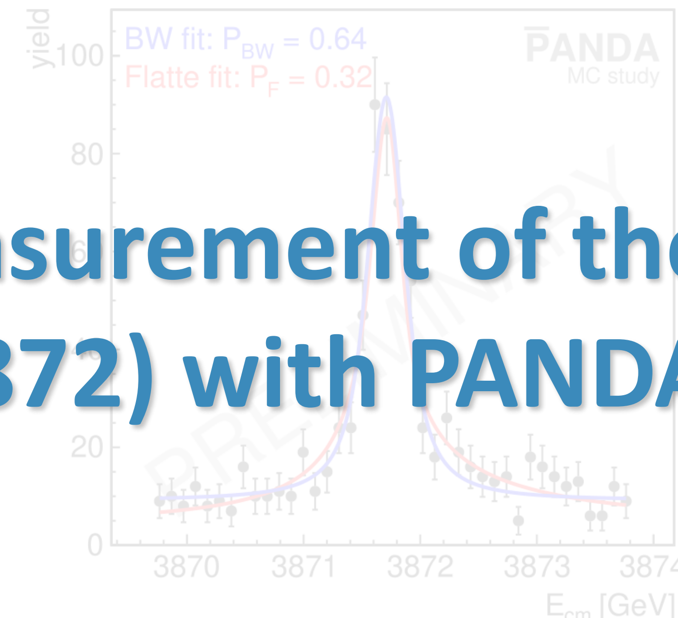


Line shape measurement of the $\chi_{c1}(3872)$ with PANDA

Klaus Götzen and Frank Nerling **for the PANDA Collaboration**

GSI Darmstadt

PhiPsi Workshop 2022

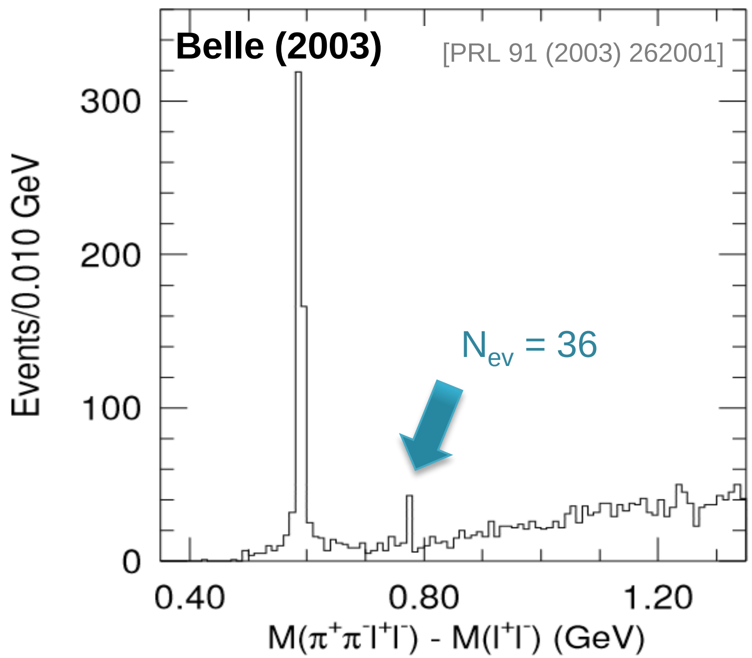
13th International Workshop on e^+e^- Collisions from Phi to Psi

Aug. 15-19, 2022

INTRODUCTION

Why Lineshapes are Important

- χ_{c1}(3872) discovered 2003 is 1st of charmonium-like XYZ states
- Nature is still not understood even after 20 years!



