Emergence in QCD matter and the future of QCD studies at the EIC

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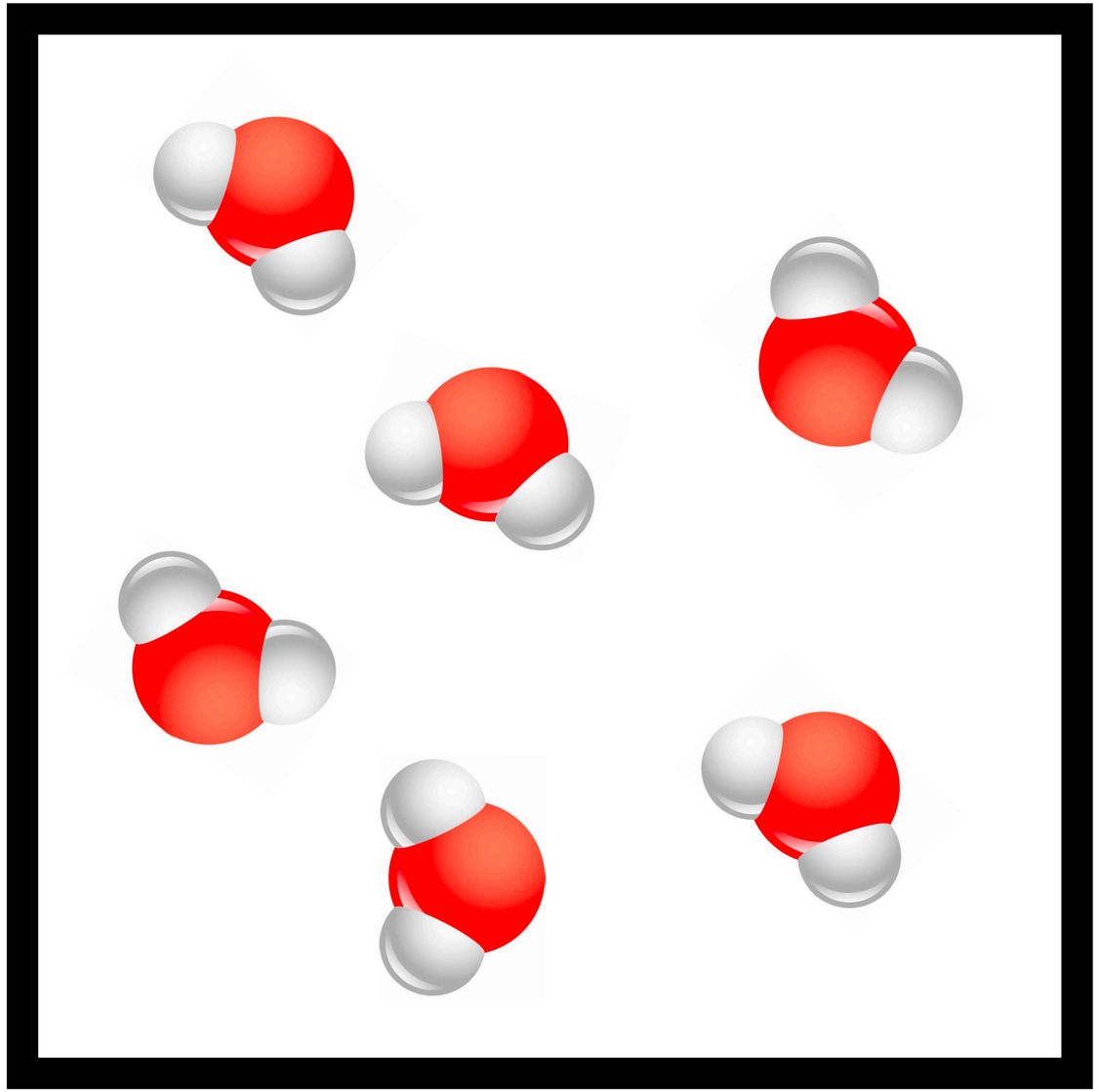
Emergent Phenomena

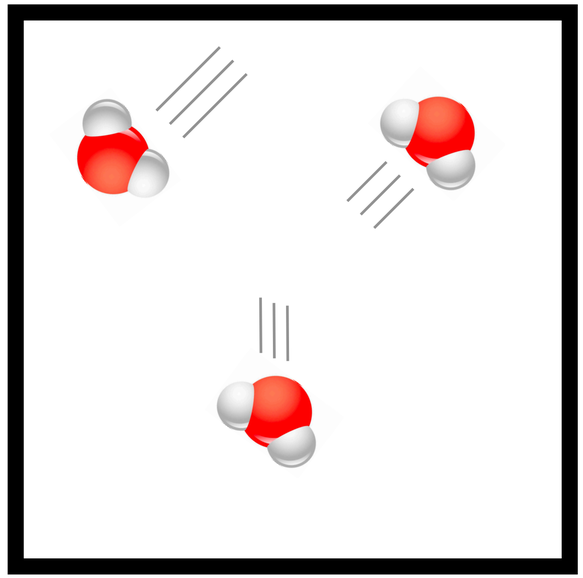
- **Consider a box of water molecules**
- **Electromagnetic interactions**

- **What macroscopic properties will the matter in the box have?**

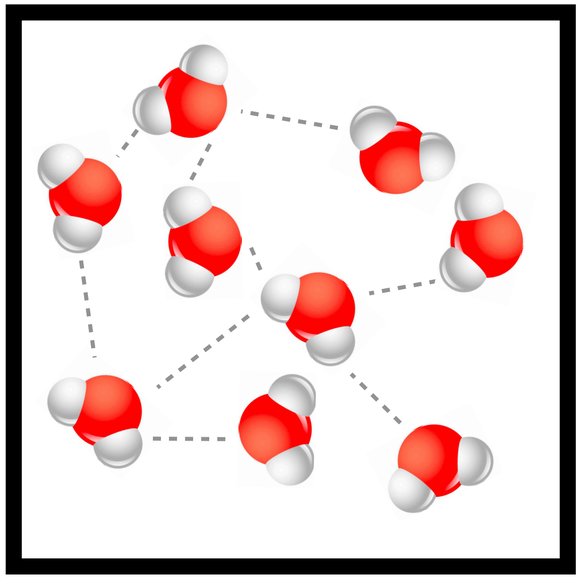


Emergent Phenomena

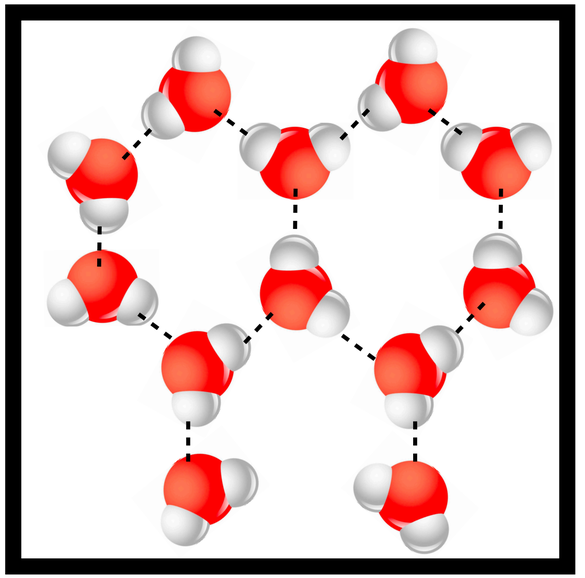
Steam



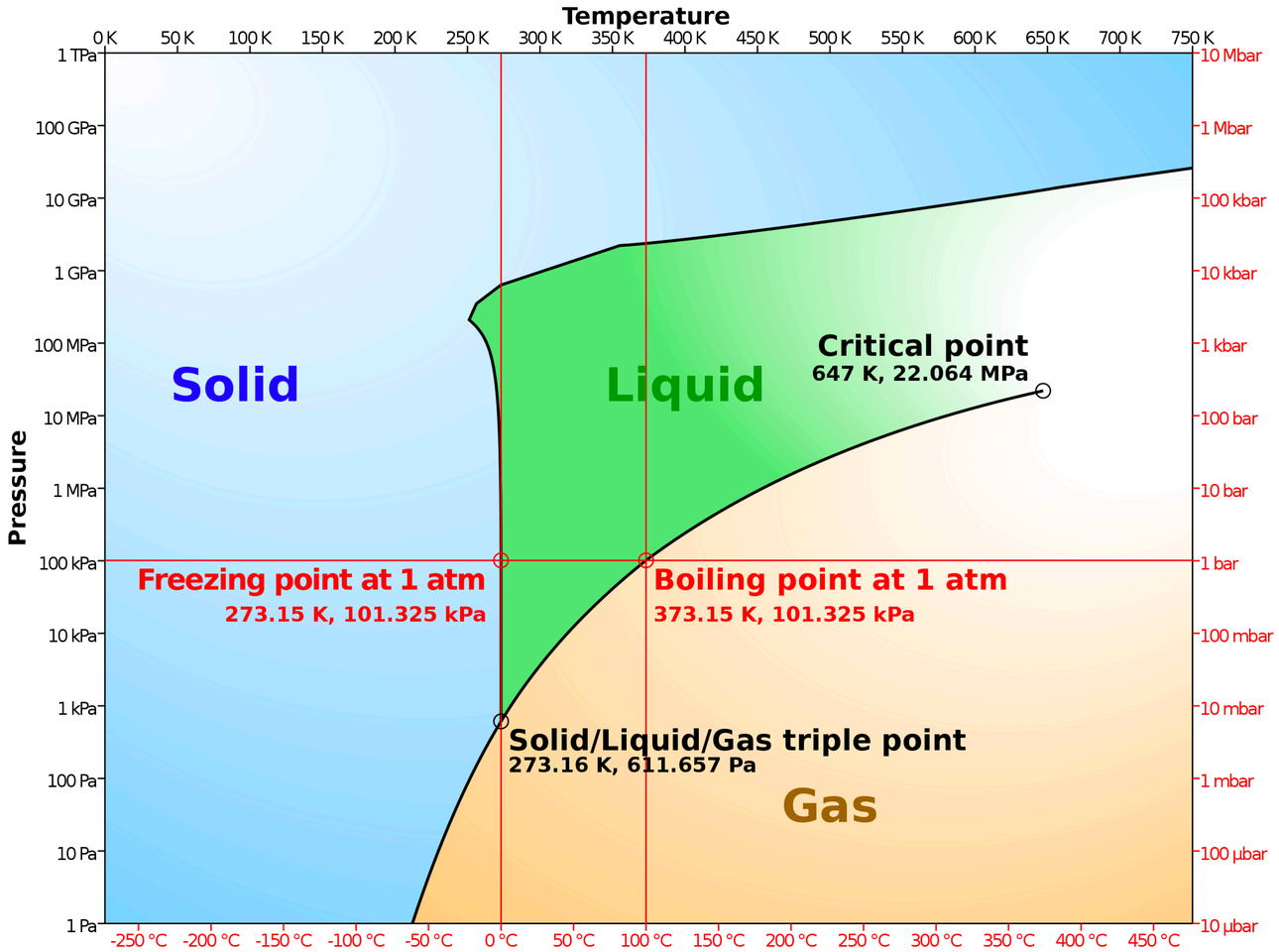
Liquid Water



Ice



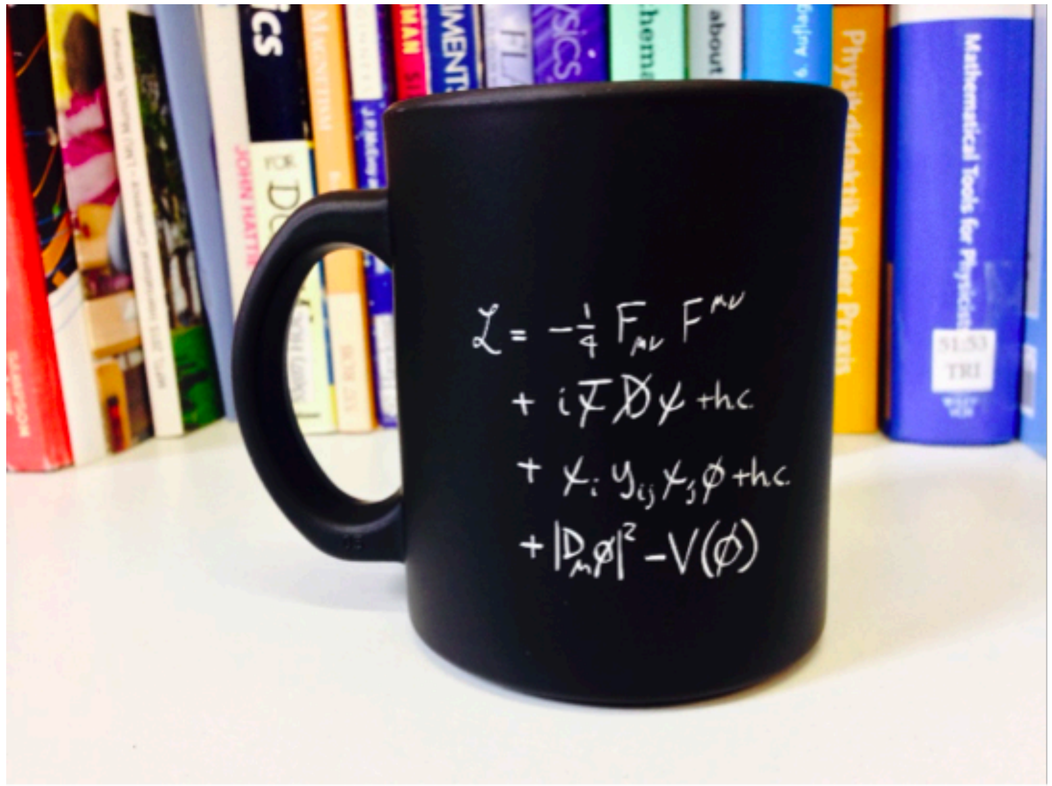
Emergence in Electromagnetic matter

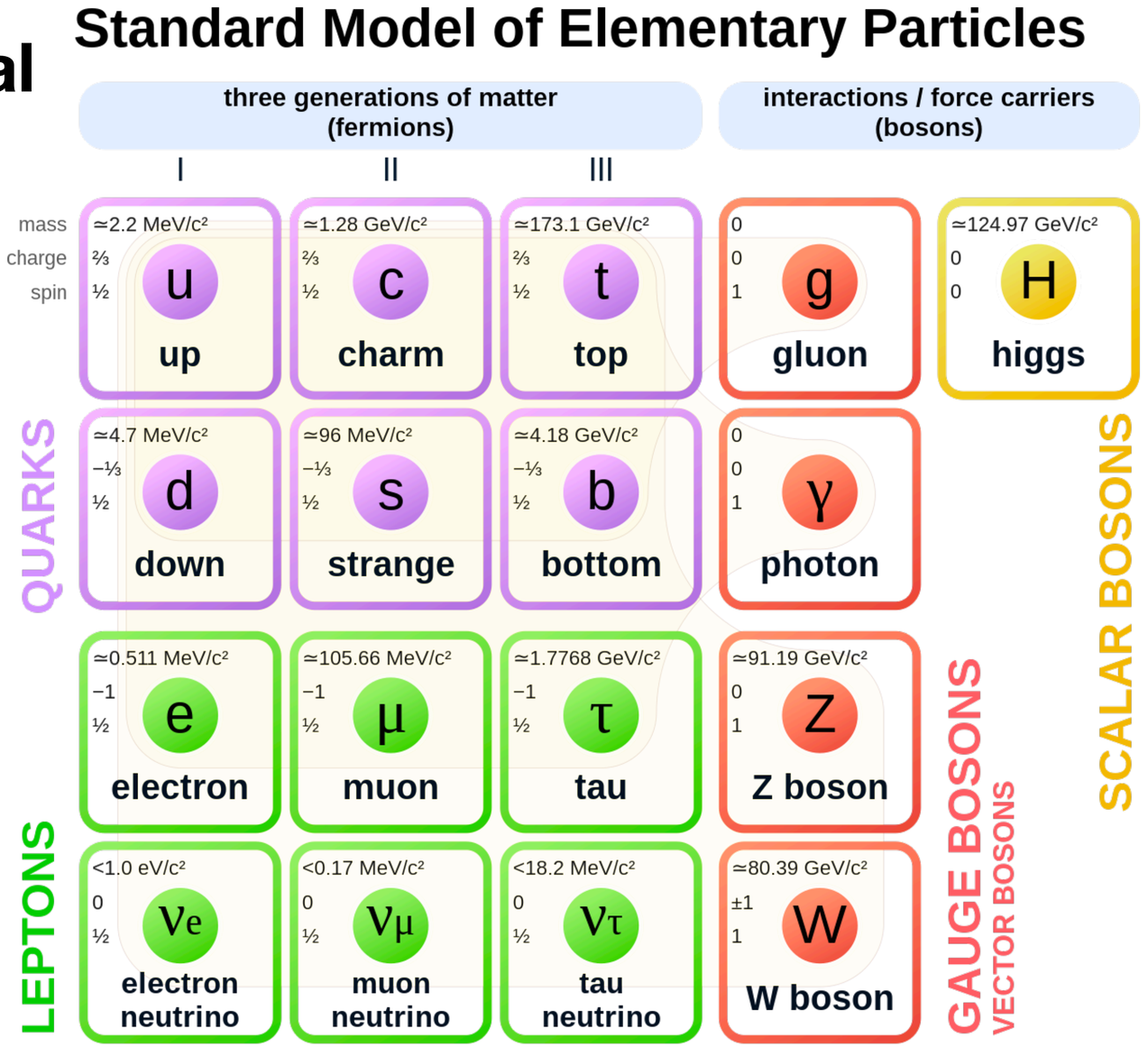


- **Electromagnetism is well understood!**
- **Do other interaction forces have different emergent phenomena?**

The Standard Model

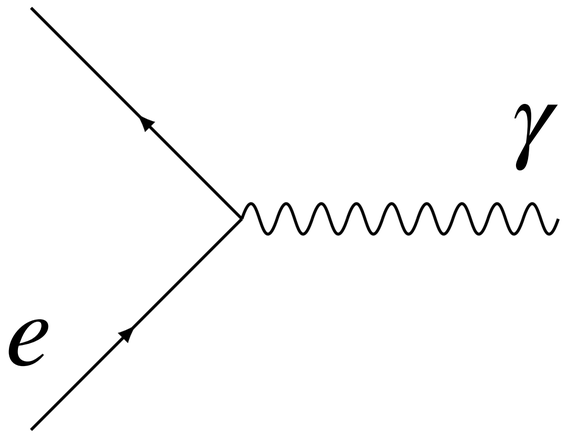
- **The SM describes 3 fundamental forces of nature**

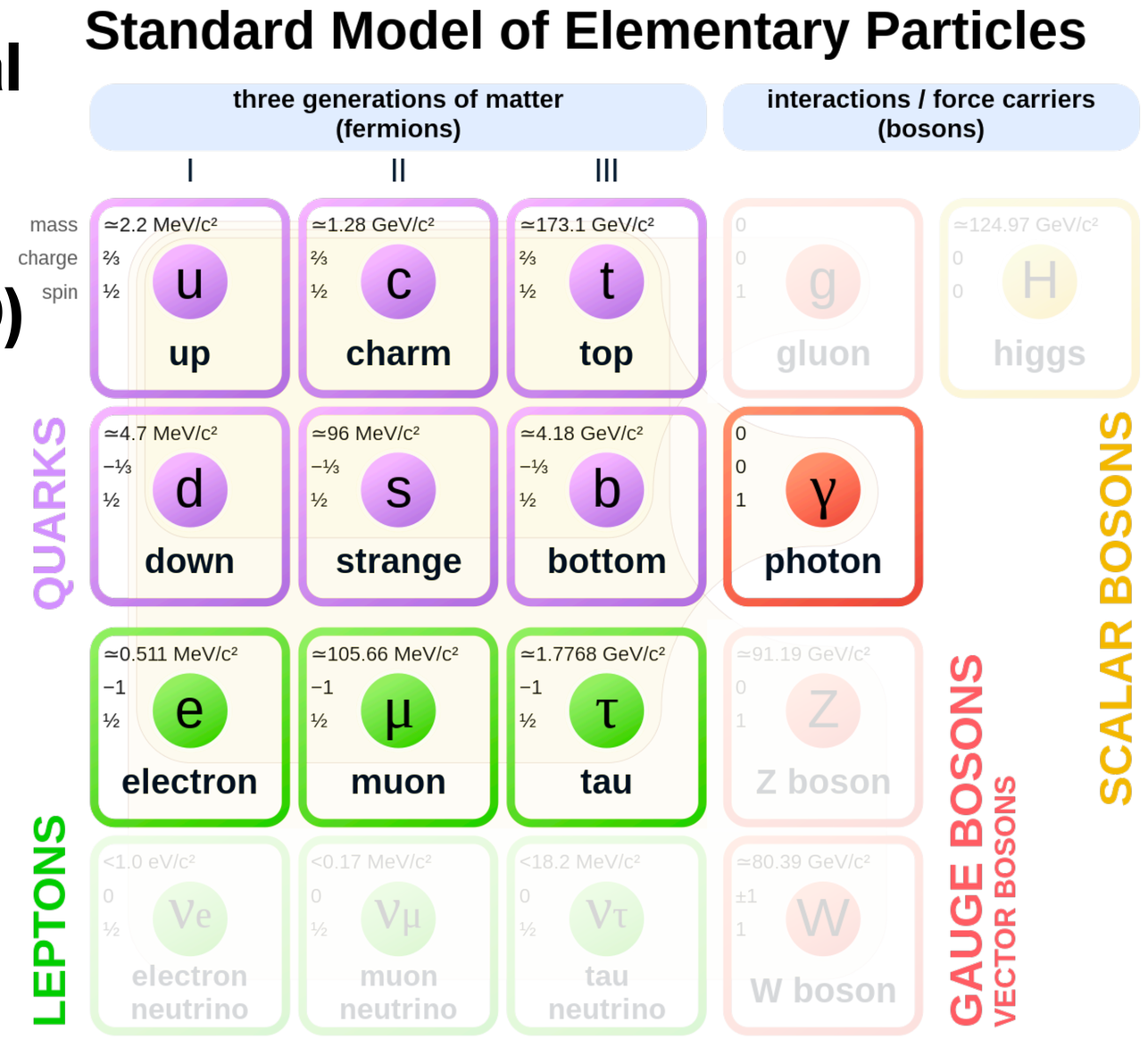




Quantum Electrodynamics

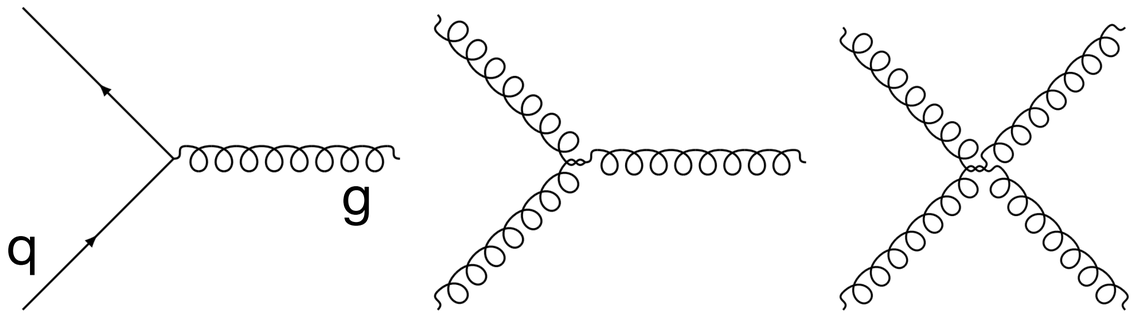
- **The SM describes 3 fundamental forces of nature**
- **Quantum Electrodynamics (QED)**
  - **Fundamental theory of electromagnetism**

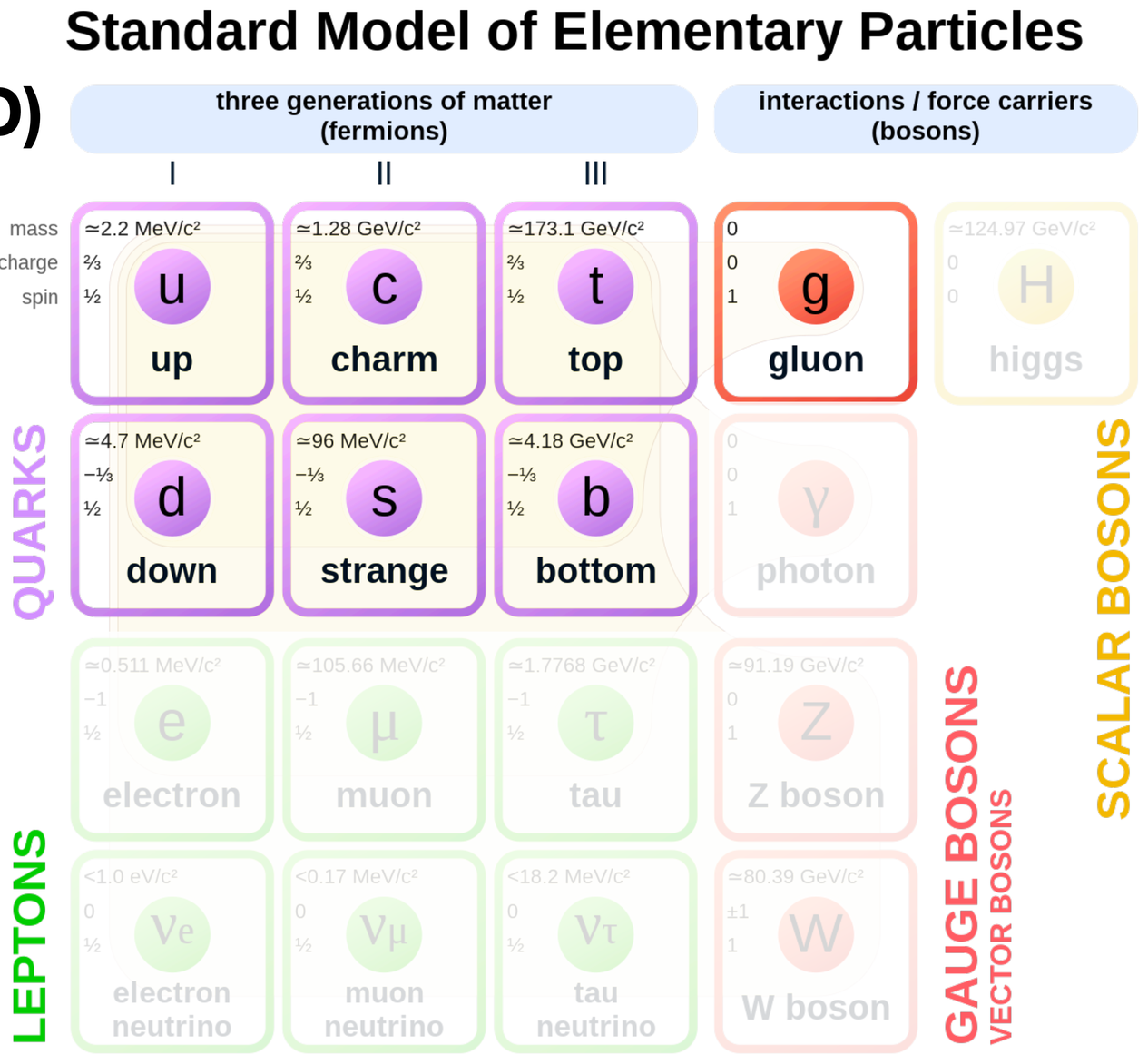




Quantum Chromodynamics

- **Quantum Chromodynamics (QCD)**
  - **Theory of strong force**
  - **Interaction between color-charged particles (3 colors)**

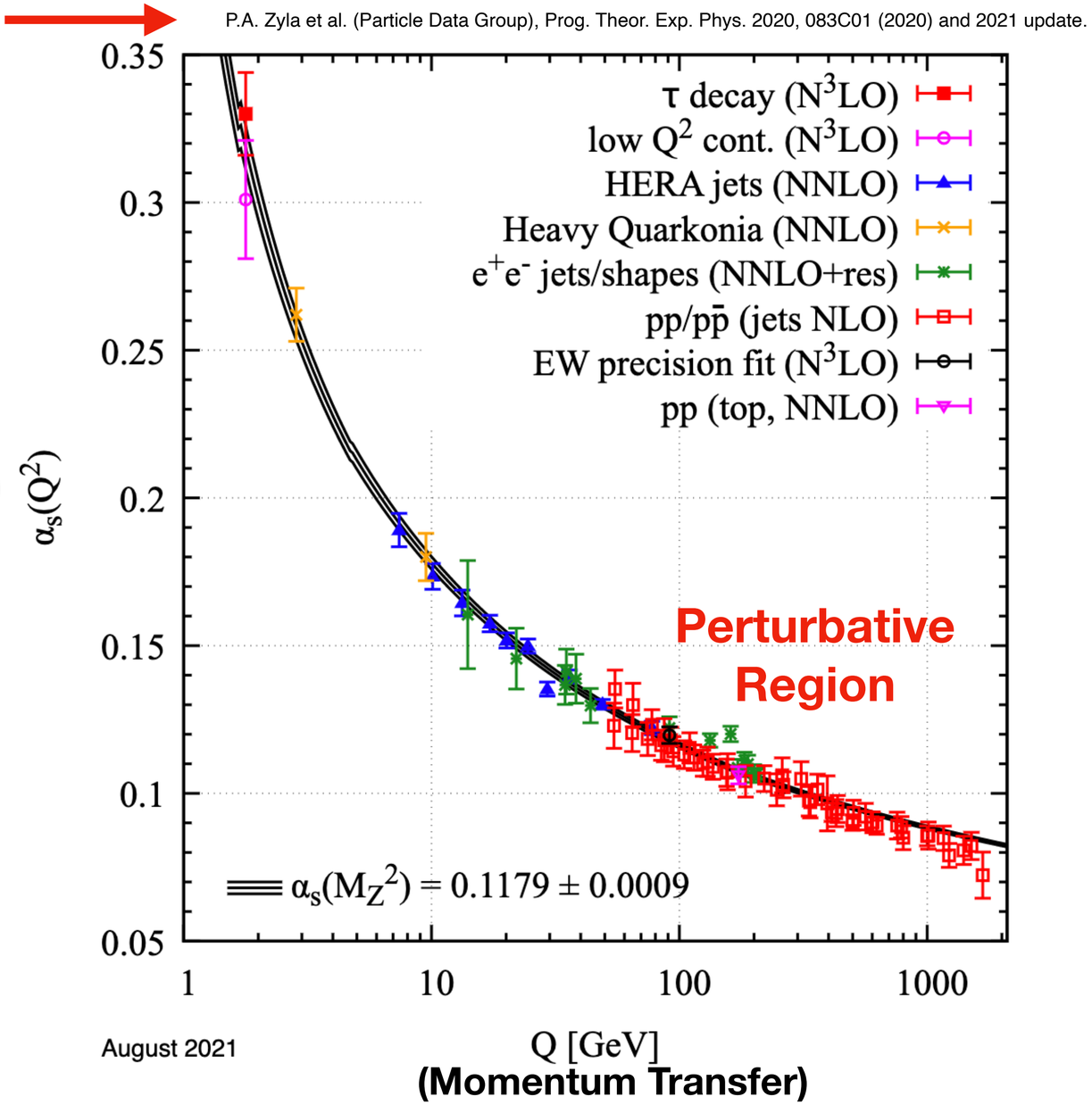




Asymptotic Freedom

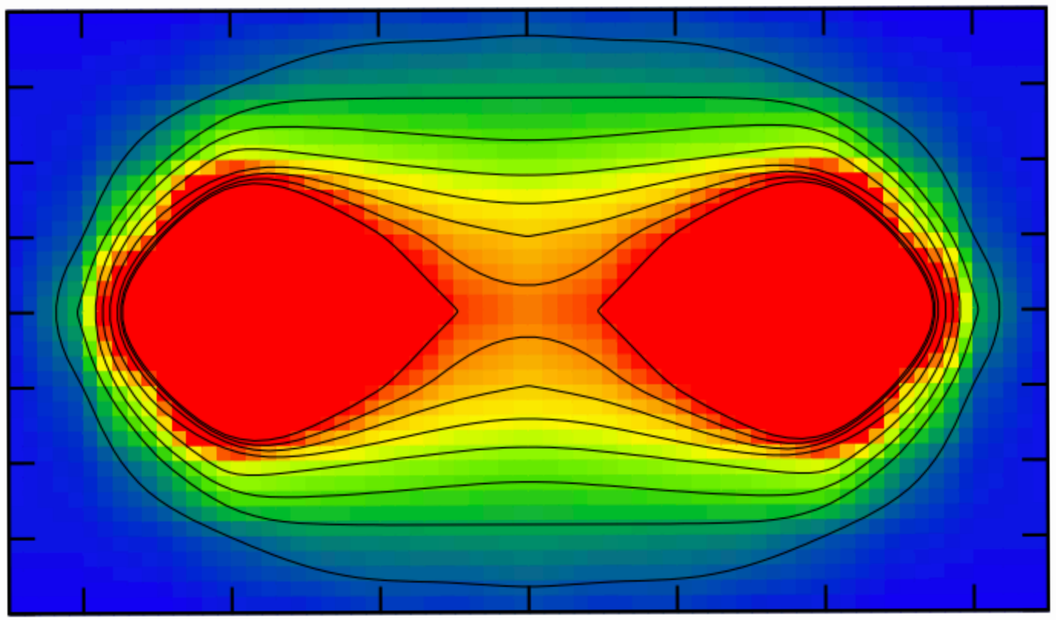
- QCD weakens at large Q^2
  - Quarks ‘asymptotically free’
  - Perturbation theory works (pQCD)
- Low Q^2 is “non-perturbative”
  - Experimental input needed

