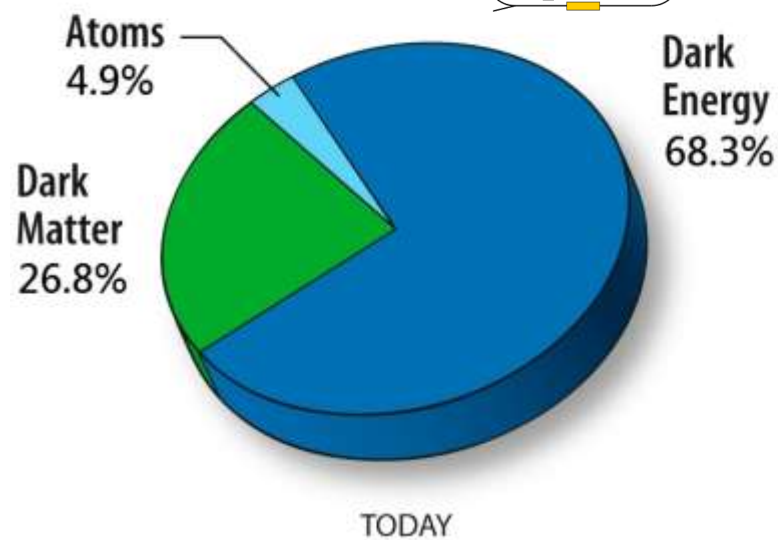
Using Antiprotons for High Precision Studies of Hadrons

J. Ritman Forschungszentrum Juelich

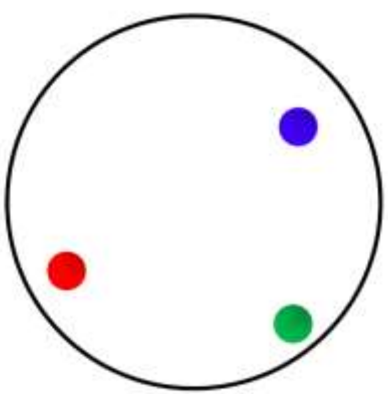
Overview

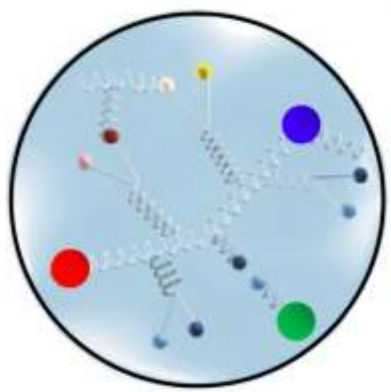
- Some Puzzles About Matter
- Using Antimatter to Learn About Matter
- Physics Topics to be Studied at PANDA
- Overview of PANDA Detector
- Summary/Conclusions

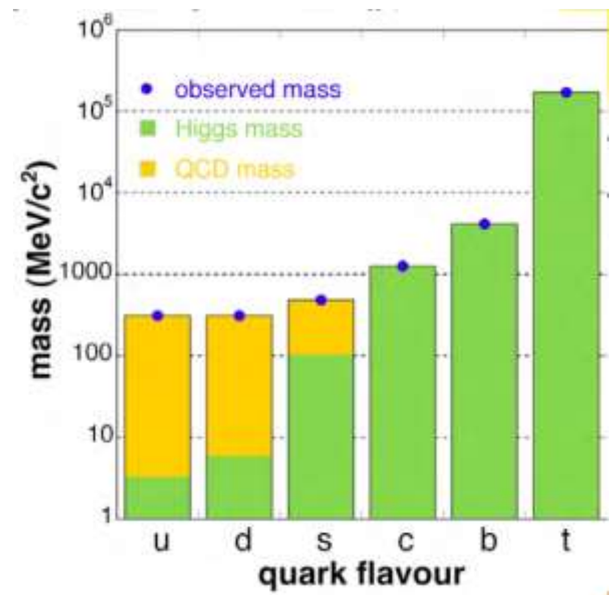
Puzzle One: Hadronic Mass



- Visible matter is mostly atoms:
- The total is the sum of the parts
  - True to ~10^{-8} for an atom
  - True to ~10^{-2} for nuclei
  - Wrong by x100 for nucleons (protons and neutrons)!

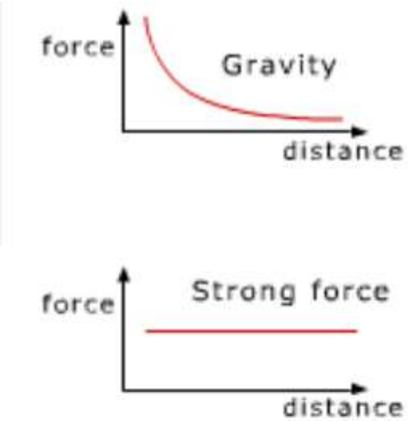


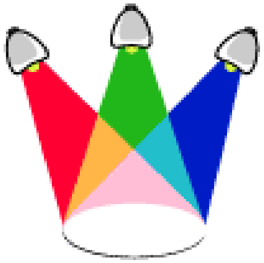


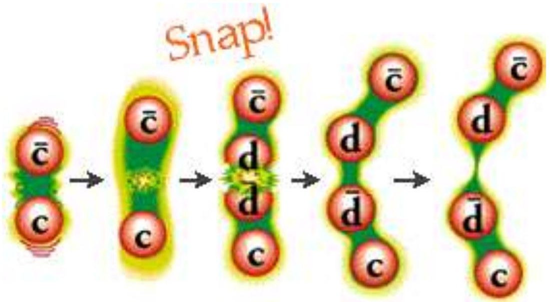


Puzzle Two: Why Only Some Types of Hadrons?

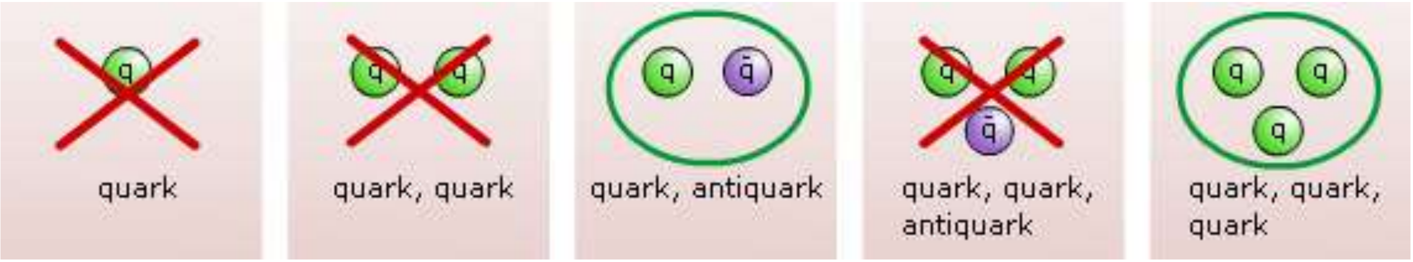
- Strong force: only “color neutral” objects (confinement)





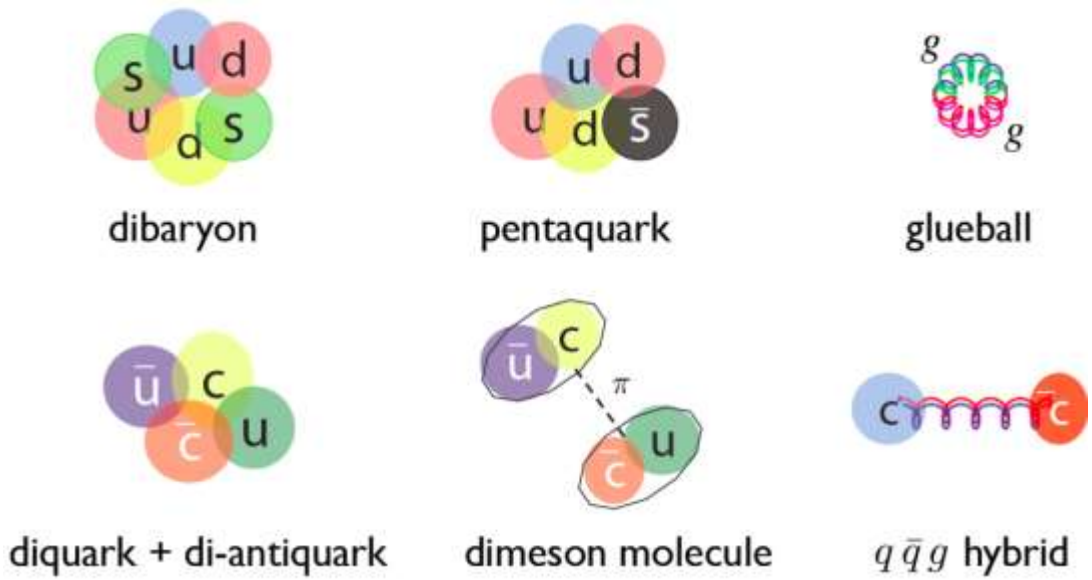


- Mesons and baryons are color neutral



Puzzle Two: What About Other Combinations?

- There are other ways to make color neutral objects:

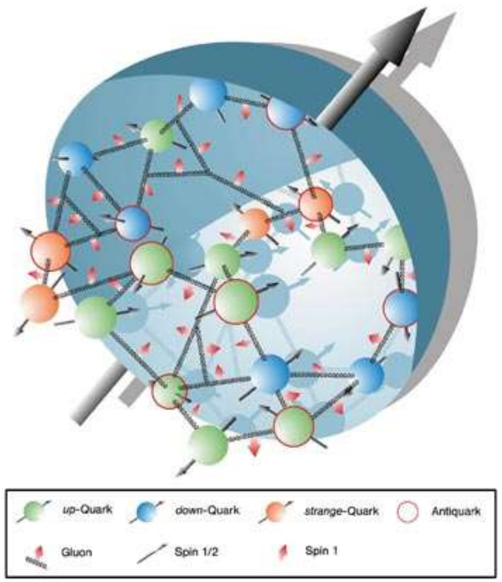


(Zhu)

- Why do we see hundreds of mesons and baryons, but it is not yet clear what the nature of some of the the new X,Y,Z states are?

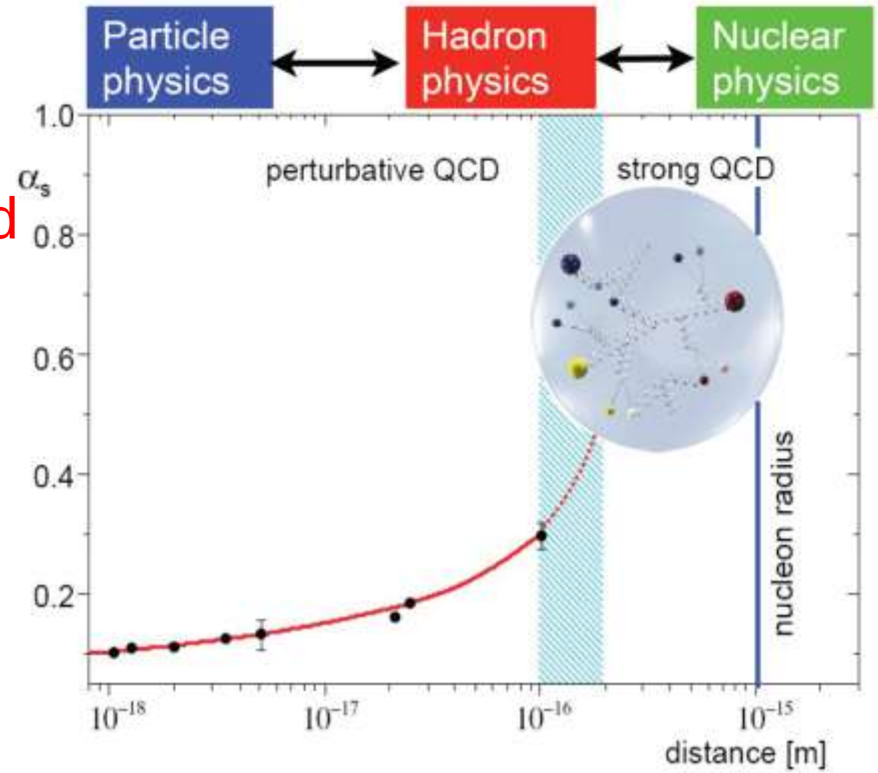
Puzzle Three: How are Properties of the Whole Derived from the Constituents?

- How do effective degrees of freedom emerge from the underlying theory (e.g. hadrons from quarks)?
- What is the deep structure of e.g. the nucleon?
- How are its macroscopic properties determined by partons?
- Can we constrain theoretical approaches?



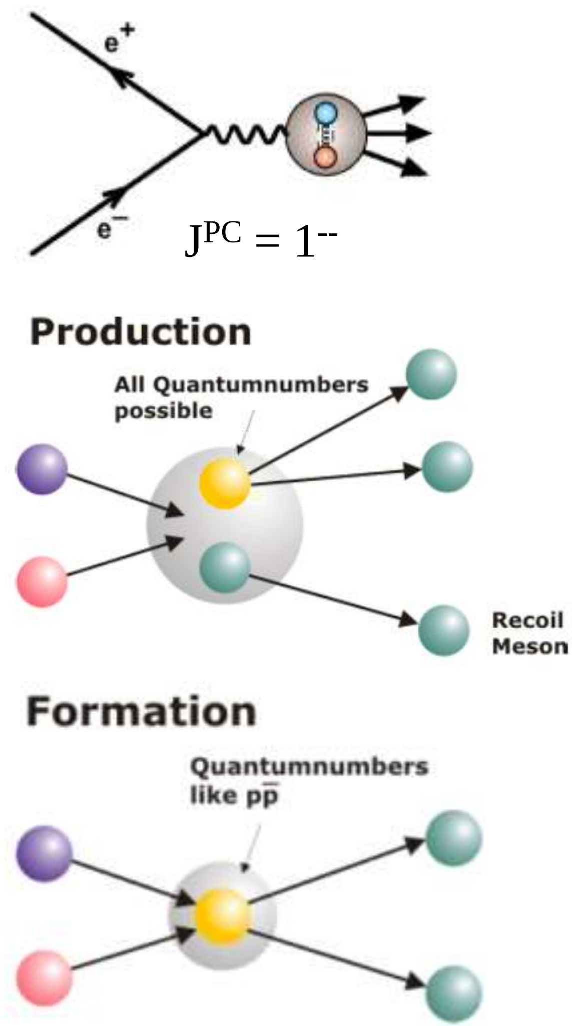
Hadron Physics with PANDA

- QCD well understood at high Q^2
  Emergence of eff. DoF at low Q^2
- Phenomena appear that are hard to predict from QCD:
  e.g. confinement, nature of hadrons, hadronic masses…
- To gain further insight precision experiments needed:
  - Statistics
  - Resolution
  - Exclusiveness

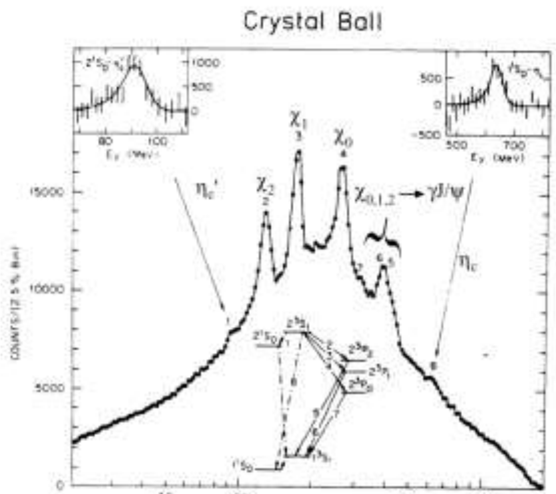


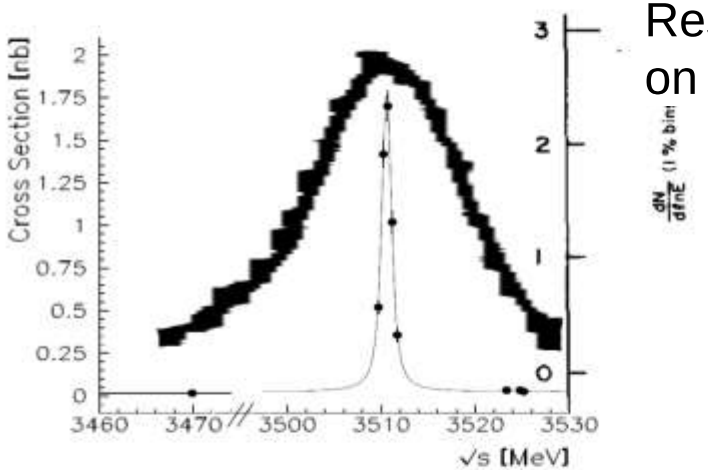
Why to Use Antiprotons ?

- Annihilation is a gluon rich process
- ~2 GeV annihilation energy "for free"
- All fermion-antifermion quantum numbers accessible (compared to e^+e^-) *production reactions*
- Very high mass resolution in *formation reactions*
- High angular momentum accessible



High Mass/Width Resolution, e.g.: $\chi_{c1,2}$





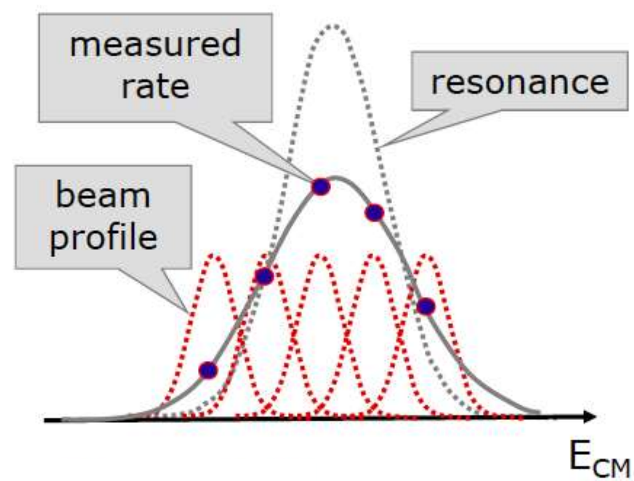
$$e^+e^- \rightarrow \psi' \rightarrow \gamma\chi_{1,2} \rightarrow \gamma(\gamma \mathrm{J}/\psi) \rightarrow \gamma\gamma e^+e^-$$

Invariant mass reconstruction depends on the detector resolution ≈ 1 - 10 MeV

Formation:

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

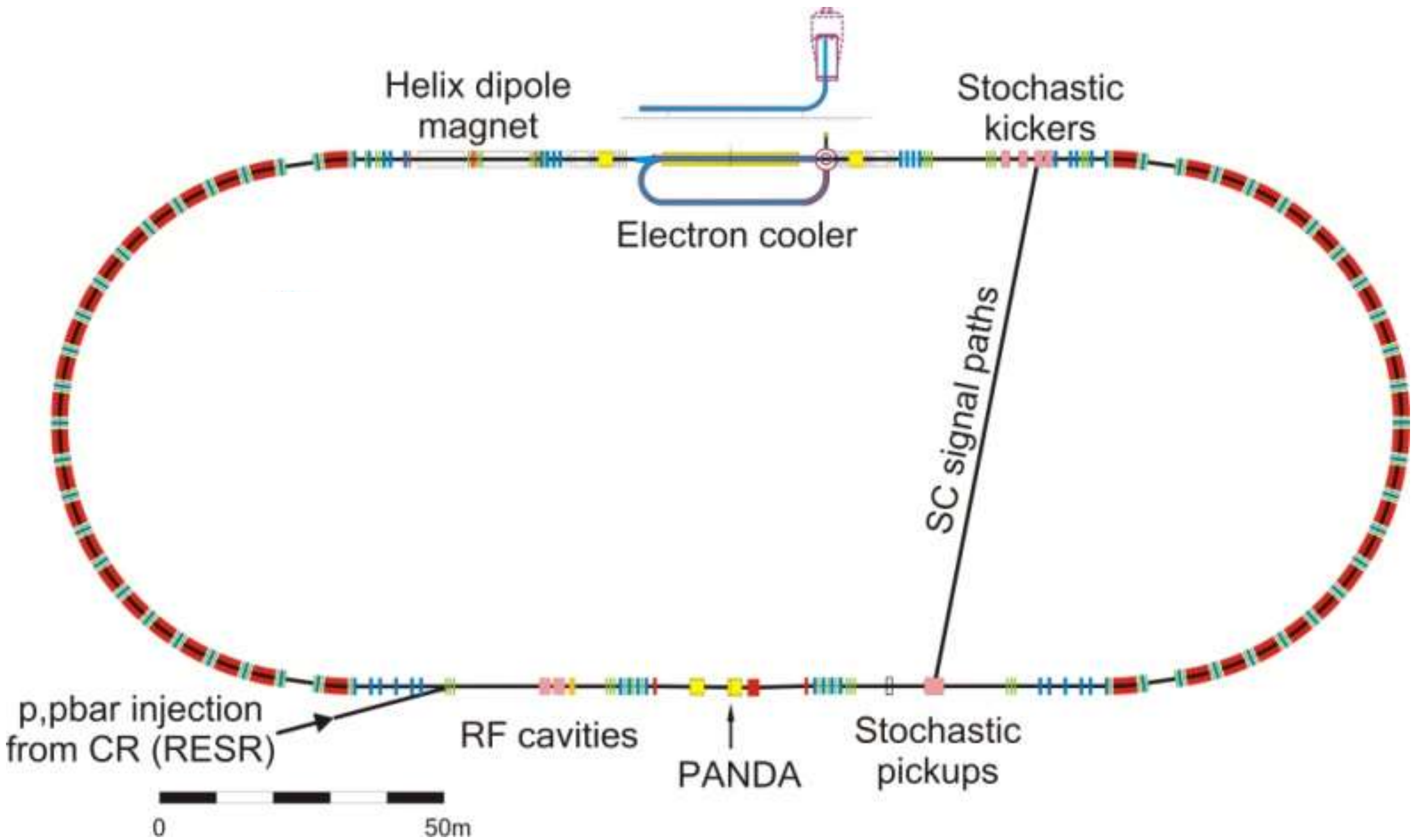
Resonance scan: resolution depends on the beam resolution



