Prospects of precision XYZ spectroscopy at PANDA/FAIR

Frank Nerling
Frankfurt University, GSI Darmstadt
on behalf of the PANDA Collaboration

XIIth Intern. Workshop on e+e- collisions from Phi to Psi,
Novosibirsk, Russia, Aug 26th – March 1st 2019

Outline

- **Introduction**
  - Motivation, PANDA physics programme
  - Advantage of anti-protons
- **Energy scans of very narrow resonances**
  - The puzzle of the X(3872) & handle for clarification
  - Comprehensive performance study
- **Importance of high-spin states**
  - Prospects for PANDA
- **Summary & outlook**

PANDA Physics Programme

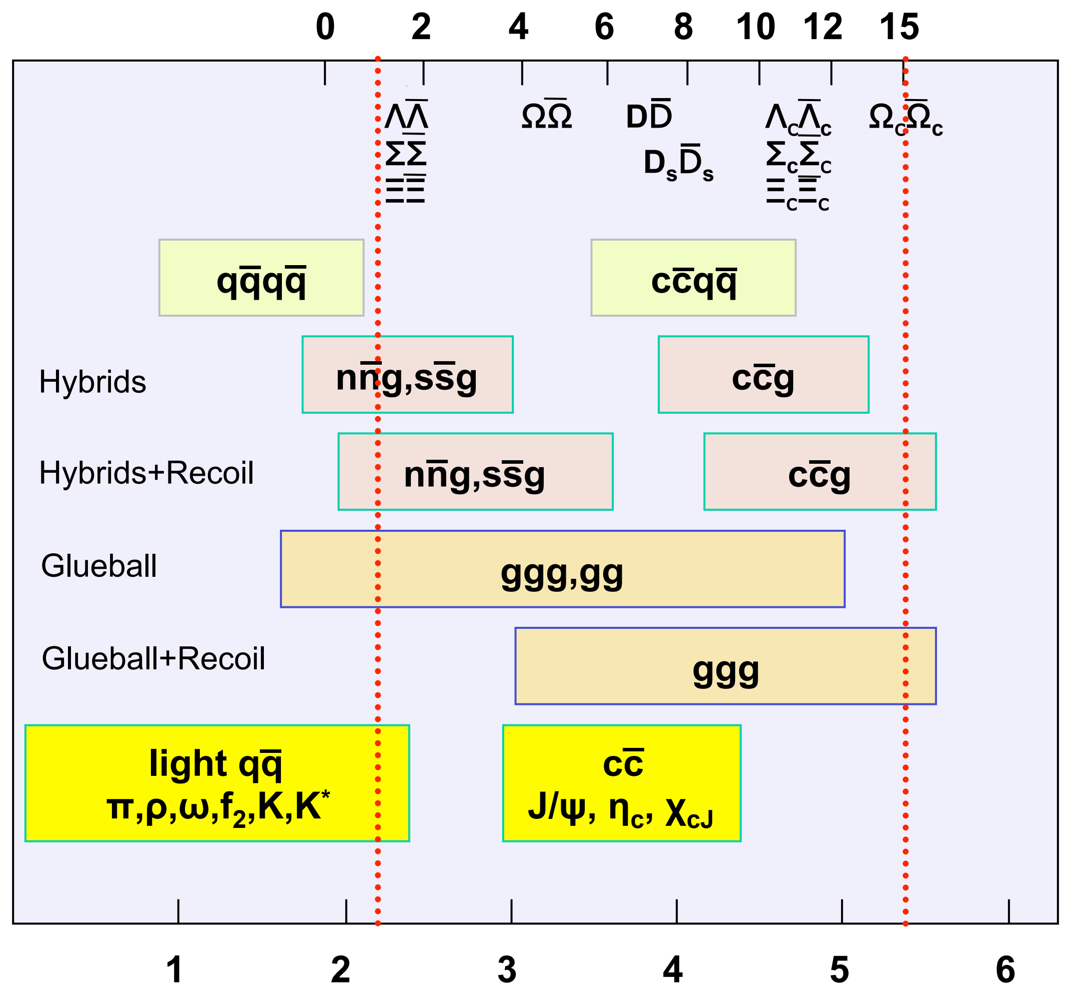
Anti-Proton ANnihilation in DArmstadt

- **Hadron spectroscopy**
  - ➢ Light mesons
  - ➢ Charmonium
  - ➢ Exotic states:

    glue-balls, hybrids,

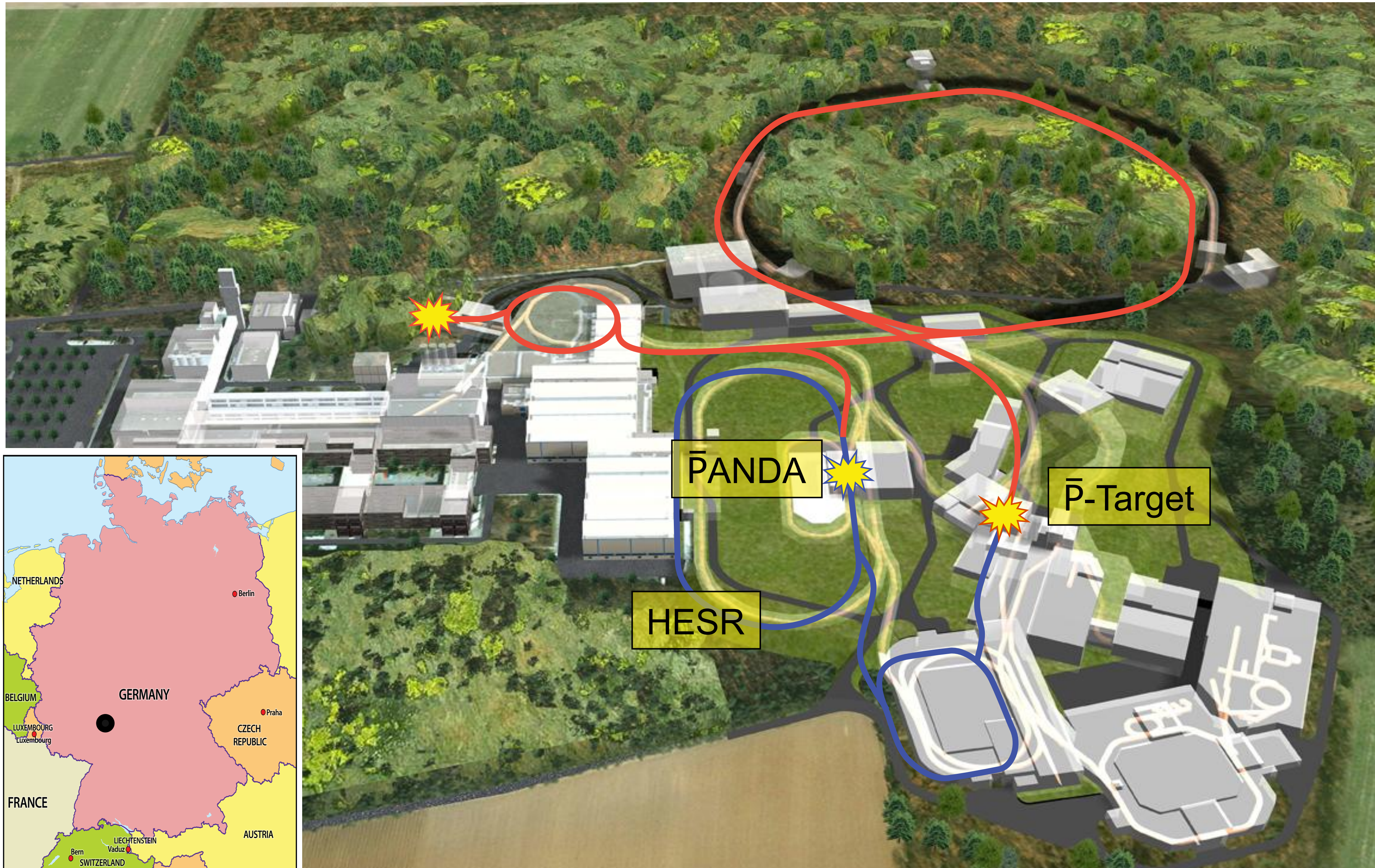
    molecules / multi-quarks
- **(Anti-) Baryon production**
- **Nucleon structure**
- **Charm in nuclei**
- **Strangeness physics**
  - ➢ hypernuclei
  - ➢ S = -2 nuclear system

$\bar{p}$ momentum [GeV/c]

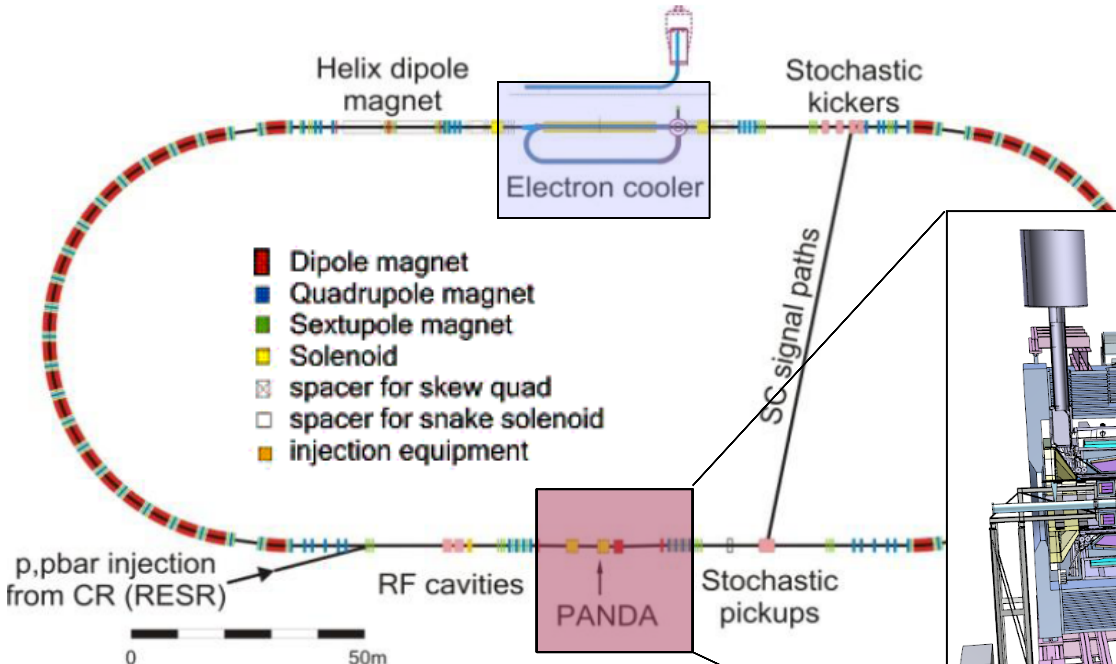


mass [GeV/c^2]

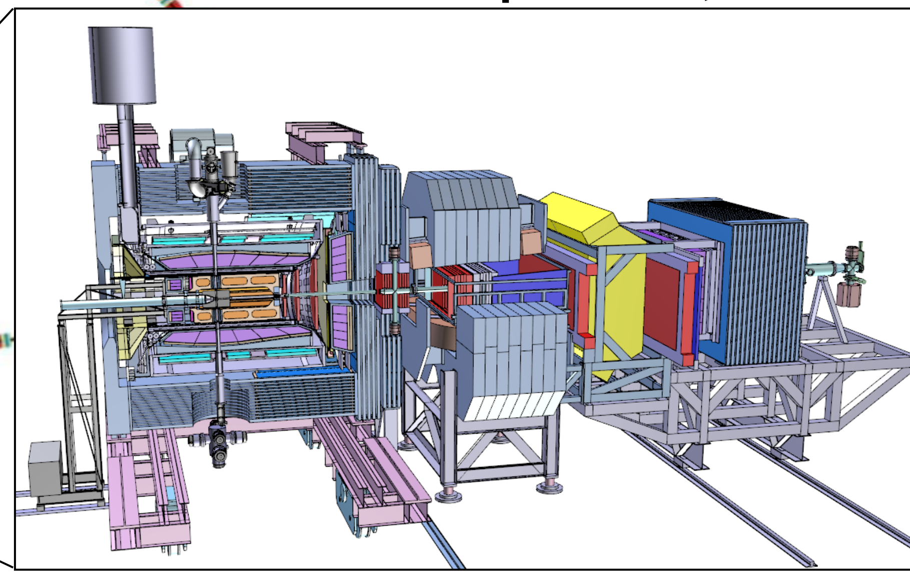
Facility for Antiproton and Ion Research



High Energy Storage Ring -- HESR



PANDA Experiment, Detector



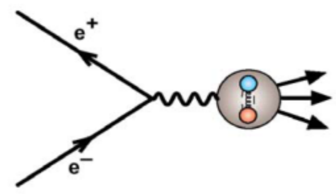
High Resolution (HR) mode:
- Luminosity up to 2 x 10^{31} cm^{-2} s^{-1}
- $\Delta p/p$ = 2 x 10^{-5}

High Luminosity (HL) mode:
- Luminosity up to 2 x 10^{32} cm^{-2} s^{-1}
- $\Delta p/p$ = 1 x 10^{-4}

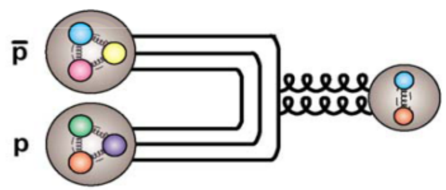
Some Advantages of Anti-Protons

- Access to all fermion-antifermion quantum numbers *(not in e^+e^-)*
- Access to states of high spin J

Formation:



only $J^{PC} = 1^{--}$

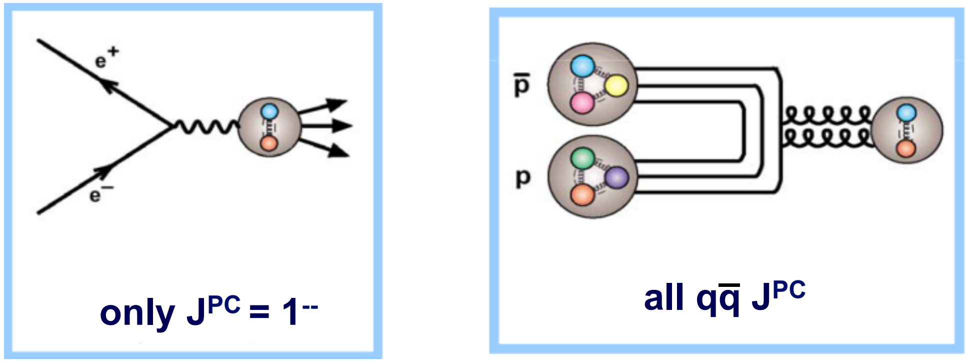


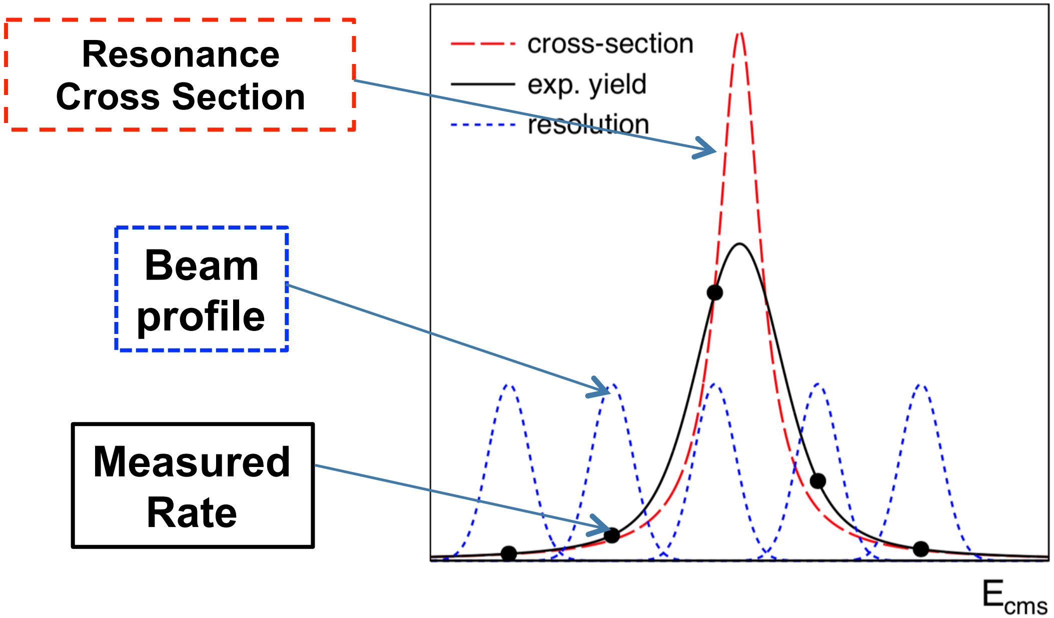
all $q\bar{q}$ J^{PC}

Some Advantages of Anti-Protons

- Access to all fermion-antifermion quantum numbers *(not in e^+e^-)*
- Access to states of high spin J
- Precise mass resolution in formation reactions

