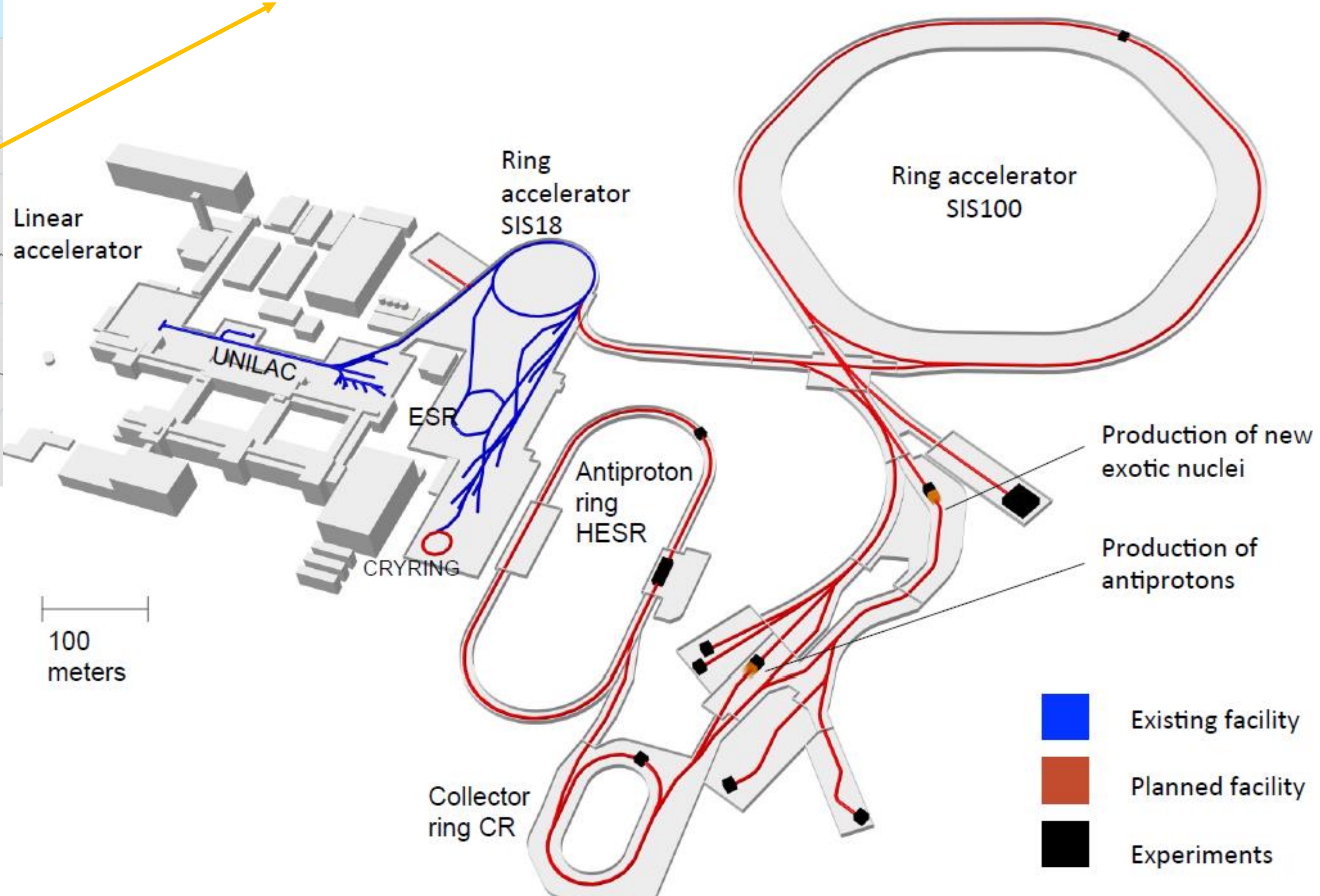
BRAID at GSI/FAIR
Hadron Physics - CBM and PANDA

BRAID

Bridging Domains: AI-Driven Agnostic Reconstruction Frameworks for Irregular High-Dimensional Data

Anastasios Tassos Belias
GSI Helmholtzzentrum für Schwerionenforschung GmbH

Facility for Antiproton and Ion Research
@ GSI, near Darmstadt, Germany



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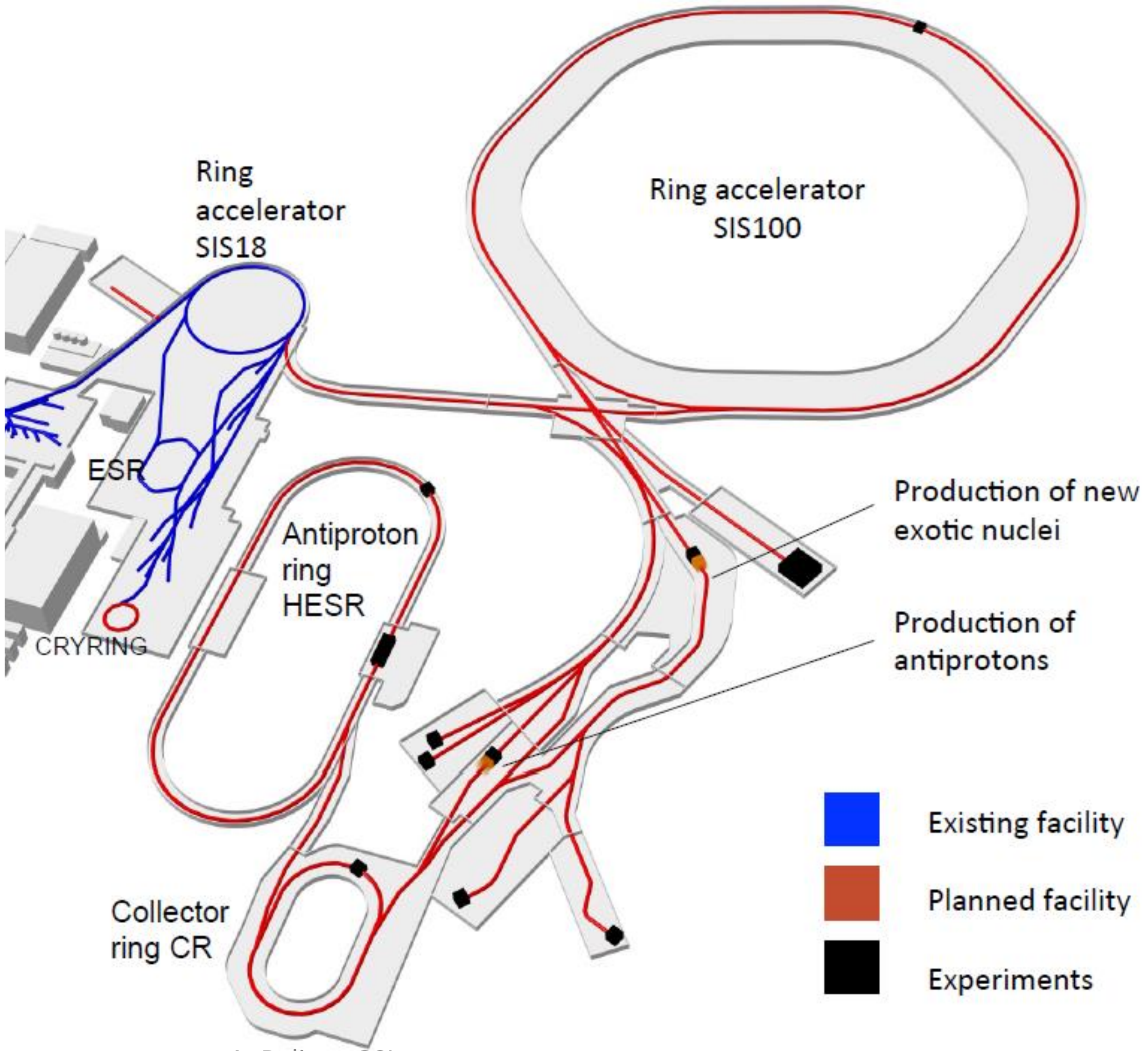
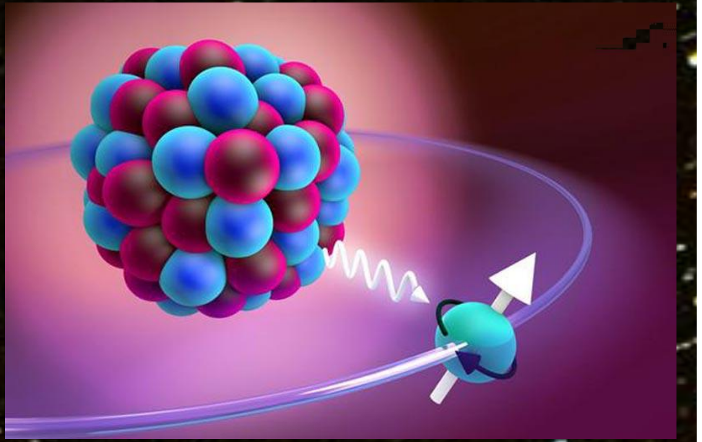
SIS-100 Capabilities			
Beam	Z	A	E_{max} [AGeV]
p	1	1	29
d	1	2	14
Ca	20	40	14
...			
Au	79	197	11
U	92	238	10

- Intensity gain: × 100–1000 (~10^{13}/s for p; ~10^{11}/s for U)
- 10× energy (compared to SIS-18@GSI)
- Spill length: 1–100 s
- Antimatter: antiproton beams
- Precision: System of storage and cooler rings

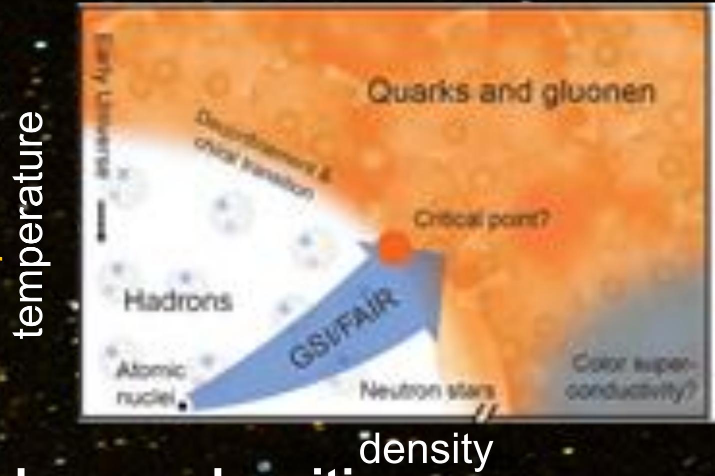


Atomic physics, biophysics, plasma physics, material research



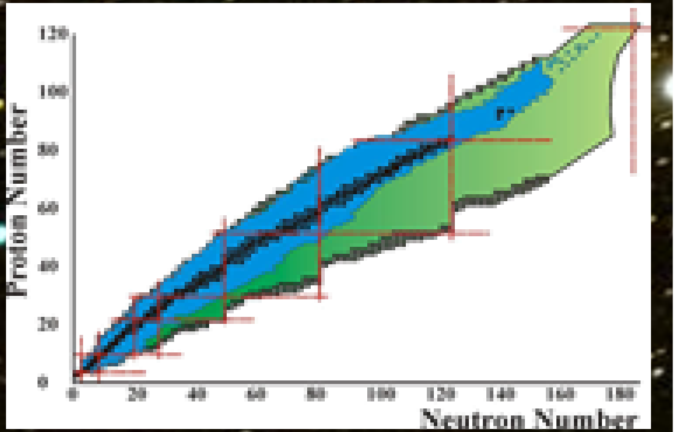
- Precision tests of QED
- Cosmic ray simulator for irradiation studies
- Materials under high pressure

Compressed Baryonic Matter
- Nuclear- and quark-matter



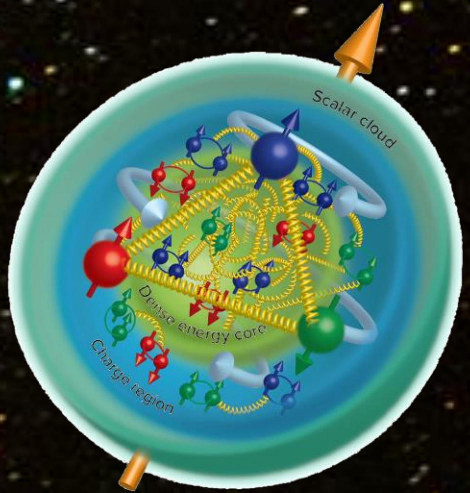
- QCD matter at high baryon densities
- Phase transition and critical point
- Particles in dense medium

Nuclear structure and nuclear astrophysics



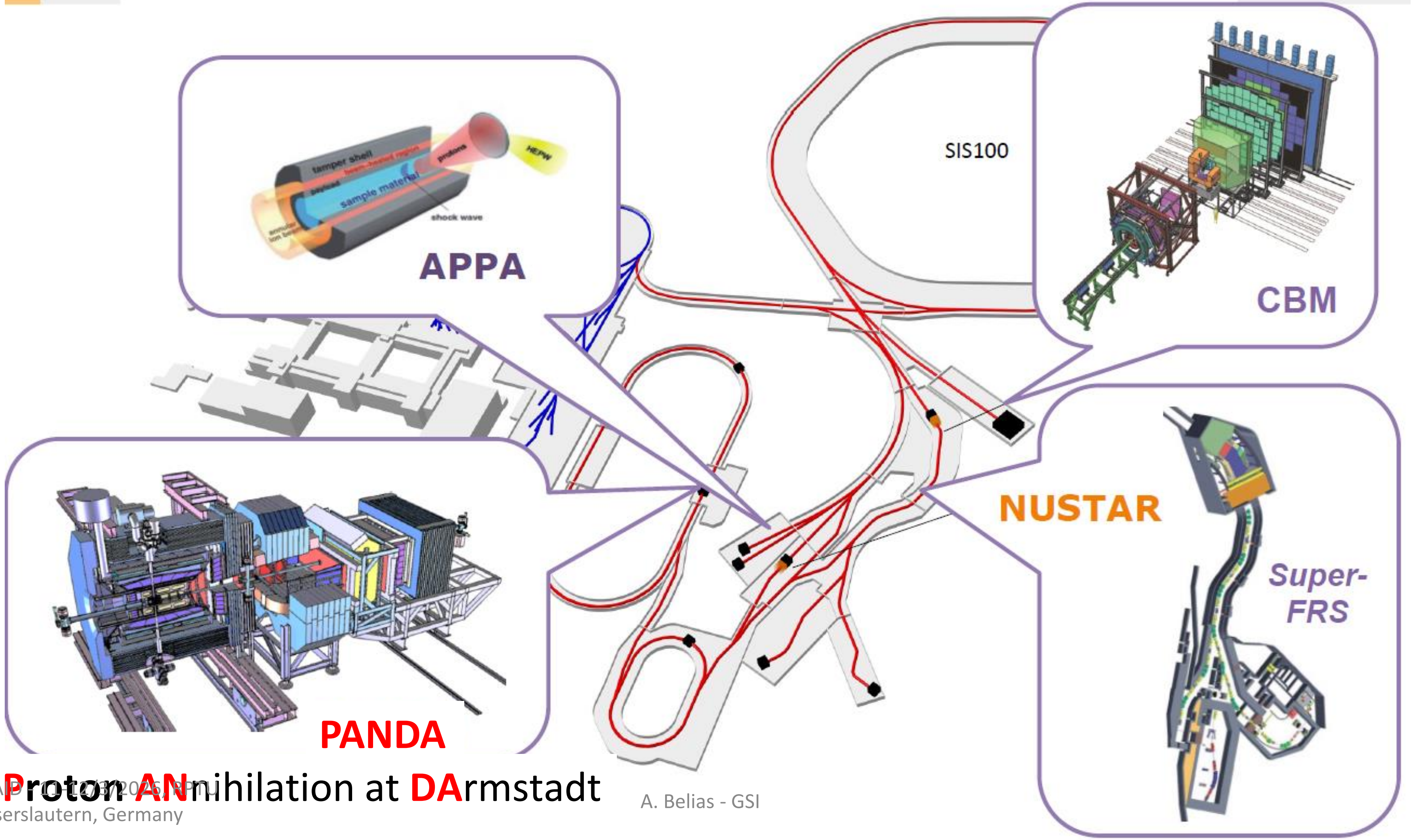
- Nucleosynthesis of heavy elements
- Structure of exotic nuclei (e.g. hyper nuclei)
- Neutron matter equaton of state

antiProton Annihilation in Darmstadt
- Hadron structure and dynamics



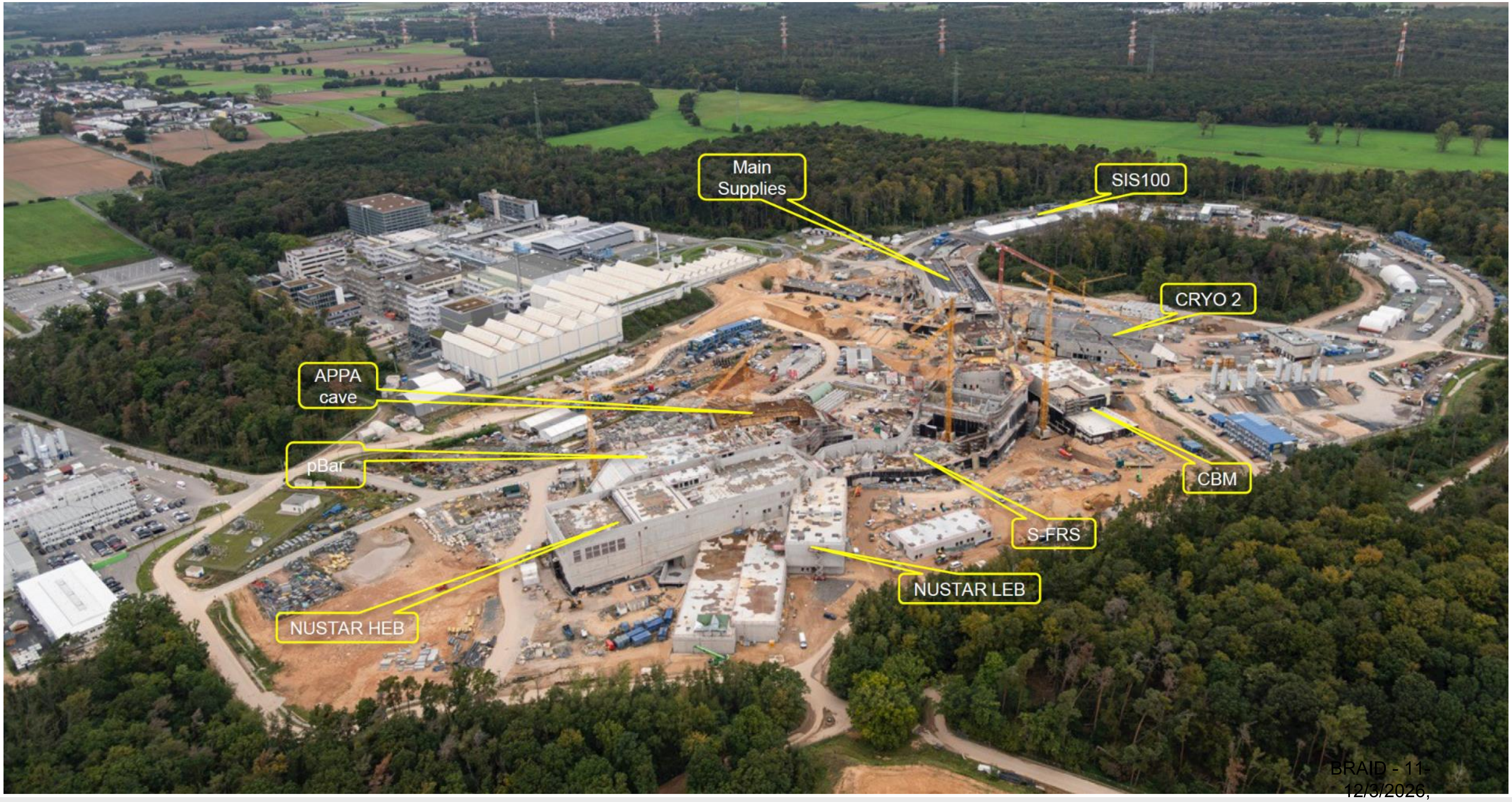
- Gluonic excitations:
  Hybrids, Glueballs
- Precision spectroscopy of charmonium states
- Time-like form factors, nucleon structure

FAIR – four research pillars



antiProton ANnihilation at DArmstadt

FAIR - Construction update



Beams at FAIR for CBM and PANDA

Ion / proton beams -> CBM

- ≤ 12 AGeV Au beam or
- ≤ 29 GeV p beam
- Fixed target: Au / p / …
- Rates: 10^9 – 10^{11} (Ions/s) (Fluka sim.)

