Relativistic heavy-ion group and the PixElφ Lab

https://pixelphilab.mit.edu

Gian Michele Innocenti

NUPAX Research Presentation

MIT Open House 2024

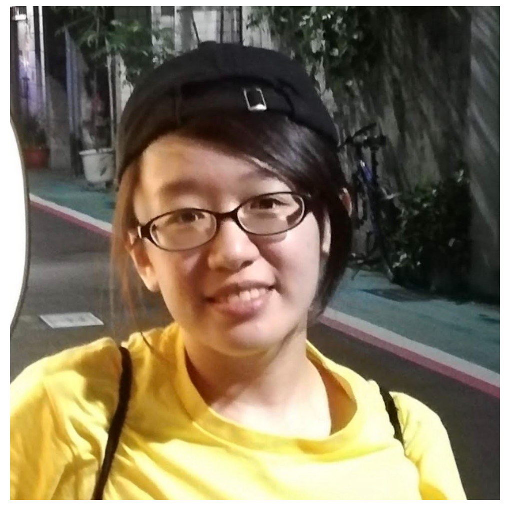
ginnocen@mit.edu

The MIT heavy-ion group

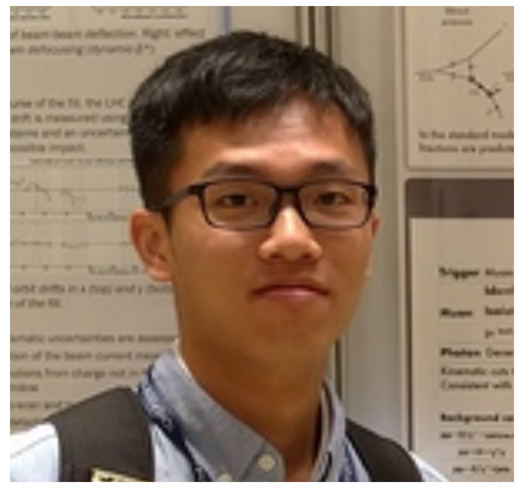

Tzu-An Sheng
joined 2019


Molly Taylor
joined 2018
NSF Fellow


Michael Peters
joined 2017


Janice Chen
joined 2021


Pin-Chun Chou
joined 2020


Hao Ren Jheng
Joined 2021


Alex Patton
joined 2022


Jordan Lang
joined 2023

8 PhD students


Christof Roland
Principal Research
Scientist


Ivan Cali
Research
Scientist

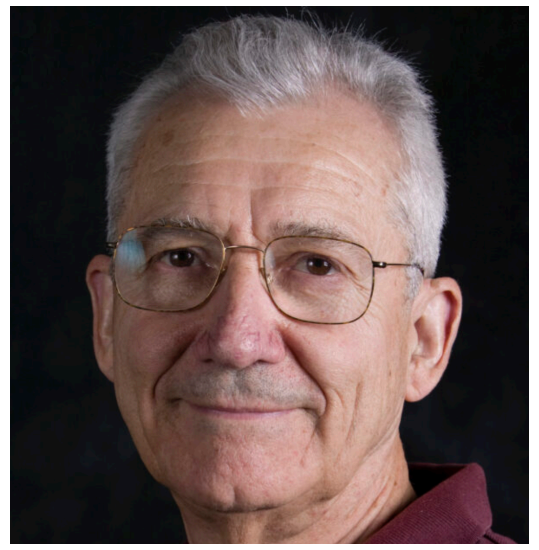

Cameron Dean
Postdoc
Joined 2022


Hannah Bossi
Postdoc
Joined 2023


Chris McGinn
Postdoc
Joined 2023


Jelena Lalic
Engineer
Joined 2024

2 research scientists
1 electronic engineer
3 postdocs


Wit Busza
Friedman Professor
Emeritus


Gunther Roland
Professor
Group Leader


Bolek Wyslouch
Professor


Yen-Jie Lee
Associate Prof.


Gian Michele Innocenti
Assistant Prof.

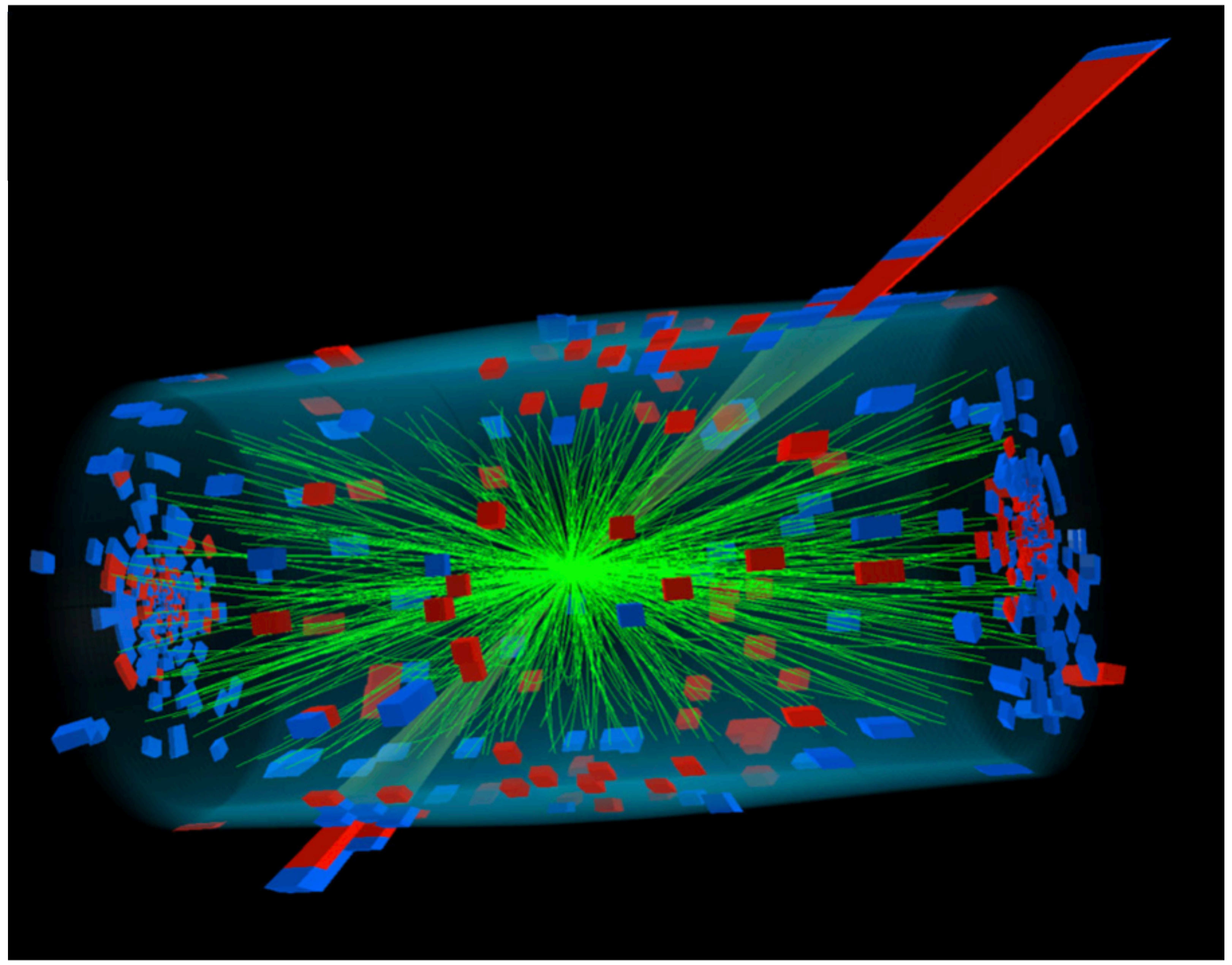
5 professors

Testing the boundary of QCD with heavy-ion collisions

W. Busza, K. Rajagopal, W. v. d. Schee,
ARNPS, Vol. 68:339-376, 2018

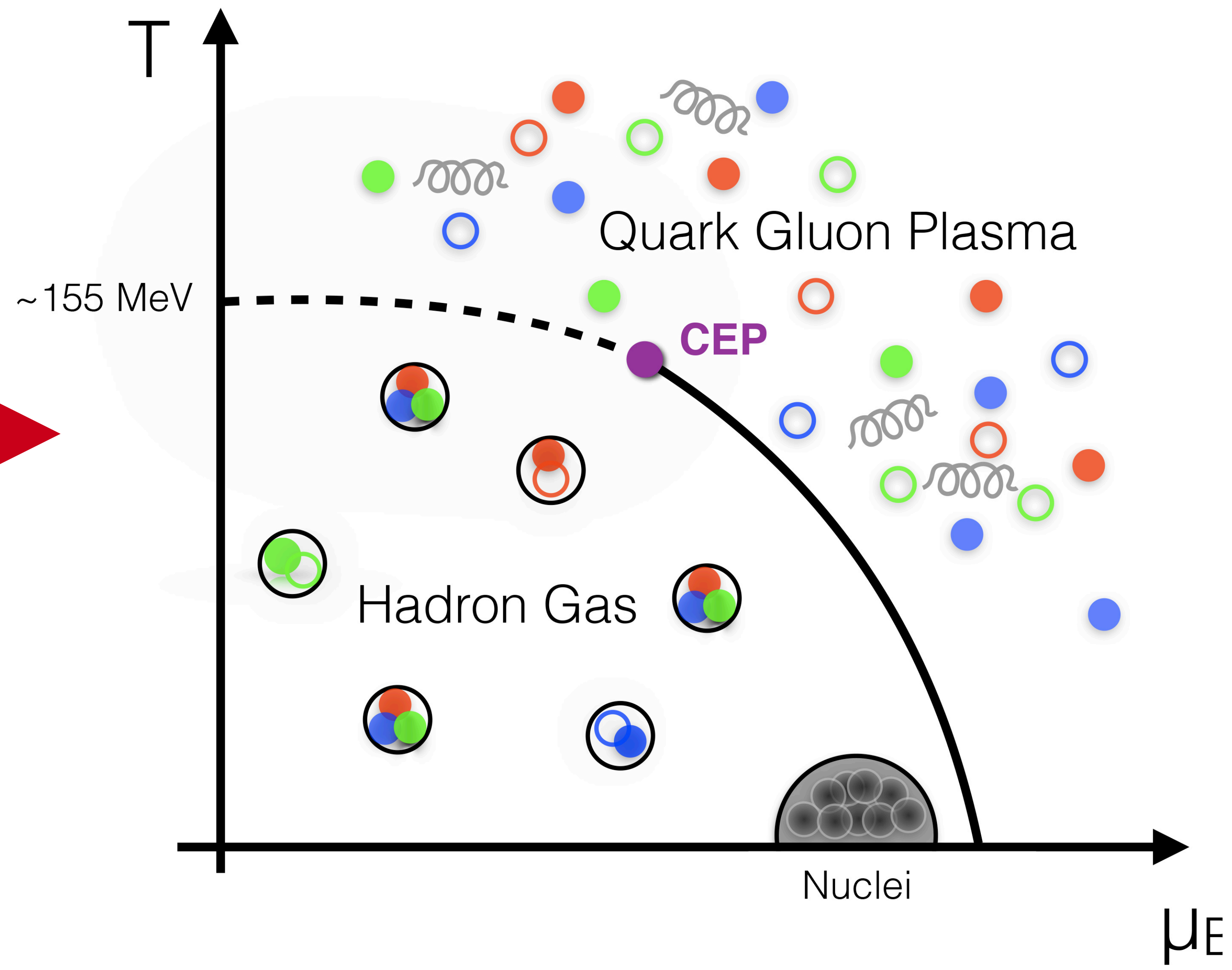
Proton-proton, proton-nucleus, and nucleus-nucleus collisions **to discover and characterize new forms of nuclear matter**

Complex experimental data

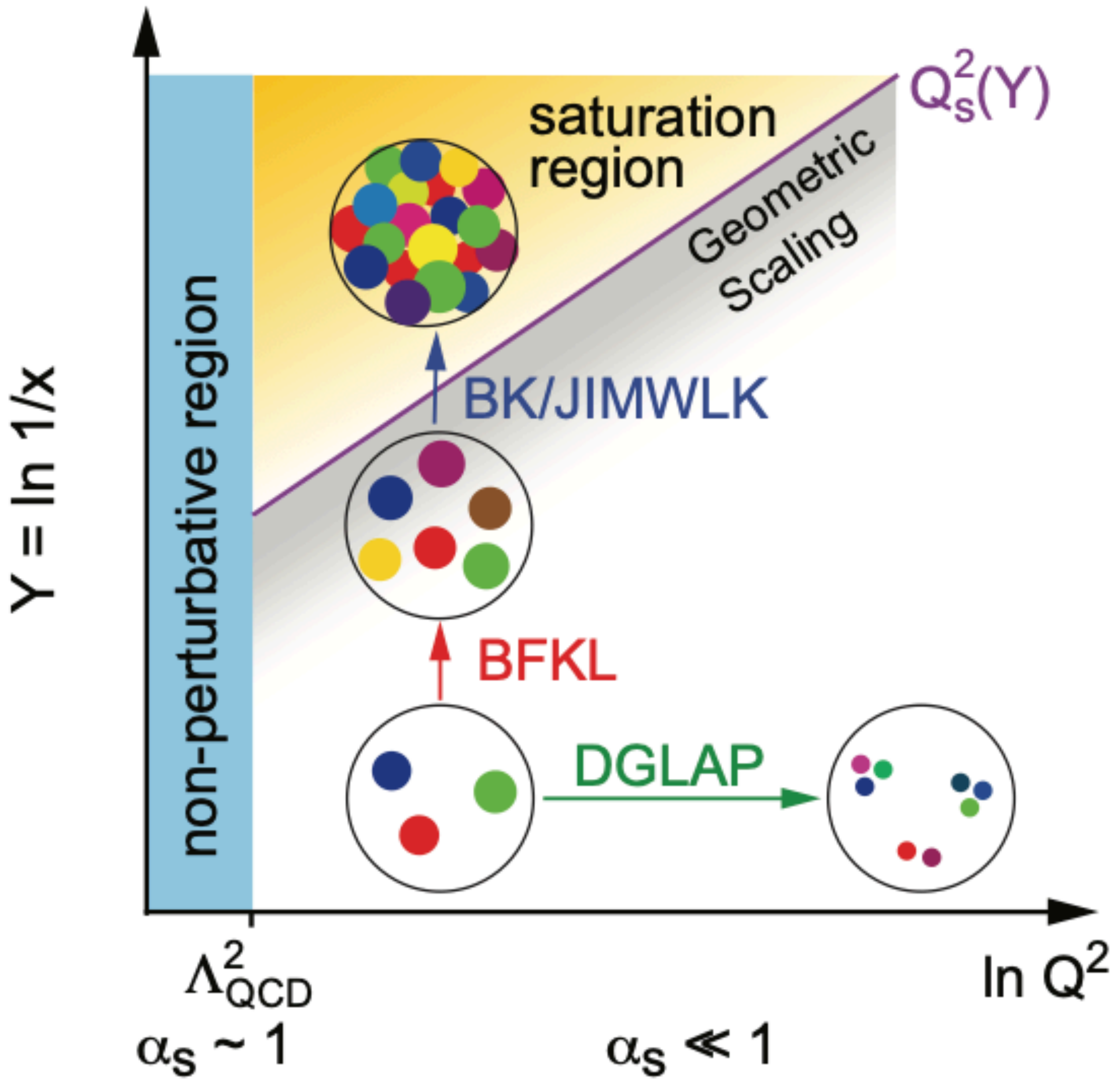


First-principle Quantum-Chromo Dynamics

$$\mathscr{L}_{QCD} = \bar{q}(i\gamma^{\mu}D_{\mu} - m)q - \frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a}$$

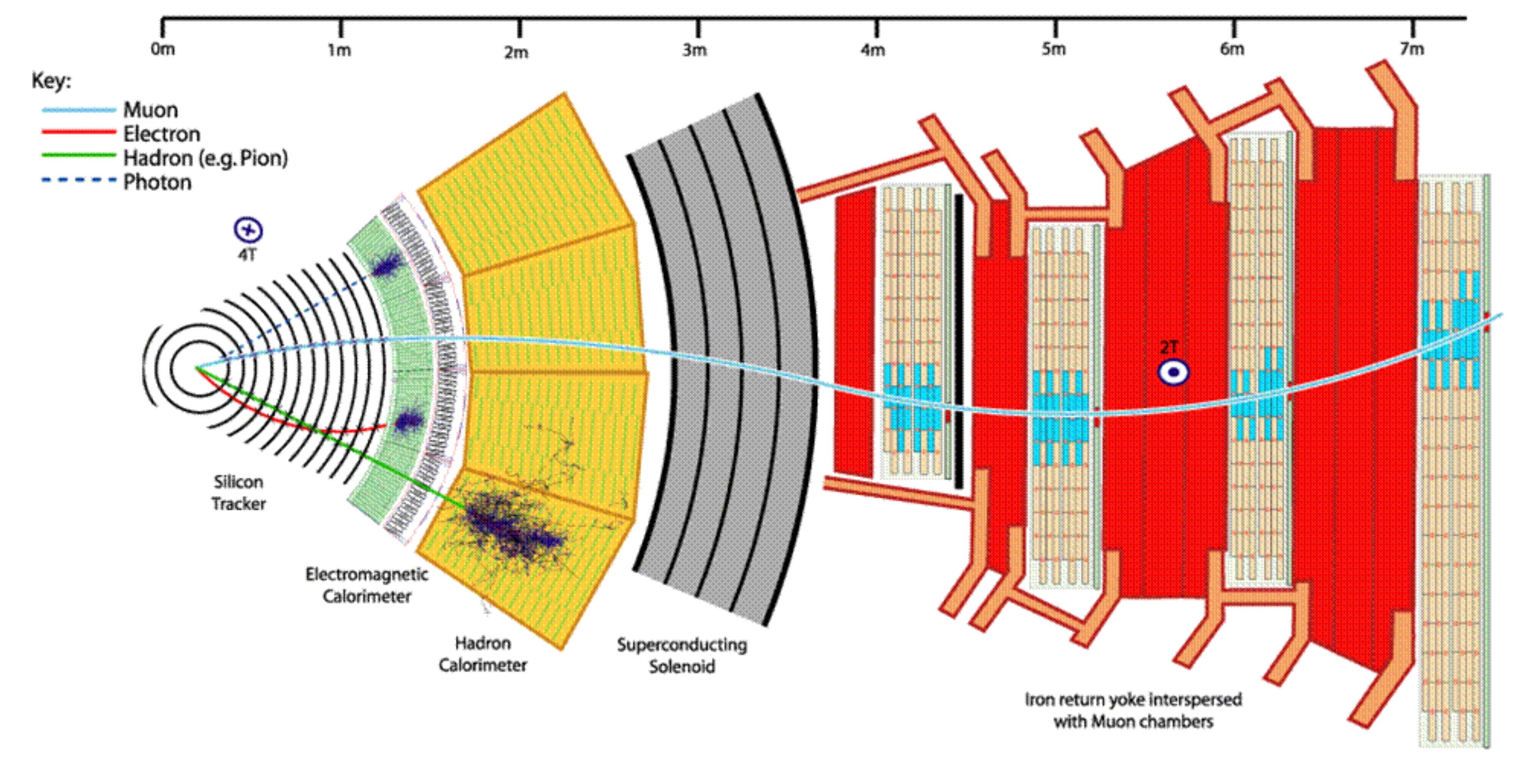


Phase diagram of nuclear matter



→ **to achieve this goal, we exploit cutting-edge software and hardware techniques**
(new data acquisition and trigger strategies, artificial intelligence, new silicon-pixel technologies, …)

CMS, sPHENIX and ePIC at the future Electron-Ion Collider

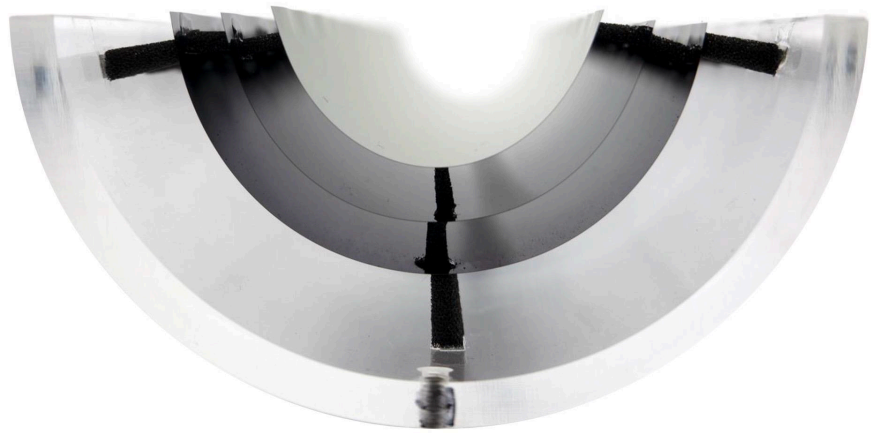


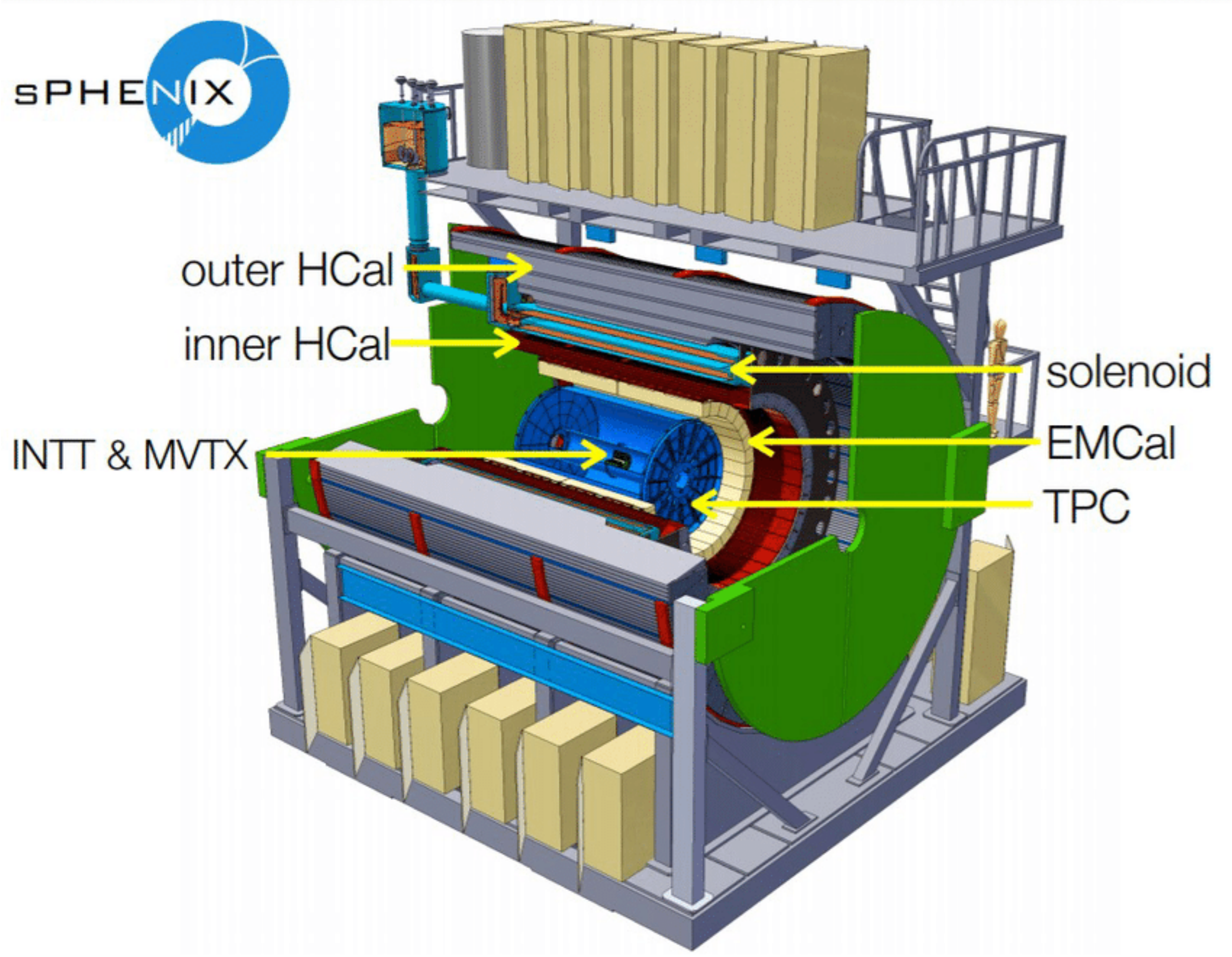
Bolek Wyslouch: **Program manager of HI computer center, CMS MTD**
Yen-Jee Lee: **MIT CMS physics XSCAPE co-PI, HEFTY co-PI, CMSHI upgrade contact**
Gian Michele Innocenti**: CMS HI UPC program, MITPixelPhi, SVT co-coordinator**
Ivan Cali: **CMS HI Run coordinator, CMS XEB, SVT R&D**
Chris McGinn**: CMS UPC analysis and run preparation**
Hannah Bossi**: CMS ZDC HCAL, CMS UPC analysis, MVTX pixel ML**
Pin-Chun Chou**: CMS Z-Jet analysis**
Molly Taylor: **CMS Photon-Jet analysis**
Tzu-An Sheng**: CMS HI HF analysis**
Janice Chen**: CMS data compression, ALEPH ridge, CMS UPC analyses**

CMS at the LHC in Run 1/2

CMS at the LHC in Run 3

2022 2023 2024 2025 2026 2027

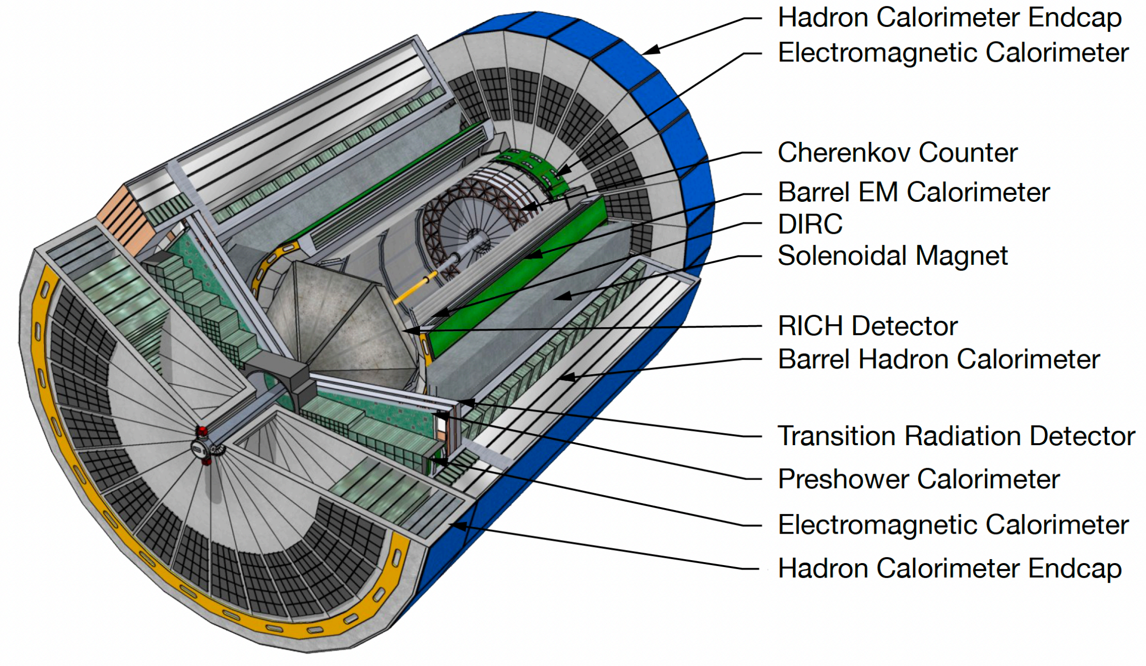




sPHENIX at the Relativistic Heavy-Ion Collider

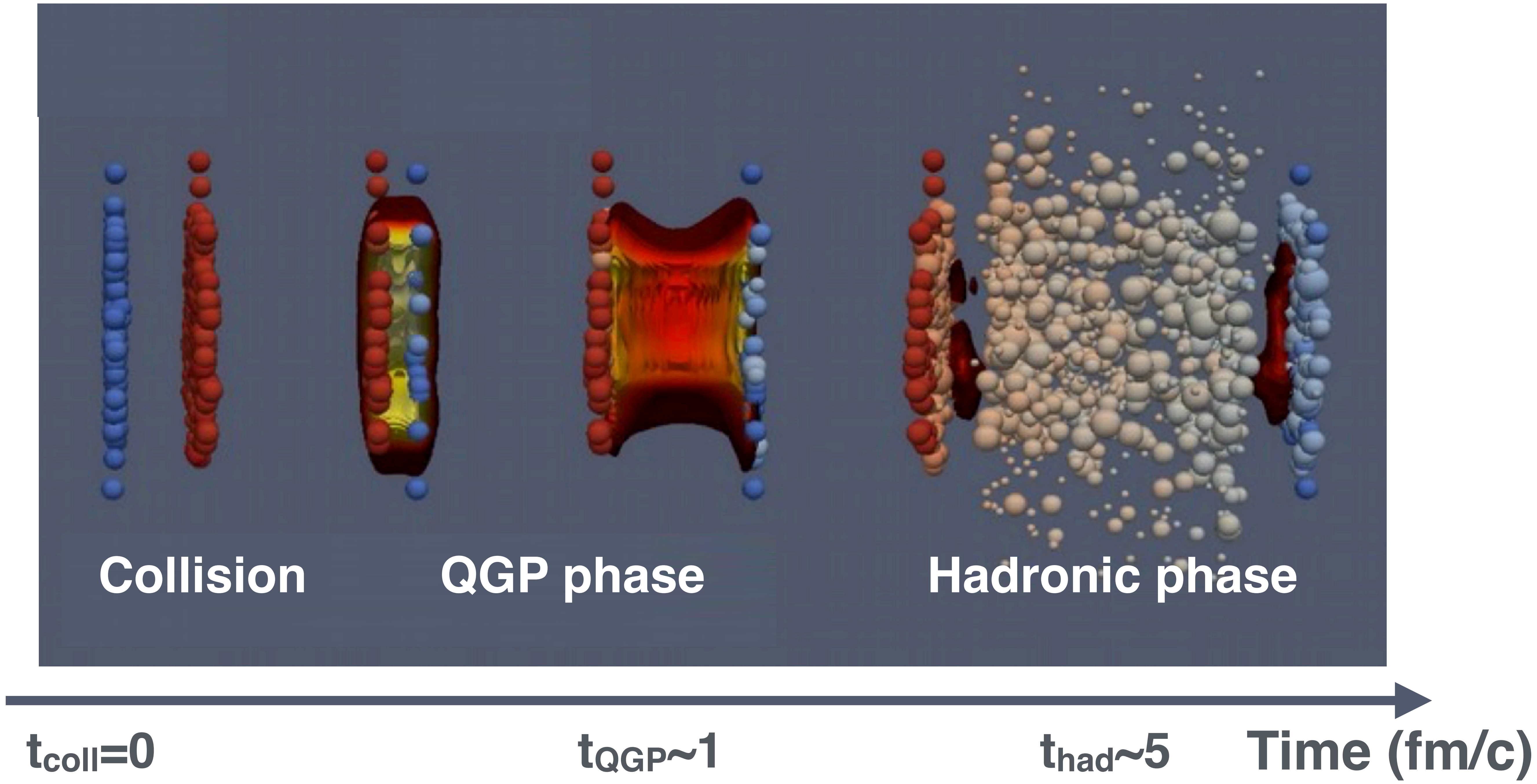
Gunther Roland: **sPHENIX co-spokesperson**
Christof Roland: **sPHENIX calibration Coordinator**
Cameron Dean**: sPHENIX MVTX/INTT readout, MVTX pixel ML**
Michael Peters: **sPHENIX MVTX tracking**
Hao Ren Jheng: **sPHENIX readout**
Alex Patton**: MVTX readout**
Jelena Lalic**: MAPS sensor R&D, MITPixelPhi**

