XII Quark Confinement and the Hadron Spectrum

Physics of FAIR

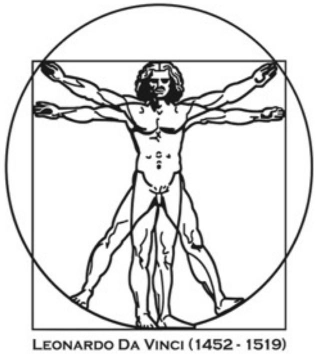
Klaus Peters

GSI / U Frankfurt

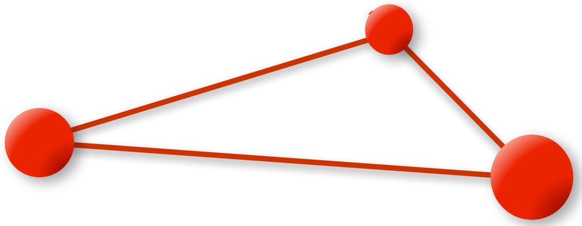
Thessaloniki, Sept 3, 2016

Frontiers

Complexity Frontier



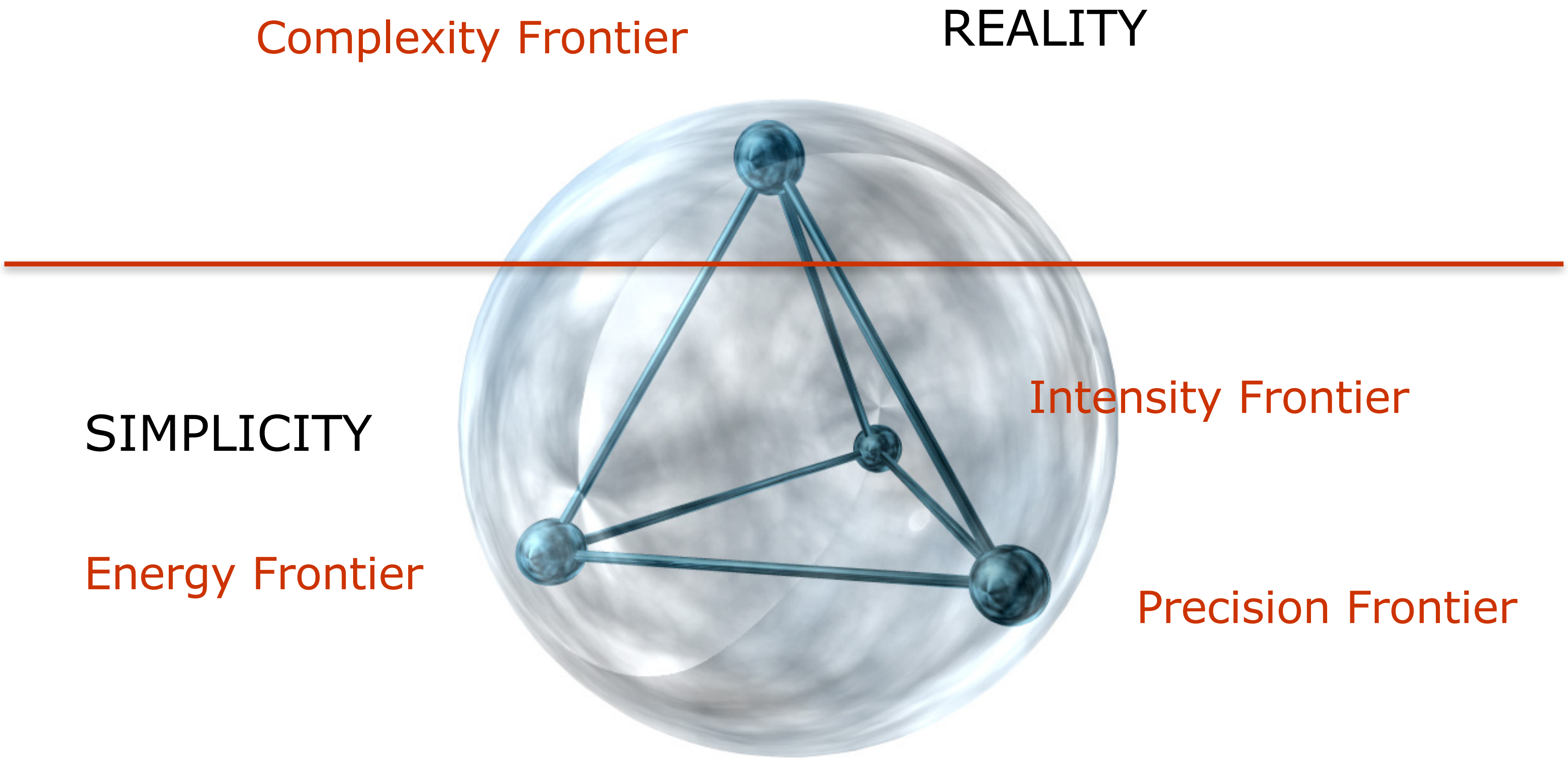
Intensity Frontier



Energy Frontier

Precision Frontier

Complexity

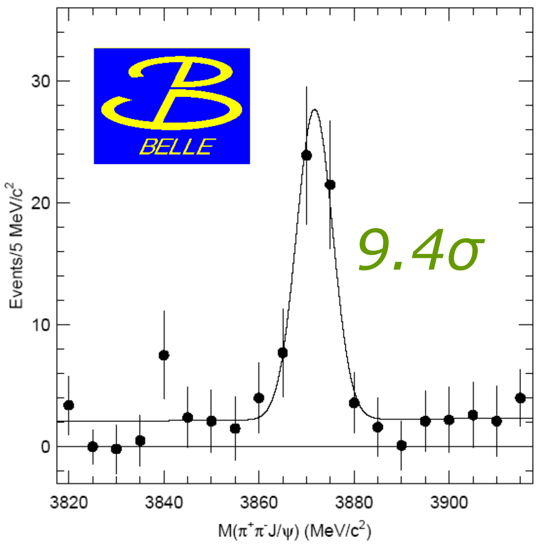

Complexity Frontier
REALITY
SIMPLICITY
Intensity Frontier
Energy Frontier
Precision Frontier

Discovery of the X(3872)

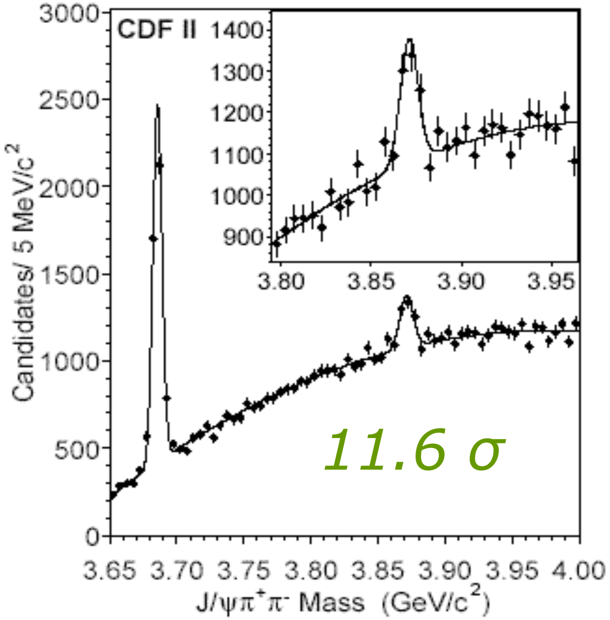
2003

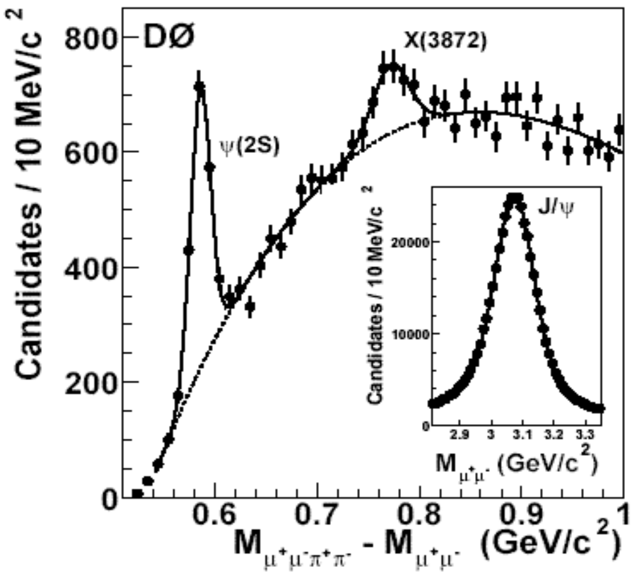
hep-ex/0312021

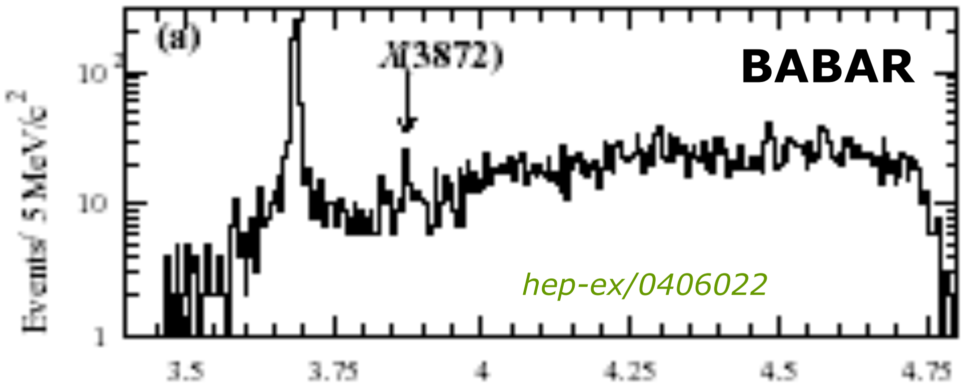
hep-ex/0405004



Phys. Rev. Lett. 91(2003)262001
152 Mill. BB





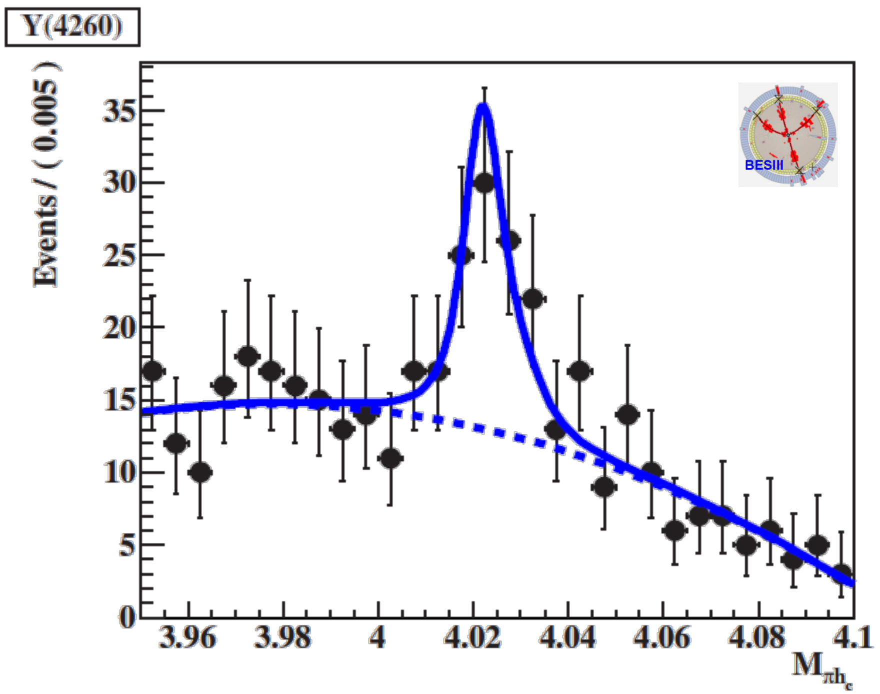


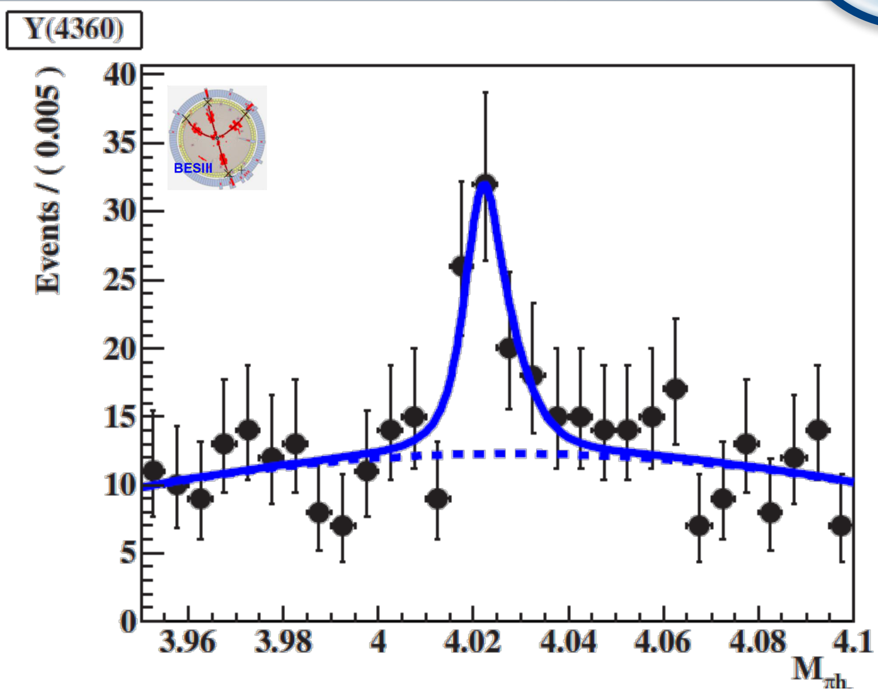
hep-ex/0406022

$Z_c(402x)$ – another new charged object

2013++

And even more Z's





Simultaneous fit to 4.26/4.36 GeV data 6.4σ

From $h_c\pi^{\pm}$

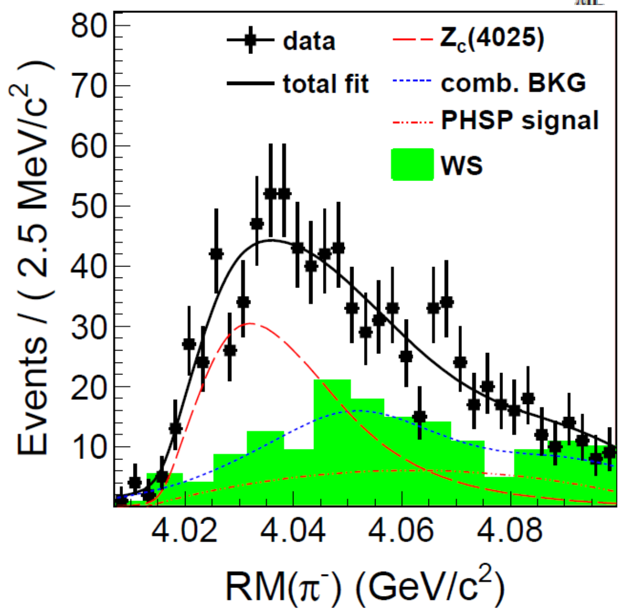
$M(Z_c(4020)) = 4021.8 \pm 1.0 \pm 2.5$ MeV

$\Gamma(Z_c(4020)) = 5.7 \pm 3.4 \pm 1.1$ MeV

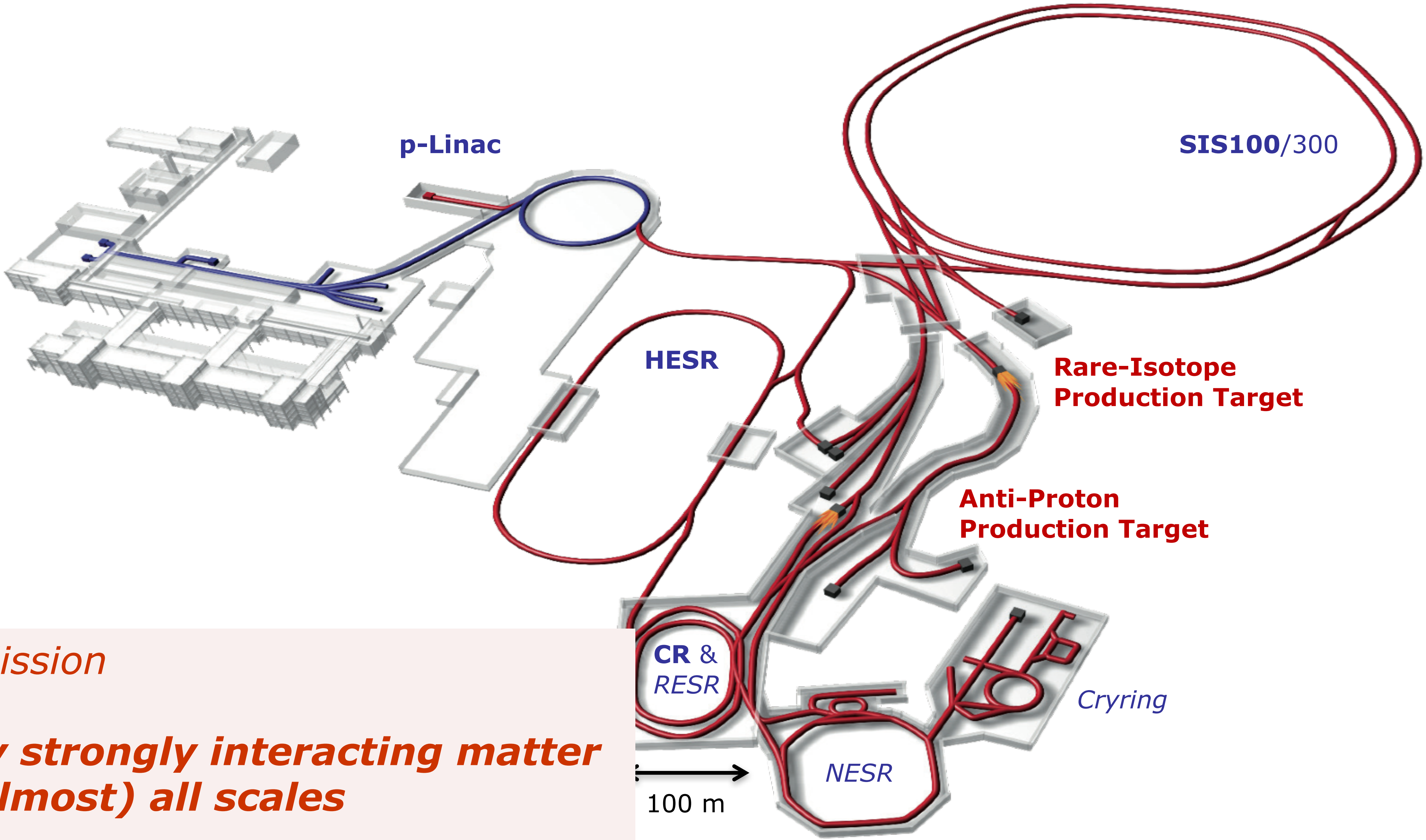
From $(D^*\bar{D}^*)^{\pm}$

$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV

$\Gamma(Z_c(4025)) = 24.8 \pm 5.7 \pm 7.7$ MeV



FAIR @ Darmstadt



The Mission

Study strongly interacting matter on (almost) all scales

FAIR @ Darmstadt

Nuclear Structure & Astrophysics
(Rare-isotope beams)

