Recent developments in Heavy Ion Collisions

Carlota Andres (she/her)

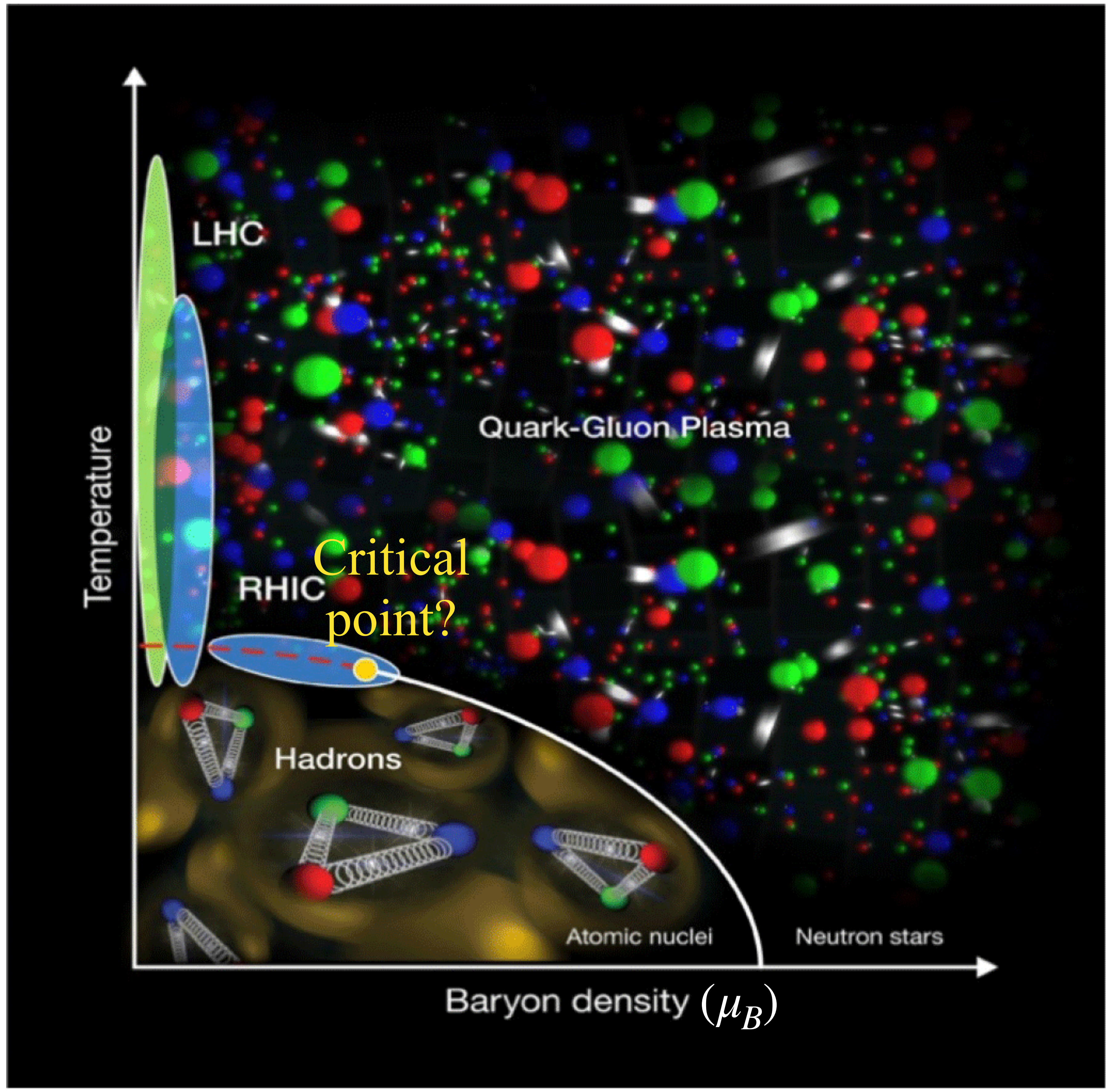
LIP, Lisbon

LHCP2024

Boston, June 3-7, 2024

QCD phase diagram

- Hot QCD emergent dynamics at reach in collider experiments!



QCD phase diagram

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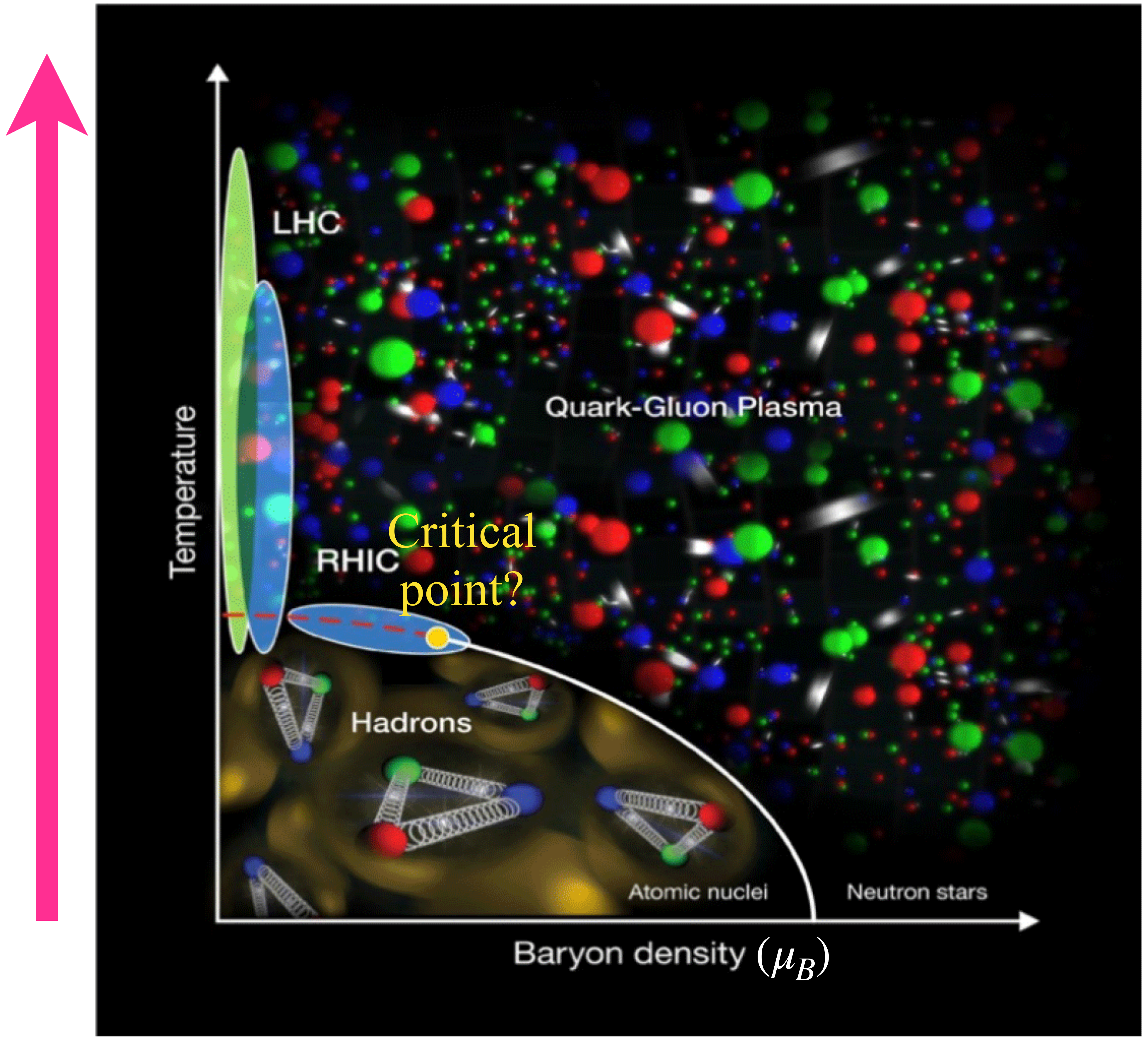
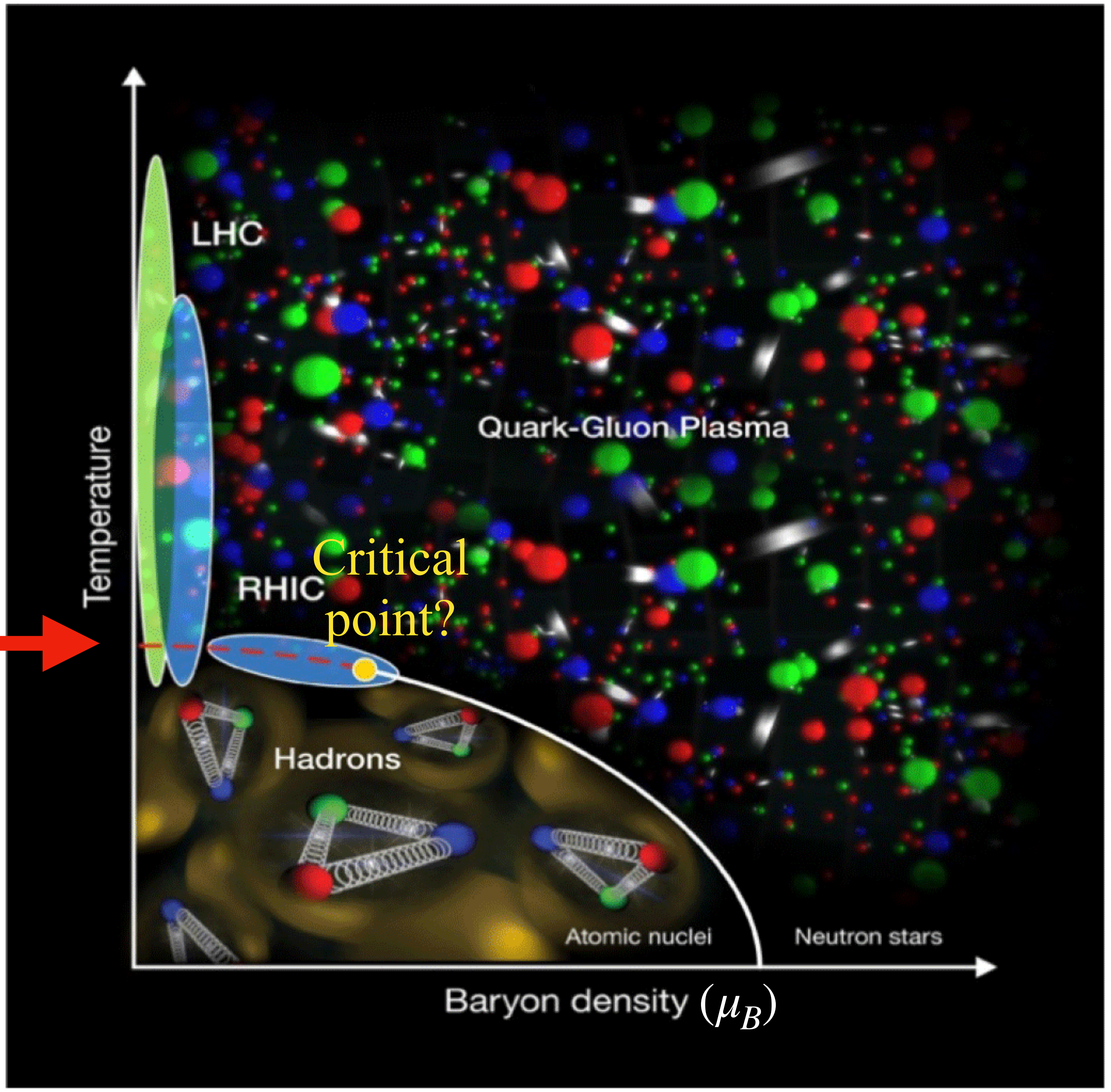


QCD phase diagram

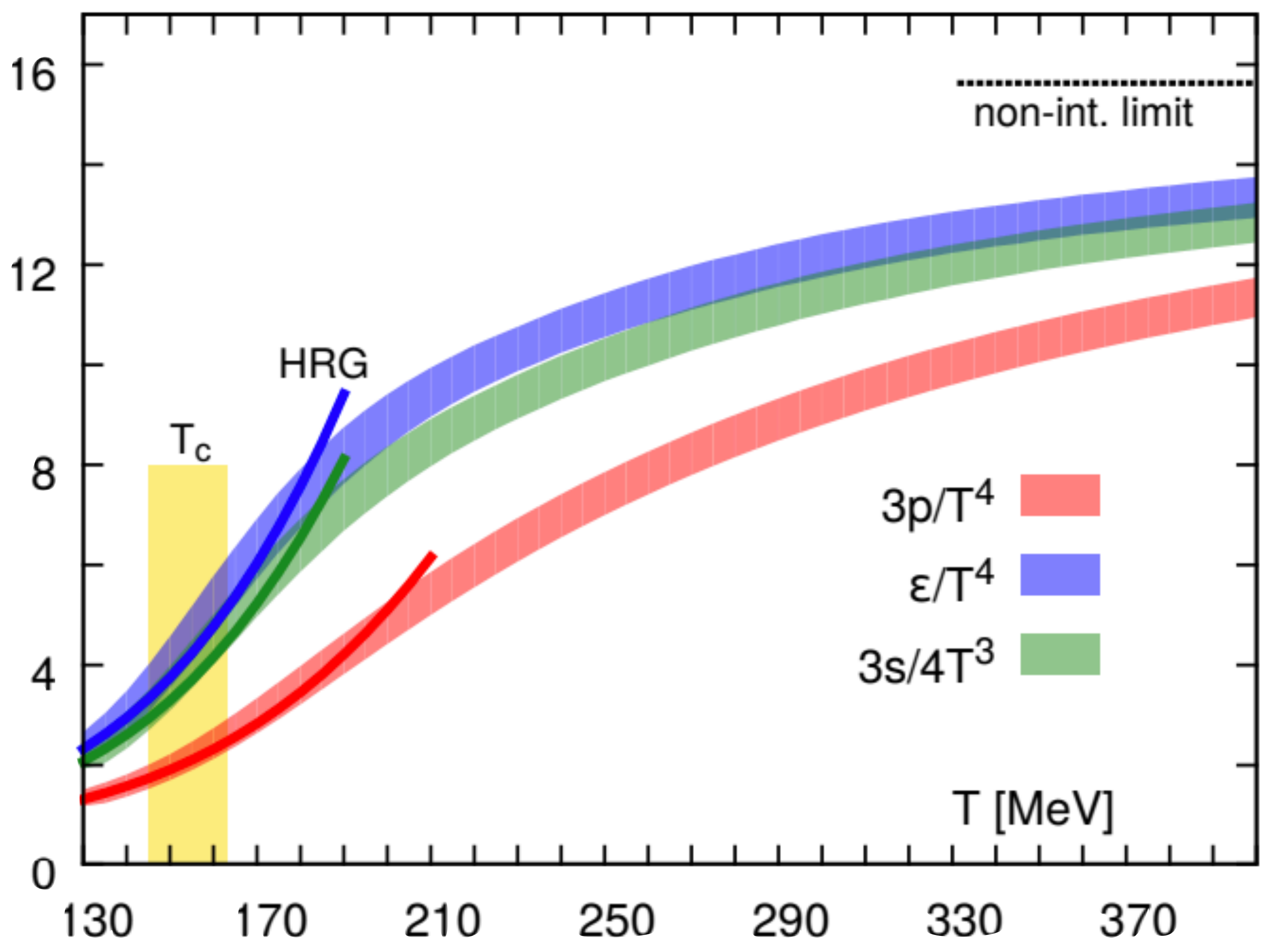
- Hot QCD emergent dynamics at reach in collider experiments!

$T \sim 154$ MeV

~1.8 trillion °C



Lattice QCD ($\mu_B = 0$)



HotQCD Collaboration
Phys. Rev. D 90 (2014) 094503

QCD phase diagram

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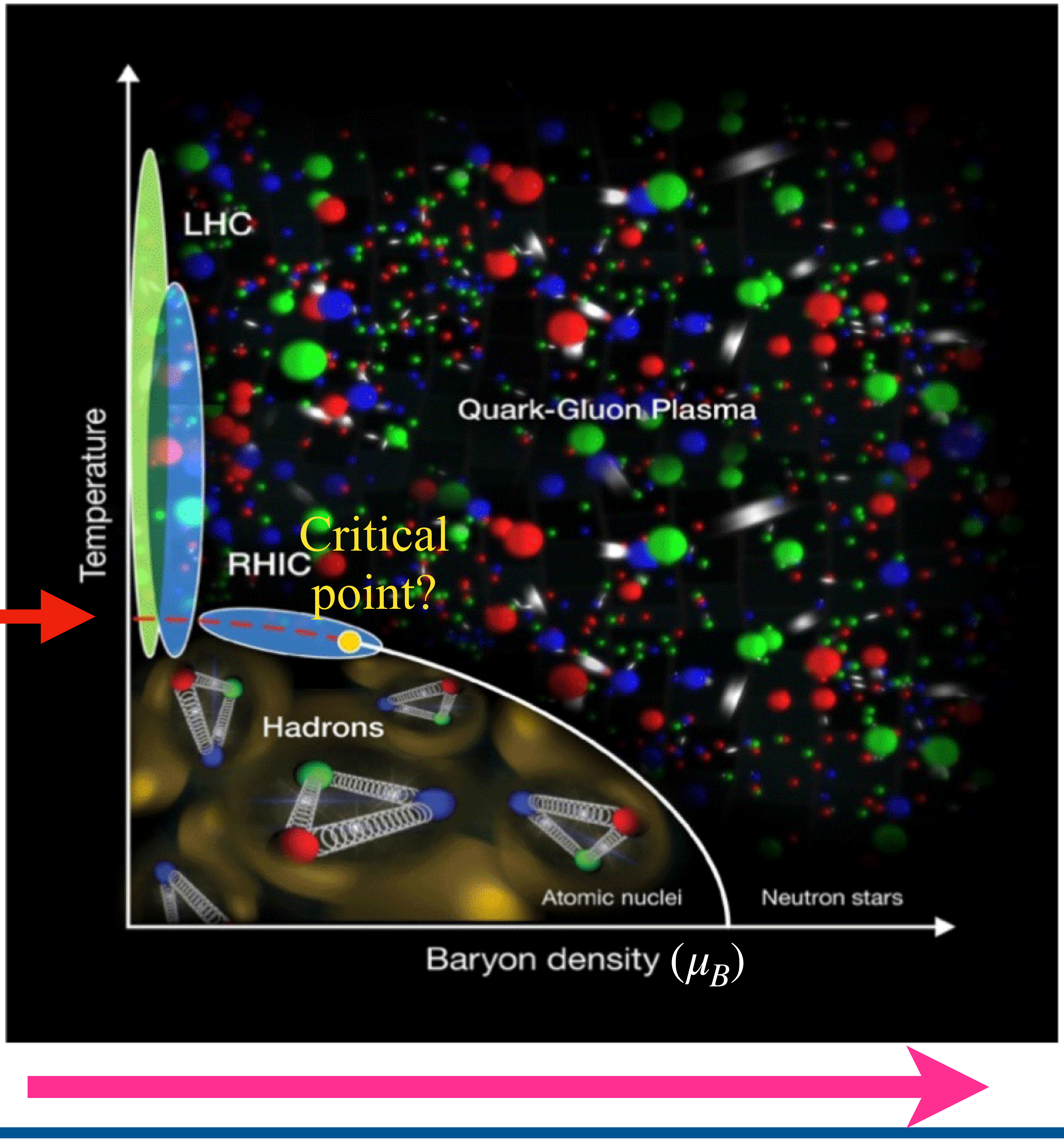

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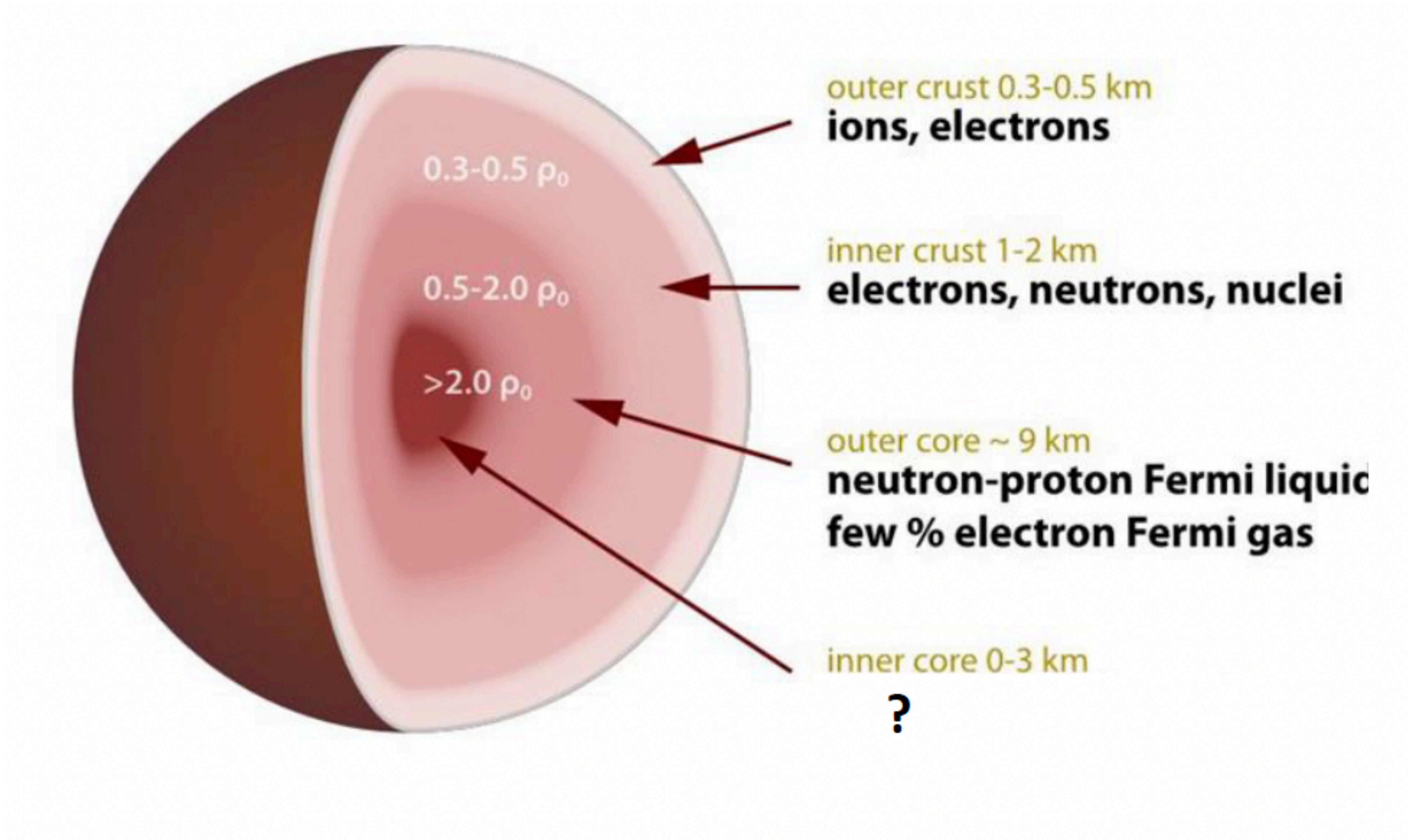
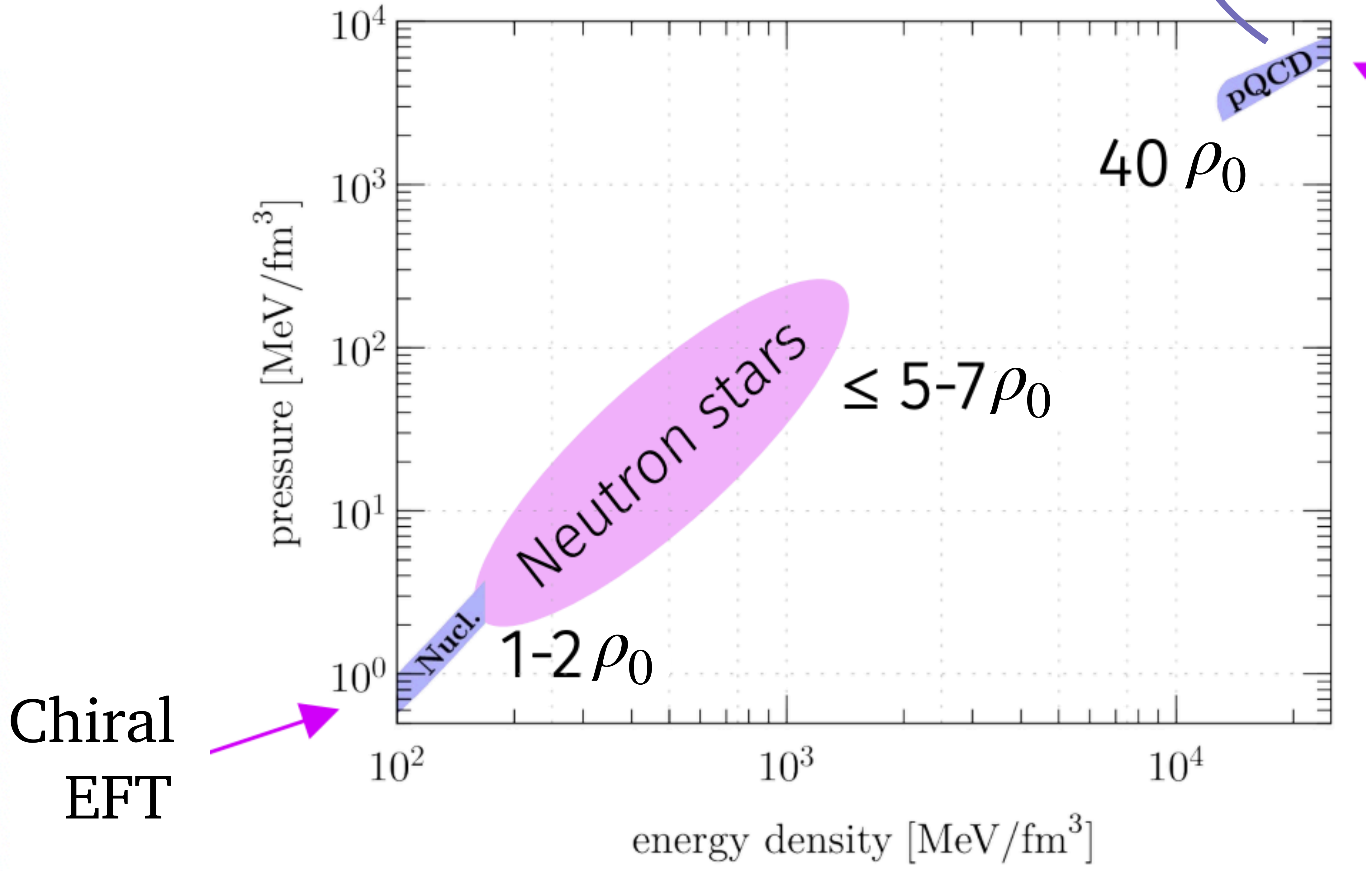
$\sim$1.8 trillion °C

Neutron stars

Kurkela, et al., PRD 81, 105021 (2010)
Gorda et al., PRL 121, 202701 (2018)
Gorda et al., PRL 131, 181902 (2023)
Navarrete et al., 2403.02180

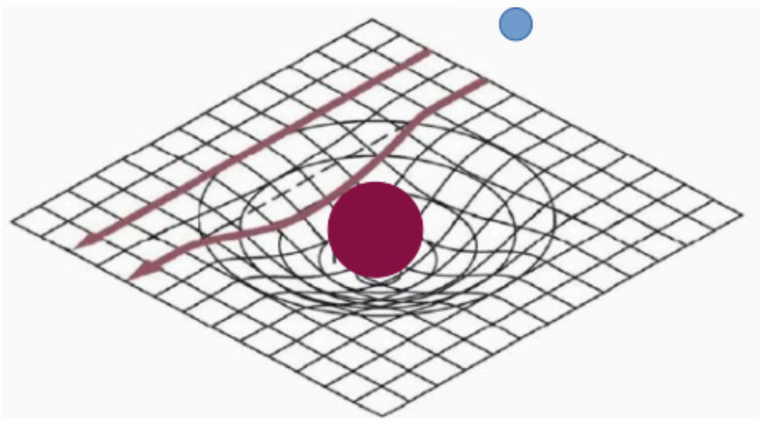
- At $T \approx 0$: No Lattice. But we have astrophysics, particle, and nuclear physics



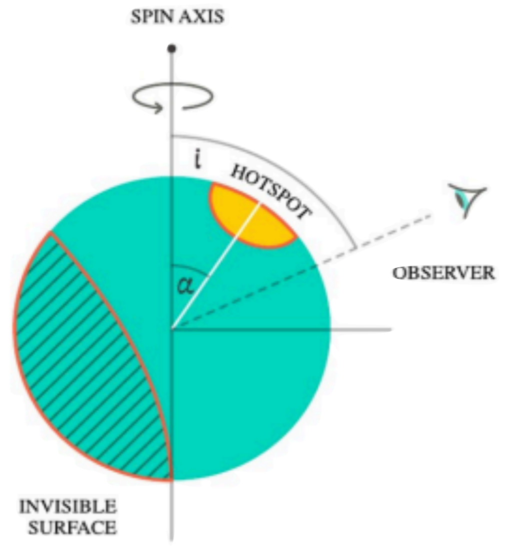


- EoS of the inner core? Upper and lower bound from pQCD and Chiral EFT + **astrophysical measurements** (including **GW data** from binary neutron star mergers)

