2023 Overview of Relativistic heavy-ion physics program

한국 고에너지물리학회 2023 가을학술대회
동신대학교, 나주
November 24th, 2023

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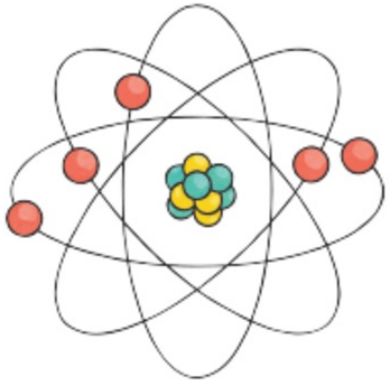
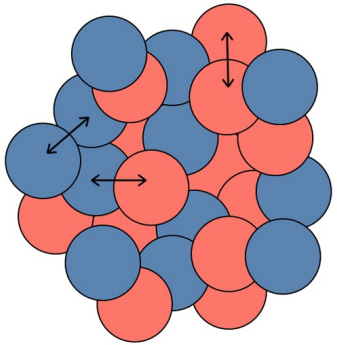
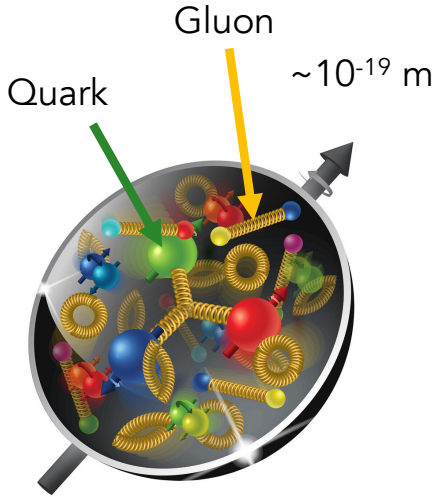
Relativistic heavy-ion physics



Atom ~ 10^{-10} m



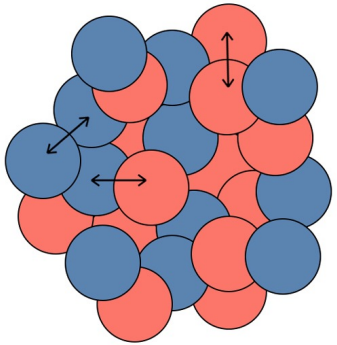
Nucleus ~ 10^{-14} m



Proton ~ 10^{-15} m

Relativistic heavy-ion physics

Atom ~ 10^{-10} m



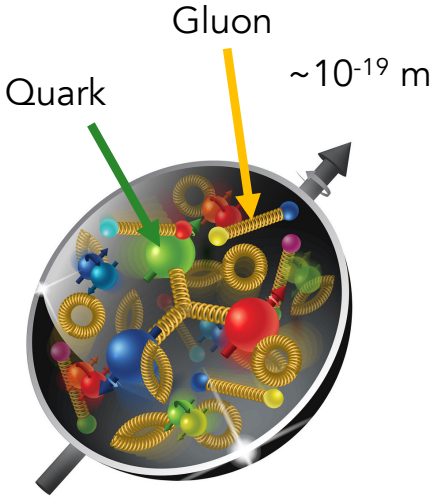
Nucleus ~ 10^{-14} m

Proton ~ 10^{-15} m

- (Traditional) Nuclear physics
  - Atomic nuclei and their constituents and interactions

Relativistic heavy-ion physics

- High-energy nuclear physics, i.e. Relativistic heavy-ion physics
  - Behavior of nuclear matter in energy regimes of high-energy physics
  - Study of the strong force – Quantum Chromodynamics



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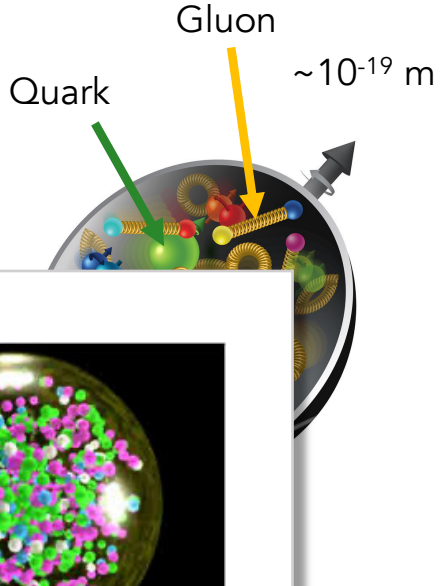
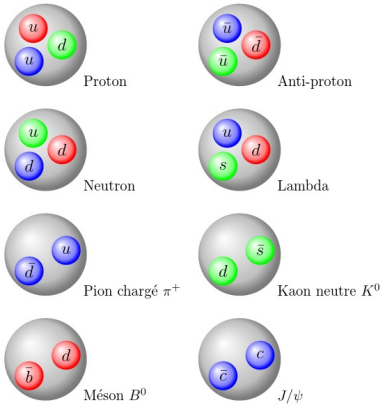
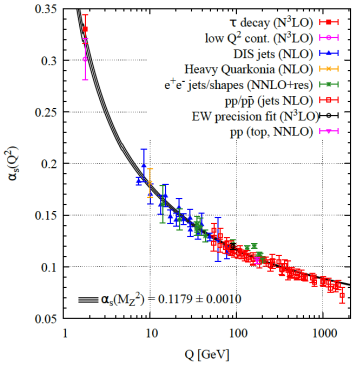
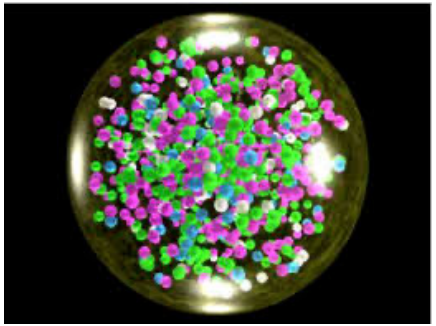




Confinement – No free quarks
Bound state = Hadrons

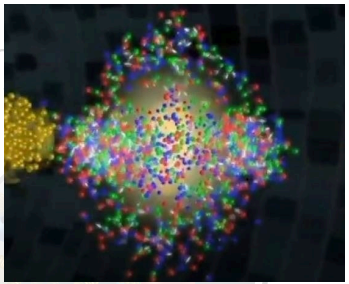


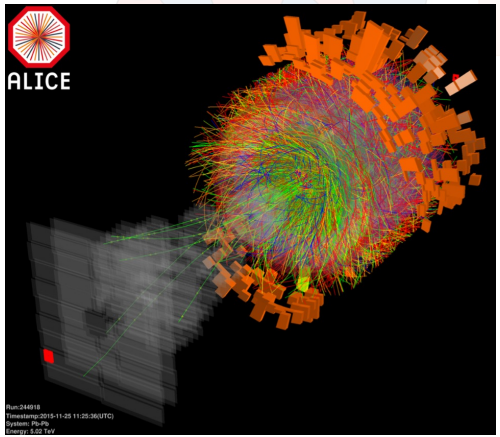


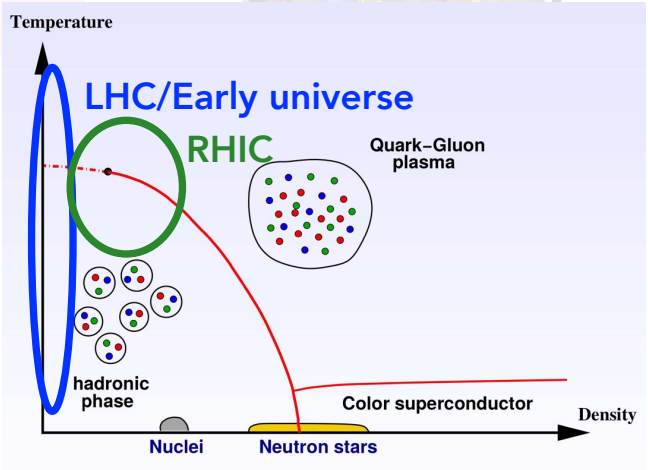
Asymptotic freedom – Weaker interaction as the length scale decreases (=energy scale increases)

Relativistic heavy-ion physics

- High-energy nuclear physics, i.e. Relativistic heavy-ion physics
  - Behavior of nuclear matter in energy regimes of high-energy physics
  - Study of the strong force – Quantum Chromodynamics
  - **Quark-Gluon Plasma** is one of the phases of QCD matter, where once the entire universe was in that state



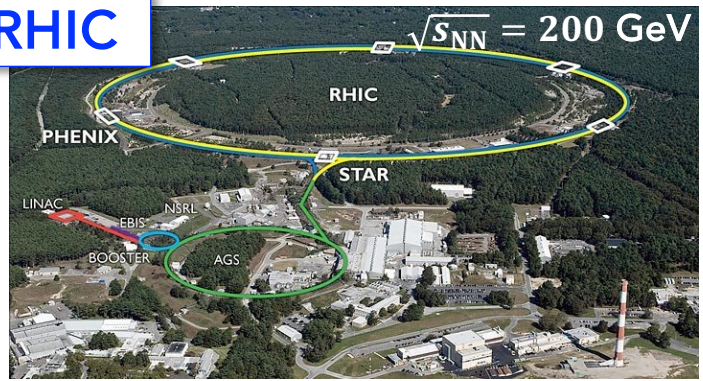




QCD phase diagram

Relativistic heavy-ion physics

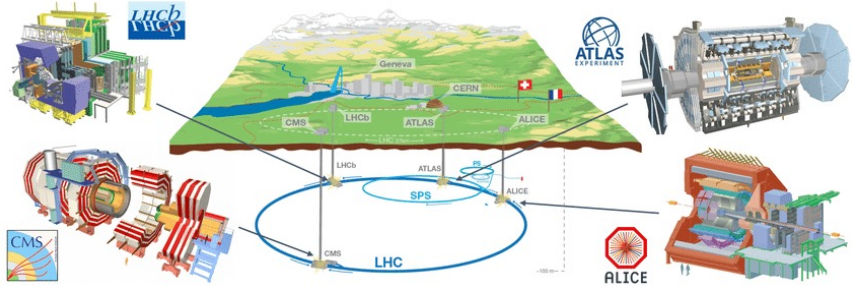
RHIC



2000 – 2025 (2026)

LHC

$\sqrt{s_{NN}}$ = 5.02 TeV



2009 – Present

EIC

FAIR

About this overview

Quark Matter 2023

Sep 3 – 9, 2023
Hilton of the Americas, 1600 Lamar, Houston, Texas, 77010, USA
US/Central timezone

- Quark Matter 2023 in Houston
  - Largest conference in the field of relativistic heavy-ion physics
  - Quark Matter 2027 to be held in Korea – Decided

About this overview

- Quark Matter 2023 in Houston
  - Largest conference in the field of relativistic heavy-ion physics
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- Topics in QM
  - Chirality
  - Collective Dynamics
  - Critical point searches
  - Electromagnetic Probes
  - Future facilities/detectors
  - Heavy flavor physics
  - Initial state of particle collisions
  - Jets
  - Light and strange flavor physics
  - New theoretical developments
  - Nuclear astrophysics
  - Physics of the Future Electron Ion Collider and the RHIC Spin program
  - Physics of ultra-peripheral collisions
  - QCD at finite density and temperature
  - Small systems

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Korea groups involved

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New in QM

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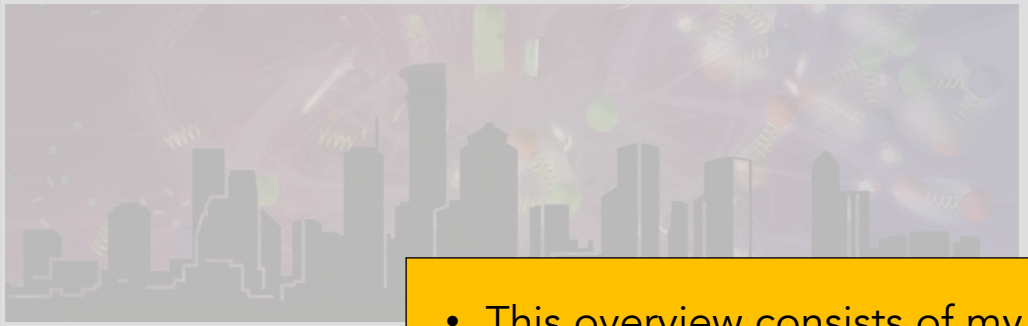

