The PANDA Experiment at FAIR

Lars Schmitt, GSI Darmstadt

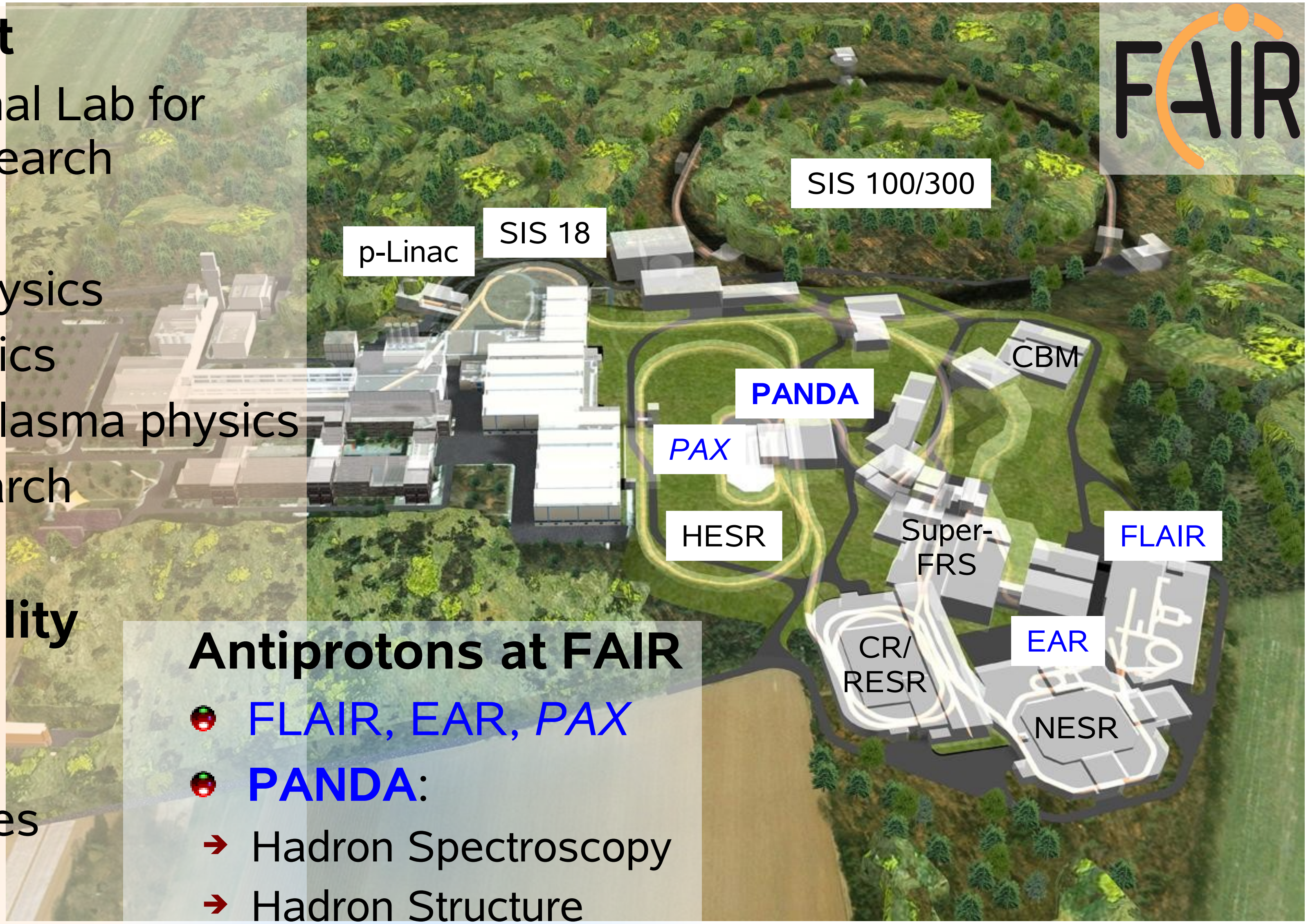
WE-Heräus-Seminar "Quarks and Hadrons in Strong QCD",
Rheinfels, 19.3.2008

- Overview of FAIR and PANDA
- Hadron Spectroscopy
- Hadron Structure
- Nuclear Physics
- The PANDA Detector

Facilitiy for Antiproton and Ion Research

GSI, Darmstadt

- German National Lab for Heavy Ion Research
- Highlights:
  - Heavy ion physics
  - Nuclear physics
  - Atomic and plasma physics
  - Cancer research



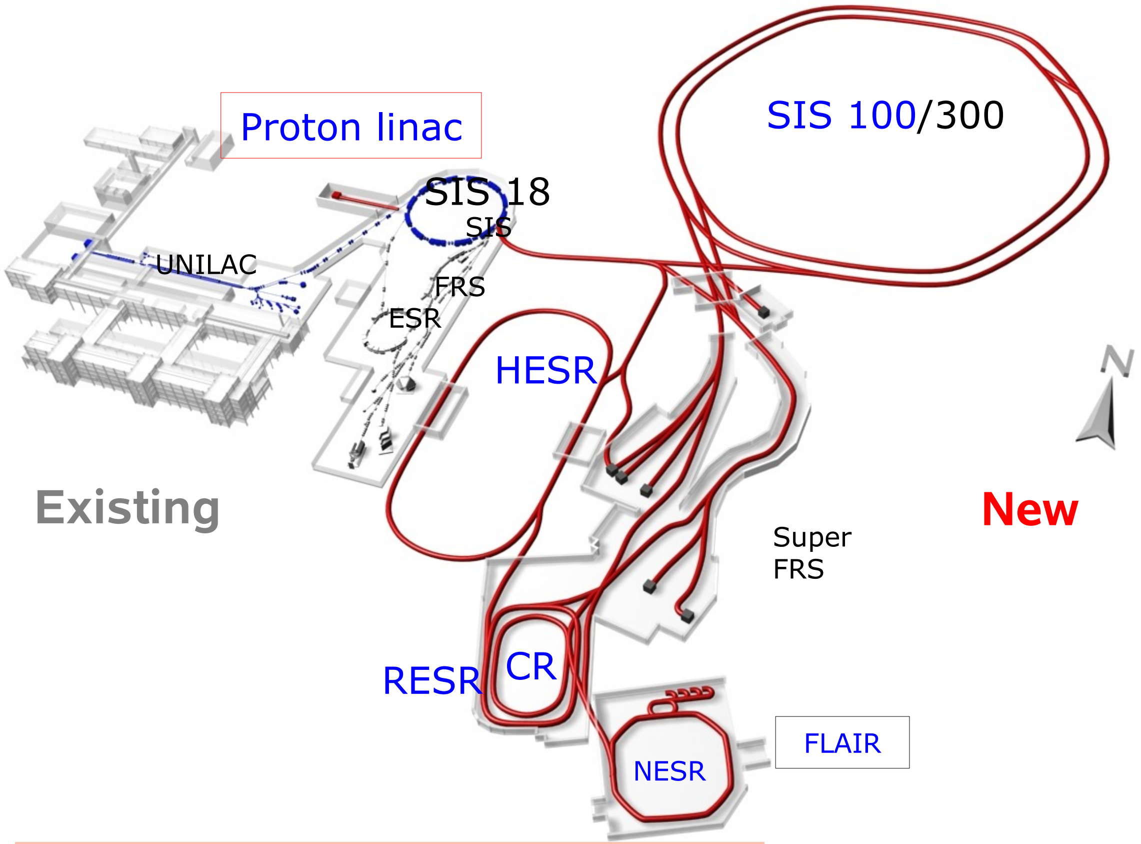
FAIR: New facility

- RIB
- Heavy ions
- → higher intensities & energies
- Antiprotons

Antiprotons at FAIR

- FLAIR, EAR, *PAX*
- **PANDA**:
  - → Hadron Spectroscopy
  - → Hadron Structure
  - → Nuclear physics

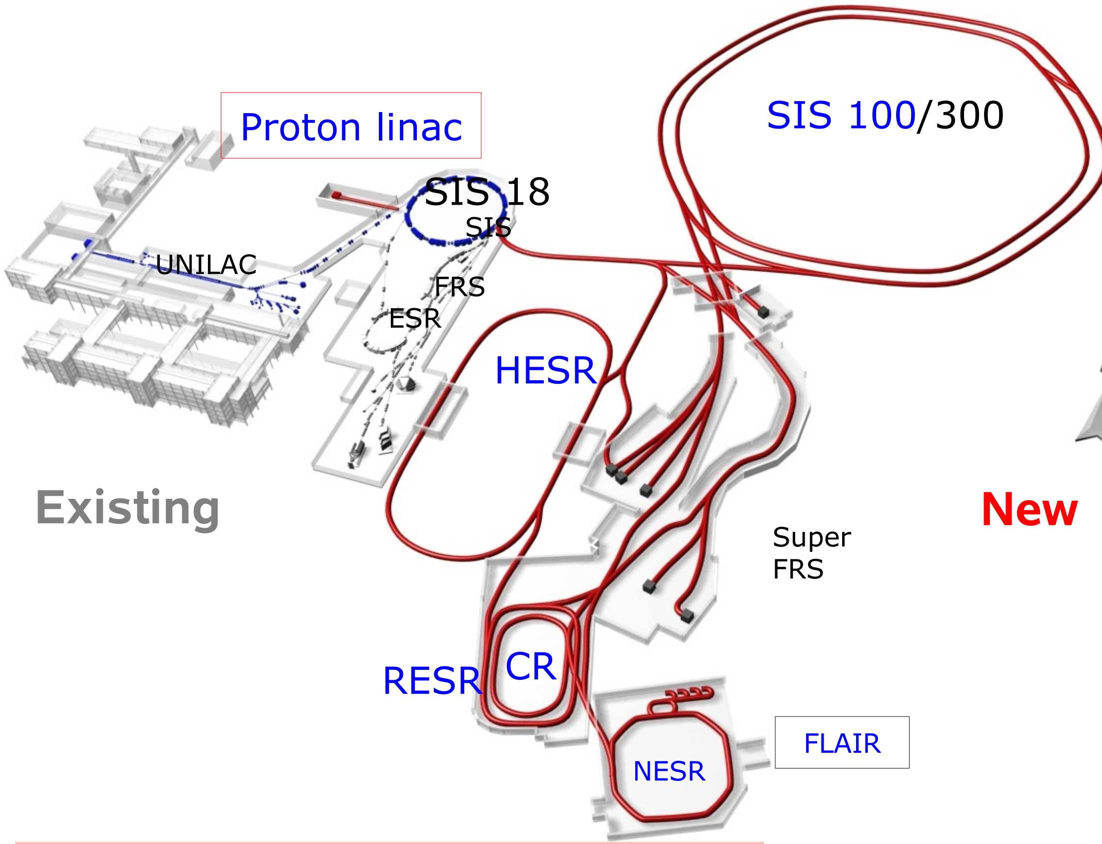
Antiprotons at FAIR



Antiproton production

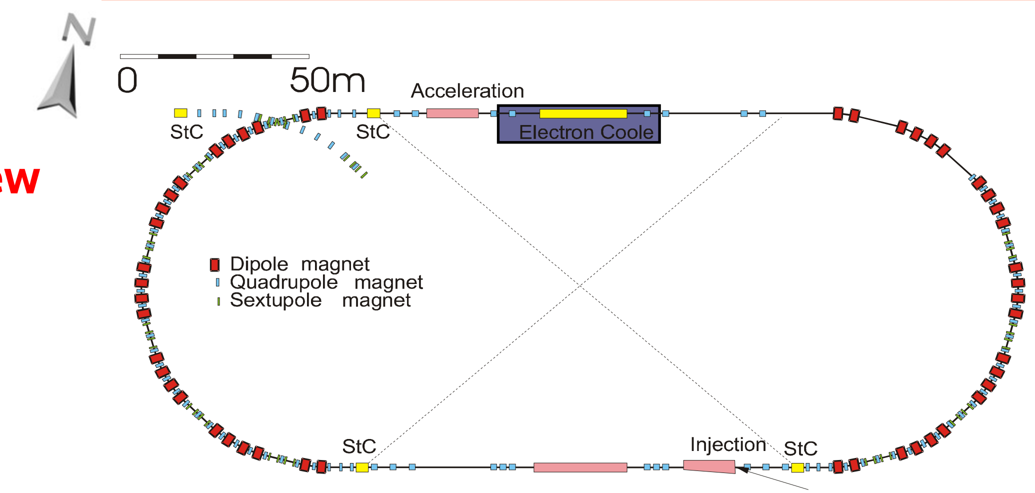
- Proton Linac 50 MeV
- Accelerate p in SIS18 / 100
- Produce $\bar{p}$ on target
- Collect in CR, cool in RESR

Antiprotons at FAIR



HESR: Storage ring for $\bar{p}$

- Injection of $\bar{p}$ at 3.7 GeV
- Slow synchrotron (1.5-15 GeV)
- Luminosity up to L~ 2×10^{32} $cm^{-2}s^{-1}$
- Beam cooling (stochastic & electron)



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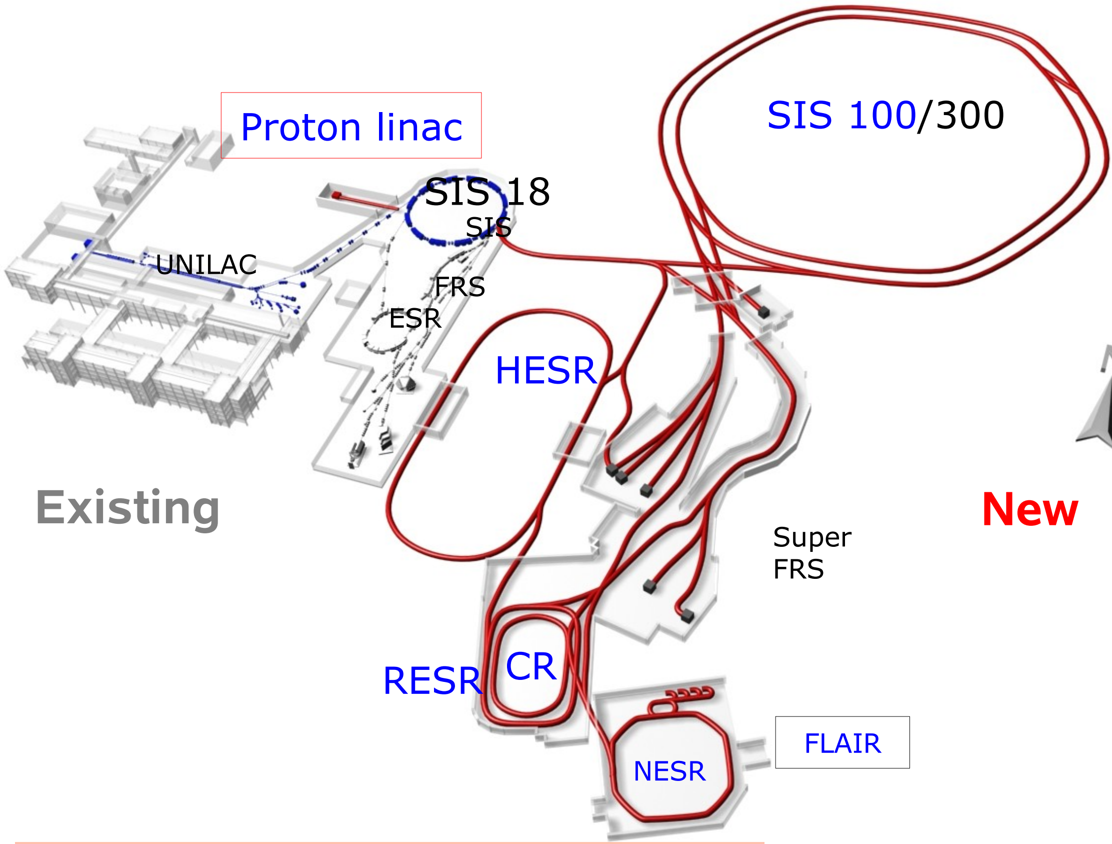
Antiprotons at FAIR



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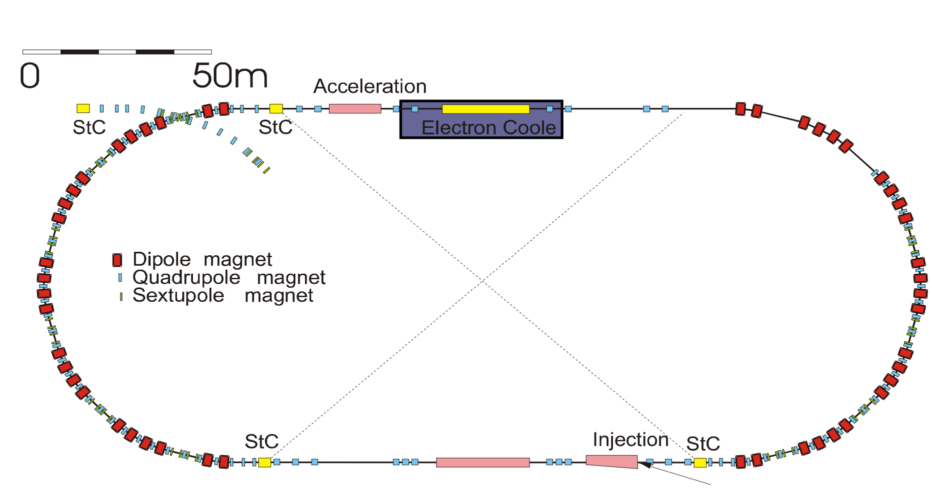

