# QCD collective phenomena in ***small*** systems – where (else) and how to find it

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U.S. DEPARTMENT OF ENERGY
Office of Science

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Intersection of nuclear structure and high-energy nuclear collisions
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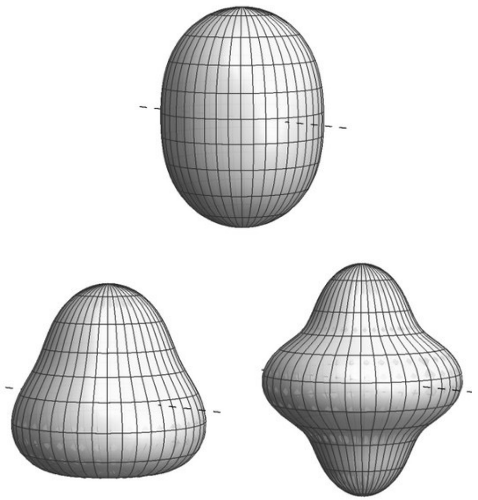
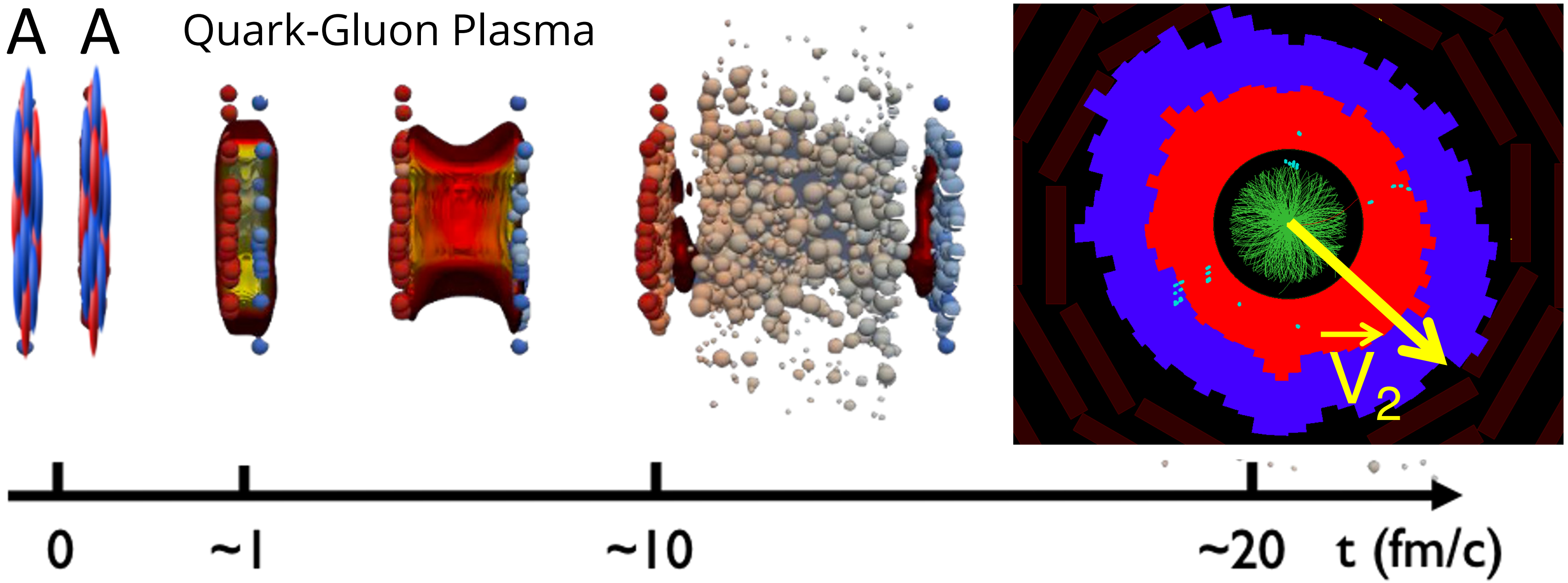
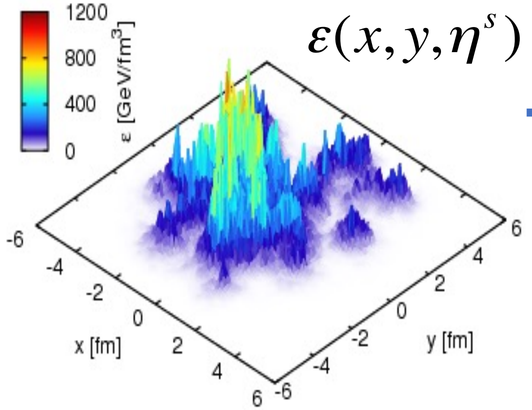
RICE

# Standard paradigm of heavy ion collisions






Initial state:




$\varepsilon(x,y,\eta^s)$

→

**Hydrodynamics**

$\partial_\mu T^{\mu\nu} = 0$ (η, ζ, ...)

→

Final-state collective flow:

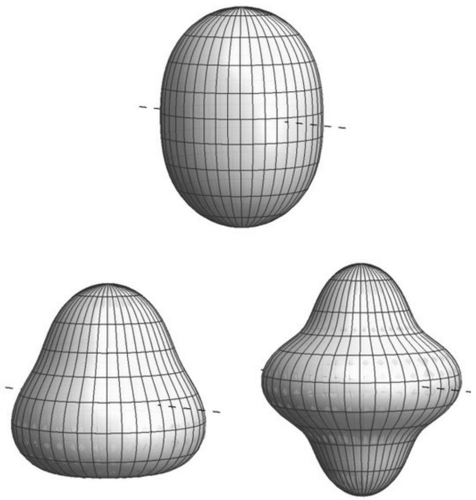
$$f(p_T,\eta,\phi) = N(p_T,\eta)\sum_{n=-\infty}^{+\infty}\vec{V}_n(p_T,\eta)e^{-in\phi}$$

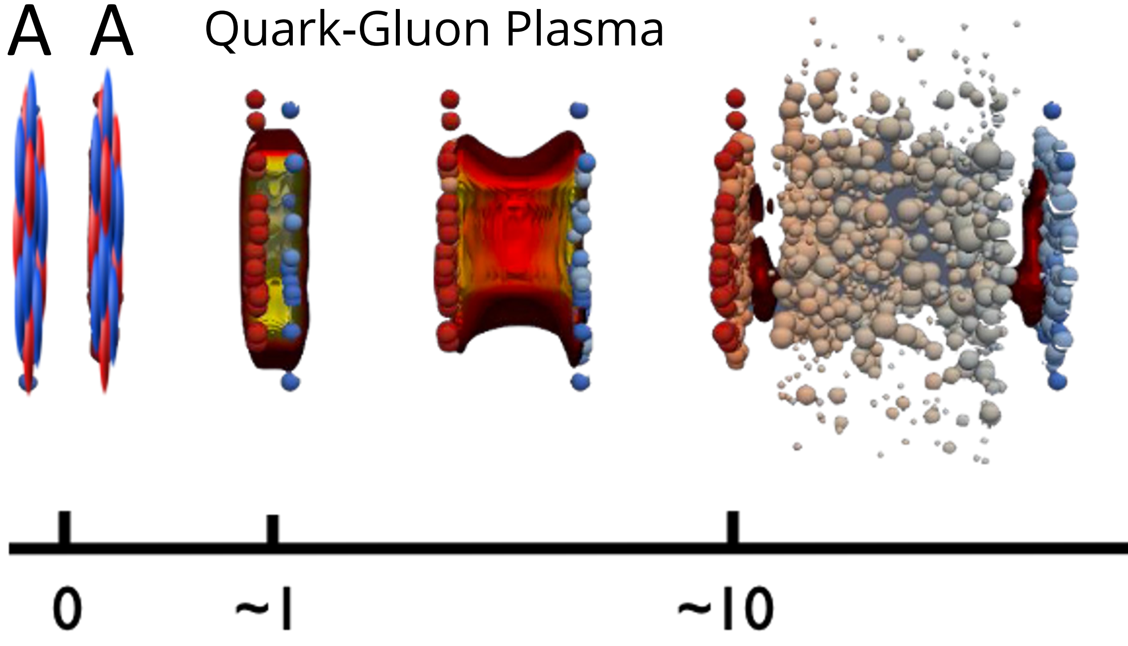
Radial flow

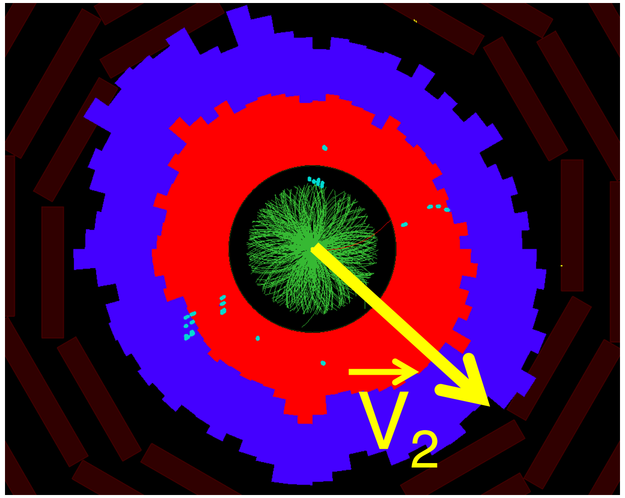
Anisotropy flow

$\vec{V}_n = v_n e^{in\Psi_n}$

# Standard paradigm of heavy ion collisions



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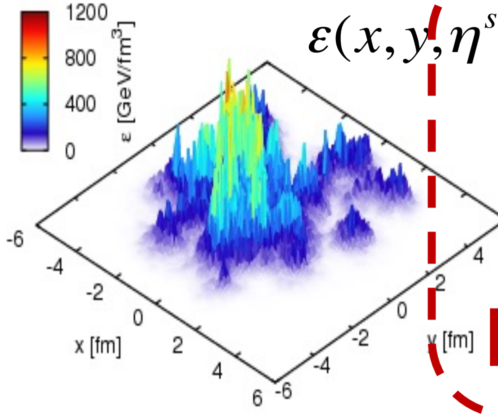


$\varepsilon(x, y, \eta^s)$ →

**Hydrodynamics**

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Radial flow

Anisotropy flow

$\vec{V}_n = v_n e^{in\Psi_n}$

**How good? Why it works?**

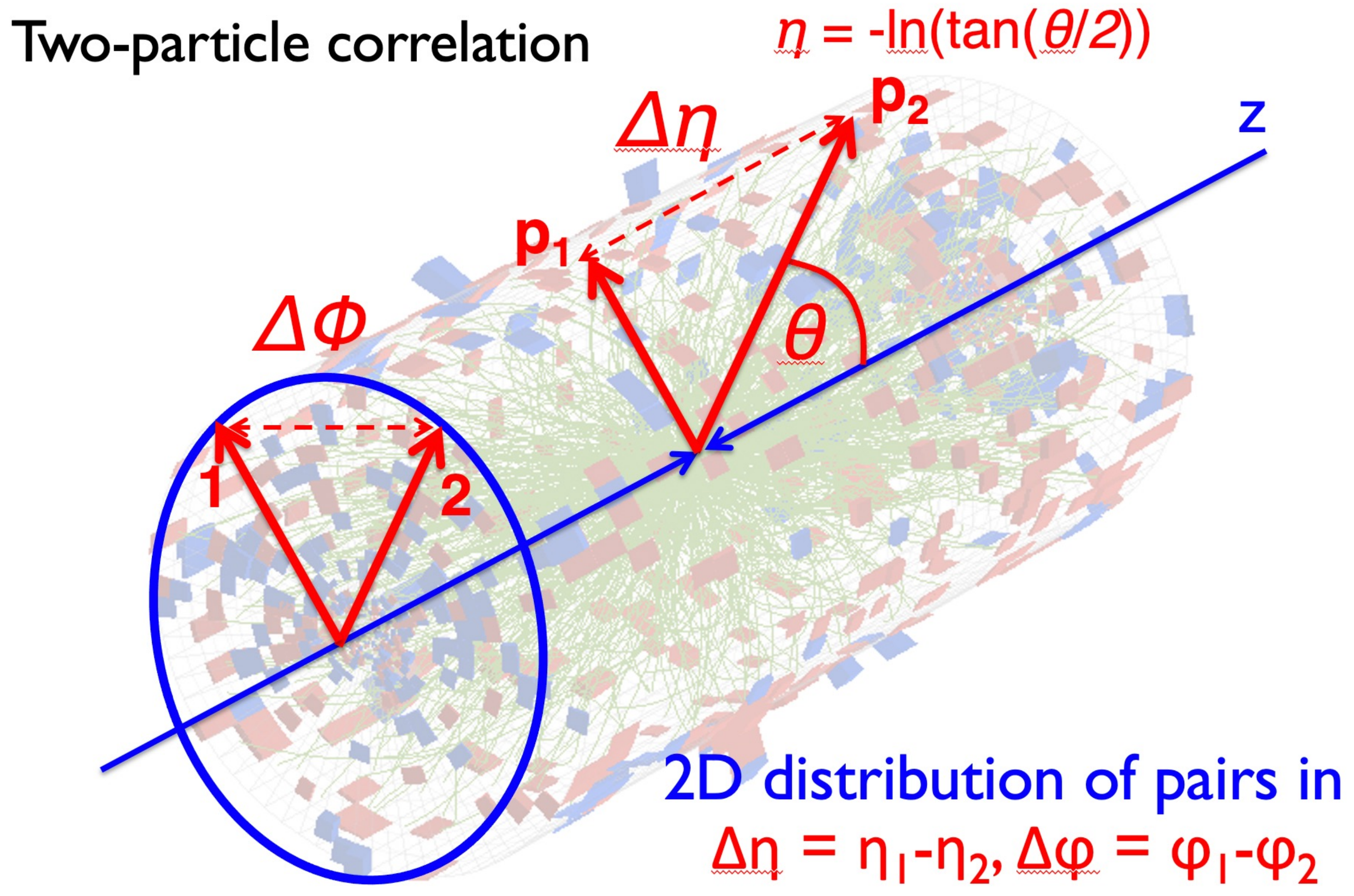
# Strong flow signal was once considered a puzzle in AA!

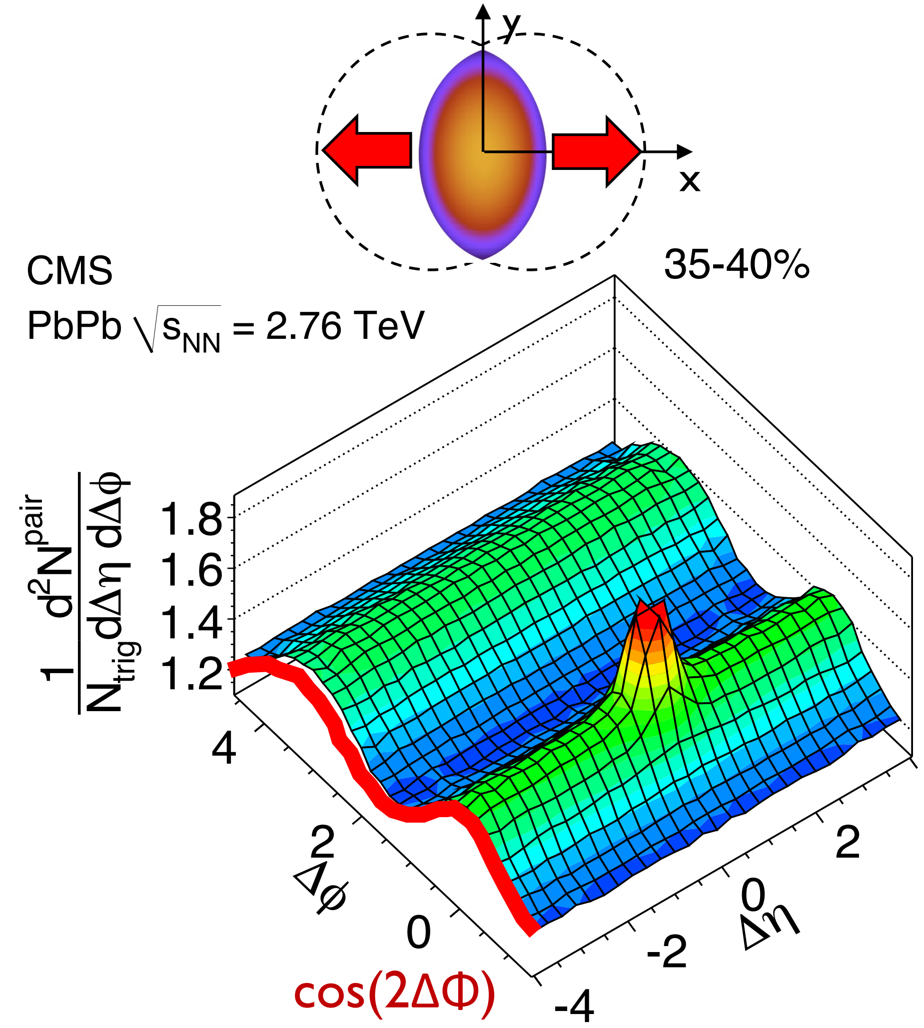
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

As a result of these recent advances, we now know that the η/s of QGP is very close to a fundamental quantum limiting value deduced for the extreme hypothetical case when the quarks and gluons have infinitely strong interactions—an extreme that can, remarkably, be theoretically related to the physics of gravitons falling into a black hole. While QCD does, of course, describe quark and gluon interactions, the emergent phenomenon that a macroscopic volume of quarks and gluons at extreme temperatures would form a nearly perfect liquid came as a complete surprise and has led to an intriguing puzzle. A perfect liquid would not be expected to have particle excitations, yet QCD is definitive in predicting that a microscope with sufficiently high resolution would reveal quarks and gluons interacting *weakly* at the shortest distance scales within QGP. Nevertheless, the η/s of QGP is so small that there is no sign in its macroscopic motion of any microscopic particlelike constituents; all we can see is a liquid. To this day, nobody understands this dichotomy: how do quarks and gluons conspire to form strongly coupled, nearly perfect liquid QGP?

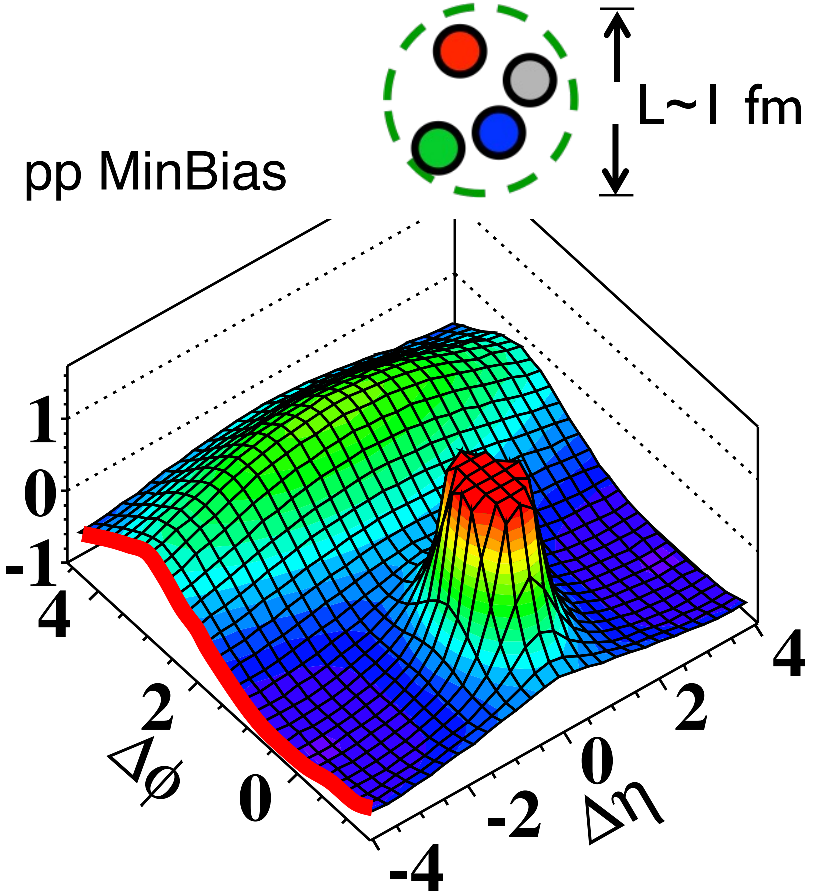
In the hindsight, is it still a puzzle?
Or it may be naturally expected and related to fundamental nature of QCD?

