# Precision resonance energy scans at PANDA

## -- Sensitivity study for width & line shape measurements of X(3872)

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*Frankfurt University, GSI Darmstadt*
**on behalf of the PANDA Collaboration**

*QWG 2019 – 13th Workshop on Heavy Quarkonium,*
*Turin, Italy, May 13th – 17th 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
- **Further unique opportunities**
  - Importance of high-spin states
- **Summary & outlook**

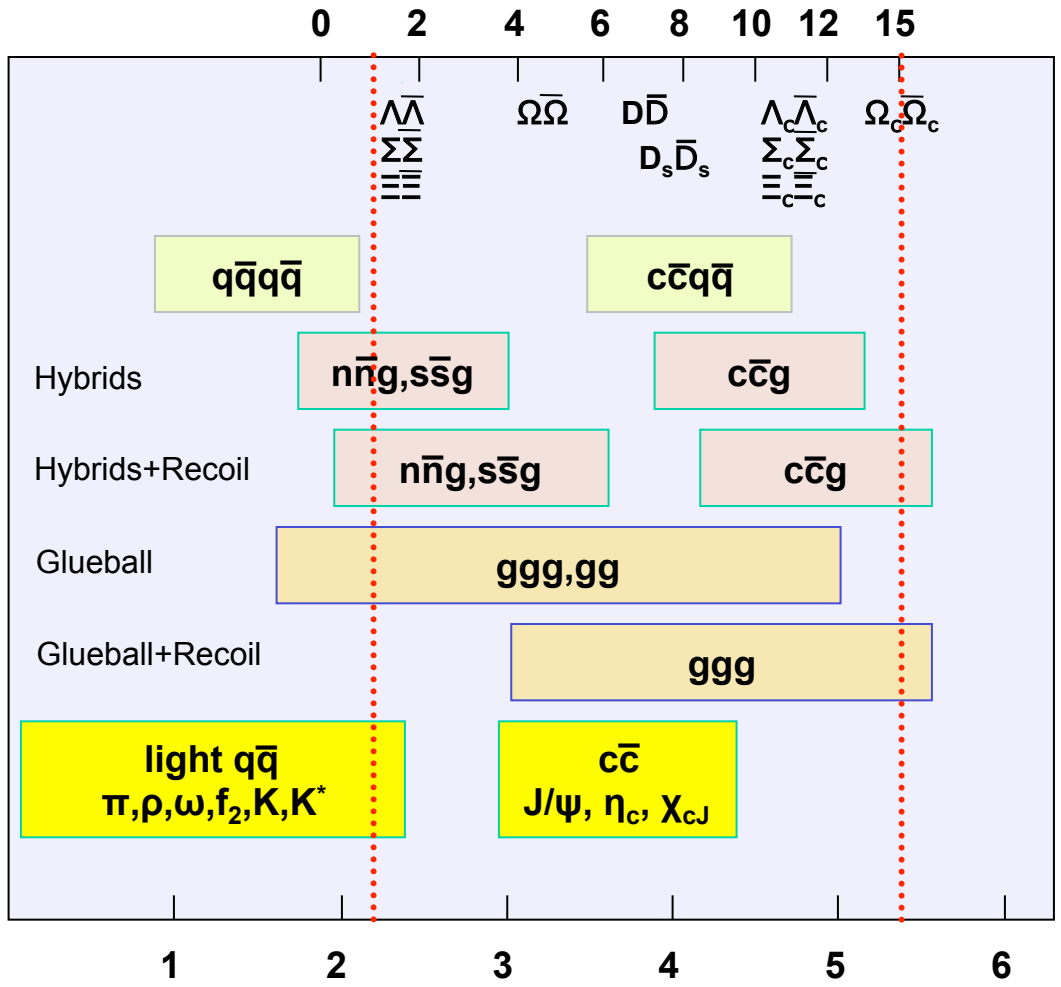
# PANDA Physics Programme

**Anti-Proton ANnihilation in DArmstadt**

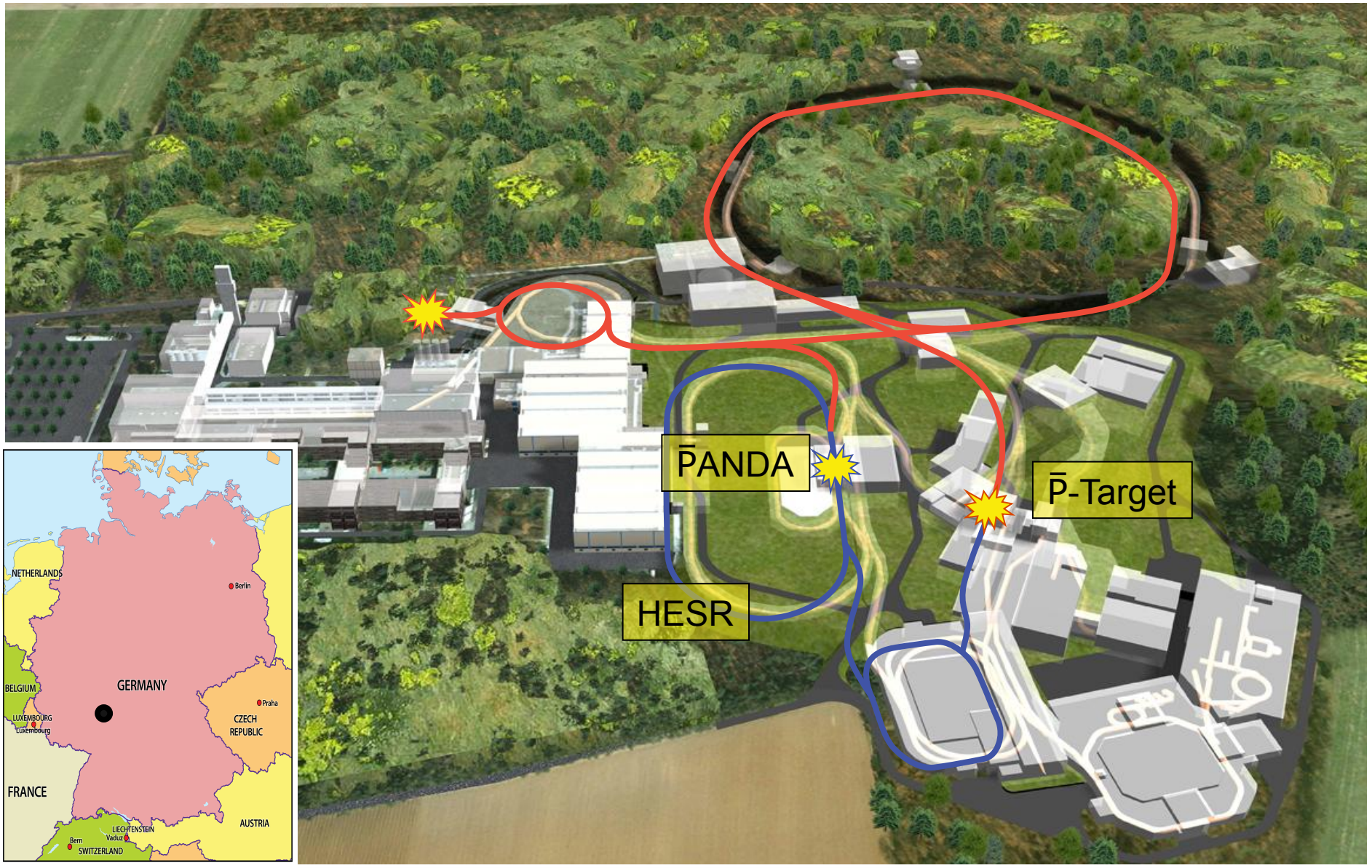
- **Hadron spectroscopy**
  - Light mesons
  - Charmonium
  - Exotic states:

    glue-balls, hybrids,

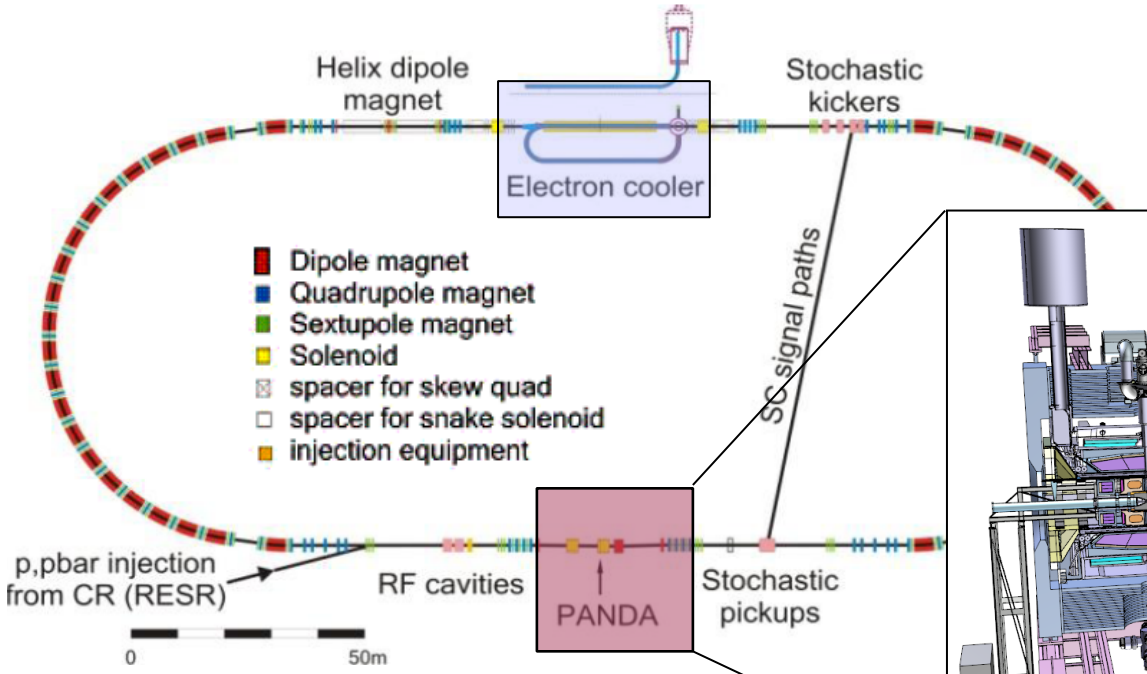
    molecules / multi-quarks
- **(Anti-) Baryon production**
- **Nucleon structure**
- **Charm in nuclei**
- **Strangeness physics**
  - hypernuclei
  - S = -2 nuclear system



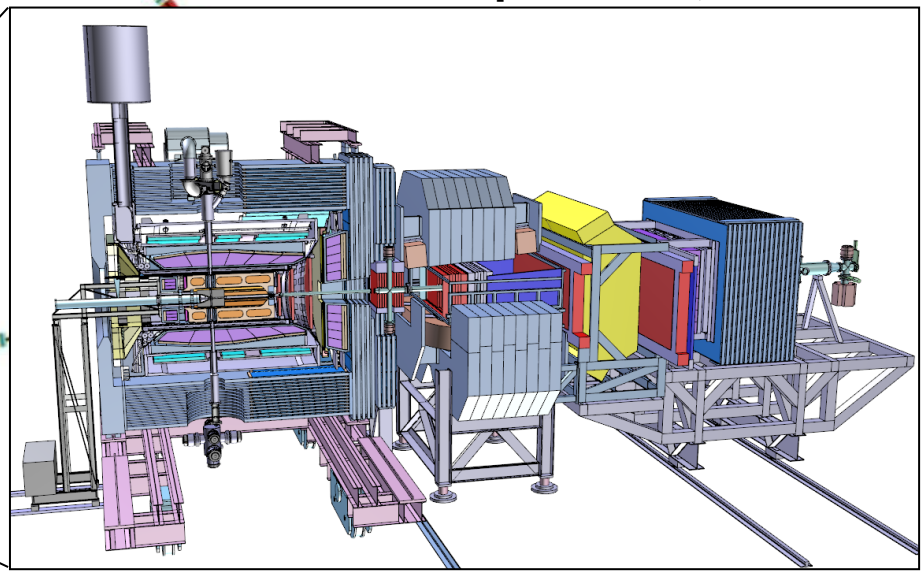
# Facility for Antiproton and Ion Research



# High Energy Storage Ring -- HESR




**PANDA Experiment, Detector**



**High Resolution (HR) mode:**

- Luminosity up to 2 x $10^{31}$ $cm^{-2}$ $s^{-1}$
- $\Delta p/p = 2 \times 10^{-5}$

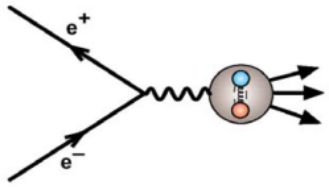
**High Luminosity (HL) mode:**

- Luminosity up to 2 x $10^{32}$ $cm^{-2}$ $s^{-1}$
- $\Delta p/p = 1 \times 10^{-4}$

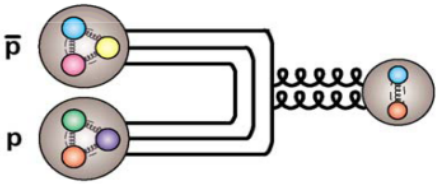
# Some Advantages of Anti-Protons

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

**Formation:**




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

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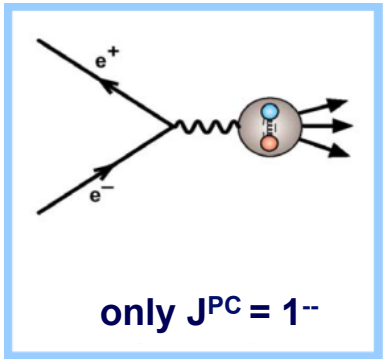


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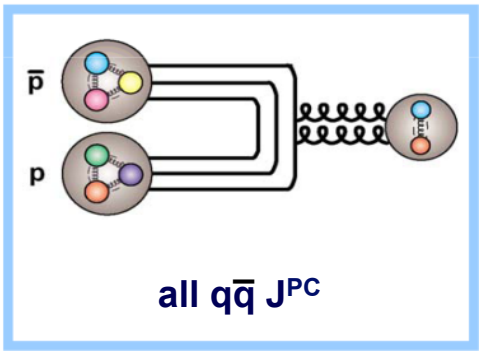