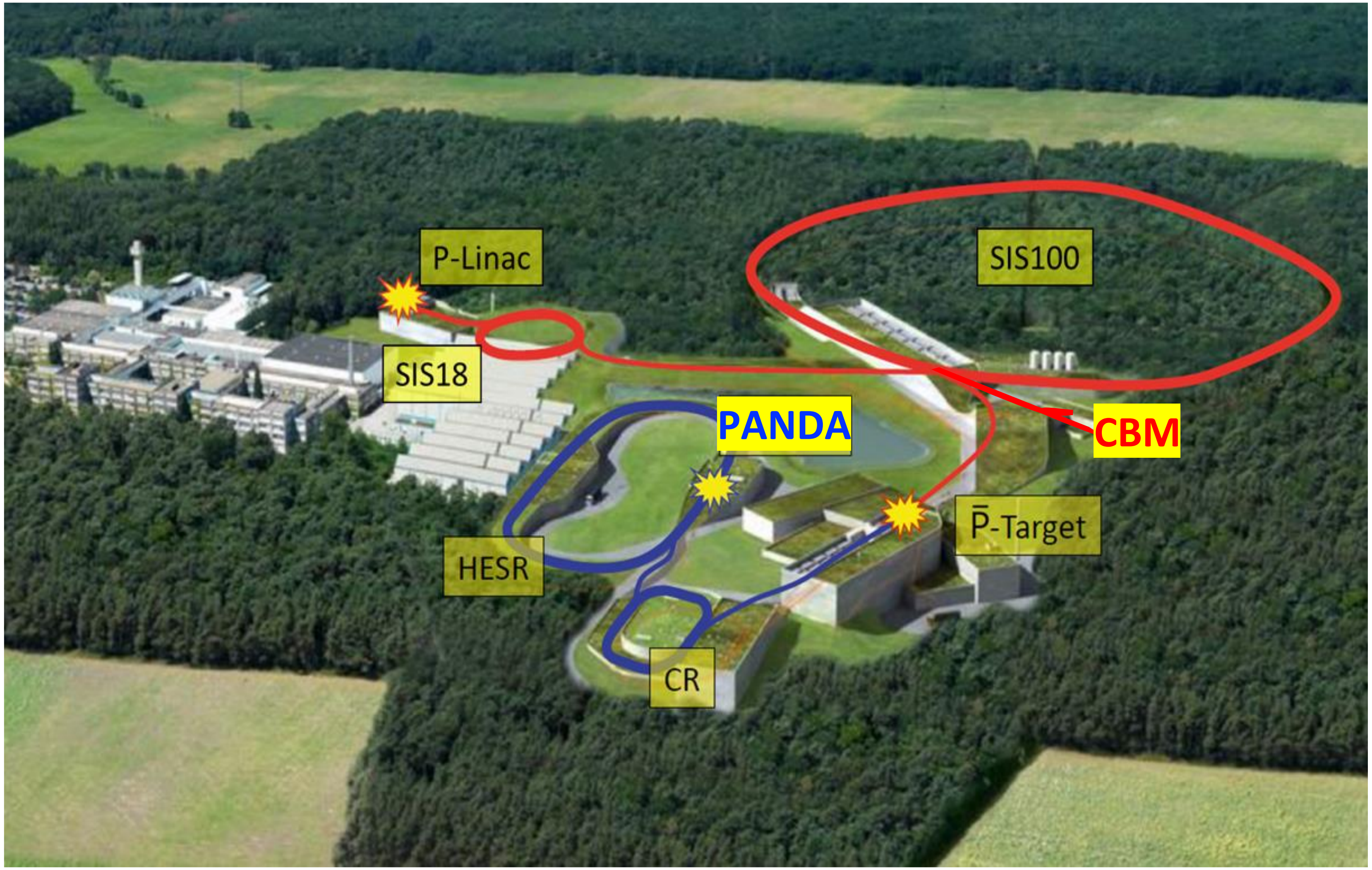
Antiproton production -> PANDA

- Proton Linac *(70 MeV)*
- Accelerate p in SIS18/100 *(4/29 GeV)*
- Produce p̄ on Ni/Cu target *(3 GeV)*
- Collection in CR, fast cooling
- Accumulation in HESR
- PANDA luminosity ≤ $2x10^{31}cm^{-2}s^{-1}$
- p̄ momentum: 1.5 – 15 GeV/c
- Fixed target: p cluster jet / pellet
- Nuclei targets
- Full FAIR version

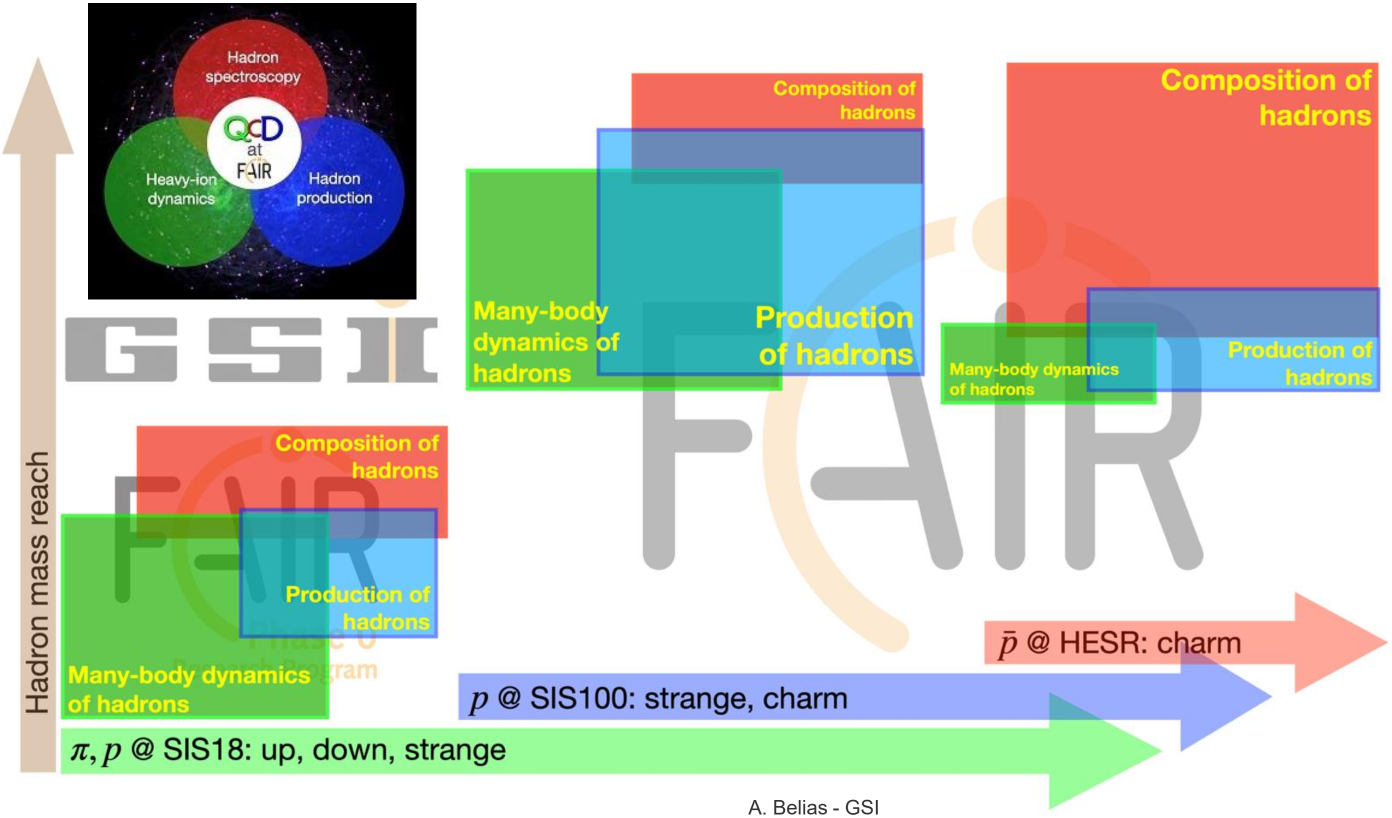
Accumulation in RESR, slow cooling

Storage in HESR

PANDA luminosity ≤ $2x10^{32}cm^{-2}s^{-1}$



QCD studies - Hadron physics at GSI/FAIR



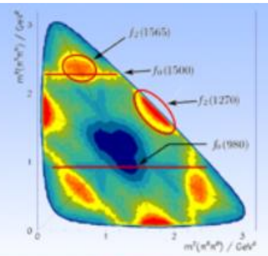
A. Belias - GSI

Roadmap

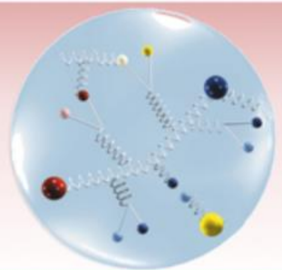
- **Versatile** program during the various phases of FAIR
- **FAIR Phase0**: pions/protons at HADES@SIS18
  - **FS+**: protons at CBM@SIS100
    - Towards **antiprotons** at HESR

Antiprotons – Unique Probes for Discoveries and Precision Physics

Hadron Spectroscopy
- Charmonium / Charmed hadrons
- Exotic QCD states
- Spectroscopy



Hadron Structure
- Time-like Nucleon Form Factors
- Generalized Parton Distributions
- Drell-Yan Process



Nuclear Physics
- Production of Λ-Hypernuclei
- Hadrons in Nuclear Medium

Hadrons physics - Beamline for CBM and storage ring for PANDA

Beamline with protons

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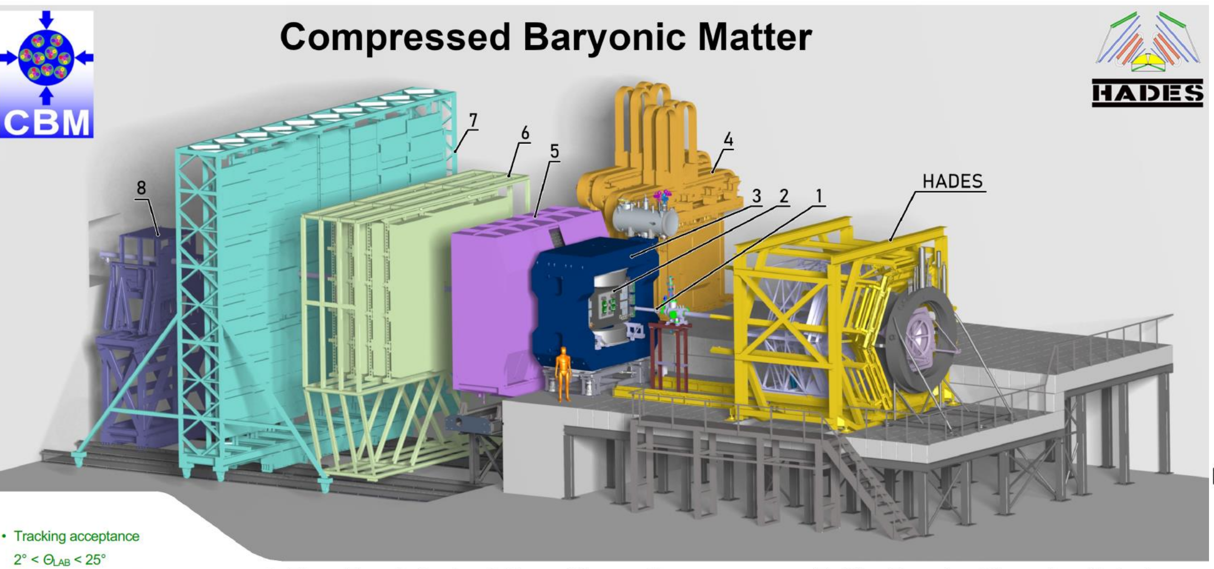

- Tracking acceptance $2° < \Theta_{LAB} < 25°$
- Free streaming readout
- Front-end connectivity up to R_{int} = 10 MHz
- Software-based event selection

1: Time-Zero Detector & Beam Diagnostics
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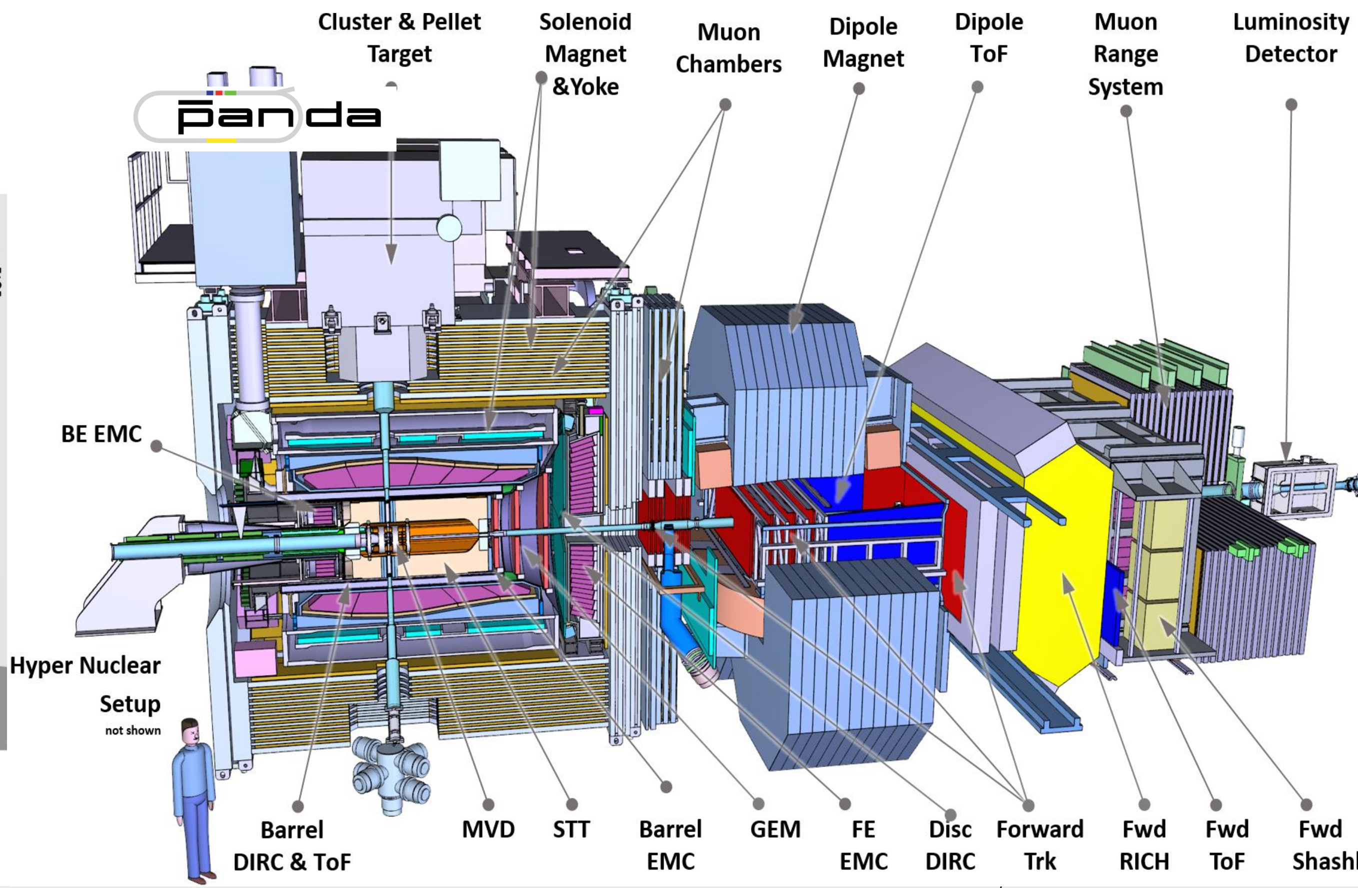
7: Time of Flight Detector
8: Forward Spectator Detector

Storage ring with antiprotons

Mode	High luminosity (HL)	High resolution (HR)
$\Delta p/p$	$\sim 10^{-4}$	$\sim 4\times10^{-5}$
L ($cm^{-2}s^{-1}$)	2×10^{32}	2×10^{31}
Stored $\bar{p}$	10^{11}	10^{10}



Hadrons physics - Beamline for CBM and storage ring for PANDA

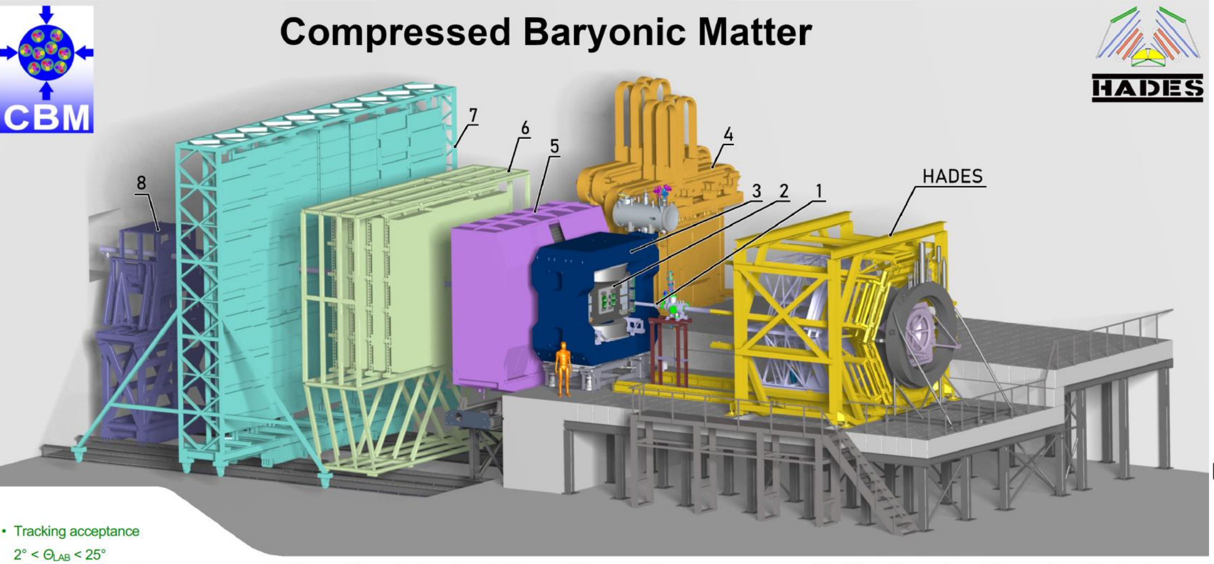
Beamline with protons

CBM Physics Context

CBM studies dense baryonic matter.