# Flow, "Ridge", two-particle correlations …

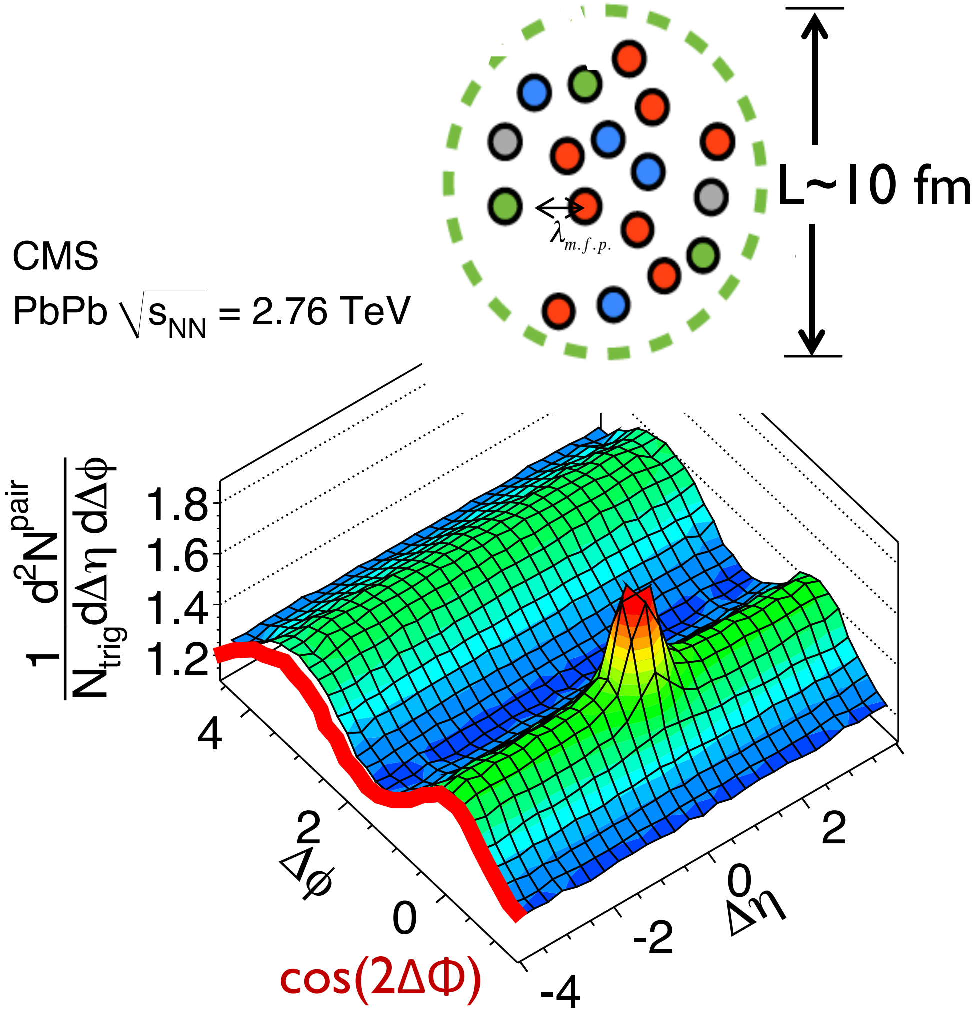


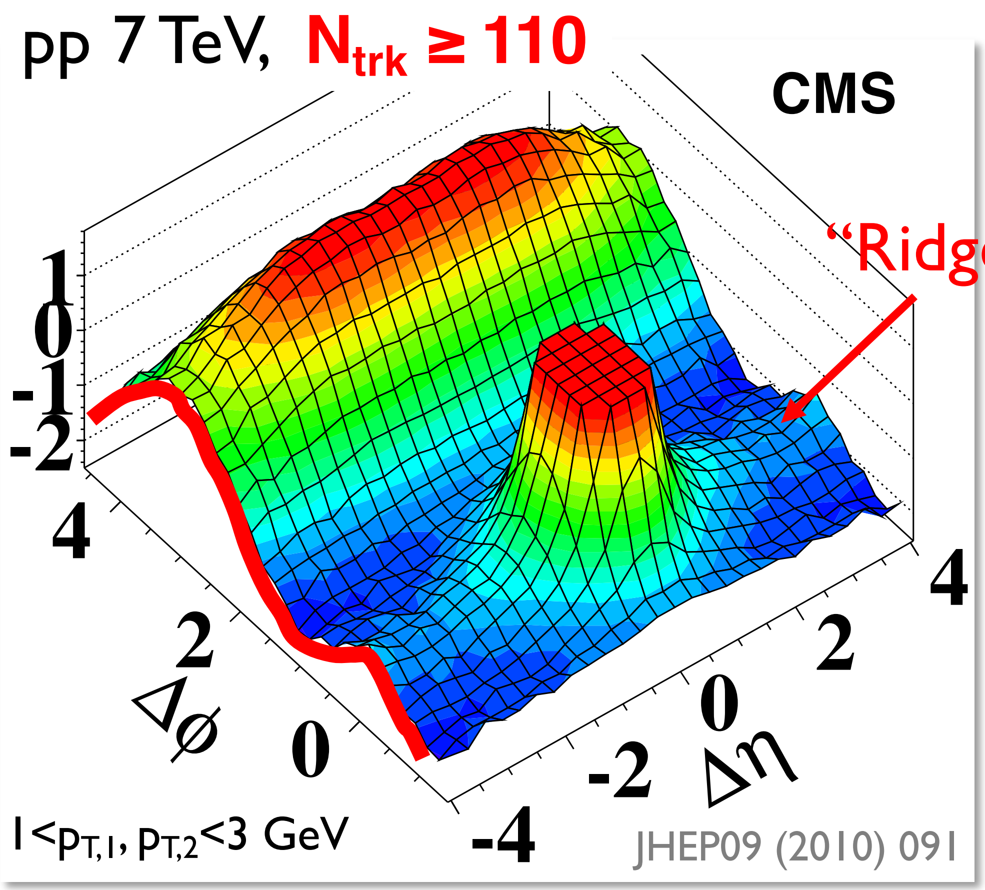
# Flow, "Ridge", two-particle correlations …



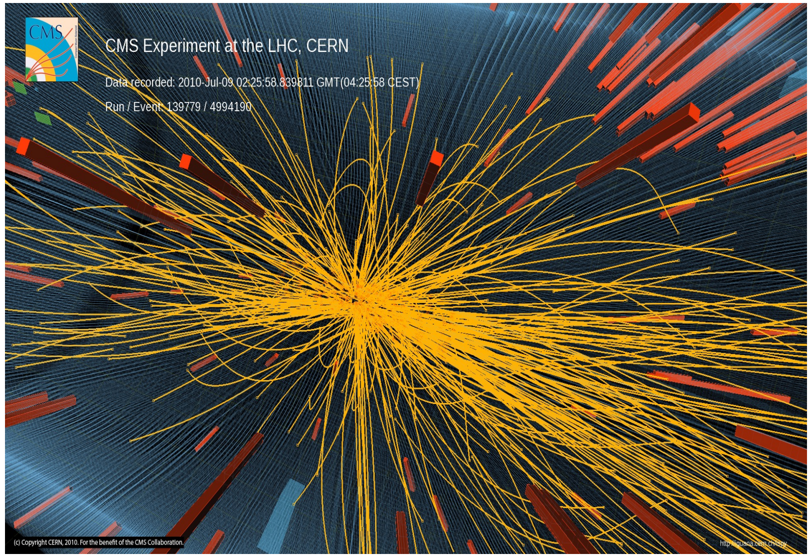

QGP diminishes as L ~ $\lambda_{m.f.p.}$(?)



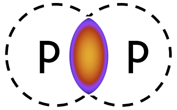
# 2010 surprise – "Ridge" in pp at the LHC




Rare, high multiplicity pp, $N_{trk}$>110

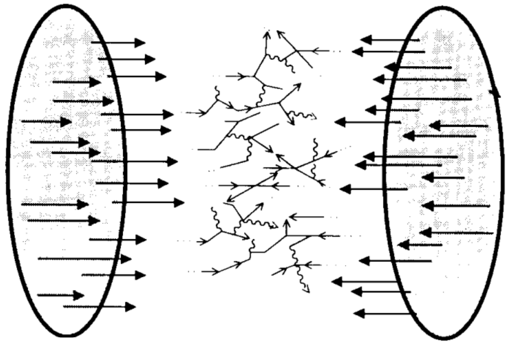



*Small but much denser!*

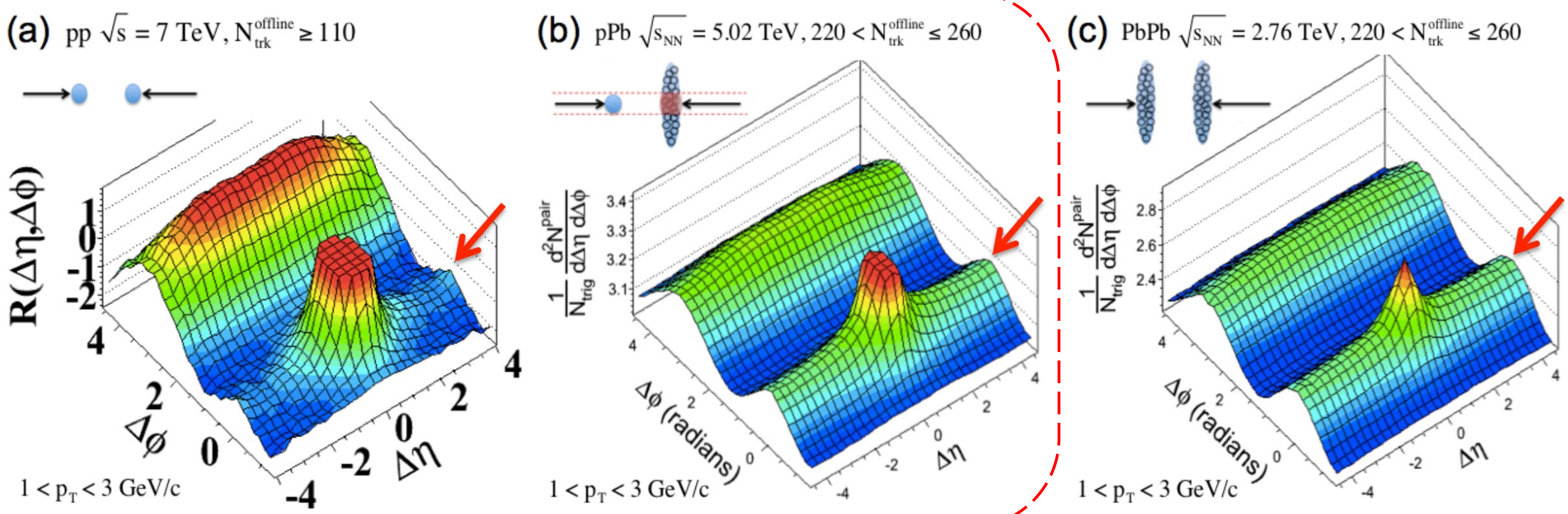
A QGP droplet at sub-fermi scales in pp?  ?

Or there is NO QGP anywhere?!

# “QGP” from large to small systems!?

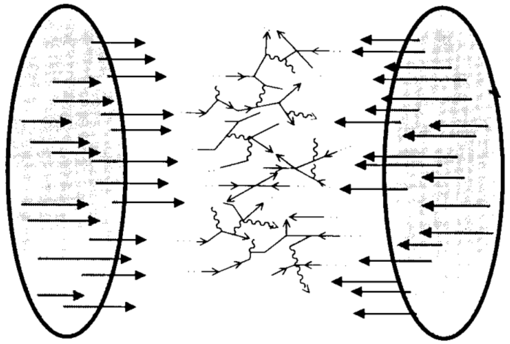


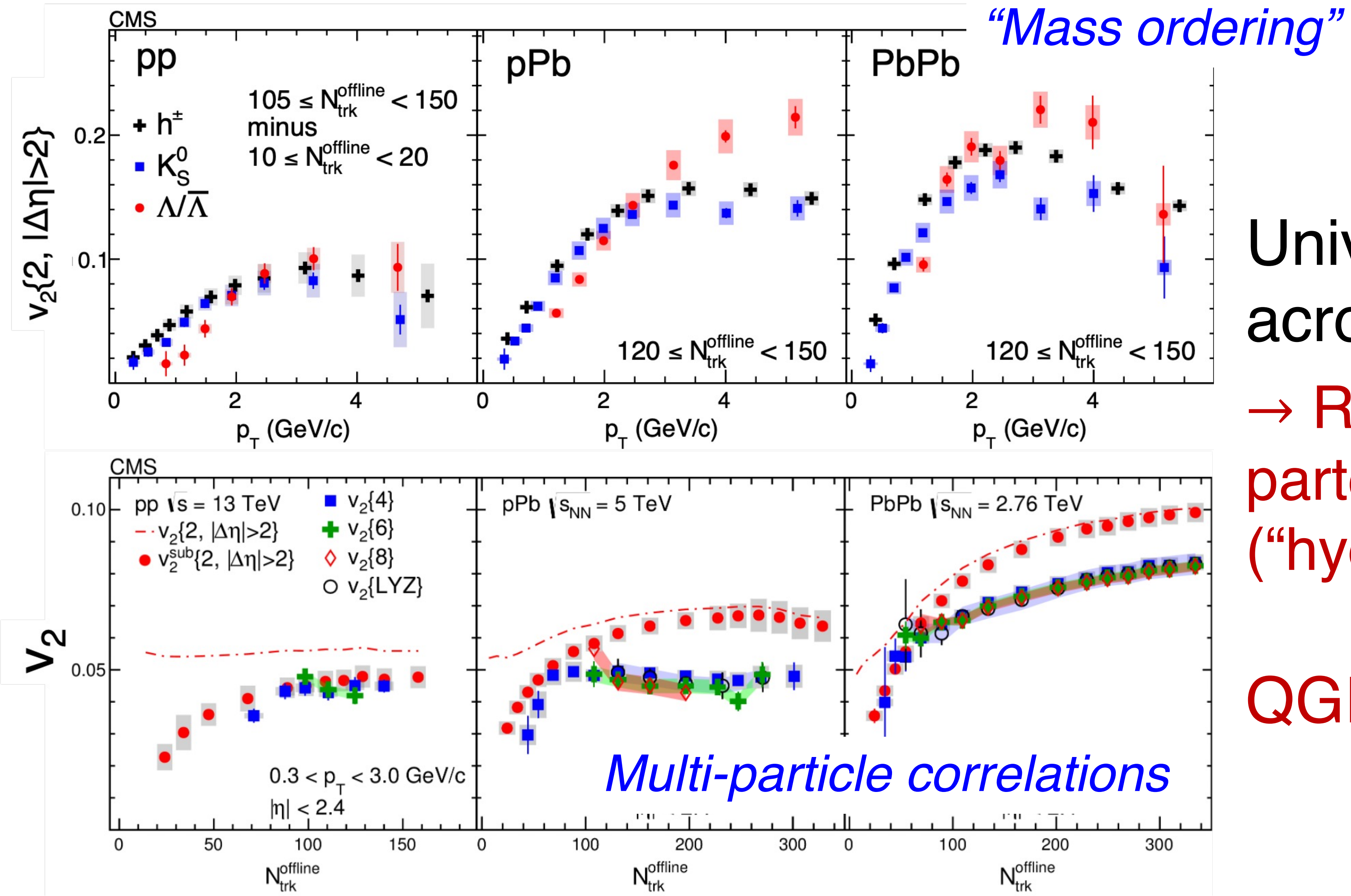
*High-multiplicity*




Surprising at a first look but not unfeasible if considering **(rare) MPIs + rescatterings** in a (longer-lived) pp system

# "QGP" signatures in small systems!?



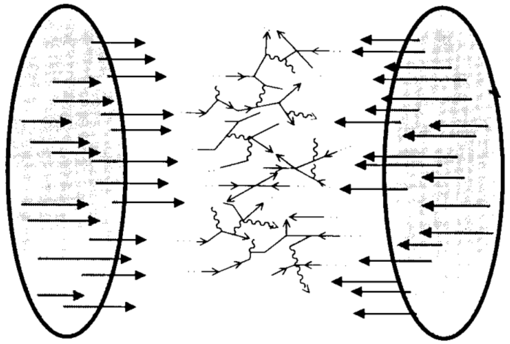


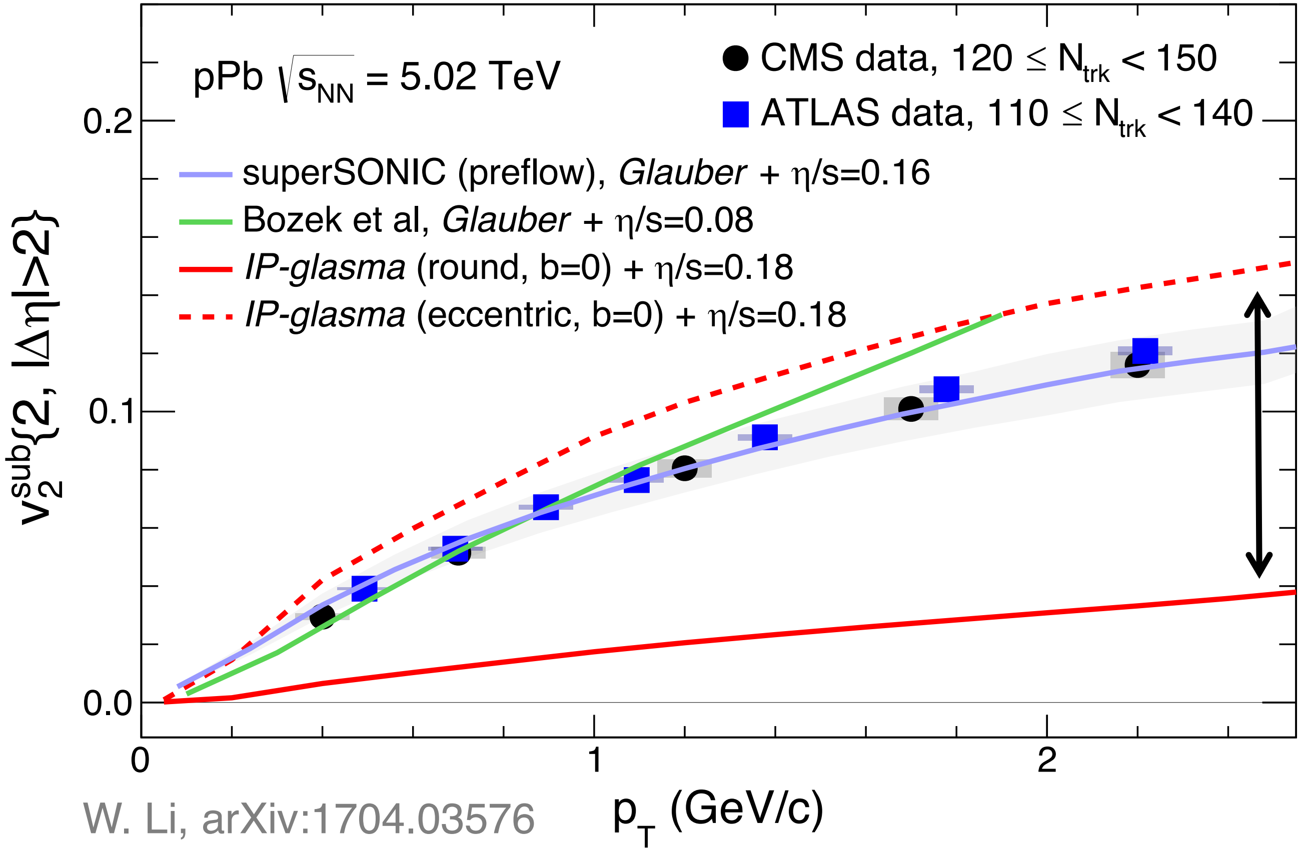

Universal QCD collectivity across AA, pA to pp

→ Role of strong final-state partonic rescatterings ("hydro") at sub-fermi scales

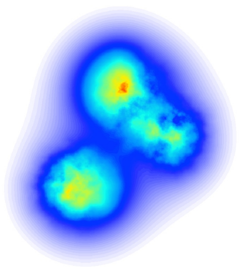
QGP everywhere!?

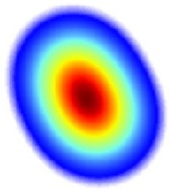
# “QGP” signatures in small systems!?





