PROBES AND TOOLS TO EXPLORE QCD MATTER

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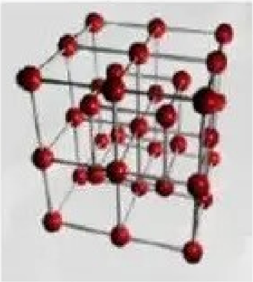
GSI, 10.11.2025

HOW DO WE PROBE THE SMALLEST SCALES OF NATURE?

Matter

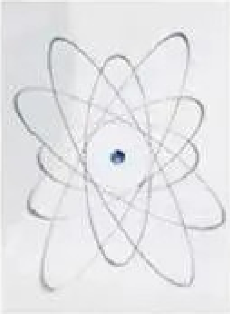
Macroscopic

Crystal



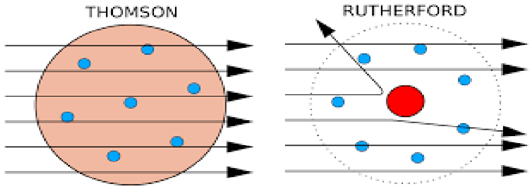
10^{-9} m

Atom

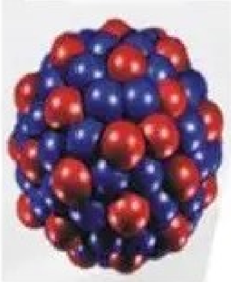


10^{-10} m

< nm: scattering experiments
Rutherford experiment
→ discovery nucleus

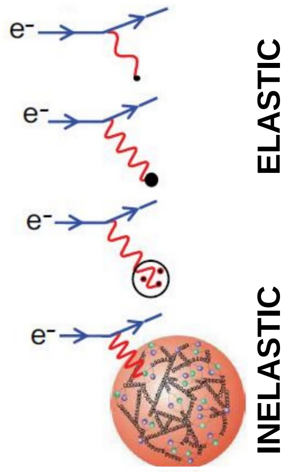


Atomic nucleus



10^{-14} m

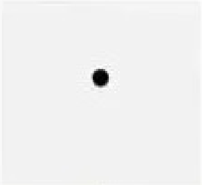
Deep Electron scattering
→ discovery quarks



Nucleon

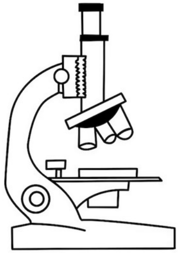
10^{-15} m

Quark



$< 10^{-18}$ m

O (100 nm)
observable optical microscope

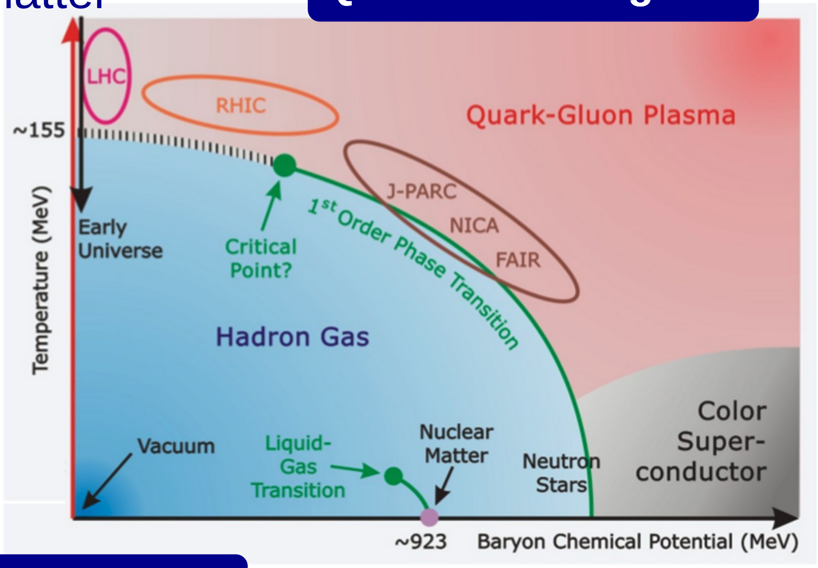


Increase energy → smaller distance scale → deeper level

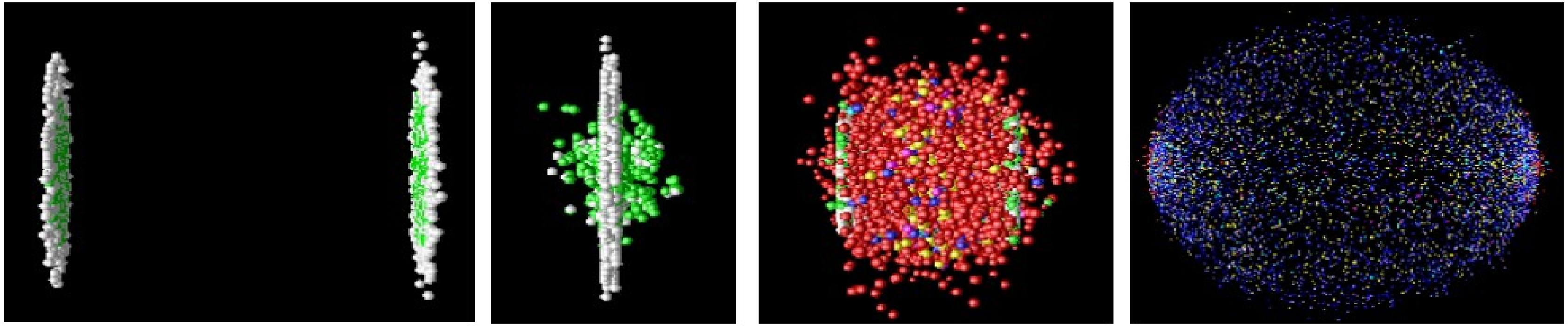
HEAVY ION COLLISIONS

- **Heavy-ion collisions:** recreate extremes → new form of matter
- **QCD Phase Diagram:** maps out the different phases of matter as a function of T and μ_B
- **Equation of State (EoS):** governs the system's dynamics
  - Hadronic phase
  - Quark Gluon Plasma (QGP)
  - Phase boundaries, critical point
- **Experimental access to QCD matter**
  - Study particles emerging from the fireball (number, momentum, composition, correlations)
  - Learn properties of the medium (density, collectivity, thermalization)

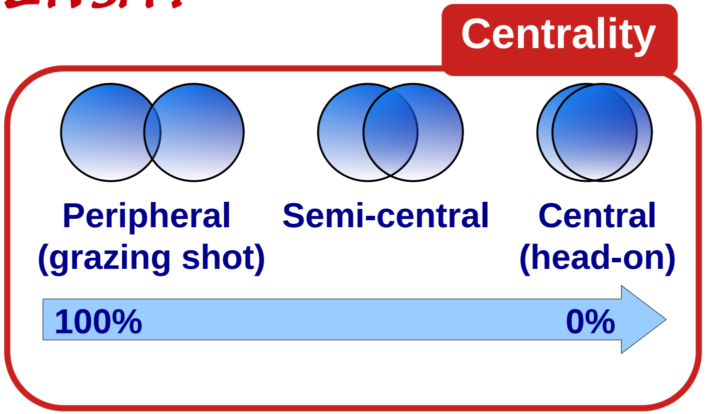
QCD Phase diagram



Heavy ion collision

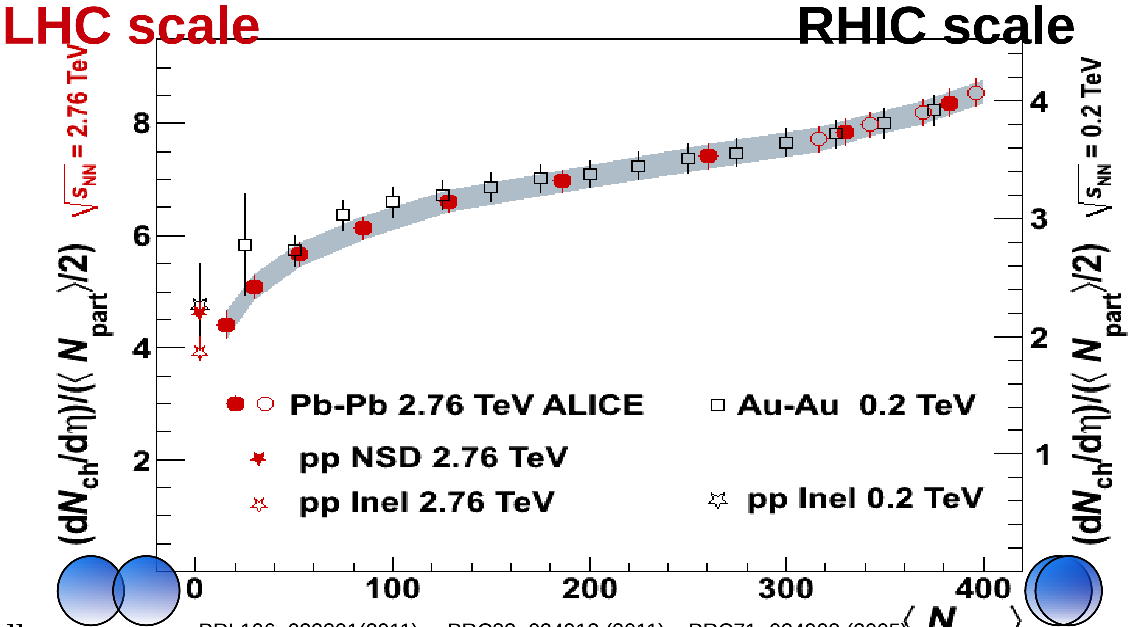


Properties of QGP: Energy Density



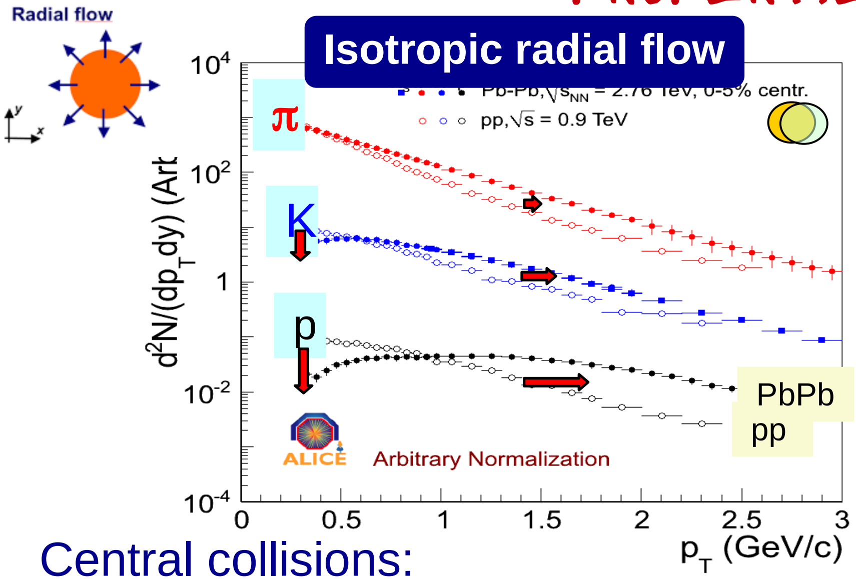
- **Extreme Particle Multiplicities**
- **Beyond Simple p+p Superposition**
  - $N_{ch}/N_{participant\text{-}pair}$ ~ 8 in Pb+Pb
    ~ 4 in p+p