Non-Perturbative Region



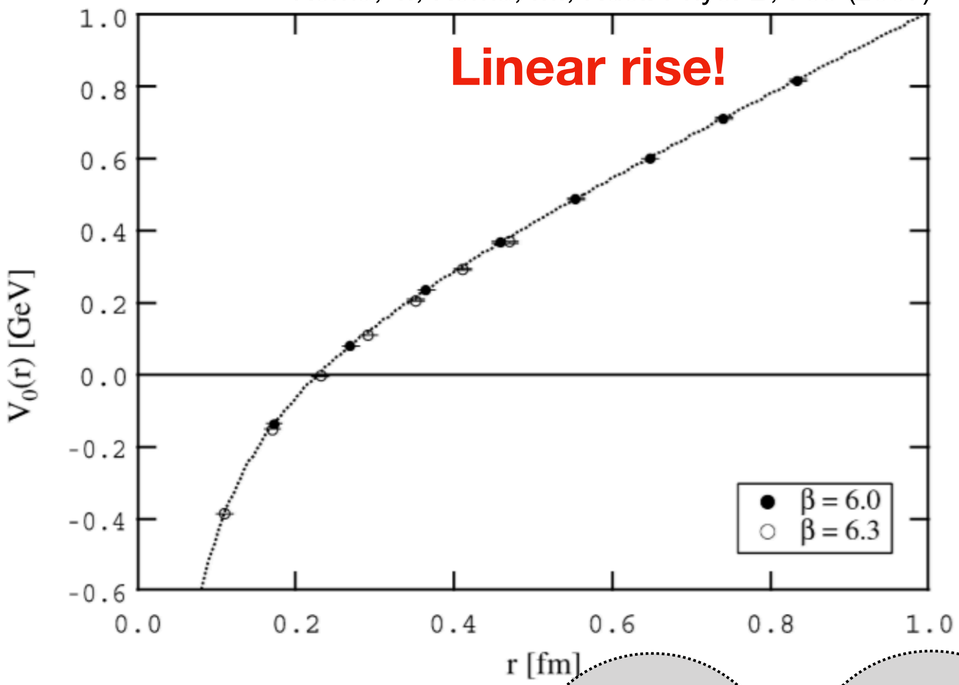
Color Confinement

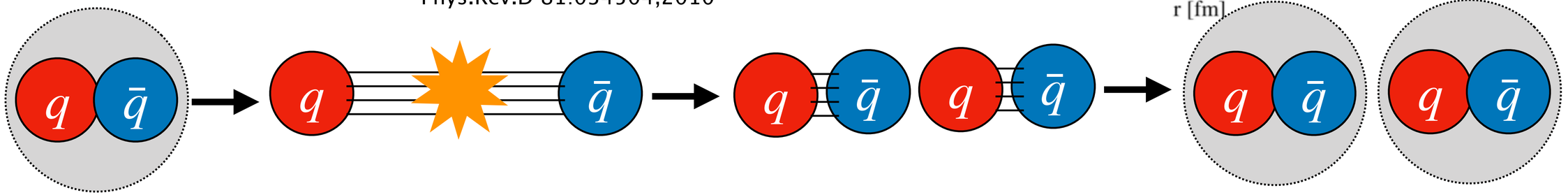
- **Quark-antiquark potential increases linearly with distance**
- **Quarks & gluons confined into color-neutral hadrons (protons, neutrons, pions)**



Phys.Rev.D 81:034504,2010

Koma, Y., Koma, M., Nucl. Phys. B, 769 (2007)

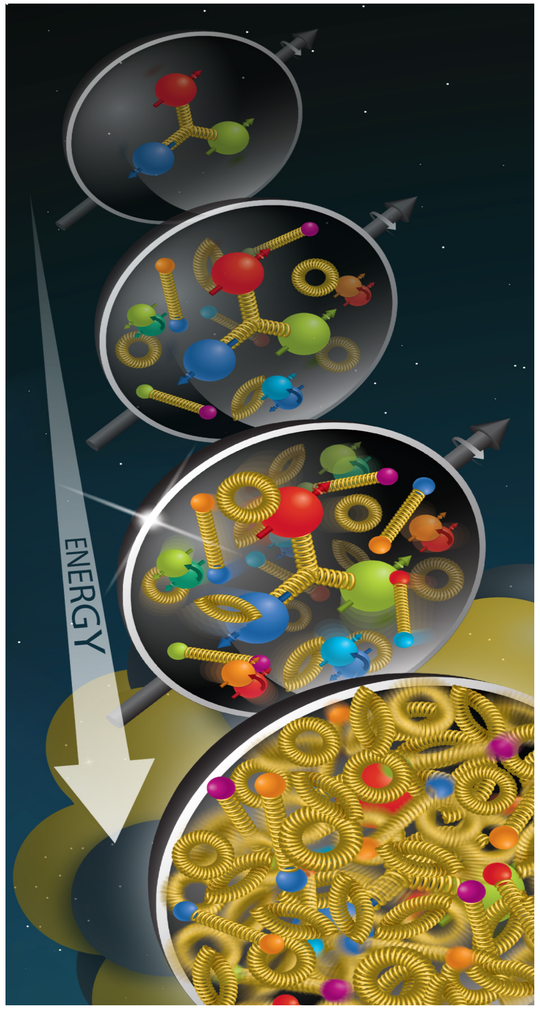


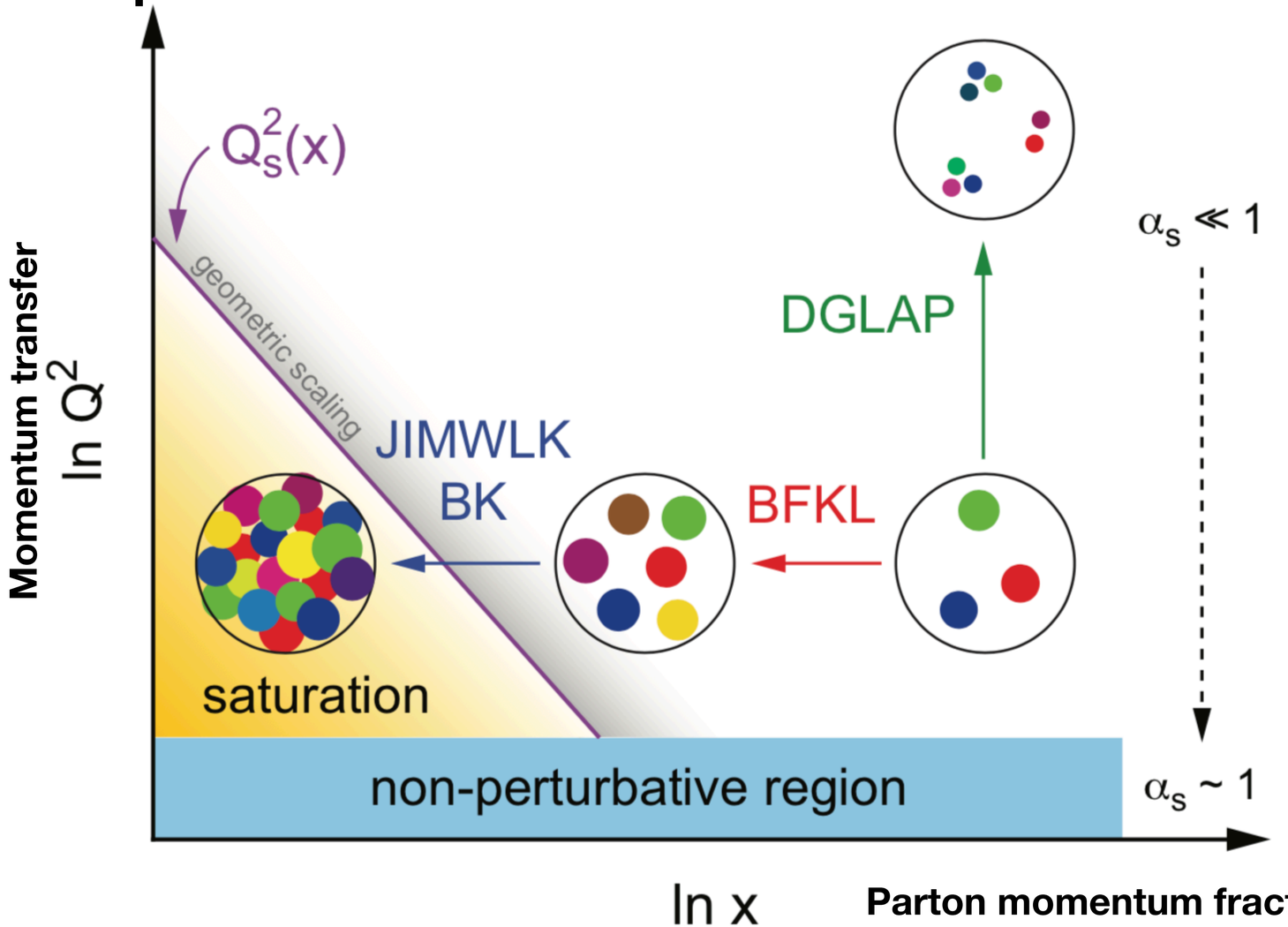


Studying QCD evolution

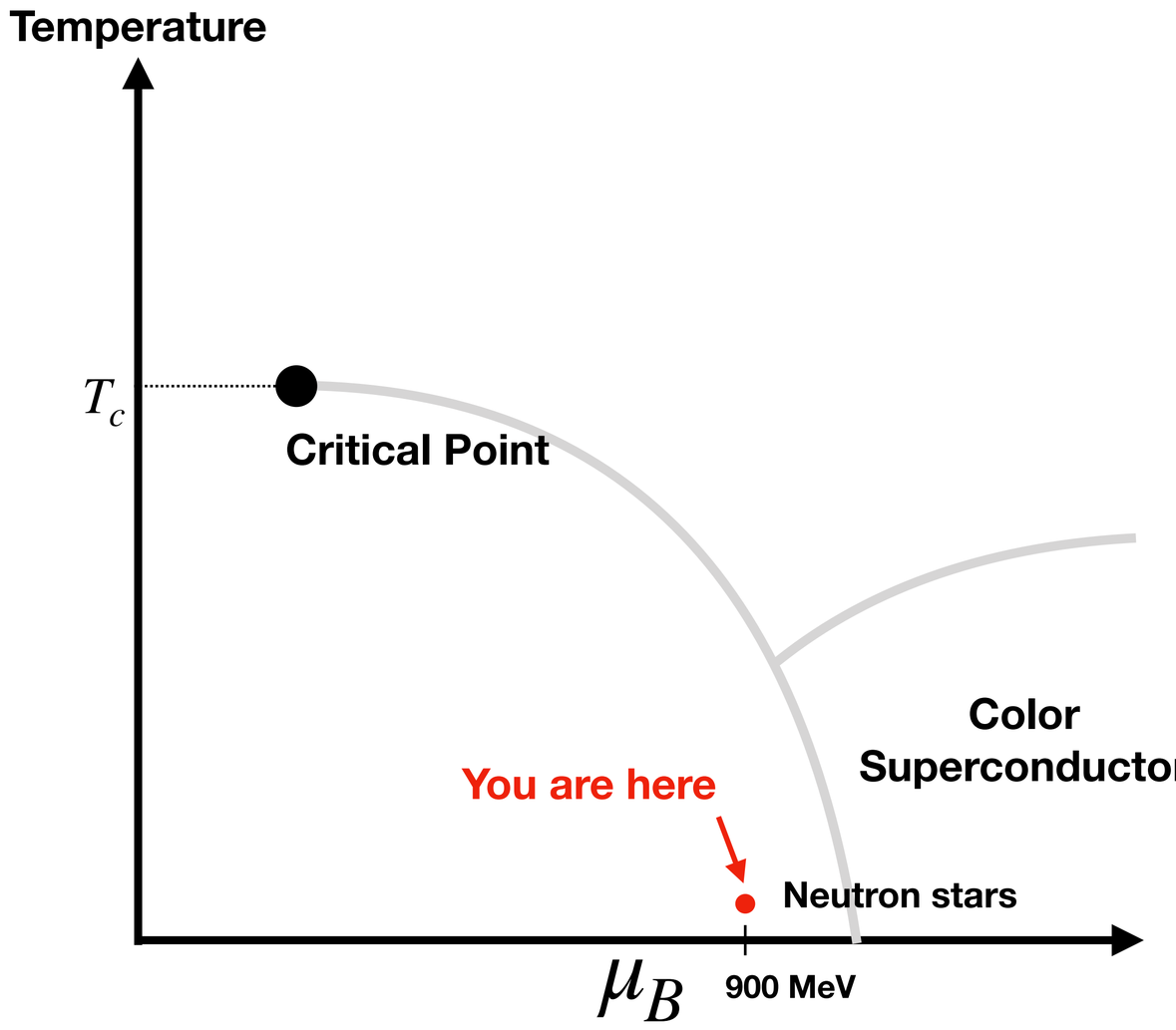
arXiv:1212.1701

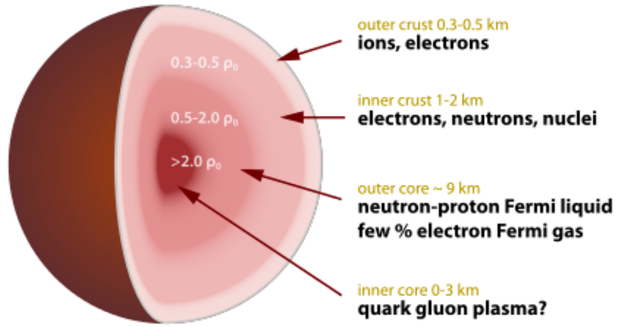
- **Study non-perturbative effects by probing internal hadron structure - ‘cold QCD’**
- **Well-defined theories let us extrapolate between kinematic scales**





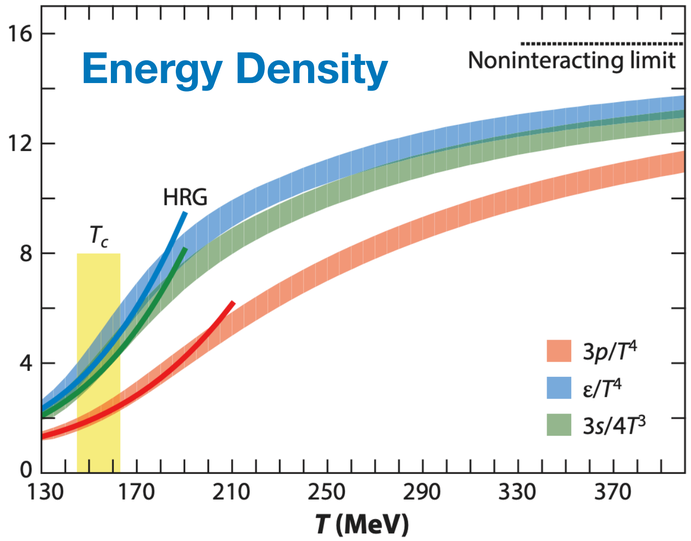
QCD Matter


Temperature
T_c
Critical Point
Color
Superconductor
You are here
Neutron stars
μ_B
900 MeV
(# quarks - # antiquarks)

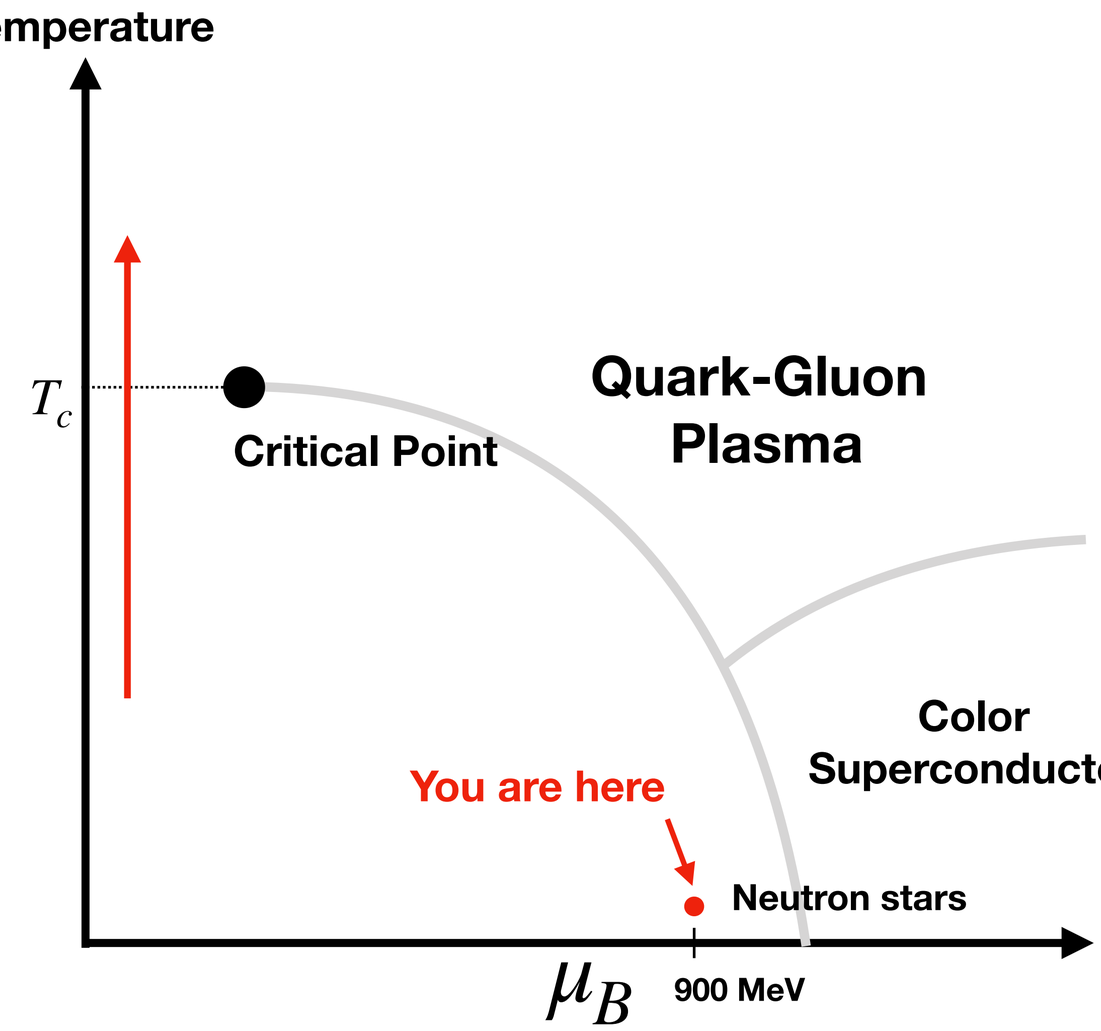

outer crust 0.3-0.5 km
ions, electrons
0.3-0.5 ρ₀
inner crust 1-2 km
electrons, neutrons, nuclei
0.5-2.0 ρ₀
>2.0 ρ₀
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas
inner core 0-3 km
quark gluon plasma?

Hot QCD Matter

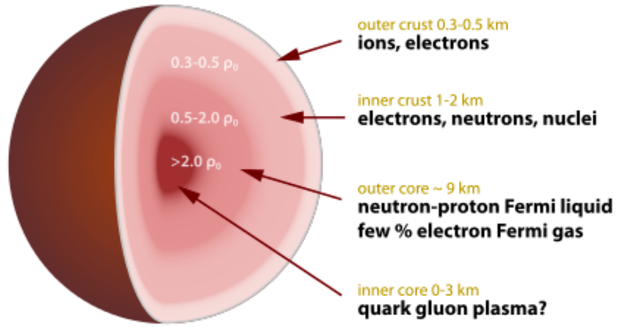
Busza, W., Rajagopal, K., van der Schee, W.
Ann. Rev. of Nucl. and Part. Sc. 2018 68:1



Lattice QCD Calculations



(# quarks - # antiquarks)



Hot QCD Matter

Busza, W., Rajagopal, K., van der Schee, W.
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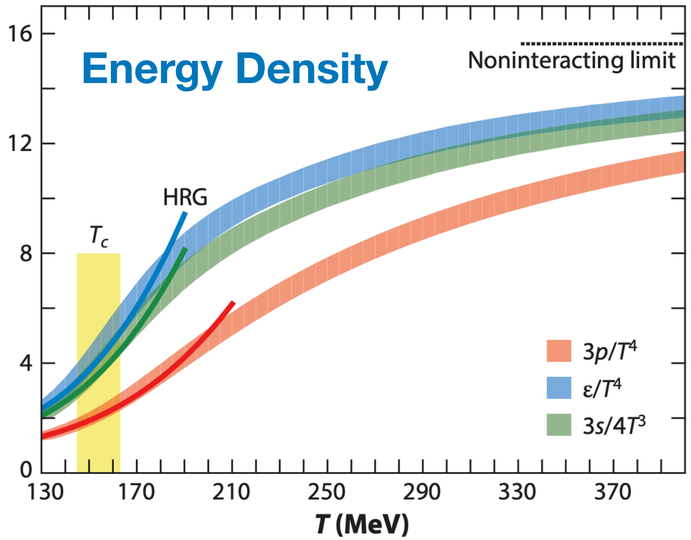
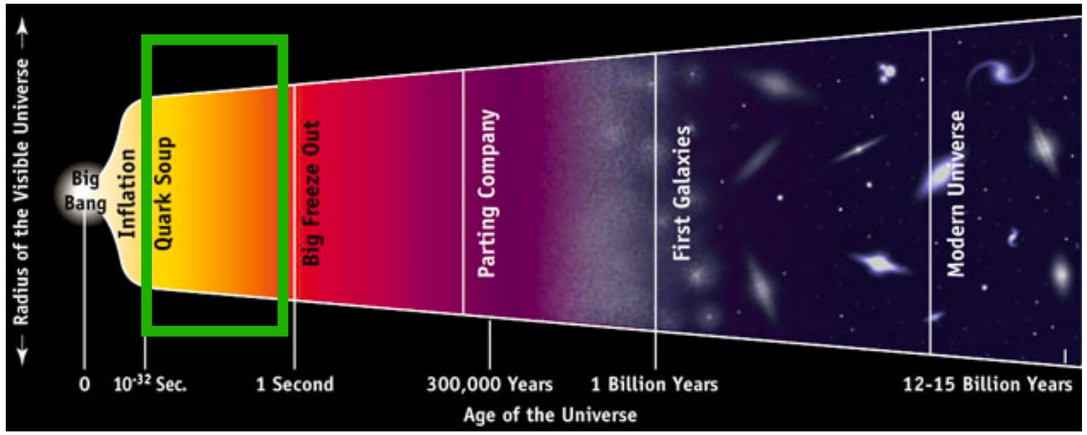
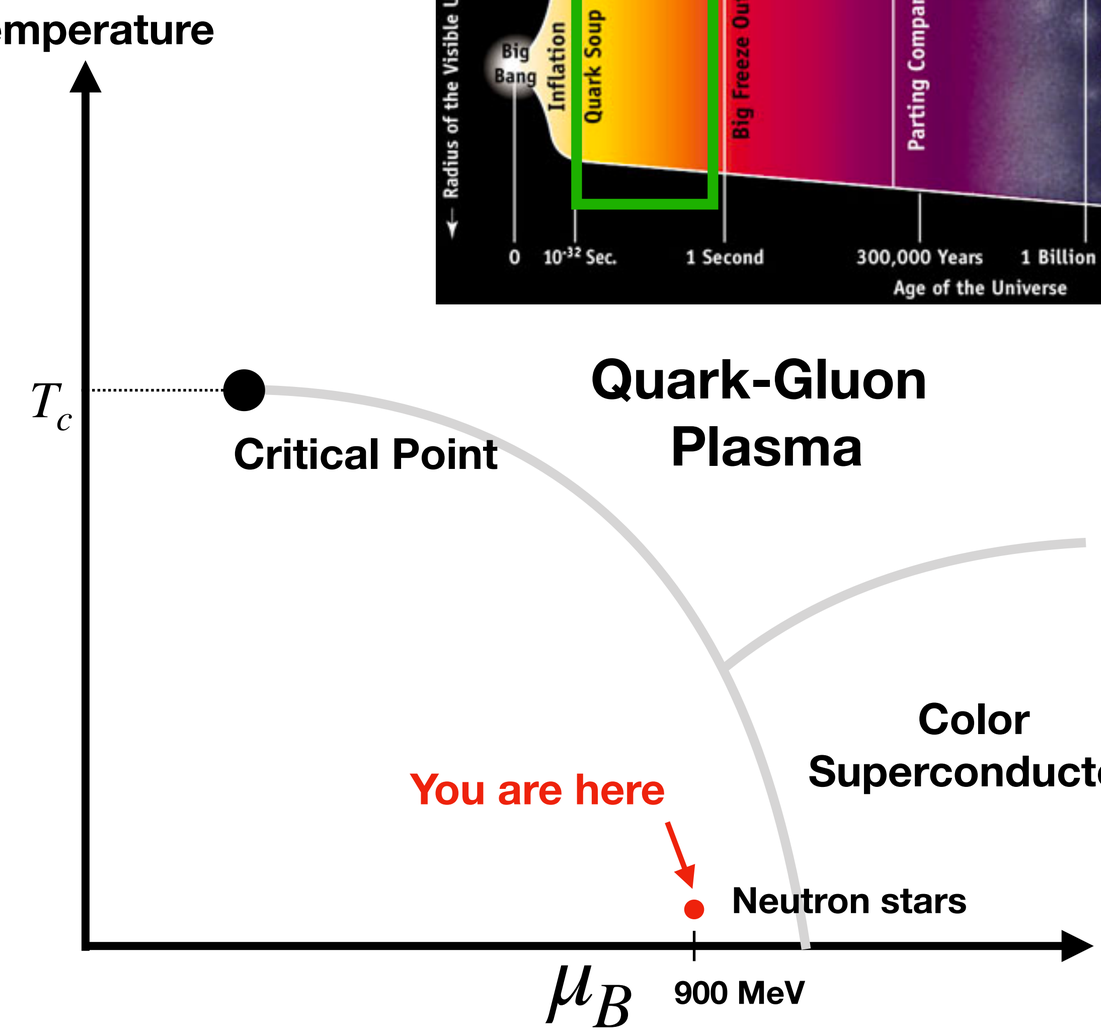
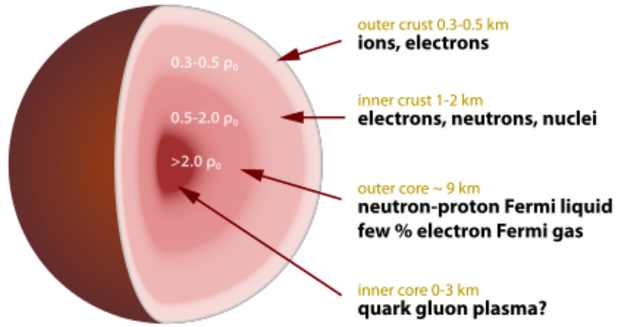


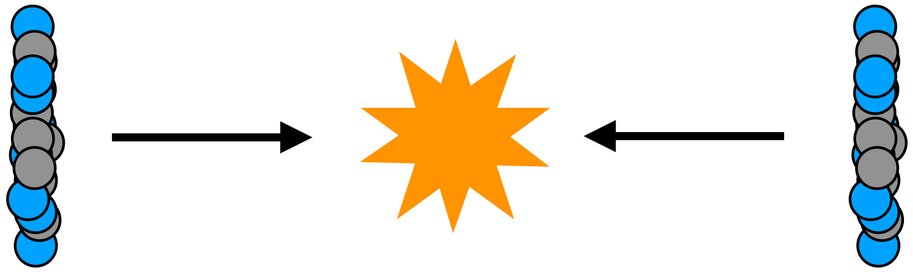
Lattice QCD Calculations



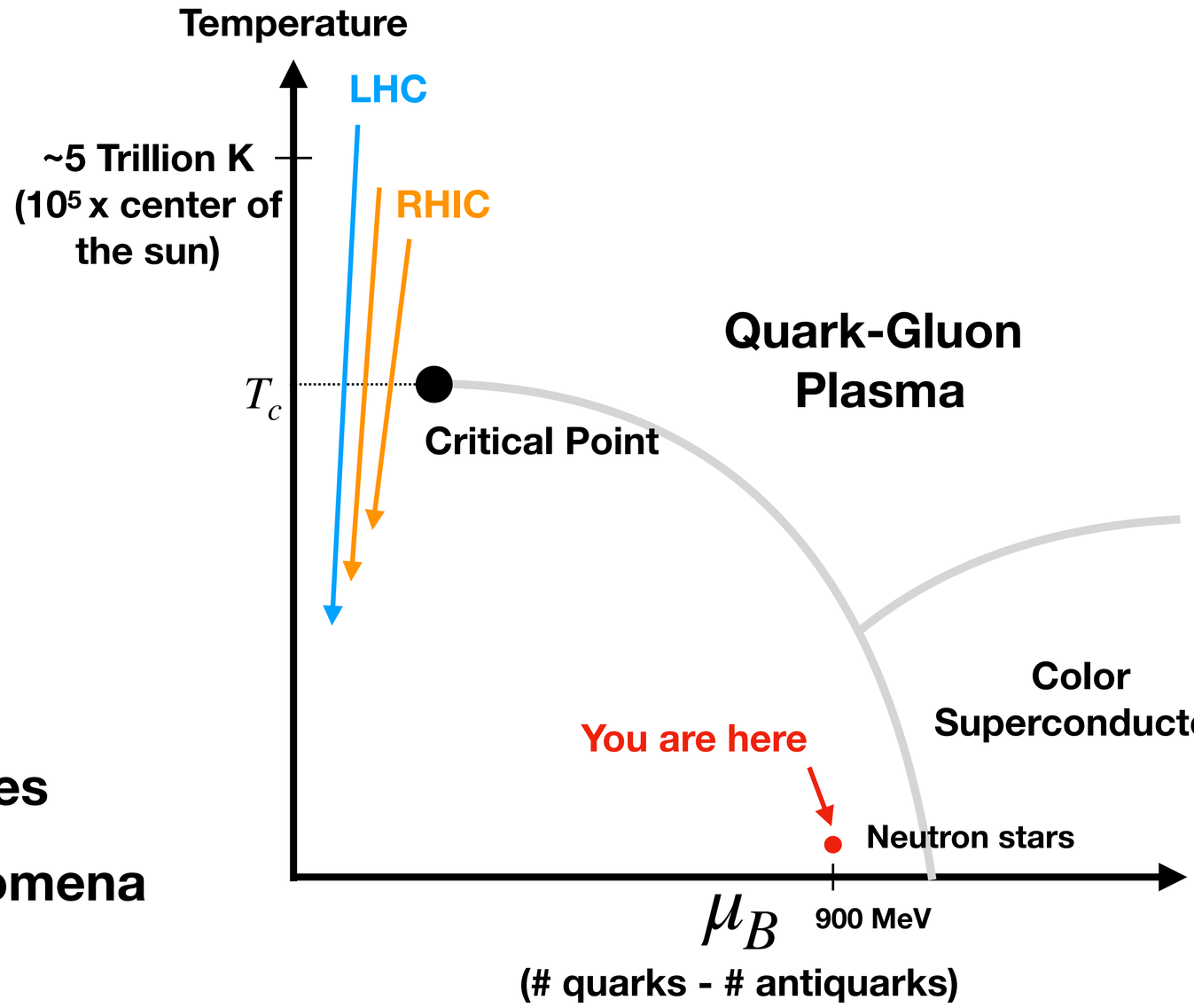




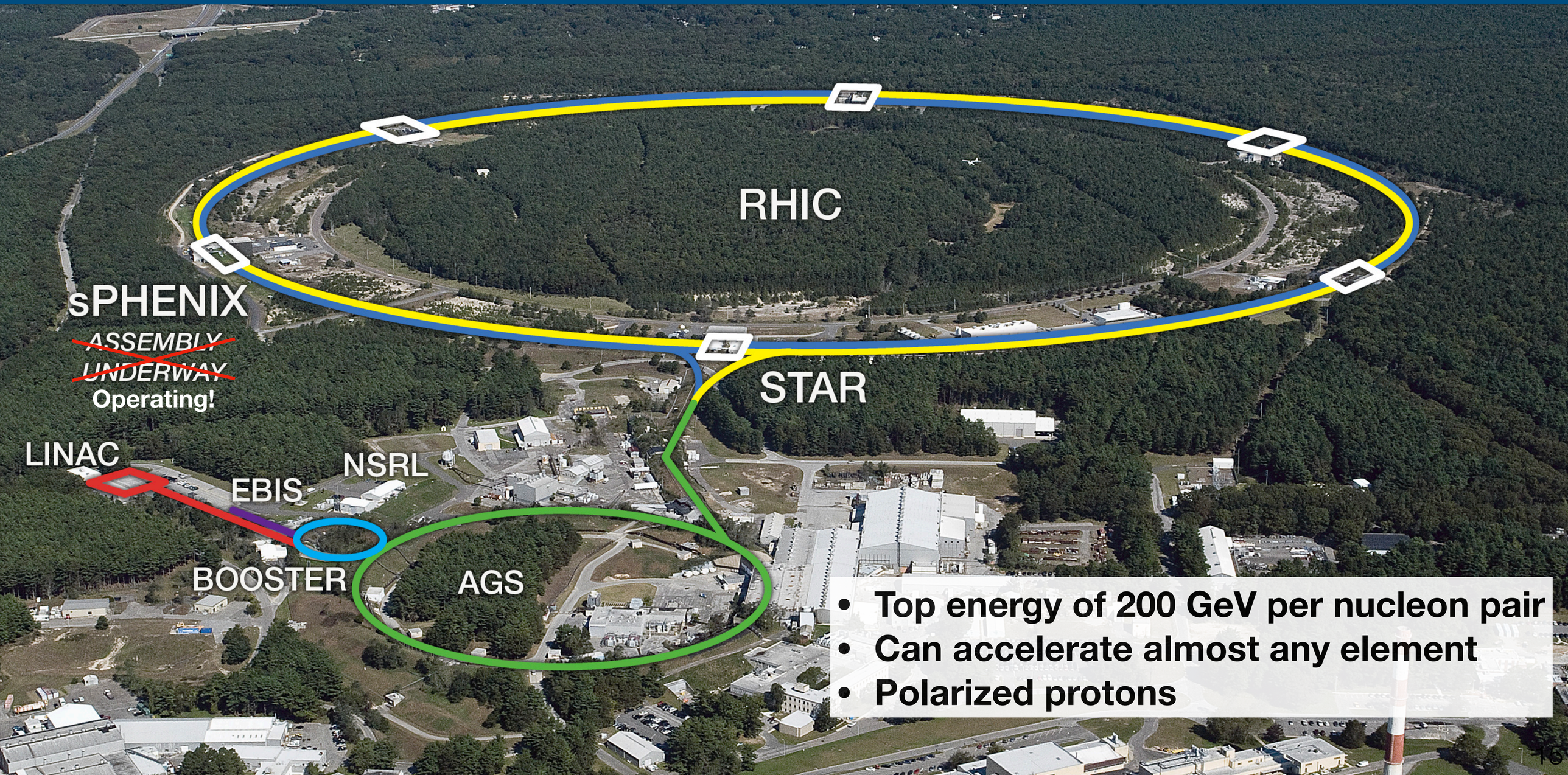
Heavy Ion Collisions



- Created with ion collisions!
- Hottest man-made form of matter
- QGP cools into hadrons
  - Detect hadrons, infer QGP properties
- QGP shows complex emergent phenomena