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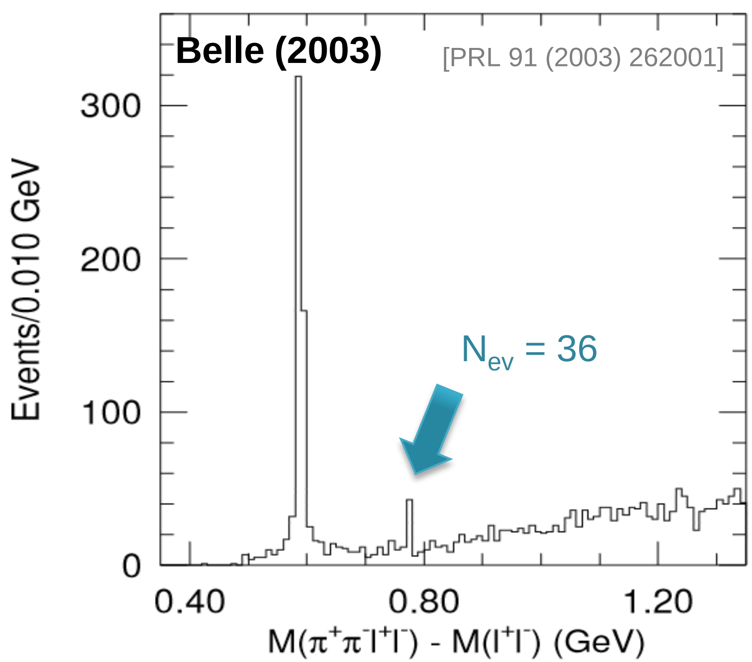
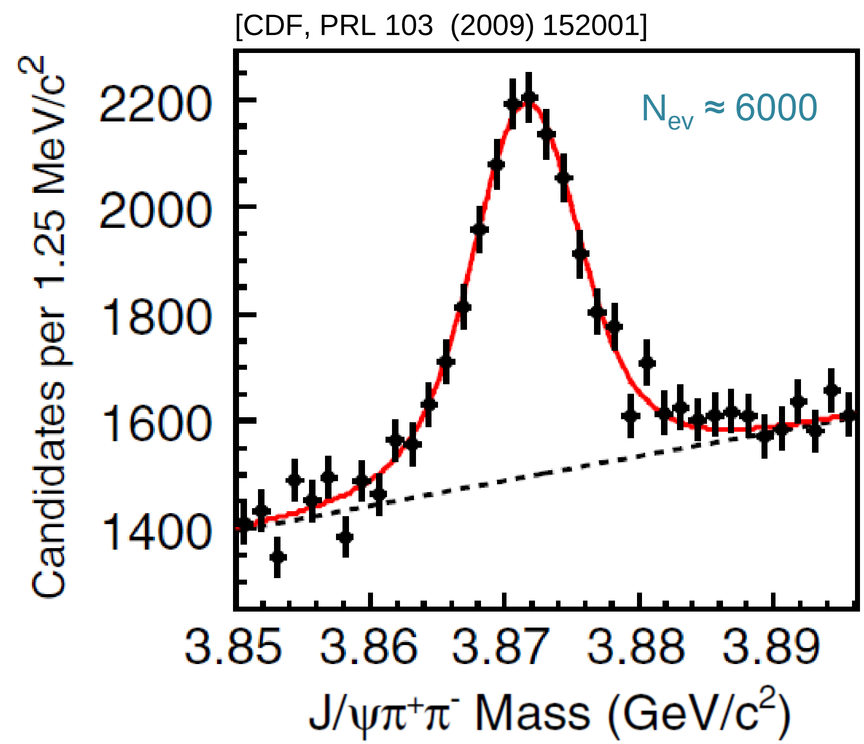
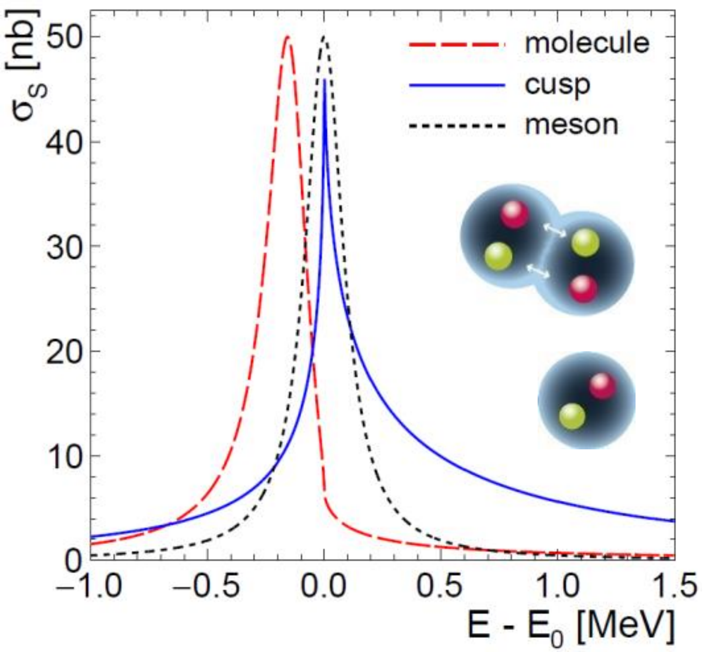