E760@Fermilab ≈ 240 keV

PANDA ≈ 50 keV

HESR with PANDA and Electron Cooler



$10^{10} – 10^{11}$ stored antiprotons

Thick targets $4 \cdot 10^{15}$ cm^{-2}

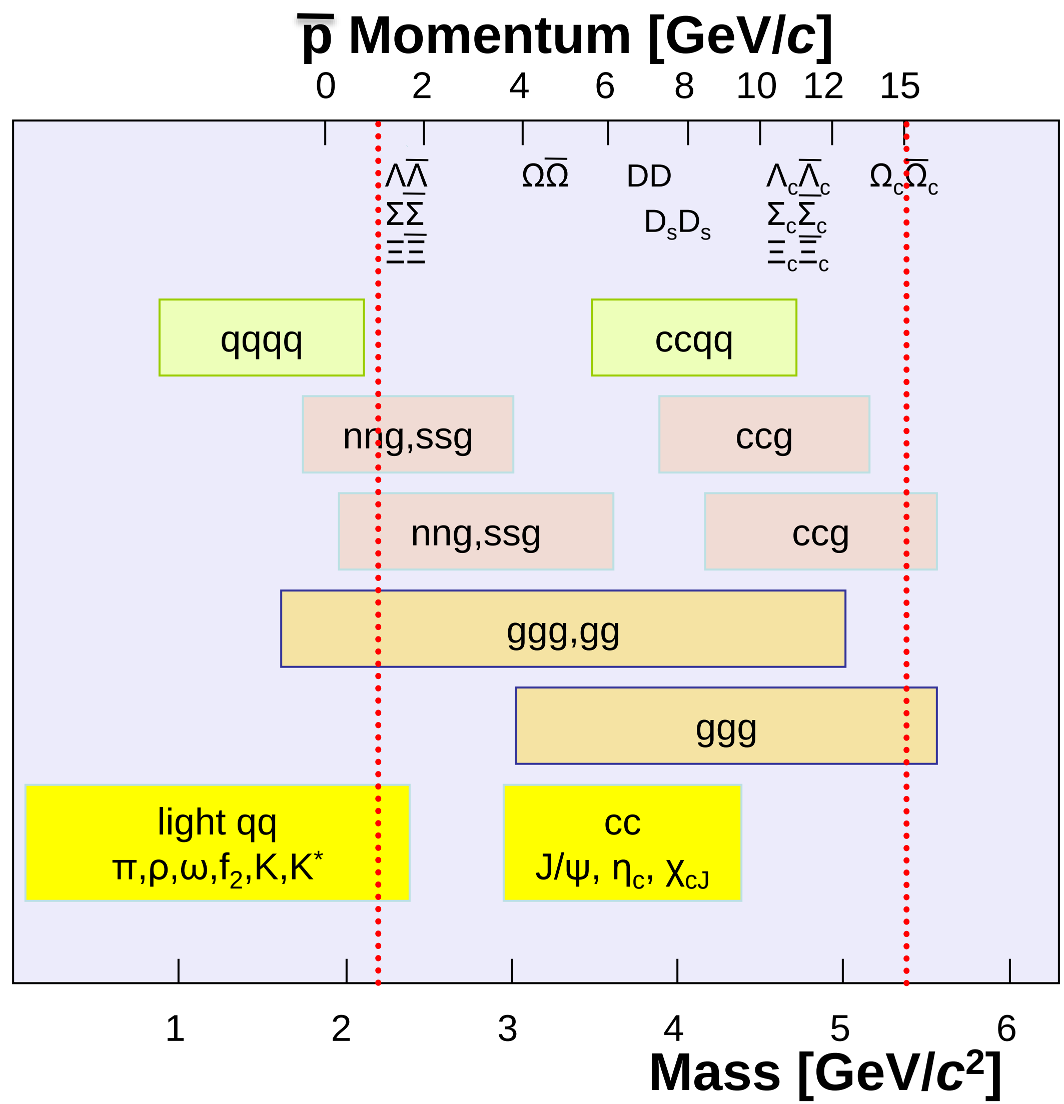
$\Delta p/p \leq 4 \cdot 10^{-5}$

Lumi up to $2 \cdot 10^{32}$ cm^{-2}s^{-1}

HESR		COSY
575 m	Circumference	184 m
1.5 – 15 GeV/c	Momentum	0.3 – 3.7 GeV/c
up to 9 GeV/c	Electron Cooling	up to 0.5 GeV/c
Full range	Stochastic Cooling	1.5 – 3.7 GeV/c

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

- Nucleon structure
  E.M. processes
- Meson spectroscopy
  - light mesons
  - charmonium
  - exotic states
    - glueballs
    - hybrids
    - molecules/multiquarks
  - open charm
- Baryon/antibaryon production
- Charm in nuclei
- Strangeness physics
  - Hyperatoms
  - S = -2 nuclear system
    - Ξ^- nuclei
    - $\Lambda\Lambda$ hypernuclei



Hadron Structure with Electromagnetic Probes

Jim Ritman

Time-Like& Space-Like EM Form Factors

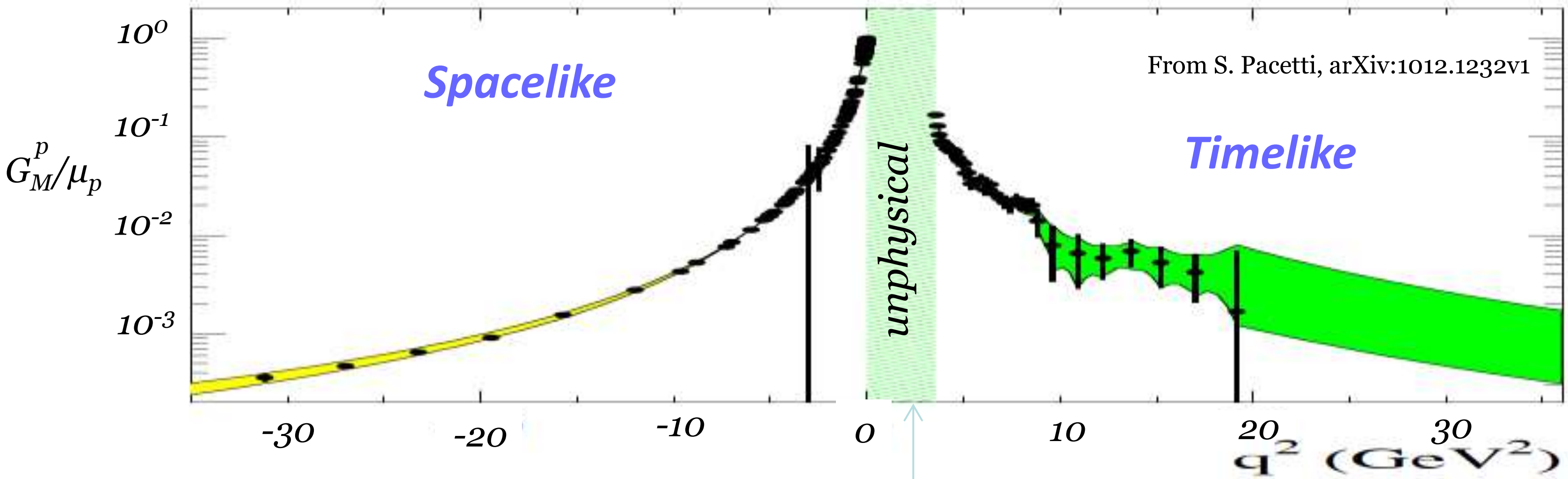
electron scattering

annihilation $\bar{p}p \leftrightarrow e^+e^-$

$q^2 > 4m_p^2$

e^- scattering (Jlab…. A2/Mainz)

$e^+e^- \leftrightarrow \bar{p}p$ (BES, Novosibirsk, PANDA)



Dispersion relations:

$q^2 < 0$

$$G(q^2) = \frac{1}{\pi}\left[\int_{4m_\pi^2}^{4m_p^2} \frac{\operatorname{Im} G(s)\,ds}{s-q^2} + \int_{4m_p^2}^{\infty} \frac{\operatorname{Im} G(s)\,ds}{s-q^2}\right]$$

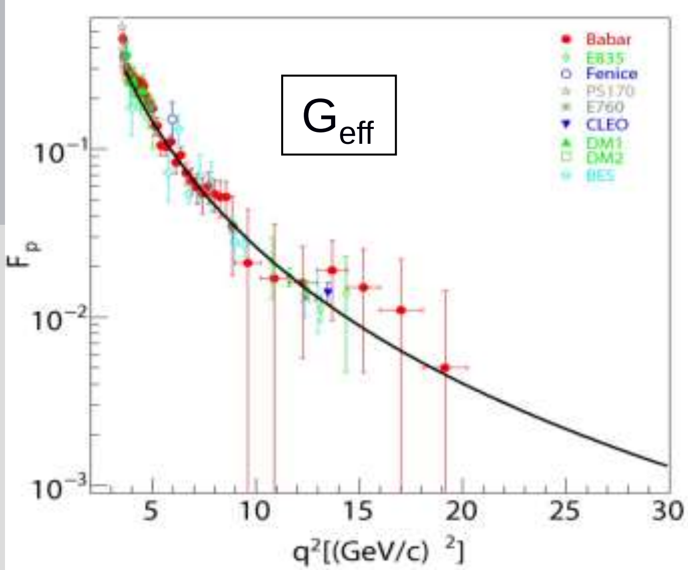
Proton EM Form Factors in Time-Like Region

Cross-sections: $\bar{p}p \rightarrow e^+e^-$

$$\sigma_{tot} \sim \left|G_{eff}\right|^2 \qquad \tau = \frac{q^2}{4M_p^2}$$

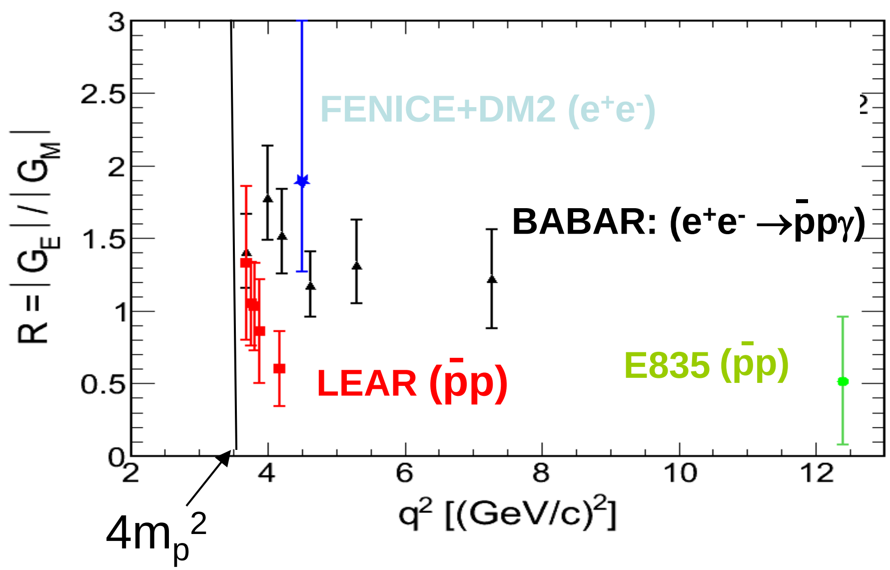
$$G_{eff} = |G_M| \quad if \quad |G_E| = |G_M| \quad or \quad \tau >> 1$$

$$\left|G_{eff}\right|^2 = \frac{2\tau\left|G_M\right|^2 + \left|G_E\right|^2}{2\tau + 1}$$



angular distributions: $\bar{p}p \rightarrow e^+e^-$

$$\frac{d\sigma}{d(\cos\theta_{CM})} = \frac{\pi\alpha^2}{8M_p^2\sqrt{\tau(\tau-1)}}\left[\tau\left|G_M^{TL}\right|^2(1+\cos^2\theta_{CM}) + \left|G_E^{TL}\right|^2\sin^2\theta_{CM}\right]$$



G_{eff} : large error bars above 13 (GeV/c)^2

$|G_E/G_M|$:

- Inconsistent data above threshold
- Lack of precise data above 5 (GeV/c)^2

Goal of PANDA Measurements

Extract Time-Like $|G_E|$ and $|G_M|$ for proton up to 14 $(GeV/c)^2$ from lepton angular distributions in $\bar{p}p \rightarrow e^+e^-$ reaction and measure G_{eff} up to 30 $(GeV/c)^2$

Two major challenges:

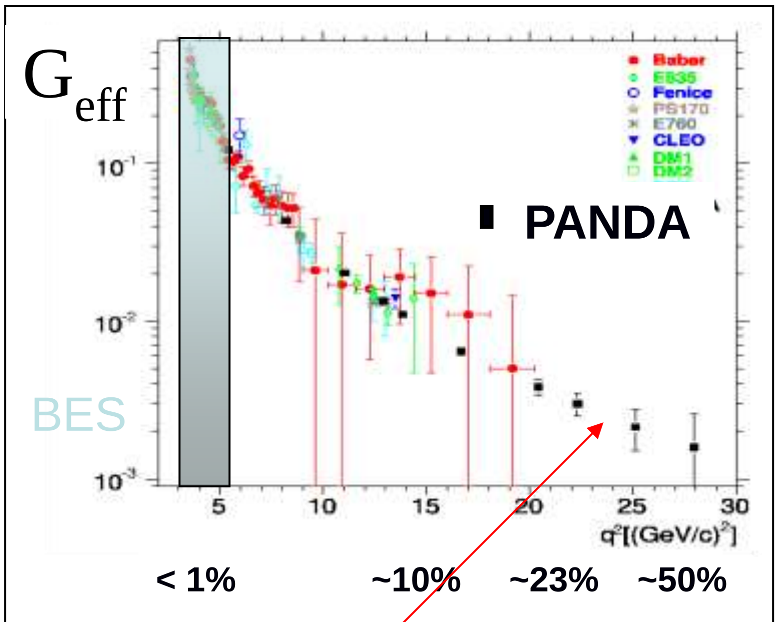
- Decrease of sensitivity to G_E with increasing q^2
- Huge hadronic background
  $\sigma(\bar{p}p \rightarrow \pi^+\pi^-) / \sigma(\bar{p}p \rightarrow e^+e^-) \sim 10^6$

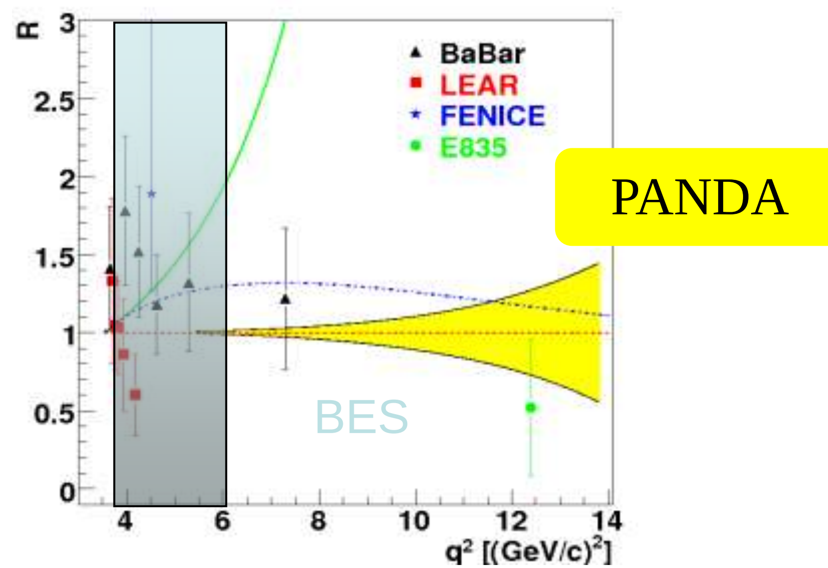
Time-Like Form Factor Measurement with PANDA : Estimates of Precision

$\mathcal{L}$ =2 fb^{-1}

Sudol et al. EPJA 44 (2010) 373

-VDM: F. Iachello et al., PLB43, 171 (1973)
…extended VDM, PRC66, 045501 (2002)
Egle Tomasi-Gustafsson et al., EPJA24 (2005) 419





pQCD ?

PANDA will bring

Precise determination of $|G_E|$ and $|G_M|$ up to 14 (GeV/c)^2

G_{eff} up to 30 (GeV/c)^2 : transition towards perturbative QCD

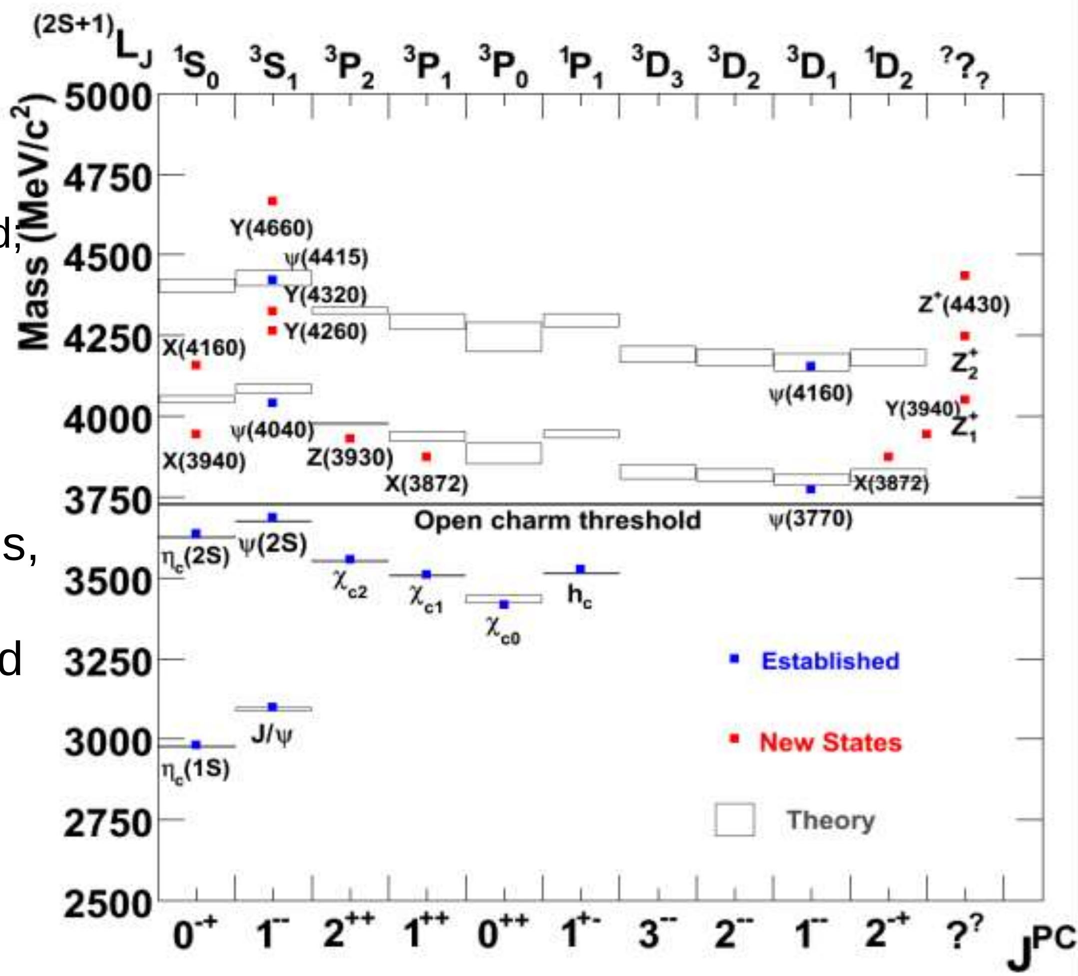
Charmonium-like Spectroscopy with Antiproton Annihilation

Jim Ritman

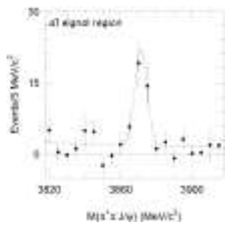
Charmonium Spectroscopy

New observations: We must go beyond simple quark models

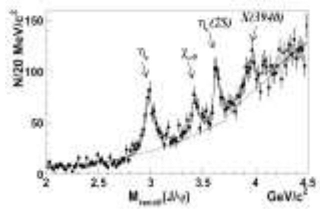
- new „XYZ“ states (Belle, BaBar, CLEO, CDF, D0, LHCb …)
  - masses are poorly known;
  - often widths are just upper limits;
  - few final states have been studied;
  - statistics are poor;
  - quantum number assignment is possible for few states;
  - some resonances need confirmation…
- new degrees of freedom: molecules, tetraquarks, gluonic excitations?
- open questions below $D\bar{D}$ threshold widths, branching
- conventional states above $D\bar{D}$
- high *L* states: access in $\bar{p}p$ but not in e^+e^-



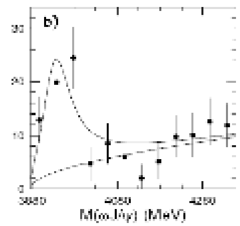
X(3872)
PRL 91,262001 (2003)



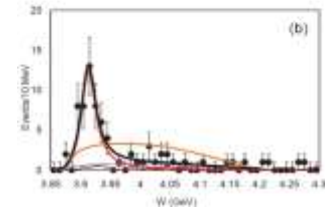
X(3940)
PRL 98,082001 (2007)