MIT PixElφ Lab and Silicon Vertex Tracker for ePIC at the Electron-Ion Collider

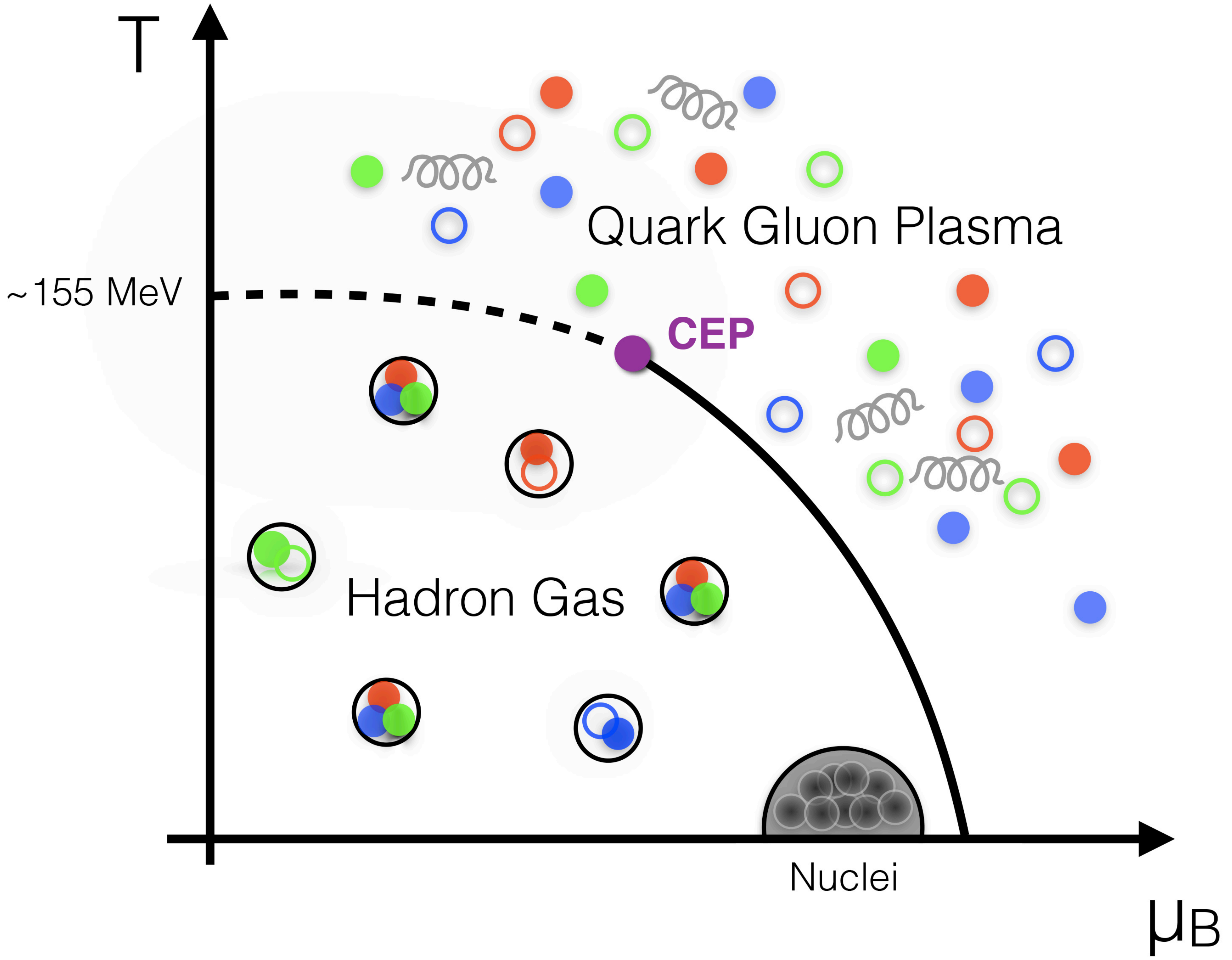


The hottest droplet of nuclear matter with heavy ions

W. Busza, K. Rajagopal, W. v. d. Schee, ARNPS, Vol. 68:339-376, 2018



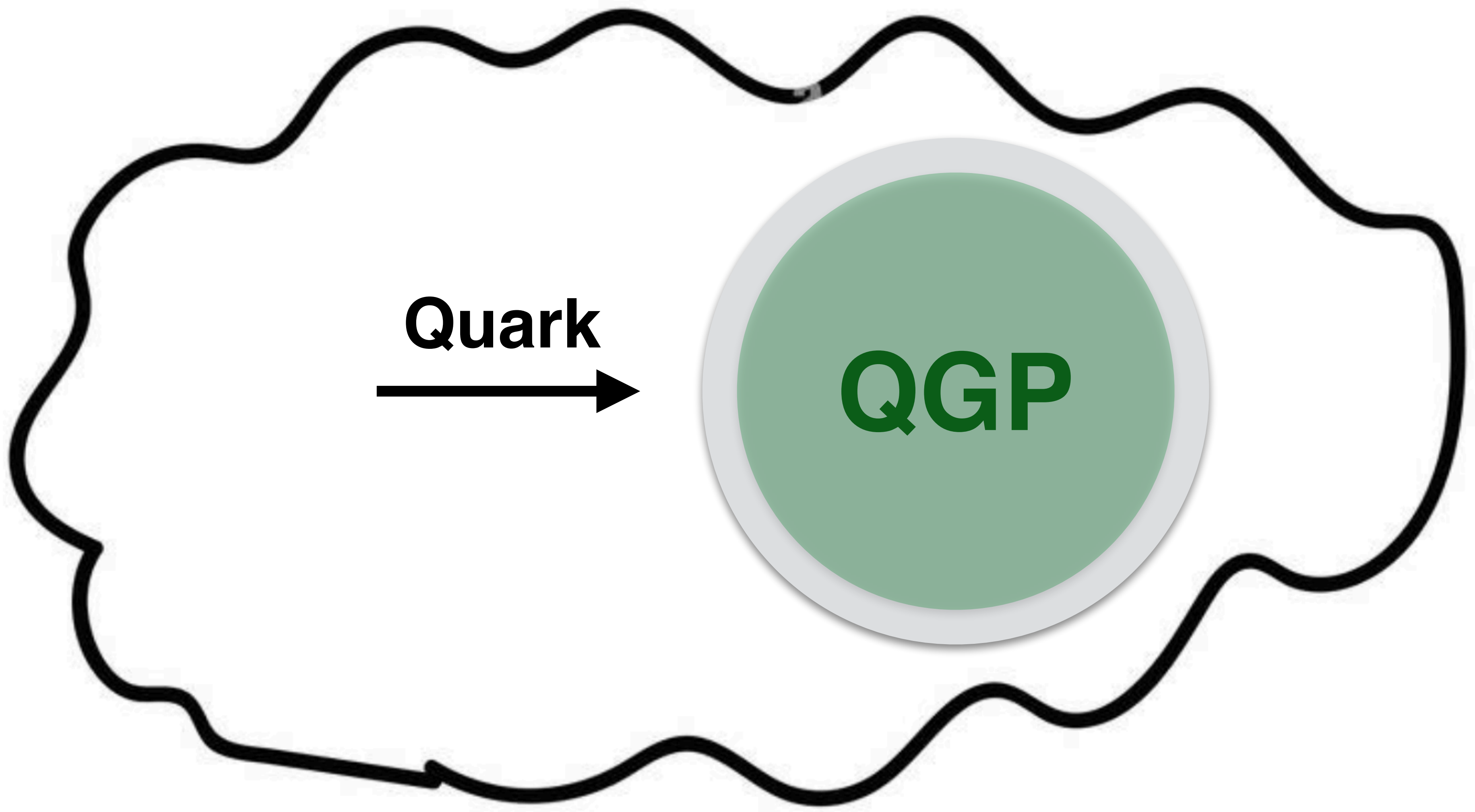
MADAI Collaboration

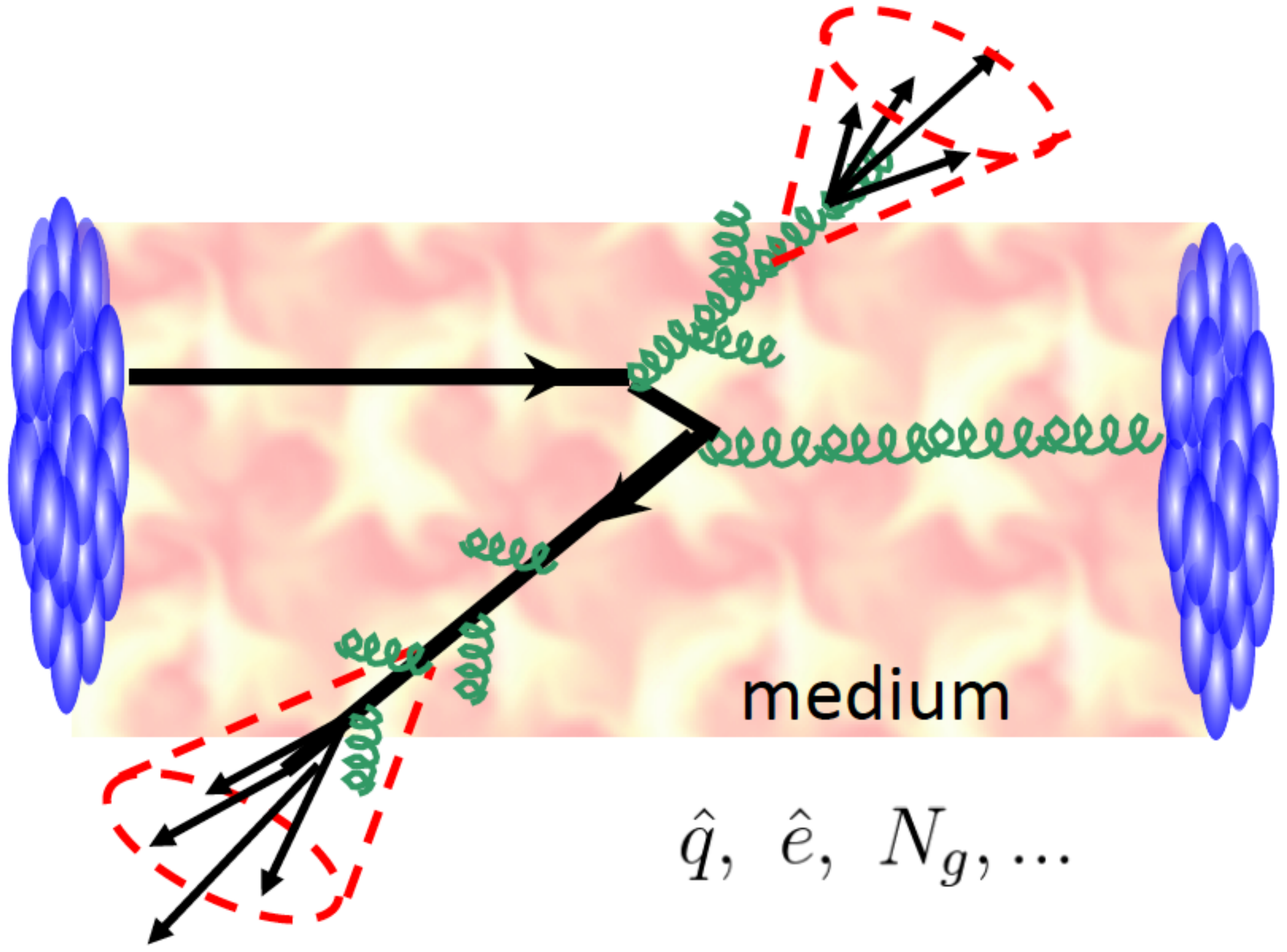


- **Can we create a medium where quarks and gluons are not "constrained" into colorless hadrons?**
- **How are hadrons formed in this phase?**
- **What is the smallest system where QGP can be formed?**

→ crucial questions to understand the nature of the strong force as well as the evolution of our early universe!

Probing the medium with high-p_T partons and heavy quarks

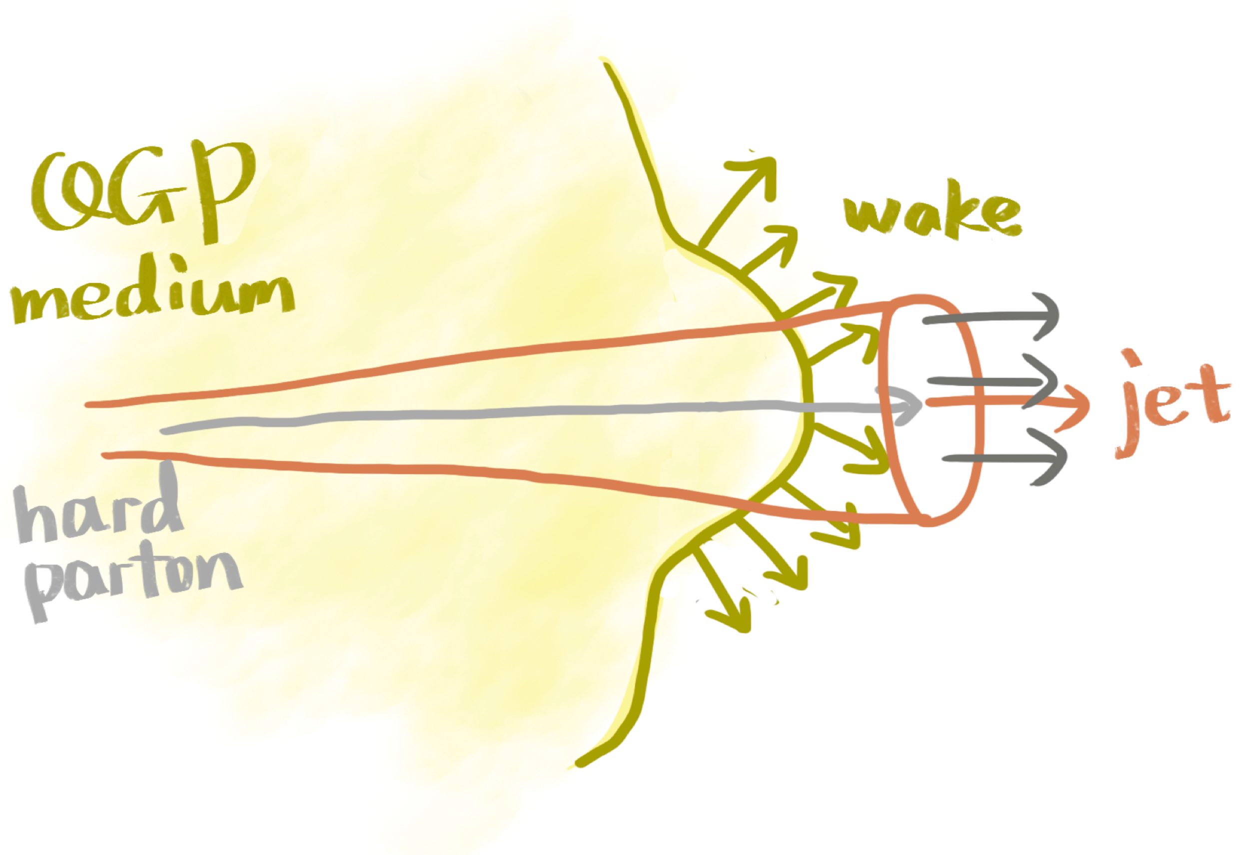




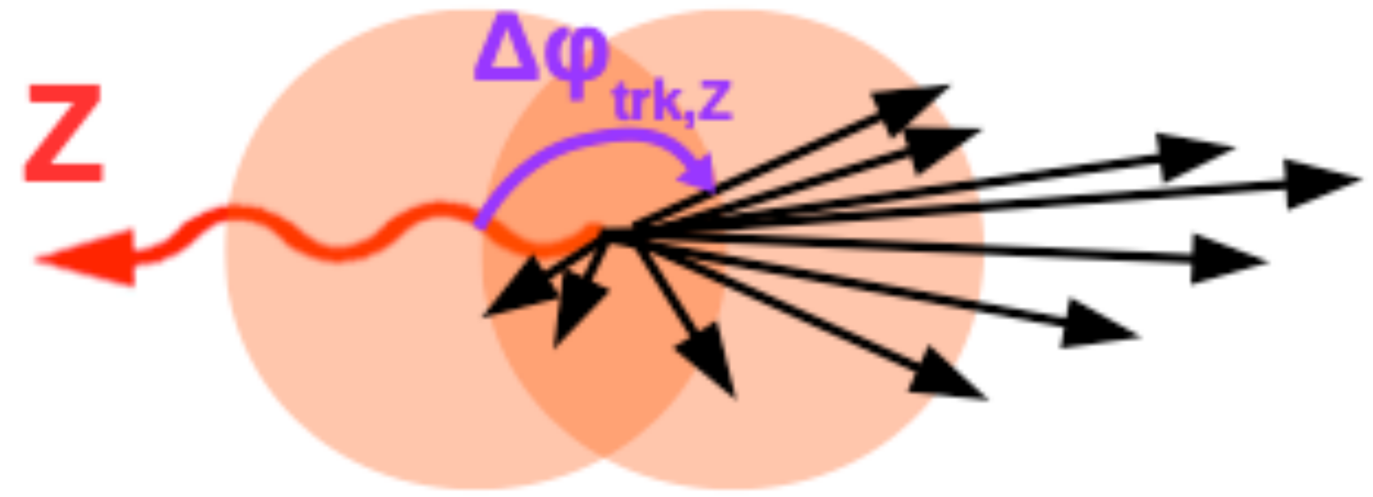
→**Use high-p_T partons as "self-generated" probes for the medium properties**

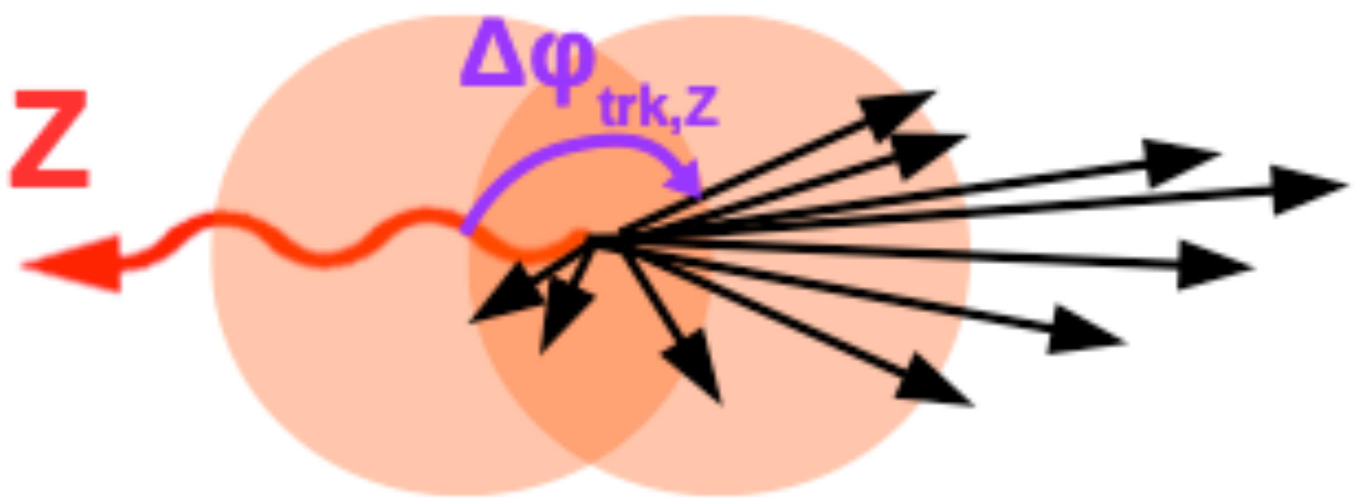
Bjorken (1982), FERMILAB-PUB-82-059-THY

Revealing the medium-recoil effect

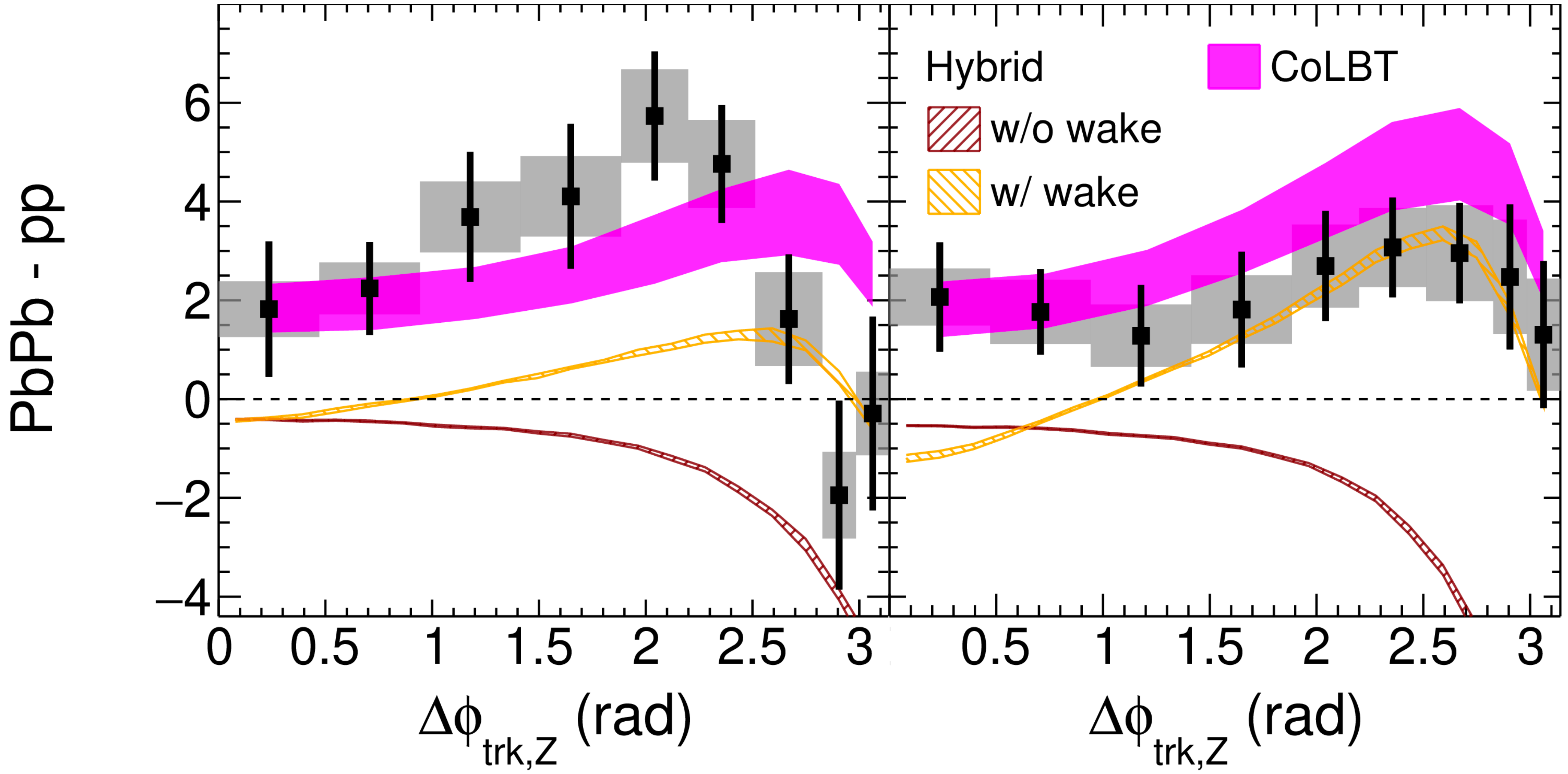


When energetic partons pass through the QGP
→ **the energy deposited could give rise to a Mach cone accompanied by a diffusion wake.**





$$\frac{1}{N_Z}\frac{dN_{trk,Z}}{d\Delta\phi_{trk,Z}}\ (1/\text{rad})$$



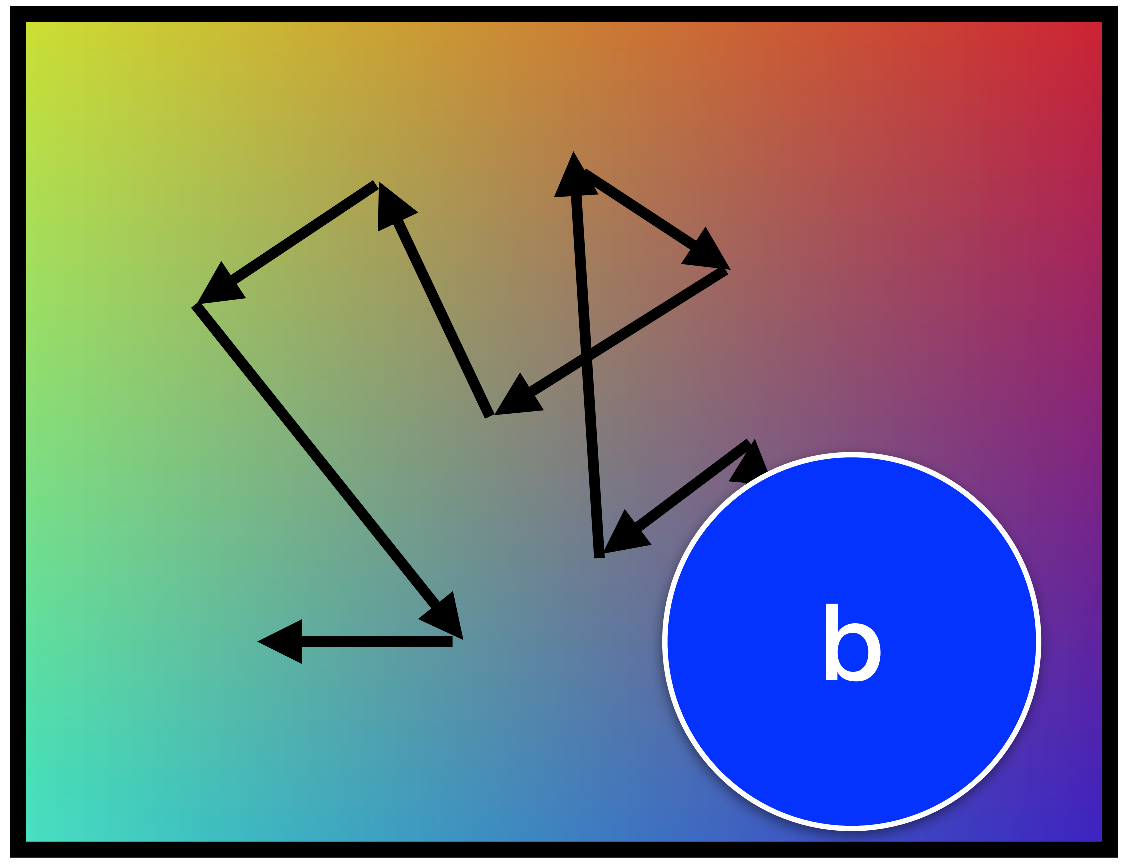
→ **strong sensitivity to medium-recoil effects**

CMS, PRL 128 (2022) 122301

→ **Over the next few years:** new "era" in the characterization of the QGP properties (e.g., transport coefficients, equation of state) with the high statistics data from sPHENIX and CMS

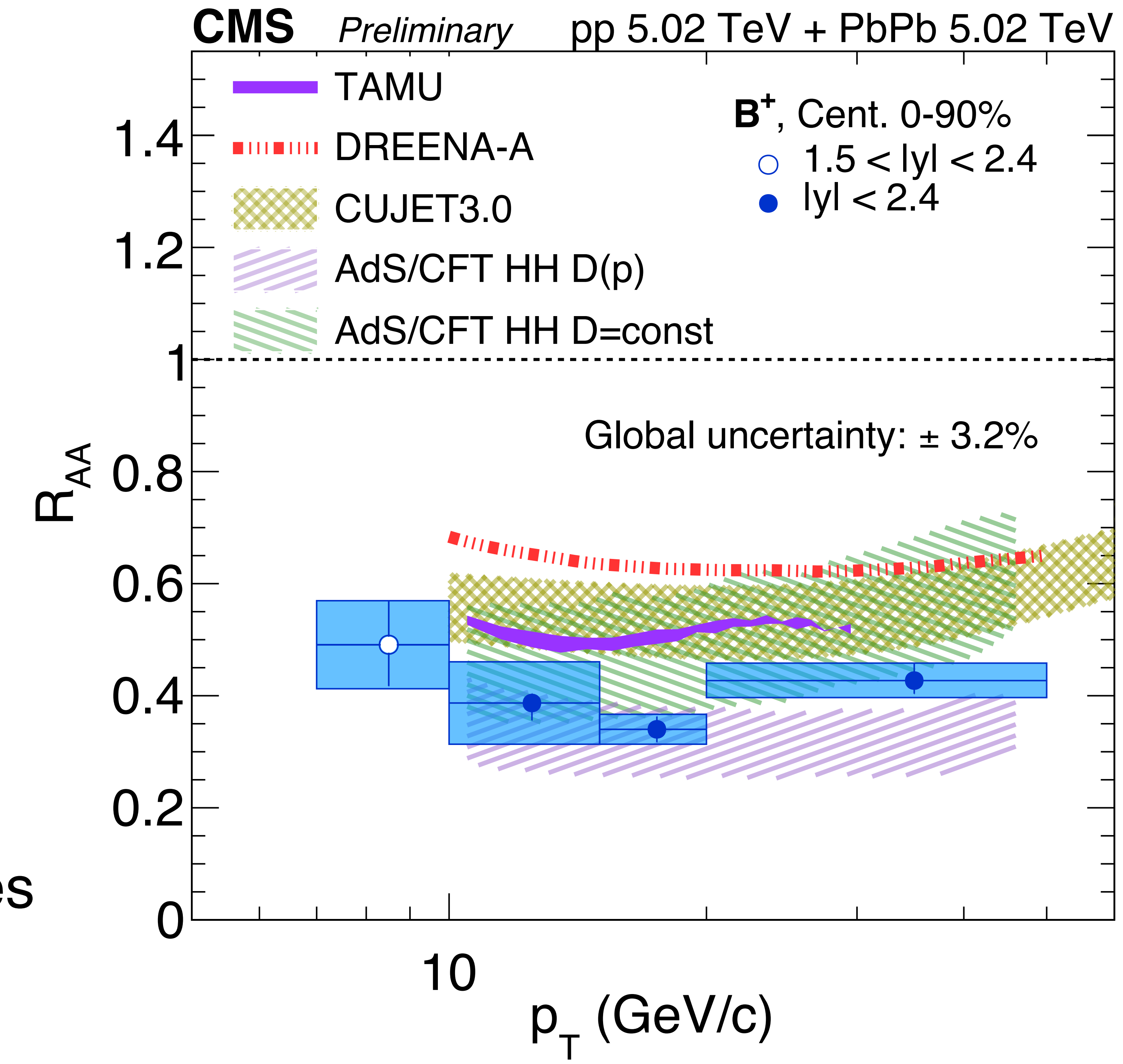
QCD structure of the hot QCD medium with beauty quarks

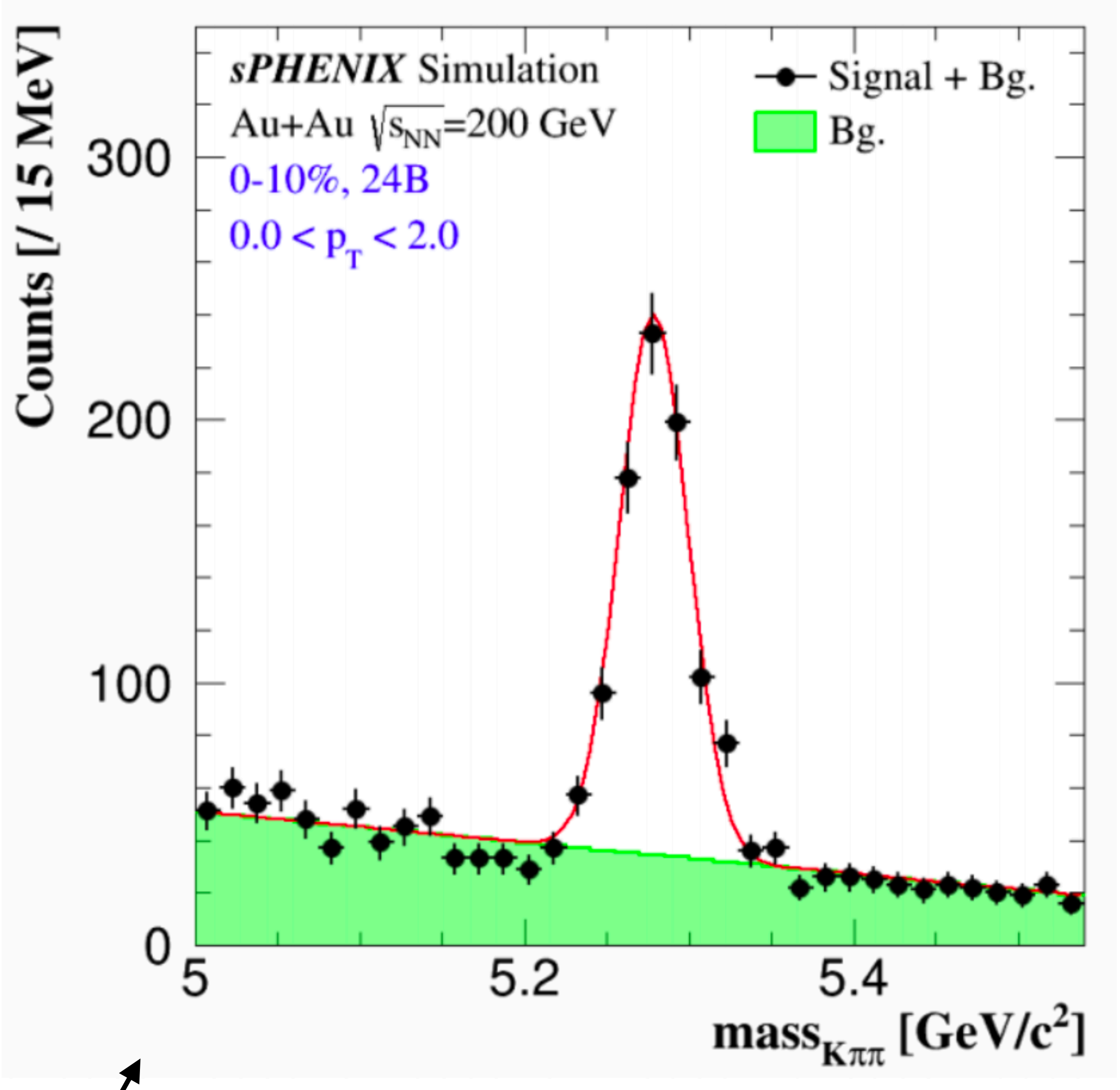
charmed and beauty mesons down to low p_T → brownian particles inside the hot medium



- **$m_{c,b} > m_{u,d,s}$: "Brownian regime" in the QGP**

→ sensitive to the **QGP diffusion** and drag properties





High-accuracy measurements are expected with future sPHENIX data!

