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Strong Interaction Physics with PANDA

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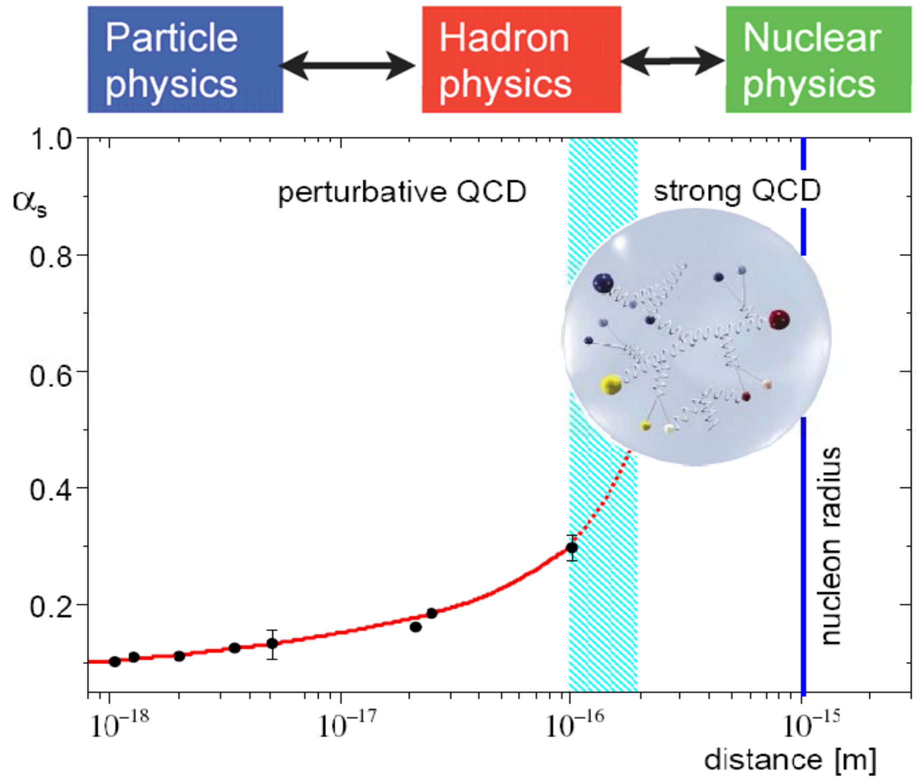
on behalf of the PANDA Collaboration

LEAP 2013, Uppsala, June 11, 2013

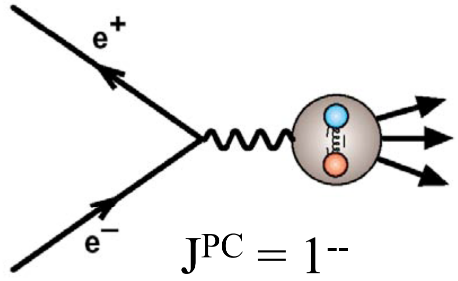
Key Questions of Hadron Physics

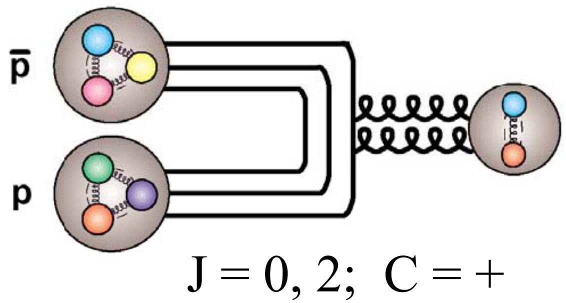
- how does confinement work?
- how is the mass of hadrons generated?
- do also non-$\bar{q}q$ or non-qqq hadrons exist and where are they?
- what is the interplay of hadron and quark-gluon degrees of freedom?

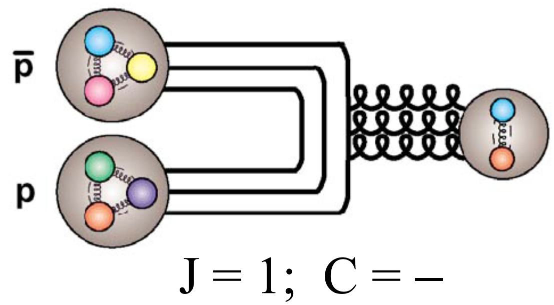


Why to Use Antiprotons ?

- annihilation is a gluon rich process
- ~2 GeV annihilation energy “for free”
- all fermion-antifermion quantum numbers accessible (in contrast to e^+e^-)
- very high resolution in formation reactions
- high angular momentum accessible







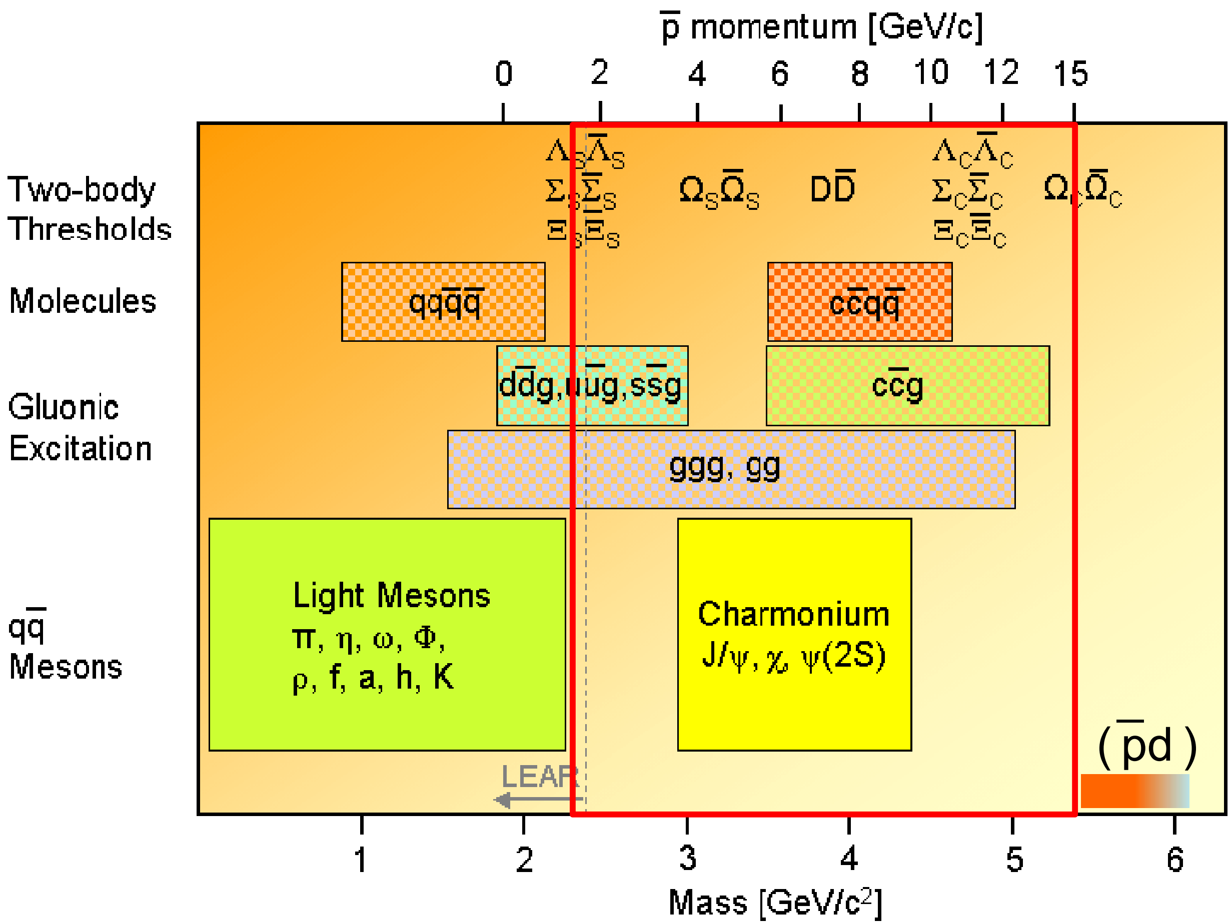
Physics Reach

$\bar{p}p$, $\bar{p}d$ collisions:

- meson spectroscopy
  - *charmonium*
  - *glueballs, hybrids, tetraquarks, molecules*
  - *D mesons*
- baryon spectroscopy
- reaction dynamics
- proton structure*

$\bar{p}A$ collisions:

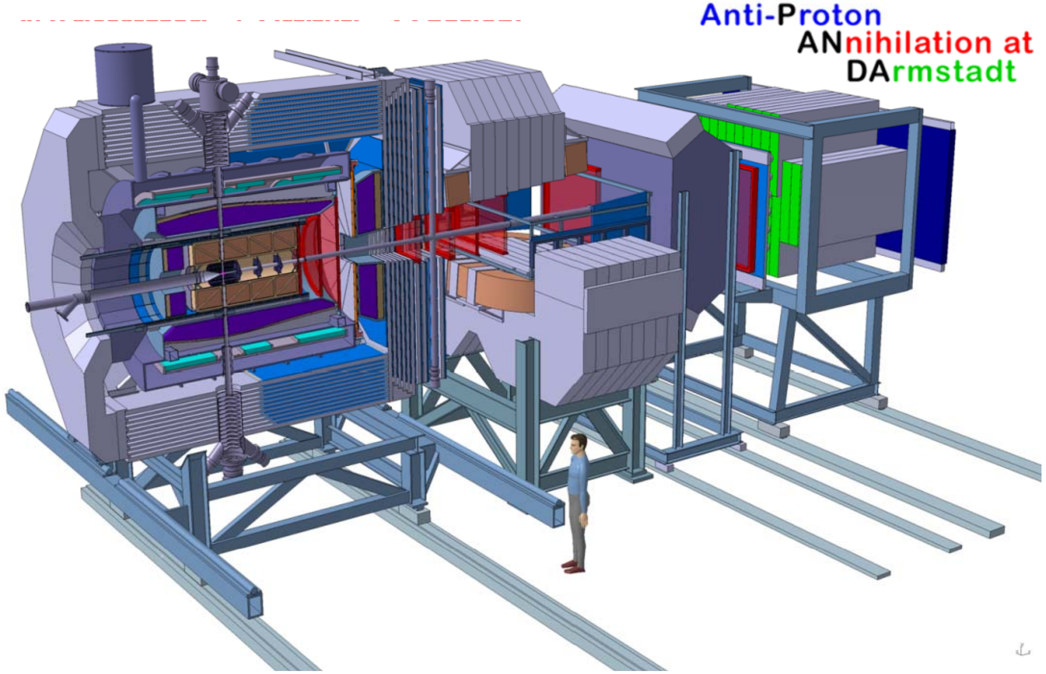
- hadrons in nuclei
- ΛΛ hypernuclei*



* talk by M. Maggiora, Thursday
* talk by A. Sanchez Lorente, Wednesday

The PANDA Detector

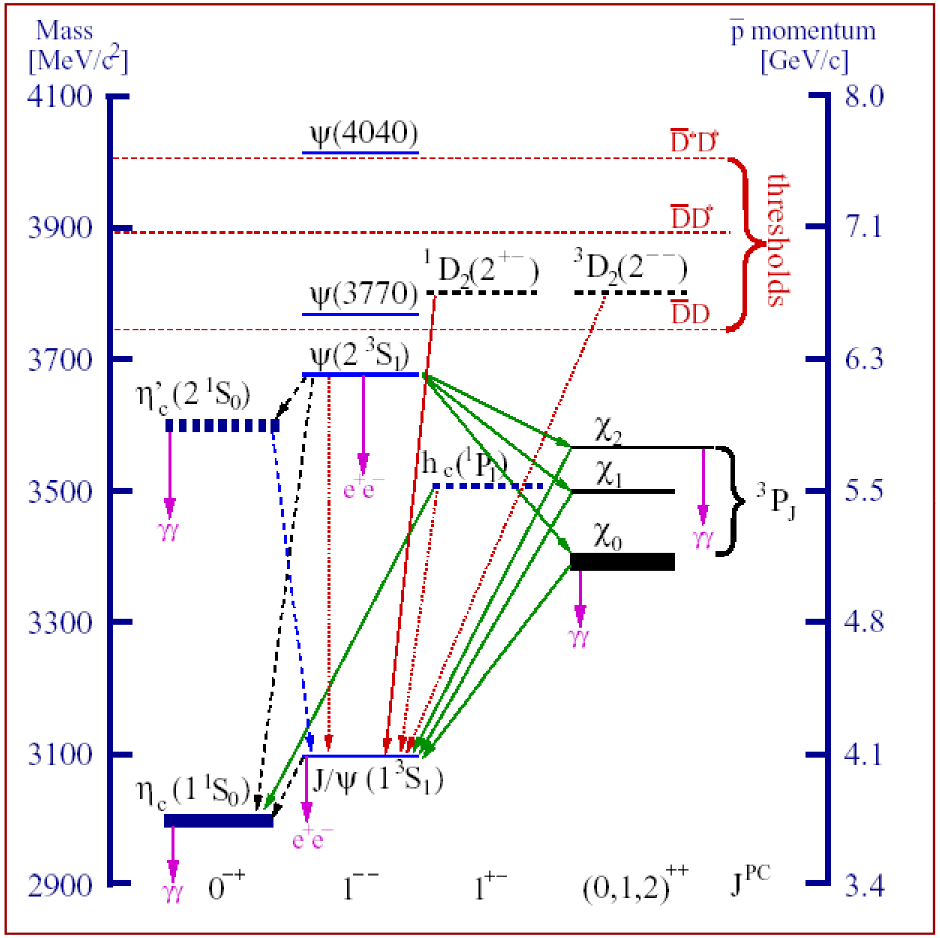
- $\bar{p}p$, $\bar{p}A$ collisions
  $p_{\bar{p}} = 1.5 – 15$ GeV/c
- almost 4π acceptance:
  - charged particles
  - photons
- tracking
  - ~50 μm vertex resolution
- calorimetry
- different PID techniques
- flexible event selection, no hardware trigger



see talks by D. Calvo, M. Mertens, P. Wintz (Thursday)

Posters by D. Melnychuk, M. Karoly, A. Pyszniak

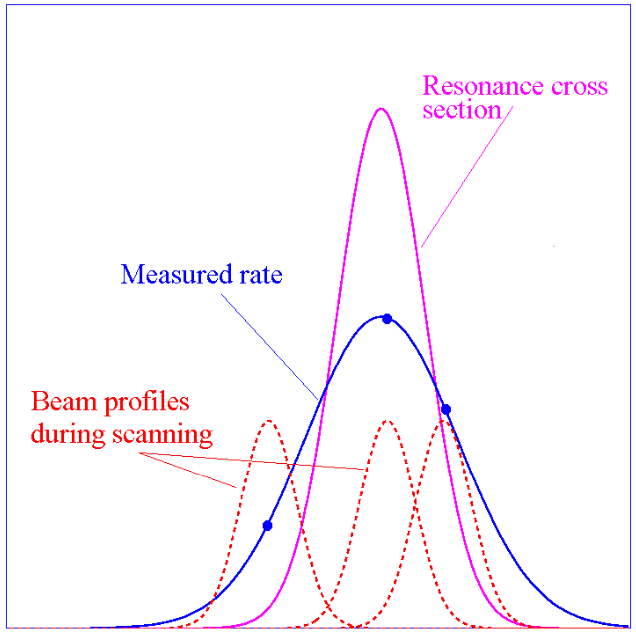
Charmonium States

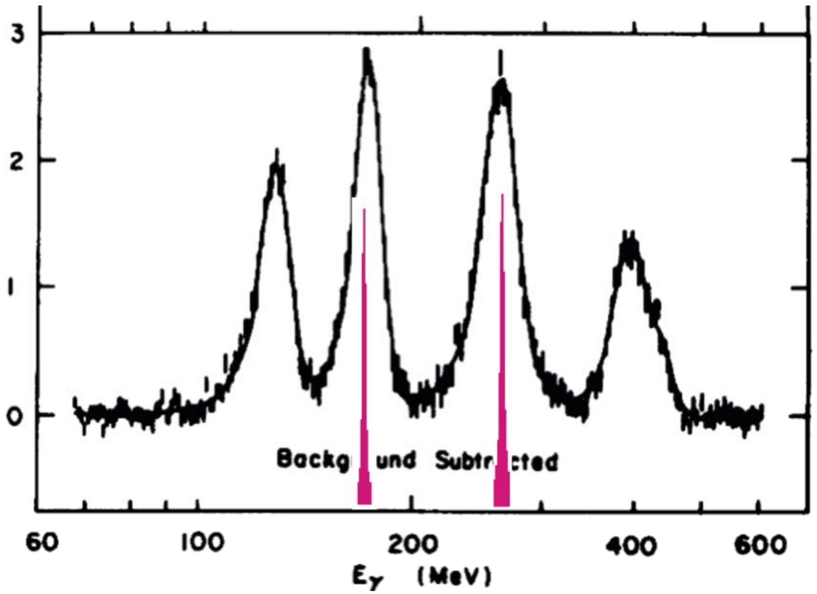


- all 8 states below $D\bar{D}$ threshold observed
- need for precision measurements:
  h_c: width (Γ < 1 MeV)
  $\eta_c(1S)$: discrepancies
  $\eta_c(2S)$: small $\Delta m(\eta_c(2S) - \psi_c(2S))$
- explore region above $D\bar{D}$ threshold
- D-wave states $^1D_2$, $^3D_2$, $^3D_3$ still missing, likely to be narrow
- understand newly discovered states X, Y, Z
- confirm vector states seen in R

Narrow Charmonium States

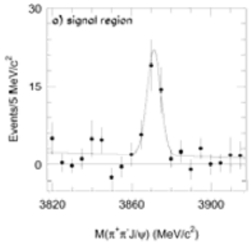
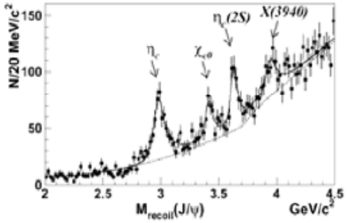
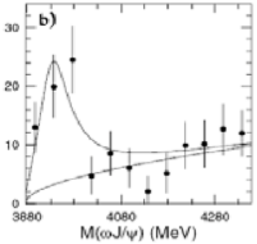
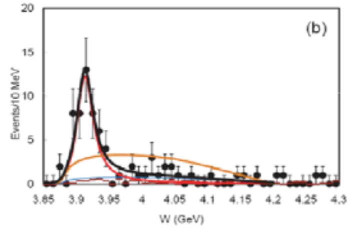
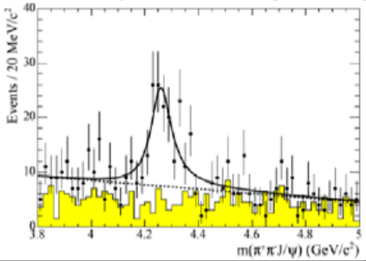
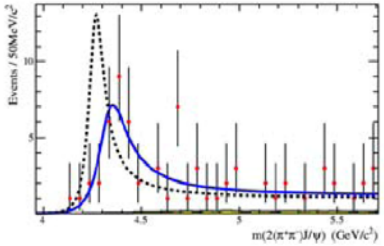
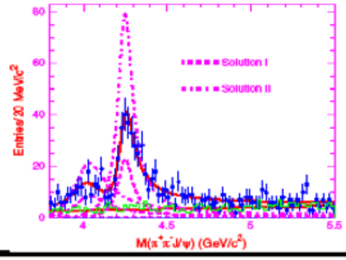
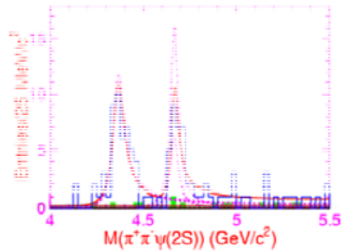
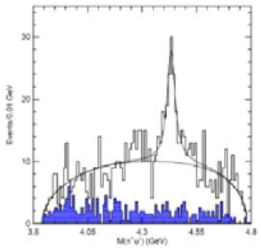
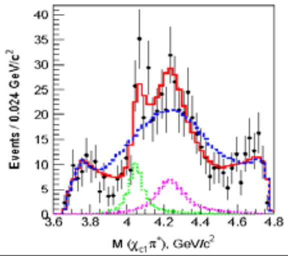
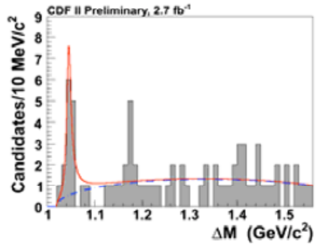
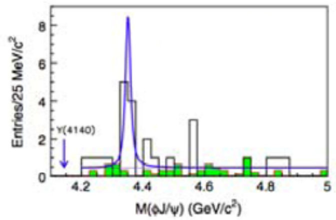
- ‘production’ experiments, e.g. $e^+e^- \rightarrow \psi' \rightarrow \gamma\, \chi_{c1,2} \rightarrow \gamma\, \gamma\, J/\psi$: mass resolution determined by detector ~10 MeV
- ‘formation’ experiments, e.g. $\bar{p}p \rightarrow \chi_{c1,2} \rightarrow \gamma\, J/\psi$: mass resolution determined by accelerator ~100 keV
- method: energy scan
- demonstrated by E760 and E835 at Fermilab





E760: δm ~ 240 keV
PANDA: δm ~ 50 keV

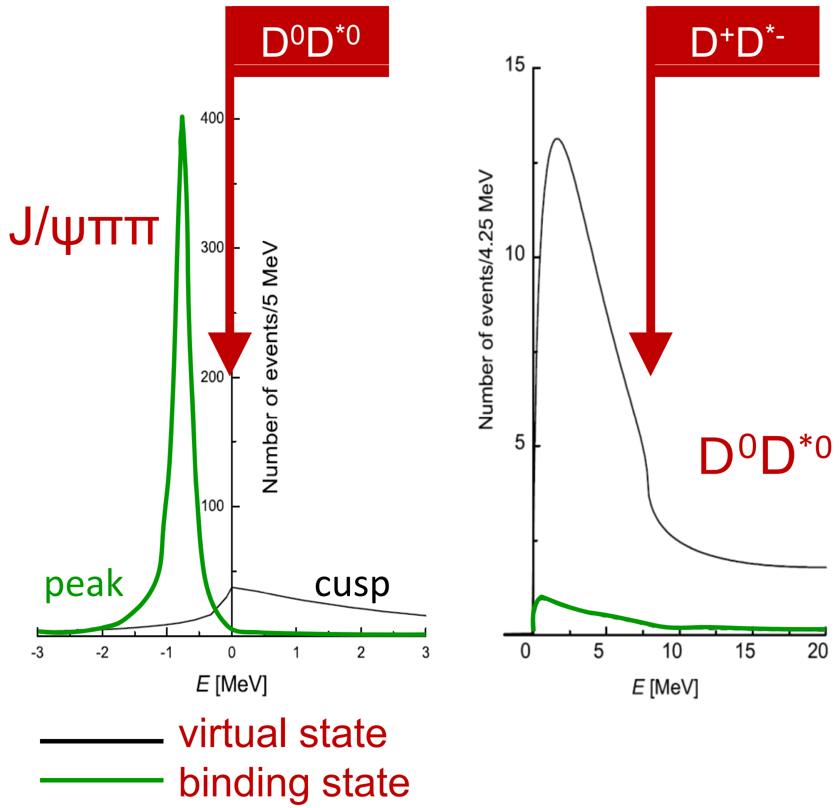
The New XYZ States: $c\bar{c}$-like but not all are $c\bar{c}$

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) 

The X(3872) State

- observed in more than one decay channel:
  $J/\psi\pi^+\pi^-$, $J/\psi\gamma$, $J/\psi\pi^+\pi^-\pi^0$, $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$, $\psi'\gamma$
- narrow width $\Gamma < 1.2$ MeV [(1)]
- $J^{PC} = 1^{++}$ [(2)]
- mass 3871.46 ± 0.19 MeV very close to $D^0\bar{D}^{*0}$ threshold:

  $$M_X - (M_{D^{*0}} + M_{D^0}) =$$
  $$-0.32 \pm 0.35 \text{ MeV}$$
- s-wave molecular state?
- needs line shape measurement in different decay channels!



