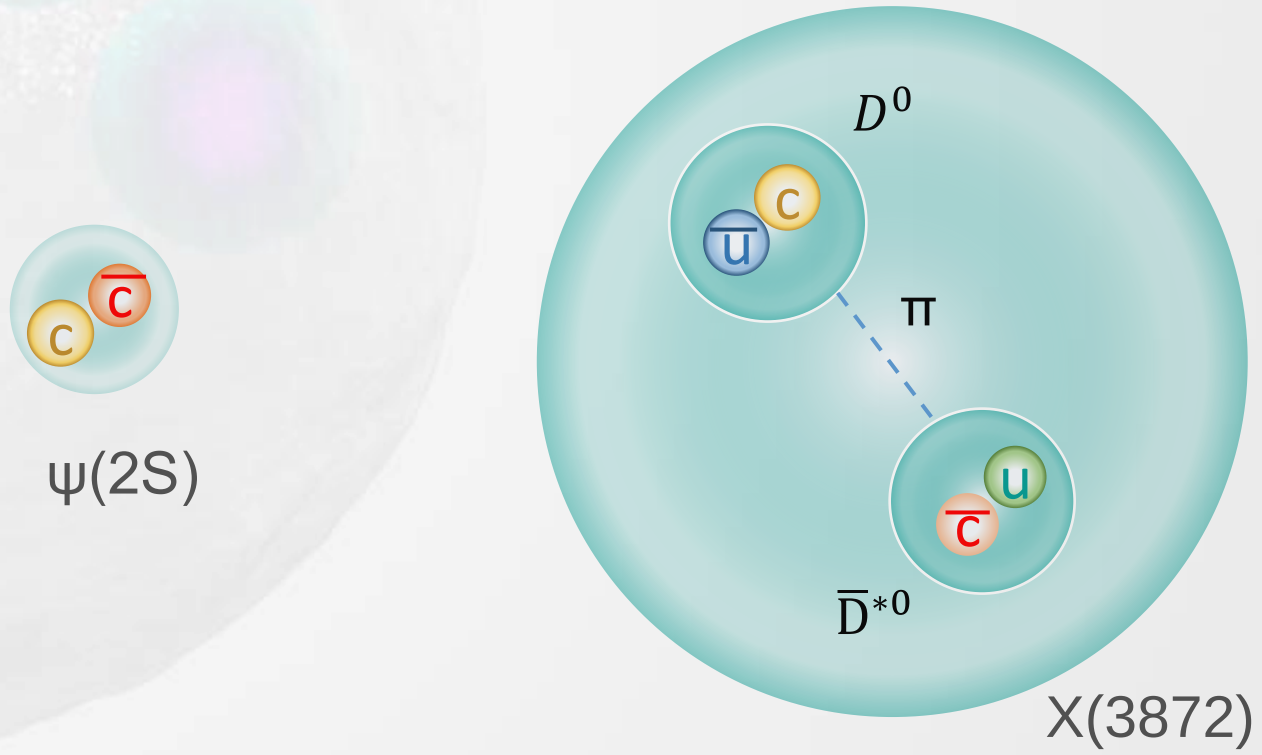
Low multiplicity → **High multiplicity**

PRL 132 (2024) 24, 242301 PRL 128 (2022) 032001

X(3872) to ψ(2S) yield ratio across collision systems:

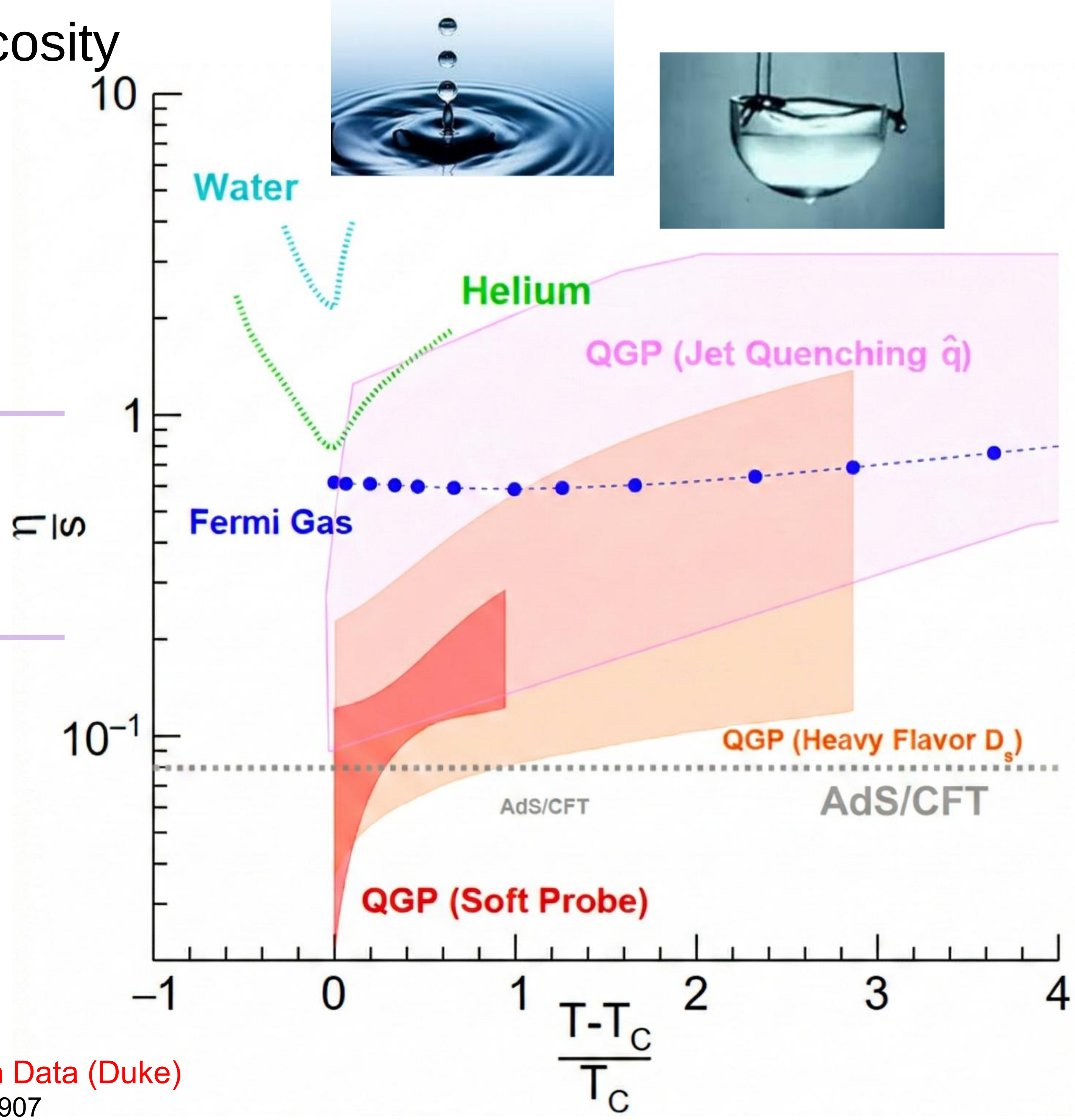
- Dissociated by interactions with comovers (pp/pPb) or medium (PbPb)
- Enhanced via recombination

$D^0 - \bar{D}^{*0}$ molecule

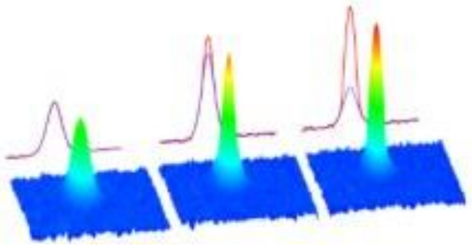


Near Perfect Fluid: Consistency from Hard Probes

Specific Shear Viscosity



Compiled by Michael Winn, Liliana Apolinario + YJL
Progress in Particle and Nuclear Physics, 103990 (2022)