Direct comparison with QCD calculations:

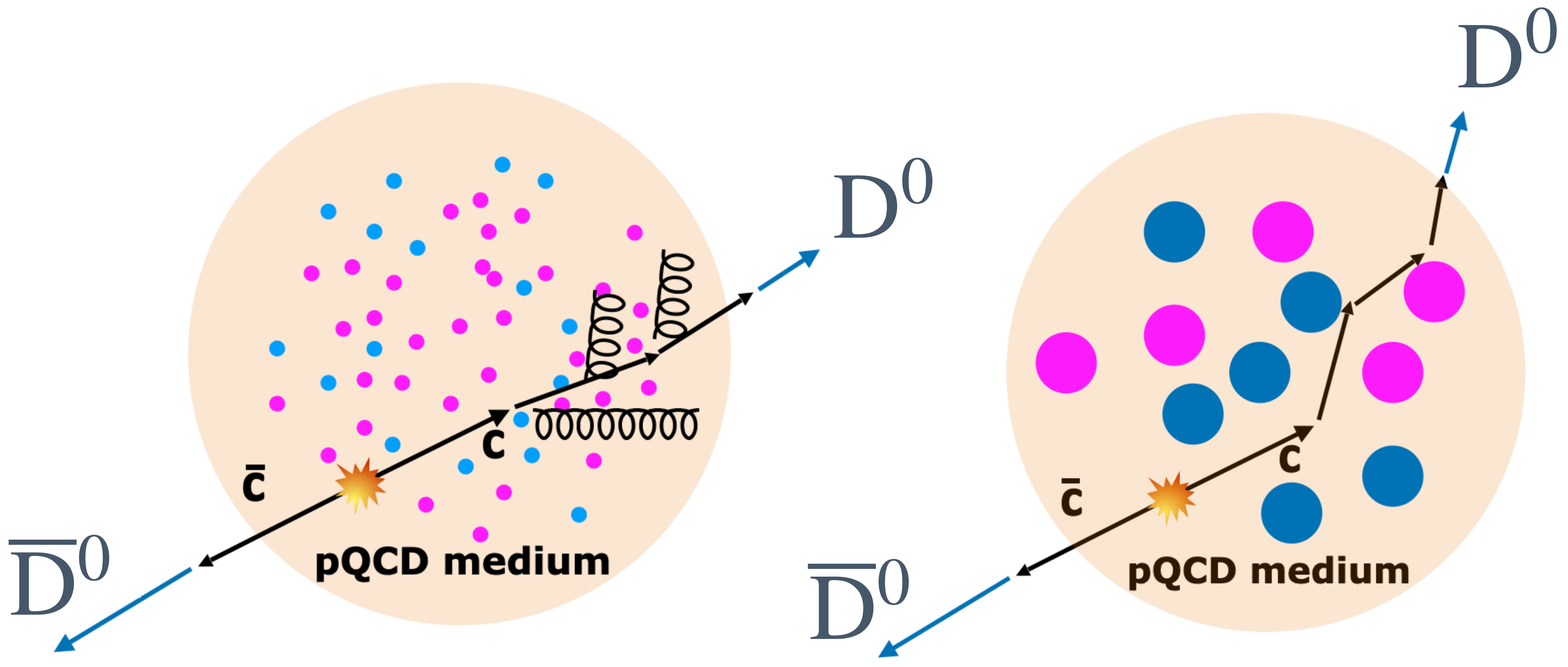
→ we have formed a very strongly interacting medium that behaves as a fluid!

→ **first direct constraints into the "structure" of the QGP**

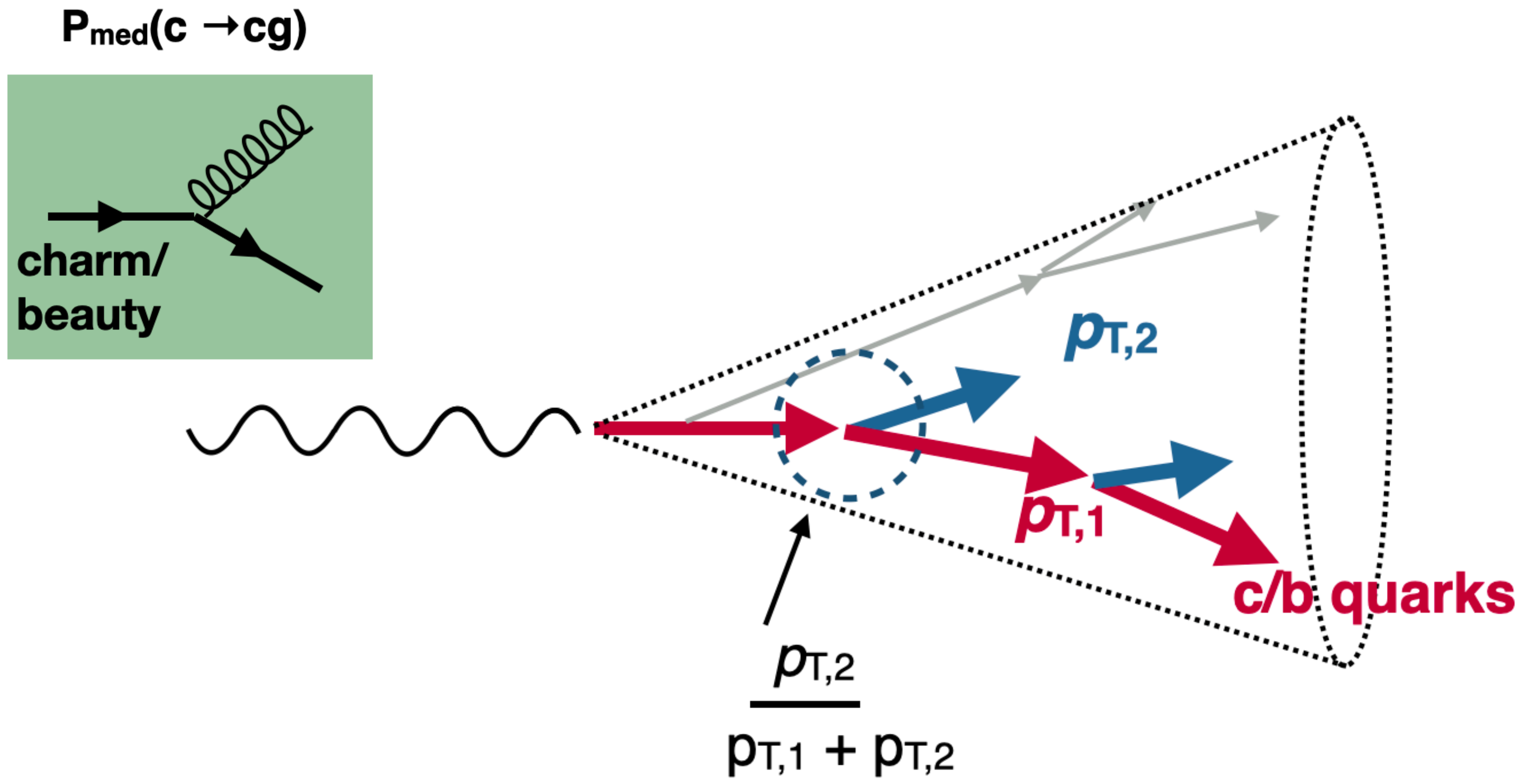
Physics with sPHENIX at RHIC is starting now!

→ unique capabilities for heavy-flavor physics thanks to the new MVTX detector

Future: "microscopic" characterization of E_{loss} and medium response

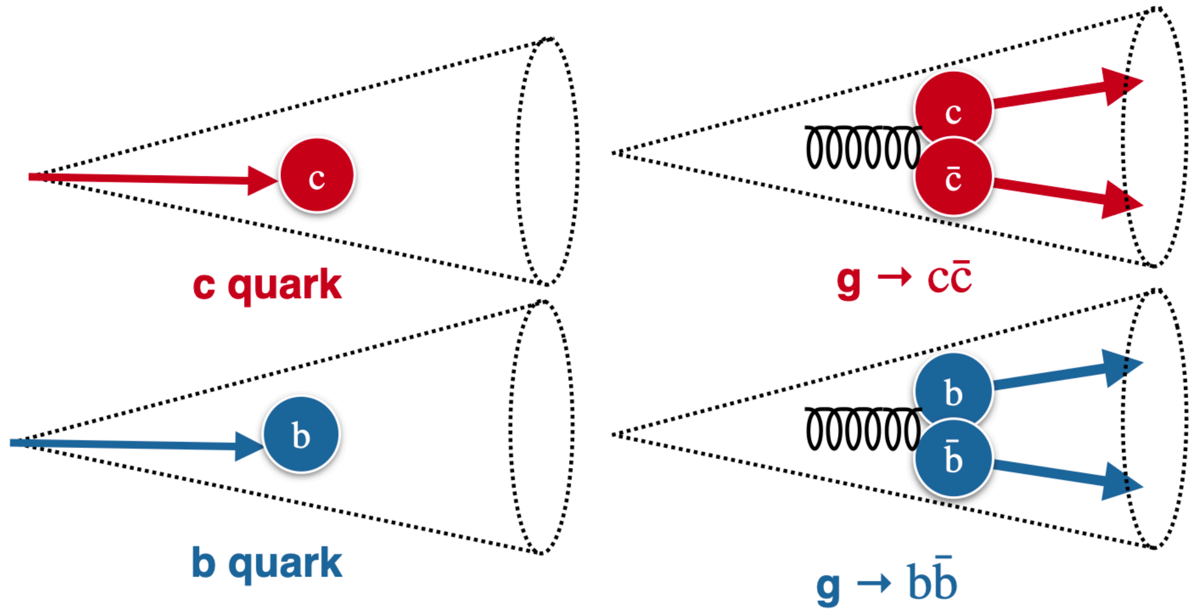


Partonic "structure" of the hot medium
→ can we observe the interactions with the "constituents" of the quark gluon plasma?



Microscopic characterization of the mechanisms of in-medium energy loss

→ Over the next few years: apply the most recent techniques of heavy-quark tagging with DNN and Graphs to HI collisions



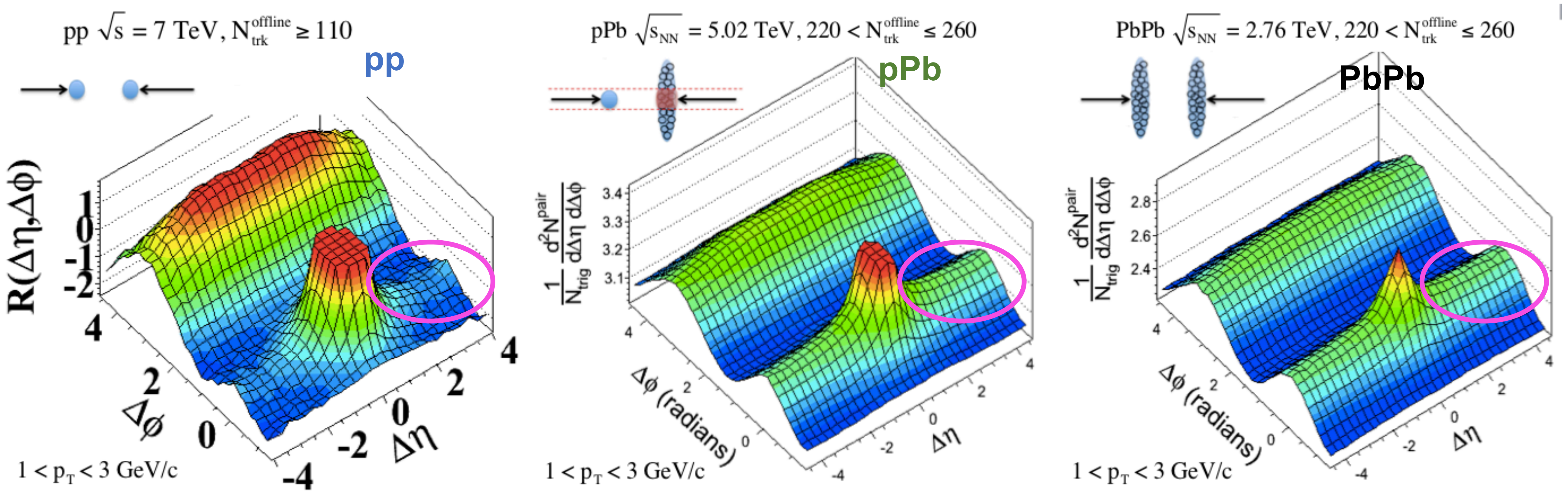
- First $D^0\overline{D}^0$ correlation in HI
- c/b-tagged jet substructure with recoiling photons
- Double quark-tagged jets (g → $c\bar{c}$) for testing time structure of the QGP
- Z-tagged energy-energy correlators (EEC)

→ QGP at different temperatures and timescales with sPHENIX and CMS

E. Bols *et al* 2020 JINST 15 P12012

What is the smallest size of a strongly-interacting medium?

Long-range "ridge" observed (by our group!) from nucleus to pp collisions

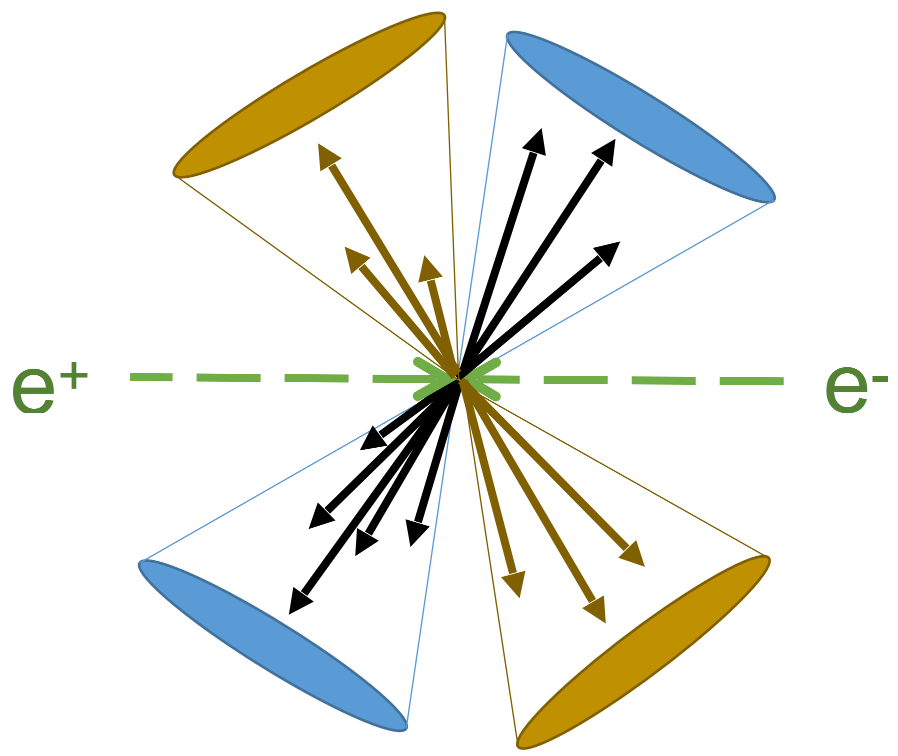


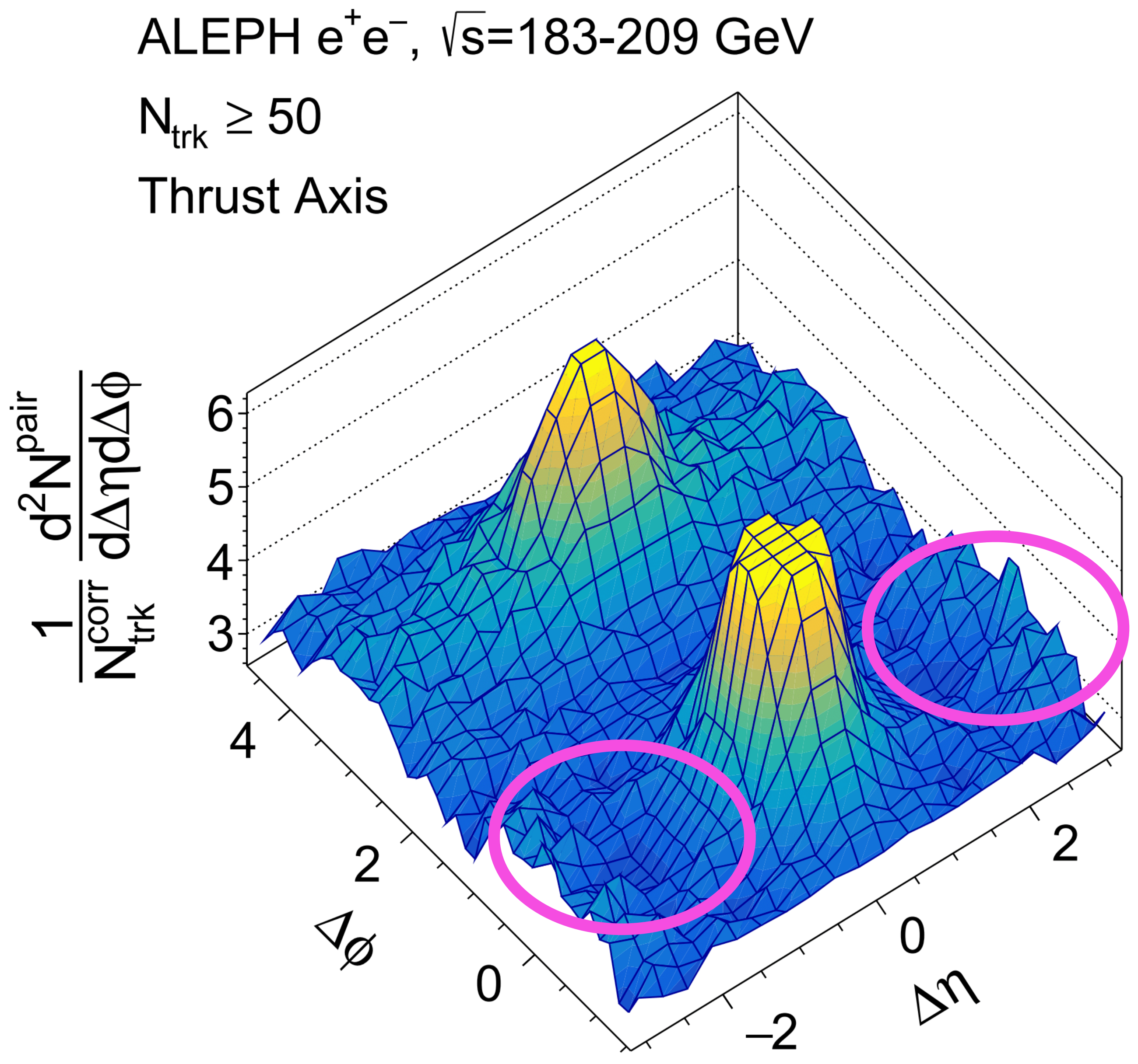
2010 **2012**

→ in nucleus-nucleus, an evidence for a strongly-interacting QGP

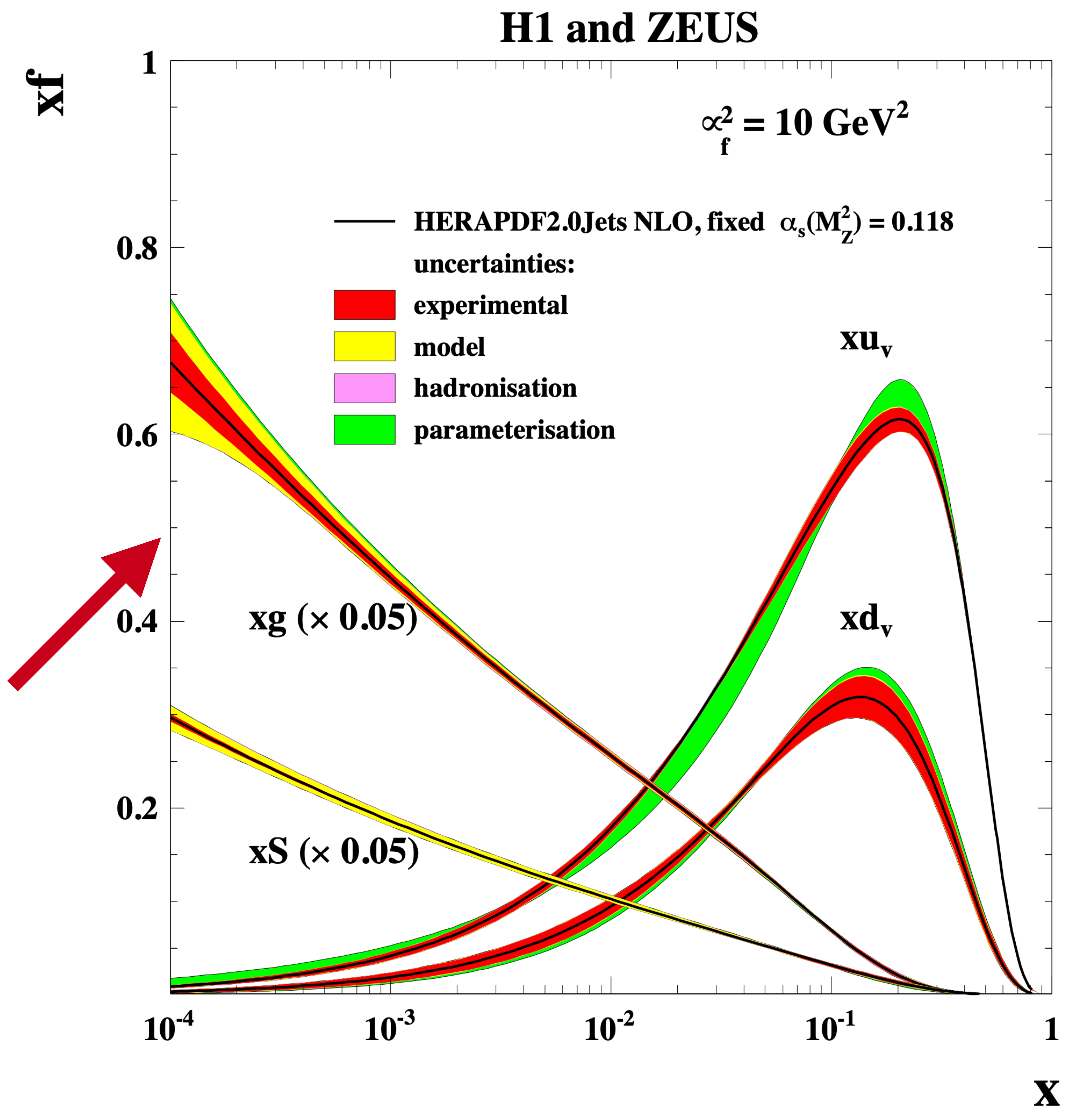
Hints of long-range near-side signal in e^+e^- collisions with ALEPH data from LEP2!
can we create a strongly interacting medium in e^+e^- collisions?

$$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$$





A new program to study cold "extreme" partonic matter



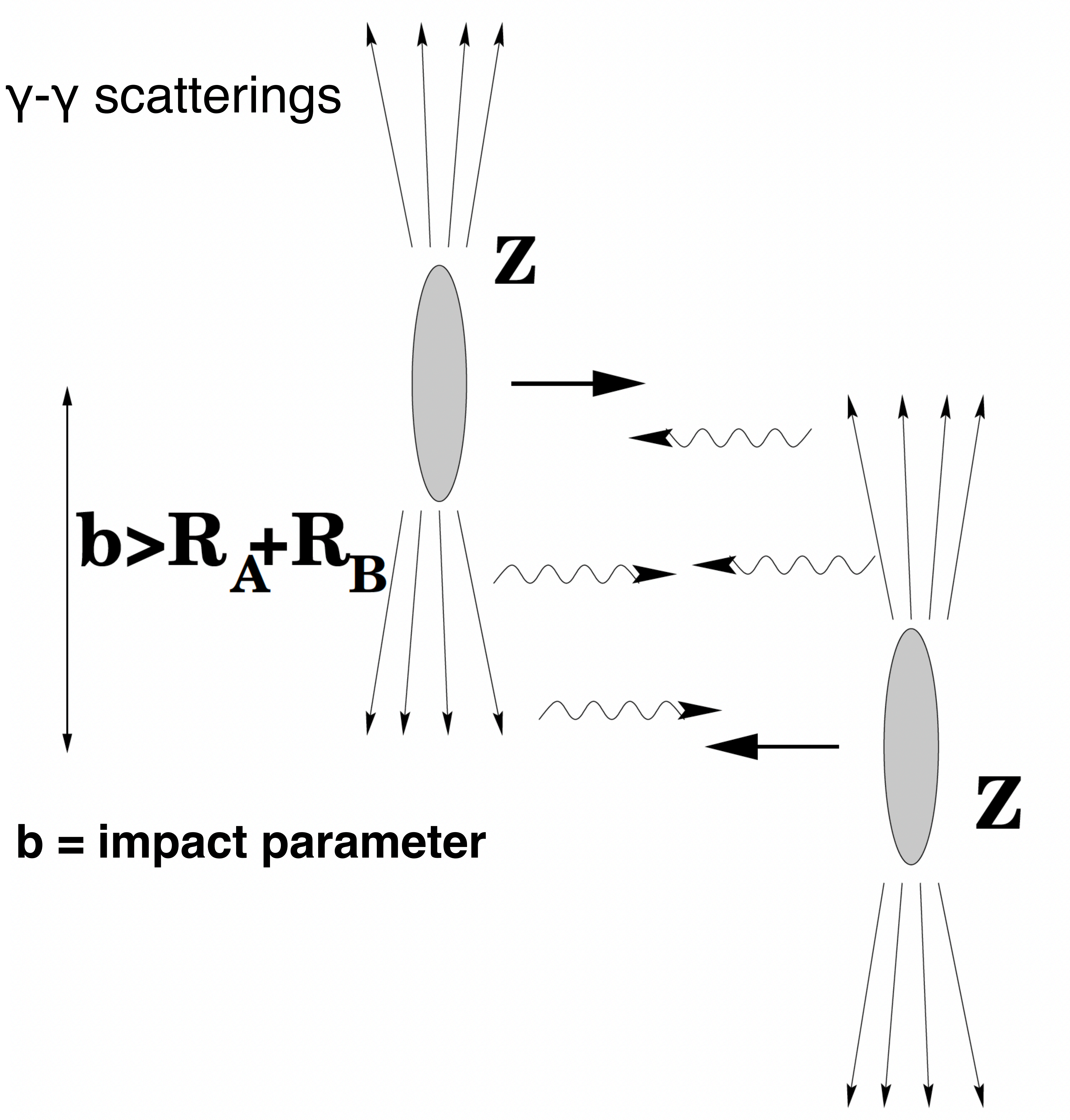
What happens to nuclear matter in the presence of very large densities of low-x gluons?

→ **Can we observe a new phase of matter characterized by the so-called gluon saturation?**

→ **"Gluon saturation" is also at the core of the program of the future Electron-Ion Collider**

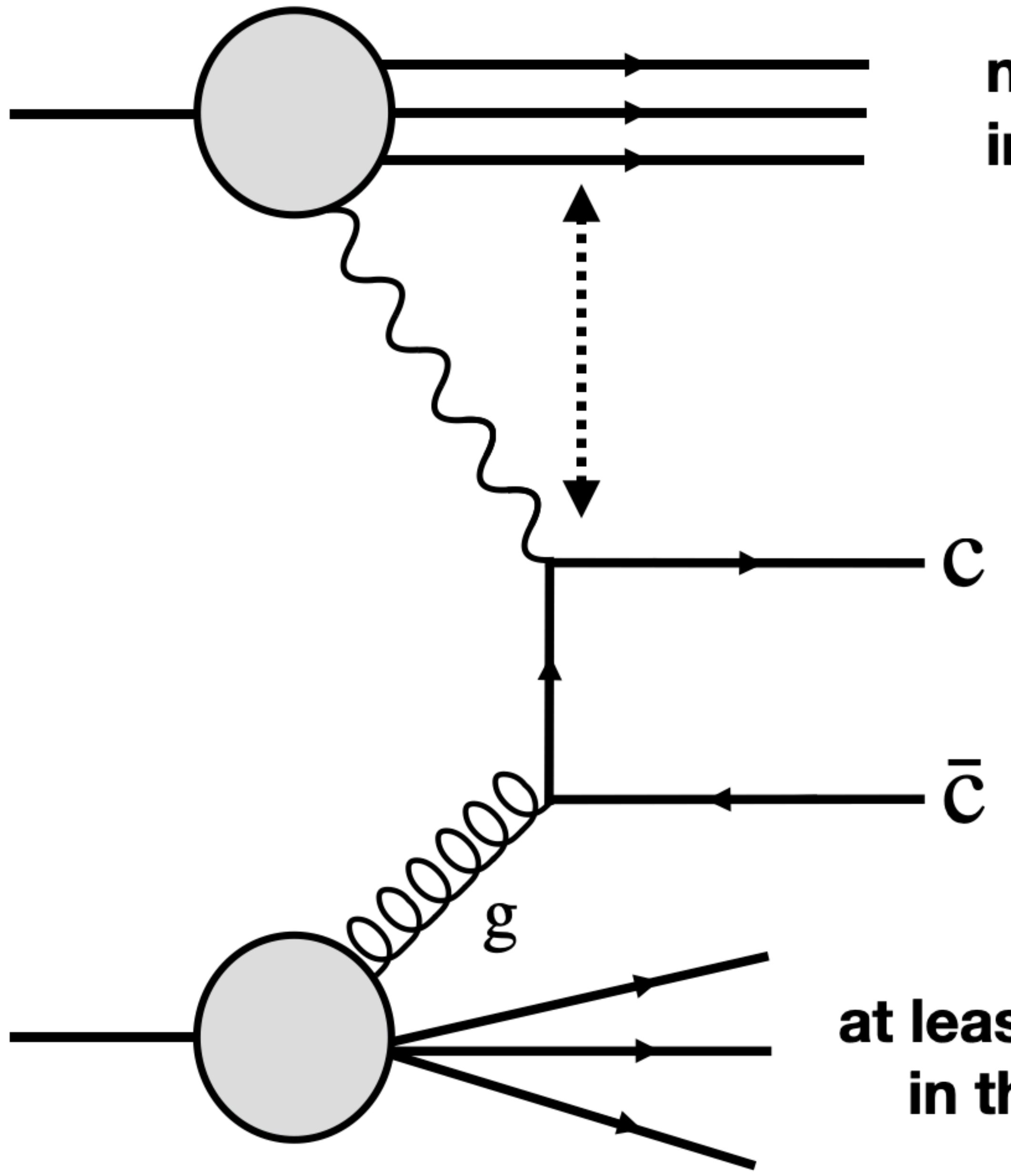
Ultra-peripheral collisions: a “factory” of γ-nucleus collisions

→ “Cloud” of quasi-real photons
→ large cross-sections of “hard” γ-N and γ-γ scatterings

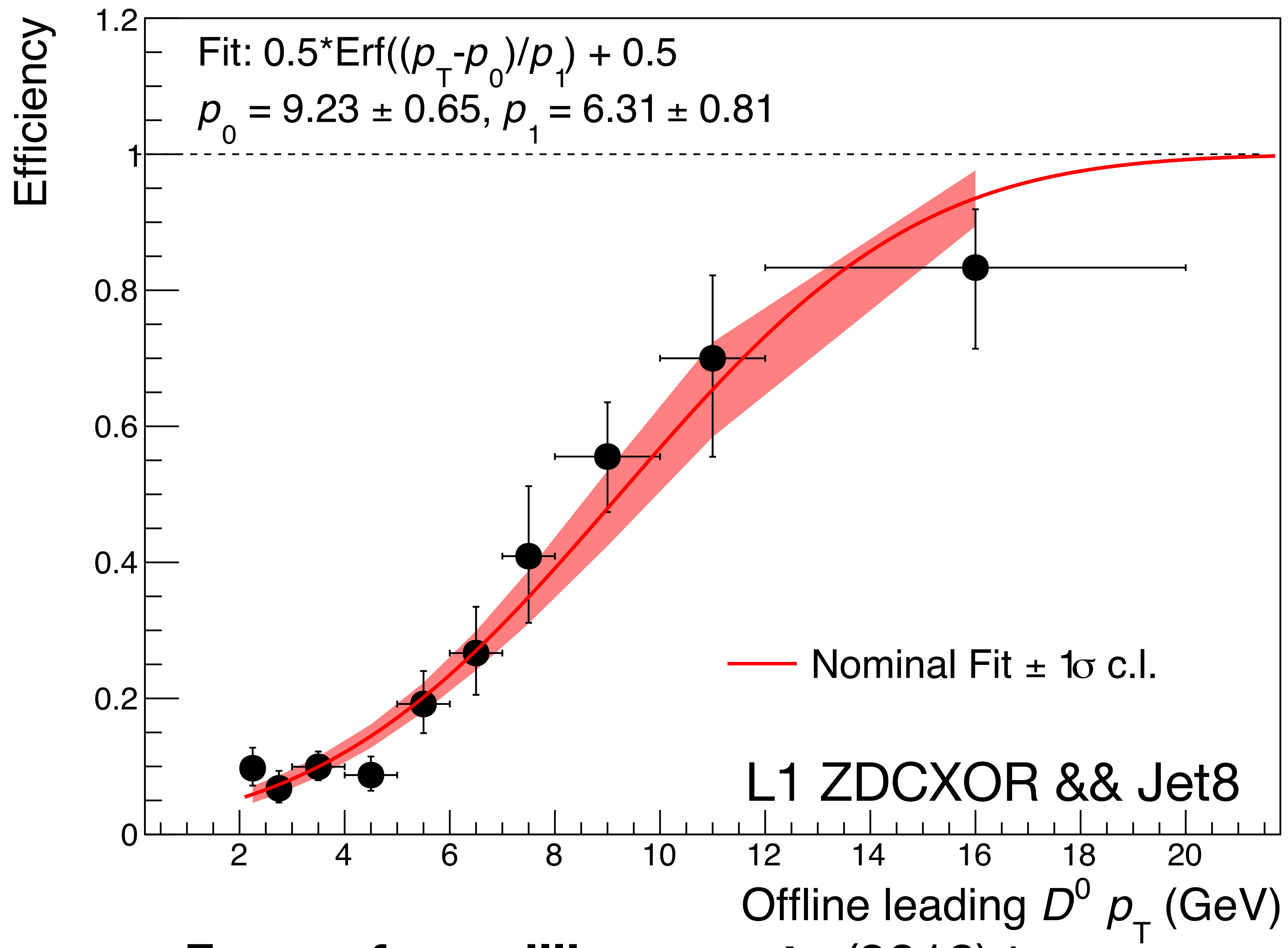


LHC is a “factory” of photon-hadron collisions that we can use to study the properties of nuclear matter!
→ wide program that involves measurements of charm/beauty hadrons, jets, correlations in γ-N and γ-γ scatterings
→ **next slides: some highlights from our first analysis**