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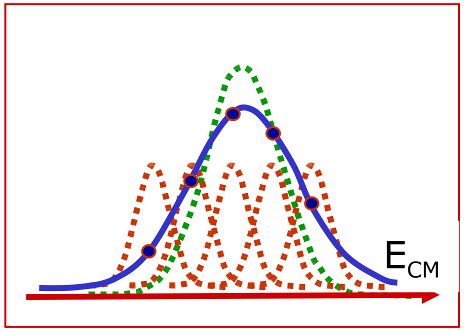
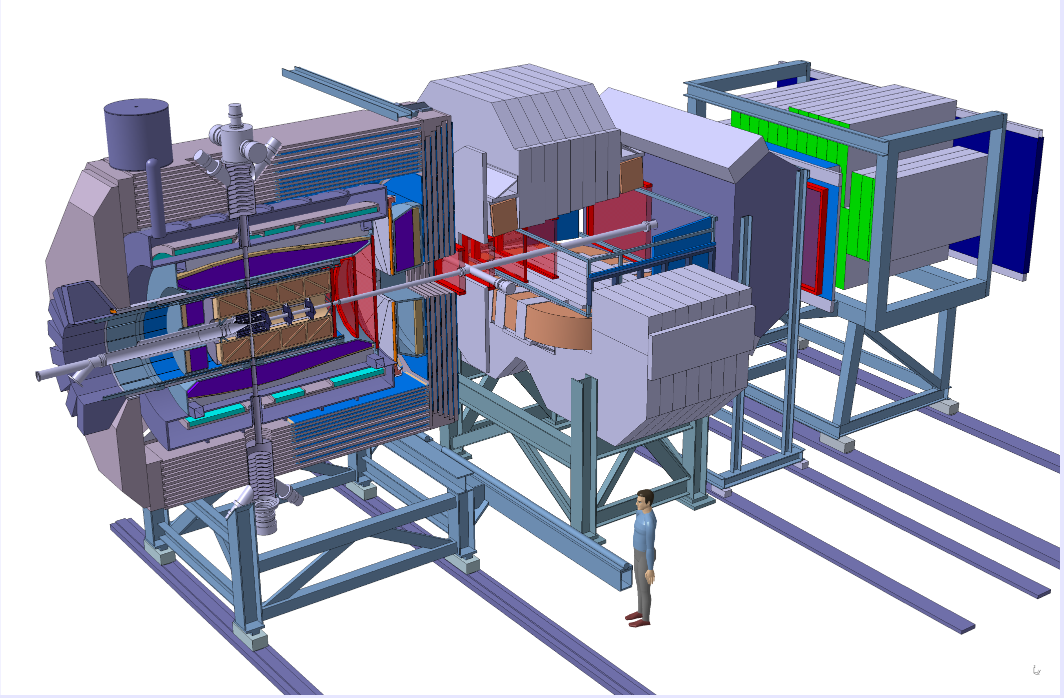


Resonance scan

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

PANDA at FAIR

PANDA Detector Setup



- Internal target experiment with cooled 1.5-15 GeV/c antiproton beams
- Double spectrometer: 4π acceptance
- Tracking, particle ID, calorimetry
- Very high interaction rates
- Sampling readout

PANDA Physics Topics

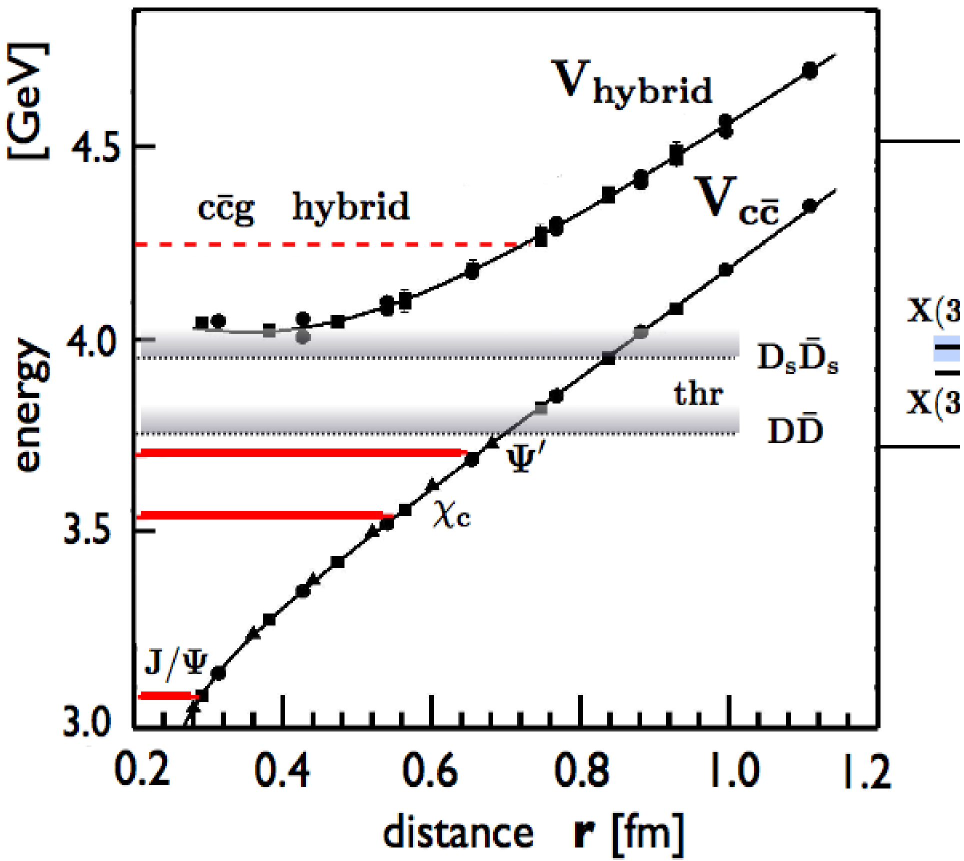
- Hadron spectroscopy
  - Charmonium
  - Charmed hybrids
  - D-mesons
  - Light mesons & hybrids
- Hadron structure
  - Timelike EM formfactor
  - Drell-Yan
  - WA Compton scattering
- Charm in medium
- Hypernuclei
  - Double hypernuclei
  - Precision γ-spectroscopy
- Electroweak physics
  - CPV with charm mesons and hyperons
  - Rare decays

Aims of Spectroscopy

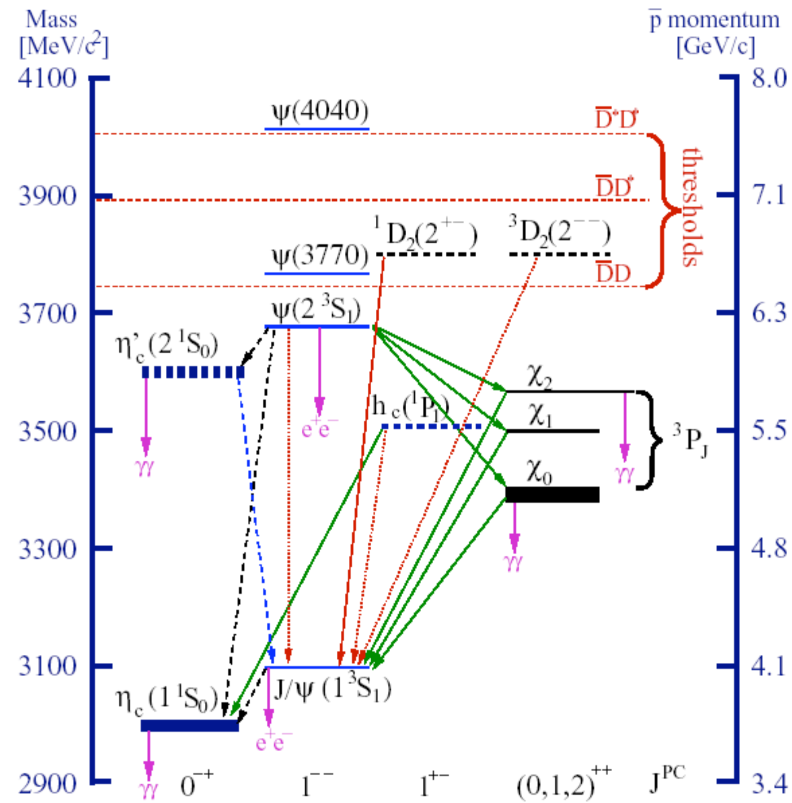
- ***Experiment***: Systematic determination of particle properties
  - Mass
  - Lifetime or width of resonance
  - Quantum number J^{PC}
- ***Theory***: Calculation of spectra
  - Knowing interaction allows prediction
  - Tuning accounting for experimental data
- ***Final aim:*** Understand composition and dynamics of matter
  - → In QCD we are still far away from precision of QED

Charmonium Spectroscopy

Charmonium
- Positronium of QCD:
  Potential of $c\bar{c}$ calculable
- ➔ Tool to understand confinement



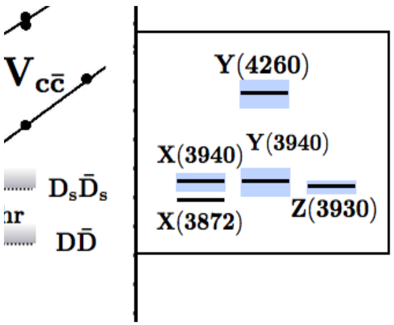
Status below $D\bar{D}$ threshold
- J=1-- well measured
- Low resolution on J=0-+ states
- η_c' was rediscovered 40 MeV higher
- Low statistics on h_c



XYZ - New Charmonium States

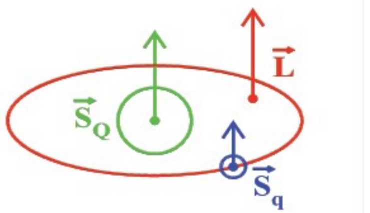
Renaissance in Charmonium Spectroscopy:

- Belle, BaBar, CLEO, CDF and D0 find new states above $D\bar{D}$
- Many of these states are problematic: mass not predicted, width too small, decay pattern unusual
- Challenge for better understanding and high precision data

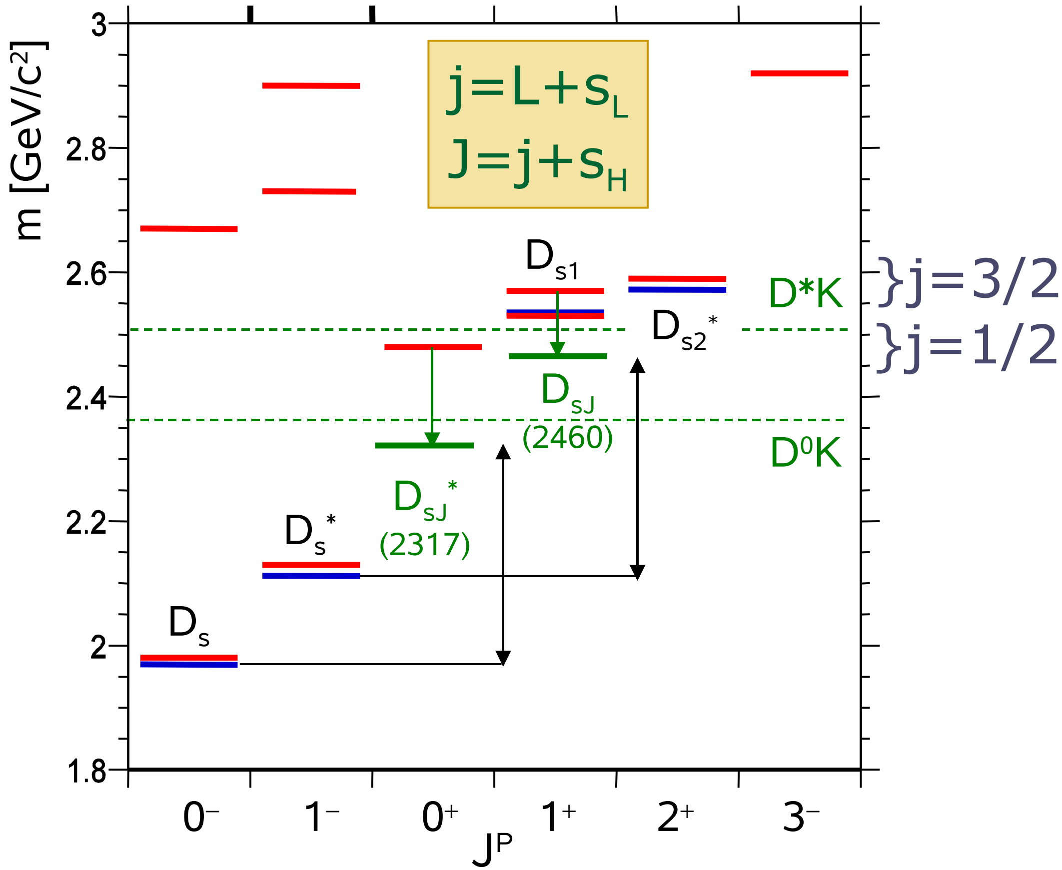


State	Experiments	Nature/Remarks
X(3872)	Belle, BaBar, CDF, D0	D^0D^{0*} molecule, 4-quark state
X(3943)	Belle	maybe η''_c
Y(3940)	Belle	maybe 2^3P_1
Z(3930)	Belle	maybe χ'_{c2}
Y(4260)	BaBar, Belle, CLEO-c	Hybrid, $\omega\chi_{c1}$ -molecule, 4q state
Y(4350)	BaBar, Belle	?
$Z^{\pm}$(4430)	Belle	No charged $c\bar{c}$, molecule or 4q state
Y(4660)	Belle	?

D-Meson Spectroscopy



A. Drutskoy



Heavy mesons like H-atom:

- Heavy quark surrounded by light quark
- ordered by property of light quark
- approximate j degeneracy
- → Spectroscopic predictions
- → Works fairly well in $\bar{c}(u/d)$ system

D_s mesons surprise

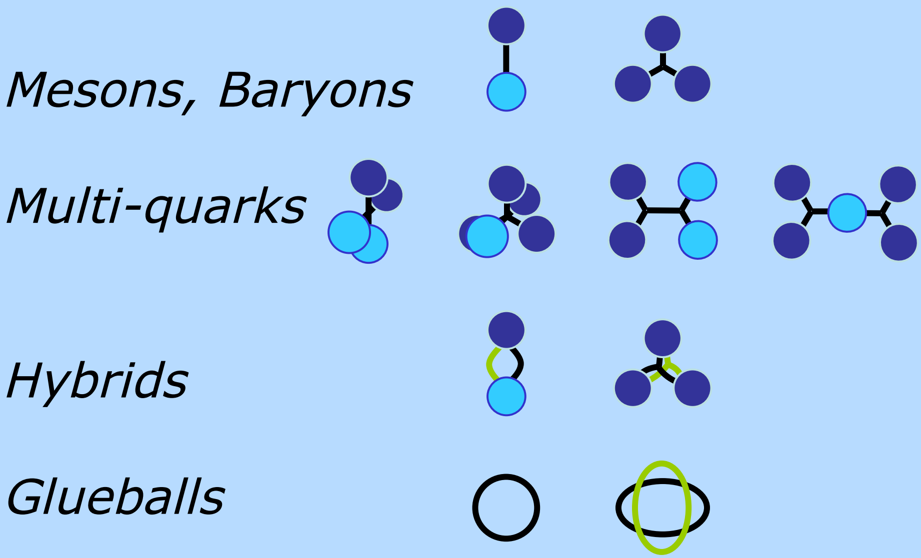
- Recent narrow $D_{s0}(2317)$ and $D_{s1}(2460)$ do not fit theoretical calculations.
- Quantum numbers for the newest states $D_{sJ}(2700)$ and $D_{sJ}(2880)$ open

- $D_{s0}(2317) \rightarrow D_s^+\pi^0$, but not $D_s^+\pi^\pm$
- $D_{s1}(2460)$ in $D_s^+\pi^0\gamma$, $D_s^+\gamma$, $D_s^+\pi^+\pi^-$
- Experimentally well established
- Nature unclear: 4q states, molecules?