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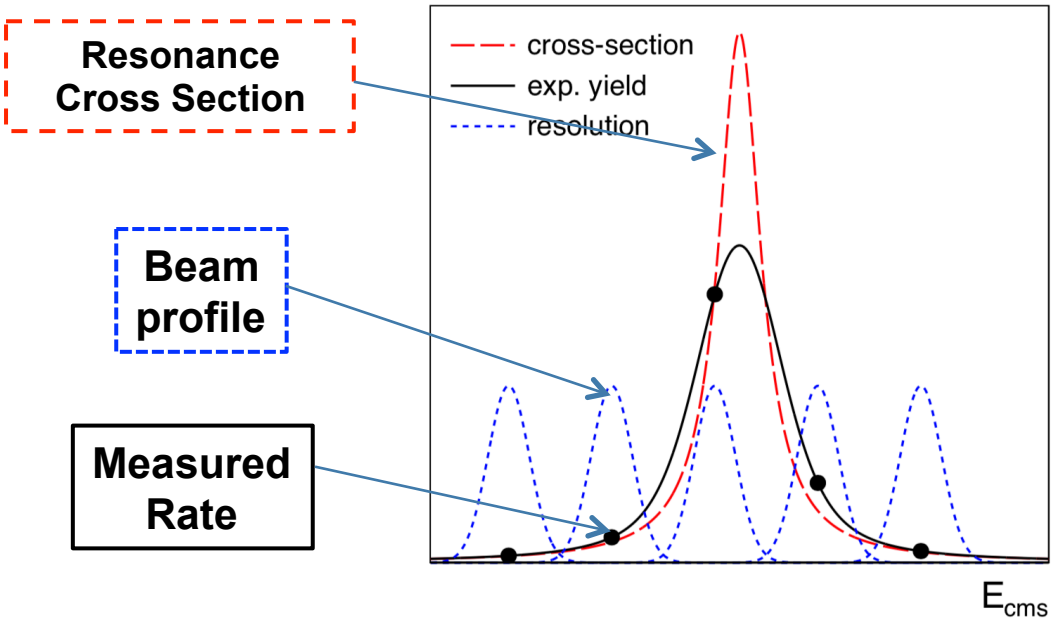

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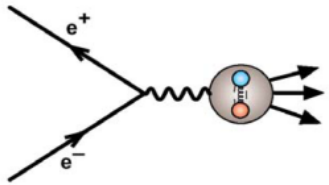


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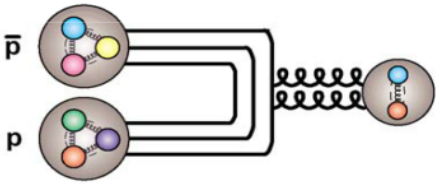


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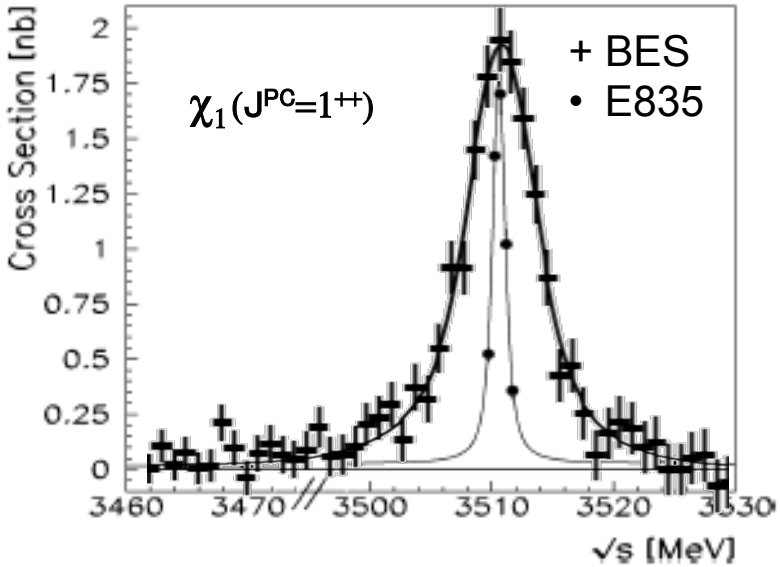



E760/835@Fermilab ≈ 240 keV

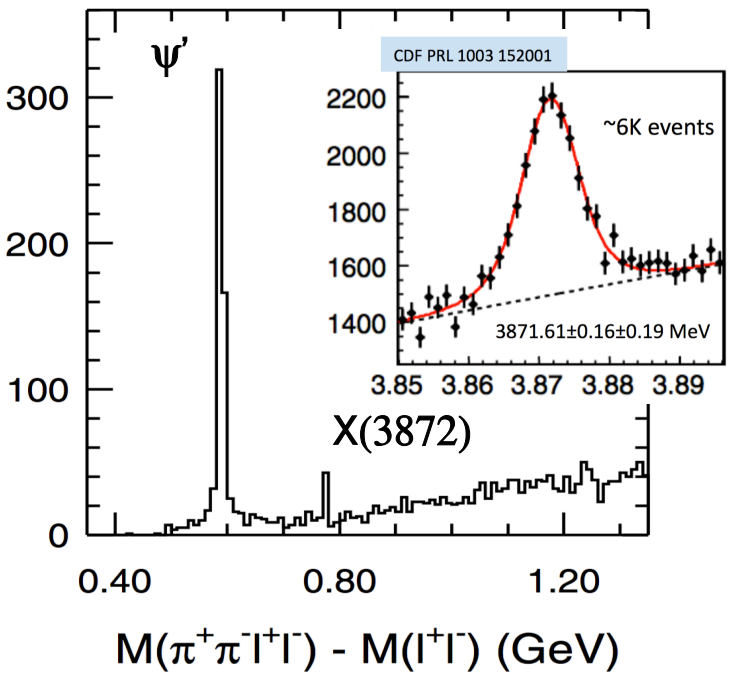
PANDA@FAIR ≈ 50 keV

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 $D^0D^0\gamma$)

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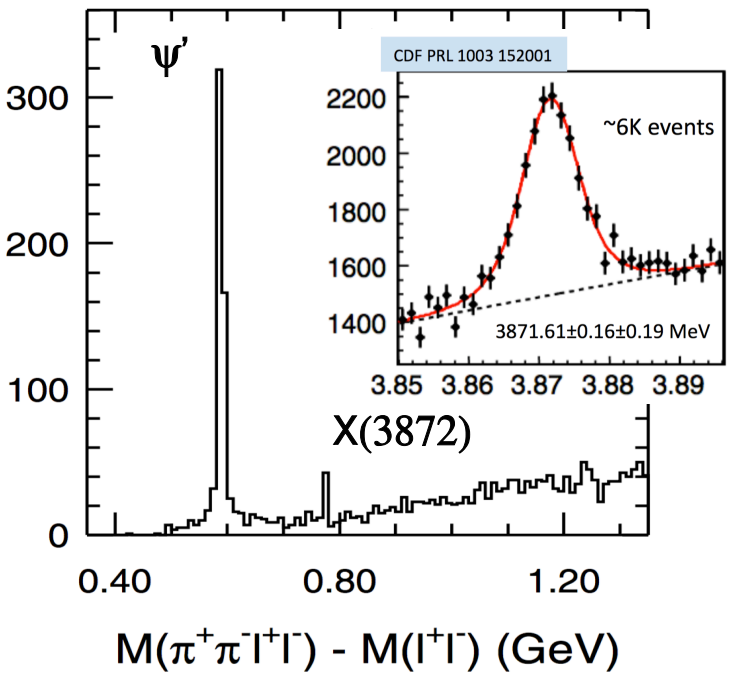


- Mass: $m(X) - m(\bar{D}^{*0}) - m(D^0) =$
  $= -0.12 \pm 0.19\ \text{MeV}/c^2$
- Width: Upper limit by Belle
  - $\Gamma_{X(3872)} < 1.2\,\text{MeV}$ (90% c.l., 2011)

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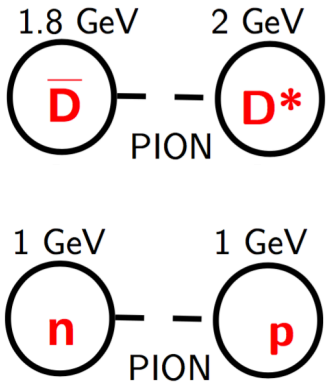

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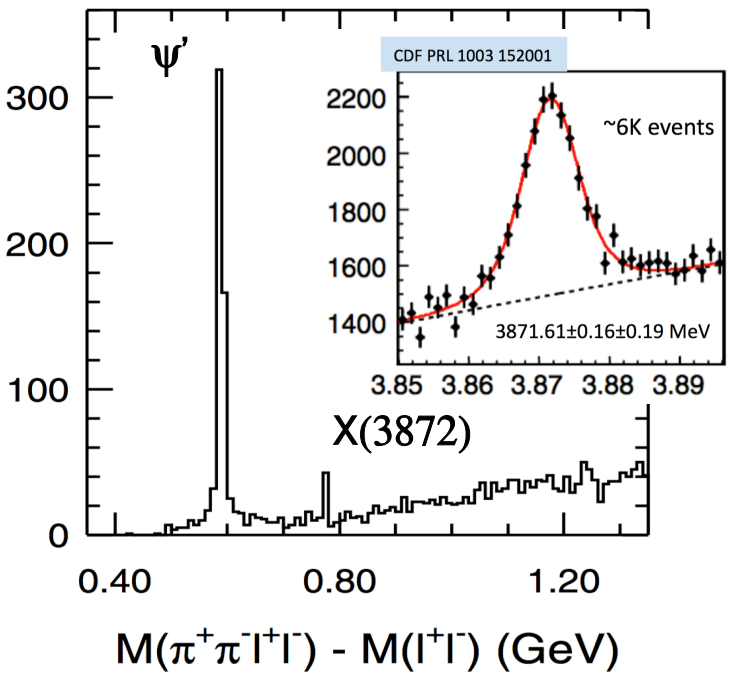


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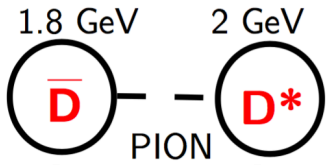
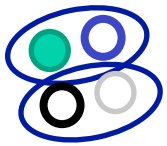


**Molecule ?**
$(q\bar{q})_1(q\bar{q})_1$

**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 $X(3872) \rightarrow J/\psi\, \rho^0$

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

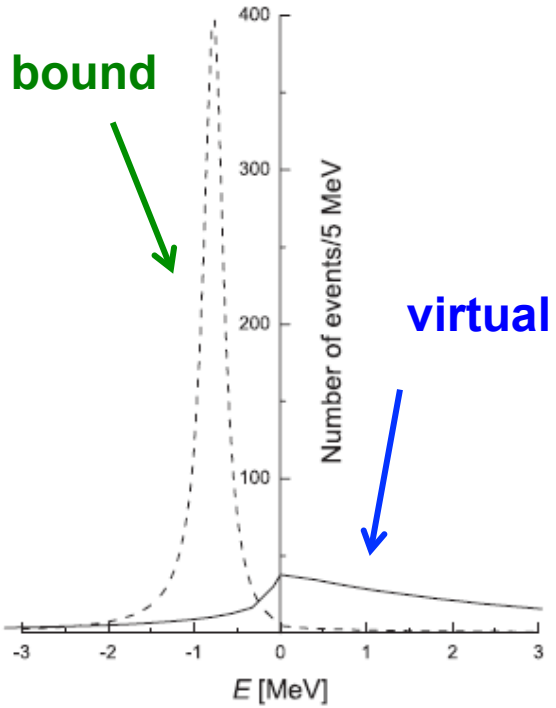
*(assuming line-shape as in B decays)*

- $$D(E) = \begin{cases} E - E_f - \frac{g_1\kappa_1}{2} - \frac{g_2\kappa_2}{2} + i\frac{\Gamma(E)}{2}, & E < 0, \\ E - E_f - \frac{g_2\kappa_2}{2} + i\left(\frac{g_1 k_1}{2} + \frac{\Gamma(E)}{2}\right), & 0 < E < \delta, \\ E - E_f + i\left(\frac{g_1 k_1}{2} + \frac{g_2 k_2}{2} + \frac{\Gamma(E)}{2}\right), & E > \delta, \end{cases}$$

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

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

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




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

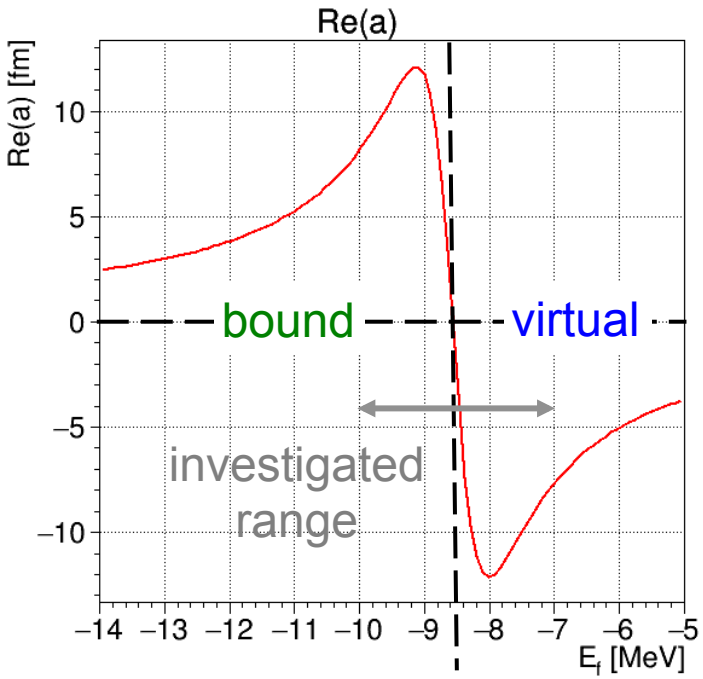
Flatte energy $E_f$ determines state to be bound or virtual

# Line shapes for different $E_f$

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

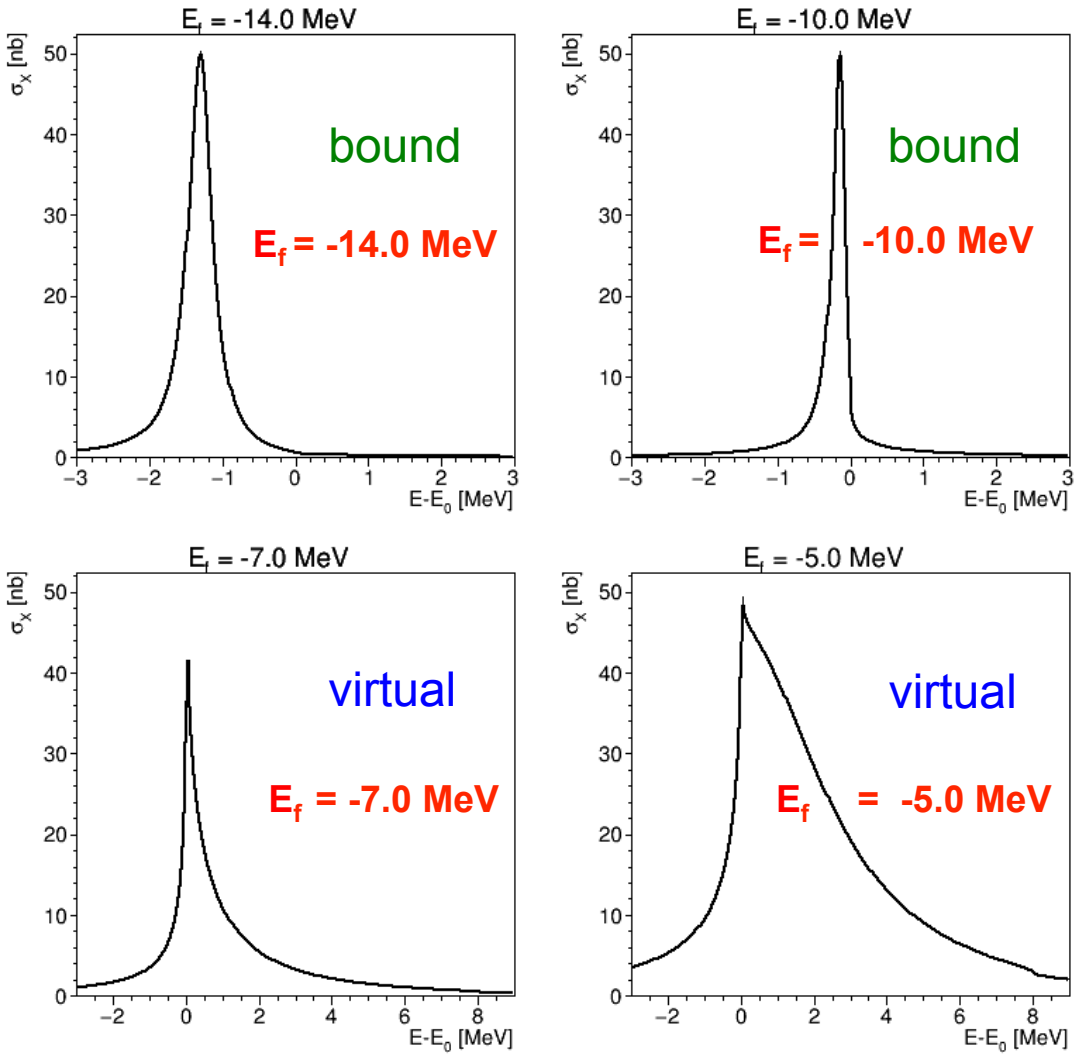
$$a = -\frac{\sqrt{2\mu_2\delta} + 2E_f/g + i\Gamma(0)/g}{(\sqrt{2\mu_2\delta} + 2E_f/g)^2 + \Gamma(0)^2/g^2}$$

Re(a) > 0 : bound state
Re(a) < 0 : virtual state




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

Examples always scaled to same $f_{max}$




(with $f_\rho$=0.00047, $f_\omega$=0.00271, g=0.137, $\Gamma_0$=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 $X(3872) \rightarrow J/\psi(\ell^+\ell^-)\ \rho^0(\pi^+\pi^-)$ channel only
  - Geant based sim/reco => signal + background efficiencies $\varepsilon_S$ and $\varepsilon_B$
  - 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.)

