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

EMMI Workshop - ***Experimental and theoretical status of and perspectives for XYZ states***

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GSI Darmstadt
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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 $3\,\text{fb}^{-1}$ 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

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

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 $D^0\overline{D}^{*0}$ state but a quasi-virtual state is still allowed at the level of 2 standard deviations.

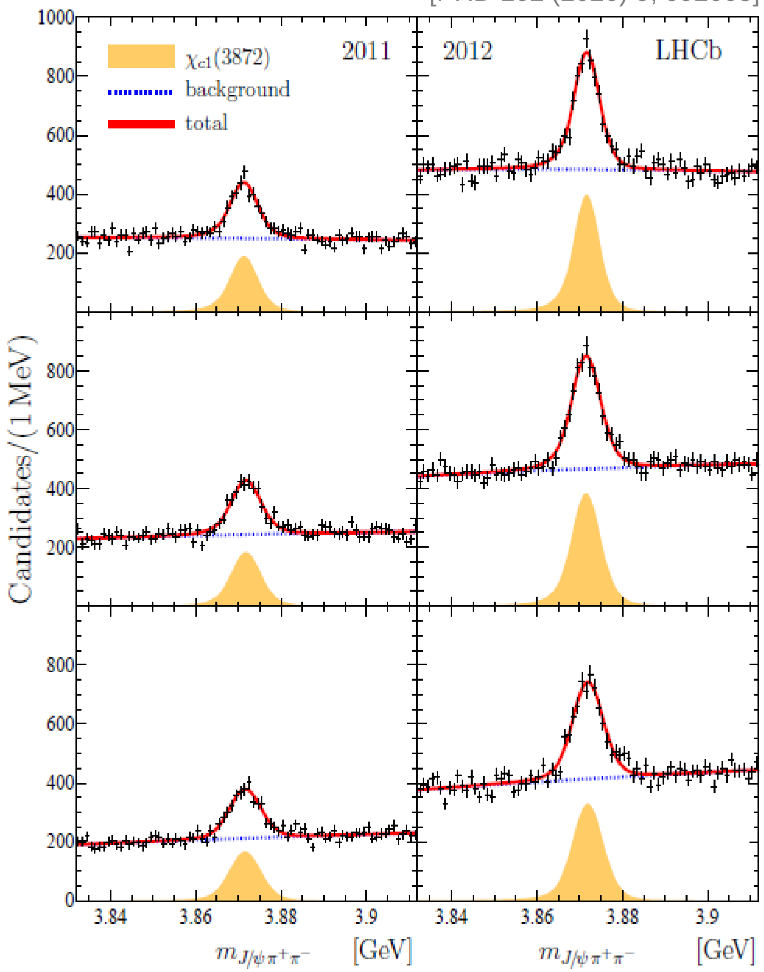
LHCb Findings

- Breit Wigner fit

$$m_{\chi_{c1}(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010\,\mathrm{MeV}$$
$$\Gamma_{\rm BW} = 1.39 \pm 0.24 \pm 0.10\ \mathrm{MeV}$$

[previous Belle result: Γ < 1.2 MeV (CL90)]

[PRD 102 (2020) 9, 092005]



- 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)

(Flatté energy E_f = -7.2 MeV)

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Factor 6.3, analysis dependent

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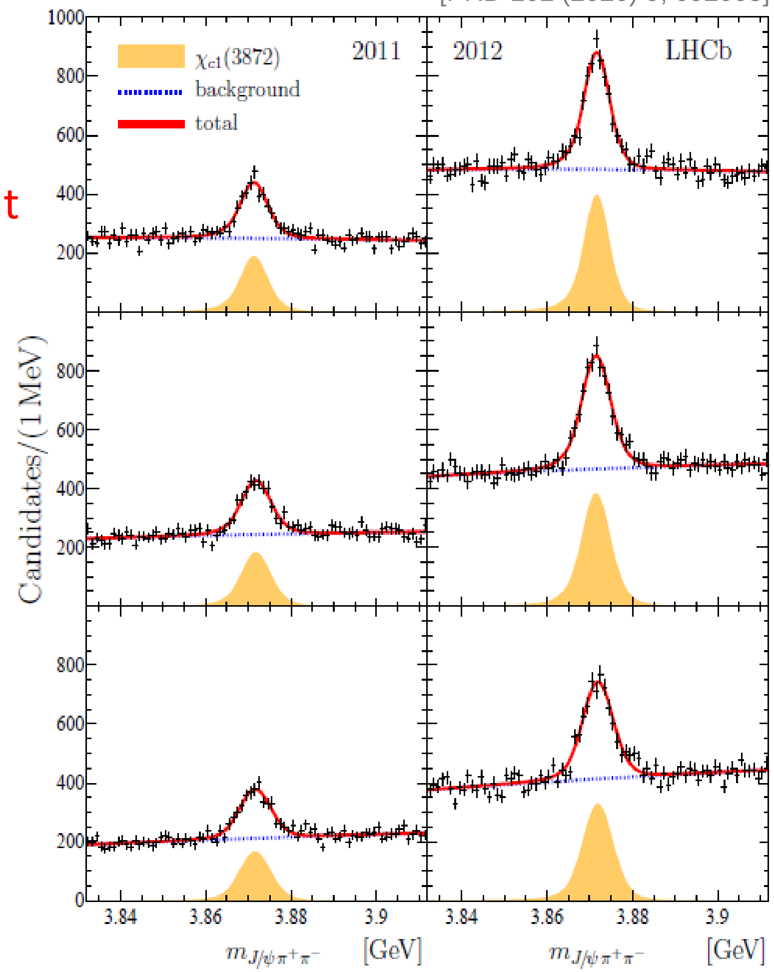
→ Need to fix the model!

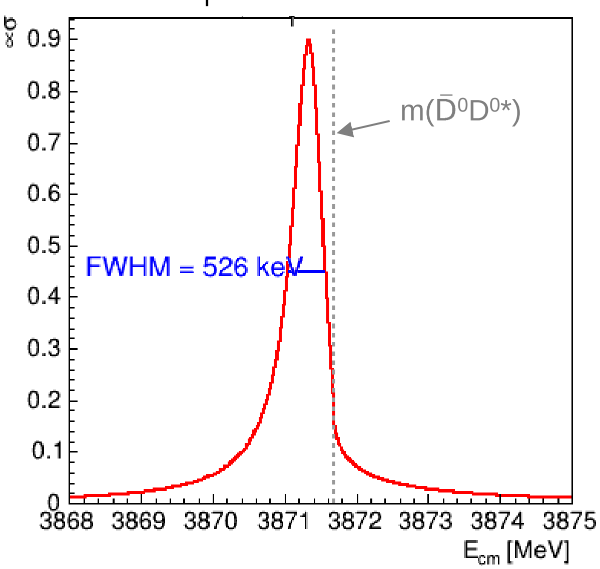
[PRD 102 (2020) 9, 092005]



$J/\psi\pi^+\pi^-$ Lineshapes

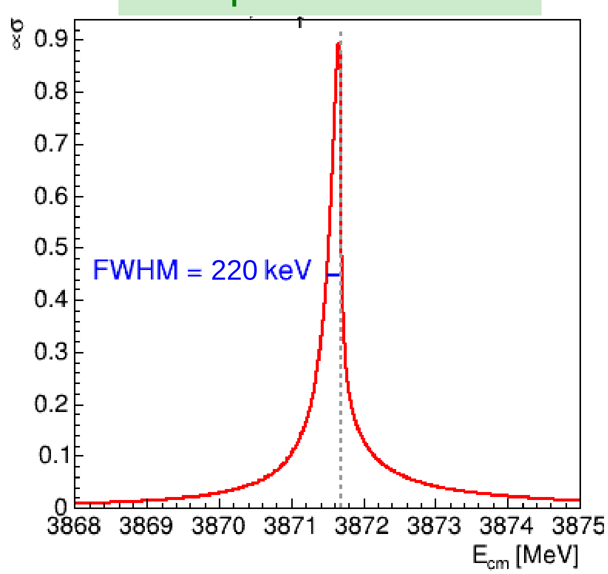
- Flatté Model by Hanhart et al. [PRD 76 (2007) 034007]
- Lineshape for various Flatté energies E_f *(other parms. const)*