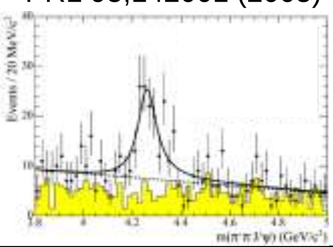
Y(3940)
PRL 94,182002 (2005)



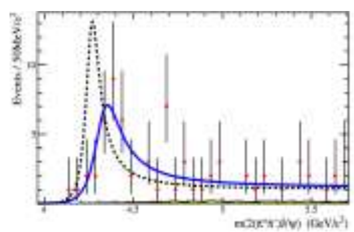
X(3915)
PRL 104,092001 (2010)



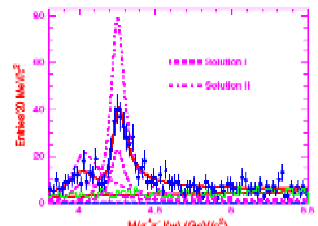
Y(4260)
PRL 95,142001 (2005)



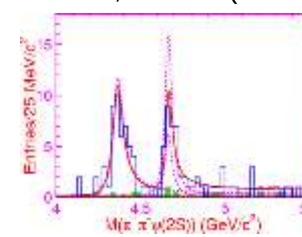
Y(4350)
PRL 98,212001 (2007)



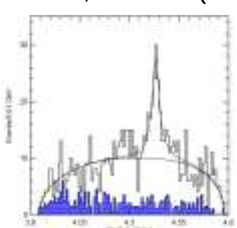
Y(4008)
PRL 99,182004 (2007)



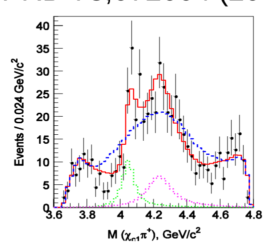
Y(4660)
PRL 99,142002 (2007)



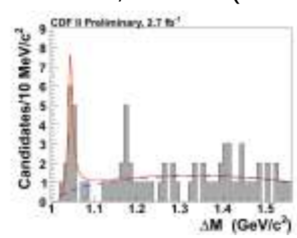
Z(4430)$^-$
PRL 100,142001 (2008)



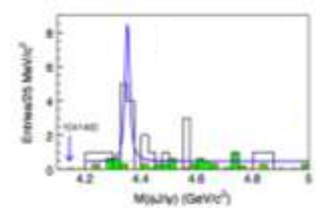
Z_1^- & Z_2^-
PRD 78,072004 (2008)



Y(4140)
PRL 102,242002 (2009)



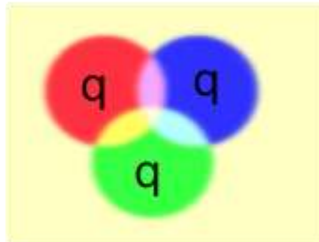
X(4350)
PRL 104,112004 (2010)



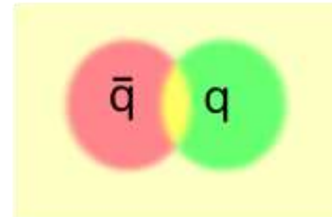
in addition to many more open charm states

Beyond standard quark configurations

- QCD allows much more than what we have observed:

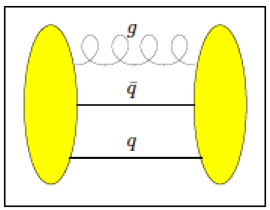


Baryons

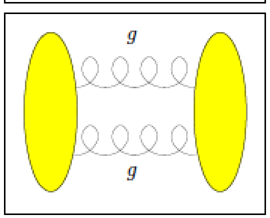


Mesons

Exotics:

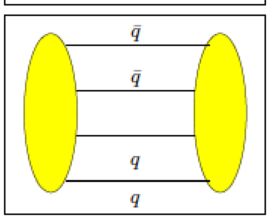


hybrid:
with gluon excitation

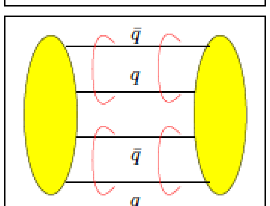


glueball:
pure gluon state

} may have J^{PC} not allowed for $q\bar{q}$



4 quark state:
compact 4–quark state

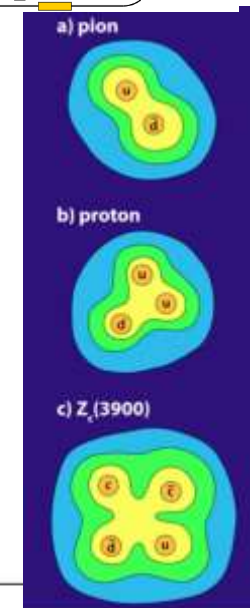


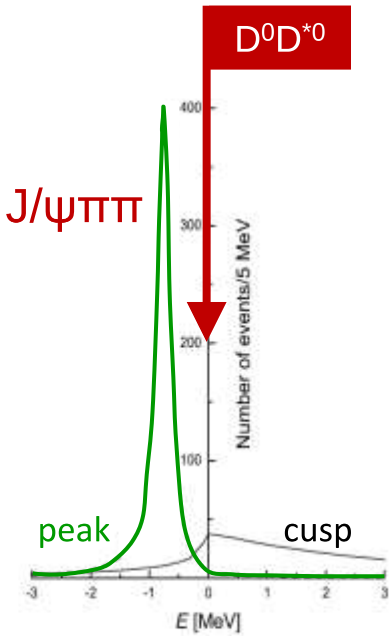
hadronic molecule:
bound state of two mesons

Courtesy C. Hanhart

How can PANDA contribute?

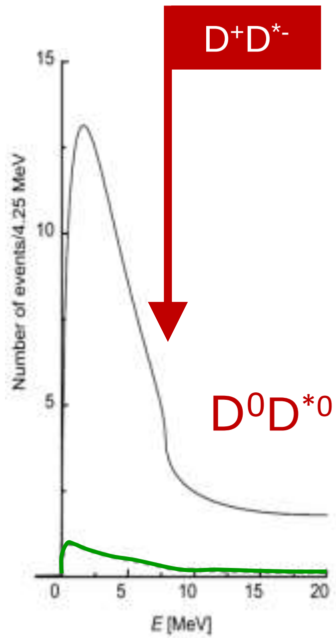
- $J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$, $\chi_c\gamma \rightarrow J/\psi\gamma\gamma$, $J/\psi\gamma$, $J/\psi\eta$, $\eta_c\gamma$
- direct formation in $\bar{p}p$: line shapes !
- Exotics: compare formation with production
- d target: $\bar{p}n$ with p spectator tagging, e.g. $Z^-(3900)$



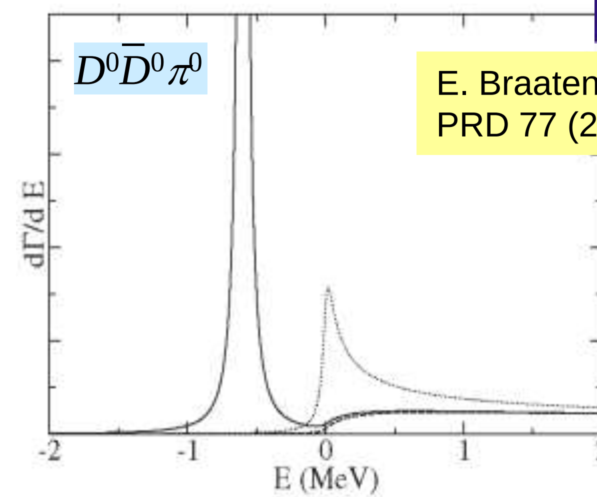


virtual state

binding state



C. Hanhart *et al.*,
PRD 76 (2007) 034007



E. Braaten, M. Lu,
PRD 77 (2008) 014029

Compare lineshapes
in different final states!

X(3872)

Upper limit on the branching ratio by LHCb

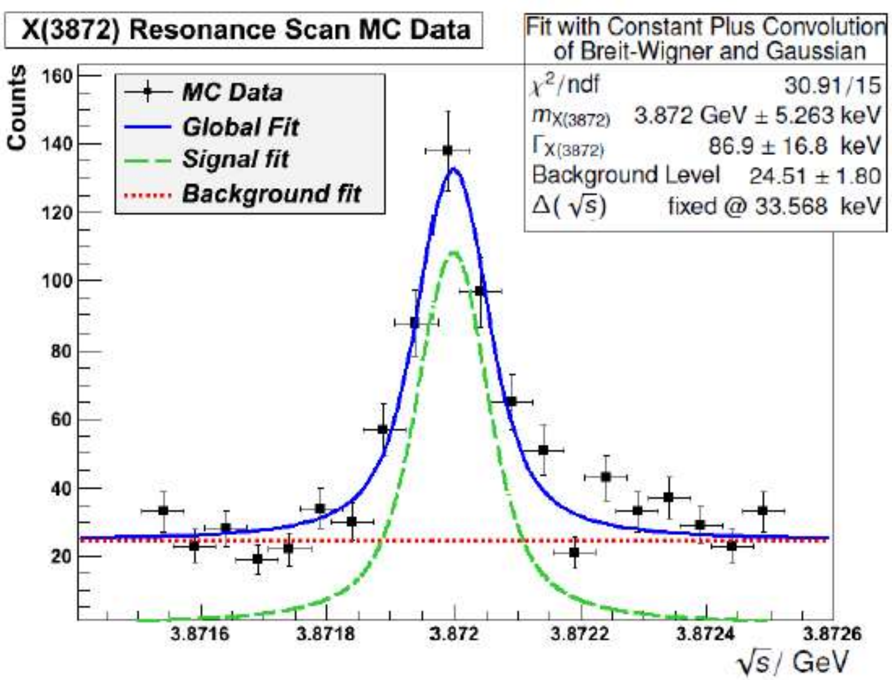
$$BR(X \rightarrow \bar{p}p) < 0.002 * BR(X \rightarrow J/\Psi \pi^+ \pi^-)$$

And $BR(J/\Psi \pi^+ \pi^-) > 0.026$ [pdg12]

Implies:

$\Gamma < 1.2$ MeV

$$\sigma(\bar{p}p \rightarrow X(3872)) \sim (67 \text{ +- ?}) \text{ nb}$$



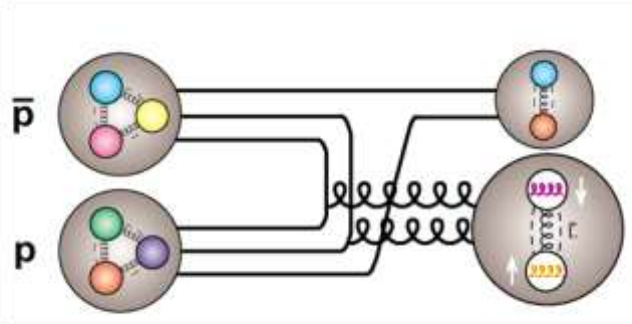
Here: assume σ=50 nb

"Low lumi" – mode $2\text{x}10^{31}$

Mass resolution < 100 keV

M. Galuska

Exotics production in $\bar{p}p$ collisions

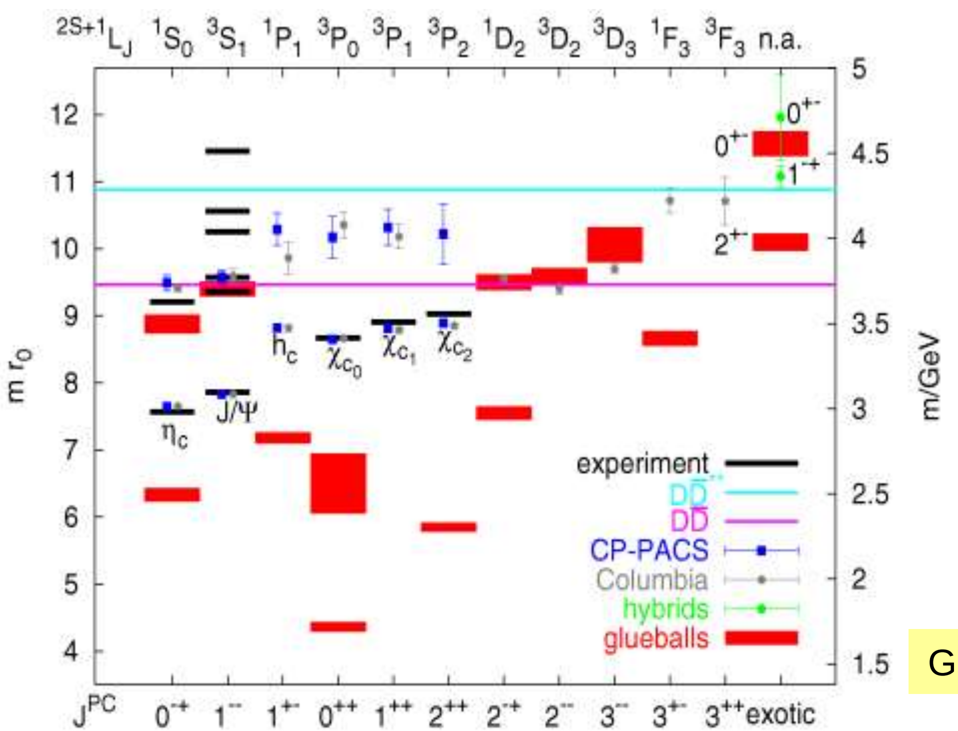


- Production: all J^{PC} accessible

Hybrids

Gluon	1^{-+}	1^{+-}
$^1S_{0,}$ 0^{-+}	1^{++}	1^{--}
$^3S_{1,}$ 1^{--}	0^{+-}	0^{-+}
	1^{+-}	1^{-+}
	2^{+-}	2^{-+}

J^{PC} exotic

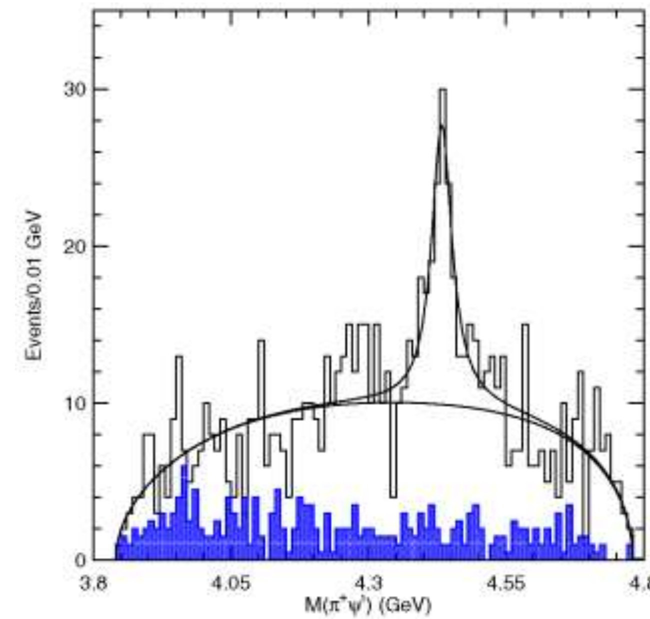


Exotic J^{PC} would be clear signal

G.Bali, EPJA 1 (2004) 1 (PS)

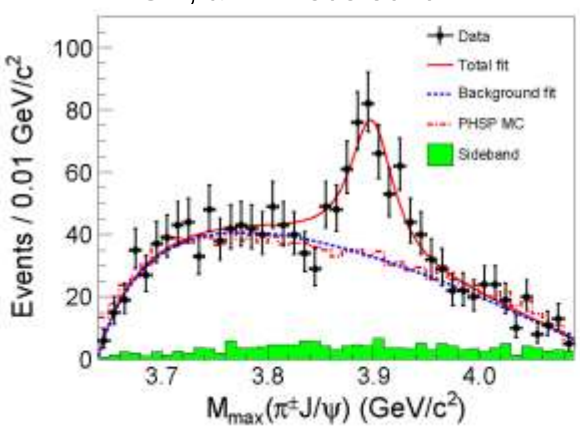
Non-$q\bar{q}$ Mesons: Charged $c\bar{c}$-like States

- Manifestly exotic: tetra-quark or molecular nature
- $Z(4430)^{\pm}$ seen by Belle, not confirmed by BaBar
- $Z(3900)^{\pm}$ seen by BESIII, Belle
- $X(4050)^{\pm}$, $X(4250)^{\pm}$ seen by Belle

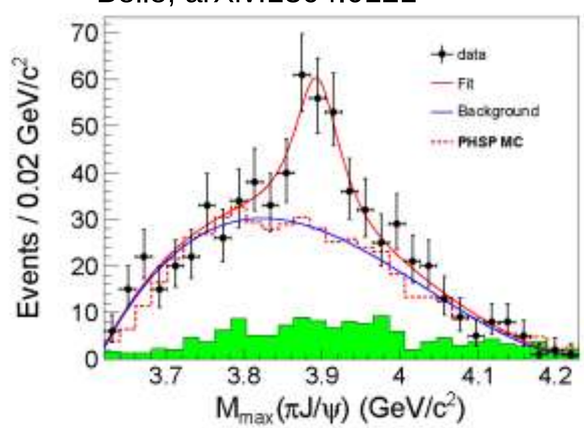


Belle,
PRL 100 (2008) 142001

BESIII, arXiv:1303.5949



Belle, arXiv:1304.0121



Non-$q\bar{q}$ Mesons: Charged $c\bar{c}$-like States

- Planned studies with PANDA
  - *production* in $p\bar{p}$:

    $\bar{p}p \rightarrow Z(4430)^{\pm}\,\pi^{\mp}$

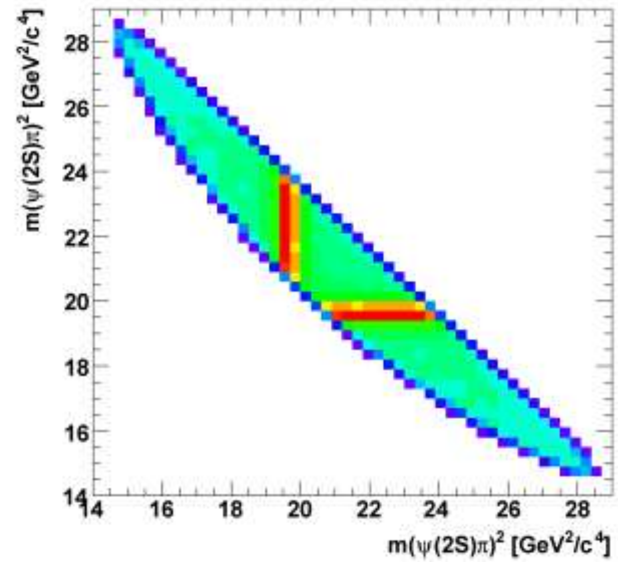
    $Z(4430)^{\pm} \rightarrow \psi(2S)\,\pi^{\pm}\,x$
  - *formation* in $\bar{p}n$:

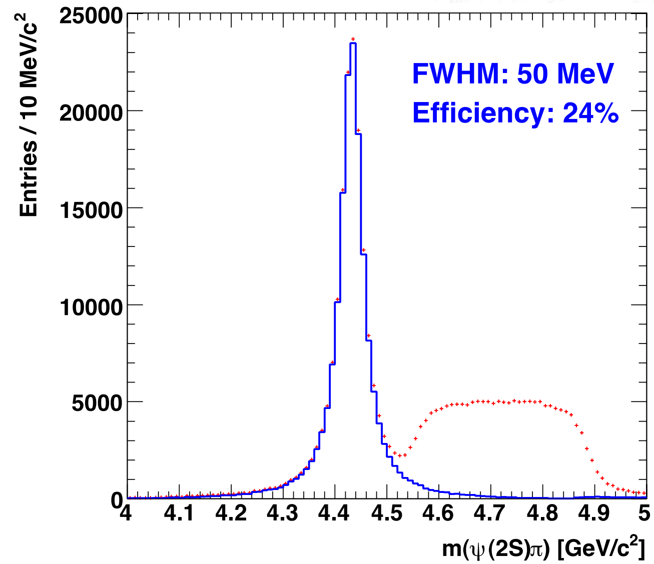
    $\bar{p}d \rightarrow Z(4430)^{-}\,p_{spectator}$