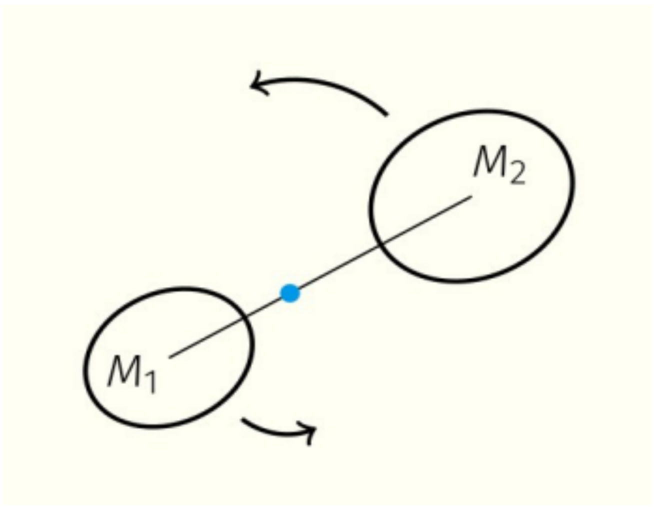
Neutron stars: EoS



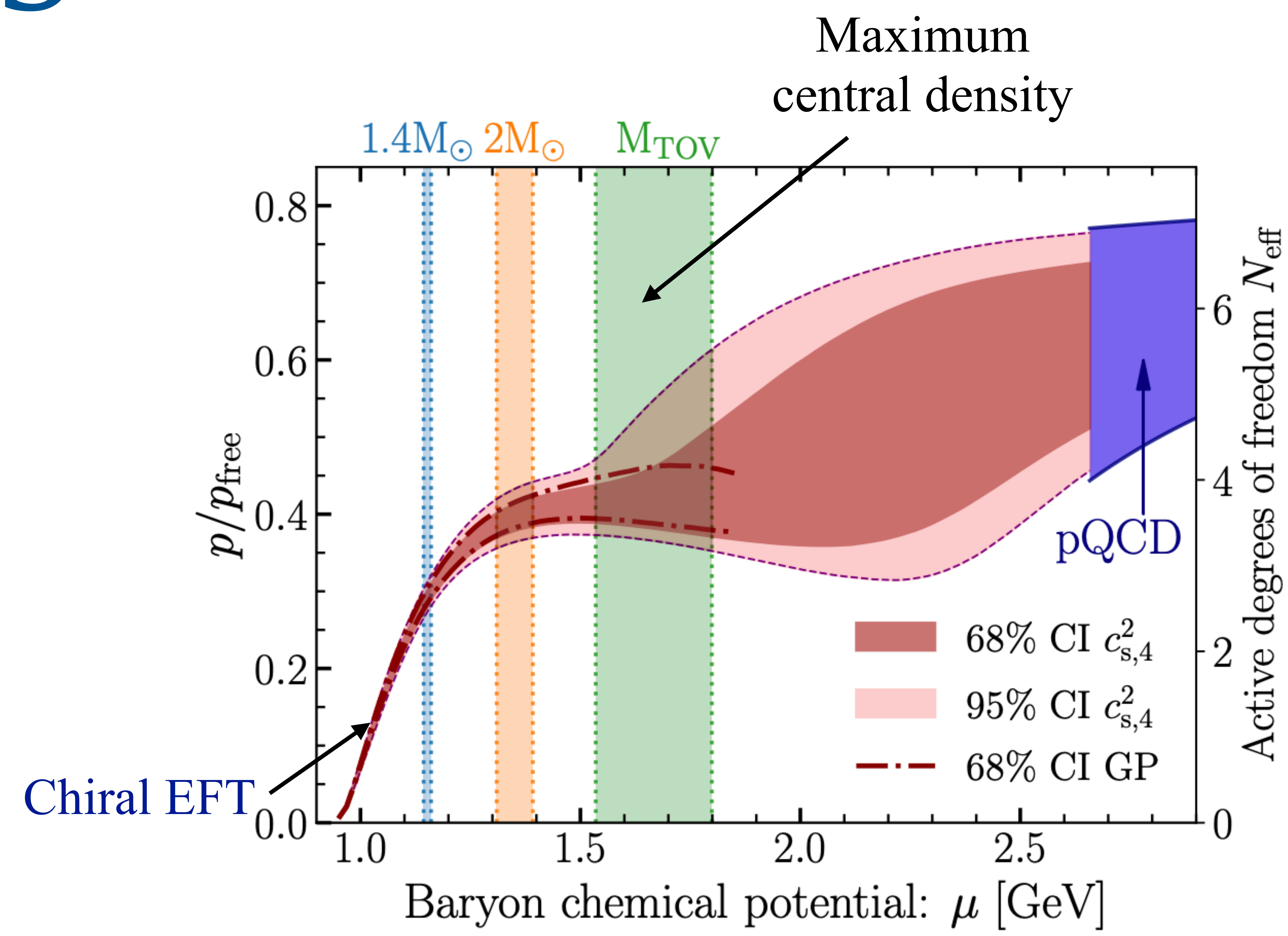
Masses



Radii, compactness



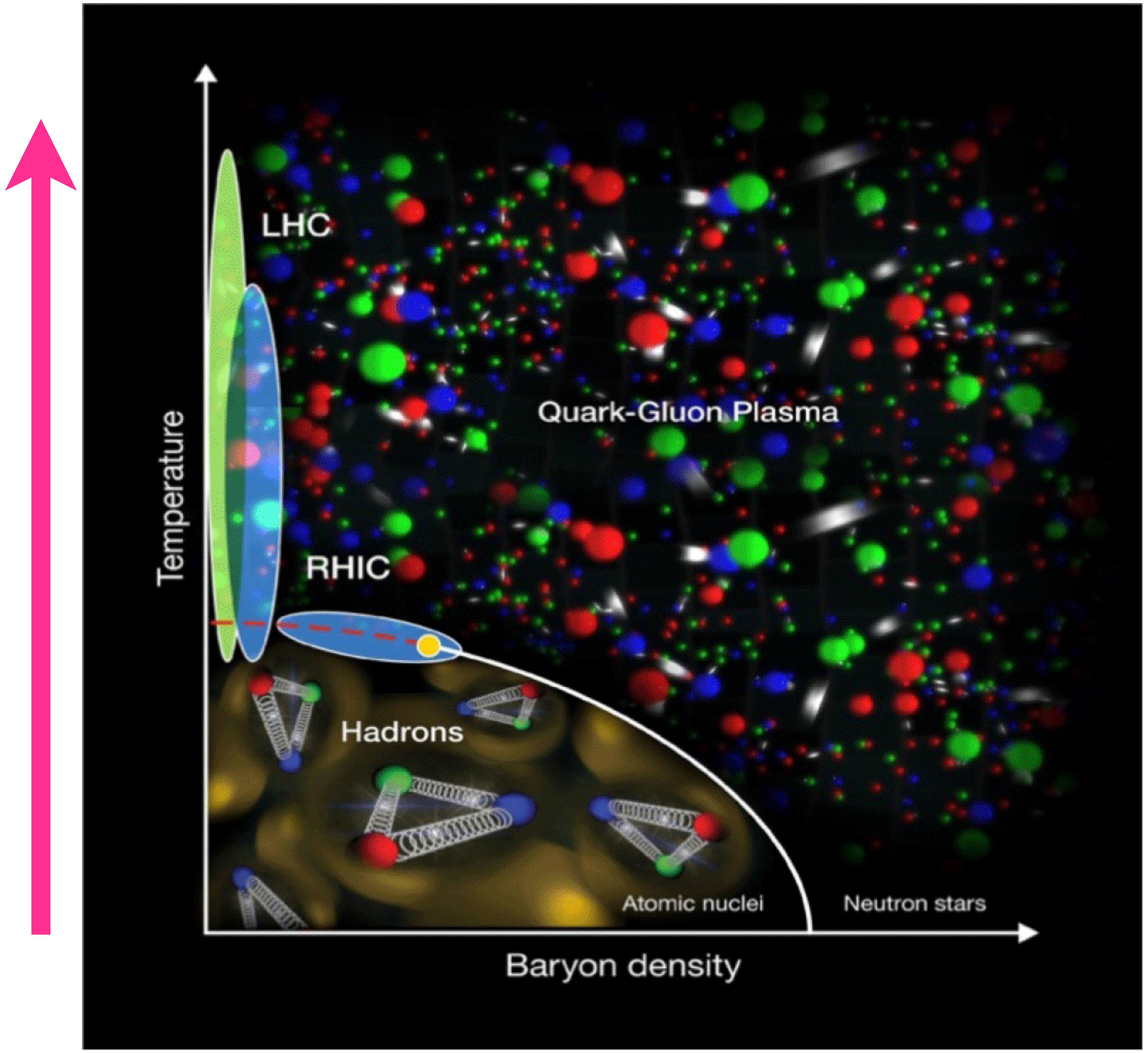
Deformabilities



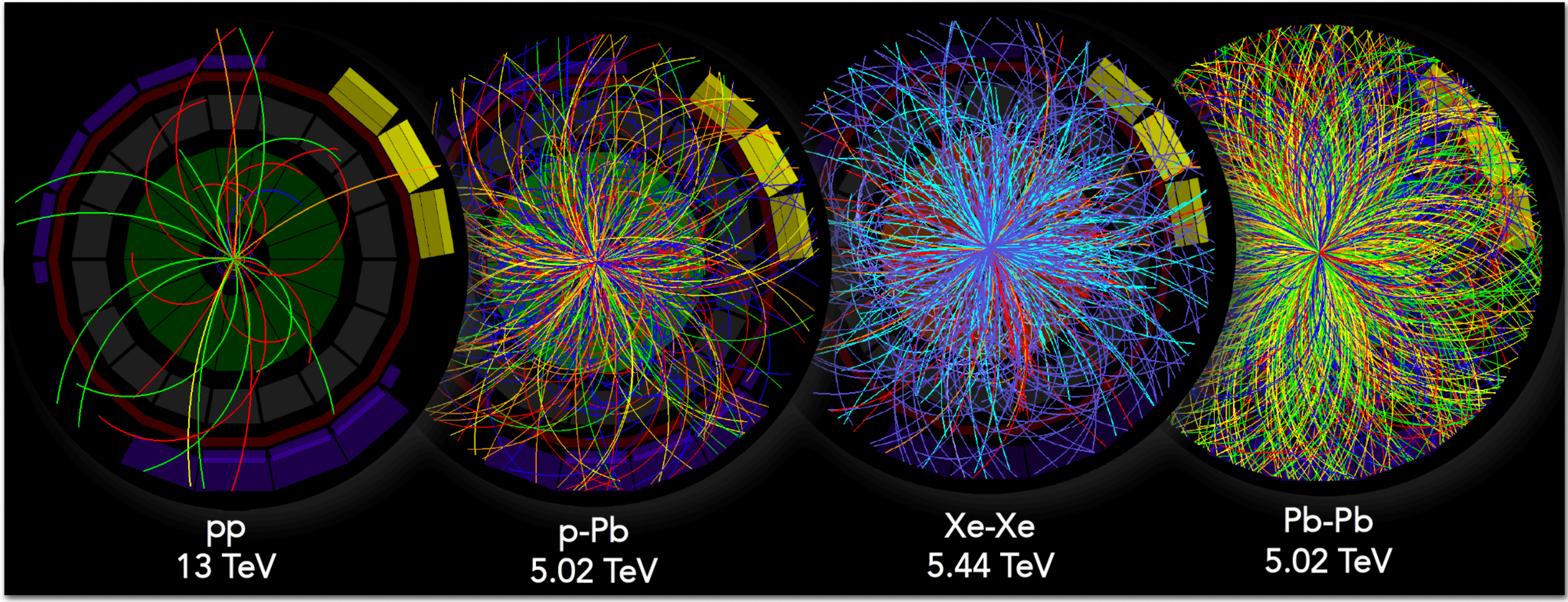
Annala, et al., Nature Commun. 14, 8451 (2023)

Number of degrees of freedom
consistent with deconfined quark matter!

Hot QCD at the LHC

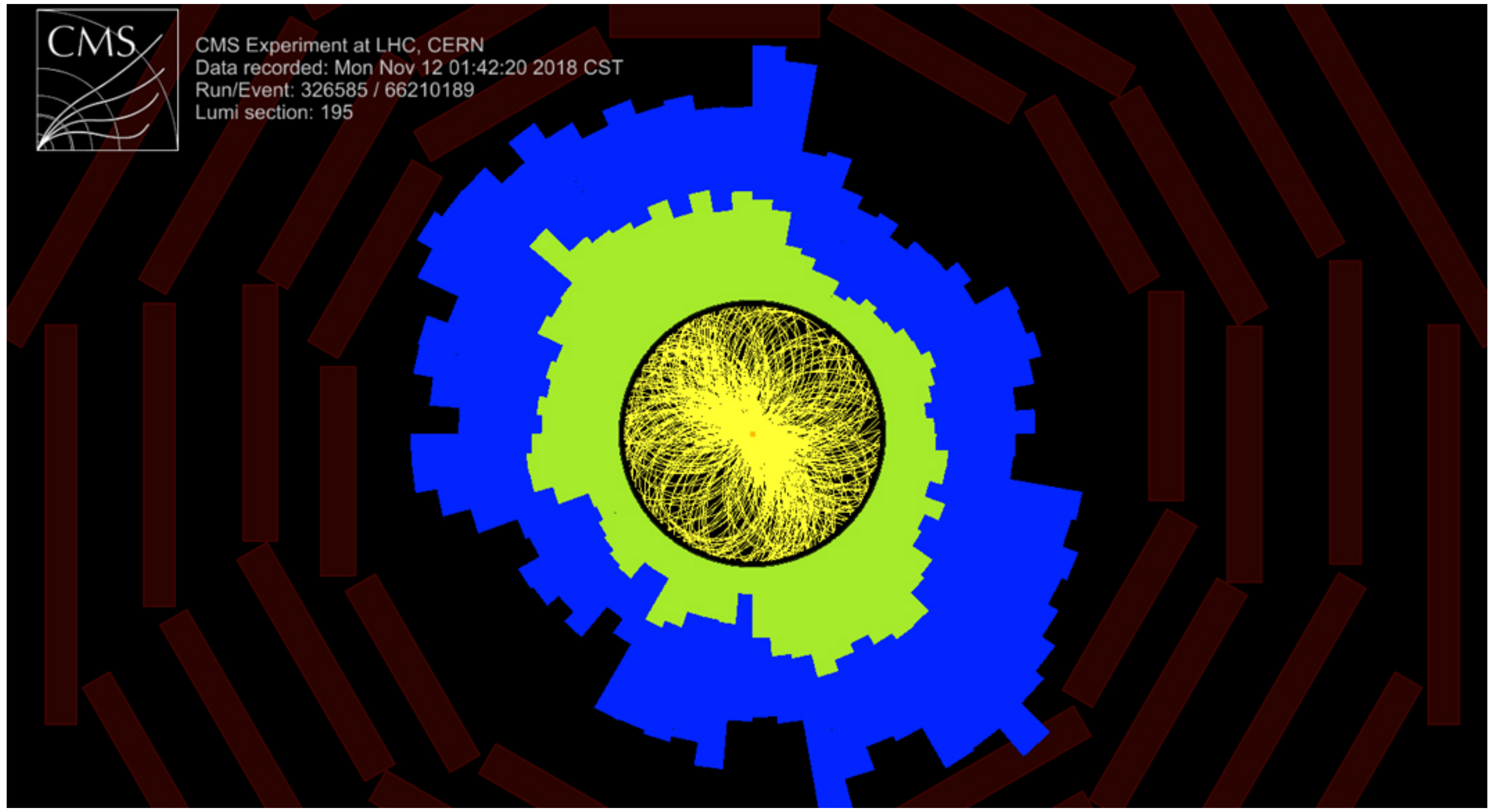


Hot QCD at the LHC

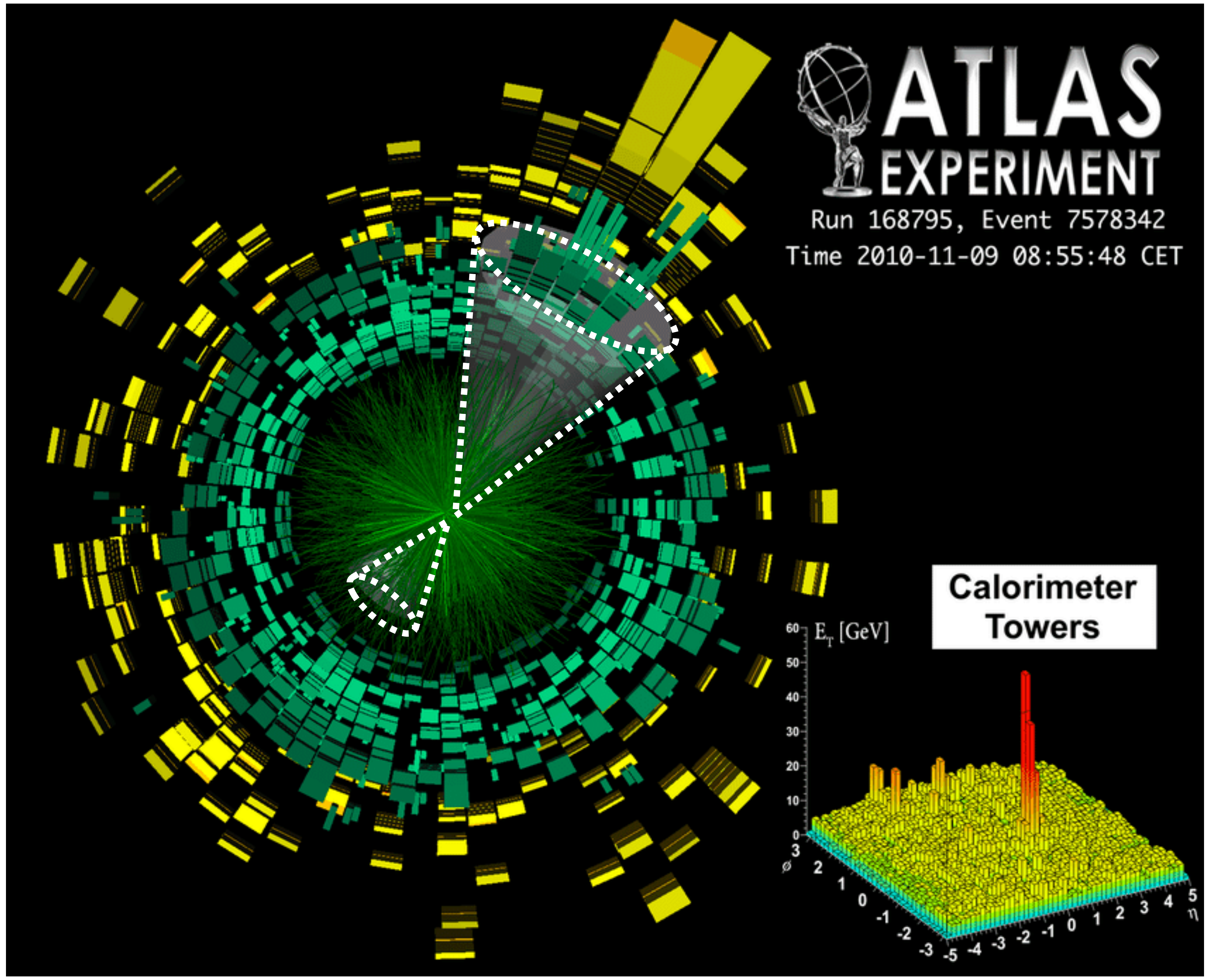


Evidence of QGP formation

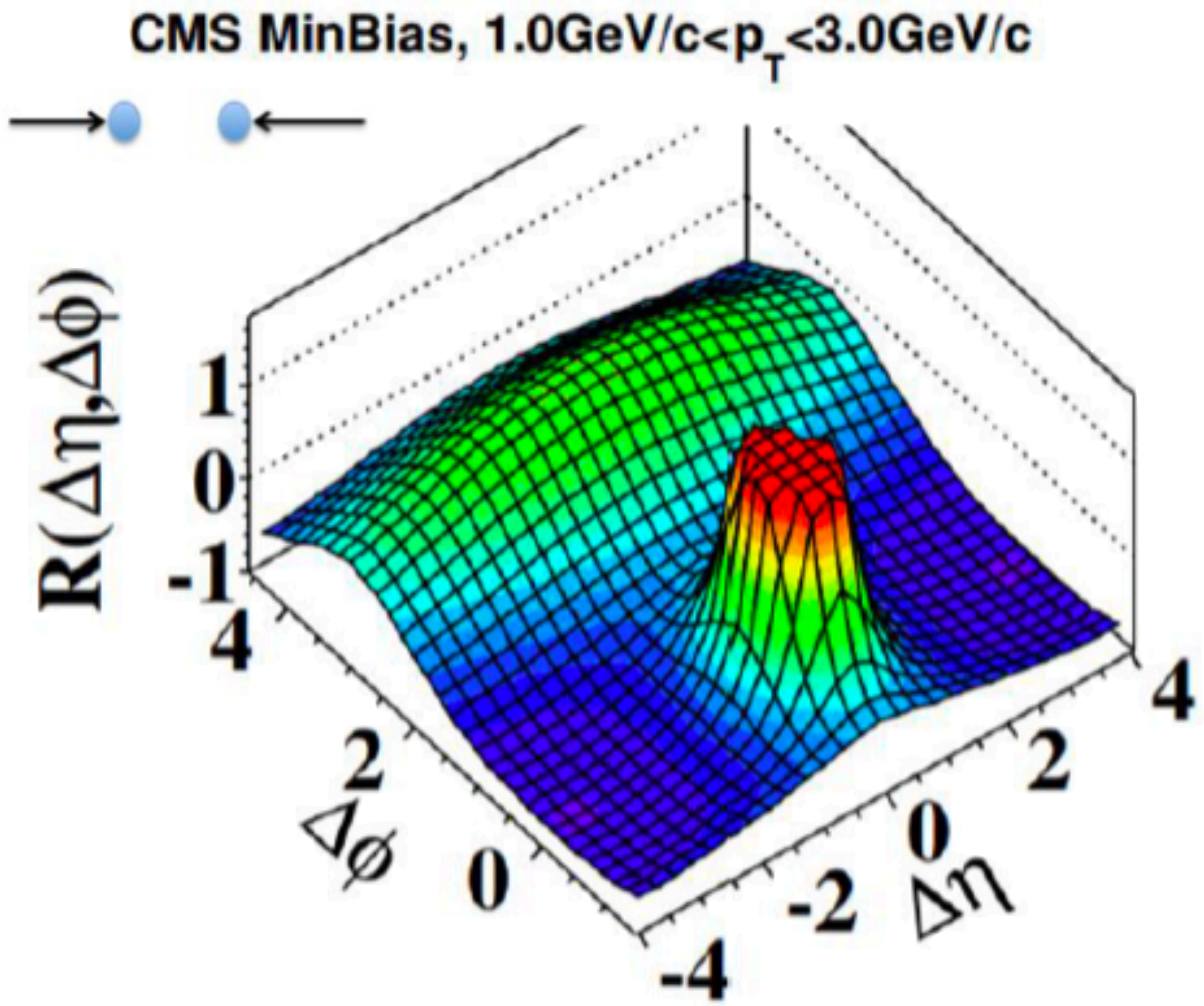
Low p_T: collectivity

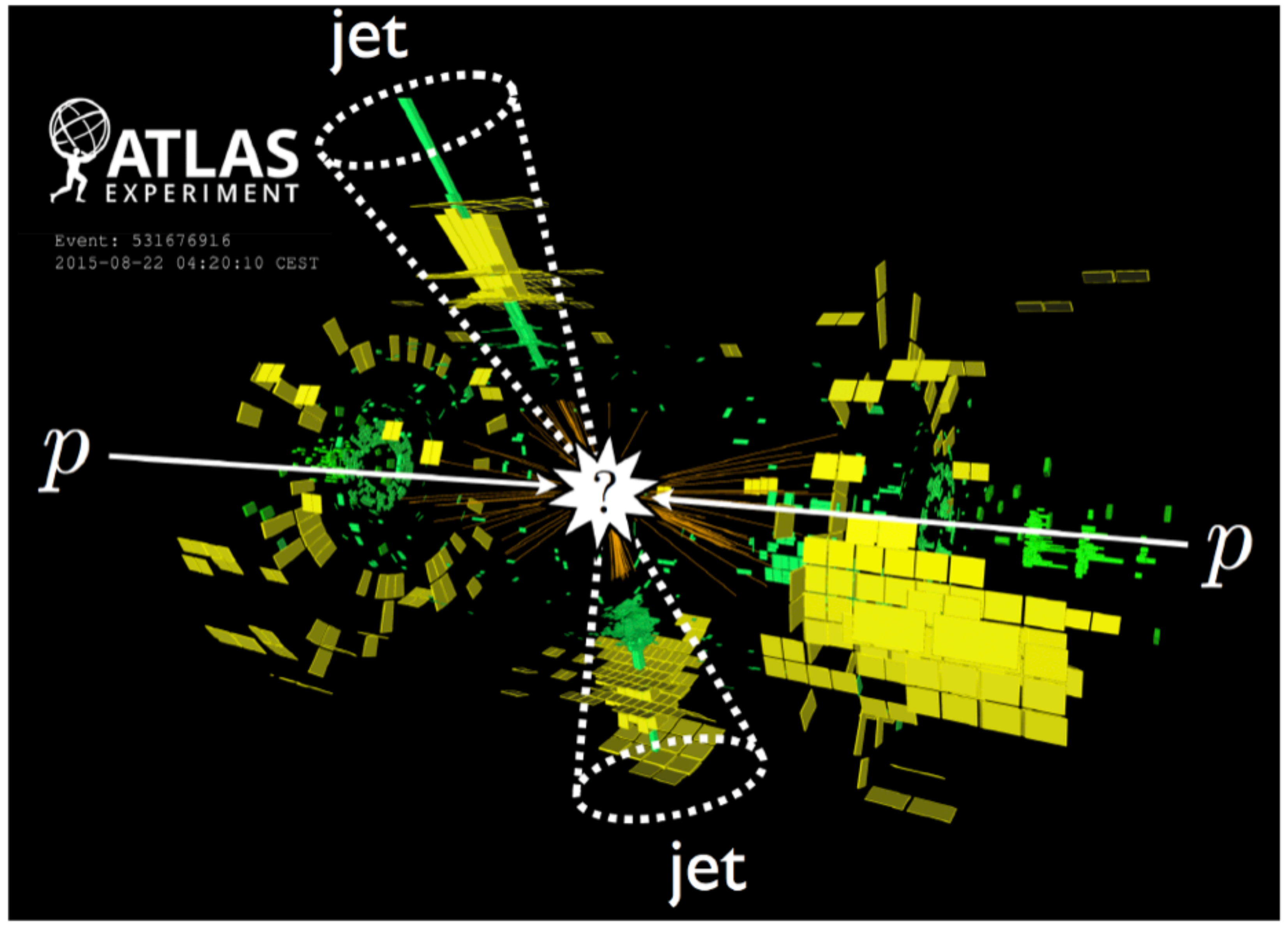


High p_T : jet quenching



Collectivity in heavy-ion collisions





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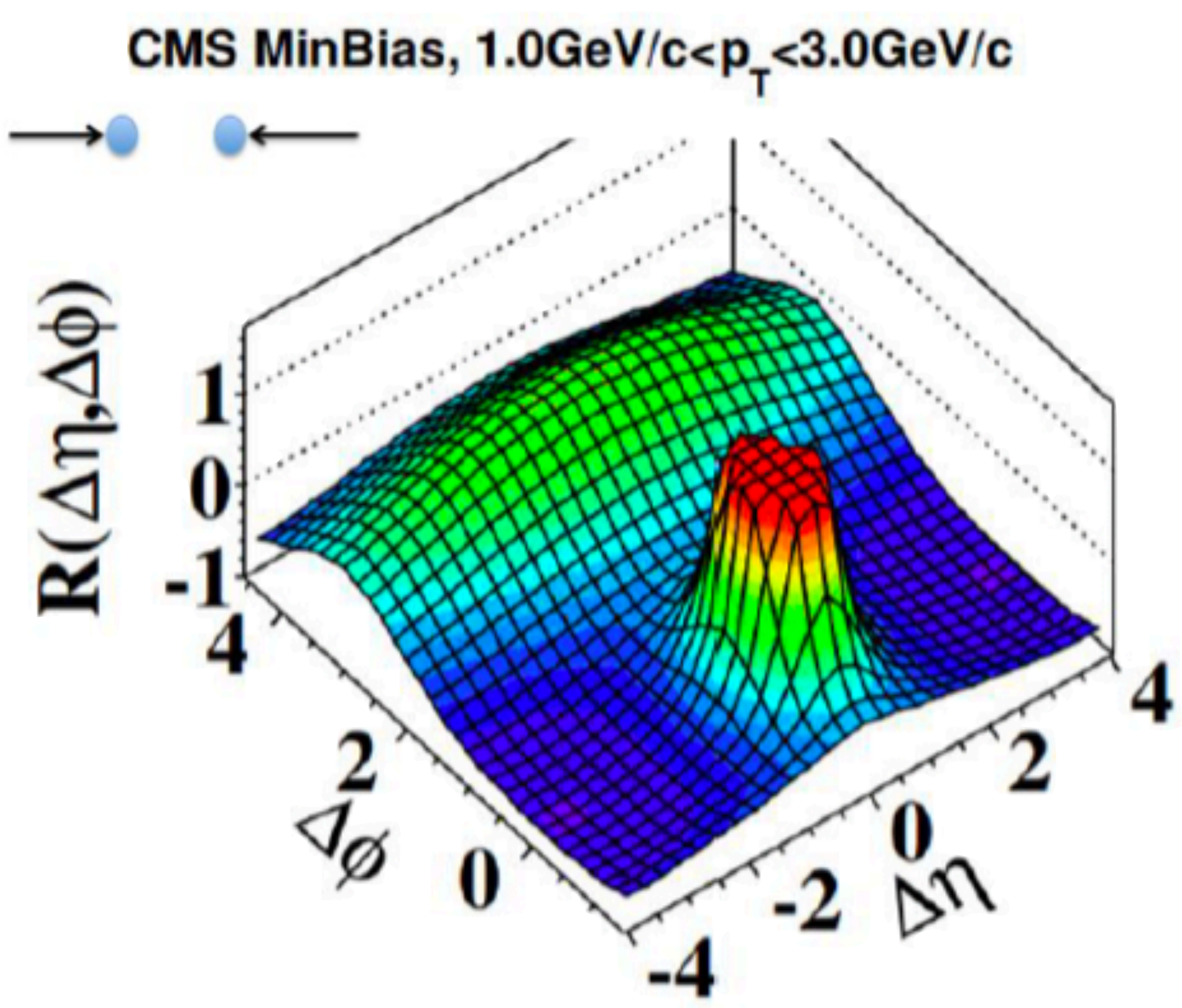