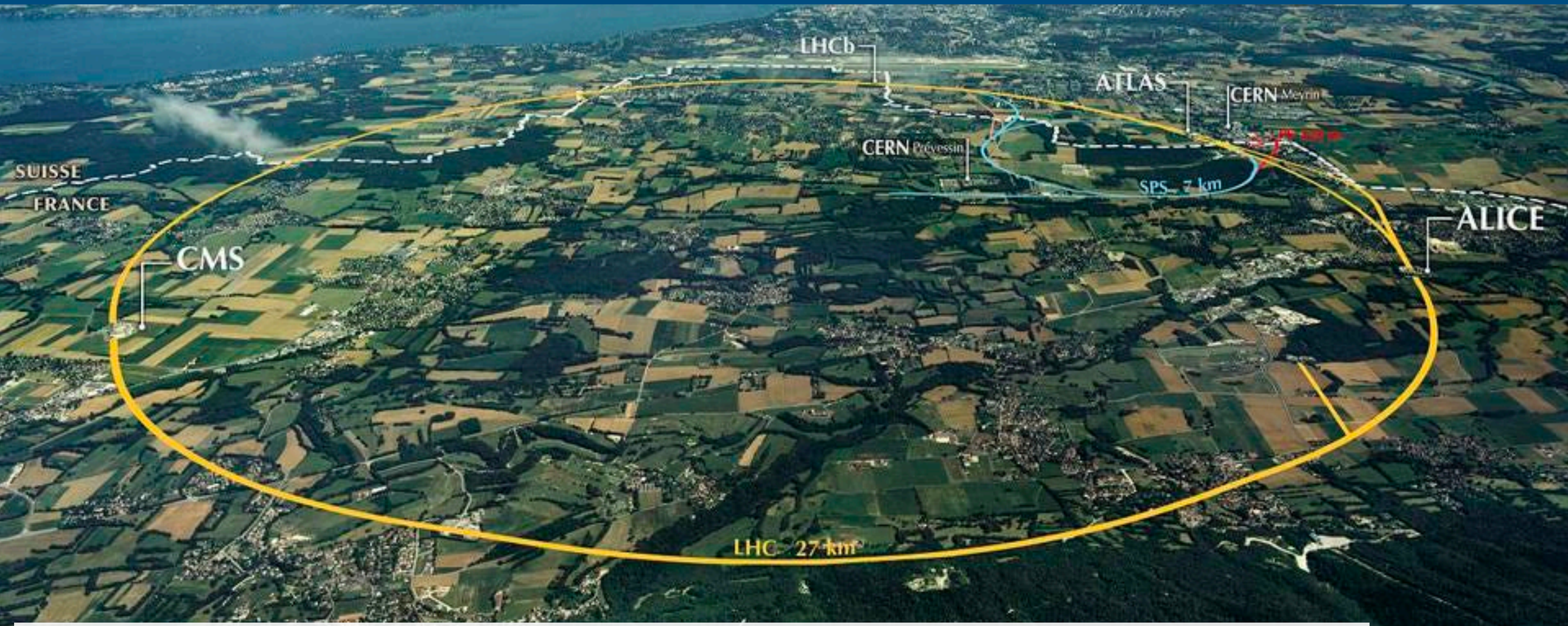


Relativistic Heavy Ion Collider



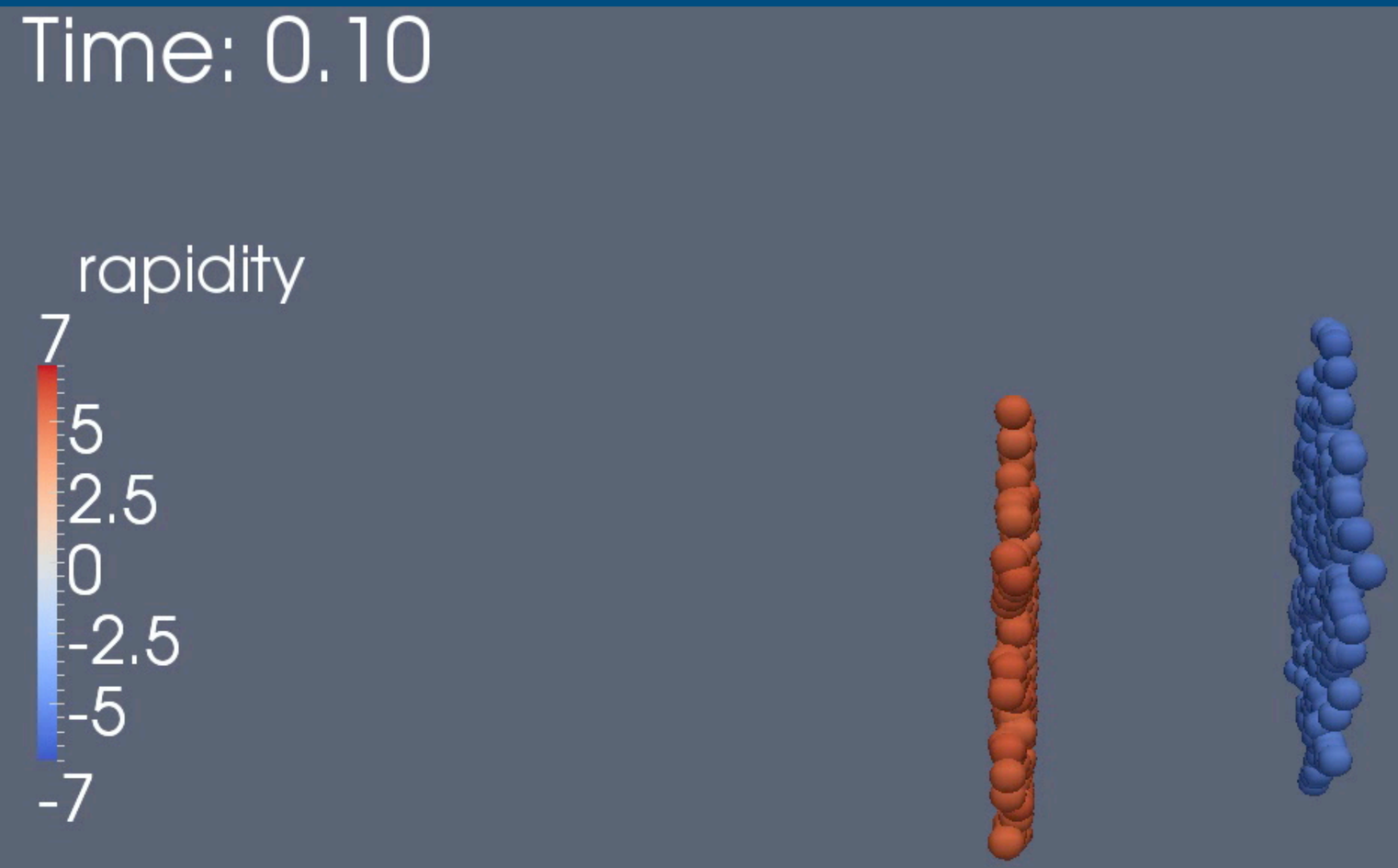
- **Top energy of 200 GeV per nucleon pair**
- **Can accelerate almost any element**
- **Polarized protons**

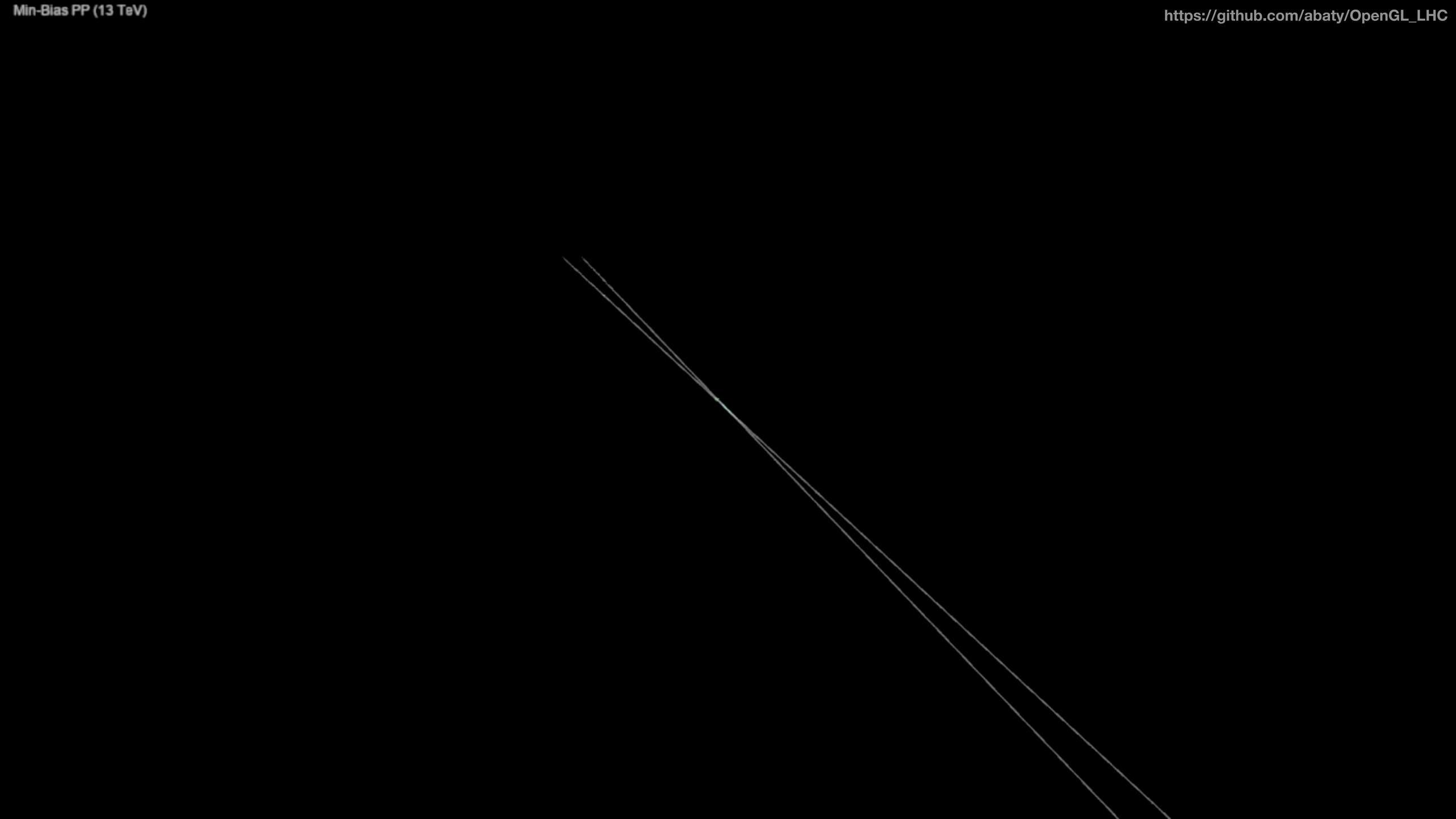
Large Hadron Collider



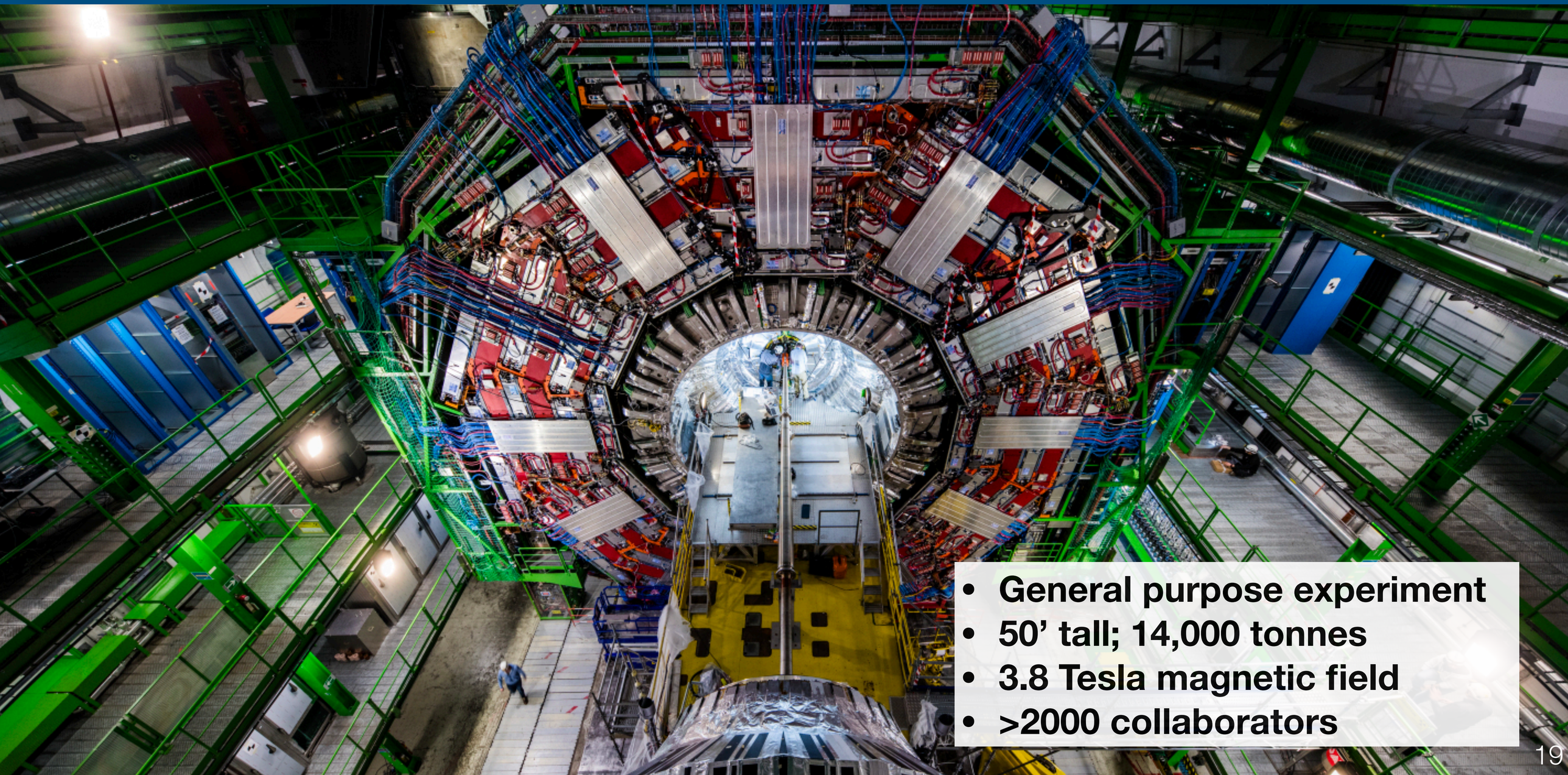
- Runs heavy ions ~1 month / year
- Top energy of 5.5 TeV per nucleon pair: 1 PeV (0.1 mJ) total collision energy
- Accelerates protons, Pb^{208}, Xe^{129}

Heavy Ion Collisions



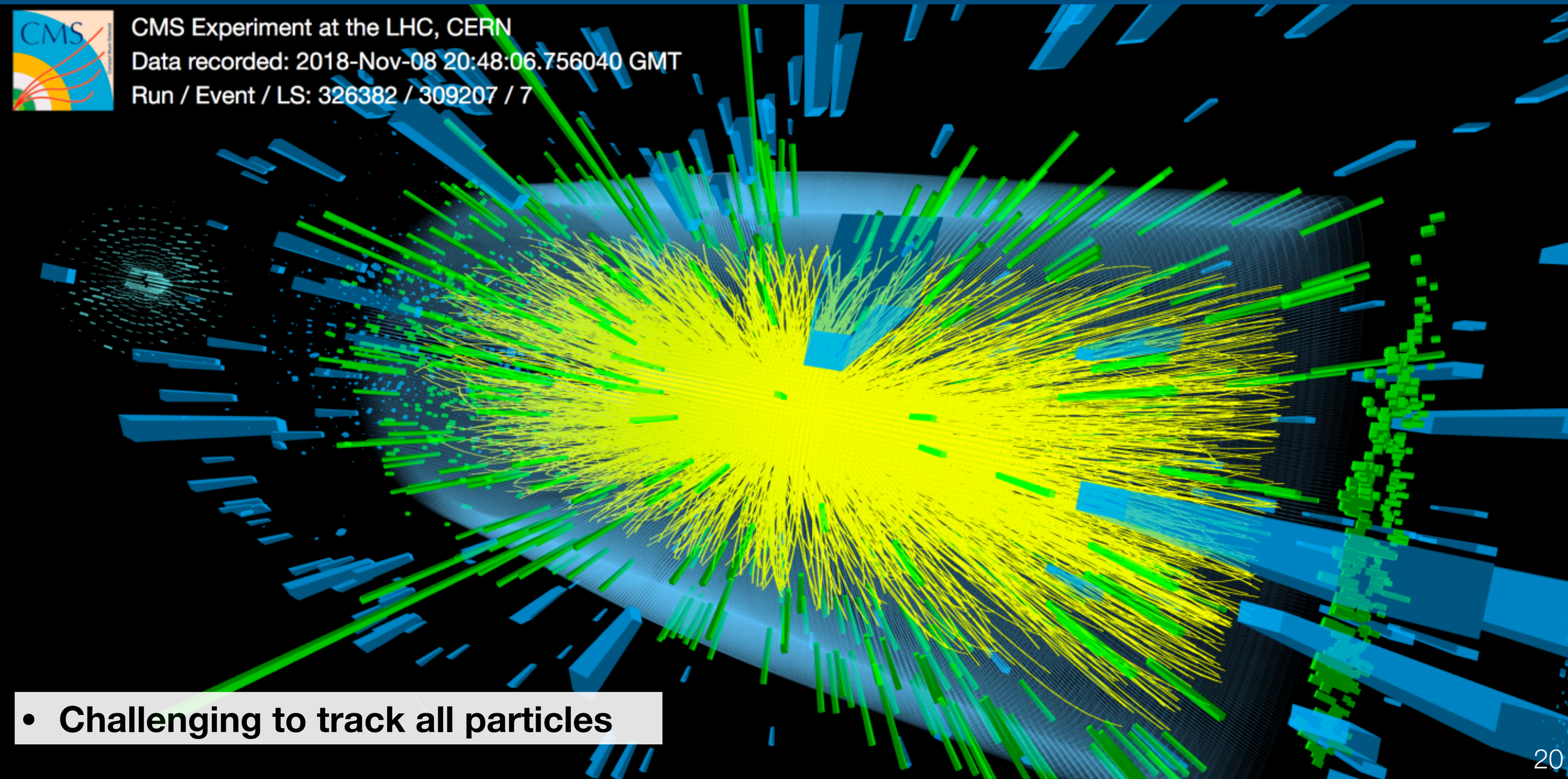

Min-Bias PP (13 TeV)
https://github.com/abaty/OpenGL_LHC

Compact Muon Solenoid



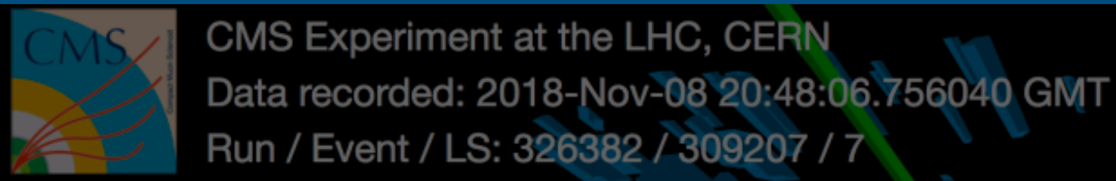
- General purpose experiment
- 50’ tall; 14,000 tonnes
- 3.8 Tesla magnetic field
- >2000 collaborators

PbPb Event

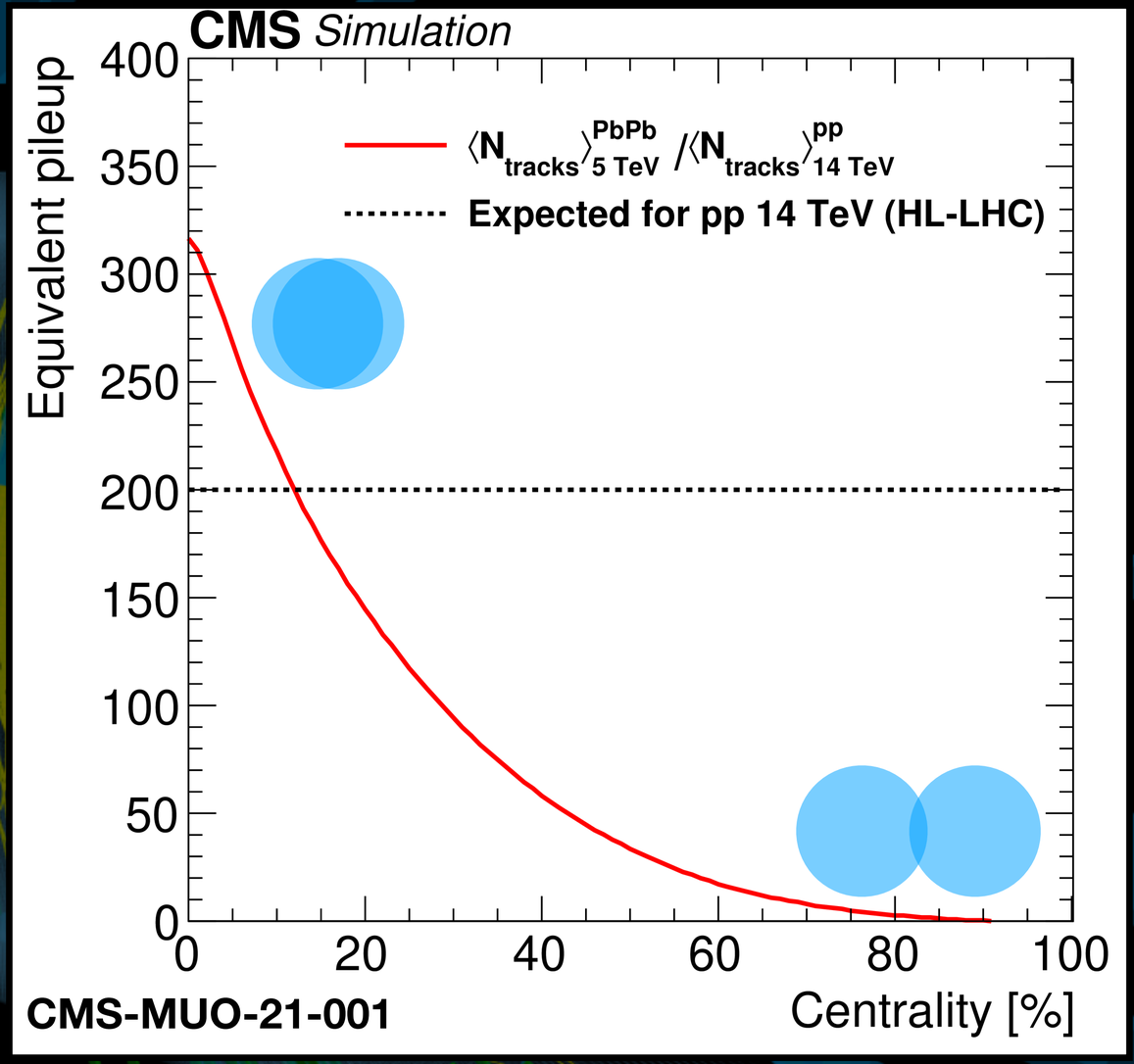


- **Challenging to track all particles**

HI-LHC Detector Occupancies

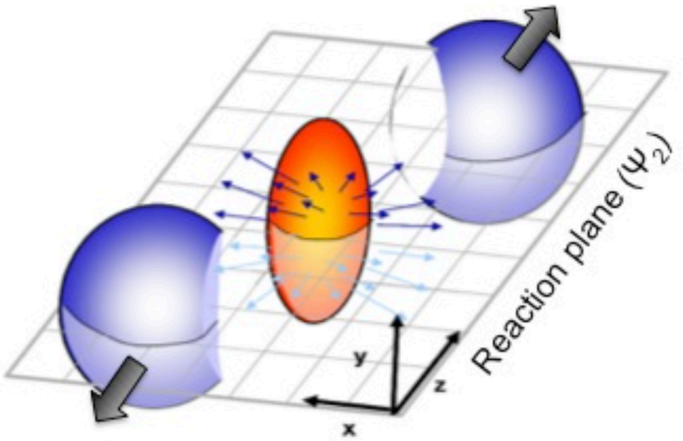


- **Detector occupancies exceed HL-LHC pp expectations**
- **Test future DAQ/Trigger strategies**
  - **Use SSDs to bypass storage disks?**
  - **Happening right now!**
- **In 2023, redefined RAW data format to optimize event throughput (+50%)**
  - **Being adopted CMS HEP community**



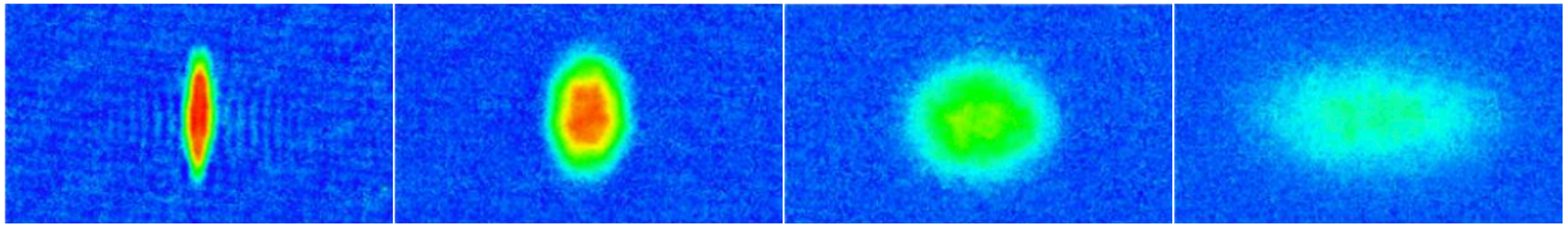
QGP Properties - hydrodynamic flow

- Initial state geometry leads to anisotropic pressure gradients
- Found to correlate with final-state particle momentum
- QGP behaves like a strongly-interacting fluid!
  - Not a weakly-interacting gas (despite being deconfined)

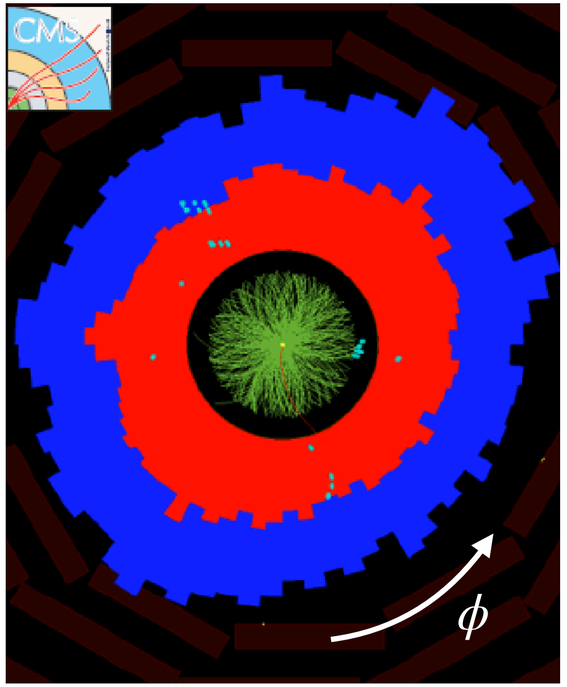


- **Hydrodynamics effectively describes QGP**

Pressure-driven expansion in ultra-cold Li 6 atoms



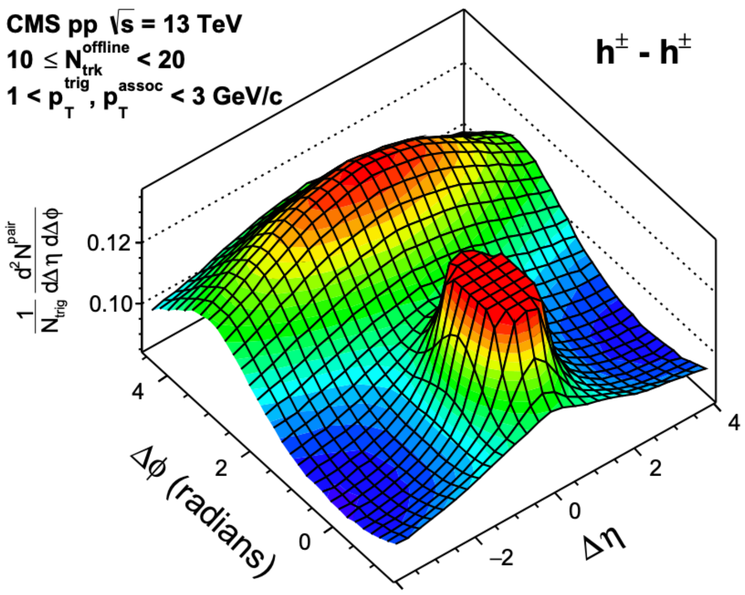
O'Hara, K. M., Et al. Science Dec 13 2002: 2179-2182



