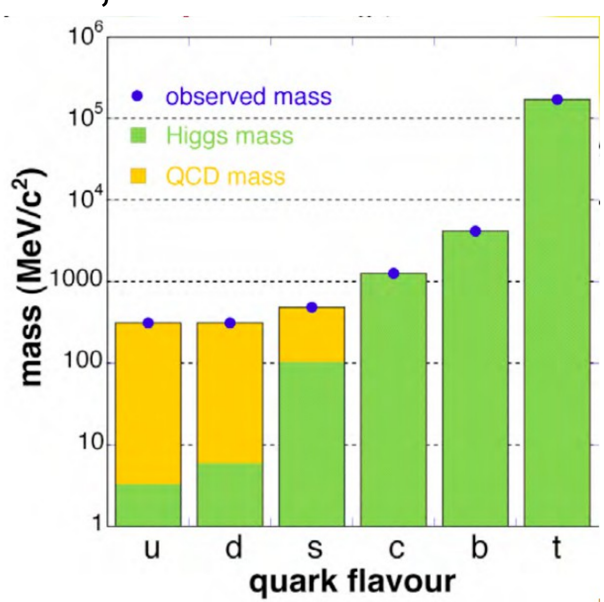
The PANDA Experiment:

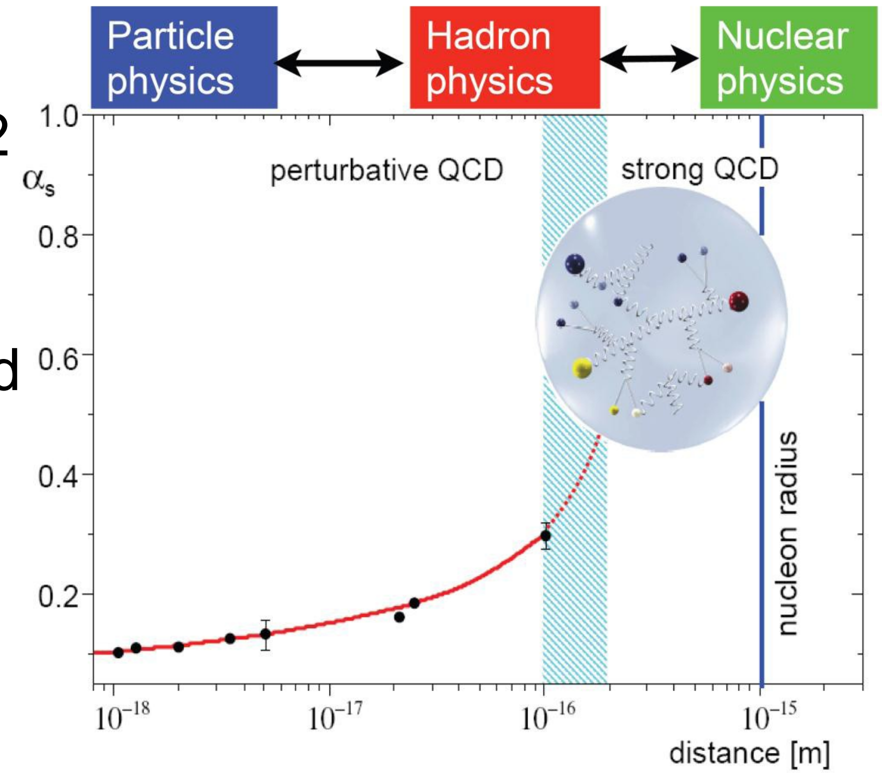
Exploring the Emergence of Structure in Matter

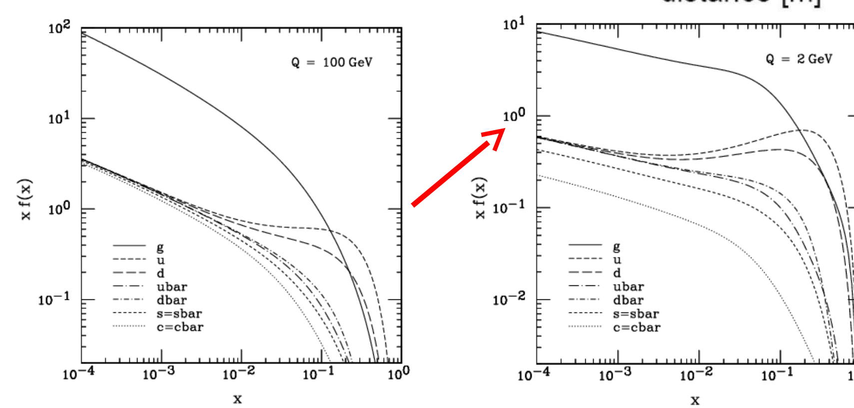
J. Ritman Forschungszentrum Juelich

Hadron Physics with PANDA

- QCD well understood at high Q2
  Emergence of eff. DoF at low Q2
- Study of the *strong interaction* in the transition region
- Phenomena appear that are hard to predict from QCD:
  e.g. confinement, nature of hadrons, hadronic masses…



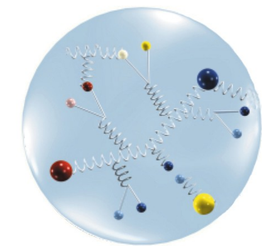




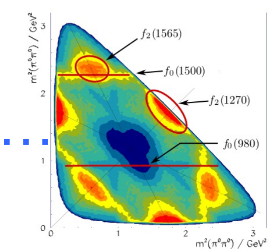
J. Pumplin et al., JHEP 0207 (2002) 012

How Do We Study the Hadrons?

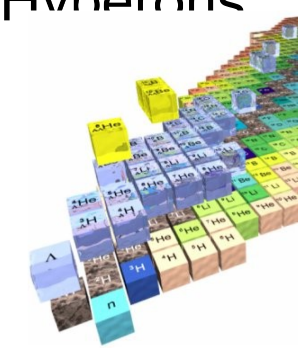
- Hadron Structure: Hard (virtual) photons, typically accessed via leptons, allow us to measure the constituents
  - Generalized parton distribution
  - Drell-Yan processes
  - Time-like form factor of the proton



- Hadron Spectroscopy: Excitation spectrum accesses rare quark/gluon configurations
  - Search for glueballs, hybrids, molecules, tetraquarks …
  - Baryon spectroscopy
  - In-medium effects

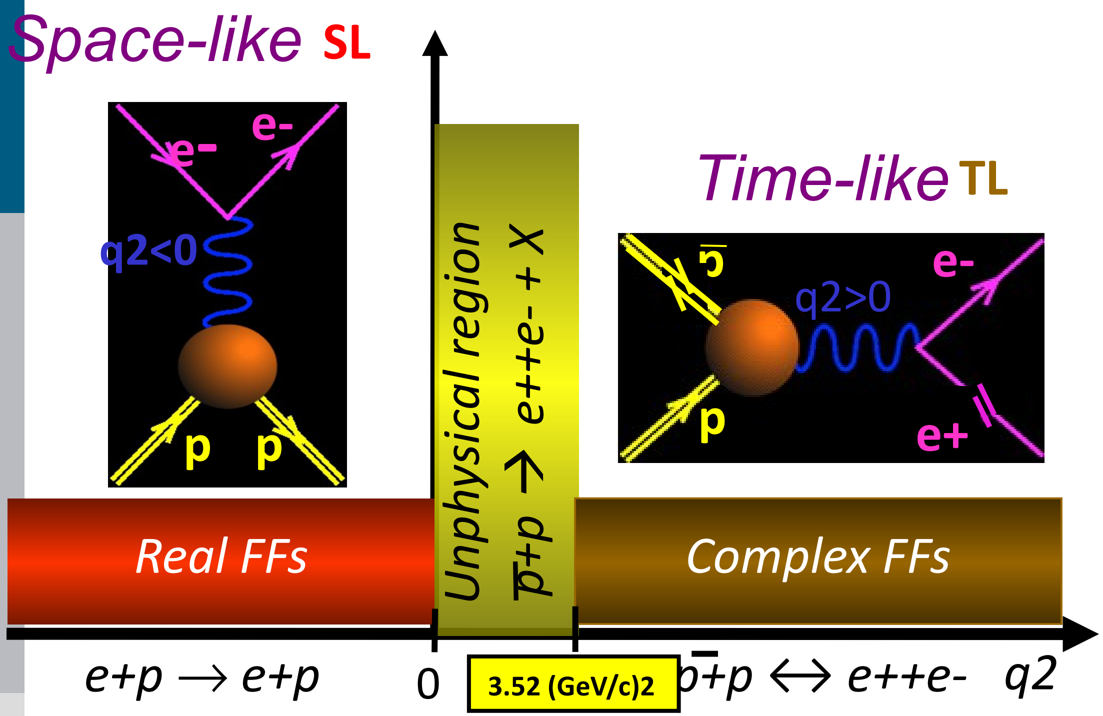


- Hadron Interactions: Pion/Kaon reactions, as well as Hyperons and Hypernuclei provide information about the strong force
  - Double hypernuclei



Hadron Structure with Electromagnetic Probes

Time-Like & Space-Like EM Form Factors



Constraints:

- GEp(0)=1
- GMp(0)=μp
- GEp(4mp²)= GMp(4mp²)

Asymptotics

- |GE,M(q²)| ~ (q²)-²

- $\lim_{q^2 \to -\infty} G^{SL}_{E,M}(q^2) = \lim_{q^2 \to +\infty} G^{TL}_{E,M}(q^2)$ (Phragmén-Lindelhöf theorem)
- Imaginary part of Time-Like form factors vanishes for q²⟶+∞

Time-Like& Space-Like EM Form Factors

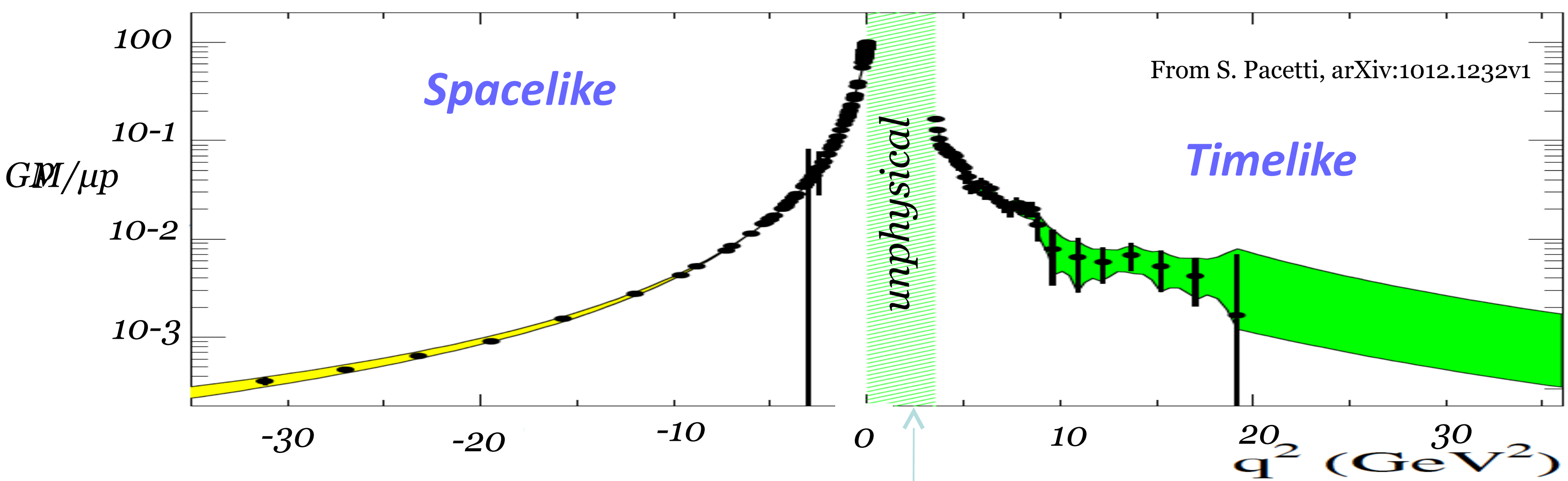
electron scattering

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

q2 > 4mp2

e- scattering (Jlab…. A2/Mainz)

e+e-↔p̄p (BES, Novosibirsk, PANDA)