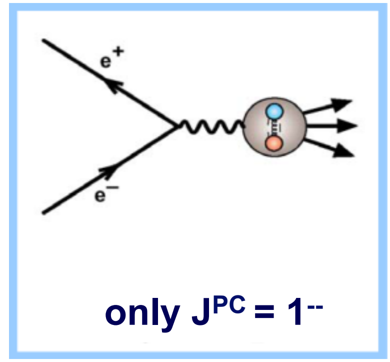
Formation:

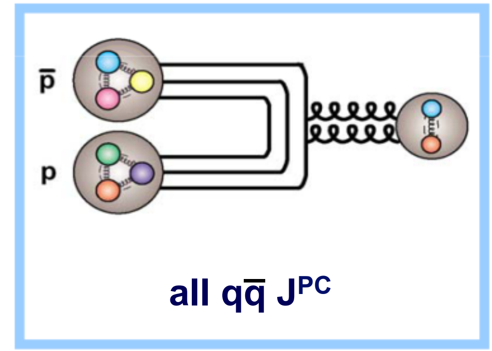




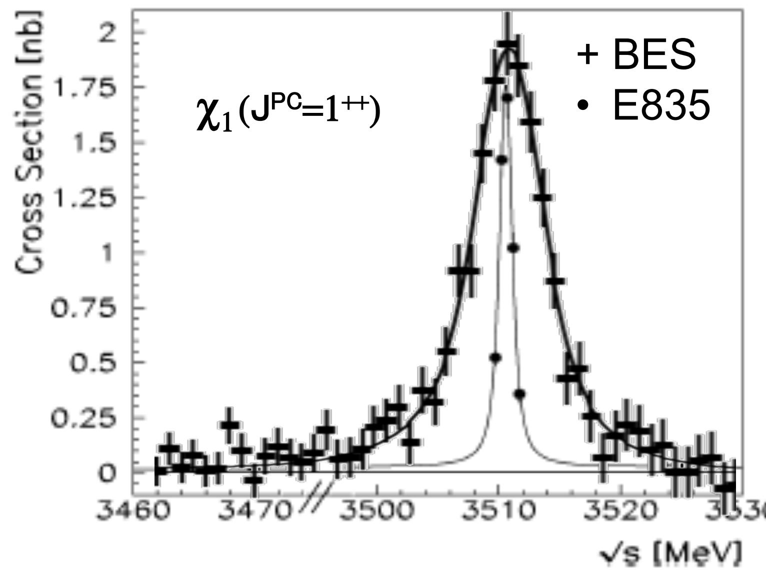
Some Advantages of Anti-Protons

Formation:





- Access to all fermion-antifermion quantum numbers *(not in e^+e^-)*
- Access to states of high spin J
- Precise mass resolution in formation reactions



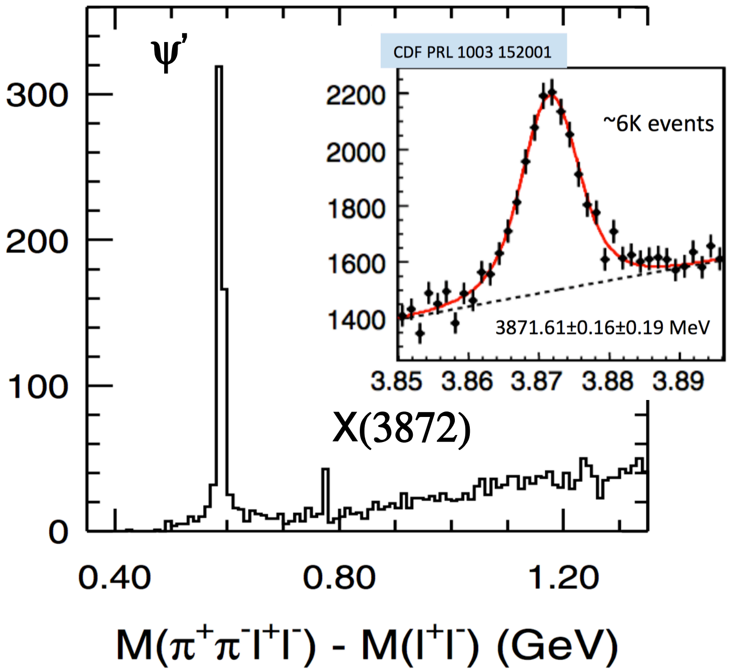
E760/835@Fermilab ≈ 240 keV
PANDA@FAIR ≈ 50 keV

Ablikim et al., Phys. Rev. D71 (2005) 092002:
BES (IHEP): 3510.3 ± 0.2 MeV/c^2

Andreotti et al., Nucl. Phys. B717 (2005) 34:
E835 (Fermilab): 3510.641 ± 0.074 MeV/c^2

Experimental Review of the X(3872)

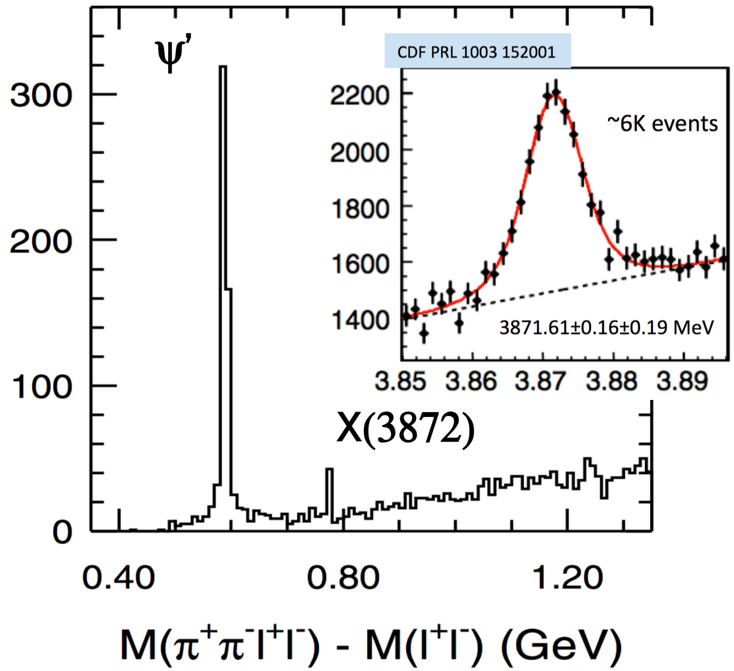
[Belle, PhysRevLett.91 (2003) 262001]



- The first unexpected states
  - ➢ and the most intriguing one
- First observed by Belle in 2003
  - ➢ $X(3872) \rightarrow J/\psi\,\pi\pi$
  - ➢ very narrow state with $J^{PC} = 1^{++}$
- Both, Belle & BaBar report signal in
  - ➢ $X(3872) \rightarrow D^0\bar{D}^{*0}$ ($D^0D^0\pi^0$ and $D^0D^0\gamma$)

Experimental Review of the X(3872)

[Belle, PhysRevLett.91 (2003) 262001]



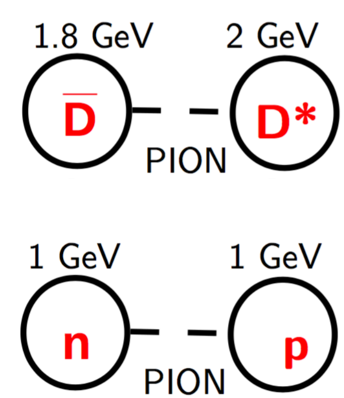
- The first unexpected states
  - and the most intriguing one
- First observed by Belle in 2003
  - $X(3872) \to J/\psi\,\pi\pi$
  - very narrow state with $J^{PC} = 1^{++}$
- Both, Belle & BaBar report signal in
  - $X(3872) \to D^0\bar{D}^{*0}$ ($D^0D^0\pi^0$ and $D^0D^0\gamma$)

- Mass: $m(X) - m(\bar{D}^{*0}) - m(D^0) =$

  $= -0.12 \pm 0.19\ \mathrm{MeV}/c^2$
- Width: Upper limit by Belle
  - $\Gamma_{X(3872)} < 1.2\,\mathrm{MeV}$ (90% c.l., 2011)

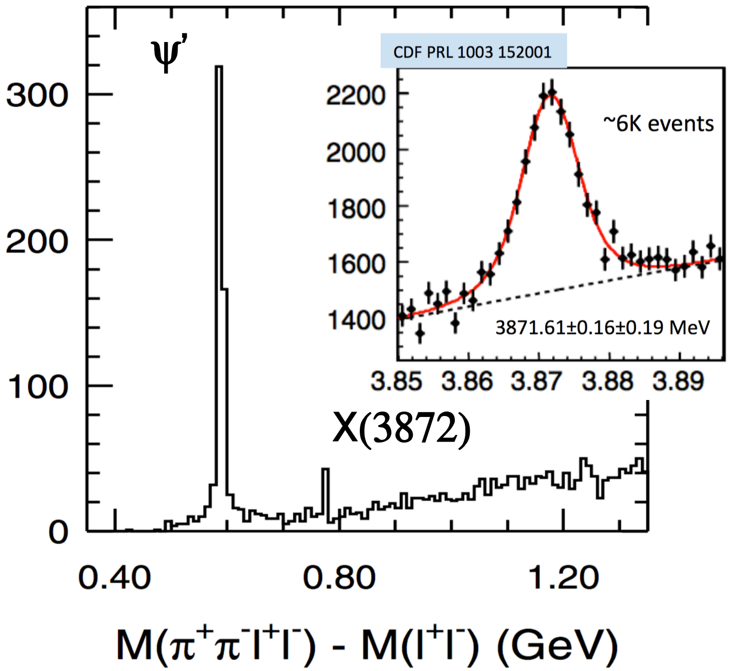
"binding energy" of
-0.12+-0.19 MeV ?

Intriguing Analogon



Experimental Review of the X(3872)

[Belle, PhysRevLett.91 (2003) 262001]

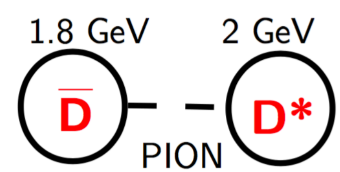


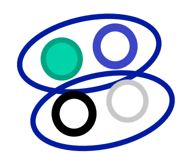
- The first unexpected states
  - and the most intriguing one
- First observed by Belle in 2003
  - $X(3872) \to J/\psi\,\pi\pi$
  - very narrow state with $J^{PC} = 1^{++}$
- Both, Belle & BaBar report signal in
  - $X(3872) \to D^0\bar{D}^{*0}$ ($D^0D^0\pi^0$ and $D^0D^0\gamma$)

- Mass: $m(X) - m(\bar{D}^{*0}) - m(D^0) =$
  $= -\,0.12 \pm 0.19\ \mathrm{MeV}/c^2$
- Width: Upper limit by Belle
  - $\Gamma_{X(3872)} < 1.2\,\mathrm{MeV}$ (90% c.l., 2011)

Intriguing Analogon

"binding energy" of -0.12+-0.19 MeV ?





Molecule ?
$(q\bar{q})_1(q\bar{q})_1$

For clarification: *Precision measurement of $\Gamma_{X(3872)}$ in the sub-MeV range needed!*

Molecular Picture

- Lineshapes from Kalashnikova et al. [Phys. Atom. Nucl. 73 (2010) 1592]
- Here only interested in X(3872) → J/ψ ρ^0

$$\boxed{\sigma(E) = C \cdot \frac{\Gamma_{\pi^+\pi^- J/\psi}(E)}{|D(E)|^2}}$$

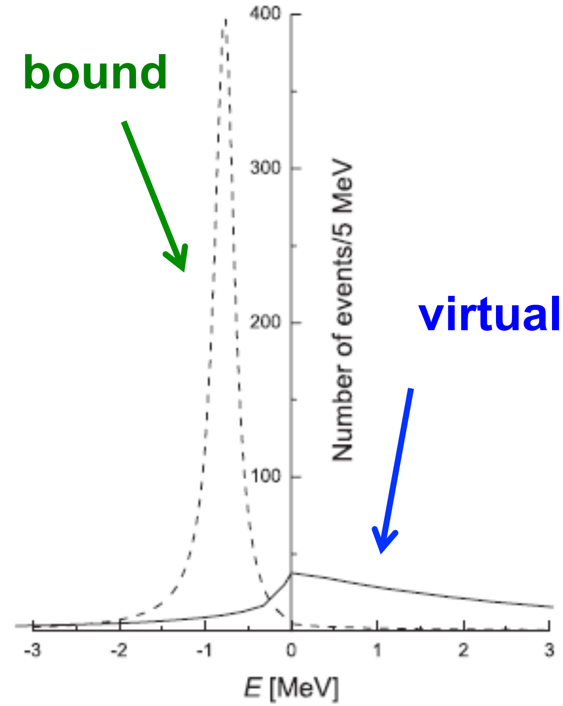
(assuming line-shape as in B decays)

- $$D(E) = \begin{cases} E - \boxed{E_f} - \frac{g_1\kappa_1}{2} - \frac{g_2\kappa_2}{2} + i\frac{\Gamma(E)}{2}, & E < 0, \\ E - \boxed{E_f} - \frac{g_2\kappa_2}{2} + i\left(\frac{g_1k_1}{2} + \frac{\Gamma(E)}{2}\right), & 0 < E < \delta, \\ E - \boxed{E_f} + i\left(\frac{g_1k_1}{2} + \frac{g_2k_2}{2} + \frac{\Gamma(E)}{2}\right), & E > \delta, \end{cases}$$

- $$\Gamma(E) = \Gamma_{\pi^+\pi^- J/\psi}(E) + \Gamma_{\pi^+\pi^-\pi^0 J/\psi}(E) + \Gamma_0$$

$$\Gamma_{\pi^+\pi^- J/\psi}(E) = f_\rho \int_{2m_\pi}^{M-m_{J/\psi}} \frac{dm}{2\pi} \frac{q(m)\Gamma_\rho}{(m-m_\rho)^2 + \Gamma_\rho^2/4}$$

$$\Gamma_{\pi^+\pi^-\pi^0 J/\psi}(E) = f_\omega \int_{3m_\pi}^{M-m_{J/\psi}} \frac{dm}{2\pi} \frac{q(m)\Gamma_\omega}{(m-m_\omega)^2 + \Gamma_\omega^2/4}$$



[Hanhardt et al., PRD 76 (2007) 034007]