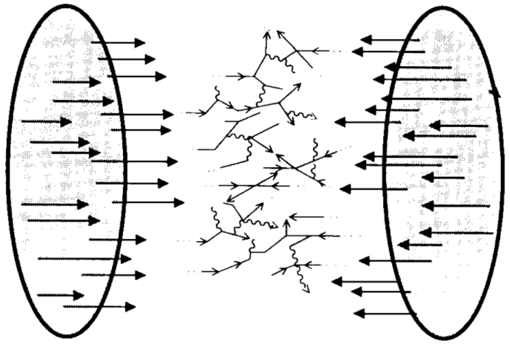

W. Li, arXiv:1704.03576



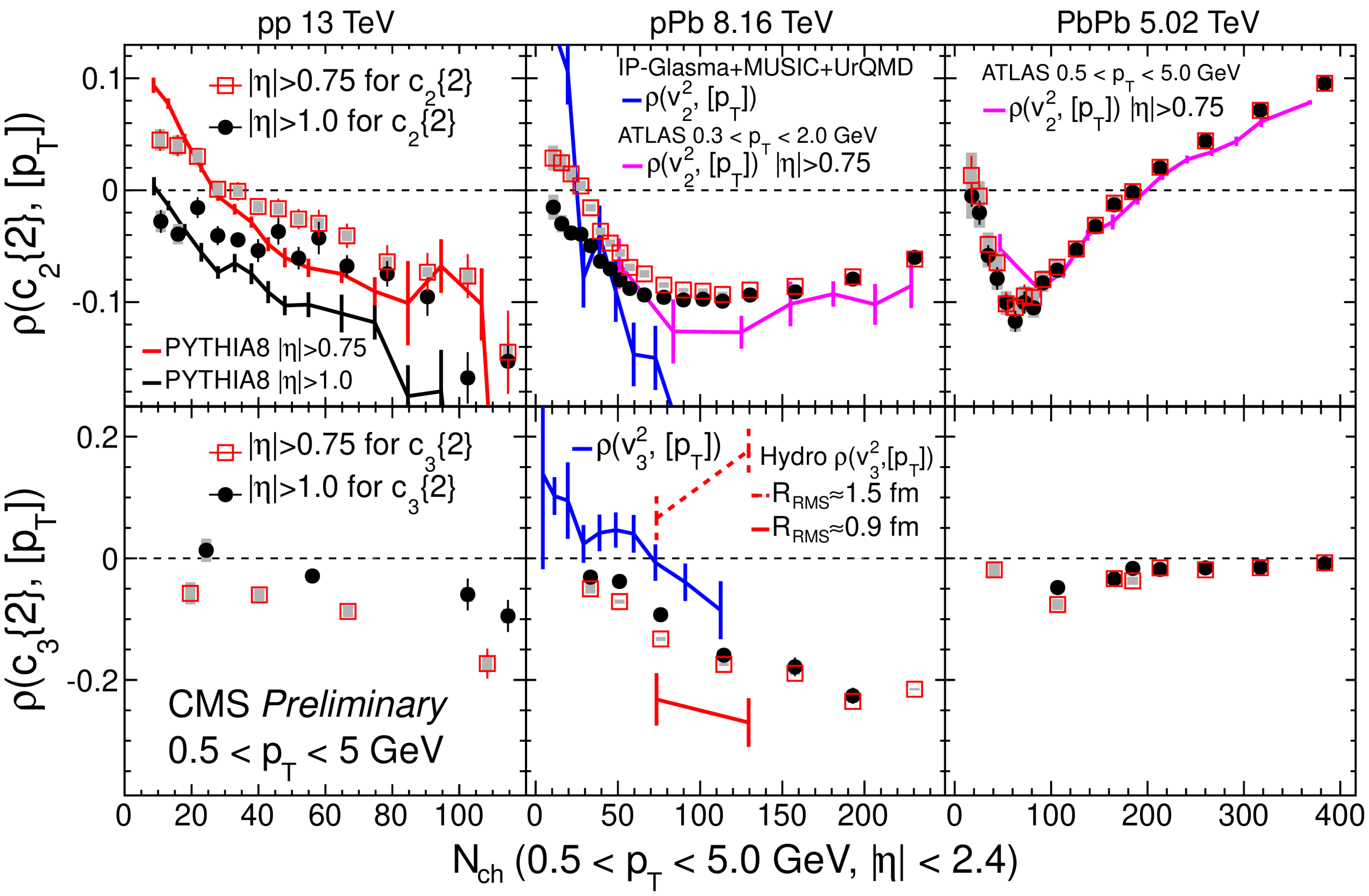


“Flow” in pp/pA sensitive to the initial geometry, esp. “proton shape”

# “QGP” signatures in small systems!?



$v_n$-$p_T$ correlation from pp, pPb to PbPb



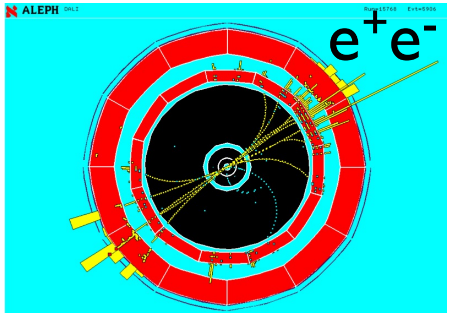
# How small a QGP droplet can be?

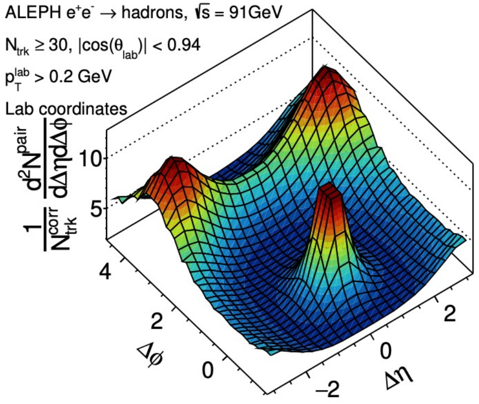
It is evident that QCD collectivity or signatures of QGP liquid are not limited to large AA systems:

- *How small is too small? Under what conditions would partonic collectivity emerge, e.g., multiplicity?*
- ***Is partonic collectivity observed at extreme small scales really unexpected or a natural consequence of QCD in its non-perturbative regime?***

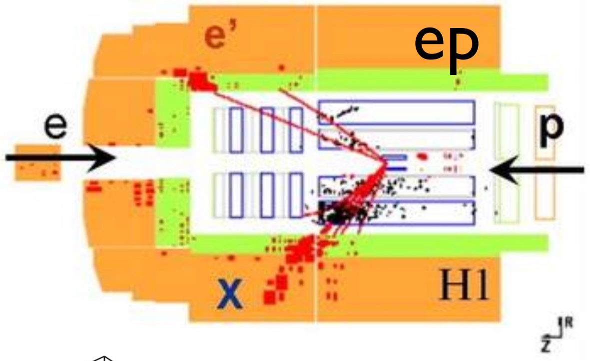
Unlike QED, QCD force is intrinsically strong at low T. In this sense, emergence of a strongly correlated QED system is more puzzling.

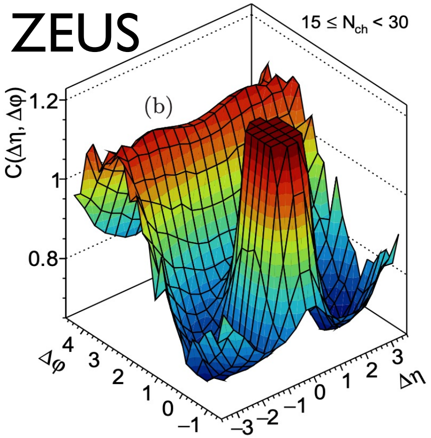
# Search for collectivity in $e^+e^-$, ep, $\gamma$A/ $\gamma$p?

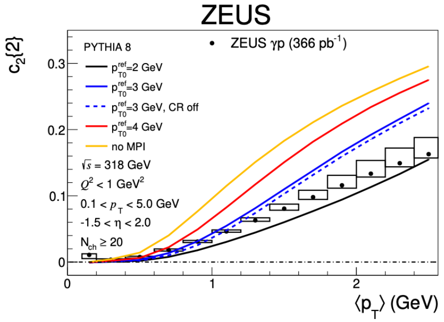


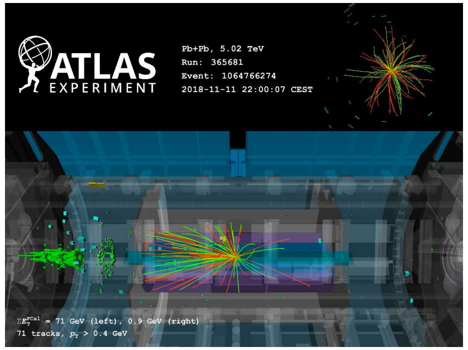

PRL 123, 212002 (2019)

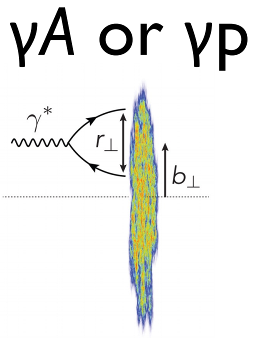


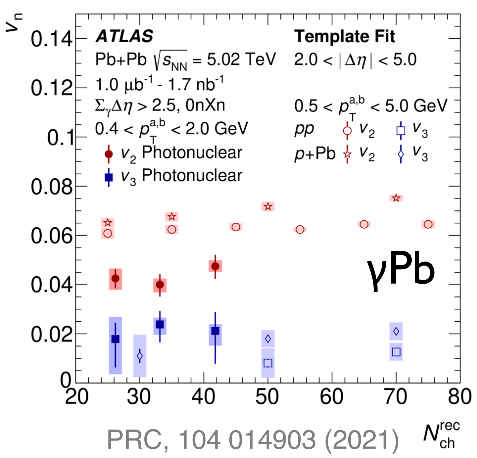



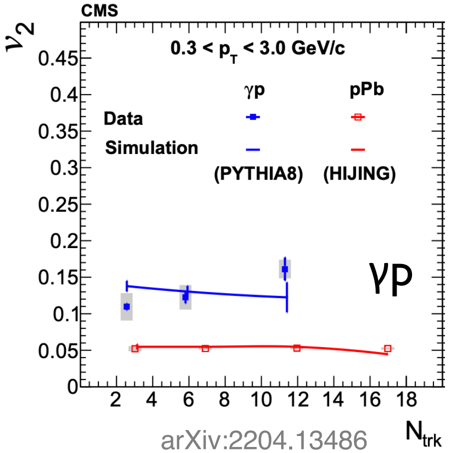

JHEP 04 (2020) 070




PRC, 104 014903 (2021)

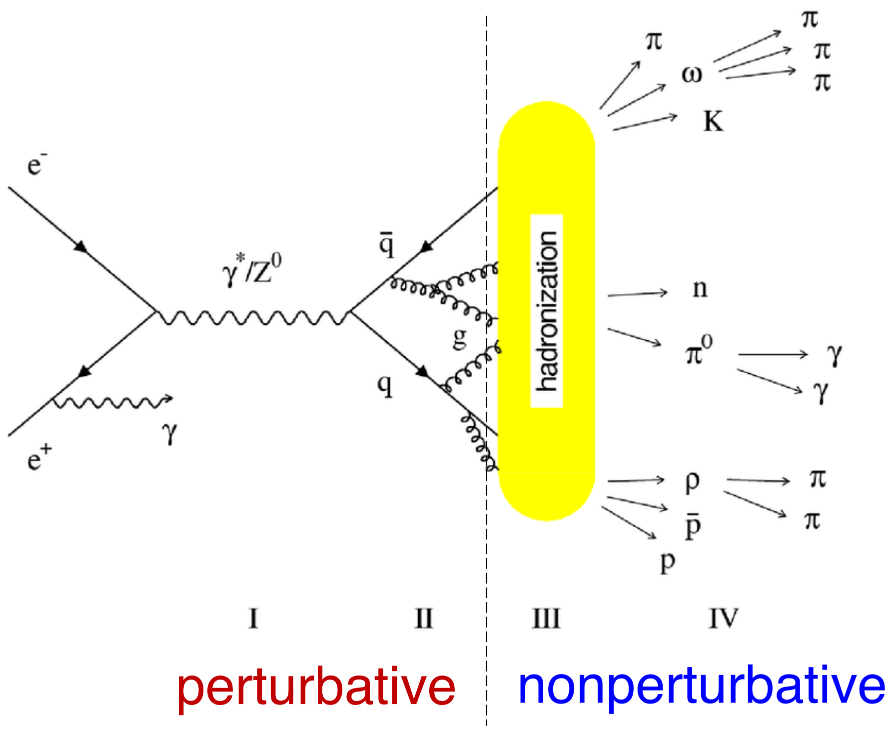



arXiv:2204.13486

Inconclusive but potentially intriguing. Multiplicity reach is a main limitation:

- ➢ High multiplicity is not necessarily a requirement for collectivity to emerge but critical in making it stand out of non-collective backgrounds.
- ➢ More observables are needed, as for pp/pA/AA.

# An earlier puzzle in $e^+e^-$




**A thermodynamical approach to hadron production in $e^+e^-$ collisions**

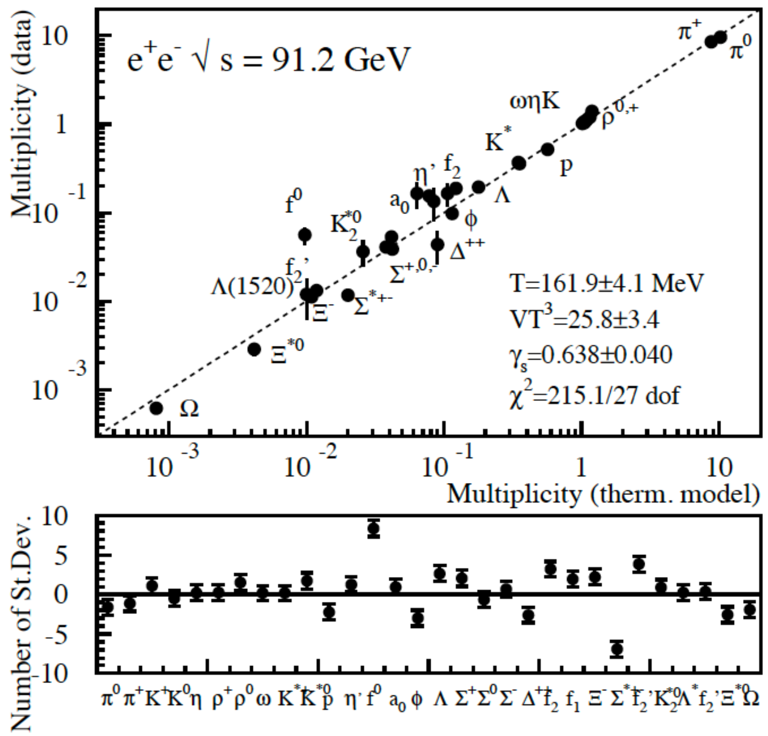

F. Becattini

Università di Firenze and INFN Sezione di Firenze, Largo E. Fermi 2, I-50125 Firenze, Italy (e-mail: becattini@vaxfi.fi.infn.it)



Received: 17 May 1995


F. Becattini et. al., EPJC (2010) 66, 377



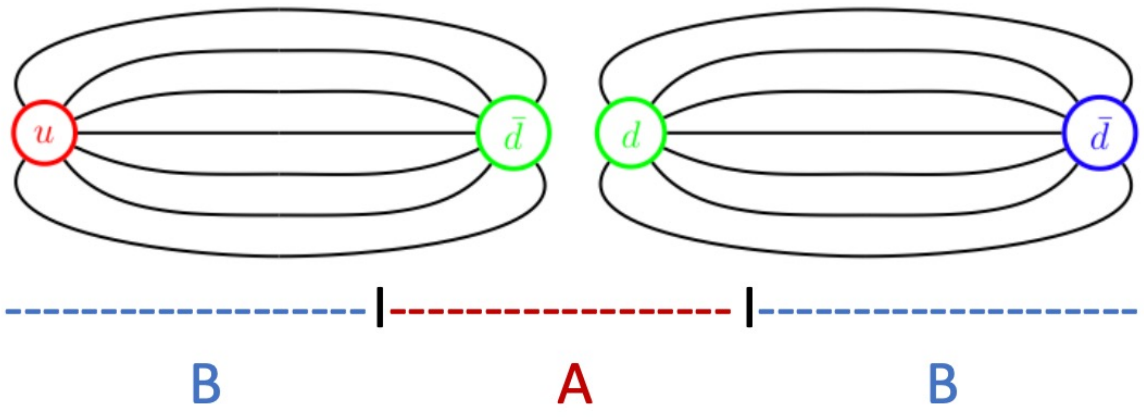

"It is commonly believed that elementary collisions, such as $e^+e^-$, do not allow the description of multiple parton rescatterings." – but not proven!

Quantum thermalization via entanglement entropy? JHEP 04 (2018) 145, PRD 98, 054007 (2018)

# Entanglement in an expanding QCD string

J. Berges, S. Floerchinger, R. Venugopalan
JHEP 04 (2018) 145, PRD 98, 054007 (2018)

Particle production from QCD strings




Different regions (A, B) in a string are entangled

A local region, A, is in a mixed state

$$\rho_A = \mathrm{Tr}_B\{\rho\}$$

Entanglement entropy $S_A = -\mathrm{Tr}_A\{\rho_A \ln \rho_A\}$ drives system to "**Thermalization**" but NO **"Ridge"** (no final-state rescatterings)

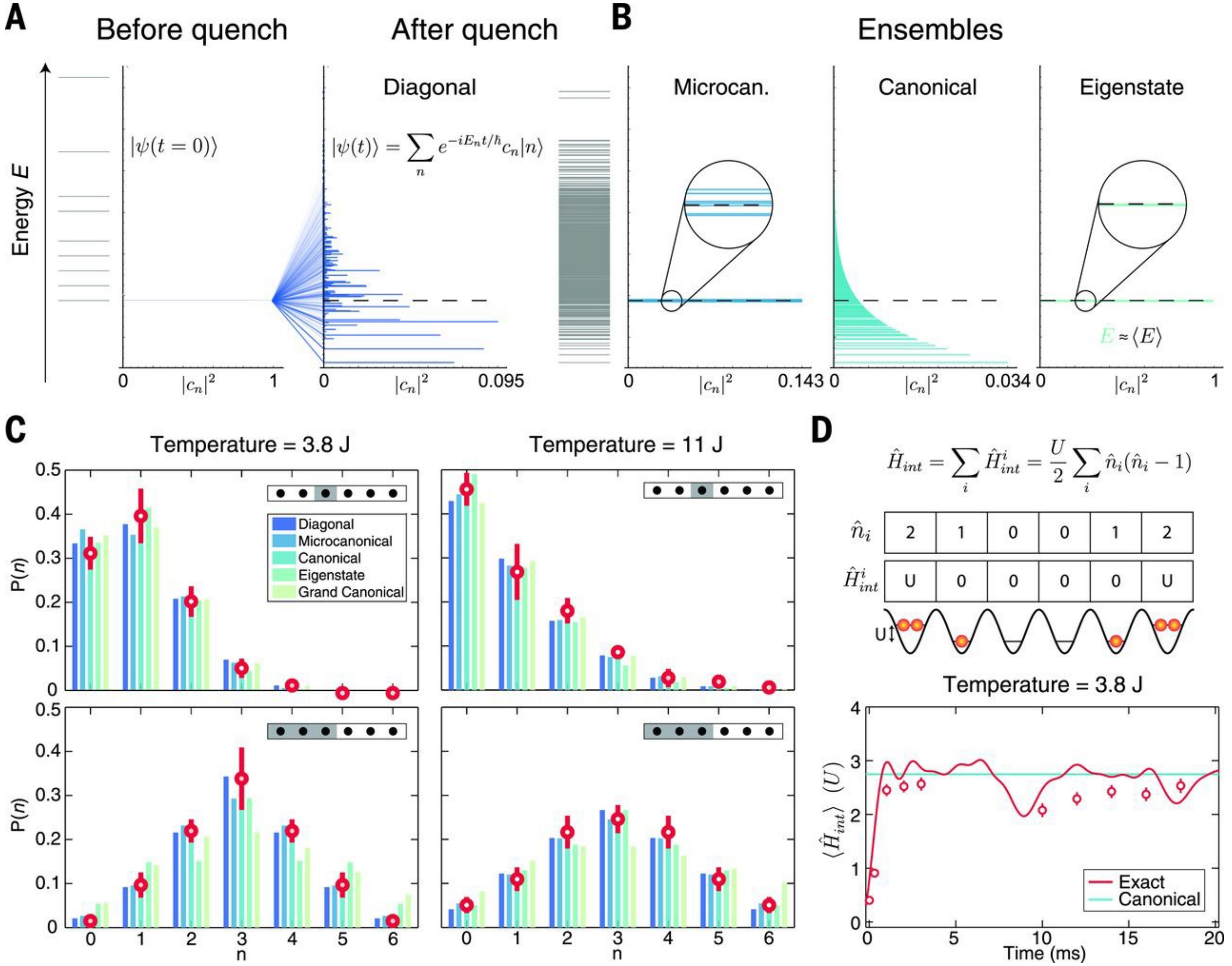
# Quantum thermalization via *entanglement*

*Ultra-cold atom system*

**Quantum thermalization through entanglement in an isolated many-body system**

Adam M. Kaufman, M. Eric Tai, Alexander Lukin, Matthew Rispoli, Robert Schittko, Philipp M. Preiss, Markus Greiner*

A. M. Kaufman et al, Science 353 (2016) 794




No classical interactions

# The Ultimate Small System – one "single parton"

arXiv.org > hep-ph > arXiv:2104.11735

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**High Energy Physics – Phenomenology**

*[Submitted on 23 Apr 2021]*

## Collective evolution of a parton in the vacuum: the ultimate partonic "droplet", non-perturbative QCD and quantum entanglement