Dispersion relations:

q2 < 0

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

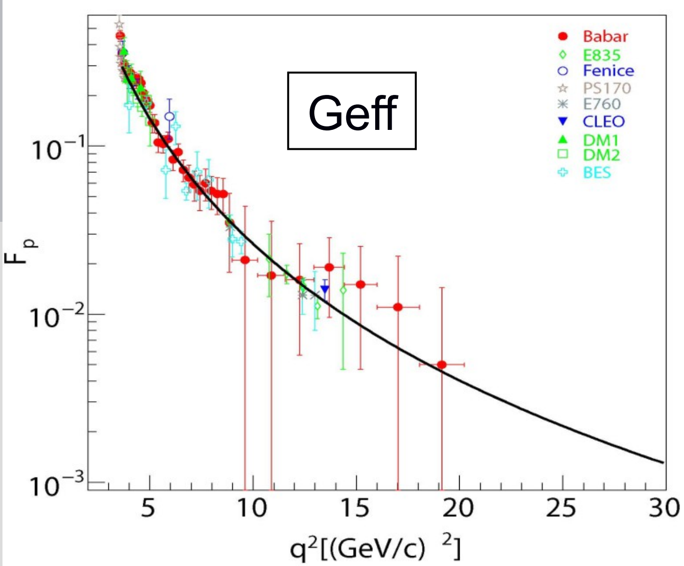
Proton EM Form Factors in Time-Like Region

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

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

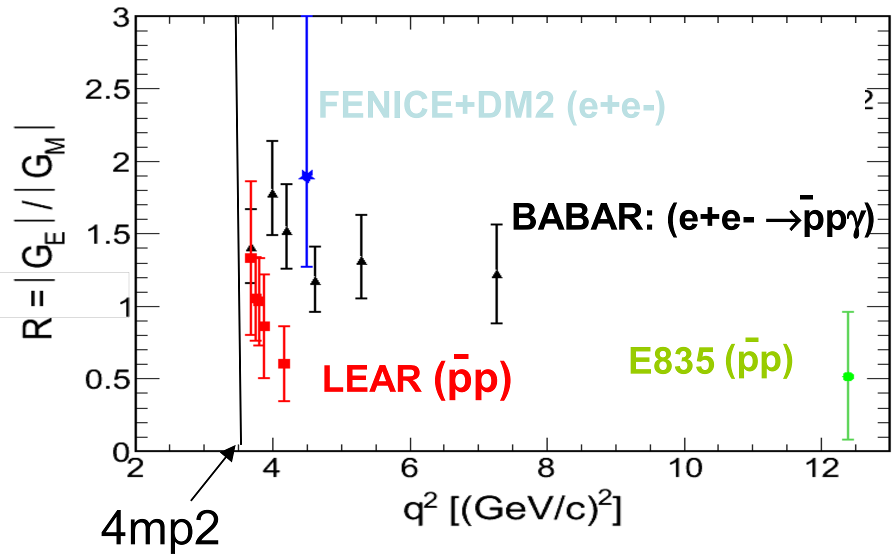
$$G_{eff} = |G_M| \quad if \quad |G_E| = |G_M| \quad or \quad \tau >> 1$$

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



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

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



- ✓ Geff : large error bars above 13 (GeV/c)2
- ✓ |GE/GM| :
  - Inconsistent data above threshold
  - Lack of precise data above 5 (GeV/c)2

Goal of PANDA Measurements

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

Two major challenges:

- ✓ Decrease of sensitivity to GE
  with increasing q2
- ✓ Huge hadronic background
  σ ($\bar{p}p \rightarrow \pi$+π-) / σ ($\bar{p}p \rightarrow$e+e-) ~ 106

Counting Rate and Sensitivity to |GE|

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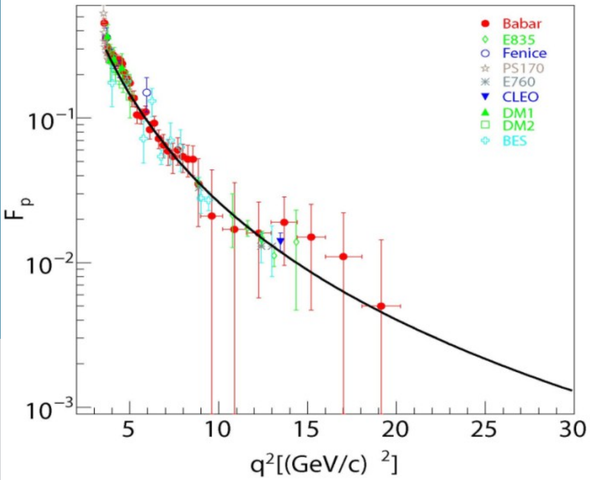
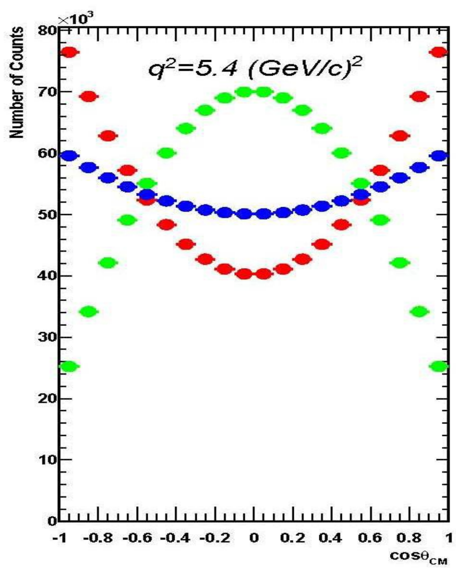


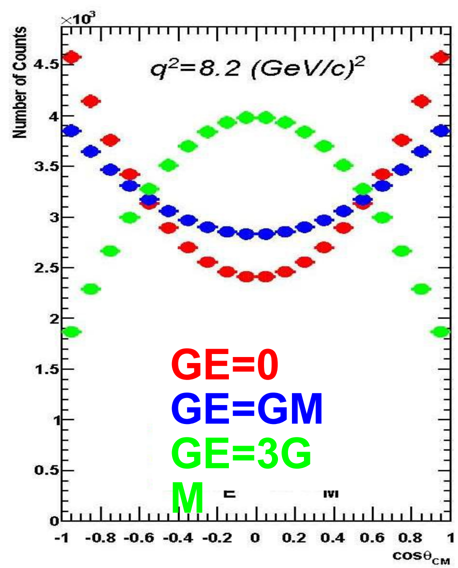
$$\frac{d\sigma}{d(\cos\theta_{CM})} = \frac{\pi\alpha^2}{8M_p^2\sqrt{\tau(\tau-1)}}\left[\tau\left|G_M^{TL}\right|^2(1+\cos^2\theta_{CM}) + \left|G_E^{TL}\right|^2\sin^2\theta_{CM}\right]$$

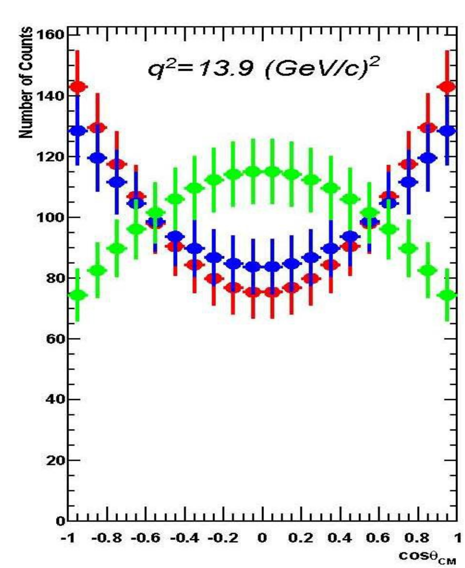
~120 days, ℒ = 2x1032 cm-2s-1

ℒ int= 2 fb-1

Statistical errors only



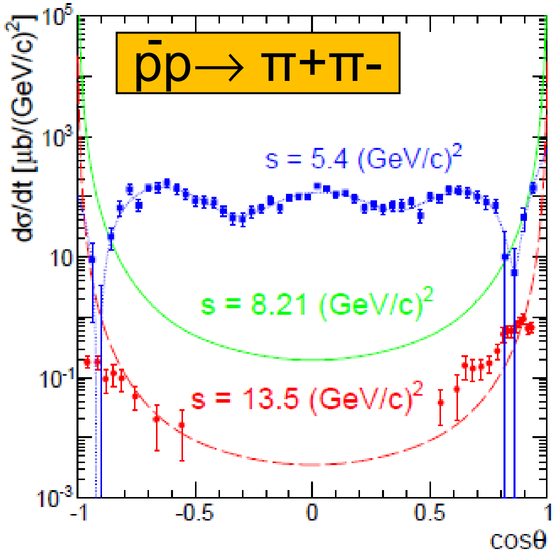




Ntot=1.1 106 **Ntot=64000** **Ntot=2000**

M. Sudol et al. EPJA 44 (2010) 373

Rejection of p̄p → π+π- Background

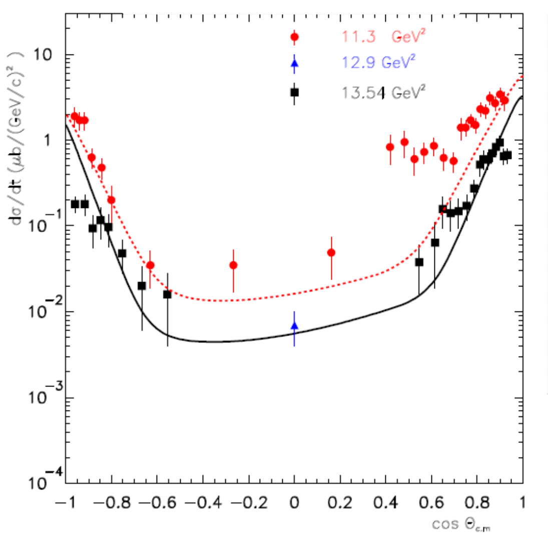


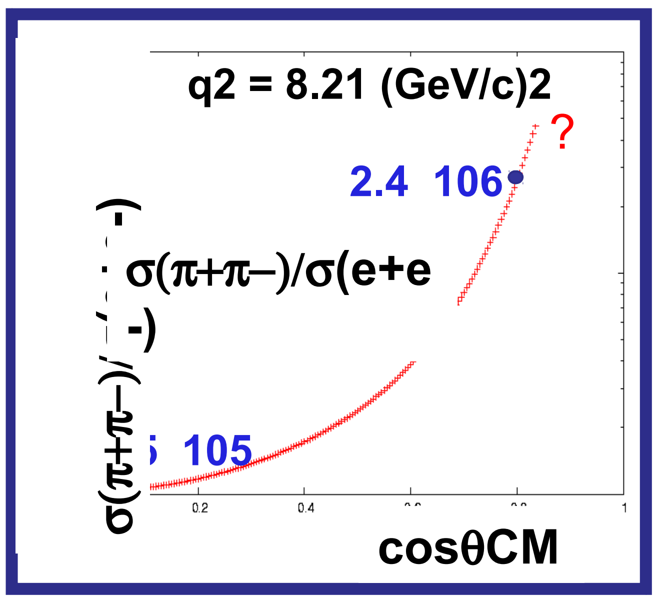
parametrization of CERN data for p̄ p → π+π-

s < 6 (GeV/c)2 : Legendre polynomial fits

s > 6 (GeV/c)2 :

counting rules (*Ong et Van de Wiele, IPNO-DR-08-01*)
or Regge trajectories (*idem, EPJA46 (2010) 291*).





