

Can We Resolve the Nature of $\chi_{c1}(3872)$ with PANDA?

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LHCb Measurement of $\chi_{c1}(3872)$



[Phys.Rev.D 102 (2020) 9, 092005]
[<https://arxiv.org/abs/2005.13419>]

CERN-EP-2020-086
LHCb-PAPER-2020-008
May 27, 2020

Study of the lineshape of the $\chi_{c1}(3872)$ state

Abstract

A study of the lineshape of the $\chi_{c1}(3872)$ state is made using a data sample corresponding to an integrated luminosity of 3 fb^{-1} collected in pp collisions at centre-of-mass energies of 7 and 8 TeV with the LHCb detector. Candidate $\chi_{c1}(3872)$ mesons from b -hadron decays are selected in the $J/\psi\pi^+\pi^-$ decay mode. Describing the lineshape with a Breit–Wigner function, the mass splitting between the $\chi_{c1}(3872)$ and $\psi(2S)$ states, Δm , and the width of the $\chi_{c1}(3872)$ state, Γ_{BW} , are determined to be

$$\begin{aligned}\Delta m &= 185.588 \pm 0.067 \pm 0.068 \text{ MeV}, \\ \Gamma_{\text{BW}} &= 1.39 \pm 0.24 \pm 0.10 \text{ MeV},\end{aligned}$$

where the first uncertainty is statistical and the second systematic. Using a Flatté-inspired lineshape, two poles for the $\chi_{c1}(3872)$ state in the complex energy plane are found. The dominant pole is compatible with a quasi-bound $D^0\bar{D}^{*0}$ state but a quasi-virtual state is still allowed at the level of 2 standard deviations.

LHCb Findings

- Breit Wigner fit

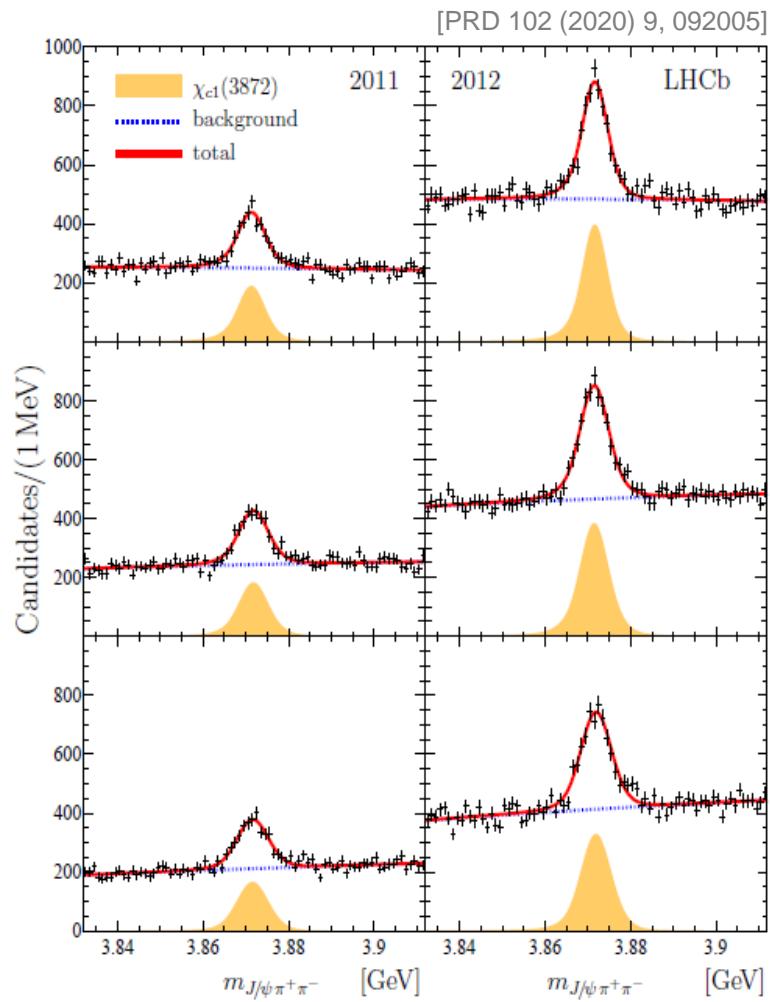
$$m_{\chi_{c1}(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010 \text{ MeV}$$

$$\Gamma_{\text{BW}} = 1.39 \pm 0.24 \pm 0.10 \text{ MeV}$$

[previous Belle result: $\Gamma < 1.2 \text{ MeV} (\text{CL90})$]

- Flatté model fit

| Mode [MeV] | Mean [MeV] | FWHM [MeV] | |
|-------------------------------------|-------------------------------------|----------------------------------|----------------|
| $3871.69^{+0.00+0.05}_{-0.04-0.13}$ | $3871.66^{+0.07+0.11}_{-0.06-0.13}$ | $0.22^{+0.06+0.25}_{-0.08-0.17}$ | |
| g | $f_\rho \times 10^3$ | Γ_0 [MeV] | m_0 [MeV] |
| 0.108 ± 0.003 | 1.8 ± 0.6 | 1.4 ± 0.4 | 3864.5 (fixed) |



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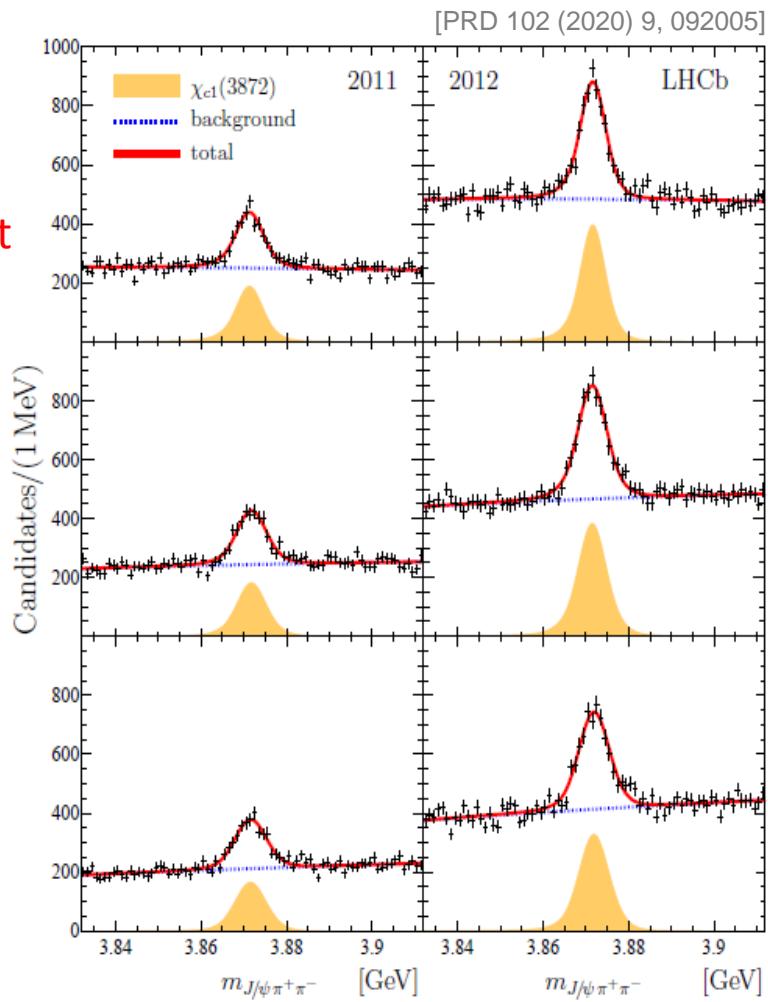
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Factor 6.3, model dependent

- Flatté model fit

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→ Need to fix the model!



Flatté Model Overview

$$\frac{dBr(B \rightarrow KD^0\bar{D}^{*0})}{dE} = \mathcal{B} \frac{1}{2\pi} \frac{gk_1}{|D(E)|^2},$$

[<https://arxiv.org/abs/0907.4901>]

$$\frac{dBr(B \rightarrow K\pi^+\pi^-J/\psi)}{dE} = \mathcal{B} \frac{1}{2\pi} \frac{\Gamma_{\pi^+\pi^-J/\psi}(E)}{|D(E)|^2}, \quad \text{J}/\psi\pi^+\pi^- \text{ lineshape}$$

with

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

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

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

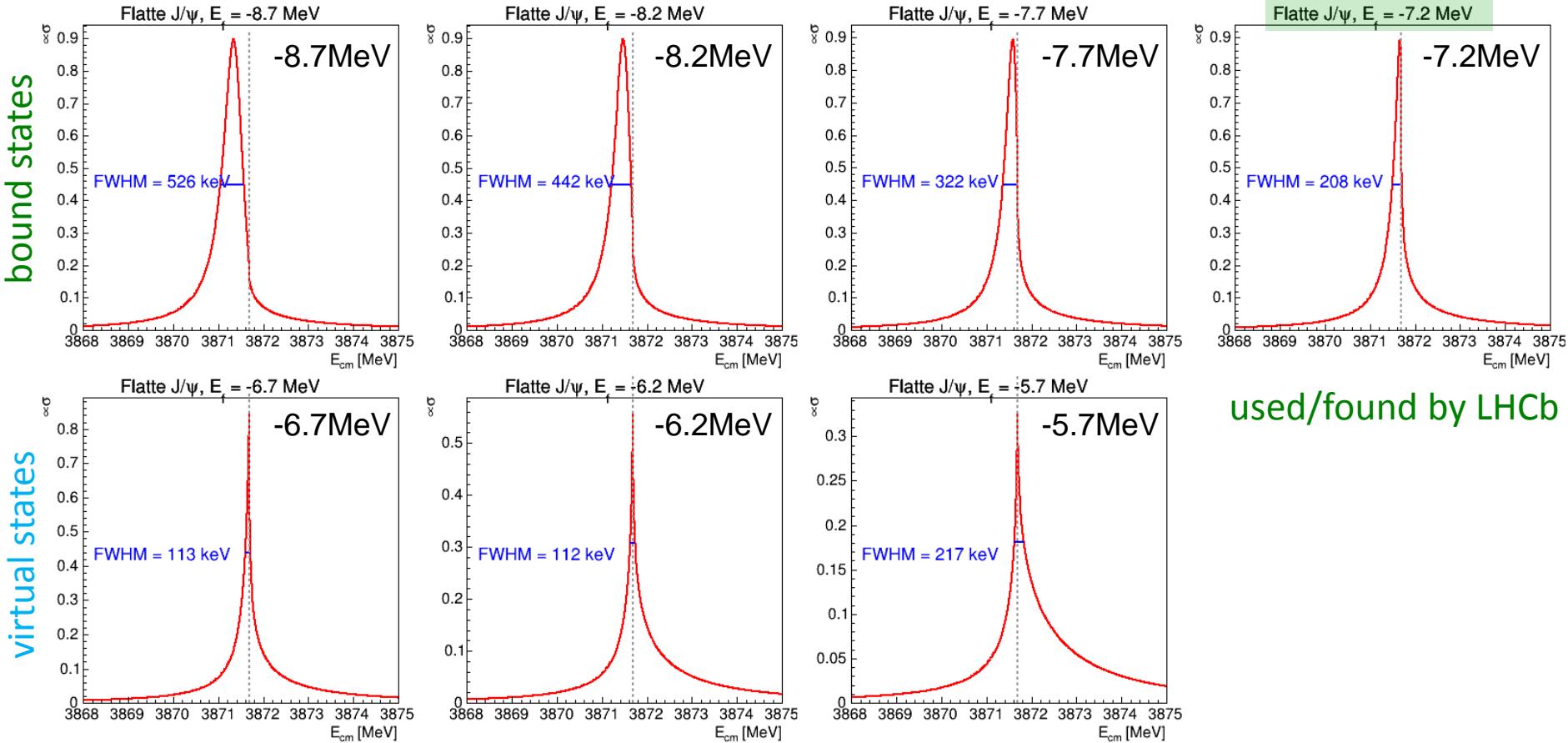
$$\Gamma_{\pi^+\pi^-\pi^0J/\psi}(E) = f_\omega \int_{3m_\pi}^{M-m_{J/\psi}} \frac{dm}{2\pi} \frac{q(m)\Gamma_\omega}{(m - m_\omega)^2 + \Gamma_\omega^2/4},$$

$$\begin{aligned} k_1 &= \sqrt{2\mu_1 E}, & \mu_1 &= \frac{m_{D^0}m_{D^{*0}}}{(m_{D^0}+m_{D^{*0}})} \\ \kappa_1 &= \sqrt{-2\mu_1 E}, & \mu_2 &= \frac{m_{D^+}m_{D^{*-}}}{(m_{D^+}+m_{D^{*-}})} \\ k_2 &= \sqrt{2\mu_2(E - \delta)} & \delta &= 8.2 \text{ MeV} \\ \kappa_2 &= \sqrt{2\mu_2(\delta - E)} \\ g_1 &= g_2 = g \\ E_{f,thr} &= -g\sqrt{\mu_2\delta/2} & \text{threshold} \\ && \text{bound/virtual} \end{aligned}$$

