UNIVERSITAT DE BARCELONA

From Jets to Wakes: Hydrodynamic Response of the QGP

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UNIVERSITAT DE BARCELONA

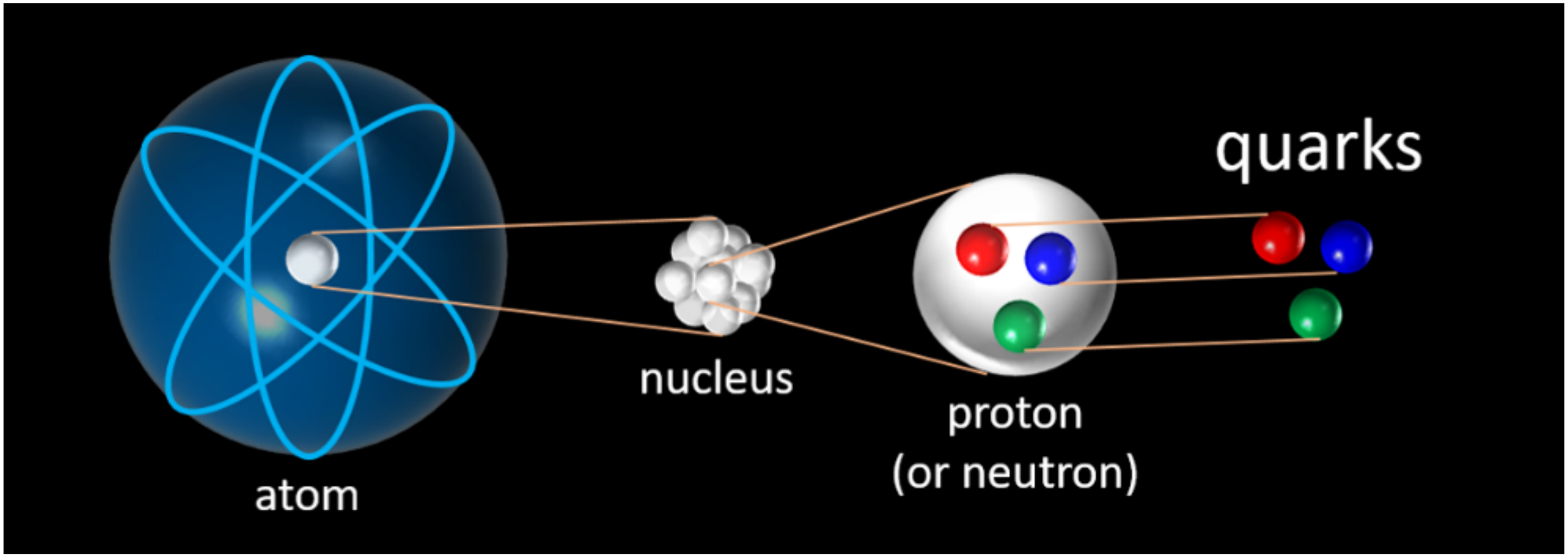
EXCELENCIA MARÍA DE MAEZTU
04/2025-03/2031

MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN

AGAUR Agència de Gestió d'Ajuts Universitaris i de Recerca

QCD Matters

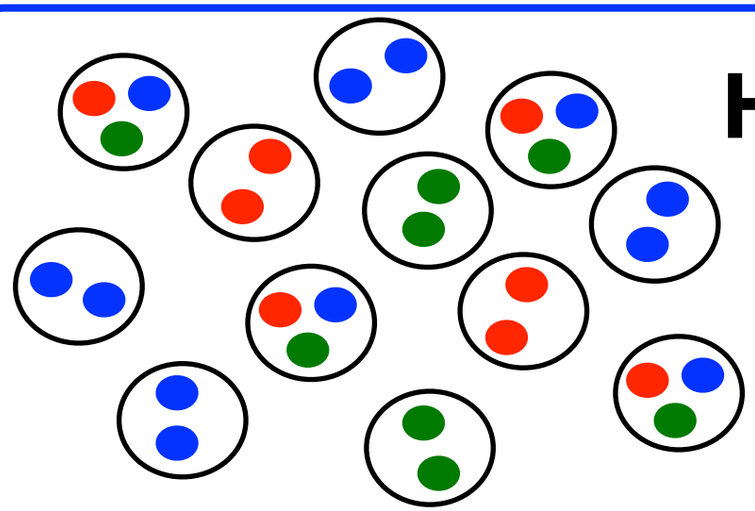
- We all know that:



- What happens when nuclei are heated to trillions of degrees?

QCD Matters

T



Hadron Gas

- Colour is confined
- Hadrons re-scatter

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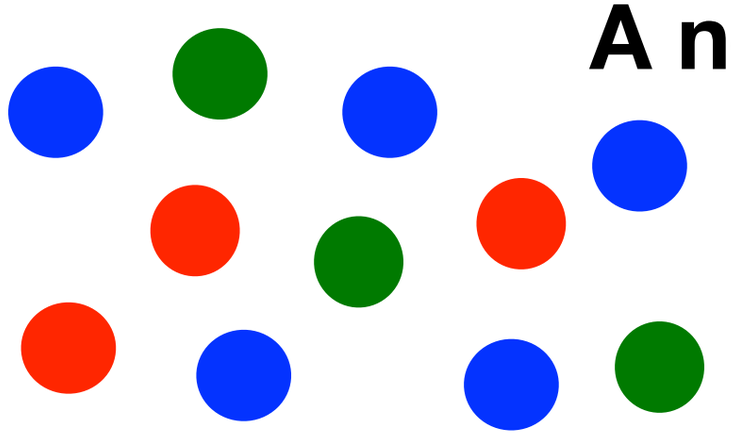
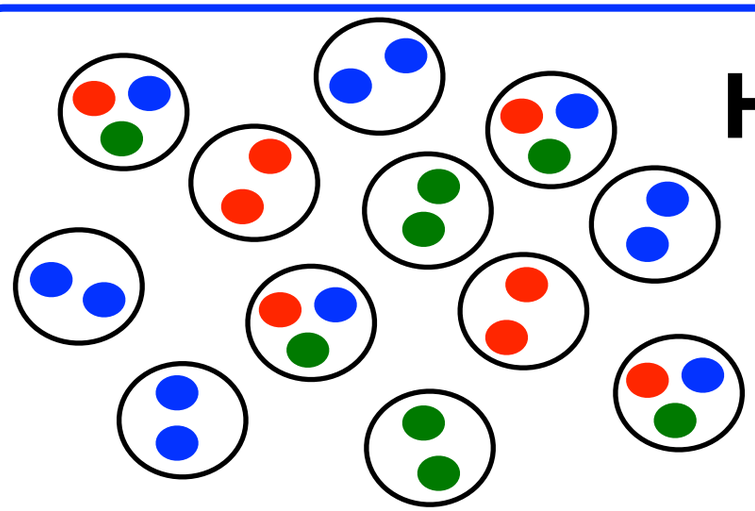


A new phase: <u>Quark Gluon Plasma</u>

- Filled the universe μs after Big Bang
- Colour is liberated
- A gas of quark and gluons



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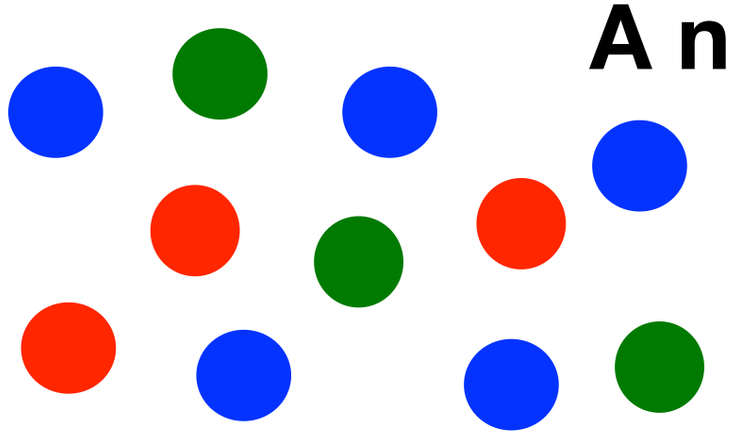

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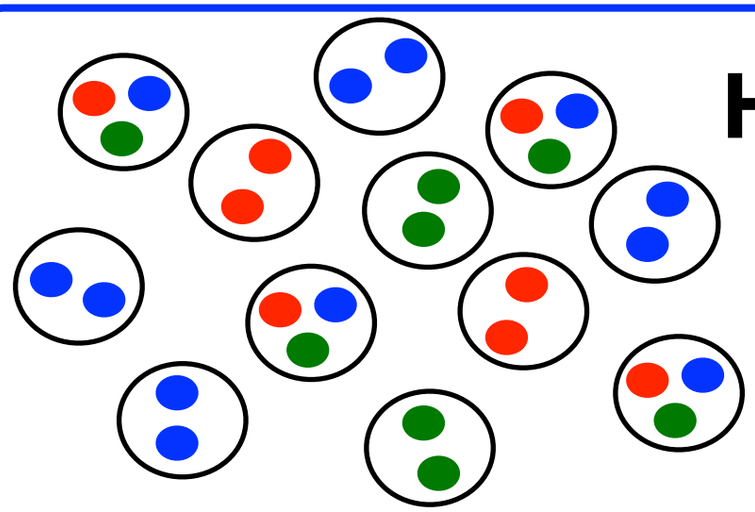
"phase transition"

$T_c \approx 2\times10^{12}$ K

$\approx$ 170 MeV

What are the properties of the plasma close to the transition?



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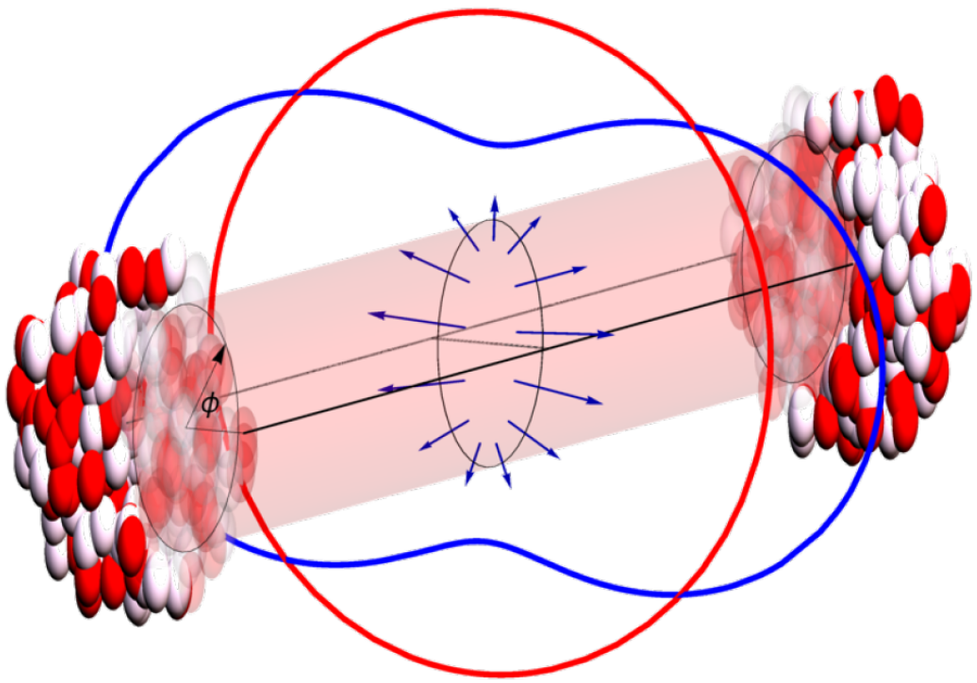
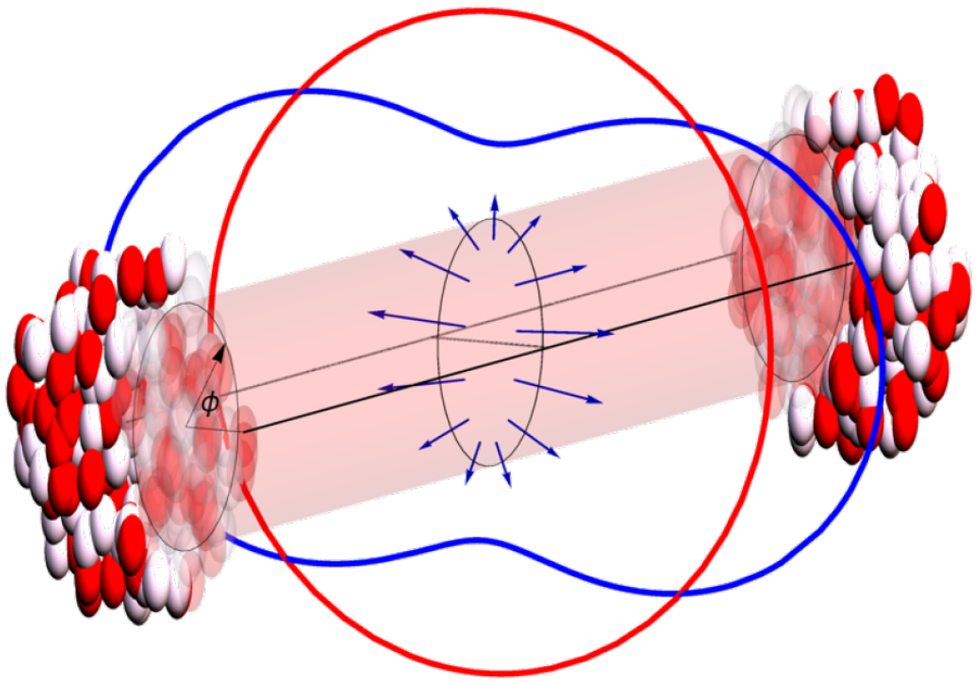
Heating Up Hadronic Matter



- Ultra relativistic heavy ion collisions
  - RHIC: 200 GeV/A
  - LHC: 5.02 TeV/A

Heating Up Hadronic Matter



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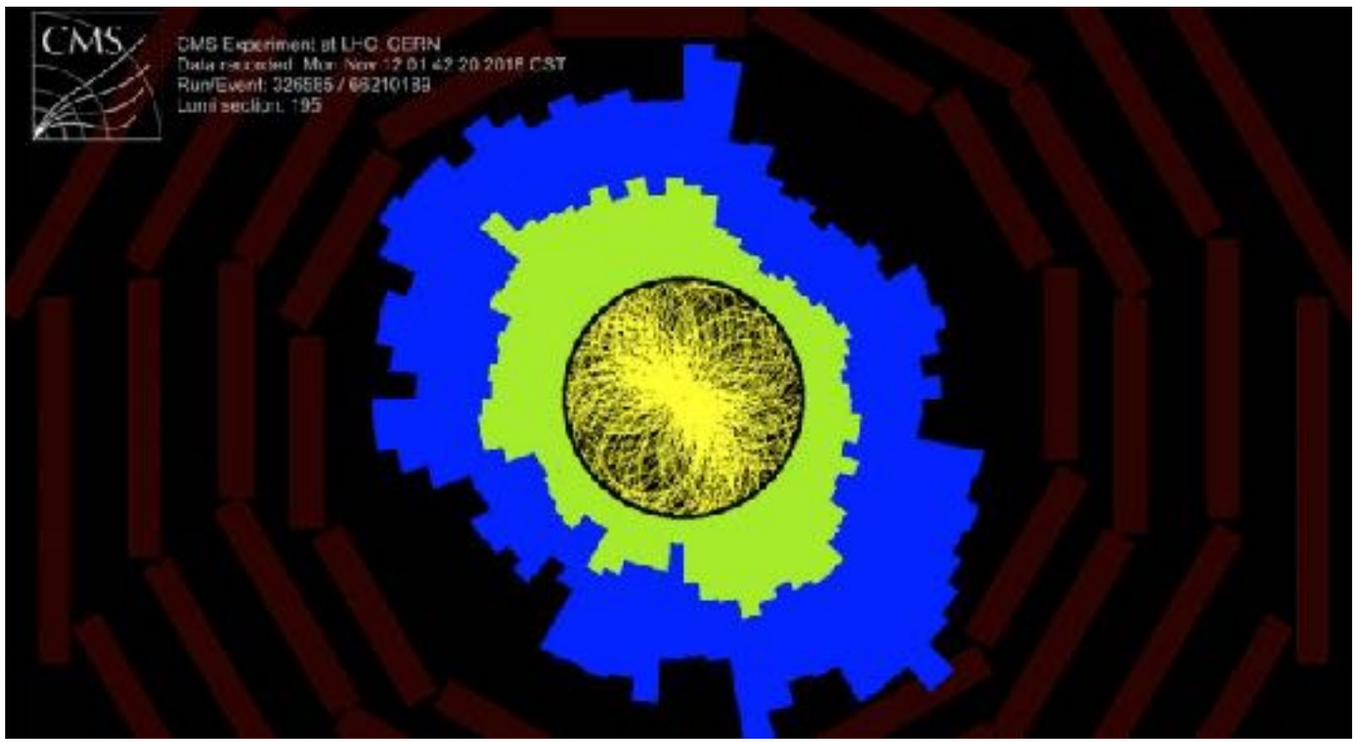
- Anisotropic event
  - Thousands of particles
  - Transverse-plane correlations



