# PANDA at FAIR - Using anti-protons to study QCD

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on behalf of the PANDA collaboration

DSpin Workshop 2007, Dubna

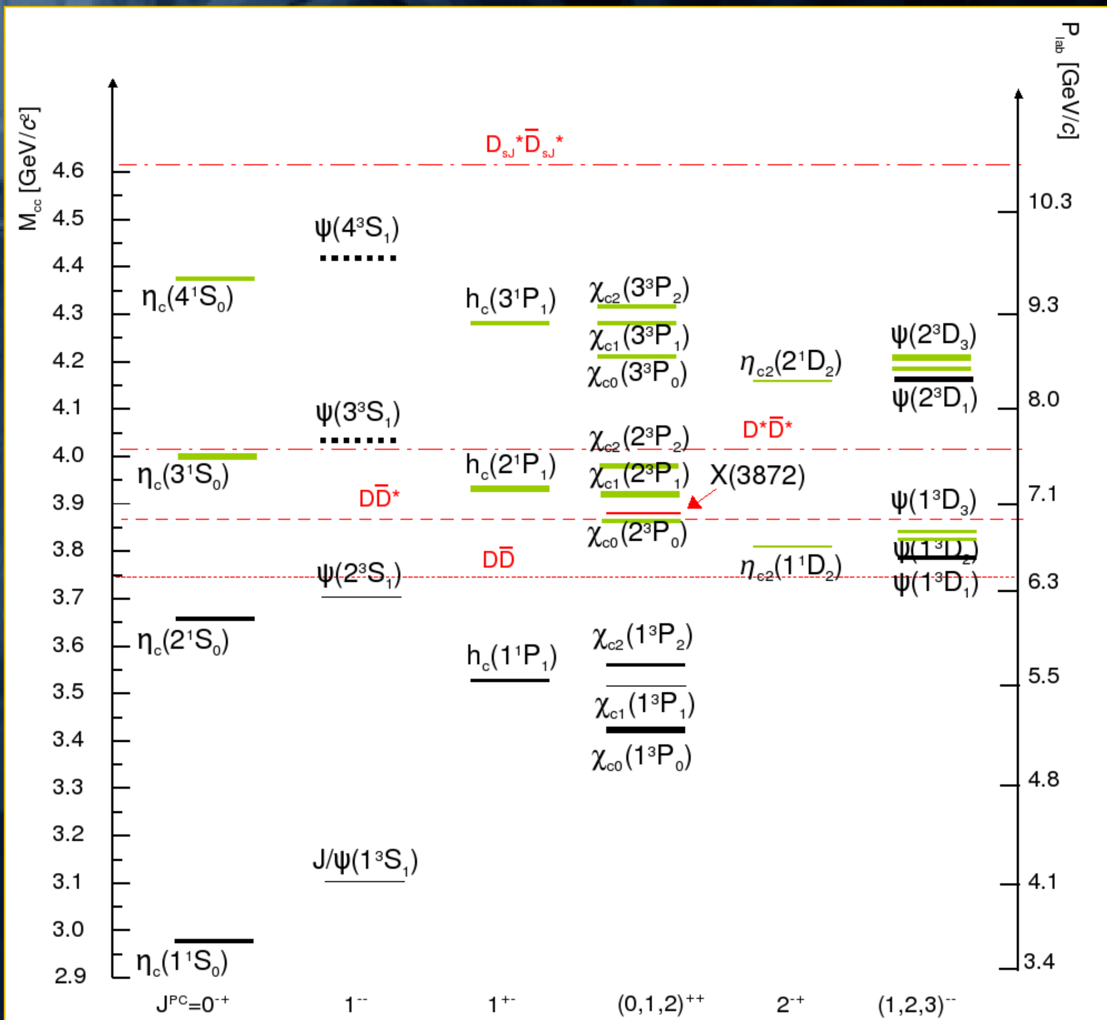
# Overview

- Charmonium Spectroscopy
- Search for Hybrids and Exotics
- Nucleon Structure
  - Drell-Yan
  - Hard exclusive processes
- FAIR
- PANDA

# Charmonium Spectroscopy

- Charmonium spectroscopy probes long range QCD potential (non-rel.)
- Study effective degrees of freedom
- Study spin effects on QCD potential
- Search for new resonances
  - Terra incognita above DD threshold
  - Surprises in the open charm sector

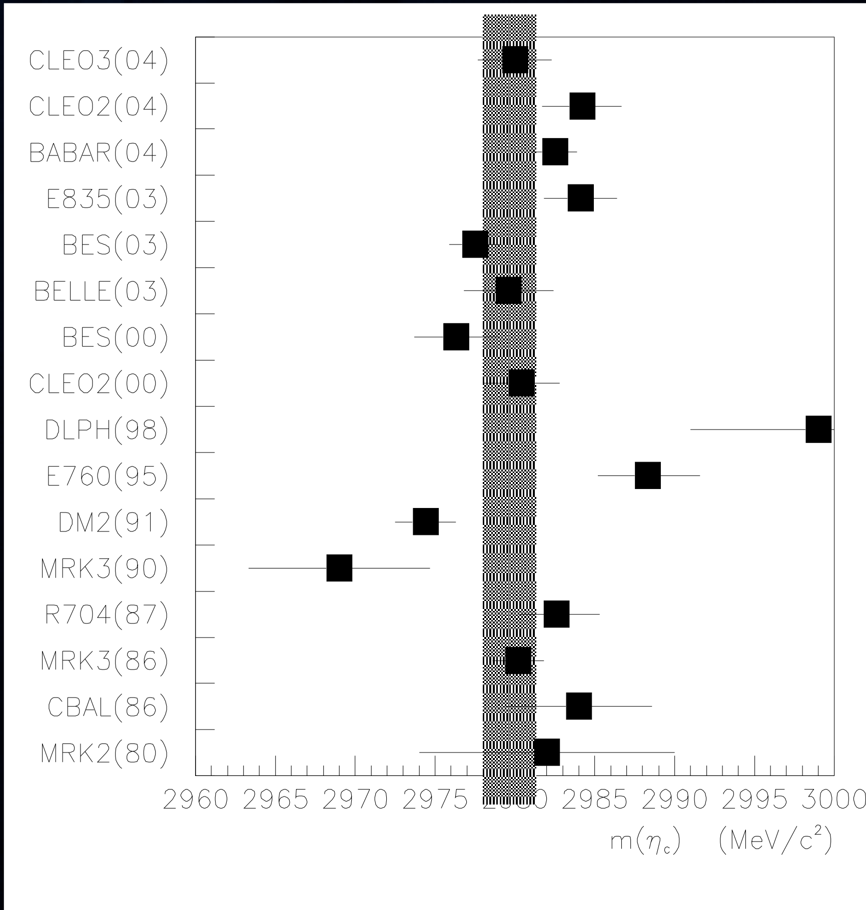
# Exploring the QCD potential - Charmonium




- Inconsistency in $\eta_c$ mass and width
- $h_c$ seen with poor statistics
- States above DD threshold are not well established
- New resonances

# Charmonium ground state $\eta_c$

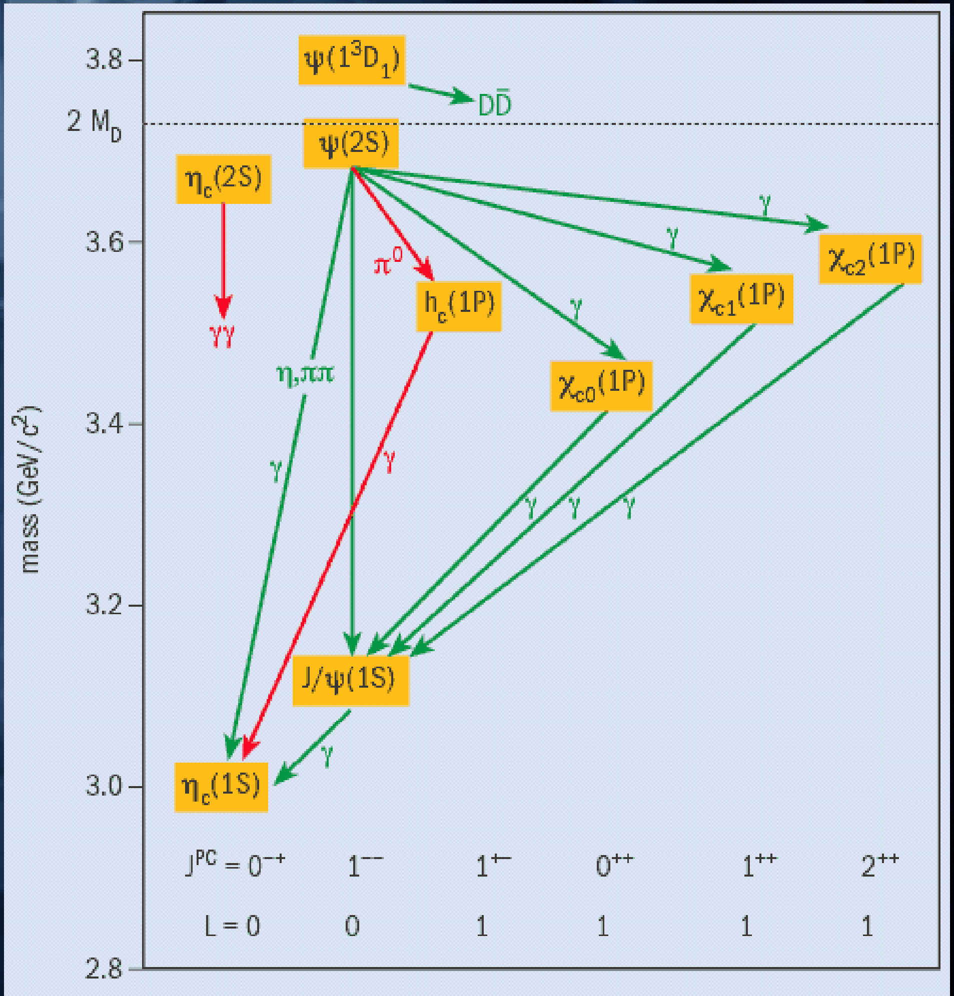
- Potential models rely heavily on the mass difference $M(J/\psi)-M(\eta_c)$ to fit the charmonium spectrum
- Many measurements of mass and $\eta_c$ width
  - Errors are still relatively large
  - Internal consistency of measurements is rather poor
- Large value of $\eta_c$ width difficult to explain in simple quark models
- Narrow width in $\gamma\gamma$-decay channel
- Decay to two photons provides estimate of $\alpha_s$