    $\rightarrow \psi(2S)\,\pi^{-}\,p_{spectator}$

    must reconstruct the spectator proton

    reduced mass resolution

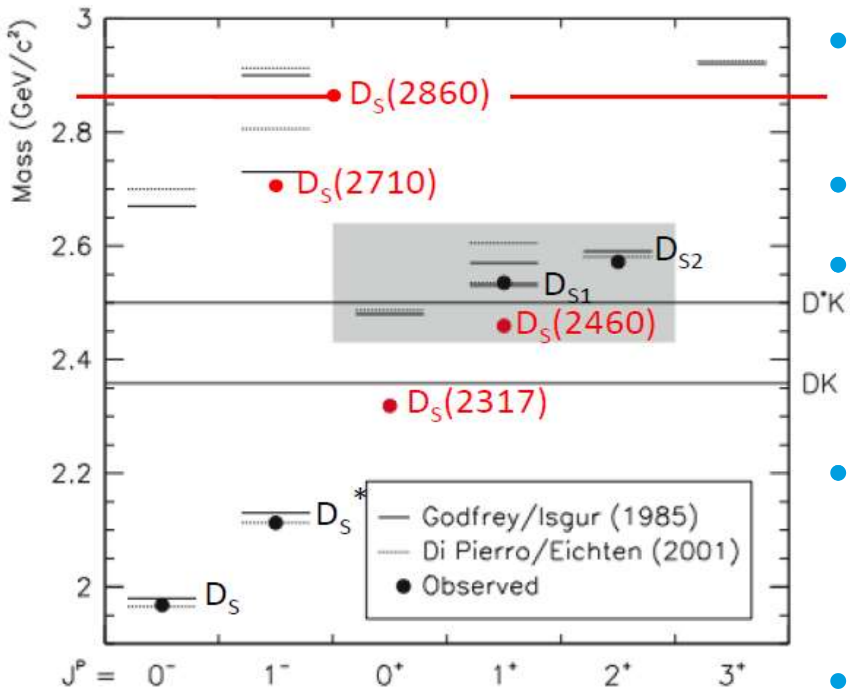


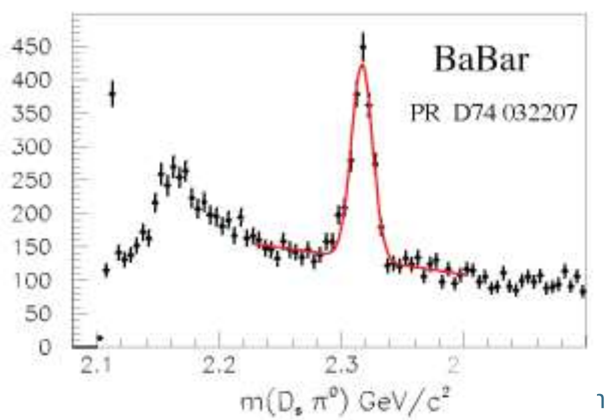


Open Charm Spectroscopy with Antiproton Annihilation

Jim Ritman

Open Charm: The D_s Spectrum



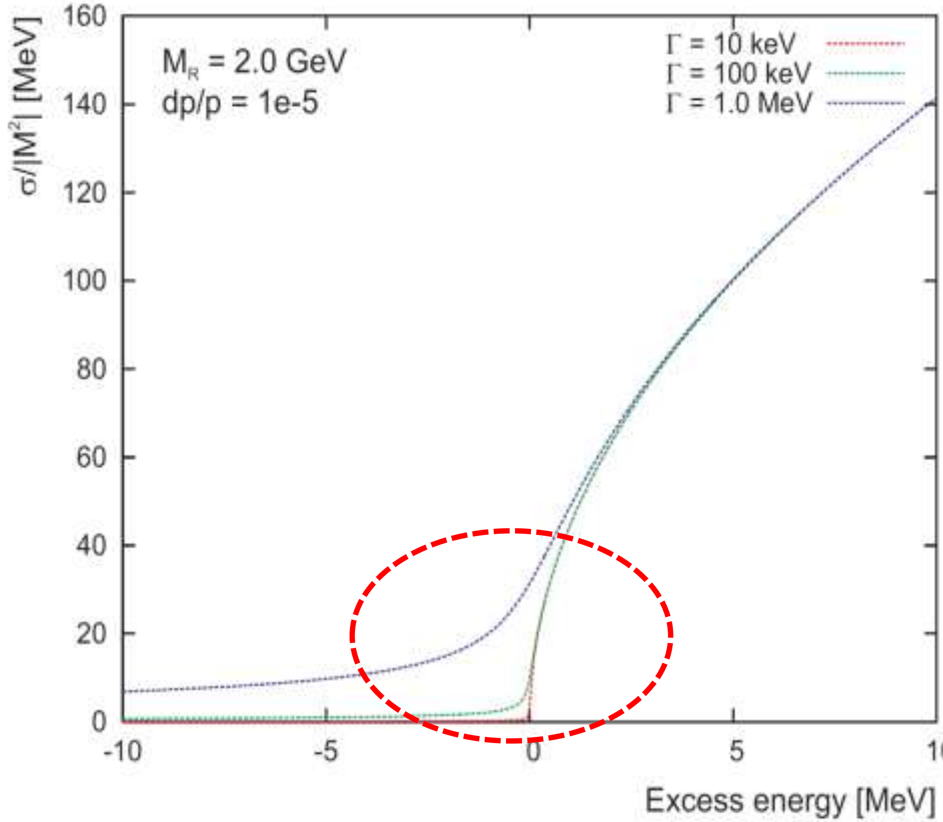


- Th./expt. in qualitative agreement for D states, but some details open
- Many new D_J mesons (e.g. LHCb)
- new narrow states (2003): $D_s^*(2317)$ and $D_s^*(2460)$, (and other broader states more recently)
- masses significantly lower than quark model expectation, and just below DK and D^*K threshold
- Widths are only upper limits
- Interpretation unclear: DK / D^*K molecules, tetraquarks, chiral doublers, …? Sensitive to width

Method: Threshold Scan

- reaction: $\bar{p}p \rightarrow D_s^{\pm} D_{s0}^{*}(2317)^{\mp}$

$$\frac{\sigma(s)}{|M^2|} = \frac{\Gamma}{4\pi\sqrt{s}} \int_{-\infty}^{\sqrt{s}-m_{D_s}} \mathrm{d}m \frac{\sqrt{\left(s-(m+m_{D_s})^2\right)\left(s-(m-m_{D_s})^2\right)}}{\left(m-m_{D(2317)}\right)^2+(\Gamma/2)^2}$$

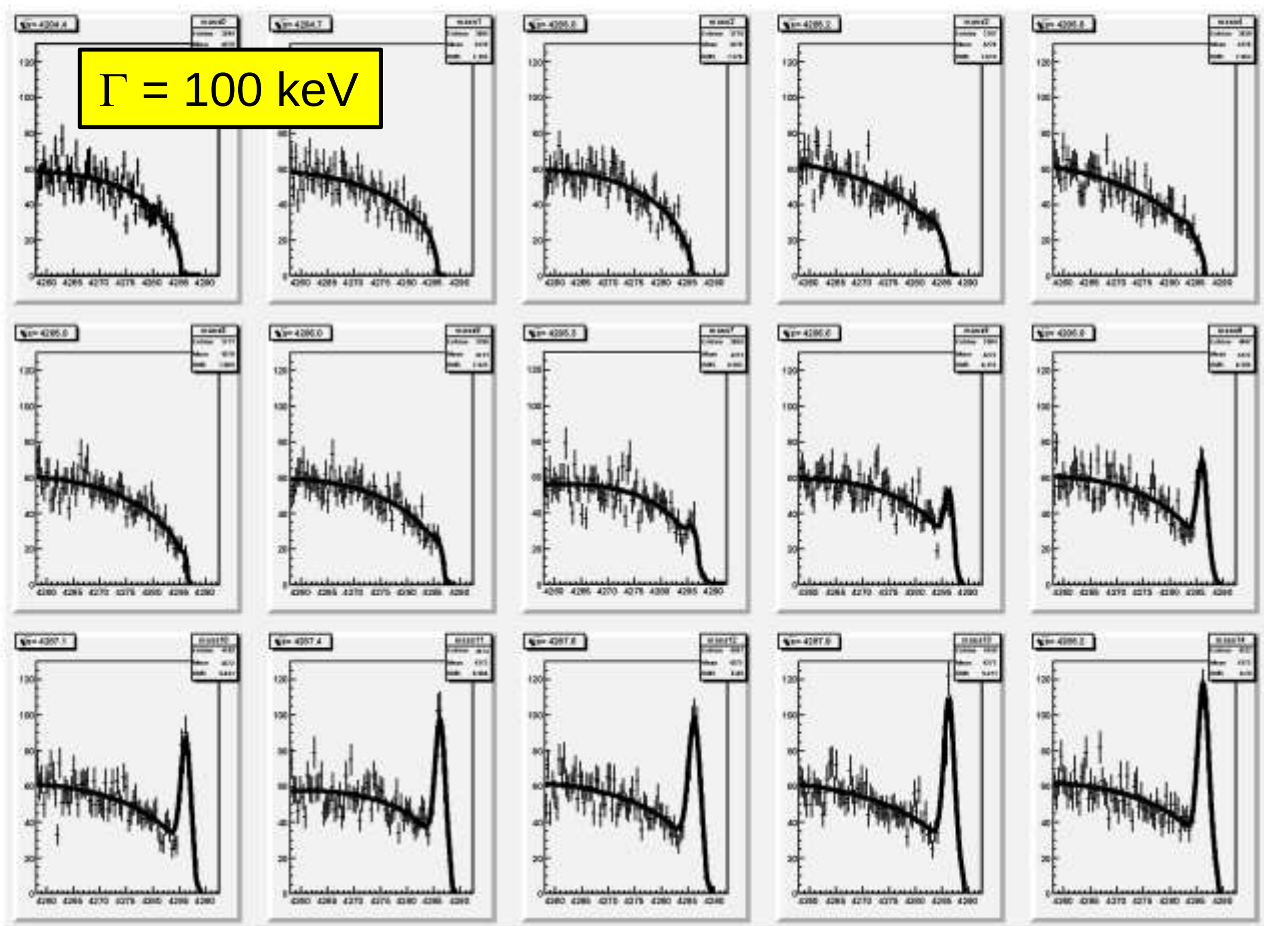


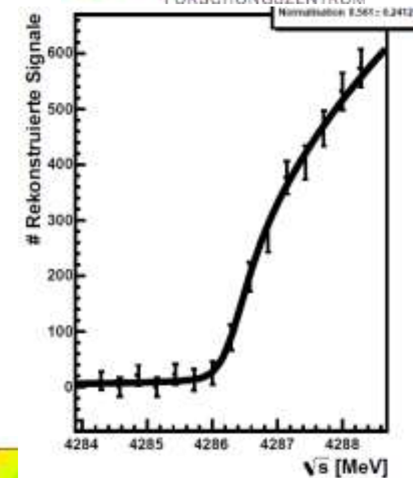
- excitation function only depends on m and Γ of $D_s(2317)$
- experimental accuracy determined by beam quality (Δp, σ_p/p), not by detector resolution

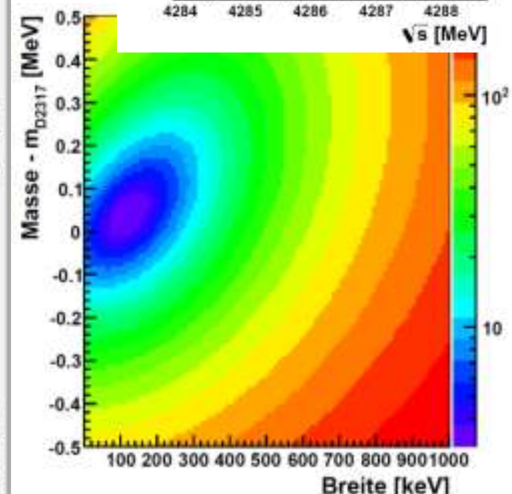
Simulation Results: Energy Scan

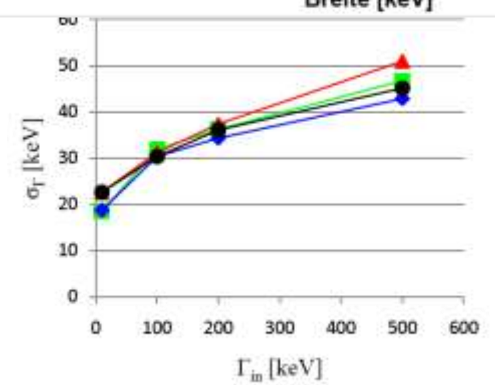
$M_{sum} = M_{miss}(D_s) + M(D_s)$

Γ = 100 keV







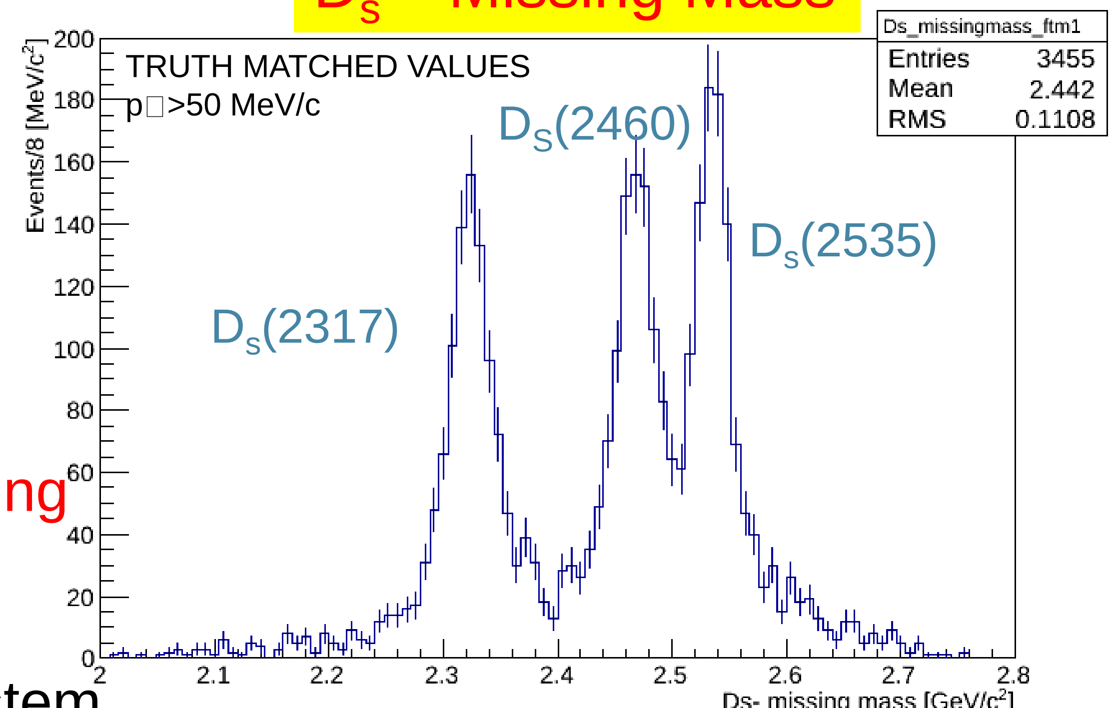


Challenges in Open Charm Spectroscopy

Goals

- Cross section measurement (1-100 nb ?)
- Measure width (&mass) with threshold scan
- Mixing between states with same spin, e.g. $D_{s1}(2460)$&$D_{s1}(2535)$
- Chiral Symmetry Breaking very precise mass measurement of chiral partners heavy light system $D_{s0}(2317)$ & $D_{s1}(2535)$

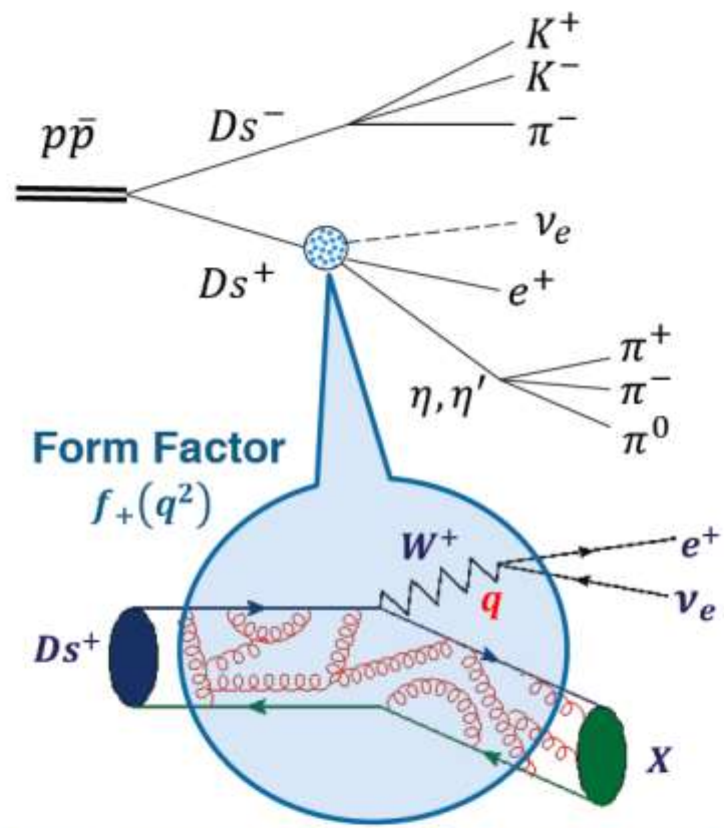
D_s^- Missing Mass



Semileptonic D_s Decays

- Semileptonic decay allow precision measurement of CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$
- Form factor quantifies transition
- FF provides new method to improve η,η' mixing angle

- Exclusive reco. of both D mesons
- Competitiveness requires full FAIR facility.



$$\frac{d\Gamma(Ds \to \nu l X)}{dq^2} = \frac{{G_F}^2}{24\pi^3}|V_{cx}|^2 {p_x}^3 |f_+(q^2)|^2$$

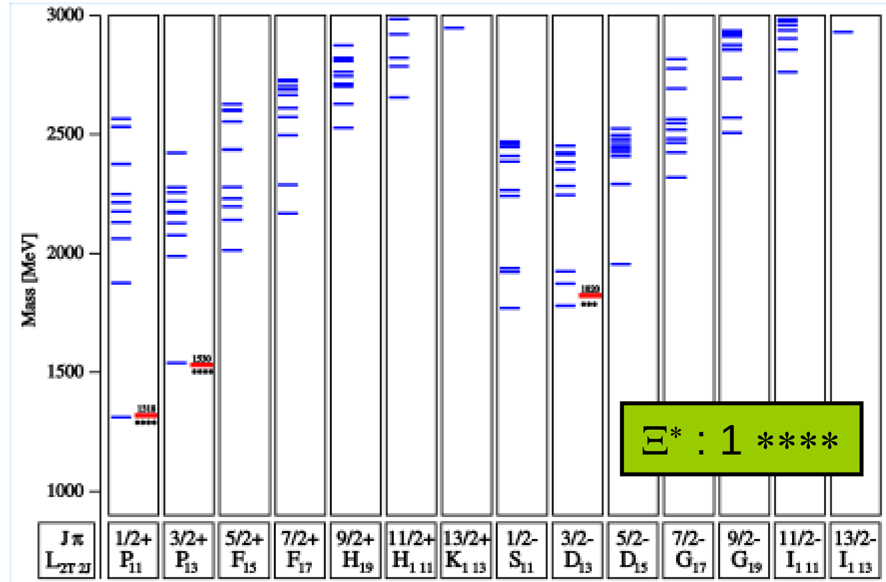
Baryon-Antibaryon Spectroscopy with Antiproton Annihilation

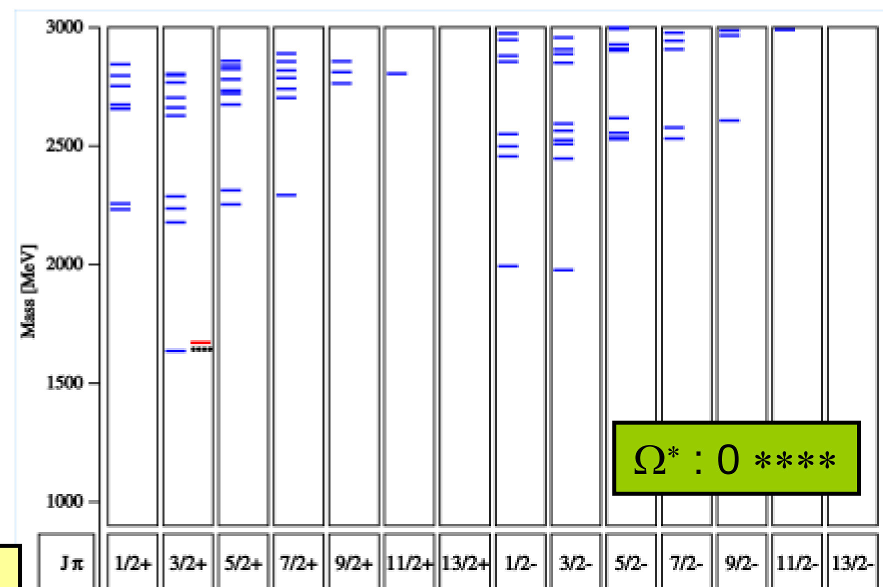
Jim Ritman

Baryon Spectroscopy

- significant fraction of $\bar{p}p$ cross section into final state $B\,\bar{B}$ + mesons
- almost nothing known on excited states of Ξ or Ω hyperons
- $\sigma(\bar{p}p \rightarrow \Xi\bar{\Xi}) \approx \mu b$

  $\sigma(\bar{p}p \rightarrow \Omega\bar{\Omega}) \approx 0.1\ \mu b$

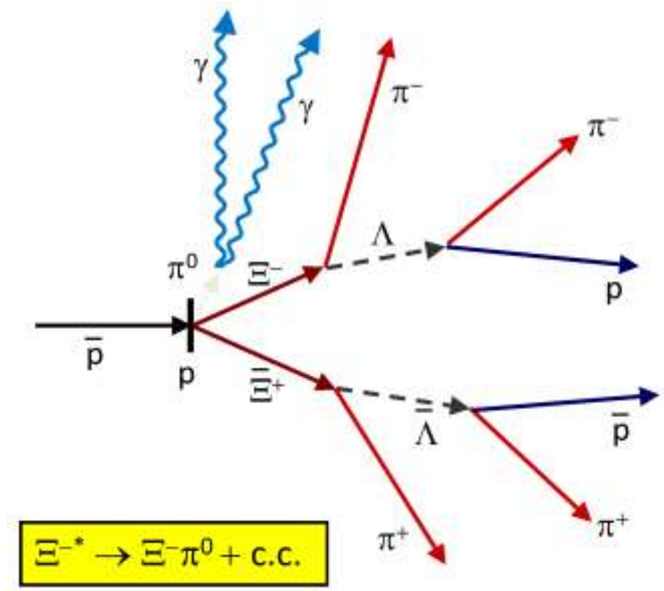


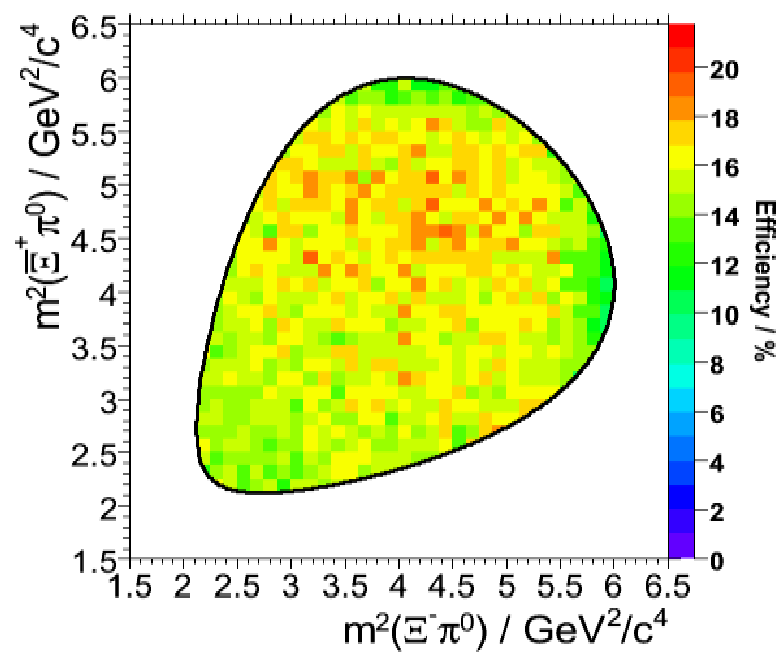


Quark Model: B. Metsch et al.