Key observables:

- Low-mass vector mesons (ρ, ω, ϕ)
- Charmonia via $\mu^+\mu^-$



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Storage ring with antiprotons

Hadron Spectroscopy

Experimental Goals: *mass, width & quantum numbers J^{PC} of resonances*

Charm Hadrons: *charmonia, D-mesons, charm baryons*

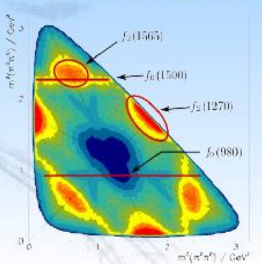
→ Understand new XYZ states, $D_s(2317)$ and others

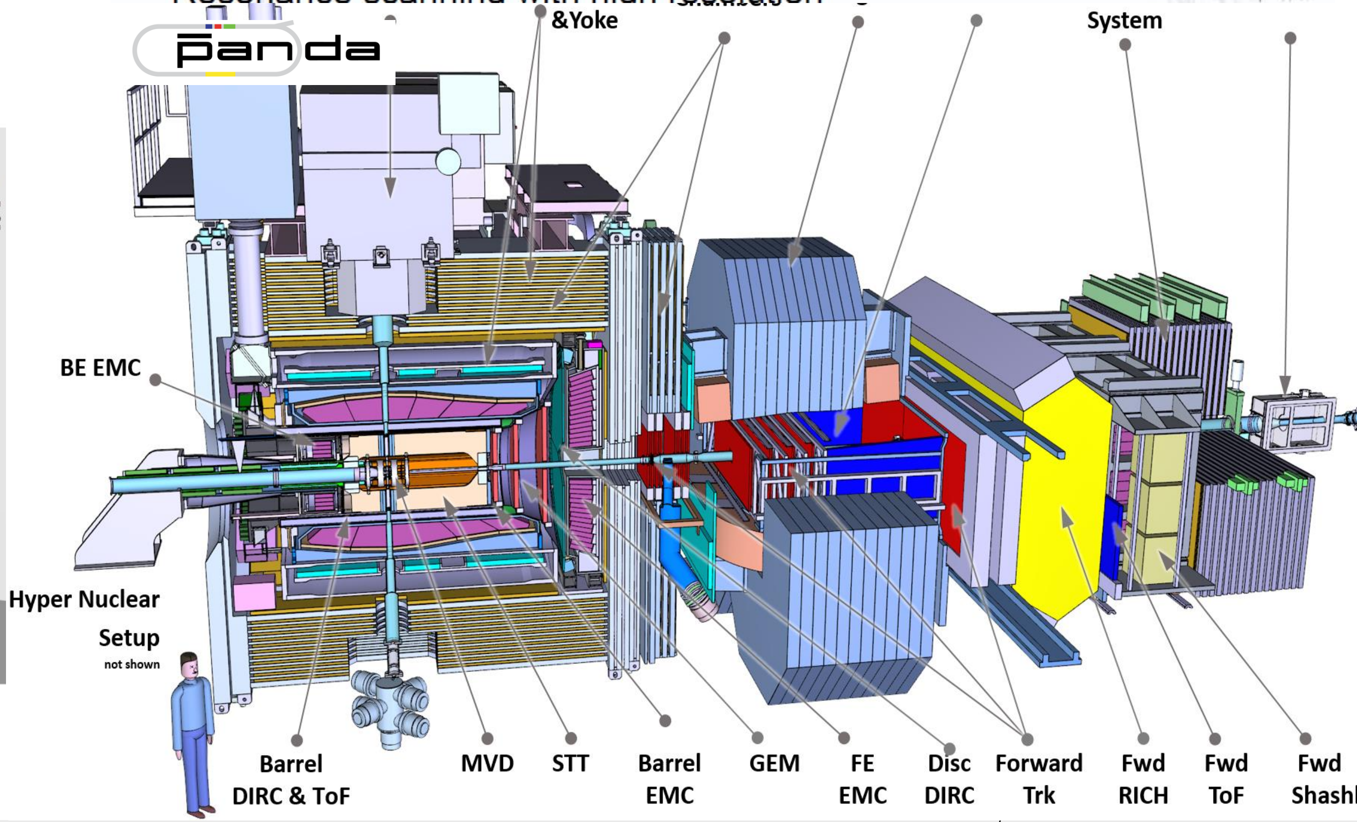
Exotic QCD States: *glueballs, hybrids, multi-quarks*

Spectroscopy with Antiprotons:

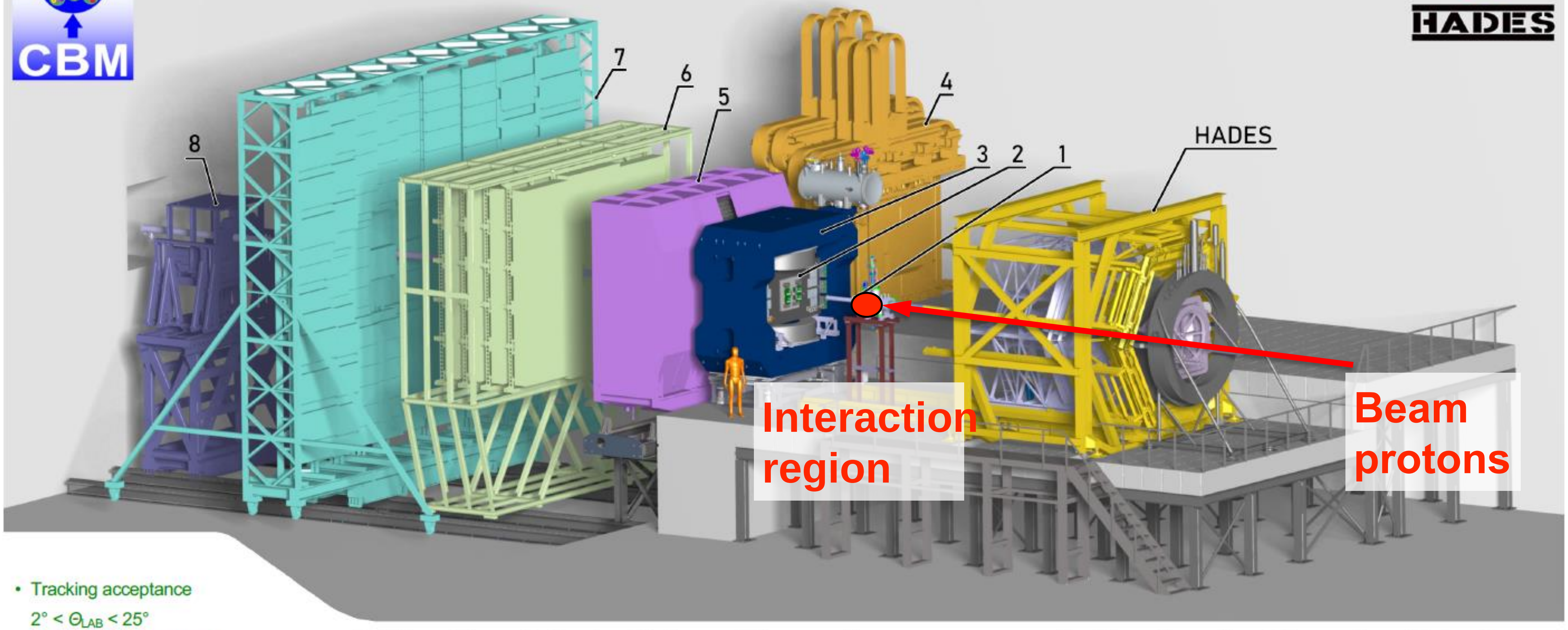
Production of states of all quantum numbers

Resonance scanning with high resolution





Compressed Baryonic Matter



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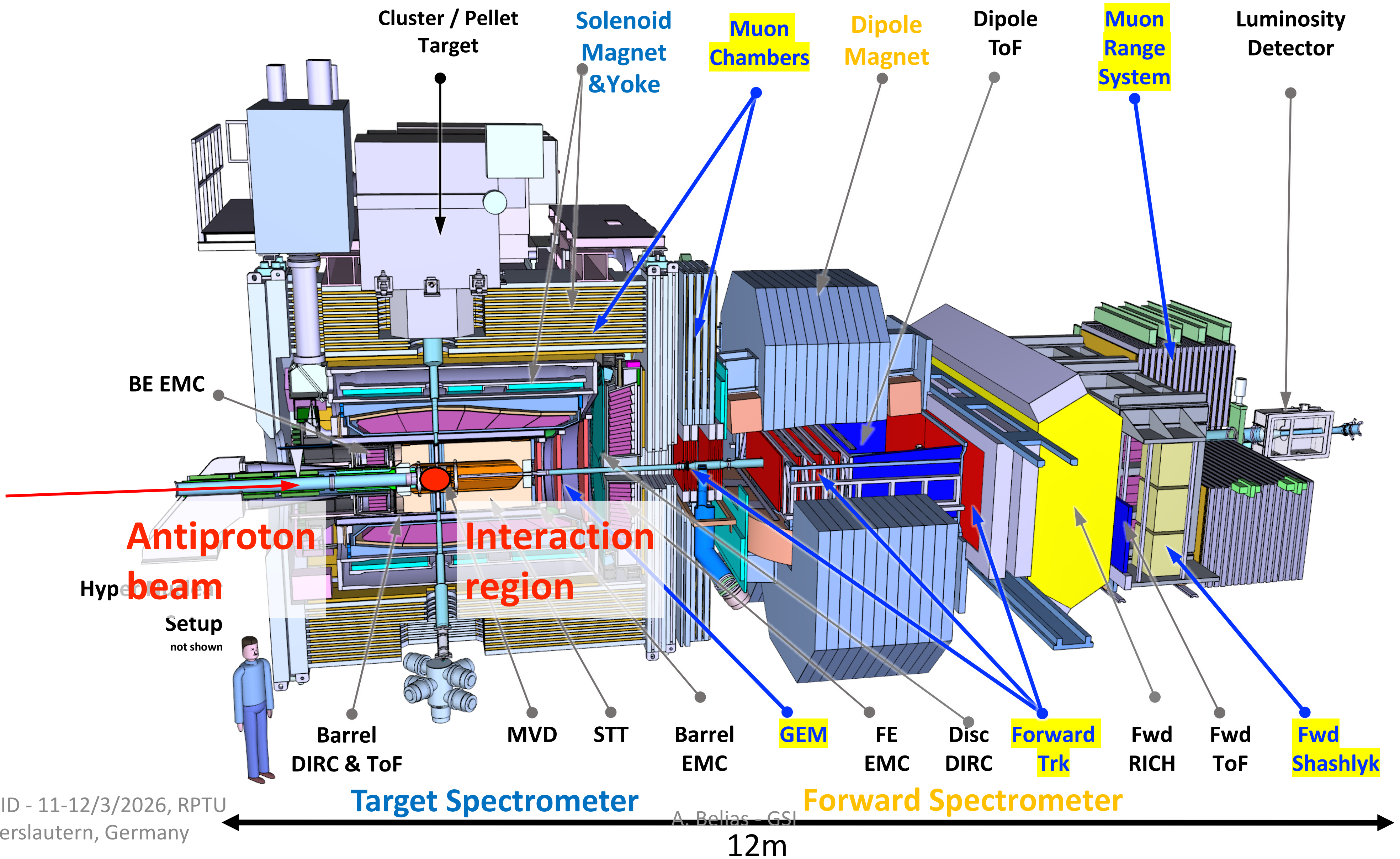
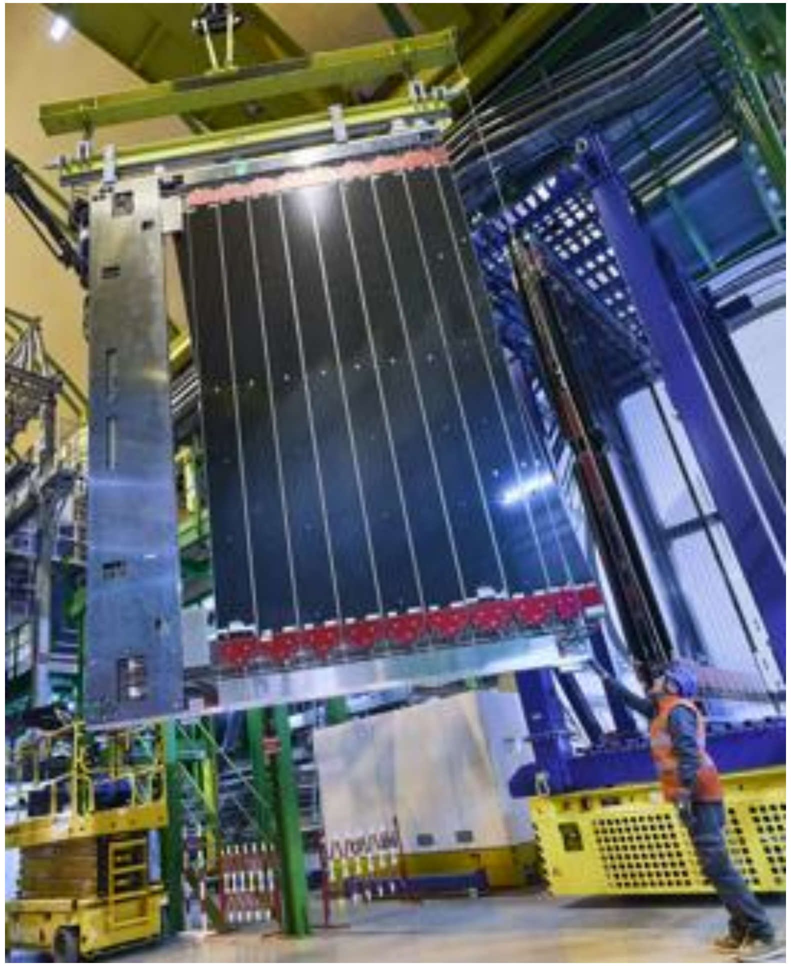
PANDA Detectors



LHCb Outer Tracker Straw Tubes in PANDA

LHCb donated the formidable Outer Tracker straw tube detector to GSI for PANDA & other experiments!!



One of 12 frames, 5x6 m^2, with 4352 straws in 18 modules. (Photo courtesy: LHCb)

Outer Tracker brief specs

Straw tube
- Diameter, length: 5 mm, 2.4 m
- Anode wire: 25µm at 1550 V
- Gas mix: $Ar/CO_2/O_2$

Module
- Two staggered layers of 64 straw tubes
- One module: $X/X_0 = 0.37\%$
- Independent upper and lower sides
- Front-end electronics (FEE) each side

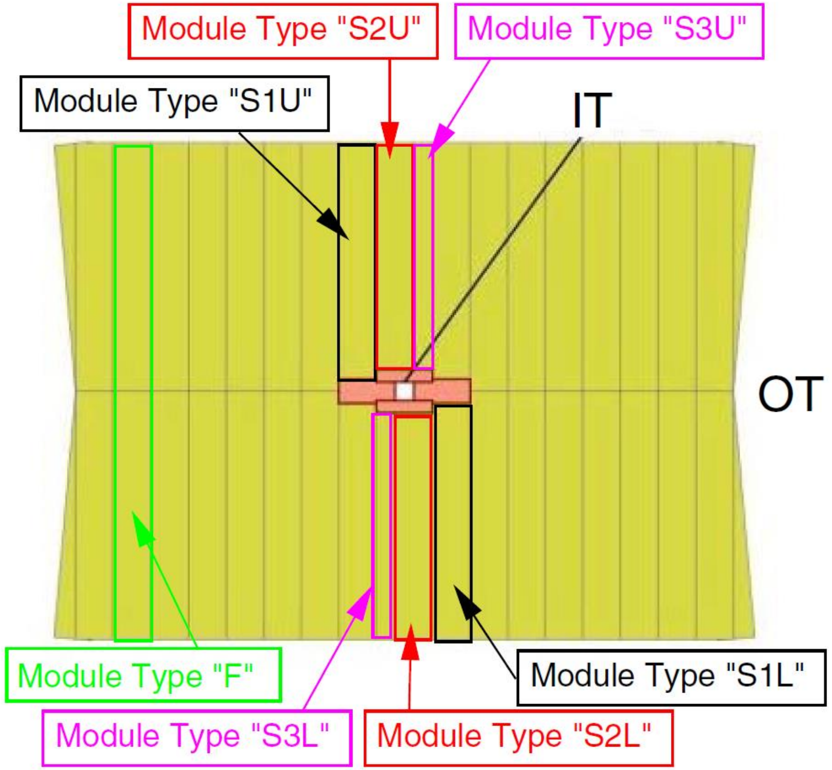
Whole Detector
- 53,760 straw tubes, 216 modules, 432 FEE
- Area coverage: 5 x 6 m^2 x12 planes

Performance (LHCb operations, Run 1&2)
- $\varepsilon \approx 98\%$, $\sigma \approx 170$ µm
- $\delta p/p \approx 0.4\%$ (2-100 GeV tracks)
- No significant ageing or gain loss