- This overview consists of my personal favorites from the conference
- Instead of the hardware-side progress, I will try to focus on (current and future) physics in the field

➢ Quark Matter 2023 in Houston
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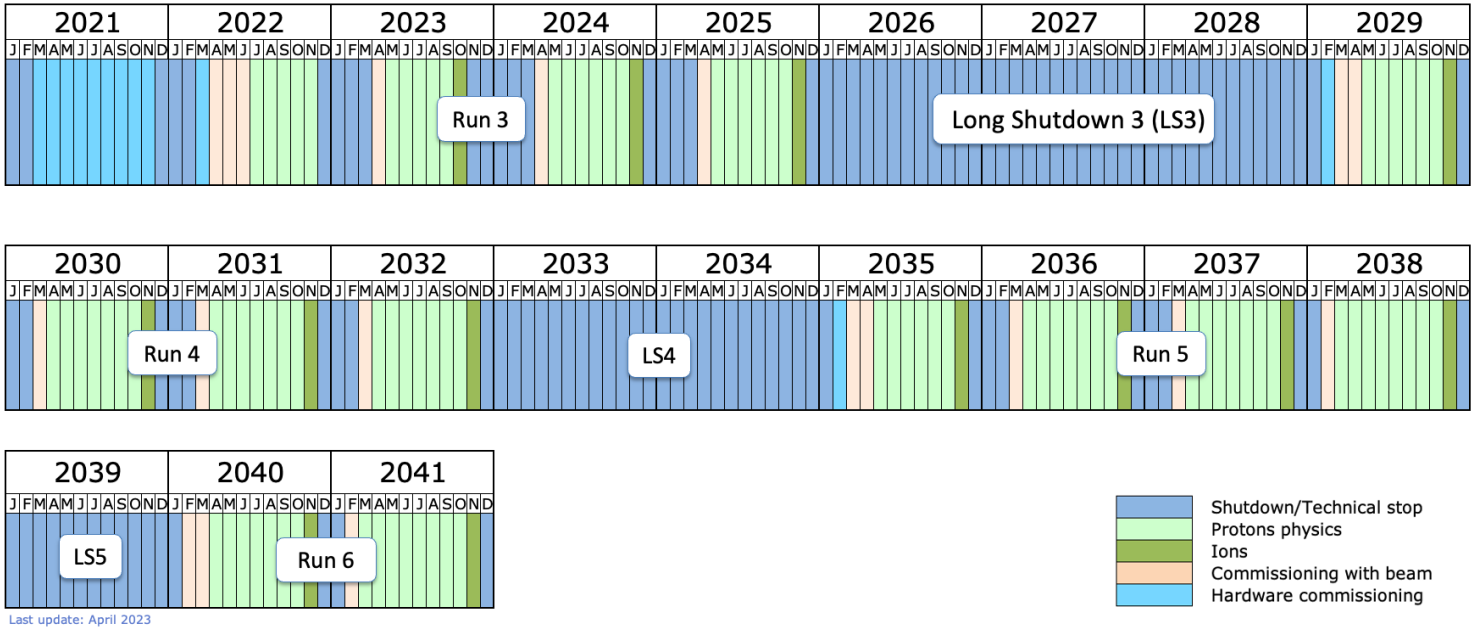
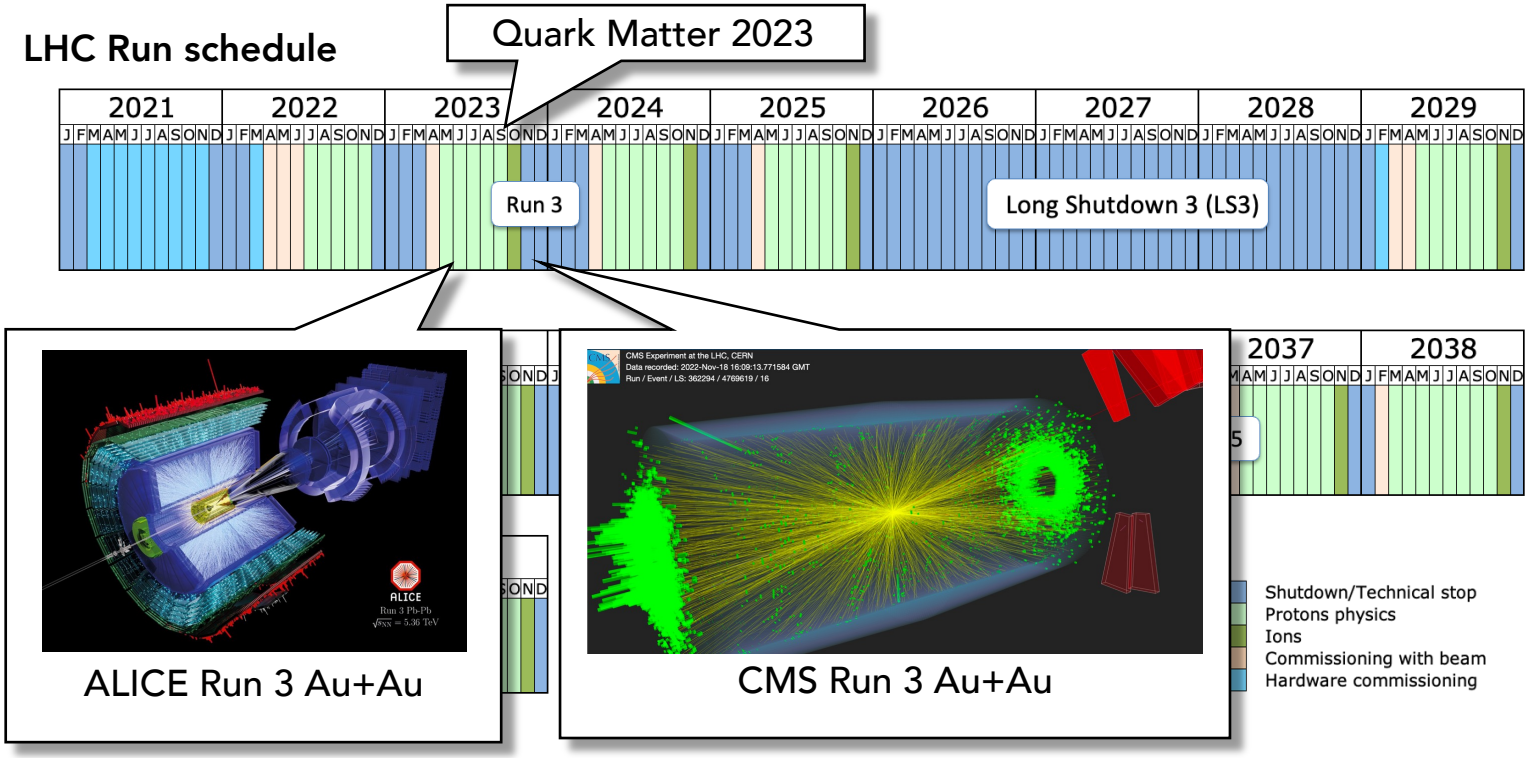
Data from the LHC and RHIC

LHC Run schedule



Data from the LHC and RHIC



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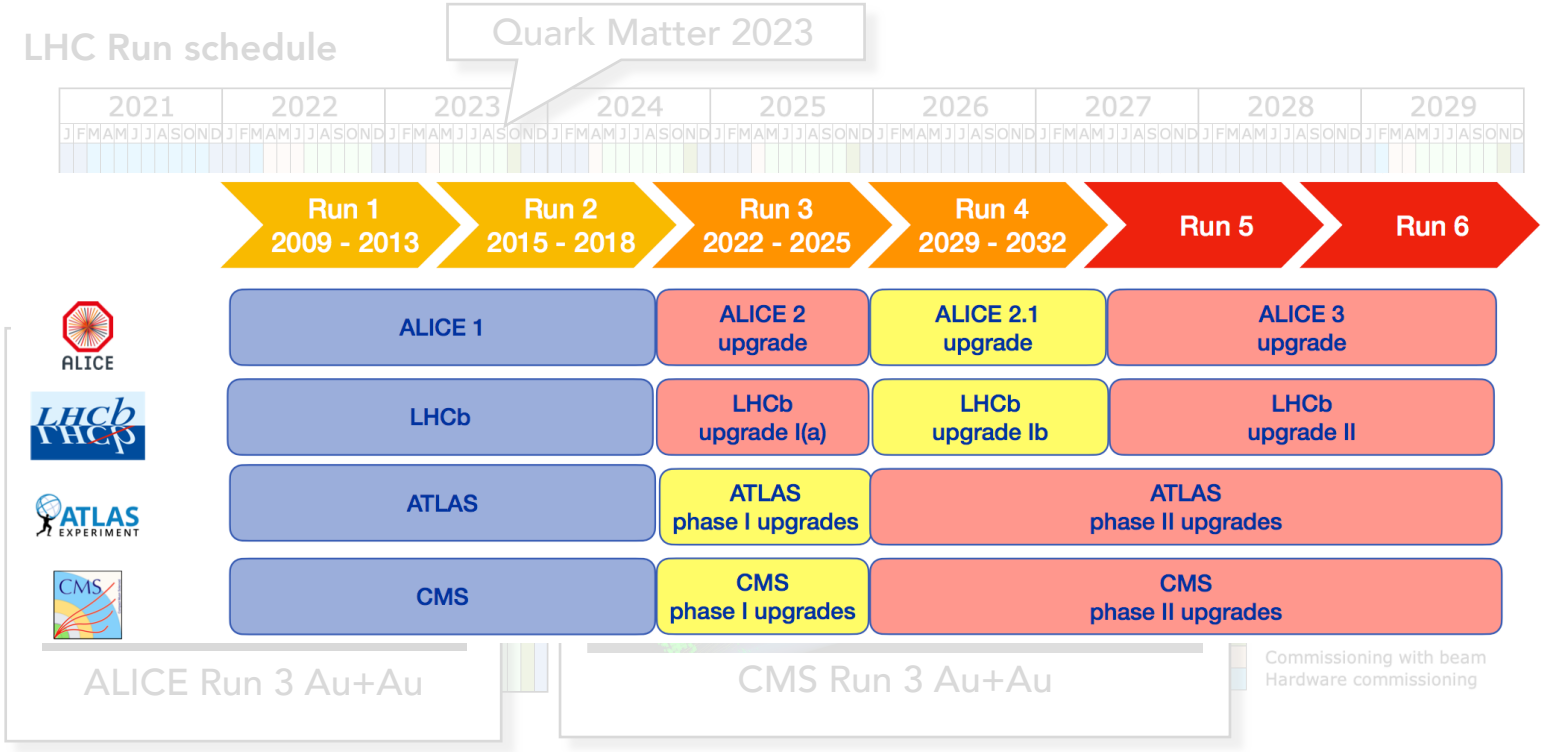

