Hot and dense QCD in high-energy colliders and neutron stars

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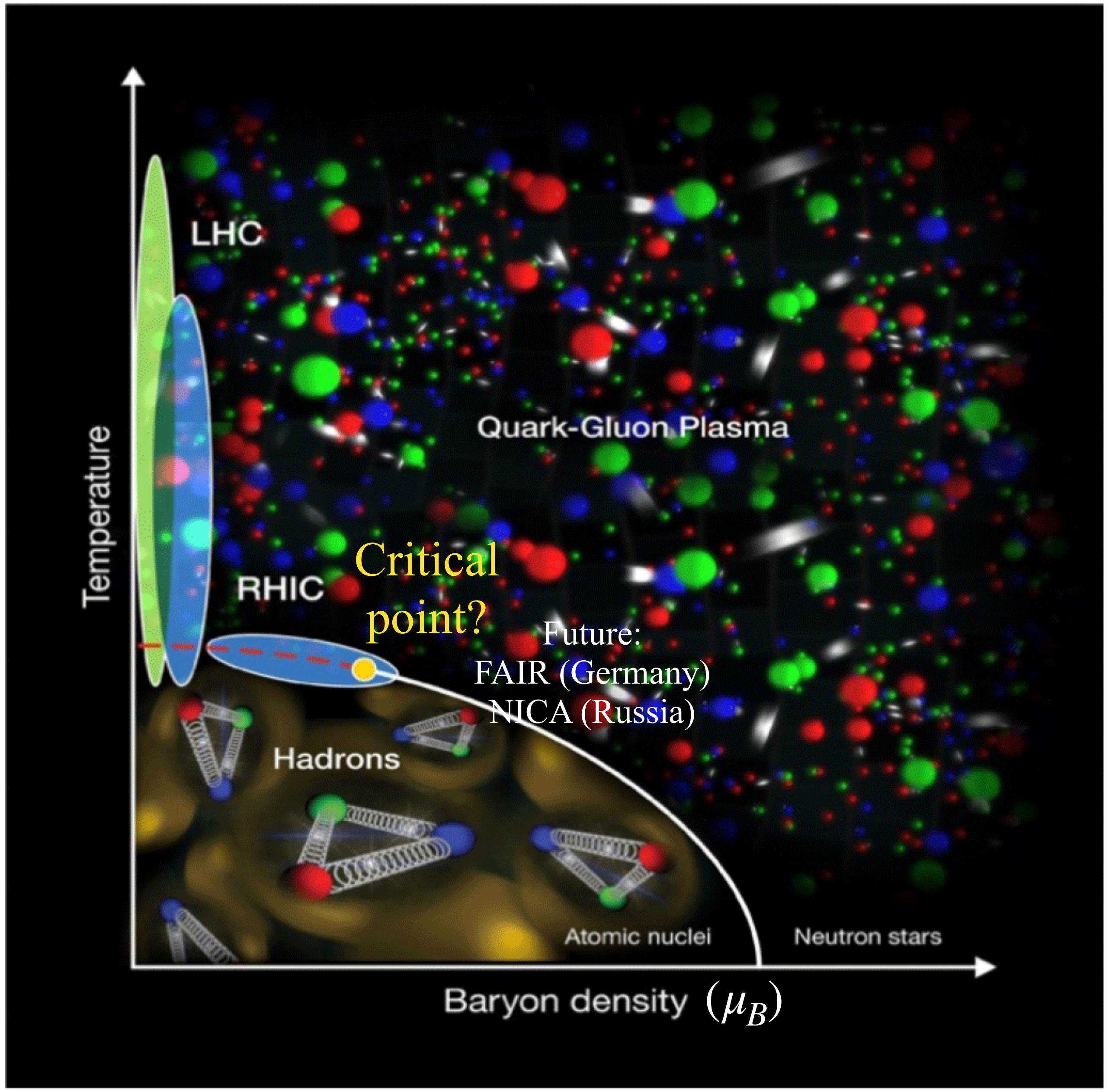
L International Meeting on Fundamental Physics and XV CPAN days
Santander, October 2-6, 2023

QCD phase diagram

- Hot QCD emergent dynamics at reach in collider experiments!



QCD phase diagram

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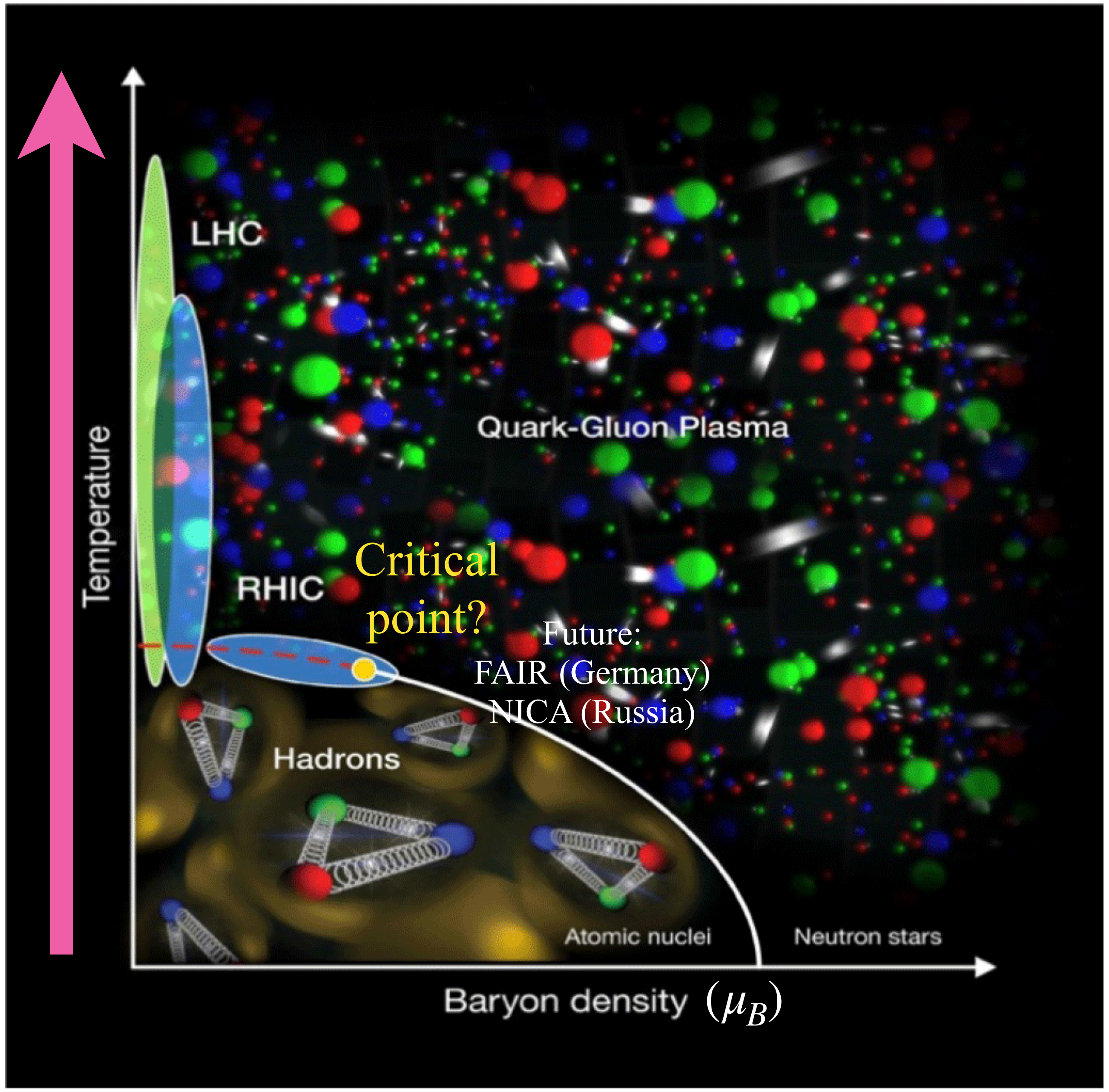
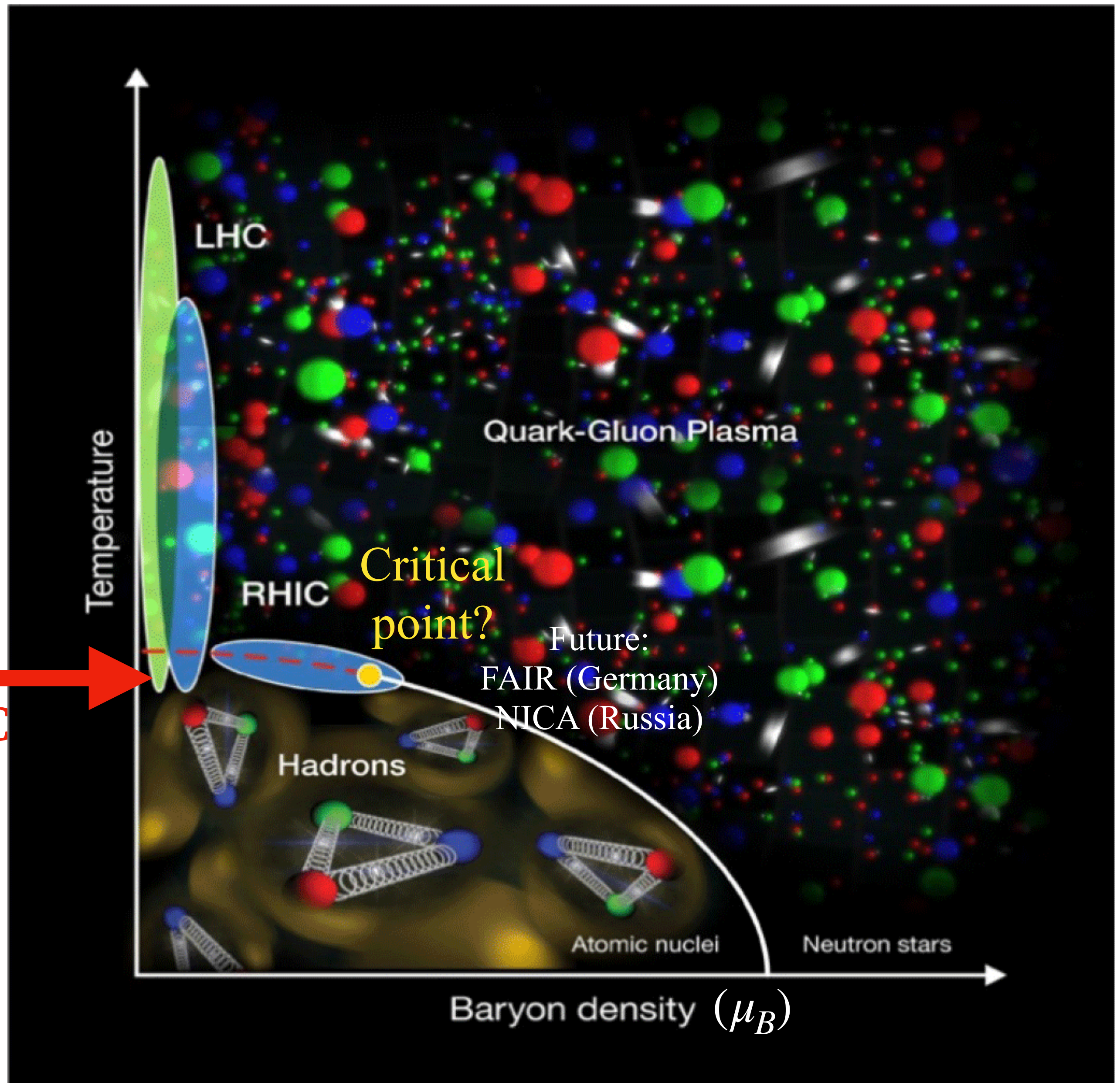


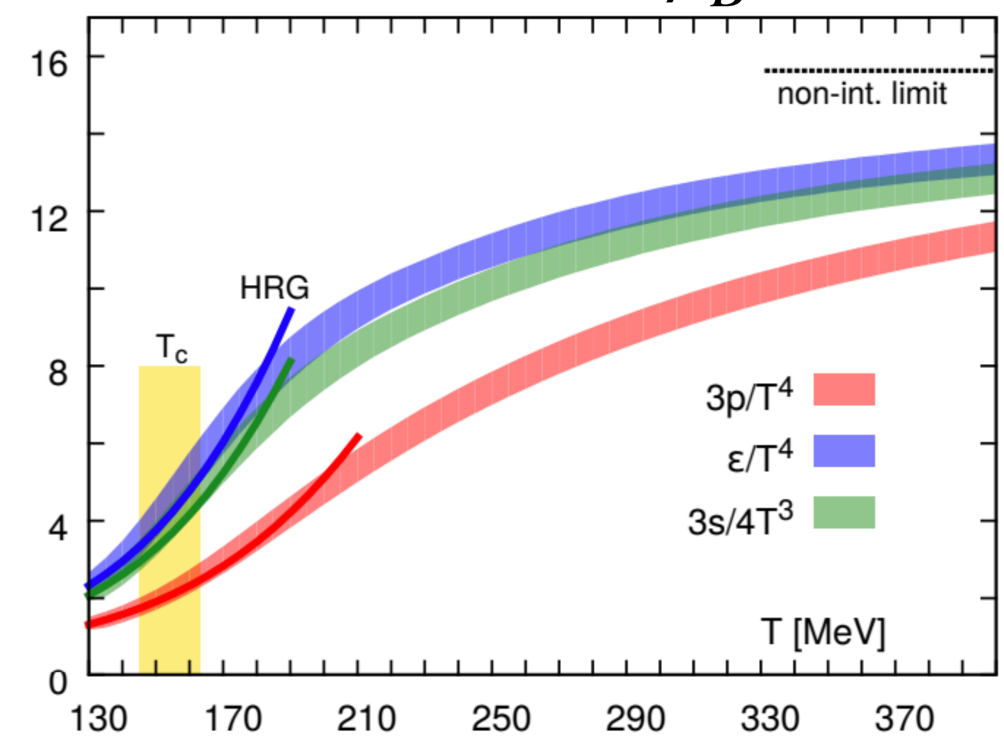
QCD phase diagram

- 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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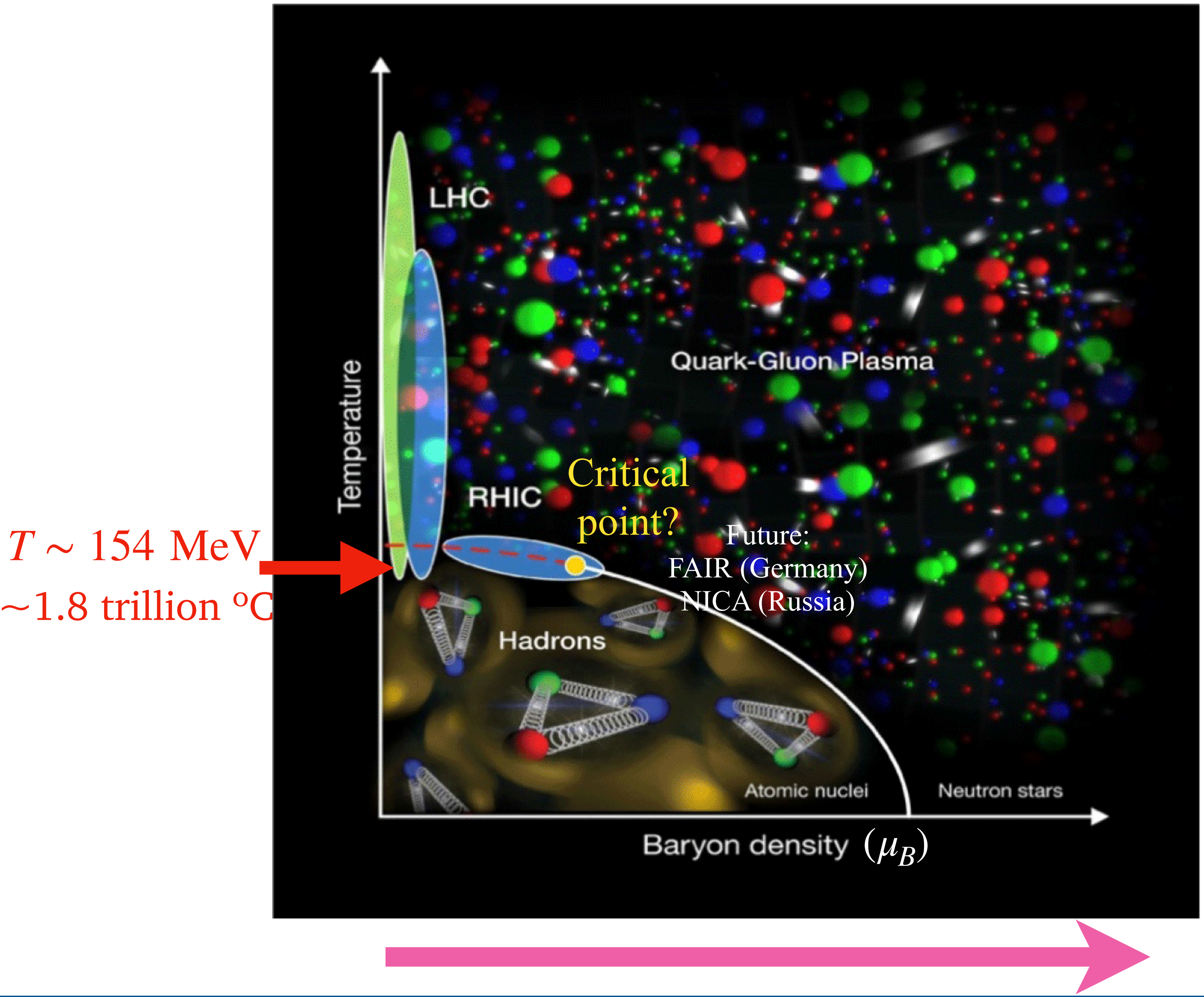
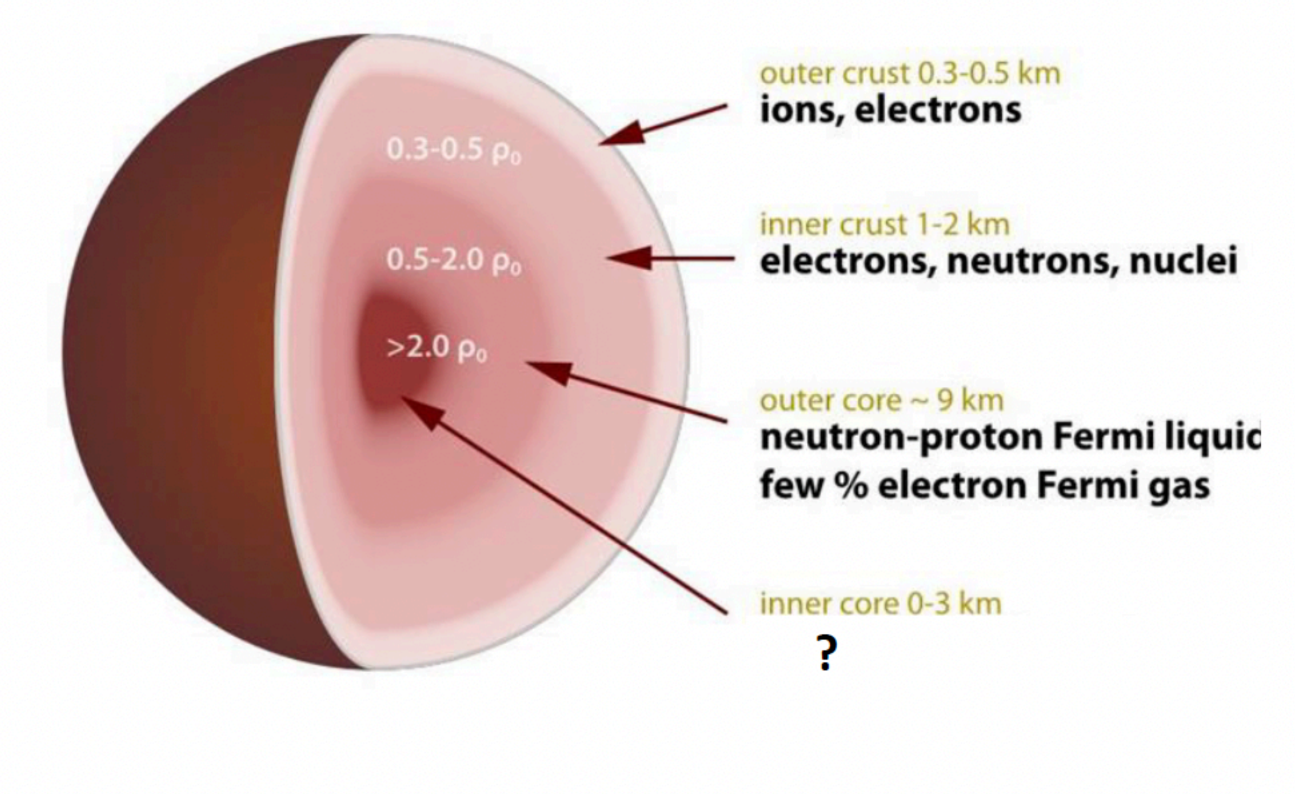
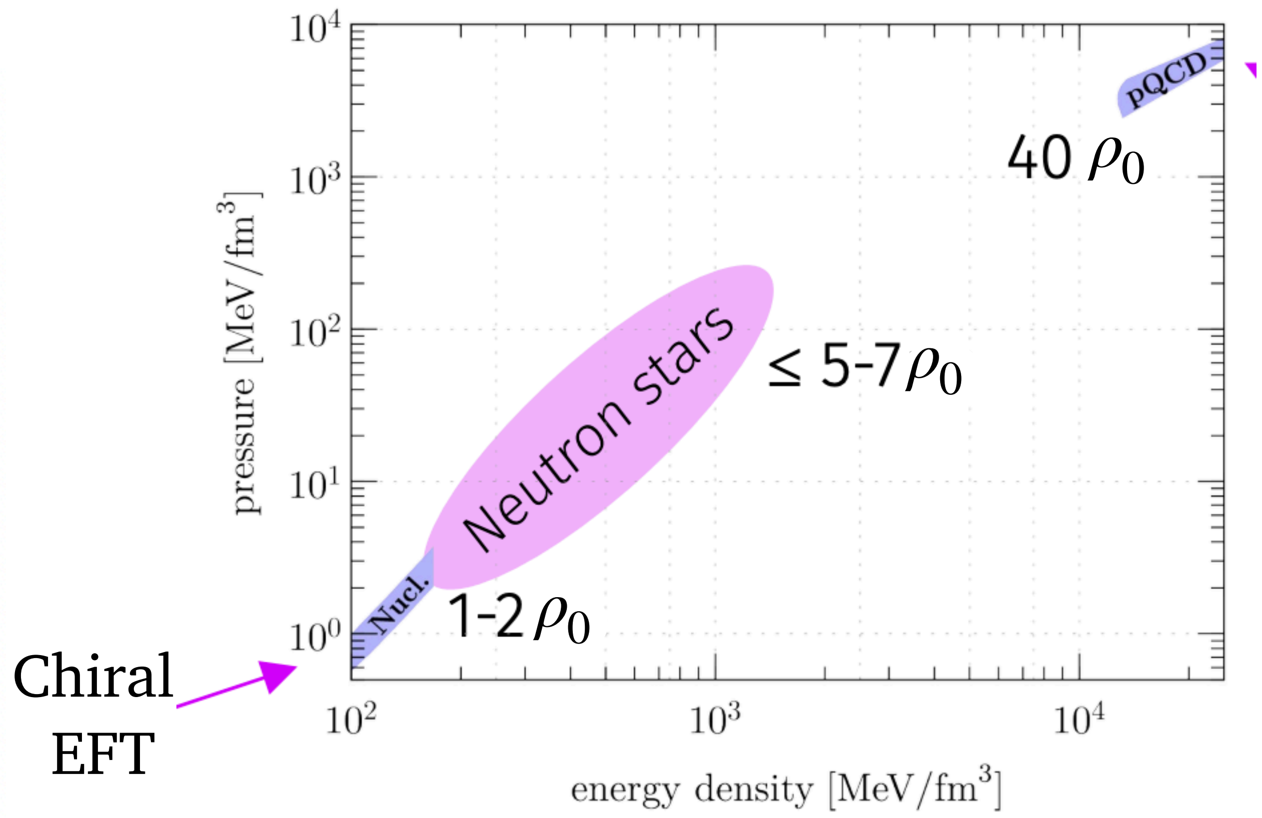


