# Emergent QCD phenomena at the LHC and connections to EIC physics

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Rice University

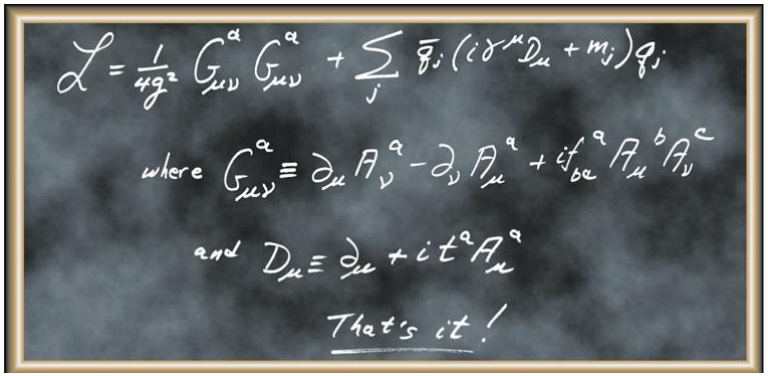
Workshop on Physics Connections between LHC and EIC
Fermilab LPC, November 13-15, 2019

# QCD: a fundamental theory of strong force

*Quarks (and Glue) at the Frontiers of Knowledge*

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

– Frank Wilczek, Quark Matter 2014



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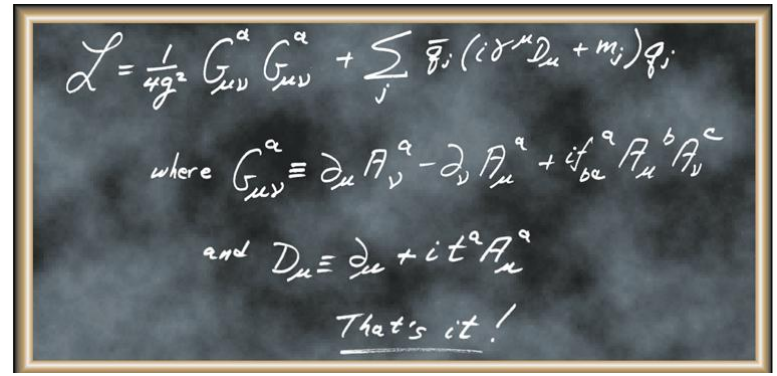
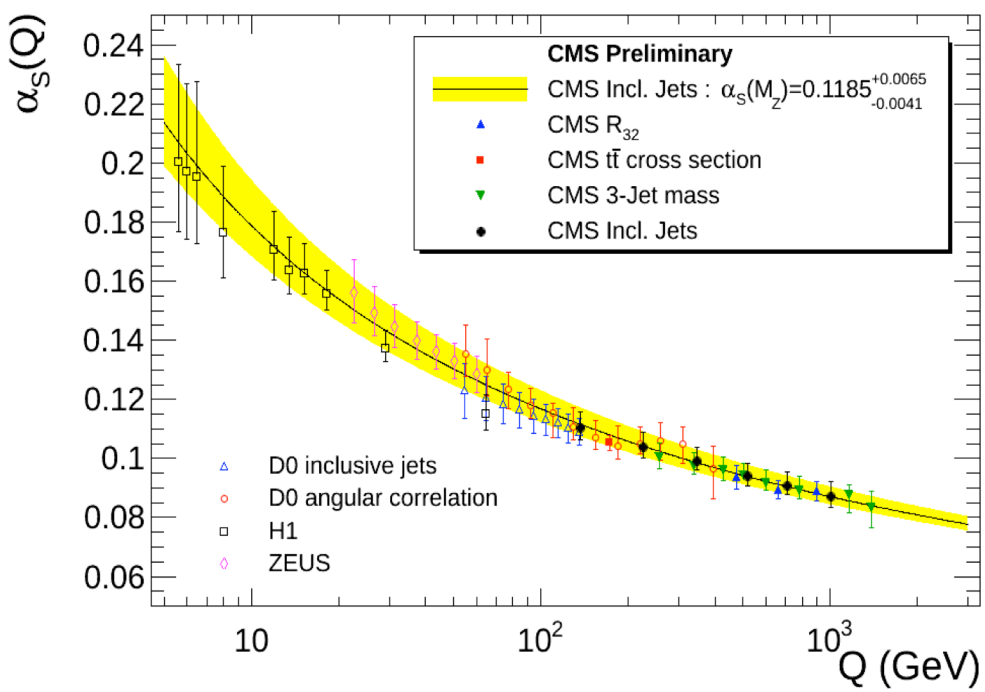
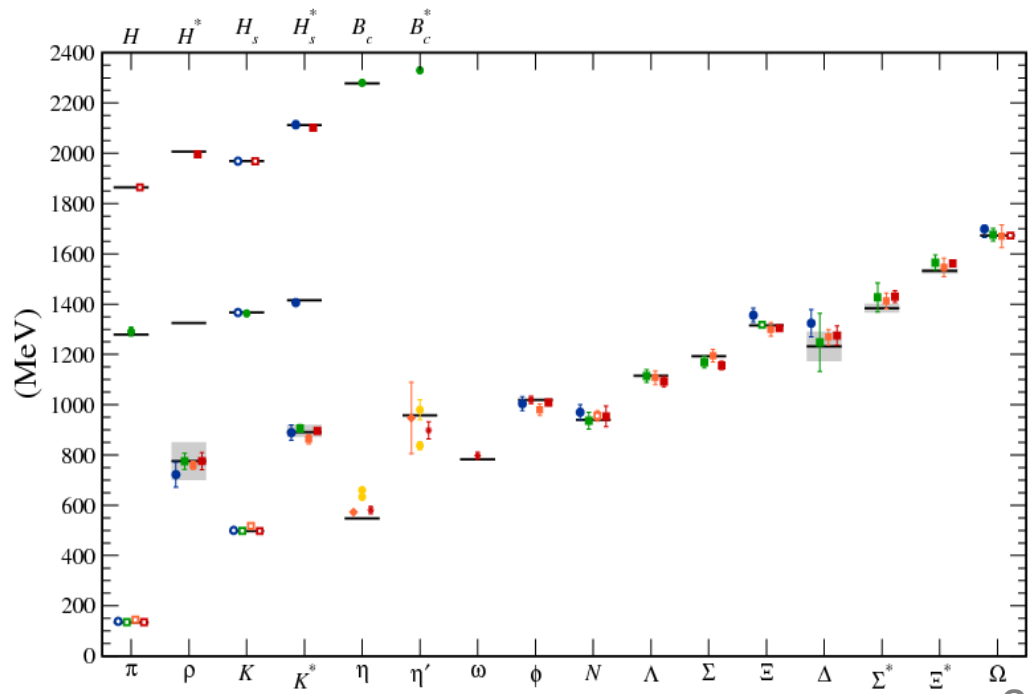



## Perturbative

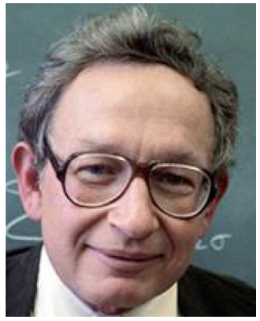



## Lattice calculations



# Emergent phenomena

*"More is different"* – P. W. Anderson



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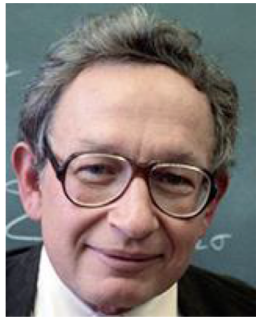

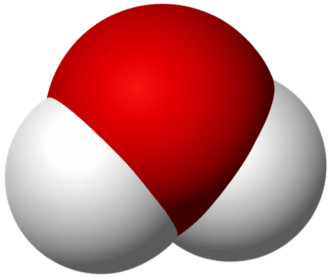

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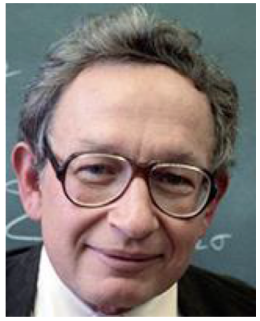

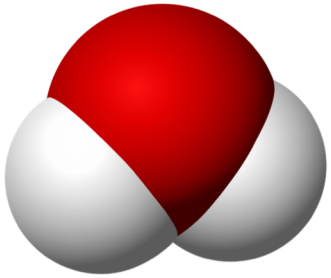

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000,000,000,000 =

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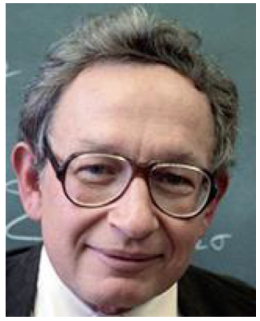

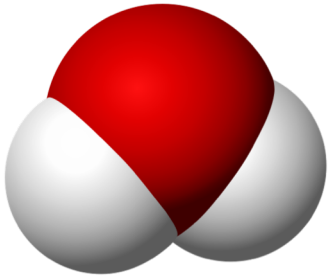

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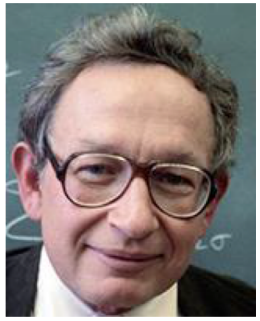

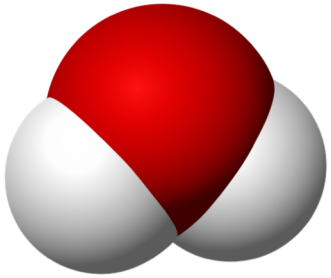

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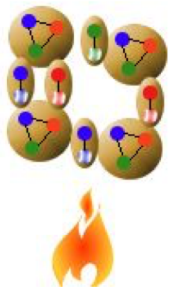
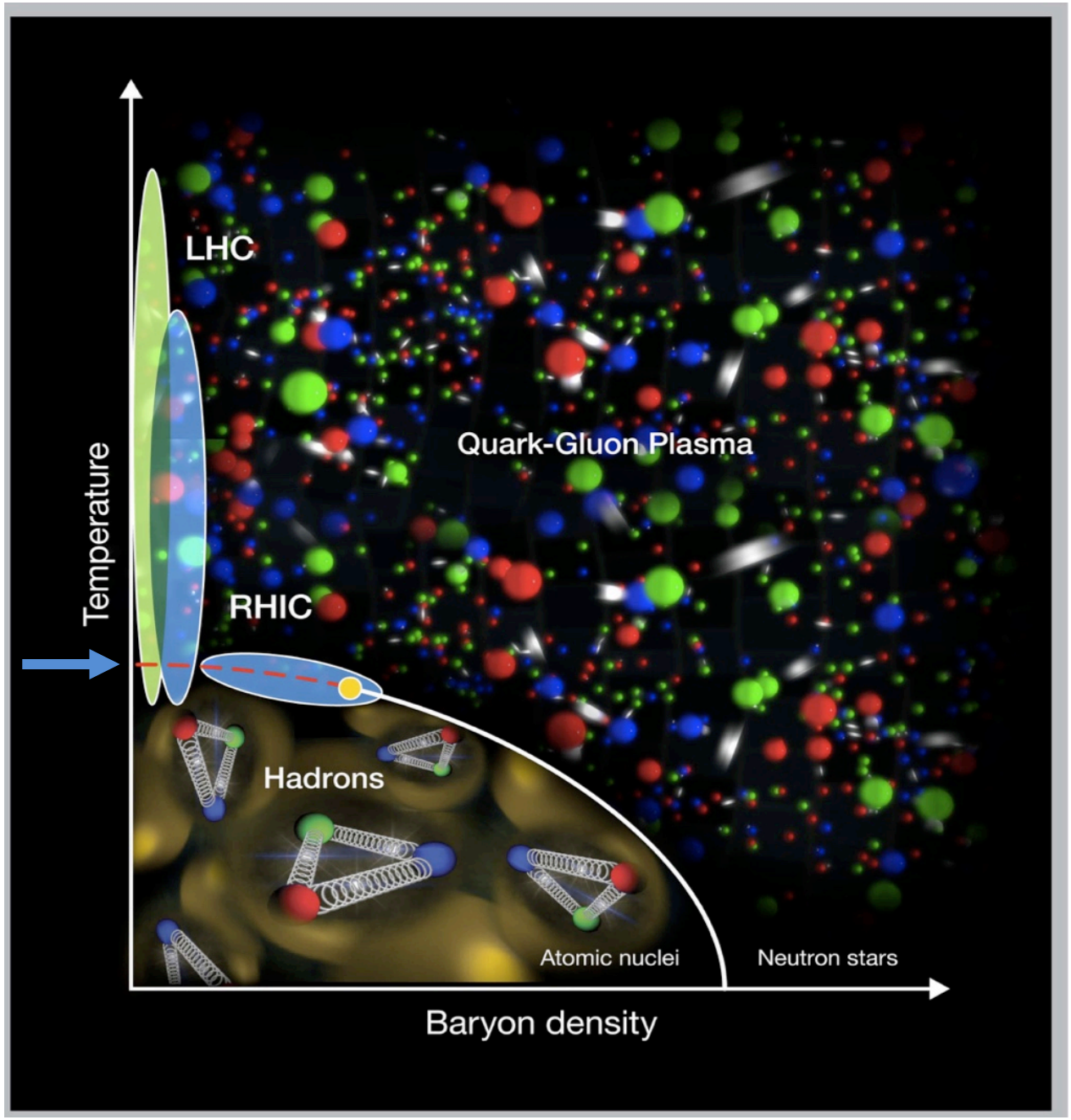
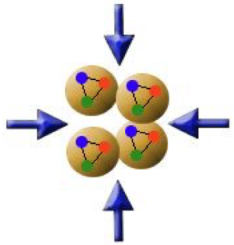
Search for and study new emergent phenomena of many-body QCD system are just as fundamental!

# Phases of many-body QCD systems



$T_C \sim 154$ MeV
(Lattice QCD)



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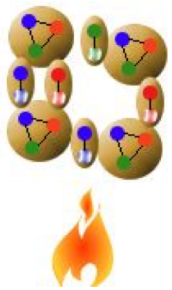

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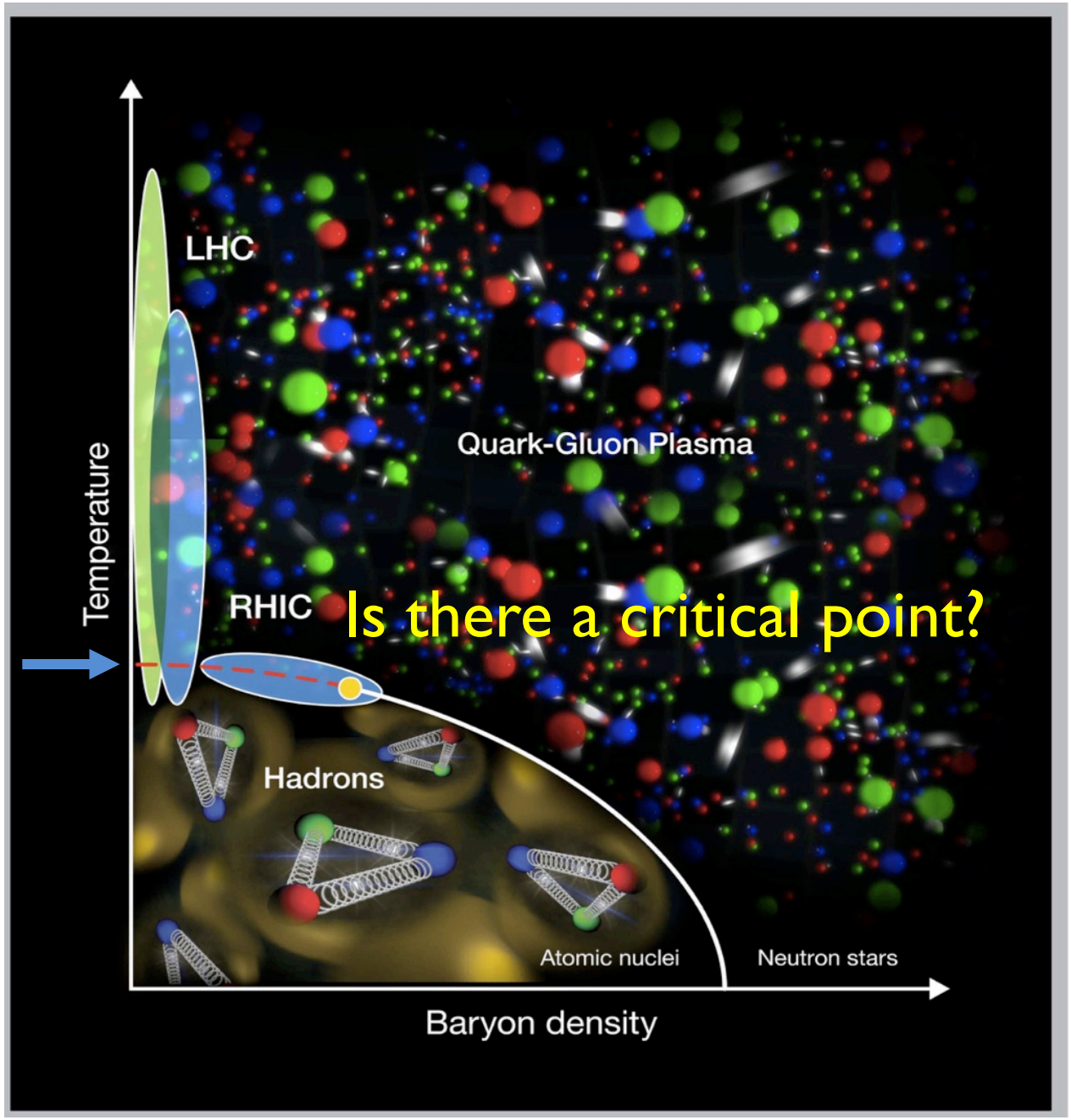


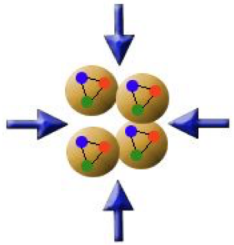

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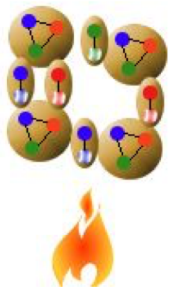

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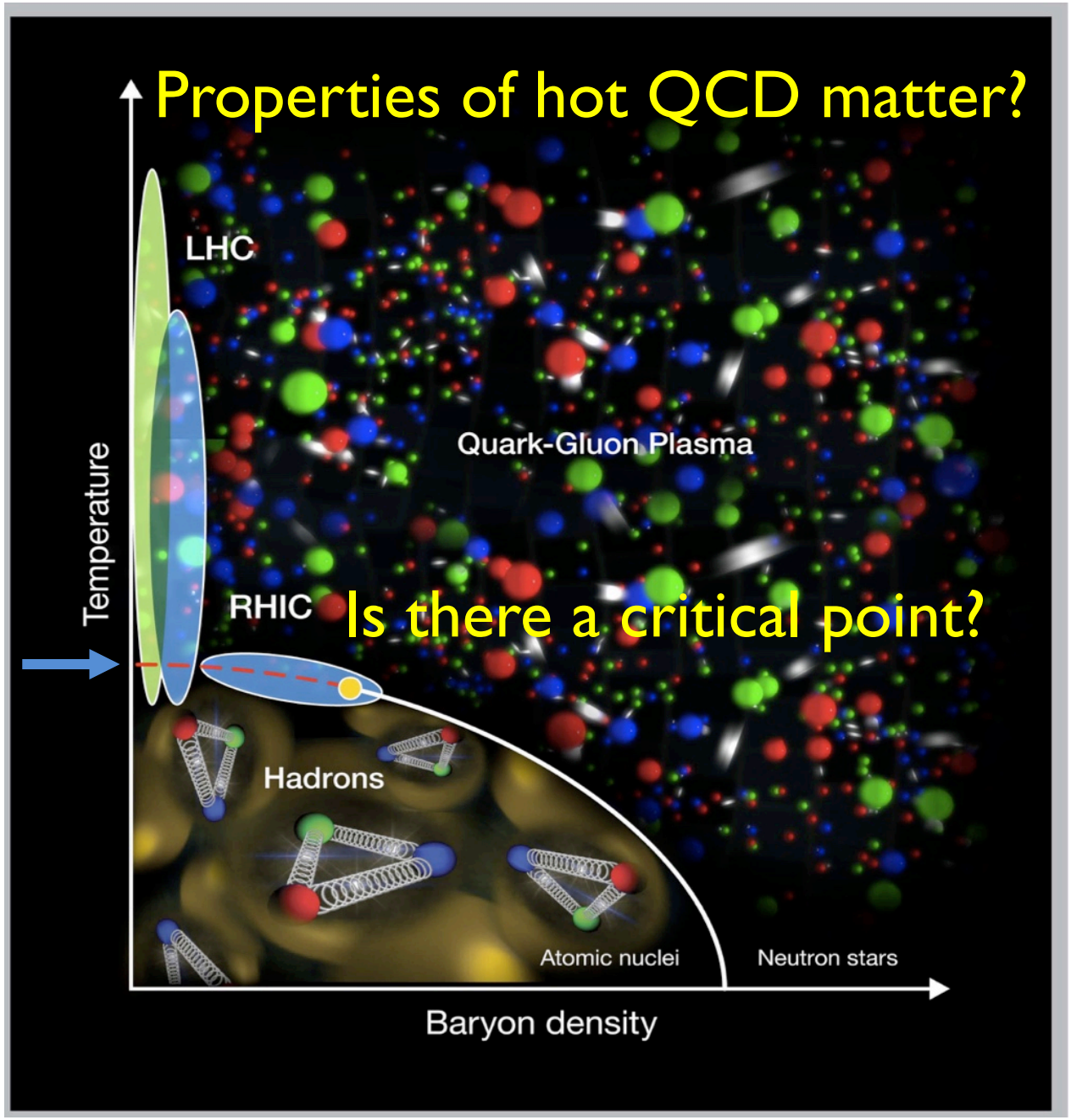
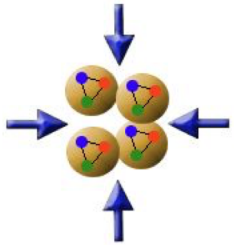
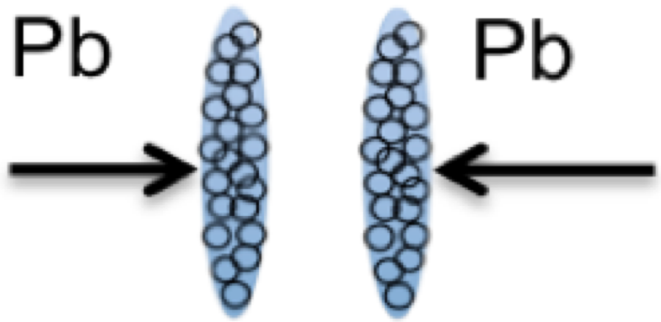