γN →open heavy flavor: a new probe for parton structure



A new set of triggers to identify "online" the presence of photo-nuclear charm events



From **a few million events** (2018) to **a few billion** events in 2023!
→ **>1000 times more statistics!**

→ **For the upcoming runs ('24-'25):** further optimization of the trigger algorithms to boost their performance with both simulation work and hands-on activities both at MIT and at CERN

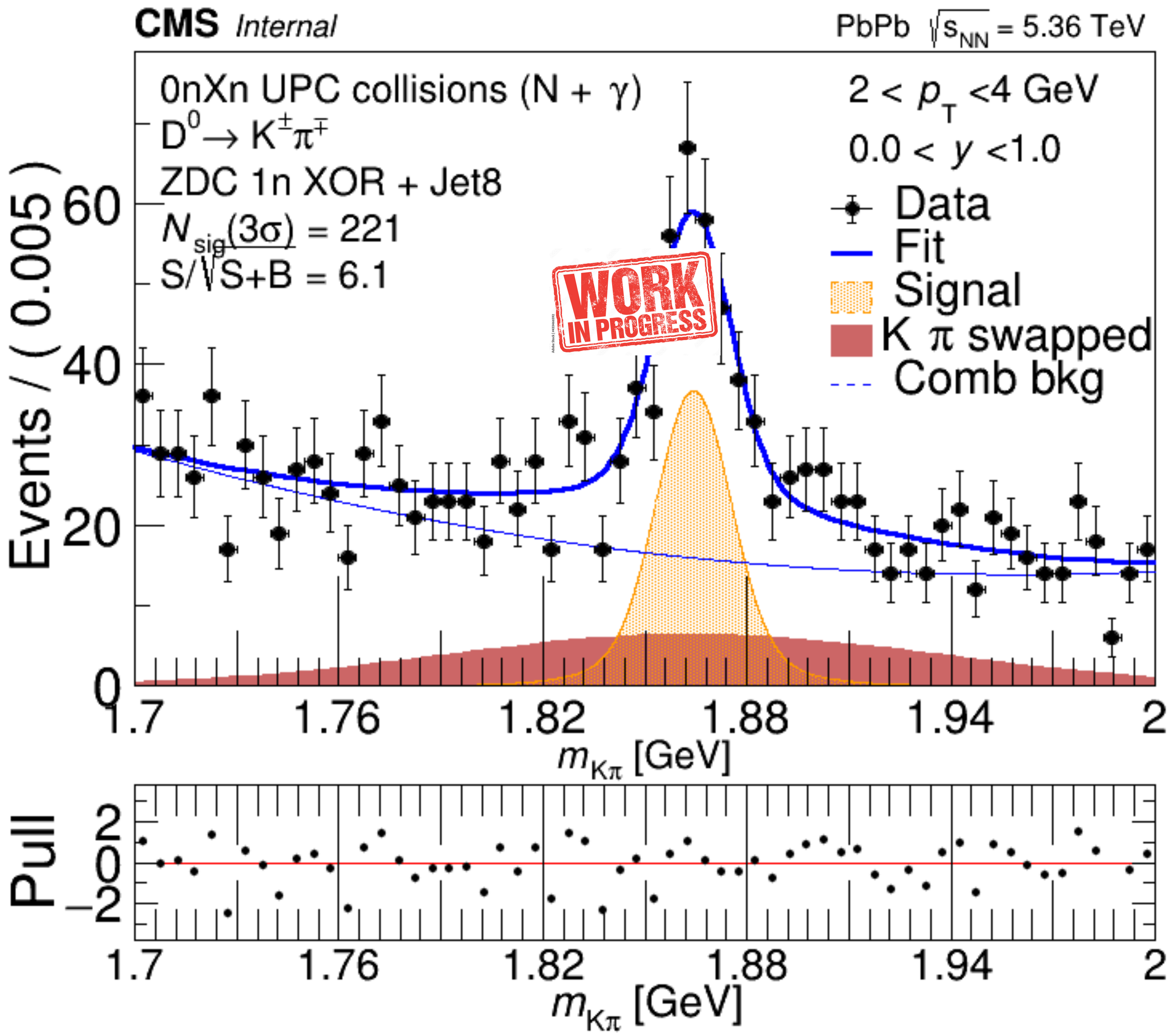
Level-1 Trigger CMS Week Parallel Meeting, DP note: HIN: UPC seeds performances in 2023

First result for the production of D^0 mesons in UPCs

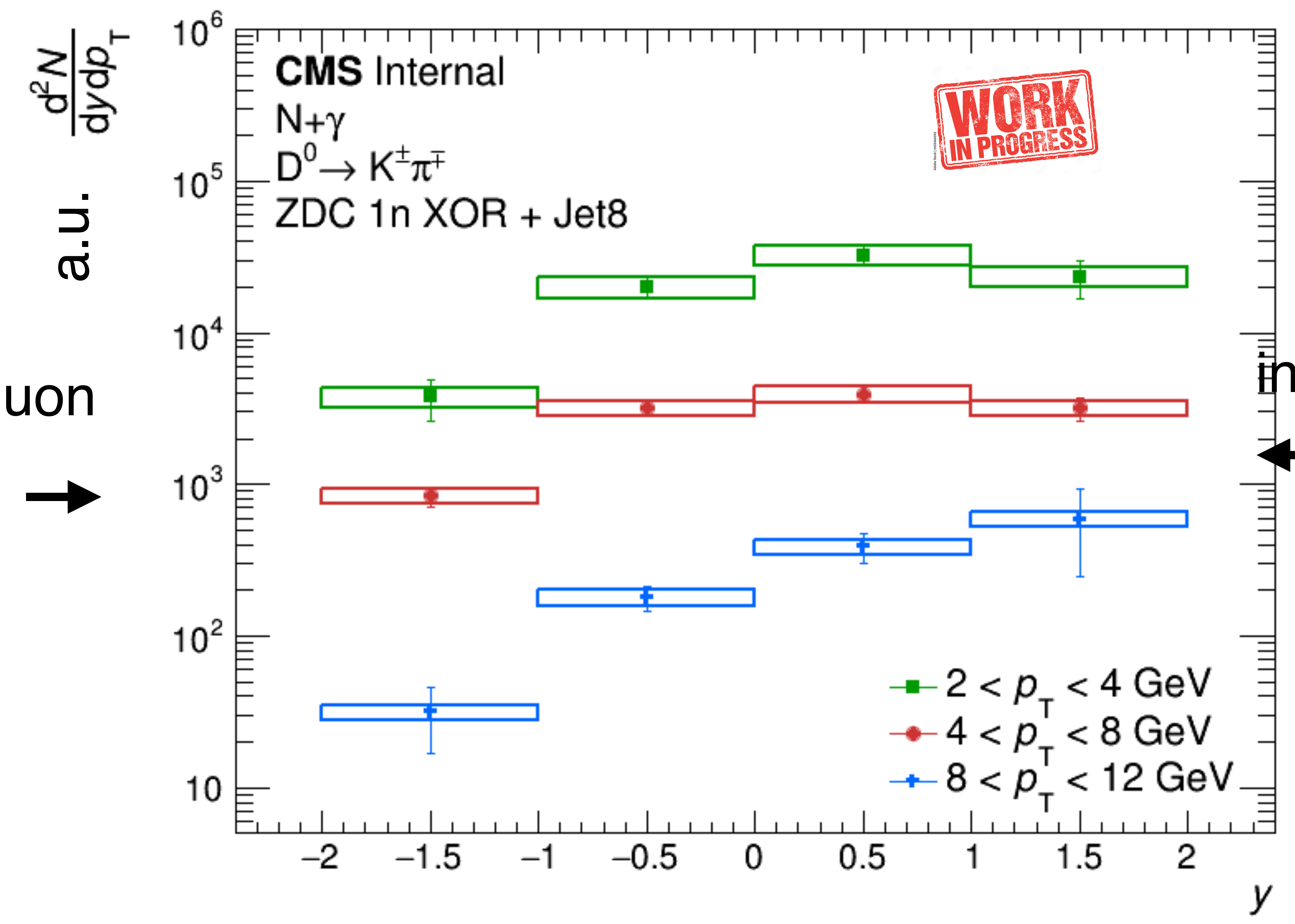
An idea probe for the low (x,Q^2) region:

- $x_{min} \approx 10^{-4}$ at LHC with probes |y|<2
- $Q^2_{min} \approx m^2_{c\bar{c}}$

$2 < p_{T,D} < 4$
$0 < y_D < 1$



incoming gluon



incoming photo

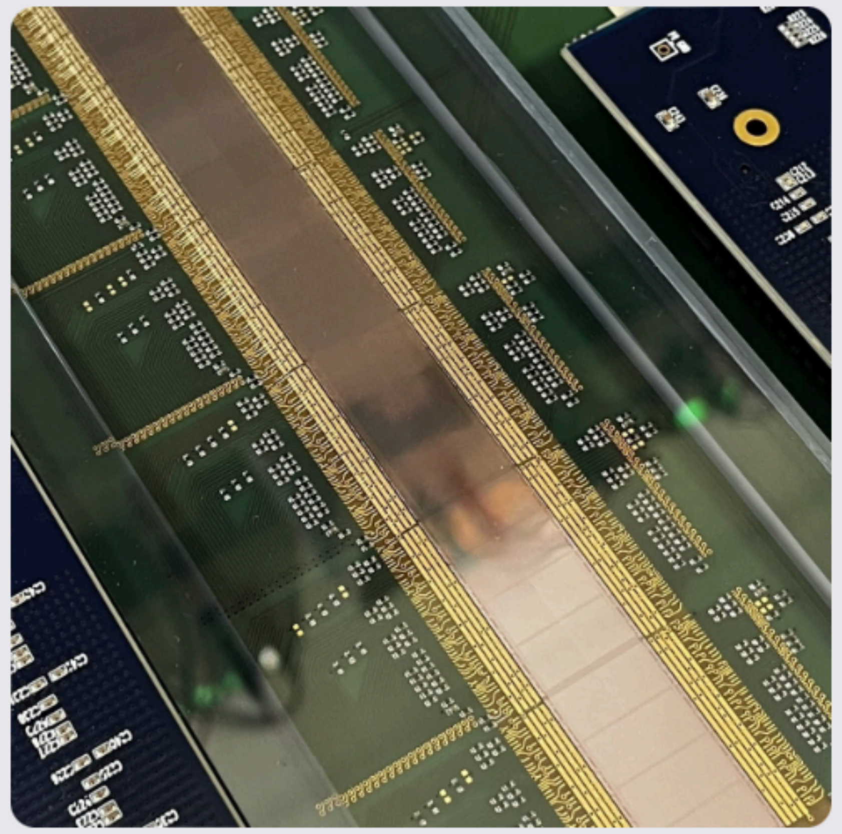
First measurement of open-charm signals in UPC events!
→ **data collected in October/November 2023**
→ **analysis already preapproved!**

→ we just opened a wide program that anticipates and complements the physics program of the future Electron-Ion Collider

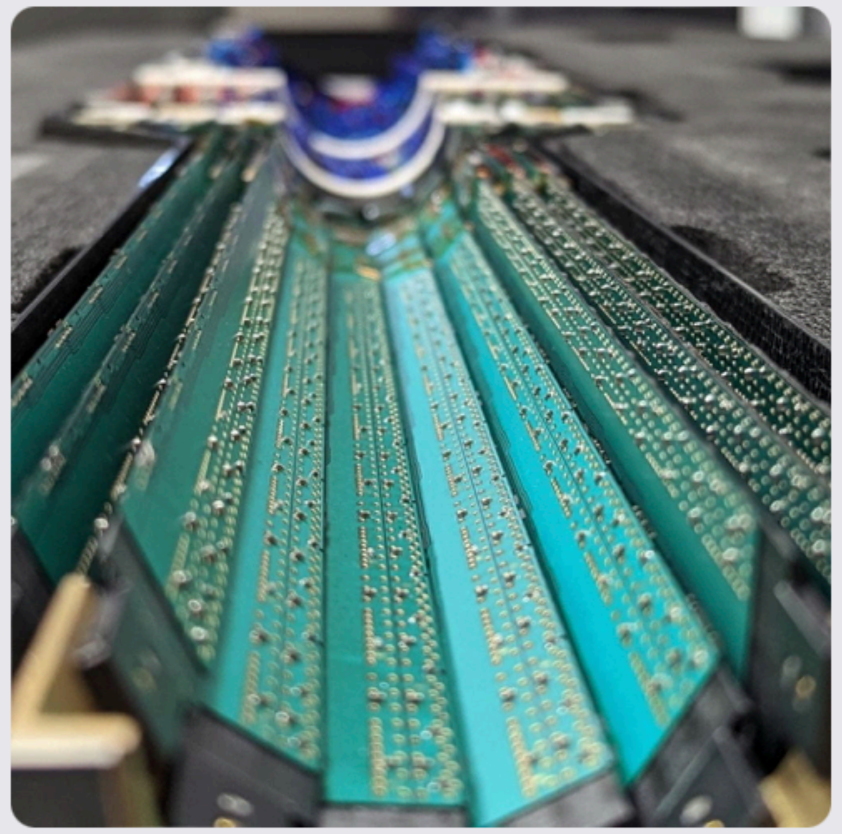
MIT PixELφ : a Silicon Pixel Lab for ELementary physics at MIT

→ **Monolithic Active Pixel Sensor (MAPS) technology** for high-accuracy detectors for high-energy and nuclear physics

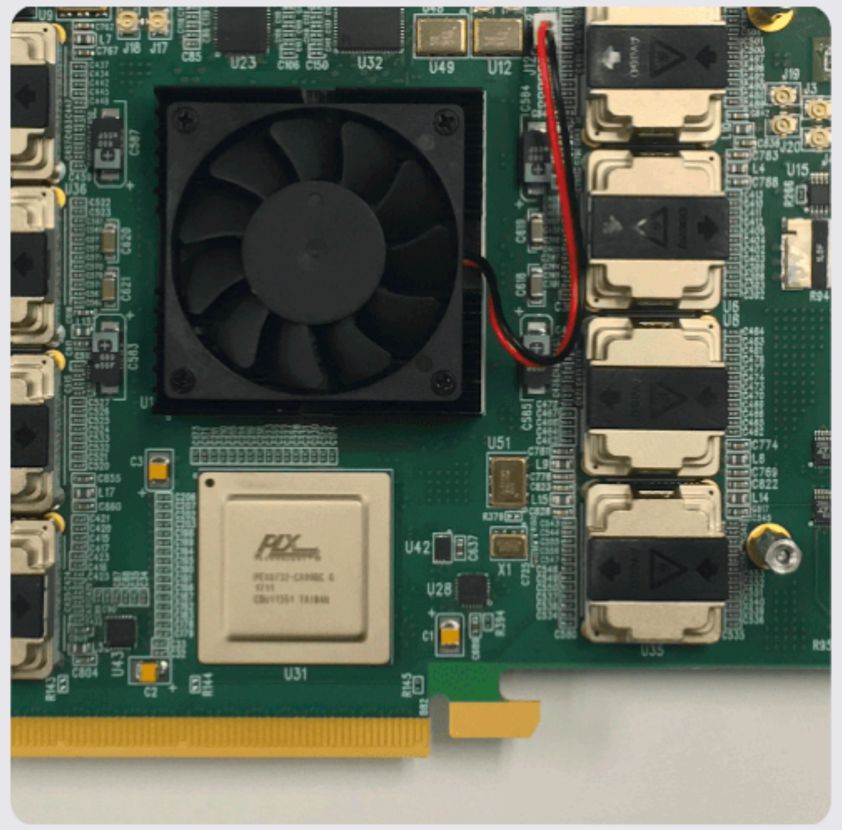
Ongoing projects



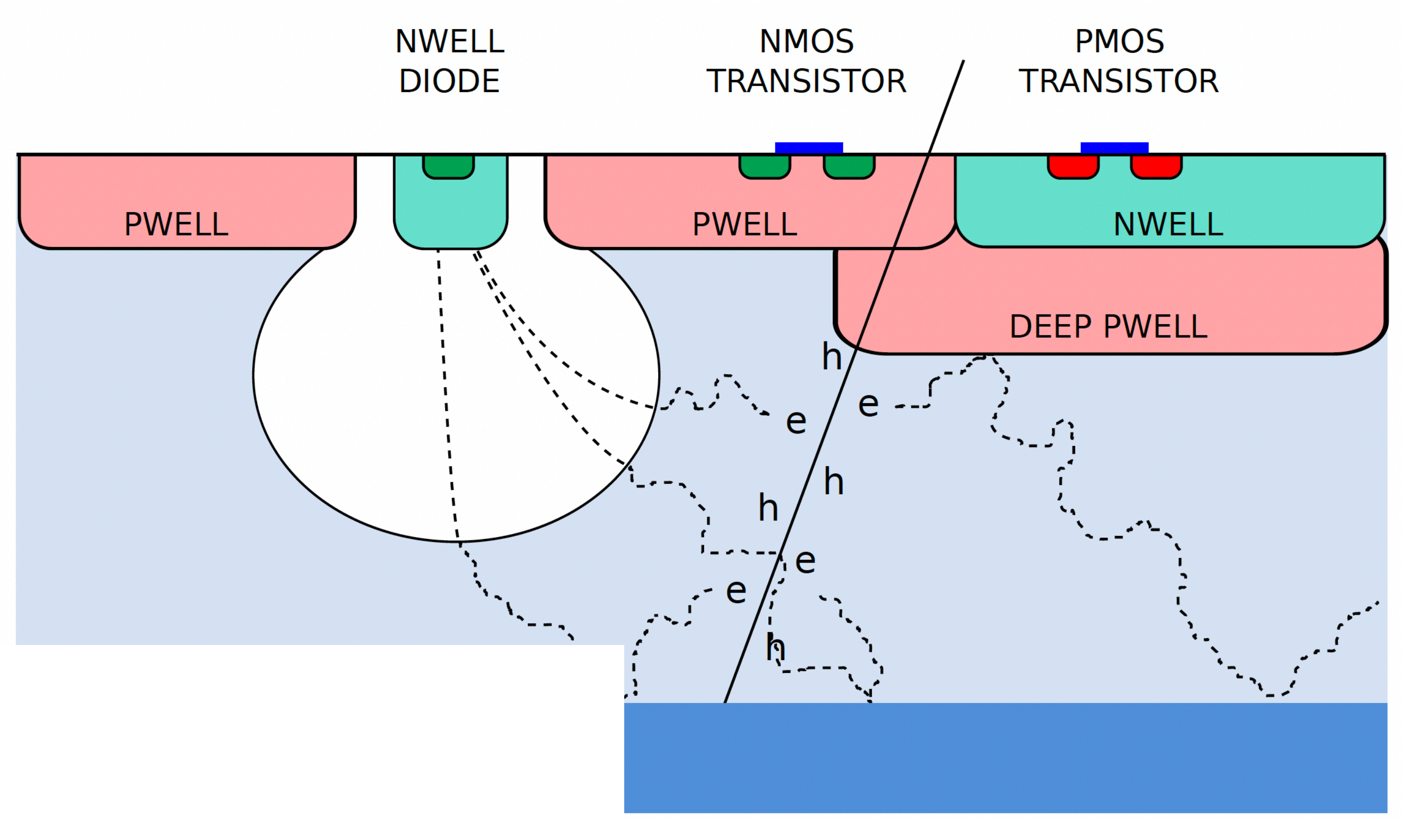
Silicon Vertex Tracker (SVT) for the ePIC experiment at the Electron-Ion Collider

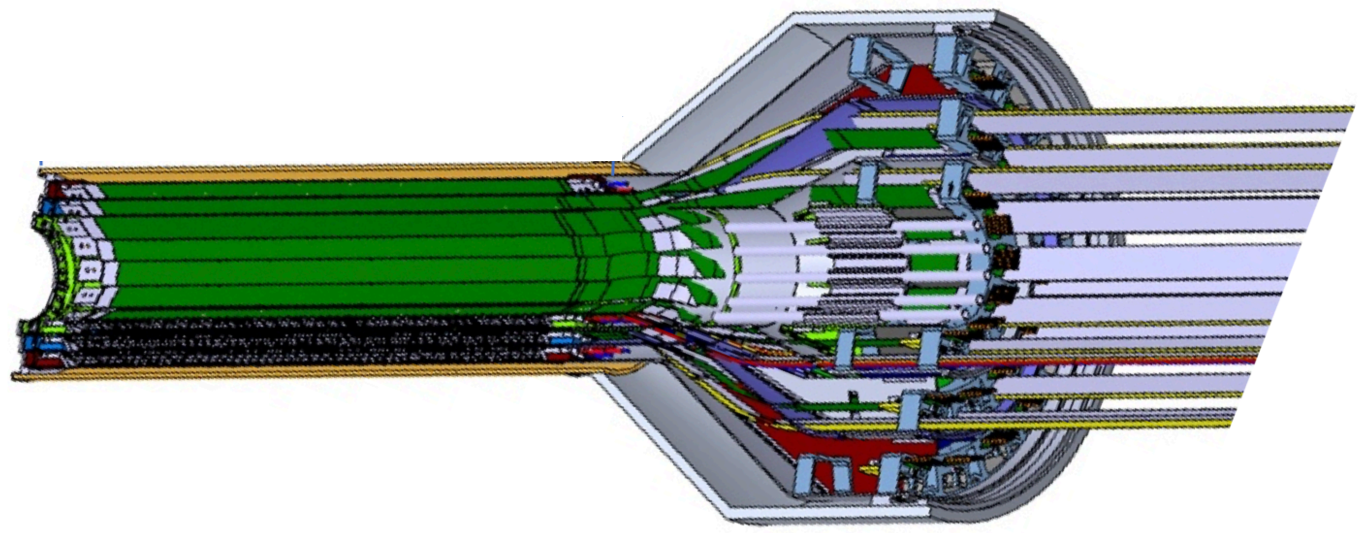


MVTX for the sPHENIX experiment



Artificial intelligence with FPGA for MAPS detectors





→**CERN-based MIT laboratory**

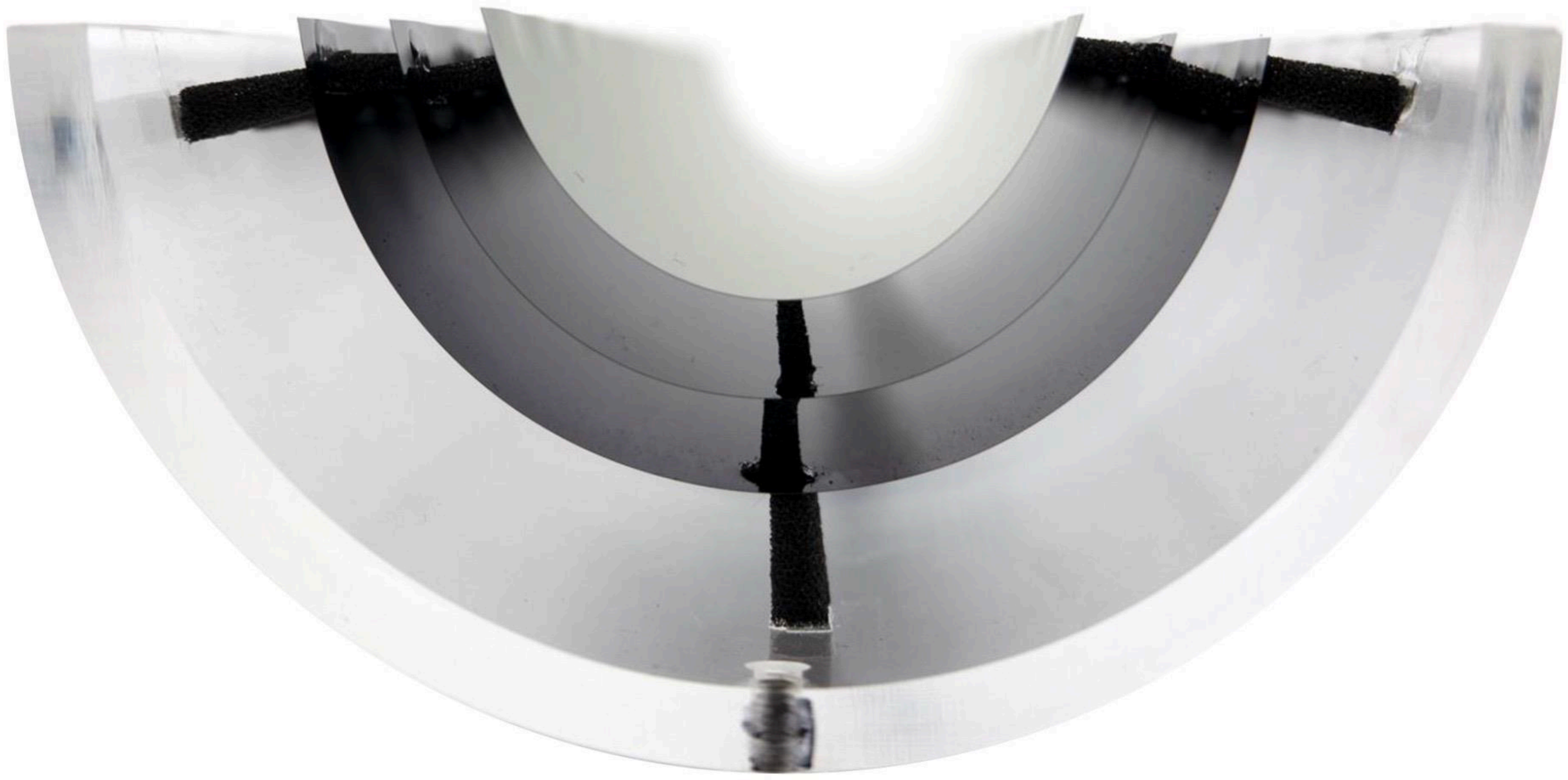
https://pixelphilab.mit.edu

“Stitched” and “thinned” MAPS in 65 nm technology

ALICE ITS3, CERN-LHCC-2024-003 / ALICE-TDR-021

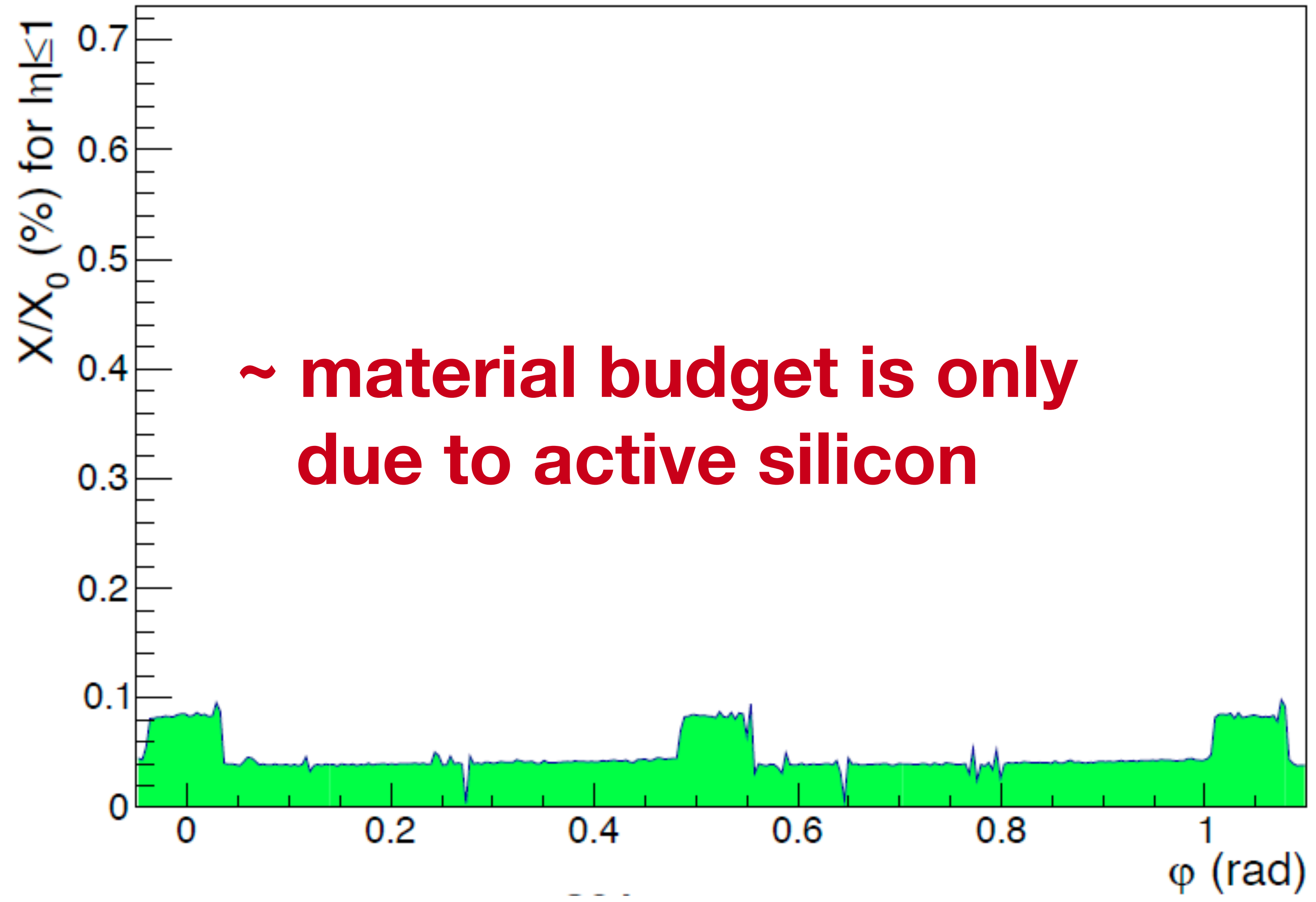
Sensor stitching is one of the key features of the MOSAIX design:
- Repeated Sensor Units (RSUs) to create **large-area MAPS sensors**

Wafers are then thinned below ~30-40 µm
→ elastic properties of silicon

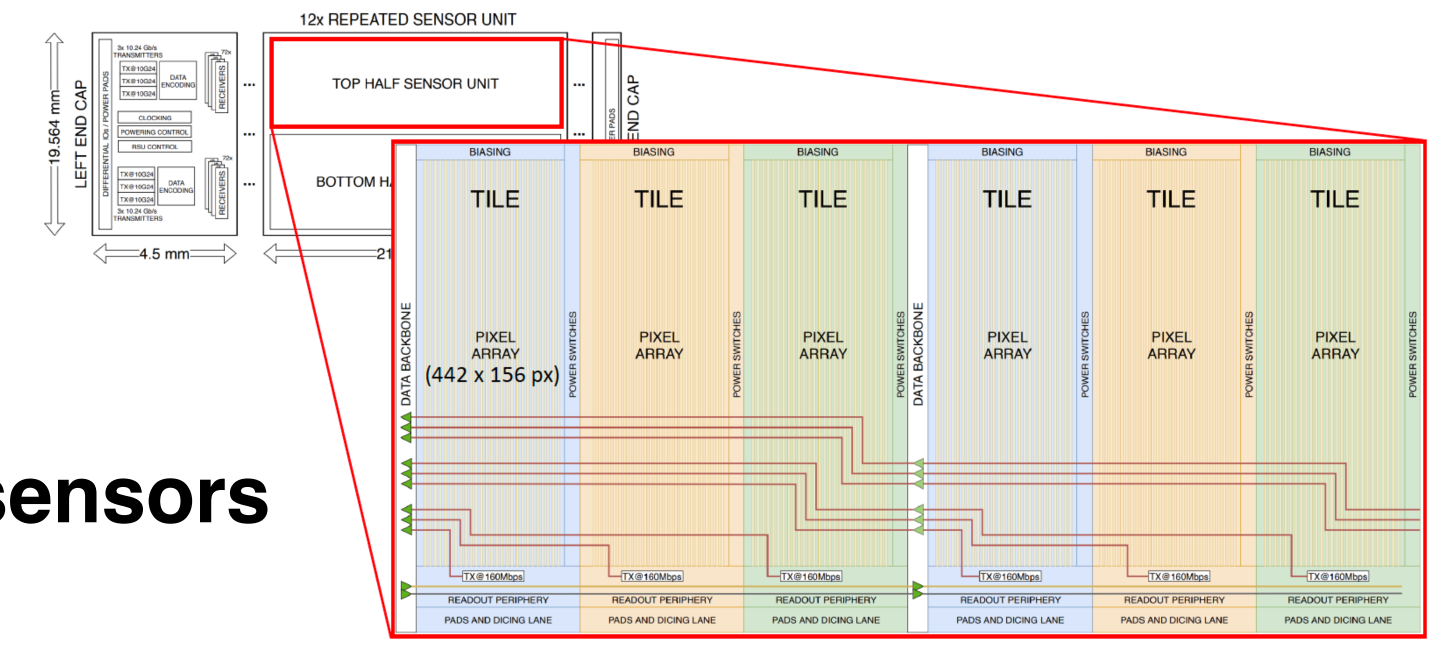


Stitched and thinned sensors in 65nm CMOS:
- low power consumption < 40 mW/cm²
- intrinsic stiffness of the curved silicon wafer