Ξ^* detection with PANDA

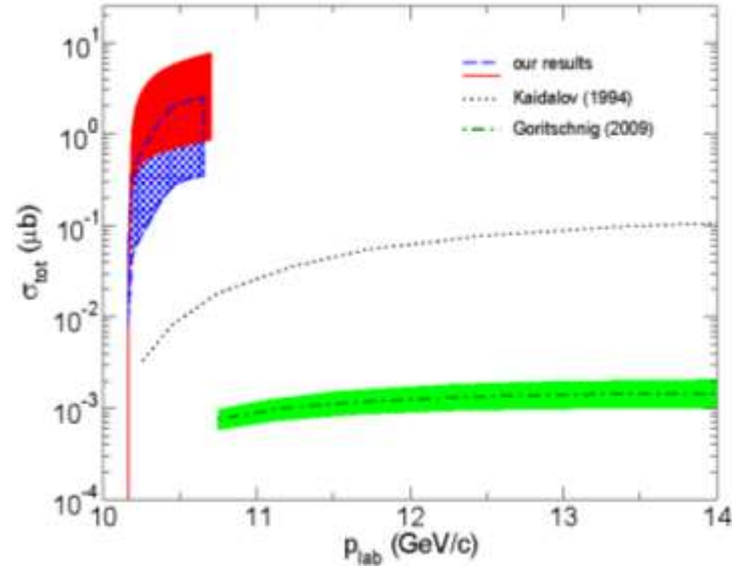
- characteristic event topology
- $\sigma \sim \mu b$: ~10^7 Ξ /d produced
- final states to be studied:
  $\Xi^* \rightarrow \Xi\,\pi,\ \Xi\,\eta,\ \Lambda\,\bar{K},\ \Sigma\,\bar{K},$
  $\Xi(1530)\,\pi,\ \Xi\,\pi\,\pi,\ \ldots$
- benchmark channel:
  6.57 GeV/c $\bar{p}\,p \rightarrow \Xi^-\,\bar{\Xi}^+\,\pi^0$
- no empty regions or discontinuities in Dalitz plot





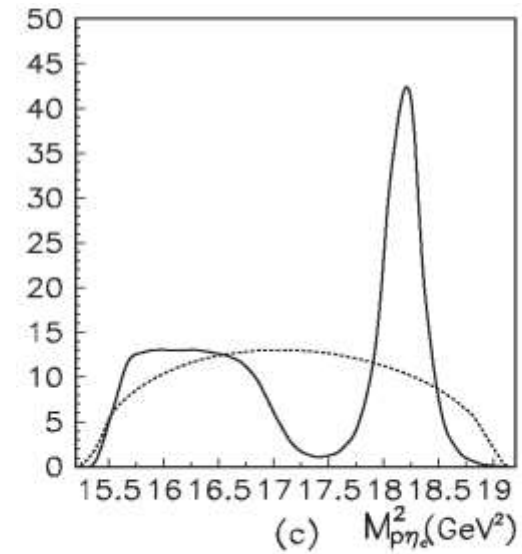
Charm Baryons with PANDA

- identification challenging
- Λ_c and Σ_c : max E* < 1 GeV
- cross section may reach ~1μb, but large uncertainty



J. Haidenbauer, G. Krein, PLB 687 (2010) 314

- predicted narrow hidden charm baryon states
- can be searched for with PANDA in $N^*_{cc} \rightarrow N\,\eta_c$ and $N^* \rightarrow N\,J/\psi$ decay

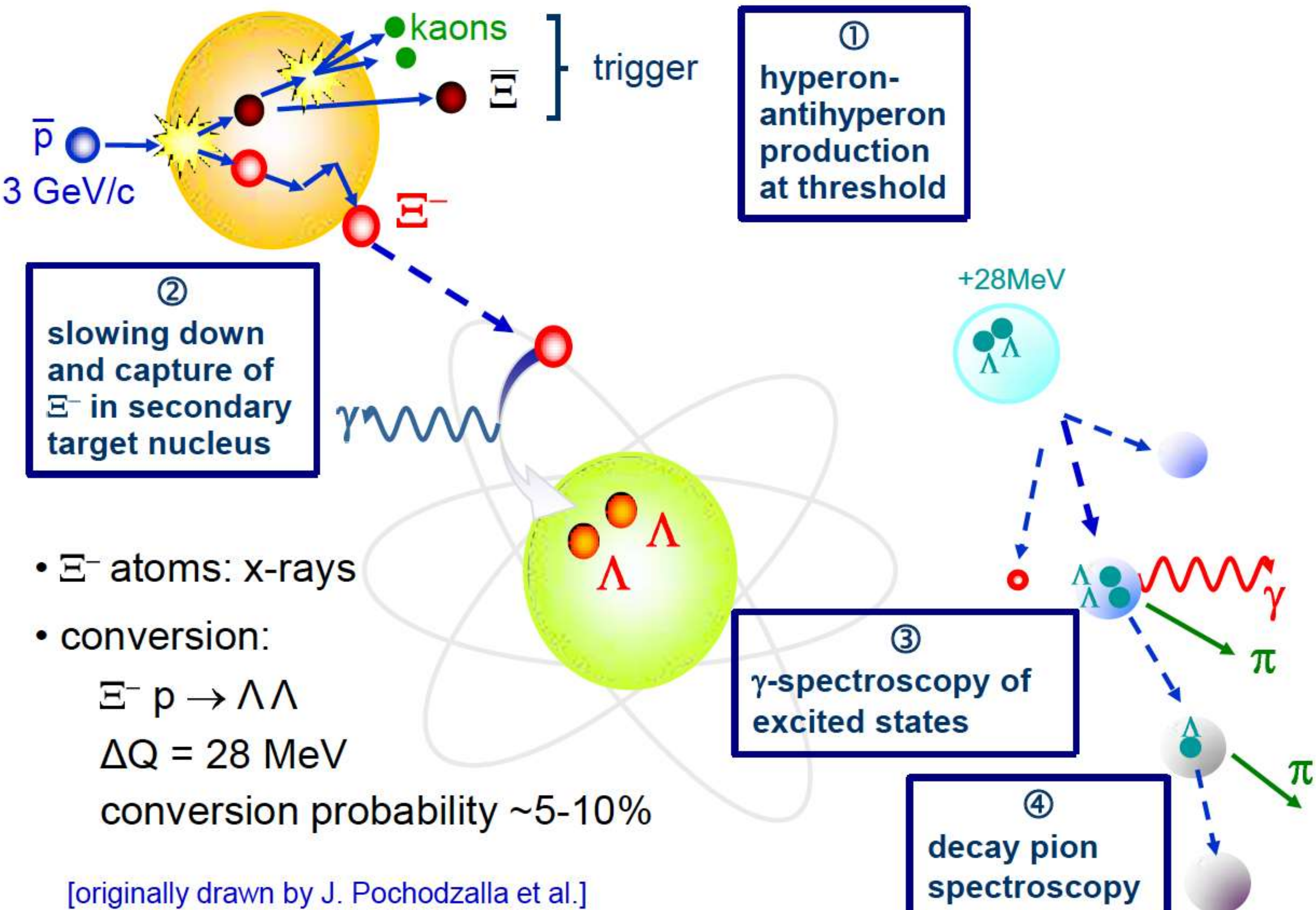


J.J. Wu *et al.*,
PRC 84 (2011) 015202

Hadron Interactions:
Double Strange Hypernuclei

Jim Ritman

Production Mechanism and Detection Strategy



- Ξ^- atoms: x-rays
- conversion:

  $\Xi^- p \rightarrow \Lambda\Lambda$

  $\Delta Q = 28$ MeV

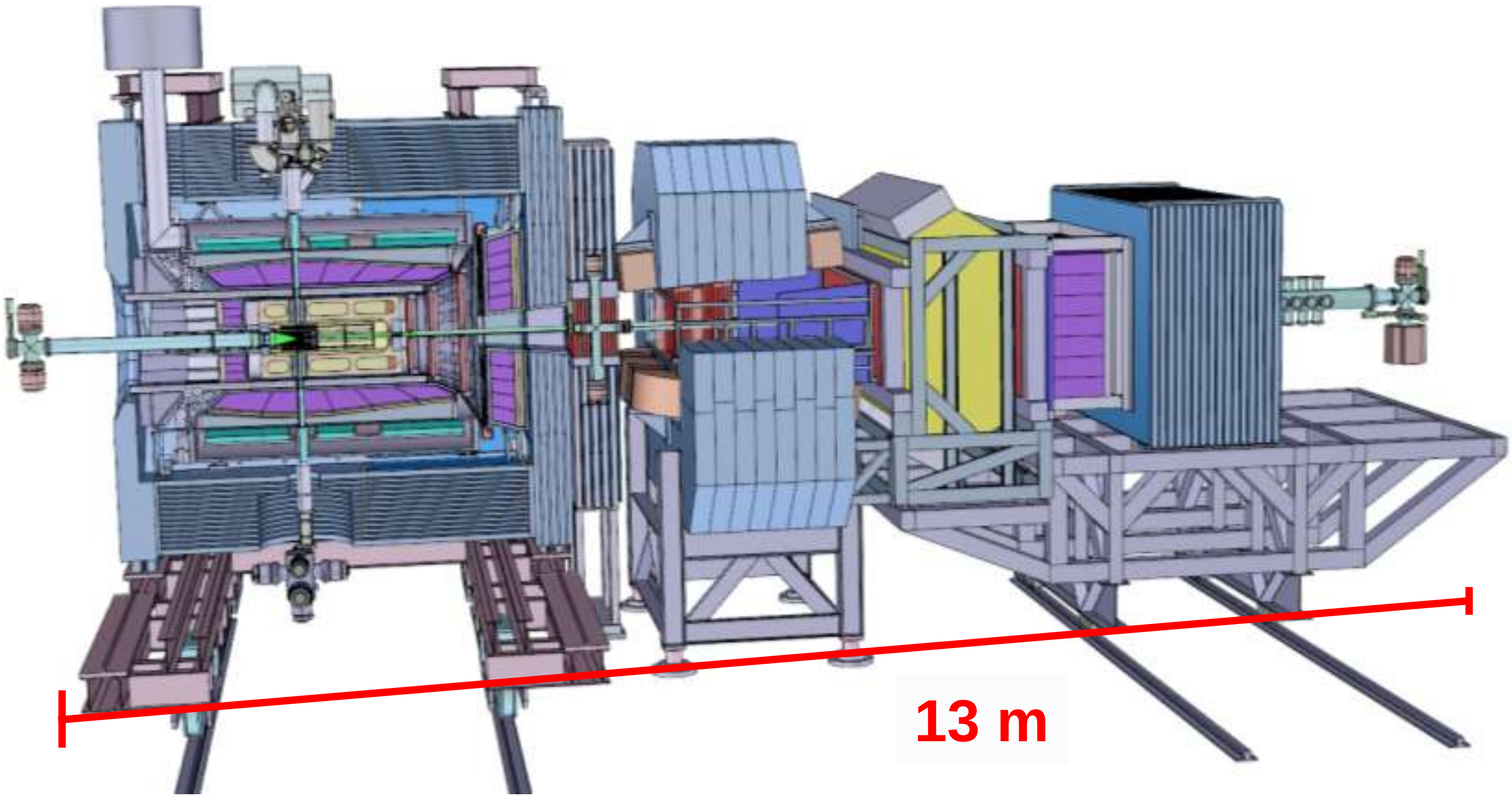
  conversion probability ~5-10%

[originally drawn by J. Pochodzalla et al.]

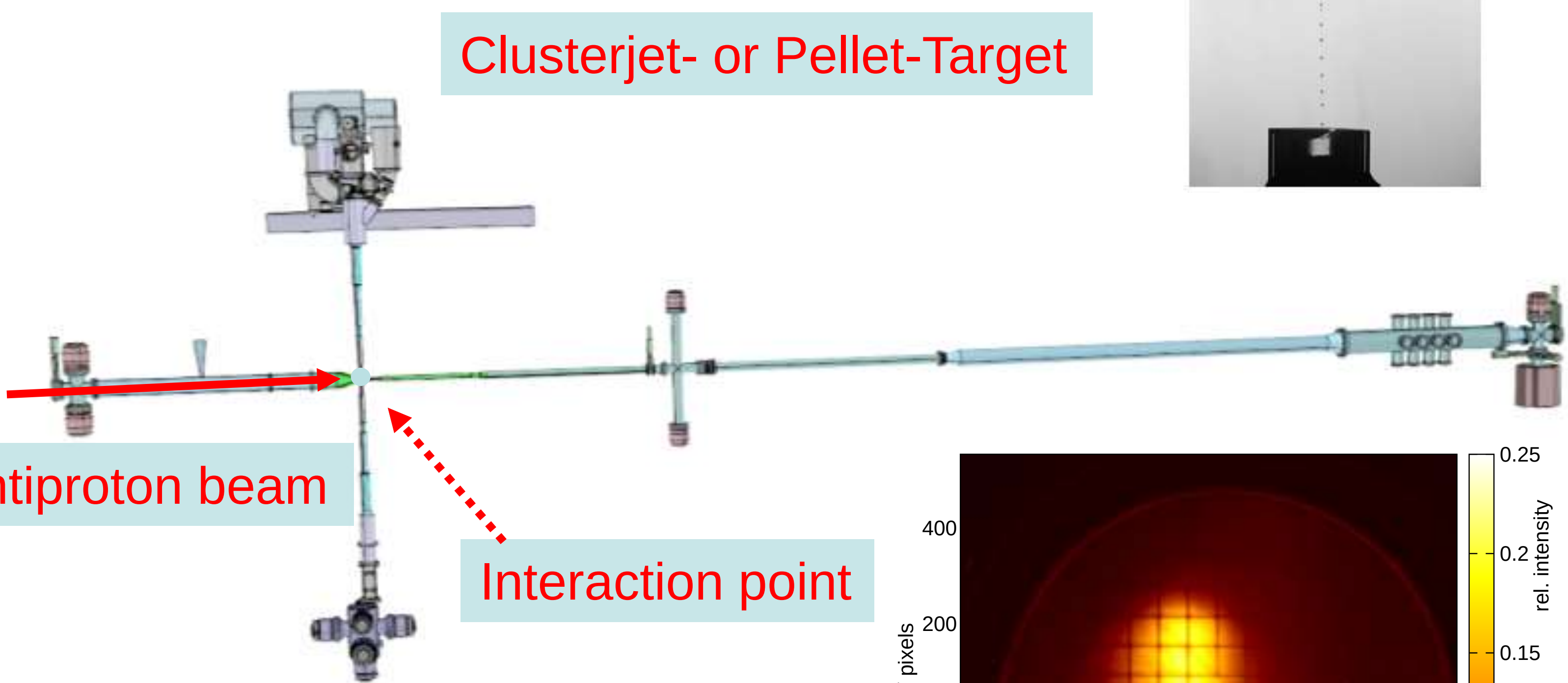
The PANDA Detector

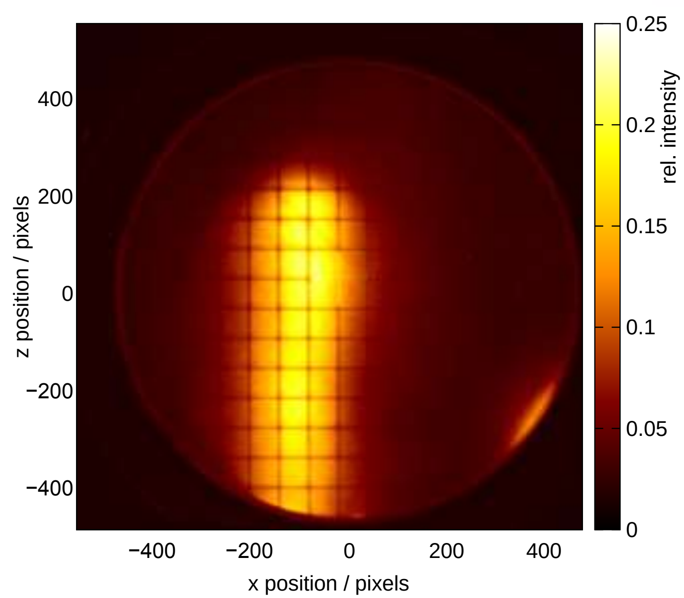
Jim Ritman

All PANDA Systems



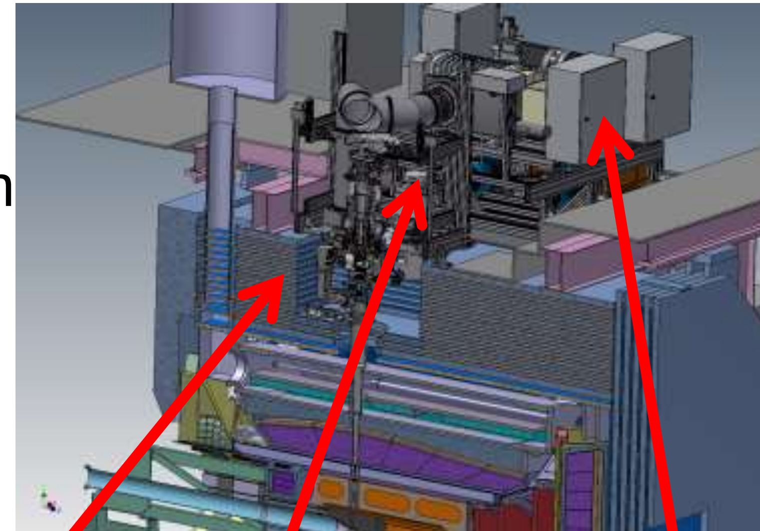
Target Systems



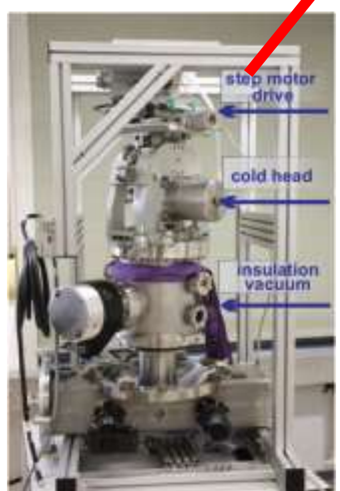


Target Systems

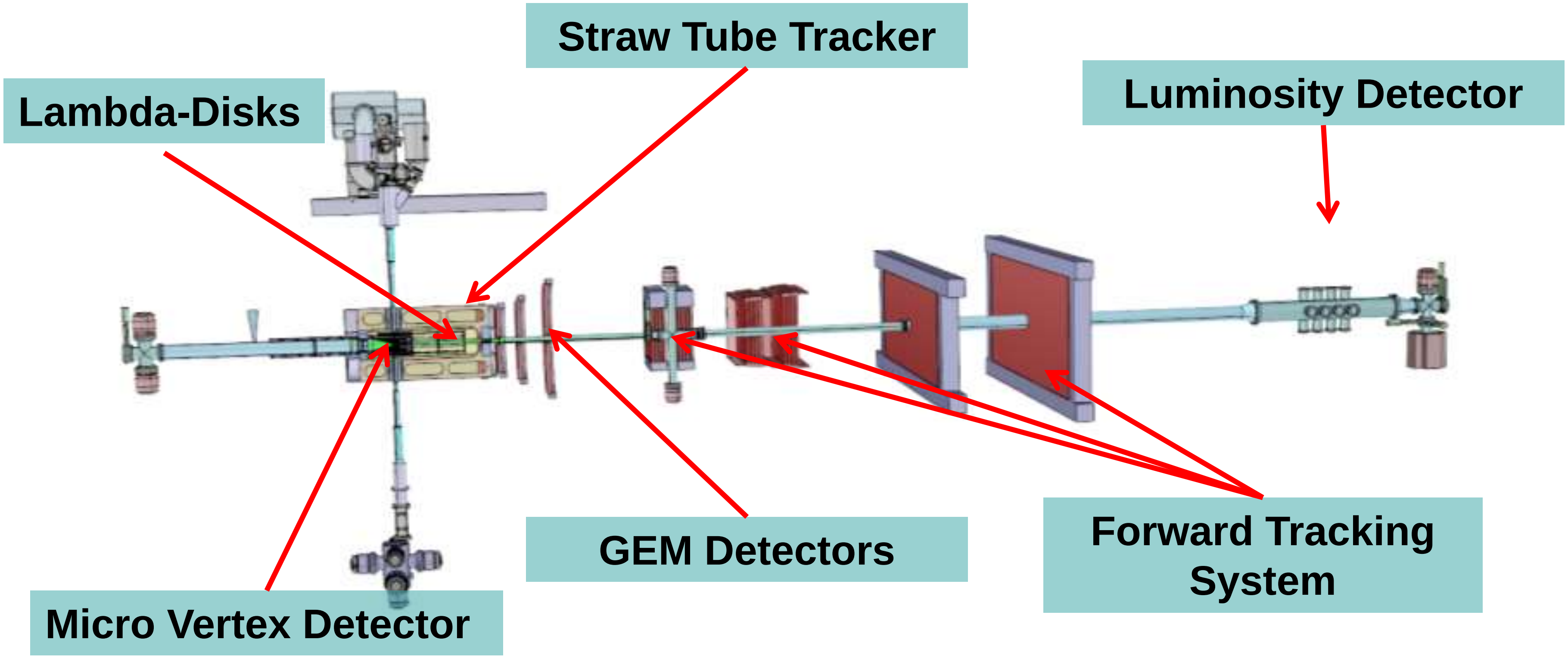
- Cluster target under construction $2x10^{15}$ / cm^2 @ 2 m from nozzle
- Pellet Target with two modes:
  - Large pellets → tracking
  - Small pellets → uniform lumi