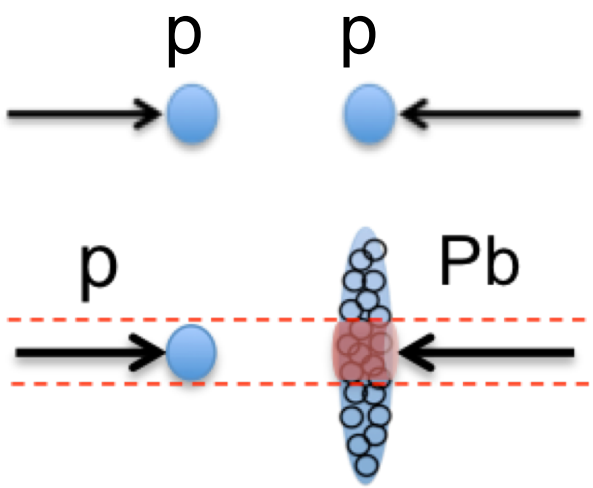
# Creating the hot QCD matter

"Large" systems




Hot QCD Matter – QGP

"Small" systems



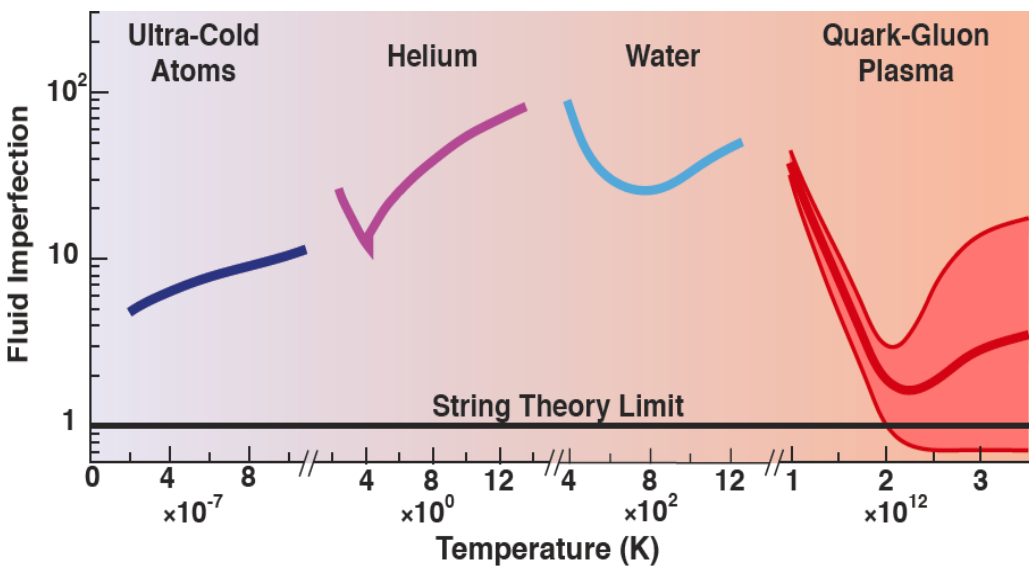

also ep, eA, $e^+e^-$

Cold QCD – reference

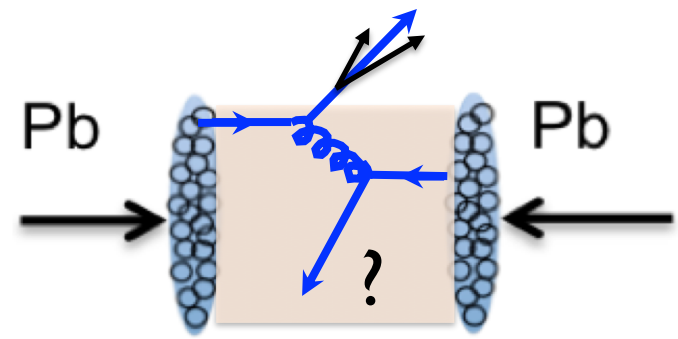
boring …

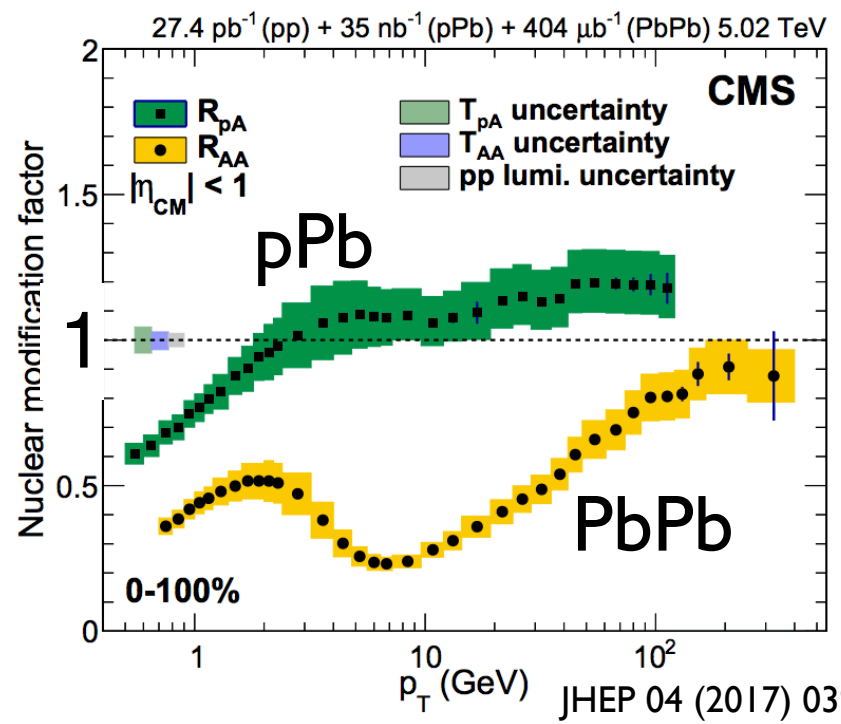
# Discovery of strongly coupled QGP

- QGP flows frictionless, as a <u>nearly perfect liquid</u>




- QGP is very opaque to color-charged particles

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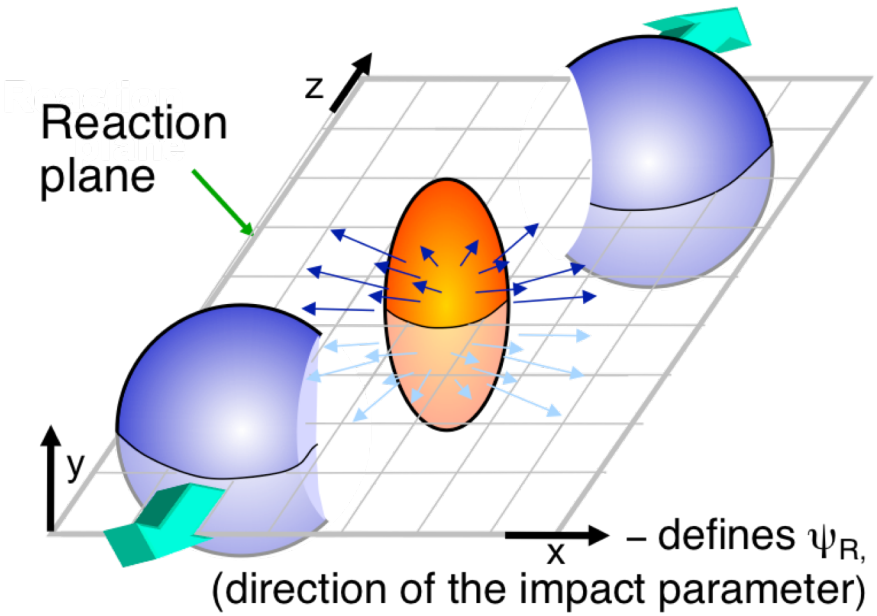
# Perfect QGP fluid Paradigm

Off-center AA collision

*Geometry! Geometry! Geometry!*



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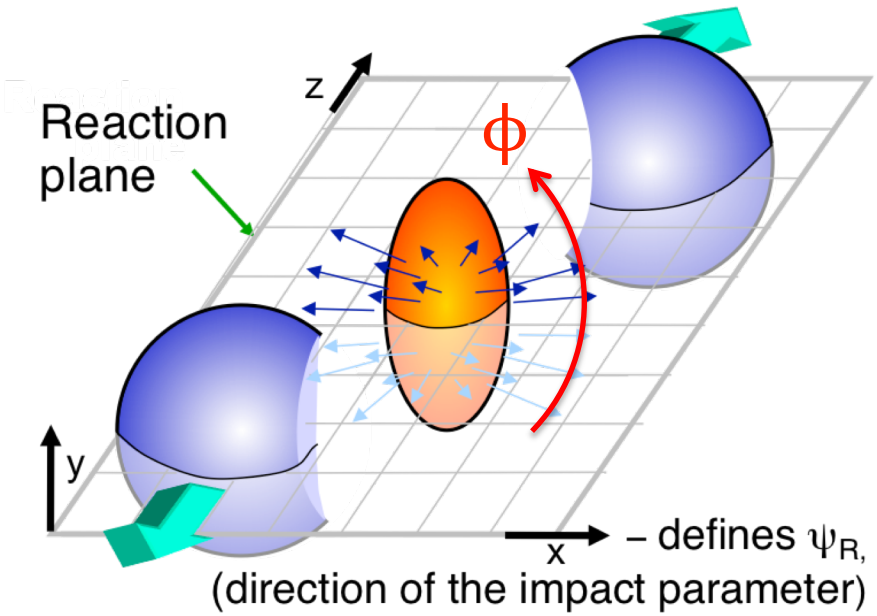

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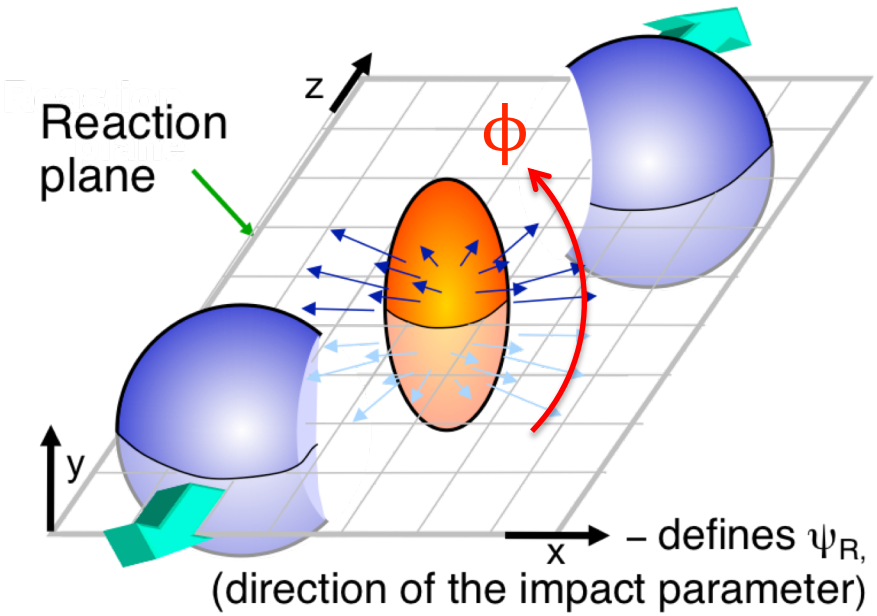
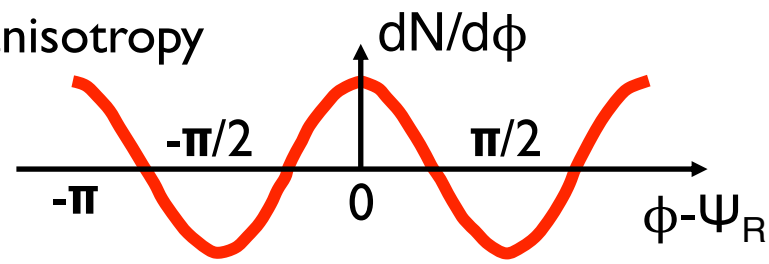



Hydrodynamic expansion

Momentum anisotropy




$$\sim 1 + 2\, v_2 \cos[2(\phi - \Psi_R)]$$

– "elliptic flow"

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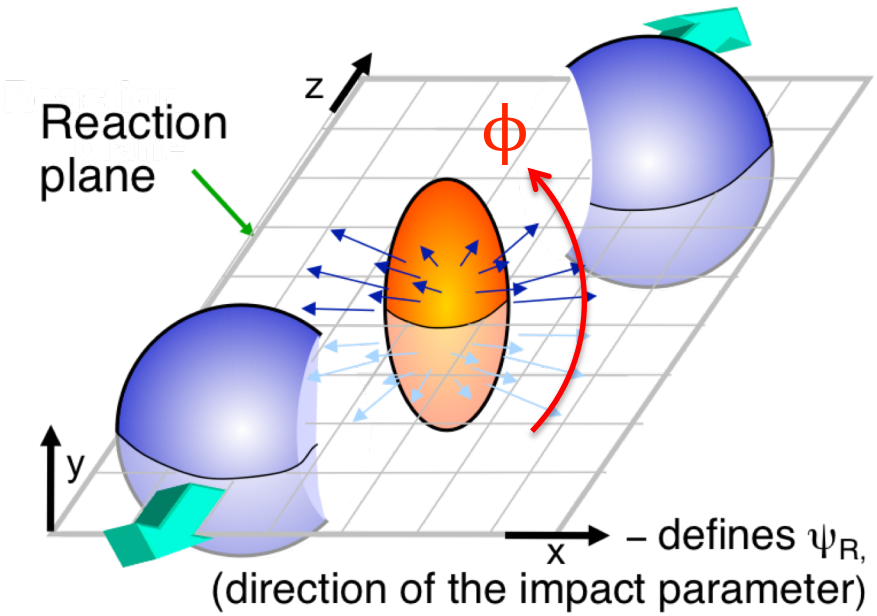


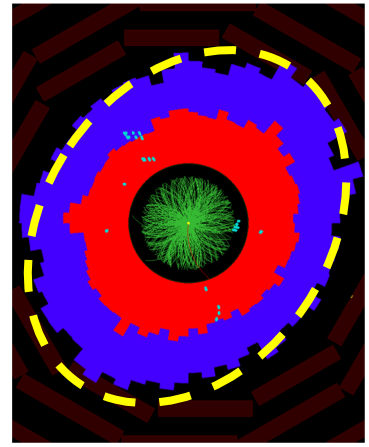

CMS event display

Hydrodynamic expansion

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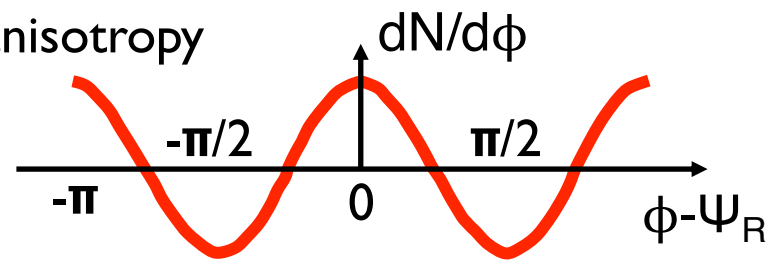


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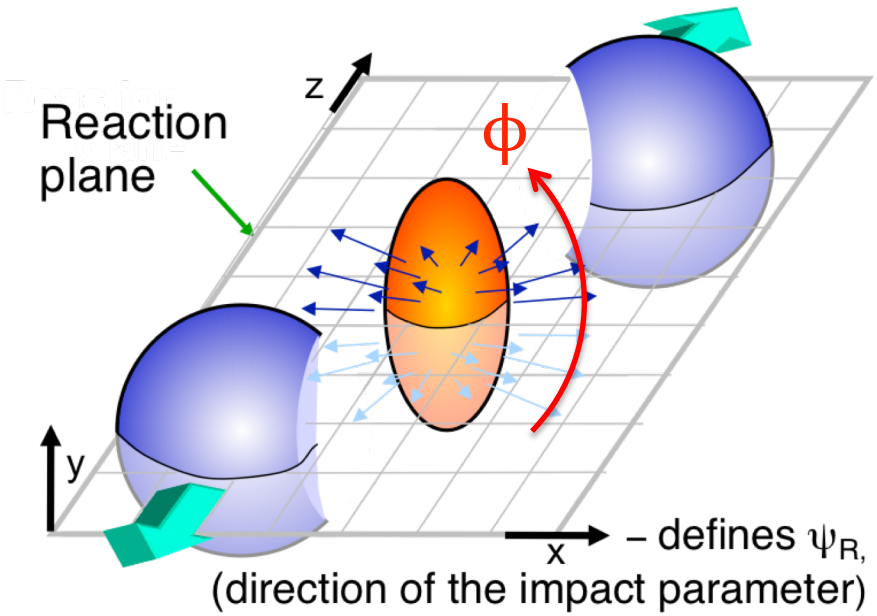


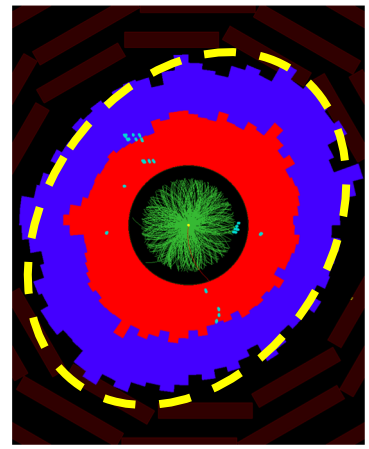

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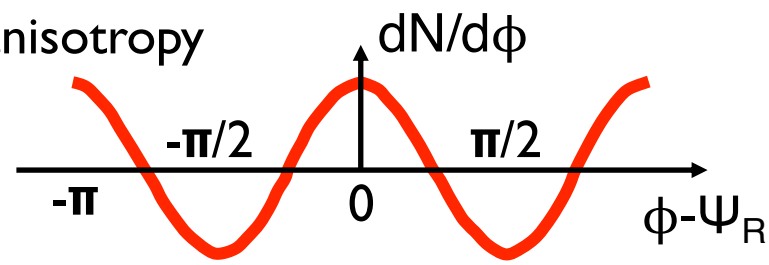


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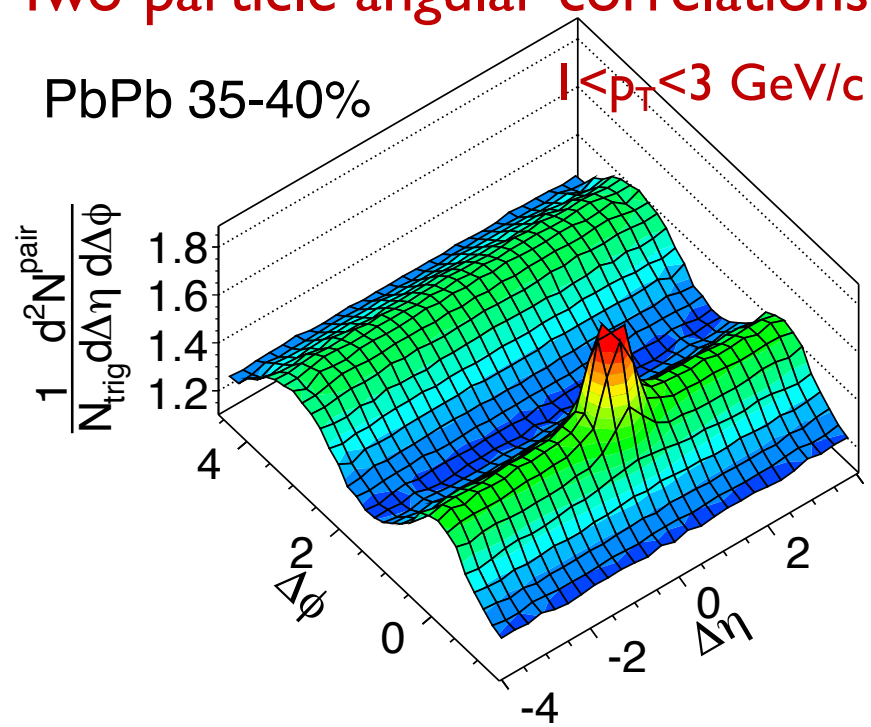
Two-particle angular correlations



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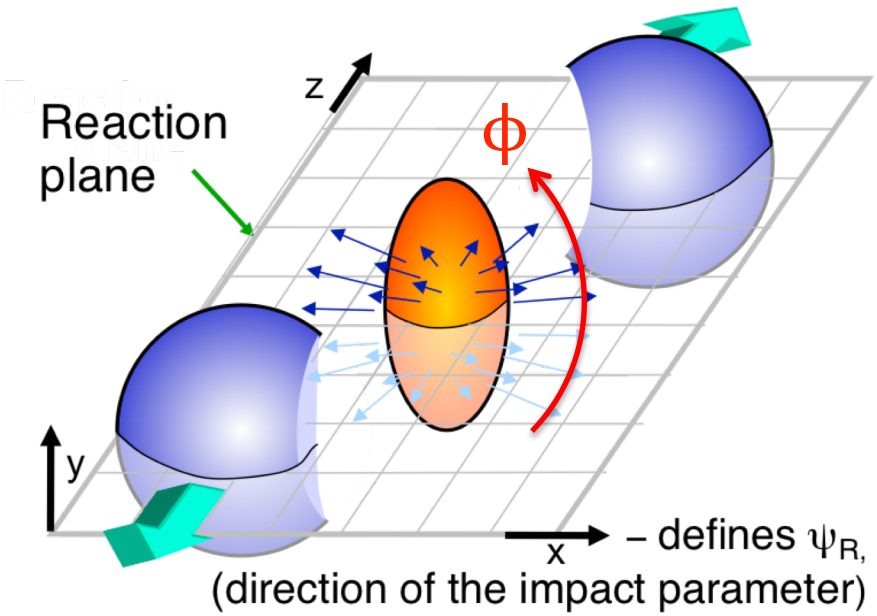


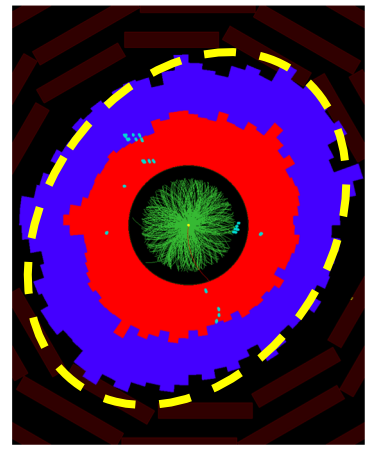

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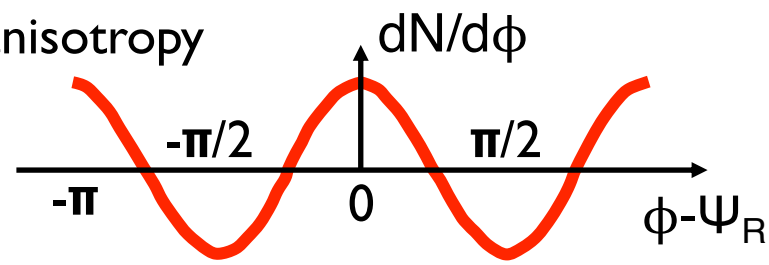


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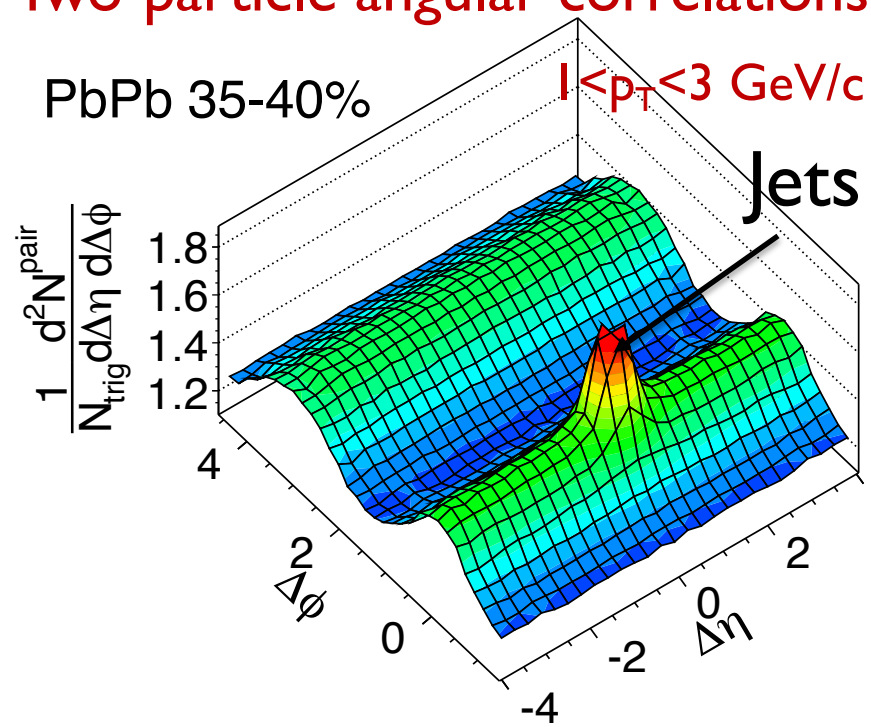