E_f = -8.7 MeV

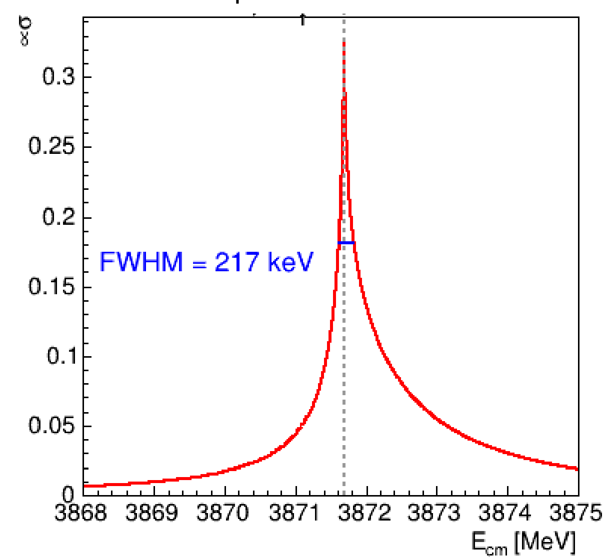


fixed by LHCb

E_f = -7.2 MeV

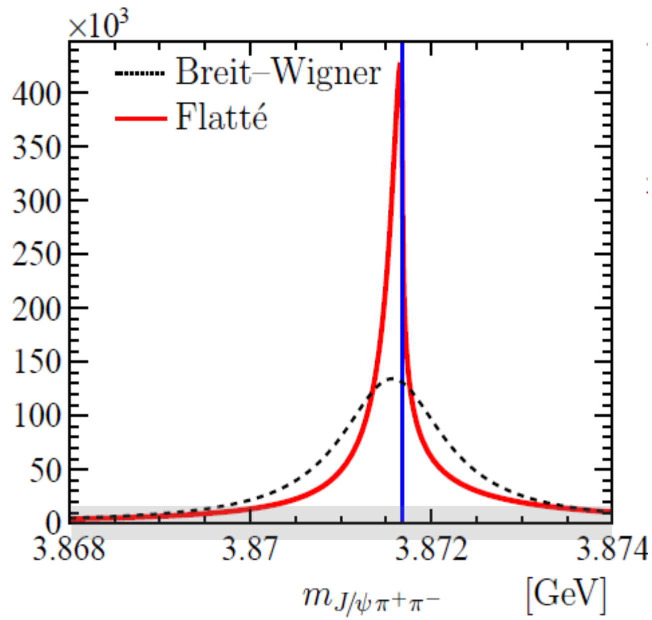


E_f = -5.7 MeV

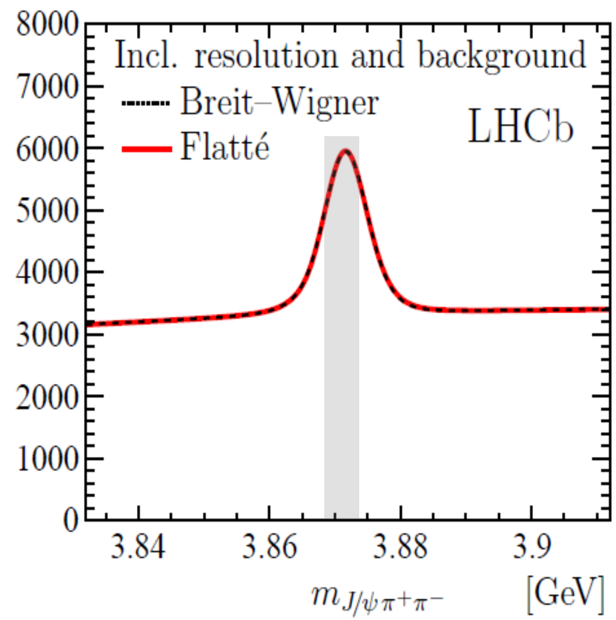


LHCb Lineshapes (incl Resolution)

Original lineshapes



Lineshapes with resolution



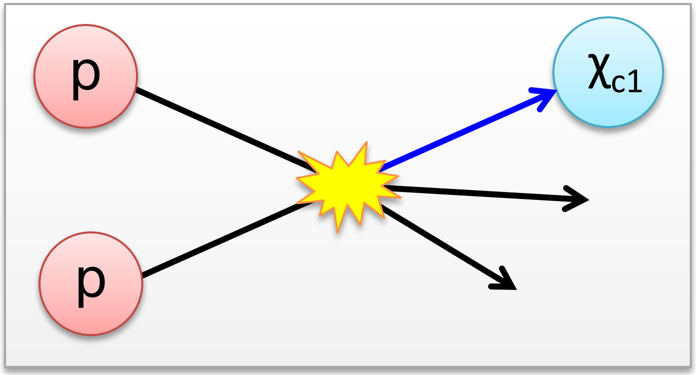
- Quote LHCb:

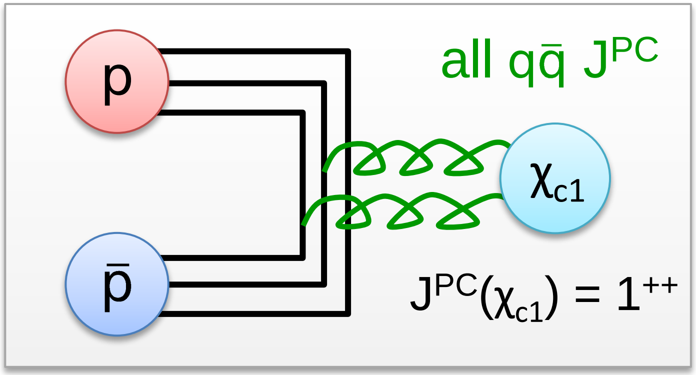
7.3 Comparison between Breit–Wigner and Flatté lineshapes

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 signifcantly narrower lineshape. However, after folding with the resolution function and adding the background, the observable distributions are indistinguishable.

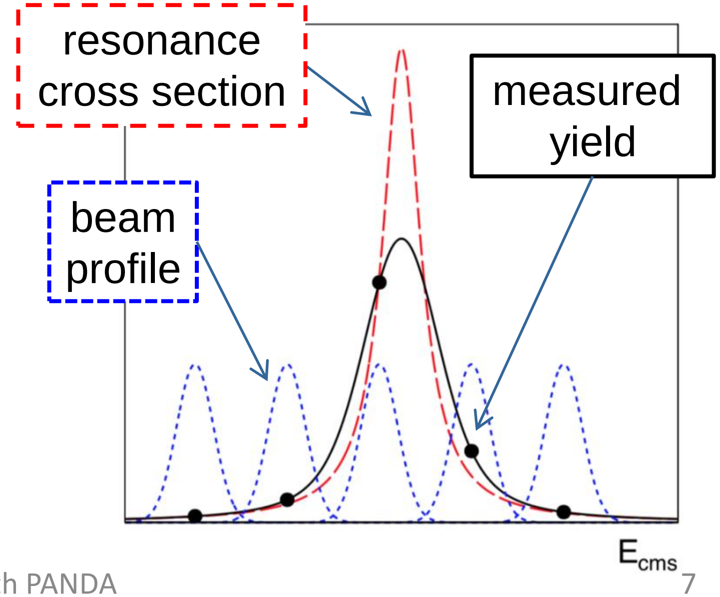
Overcome Detector Resolution with Formation