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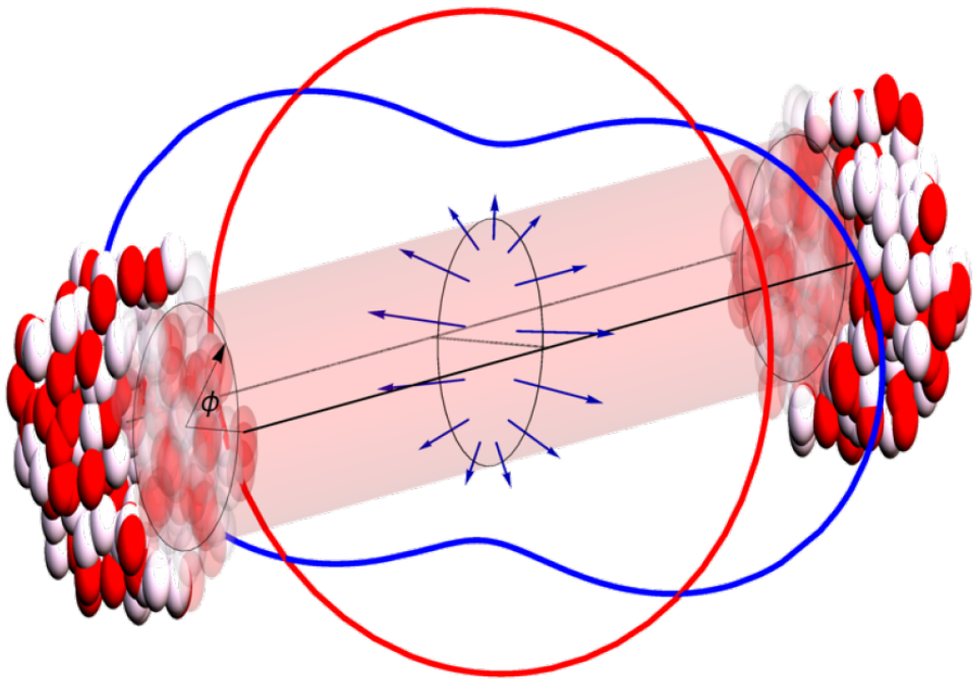
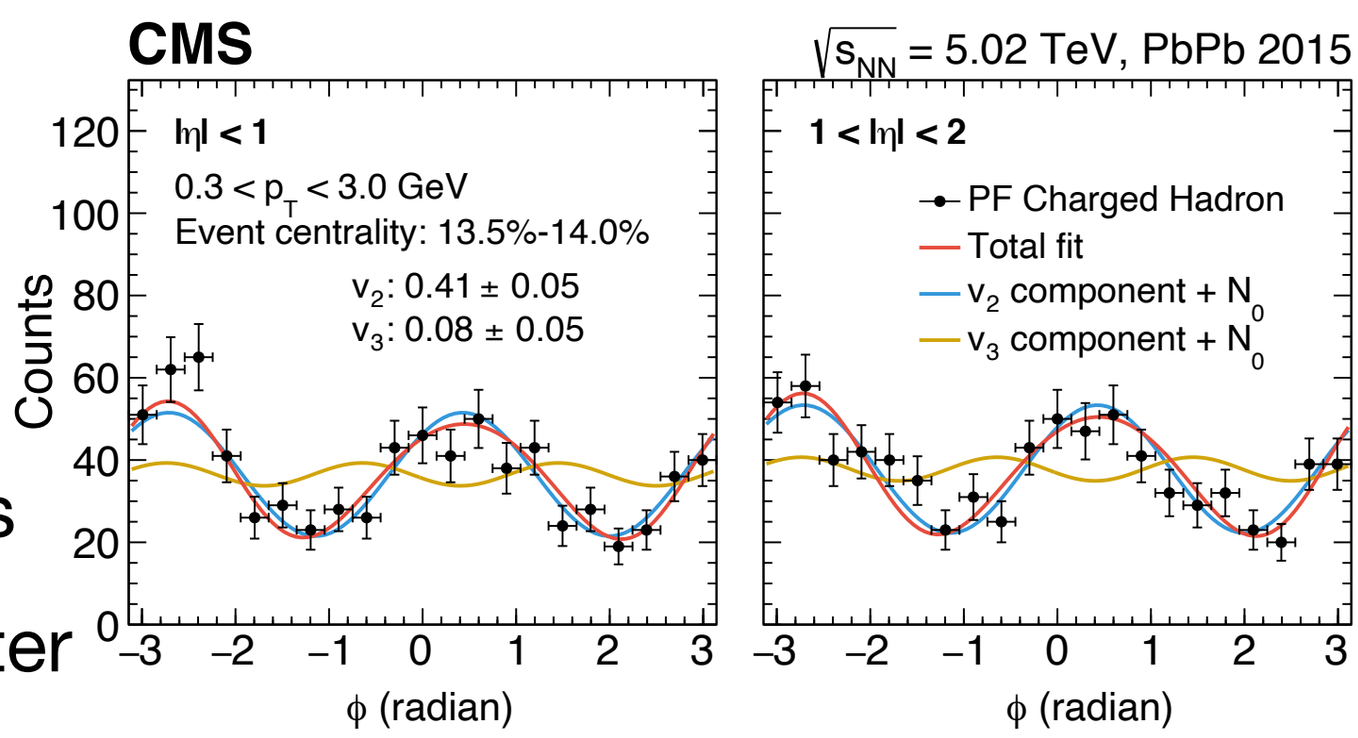
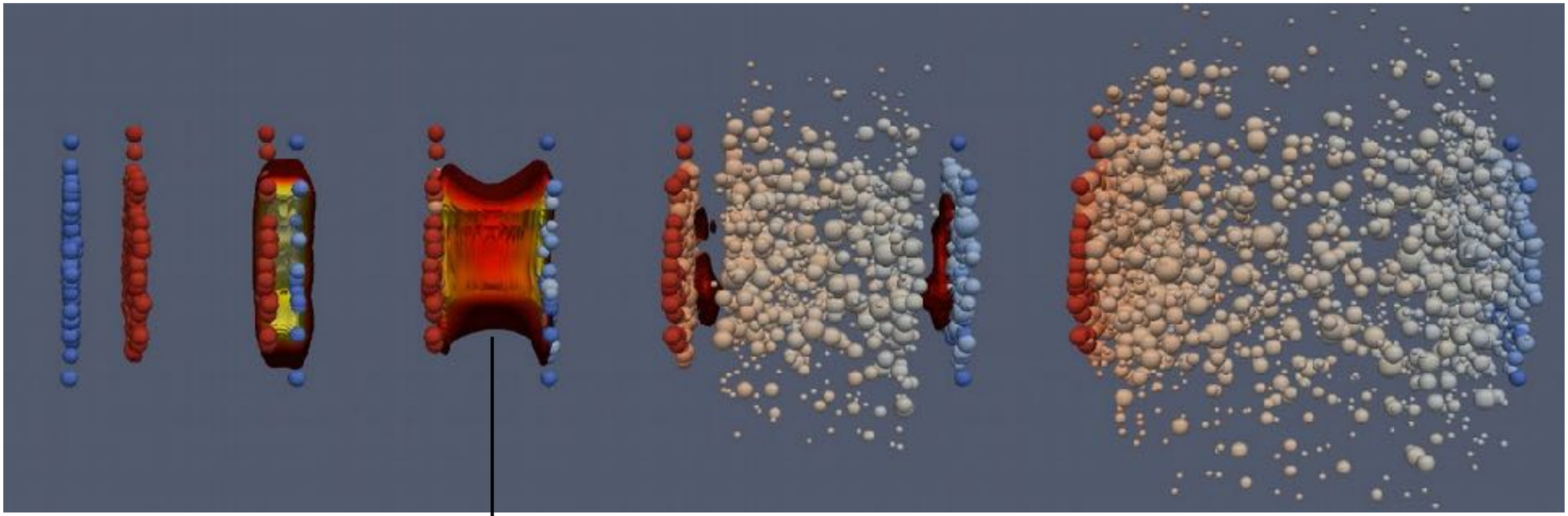


- Ultra relativistic heavy ion collisions
  - RHIC: 200 GeV/A
  - LHC: 5.02 TeV/A

- Anisotropic event
  - Thousands of particles
  - Transverse-plane correlations
  - Remembers impact parameter



Simulation of Heavy Ion Collisions



MADAI collaboration, Hannah Petersen and Jonah Bernhard

- The QGP is treated as a relativistic fluid

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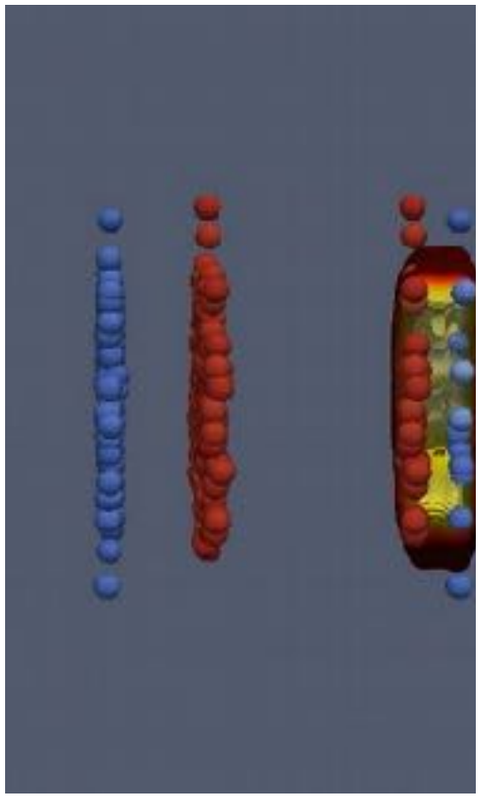

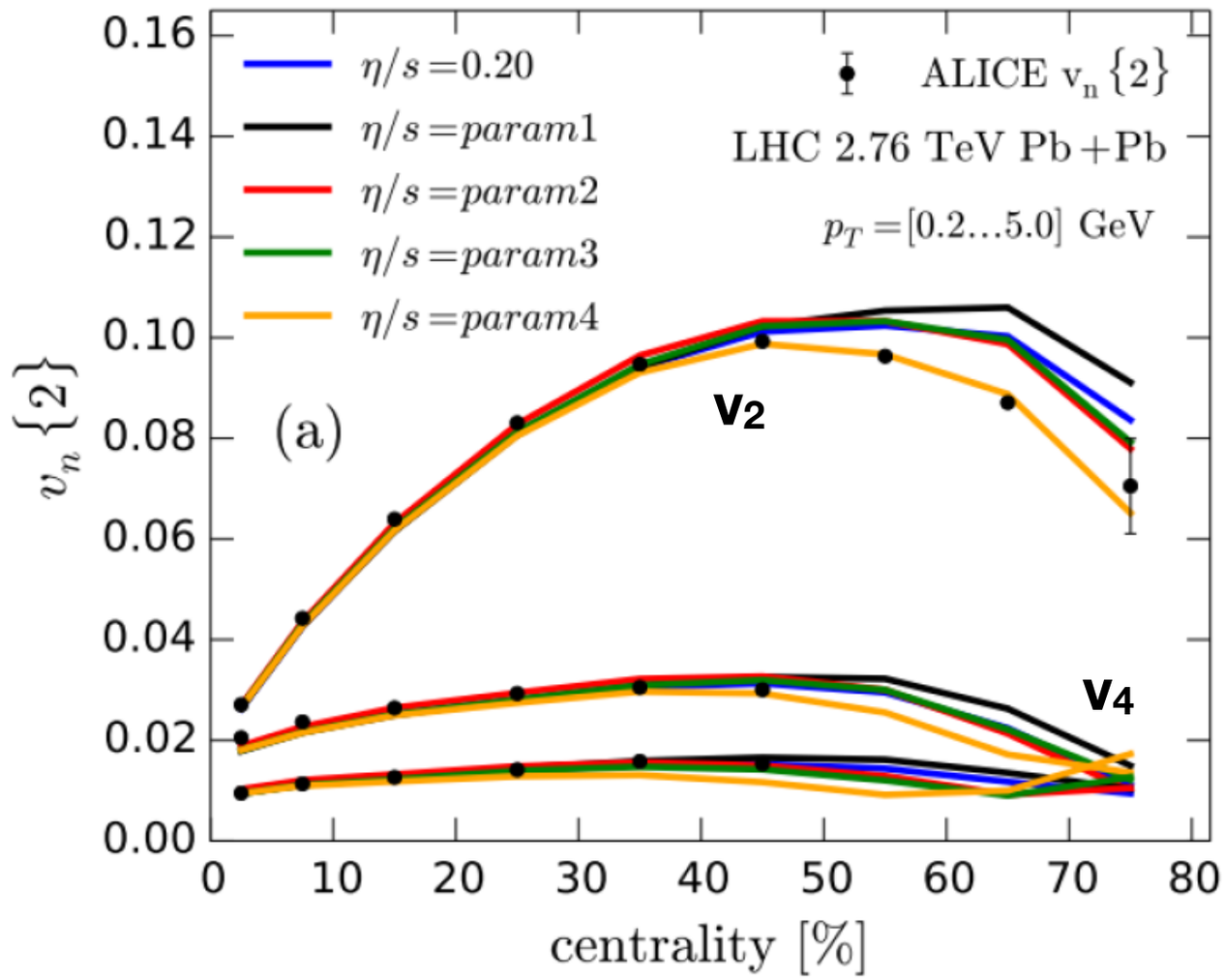

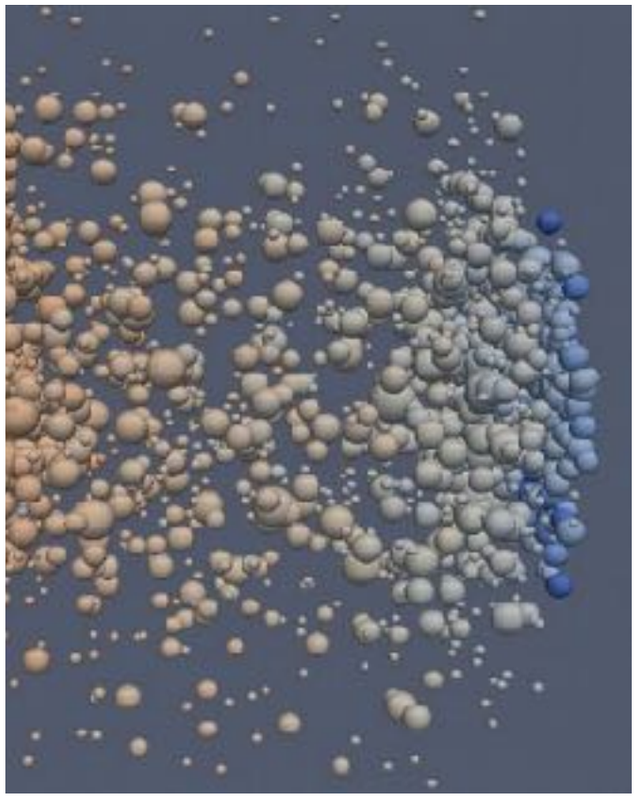

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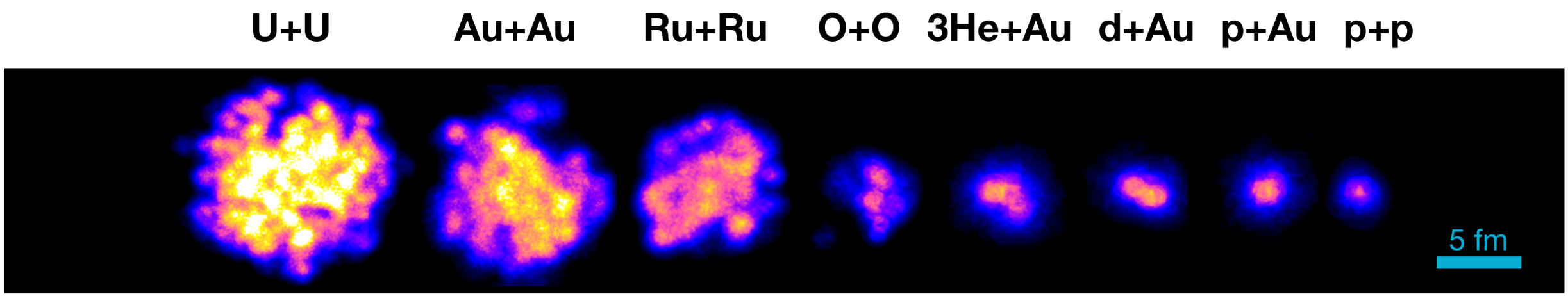
Impact parameter