Hadron Physics
(Stored and cooled
14 GeV/c anti-protons)

QCD-Phase Diagram
(HI beams 2 to 45 GeV/u)

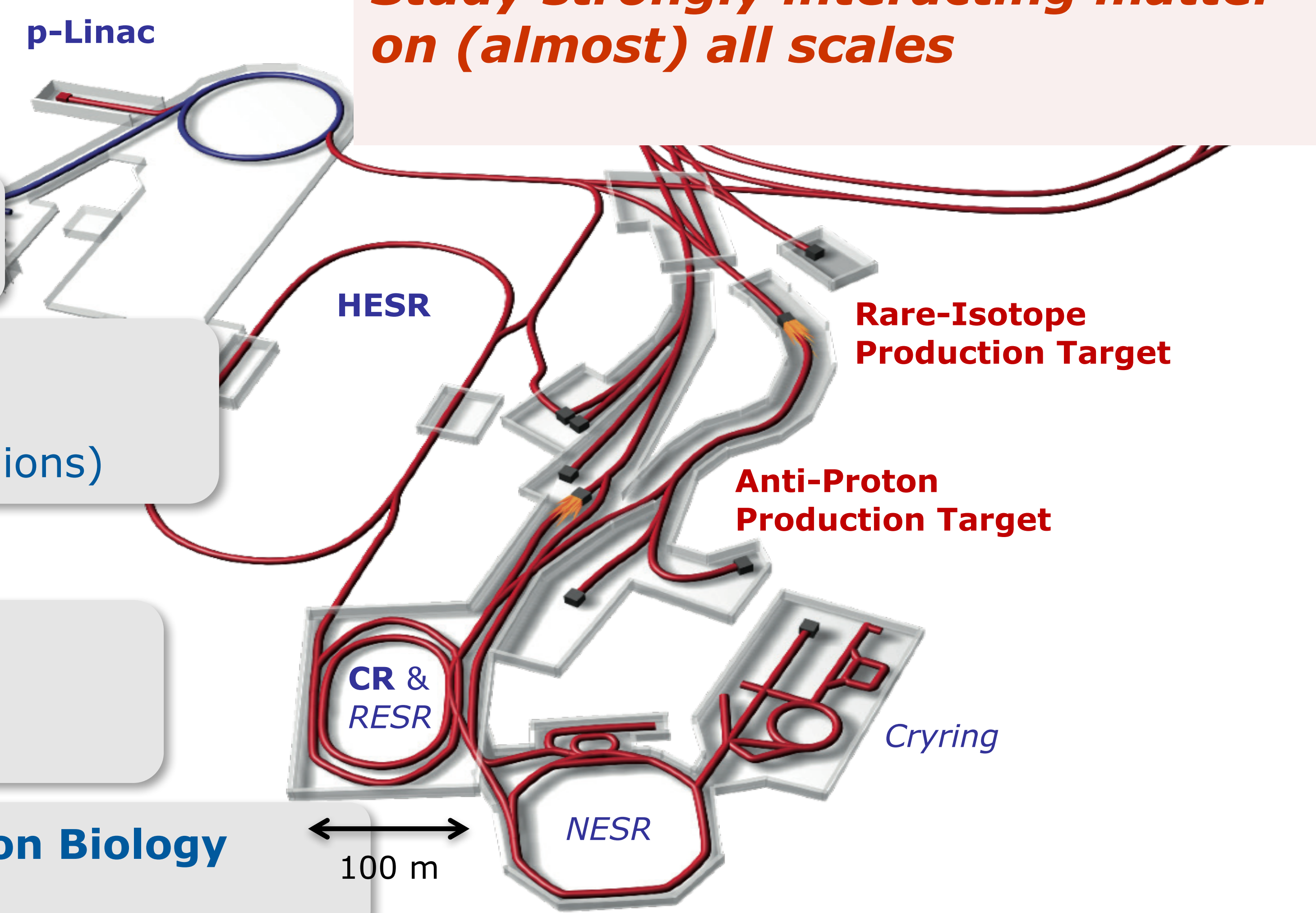
**Fundamental Symmetries
& Ultra-High EM Fields**
(Antiprotons & highly stripped ions)

Dense Bulk Plasmas
(Ion-beam bunch compression
& petawatt-laser)

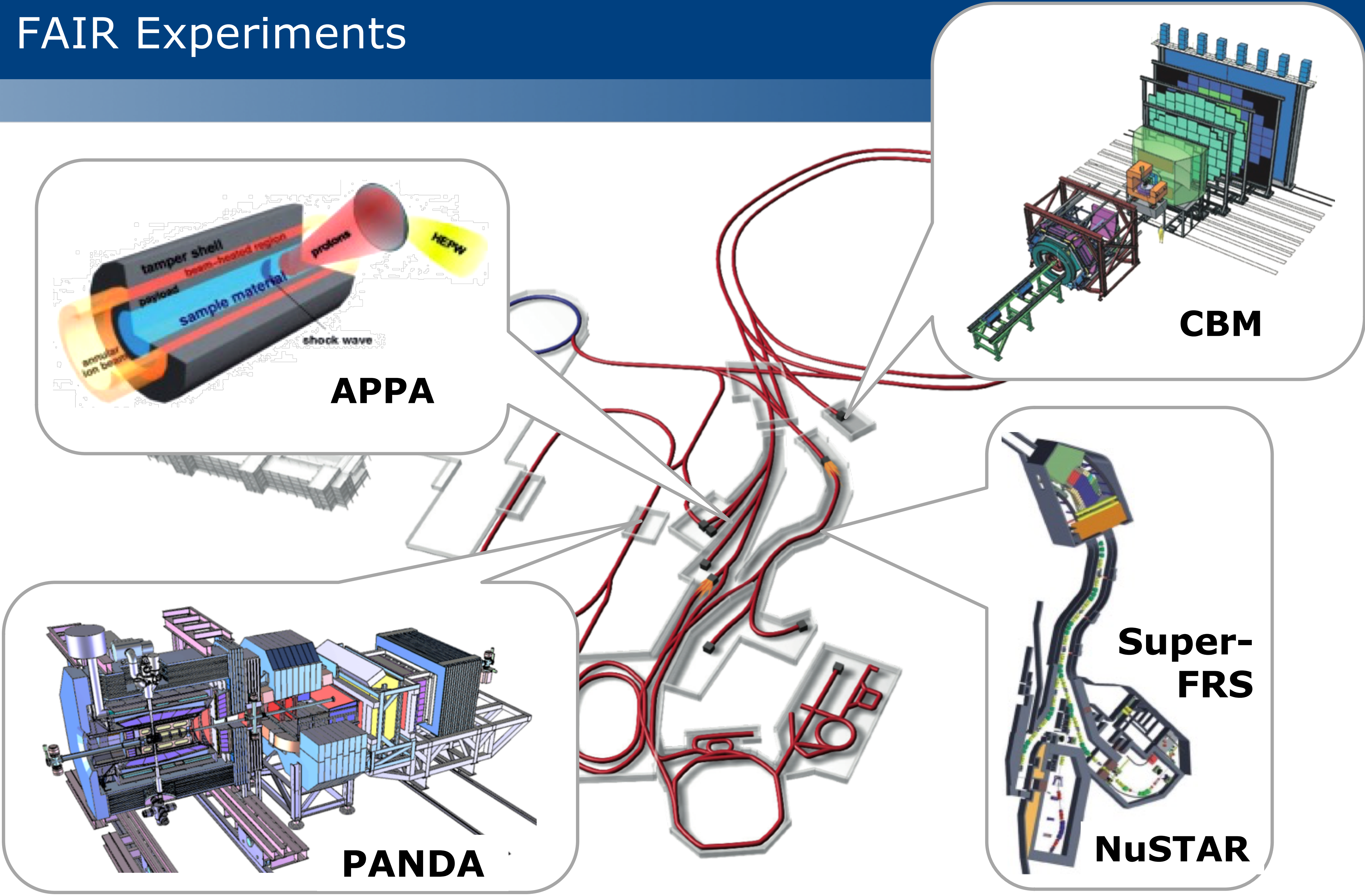
Materials Science & Radiation Biology
(Ion & antiproton beams)

The Mission

Study strongly interacting matter on (almost) all scales



FAIR Experiments



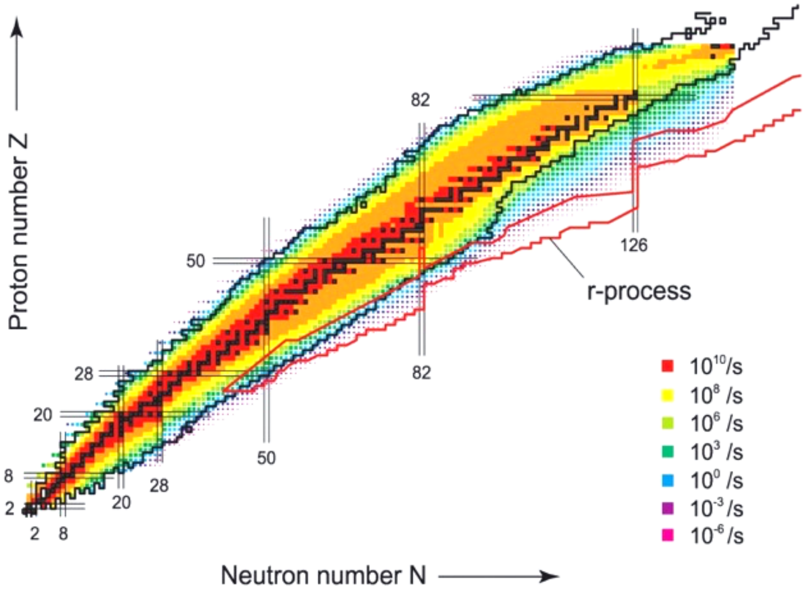
NUSTAR @ FAIR: physics of the nuclei

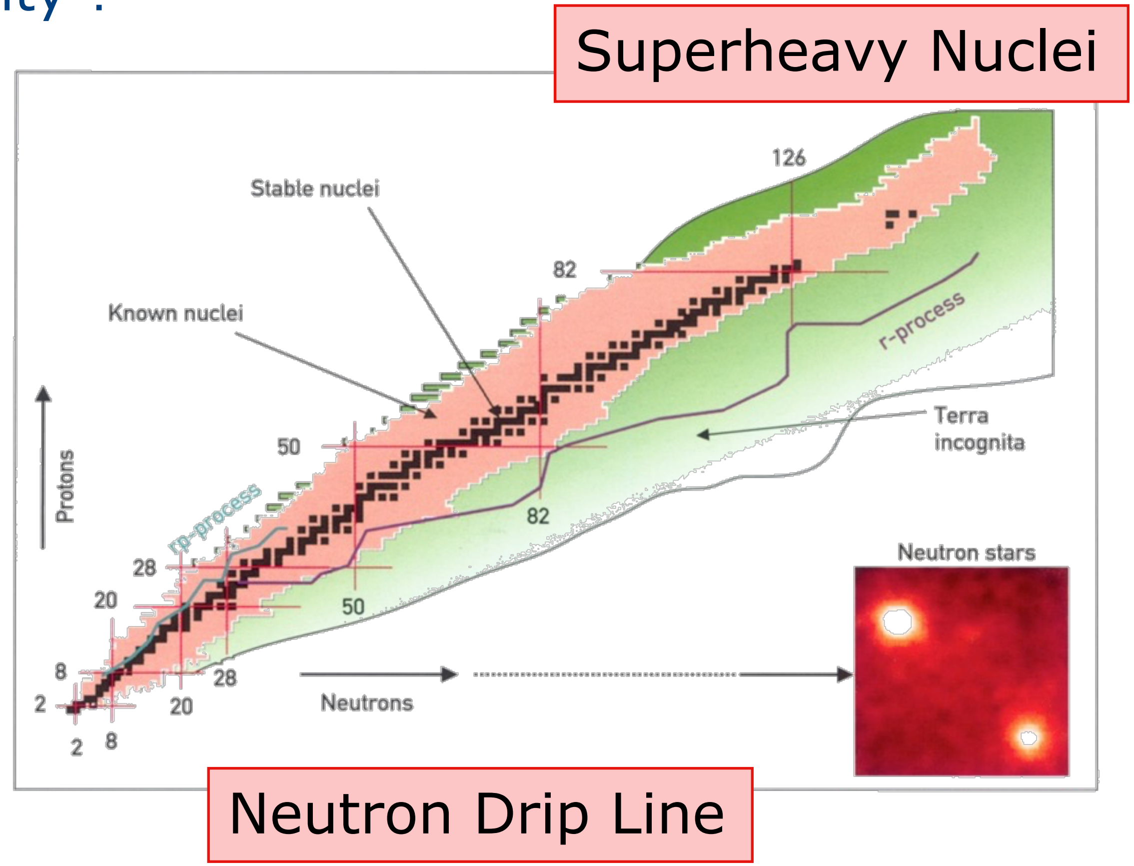
How Are Elements Made ?

Structure of exotic nuclei far off stability ?