→ **Air-based cooling**
→ **Minimal mechanical support (carbon foam)**



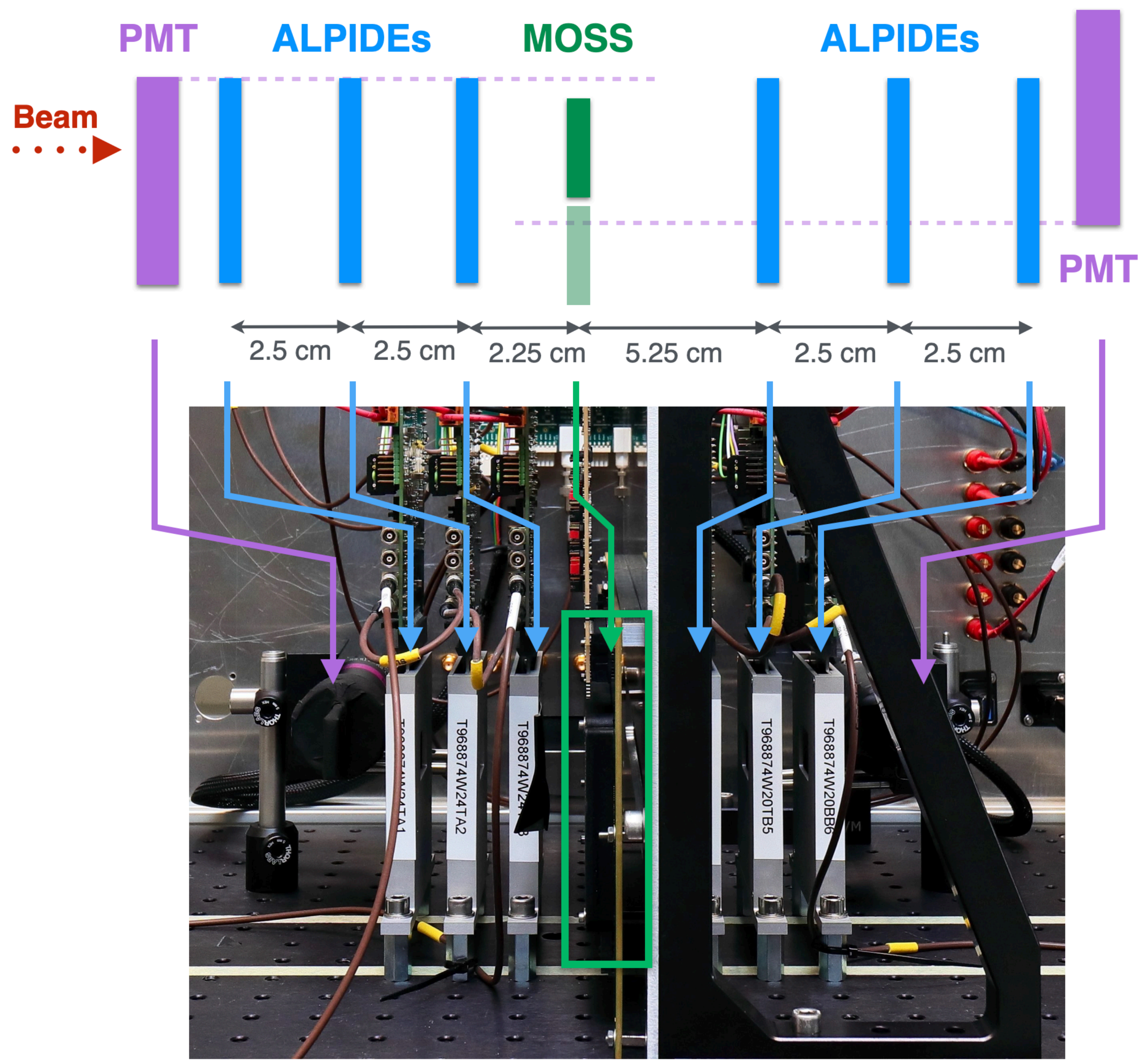
Leading the R&D for the pixel sensors for future MAPS detectors



Sensor design for new MAPS sensors
- with ASIC development digital R&D

New techniques of high-frequency tests of MAPS sensors
- with probe cards and automatized software tools

New readout techniques for data compression
- with multiplexing techniques on FGPA or with Artificial Intelligence on CMOS integrated circuits



EIC , BNL-98815-2012, arXiv:1212.1701

MITHIG is pioneering the use of ultra-light large-area MAPS sensors for HEP (brand-new MIT lab being equipped at CERN)
→ SVT at the EIC is our first experimental goal, with countless applications for future experiments (FCC, neutrino experiments, ..)
→ great time to join the R&D of one of the most promising technology in our field

MIT alumni


Heinz Pernegger
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1997-2000
CERN Staff
ATLAS-HEP


Patrick Decowski
PhD 2001
Assoc. Professor
(Amsterdam)
Neutrinos


Kristjan Gulbrandsen
PhD 2003
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ALICE


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CMS


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CMU (MBA)


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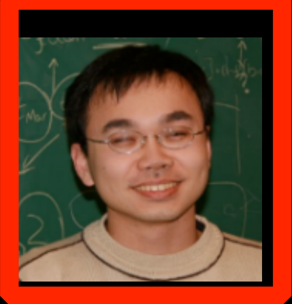
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Alphagen


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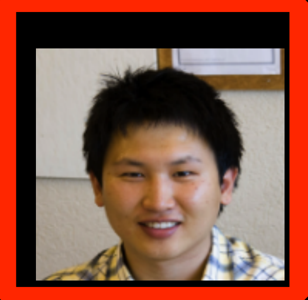
Yongsun Kim
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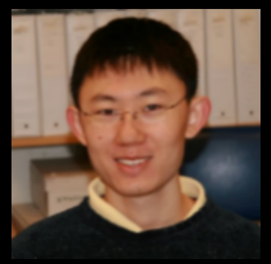
Frank Ma
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Google


Doga Gulhan
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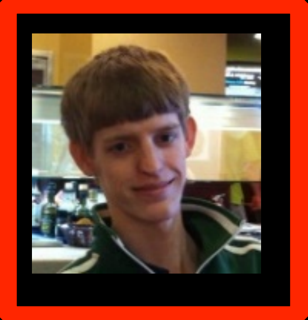
Harvard-MGH
Cancer genomics

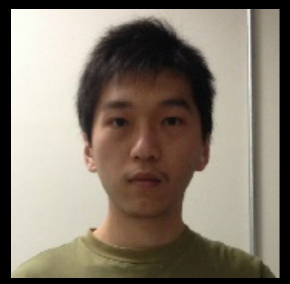

Yue Shi Lai
Postdoc 2016
Staff Scientist
(Berkeley)


Gian Michelle Innocenti
Assist. Professor
MIT, CMS, sPHENIX

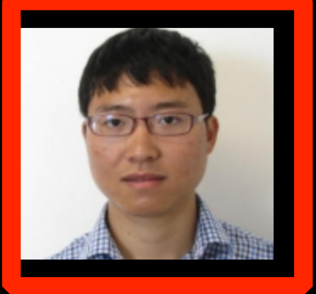

Ta-Wei Wang
PhD 2019
Quantitative
Researcher
DRW


Austin Baty
PhD 2019
Ass. Prof.
Vanderbilt,
CMS

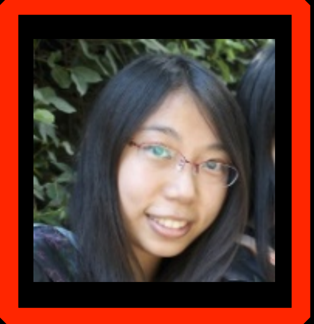

Chris McGinn
PhD 2019
Postdoc
MIT, CMS


Ran Bi
PhD 2020
Data Science


Kaya Tatar
PhD 2020
Data Science


Zhaozhong Shi
PhD 2021
Director's
Postdoctoral Fellow
LANL
sPHENIX


Camelia Mironov
Postdoc - 2022
Directeur de
recherche au
CNRS
Dune


Jing Wang
PhD 2019
Postdoc (MIT)
CMS


Yi Chen
PhD 2002
Assoc. Prof.
(Vanderbilt)
CMS


Jing Wang
PhD 2016
CERN fellow
CMS

Still in the field!

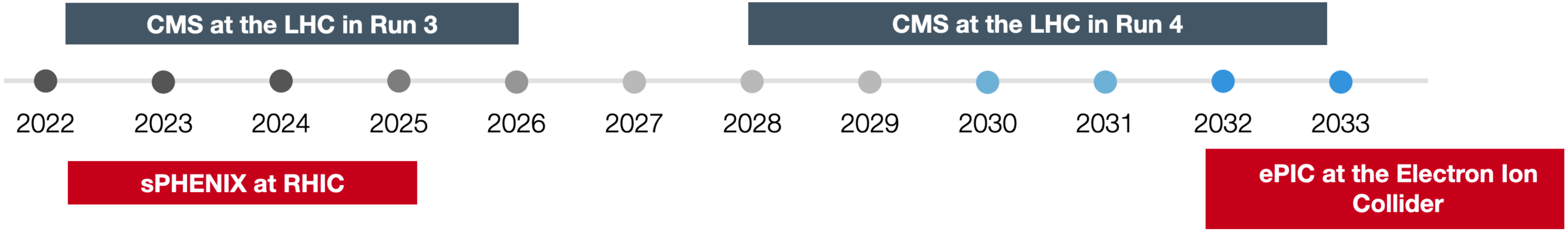
Conclusions

MITHIG is a unique group that explores the boundaries of QCD with the most advanced detectors and experimental tools
→ **a great moment for our group and for high-density QCD physics**
→ physics program that connects our group to the physics of the EIC and of future experiments

CMS: largest sample of hadronic (MB) and UPC events from 2023 **on tape** and being analyzed!
→ Two high-statistics runs are expected in ’24-’25

Cutting-edge hardware programs for CMS in Run 4 (MTD detector) and a big program for exploiting MAPS sensors in HEP for EIC and beyond

sPHENIX: commissioned and ready to collect huge statistics of AuAu and pp collisions

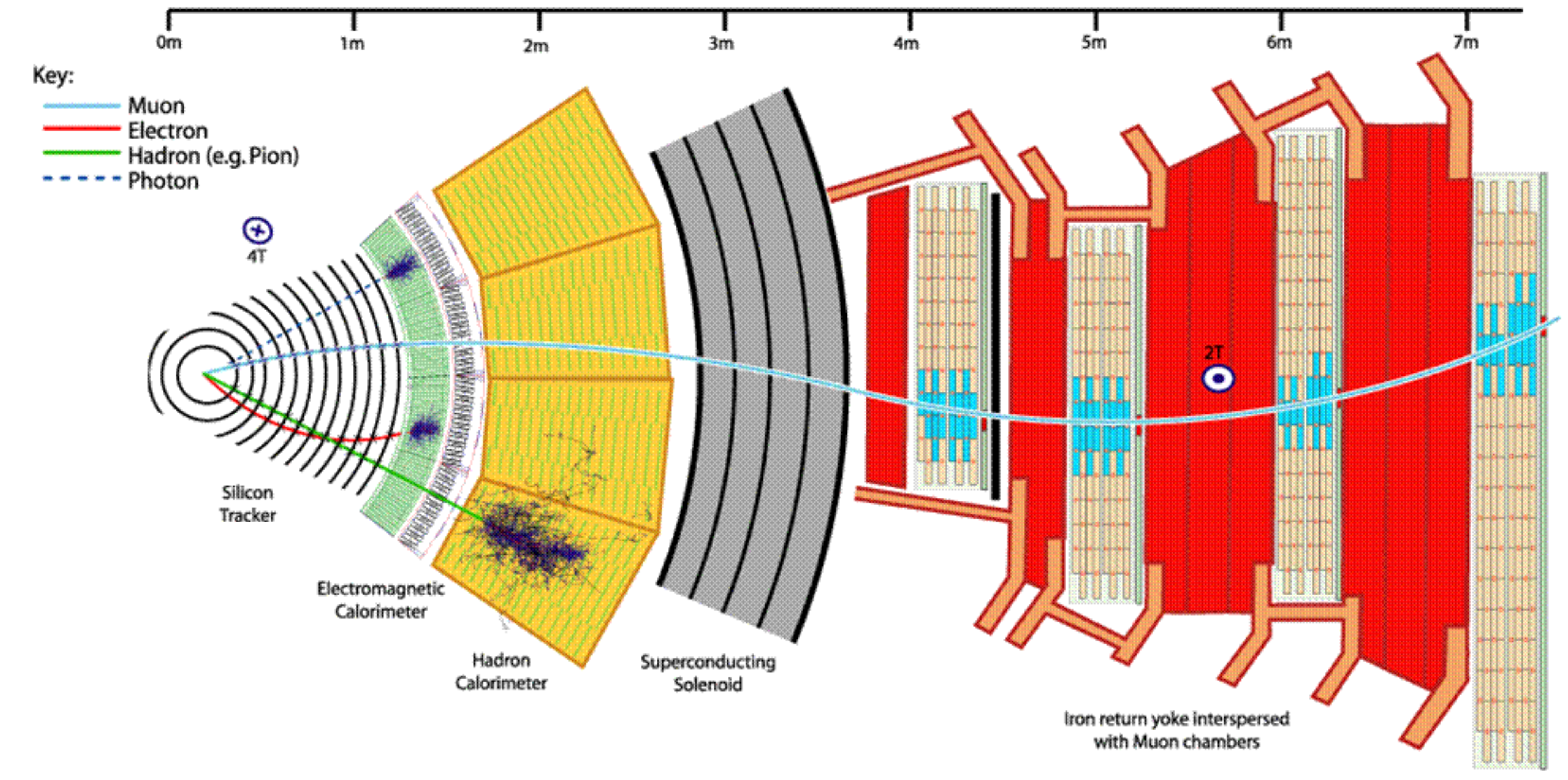


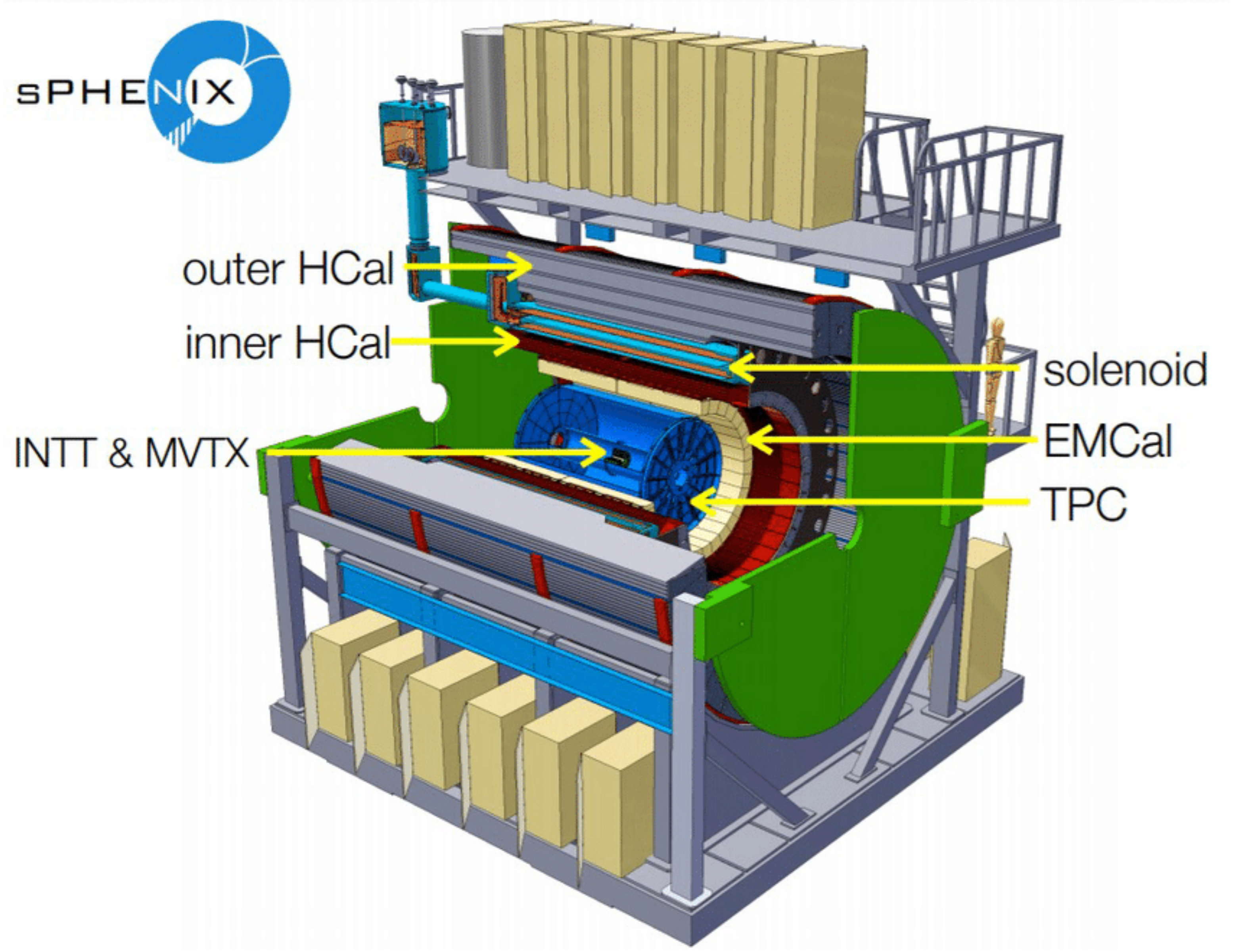
→ We look forward to seeing you at MIT!

BACKUP

CMS in Run 3 at the LHC and sPHENIX at RHIC

→ **Most complete detectors** for jets, photons, heavy-flavour hadrons
→ access to **heavy-ion collisions at very different energies** (5.5 TeV vs 200 GeV)



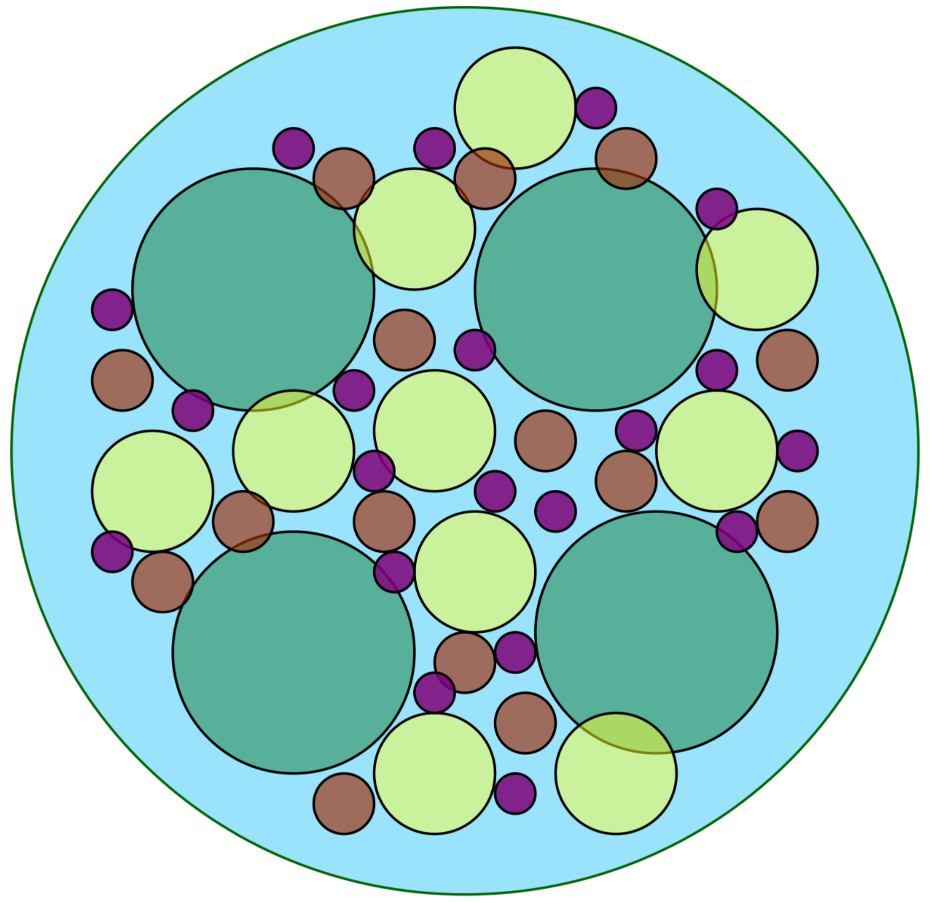


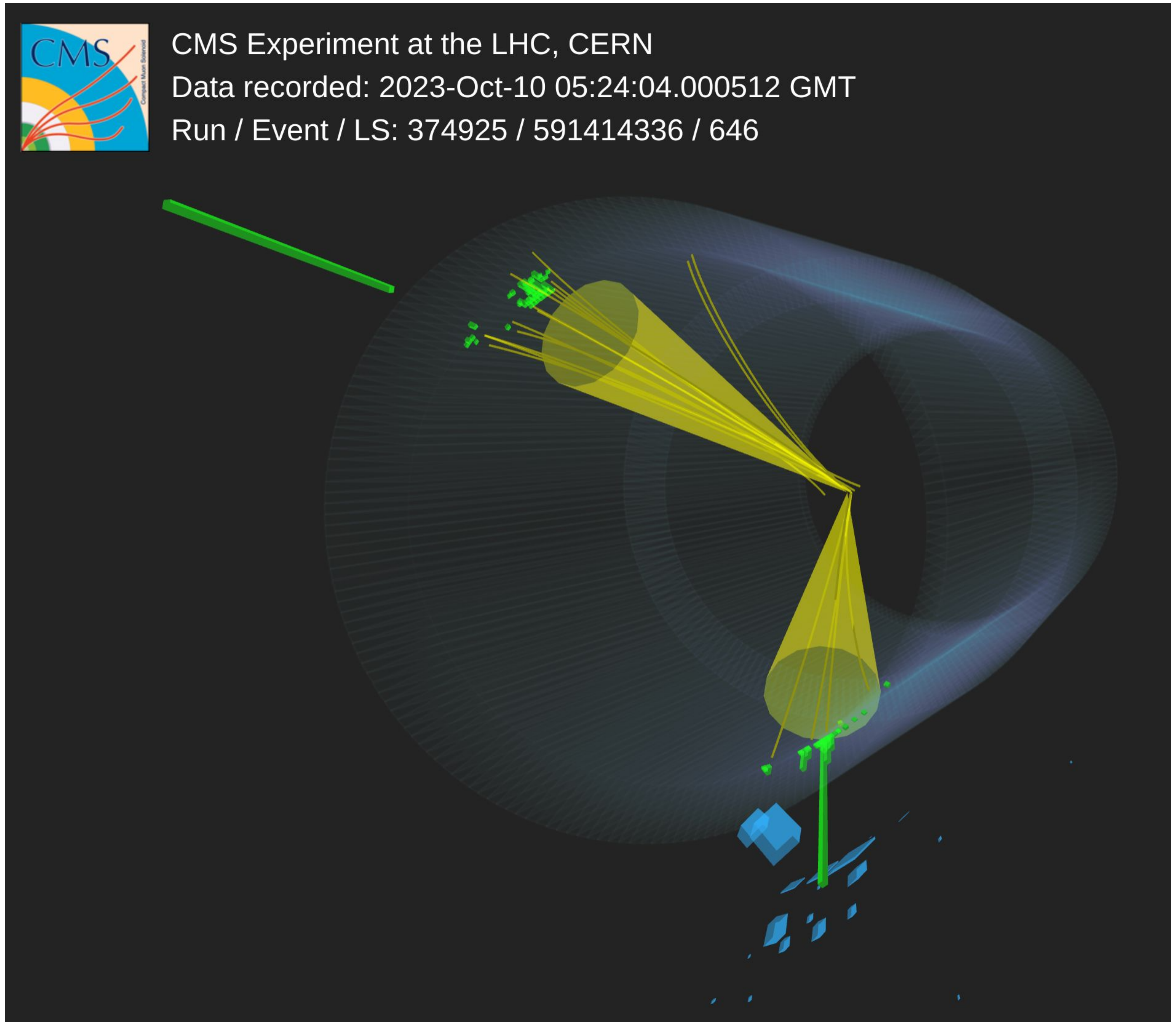
CMS at the Large Hadron Collider:
High-luminosity, full “barrel” coverage $|\eta|<2.4$
- Large acceptance tracking $|\eta|<2.4$ in Run 3
- Muon detectors, ECAL and HCAL
- Outstanding trigger system

sPHENIX at RHIC:
- **Time-Projection Chamber** (GEM readout)
→ 240 billion AuAu events in continuous readout mode
- **MVTX vertex detector** (based on ALICE ITS2 technology)
→ impact parameter resolution ~20 μm for $p_T = 1$ GeV/c

In-vacuum jet physics!

While searching for evidence for QCD at very high “gluonic” densities…





negligible background from pileup, MPI, ..

We “accidentally” collected a huge sample of ultra-clean QCD jets → an ideal laboratory for in-vacuum QCD

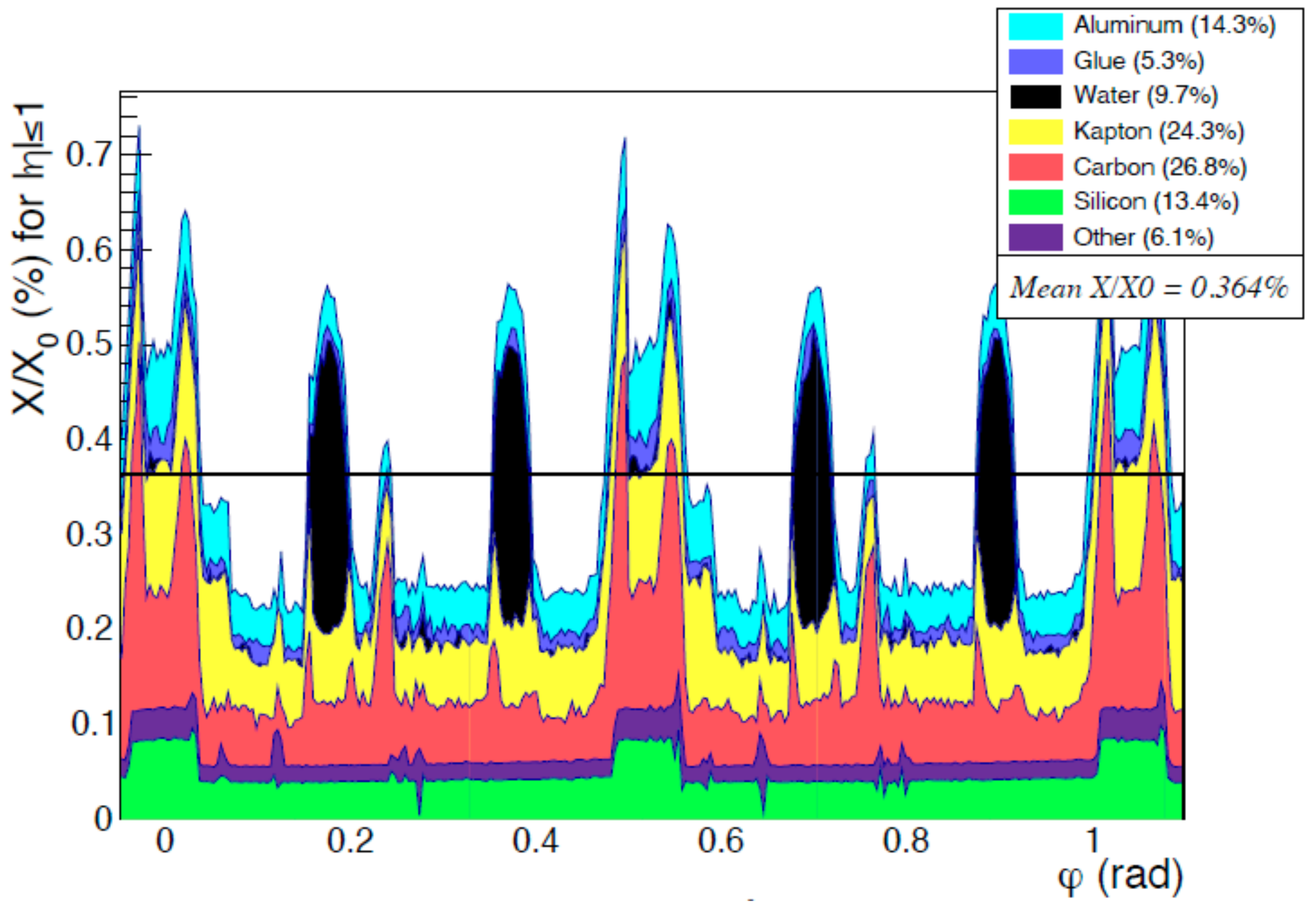
- heavy quark substructure with improved tagging techniques **(work is also starting now)**
- large R jets, N(N)LL parton showers, …

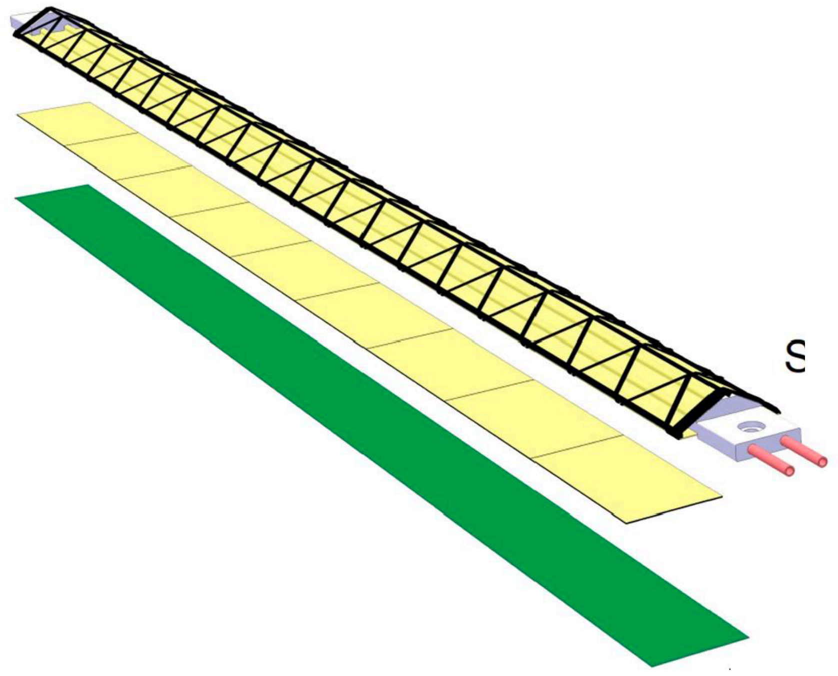
H.-S. Shao, D. d’Enterria, 10.1007/JHEP09(2022)248
L. Bonino, M. Cacciari, G. Stagnitto, arXiv.2306.02953

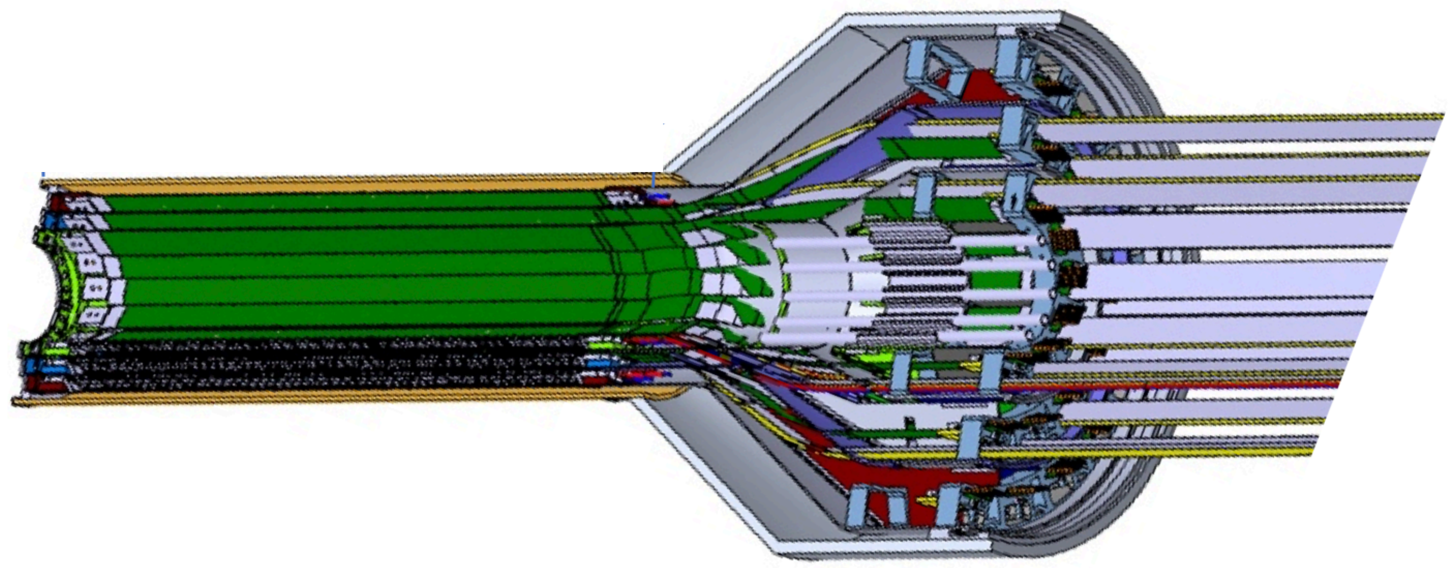
Monolithic Active Vertex Tracker (MVTX) for sPHENIX detector