Neutron stars

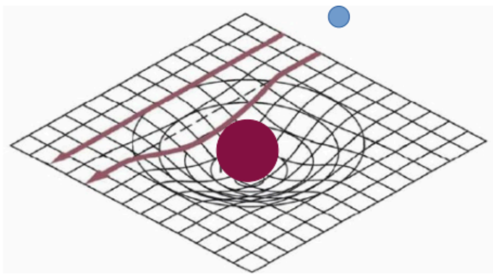
- At T=0: No Lattice. But we have astrophysics and both particle and nuclear physics



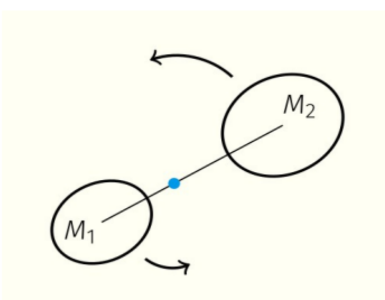


- EoS of the inner core? Upper and lower bound from pQCD and Chiral EFT + **astrophysical measurements** (including **GW data** from binary neutron star mergers)

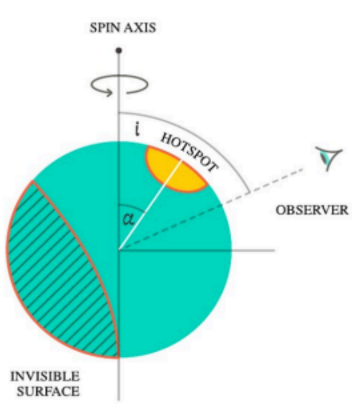
Neutron stars: EoS



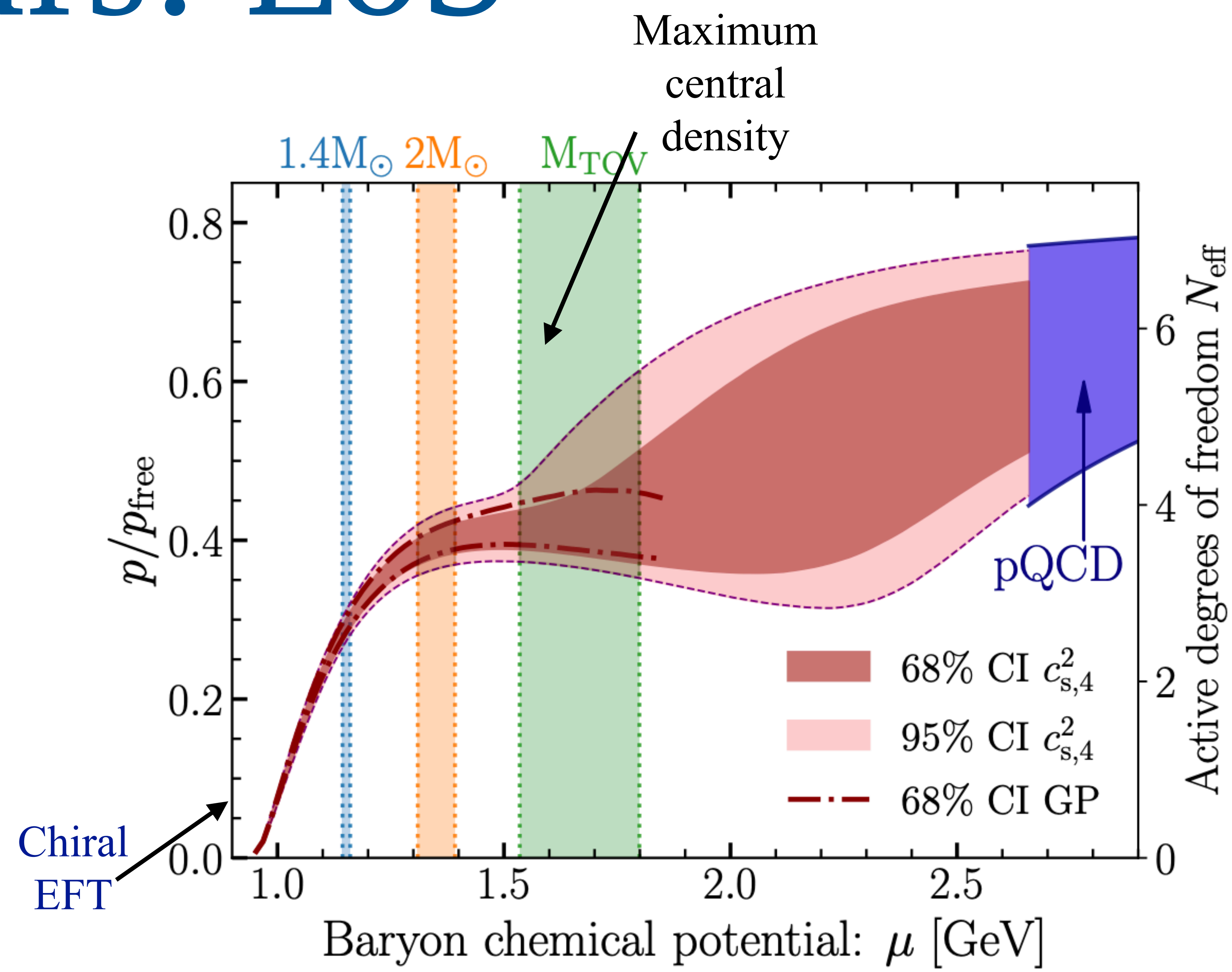
Masses



Deformabilities



Radii, compactness

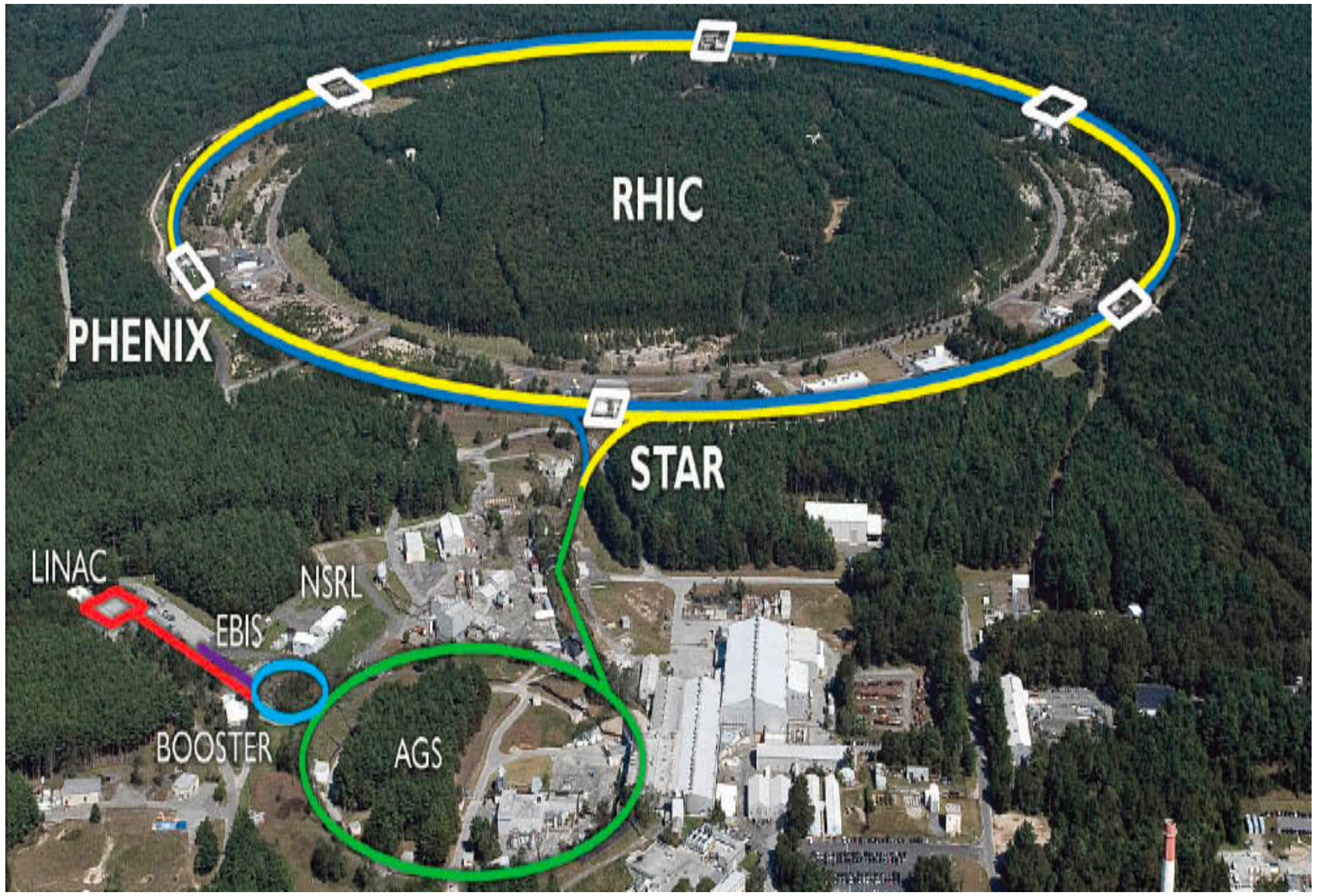


Annala, Gorda, Hirvonen, Komoltsev, Kurkela, Nättilä, Vuorinen, 2303.11356

Number of degrees of freedom
consistent with deconfined quark matter!

Hot QCD in colliders

Where?



Relativistic Heavy Ion Collider (RHIC)

Au-Au collisions

$$\sqrt{s_{\rm NN}} = 7.7 - 200\,\text{GeV}$$

(Also d-Au, He-Au, Cu-Cu, O-O…)

Large Hadron Collider (LHC)

Pb-Pb collisions

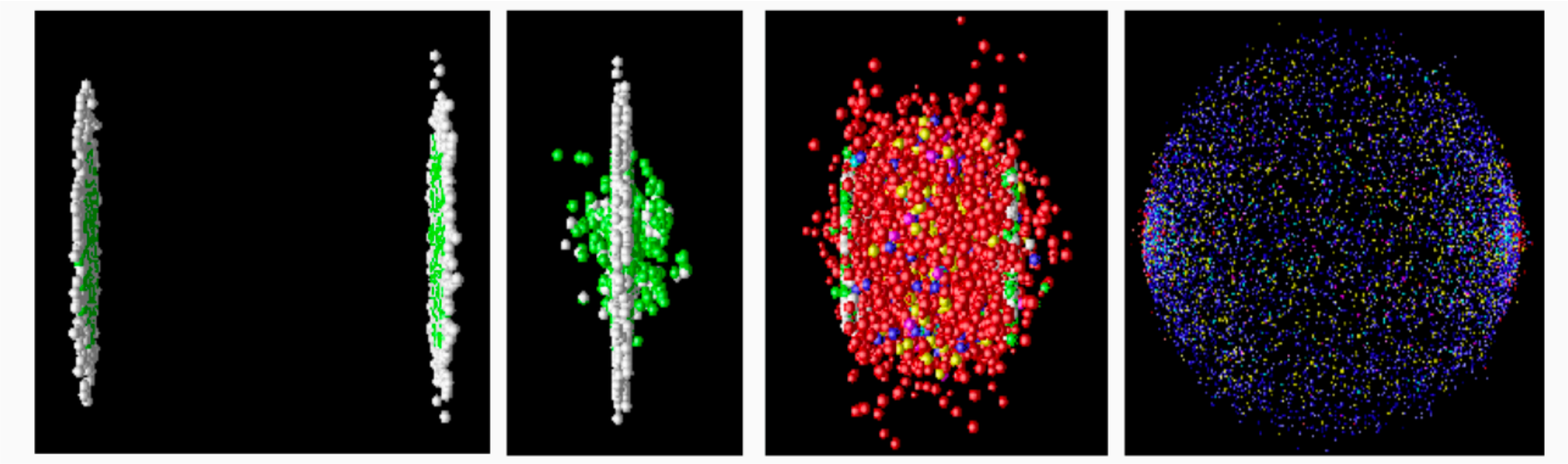
$$2010 - 2011 : \sqrt{s_{\rm NN}} = 2.76\,\text{TeV}$$
$$2011 - 2015 : \sqrt{s_{\rm NN}} = 5.02\,\text{TeV}$$
$$2023 - 2025 : \sqrt{s_{\rm NN}} = 5.36\,\text{TeV}$$

(Also p-Pb, Xe-Xe)

Heavy-ion program

- The LHC does not only collide protons on protons

- One month of running time per year is dedicated to **the Pb-Pb program**



- Other (lighter) ions runs (O-O) in Run 3

Heavy-ion program

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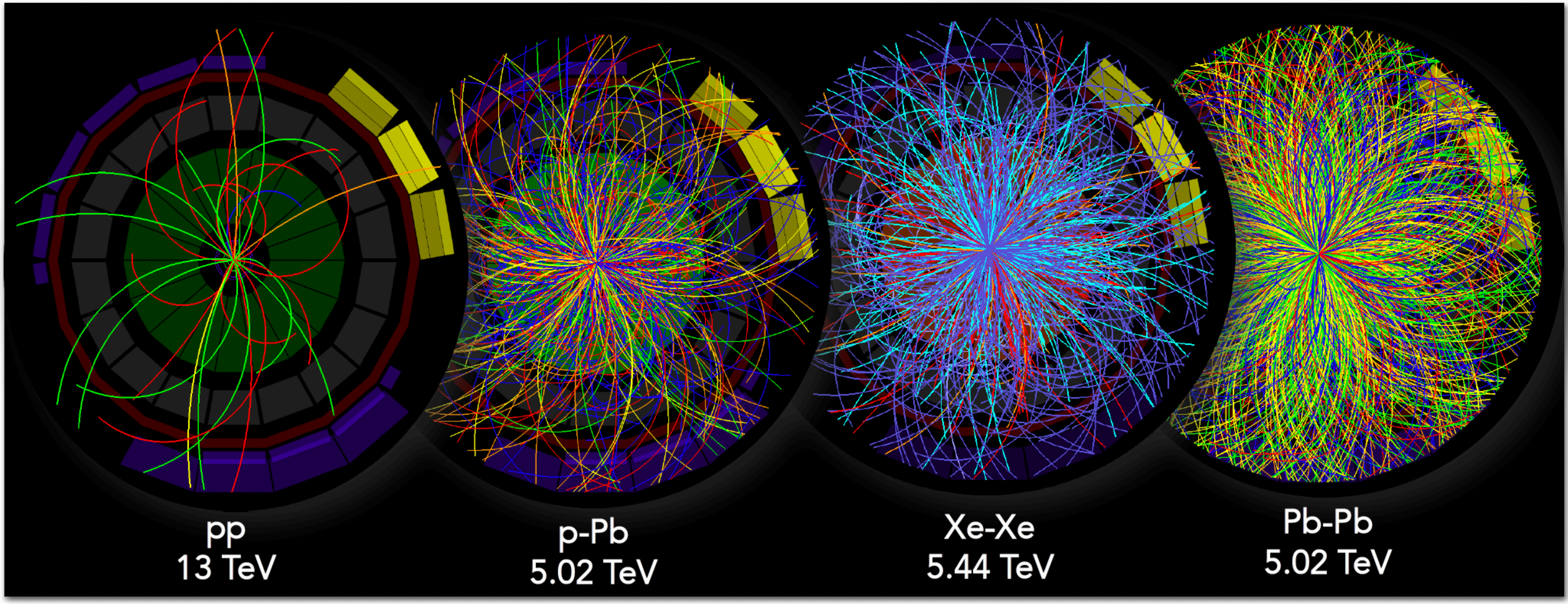
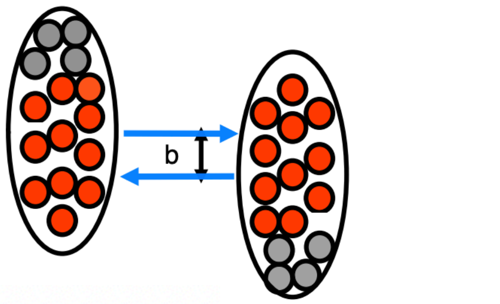
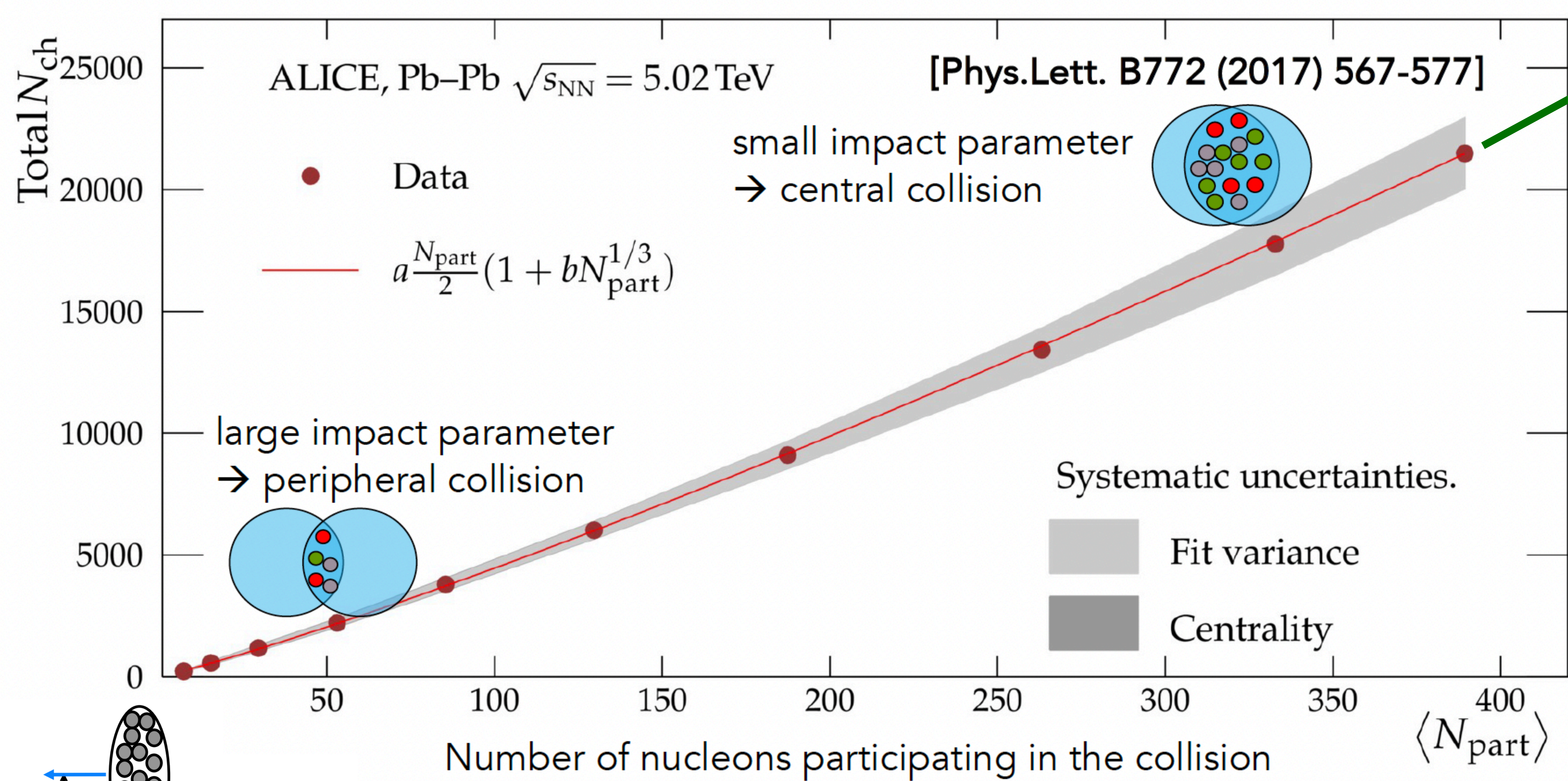
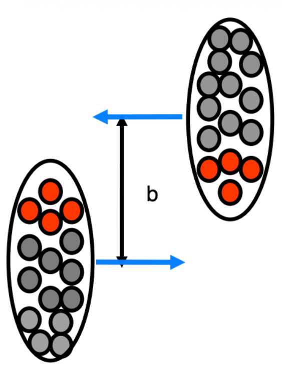