- The QGP is treated as a relativistic fluid

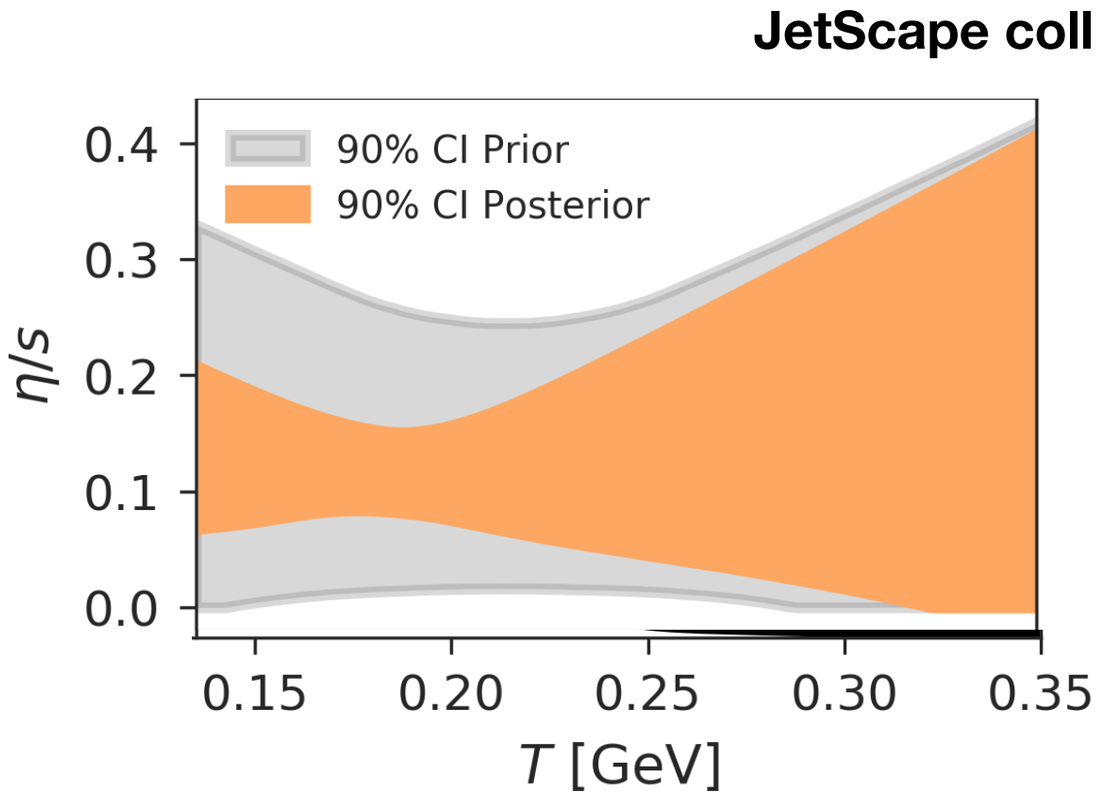
Flow is everywhere



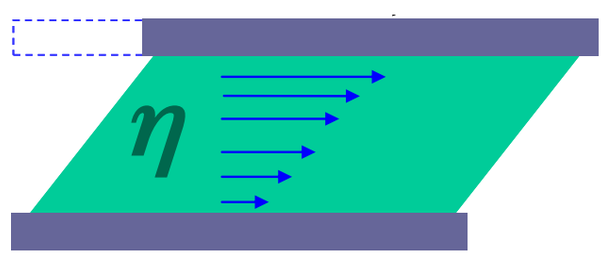
NUCL SCI TECH (2020) 31:122

- We have seen strong flow in many different collisions systems
  - All show anisotropic flow
  - Well described by hydrodynamics
  - Responding to different nucleon nucleon event by event

The Most Perfect Fluid



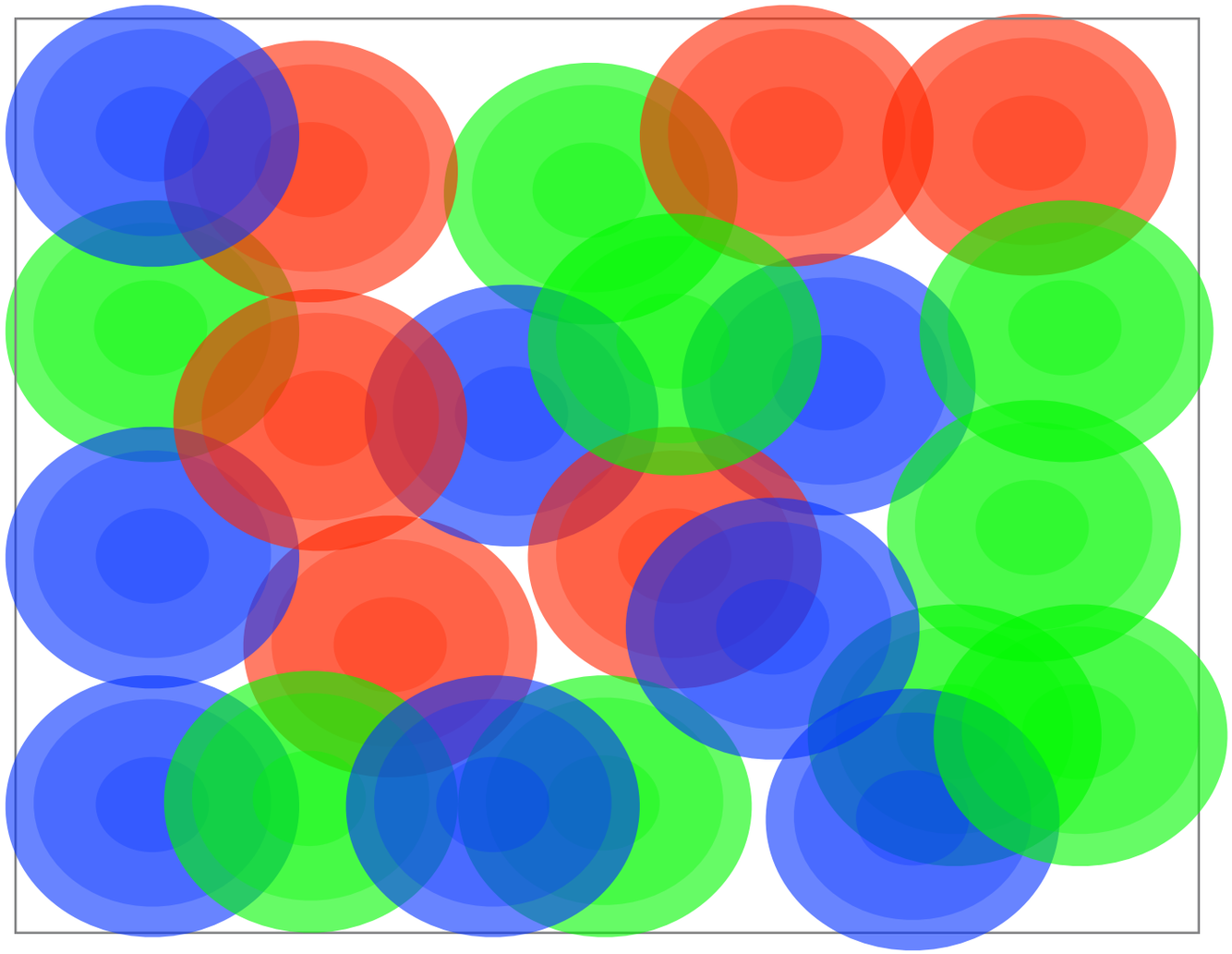
Shear viscosity



- Smallest “kinematical viscosity” of any fluid ever measured

Microscopic Structure of Plasma

- Can we probe the system?



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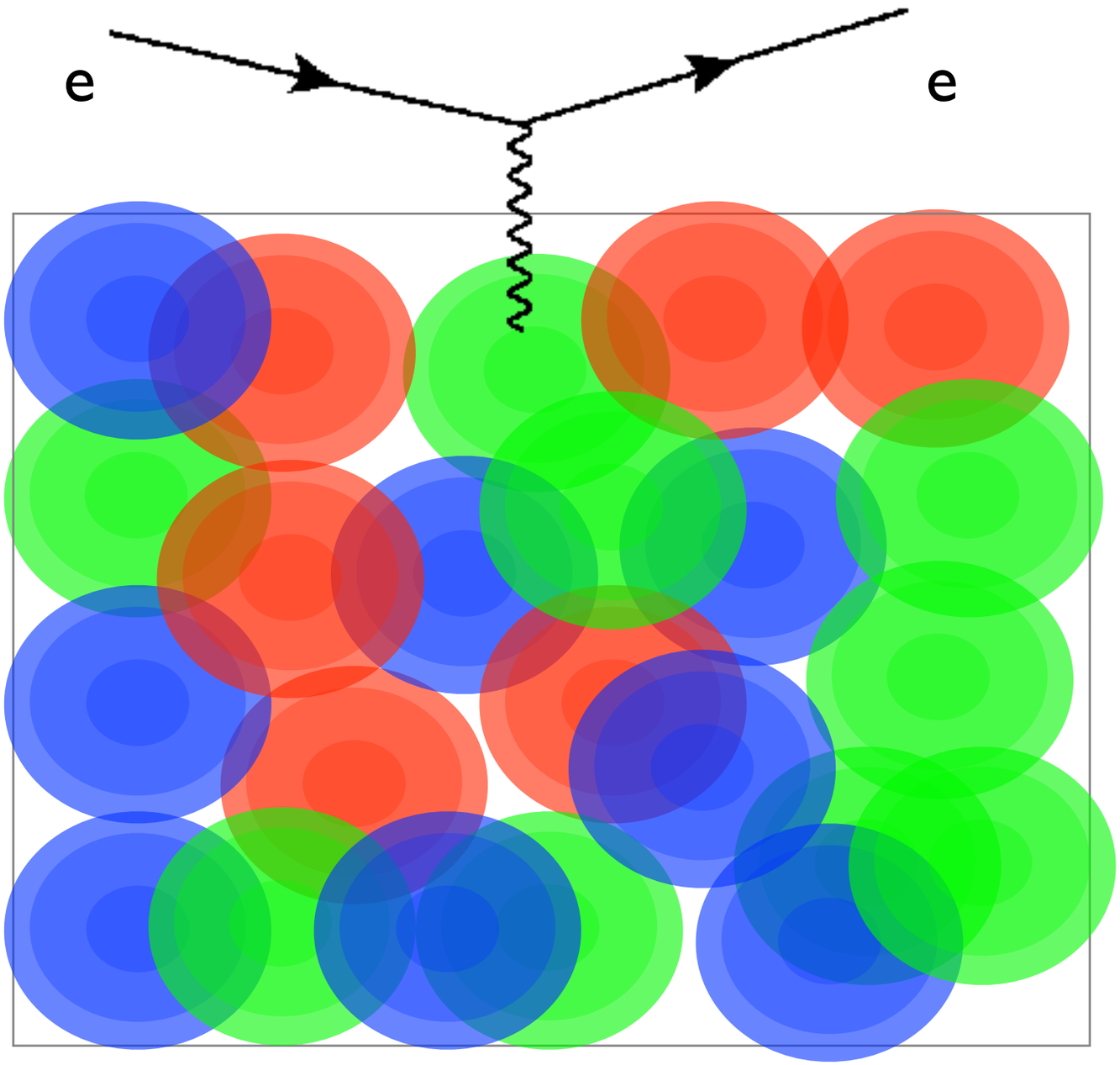
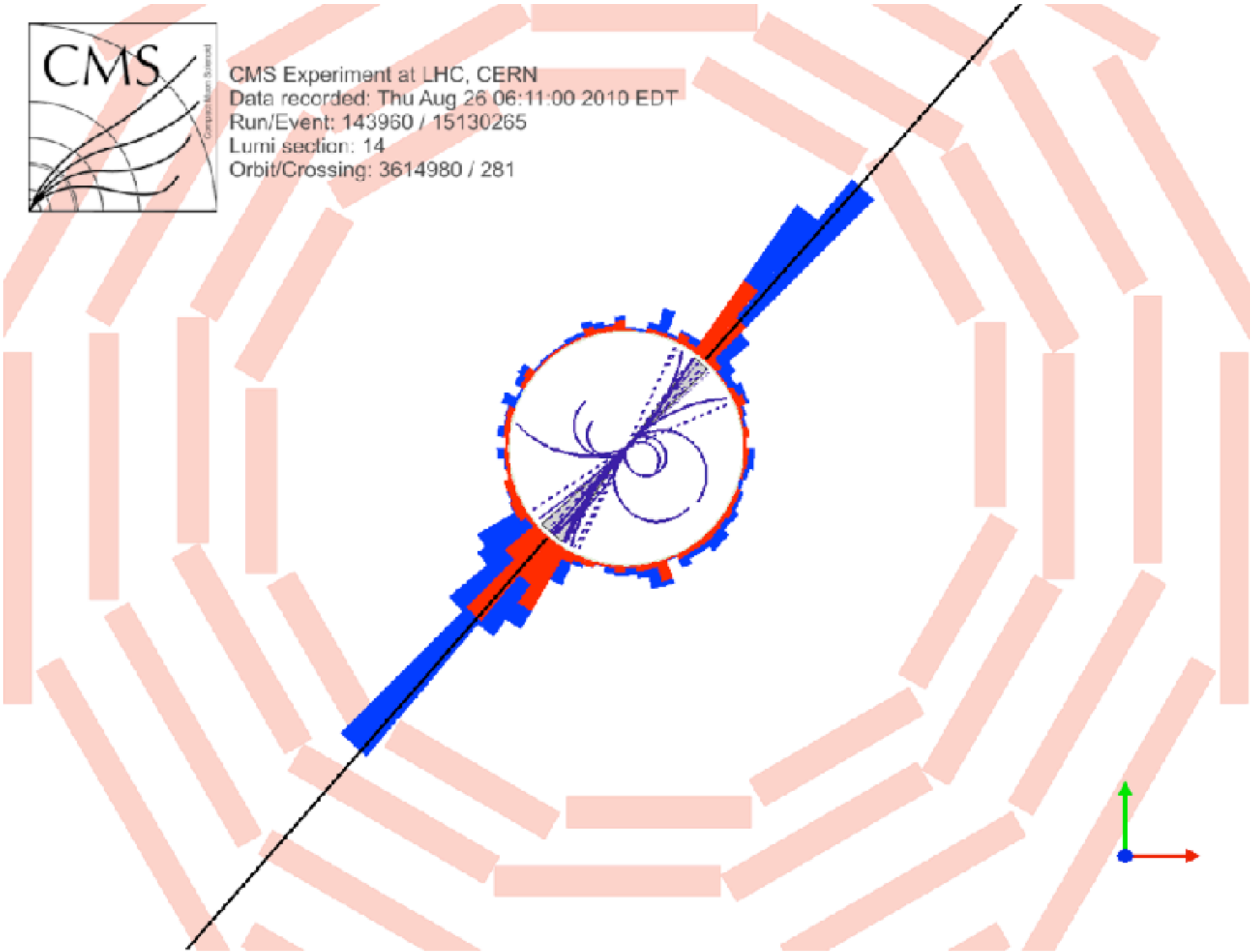
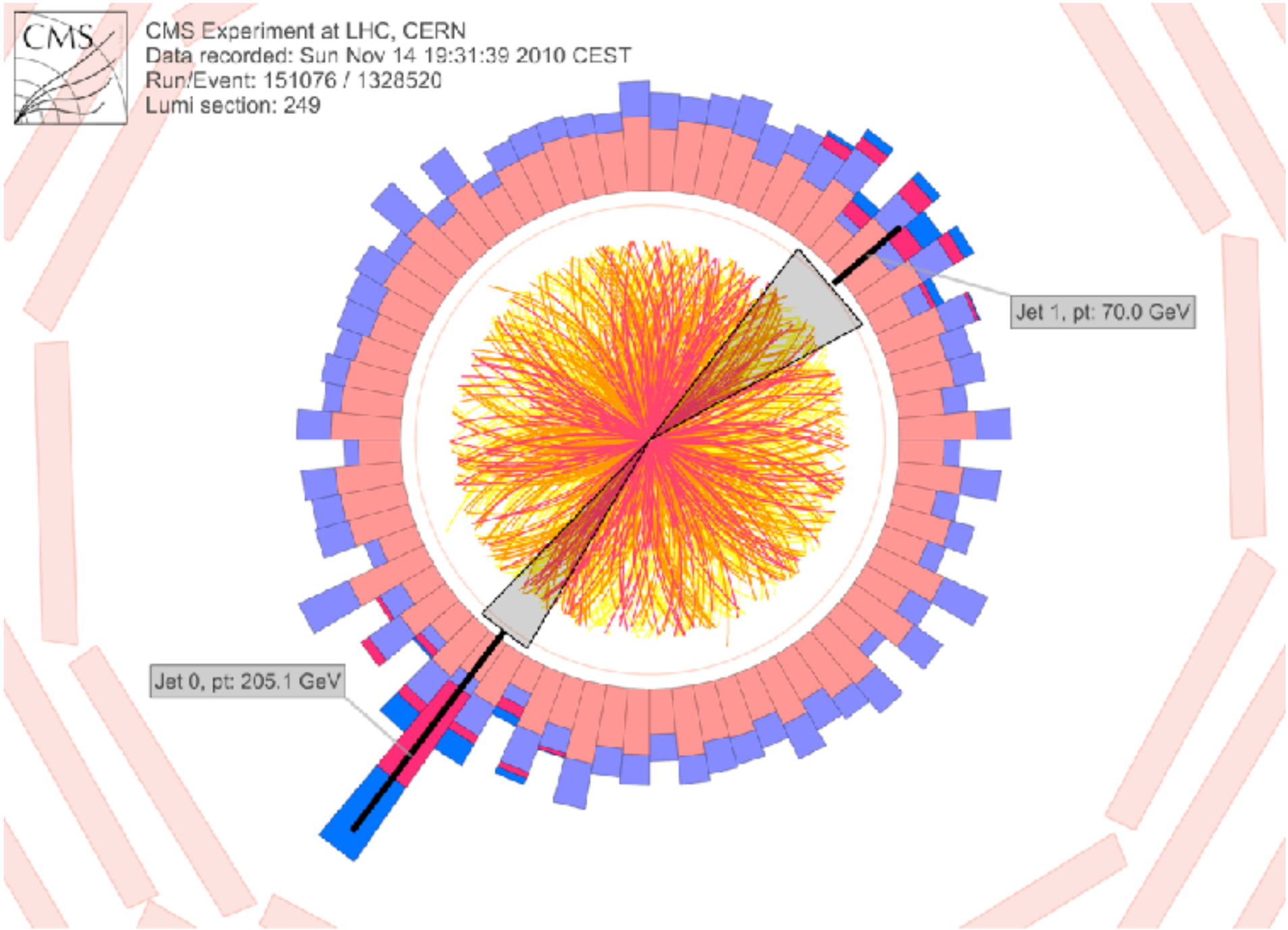