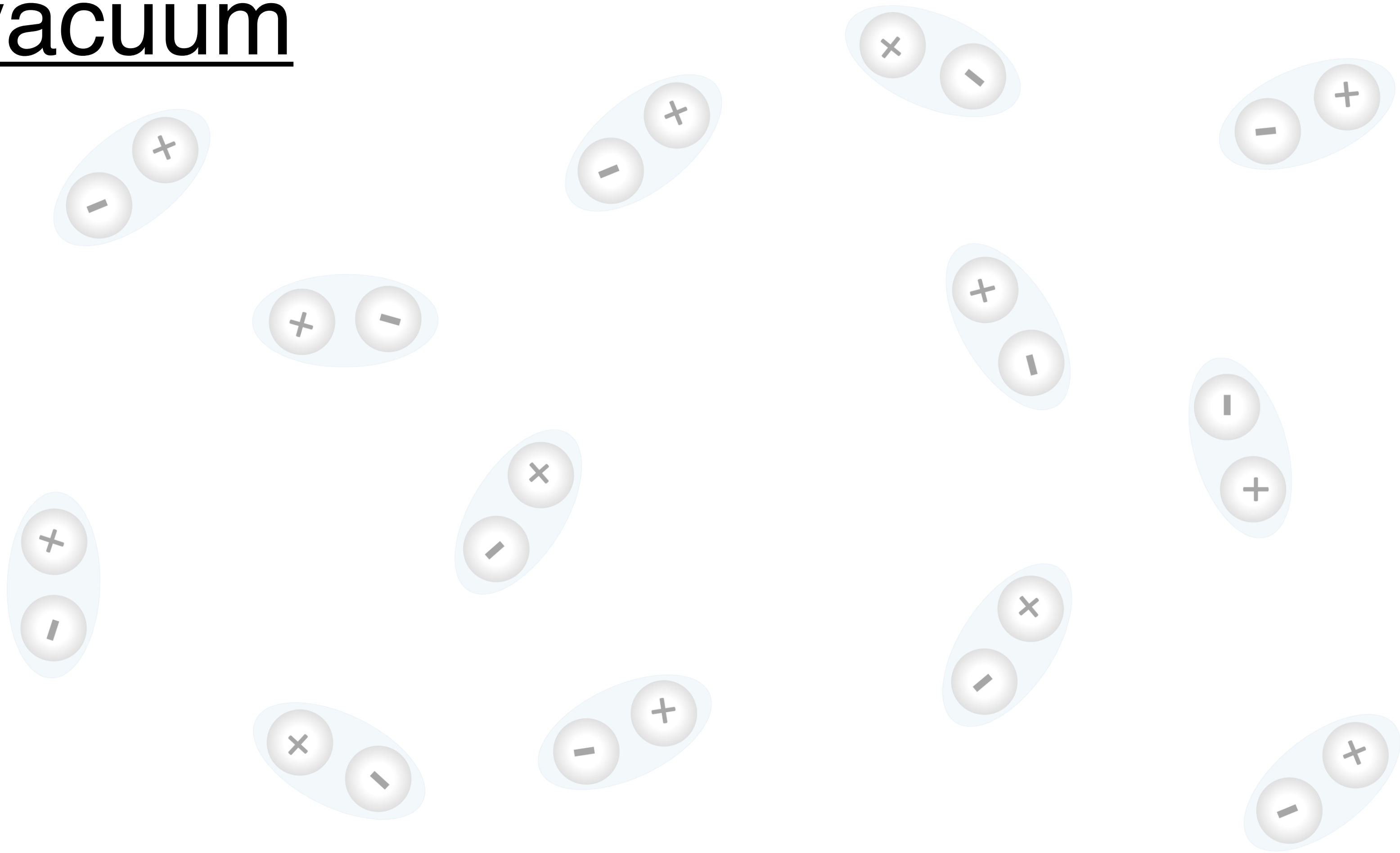
Austin Baty, Parker Gardner, Wei Li

We postulate that non-perturbative QCD evolution of a single parton in the vacuum will develop the long-range collective effects of a multi-parton system, reminiscent of those observed in high-energy hadronic or nuclear interactions with large final-state particle multiplicity final-state particles. Proton-Proton collisions at the Large Hadron Collider showed surprising signatures of a strongly interacting, thermalized quark-gluon plasma, which was thought only to form in collisions of large nuclear systems. Another puzzle observed earlier in $e^+e^-$ collisions is that production yields of various hadron species appear to follow a thermal-like distribution with a common temperature. We propose searches for thermal and collective properties of a single parton propagating in the vacuum using high multiplicity jets in high-energy elementary collisions. Several observables are studied using the PYTHIA 8 Monte Carlo event generator. Experimental observation of such long-range collectivity will offer a new view of non-perturbative QCD dynamics of multi-parton systems at the smallest scales. Absence of any collective effect may offer new insights into the role of quantum entanglement in the observed thermal behavior of particle production in high energy collisions.

*Is QGP-like collective behavior intrinsic to non-perturbative QCD dynamics in general (e.g., hydro. to describe parton fragmentation in vacuum)?*

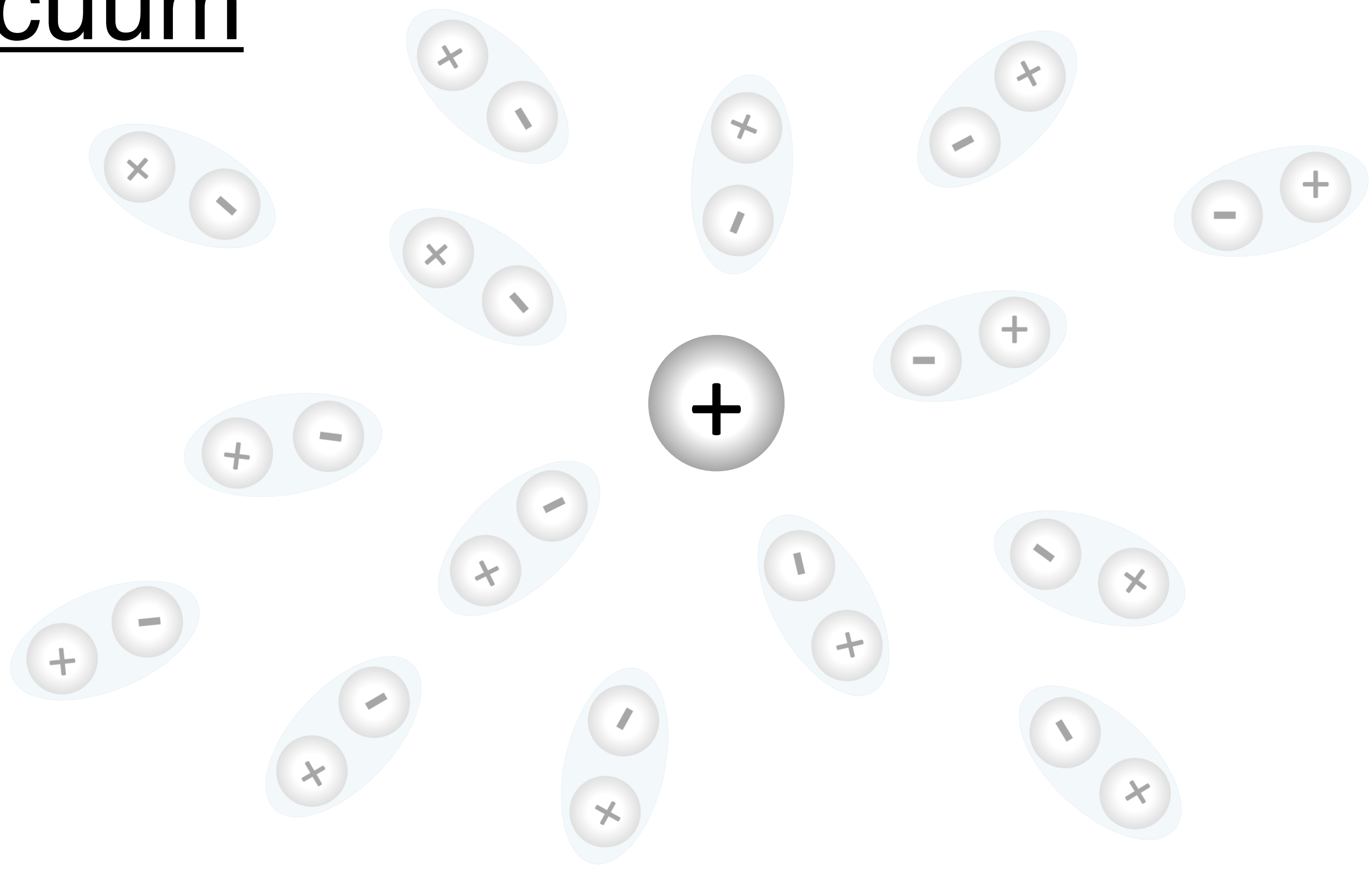
– "QGP droplet" from a single parton in the vacuum?!

# QED vacuum




Filled with virtual electric charges

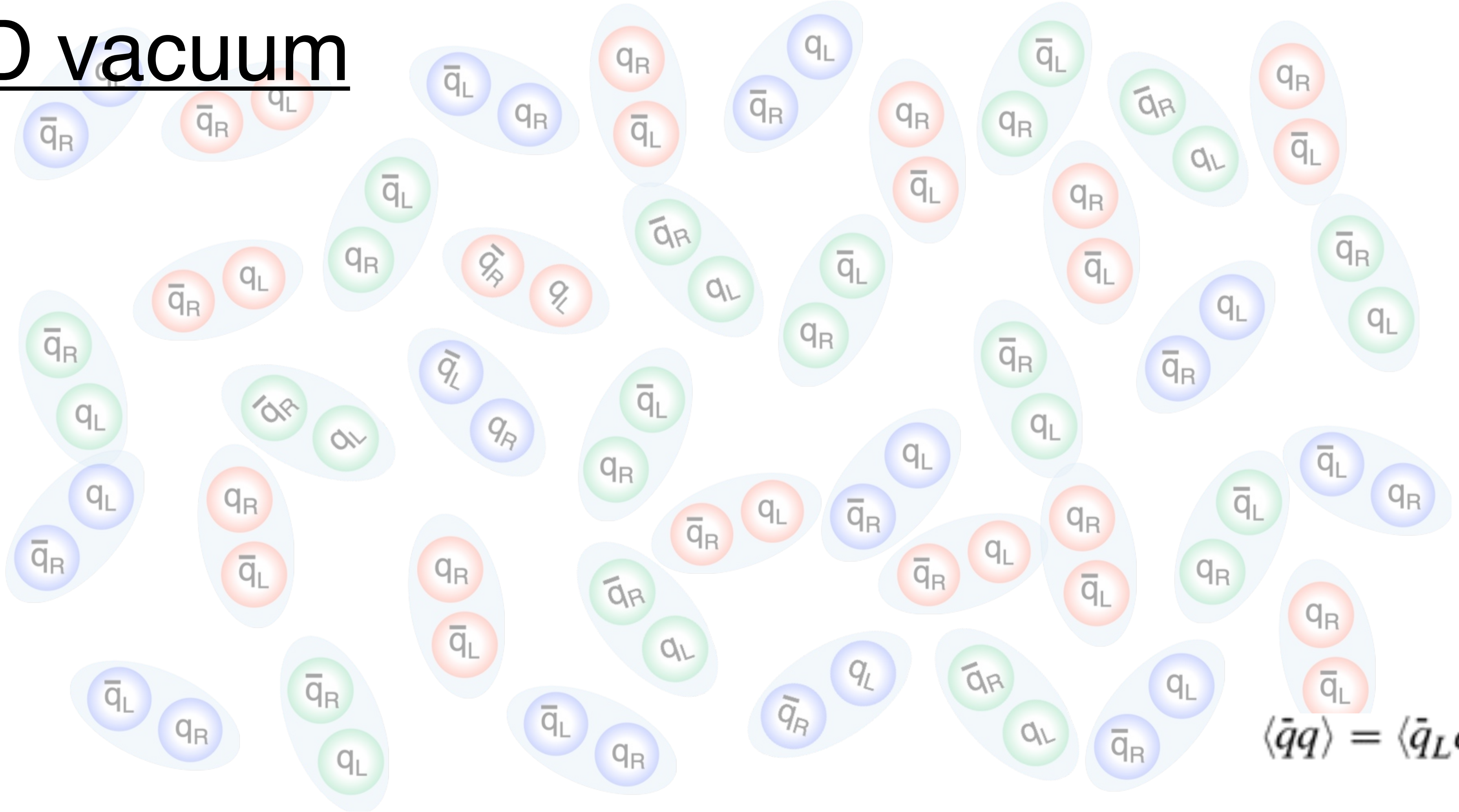
# QED vacuum



Putting in a free electric charge → polarization and screening

Free charges popping out only when E-field extremely strong (Schwinger effect)

# QCD vacuum

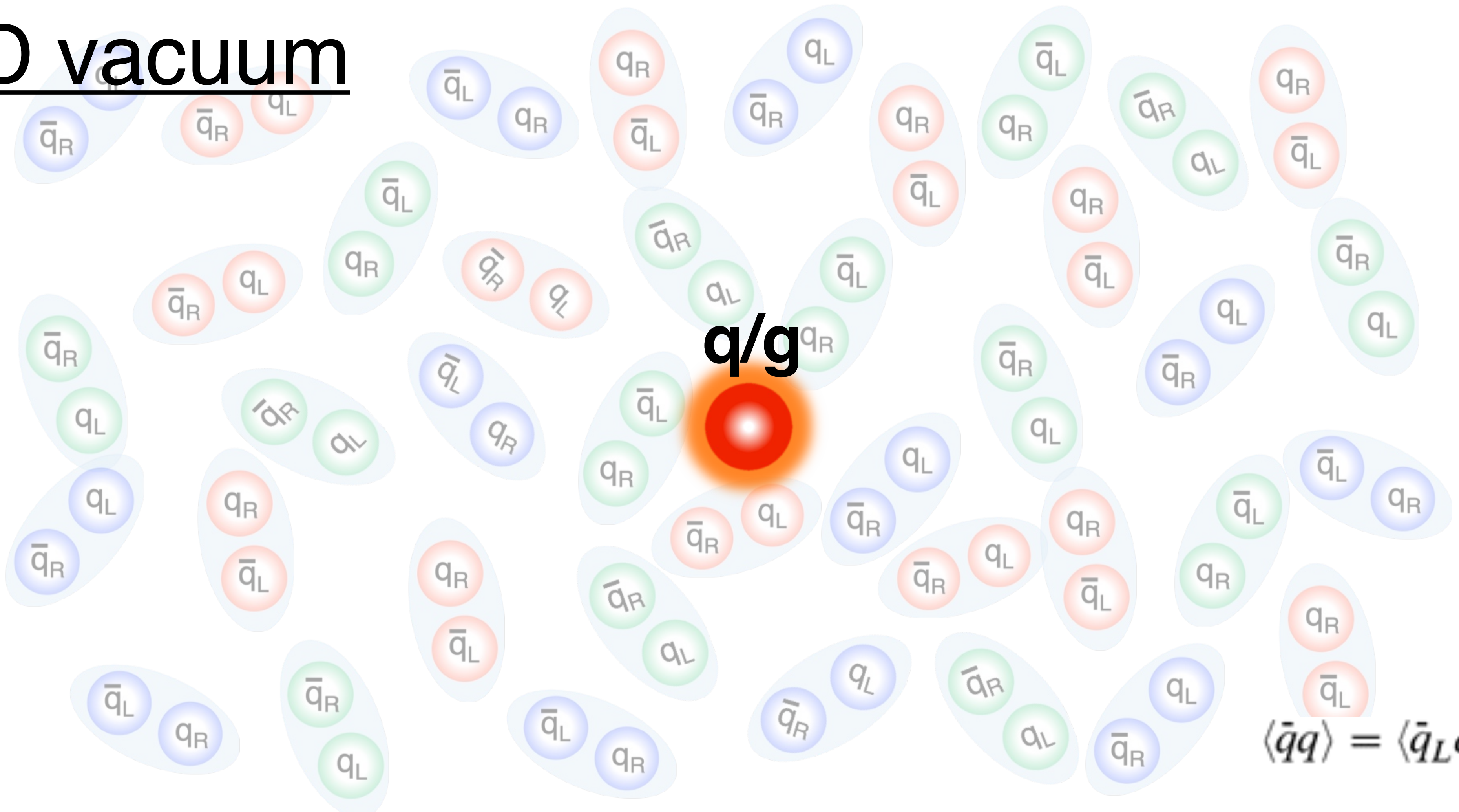


$$\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle$$

Filled with virtual color charges – chiral condensates

$$\langle \bar{q}q \rangle \sim \Lambda^3_{QCD} \qquad \langle G_{\mu\nu} G^{\mu\nu} \rangle \sim \Lambda^4_{QCD}$$

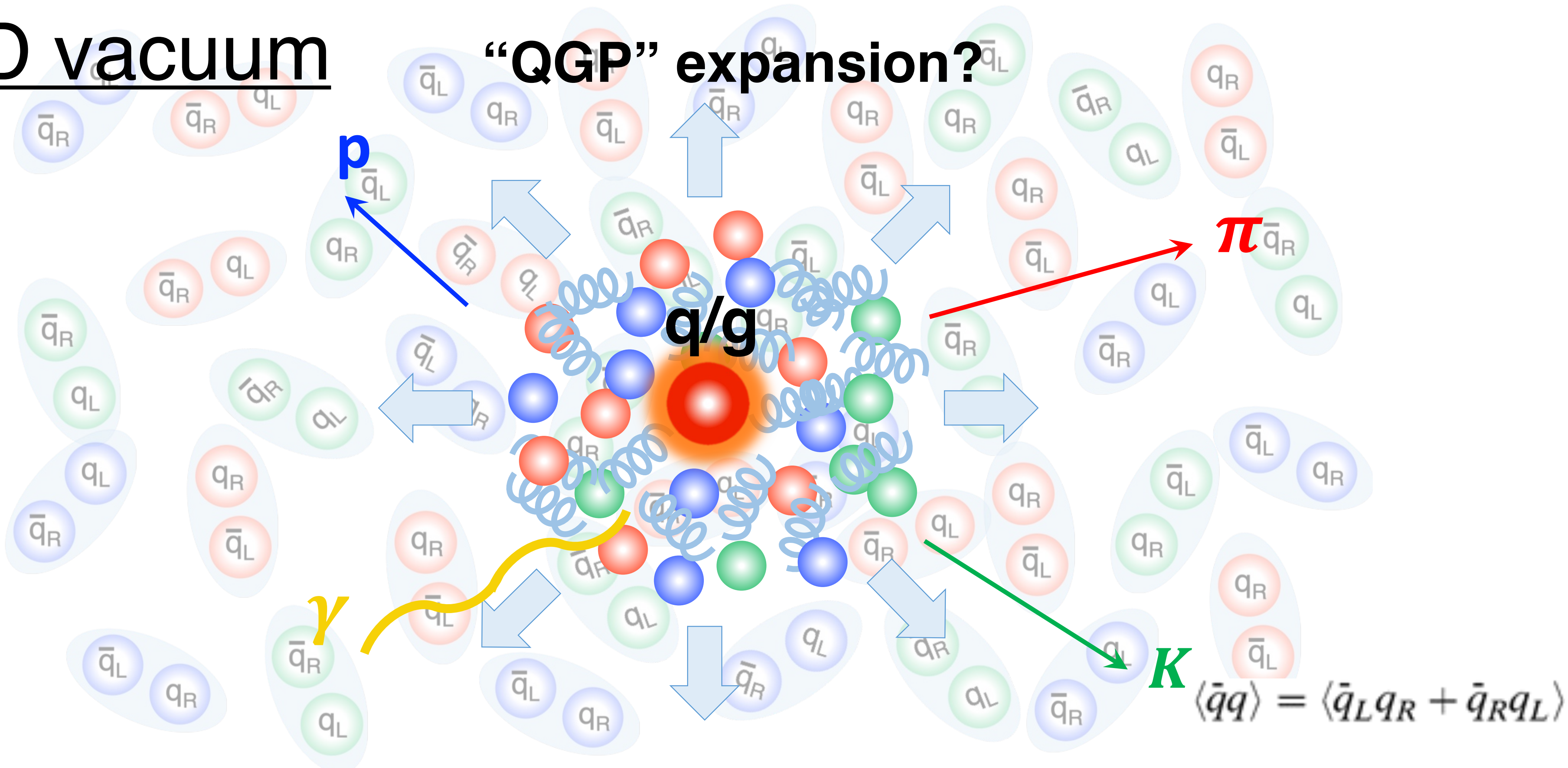
# QCD vacuum



$$\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle$$

Putting in a free quark (requires inf. energy)