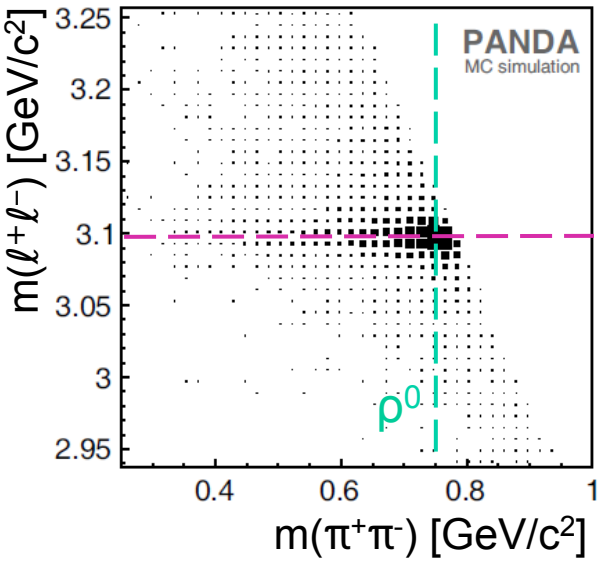
# Reconstruction Part

# Input Parameters

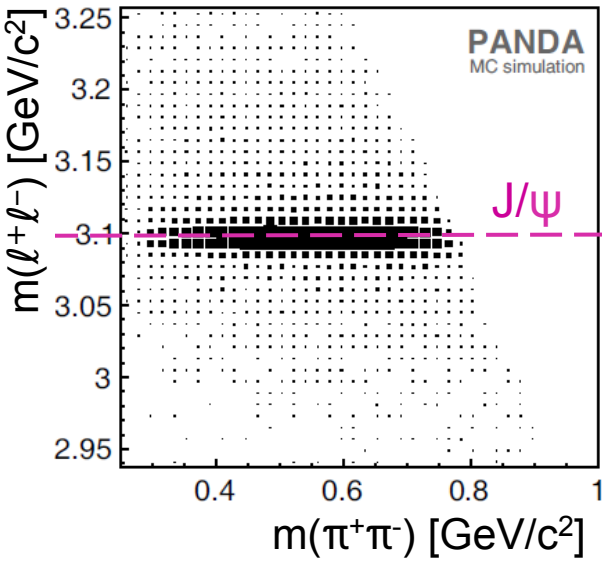
| | Parameter | Value |
|---|---|---|
| Branching Fractions | BR($J/\psi \to e^+ e^-$) | 5.97 % |
| | BR($J/\psi \to \mu^+ \mu^-$) | 5.96 % |
| | BR($\rho^0 \to \pi^+ \pi^-$) | 100% |
| | BR($X \to J/\psi \rho^0$) | 5 % (UL: 6.6%) |
| Cross sections | $\sigma_{peak}(p\bar{p} \to X)$ | [20,30,50,75,100,150]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

# Kinematic Distributions
## (after 4C fit applied)

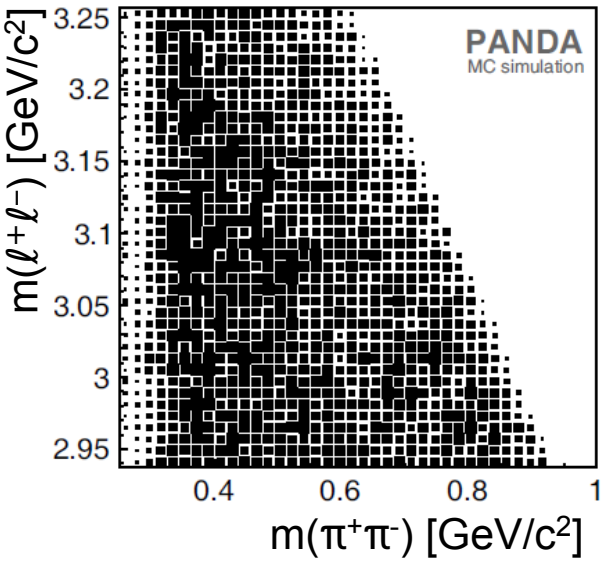
signal




non-resonant bkg



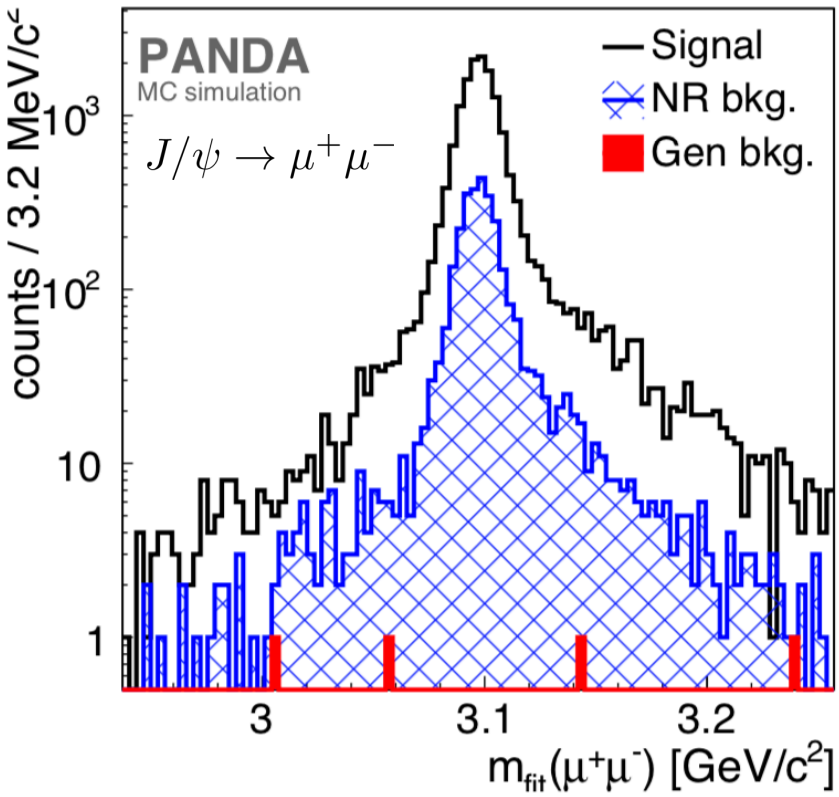

generic bkg

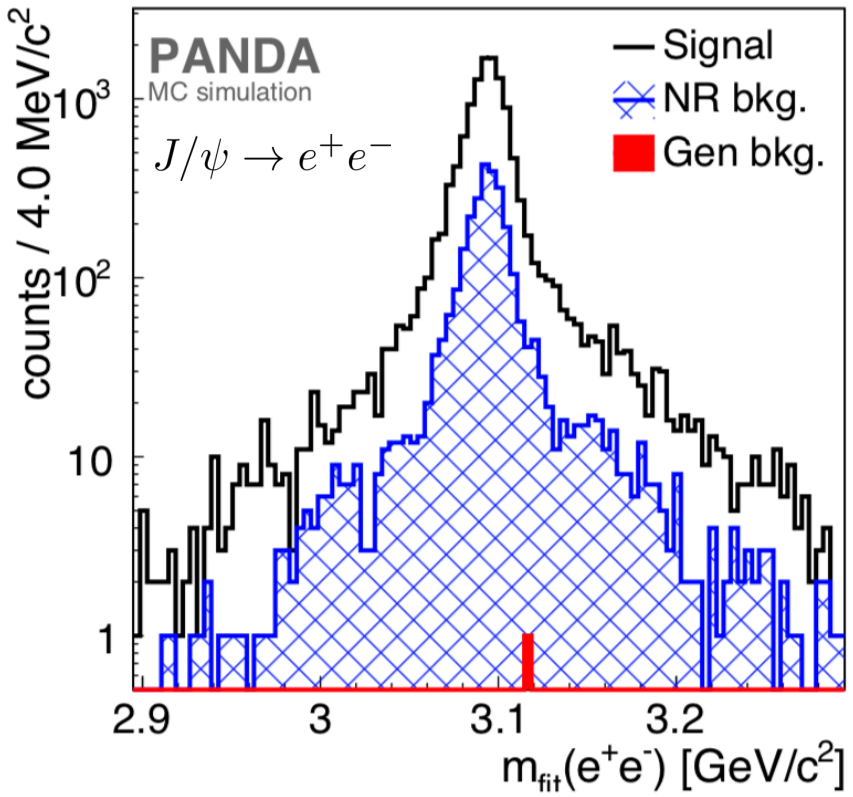



| Type | Description | Generated Events |
|---|---|---|
| signal | $\bar{p}p(\to X) \to J/\psi\rho^0 \to e^+e^-\pi^+\pi^-$<br>$\bar{p}p(\to X) \to J/\psi\rho^0 \to \mu^+\mu^-\pi^+\pi^-$ | 100k each |
| non-resonant bkg | $\bar{p}p \to J/\psi\,(\to e^+e^-)\,\pi^+\pi^-$<br>$\bar{p}p \to J/\psi\,(\to \mu^+\mu^-)\,\pi^+\pi^-$ | |
| generic bkgd | $\bar{p}p \to$ anything (Dual Parton Model) | 10B (10M sim.) |

[PANDA, arXiv:1812.05132, hep-ex]

# Event Selection Results
## (after final selection and 4C fit)




| $X(3872) \to J/\psi\pi^+\pi^-$ | $\epsilon_S$ | $\epsilon_{B,\mathrm{gen}}$ | $\epsilon_{B,\mathrm{NR}}$ |
|---|---|---|---|
| $J/\psi \to e^+e^-$ | 12.2% | $1.0 \cdot 10^{-10}$ | 2.8% |
| $J/\psi \to \mu^+\mu^-$ | 15.2% | $4.5 \cdot 10^{-10}$ | 3.0% |

[PANDA, arXiv:1812.05132, hep-ex]