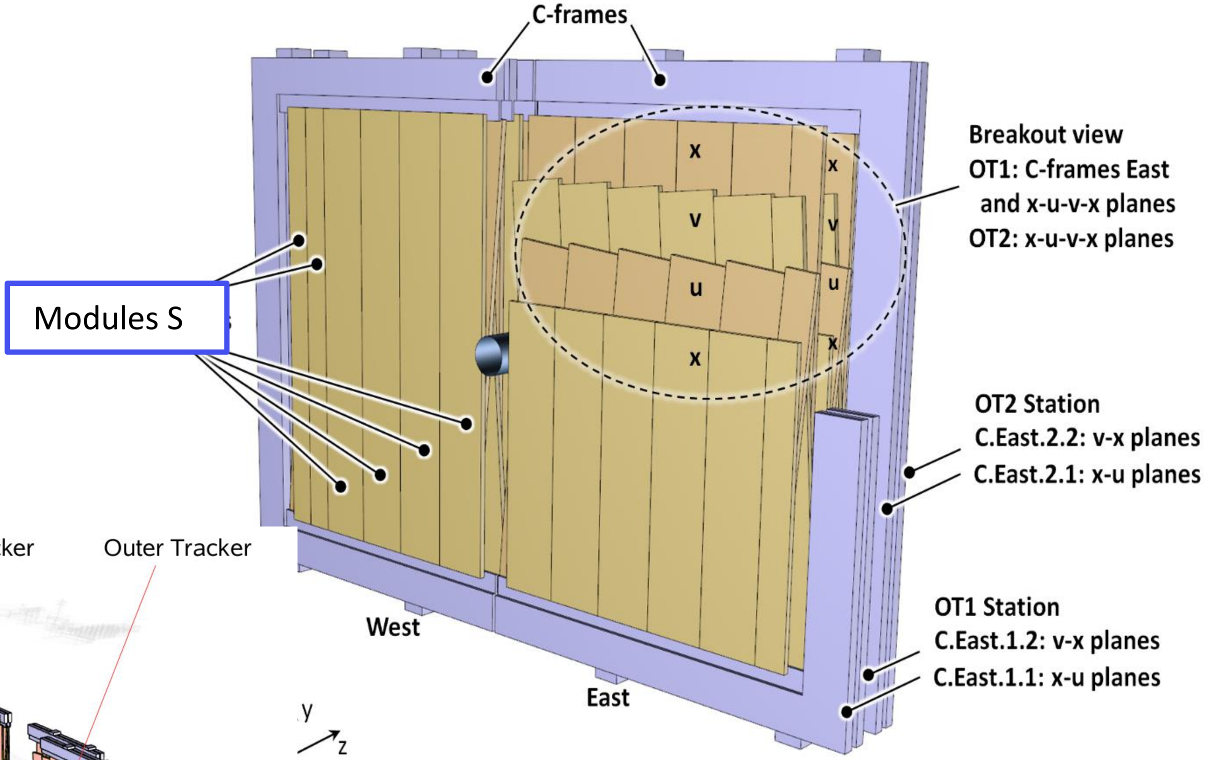
Whole OT in transport frame, 7x5.5x3.5 m^3, 24t, arrival at GSI, Aug. 25, '23. (Photo courtesy: GSI)

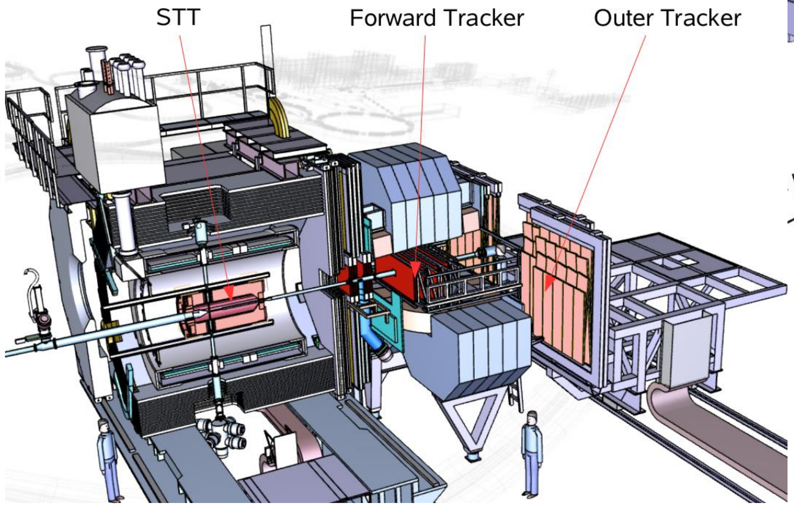
OT use case I: PANDA Forward Tracking

LHCb: Modules S separable in “U” and “L” parts

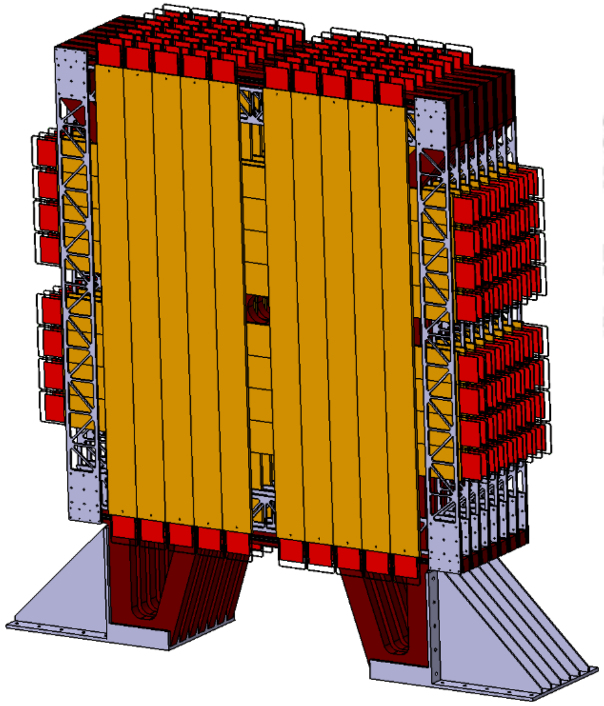


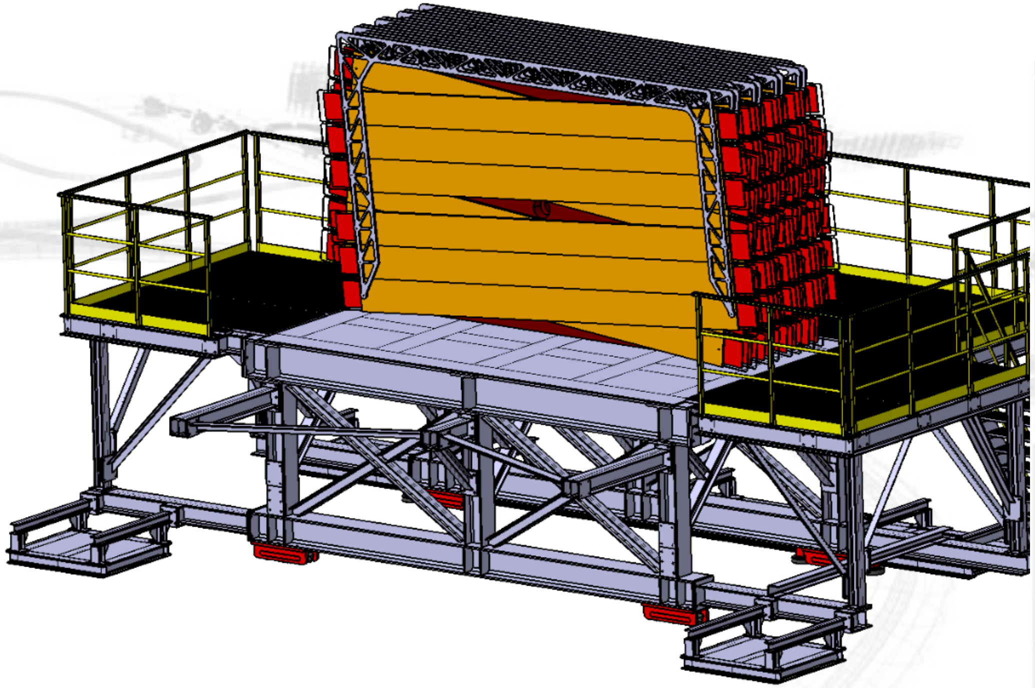
PANDA: Split & pair “U” and “L” parts of S Modules





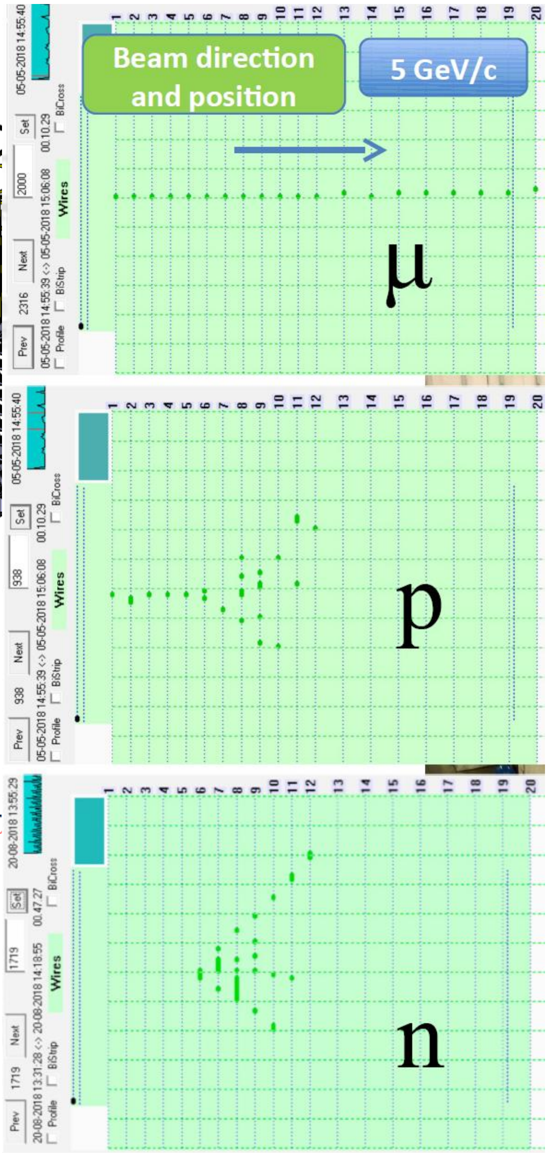
OT use case II – PANDA Muon Range System



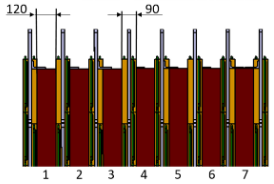


Initial tests: Mini Drift tubes

- μ, p and n can be resolved



- LHCb Outer Tracker long modules for PANDA Muon Range System,
- Option 1 (right): +-5° angle, same size as original FRS
- Option 2 (left): 90° angle, fixed absorber planes



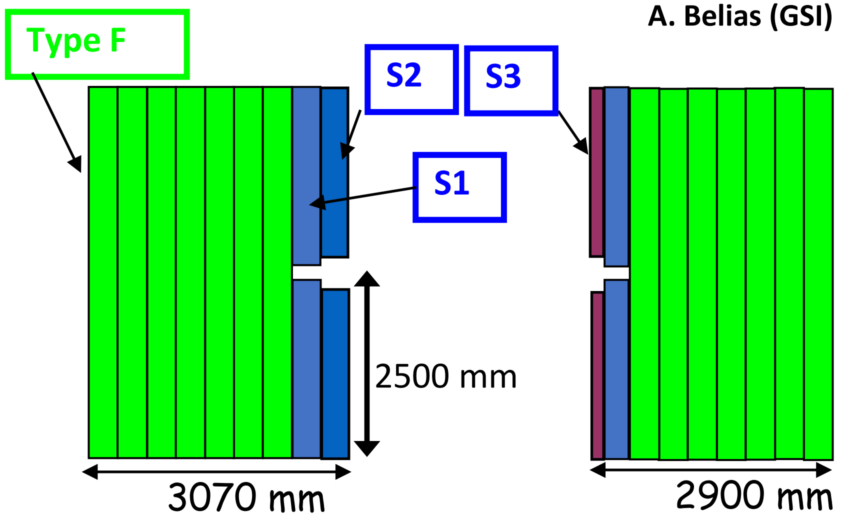
Less layers, thicker absor

New design with OT

- **μ, p and n resolution performance?**

LHCb OT – Use cases

A. Belias (GSI)



OT has 12 Layers, and each layer has

- 14 type F modules; full height
- 4 type S modules; 2 x half height

Various Projects in progress

PASTA - PAnda STrAws

→ use type S modules in PANDA

→ @mCBM: Beam times Feb/Mar/May 2025

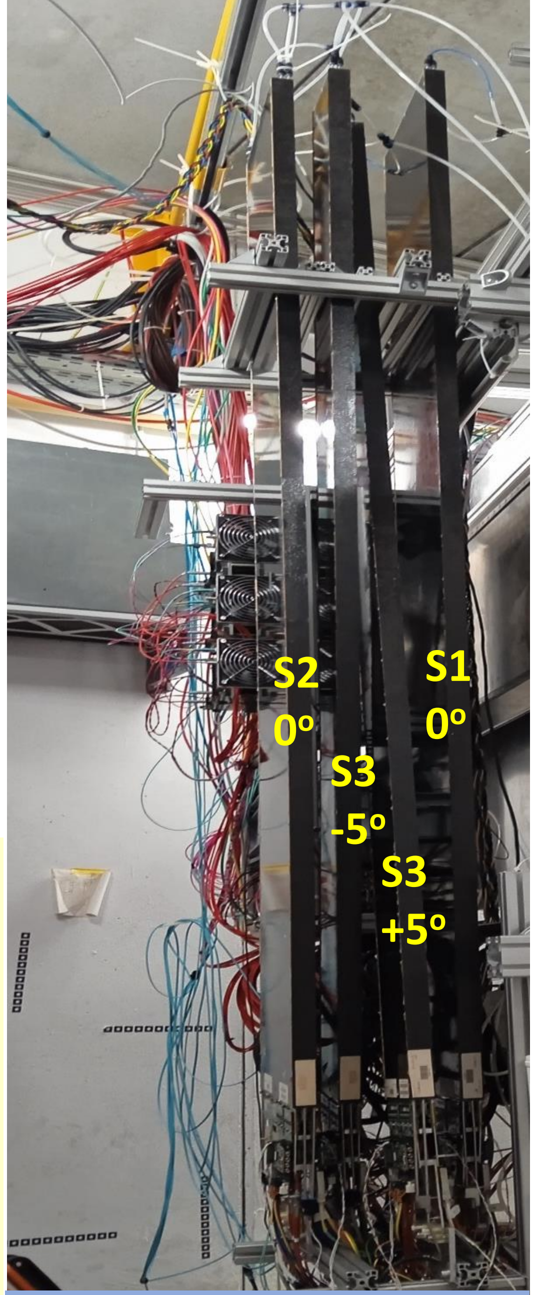
MUST - Muon Straws

→ use type F modules in CBM and PANDA

→ Task Force examines feasibility

→ MoU between CBM & PANDA

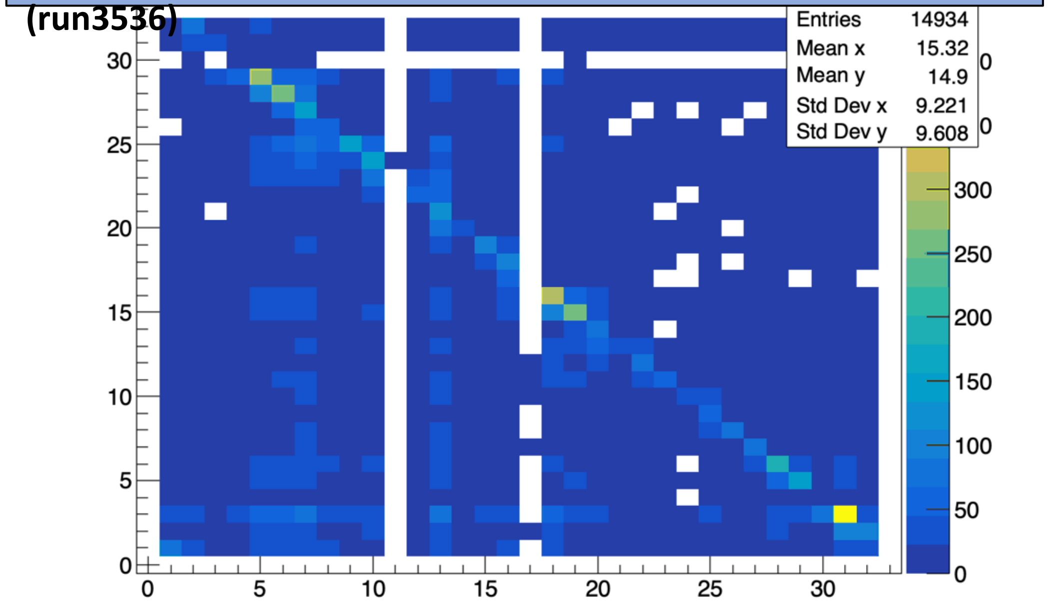
→ No Beam times in 2026 due to fire at GSI

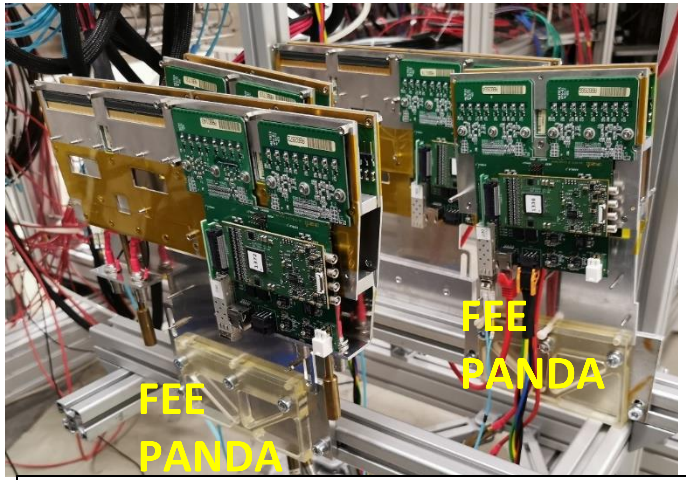


PASTA –
4 S modules in mCBM

Beam time with mCBM

Feb.2025, at GSI: Ag+Ag, 1.58 and 1.23 AGeV
→ Preliminary Correlation between layers