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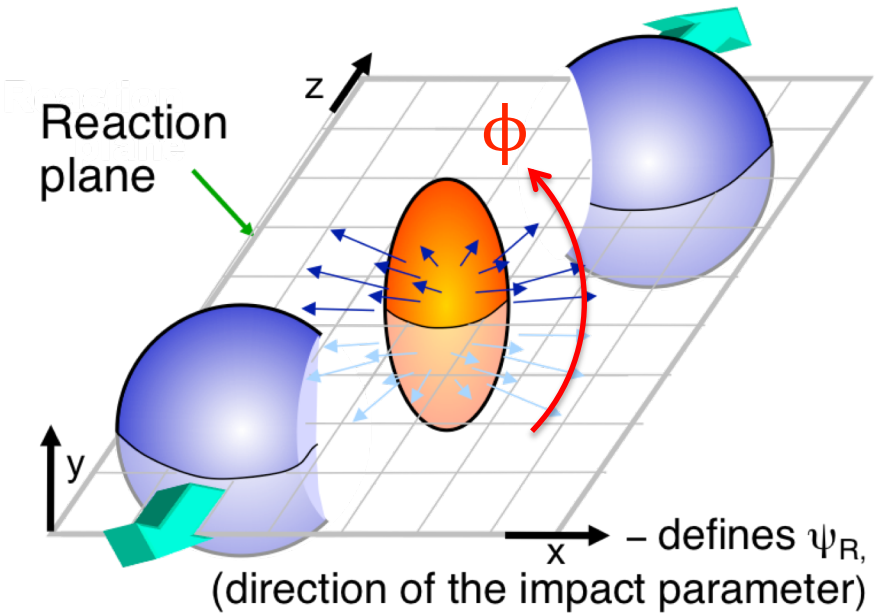


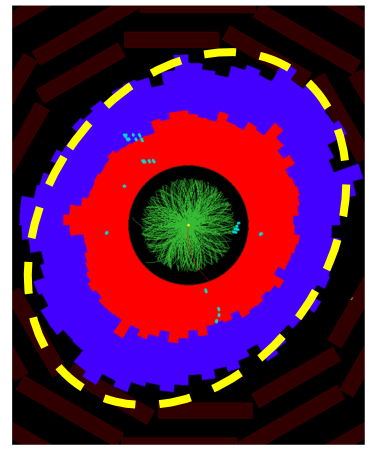

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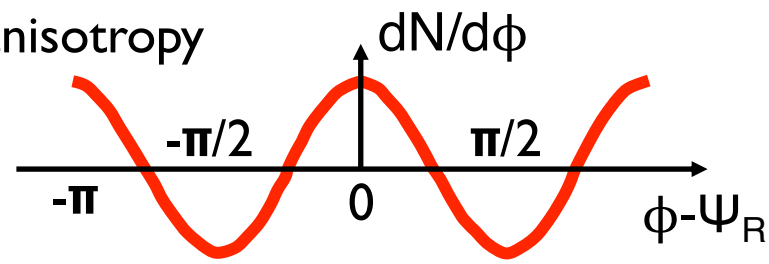


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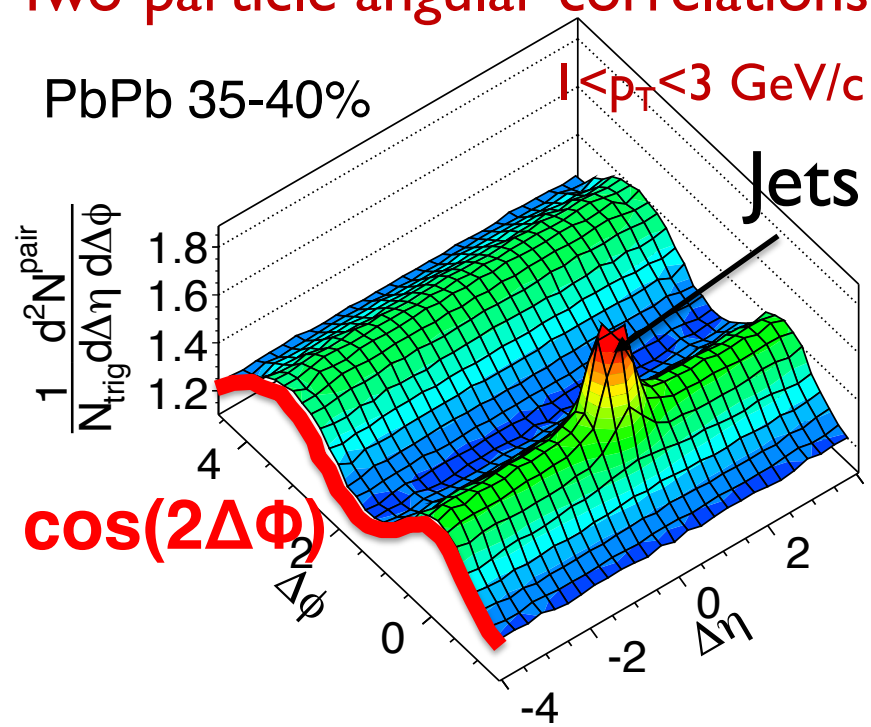

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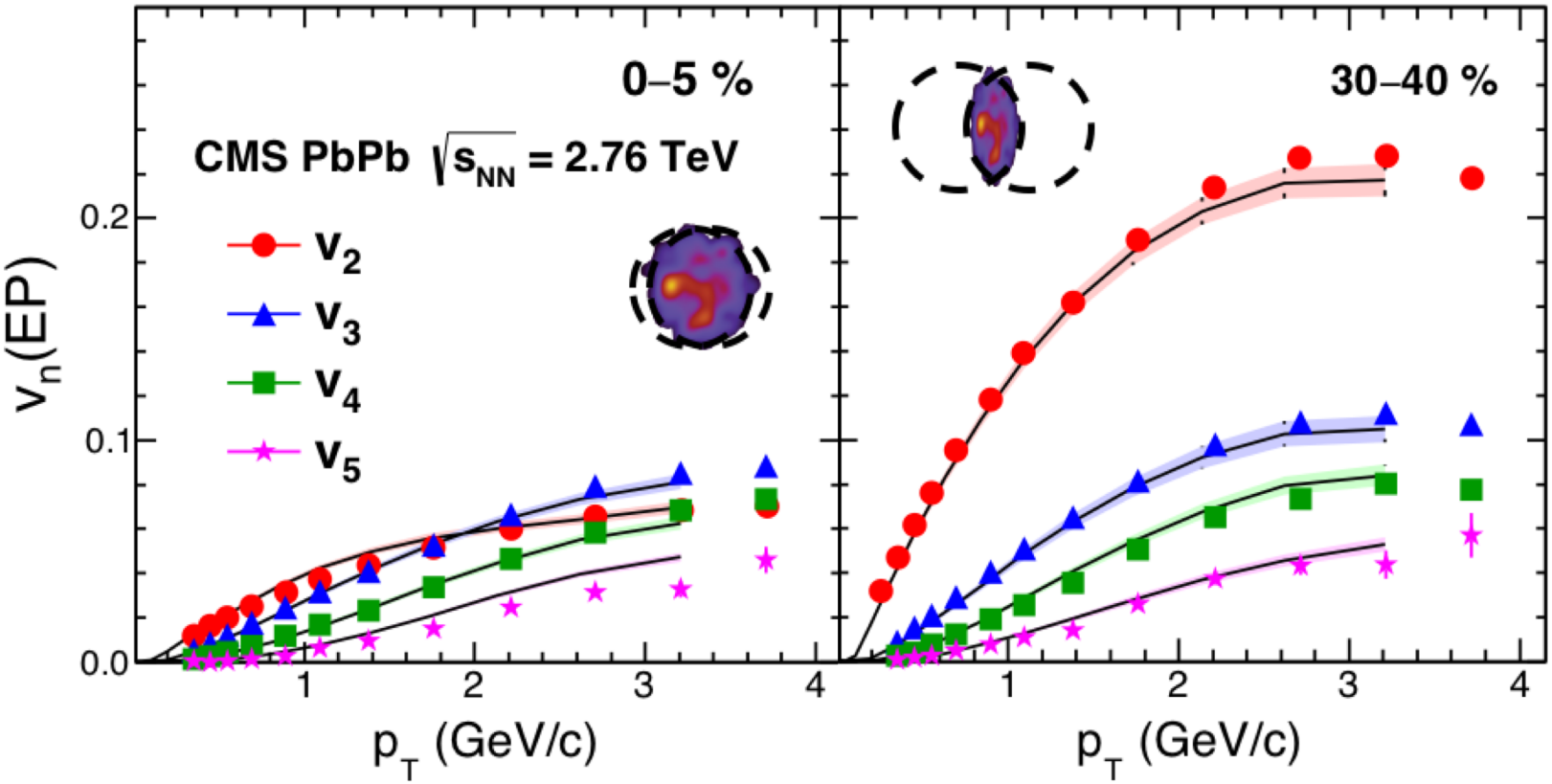
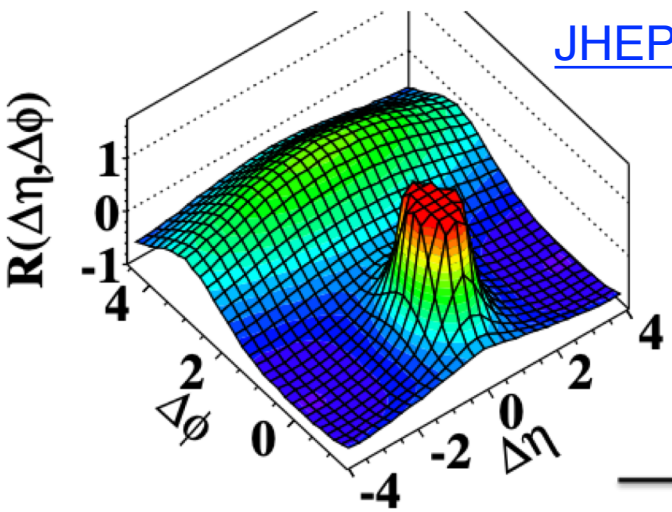



Well described by nearly ideal hydrodynamics with minimal fluid imperfection ($\eta/s \sim 0.2$)

# Revenge of small systems (2010)

(b) CMS MinBias, 1.0GeV/c<$p_T$<3.0GeV/c

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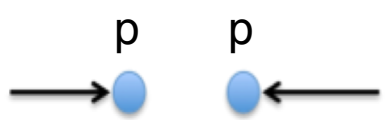
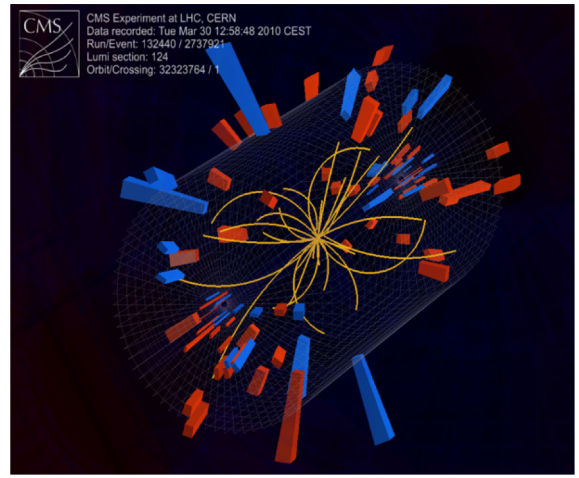
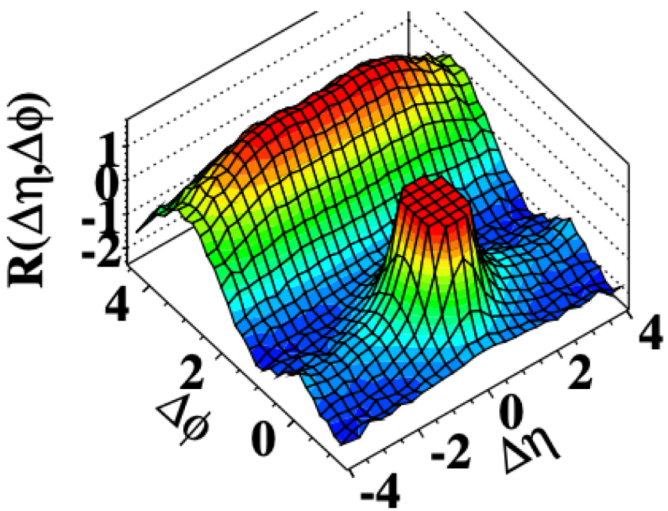



Minimum bias pp

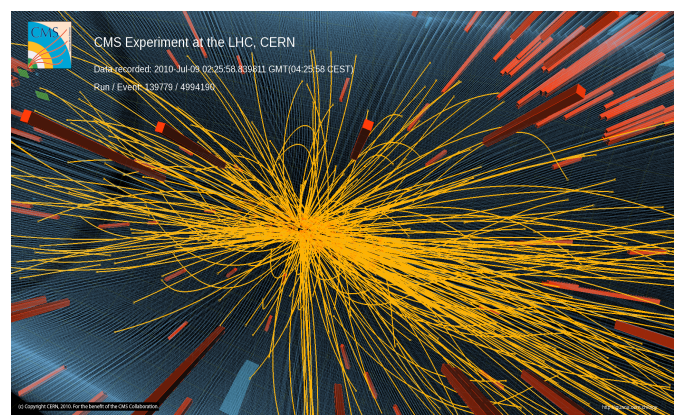



1<$p_T$<3 GeV/c

(d) CMS N ≥ 110, 1.0GeV/c<$p_T$<3.0GeV/c




High multiplicity pp ($N_{trk}$>110)



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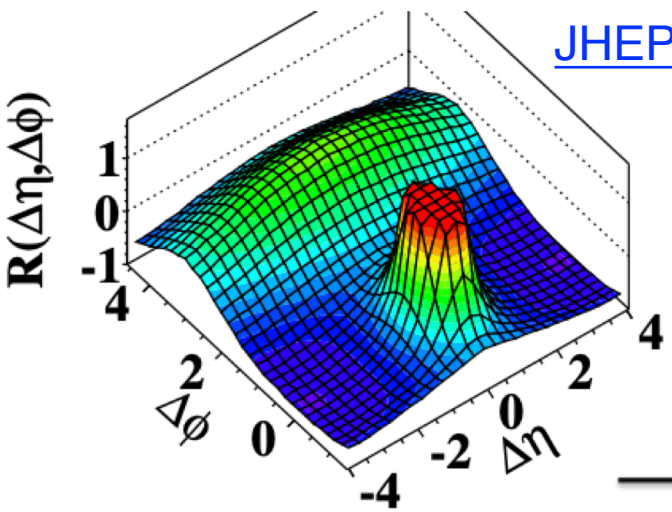


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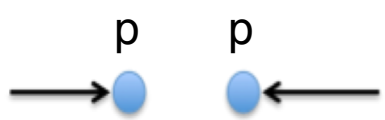
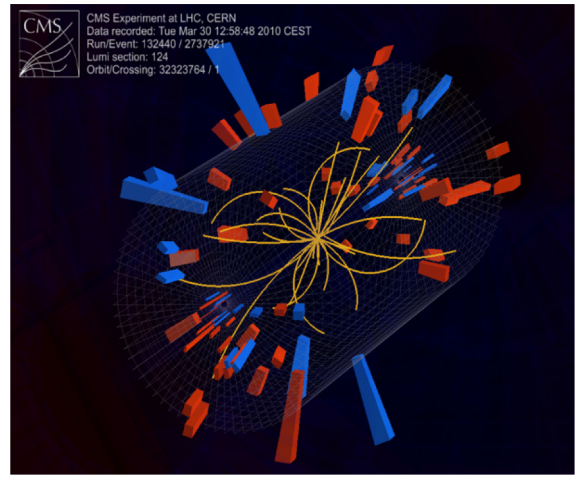
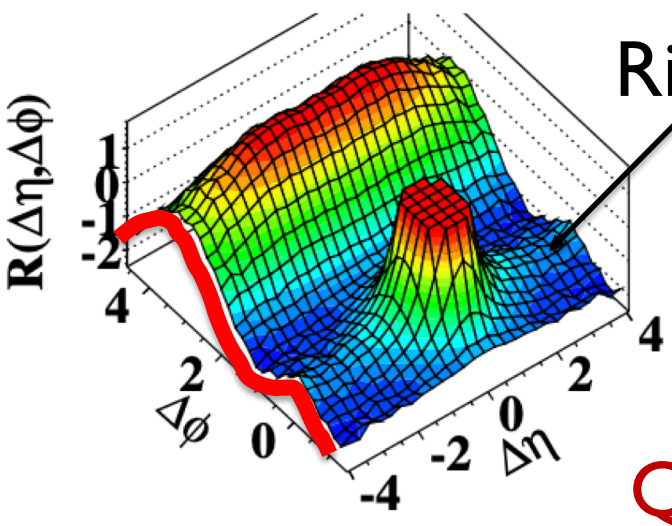



Minimum bias pp



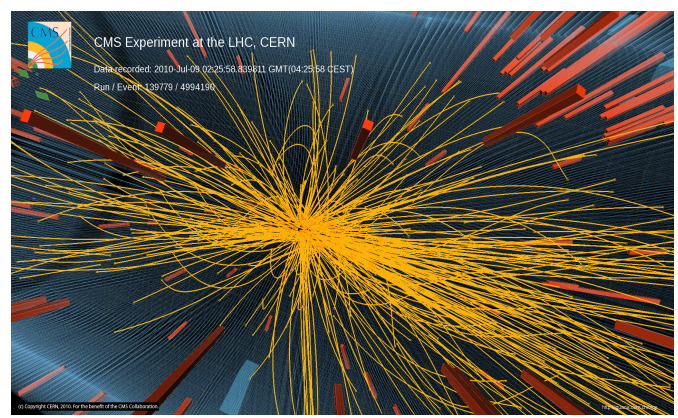

$1<p_T<3$ GeV/c

(d) CMS N ≥ 110, 1.0GeV/c<$p_T$<3.0GeV/c




Ridge

High multiplicity pp ($N_{trk}$>110)

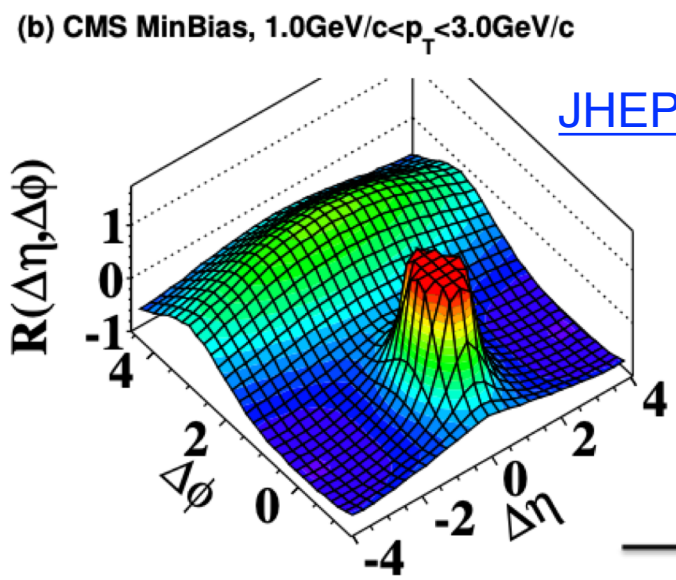


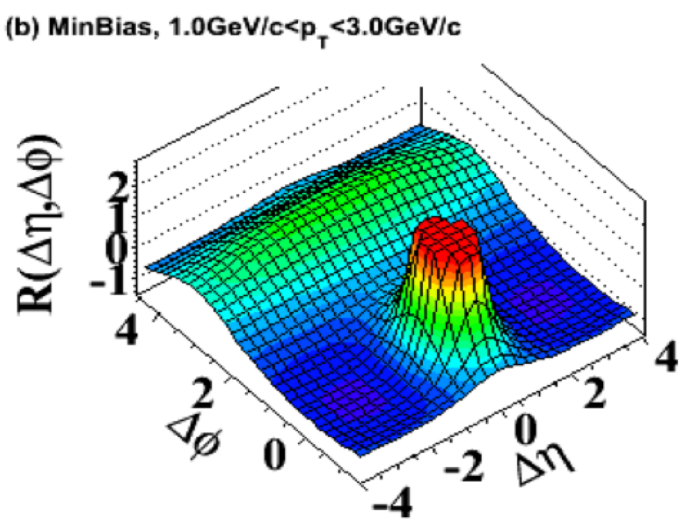

QGP droplet in pp?