Flatte energy E_f determines state to be bound or virtual

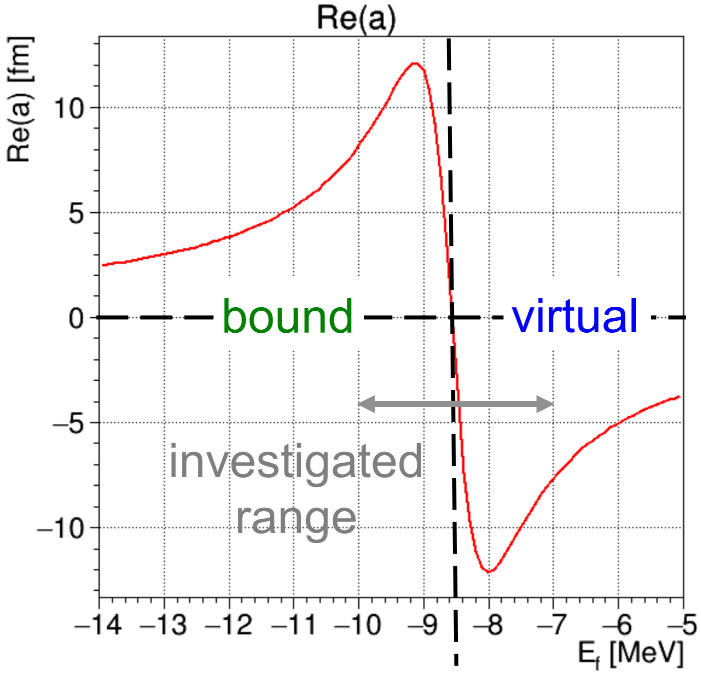
Line shapes for different E_f

Scattering length D^0D^{0*}:

$$a = -\frac{\sqrt{2\mu_2\delta} + 2E_f/g + i\Gamma(0)/g}{(\sqrt{2\mu_2\delta} + 2E_f/g)^2 + \Gamma(0)^2/g^2}$$

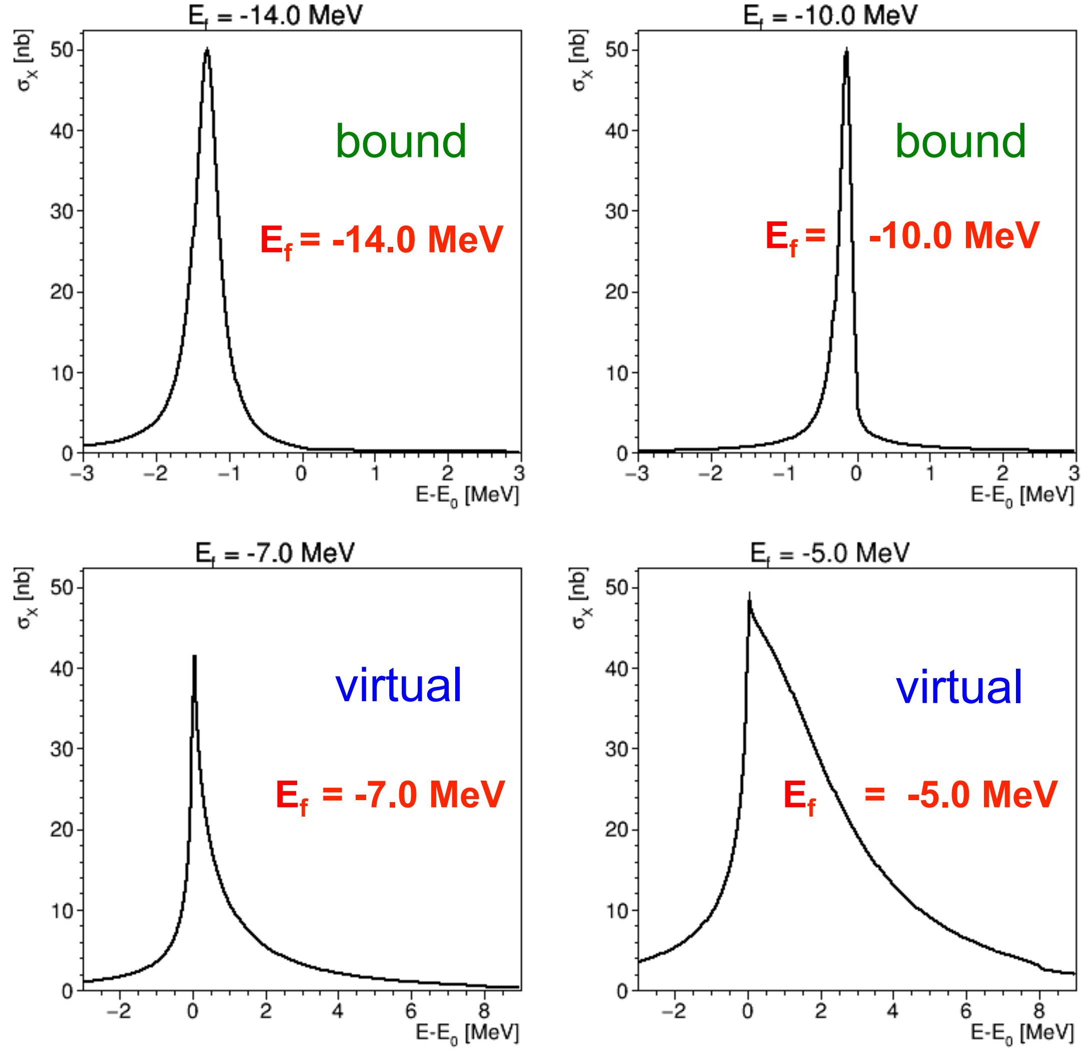
Re(a) > 0 : bound state

Re(a) < 0 : virtual state



$E_{f,th}$ = -8.56 MeV

Examples always scaled to same f_{max}



(with f_ρ=0.00047, f_ω=0.00271, g=0.137, Γ_0=1.0 MeV)

Energy scan of the X(3872)

Initial Remarks

- **Nature of X(3872)**
  - Need line-shape and width to understand structure
  - PANDA: Fine scan around nominal mass
    => energy-dependent cross-section

- **Analysis goals**
  - Sensitivity of Γ measurement *(conventional BW)*
  - Sensitivity for virtual/bound state *(molecular picture)*

- **Analysis strategy**
  - Analysis of $X(3872) \to J/\psi(\ell^+\ell^-)\ \rho^0(\pi^+\pi^-)$ channel only
  - Geant based sim/reco => signal + background efficiencies ε_S and ε_B
  - MC scan simulation with assumption for cross-sections, and integrated luminosities, BRs

- **Three accelerator modes**
  - HL (High Lumi) and HR (High Resolution), P1 (Phase-1, reduced lumi/resol.)

Reconstruction Part

Input Parameters

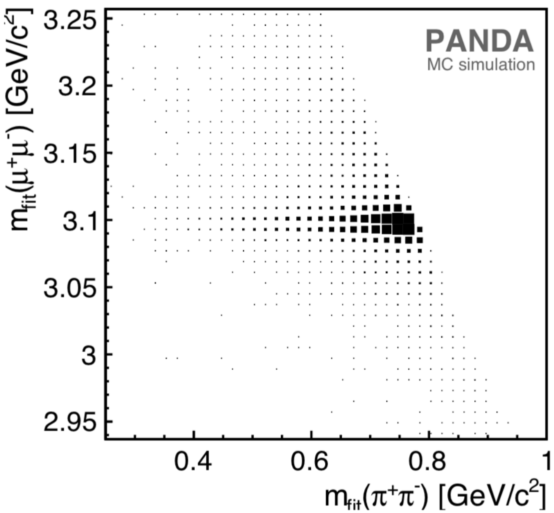
	Parameter	Value
	BR($J/\psi \to e^+ e^-$)	5.97 %
Branching Fractions	BR($J/\psi \to \mu^+ \mu^-$)	5.96 %
	BR($\rho^0 \to \pi^+ \pi^-$)	100%
	BR($X \to J/\psi\ \rho^0$)	5 % (UL: 6.6%)
	$\sigma_{peak}(p\bar{p} \to X)$	[20,30,50,75,100,150] nb
Cross sections	$\sigma(pp \to J/\psi\ \pi^+\pi^-$ non-res)	1.2 nb [theory]
	$\sigma(pp \to$ inelastic) @ 3.872 GeV	46 mb [CERN-HERA-84-01 (1984)]
	L_{HL} (3.872 GeV)	13683 $(nb \cdot d)^{-1}$
Luminosities	L_{HR} (3.872 GeV)	1368 $(nb \cdot d)^{-1}$
	L_{P1} (3.872 GeV)	1170 $(nb \cdot d)^{-1}$
	ΔE_{abs} *(energy prec. w/ calibration)*	168 keV ($dp/p = 10^{-4}$)
	ΔE_{rel} *(relative energy positioning)*	1.7 keV ($dp/p = 10^{-6}$)
Resolutions	ΔE_{mom} (HL)	168 keV ($dp/p = 10^{-4}$)
	ΔE_{mom} (HR)	34 keV ($dp/p = 2 \cdot 10^{-5}$)
	ΔE_{mom} (P1)	84 keV ($dp/p = 5 \cdot 10^{-5}$)

Kinematic Distributions

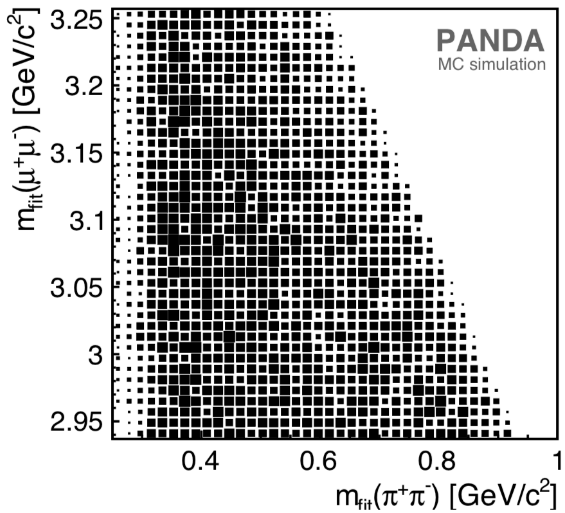
(after 4C fit applied)

$m(\mu\mu)$ vs. $m(\pi\pi)$

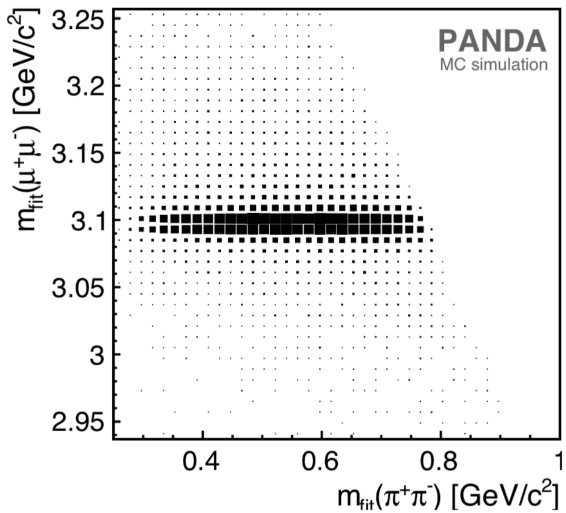
Signal



Generic bkgd



Non-resonant J/ψ



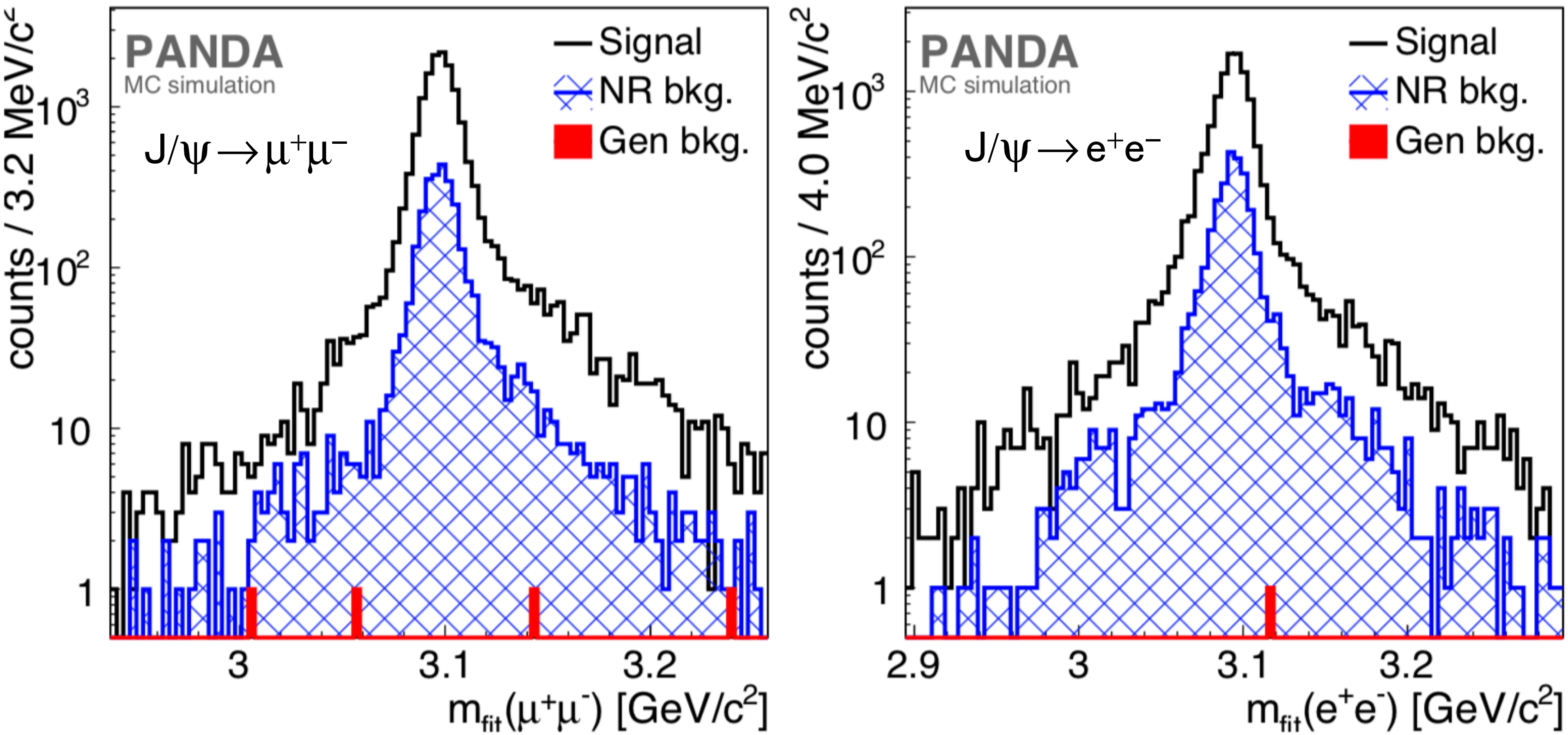
Numbers of generated events of the different signal & bkgd types:

Event type	Description	Number of Events
I	$\bar{p}p \to J/\psi\rho^0 \to e^+e^-\pi^+\pi^-$	98 000
	$\bar{p}p \to J/\psi\rho^0 \to \mu^+\mu^-\pi^+\pi^-$	100 000
II	$\bar{p}p \to J/\psi\pi^+\pi^- \to e^+e^-\pi^+\pi^-$ (non-res)	100 000
	$\bar{p}p \to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$ (non-res)	99 000
III	DPM ($J/\psi \to e^+e^-$ pre-filter)	$\approx 10^7 = 9.58 \cdot 10^9$ generated
	DPM ($J/\psi \to \mu^+\mu^-$ pre-filter)	$\approx 10^7 = 8.87 \cdot 10^9$ generated

[PANDA, arXiv:1812.05132, hep-ex]

Event Selection Results

(after final selection and 4C fit)