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

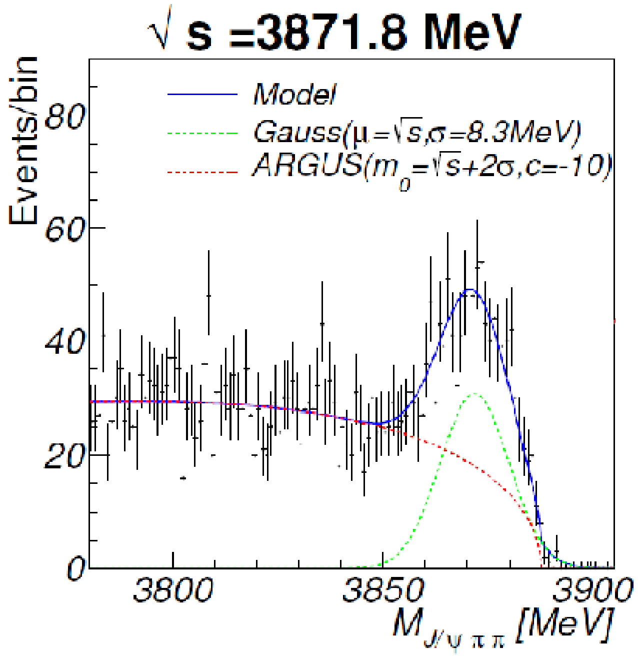
(1) Belle, PRD 84 (2011) 052004
(2) LHCb, arXiv:1302.6269

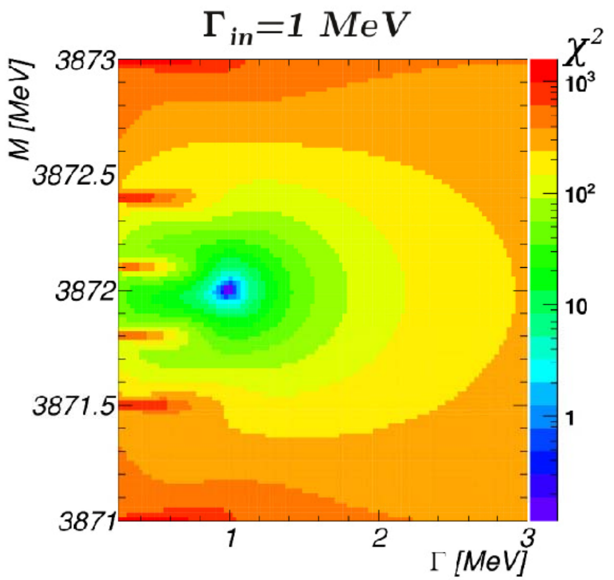
The X(3872) State: Simulation Results

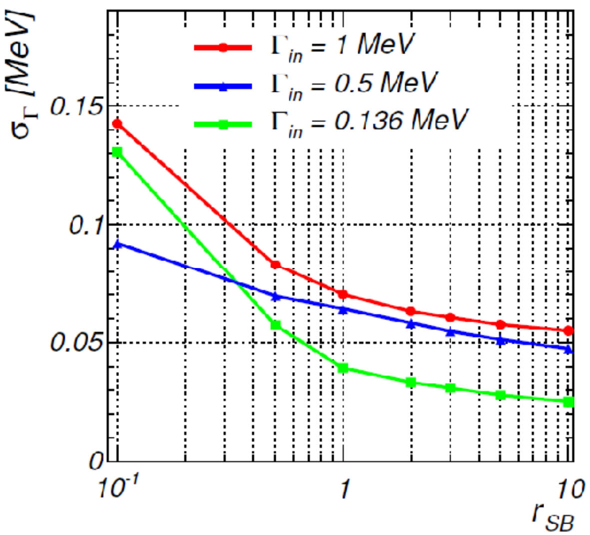
- simulation of energy scan of
  $\bar{p}p \rightarrow X(3872) \rightarrow J/\psi\pi^+\pi^-$
- result: a width of ~100 keV can be measured:

  $\Delta\Gamma/\Gamma < 20\%$ (Γ_{in} = 136 keV)

  $\Delta\Gamma/\Gamma < 4\%$ (Γ_{in} = 0.5, 1 MeV)





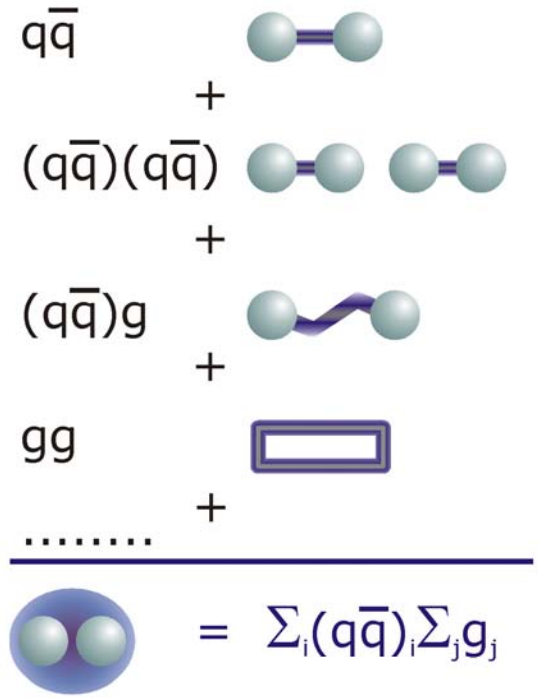


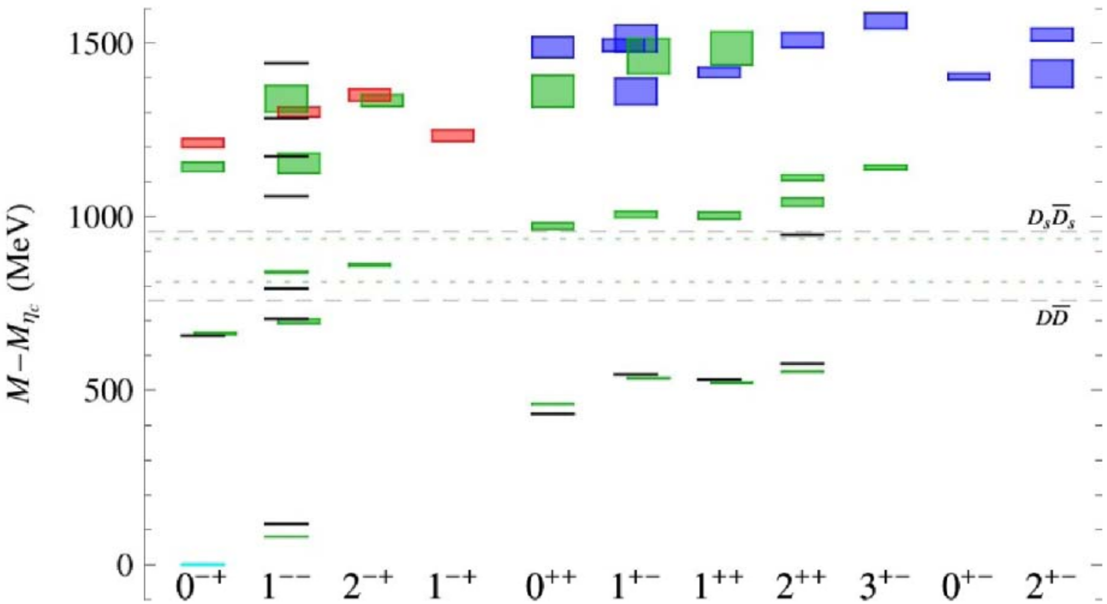
T. Randriamalala,
PhD thesis Univ. Bochum 2011

similar results:
M. Galuska,
M. Sc. thesis Univ. Giessen 2011

“Exotic” non-$q\bar{q}$ Mesons

- wave function may have higher Fock states in addition to $q\bar{q}$
- $q\bar{q}$ and non-$q\bar{q}$ components with same J^{PC} will mix
- Y(4260): candidate for $c\bar{c}g$ hybrid





predictions from recent lattice QCD calculations:

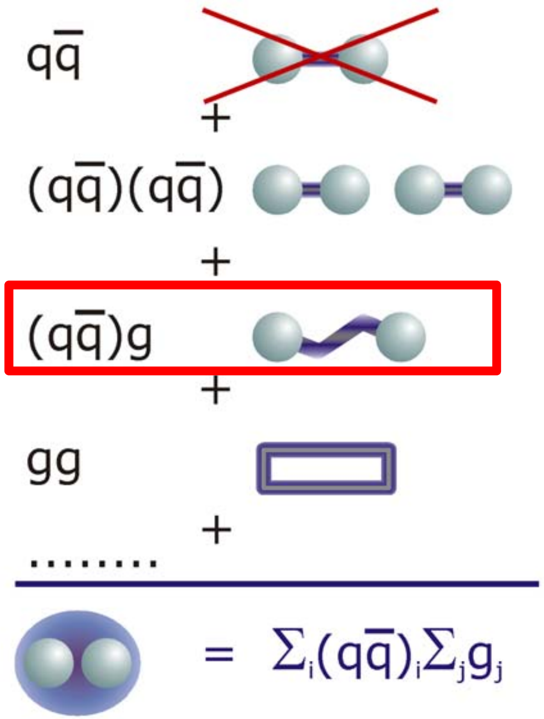
L. Liu *et al.*, JHEP 07 (2012) 126

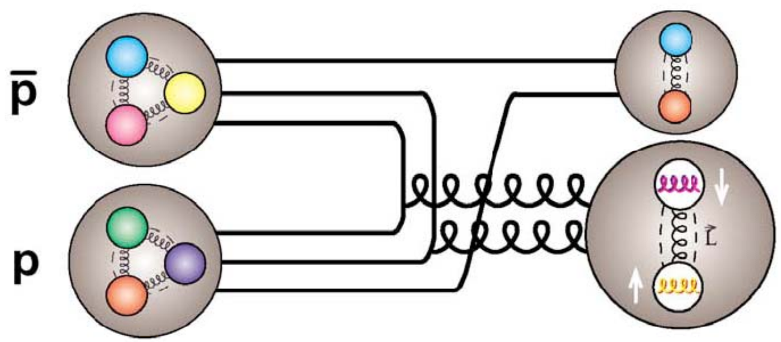
- lightest hybrid supermultiplet (red)
- 1st excited hybrid supermultiplet (blue)
- other states (green)