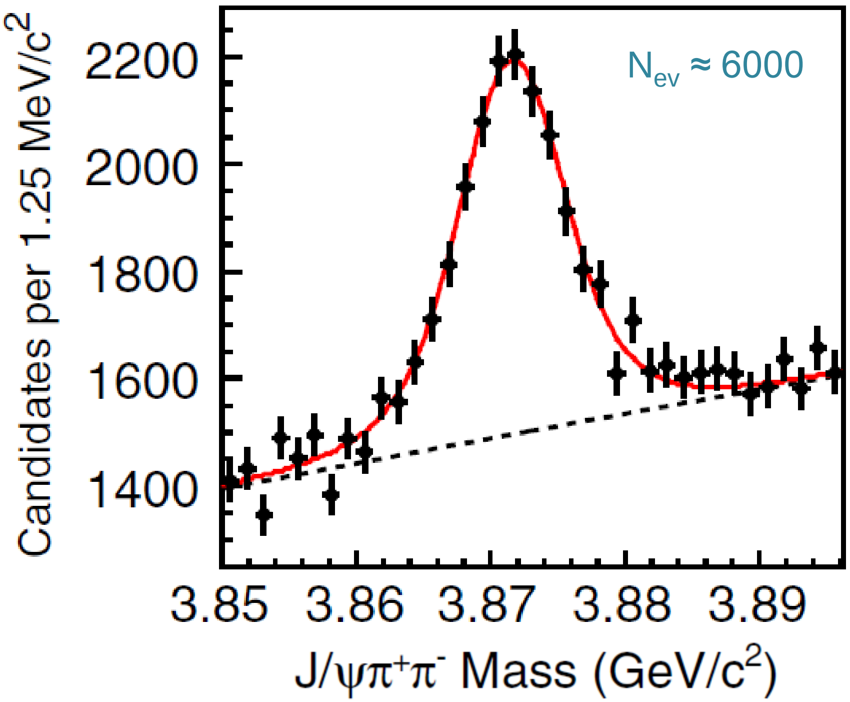


Why Lineshapes are Important

- χ_{c1}(3872) discovered 2003 is 1st of charmonium-like XYZ states
- Possible solution:
  - Different internal structure → different production/decay dynamics
  - Line shape of resonance reveals nature!