Technical Design Report for the
PANDA Internal Targets:
The Cluster-Jet Target and Developments for the Pellet Target
PANDA Collaboration



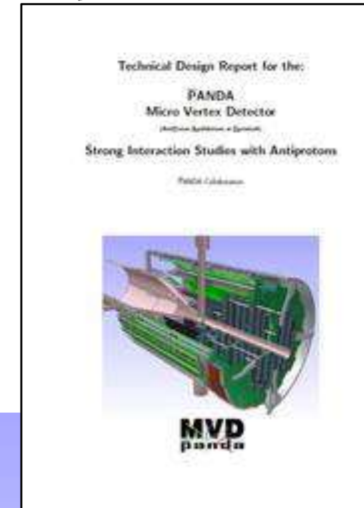
Tracking Detectors

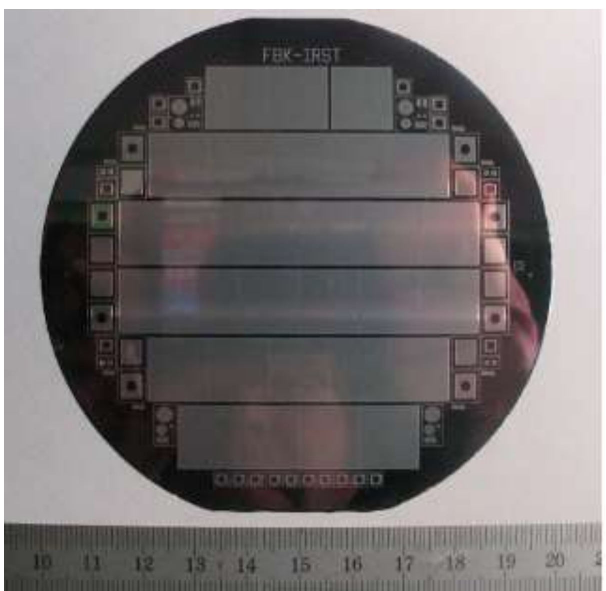


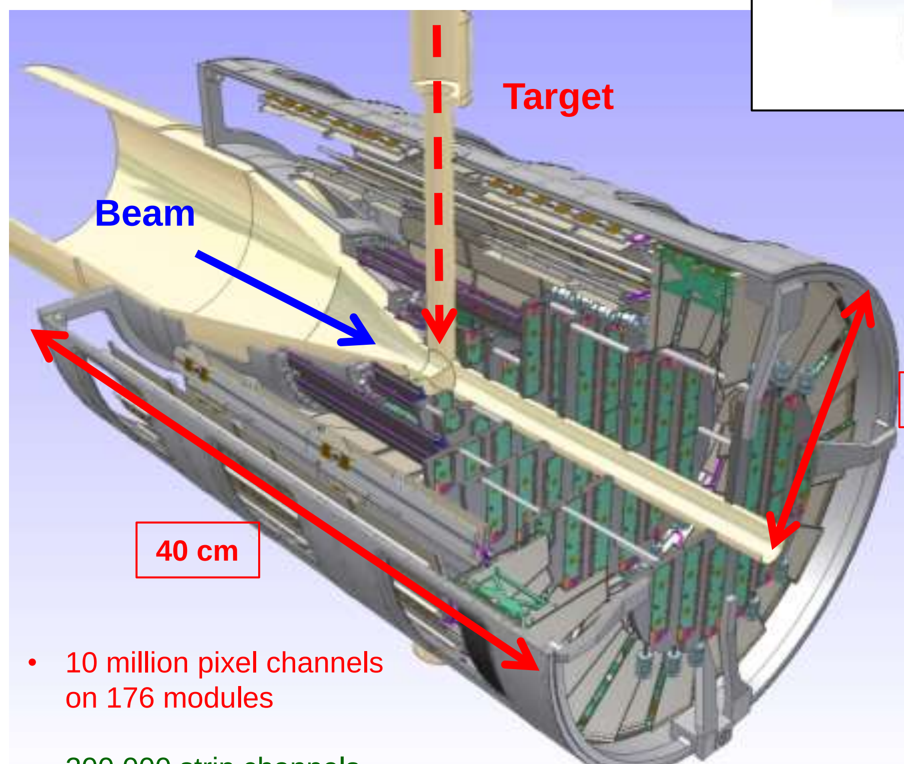
Micro Vertex Detector   MVD

- Measure open charm and strangeness, improve tracking resolution, self-triggering continuous readout

- Realize strip readout
  with PASTA ASIC (modified TOFPET)







- 10 million pixel channels on 176 modules

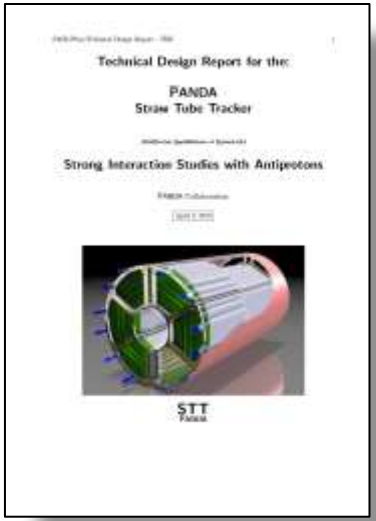
- 200,000 strip channels on 254 modules

Central Tracker

- STT Production under way

Self-supporting→Ultra-lightweight construction

~1% X_0, σ_r~140 μm, specific energy loss


Technical Design Report for the:

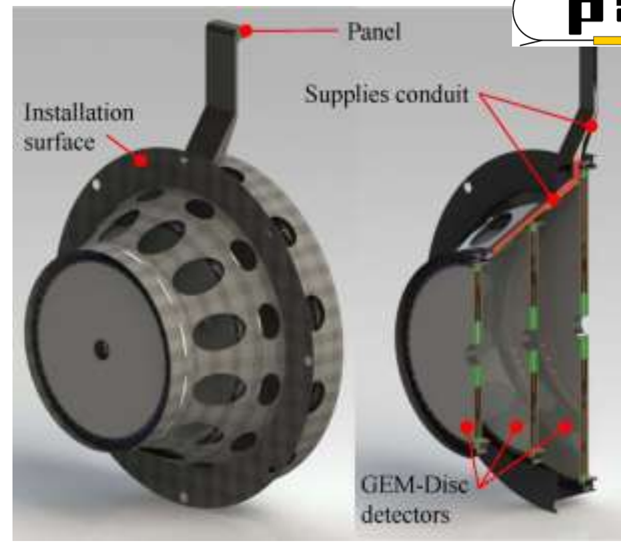
PANDA
Straw Tube Tracker

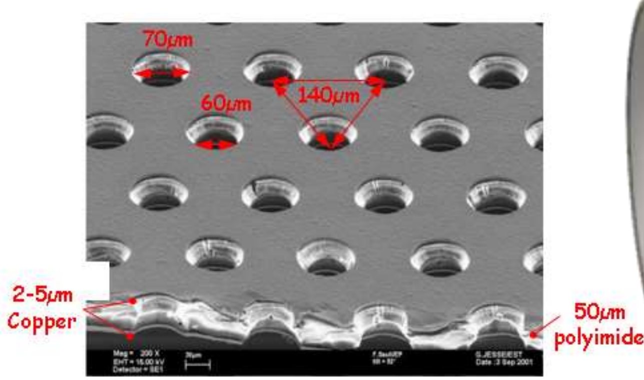
Strong Interaction Studies with Antiprotons

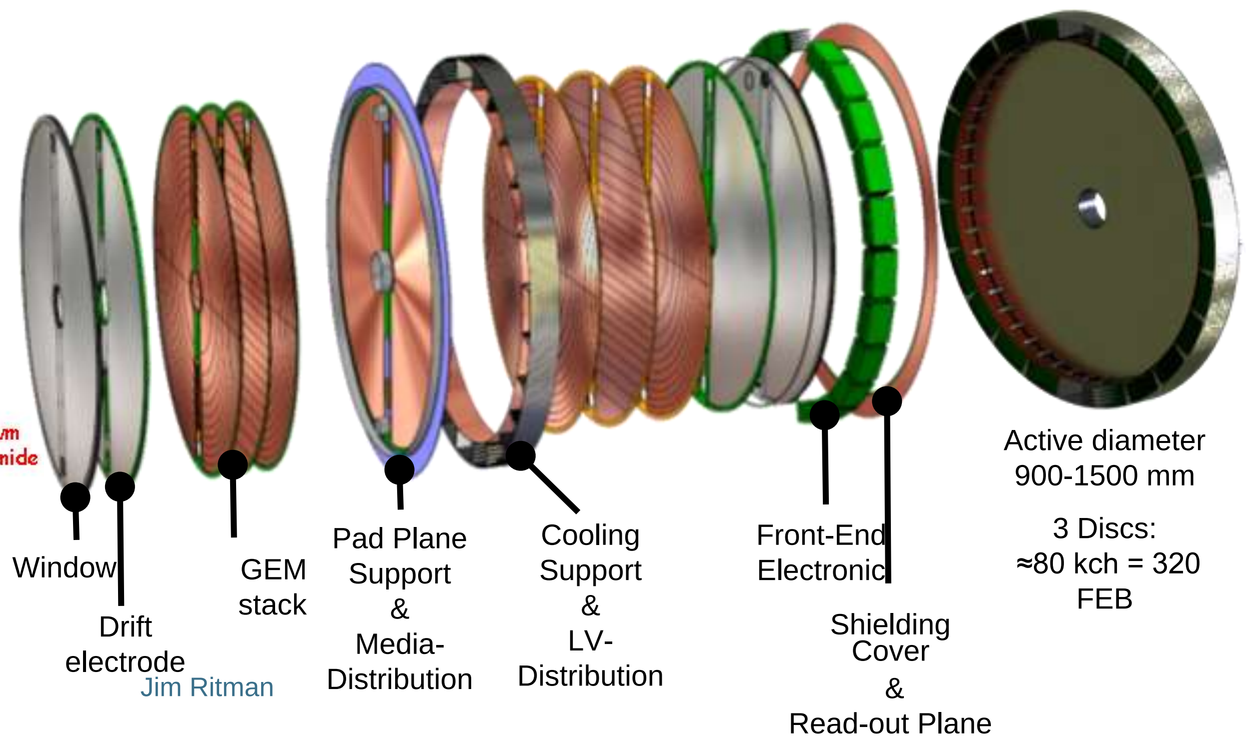
STT

GEM Planar Tracker

- 3 disks in forward polar angles
- Detailed design ongoing





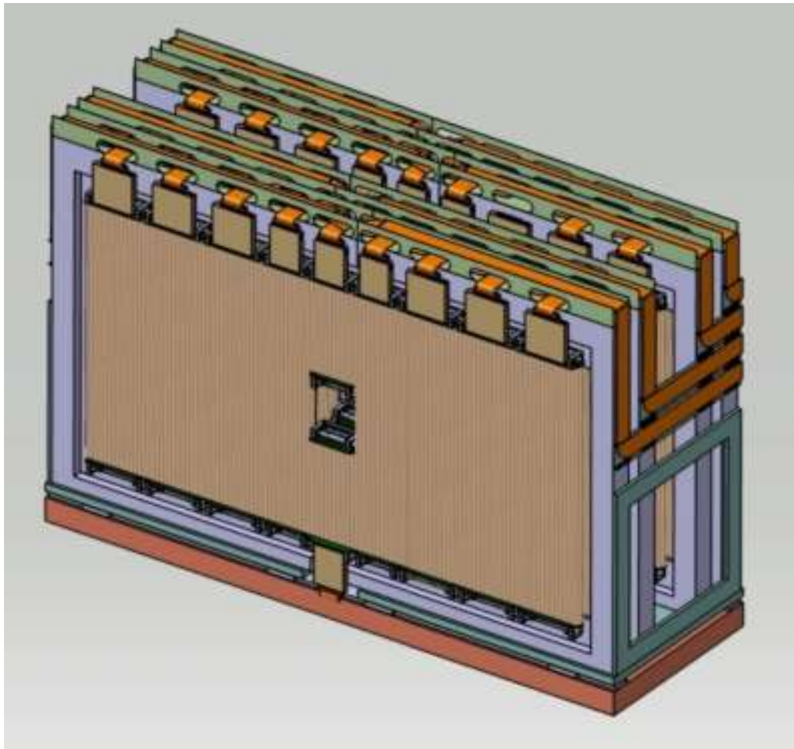


Active diameter 900-1500 mm

3 Discs: ≈80 kch = 320 FEB

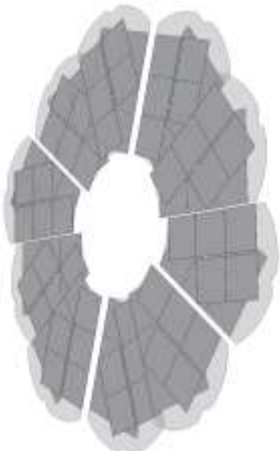
Forward Tracking Station

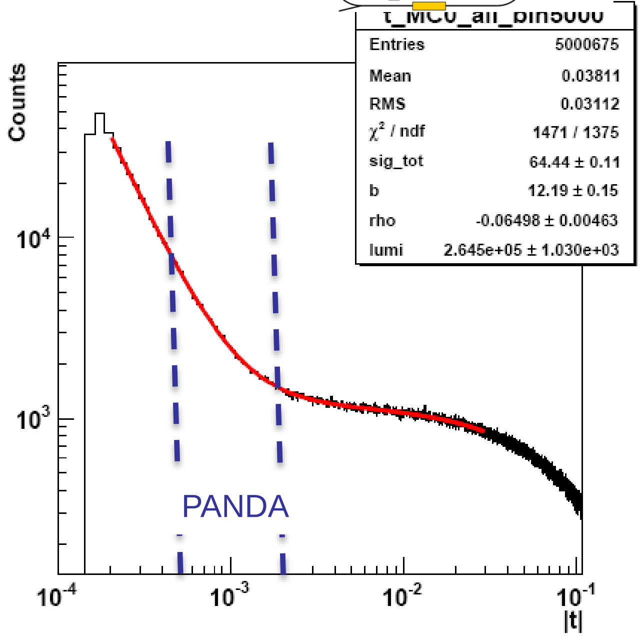
- 3 pairs of tracking stations,
  4 double layers of straw tubes each
- 2 design options for station 6
- Very high particle fluxes in stations 1&2
- Various prototypes completed
- Readout: on track

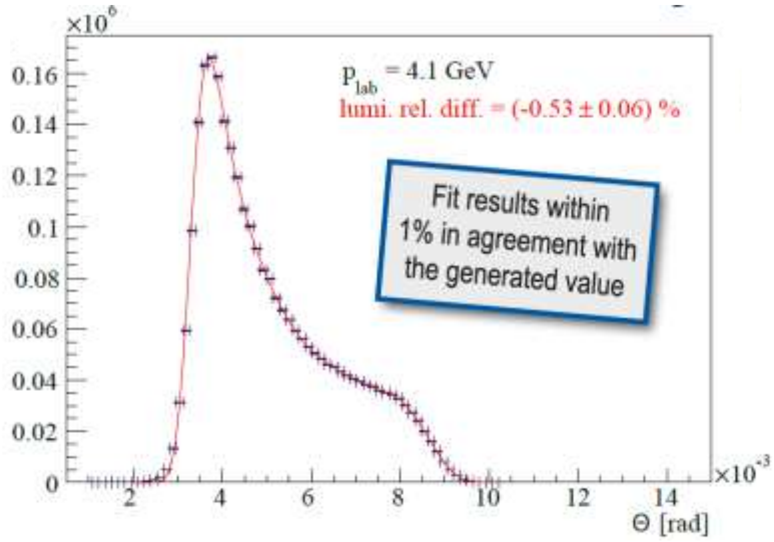


Luminosity Detector

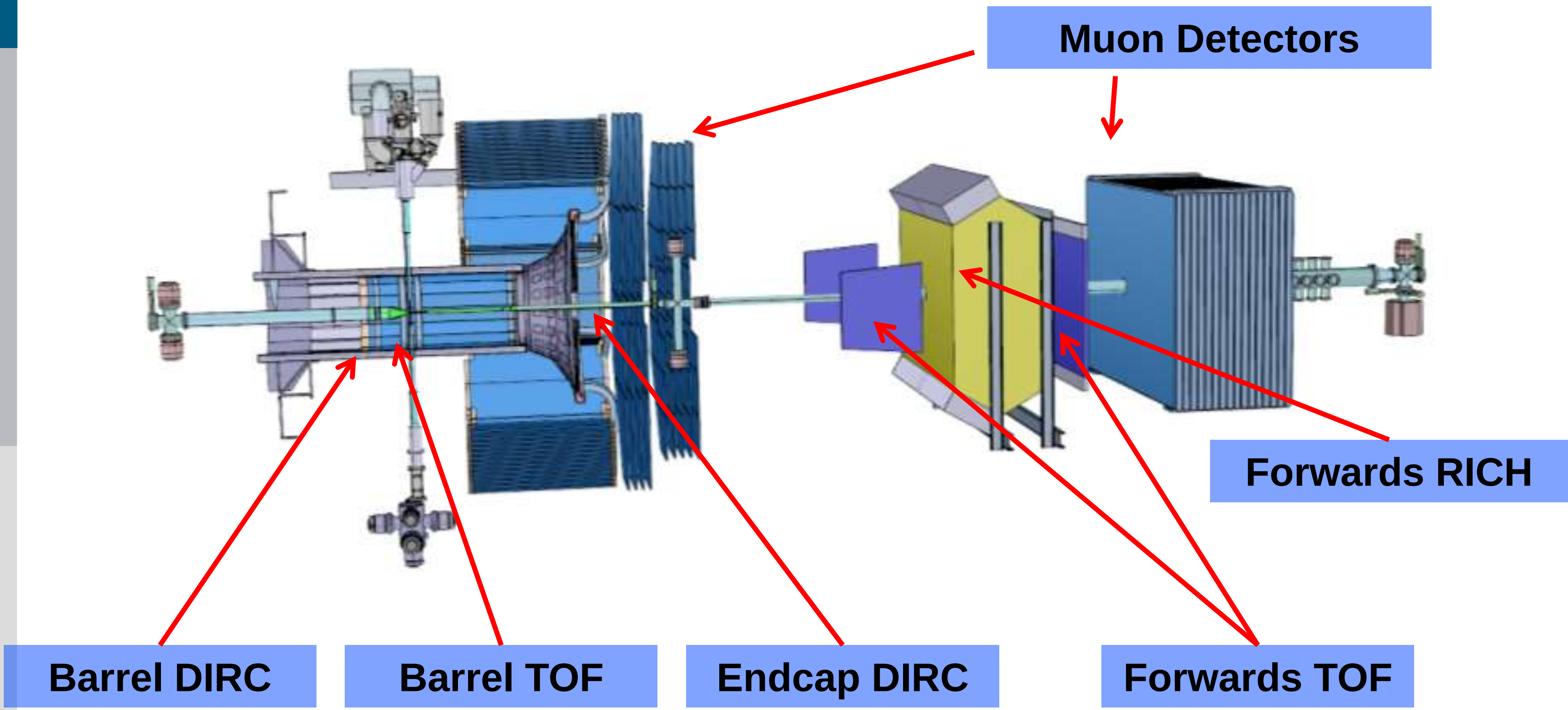
- Measure low-t elastic scattering
- Design based on 4 planes of HVMAPS