"Exotic" non-$q\bar{q}$ Mesons

- clear evidence for hybrid or glueball (oddball) nature only if $q\bar{q}$ component is forbidden
- $q\bar{q}$ pair and constituent gluon may form exotic quantum numbers
- experimental indication:

  $\bar{p}p \rightarrow X\pi$ but $\bar{p}p \not\rightarrow X$

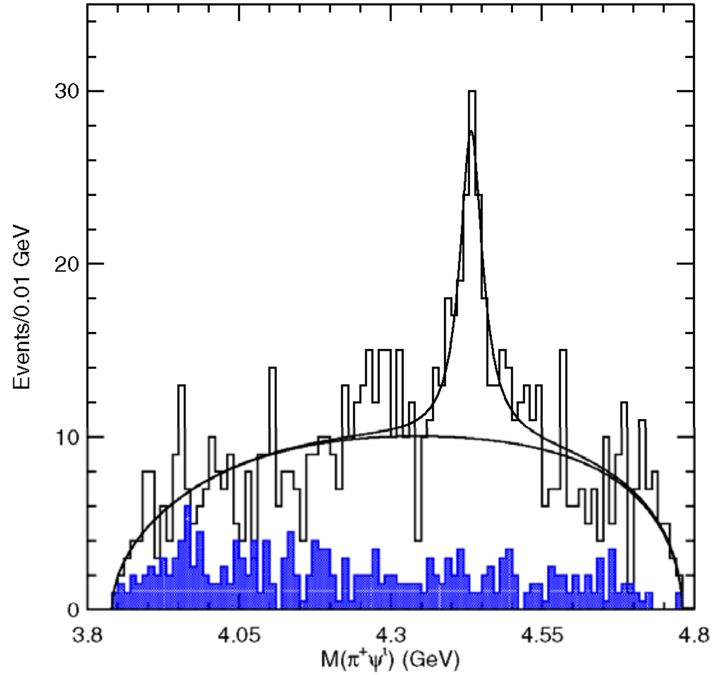




$q\bar{q}$ \ Gluon	1^{--} (TM)	1^{+-} (TE)
$^1S_0$, 0^{-+}	1^{++}	1^{--}
$^3S_1$, 1^{--}	0^{+-} 1^{+-} 2^{+-}	0^{-+} 1^{-+} 2^{-+}

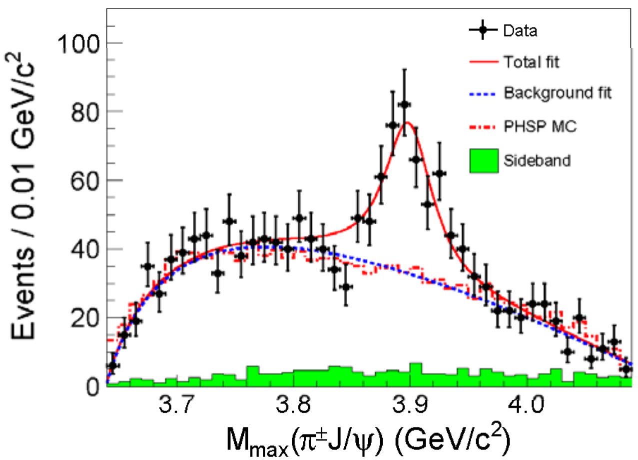
Non-$q\bar{q}$ Mesons: Charged $c\bar{c}$-like States

- 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

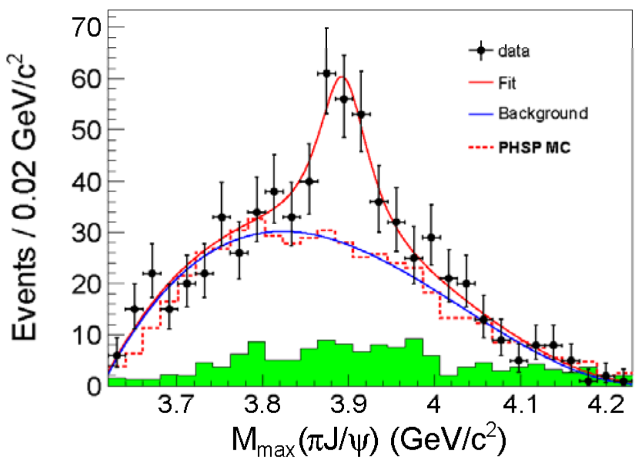


Belle,
PRL 100 (2008) 142001

BESIII, arXiv:1303.5949

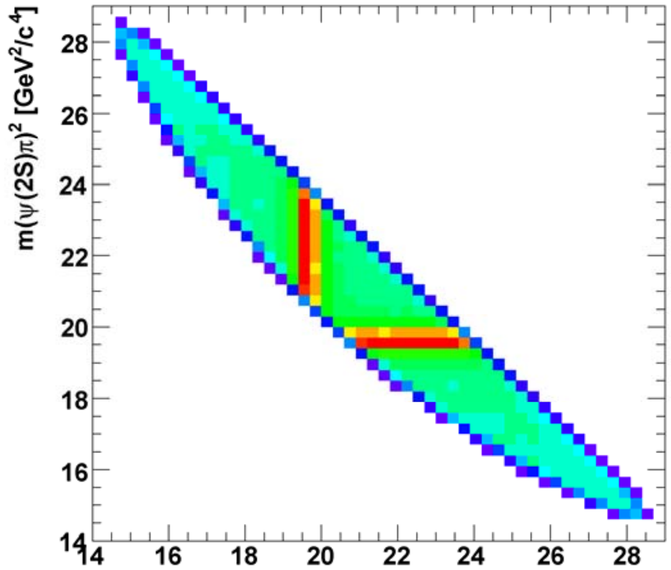


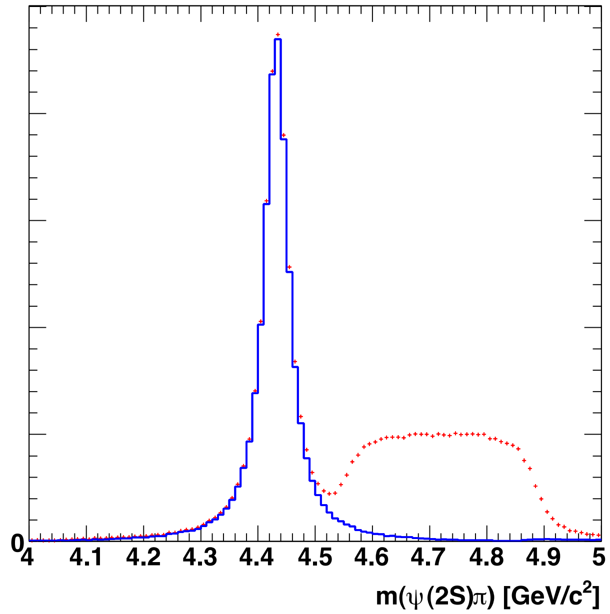
Belle, arXiv:1304.0121



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

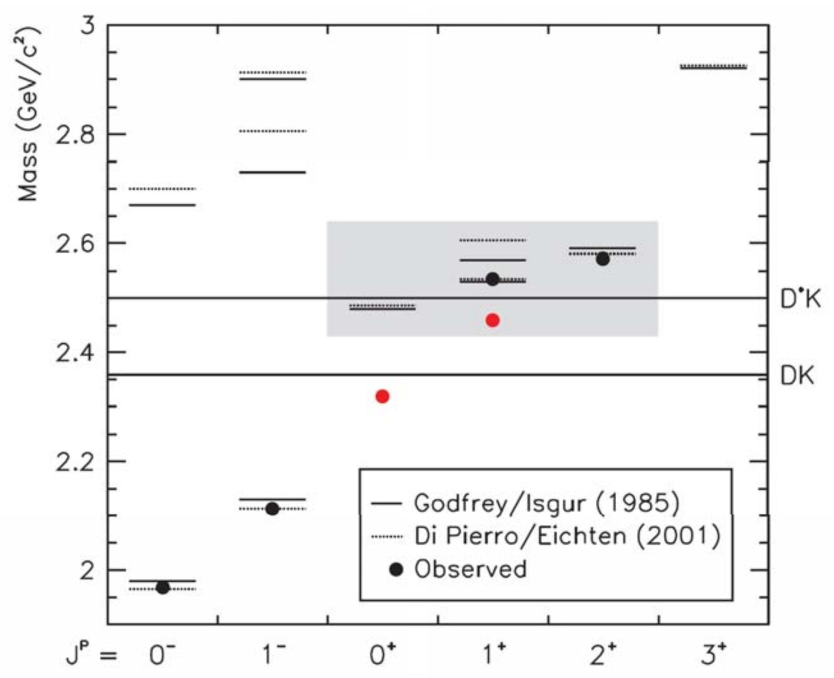
- can be studied with PANDA
  - production in $\bar{p}p$:
    $\bar{p}p \rightarrow Z(4430)^{\pm}\,\pi^{\mp}$
    $Z(4430)^{\pm} \rightarrow \psi(2S)\,\pi^{\pm}\,x$
  - formation in $\bar{p}n$:
    $\bar{p}d \rightarrow Z(4430)^{-}\,p_{spectator}$
    $\rightarrow \psi(2S)\,\pi^{-}\,p_{spectator}$
    spectator proton has low energy, must be reconstructed
    reduced mass resolution

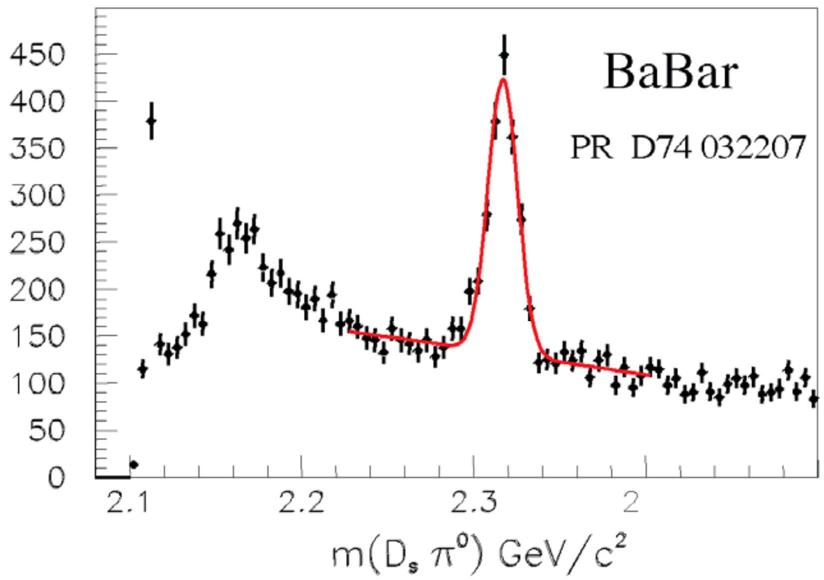




Open Charm Mesons

- Discovery of narrow states $D_s(2317)$ and $D_s(2460)$ came as a surprise
- remarkably close to DK and D^*K threshold
- fit into QM only after tuning of parameters
- interpretation as DK/D^*K molecule
- $D_s(2317)$: $\Gamma_{exp} < 3.8$ MeV, $\Gamma_{theo} = 4 - 320$ keV