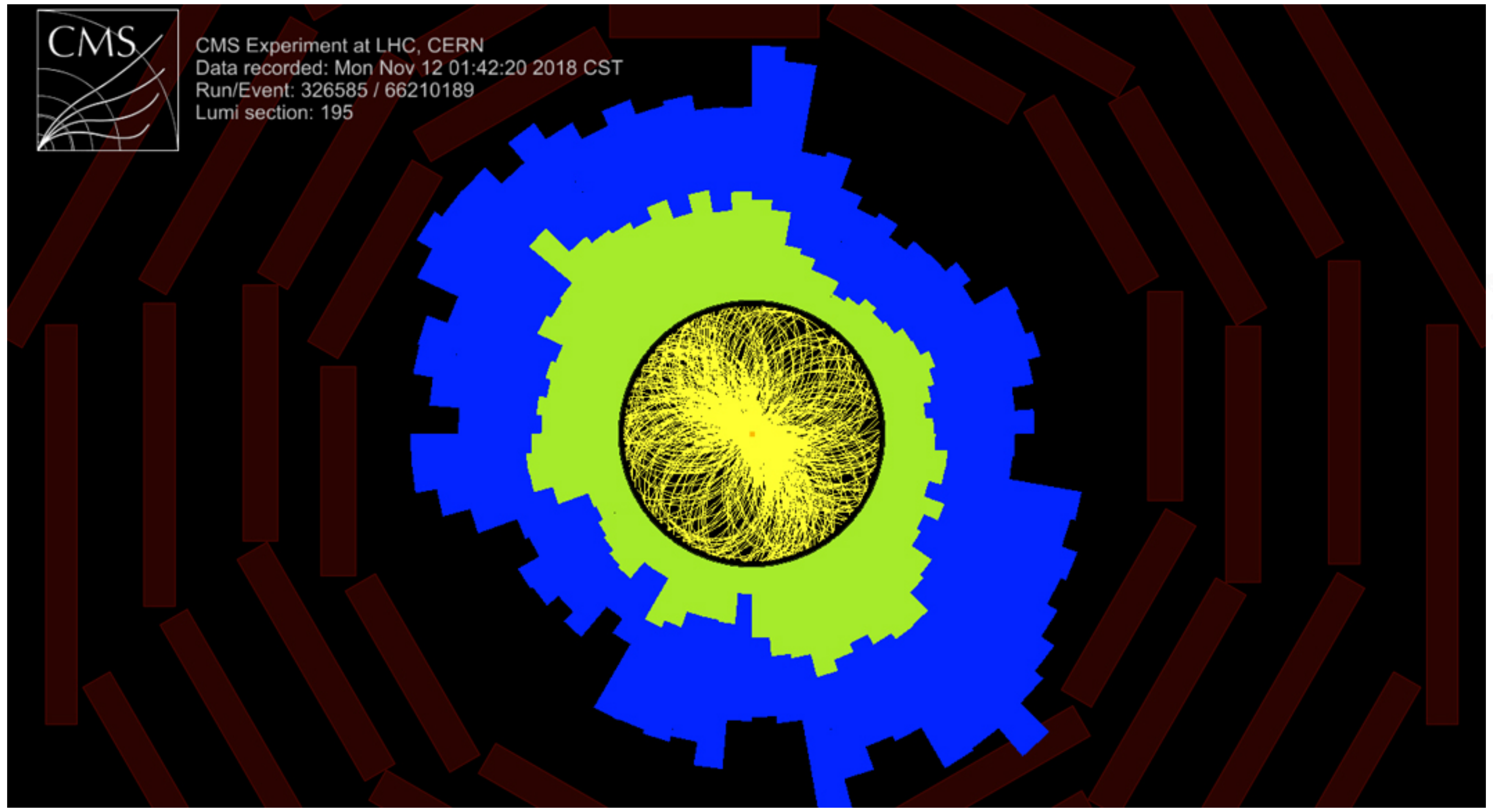

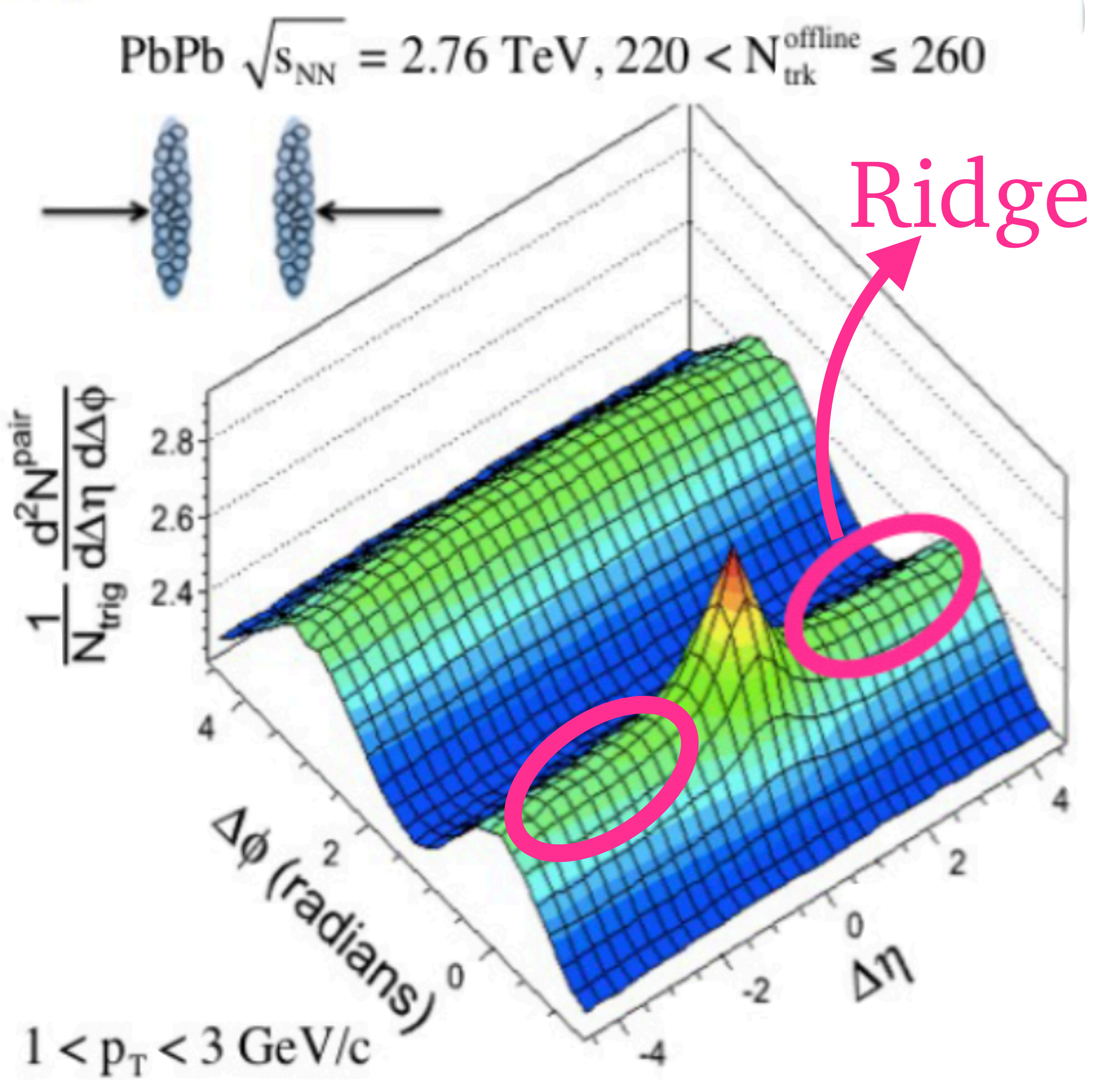

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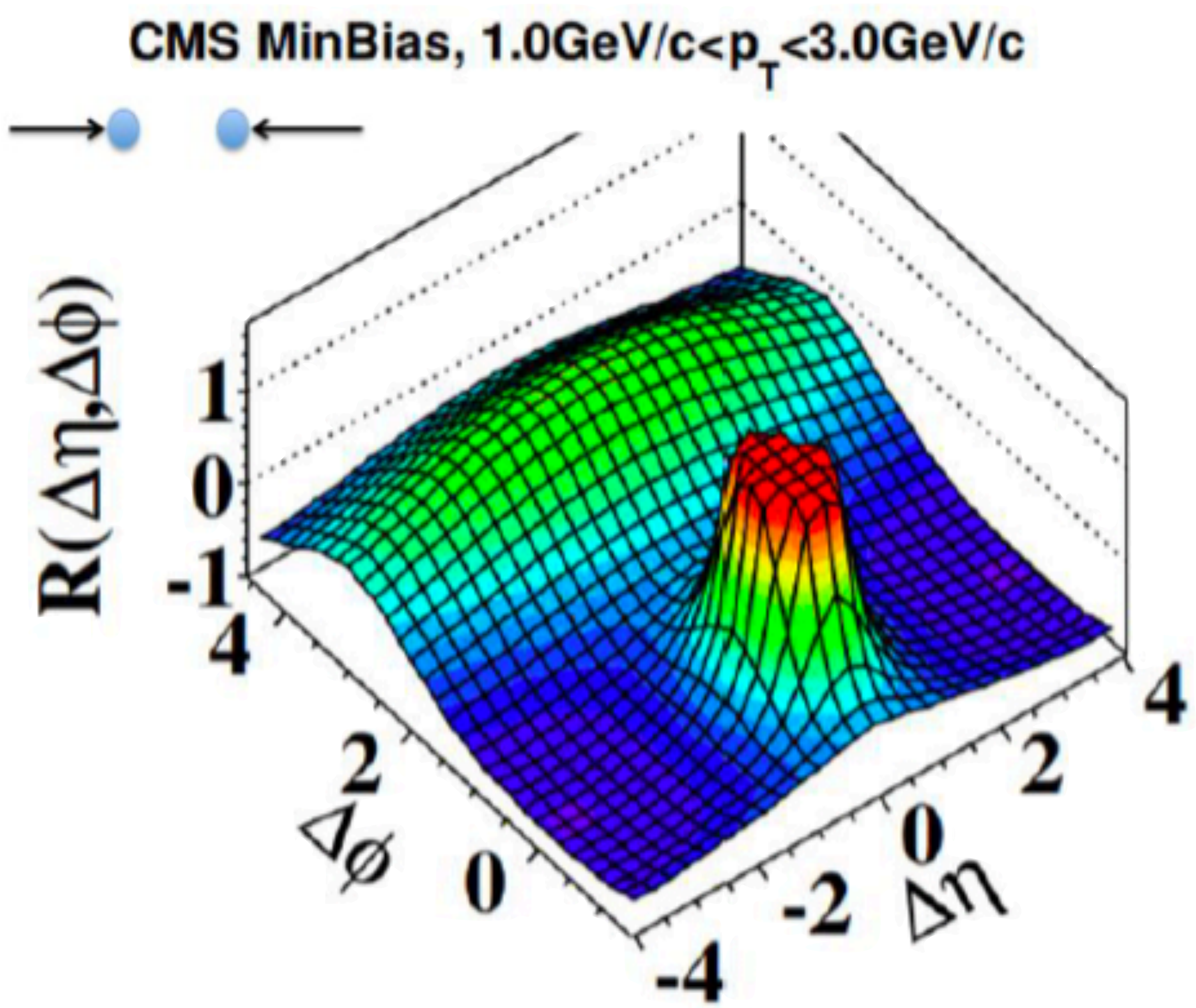
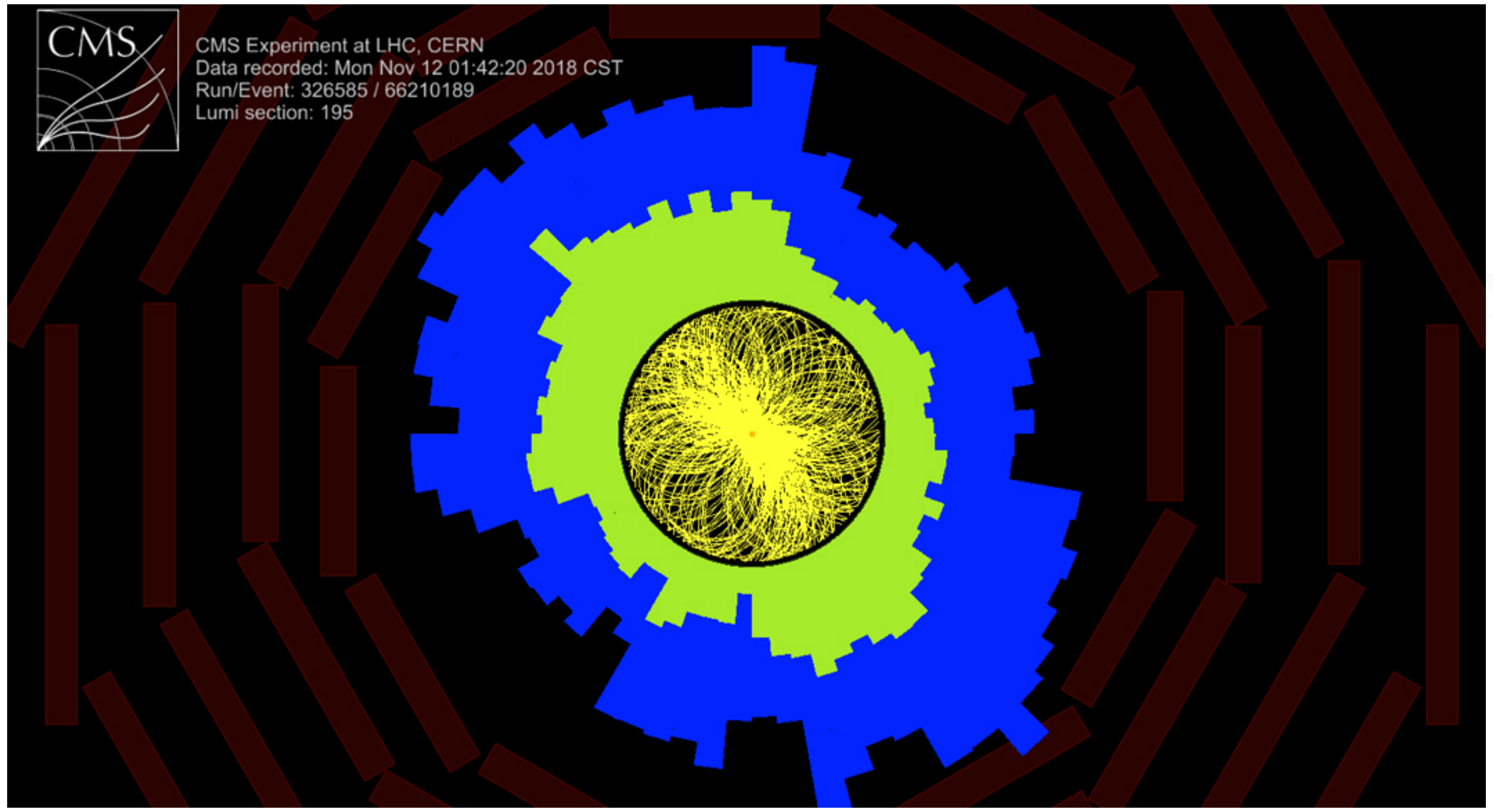
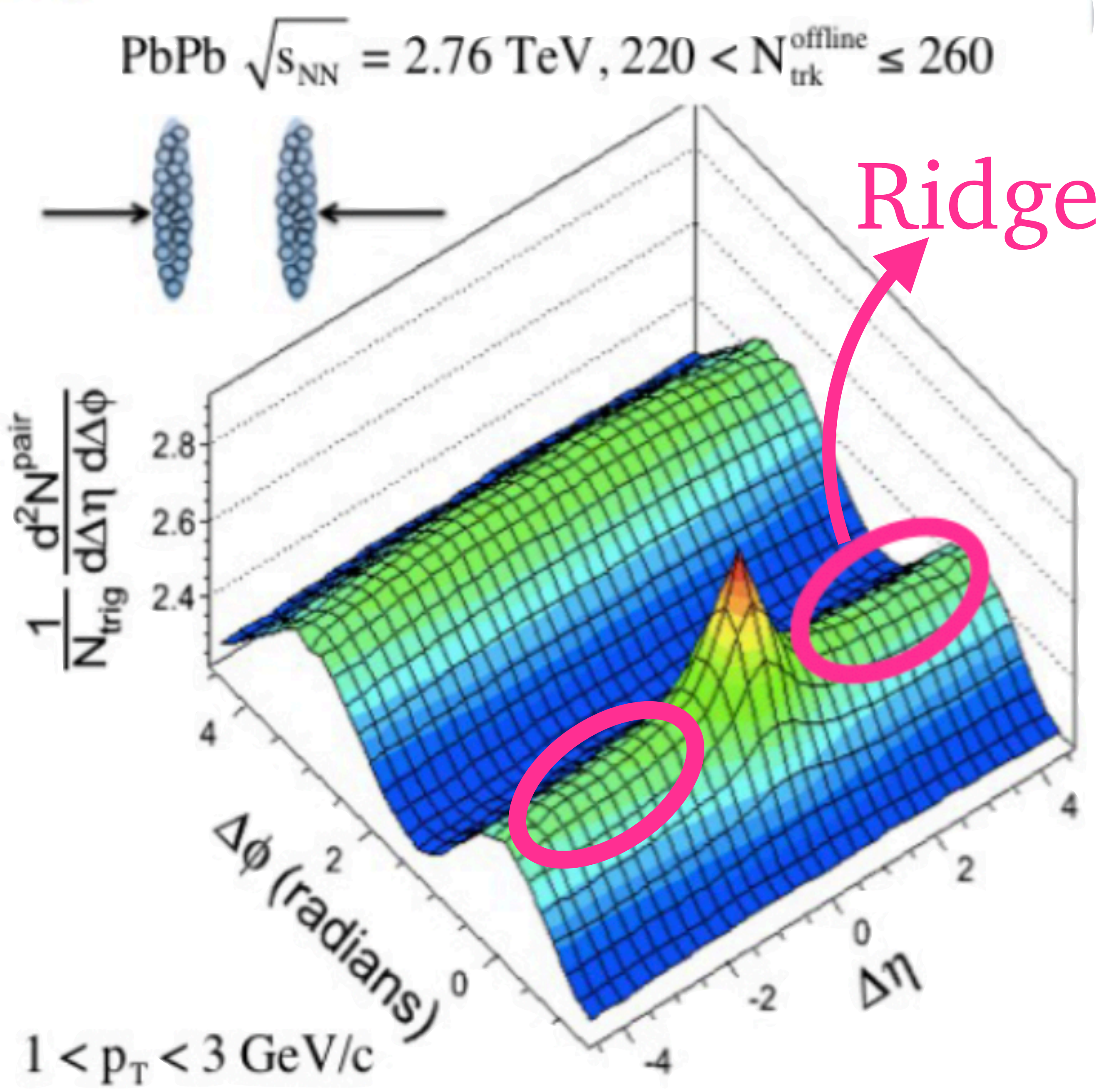
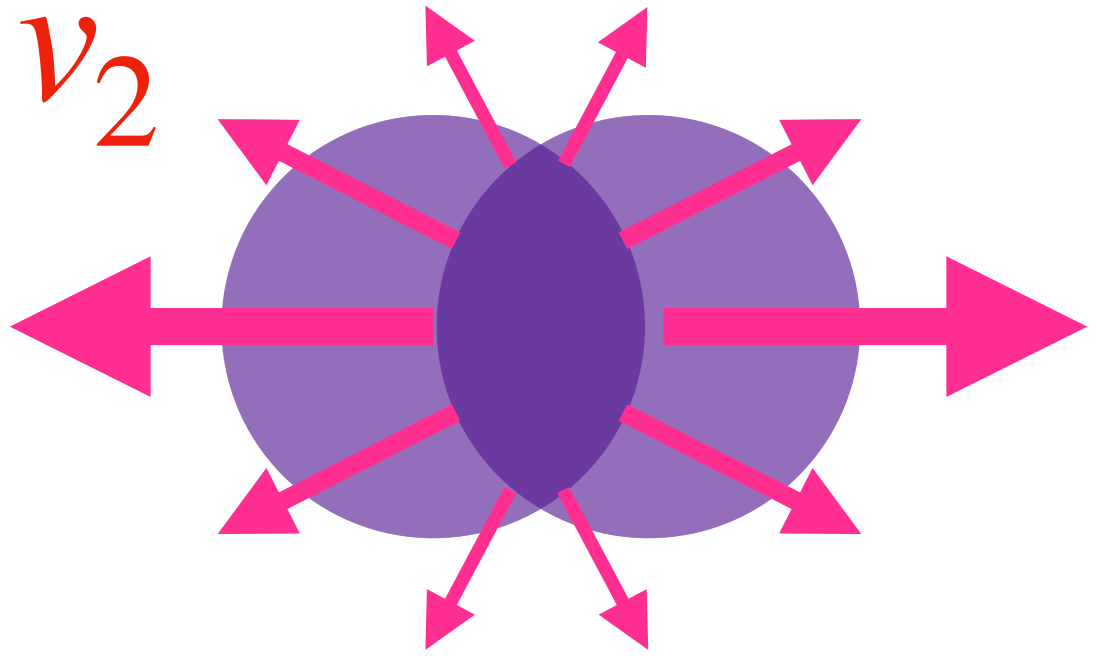




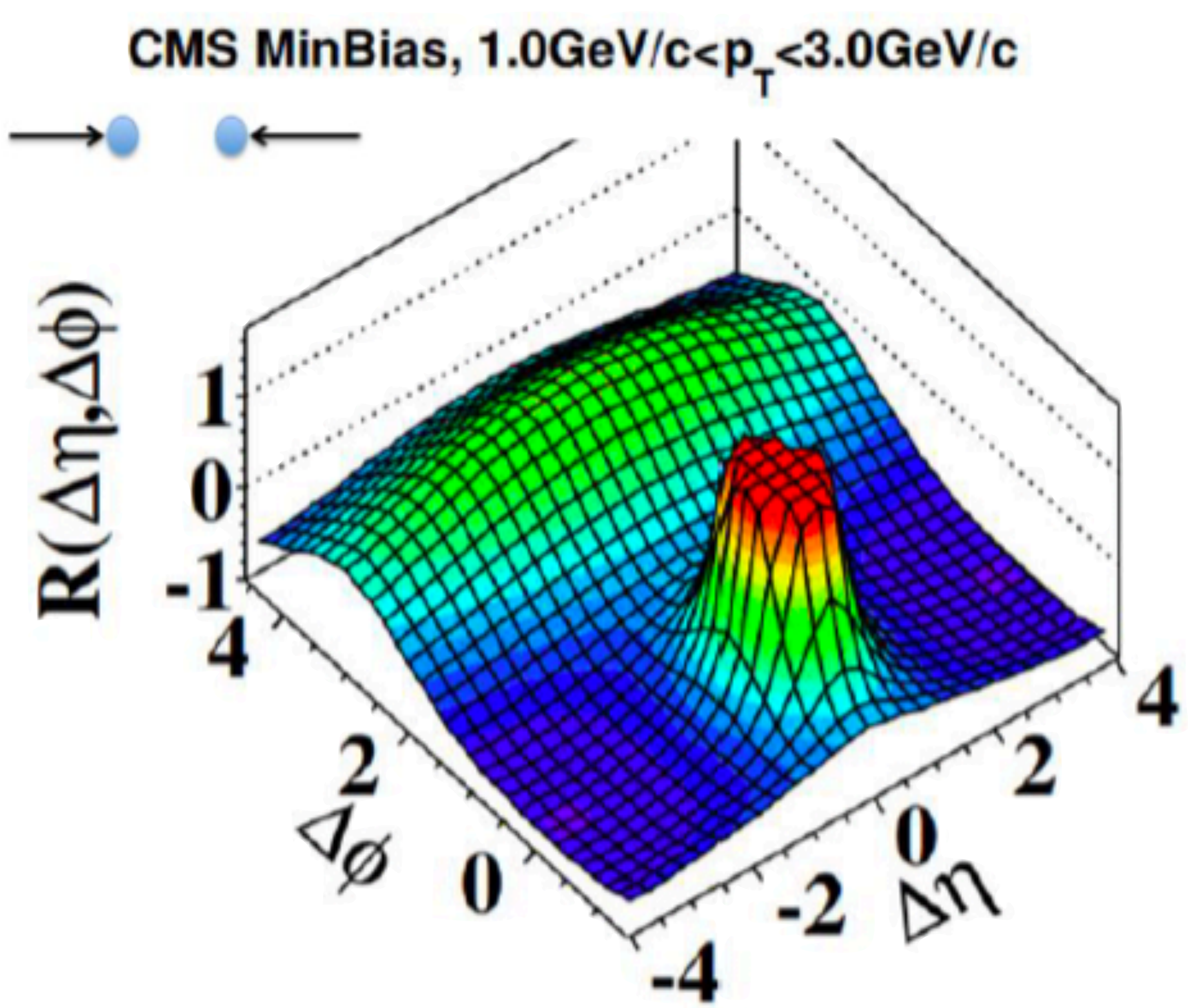


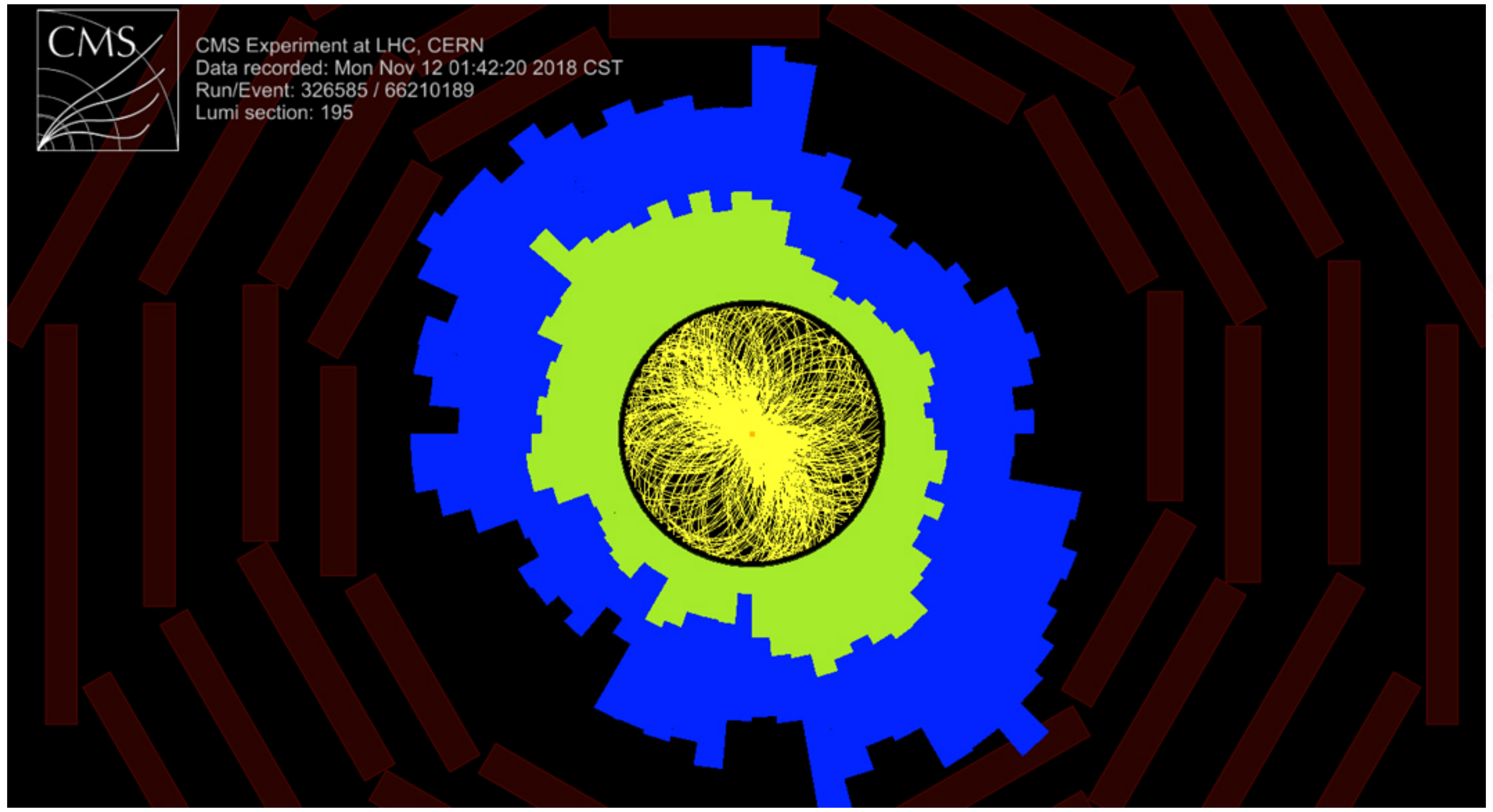
Spatial anisotropy of the initial state induces **momentum anisotropy** in the **final state**

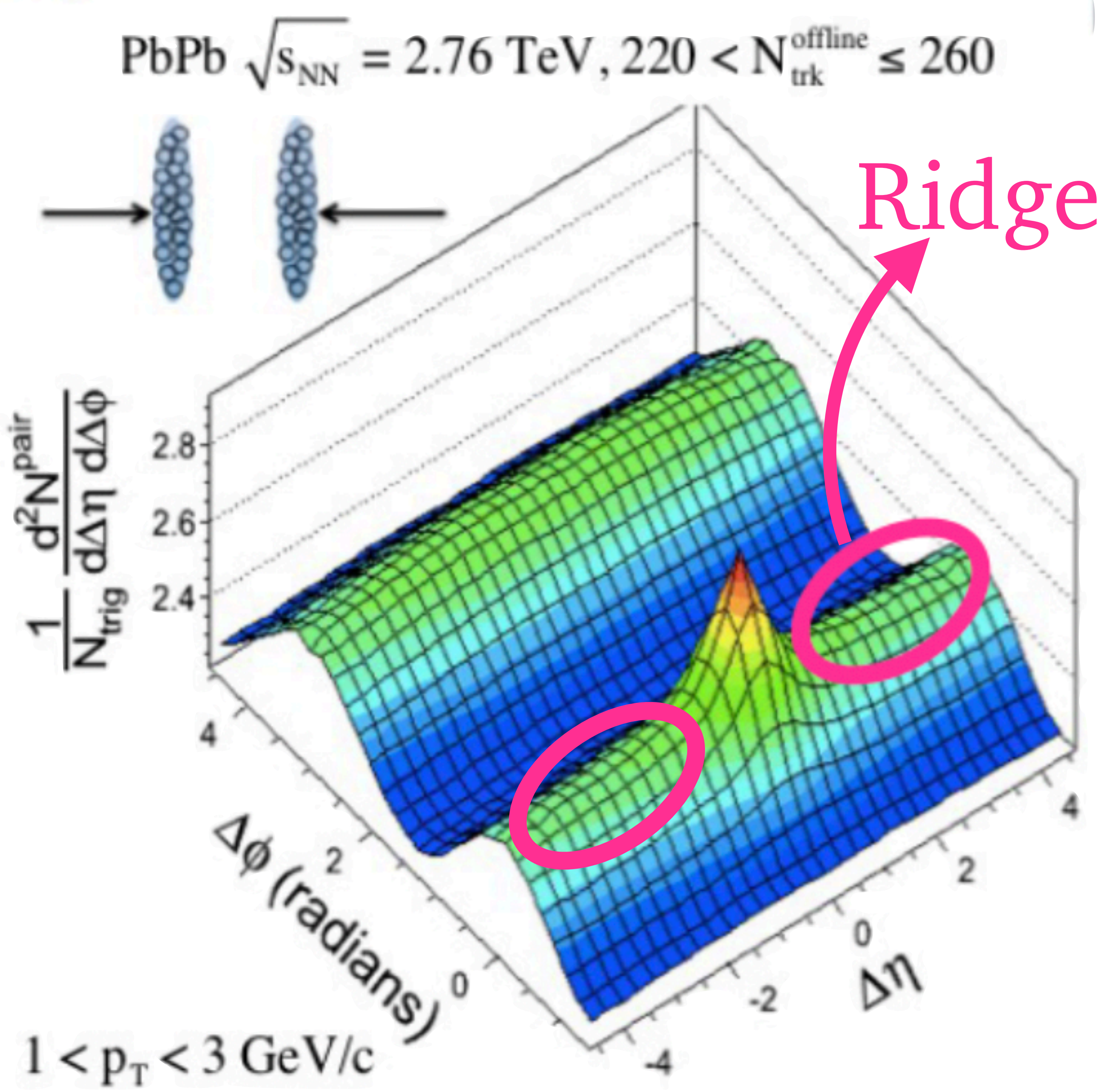


$$\frac{dN}{d\phi} \sim 1 + v_2(p_T)\cos(2\phi)$$

Collectivity in heavy-ion collisions







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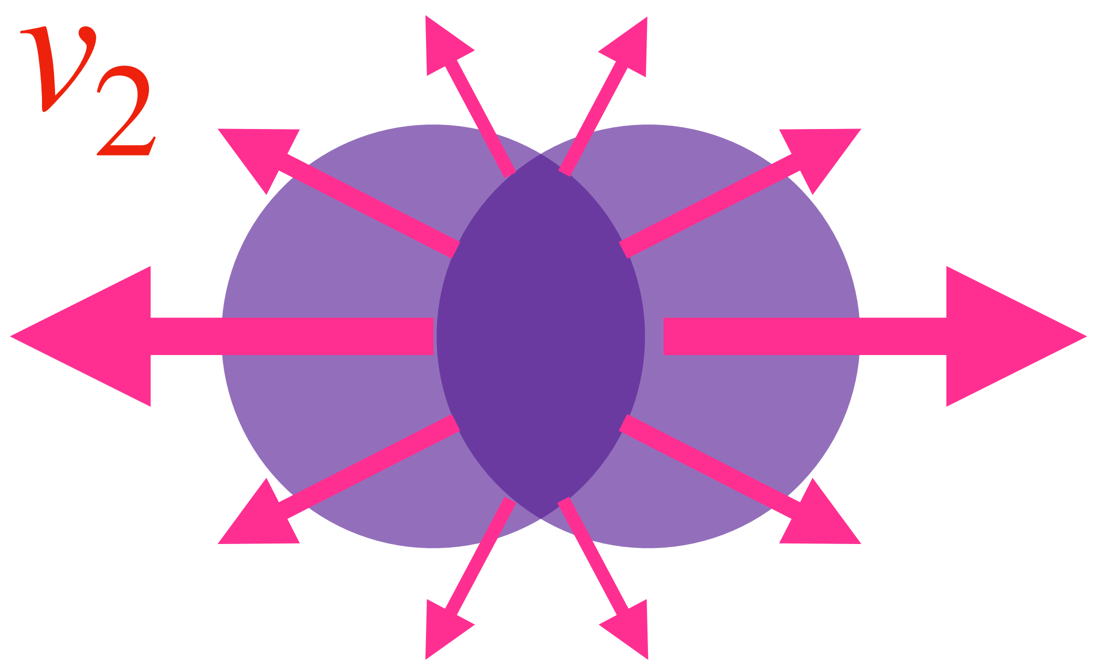
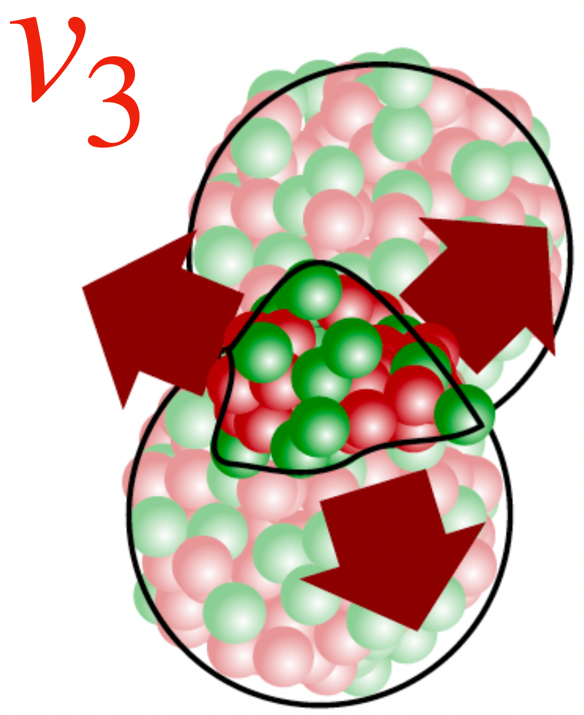




$$\frac{dN}{d\phi} \sim 1 + v_2(p_T)\cos(2\phi) + v_3(p_T)\cos(3\phi)$$

Relativistic hydrodynamics

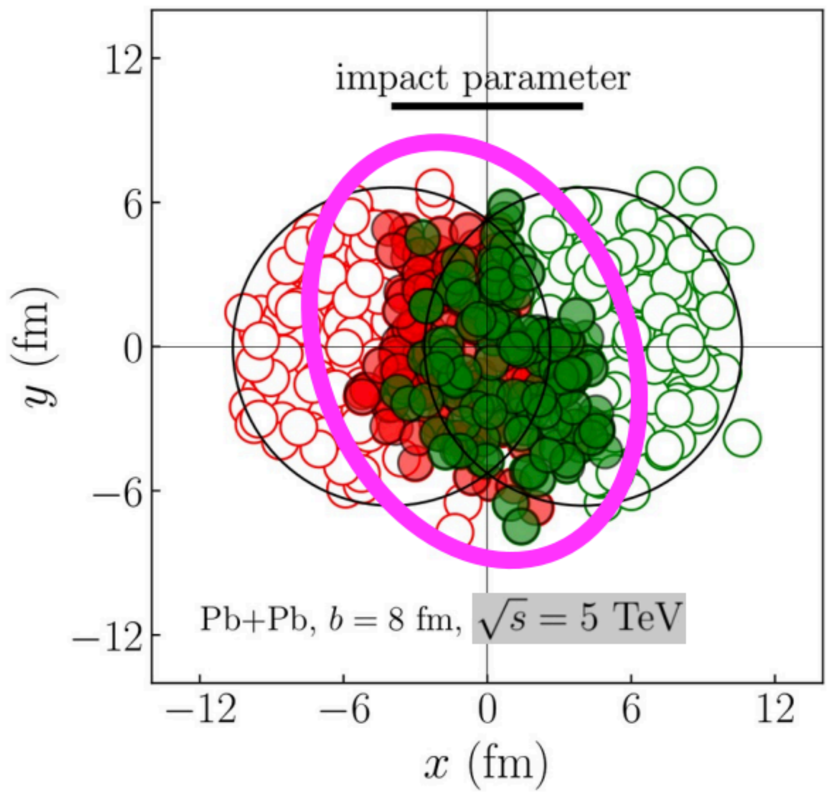
Solve numerically: $\delta_\mu T^{\mu\nu} = 0$