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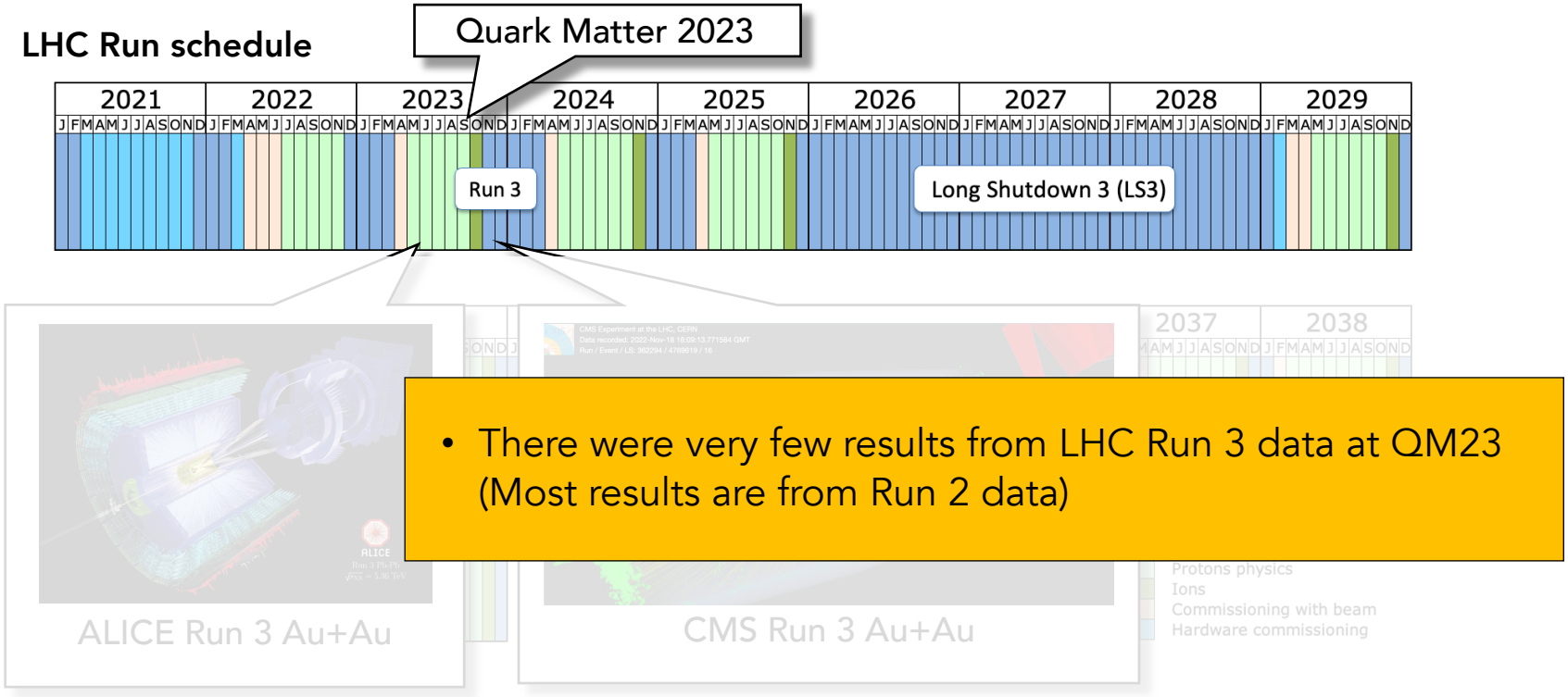
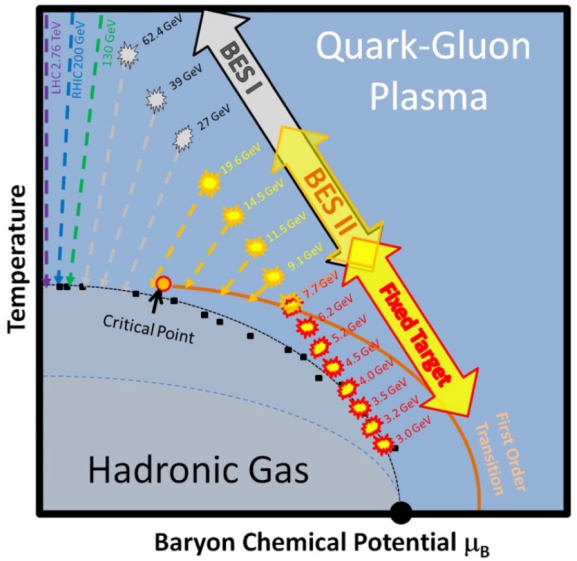
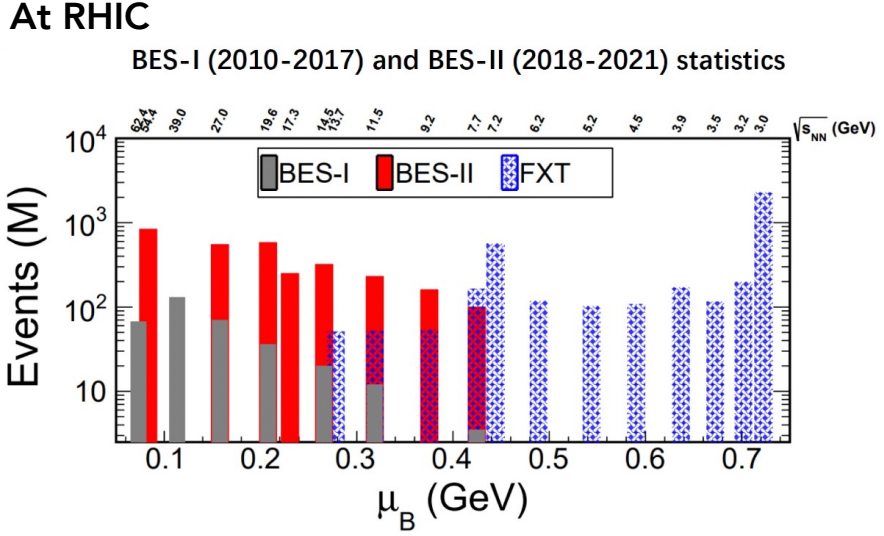


- There were very few results from LHC Run 3 data at QM23 (Most results are from Run 2 data)

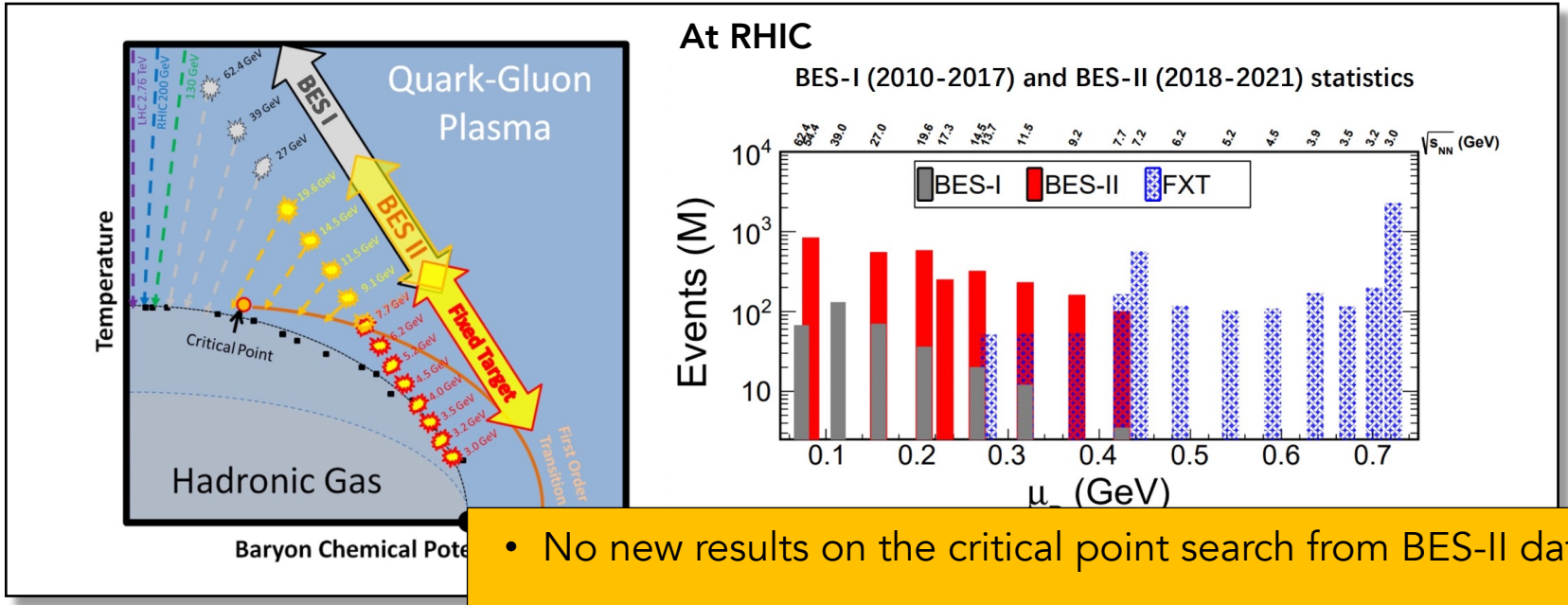
Data from the LHC and RHIC





2023	2024	2025
Au+Au, 200 GeV	p+p, 200 GeV p+Au, 200 GeV	Au+Au, 200 GeV

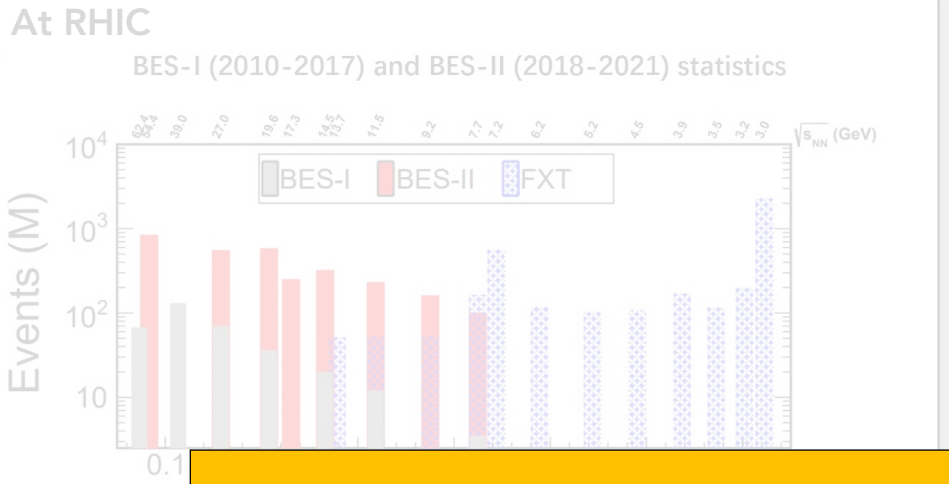
Data from the LHC and RHIC



- No new results on the critical point search from BES-II data
- Analyses nearing completion (e.g. net-proton fluctuation), and no major issue reported