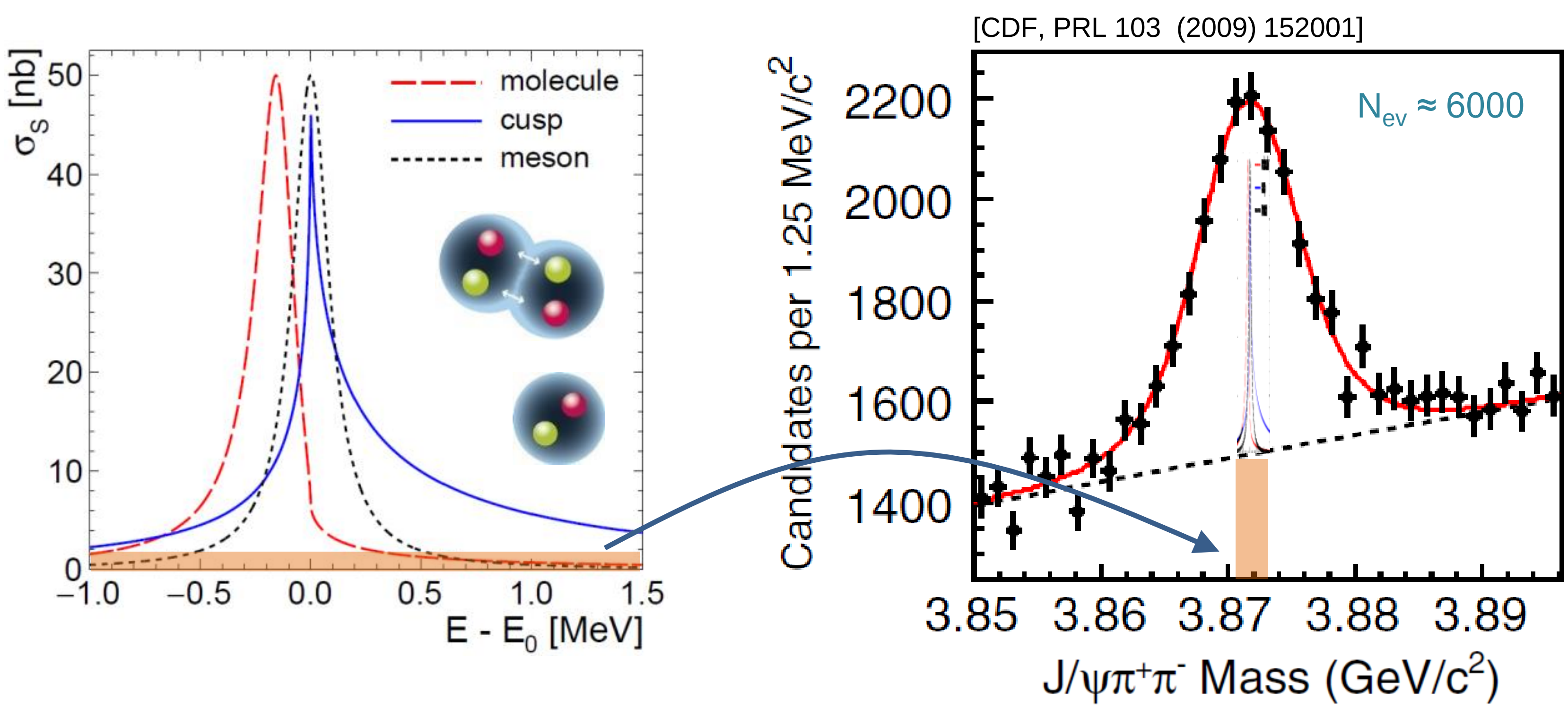


[CDF, PRL 103 (2009) 152001]



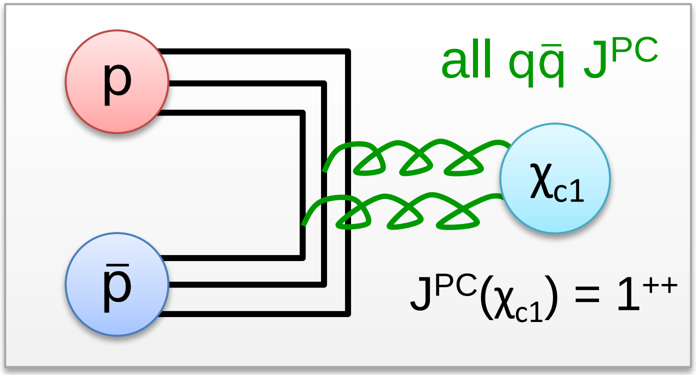
Why Lineshapes are Important

- χ_{c1}(3872) discovered 2003 is 1st of charmonium-like XYZ states
- Possible solution:
  - Different internal structure → different production/decay dynamics
  - Line shape of resonance reveals nature!
  - High resolution needed to resolve structures!