Jets in p-p

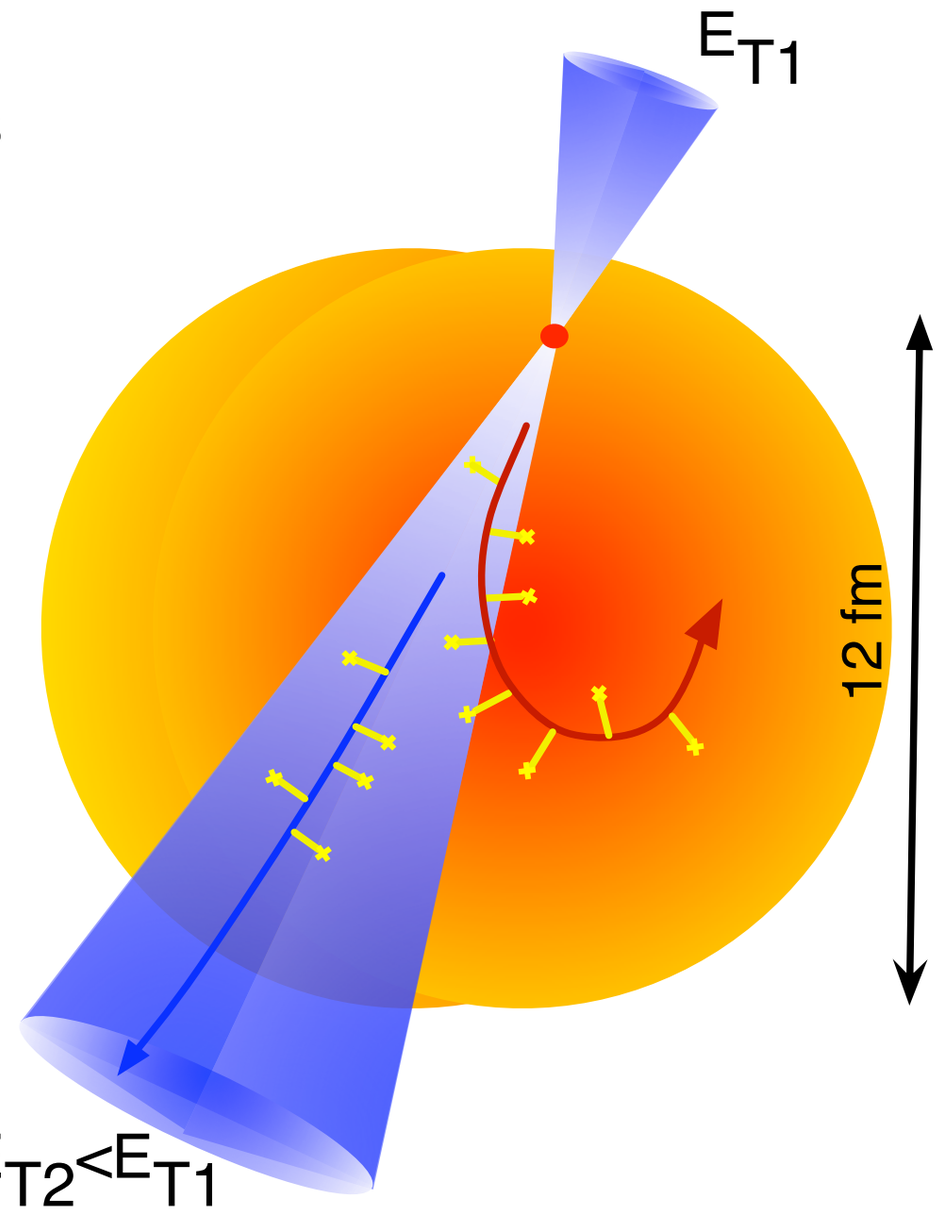

CMS
CMS Experiment at LHC, CERN
Data recorded: Thu Aug 26 06:11:00 2010 EDT
Run/Event: 143960 / 15130265
Lumi section: 14
Orbit/Crossing: 3614980 / 281

Jets in Pb-Pb


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV

Jets in Pb-Pb

- Jets signal high energy quarks and gluons
  - They fragment into les energetic partons
  - Measured as fluxes of energy
  - Defined through “cones”



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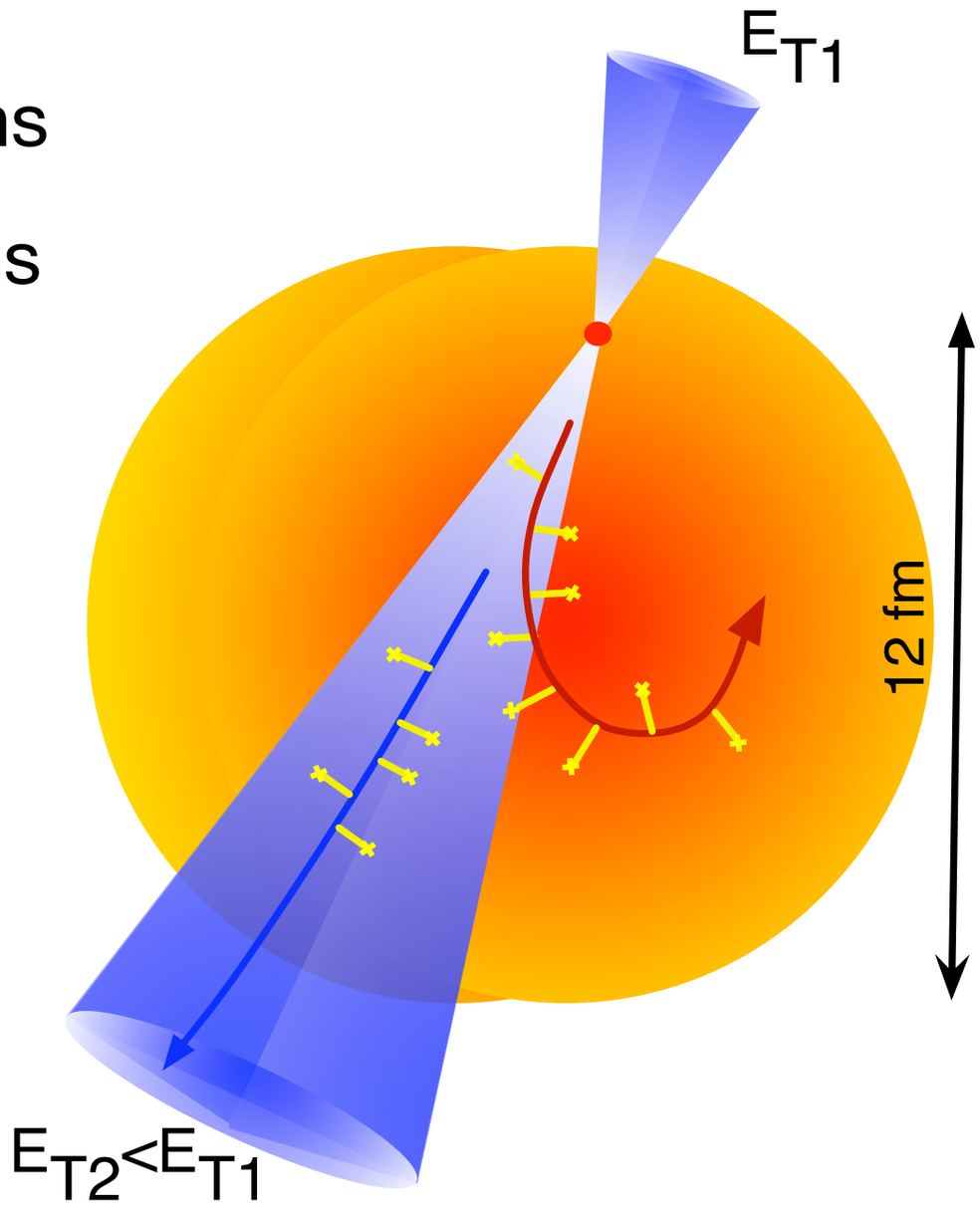
- In the plasma they interact
  - Partons loose energy
  - Momentum is randomised
  - Jet Quenching



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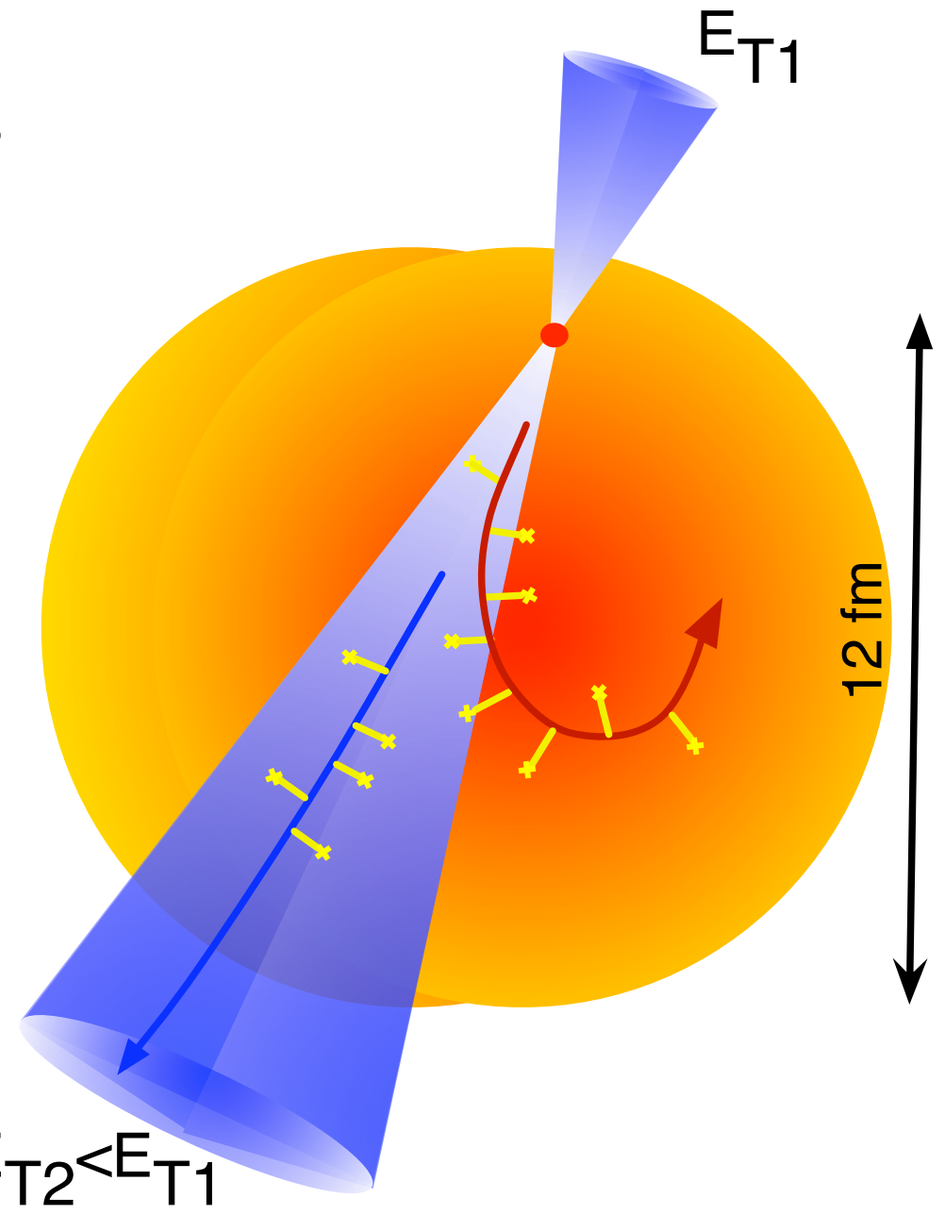