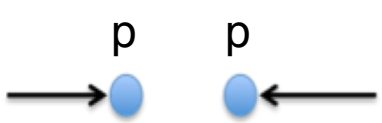
# Revenge of small systems (2010)

Not reproduced by pp MC

JHEP 09 (2010) 091

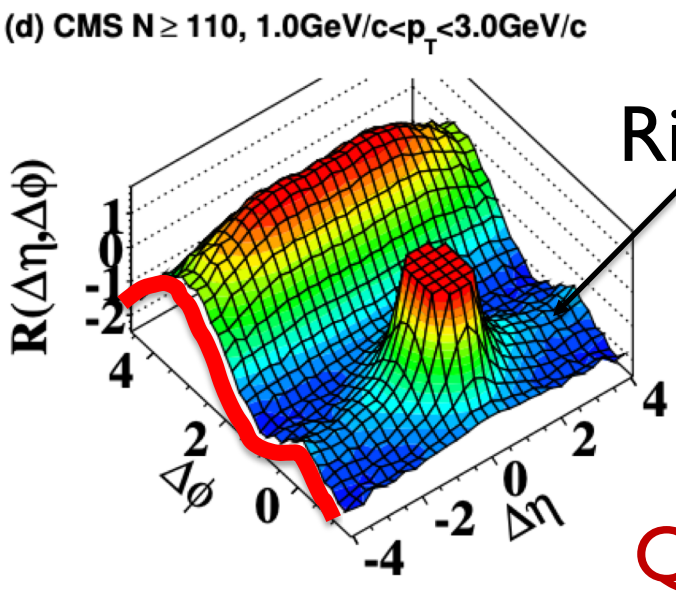


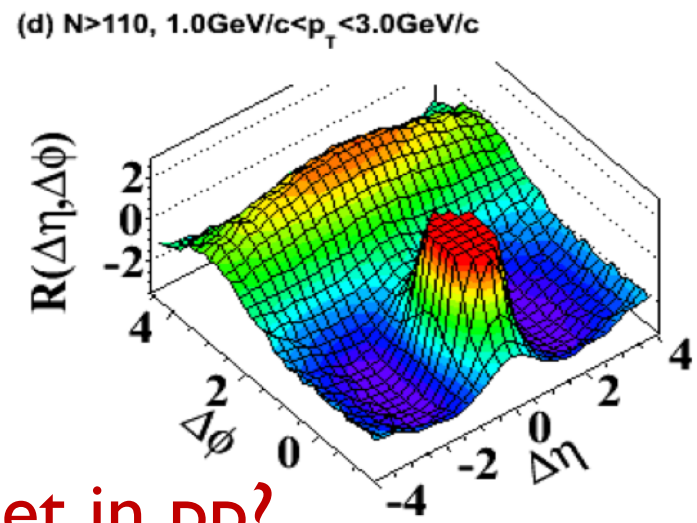




$1<p_T<3$ GeV/c

PYTHIA 8




Ridge

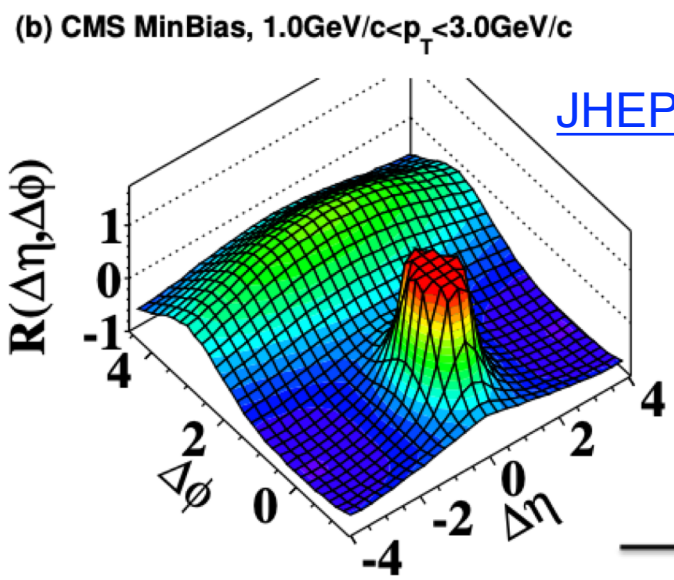


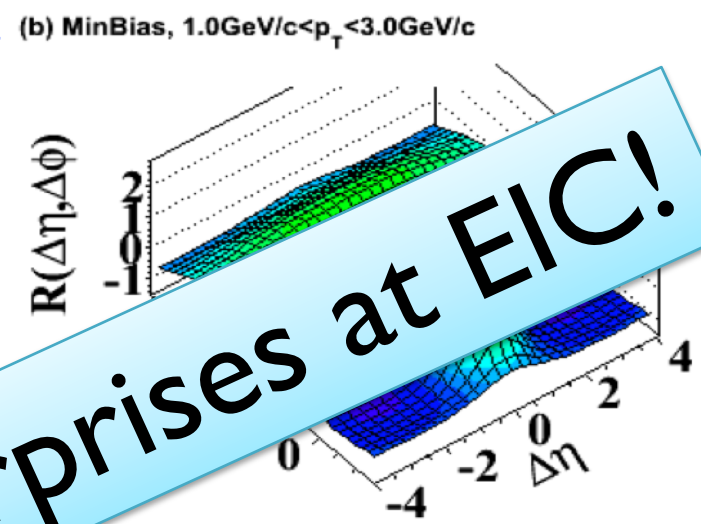

QGP droplet in pp?

# Revenge of small systems (2010)

Not reproduced by pp MC

JHEP 09 (2010) 091



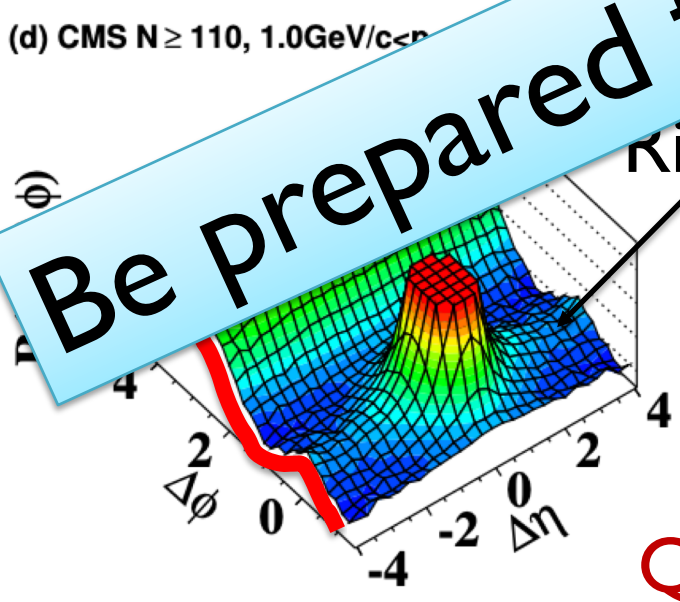




p p

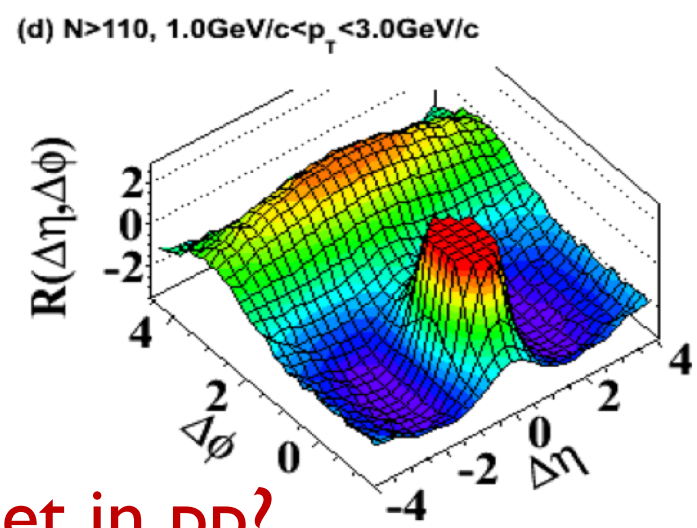
$1<p_T<3$ GeV/c

PYTHIA 8

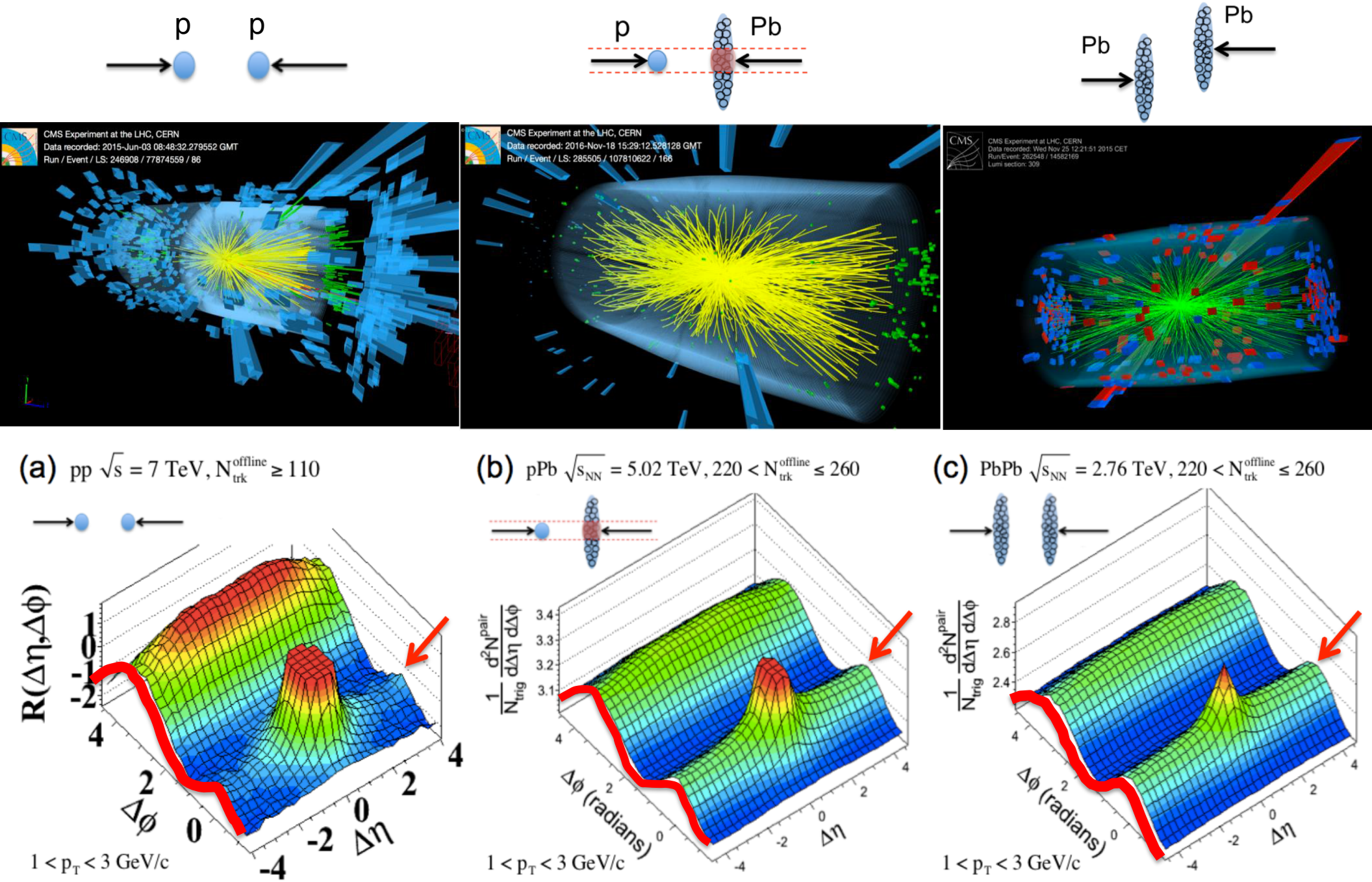
Be prepared for surprises at EIC!



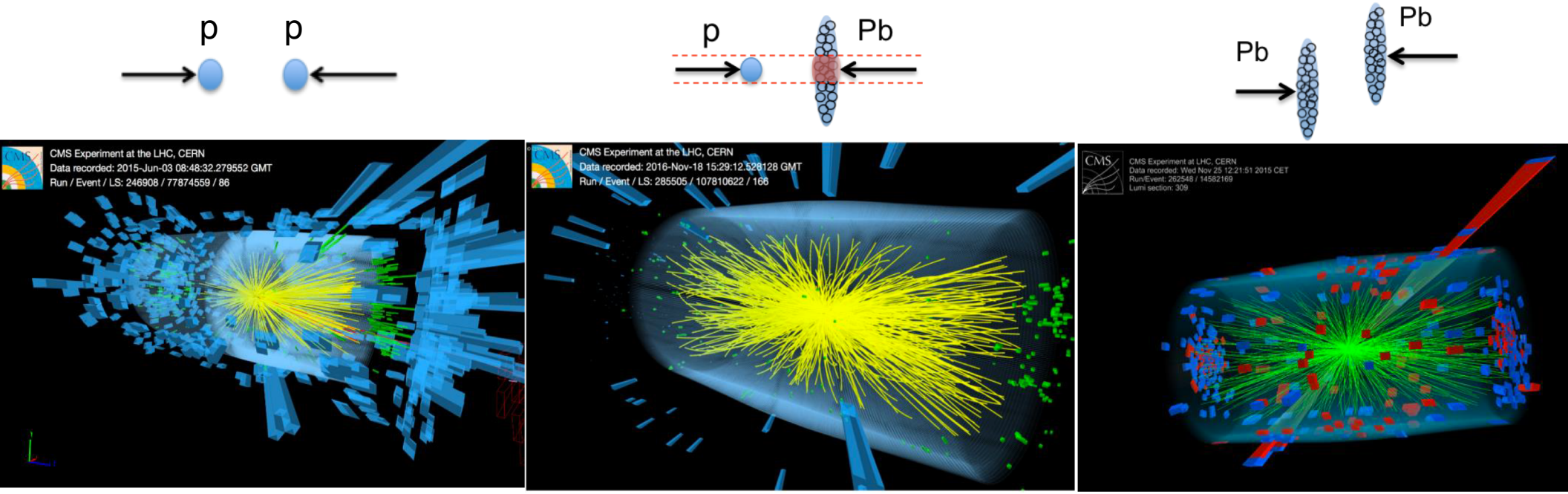

Ridge




QGP droplet in pp?




Universal collective effects in high-density QCD final states?

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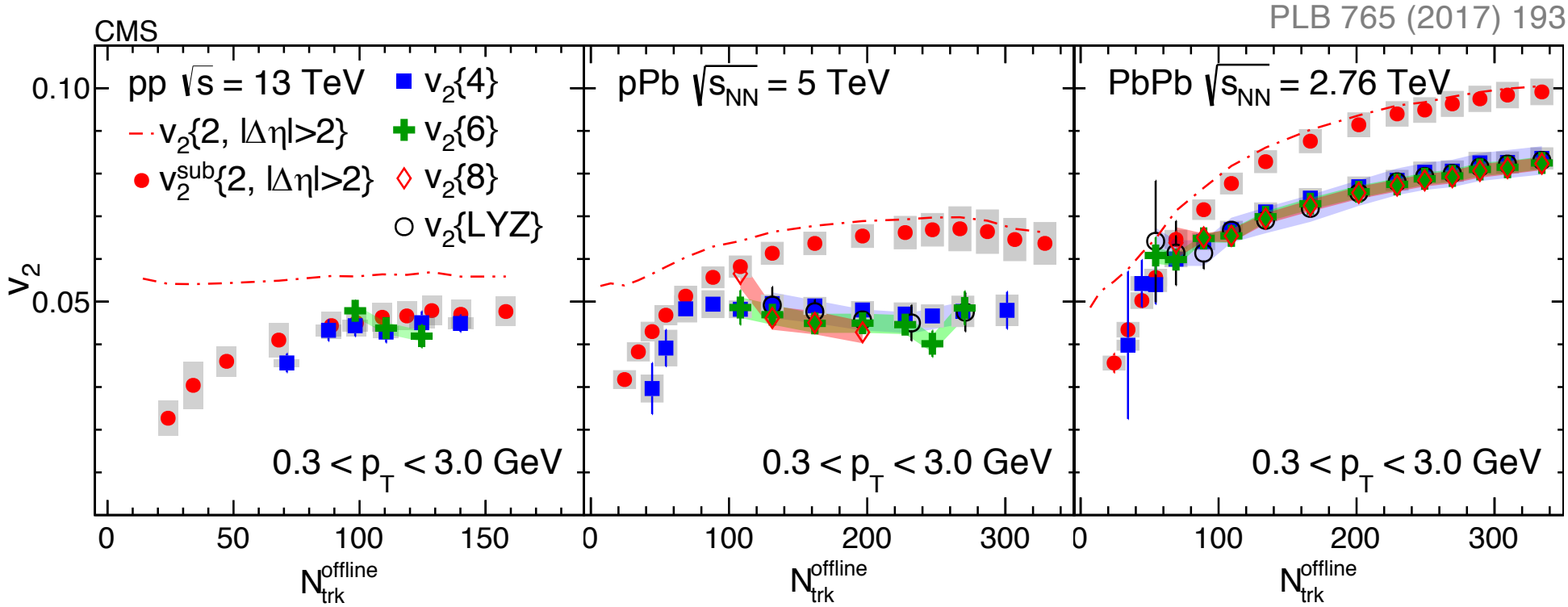
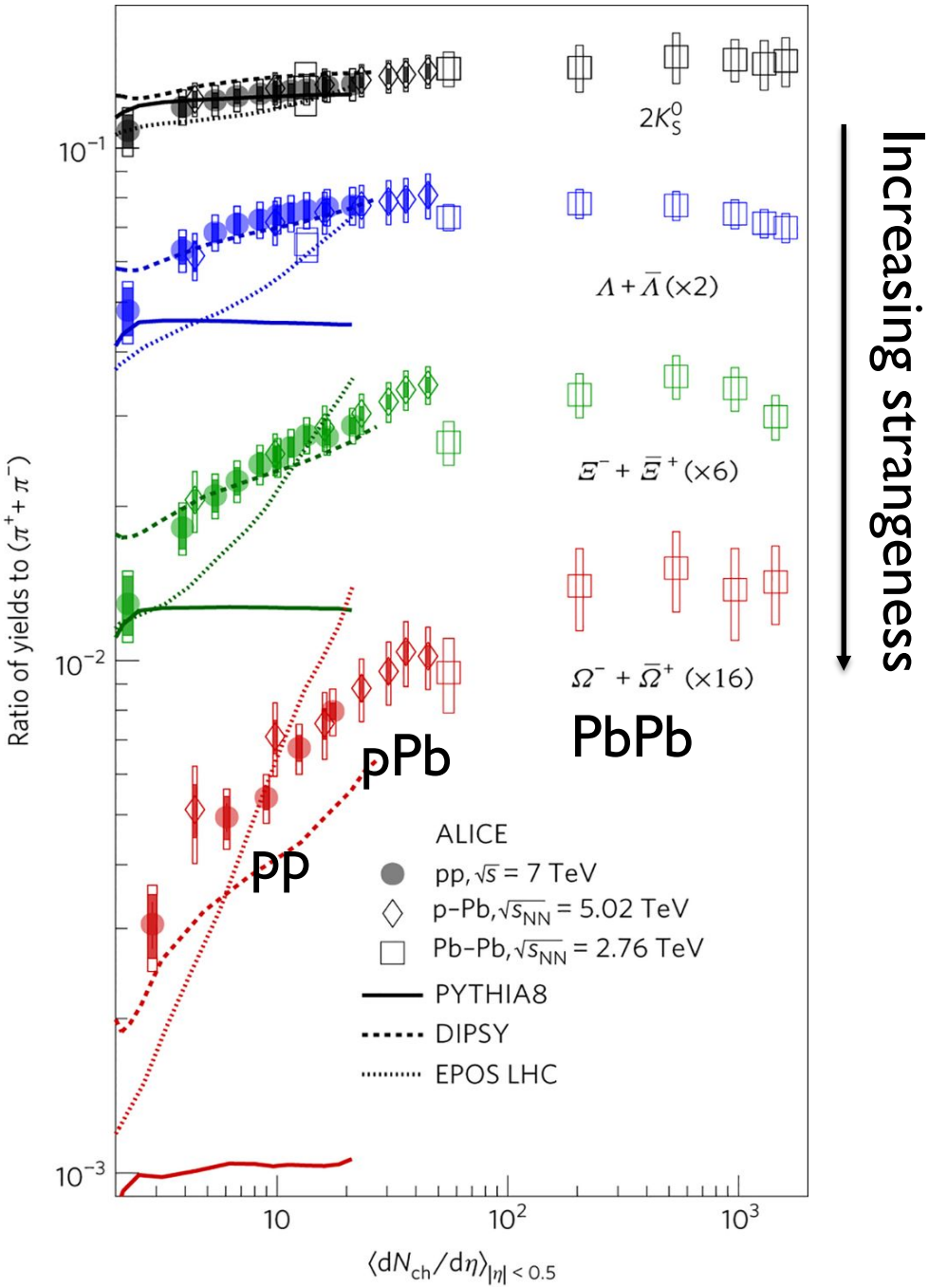



Universal collective effects in high-density QCD final states?

# Strangeness enhancement

## – as a QGP signature

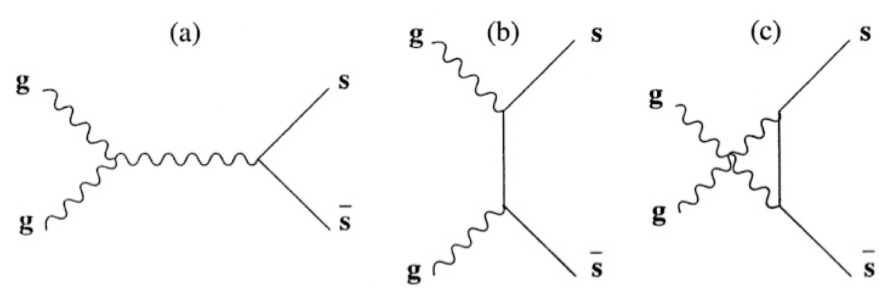
J. Rafelski and B. Müller, PRL 48, 1066 (1982);
P. Koch et. al. Phys. Rep. 142, 167 (1986)




Increasing strangeness

Not described by the Lund string model (PYTHIA)

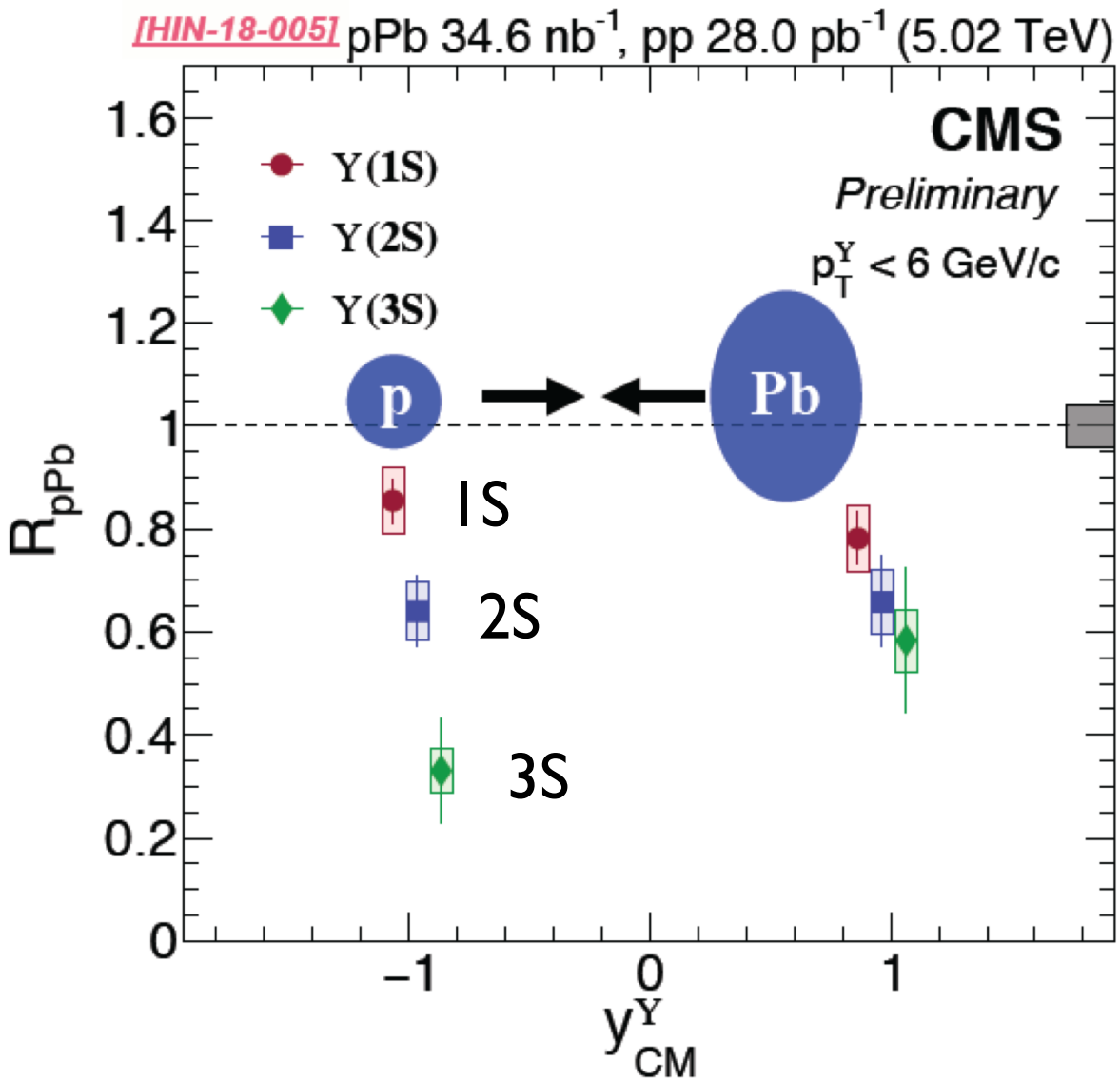
Captured by models w/ dense color environment