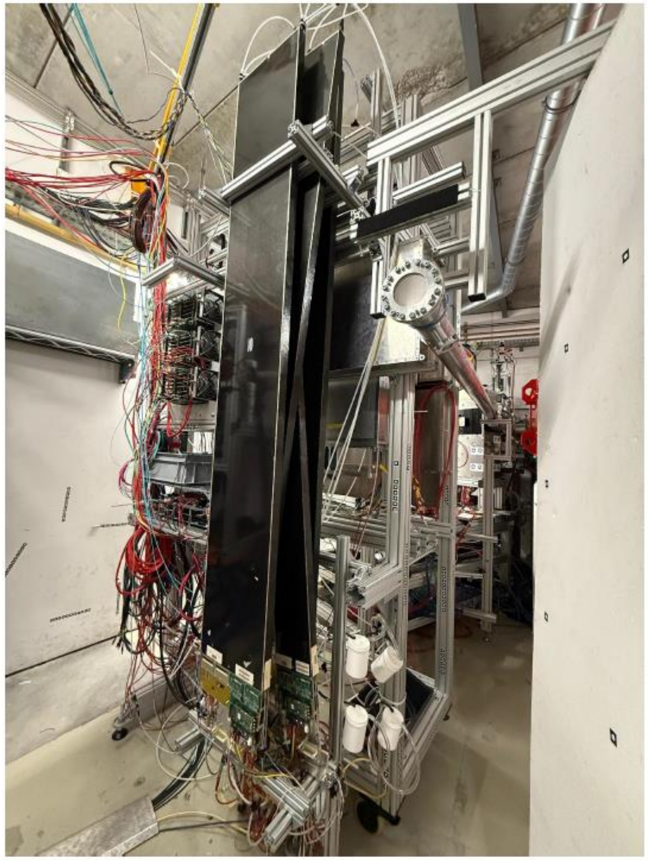




FEE PANDA – Combiner_PCB readout - CBM DAQ

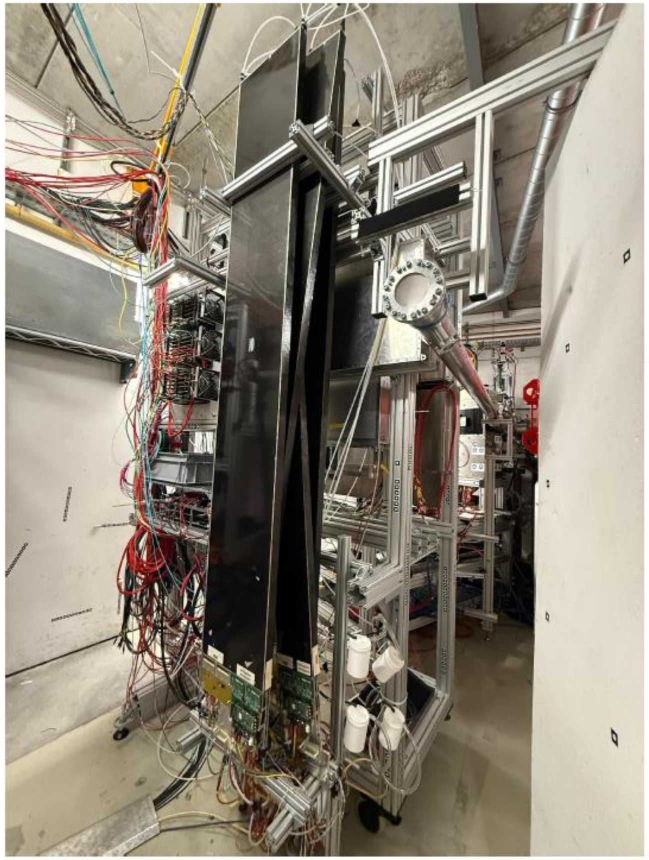
OT use case III – CBM Muon Stations (MuSt)

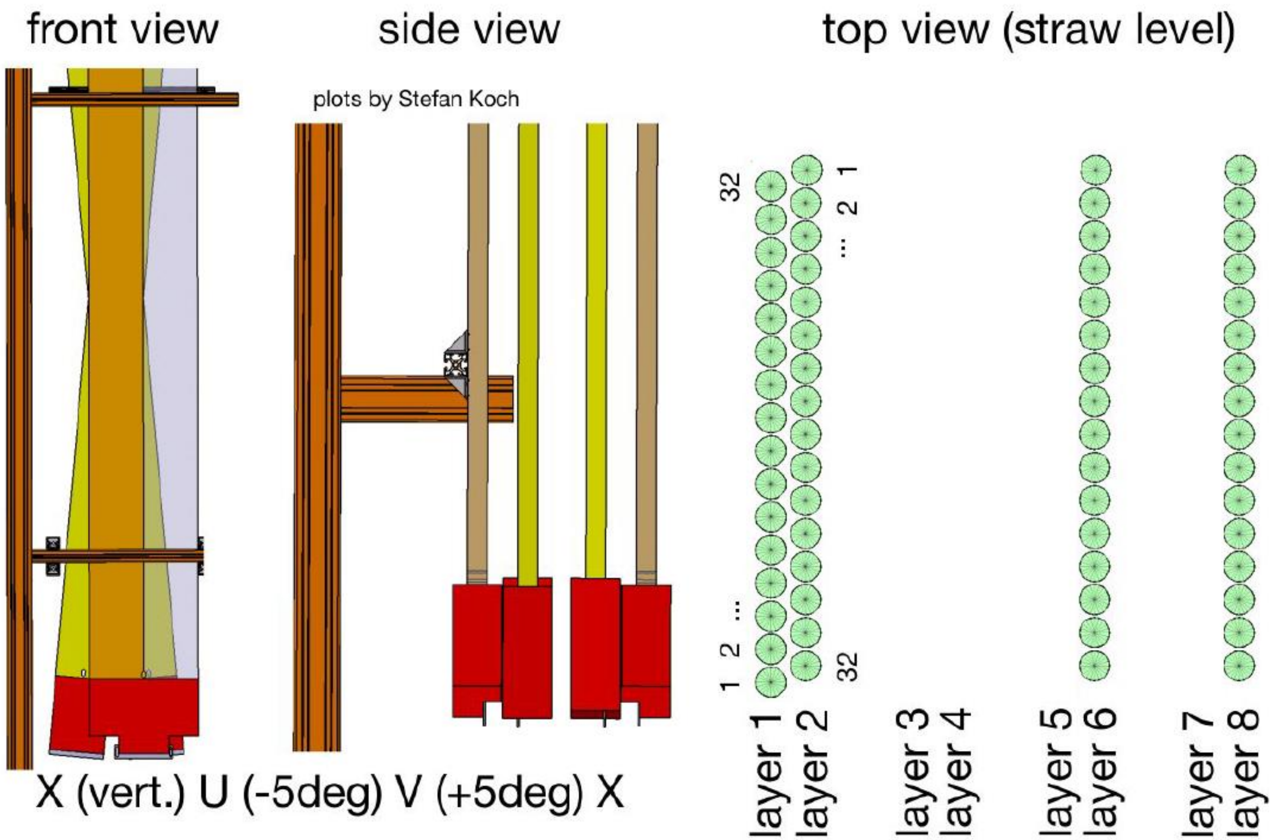
MUST have PASTA (PANDA STrAws in mCBM)



OT use case III – CBM Muon Stations (MuSt)

MUST have PaSTa (**PANDA STrAws** in mCBM)





OT use case III – CBM Muon Stations (MuSt)

MUST fits well in the CBM-MuCh

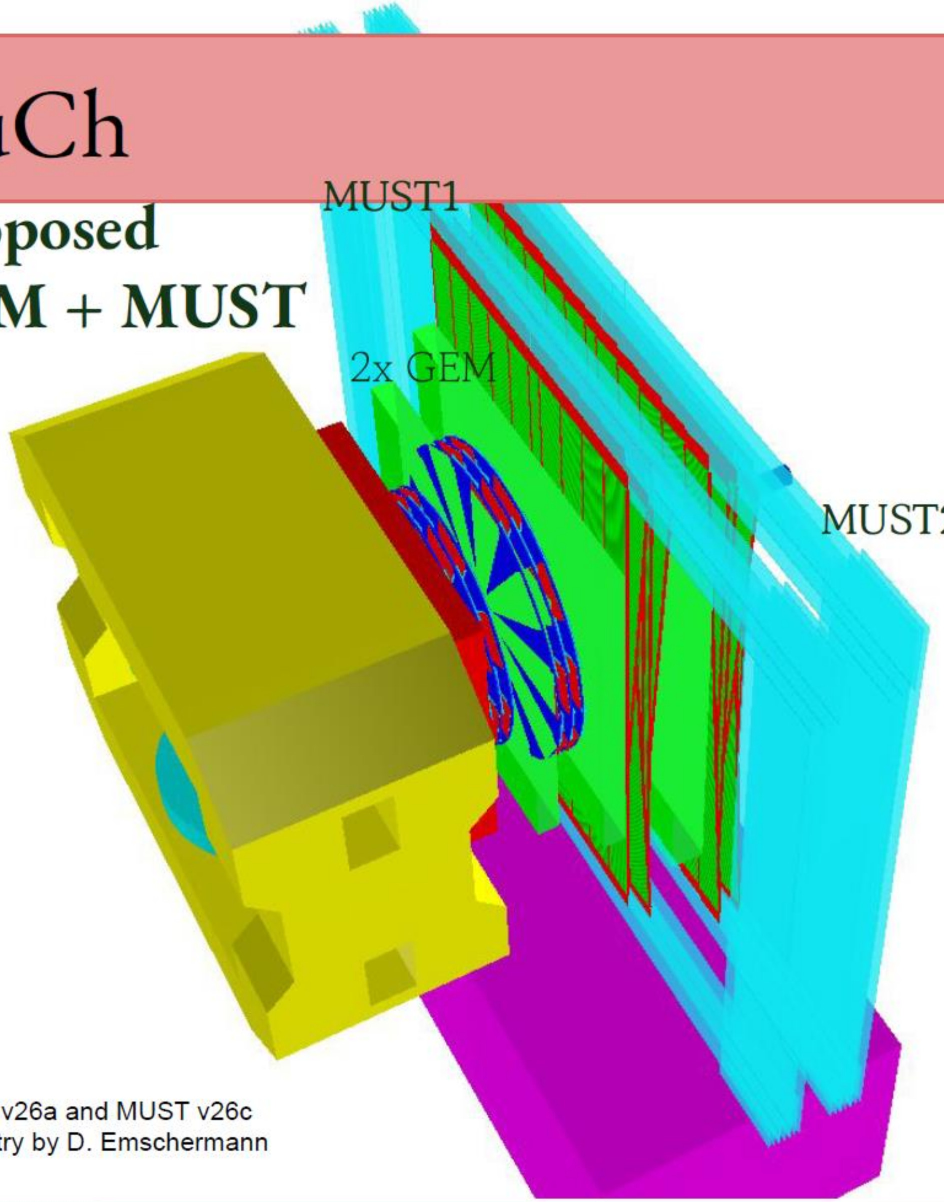
Where MUST sits : Upstream of absorber stack in MUCH station 3 and 4 respectively

Why MUST :

- Optimized geometry to fit between absorbers and cover the MUCH acceptance (St. 3–4).
- Provides the spatial and timing resolution required for muon identification.
- Have handled high rates~MHz in LHCb environment

Next step: evaluate the rate capability of the MUST / LHCb OT concept under CBM particle flux conditions

Proposed GEM + MUST

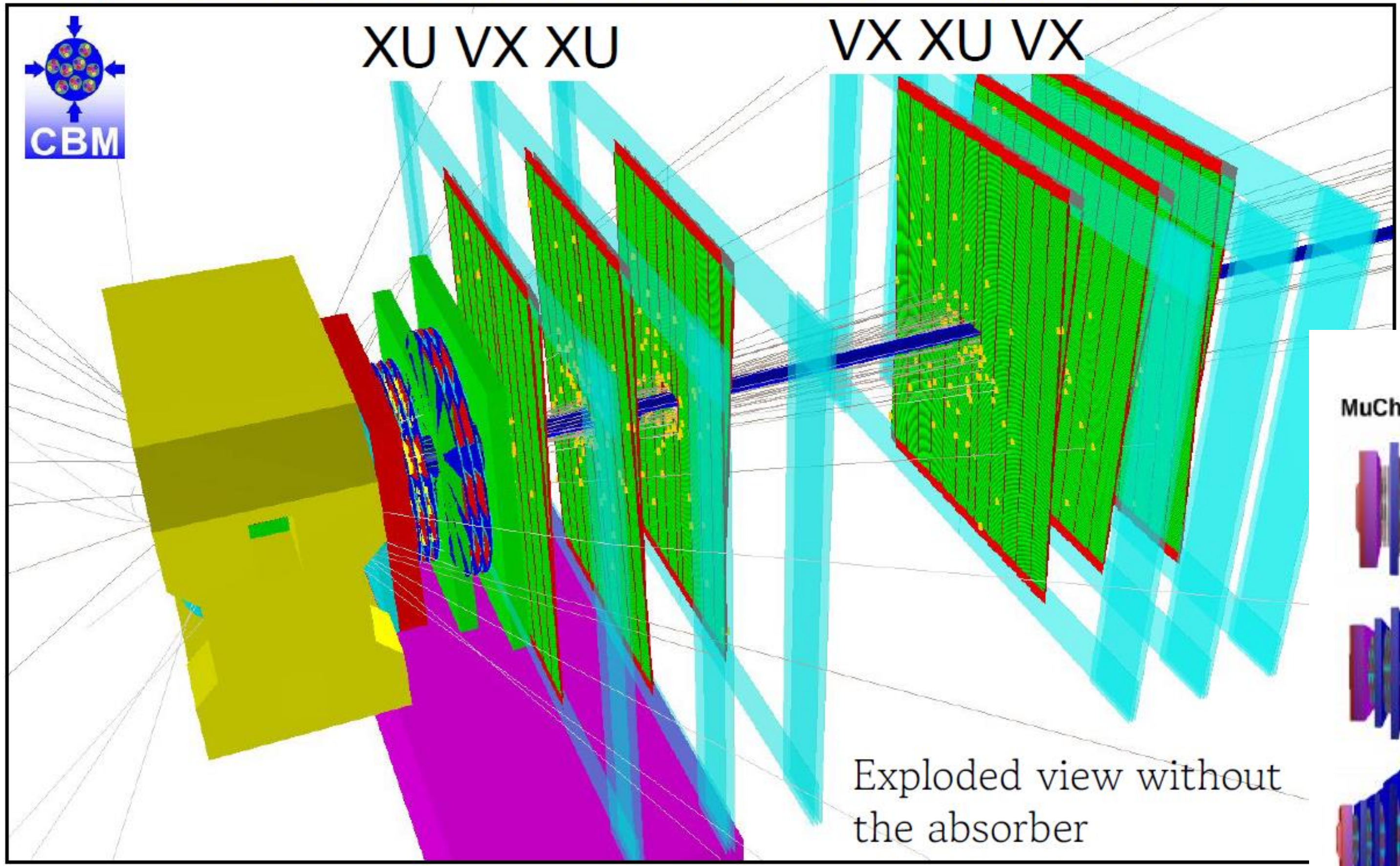


MUCH v26a and MUST v26c geometry by D. Emschermann

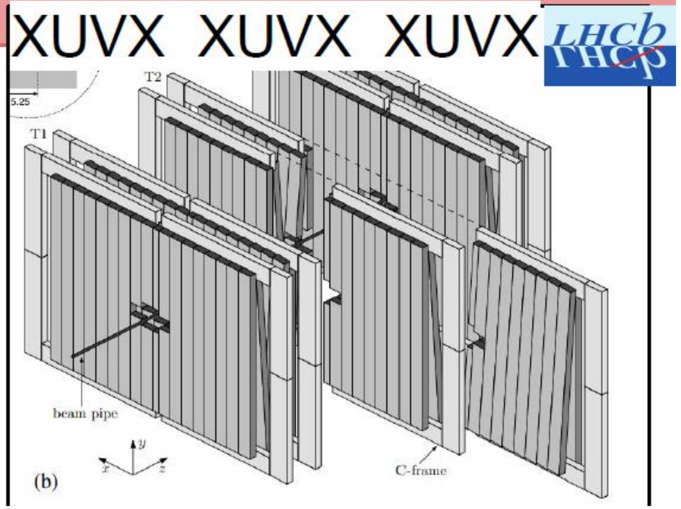
OT use case III – CBM Muon Stations (MuSt)

MUST geometry

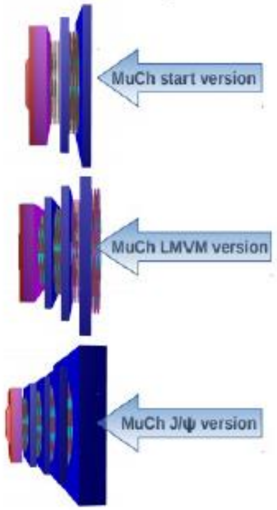
The full realistic geometry is now implemented in CBMROOT.
https://git.cbm.gsi.de/CbmSoft/cbmroot_geometry/-/merge_requests/342



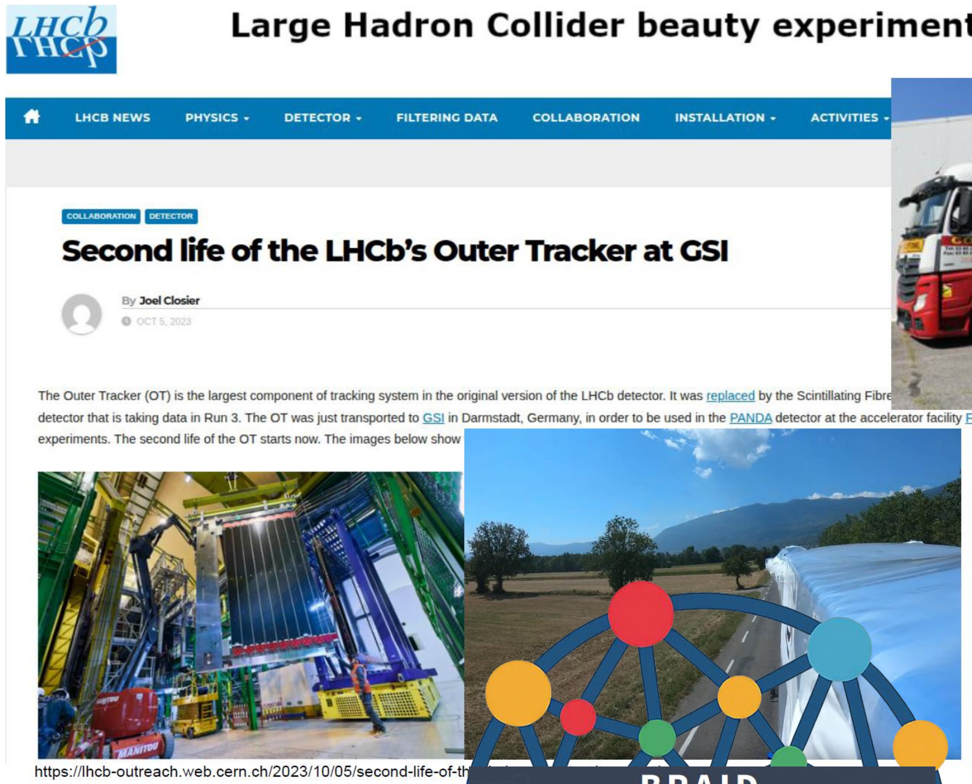
Exploded view without the absorber

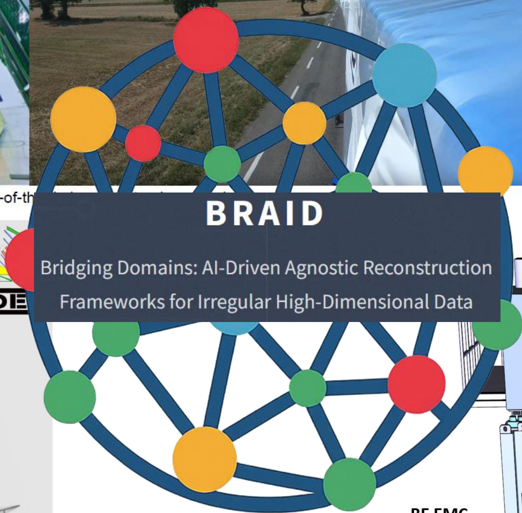


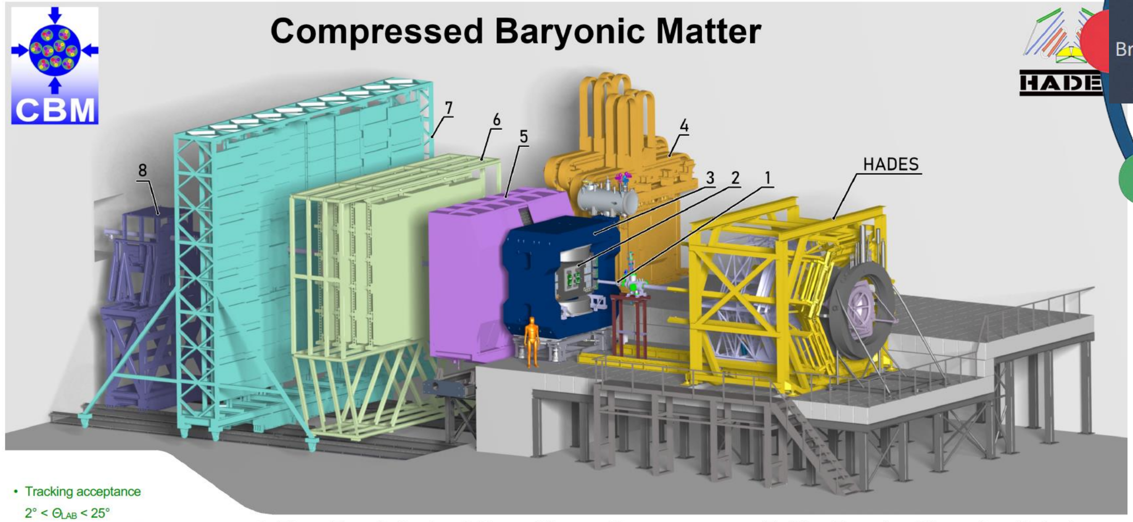
MuCh geometry variants



MuCh Geometry variant	No of absorbers	Configuration of the absorbers	No of detector stations	Purpose
LE version	3	1st : 58 cm (28 C + 30 cm concrete) 2nd & 3rd : 20 cm Iron	2 (GEM stations)	LMVM detection $E_b < 4$ A GeV (Au beam)
LVMV version	4	1st : 58 cm (28 C + 30 cm concrete) 2nd & 3rd : 20 cm Iron 4th : 30 cm Iron	2 (GEM stations) 2 (RPC stations)	LMVM detection $E_b > 4$ A GeV (Au beam)
J/Ψ version	5	1st : 58 cm (28 C + 30 cm concrete) 2nd & 3rd : 20 cm Iron 4th : 30 cm Iron 5th : 100 cm Iron	2 (GEM stations) 2 (RPC stations)	J/ψ detection