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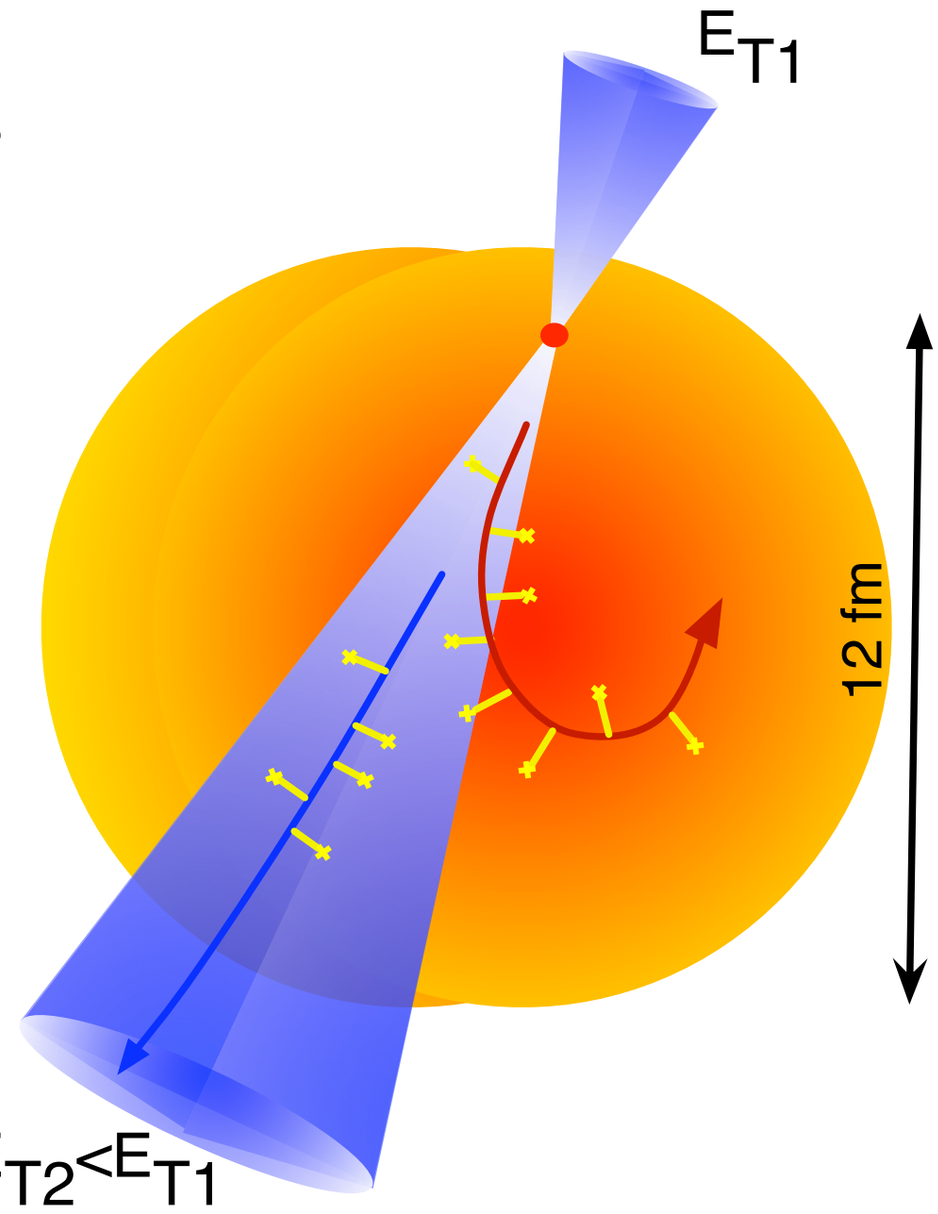
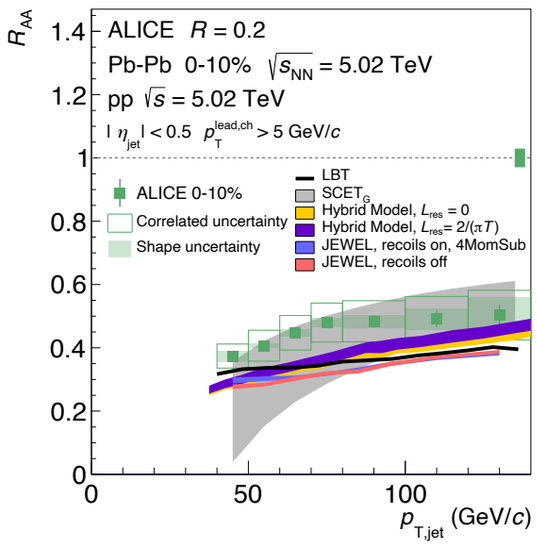


- Many successful models on how jets are quenched
  - One developed here: “The Hybrid strong/weak coupling model”

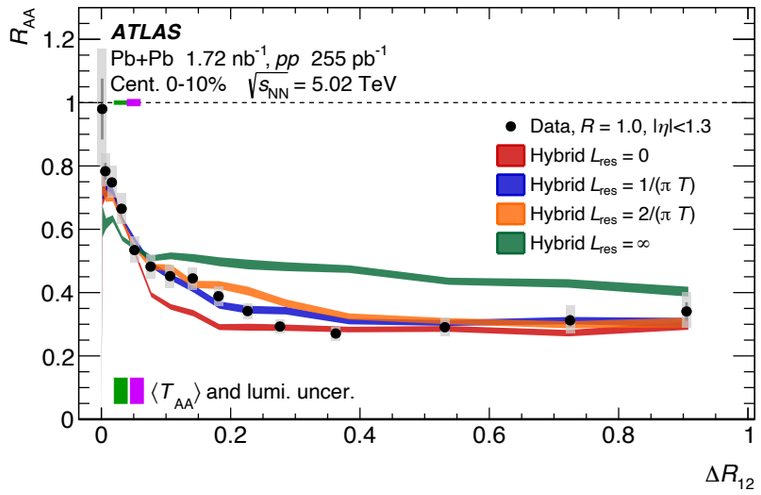
JCS, Gulham, Milhano Pablos, Rajagopal 14

Jet Data vs Models

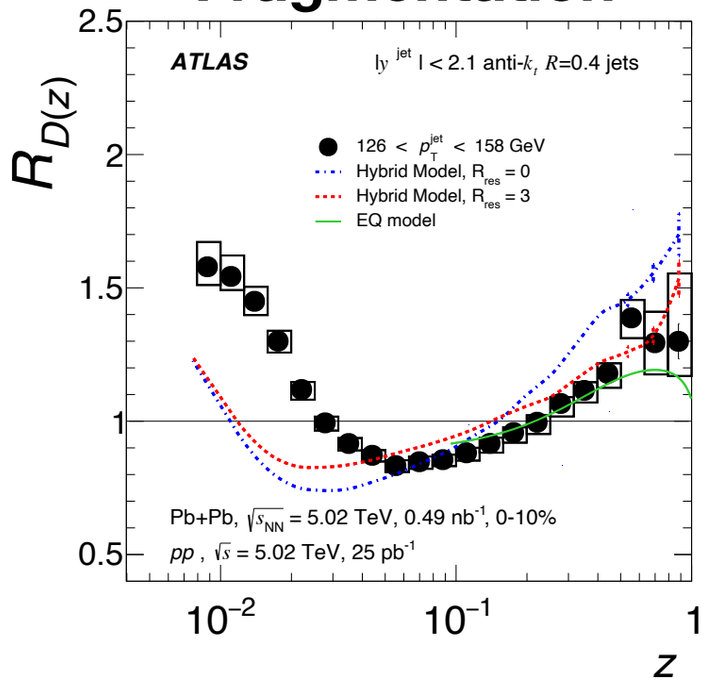
How Many jets



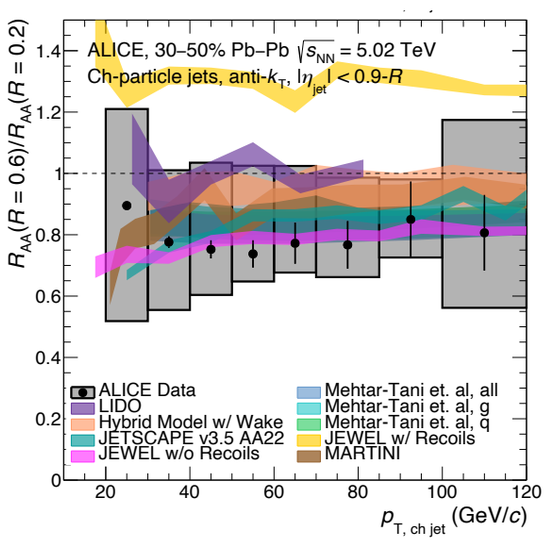
Separation of subjects

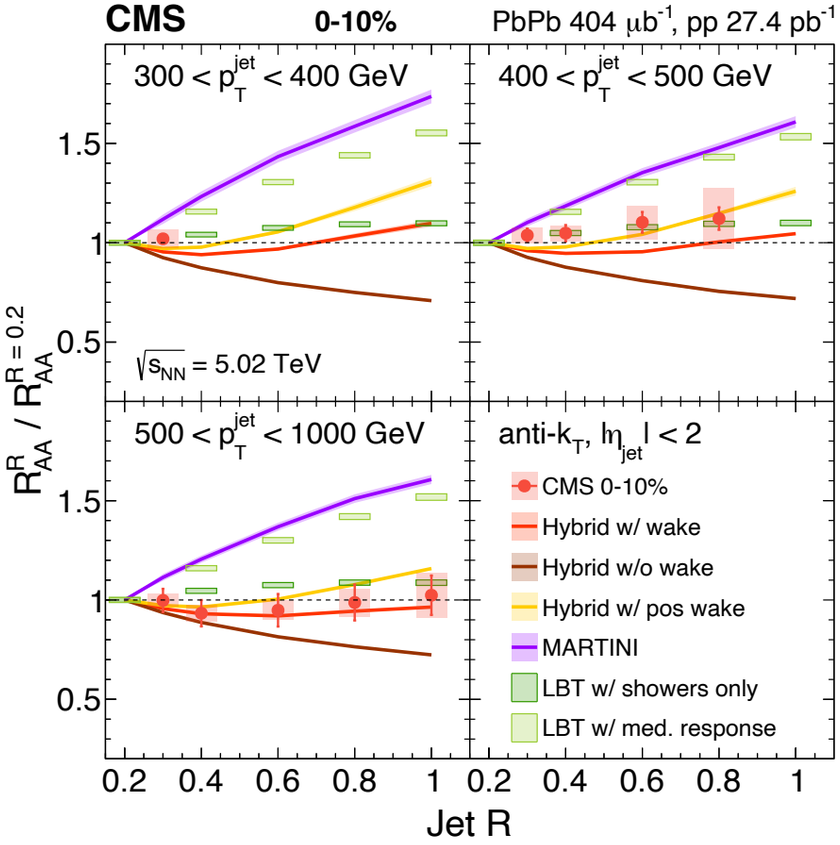


Fragmentation

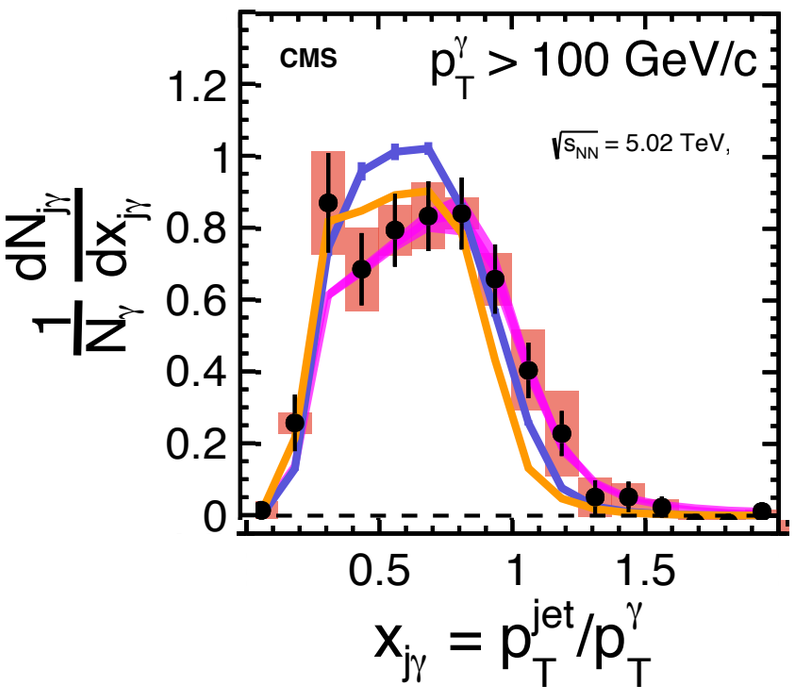


Jet size distribution



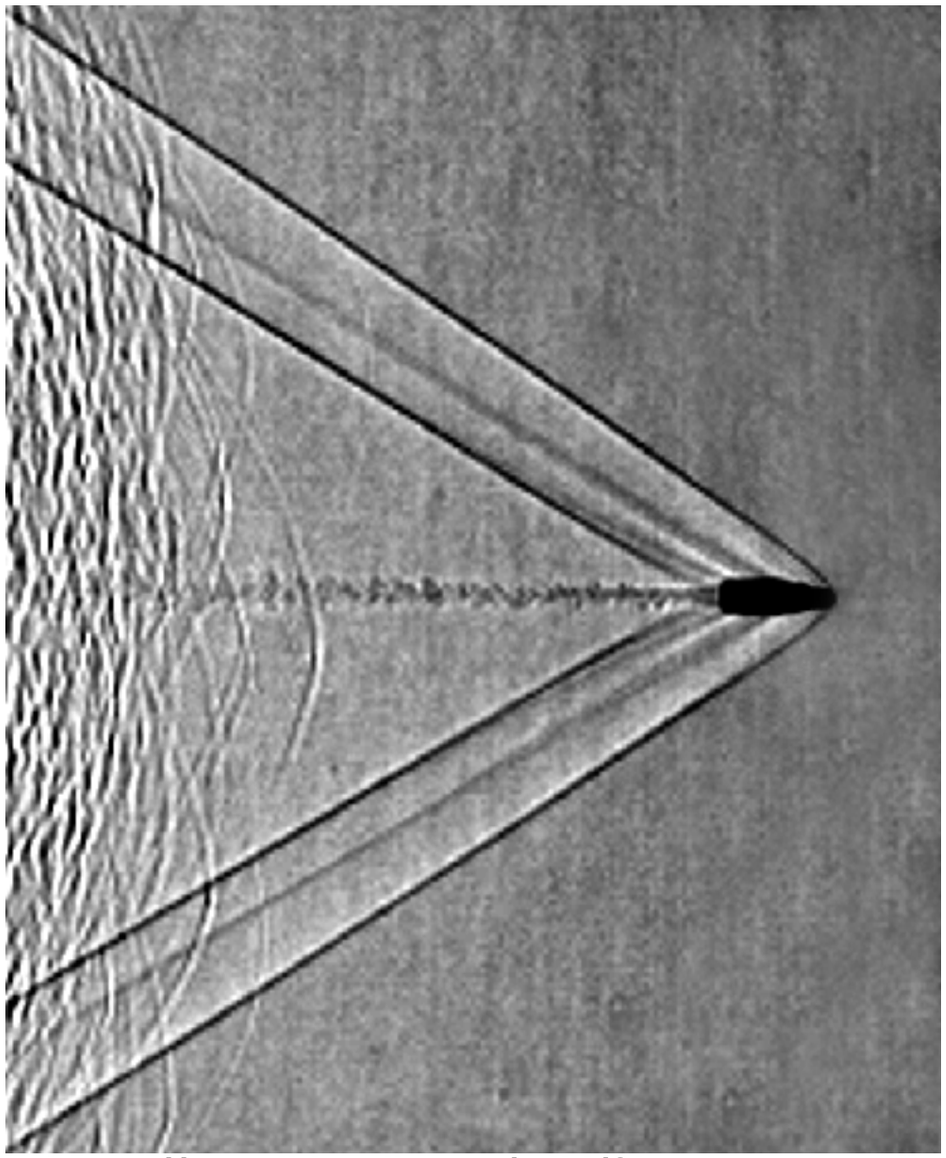


Jets with photons



Where Does Energy Go?