Exotic Hadrons

Exotic Hadrons

- Normal hadrons: $(q\bar{q})$ or (qqq)
- Gluonic degrees of freedom:
  - Hybrid mesons $(q\bar{q}g)$
  - Glueballs
- Multi-quark states
- Molecules
- Exotic mesons can have exotic quantum numbers



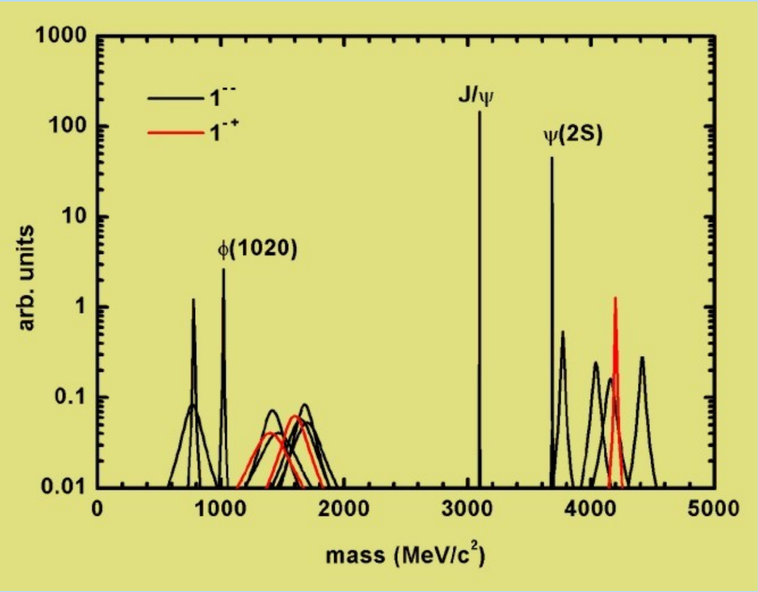
Charm Spectroscopy

- Charm quark: $m_c \gg m_{u,d,s}$

➔ Perturbative to strong coupling

Charm Hybrids

- $c\bar{c}$-states narrow, understood
- Little interference of $c\bar{c}g$ & $c\bar{c}$-states
- Mass 4–4.5 GeV, $c\bar{c}g$ narrow,
- $\sim \sigma(p\bar{p} \rightarrow c\bar{c})$



Spectroscopy with Antiprotons

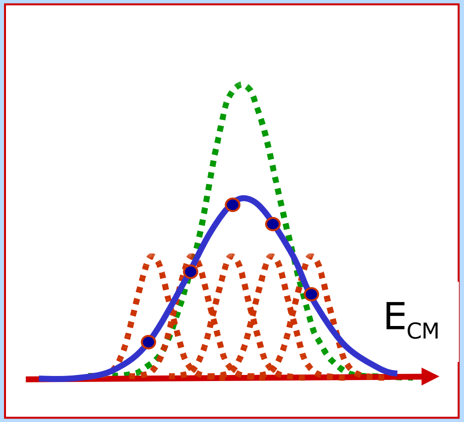
Spectroscopy with antiprotons

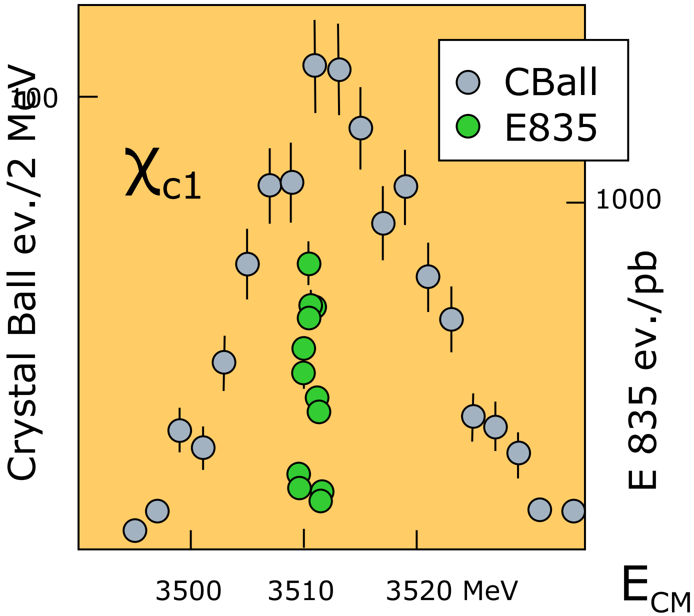
- $p\bar{p}$ machine allows $\Delta E \sim 50$ keV (beam) vs. $\Delta E \sim 5$ MeV in e^+e^- (detector)
- e^+e^- directly produces only $J^{PC} = 1^{--}$ (γ) others via ISR and other higher orders
- $p\bar{p}$ accesses all states

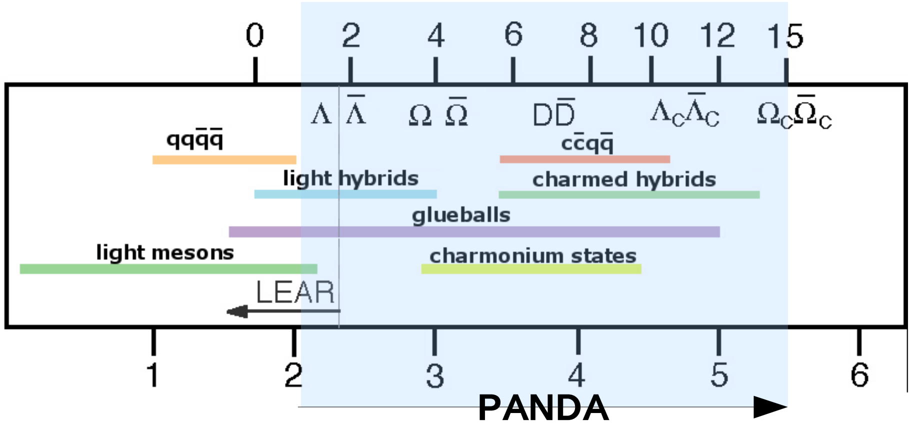
Resolution with antiprotons

Resonance scan:

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



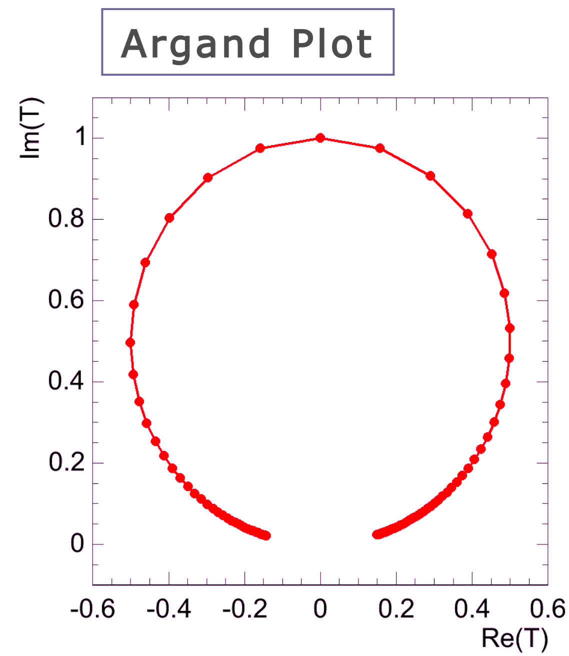


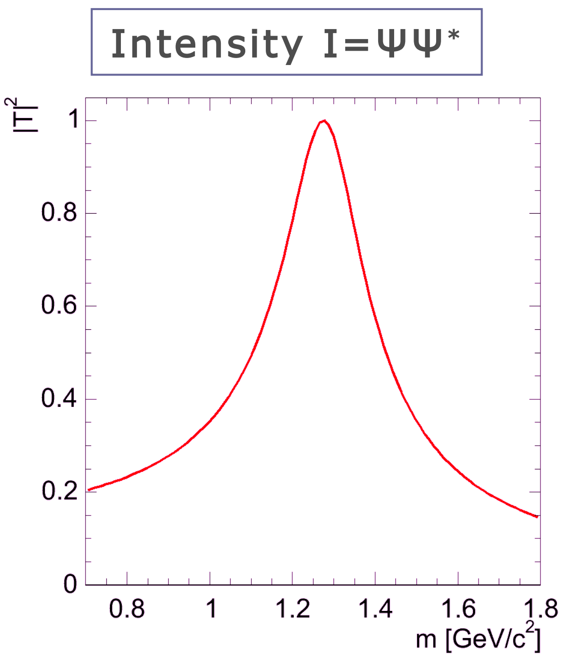


Principles of Partial Wave Analysis

Goals of PWA:

- N-particle phase space
- Description of resonance properties:
  - mass
  - width
  - quantum numbers
- Treatment of interferences





Schrödinger Equation

$$-\frac{\hbar}{2\mu}\nabla^2\Psi(\vec{r})+V(\vec{r})\Psi(\vec{r})=E\Psi(\vec{r})$$

$$\Psi_i=\sum^{\infty}U_l(r)P_l(\cos\vartheta)$$

$$\Psi_S=\Psi_f-\Psi_i=\frac{1}{k}\sum_{l=0}^{\infty}(2l+1)\underbrace{\frac{\eta_l e^{2\imath\delta_l}-1}{2\imath}}_{T_l}P_l(\cos\vartheta)\frac{e^{\imath kr}}{r}$$

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Schrödinger Equation

$$-\frac{\hbar}{2\mu}\nabla^2\Psi(\vec{r}) + V(\vec{r})\Psi(\vec{r}) = E\Psi(\vec{r})$$

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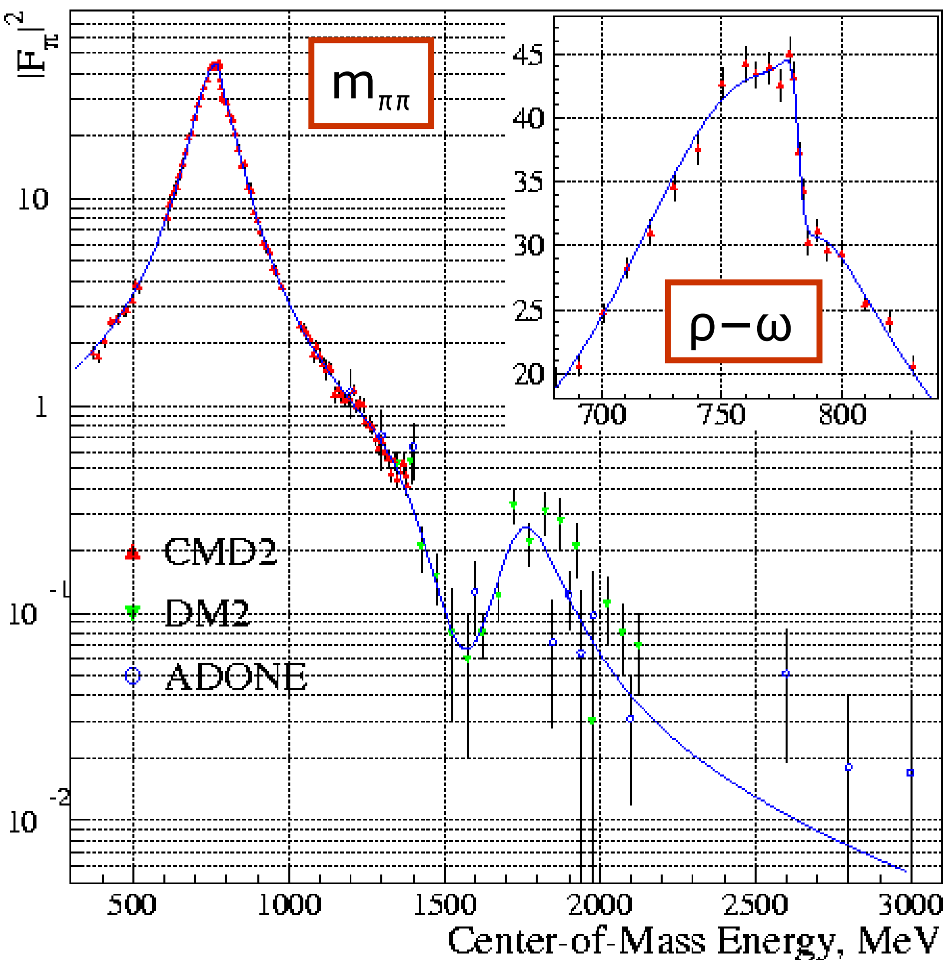
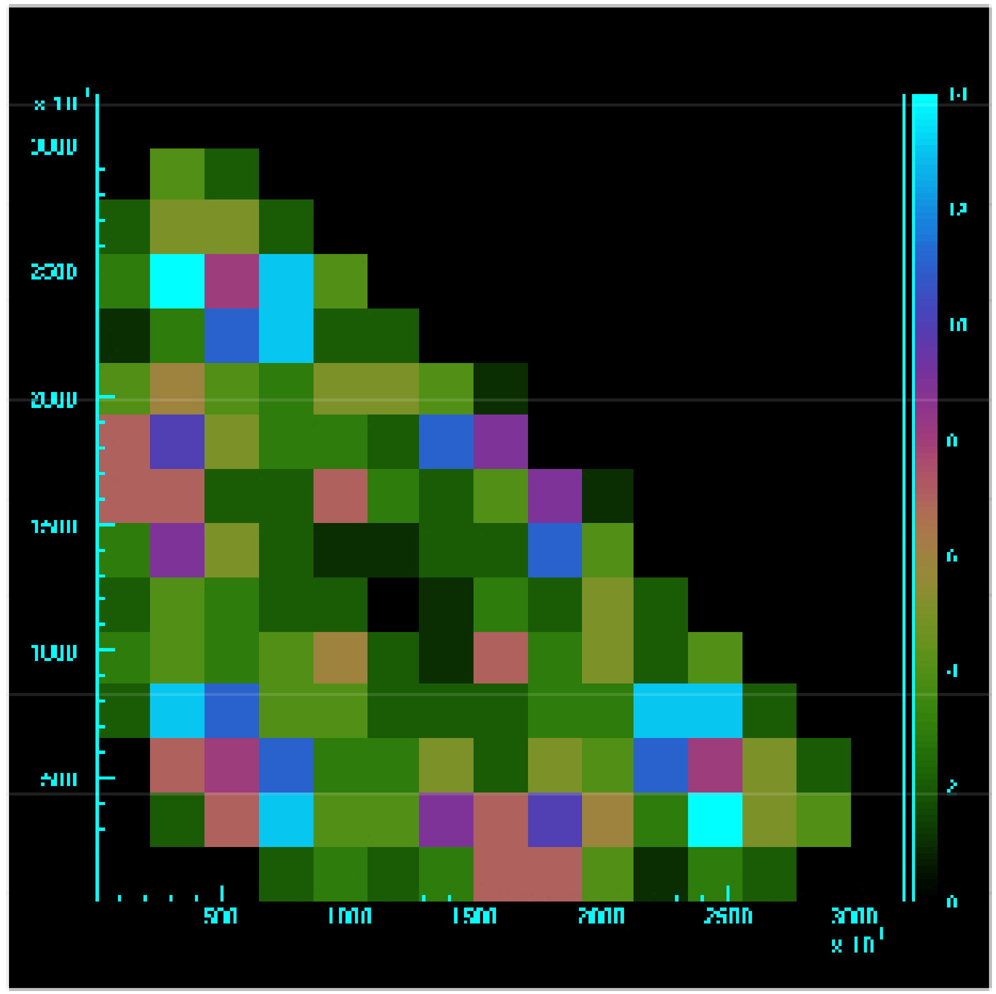