Nuclear synthesis in stars
and star explosions

Fundamental interactions
and symmetries



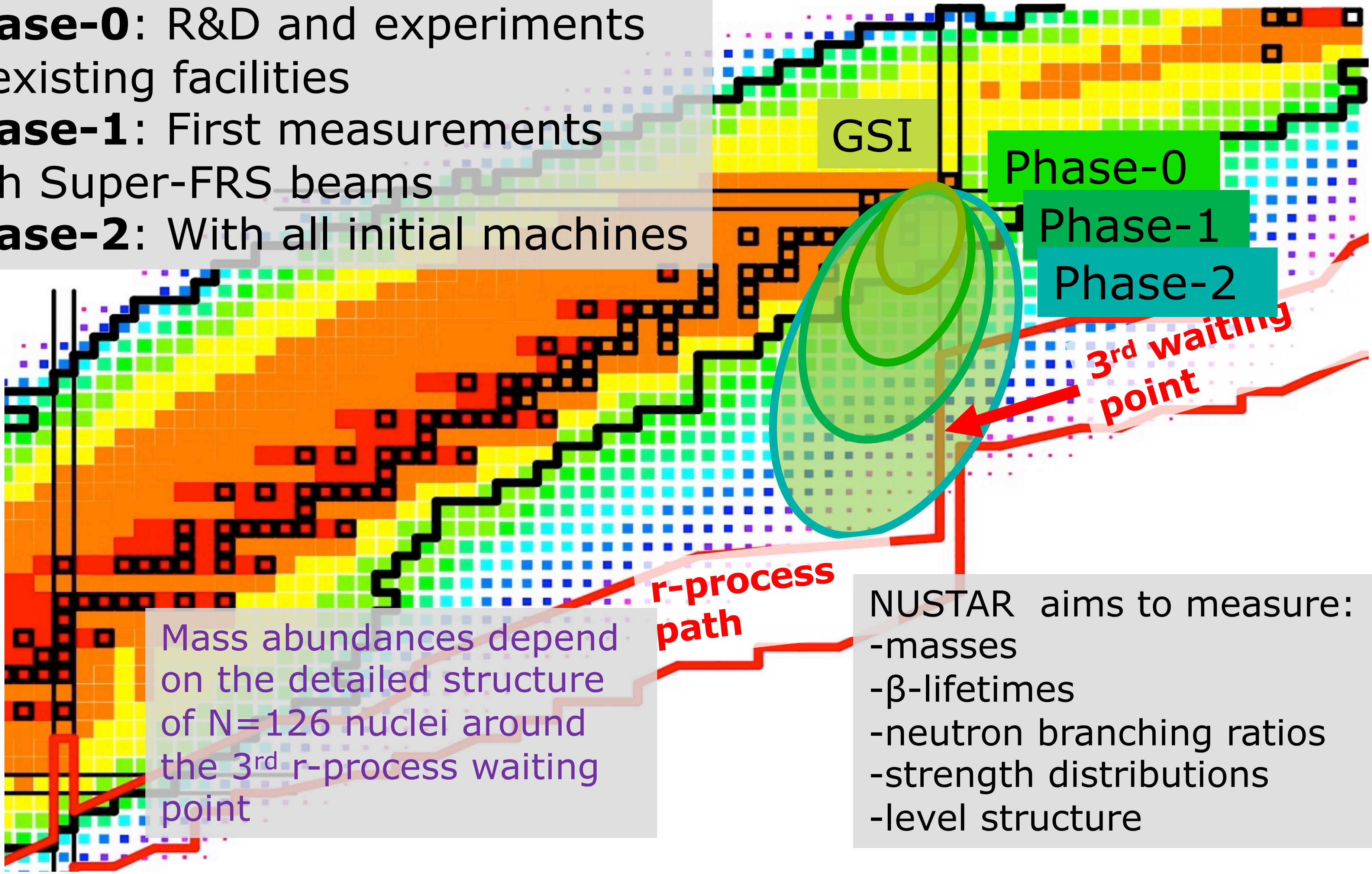


NUSTAR @ FAIR: Day-1

NUSTAR phases

- **Phase-0**: R&D and experiments in existing facilities
- **Phase-1**: First measurements with Super-FRS beams
- **Phase-2**: With all initial machines

One example

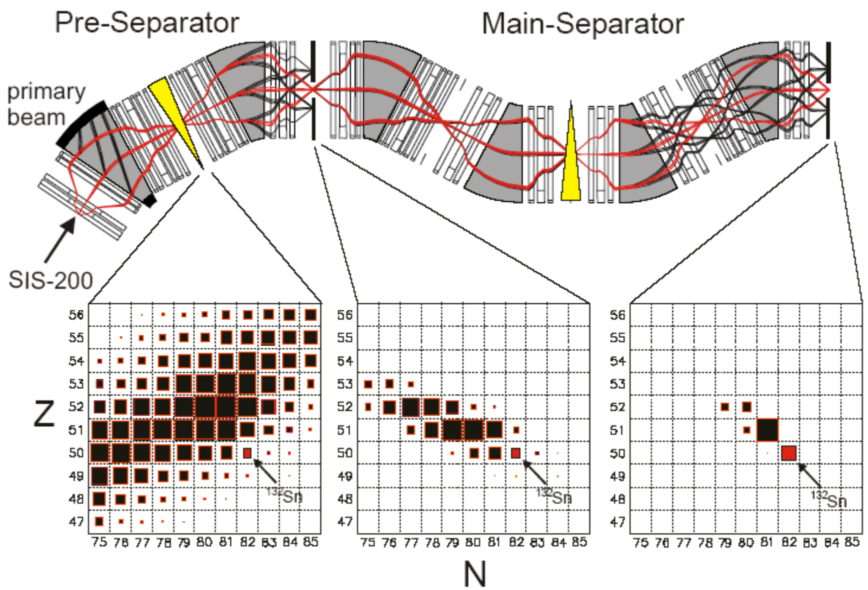


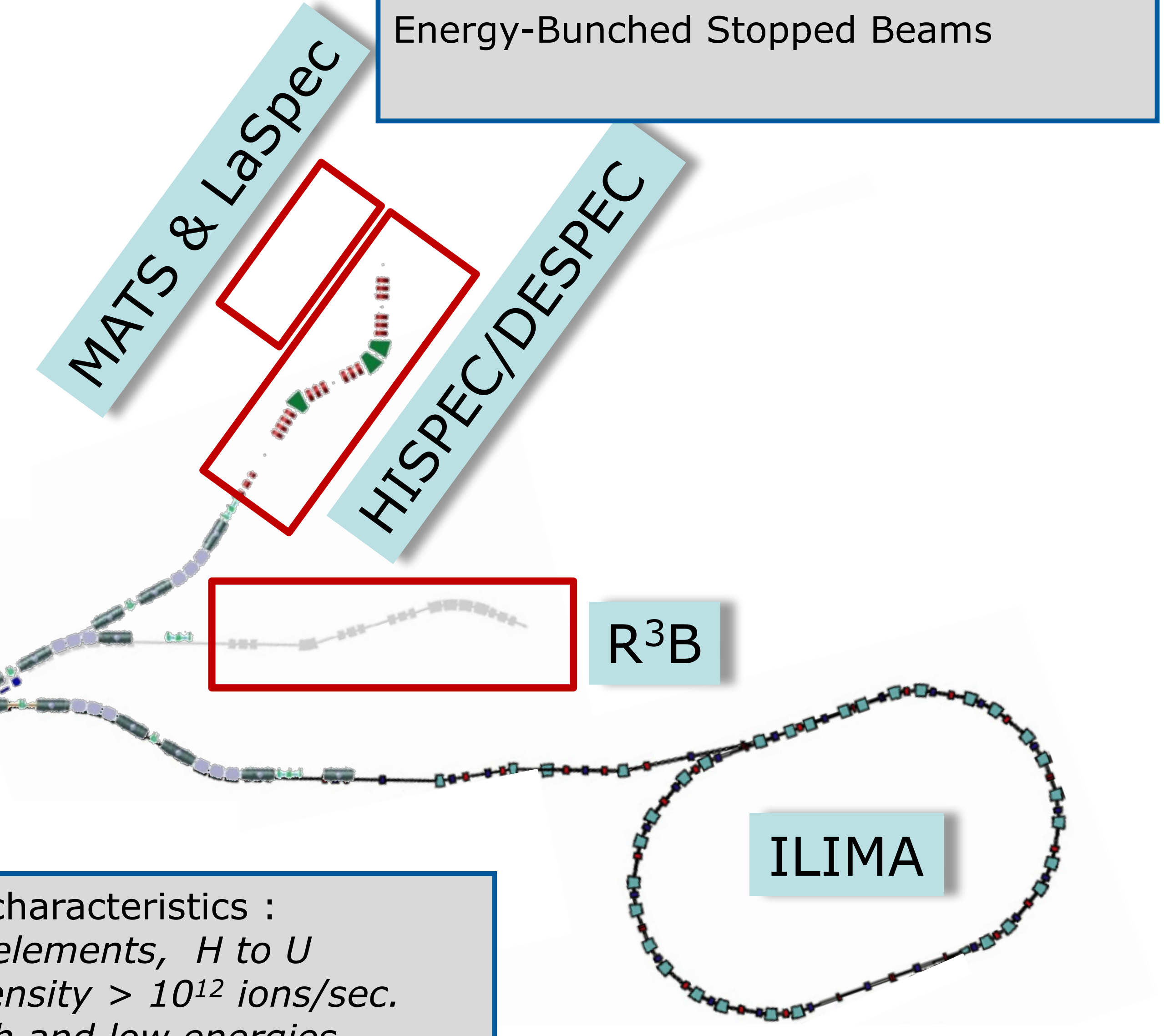
Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

NUSTAR aims to measure:
-masses
-β-lifetimes
-neutron branching ratios
-strength distributions
-level structure

NUSTAR @ FAIR: Installations

Superconducting **FR**agment **S**eparator
High-Energy Reaction Setup
Multi-Storage Rings (CR, NESR, eA)
Energy-Bunched Stopped Beams



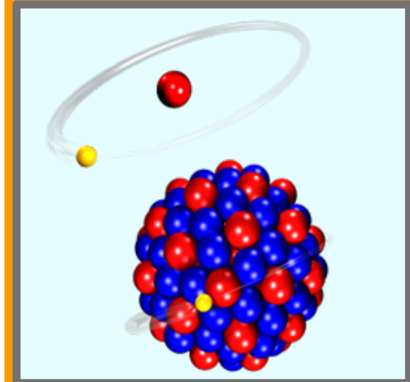


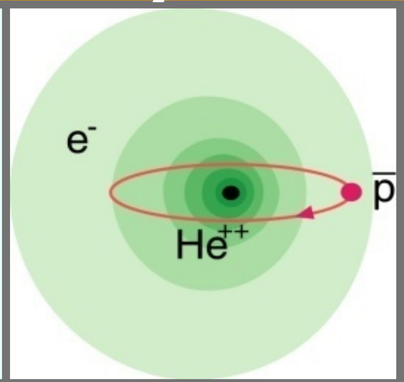
Key characteristics :
- *all elements, H to U*
- *intensity > 10^{12} ions/sec.*
- *high and low energies*
- *pulsed and CW beams*

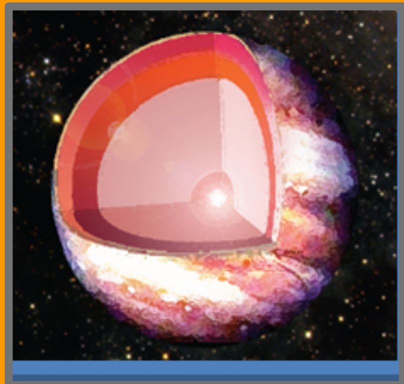
APPA @ FAIR

FACILITY CAPABILITY	SCIENTIFIC CAPABILITY
Highest Charge States	*Extreme Static Fields*
Relativistic Energies	*Extreme Dynamical Fields and Ultrashort Pulses*
High Intensities	*Very High Energy Densities and Pressures*
High Charge at Low Velocity	*Large Energy Deposition*
Low-Energy Anti-Protons	*Antimatter Research*

Atomic Physics — **Plasma** — **Materials** — **Bio**

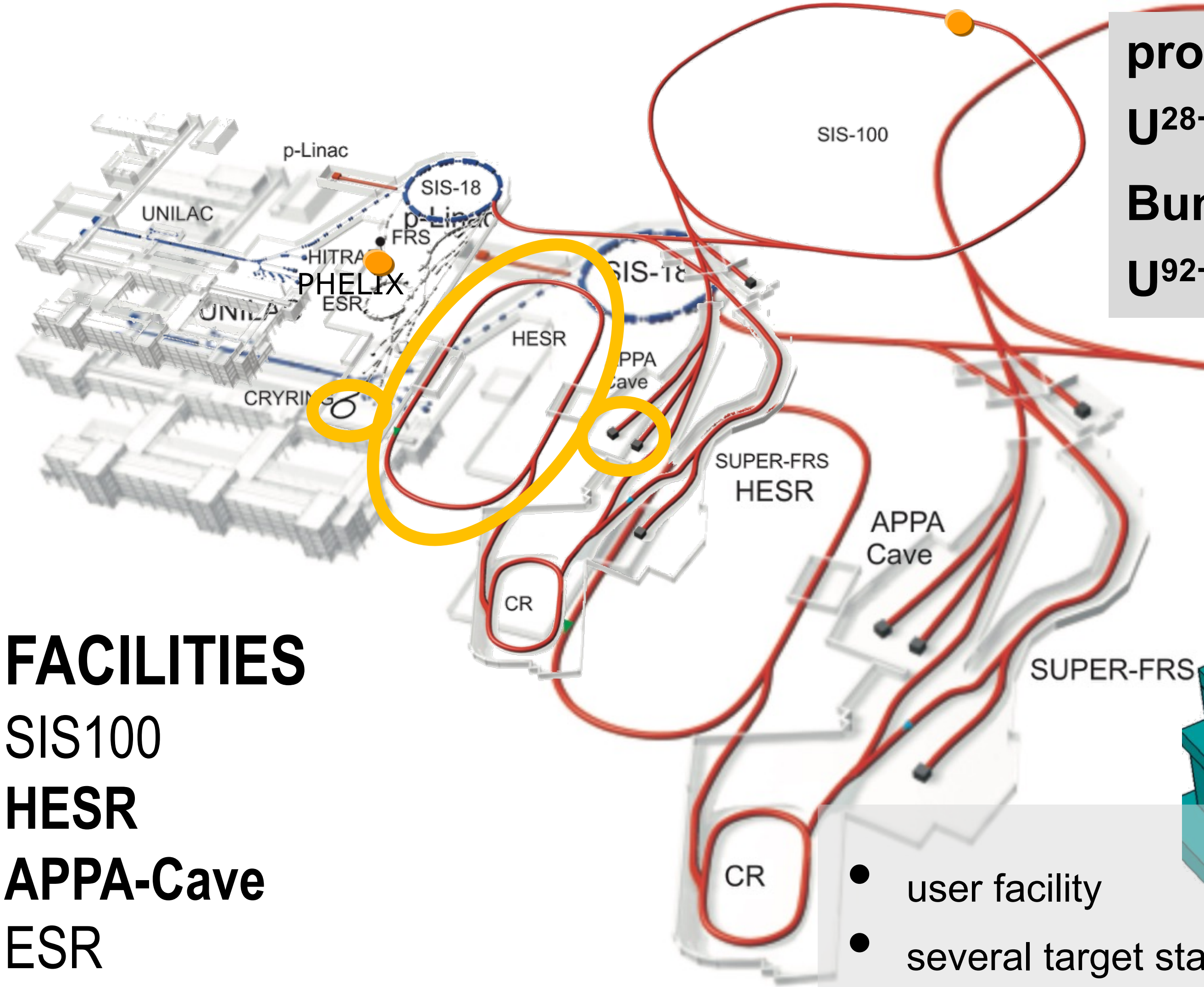






SPARC	FLAIR	PP@FAIR	MAT/BIOMAT	BIO/BIOMAT
strong field research … probing of fundamental laws of physics	**antimatter** … matter / anti-matter symmetry	**extreme states of matter** … states of matter common in astrophysical objects	**radiation effects** … degradation and nanostructuring of materials	**space travel & therapy** … cosmic radiation risk and theranostics

APPA @ FAIR: Installations



protons (10 GeV) 2 x 10^{13} p/bunch

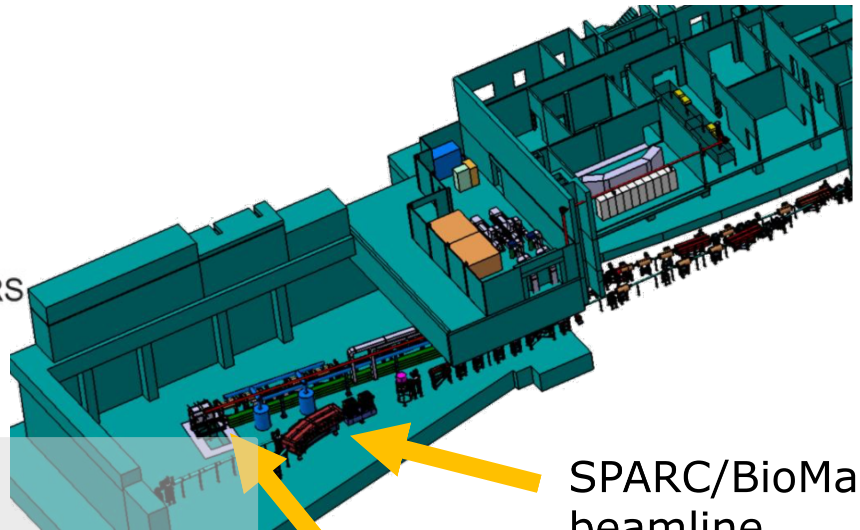
U^{28+} (2 GeV/u): 5 × 10^{11} ions/bunch

Bunched operation ≈100ns

U^{92+} (10 GeV/u) 10^{8} ions/s

FACILITIES

SIS100
HESR
APPA-Cave
ESR
CRYRING
HITRAP

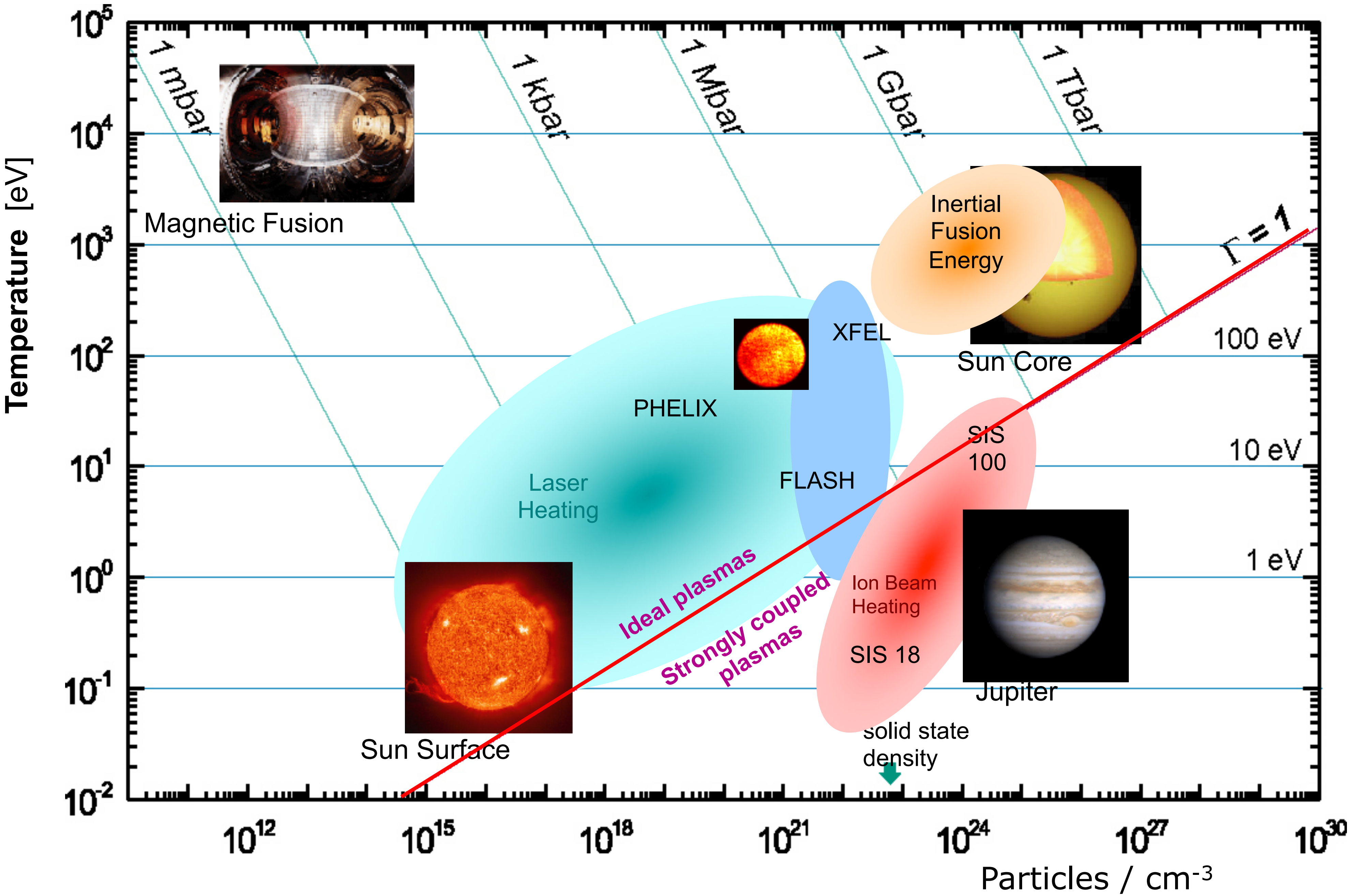


SPARC/BioMat beamline

PP@FAIR/BioMat beamline

- user facility
- several target stations
- flexible detector settings
- flexible beam shaping
- external drivers

