RUHR-UNIVERSITÄT BOCHUM

RUB

The PANDA Experiment at FAIR

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(on behalf of the PANDA Collaboration)

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p̄anda

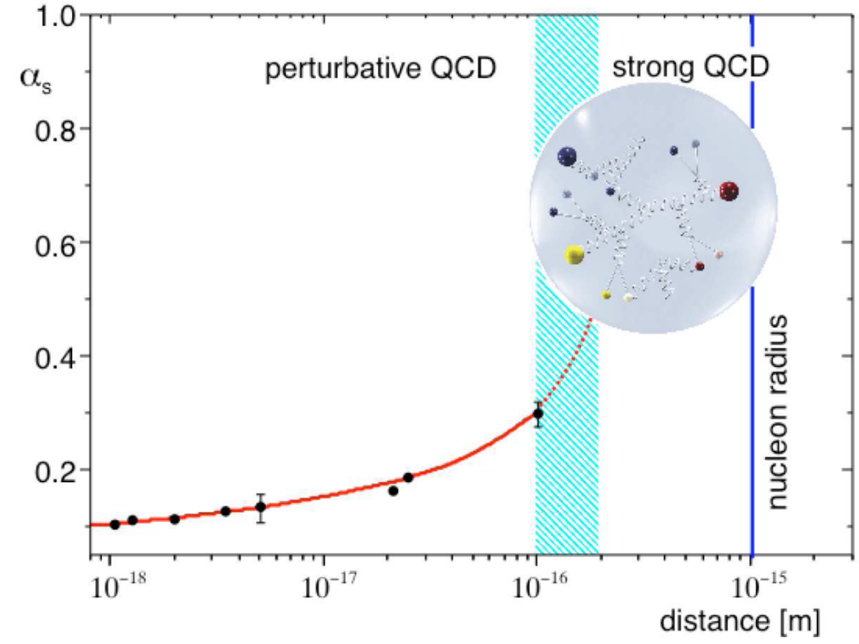
Physics Scope

- One of the open problems in the Standard Model is a full understanding of Quantum Chromodynamics (QCD)

- QCD well tested at high energies (perturbative regime)

- At low energies, QCD becomes a strongly coupled theory and many aspects are not understood

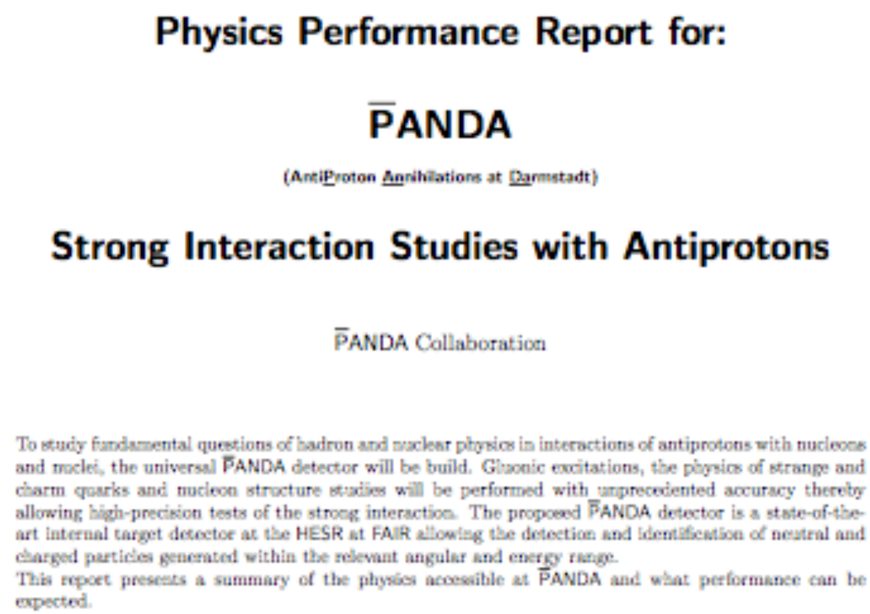
- PANDA will study p̄p and p̄A annihilations, providing unique and decisive measurements on a wide range of QCD aspects



PANDA Physics Program

- Hadron spectroscopy
  - Charmonium
  - Gluonic excitations
  - Open charm
  - (Multi-)strange baryons
- Nucleon structure
  - Electromagnetic formfactors
  - GPDs, TDAs
- Hadronic interactions
  - Hyperons (e.g. spin observables)
  - Hypernuclear physics
  - Hadrons in nuclear medium

$$\sqrt{s} = 2 \ldots 5.5\,\mathrm{GeV}$$



Physics Performance Report for:

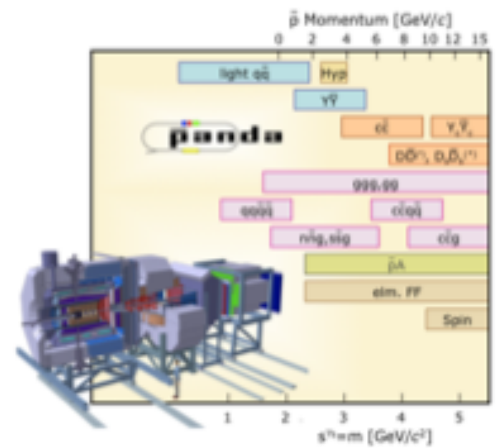
$\overline{\text{P}}$ANDA

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

$\overline{\text{P}}$ANDA Collaboration

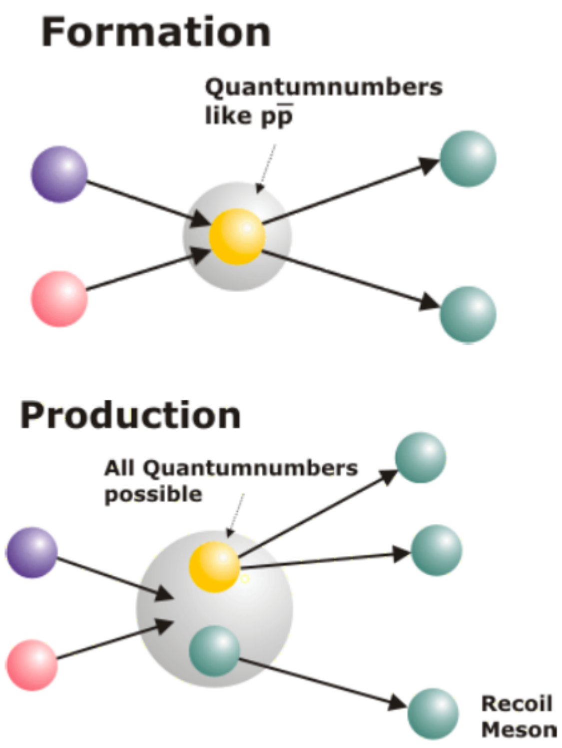
To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed $\overline{\text{P}}$ANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.
This report presents a summary of the physics accessible at $\overline{\text{P}}$ANDA and what performance can be expected.



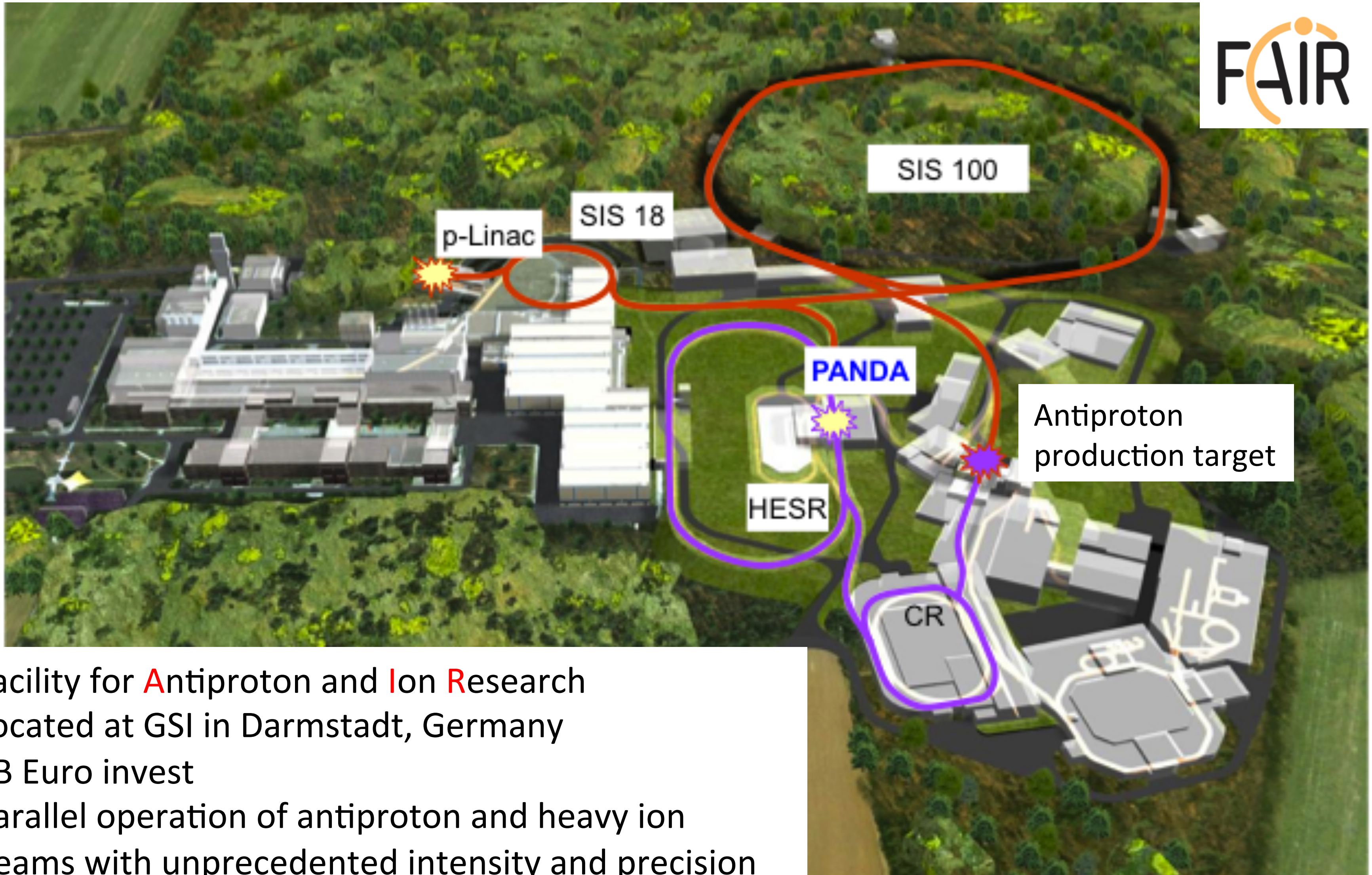
arXiv:0903.3905 [hep-ex]