$M(\eta_c) = 2979.8 \pm 1.2$ MeV/c$^2$

$\Gamma(\eta_c) = 26.5 \pm 3.5$ MeV

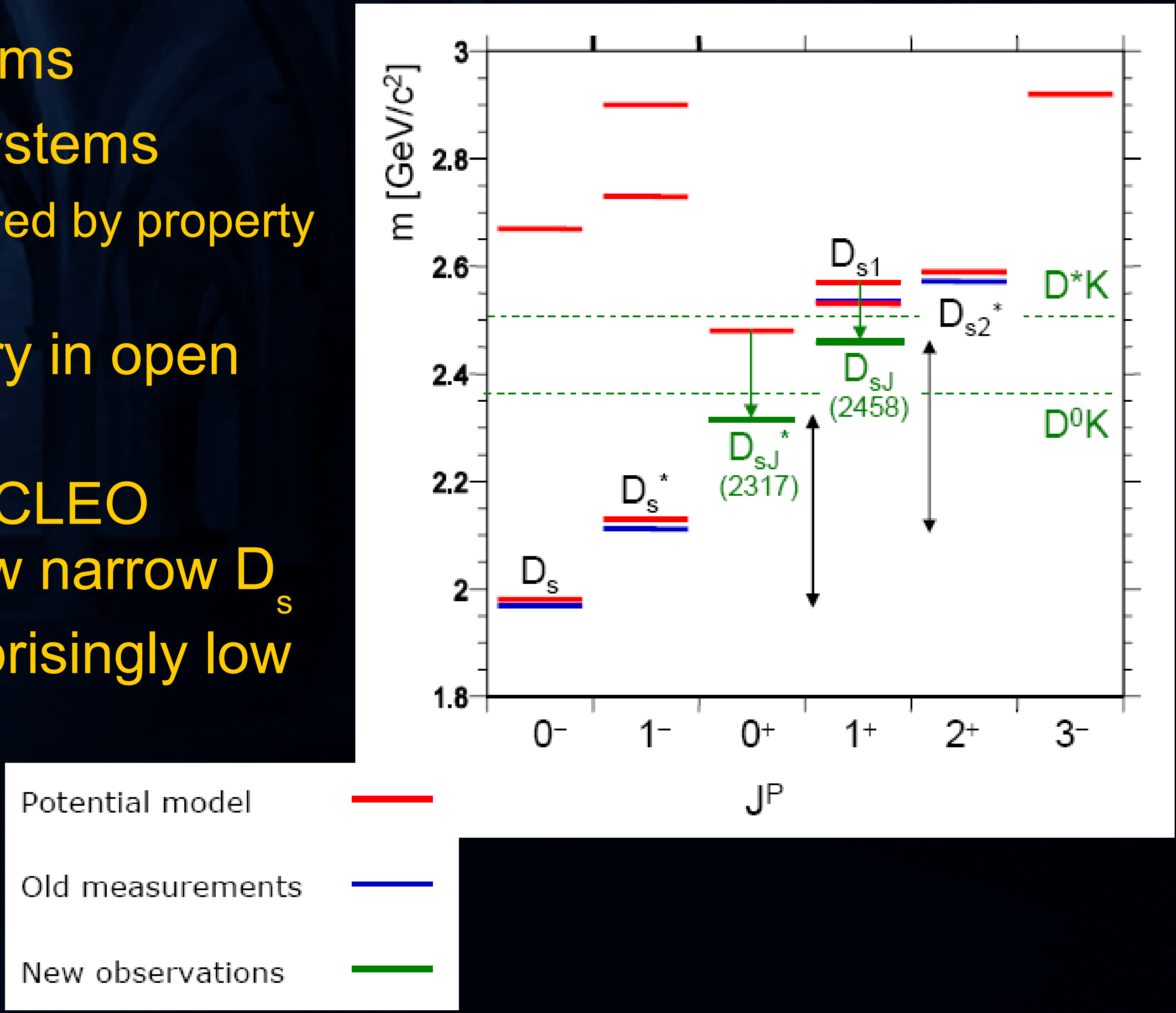
# Spin effects in Charmonium - $h_c$




- $h_c$ is a spin-singlet
- Splitting between singlet and triplet given by spin-spin interaction
  - spin-dependent component of potential
- Comparison of the $h_c$ mass with the masses of the triplet P states ($\chi_{cJ}$) measures the deviation from pure one-gluon (1/r) exchange.
- Statistics poor on mass and width

# Open Charm

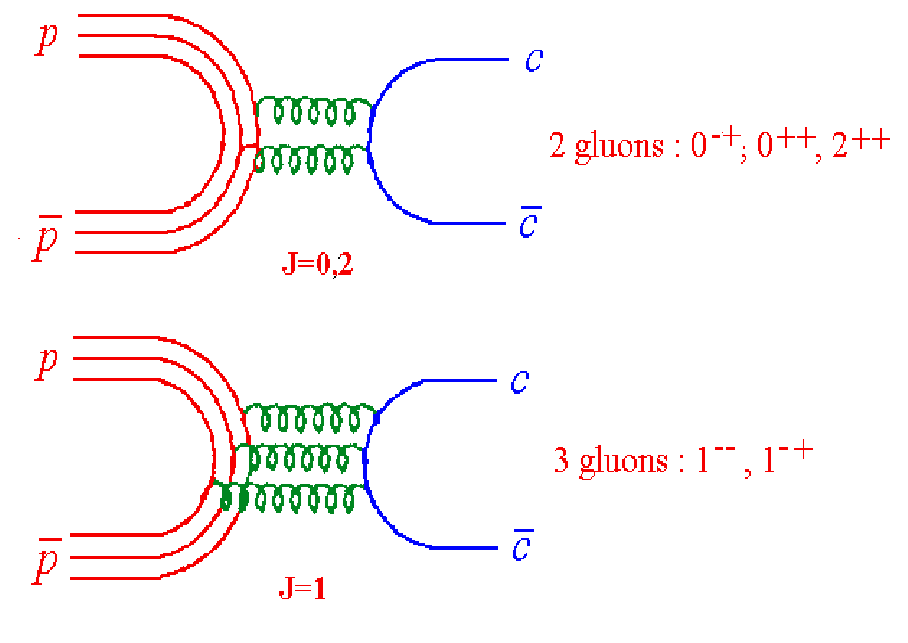
- Heavy-light systems
- In Heavy-Light systems
  - like H-atom ordered by property of the light quark
- Surprise discovery in open charm sector
- 2003 BaBar and CLEO observed two new narrow $D_s$ mesons with surprisingly low masses.



# Recent Discoveries

- **X(3872),** Belle 09’2003, $1^{++}$, $\chi_{c1}'$ or $D_0D^*$ molecule
  - decays into $J/\psi\ \pi^+\pi^-$, $J/\psi\ \pi^+\pi^-\pi^0$, $J/\psi\ \gamma$, $D_0D^*$
- **Y(3940),** Belle 09’2004, $JP^+$, $2^3P_1$ or Hybrid??
  - decays into $J/\psi\ \omega$
- **Y(4260),** BaBar 06’2005, $1^{--}$, $2^3D_1$(BaBar) or $4^3S_1$ (CLEO) or Hybrid
  - decays into $e^+e^-$, $J/\psi\ \pi^+\pi^-$, $J/\psi\ \pi^0\pi^0$, $J/\psi\ K^+K^-$
- **X(3943),** Belle 07’2005, $0^{-+}$, $\eta_c''$
  - decays into $D_0D^*$
- **Z(3934),** Belle 07’2005, $2^{++}$, $\chi_{c2}'$
  - decays into $\gamma\gamma$, DD
- **Ψ (4320),** BaBar 06’2006, ?, Hybrid

# Charmonium production with Antiprotons

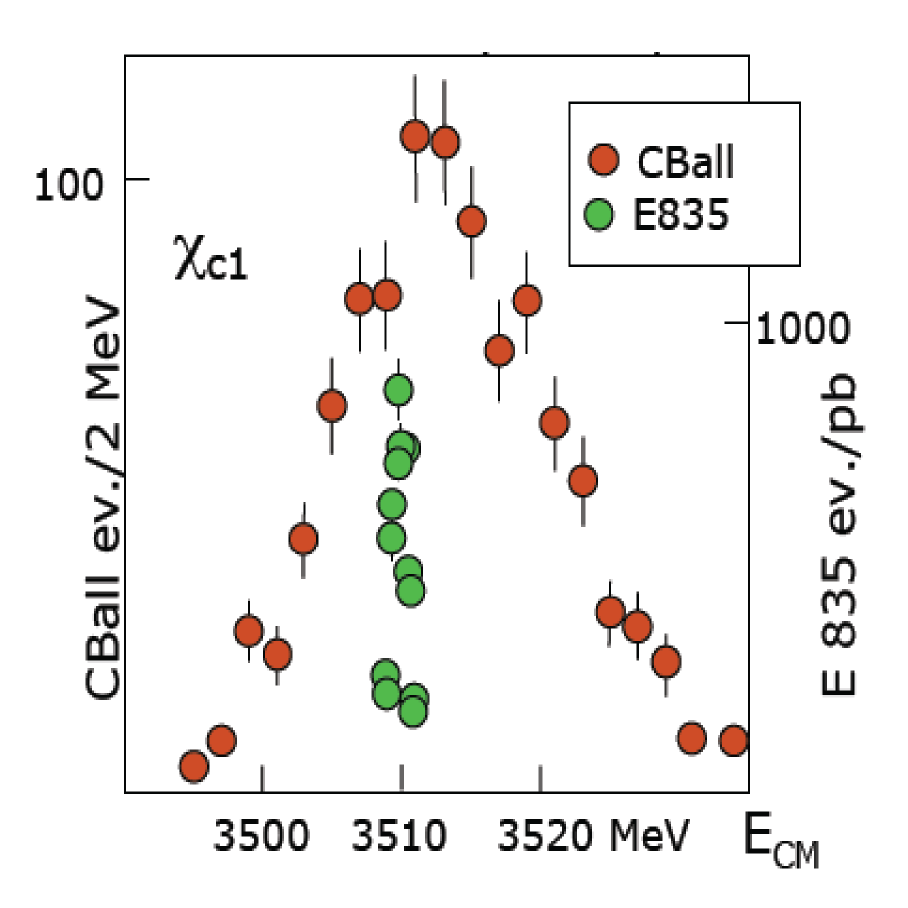



- $e^+e^-$ annihilation fixes quantum numbers of initial state $J^{PC} = 1^{--}$
- Other states by radiative decays only
  - Not all states possible
  - Reduces mass resolution
- Direct formation in ppbar annihilation
  - Significantly improved mass resolution

$$e^+e^- \to \Psi' \to \gamma\chi_{c1} \to \gamma\gamma J/\Psi \to \gamma\gamma e^+e^-$$