Plasmas



Temperature [eV]
Particles / cm-3
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^12
10^15
10^18
10^21
10^24
10^27
10^30
1 mbar
1 kbar
1 Mbar
1 Gbar
1 Tbar
Magnetic Fusion
Inertial Fusion Energy
Sun Core
XFEL
PHELIX
Laser Heating
FLASH
SIS 100
Γ = 1
100 eV
10 eV
1 eV
Ideal plasmas
Strongly coupled plasmas
Ion Beam Heating
SIS 18
Jupiter
Sun Surface
solid state density

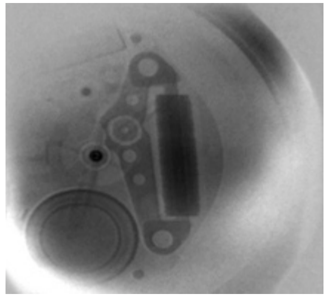
APPA – Day 1 (some examples)

BIOMAT (Biophysics and Materials Research)
- Materials under extreme conditions (pressure, heat, irradiation)
- Radiation shielding of cosmic radiation

Day-1 experiments
- Sample irradiation at APPA cave using high pressure cells
- Irradiation of biological samples at APPA cave

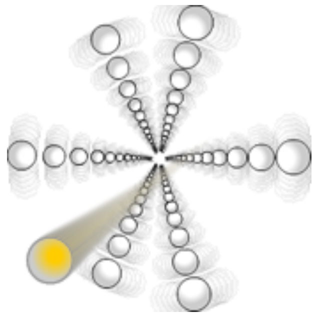
HEDgeHOB/WDM (Plasma Physics)
- Phase transitions shocked/compressed matter
- Opacity measurements of Warm Dense Matter

Day-1 experiments
- Proton microscopy of shocked/compressed materials at APPA cave
- Opacity changes from Cold- to Warm Dense-Matter at APPA cave



SPARC (Atomic Physics)
- Precision test of QED in the strong field domain ($\alpha Z \approx 1$)
- Model independent determination of nuclear parameter

Day-1 experiments
- Ion channeling at APPA cave
- Laser spectroscopy at HESR (fine-structure) and at CRYRING (hyperfine)



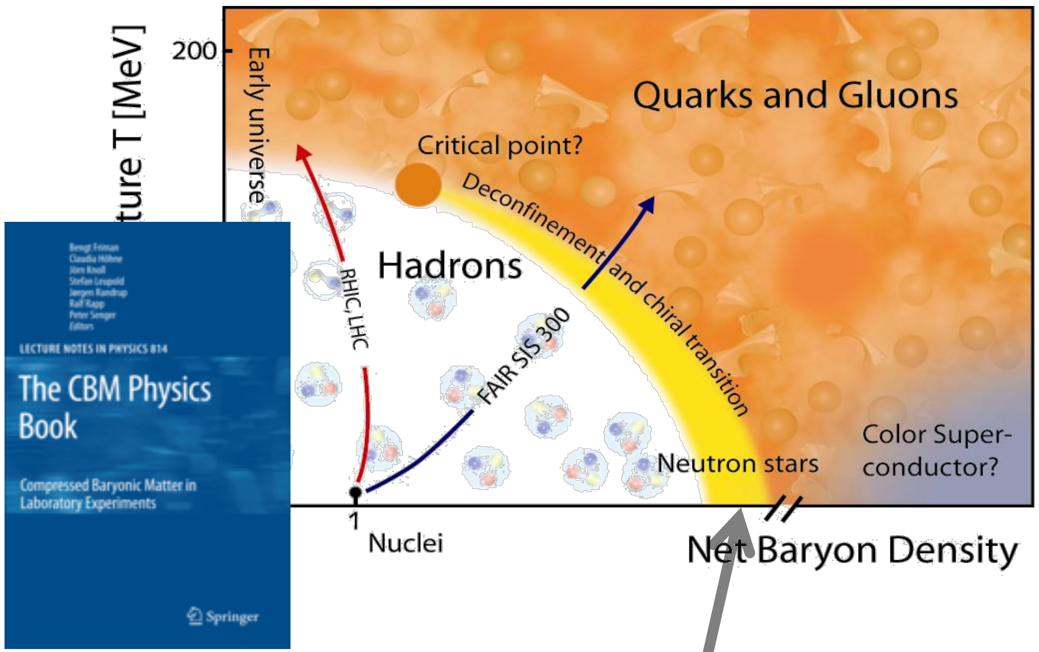
Nuclear Equation-of-state at high density

Search for phase transitions

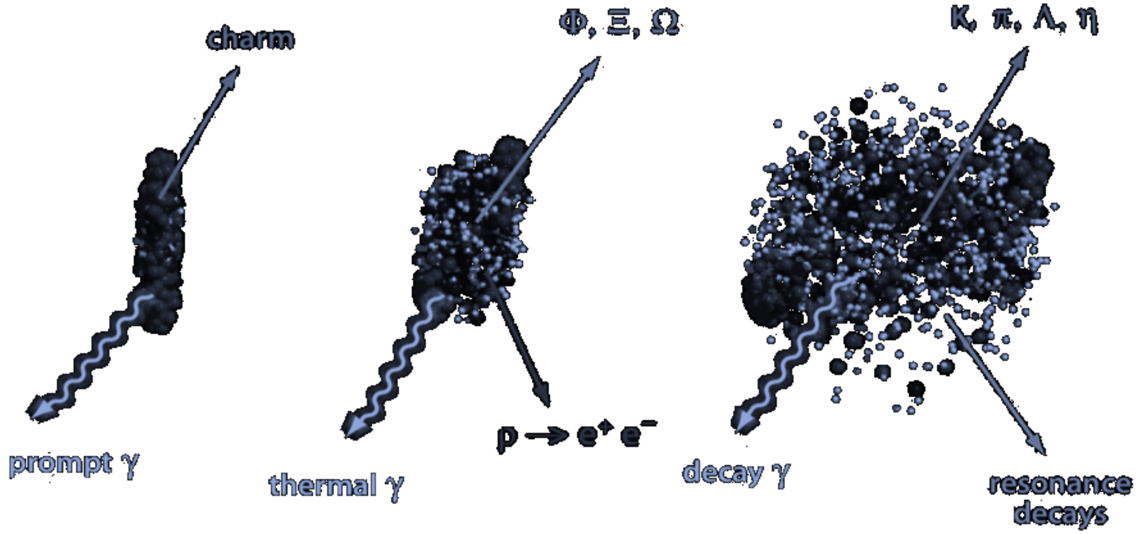
Search for the QCD critical endpoint

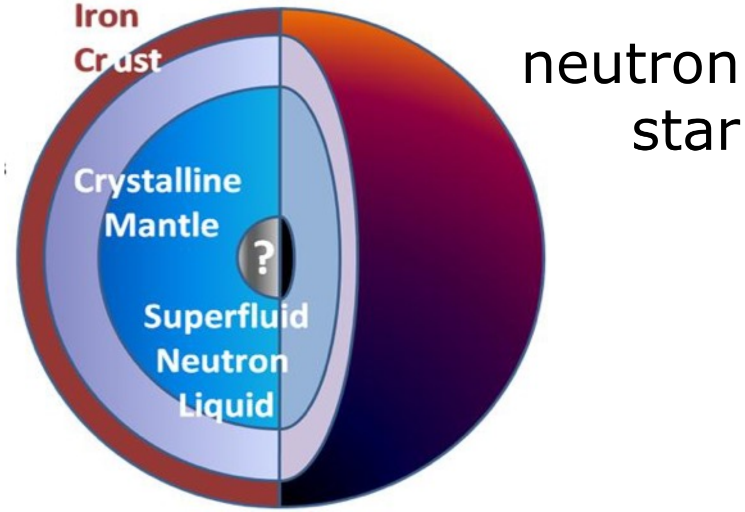
Study chiral symmetry restoration and

the origin of the hadron mass



Observables

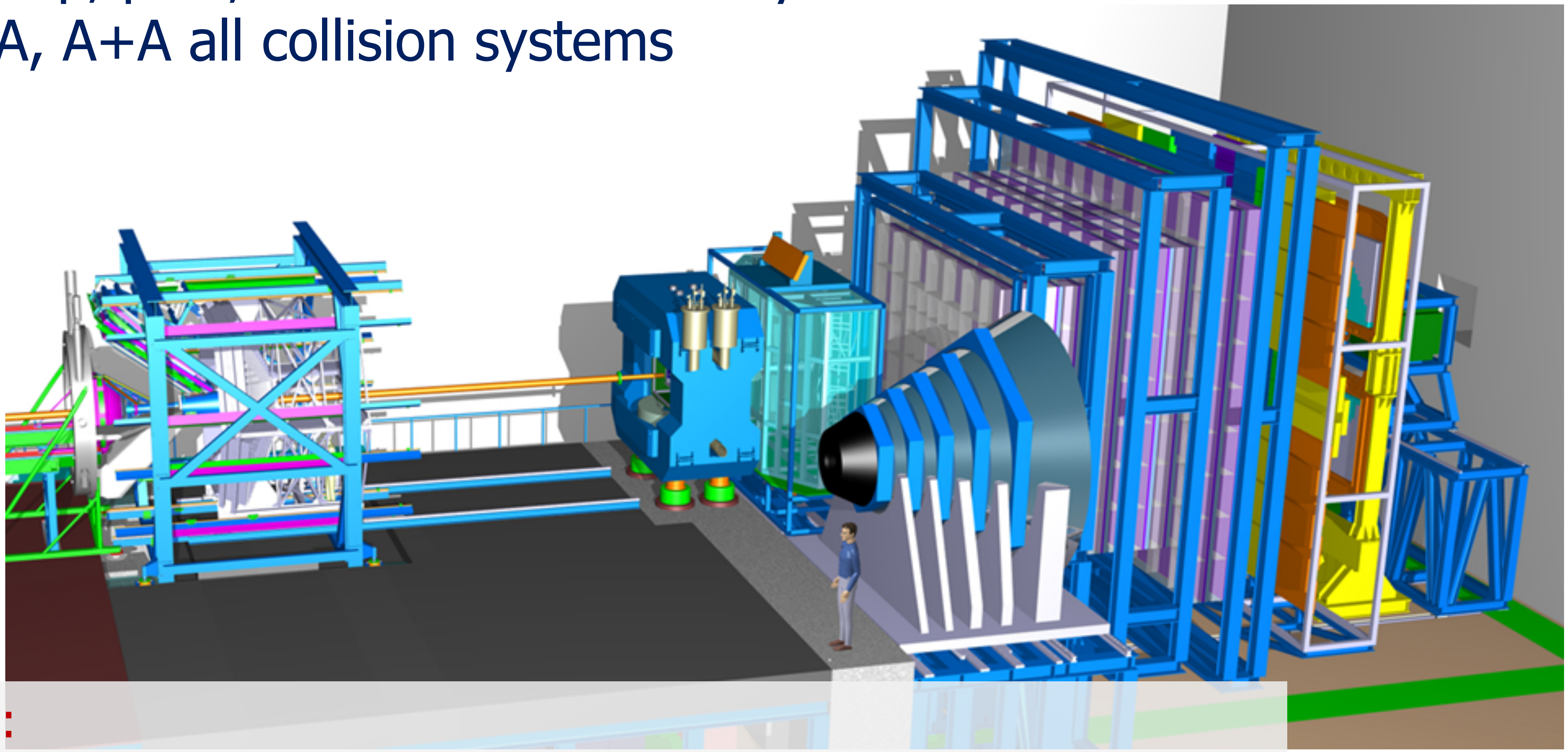




CBM Cave

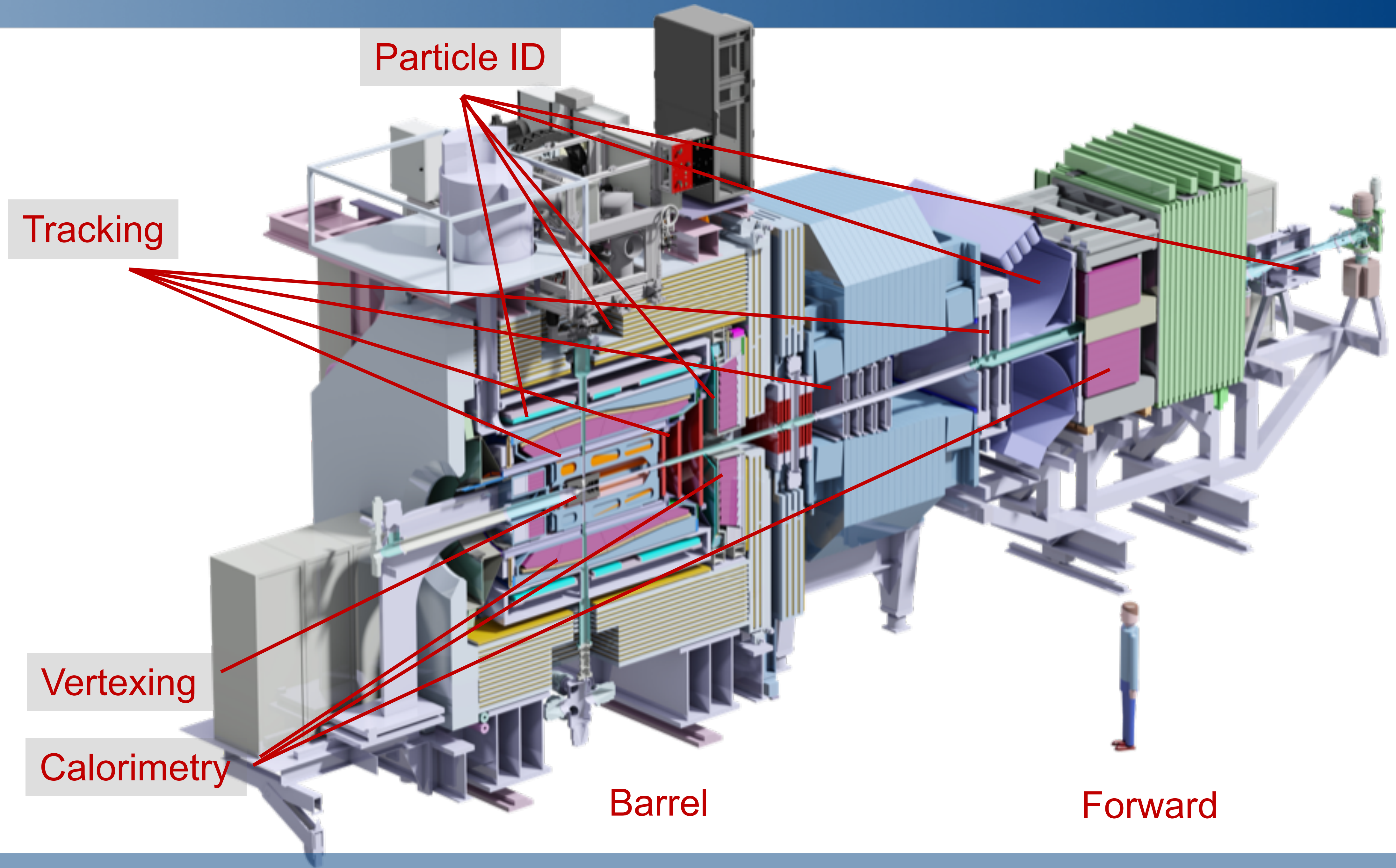
CBM @ FAIR

- HADES: p+p, p+A, A+A small collision systems
- CBM: p+A, A+A all collision systems



Observables:
Excitation function of yields and phase-space distributions of multi-strange hyperons and lepton pairs in Au+Au collisions from 2-11 A GeV (no data available in this energy range).