Particle correlations

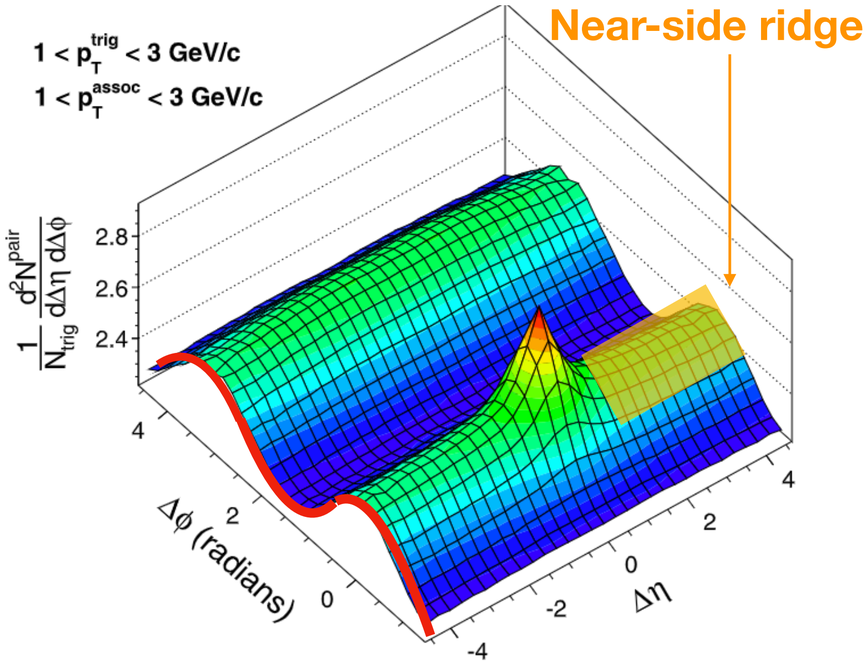
- **Use two-particle correlations to see collective motion**
- **‘near-side ridge’ indicates collective effects**

Inclusive pp

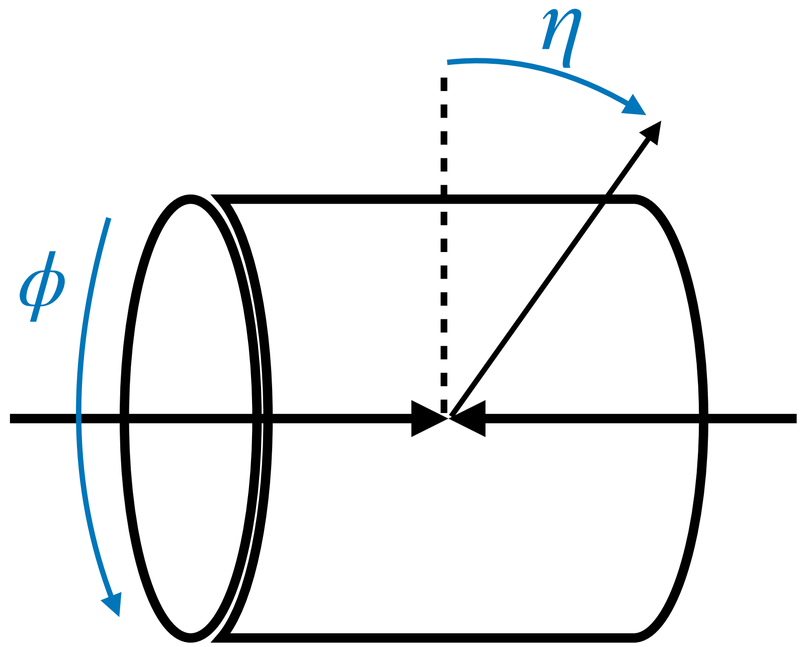


Phys. Lett. B 765 (2017) 193

PbPb



Phys. Lett. B 724 (2013) 213

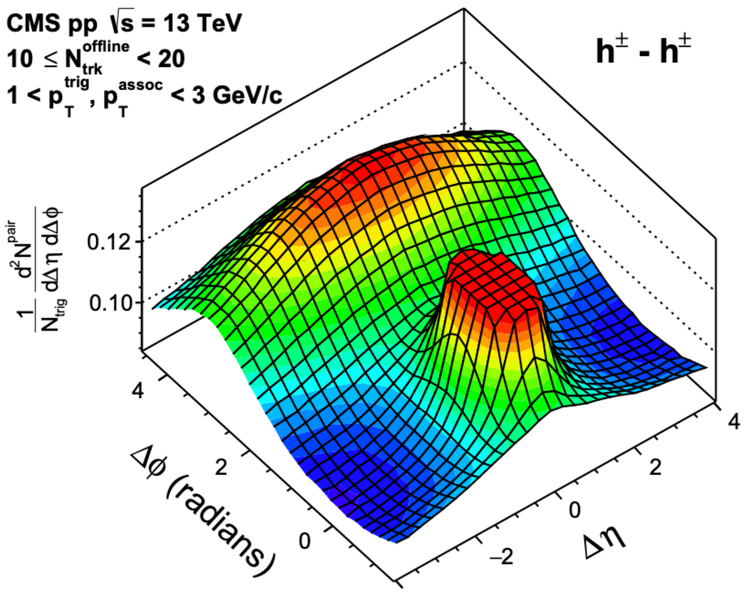


Particle correlations

- **Use two-particle correlations to see collective motion**
- **‘near-side ridge’ indicates collective effects**
- **Fourier decomposition → anisotropy coefficients v_n**

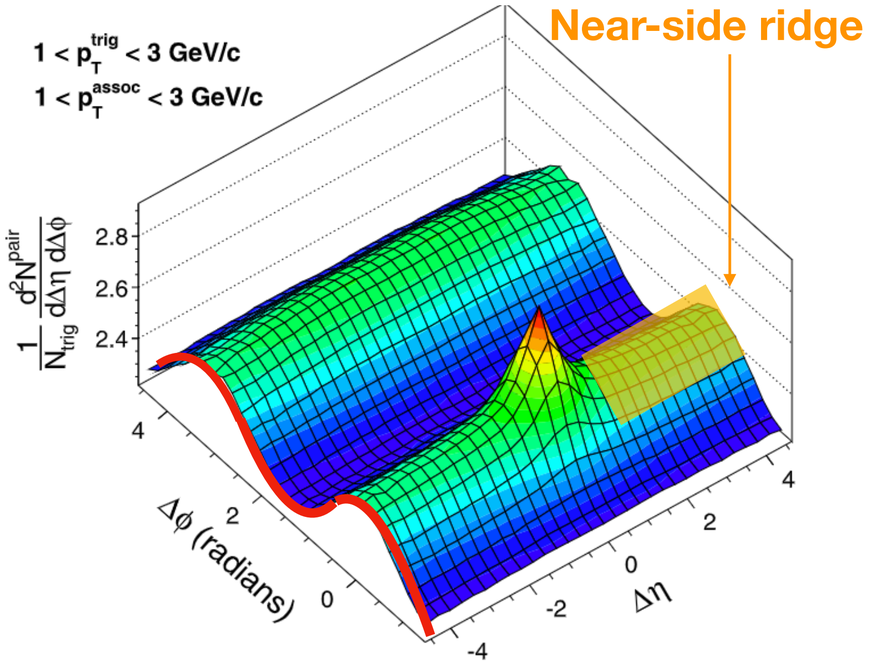
$$\frac{dN^{pairs}}{d\Delta\phi} = \frac{N^{pairs}}{2\pi}\left(1 + \sum_n 2v_n^2 \cos(n\Delta\phi)\right)$$

Inclusive pp

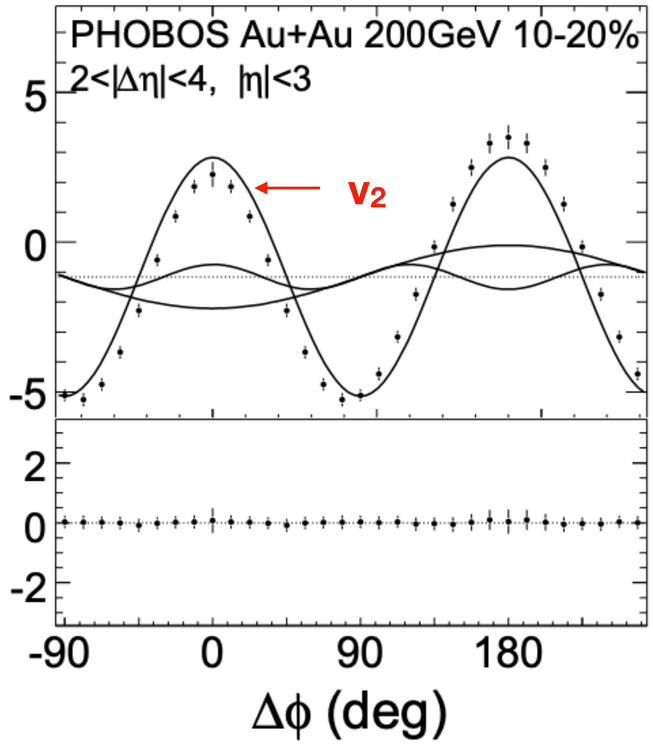


Phys. Lett. B 765 (2013) 193

PbPb



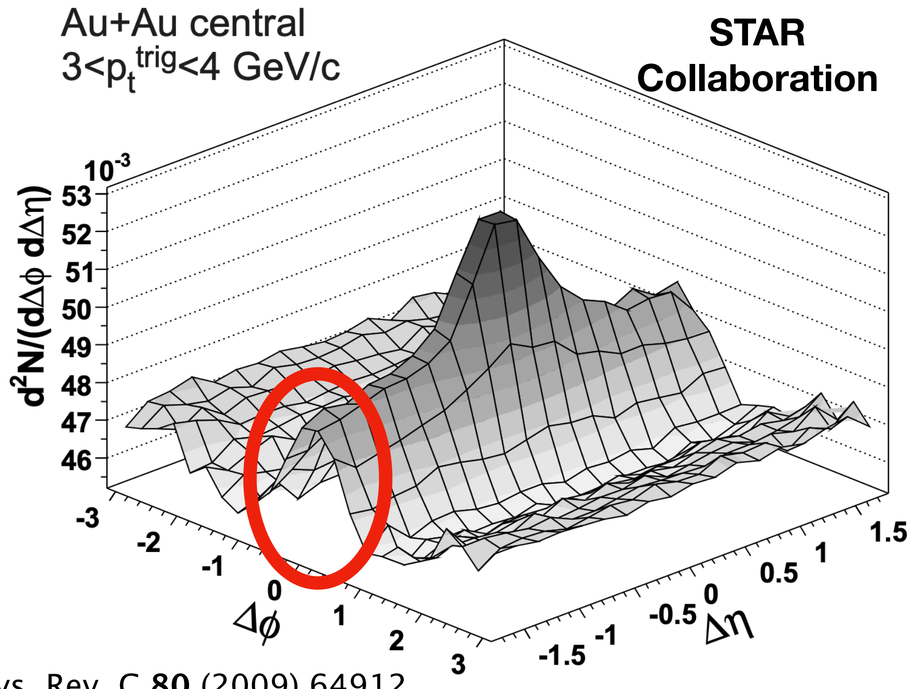
Phys. Lett. B 724 (2013) 213



Alver, B., Roland, G., Phys. Rev. C 81:054905,2010

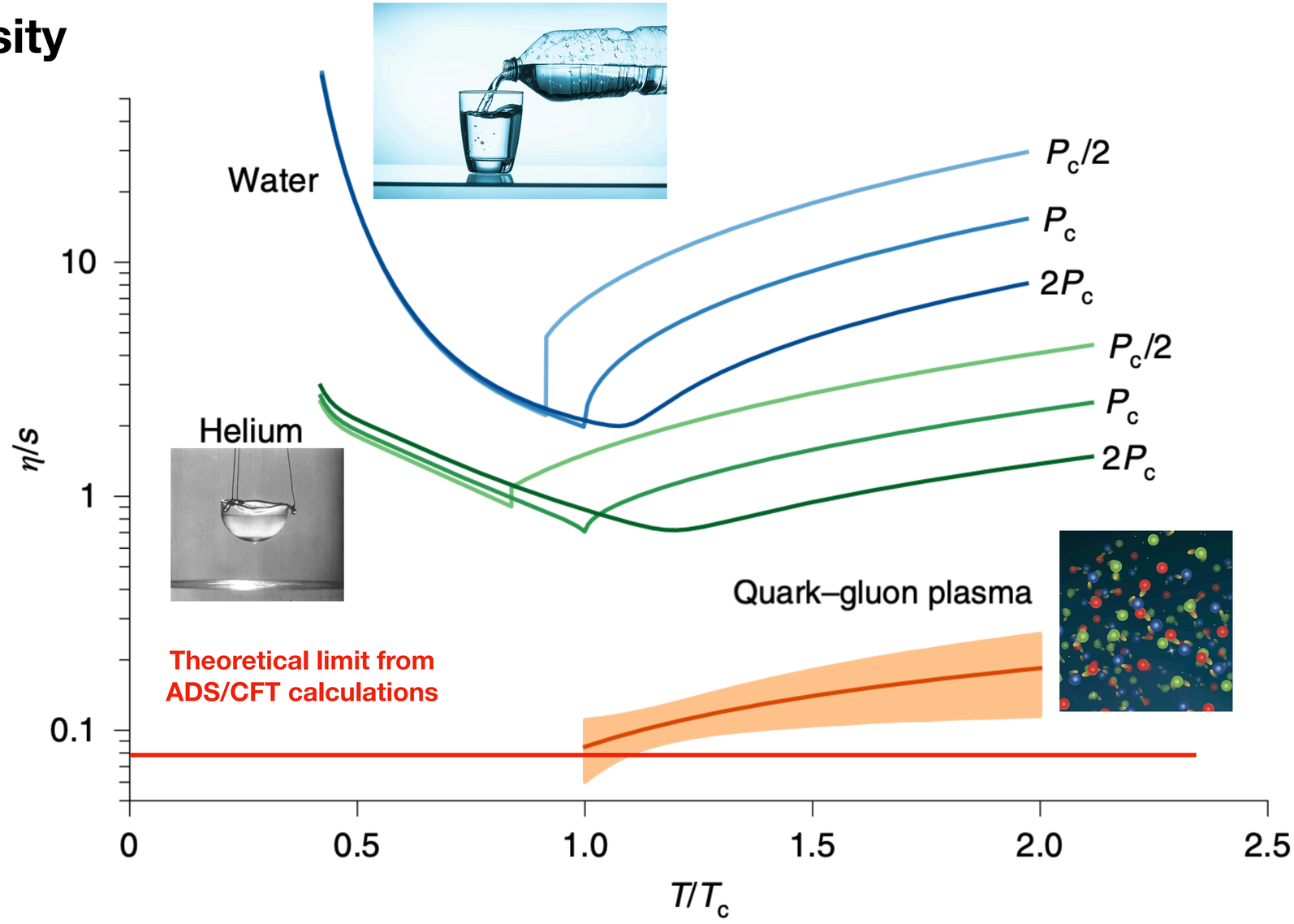
“Perfect Liquid”

- **Shear viscosity to entropy density ratio near theoretical limit**
- **Deconfined but not gas-like**
- **Study microscopic dynamics**



Phys. Rev. C **80** (2009) 64912

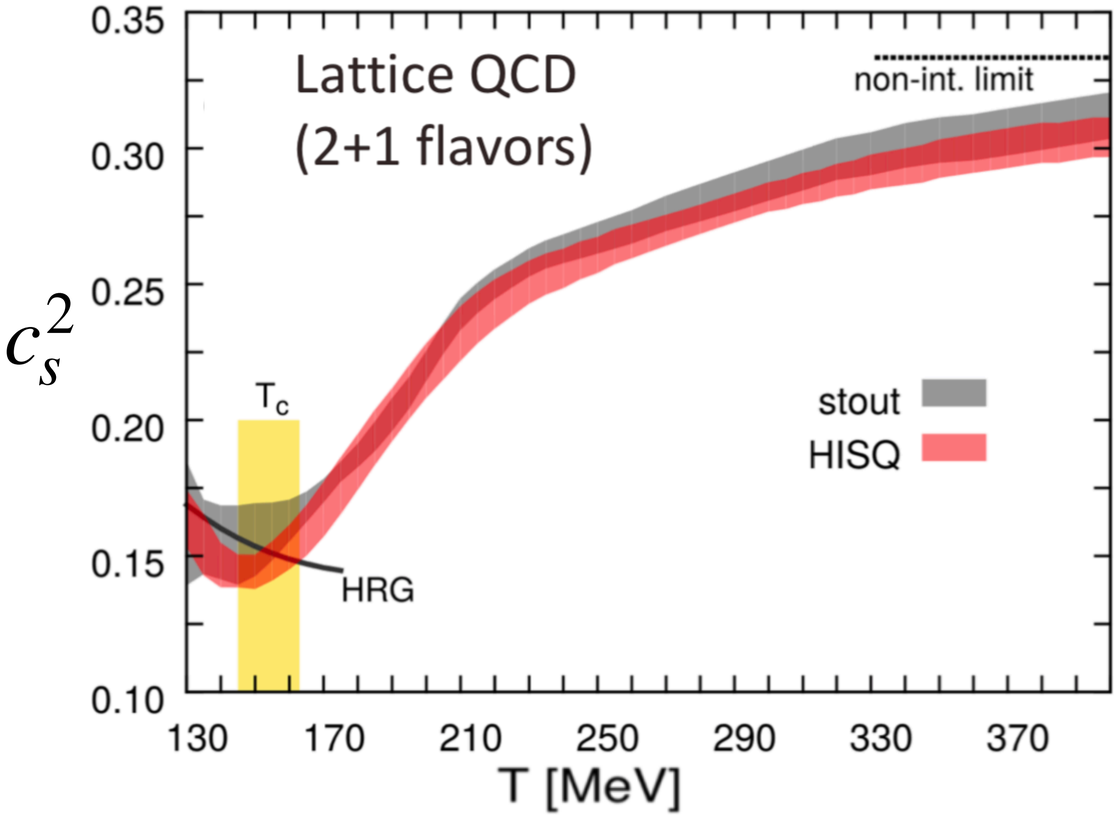
Nature Physics volume 15, 1113–1117 (2019)

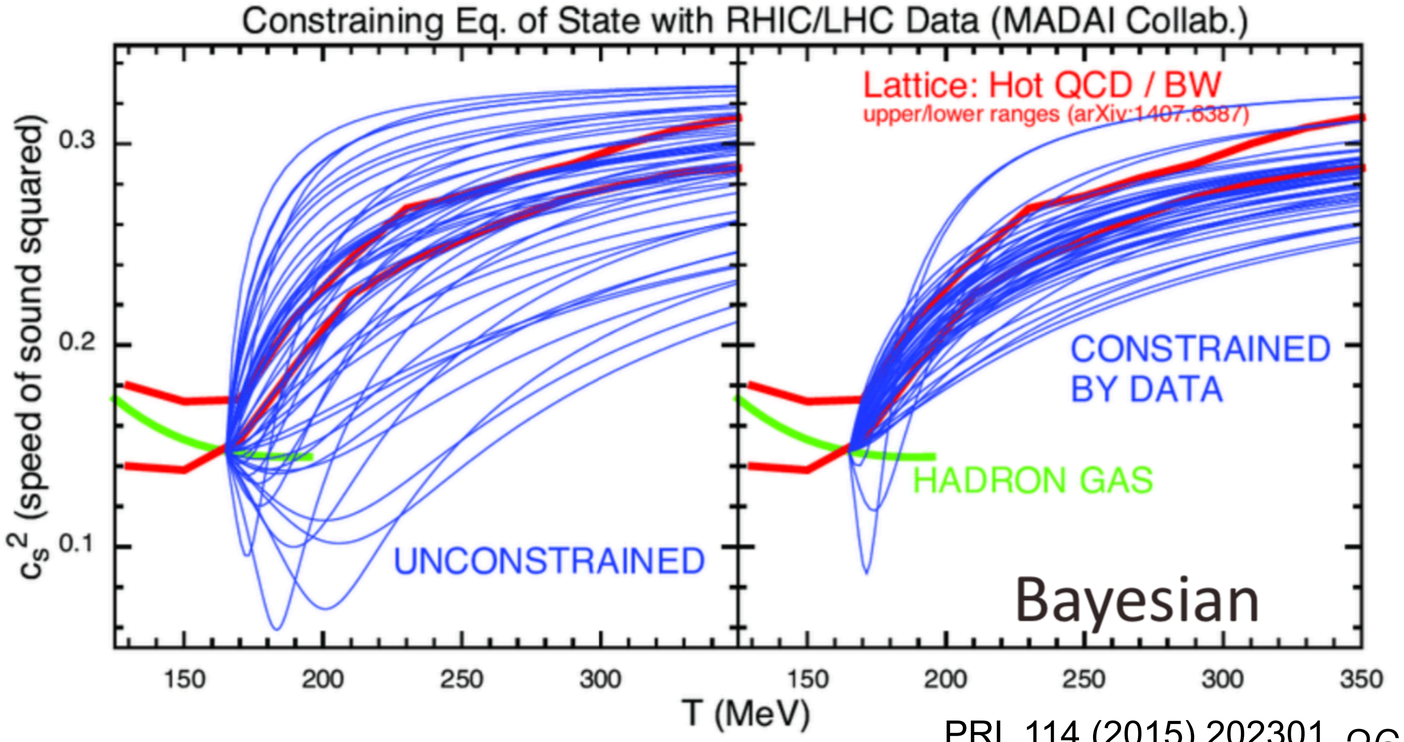


Speed of Sound

- **Longitudinal compression waves propagate in QGP medium**
  - **Speed of sound related to pressure and energy density via:** $c_s^2 = \frac{dP}{d\epsilon}$
- **Potential direct constraint on QGP Equation of State - but more data needed!**

PRD **90** (2014) 094503





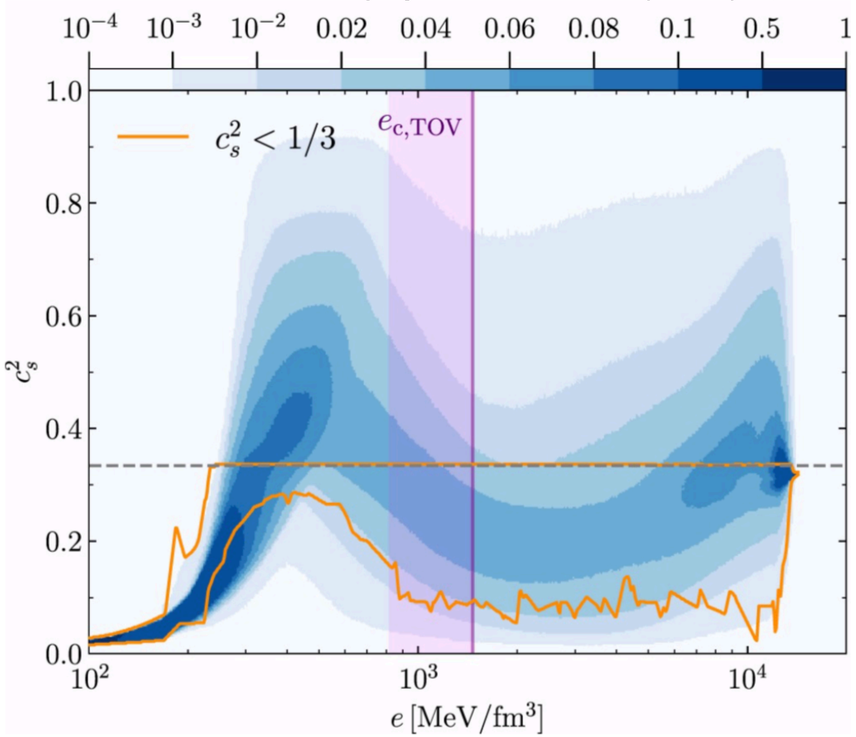
PRL 114 (2015) 202301

Other implications

- **Similar efforts to constrain QCD EoS from astrophysical data (at lower T)**
  - **What is the matter at the center of a neutron star?**

- **Shockwave may form when color charge moves at $v>c_s$**
  - **Is this an observable phenomenon?**

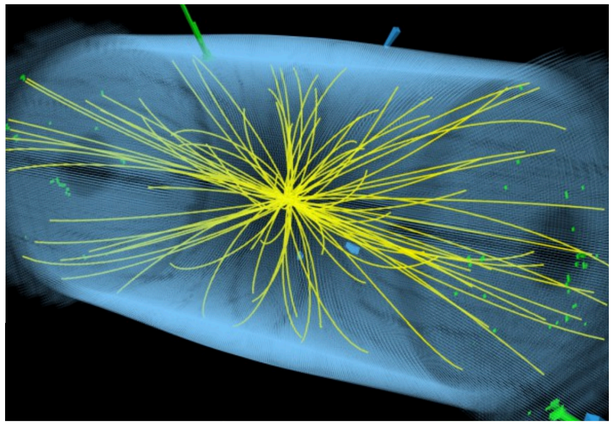
Astrophys. J. Lett. 939 (2022) 2, L34



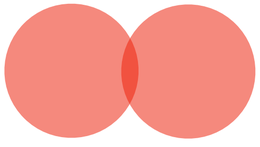
Centrality

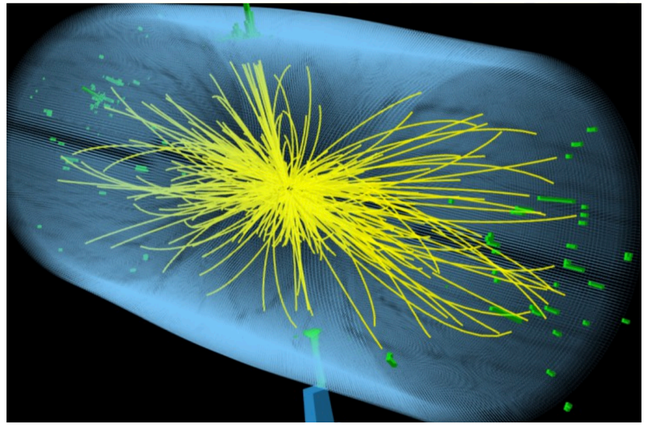
- No control over collision impact parameter
- More event activity = more overlap between nuclei
- Classified into ‘centrality’ ranges from 0-100%
- Central events produce the most QGP

Proton-Proton

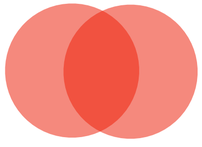


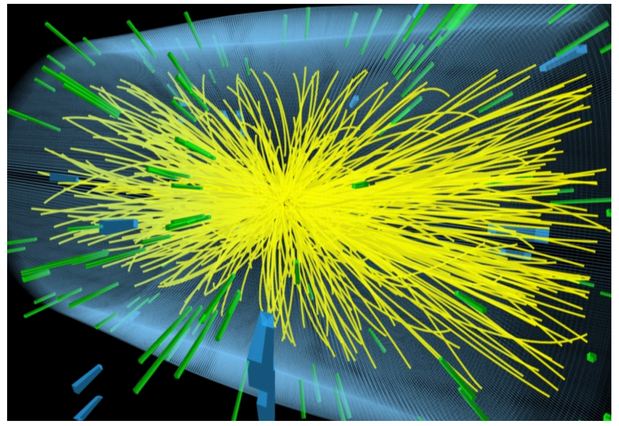
Peripheral
(100%)



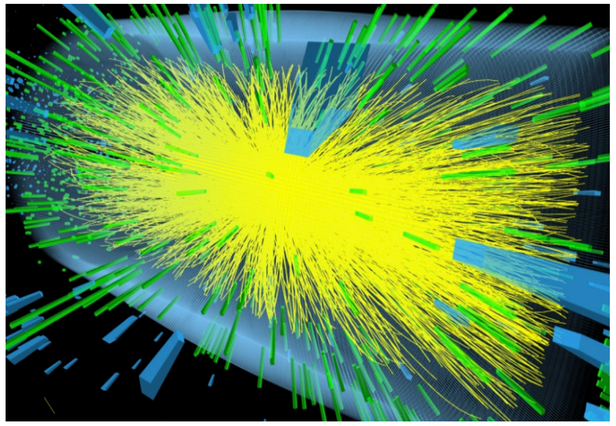


Middle
(50%)



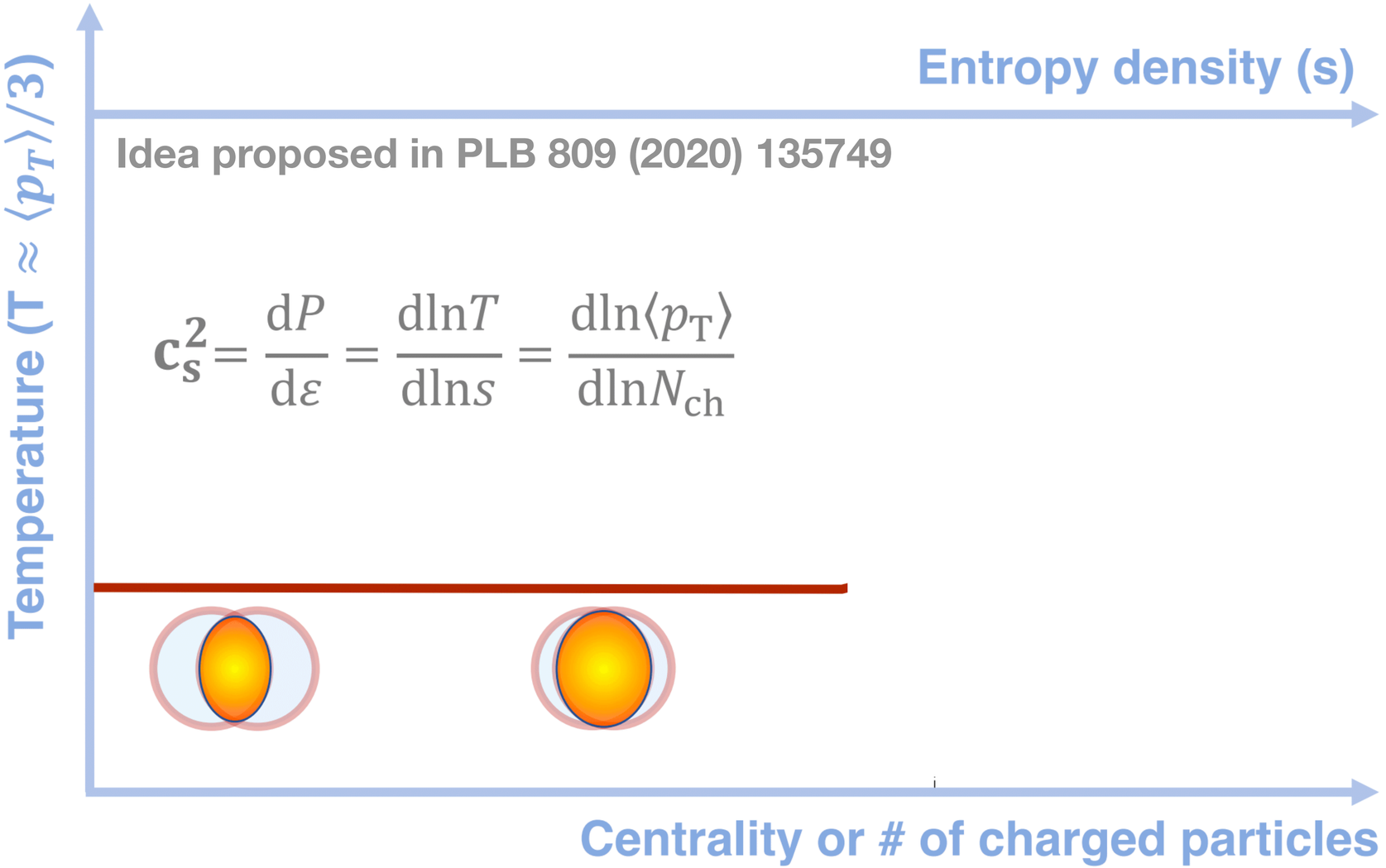


Central
(0%)