Advantages of $\bar{p}p$ Annihilations

- Gluon-rich environment
- Direct formation of resonances with all non-exotic quantum numbers
  - excellent precision for mass and width measurements with cooled antiprotons
- Access to states with exotic and non-exotic quantum numbers via production reactions
- Versatility of physics program (if coupled with universal detector)
- Uniqueness of antiproton probe (no other facility in the corresponding energy range in the world)

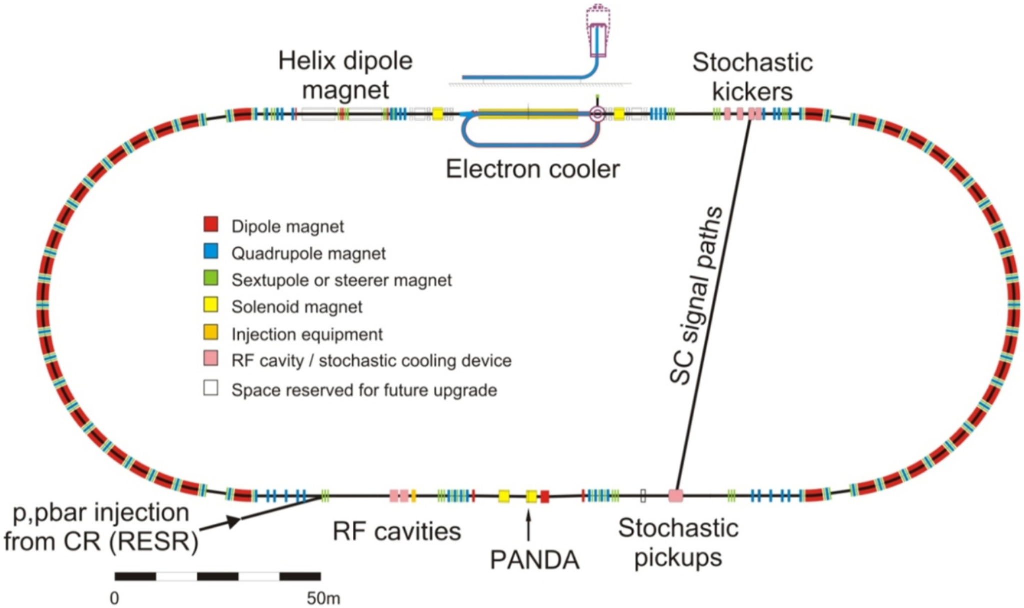


PANDA at FAIR



Facility for Antiproton and Ion Research
Located at GSI in Darmstadt, Germany
1B Euro invest
Parallel operation of antiproton and heavy ion beams with unprecedented intensity and precision

High Energy Storage Ring (HESR)



Antiproton momentum range

1.5 to 15 GeV/c

(E_{CMS} = 2 … 5.5 GeV)

Internal target ($\bar{p}p$, $\bar{p}A$)

cluster jet / pellet target

high density 4×10^{15} cm^{-2}

High luminosity mode

Luminosity: L ~ 10^{32} $cm^{-2}s^{-1}$

Stochastic cooling: $\Delta p/p \sim 10^{-4}$

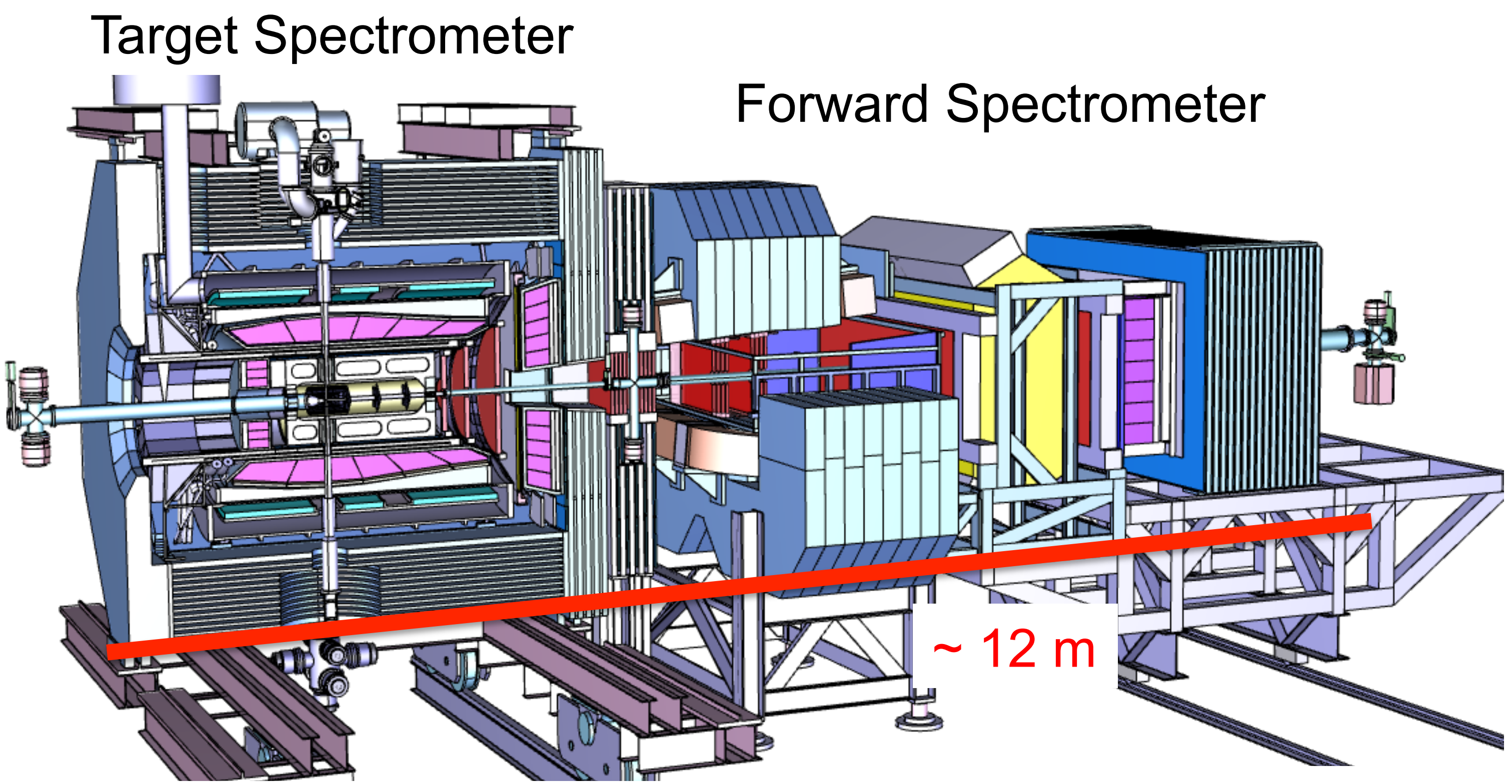
High resolution mode, p($\bar{p}$) < 9 GeV/c