$$p\bar{p} \to \chi_{c1} \to \gamma J/\Psi \to \gamma e^+e^-$$

# Charmonium production with Antiprotons

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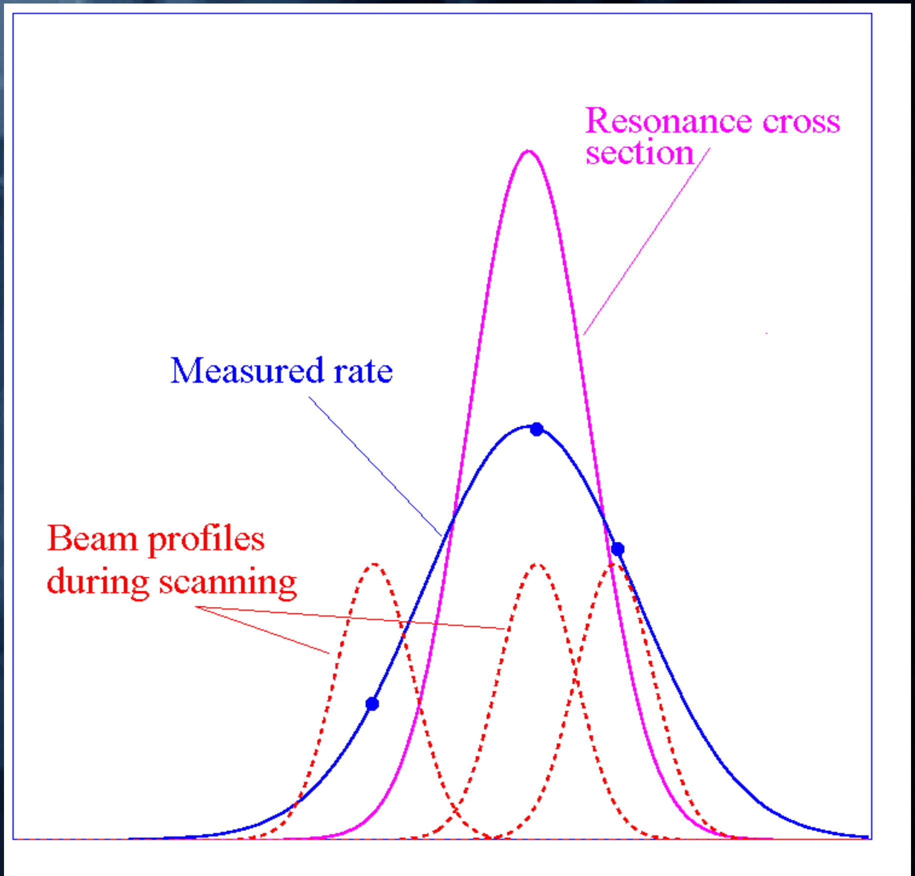
# Ultimate Precision – Resonance Scan



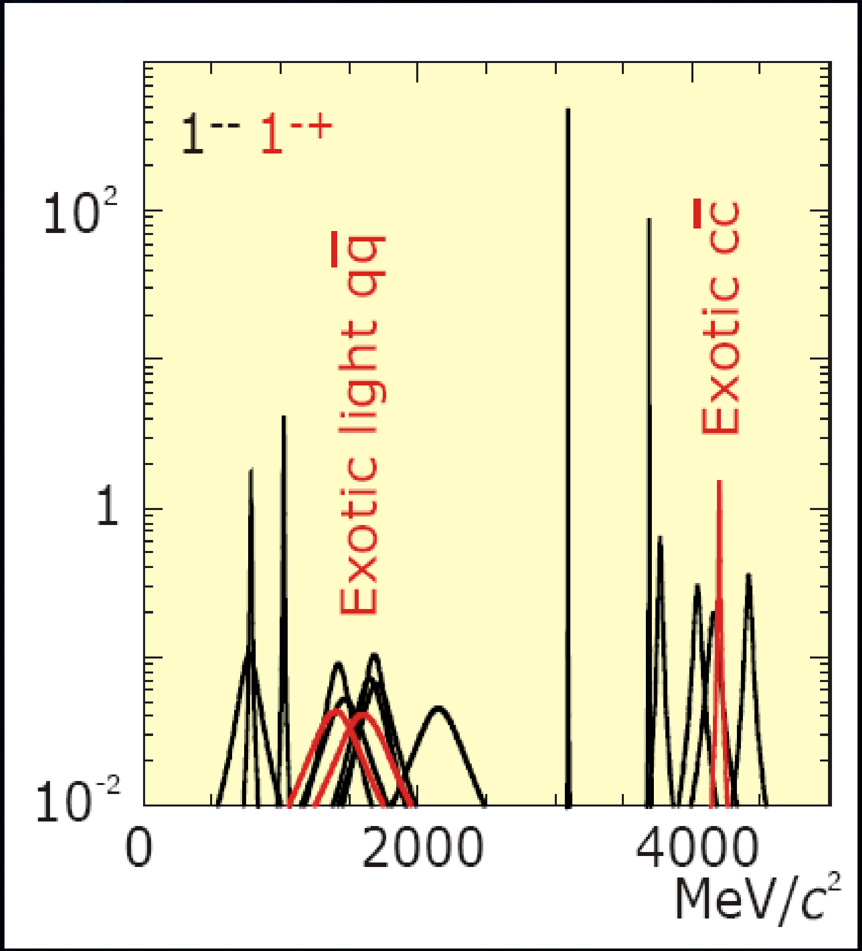

- Production rate is a convolution of cross section and beam energy distribution
- Determination of mass and width depends only on beam parameters
  - Excellent control of beam momentum
- Independent on detector resolution

# Hybrids & Exotics

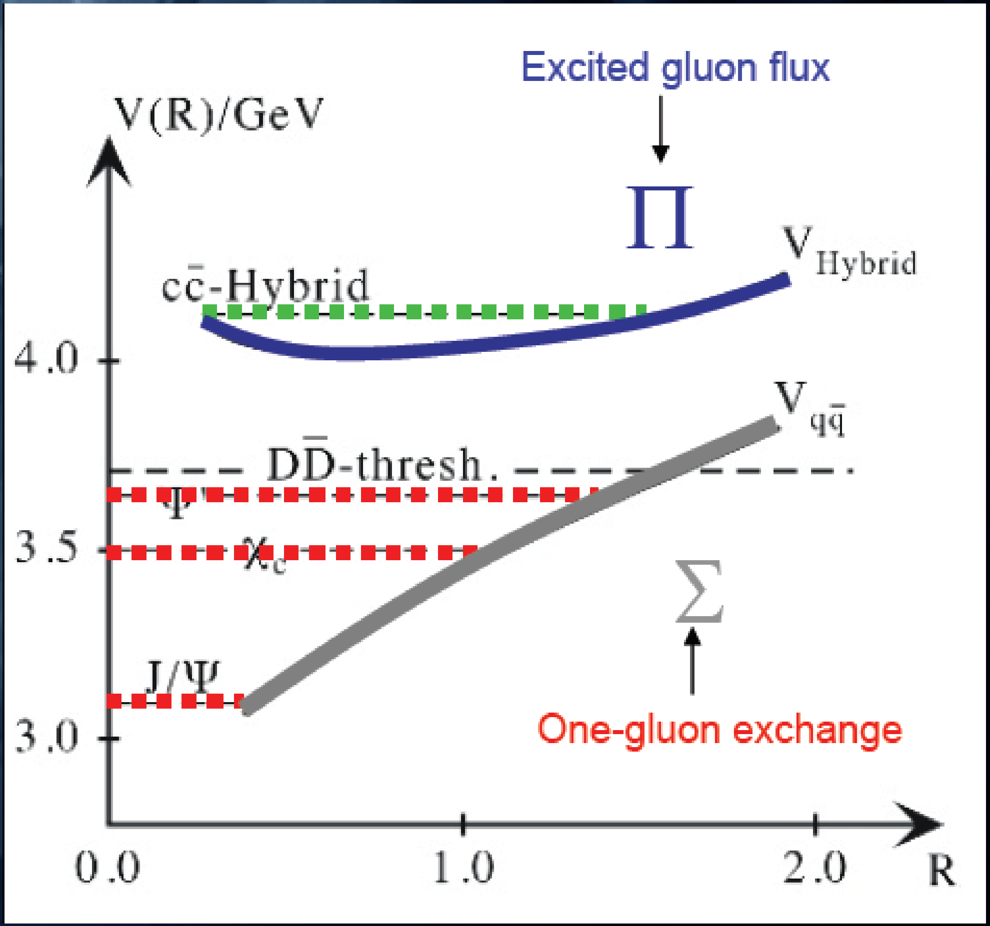
- QCD predicts hybrids and glueballs
  - Search inconclusive so far
- Hybrids and Glueballs Search
  - Look for exotic quantum numbers
- Charm sector promising for discoveries

# Identifying Exotic States

- High level density and broad states in light quark sector
  - Exotic states difficult to identify
- Turn to heavier quarks (charm)
  - States are not as broad
  - Level density is lower
  - Better chances to discover exotic states

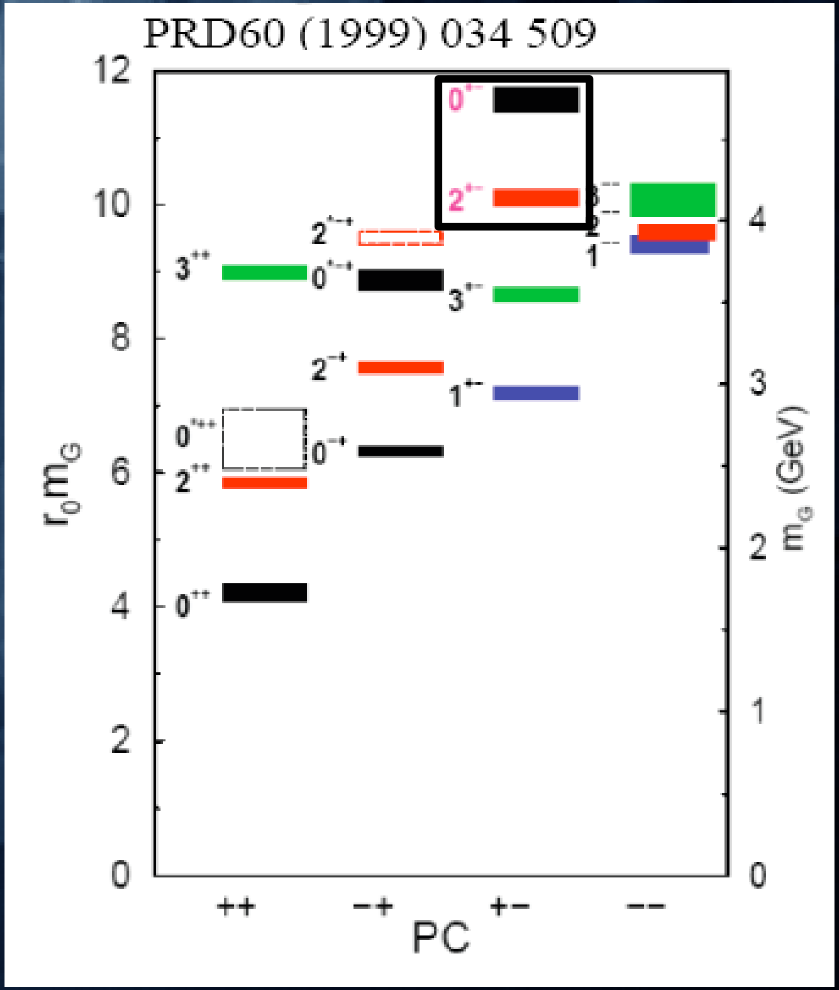


# Hybrids and Exotics




- Gluonic excitations of the quark-antiquark potential may lead to bound states
- predicted in various QCD models (LQCD, bag, flux tubes ...)
- Charmonium hybrids
  - narrow states
  - exotic quantum numbers
  - less ordinary mesons
- Production cross section similar to other charmonia (~150pb)