- Other (lighter) ions runs (O-O) in Run 3

Charged hadrons in Pb-Pb



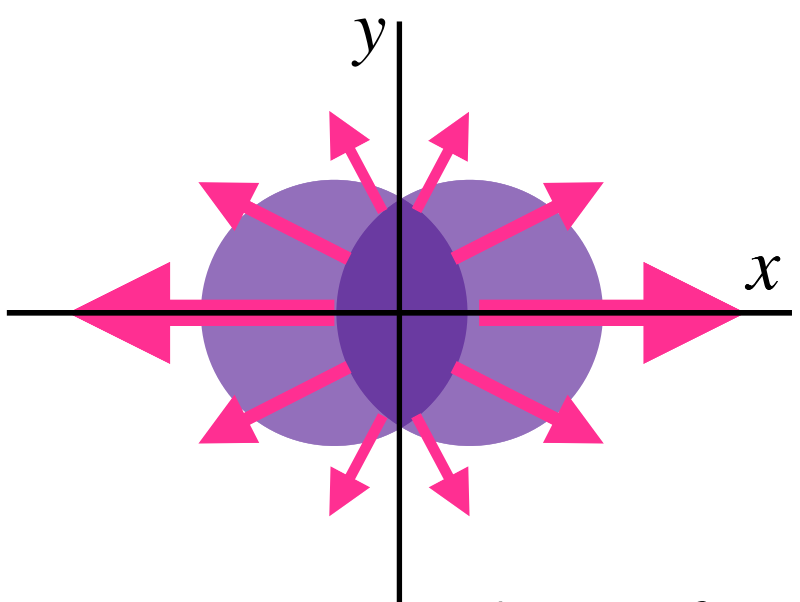




Access to **multi-body QCD** phenomena

Harmonics [simplified]

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



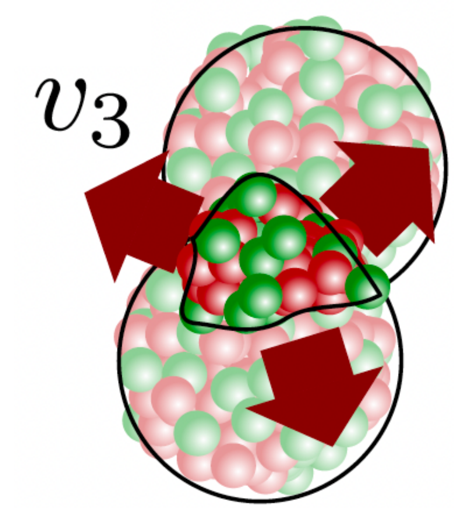
Transverse plane of the collision

- Final state anisotropies are **measurable**

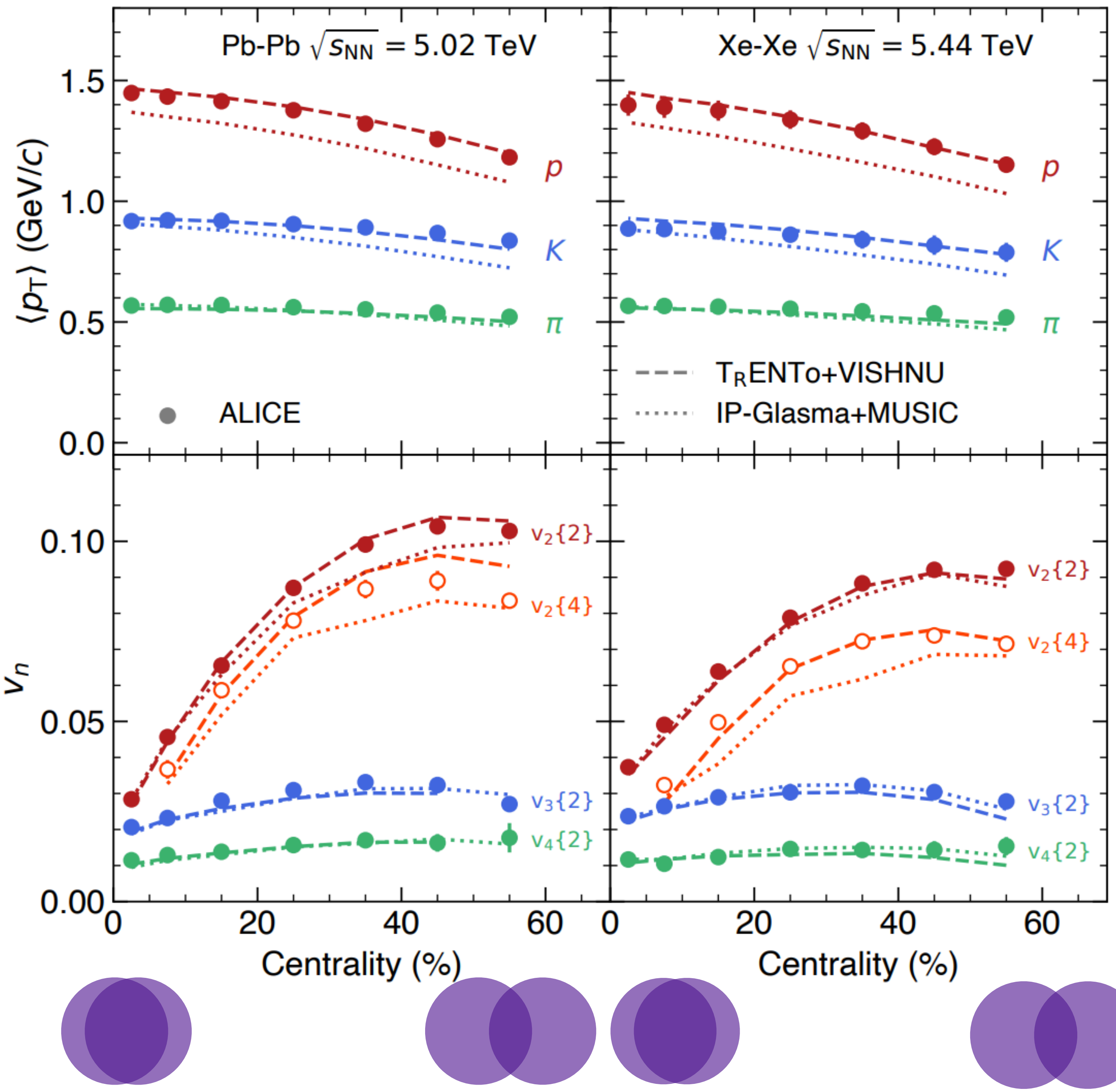
$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2 v_n(p_T) \cos\left(n(\phi - \Psi_n)\right)$$

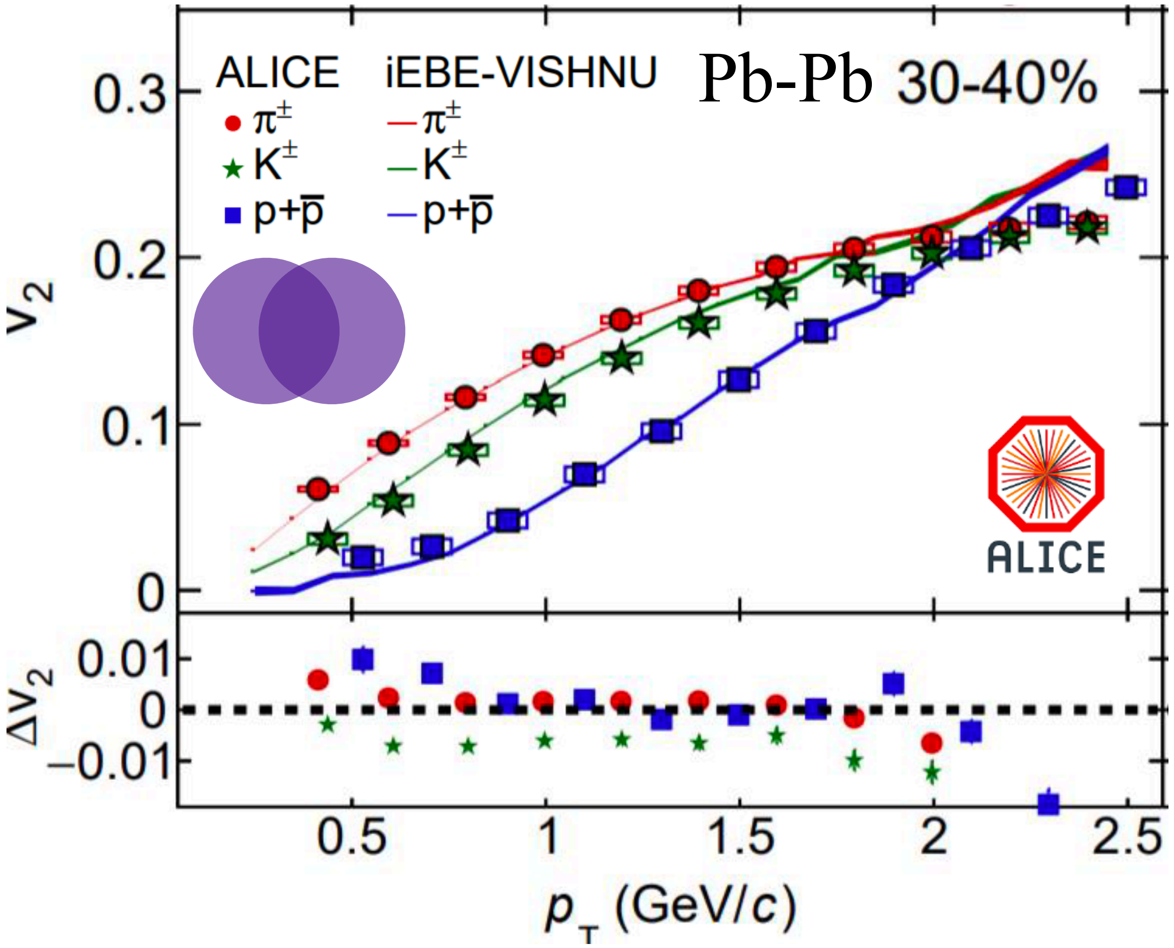
- Elliptic flow: $v_2 > 0$: collective expansion

- Higher harmonics: due to fluctuations in the initial state



Harmonics in HICs





Relativistic hydrodynamics

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

Input: EoS from Lattice

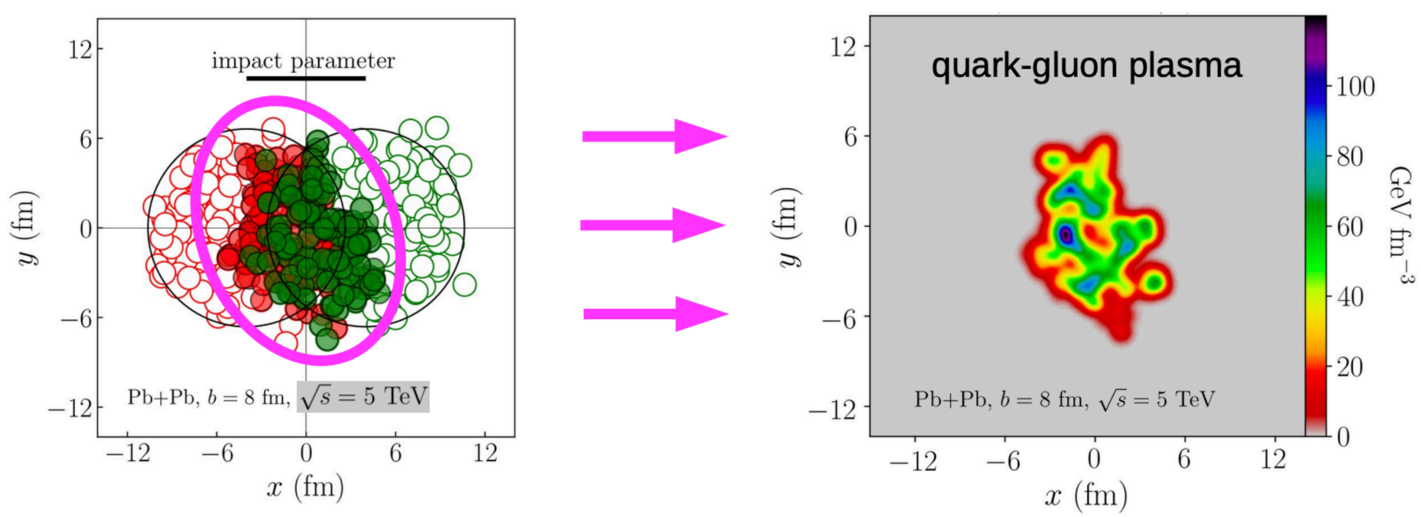
Output: extracted from data

$$T_{\mu\nu} = \varepsilon\, u_\mu u_\nu + p[\varepsilon]\Delta_{\mu\nu} - \eta[\varepsilon]\,\sigma_{\mu\nu} - \zeta[\varepsilon]\Delta_{\mu\nu}\nabla_\mu u^\mu + \mathcal{O}$$

$$\sigma_{\mu\nu} = \Delta_{\mu\alpha}\Delta_{\nu\beta}(\nabla^\alpha u^\beta + \nabla^\beta u^\alpha) - \frac{2}{3}\Delta_{\mu\nu}\Delta_{\alpha\beta}\nabla^\alpha u^\beta,$$

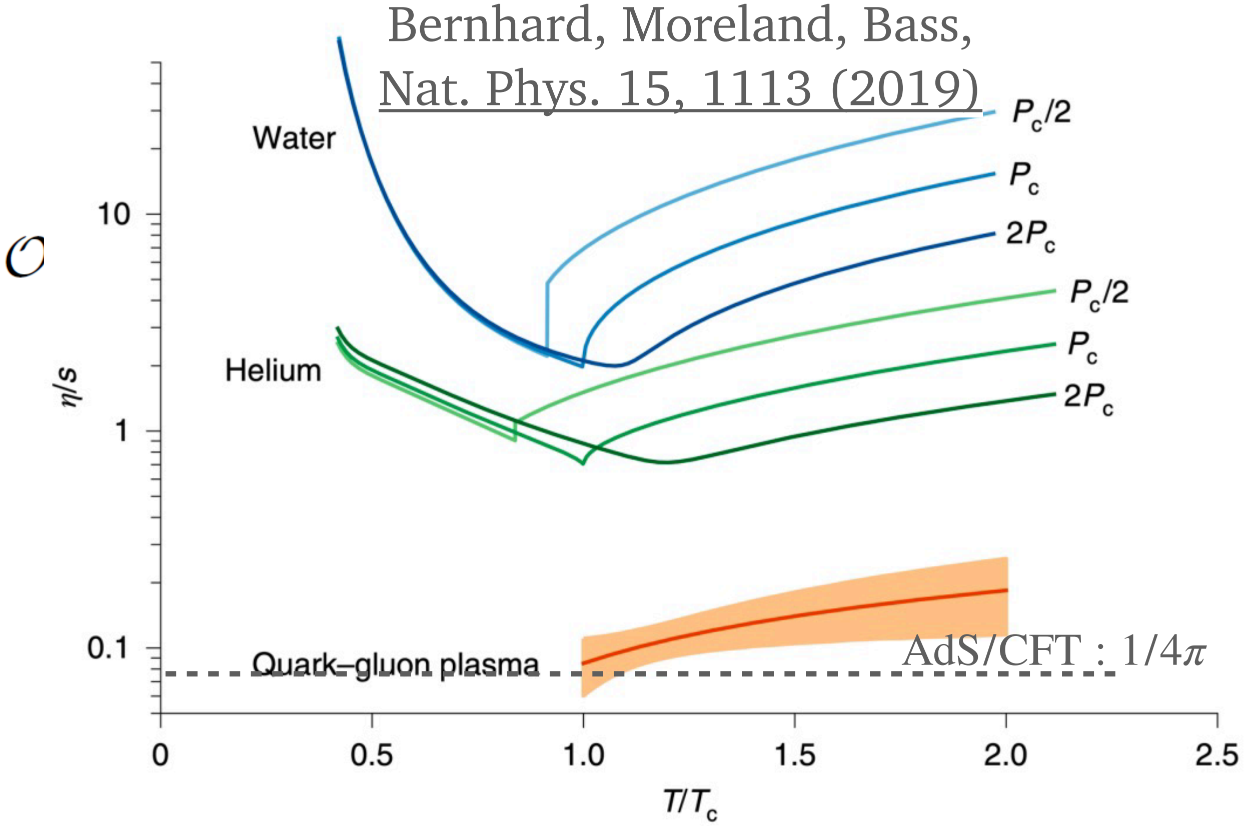
$$\Delta_{\mu\nu} = g_{\mu\nu} + u_\mu u_\nu,$$

+ initial condition



Global fits

Bernhard, Moreland, Bass, Nat. Phys. 15, 1113 (2019)



See also:

Schenke, Shen, Tribedy, Phys. Rev. C 102 (2020) 044905

JETSCAPE,s Phys. Rev. C 103 (2021) 054904

Nijs, van der Schee, Gürsoy, Snellings, Phys. Rev. C 103 (2021) 054909

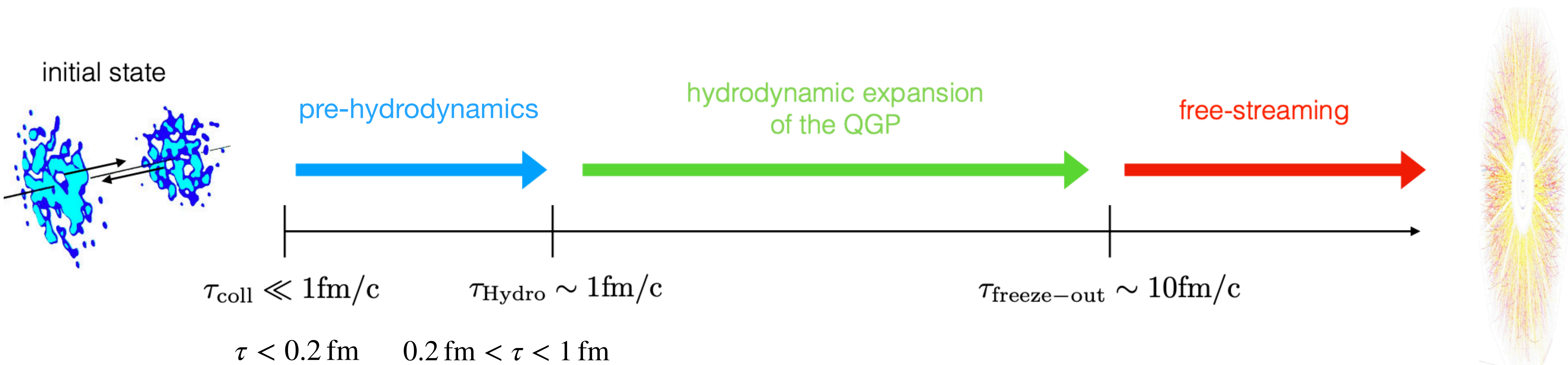
Very small η/s: **most perfect** fluid in Nature

Current focus: increasing precision, reducing systematics, accessing new properties

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



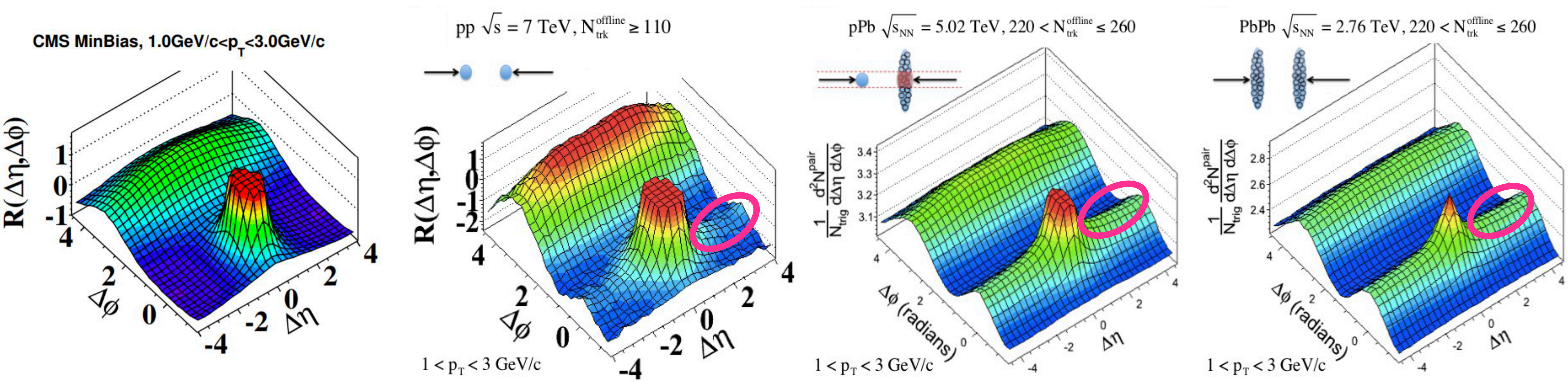
$\tau < 0.2$ fm
Strong QCD fields
CGC

$0.2 \text{ fm} < \tau < 1$ fm
Quasiparticles
EKT

[Courtesy of S. Schlichting]