Luminosity: L ~ 10^{31} $cm^{-2}s^{-1}$

Additional electron cooling: $\Delta p/p < 5 \times 10^{-5}$

Modularized Start Version of FAIR: L ~ 10^{31} $cm^{-2}s^{-1}$

The PANDA Detector



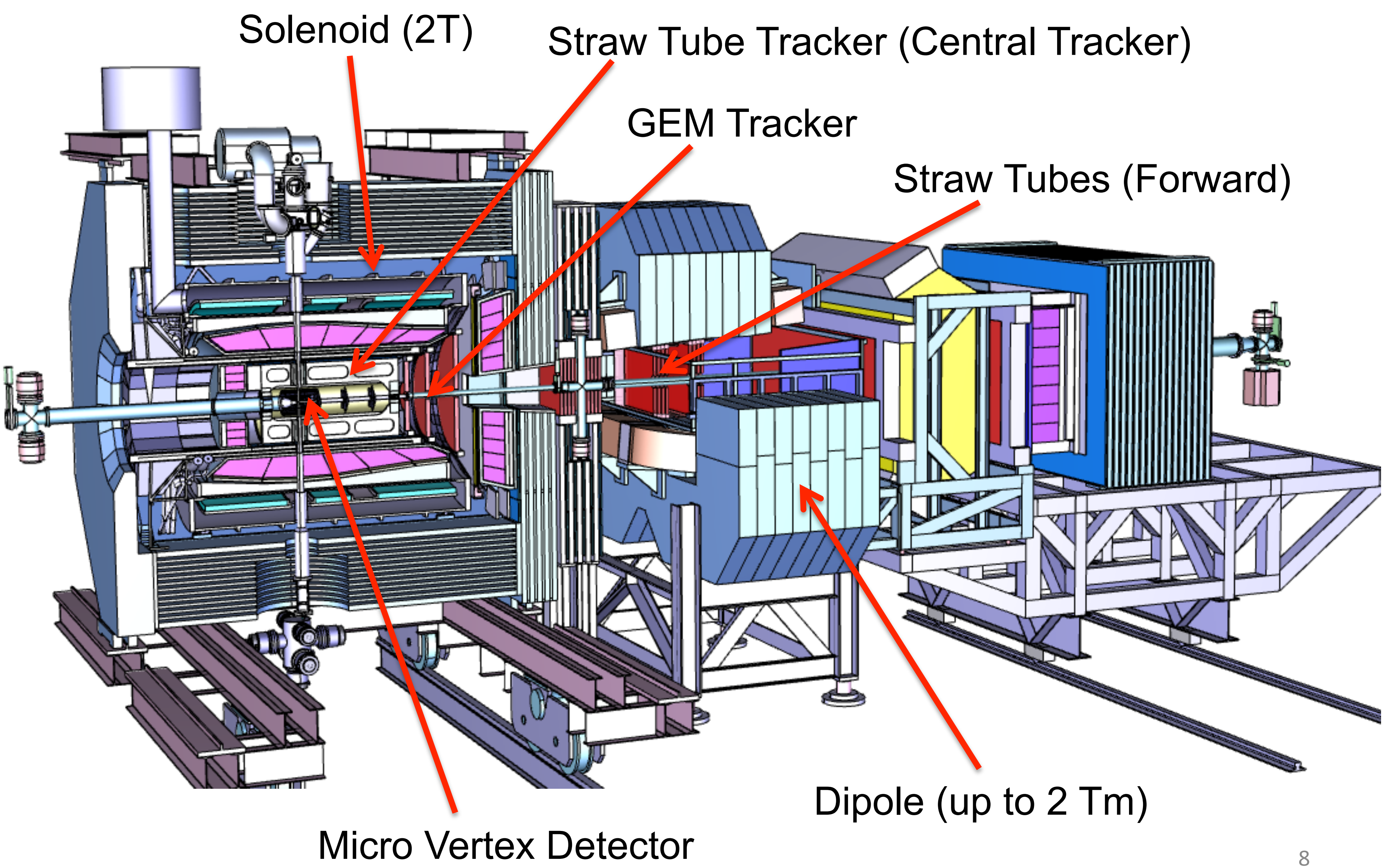
Exclusive measurements
almost 4π coverage
target and forward spectrometer

High event rates [10^7/s]
sophisticated online processing
detection of rare decay modes

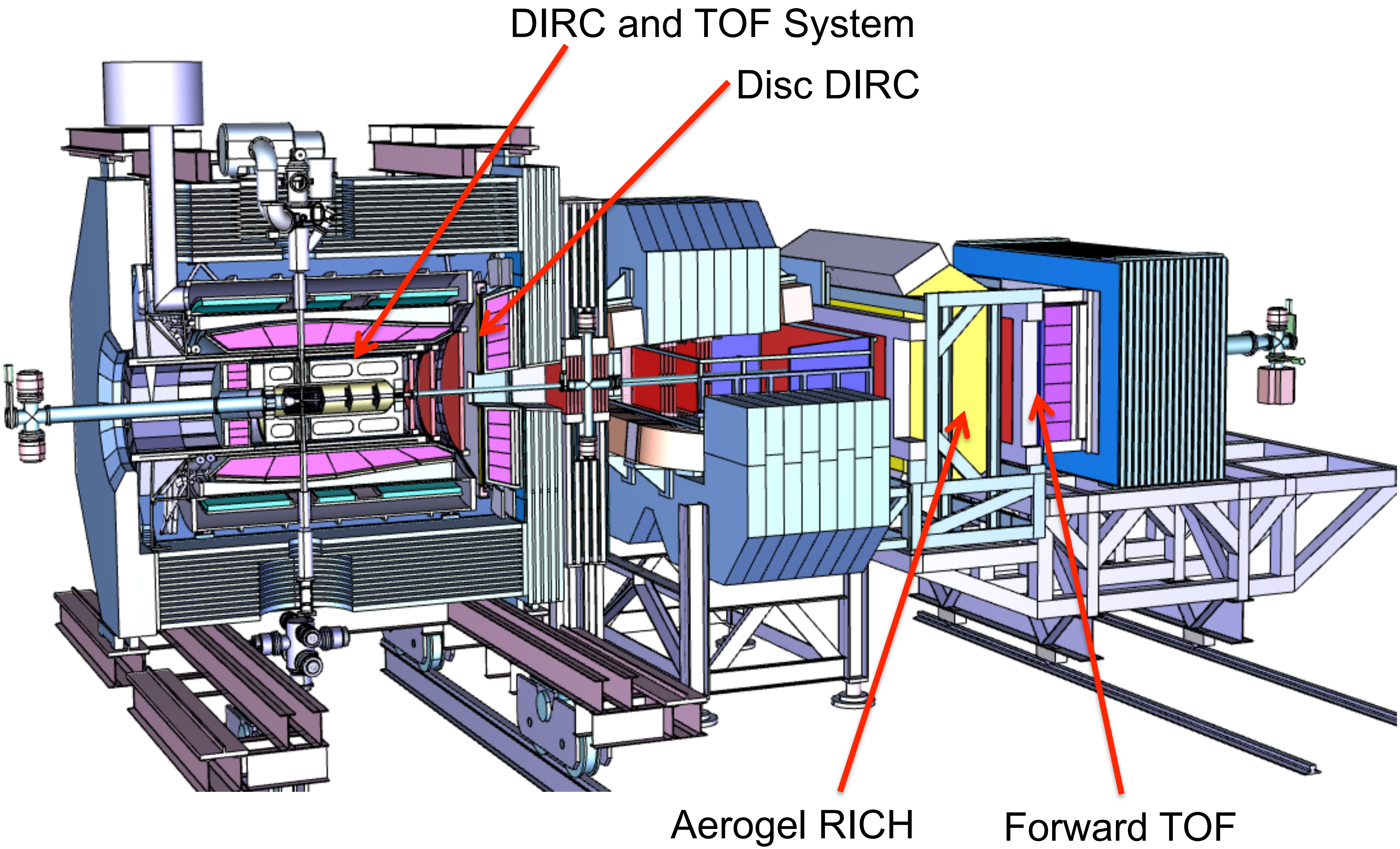
Charged particle tracking [p<10 GeV/c]
good momentum / vertex resolution
good PID capabilities

Photon detection [E=0.02-10 GeV]
excellent energy / angular resolution
detection of low energetic photons

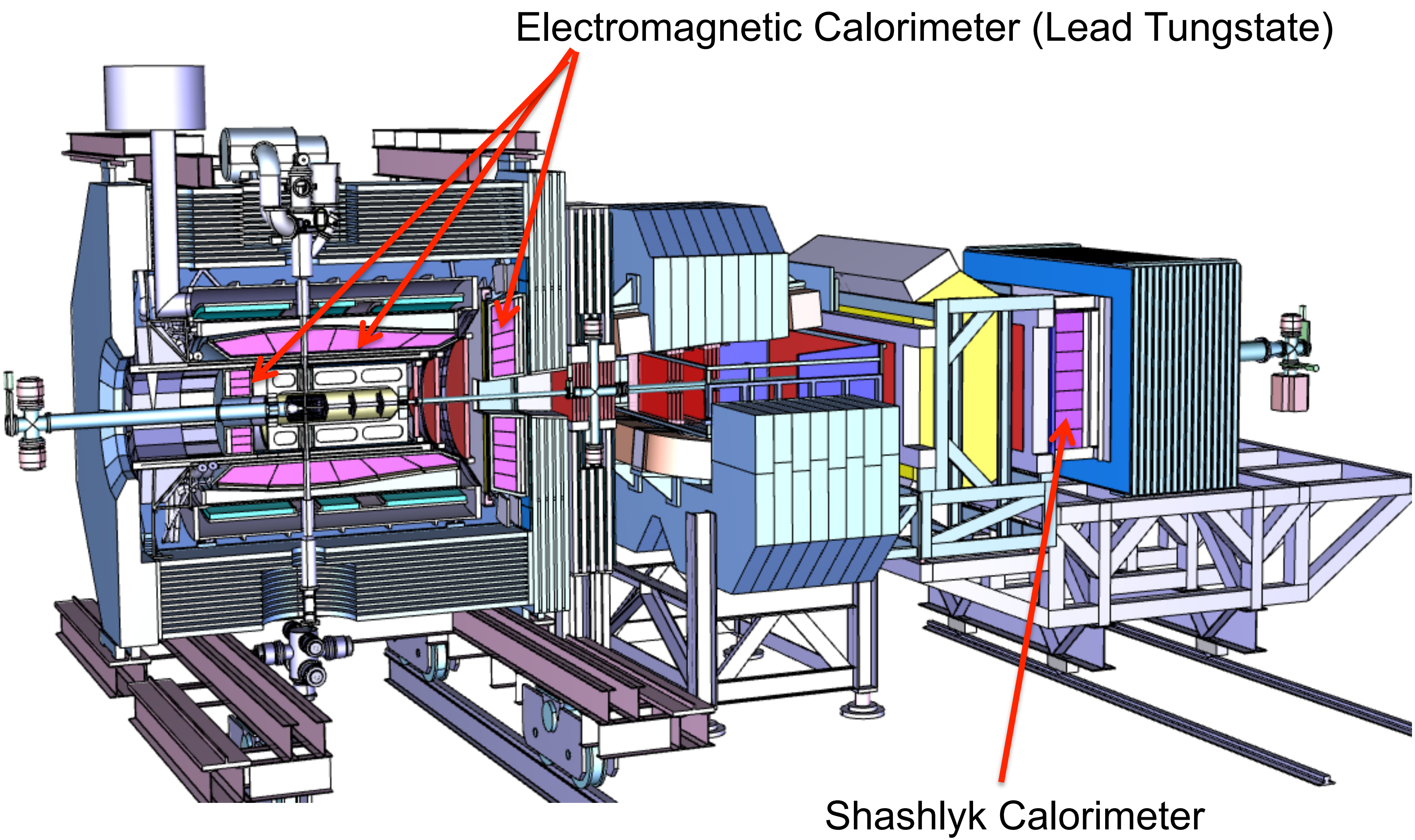
The PANDA Detector (Tracking System)



