The Search for Quark-Gluon Plasma at the Large Hadron Collider: What is Next?

Raghunath Sahoo
Indian Institute of Technology Indore, India
(Professor & Chairperson, ALICE-STAR-India Collaboration Board)

Scientific Council of JINR, Dubna, Russia

Raghunath.Sahoo@cern.ch, raghunath@iiti.ac.in

Experimental High-Energy Physics Group


ALICE@CERN, Switzerland


CBM@GSI, Germany


Kshitish K. Pradhan

Dr. Captain R. Singh

Dr. Suman Deb

Purnima Srivastava

Dr. Jayanta Dey

Aswathy Menon K. R.

Girija Sankar Pradhan

Bhagyarathi Sahoo

Dushmanta Sahu

Kamaljeet Singh

Prof. Raghunath Sahoo, FInstP
PI and Group Leader

Debadatta Behera

Neelkamal Mallick

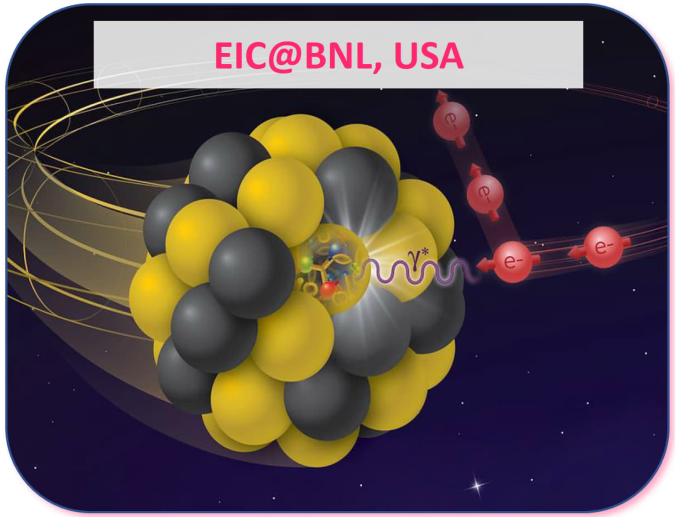
Ronald Scaria

Suraj Prasad

Kangkan Goswami

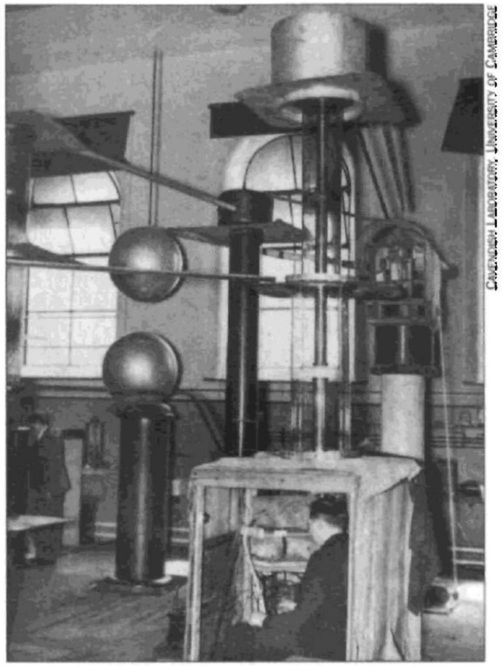
Contact: Prof. Raghunath Sahoo, FInstP
e-mail: raghunath@iiti.ac.in
Web: www.iiti.ac.in/~raghunath


GRAPES-3@Ooty, India


EIC@BNL, USA

Atom Smashing

Artificial disintegration of the atom ushered the machine age of nuclear physics: establishing the regime of "atom smashing": From Cambridge to CERN!



Cavendish Laboratory, University of Cambridge

(Cambridge: 1932)

Cockcroft-Walton's artificial nuclear disintegration by the particle accelerator.

$^{1}p + {}^{7}Li \rightarrow {}^{4}He\ (\alpha) + {}^{4}He\ (\alpha)$

(CERN LHC: 2008---)

From an accelerator of ~ 30 cm length……we now collide atoms using an accelerator of dimension ~27 km (slow transition from nuclear to partonic degrees of freedom)

A Journey from Electrons to Quarks

SLAC: Stanford Linear Accelerator Center (3.2 Kms)

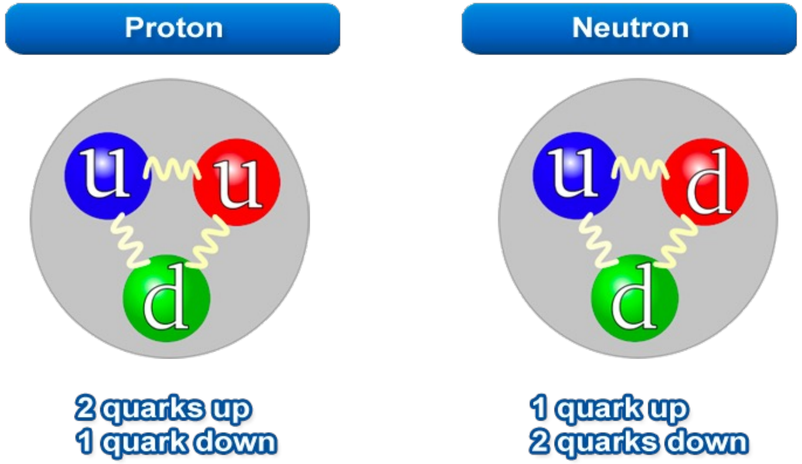
Electron-on-proton with E_e ~ 42 GeV

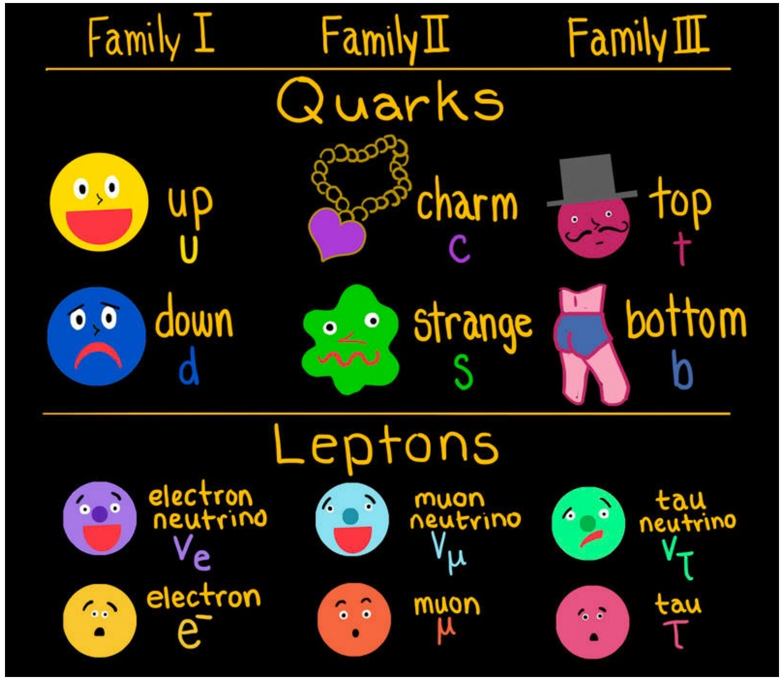
$$\lambda = h / p : \propto 1/E$$

This universal formula of de Broglie helps in deciding the energy of the probe.

Proton charge radius ~ 0.843 fermi.

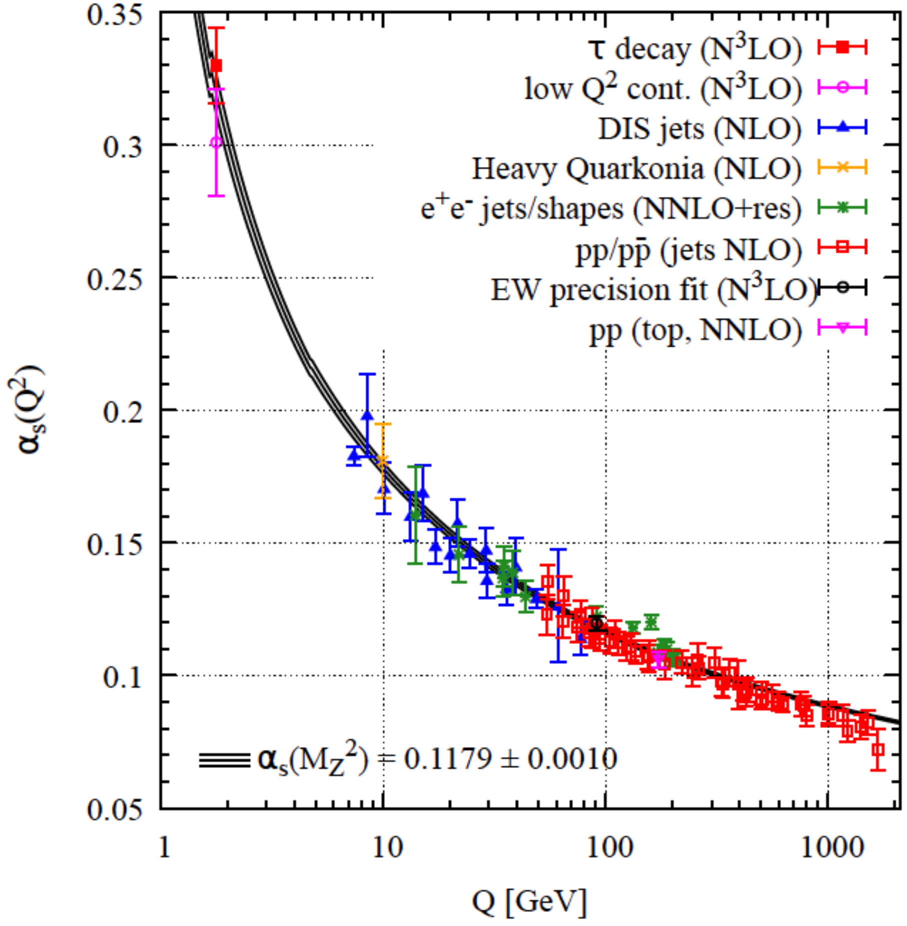
(1 fermi = 10^{-15} meter)





Can we find free quarks?

$$V_{QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$



To the leading order:

$$\alpha_s(Q^2) = \frac{4\pi}{(33-2n_f)ln(Q^2/\Lambda^2)}$$

n_f is the no. of quark flavors, with a mass less than Q/2,
Λ is the QCD scale parameter, obtained experimentally ~ 200 MeV

👉Coupling becomes weaker as the momentum transfer increases,

Or as we go smaller in the length-scale ➔ small distance, partons move freely (asymptotic freedom of QCD)

👉As the inter-quark distance increases, strong coupling grows faster making the quarks confined inside the cage of the hadrons → Quark confinement

Asymptotic freedom and infrared slavery is an inbuilt property of QCD (Strong interaction)→ No free quarks in nature!

Can we find free quarks?

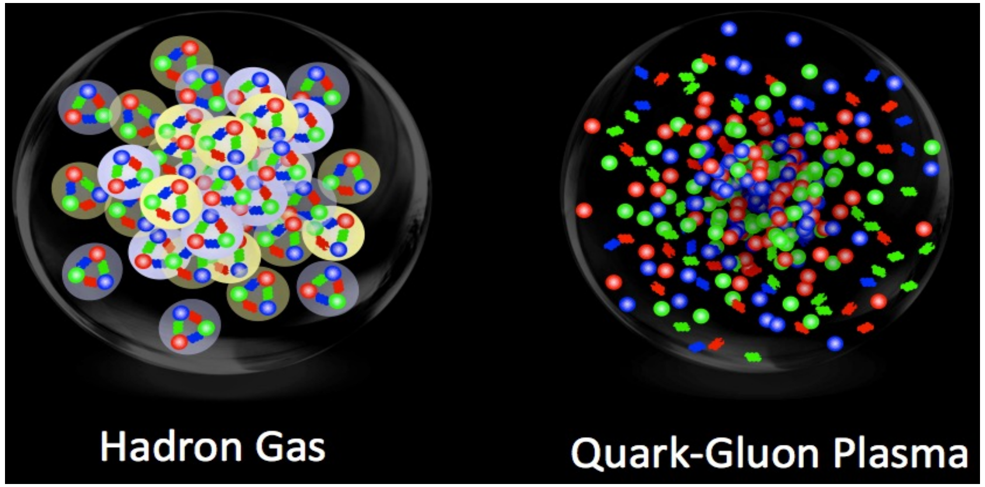
1973: Asymptotic freedom
D.J. Gross, F. Wilczek, H.D. Politzer

1975: Asymptotic QCD & deconfinement:
N. Cabibbo and G. Parisi;
J. Collins and M. Perry

2004: Nobel Prize

QCD predicts that normal nuclear matter undergoes a phase transition to quark-gluon plasma (QGP) under extreme temperatures and energy densities.

Quark Gluon Plasma

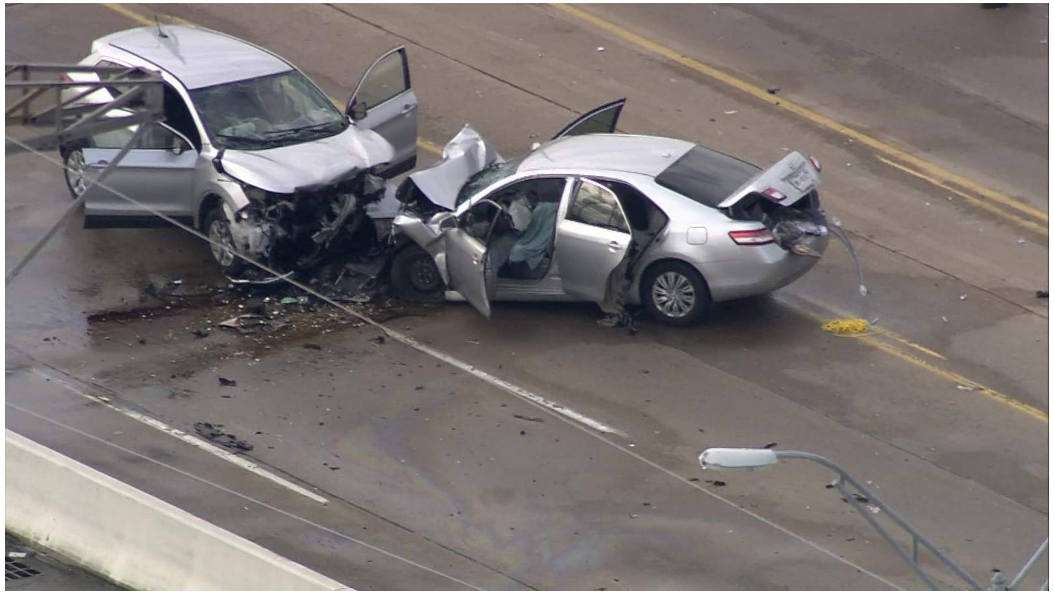


Quark Gluon Plasma (QGP): (locally) thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes.

A journey to the beginning of the universe…..

Why Collider Experiments?

The severity of damage is less.



The damage is much higher !

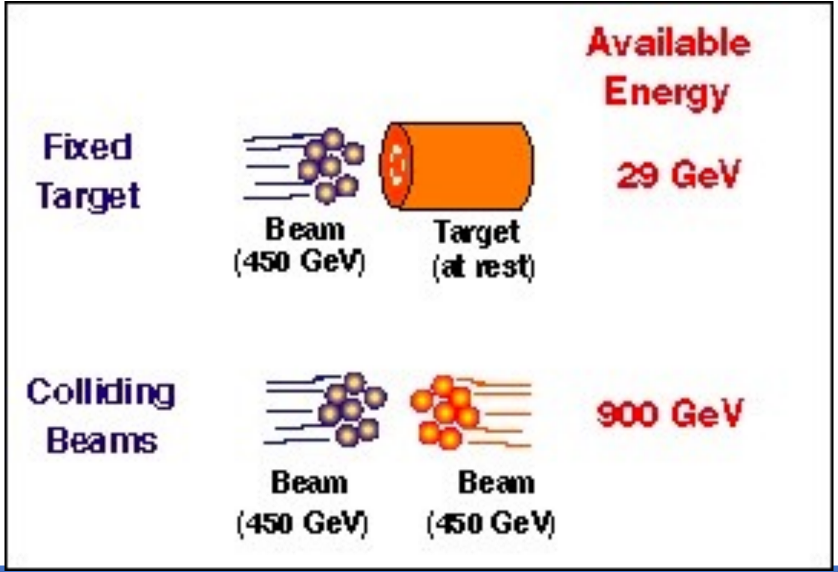
Energy available for particle production:

In laboratory frame (fixed target):

$E_{cm} = \sqrt{(2m_t E_{beam})}$

In CM frame (collider):

$E_{cm} = (2E_{beam})$



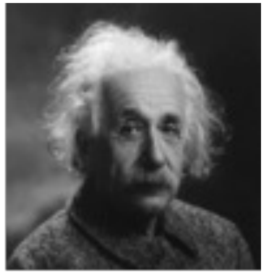
How much high is high-energy?

High energies allow us:

To look deeper into Nature (E α 1/size),
("powerful microscopes")

de Broglie

To discover new particles with
high(er) mass ($E = mc^2$)



Einstein

To study the early universe ($E = kT$)

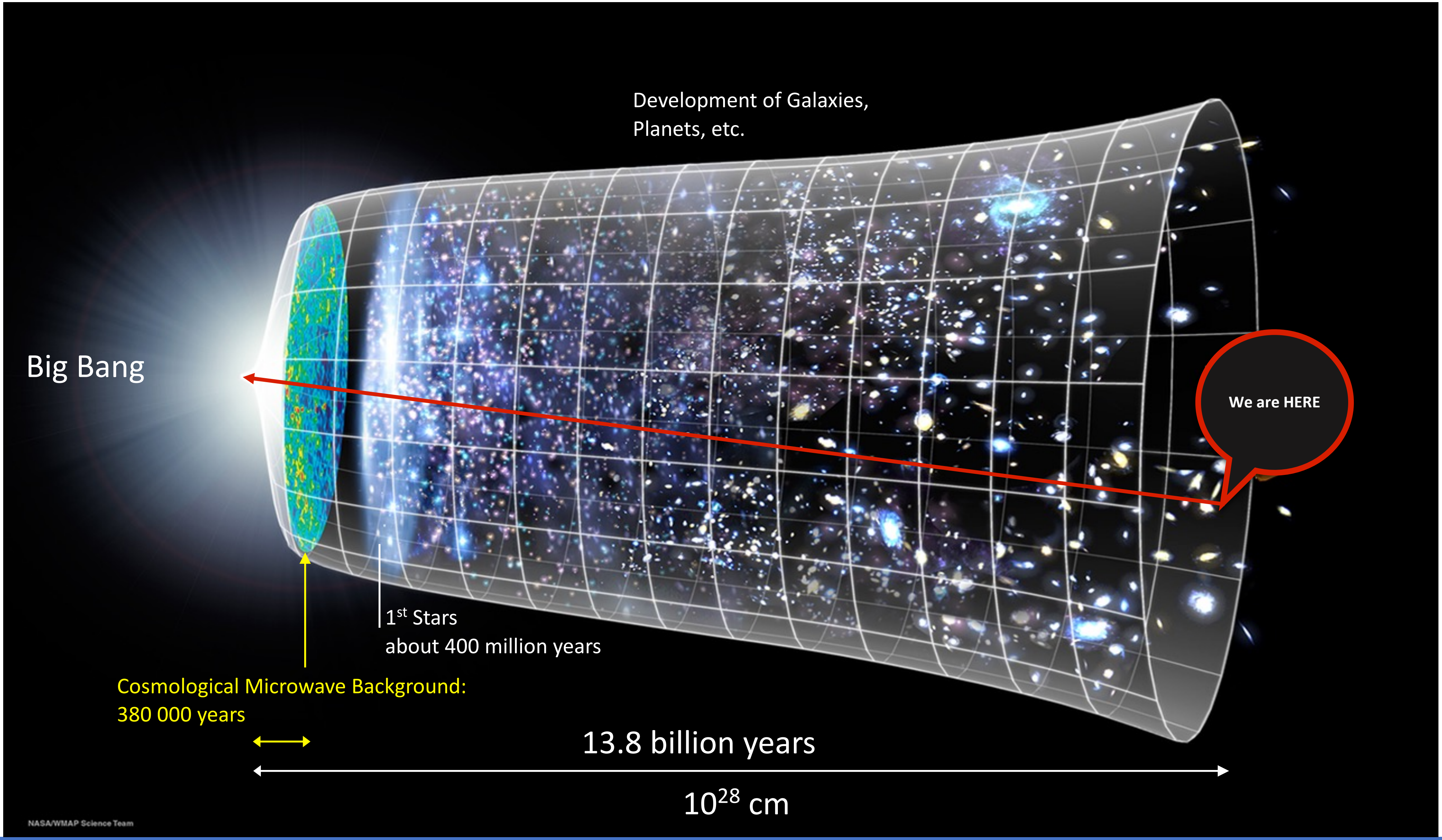
Boltzmann

Lesson: To probe the subatomic universe, we need very high energies, which could produce many particles in the final state with very high temperature system.

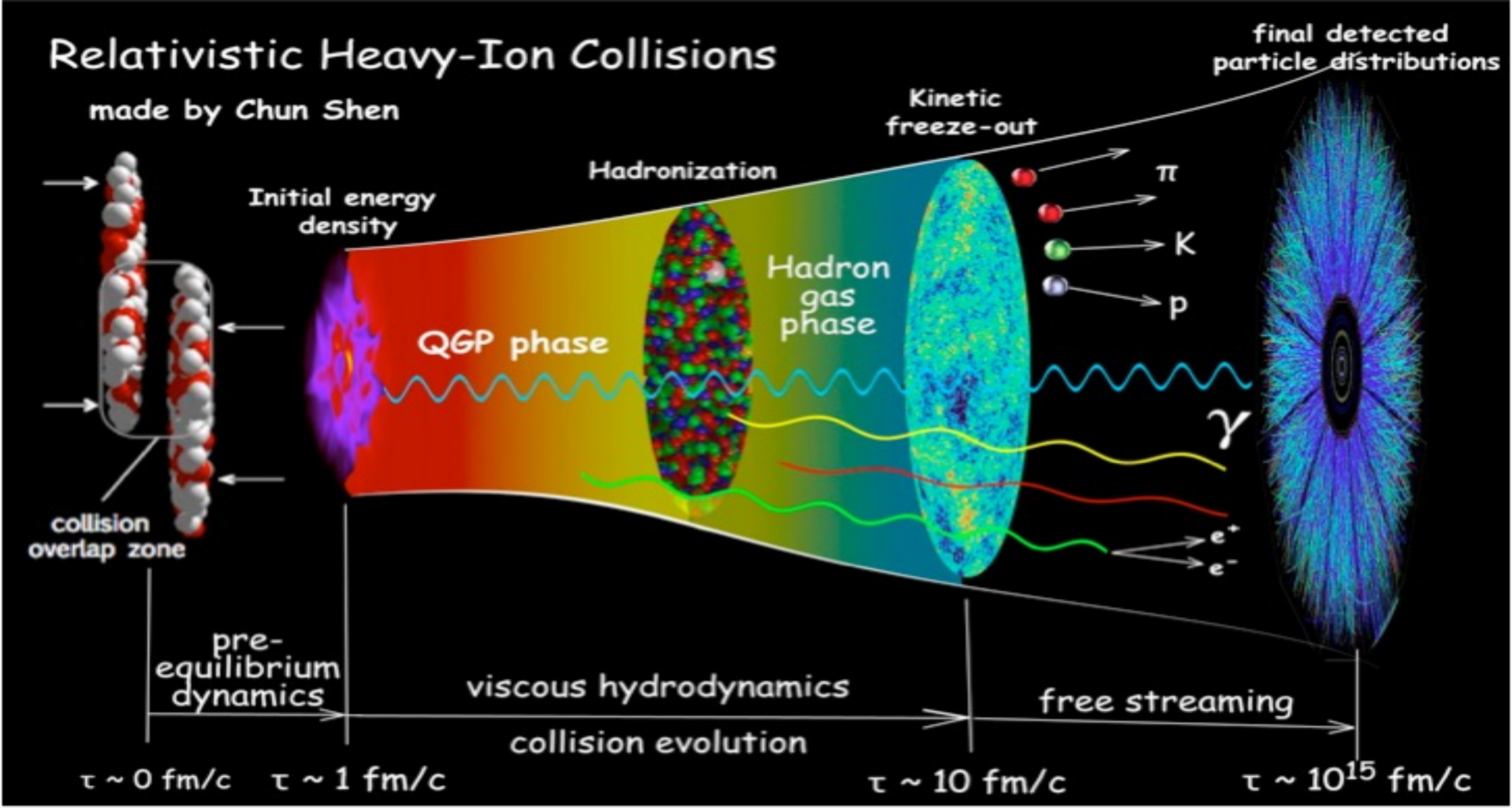
How do we do that?