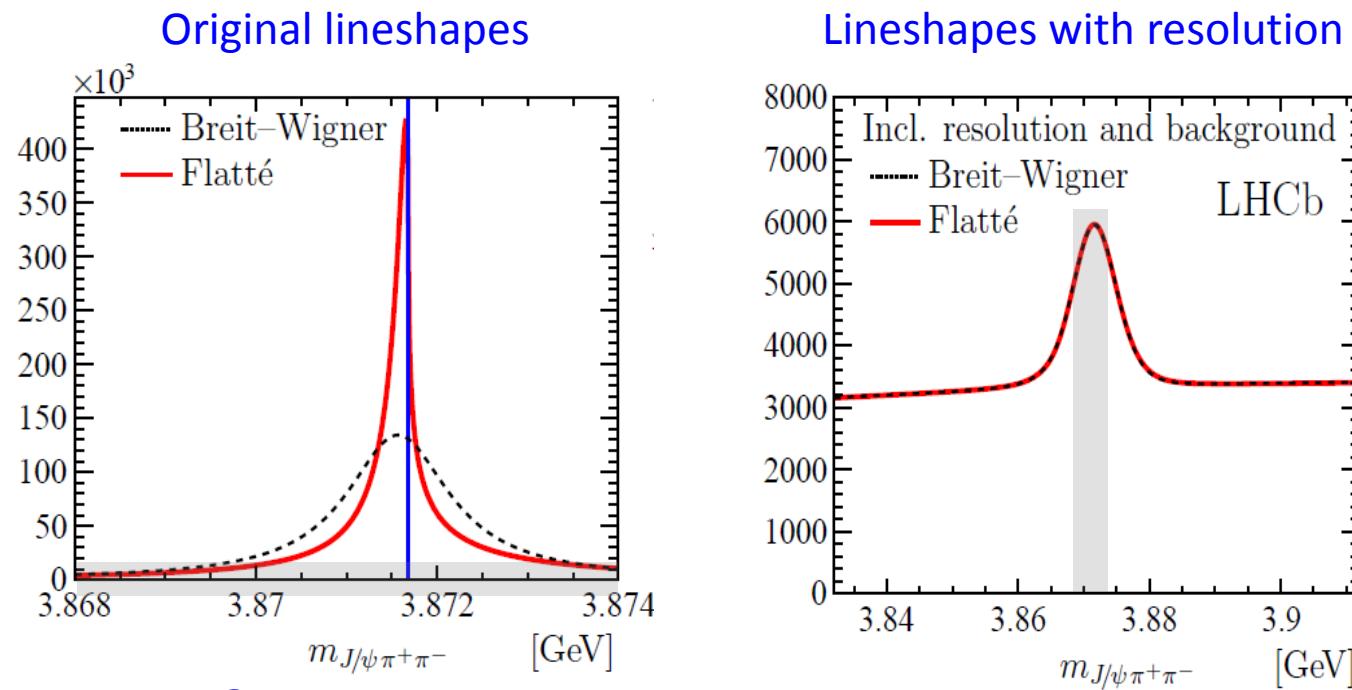
| Param. | EPJ A 55 42 (PANDA, 2019) | PRD 102 092005 (LHCb, 2020) |
|-------------|------------------------------|--------------------------------|
| g | 0.137 | 0.108 |
| Γ_0 | 1.0 | 1.4 |
| f_ρ | 0.007 | 0.0018 |
| f_ω | 0.036 | 0.01 |
| $E_{f,thr}$ | -8.56 MeV | -6.82 MeV |

J/ ψ $\pi^+\pi^-$ Lineshapes

- Lineshapes for various E_f



LHCb Lineshapes (incl Resolution)

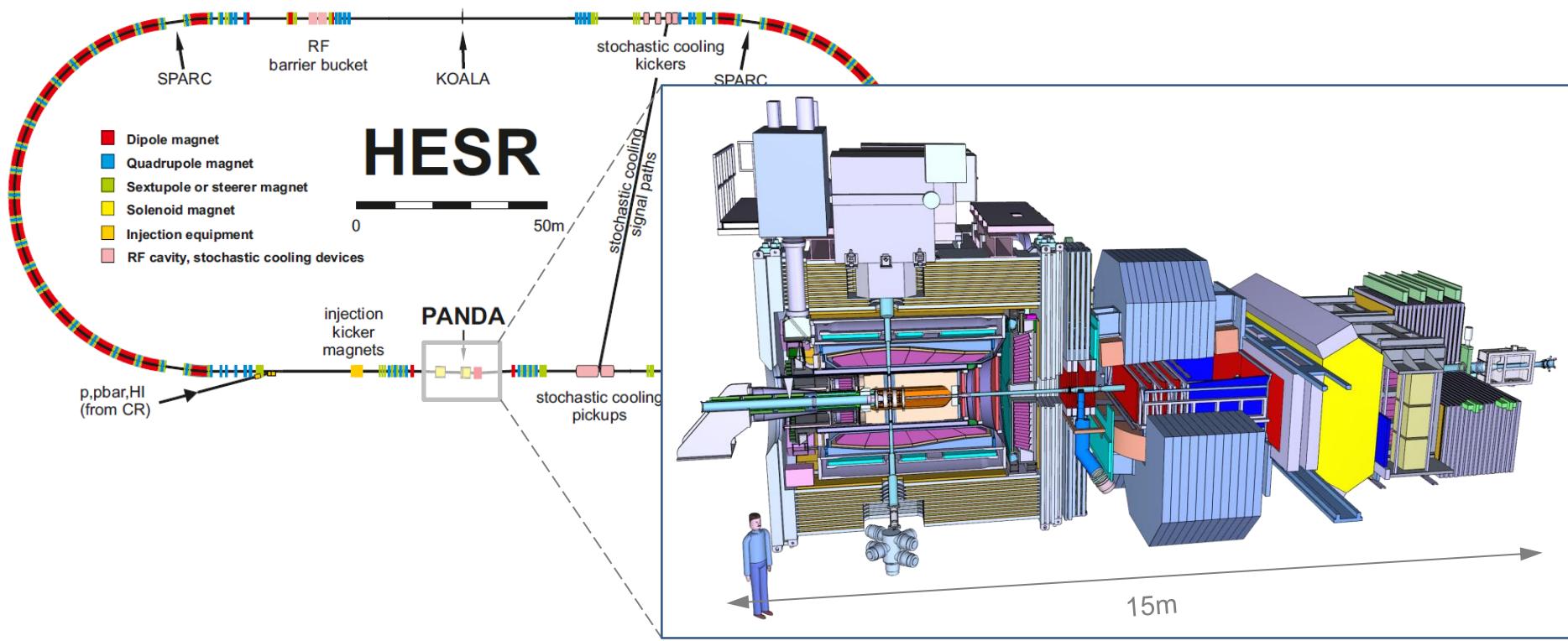


- **Quote LHCb:**

7.3 Comparison between Breit–Wigner and Flatté lineshapes

Figure 4 shows the comparison between the Breit–Wigner and the Flatté lineshapes. While in both cases the signal peaks at the same mass, the Flatté model results in a significantly narrower lineshape. However, after folding with the resolution function and adding the background, the observable distributions are indistinguishable.

PANDA and HESR

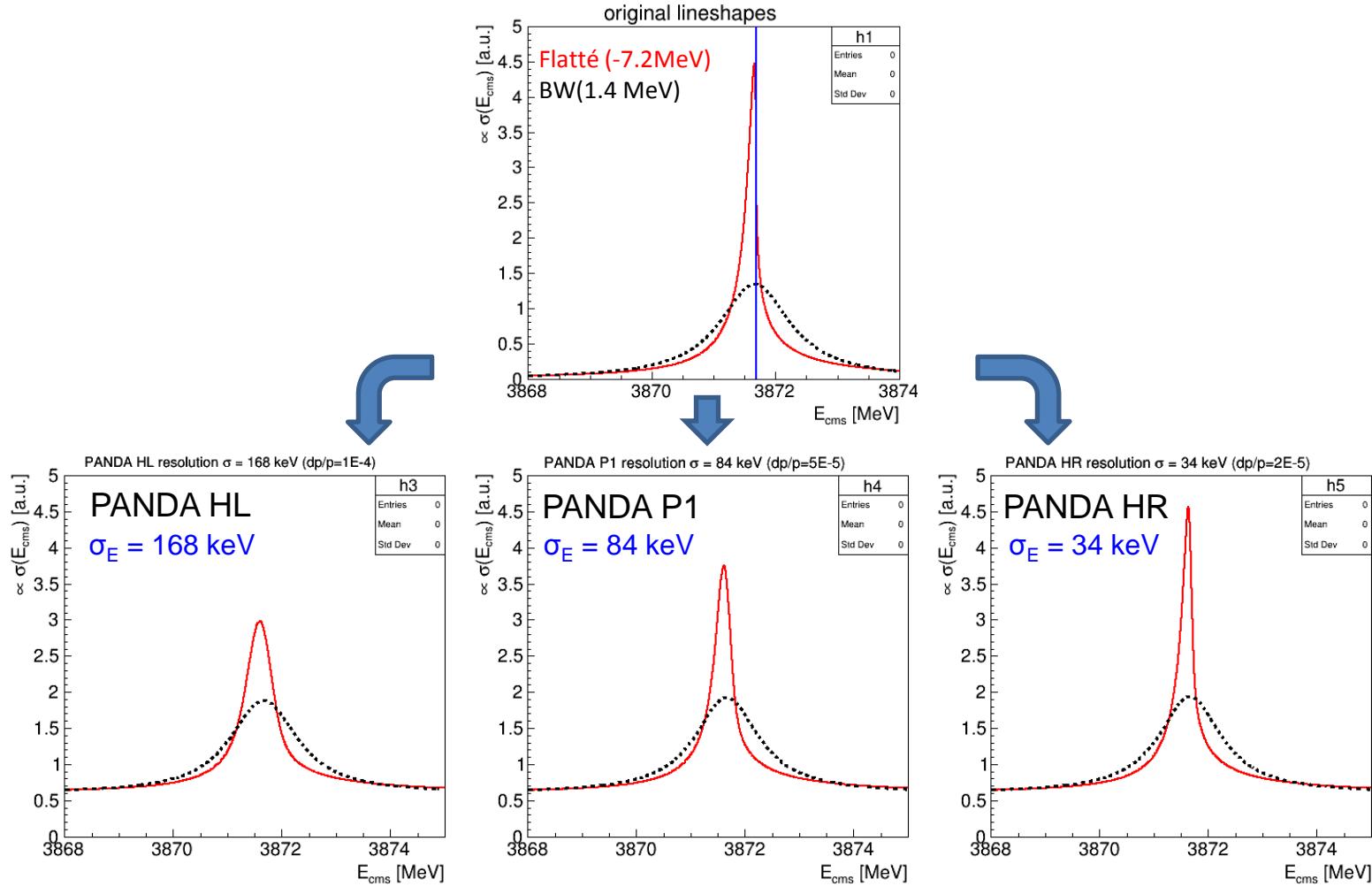


| HESR mode | $d\mathbf{p}/\mathbf{p}$ | $L_{\max} [1/\text{cm}^2 \cdot \text{s}]$ | $dE_{\text{cm}} [\text{keV}]$ |
|----------------------|--------------------------|---|-------------------------------|
| High Luminosity (HL) | $1 \cdot 10^{-4}$ | $2.0 \cdot 10^{32}$ | 168 |
| High Resolution (HR) | $2 \cdot 10^{-5}$ | $2.0 \cdot 10^{31}$ | 34 |
| Phase 1 Mode (P1) | $5 \cdot 10^{-5}$ | $2.0 \cdot 10^{31}$ | 84 |

@ $E_{\text{cm}} = 3872 \text{ MeV}$

What can PANDA do?

Due to precise beam resolution
→ Breit-Wigner and Flatté-model **are distinguishable!**



Production Cross Section Estimate $\chi_{c1}(3872)$

- Cross section $\sigma(p\bar{p} \rightarrow \chi_{c1}(3872))$ yet unknown
- Estimate from $\mathcal{B}(\chi_{c1}(3872) \rightarrow p\bar{p})$ via crossing symmetry

$$\sigma_{i \rightarrow X}(M_X) = \frac{3 \cdot 4\pi}{M_X^2 - 4m_p^2} \cdot \mathcal{B}(X \rightarrow i) = 1.28\text{mb} \cdot \mathcal{B}(X \rightarrow i)$$

- Relevant publications

a) *Eur. Phys. J C73, 2462 (2013) (LHCb):*

$$\mathcal{B}(X \rightarrow p\bar{p}) < 0.002 \cdot \mathcal{B}(X \rightarrow J/\psi\pi^+\pi^-) \text{ with } \mathcal{B}(X \rightarrow J/\psi\pi^+\pi^-) > 3.2\% \\ \rightarrow \sigma(p\bar{p} \rightarrow X) \sim 81.9 \text{ nb} (< 535 \text{ nb}^*)$$

* using $\text{BR}(X \rightarrow J/\psi\pi\pi) < [100\% - \text{sum of all other lower limits BR}] = 20.9\%$ as UL

b) *Phys. Lett. B 769 (2017) 305-313 (LHCb):*

$$\mathcal{B}(B^+ \rightarrow XK^+ \rightarrow p\bar{p}K^+) / \mathcal{B}(B^+ \rightarrow J/\psi K^+ \rightarrow p\bar{p}K^+) < 0.002$$

- with $\mathcal{B}(B^+ \rightarrow J/\psi K^+ \rightarrow p\bar{p}K^+) = 2.2 \cdot 10^{-6}$ and $\mathcal{B}(B^+ \rightarrow XK^+) < 2.6 \cdot 10^{-4}$
 $\rightarrow \sigma(p\bar{p} \rightarrow X) \sim 21.7 \text{ nb} (< 46.9 \text{ nb}^{**})$

- with $\mathcal{B}(B^+ \rightarrow XK^+ \rightarrow p\bar{p}K^+) < 5 \cdot 10^{-9}$
 $\rightarrow \sigma(p\bar{p} \rightarrow X) \sim 24.6 \text{ nb} (< 53.3 \text{ nb}^{**})$

** using $\text{BR}(B^+ \rightarrow XK^+) = 1.2 \cdot 10^{-4}$ from Belle paper PRD 97 (2018) 1, 012005

- Using $\sigma(p\bar{p} \rightarrow X) = 50 \text{ nb}$ (default from our publication)

Our X-Scan Paper: The Missing Part

- Subjects of investigation in EPJ A 55 (2019) 42
 - Analysis of: $\bar{p}p \rightarrow \chi_{c1}(3872) \rightarrow J/\psi (\rightarrow e^+e^- / \mu^+\mu^-) \rho^0 (\rightarrow \pi^+\pi^-)$
 1. Breit-Wigner model: Precision $\Delta\Gamma/\Gamma$ of width Γ measurement (as function of σ_X , HESR mode and Γ)
 2. Flatté model: Mis-ID rate to identify bound/virtual state (as function of σ_X , HESR mode and Flatté-energy E_f)
- What we did not investigate yet:
 - (How well) can we distinguish Breit-Wigner and Flatté model?
 - We will catch up for that now!