New measurements of p̄ p → π+π- will be provided by PANDA (also important for pQCD mechanism studies)

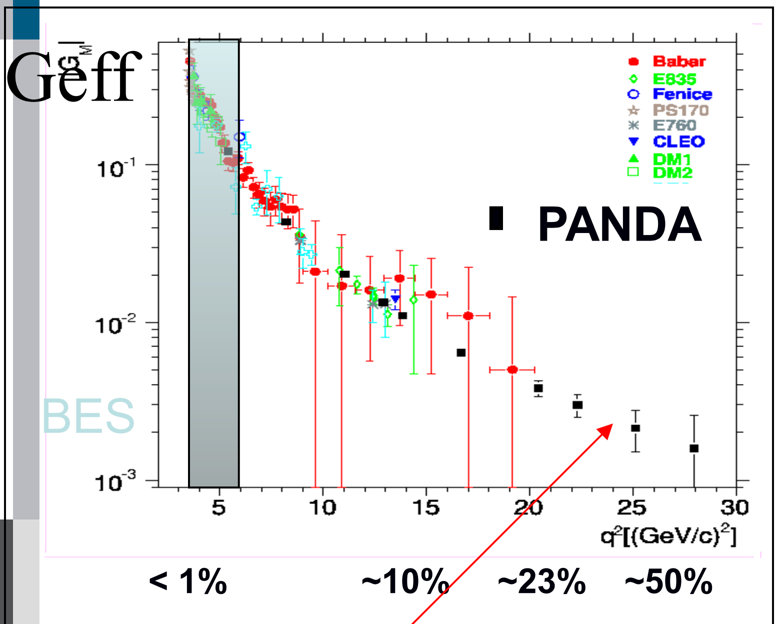
Time-Like Form Factor Measurement with PANDA : Estimates of Precision

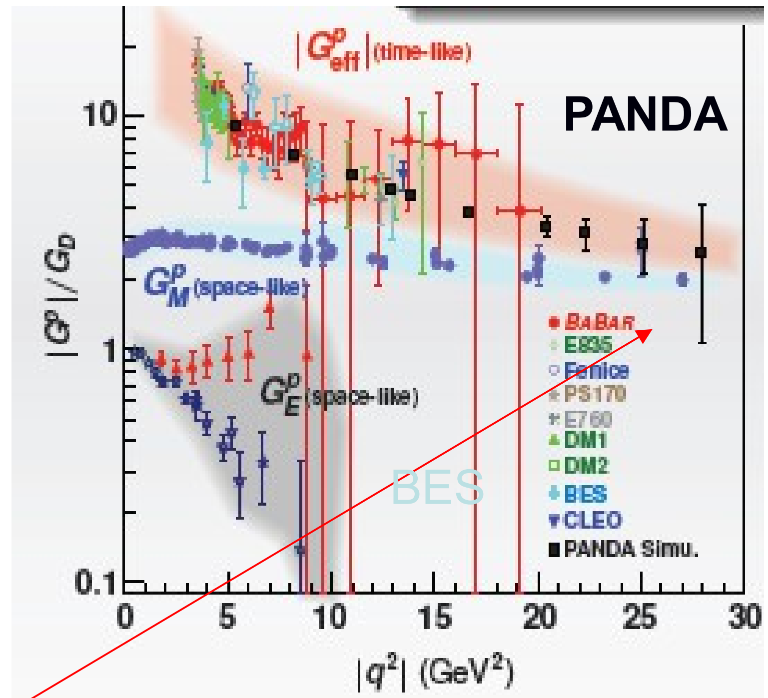
$\mathcal{L}$ =2 fb-1

Sudol et al. EPJA 44 (2010) 373

Courtesy of S. Pacetti

E. Tomasi-Gustafsson and M.P. Rekalo, PLB504,291
E. Tomasi-Gustafsson, arXIv:0907.4442





pQCD ?

Phragmèn-Lindelöf theorem ?

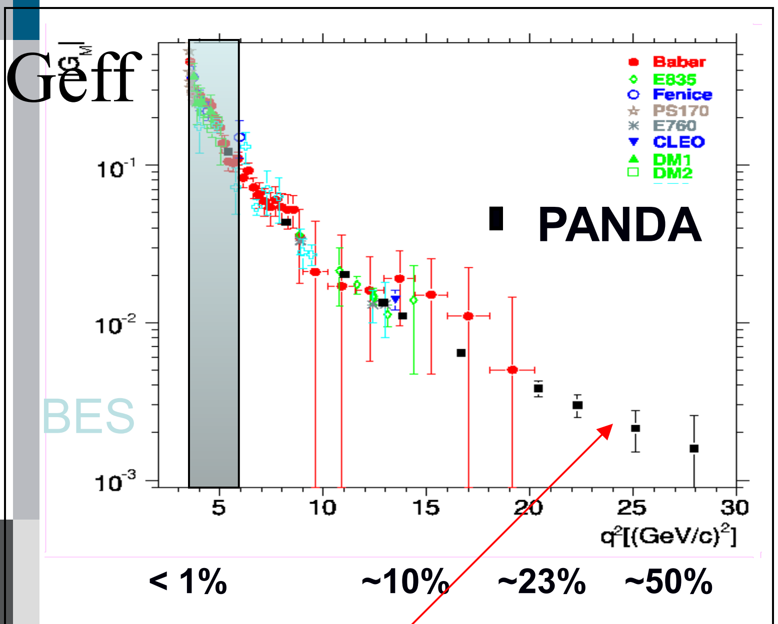
$$\lim_{q^2 \to -\infty} G^{SL}(q^2) \quad \lim_{q^2 \to +\infty} G^{TL}(q^2)$$

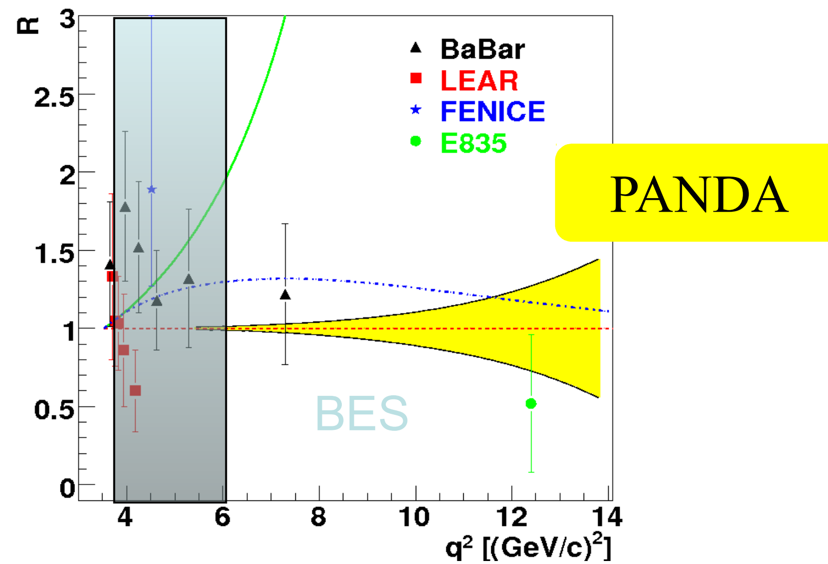
Time-Like Form Factor Measurement with PANDA : Estimates of Precision

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





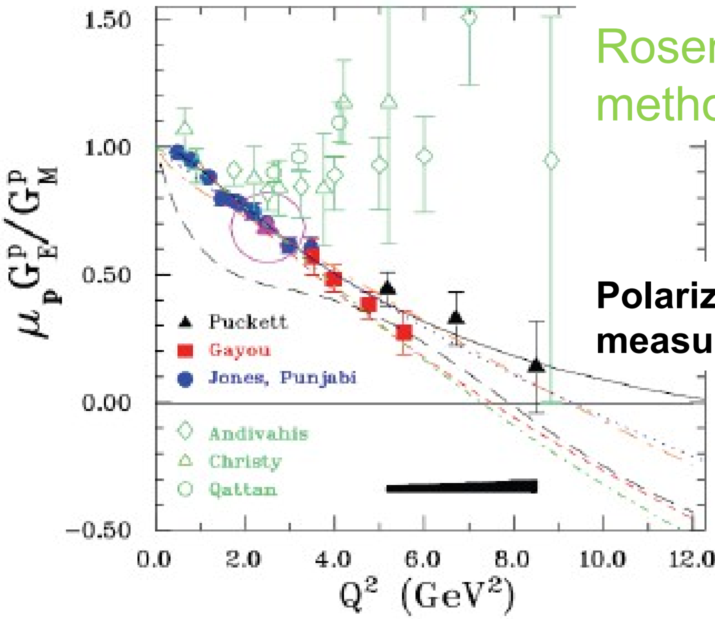
pQCD ?

PANDA will bring

Precise determination of |GE| and | GM | up to 14 (GeV/c)2

Geff up to 30 (GeV/c)2 : transition towards perturbative QCD

2γ Contributions and Radiative Corrections



Rosenbluth method

Polarization measurements

Important role of 2γ exchange and radiative corrections

$$\mathcal{S} = \frac{1}{2}\left(\frac{d\sigma}{d\Omega_{e^+}} + \frac{d\sigma}{d\Omega_{e^-}}\right)$$

No C-odd terms contribution

$$\mathcal{A} = \left(\frac{d\sigma}{d\Omega_{e^+}} - \frac{d\sigma}{d\Omega_{e^-}}\right) \Big/ \left(\frac{d\sigma}{d\Omega_{e^+}} + \frac{d\sigma}{d\Omega_{e^-}}\right)$$

C-odd terms contribution

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

The e+ and e- angular distributions are measured in the same experiment

- PANDA measurements are sensitive to *odd cos* θ terms

dσ/dcosθe ~ A (1+ b cosθesin2 θe + c cos2θe+..) with b=5% or more

(M. Sudol et al EPJA 44(2010) 373).

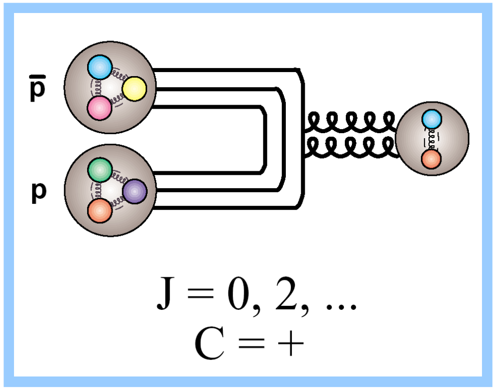
Hadron Spectroscopy with Antiproton Annihilation

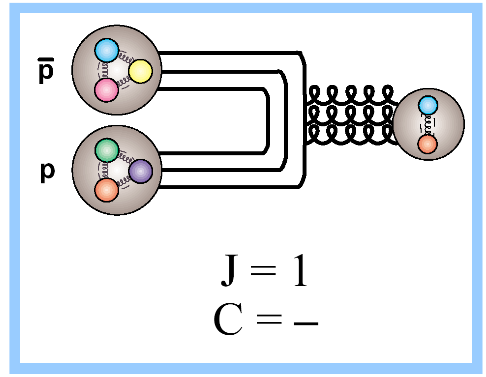
Why Antiprotons?

- difficult to make
- BUT:
- gluon rich process
- gain ~2 GeV in annihilation, reduced momentum transfer
- all fermion-antifermion quantum numbers accessible
- very high resolution in formation reactions
- high angular momentum accessible

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

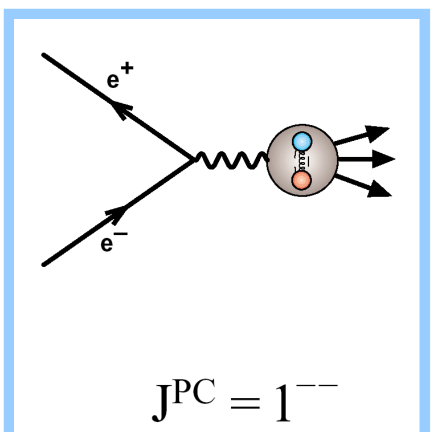
Formation:





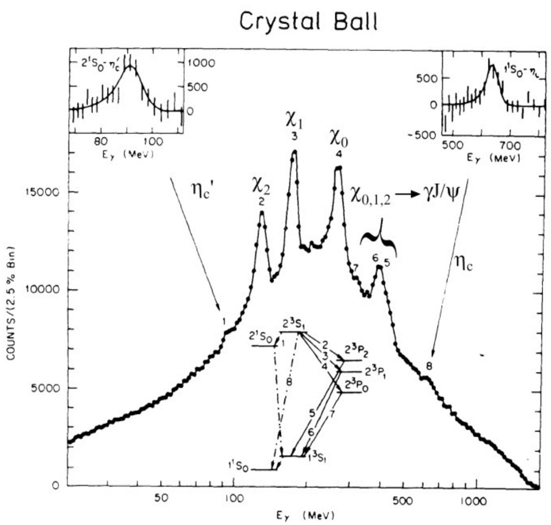
➡ All JPC allowed for $(\bar{q}q)$ accessible in $\bar{p}p$

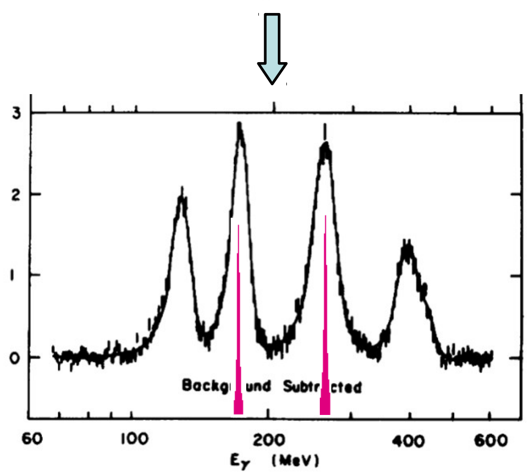
c.f.