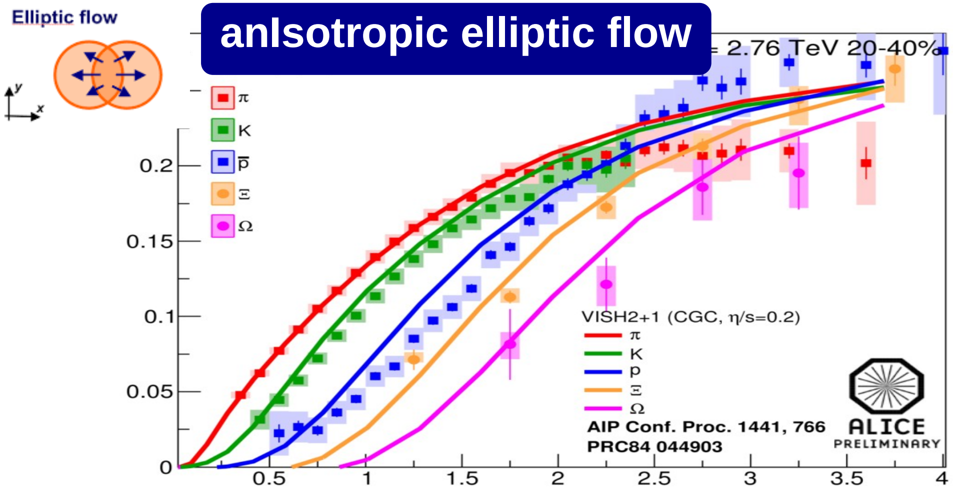
→ **Creation of a Dense Medium**
- Large **energy density**
- Large **entropy**
  well above QCD critical threshold
- Conditions ideal for forming QGP



PRL106, 032301(2011) PRC83, 024913 (2011) PRC71, 034908 (2005)

PROPERTIES OF QGP: COLLECTIVITY





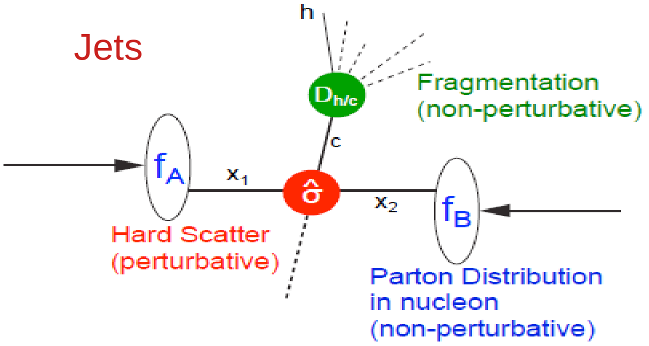
Central collisions:
- High internal pressure
  → **explosive early expansion**
- **Hardening of spectra**
  - Stronger for heavier particles

Semi-peripheral collisions:
- Initial spatial asymmetry
  → **Asymmetry** in momentum space

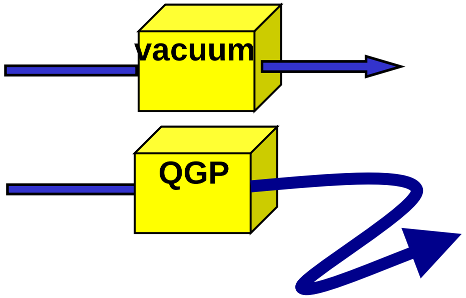
- **Evidence of Strong Collective Behavior**
- Fast hydrodynamic-like expansion
  → **QGP: strongly interacting liquid** (low viscosity)

PRC.93.034916 PRL 105, 252302 (2010)
PRC 84, 044903 (2011) PRL 109, 252301 (2012)

HARD SCATTERING



- **high-p_T parton** produced in a **hard** scattering process (high momentum transfer)
- **calculable in pQCD** (at high-p_T)
- created **early in the collision**



In Pb+Pb Collisions:

Before hadronizing, high-p_T partons interact with the medium:

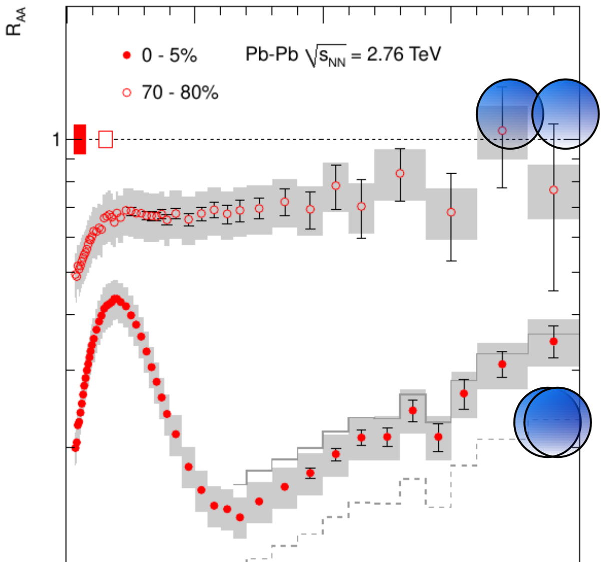
→ **"jet quenching"**

The **nuclear modification factor R_{AA}** is defined as:

$$R_{AA} = \frac{Yield\ in\ A+A}{N_{binary} \times Yield\ in\ p+p}$$

- N_{binary}: NN collisions in AA
- **Strong** (15%) **suppression** observed in central AA

→ strong parton energy loss and large medium density

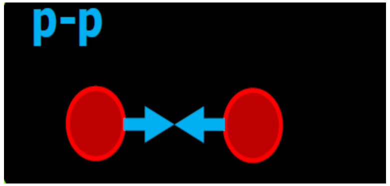


PLB 696 30–39 (2011).

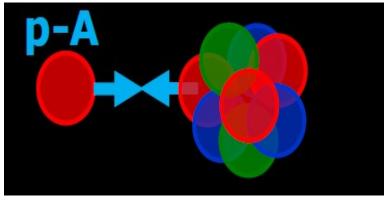
A CONTROL EXPERIMENT

- Probe well calibrated → behaviour in “standard” matter under control
- Colorless probes:
  - Electro-weak bosons
  - Direct photons

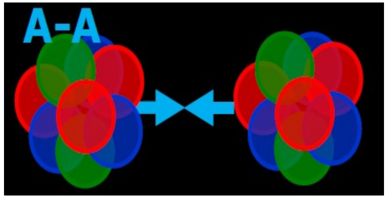
  scale with N_{coll}



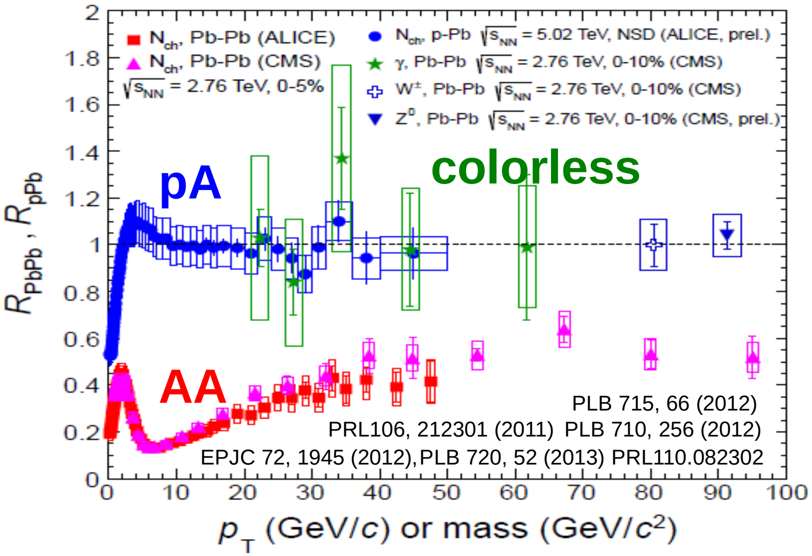
- **p-p: Reference** process to understand behaviour in pA, AA collisions



- **p-A:** Investigation of **cold nuclear matter** effects (shadowing, energy loss…)

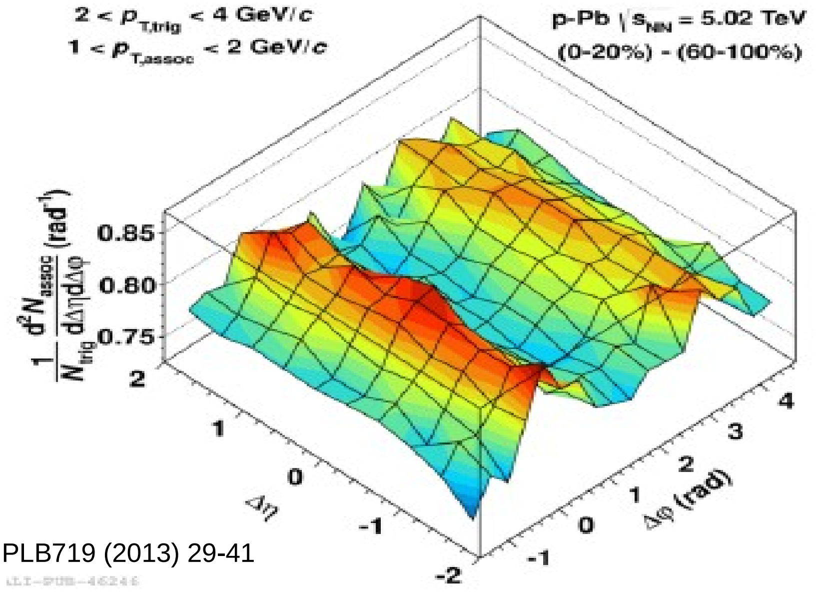


- **A-A:** Probe **parton energy loss** in the hot medium created in the collision (QGP)



provide experimental demonstration that suppression = parton energy loss

COLLECTIVITY IN SMALL SYSTEMS



PLB719 (2013) 29-41

Long range Two-particle correlation:
Double (near+away side) ridge
structure emerging

→ **common underlying physics?**

Other signs of collectivity

- Hardening of the particle spectra
  → **common radial boost?**
- Mass ordering of elliptic flow typically arising from initial anisotropy of local energy density
  → **interactions with the medium?**
- Baryon-over-meson enhancement
  → collective flow or recombination?