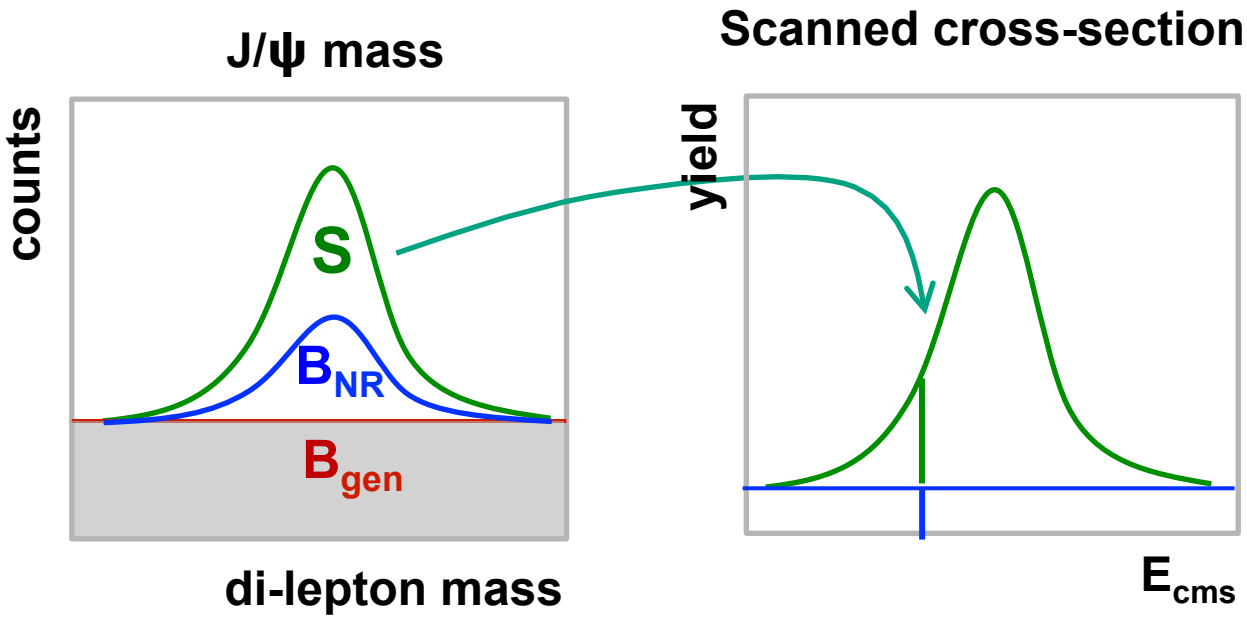
# Energy scan part

# Yield Extraction

## Simulated extraction of energy-dependent yield:

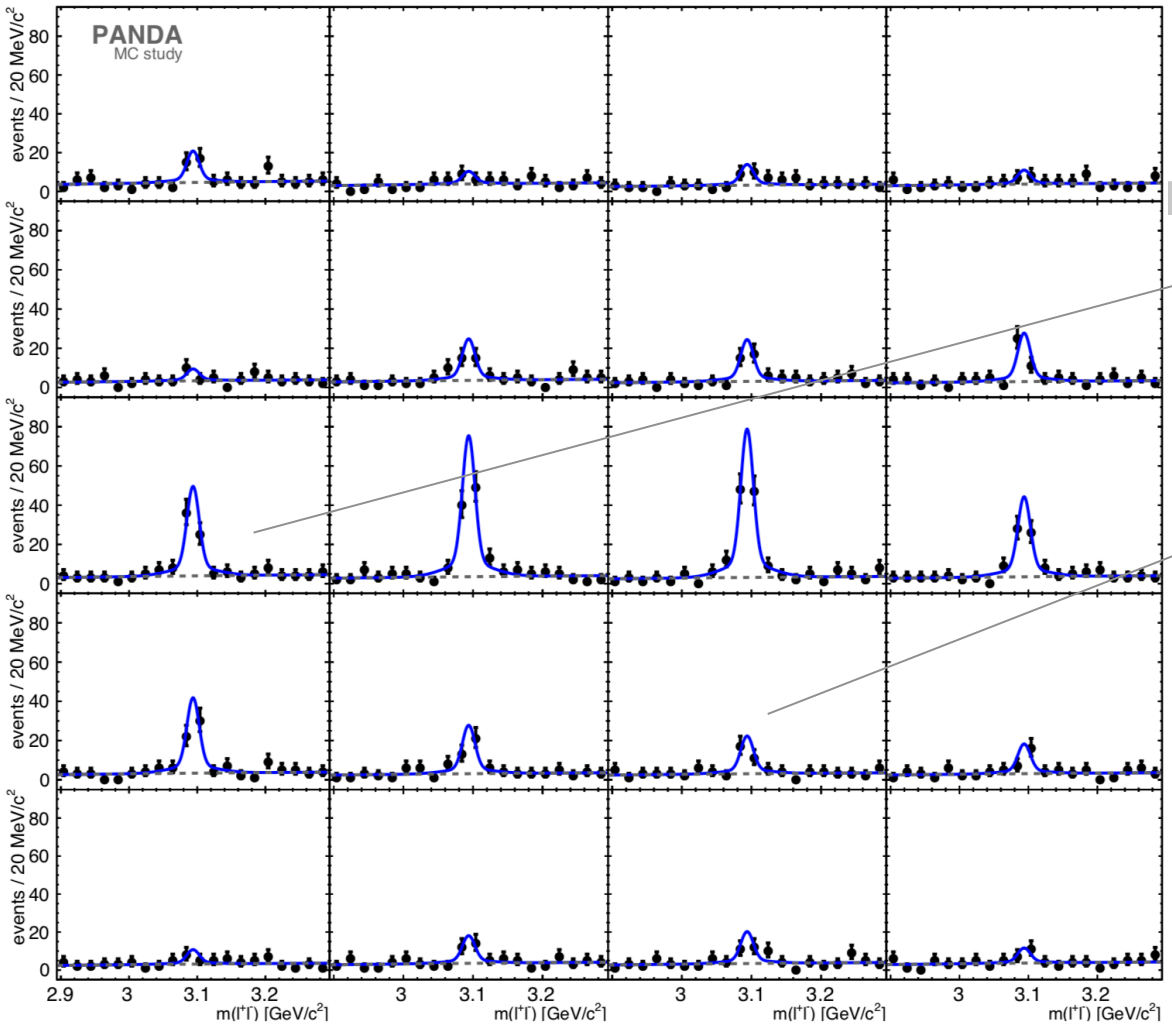
- Fit signal in J/ψ mass
  - Removes generic background
  - NR background still present

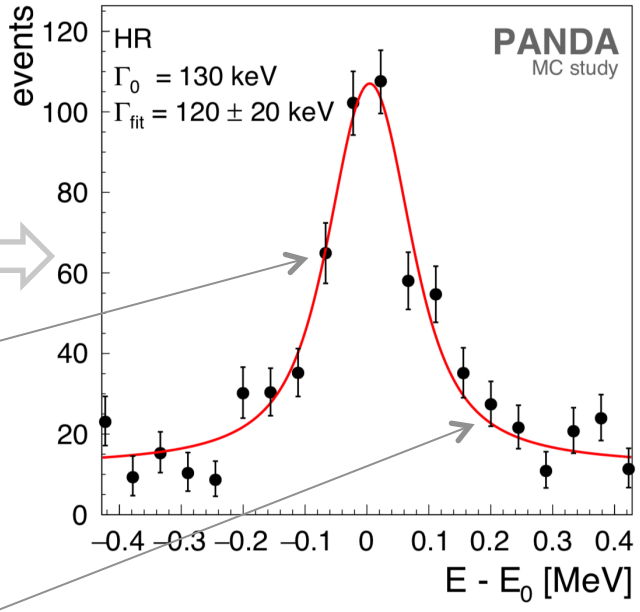
- Requires sufficiently large J/ψ mass window



# Scan Procedure Principle (Example)

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

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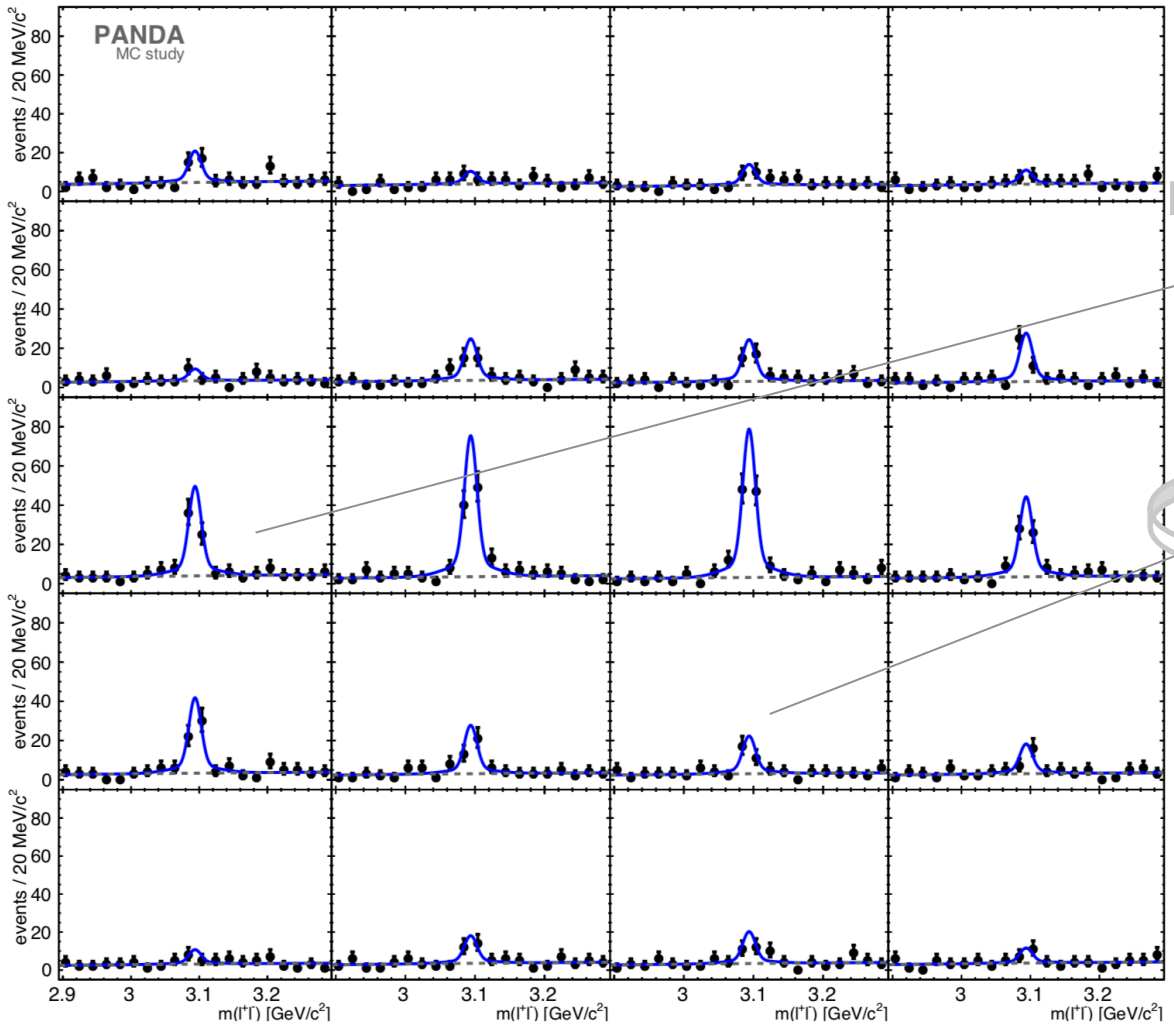
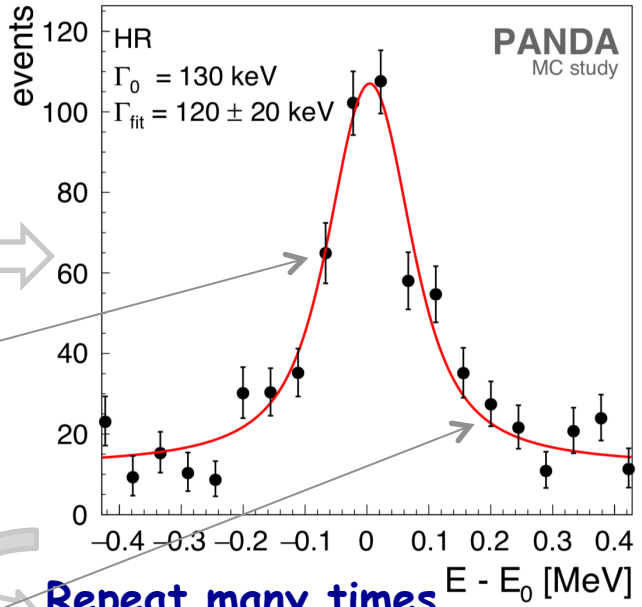
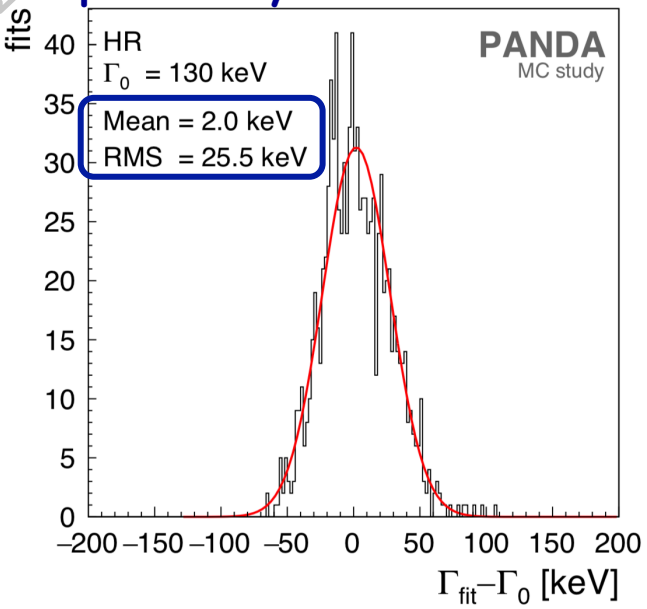



Repeat many times ...



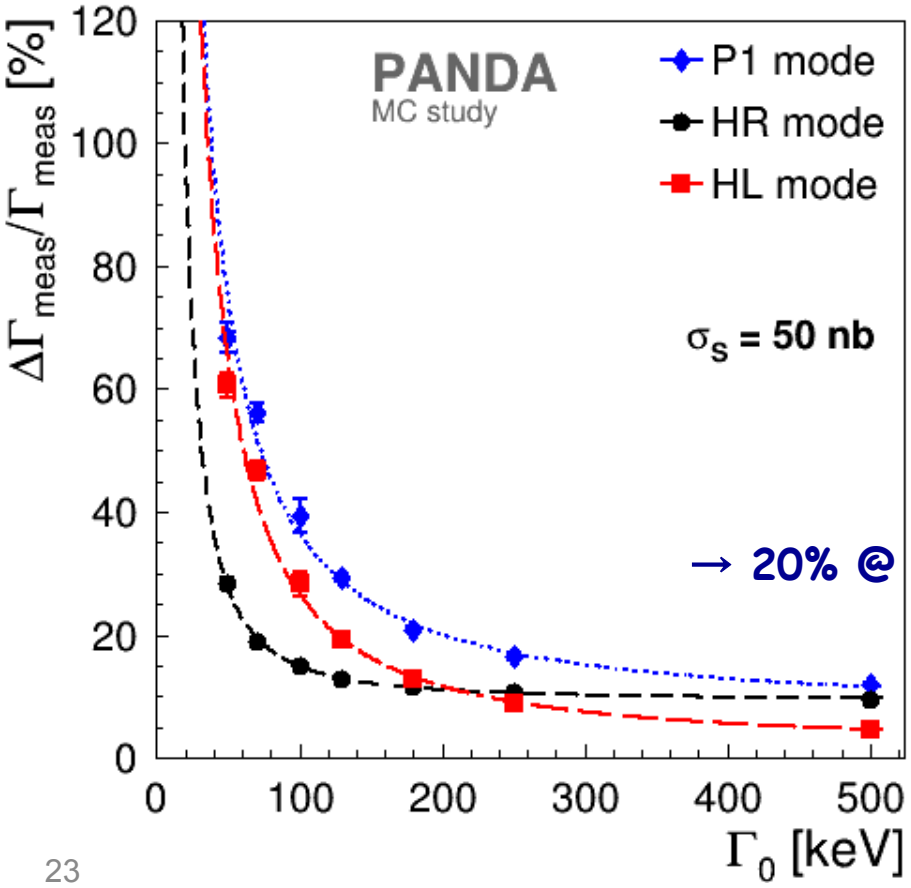

[PANDA, arXiv:1812.05132, hep-ex]

# Sensitivities Breit-Wigner Γ (40 x 2d)

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

Sensitivity

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




→ 20% @ Γ= 50 ... 120 keV
HR HL

[PANDA, arXiv:1812.05132, hep-ex]