Understand the first few moments of our universe

a couple of micro-seconds after the Big-Bang



NASA/WMAP Science Team


Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
QGP phase
Hadron gas phase
π
K
p
γ
e^+
e^-
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^{15} fm/c

Accelerator facilities for heavy-ions

USA

1984

Bevalac

Bevalac

Fixed Target
Au at 1GeV/A

USA

1991

AGS Layout

AGS

Fixed Target Au at 11.7 GeV/A
(Ec.m.=4.86GeV)

CERN

1993 -

SPS Layout

SPS

Fixed Target
Pb at 158GeV/A
(Ec.m.=17.3GeV)

1988:
WA98
NA49
CERES

USA

2001 -

RHIC

Collider
Au+Au @ 200GeV/A

2001:
STAR
PHENIX
PHOBOS
BRAHMS

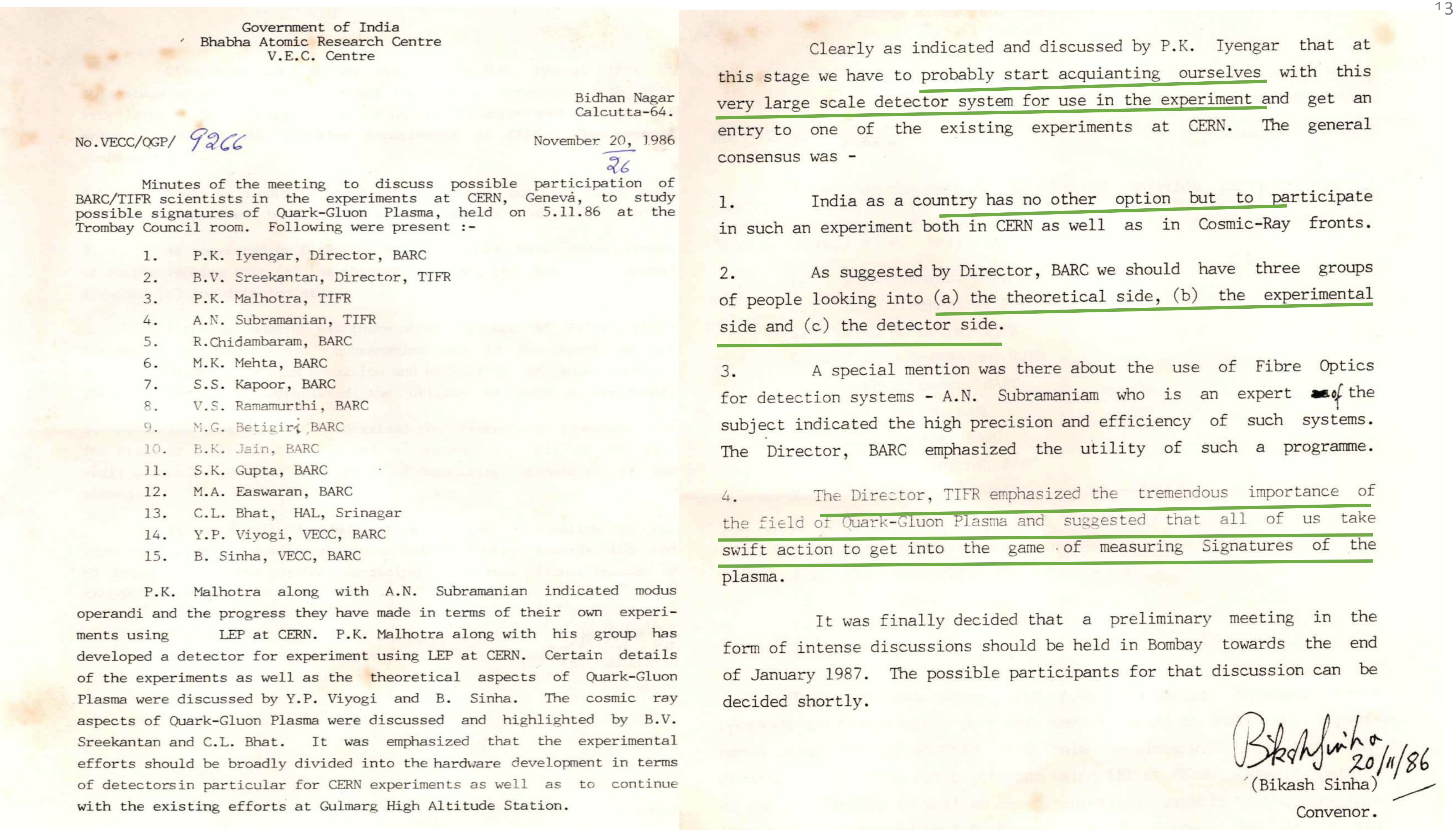
CERN

2009 -

LHC

Collider
Pb+Pb @5.5TeV/A

2009:
ALICE
CMS
ATLAS
LHCB



Government of India
Bhabha Atomic Research Centre
V.E.C. Centre

Bidhan Nagar
Calcutta-64.

No.VECC/QGP/ 9266

November 20, 1986
26

Minutes of the meeting to discuss possible participation of BARC/TIFR scientists in the experiments at CERN, Genevá, to study possible signatures of Quark-Gluon Plasma, held on 5.11.86 at the Trombay Council room. Following were present :-

1. P.K. Iyengar, Director, BARC
2. B.V. Sreekantan, Director, TIFR
3. P.K. Malhotra, TIFR
4. A.N. Subramanian, TIFR
5. R.Chidambaram, BARC
6. M.K. Mehta, BARC
7. S.S. Kapoor, BARC
8. V.S. Ramamurthi, BARC
9. M.G. Betigiri, BARC
10. B.K. Jain, BARC
11. S.K. Gupta, BARC
12. M.A. Easwaran, BARC
13. C.L. Bhat, HAL, Srinagar
14. Y.P. Viyogi, VECC, BARC
15. B. Sinha, VECC, BARC

P.K. Malhotra along with A.N. Subramanian indicated modus operandi and the progress they have made in terms of their own experiments using LEP at CERN. P.K. Malhotra along with his group has developed a detector for experiment using LEP at CERN. Certain details of the experiments as well as the theoretical aspects of Quark-Gluon Plasma were discussed by Y.P. Viyogi and B. Sinha. The cosmic ray aspects of Quark-Gluon Plasma were discussed and highlighted by B.V. Sreekantan and C.L. Bhat. It was emphasized that the experimental efforts should be broadly divided into the hardware development in terms of detectorsin particular for CERN experiments as well as to continue with the existing efforts at Gulmarg High Altitude Station.

Clearly as indicated and discussed by P.K. Iyengar that at this stage we have to probably start acquianting ourselves with this very large scale detector system for use in the experiment and get an entry to one of the existing experiments at CERN. The general consensus was -

1. India as a country has no other option but to participate in such an experiment both in CERN as well as in Cosmic-Ray fronts.

2. As suggested by Director, BARC we should have three groups of people looking into (a) the theoretical side, (b) the experimental side and (c) the detector side.

3. A special mention was there about the use of Fibre Optics for detection systems - A.N. Subramaniam who is an expert ~~as~~ of the subject indicated the high precision and efficiency of such systems. The Director, BARC emphasized the utility of such a programme.

4. The Director, TIFR emphasized the tremendous importance of the field of Quark-Gluon Plasma and suggested that all of us take swift action to get into the game of measuring Signatures of the plasma.

It was finally decided that a preliminary meeting in the form of intense discussions should be held in Bombay towards the end of January 1987. The possible participants for that discussion can be decided shortly.

Bikash Sinha 20/11/86
(Bikash Sinha)
Convenor.

India’s joining high energy nuclear physics experiments: starting off a new Era!

From tabletop nuclear experiments to the organized production of large-scale detectors!

A brief history of the QGP Experimental Program

Funded by DAE & DST

Growing Indian team with a global footprint!

SPS	**WA93 and WA98**	1988 – 1996	Completed
	(VECC, IOP, Chandigarh, Jaipur, Jammu)		
RHIC	**STAR**	2000 onwards	Data Taking
	(VECC, IOP, Chandigarh, Jammu, IISER-Berhampur, IIT-P…)		
	PHENIX	1995 onwards	Completed
	(BARC and BHU)		
LHC	**ALICE**	1995 onwards	Data Taking/Upgrade
	(VECC, SINP, IOP, AMU, Chandigarh, Jammu, IIT-B, Bose Inst., Guwahati Univ., IIT-Indore, NISER, DAV Coll., CU,)		
	CMS		Data Taking
	(BARC), IITM, NISER, IoP, IISER-Pune, PU,DU….		

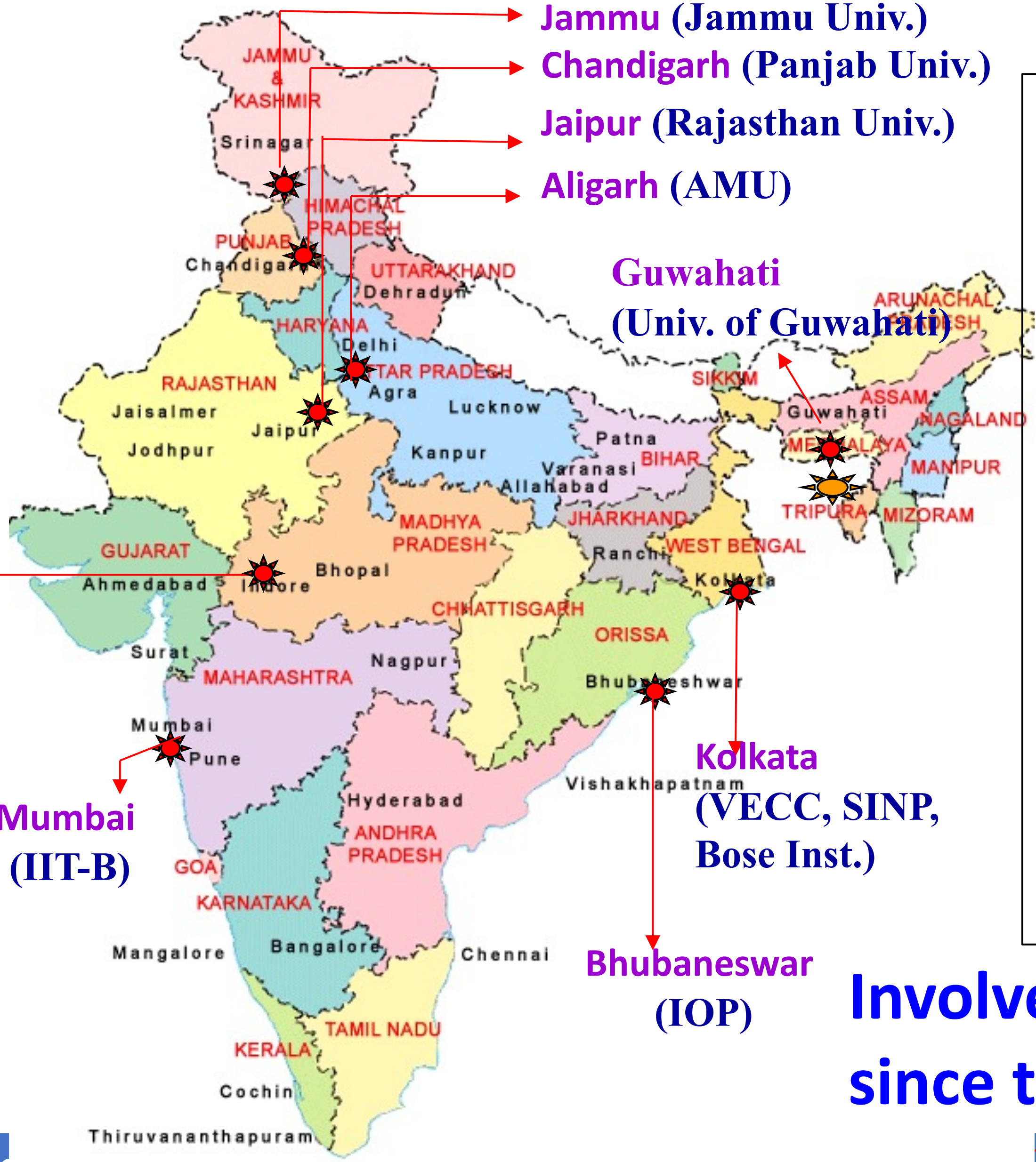
Contributions: Detector design and fabrication, electronics, ASIC development, mechanics, control, online/offline software, physics

No. of Ph.D. produced in experimental QGP program in the country: 147

Continuing: 55

Indian members in ALICE

70 Members, expanding….



Jammu (Jammu Univ.)

Chandigarh (Panjab Univ.)

Jaipur (Rajasthan Univ.)

Aligarh (AMU)

Guwahati (Univ. of Guwahati)

Indore (IITI)

Mumbai (IIT-B)

Kolkata (VECC, SINP, Bose Inst.)

Bhubaneswar (IOP)

- Aligarh: Aligarh Muslim University
- Bhubaneswar: Institute of Physics
- Bhubaneswar: NISER
- Chandigarh: Panjab University
- Guwahati: University of Guwahati
- Indore: IIT
- Jaipur: Rajasthan University
- Jammu: University of Jammu
- Kolkata: SINP
- Kolkata: VECC
- Kolkata: Bose Institute
- Mumbai: Indian Institute of Technology, Bombay

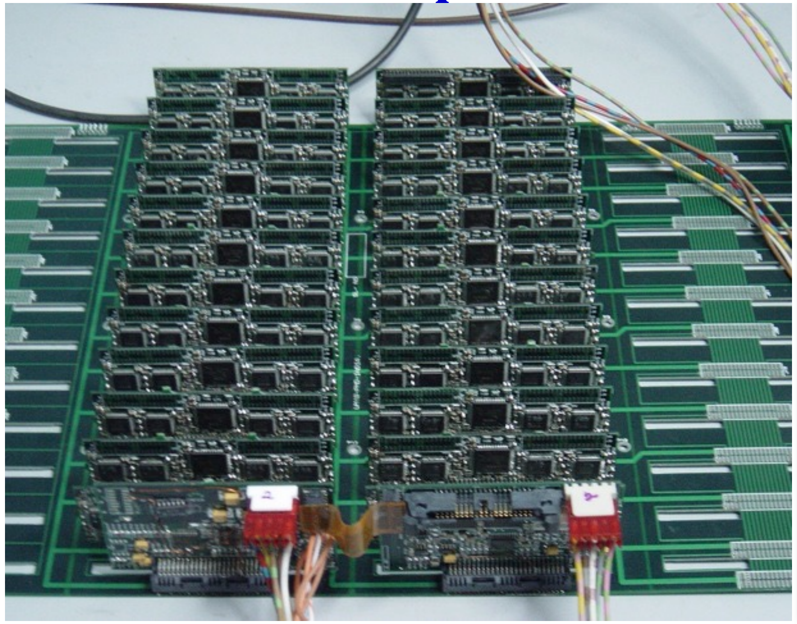
Involvement of Indian Scientists since the beginning of ALICE

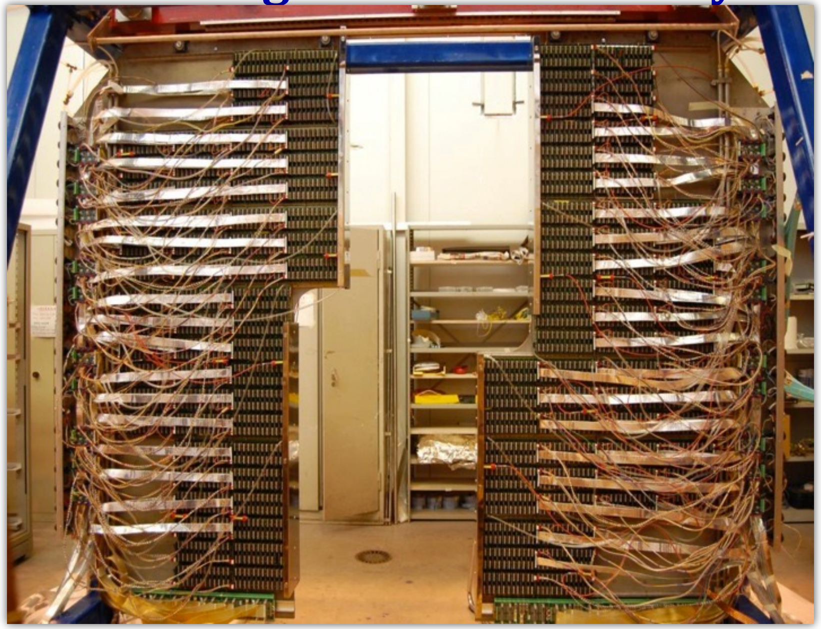
PMD: Photon Multiplicity Detector

100 % Indian effort: from conception to commissioning

(Design, Fabrication, Installation, Detector Control and Data Acquisition)

Goal: Measurement of photon multiplicity and spatial distribution of photons in the forward region on an event-by-event basis