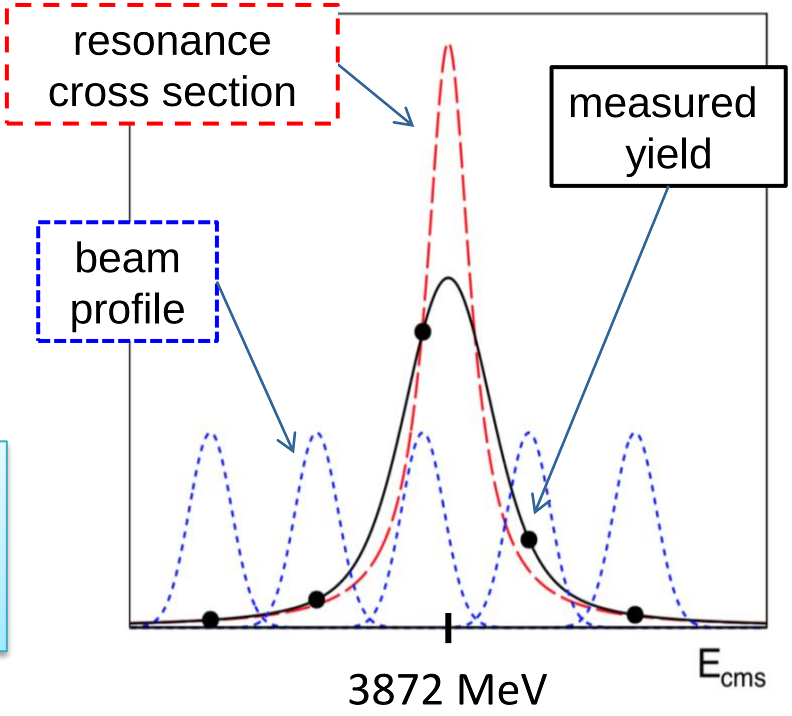


Overcome Detector Resolution ⇒ Formation

- Formation reaction → produce $\chi_{c1}(3872)$ [$J^{PC} = 1^{++}$] w/o recoils



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

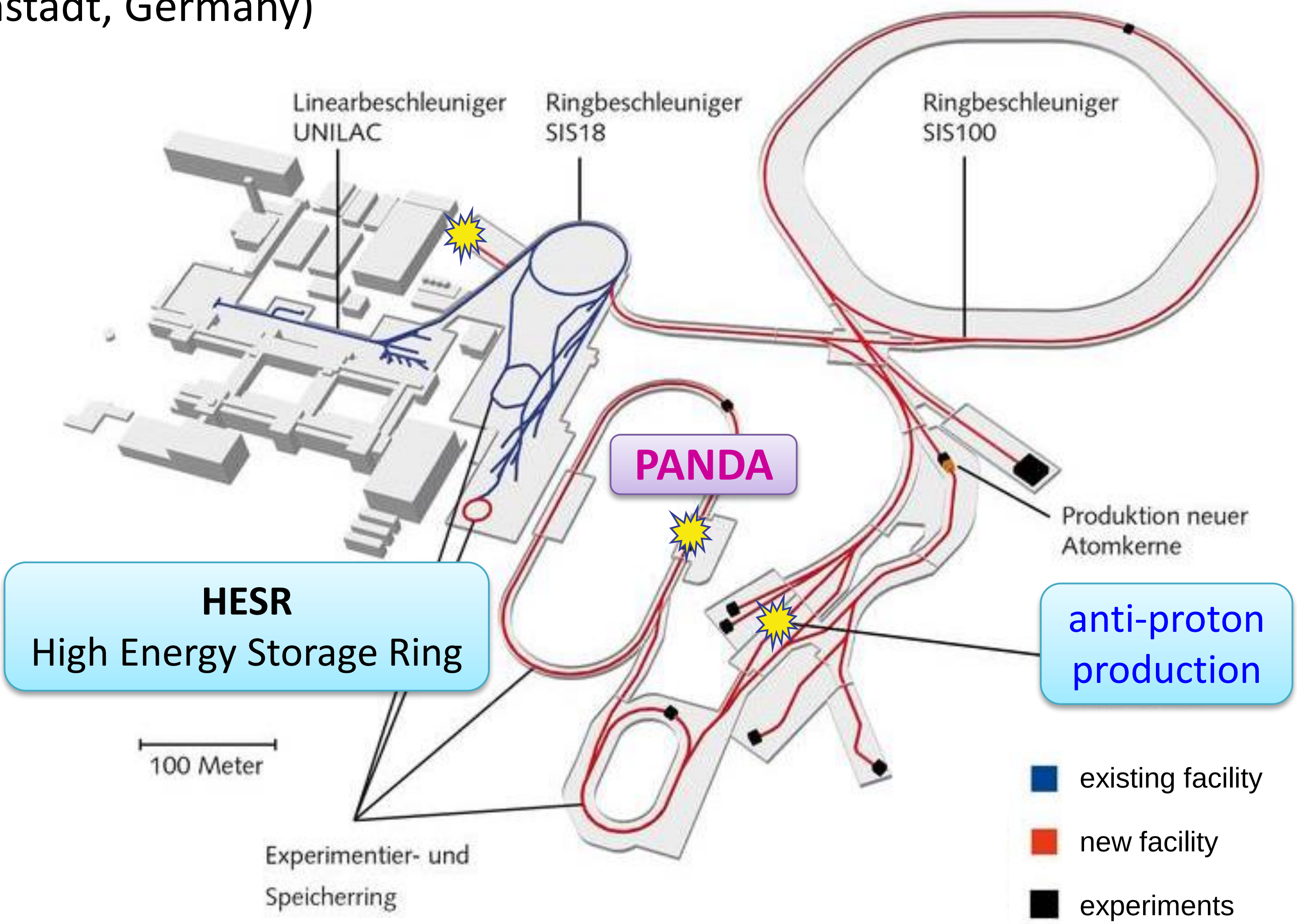


Typical Detector Resolution ≈ 5 MeV
PANDA Beam Resolution ≈ 0.05 MeV

PANDA at FAIR

PANDA at FAIR

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



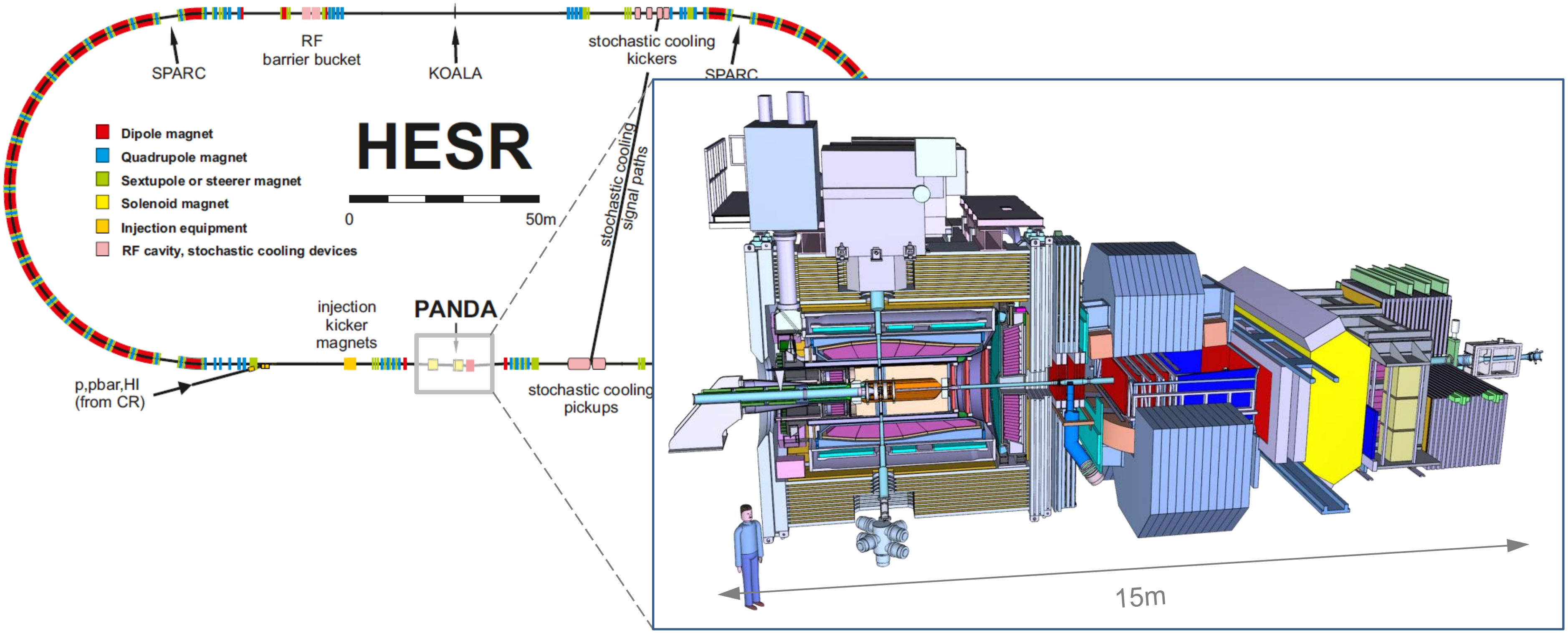
FAIR Construction Site

- Good progress at construction site

FAIR Construction Site

- Good progress at construction site

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

SENSITIVITY STUDY

Comprehensive Sensitivity 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: $\bar{p}p \rightarrow \chi_{c1}(3872) \rightarrow J/\psi$ ($\rightarrow e^+e^-$ / $\mu^+\mu^-$) ρ^0 ($\rightarrow \pi^+\pi^-$)
- Determine the precision for line-shape measurement at PANDA of
  - Breit-Wigner Width **Γ**
  - Flatté Energy $\mathbf{E_f}$
- Investigated Parameter Space:

Total beam time: T = 40 × 2d = 80 d

Cross section assumption: $\sigma_{peak}(\bar{p}p \rightarrow \chi_{c1})$ = 20 .. 150 nb