# Hybrids and Exotics - Glueballs



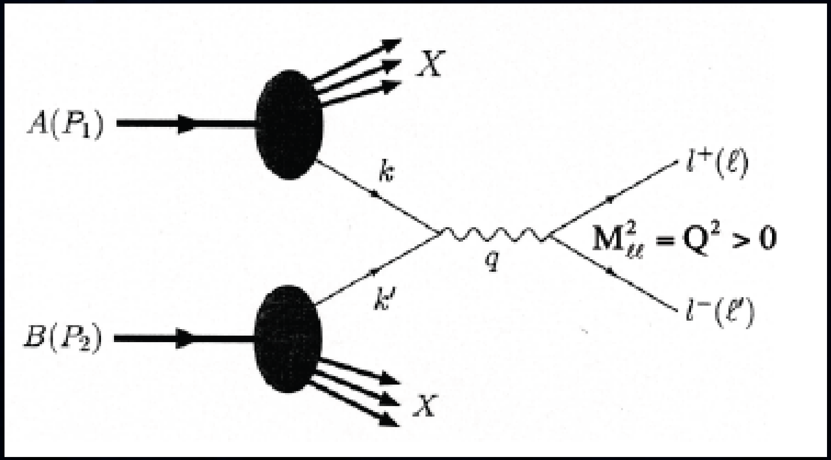

- Self interaction of gluons allows pure glue objects
- Exotic quantum numbers
  - Partial wave analysis
- LQCD predicts two interesting glueball candidates for PANDA mass range which should be easily indentified

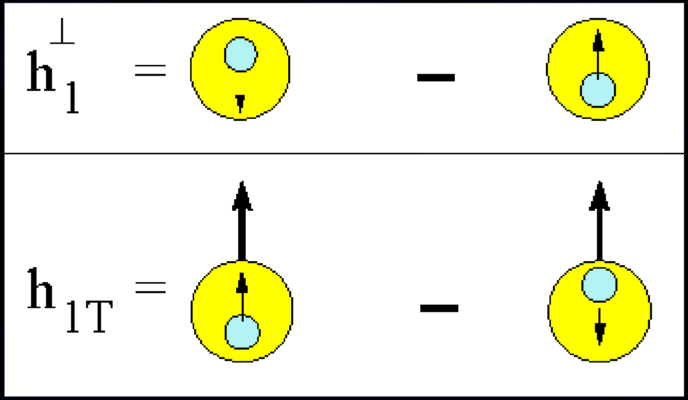
# Nucleon Structure

- Transverse parton distributions in Drell-Yan processes
- GPDs in hard exclusive processes
- Timelike Formfactors

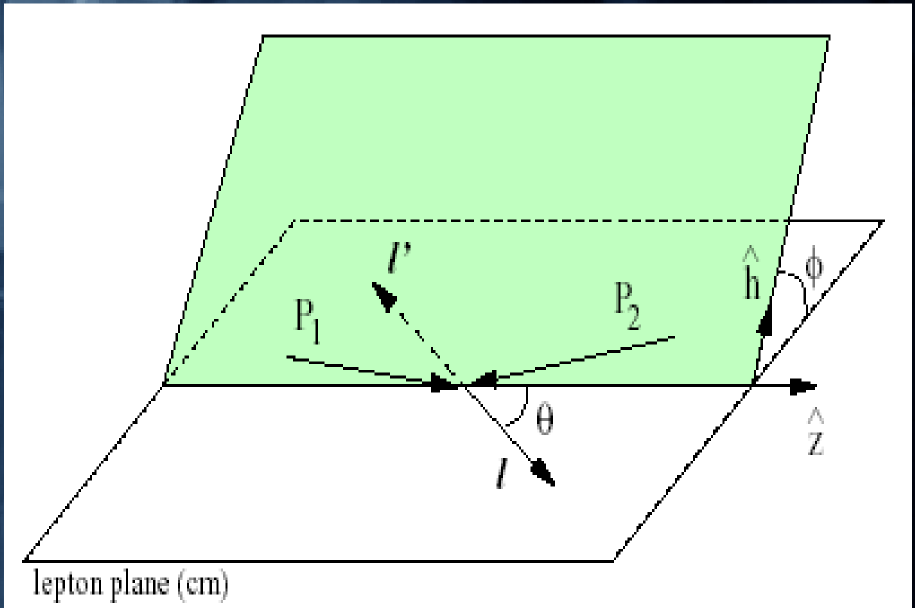
# Drell-Yan Processes

- Unpolarised and polarised DY processes yield
  - Access to Boer-Mulders function $h_1^{\perp}$
  - Access to transversity distributions $h_{1T}$
- DY cross section depends on elementary qq → γ*
- Directly related to objects of interest (no fragmentation function)



# Drell-Yan Processes




$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

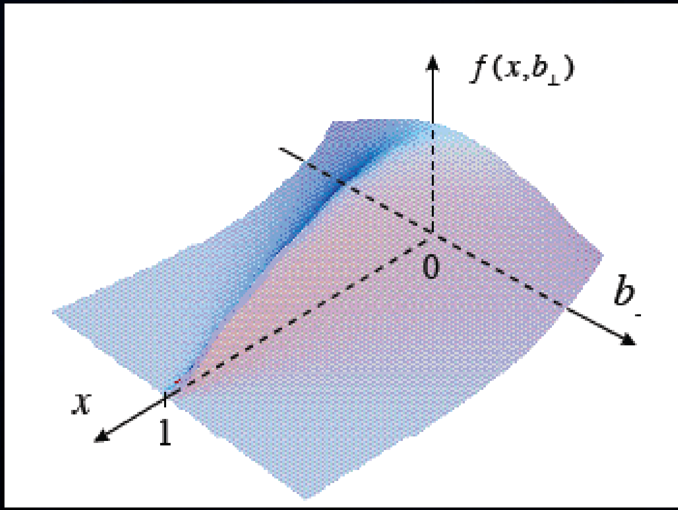
$$\nu \propto \sum_a e_a^2 h_1^\perp \bar{h}_1^\perp / f_1 \bar{f}_1$$

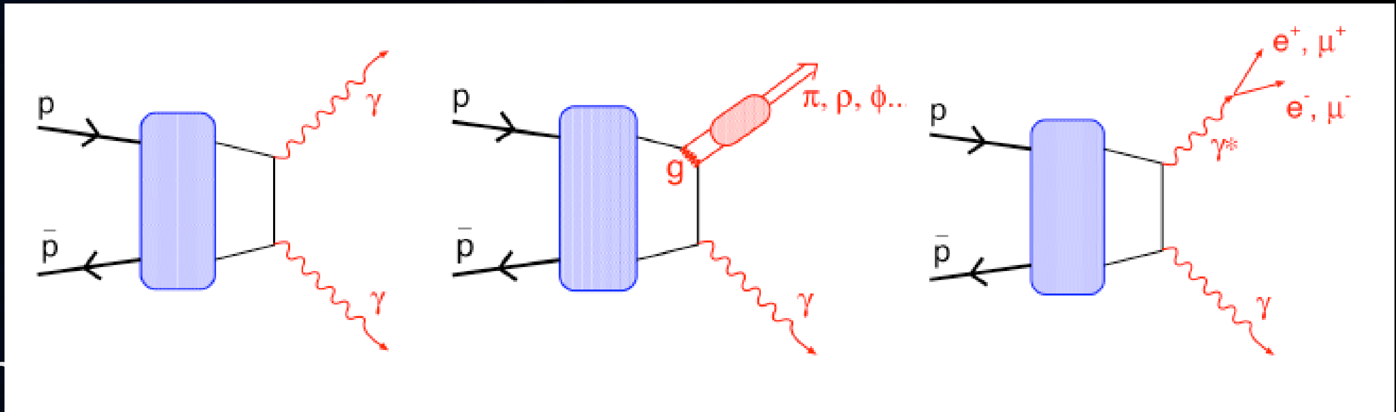
- Measure as function of polar and azimuthal angle
- DY azimuthal asymmetries in ppbar not suppressed by nonvalence-like contributions
- Large *cos2ϕ* observed
  - Higher twist
  - Non-zero Boer-Mulders function $h_1^\perp$

[Boer, PRD60,014012(1999)]

# Parton Distribution Functions

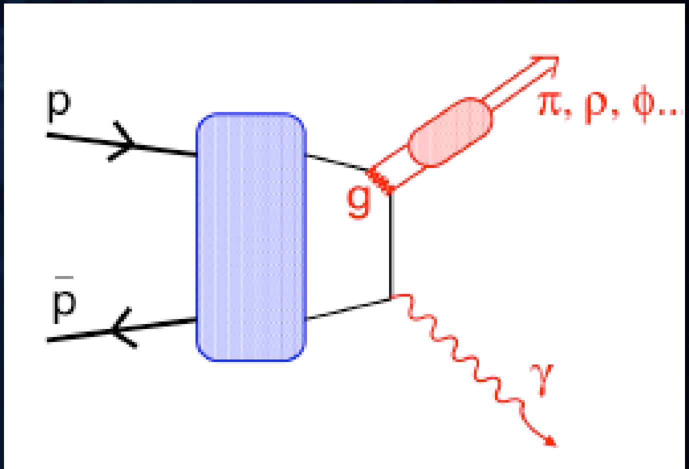
- Exclusive final states in ppbar annihilation
  - Generalised Parton Distributions and Transition Distribution Amplitudes
    [B.Pire, L.Szymanowski,PLB 622 (2005) 83]
- Impact parameter space interpretation for TDAs
- Fourier transform gives a transverse picture of the pion cloud in the proton
- Complemantary to hard exclusive scattering