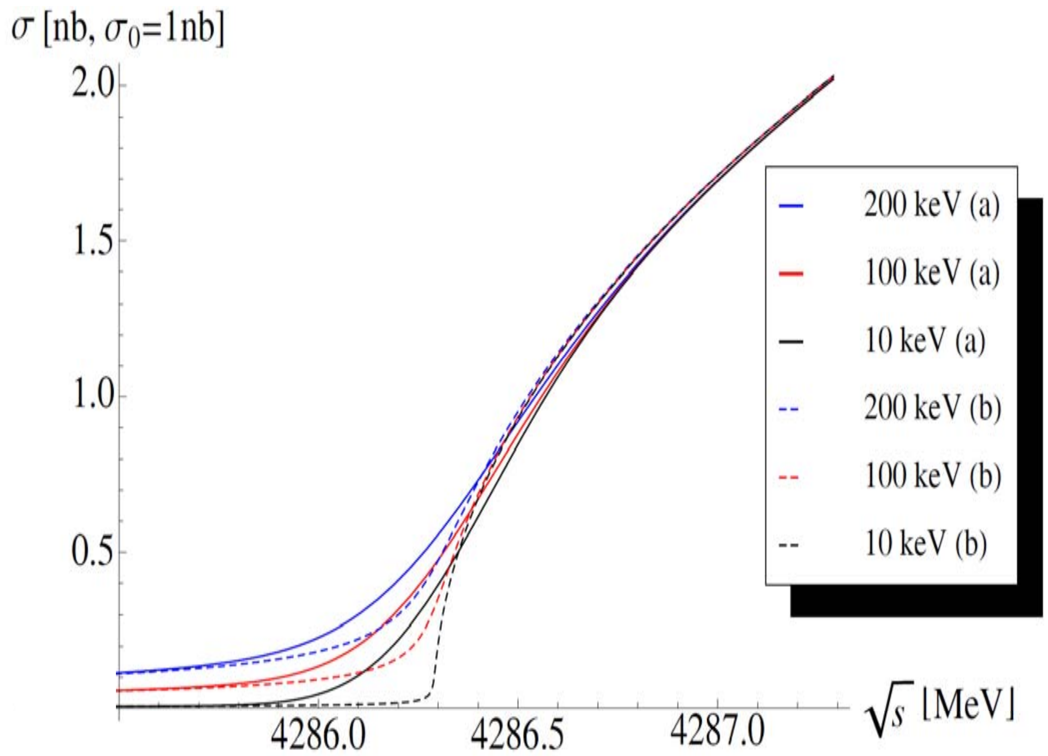
Open Charm Mesons: $D_s(2317)$ Width

- Reaction:

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

$$D_s^{\pm} \rightarrow \phi\pi^{\pm}, \quad \phi \rightarrow K^+K^-$$

$$D_{s0}^{*}(2317)^{\mp} - D_s^{\mp}\pi^0$$



- Excitation function:

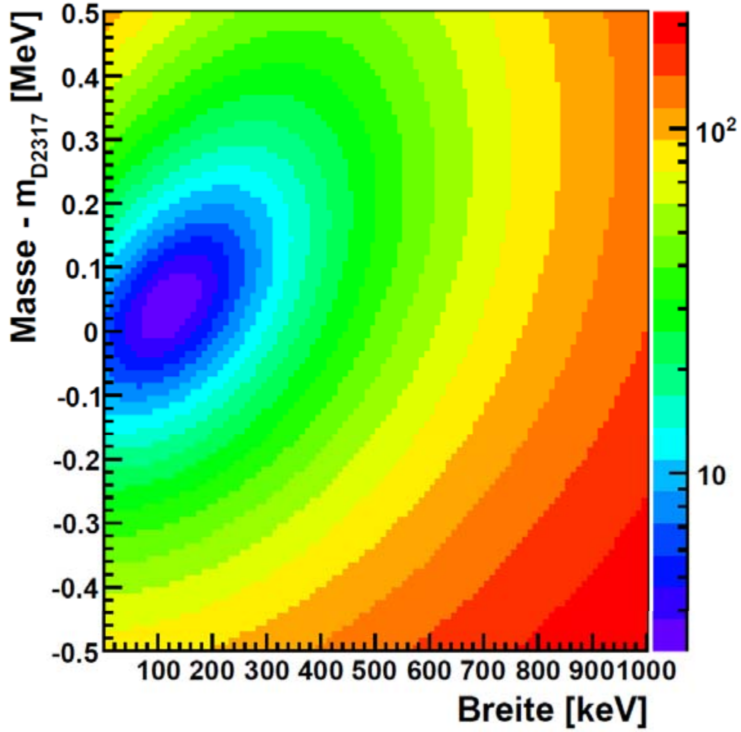
$$\frac{c(s)}{|M|^2} = \frac{\Gamma}{4\pi * \sqrt{s}} \cdot \int_{-\infty}^{\sqrt{s} - m_{D_s}} \frac{\sqrt{\left(s - \left(m + m_{D_s}\right)^2\right) \cdot \left(s - \left(m - m_{D_s}\right)^2\right)}}{\left(m - m_{D2317}\right)^2 + \left(\frac{\Gamma}{2}\right)^2} dm$$

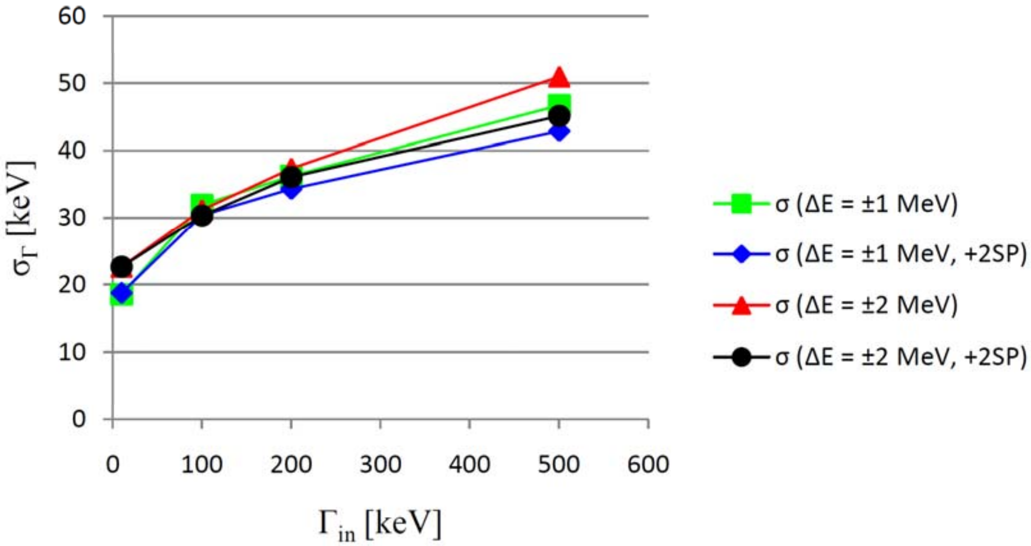
C. Hanhart *et al.*

$D_s(2317)$ Width: Simulation Results

- inclusive $D_s(2317)$ reconstruction
- beam momentum spread $\delta p/p = 1 \cdot 10^{-4}$
- threshold energy scan with 15(+2) scan points
- used: σ = 1nb, S/B = 1, t_{run} = 60 d
- result:

  $D_s(2317)$ width ≲100 keV can be measured



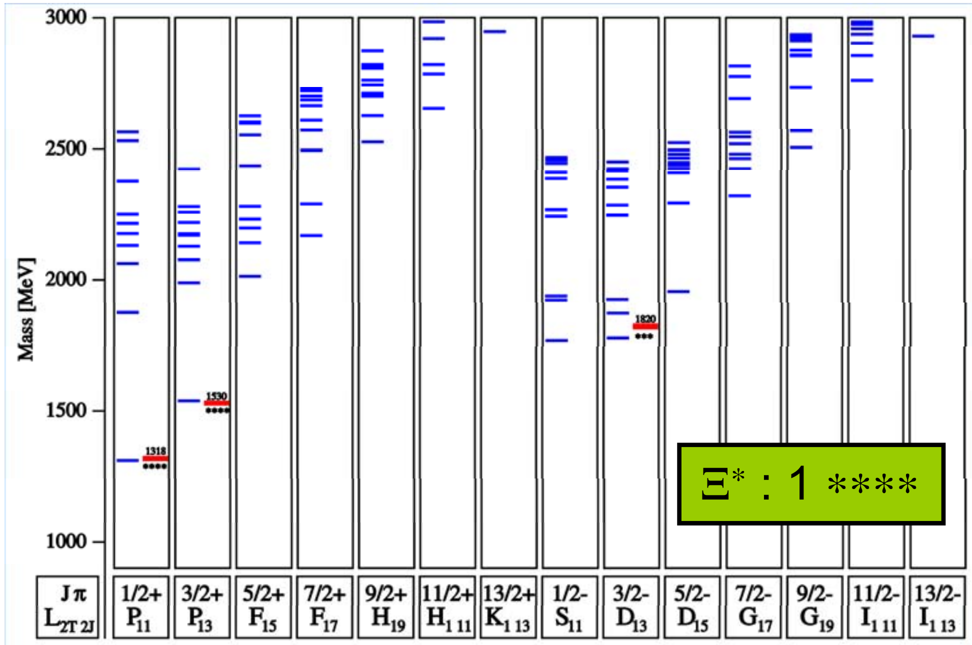


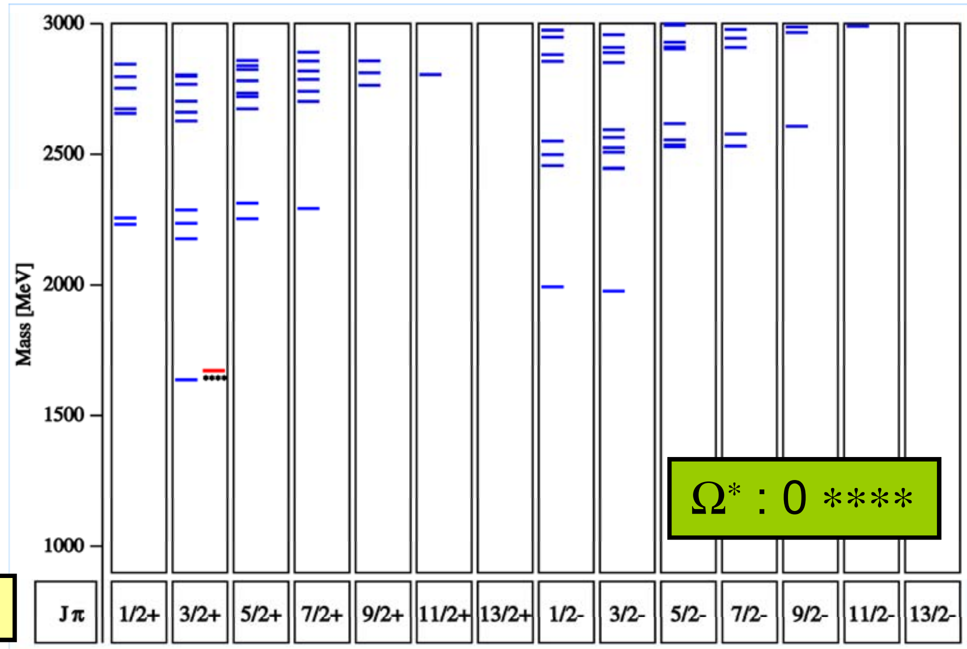
M. Mertens, PhD thesis Univ. Bochum 2010

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.