# Quarkonia suppression

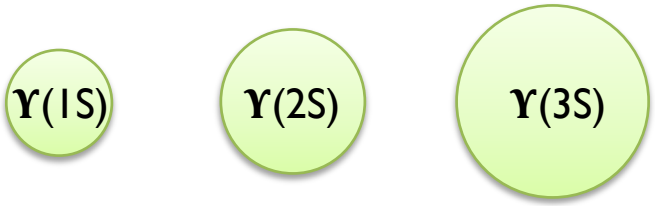
– as a QGP signature

Suppression of Upsilon states in pPb

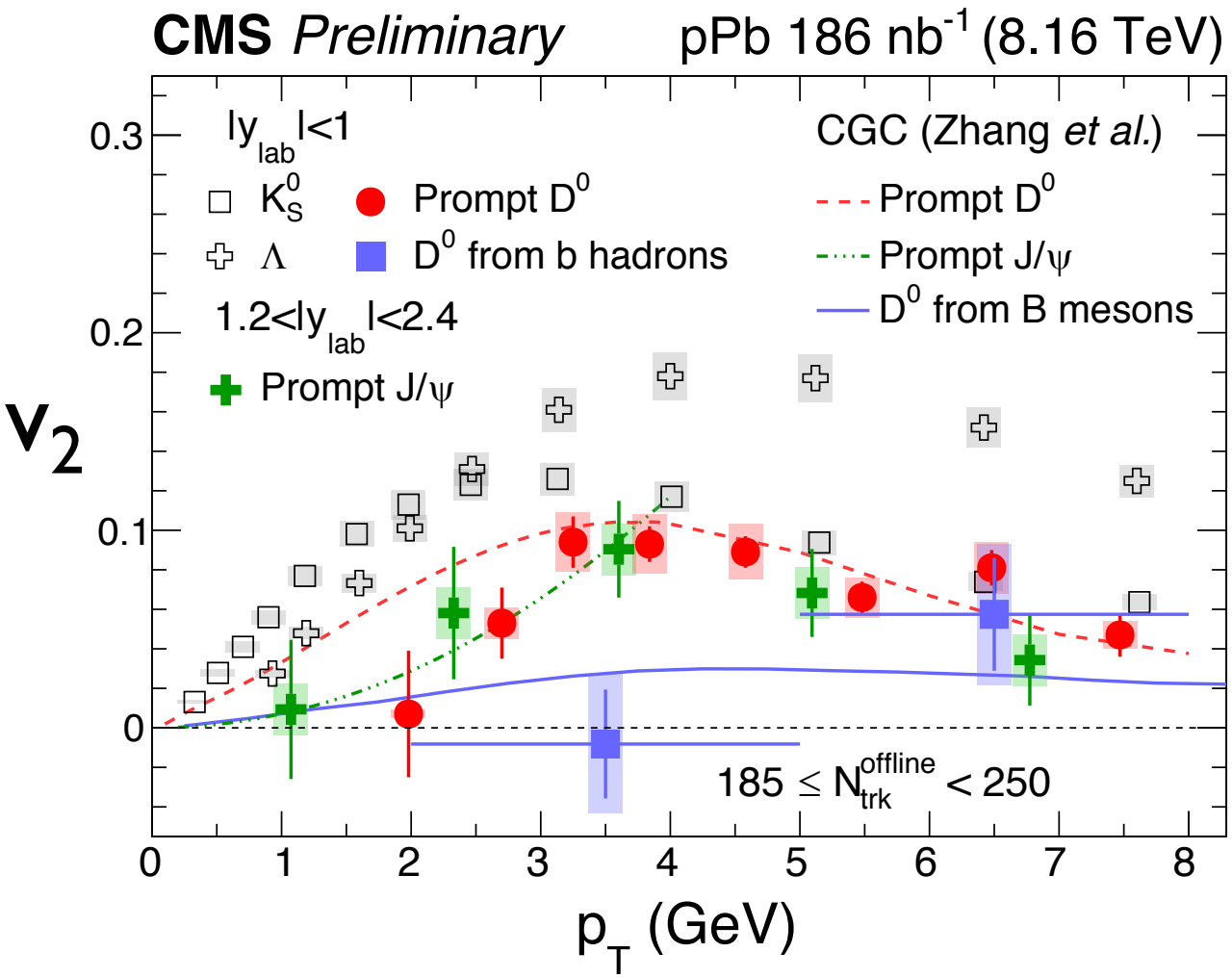



Stronger suppression for excited states, esp. at backward rapidity

Medium effect needed?!



# Elliptic flow of heavy flavor hadrons!



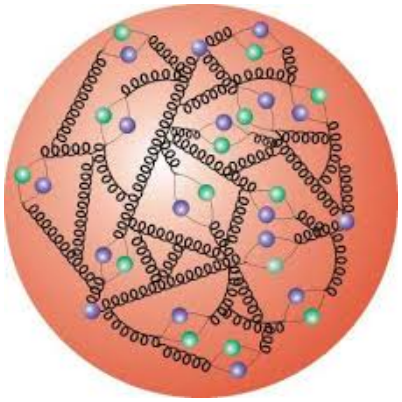

*New at QM2019!*

Strong flow of *charm*, not *beauty* hadrons

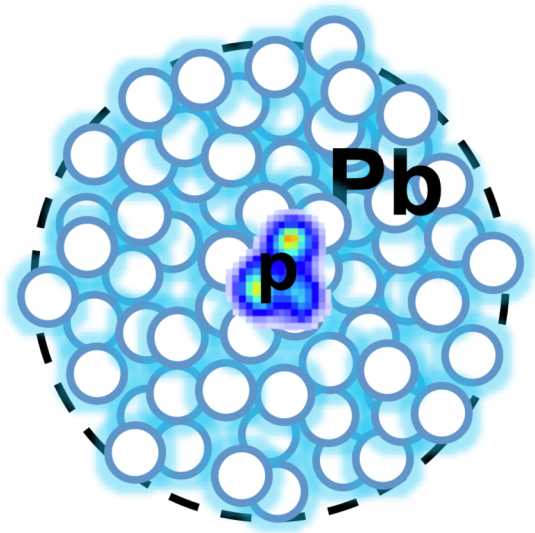
Latest results at Quark Matter 2019: https://indico.cern.ch/event/792436/

Many dozens of papers on “small” (used to be cold) systems at the LHC

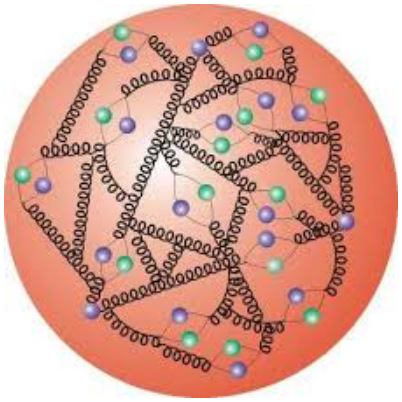
# Proton as an emergent QCD many-body phenomenon



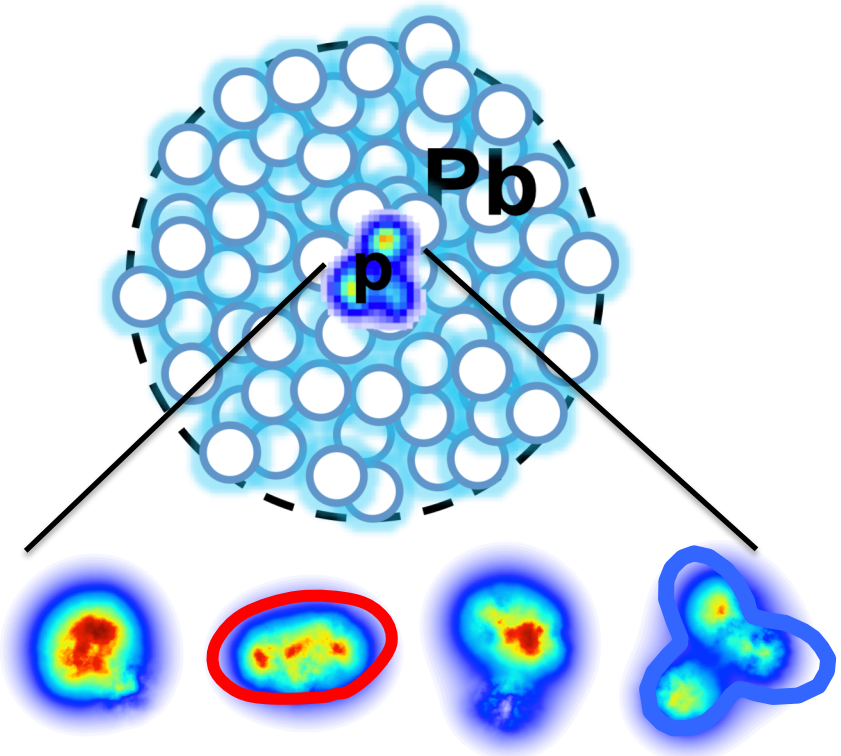
Role of initial proton "geometry"



# Proton as an emergent QCD many-body phenomenon

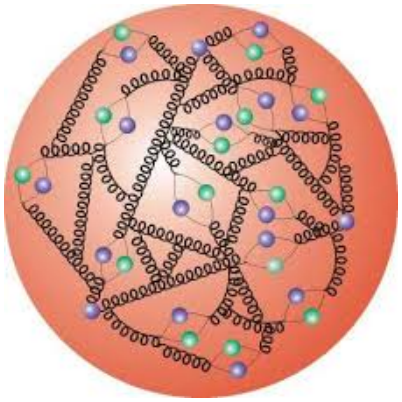


Role of initial proton "geometry"

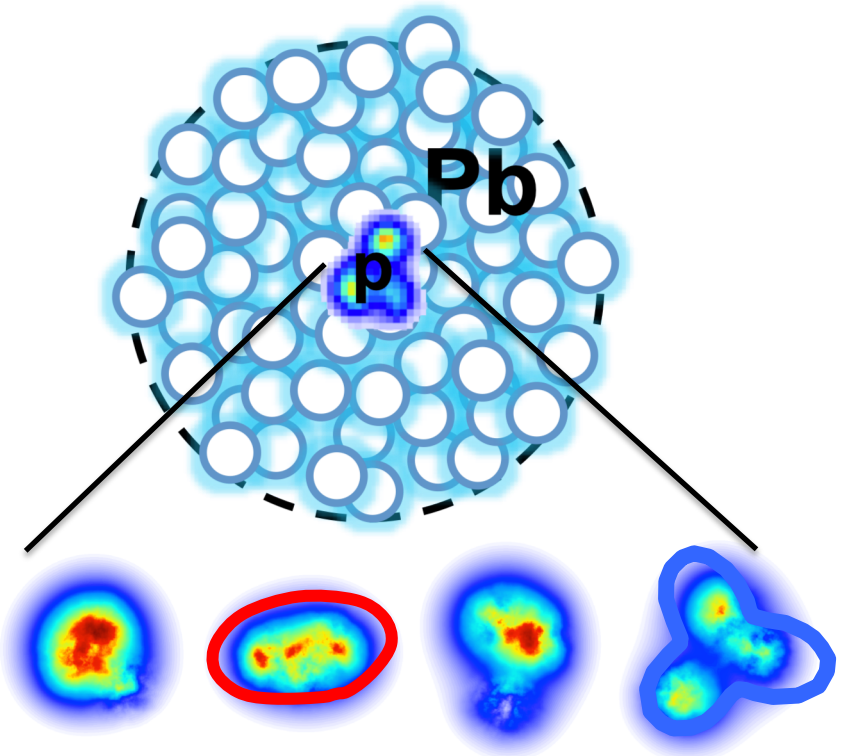



Proton "geometry" fluctuation?

# Proton as an emergent QCD many-body phenomenon

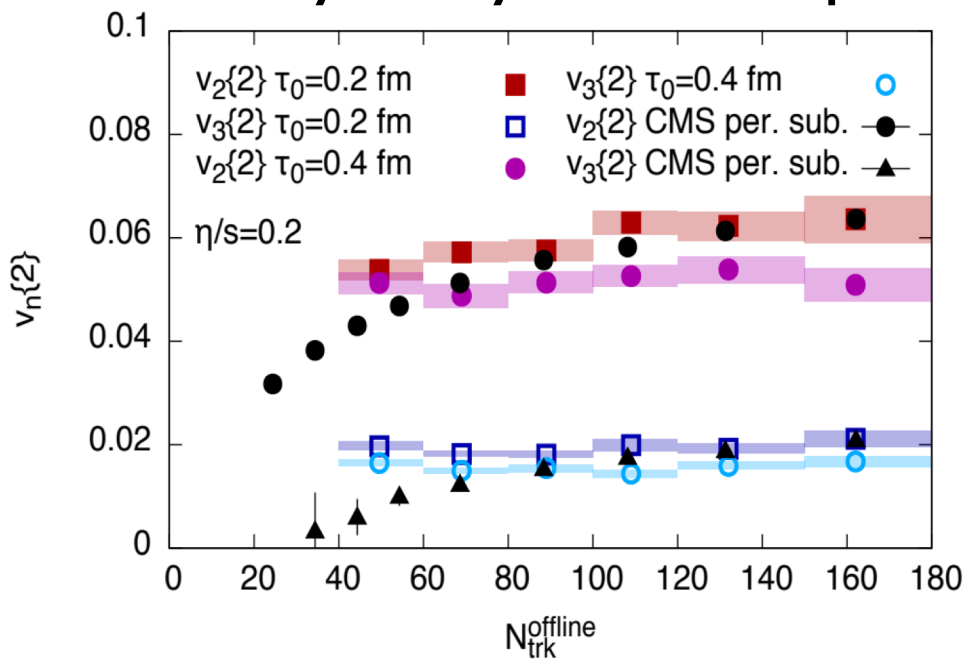


Role of initial proton "geometry"



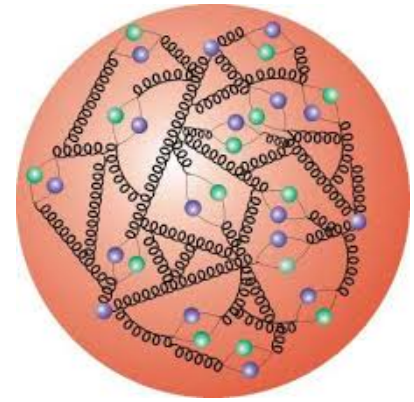

Proton "geometry" fluctuation?

Hydrodynamics in pA

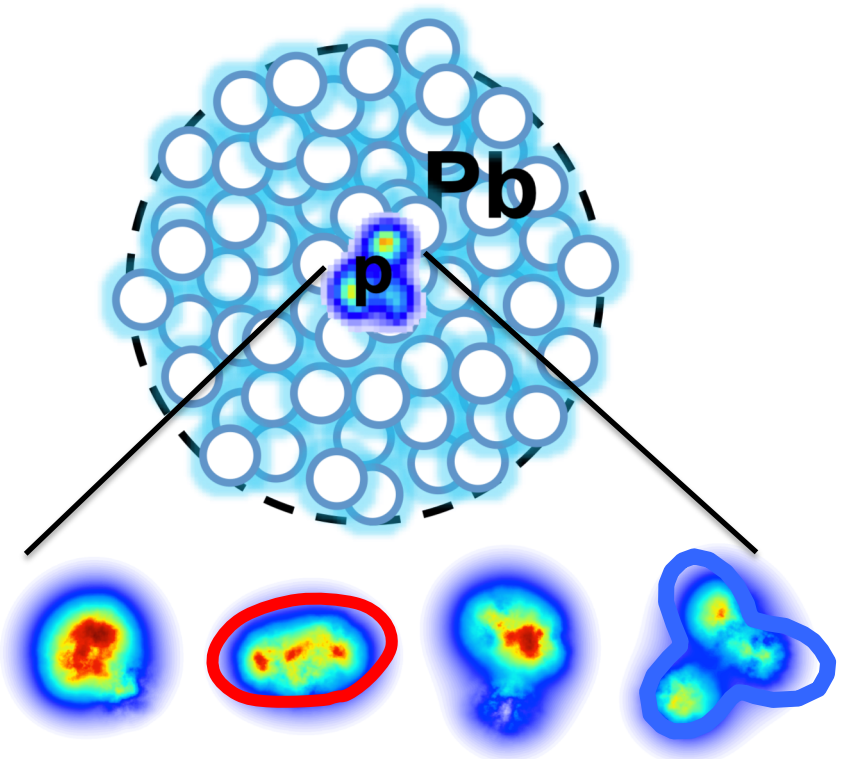



Mäntysaari, Schenke, PLB 772 (2017) 681

# Proton as an emergent QCD many-body phenomenon

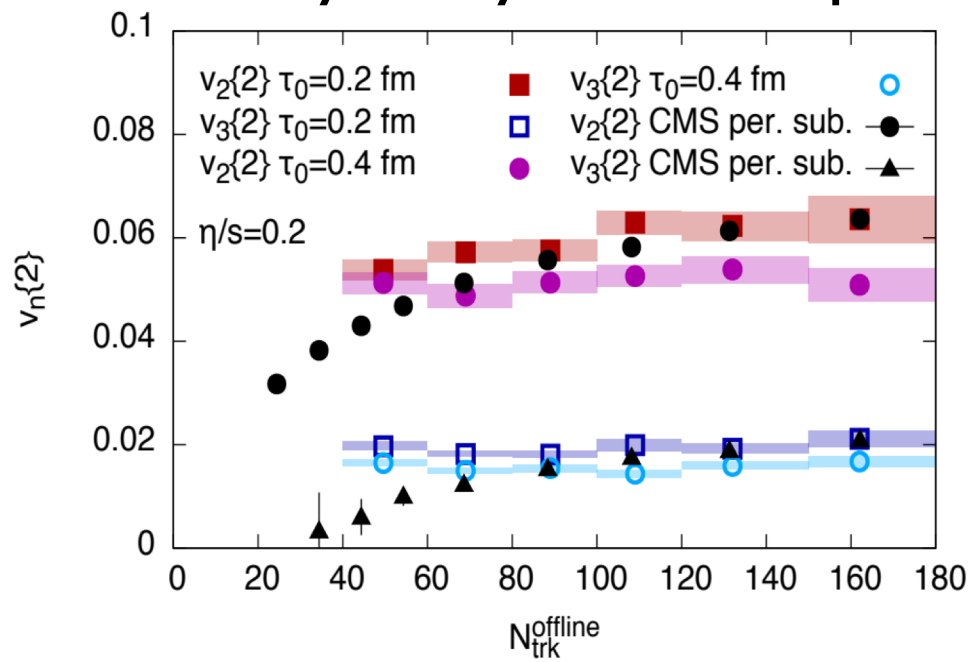


Role of initial proton "geometry"




Proton "geometry" fluctuation?