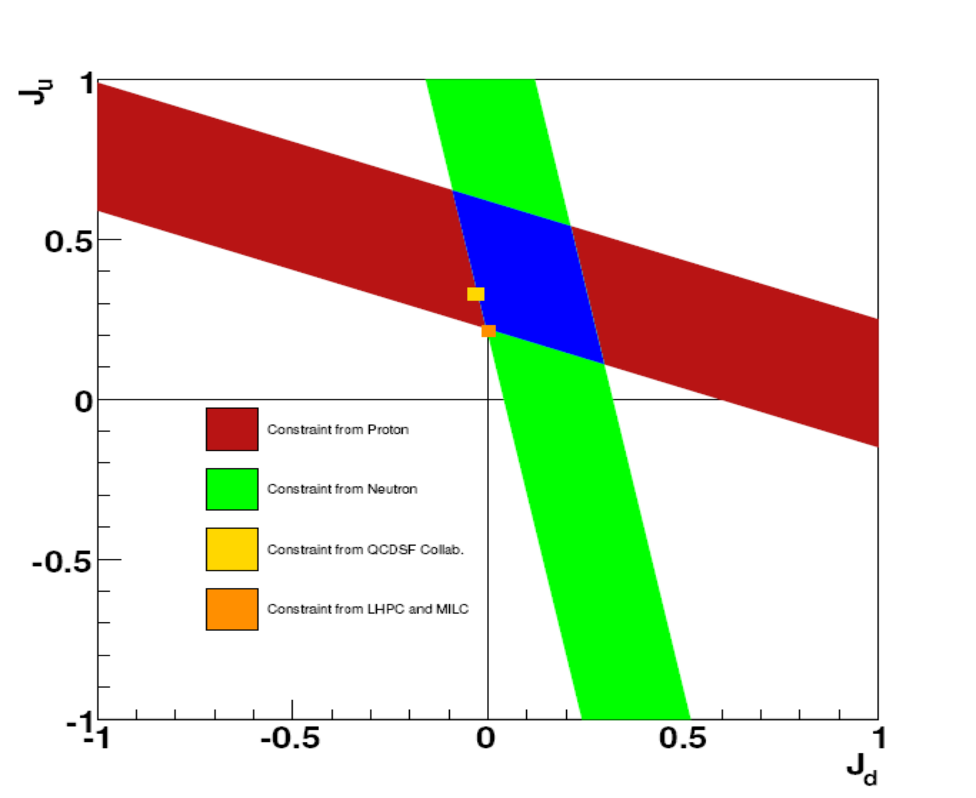


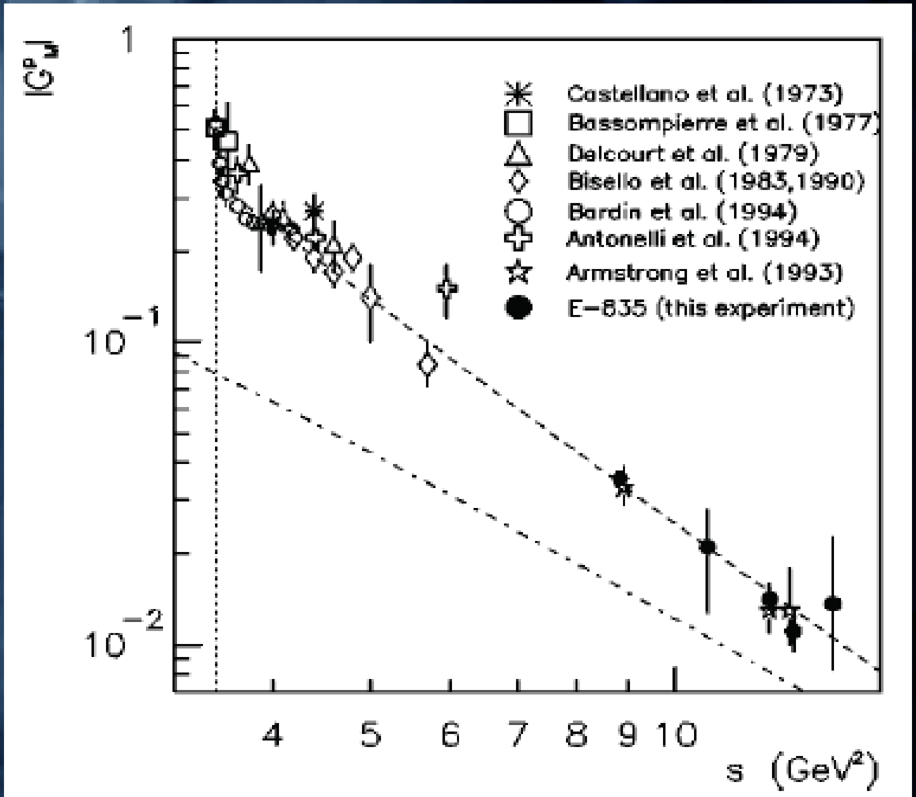
# Generalised Parton Distributions

- Meson wave function acts as spin filter (PRL 90 (2003) 092001)
- Linked to time-like form factor and PDFs
- GPD models can be used to constrain the total angular momentum of quarks inside nucleons
- First attempts by DESY and JLAB



# Timelike form factors



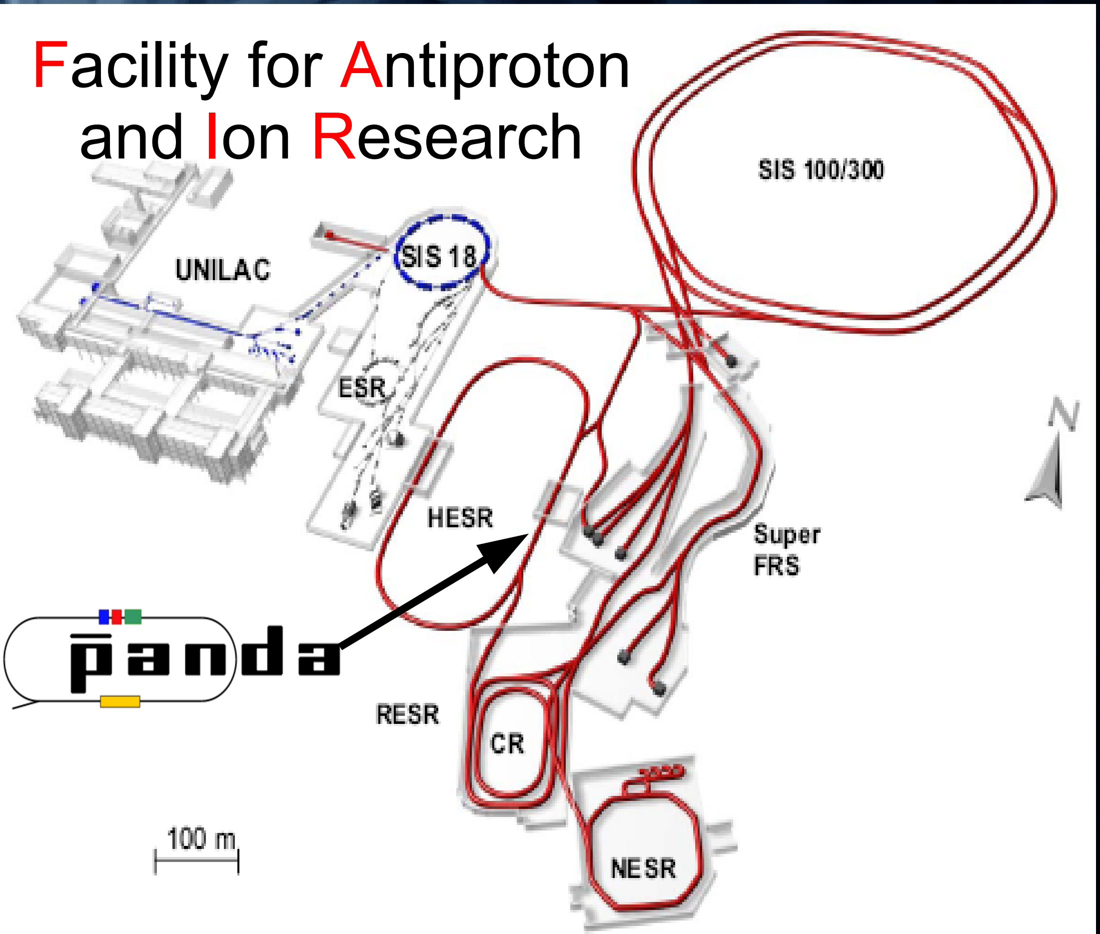

- ppbar → $e^+e^-$
- Space-like vs time-like behaviour
- Widest kinematical range in a single experiment so far
- Expect improved measurement due to larger statistics and large solid angle acceptance
- Independent measurement of $G_E$ and $G_M$

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2xs}\left[|G_M|^2(1+\cos^2\theta^*) + \frac{4m_p^2}{s}|G_E|^2\sin^2\theta^*\right]$$

# FAIR and PANDA at GSI

- FAIR
  - HESR
- PANDA
  - Requirements
  - Target
  - Detector system

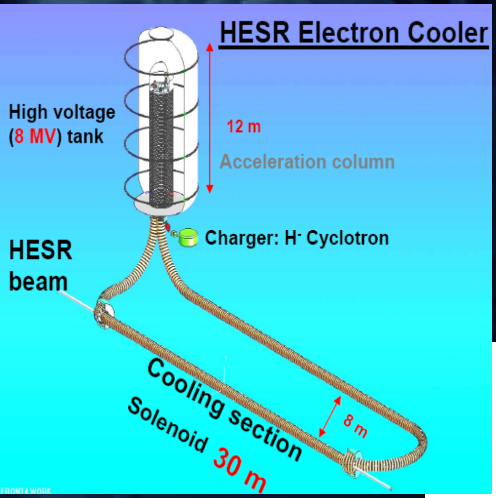
# FAIR at GSI

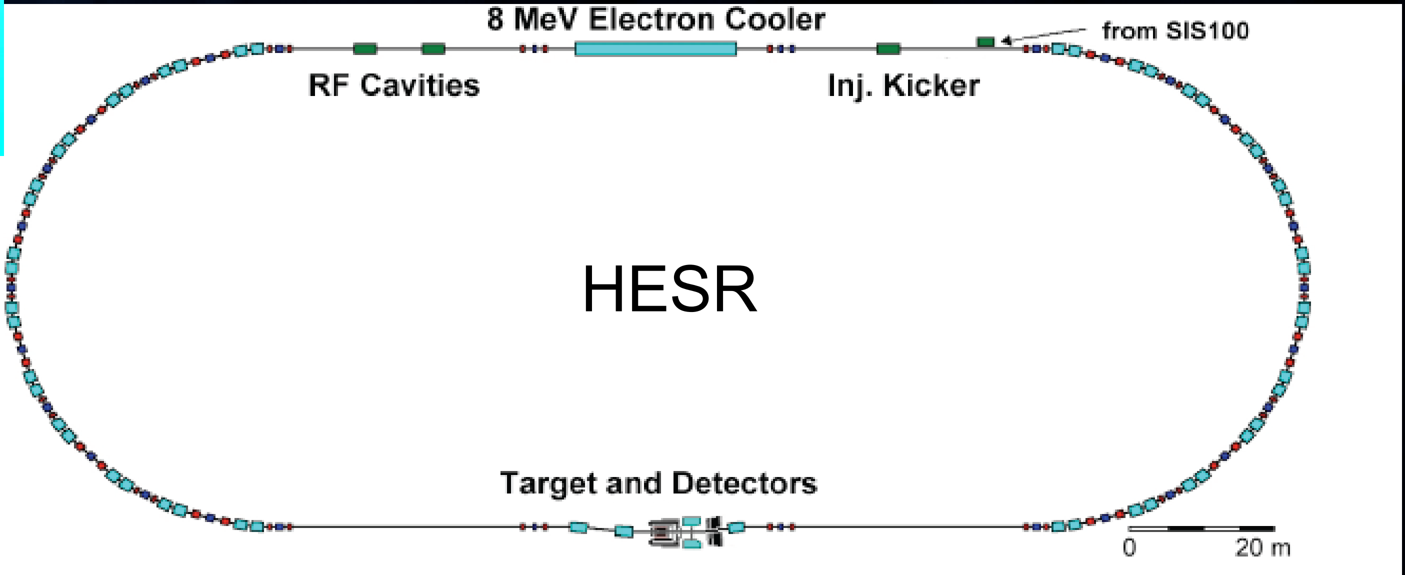



- Primary beams
  - $10^{12}$/s, 1.5 GeV/u, $^{238}U^{28+}$
  - $2(4)\cdot10^{13}$/s 30 GeV protons
  - $10^{10}$/s $^{238}U^{73+}$ up to 25 (-35) GeV/u
- Secondary beams
  - Broad range of radioactive beams up to 1.5 – 2 GeV/u
  - Antiprotons 3(0) – 30 GeV
- Storage and cooler rings
  - Radioactive beams
  - $5\cdot10^{10}$ stored and cooled 0.8 -14.5 GeV antiprotons
- Parallel operation to accommodate large physics program