Key Parameters from EPJ A 55 (2019) 42

Reconstruction of: $\bar{p}p \rightarrow \chi_{c1}(3872) \rightarrow J/\psi (\rightarrow e^+e^- / \mu^+\mu^-) \rho^0 (\rightarrow \pi^+\pi^-)$

| Category | Parameter | Value |
|-------------------------|---|---|
| Reco Efficiencies | Signal (average $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$) | 13.7 % |
| | Non-resonant background ("") | 2.9 % |
| | $\bar{p}p \rightarrow$ multi-hadron background | $2.8 \cdot 10^{-10}$ |
| Branching fractions | $BR(J/\psi \rightarrow e^+e^-)$ | 5.97 % |
| | $BR(J/\psi \rightarrow \mu^+\mu^-)$ | 5.96 % |
| | $BR(\rho^0 \rightarrow \pi^+\pi^-)$ | 100 % |
| | $BR(X \rightarrow J/\psi \rho^0)$ | 5 % |
| Cross sections | $\sigma_{peak}(\bar{p}p \rightarrow X)$ | [20,30, 50 ,75,100,150] nb |
| | $\sigma(\bar{p}p \rightarrow J/\psi \pi^+\pi^-$ non-res) | 1.2 nb [PRD 77 (2008) 097501] |
| | $\sigma(\bar{p}p \rightarrow$ inelast.) @ 3.872 GeV | 46 mb |
| Luminosity & Resolution | $HL : L_{HL} / dE_{HL}$ | 13680 (nb·d) ⁻¹ / 168 keV |
| | $HR : L_{HR} / dE_{HR}$ | 1370 (nb·d) ⁻¹ / 34 keV |
| | $P1 : L_{P1} / dE_{P1}$ | 1170 (nb·d) ⁻¹ / 84 keV |
| Scan time | T_{tot} | $40 \times 2d = 80d$ |
| Model Parameters | Breit Wigner Width Γ | [50, 70, 100, 130, 180, 250, 500] keV |
| | Flatté Model Energy E_f | - [10.0, 9.5, 9.0, 8.8, 8.3, 8.0, 7.5, 7.0] MeV |

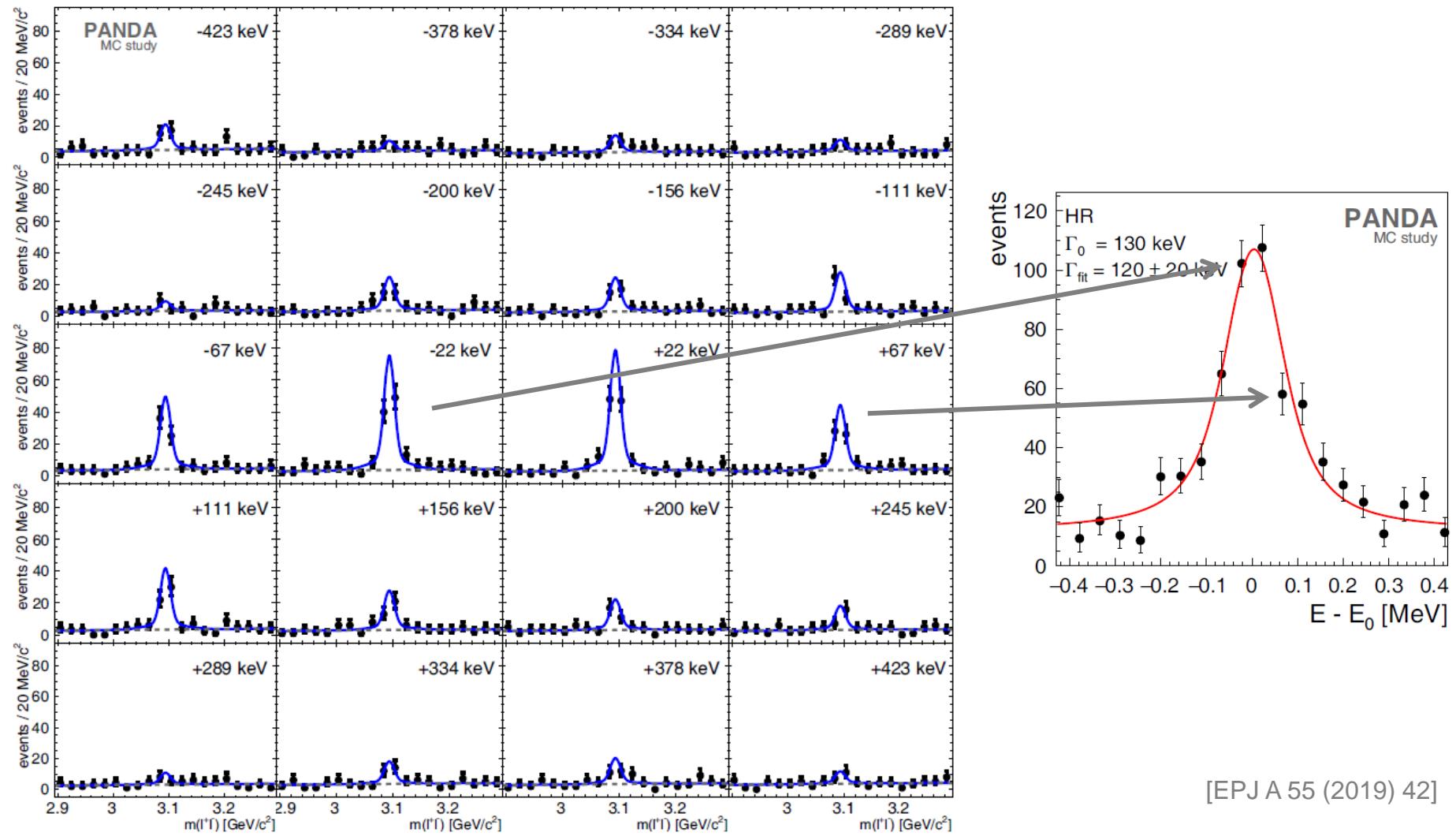
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| Scan time | T_{tot} | $40 \times 2d = 80d$ |
| Model Parameters | Breit Wigner Width Γ | <i>adapted to FWHM range of Flatté</i> [100, 150, 200, 250, 300, 350, 400, 450, 500, 550] keV |
| | Flatté Model Energy E_f | <i>adapted to new $E_{f,thr}$ and LHCb measurement</i> - [8.7, 8.2, 7.7, 7.2, 6.7, 6.2, 5.7, 5.2] MeV |

Scan Procedure Principle (Example)

Example: Breit-Wigner scenario, $\Gamma = 130$ keV, 20 points, ± 0.4 MeV window



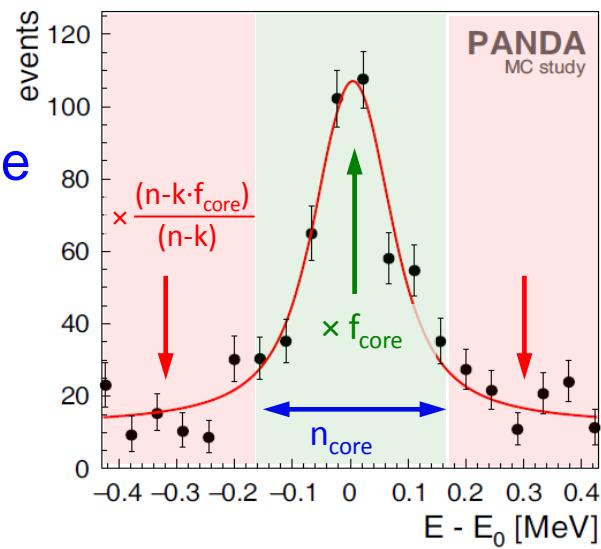
Methode

We use the following approach:

1. Use key parameters from EPJ A 55 (2019) 42
2. Generate many (toy) spectra for Flatté (BW) model
3. Fit both BW and Flatté to each generated distribution and determine fit probabilities P_{BW} and P_F
4. Identification considered correct, if $P_F > P_{BW}$ ($P_{BW} > P_F$)
5. Count fraction of incorrect assignments $\rightarrow P_{mis}$
6. $P_{mis} (< 50\%)$ measure for accuracy
7. $P_{mis} = 50\%$ means: models indistinguishable

Scan Optimization

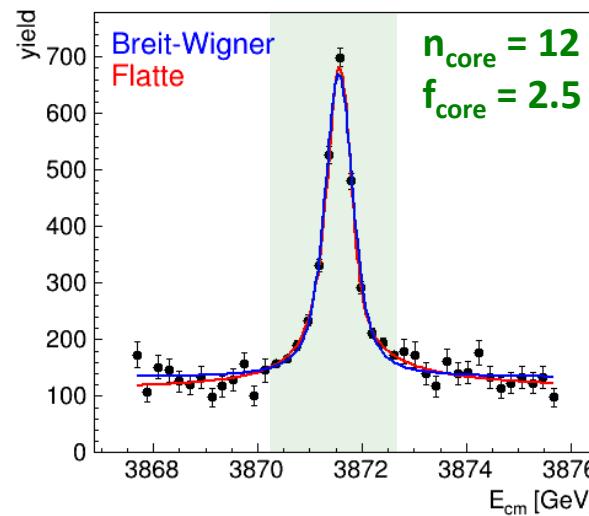
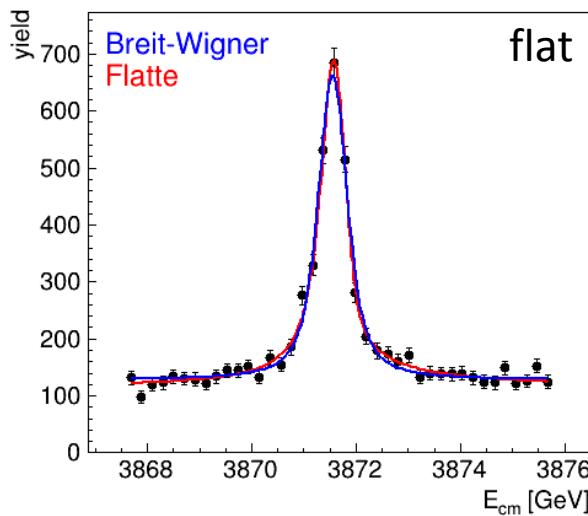
- Our paper: Constant time per equidistantly spaced scan point
 - Most likely gives suboptimal results
- Questions for optimization (n scan energy points):
 - What are the best n energies E_{cms} to take data at?
 - How much data to be taken at each energy E_{cms} ?
- Global optimum: Search $2n$ -dimensional space
- Idea for simplified approach:
 - 40 equidistant energies in defined energy range
 - Choose number n_{core} of central energy points
 - Take factor f_{core} more data there at expense of tails to keep total beam time constant
- 2-dimensional (coarse) grid search feasible



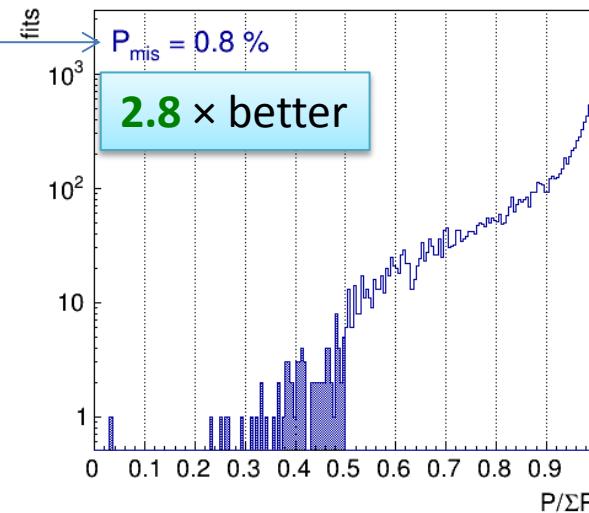
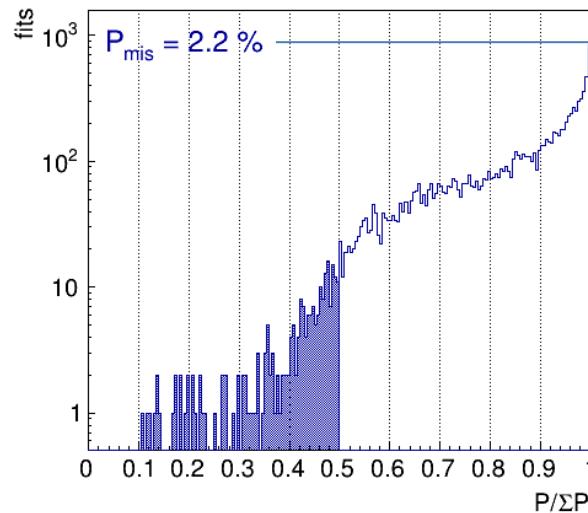
Scan Optimization Example (HL)

- **HL Mode:** Generated with Flatté model ($E_f = -7.2\text{MeV}$)