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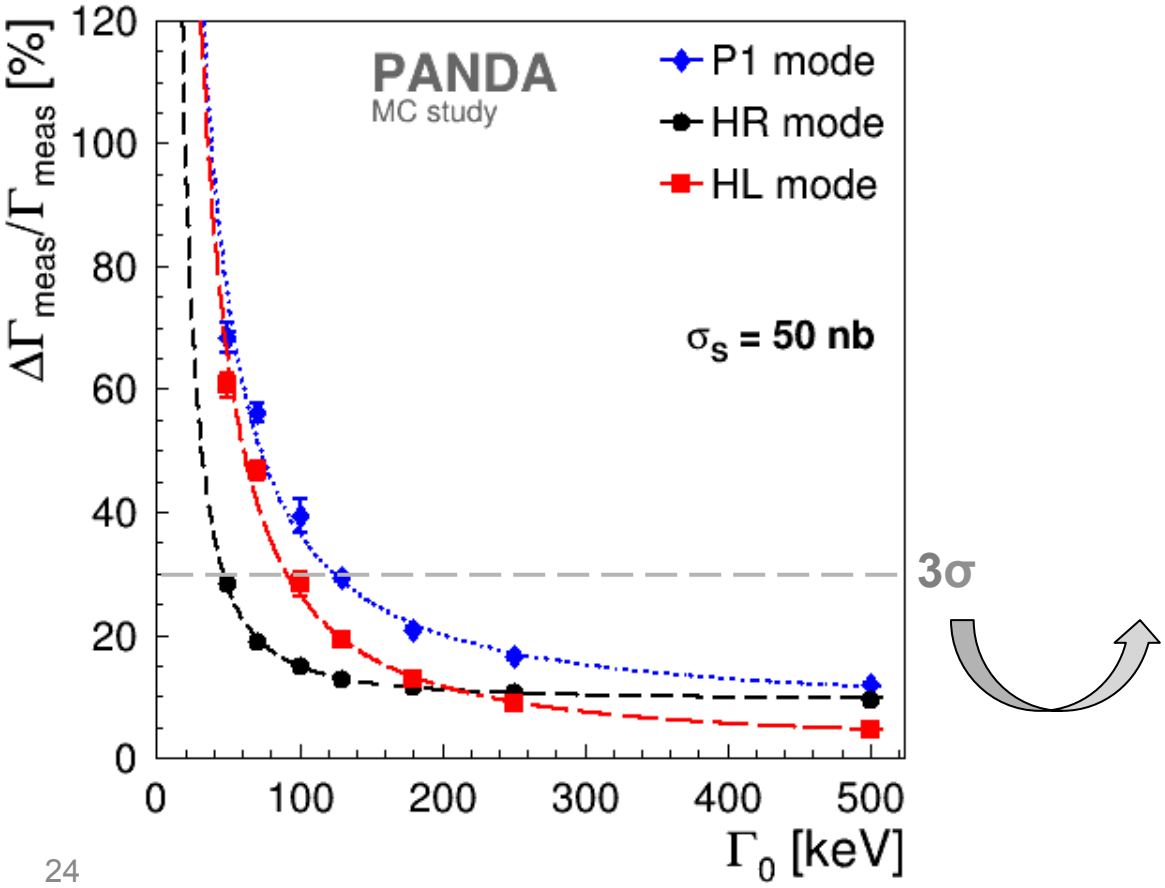


[PANDA, arXiv:1812.05132, hep-ex]

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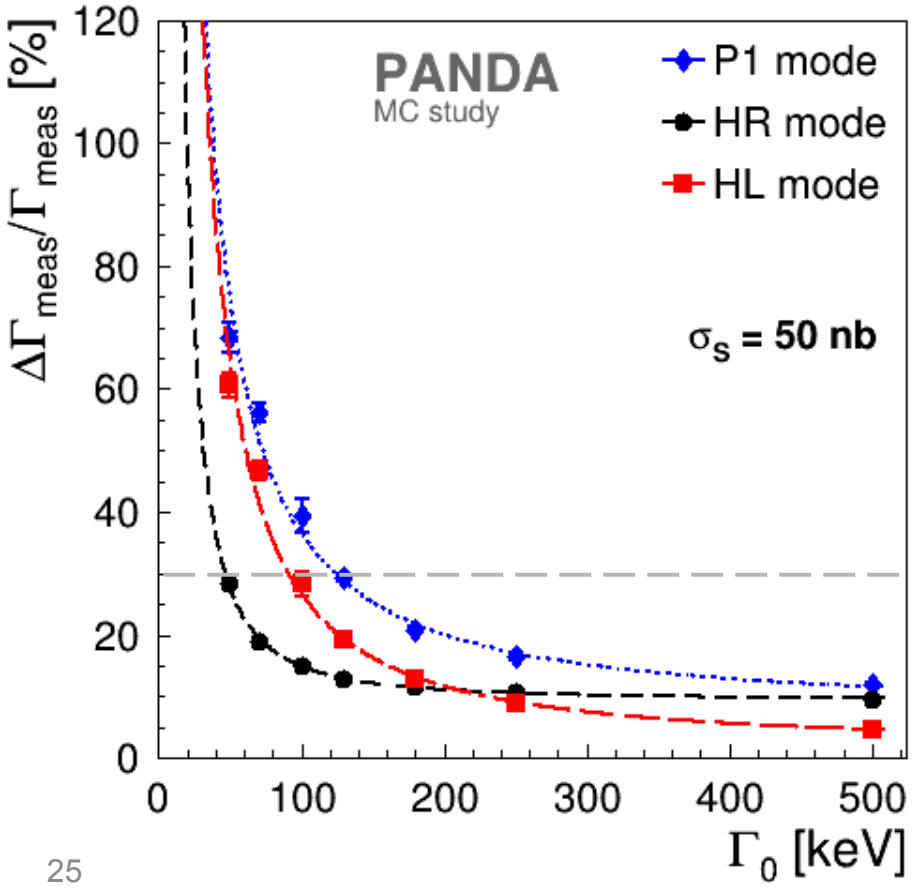
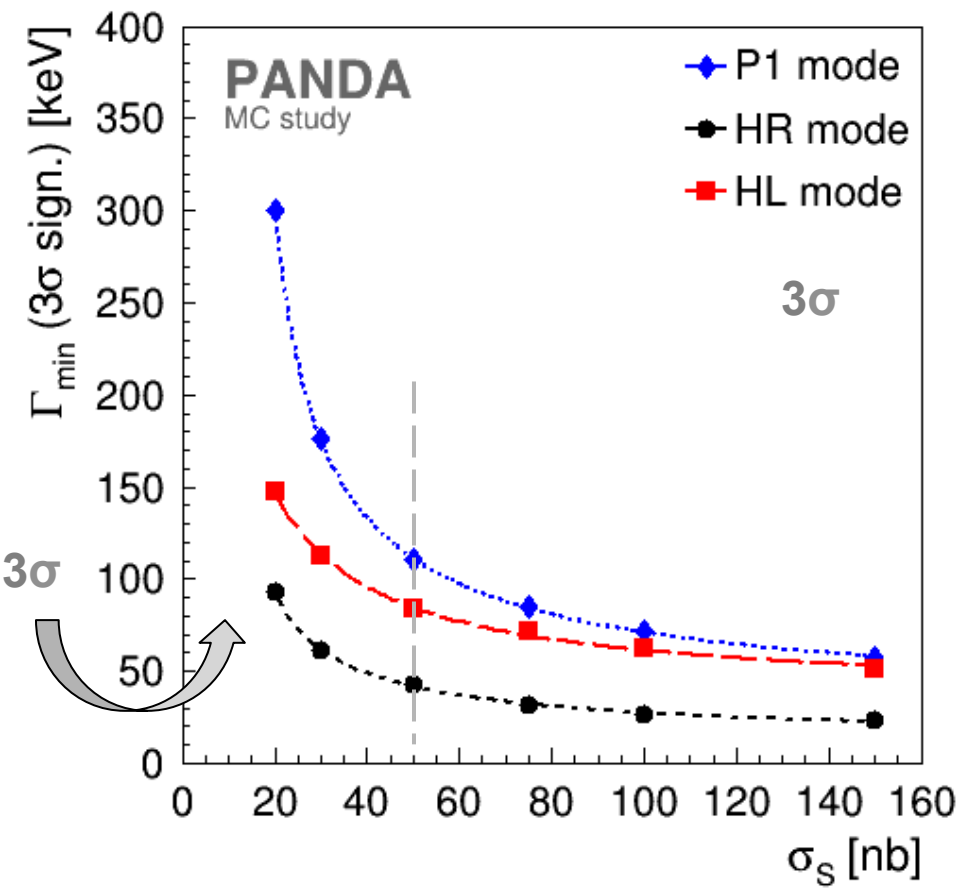
- Extract standard deviation from toy MC fits
- Show relative error $rms_{fit}/\bar{\Gamma}_{fit}$ in [%]

Sensitivity

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



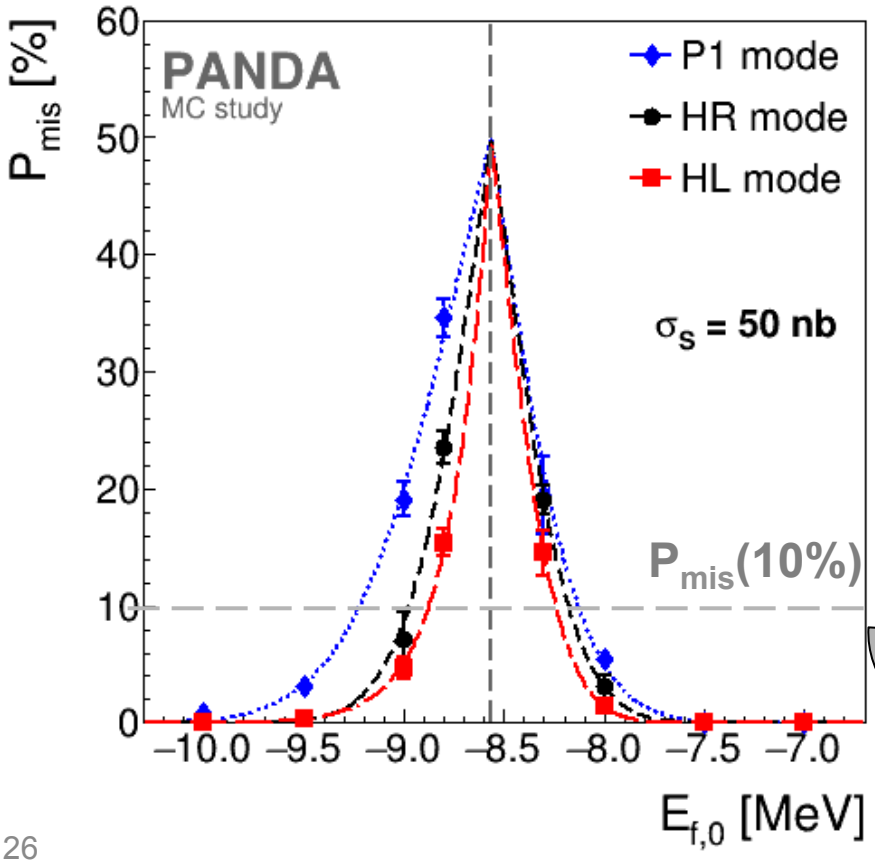



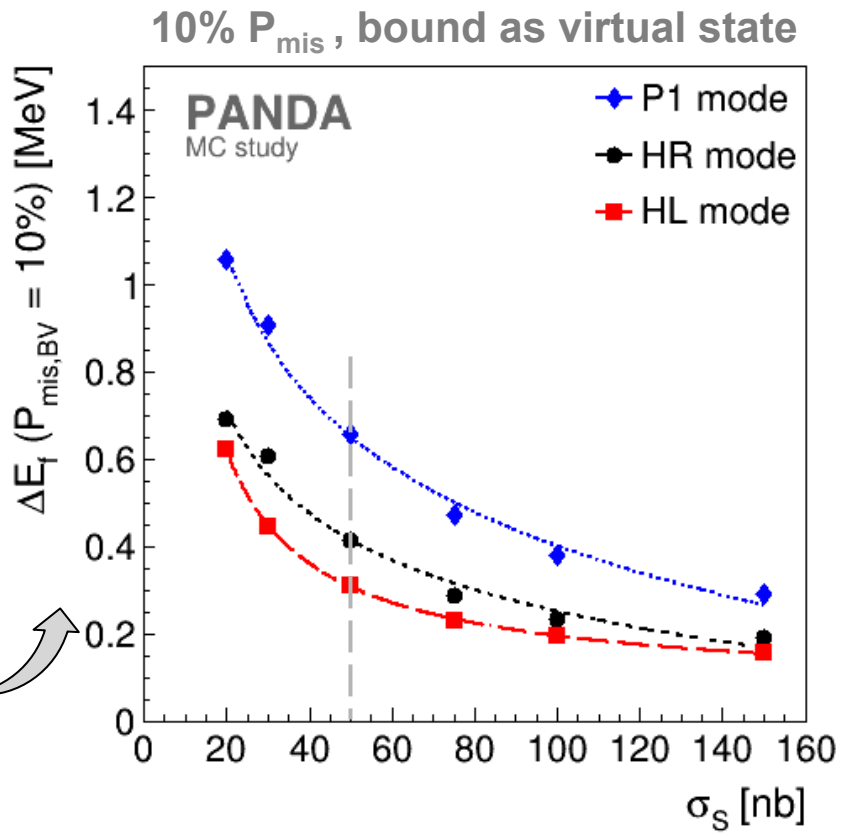
# Distinction of Lineshapes (40 x 2d)

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

Sensitivity

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



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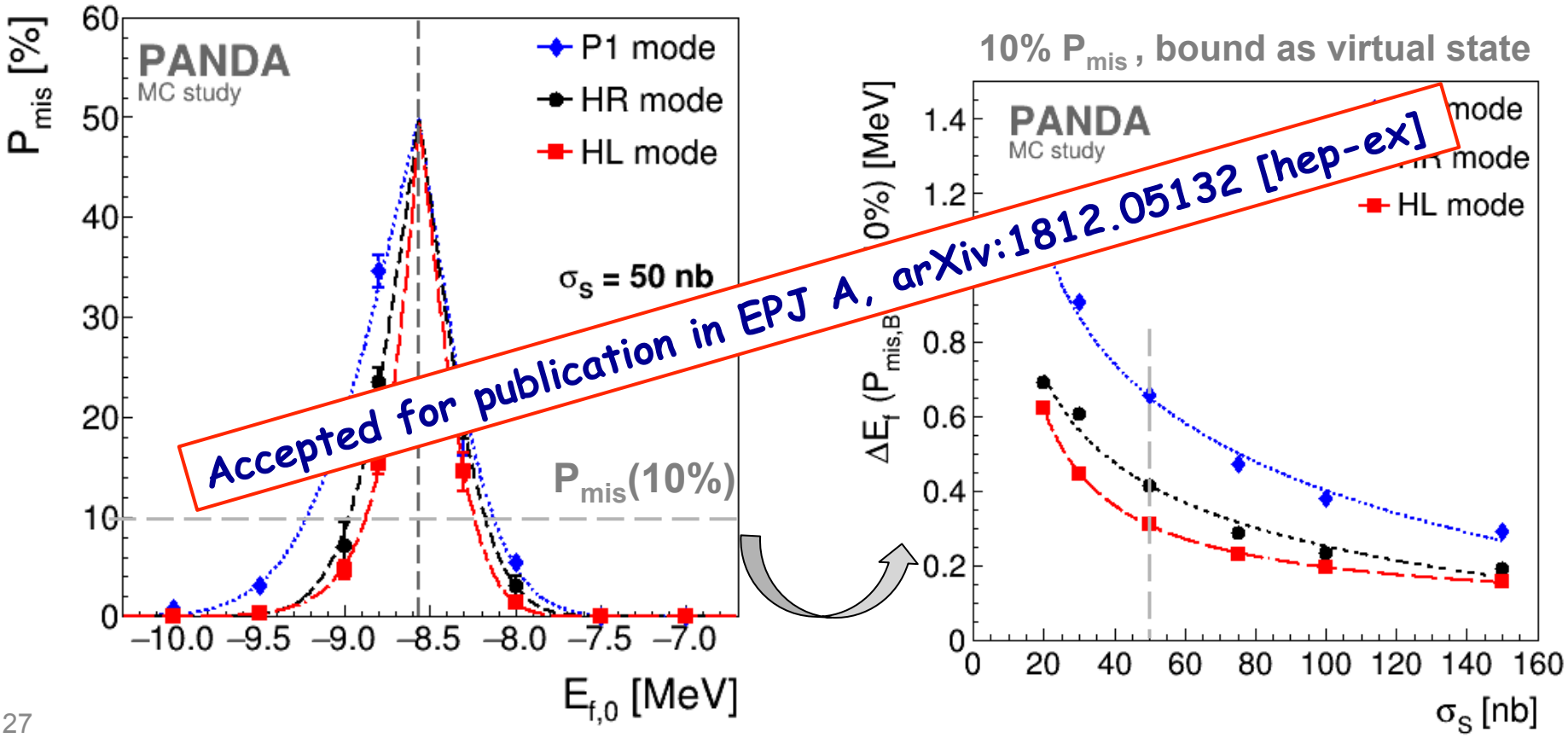