# High Energy Storage Ring

- $5 \cdot 10^{10}$ antiprotons
- Mom. range 1.5 to 15 GeV/c
- Two different operation modes:
  - High luminosity mode $\Delta p/p = 10^{-4}$ with stochastic cooling, $L = 10^{32}\ cm^{-2}s^{-1}$
  - High precision mode $\Delta p/p = 3x10^{-5}$ with electron cooling, $L = 10^{31}\ cm^{-2}s^{-1}$



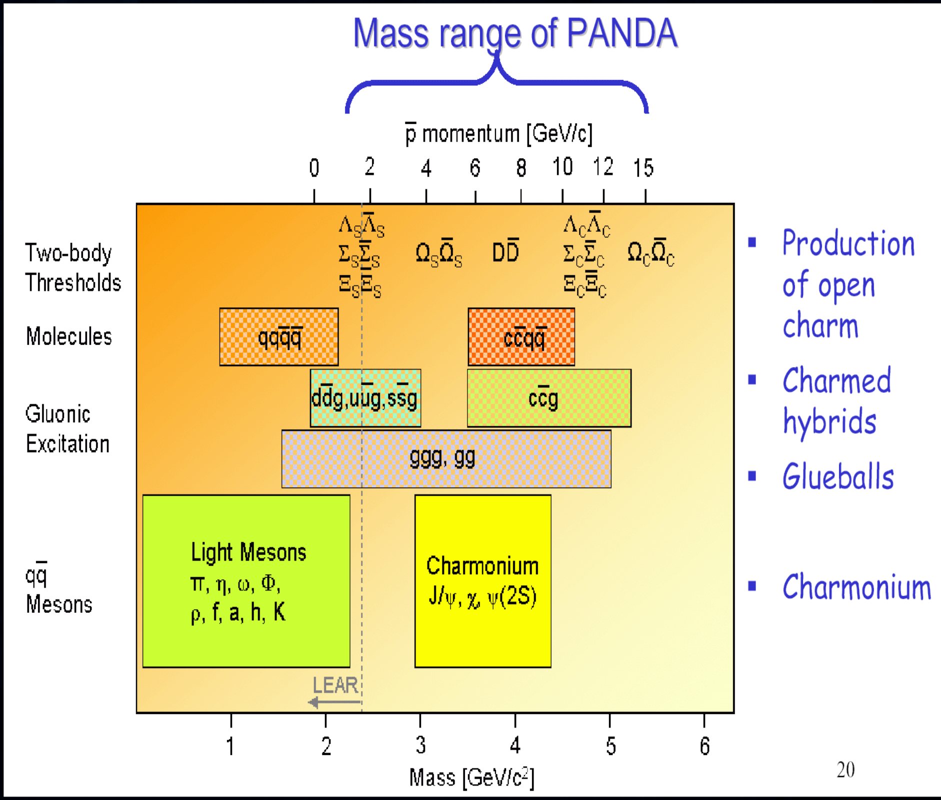



# PANDA Physics Program

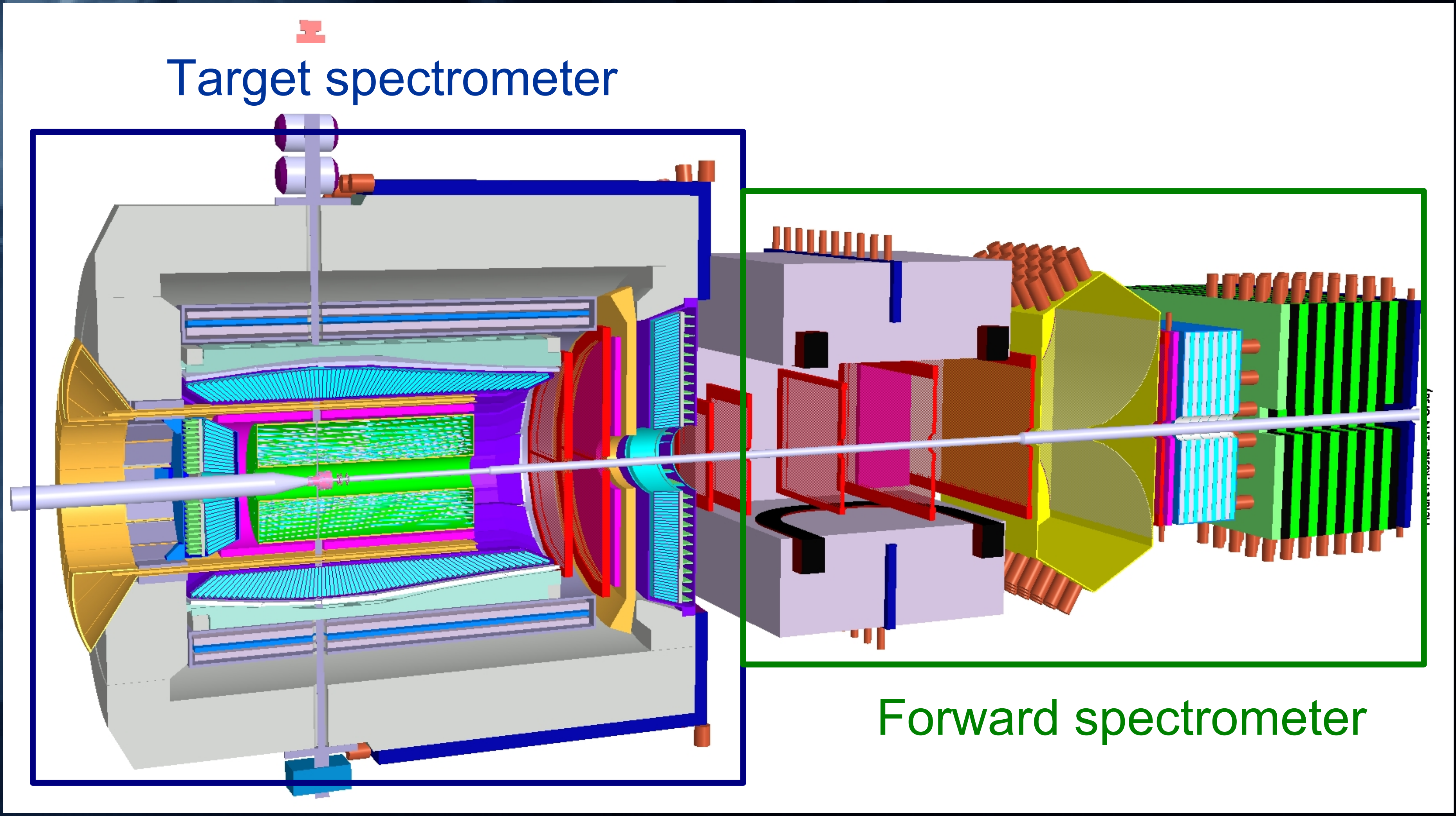
- Charmonium spectroscopy
- Search for exotic hadrons, especially glueballs and hybrids
- D-meson spectroscopy
- Medium modifications of charmed mesons in nuclei
- Nucleon structure and spin physics
- Hypernuclei
- CP violation in the charm sector

# The PANDA Detector

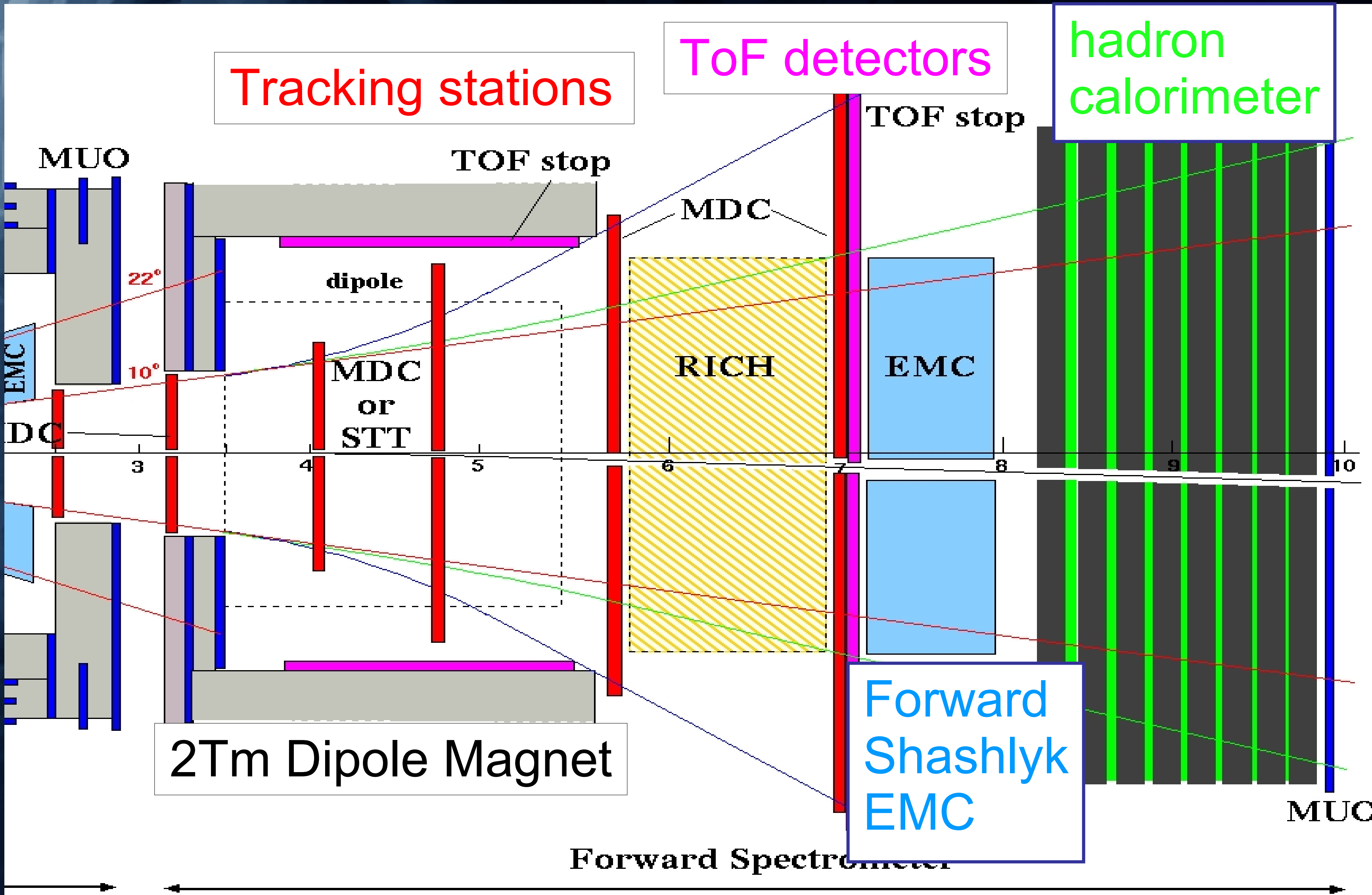
- Detector Requirements:
  - (Nearly) $4\pi$ solid angle coverage
  - High-rate capability ($2 \cdot 10^7 s^{-1}$)
  - Good PID ($\gamma$, e, $\mu$, $\pi$, K, p)
    - Lepton identification
  - Momentum resolution ($\approx$ 1 %)
  - Excellent calorimetry
    - Energy resolution
    - sensitivity to low-energy photons
  - Vertex reconstruction for D, $K^0_s$, $\Lambda$
  - Efficient trigger
  - Pointlike interaction region