Fit Example



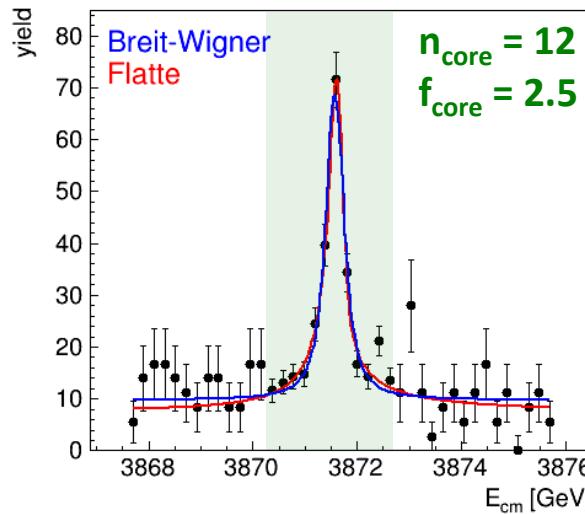
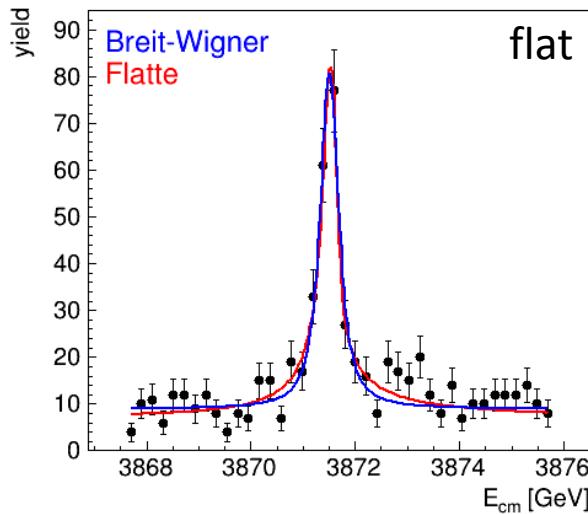
mis-ID from 10000 fits



Scan Optimization Example (P1)

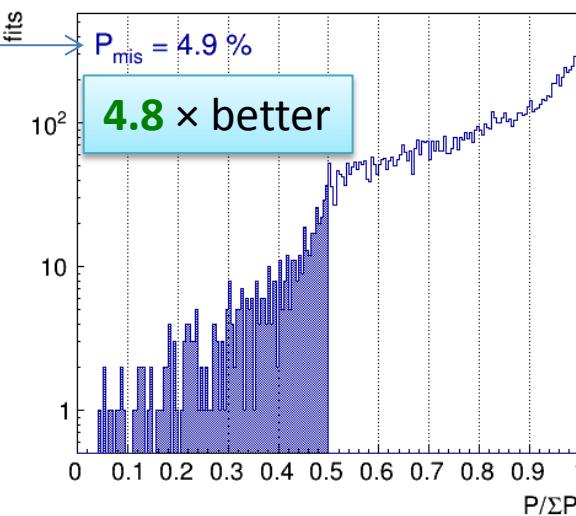
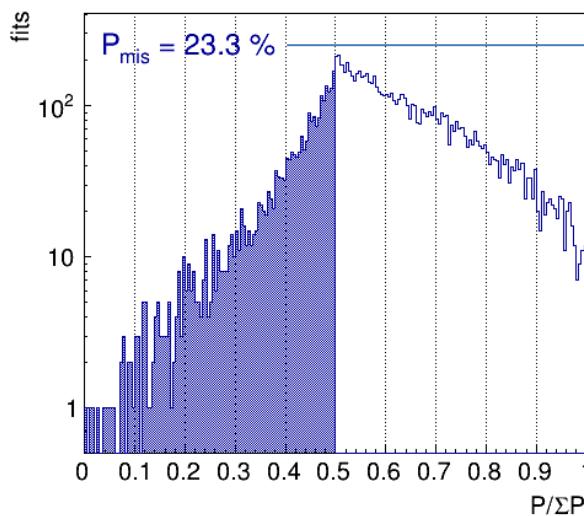
- **P1 Mode:** Generated with Flatté model ($E_f = -7.2\text{MeV}$)

Fit
Example



(Yields scaled back, only errors reduced)

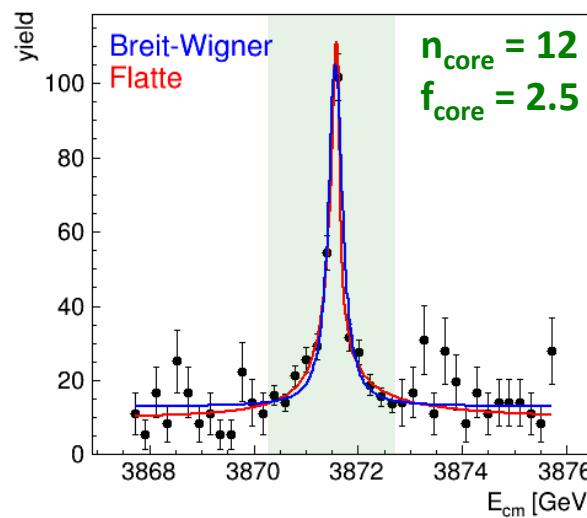
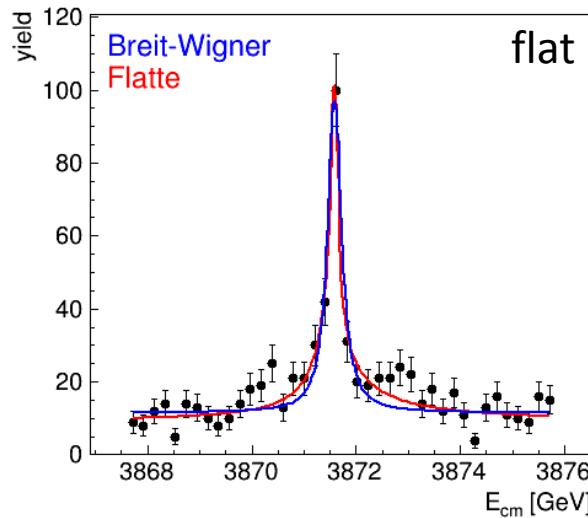
mis-ID from
10000 fits



Scan Optimization Example (HR)

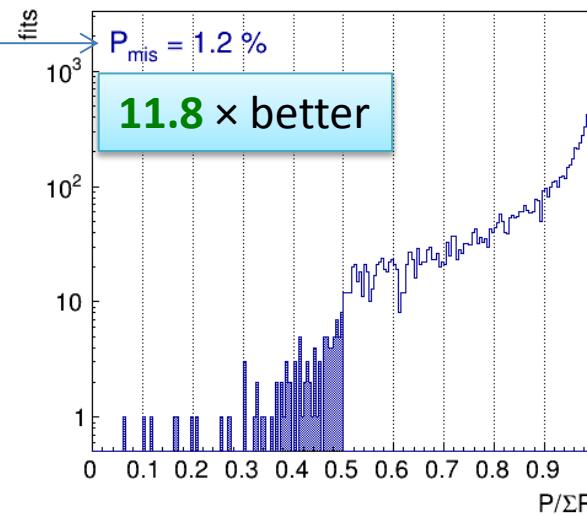
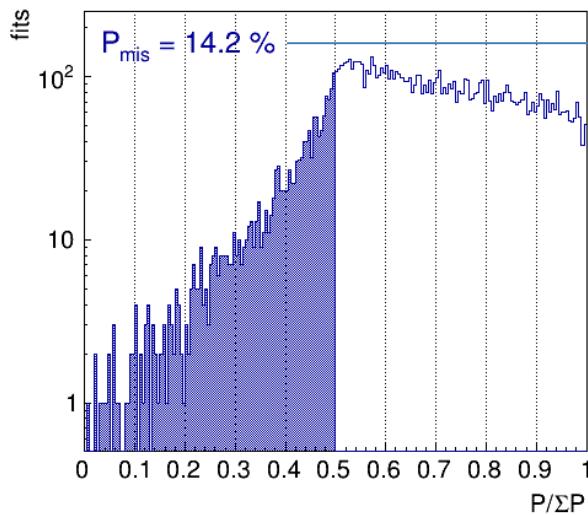
- **HR Mode:** Generated with **Flatté model** ($E_f = -7.2\text{MeV}$)

Fit Example



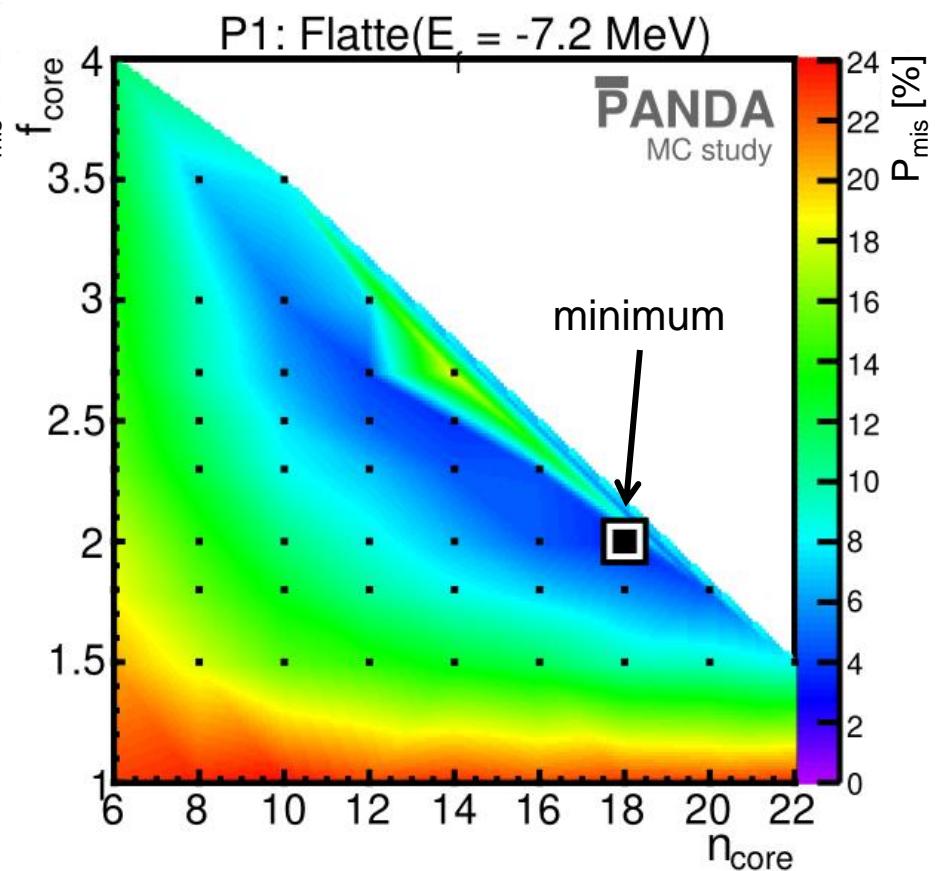
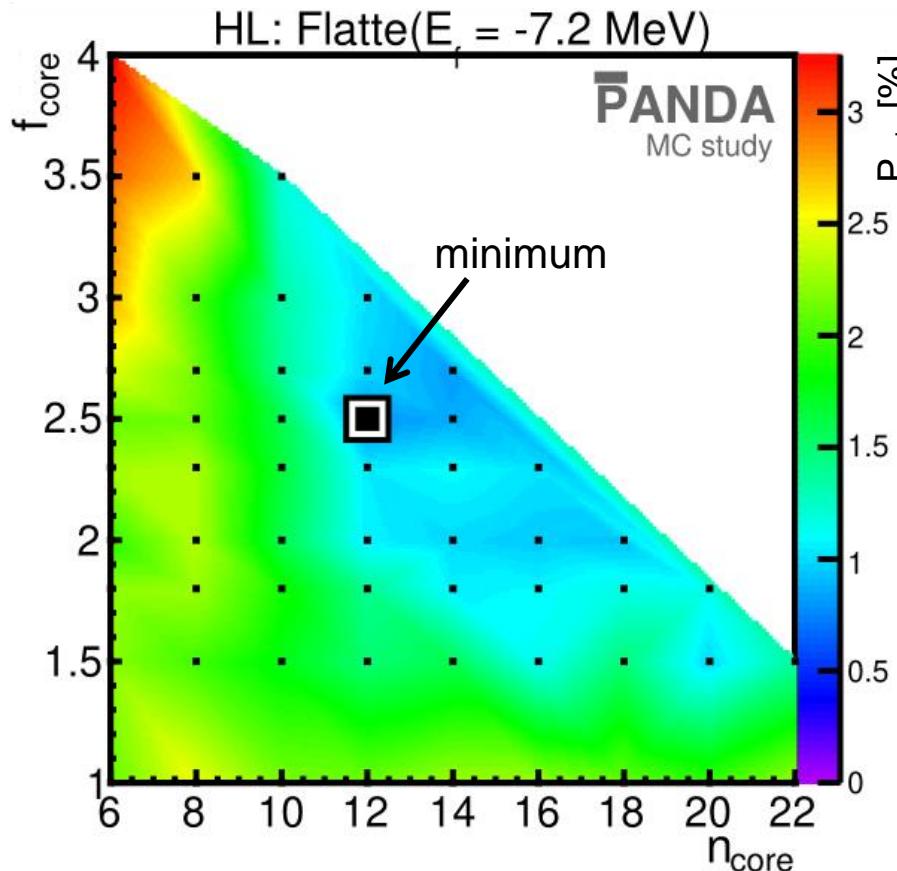
(Yields scaled back, only errors reduced)