	$X(3872) \to J/\psi(e^+e^-)\pi^+\pi^-$			$X(3872) \to J/\psi(\mu^+\mu^-)\pi^+\pi^-$			
Efficiency	ϵ_S [%]	$\epsilon_{B,\mathrm{gen}}$ [10^{-10}]	$\epsilon_{B,\mathrm{NR}}$ [%]	ϵ_S [%]	$\epsilon_{B,\mathrm{gen}}$ [10^{-10}]	$\epsilon_{B,\mathrm{NR}}$ [%]	$S{:}N_{\mathrm{comb}}$
Final selection	**12.2**	**1.0**	**2.8**	**15.2**	**4.5**	**3.0**	**2.7 : 1**

[PANDA, arXiv:1812.05132, hep-ex]

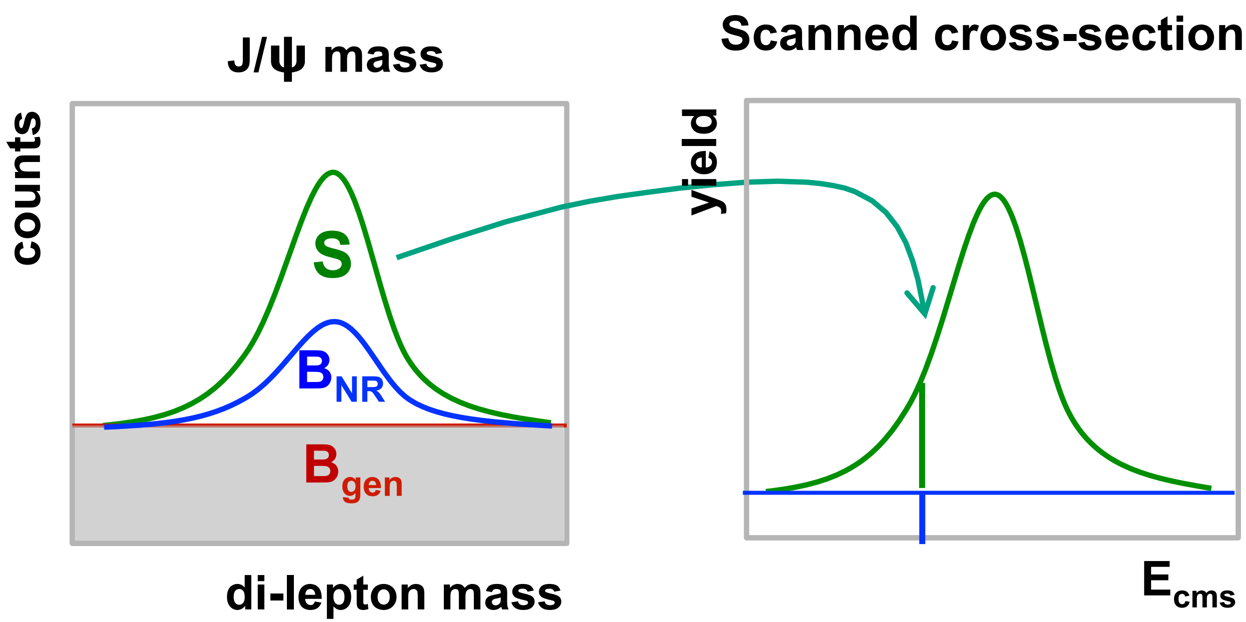
Energy scan part

Yield Extraction

Simulated extraction of energy-dependent yield:

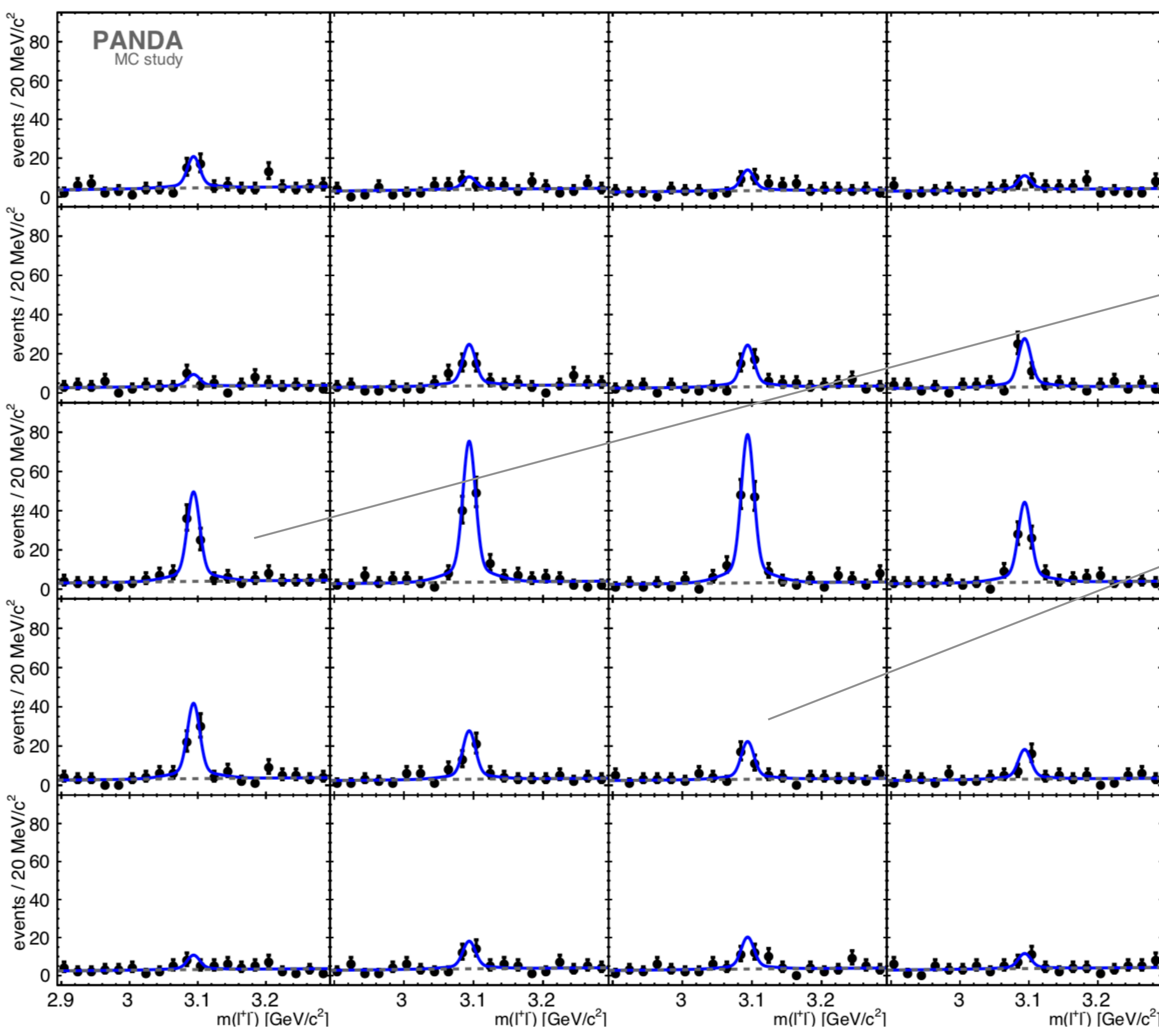
- Fit signal in J/ψ mass
  - Removes generic background
  - NR background still present

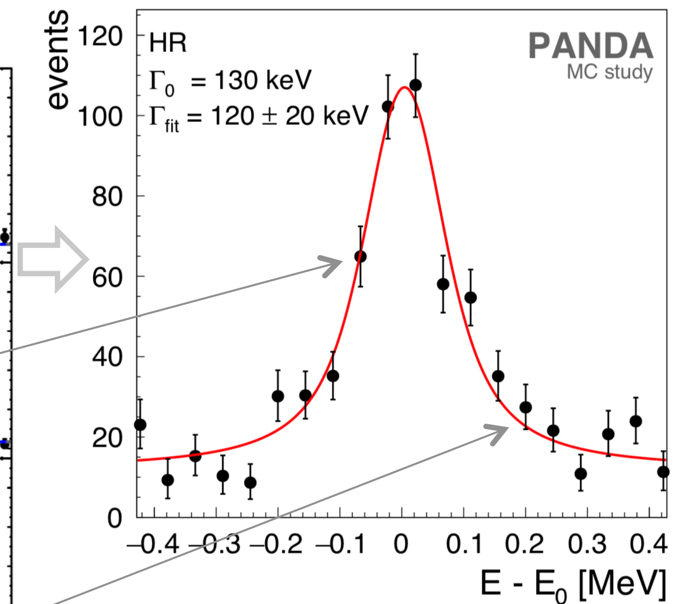
- Requires sufficiently large J/ψ mass window



Scan Procedure Principle (Example)

20 E_{cms} scan point within ±0.4 MeV window around nominal mass

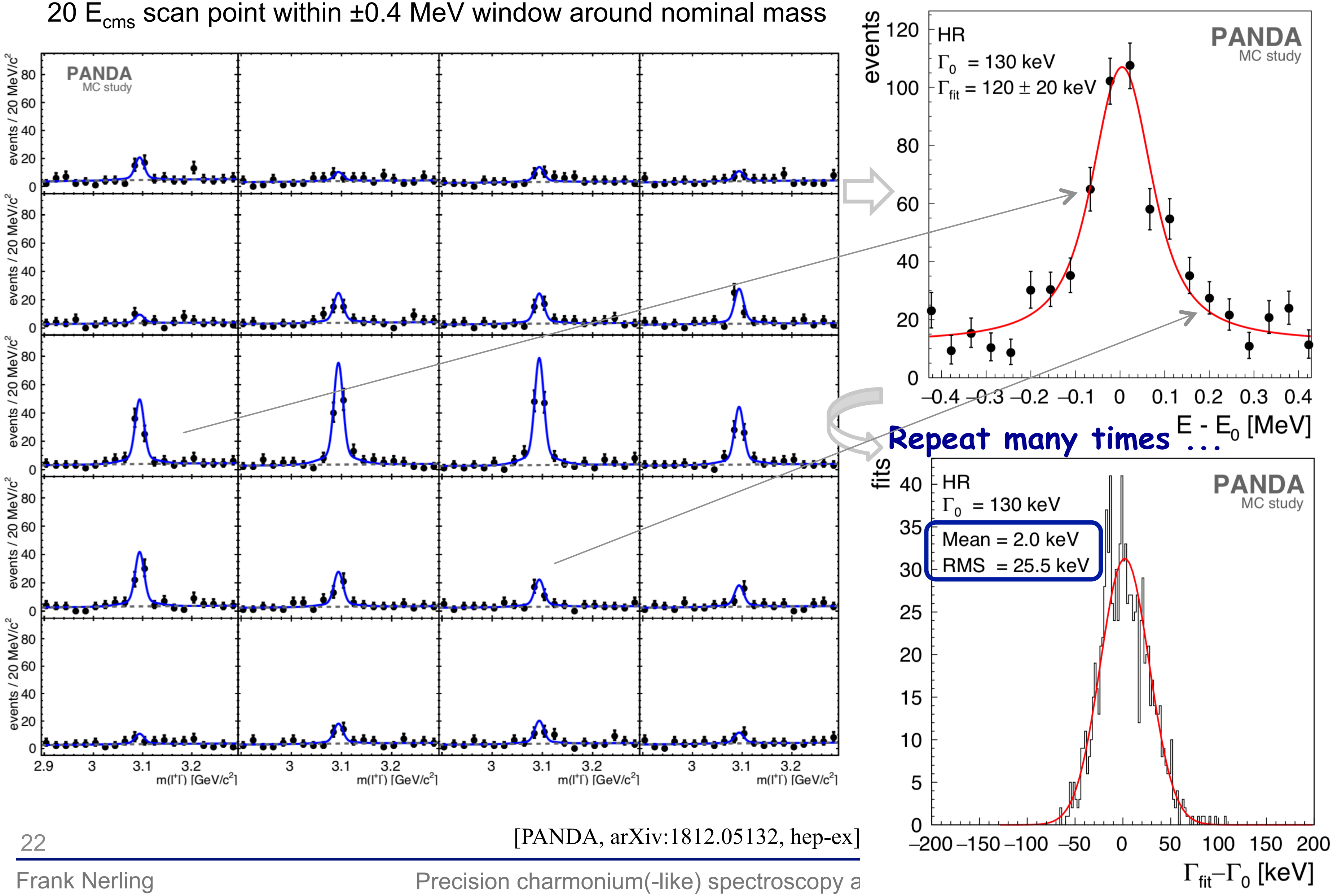




[PANDA, arXiv:1812.05132, hep-ex]

Scan Procedure Principle (Example)

20 E_{cms} scan point within ±0.4 MeV window around nominal mass



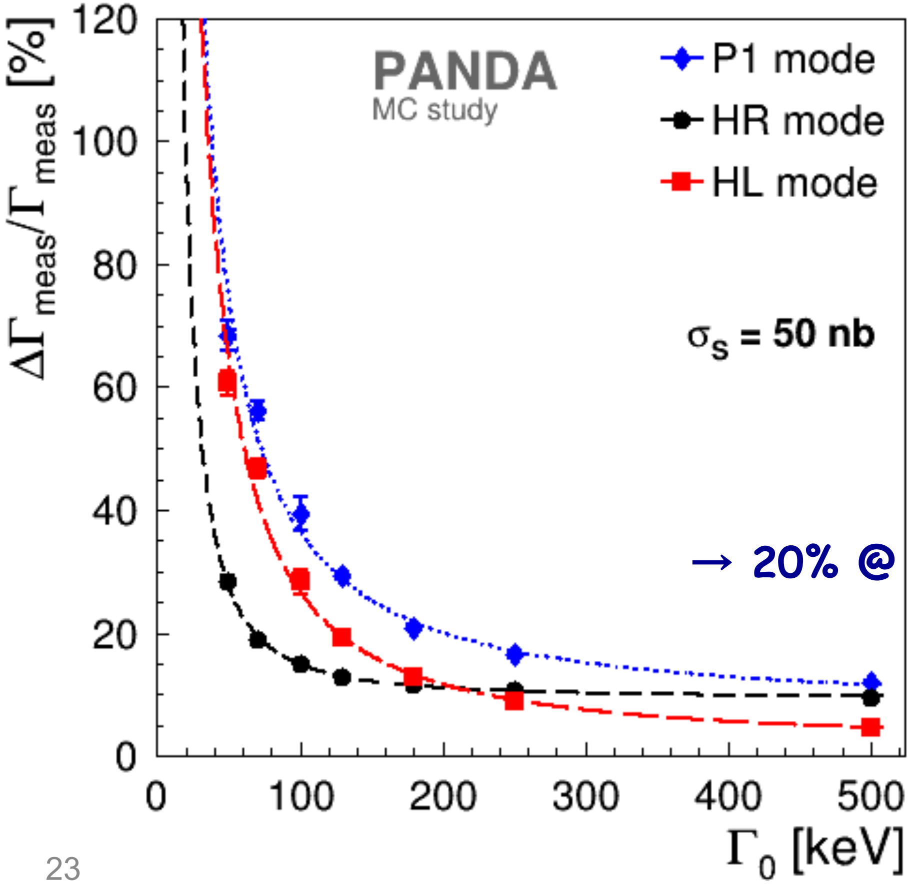
[PANDA, arXiv:1812.05132, hep-ex]

Sensitivities Breit-Wigner Γ (40 x 2d)

- Extract standard deviation from toy MC fits
- Show relative error $\mathrm{rms}_{fit}/\bar{\Gamma}_{fit}$ in [%]

Sensitivity

$$\frac{\Delta\Gamma_{\mathrm{meas}}}{\Gamma_{\mathrm{meas}}} = \frac{\mathrm{RMS}}{\mathrm{Mean} + \Gamma_0} \qquad \text{(Breit-Wigner case)}$$