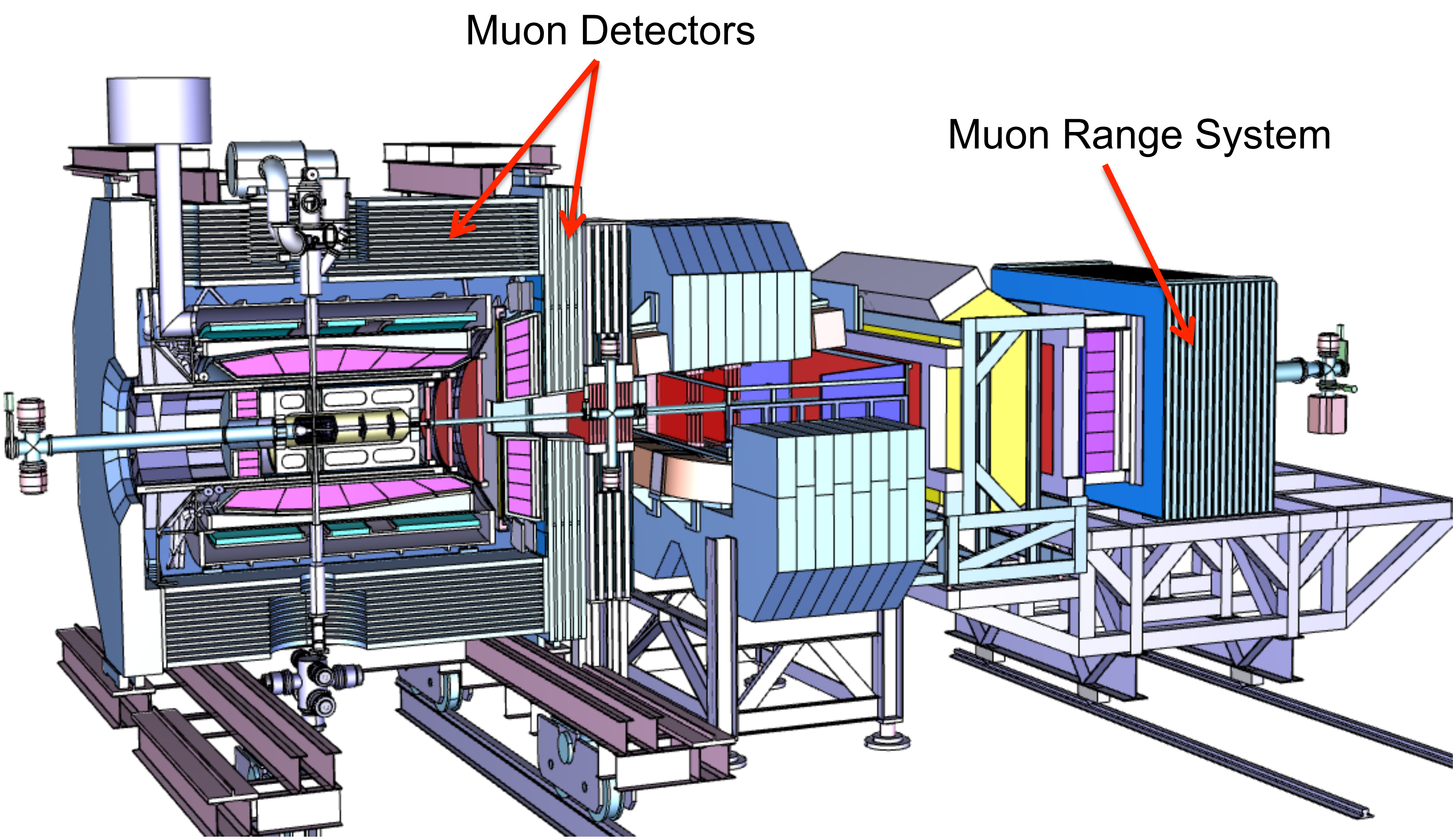
The PANDA Detector (PID Detectors)



The PANDA Detector (Em. Calorimetry)



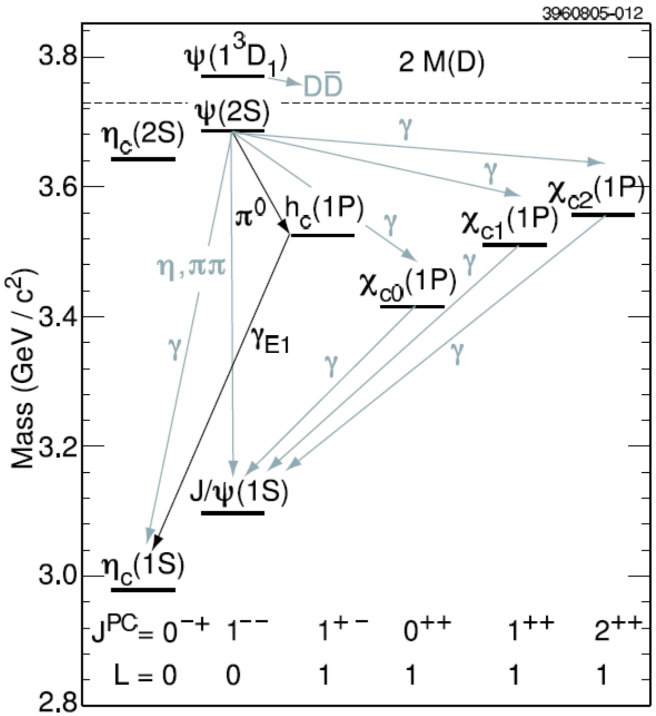
The PANDA Detector (Muon Detectors)

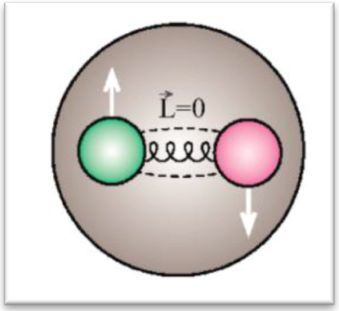


Hadron Spectroscopy

Charmonium Spectroscopy

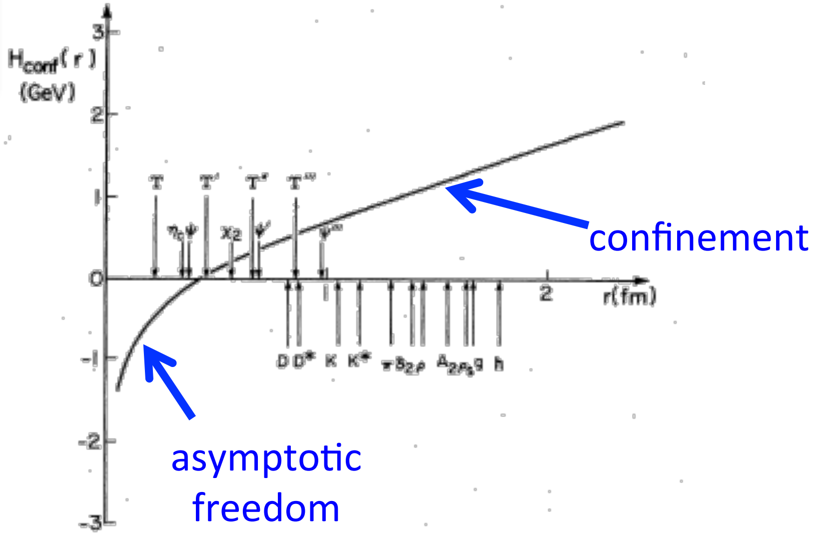
Study of charmonium states plays a crucial role in understanding QCD





non relativistic: $v_c^2 \sim 0.3$

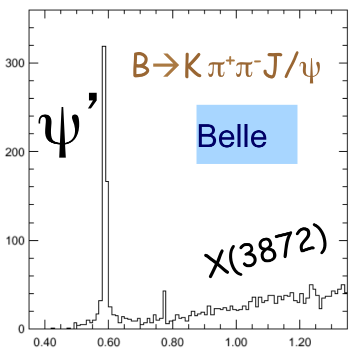
mass scale is perturbative: $m_c \sim 1.5$ GeV