PANDA @ FAIR: Detector

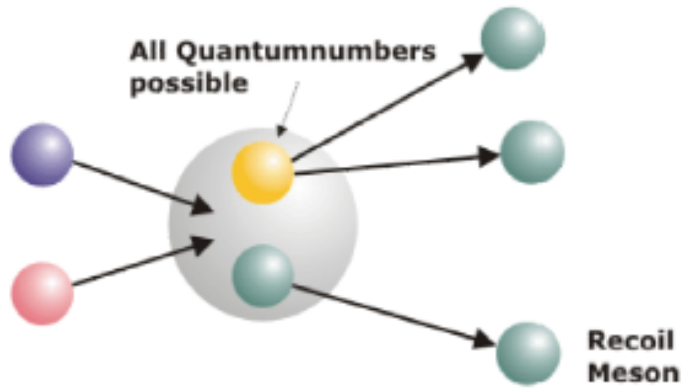


Antiproton annihilations: gluon rich environment

Production: all states with exotic and non-exotic quantum numbers accessible with a recoil

- high discovery potential

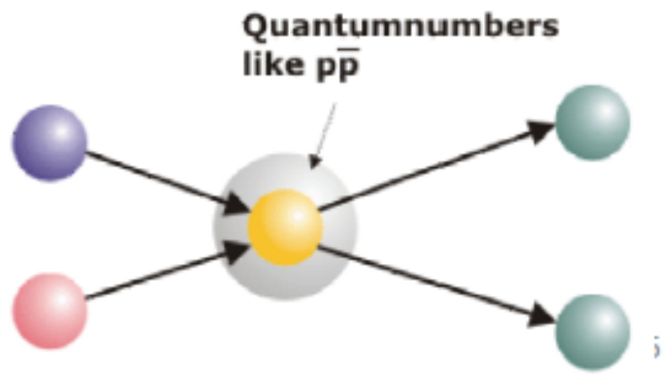
Associated, access to all quantum numbers (exotic)



Formation: all states with non-exotic quantum numbers accessible

- not only limited to 1^{--} as e^+e^- colliders
- precision physics of known states

Resonant, high statistics, extremely good precision in mass and width



antiproton probe is unique

PANDA unique: comparison with other techniques

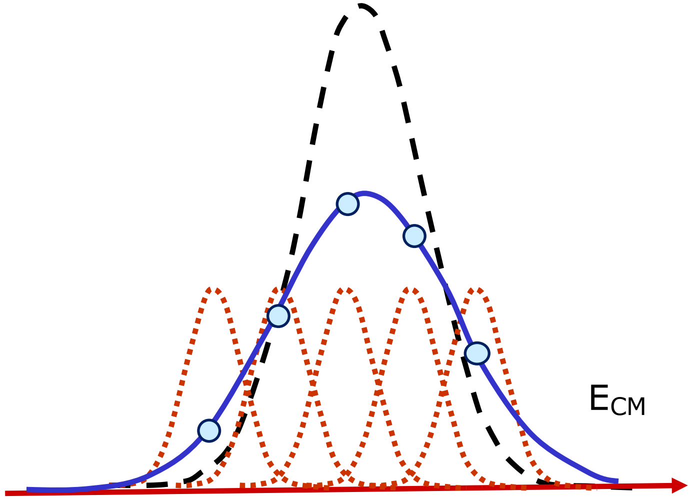
- **e^+e^-** (BaBar, BES-III, CLEO-C, Belle II)
  - Direct formation limited to $J^{PC}=1^{--}$
  - Sub-MeV for masses and widths close to impossible
  - High L not accessible
- **High-energy** (several TeV) **hadroproduction** (LHC)
  - High combinatorial background: discovery very difficult
  - Width measurements limited by detector resolution
- **B-decays** (both for e^+e^- and hadroproduction)
  - Limited J^{PC}
  - C cannot be determined (not conserved in weak decay)
  - High L not accessible

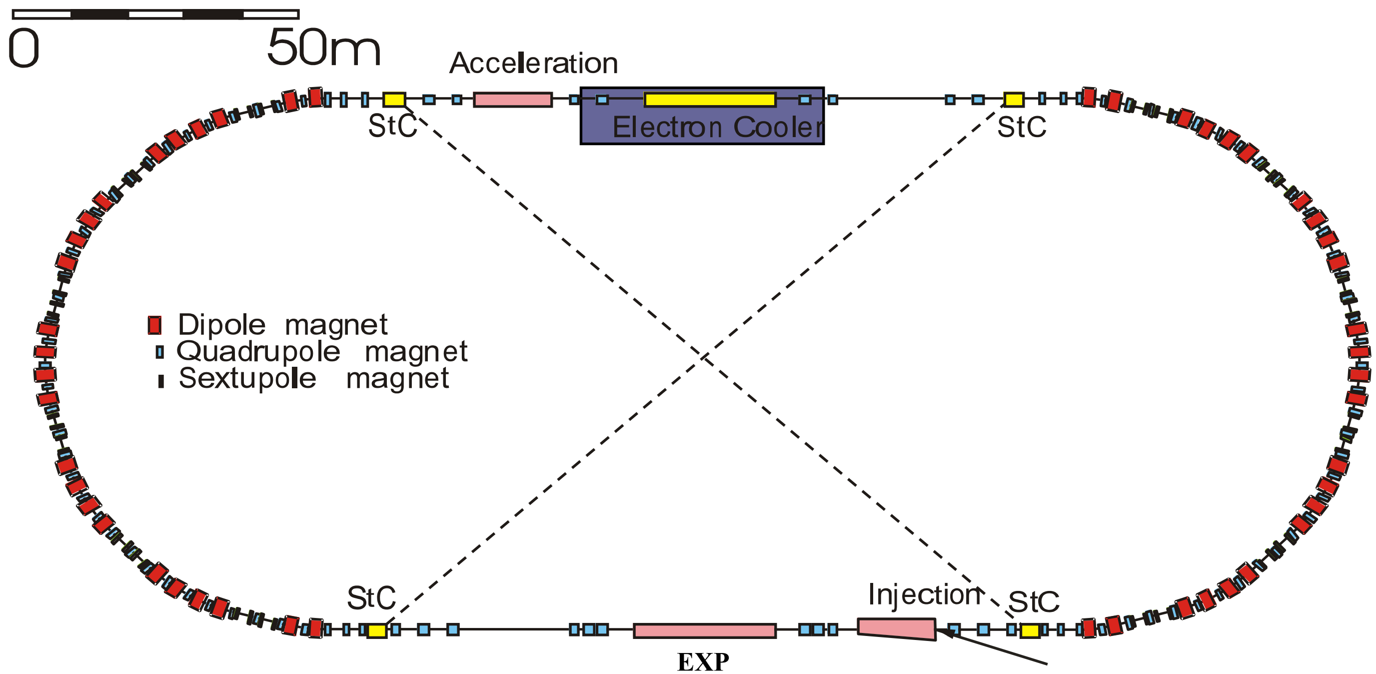
HESR – Storage Ring for Antiprotons

Precision spectroscopy with $\bar{p}$ beams

Parameters of HESR

- Injection of p at 3.7 GeV
- Slow synchrotron (1.5-14.5 GeV/c)
- Storage ring for internal target operation
- Luminosity up to L~ 2×10^{32} cm^{-2}s^{-1}
- Beam cooling (stochastic & electron)



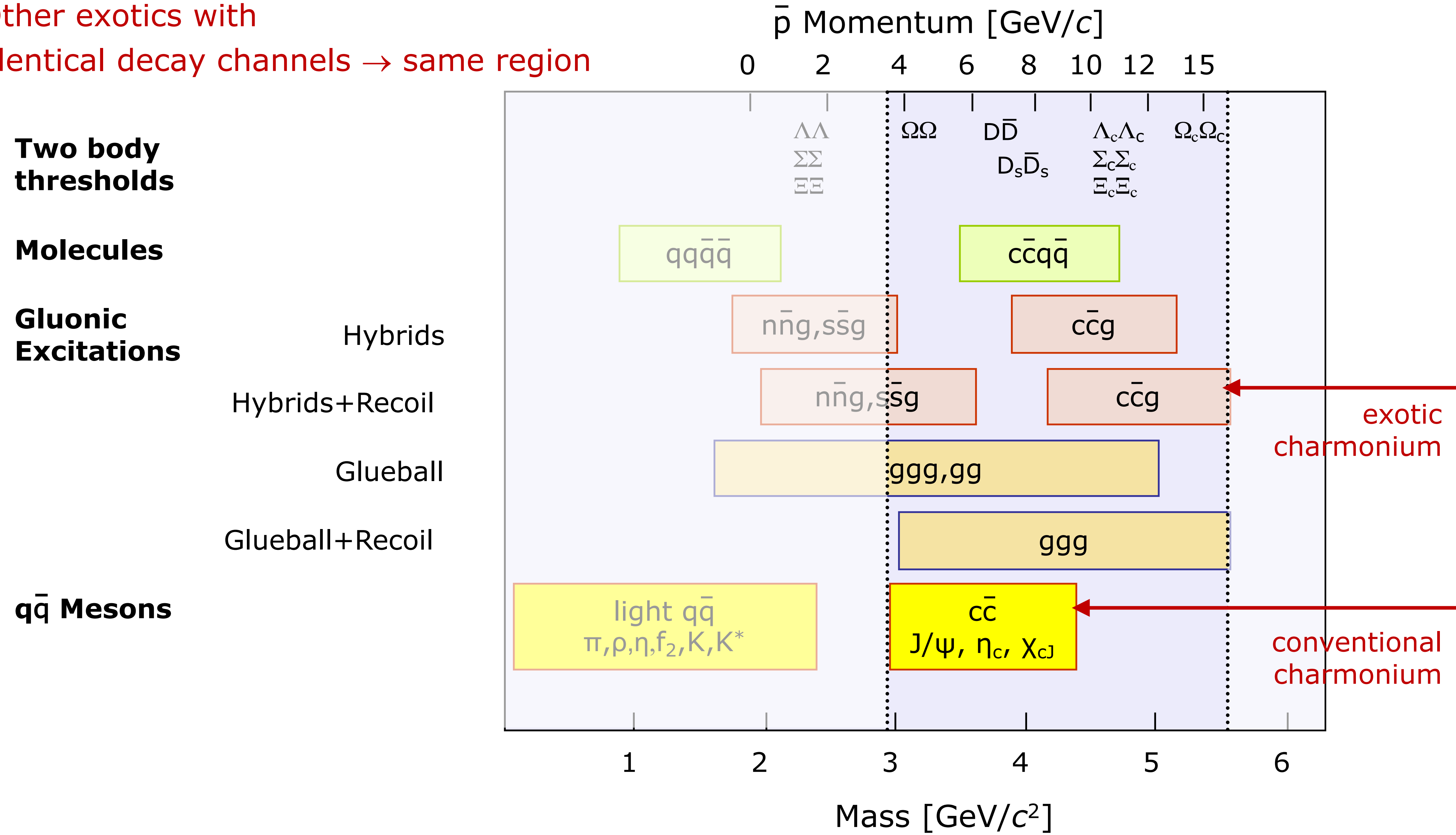


Resonance scan

- Energy resolution ~50 keV
- Tune E_{CM} to probe resonance
- Get precise mass and width

Accessible Charmed Hadrons at $\bar{\text{P}}$ANDA

Other exotics with
identical decay channels → same region



Light Mesons in Antiproton Annihilations at PANDA

- Light meson production in $\bar{p}p$ is huge 100 nb – 10 µb
- Neutral states with m>2.25 GeV/c^2 accessible in $\bar{p}p$ formation, charged states in $\bar{p}n$ (or in production)
- Unfortunately many overlapping broad states – amplitude analysis needed

Example Y(2175)

- $\bar{p}p \rightarrow Y(2175)\pi\pi, Y(2175)\pi^0$ at E_{CMS}= 3 GeV
  - Y(2175) reconstructed in $\Phi\pi^+\pi^-$ and $\Phi\pi^0\pi^0$
  - assumed signal cross section: 100 nb
  - background cross section: 70 mb

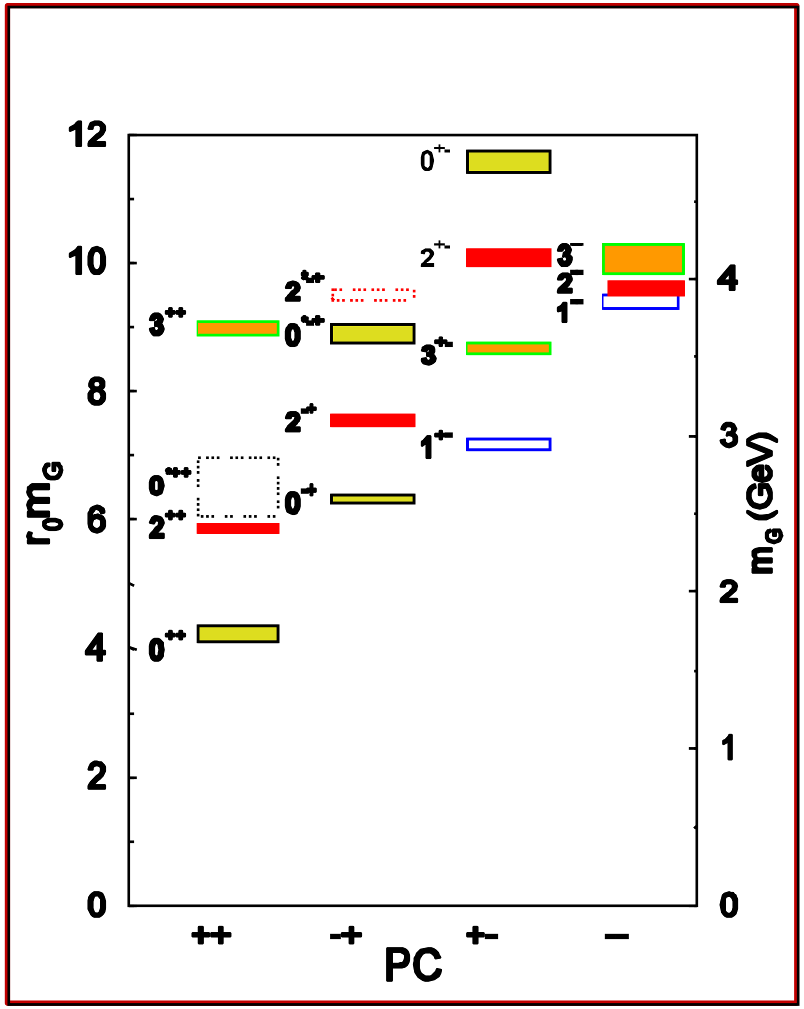
Beam-time to record 1000 reconstructed events in the $\Phi\pi^+\pi^-\pi^0$ decay mode

	$f_{BR} = 5\,\%$	$f_{BR} = 10\,\%$	$f_{BR} = 30\,\%$
$L = 2 \cdot 10^{30}$	99.5 d	24.9 d	2.8 d
$L = 2 \cdot 10^{31}$	9.95 d	2.49 d	0.28 h
$L = 2 \cdot 10^{32}$	0.995 d	0.249 d	0.028 h

Glueball studies in PANDA

Morningstar und Peardon, PRD60 (1999) 034509
Morningstar und Peardon, PRD56 (1997) 4043

- Study of glueball production in $K^+K^-\pi^0$, $K^+K^-\pi^0\pi^0$, and $\Phi\Phi\pi^0$
  - assuming cross section of 10 nb (including decay to final state)
  - background cross sections 50 to 80 mb
- "Light" glueball m = 2400 MeV/c² (could be 2^{++} or 0^{-+})
  - E_{CMS} = 2.57 GeV and 5.47 GeV
  - could be broad, study final states w/o intermediate resonances
- "Heavy" glueball m = 3900 MeV/c²
  - E_{CMS} = 5.47 GeV
  - could be narrow, assume Γ=10 MeV
  - search for narrow signal in production followed by detailed studies in formation [unique at PANDA]



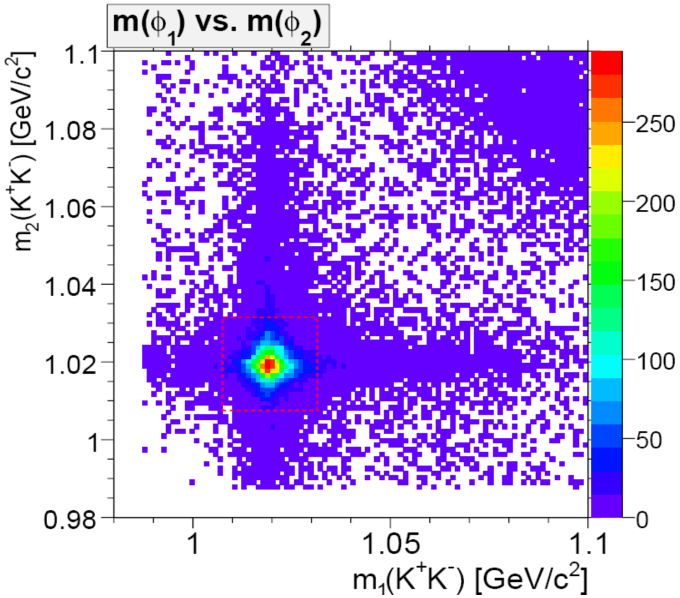
Benchmark $p\bar{p} \rightarrow \phi\phi$