→ 20% @ Γ= 50 ... 120 keV
HR HL

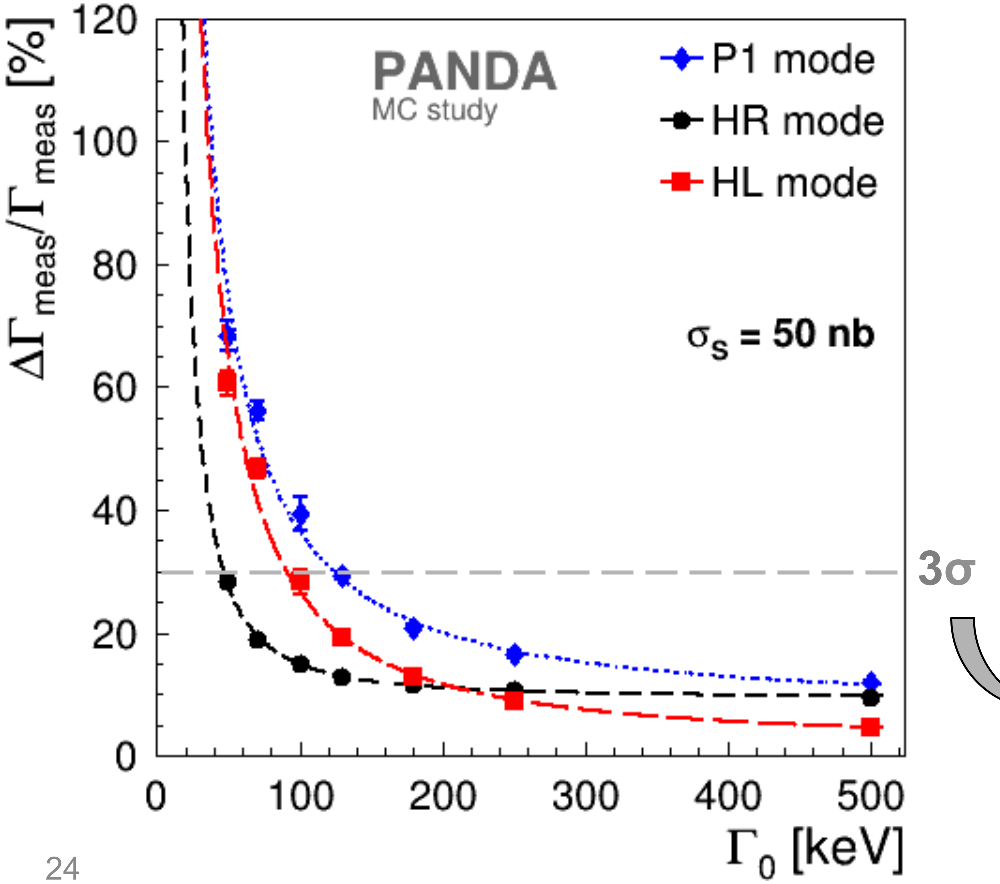
[PANDA, arXiv:1812.05132, hep-ex]

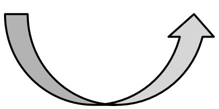
Sensitivities Breit-Wigner Γ (40 x 2d)

- Extract standard deviation from toy MC fits
- Show relative error $rms_{fit}/\bar{\Gamma}_{fit}$ in [%]

Sensitivity

$$\frac{\Delta\Gamma_{\mathrm{meas}}}{\Gamma_{\mathrm{meas}}} = \frac{\mathrm{RMS}}{\mathrm{Mean} + \Gamma_0} \qquad \text{(Breit-Wigner case)}$$





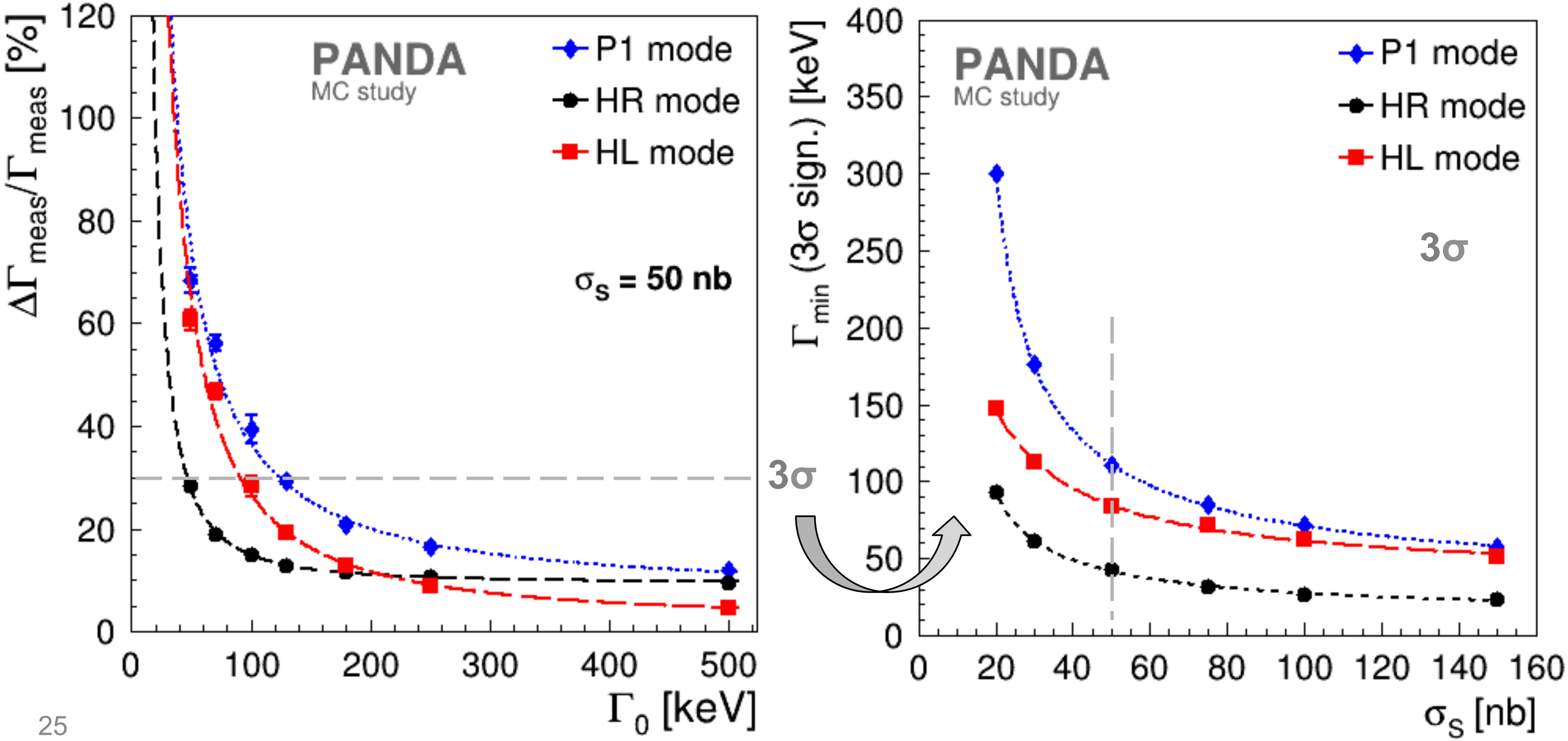
[PANDA, arXiv:1812.05132, hep-ex]

Sensitivities Breit-Wigner Γ (40 x 2d)

- Extract standard deviation from toy MC fits
- Show relative error $\mathrm{rms}_{fit}/\bar{\Gamma}_{fit}$ in [%]

Sensitivity

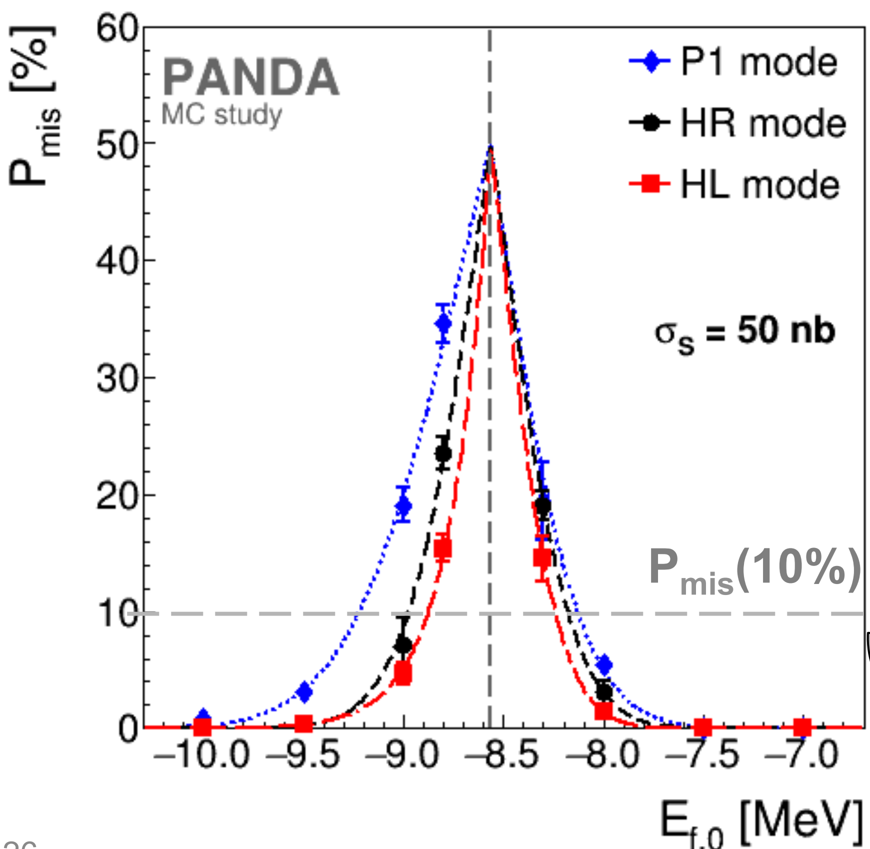
$$\frac{\Delta\Gamma_{\rm meas}}{\Gamma_{\rm meas}} = \frac{\rm RMS}{{\rm Mean} + \Gamma_0} \qquad \text{(Breit-Wigner case)}$$

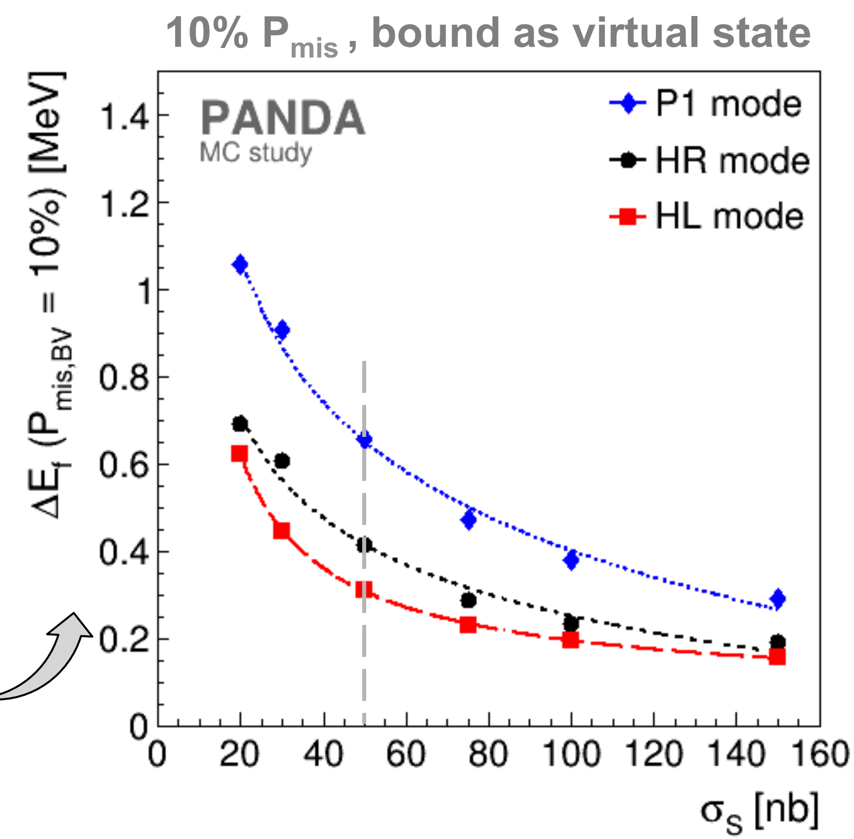


Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
- How well can virtual vs bound state be distinguished? → *integrate mismatch region:*

Sensitivity $\boxed{P_{\rm mis} = N_{\rm mis-id}/N_{\rm MC} \quad \text{(Molecule case)}}$

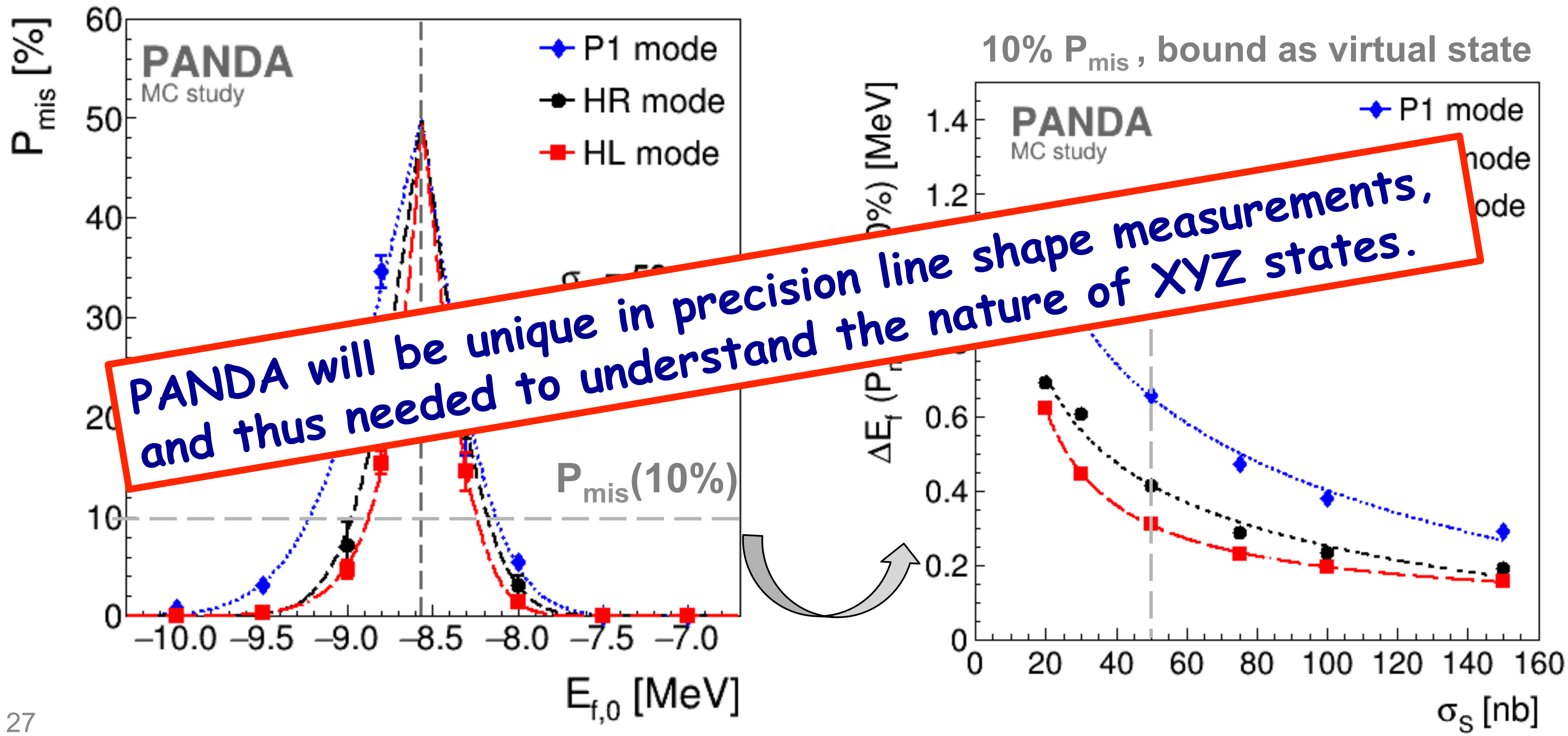




Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
- How well can virtual vs bound state be distinguished? → *integrate mismatch region:*

Sensitivity $\boxed{P_{\mathrm{mis}} = N_{\mathrm{mis-id}}/N_{\mathrm{MC}} \quad \text{(Molecule case)}}$



PANDA will be unique in precision line shape measurements, and thus needed to understand the nature of XYZ states.