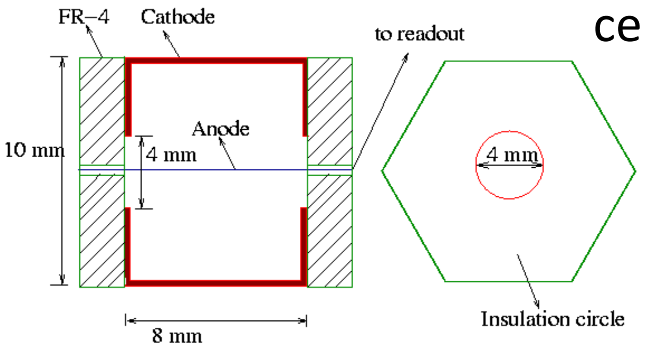




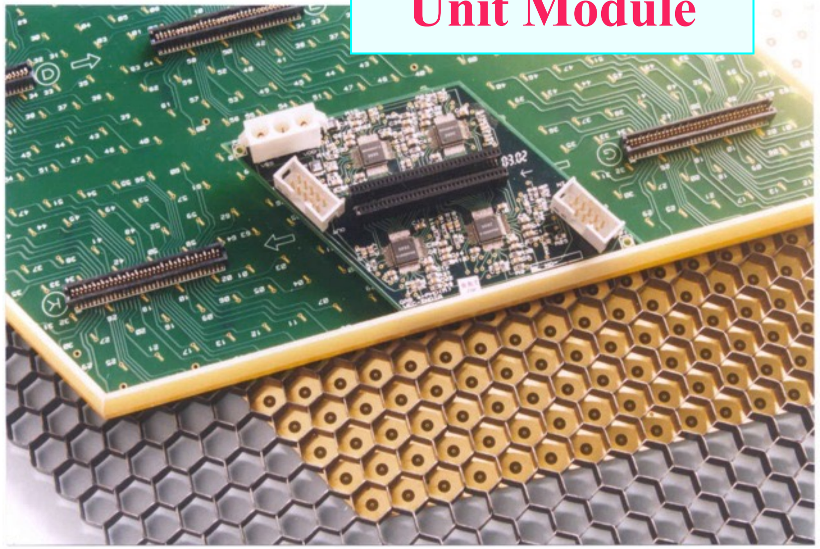
PMD Module Fabrication for STAR

Indian Effort

85,000 Honeycomb cell gas detectors



Extended cathode honeycomb cell



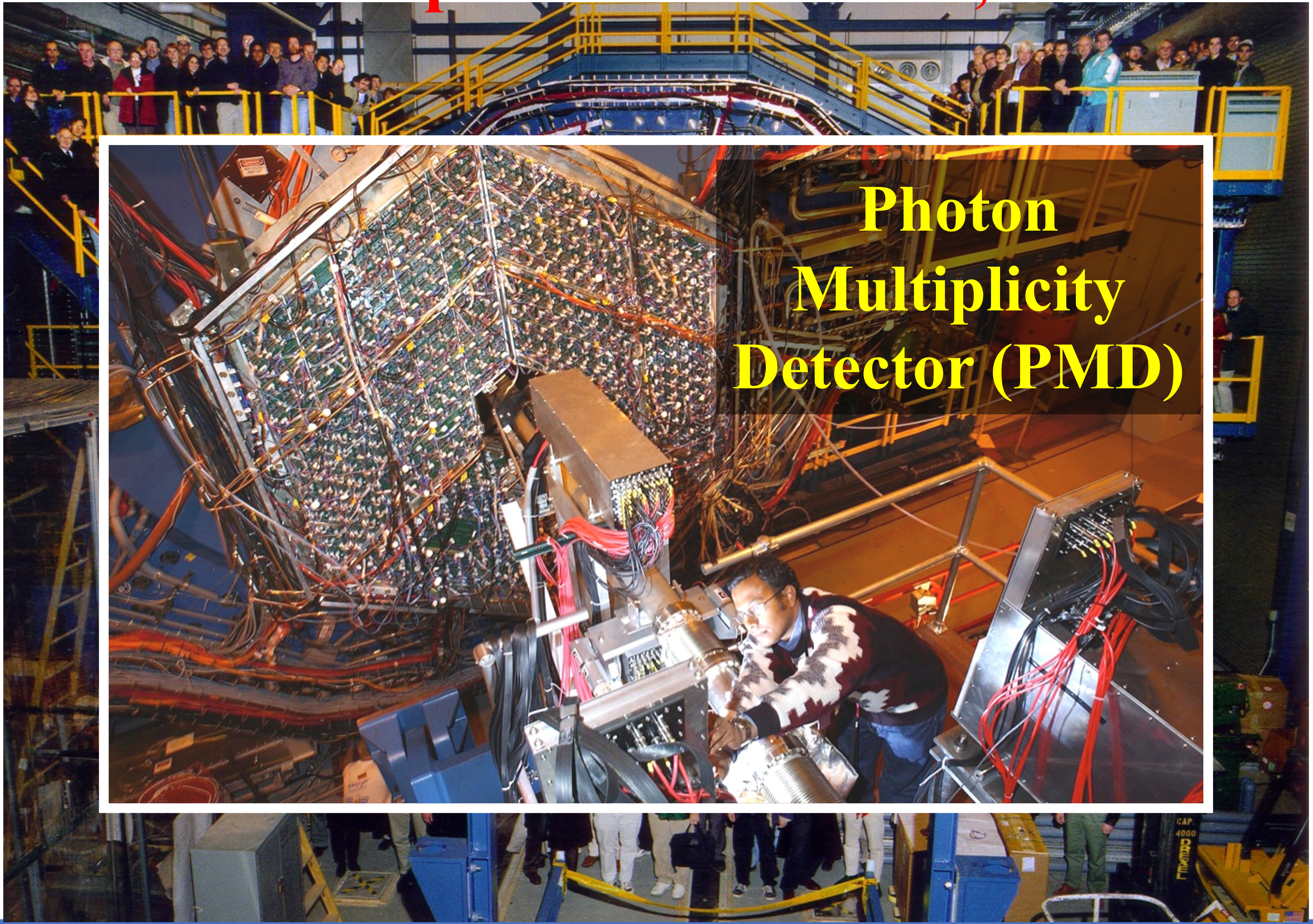
Unit Module

My involvement in ALICE/STAR: 2001

Unit module
fabrication@ IOP, Bhubaneswar

Preproduction prototype test
@ CERN PS (T10 beamline): 2003

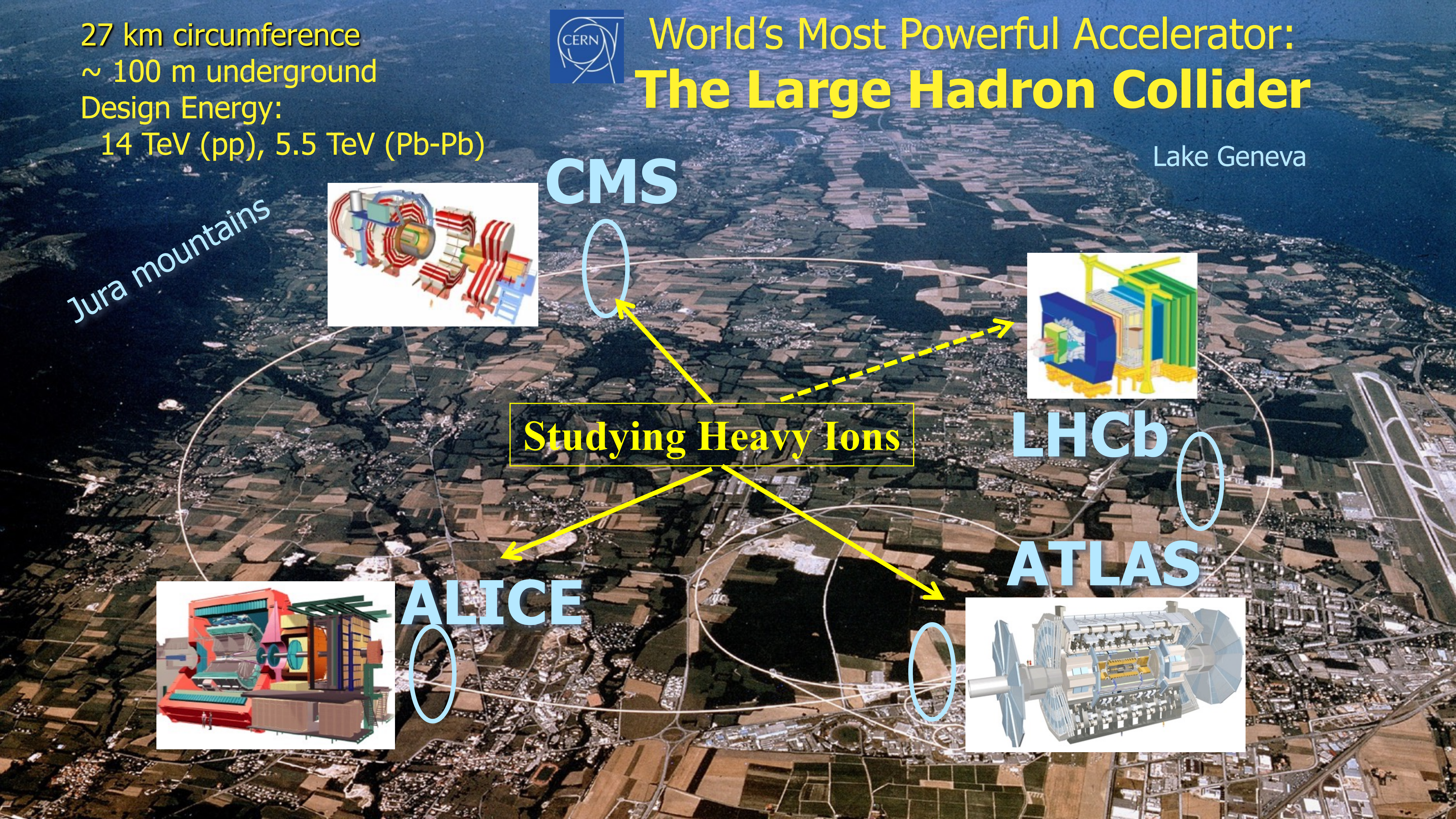
STAR experiment at RHIC, BNL



Photon Multiplicity Detector (PMD)

World's Most Powerful Accelerator:
The Large Hadron Collider

27 km circumference
~ 100 m underground
Design Energy:
14 TeV (pp), 5.5 TeV (Pb-Pb)



Jura mountains

Lake Geneva

CMS

LHCb

ALICE

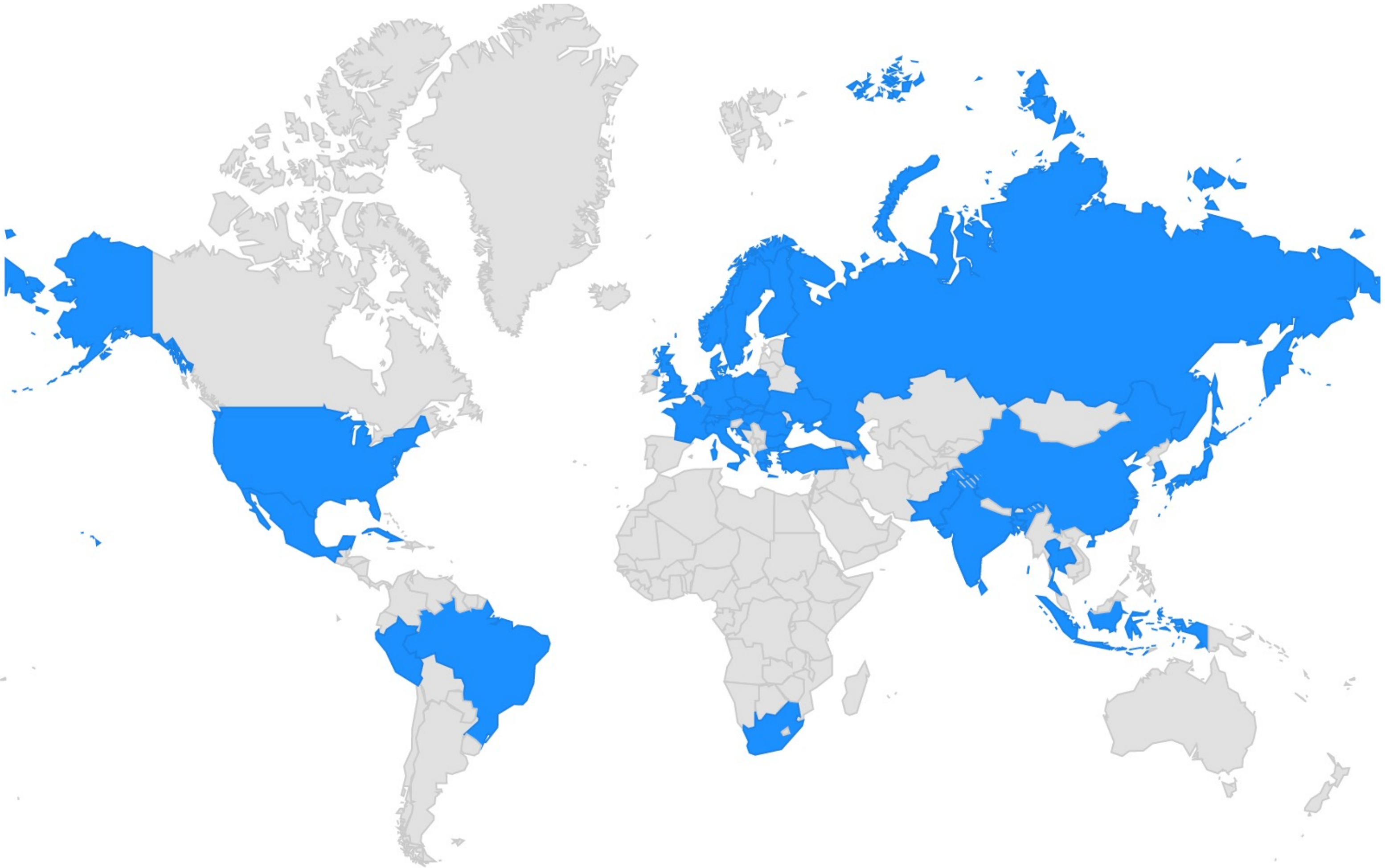
ATLAS

Studying Heavy Ions

ALICE Collaboration

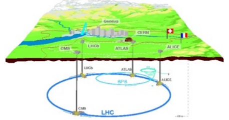
alice.cern

40 countries, 171 institutes, 1996 members



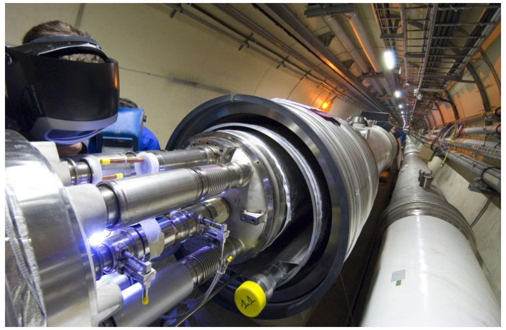
The Large Hadron Collider (LHC)

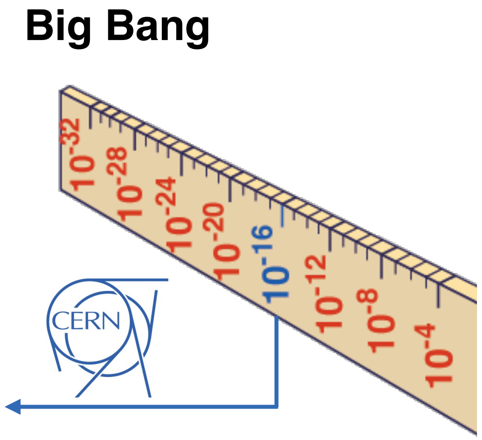
- The LHC is currently the largest and most powerful proton and ion collider.



~100 m underground & 27 km circ.

System	Year	Centre of mass energy (TeV)	Integrated luminosity
Pb-Pb	2010, 2011 2015, 2018 2022, 2023	2.76 5.02 5.36	75 mb^{-1} 800 mb^{-1} 29 pb^{-1}
Xe-Xe	2017	5.44	0.3 mb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	15 nb^{-1} 3 nb^{-1} , 25 nb^{-1}
p-p	2009-2013 2015, 2017 2015-2018 2022-2023	0.9, 2.76, 7, 8 5.02 13 13.6	200 mb^{-1}, 100 nb^{-1}, 1.5 pb^{-1}, 2.5 pb^{-1} 1.3 pb^{-1} 136 pb^{-1} 30 pb^{-1}





ALICE - The detectors (Run 1, Run 2)

Acronyms:
- ITS - Inner Tracking System
- TPC - Time Projection Chamber
- TOF - Time Of Flight
- TRD- Transition Radiation Detector

- Designed to reconstruct and identify charged particles in a central rapidity window → central barrel down to low transverse momentum (p_T~100 MeV/c for pions)
- Central barrel ($|\eta|<1$):

tracking (ITS, TPC), PID (TOF,TRD), calorimeters.

- Muon spectrometer:

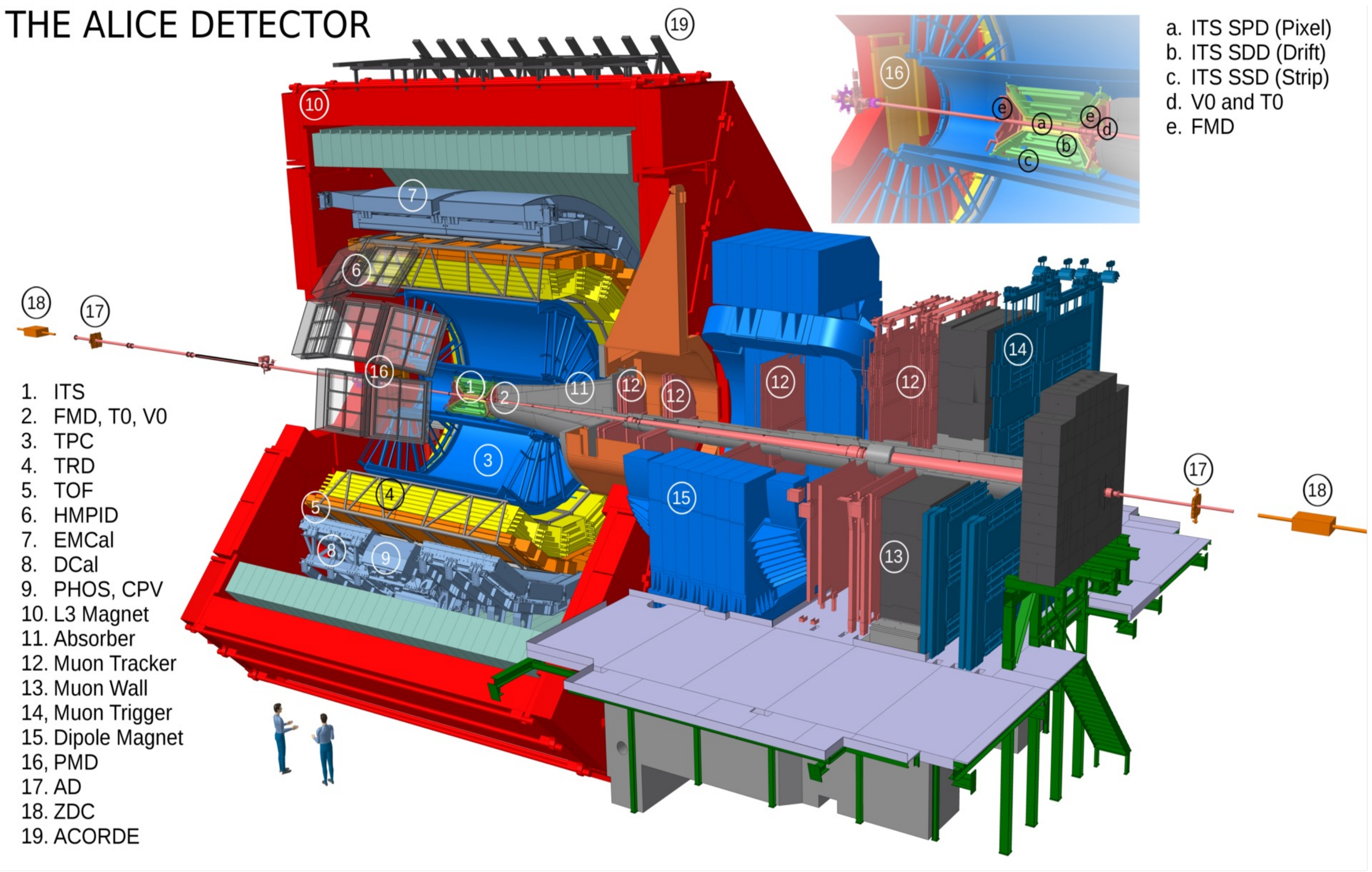
$-4<\eta<-2.5$

- Forward detectors:

triggering, centrality, timing.

- Event recording bandwidth: 1.25 GB/s for Pb-Pb events
- Overall data (MC, raw and reconstructed) on permanent storage:

➡️ **Tier-0-1-2 tape/disk: ~45/55 PB**

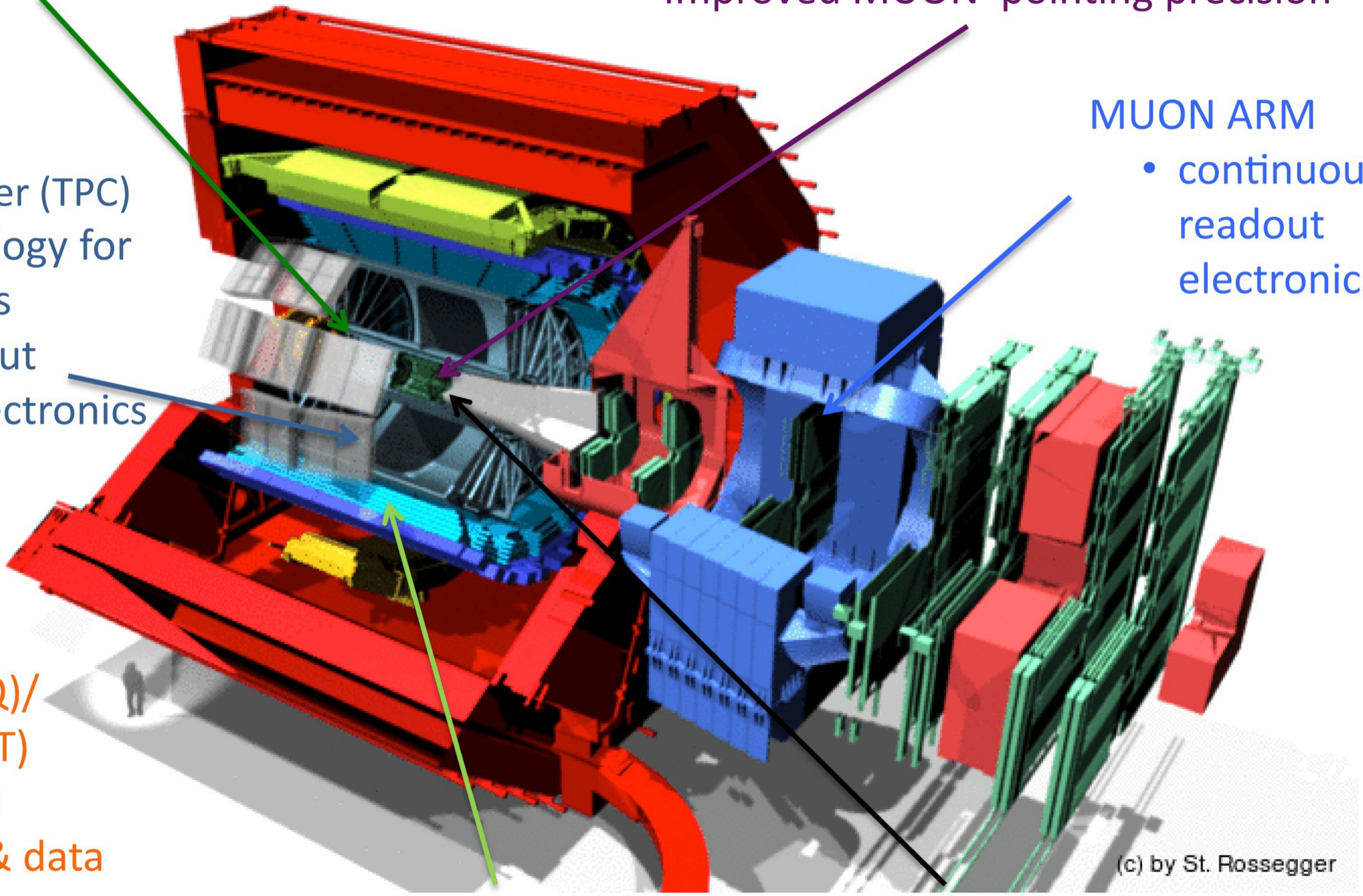


THE ALICE DETECTOR

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

ALICE - The detectors (Run 3)



New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics

New Central Trigger Processor

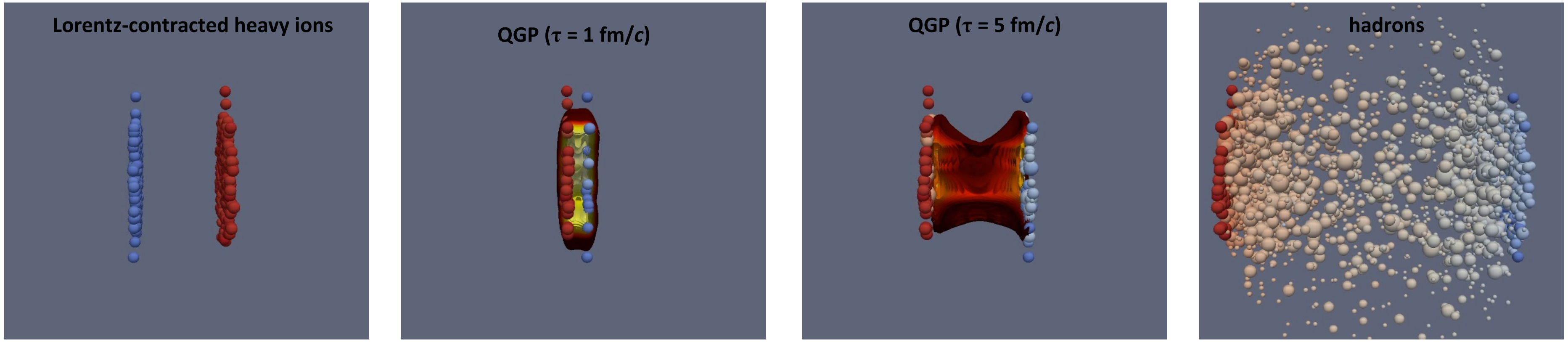
Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD, ZDC
- Faster readout

New Trigger Detectors (FIT)

Obtaining a mini-big-bang: the quark-gluon plasma (QGP)

- accelerate and collide heavy nuclei → multiple (almost) simultaneous collisions
- extreme energy densities and huge temperature → Mini-Big-Bang in the laboratory



Simulation: MADAI.us

QGP → thermalised system of deconfined quarks and gluons
(the energy density is so high that it is not compatible with hadrons such as protons or neutrons)

expected temperature: ~ 2 000 billion degrees

10^5 times the temperature at the core of the Sun

similar conditions are thought to have existed about 10 μs after the Big Bang

quarks are no more confined inside protons, neutrons, etc…

Exploring the phase diagram of matter at the LHC

- Study nuclear matter under extreme conditions of temperature and energy density

- Conditions at LHC energies:

  close to the ones of the Early Universe

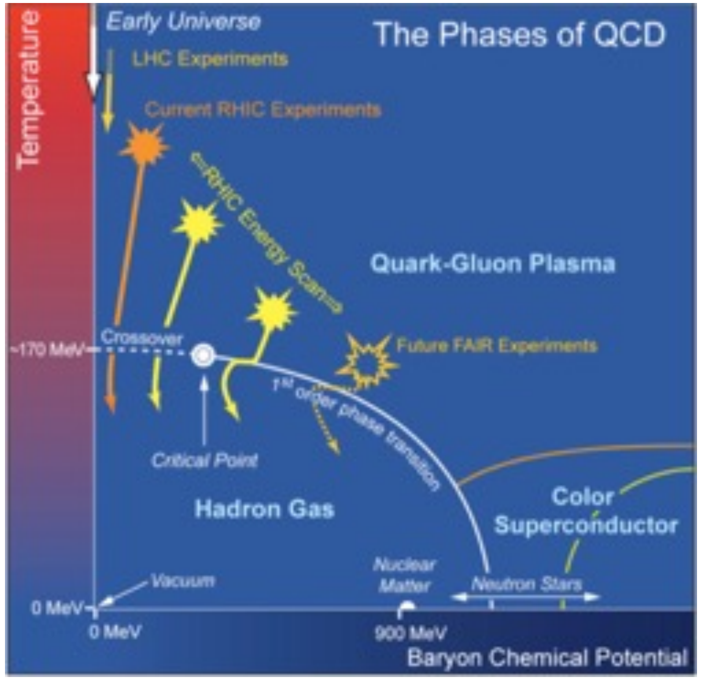
  high temperature: O(10^{12} K) .