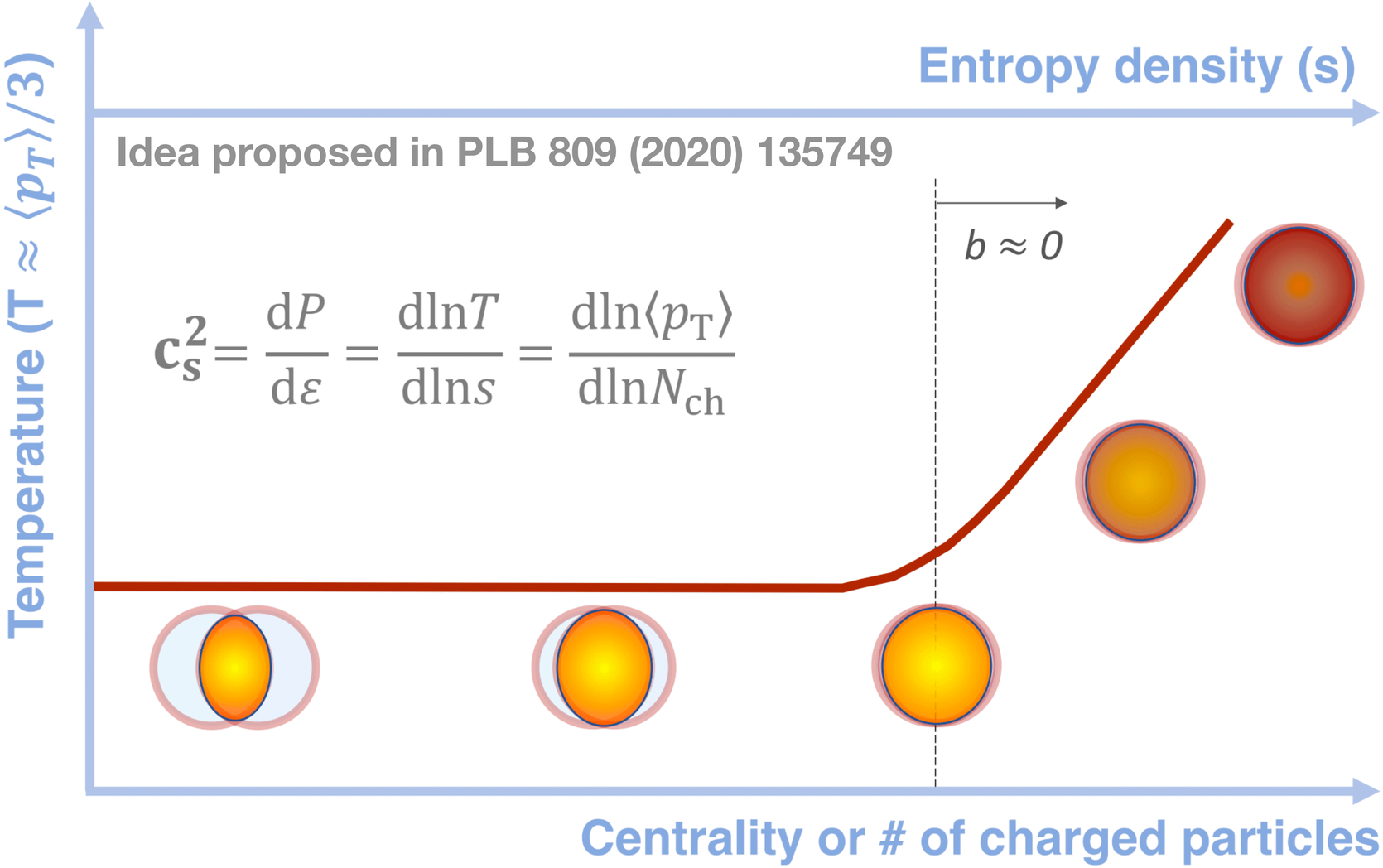
New analysis method

- **QGP c_s extracted from measurements of $\langle p_T \rangle$ vs N_{ch} vs centrality at same $\sqrt{s_{NN}}$**

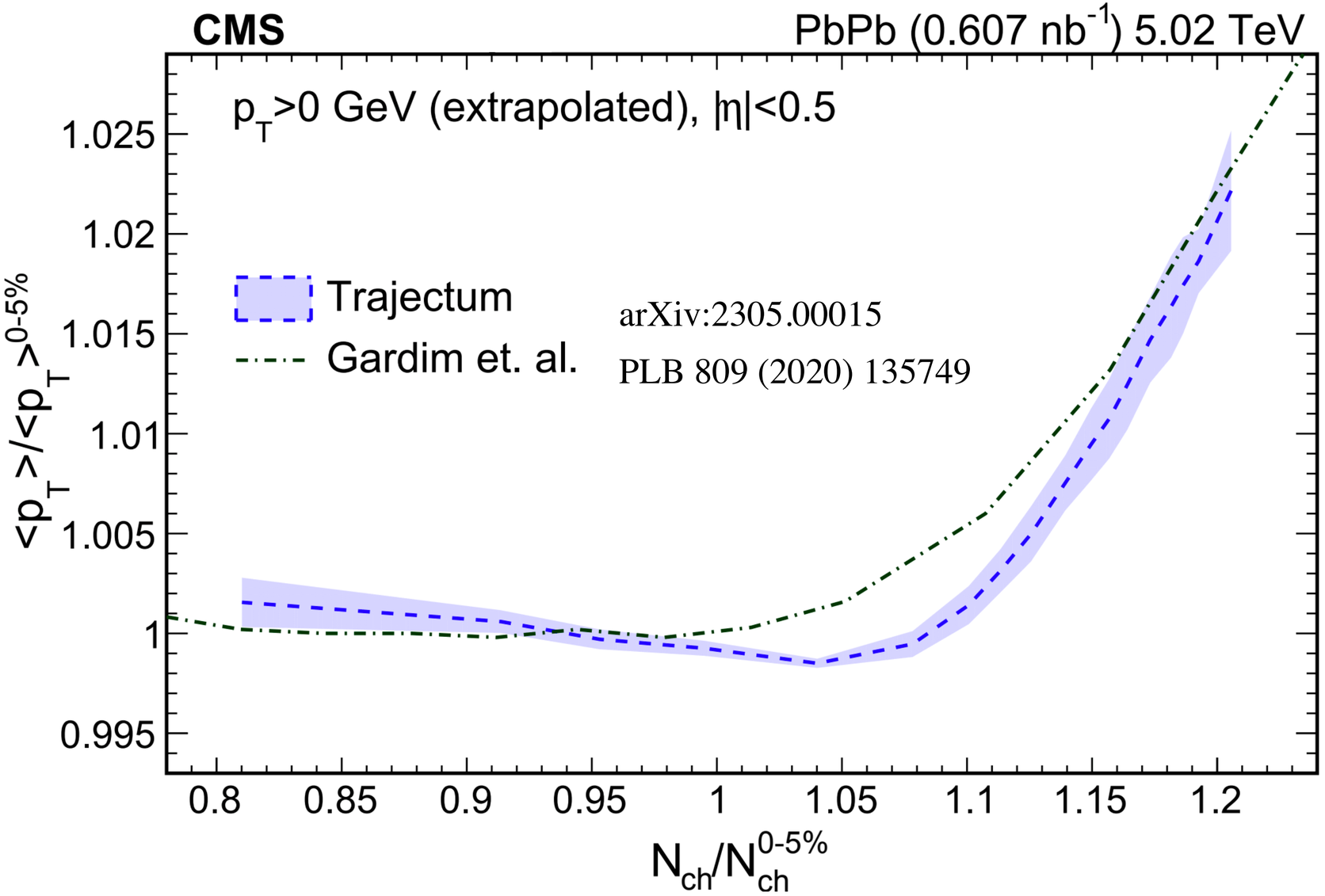


New analysis method

- **QGP c_s extracted from measurements of $\langle p_T \rangle$ vs N_{ch} vs centrality at same $\sqrt{s_{NN}}$**
- **Use fluctuations in b=0 collisions to vary energy density at fixed volume**

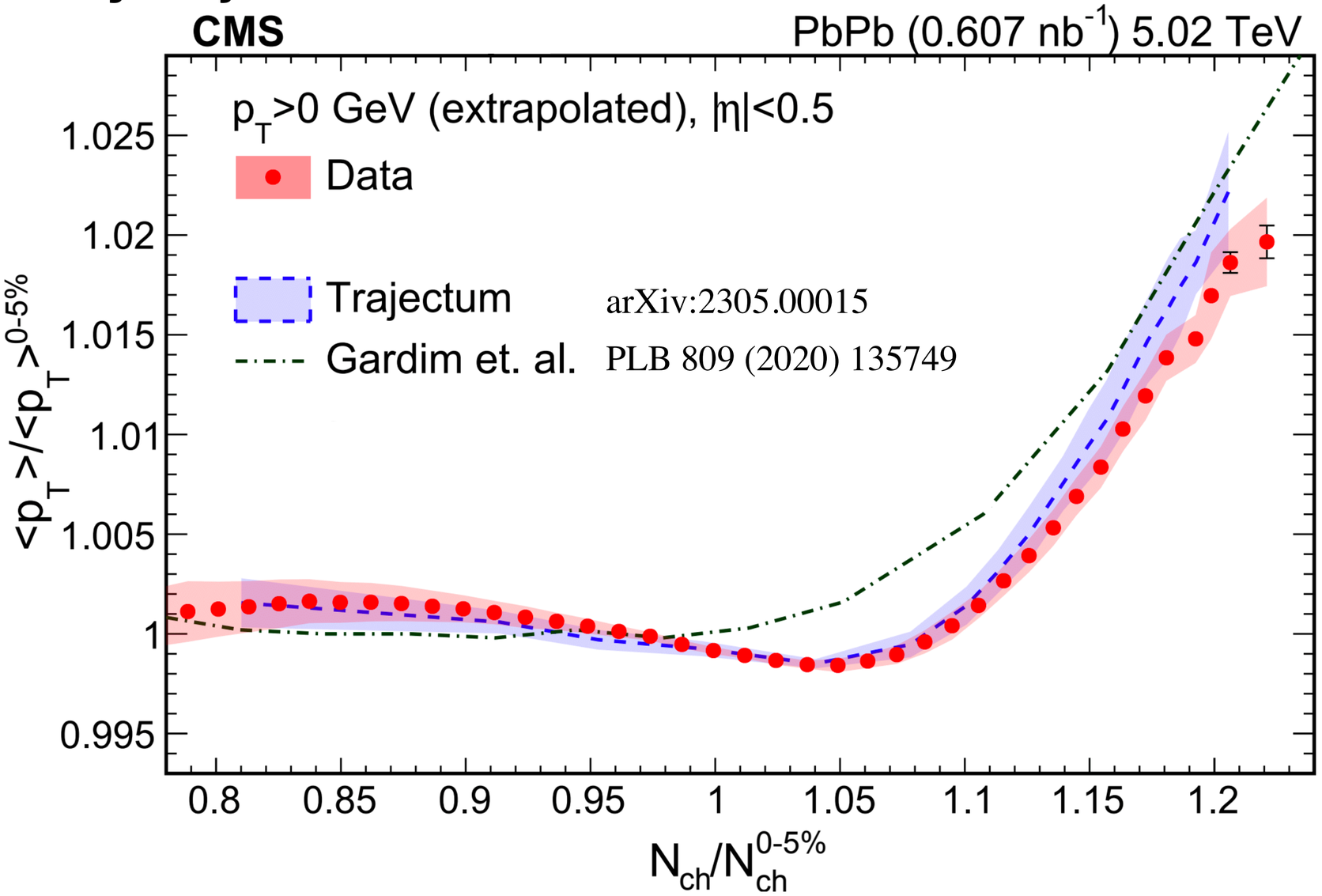


Hydro predictions



Speed of Sound in QGP

- **Slope of data matches models closely!**
- **'Dip' predicted by Trajectum also in the data!**



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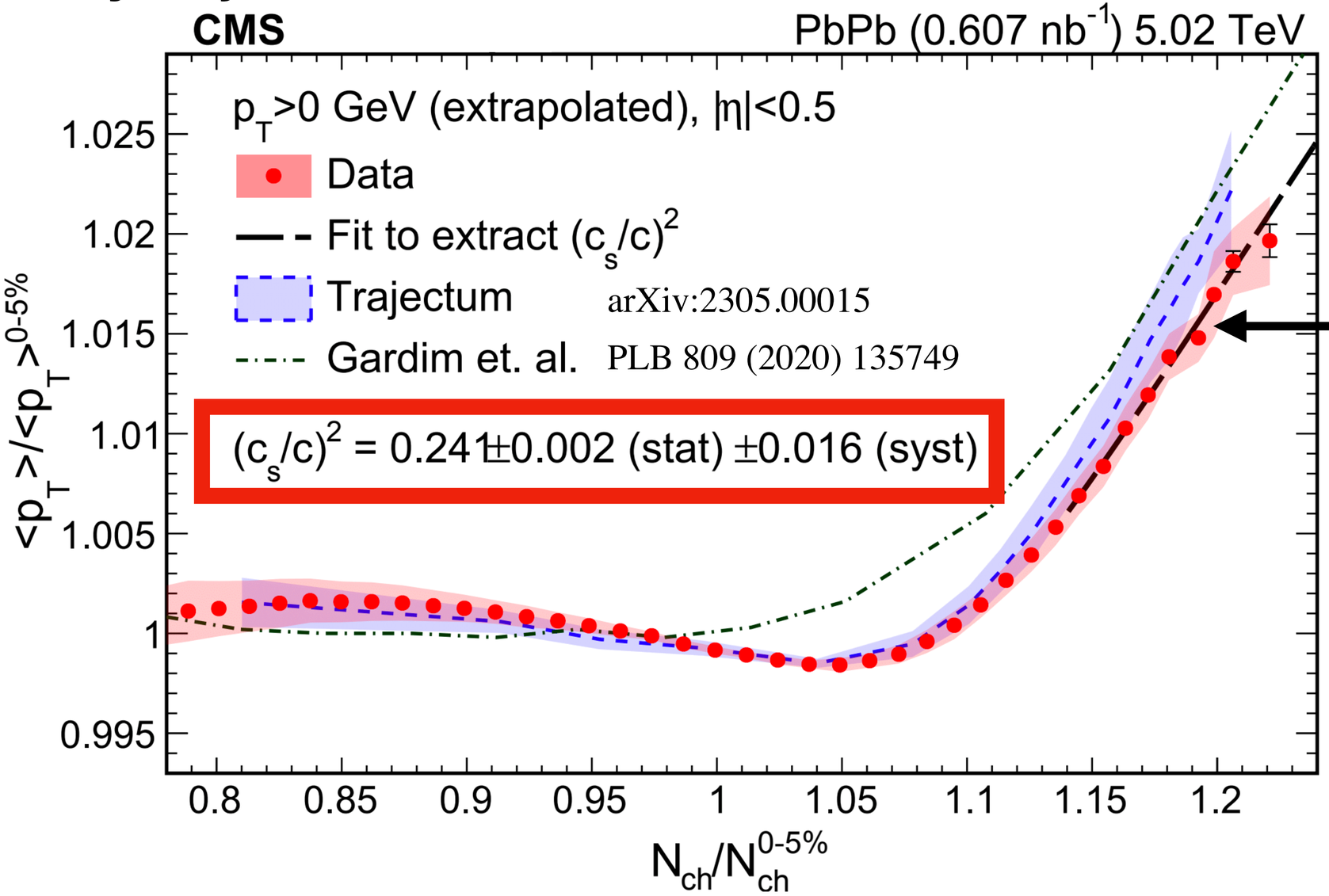
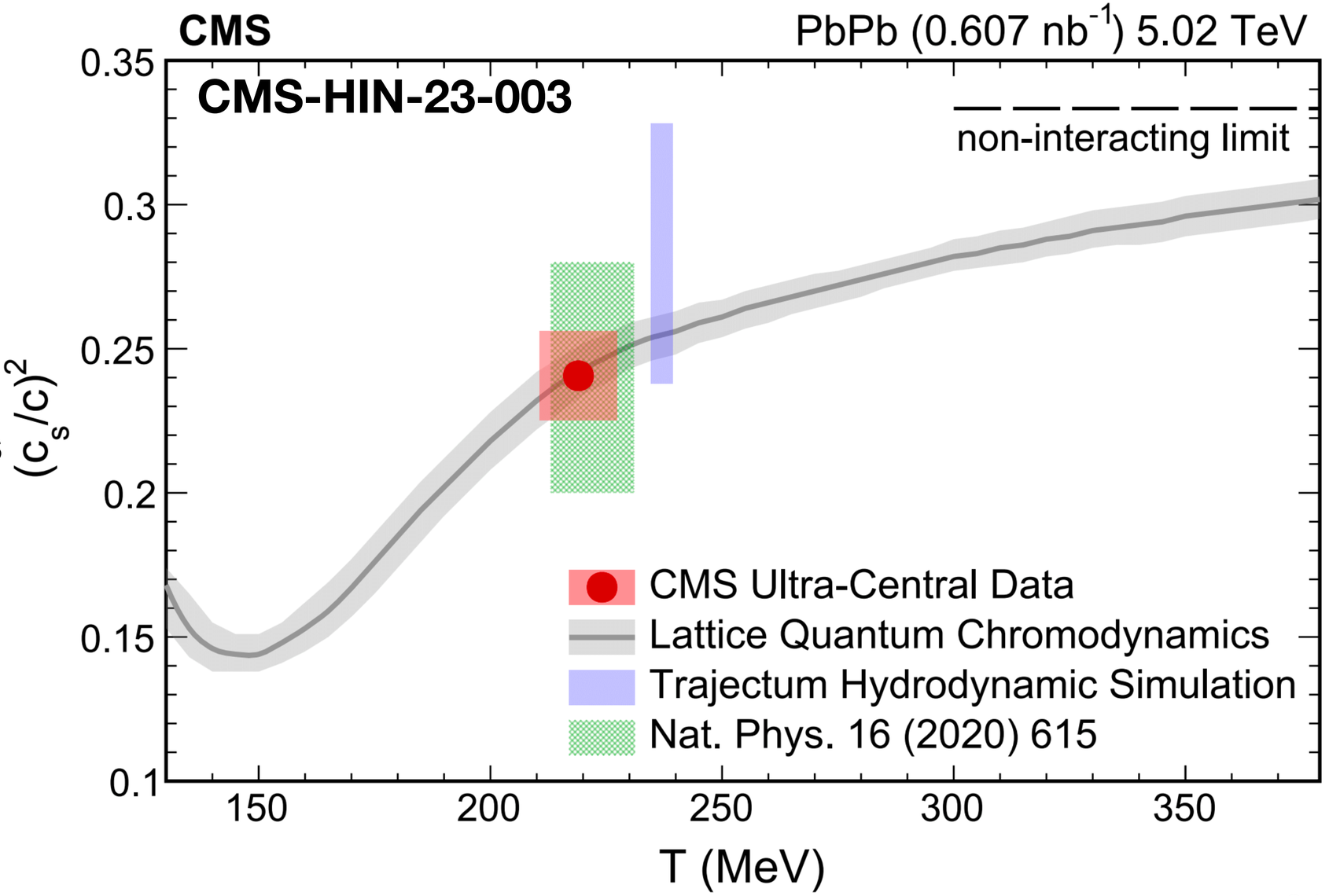


Fit slope to get c_s^2

QGP Speed of Sound

- **c_s in air: 343 m/s**
- **c_s in water: 1500 m/s**
- **c_s in steel: 5000 m/s**
- **c_s in QGP: 150,000,000 m/s**

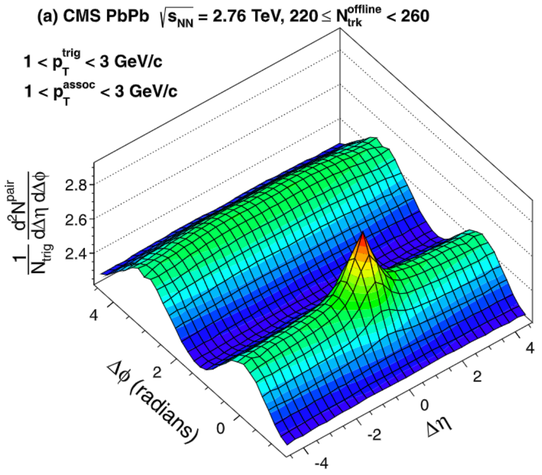
- **Excellent agreement with Lattice QCD**



Smaller Systems Surprises

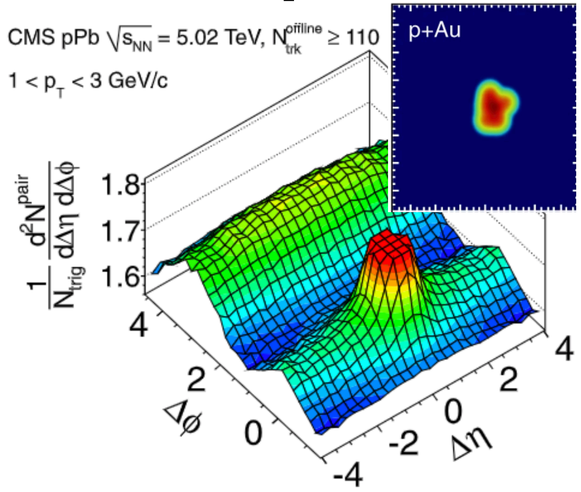
- **‘Fluid-like’ signal observed in both pPb and high-multiplicity pp collisions, not e^+e^-**
  - **Perhaps a small drop of QGP is formed!**
  - **One of the major discoveries at the LHC**
- **Alternative interpretations**
  - **Parton rescattering, initial-state effects, ‘escape mechanism’**

PbPb



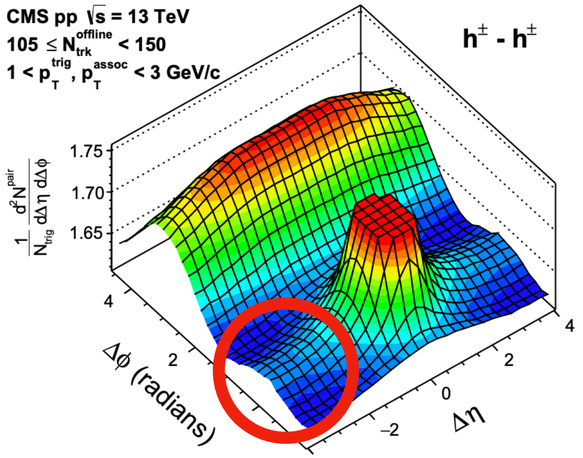
Phys. Lett. B 724 (2013) 213

pPb



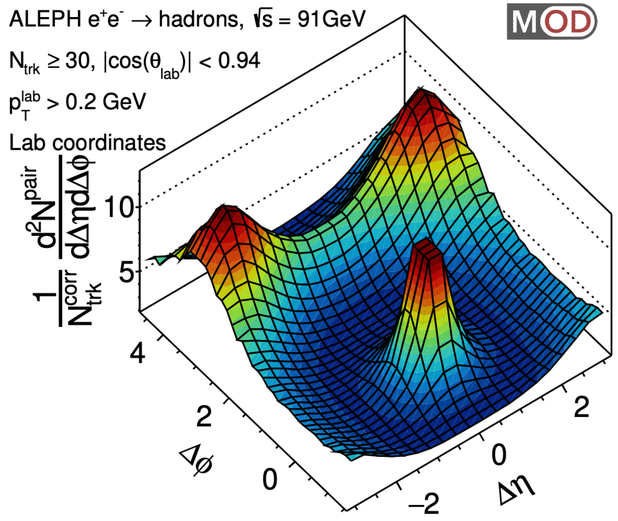
Phys. Lett. B 718 (2013) 795

High-multiplicity pp



Phys. Lett. B 765 (2017) 193

High-multiplicity e+e-



Badea, A., AB, et. al. PRL 123, 212002 (2019)

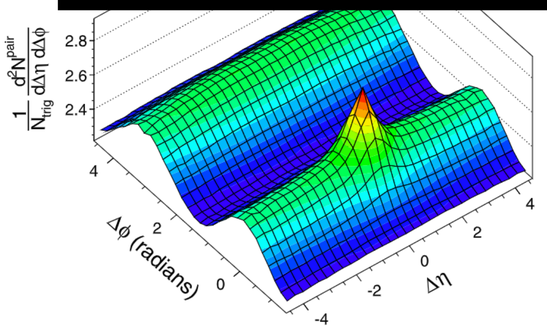
Smaller Systems Surprises

- ‘Fluid-like’ signal observed in both pPb and high-multiplicity pp collisions, not e^+e^-
  - Perhaps a small drop of QGP is formed!
  - One of the major discoveries at the LHC
-

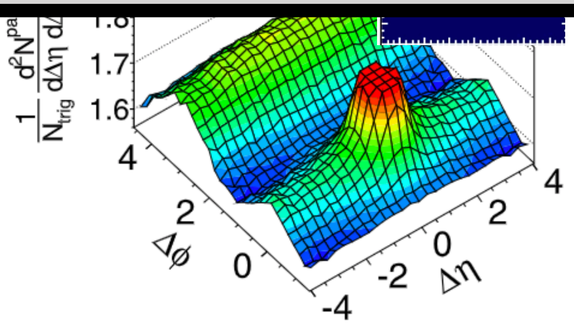
Are correlations in dense systems a general consequence of QCD?

From how small of a system can collectivity emerge?

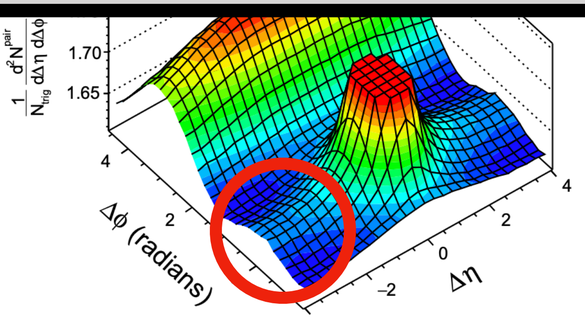
Can hydrodynamics be applied on other non-perturbative processes?



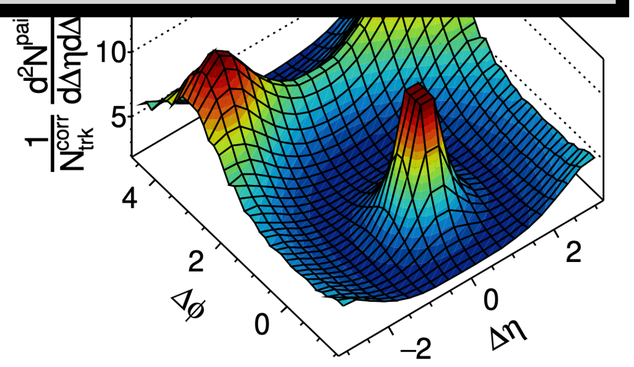
Phys. Lett. B 724 (2013) 213



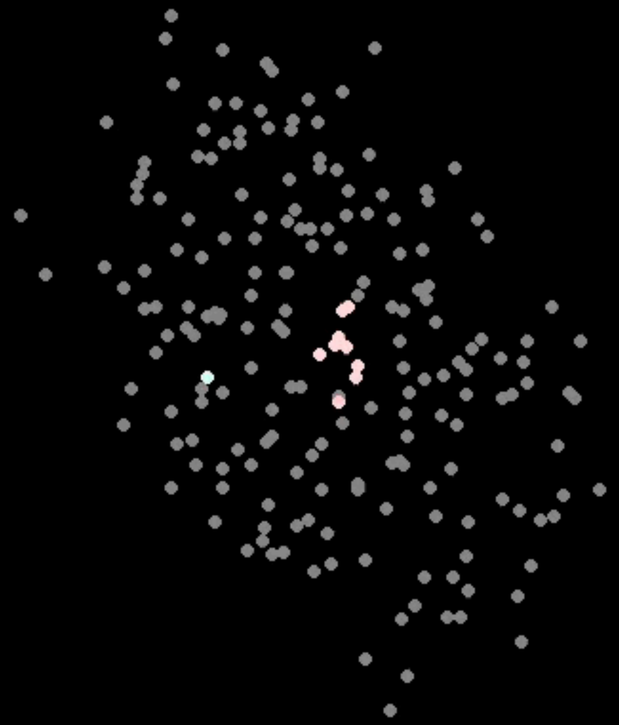
Phys. Lett. B 718 (2013) 795

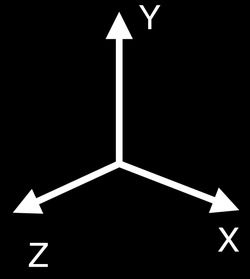


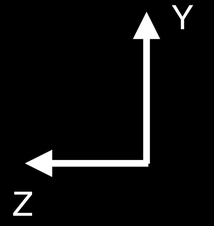
Phys. Lett. B 765 (2017) 193



Badea, A., AB, et. al. PRL 123, 212002 (2019)







Simulation from Chun Shen

The Electron-Ion Collider

A machine that will unlock the secrets of the strongest force in Nature

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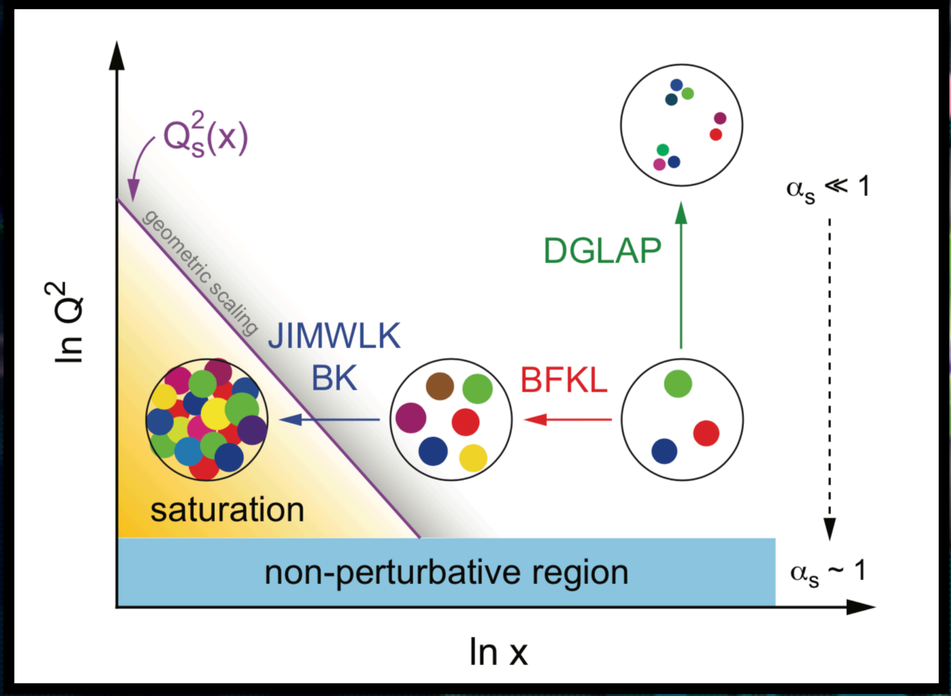
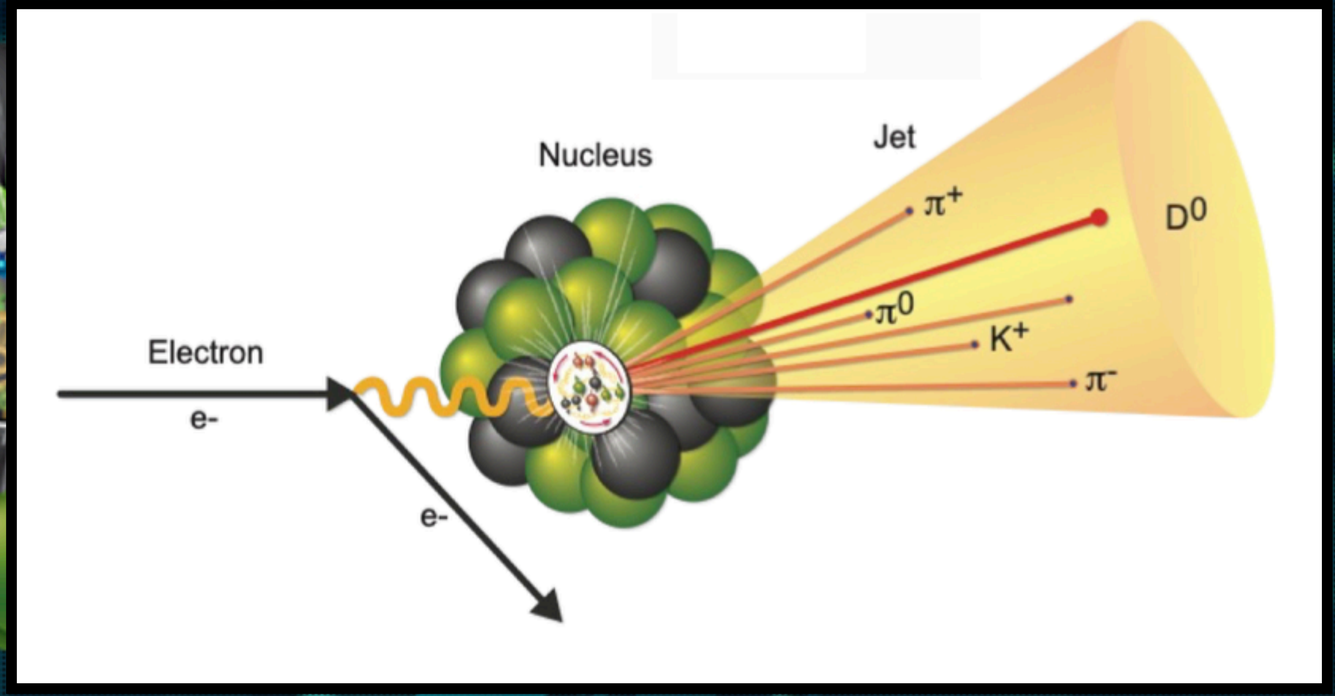
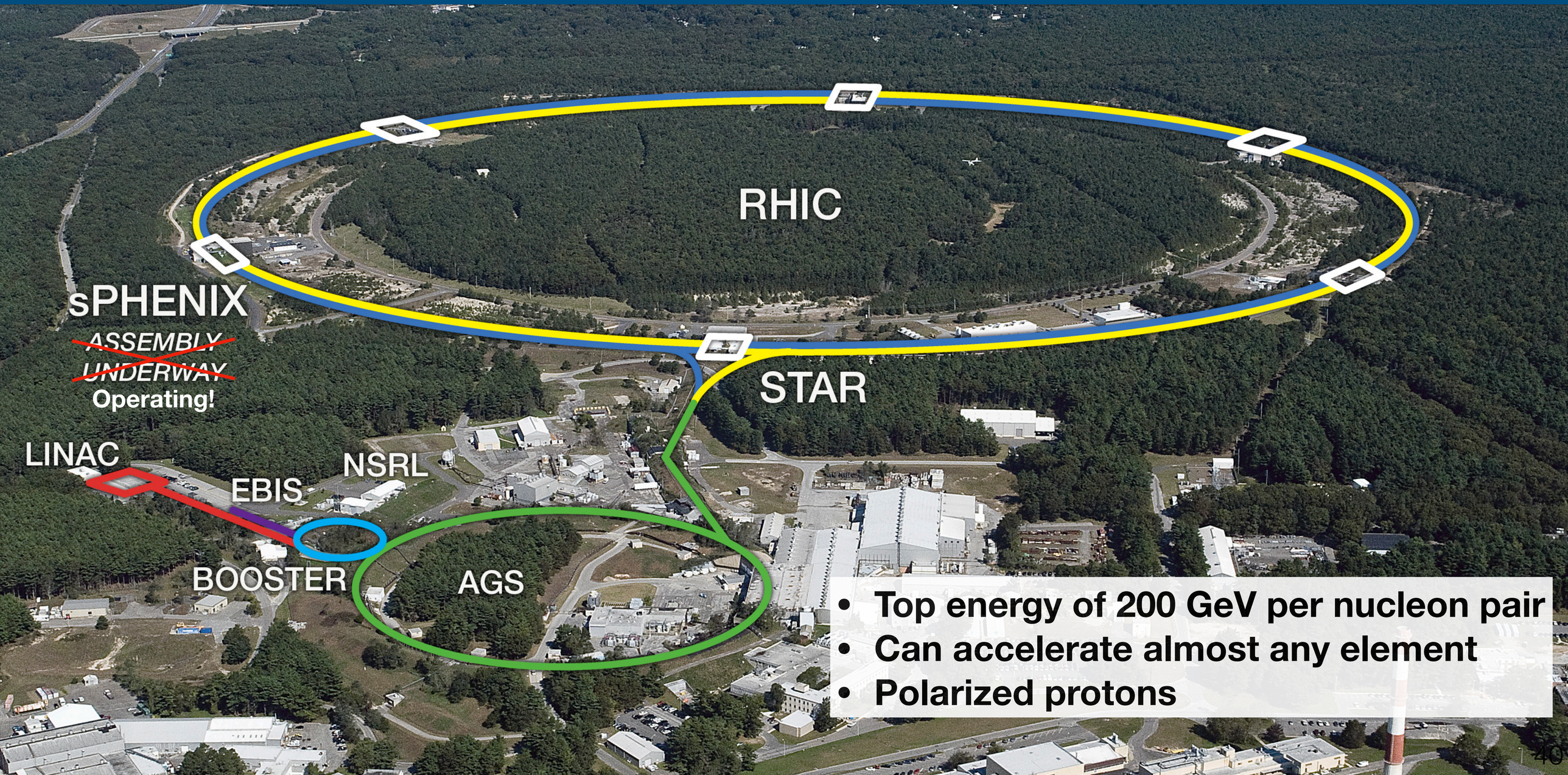