mis-ID from
10000 fits



Global Optimization

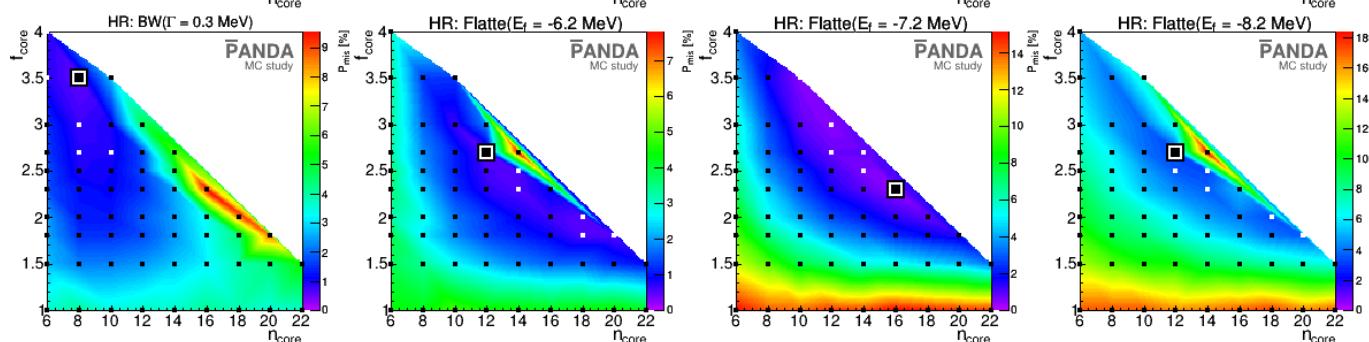
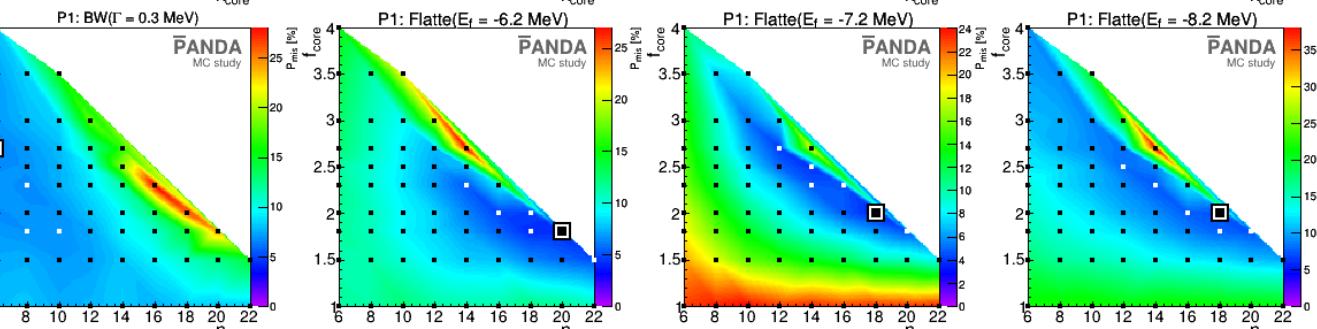
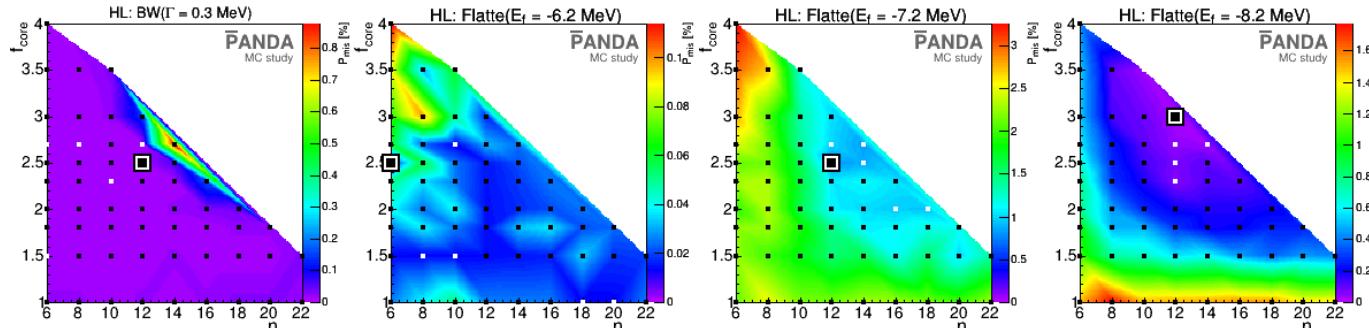
- Systematic investigation of parameter space (n_{core} , f_{core})



Global Optimization

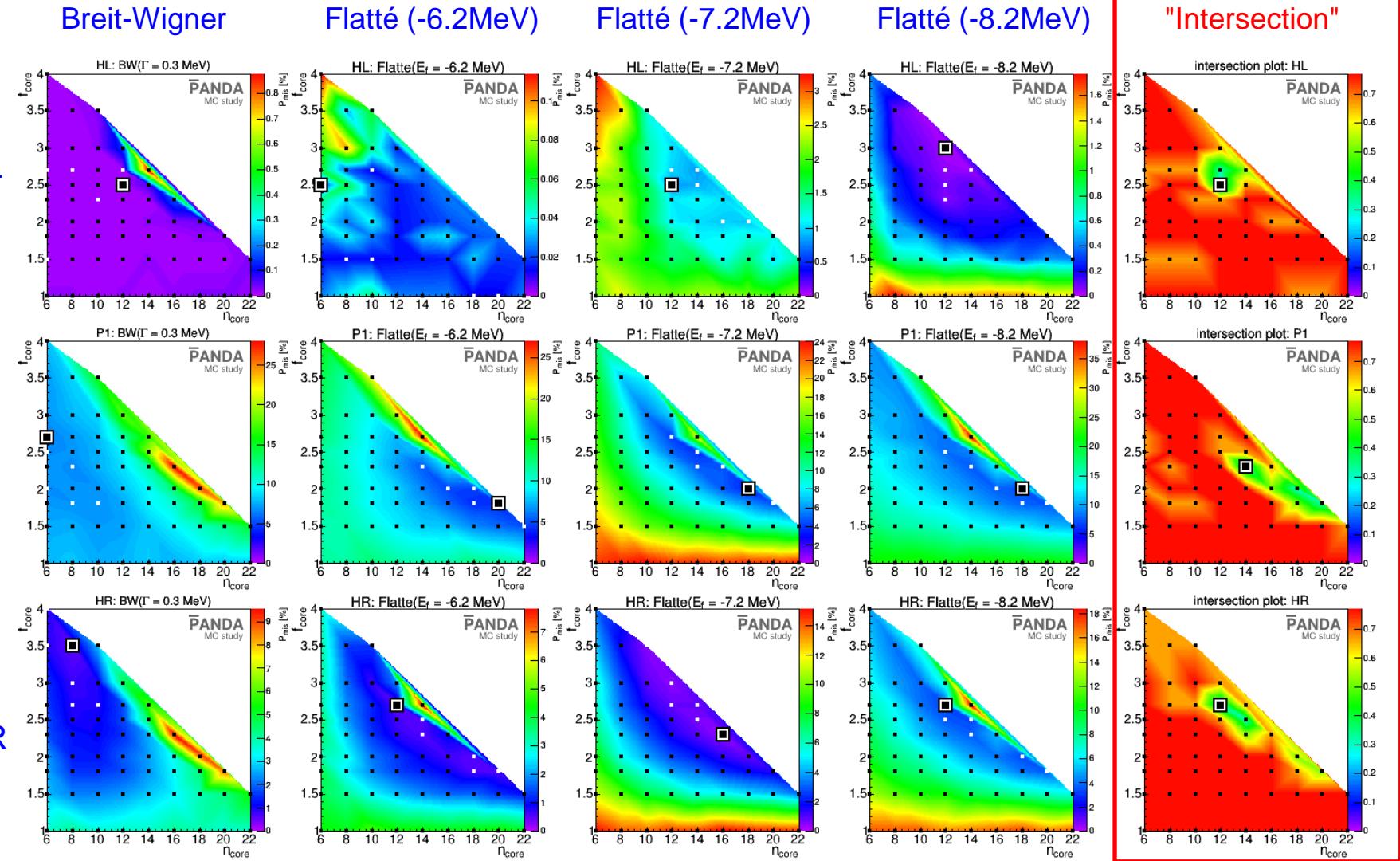
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Breit-Wigner



Global Optimization

- Systematic investigation of parameter space (n_{core} , f_{core})



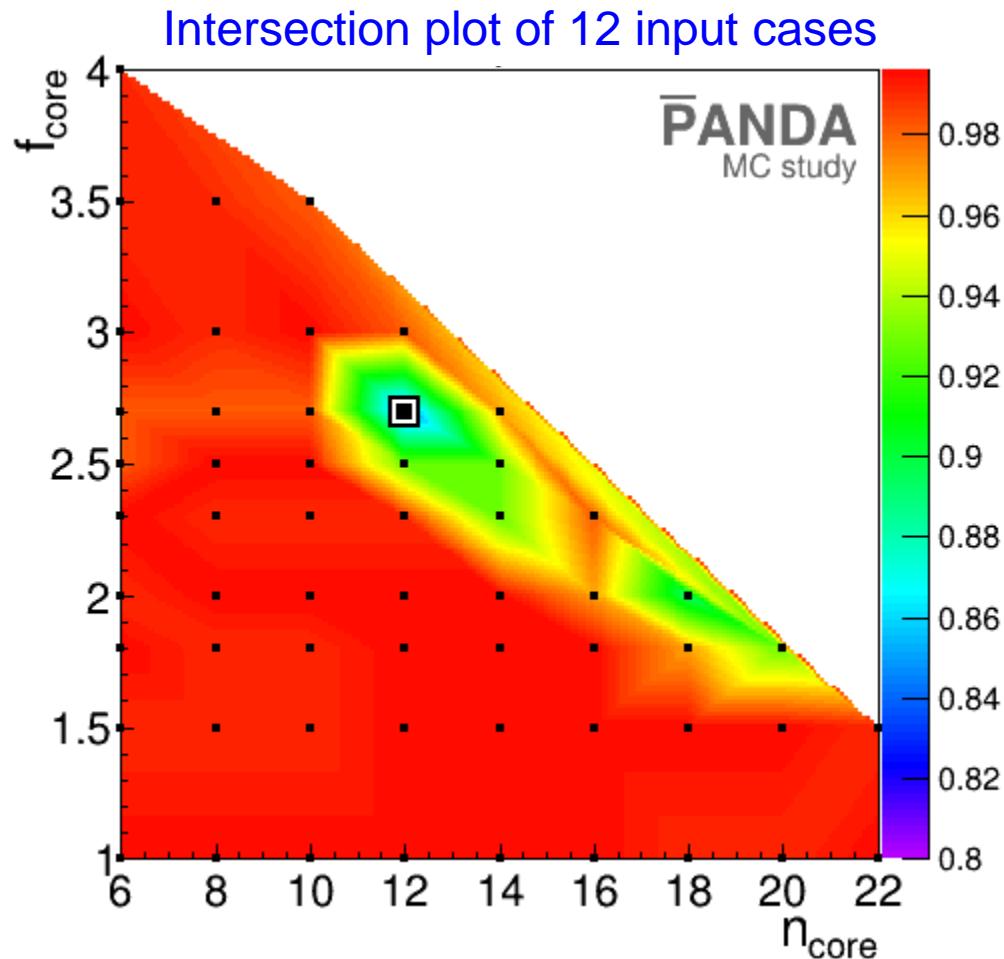
Global Optimization

- Compute global intersection plot of all 12 input cases

- Global optimum from plot

$$n_{\text{core}} = 12$$

$$f_{\text{core}} = 2.7$$



Global Optimization

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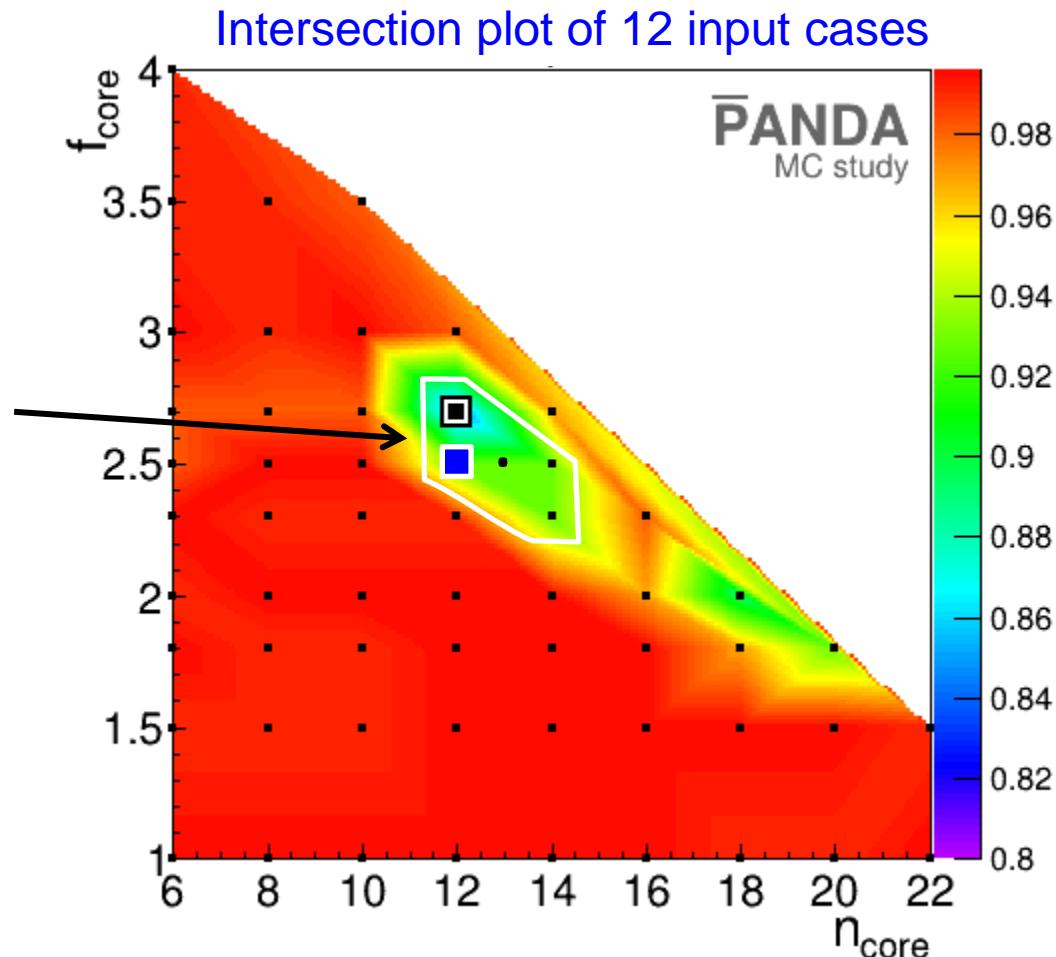
$$n_{\text{core}} = 12$$