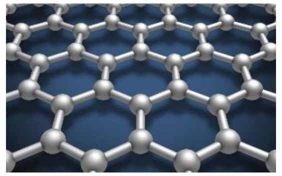


MIT cold atom group

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

String theory

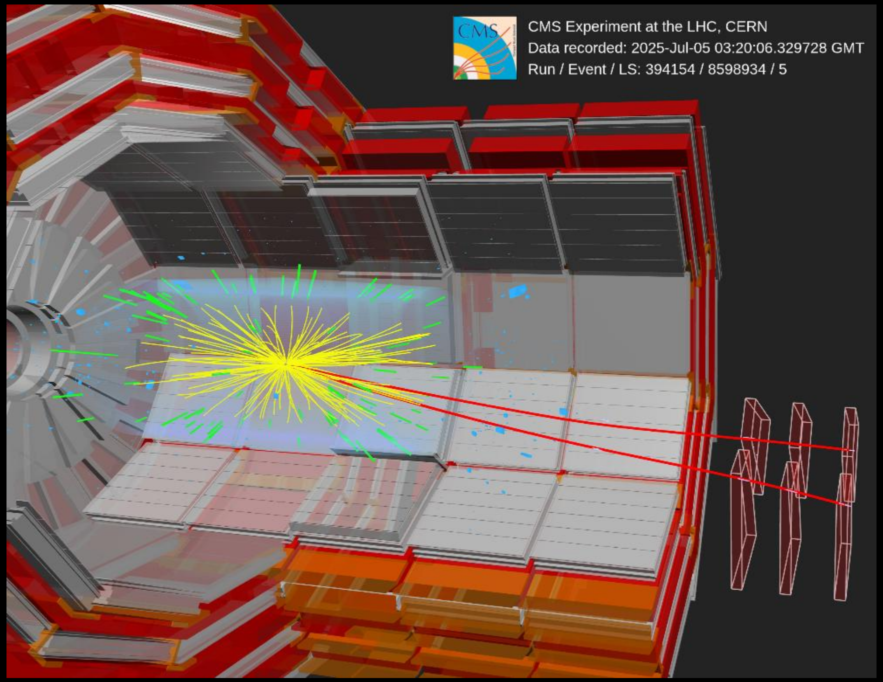
Electron fluid in Graphene
PRL103,025301 (2009)