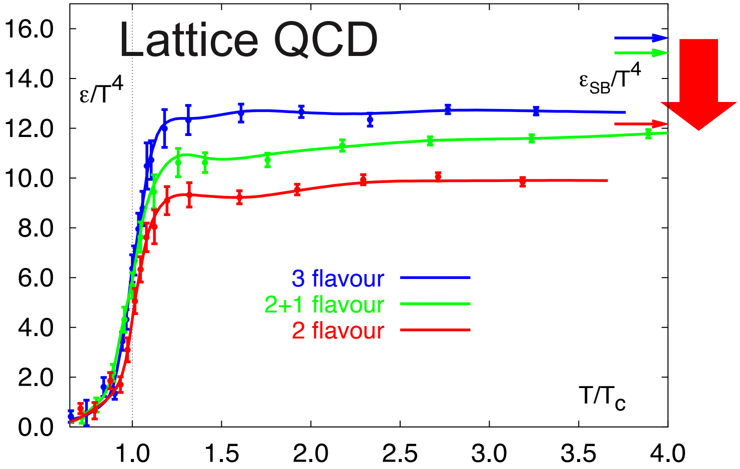
  vanishing baryon chemical potential: equal number of baryons and anti-baryons

- Phase transition predicted by Lattice QCD calculations (state of the art):

  $T_C \approx 155$ MeV and $\varepsilon_C \approx 0.5\text{-}1.0$ GeV/fm^3

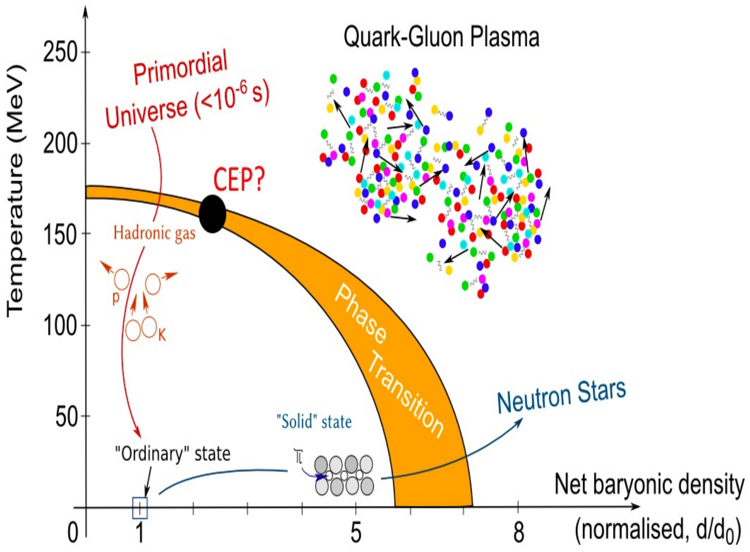
- Study the properties of a state where quarks and gluons are deconfined (QGP).



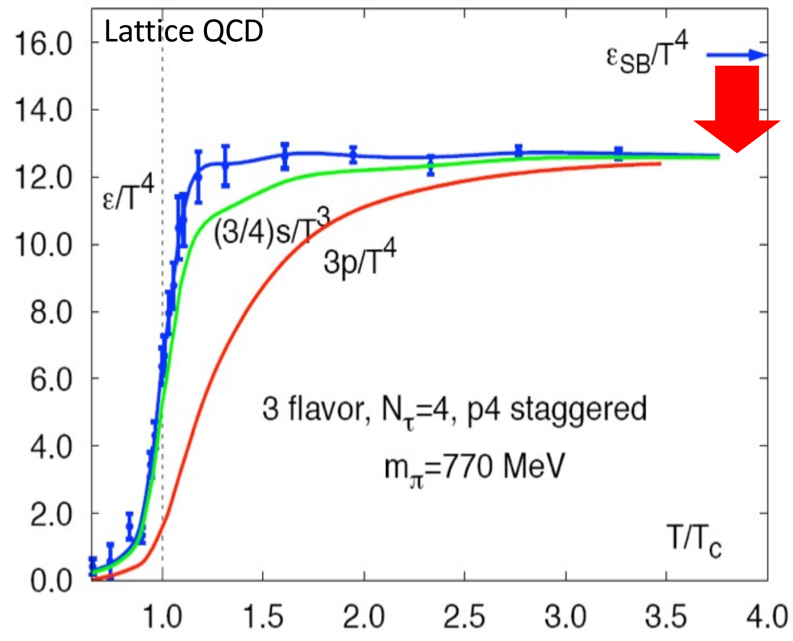


F. Karsch, Nucl. Phys. A 698, 199 (2002).

The QCD Phase Diagram and QGP



T_c ~ 170 ±15 MeV
ε_c ~ 0.7-1.2 GeV/fm^3
ε_0 ~ 0.16 GeV/fm^3



Energy density $$\varepsilon = g\frac{\pi^2}{30}T^4$$

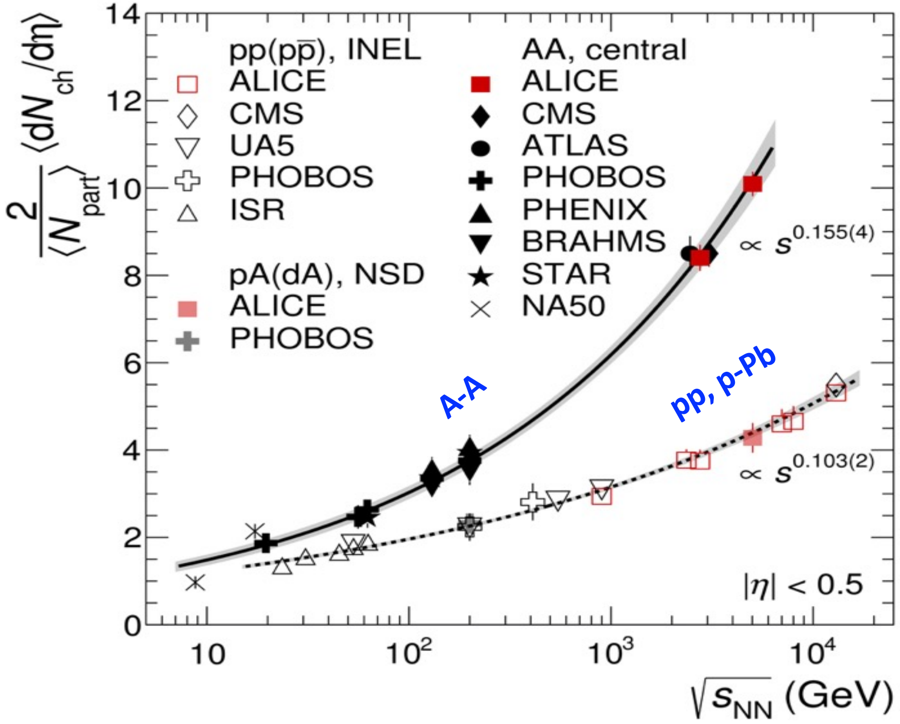
Degrees of Freedom of QGP

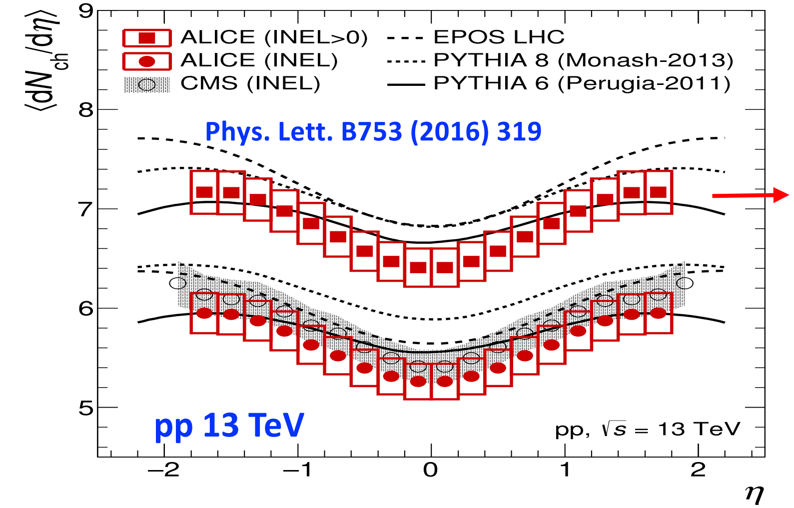
$$g_q = (\text{spin}) \times (\text{particle/antiparticle}) \times (\text{color}) \times (\text{flavor})$$
$$= 2 \times 2 \times 3 \times 6 = 72$$
$$g_g = (\text{spin}) \times (\text{flavor}) = 2 \times 8 = 16$$
$$\boxed{g_{\text{QGP}} = [g_g + \frac{7}{8}g_q] = [16 + \frac{7}{8} \times 72] = 79}$$

D.o.F. increases x 10

Reaches 80% of the non-interacting gas limit

Particle density



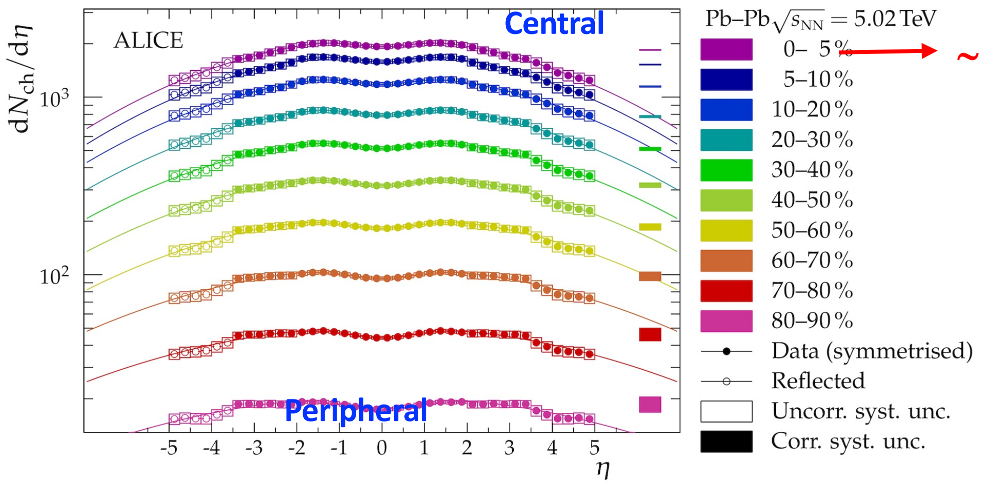


Phys. Lett. B753 (2016) 319

pp 13 TeV

~7

ALI-PUB-102498



Central

Peripheral

~2000

ALI-PUB-115086

Beam energy dependence:

- Pb-Pb curve rises faster ($s^{0.15}$) and stronger than in pp ($s^{0.11}$).

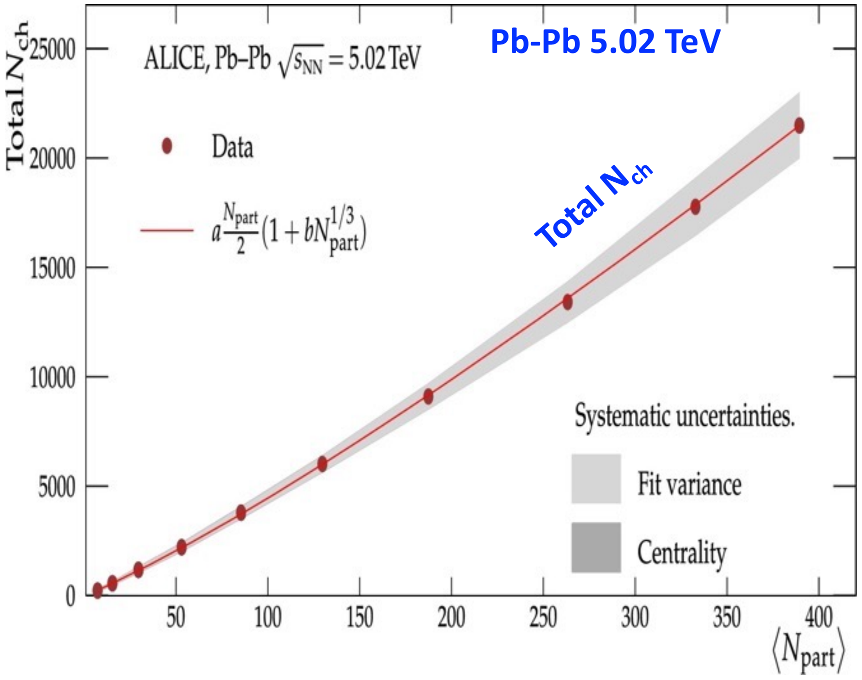
The mechanism of multiparticle production in hadronic and heavy-ion collisions are different even at the same available collision energy.

Phys.Lett. B 772 (2017) 567577
Phys. Rev. Lett. 116 (2016) 222302

Total number of charged particles:

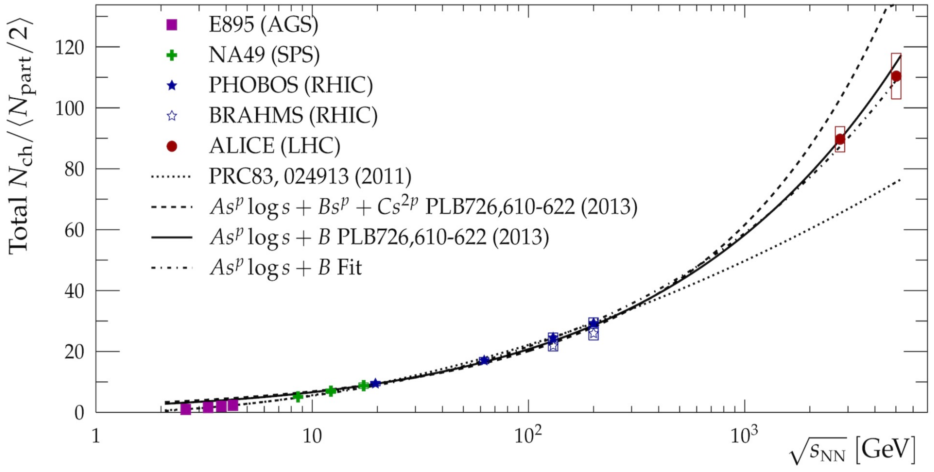
- most central (0–5%) collisions: 21400 ± 1300
- most peripheral (80–90%) collisions: 230 ± 38

Total Particle Multiplicity



Pb-Pb 5.02 TeV

Total N_{ch}



ALI-PUB-115101

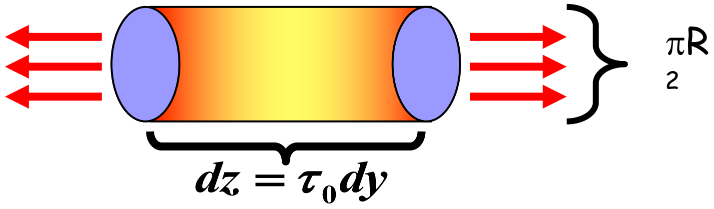
LARGE NUMBER OF PRODUCED PARTICLES ....

Paves a way to apply statistical mechanics and derive various thermodynamic properties of the system from first principle.

Phys.Lett. B 772 (2017) 567577
Phys. Rev. Lett. 116 (2016) 222302

Estimated energy density

J. D. Bjorken, Phys. Rev. D 27, 140 (1983).



$$\varepsilon_{Bj}(\tau) = \frac{1}{\pi R^2 \tau}\frac{dE_T}{dy}$$

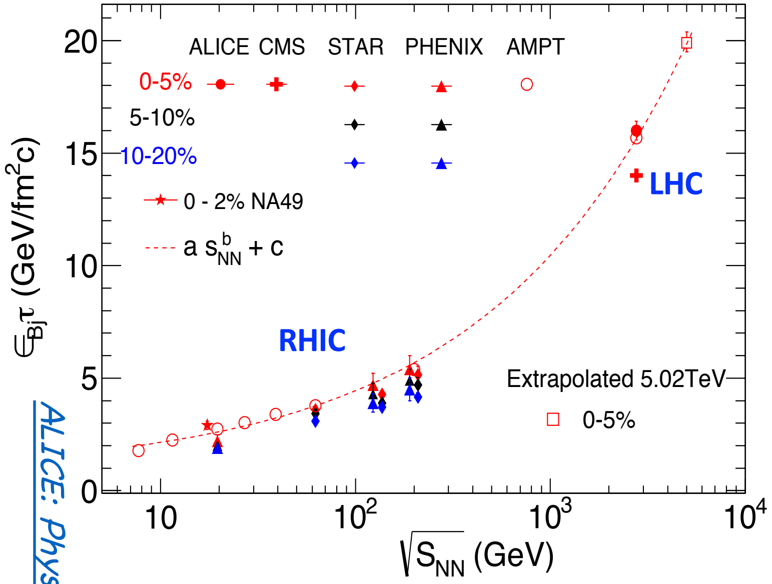
$$\approx \frac{1}{\pi R^2 \tau} < m_T > \frac{3}{2}\frac{dN_{ch}}{d\eta}$$

τ : proper time
y : rapidity
η : pseudo-rapdity
E_T: transverse energy
N_{ch} : Number of charged particles
m_T : transverse mass
R: effective transverse radius

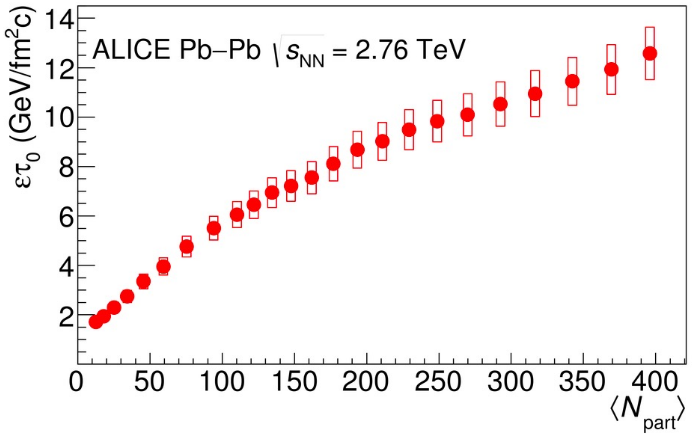
$\boxed{\varepsilon.\tau \sim 16\ \text{GeV/fm}^2\text{c}}$

Energy Density at LHC: More than what had been predicted for the formation of QGP.

Collision energy dependence of energy density



ALICE: Phys. Rev. C 94 (2016) 034903

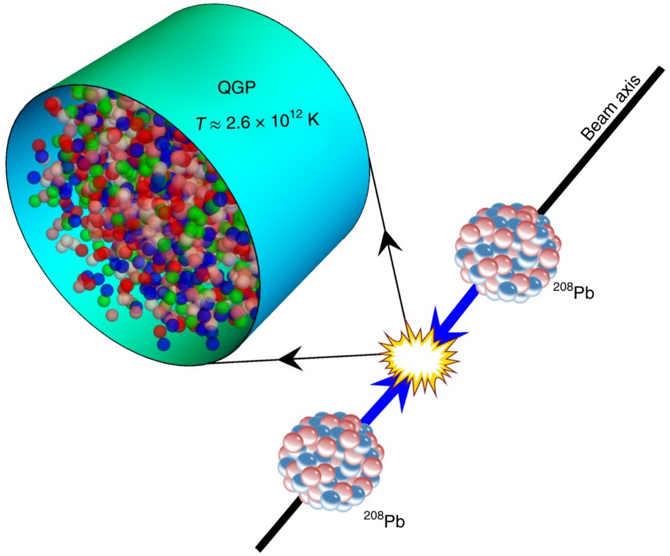


S. Basu et al. PRC 93 (2016) 064902
R. Sahoo et al. Adv. in High Energy Physics, Vol. 2015

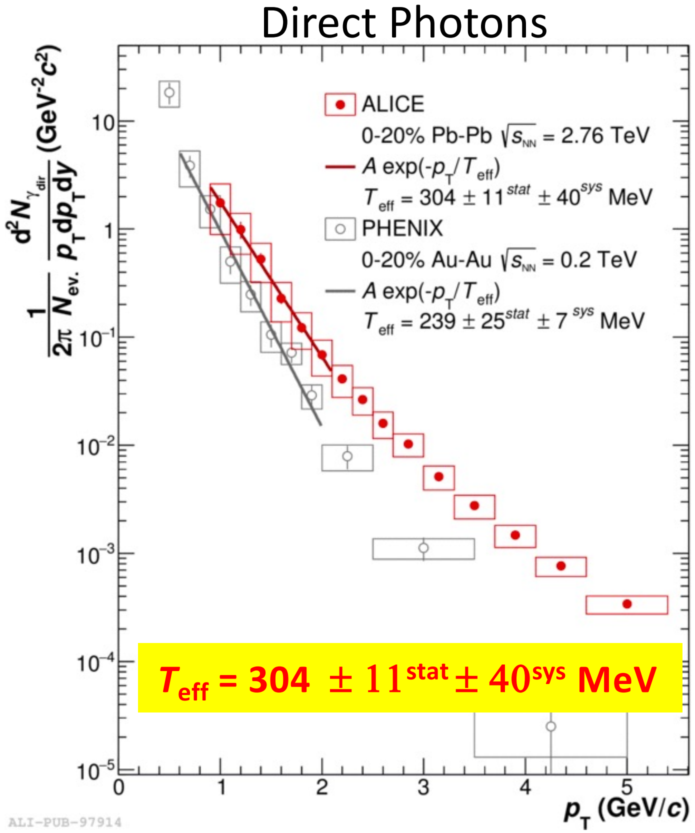
Heavy-ion collisions at the LHC: Medium properties

When the two beams collide, they will create a hot fireball with very high **temperatures:**

10^5 times hotter than the heart of the sun, but in a minuscule space.