2023		
Au+Au, 200 GeV	p+p, 200 GeV p+Au, 200 GeV	Au+Au, 200 GeV

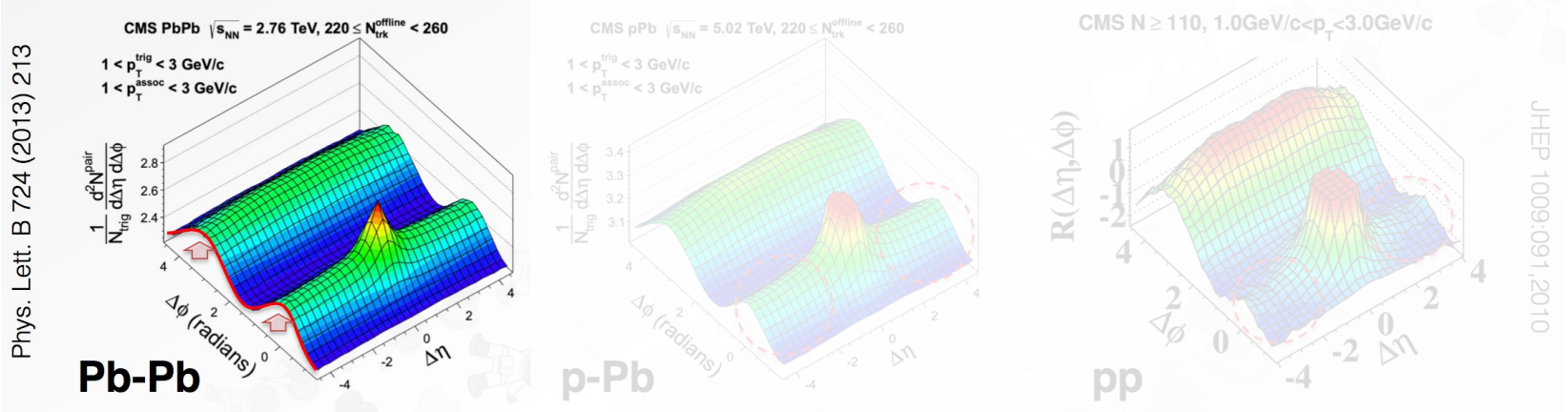
Data from the LHC and RHIC

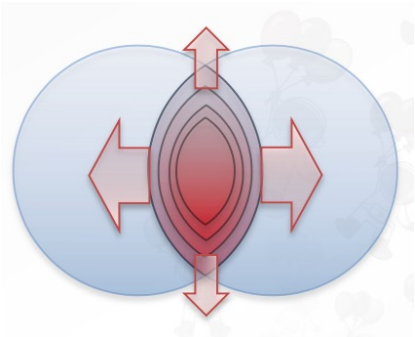


- sPHENIX and STAR in 2023-2025
- No physics results yet from the data

2023	2024	2025
Au+Au, 200 GeV	p+p, 200 GeV p+Au, 200 GeV	Au+Au, 200 GeV

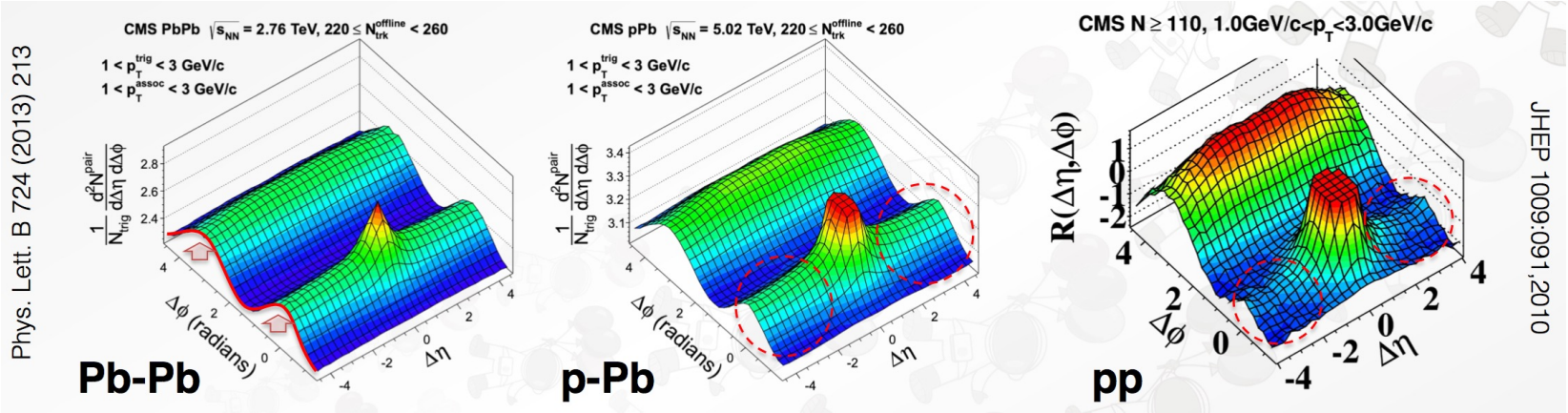
Collective dynamics

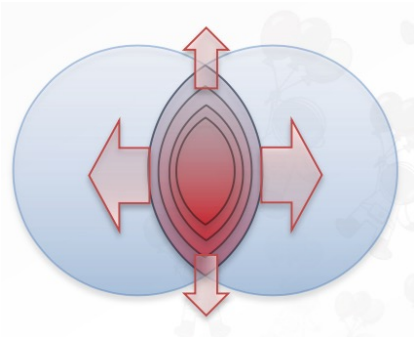




- Collective expansion of an elliptic initial geometry in non-central heavy-ion collisions ← Hydrodynamic behavior

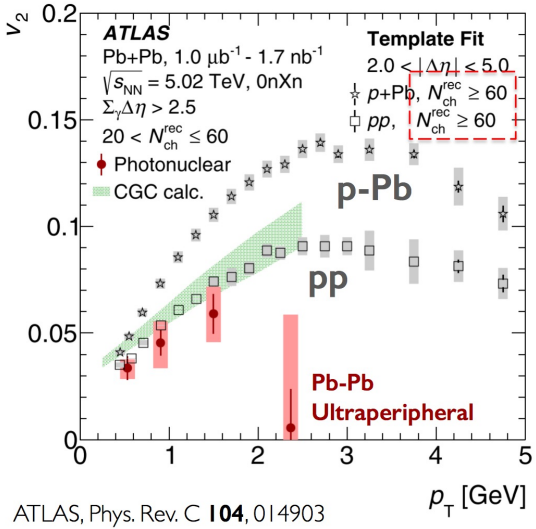
Collective dynamics



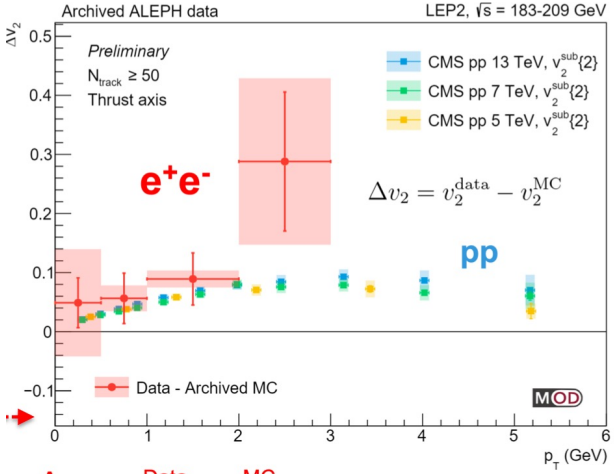


- Collective expansion of an elliptic initial geometry in non-central heavy-ion collisions ← Hydrodynamic behavior
- Similar behavior at high-multiplicity p-Pb and pp collisions? ← Momentum anisotropy in the initial condition in CGC framework? Underlying event e.g. Multi-parton interaction?

Collective dynamics



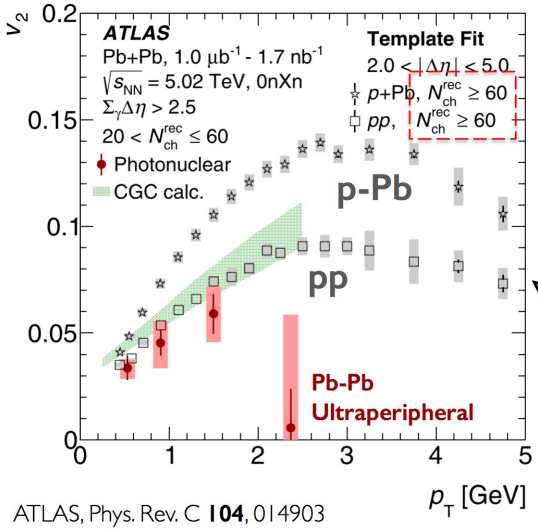
ATLAS, Phys. Rev. C **104**, 014903



- $\Delta v_2 = v_2^{Data} - v_2^{MC}$

- Collective behavior is now observed in high-multiplicity photon-ion collisions (Ultra-peripheral collisions) and electron-position collisions (ALEPH data)

Collective dynamics



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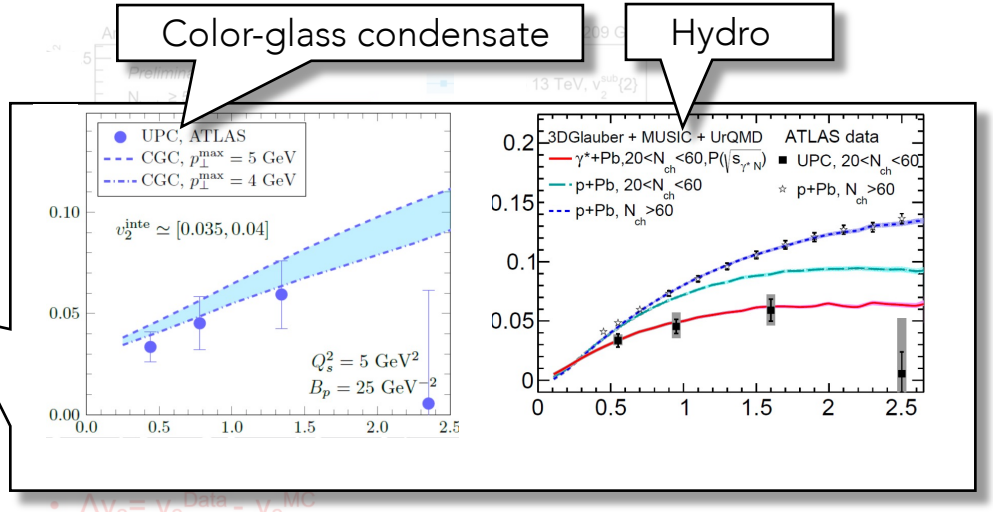
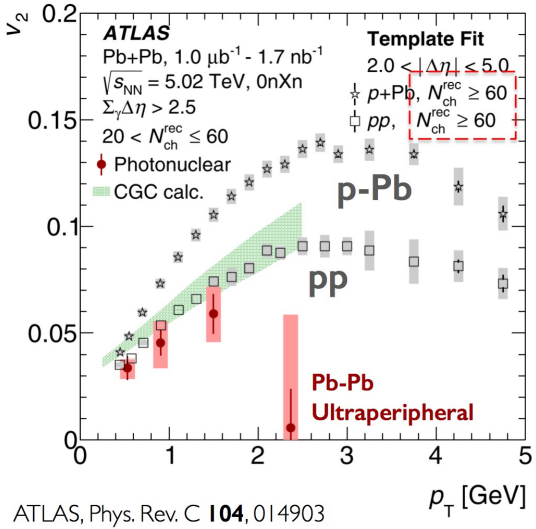


- Collective behavior is now observed in high-multiplicity photon-ion collisions (Ultra-peripheral collisions) and electron-position collisions (ALEPH data)
- Theory approach – How to disentangle each contribution (initial state, QGP evolution, hadronic afterburner) qualitatively/quantitatively? → Hydro Monte-Carlo event generator + statistical tool

Collective dynamics



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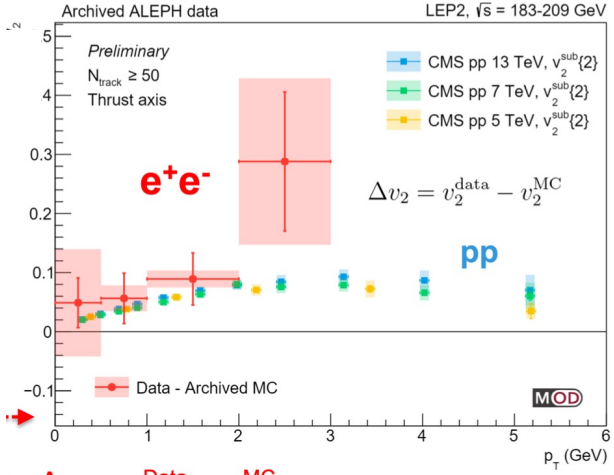

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- Experimental approach – Further differential studies and flow correlations / Hard-soft interplay