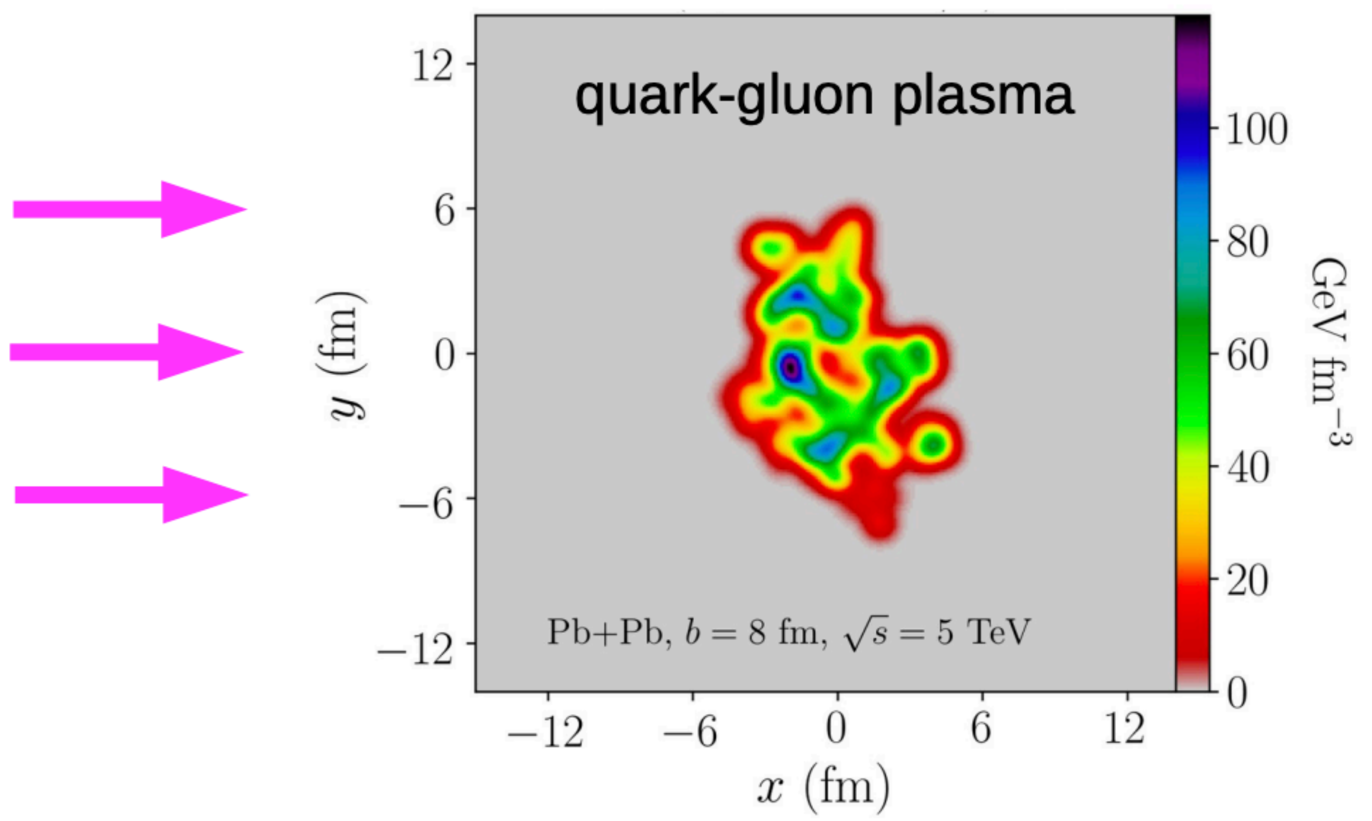
Input: EoS from Lattice QCD

Output: extracted from data

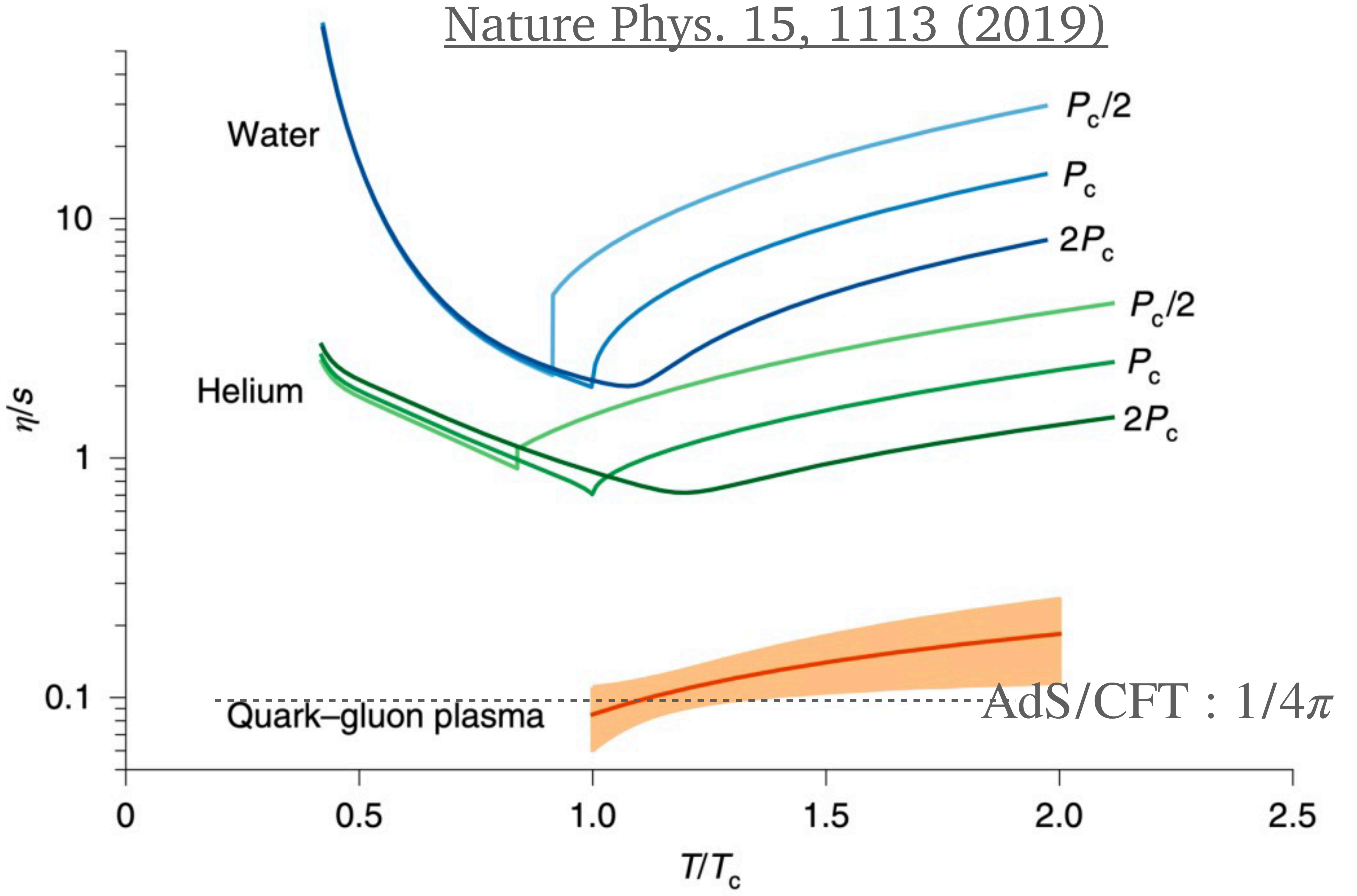
$$
\begin{aligned}
T_{\mu\nu} &= \varepsilon u_\mu u_\nu + p[\varepsilon]\Delta_{\mu\nu} - \eta[\varepsilon]\,\sigma_{\mu\nu} - \zeta[\varepsilon]\Delta_{\mu\nu}\nabla_\mu u^\mu + \mathcal{O}(\partial^2),\\
\sigma_{\mu\nu} &= \Delta_{\mu\alpha}\Delta_{\nu\beta}(\nabla^\alpha u^\beta + \nabla^\beta u^\alpha) - \frac{2}{3}\Delta_{\mu\nu}\Delta_{\alpha\beta}\nabla^\alpha u^\beta,\\
\Delta_{\mu\nu} &= g_{\mu\nu} + u_\mu u_\nu,
\end{aligned}
$$

+ initial condition





Bernhard et al., Nature Phys. 15, 1113 (2019)



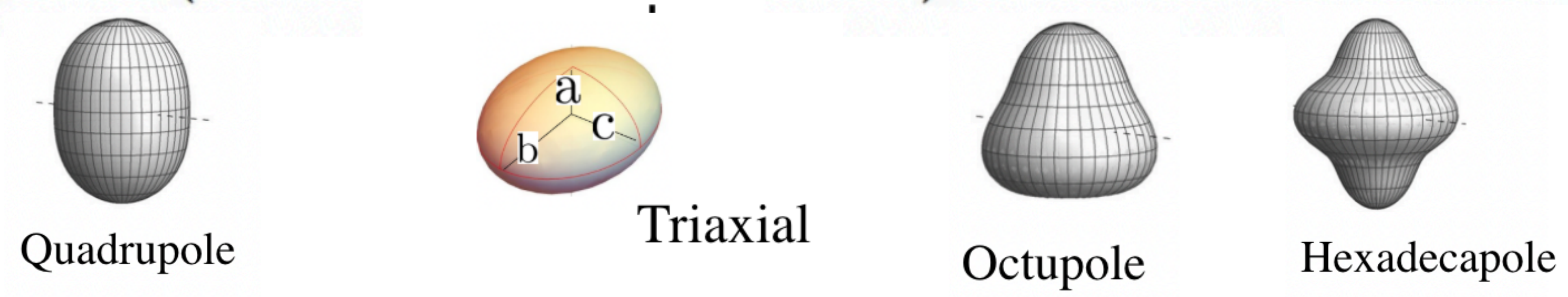
See also:
Schenke, et al., PRC 102 (2020) 044905
JETSCAPE, PRC 103 (2021) 054904
Nijs, et al., PRC 103 (2021) 054909

Very small η/s: **most perfect** fluid in Nature

Nuclear structure

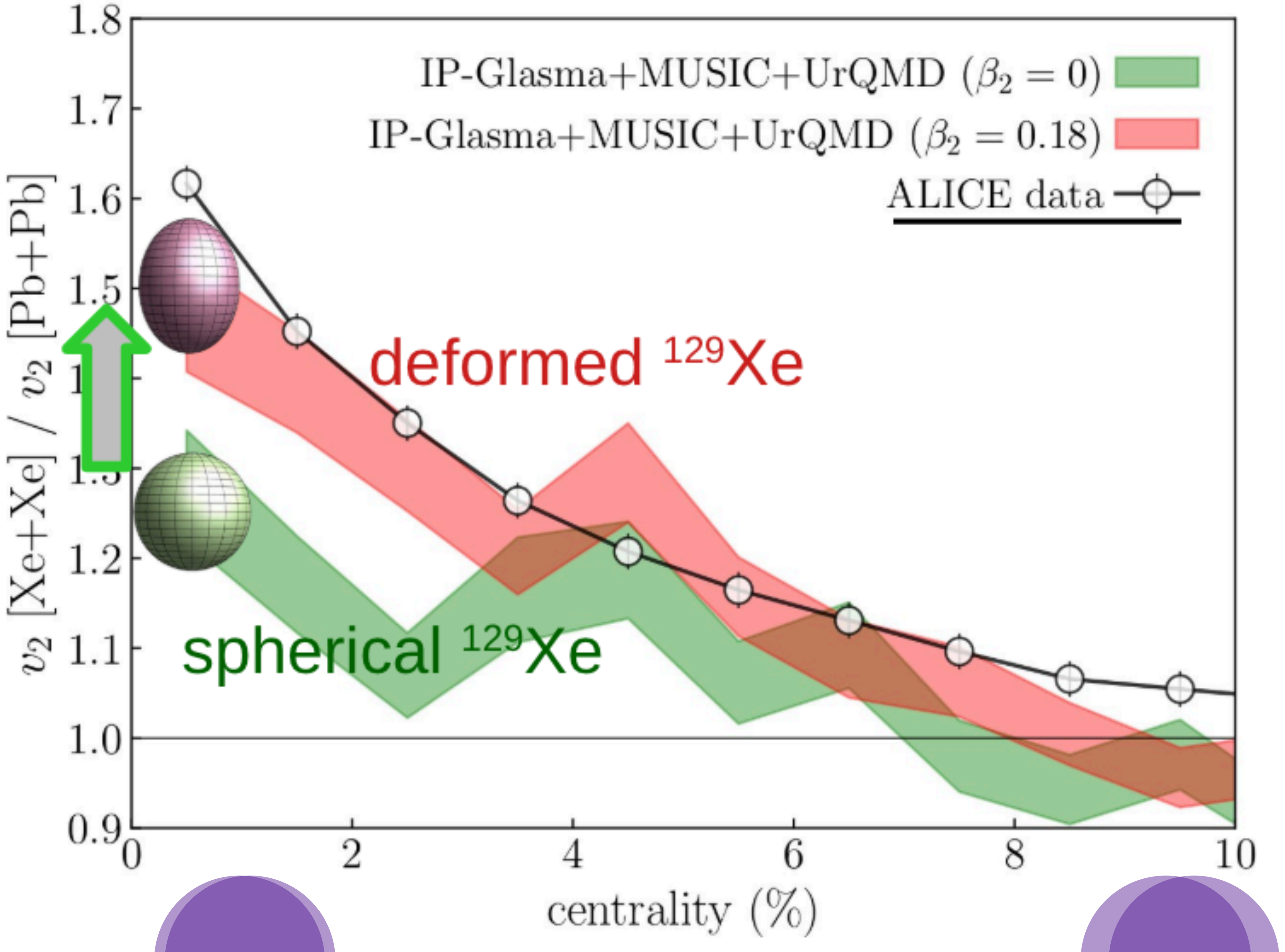
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)}$$

$$R(\Theta,\Phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\beta_3 Y_{30}(\Theta)+\beta_4 Y_{40}(\Theta)\right]$$



First evidence of ^{129}Xe deformation

ALICE PLB 784, 82 (2018)



See also Xe results:
CMS, PRC. 100, 044902 (2019)
ATLAS, PRC 101 024906 (2020)

^{129}Xe: Evidence of full triaxial shape

^{238}U: signatures of quadrupole and hexadecapole

^{96}Zr: evidence of octuple deformation

Fixed target LHCb: ^{208}Pb+^{20}Ne

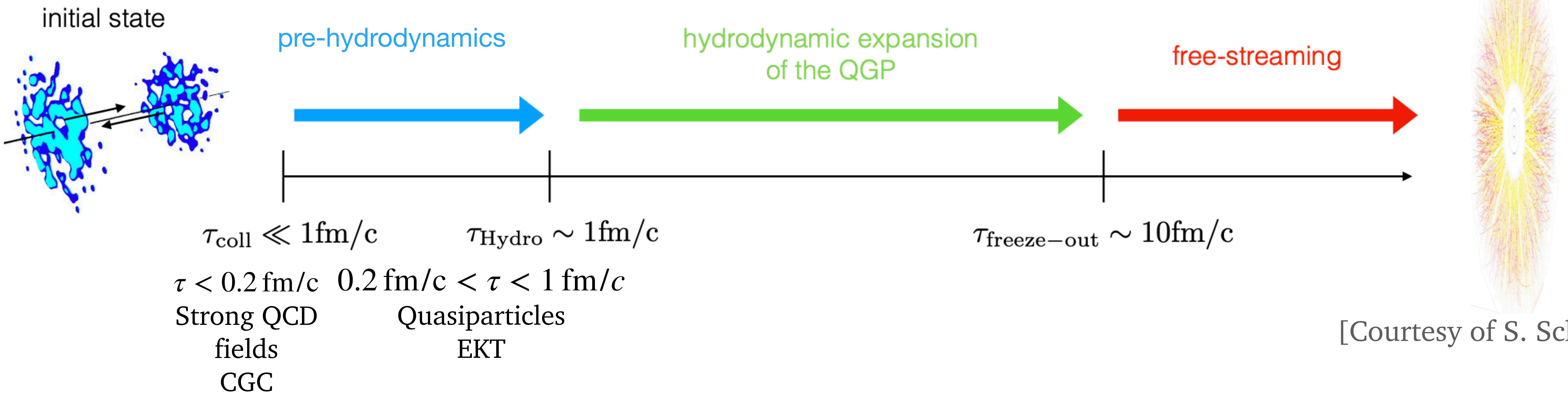
Giacalone et al., 2405.20210

See works by: G. Giacalone, J. Jia, A. Timmins, W. Broniowski, Jean-Yves Ollitrault, B. Schenke, C. Shen, W. Li, J. Noronha-Hostler, M. Luzum

Heavy-ion collisions

- Dynamical description of heavy-ion collisions from underlying theory of QCD remains a challenge

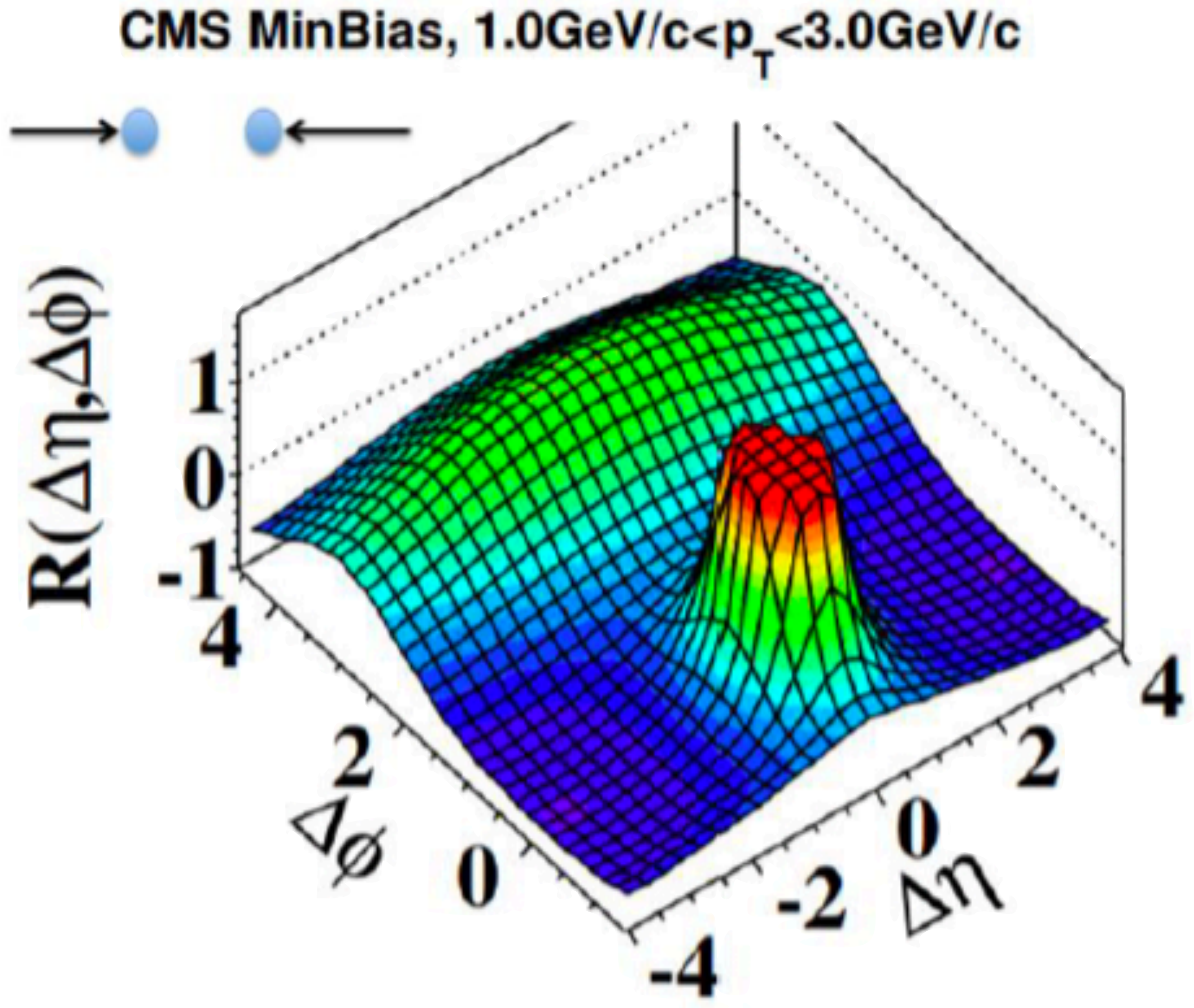
- Standard picture based on **effective descriptions of QCD** exploiting the clear separation of time scales

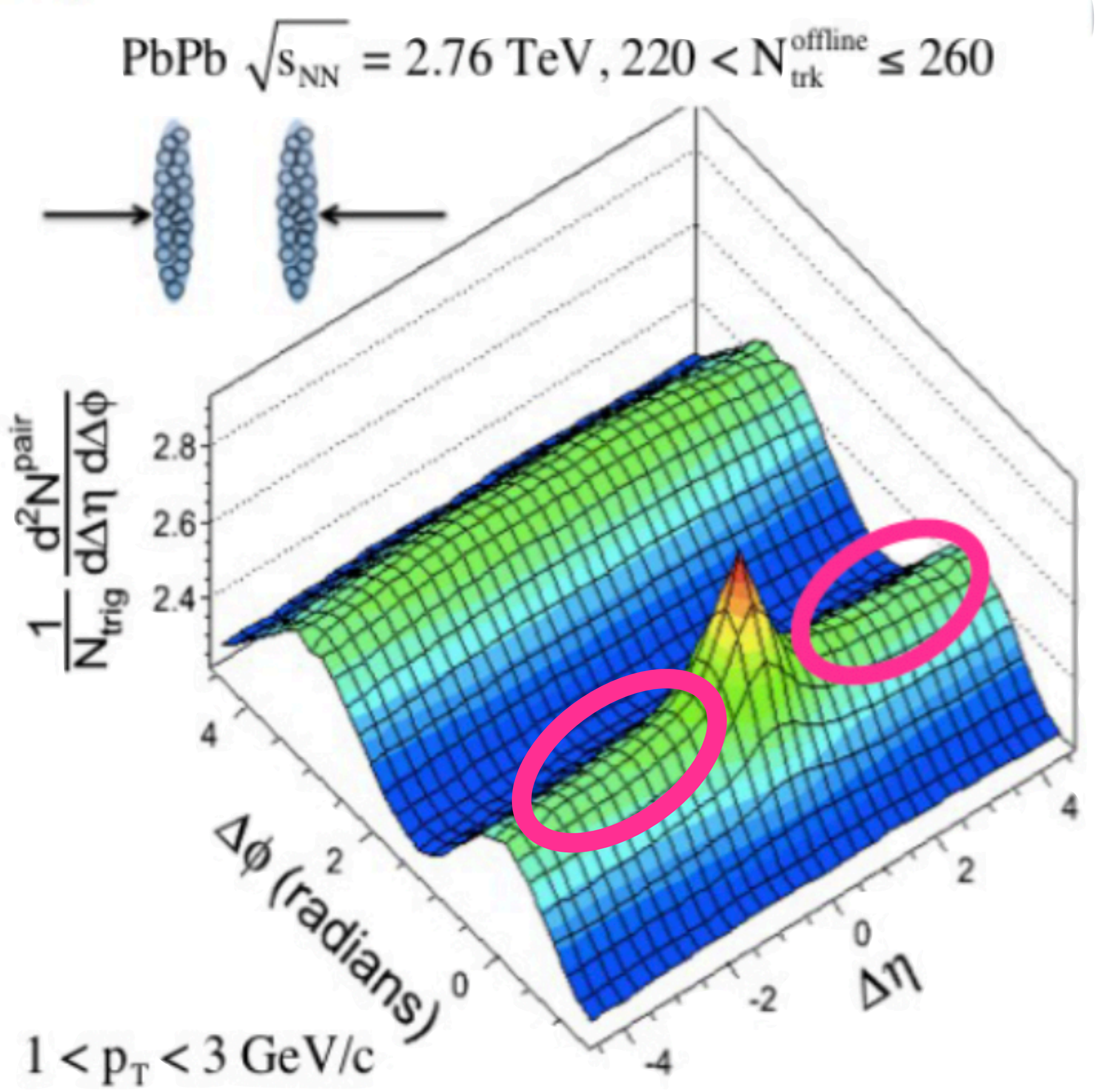


[Courtesy of S. Schlichting]

How does the system hydrodynamizes in $\sim 1\,{\rm fm/c}$?

Ridge in small systems





- Observed by all RHIC and LHC experiments. Well described by hydro simulations
- No jet quenching in small systems
- The origin **may not necessary be hydrodynamics** (pre-hydro effects?)

See A. Dobrin Frid 9 am

Ridge in small systems

CMS, JHEP 09 (2010) 091

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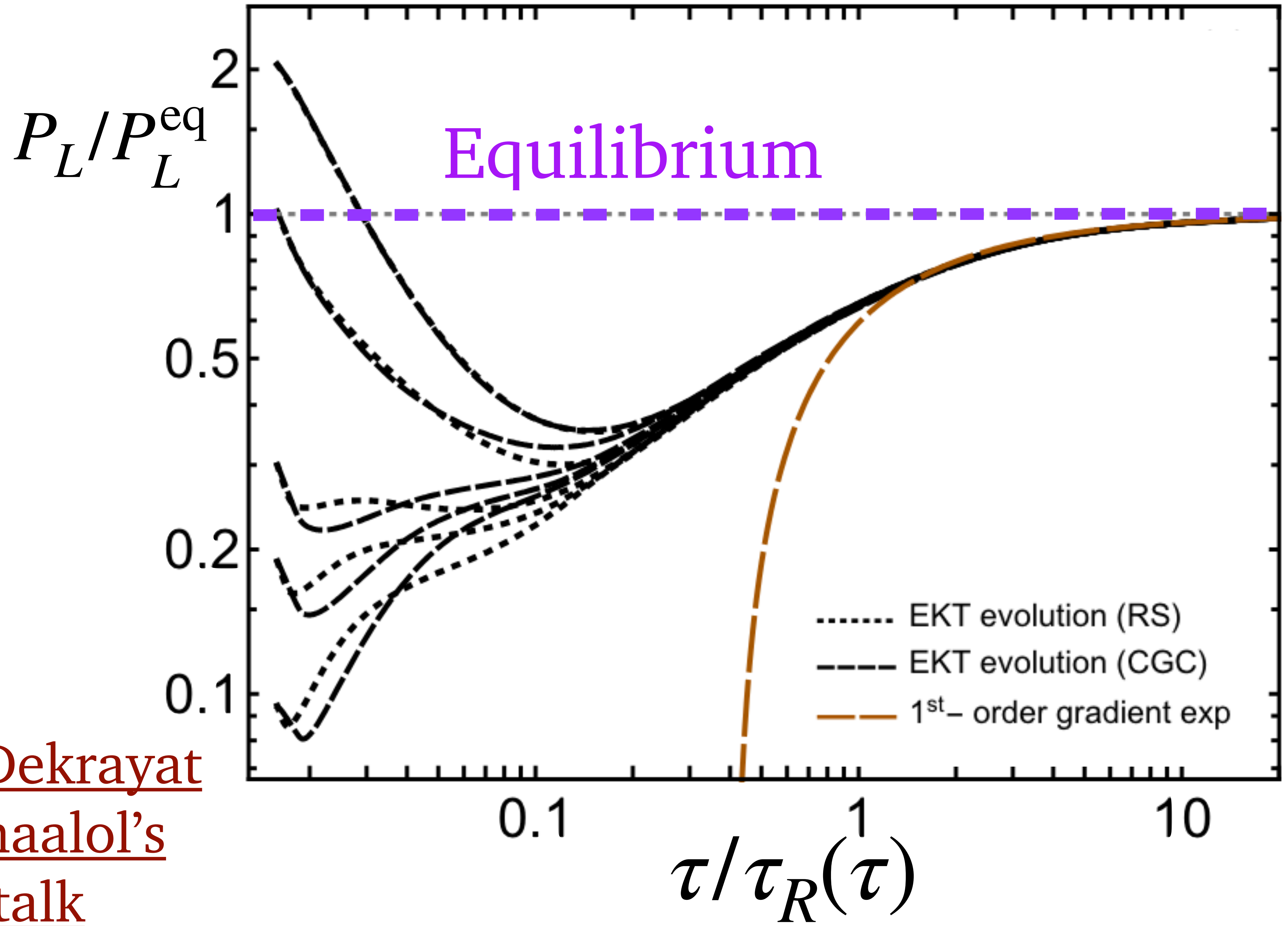
See A. Dobrin Frid 9 am

Non-equilibrium attractors

Heller & Spalinski, PRL 115, 072501 (2015)

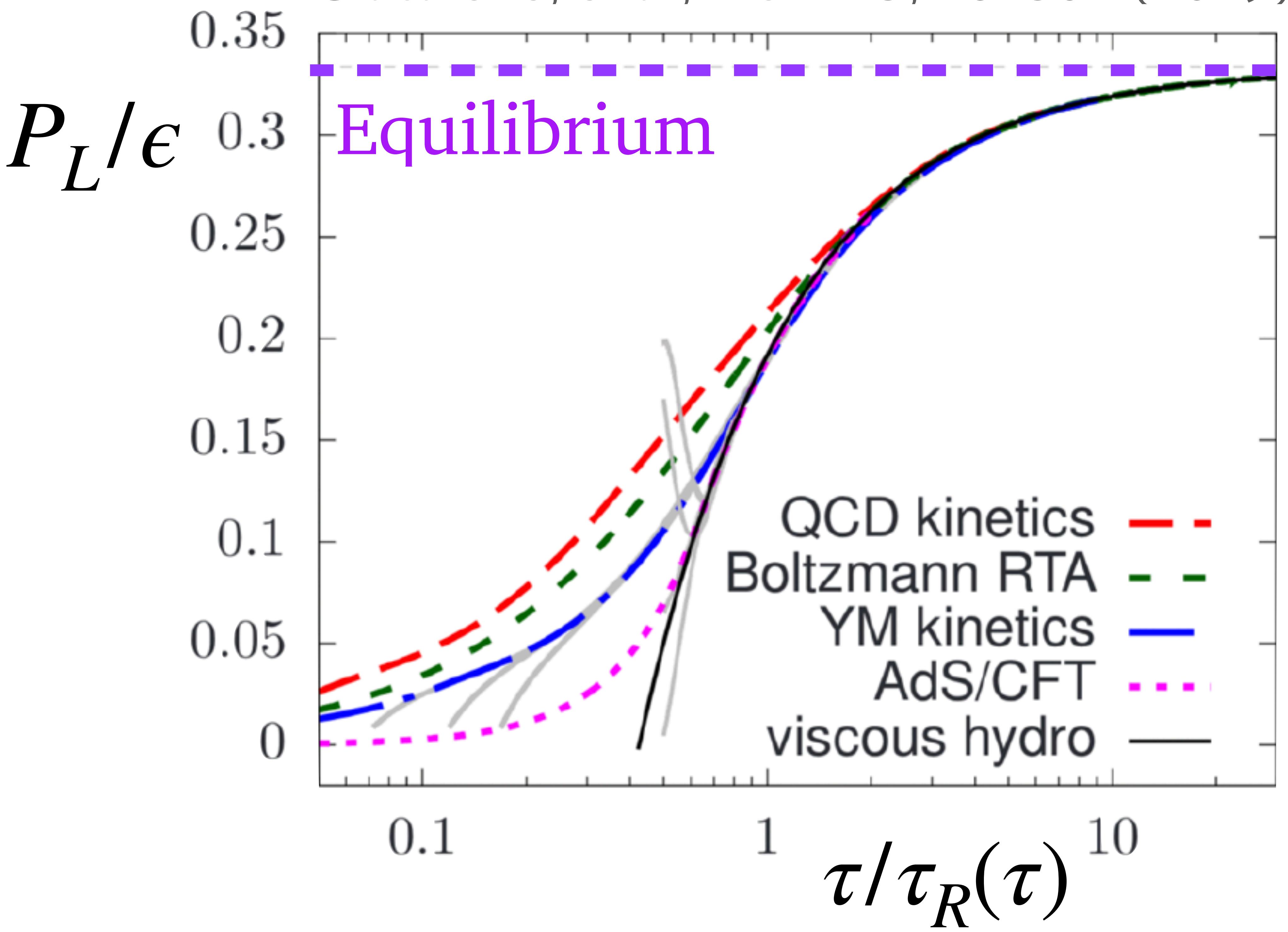
How far from equilibrium the system can be such its dynamics is quantitatively described by hydrodynamics?