Nature Physics 16, 615–619 (2020)



Recall: $T_C \approx 155$ MeV

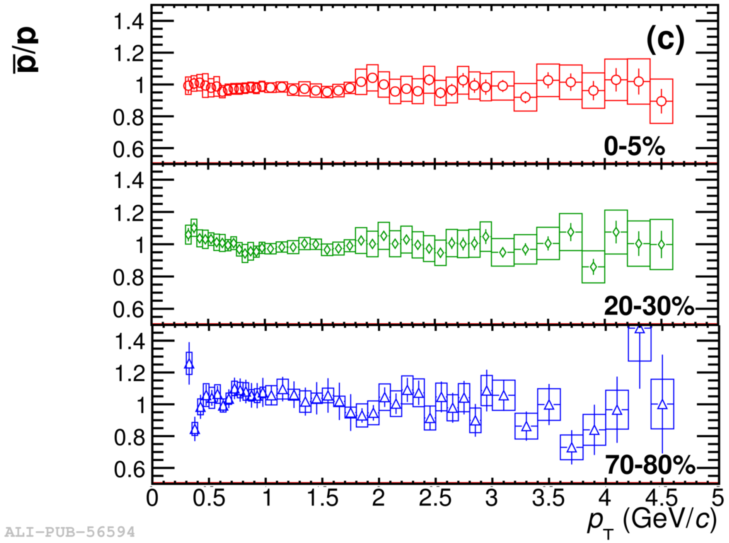
- anti-particle-to-particle ratio ~ 1

  μ_B ~ 0 MeV

"Temperature" ~ 300 MeV → largest ever reached in any laboratory (1 MeV = 116 x 10^8 degree Kelvin): 3.48 x 10^{12} deg. Kelvin

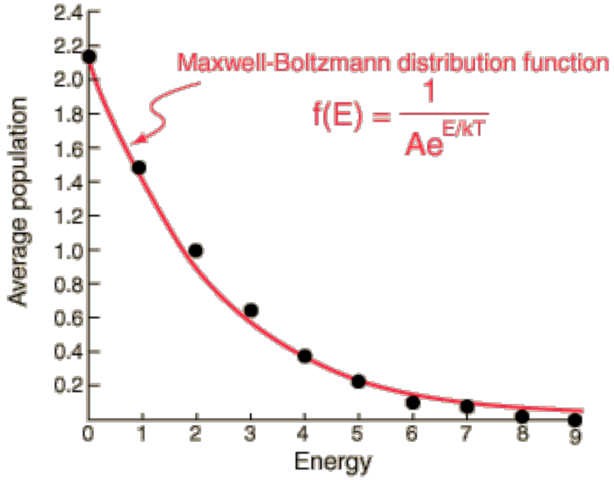
Core of the Sun temperature is ~ 1.57 x 10^7 Kelvin.

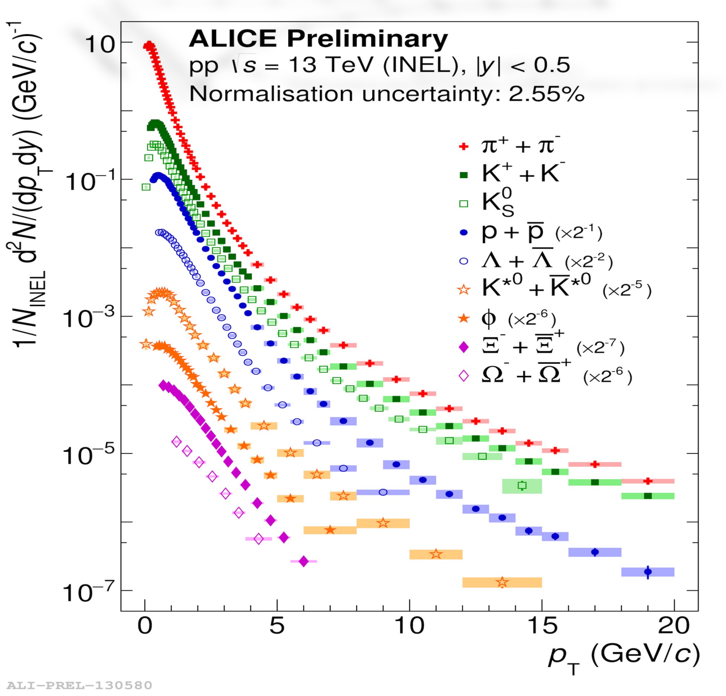
Lesson: We have created temperature and energy density, sufficient enough to produce a plasma of quarks and gluons in heavy-ion collisions at RHIC and the LHC.



Phys. Rev. C 88, 044910 (2013)

Multiparticle Production Follows a Statistical Distribution





Boltzmann Distribution: $f(p_{\rm T}) = A p_{\rm T}\; e^{-m_{\rm T}/T}$

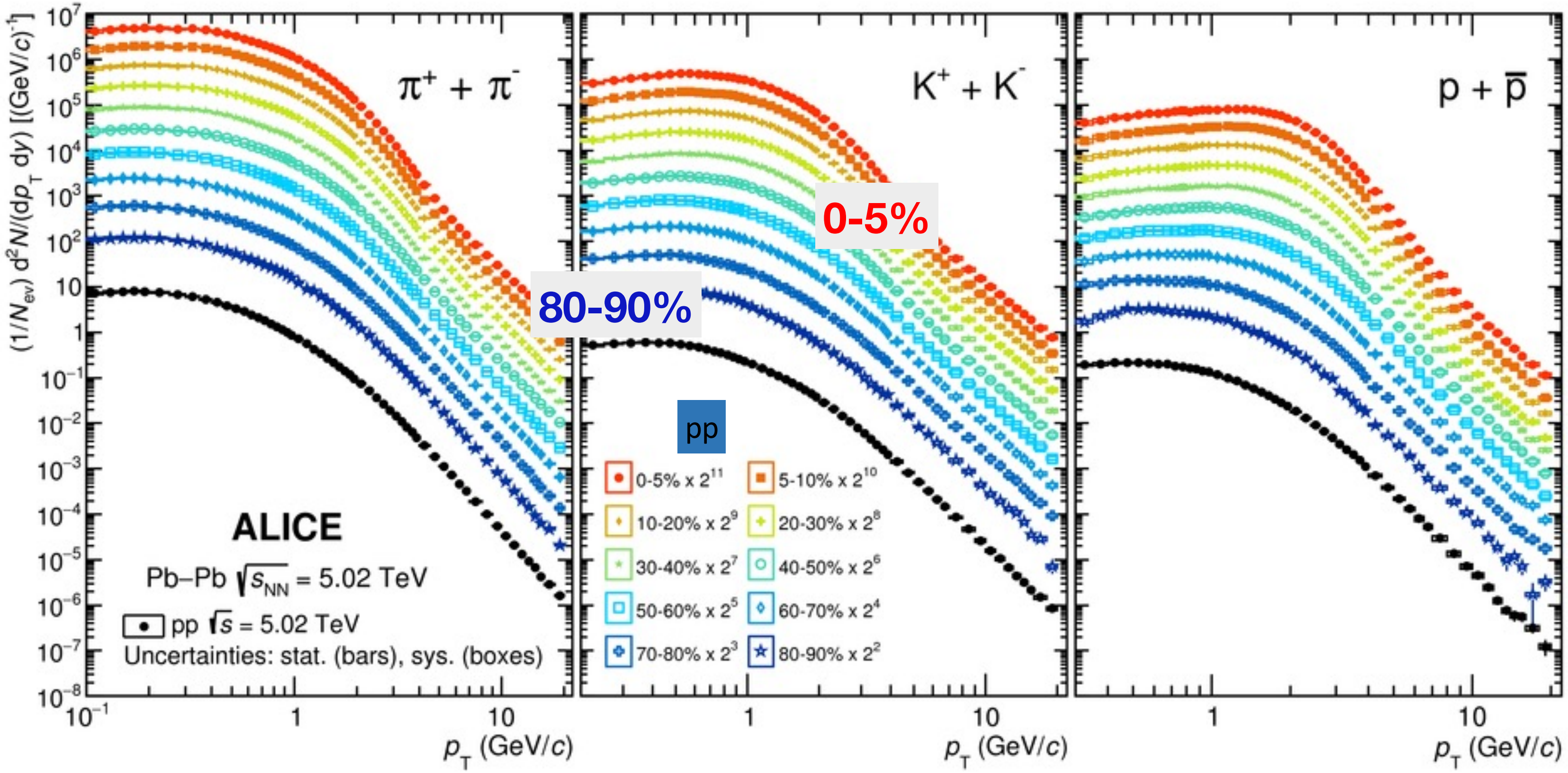
Particle yield exponentially drops down with an increase of mass.

Note:

- low-$p_{\rm T}$ part is dominated by soft processes, high-$p_{\rm T}$ has pQCD contributions
- Spectra deviates from Boltzmann-type
- Follows Levy-Tsallis's distribution

Particle Spectra

Pb-Pb 5.02 TeV



0-5%

80-90%

pp

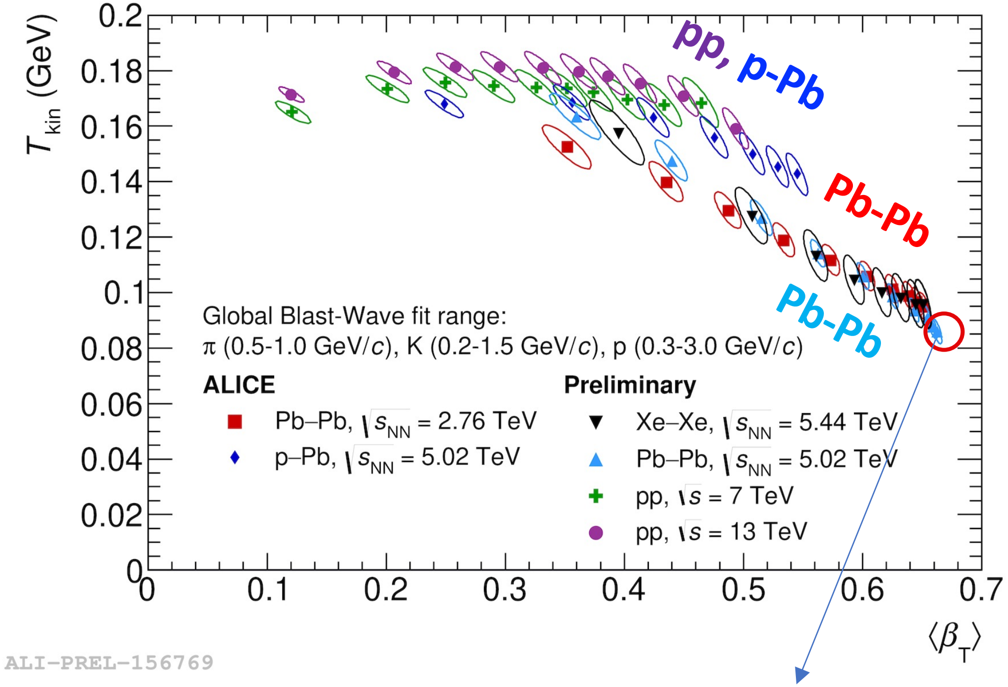
ALICE: Phys. Rev. C 101, 044907 (2020)

Spectral analysis: very powerful tool !

Fits to the spectra give information of QGP hadronization, radial expansion, freeze-out, …

- ❖ Inverse slope of the spectra: Effective temperature, T_{eff}
- ❖ $T_{eff} = T_{th} + 0.5\, m\langle\beta\rangle^2$, thermal random motion + collective radial motion
- ❖ Integrate the spectra: $dN/d\eta$ (yield) → use for chemical freeze-out properties

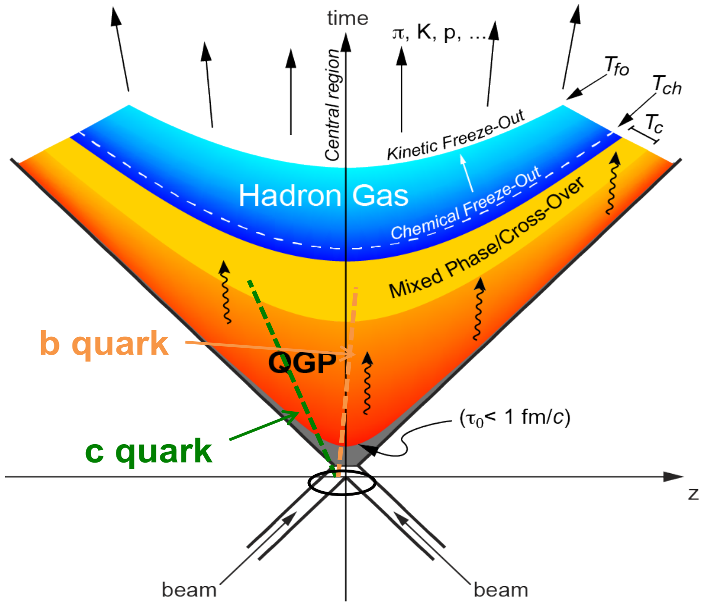
Blast wave fits to particle spectra
(Kinetic Freeze-out)



ALI-PREL-156769

Largest β_T ever

Extracting $T_{\rm kin}$ (Kinetic freeze-out temperature) and $\langle\beta_T\rangle$ (Radial Flow velocity)



Boltzmann-Gibbs Blast-Wave model:

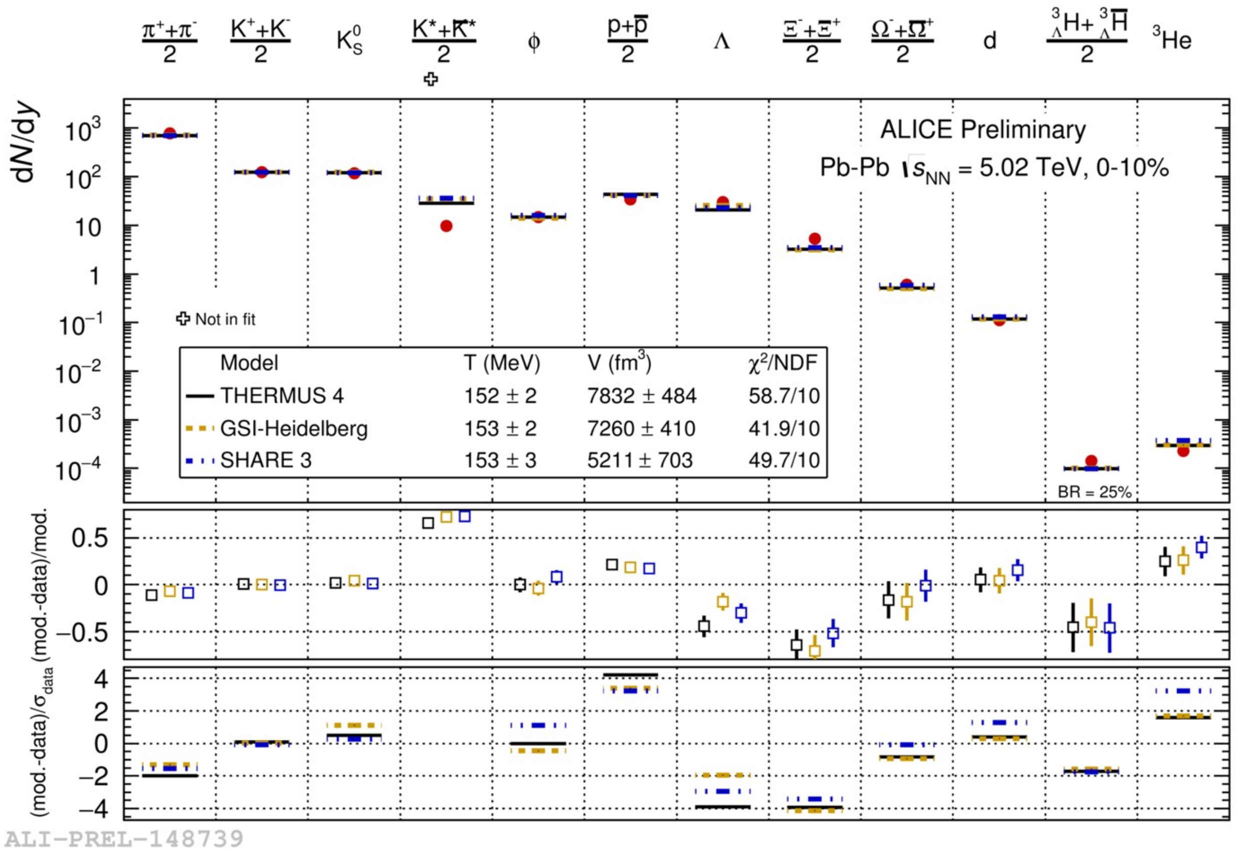
Thermodynamic model with 3 fit parameters: $T_{\rm kin}$, $\langle\beta_T\rangle$ and n (velocity profile)

Describes the particle production from a thermalized source + a radial flow boost

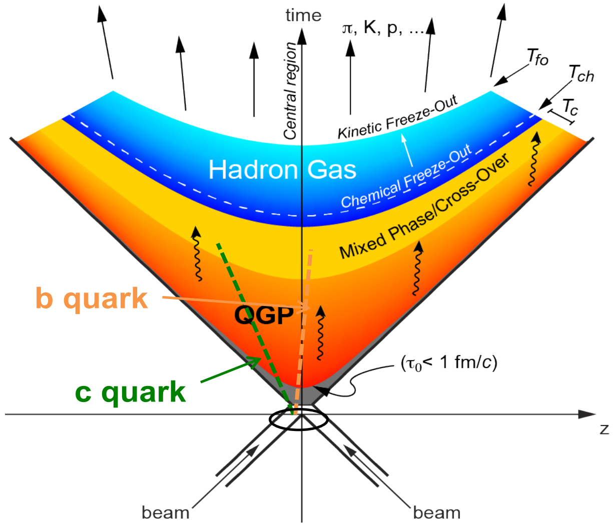
Simultaneous fits to *π, K, p* spectra gives:

- increase of $<\beta_T>$ with centrality
- **Similar evolution of fit parameters in case of pp and p-Pb collisions**
- At similar multiplicities, $<\beta_T>$ is larger for smaller systems

Particle Yields
(Chemical Freeze-out)



Pb-Pb at 5.02 TeV



Thermal models:

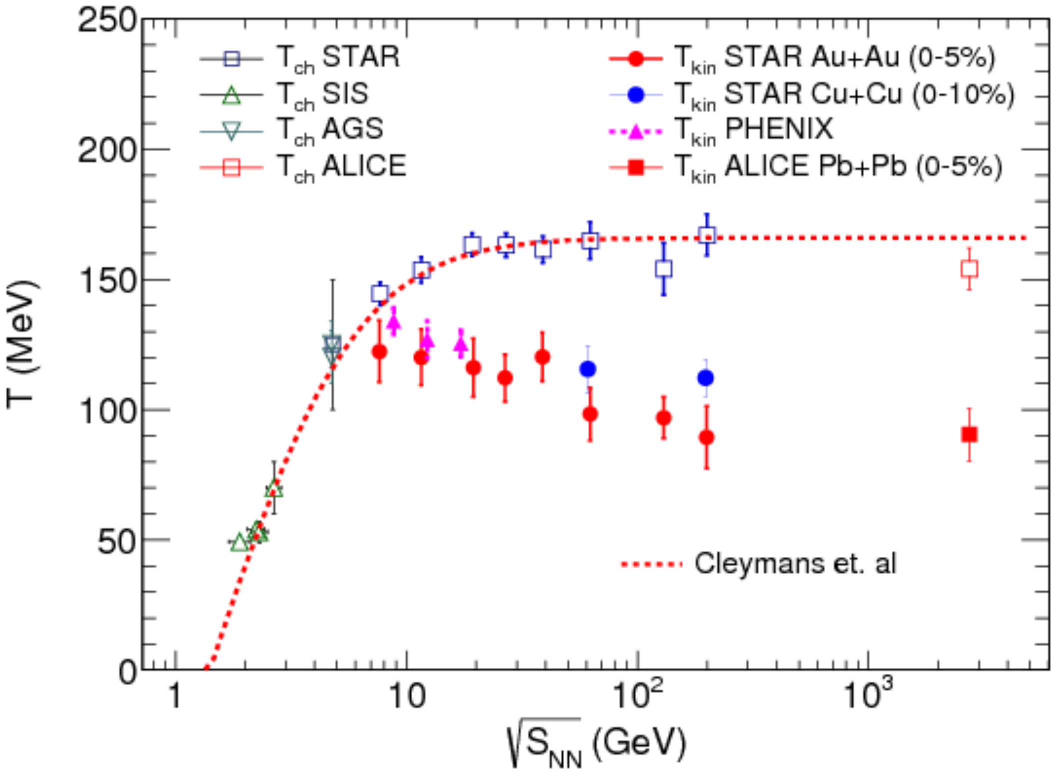
- At Chemical freeze-out => Particle yields get fixed.
- Abundance is determined by thermodynamic equilibrium:

$$\frac{dN}{dy} \propto \exp\left(\frac{-m}{T_{chem}}\right)$$

Particle yields well described by statistical models

T_{ch} (Chemical freeze-out temperature) ~153 MeV

Chemical and kinetic freeze-out temperatures



Collision energy dependence of T_{kin} and T_{ch}

The difference between T_{kin} and T_{ch} increases with the increase of collision energy.