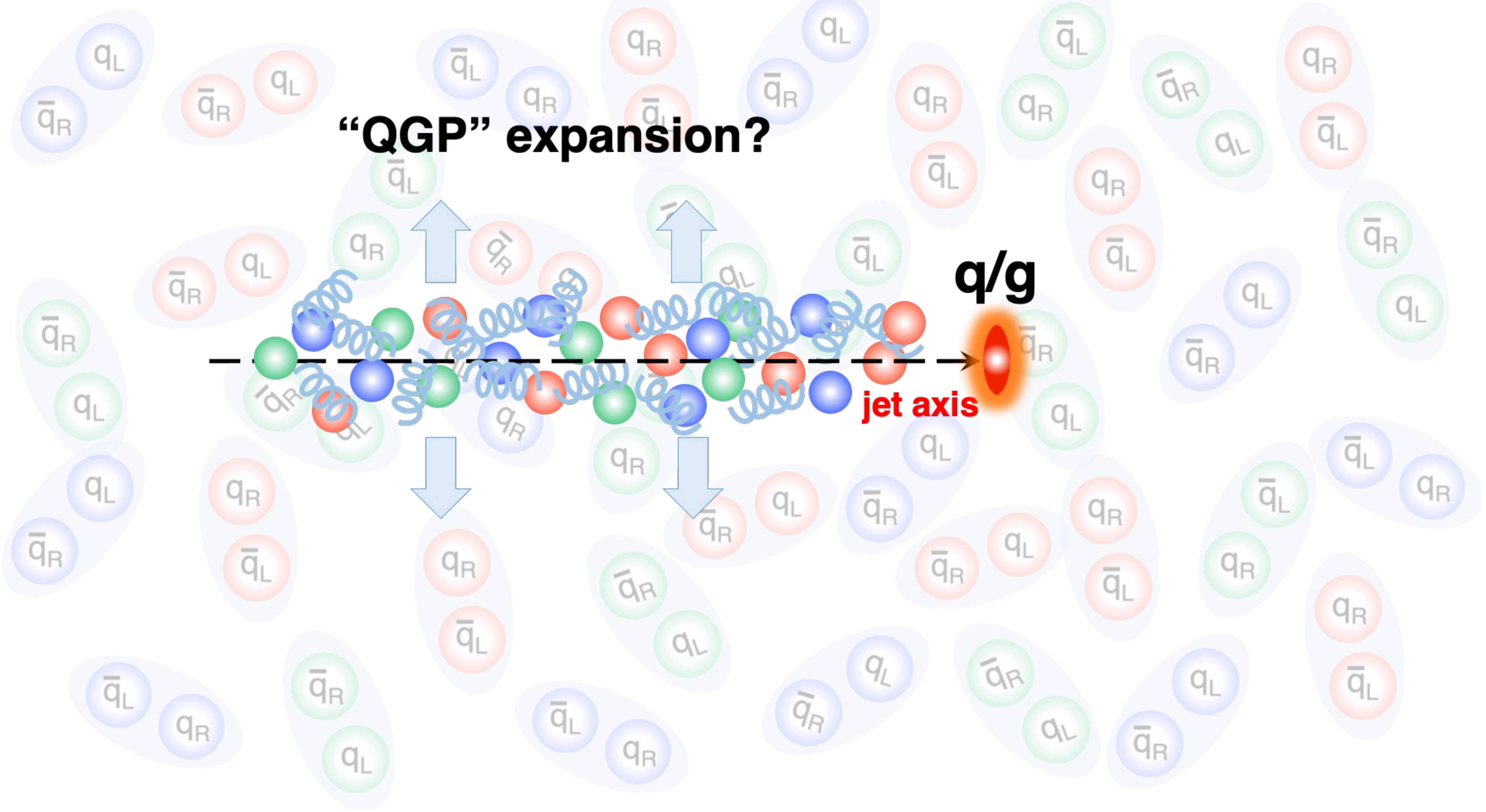
# QCD vacuum



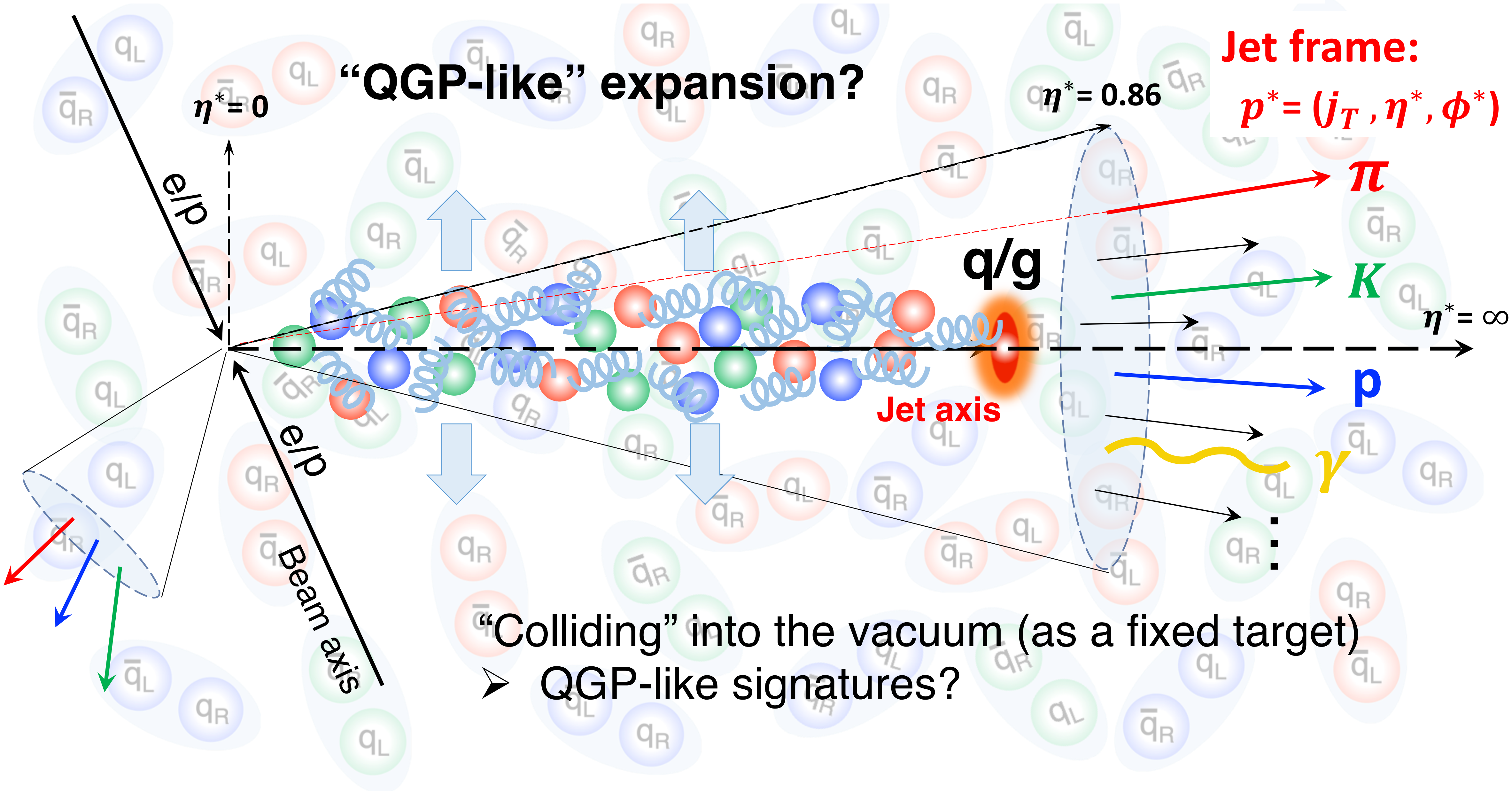

Putting in a free quark (requires inf. energy)

The quark gains “mass” via interactions and expands like a QGP?

# Boosting to a moving parton in the vacuum

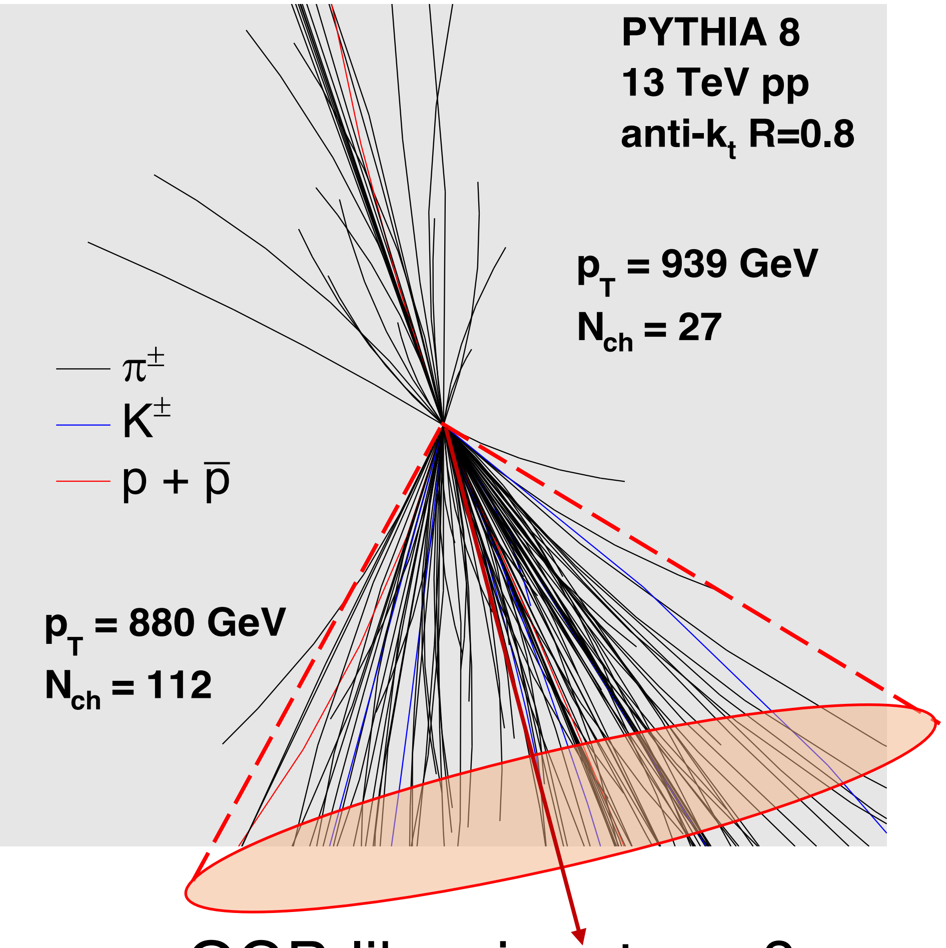


# Boosting to a moving parton in the vacuum




"Colliding" into the vacuum (as a fixed target)
- QGP-like signatures?

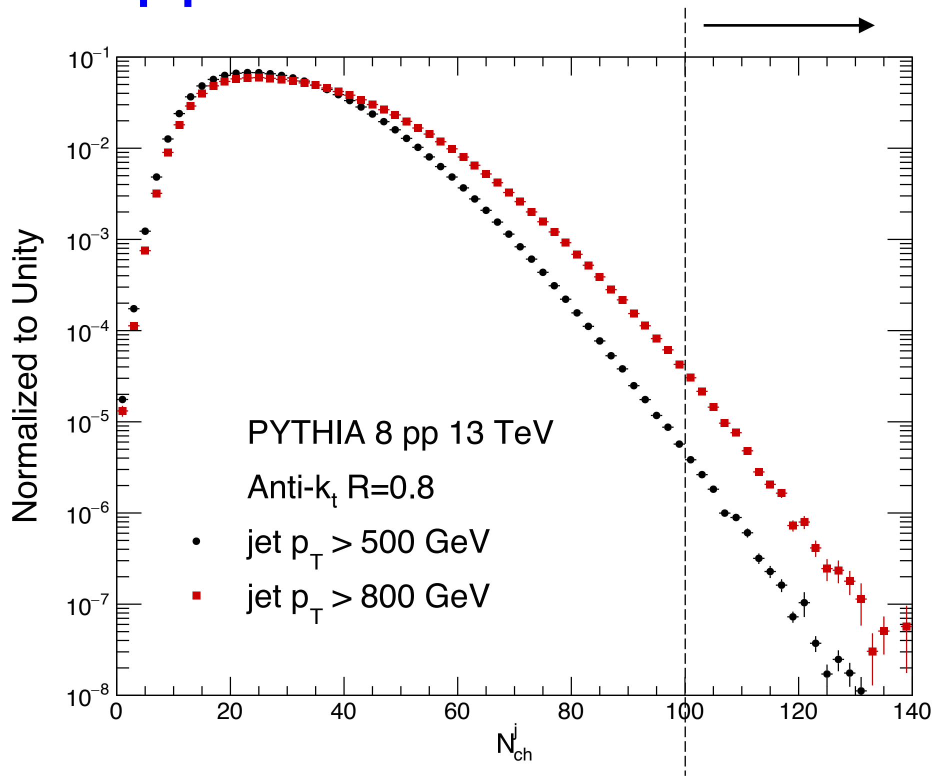
# Search for "QGP" from a single parton




QGP-like signatures?

- Collective correlations
- Thermal production
- …

Jets in pp to mimic $e^+e^-$ at the TeV!



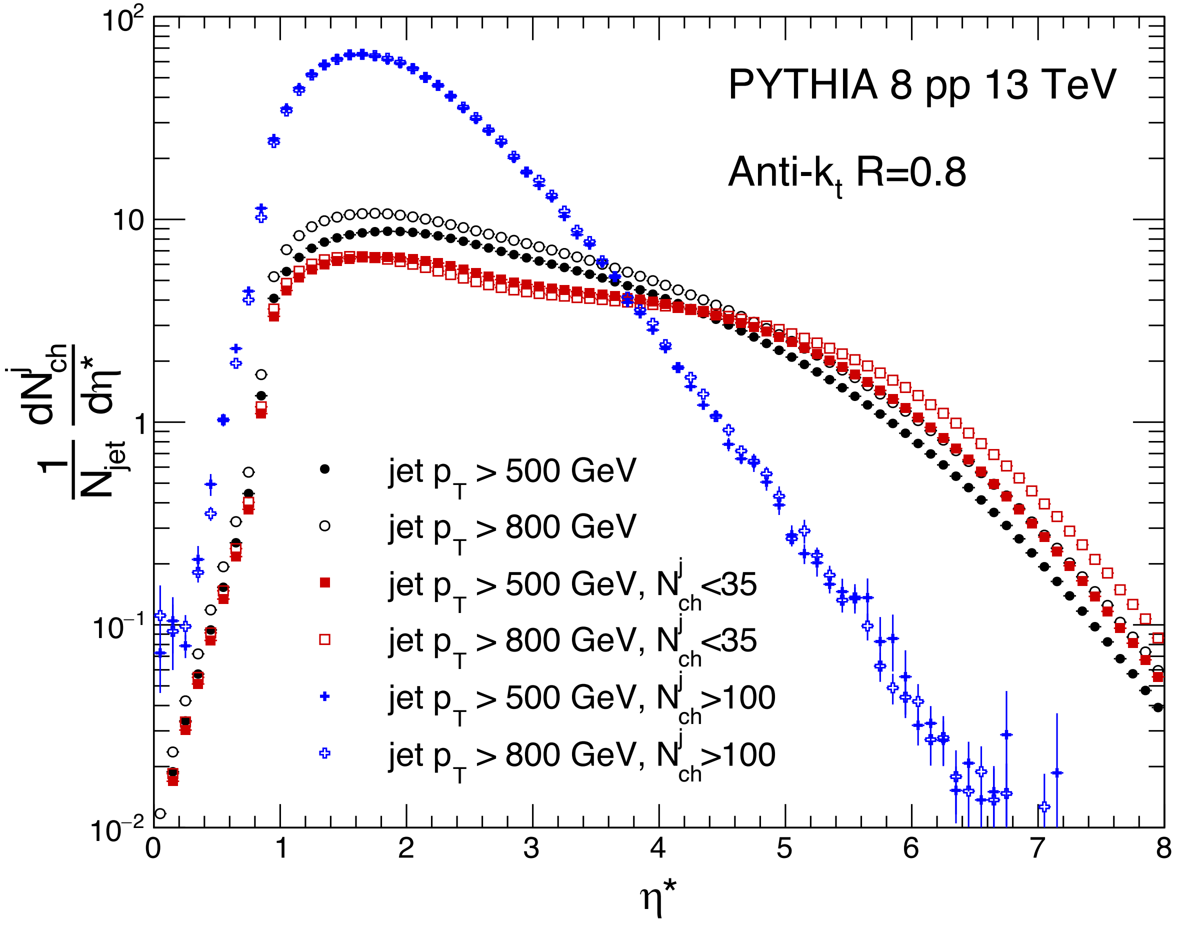

High-multiplicity ($N^j_{ch}$>100) jets: $10^{-4}$ – $10^{-5}$, dominated by gluons.

**Abundant high-$p_T$ jets in pp at the (HL)-LHC**

# Search for "QGP" from a single parton

$dN_{ch}^{j}/d\eta^{*}$ in the jet frame

Similar to lab-frame collisions




In high-multiplicity jets,

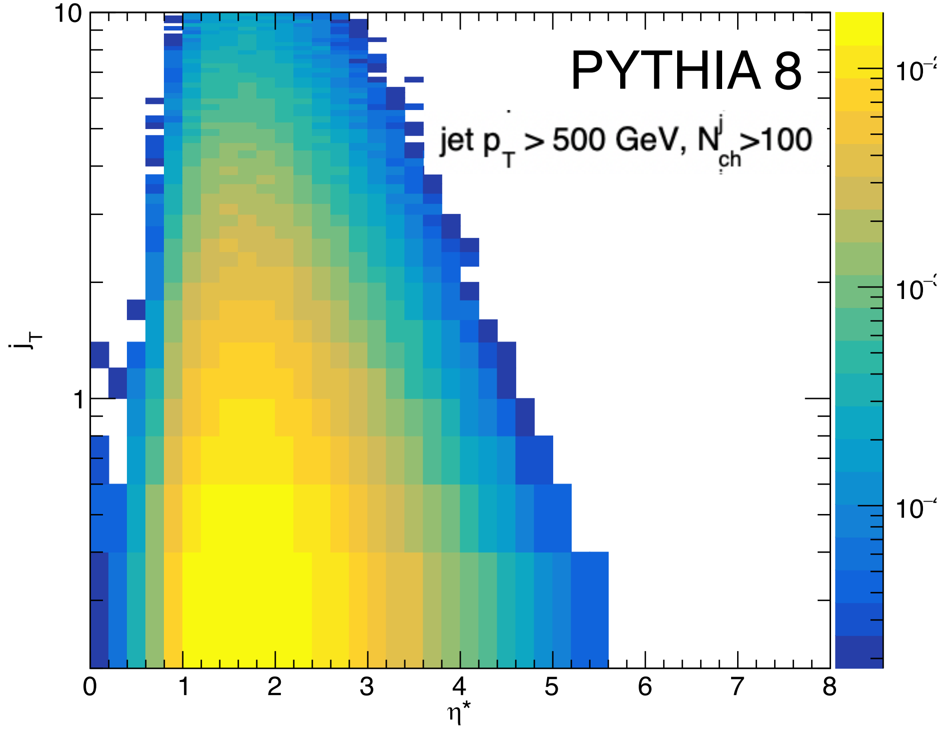
$$\frac{dN_{ch}^{j}}{d\eta^{*}} \sim 60 - 70$$

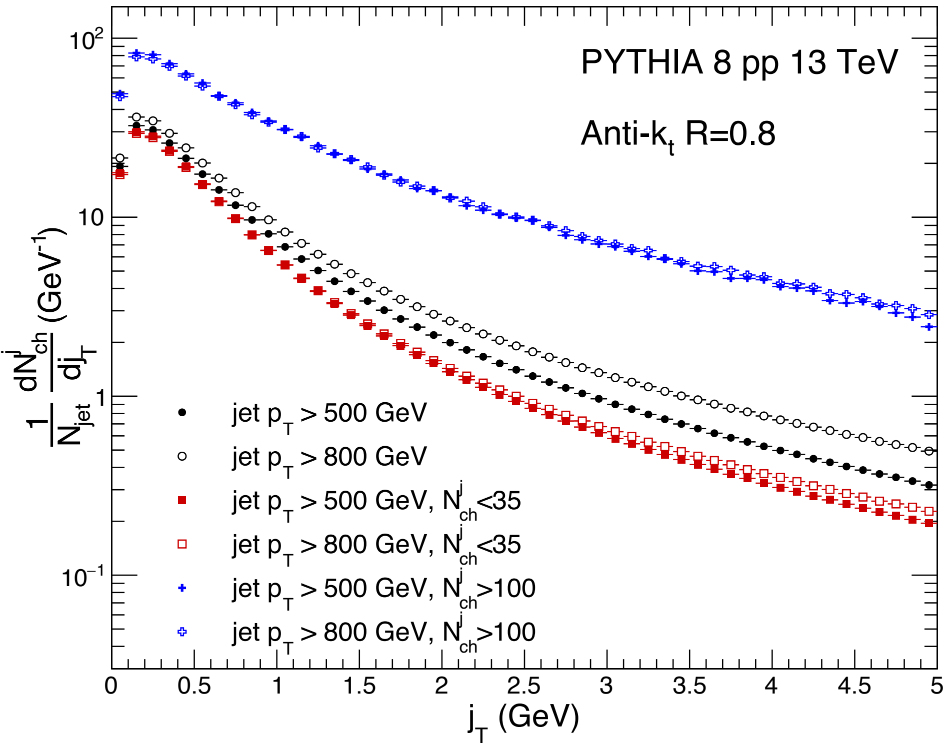
comparable to mid-central CuCu, peripheral PbPb, central pPb