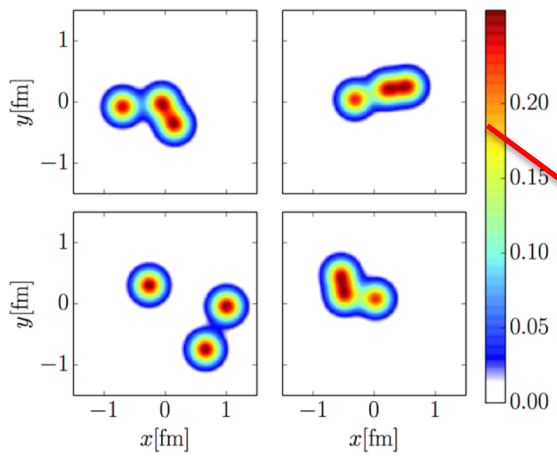
Hydrodynamics in pA



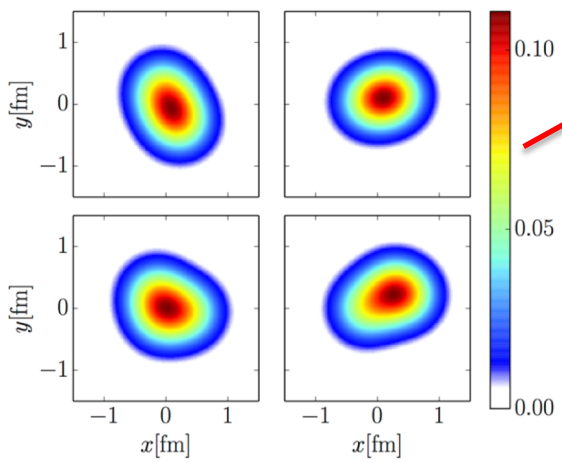

Mäntysaari, Schenke, PLB 772 (2017) 681

**Opportunity of probing quantum fluctuations at sub-fermi and yoctosec scales!**

# Proton "geometry" fluctuations?

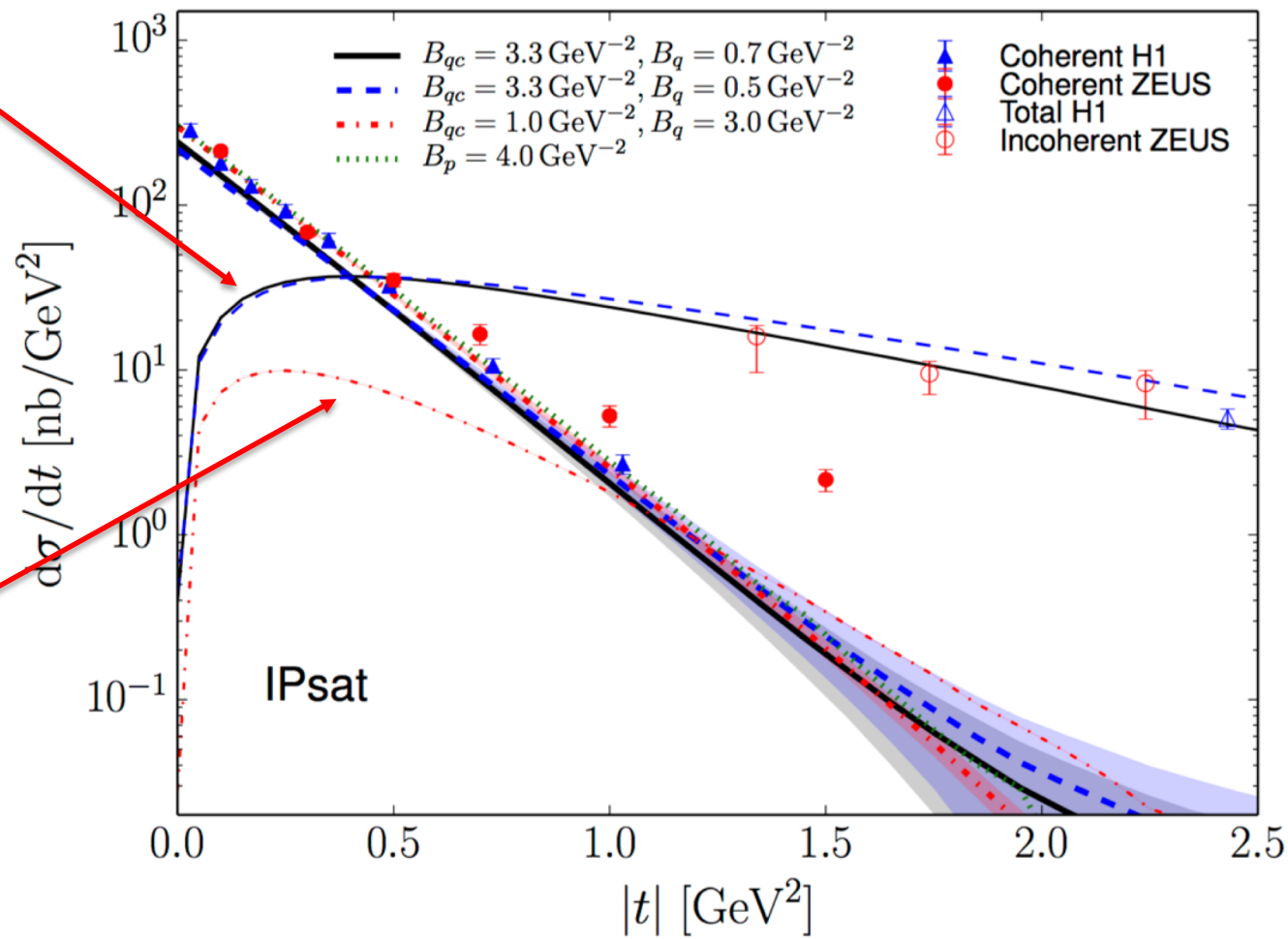



(a) $B_{qc} = 3.3\ \mathrm{GeV}^{-2}, B_q = 0.7\ \mathrm{GeV}^{-2}$




(b) $B_{qc} = 1.0\ \mathrm{GeV}^{-2}, B_q = 3.0\ \mathrm{GeV}^{-2}$

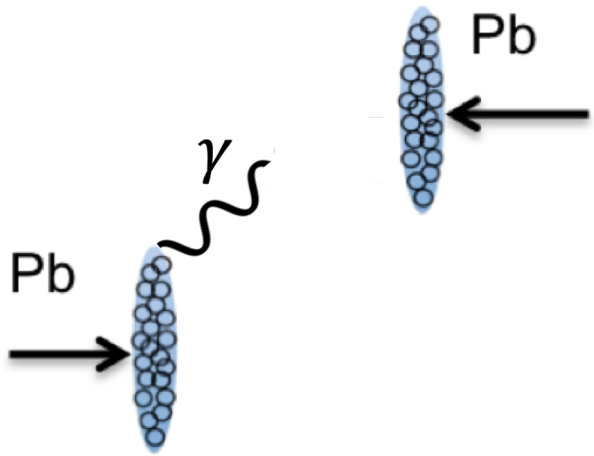
## J/ψ production in e+p

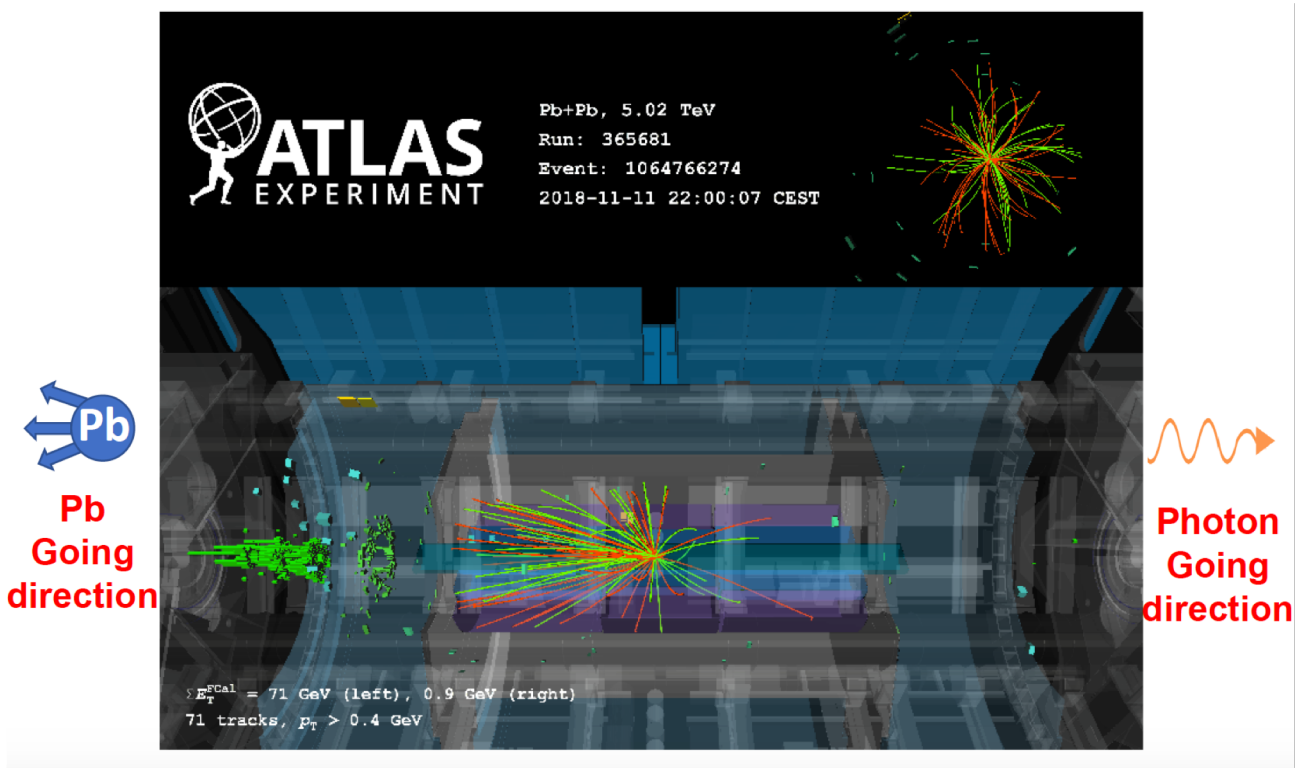



H. Mäntysaari, B. Schenke, PRL 117 (2016) 052301
PRD 94 (2016) 034042

# Hot QCD matter at EIC?

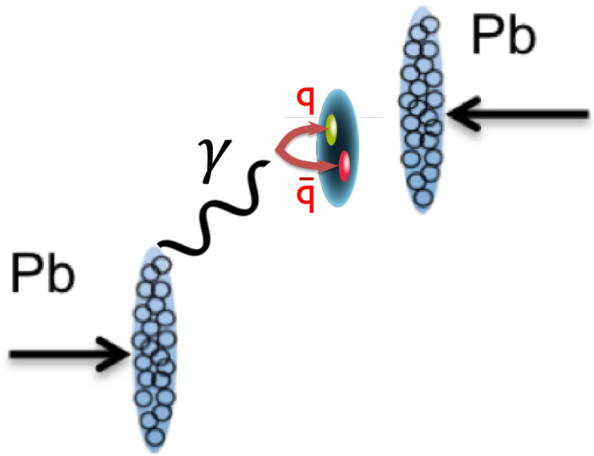
## Ultraperipehral AA

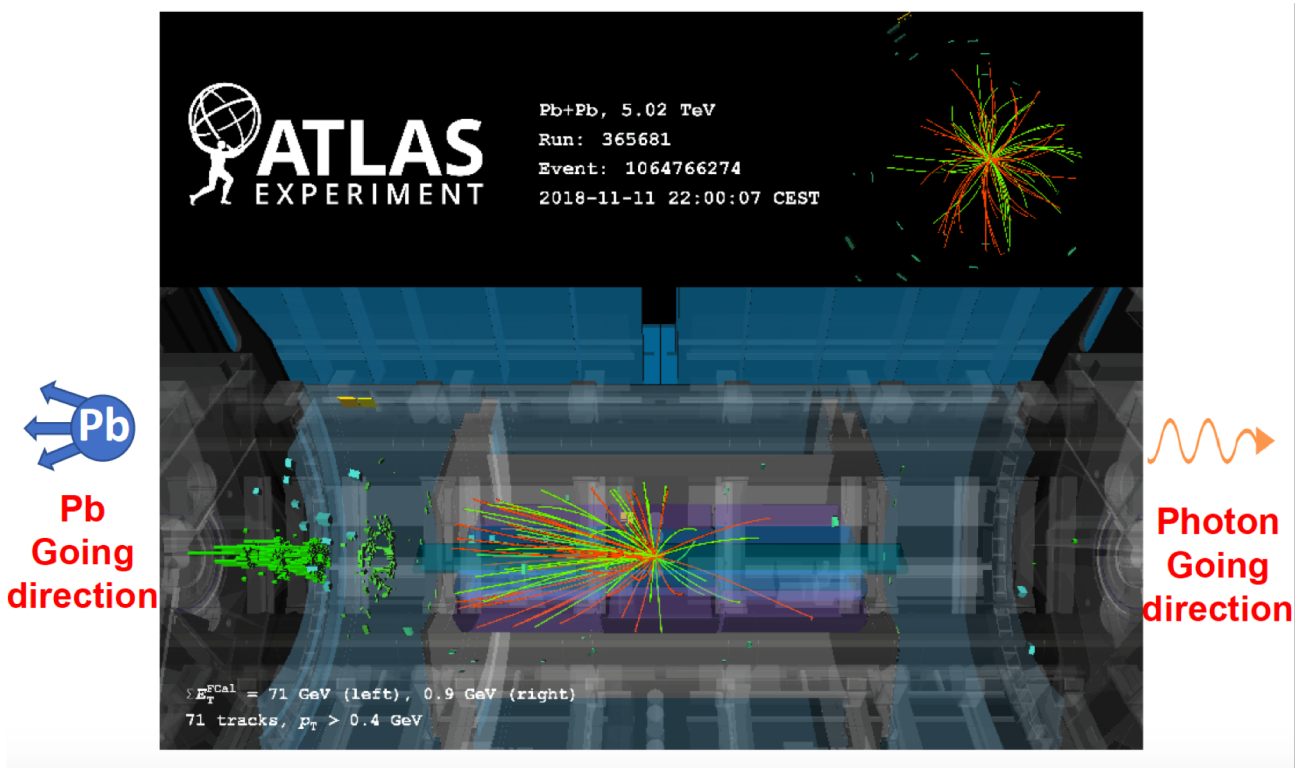


# Hot QCD matter at EIC?

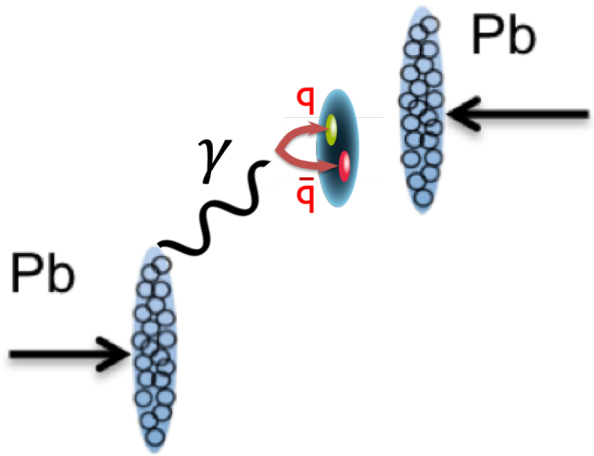
## Ultraperipehral AA

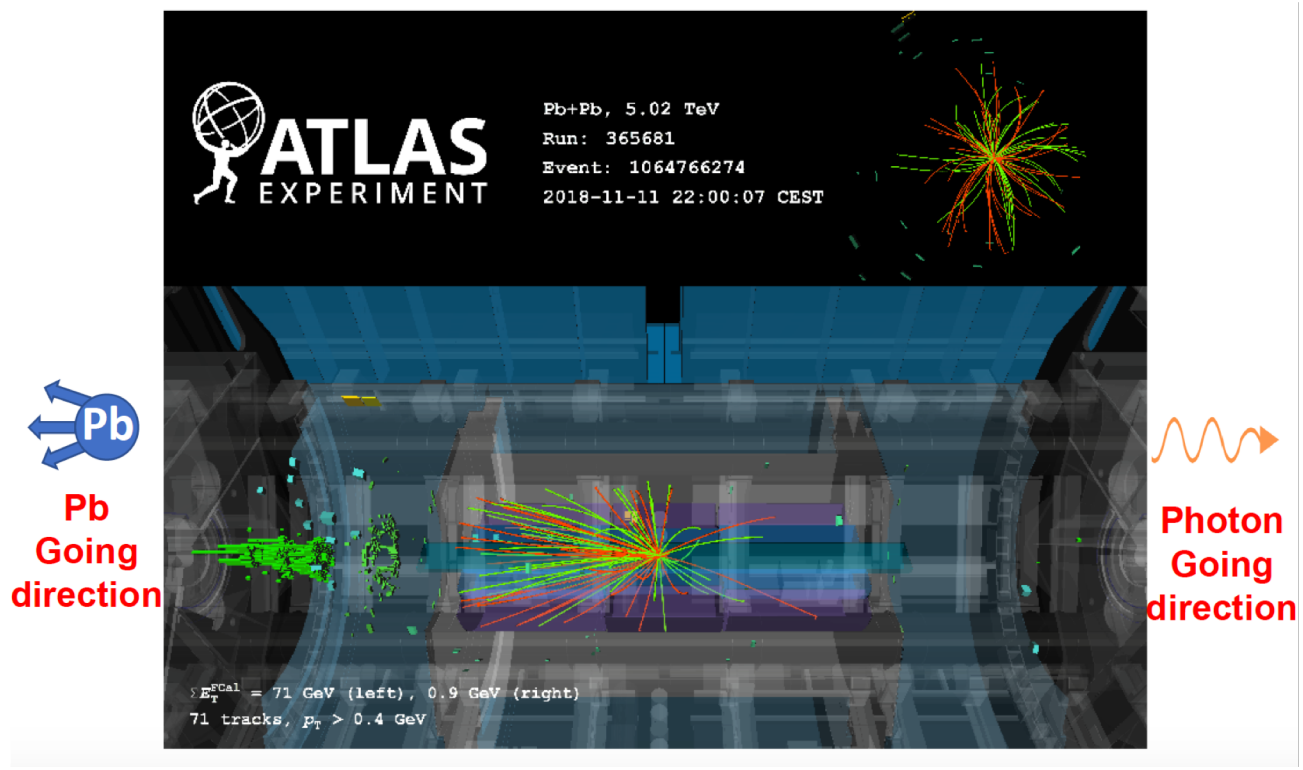


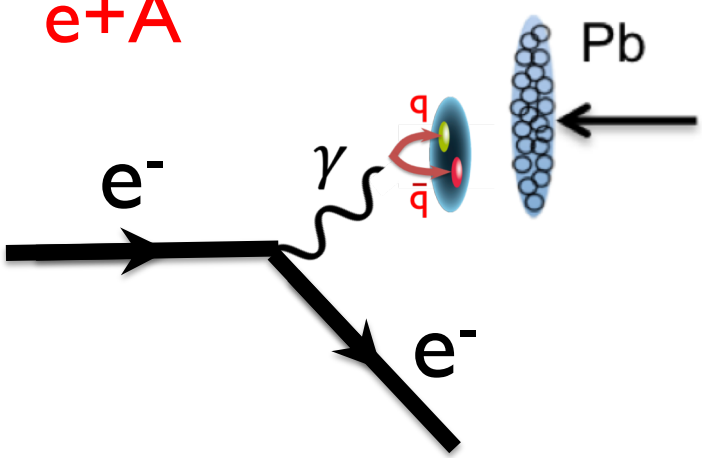
# Hot QCD matter at EIC?

Ultraperipehral AA




e+A

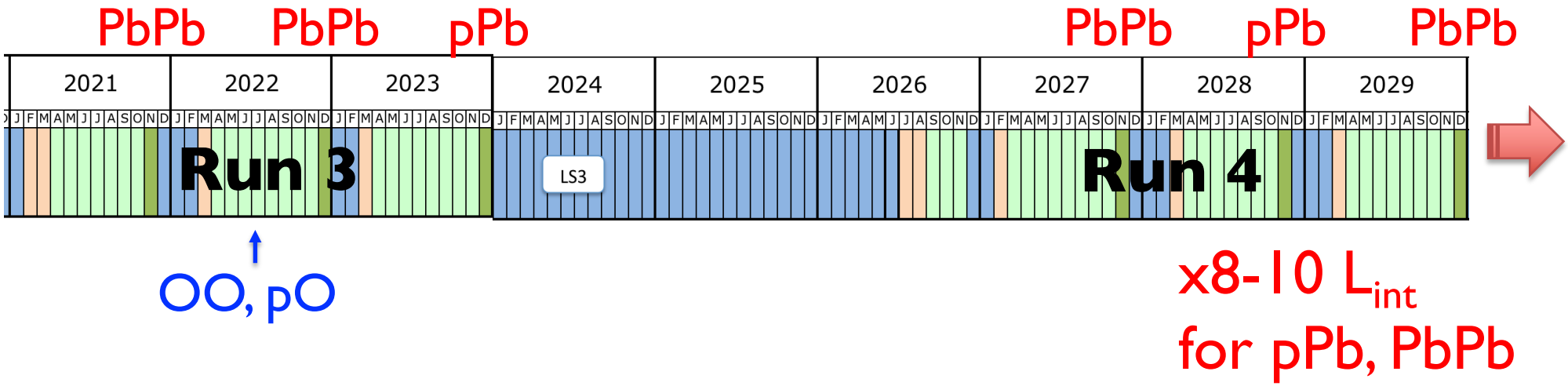



High-multiplicity e+A = ($q\bar{q}$)+A

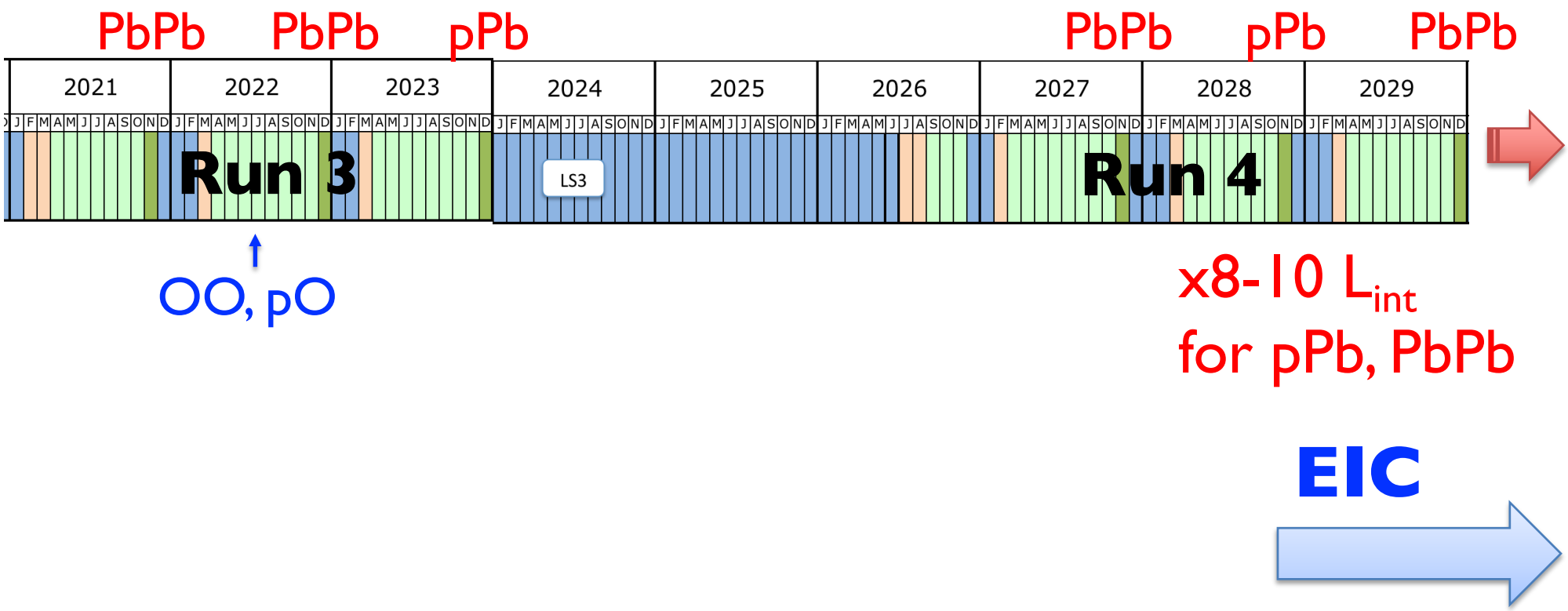
(small $Q^2$, large W)

Collectivity should be observable!