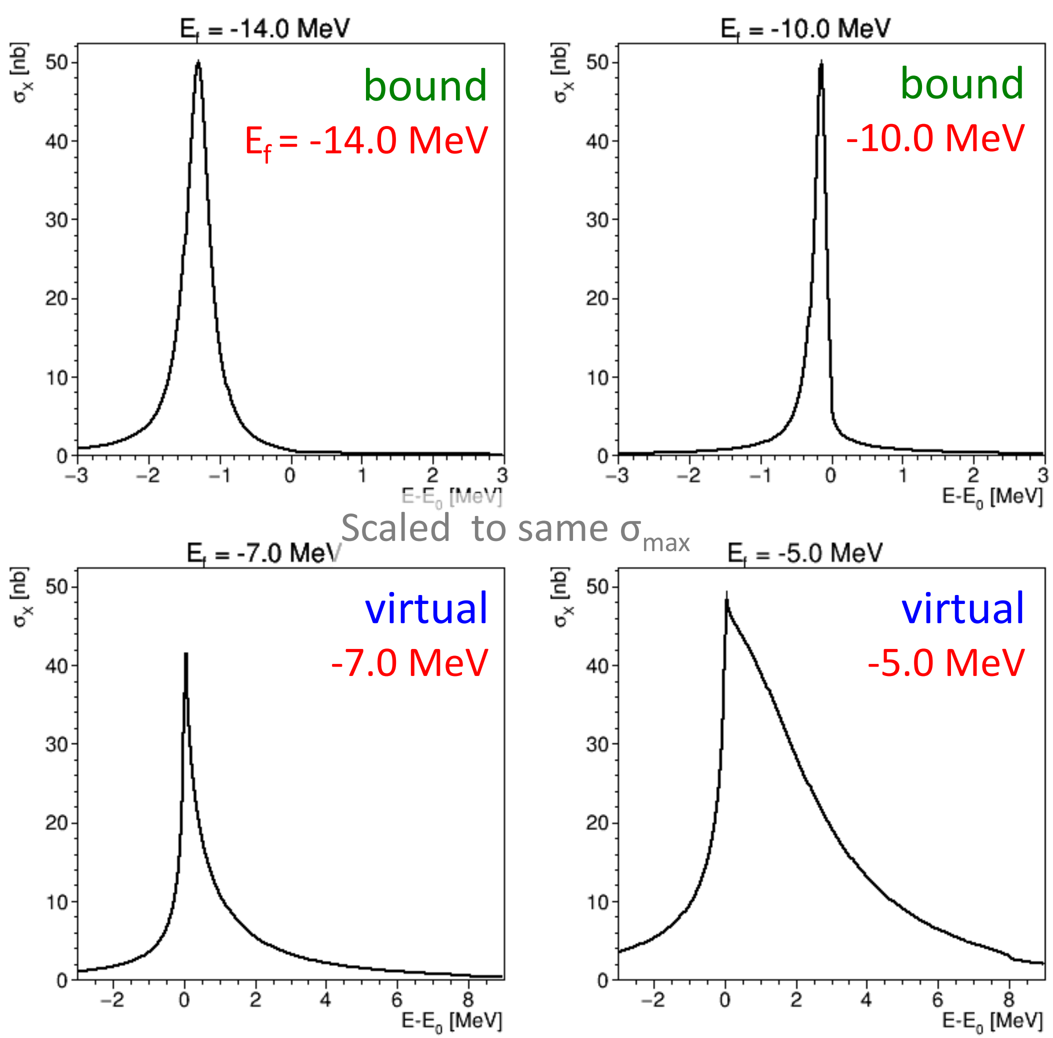
BW Width: Γ = [50, 70, 100, 180, 250, 500] keV

Flatté energy: E_f = [-10.0, -9.5, -9.0, -8.8, -8.3, -8.0, -7.5, -7.0] MeV

Flatté Model

- Line shapes for Flatté model [Hanhart et al, PRD 76 (2007) 034007]
- Channel: $\chi_{c1}(3872) \rightarrow J/\psi\ \rho^0$