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





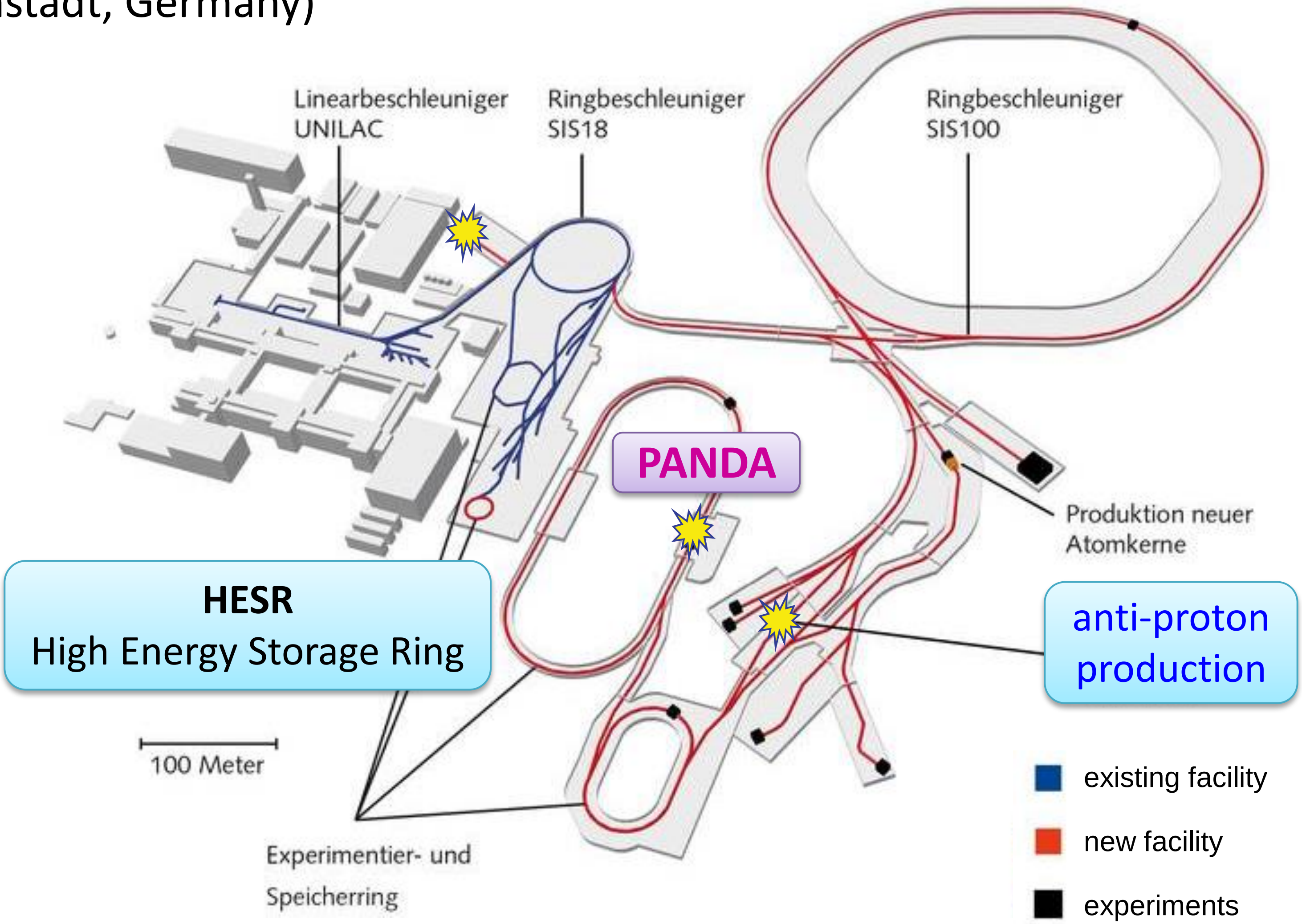
- Beam energy spread → resolution
- Measure yield at different E_{cms}



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

PANDA at FAIR

Facility for **A**ntiproton and **I**on **R**esearch
(GSI, Darmstadt, Germany)



FAIR Construction Site

- Good progress despite pandemic

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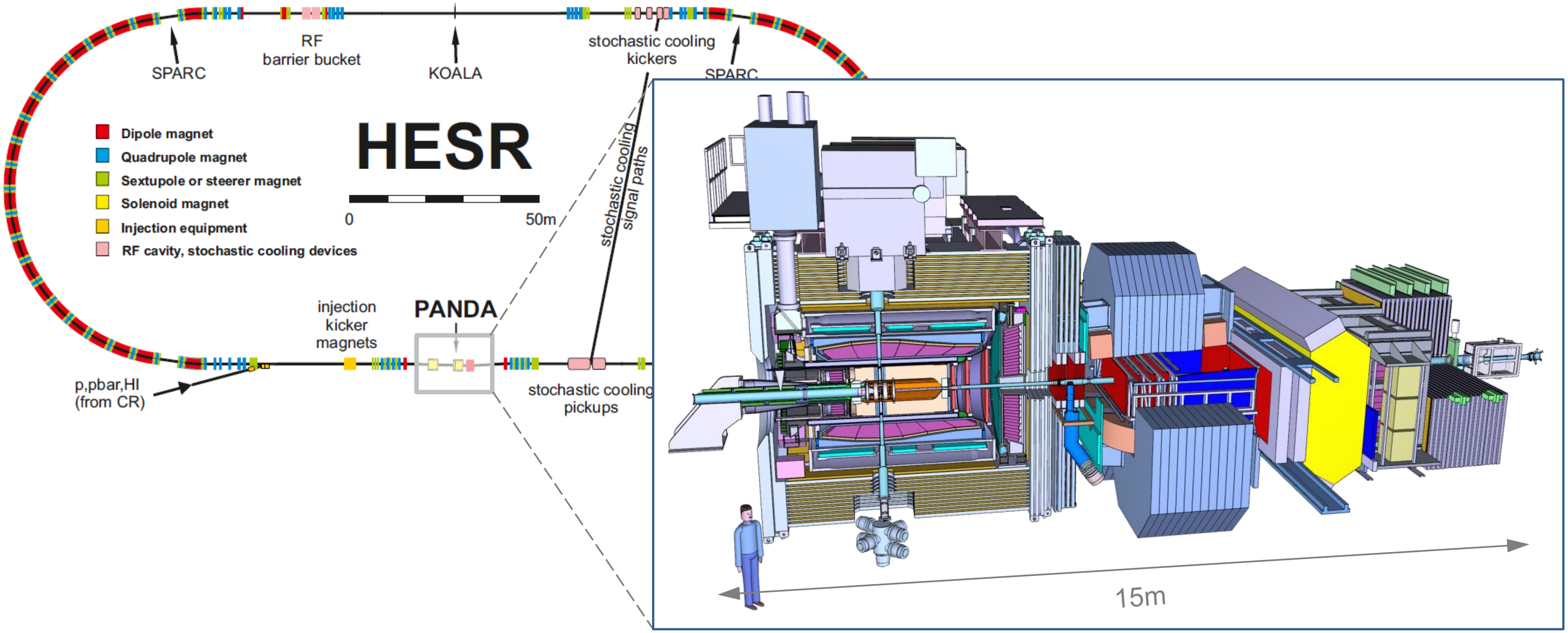
PANDA and HESR