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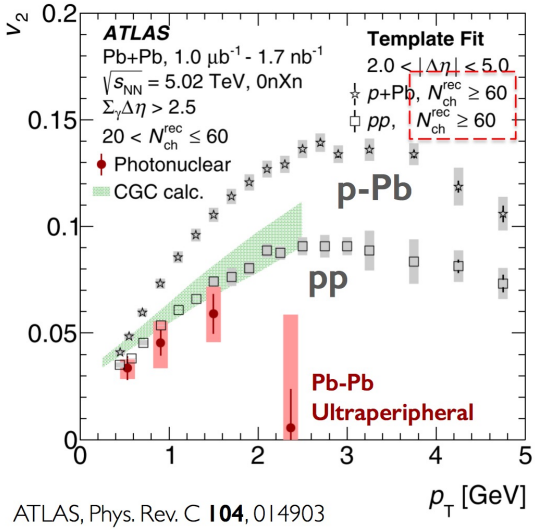

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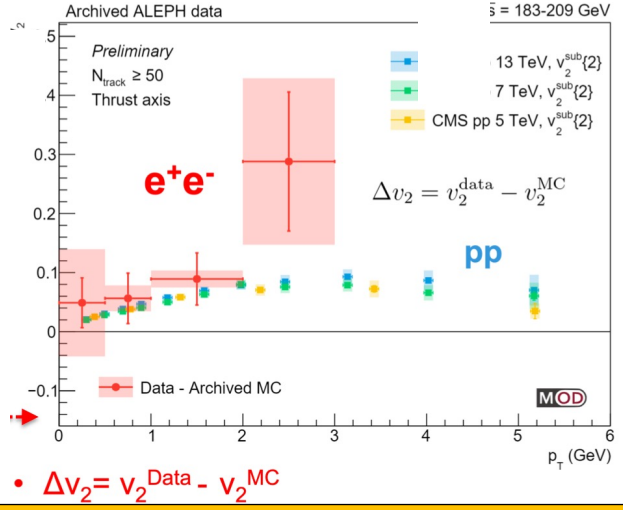

- $\Delta v_2 = v_2^{Data} - v_2^{MC}$

- HIC is now precision science (Statement from the Collective Dynamics plenary talk)

- Collective behavior is now observed in [illegible] collisions) and electron-position collisions (ALEPH data)
- Theory approach – How to disentangle each contribution (initial state, QGP evolution, hadronic afterburner) qualitatively/quantitatively? → Hydro Monte-Carlo event generator + statistical tool
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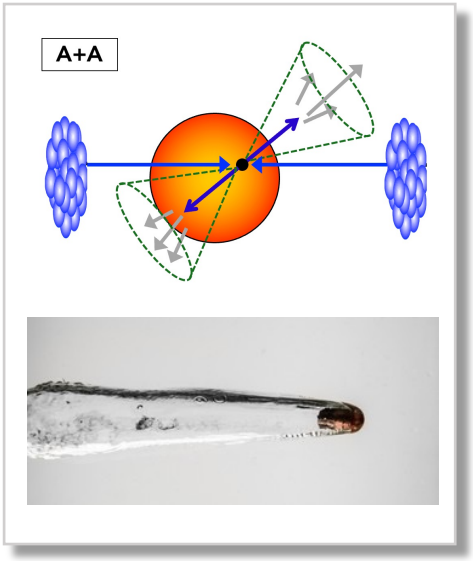
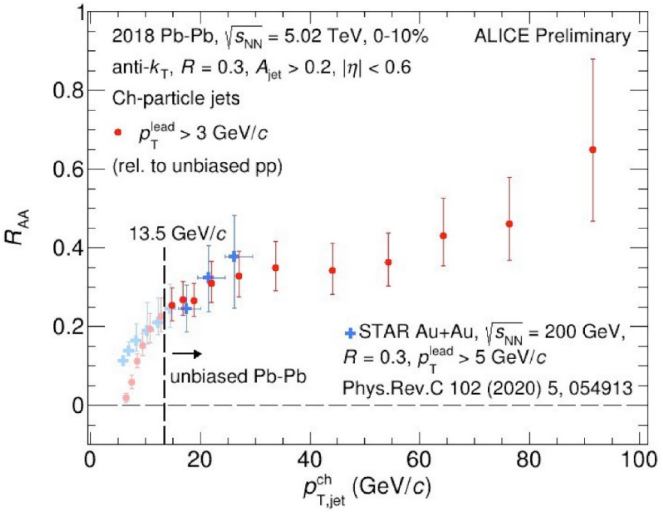
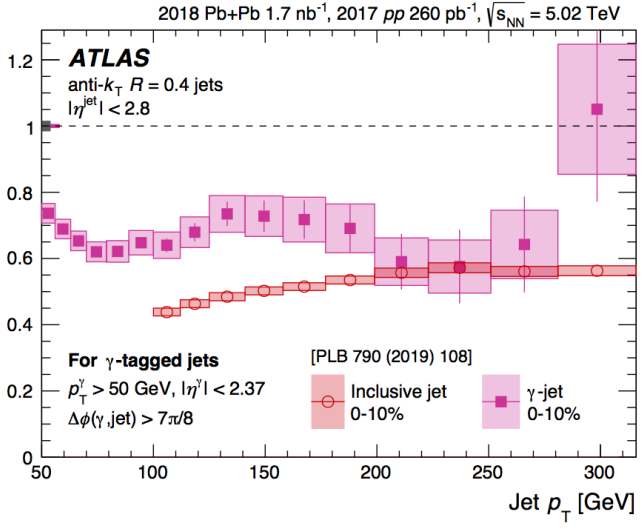
Energy loss of jets to QGP



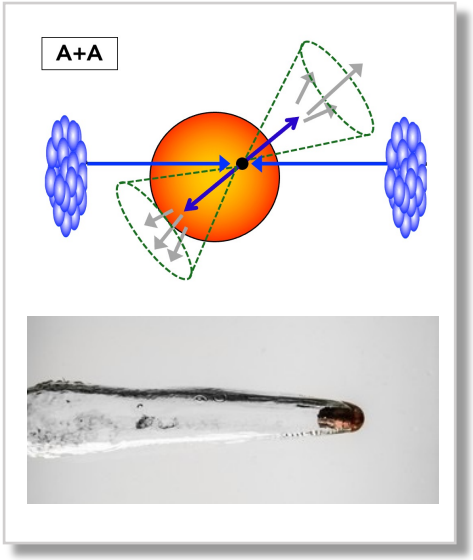


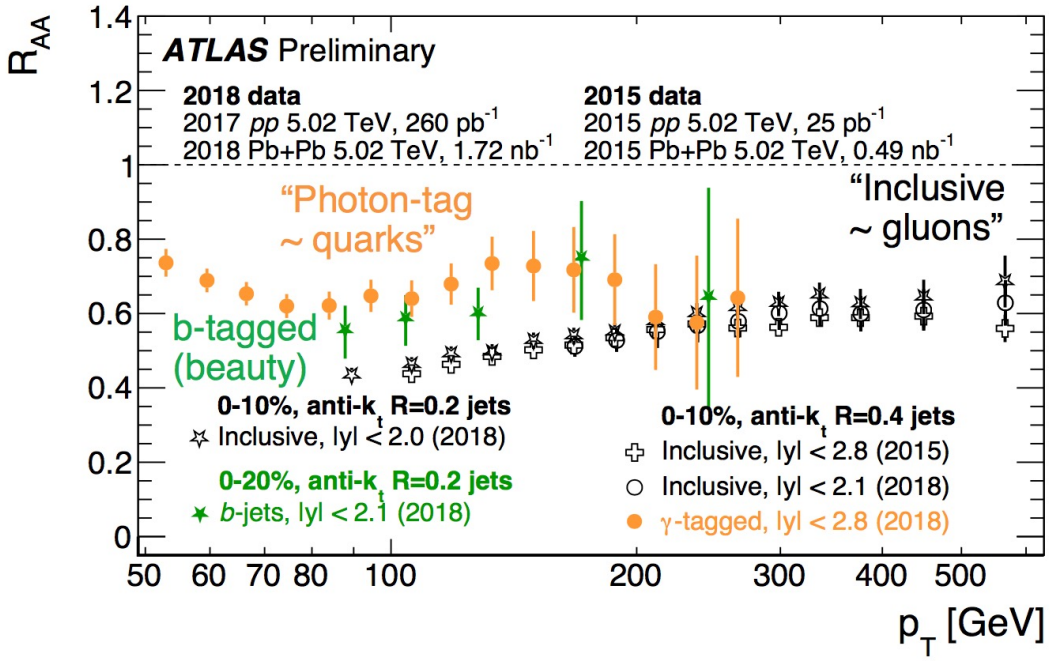


- Charged jet nuclear modification factor similar for both LHC and RHIC energies (Low transverse momentum jet results from ALICE)

- Clear difference between inclusive and photon-tagged jets → quark jet vs. gluon jet