$$f_{\text{core}} = 2.7$$

- In depth investigation in white area results in final optimum*

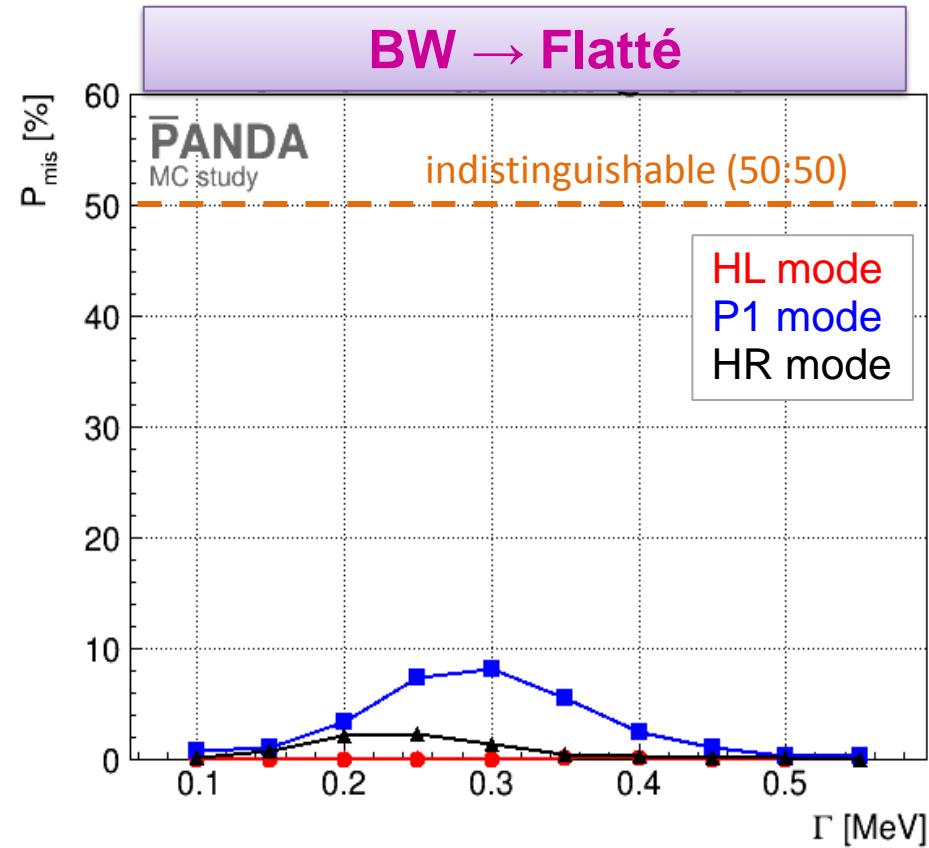
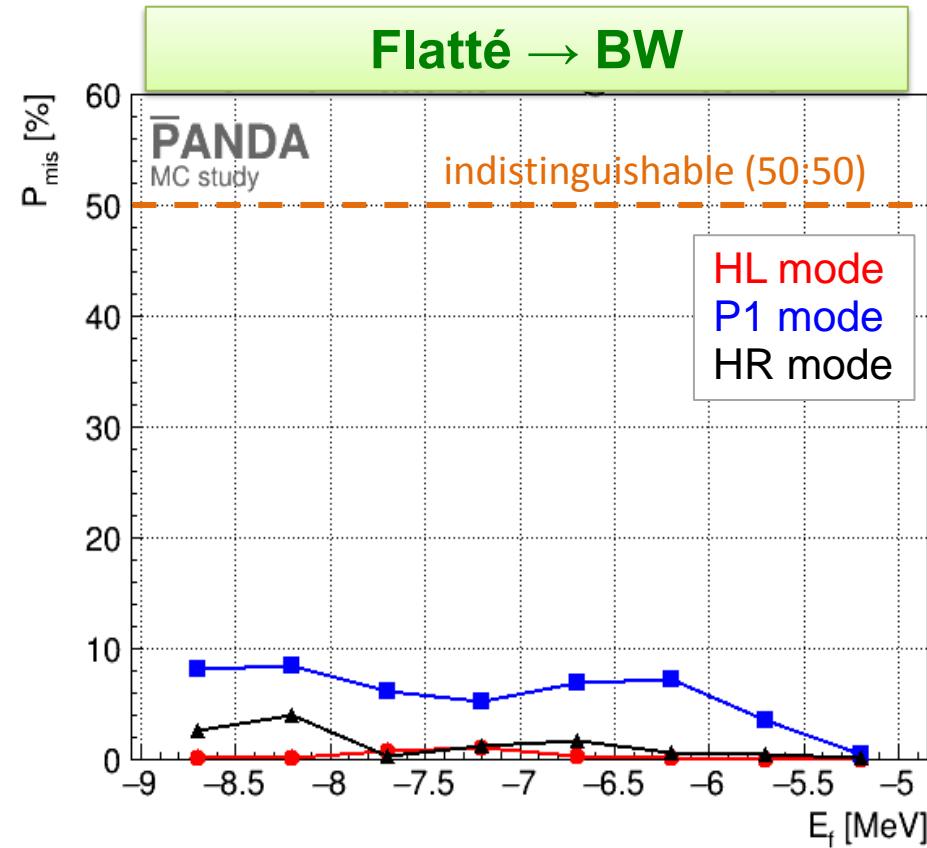
$$\begin{aligned} n_{\text{core, opt}} &= 12 \\ f_{\text{core, opt}} &= 2.5 \end{aligned}$$

* same results from computing
mean or median of $n_{\text{core}}/f_{\text{core}}$



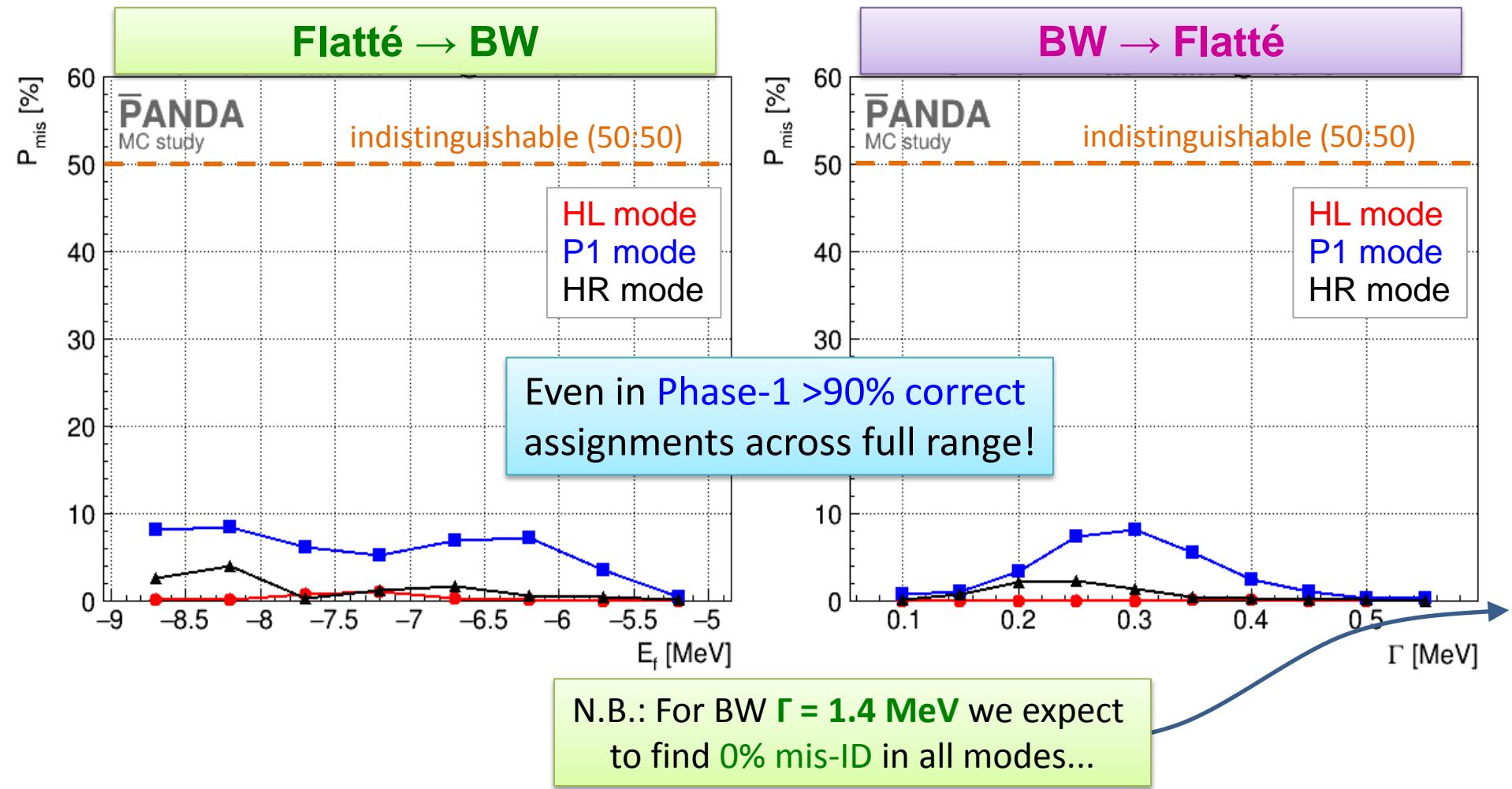
Parameter Dependent Performance

- Performance across Flatté energy E_f / Breit-Wigner Γ range



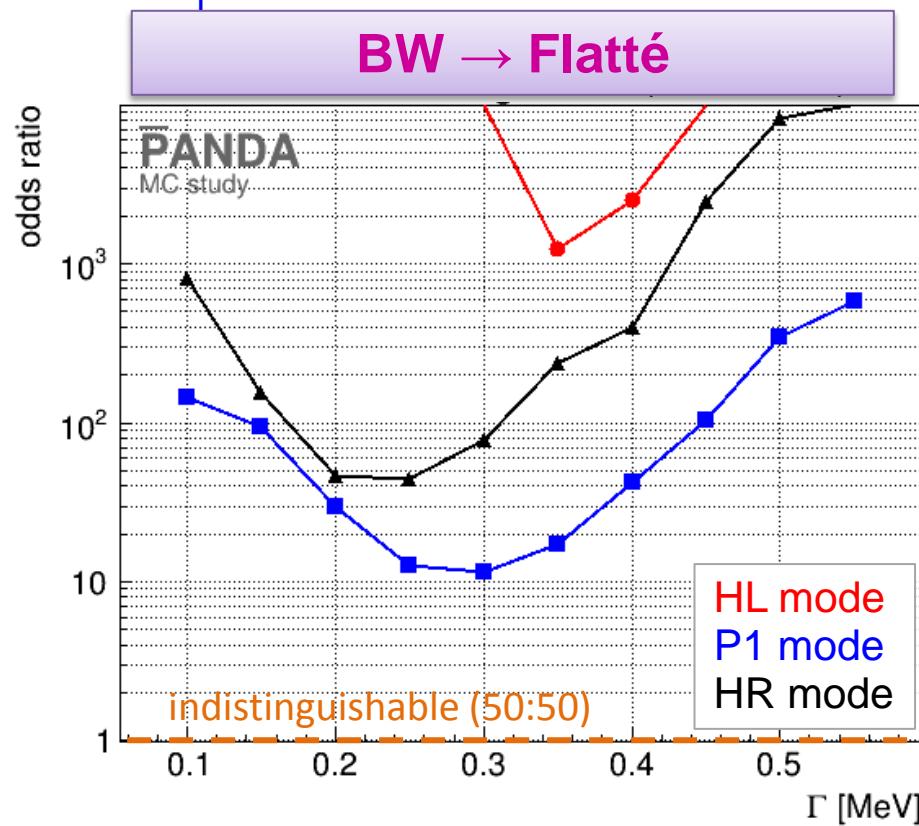
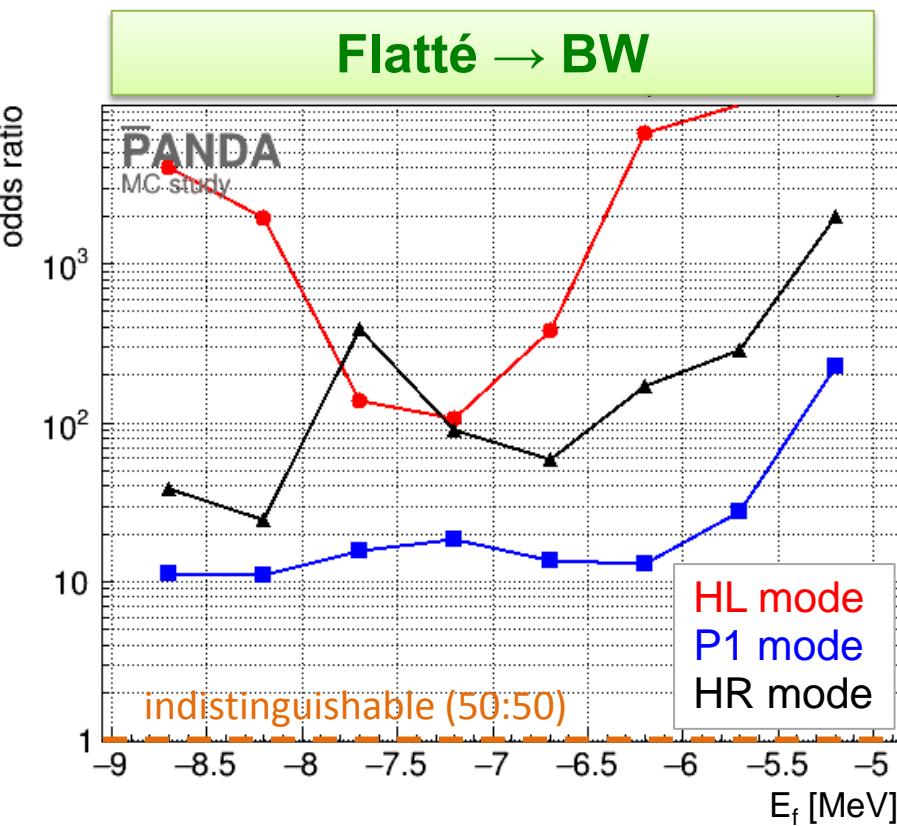
Parameter Dependent Performance