- If the plasma is such a good fluid:



https://en.wikipedia.org/wiki/Shock_wave

- We should see wakes!

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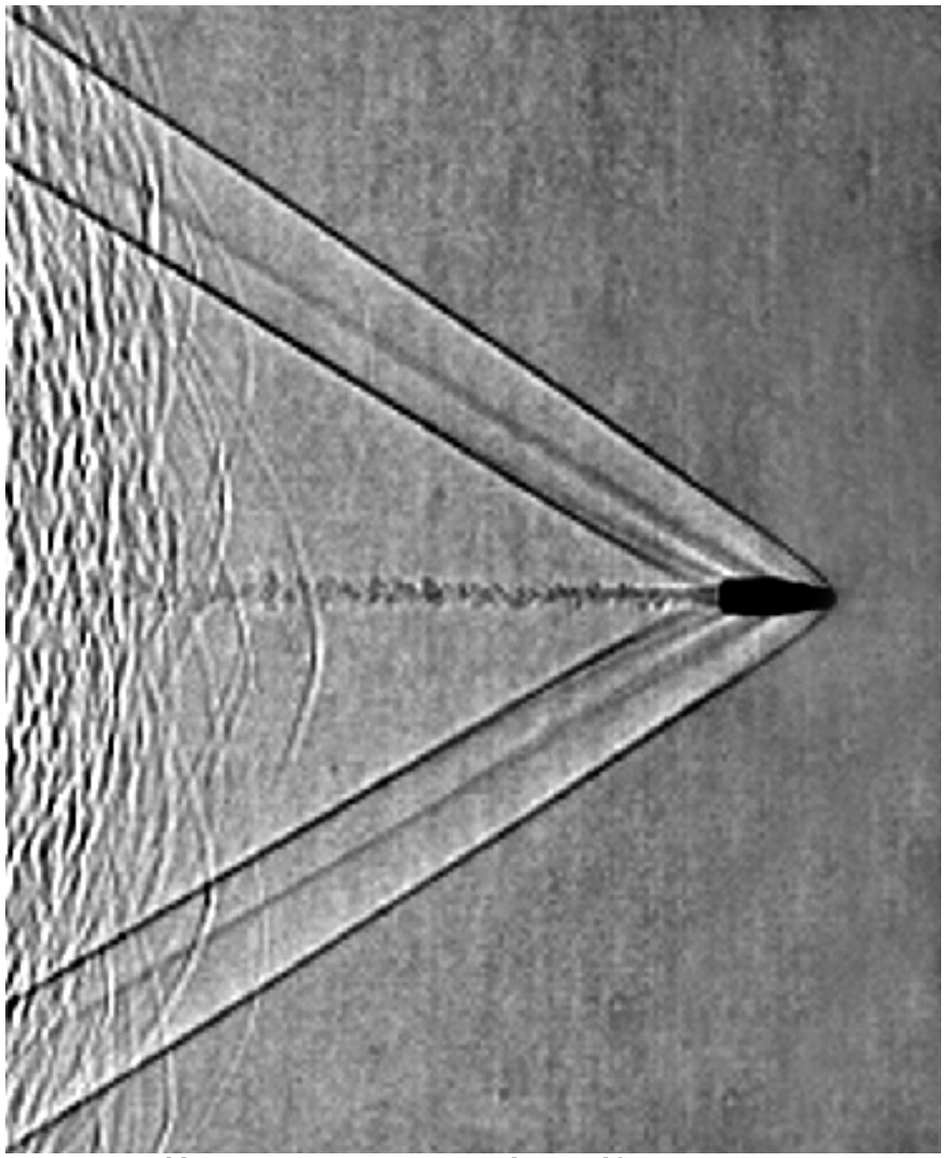

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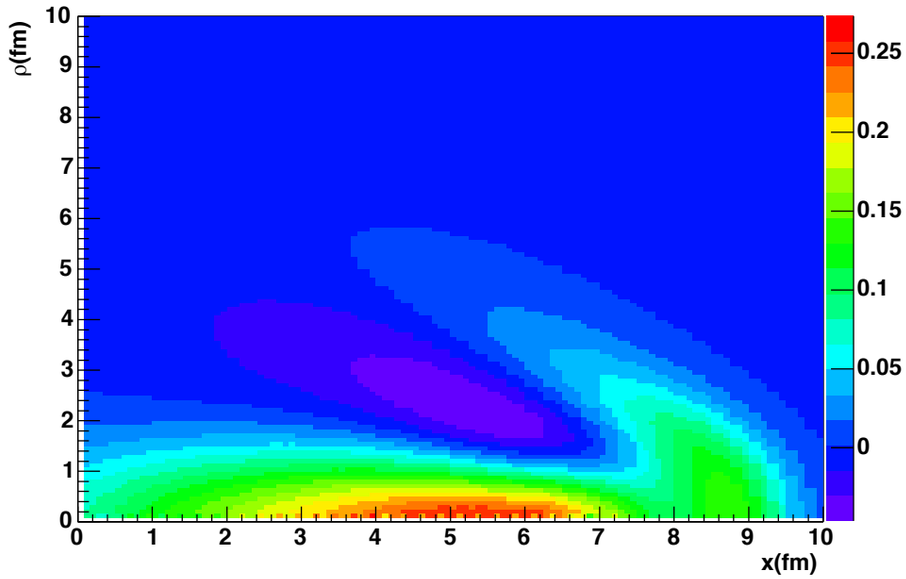

JCS, Teaney, Suryak 04

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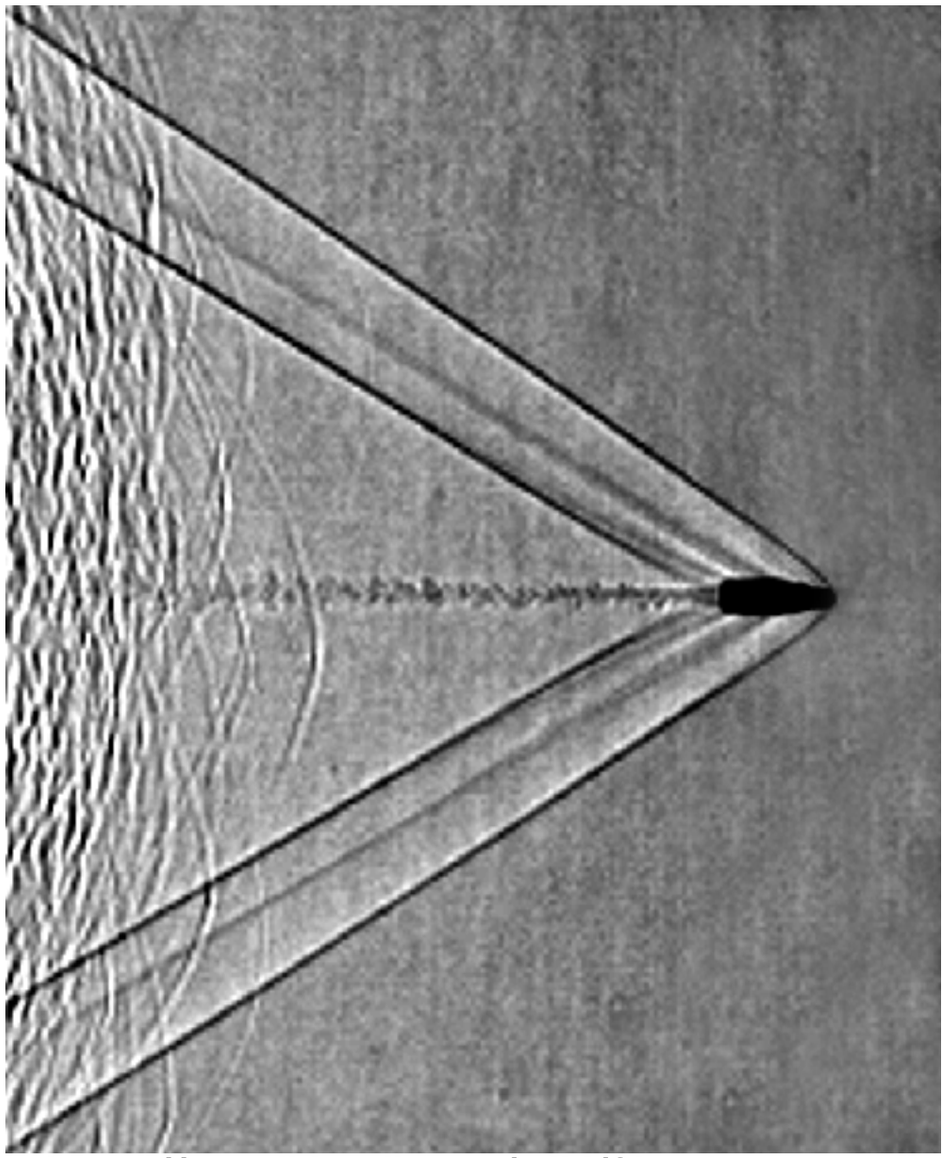

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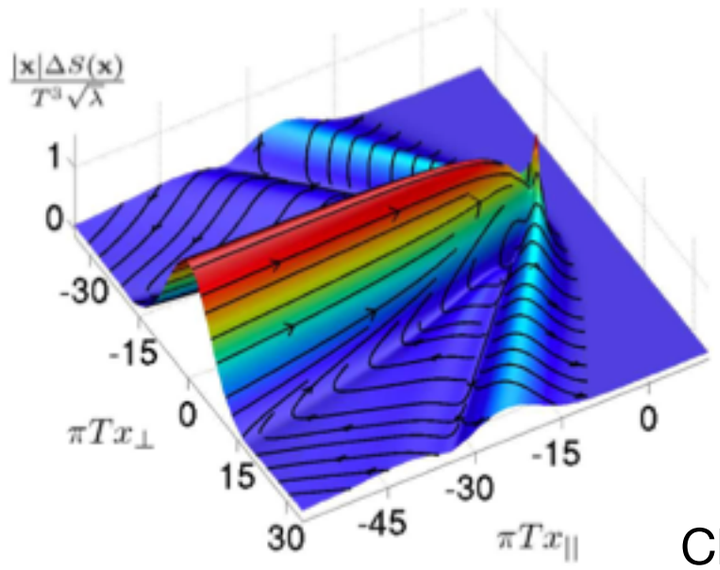

Chester & Yaffe 06

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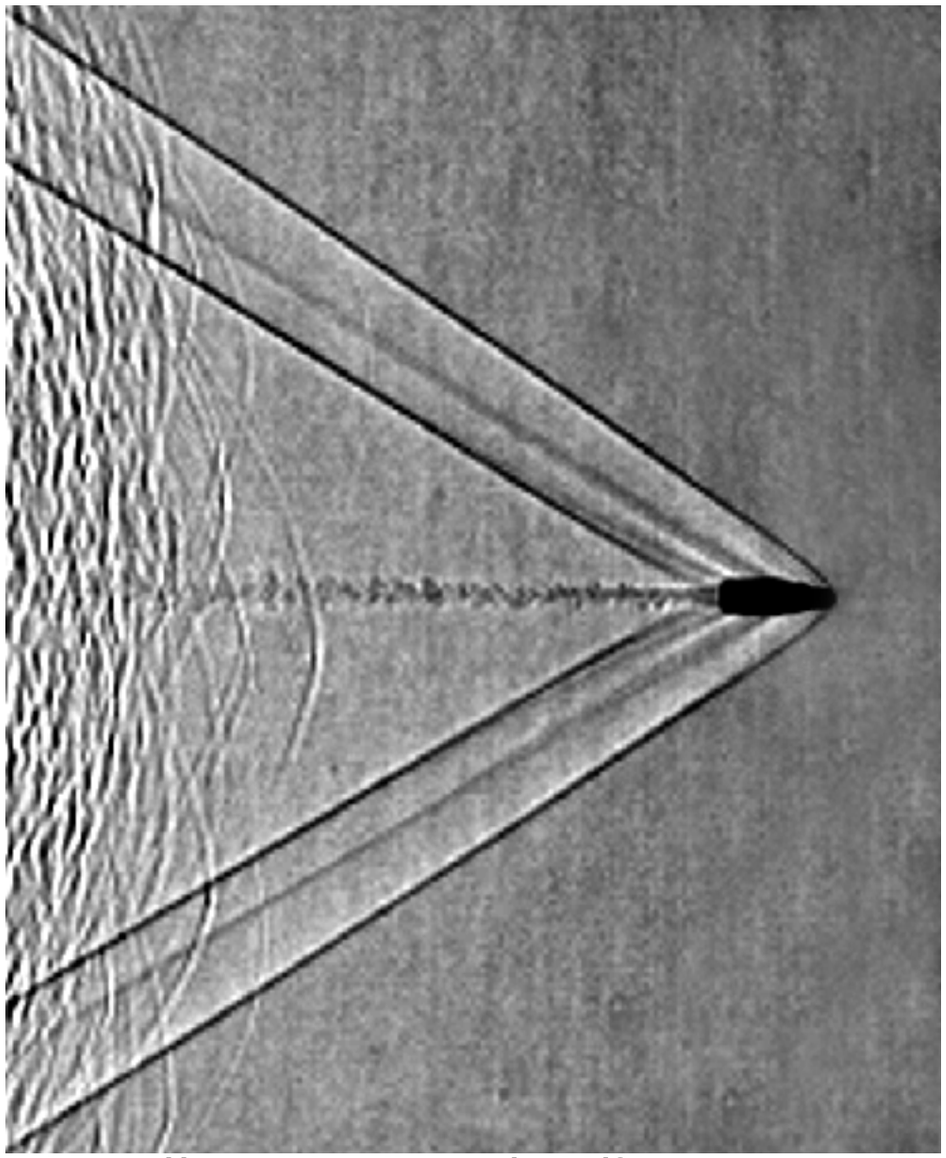