L. Schmitt, GSI

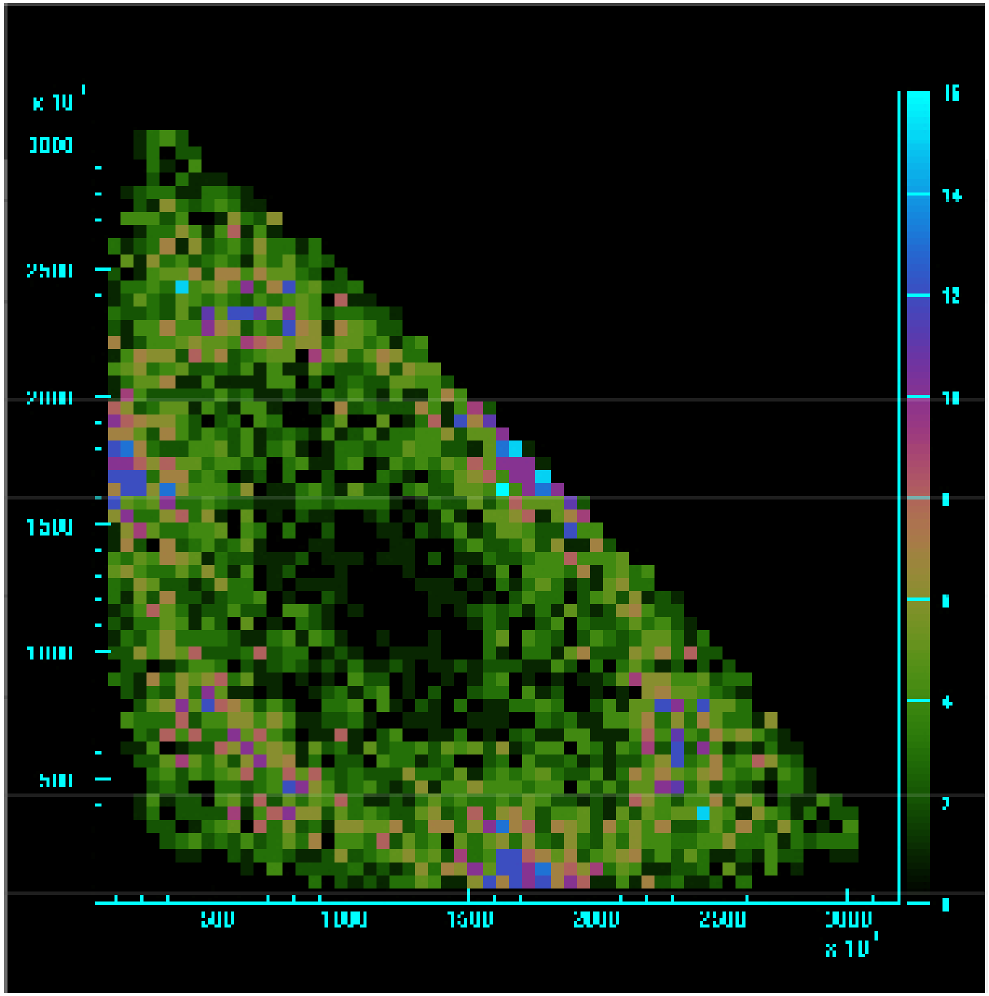
Requirement: High Statistics

Crystal barrel $p\bar{p} \rightarrow 3\pi^0$
with 100 events



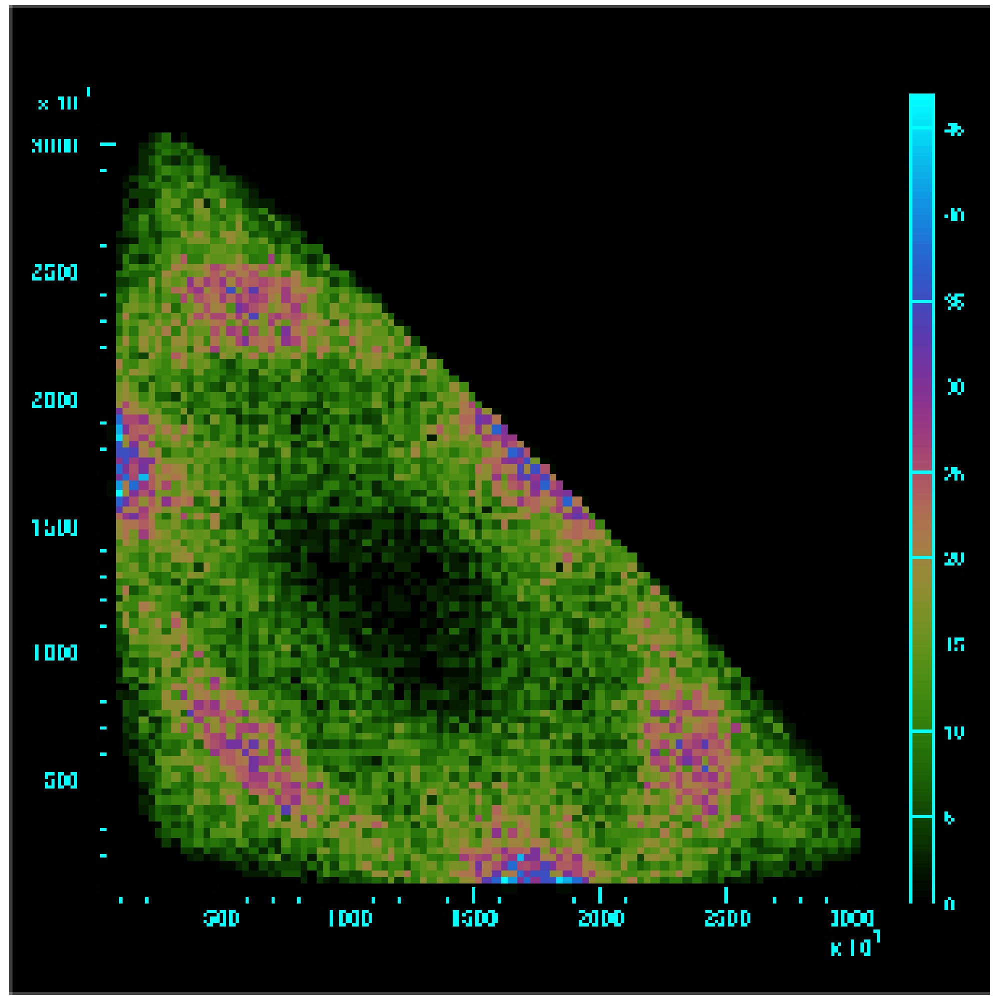
Requirement: High Statistics

Crystal barrel $p\bar{p} \rightarrow 3\pi^0$
with 1000 events



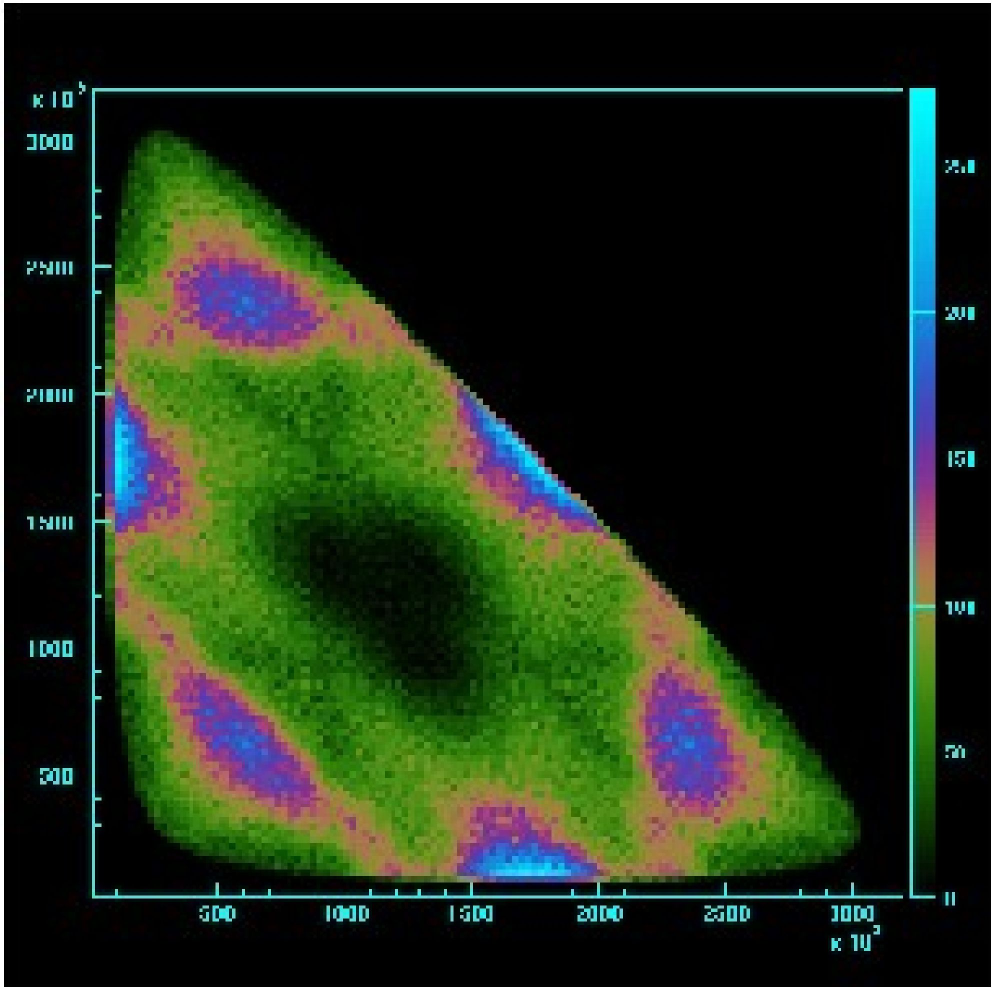
Requirement: High Statistics

Crystal barrel $p\bar{p} \rightarrow 3\pi^0$
with 10000 events

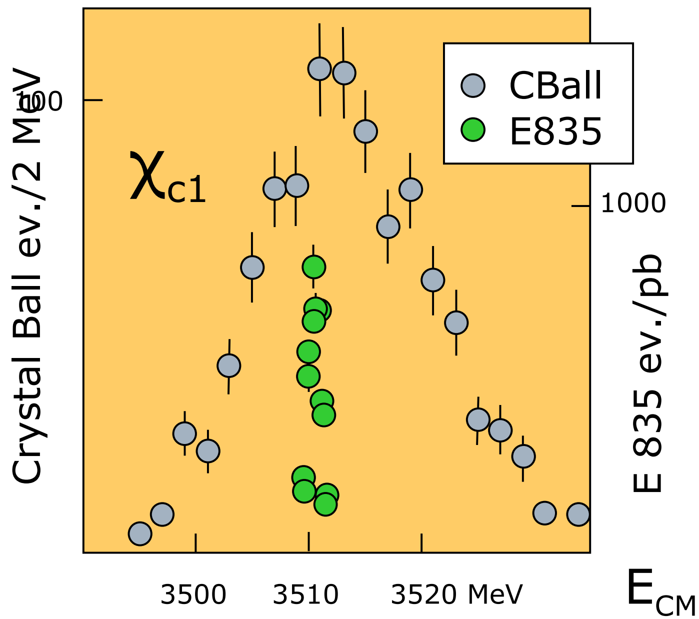


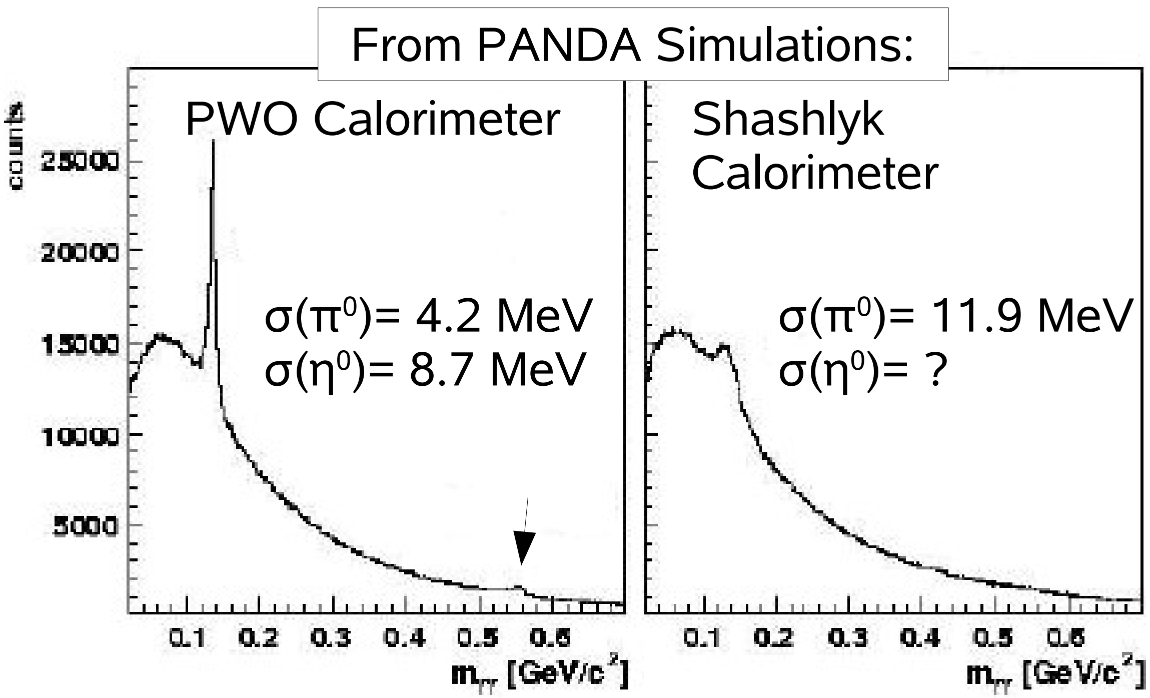
Requirement: High Statistics

Crystal barrel $p\bar{p} \rightarrow 3\pi^0$
with 100000 events



Requirement: Good Resolution





Importance of high resolution:

- to find and investigate narrow resonances
- for multi hadron final states
- to reduce the background

Achieving high resolution:

- Production process
- Detector resolution
- Kinematical constraints

Partial Wave Analysis in PANDA

Purpose of PWA for PANDA in the field of spectroscopy:

- Disentangle interfering resonances
- Determine quantum numbers
- → Uncover the nature of new resonances
- → Discover spin-exotic states

Applications by PANDA in the field of spectroscopy:

- Charmonium and Charmonium hybrids
- D-mesons and D-hybrids
- Light quark resonances
- Glueballs

Prerequisites for the spectrometer:

- 4π acceptance, hermeticity
- Particle identification
- High resolution
- High statistics
- Over-constrain systems

Studying Hadron Structure

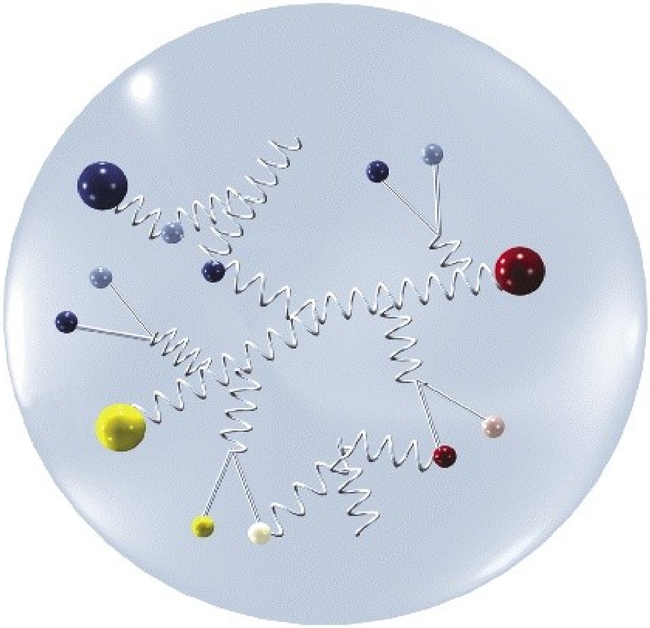
Bjorken scaling:
At high Q^2 dependence only on x
➔ Scattering on point-like *partons*

Parton distributions:
- Valence quarks
- Sea quarks
- Gluons

Factorization: hard scattering and non-perturbative structure

Structure Functions:
- Unpolarized F_1 and F_2
- Longitudinally polarized g_1 (and g_2)
- Transverse polarized h_1

Measurements:
- Deep inelastic scattering
- Drell Yan process

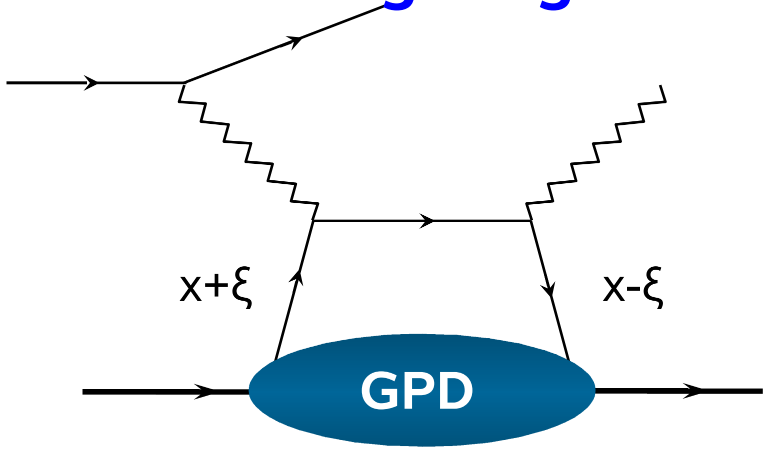


Proton spin:

$\langle s_z \rangle = ½ = ½ (\Delta u+\Delta d+\Delta s)+L_q+\Delta G+L_G$

- Quark contribution: $\Delta\Sigma=(\Delta u+\Delta d+\Delta s) \approx 0.3$ (Expt.)
- Other contributions: gluons, orbital angular momentum

Handbag Diagram



Generalized Parton Distributions

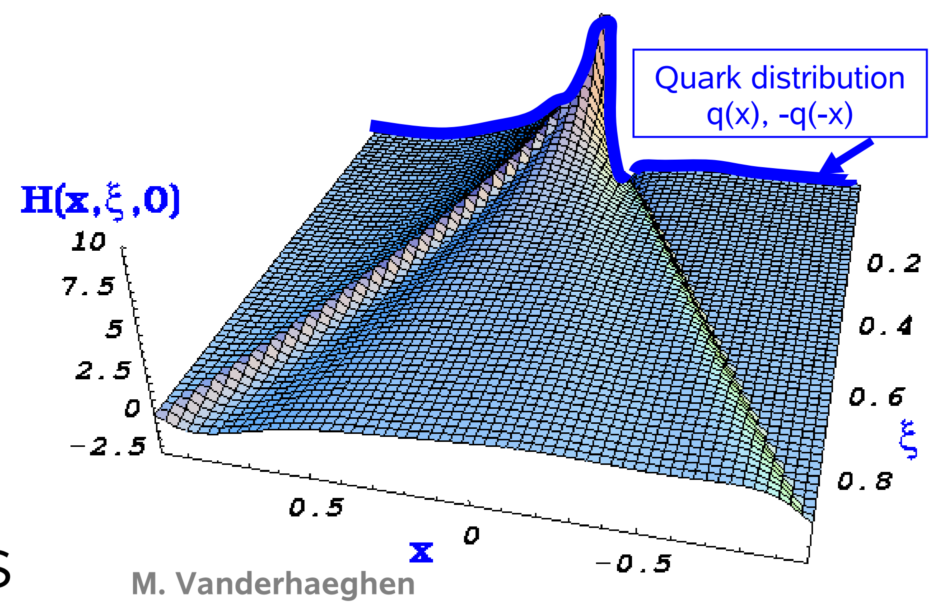
- A fractional momentum ξ is taken out
- GPDs: 4 functions $H(x,\xi,t)$, $E(x,\xi,t)$, $\tilde{H}(x,\xi,t)$, $\tilde{E}(x,\xi,t)$ (polarized)

Properties of GPDs:

- GPDs carry information on *longitudinal* and *transverse* distribution of partons