ALICE Collaboration PRD 88 (2013) 044910
STAR Collaboration PRC 79 (2009) 034909
Cleymans et al. PRC 73 (2006) 034905

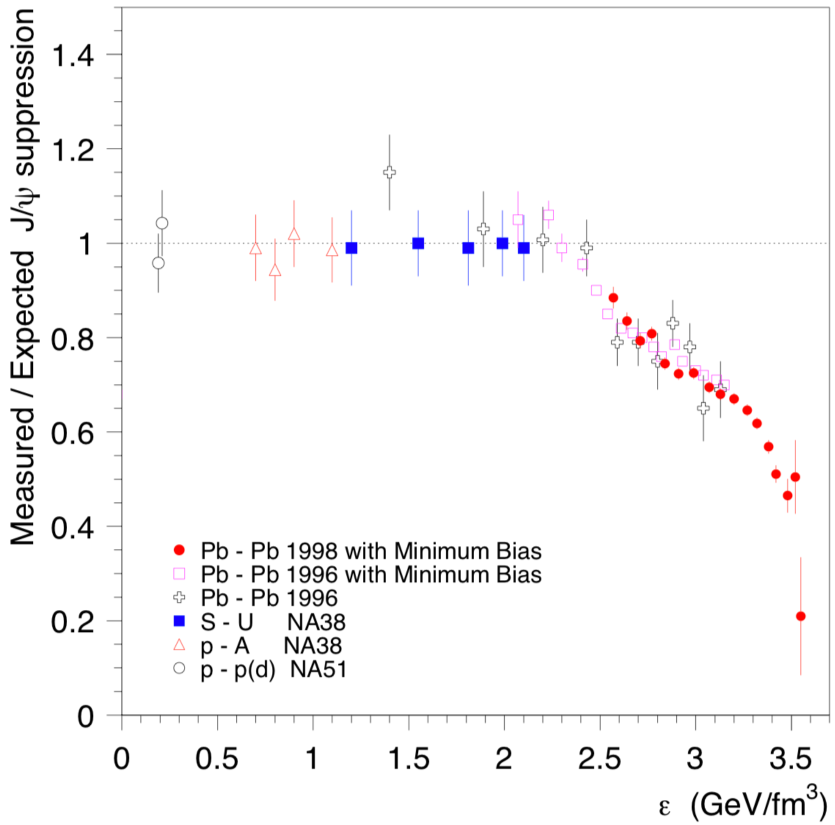
Different formalisms:

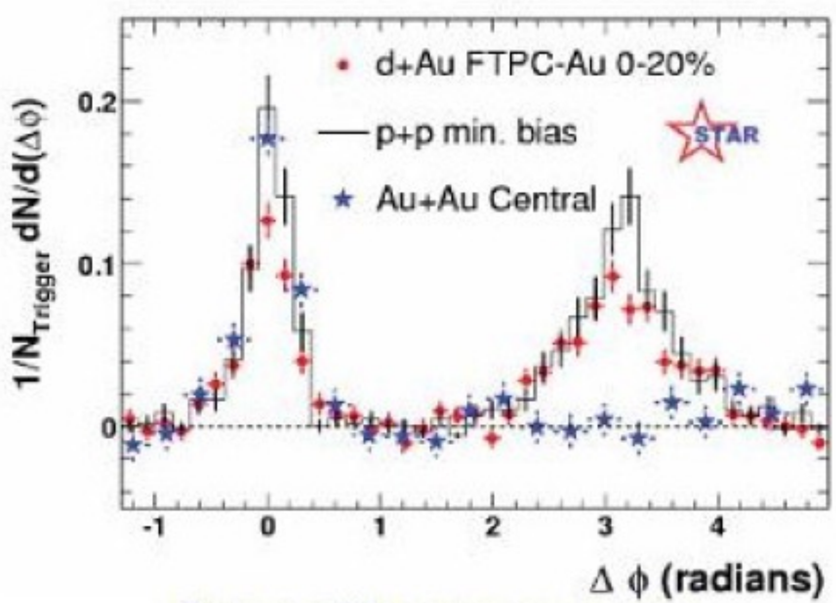
- ✓ Differential Freeze-out
- ✓ **Strange, non-strange freeze-out**

Review: "Freeze-out Parameters in Heavy-Ion Collisions at AGS, SPS, RHIC and LHC Energies."
S. Chatterjee, S. Das, L. Kumar, D. Mishra, B. Mohanty, **Raghunath Sahoo**, and N. Sharma, Adv. in High Energy Physics (AHEP) (2015) Vol. 2015, Article ID 349013,

"Indication of a Differential Freeze-out in Proton-Proton and Heavy-Ion Collisions at RHIC and LHC energies."
D. Thakur, S. Tripathy, P. Garg, **Raghunath Sahoo**, and J. Cleymans. arXiv:1601.05223, Advances in High Energy Physics Volume 2016 (2016), Article ID 4149352,

Some Early Signatures





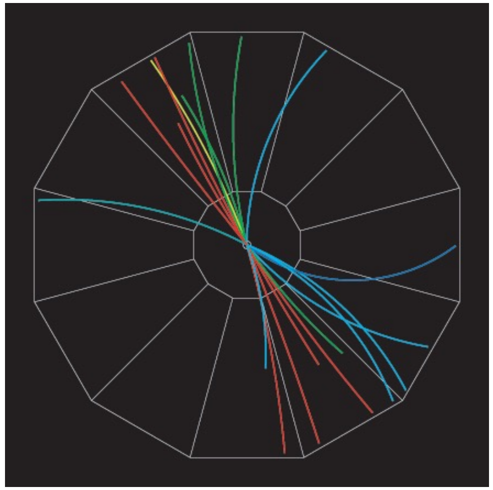
Away side suppression

CERN SPS (NA50): observed J/ψ suppression as a function of energy density for various collision species. Note that the critical energy density for a partonic medium is 1 GeV/fm³.

BNL RHIC (STAR): Suppression of away side jets (cone of hadrons), signaling the formation of a highly dense matter created at RHIC.

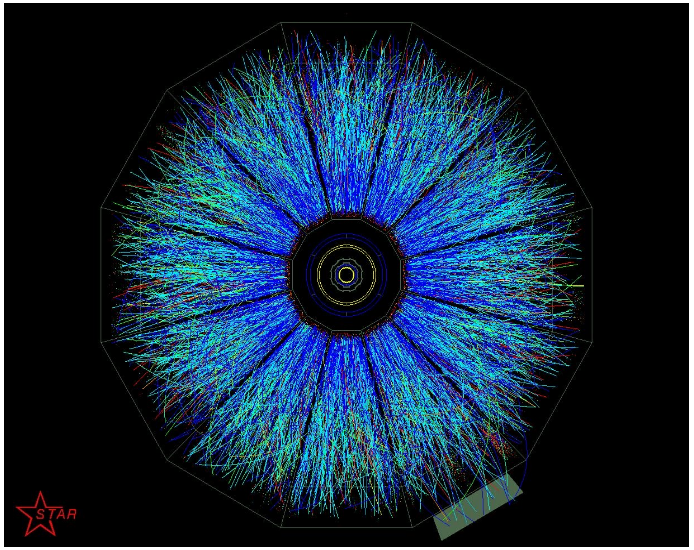
Jet Quenching

Hard to observe in A+A collisions ?

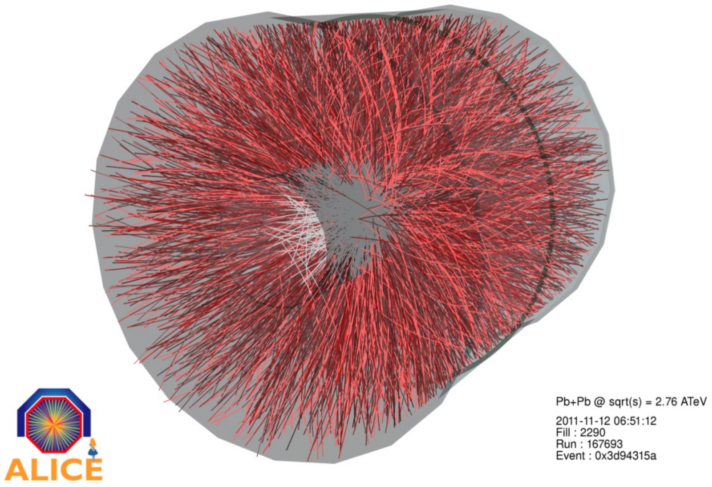


p+p →jet+jet

@ 200 GeV



Au+Au @ 200 GeV



Pb+Pb @ 2.76 TeV

- *How do we observe it?*

Nuclear Modification Factor: R_{AA}

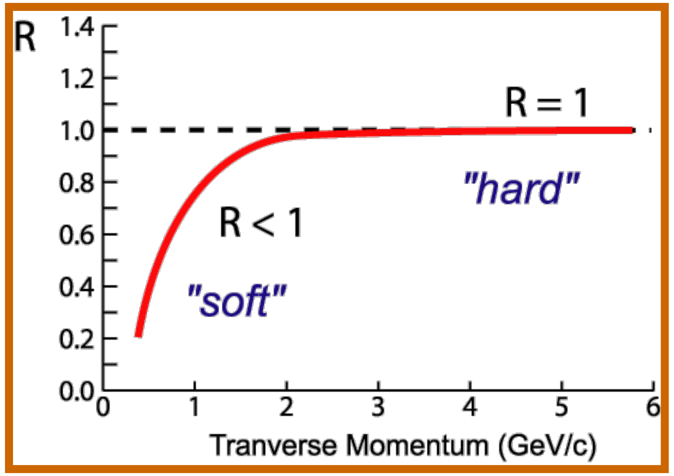
- **Indirect measurement**
  - ❑ In high-density matter, partons lose energy by radiating gluons

⬇

Suppression of high p_T particles with reference to pp-collisions

➢ *Study of* $$R_{AA} = \frac{\mathrm{Yield}_{AA} / \langle N_{binary} \rangle_{AA}}{\mathrm{Yield}_{pp}}$$

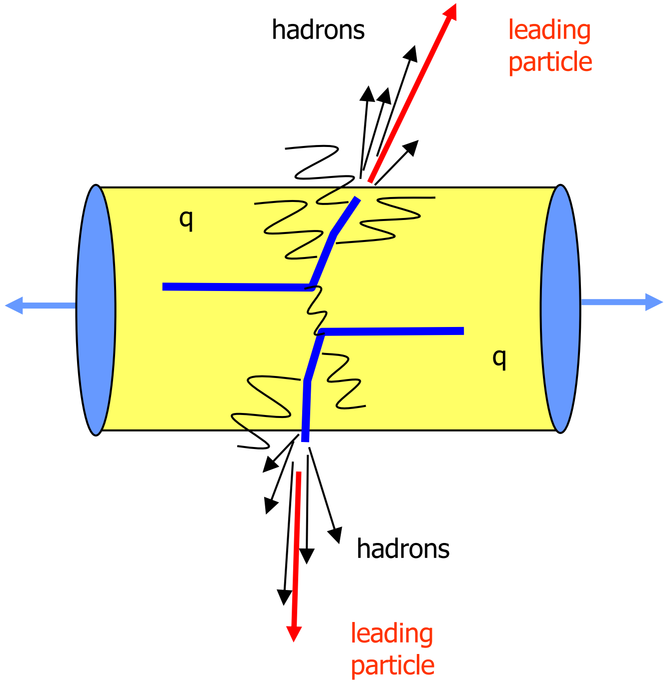
as a function of p_T



$R_{AA} > 1$: enhancement

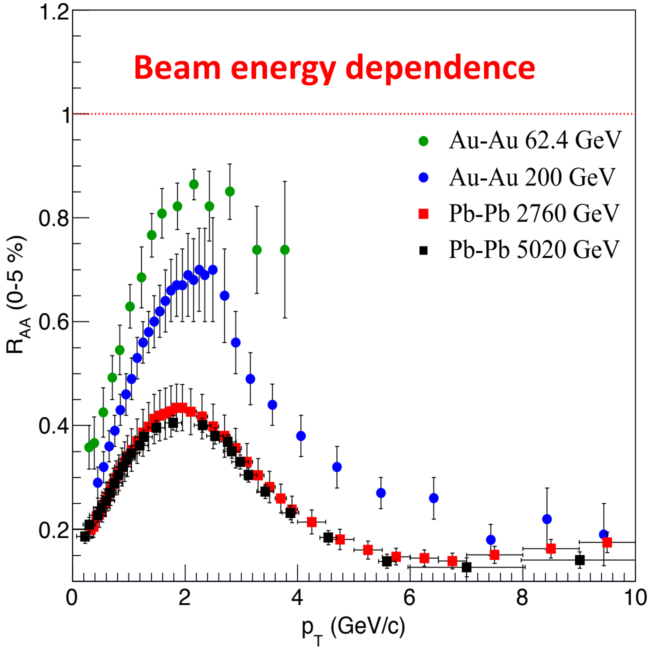
$R_{AA} = 1$

$R_{AA} < 1$: suppression

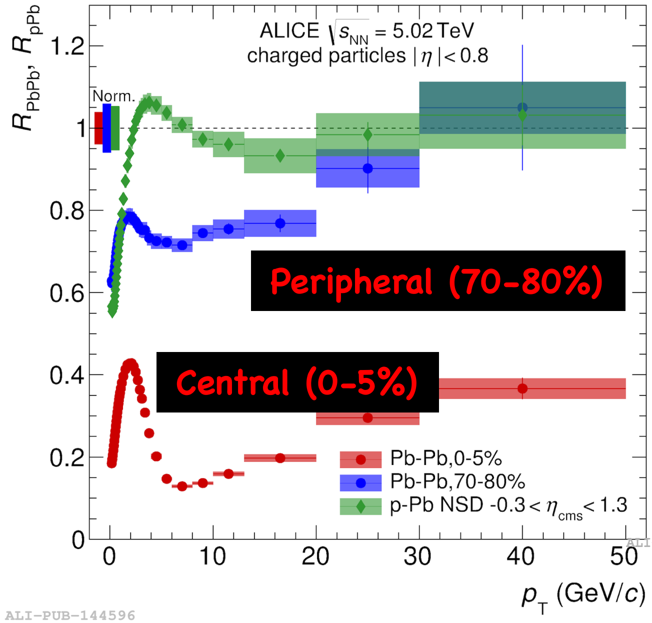


Nuclear Modification Factor: R_{AA}

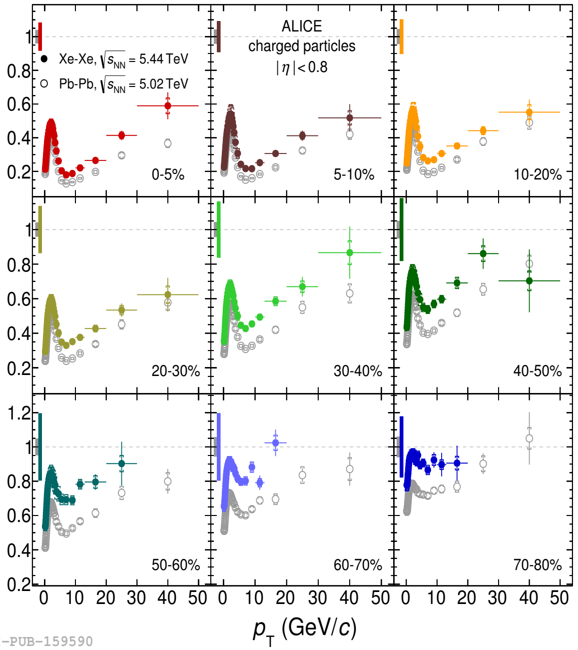
- Study of $$R_{AA} = \frac{\text{Yield}_{AA}/\langle N_{binary}\rangle_{AA}}{\text{Yield}_{pp}}$$ of charged hadrons as a function of p_T


Beam energy dependence

ALICE: JHEP 1811 (2018) 013



ALI-PUB-144596



ALI-PUB-159590

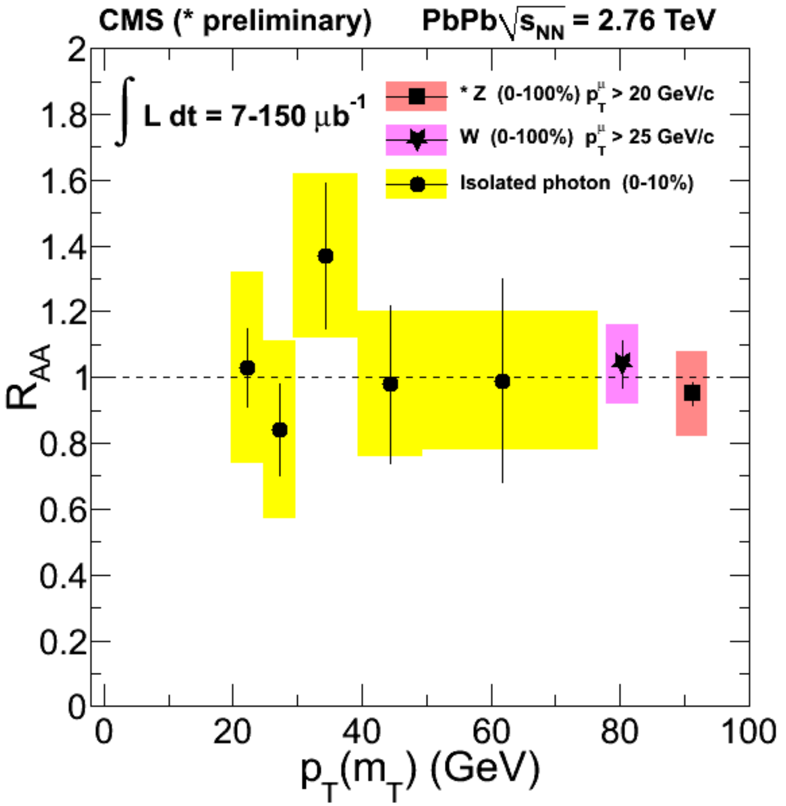
ALICE: Phys. Letts. B 788 (2019) 166

- **p-Pb:** no evidence of jet quenching for NSD events. Small system size – hence effect is very small.
- **Pb-Pb:** Strong suppression with increasing centrality.
  Strong suppression at intermediate p_T; stronger in more central collisions.

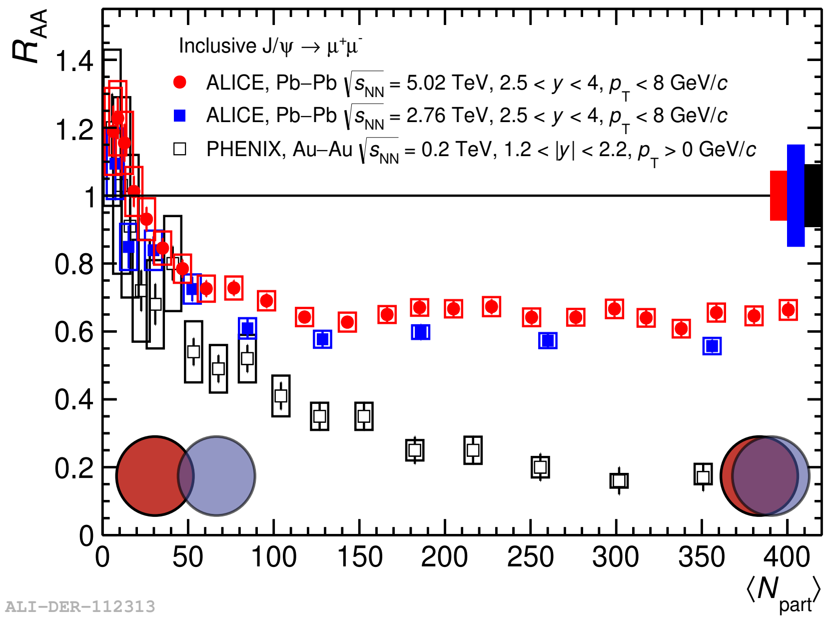
➢ *The matter is denser at LHC energy compared to RHIC energy*

Nuclear Modification Factor (R_{AA}): Gauge Bosons & Charmonia

- Study of $R_{AA} = \frac{\text{Yield}_{AA} / \langle N_{\text{binary}} \rangle_{AA}}{\text{Yield}_{pp}}$ of gauge bosons



ALICE Collaboration, Phys. Lett. B766 (2017) 212



J/ψ suppression with collision energy in the forward region

- *No suppression for photons and Z^0*

New Results from pp@LHC

Do we see QGP in pp collisions at TeV energies?

1. "Early universe signals in proton collisions at the Large Hadron Collider." Raghunath Sahoo and Tapan K. Nayak, Current Science (2021)

2. "Possible Formation of QGP-droplets in Proton-Proton Collisions at the CERN Large Hadron Collider."
Raghunath Sahoo, arXiv:1908.10566, [Bulletin of Association of Asia Pacific Physical Societies (AAPPS), Vol-29, Page-16, August 2019 (Invited Article)]

nature physics

JUNE 2017 VOL 13 NO 6
www.nature.com/naturephysics

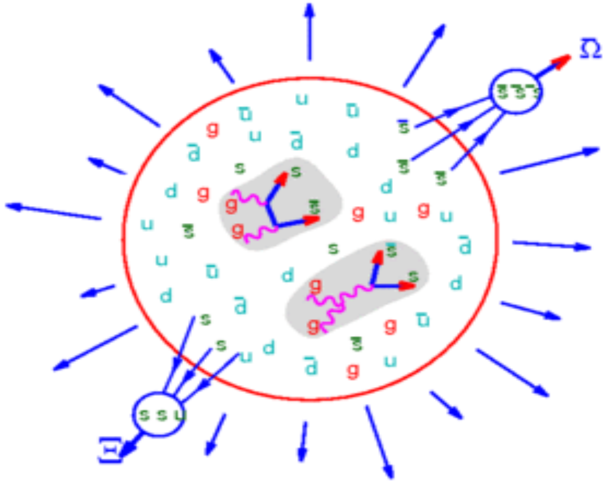
Stranger and stranger says ALICE

Strangeness enhancement

- *s*-quarks are not part of the colliding nuclei (hadrons)
- *(u,d)*-quarks form ordinary matter
- *s(95 MeV):* are sufficiently light to be produced abundantly during the collision
- Strangeness is produced in hard partonic scattering processes by
- flavour creation: $gg \to s\bar{s}$

  $q\bar{q} \to s\bar{s}$
- flavour excitation: $gs \to gs$

  $qs \to qs$
- gluon splitting: $g \to s\bar{s}$

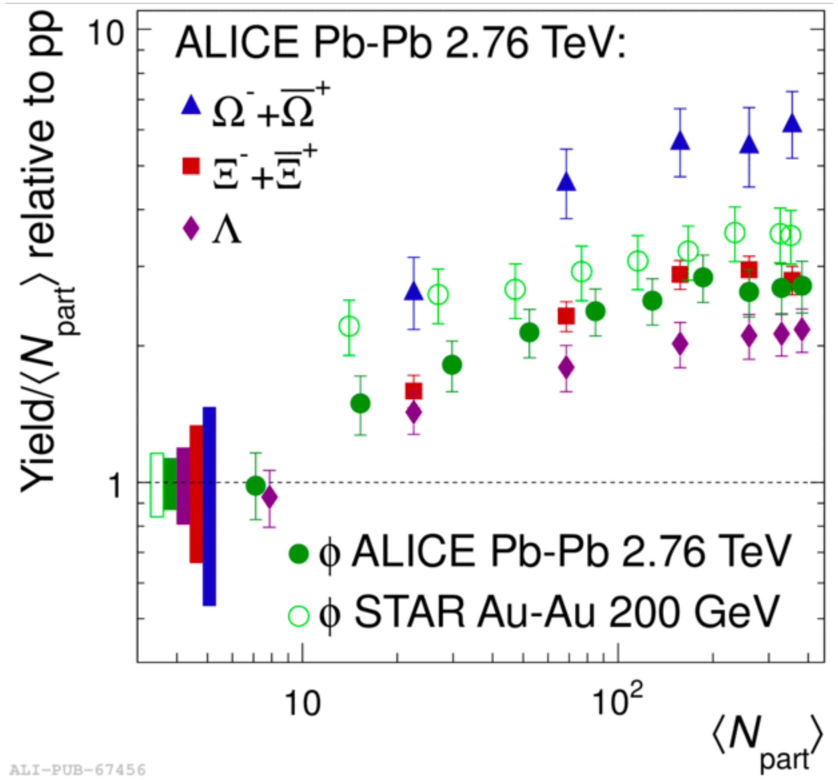


J. Rafelski and B. Müller, PRL48, 1066 (1982)
P. Koch, B. Müller, J. Rafelski, Phys. Rep. 142, 167 (1986)

Strangeness enhancement in heavy-ion collisions

- Observed strangeness enhancement hierarchy: with s-content (relative to pp)

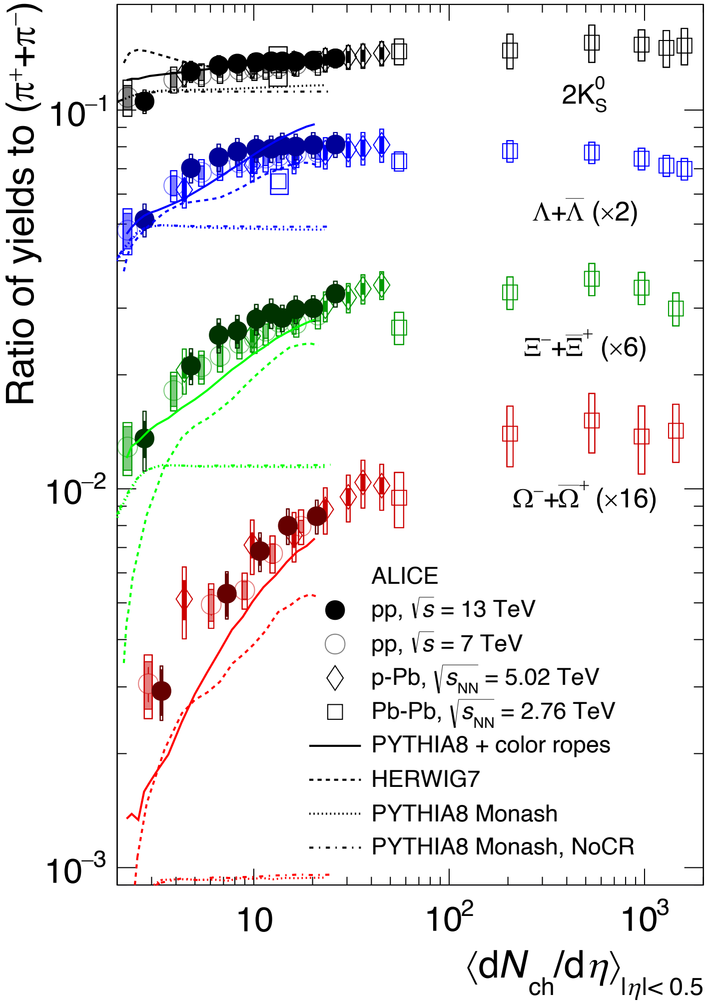
What do we observe in small systems like pp collisions at the LHC?