- Also observed in high multiplicity pp collisions
  → **collectivity in small systems ?**

PERSONAL CONTRIBUTION

MAIN RESULTS IN A NUTSHELL

- **First Physics Task Force**
- Particle Production
- Centrality Framework
- **PWG Convener**
Event Characterization

- **Chair pPb Task Force**
- Collectivity in small systems
- Centrality Bias
- Unbiased centrality determination

The LHC experiment collaborations at CERN receive Breakthrough Prize

The Breakthrough Prize in Fundamental Physics was awarded to the ALICE, ATLAS, CMS and LHCb collaborations during a ceremony held in Los Angeles on 5 April

7 APRIL, 20

1 / 13000

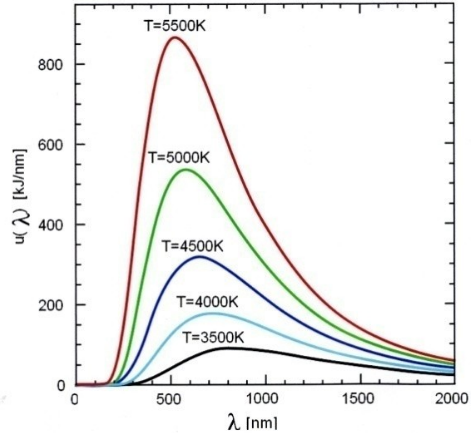
The prize was awarded to the collaborations for their "detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, and ***the exploration of nature at the*** *shortest distances and* ***most extreme conditions at CERN's Large Hadron Collider".***

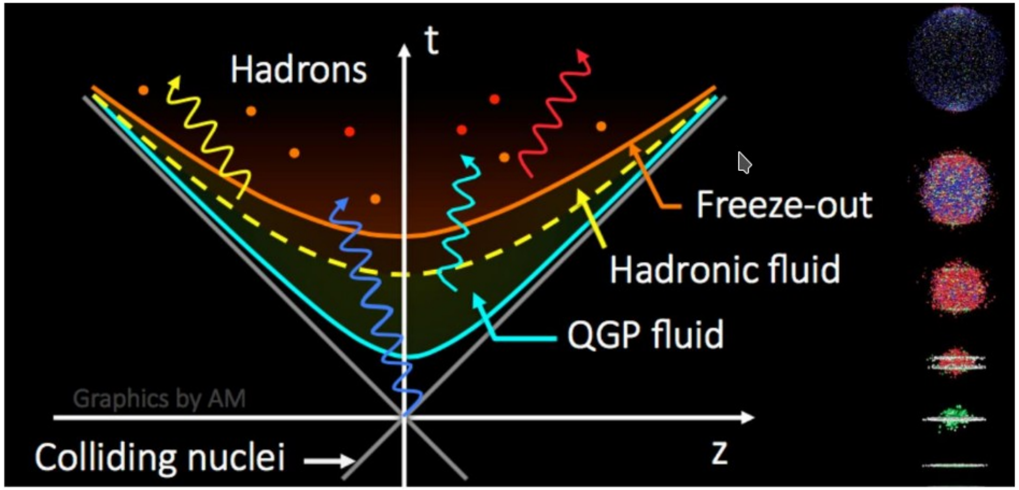
PUBLICATIONS

- [ALICE] PLB 790 (2019) 35-4
- [ALICE] PLB 788 (2019) 166-179
- [ALICE] PLB 784 (2018) 82
- [ALICE] JHEP 1811 (2018) 013
- [ALICE] PLB 753 (2016) 319-329
- [ALICE] PRL 116 (2016) 22, 222302
- [ALICE] PLB 753 (2016) 319-329
- [ALICE] PRL 105:252301 (2010)
- VIEWPOINT Edvard Shuryak
https://physics.aps.org/articles/v3/105
- [ALICE] PRL 110 032301 (2013).
- [ALICE] PRC 88 044909 (2013).
- [ALICE] PRL 106:230301 (2011).
- [ALICE] PLB 696 30–39 (2011).
- [ALICE] PRL 105:252302 (2010).
- [ALICE] JPCS 668 (2016) 1, 012086
- [ALICE] EPJC 77 (2017) 1, 33
- [ALICE] PLB 754 (2016) 373-385
- [ALICE] JHEP 11 (2015) 127
- [ALICE] IJMPA 29 (2014) 1430044
- [ALICE] PLB 727 (2013) 371-380
- [ALICE] PRL 110 082302 (2013).

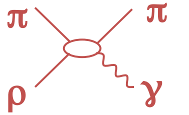
ELECTROMAGNETIC RADIATION

- **Thermal black body radiation (γ, γ*→e+e-)**
  - Hot matter emits thermal radiation
  - Temperature from emission spectrum
- **No strong final state interaction**
  - Leave reaction volume undisturbed
- **Emitted at all stages of the space time evolution**
  - Information must be deconvoluted



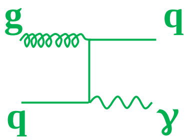


QGP

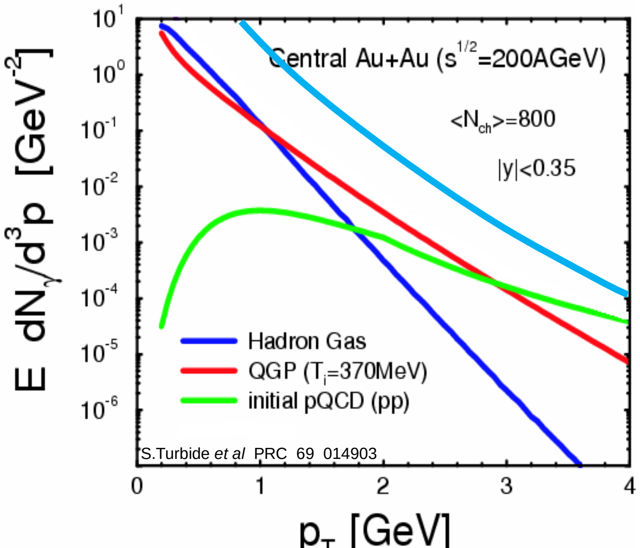


Hadron gas

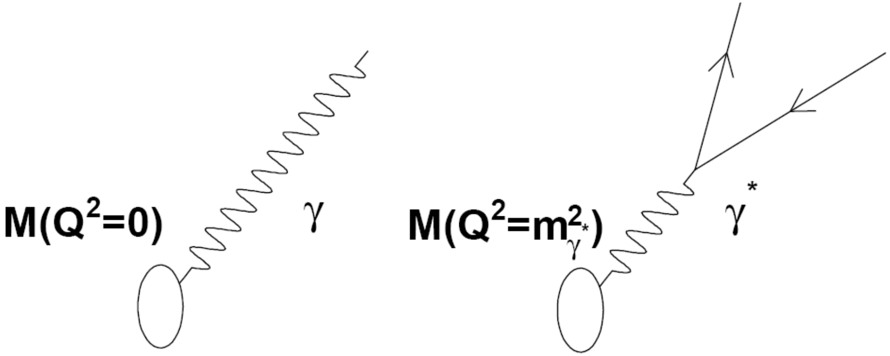
pQCD



Hadron decay photons



PHOTON AND DILEPTON EMISSION



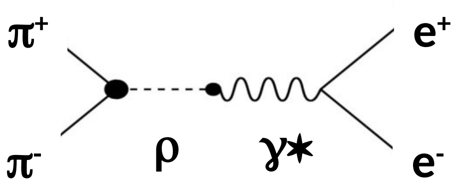
1. measure real photons

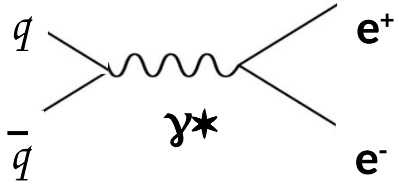
2. measure external conversion
in detector material

3. measure internal conversion of virtual photon into e+e- pairs

- Source of real photon also emits virtual photon
- observed as low mass e+e- pairs
- **Advantage:**
  - Reduce hadron decay background
  - photon ID, energy resolution, etc
- **Disadvantage:**
  - Reduce the yield

From dilepton spectrum:
- **medium effect** on the EM correlator
- **temperature of the medium**

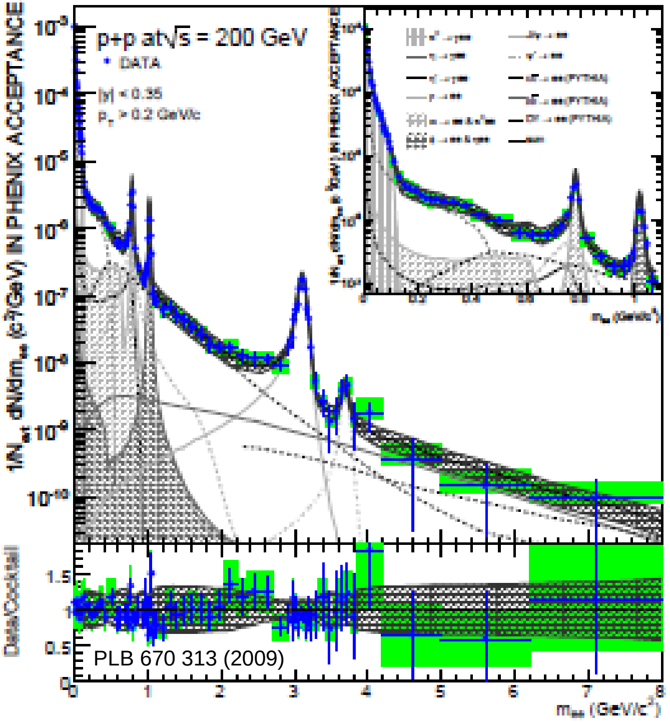




COCKTAIL OF KNOWN CONTRIBUTIONS

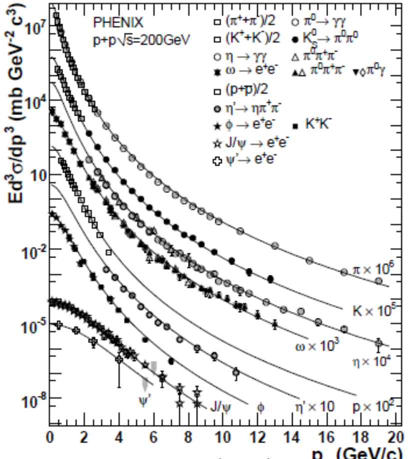
pp measurement

- Agreement of dilepton spectra with hadronic cocktail
- **Indirect Measurement of Heavy Flavour**
  - Charm and beauty cross section
- **Production Mechanism**