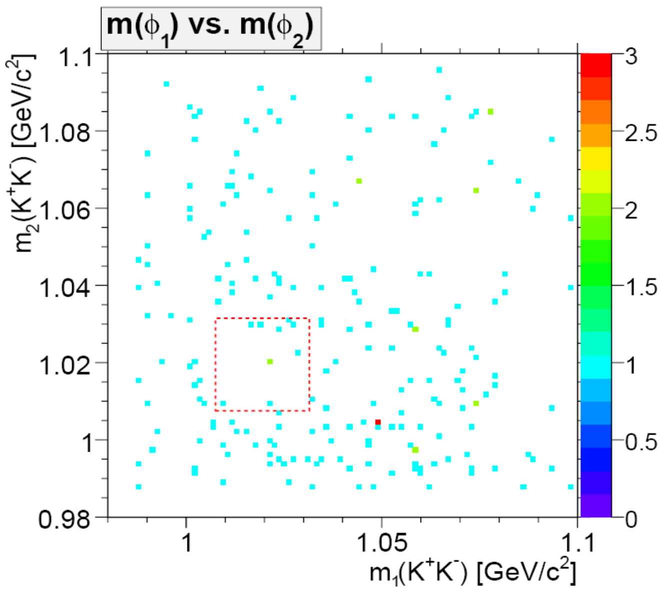
Input

$M = 2.235$ GeV/c²

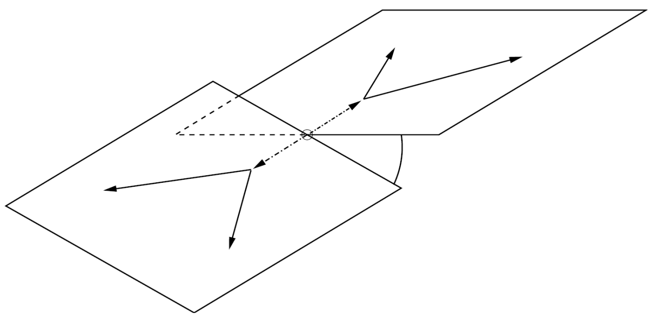
$\Gamma = 15$ MeV/c²

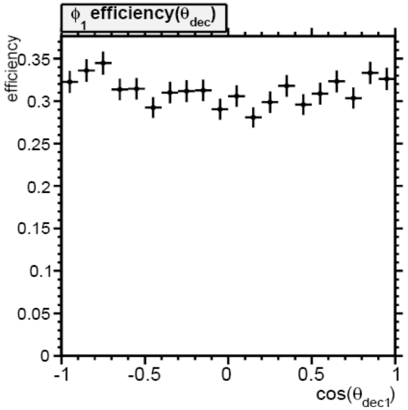
σ_S [nb]	Beam time T_b ($\approx$)
1	13.7 y
5	200 d
10	50 d
100	12 h
500	0.5 h
1000	7.2 min

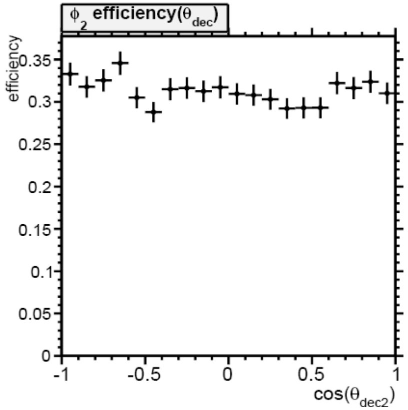


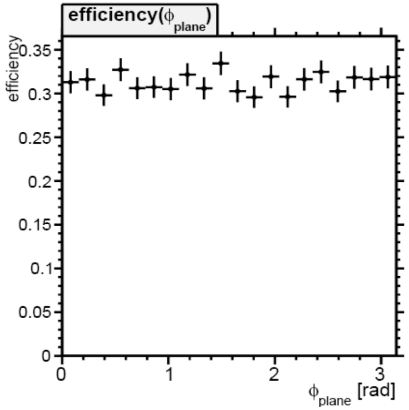


Channel	rel. X-sec	ϵ(VL)[%]	ϵ(L)[%]	ϵ(T)[%]	ϵ(VT)[%]
Signal	1	30.1	28.5	23.7	18.8
DPM generic	10^6	$< 4.3 \cdot 10^{-4}$	$< 4.3 \cdot 10^{-4}$	$< 4.3 \cdot 10^{-4}$	$< 4.3 \cdot 10^{-4}$
r_{SN}	–	$> 1:14$	$> 1:14$	$> 1:17$	$> 1:22$

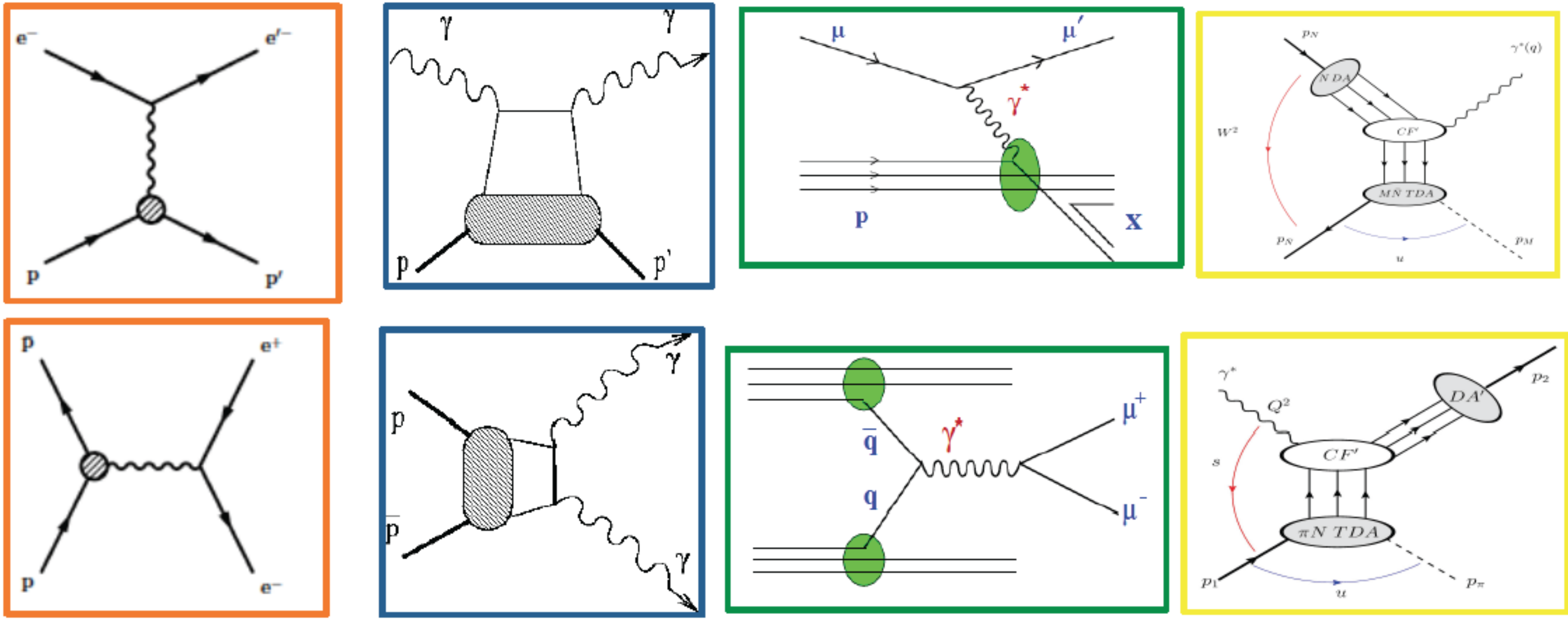








(Virtual) photon in intermediate state



Crossing symmetry: different kinematical regions, observables are counterparts

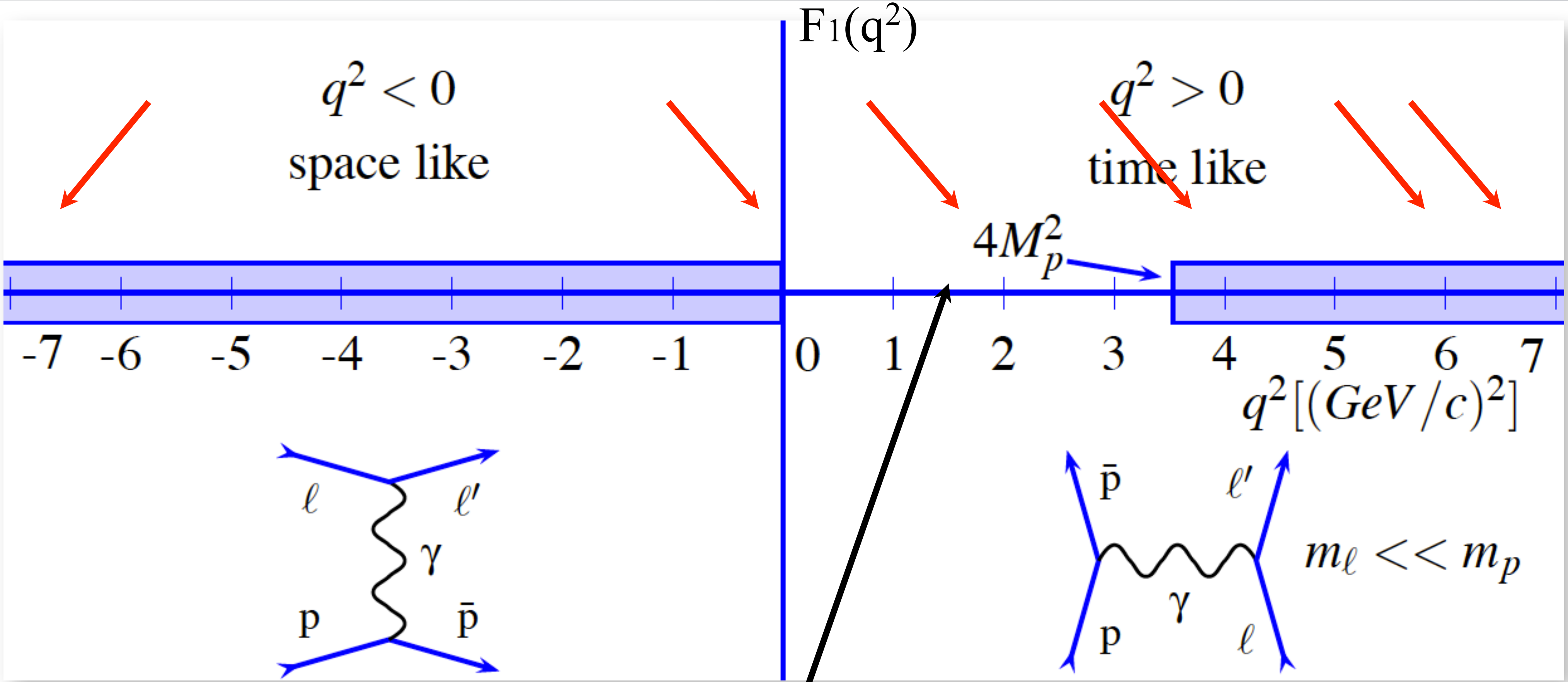
PANDA: Excellent tool for nucleon structure studies complementary to electron or photon experiments

Electromagnetic processes in PANDA

Feasibilty study for the measurement of many electromagnetic processes at PANDA are done

Signal	Physics	s [Gev²]	S/B	Status
$\bar{p}p \to e^+e^-$	FFs	5.4, 8.2, 13.9	>100	Feasibile
$\bar{p}p \to \mu^+\mu^-$	FFs	5.4	¼	Feasibile
$\bar{p}p \to \gamma^*\pi^0$	TDAs	5.0 10.0	5 . 10^7 (1 . 10^7) 1 . 10^8 (6 . 10^6)	Feasibile
$\bar{p}p \to J/\psi\pi^0$	TDAs	P=5.513 P=8.0 P=12.0	>8 >70 >600	Feasibile
$\bar{p}p \to \gamma\gamma$ $\bar{p}p \to \pi^0\gamma$	GDAs	2.5, 3.5, 4.0, 5.5	1 2	Feasibile
$\bar{p}p \to \mu^+\mu^-X$	TMD PDFs	30	in progress	Feasibile

Example: e.m. Form factors of the Nucleon



unphysical region

Form Factor real

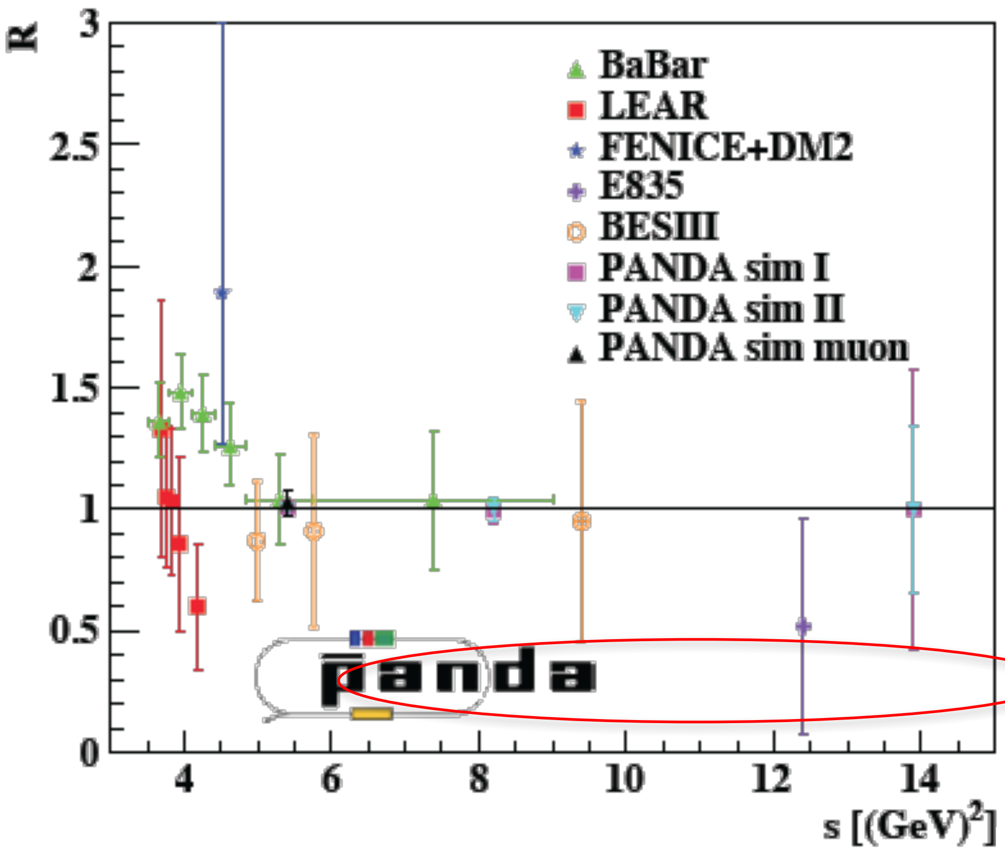
cross section (Rosenbluth)
no single spin observables
double spin observables

Form Factor complex

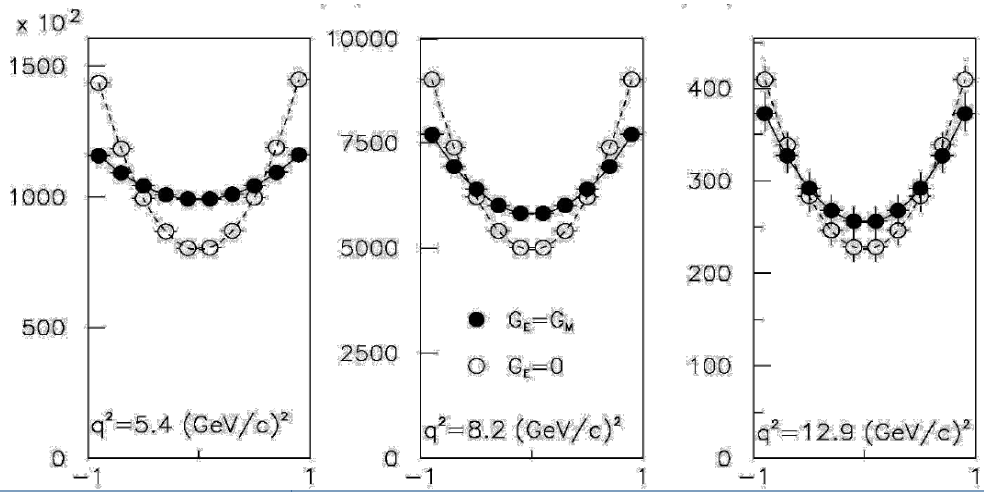
cross section (angular Distr.)
single spin observables (P_y)
double spin observables

connected by dispersion relations

Time-like proton form factors from PANDA



s (GeV)²	5.4	8.2	13.9
sim I $\bar{p}p \rightarrow e^+e^-$			
$R=\lvert G_E\rvert/\lvert G_M\rvert$	1.5 %	5.3 %	57 %
$\lvert G_E\rvert$	3.3 %	6.8%	45%
$\lvert G_M\rvert$	1.7%	2.3 %	9%
MVA $\bar{p}p \rightarrow \mu^+\mu^-$			
$R=\lvert G_E\rvert/\lvert G_M\rvert$	5.1%	-	-
$\lvert G_E\rvert$	8.6%	-	-
$\lvert G_M\rvert$	4.1%	-	-



PANDA can fill the gap in the s-baryon sector

Excited strange Hyperon spectrum

- SU(6) x O(3) classification (spin, flavour and *L*)
- Very scarce data bank on double and triple strangeness
- Octet Ξ* partners of *N** ?
  - Only a few found
- Decuplet Ξ* and Ω* partners of Δ*?
  - Nothing found