Monolithic Active Vertex Tracker (MVTX) for sPHENIX
→ MAPS sensors in 180 nm technology used for ITS2, MVTX detectors

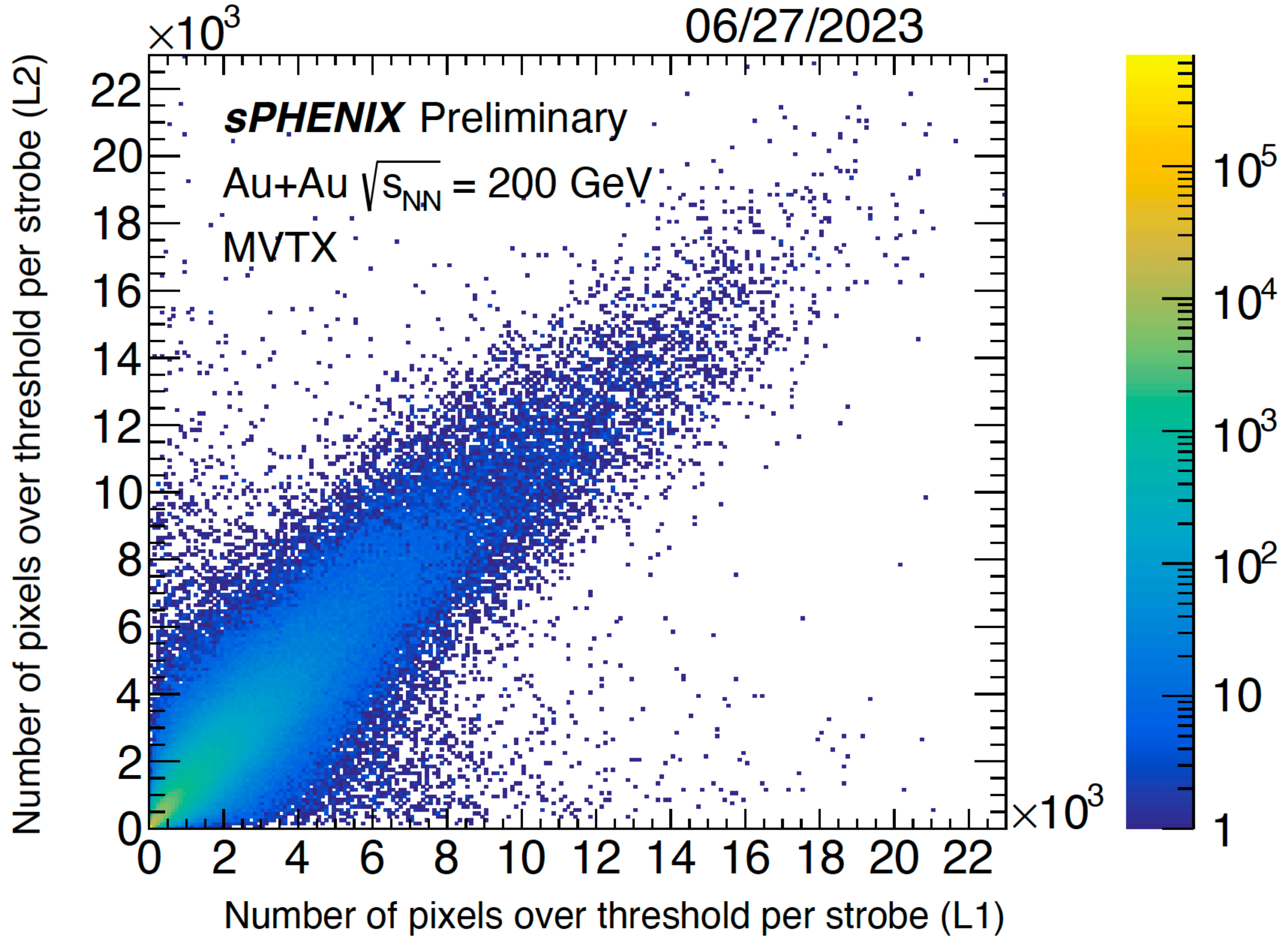
MITHIG had a leading role in:
- mechanical design, cooling, and integration, module characterization
- DCS design, installation and commissioning







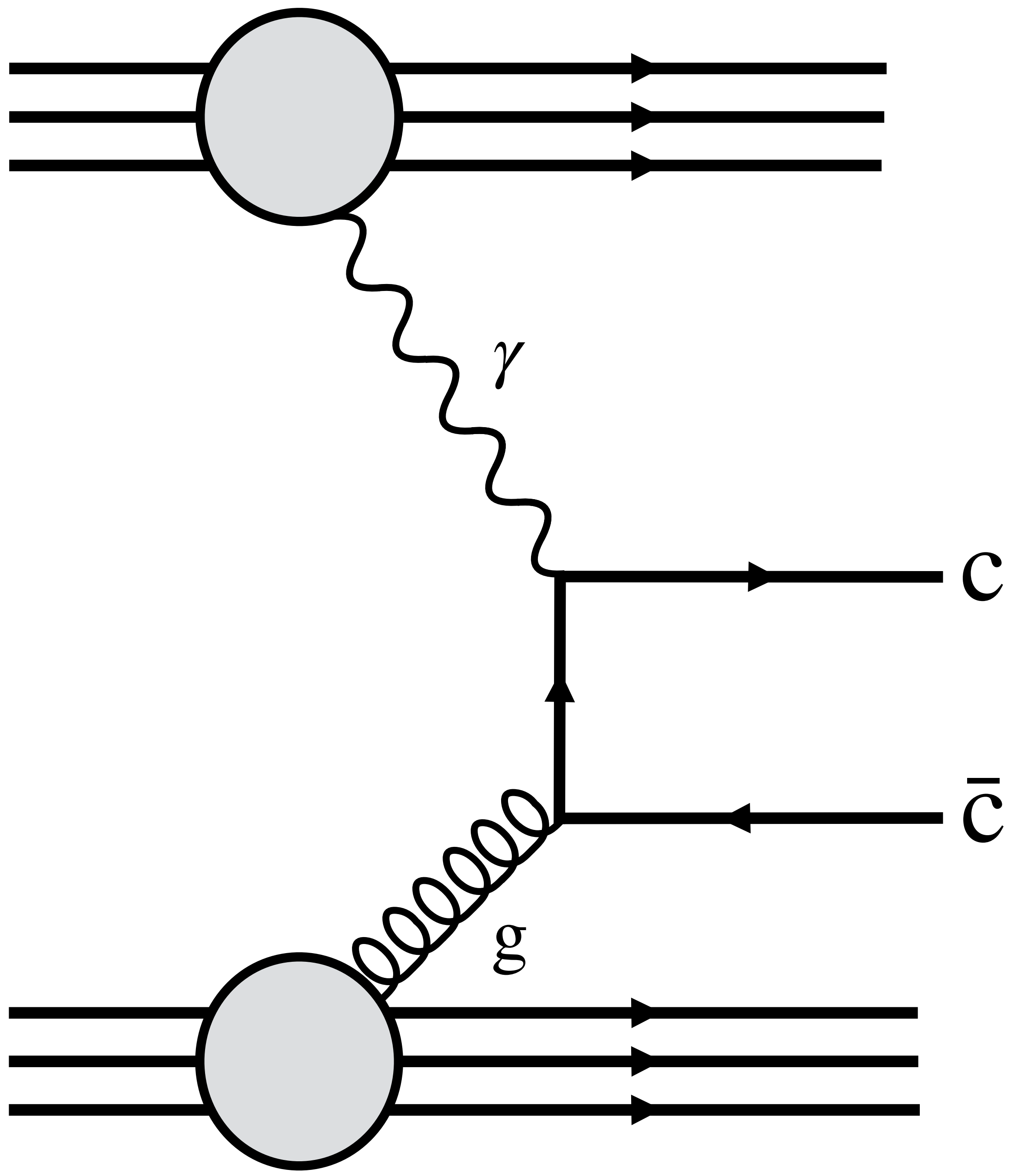
The MVTX was successfully reinstalled on March 13th, 2024



Physics with sPHENIX is starting now!
→ unique capabilities for both jet, photon and heavy-flavor physics
→ rare opportunity to witness the starting phase of sPHENIX high-luminosity phase and profit from unprecedented statistics of MB events

γN → open charm: a golden probe for low-x physics!

pQCD description down to p_T=0
→ optimal theoretical control



heavy-hadron reconstruction down to p_T=0

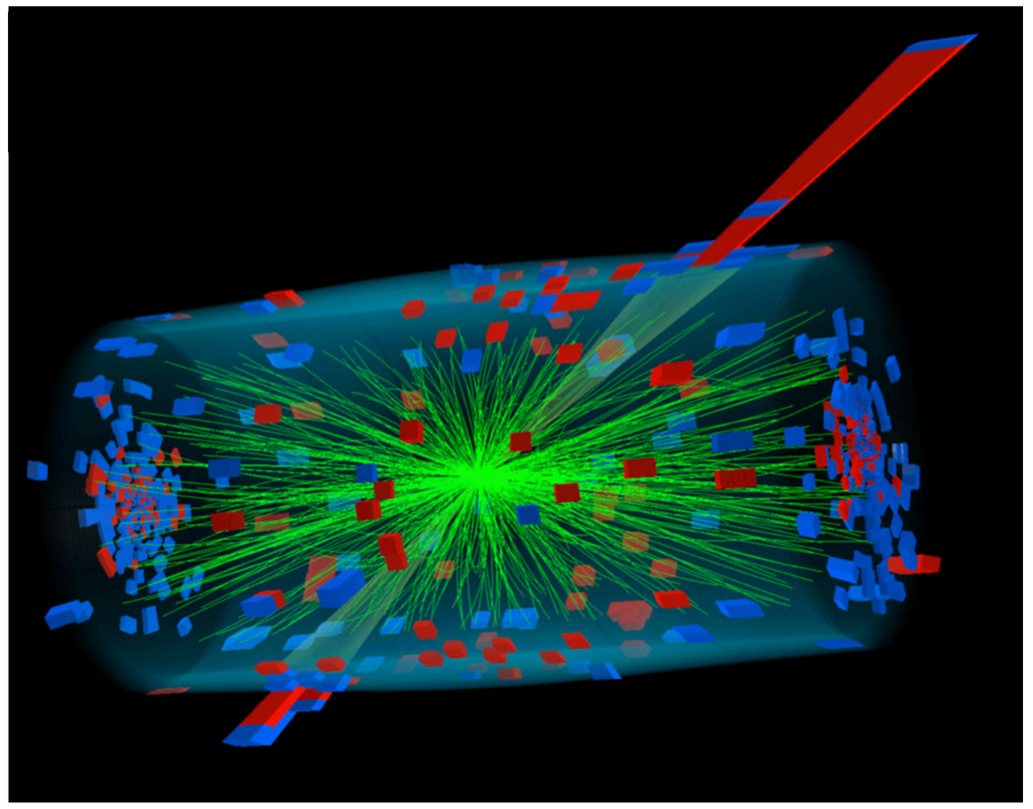
An idea probe for the low (x,Q^2) region:

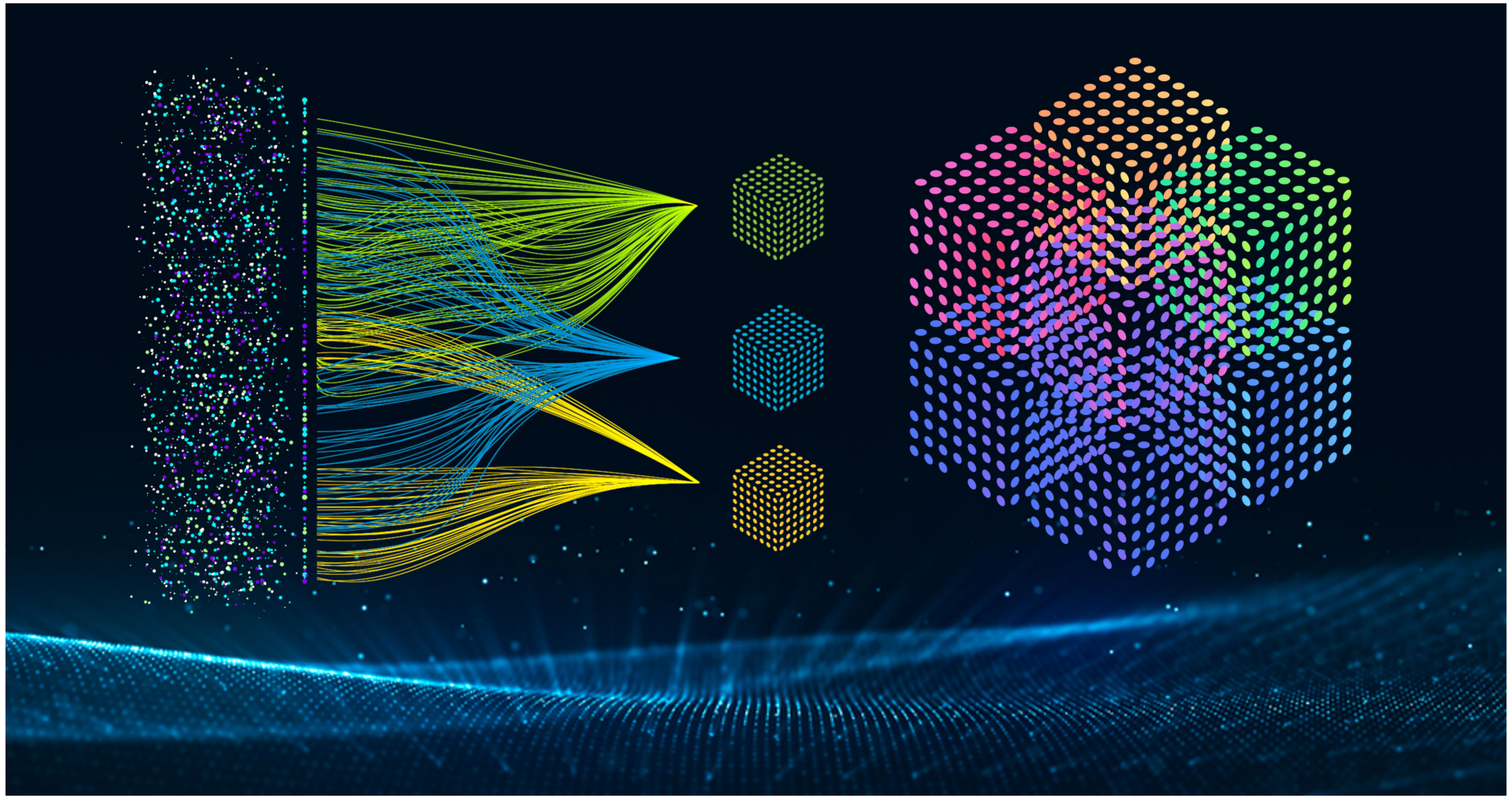
- $x_{min} \approx 10^{-4}$ at LHC with probes |y|<2
- $Q^2_{min} \approx m^2_{c\bar{c}}$

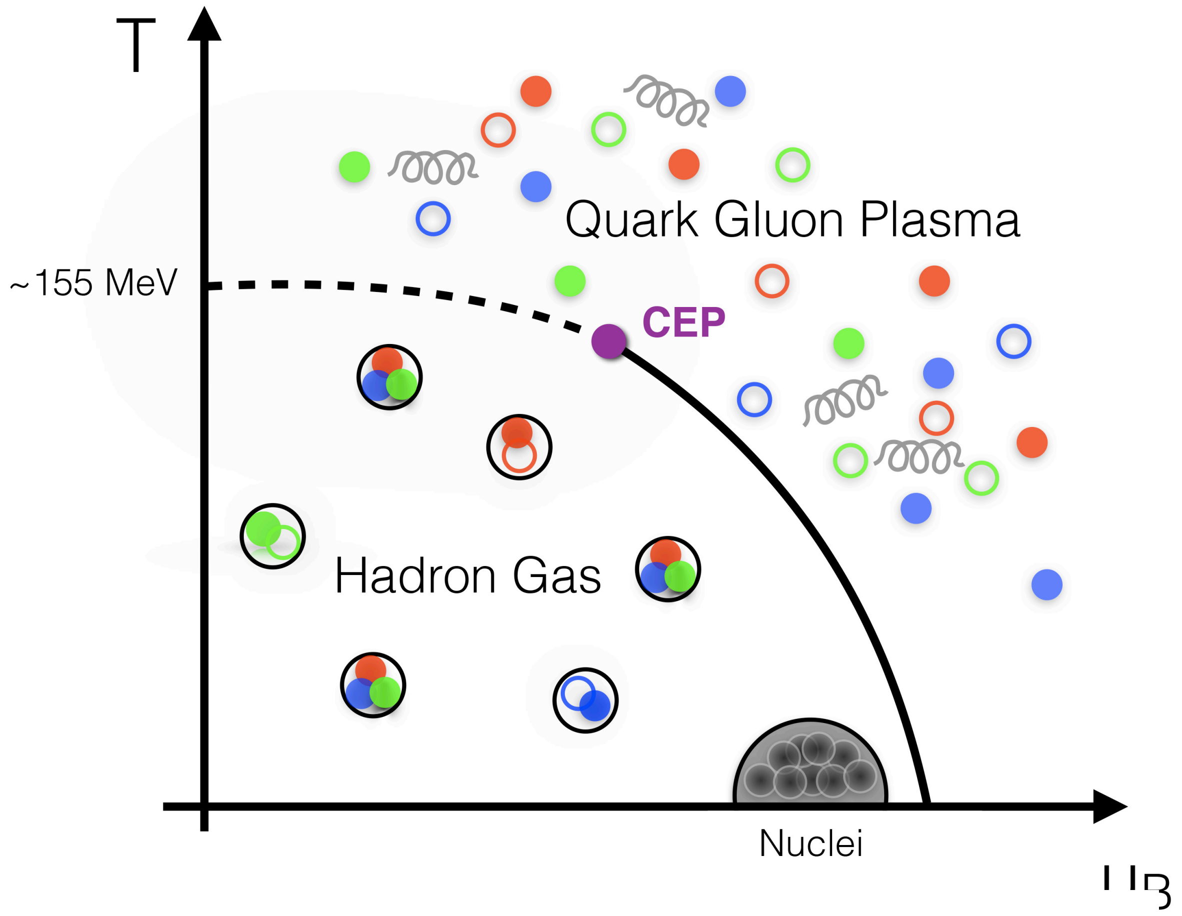
S. Klein, R. Vogt et al: Phys. Rev. C, v66, 2002

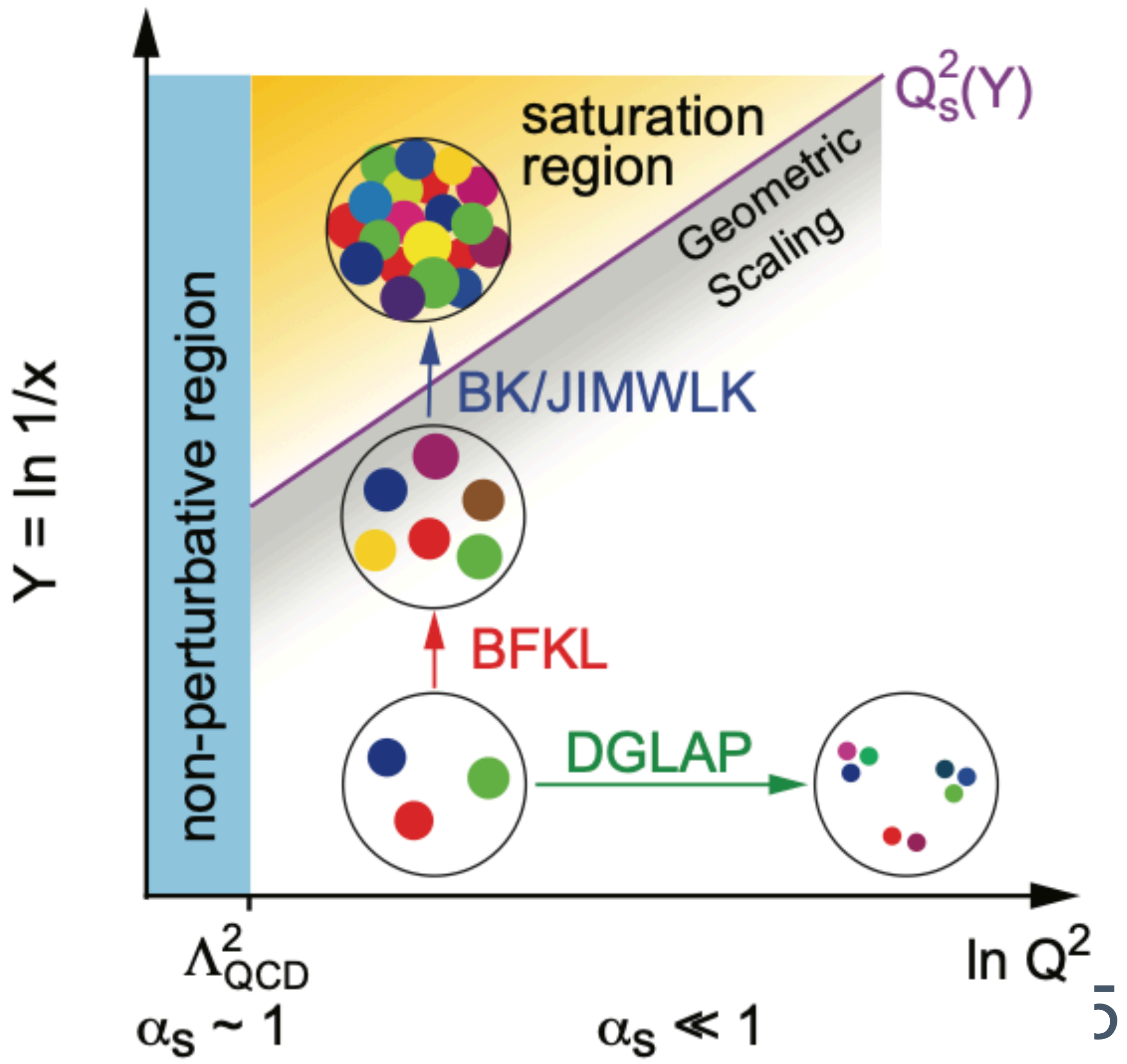
One of the most challenging “pattern-recognition” challenges

→ to reveal the inner and hidden workings of QCD in one of the most complex systems ever created



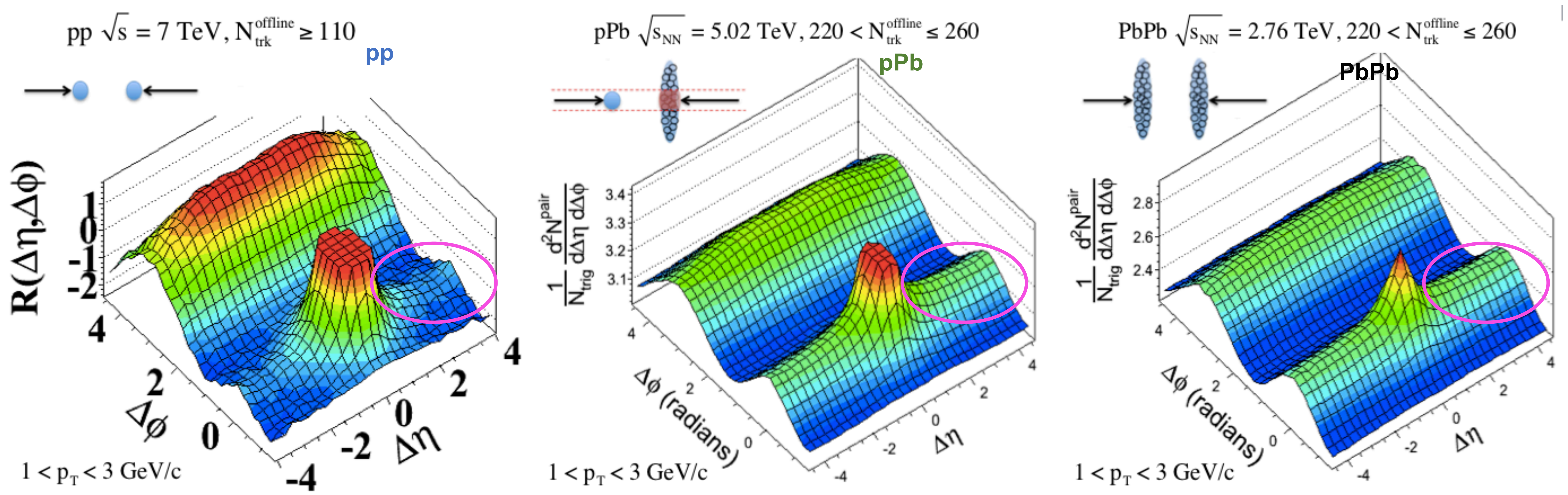






→ **to achieve this goal, we exploit cutting-edge software and hardware techniques**
(new data acquisition and trigger strategies, AI, new silicon-pixel technologies, …)

What is the smallest size of a strongly-interacting medium?

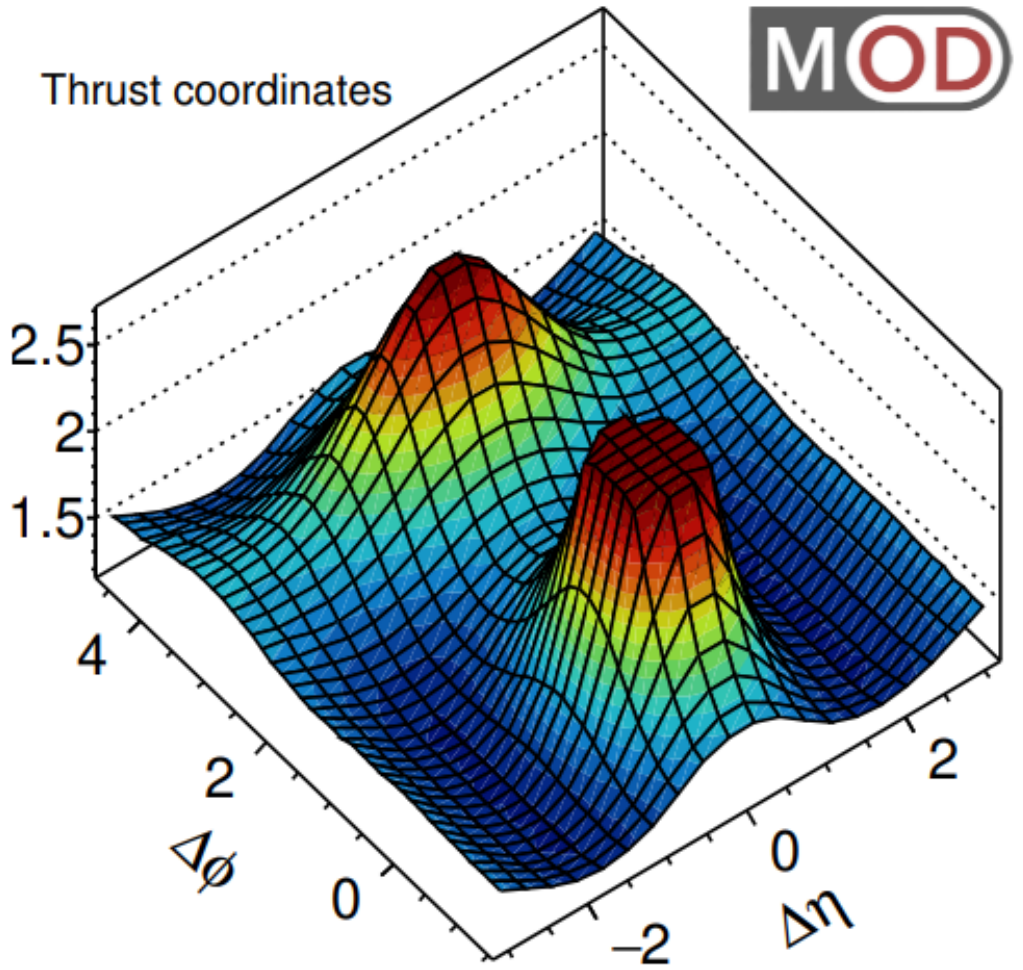


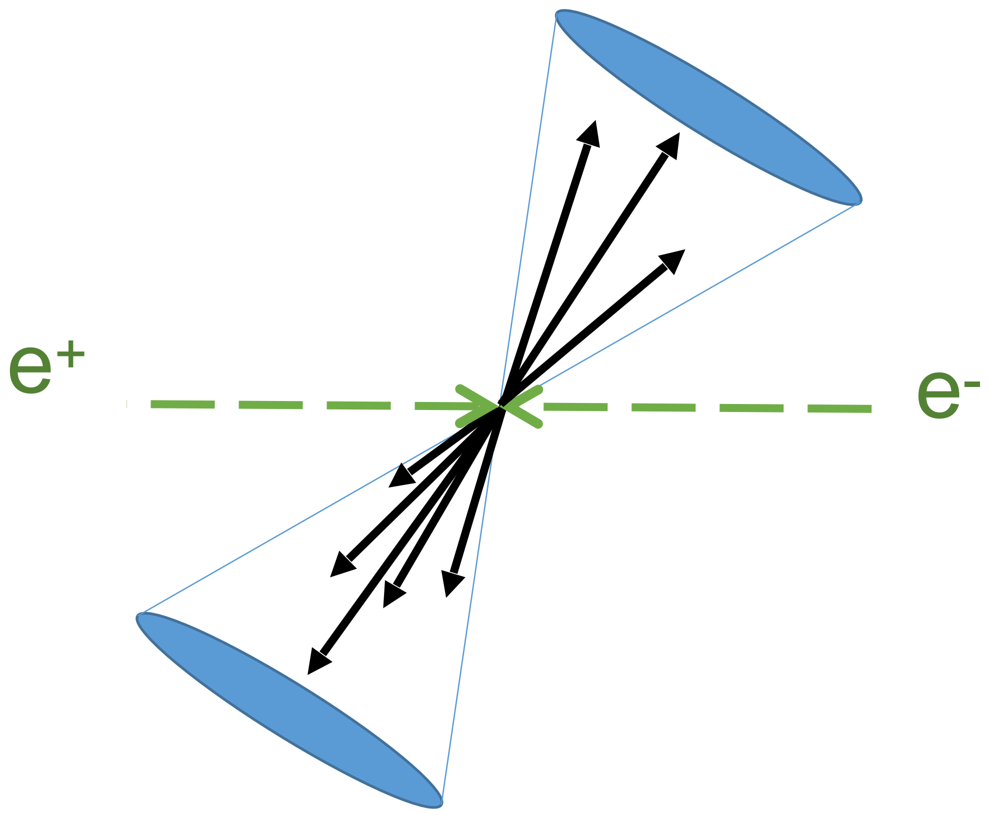
2010 2012

Long-range “ridge” observed from nucleus-nucleus to pp collisions:
→ in nucleus-nucleus, an evidence for a strongly-interacting QGP