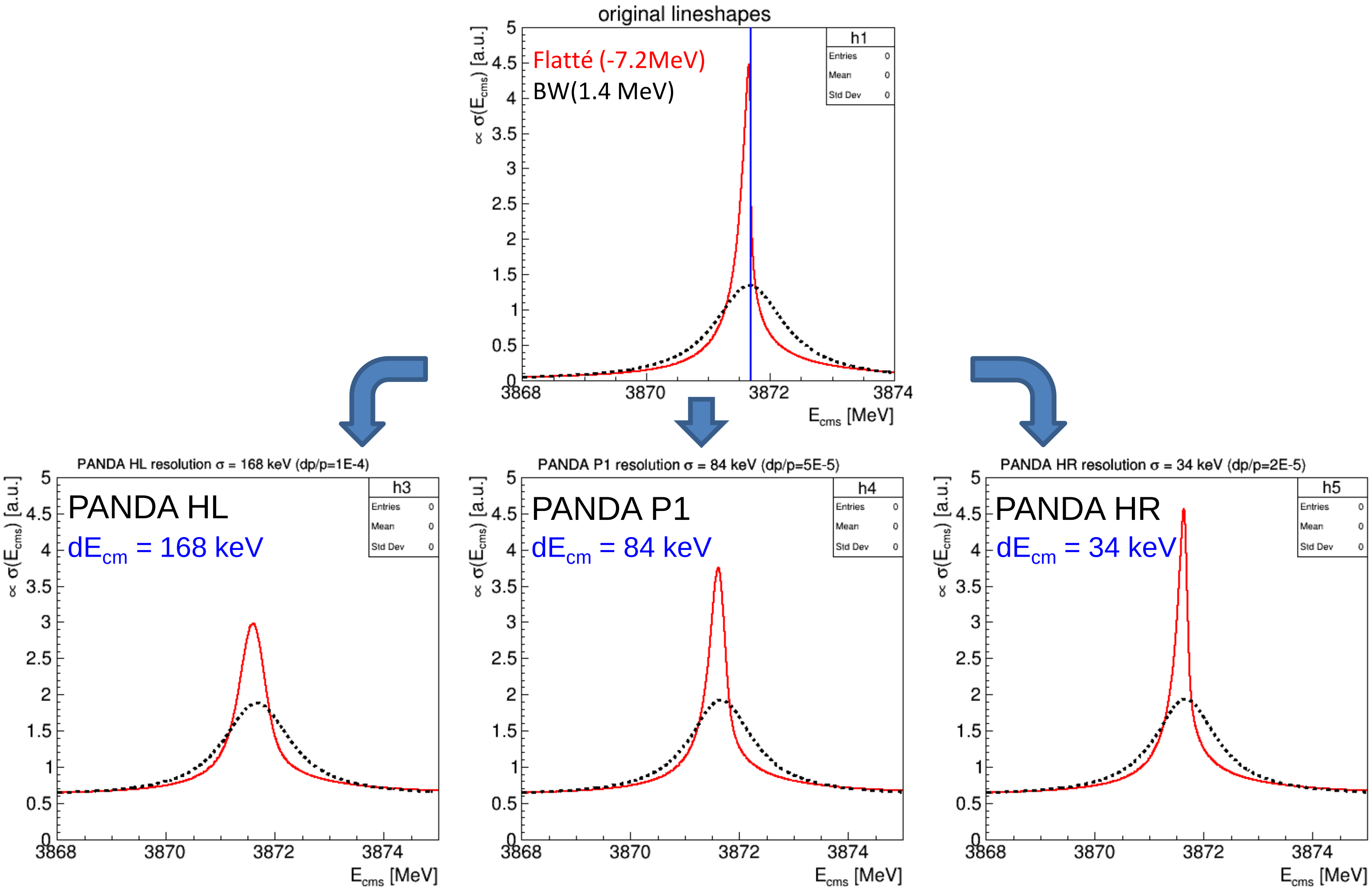


HESR mode	d*p*/*p*	L_{max} [1/cm²·s]	dE_{cm} [keV]
High Luminosity (HL)	$1 \cdot 10^{-4}$	$2.0 \cdot 10^{32}$	168
High Resolution (HR)	$2 \cdot 10^{-5}$	$2.0 \cdot 10^{31}$	34
Phase 1 Mode (P1)	$5 \cdot 10^{-5}$	$2.0 \cdot 10^{31}$	84

@ E_{cm} = 3872 MeV

What can PANDA do?

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



Strategy

Ingredients from our Simulation Study

Eur. Phys. J. A (2019) 55: 42
DOI 10.1140/epja/i2019-12718-2

[https://arxiv.org/abs/1812.05132]

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Precision resonance energy scans with the PANDA experiment at FAIR

Sensitivity study for width and line shape measurements of the X(3872)

- Reaction: $\bar{p}p \to \chi_{c1}(3872) \to J/\psi$ ($\to e^+e^-$ / $\mu^+\mu^-$) ρ^0 ($\to \pi^+\pi^-$)
- Take parameters (σ, L, $\mathcal{B}$, ε_{reco}, ...) from study to estimate expected yields

$$N_{exp}(E_{cms}) = \sigma(E_{cms}) \cdot L \cdot t \cdot \prod \mathcal{B}_i \cdot \varepsilon_{reco}$$

- **Investigate separation power between Flatté & BW lineshapes**

Total beam time: $T = 40 \times 2d = 80$ d

Cross section assumption: $\sigma_{peak}(\bar{p}p \to \chi_{c1}) = 50$ nb

Flatté energy: E_f = [-8.7, -8.2, -7.7, **-7.2**, -6.7, -6.2, -5.7, -5.2] MeV

BW Width: Γ = [100, 150, 200, 250, 300, ... , 550] keV

Procedure

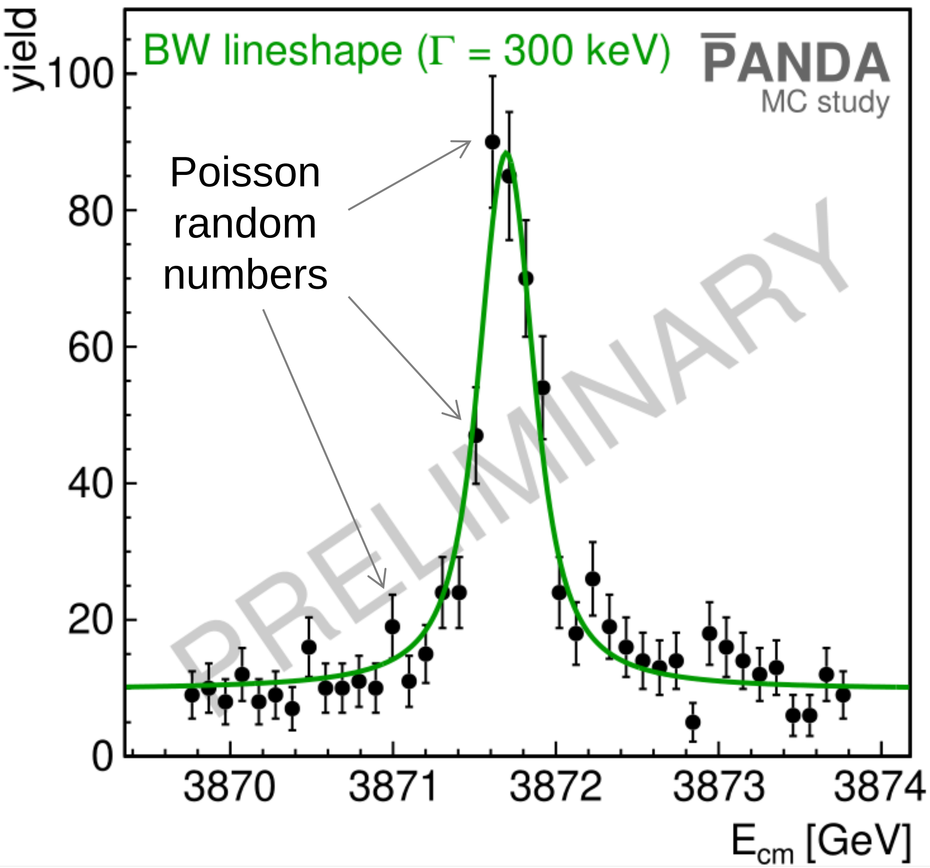
We use the following approach:

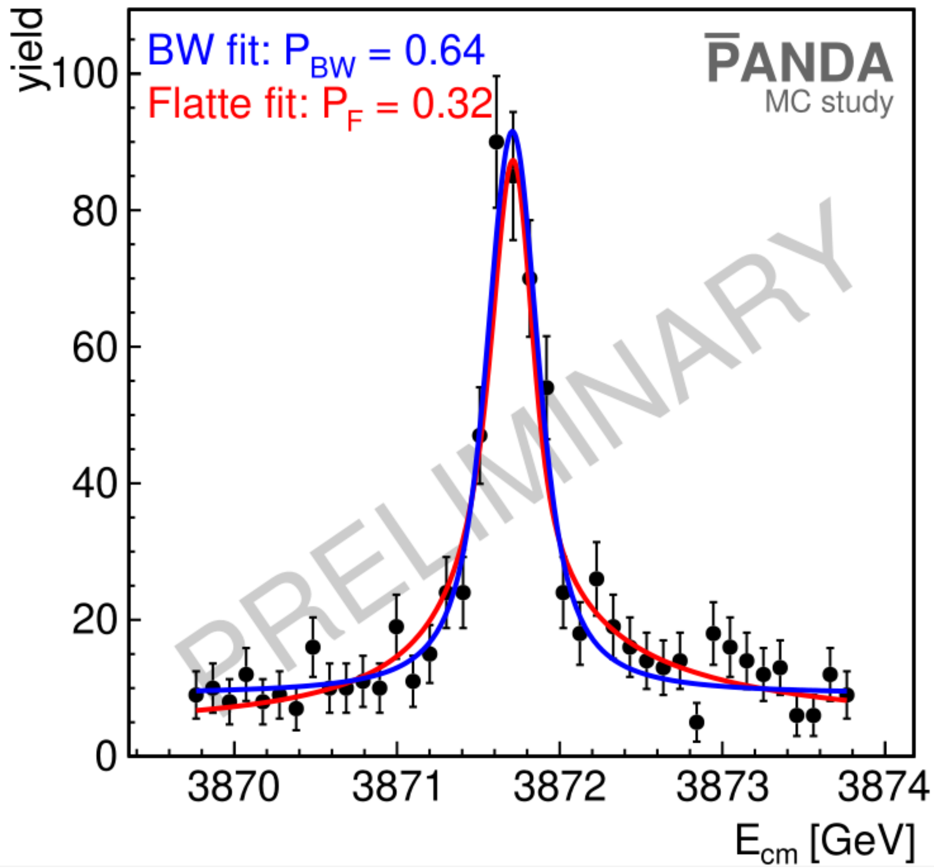
1. Use key parameters from EPJ A 55 (2019) 42
2. Generate many (toy) spectra for Flatté (BW) model
3. Fit both BW and Flatté to each generated distribution and determine fit probabilities P_{BW} and P_F
4. Identification considered correct, if $P_F > P_{BW}$ ($P_{BW} > P_F$)
5. Count fraction of incorrect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

Scan Procedure Principle (Example)

Example: Breit-Wigner, Γ = 300 keV (P1 mode)

1. Compute true lineshape reflecting the expected yields
2. Generate poisson random number $N_{poisson}$ for each E_{cm} and fill into graph
3. Fit lineshapes to extract fit probabilities P_{BW} and P_F





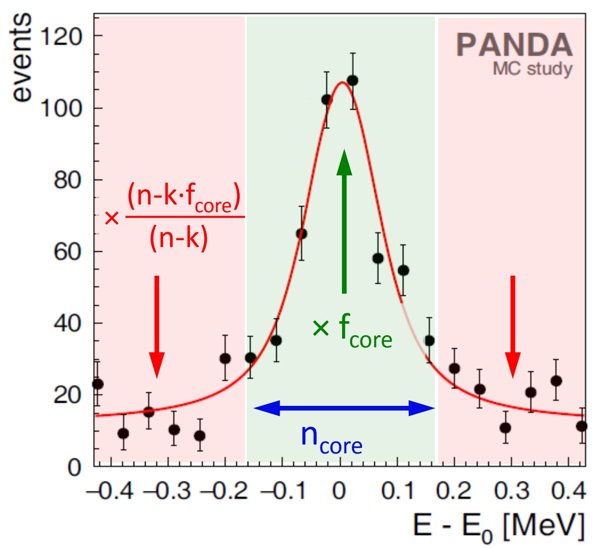
Scan Time Optimization

Scan Time Optimisation

- Idea: Find better scan time distribution than constant time per energy

- Simple idea for optimisation approach:
  → Keep 40 equidistant energies in fixed energy range
  → Enhance the scan precision in center

- For that purpose:
  - Choose number $\mathbf{n_{core}}$ of central energy points
  - Take factor $\mathbf{f_{core}}$ more data at expense of tails to
  - Keep total beam time constant (T = 80d)

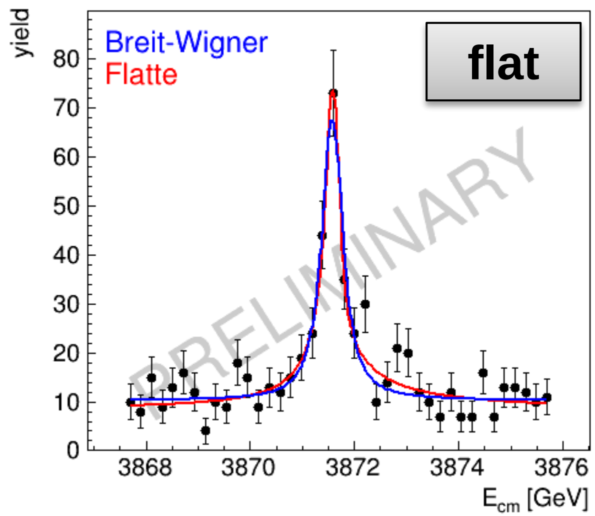


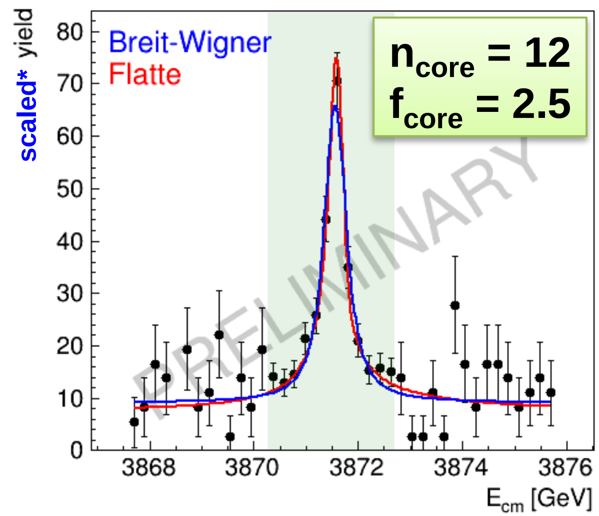
- Perform 2-dimensional grid search to identify optimum combination of (n_{core}, f_{core})

Scan Optimisation Example (P1)

- **P1 Mode**: Generated with Flatté model (E_f = -7.2MeV)