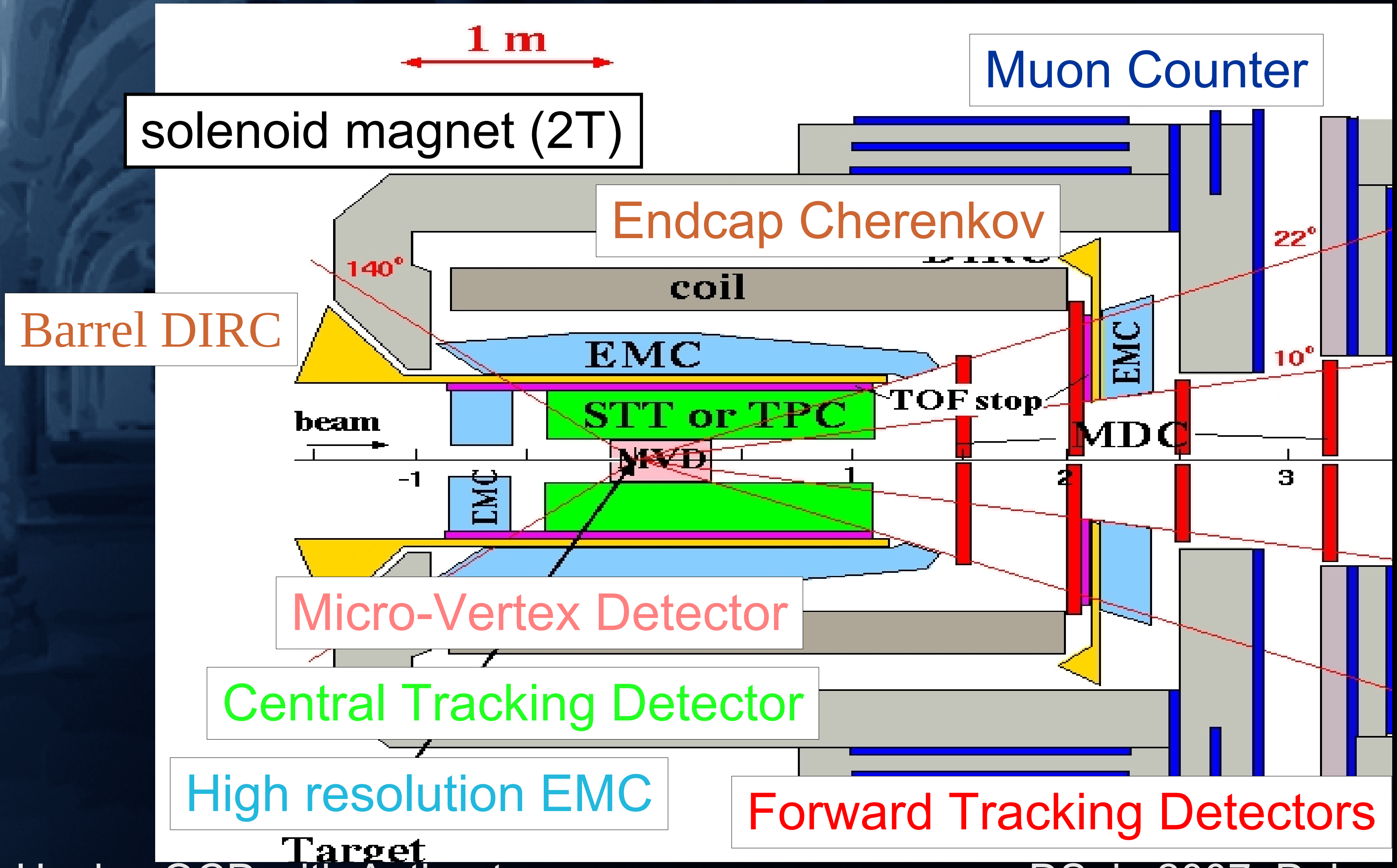
# The PANDA Detector



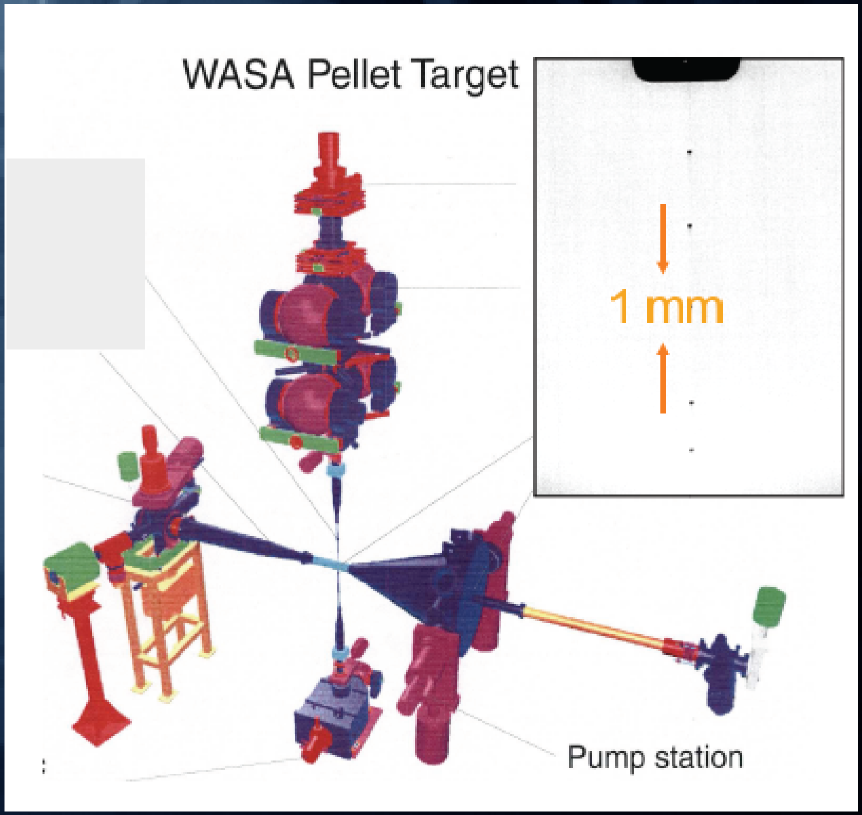
# PANDA – Forward Spectrometer



# PANDA – Target Spectrometer



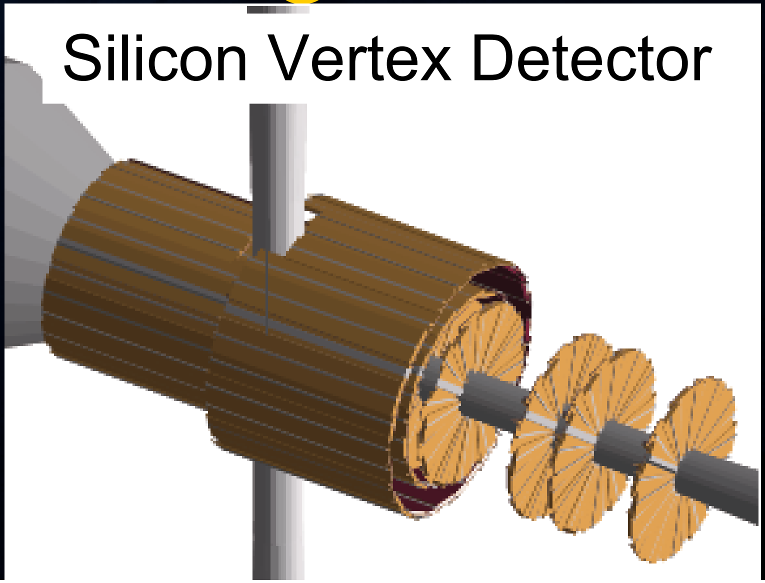
# Target for PANDA

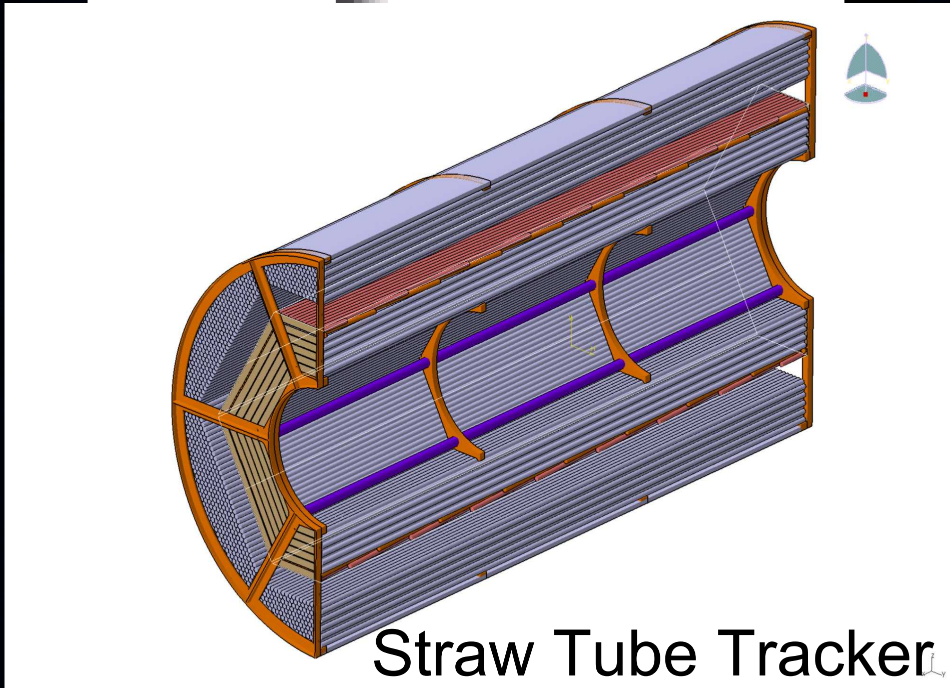



- Required target density $3.8 \cdot 10^{15}$ atoms/cm$^2$
- Small cross section
- Variety of target materials
- Frozen hydrogen pellets
  - Existing at WASA
- High density target options
  - Cluster jet
  - Wire/Strip target for heavy elements