	(D, L_N^P)	S	Octet members				Singlets
$^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$3/2^-$	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
$3/2^-$	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
$3/2^+$	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^-$	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$9/2^+$	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	

			Decuplet members			
$3/2^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$
$3/2^+$	$(56,0_2^+)$	3/2	$\Delta(1600)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$1/2^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$3/2^-$	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$5/2^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$7/2^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$
$11/2^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$

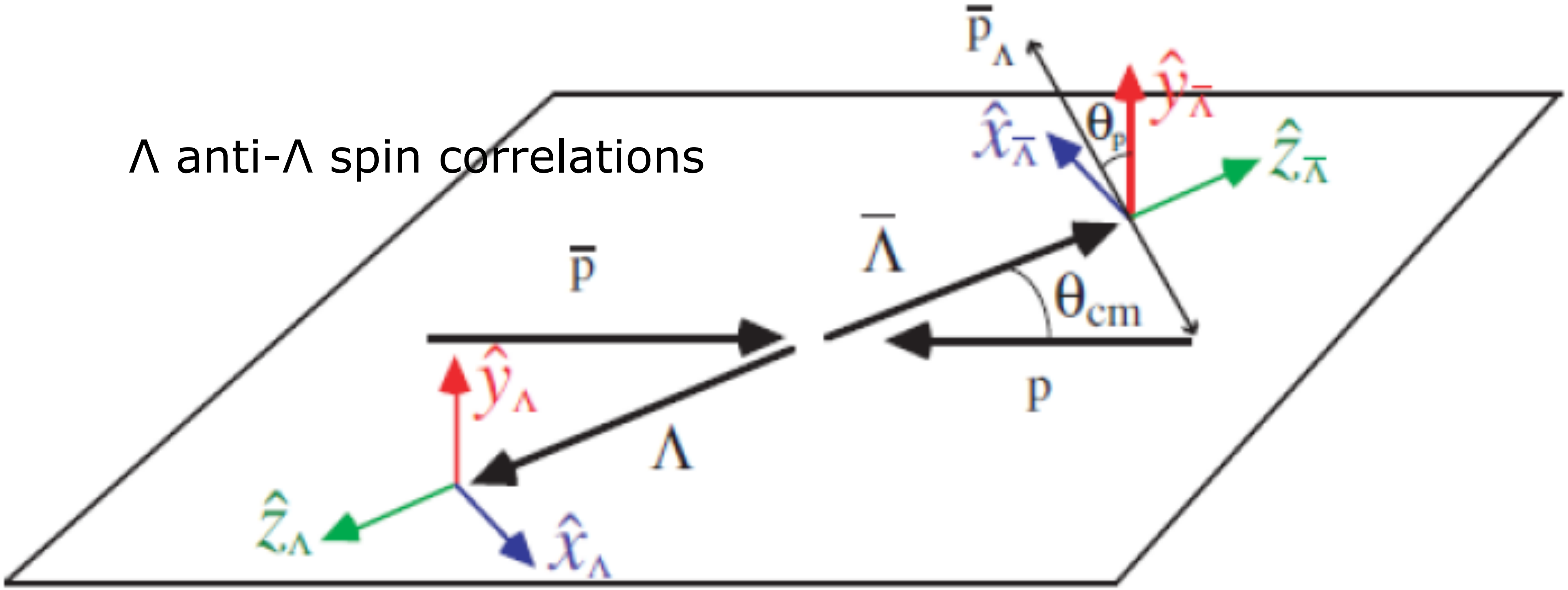
the full Ξ and Ω spectra are accessible with PANDA

Spin observables in hyperon decay

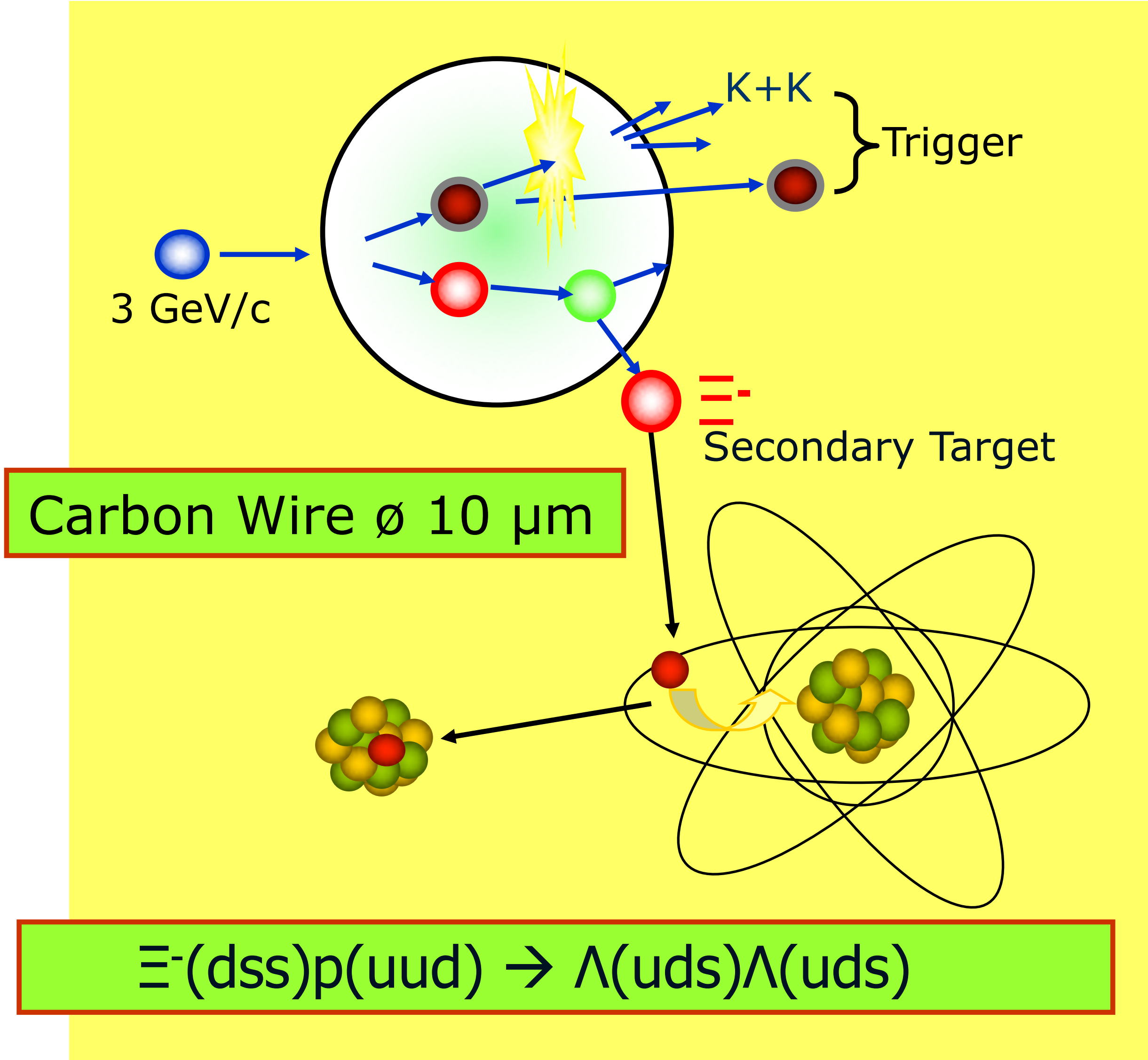
- *Vector polarisation* P the most straight-forward observable for spin $\frac{1}{2}$ hyperons.

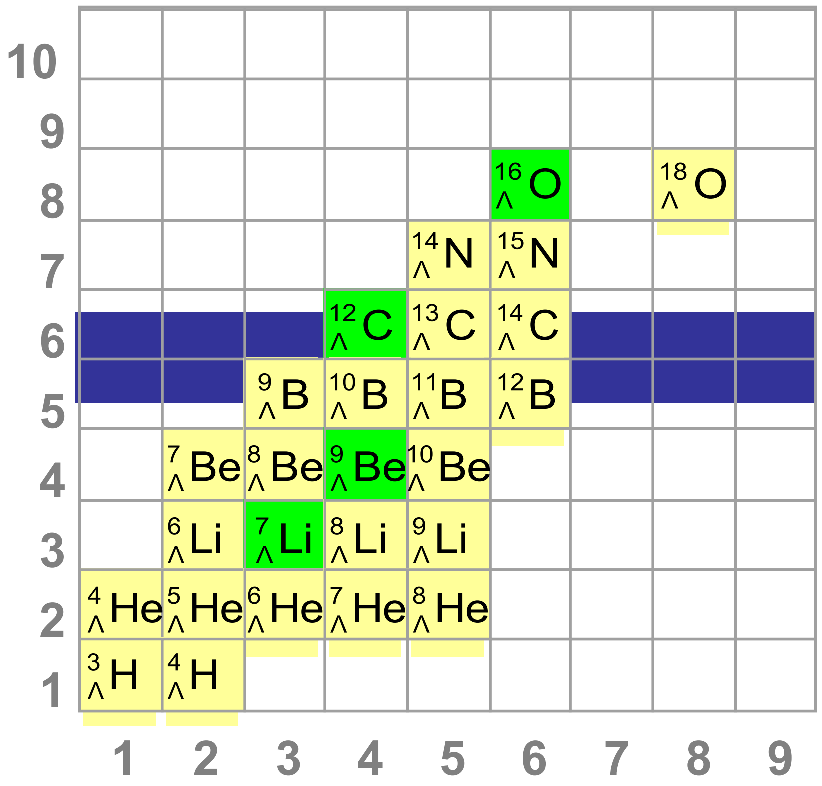
- Strong interactions: normal to the production plane (y-direction)

Λ anti-Λ spin correlations



Hypernuclear Physics @ PANDA



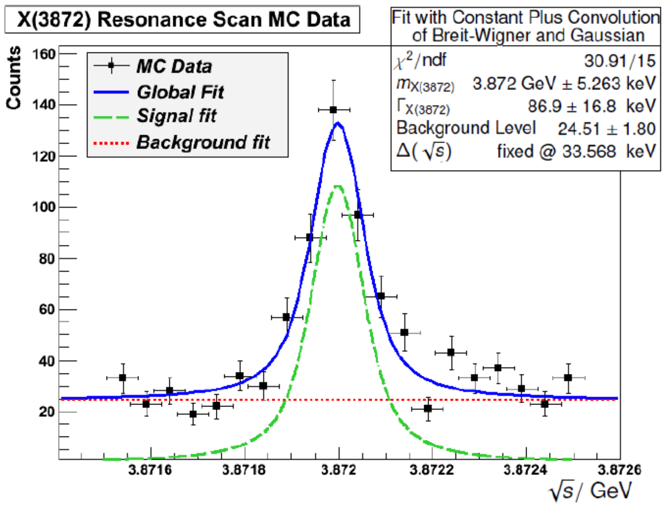


minimum 8 months full running

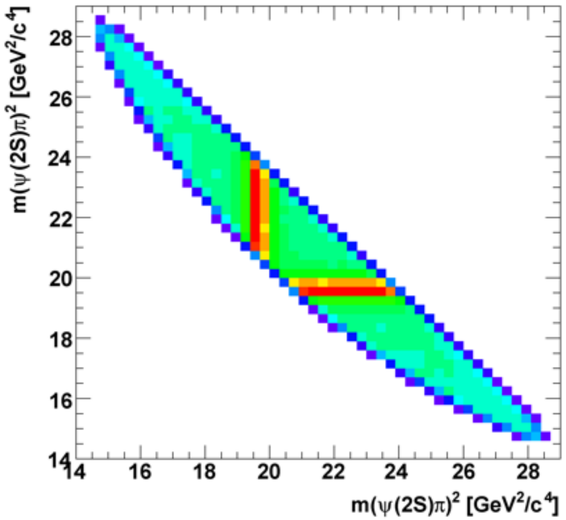
Key-Experiments of the first phase

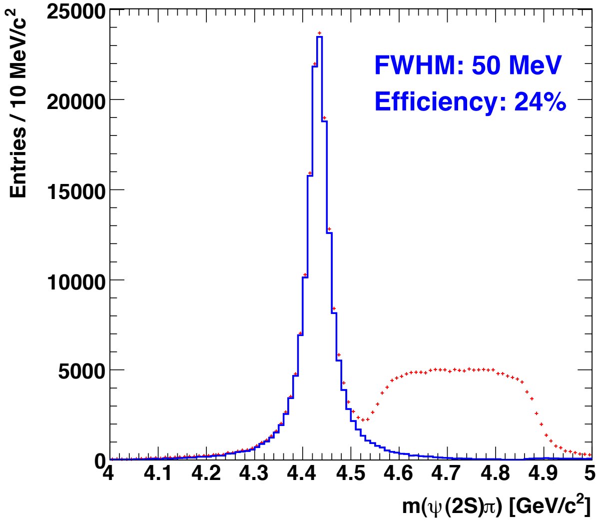
Concentration on unique and forefront physics topics

- Precise measurement of the line shape of narrow XYZ-states, e.g. X(3872)
  (only in pp, counting experiment, → nature of the states)
- Resonant formation of the negative and uncharged partners of the Z-States
  (only possible in proton–antiproton, → nature of the states)



Reconstructed width $\Gamma_{X(3872)}$ is consistent with input width of 100 keV.*



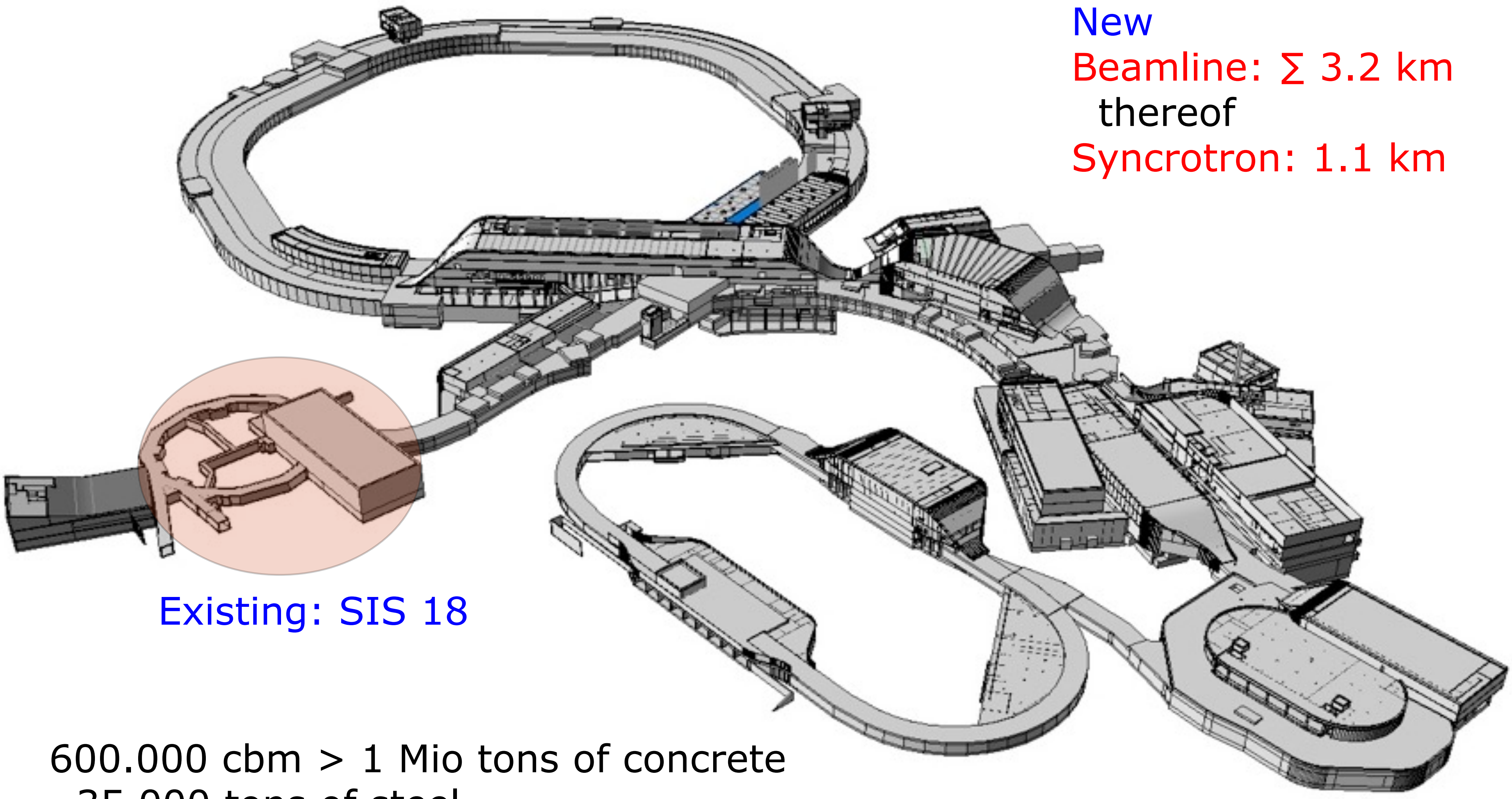


Key-Experiments of the first phase

Concentration on unique and forefront physics topics

- Precise measurement of the line shape of narrow XYZ-states, e.g. X(3872)
  (only in pp, counting experiment, → nature of the states)
- Resonant formation of the negative and uncharged partners of the Z-States
  (only possible in proton–antiproton, → nature of the states)
- (Parasitic) production of multi-strangeness baryons
  (unexplored, new territory, „Strangeness-Factory")
- Parasitic production of high spin charmonia (only possible in proton–antiproton)
  light mesons, baryons and production of hybrids und glueballs
- Measurement of the electromagnetic form factors of the proton in the time-like domain with electrons and muons in the final state