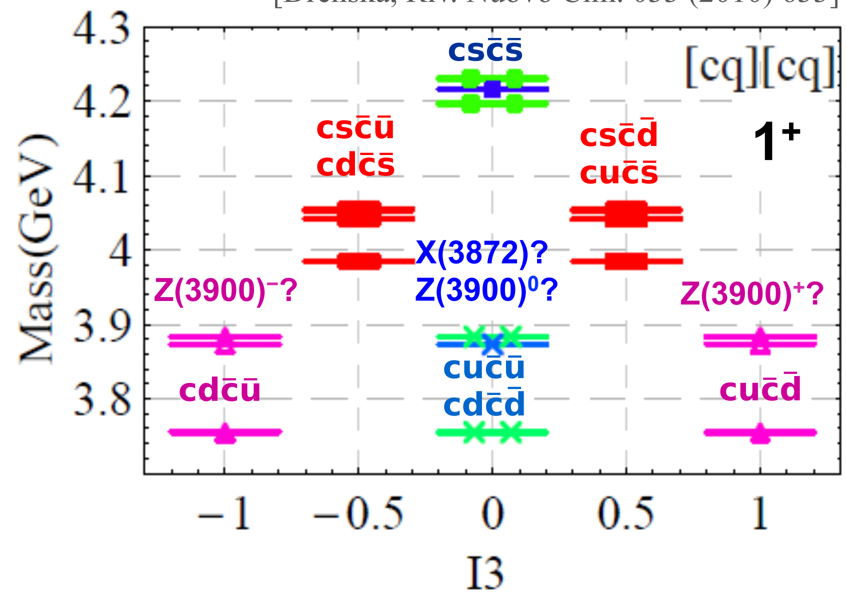
Models and Multiplets for XYZ

- Need to measure complete multiplets
  → *to really understand XYZ nature*

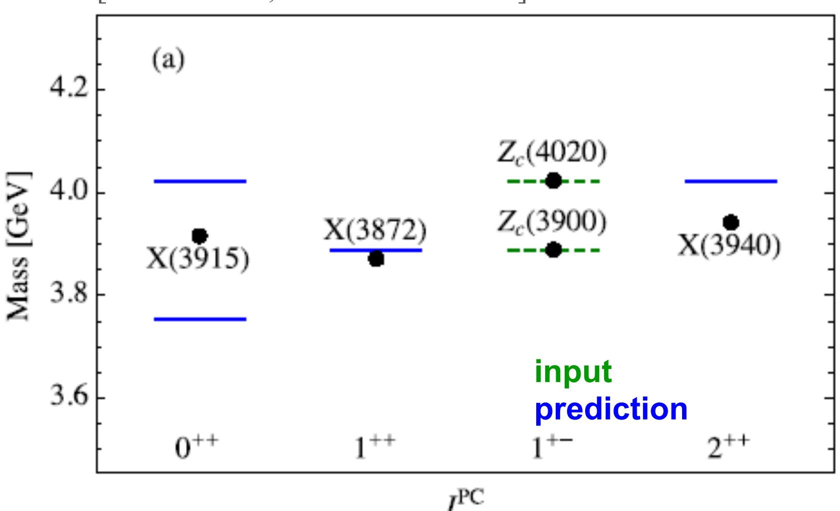
- e.g. di-quarkonium $[cq][\bar{c}\bar{q}]$ models provide predictions

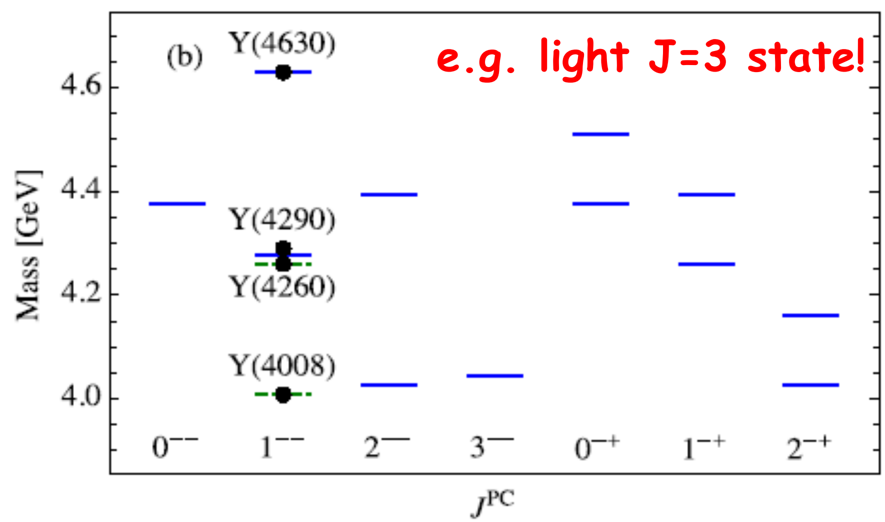
  - ➢ Look for stranged partners
  - ➢ Look for light high spin states

[Drenska, Riv. Nuovo Cim. 033 (2010) 633]



[Cleven et al., arXiv:1505.01771]



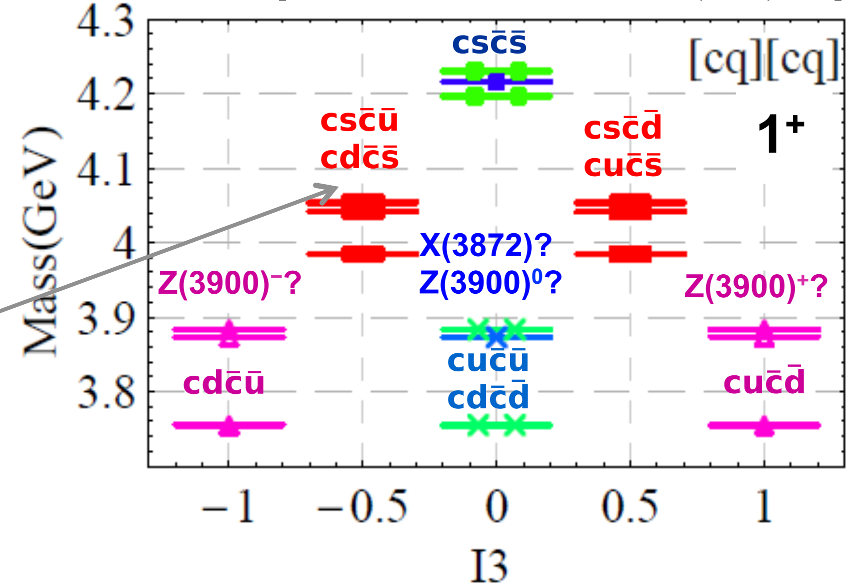


Models and Multiplets for XYZ

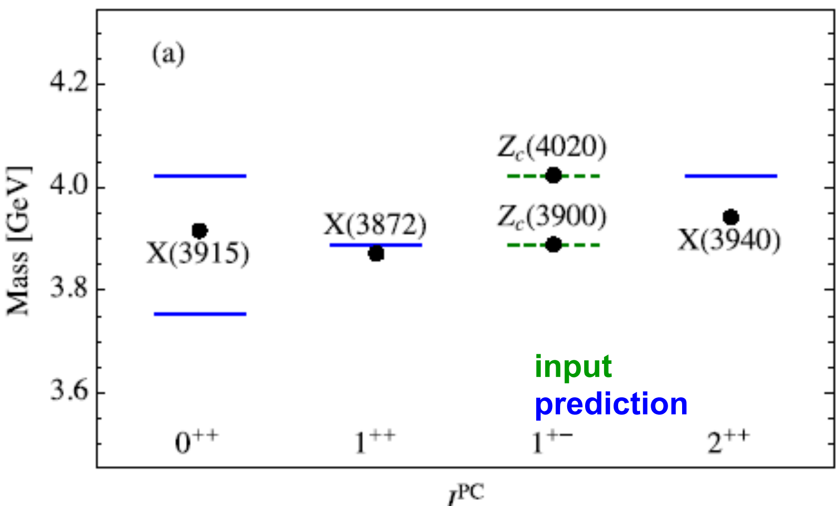
- Need to measure complete multiplets
  → *to really understand XYZ nature*

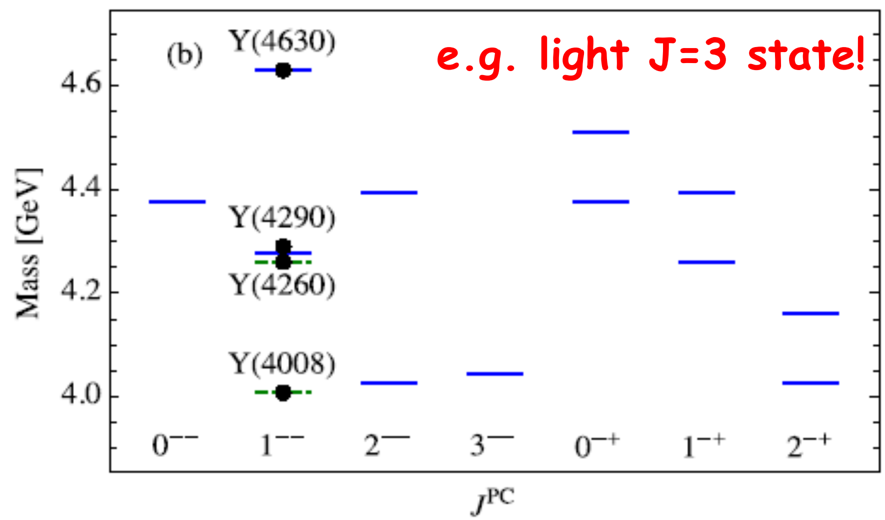
- e.g. di-quarkonium $[cq][\bar{c}\bar{q}]$ models provide predictions
  - ➢ Look for stranged partners
  - ➢ Look for light high spin states

[Drenska, Riv. Nuovo Cim. 033 (2010) 633]



[Cleven et al., arXiv:1505.01771]



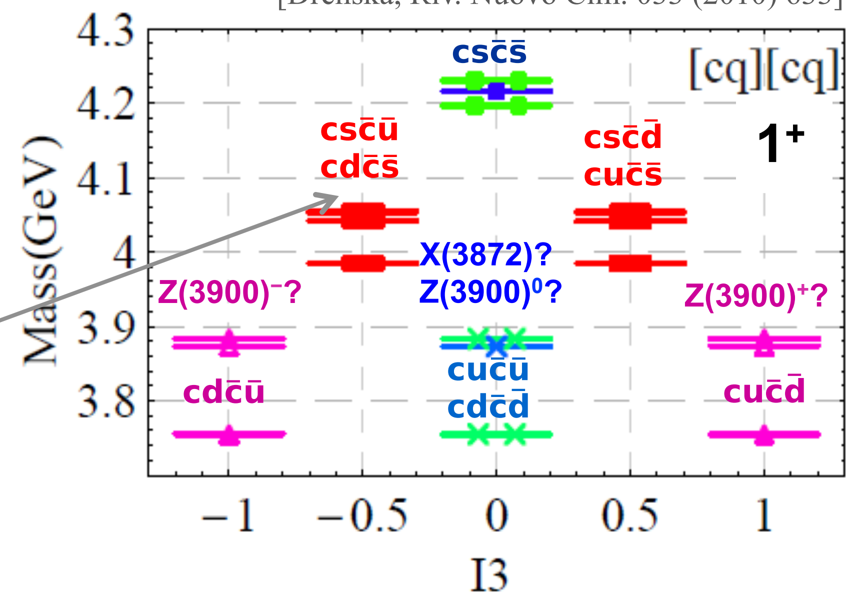


Models and Multiplets for XYZ

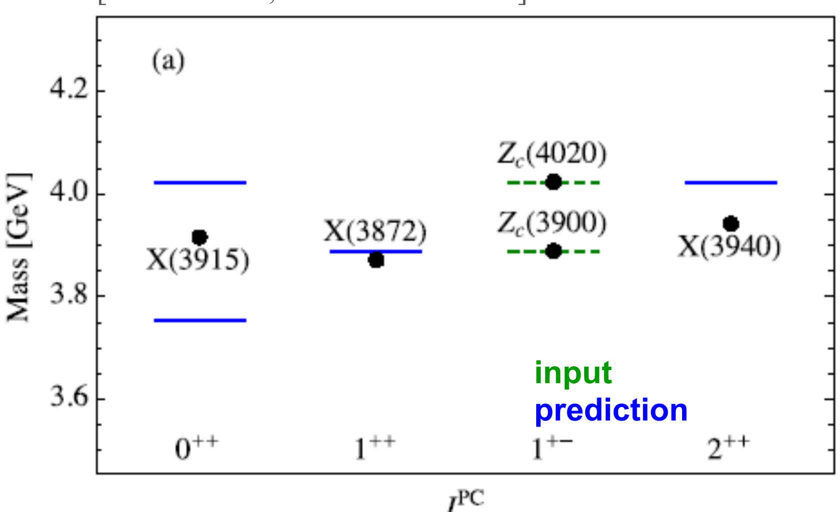
- Need to measure complete multiplets
  → *to really understand XYZ nature*

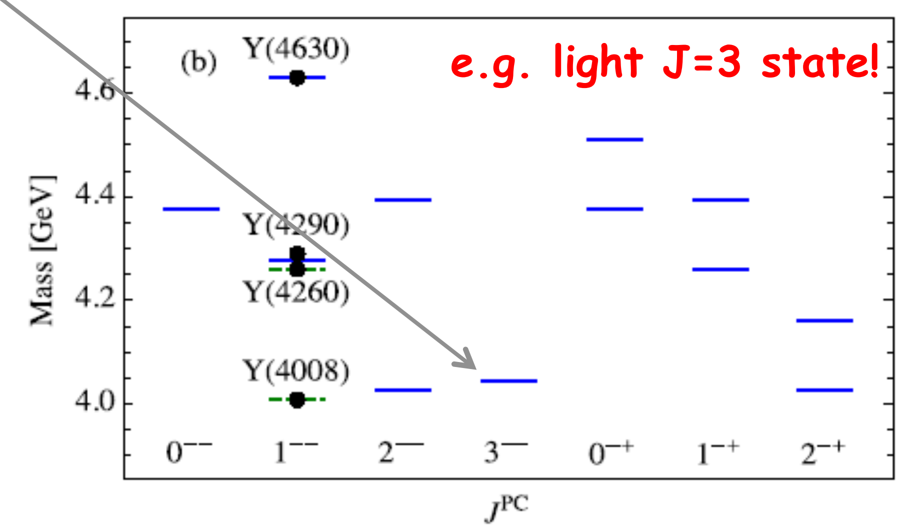
- e.g. di-quarkonium [cq][c̄q̄] models provide predictions
  - ➤ Look for stranged partners
  - ➤ Look for light high spin states

[Drenska, Riv. Nuovo Cim. 033 (2010) 633]