- Significant **progress** on understanding kinetic & chemical **equilibration** and incipient phenomenology in the pre-hydrodynamics stages

Collectivity in small systems

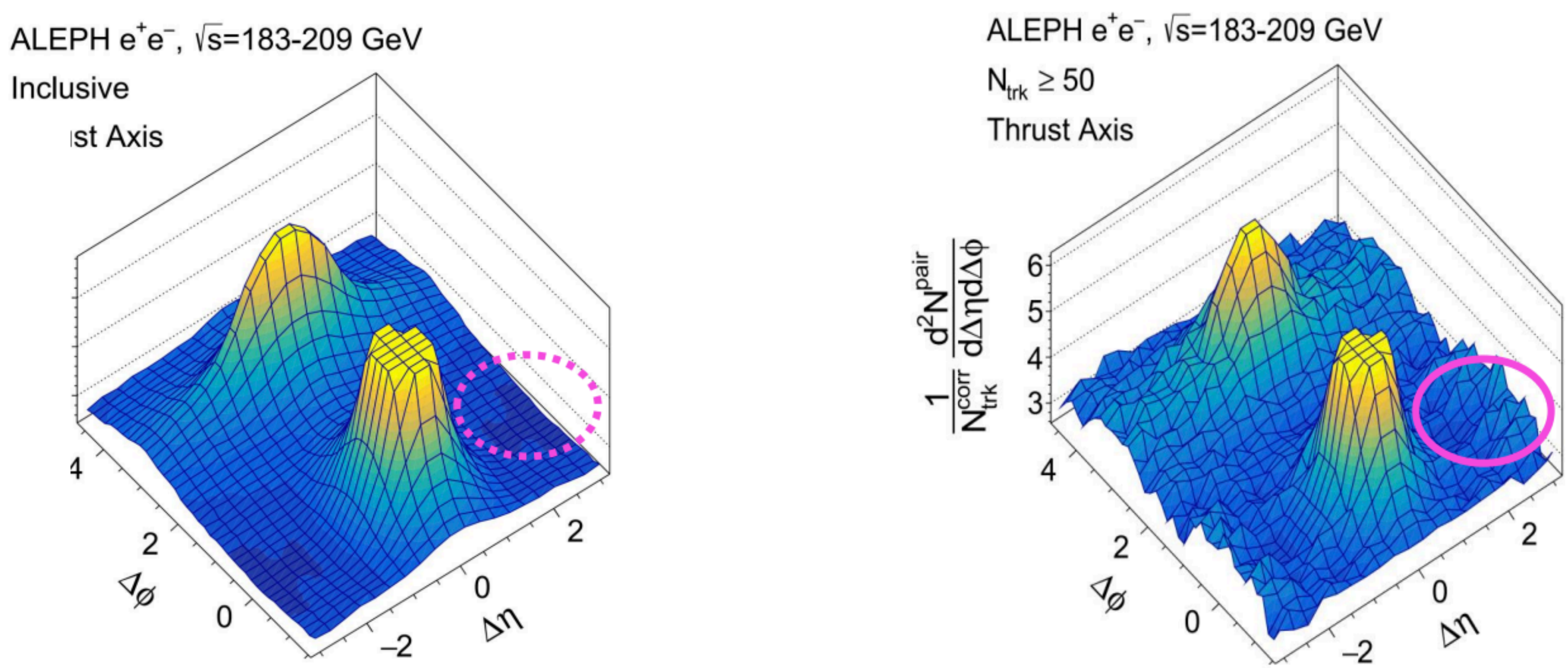


CMS, JHEP 09 (2010) 091
[1146 citations!]

- Near-side ridge observed in p-Pb and d-Au by all RHIC and LHC experiments
- Hydro simulations able to describe the harmonics from these data
- The origin **may not necessary be hydrodynamics** (pre-equilibrium effects?)

Collectivity in small systems

Re-analysis of ALEPH LEP2 data

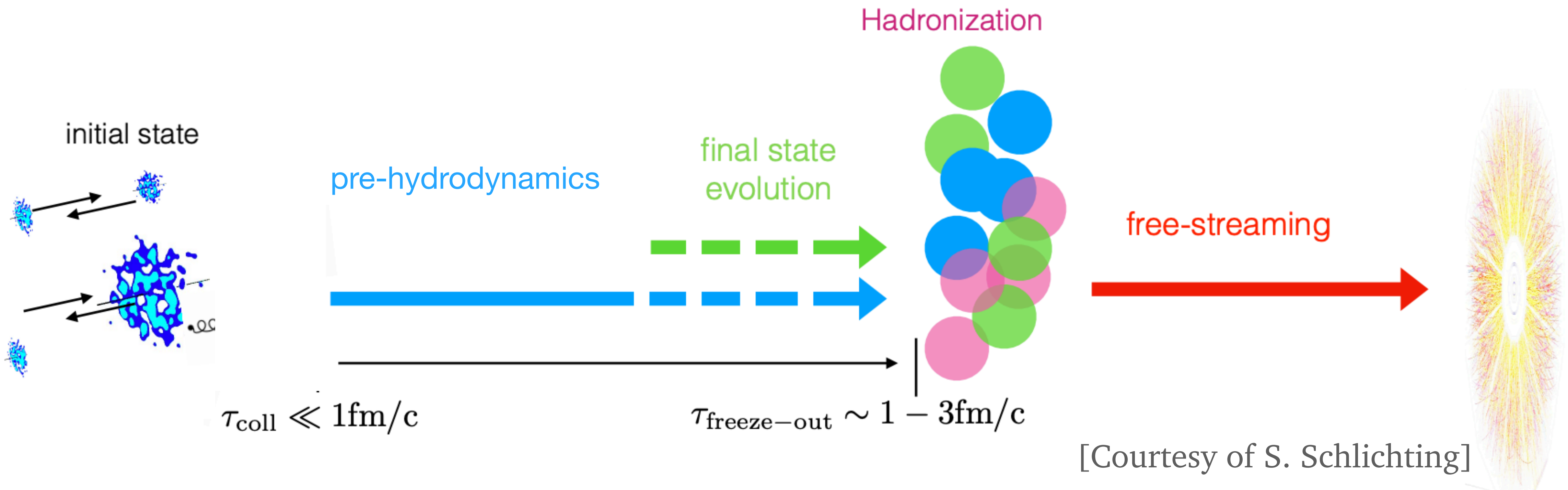


Chen Lee, Chen, Chang, McGinn, Sheng, Innocenti, Maggi,
arXiv.2309.09874

Data suggest that small systems lacking hadronic initial state effects could still yield a ridge-like signal

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

- No jet quenching found in small systems!

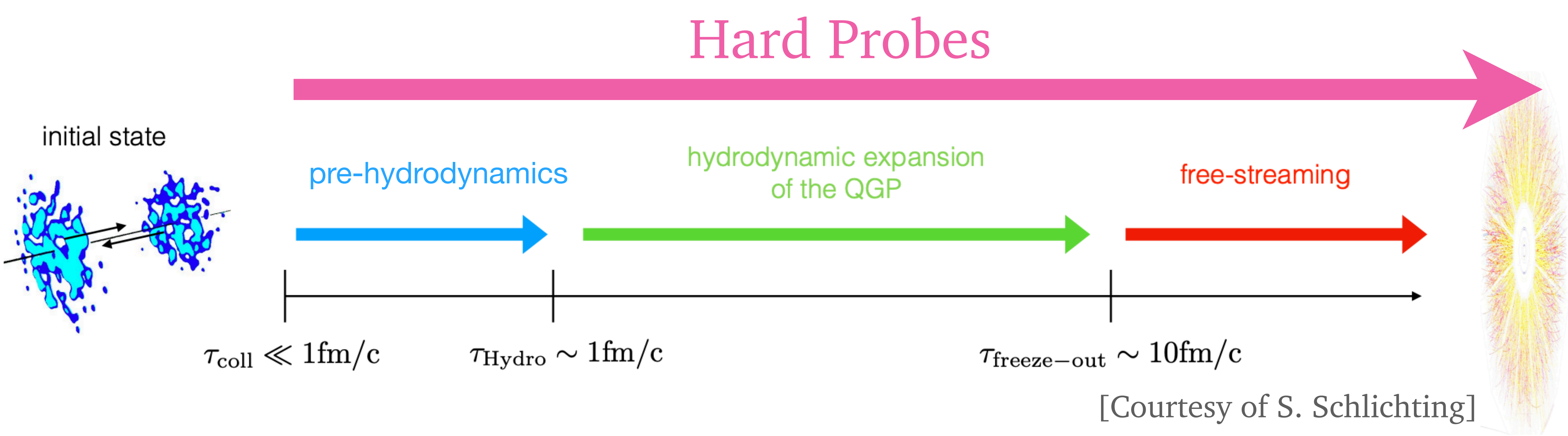
Hard probes

- Hard probes ($Q \sim p_{\rm T}, M_{\rm Q}$) are **produced** in the **initial hard scattering**

$$\tau_{\rm p} \sim \frac{1}{Q} \ll \frac{1}{Q_s} \ll \tau_{\rm hydro}$$

- $Q \gg \Lambda_{\rm QCD}$: their production is perturbative

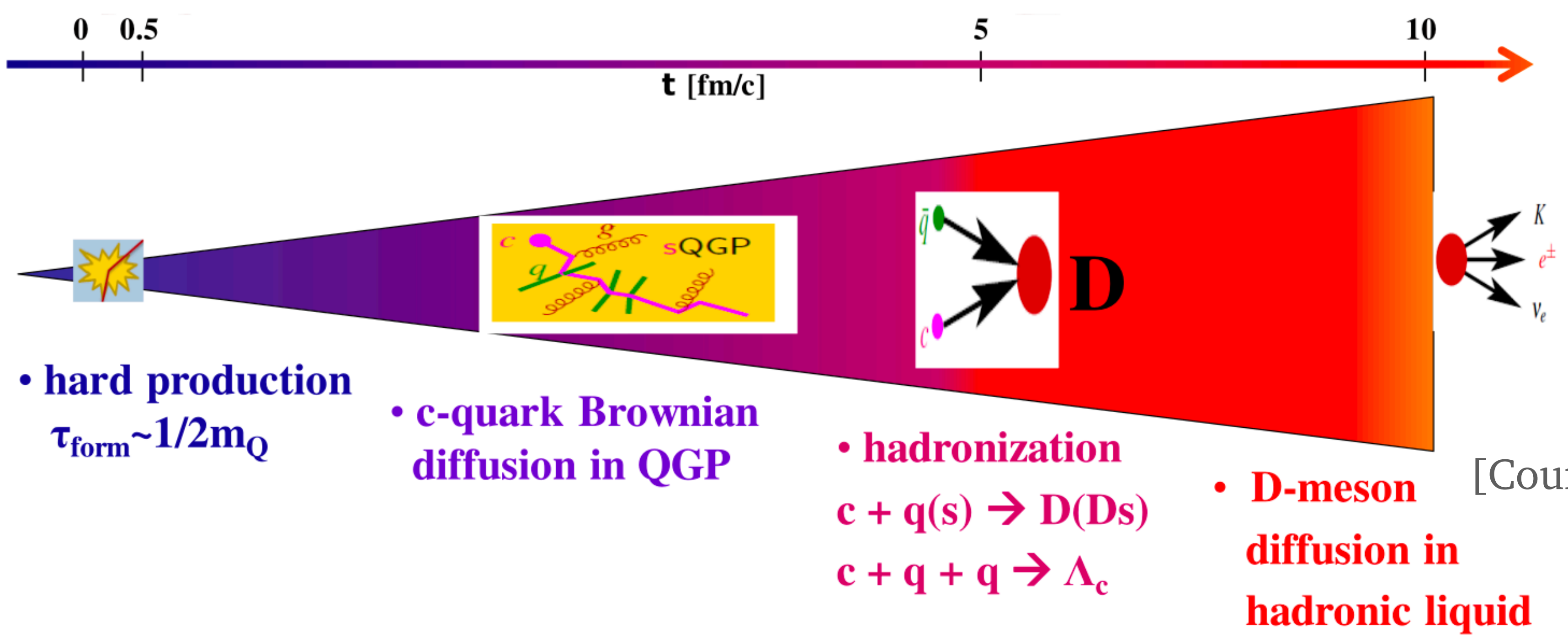
- $Q \gg T$: their production is not affected by the medium



[Courtesy of S. Schlichting]

Open heavy flavor

- Hadrons that carry one charm or beauty quark
- At low p_T: **Brownian motion** due to kicks with the medium constituents



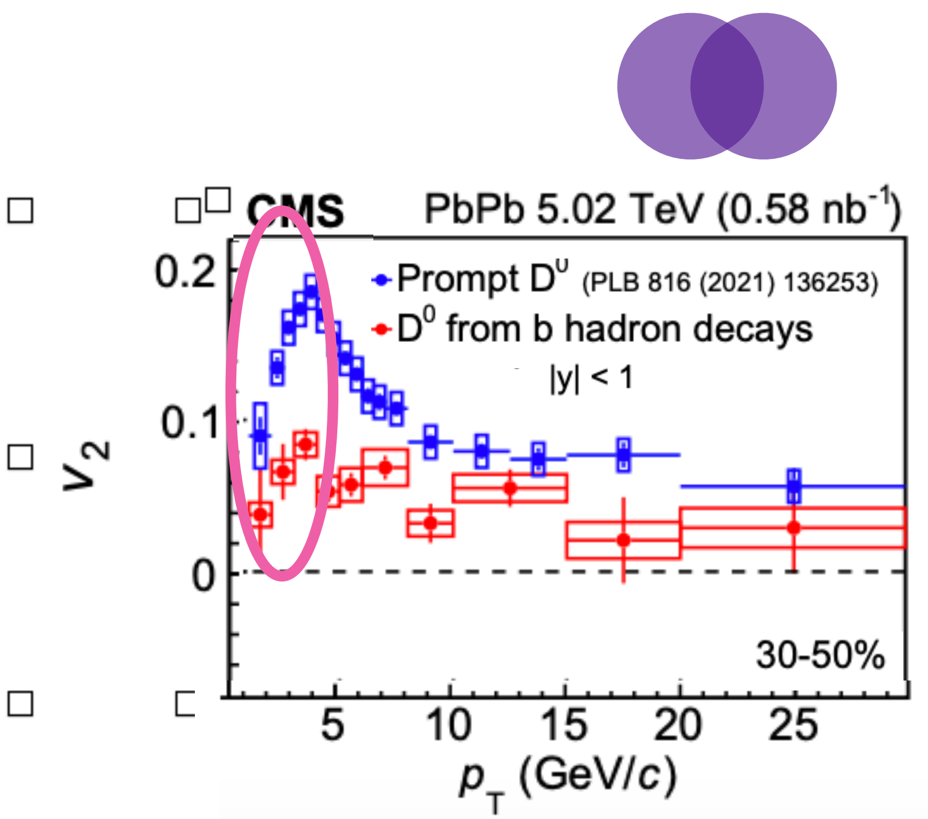
[Courtesy of Min He]

- Flavor preserved — they can be tagged

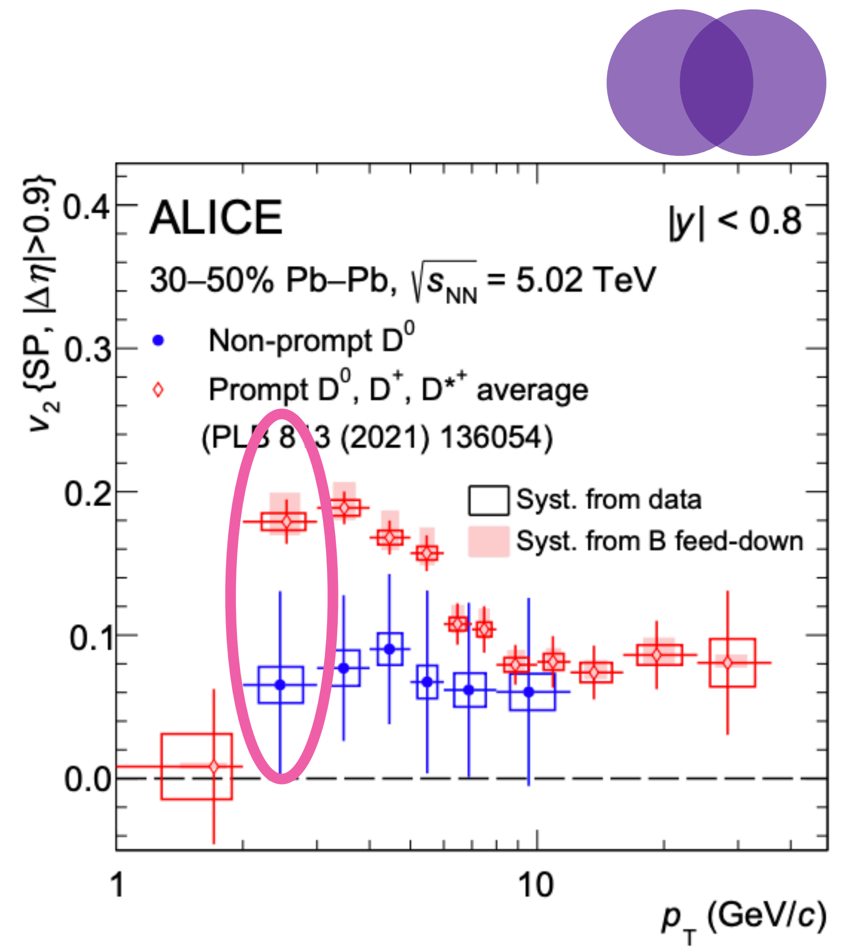
Focus on understanding **heavy quark co-flow with the medium**

Open heavy flavor

- Due to their large mass, they need to experience many kicks to flow with the QGP bulk



CMS Collaboration, arXiv:2212.01636

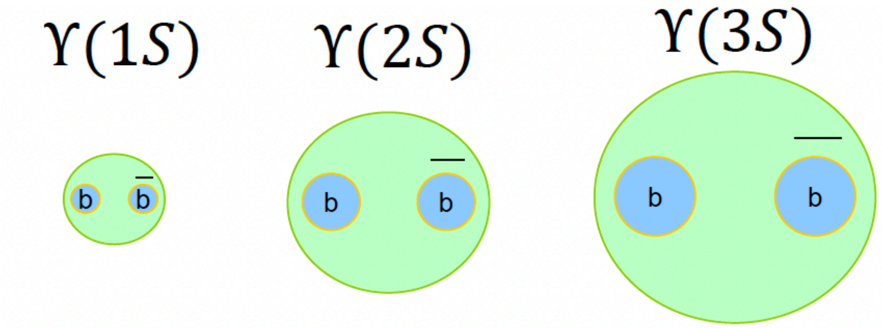


ALICE Collaboration, arXiv:2307.14084

- Charm quark flows

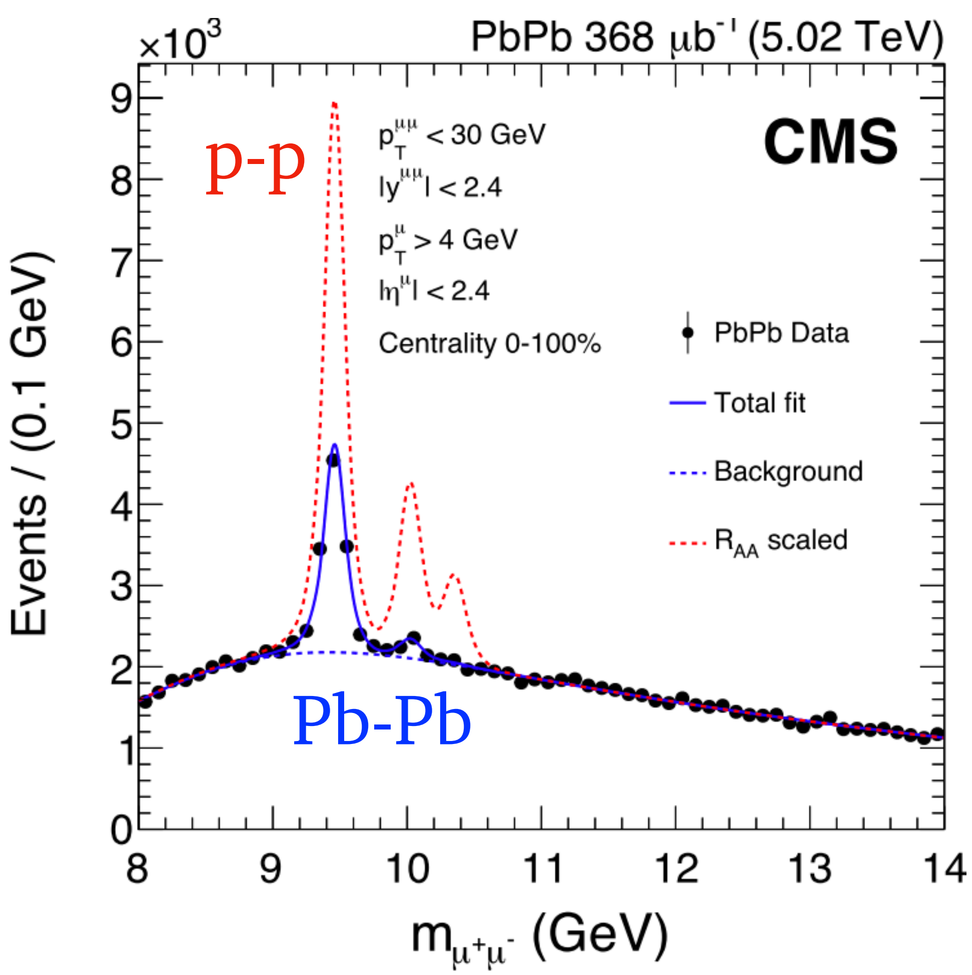
- **Possible flow of beauty** quark in the QGP?