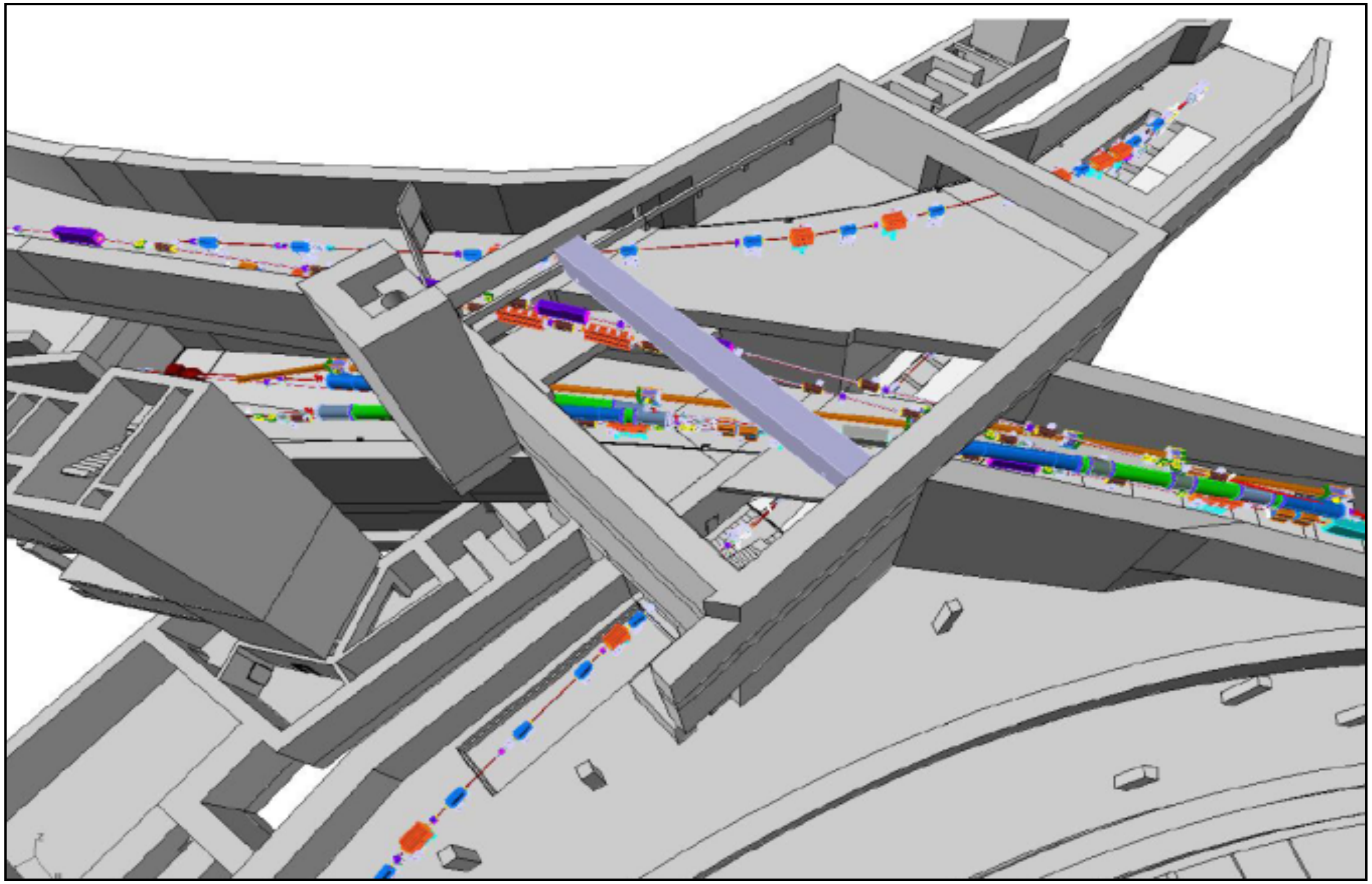
XYZ- and hyperon factory

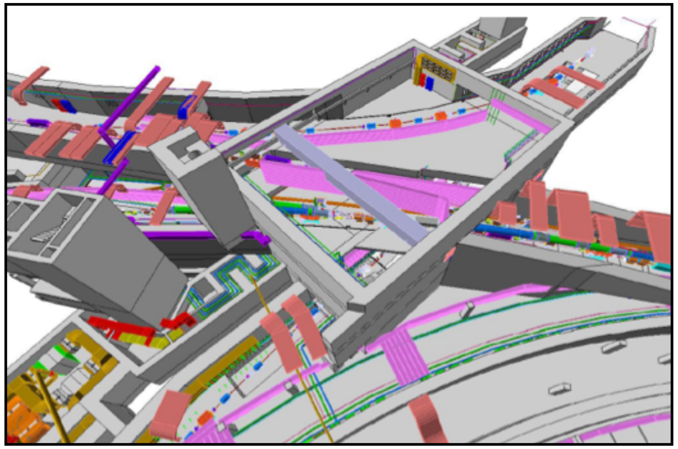


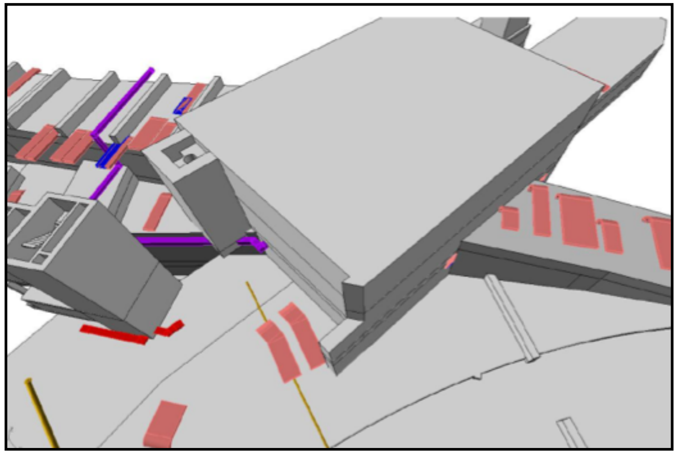
New
Beamline: ∑ 3.2 km
thereof
Syncrotron: 1.1 km

600.000 cbm > 1 Mio tons of concrete
35.000 tons of steel

Planning Activities







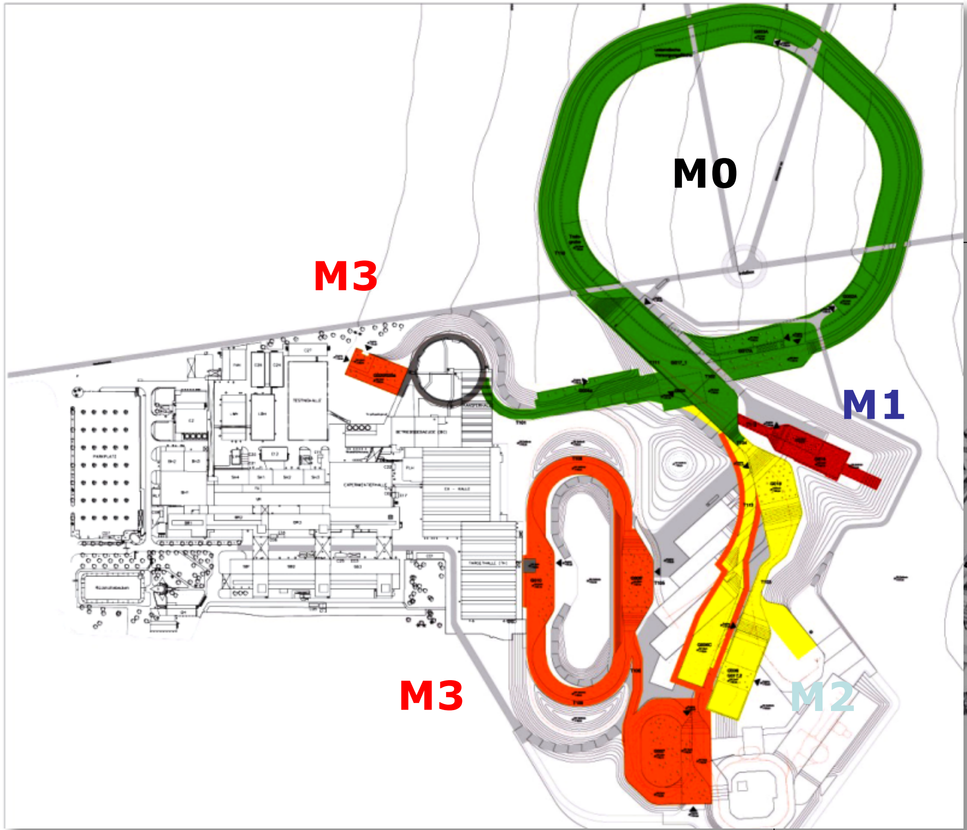
Piling works finished in 2014

Current Status of the FAIR-Experiments

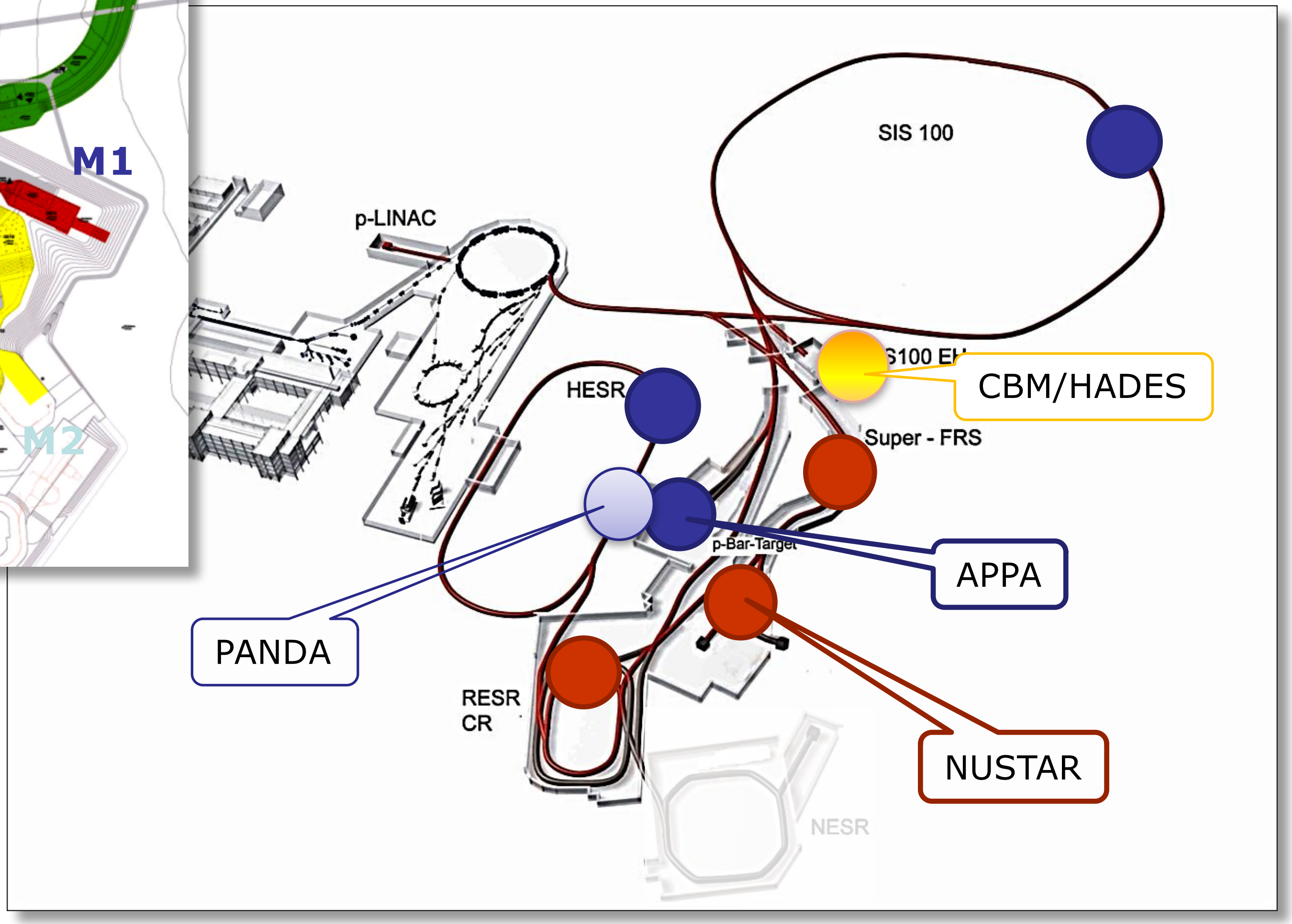
- All four FAIR Collaborations have re-assessed their experimental programme and instrumentation in view of
  - Progress in science,
    the changed timeline
    and availability of funding

- The programme for day-one experiments starting in 2022 has been developed
  - Prioritising for max. scientific merit and concentrating on the initially required equipment

The Modularised Start Version (MSV)



Cost about 1.6 billion by 2018
(1 billion 2005 Euros)



Modules

M0: SIS100

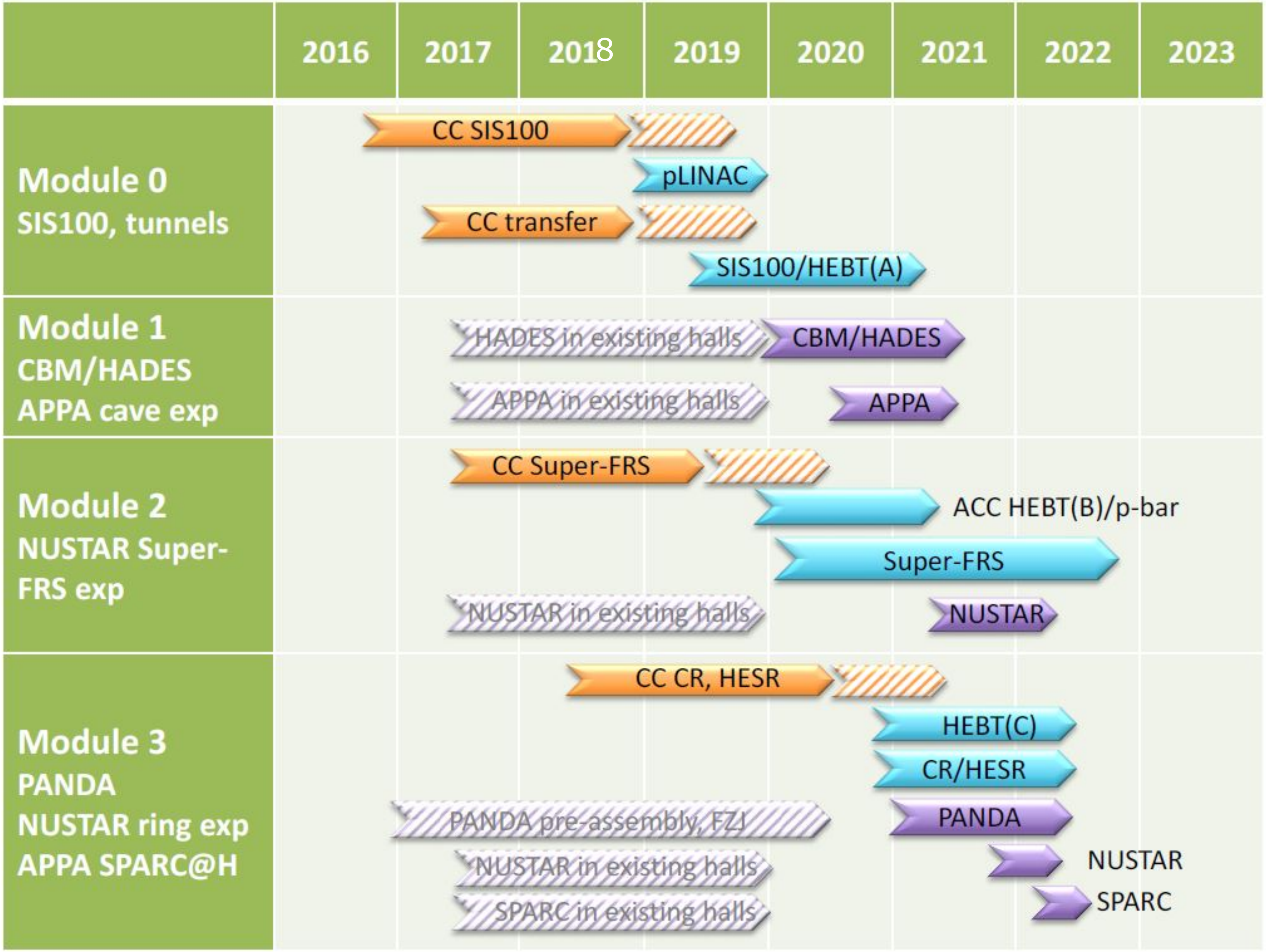
M1: APPA

M1: CBM/HADES

M2: NUSTAR

M3: PANDA, NuSTAR, APPA

High Level Schedule of the MSV



Conclusions

- Despite of certain delays FAIR is progressing well.
- Rich scientific program and discovery potential already with completion of Modularized Start Version.
- FAIR will allow for unique measurements in many fields and remain competitive for decades.
- Versatile detector configurations for optimal performance are under construction.
- Day-one physics with start version for high interaction rates in preparation.
- Strong and experienced international collaborations are active, more scientists expected to join in the coming years.


THANK YOU