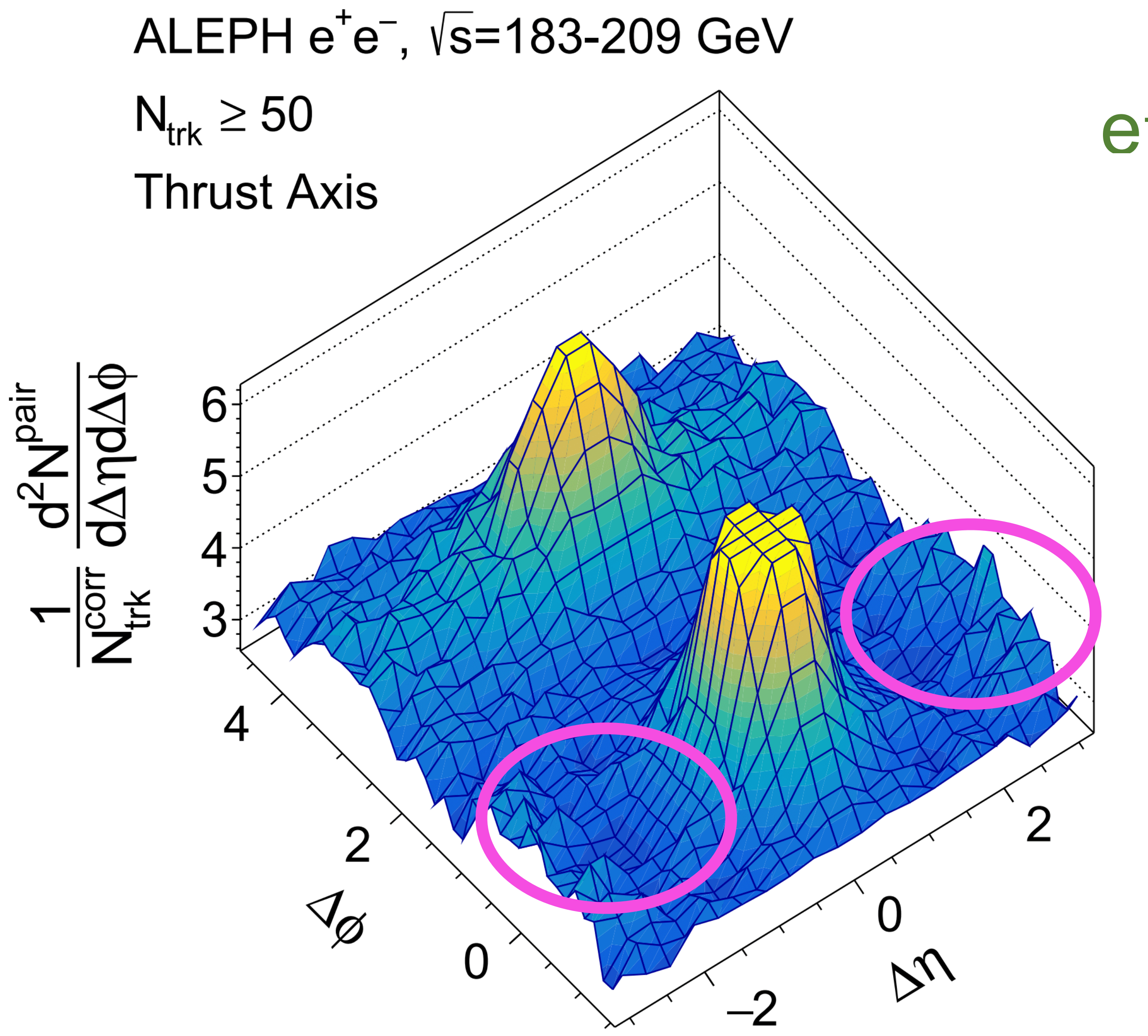
ALEPH e+e- data from LEP1 and LEP2

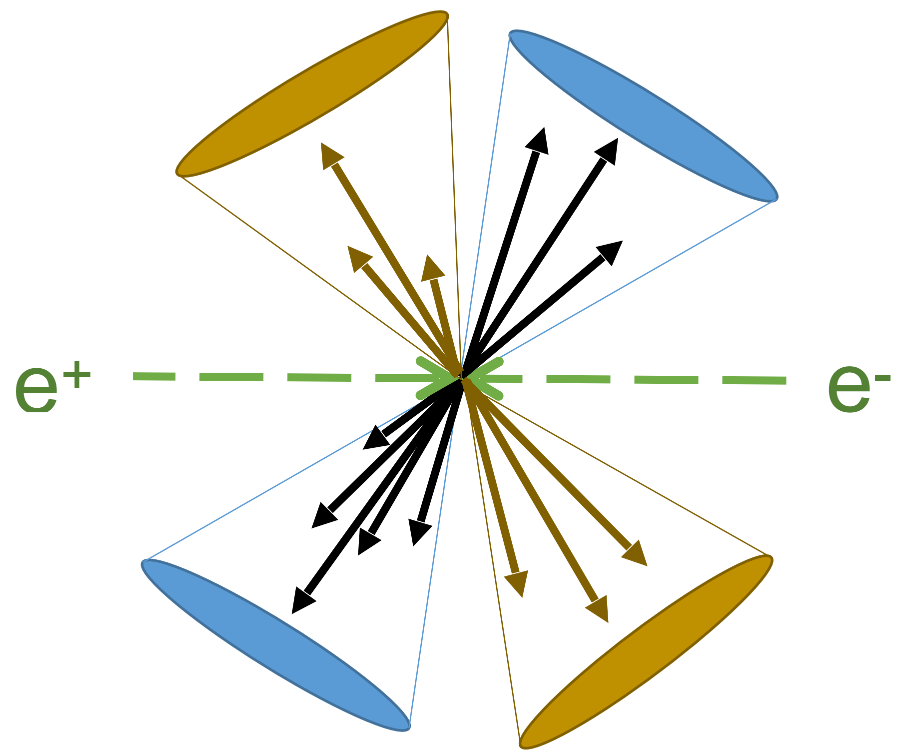
$$e^+e^- \rightarrow q\bar{q}$$





$$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$$



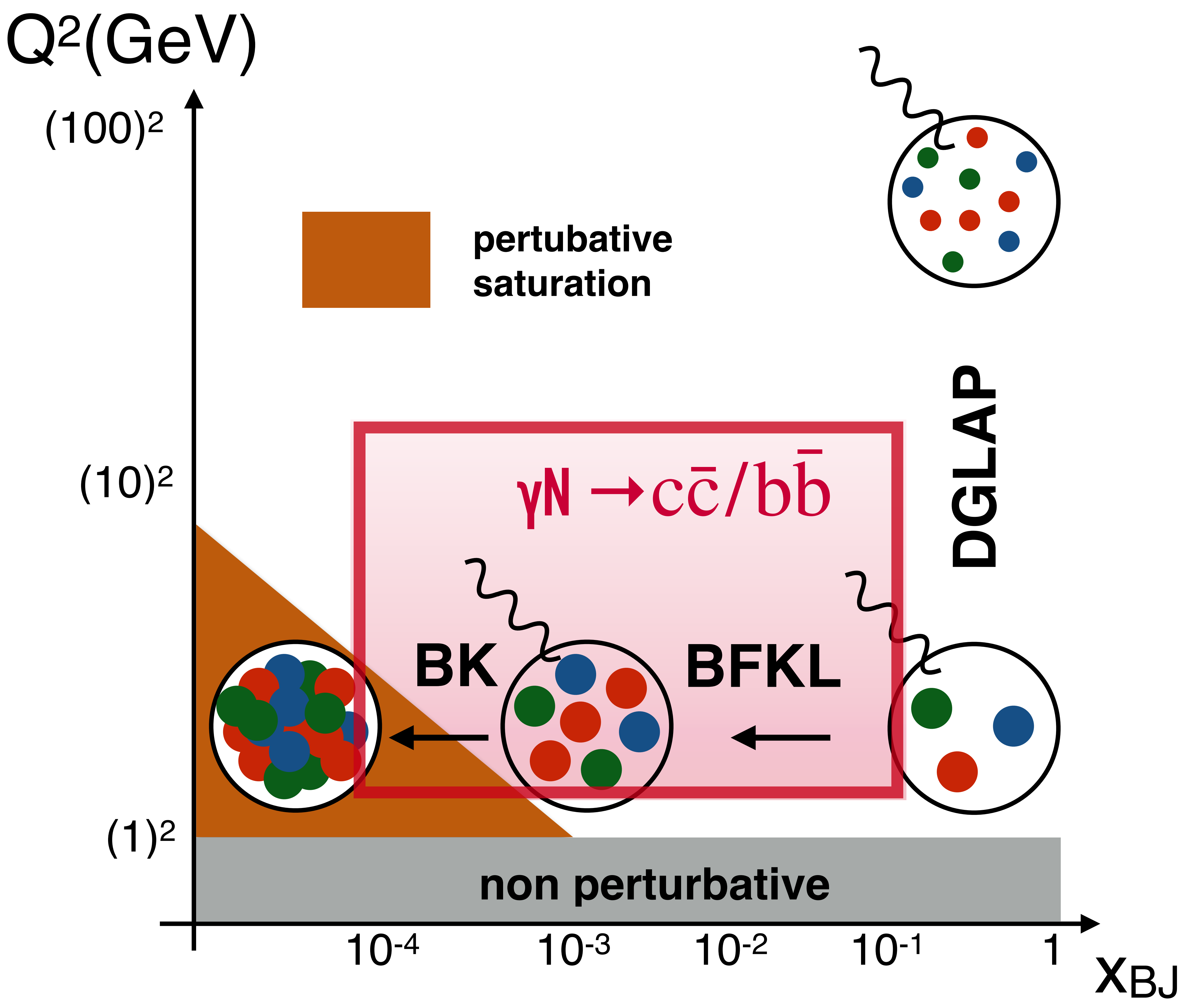


No ridge-like structure at LEP1
(lower energy and lower multiplicity)

Long-range near-side signals at LEP2?!
what is the “medium” that is generating these signals?

→ Over the next few years, we plan to continue developing new tools to test the formation of QCD medium in “small” collisions and apply modern jet techniques to e^+e^- LEP data

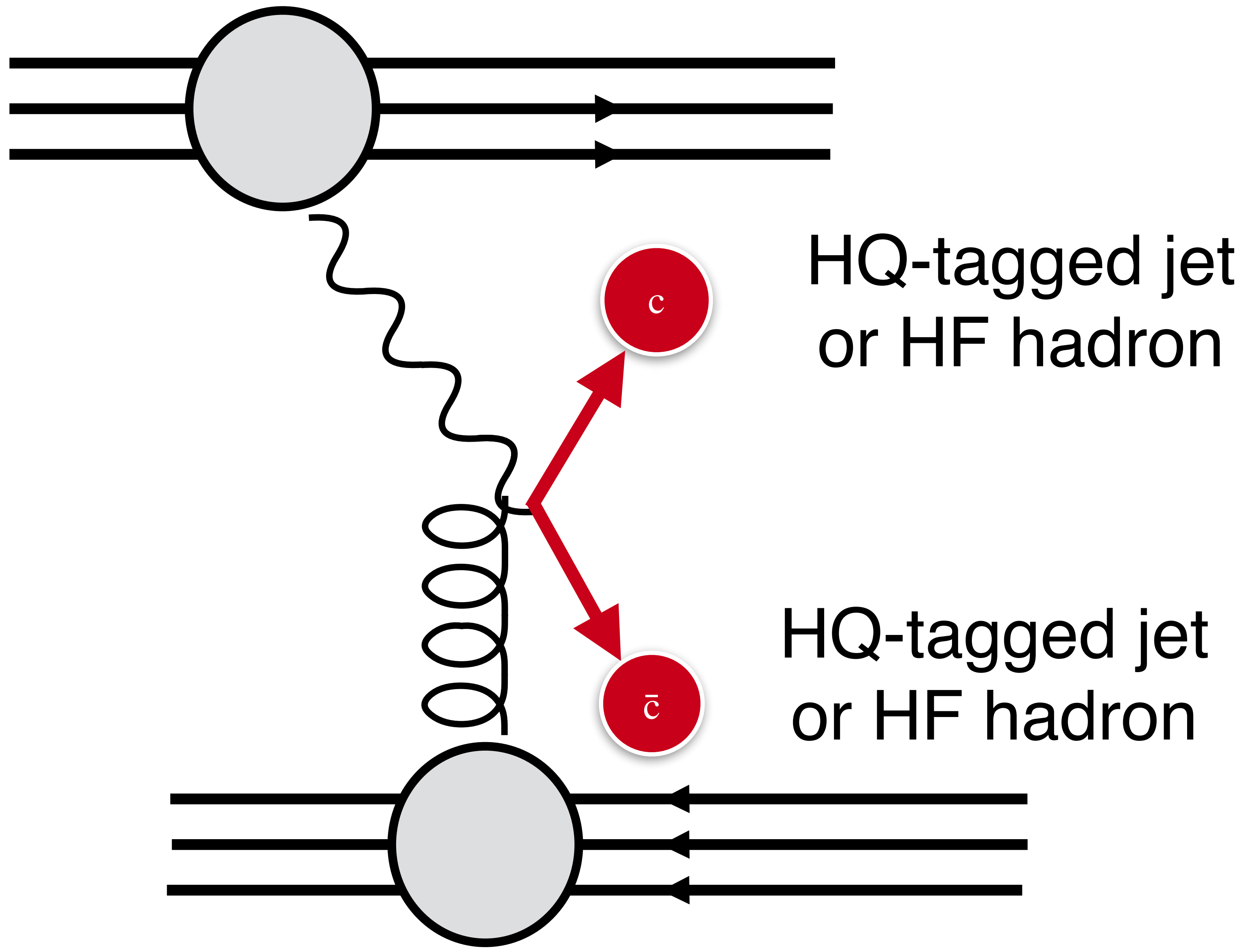
CMS and sPHENIX uniqueness and complementarity

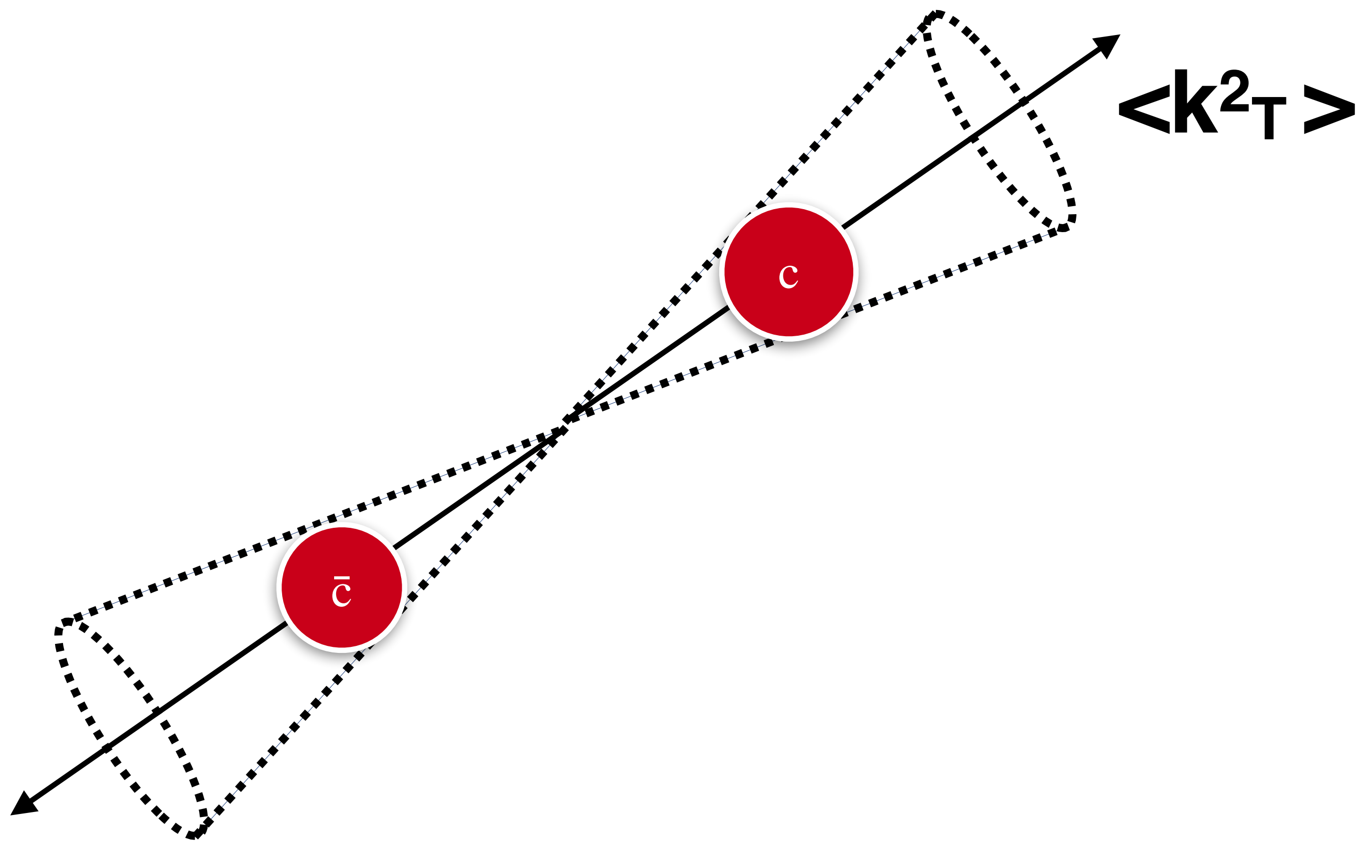


By combining measurements with CMS in Run 3 (lower x-values) and sPHENIX (higher x-values)

→ x-coverage from to x ≈ 0.1 down to x ≈ 10^{-4} at low-intermediate Q^2

Measurement of di-cjets and di-bjets in γN scatterings





$\Delta\varphi$ correlations of di-HQ jets or hadrons:

→ **strong sensitivity to the Q_s scale via $<k^2_T>$ broadening**

Measurement of charm and beauty tagged dijet system in pp, PbPb, AuAu

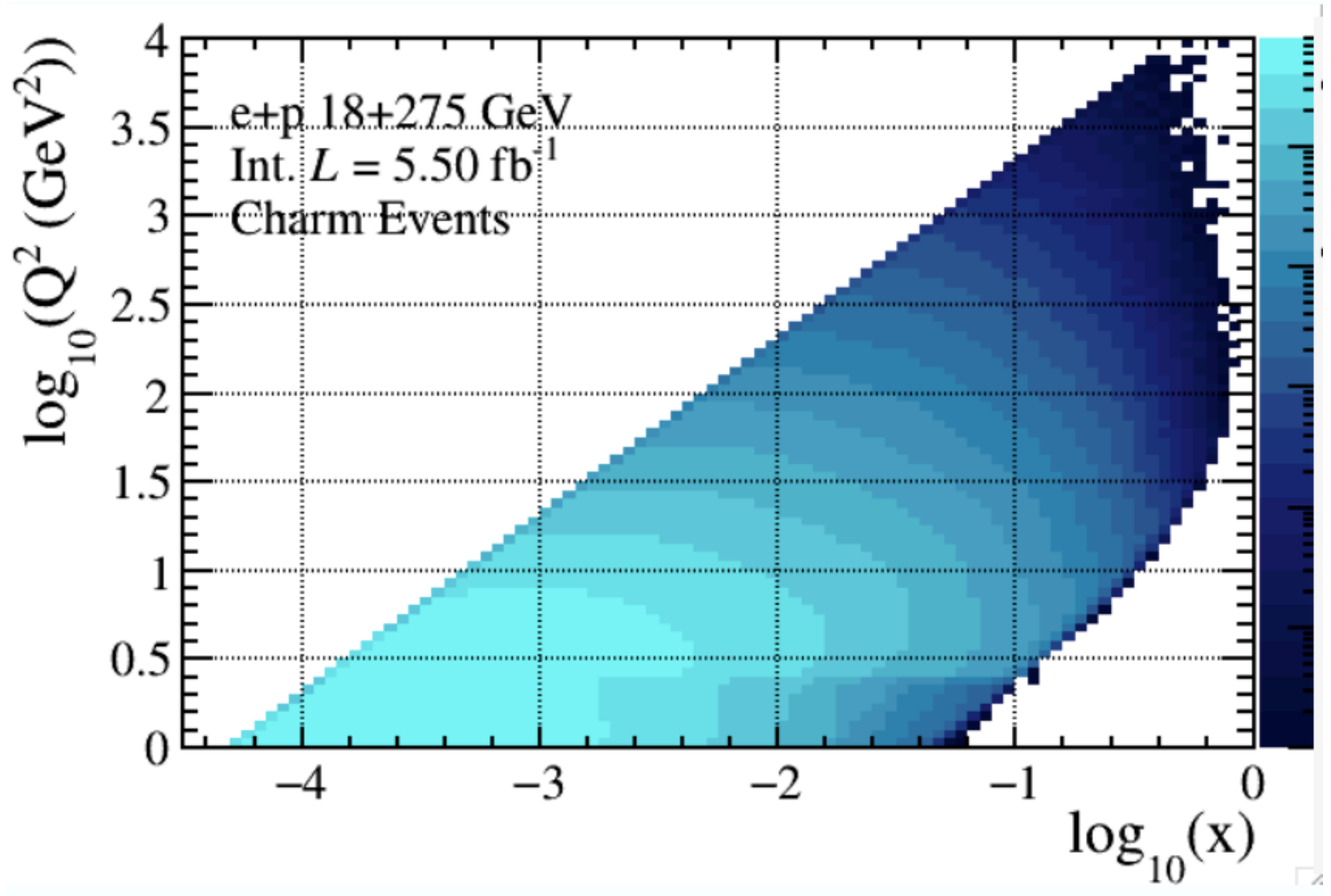
→ stronger constraints on x,Q^2

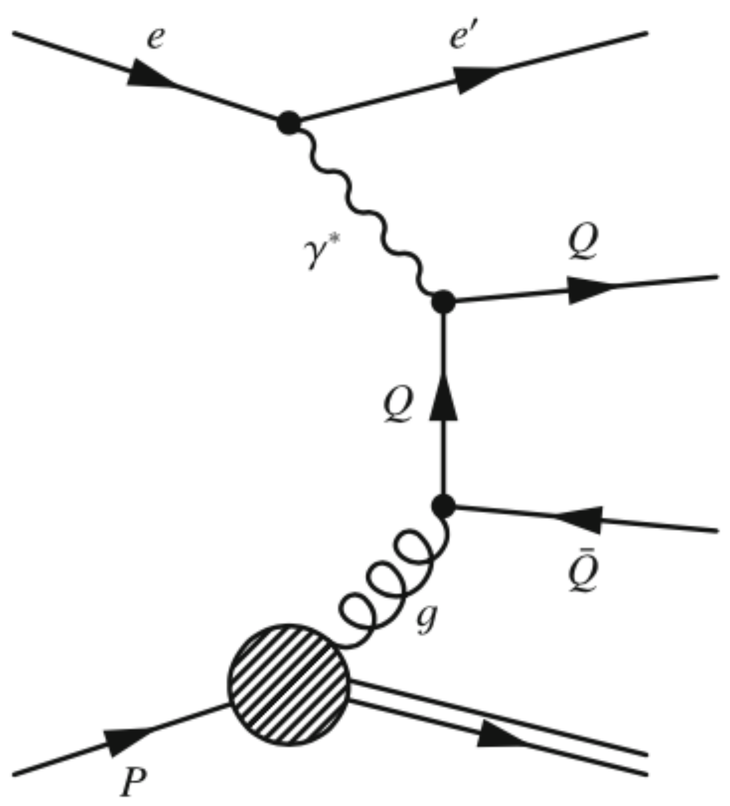
→ **enable the study of low-p_T dijet decorrelation!**

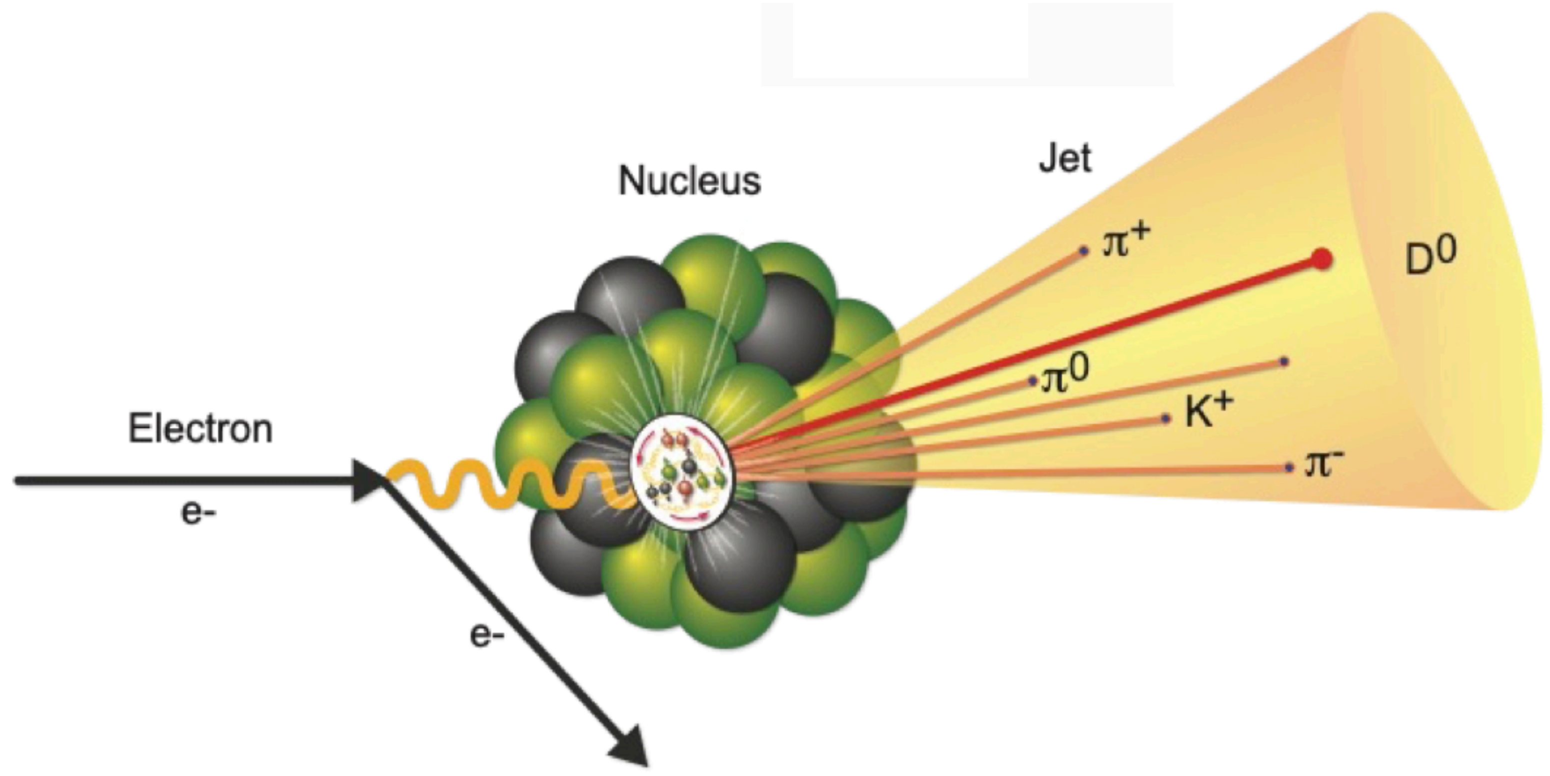
Heavy-flavor physics at the Electron-Ion Collider

B.S. Page et al. Phys. Rev. D 101, 072003
H. T. Li and I. Vitev, Phys. Rev. Lett. 126, 252001
EIC , BNL-98815-2012, arXiv:1212.1701

→ **Heavy-flavor observables are crucial to address the key physics questions of the EIC physics program**







Inclusive heavy-flavor measurements in ep/eA collisions:
→ gluon (n)PDFs down to moderate/low x_{BJ}
→ **evolution equations beyond DGLAP?**

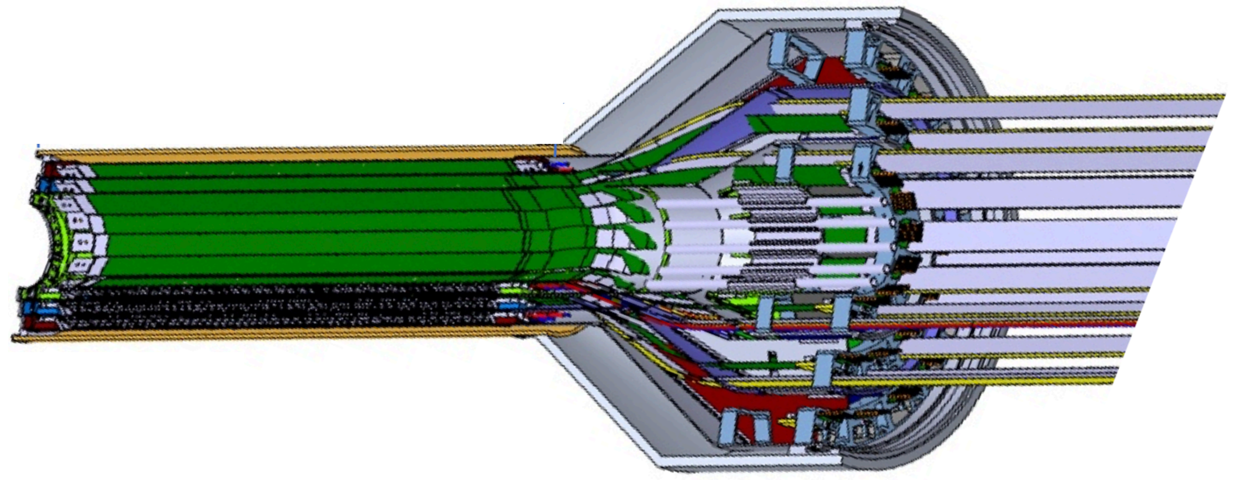
$D\bar{D}$ **correlations:**
→ access to gluon TMDs
→ **nuclear structure beyond the collinear limit**

Heavy-quark jet production and substructure in ep/eA:
→ **parton-propagation inside the "cold" nuclear matter**
→ parton-shower evolution in a vacuum-like environment

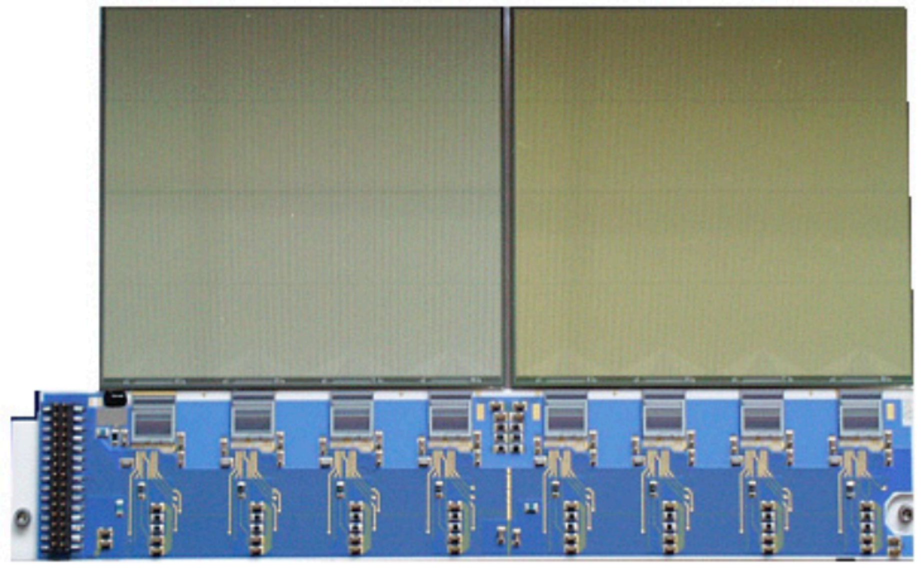
Heavy-flavor hadrochemistry and collectivity:
→ hadronization modification in cold-nuclear matter
→ **what is the time scale of hadronization?**

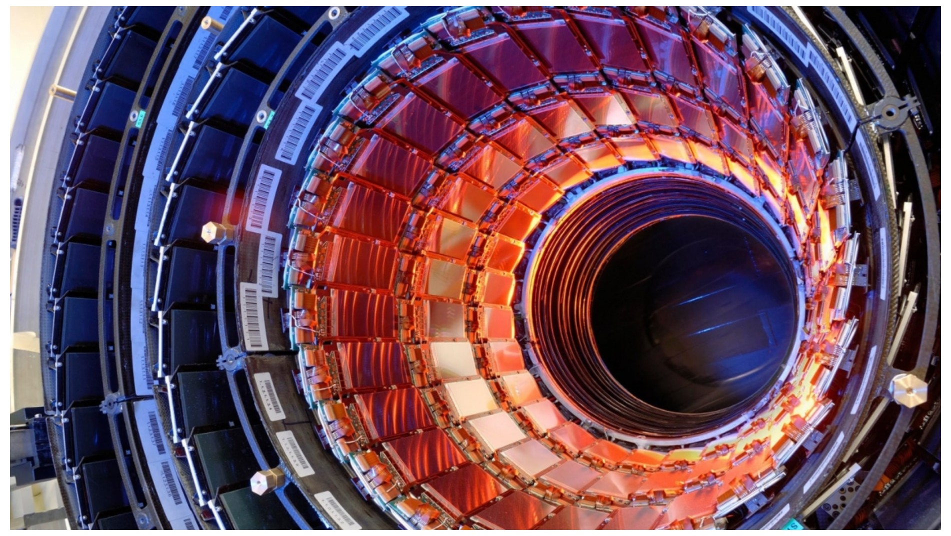
Silicon detectors in the MIT heavy-ion group

→ Almost 30 years of experience in pixels detector design, construction, commissioning



PHOBOS experiment at RHIC
AC-coupled, single-sided, silicon pad
for tracking, vertexing, and multiplicity





Monolithic Active Vertex Tracker (MVTX) for sPHENIX with ALICE ITS2 technology
- mechanical design, cooling, and integration
- module characterization
- DCS design, installation and commissioning

CMS tracker ("hybrid pixels")
commissioning pixel and strip
detectors for heavy-ion runs

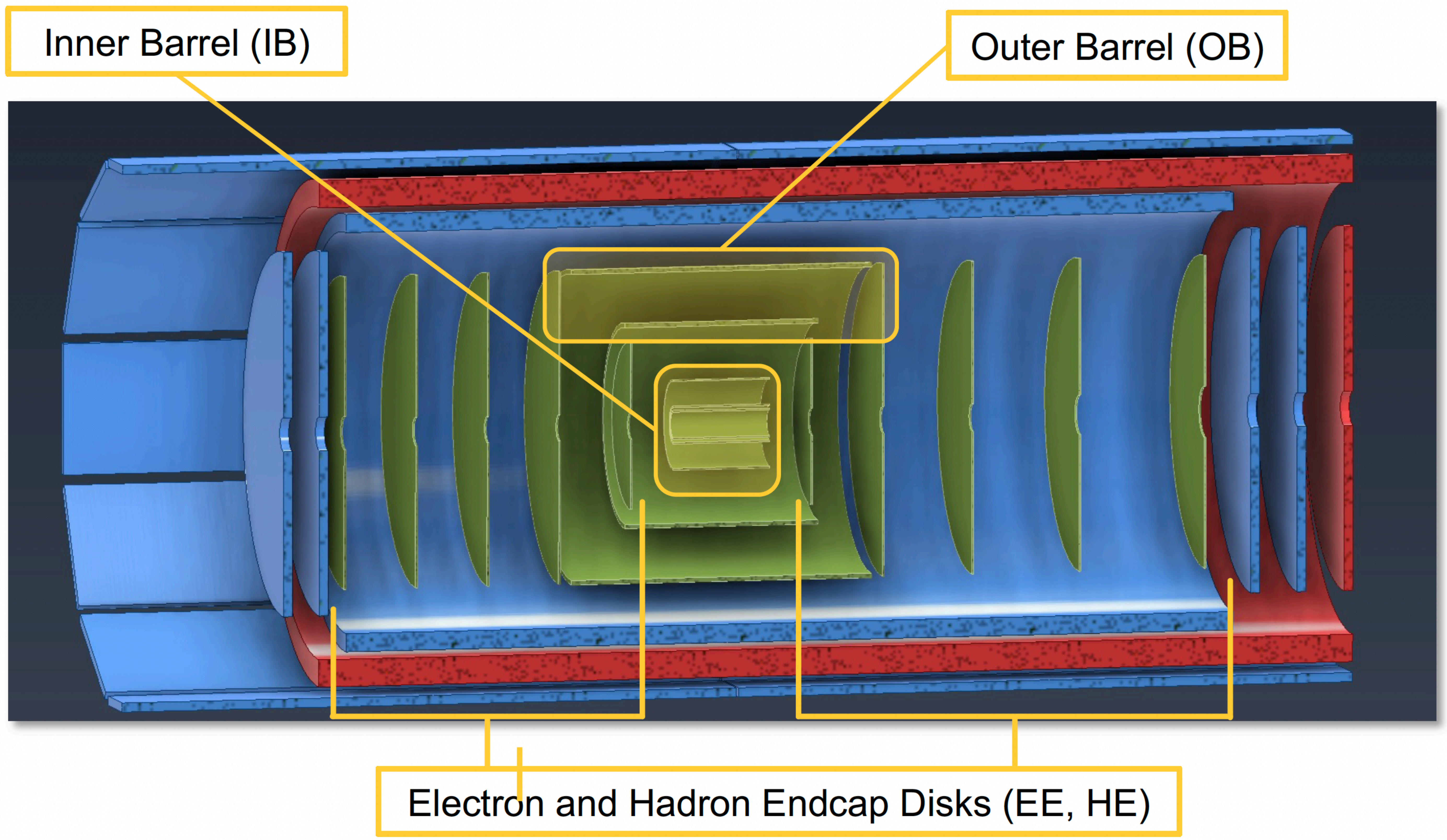
Ultra-fast silicon timing detector for CMS in Run 4

IST for STAR at RHIC

1990 2000 2010 2020 2030

IST for STAR at RHIC

Silicon Vertex Tracker for ePIC: detector concept



Outer Barrel (OB)
- Two layers, L3, L4
- Radii of 27 and 42 cm
- X/X0 ~ 0.25% and ~ 0.55%
- **Conventional staved structure with LAS EIC MAPS sensors**

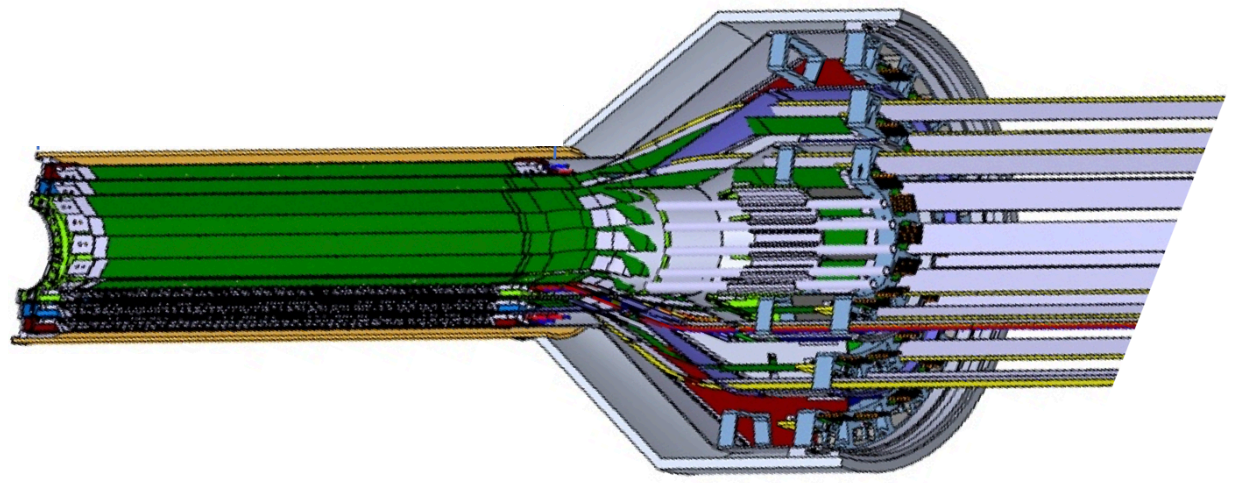
~ 8 m² of silicon sensors!