→ 3D picture of nucleon

- GPDs contain also information on quark (orbital) angular momentum
- $H(x,0,0) = q(x)$ structure functions of DIS
- $\int H(x,0,t)\,dx = F(t)$ nucleon formfactor

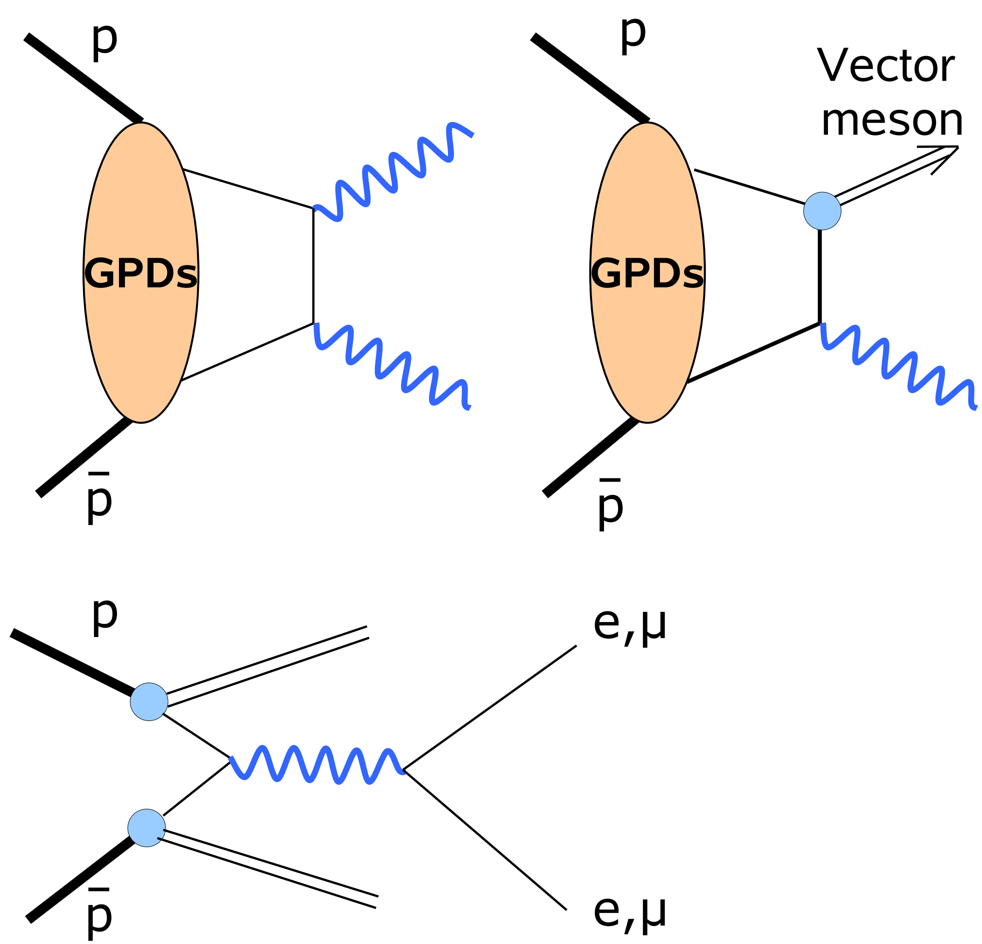


Nucleon Structure in PANDA

Generalized Parton Distributions
- Wide angle Compton scattering
- Hard exclusive meson production

Transverse nucleon spin
- Drell Yan Process
  (full PWA or polarized beam/target)

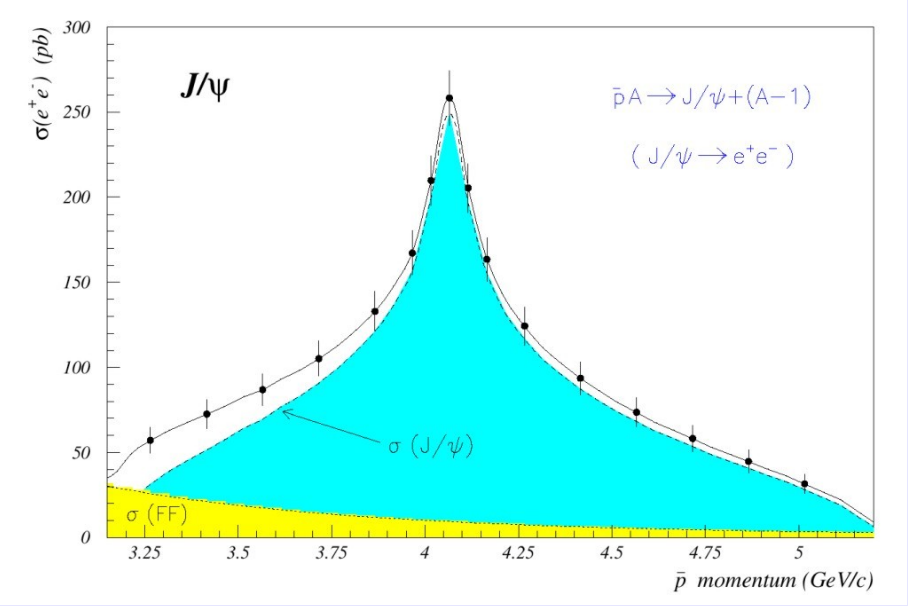
Electromagnetic formfactors
- Discrepancy between timelike and spacelike region
- Measure $p\bar{p} \rightarrow e^+e^-$



Hadrons in Nuclear Medium

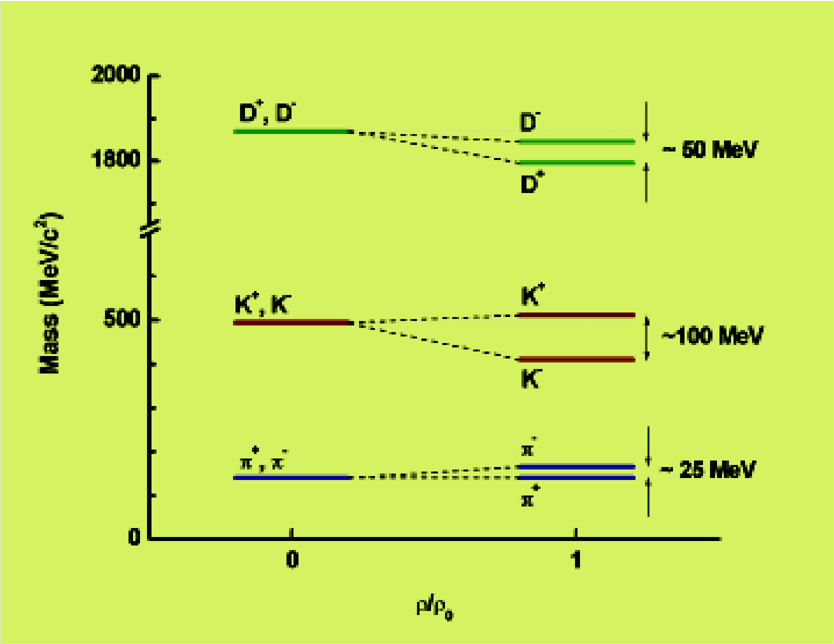
Charmonium in Nuclei

- Enhanced charmonium states due to lower $D\bar{D}$ threshold
- J/Ψ absorption in nuclei → comparison with heavy ion collisions



Modification of Meson Masses

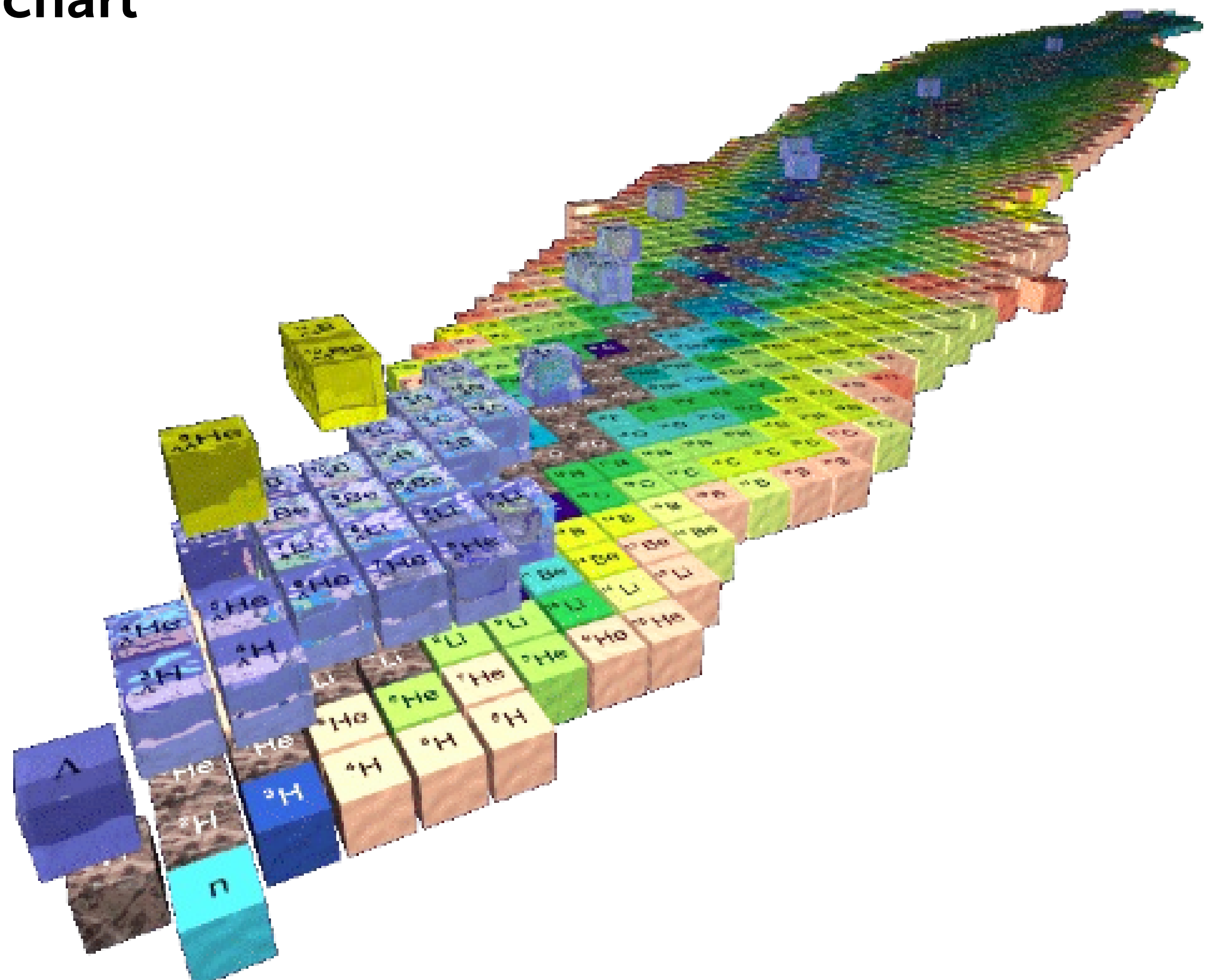
- Mass change in nuclear medium
- D masses lowered, mass split
- Need to stop D in nucleus



The Hypernuclear Landscape

Hypernuclei: Strangeness as 3rd dimension in the nuclear chart

Objectives:
- Study of nuclear structure
- Understanding of nuclear potential and *NN* force
-

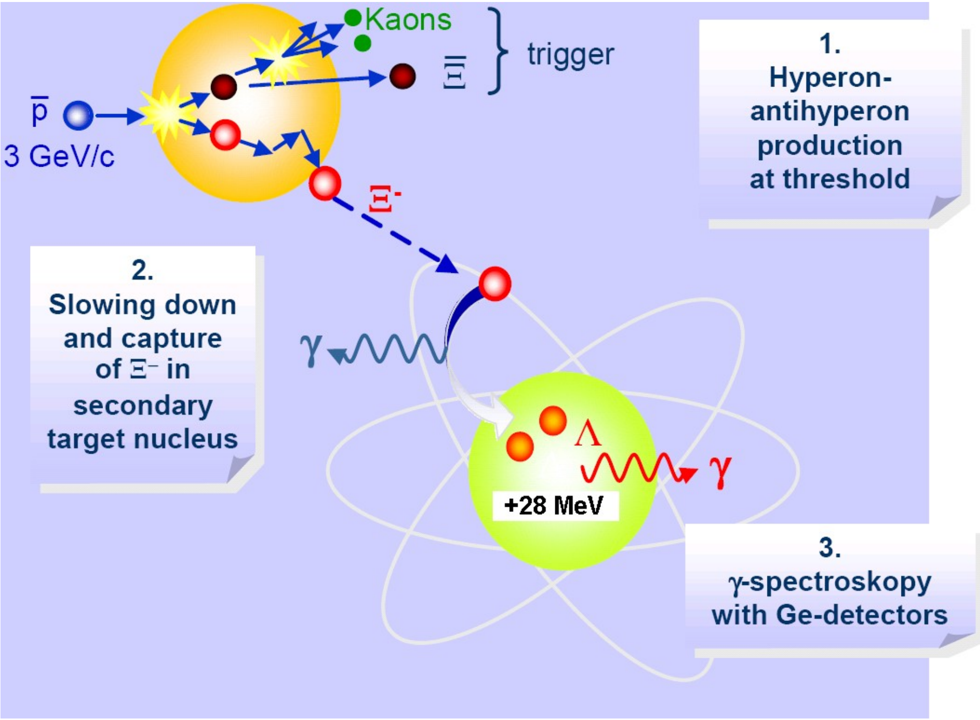


Hypernuclear puzzle:
- Spin-orbit force small in hypernuclei while large in normal nuclei

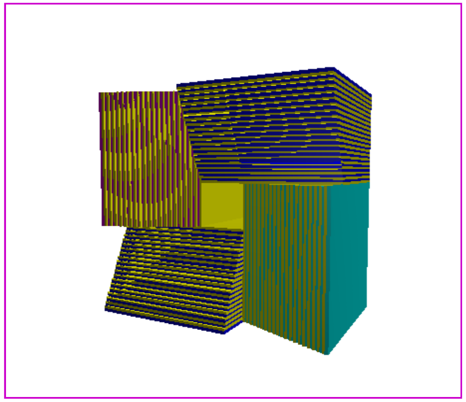
→ Spectroscopy of double hypernuclei

→ Study of *YY* interaction

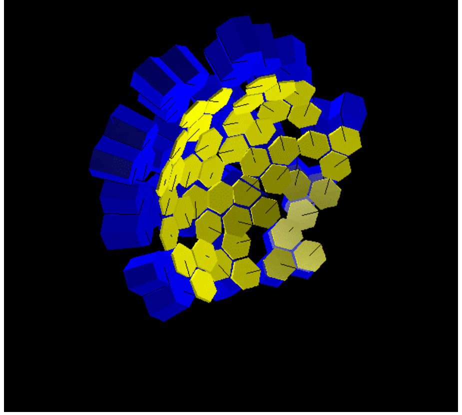
Hypernuclear Physics in PANDA



Secondary target



Germanium detector



Production of double hypernuclei:

Two-stage process

- Hyperon production at threshold
- Fast kaons or hyperons as trigger
- Slow-down and capture in secondary active target

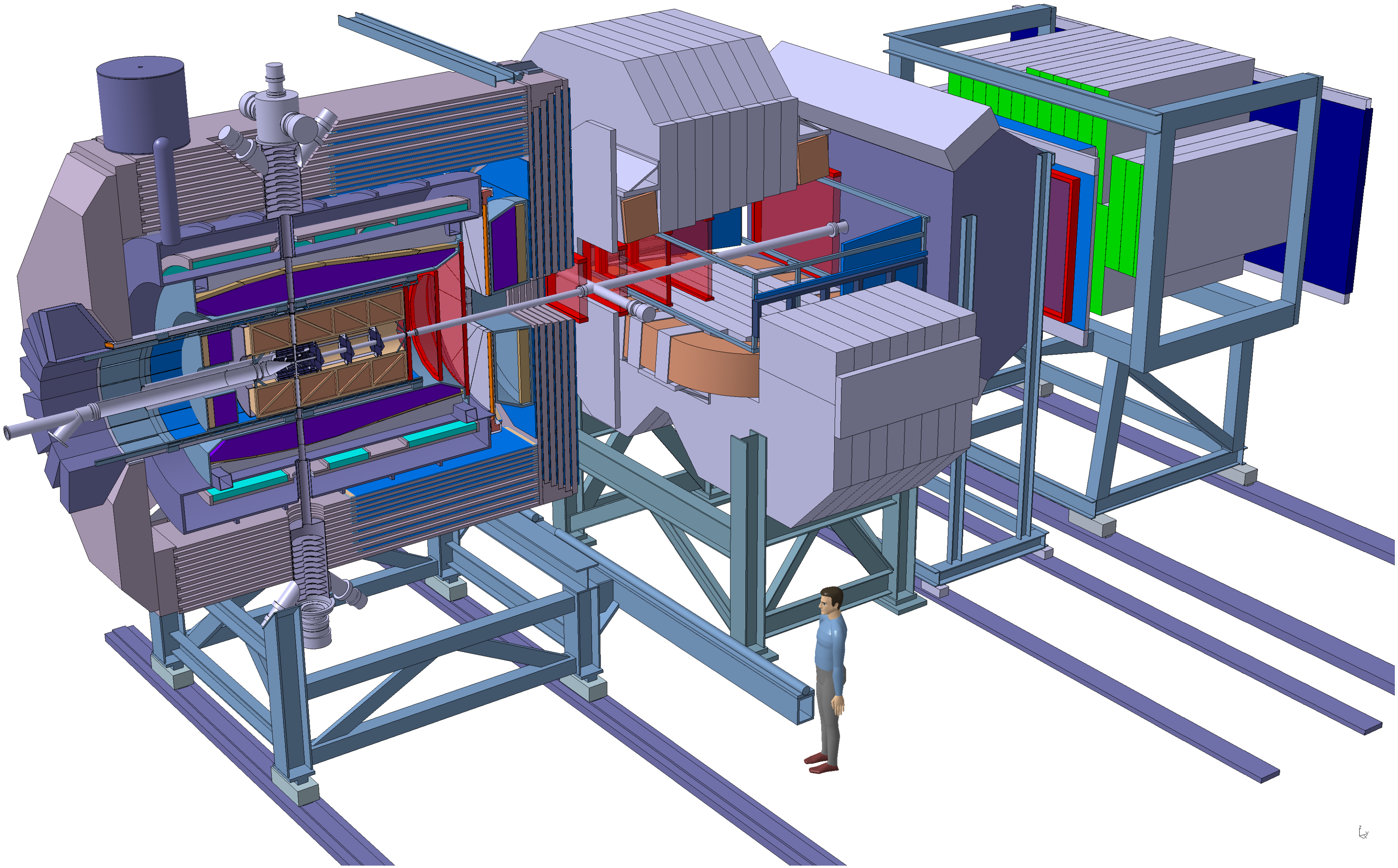
→ several 10^5 stopped Ξ/day

γ-Spectroscopy :