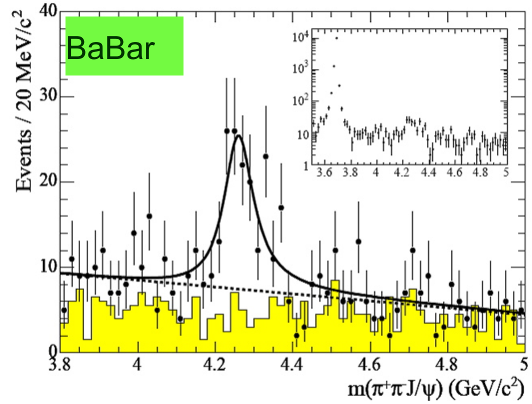
Ideal probe of (de)confinement and the transition regime between perturbative and non-perturbative QCD

Exotic Charmonium: X, Y, Z

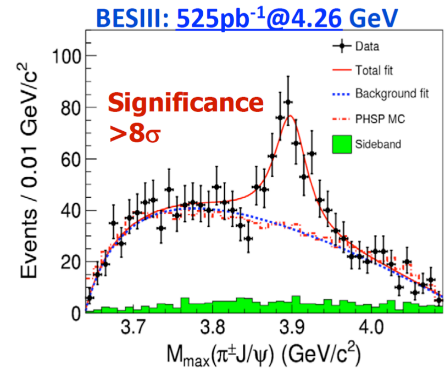
X(3872)



Y(4260)



Zc(3900) at BESIII



Understanding the nature of these states:

- systematic approach
- map out completely the spectrum
- high precision measurements
- consistent experimental tools and methods

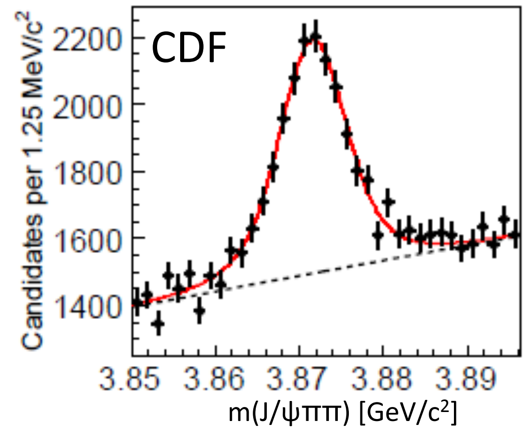
PANDA will be unique in achieving this !

The *mysterious* X(3872)

- Seen by 7 experiments in 6 channels
  ($J/\psi\rho$, $J/\psi\omega$, $J/\psi\gamma$, $\psi'\gamma$, $D\bar{D}\pi^0$, $D^*\bar{D}$)

- $J^{PC} = 1^{++}$ → natural candidate for $\chi_{c1}(2P)$

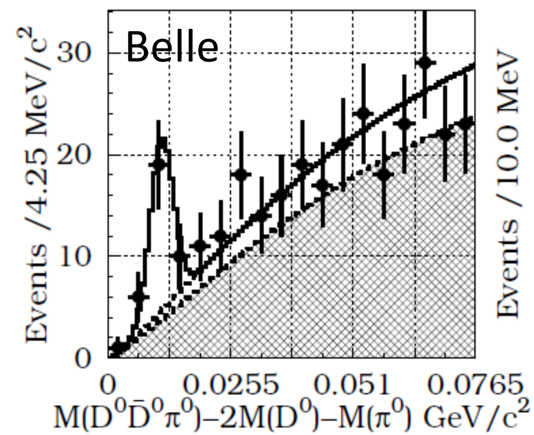
[arXiv:0906.5218]



Oddities

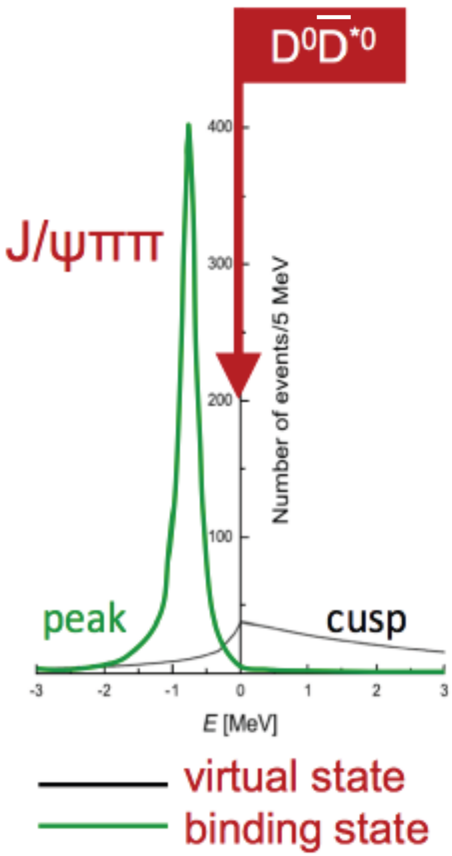
- 50 - 100 MeV to light for $\chi_{c1}(2P)$
- Extremly narrow: $\Gamma < 1.2$ MeV
- Extremly close to $D^0\bar{D}^{0*}$ threshold:
  $m_X - m_{D\bar{D}^*} = 0.11 \pm 0.21$ MeV
  → Molecule ?

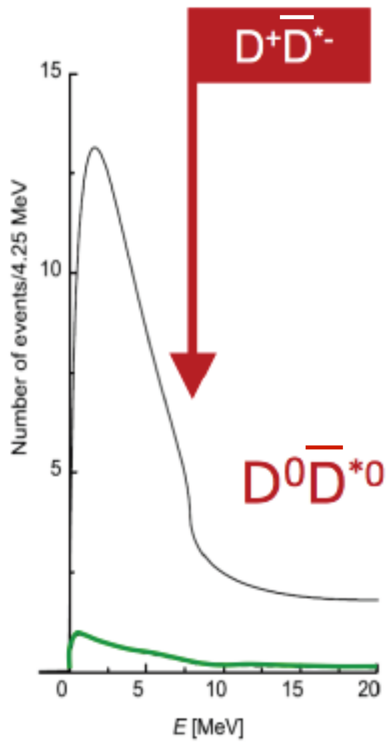
[arXiv:hep-ex/0606055]



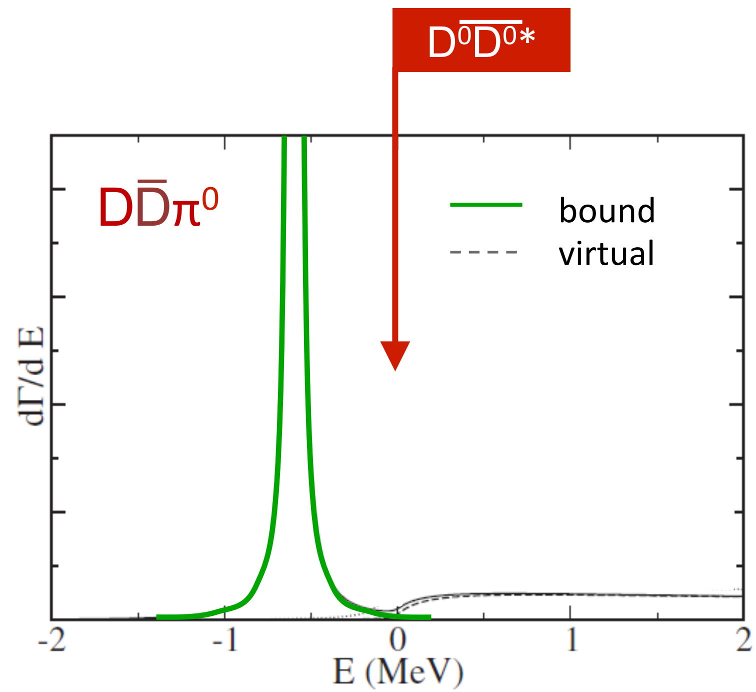
X(3872) Lineshape

To clarify nature: line shape + width measurements essential





[Hanhart, PRD76 (2007) 034007]