Phys. Rev. C **91**, 024609 (2015) [ALICE Collaboration]

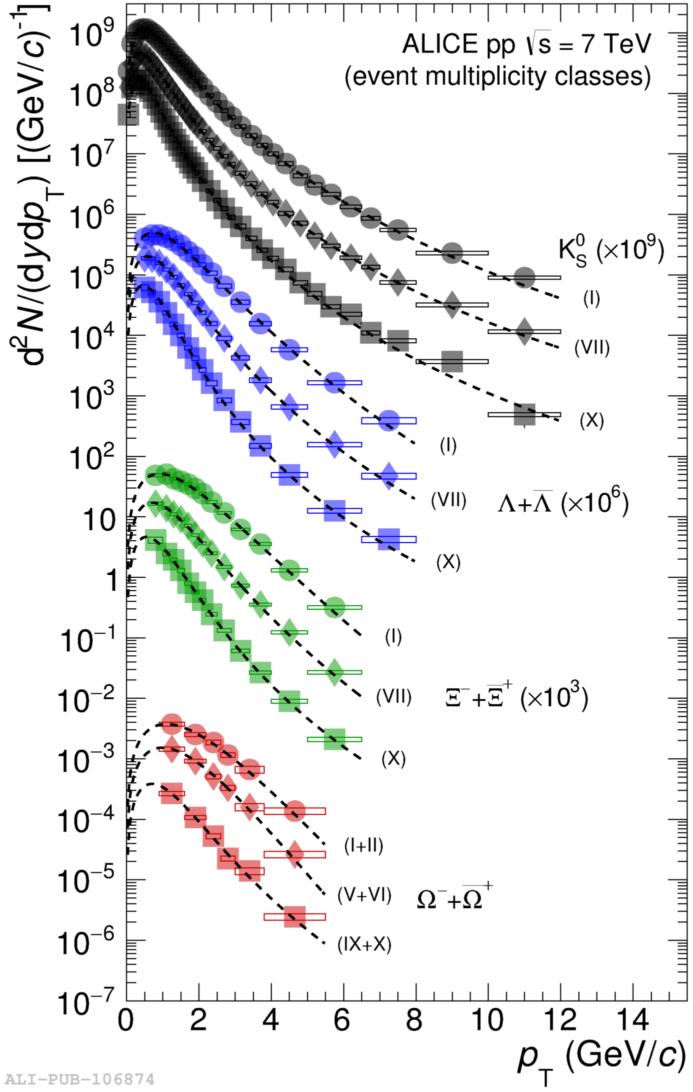
Strangeness enhancement

- ✓ Significant enhancement of strange-to- non-strange ratio with particle multiplicity
- ✓ Origin of strangeness production in hadronic collisions is driven by the characteristics of the final state rather than by the collision system and energy
- ✓ At high-multiplicity, the yield ratios reach values similar to that observed in Pb-Pb collisions
- ✓ Non-trivial Observation: Particle ratios in *pp* and p-Pb are identical at the same $dN_{ch}/d\eta$: final state particle density might be a good scaling variable between systems



ALICE Collaboration, Eur. Phys. J. C, 80, 693 (2020)

Spectra and collectivity

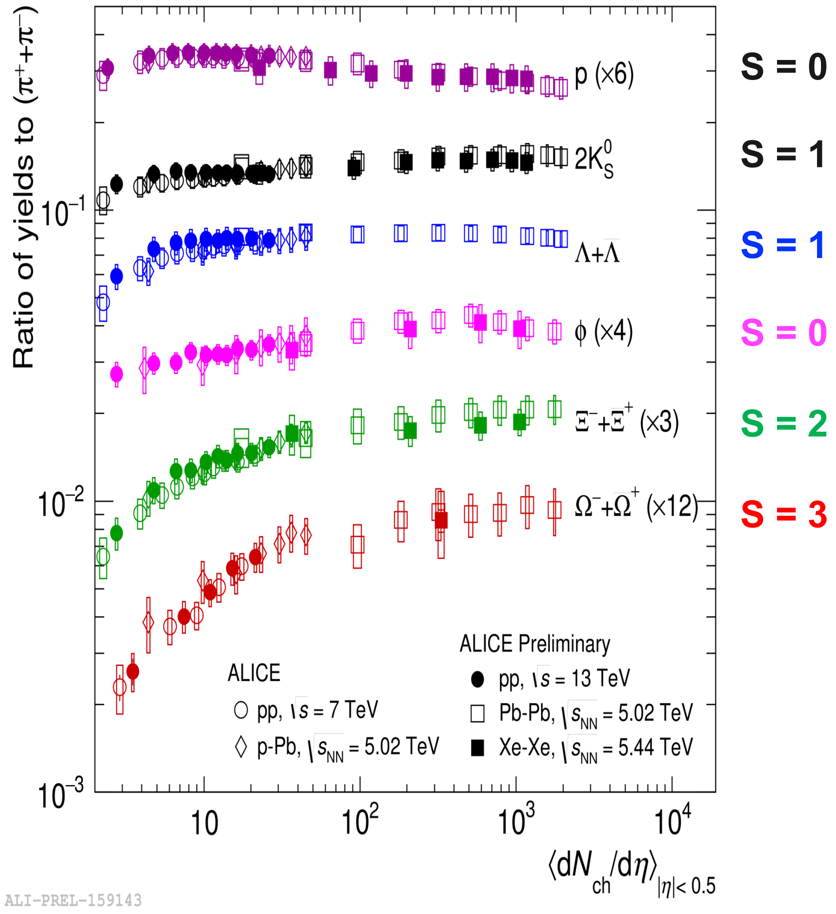


- ✓ Spectra become harder as multiplicity increases
- ✓ Hardening is more pronounced for higher-mass particles
- ✓ Similar observations like p-Pb and Pb-Pb showing collective behavior

- ✓ Simultaneous fit: T_{fo} = 163 ± 10 MeV, $\langle\beta_T\rangle$ = 0.49 ± 0.02
  → Similar to the same class of events in p-Pb with comparable $dN_{ch}/d\eta$

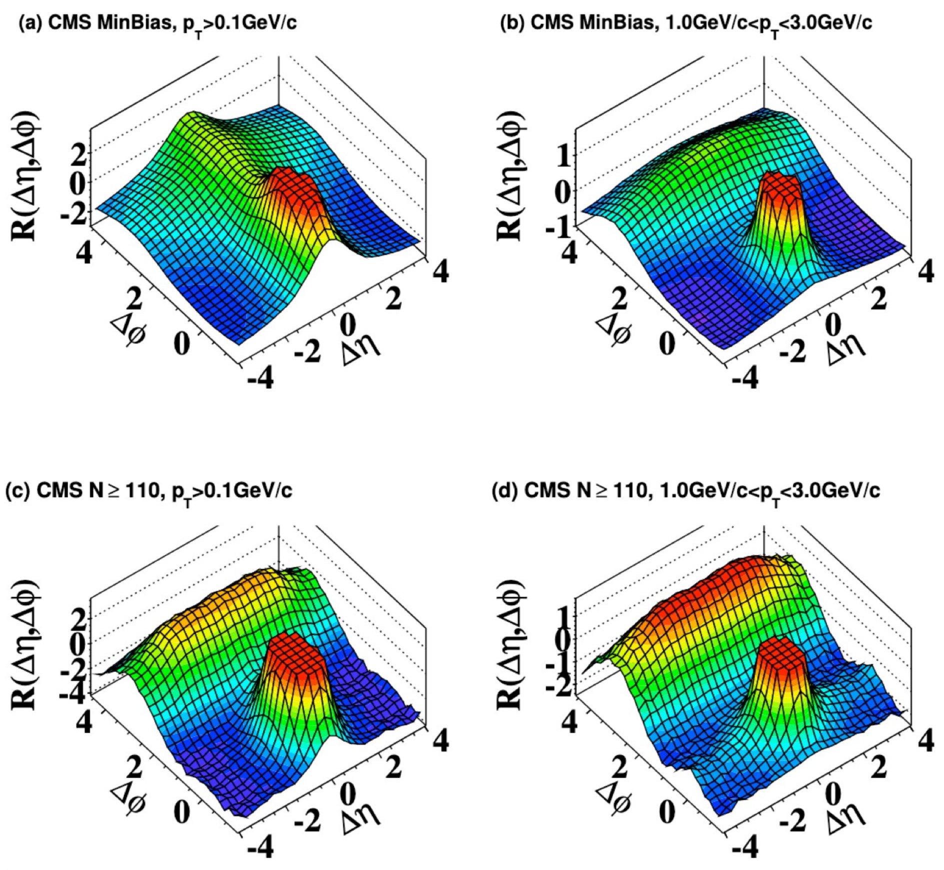
ALICE: Nature Phys. 13 (2017) 535

Strangeness hierarchy



- ✓ Smooth evolution as a function of event multiplicity (in pp, p-Pb and Pb-Pb collisions)
- ✓ Measurement at different energies as a function of multiplicity indicates that the hadron chemistry is driven by multiplicity regardless of the collision energy
- ✓ Ratios increase from low to high multiplicity in small systems and reach values similar to those observed in Pb-Pb collisions.
- ✓ Strangeness enhancement increases with strangeness content.

Long-range Correlations



CMS, JHEP 1009:091,2010

The collective flow of strongly interacting matter gives rise to an azimuthally collimated long-range (large Δη), near-side (small Δϕ) ridge-like structure in two-particle azimuthal correlations.

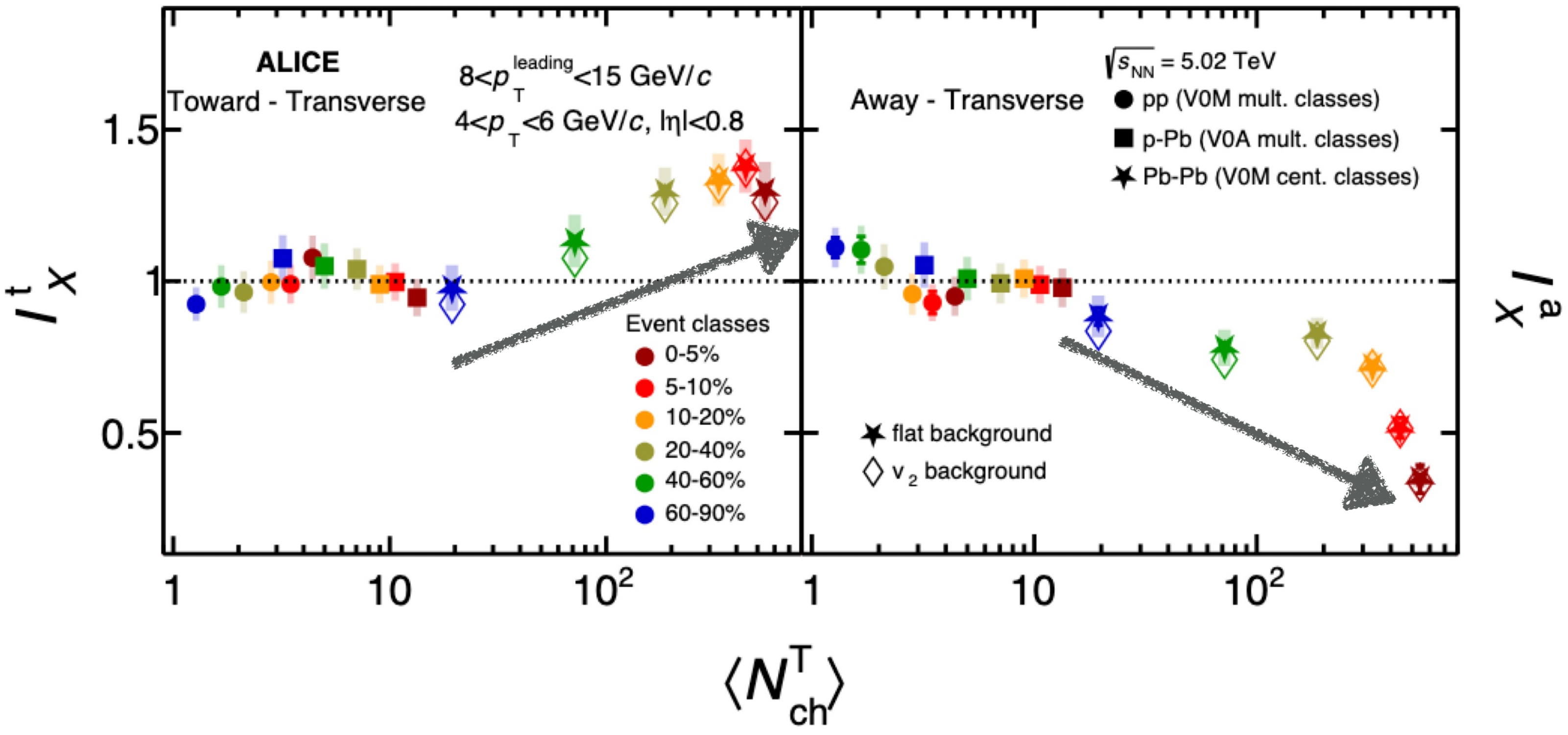
It was first observed at the RHIC in Cu–Cu and Au–Au collisions and later at the LHC in Pb–Pb collisions.

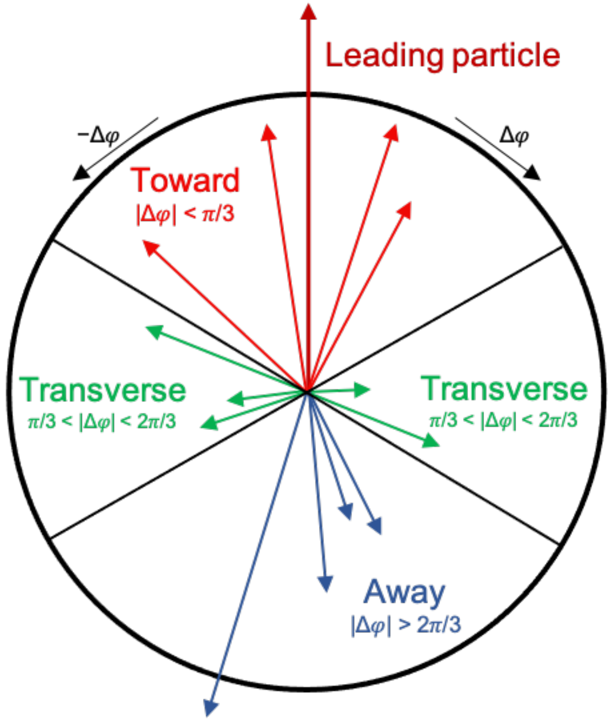
Most of the pQCD based models fail to explain the ridge formation.

Belle at KEK has reported no ridge-like structure in e+e- collisions at 10.52 GeV

Observation of ridge structure in high-multiplicity pp collisions: a feature seen in heavy-ion collisions possibly due to collectivity

Jet-like region modifications



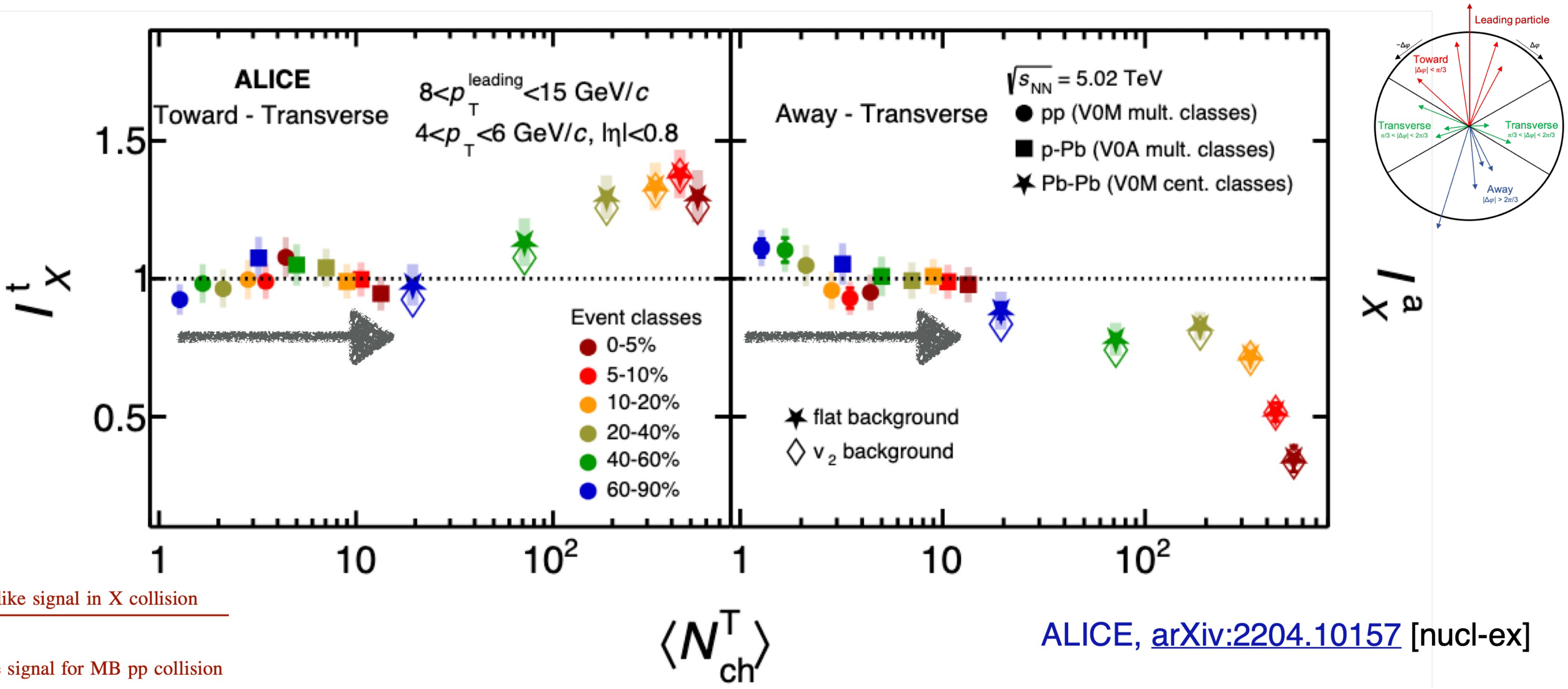


$$I_X = \frac{\left.\frac{dN_{ch}}{dp_T}\right|_{\text{jet−like signal in X collision}}}{\left.\frac{dN_{ch}}{dp_T}\right|_{\text{jet−like signal for MB pp collision}}}$$

ALICE, arXiv:2204.10157 [nucl-ex]

- Pb–Pb collisions: I_X values in the toward (away) region exhibit an enhancement (suppression) relative to MB pp with $<N_{ch}^T>$

Jet-like region modifications



ALICE, arXiv:2204.10157 [nucl-ex]

$$I_X = \frac{\left.\frac{dN_{ch}}{dp_T}\right|_{\text{jet−like signal in X collision}}}{\left.\frac{dN_{ch}}{dp_T}\right|_{\text{jet−like signal for MB pp collision}}}$$

- pp and p–Pb collisions: Absence of jet-like modifications in pp and p–Pb collisions

A Covid-19 time engagement!

Possible early universe signals in proton collisions at the Large Hadron Collider

Raghunath Sahoo and Tapan K. Nayak*

Our universe was born about 13.8 billion years ago from an extremely hot and dense singular point, in a process known as the Big Bang. The hot and dense matter which dominated the system within a few microseconds of its birth was in the form of a soup of elementary quarks and gluons, known as the quark–gluon plasma (QGP). Signatures compatible with the formation of QGP matter have experimentally been observed in heavy-ion (such as Au or Pb) collisions at ultra-relativistic energies. Recently, experimental data of proton–proton (pp) collisions at the CERN Large Hadron Collider (LHC) have also shown signals resembling those of QGP formation, which made these studies stimulating as to how the collision of small systems features in producing the early universe signals. In this article, we discuss some of the compelling experimental results and give an account of the present understanding. We review the pp physics programme at the LHC and discuss future prospects in the context of exploring the nature of primordial matter in the early universe.

Keywords: Big Bang, early universe, quark–gluon plasma, proton collisions, primordial matter.