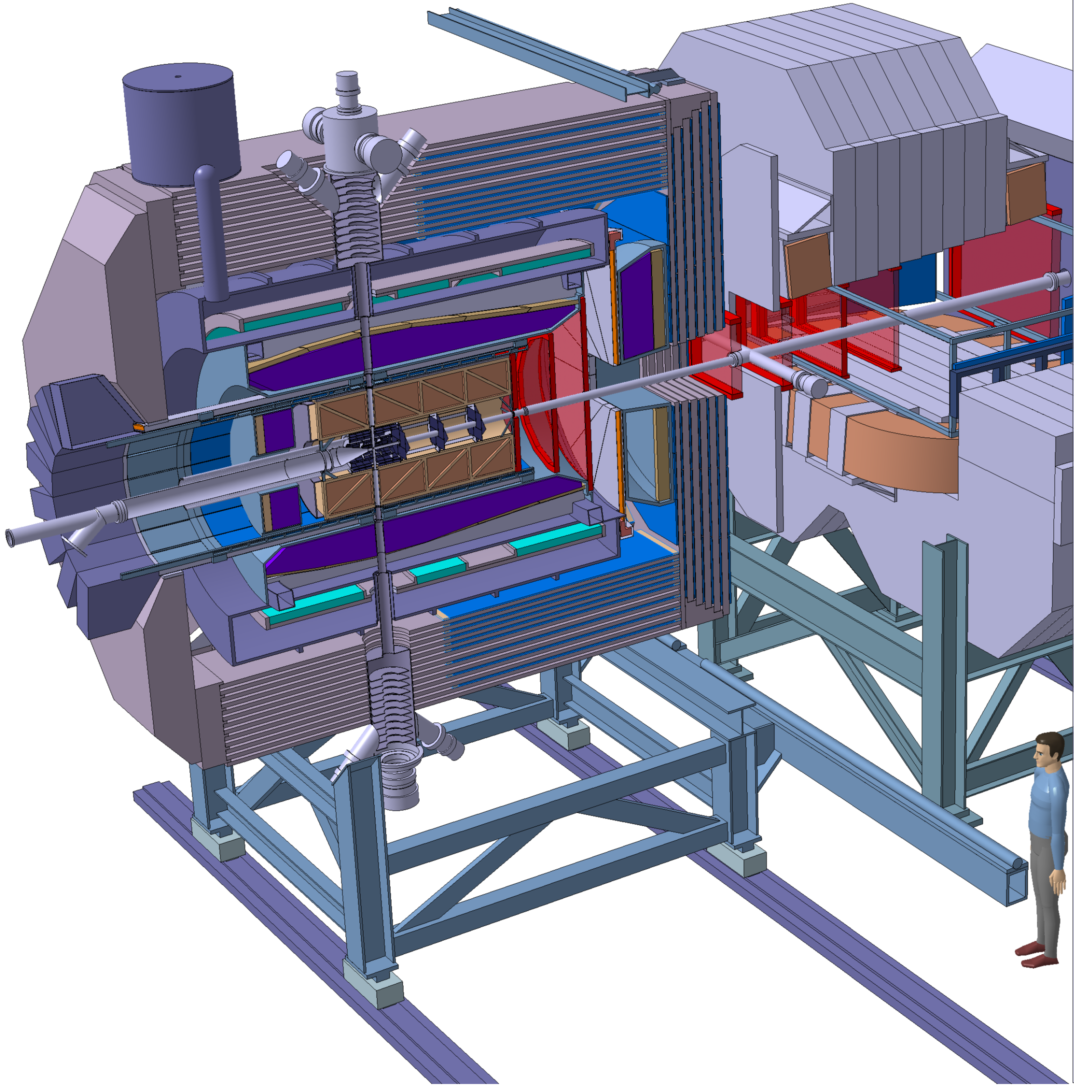
- Germanium detector in backward hemisphere
- Consecutive weak Λ decay and nuclear level cascade

→ Measure ΛΛ interaction

The PANDA Detector



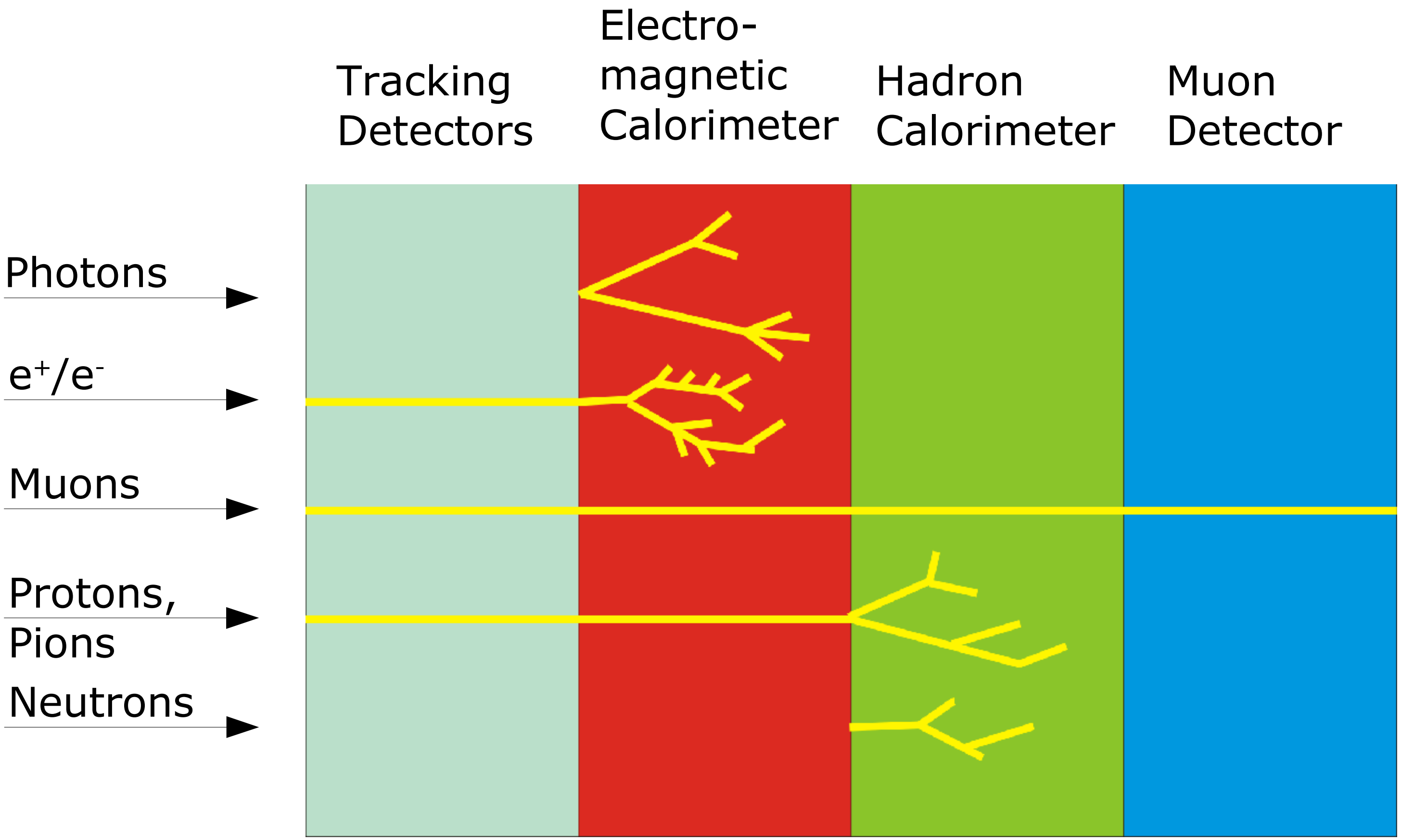
The PANDA Detector



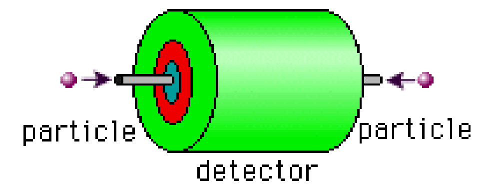
Detector requirements:

- 4π acceptance
- High rate capability: 2×10^7 s^{-1} interactions
- Efficient event selection
- → Sampling acquisition
- Momentum resolution ~1%
- Vertex info for D, K^0_S, Y ($c\tau$ = 317 μm for $D^\pm$)
- → *Good tracking*
- Good PID (γ, e, μ, π, K, p)
- → *Cherenkov, ToF, dE/dx*
- γ-detection 1 MeV – 10 GeV
- → *Crystal Calorimeter*

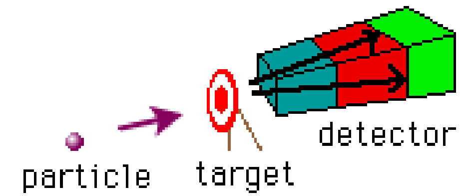
Interaction of Particles with Matter



Collider experiment

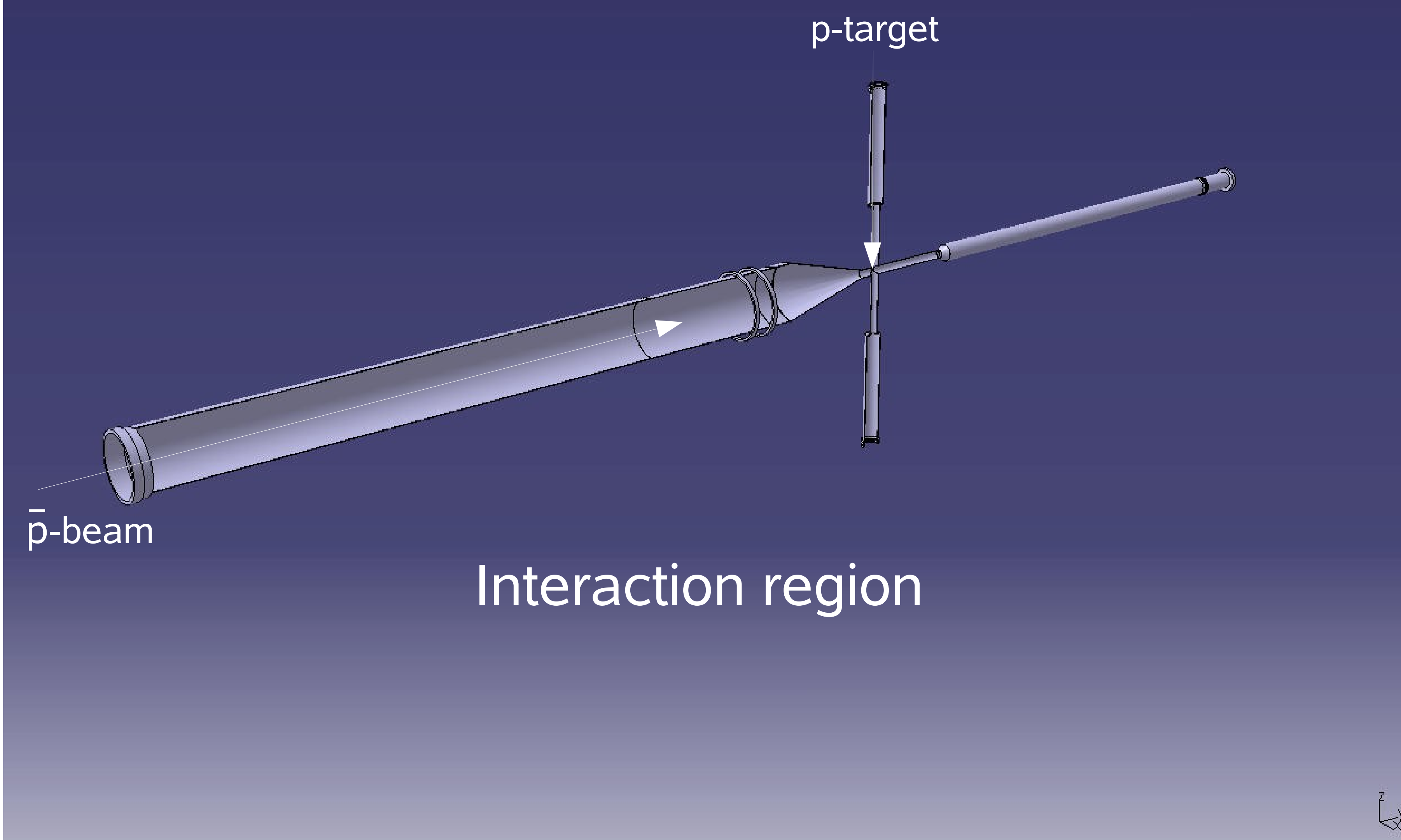


Fixed target experiment



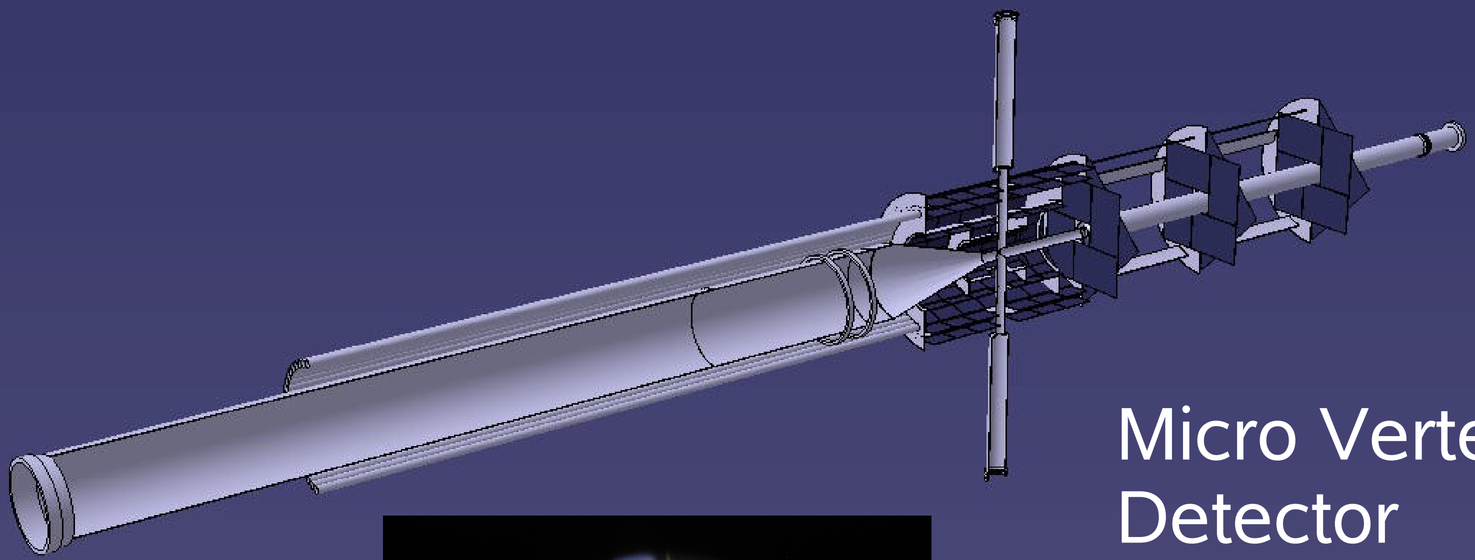
Momentum determination of charged tracks in magnetic field