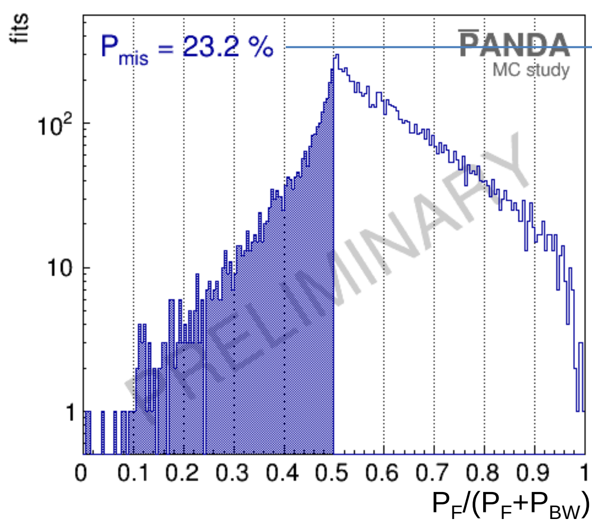
Fit Example

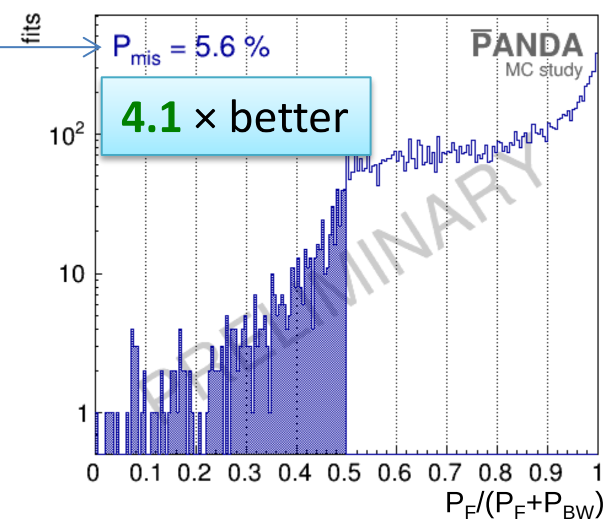




* yields scaled, errors adapted

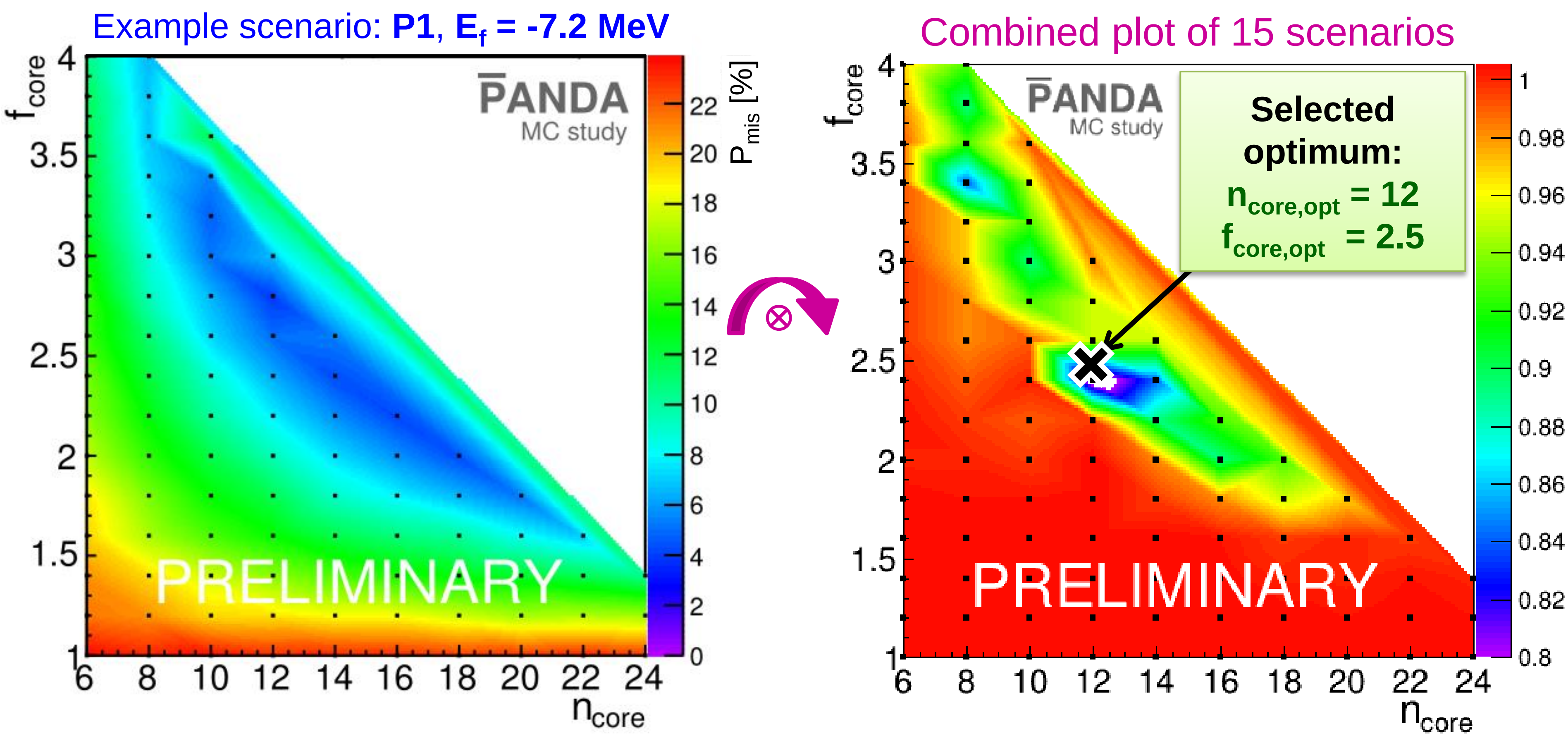
mis-ID from 10000 fits





Overall Optimisation

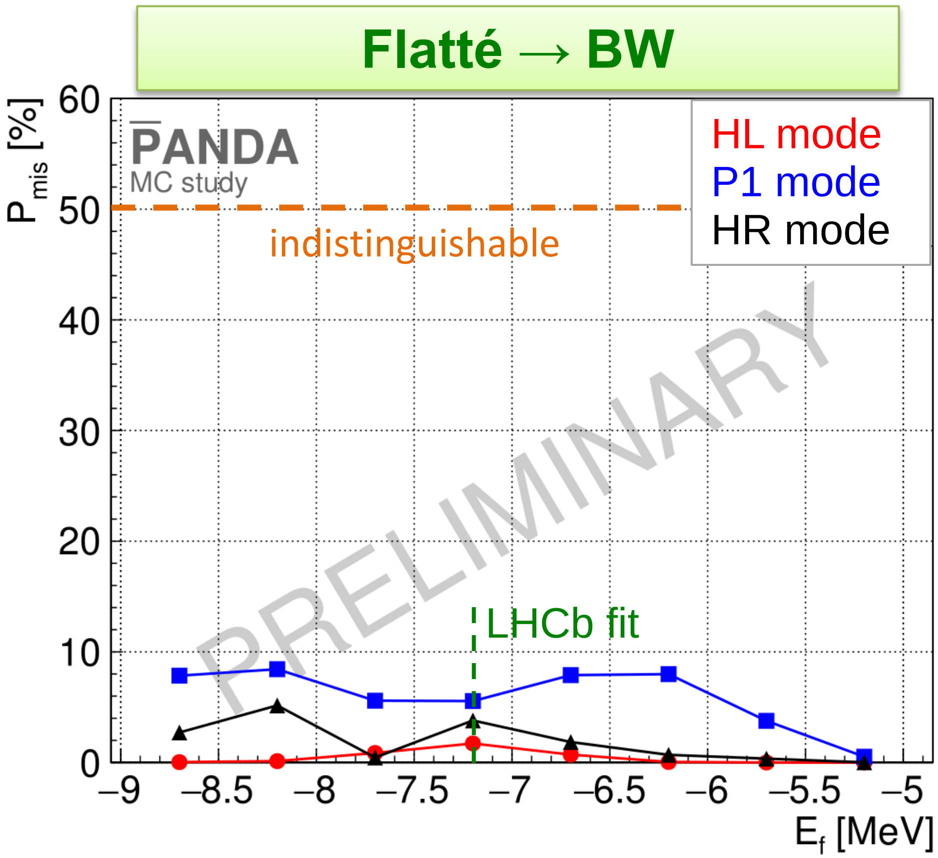
- Compute P_{mis} for 15 different scenarios with 91 $(f,n)_{core}$ combi's each
  (HL, P1, HR) ⊗ (E_f = [-6.2, -7.2, -8.2] MeV & Γ = [0.3, 0.5] MeV)
- Combine plots of 15 scenarious