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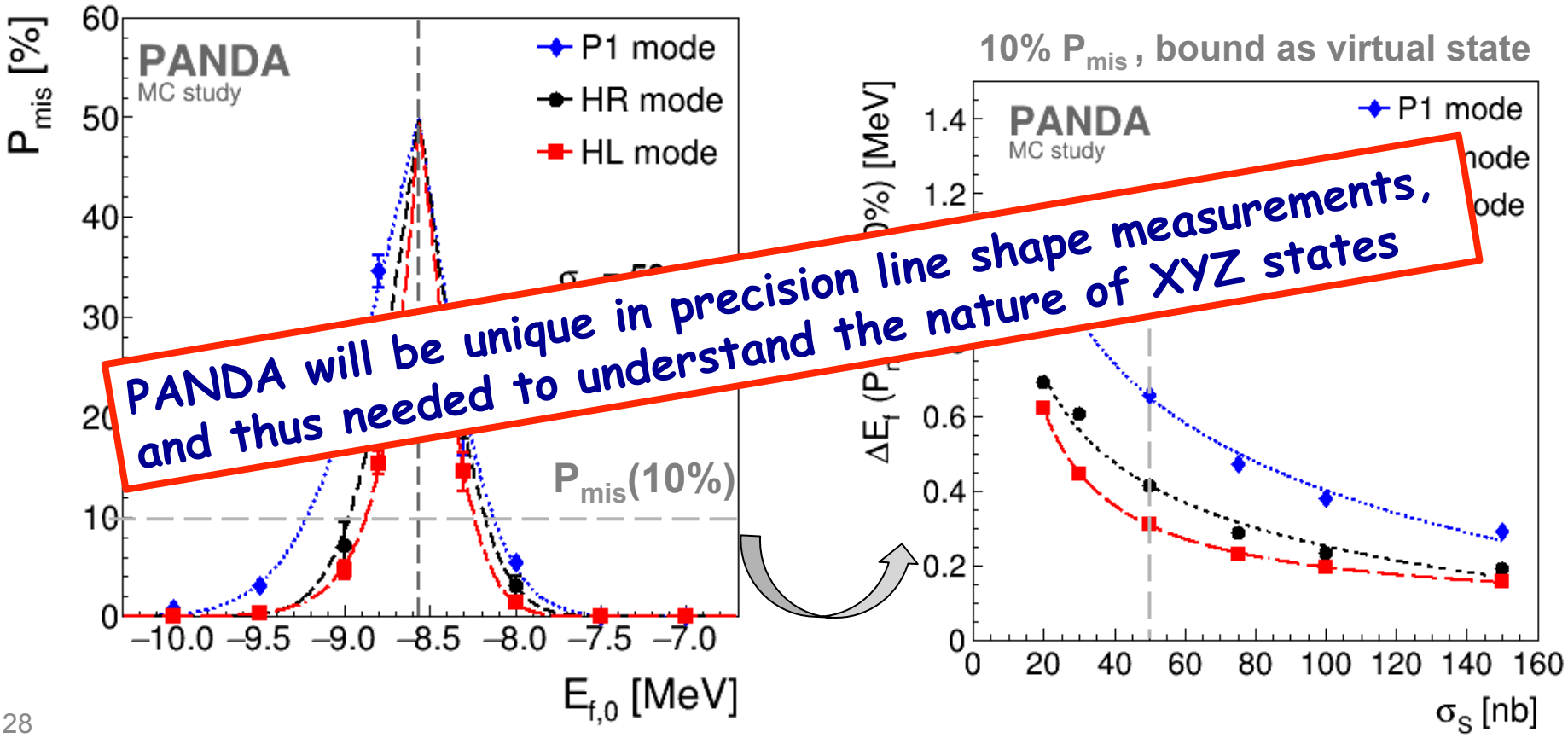
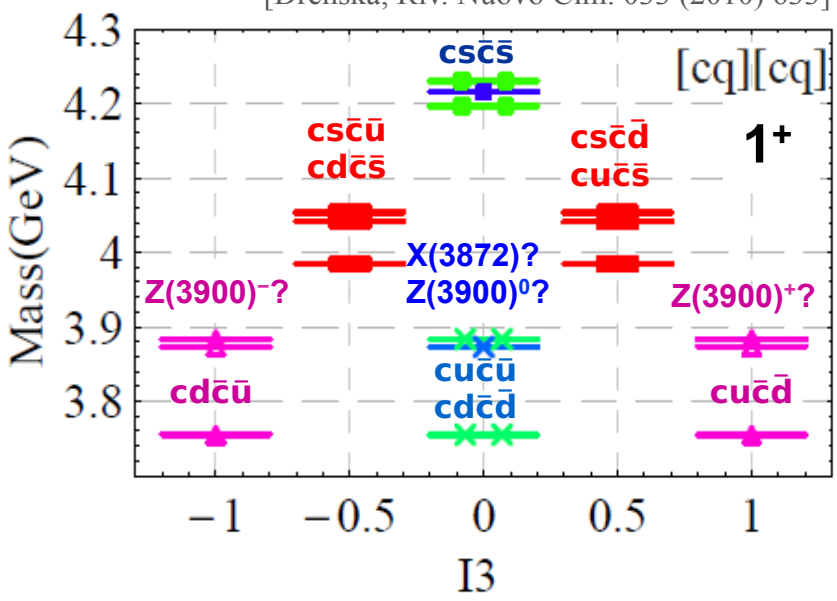


# Models and Multiplets for XYZ

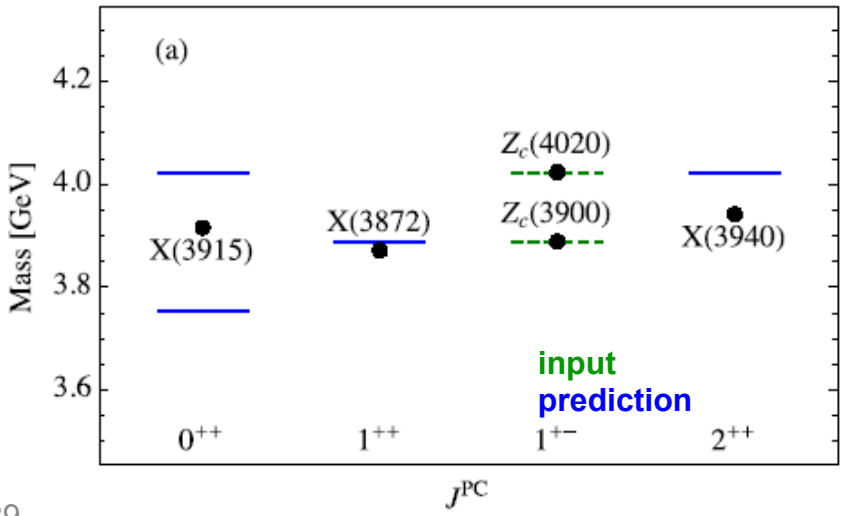
- Need to measure complete multiplets
  → *to really understand XYZ nature*

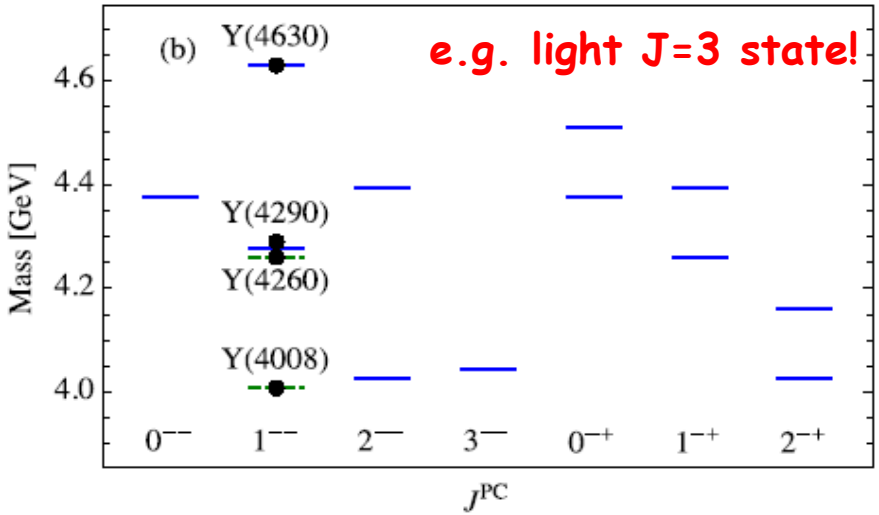
- e.g. di-quarkonium [cq][c̄q̄] models provide predictions
  - ➢ Look for stranged partners
  - ➢ Look for light high spin states

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




[Cleven et al., arXiv:1505.01771]



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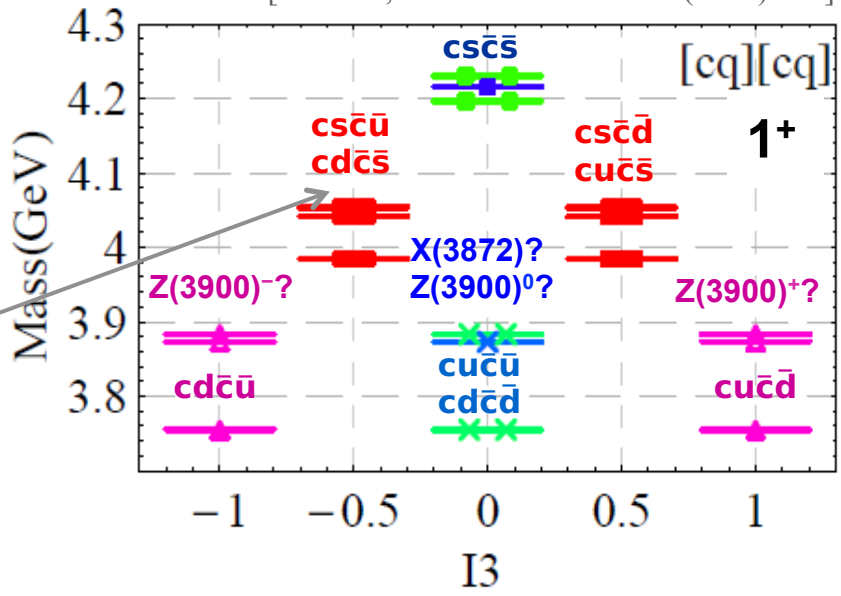


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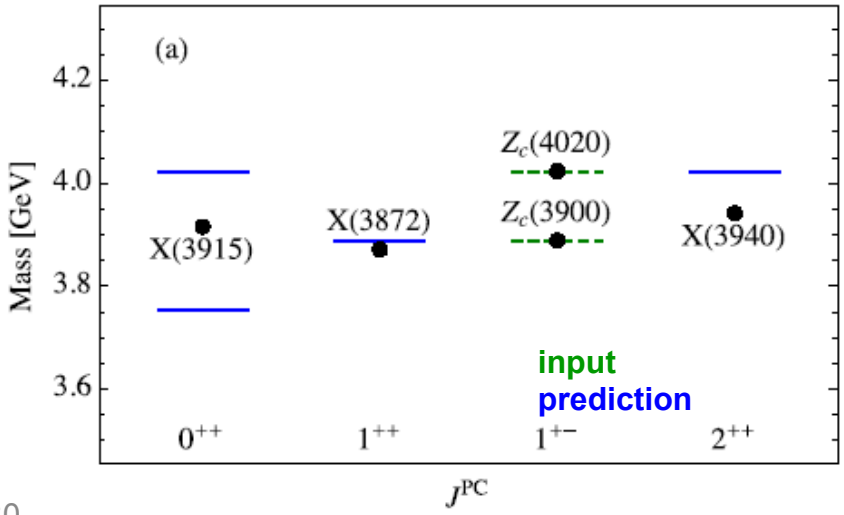


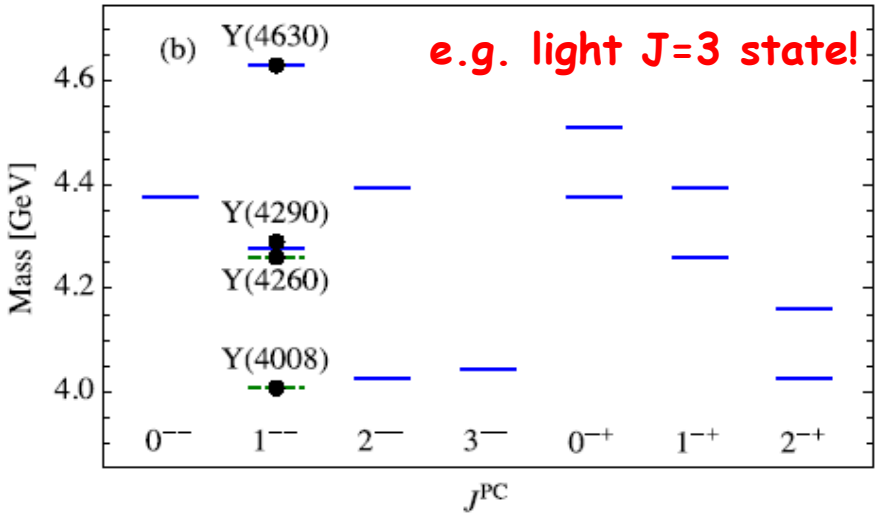

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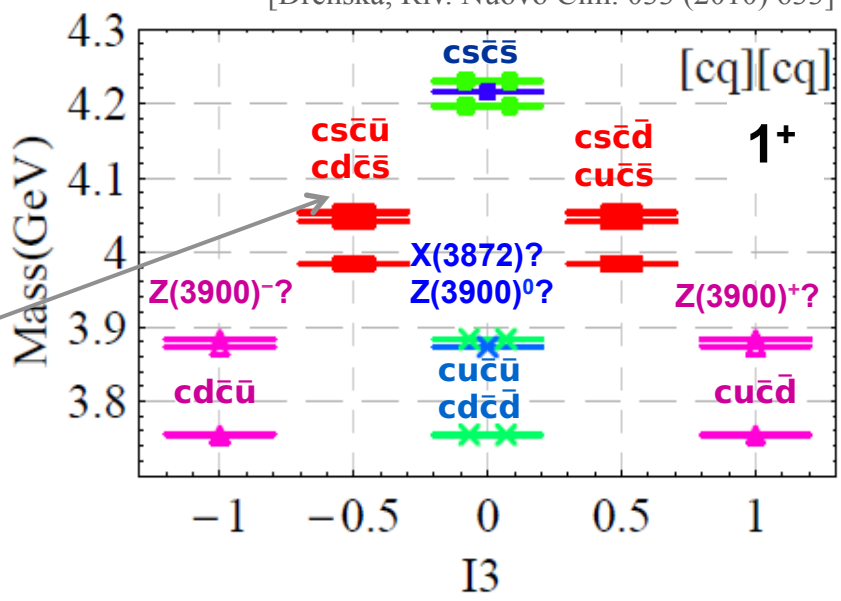