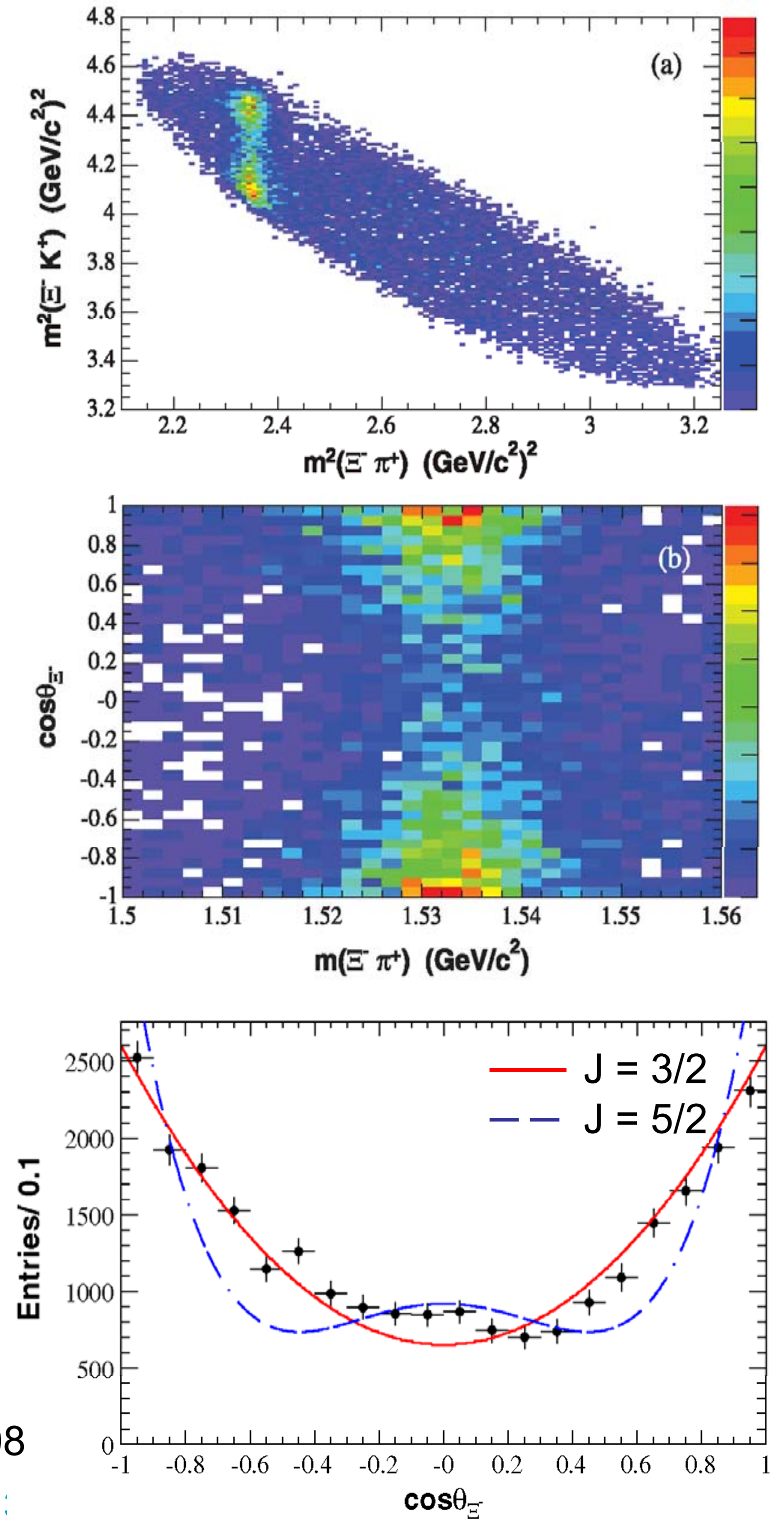
Baryon Spectroscopy: Ξ States

- Only one well studied Ξ resonance:

  Ξ(1530) - decuplet g.s.
- $J^P = 3/2^+$
- Γ = 9…10 MeV
- decay: ~100% Ξπ
- BaBar measured the $\Xi(1530)^0$ spin J = 3/2 in $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$

BaBar 2008

B. Aubert *et al.*,
PRD 78 (2008) 034008

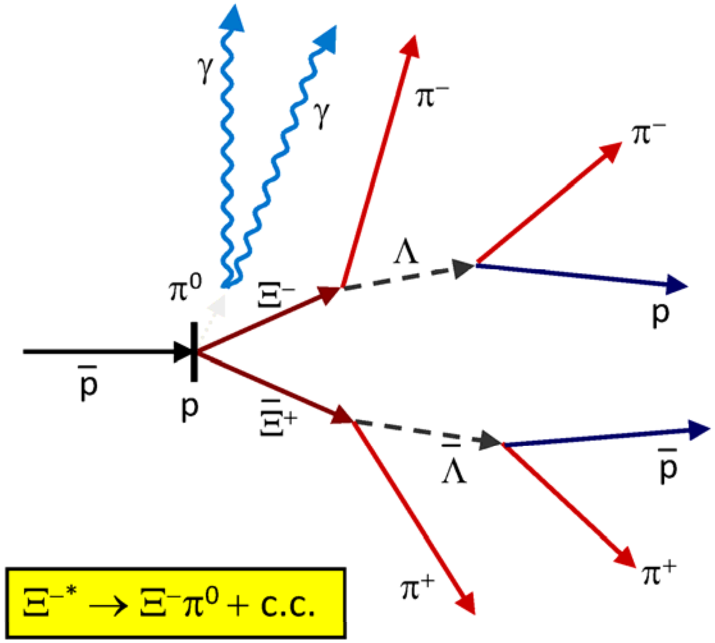


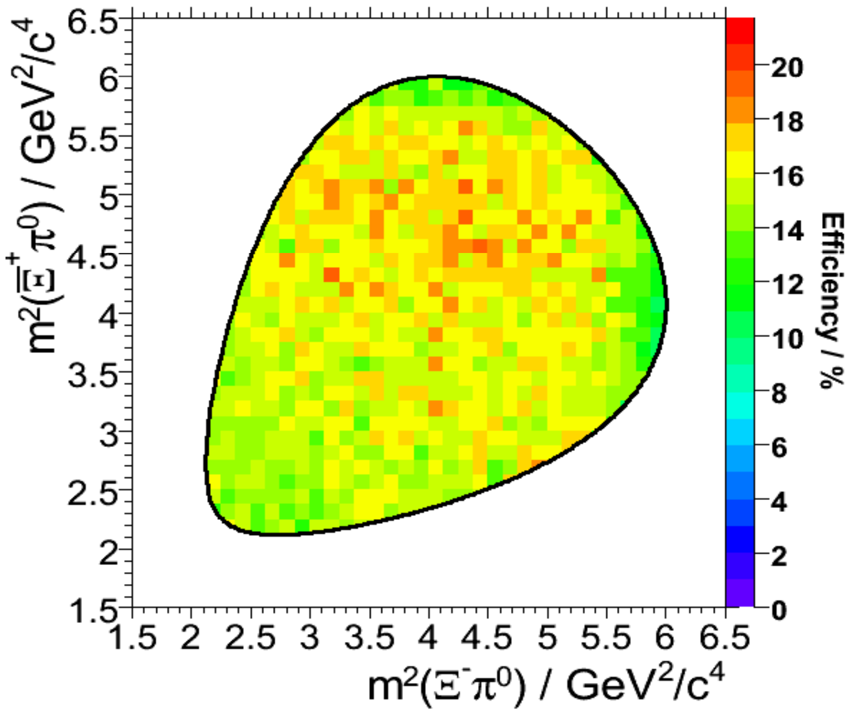
Ξ^* detection with PANDA

- characteristic event topology
- σ ~ μb: ~10^7 Ξ /d produced
- final states to be studied:
  $\Xi^* \rightarrow \Xi\,\pi$, $\Xi\,\eta$, $\Lambda\,\bar{K}$, $\Sigma\,\bar{K}$,
  $\Xi(1530)\,\pi$, $\Xi\,\pi\,\pi$, …
- benchmark channel:
  6.57 GeV/c $\bar{p}\,p \rightarrow \Xi^-\,\bar{\Xi}^+\,\pi^0$
- no empty regions or discontinuities in Dalitz plot
- $\Xi^-\pi^0$ mass resolution < 4 MeV; rec. eff. ~15%, S/B >19*

*DPM generated background

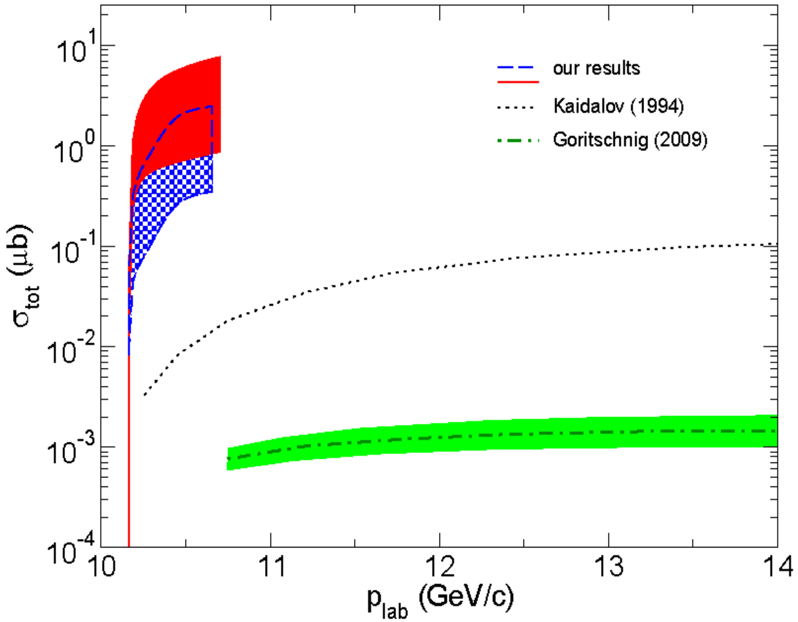
talk by B. Kopf, Thursday





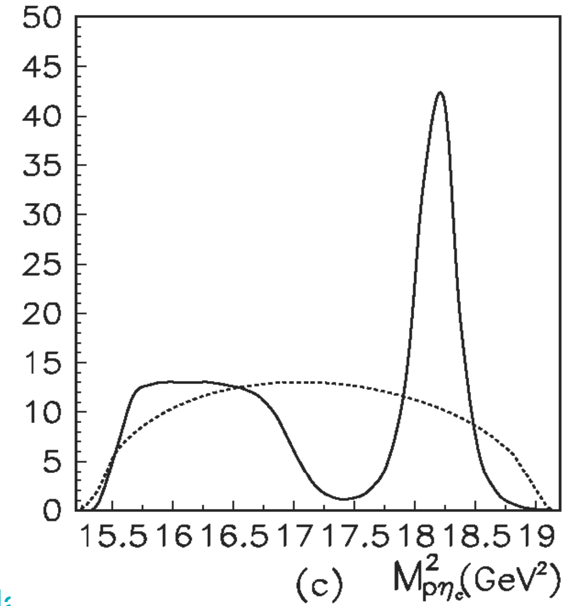
Charm Baryons with PANDA

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



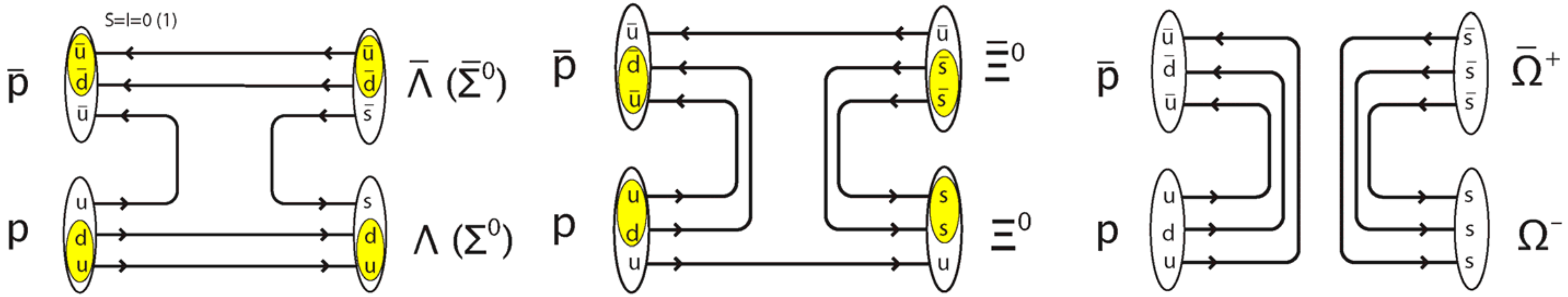
J. Haidenbauer, G. Krein, PLB 687 (2010) 314