Narrowing as multiplicity increases → larger "stopping by the vacuum"

# Search for "QGP" from a single parton

$j_T$ and $\eta^*$ distribution in the jet frame



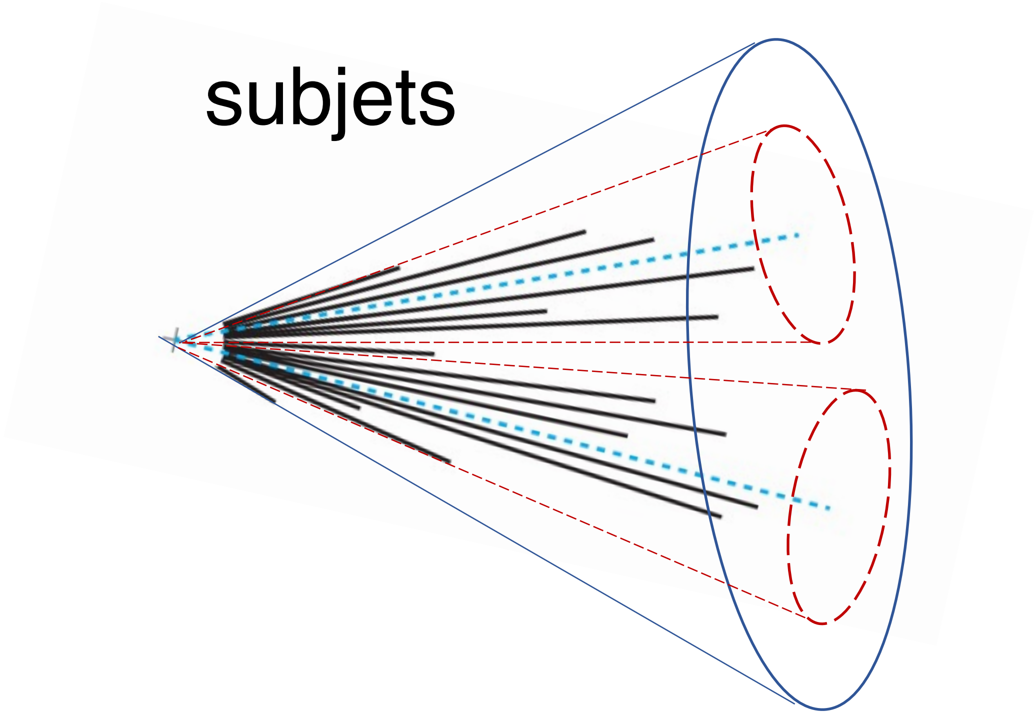




similar to the LUND plane

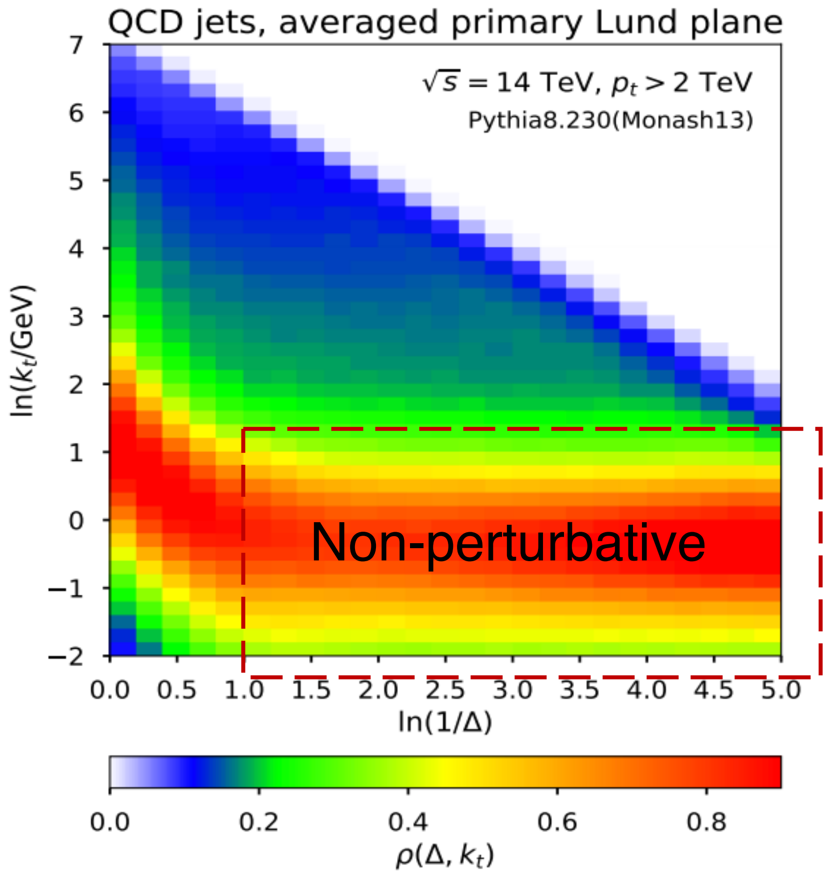
$j_T$ spectra becomes harder as multiplicity in jet increases

General features reminiscent of pp collisions in the lab frame

# Complementarity to Jet substructure studies



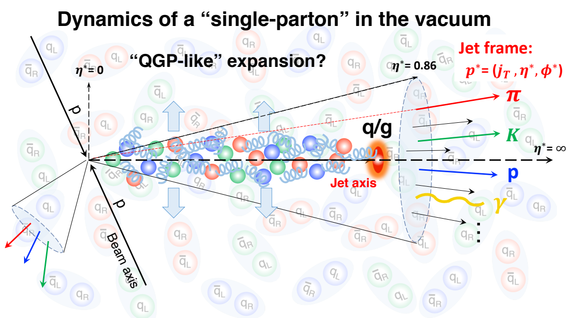

R. Kogler, RMP 91, 45003 (2019)



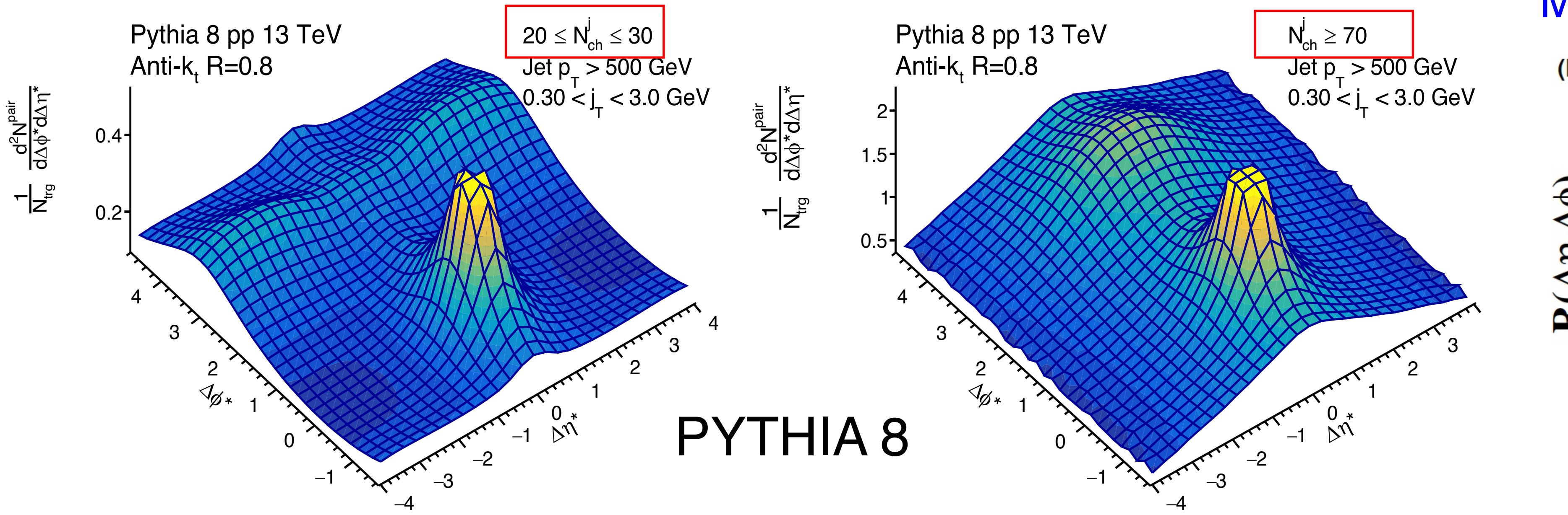

F. Dreyer, G. Salam, G. Soyez JHEP 12 (2018) 064

Non-pert. components tend to be trimmed away in jet substructure observables (e.g., SoftDrop), while **they are of primary interest for us!**

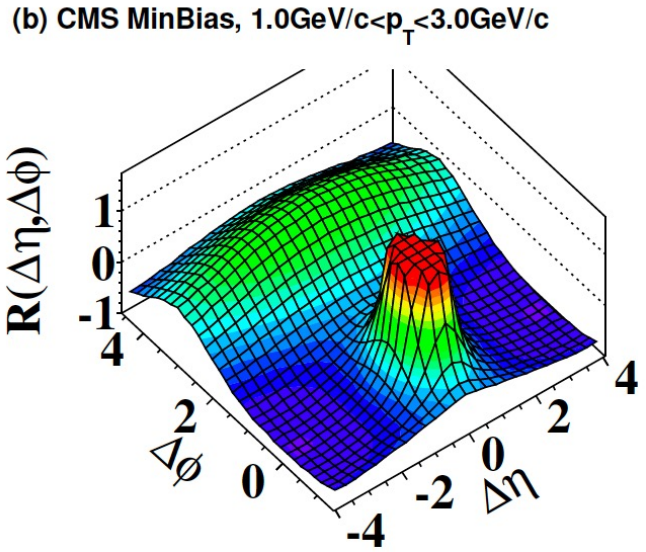
# Search for a "Ridge" in a jet




## Two-particle correlations in the jet frame




MB pp data in the lab frame




- No ridge in PYTHIA jets, as expected
- Particle production dynamics in a jet not very different from a pp collision in the lab frame.

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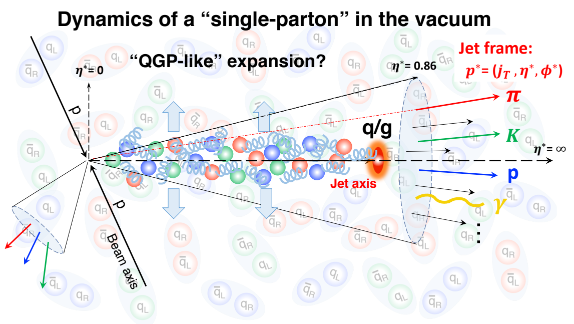


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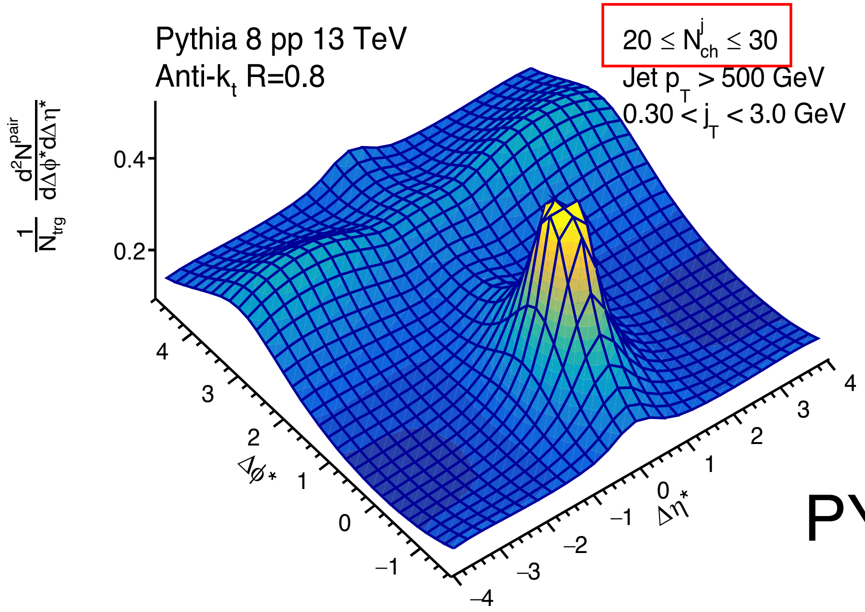
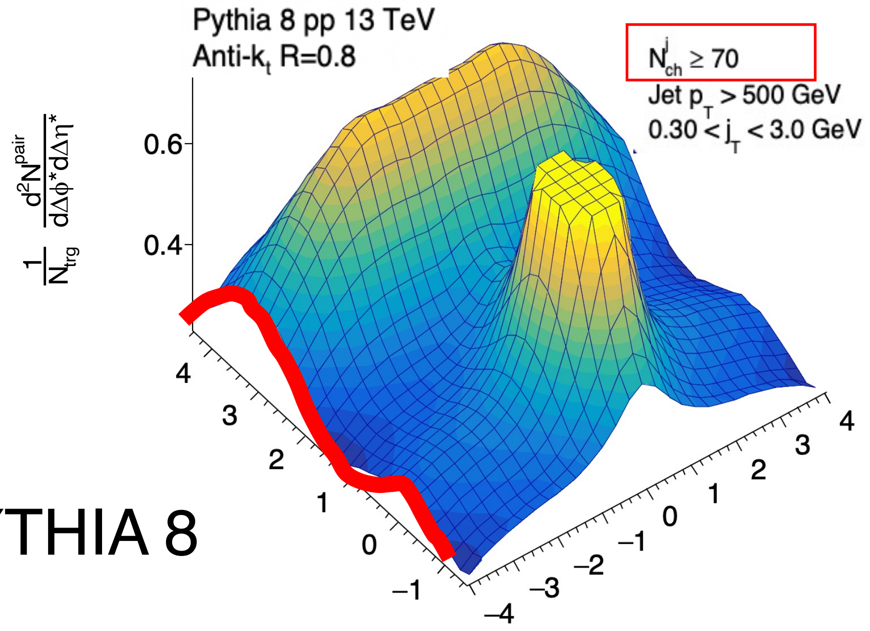
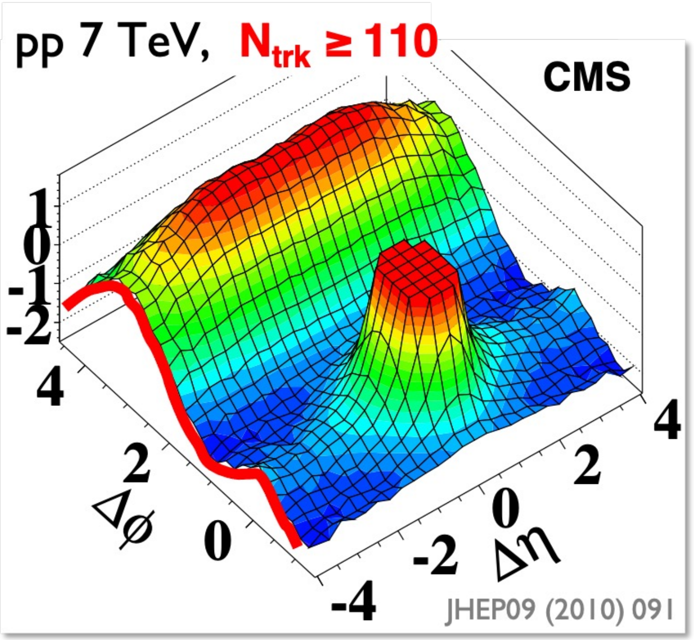



PYTHIA 8




**If adding $v_2$=0.2**

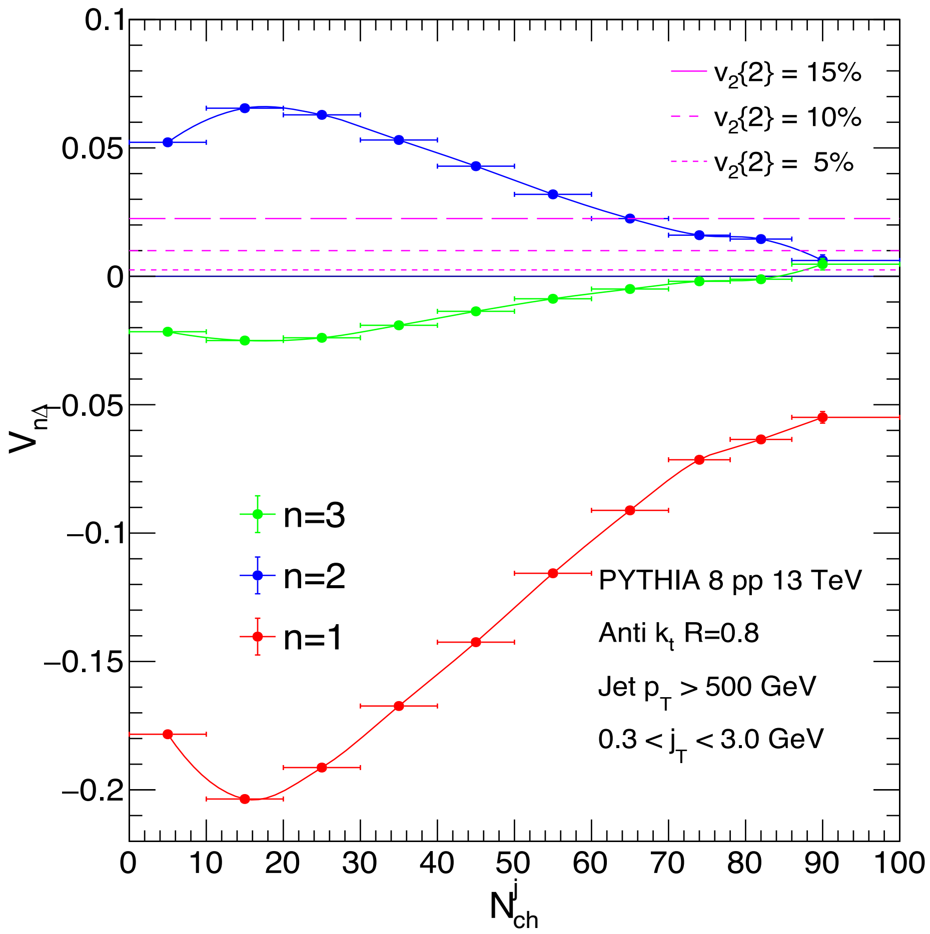
HM pp data in the lab frame

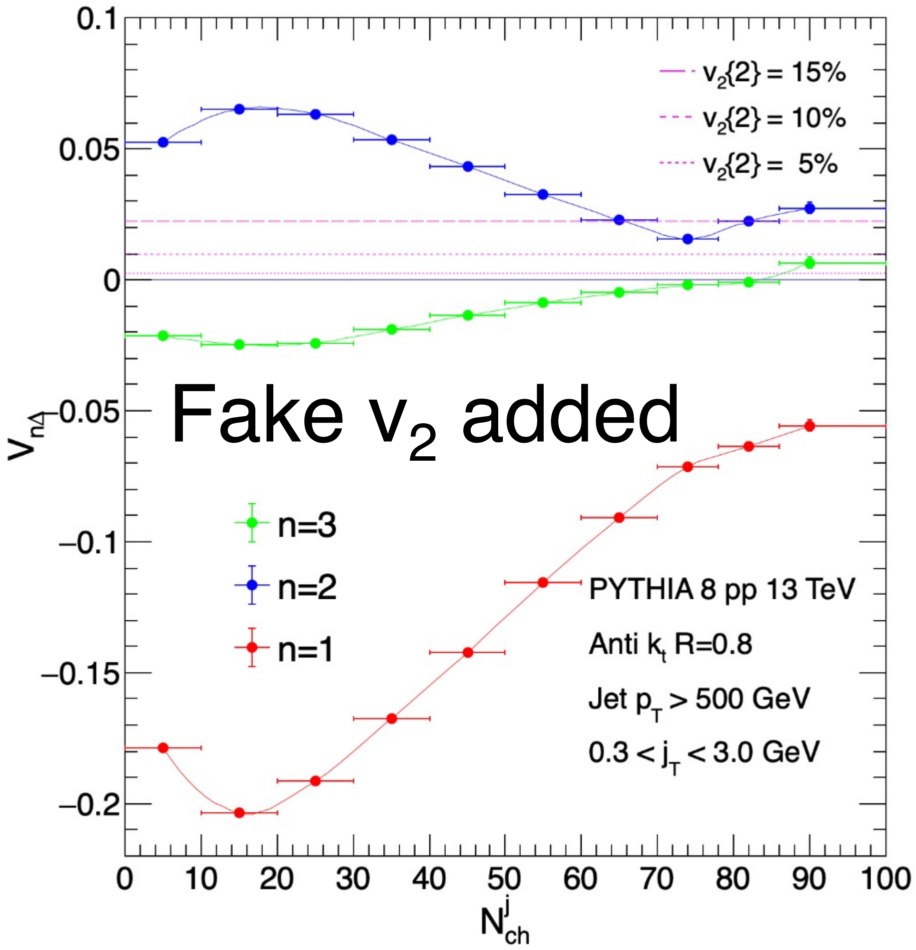



Ridge and “QGP” signatures observable in high-multiplicity jets?