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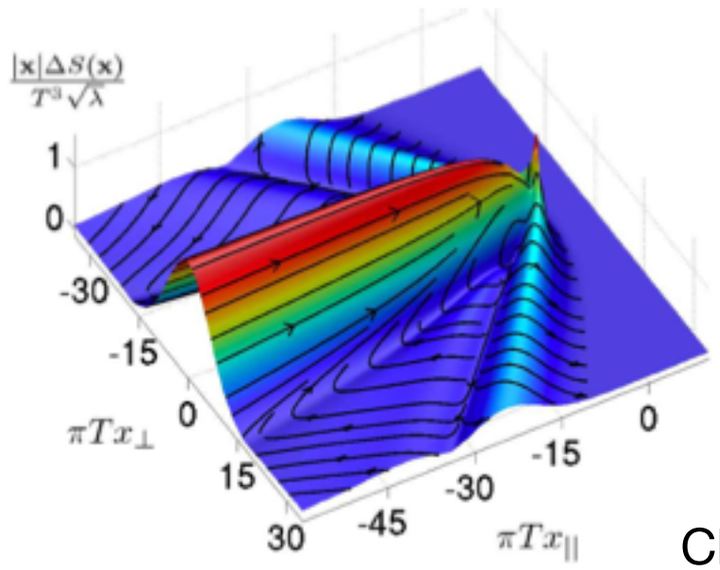
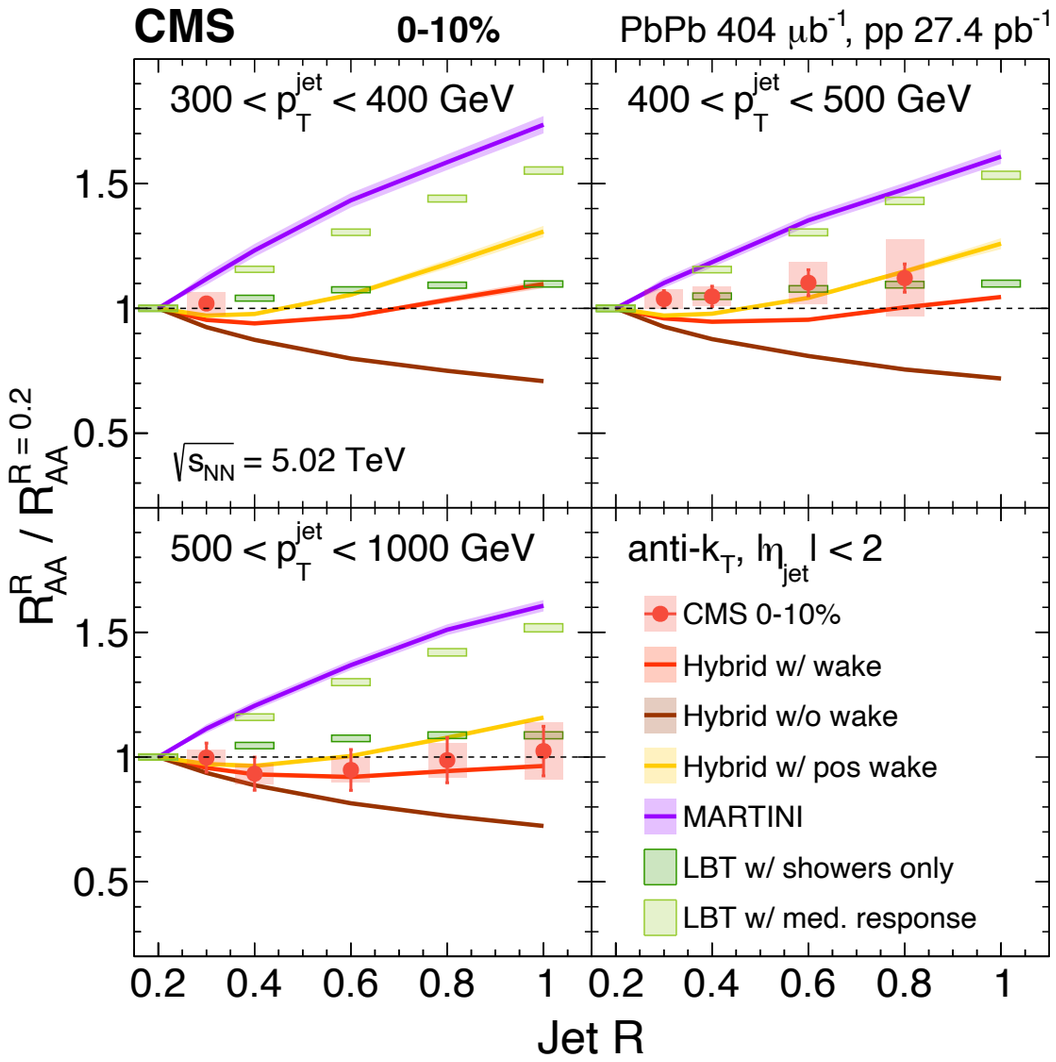


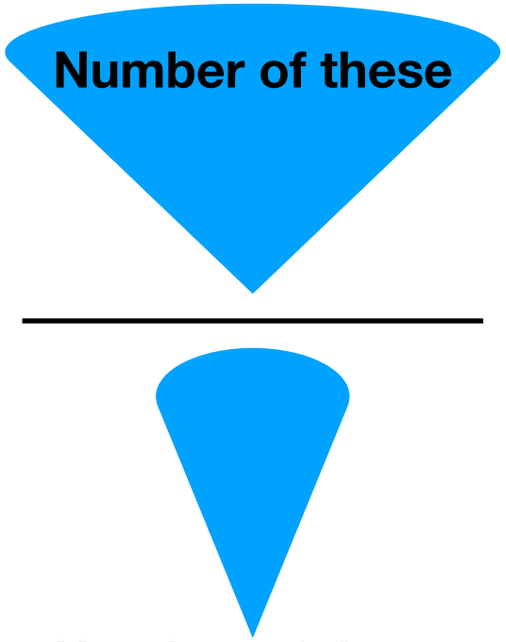
Chester & Yaffe 06

- A defining feature of our hybrid model

The wake was hiding

- Evidence for wakes was hard to extract from data.





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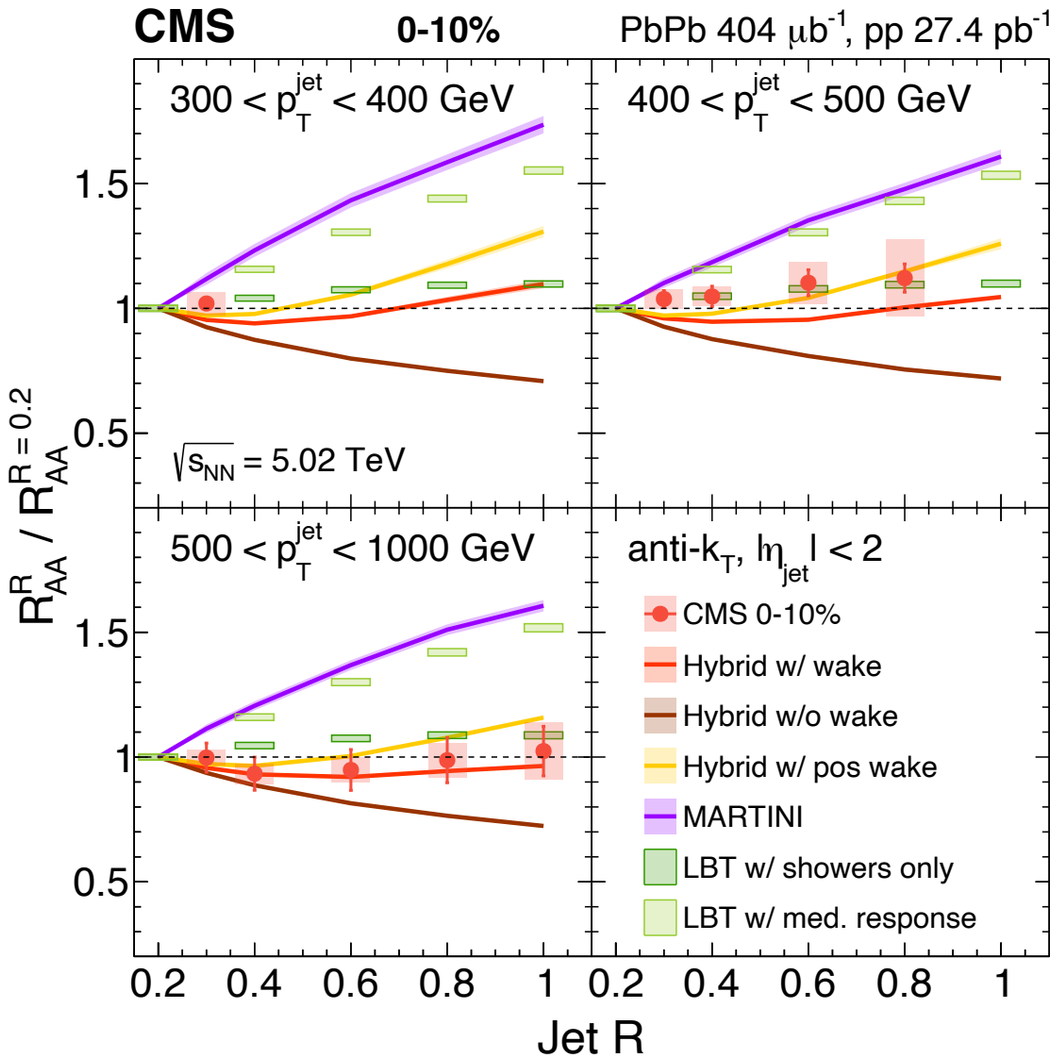
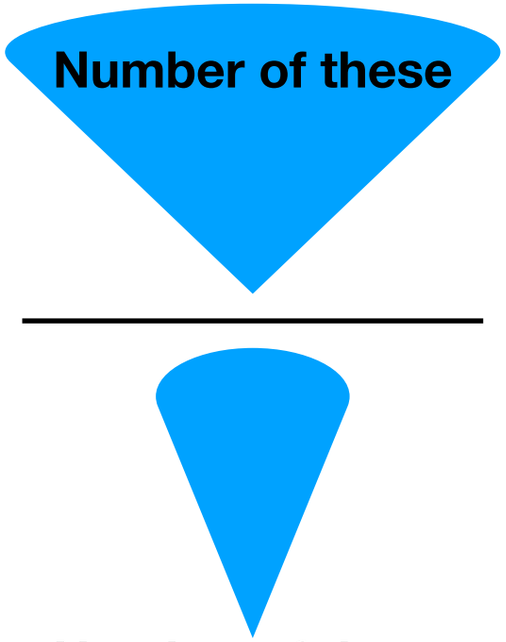
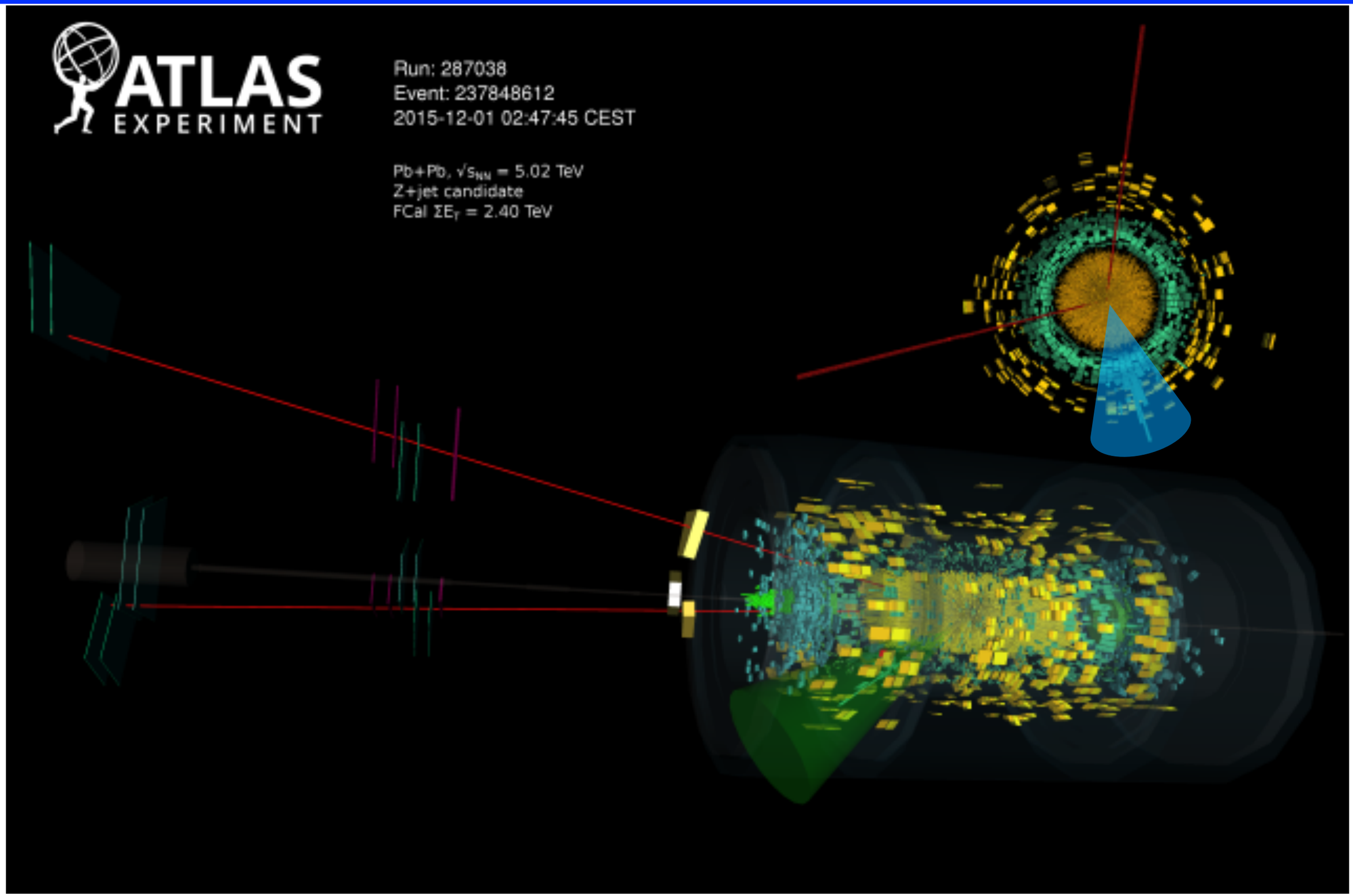


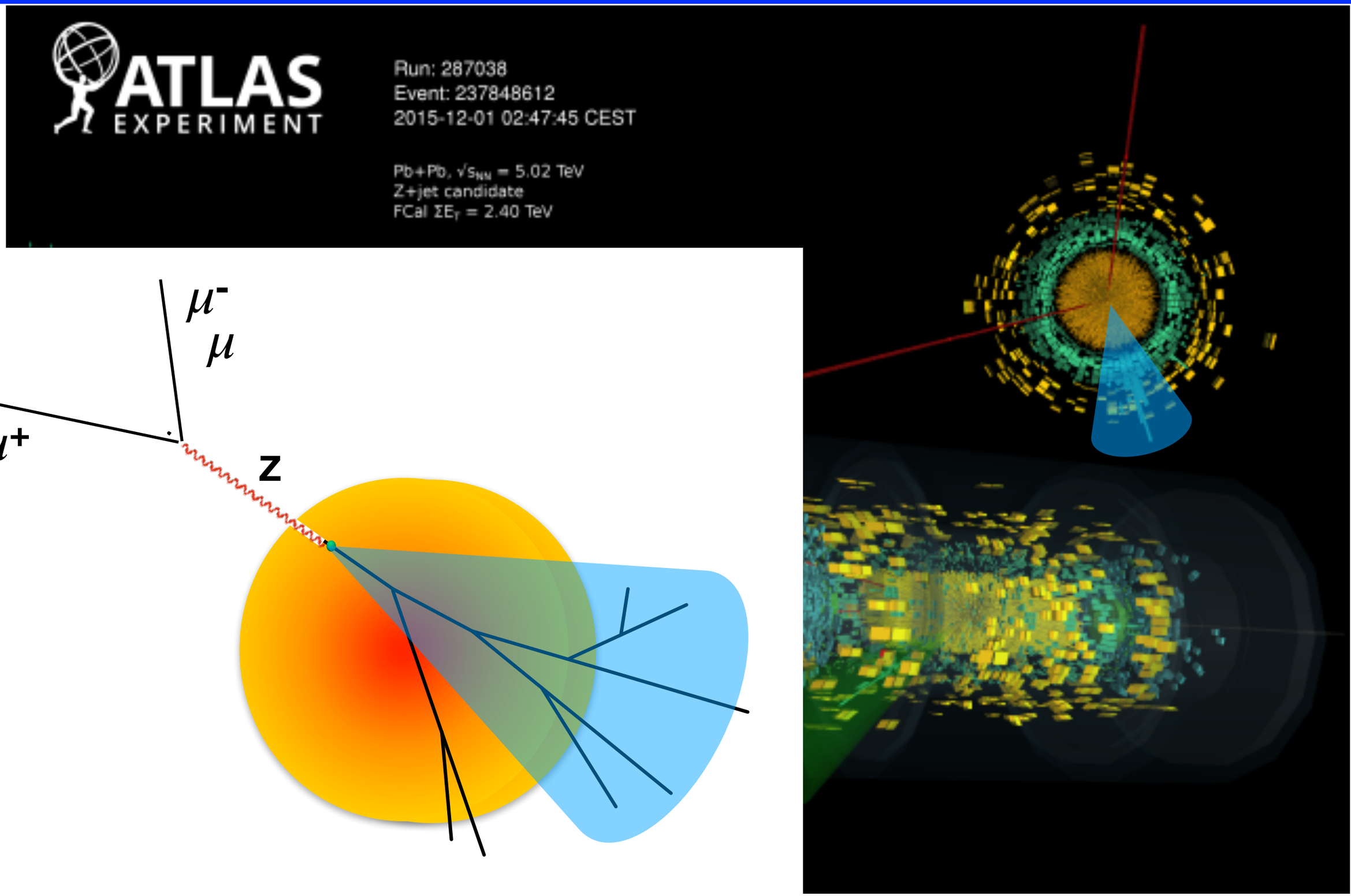


Until….