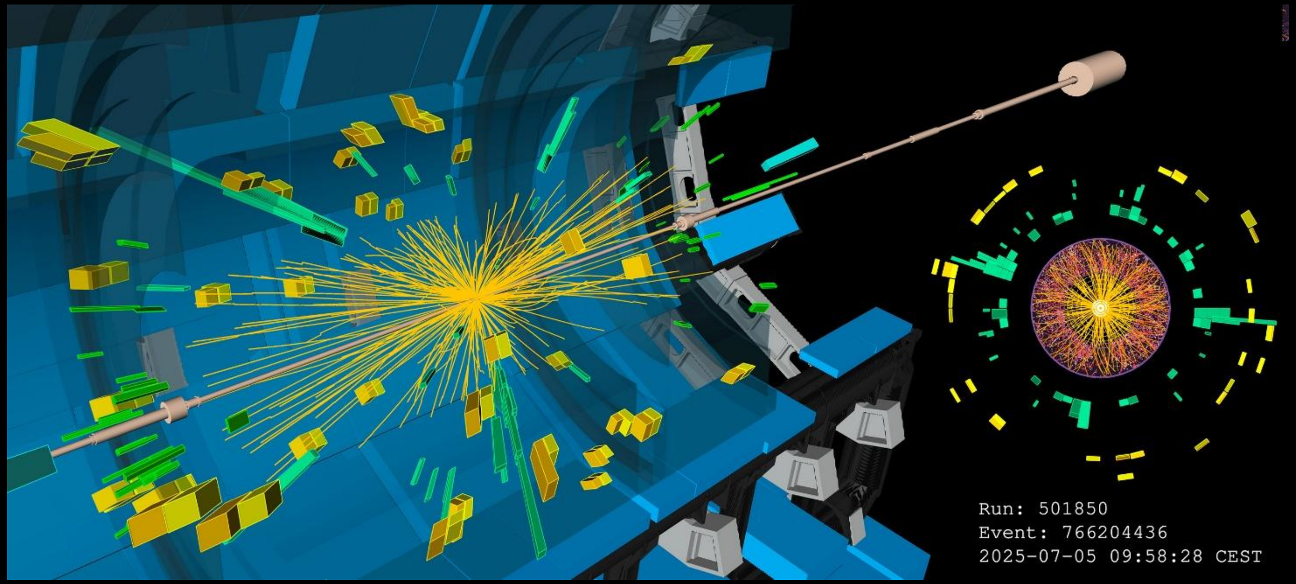


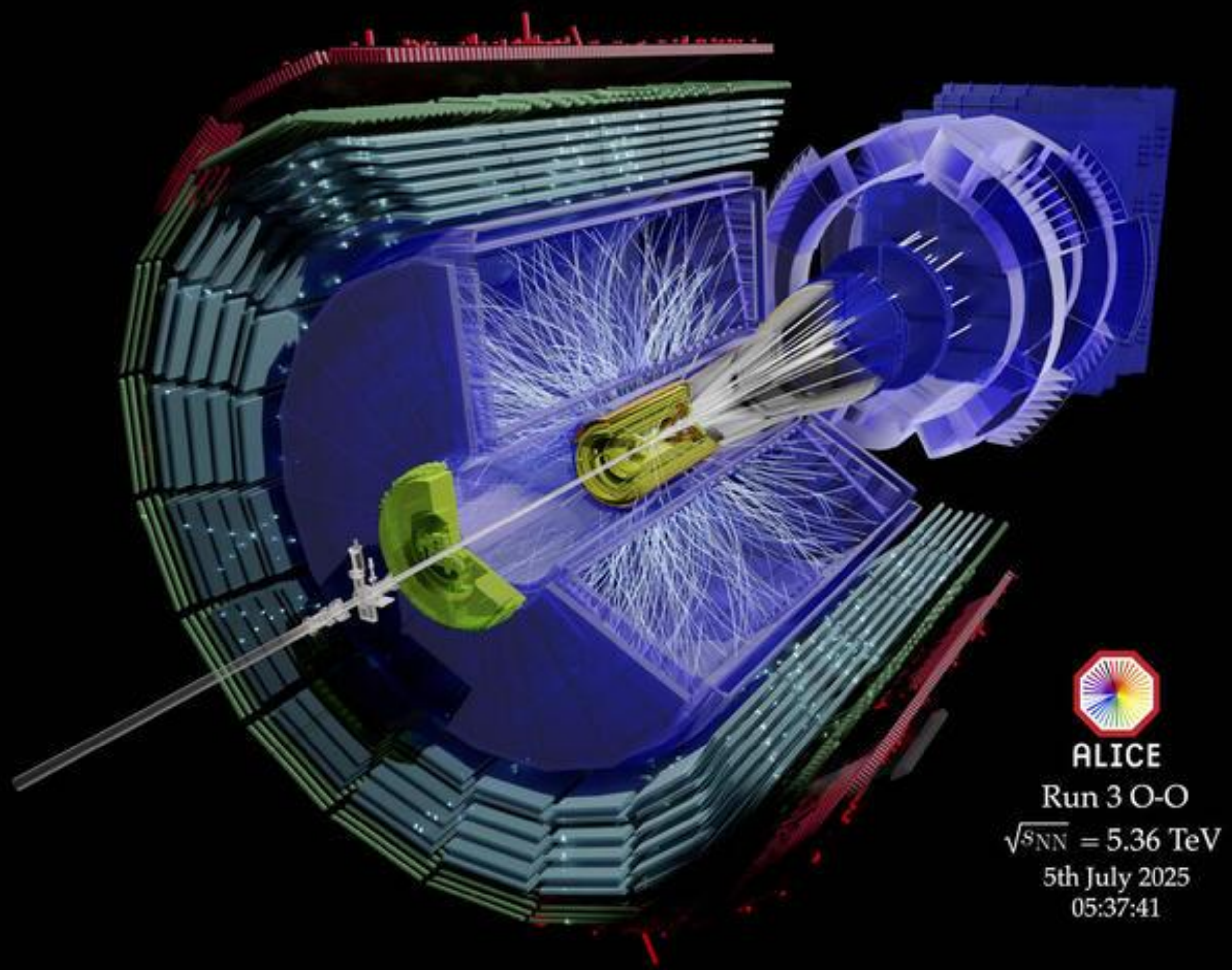
Bayesian Analysis on Data (Duke)
PRC94 (2016) no.2, 024907