Almaalol et al, PRL 125, 122302



See Dekrayat Almaalol's talk

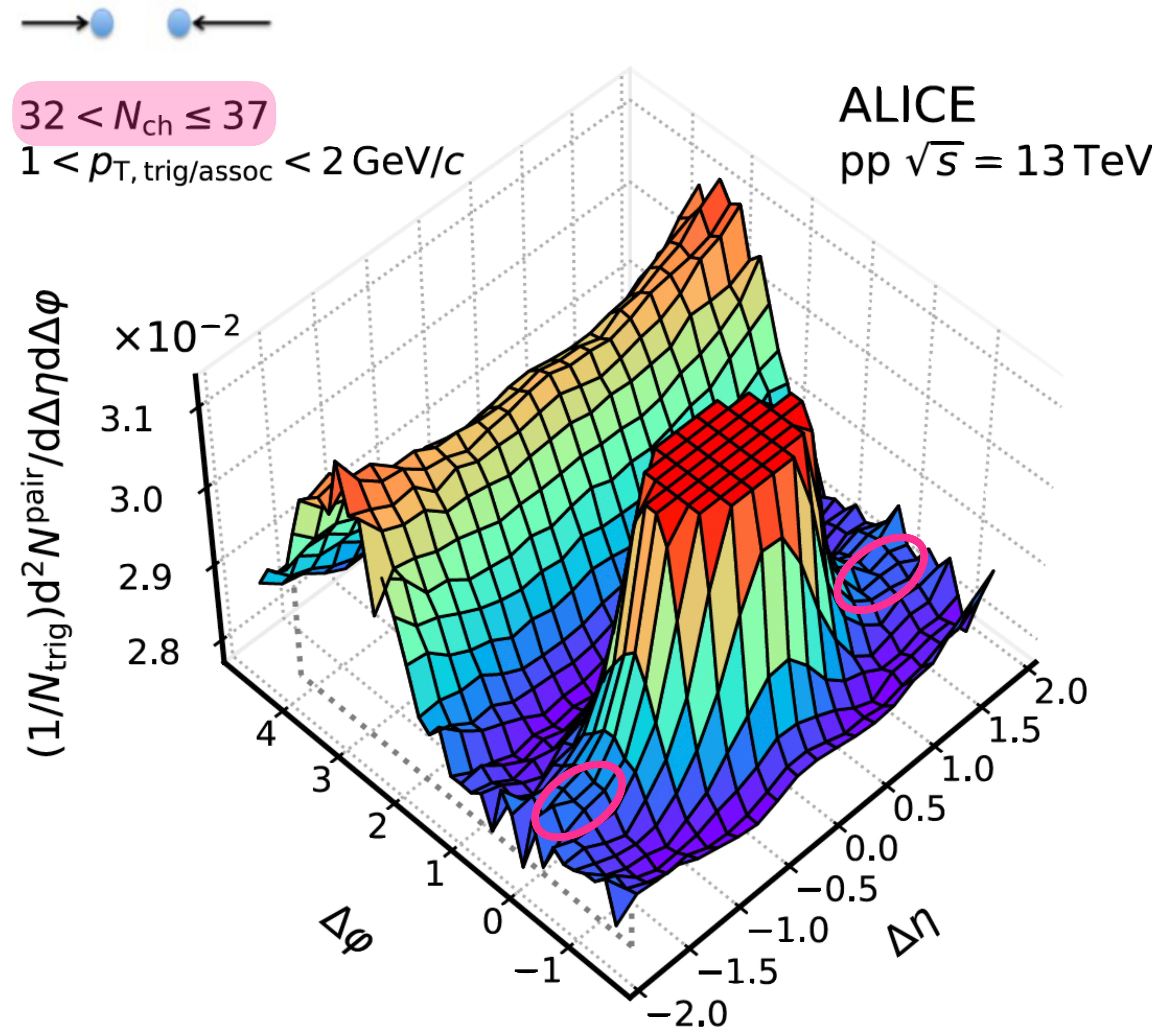
Giacalone, et al, PRL 123, 262301 (2019)



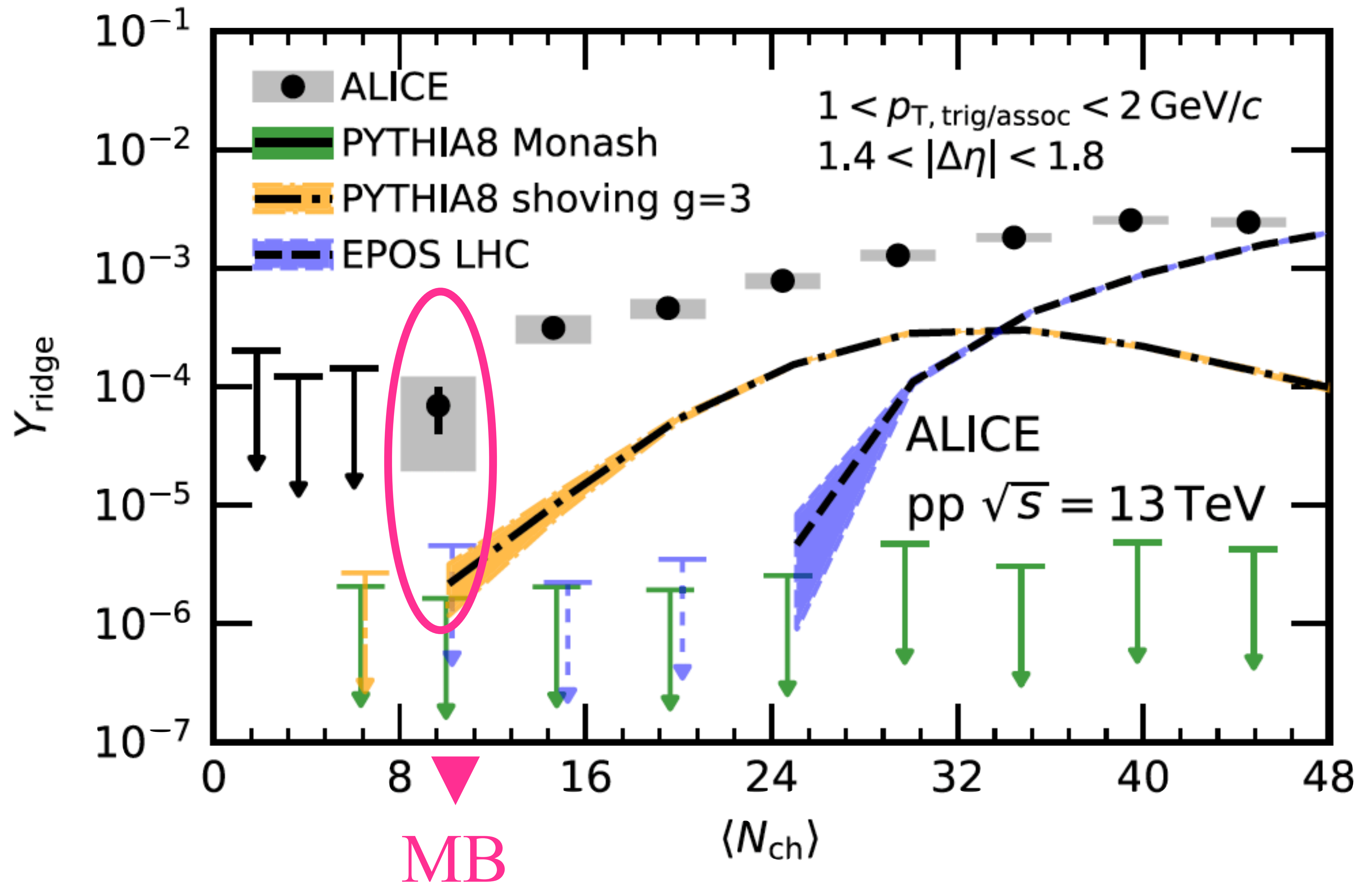
Small systems: might be too far from equilibrium for hydrodynamics to apply

Ambruş et al, PRL 130, 152301 (2023)

Ridge in p-p (min. bias)



ALICE, PRL 132 172302 (2024)

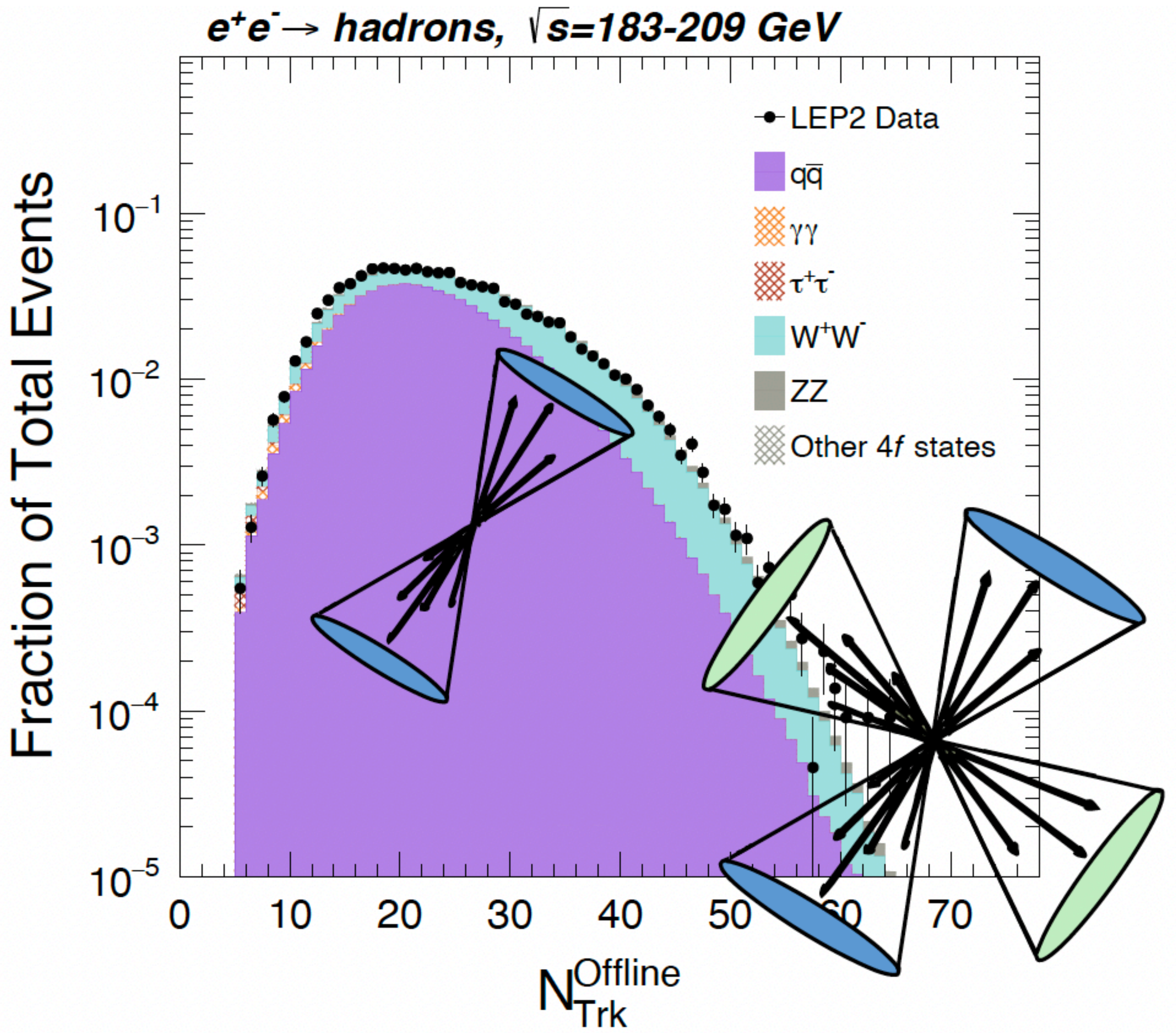


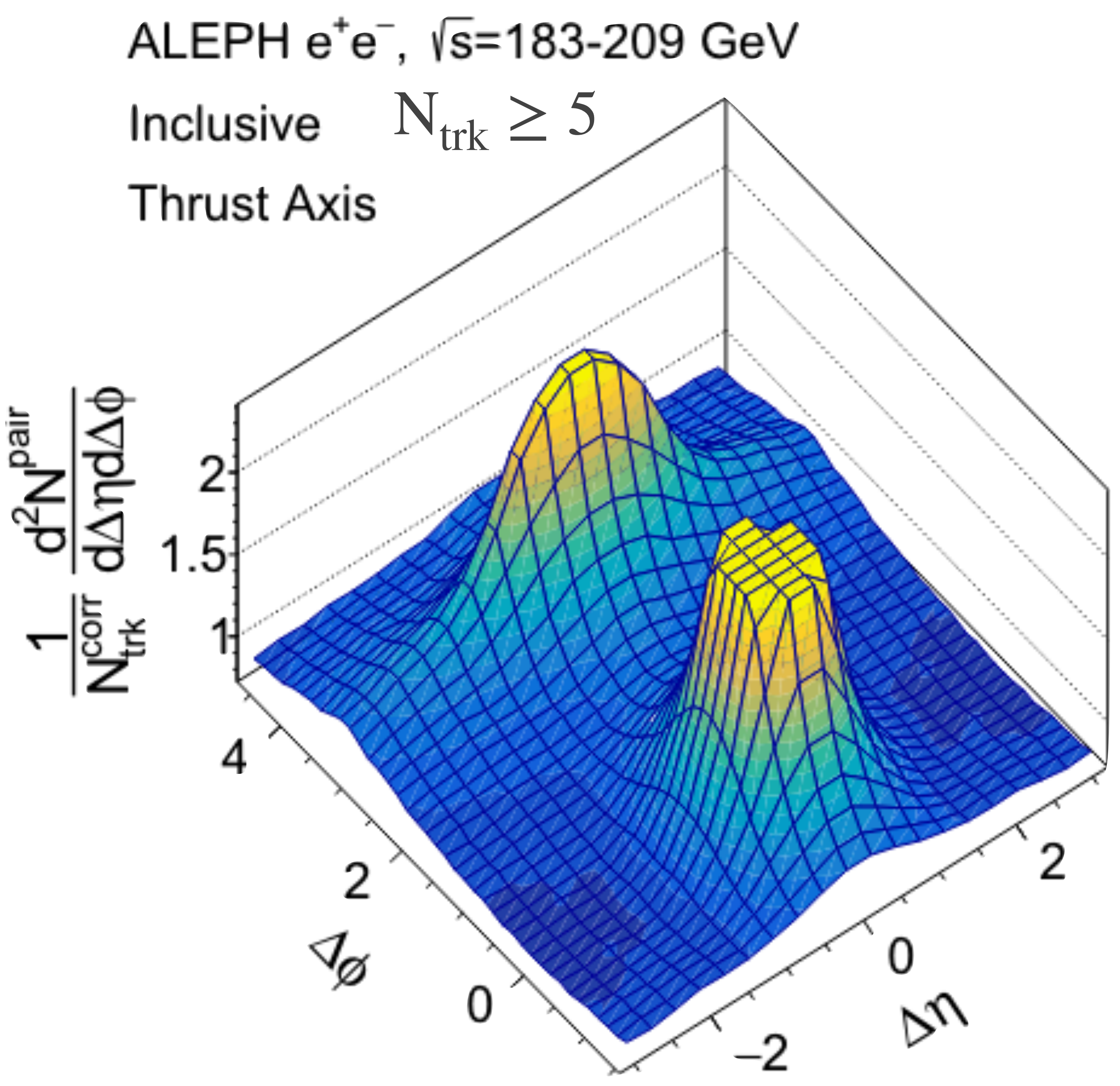
See A. Dobrin
Frid 9 am

Near-side ridge signal for minimum bias p-p collisions!!

Ridge at LEP?

Chen et al, 2309.09874, 2312.05084





See A. Dobrin
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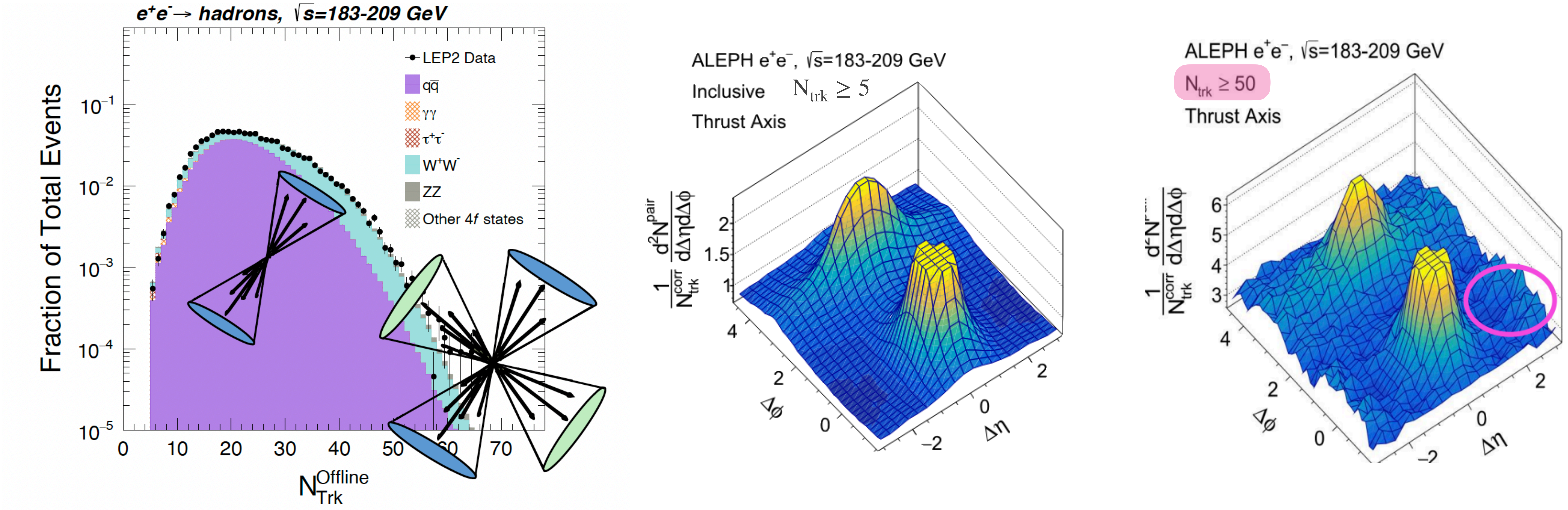
Ridge at LEP?

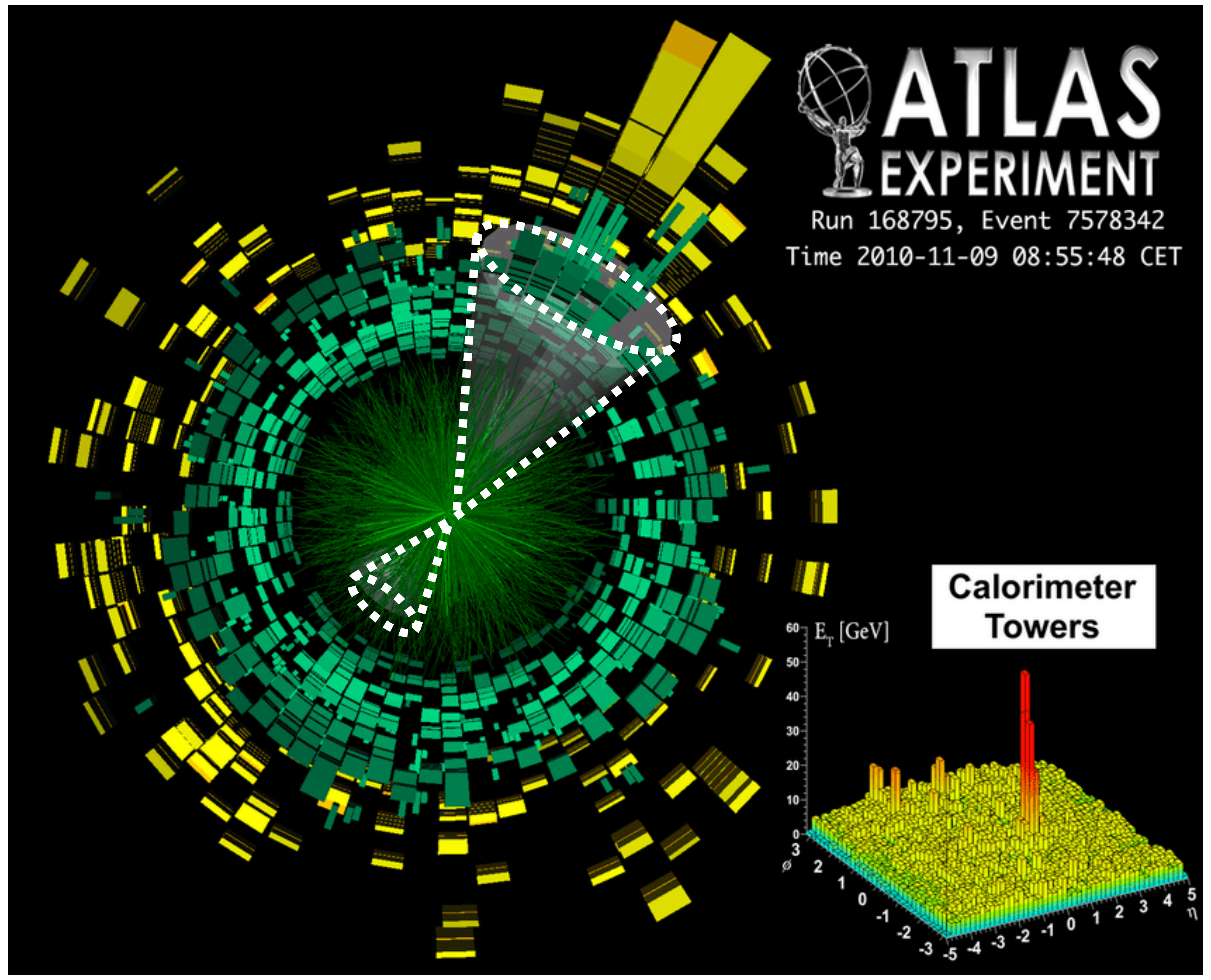
Chen et al, 2309.09874, 2312.05084

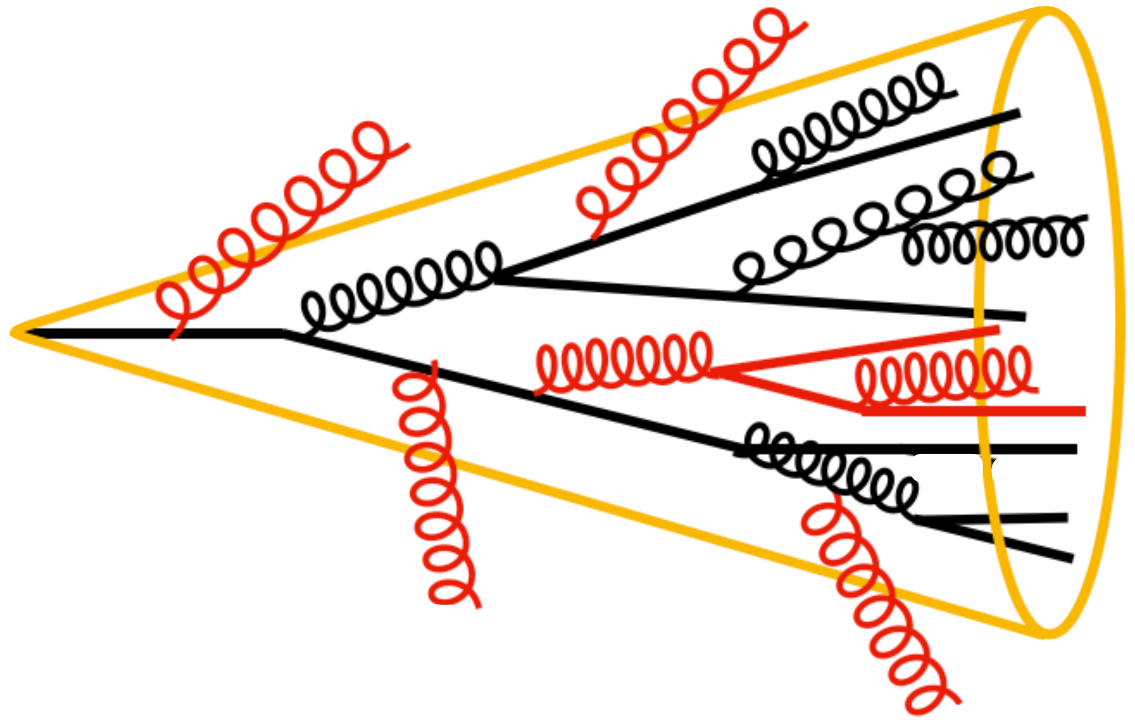


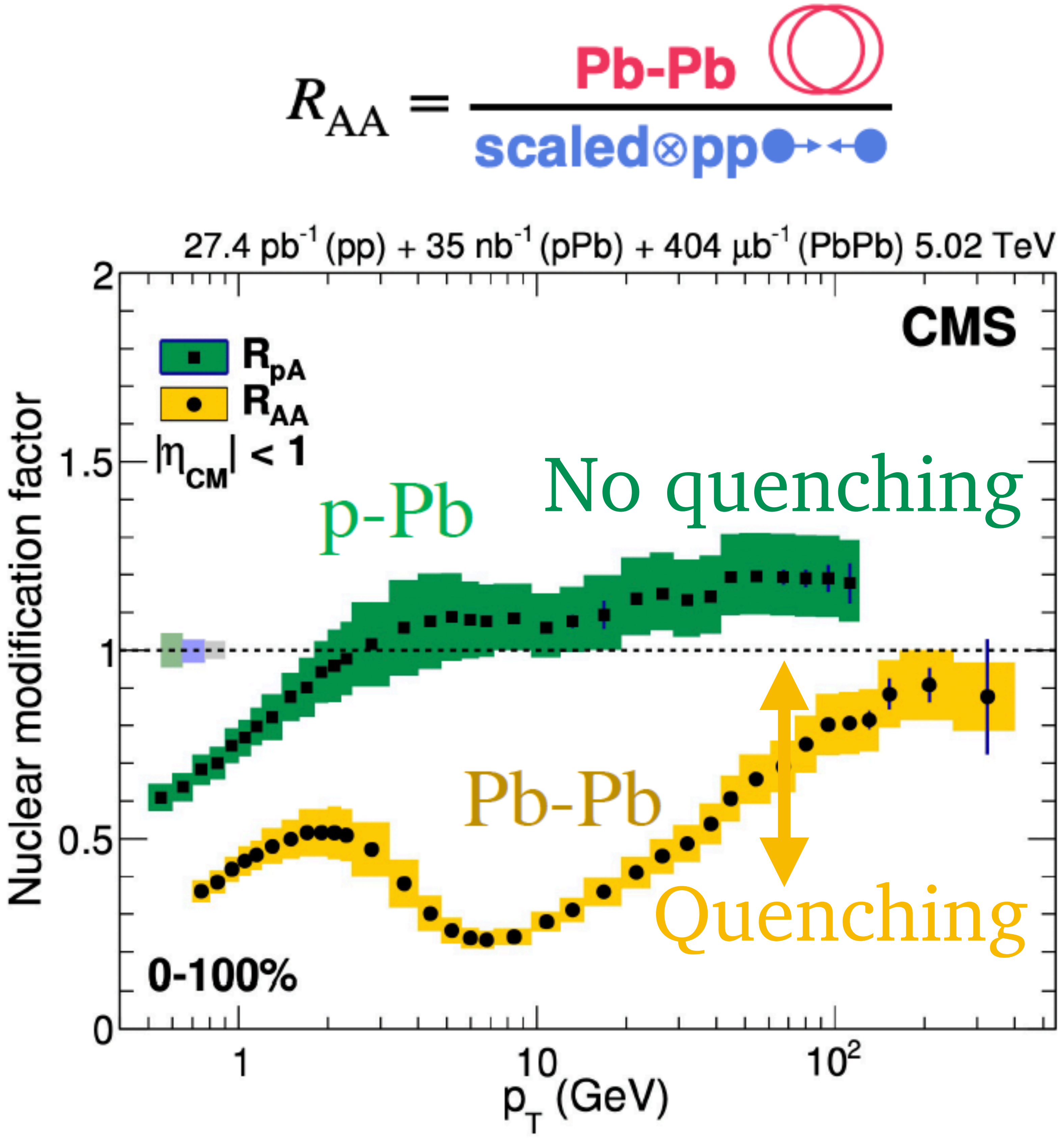
Data hint at small systems lacking hadronic initial state effects could still yield a ridge-like signal!