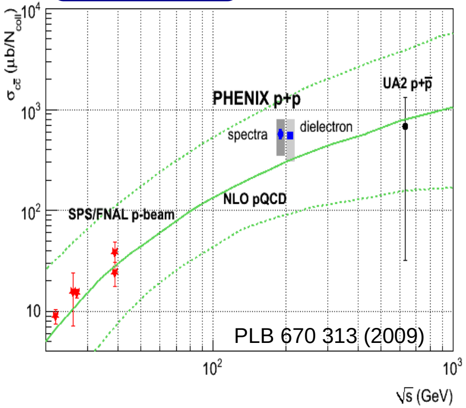
PLB 670 313 (2009)

Mesons



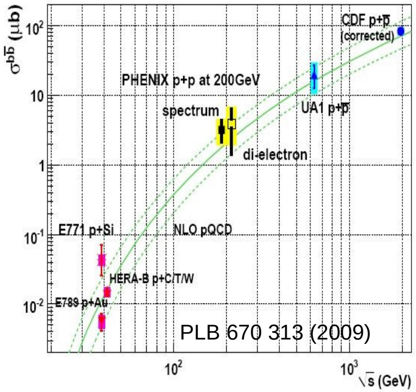
PRD 83 052004 (2011)

Charm



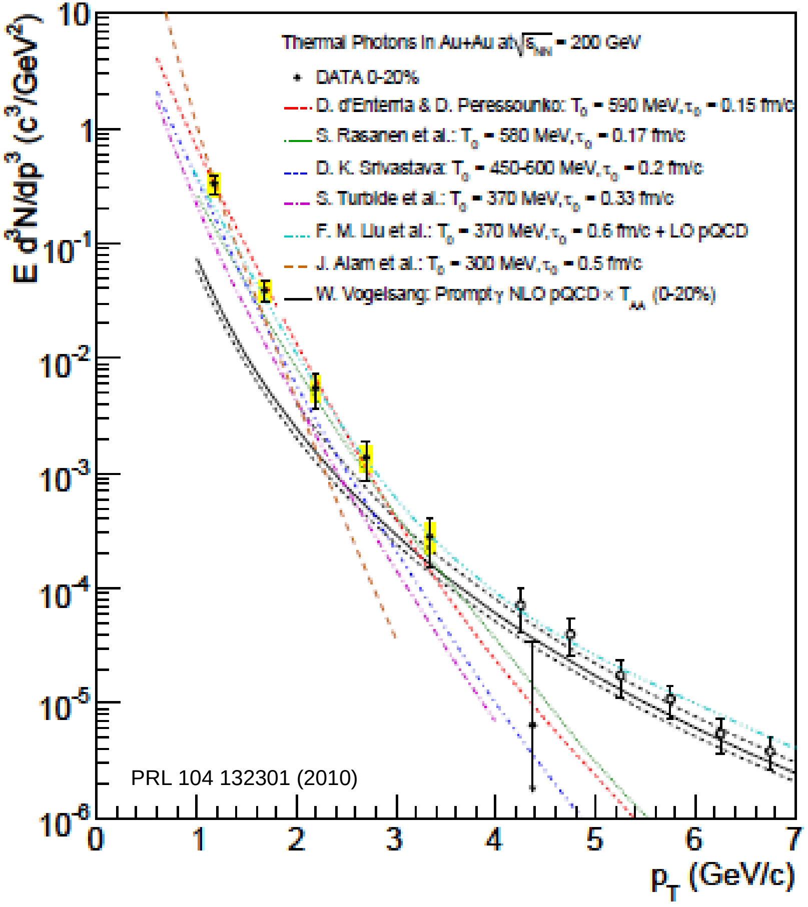
PLB 670 313 (2009)

Beauty



PLB 670 313 (2009)

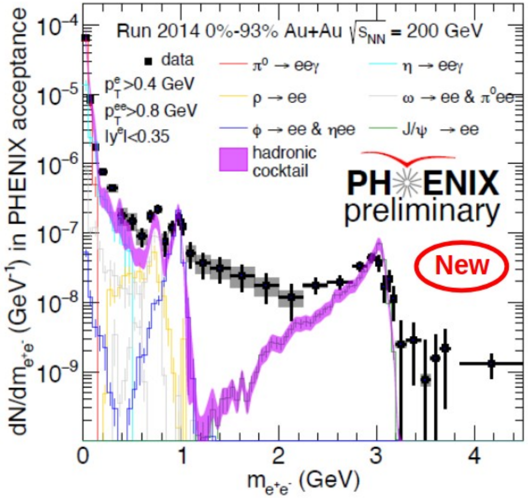
HOTTEST TEMPERATURE



AA measurement

- **Temperature of QCD via photon spectrum**
- 1st Measurement of **direct photon spectrum**

- 1st indication of **thermal photons**
  - → Time-average Temperature: ~220 MeV > T_c
  - → Initial Temperature (theory models) 300-600 MeV well above T_C



arxiv:2308.16704

Personal Contribution

Main Results in a Nutshell

- Meson Systematics
- Charm and beauty cross-section
- Photons and Dileptons
  - p+p
  - Au+Au
  - d+Au
  - Cu+Cu

→ **QGP Temperature**

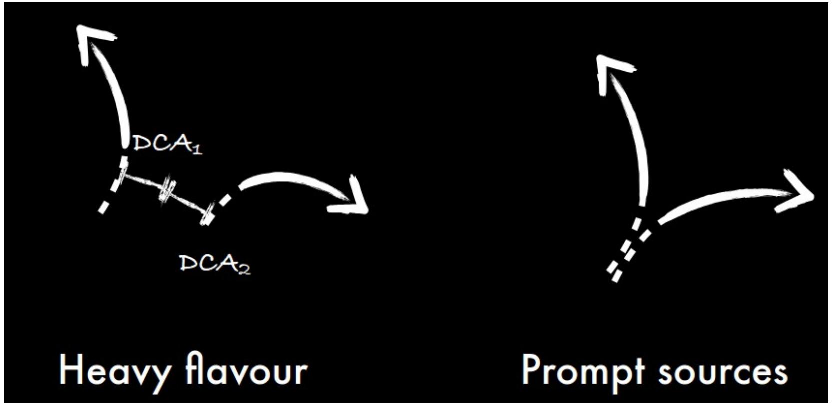
→ in-medium modification vector mesons

- **PWG Convener** Light vector meson
- Hadron Blind Detector

Publications

- [PHENIX] PRL 104 132301 (2010)
- [PHENIX] arXiv:0706.3034
- [PHENIX] PLB 670 313 (2009)
- [PHENIX] PRC 81 034911 (2010)
- [PHENIX] PRL 109 122302 (2012)
- [PHENIX] PRD 83 052004 (2011)
- Viewpoint (Charles Gale) http://physics.aps.org/articles/v3/28

A WAY TO IMPROVE

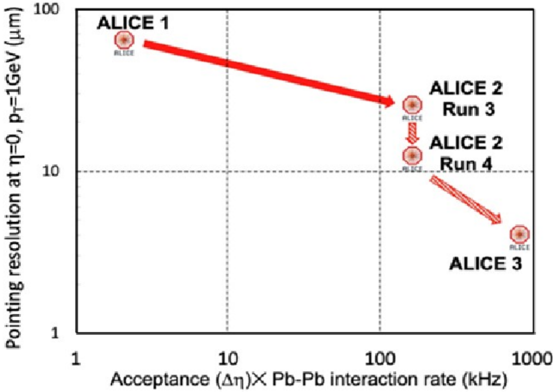


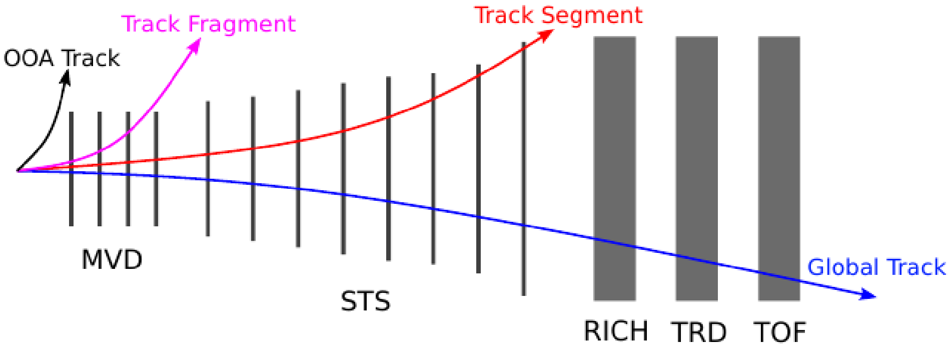
- Remove conversion pairs
  experimentally accessing all track fragments

- Experimentally assess **heavy flavour decays**
  finite decay length (150 - 500 μm)
  → **Improve in pointing resolution**
  → **Silicon Vertex Detector**