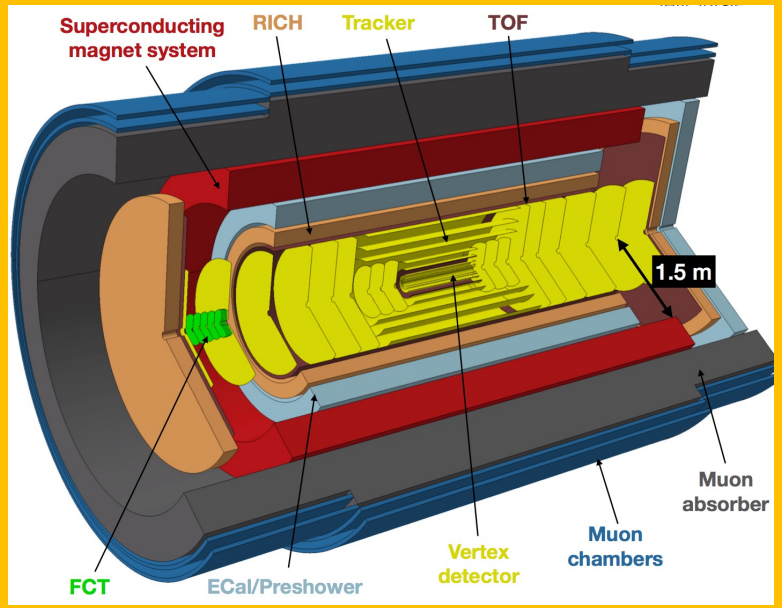
Energy loss of jets to QGP



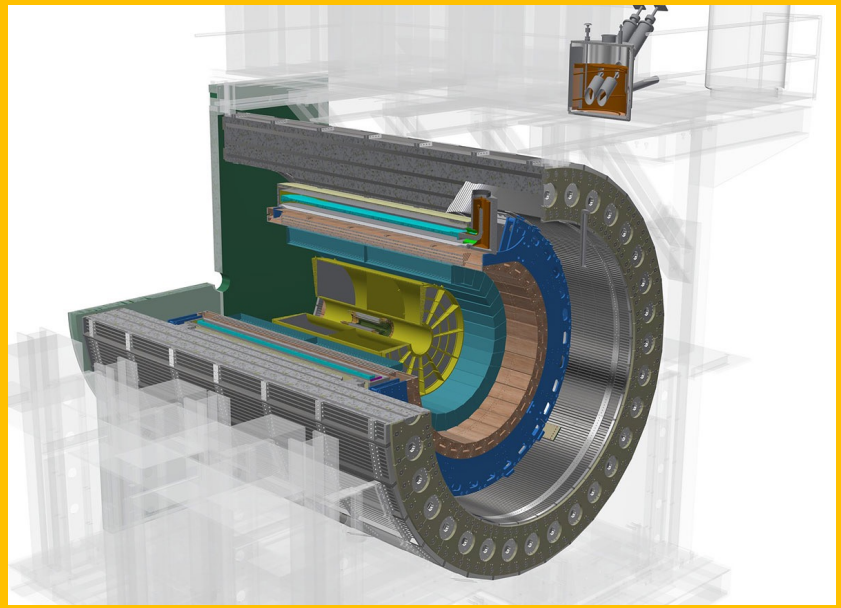


- Flavor (mass) dependence of jet energy loss

Energy loss of jets to QGP



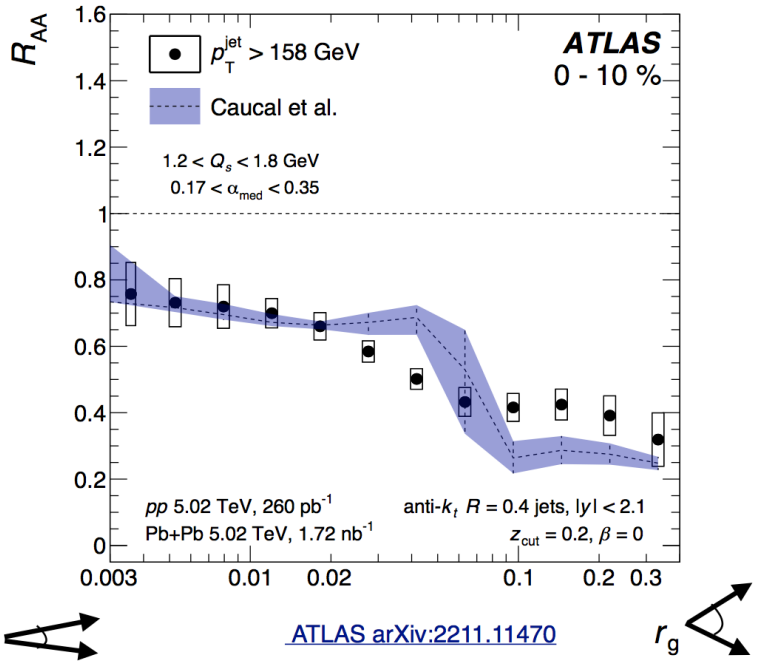
ALICE 3 (LHC Run 5 & 6)



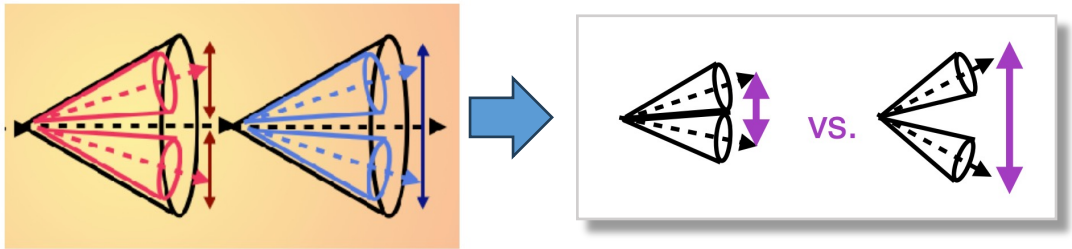
sPHENIX (2023-2025)

- Heavy-flavor jets are one of the main physics motivations for ALICE 3 and sPHENIX
- Heavy-quark and QGP interactions are calculable with lattice QCD framework – good theoretical control

Relativistic heavy-ion physics



ATLAS arXiv:2211.11470

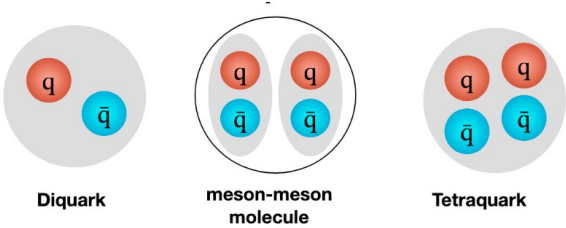


- What is the resolution length of the QGP?

- Results are consistent with predictions from decoherence model

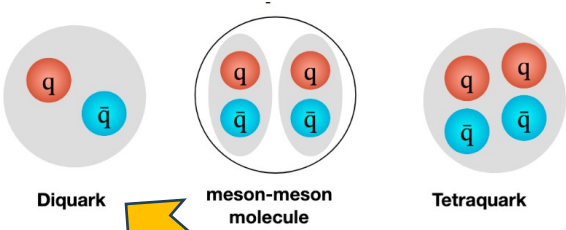
$f_0(980)$ quark content

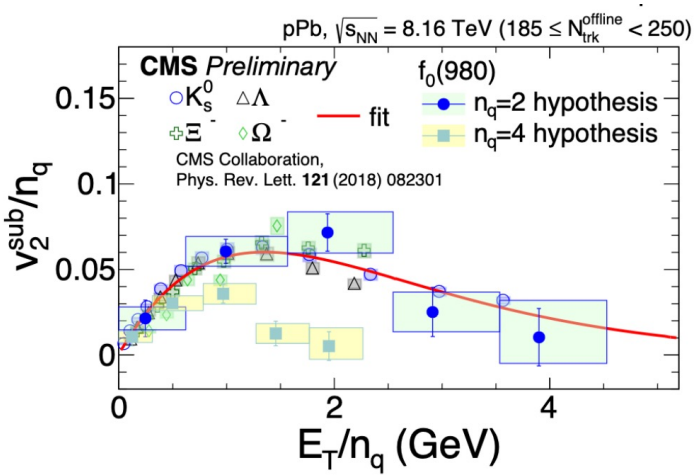
- Longstanding question – Is f_0 a diquark, molecular, or tetraquark? ← Difficult to answer theoretically



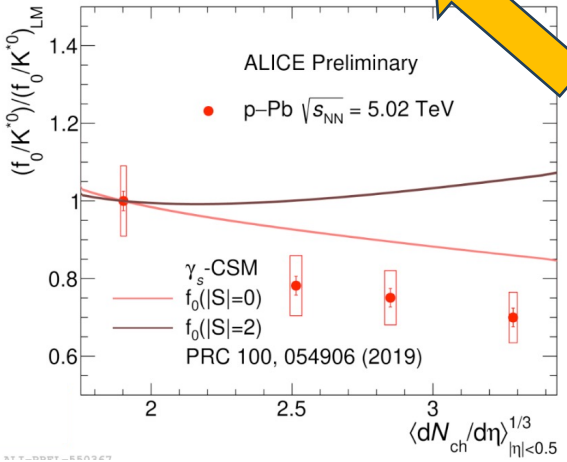
$f_0(980)$ quark content

- Longstanding question – Is f_0 a diquark, molecular, or tetraquark? ← Difficult to answer theoretically





- Elliptic flow – NCQ scaling when $n_q = 2$

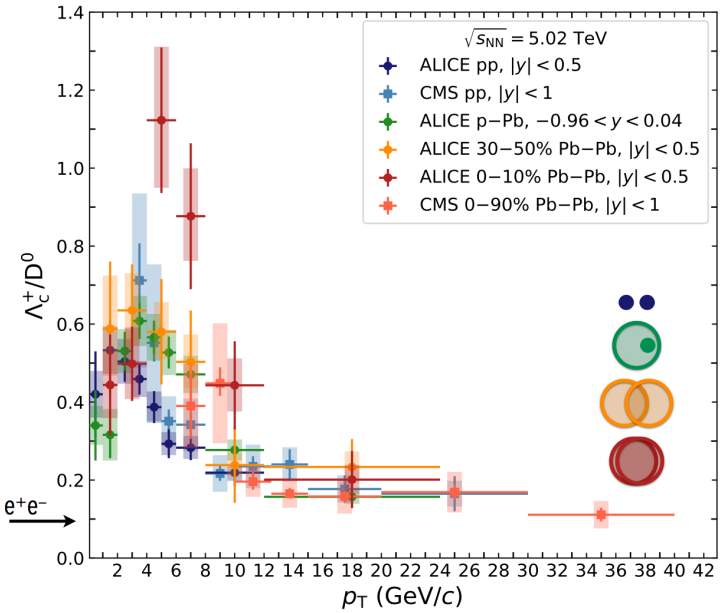


Both results are consistent with the diquark picture

- F_0/K^{*0} ratio – consistent with calculation assuming |S|=0 $[\frac{u\bar{u}+d\bar{d}}{2}]$

Heavy-quark hadrochemistry

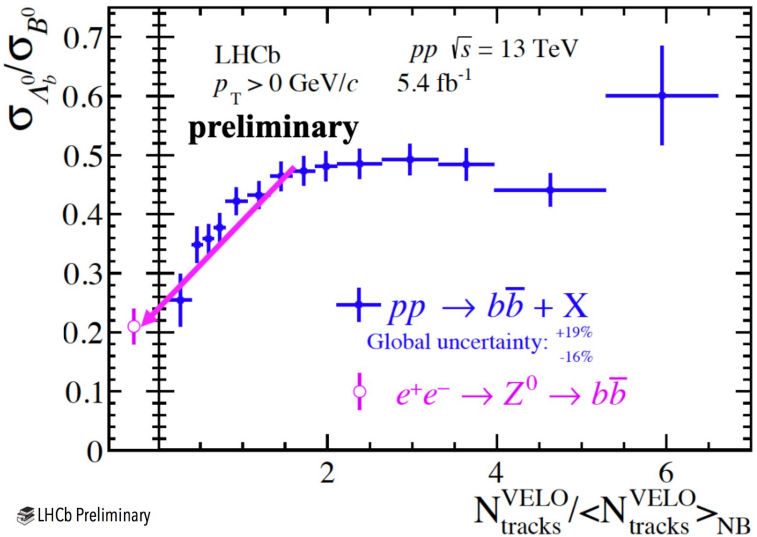
- Heavy-quark : produced in shorter time scales than the QGP formation
- Hadrochemistry – study hadronization from the medium (Fragmentation, recombination/coalescence)



- Strong enhancement of charm baryon-to-meson ratio in pp collisions (Consistent between ALICE and CMS)
- Modification of Λ_c^+/D^0 in p-Pb (quark recombination?)
- Similar modification in Pb-Pb collisions increasing with centrality

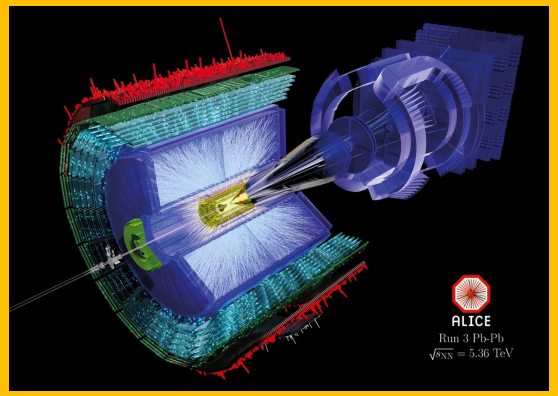
Heavy-quark hadrochemistry

- Heavy-quark : produced in shorter time scales than the QGP formation
- Hadrochemistry – study hadronization from the medium (Fragmentation, recombination/coalescence)