See A. Dobrin
Frid 9 am

Jet quenching

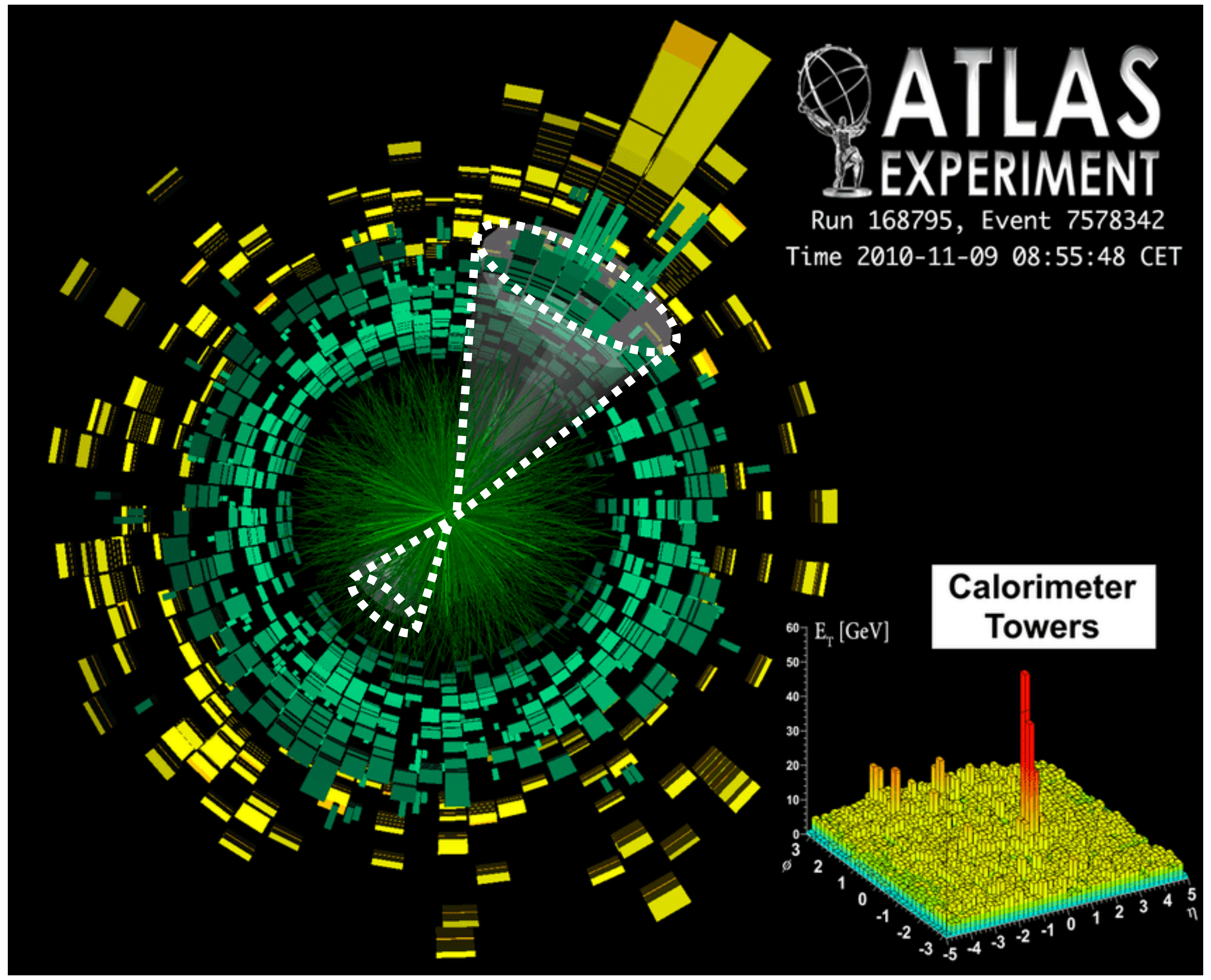


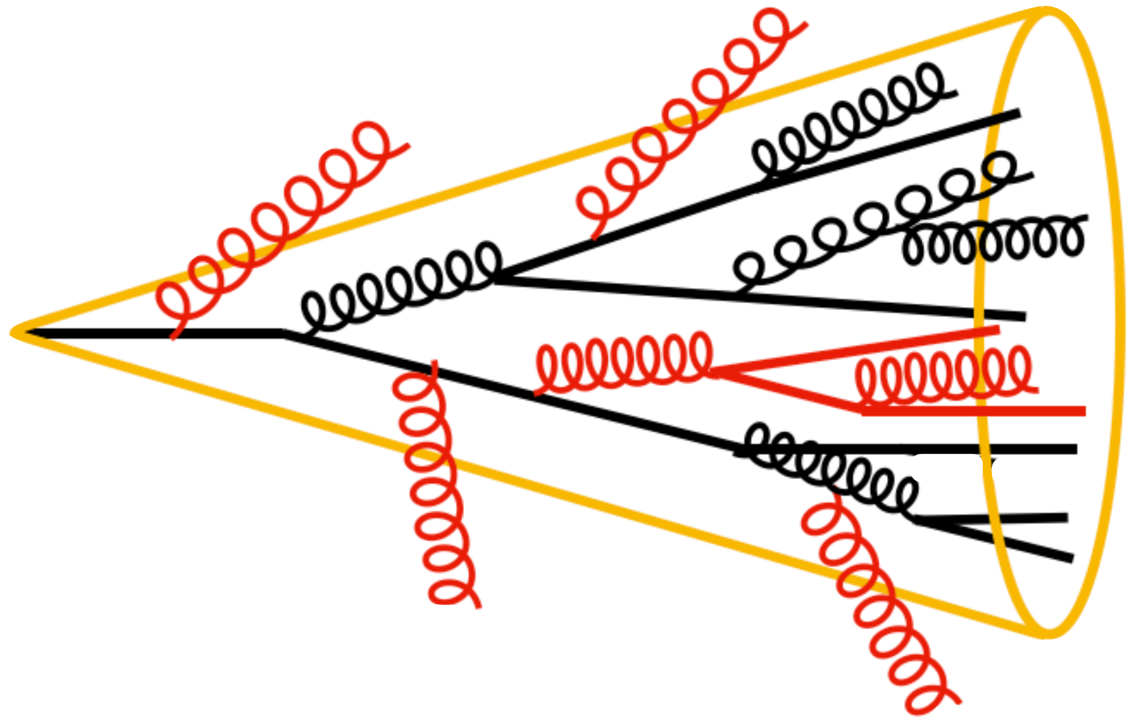




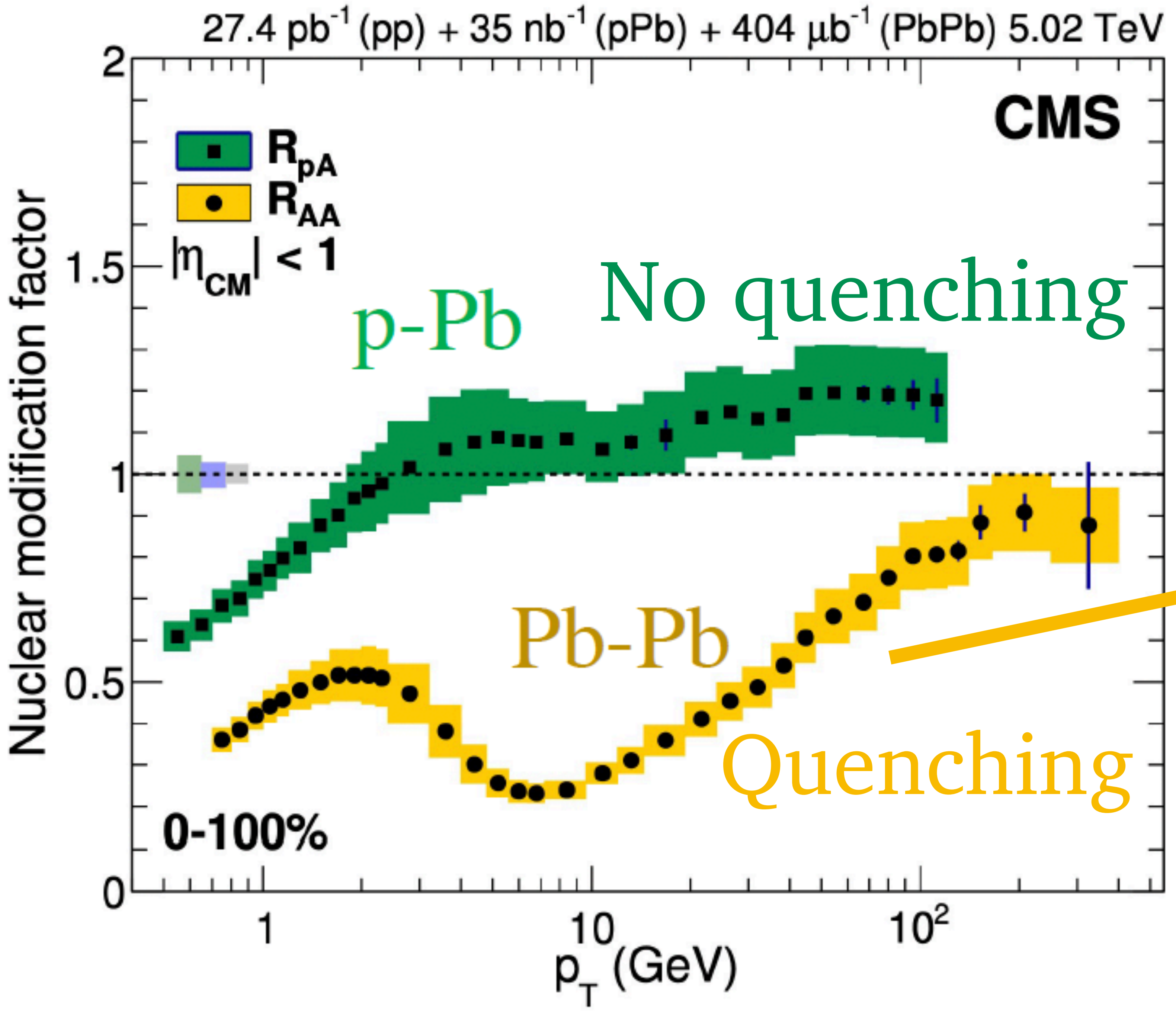
JHEP 04, 039 (2017)

Jet quenching

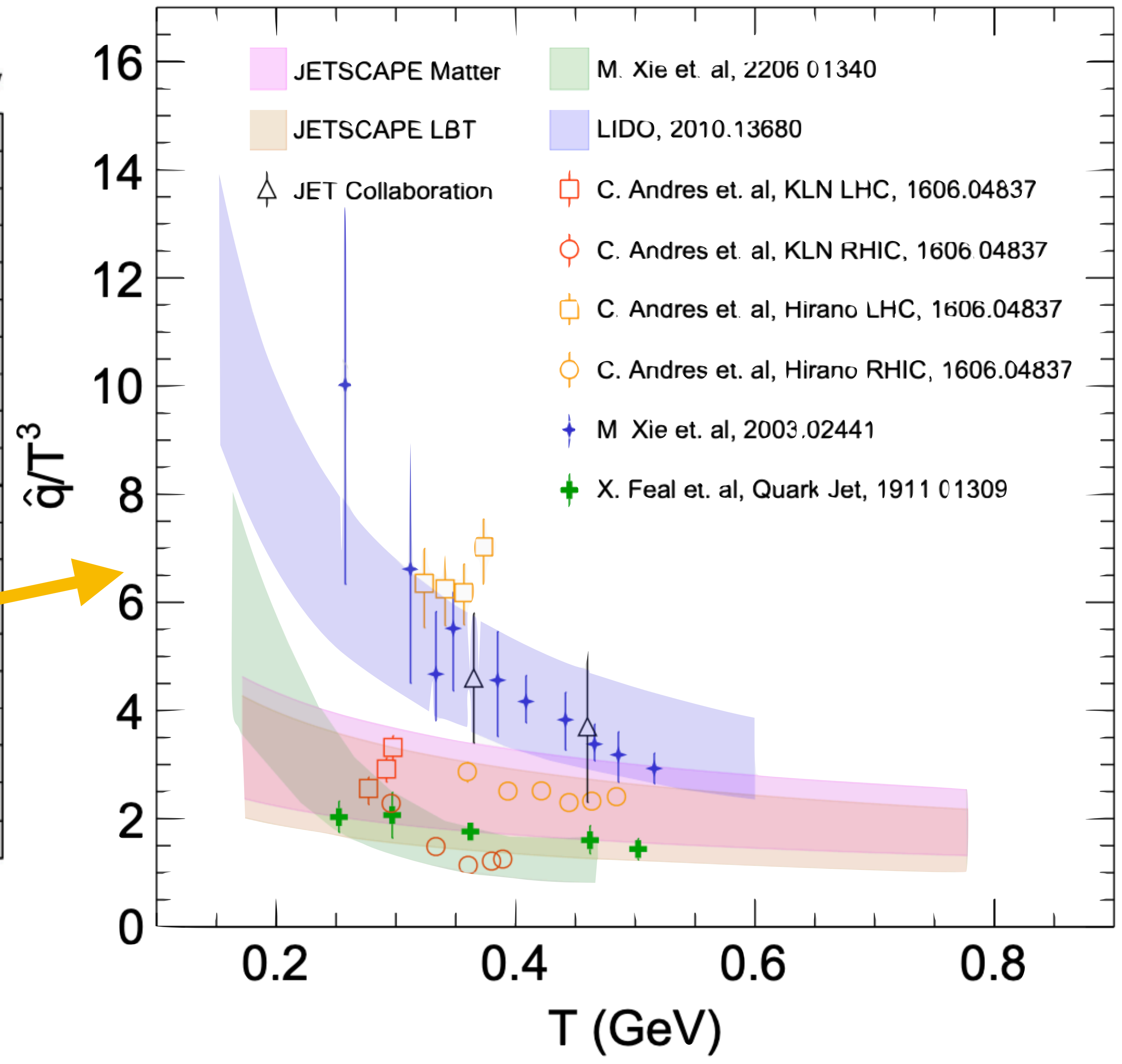




$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled}\otimes\text{pp}}$$



JHEP 04, 039 (2017)

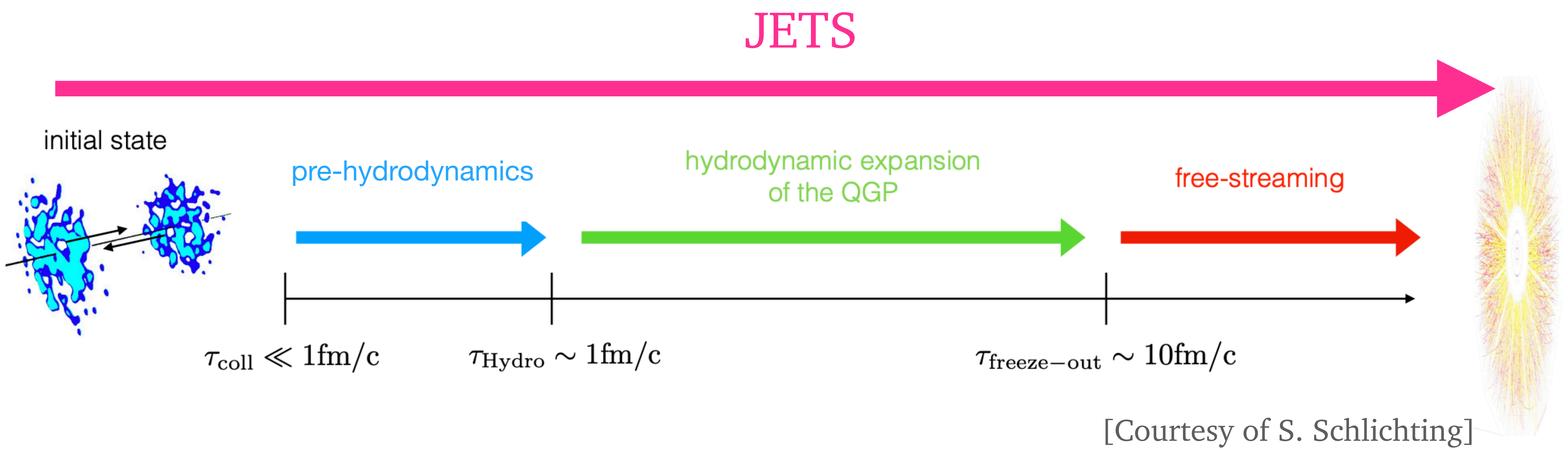


Apolinário et al., Prog. Part. Nucl. Phys. 127, 103990 (2022)

Jets in heavy-ion collisions

- Hard probes/jets ($Q \sim p_T, M$) are **produced** in the **initial hard scattering**

$$\tau_p \sim \frac{1}{Q} \ll \tau_{hydro} \sim 1\,\mathrm{fm/c}$$

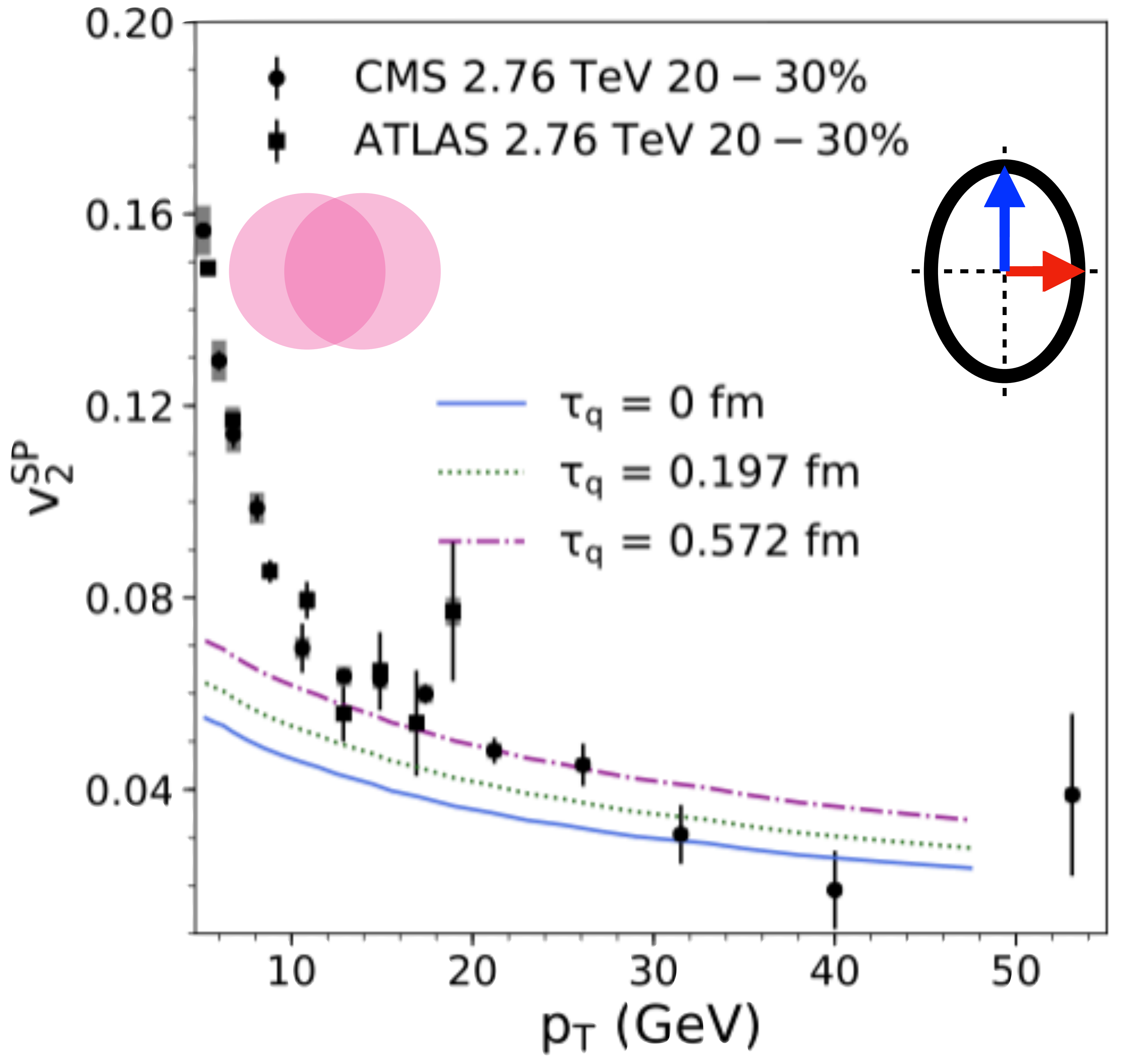


[Courtesy of S. Schlichting]

Can we use jets to study the pre-hydrodynamization stages?

Jet quenching in the pre-hydro stages

Jets can be **sensitive** to the **pre-hydrodynamics stages**



CA et al., PLB 803 135318, (2020)

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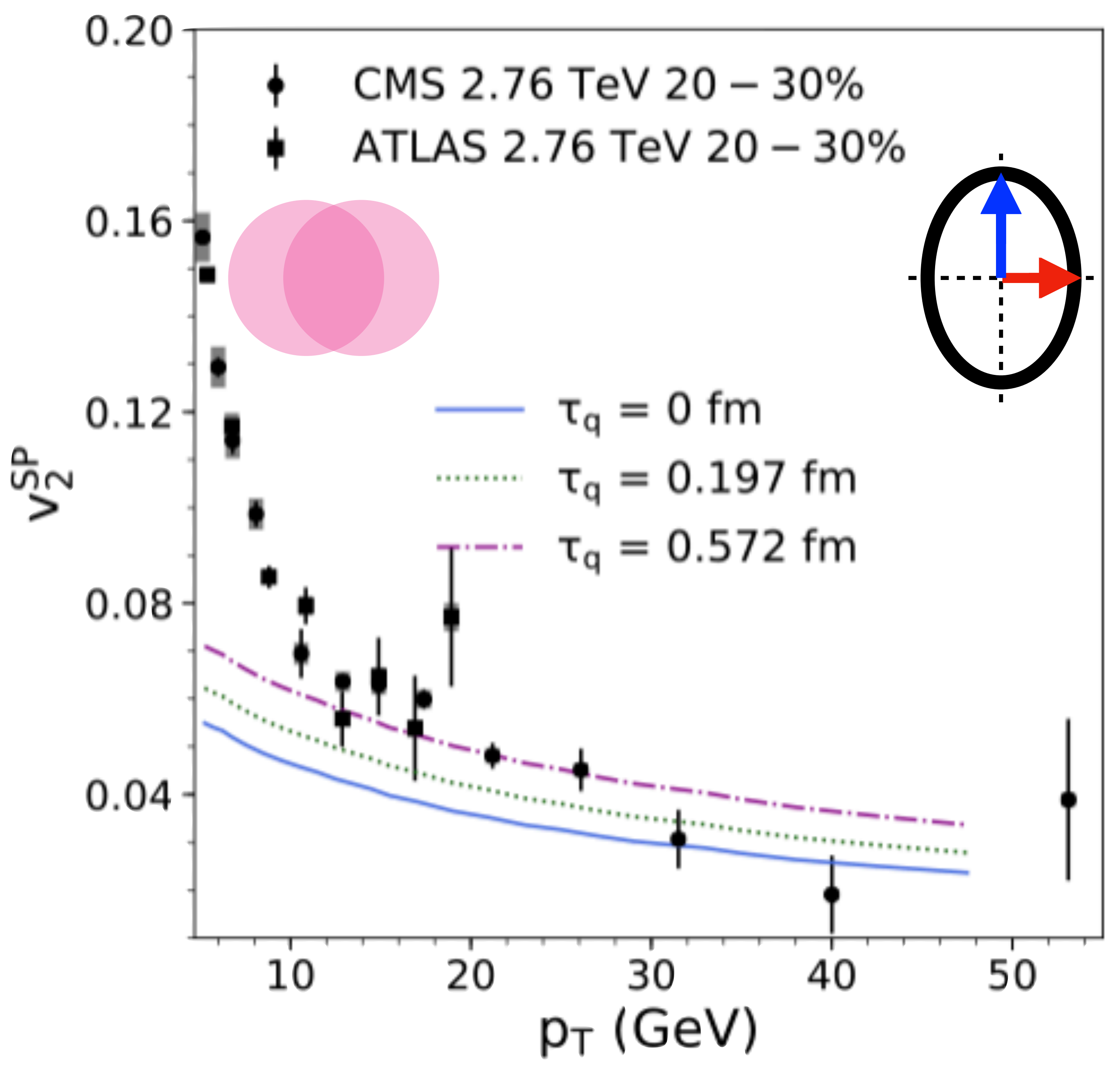
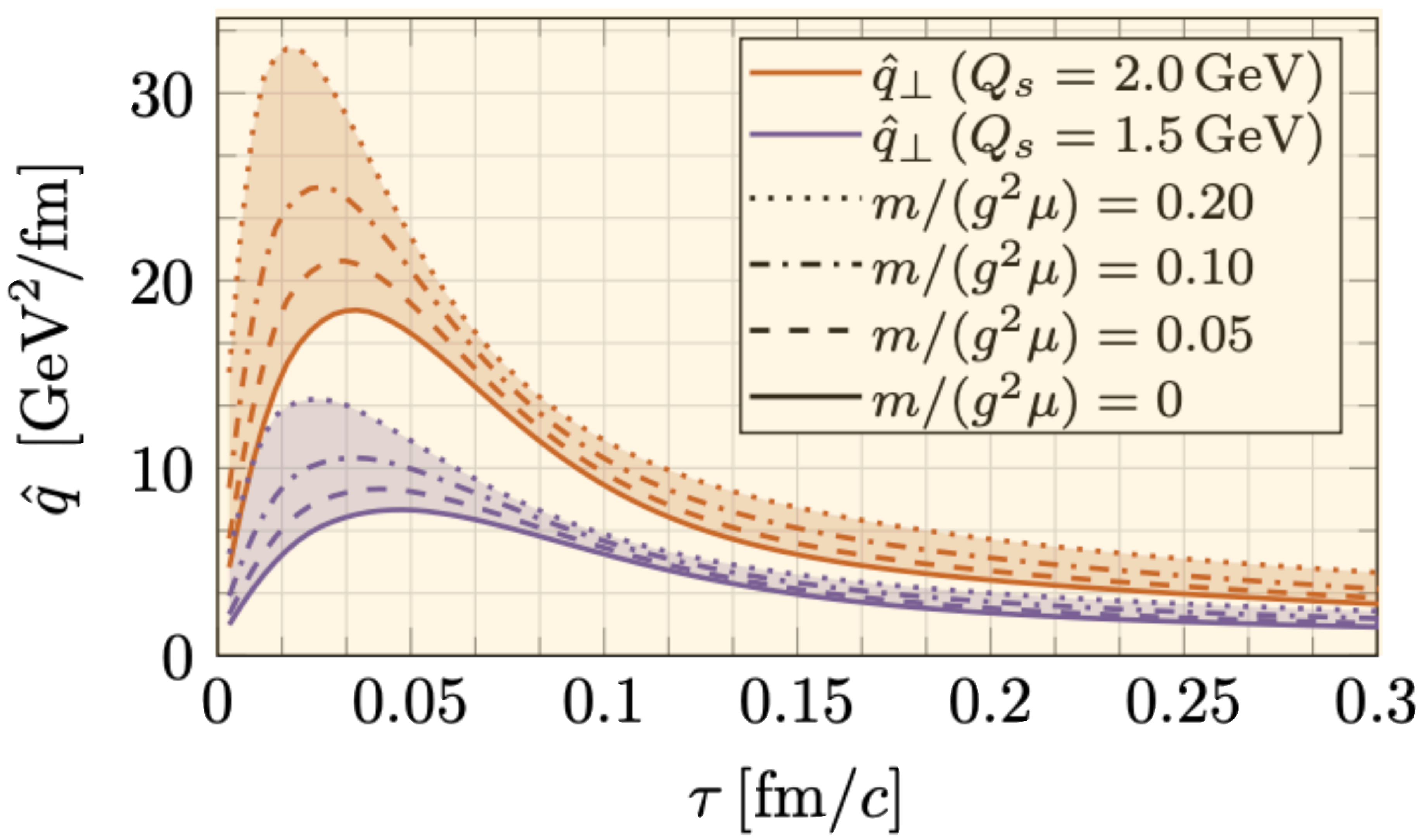


CA et al., PLB 803 135318, (2020)

First computations of **broadening in the pre-hydrodynamic stages**

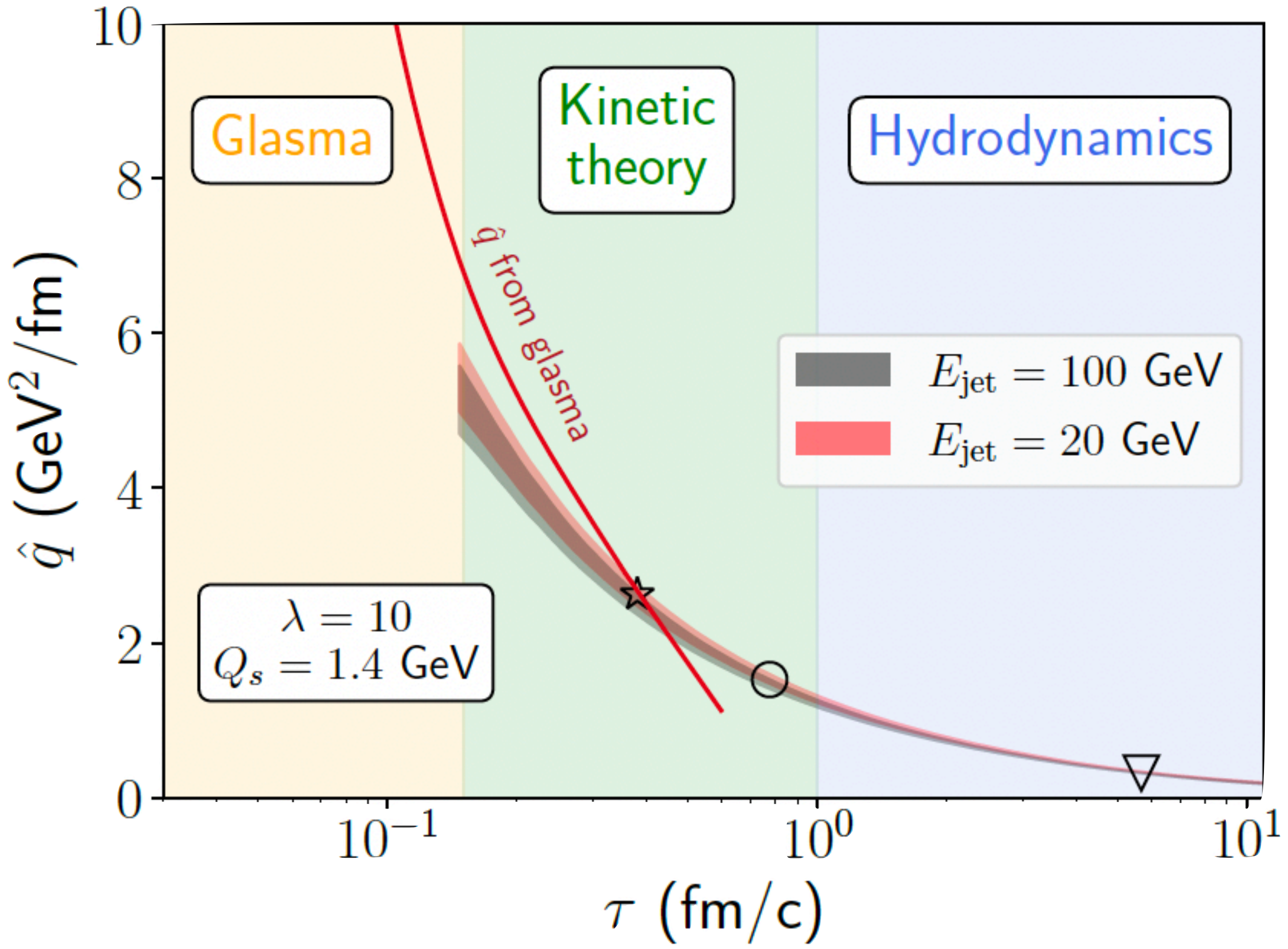
Glasma

Ipp, et al., PLB (2020) 135810



See also:
Carrington et al., PLB 834 (2022) 137464 , PRC (2022) 6, 064910, and Avramescu et al., PRD 107 (2023), 114021

Kinetic theory



Boguslavski et al., PLB 850, 138525 (2024)