ALICE1 → ALICE2 → ALICE3

- Increasing acceptance
- Improving resolution



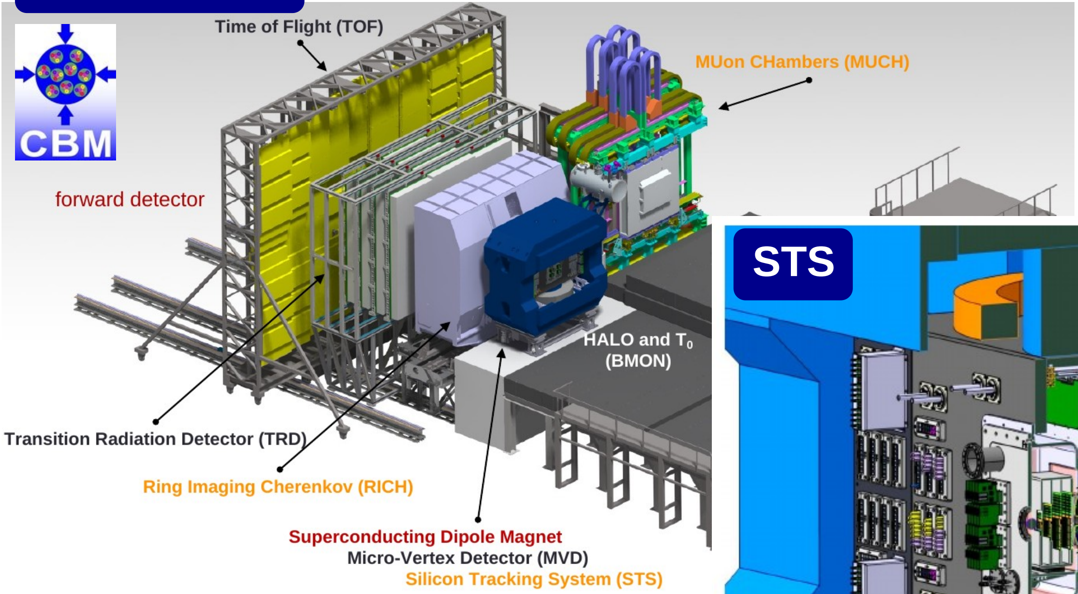


CBM tracking layers

- High resolution near vertex

The Silicon Tracking System of CBM

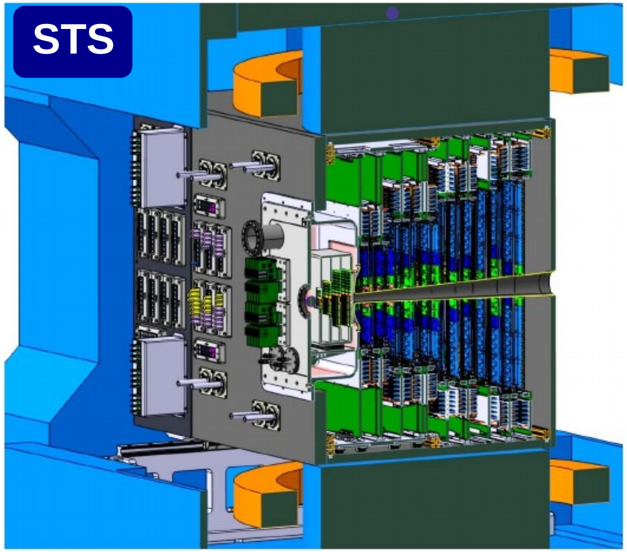
CBM @ FAIR



Minimal material, maximum coverage

- 8 tracking stations, 4 m^2 of Si strip sensors
- **Light-weight:** 0.4% – 1.4% X_o per station
- FE-electronics outside acceptance

STS



Requirements:

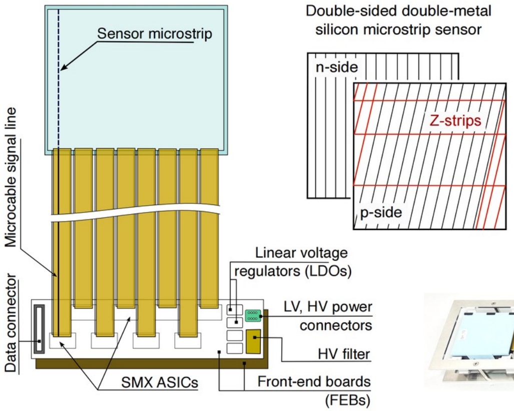
- High-rate collision **10^7 Hz Au+Au**
- Hit spatial resolution: 25 μm
- Δp/p: 1.8%
- Track reconstruction efficiency: 96%
- Self-triggering front-end electronics with **free-streaming readout**
- **Online tracking and event selection**

STS group @ GSI – Uni Frankfurt

W3 Professor at Frankfurt Uni
Supervisor for 3 Post-Doc, 11 PhD

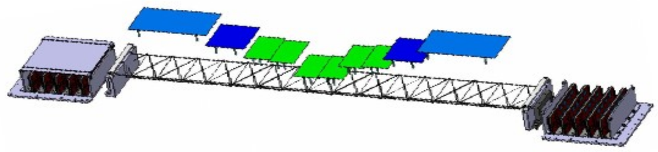
on different detector projects
- Detector development
- Charcterization
- Performance studies

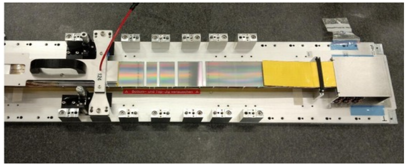
THE STS FOUNDATION



MODULE

- Large area **double-sided, double-metal Si sensors**:
  - 1024 strips/side, 58 µm pitch
  - Thickness:~320 µm, Strip length 2/4/6/12 cm
  - 7.5° stereo angle for p-side strips
  - Radiation tolerance: 10^{14} neq (1 MeV) /cm²
- Light weight polyimide **microcables**
- **2 Front-end boards** (FEB) carrying 16 SMX ASIC

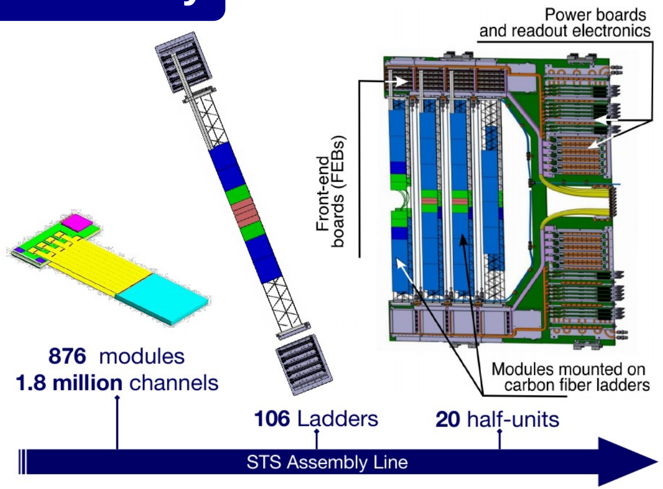




LADDER

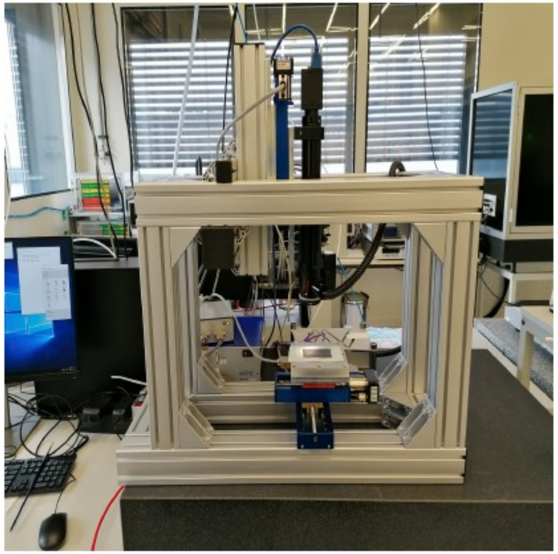
- Up to 10 modules mounted onto **low-mass carbon-fiber structure**
- Assembly precision <100 μm monitored via optical inspection

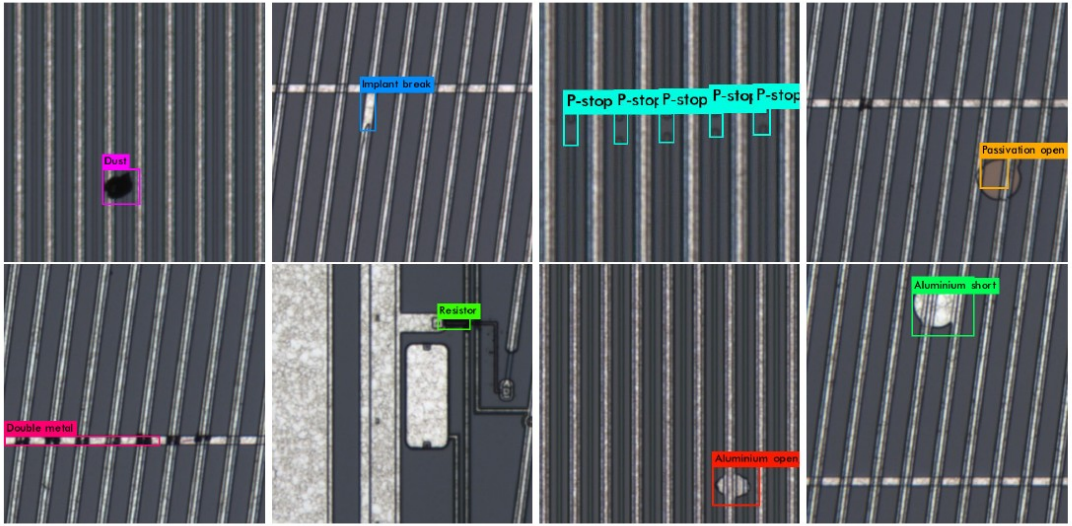
STS in assembly



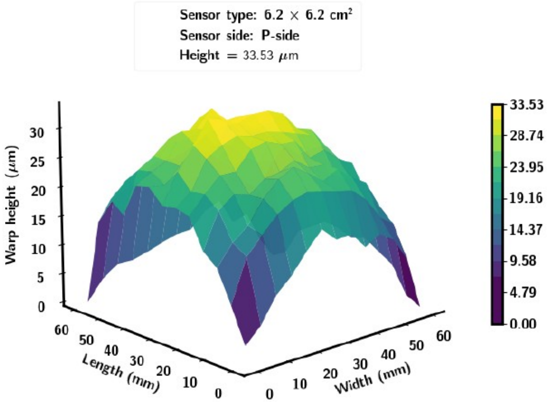
SENSOR QUALIFICATION

MASTER THESIS
M.SHIROYA



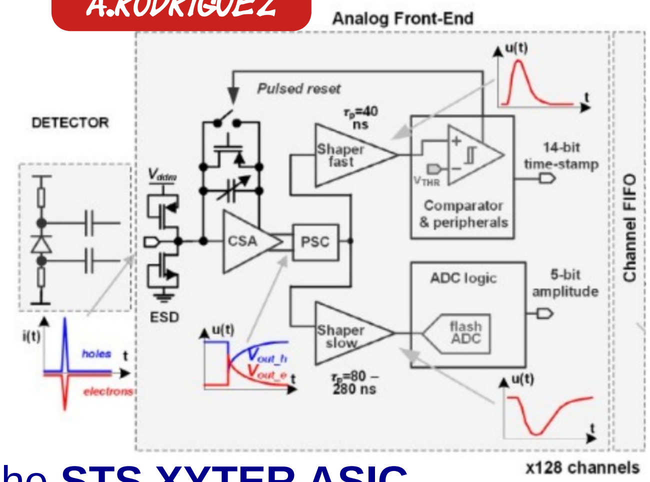


- Surface scanning of **1191 sensors**
  - custom made, automated optical inspection setup
  - analyzed with advanced methods using ComputerVision and Deep Convolutional **Neural Networks**
  - sensors geometry **metrology**