Quarkonia

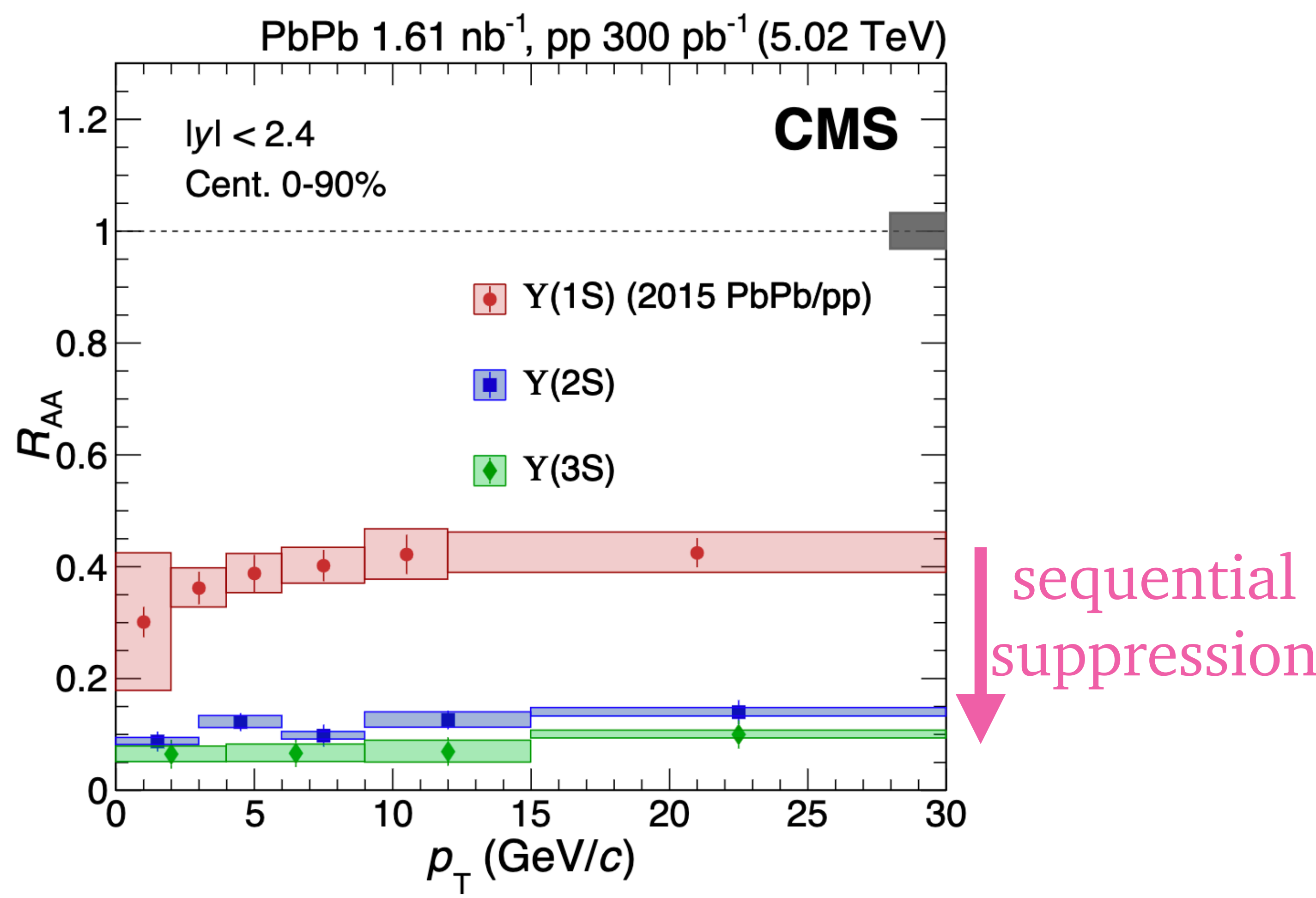


- **Sequential suppression of bottomonia**: less tightly bound states are more suppressed

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

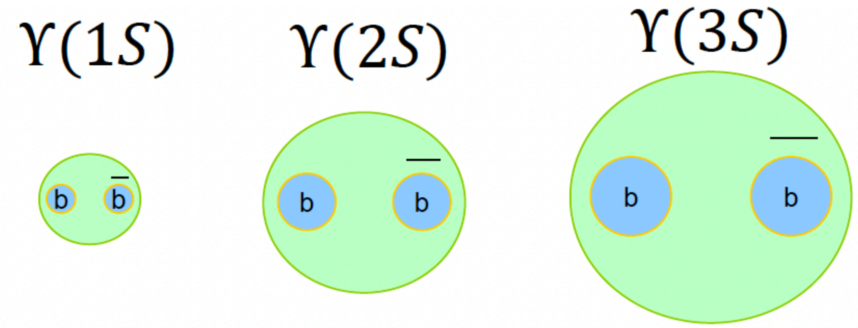


CMS, Phys Lett. B 790 (2019) 270



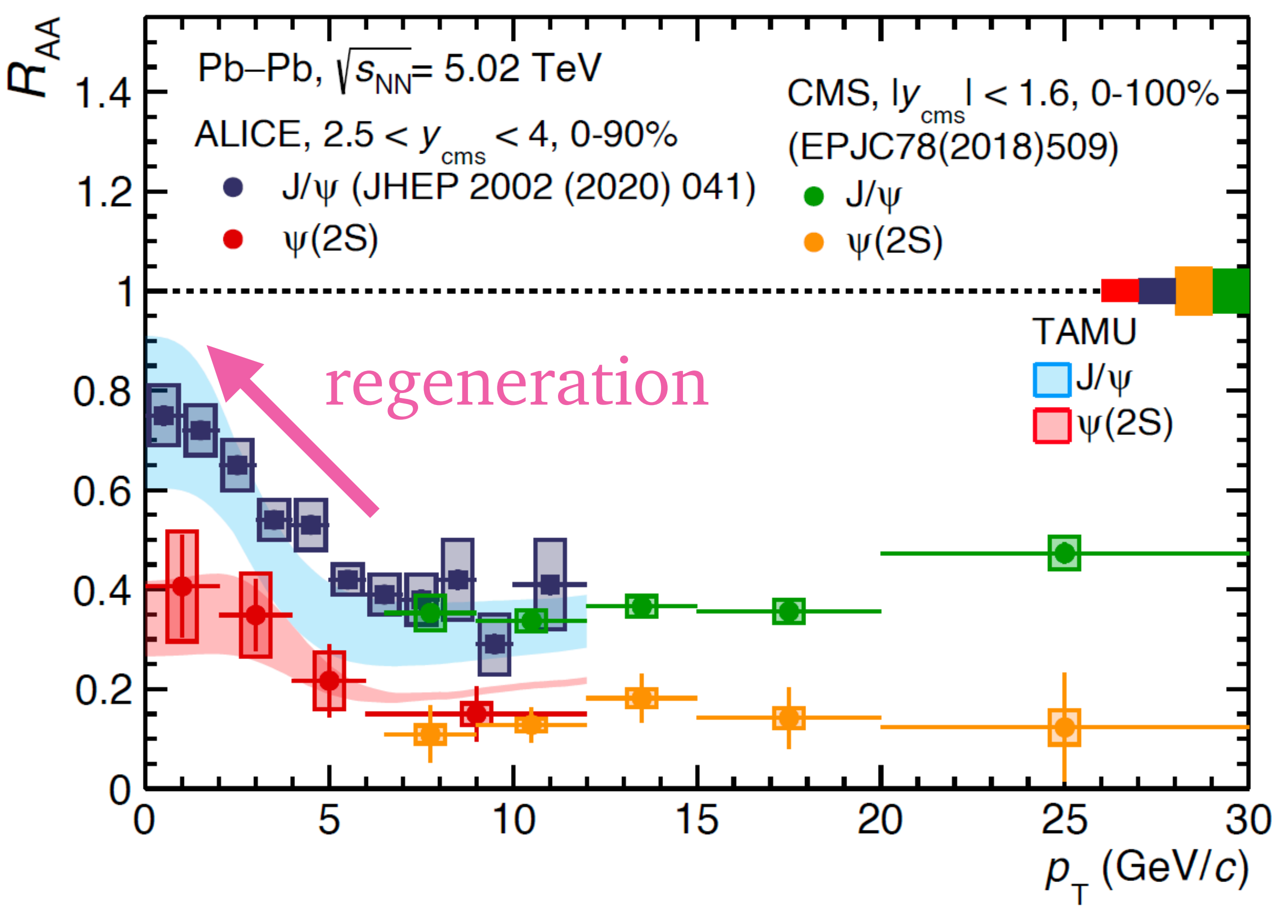
CMS Collaboration, arXiv.2303.17026

Quarkonia

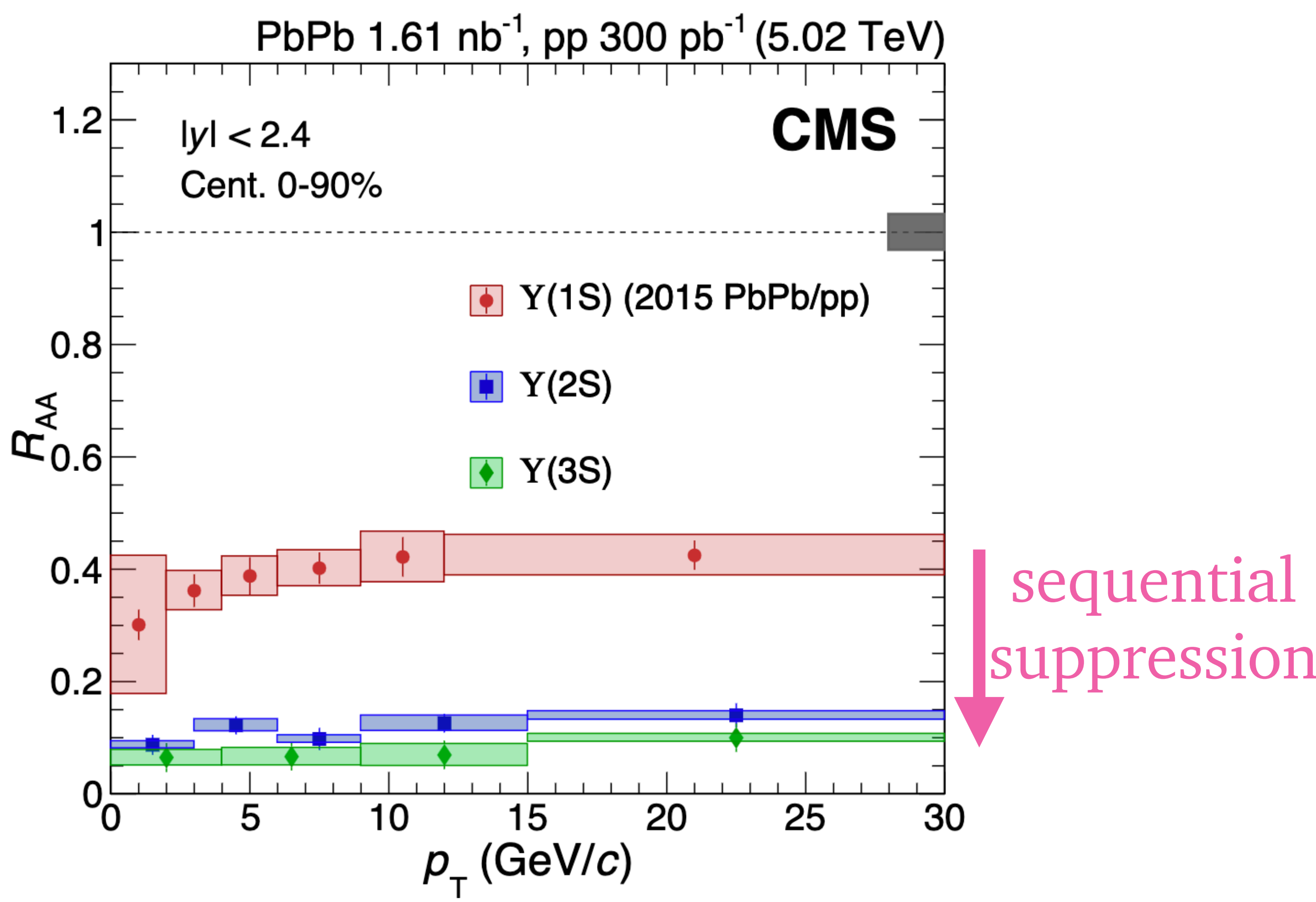


- **Sequential suppression of bottomonia**: less tightly bound states are more suppressed
- Charmonia: sequential suppression + regeneration

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



ALICE Collaboration, arXiv:2210.08893

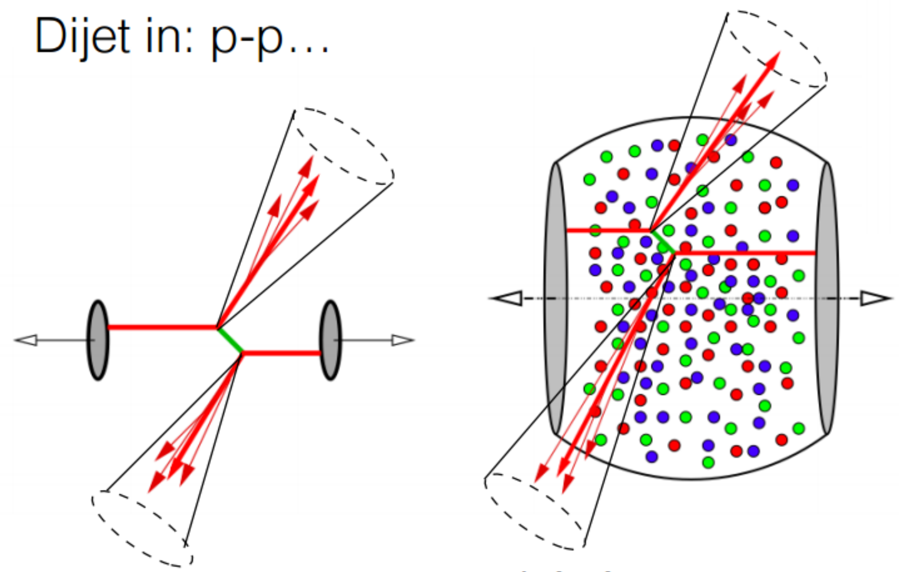


CMS Collaboration, arXiv.2303.17026

Why jets?

- Production of high-energy partons unlikely to interfere with the medium formation

- Sensitive to the QGP dynamics through **jet quenching: jets interact with the QGP getting modified w.r.t p-p jets**
    - In principle: under control in p-p collisions

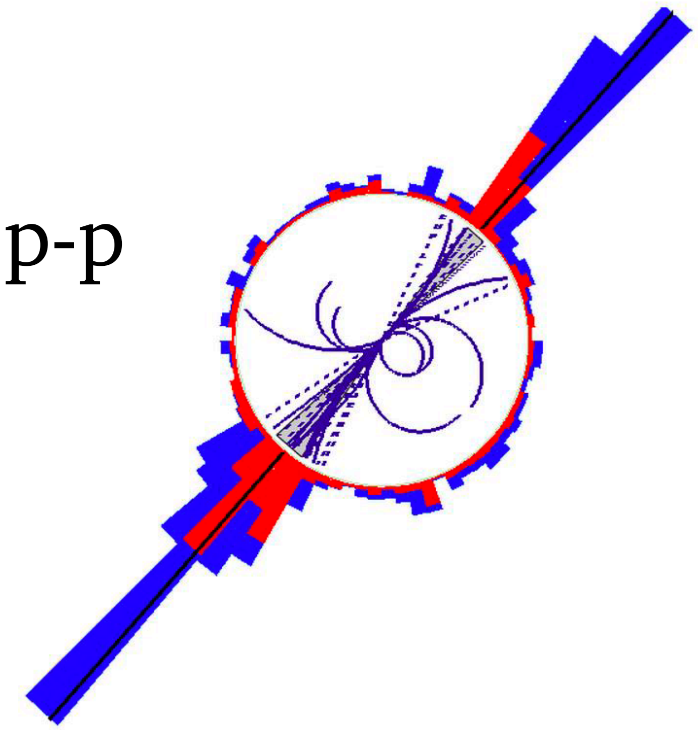


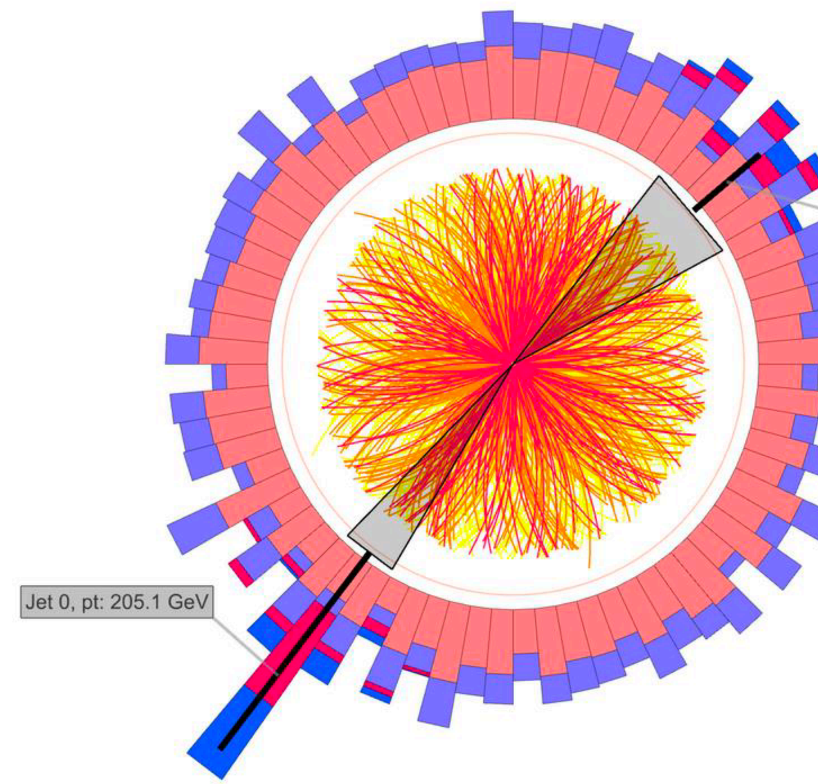
- They witness the full system evolution

- **Multi-scale** objects: access to **different time** and **energy scales**

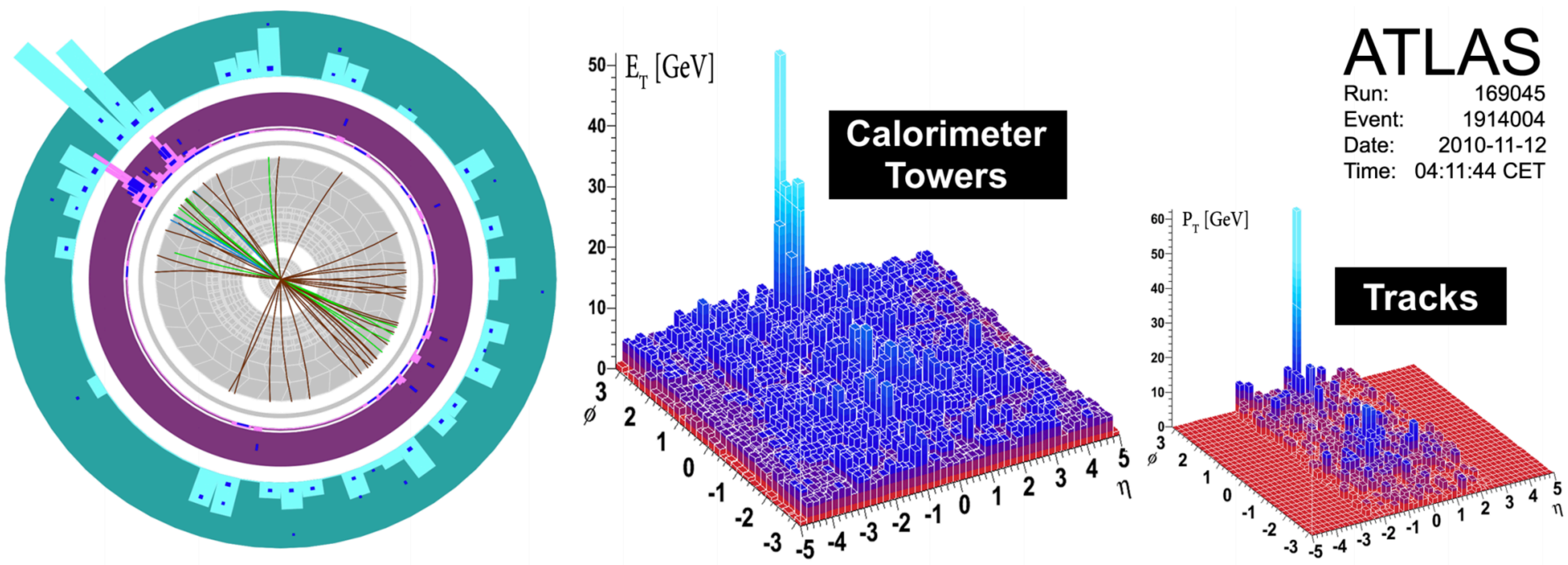
Jet quenching

p-p





Pb-Pb



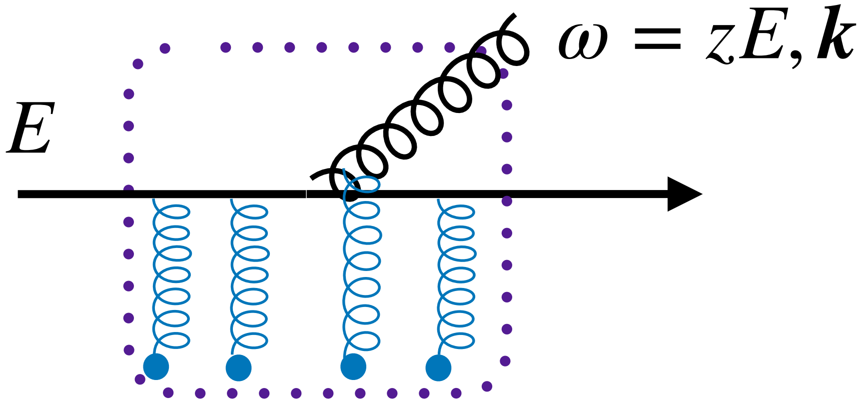
Medium-induced radiation

- The main contribution to energy loss in the QGP is radiative energy loss
  Dominant for light quarks and gluons