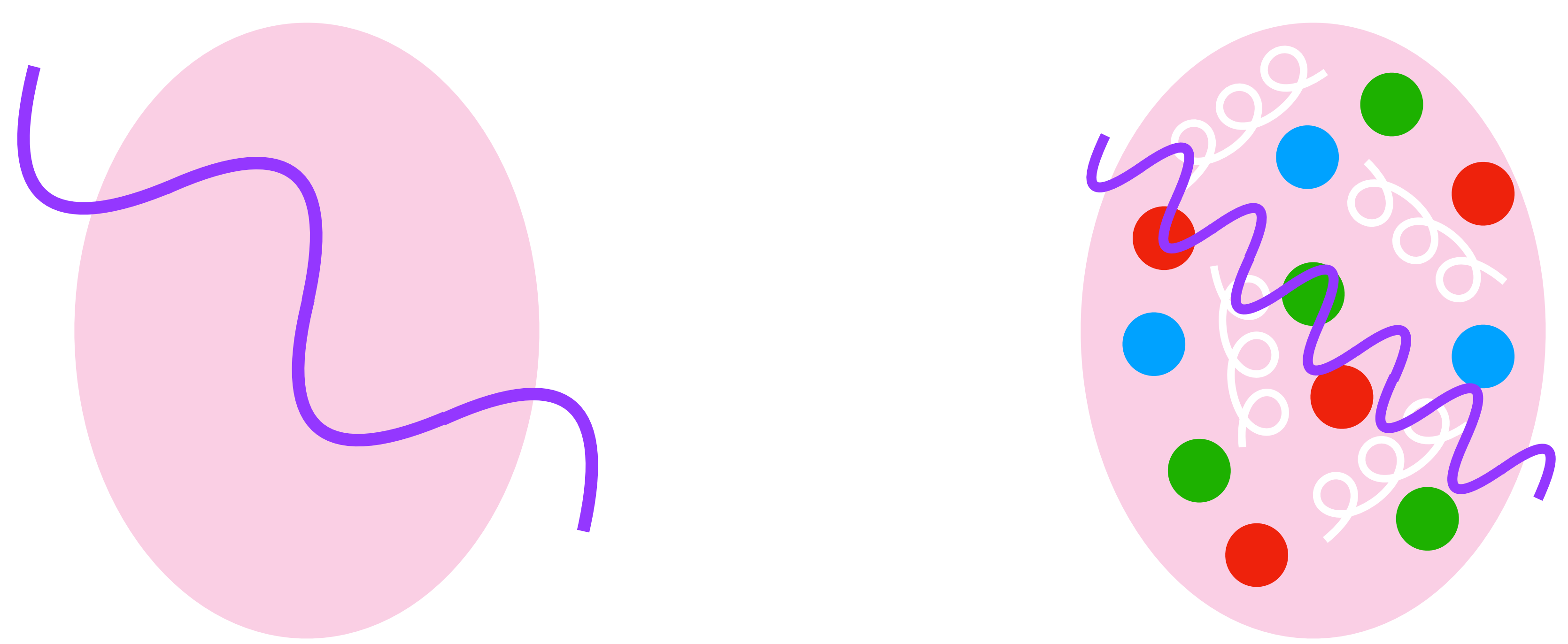
Jet substructure

Raymond Ehlers' talk Thus 10:00

Can we use jet substructure to probe the QGP at **various resolution scales?**

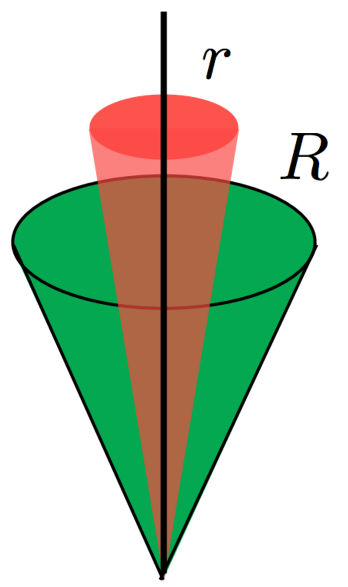
Fluid-like QGP

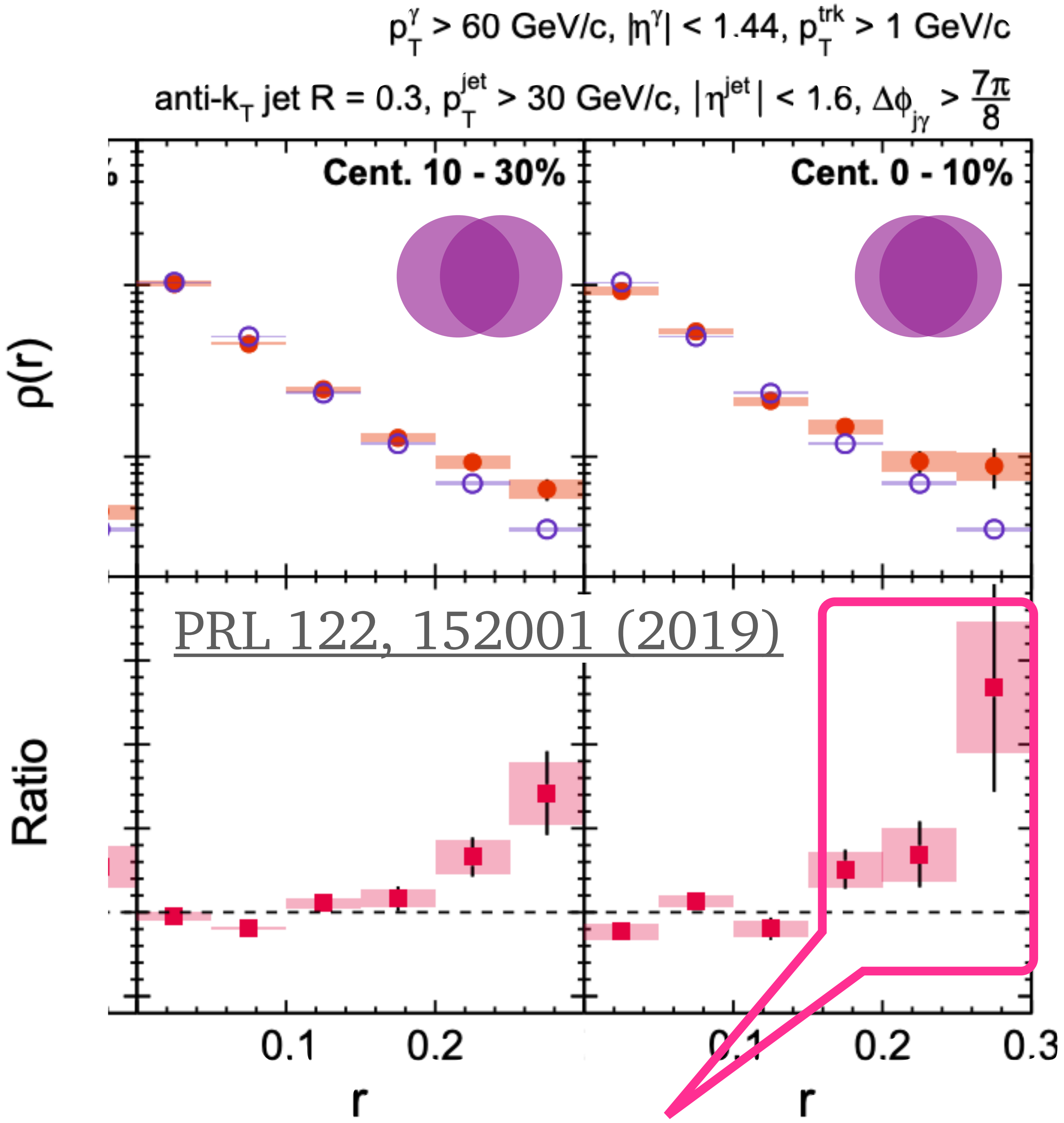
Particle-like QGP



Increasing the resolution scale

Jet shapes





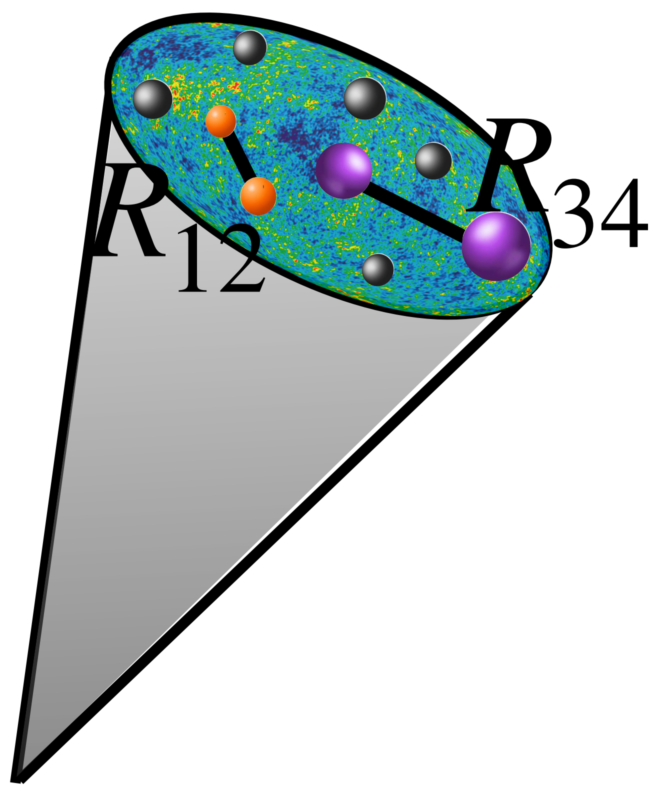
Pb-Pb jets **more energy toward the edge of the cone** than p-p jets

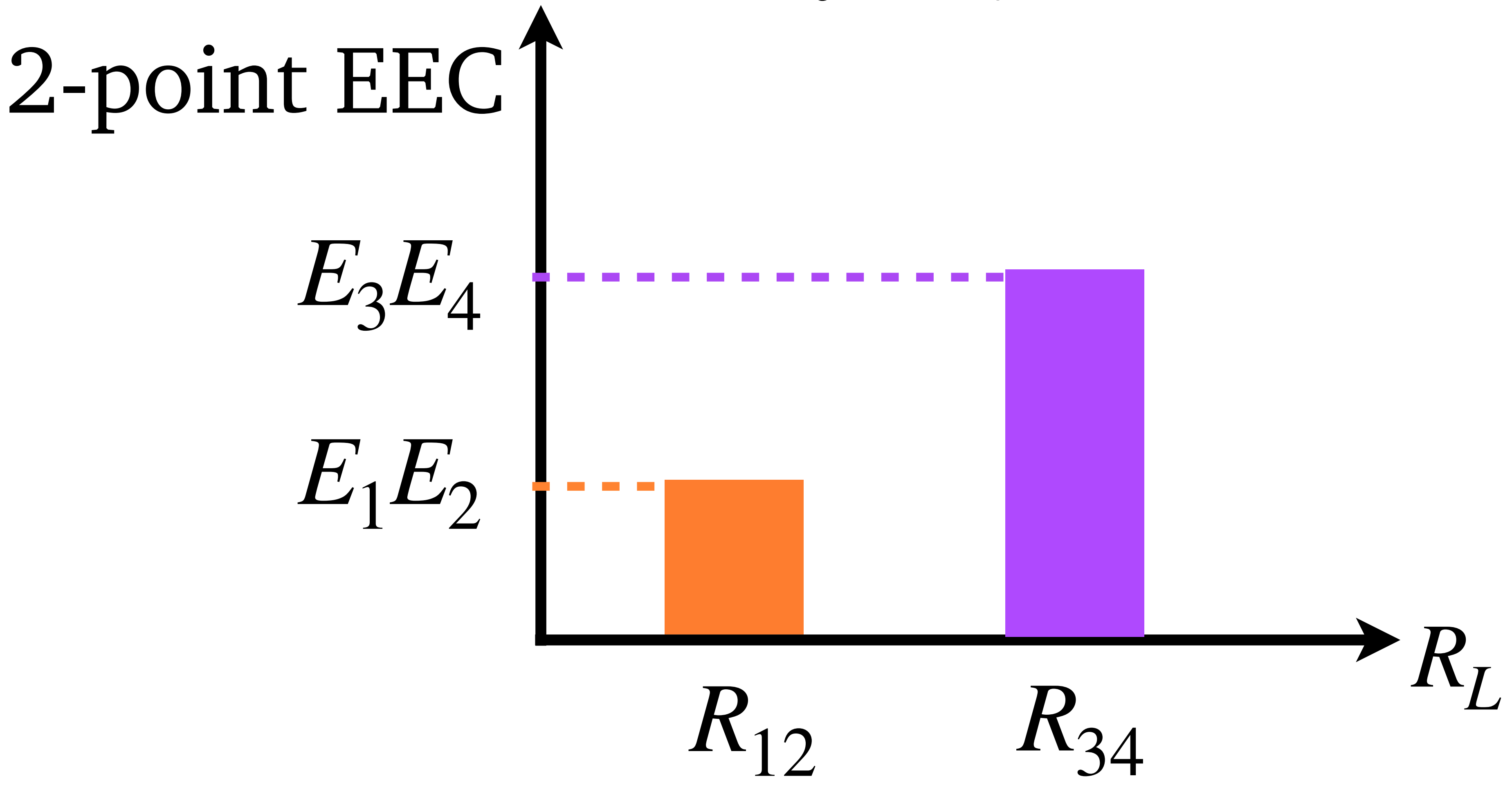
New tool: energy correlators

Ian Moult's talk
Mond 17:20

- Correlators $\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\cdots\mathcal{E}(\vec{n}_k)\rangle$ of the **energy flux**

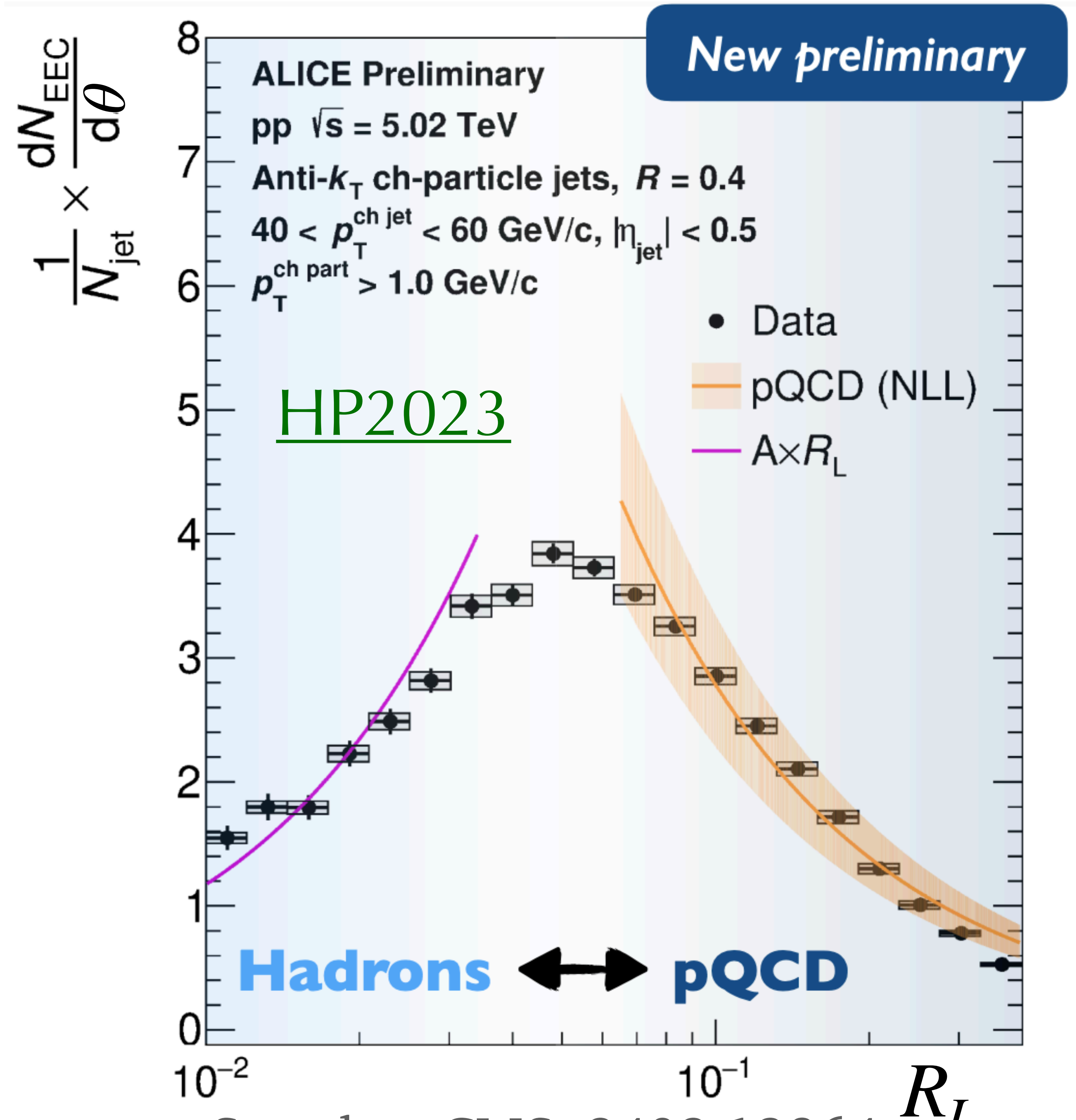
$$\text{2-point EEC} = \frac{1}{N_{\text{jets}}}\sum_{\text{jets}}\sum_{i,j}\frac{P_{T,i}P_{T,j}}{P^2_{T,\text{jet}}}\,\delta(R_{ij}-R_L)$$





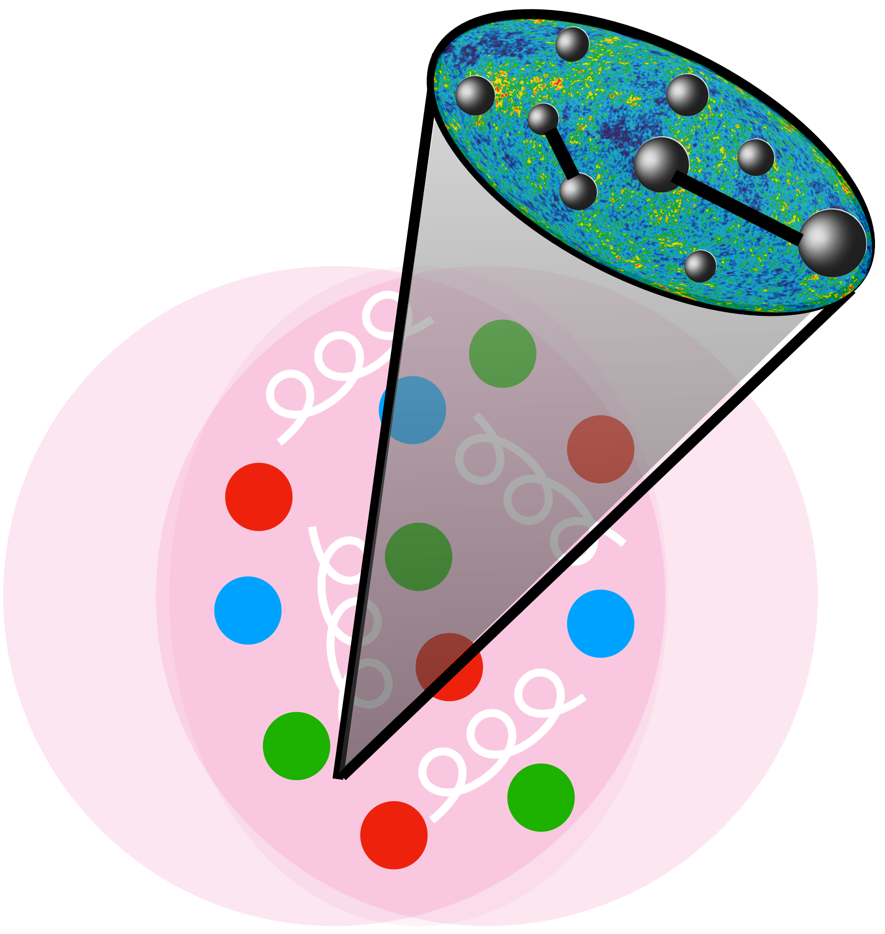
- Excellent theoretical properties: good candidates for a heavy-ion substructure program

EEC in proton-proton



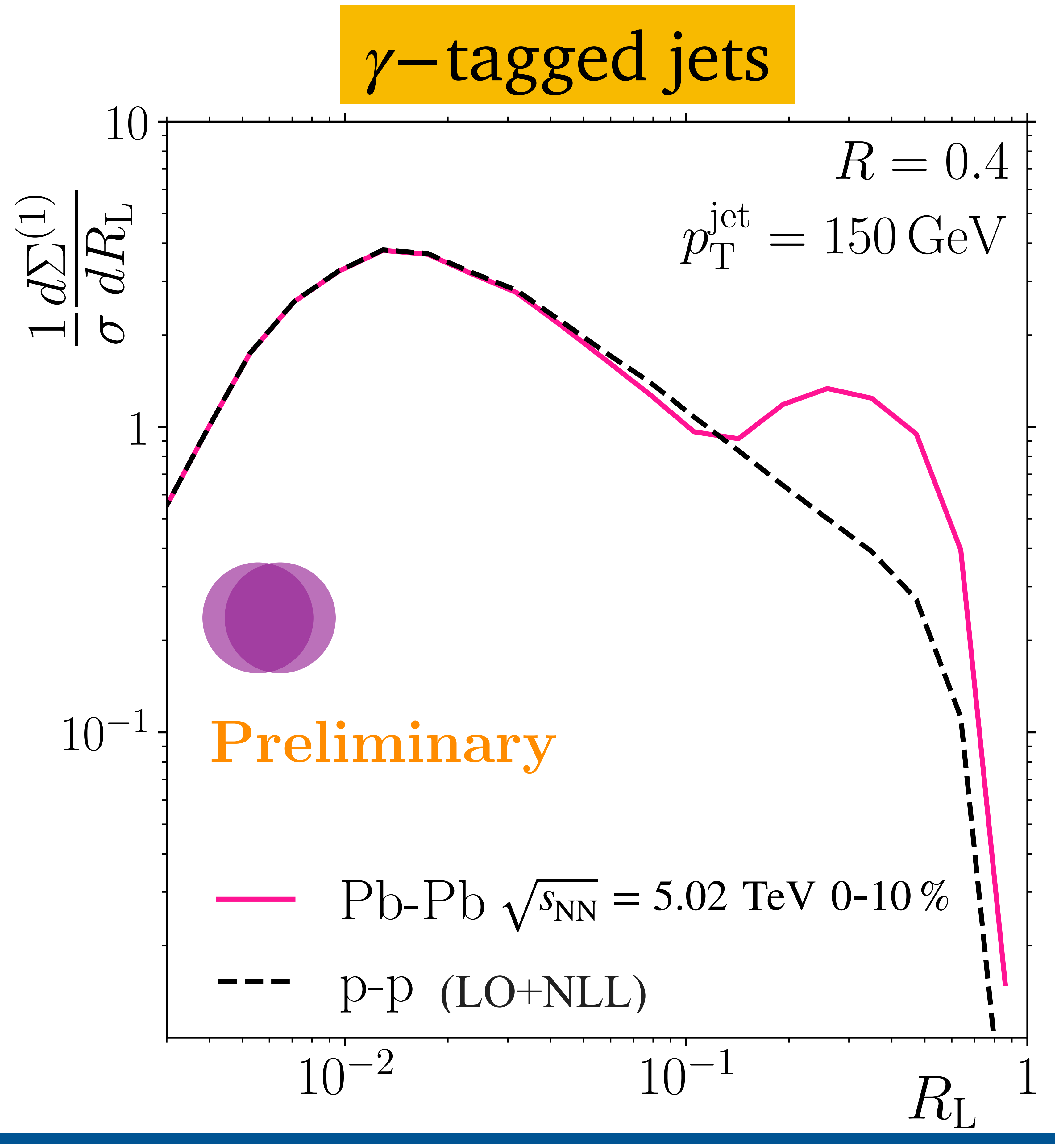
See also: CMS, 2402.13864
STAR, 2309.05761
Simon Rothman's talk Mond 14:36and
Hannah Bossi's poster

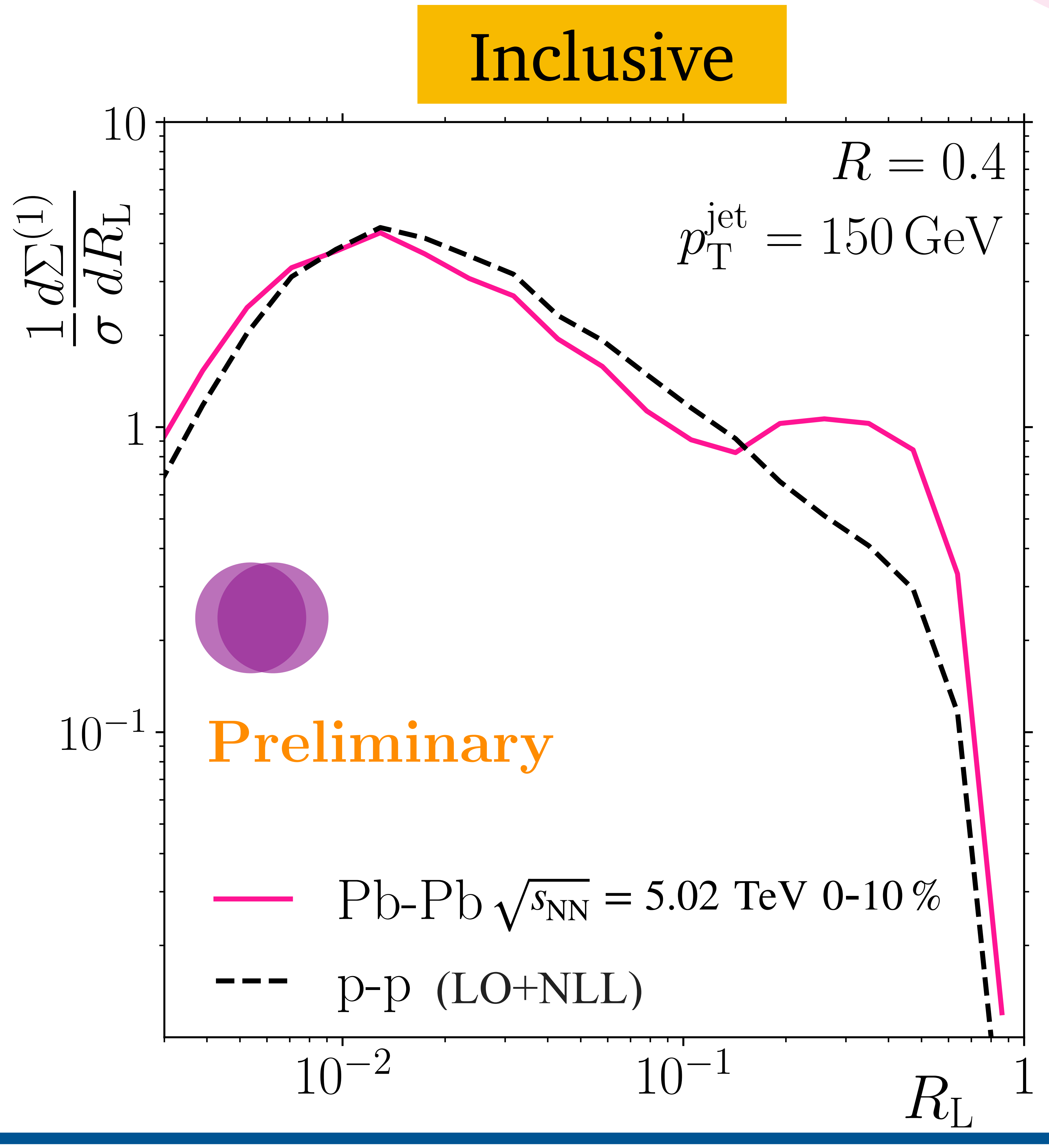
Energy correlators in heavy-ions



- Introduction of energy correlators in heavy-ion collisions

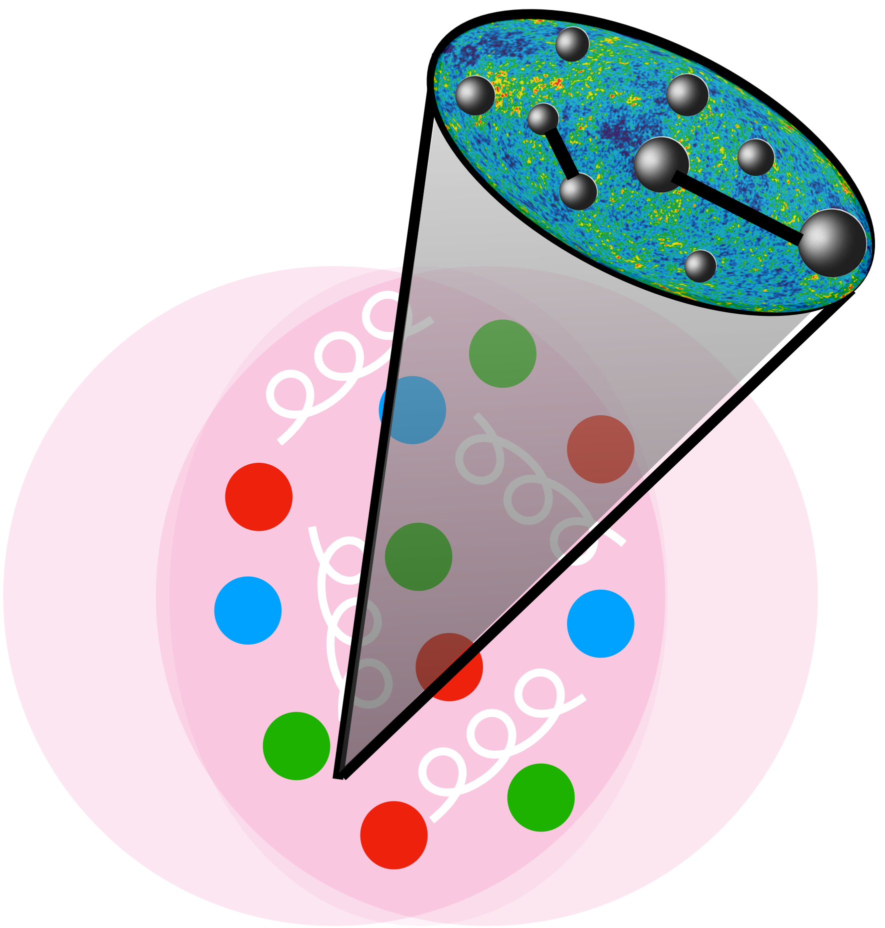
  CA, Dominguez, Elayavalli, Holguin, Marquet, Moult,
  PRL 130, 262301 (2023), JHEP 09 088 (2023), 2307.15110





See also: Yang et al., PRL 132 1 (2024), Barata et al. 2312.12527

Energy correlators in heavy-ions



- Introduction of energy correlators in heavy-ion collisions

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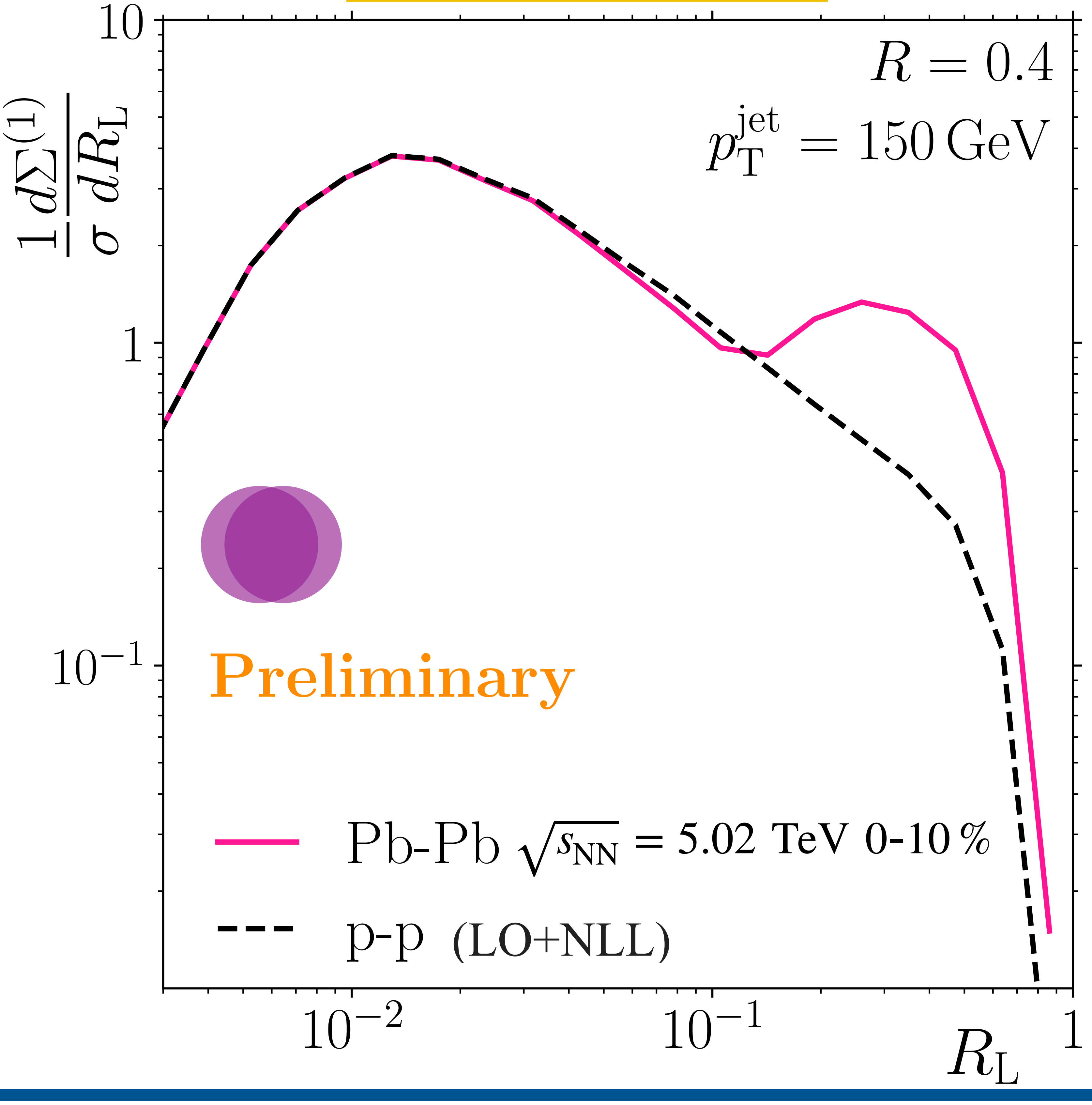
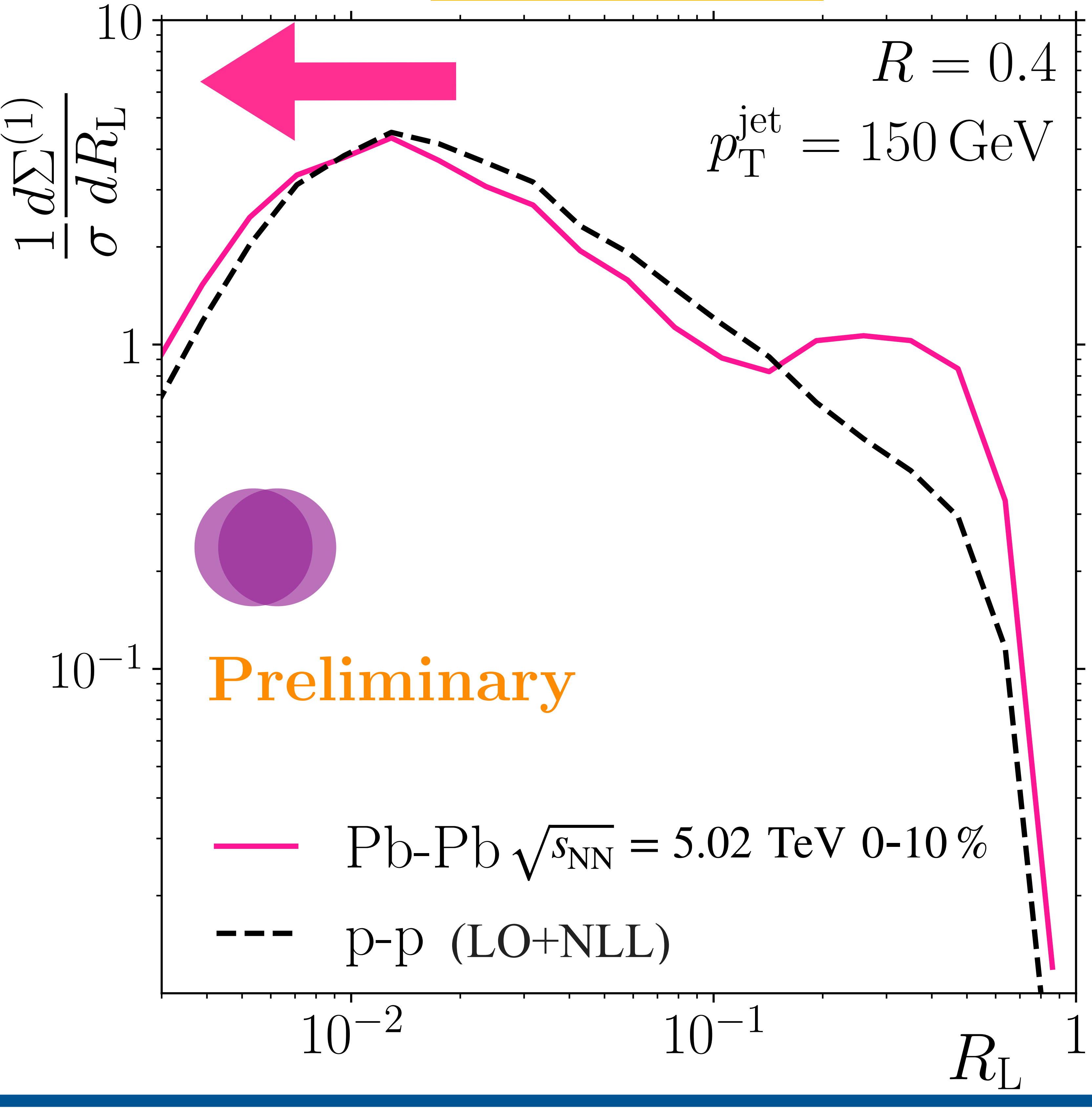
$\gamma-$tagged jets