Medium properties extracted from **Jet Quenching** and **Open Heavy Flavor** after model-dependent mapping confirming the results from **Soft Probes**, but within rather large uncertainties

Recent Excitement: **Oxygen-Oxygen** Collisions

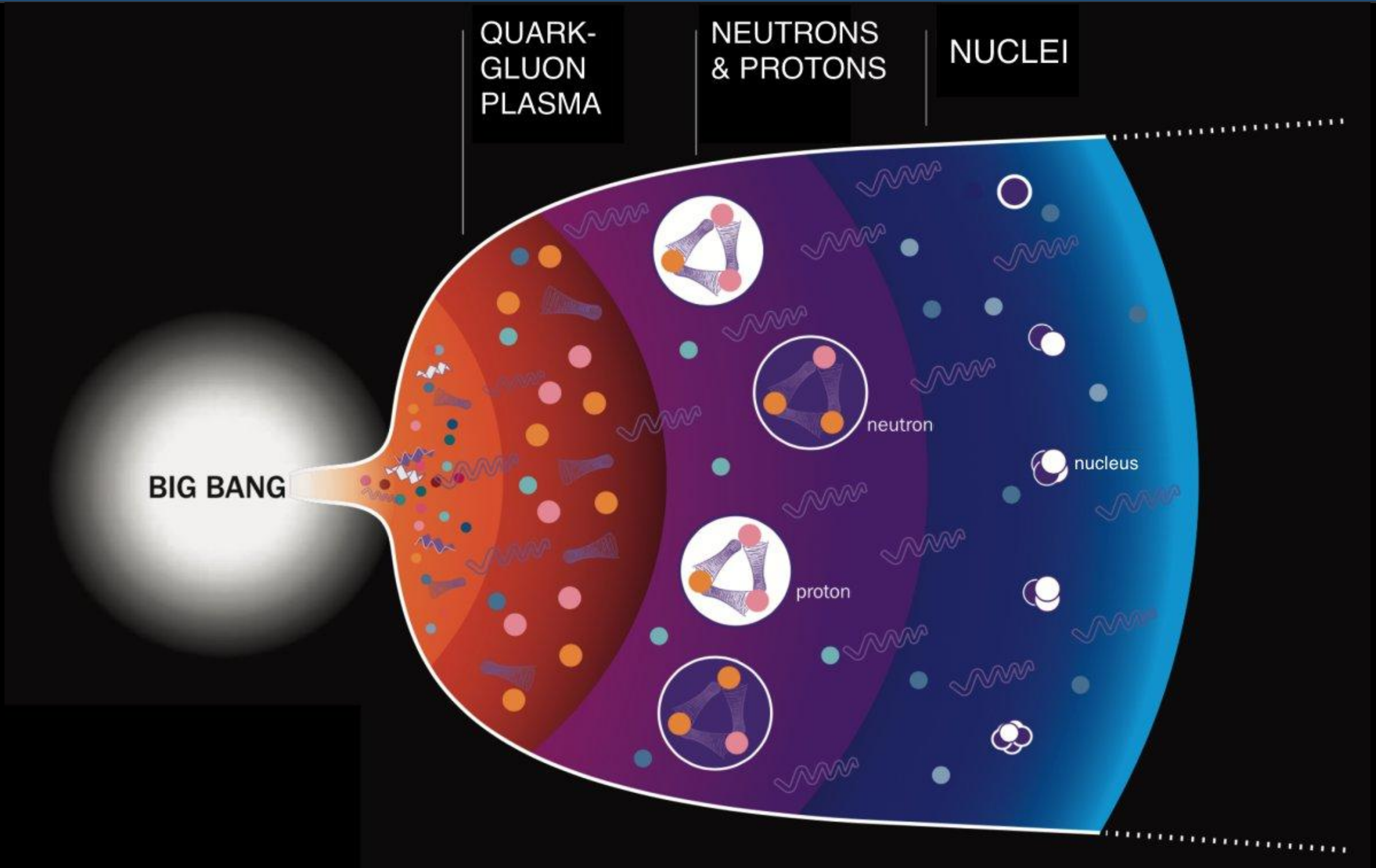






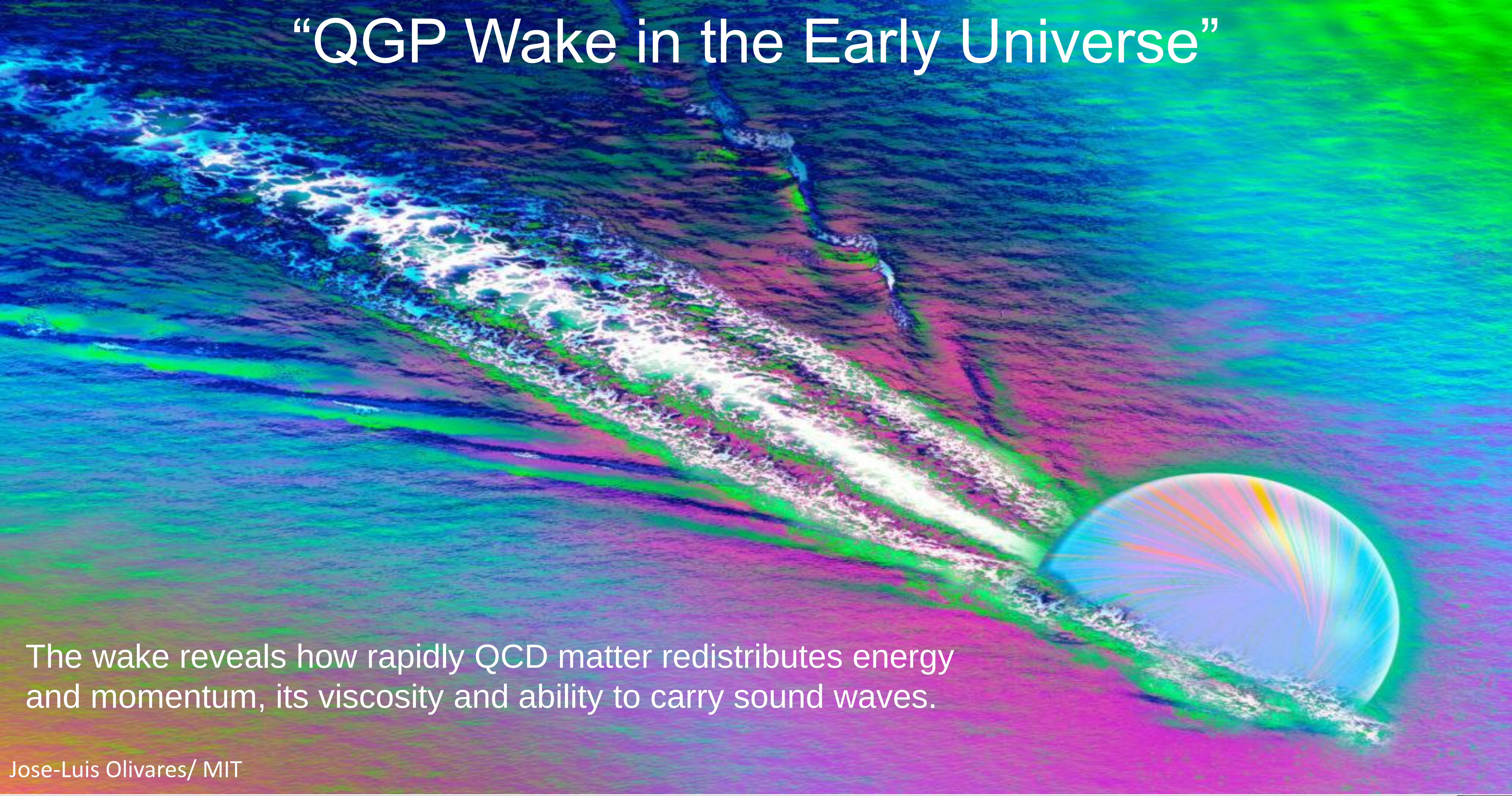
The smallest system that has
Jet Quenching, Flow and Charm Diffusion
The field is actively digesting this data!