Only JPC = 1-- allowed in e+e-
(to 1st order)

Example: χc1,2





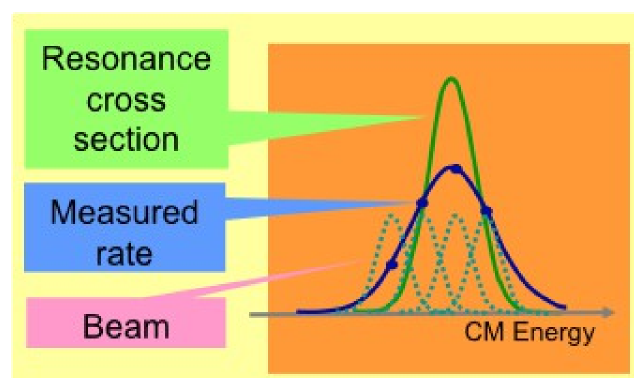
$$e^+e^- \to \psi' \to \gamma\chi_{1,2} \to \gamma(\gamma J/\psi) \to \gamma\gamma e^+e^-$$

- 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: Resolution depends on the beam resolution



E760@Fermilab ≈ 240 keV PANDA ≈ 30 keV

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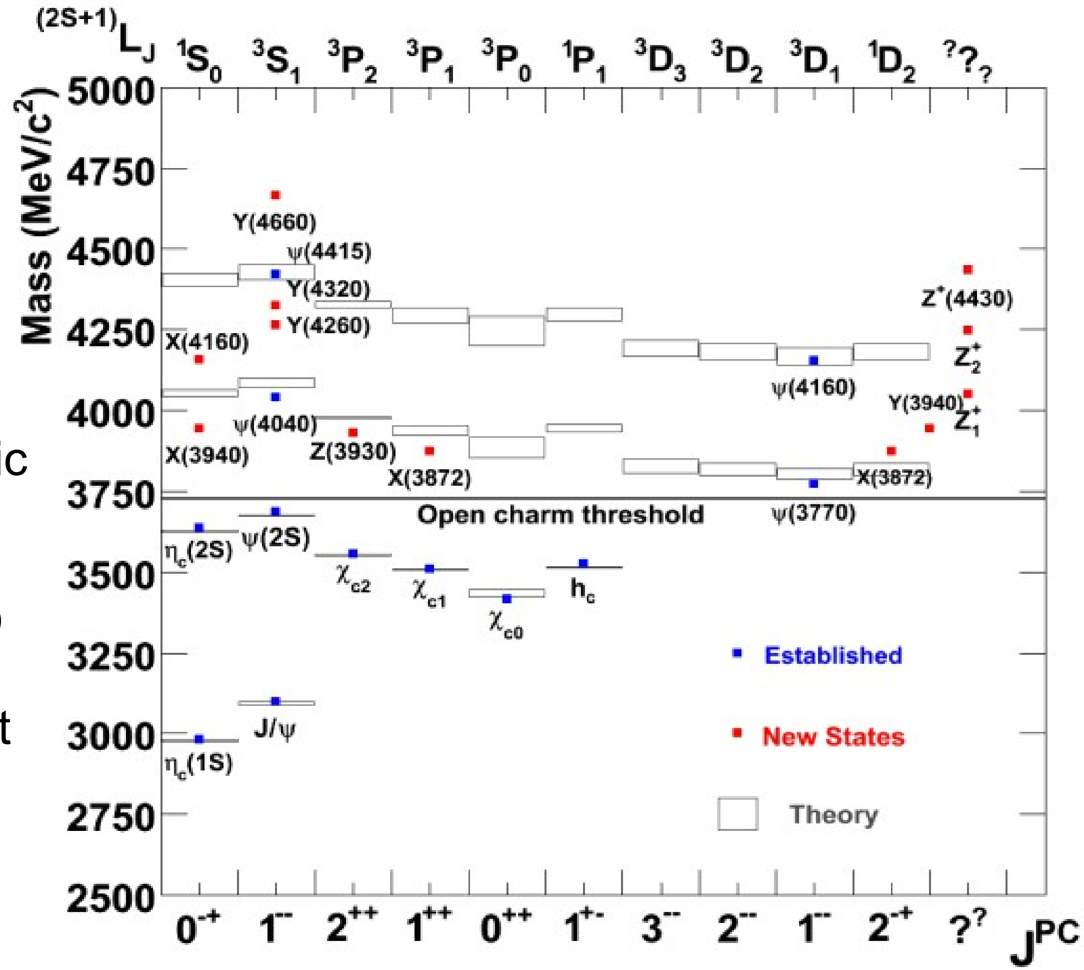
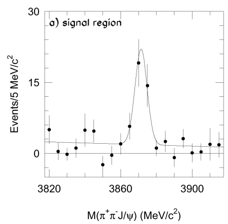
Charmonium Spectroscopy

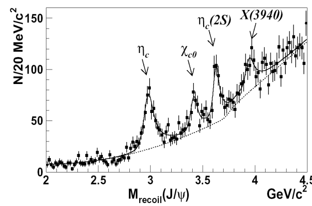
- open questions below $D\bar{D}$ threshold: widths, branching
- new „XYZ“ states (Belle, BaBar, CLEO, CDF, D0, …)
- new degrees of freedom: molecules, tetraquarks, gluonic excitations?
- conventional states above $D\bar{D}$
- high *L* states: access in $p\bar{p}$ but not in e+e-



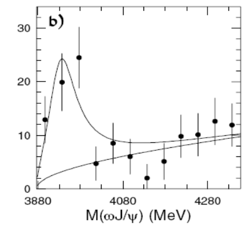
X(3872)
PRL 91,262001 (2003)



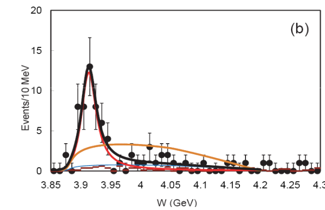
X(3940)
PRL 98,082001 (2007)



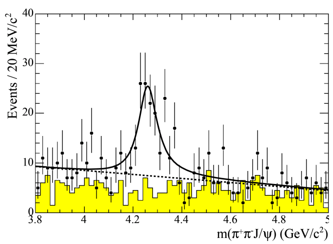
Y(3940)
PRL 94,182002 (2005)



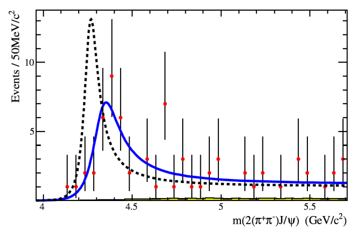
X(3915)
PRL 104,092001 (2010)



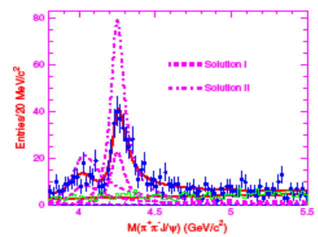
Y(4260)
PRL 95,142001 (2005)



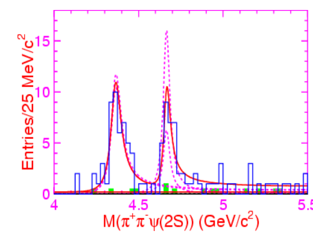
Y(4350)
PRL 98,212001 (2007)



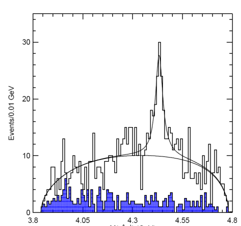
Y(4008)
PRL 99,182004 (2007)



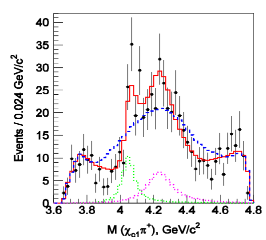
Y(4660)
PRL 99,142002 (2007)



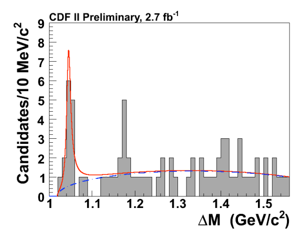
Z(4430)-
PRL 100,142001 (2008)



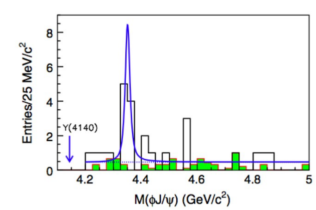
Z1- & Z2-
PRD 78,072004 (2008)



Y(4140)
PRL 102,242002 (2009)



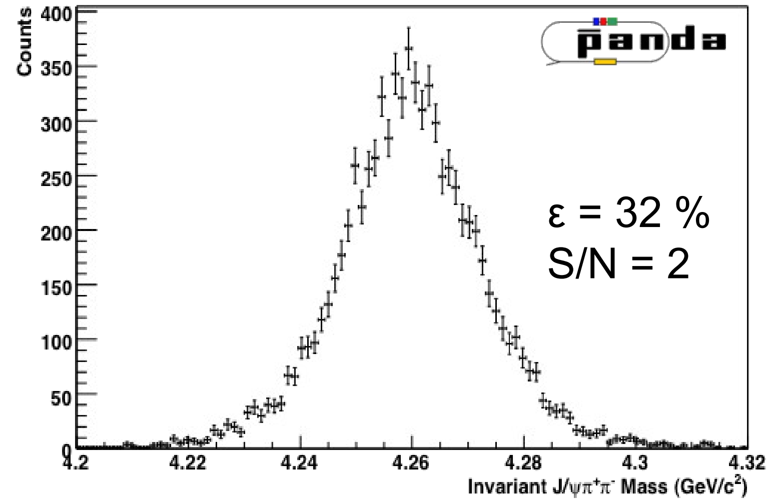
X(4350)
PRL 104,112004 (2010)



in addition to many more open charm states

How can PANDA contribute?