# Central Tracking

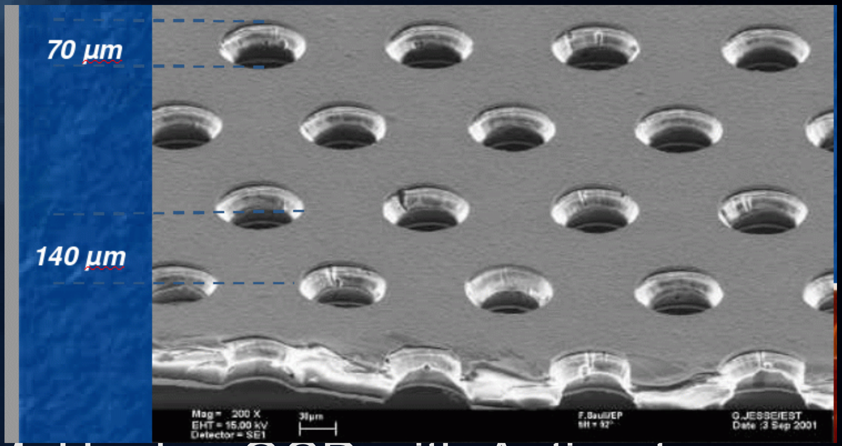
- High momentum resolution
  - $\delta p/p \sim 1\%$
- High spatial resolution
  - $\sigma_{r\phi} \sim 150\mu m$, $\sigma_z \sim 1\text{-}3mm$
- Minimal detector material budget ($X_0 \sim 1\%$)
- High rate capability ($10^7$ ev/s)
- Displaced vertices of open charm and strangeness with precision ~ 70 $\mu m$
- Silicon Vertex Detector
  - ~7.2 million barrel pixels
  - ~2 million forward pixels



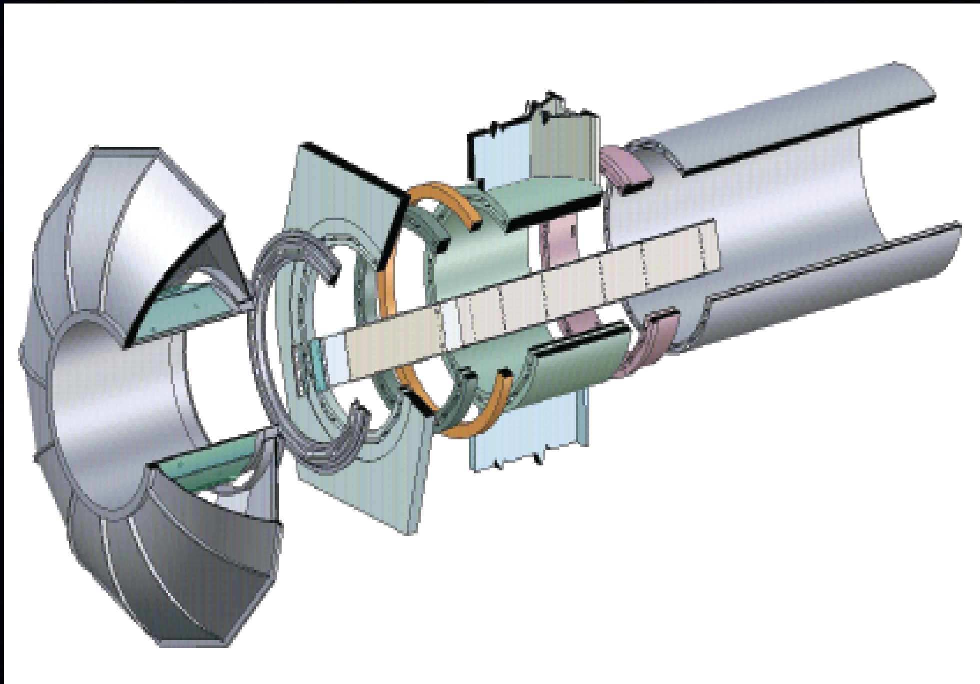
# Forward Tracking

- Occupancy 18 $kHz/cm^2$
- Difficult for conventional drift chambers
- GEM tracking stations
  - High granularity
  - Adapt to occupancy
  - Only 0.2% $X_0$ total thickness
- R&D for large size GEM foils



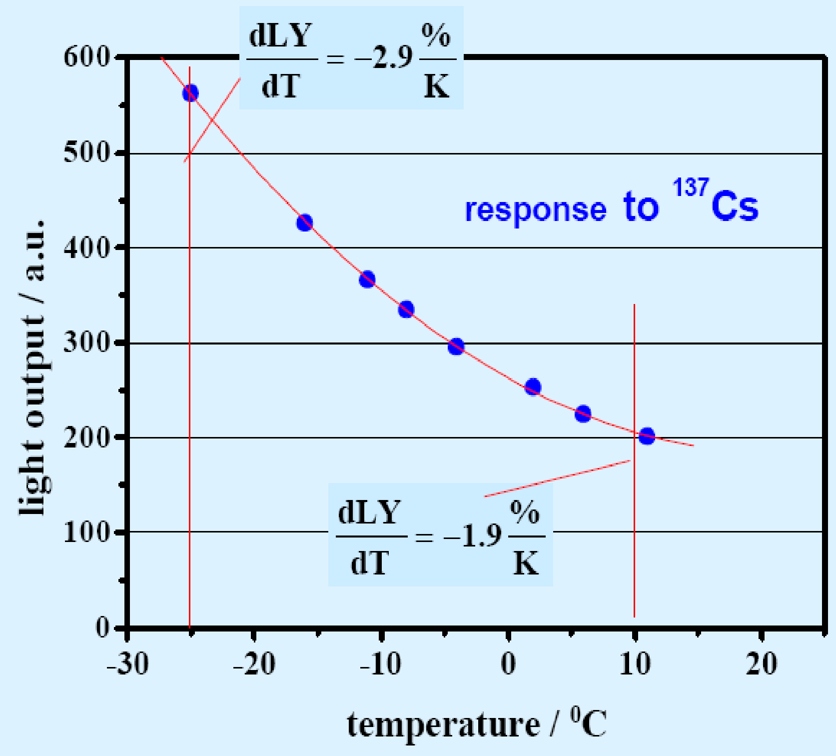

# Particle Identification at PANDA

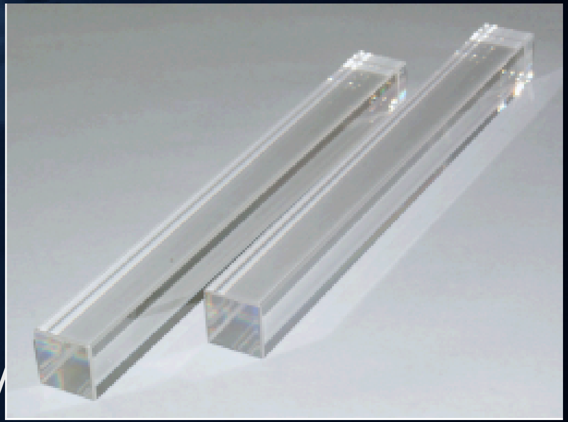
- Excellent PID necessary to achieve physics program
  - $\pi$/K separation up to 4-5 GeV/c
- Combination of different techniques
  - ToF, Cherenkov and ΔE (TPC), EMC
- Barrel (20° < $\theta$ < 170°)
  - DIRC, (TPC), ToF, EMC
- Endcap (5° < $\theta$ < 20°)
  - Disc DIRC, EMC
- Forward Spectrometer (<5°)
  - ToF, ECAL, HCAL, (RICH)

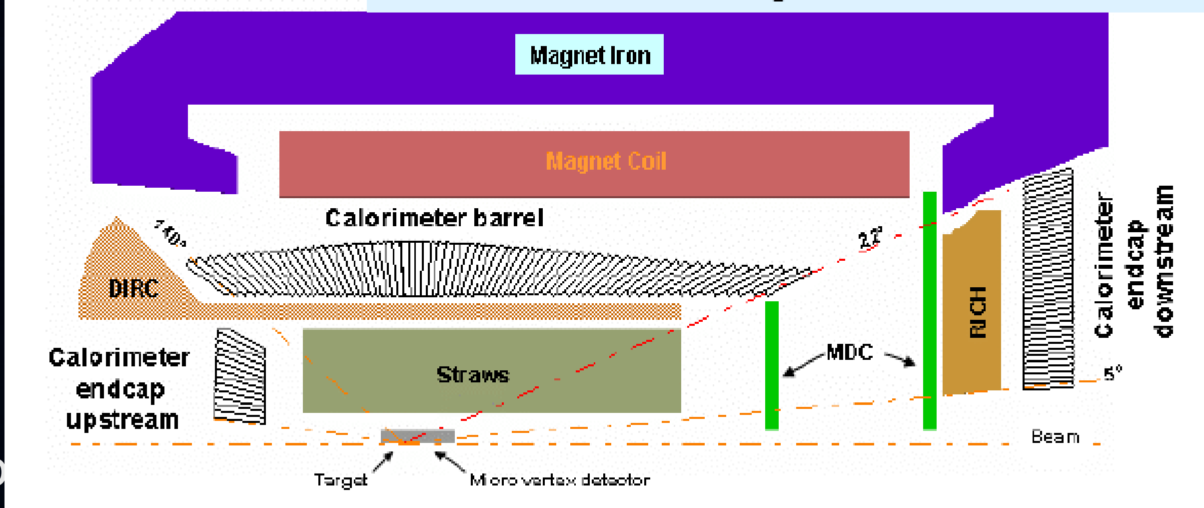


# EM Calorimeter

- $PbWO_4$
  - Compact and fast scintillator
- Temp stabilised at -25°C
  - Light yield temp dependend
- High granularity & resolution
  - ~ 18000 crystals
  - 17 $X_0$
- APD readout (inside mag field)





# Outlook

- PANDA at HESR will be a versatile multi purpose detector offering a broad physics program
  - Precision charmonium spectroscopy
  - Hybrids and Glueball search
  - Drell-Yan processes sensitive to variety of parton distribution functions
  - Hard exclusive processes offer access to GPDs
  - Measurement of time-like form factors over large kinematic range
- Kick-off in 2014