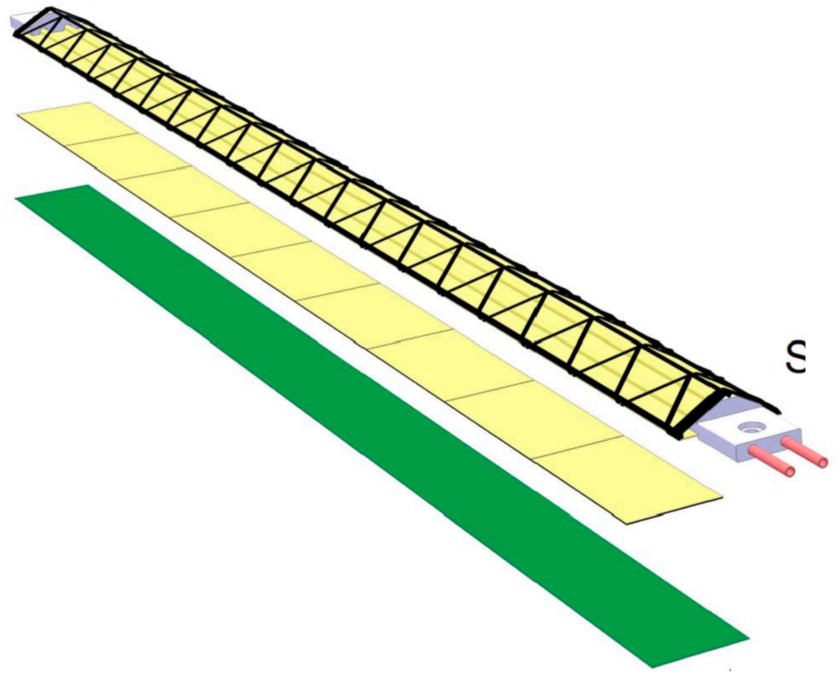
Inner Barrel (IB)
- Three layers, L0, L1, L2
- Radii of 36, 41, 120 mm
- Length of 27 cm
- X/X0 ~ 0.05% per layer
- **"Bent" MOSAIX MAPS sensors**

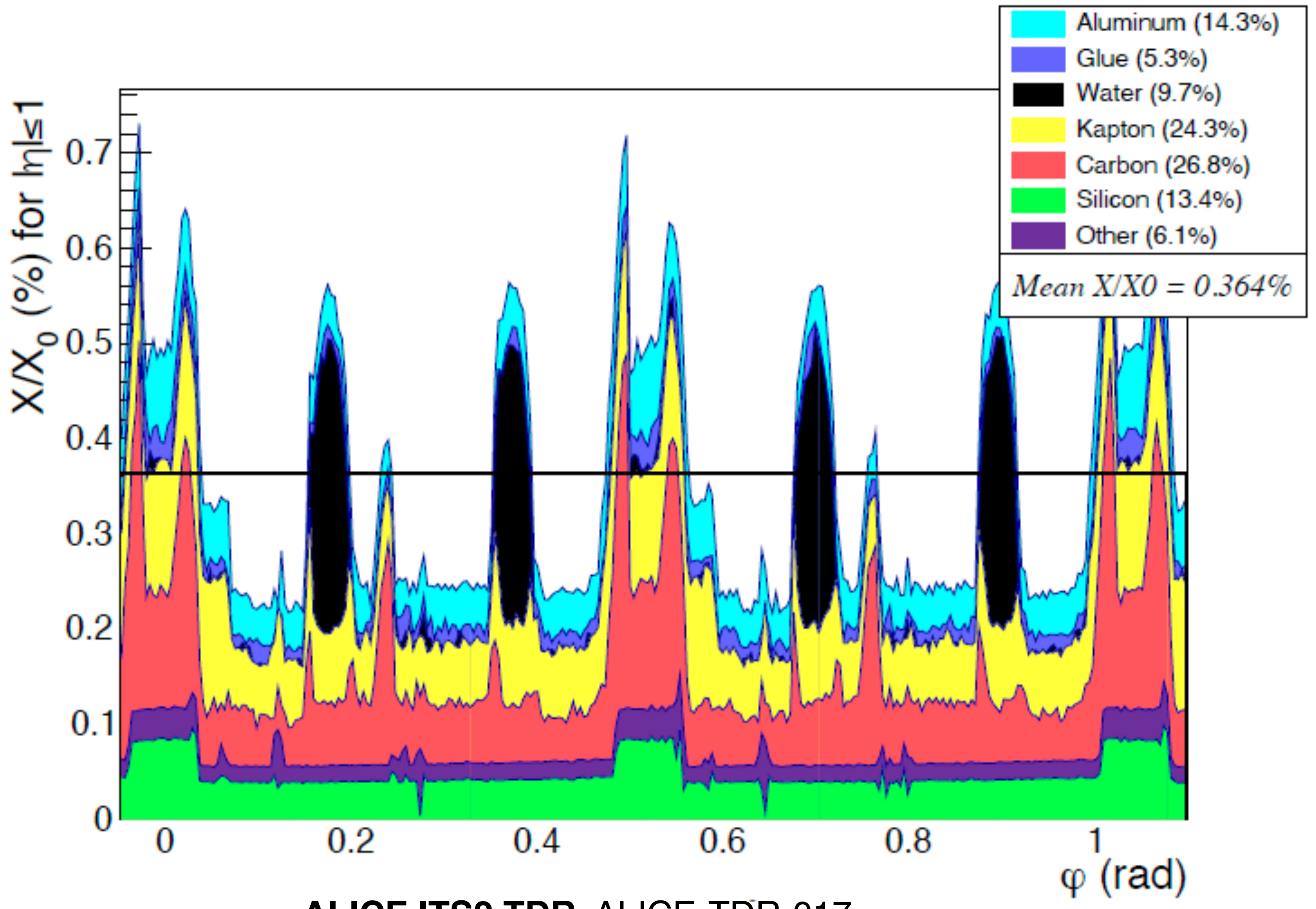
Electron/Hadron Endcaps:
- Two arrays with five disks
- X/X0 ~ 0.25% per disk
- **Conventional staved structure with LAS EIC MAPS sensors**

Material-budget reduction with next-generation MAPS

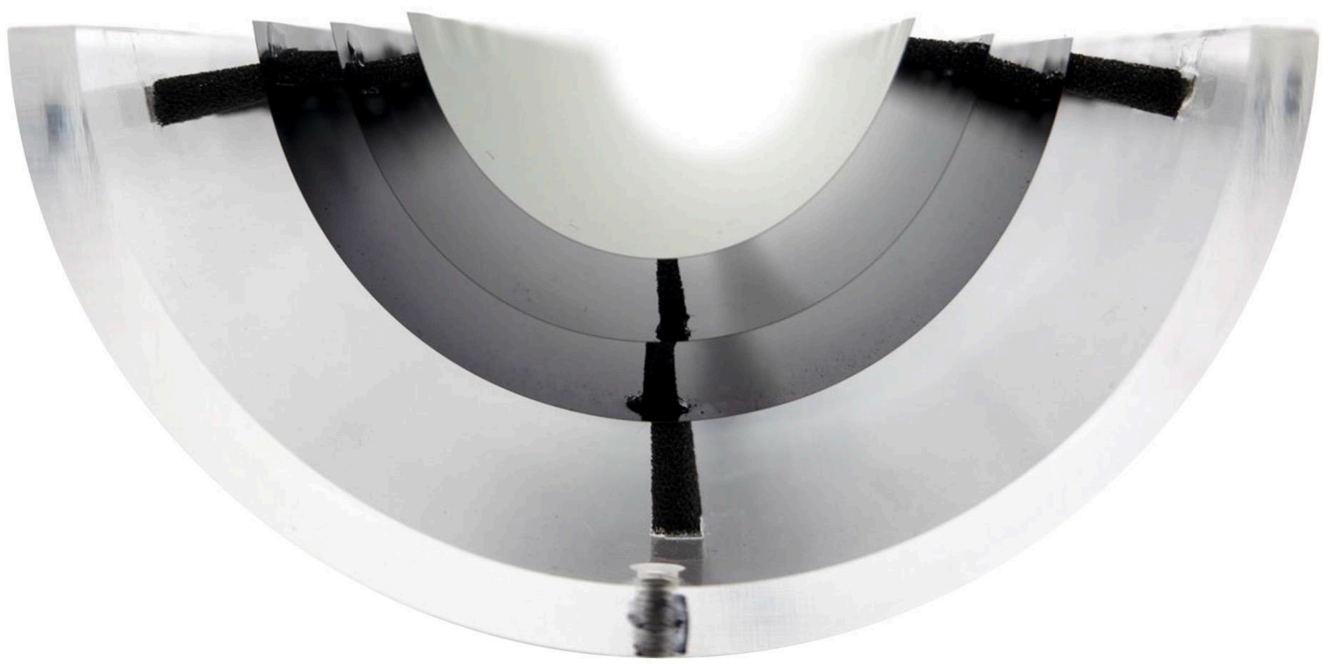
Existing MAPS sensors in 180 nm technology used for ITS2, MVTX detectors







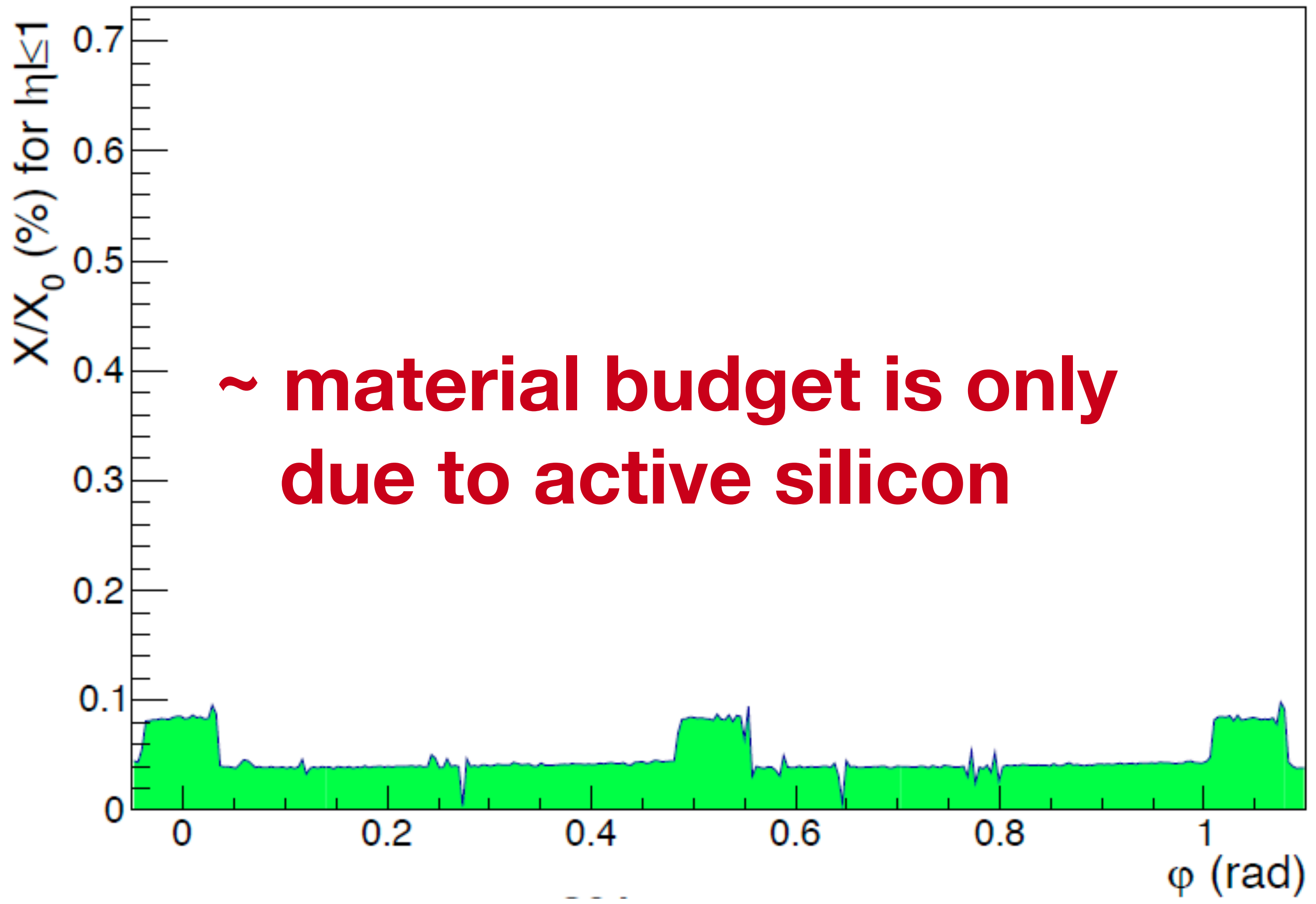
ALICE ITS2 TDR, ALICE-TDR-017



Stitched and thinned sensors in 65nm CMOS:

- low power consumption < 40 mW/cm^2
- intrinsic stiffness of the curved silicon wafer

→ **Air-based cooling**
→ **No FPC for data readout and powering**
→ **Minimal mechanical support**



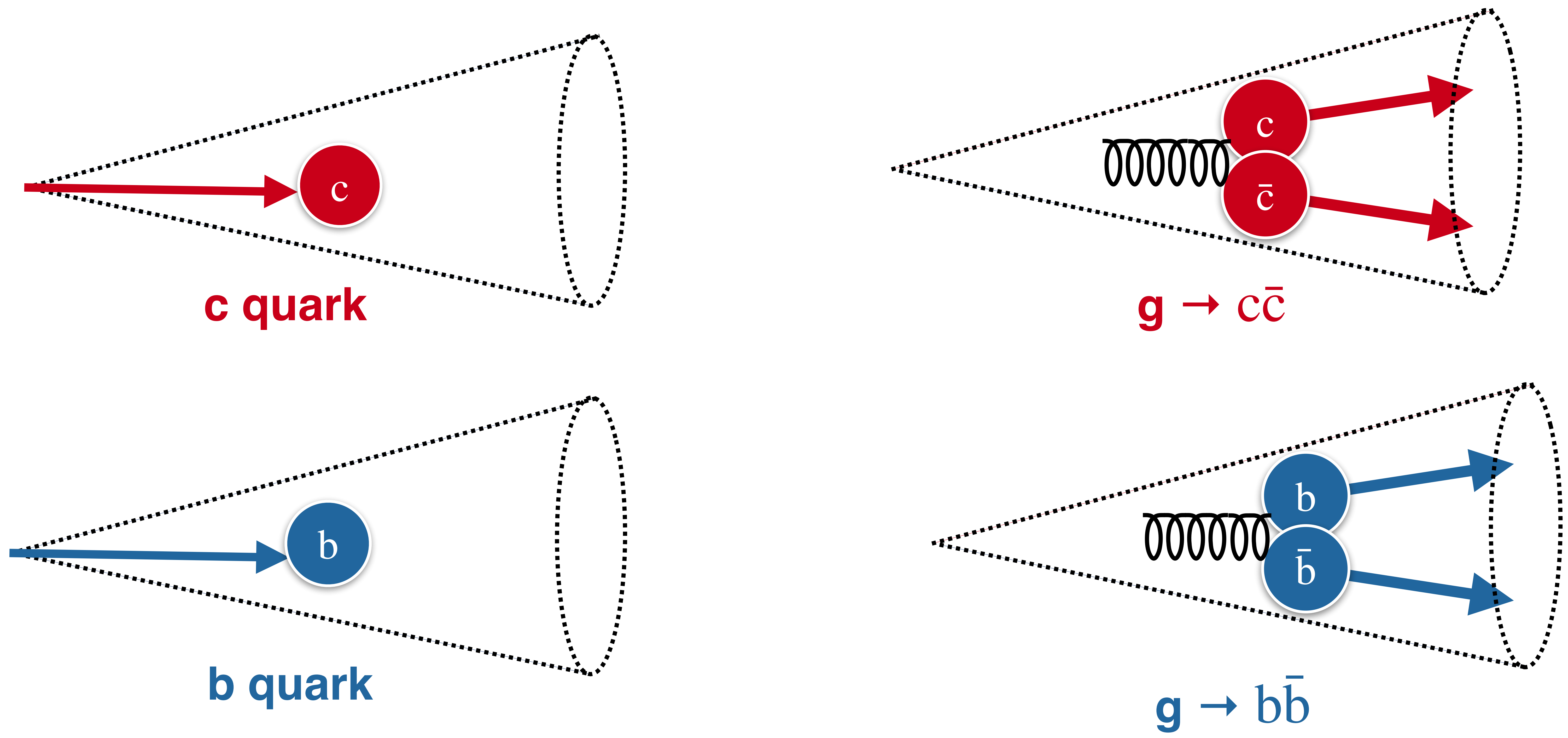
~ material budget is only due to active silicon

Deep Neural Network techniques for flavor tagging in HI

Multi-label classification algorithms for tagging of:

- c-quark, b-quark, g → $c\bar{c}$ and g → $b\bar{b}$

→ based on DNN and BDT techniques

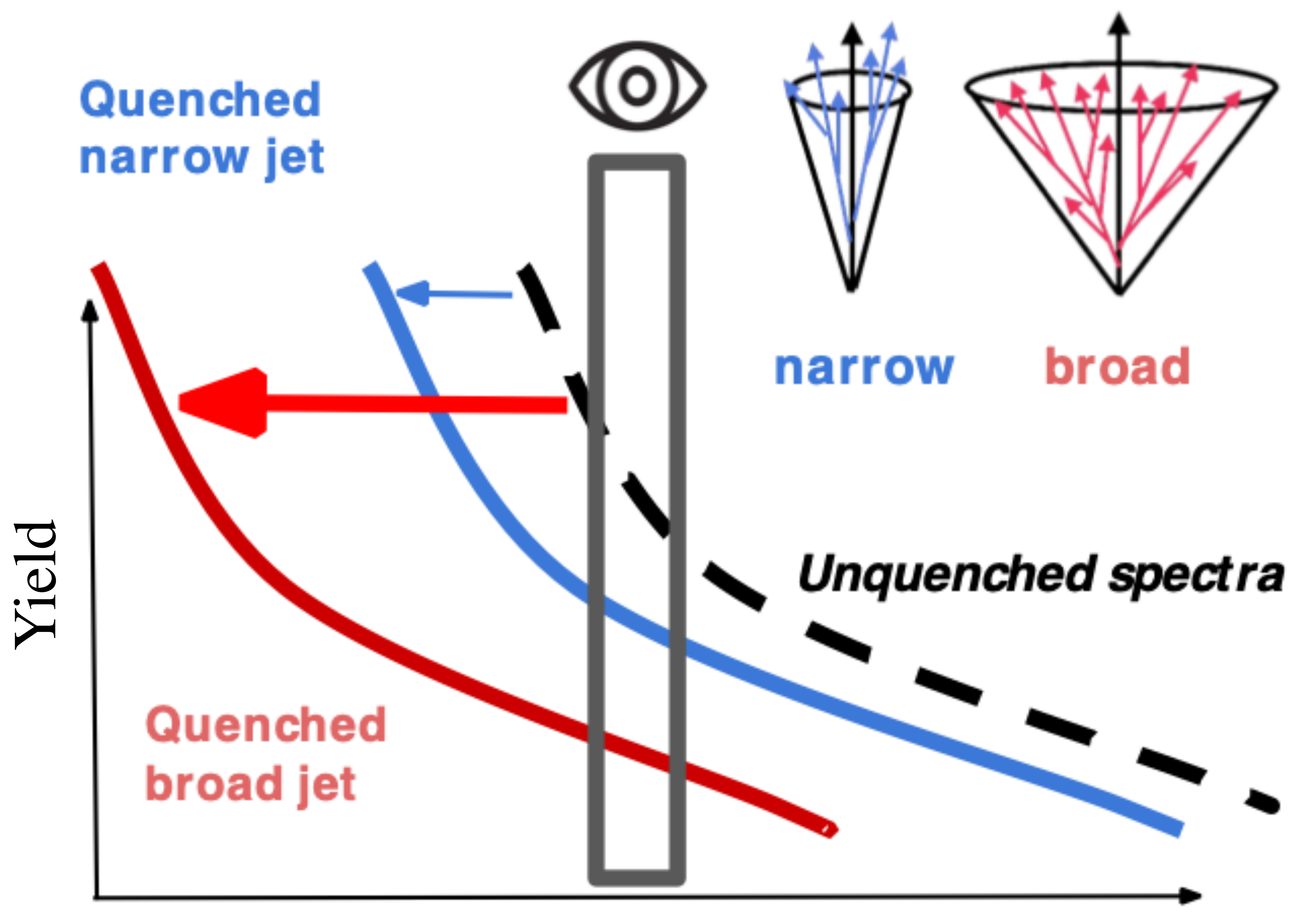


→ O(1000) signal increase w.r.t. $D^0\overline{D}^0$-tagging technique
→ new opportunities for c-jet correlation measurements in HI

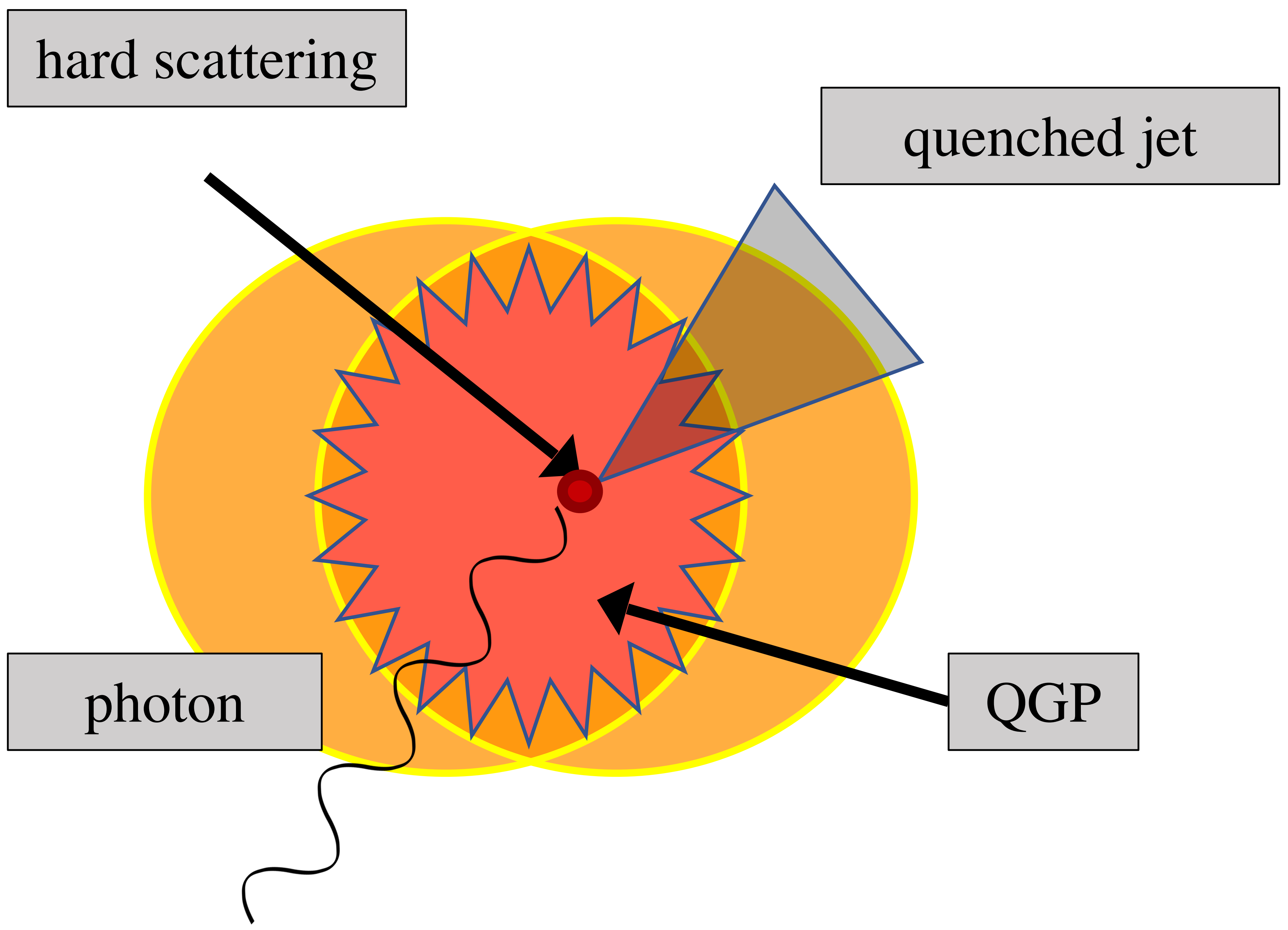
E. Bols *et al* 2020 JINST 15 P12012

Photon-tagged jet axis decorrelation

Jet quenching bias



HI Collision



- Broader jets are expected to be more quenched than narrower jets
- Potential effect in a measured jet p_T bin → higher population of narrow jets
- Photon does not interact strongly in QGP → tags initial parton p_T
- Less bias from photon selection, compare pp/PbPb with same p_T^{γ}, but sttill some remaining bias from minimum jet p_T requirement

Photon-tagged jet axis decorrelation

Studying the jet axis decorrelation, which is the angular difference between the WTA and E-Scheme jet axes

- WTA axis = direction of leading energy flow in jet
- E-Scheme axis = direction of average energy flow in jet

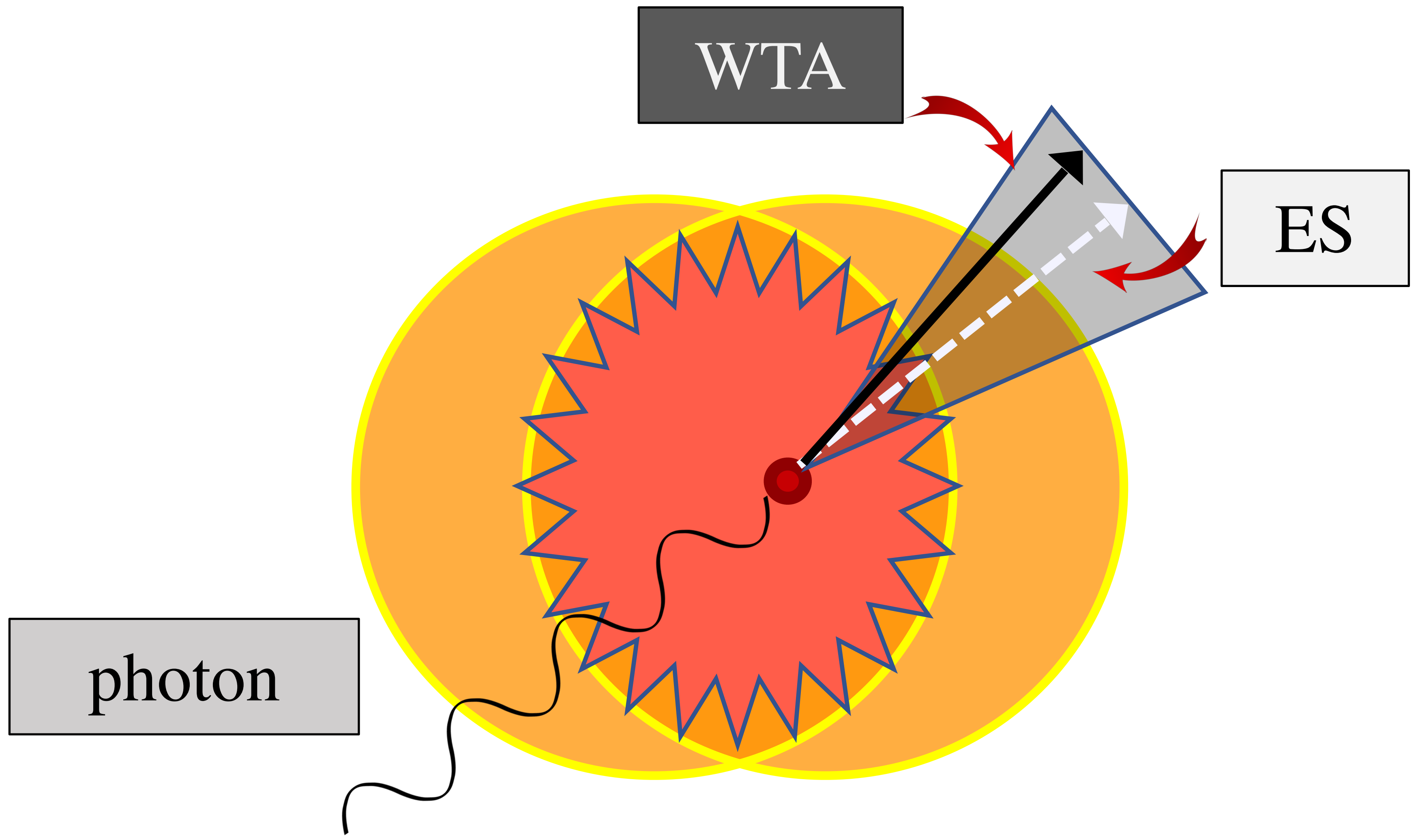
$$\delta j = \sqrt{\left(\eta^{E-Scheme} - \eta^{WTA}\right)^2 + \left(\phi^{E-Scheme} - \phi^{WTA}\right)^2}$$

Look at δj of jets in photon tagged -jet events with $60 < p_T^{\gamma} < 200$ GeV, $30 < p_T^{j} < 120$, and $\Delta\phi_{j\gamma} > 2\pi/3$

Observable is expected to be sensitive to mechanisms of energy loss in the quark gluon plasma

Hybrid model predicts sensitivity to 2 → 2 elastic scatterings with medium particles

HI Collision



Hybrid Model Prediction