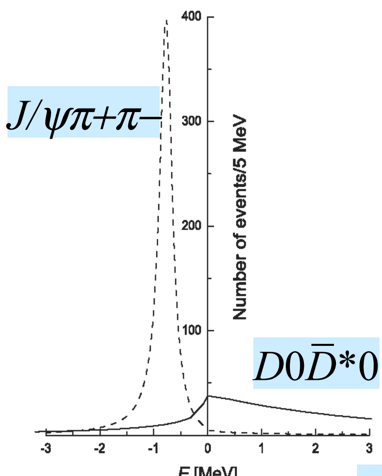
- simulation studies for several channels and √s:
- *J/ψπ+π-, J/ψπ0π0, χcγ → J/ψγγ, J/ψγ, J/ψη, ηcγ*
- direct formation in $\bar{p}p$: line shapes !
- d target: $\bar{p}n$ with p spectator tagging, e.g. Z-(4430)

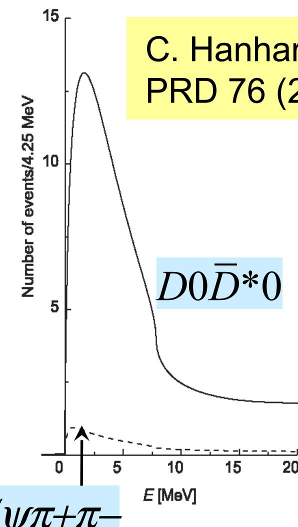


$\bar{p}p \rightarrow Y(4260) \rightarrow J/\psi\pi^+\pi^-$ ≈ 100 events/day

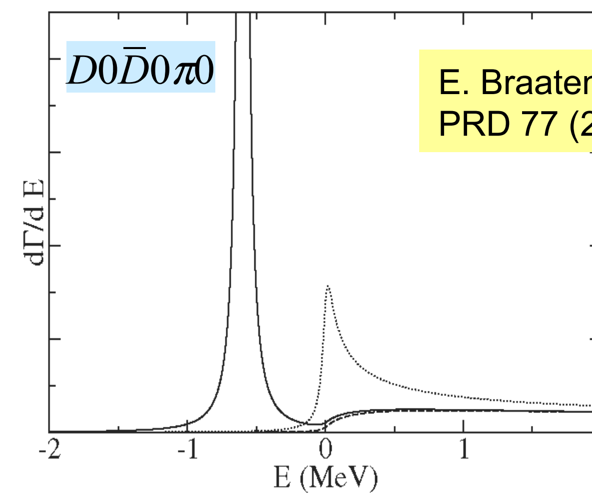
$\rightarrow J/\psi\pi^0\pi^0$ ≈ 40 events/day

S/N =25





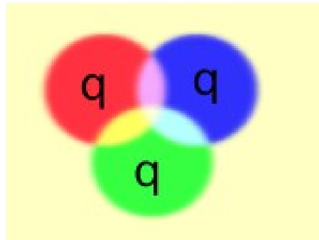
C. Hanhart *et al.*, PRD 76 (2007) 034007



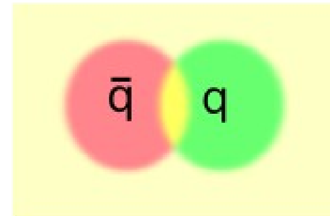
E. Braaten, M. Lu, PRD 77 (2008) 014029

Beyond standard quark configurations

- QCD allows much more than what we have observed:

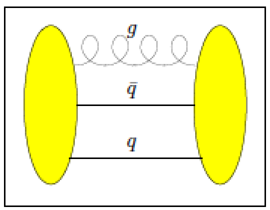


Baryons

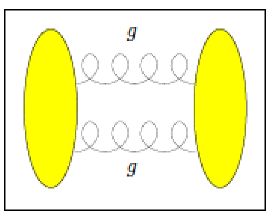


Mesons

Exotics:

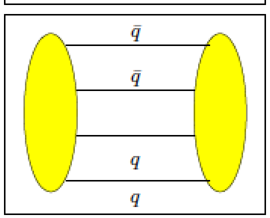


hybrid:
with gluon excitation

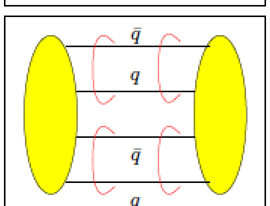


glueball:
pure gluon state

may have JPC not allowed for q$\bar{q}$



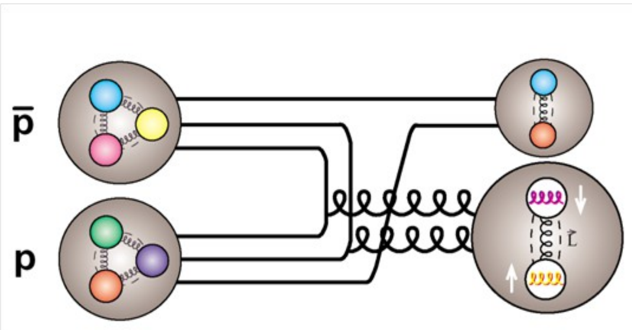
4 quark state:
compact 4–quark state



hadronic molecule:
bound state of two mesons

Courtesy C. Hanhart

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

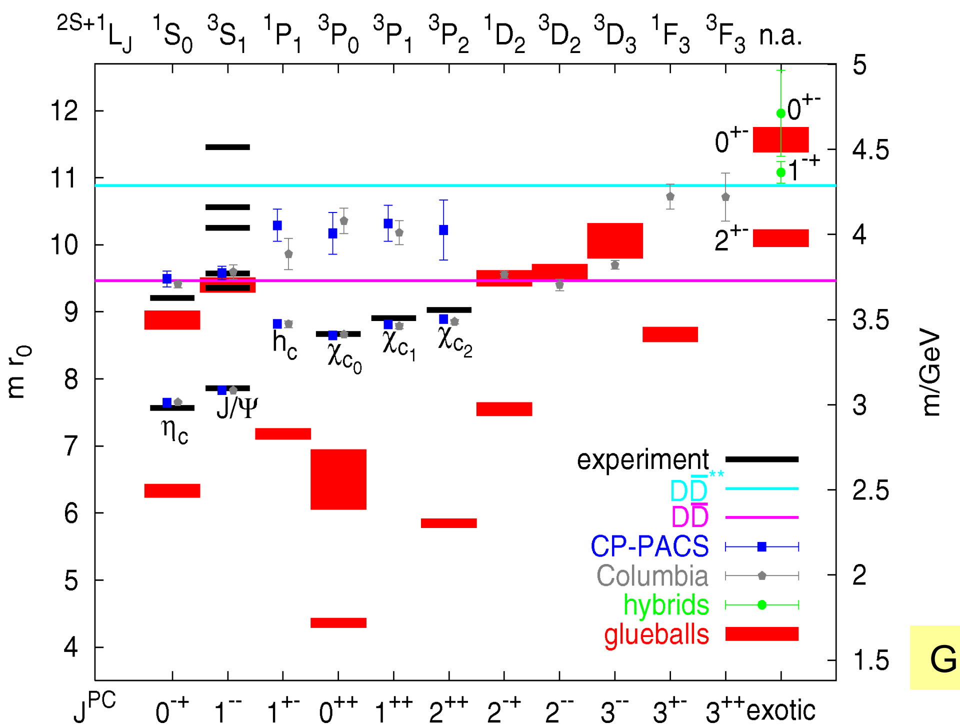


- Production: all JPC accessible

Hybrids

Gluon	1^{-+}	1^{+-}
$^1S_0$, 0^{-+}	1^{++}	1^{--}
$^3S_1$, 1^{--}	0^{+-}	0^{-+}
	1^{+-}	1^{-+}
	2^{+-}	2^{-+}

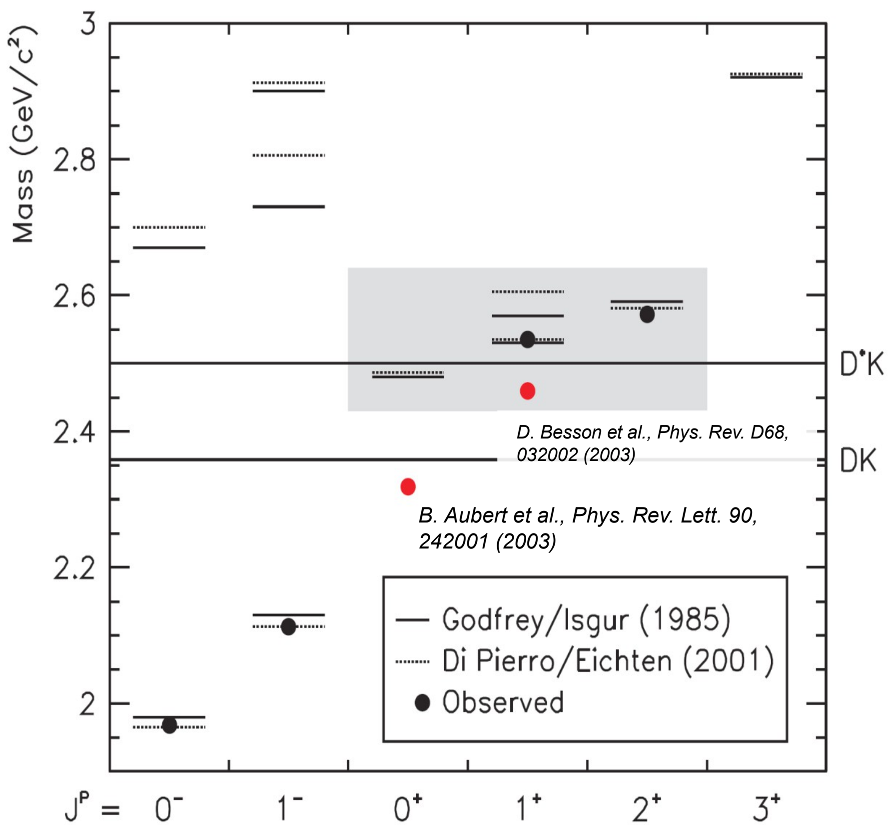
JPC exotic



Exotic JPC would be clear signal

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

Open charm: The Ds spectrum



B. Aubert et al. (BaBar Collab.), Phys. Rev. D 74 (2006) 032007

- new narrow states Ds*(2317) and Ds*(2460) seen by BaBar, Belle, CLEO
- masses significantly lower than quark model expectation
- states are just below DK and D*K threshold
- interpretation unclear: DK / D*K molecules, tetraquarks, chiral doublers, …?

Ds0*(2317) Theoretical Predictions

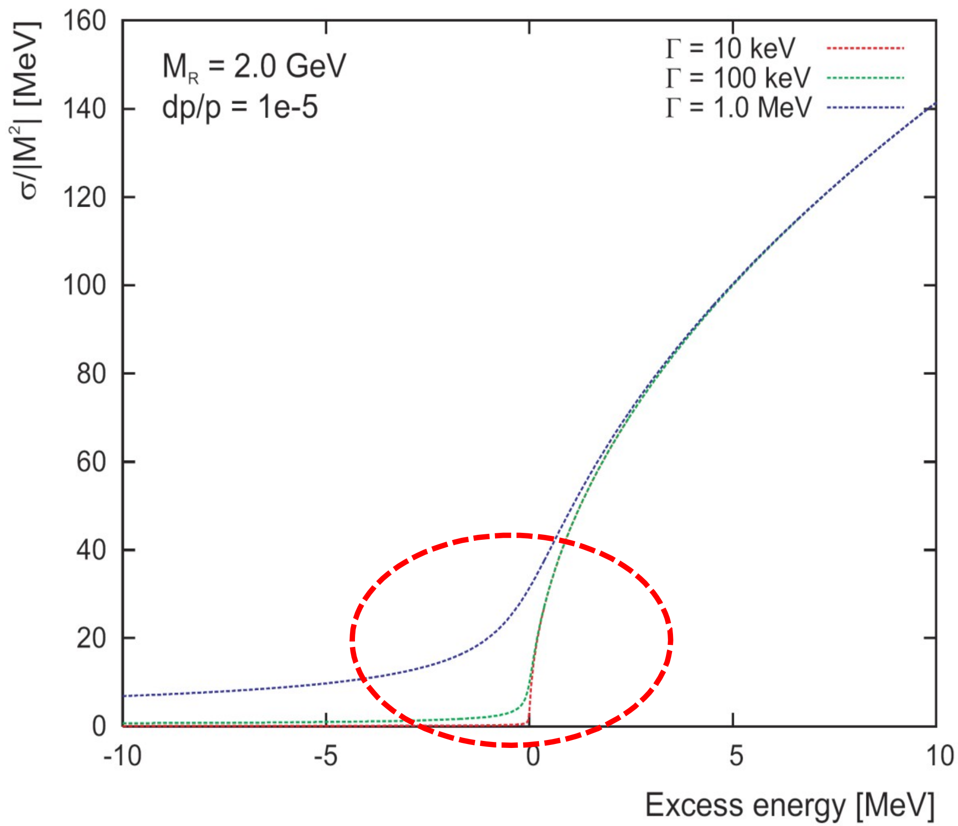
Approach	Γ(Ds0*(2317) → Dsπ0) (keV)
M. Nielsen, Phys. Lett. B 634, 35 (2006)	**6 ± 2**
P. Colangelo and F. De Fazio, Phys. Lett. B 570, 180 (2003)	**7 ± 1**
S. Godfrey, Phys. Lett. B 568, 254 (2003)	**10**
Fayyazuddin and Riazuddin, Phys. Rev. D 69, 114008 (2004)	**16**
W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D 68, 054024 (2003)	**21.5**
J. Lu, X. L. Chen, W. Z. Deng and S. L. Zhu, Phys. Rev. D 73, 054012 (2006)	**32**
W. Wei, P. Z. Huang and S. L. Zhu, Phys. Rev. D 73, 034004 (2006)	**39 ± 5**
S. Ishida, M. Ishida, T. Komada, T. Maeda, M. Oda, K. Yamada and I. Yamauchi, AIP Conf. Proc. 717, 716 (2004)	**15 - 70**
H. Y. Cheng and W. S. Hou, Phys. Lett. B 566, 193 (2003)	**10 - 100**
A. Faessler, T. Gutsche, V.E. Lyubovitskij, Y.L. Ma, Phys. Rev. D 76 (2007) 133	**79.3 ± 32.6**
Y. I. Azimov and K. Goeke, Eur. Phys. J. A 21, 501 (2004)	**129 ± 43 (109 ± 16)**
M.F.M. Lutz, M. Soyeaur, arXiv: 0710.1545 [hep-ph]	**140**
Feng-Kun Guo, Christoph Hanhart, Siegfried Krewald, Ulf-G. Meißner Phys Lett. B 666 (2008) 251-255	**180 ± 40 ± 100**