# Search for a "Ridge" in a jet

## Fourier harmonics ($V_n$) in the jet frame

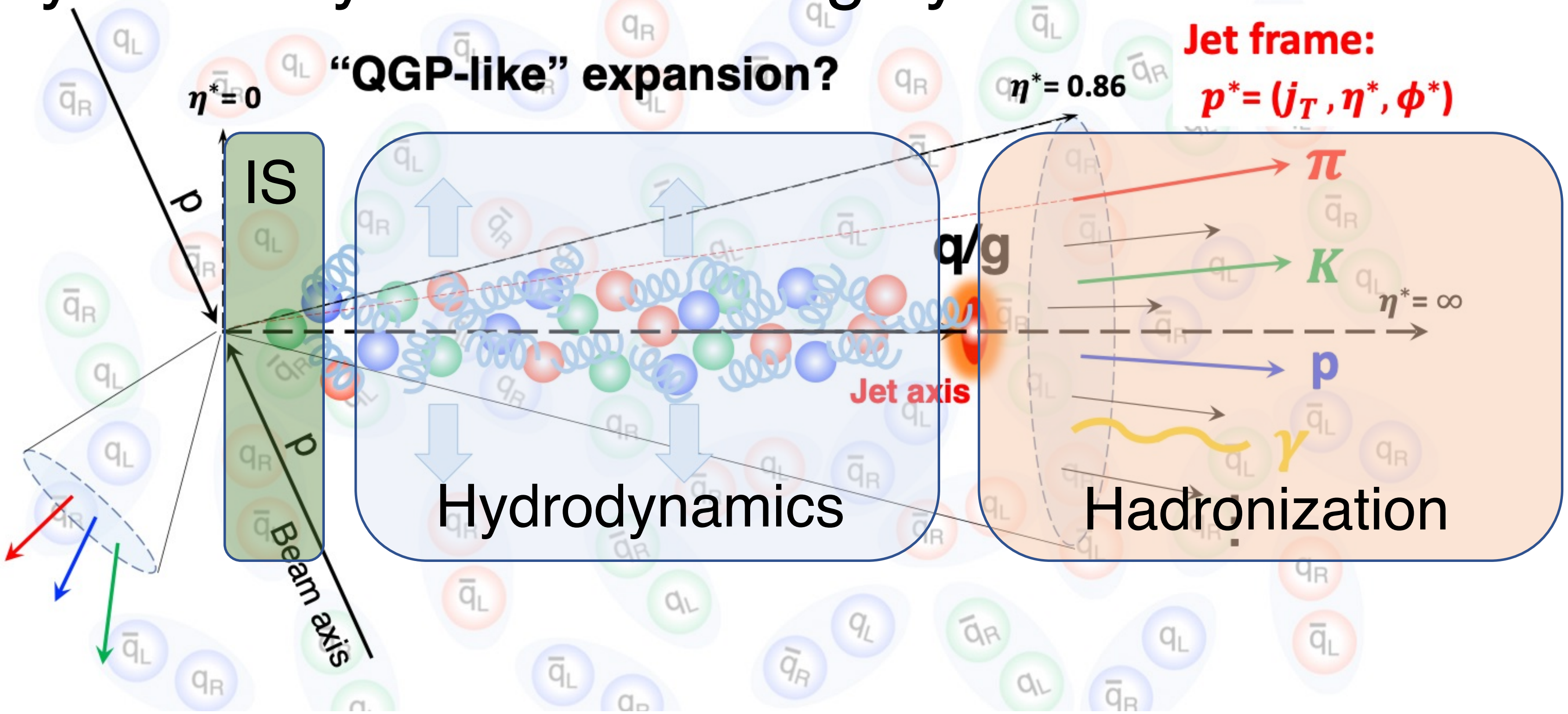



Enhancement of $V_n$ at high $N_{ch}^{j}$ would be indicative of flow signal

# Search for a "Ridge" in a jet

Can we model parton fragmentation (soft part) as a hydrodynamic system that is highly boosted?



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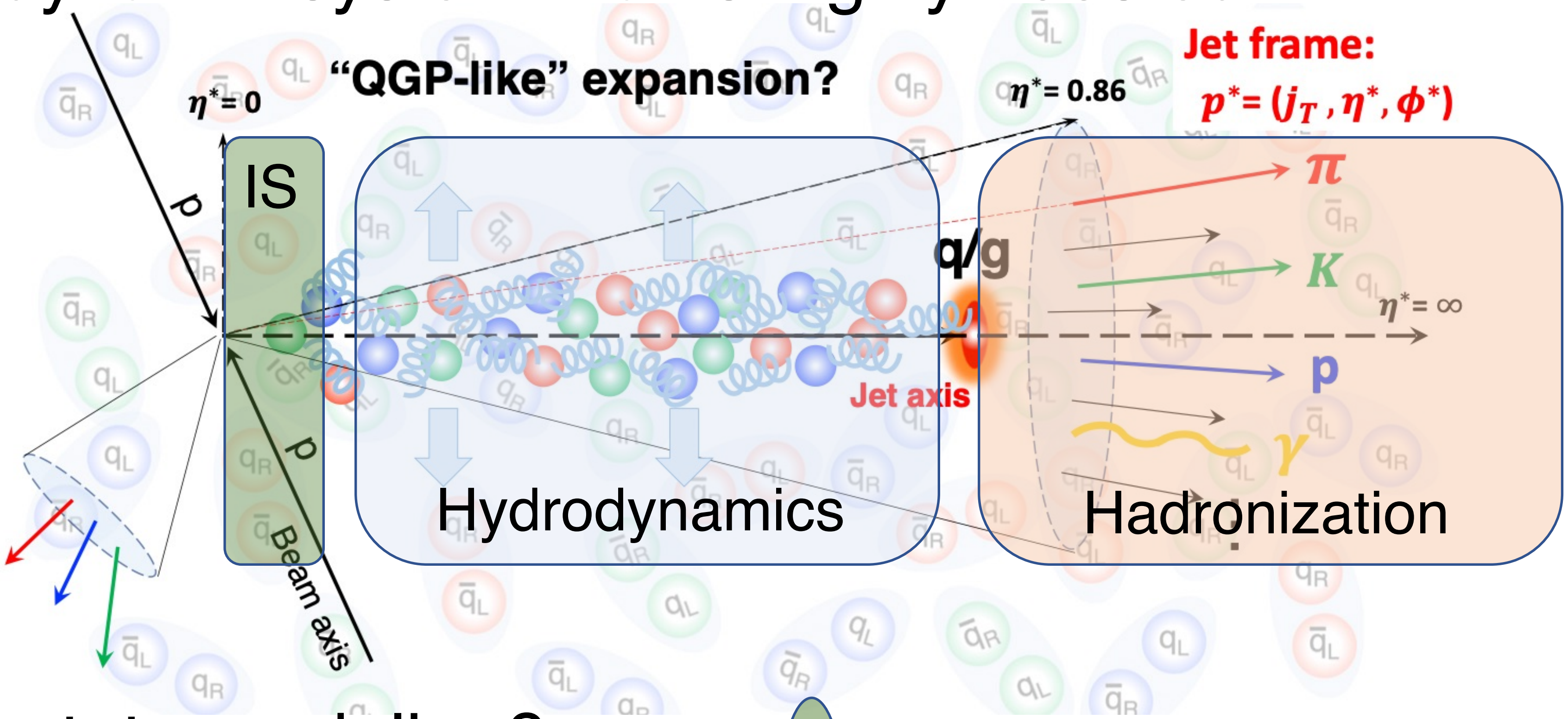
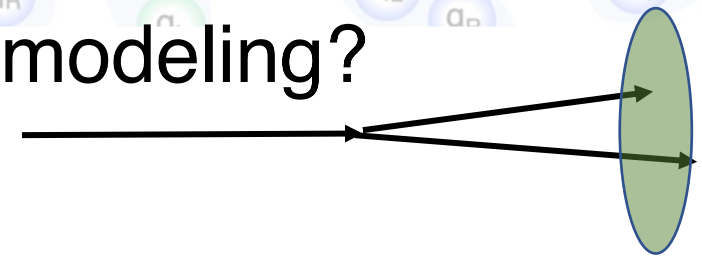


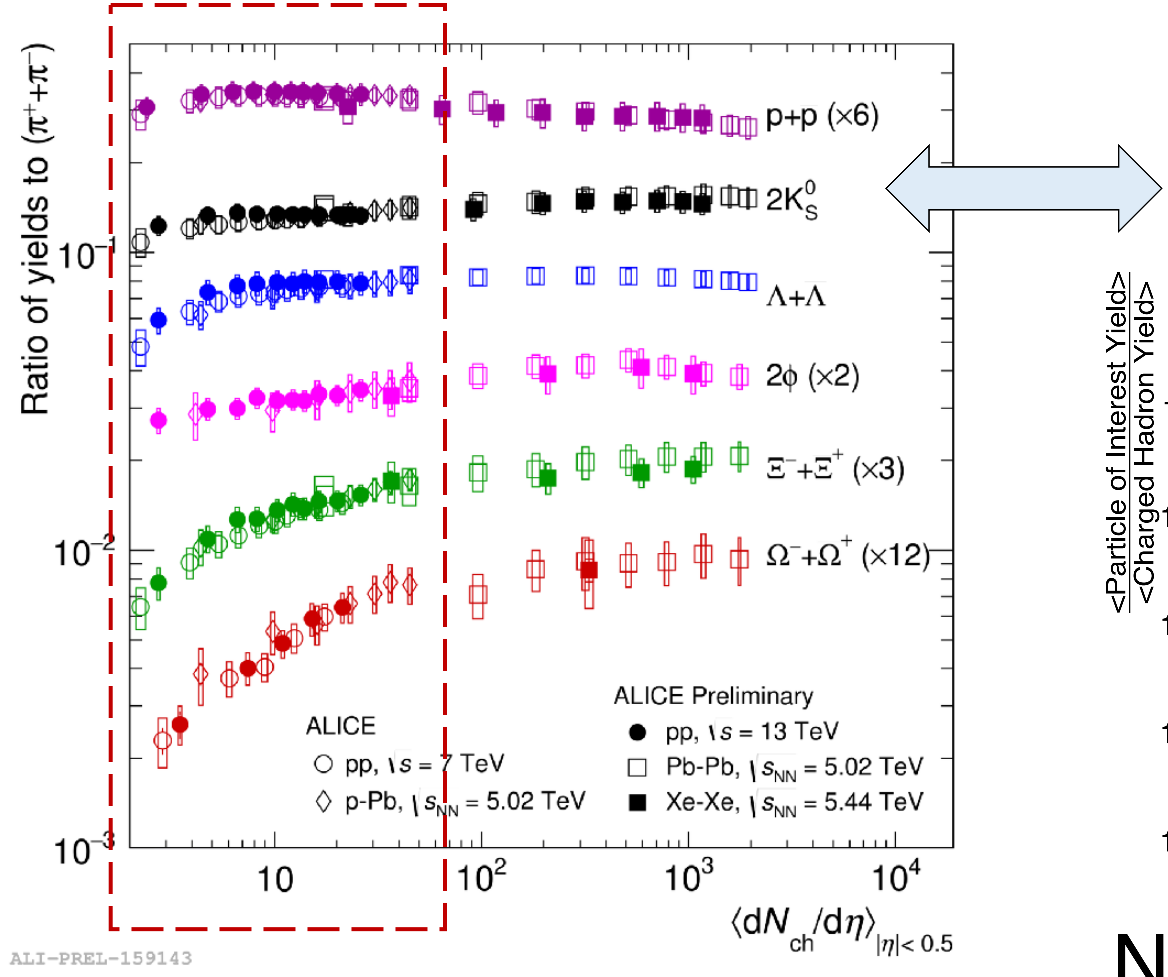

Initial state modeling?

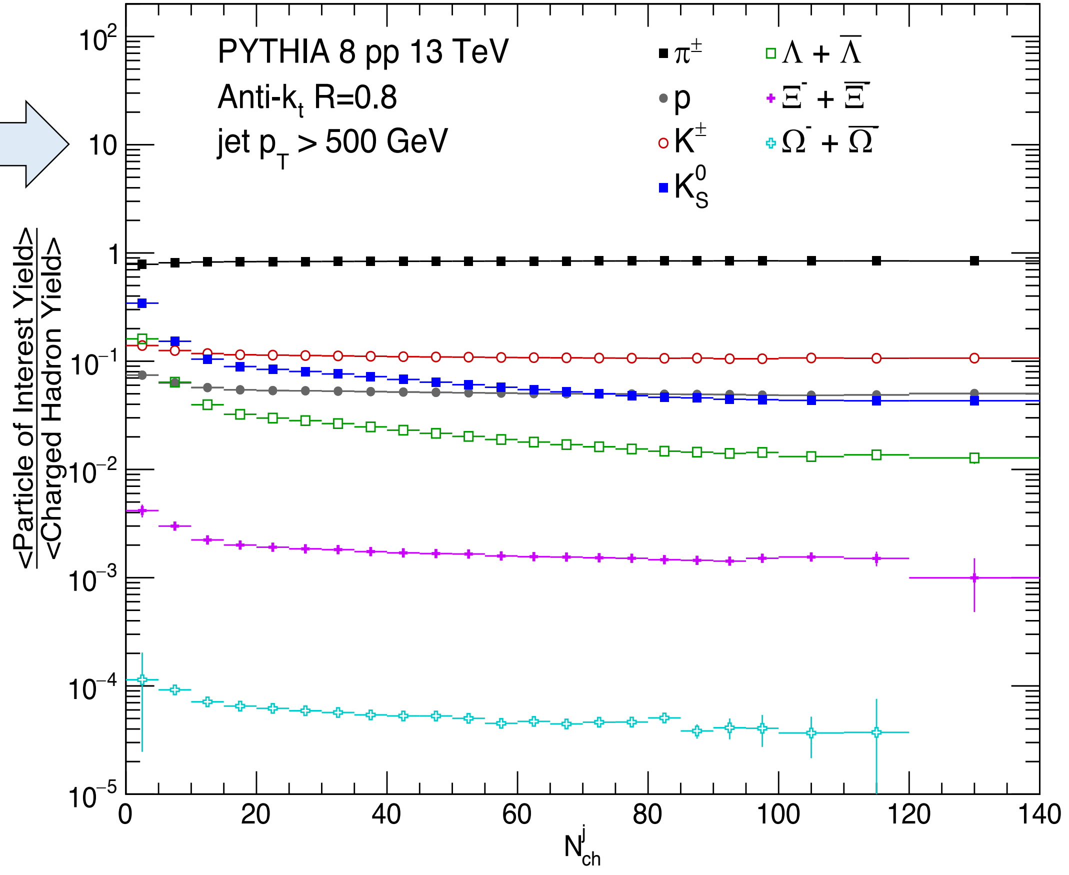


Elliptical from an early first branching?

# Strangeness enhancement in a jet

High particle density in a jet
→ Strangeness enhancement?



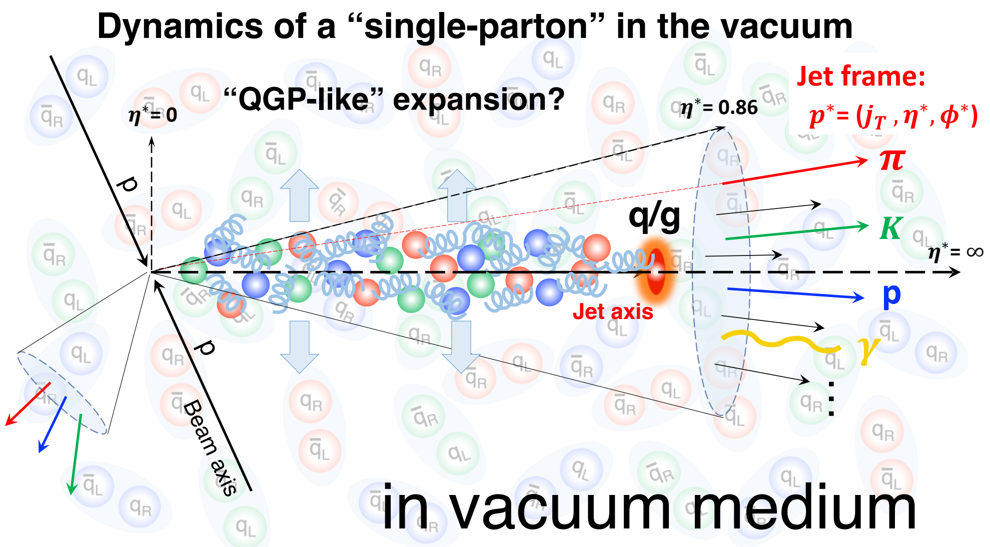




No enhancement in PYTHIA 8

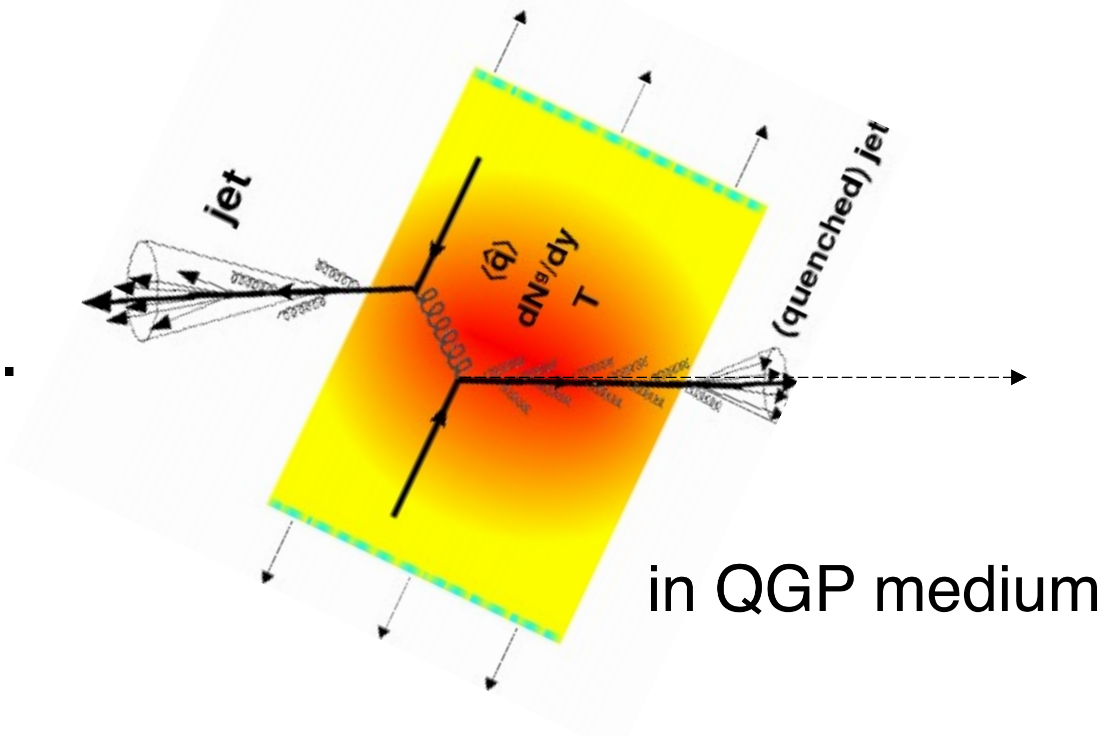
# Many "QGP" signatures to search for in HM jets

Jet quenching? In our view, parton fragmentation in the vacuum is also an energy loss process.

It has NO fundamental difference from parton energy loss in QGP. Same analyses in the jet frame can be performed to jets in HI.




V.S.