RESULTS

Parameter Dependent Performance

- Performance across Flatté energy E_f range

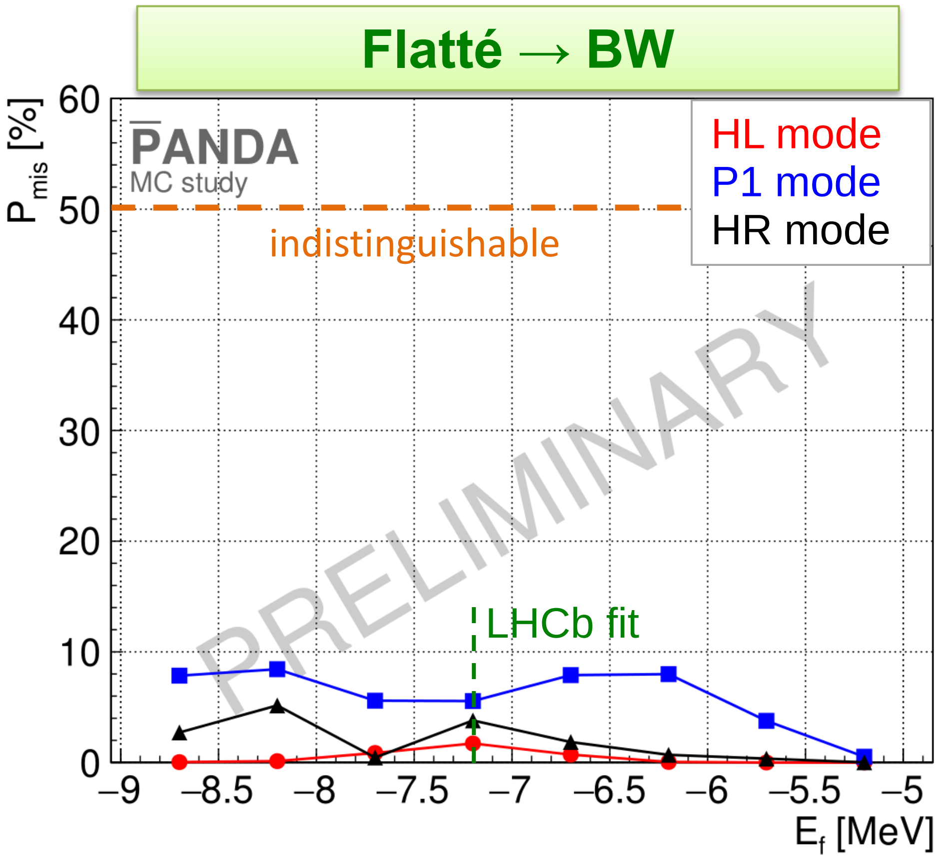


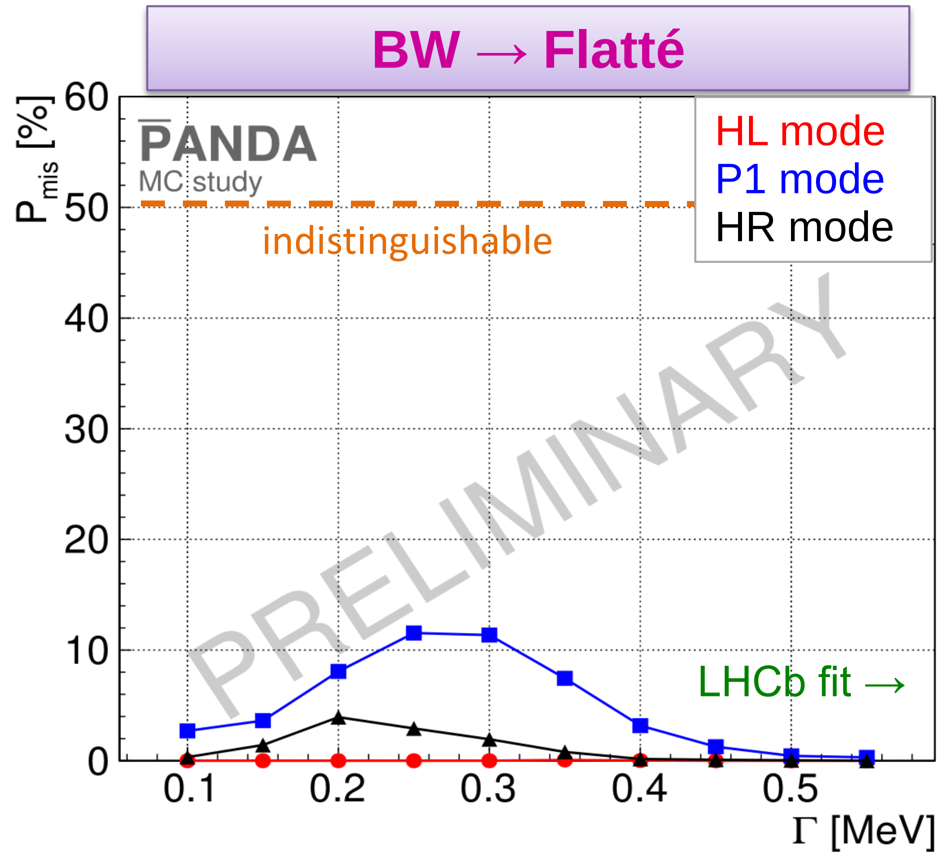
For Mis-match of Flatté as BW we see

- for the three beam modes **HL**, **HR**, **P1**
- the mis-identification probability $\mathbf{P_{mis}}$
- across range of input parameters $\mathbf{E_f}$
- with **LHCb** best fit E_f = -7.2 MeV
- and $\mathbf{P_{mis}}$ **= 50%** for "indistinguishable"

Parameter Dependent Performance

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





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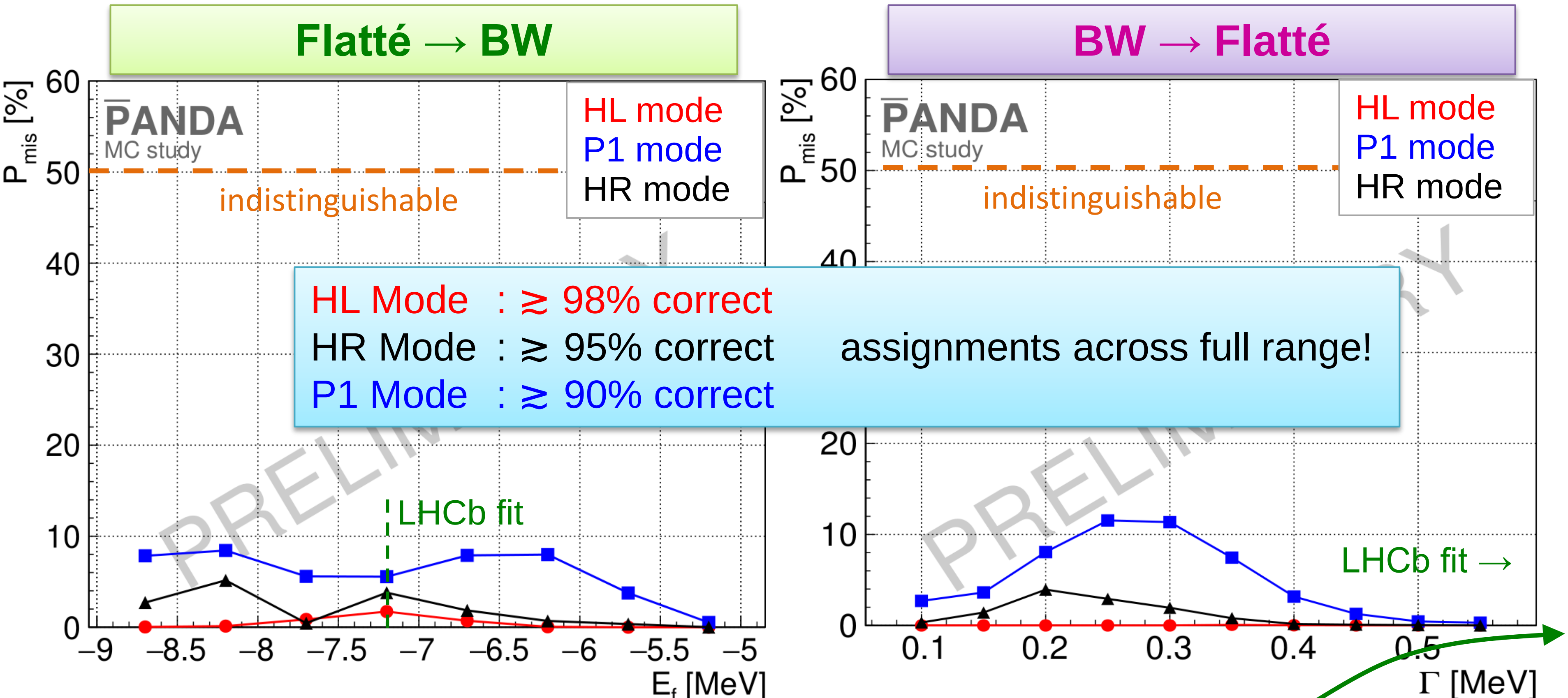