High-energy partons experience **multiple scatterings with the medium** which induce **extra gluon radiation** (w.r.t. p-p)

- During the formation time of the gluon **multiple scatterings** act **coherently**

LPM effect $t_f \sim \frac{\omega}{\boldsymbol{k}^2}$



Suppression of the spectrum for **large formation times**

- Resummation of multiple scatterings: **BDMPS-Z formalism (1990's)**

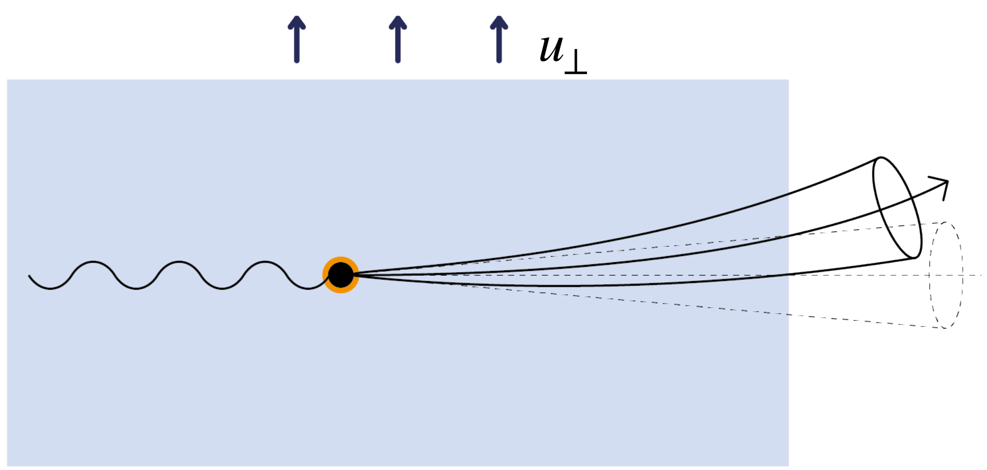
CA, Apolinario, Martinez, Dominguez, JHEP 07 (2020) 114, JHEP 03 (2021) 102

Mehtar-Tani, Barata, JHEP 07 (2019) 057, JHEP 10(2020) 176

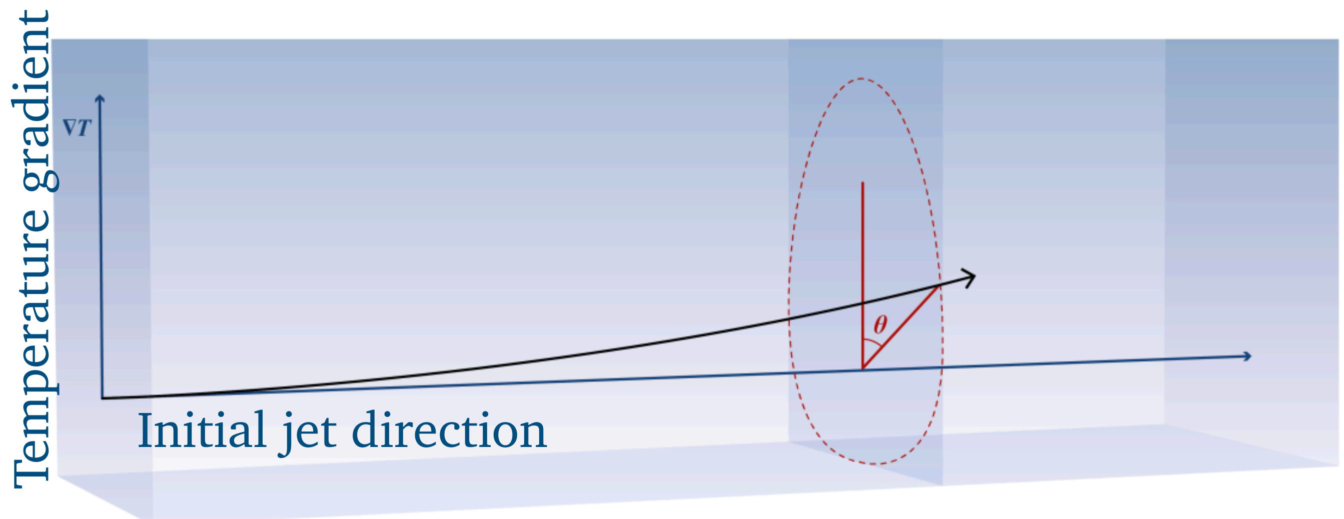
Schlichting, Soudi Phys. Rev. D 105 (2022) 076002

Medium-induced radiation and transverse dynamics

- **Jets decouple** from the medium **transverse** dynamics in the **usual** (*eikonal*) **medium-induced approaches**



Uniform transverse flow



Transverse temperature gradients

- Need of **generalizing** the medium-induced formalisms to account for $\mathcal{O}(1/\omega)$ *(subeikonal)* terms

Sadofyev, Sievert, Vitev, 2104.09513

CA, Dominguez, Sadofyev, Salgado, 2207.07141

Barata, Sadofyev, Wang 2210.06519

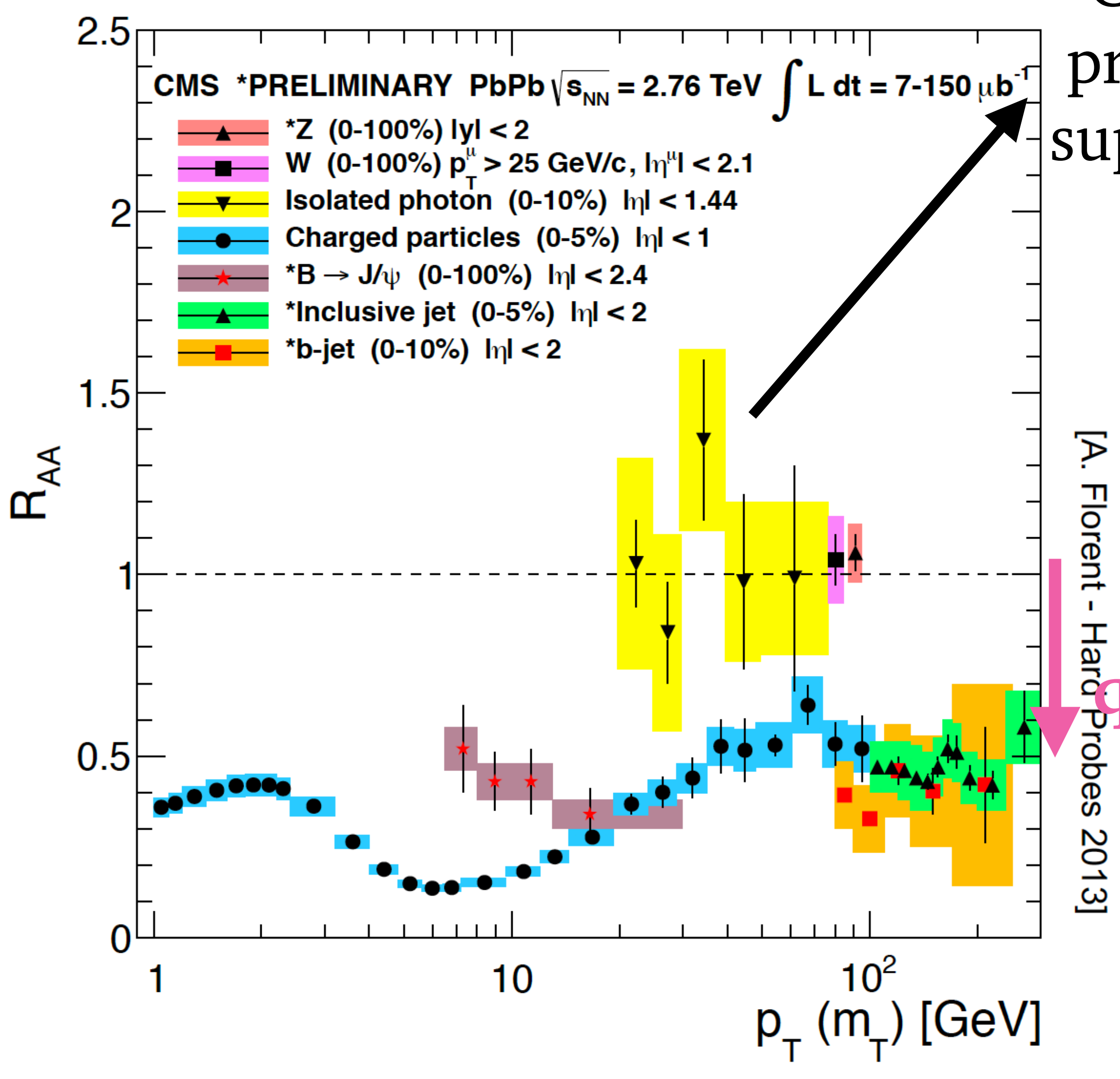
Barata, Mayo López, Sadofyev, Salgado, 2304.03712

Kuzmin, Mayo López, and Reiten, and Sadofyev, 2309.00683

Jet quenching

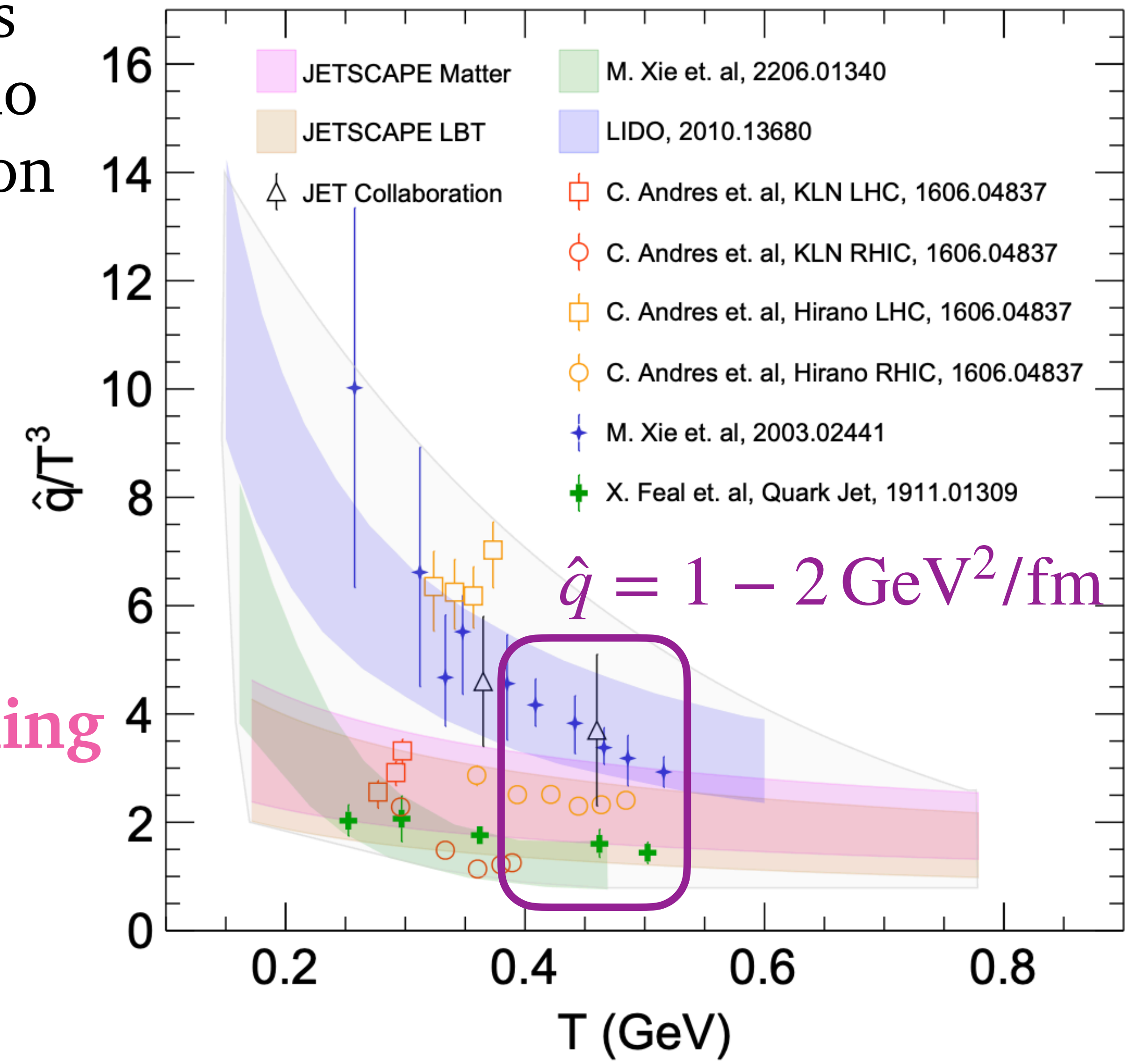
- Traditionally, jet quenching aims at extracting **properties of the QGP**
- $\hat{q}$: average transverse momentum transfer per unit length

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



Colorless probes: no suppression

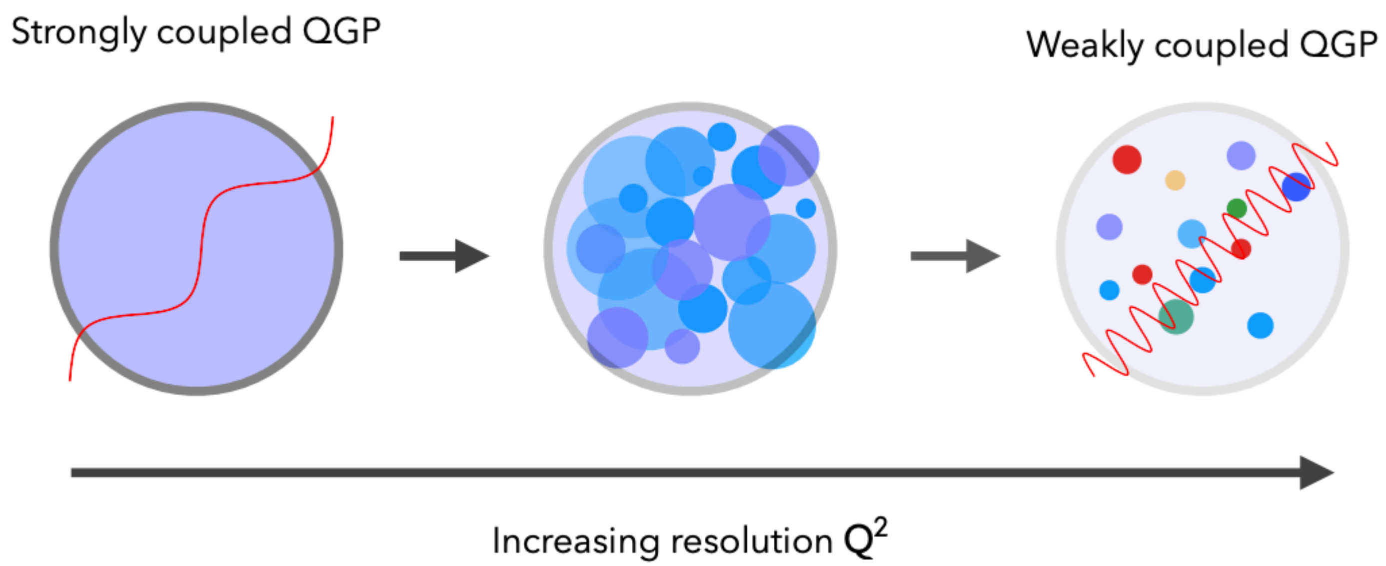
Jet quenching

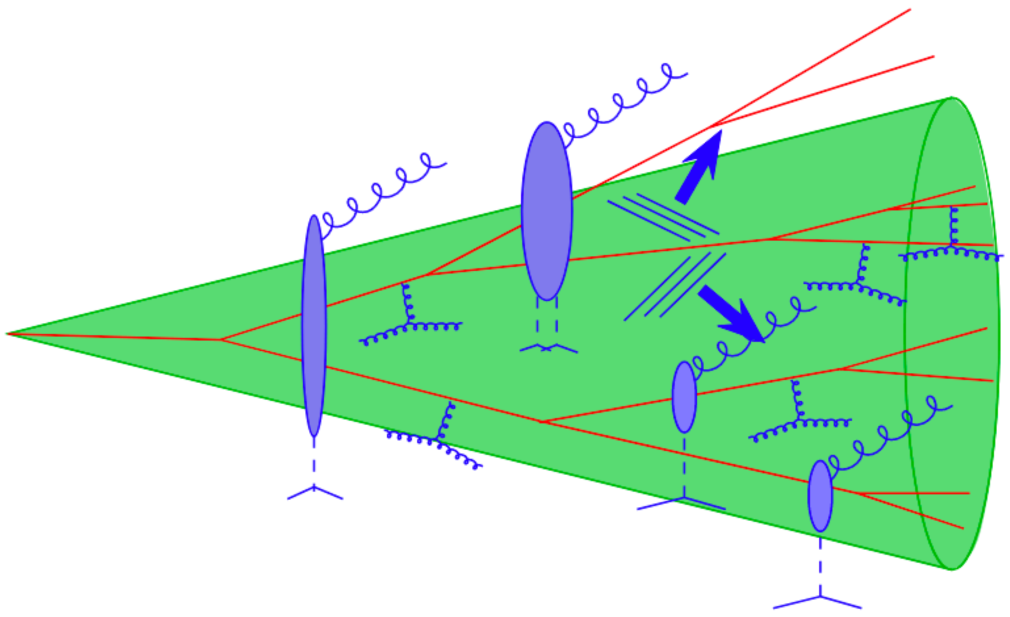


Apolinario, Lee, Winn, 2203.16352

Jet substructure

How does a **strongly-coupled fluid** emerge from the **weakly-coupled quarks and gluons**?