- Performance across Flatté energy E_f / Breit-Wigner Γ range



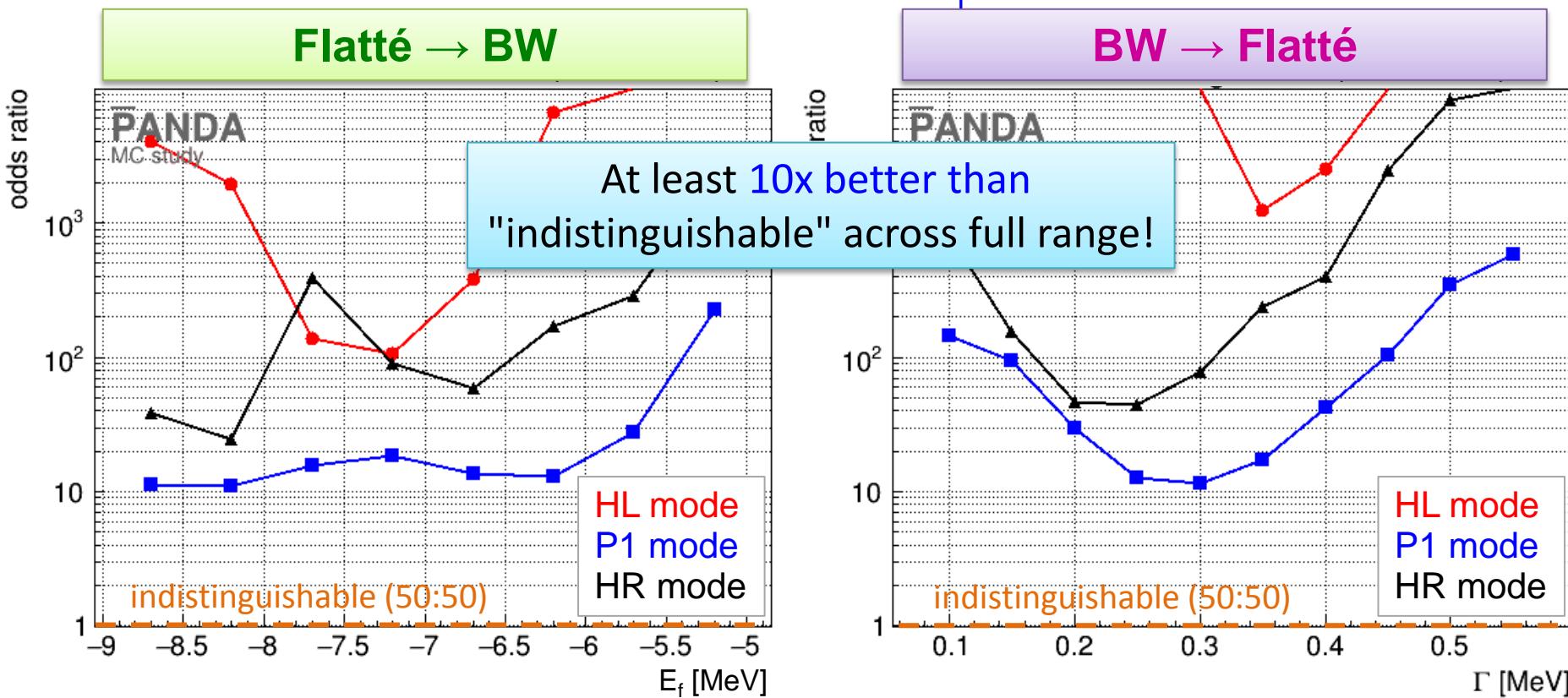
Performance as Odds Ratio

- How much better than "indistinguishable" (= flipping a coin or guess)?
- Idea: Consider so-called **odds-ratio (OR)**
 - $\text{odds}_{\text{scan}} = n_{\text{correct}} : n_{\text{wrong}} = (1 - P_{\text{mis}}) : P_{\text{mis}}$
 - $\text{OR} = \text{odds}_{\text{scan}} / \text{odds}_{\text{guess}} = \text{odds}_{\text{scan}} / (50:50) = (1 - P_{\text{mis}}) : P_{\text{mis}}$



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Summary and Conclusion

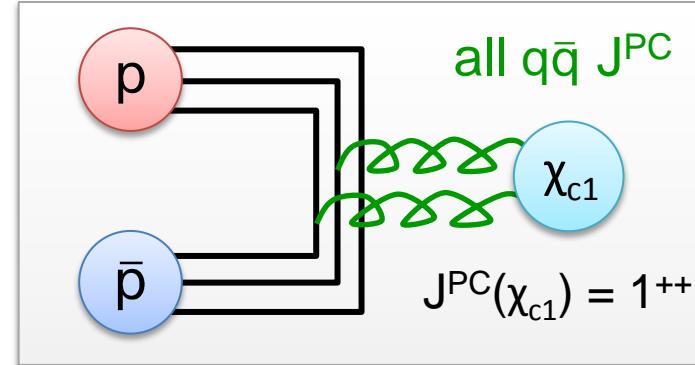
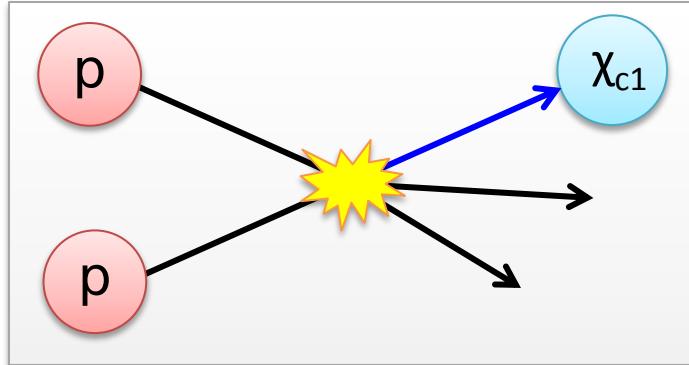
- Narrow resonances in production reactions suffer from limited detector resolution
- Interpretation of results are strongly model dependent
- High precisions $p\bar{p}$ energy scan can overcome this limitation
- Simulation of line shape measurement of $\chi_{c1}(3872)$ at PANDA
⇒ Different models can be distinguished
- Correct assignment of fit model between 91% and 99.9..% for $\sigma = 50\text{nb}$ in the different beam modes
- At least 10x higher chance to identify correct model than LHCb*
- Full (2n-dim.) optimization might even improve performance

* if their "indistinguishable" means 50:50

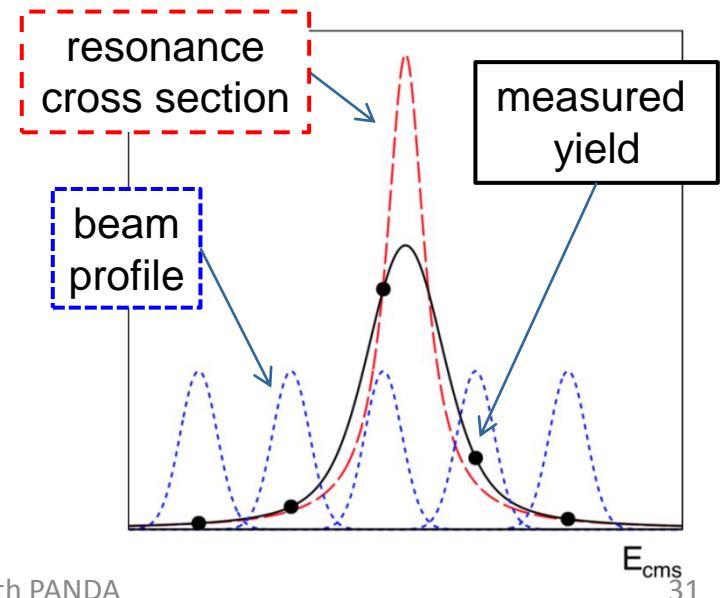
BACKUP

Overcome Detector Resolution with Formation

- Production with recoils dominated by detector resolution (~ MeV)
- Formation reaction → produce $\chi_{c1}(3872)$ [$J^{PC} = 1^{++}$] w/o recoils



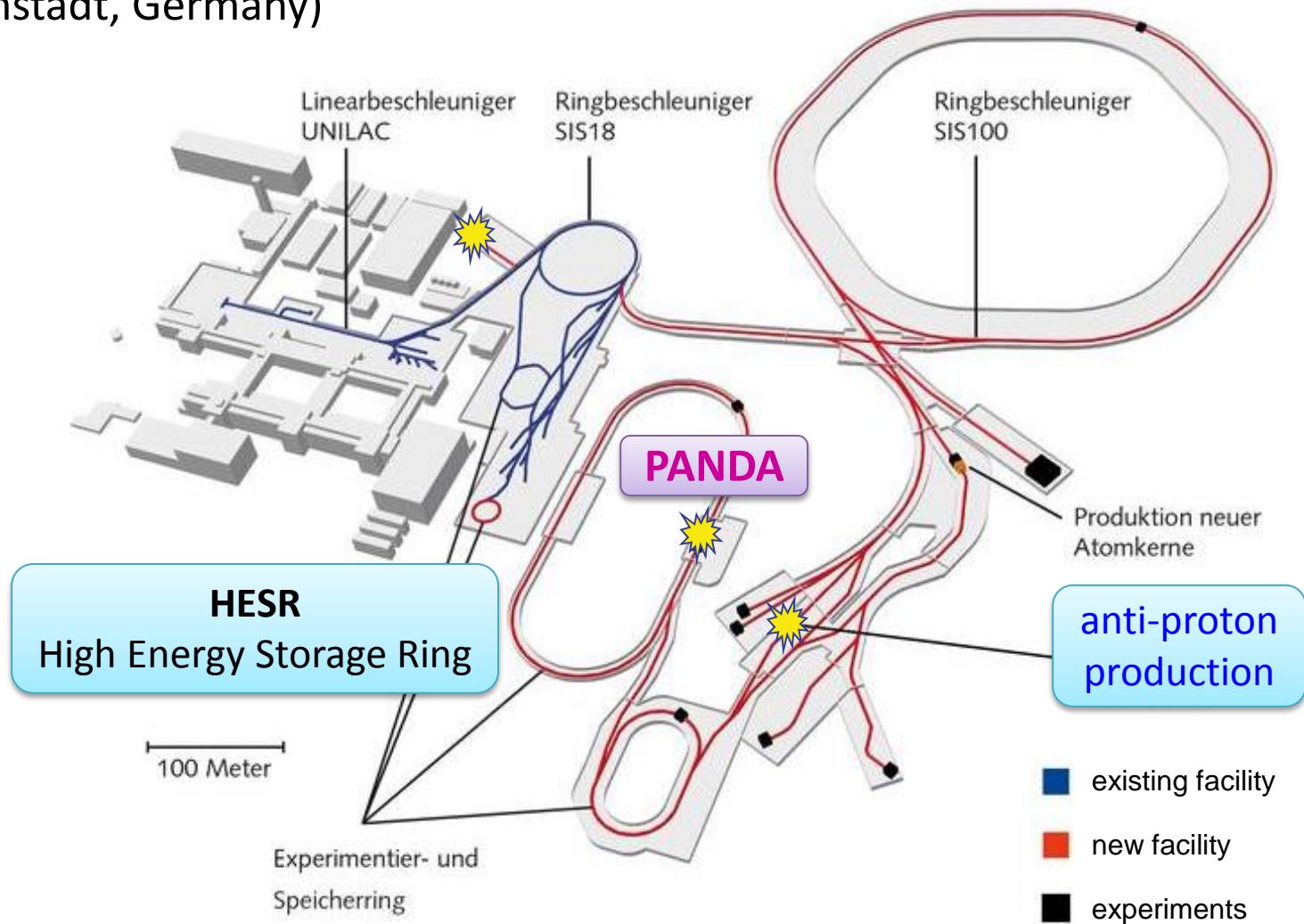
- Measure yield at different E_{cms}
- Beam energy spread → resolution