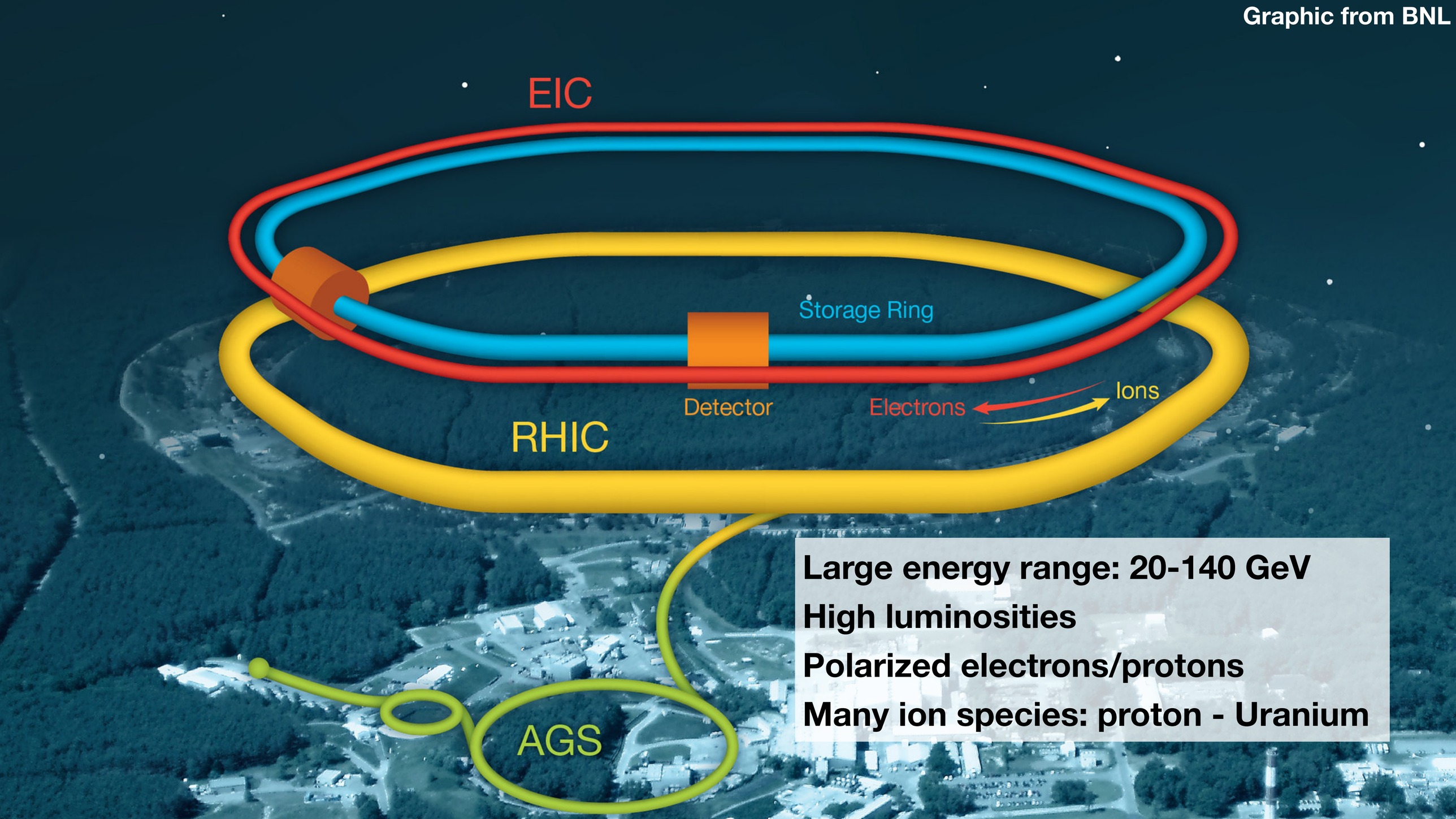


Relativistic Heavy Ion Collider



- **Top energy of 200 GeV per nucleon pair**
- **Can accelerate almost any element**
- **Polarized protons**

Graphic from BNL



Large energy range: 20-140 GeV

High luminosities

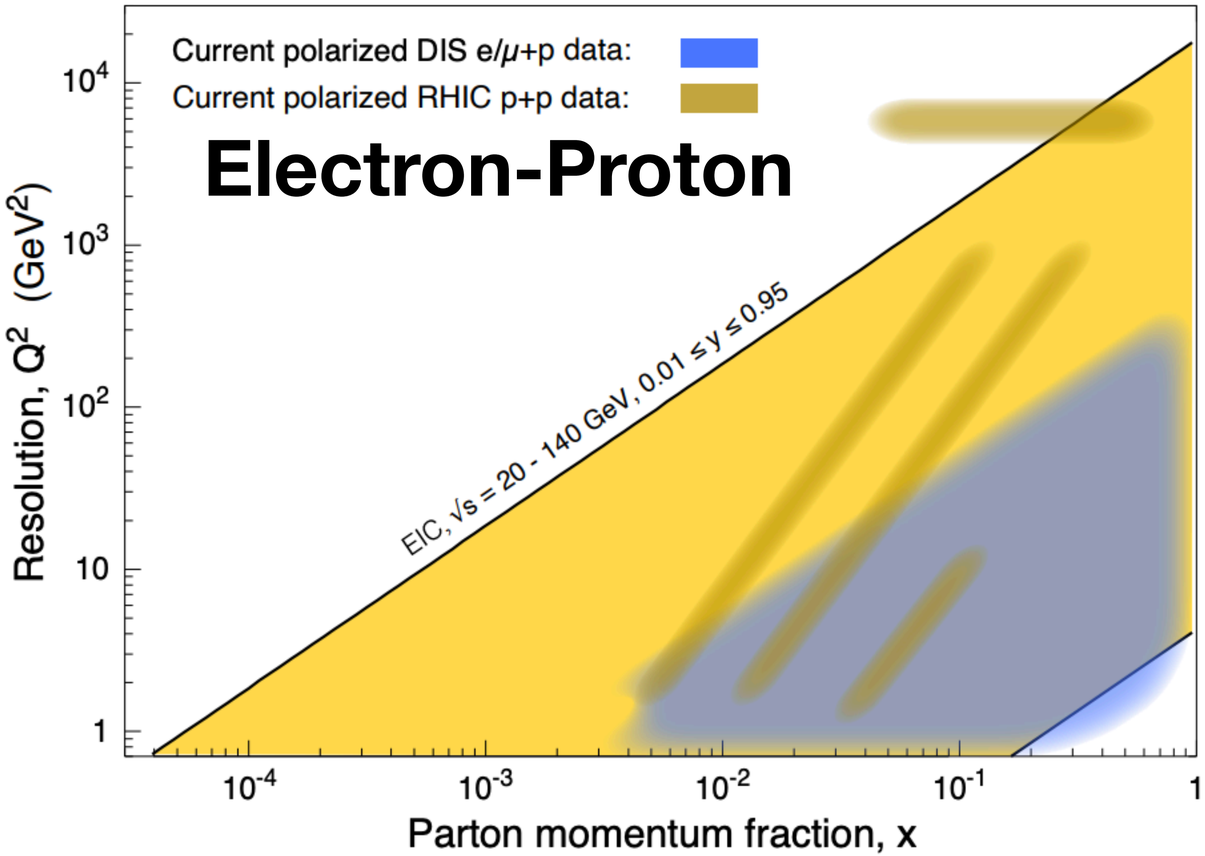
Polarized electrons/protons

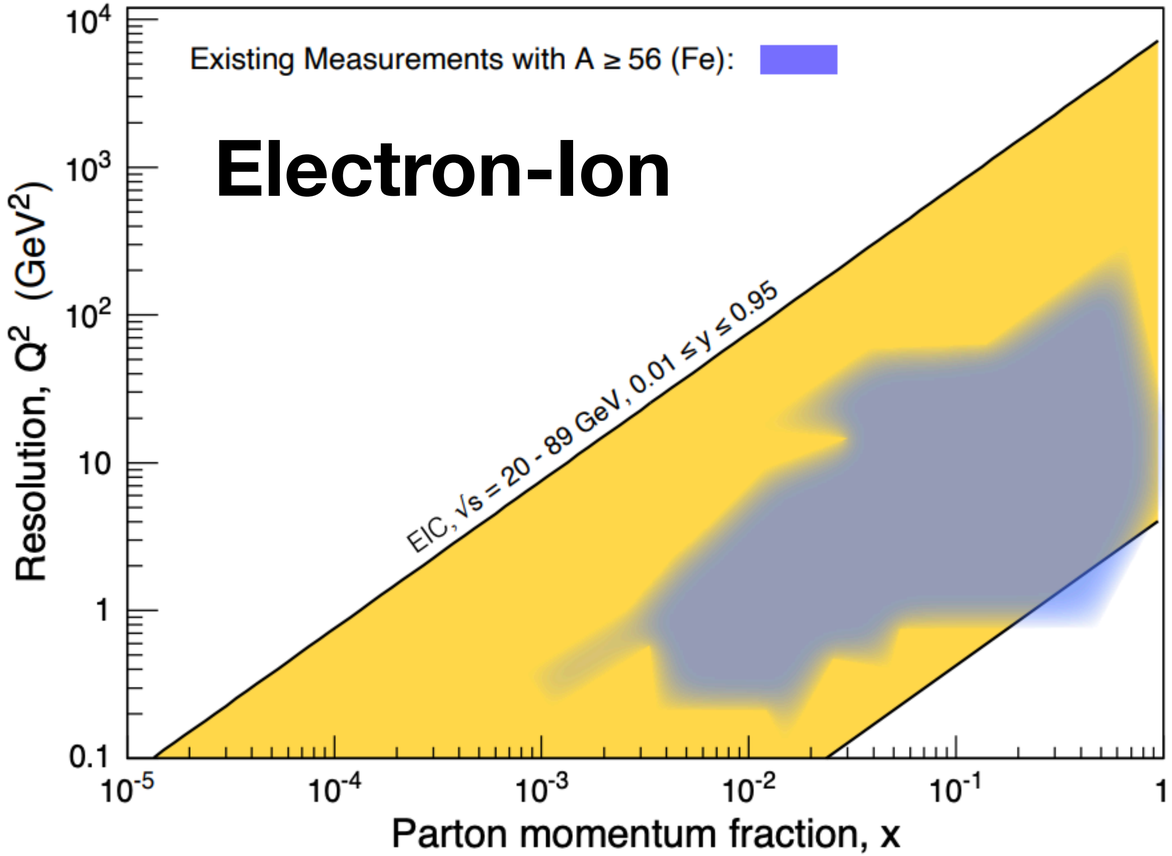
Many ion species: proton - Uranium

EIC Parameters

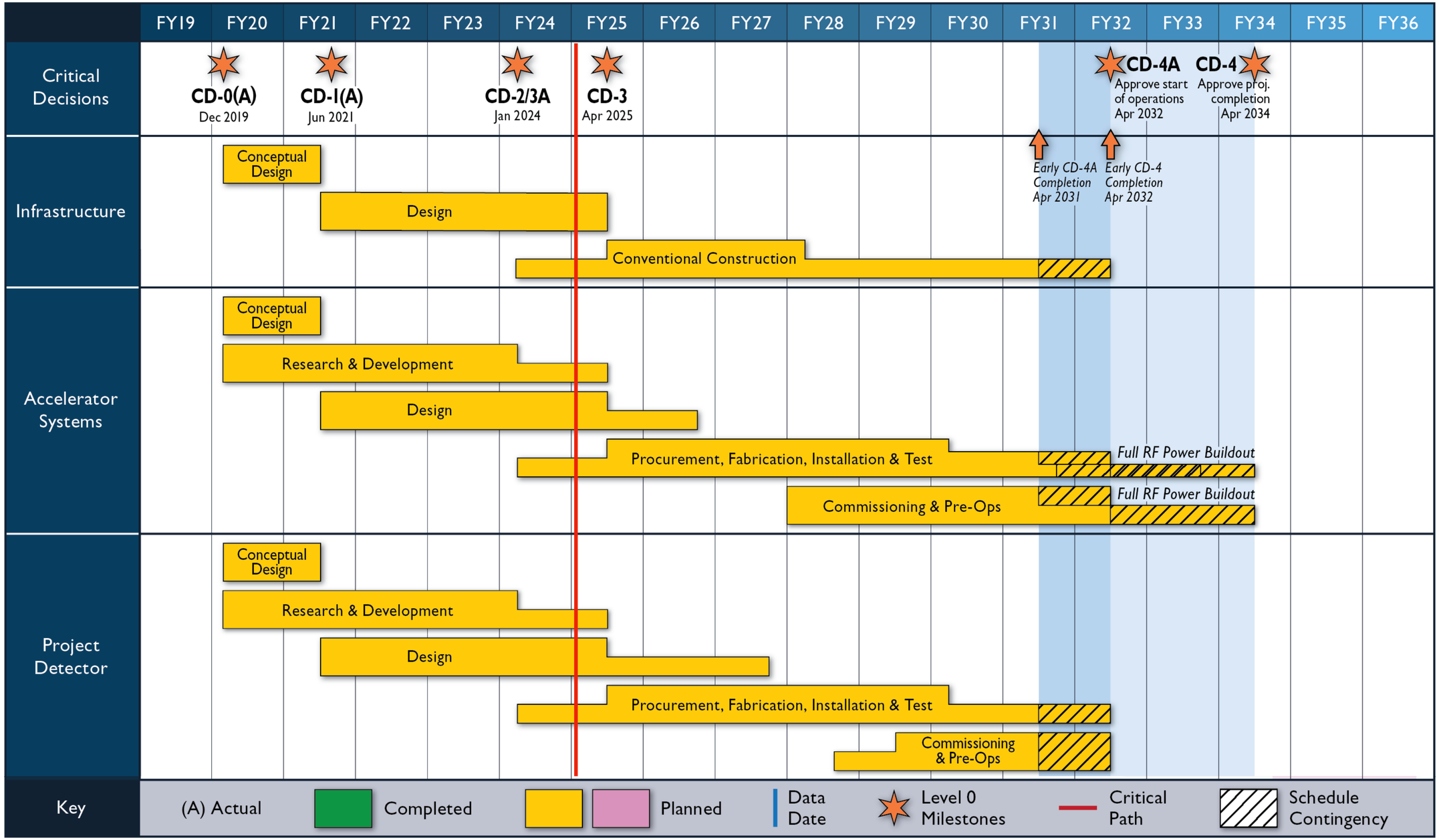
- **Huge increase in coverage for x, Q^2**
- **Can study any ion with high precision**
  - **Polarization allows access to studies of angular momentum/spin**

arXiv:2103.05419



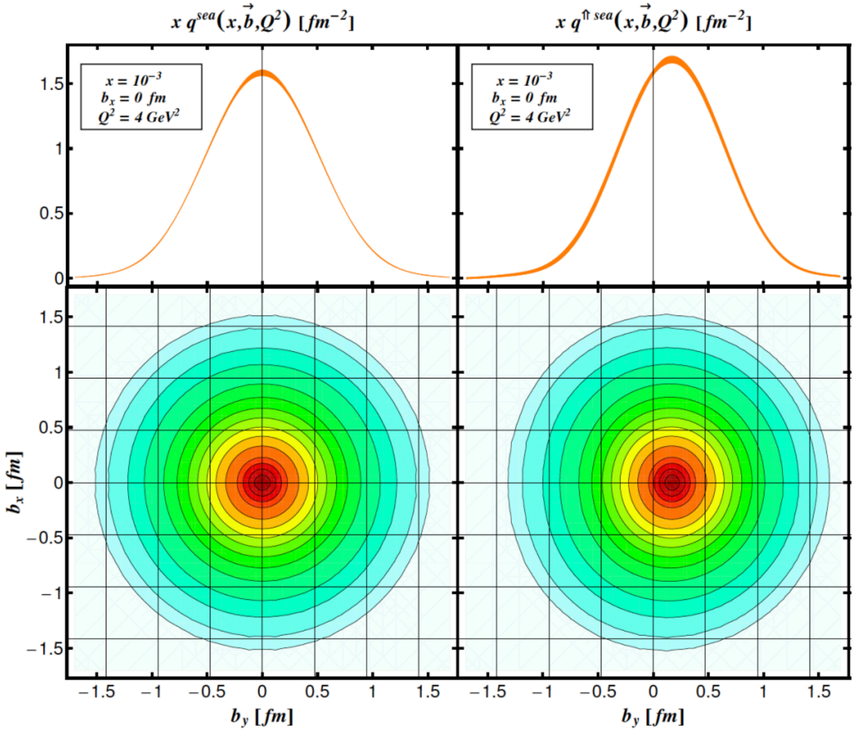


EIC Schedule

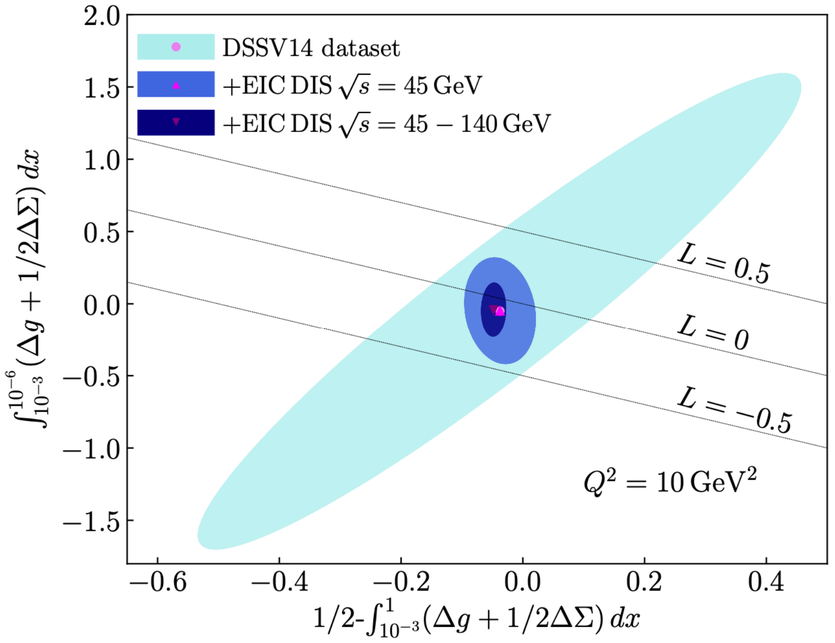


EIC Physics

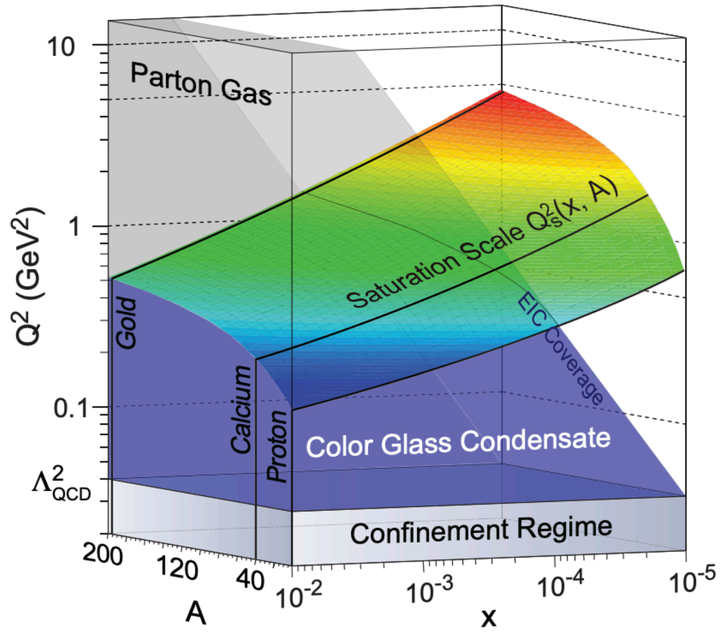
Tomography of partons inside proton/nuclei

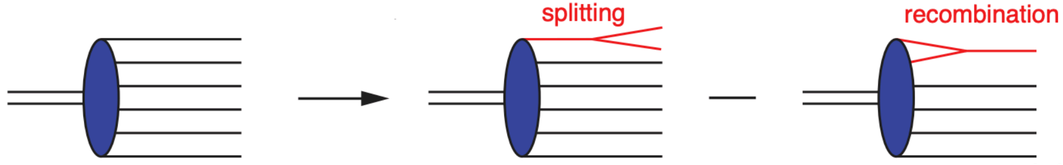


Proton Spin Puzzle



Search for Color-Glass Condensate



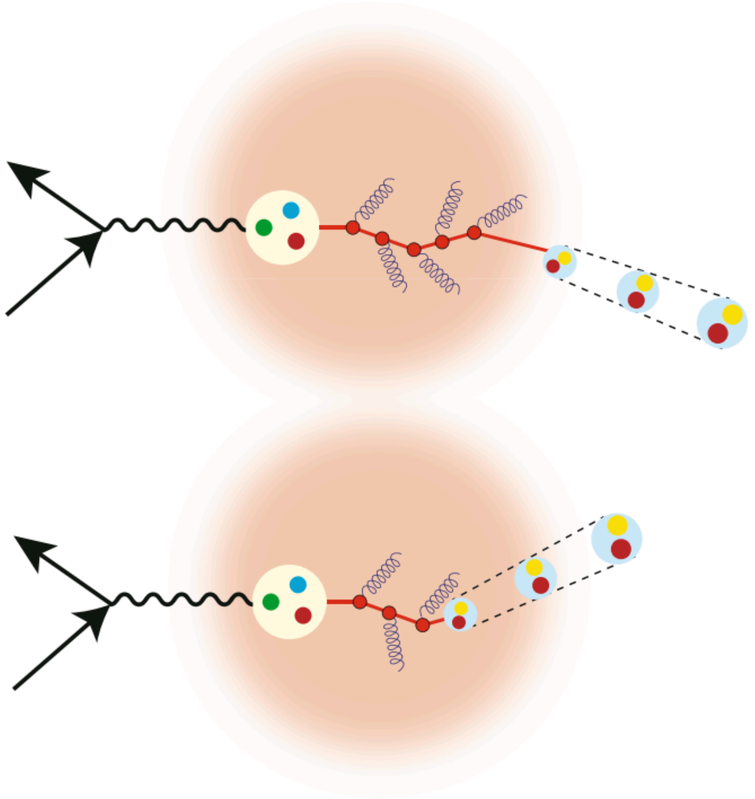


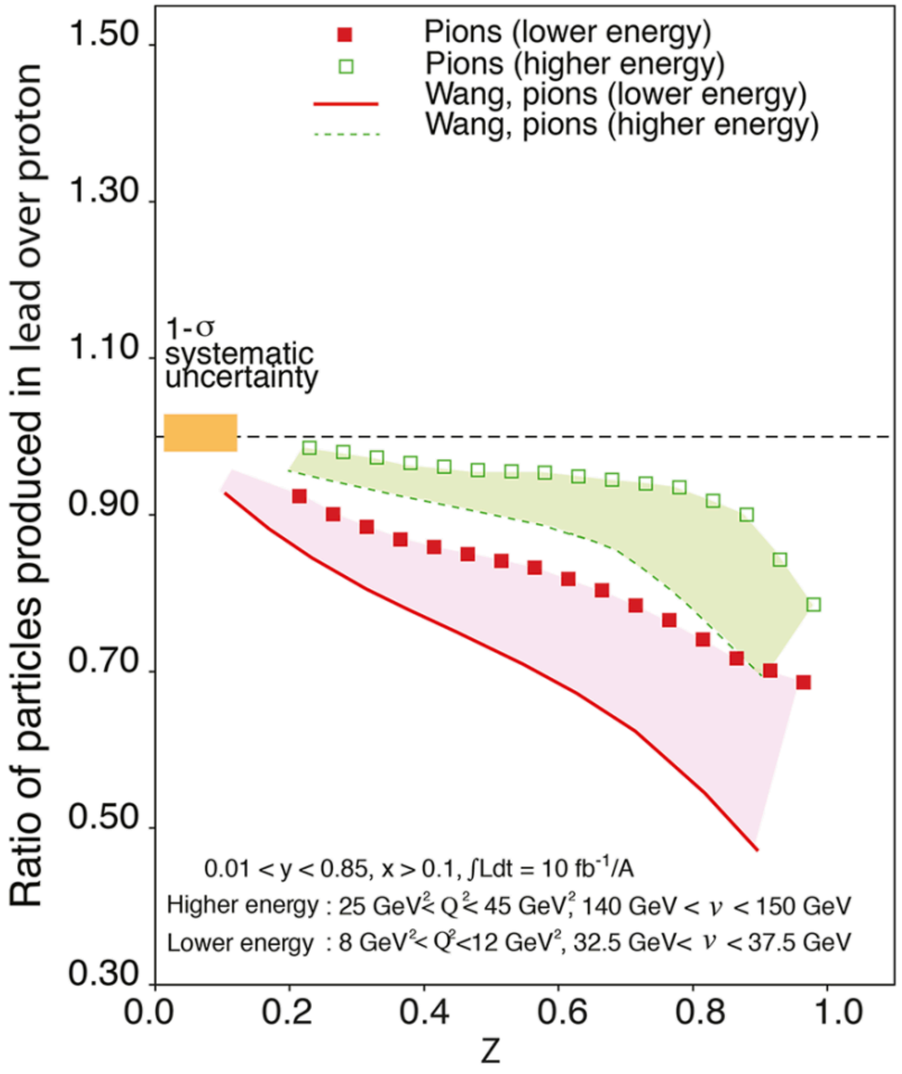
arXiv:2103.05419
Eur. Phys. J. A (2016) 52: 268

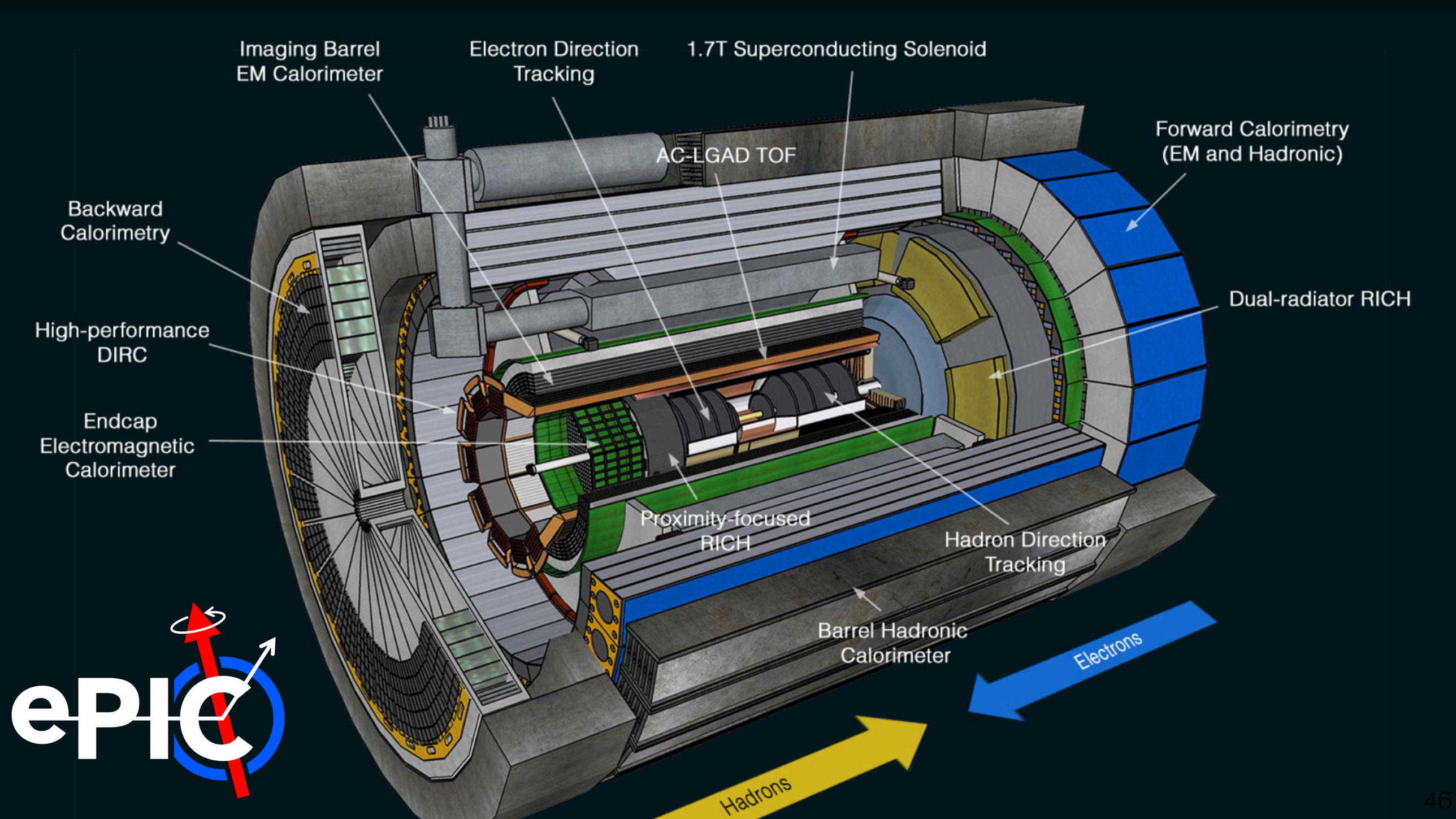
Hadronization studies

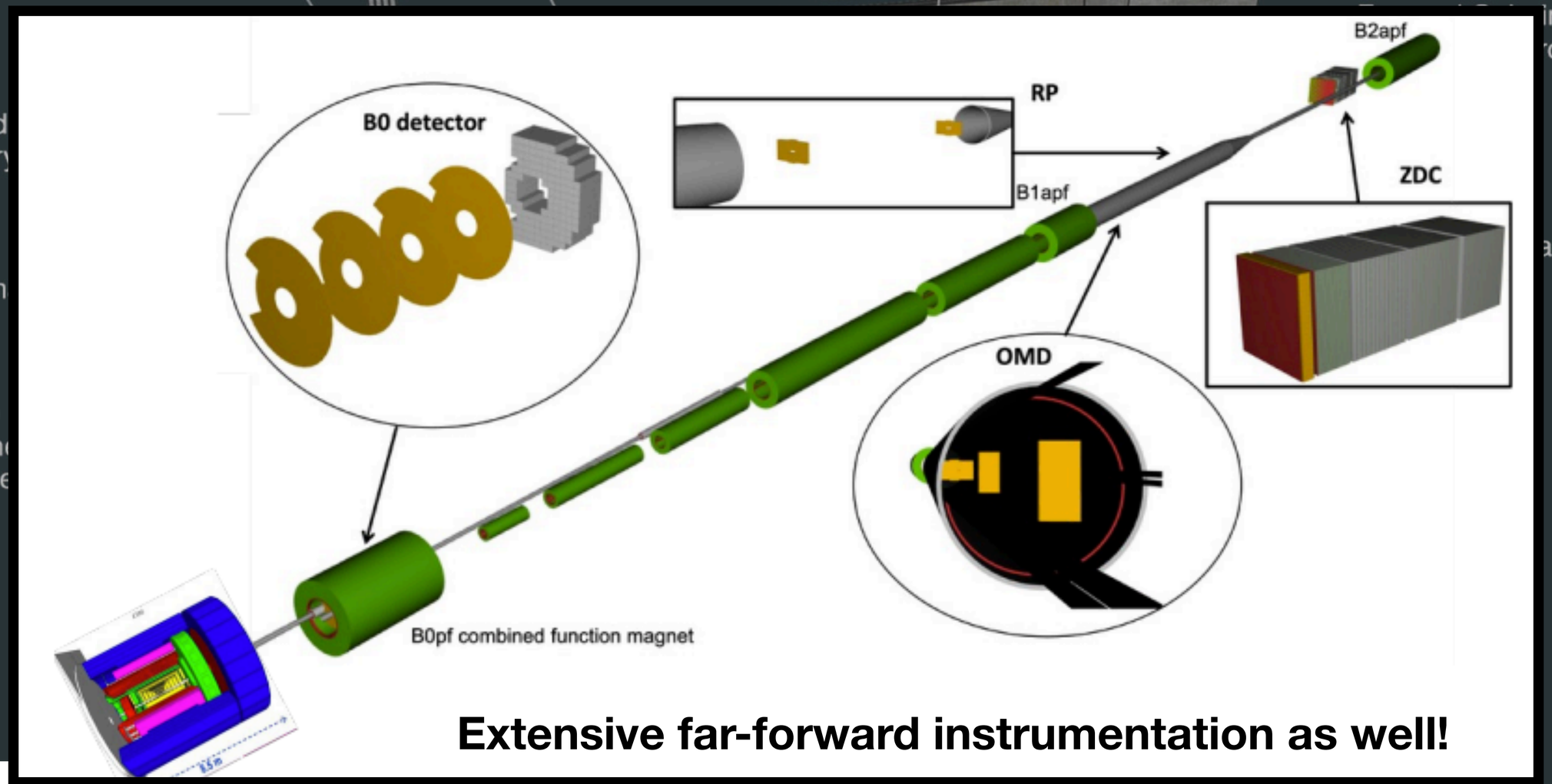
Eur. Phys. J. A (2016) 52: 268

- **Test hadronization models of high-momentum partons**
- **Does hadron form inside or outside nucleus?**
  - **Vary size of nucleus and particle energy**