Z-jet


ATLAS
EXPERIMENT
Run: 287038
Event: 237848612
2015-12-01 02:47:45 CEST
Pb+Pb, √sNN = 5.02 TeV
Z+jet candidate
FCal ΣET = 2.40 TeV

Z-jet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Pb+Pb, √sNN = 5.02 TeV
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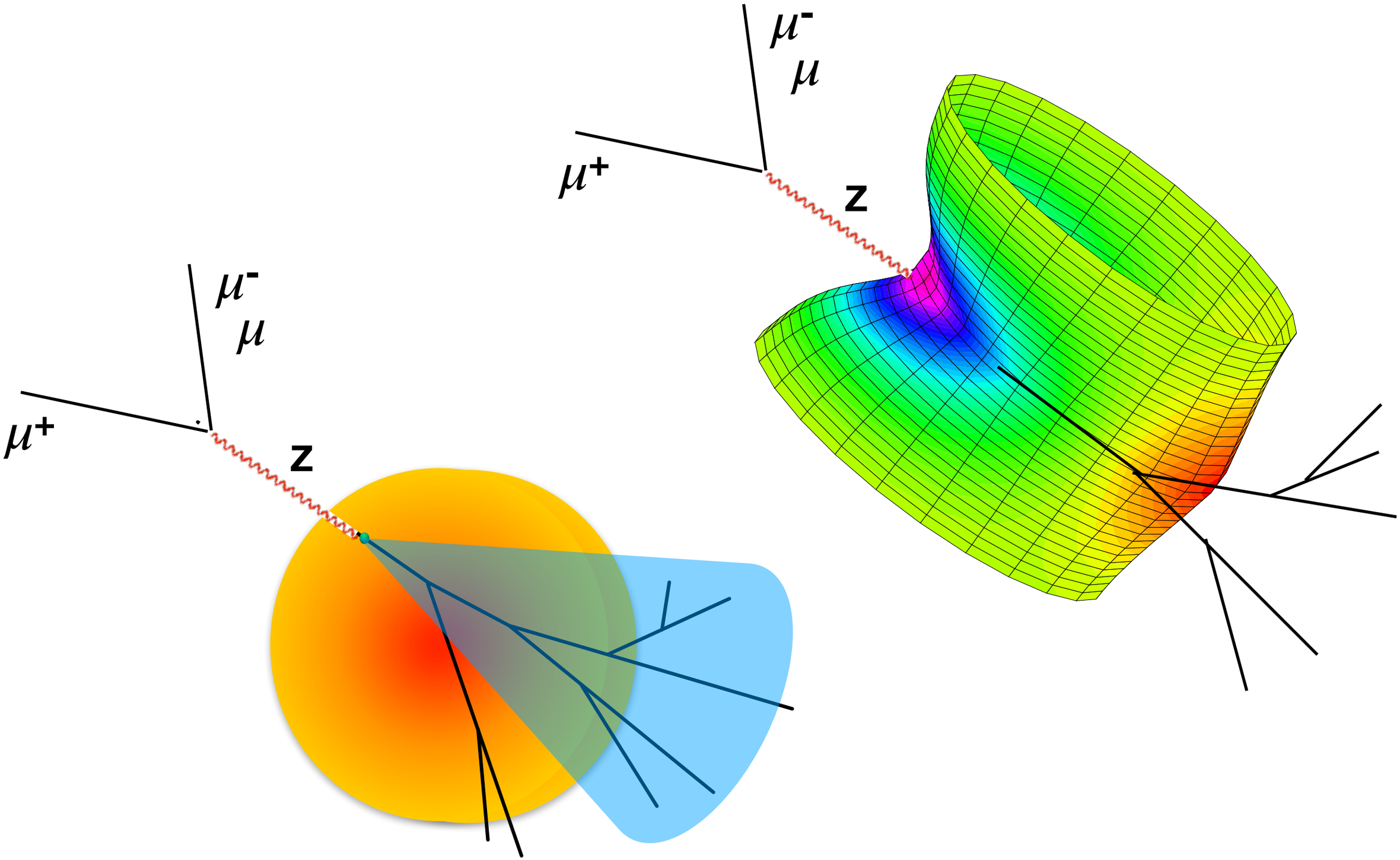
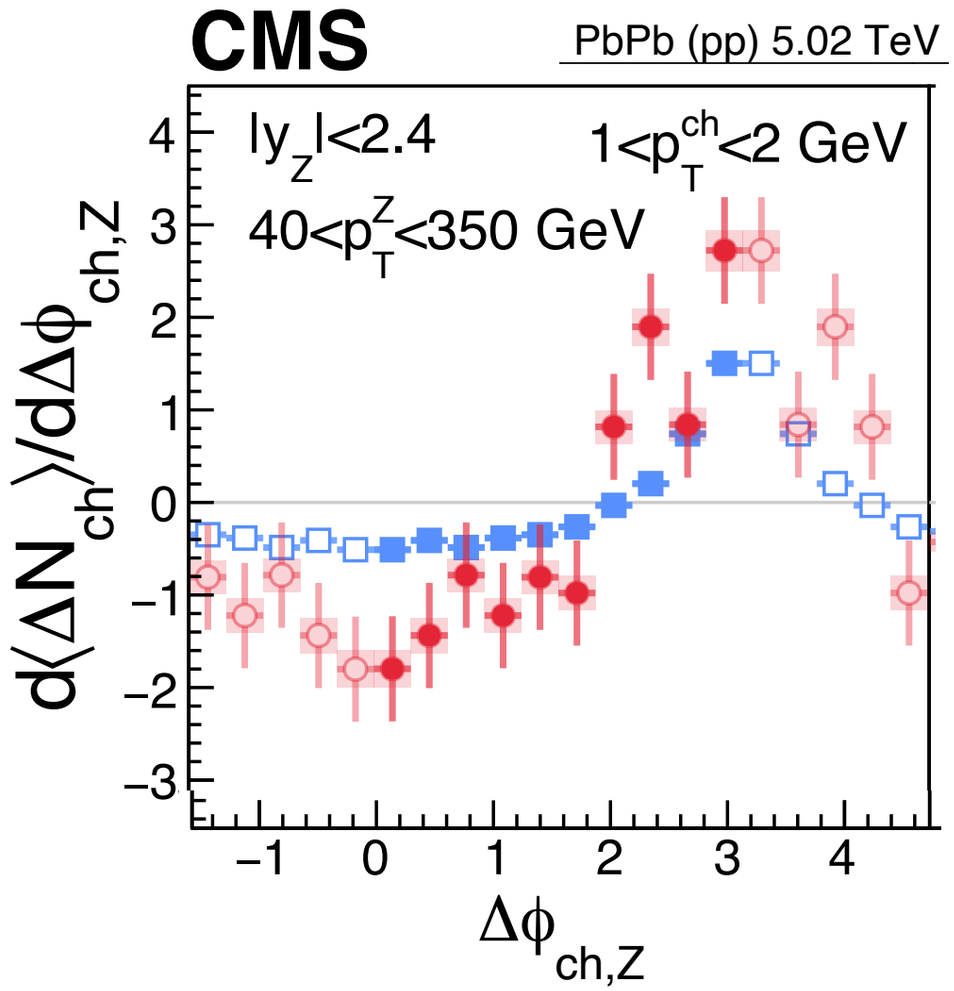
μ-
μ
μ+
Z

Fluid pushed by the jet



The Measurement

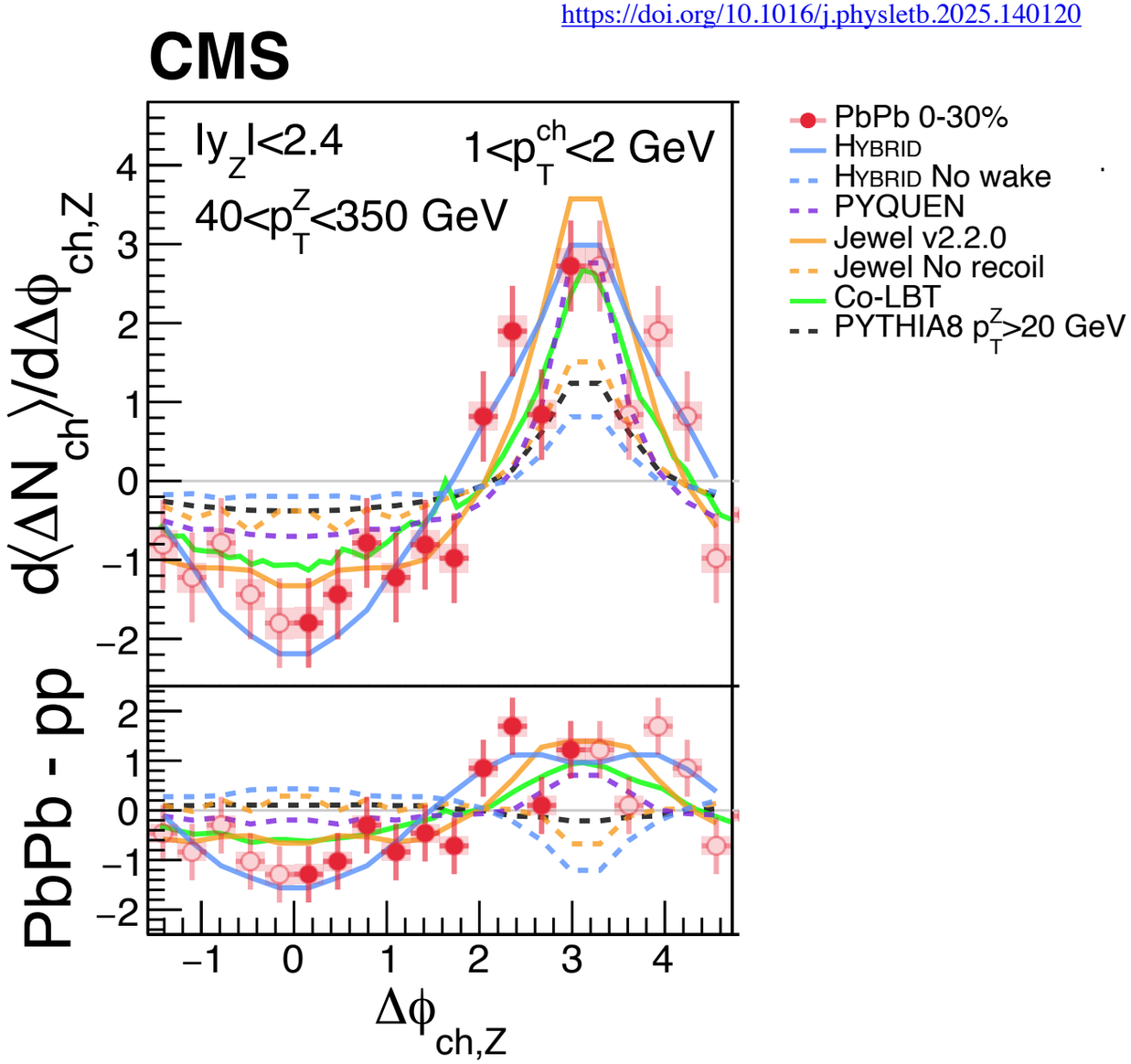
https://doi.org/10.1016/j.physletb.2025.140120



Fewer particles produced on the Z side

The Prediction

https://doi.org/10.1016/j.physletb.2025.140120



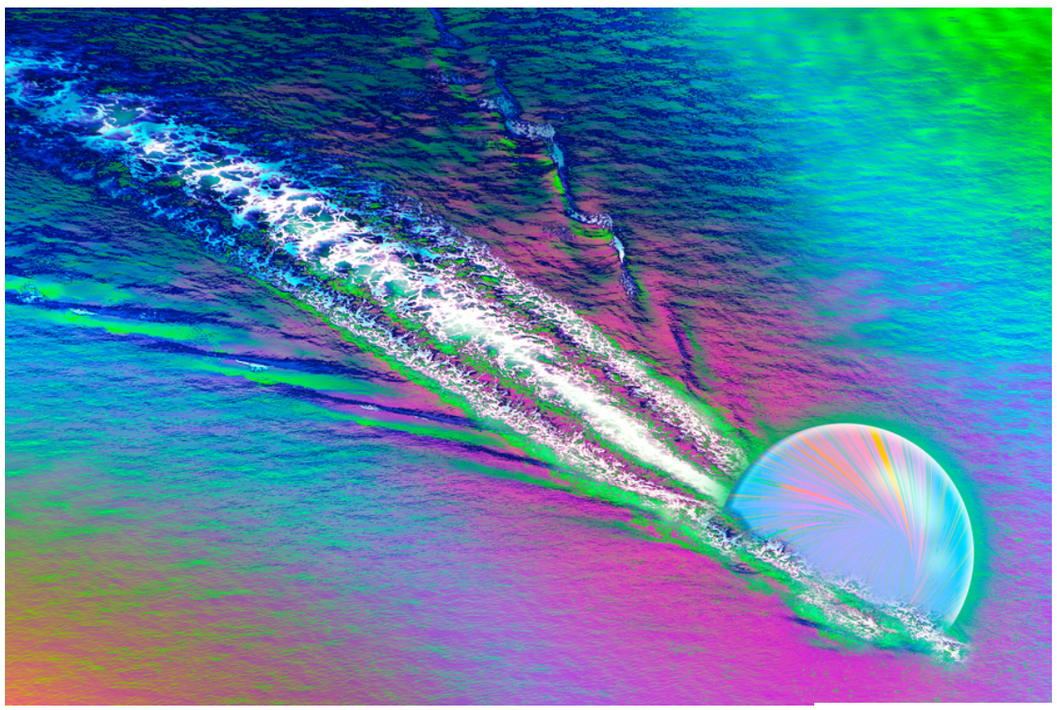
Direct measurement of the wake

MIT News
ON CAMPUS AND AROUND THE WORLD

Study: The infant universe's "primordial soup" was actually soupy

MIT physicists observed the first clear evidence that quarks create a wake as they speed through quark-gluon plasma, confirming the plasma behaves like a liquid.

Jennifer Chu | MIT News
January 28, 2026



Credit: Jose-Luis Olivares, MIT

We Found It — Now What?

- New flow signature beyond azimuthal flow
  - Sensitive to different sizes (partonic)
  - A harder challenge for hydrodynamics
  - They probe thermalization in a new regime
  - Characterizing wakes leads to different constraints on viscosities
    - Fast, detailed simulations will be crucial to unlock its physics.