LHCb Detector Resolution ≈ 2.6 MeV
PANDA Beam Resolution ≈ 0.05 MeV

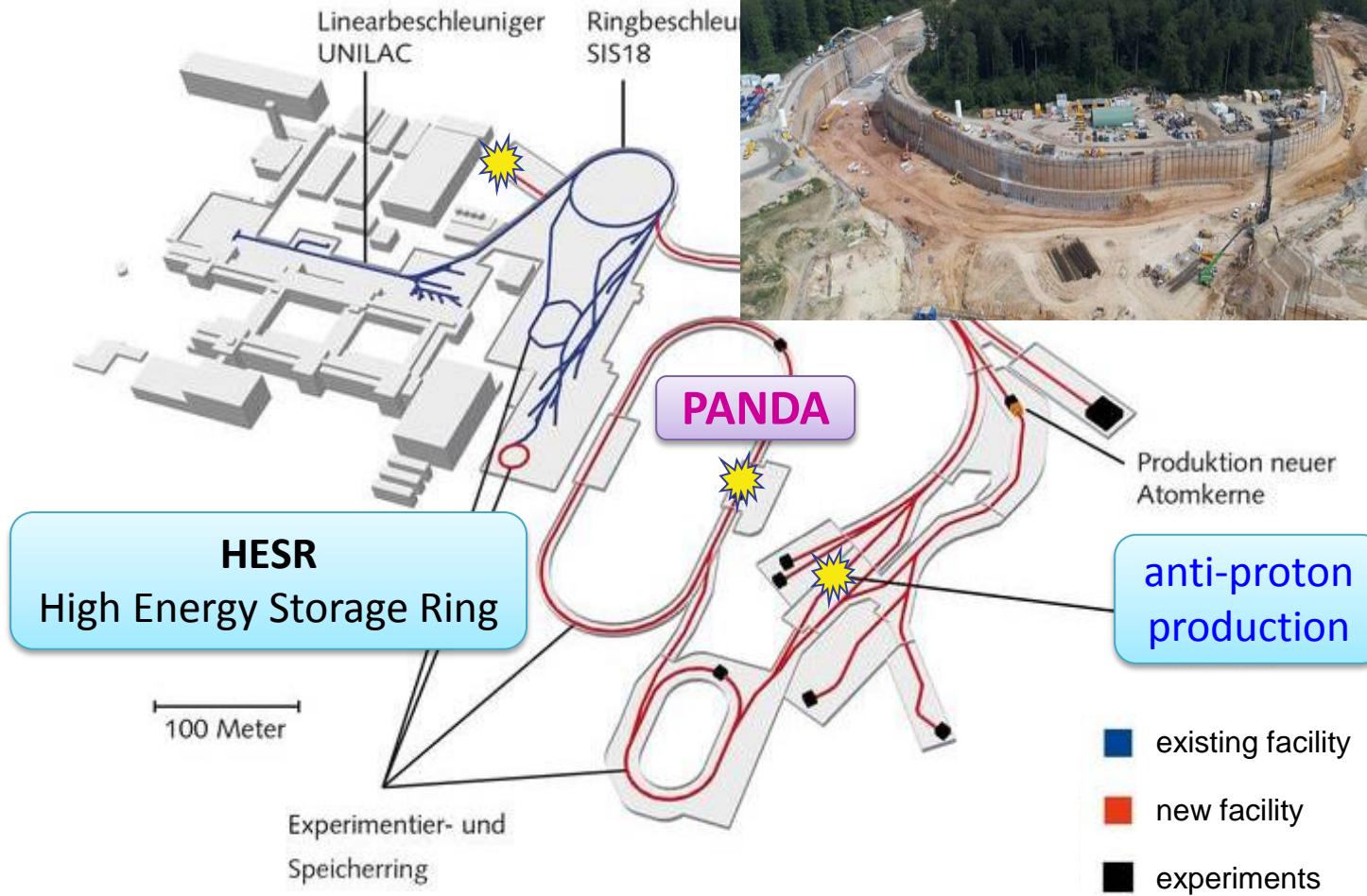
PANDA at FAIR

Facility for Antiproton and Ion Research
(GSI, Darmstadt, Germany)



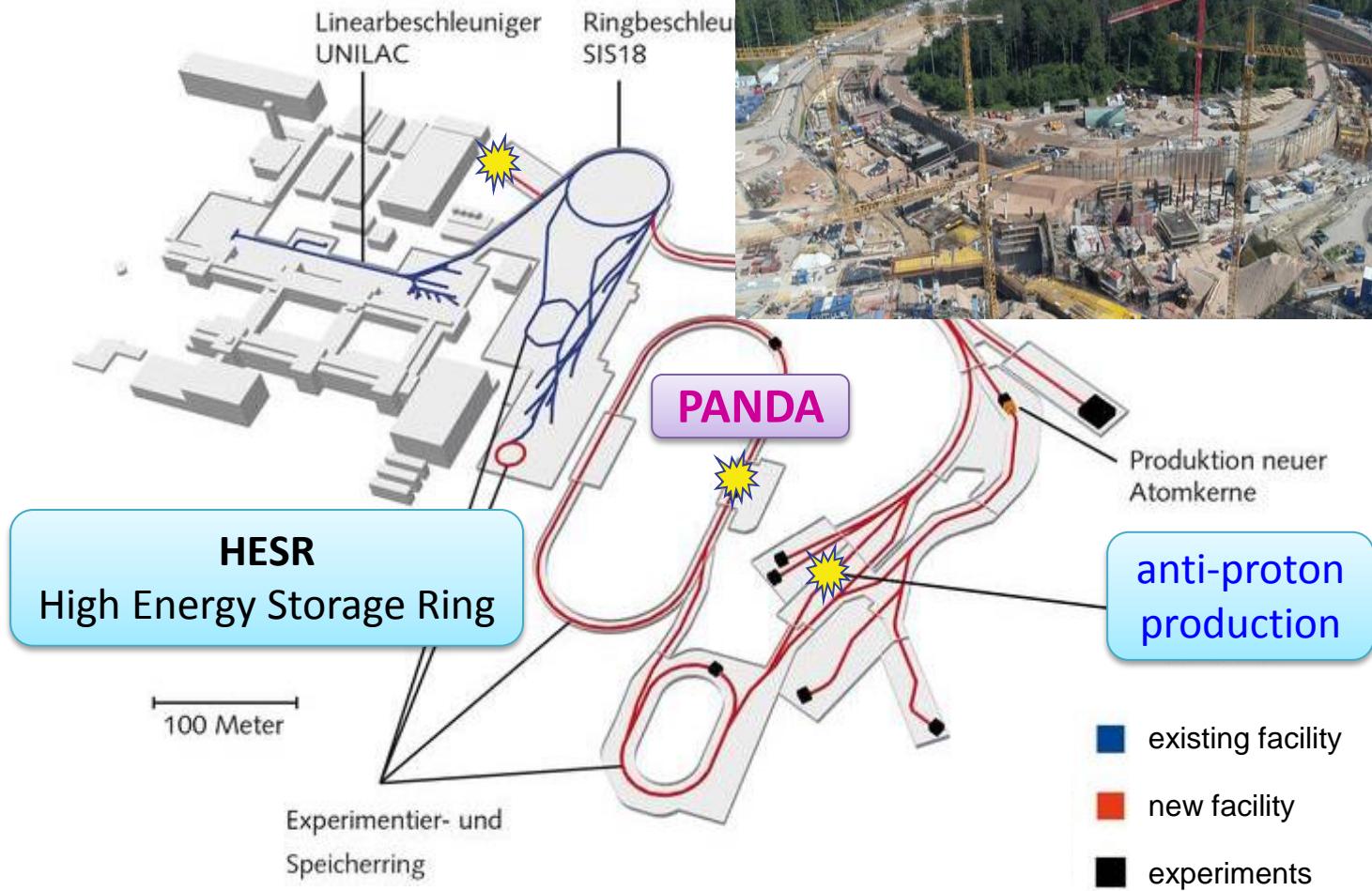
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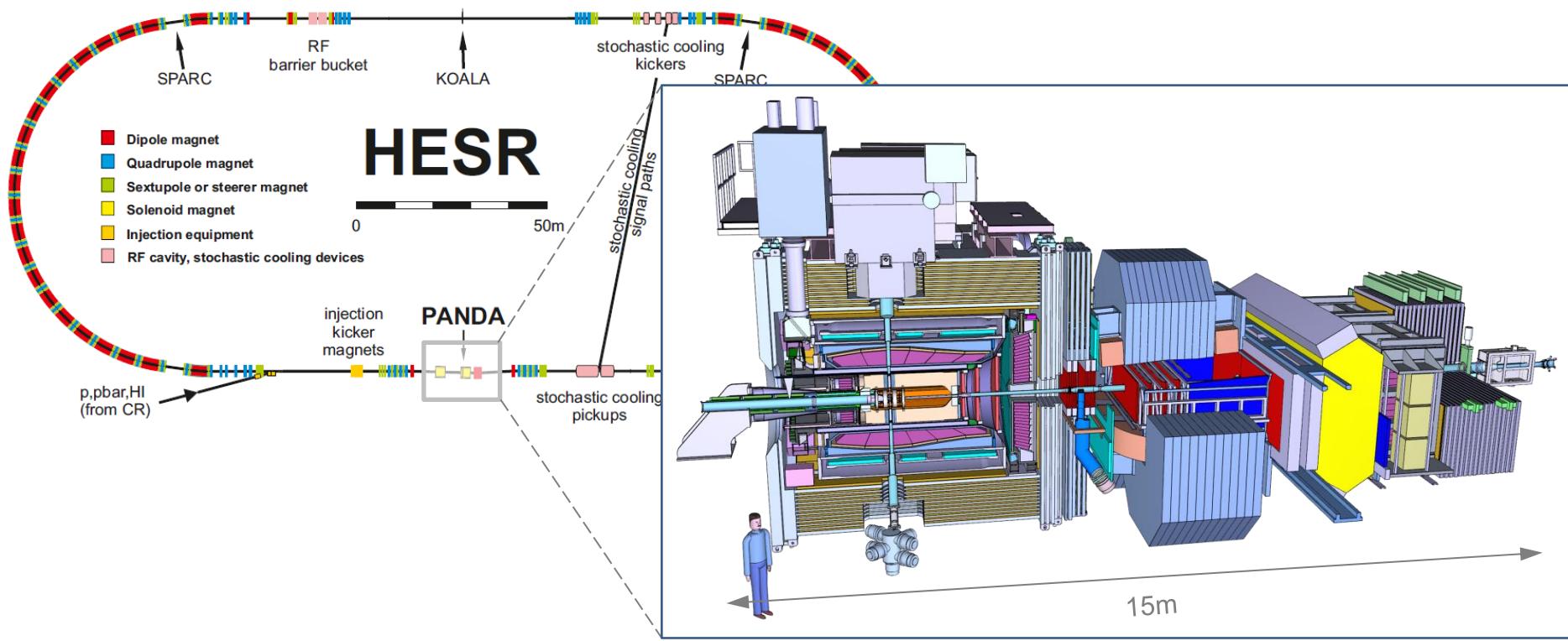


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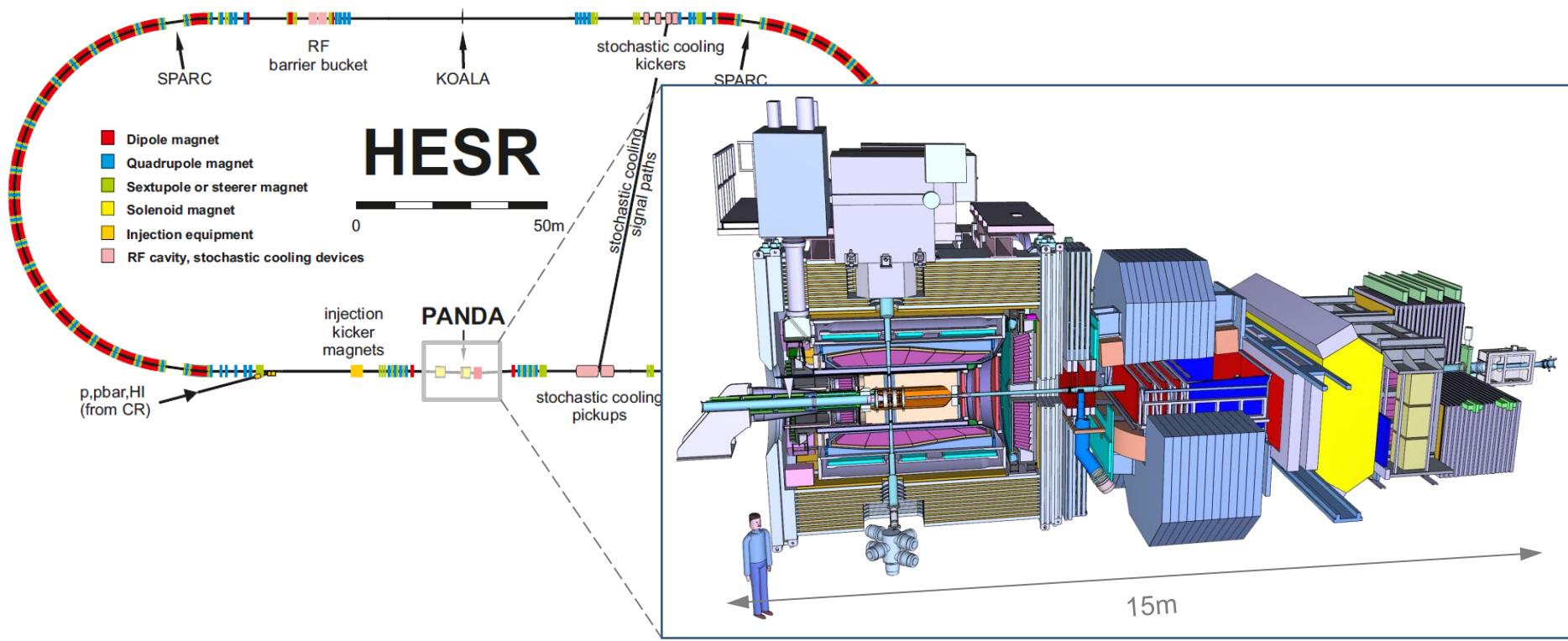


PANDA and HESR



| HESR mode | $d\mu/p$ | $L_{\max} [1/\text{cm}^2 \cdot \text{s}]$ |
|----------------------|-------------------|---|
| High Luminosity (HL) | $1 \cdot 10^{-4}$ | $2.0 \cdot 10^{32}$ |
| High Resolution (HR) | $2 \cdot 10^{-5}$ | $2.0 \cdot 10^{31}$ |
| Phase 1 Mode (P1) | $5 \cdot 10^{-5}$ | $2.0 \cdot 10^{31}$ |

PANDA and HESR



| HESR mode | $d\mathbf{p}/\mathbf{p}$ | $L_{\max} [1/\text{cm}^2 \cdot \text{s}]$ | $dE_{\text{cm}} [\text{keV}]$ |
|----------------------|--------------------------|---|-------------------------------|
| High Luminosity (HL) | $1 \cdot 10^{-4}$ | $2.0 \cdot 10^{32}$ | 168 |
| High Resolution (HR) | $2 \cdot 10^{-5}$ | $2.0 \cdot 10^{31}$ | 34 |
| Phase 1 Mode (P1) | $5 \cdot 10^{-5}$ | $2.0 \cdot 10^{31}$ | 84 |

@ $E_{\text{cm}} = 3872 \text{ MeV}$

Importance of Identifying Model

- Model dependence of even high precision measurements significantly limits gain of knowledge
- Example:
 - a) Flat earth model: Thickness with $\Delta d/d = 0.1\%$ precision
 - b) Spherical earth model: Radius with $\Delta r/r = 2\%$ precision

What do we learn from measurement a)?

a)



?

b)