Characterization of module and ASIC

PHD THESIS A.RODRIGUEZ

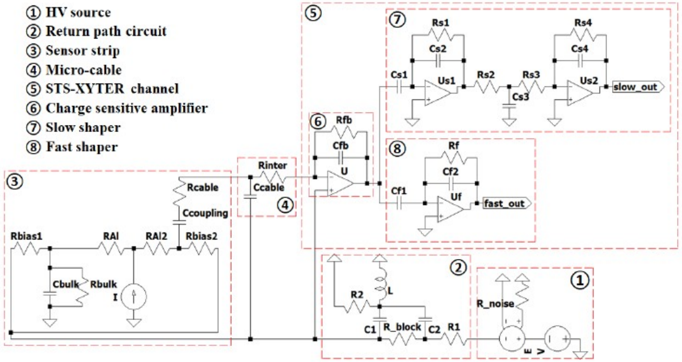


The **STS XYTER ASIC**

- Self-triggered signal, dual path processing:
  - Timing comparator (< 5ns resolution)
  - 5 bit flash ADC (15 fC dynamic range)
- From 1 to 5 data uplinks (9.41 Mhits/s per link)

Understanding, modeling and implementing the analogue response

SAFE



PHD THESIS O. KSHYVANSKYI

QA protocols
for series production

PHD THESIS D.RODRIGUEZ

Clean Tent @ Heckhalle

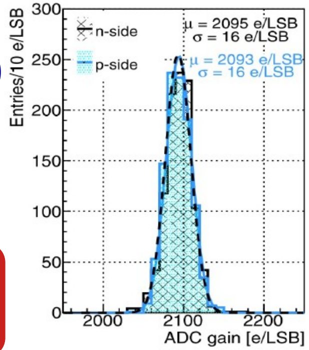
ASSEMBLY STATUS
01.11.2025

- ☑ MODULES: 672
- ☑ M. Testing: 550
- ☑ LADDERS: 21
- ☑ L. Testing: 15

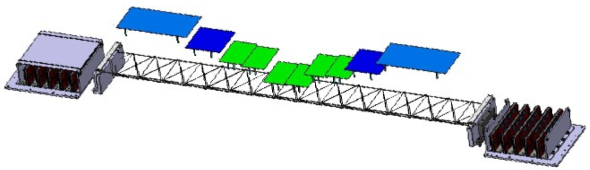
PHD THESIS L.M.COLLAZO

Gain and Threshold calibration
with built-in calibration circuit

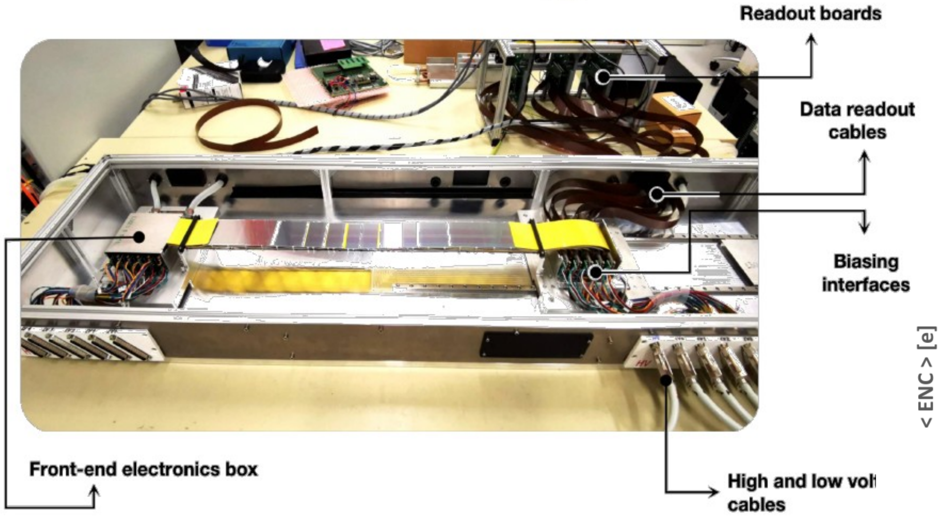
PHD THESIS O.MARAGOTO



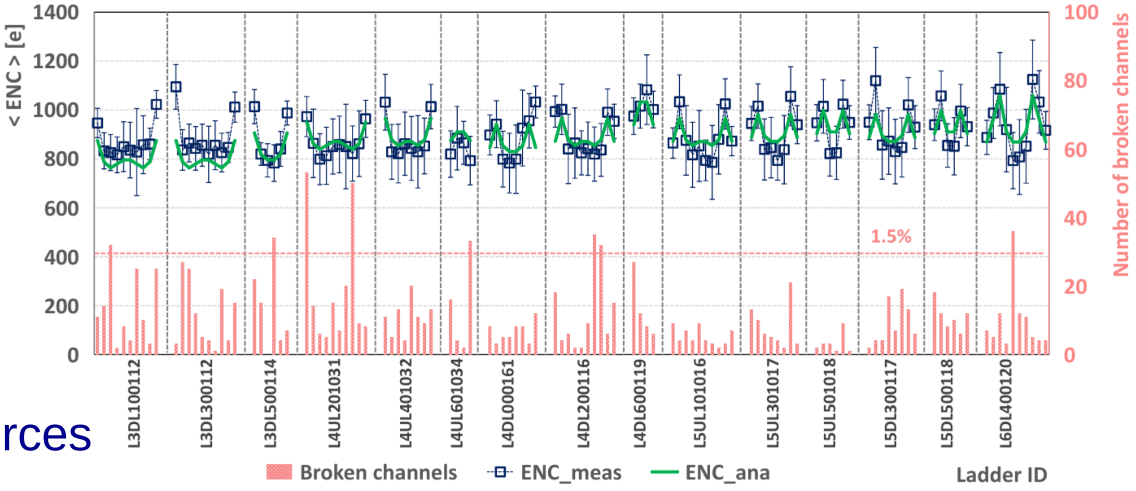
CHARACTERIZATION OF LADDERS



Ladder characterization
- Quality of the assembled ladders
- Functional performance of the modules on the ladders
- Detailed noise and signal response



PHD THESIS
L.M.COLLAZO



Ladder test setups
- All interfaces for operation (LV, HV, data readout, cooling)
- Slit for measurements with radioactive sources

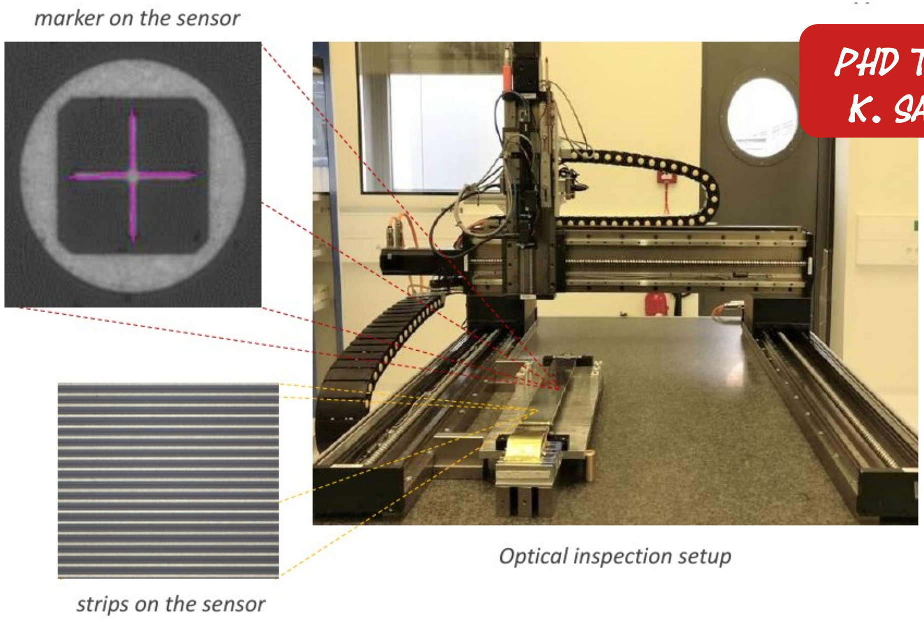
DETECTOR INTEGRATION

Ladder Metrology

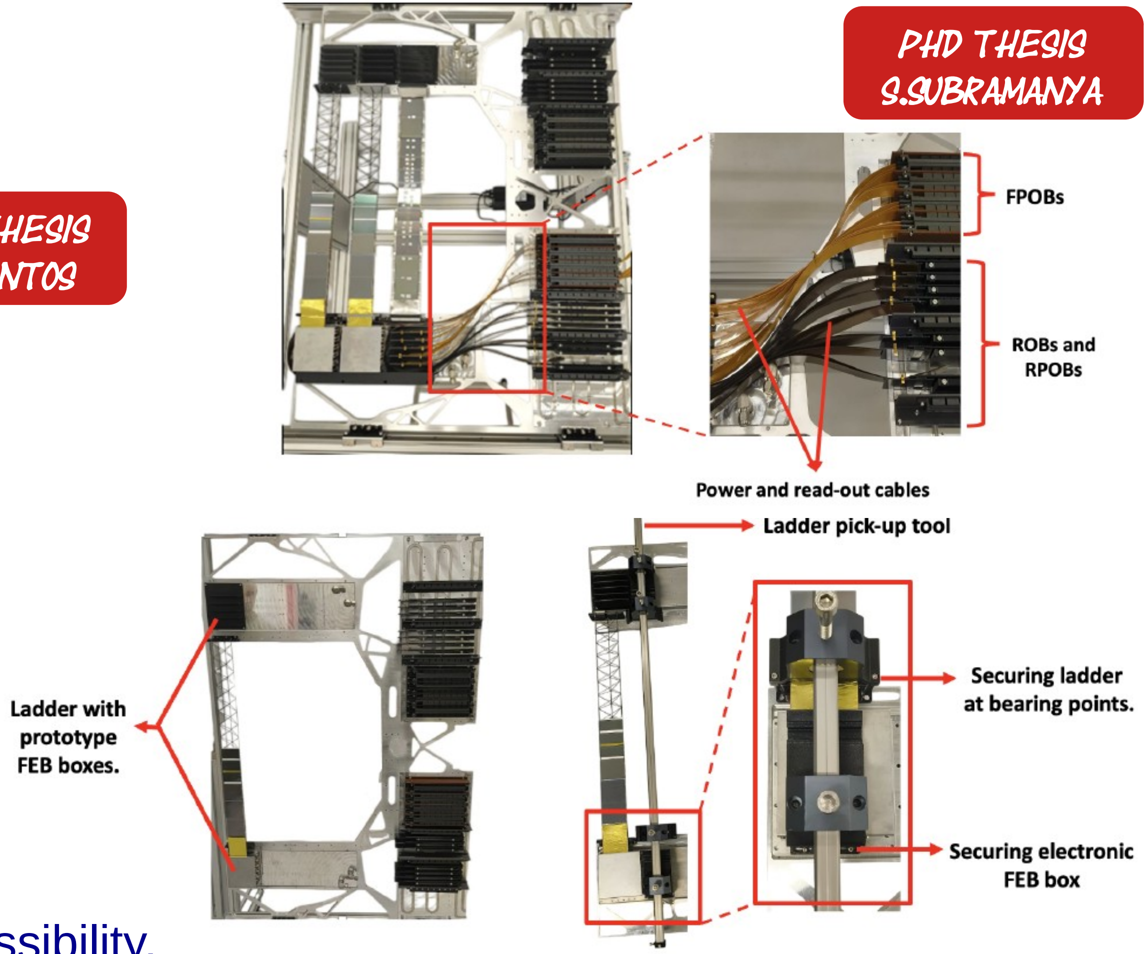
- optical inspection of the sensor surface