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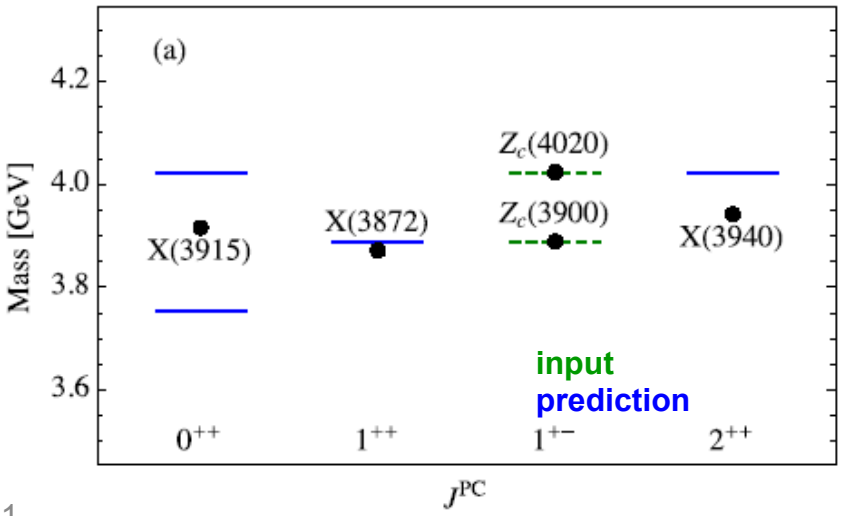


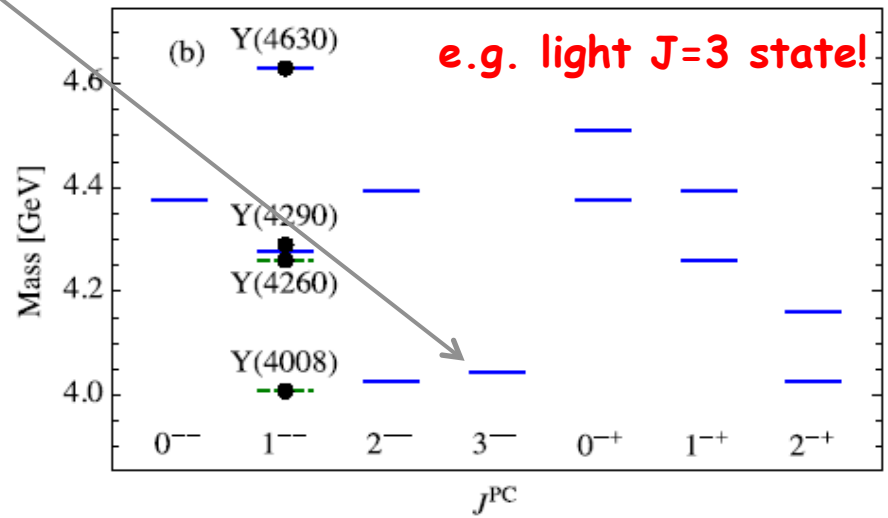

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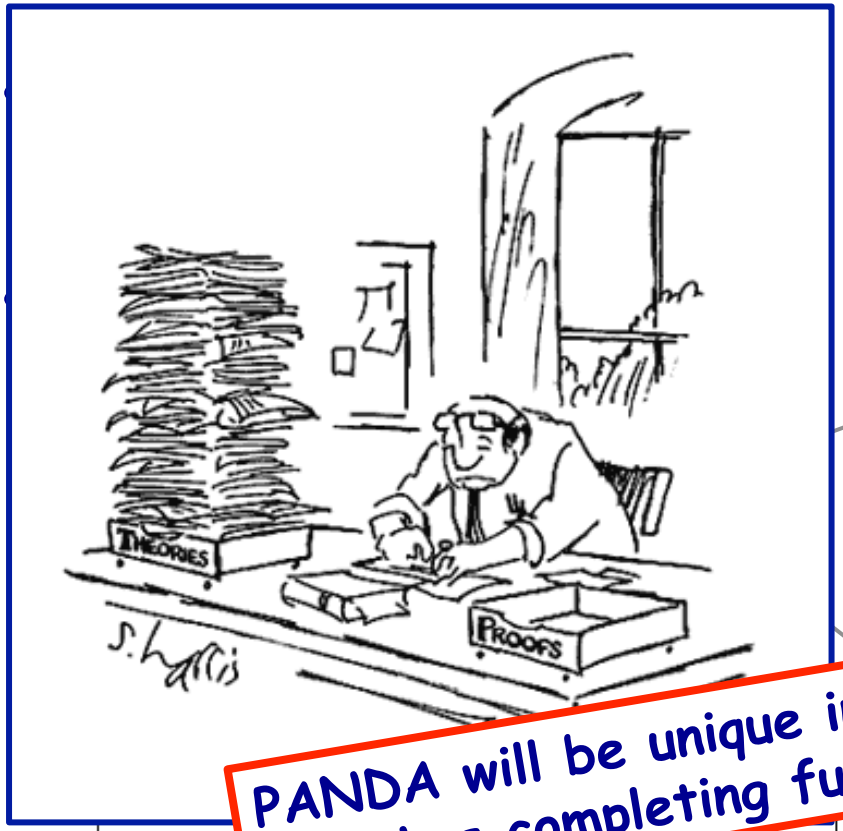


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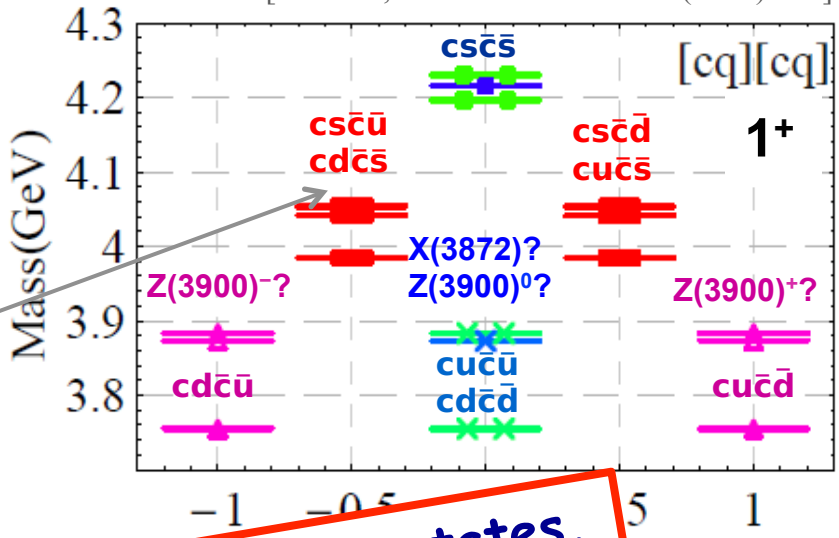
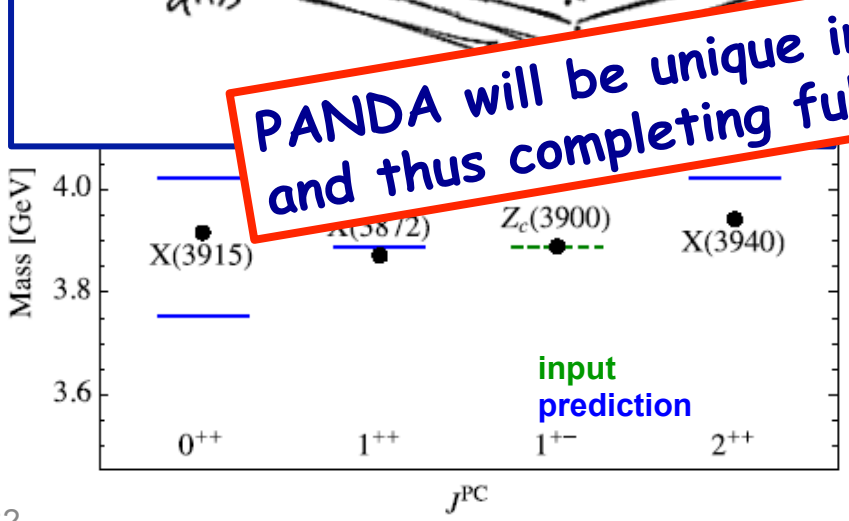
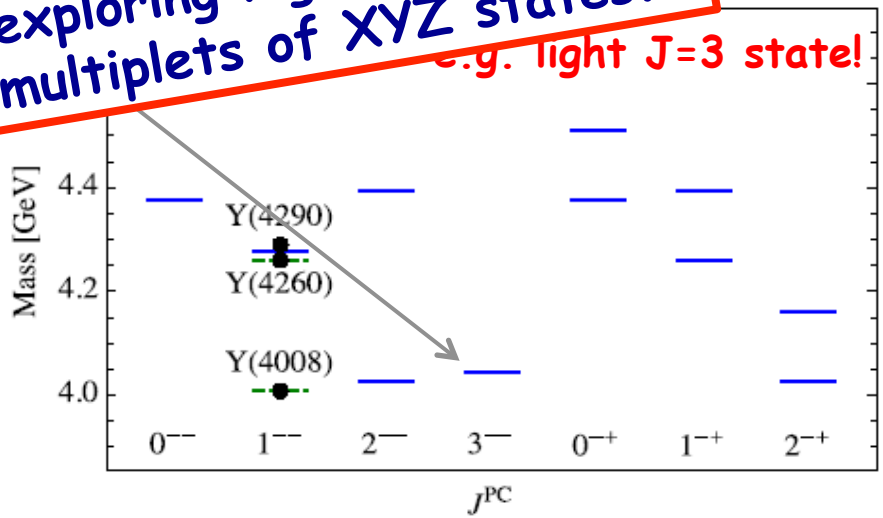



**PANDA will be unique in exploring high spin states, and thus completing full multiplets of XYZ states.**



# 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)
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Meanwhile published: Eur. Phys. J. A 55 (2019) 42

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Meanwhile published: Eur. Phys. J. A 55 (2019) 42

- 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*

# Facility for Antiproton and Ion Research

FAIR construction site at night -- Feb 2019

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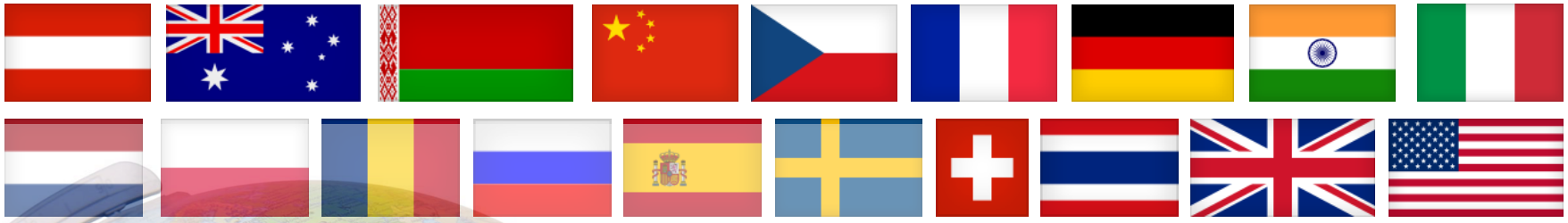
# Thank you for your attention!

**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
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U Edinburgh
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FIAS Frankfurt
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LNF-INFN Frascati
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U Glasgow
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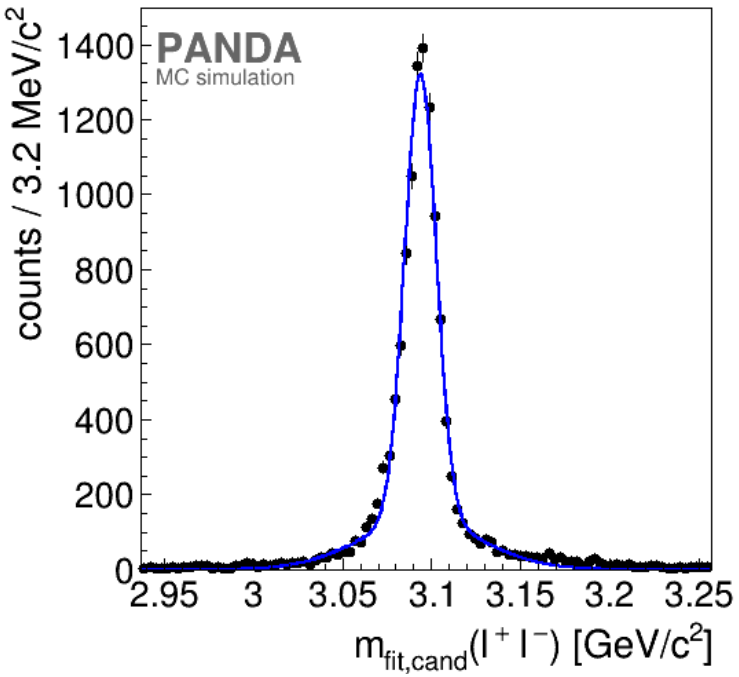
U & INFN Torino
Politecnico di Torino
U & INFN Trieste
U Uppsala
U Valencia
SMI Vienna
U Visva-Bharati
SINS Warsaw