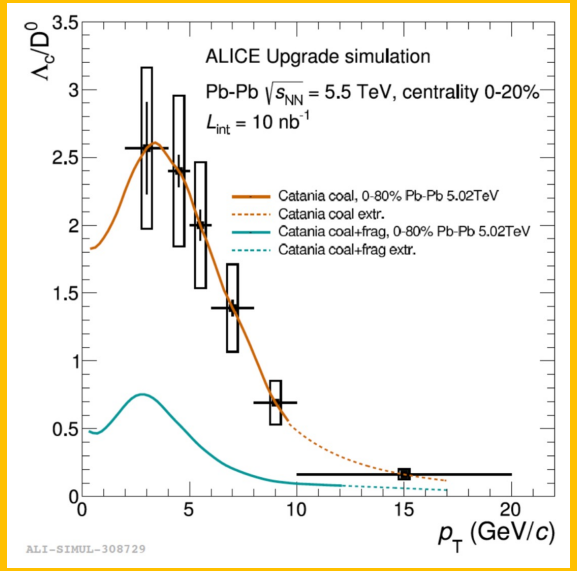


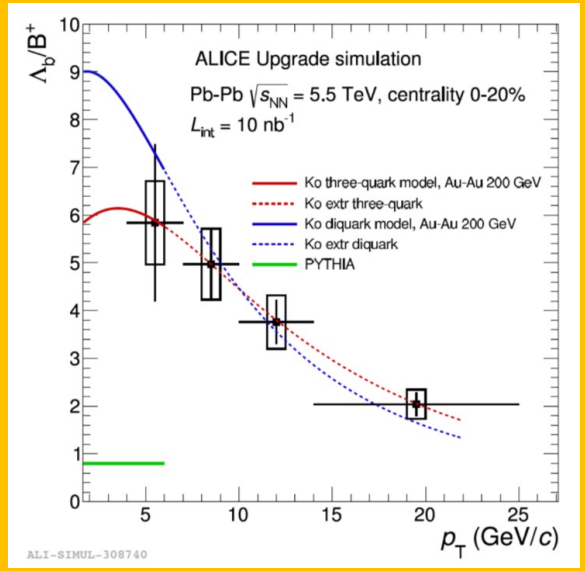
- Modification of Λ_b^0/B^0 as a function of multiplicity in pp collisions (saturation at high multiplicity)

Relativistic heavy-ion physics



ALICE Run 3
(2022-2025)





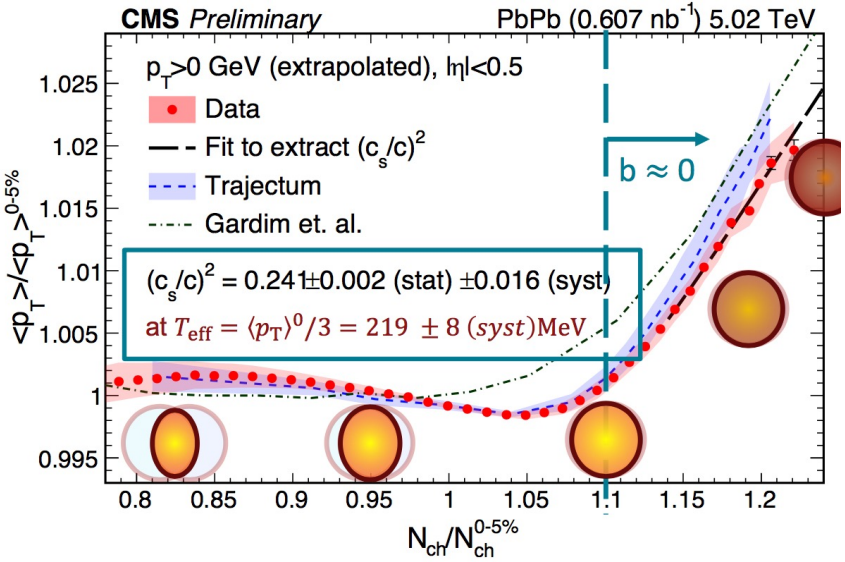
- With the improved detector performance and statistics and ALICE Run 3 (2022-2025), we will have much better results soon

Speed of sound in QGP

- Speed of sound – velocity of the longitudinal compression wave propagating in the medium
- Simple, but elegant analysis

$$c_s^2(T_{\mathrm{eff}}) = \frac{dP}{d\varepsilon} = \frac{sdT}{Tds}\Big|_{T_{\mathrm{eff}}} = \frac{dln\langle p_T\rangle}{dln(dN_{\mathrm{ch}}/d\eta)}$$

- Focus on ultra-central events (no geometrical fluctuation)



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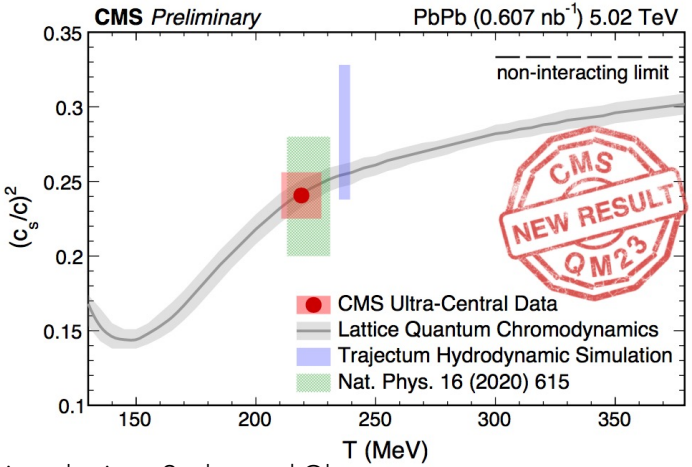
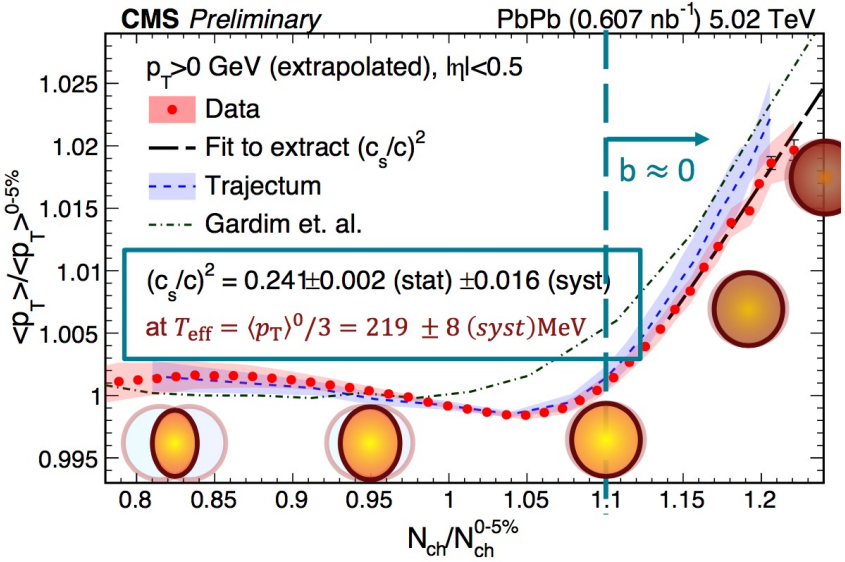
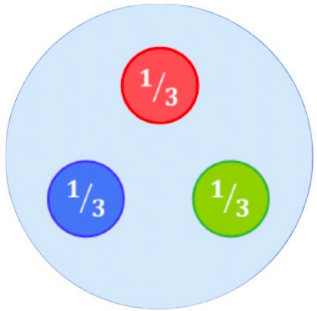




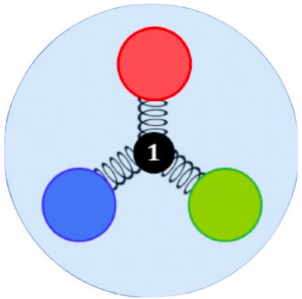
- Good agreement with the Lattice QCD calculation
- PID dependence? Any other collision systems?

Search for evidence of baryon junction

Conventional picture



Baryon Junction [1, 2]



Which carries baryon number – quark vs. baryon junction?

- Quark carries most of momentum and contracted into thin "pancakes" at high energy
- Quarks have less time to interact due to contracted longitudinal length

- Junction carries lower momentum and less contracted (made of low-x gluons)
- More time to interact with other partons
- Enhanced baryon stopping at mid-rapidity

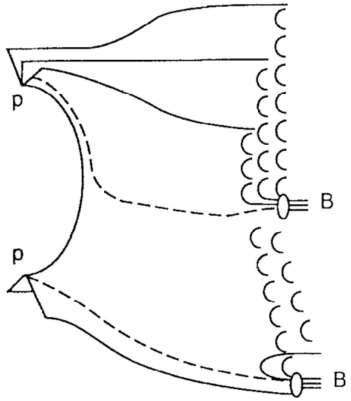
Search for evidence of baryon junction

Physics Letters B 378 (1996) 238–246

Can gluons trace baryon number?

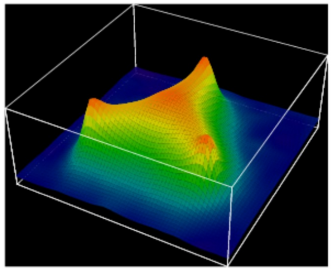
D. Kharzeev
Theory Division, CERN, CH-1211 Geneva, Switzerland
and Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany

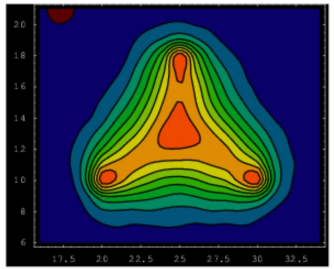
Received 15 March 1996
Editor: R. Gatto



The lattice results show the presence of a "baryon junction" inside proton – a purely gluonic field configuration that represents entanglement among the quarks and carries baryon number.

- Suganuma, Ichie, Takahashi, 2024





contracted into thin "pancakes" at high energy

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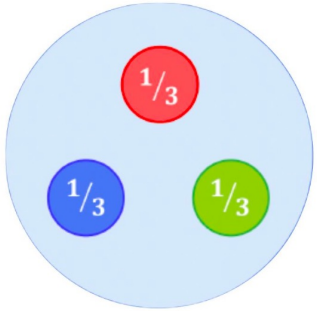
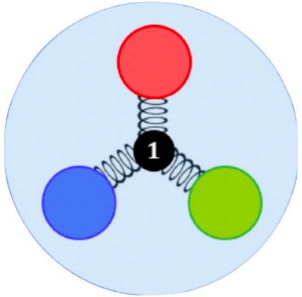
Search for evidence of baryon junction

Conventional picture



Baryon Junction [1, 2]

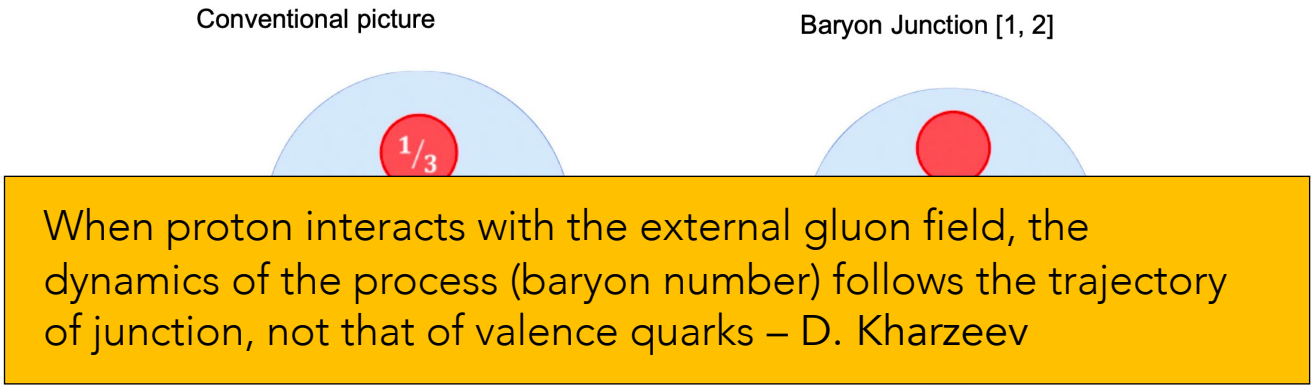


How to test experimentally it?

- Net-proton yield as a function of rapidity in hadronic Au+Au collisions
- Net-Baryon vs. Net-Electric charge in Isobar collisions
- Net-Baryon in photonuclear collisions

- All results disfavor the assertion that valence quarks carry the baryon number

Search for evidence of baryon junction



When proton interacts with the external gluon field, the dynamics of the process (baryon number) follows the trajectory of junction, not that of valence quarks – D. Kharzeev

How to test experimentally it?