Evolution of the Early Universe



The early universe passed through a quark-gluon plasma stage microseconds after the Big Bang; heavy ion collisions recreate tiny versions of that epoch.

“QGP Wake in the Early Universe”

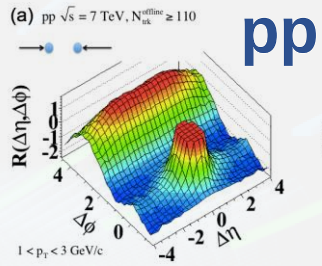


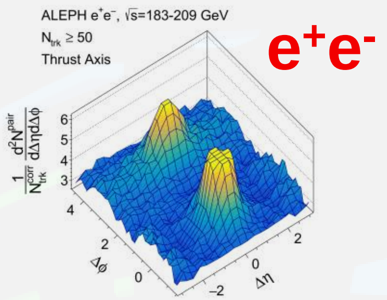
The wake reveals how rapidly QCD matter redistributes energy and momentum, its viscosity and ability to carry sound waves.

Jose-Luis Olivares/ MIT

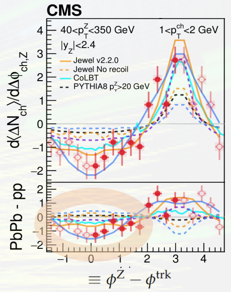
What Have We Learned about the Quark Soup?

- **Making the soup**: Colliding heavy ions creates a 2-5 × 10^{12} K QGP that flows nearly perfectly; Ridge-like signals also appear in the smallest systems; its origin remains under investigation.

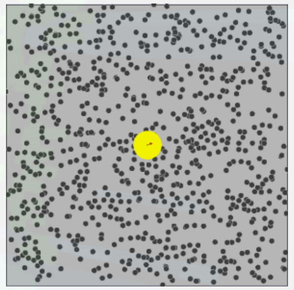




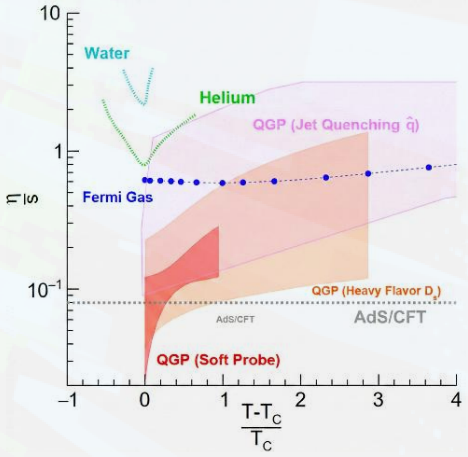
- **Stirring the soup**: Z^0-tagged hadron spectra and dijet data provide direct evidence of QGP's wake



- **Tasting the soup**: Heavy flavor hadrons probe heavy-quark diffusion, recombination and hadron formation.



- **A consistent picture**: flow, heavy quark diffusion and jet quenching give broadly compatible, though model-dependent, transport properties



- **Outlook:** High-statistics LHC data will probe the initial stages of HIC and resolve QGP substructure, while the future FAIR/CBM is designed to explore baryon-rich matter and a possible first-order transition

Thank You!