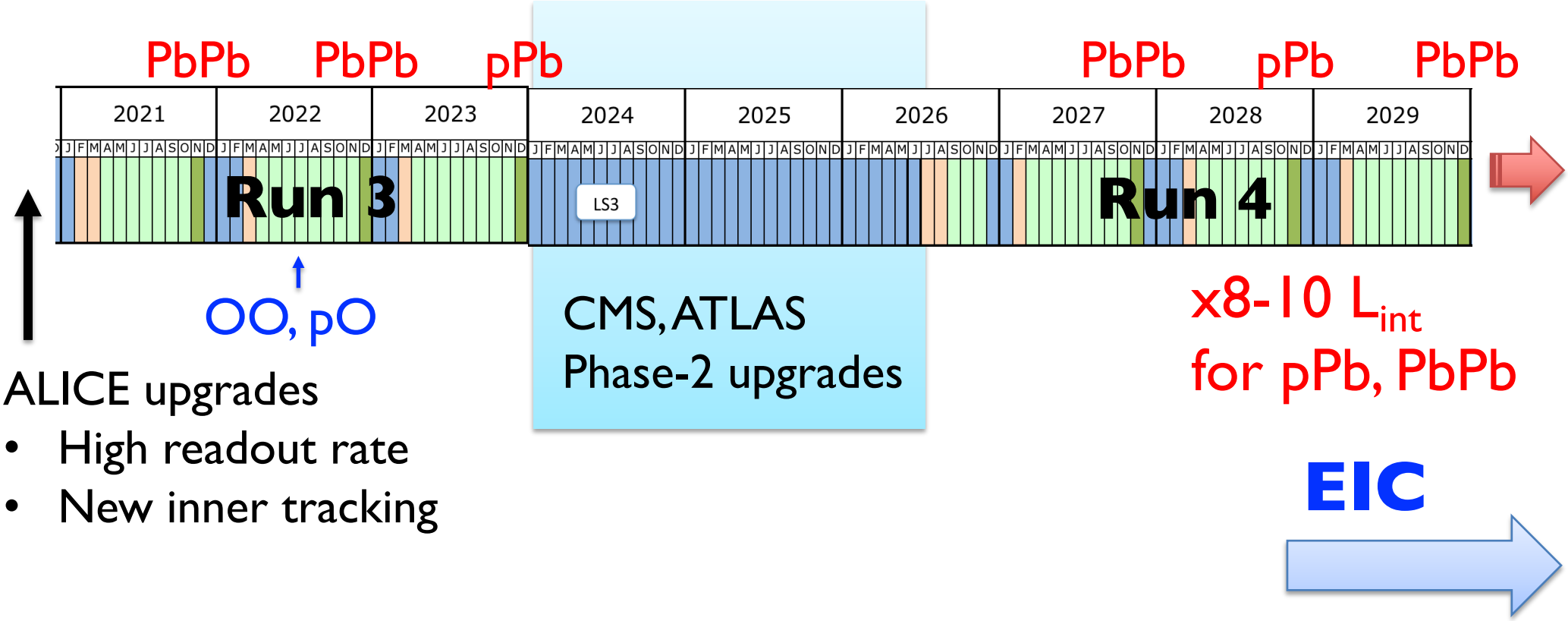
# Future


PbPb
PbPb
pPb
PbPb
pPb
PbPb
2021
2022
2023
2024
2025
2026
2027
2028
2029
Run 3
LS3
Run 4
OO, pO
x8-10 $L_{int}$
for pPb, PbPb

# Future


PbPb
PbPb
pPb
PbPb
pPb
PbPb
2021
2022
2023
2024
2025
2026
2027
2028
2029
Run 3
LS3
Run 4
OO, pO
x8-10 $L_{int}$
for pPb, PbPb
EIC

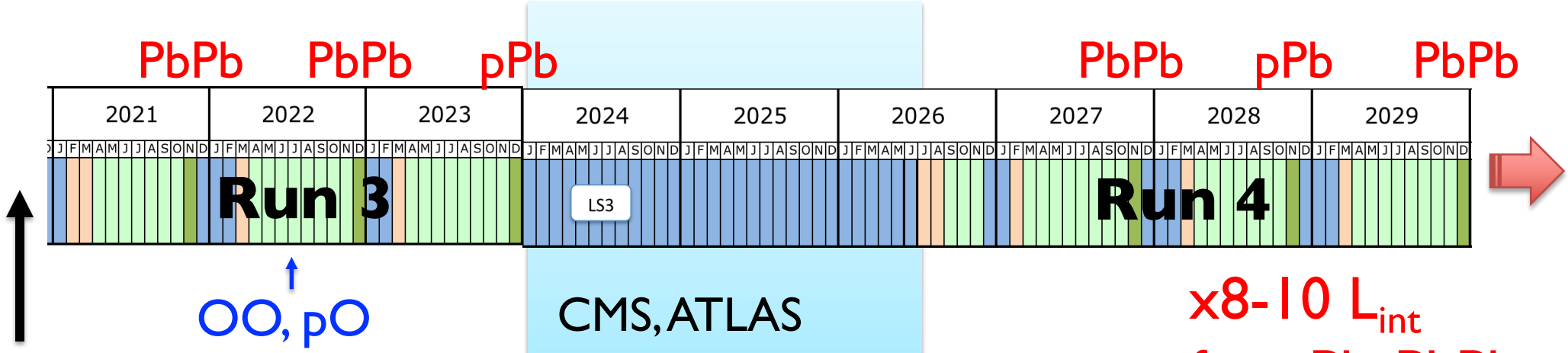
# Future




ALICE upgrades

- High readout rate
- New inner tracking

# Future



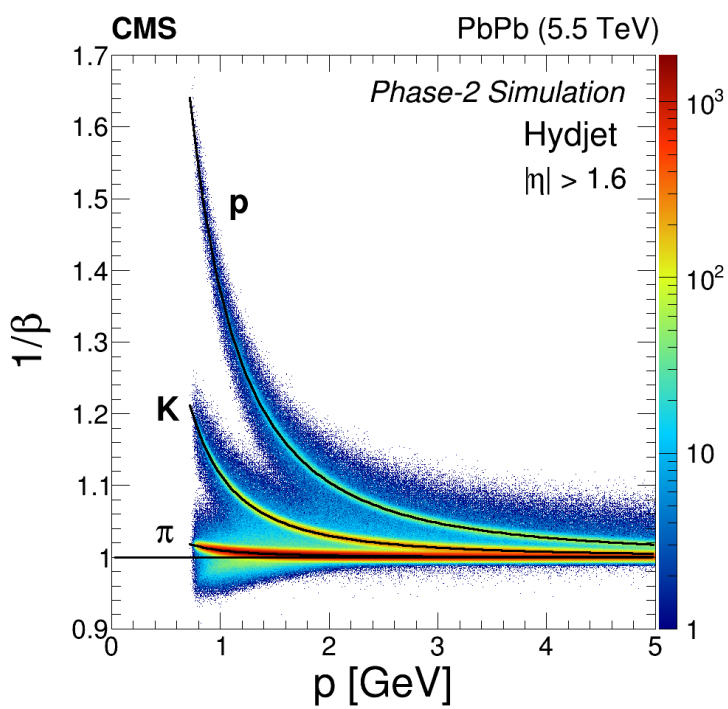

CMS, ATLAS
Phase-2 upgrades

x8-10 $L_{int}$
for pPb, PbPb

ALICE upgrades

- High readout rate
- New inner tracking

CMS Time-Of-Flight: |η|<3

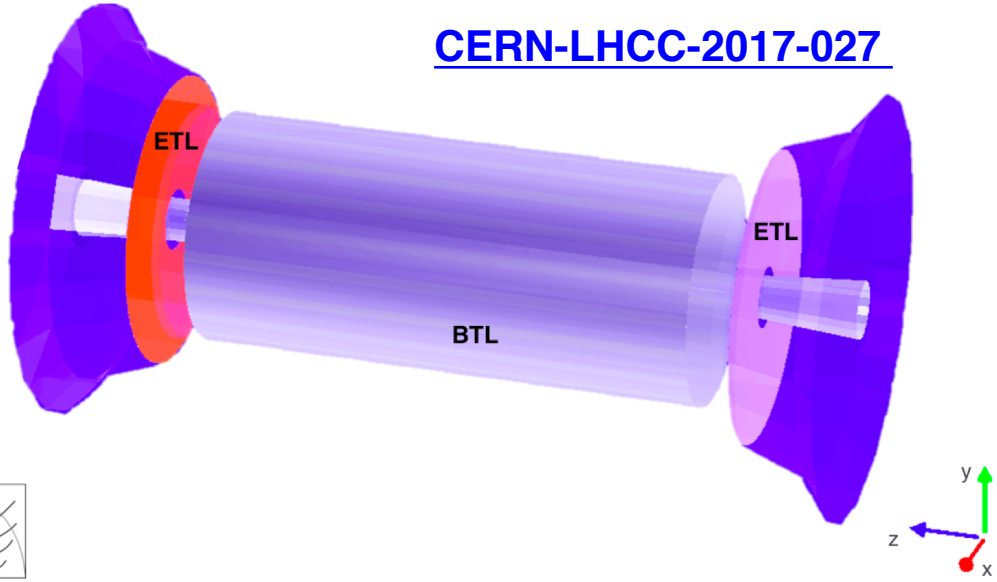



**EIC**

Particle identification!

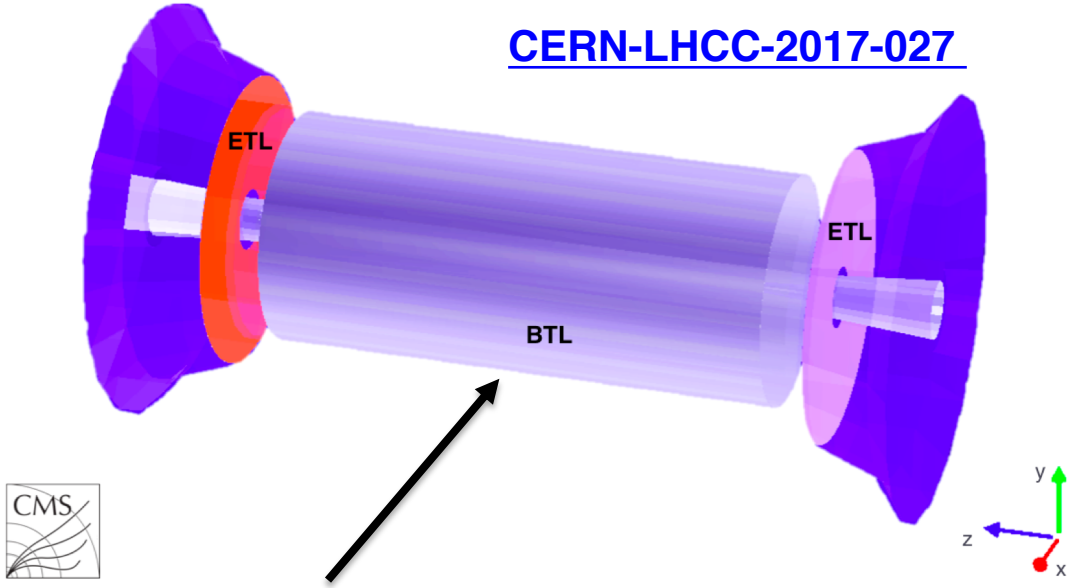
# CMS Mip Timing Detector

CERN-LHCC-2017-027



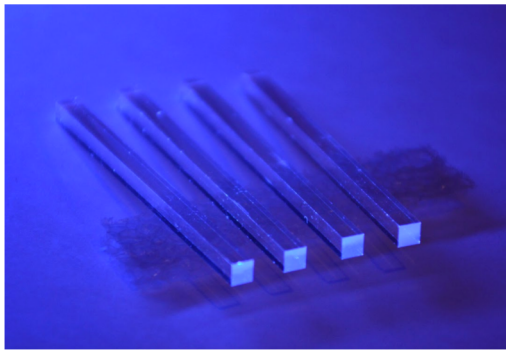
# CMS Mip Timing Detector

CERN-LHCC-2017-027

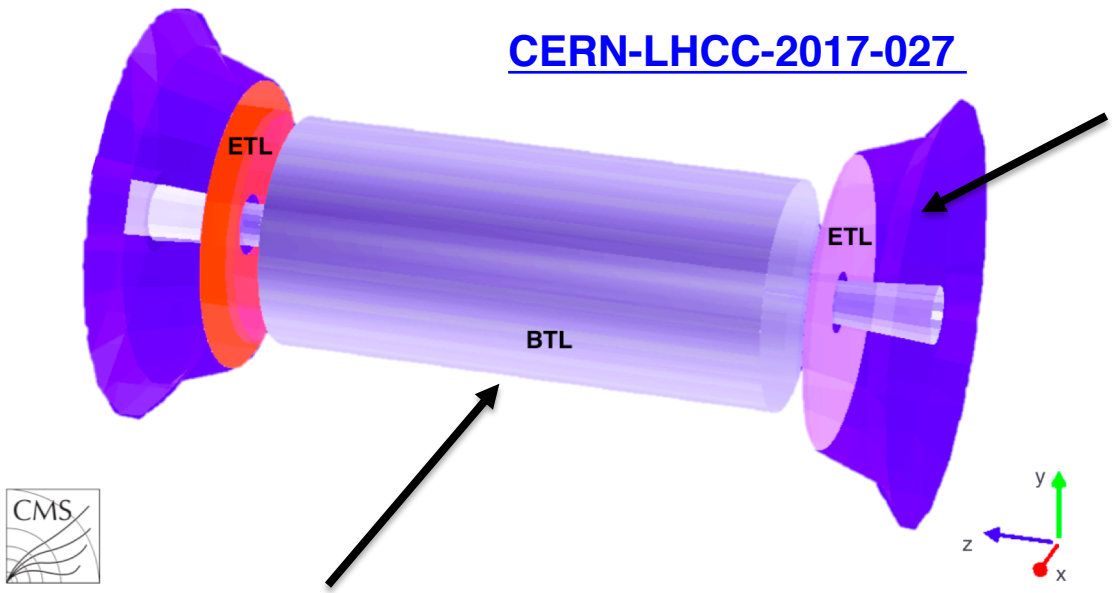



**Barrel Timing Layer:**

- L(Y)SO:Ce crystal bars + SiPM
- Coverage: $|\eta|<1.5$
- Material: $< 0.4\ X_0$
- Time resolution: **~ 30ps**



# CMS Mip Timing Detector

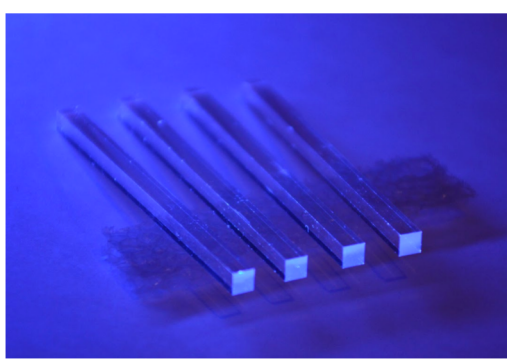


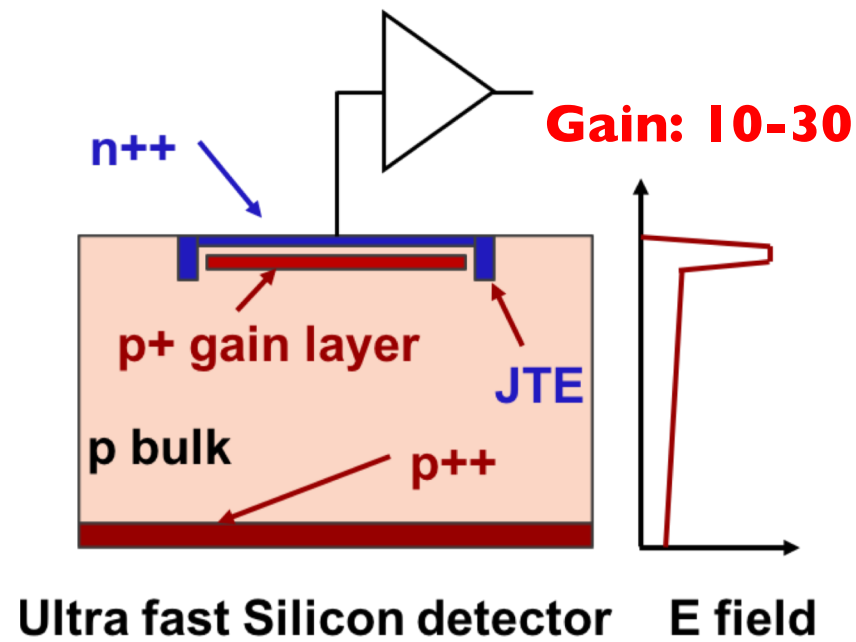

**Endcap Timing Layer:**

- Ultra-fast silicon detectors
- Coverage: $1.6<|\eta|<3.0$
- Material: $< 0.2\ X_0$
- Time resolution: **~ 30ps with two layers**

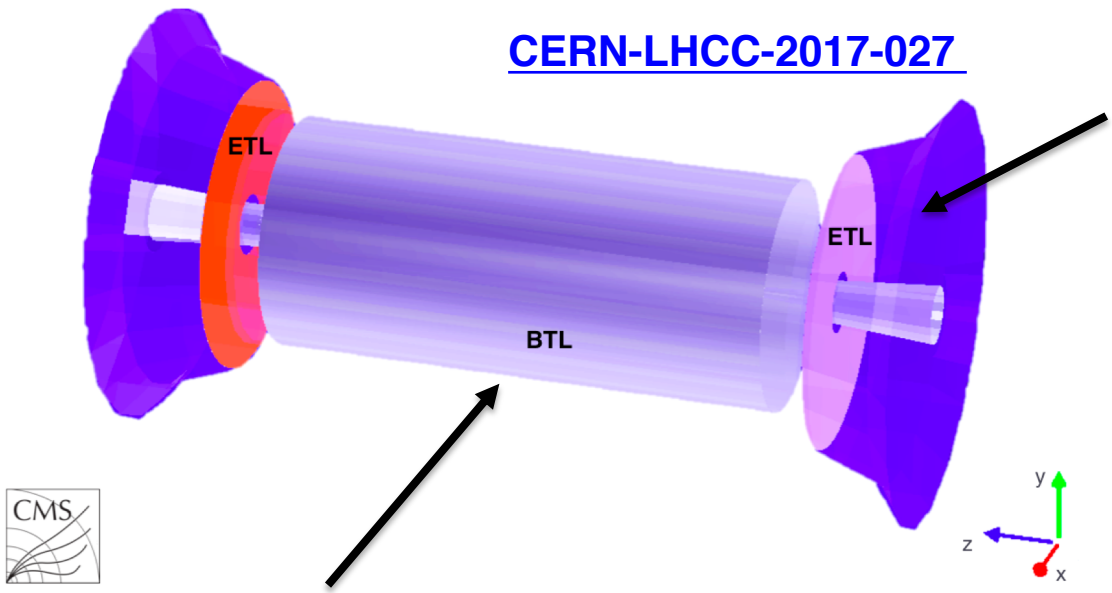
**Barrel Timing Layer:**

- L(Y)SO:Ce crystal bars + SiPM
- Coverage: $|\eta|<1.5$
- Material: $< 0.4\ X_0$
- Time resolution: **~ 30ps**





# CMS Mip Timing Detector

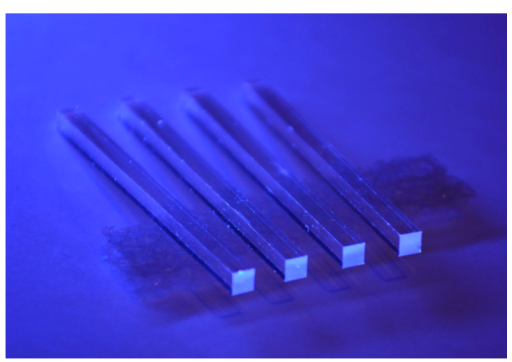


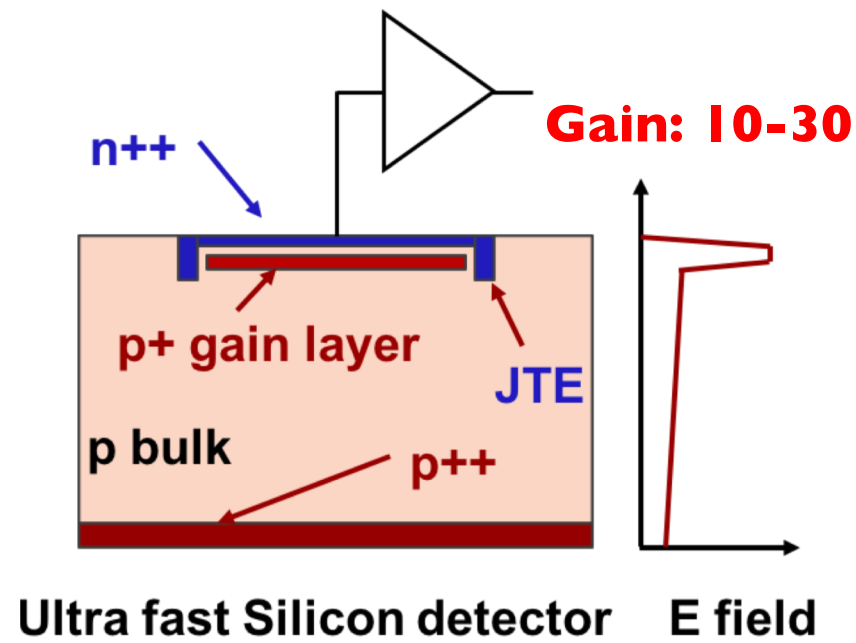

**Endcap Timing Layer:**

- Ultra-fast silicon detectors
- Coverage: $1.6<|\eta|<3.0$
- Material: $< 0.2\ X_0$
- Time resolution: **~ 30ps with two layers**

**Barrel Timing Layer:**

- L(Y)SO:Ce crystal bars + SiPM
- Coverage: $|\eta|<1.5$
- Material: $< 0.4\ X_0$
- Time resolution: **~ 30ps**






Technology for future precision tracker!

# Summary

Remarkable collective phenomena observed across all high-density QCD systems (pp/pA/AA)

- Perfect QGP fluid paradigm in AA

In small systems,

- Origin still under debate in small systems
- New window to probe subnucleonic fluctuations!

Hot QCD physics at EIC? Be prepared for surprises!

# Summary

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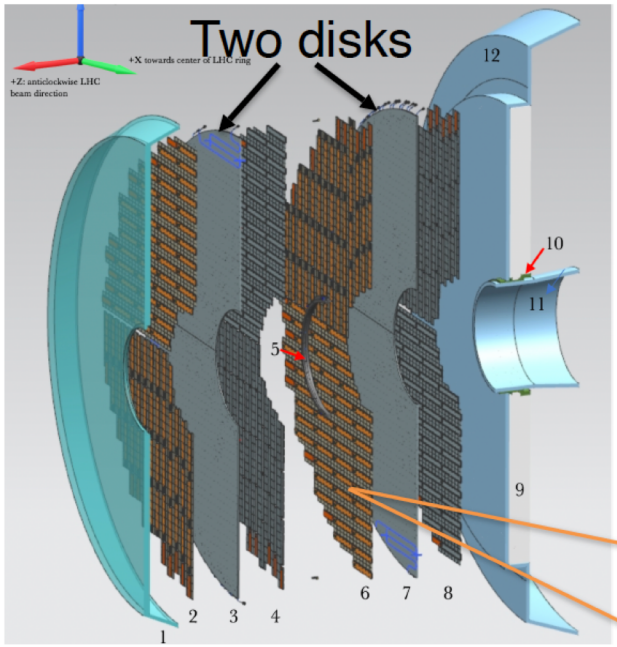
Hot QCD physics at EIC? Be prepared for surprises!

Strong synergy among hot QCD, cold QCD and HEP communities in terms of physics interests and detector innovations

# Backups

# Endcap Timing Layer (ETL)

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## Design:

- 2 disks covering a surface of ~14 $m^2$
- Material budget: < 0.2 $X_0$
- Rapidity coverage: 1.6 < |η| < 3.0
- x10 higher radiation level than BTL
- Timing resolution: ~ 30-50 ps

## Sensors:

- **Ultra fast silicon detectors:**
  - Low gain avalanche diodes optimised for precision timing.