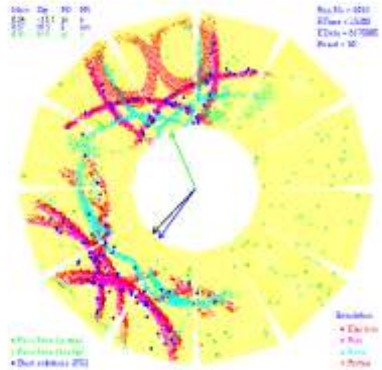


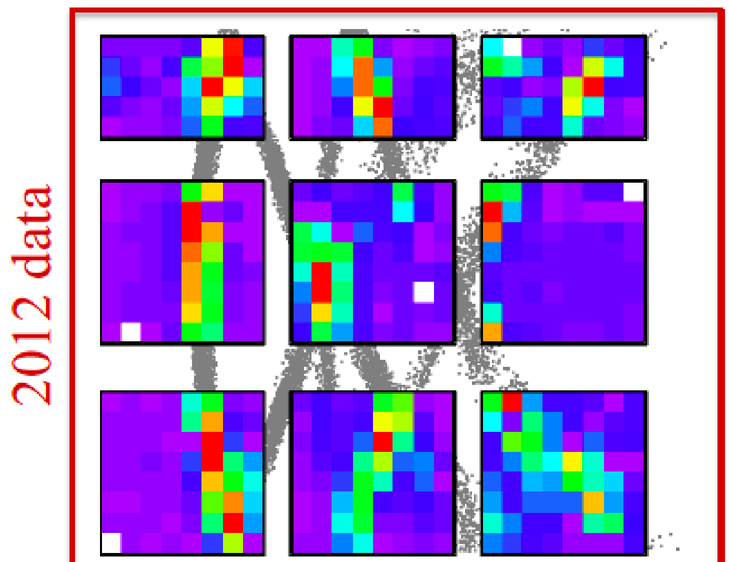
Particle Identification Detectors



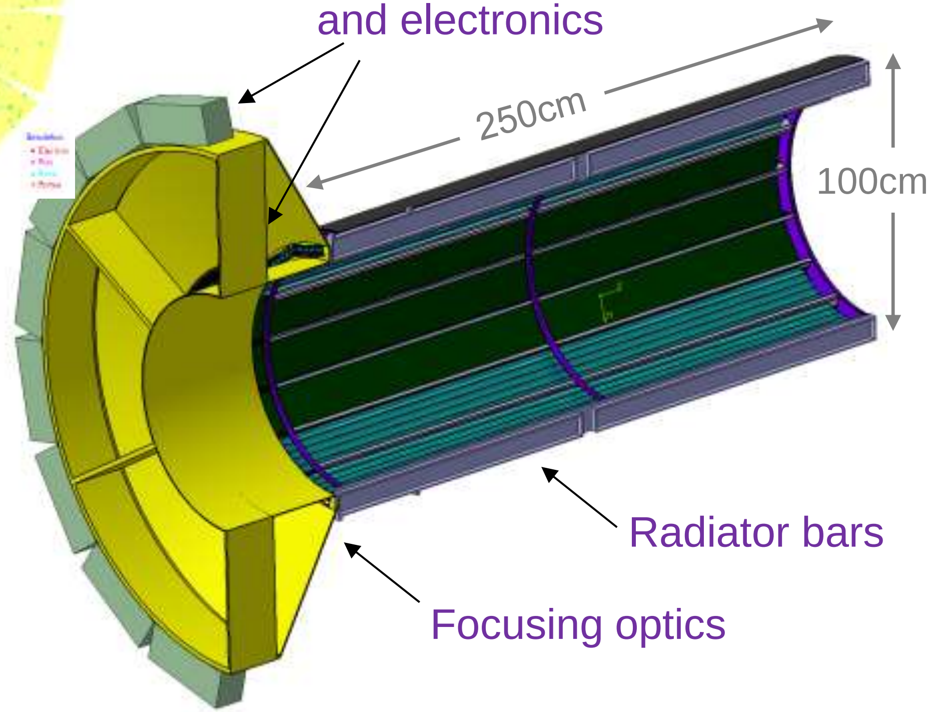
Barrel DIRC

- Compact design
- Profits from late technology decision (light readout)
- Still in R&D (test beams)

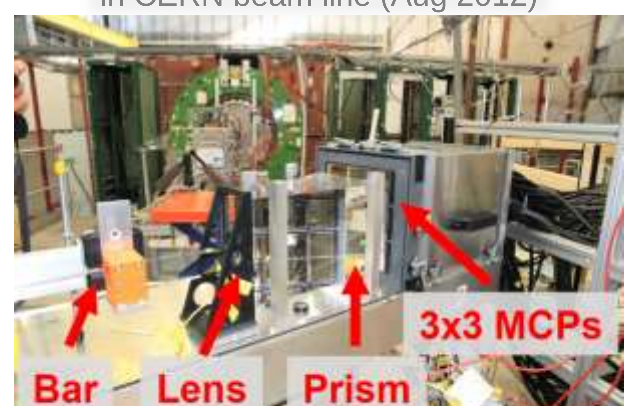




2012 data: track polar angle 122 deg

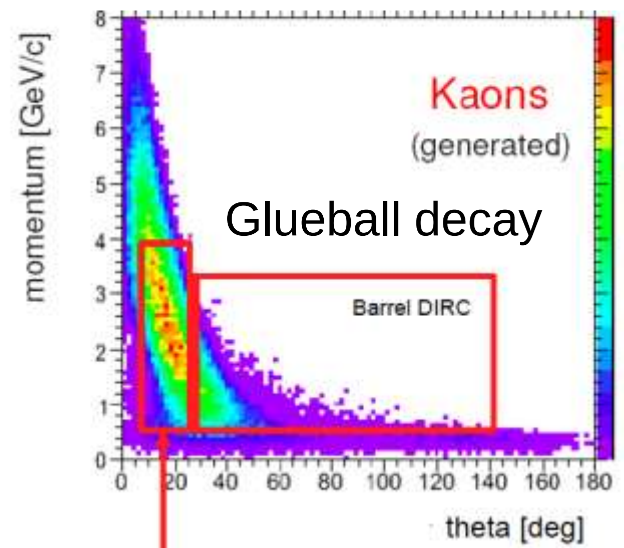


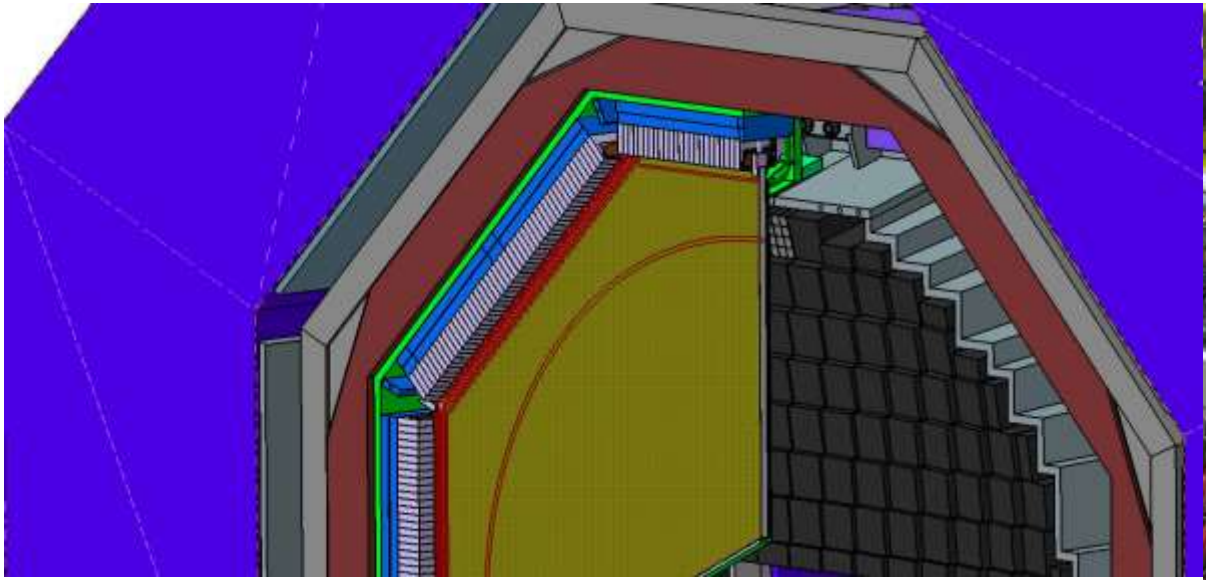
PANDA DIRC prototype
in CERN beam line (Aug 2012)



Disk DIRC

- Novel, compact PID detector developed for PANDA suitable for future detectors, prototype operated successfully
  R&D: Photosensors (lifetime)
  Readout/DAQ, Mechanics

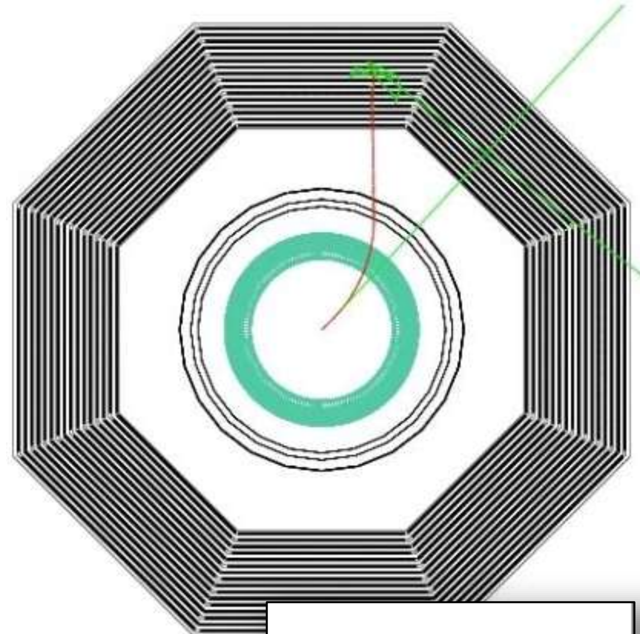


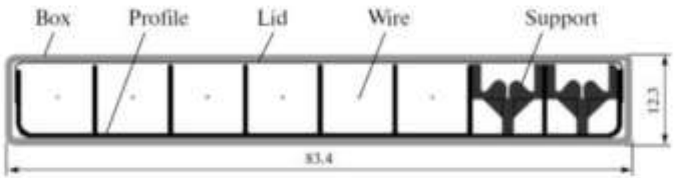


Jim Ritman

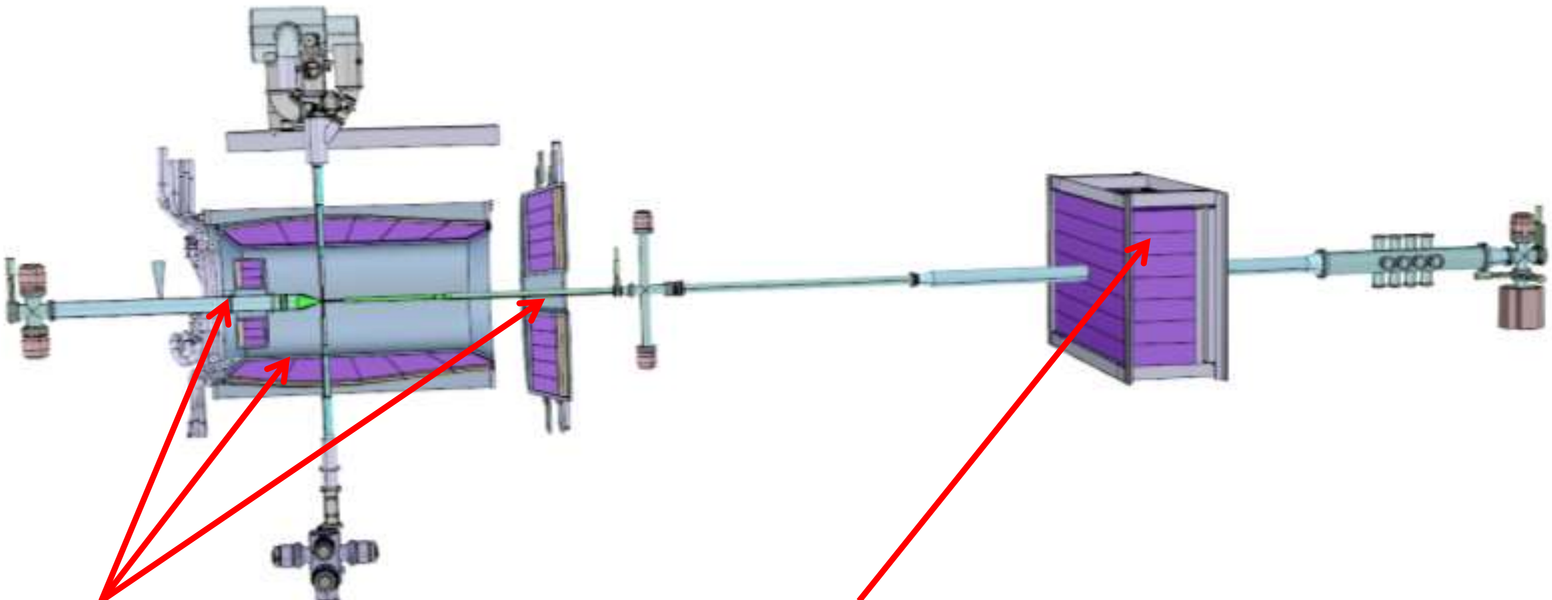
Muon Detectors

- Barrel, Endcap, Muonfilter, Forward
- Various number of layers interleaved in the yoke
- Drift tubes with wire and cathode strip readout





Calorimeters

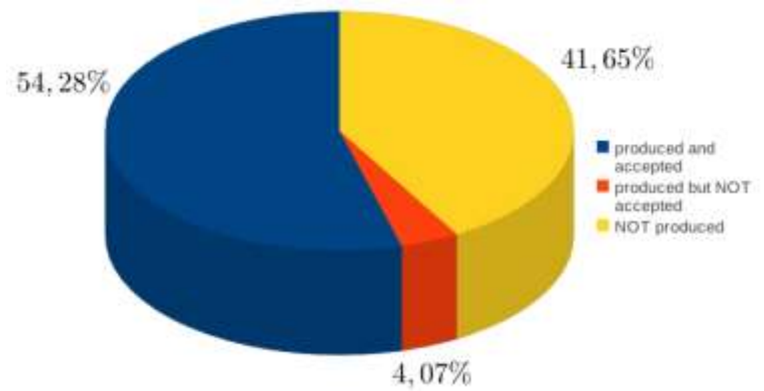


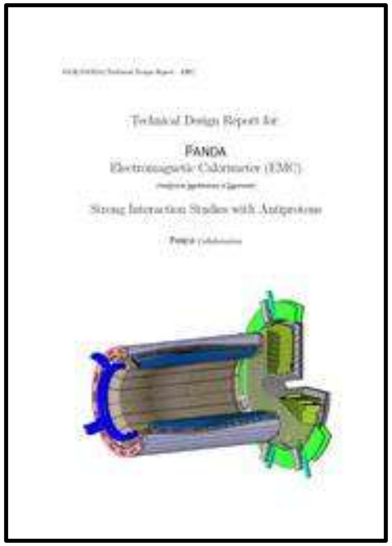
PWO Calorimeter

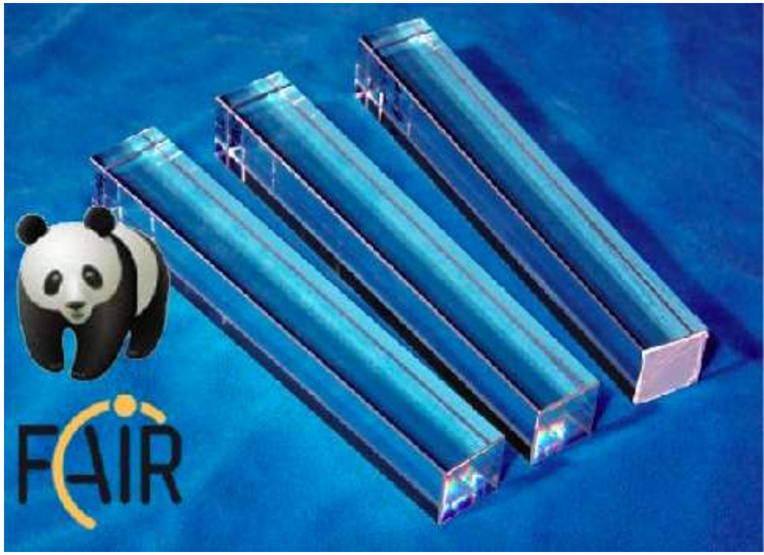
Forward Shashlyk EMC

Target Spectrometer Electro-Magnetic Calorimeter

- Rad. hard, fast, largest dynamic range (cooling)
- All endcap crystals produced
- Crystals for a barrel slice available
- Original producer no longer available: R&D needed to confirm alternatives



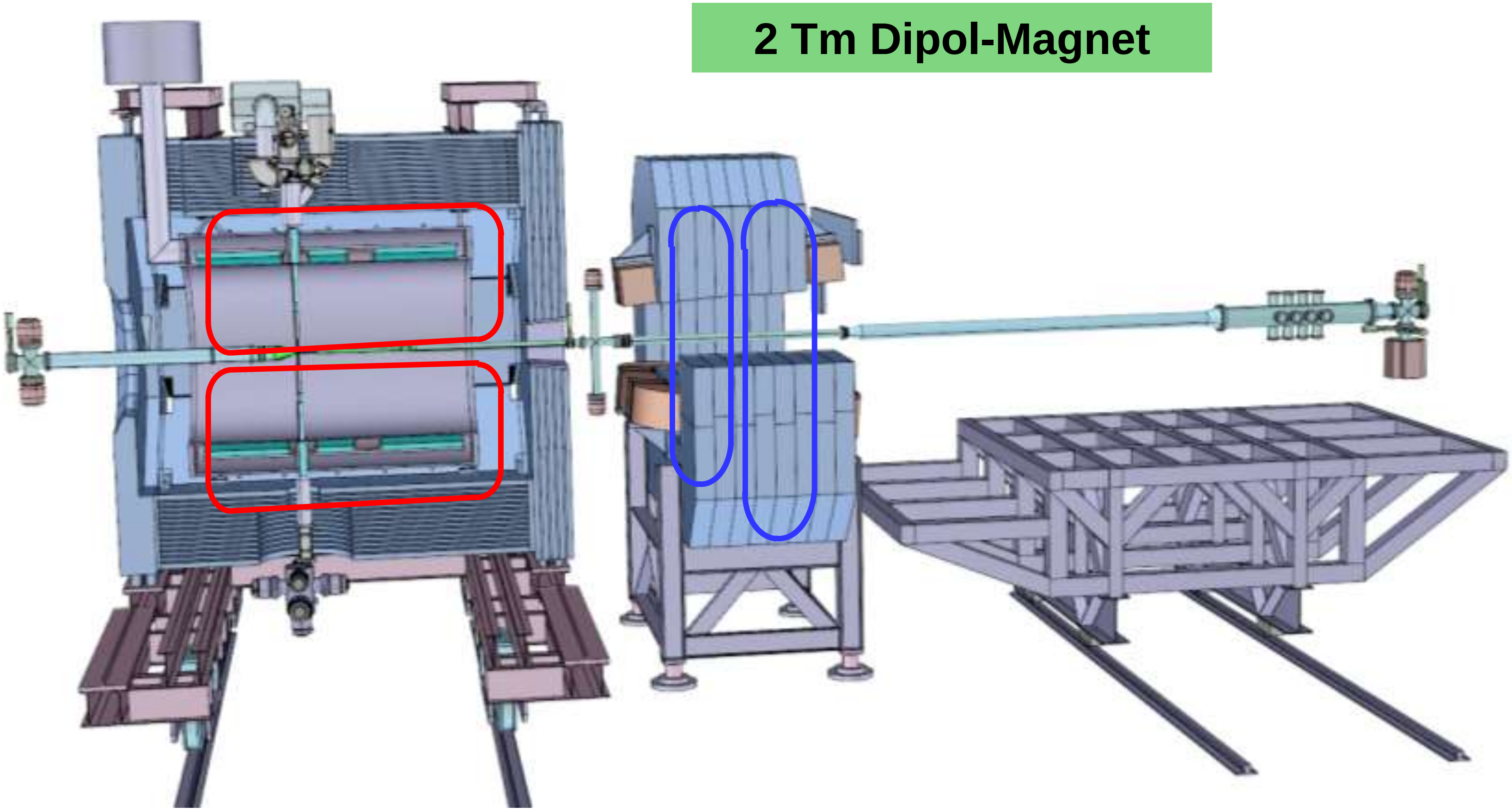

Technical Design Report for
PANDA
Electromagnetic Calorimeter (EMC)
Strong Interaction Studies with Antiprotons