[Courtesy of K. Zapp]

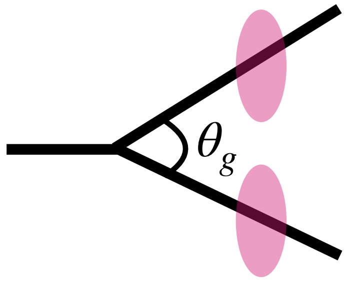
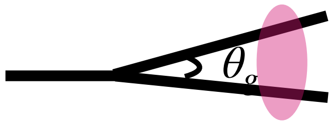
Use **jets' inner structure** to probe the QGP at **various length scales**

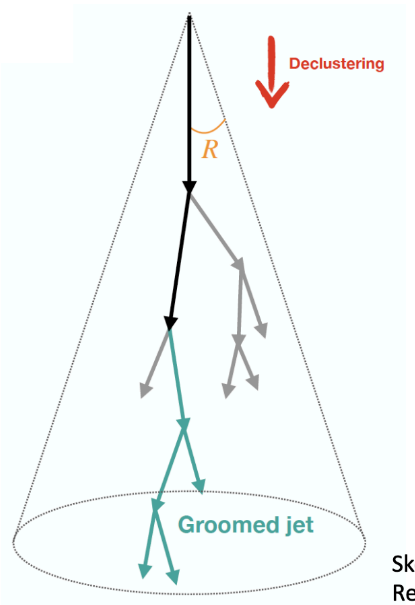
Color coherence

Mehtar-Tani, Salgado, Tywoniuk, Phys. Rev. Lett. 106 (2011) 122002, Phys. Lett B 707 (2012) 156, JHEP 10 (2012) 197

J. Casalderrey-Solana and E. Iancu, JHEP 08 (2011) 015

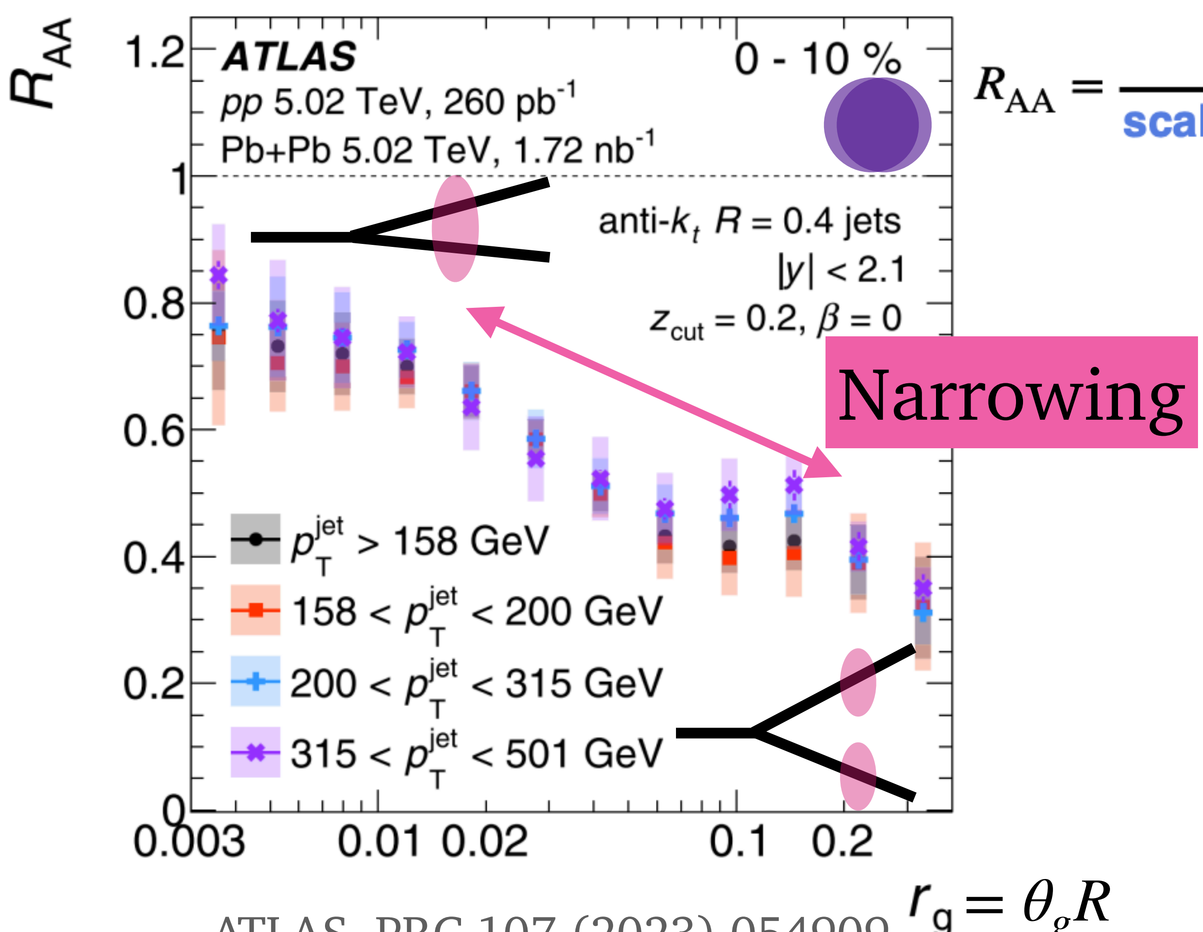
- Splittings with small opening angle cannot be resolved by the medium:

$\theta_g > \theta_c$  $\theta_g < \theta_c$ 



Sketch by Rey Torres

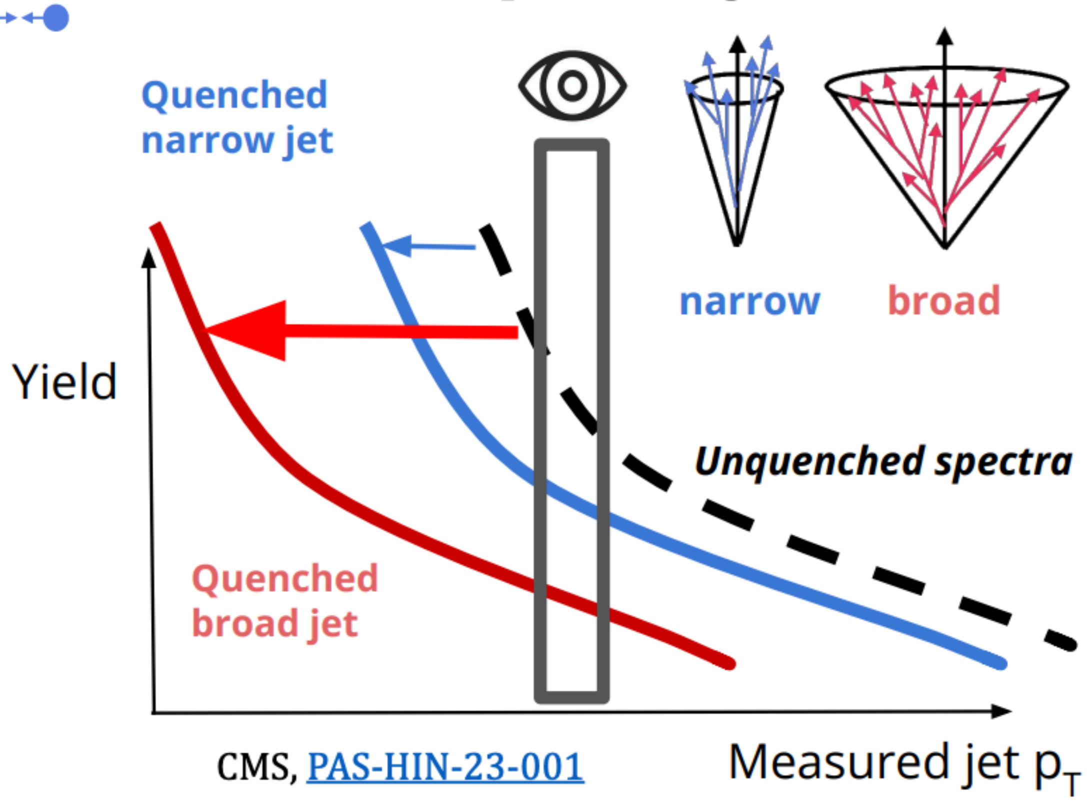
Groomed jet radius



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

ATLAS, PRC 107 (2023) 054909

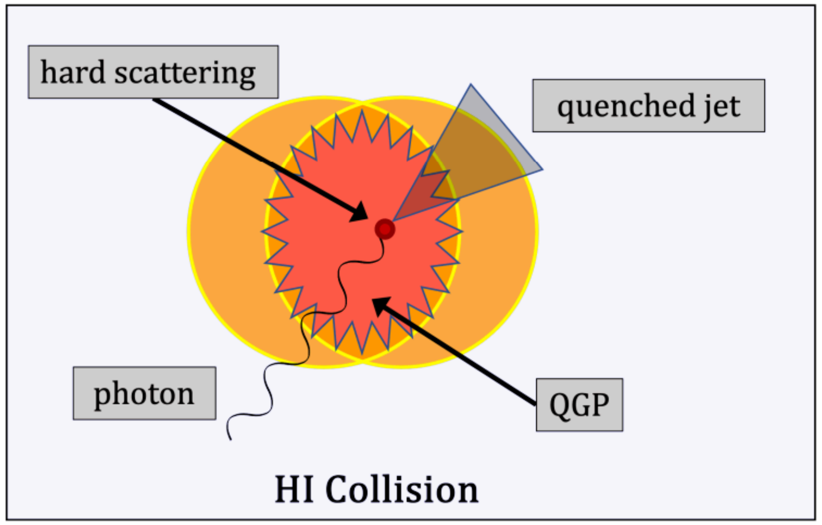
Jet quenching bias



CMS, PAS-HIN-23-001

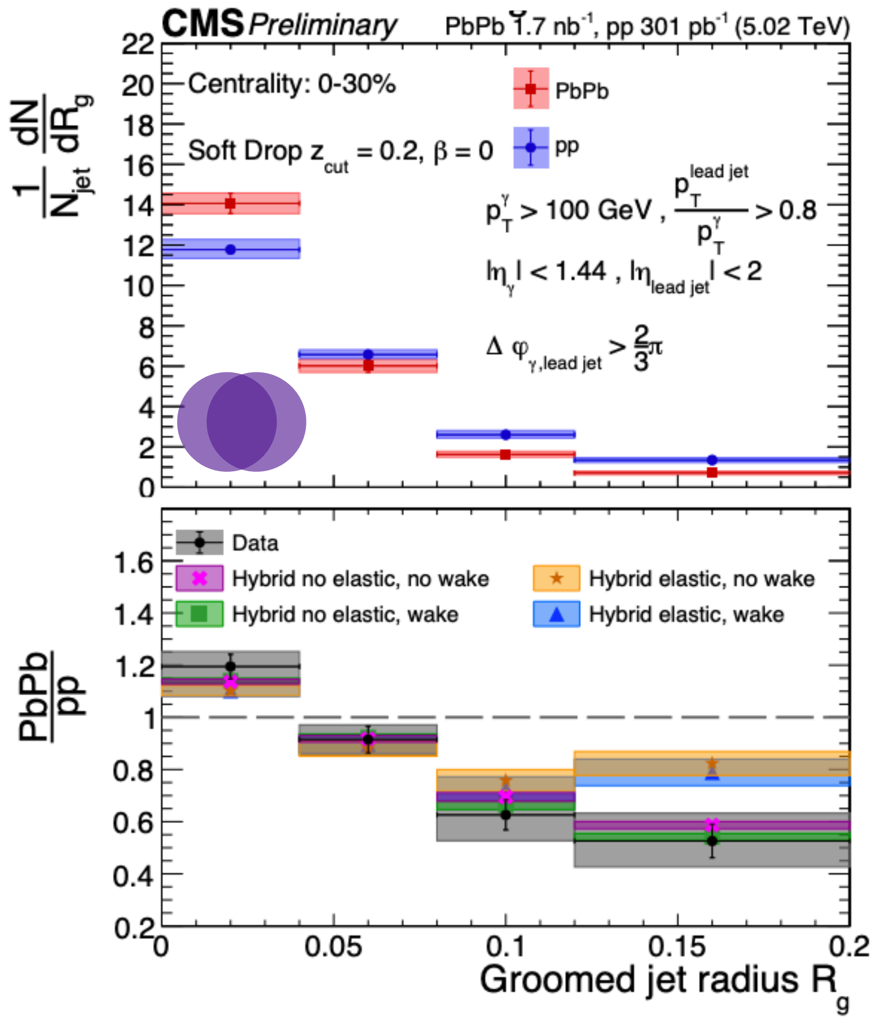
Color coherence

- Use photon-tagged jets



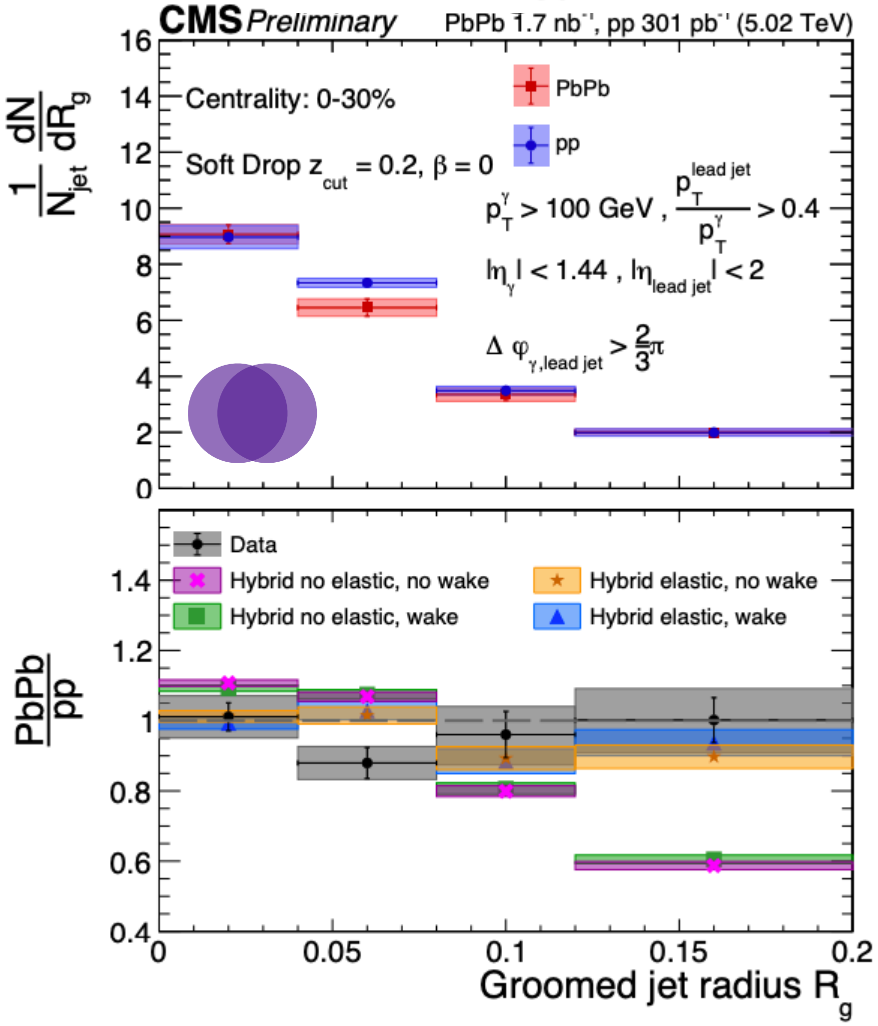
CMS-PAS-HIN-23-001

$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.8$



Less quenched jets
Narrowing

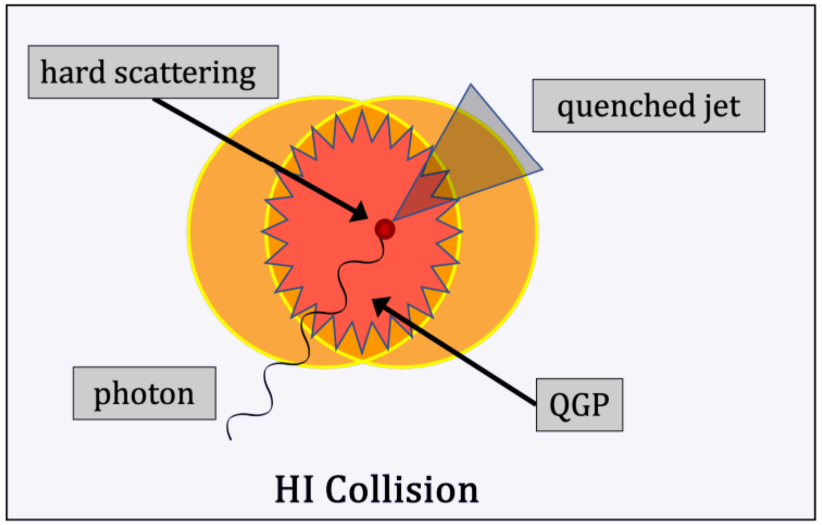
$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.4$



Quenched and unquenched jets
No narrowing

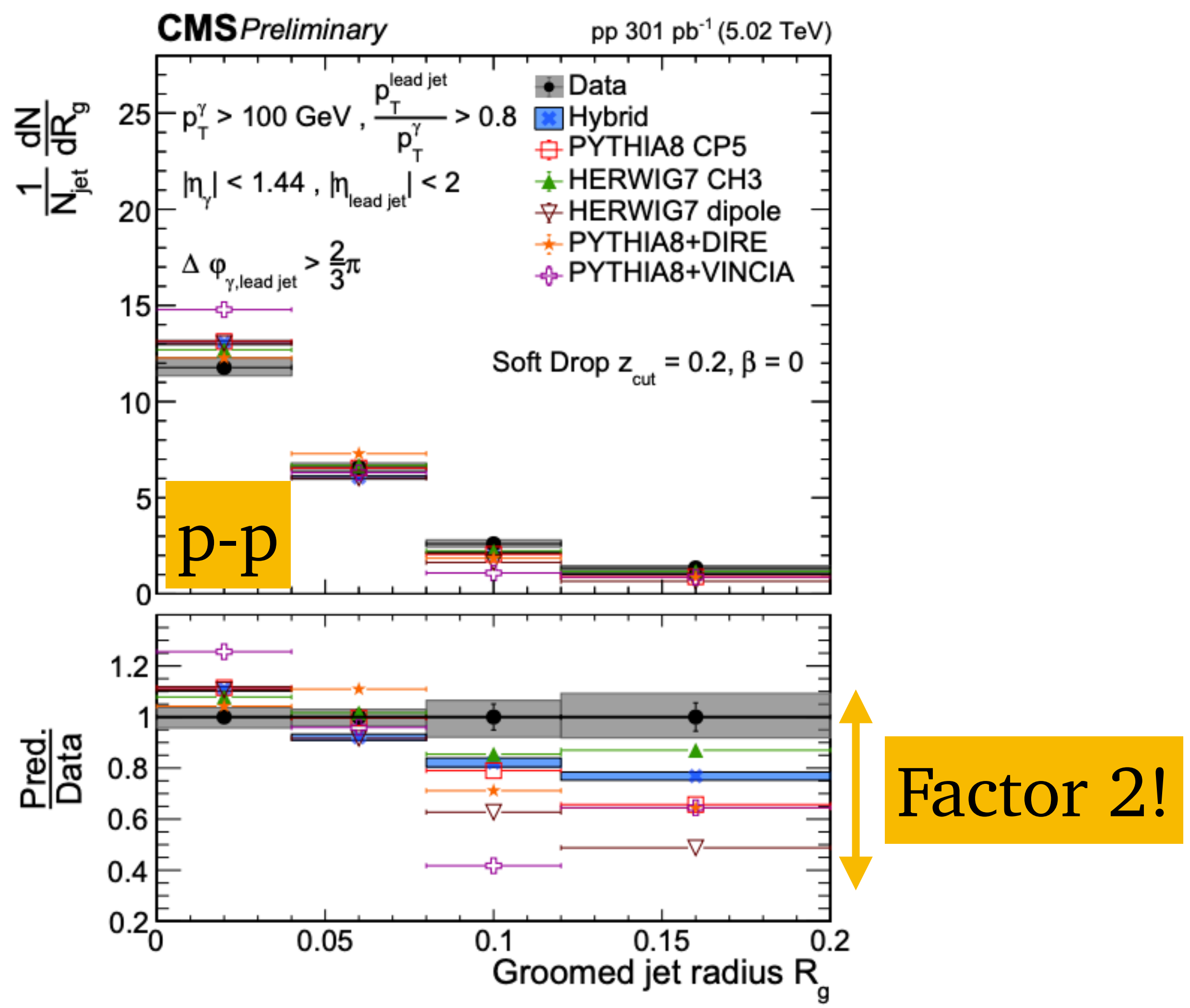
Color coherence

- Use photon-tagged jets



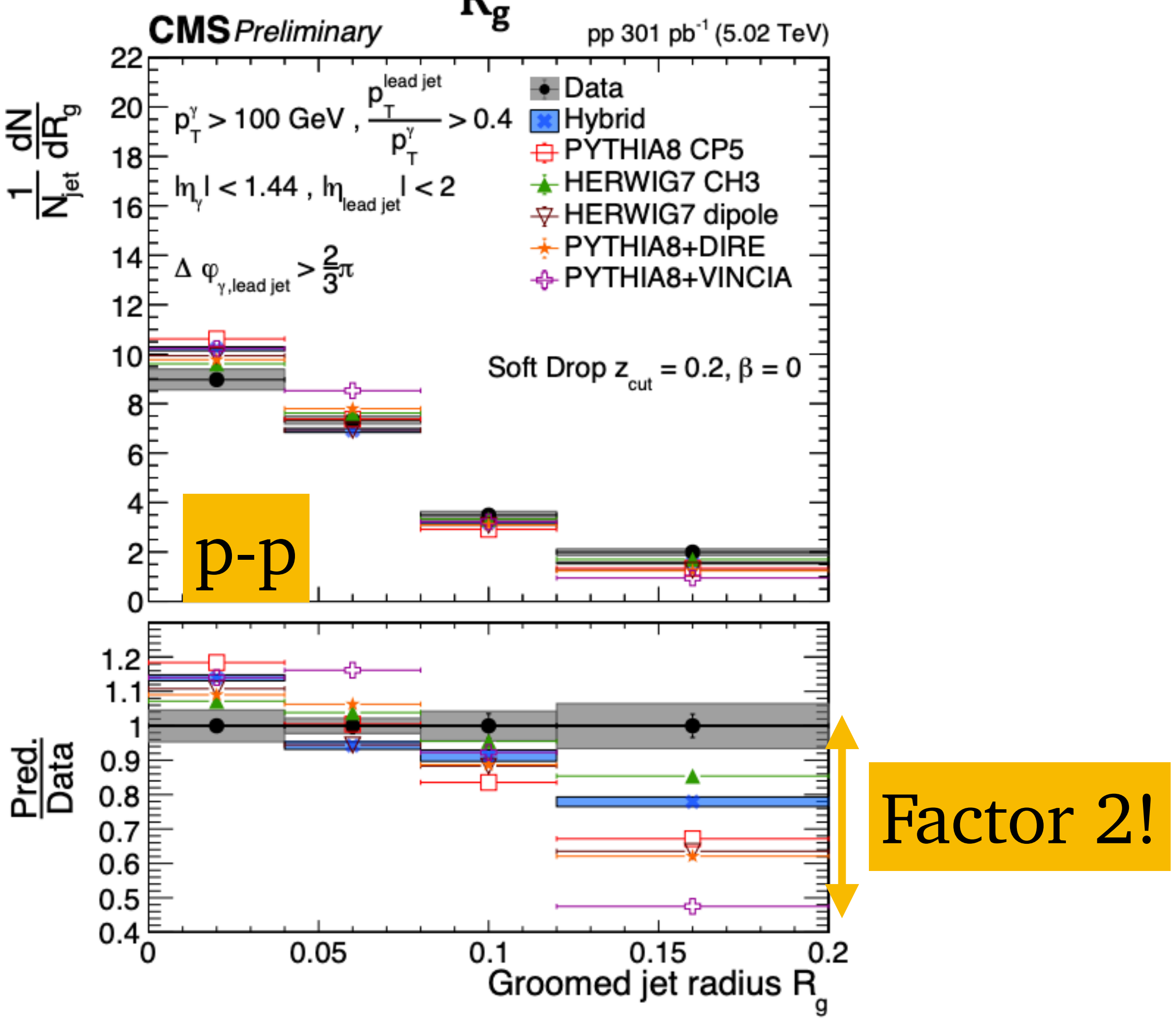
CMS-PAS-HIN-23-001

$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.8$



$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.4$

$\mathbf{R_g}$

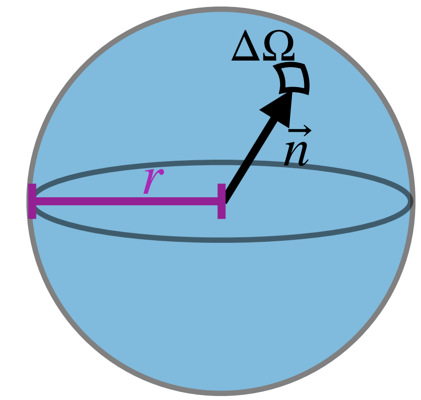


p-p baseline not under control!