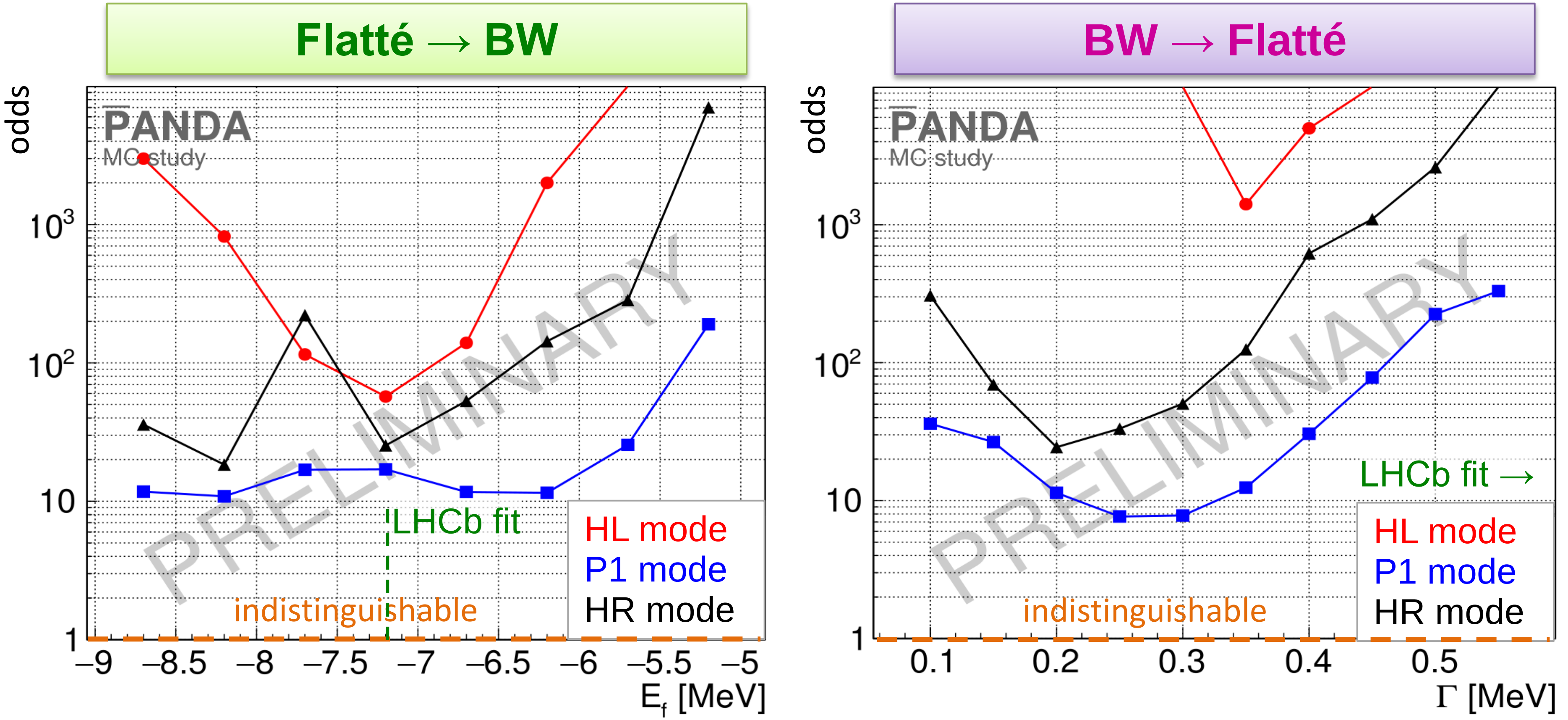
HL Mode : ≳ 98% correct
HR Mode : ≳ 95% correct
P1 Mode : ≳ 90% correct
assignments across full range!

N.B.: For BW **Γ = 1.4 MeV** we find 0% mis-ID in all modes...

Performance - Alternative Representation

- How much better than "indistinguishable" is it?
- Idea: Consider so-called **odds** = correct identifications per wrong one

$$\text{odds} = (1 - P_{mis}) / P_{mis}$$



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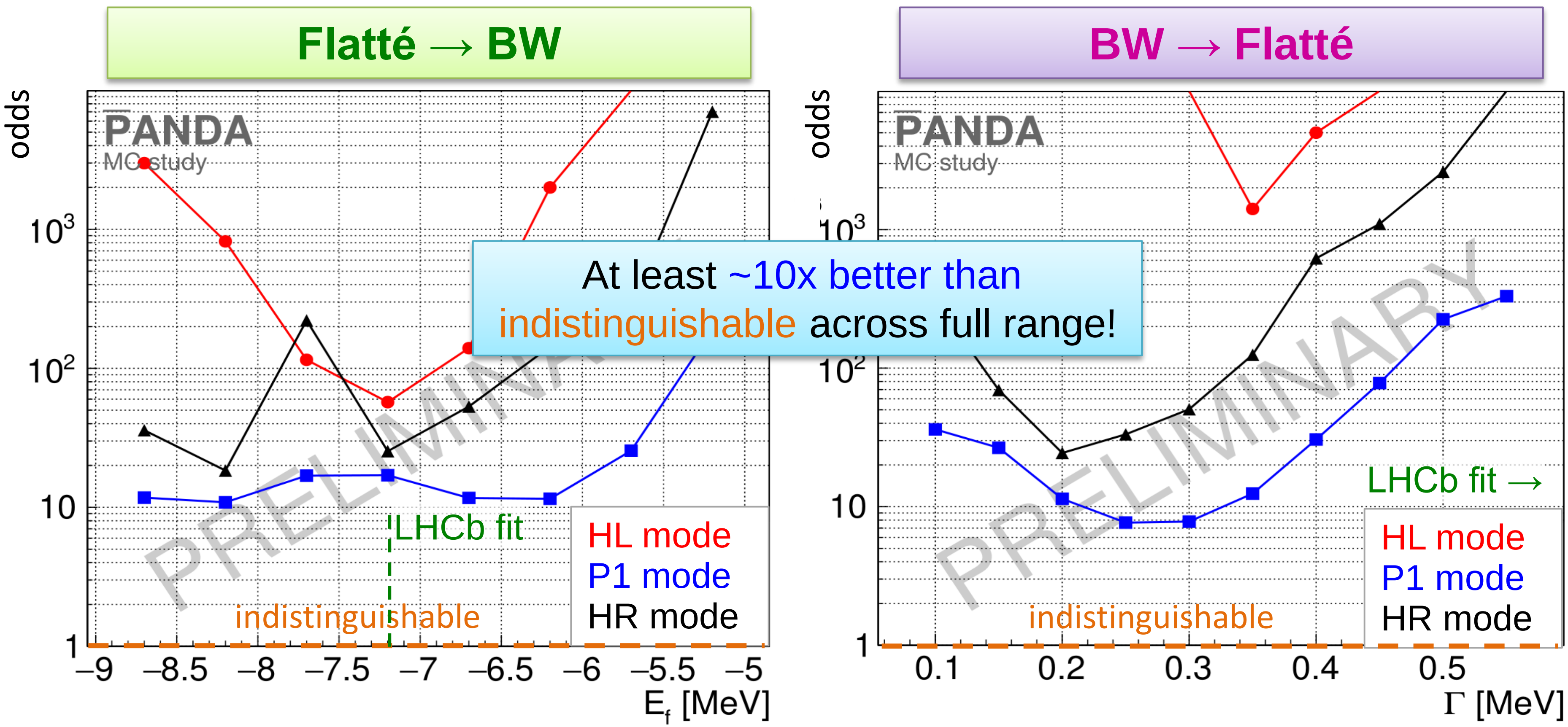

Summary and Conclusion

- Simulation of line shape measurement of $\chi_{c1}(3872)$ at **PANDA**
  ⇒ Different models can be well distinguished

- Correct assignment of fit model over full range between
  ≳90% (P1) and **≳98% (HL)** depending on beam mode

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Thank you very much for your attention!