- 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



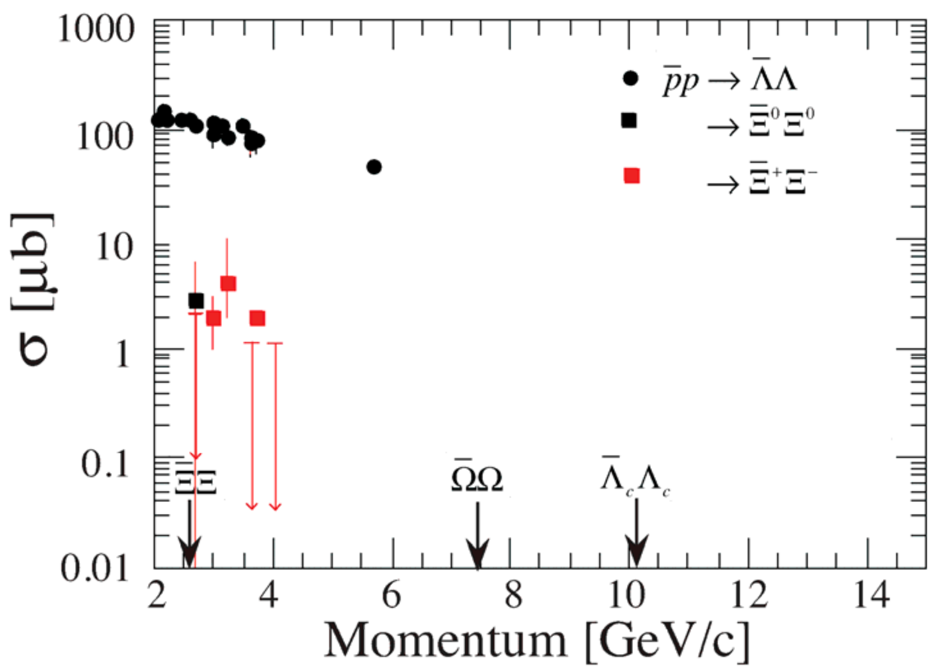
J.J. Wu *et al.*,
PRC 84 (2011) 015202

QCD Dynamics: $\bar{p}p \rightarrow \bar{Y}Y$



compare to $\bar{p}p \rightarrow 3\Phi$

- hyperon-antihyperon production: weak decay gives access to polarisation and spin correlations
- practically nothing known about multiple strange and charmed hyperon channels

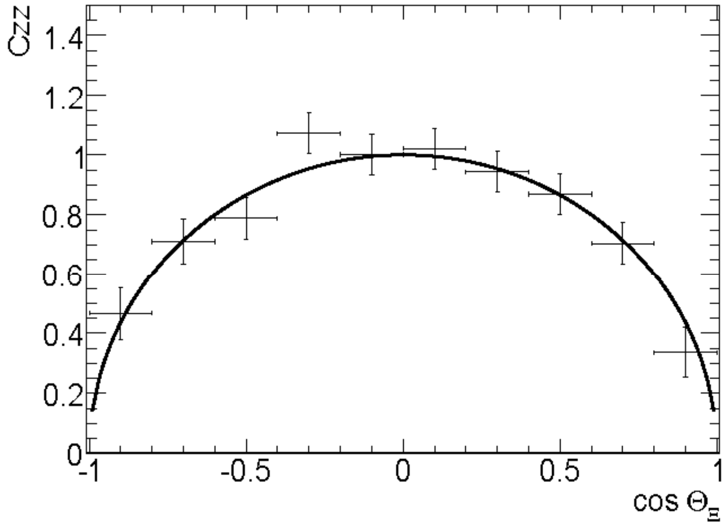


$\bar{p}p \to \bar{Y}Y$: Simulation Results

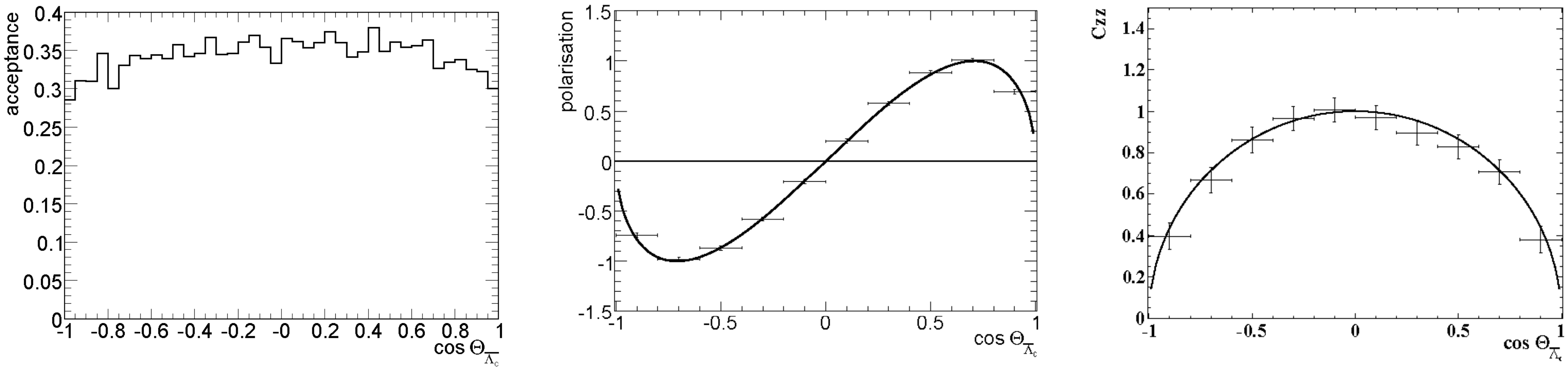
Reconstruction of spin correlations
in 4 GeV/c $\bar{p}p \to \bar{\Xi}^+\Xi^- \to (\bar{\Lambda}\pi^+)(\Lambda\pi^-)$

Event rate: ~30/s

E. Thomé, PhD thesis U Uppsala 2012



12 GeV/c $\bar{p}p \to \bar{\Lambda}_c^- \Lambda_c^+ \to (\Lambda\pi^-)(\Lambda\pi^+)$



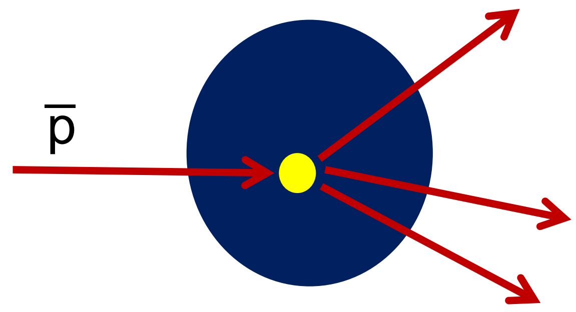
Reconstruction efficiency: 0.35

Event rate: ~25/day with $\sigma_{\bar{\Lambda}_c^+\Lambda_c^-}$ = 100 nb

poster by
L. Caldeira Balkeståhl

Hadrons in Nuclei: Why to Study $\bar{p}$A Collisions?

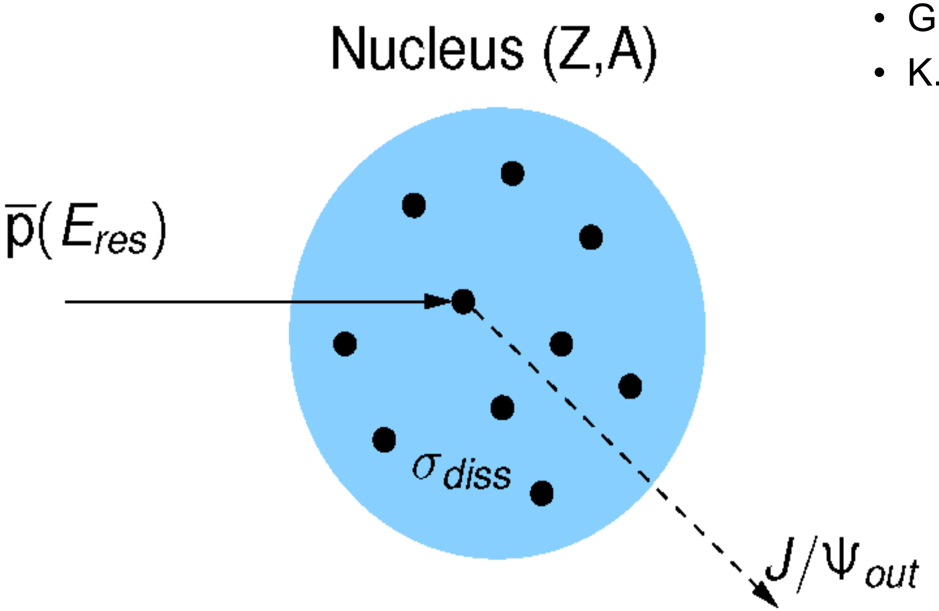
- new insight into interaction of hadrons with nucleons
- new insight into short-range properties of nuclear matter
- ~2 GeV annihilation energy ‘for free’ → hadrons produced at lower lab momenta
- (double) strangeness and charm in nuclear matter
- Color Transparency
- Short Range Correlations



here:
J/ψ absorption in nuclei

J/ψ N dissociation cross section with $\bar{p}$

- **S.J. Brodsky, A.H. Müller, PLB 206 (1988) 685**
- G.R. Farrar *et al*., NPB 345 (1990) 125
- K. Seth, NPA 629 (1998) 358c, Proc. Hirschegg 2001, 183



N_{form} N_{esc}

$$\sigma_{J/\psi N} = \frac{1}{\langle \rho L \rangle}\left(1 - \frac{N_{esc}}{N_{form}}\right)$$