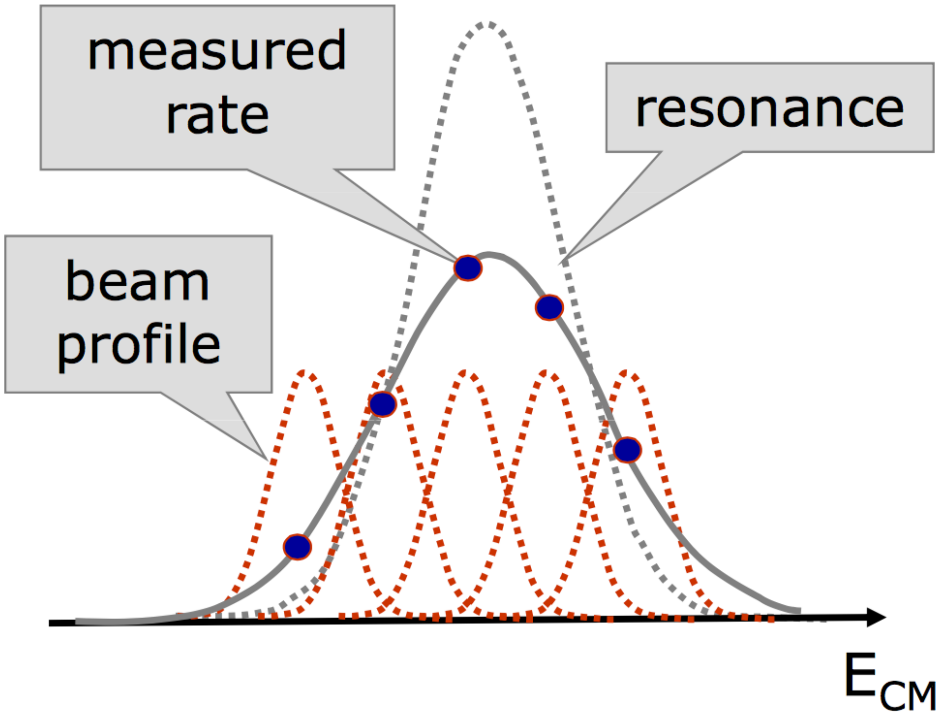
[Braaten, PRD77 (2008) 014029]

→ Lineshape only accessible at PANDA

Resonance Scans

Cooled antiproton beam with high momentum resolution

Precise measurement of masses and widths of resonances
- only dependent on beam resolution (HESR: <5x10^{-5})



Resonance Scan – An Example: χ_{c1}

Production:

$$e^+e^- \to \psi' \to \gamma\chi_{1,2} \to \gamma\left(\gamma J/\psi\right) \to \gamma\gamma e^+e^-$$

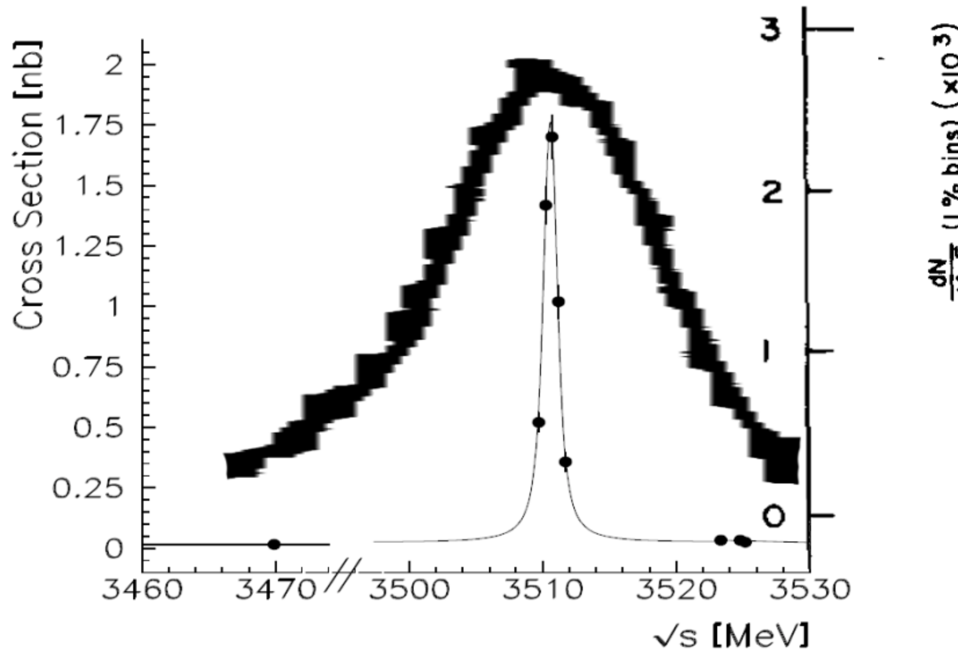
- Invariant mass reconstruction depends on the detector resolution ≈ 10 MeV

Formation:

$$\bar{p}p \to \chi_{1,2} \to \gamma J/\psi \to \gamma e^+e^-$$

- Resonance scan:
  → mass resolution depends on the beam resolution

E760/835@Fermilab ≈ 240 keV
PANDA@FAIR ≈ 50 keV



Gaiser et al., Phys. Rev. D34 (1986) 711:
CrystalBall (SLAC): 3512.3 ± 4 MeV/c^2
Andreotti et al., Nucl. Phys. B717 (2005) 34-47:
E835 (Fermilab): 3510.641 ± 0.074 MeV/c^2

X(3872) Scan at PANDA

PANDA MC simulation study

Input parameters:

m = 3.872 GeV/c^2

Γ = 100 keV

$\bar{p}p \rightarrow X(3872)$ (σ = 50 nb)