New tools: energy correlators

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

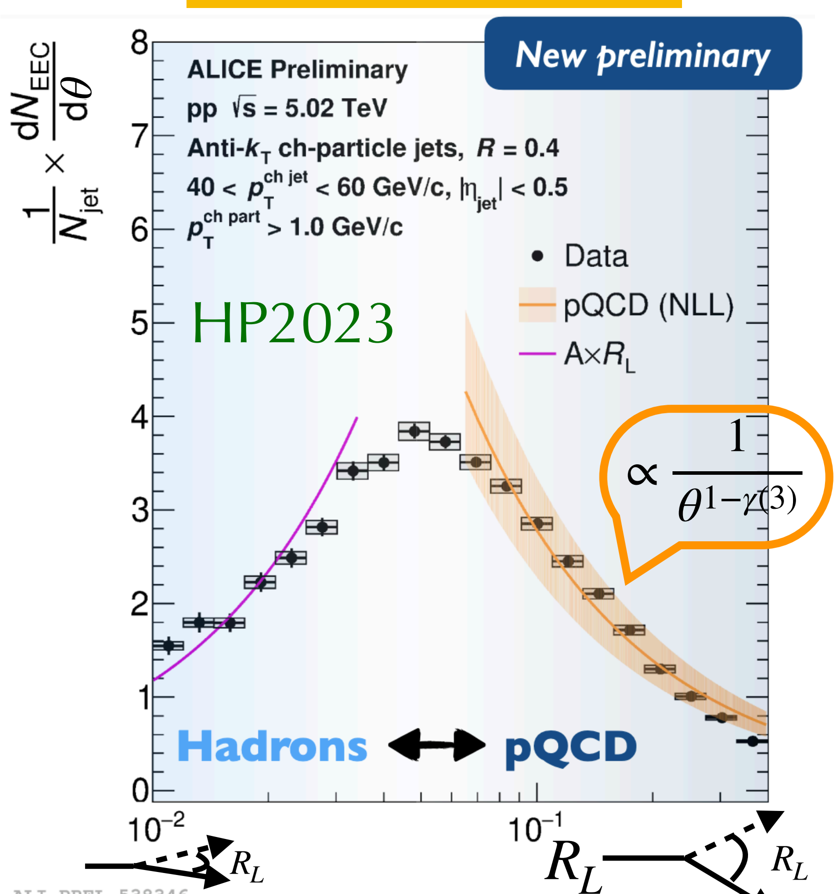
$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty}\int \mathrm{d}t\, r^2 n^i\, T_{0i}(t, r\vec{n})$$

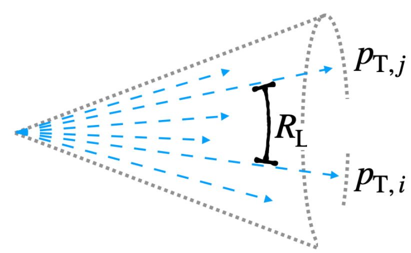


- Substructure without declustering
- Well-controlled p-p baseline (measured this year for the first time)

Komiske, Moult, Thaler, Zhu, Phys. Rev. Lett. 130 (2023) 051901

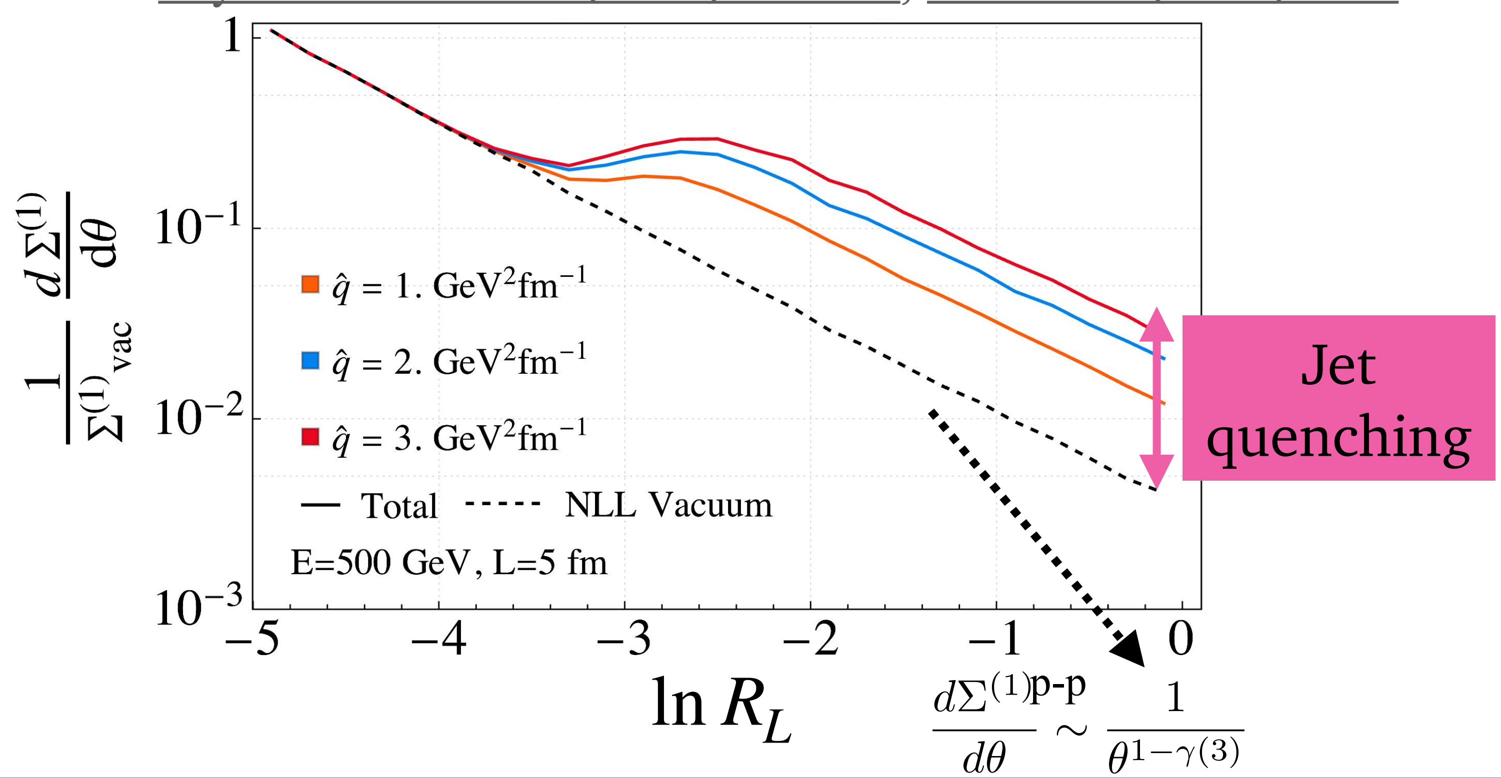
2-point EEC in p-p





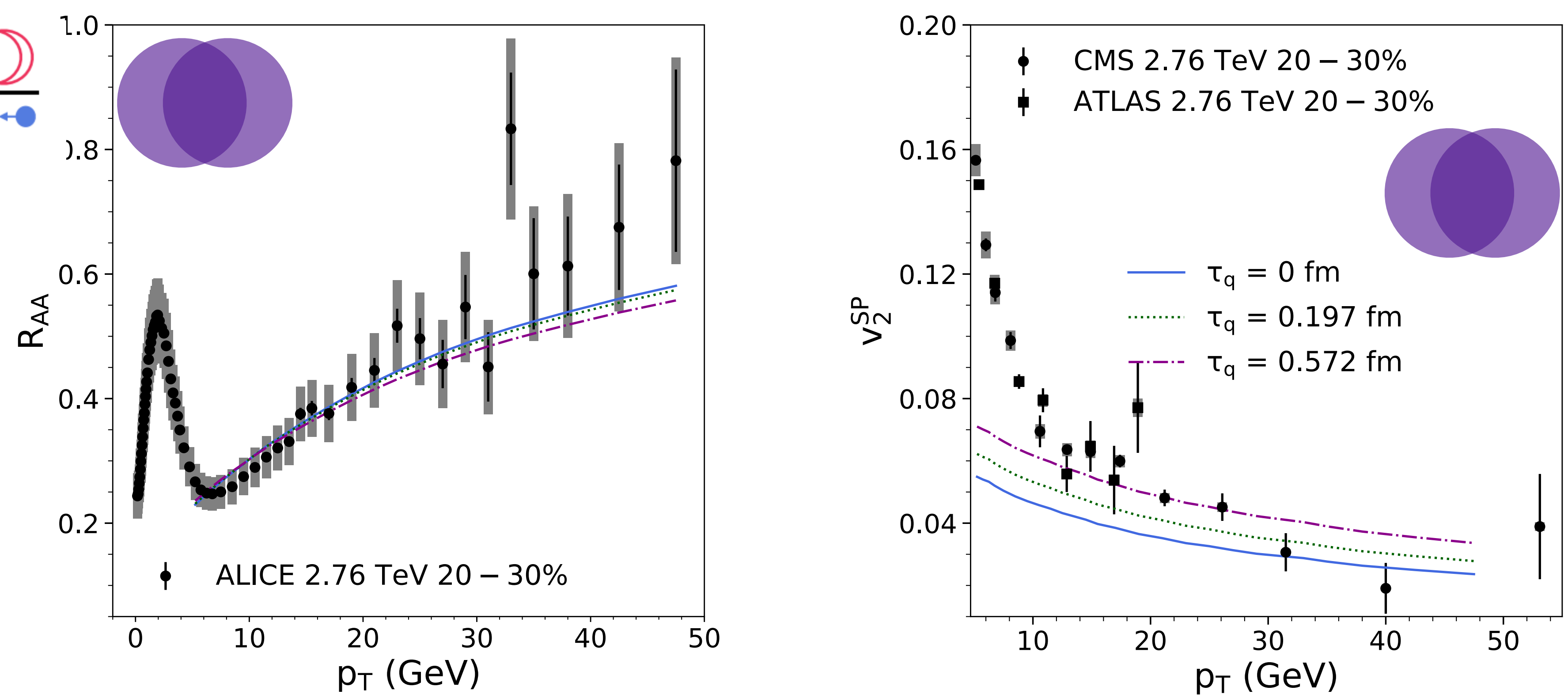
2-point EEC in A-A

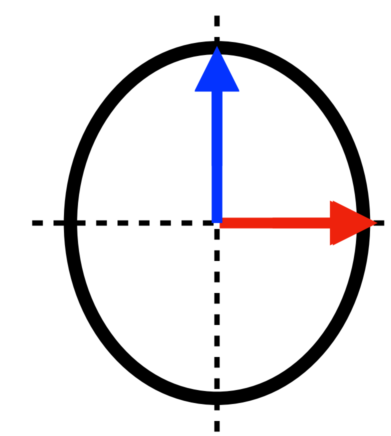
CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, Phys. Rev. Lett. 130 (2023) 262301, JHEP 09 (2023) 088



Jet quenching in the initial stages?

- **Jet quenching not** (yet?) **observed** in **small systems**
- In small systems the **pre-hydrodynamics stages** are specially important
- Jets **sensitive to the pre-hydrodynamics** stages





CA, Armesto, Niemi, Paatelainen, Salgado, Phys. Lett. B 803 (2020) 135318

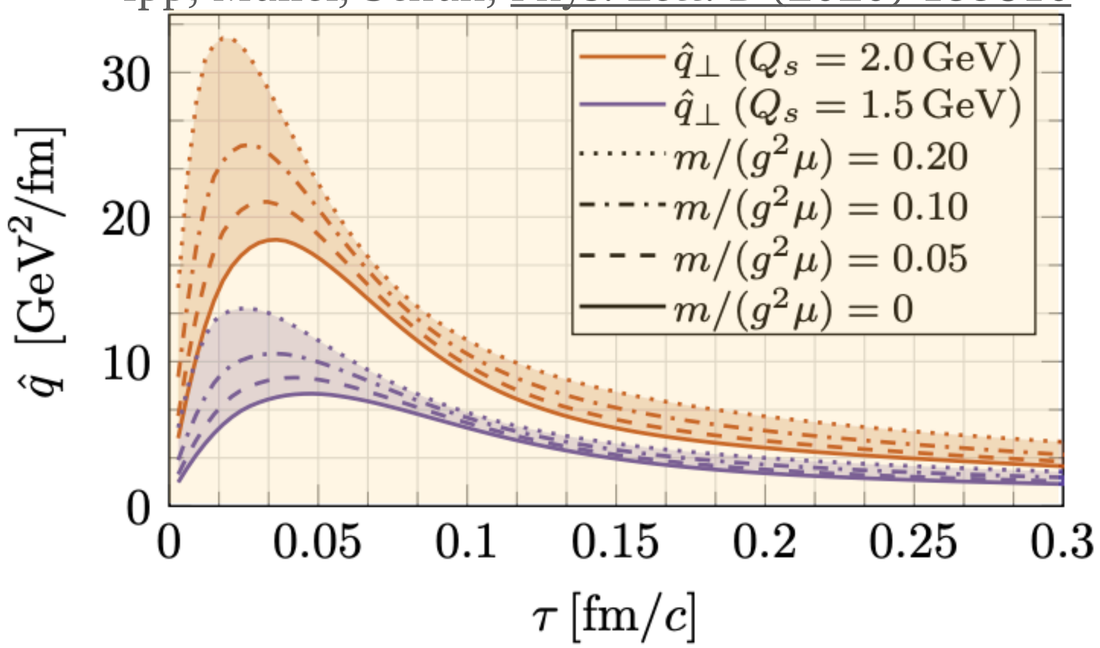
Understanding jet quenching in these stages becomes crucial!

Jet quenching in the initial stages?

- Many new developments in the computation of the **broadening in the pre-hydrodynamic stages**

Glasma

Ipp, Müller, Schuh, Phys. Lett. B (2020) 135810

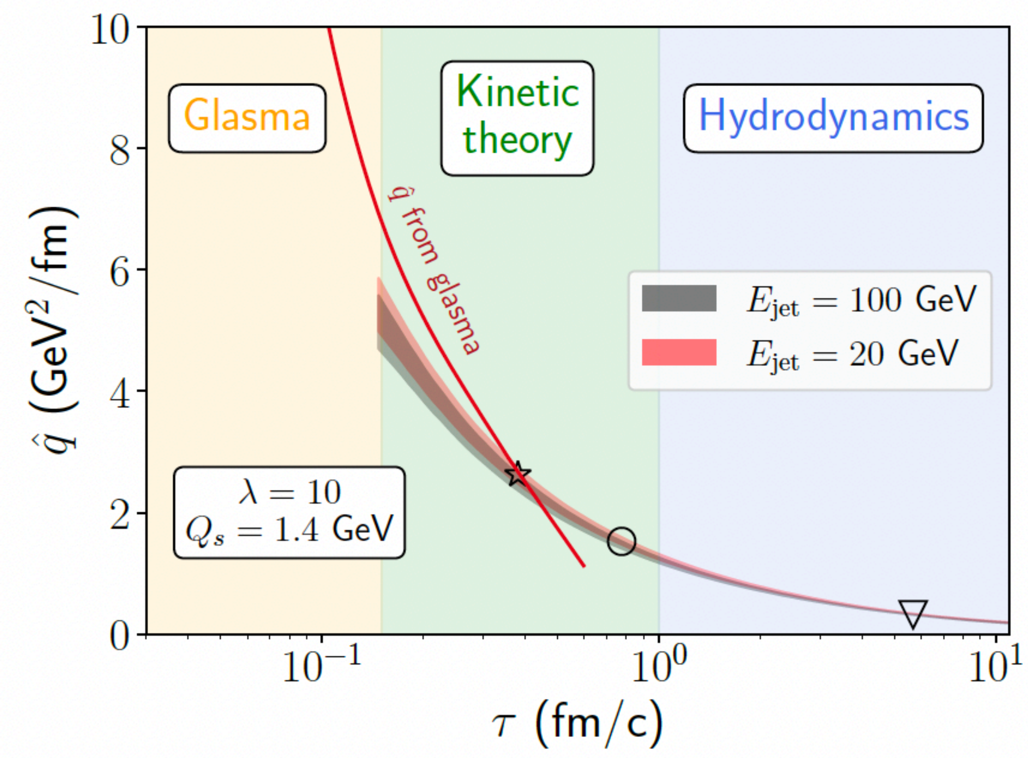


In the Glasma phase:

Ipp, Müller, Schuh,
Phys. Rev. D 102, 074001 (2020)
Phys. Lett. B 810 (2020) 135810

Carrington, Czajka, Mrówczynski,
Phys. Lett.B 834 (2022) 137464
Phys Rev C. 105 (2022) 6, 064910

Avramescu, Baran, Greco, Ipp, Müller, Ruggieri, Phys. Rev. D 107 (2023), 114021



Within Kinetic theory

Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron, 2303.12595

$\hat{q}$ relatively large!

Conclusions

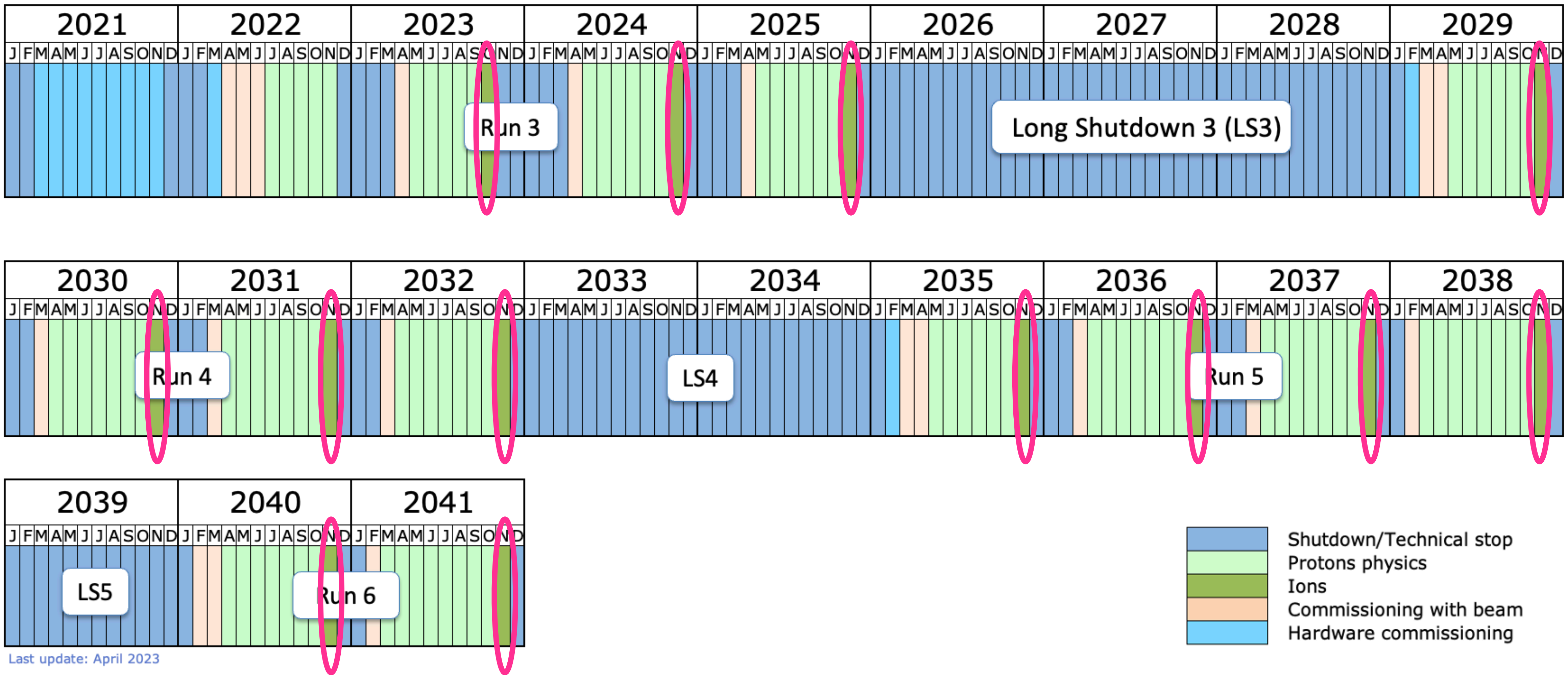
- QCD has a **rich dynamics** within experimental reach
- QCD **EoS for both hot and cold dense matter** can be studied using different experimental tools
  - Heavy-ion colliders: for hot and low baryon chemical potential
  - First constraints from **gravitational waves** on EoS of the core of **neutron stars**
- Hot QCD at RHIC and at the LHC
  - Continuous progress on the characterization of the QGP
  - Many interesting questions to be answered in the next decade

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

Future of HICs

- sPHENIX experiment at RHIC (BNL): HI runs up to 2025
- HI runs at the LHC (CERN) up to 2041!

18 more years of heavy-ion physics at the LHC!



- New ion facilities: FAIR (Germany), NICA (Russia), EIC (USA)

Gracias!