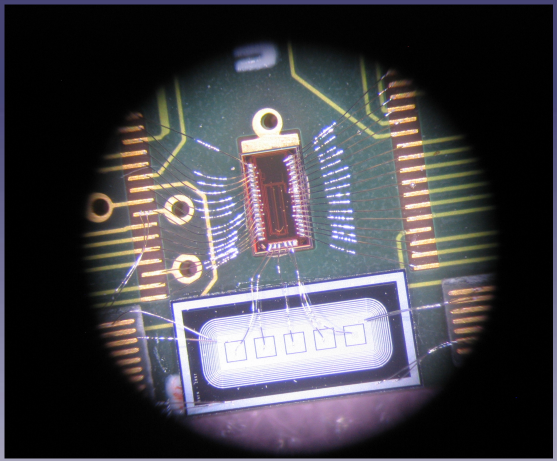
Overview of PANDA



Interaction region

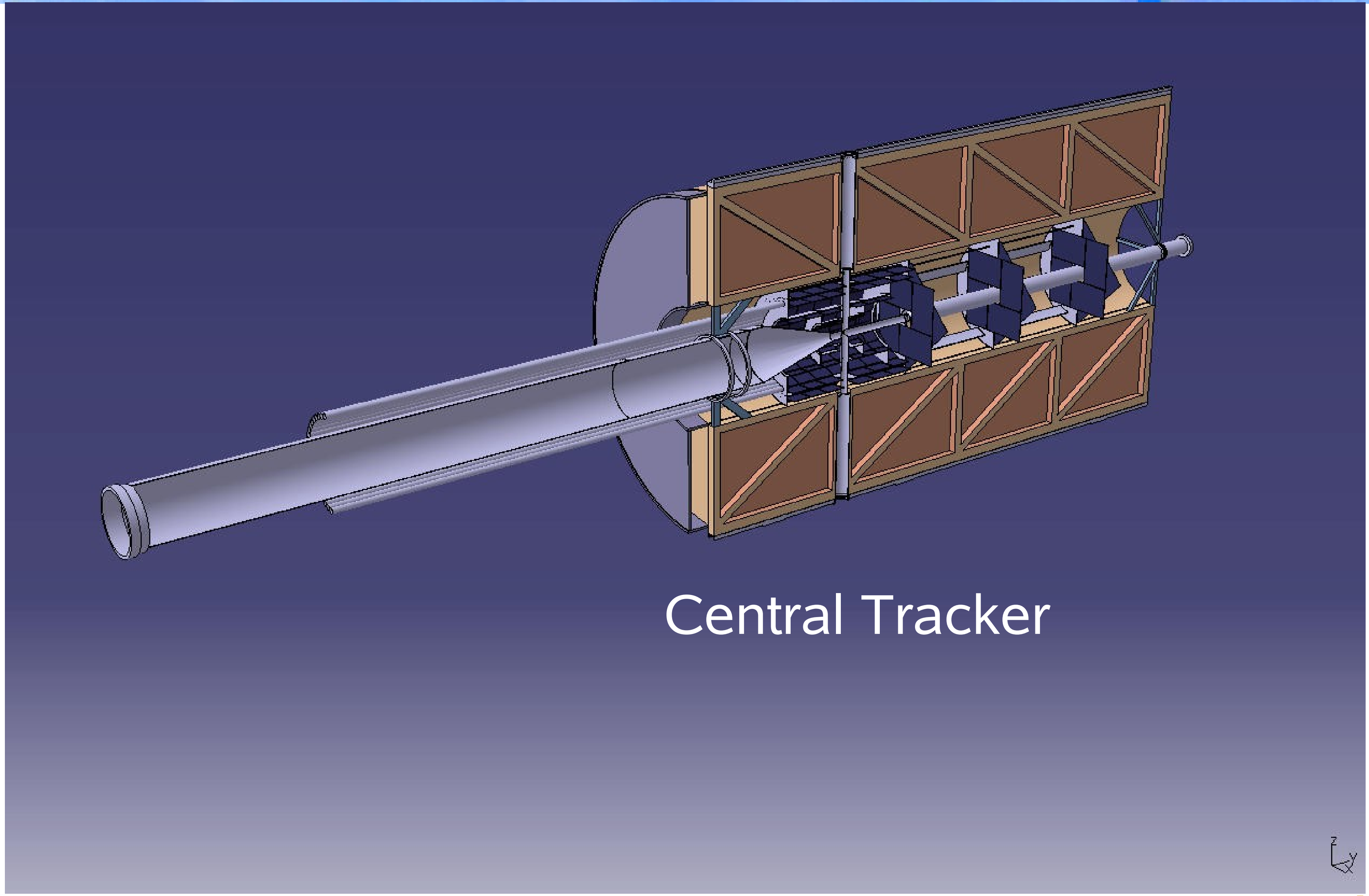
Overview of PANDA



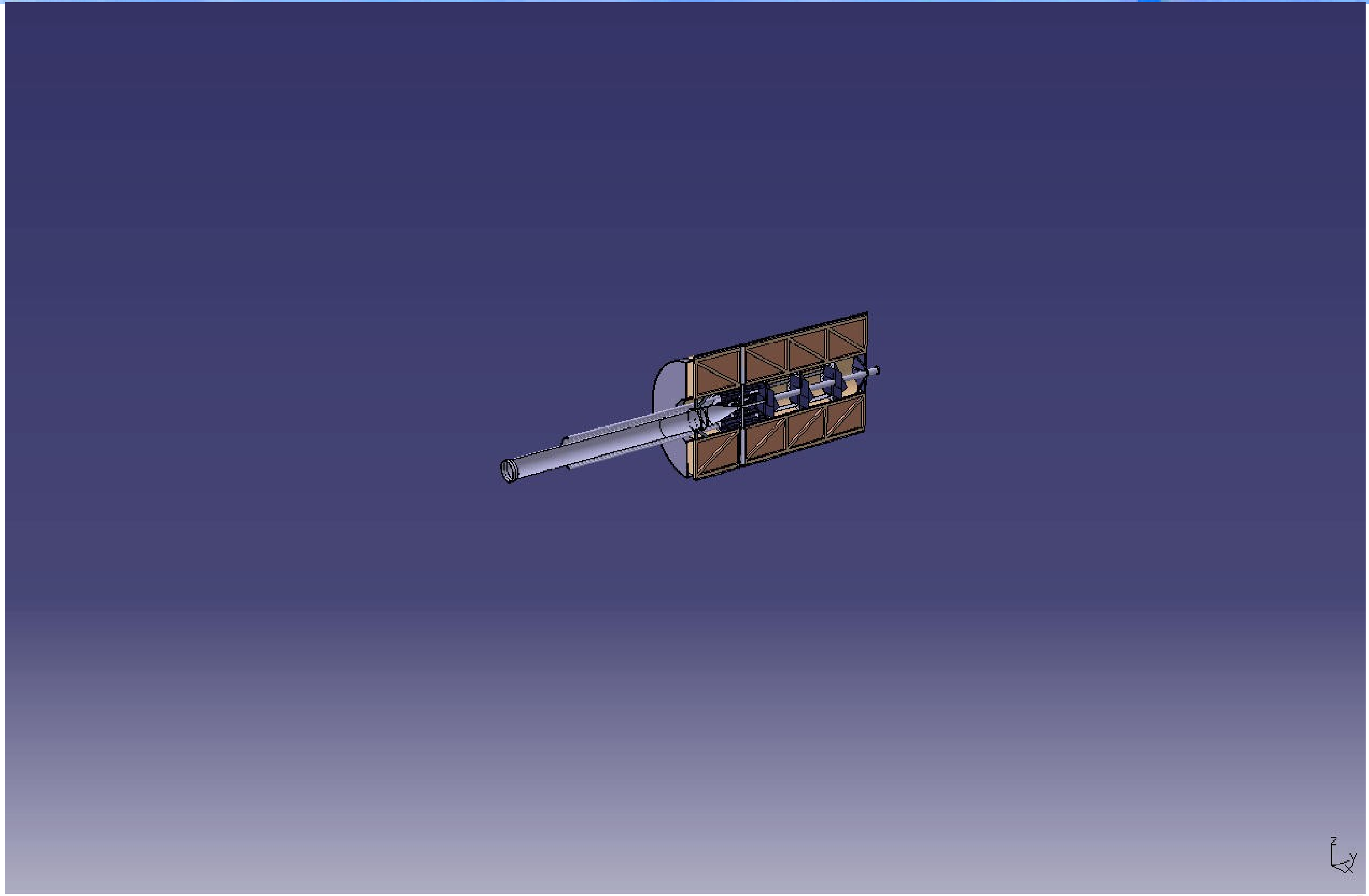


Micro Vertex Detector

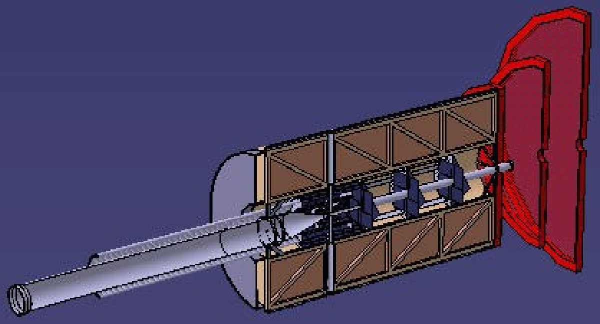
Overview of PANDA



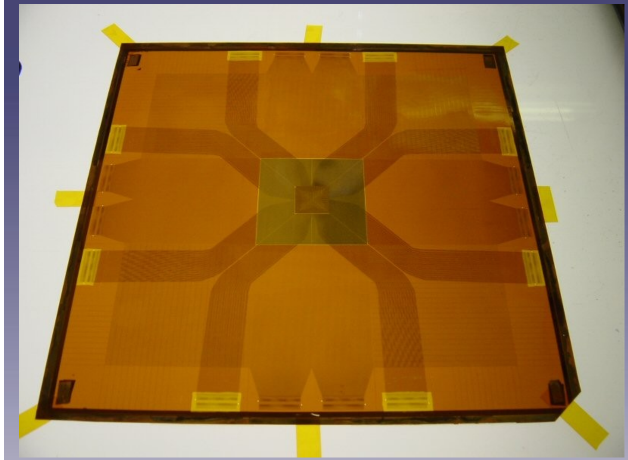
Overview of PANDA



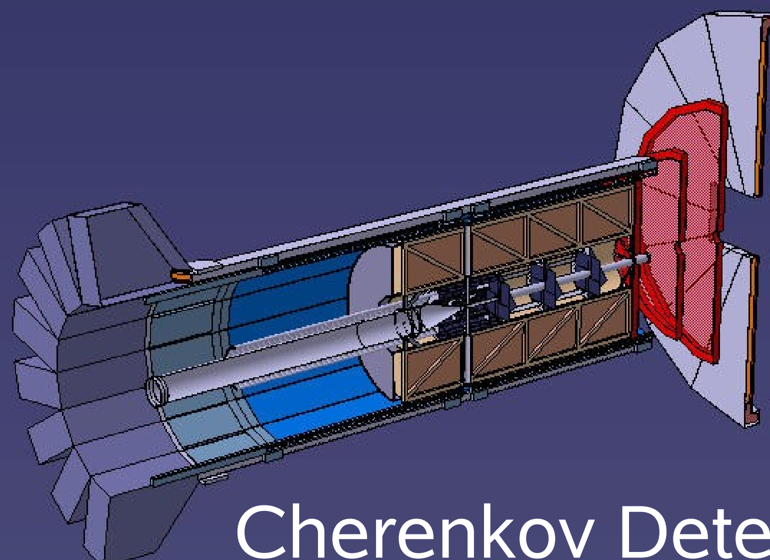
Overview of PANDA



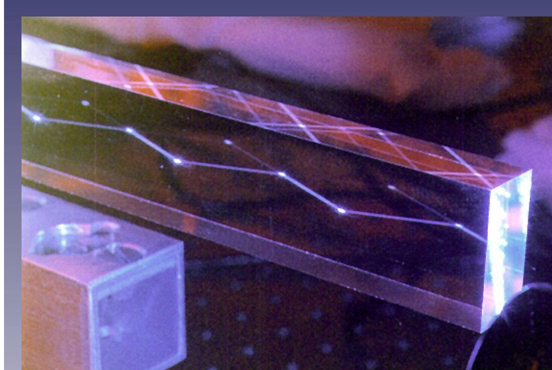
GEM Trackers



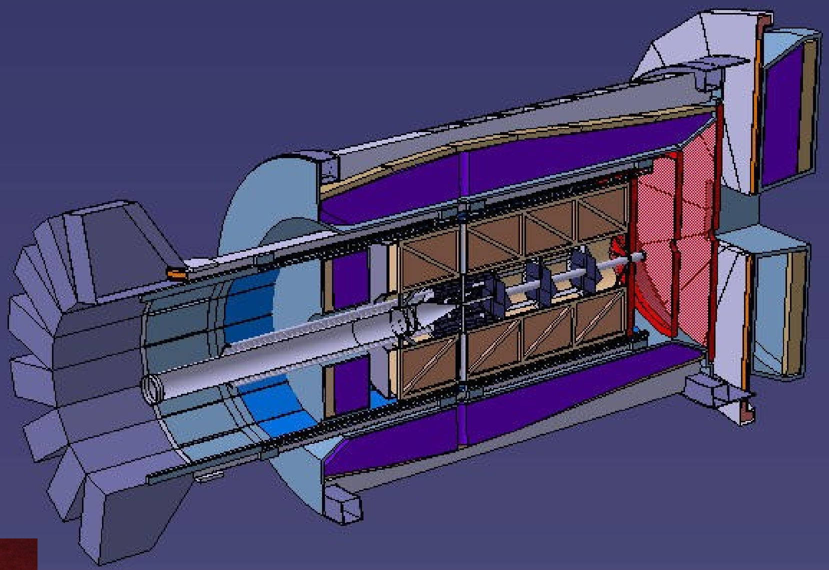
Overview of PANDA



Cherenkov Detectors

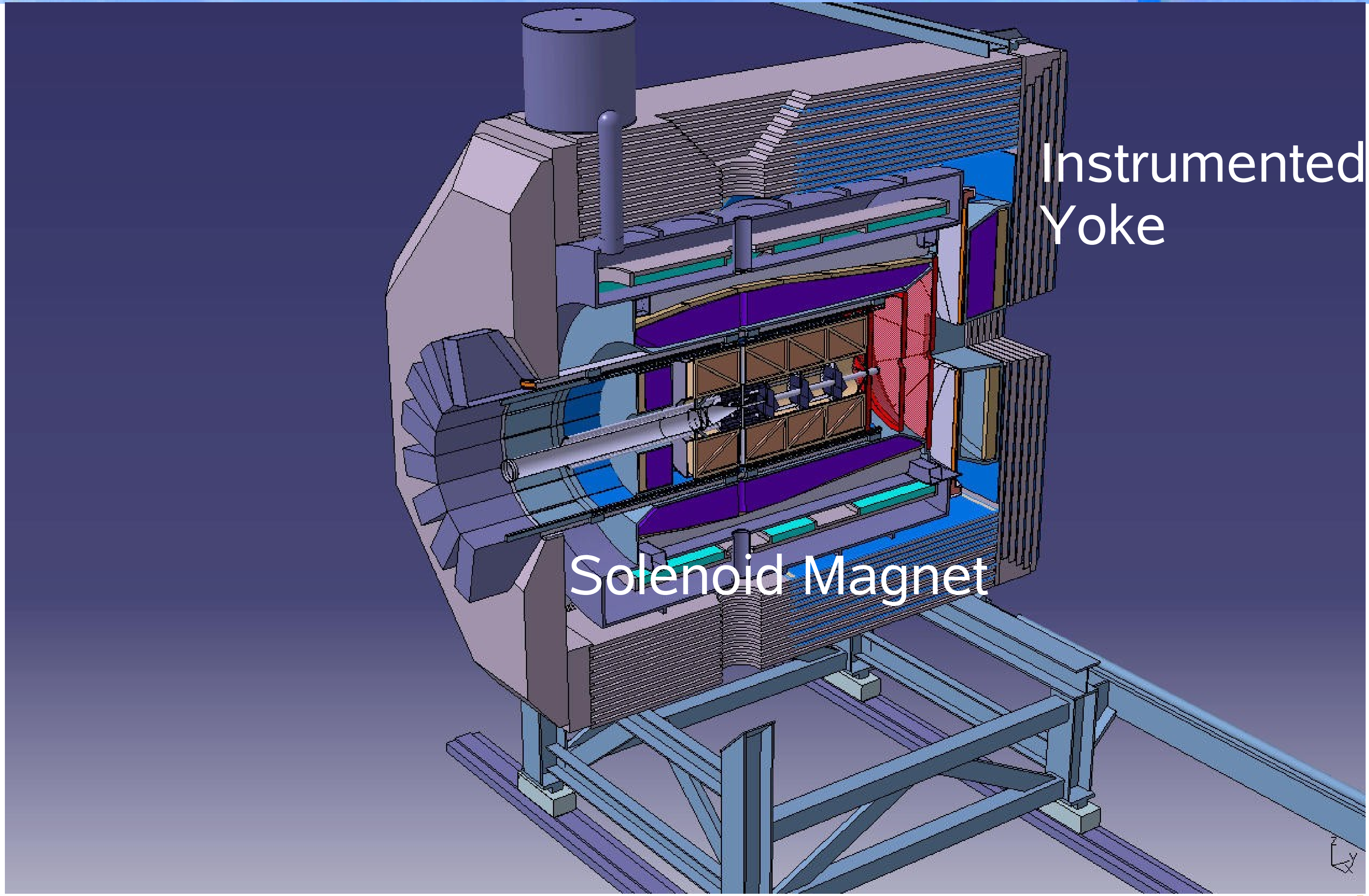


Overview of PANDA

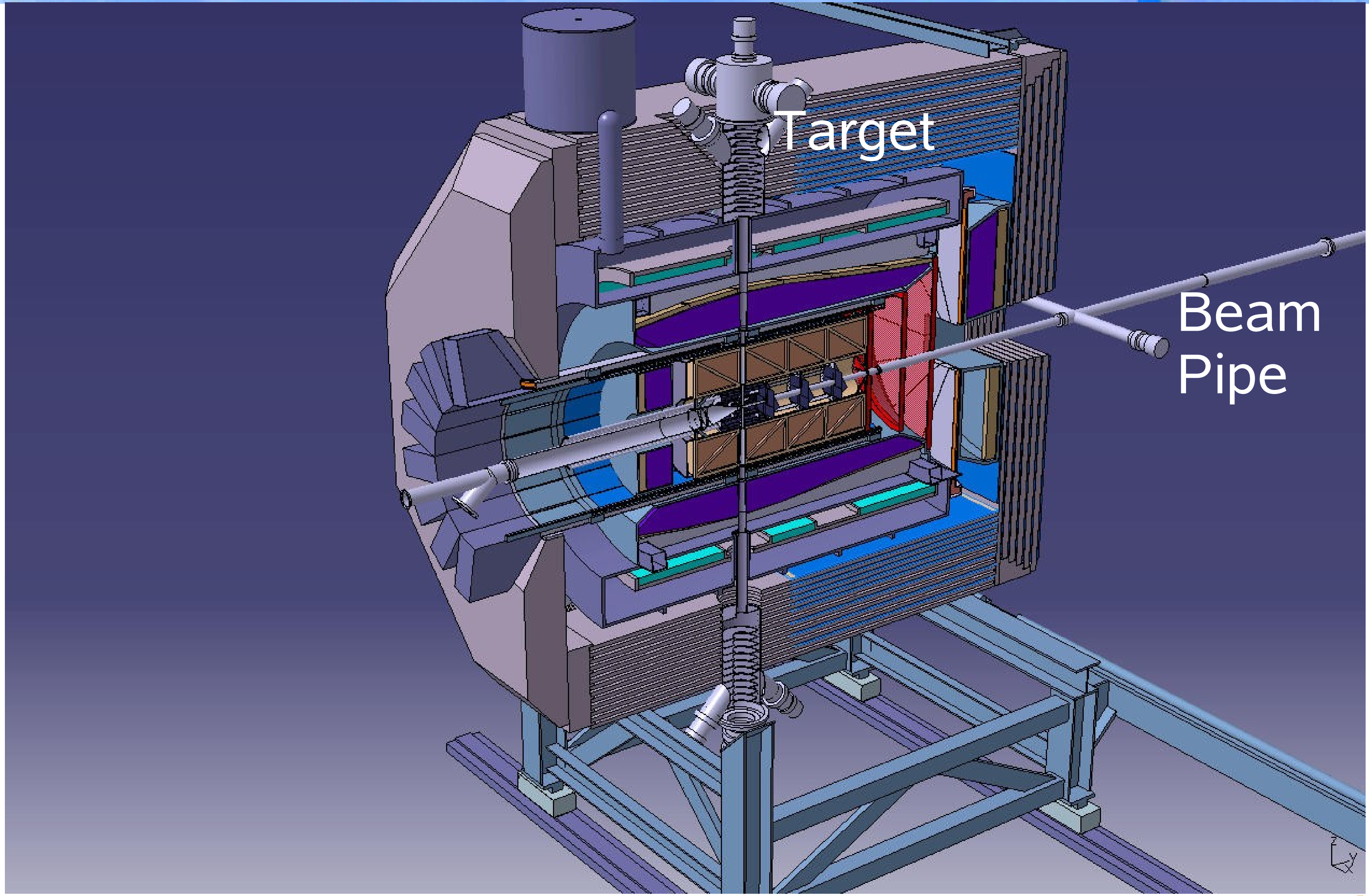


Electromagnetic
Crystal Calorimeters

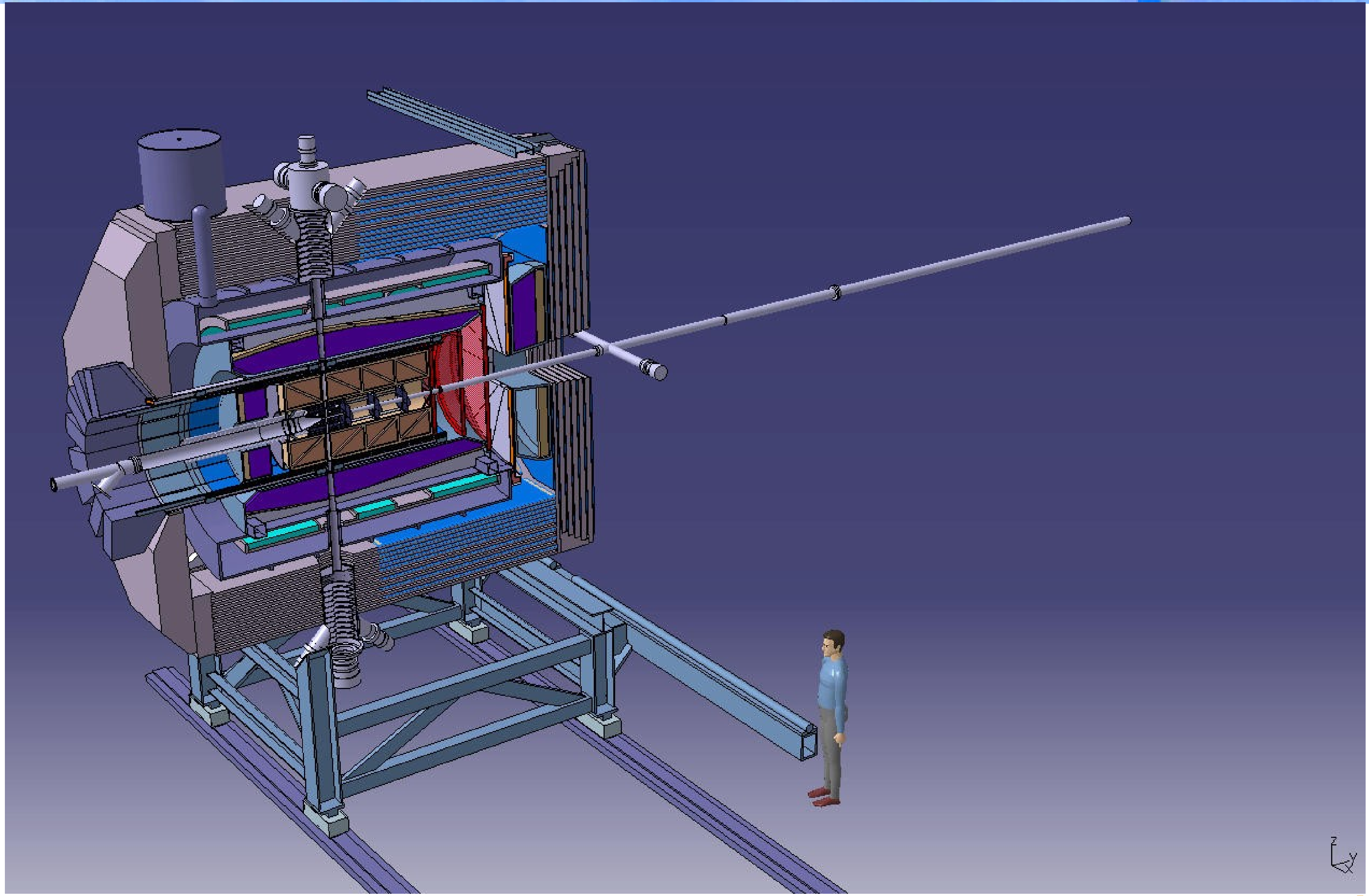
Overview of PANDA



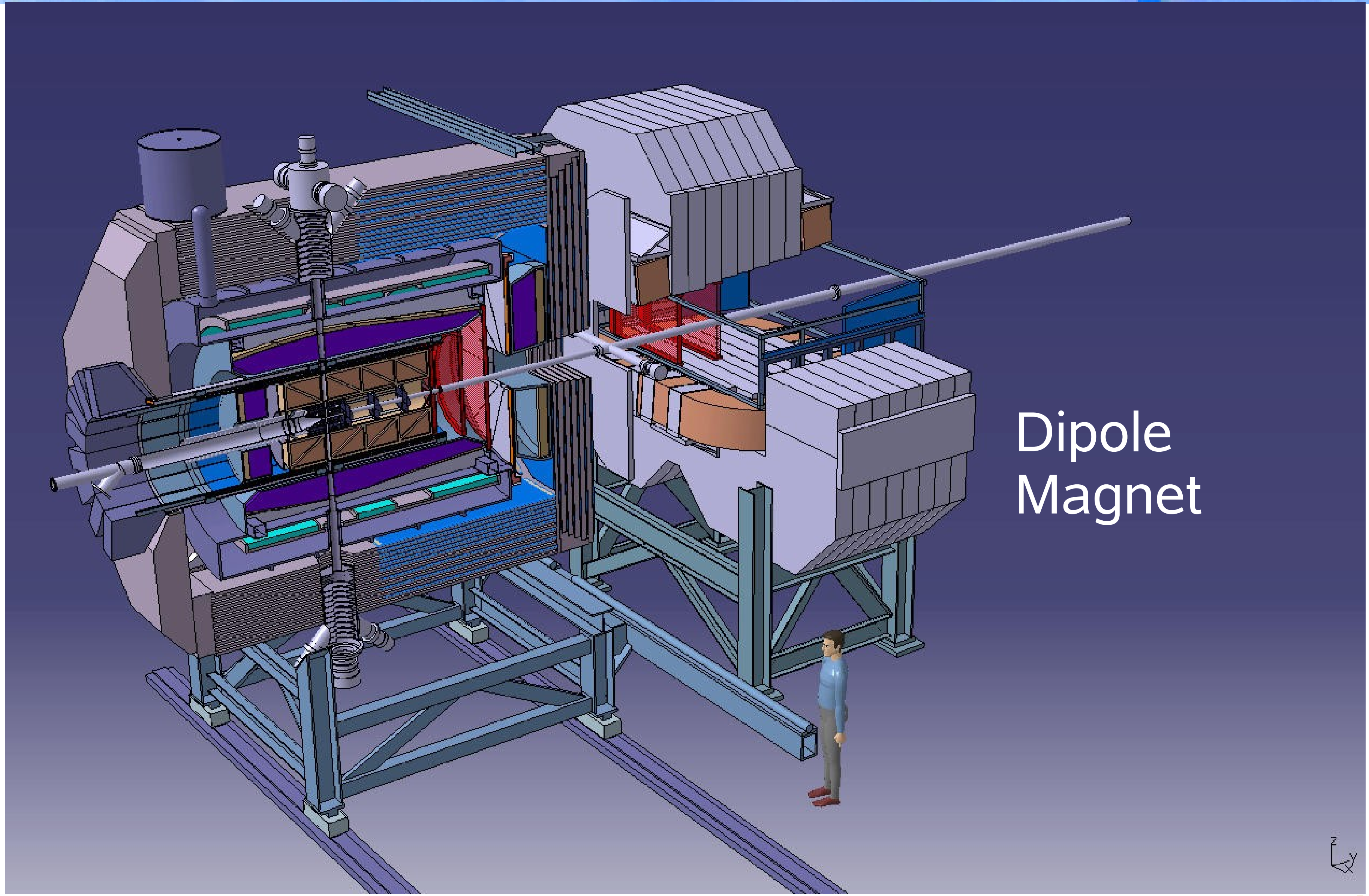
Overview of PANDA



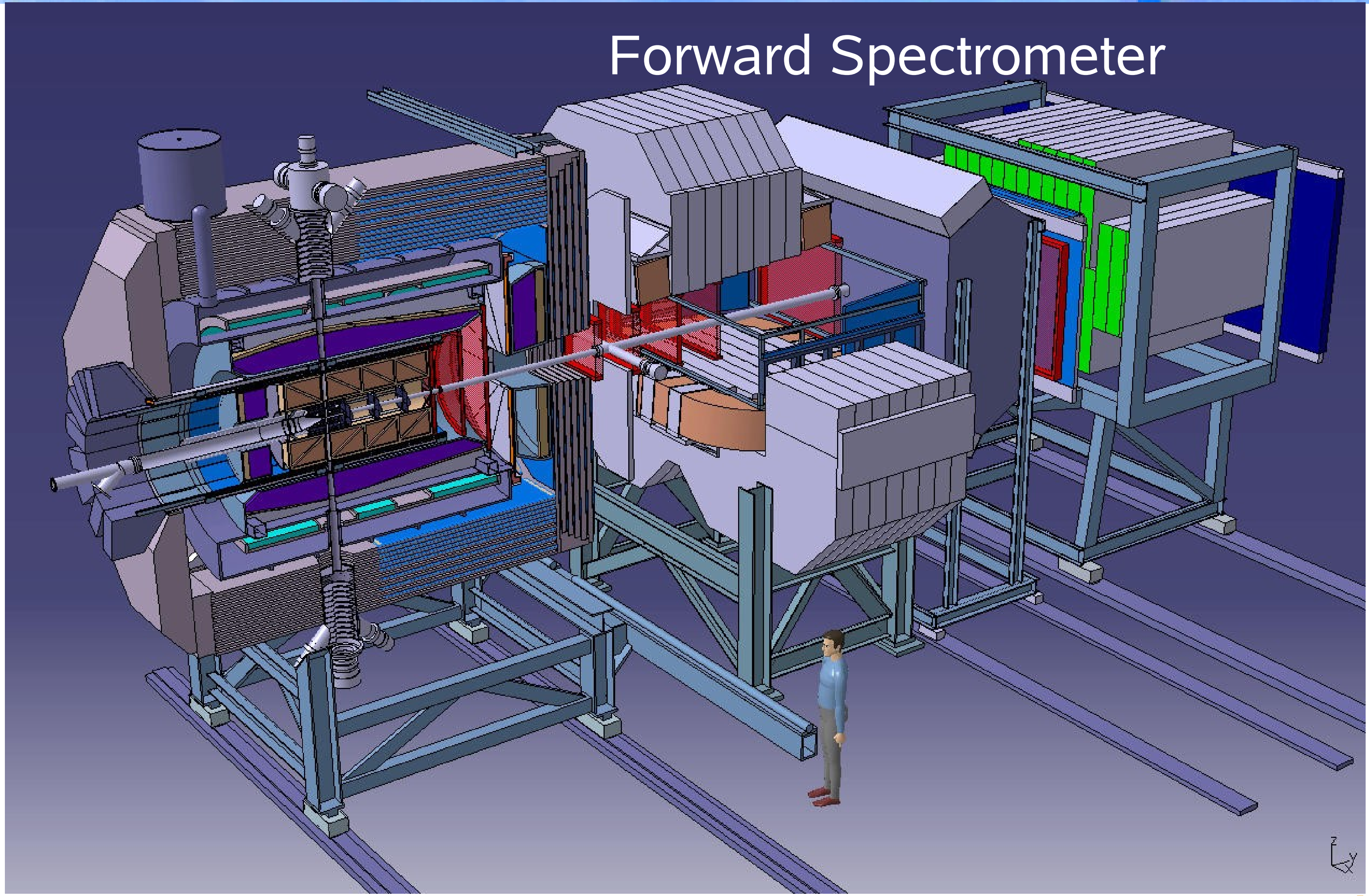
Overview of PANDA



Overview of PANDA



Overview of PANDA



Conclusions

Hadron physics sees a significant renaissance

- New observations probe our present understanding
- News on nucleon structure: HERMES, COMPASS, RHIC
- Future hadron facilities: GLUE-X, J-PARC, PANDA at FAIR

New methods broaden our horizon