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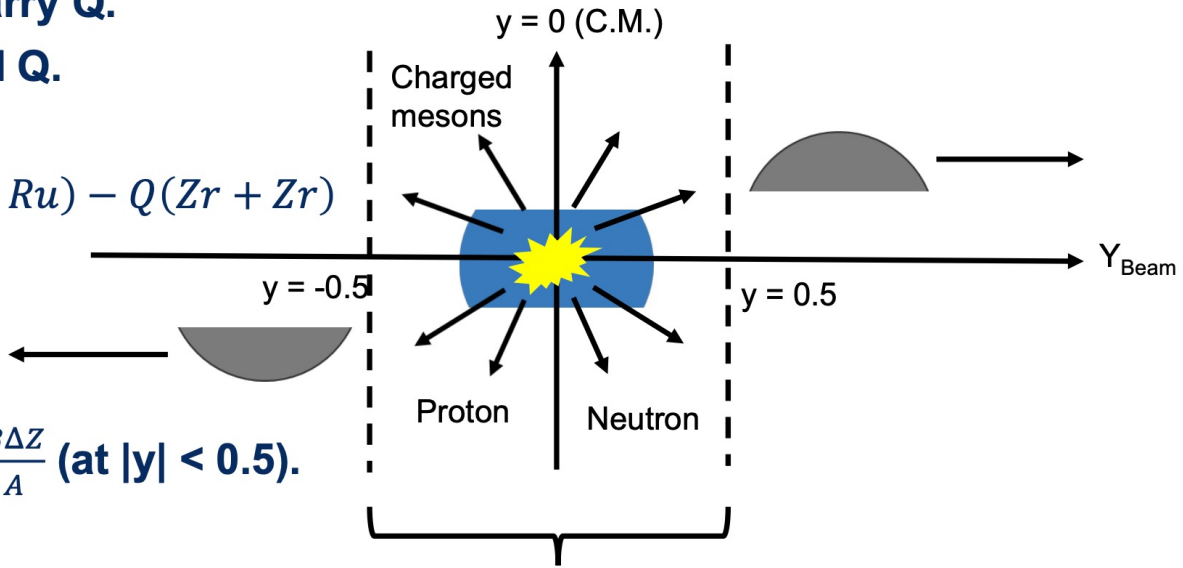
Results will be submitted to Nature

Summary

- Precision area is being reached in the heavy-ion community
- Wealth of high-quality data across collision energies, PID, centralities allows detailed studies that highlight the underlying physics that we pursued for a long time
- Still more exciting results are on the way in coming years!

Search for evidence of the baryon junction

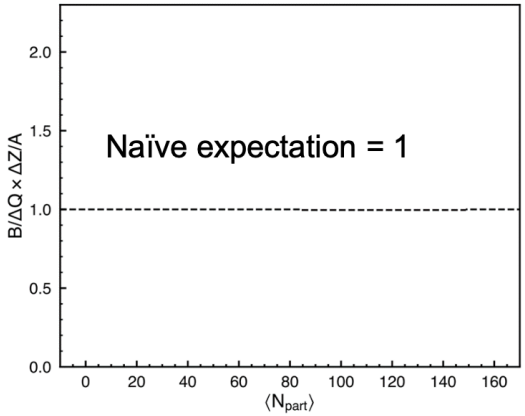
- **Charged meson: Carry Q.**
- **Proton: Carry B and Q.**
- **Neutron: Carry B.**
- **Define** $\Delta Q = Q(Ru + Ru) - Q(Zr + Zr)$

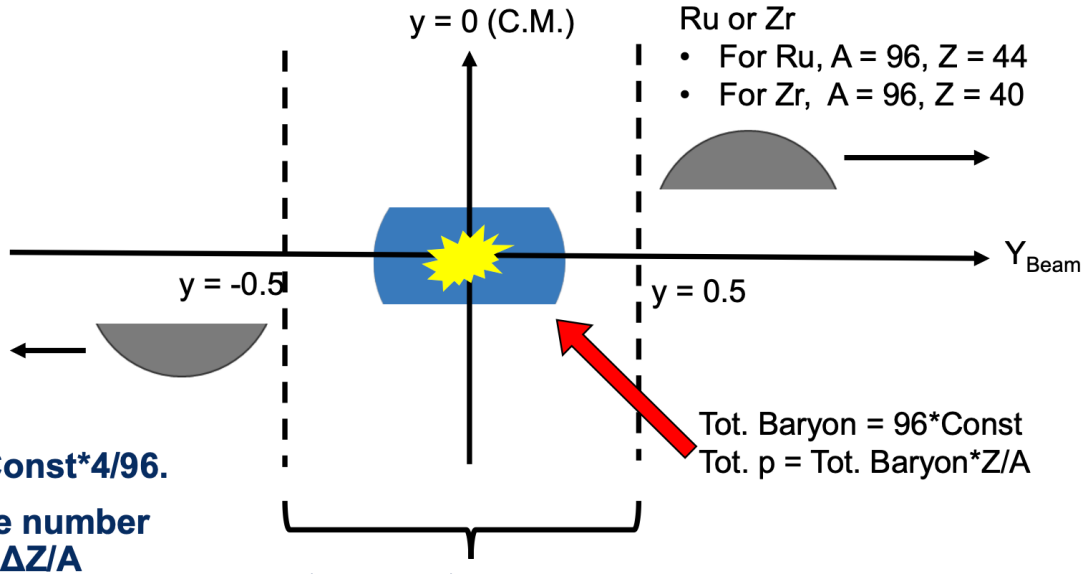


- **Question:** $\Delta Q = ??? \frac{B\Delta Z}{A}$ **(at |y| < 0.5).**

- $B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$
- $Q = (N_{\pi}^{+} + N_K^{+} + N_p) - (N_{\pi}^{-} + N_K^{-} + N_{\bar{p}})$

Search for evidence of the baryon junction

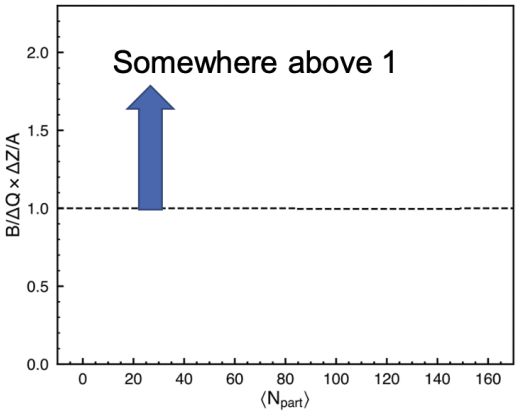


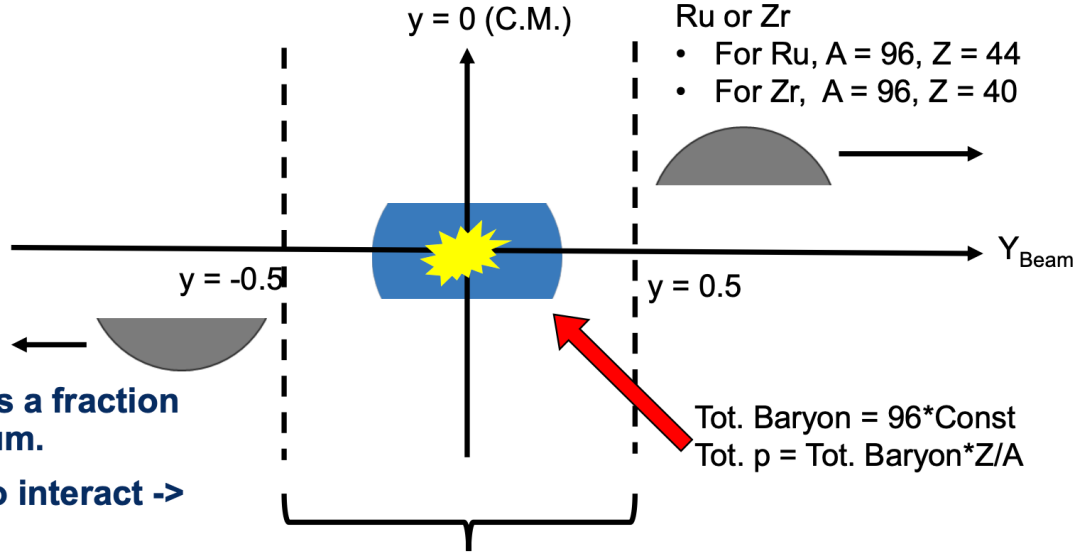


- B_{init}**=96*Const.**
- $\Delta Q_{init} = Q_{init}\,(Ru - Zr)$**=96*Const*4/96.**
- **If baryon number and charge number are carried by quarks, B/ΔQ*ΔZ/A should be 1 throughout the collision evolution at mid-rapidity.**

- $B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$
- $Q = (N_{\pi}^{+} + N_K^{+} + N_p) - (N_{\pi}^{-} + N_K^{-} + N_{\bar{p}})$

Search for evidence of the baryon junction

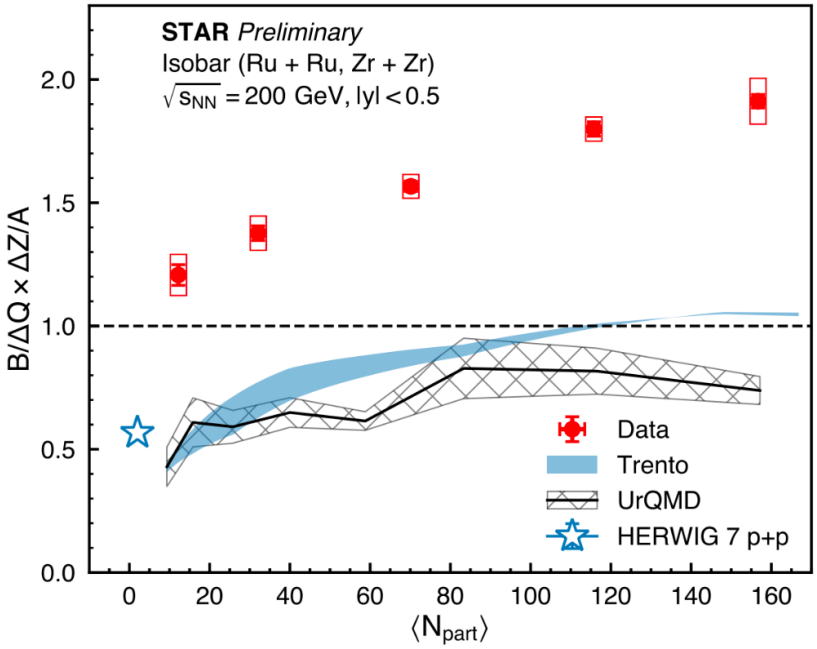




- **Baryon Junction only carries a fraction of valence quark's momentum.**
- **Junction has enough time to interact -> More baryon stopping.**
- **Net-Baryon > Net-Charge.**

- $B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$
- $Q = (N_\pi^+ + N_K^+ + N_p) - (N_\pi^- + N_K^- + N_{\bar{p}})$

Search for evidence of the baryon junction



- $B/\Delta Q * \Delta Z/A > \mathbf{1}$.
- Model calculations (Herwig $p + p$ (B/Q*Z/A, Z=A=1) [1] and UrQMD [2]) cannot describe our data
- Decrease with decreasing $\boldsymbol{N_{part}}$.
  - ✓ Similar trend seen in Trento model
  - ✓ Trento model accounts for initial conditions only
  - ✓ Consistent with change in neutron skin thickness differences.
- **This result disfavors the assertion that valence quarks carry the baryon number**

Search for evidence of the baryon junction

- Conserved baryon current is associated with quarks
- How baryon current interacts with the external fields? Proton interacts with the external gluon field – You have to allow to separate these quarks in space – once they are separated, the gluon junction appears. Dynamics of the process (baryon number) follows the trajectory of junction, not the trajectory of valence quarks
- From the point of view of symmetry, valence quarks carries the baryon number. But from the point of view of dynamics, baryon junction works. 4