Imaging Barrel
EM Calorimeter
Electron Direction
Tracking
1.7T Superconducting Solenoid
AC-LGAD TOF
Forward Calorimetry
(EM and Hadronic)
Backward
Calorimetry
Dual-radiator RICH
High-performance
DIRC
Endcap
Electromagnetic
Calorimeter
Proximity-focused
RICH
Hadron Direction
Tracking
Barrel Hadronic
Calorimeter
Electrons
Hadrons
ePIC


Imaging Barrel
EM Calorimeter
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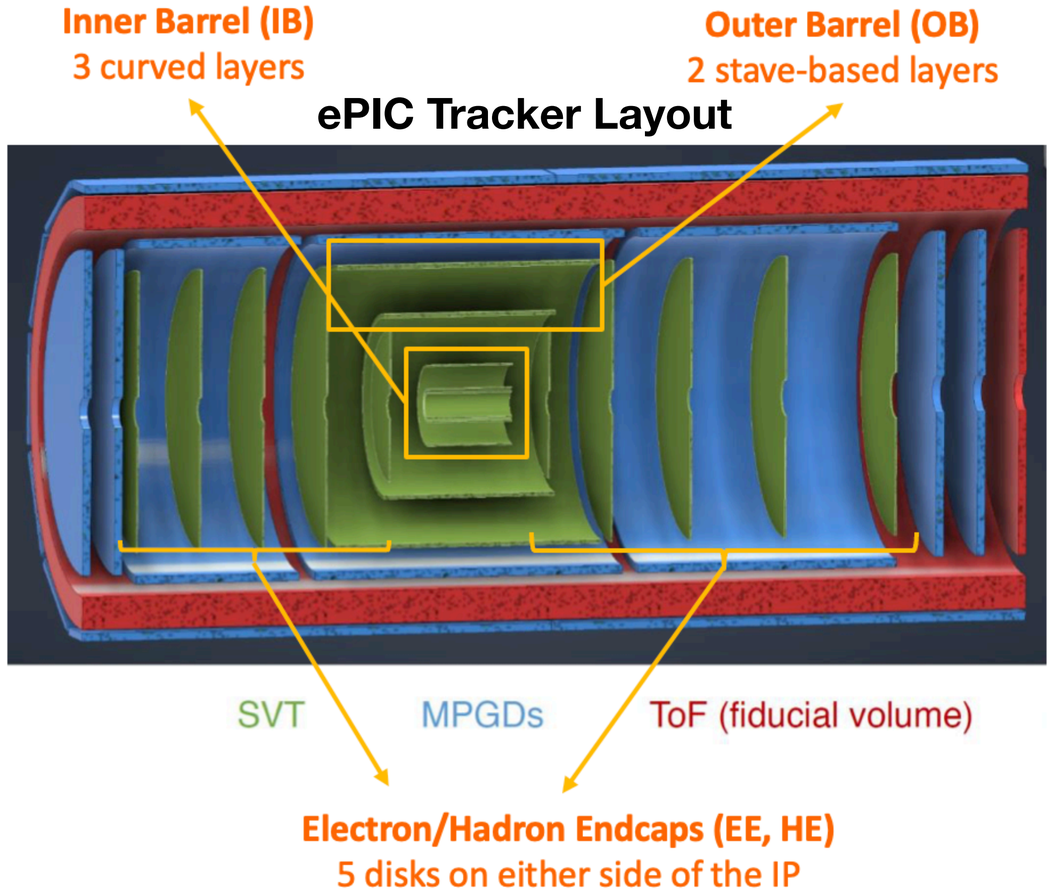
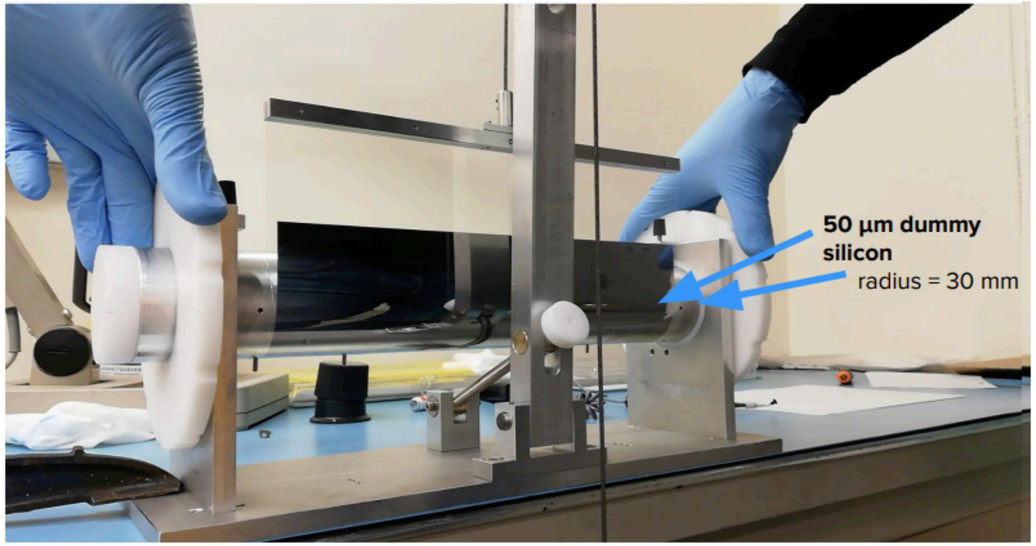
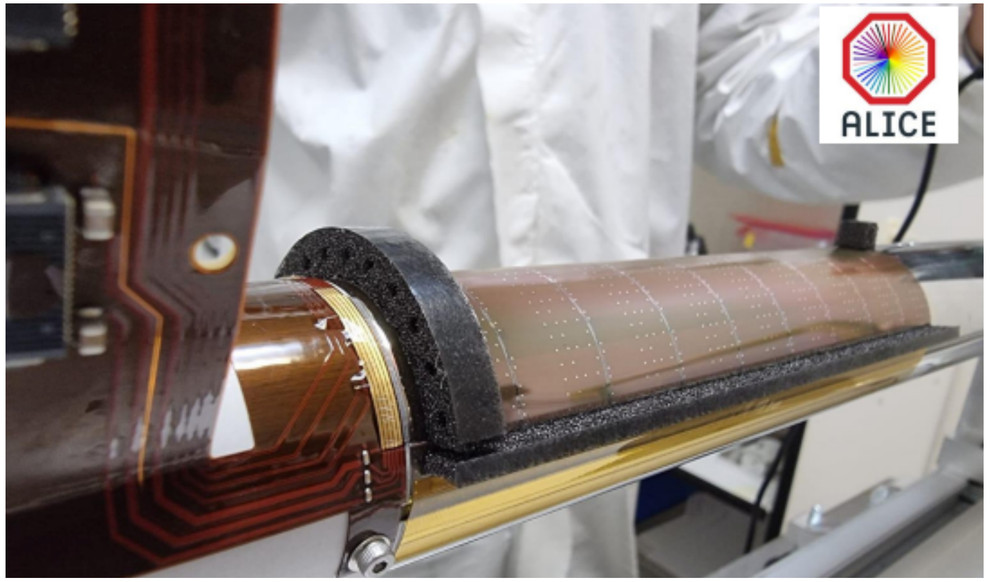
Tracking
1.7T Superconducting Solenoid
Backward
Calorimetry
High-perform
DIRC
Endcap
Electromagn
Calorimete
imetry
onic)
adiator RICH
B0 detector
RP
B1apf
B2apf
ZDC
OMD
B0pf combined function magnet
Extensive far-forward instrumentation as well!
Hadrons

Silicon Vertex Tracker

- **Using same technology as ALICE ITS3 upgrade**
- **Inner pixel tracker using bent silicon**
- **20x20 um pixels, 0.05% X_0**
- **Power, cooling a significant challenge**





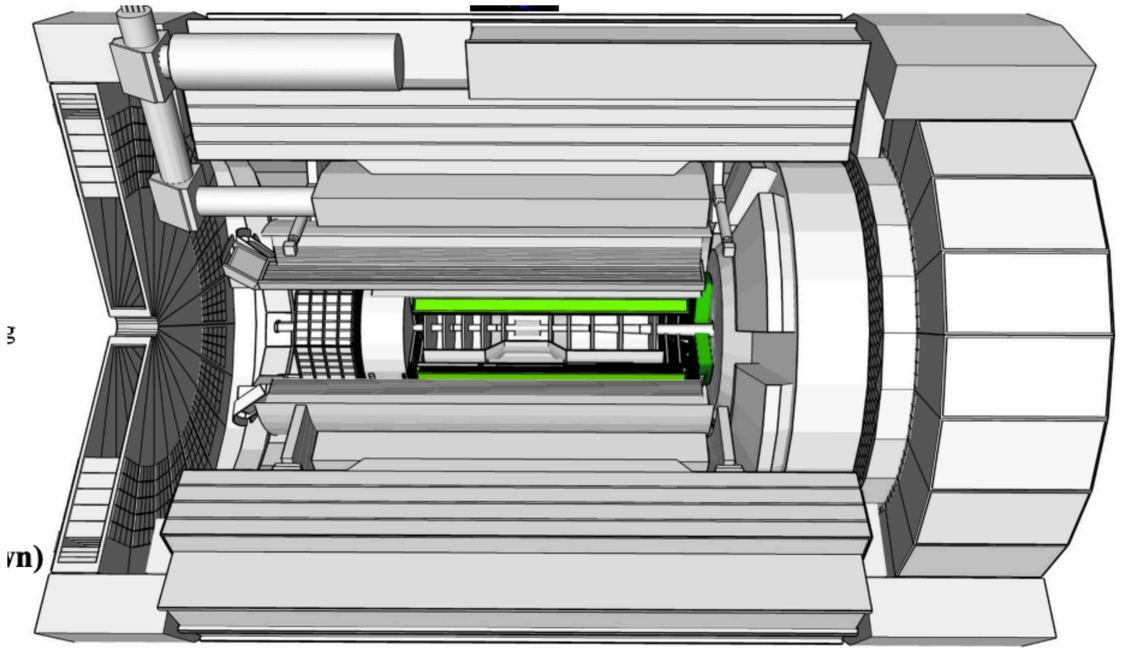


Images from Jory Sonneveld's talk at Hard Probes 2023

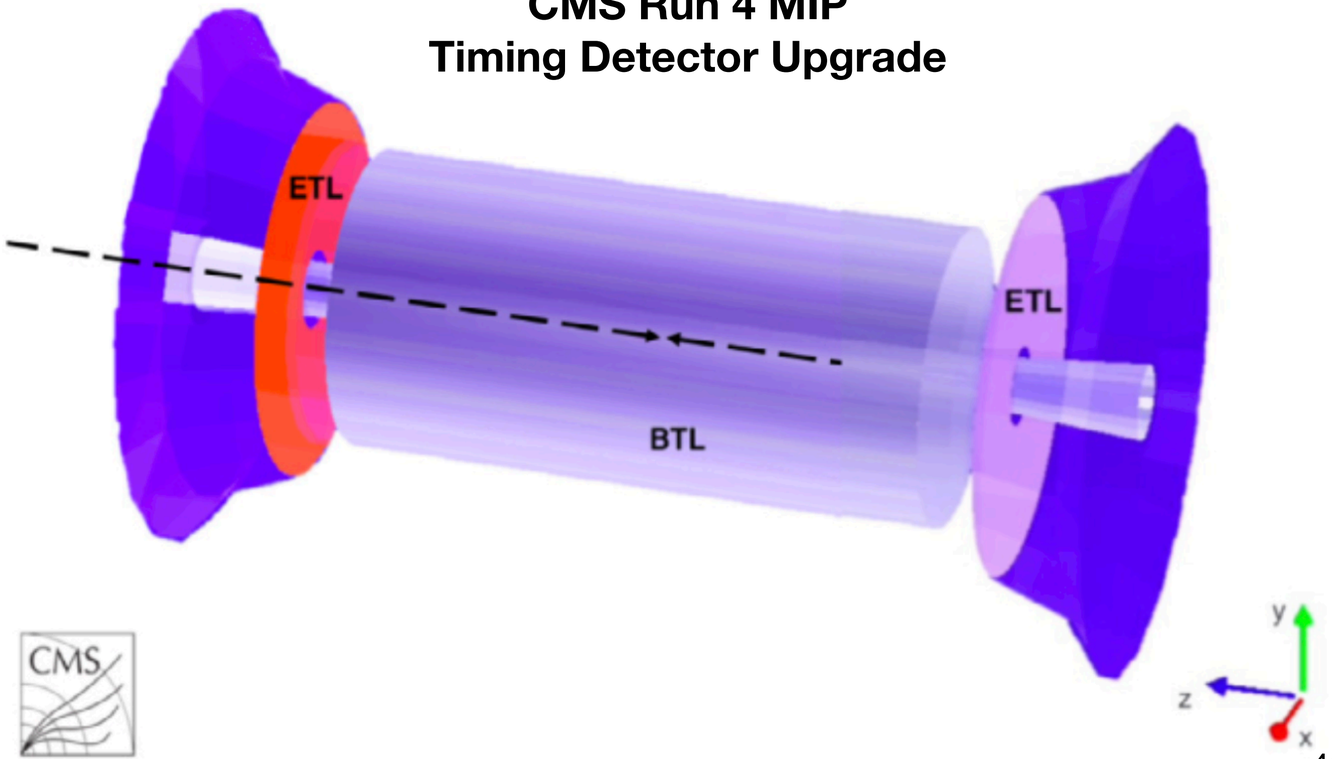
LGAD Time of Flight

- **Clear synergies between ePIC TOF and LHC Run 4 Time of Flight upgrades**
- **Both using Low-Gain Avalanche Diode (LGAD) technologies (~30ps timing resolution)**
- **CMS, ATLAS using DC-coupled, while ePIC pursuing AC-coupled**
  - **Similar test equipment, beam test setups, etc. can be used**

ePIC AC-LGAD TOF

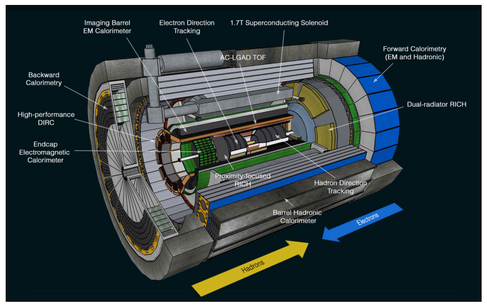


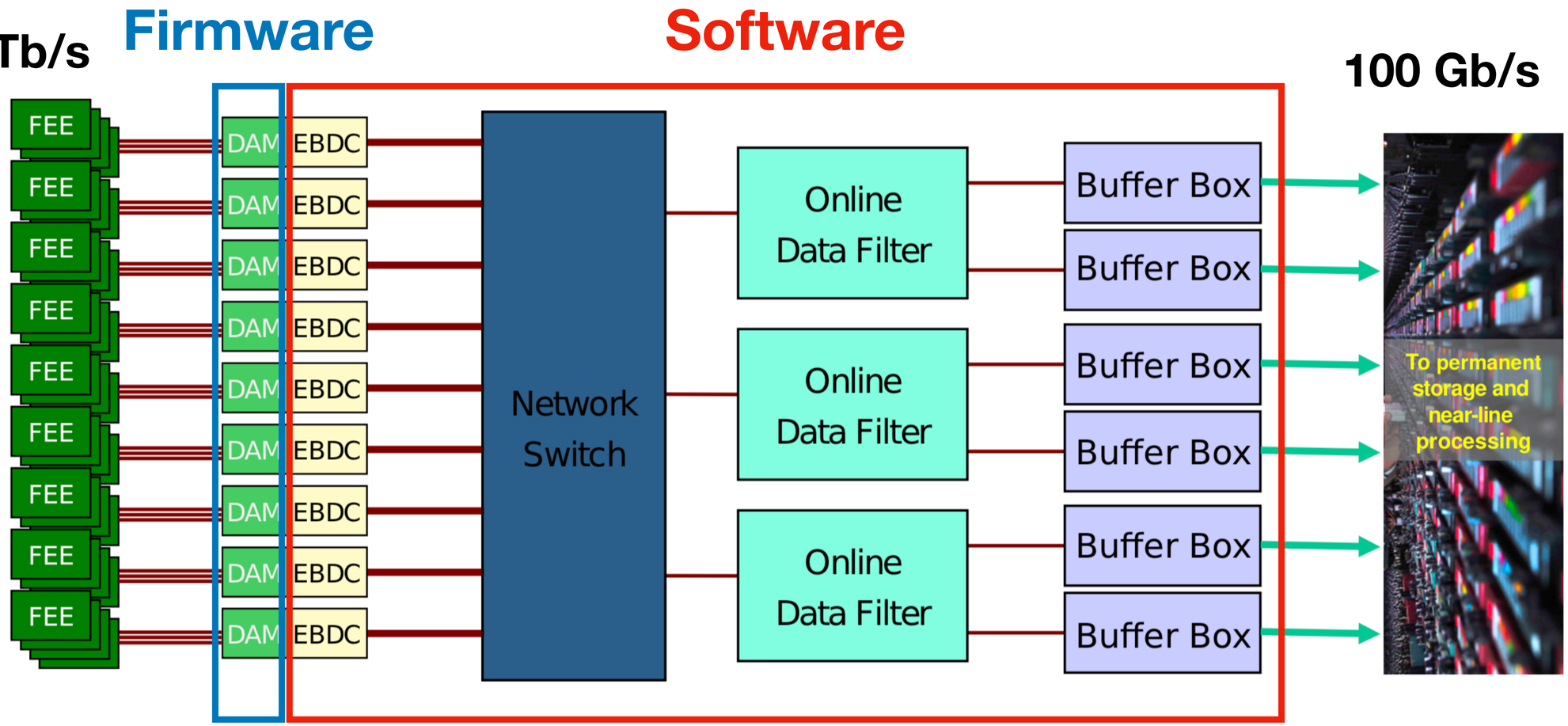
CMS Run 4 MIP Timing Detector Upgrade



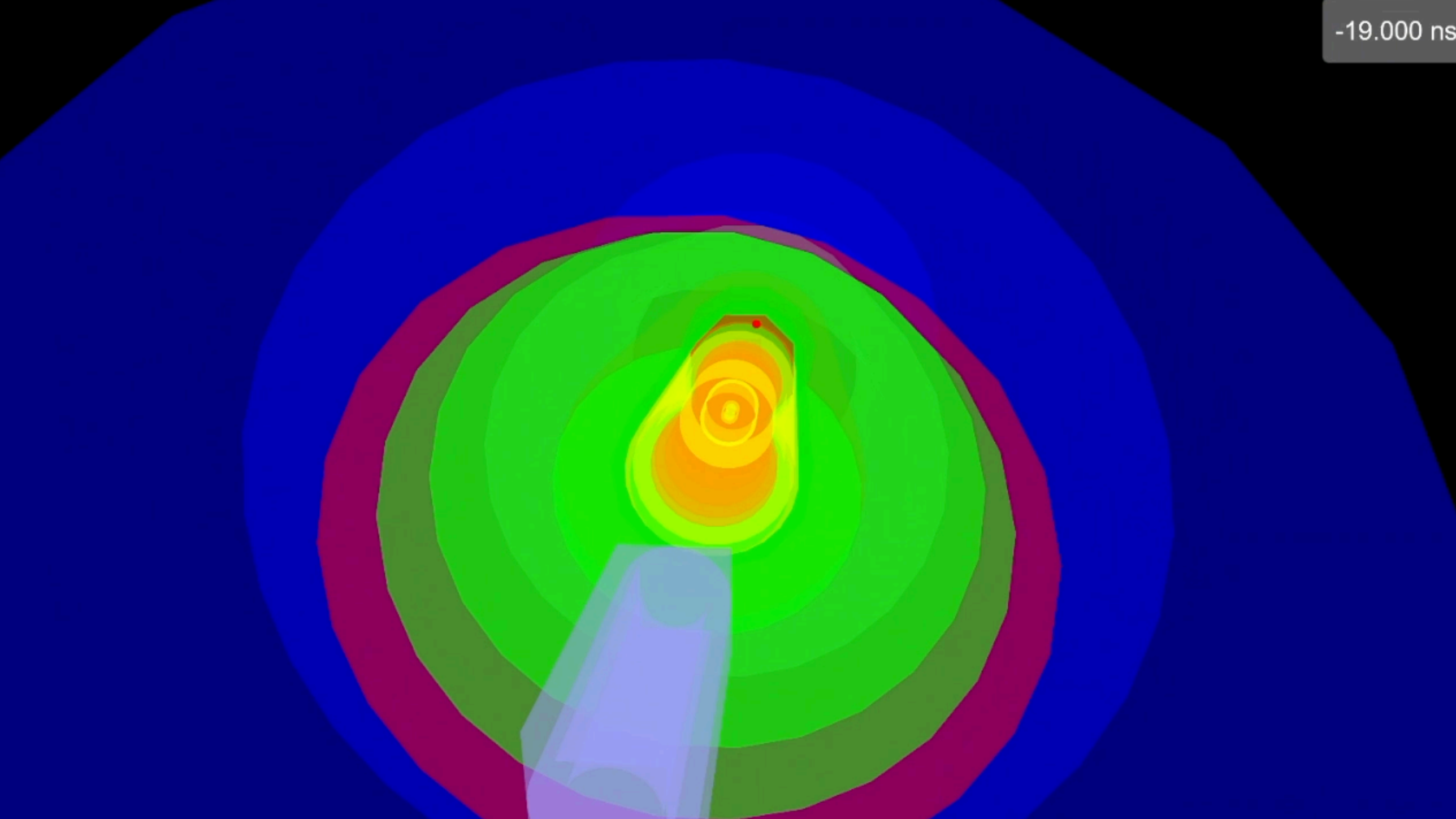
ePIC Streaming Readout

arXiv:2209.02580

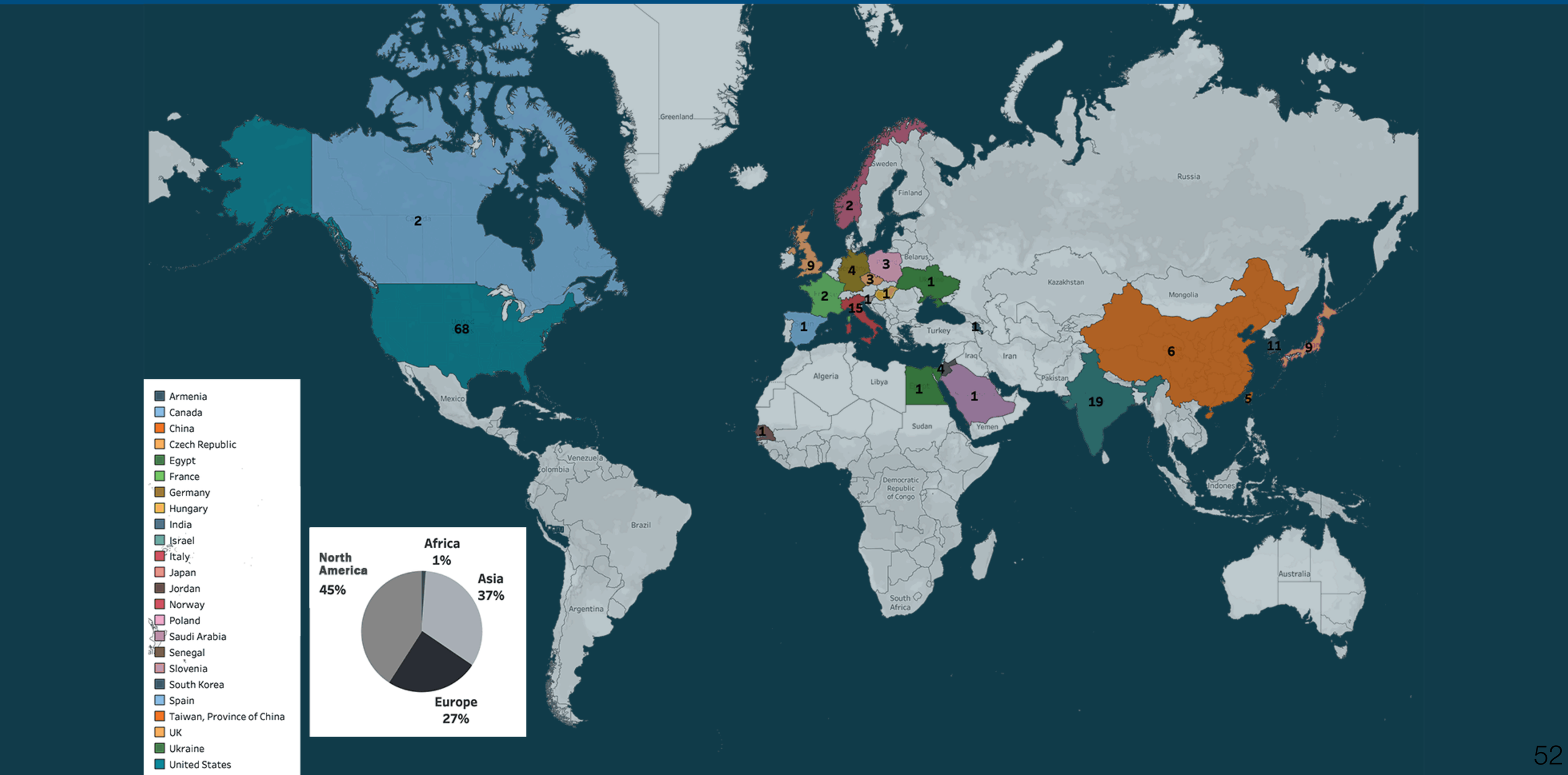




- **All filtering done with full detector info (following LHCb, sPHENIX, etc.)**
- **Opportunities for heterogeneous computing, data compression, ML, AI, etc.**

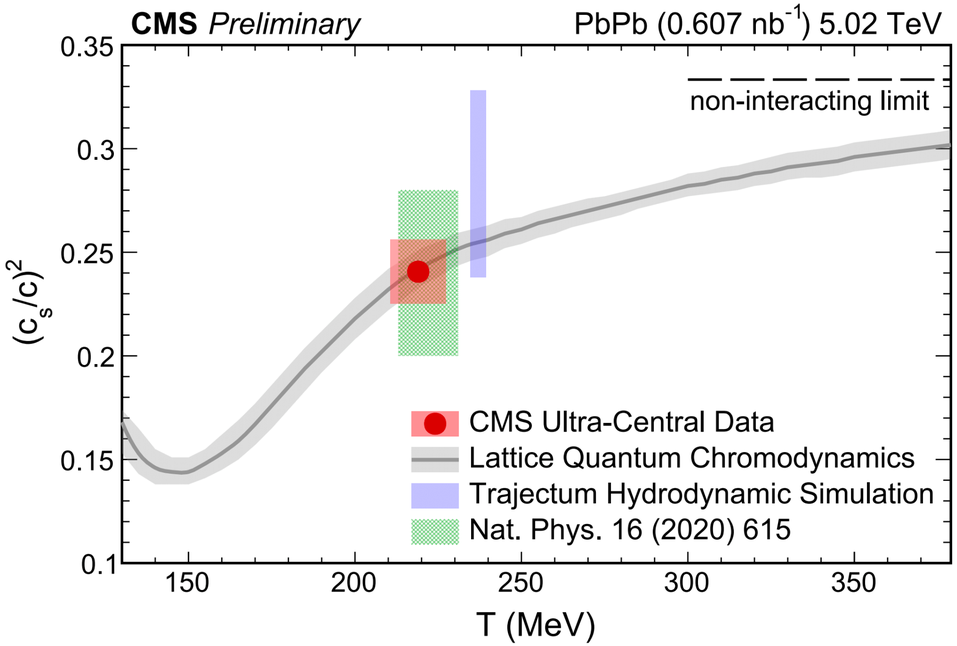

-19.000 ns

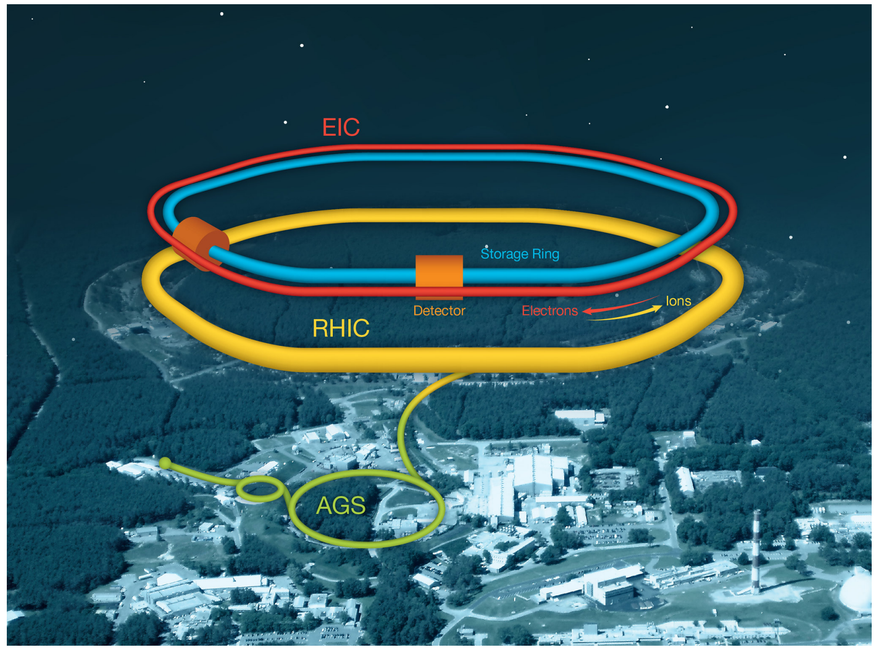
ePIC Collaboration



Summary

- **The strong interactions of QCD result in confinement/asymptotic freedom**
- **QGP shows emergent phenomena - perfect fluidity**
  - **LHC is characterizing this medium in a variety of ways**
- **EIC will enable discoveries and precision QCD analyses**
  - **Planning/Construction are happening *now!***
- **Strong synergies between HEP and NP programs now and in the future**