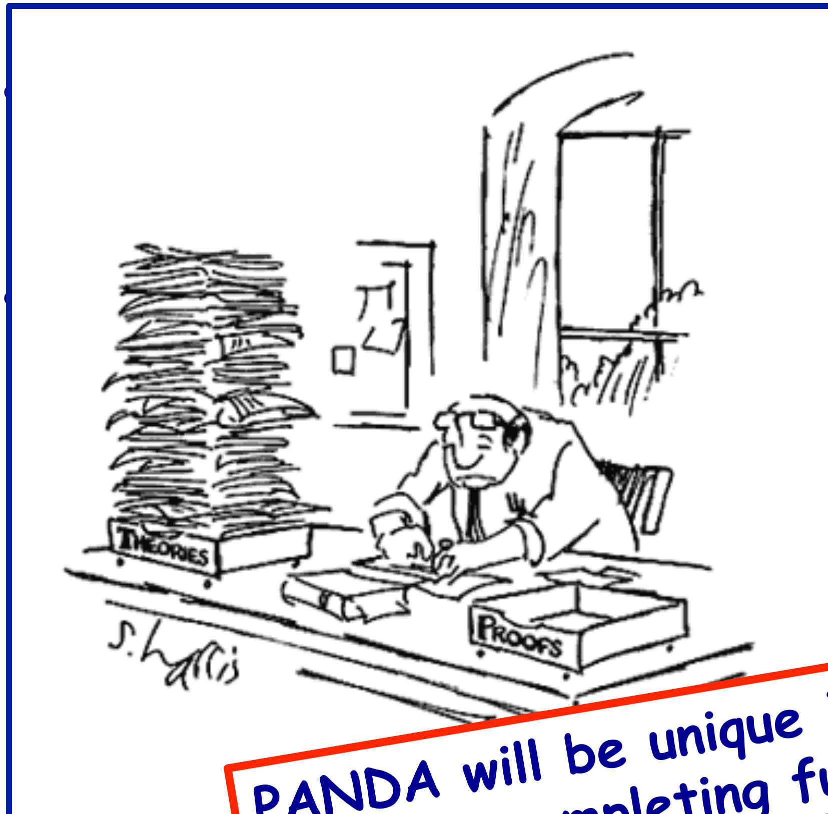


[Cleven et al., arXiv:1505.01771]

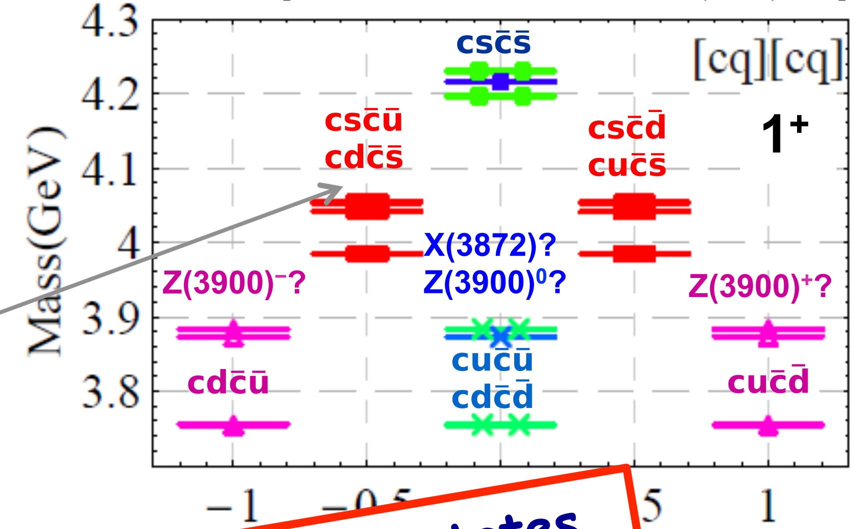




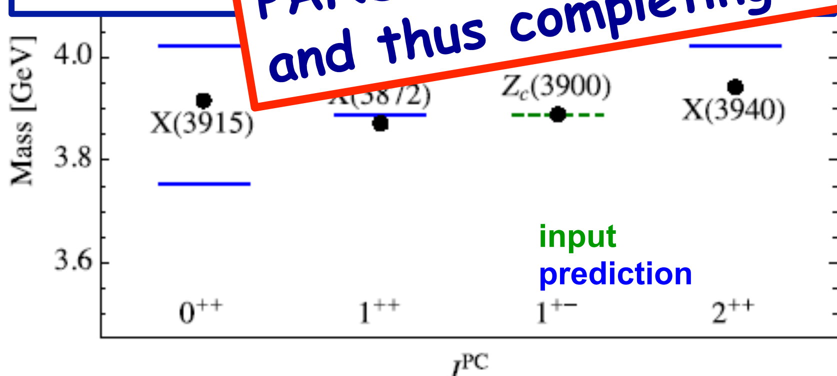
Models and Multiplets for XYZ

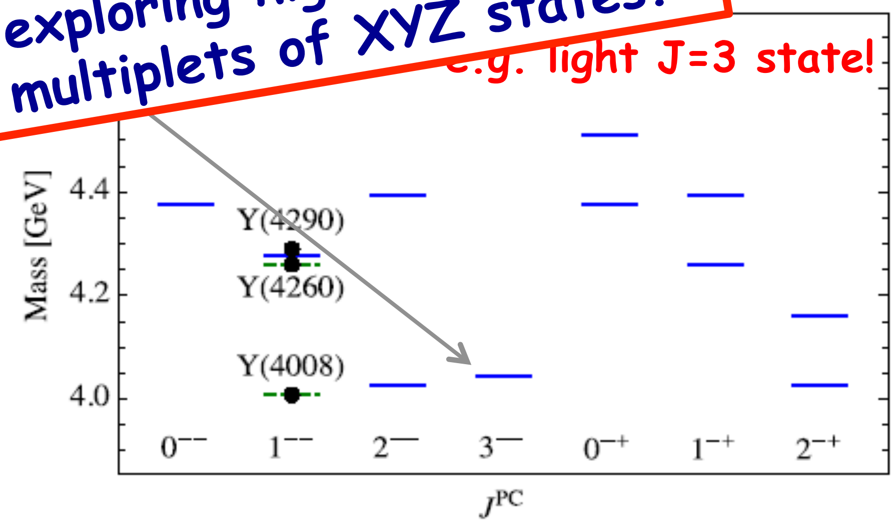


[Drenska, Riv. Nuovo Cim. 033 (2010) 633]



PANDA will be unique in exploring high spin states, and thus completing full multiplets of XYZ states.





Summary & Conclusions

- Feasibility study for resonance energy scans at PANDA
  - Lineshape and width measurements for X(3872)
  - Achievable performance quantified
- Determined sensitivity for BW width measurement
  - Sensitivity $\Gamma/\Delta\Gamma > 5$ at $\Gamma \gtrsim 50 \ldots 120$ keV
  - HR mode performs better for smaller widths
- Determined sensitivity for molecular line-shape measurement
  - Possible to distinguish bound/virtual state
  - $P_{HR,HL} > 90\%$ for $|E_f - E_{f,th}| \gtrsim 700$ keV
  - Sub-MeV resolution on $|E_f - E_{f,th}|$ already for Phase-1 (P1)
  - HL mode performs better over investigated

Summary & Conclusions

- Feasibility study for resonance energy scans at PANDA
  - Lineshape and width measurements for X(3872)
  - Achievable performance quantified
- Determined sensitivity for BW width measurem…
  - Sensitivity $\Gamma/\Delta\Gamma > 5$ at $\Gamma \gtrsim 50 \ldots 120$ …
  - HR mode performs bette… widths
- Determined s… molecular line-shape measurement
  - … distinguish bound/virtual state
  - $P_{HR,HL} > 90\%$ for $|E_f - E_{f,th}| \gtrsim 700$ keV
  - Sub-MeV resolution on $|E_f - E_{f,th}|$ already for Phase-1 (P1)
  - HL mode performs better over investigated

Accepted for publication in EPJA, arXiv:1812.05132 [hep-ex]

Summary & Conclusions

- Feasibility study for resonance energy scans at PANDA
  - Lineshape and width measurements for X(3872)
  - Achievable performance quantified
- Determined sensitivity for BW width measurem…
  - Sensitivity $\Gamma/\Delta\Gamma > 5$ at $\Gamma \gtrsim 50$ ... 120 …
  - HR mode performs bett… widths
- Determined s… molecular line-shape measurement
  - … distinguish bound/virtual state
  - $P_{HR,HL} > 90\%$ for $|E_f - E_{f,th}| \gtrsim 700$ keV
  - Sub-MeV resolution on $|E_f - E_{f,th}|$ already for Phase-1 (P1)
  - HL mode performs better over investigated
- Precision spectroscopy to understand exotic XYZ states
  - Precise knowledge of decay width and line shape essential
  - Complete the exotic multiplets

  → *PANDA unique:*

  High statistics + precision resonance scans + high spin states

Accepted for publication in EPJA, arXiv:1812.05132 [hep-ex]

Facility for Antiproton and Ion Research

FAIR construction site at night -- Feb 2019

Facility for Antiproton and Ion Research

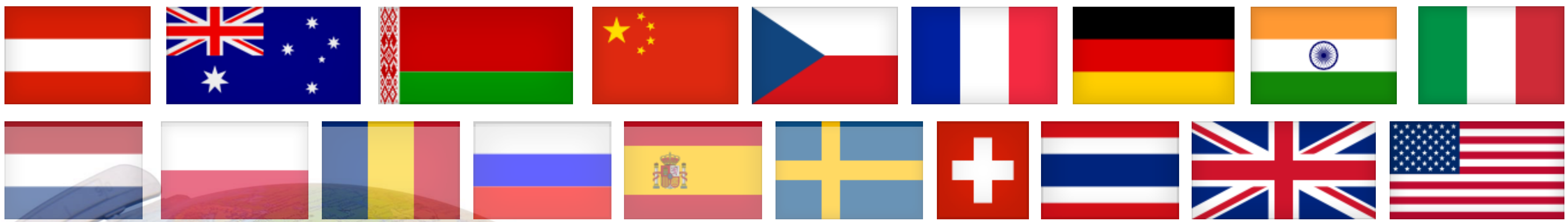
FAIR construction site at night -- Feb 2019

Thank you for your attention!

The PANDA collaboration:
~ 500 Members, 72 Institutes, 20 Countries

Austria, Australia, Belarus, China, France, Germany, India, Italy, Poland, Romania, Russia, Spain, Sweden, Switzerland, Thailand, Netherlands, USA, UK, ... (to be updated/completed)

Collaboration



UniVPM Anconca
U Basel
IHEP Beijing
U Bochum
U Bonn
U Brescia
IFIN-HH Bucharest
AGH UST Cracow
IFJ PAN Cracow
JU Cracow
U Cracow
FAIR Darmstadt
GSI Darmstadt
JINR Dubna
U Edinburgh
U Erlangen
NWU Evanston

U & INFN Ferrara
FIAS Frankfurt
U Frankfurt
LNF-INFN Frascati
U & INFN Genova
U Gießen
U Glasgow
BITS Pilani KKBGC, Goa
KVI Groningen
Sadar Patel U, Gujart
Gauhati U, Guwahati
FH Iserlohn
FZ Jülich
IMP Lanzhou
INFN Legnaro
U Lund
HI Mainz

U Mainz
INP Minsk
ITEP Moscow
MPEI Moscow
BARC Mumbai
U Münster
BINP Novosibirsk
Novosibirsk State U
Novosibirsk STU
IPN Orsay
U & INFN Pavia
Charles U, Prague
Czech TU, Prague
IHEP Protvino
Irfu Saclay
U of Sidney

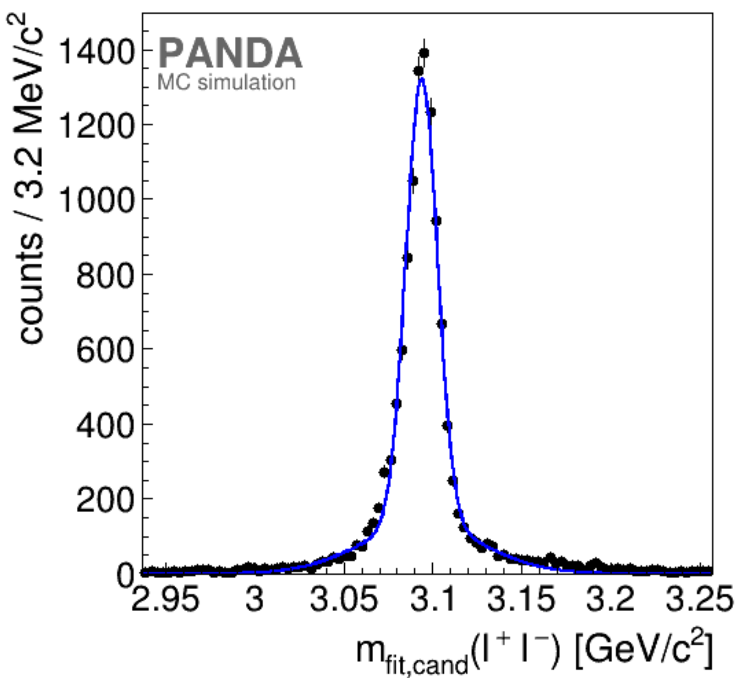
PNPI St. Petersburg
KTH Stockholm
U Stockholm
Suranaree University
SVNIT Surat-Gujarat
South Gukarat U, Surat-Gujarat
FSU Tallahassee
U & INFN Torino
Politecnico di Torino
U & INFN Trieste
U Uppsala
U Valencia
SMI Vienna
U Visva-Bharati
SINS Warsaw

Backup

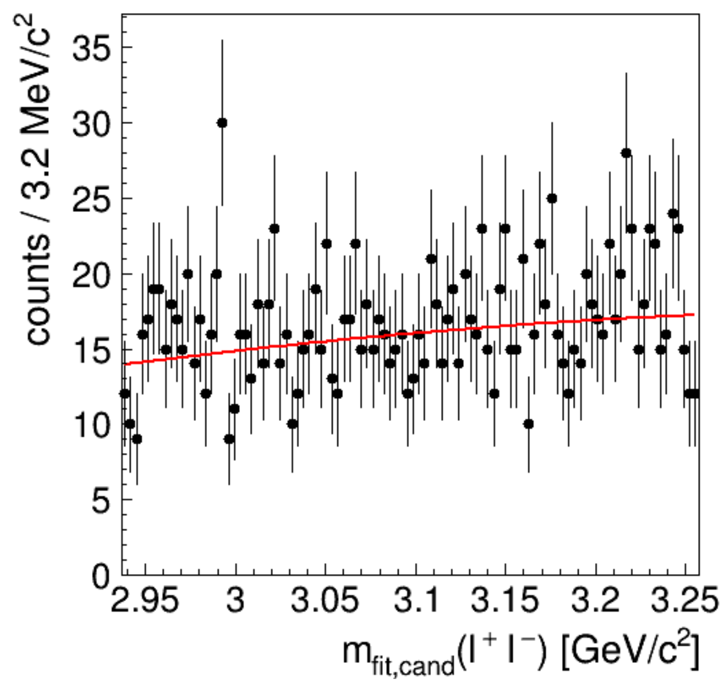
Signal/Background PDF for ML fits

- Softened selection for $\mu^+\mu^-$ (only to define reasonable PDF's)
  - ➢ Muon PID($\mu^\pm$) > 0.8
  - ➢ $m_{fit}(\mu^+\mu^-) + m_{fit}(\pi^+\pi^-) > 3.65$ GeV/c^2
- Signal: Double-Gauss, Background: Parabola