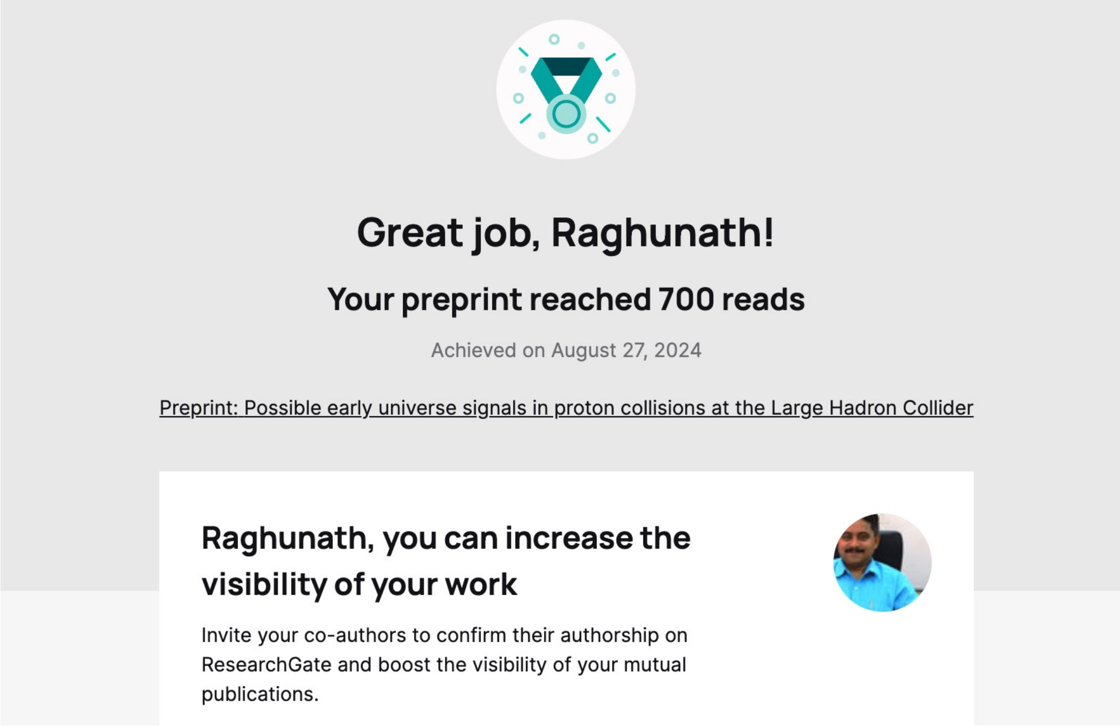
THE discovery of electron as the first elementary particle by J. J. Thomson in 1897 was a major milestone in our quest to explore and understand the subatomic universe. Further down the line in 1911, the nucleus as a centrally placed heavy object inside an atom with protons and neutrons (collectively known as nucleons) as its constituents was probed through the famous Rutherford alpha-particle scattering experiment. The structure of nucleons was further probed by the famous deep inelastic scattering of electrons on protons which led to the discovery of the substructure of protons in the Stanford Linear Accelerator Centre (SLAC), USA in 1968. Later experiments used muons and neutrinos to understand the detailed structure of the hadrons. It has now been understood that protons and neutrons are composed of quarks and are bound together by gluons. The gluon was discovered at the electron–position collider (PETRA) of DESY, Germany in 1979. The fact that independent existence of these quarks and gluons is not yet directly observed in experiments, is supported by their underlying dynamics, which is known through the theory of strong interaction – quantum chromodynamics (QCD). The strong interaction, one of the four fundamental interactions of nature, predicts the confinement of partons (quarks and gluons) inside the cage of hadrons (the bound state of partons, e.g. proton, neutron).

However, the human curiosity of creating matter with quarkonic degrees of freedom in the laboratory has led to a completely new field of research – search and study of the quark–gluon plasma (QGP). Incidentally, the QGP matter dominated our universe till about a few microseconds after the Big Bang. Our universe began with a Big Bang about 13.8 billion years ago from a 'point' called the singularity, which exploded and started to expand rapidly. (The Wilkinson Microwave Anisotropy Probe (WMAP) has estimated the age of the universe to be 13.8 billion years, within a percentage of uncertainty (https://map.gsfc.nasa.gov/).) In the first few instants of time, between 10^{-35} and 10^{-32} sec, it underwent a period of exponential 'inflation'. Until a few microseconds from the beginning (time $t = 0$), this hot and dense matter was in the form of QGP, consisting of deconfined (free) quarks and gluons[1,2].

Understanding the evolution of our universe during its infancy involves creating and studying the formation of QGP in the laboratory. To achieve this, first we need to probe the sub-nucleonic scale of matter. For this, we use the general principle of optics, where the wavelength, λ of light (wave associated with the probe) should be less than or equal to the dimension of the object. To have a grasp on the associated energy scale, the famous de Broglie equation, $\lambda = h/p$ (h is the Planck's constant and p is the momentum) helps us in making an estimate that to probe the proton structure one needs energy of the order of giga-electron Volt (GeV) (note that the charge radius of a proton is around 0.877 fm, where 1 fm = 10^{-15} m). The next step involves accelerating heavy nuclei (such as gold or

---

Raghunath Sahoo is at the Indian Institute of Technology Indore, India and Tapan K. Nayak is at National Institute of Science Education and Research, Jatni 752 050, India. The authors are also at CERN, CH 1211, Geneva 23, Switzerland.
*For correspondence. (e-mail: Raghunath.Sahoo@cern.ch)



Great job, Raghunath!

Your preprint reached 700 reads

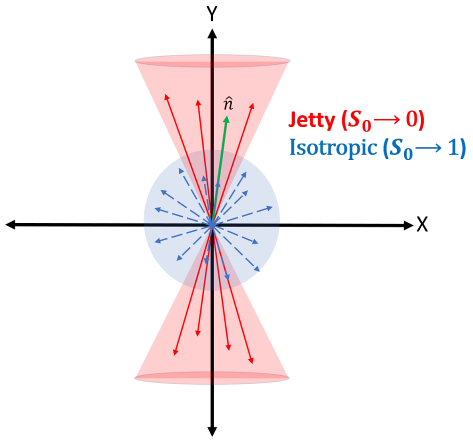
Achieved on August 27, 2024

Preprint: Possible early universe signals in proton collisions at the Large Hadron Collider

Raghunath, you can increase the visibility of your work

Invite your co-authors to confirm their authorship on ResearchGate and boost the visibility of your mutual publications.

What is Next?

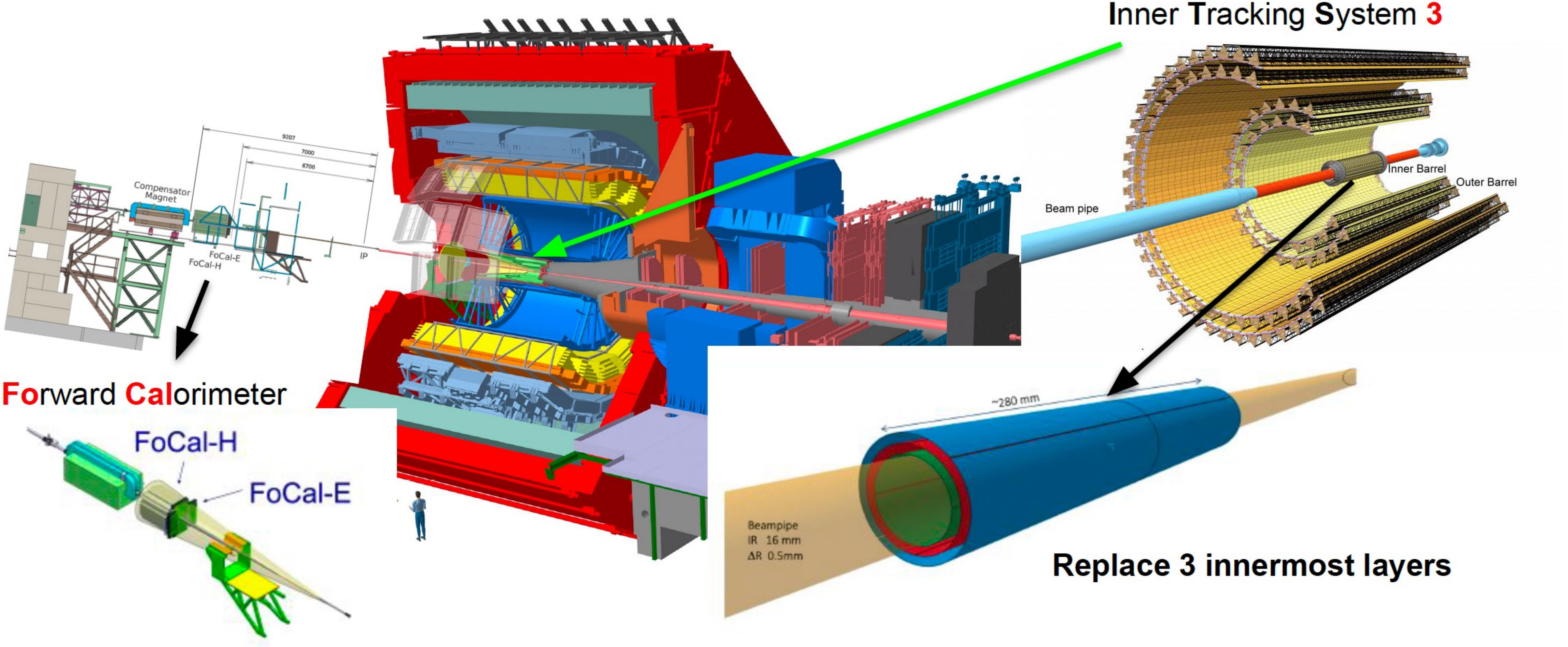


- Differential topological studies in pp collisions and extending the same to heavy-ion collisions: multiparticle production dynamics
- Focus on heavy flavor measurements in view of the detector upgrades: secondary vertexing, tracking efficiency etc.
- Application of ML techniques to have a better understanding and interpretation of data
- Study of transport properties, vorticity, and effect of magnetic field in HIC
- Interdisciplinarity
- Future facilities: FAIR, NICA

**For the Physics results of Run 1 and Run 2:
The ALICE experiment -- A journey through QCD:
arXiv:2211.04384**

http://people.iiti.ac.in/~raghunath/publications.html

The Future: Upgrades for Run 4 (LS3: 2025)



Inner Tracking System 3

Forward Calorimeter

FoCal-H

FoCal-E

Replace 3 innermost layers

ALICE - The timeline

2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

LHC Run 2

LHC LS2

LHC Run 3

LHC LS3

LHC Run 4

LHC LS4

LHC Run 5

ALICE 1

ALICE 2

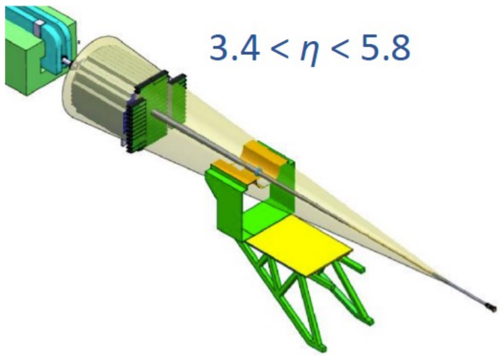
ALICE "2.1"

ITS3, FoCal

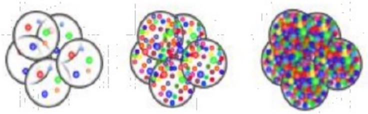
ALICE 3

Letter of Intent: CERN-LHCC-2020-009

FoCal = ECal+HCal

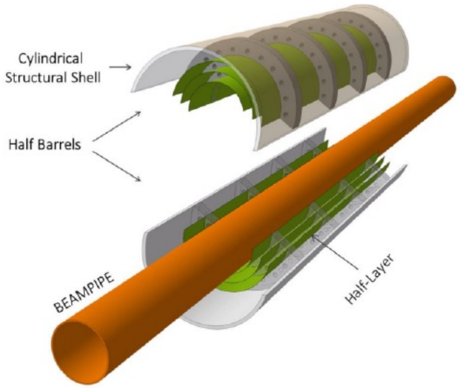


- direct photon detection to probe **gluon density at small *x***, forward π^0
- prototyping, beam tests



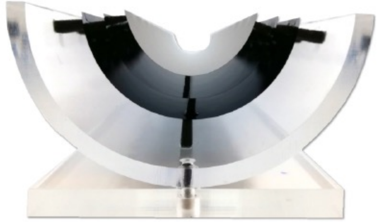
Letter of Intent: CERN-LHCC-2019-018

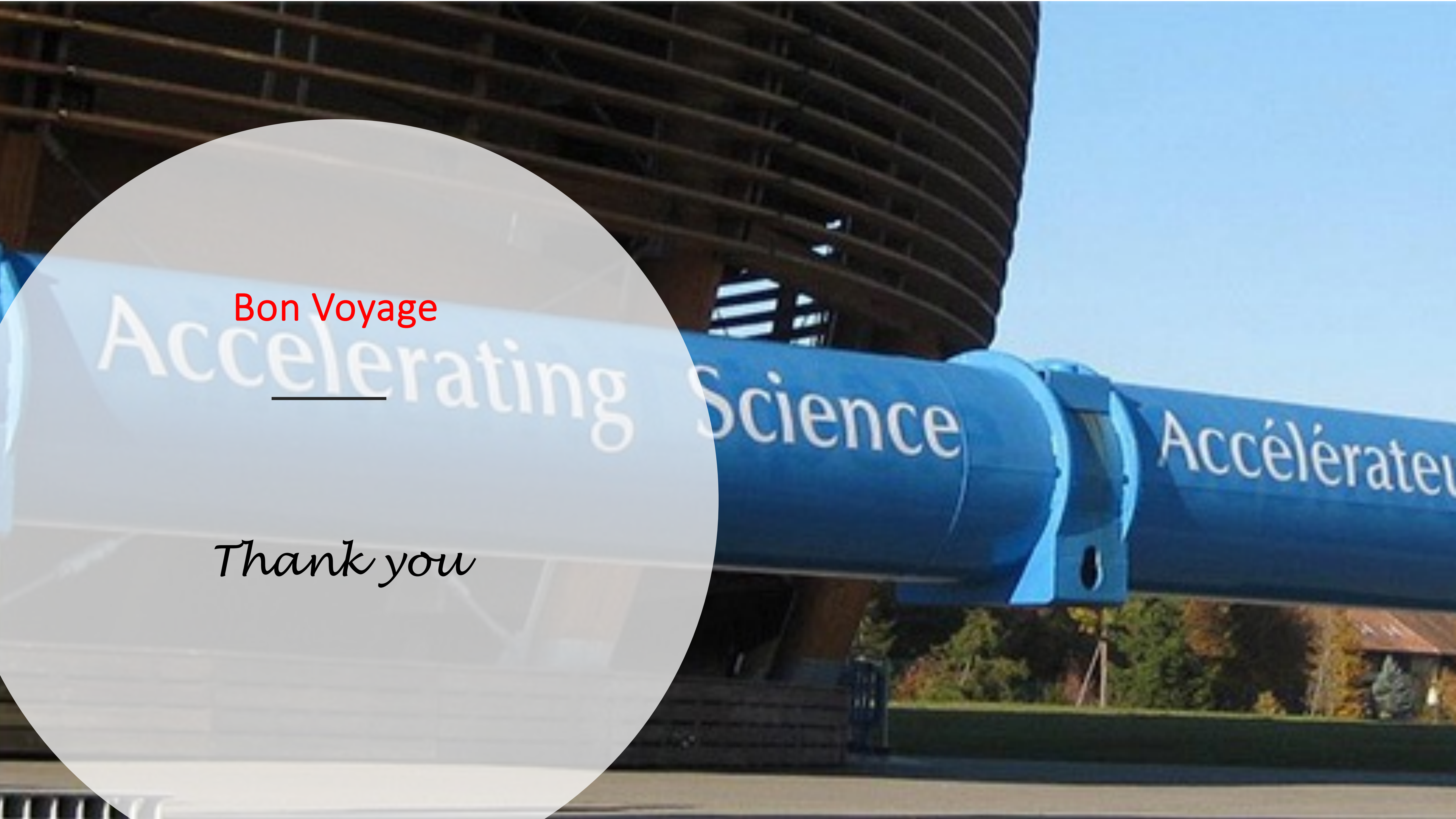
ITS3



- truly cylindrical inner layers
- closer to the interaction point, reduced material budget

→ Improved vertexing for heavy flavour probes, thermal dielectrons





Bon Voyage

Thank you

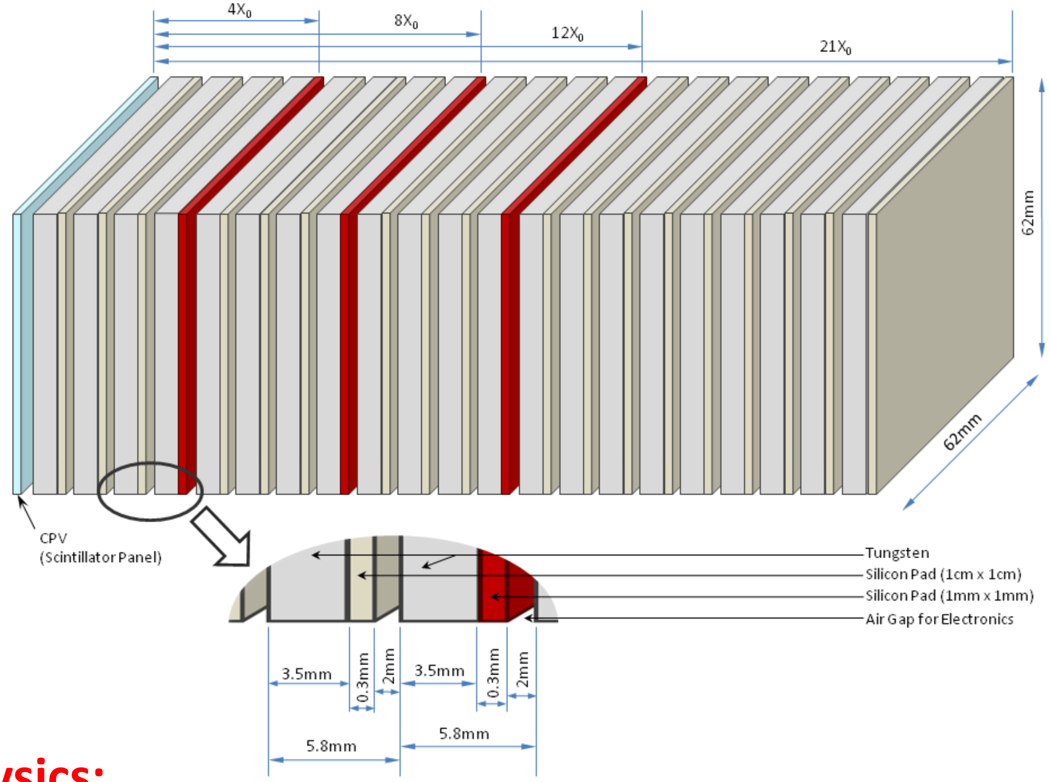
Backups

ALICE Upgrade: Forward Calorimeter in ALICE

Tungsten – Silicon Calorimeter

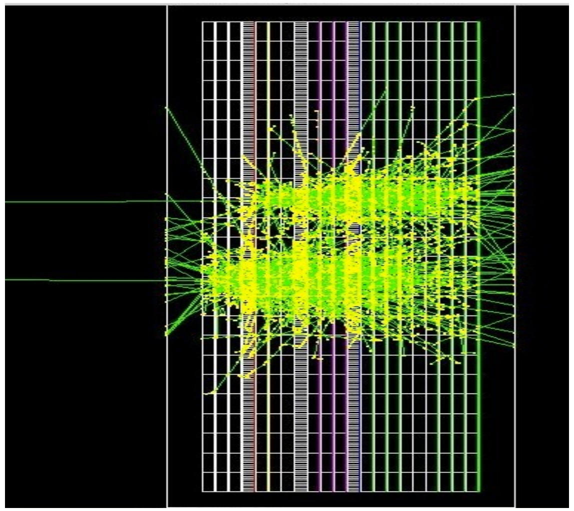
Collaboration with BEL and BARC

Needs High Resolution Silicon Sensors



25 Layers Silicon layers

- **22 layers of 1cm x 1cm silicon pads (500 K channels)**
- **3 layers of 1mmx1mm silicon pads (3 Million channels)**



Physics:

- **Initial State: Low-x Gluon Saturation**
- **Initial State: Nuclear PDFs**
- **Probing the strongly interacting matter thru jet quenching, flow and correlations.**

Operational in Run 4 (2029)

Further info: FoCal-LoI

$3.2 < \eta < 5.8$

General:

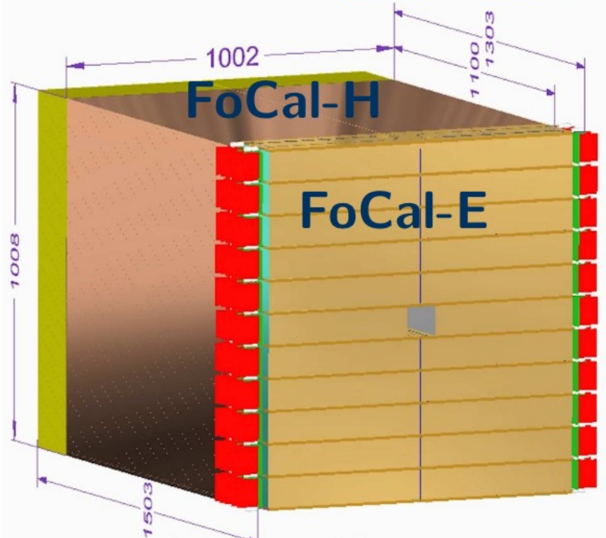
- very forward calorimeter consisting of two parts (FoCal-E and FoCal-H) located $\approx 7\,\text{m}$ from IP of ALICE

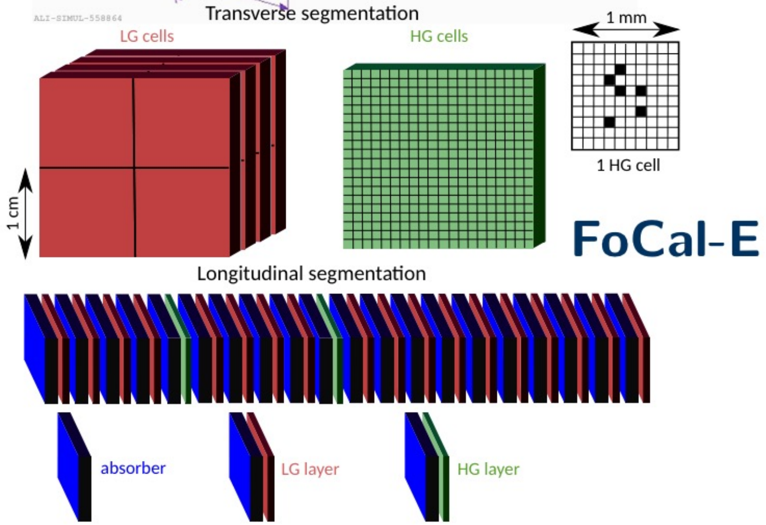
FoCal-E (electromagnetic):

- high-granularity Si-W sampling calorimeter combining two readout granularities:
  - 18 pad layers with silicon pads $(1 \times 1\,\text{cm}^2)$
  - two pixel layers with digital readout $(30 \times 30\,\mu\text{m}^2)$
- ability to "track" longitudinal component of shower!
- used to measure **photons and** π^0 $(40\,\mu\text{m}$ position res.)

FoCal-H (hadronic):

- conventional metal-scintilator **hadronic calorimeter** behind FoCal-E
- design using scintillation fibres embeded in Cu tubes
- used to measure **photon isolation, jet energy** etc.





F. Jonas, QM-23