→ ladder on C-frame and in the STS box

PHD THESIS K. SANTOS



PHD THESIS S.SUBRAMANYA



Half-Unit Assembly

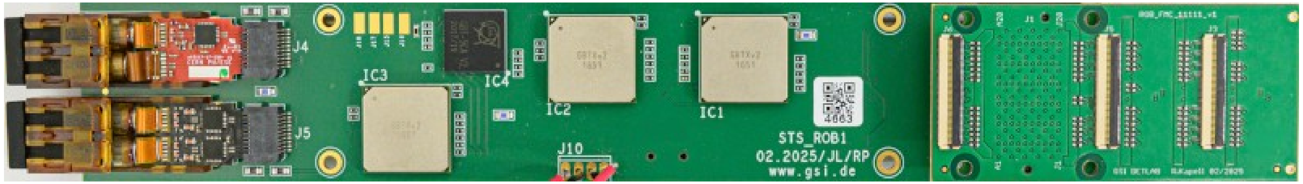
- mockups studies → verification of mechanical fit, alignment, component accessibility, assembly workflow → integration methods, cabling sequence, assembly procedures

READOUT AND CONTROLS

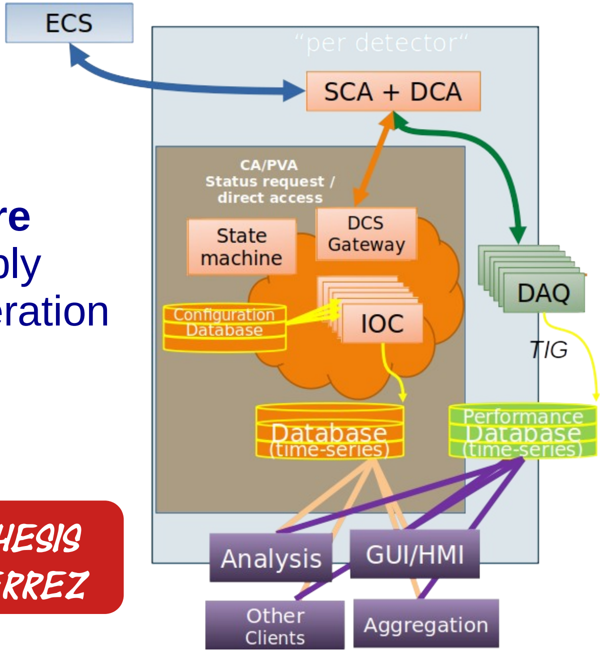
STS Readout chain

Front-End Board → CROB/ STS-ROB → CRI → FLES Entry nodes

New developments for
Readout Board:

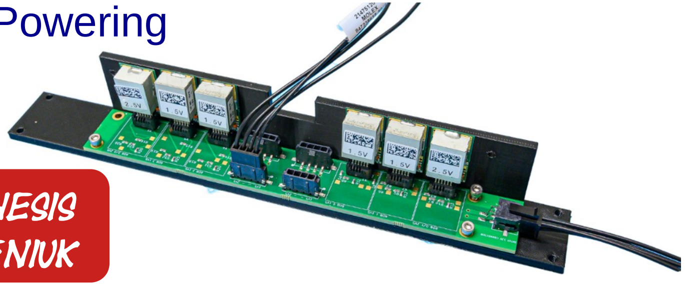


Detector Control System



STS-ROB Testing and Characterization

- Extensive evaluation of operational functionality and data transmission
- Add-on Board for commissioning
- Readout Powering



PHD THESIS
P.SEMENIUK

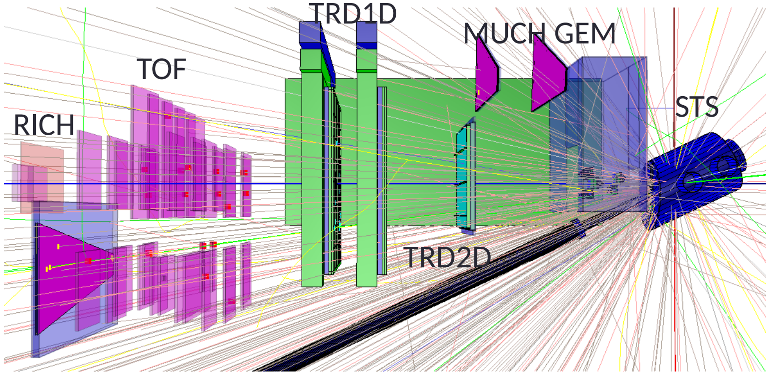
DCS / ECS
Computing Infrastructure

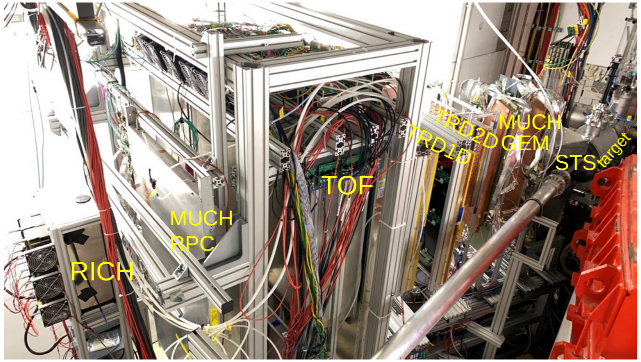
- Lab tests during assembly
- Commissioning and operation full STS

PHD THESIS
D.GUTIERREZ

IN-BEAM TESTS

STS in mCBM @ SIS18



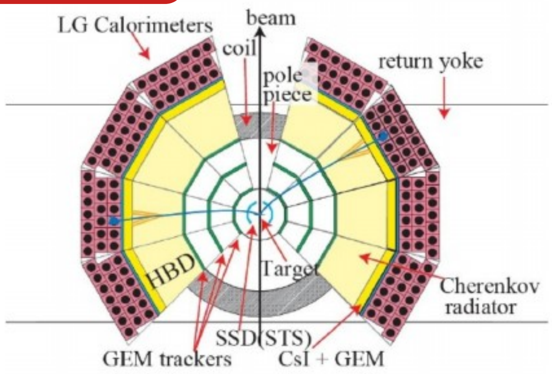


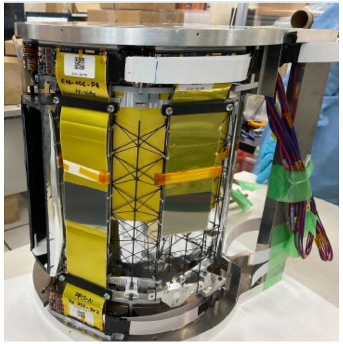
3 tracking stations
- 6x6 cm^2 (1 module / 1 ladder)
- 12×12 cm^2 (4 modules / 2 ladders)
- 18×18 cm^2 (7 modules / 3 ladders)

- Various **beam-test campaigns** since 2018:
- Various intensities up to p: 10^{10}, A: 10^9 /spill

PHD THESIS D.RODRIGUEZ

STS in E16 @ J-PARC



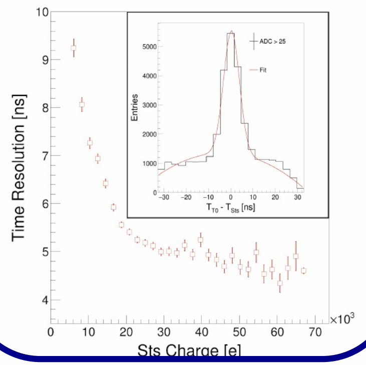


10 pre-series STS modules were built, assembled and tested at GSI and are installed as innermost tracking detector of the E16 experiment at J-PARC.

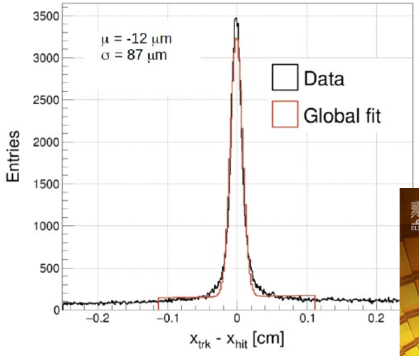
PERFORMANCE

PHD THESIS D.RAMIREZ

Time resolution

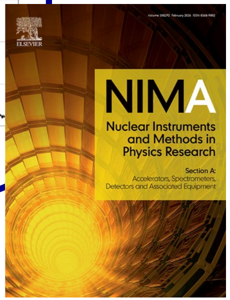


Space resolution



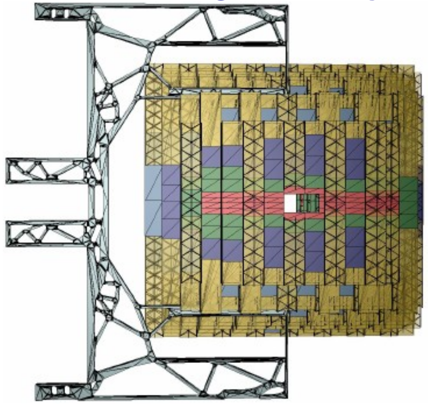
Expected for CBM

1st CBM paper

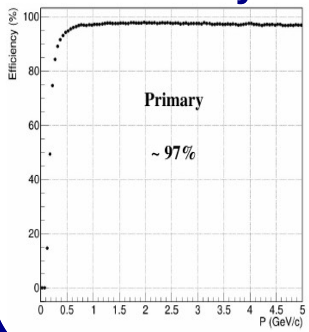


PHD THESIS M.SHIROYA

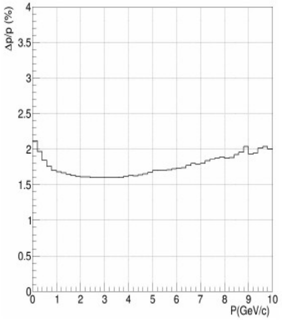
Detector geometry



Efficiency



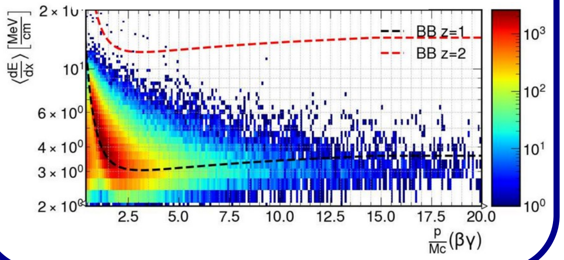
Resolution



Measured in beam test

- time resolution: 5 ns
- space resolution: 20 μm
- hit reconstruction efficiency 98%
- tracking and vertexing
- deadtime: 200 – 350 ns
- signal rates up to 56 kHz/ch
- PID capabilities with dE/dx