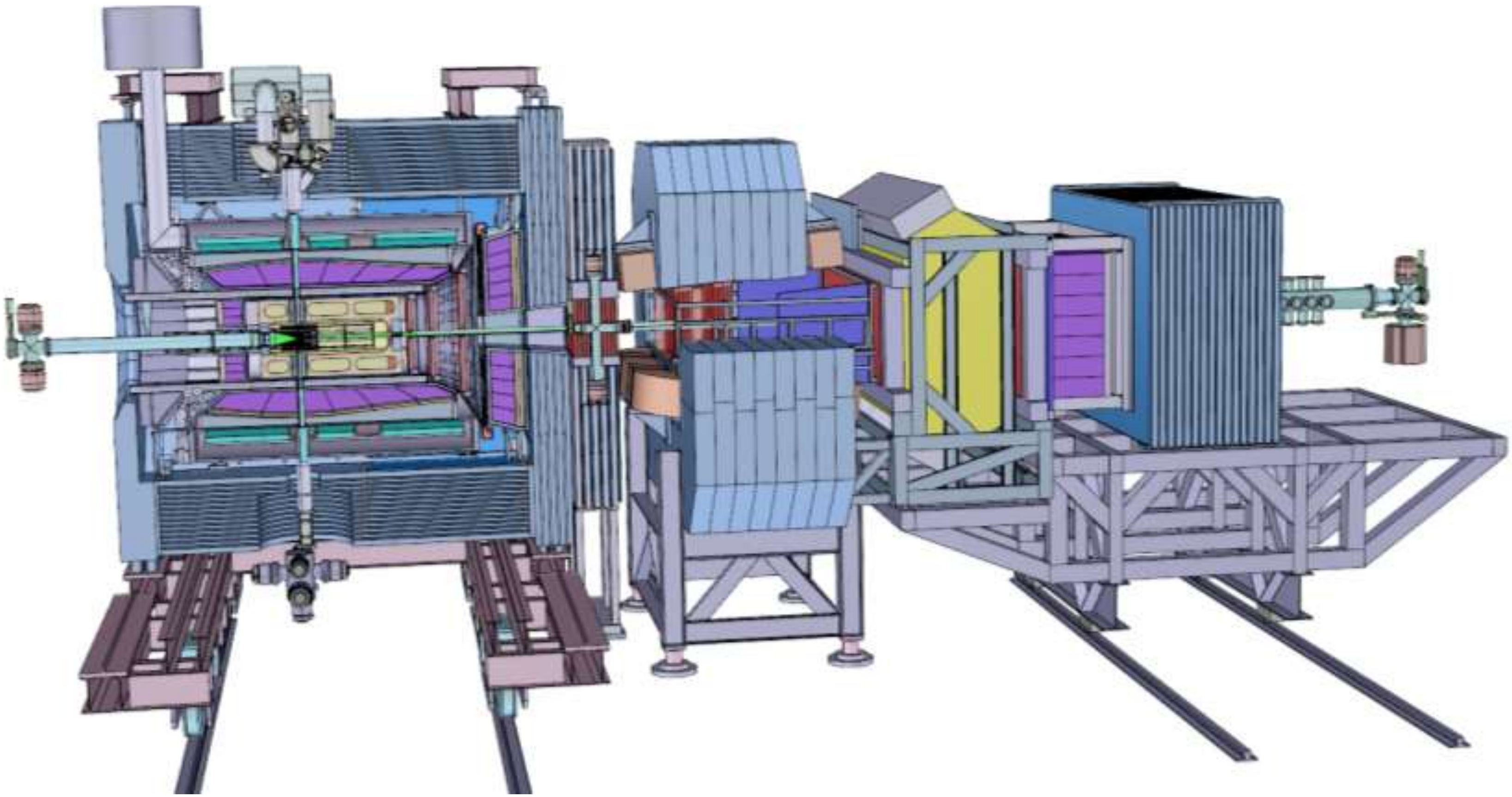
Magnet Systems

2T Solenoid Magnet

2 Tm Dipol-Magnet

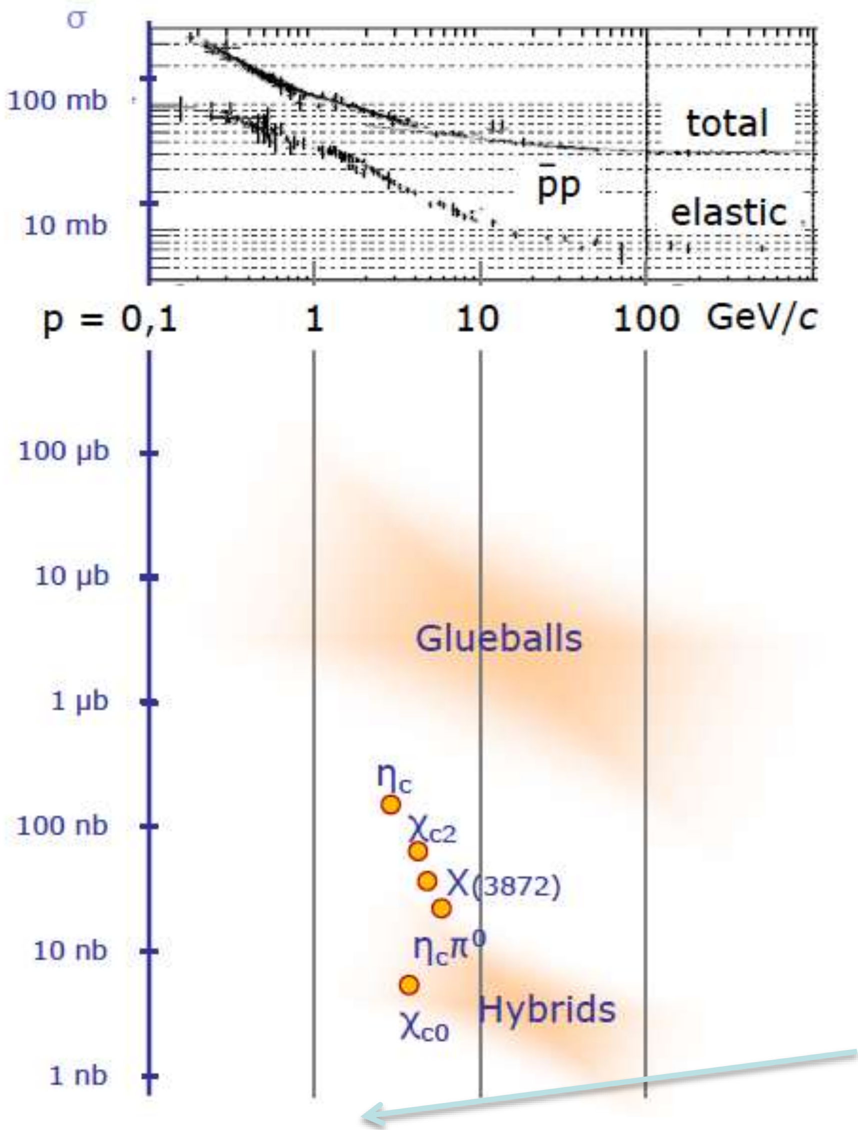


All PANDA Systems



The Computing Challenge

Detector Requirements from Physics Case



High luminosity and hadronic cross sections

High rate capability, $2 \cdot 10^7$ s^{-1} interactions

High data rate

High degree of radiation resistance

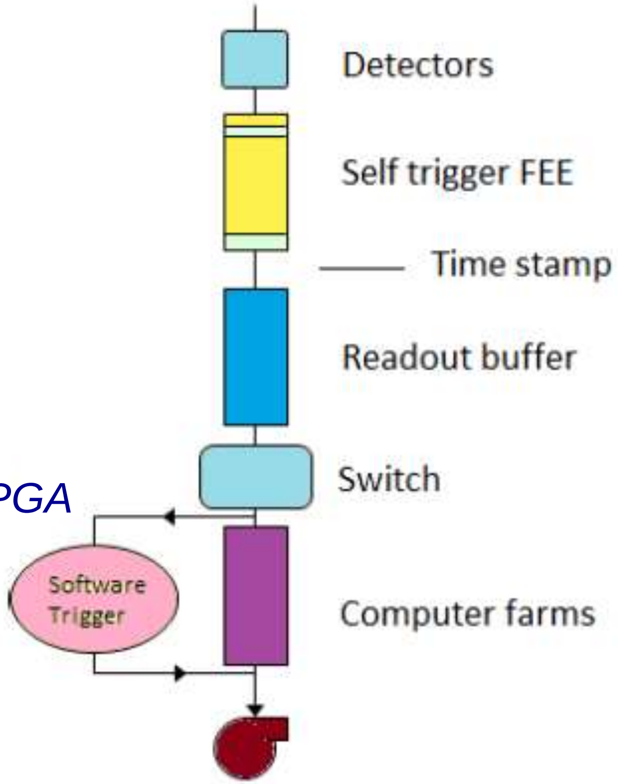
Cross section for electromagnetic Processes

PANDA Trigger

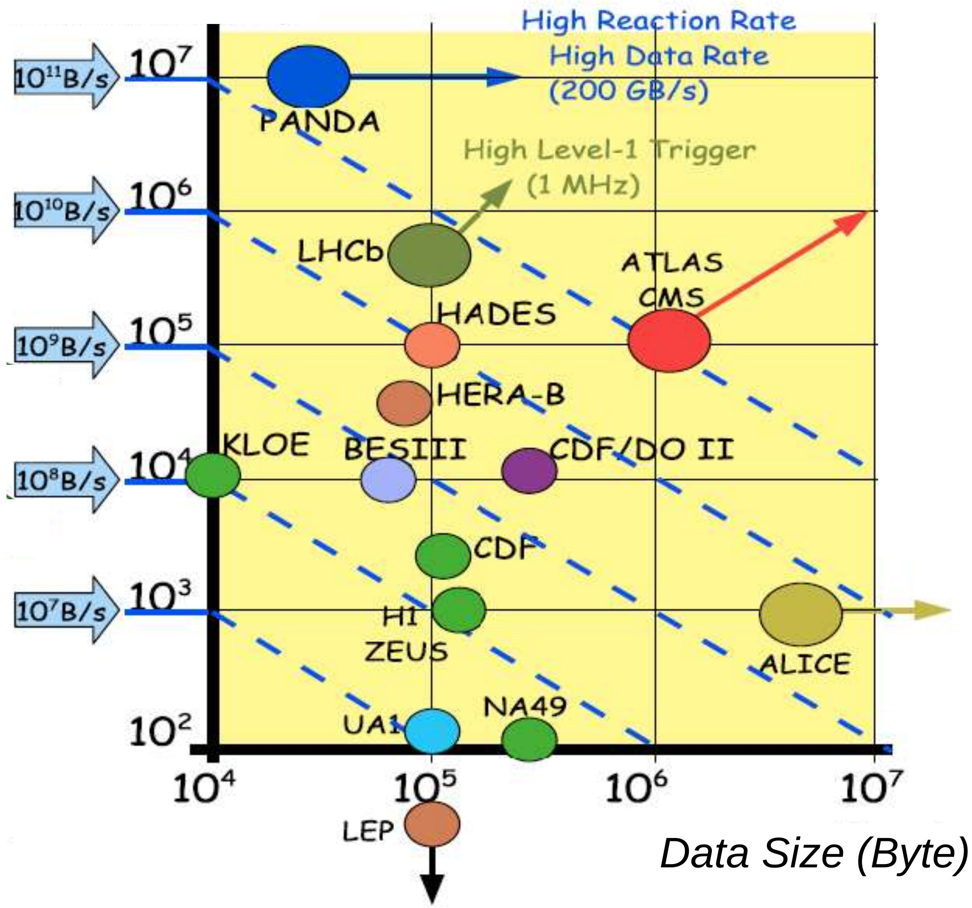
"Trigger-less" DAQ

Software Trigger

FPGA

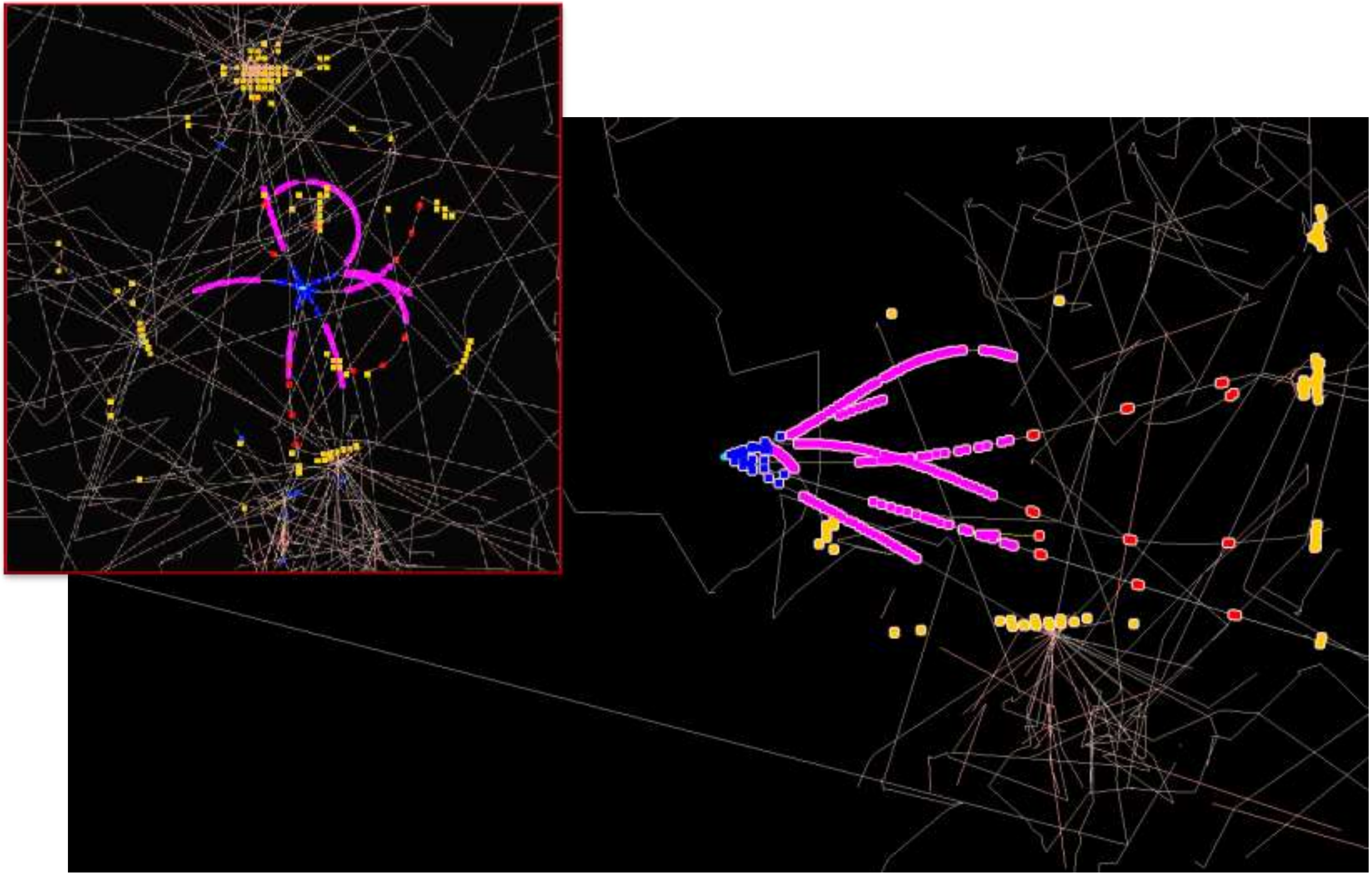


Reaction Rate (Hz)

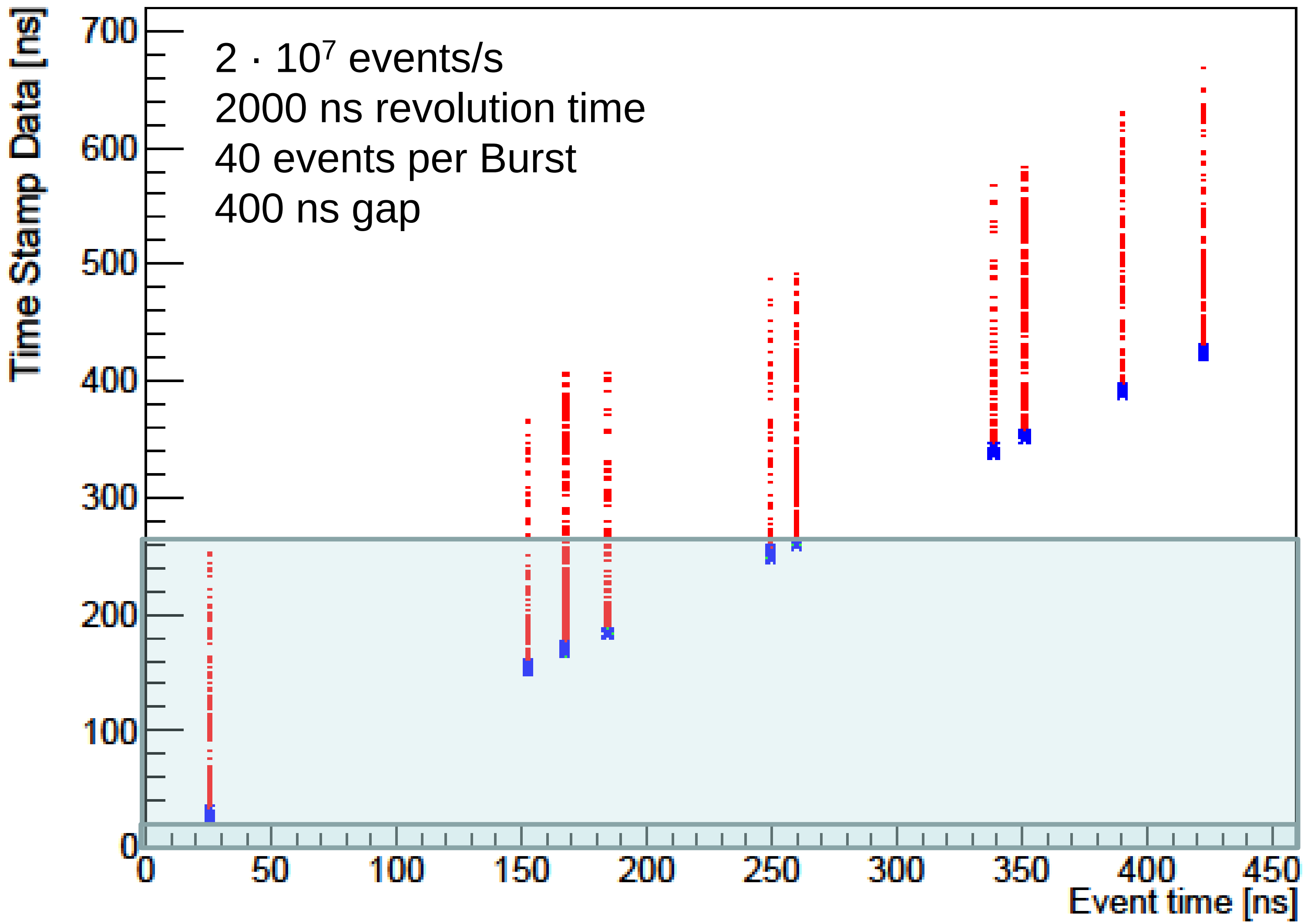


Data Size (Byte)

PANDA – Event Simulation

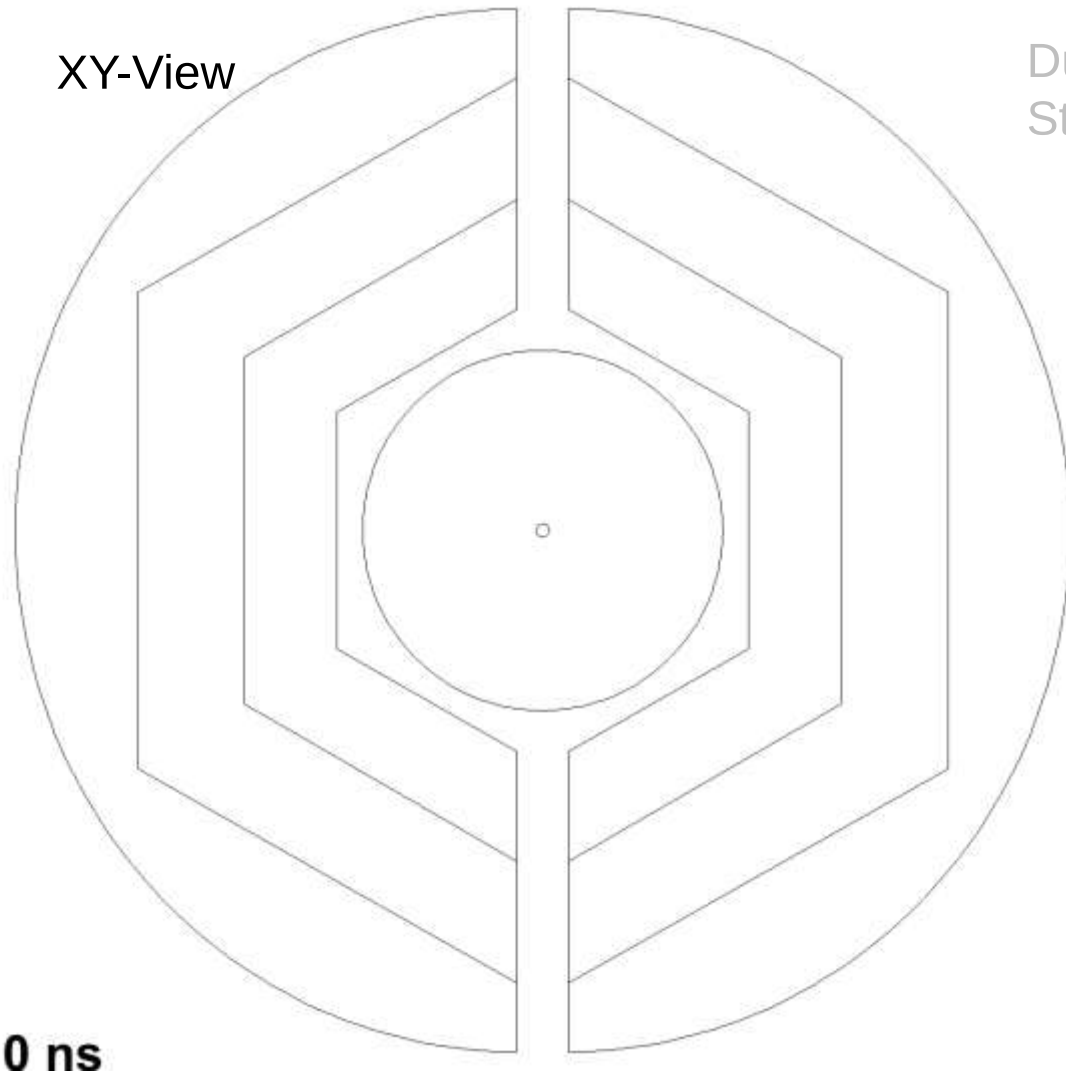


Event Structure



Time based simulation by T. Stockmanns

Hitstream Display:



Dual Parton Model (DPM):
Standard p̄p background generator

Black circles: Early isochrone
Blue circles: Early skewed isochrone
Green circles: Close isochrone
Red circles: Late isochrone
Black dots: MVD hits
Green dots: MVD hits r/z > 0.3
Black+Red dots: Triplets/Skewlets
Yellow tracks: Timed out track
Blue tracks: Current track

DPM Benchmark:
Realistic event rate
and structure,
continuous operation

Summary/Conclusions

- Many open questions on how complex structures are derived from underlying degrees of freedom
- Antiprotons provide precision measurements
- Broad/fascinating physics program at PANDA
- Accelerator and detector are on track

The PANDA Collaboration

~ 520 Members, 69 Institutes, 18 Countries
Austria, Australia, Belarus, China, France, Germany, India, Italy, Poland, Romania, Russia, Spain, Sweden, Switzerland, Thailand, Netherlands, USA, UK