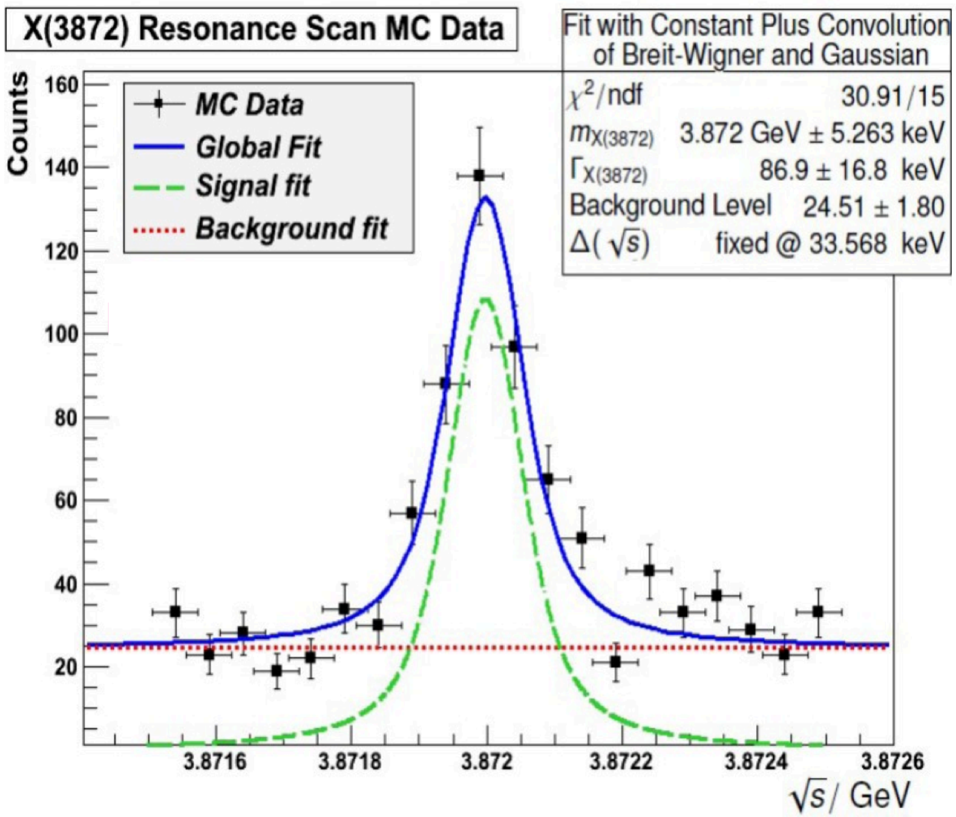
X(3872) → $J/\psi\pi^+\pi^-$

Background from $\pi^+\pi^-\pi^+\pi^-$

reduction factor $>10^6$ achieved

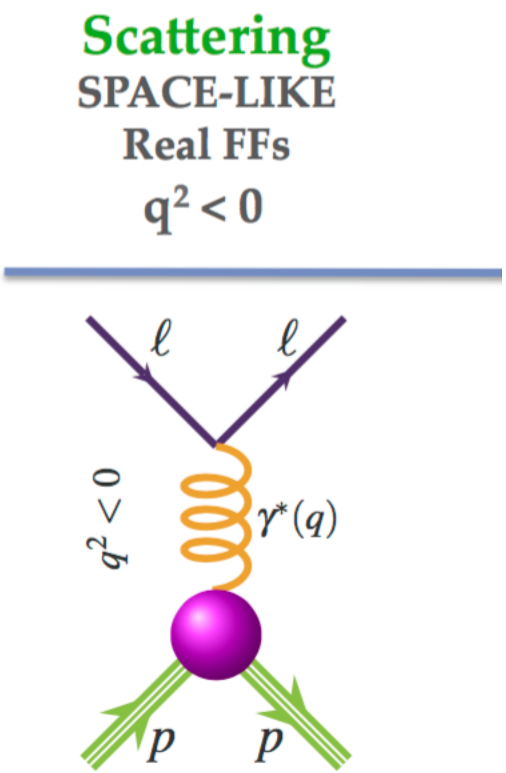
Mass uncertainty ~ 5 keV/c^2

Sensitive to widths of ~100 keV



Nucleon Structure

Electromagnetic Formfactors of the Proton



Internal structure and dynamics of the proton

Parameterization of hadronic vertex with two form factors

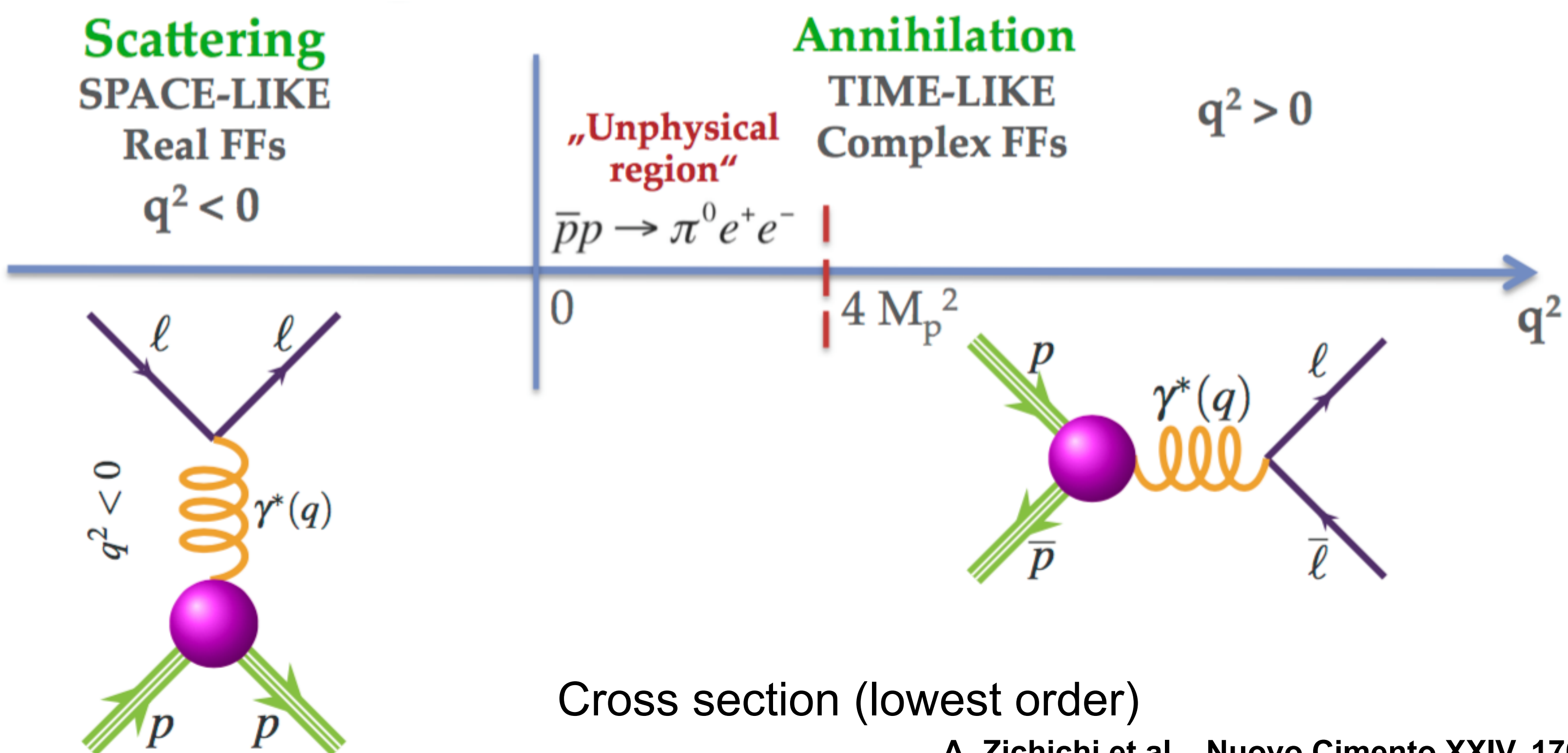
$$\Gamma^{\mu} = F_1(q^2)\,\gamma^{\mu} + \frac{i\kappa}{2m_p} F_2(q^2)\,\sigma^{\mu\nu} q_{\nu}$$

Sachs form factors:

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m_p^2} F_2(q^2), \quad G_E(0) = 1$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2), \quad G_M(0) = \mu_p$$

Electromagnetic Formfactors of the Proton



Cross section (lowest order)

A. Zichichi et al. , Nuovo Cimento XXIV, 170 (1962)

$$\frac{d\sigma}{d\cos\theta^*} = \frac{\pi\alpha^2}{2s}\,\frac{1}{\beta}\left\{(1+\cos^2\theta^*)\,|G_M|^2 + \frac{1}{\tau}(1-\cos^2\theta^*)\,|G_E|^2\right\}$$

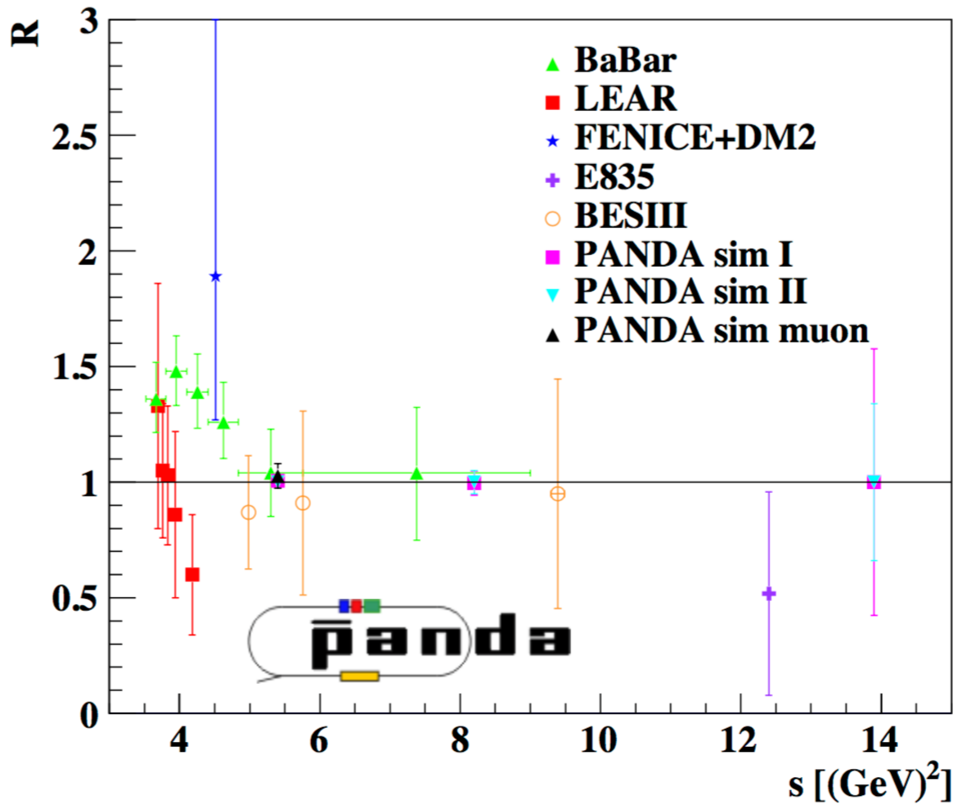
$$= \frac{\pi\alpha^2}{2s\tau}\,\frac{1}{\beta}\,|G_M|^2\left\{\tau\,(1+\cos^2\theta^*) + (1-\cos^2\theta^*)\frac{|G_E|^2}{|G_M|^2}\right\}$$

$$\tau = q^2/4M^2$$

Scarce data with low statistics for individual measurement of $|G_E|$ and $|G_M|$

Timelike Electromagnetic Proton FFs

PANDA MC simulation studies for
$\bar{p}p \rightarrow e^+e^-$ and $\bar{p}p \rightarrow \mu^+\mu^-$ for R=1
integrated luminosity: 2/fb



Measurement of effective form factor over wide q^2 range (30 GeV^2)

Individual measurement of $|G_E|$ and $|G_M|$ and their ratio R

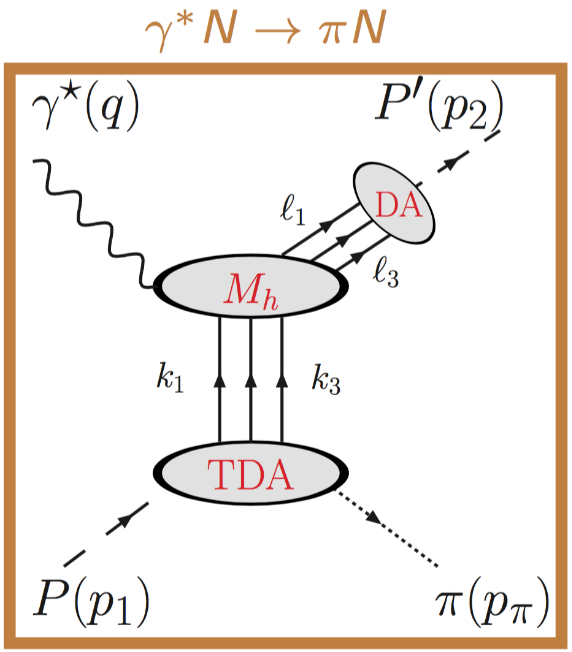
First measurement of form factors with muons