- Theory: fundamental methods based on low energy QCD
- Computing: lattice gauge theory, coupled channels, PWA
- Experiments: precision detectors with flexible readout

PANDA will be a major player in hadron physics

- 4π acceptance, hermeticity, high resolution and statistics
- Versatile physics machine with full detection capabilities
- PANDA will be able to resolve many of today's puzzles

The PANDA Collaboration

About 400 physicists from 55 institutions in 17 countries

U Basel
IHEP Beijing
U Bochum
U Bonn
U & INFN Brescia
U & INFN Catania
Cracow JU,TU, IFJ PAN
GSI Darmstadt
TU Dresden
JINR Dubna
(LIT,LPP,VBLHE)
U Edinburgh
U Erlangen
NWU Evanston
U & INFN Ferrara
U Frankfurt
LNF-INFN Frascati
U & INFN Genova
U Glasgow
U Gießen
KVI Groningen
U Helsinki
IKP Jülich I + II
U Katowice
IMP Lanzhou
U Mainz
U & Politecnico & INFN
Milano
U Minsk
Moscow, ITEP & MPEI
TU München
U Münster
BINP Novosibirsk
LAL Orsay
U Pavia
IHEP Protvino
PNPI Gatchina
U of Silesia
U Stockholm
KTH Stockholm
U & INFN Torino
Politechnico di Torino
U Oriente, Torino
U & INFN Trieste
U Tübingen
U & TSL Uppsala
U Valencia
SMI Vienna
SINS Warsaw
U Warsaw