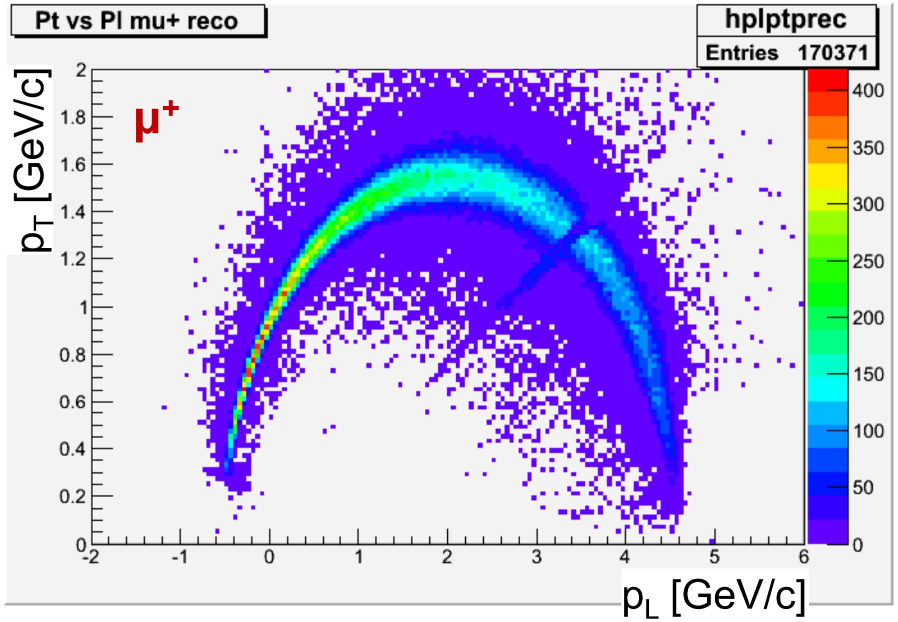
- well-defined conditions: exclusive resonant J/ψ formation on target proton at rest at 4.05 GeV/c
- no ambiguities due to feed-down, co-movers, …
- antiproton mean free path sufficiently known

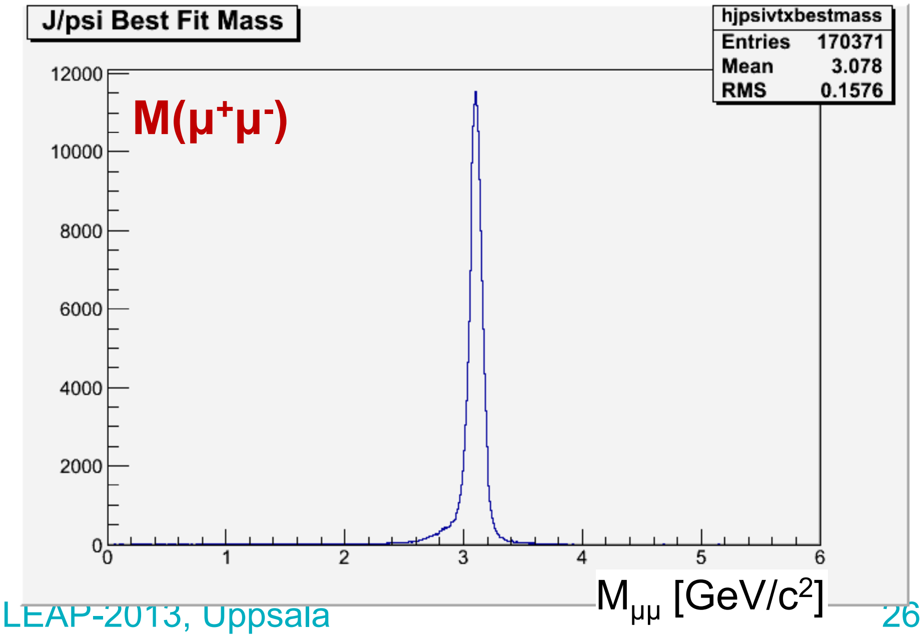
→ **PANDA is unique !**

recent study with Glauber model: A. Larionov *et al*., PRC 87 (2013) 054608

$\bar{p}$ A → J/ψ X: Simulation Results

- Simulation of 10^8 collisions of $\bar{p}\,^{40}Ca$ with GiBUU
- peak cross section × dilepton branching ~ 1nb
- scale factor: ~$2 \cdot 10^6$
- about $2 \cdot 10^5$ J/ψ obtained
- PandaRoot simulation of created e^+e^- / $\mu^+\mu^-$ pairs
- mass resolution $\sigma_M \sim 40$ MeV



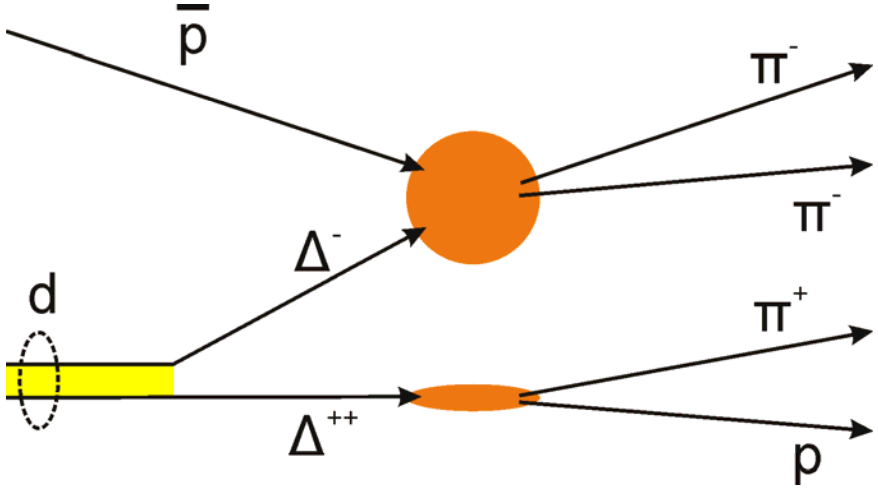


Special Case: $\bar{p}d$ Collisions

- bridge between $\bar{p}N$ and $\bar{p}A$ collisions
- n target, e.g. $\bar{p}n \rightarrow Z(4430)^-$
- link inclusive $\bar{p}A$ results with exclusive $\bar{p}d$ results: interaction cross sections, e.g. $\bar{p}p \rightarrow J/\psi$, $J/\psi n \rightarrow \Lambda_c^+ D^-$
- hard reactions with a bound constituent: study the ΔΔ component in the deuteron

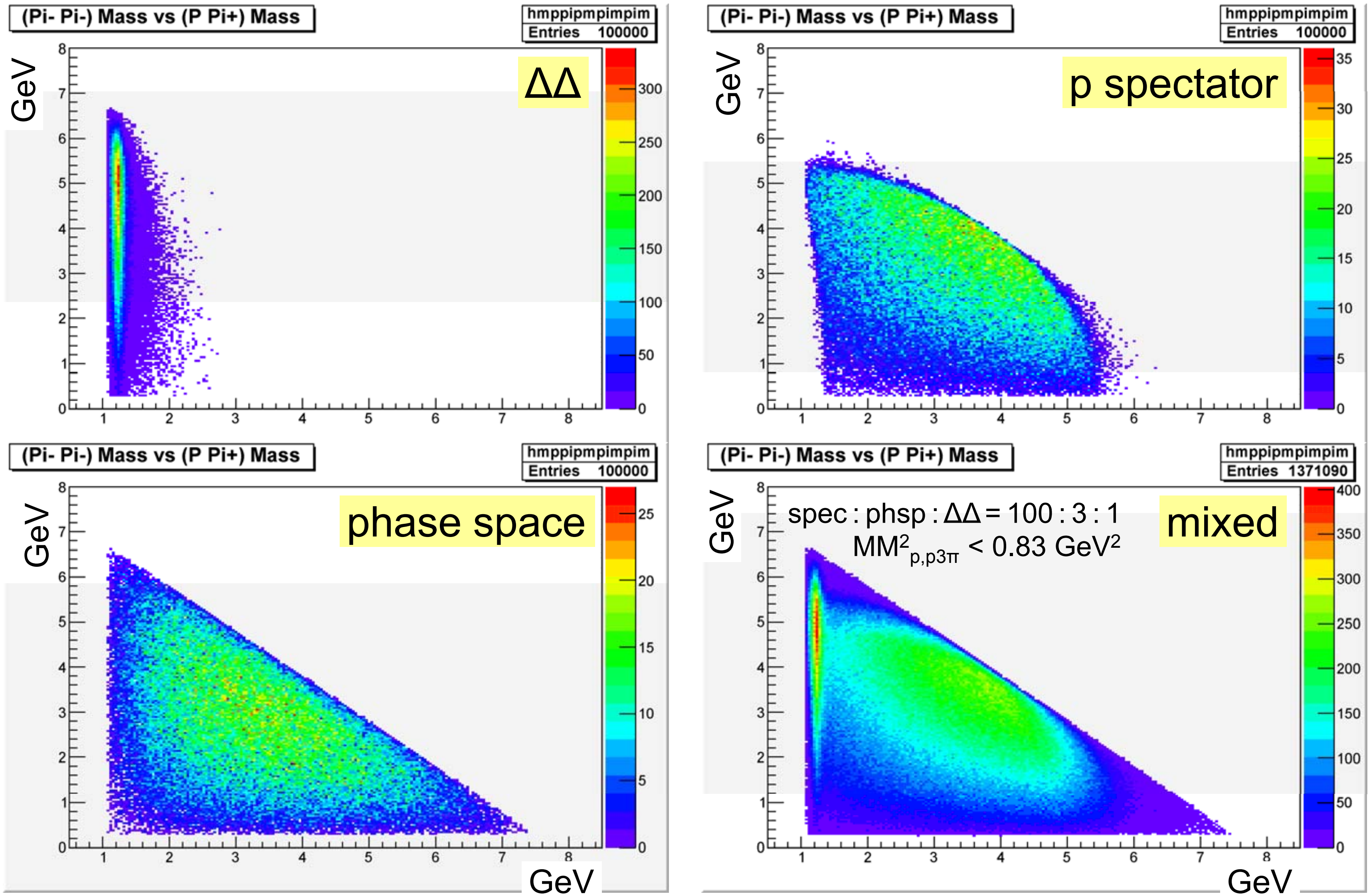
S. Brodsky
M. Strikman, M. Sargsian

see e.g. C. Granados, M. Sargsian, PRC 83 (2011) 054606



Access to the ΔΔ Component in the Deuteron?

Simulation of 15 GeV/c $\bar{p}d \rightarrow p\pi^+\pi^-\pi^-$: 1st *preliminary* results



PANDA Physics Performance Report

- More details in the Physics Performance Report
- available at arXiv:0903.3905v1
- at least one benchmark channel for each physics topic simulated

FAIR/PANDA/Physics Book i

Physics Performance Report for:

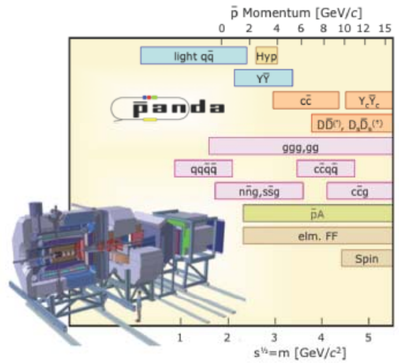
$\overline{\text{P}}$ANDA

(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.



A Strong International Collaboration:

~500 scientists from 67 institutes in 18 countries

Conclusion and Outlook

The hadron physics program at PANDA

- addresses key questions
- has a high discovery potential
- is open to new ideas
- will deliver high statistics and high precision results