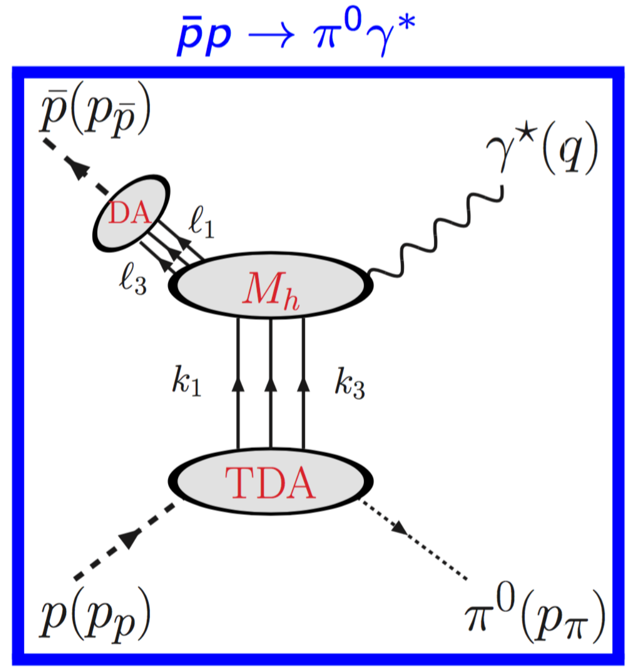
Measurement of form factors in unphysical region $\bar{p}p \rightarrow \pi^0 e^+e^-$

Longer range goal: measurement of phase of $|G_E|$ and $|G_M|$ via polarisation observables

Transition Distribution Amplitudes (TDAs)

Large q^2,
small u





Large q^2,
small t or u

$\bar{p}p \to e^+e^-\pi^0, e^+e^-\rho^0, e^+e^-\eta, \ldots$

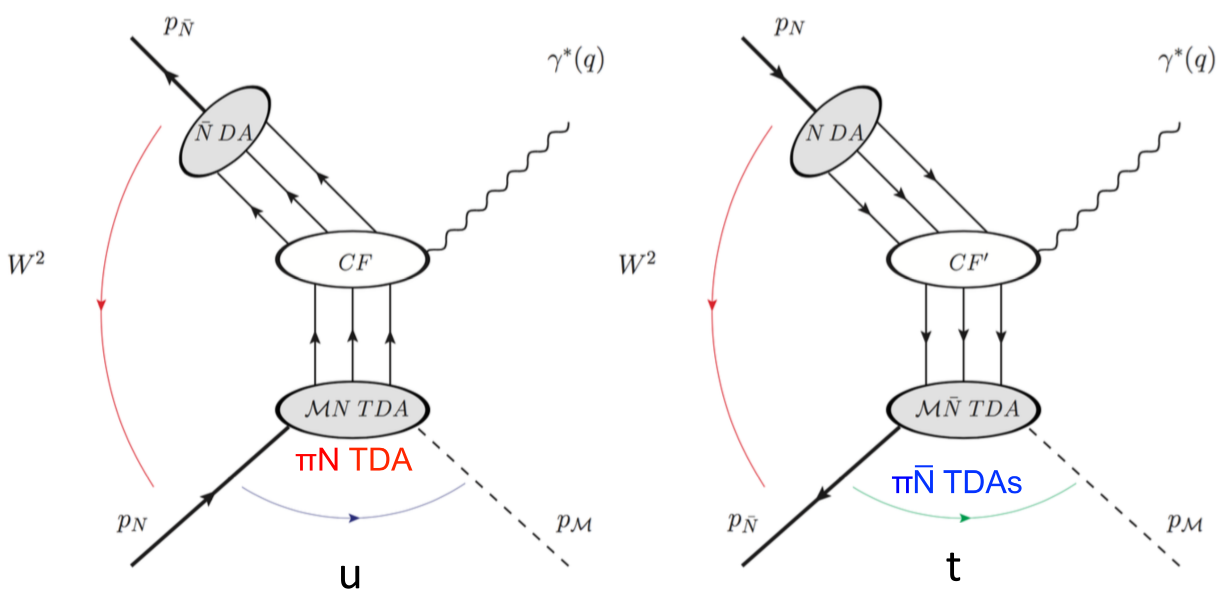
- TDAs occur in factorization description of various interactions
  - describe the transition between two particles
  - Fourier transforms of non-perturbative hadronic matrix elements
- Explore pionic components in the nucleon wave function
- Universality: The same TDA could be measured in different kinematics / reactions
- Test of factorization

TDAs in the timelike region
only accessible at PANDA

Transition Distribution Amplitudes (TDAs)

$\bar{p}p \rightarrow \pi^0\gamma^*$

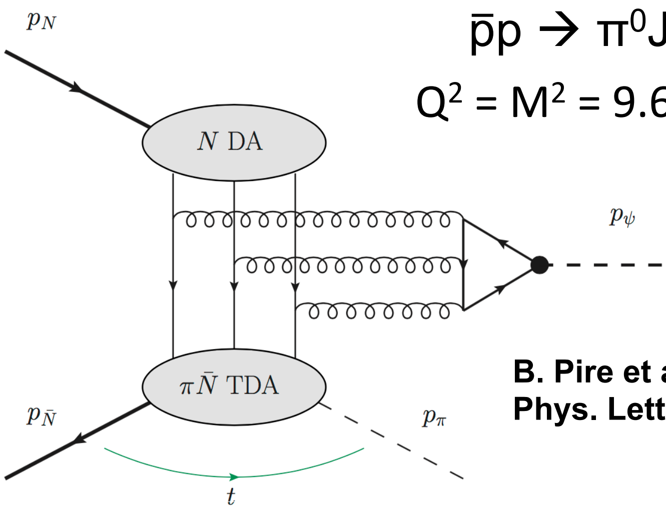
J. P. Lansberg et al., Phys Rev D 76, 111502(R) (2007)



For large Q^2:
Backward kinematics (small |u|), π^0 in direction of nucleon probes πN TDAs
Forward kinematics (small |t|), π^0 in direction of anti-nucleon probes π$\bar{N}$ TDAs

→ Test of matter – antimatter symmetry

Transition Distribution Amplitudes (TDAs)

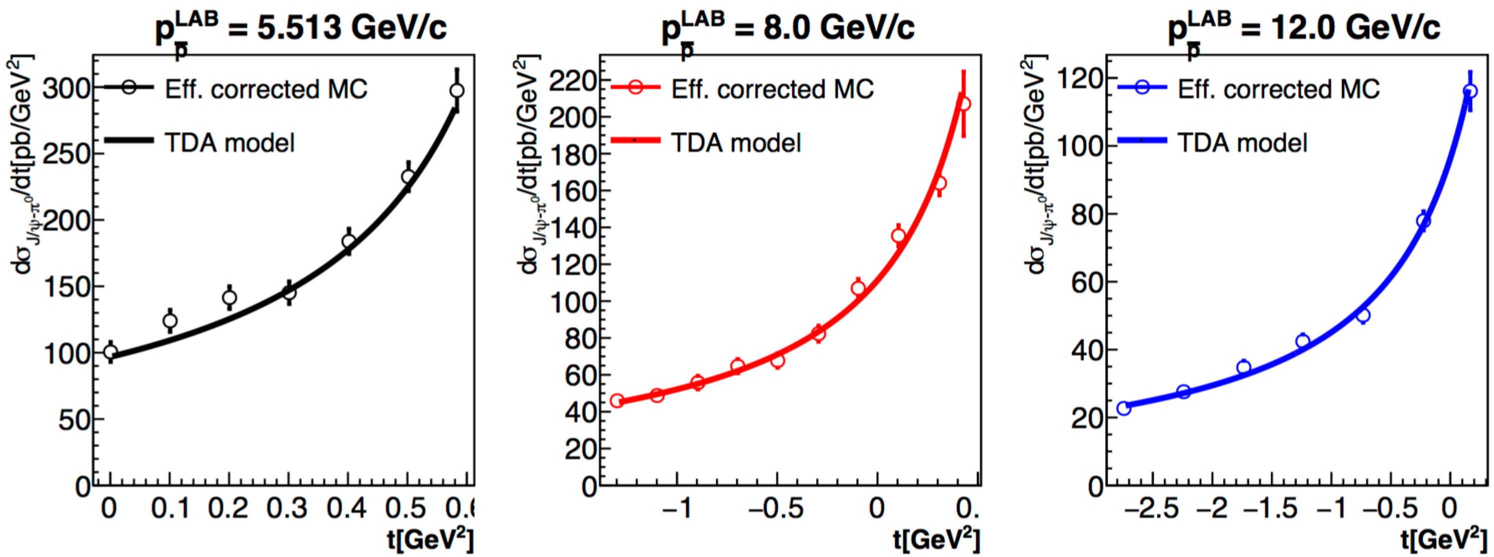


$\bar{p}p \rightarrow \pi^0 J/\psi$

$Q^2 = M^2 = 9.6\ GeV^2$

B. Pire et al., Phys. Lett. B. 724 99-107 (2013)

PANDA MC simulation study
2/fb at each energy point
→ sensitive to TDA model predictions



Summary / Outlook

- PANDA experimental program is covering the three pillars of hadron physics
  - hadron spectroscopy
  - hadron structure
  - hadron interaction

- PANDA is unique in combining the potential for discoveries with the ability to carry out precise and systematic measurements

- The collaboration, detector developments and funding are in good shape and we are on track to produce excellent physics results at the beginning of the next decade