Method: Threshold Scan

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

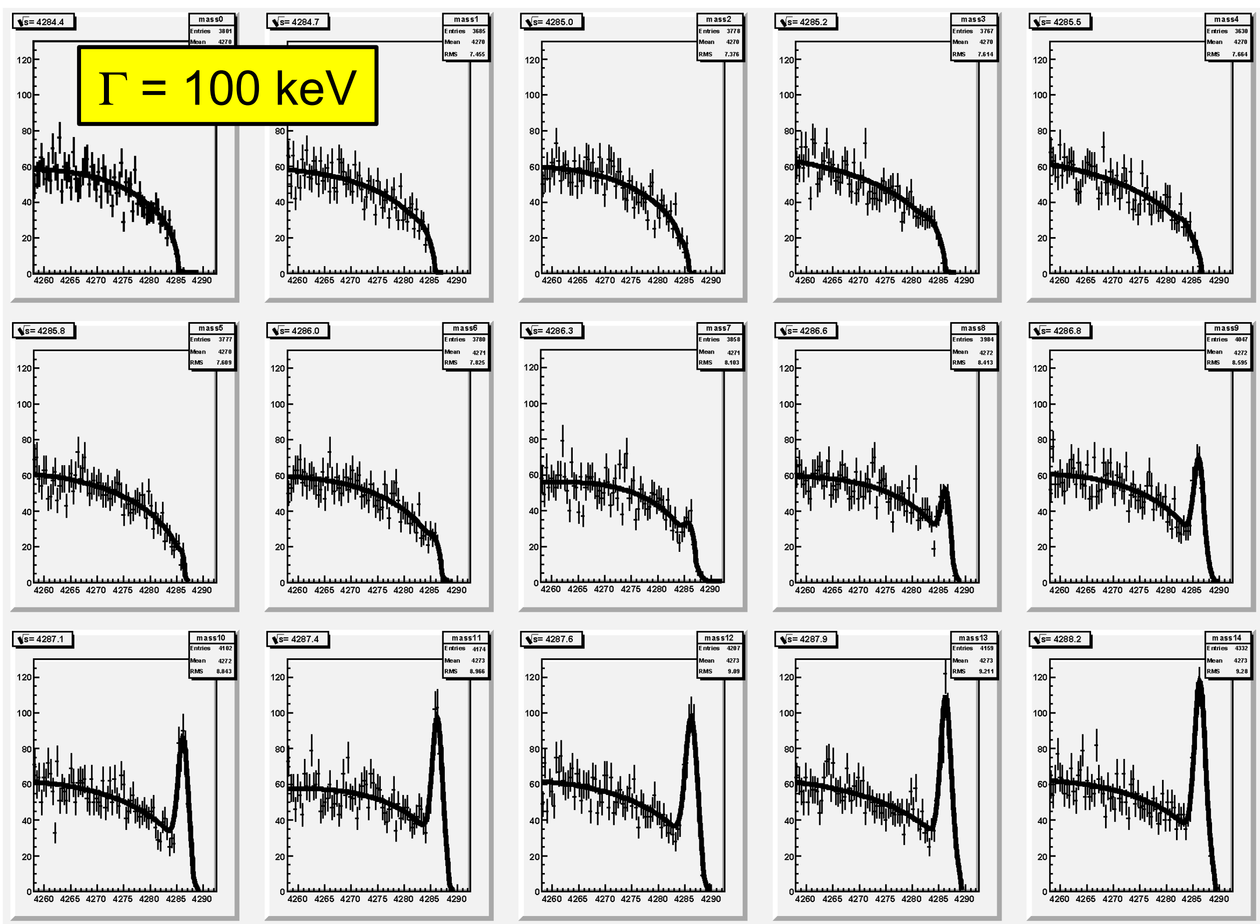
$$\Rightarrow \quad \frac{\sigma(s)}{|M^2|} = \frac{\Gamma}{4\pi\sqrt{s}} \int_{-\infty}^{\sqrt{s}-m_{D_s}} \mathrm{d}m \frac{\sqrt{\left(s-(m+m_{D_s})^2\right)\left(s-(m-m_{D_s})^2\right)}}{\left(m-m_{D(2317)}\right)^2+(\Gamma/2)^2}$$

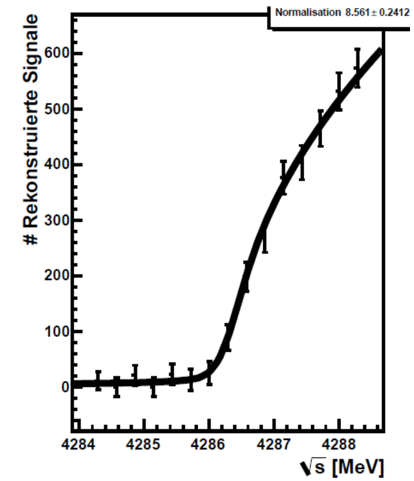
- excitation function only depends on m and Γ of Ds(2317)
- experimental accuracy determined by beam quality (Δp, σp/p), not by detector resolution

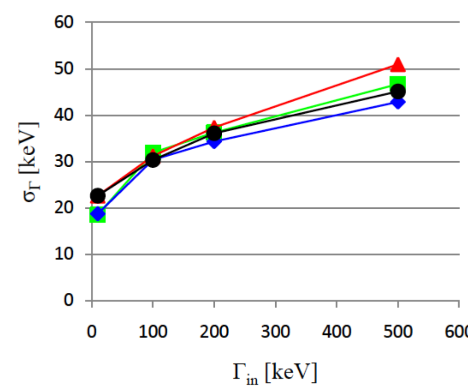


Simulation Results: Energy Scan

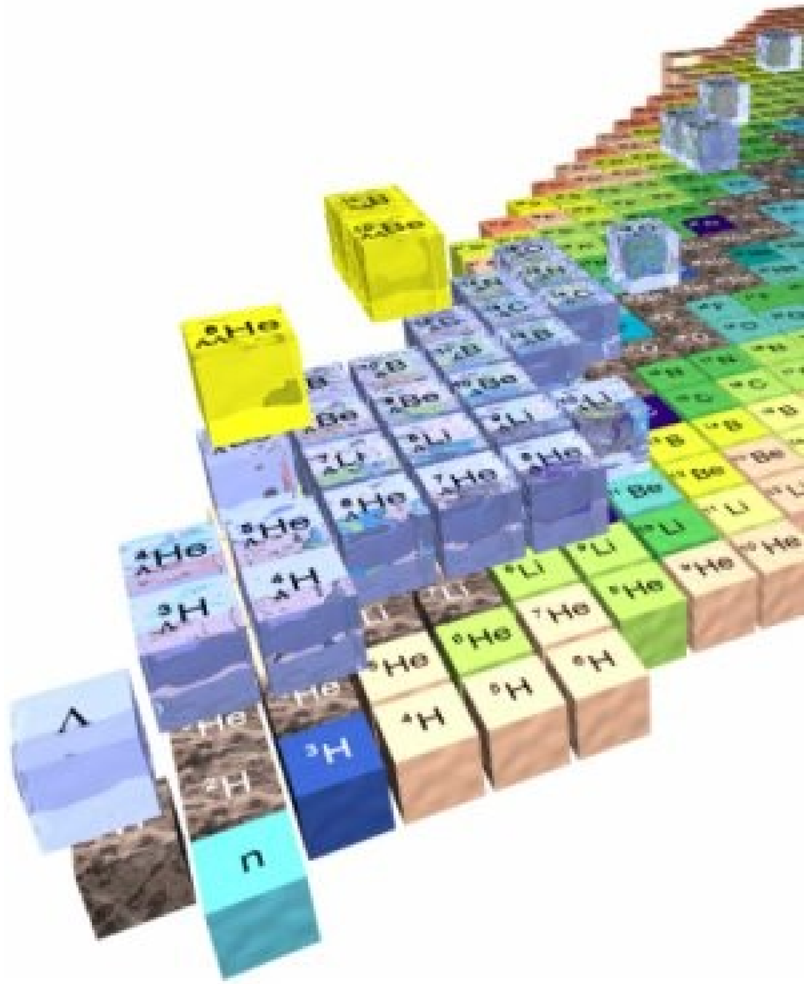
Msum = Mmiss(Ds) + M(Ds)





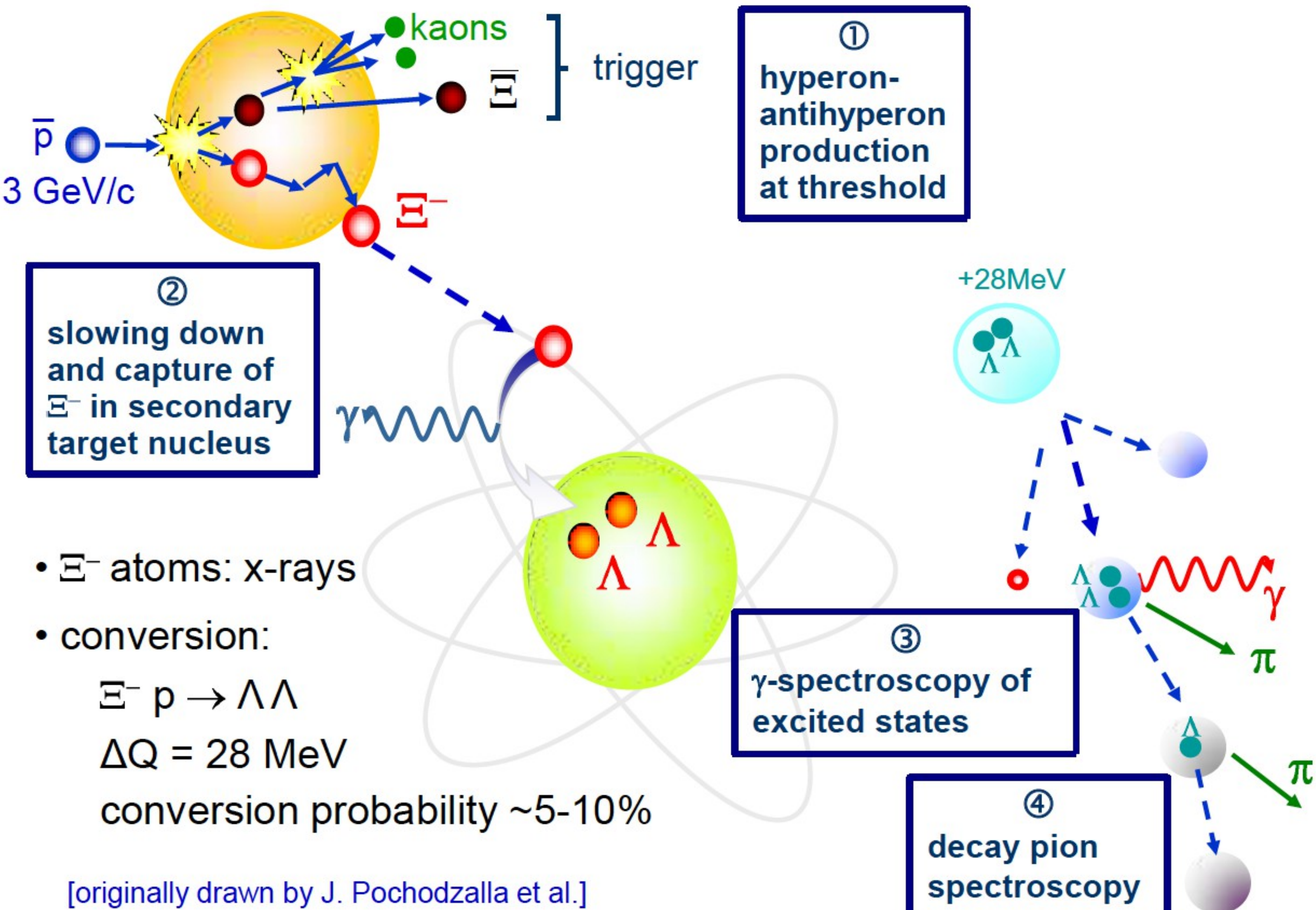


Hadron Interactions:
Double Strange Hypernuclei



Jim Ritman

Production Mechanism and Detection Strategy



① hyperon-antihyperon production at threshold

② slowing down and capture of Ξ^- in secondary target nucleus

③ γ-spectroscopy of excited states

④ decay pion spectroscopy

- Ξ^- atoms: x-rays
- conversion:

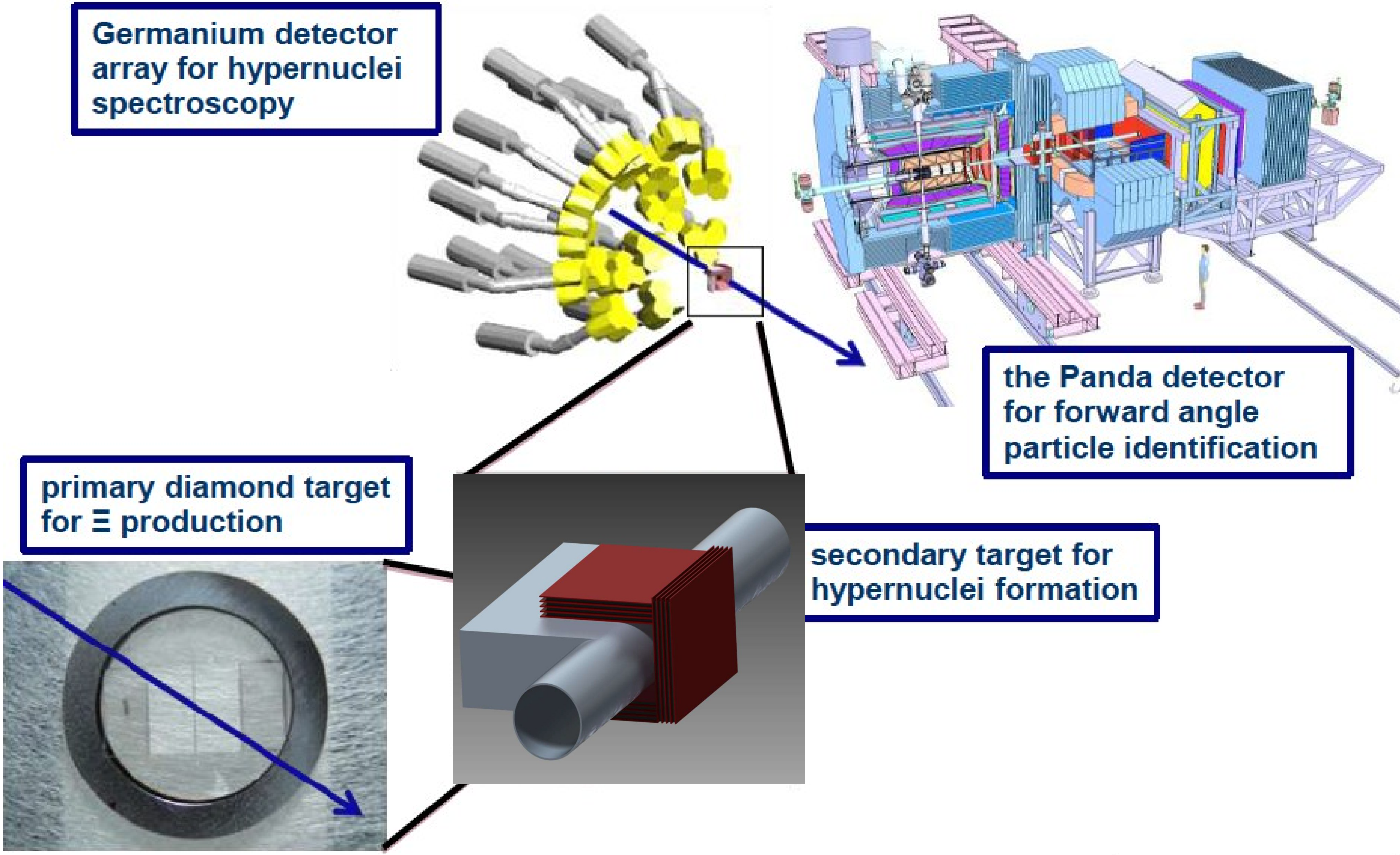
  $\Xi^- p \rightarrow \Lambda\Lambda$

  $\Delta Q = 28$ MeV

  conversion probability ~5-10%

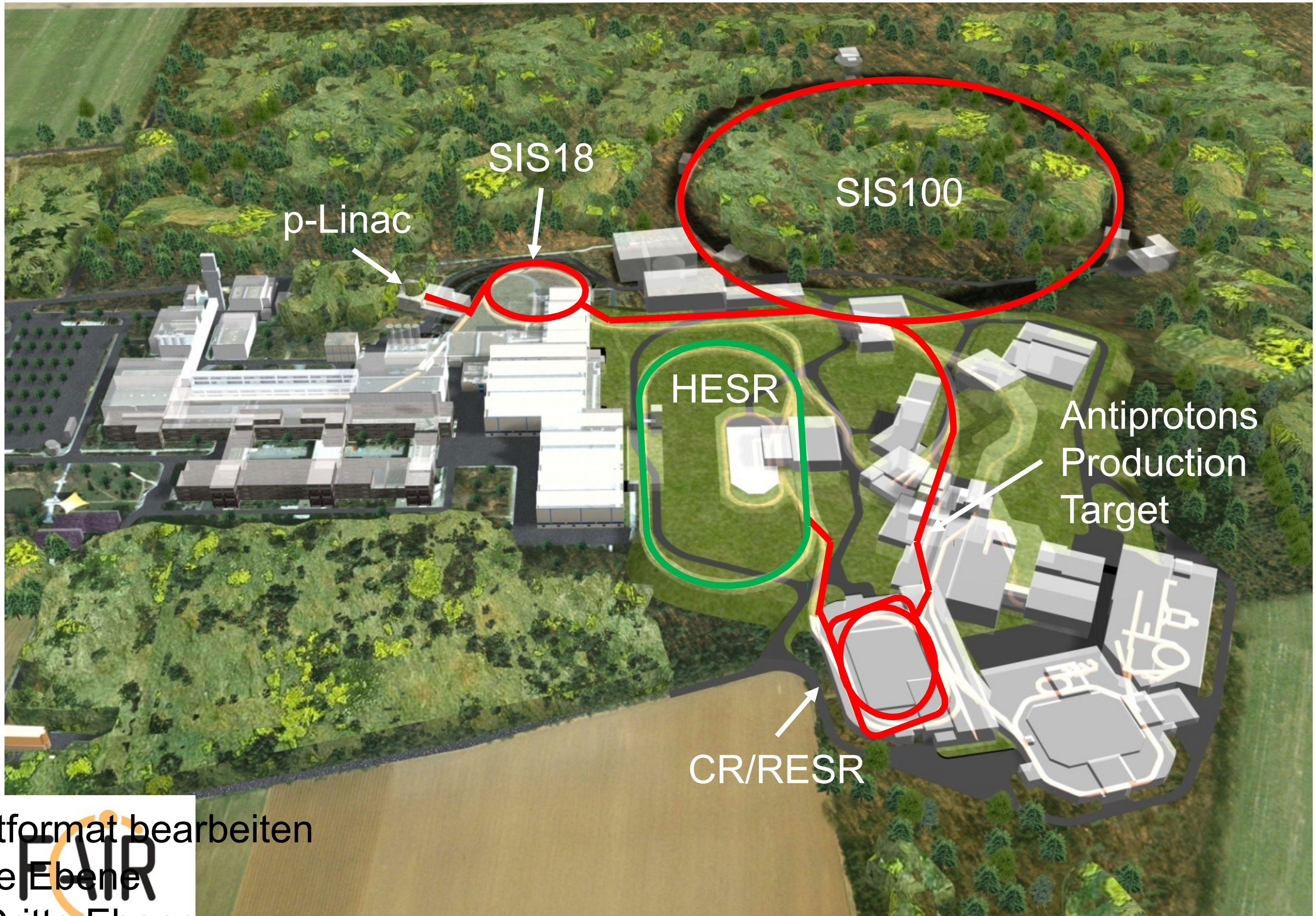
[originally drawn by J. Pochodzalla et al.]

Instrumentation



FAIR and the PANDA Detector

Facility for Antiproton and Ion Research



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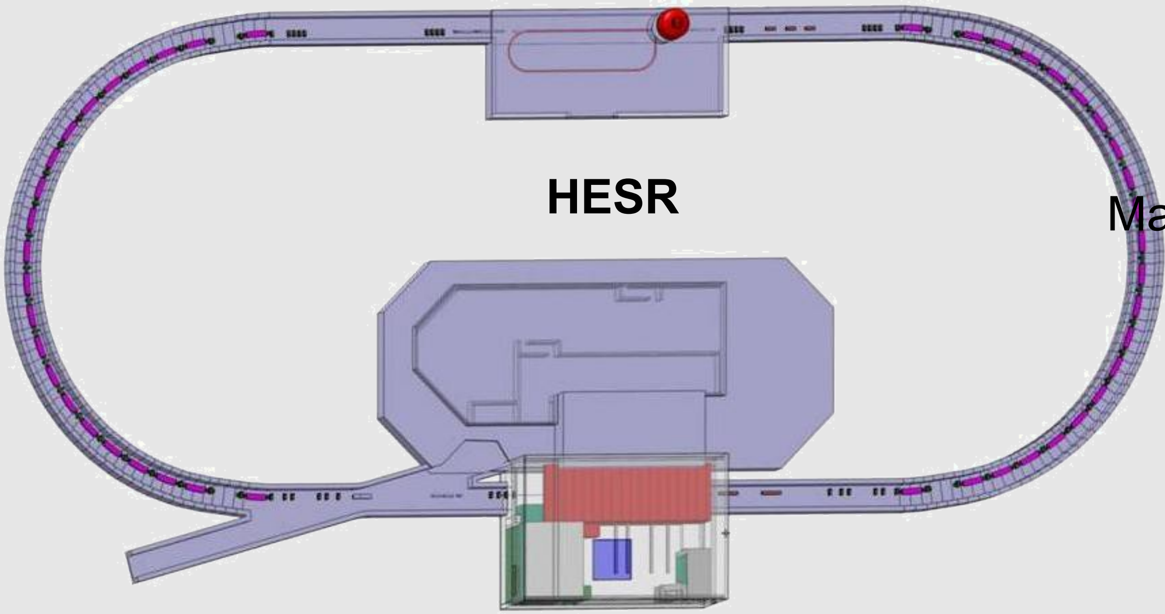
Dritte Ebene
Vierte Ebene

Facility for Antiproton and Ion Research

Areal view May 2013

HESR with PANDA and Electron Cooler



1010 - 1011 Antiprotons stored

Thick target 4·1015 cm-2

Δp/p ≤ 4·10-5

Lumi up to 2·1032 cm-2s-1

Phase space cooling

beam life time: > 30 min

HESR	
575 m	Circumference
1.5 – 15 GeV/c	Momentum
up to 9 GeV/c	Electron Cooling
Full range	Stochastic Cooling

Electron Cooler, HESR Injection energies

- HESR Injection energies (3.5 GeV/c)
- 2 MV x 1 A
- Installation in COSY in spring 2013

PANDA Detector Characteristics

Antiproton momentum: from 1.5 to 15 GeV/c
Lmax ~ 2 · 1032 cm-2s-1 →   0.5 fb-1 / mo.
high rate capability: 2 · 107 s-1 interactions
nearly 4π solid angle needed to measure full decay chain and for PWA
high acceptance
π±, K±, p±, e±, μ±, γ identification   PID in all regions
displaced vertex detection –
vertex info for D, KS, Σ, Λ (cτ = 317 μm for D±)
photon detection from 10 MeV to 10 GeV
efficient event selection & good momentum resolution