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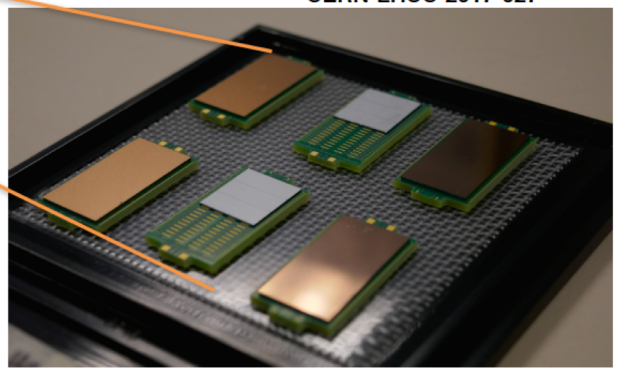

# Barrel Timing Layer (BTL)

## Design:

- 72 trays covering a surface of ~38 $m^2$
- Material budget: < 0.4 $X_0$
- Rapidity coverage: $|\eta| < 1.5$
- Timing resolution: ~ 30 ps


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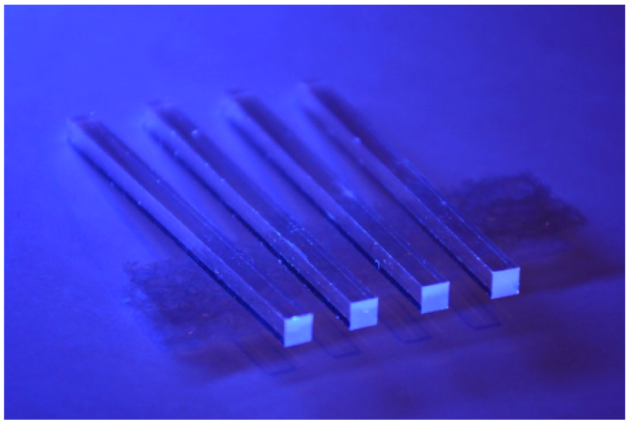
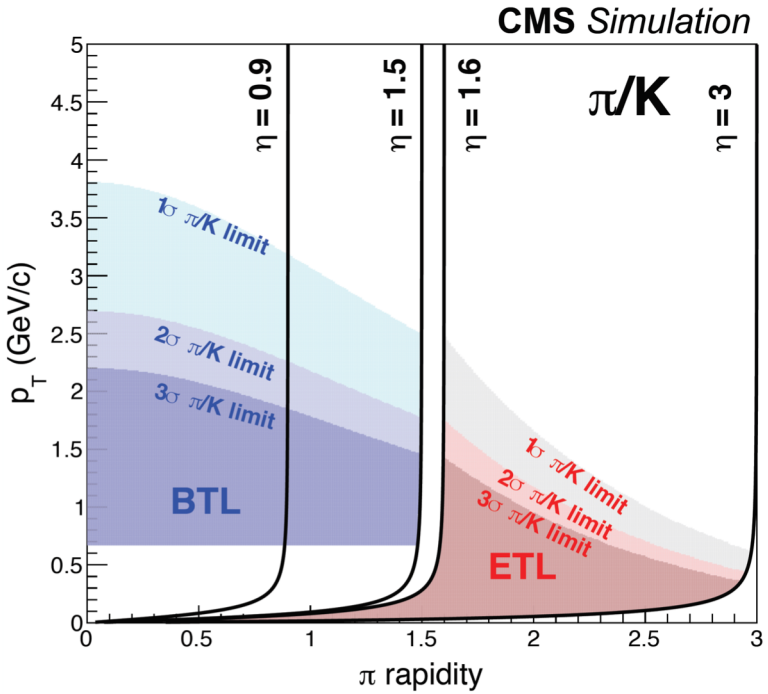
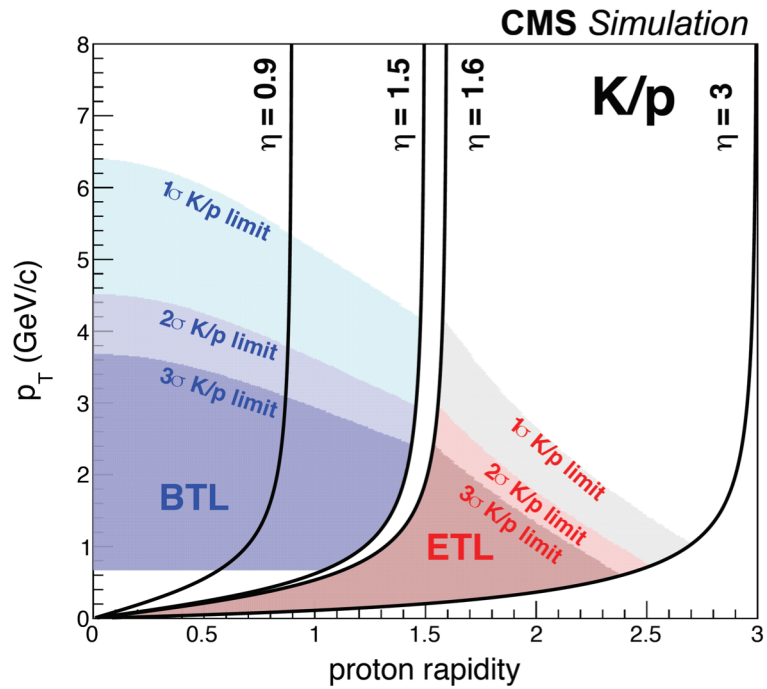
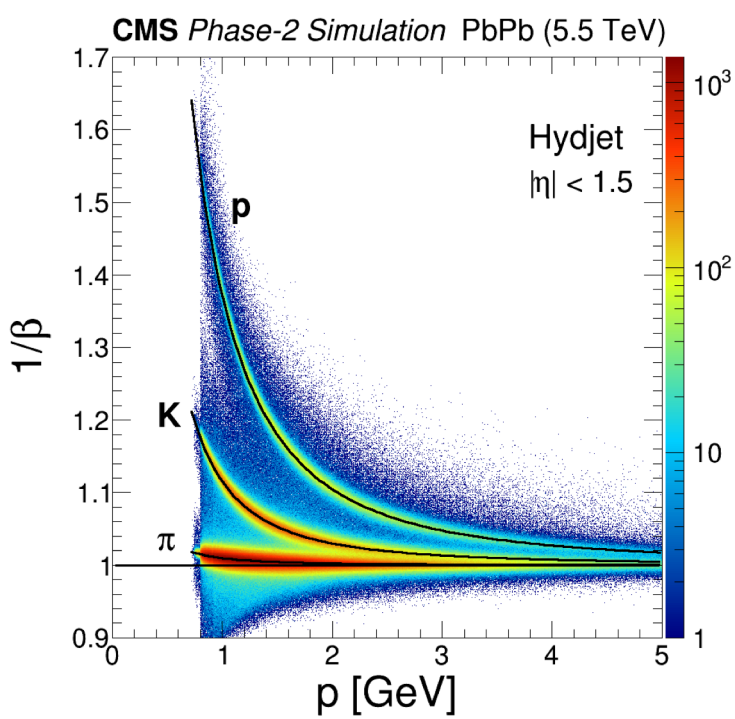


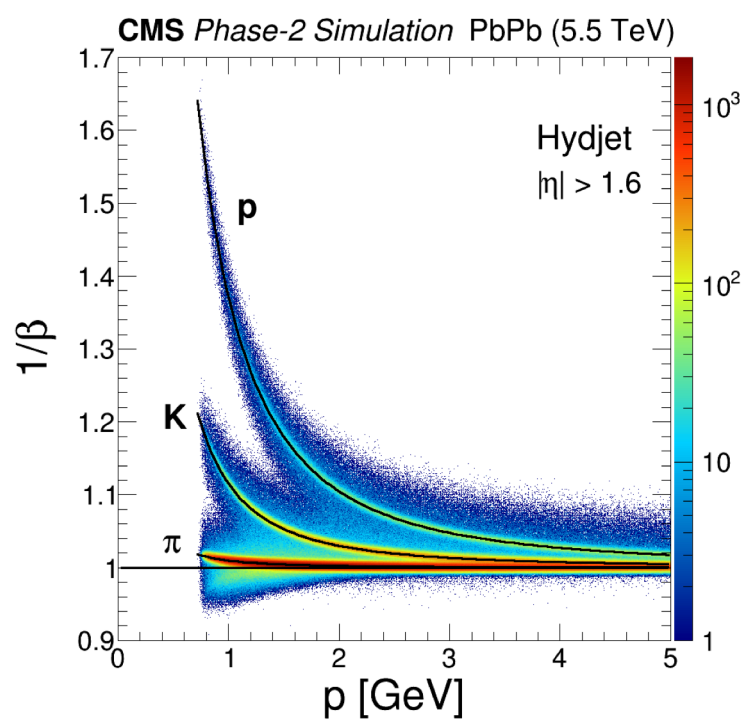
## Sensors:

- **L(Y)SO:Ce crystal** bars as scintillator**:**
  - Excellent radiation tolerance, high signal and fast response time.
- **Silicon Photomultipliers** as detectors:
  - Compact, fast and insensitive to magnetic fields.


CMS Simulation
π/K
η = 0.9
η = 1.5
η = 1.6
η = 3
1σ π/K limit
2σ π/K limit
3σ π/K limit
BTL
ETL
p_T (GeV/c)
π rapidity

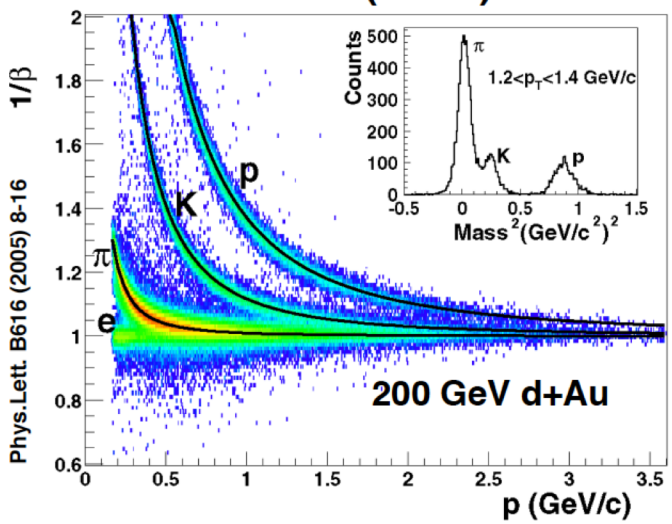

CMS Simulation
K/p
η = 0.9
η = 1.5
η = 1.6
η = 3
1σ K/p limit
2σ K/p limit
3σ K/p limit
BTL
ETL
p_T (GeV/c)
proton rapidity


CMS Phase-2 Simulation PbPb (5.5 TeV)
Hydjet
|η| < 1.5
p
K
π
1/β
p [GeV]

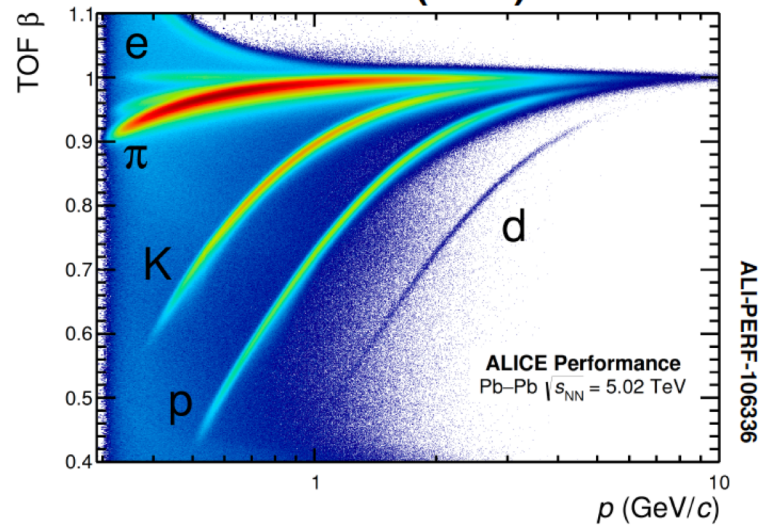

CMS Phase-2 Simulation PbPb (5.5 TeV)
Hydjet
|η| > 1.6
p
K
π
1/β
p [GeV]

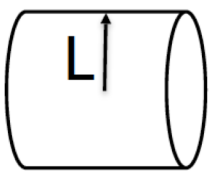
# TOF-PID comparison with ALICE and STAR

**STAR (RHIC)**




**ALICE (LHC)**




| Experiment | $\eta$ coverage | $L$ at $\eta = 0$ (m) | $\sigma_T$ (ps) | $L/\sigma_T$ ($\times 100$) |
|---|---|---|---|---|
| CMS | $\lvert\eta\rvert < 3.0$ | 1.16 | 30 | 3.9 |
| ALICE | $\lvert\eta\rvert < 0.9$ | 3.7 | 56 | 6.6 |
| STAR | $\lvert\eta\rvert < 0.9$ | 2.2 | 80 | 2.2 |

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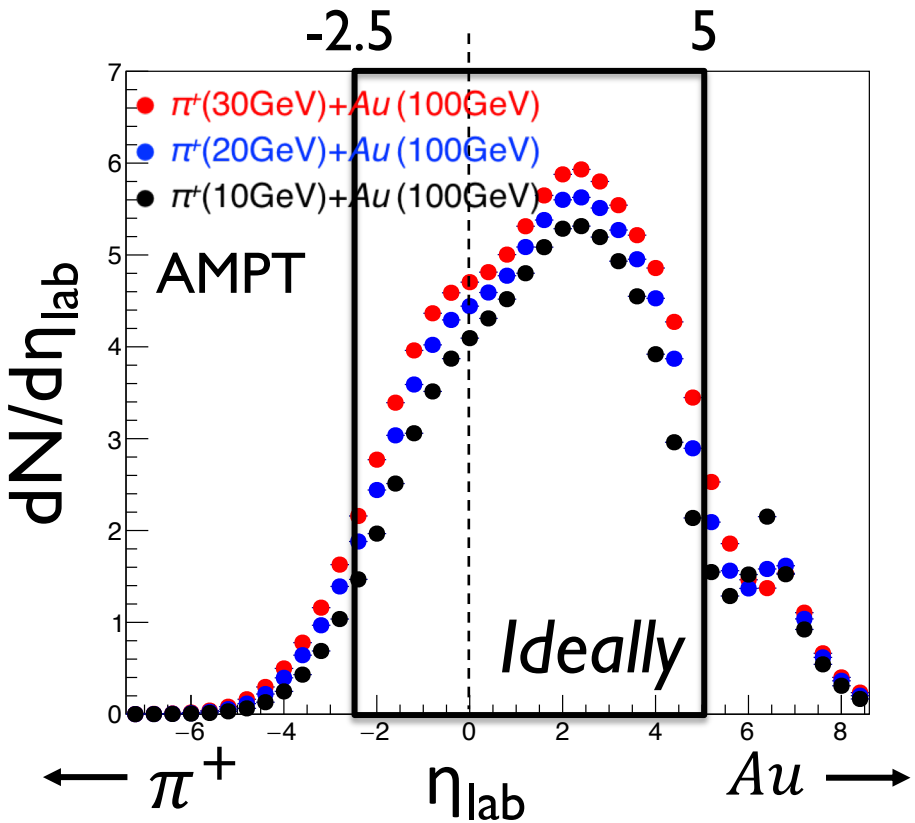
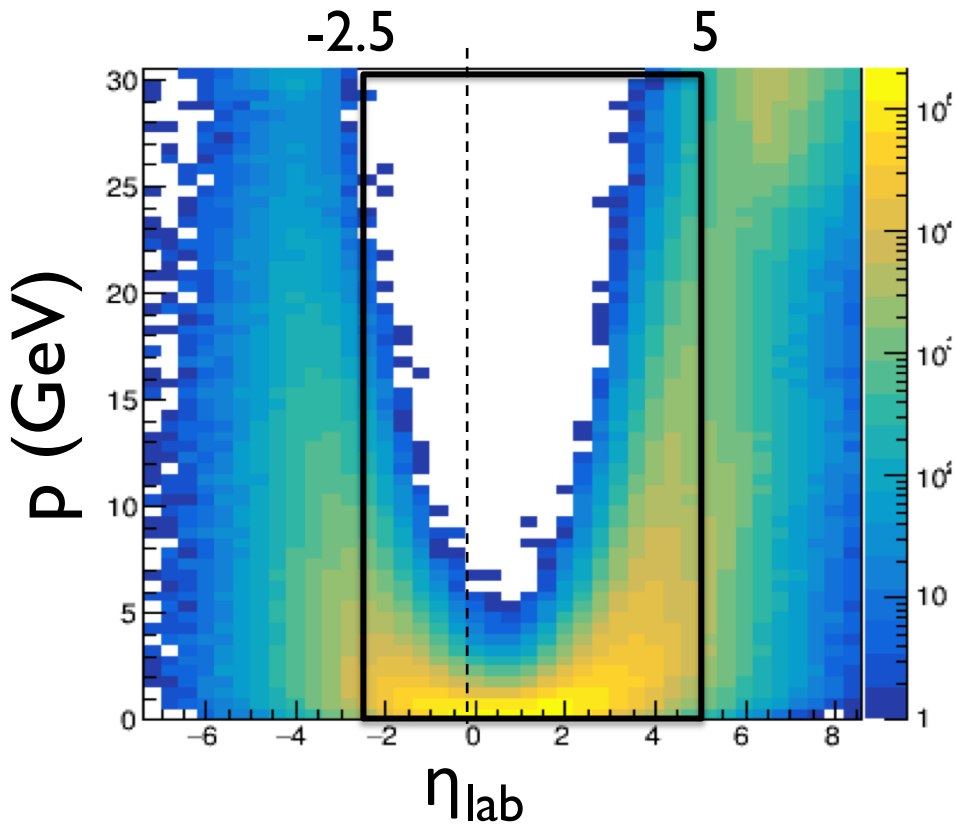
- Competitive momentum coverage compared to ALICE and STAR
- **Unique wider rapidity coverage**

# "Hot QCD matter" at EIC?

## Experimental requirements



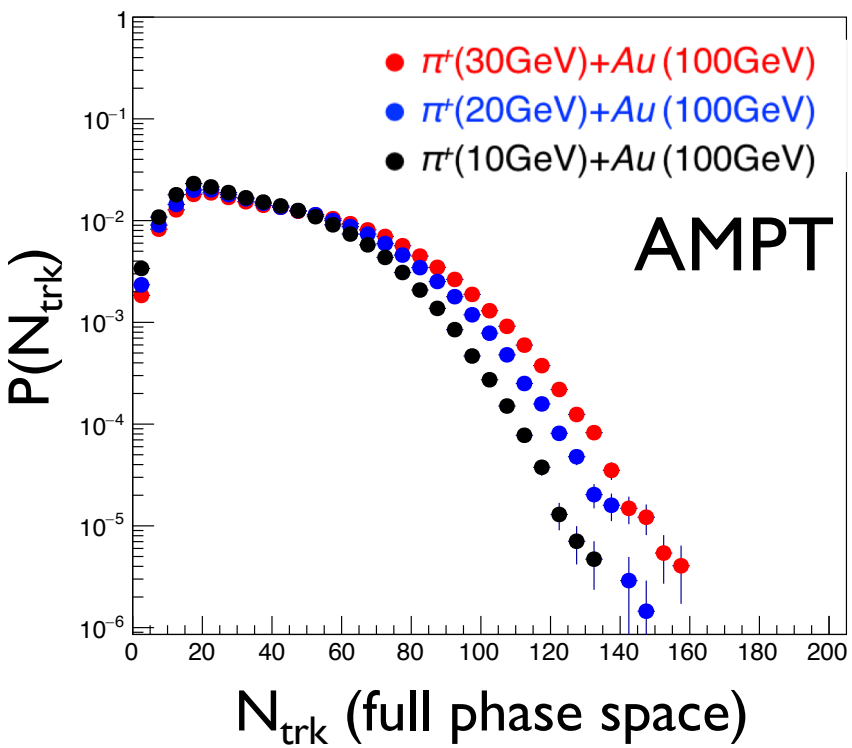




- ✓ Wide η coverage (> 5-6 units)
- ✓ Good $p_T$ resolution (forward tracking)
- ✓ PID up to high momentum (RICH)
- ✓ Fast online trigger (w/ tracking)

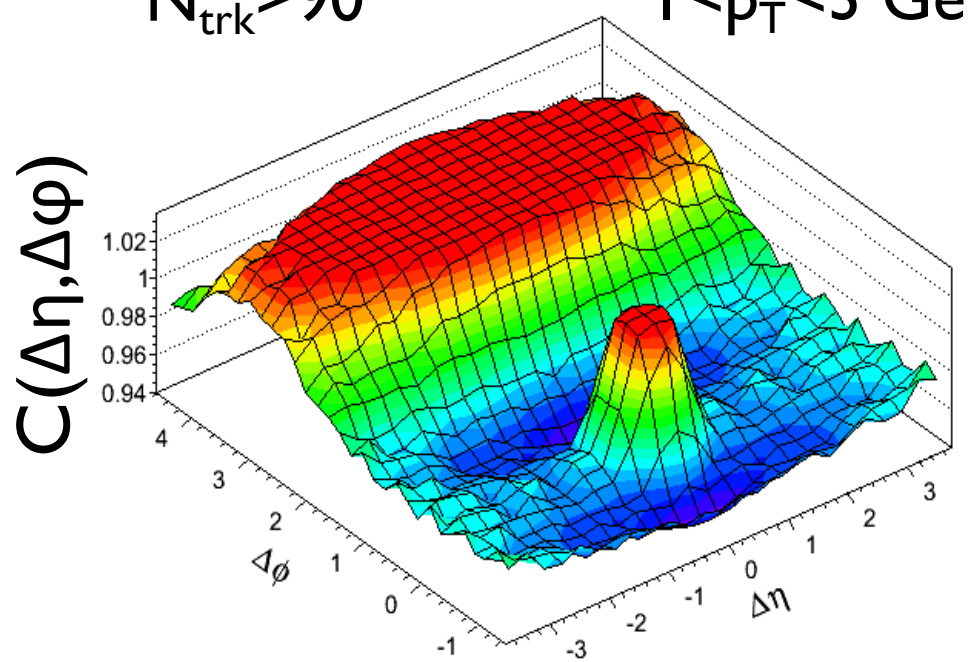
# Hot QCD matter at EIC?

***π⁺***(30GeV)+***Au***(100GeV) from AMPT

Multiplicity distribution



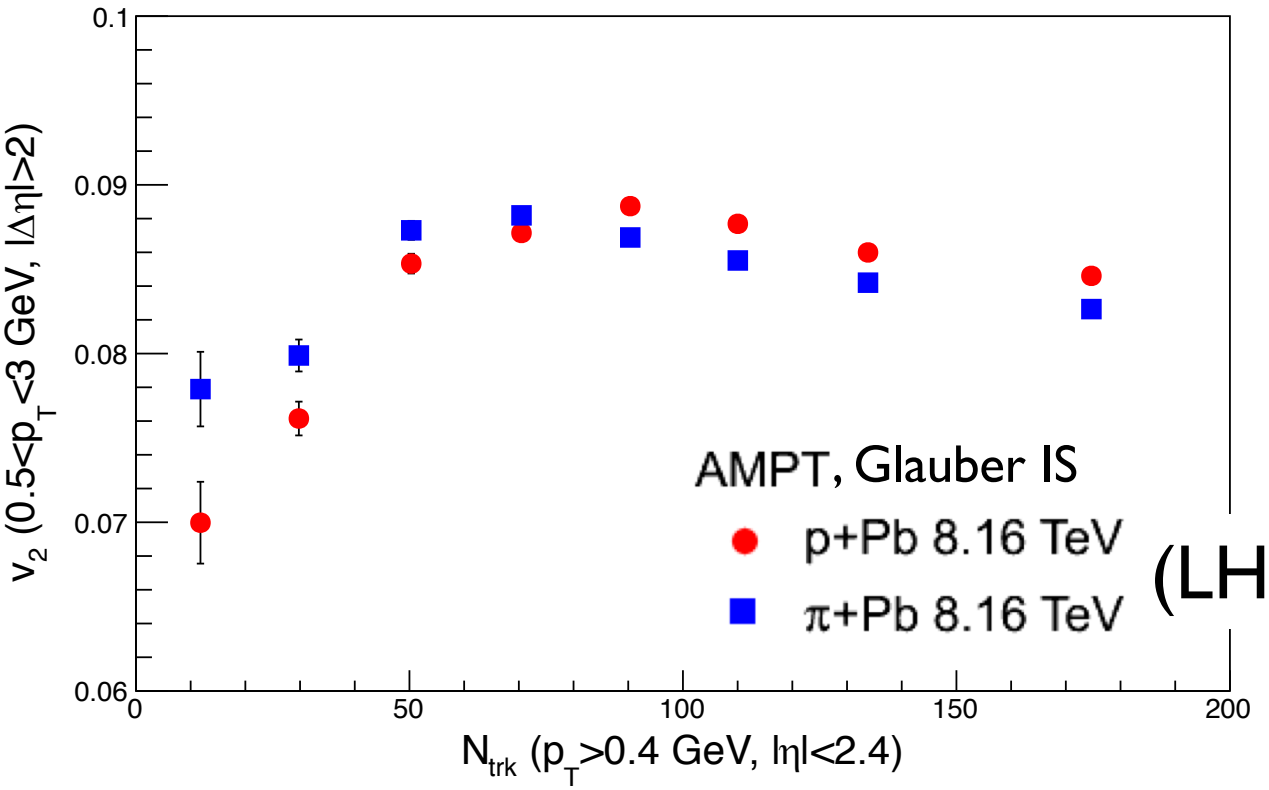

$N_{trk}$>90 $1<p_T<3$ GeV




A long-range ridge can be observed at EIC in high-multiplicity e+Au events!

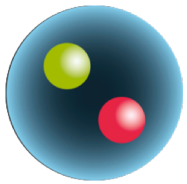
# Hot QCD matter at EIC?

Comparing $v_n$ in (qqq)+A vs ($q\bar{q}$)+A




(LHC energies)

- Disentangle "hydro" vs CGC?
- Insight on subnucleonic fluctuations?



v.s.