Energy loss vs p



PHD THESIS D.GUTIERREZ

PERSONAL CONTRIBUTION

MAIN RESULTS IN A NUTSHELL

- **Group for STS:**
3 Post-Doc, ~11 PhD

- Sensor qualification
- ASIC characterization
- Module characterization
- Ladder characterization
- System integration
- Readout
- Data analysis
- Physics performance
- Tracking, vertexing
- Simulation: geometry, digitizer
- Detector Control
- Alignment

- Software responsible STS
- **PWG Convener**
Physics performance studies

PUBLICATIONS

- [CBM], NIM A 1082 (2026) 171059
- [E16], E16-STS in prep. NIM A
- [CBM], NIM A 1080 (2025) 170714
- [CBM] JINST 20 C03020 (2025)
- [E16] JSPC 3 100019 (2025)
- [CBM] NIM A 1066 169620 (2024)
- [CBM] JINST 19 C07002 (2024)
- [CBM], NIM A 1058 168813 (2024)
- [CBM], PoS p.64 (2024)
- [CBM], PoS p.050 (2023)
- [CBM] NIM A 1021 165932 (2022)
- [CBM] NIM A 908 225–235 (2018)

SUPERVISION

PHD

- ARR: From the bare ASIC to a full module
- OMR: Full module characterization
- DRZ: Hit reconstruction, tracking and vertexing in miniCBM
- MS: Simulation geometry, digitizer and performance
- DRG: The STS of the E16 experiment at J-PARC
- LMCS: Assembly, QA and operation of modules and ladders
- DGM: Detector Control System
- PS: Developments of Readout Board and operation of readout chain
- OK: Modelling the analogue response
- KSM: Ladder metrology and alignment
- GSS: Detector integration and commissioning

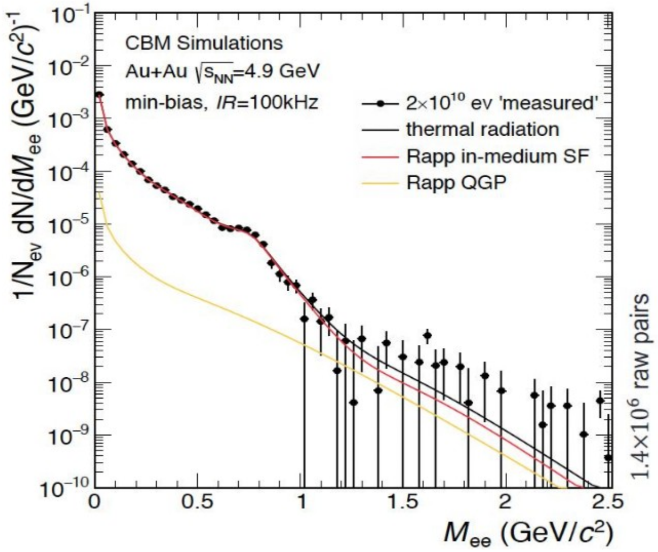
MASTER

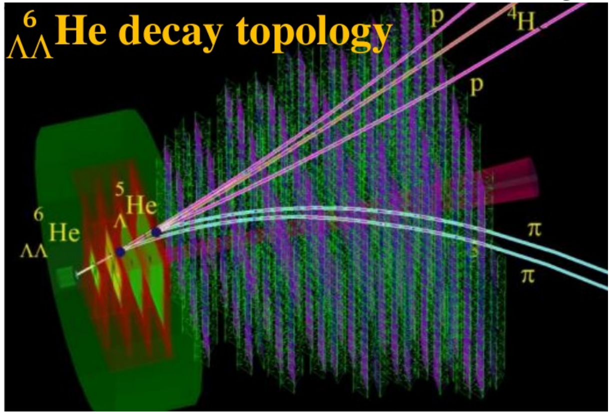
- MS: Optical Inspection of Micro-strips Silicon Sensors

POST-DOC

- VA: tracking in CBM
- ARR: Characterization and test of modules and ladders
- DRZ: alignment

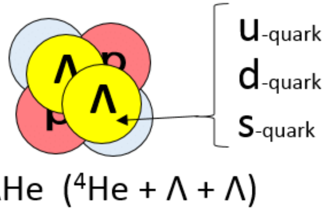
CBM PHYSICS

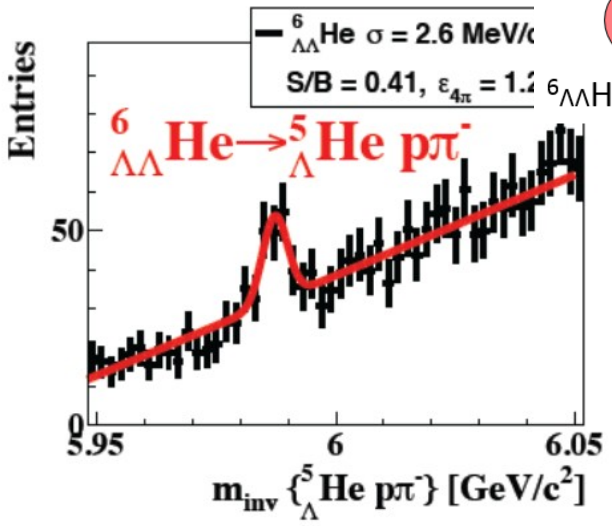




Hypernuclei:

- Strong interaction with s-quarks
- Production mechanism
  → EoS
  → Astrophysical implications
- Need:
- good tracking
- dE/dx PID





Dileptons:

- Unique opportunity to measure e+e- and μ+μ-
- Temperature of the medium

→ caloric curve: 1st order phase transition?

- In medium modification of vector mesons

→ chiral symmetry restoration?

CBM DEPARTMENT: VISION FOR THE FUTURE

BALANCE SCIENTIFIC VISION WITH OPERATIONAL EXCELLENCE
SUPPORTED BY THE VARIEGATED CHARACTER OF THE GROUP

SILICON TRACKING SYSTEM

CORE SOFTWARE

PHYSICS RESEARCH

CBM Department: Vision for the Future

Balance scientific vision with operational excellence supported by the variegated character of the group

Silicon Tracking System

- Complete **STS Construction**
  - Finalize assembly, testing, integration, cooling
  - Prepare and test readout electronic chain
  - Prepare control systems
- **Commission**
  - Lab, Cave, Beam
- **Operation**
  - Shift, Monitor, Experts
- **Data Analysis**
  - Calibrations
  - Simulations
  - Analysis

CBM DEPARTMENT: VISION FOR THE FUTURE

BALANCE SCIENTIFIC VISION WITH OPERATIONAL EXCELLENCE
SUPPORTED BY THE VARIEGATED CHARACTER OF THE GROUP

CORE SOFTWARE

- Core **framework and integration**
  - Development and maintenance
  - Integration of detector-specific code
- **Algorithms** and performance
  - reconstruction, simulation
- **Data management** and infrastructure
  - Data management and storage solutions
  - Coordination with computing infrastructure
- **Quality assurance** and collaboration support
  - Continuous integration, testing, version control
  - Monitoring and QA
  - User support and documentation

CBM Department: Vision for the Future

Balance scientific vision with operational excellence supported by the variegated character of the group

Core Software

- Core **framework and integration**
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  - Coordination with computing infrastructure
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  - Continuous integration, testing, version control
  - Monitoring and QA
  - User support and documentation

- **Data Acquisition (DAQ)**
  - Data readout and event building systems
  - Synchronization and trigger
  - Data quality monitoring
- **Detector Control System (DCS)**
  - Monitor and control of detector parameters
  - Safety interlocks and recovery procedures.
  - Archiving and visualization
- **Experiment Control System (ECS)**
  - State, run control, configuration management
  - User interfaces and automation tools
  - Integration of DAQ, DCS, ECS

CBM DEPARTMENT: VISION FOR THE FUTURE

BALANCE SCIENTIFIC VISION WITH OPERATIONAL EXCELLENCE
SUPPORTED BY THE VARIEGATED CHARACTER OF THE GROUP

PHYSICS RESEARCH

- **Explore QCD Matter with Penetrating Probes**
  - Chiral symmetry restoration
  - Thermodynamics of QCD under extreme conditions
- **High-Precision Measurements at FAIR**
  - Vector mesons & dileptons
  - Thermal radiation
  - Hypernuclei

CBM Department: Vision for the Future

BALANCE SCIENTIFIC VISION WITH OPERATIONAL EXCELLENCE
SUPPORTED BY THE VARIEGATED CHARACTER OF THE GROUP

SILICON TRACKING SYSTEM | CORE SOFTWARE | PHYSICS RESEARCH

Group Structure and Collaboration Dynamics

- **Interdisciplinary approach**
  - physics, computer science, engineering
- **Experience & innovation**
  - Senior researchers, postdocs, and students
  - Training and mentoring (Master, PhD, internships)
- **Internationalization**
  - exchange programs, grants, fellowships, mobility schemes
- **Synergies with other groups**
  - ALICE, HADES, PANDA, Theory, NuSTAR, Detector Lab
- **Knowledge exchange**
  - open-source initiatives, shared technical standards
- **Visibility and outreach**

CBM DEPARTMENT EXCURSION, 30.09.2025