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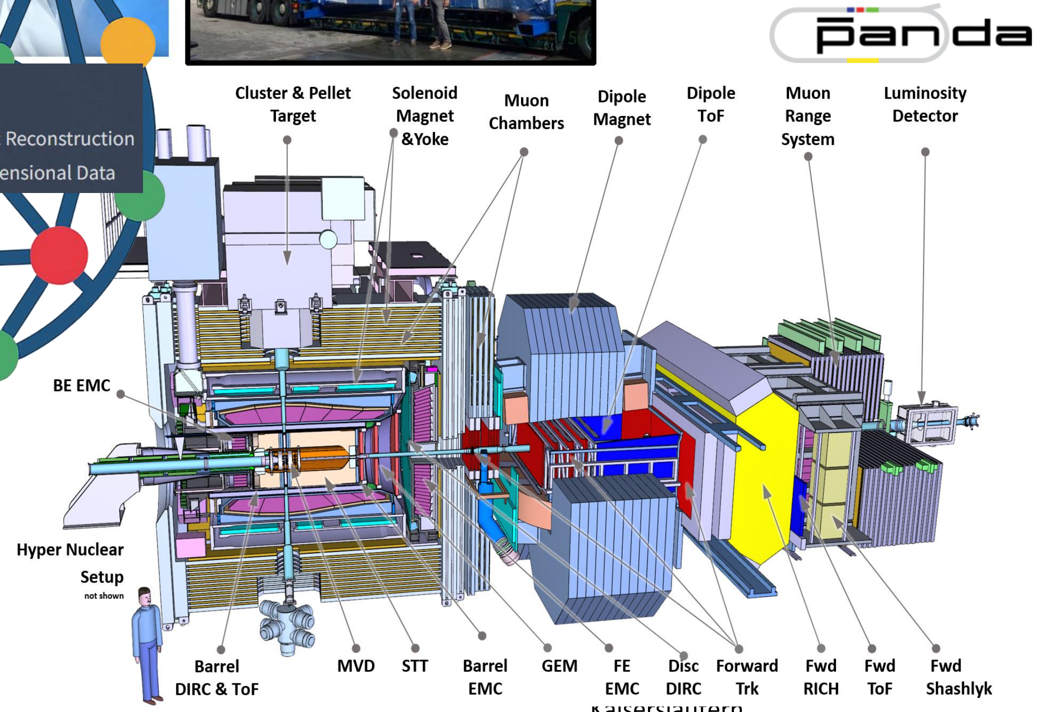
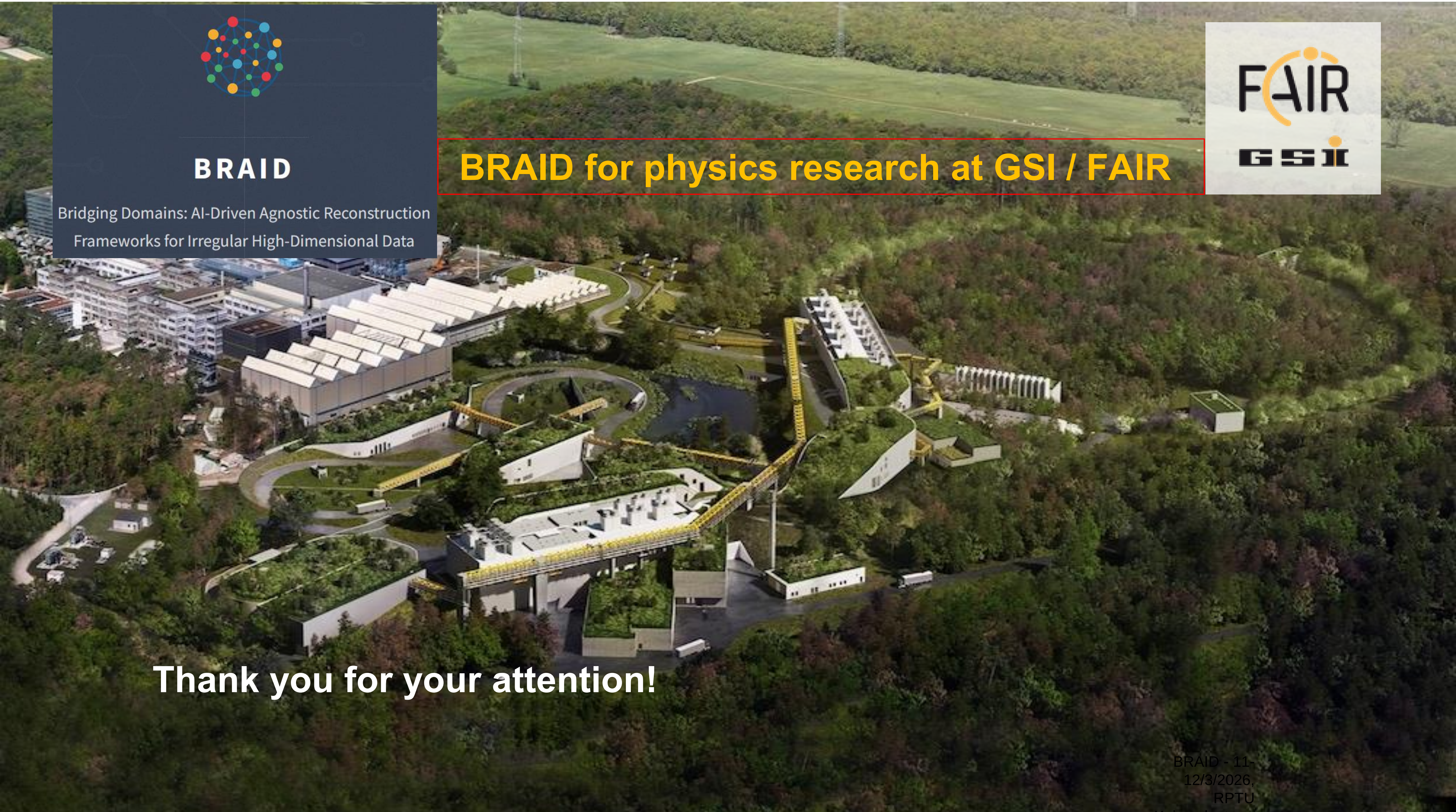


Kaiserslautern.



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BRAID for physics research at GSI / FAIR

FAIR

GSI

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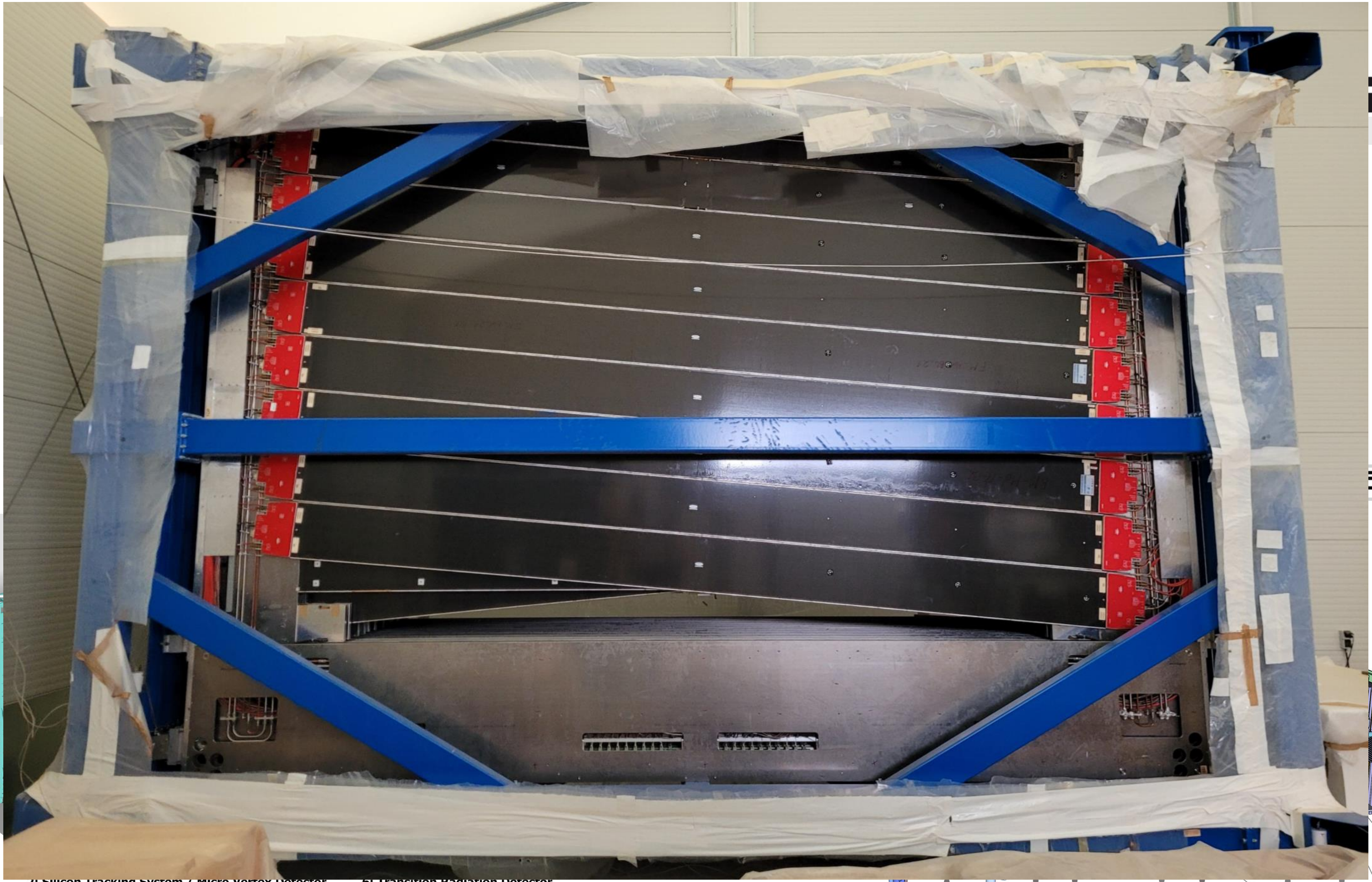

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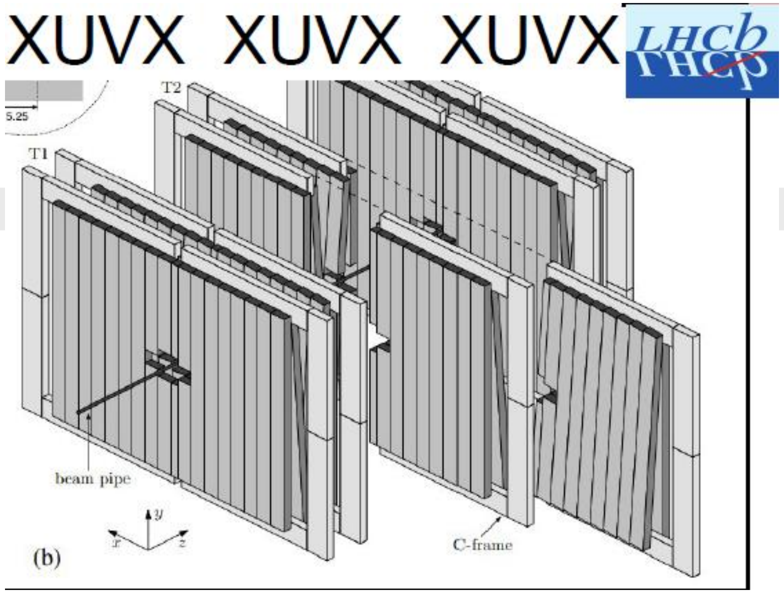
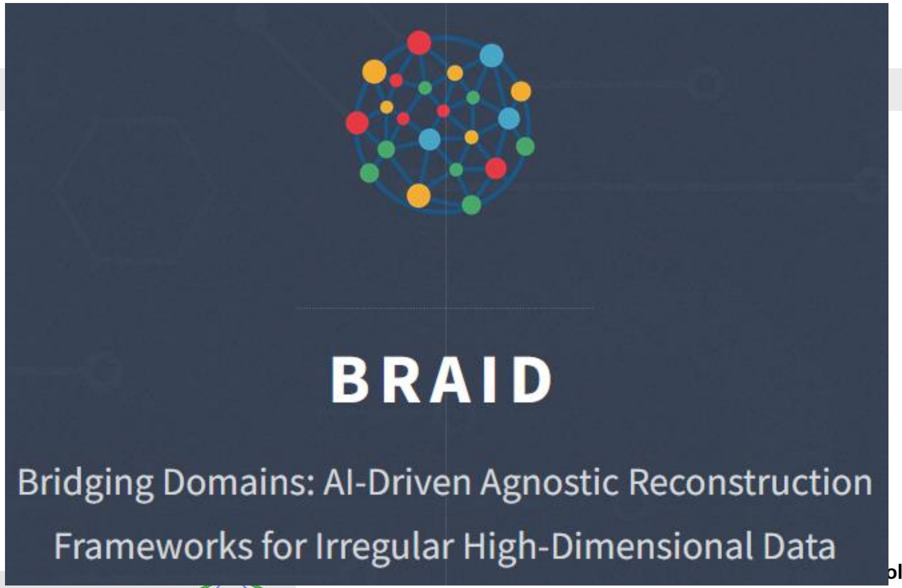
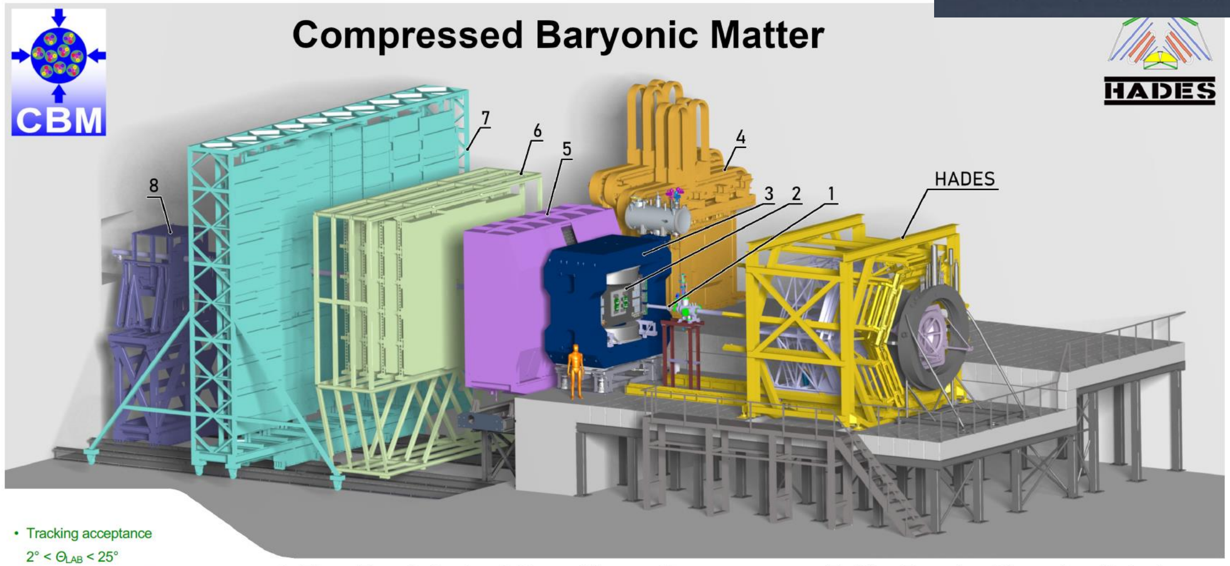
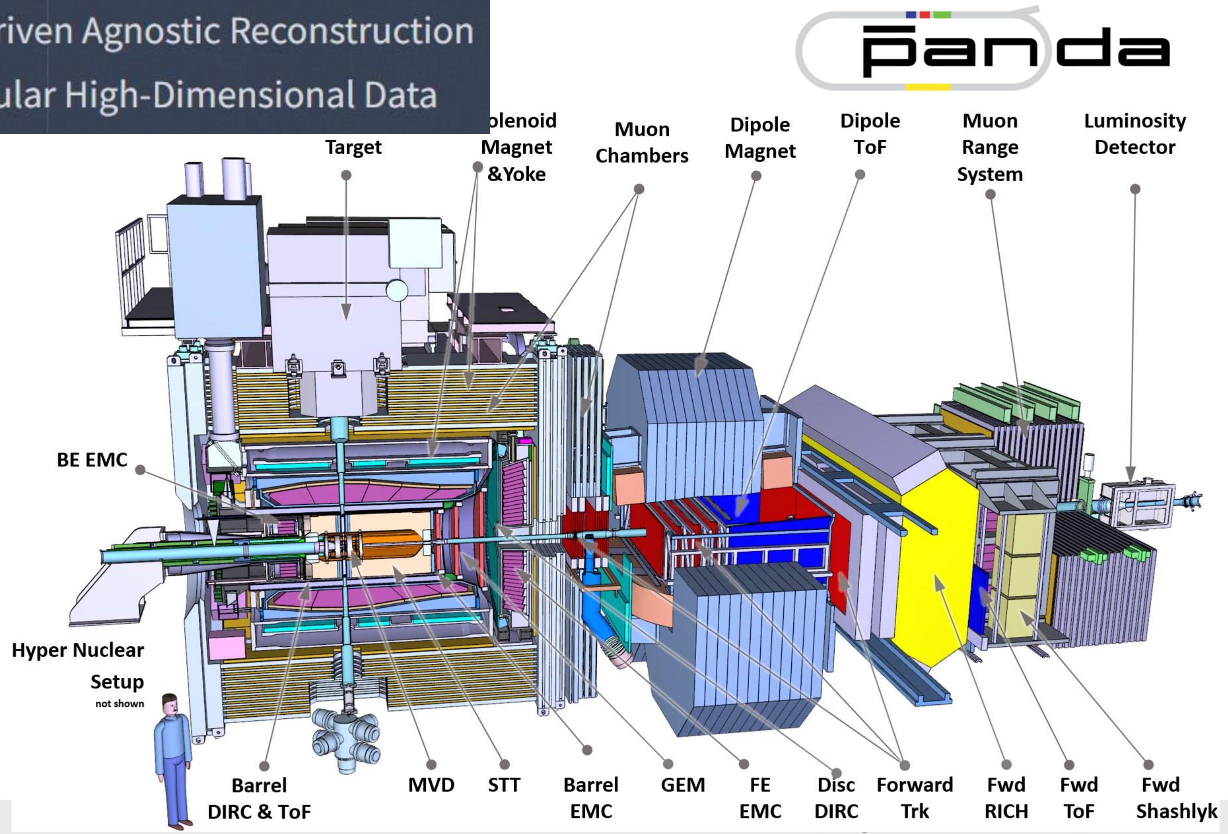