PANDA Detector Scenario

- High background: exclusive event reconstruction essential
  → simultaneous neutral and charged particles
  → close to full 4π acceptance
- Glueballs/Hybrids/etc.: high kaon yield
  → PID over full forward hemisphere
- Resonances/Molecular states/etc.:
  concurrent measurement of different decay branches
  → MVD and EMC
- Electromagnetic final states: e+/- and μ+/-
  → EMC and Muon Detectors

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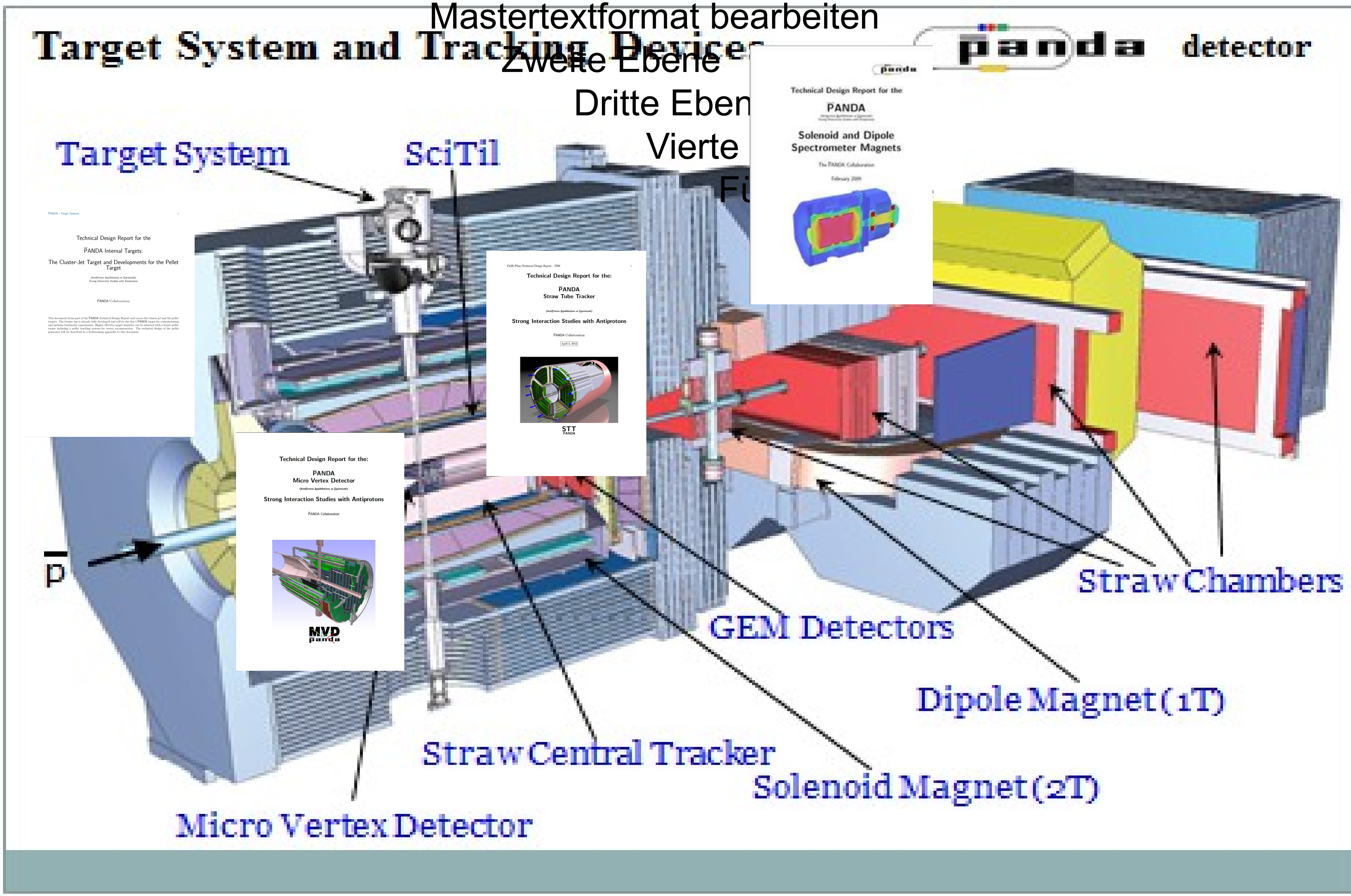

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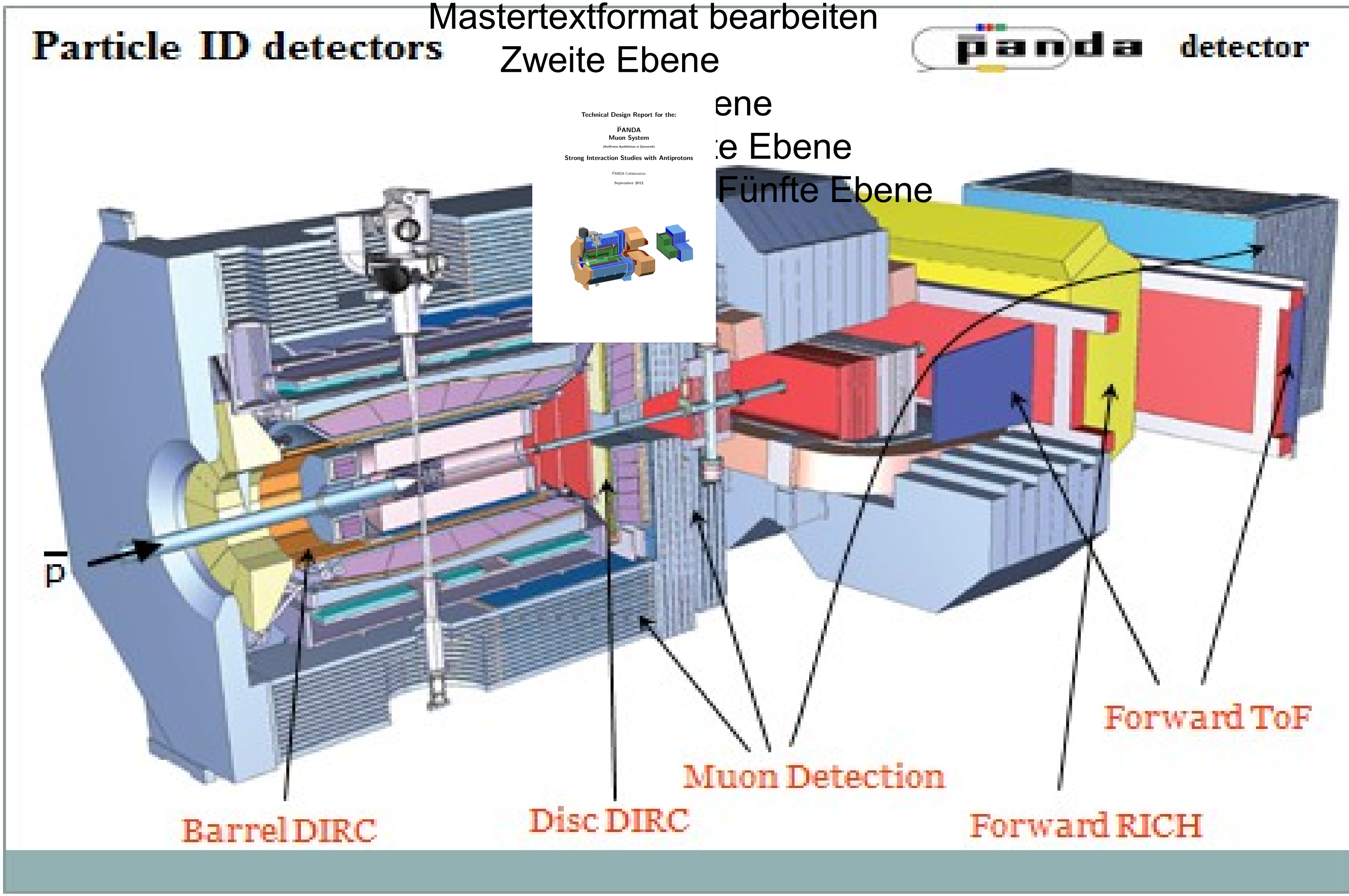

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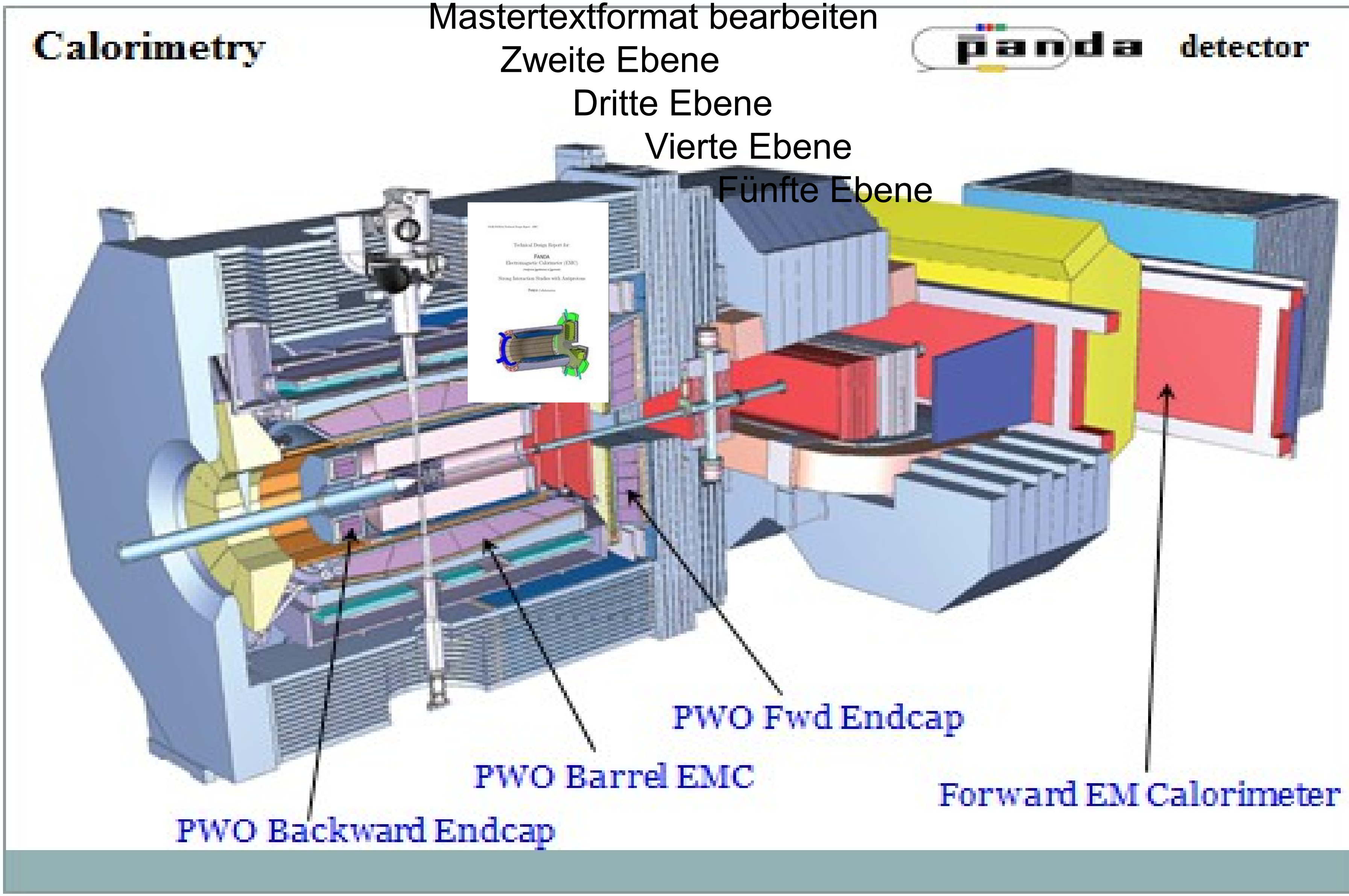
    - Vierte Ebene
      - Fünfte Ebene



The PANDA Collaboration

517 Members from

67 Institutes

18 Countries

Australia, Austria, Belarus, China, France, Germany, India, Italy, Poland, Romania, Russia, Spain, Sweden, Switzerland, Thailand, The Netherlands, USA, UK