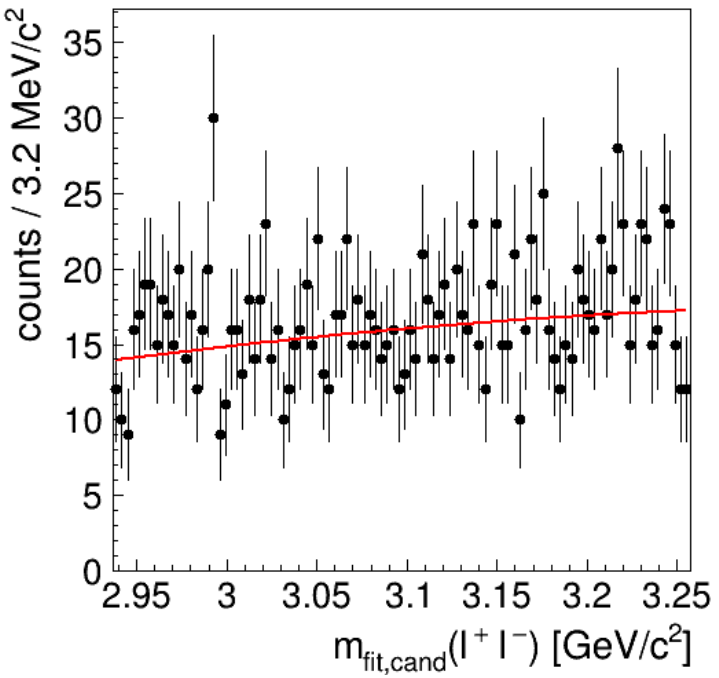
# Signal/Background PDF for ML fits

- 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**

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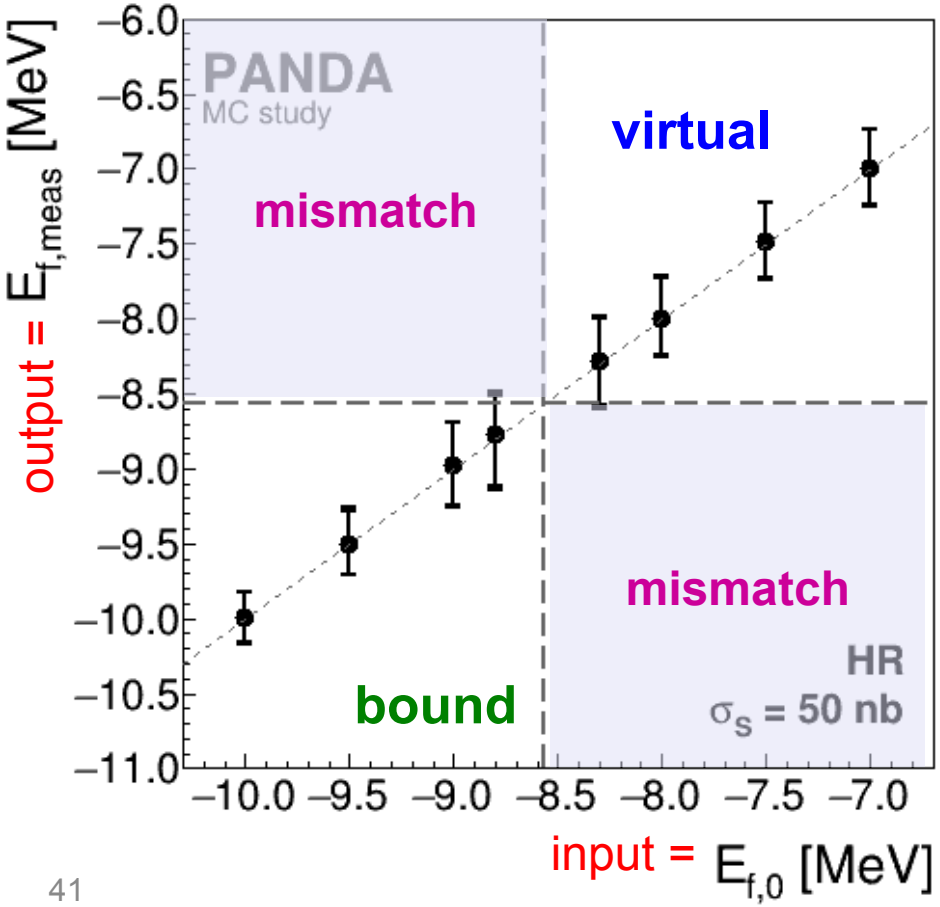


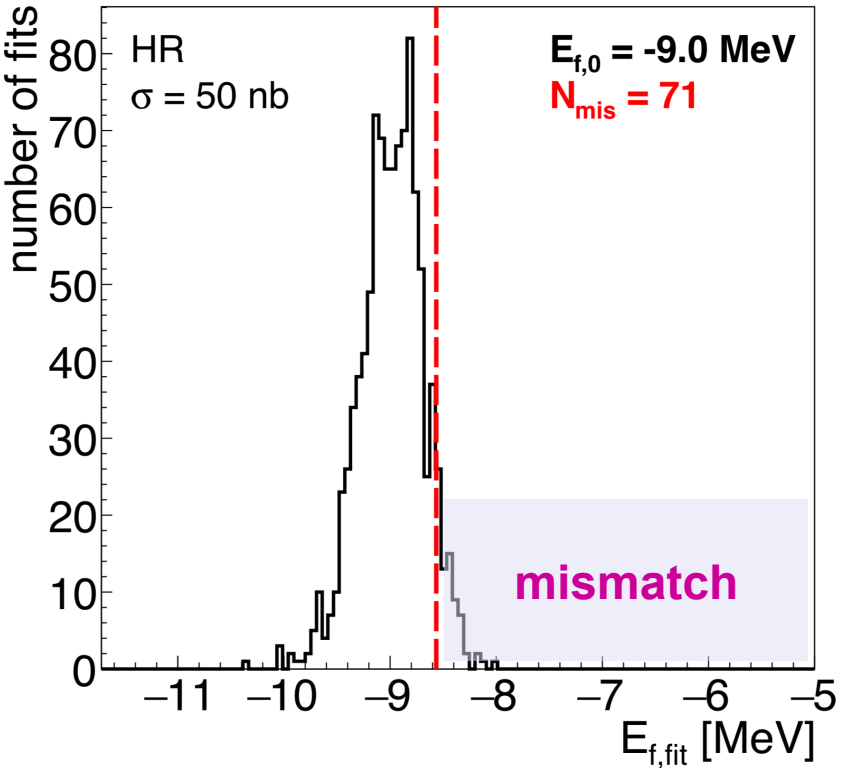


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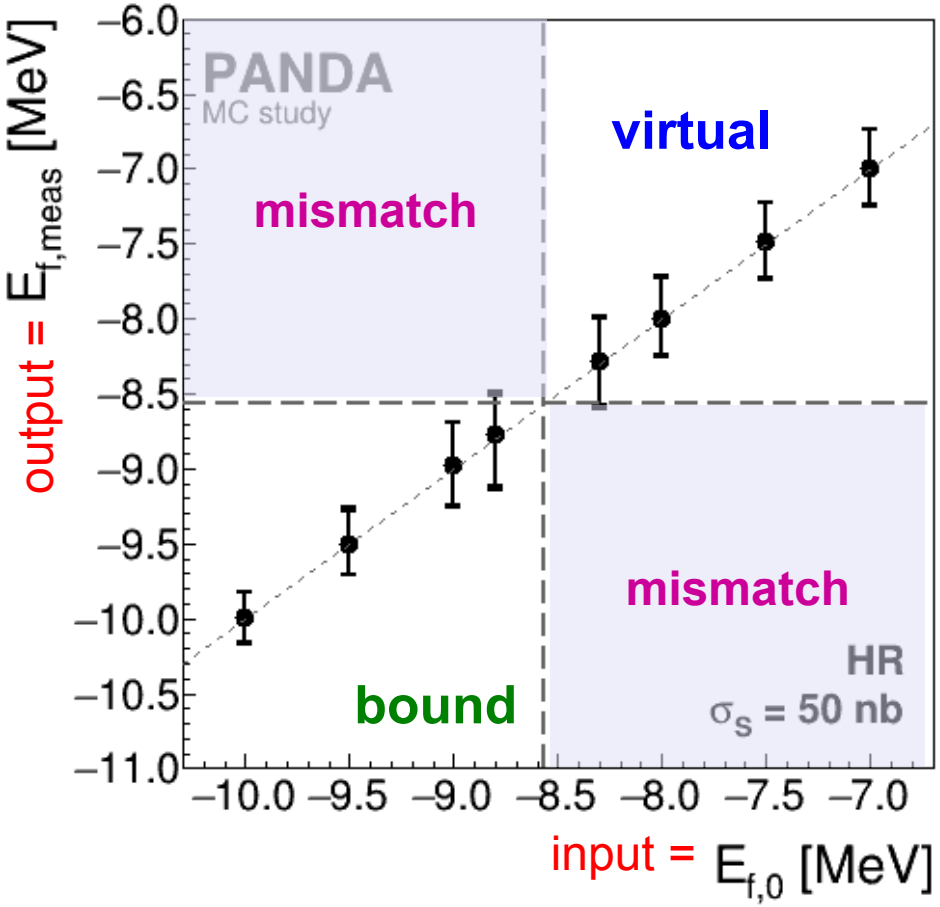


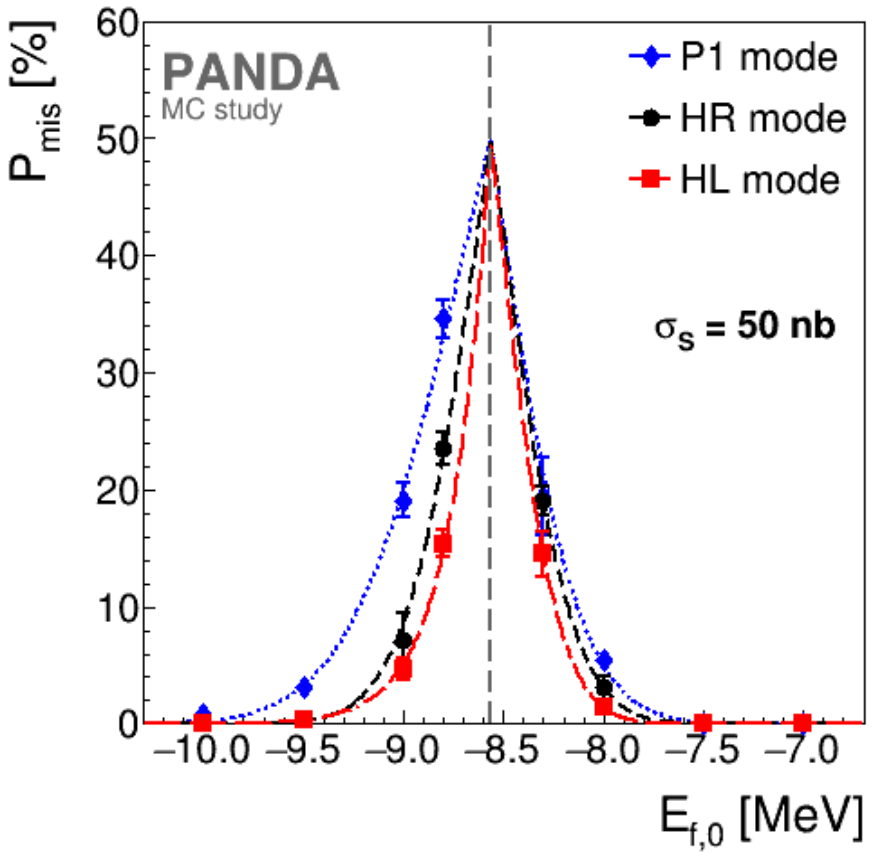

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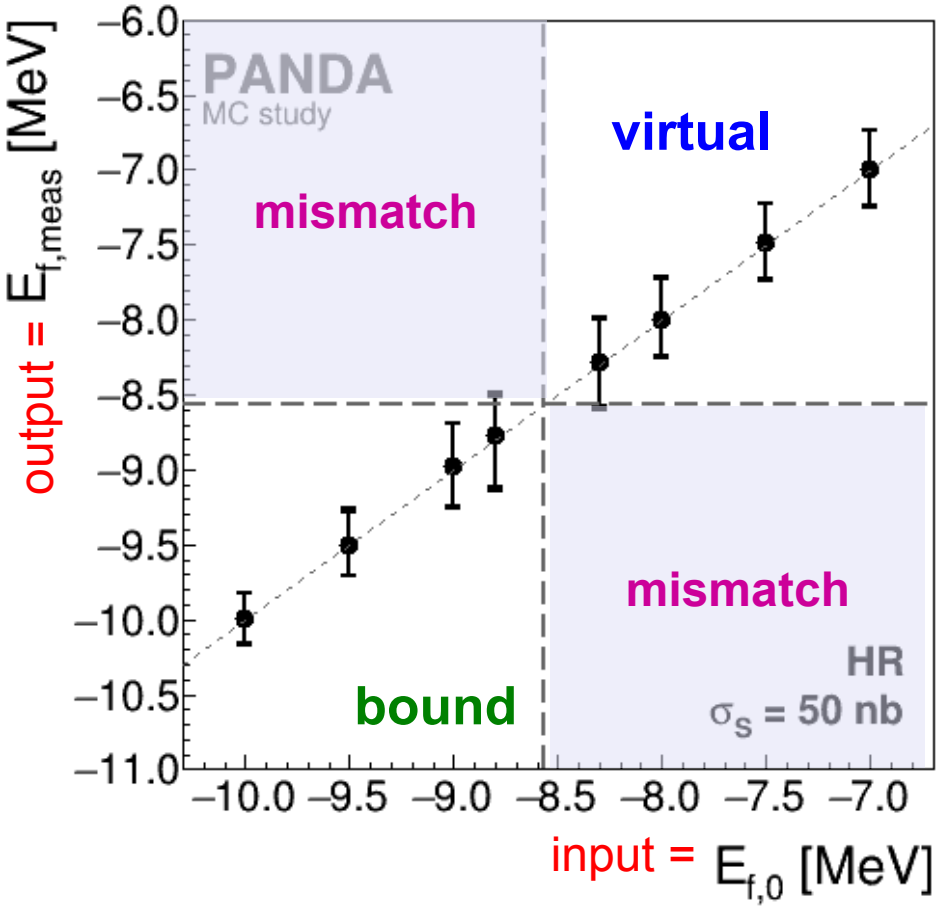


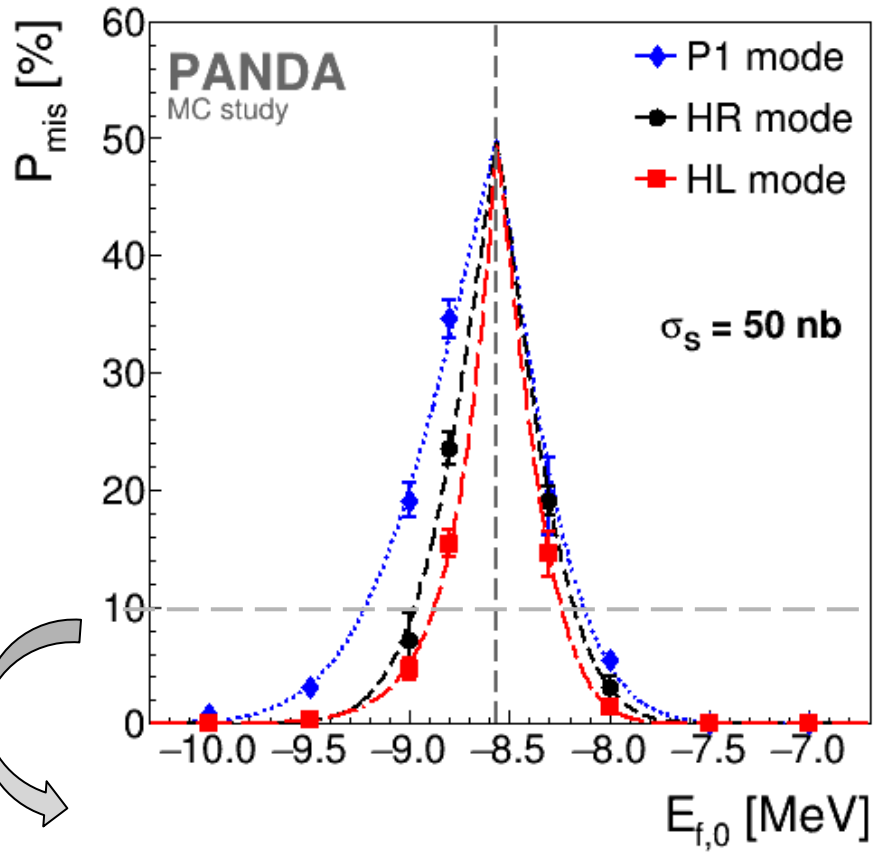

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