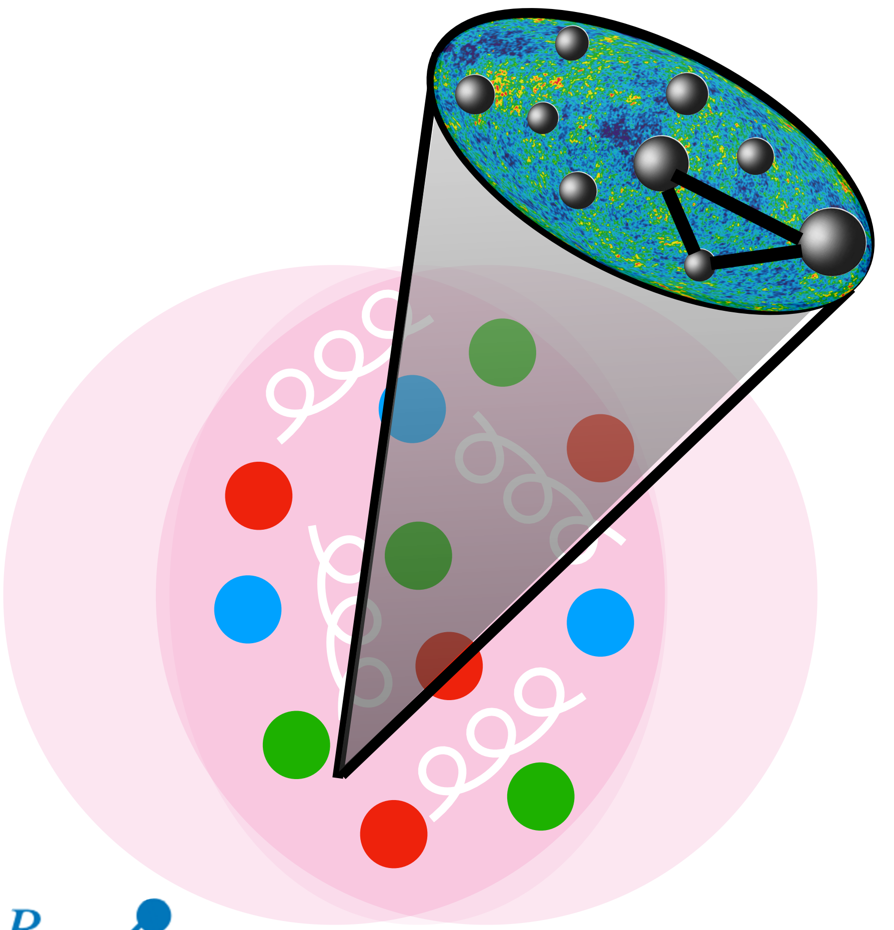
Energy loss

Inclusive



See also: Yang et al., PRL 132 1 (2024), Barata et al. 2312.12527

Energy correlators in heavy-ions

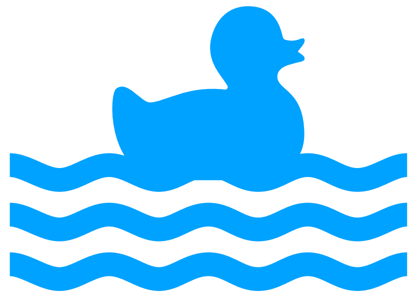


- First studies of the shape of the E3EC

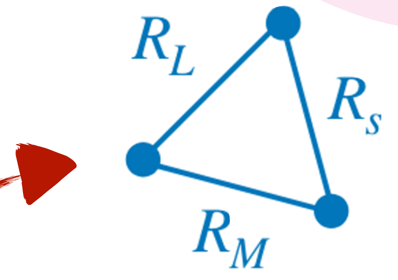
Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal

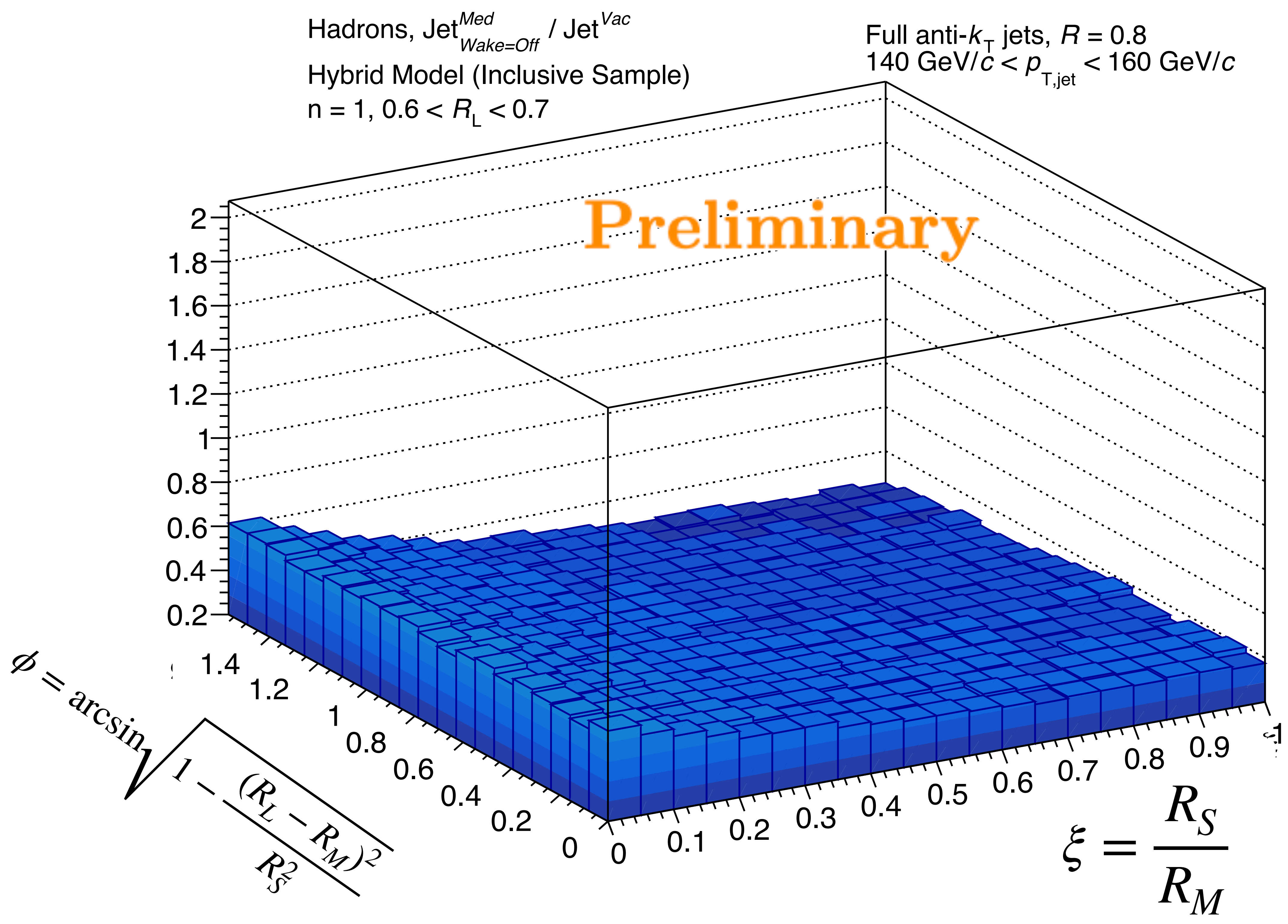
See Ananya Rai's poster

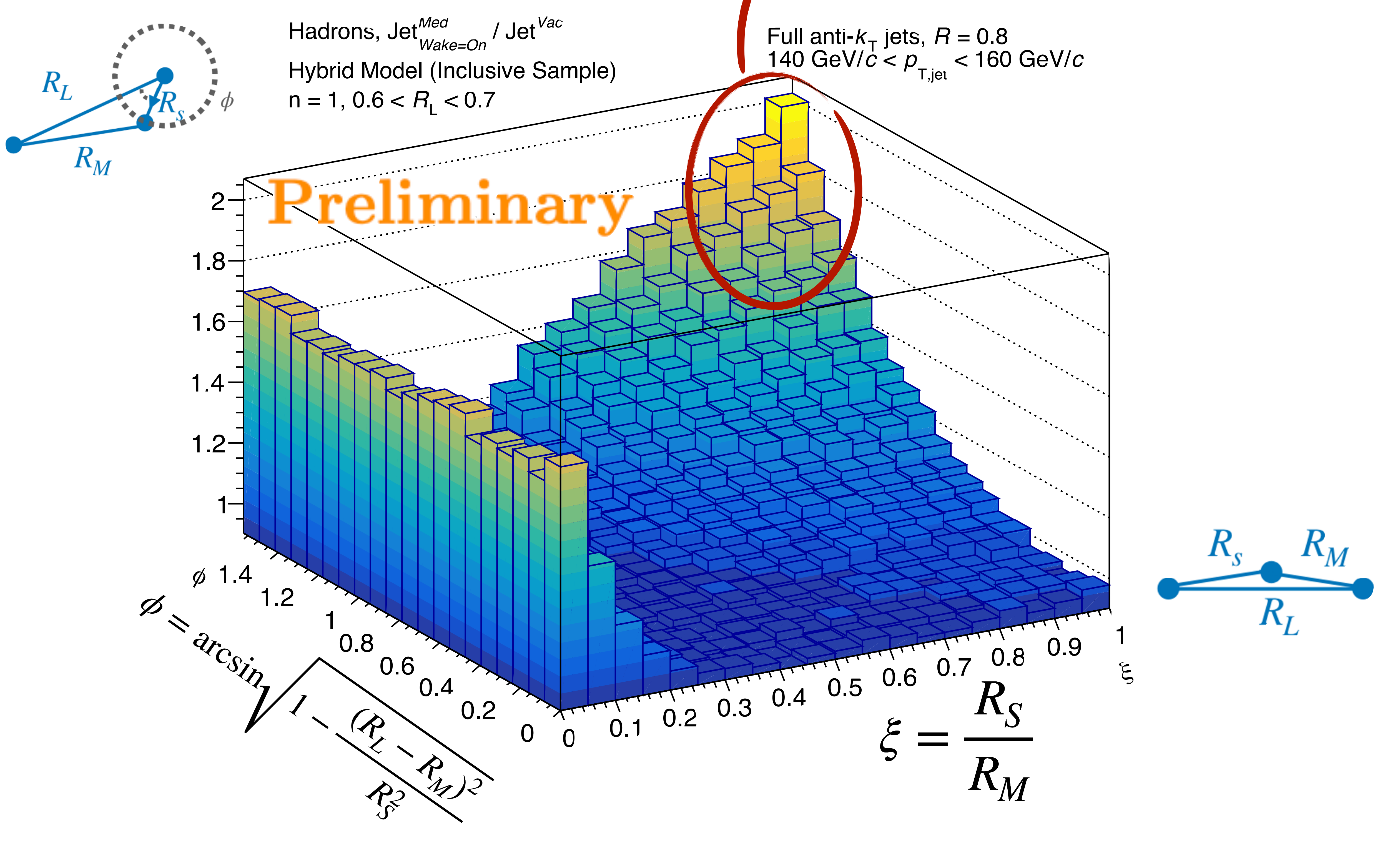
No wake/p-p



With wake/p-p





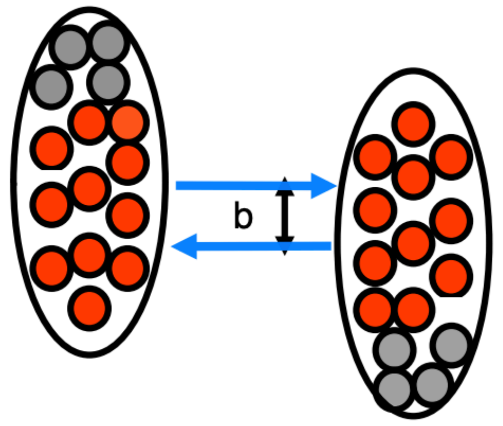


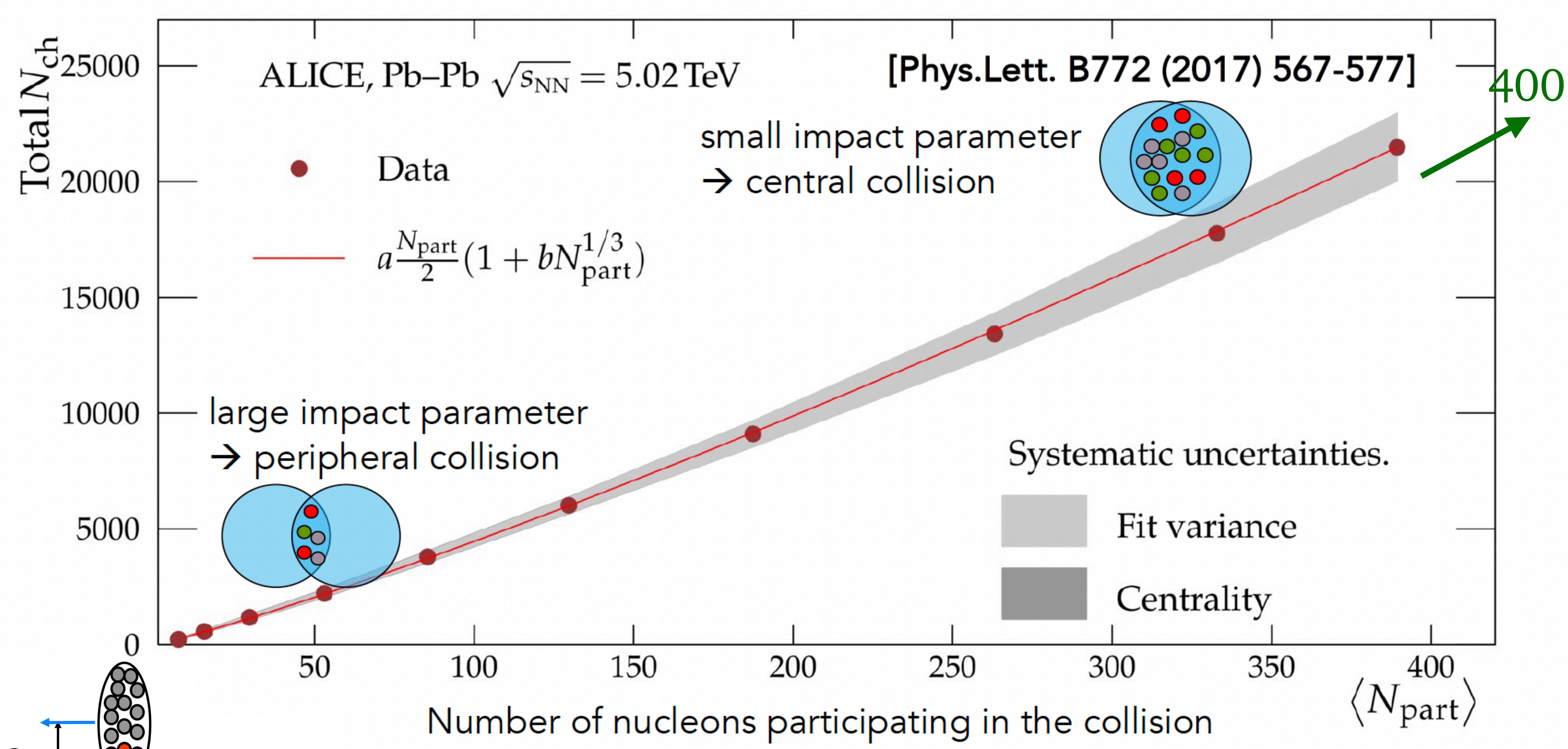
Conclusions

- QCD has a **rich dynamics** within experimental reach
- QCD **EoS for both hot and cold dense matter** can be studied using different experimental tools
  - Colliders (LHC and RHIC): for hot and low baryon chemical potential
  - First constraints from **gravitational waves** on EoS of the core of **neutron stars**
- **Hot QCD at the LHC** and RHIC:
  - Impressive progress on the study of the QGP and its pre-hydro stages
  - Many interesting questions to be answered in the next decade

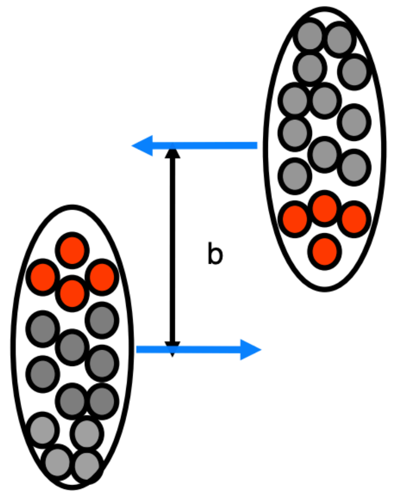
How does a strongly-coupled fluid emerge from an asymptotically free gauge theory?

Charged hadrons in Pb-Pb



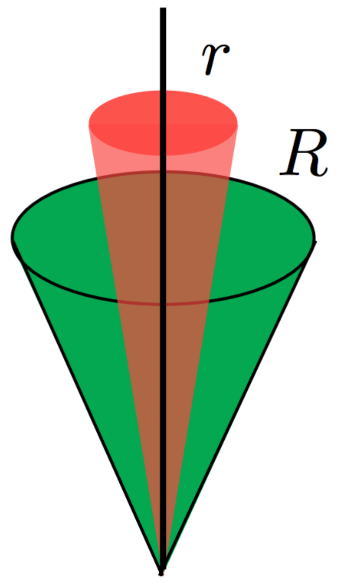


400 x N_{ch} in p-p

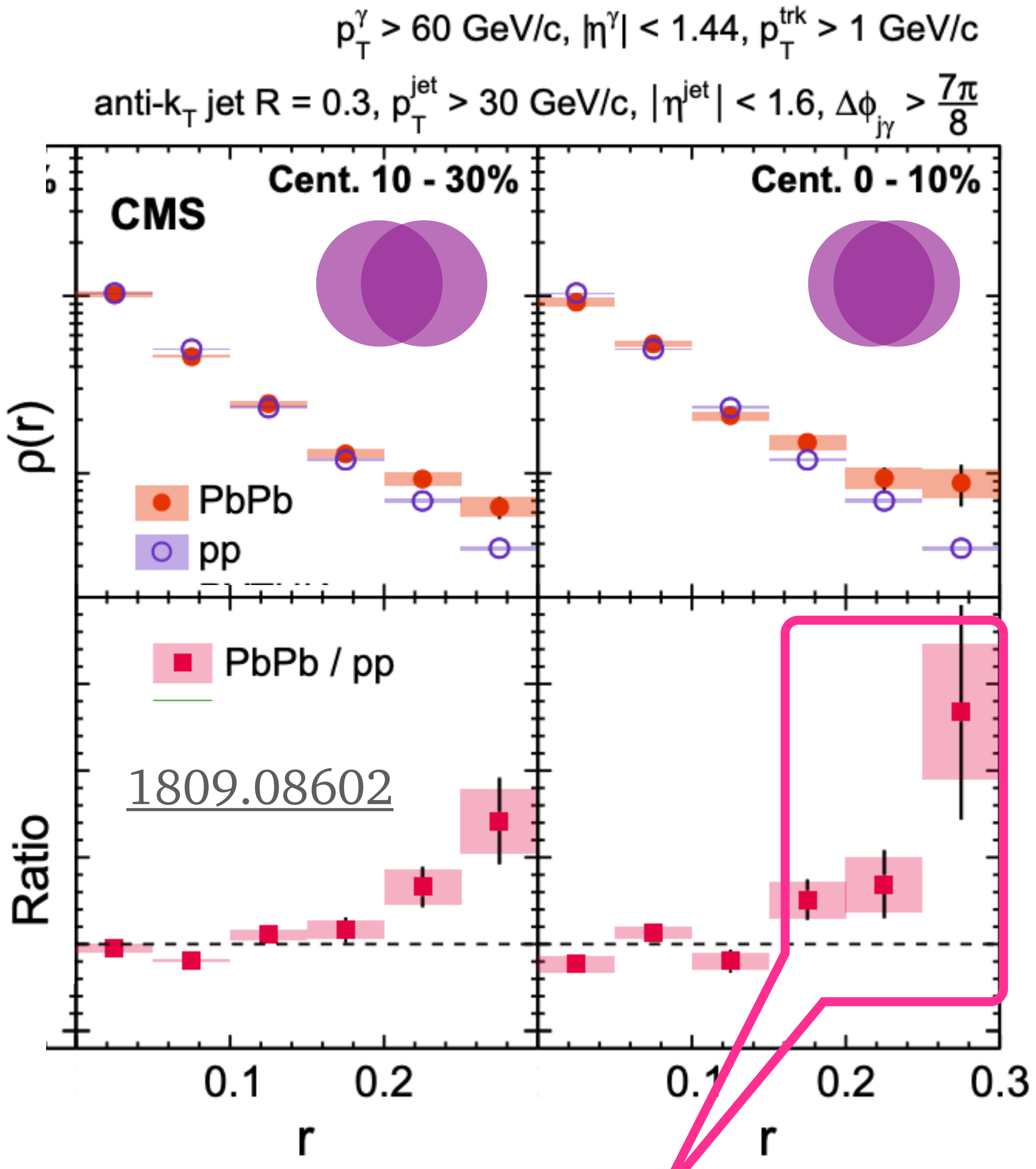


Access to **multi-body QCD** phenomena

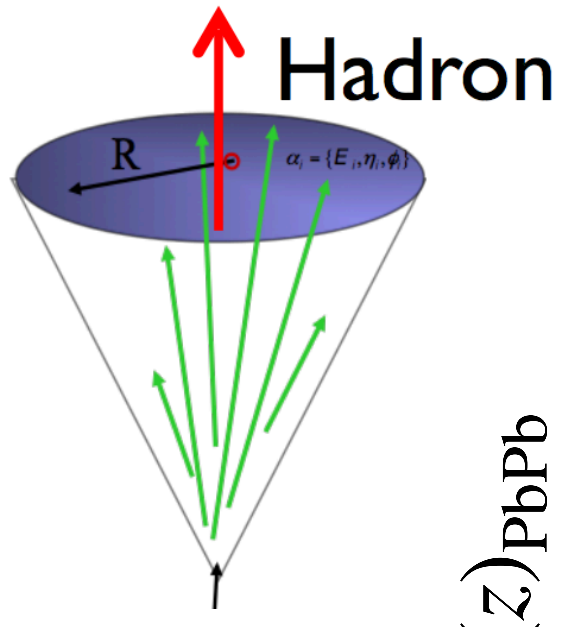
Jet substructure: some examples



Jet shapes

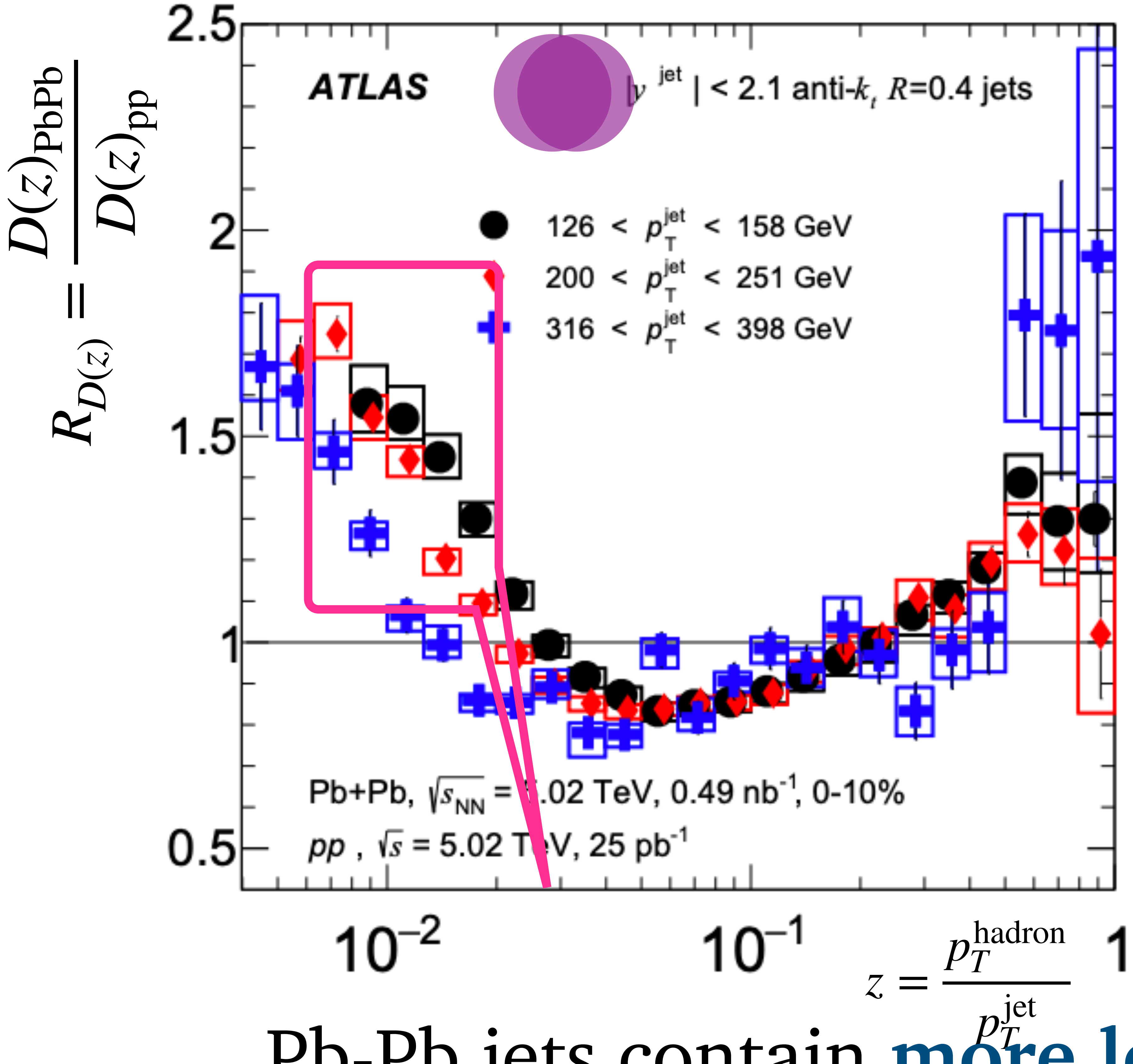


Pb-Pb jets **more energy toward the edge of the cone** than p-p jets



Jet fragmentations

1805.05424

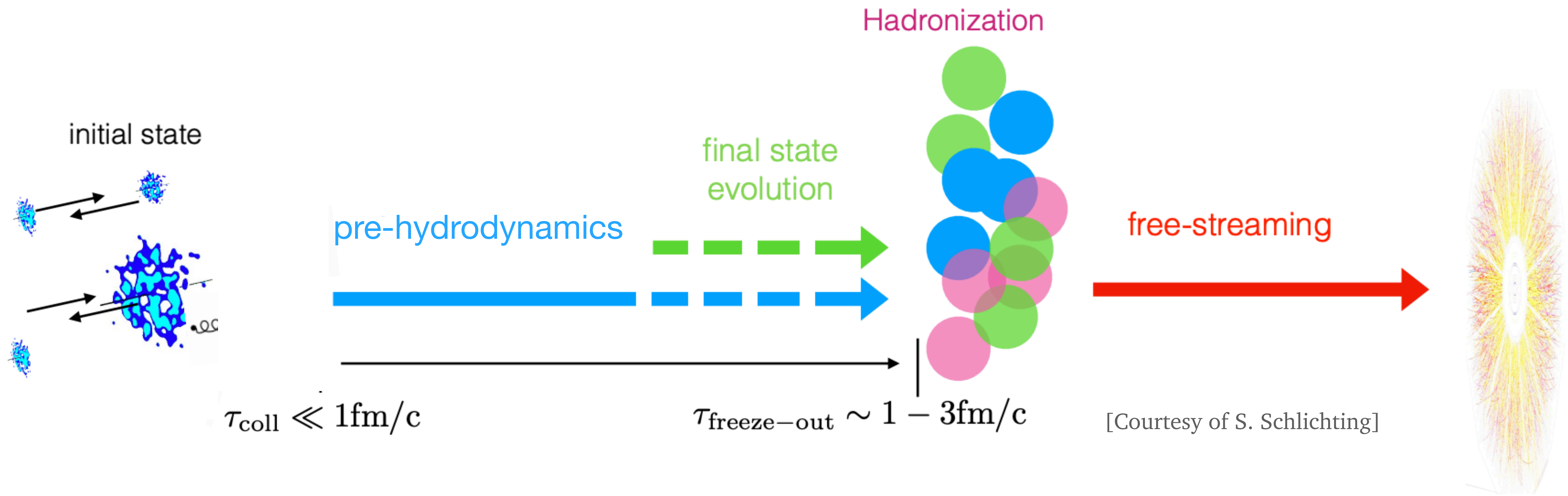


$$D(z) = \frac{1}{N_{jet}} \frac{dn_{ch}}{dz}$$

Pb-Pb jets contain **more low-p_T particles** than p-p jets

Small systems

- Shorter lifetime: **larger sensitivity to pre-hydrodynamization**



[Courtesy of S. Schlichting]

- System can fall apart before hydrodynamics start to apply!

Ambruş, Schlichting, Werthmann, Phys. Rev. Lett. 130 (2023)152301