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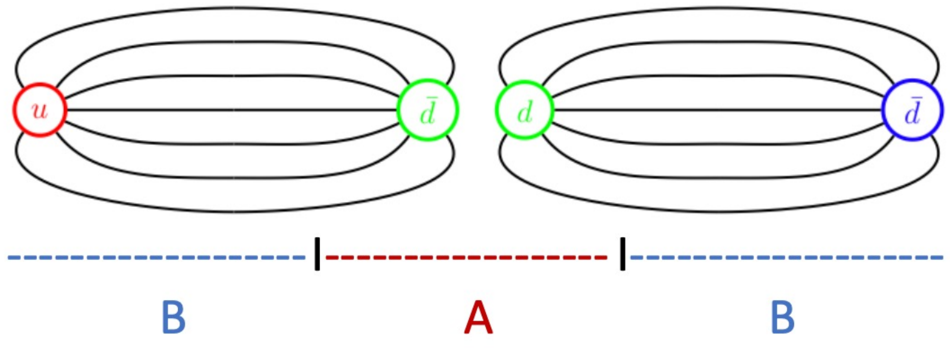
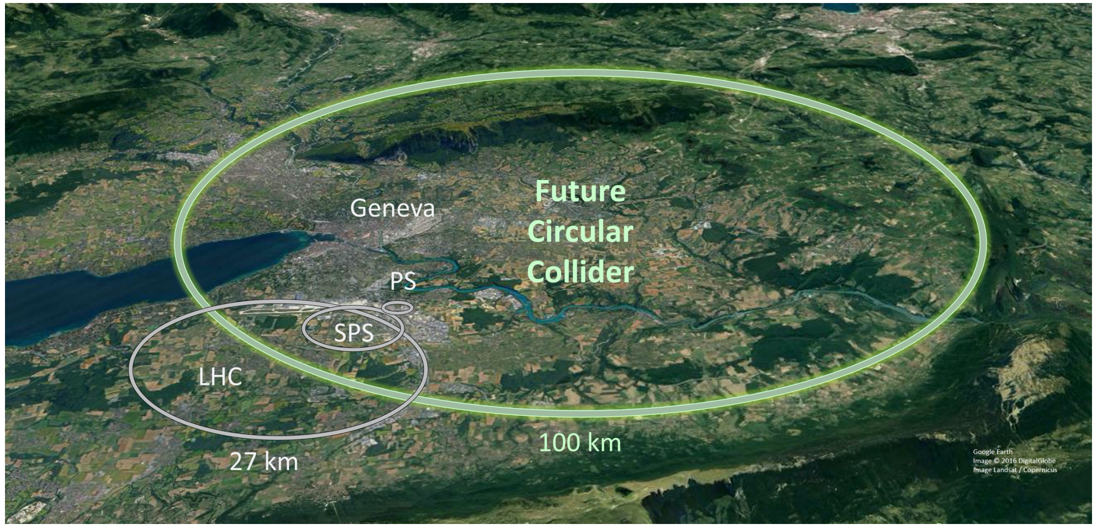
Absence of any “QGP” signatures in **HM jets** may be indicative of quantum entanglement effects in $e^+e^-$




**Stay tuned for the first result soon!**

# Search for single-particle QGP at future facilities

pp at (HL-)LHC and FCC




PYTHIA 8 (CP5) at 14 TeV, 4/ab (HL-LHC)

| $N_{ch}^{j}$ | # of events |
|---|---|
| >70 | 8.8M |
| >80 | 1.4M |
| >90 | 216k |
| >100 | 24K |

Ample HM jets produced

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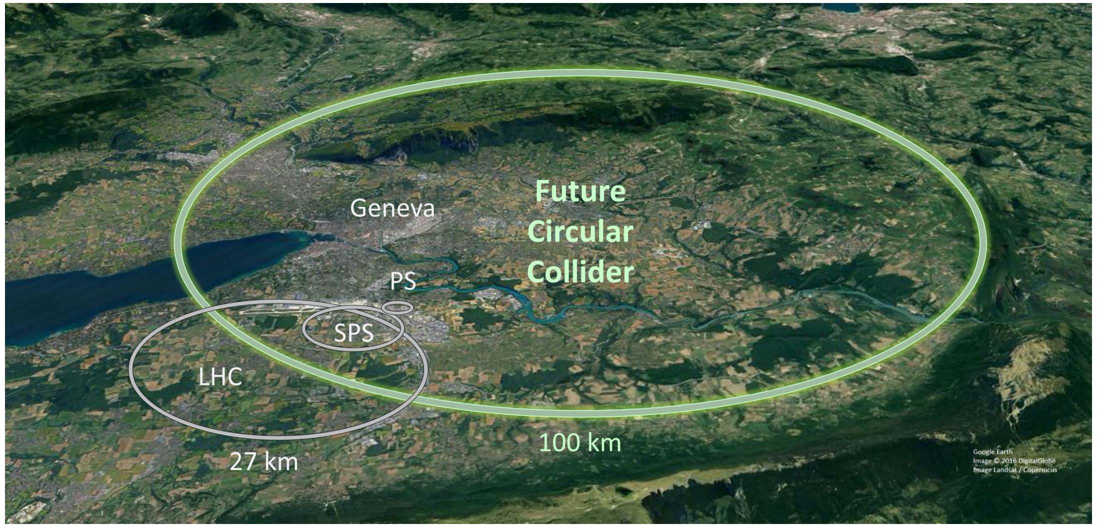


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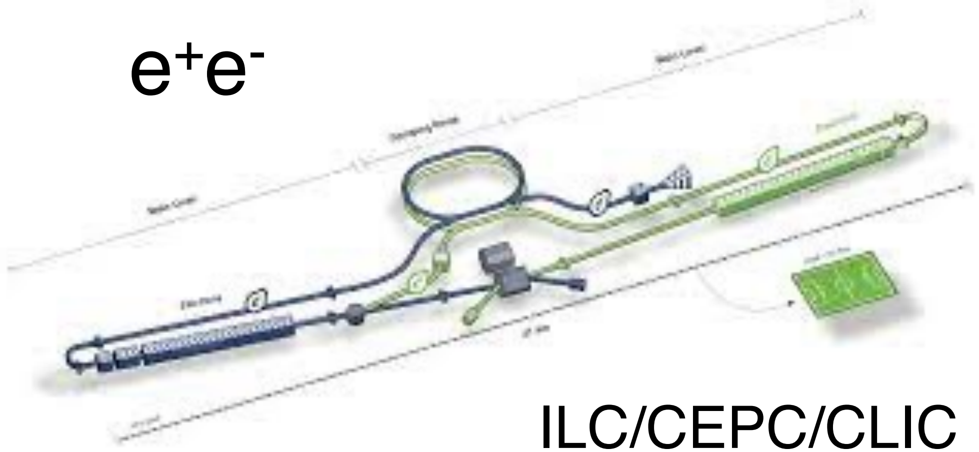
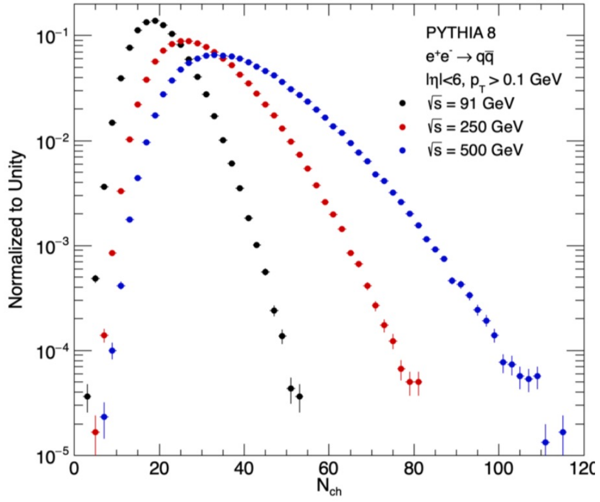
# Search for single-particle QGP at future facilities

e⁺e⁻

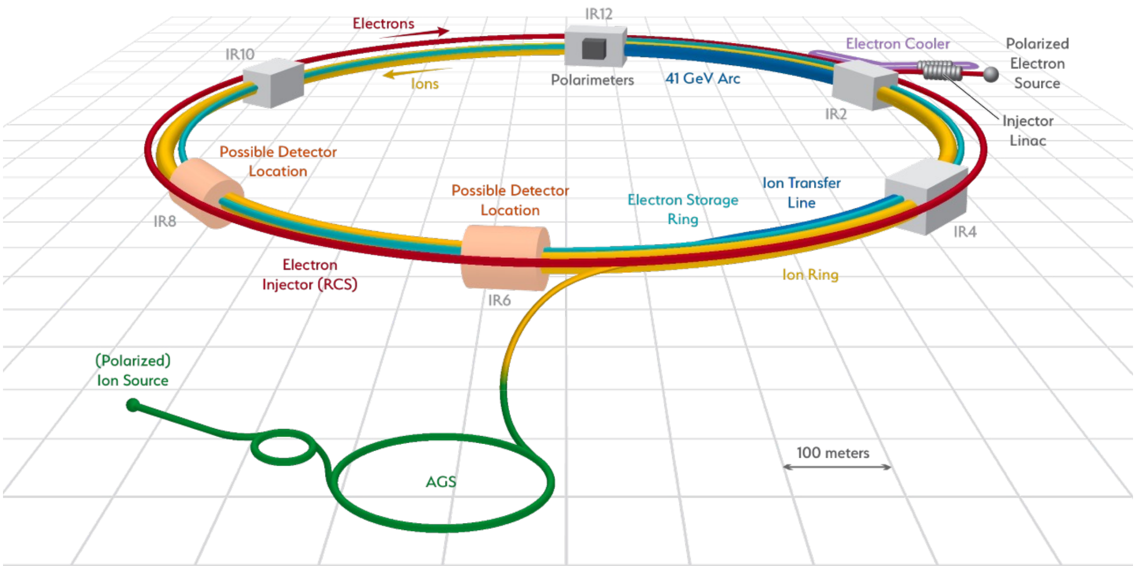


ILC/CEPC/CLIC

A. Baty




Lepton (e, $\mu$)-hadron




Muon-ion collider (to succeed the EIC)
D. Acosta, W. Li, *NIM A* 1027 (2022) 166334

– First workshop at Rice in 2023!

# Summary

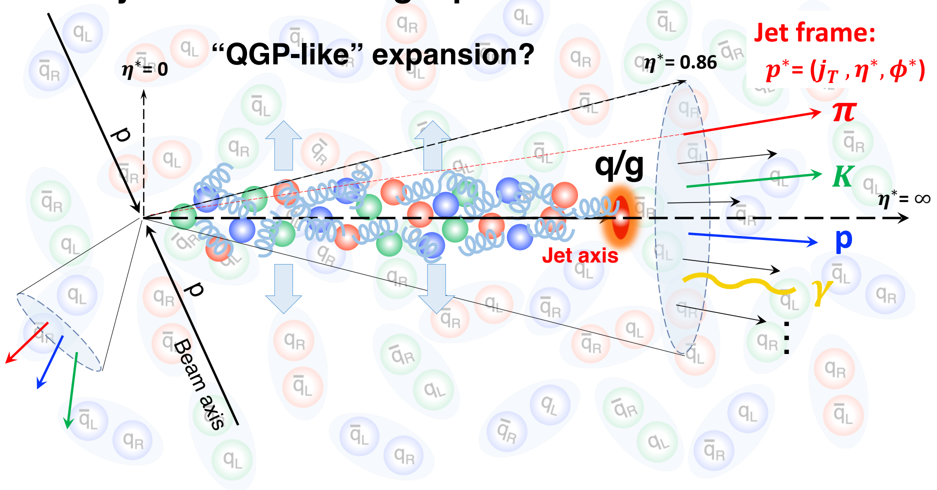
Tremendous progress made in finding and understanding QCD collectivity in small systems that was not originally expected

How small is too small? Where else to find the collectivity?

- ➢ **Collectivity may be intrinsically built into any QCD many-body system because ot its non-perturbative nature.**
- ➢ Pushing to the ultimate small system – **a single parton!**

We conjecture that jet fragmentation shows QGP-like signatures. Observing them will shed light on: **QCD vacuum,**
**QCD non-perturbative dynamics,**
**quantum entanglement in QCD.**

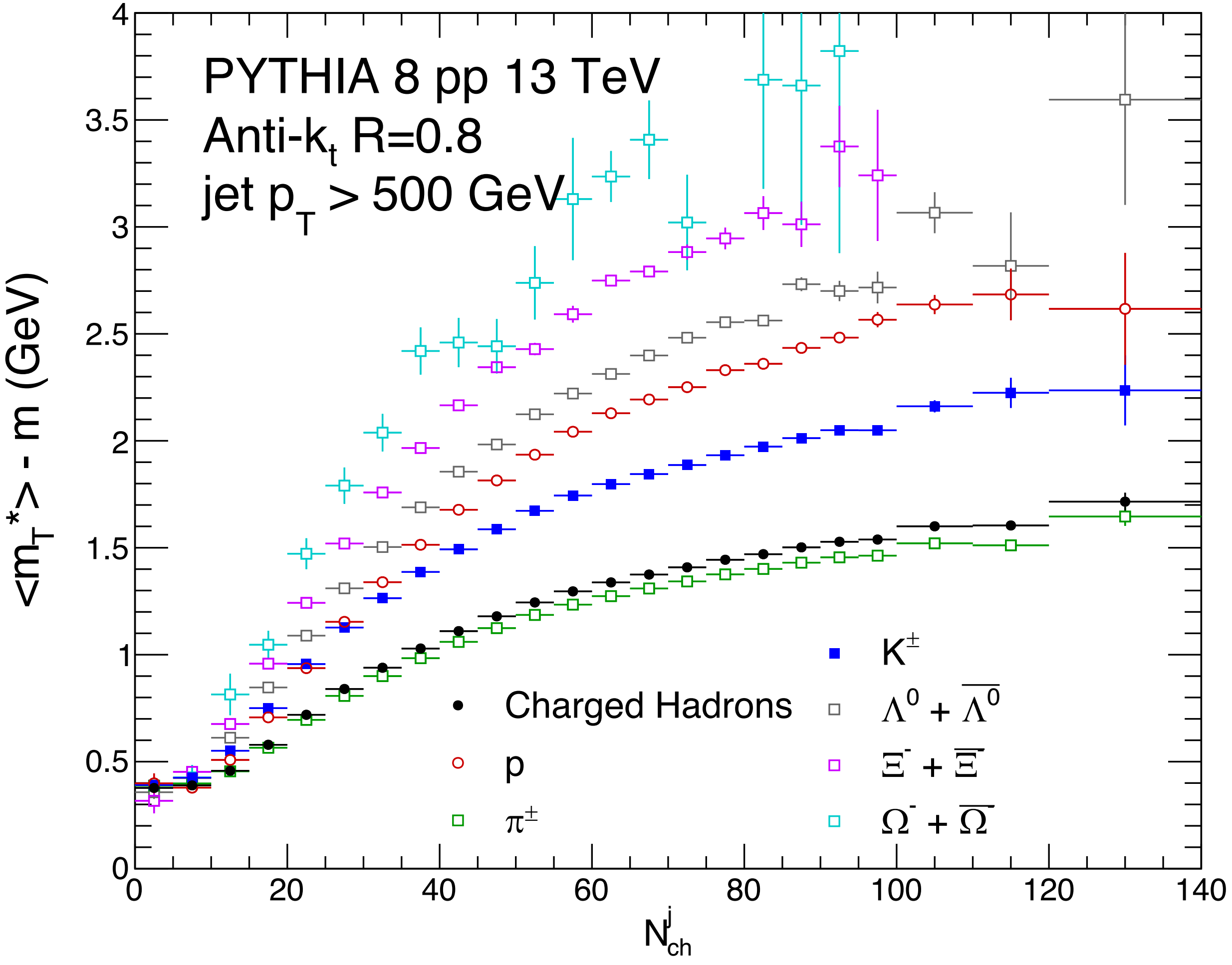
Dynamics of a "single-parton" in the vacuum



# Backups

# Radial flow in a jet

Average kinetic energy vs $N_{ch}^{j}$ in jets

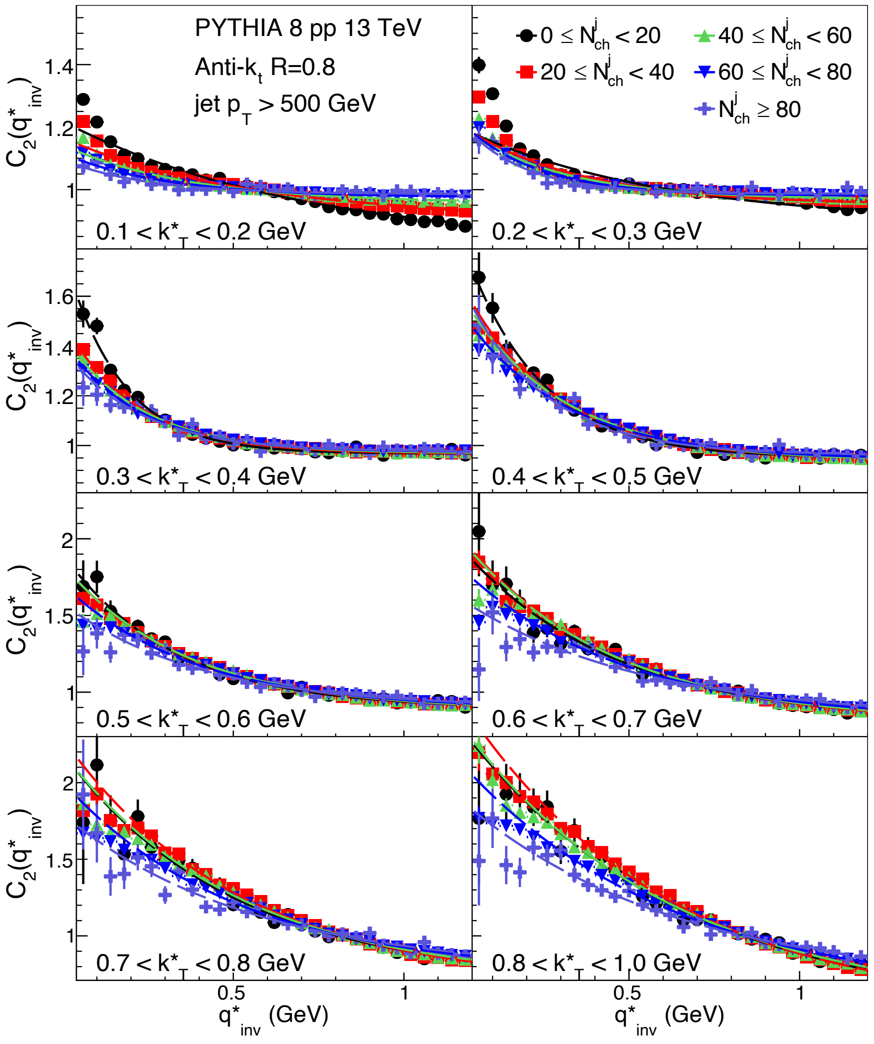



"Radial flow" effect is qualitatively in PYTHIA jets

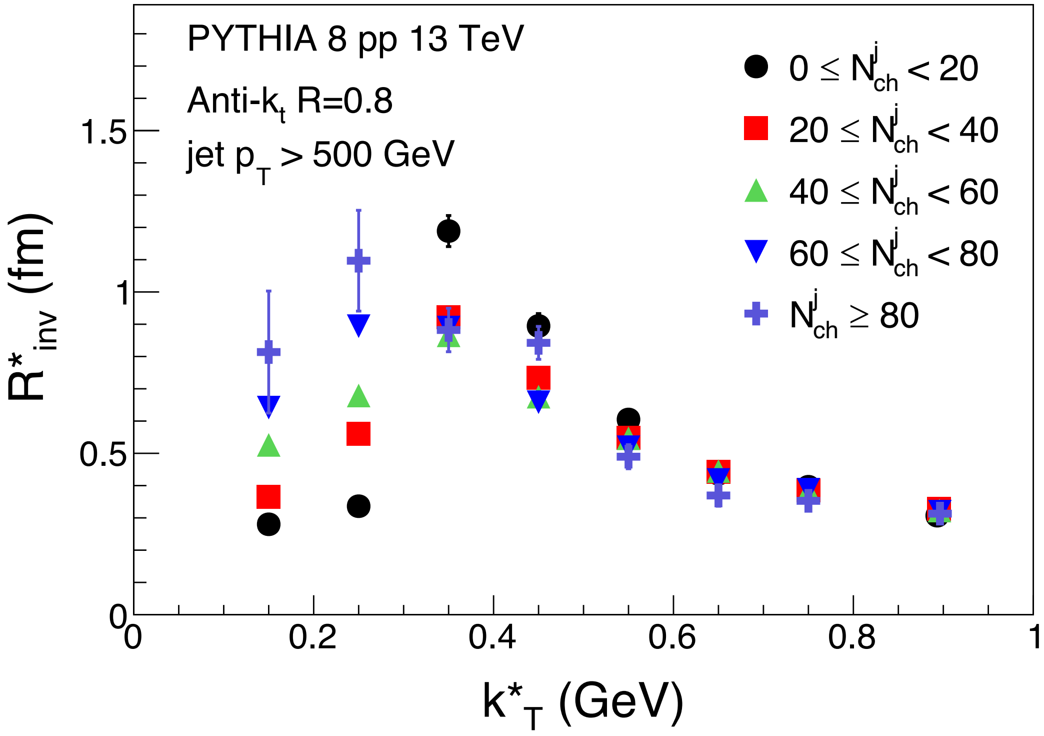
Color reconnection as for in the lab frame?

# HBT correlations in a jet – “size” of a parton

1-D HBT correlation functions




HBT radii of a jet:




Non-zero but dropping toward low $k_T^*$, opposite to AA collisions