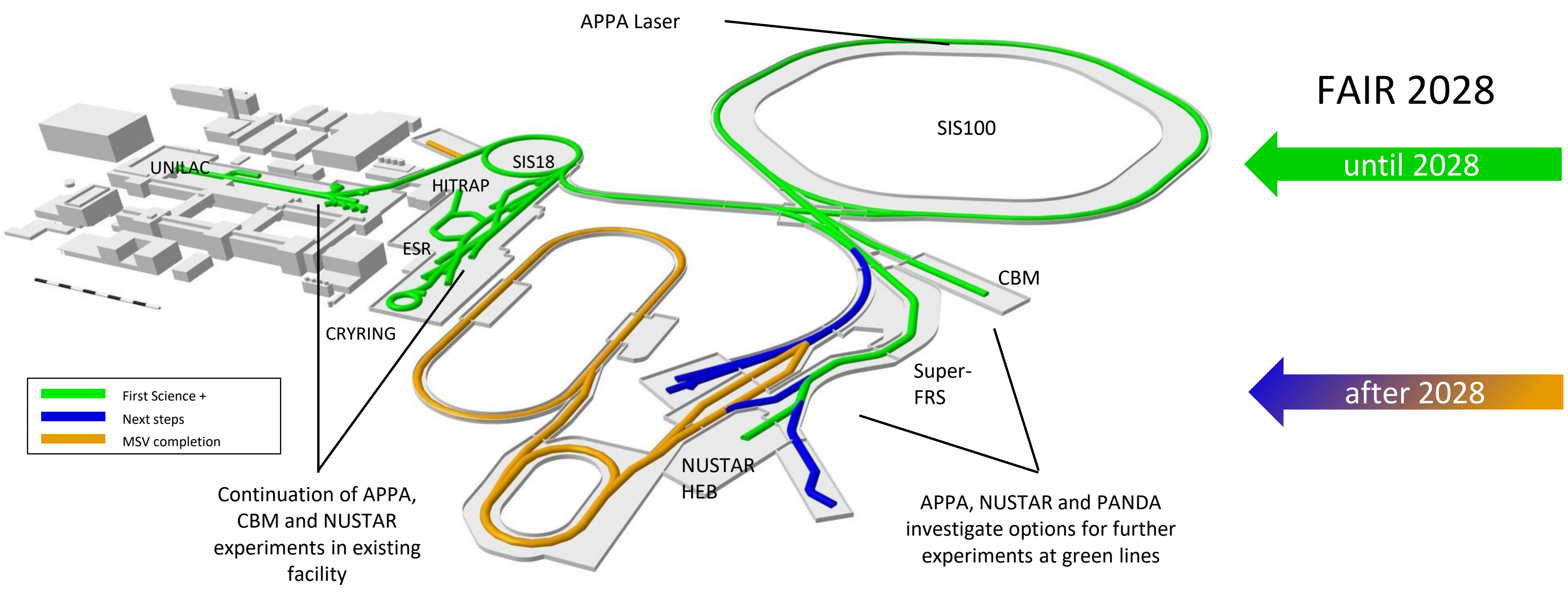


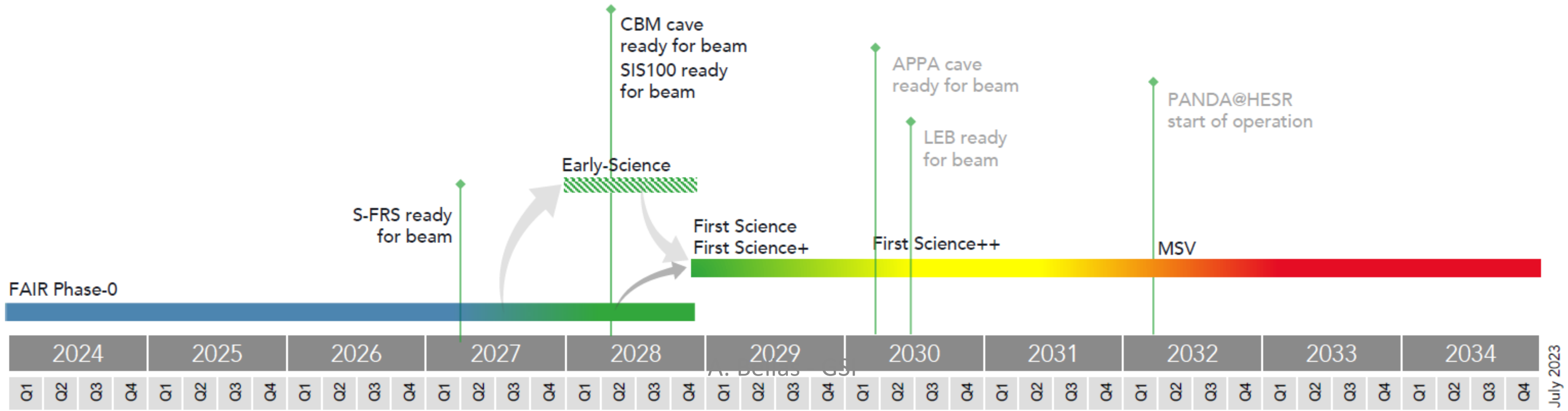
- Tracking acceptance
  2° < Θ_{LAB} < 25°
- Free streaming readout
- Front-end connectivity up to
  R_{int} = 10 MHz
- Software-based event selection

1: Time-Zero Detector & Beam Diagnostics
2: Silicon Tracking System / Micro Vertex Detector
3: Superconducting Dipole Magnet
4: Muon Chambers
5: Ring Imaging Cherenkov Detector
6: Transition Radiation Detector
7: Time of Flight Detector
8: Forward Spectator Detector

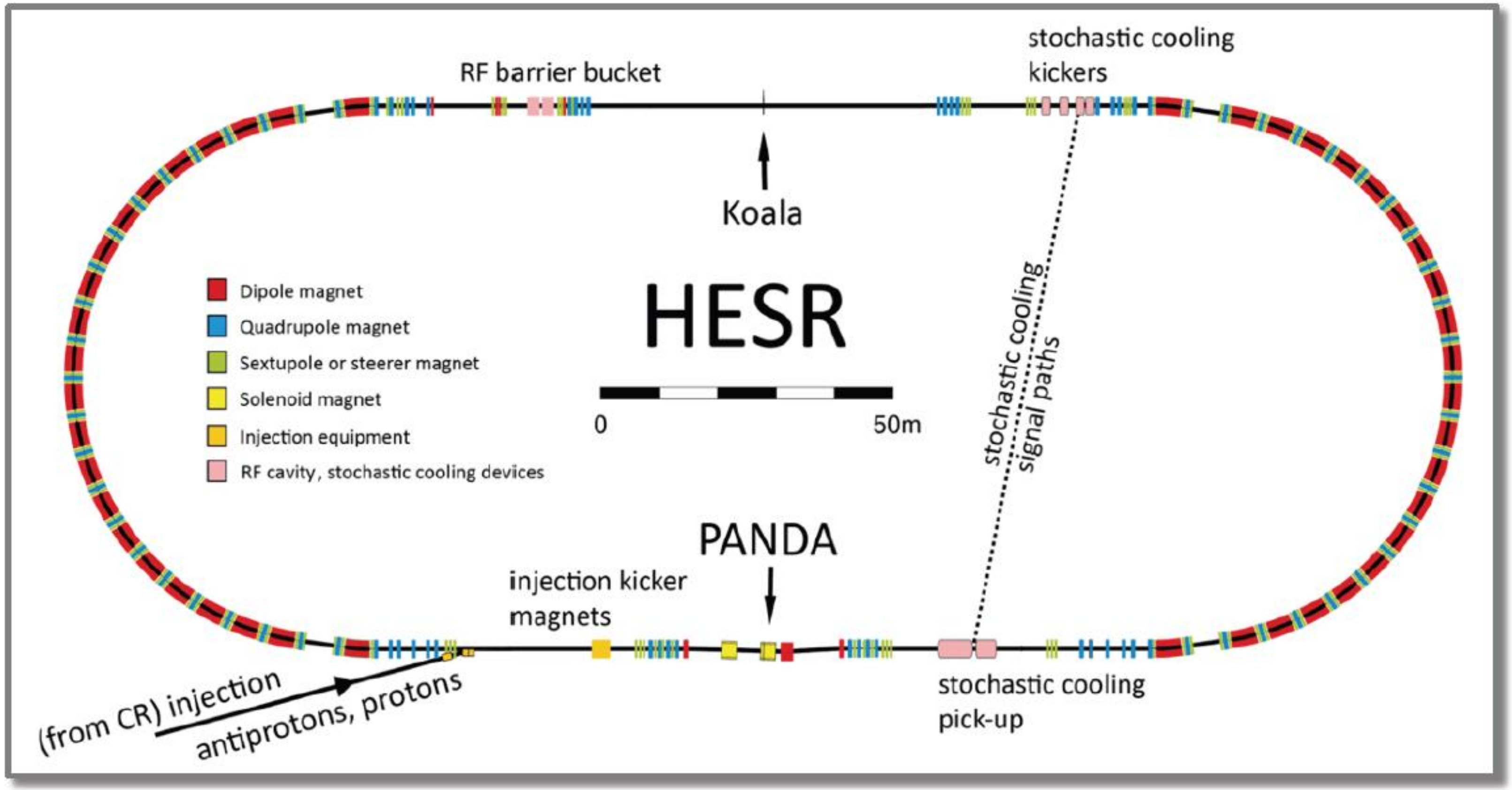


Current prospects and timeline





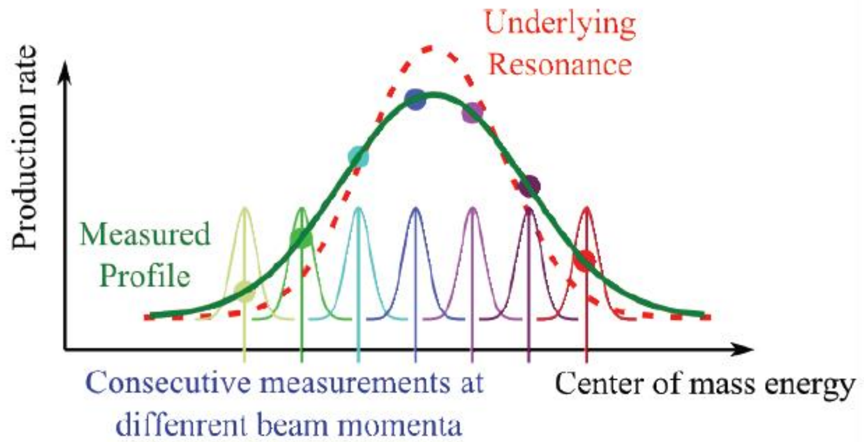
HESR - High Energy Storage Ring



Circumference	575 m
Momentum	1.5 – 15 GeV/c

Stochastic cooling
over full momentum range
$\longrightarrow \Delta E \approx 50$ keV

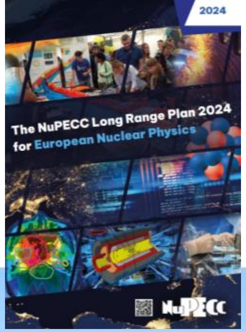
Production experiments
with high-precision beam energy



Mode	High luminosity (HL)	High resolution (HR)
$\Delta p/p$	$\sim 10^{-4}$	$\sim 4\times10^{-5}$
L ($cm^{-2}s^{-1}$)	2×10^{32}	2×10^{31}
Stored $\bar{p}$	10^{11}	10^{10}

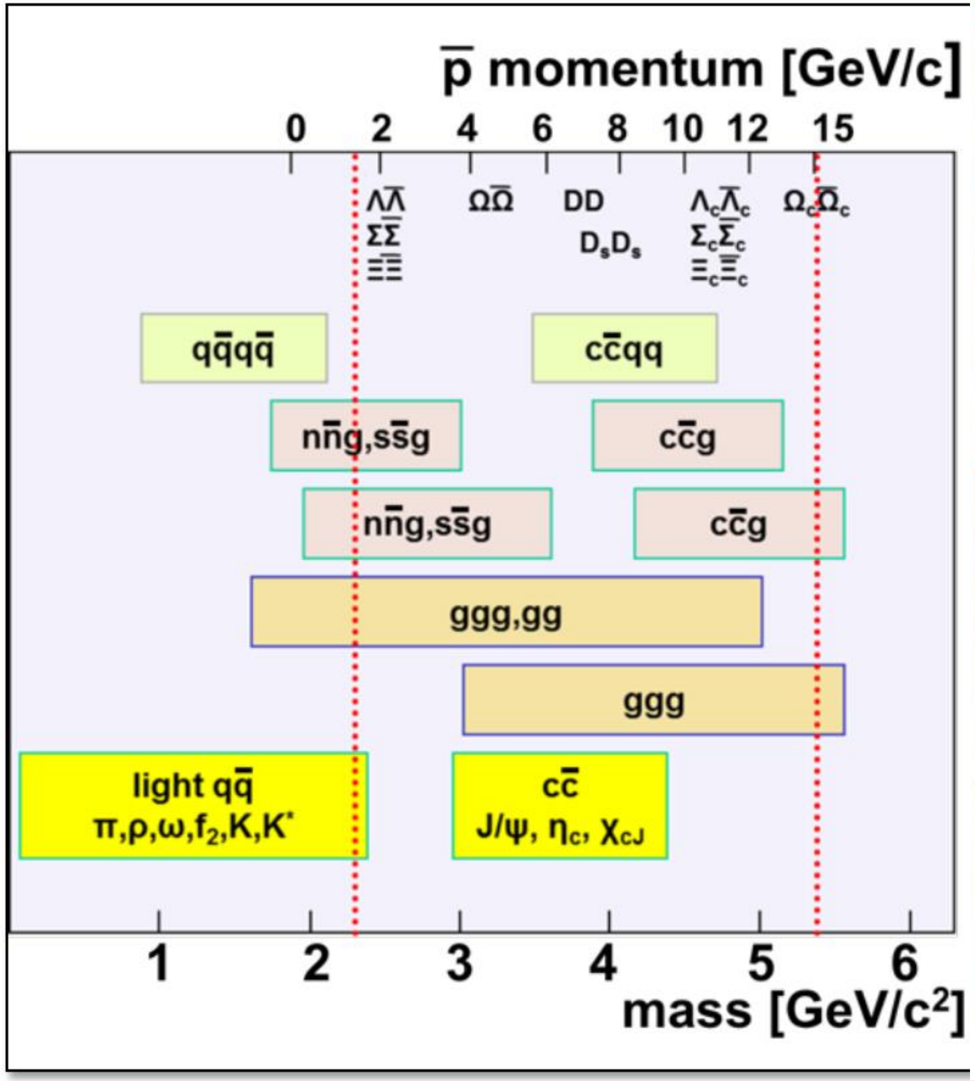
PANDA Physics Objectives

Antiprotons – Unique Probes for Discoveries and Precision Physics



NuPECC
Long Range Plan 2024
arXiv:2503.15575

Panda Phase One
Eur. Phys. J. A 57, 184 (2021)



Hadron Spectroscopy

Experimental Goals: *mass, width & quantum numbers J^{PC} of resonances*

Charm Hadrons: *charmonia, D-mesons, charm baryons*

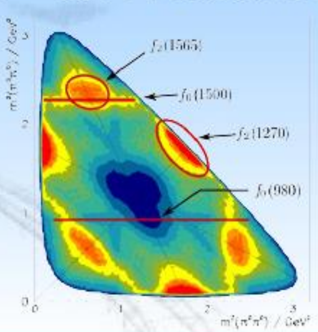
→ Understand new XYZ states, $D_s(2317)$ and others

Exotic QCD States: *glueballs, hybrids, multi-quarks*

Spectroscopy with Antiprotons:

Production of states of all quantum numbers

Resonance scanning with high resolution



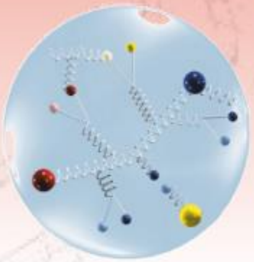
Hadron Structure

Time-like Nucleon Formfactors

→ Measurable in annihilation, discrepancy with space-like

Generalized Parton Distributions

Drell-Yan Process



Nuclear Physics

Hypernuclei: Production of double Λ-hypernuclei

→ γ-spectroscopy of hypernuclei, YY interaction

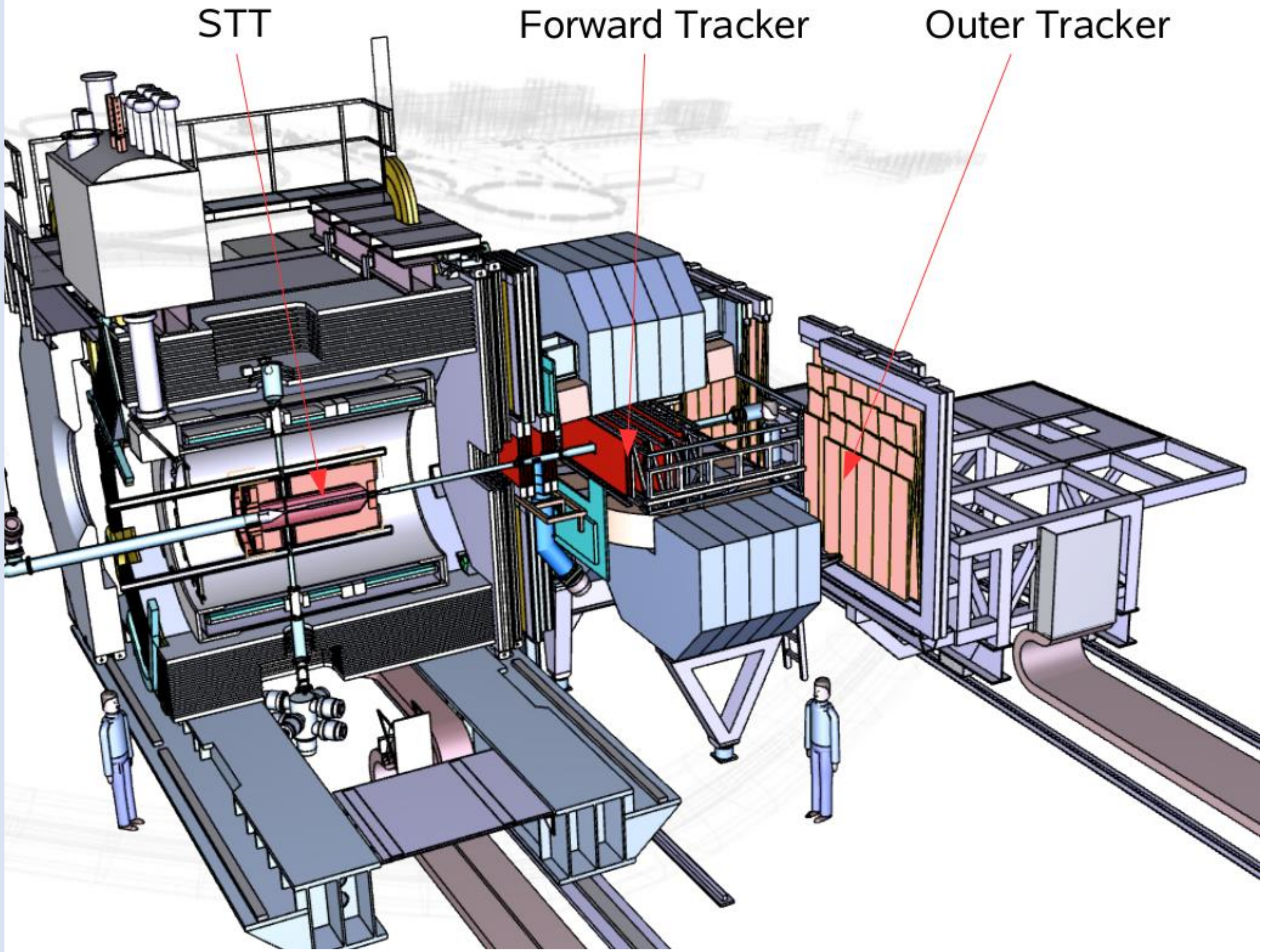
Hadrons in Nuclear Medium

PANDA - Straw Trackers

Central Tracker STT
- 4224 straws, Ø 1cm
- Ar CO_2 at 2 bar (absolute)
- 19 axial layers, 8 skewed
- 0.04% X_0/layer
- ASIC readout

Forward Tracker 1-4
- 2+2 planar stations,
- 5600 straws, 1 cm diameter
- Ar CO2 at 2 bar (absolute)
- 4 DL/station (x,u,v,x)
- ASIC readout

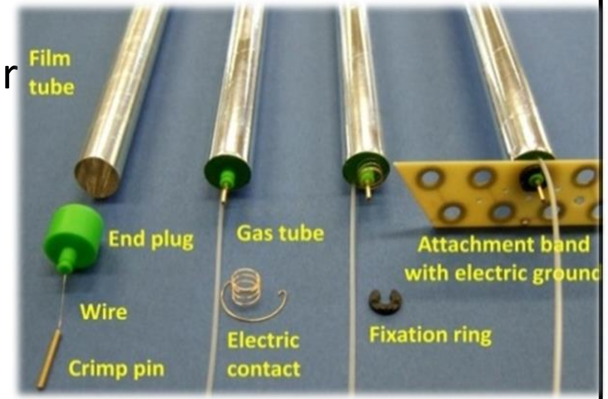
OuterTracker (LHCb straws)
- Inner half length modules 2.4m
- 10800 straws, Ø 0.5cm
- 4 DL/station (x,u,v,x)
- 0.1% X_0/layer
- LHCb ASIC readout + PANDA interface



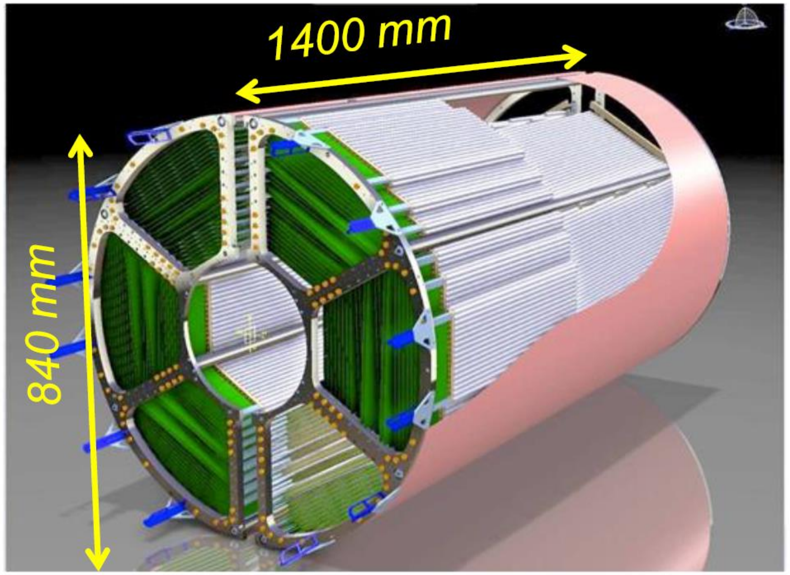
PANDA - Straw Tube Tracker - Barrel

Tracking in Target Spectrometer
- Layers of drift tubes
- R_{in}= 150 mm, R_{out}= 420 mm, l=1500 mm
- Tube made of 27 µm thin Al-Mylar, O=1cm
- **Self-supporting straw double layers at ~1 bar overpressure (Ar/CO_2) developed at FZ Jülich**
- 4224 straws in 19 /8 Axial /stereo layers at ~3°
- **Resolution: σ(r) ~150µm, σ(z) ~2-3mm**

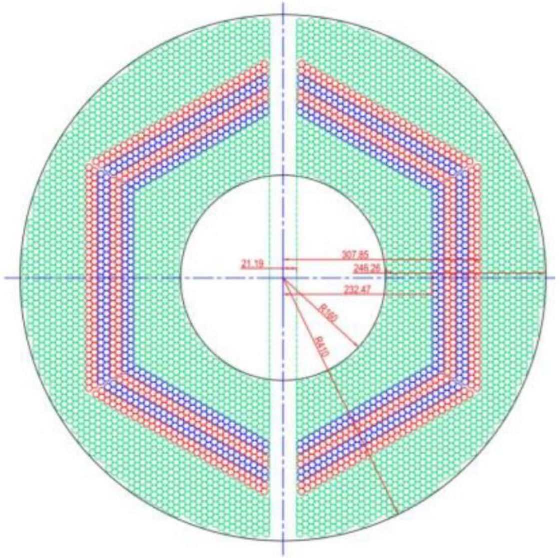
Material Budget
- 0.05 % X/X_0 per layer
- **Total 1.3% X/X_0**



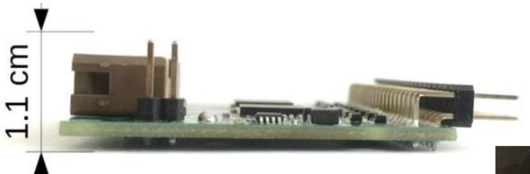
Project Status
- TDR Approved
- **ASIC (PASTTREC) &TDC FPGA**
  AMS 0.35µm CMOS - time and ToT, PID capability
- Extensive beam tests at COSY and QA done
- Ageing tests: up to 1.2 C/cm^2
- Straw module production complete
- Preparations assembly of first STT sector



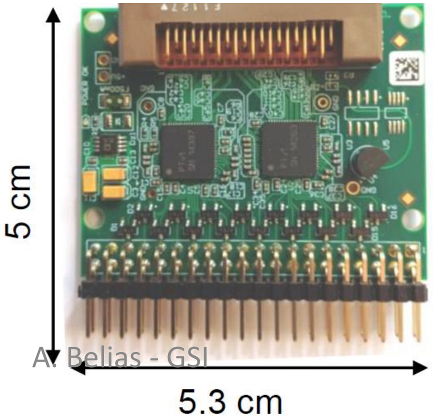
PANDA-STT (3D-view)

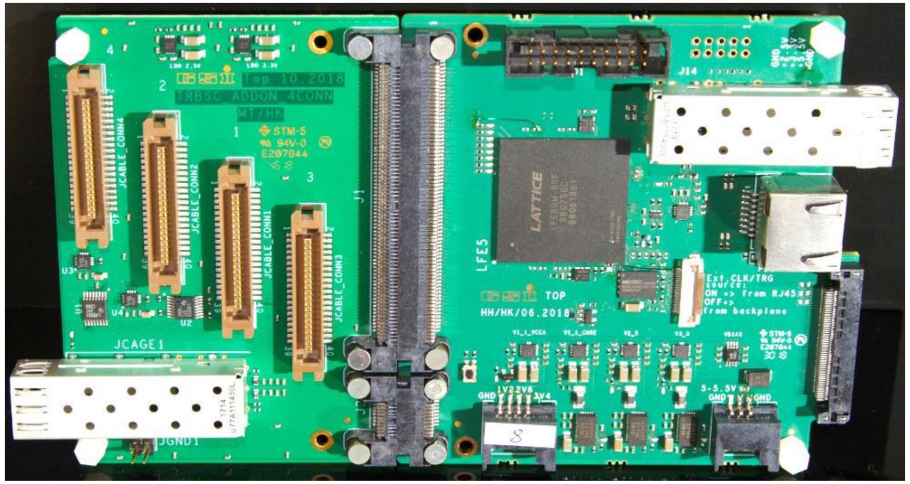


Straw layout (cross-view), stereo layers in red/blue.



New FEBv4 (with temperature sensor & chip e-ID)





PANDA - Forward Straw Tube Tracker

Tracking in Forward Spectrometer

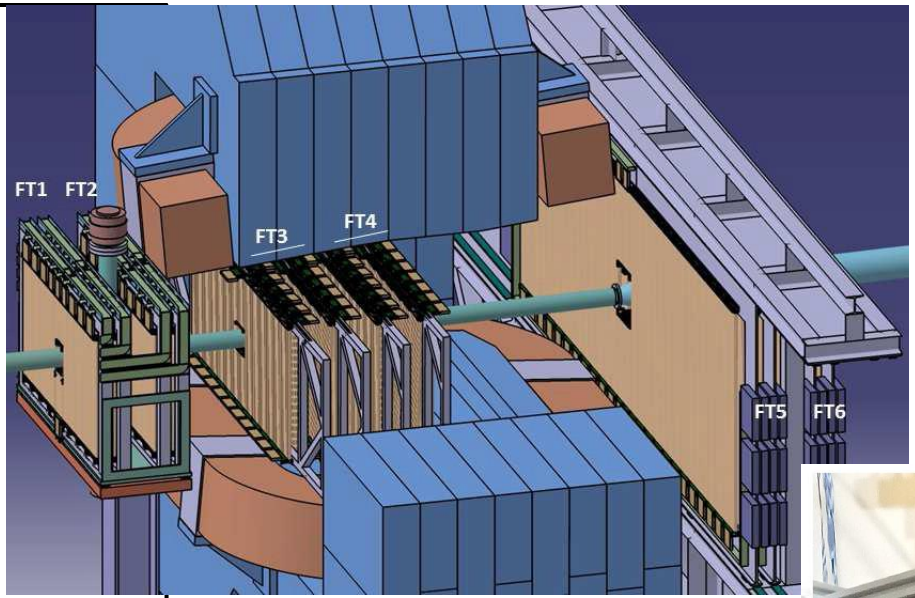
Stations 3 with 2 chambers each

- FT1&2 : in front of dipole
- FT3&4 : inside the dipole gap
- FT5&6 : behind the dipole

Straw tubes arranged in double layers

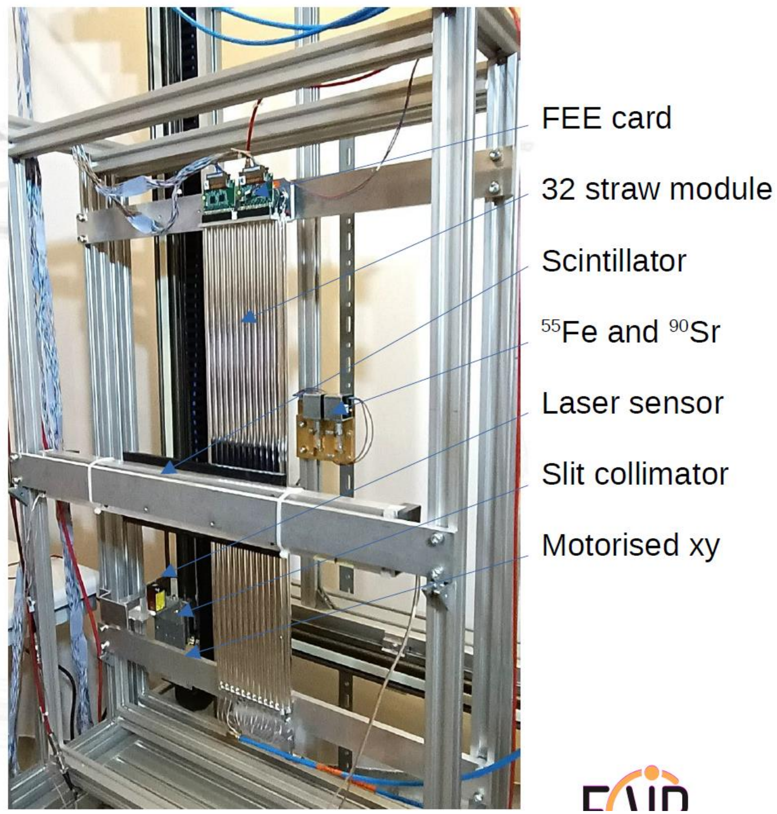
- Same technology as for STT Barrel
- 27 μm thin Al-mylar, O=1cm tubes
- Stability by 1 bar overpressure

- 4 projections 0°/+ -5°/0° per chamber
- Readout ASIC (PASTREC) & TDC FPGA (same as STT Barrel)



Project status - TDR approved

- Tender for HV system and gas flow regulators
- Prototype purified gas system used for tests
- Ageing tests: up to 1.2 C/cm^2
- Straw and module production ongoing
- Straw modules for FT1 & FT2 ready
- Production for FT3 & FT4 in progress



PANDA - Muon Detector System

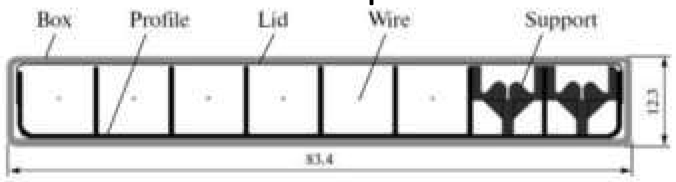
Muon system rationale

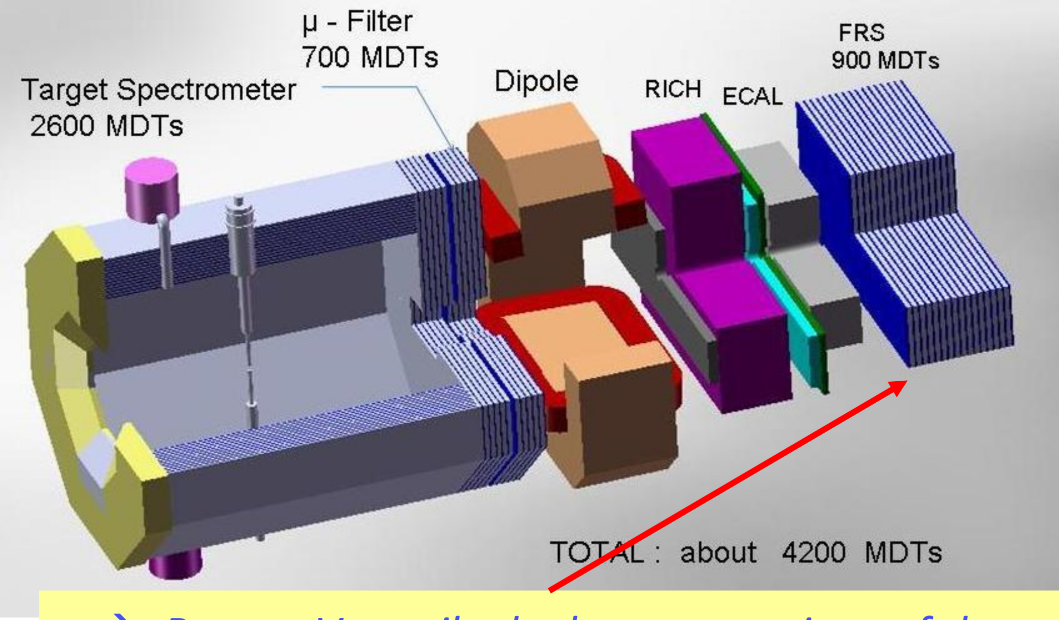
- Low momenta, high BG of pions

➔ Multi-layer range system

Muon system layout

- *Barrel*: 12+2 layers in yoke
- *Endcap*: 5+2 layers
- *Muon Filter*: 4 layers
- *Fw Range System*: 16+2 layers
- *Detectors:* Mini Drift Tubes (MDT) wire & cathode strip readout



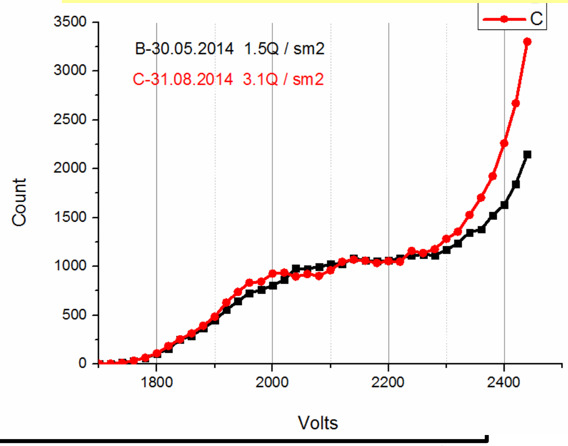


→ Poster: *Versatile deployment options of the former LHCb gaseous detector in PANDA at FAIR*

Project status

- TDR approved
- Testbeams at CERN, aging, cosmics
- Digital FEE developments

Project freeze!



Testbeam results:

- μ, p and n can be resolved