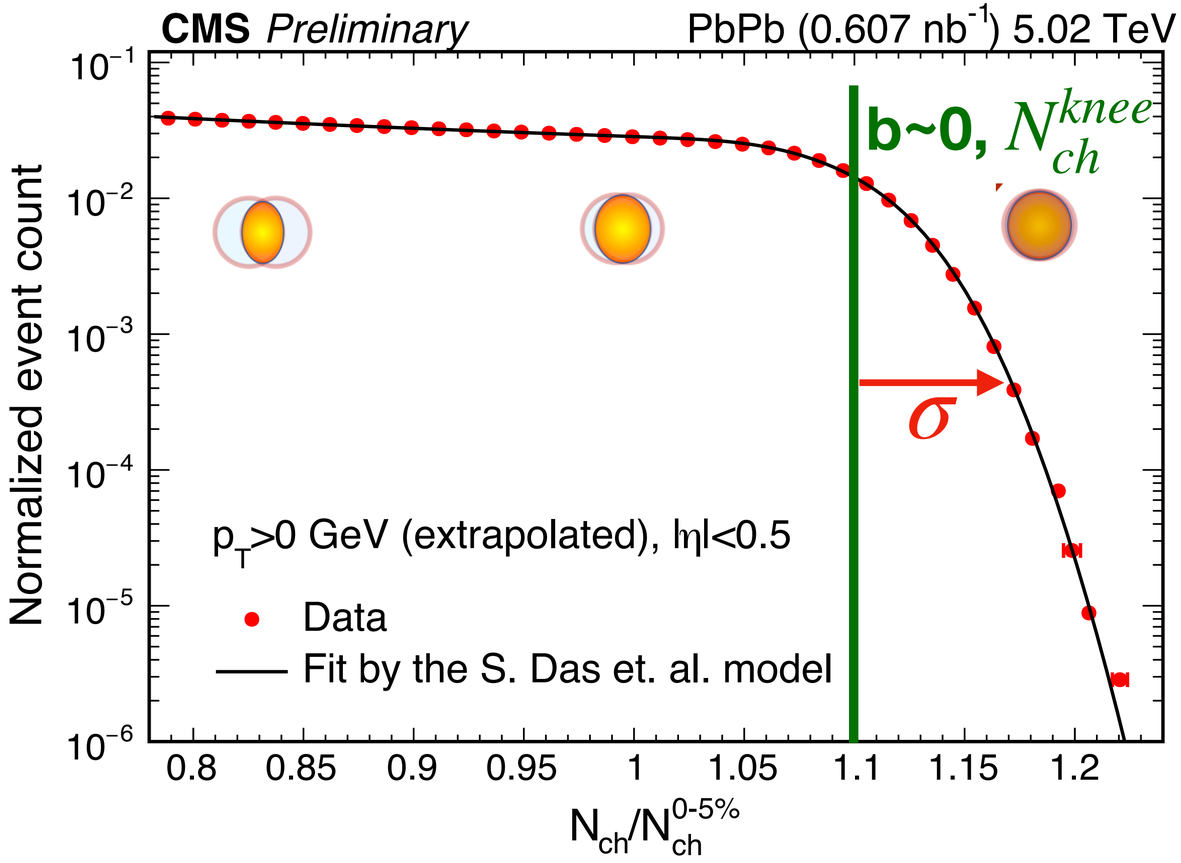




Backup

Constraining with N_{ch} distribution

- **Spread of multiplicities produced at a given b**
- **Cannot directly isolate events with exactly b=0 by cutting on N_{ch}**
- **Must account for the effects of a distribution of initial b at given N_{ch}**



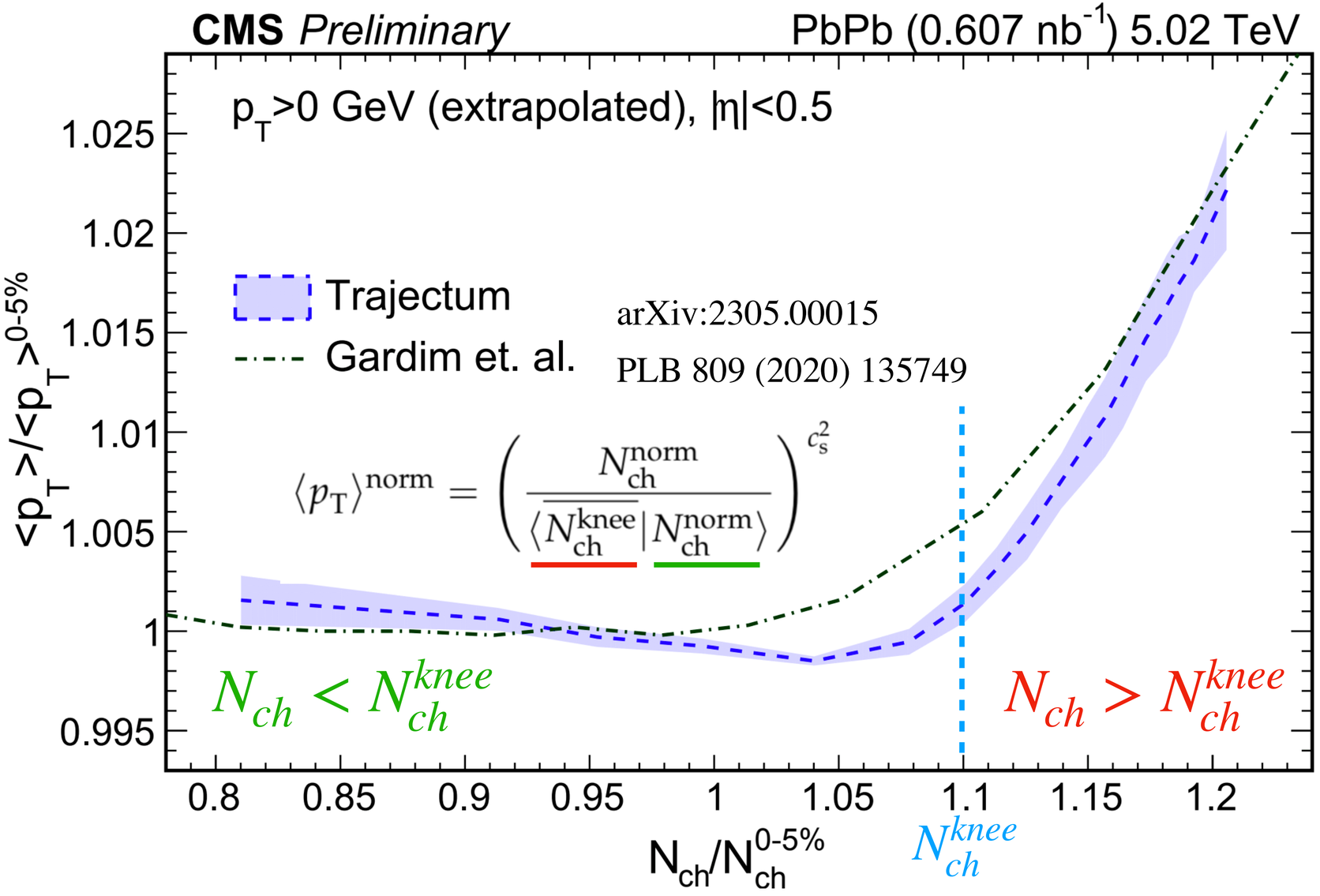
$$\langle p_{\mathrm{T}} \rangle^{\mathrm{norm}} = \left(\frac{N_{\mathrm{ch}}^{\mathrm{norm}}}{\langle \overline{N_{\mathrm{ch}}^{\mathrm{knee}}} | N_{\mathrm{ch}}^{\mathrm{norm}} \rangle} \right)^{c_{\mathrm{s}}^2}$$

$$\langle \overline{N_{\mathrm{ch}}^{\mathrm{knee}}} | N_{\mathrm{ch}}^{\mathrm{norm}} \rangle = N_{\mathrm{ch}}^{\mathrm{norm}} - \sigma \sqrt{\frac{2}{\pi}} \frac{\exp\left(-\frac{(N_{\mathrm{ch}}^{\mathrm{norm}} - \overline{N_{\mathrm{ch}}^{\mathrm{knee}}})^2}{2\sigma^2} \right)}{\mathrm{erfc}\left(\frac{N_{\mathrm{ch}}^{\mathrm{norm}} - \overline{N_{\mathrm{ch}}^{\mathrm{knee}}}}{\sqrt{2}\sigma} \right)}$$

2 Free parameters: σ, N_{ch}^{knee}

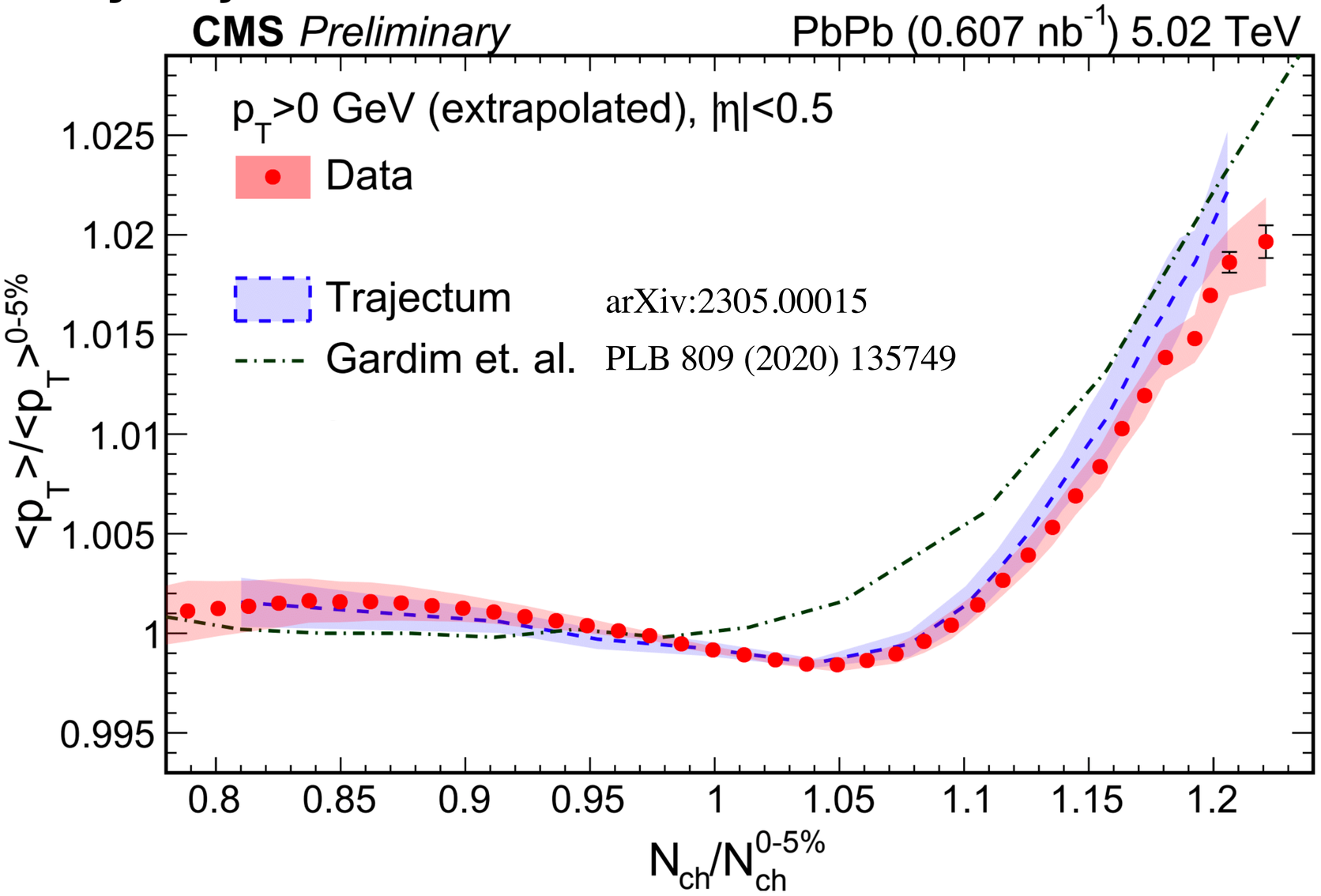
From PLB 809 (2020) 135749

Reminder of hydro predictions



Speed of Sound in QGP

- **Slope of data matches models closely!**
- **'Dip' predicted by Trajectum also in the data!**



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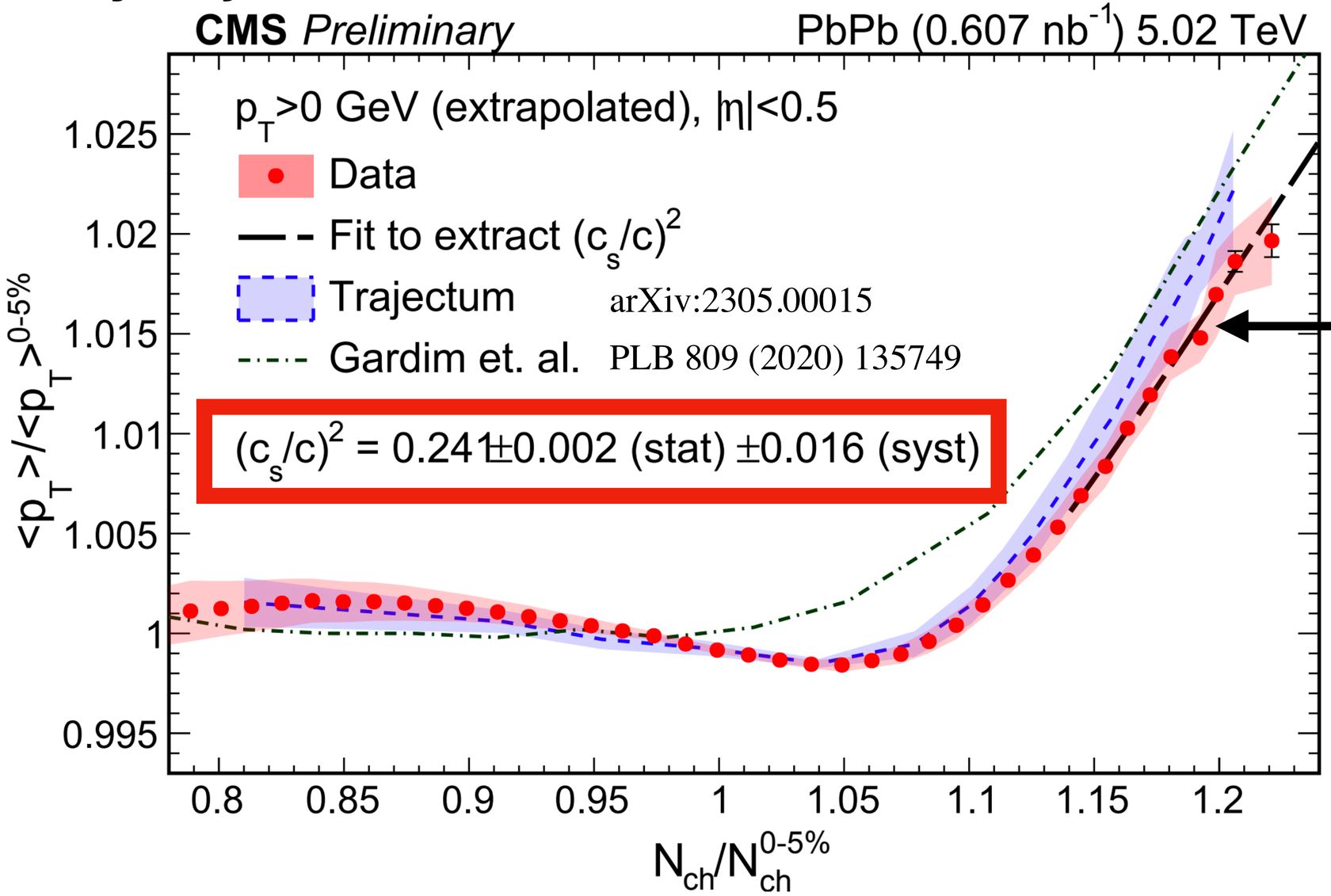

Fit slope to get c_s^2

$$\langle p_T \rangle^{\text{norm}} = \left(\frac{N_{ch}^{\text{norm}}}{\langle N_{ch}^{\text{knee}} | N_{ch}^{\text{norm}} \rangle} \right)^{c_s^2}$$

Speed of Sound in QGP

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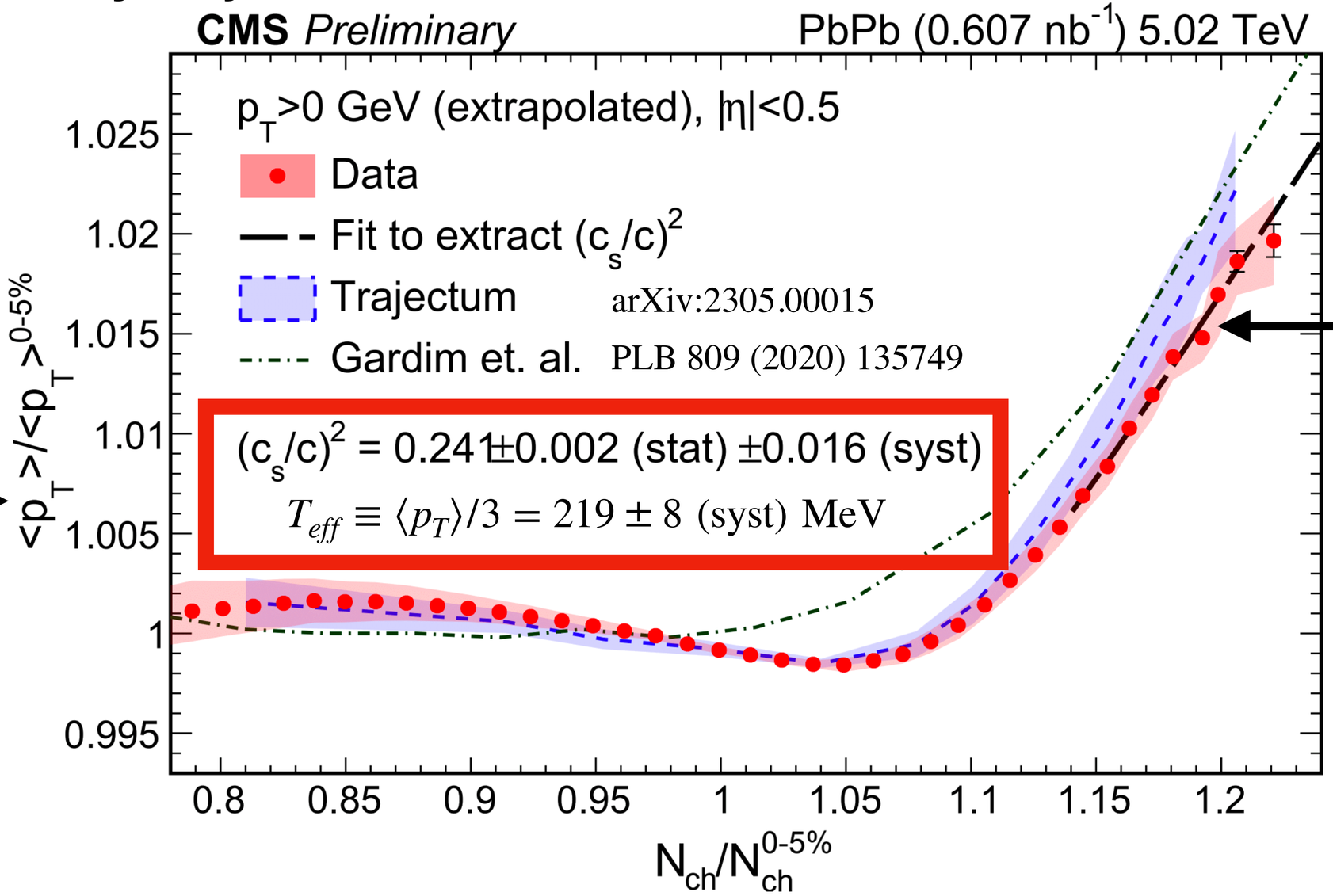


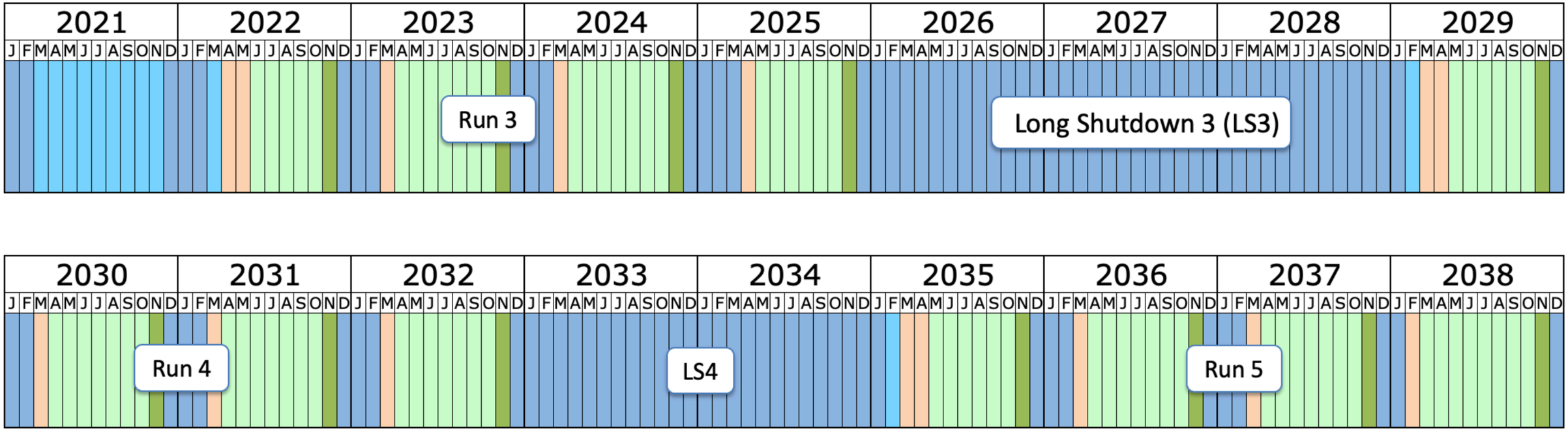
Get T_{eff} from $\langle p_T \rangle/3$

Fit slope to get c_s^2

$$\langle p_T \rangle^{\text{norm}} = \left(\frac{N_{ch}^{\text{norm}}}{\langle \overline{N_{ch}^{\text{knee}}} | N_{ch}^{\text{norm}} \rangle} \right)^{c_s^2}$$

LHC Future

- **LHC Heavy Ion runs have entered high-luminosity era**
- **Expect to accumulate ~10 /nb of data by end of Run 4**
- **Detector upgrades in Run 4**
- **Huge proton-proton datasets**

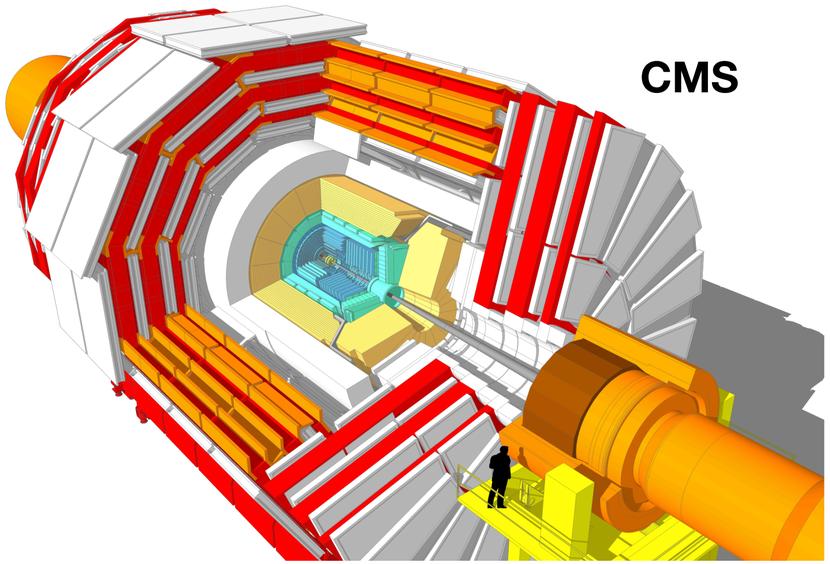


Last updated: January 2022

Future Opportunities

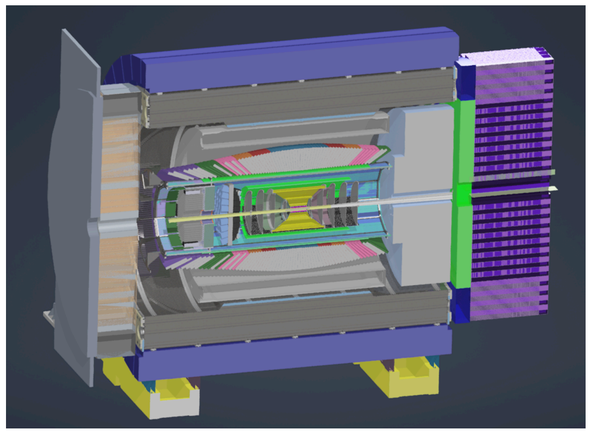
LHC Run 3

Jet measurements with
Fast detector+large acceptance



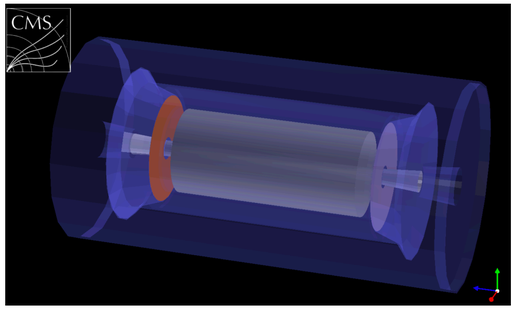
Electron-Ion Collider

ePIC



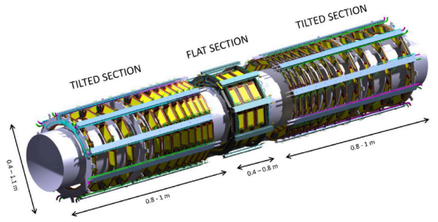
High-Luminosity LHC

CMS MTD



O Ar Ca Kr

CMS Phase 2 tracker



Xe Pb

2023 ‘24 ‘25 ‘26 ‘27 ‘28 ‘29 ‘30 ‘31 ‘32 ‘33 ‘34 ‘35 2036

pp, pPb, PbPb

R&D, Design

Construction

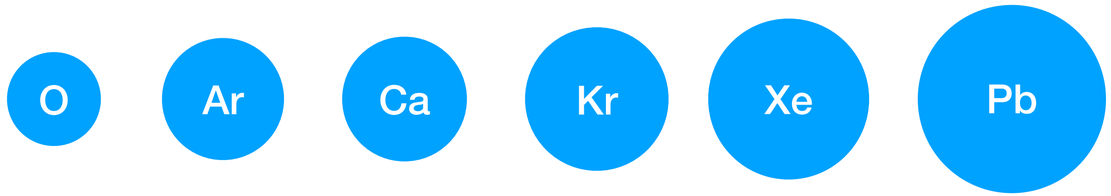
EIC (eA, ep)

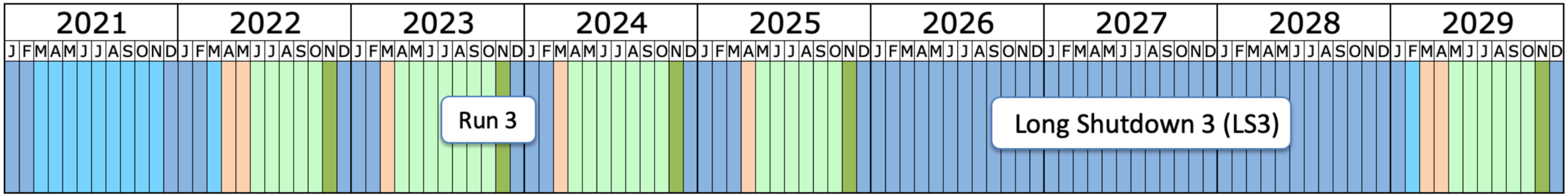
Run 4 (pp/pPb/PbPb)

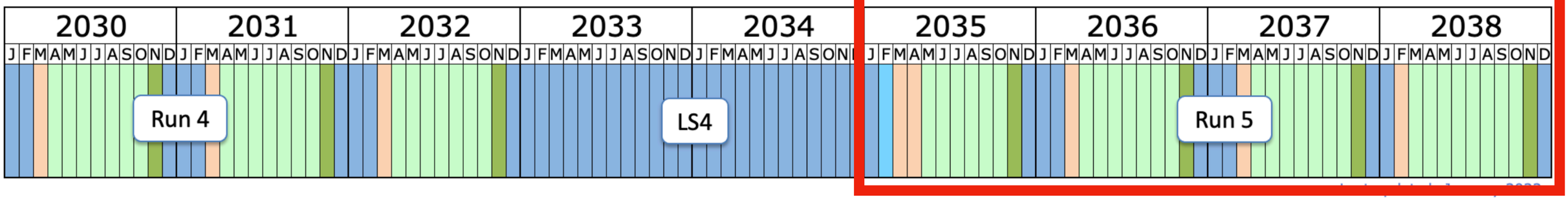
Run 5 (AA)

LHC Run 5

- **Different ion species (OO, CaCa, XeXe, etc.)**
  - **Higher nucleon-nucleon luminosities (more jets)**







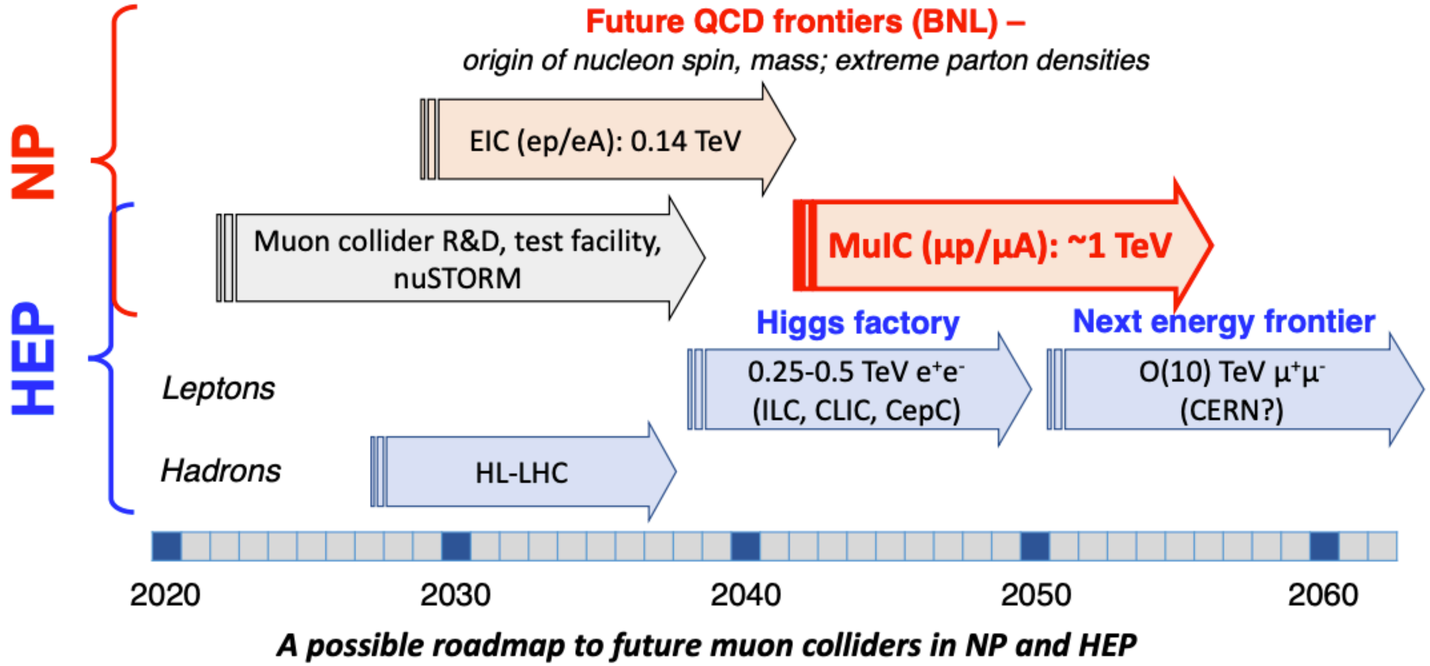
Muon-Ion Collider?

A Muon-Ion Collider at BNL: the future QCD frontier and path to a new energy frontier of $\mu^+\mu^-$ colliders

Darin Acosta[1,*] and Wei Li[1,†]

[1] *Physics Department, Rice University, Houston, Texas 77251, USA*

- **Potential accelerator technology synergies with HEP plans**
- **Cross-talk between NP and HEP communities crucial!**



A possible roadmap to future muon colliders in NP and HEP

Progress on the Production of Muon and Photon Beams for Applications in Muon-Ion Colliders

Tuesday Mar 26, 2024, 2:08 AM → 4:00 PM America/New_York

https://arxiv.org/abs/2107.02073