Signal PDF



Background PDF

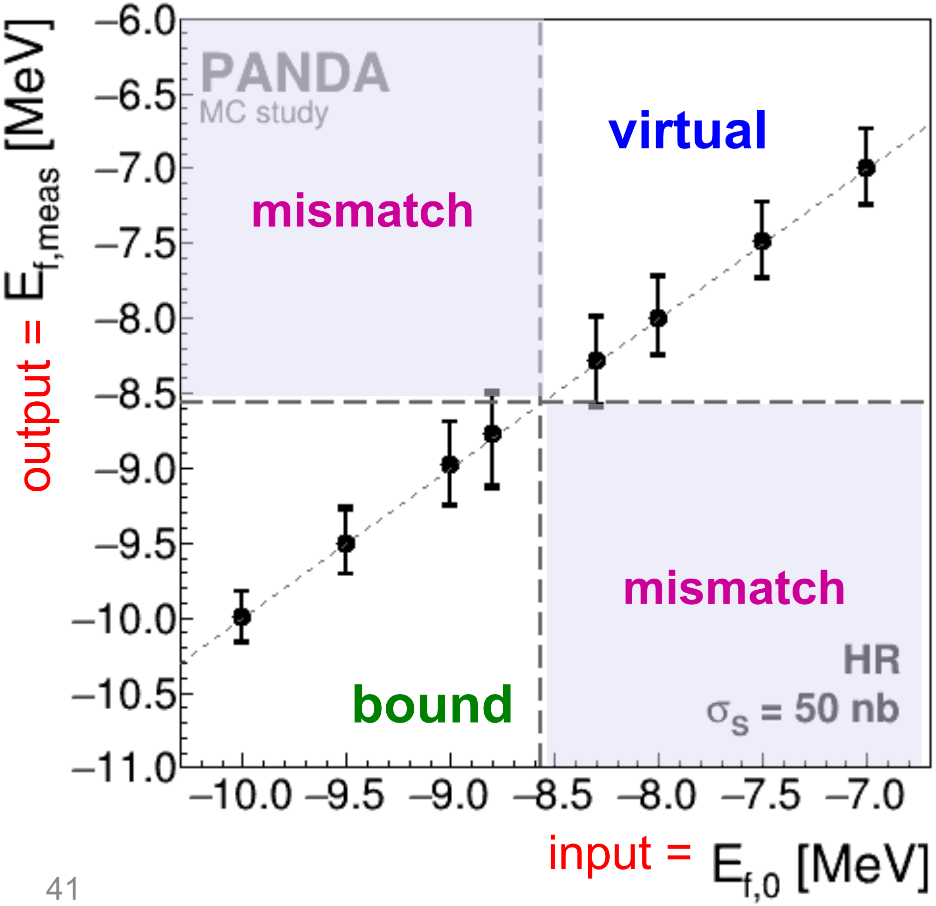


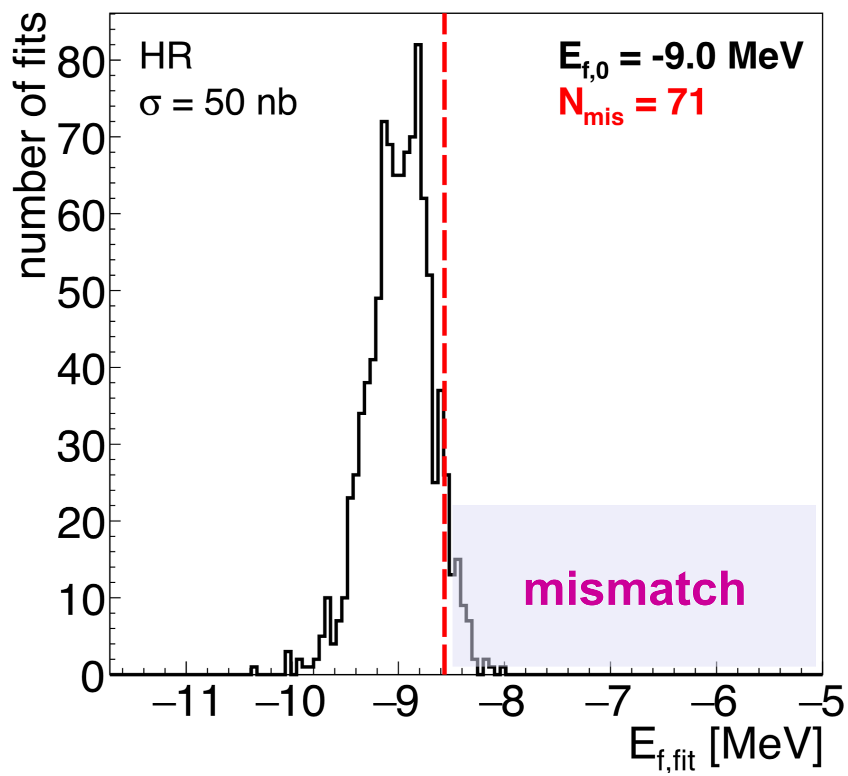
[PANDA, arXiv:1812.05132, hep-ex]

Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
- How well can virtual vs bound state be distinguished? → *integrate mismatch region:*

Sensitivity $$P_{\rm mis} = N_{\rm mis-id}/N_{\rm MC} \quad \text{(Molecule case)}$$



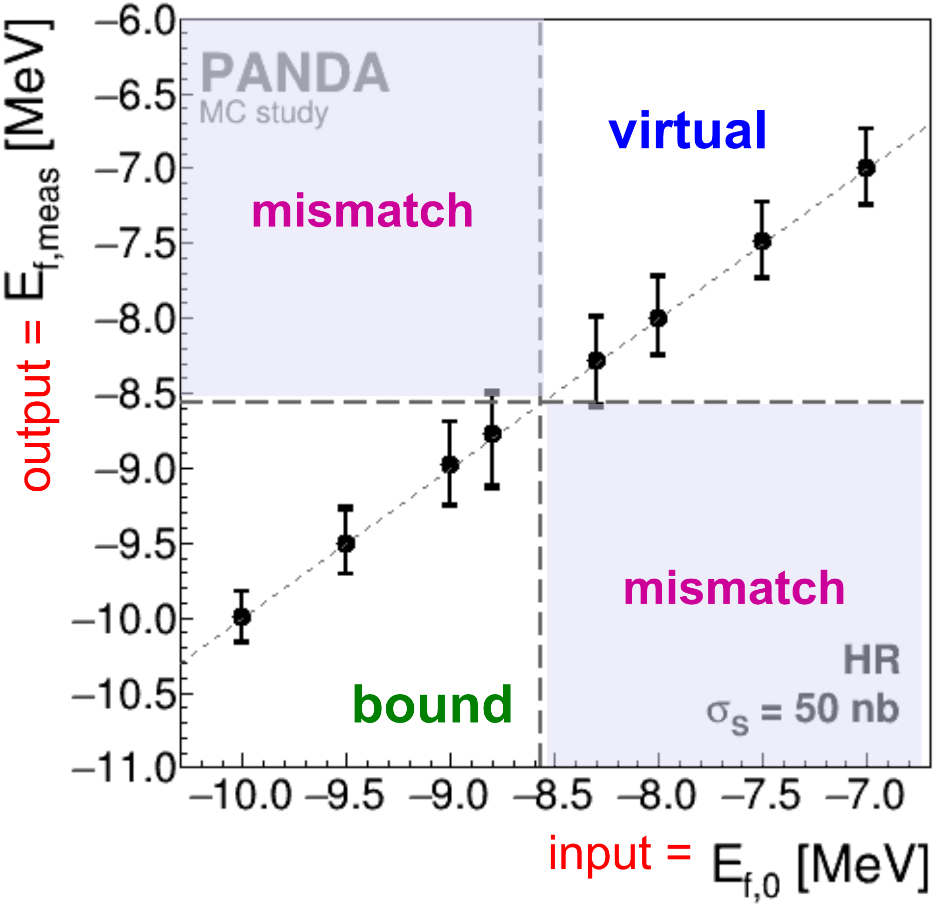


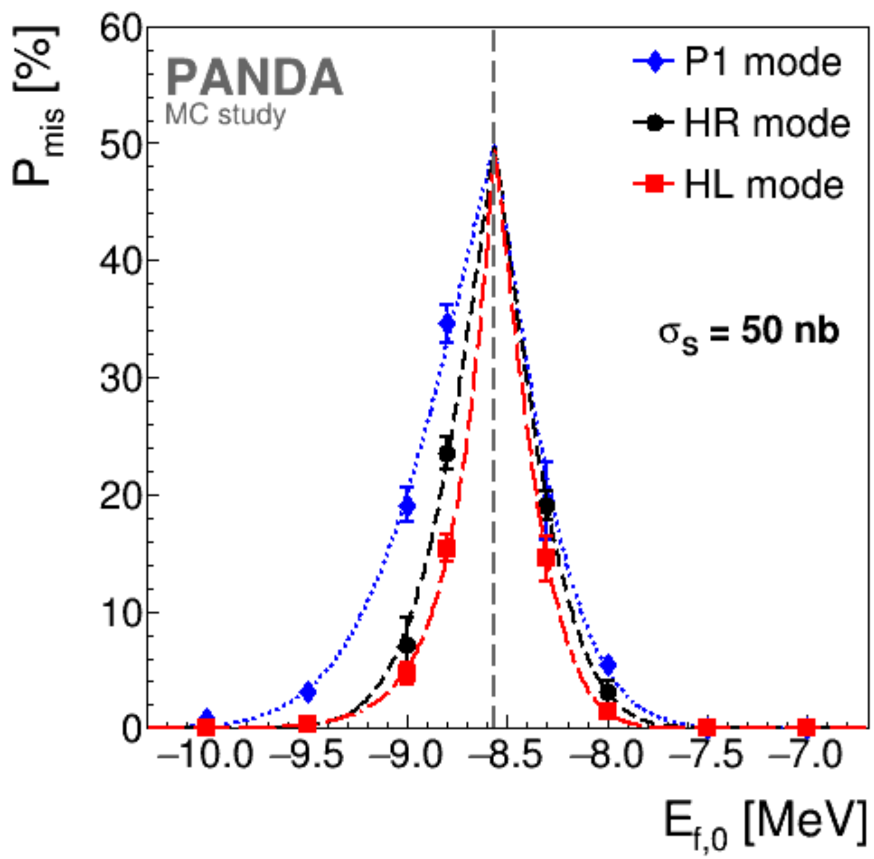
[PANDA, arXiv:1812.05132, hep-ex]

Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
- How well can virtual vs bound state be distinguished? → *integrate mismatch region:*

Sensitivity $$P_{\text{mis}} = N_{\text{mis-id}}/N_{\text{MC}} \quad \text{(Molecule case)}$$

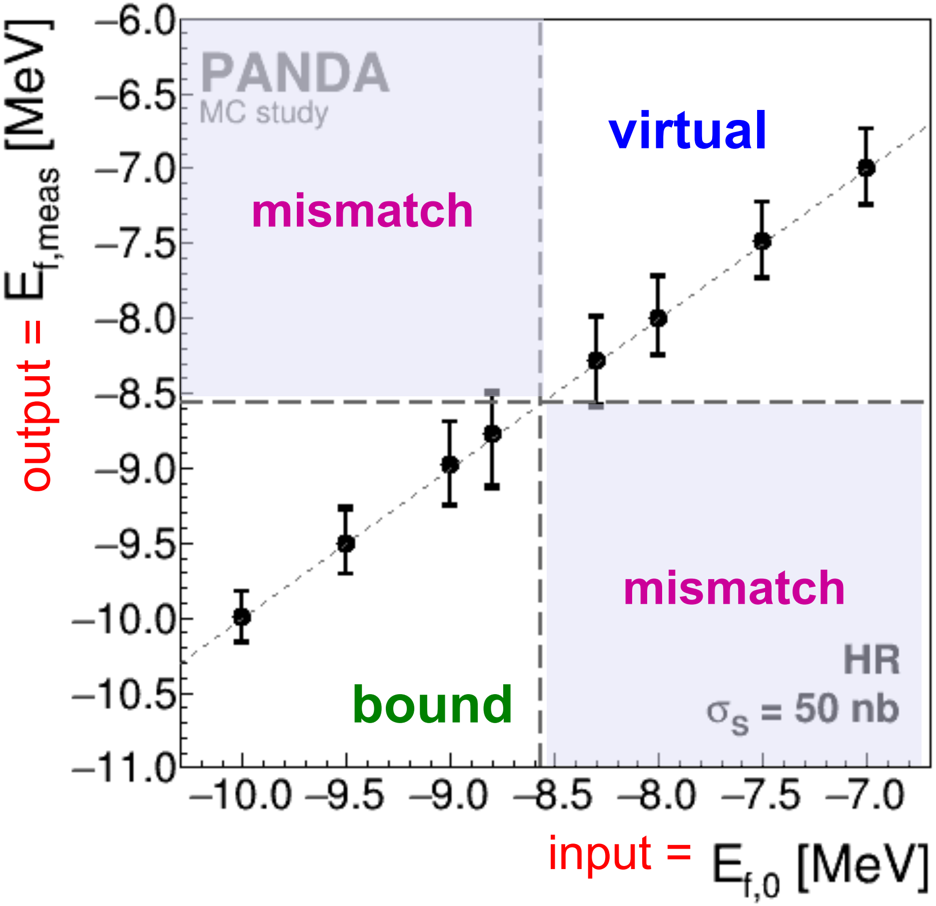


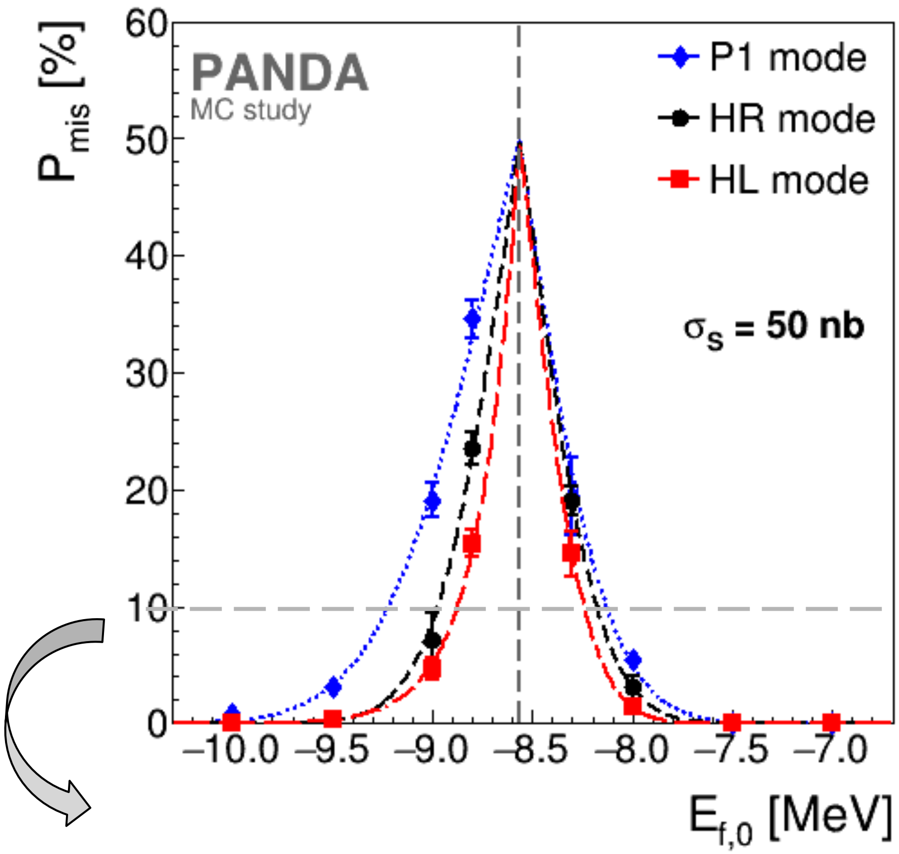


Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
- How well can virtual vs bound state be distinguished? → *integrate mismatch region:*

Sensitivity $P_{\text{mis}} = N_{\text{mis-id}}/N_{\text{MC}} \quad (\text{Molecule case})$





Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
- How well can virtual vs bound state be distinguished? → *integrate mismatch region:*

Sensitivity $\boxed{P_{\mathrm{mis}} = N_{\mathrm{mis-id}}/N_{\mathrm{MC}} \quad \text{(Molecule case)}}$