$$\sigma(E; E_f) \sim \frac{\Gamma_{\pi^+\pi^- J/\psi}(E)}{|D(E; E_f)|^2}$$

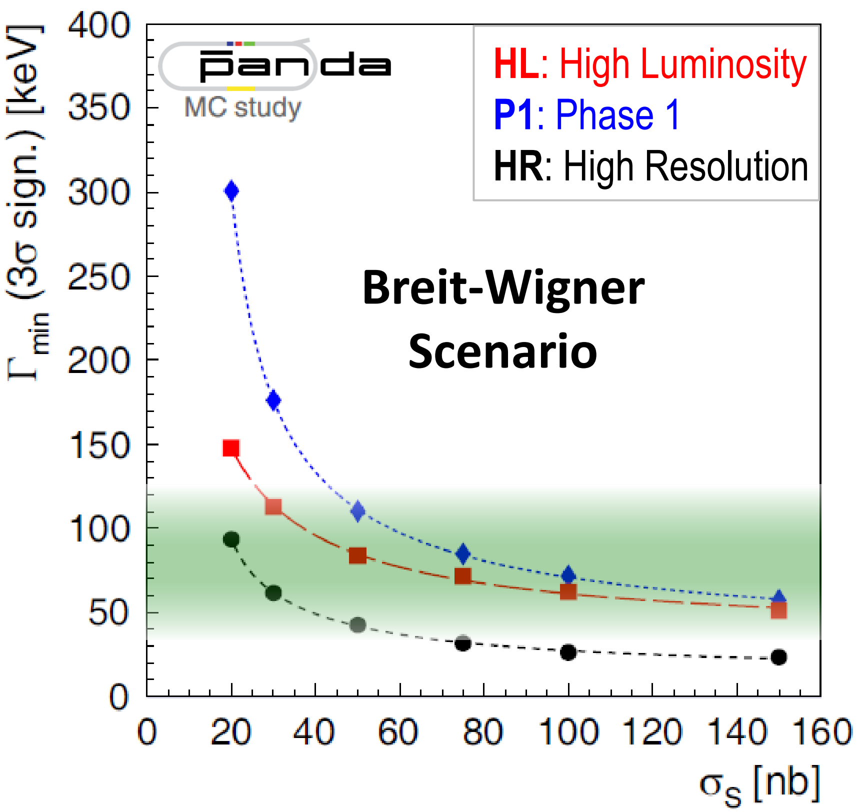


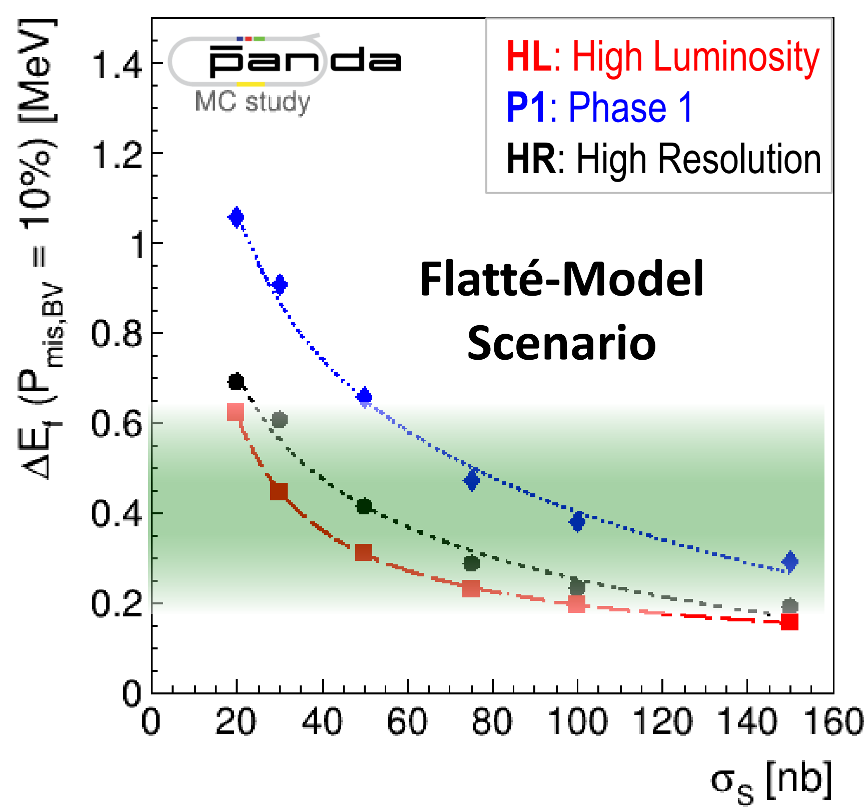
(with f_ρ=0.00047, f_ω=0.00271, g=0.137, Γ_0=1.0 MeV)

Precise Line Shape Sensitivity Study

- Expected sensitivity for BW Width Γ & Flatté Parameter E_f
- Breit-Wigner: 3σ precision at down to Γ = O(50 − 100) keV!
- Flatté: Precision in sub-MeV range!

[Eur. Phys. J. A 55 (2019) 3, 42, arXiv:1812.05132]





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.

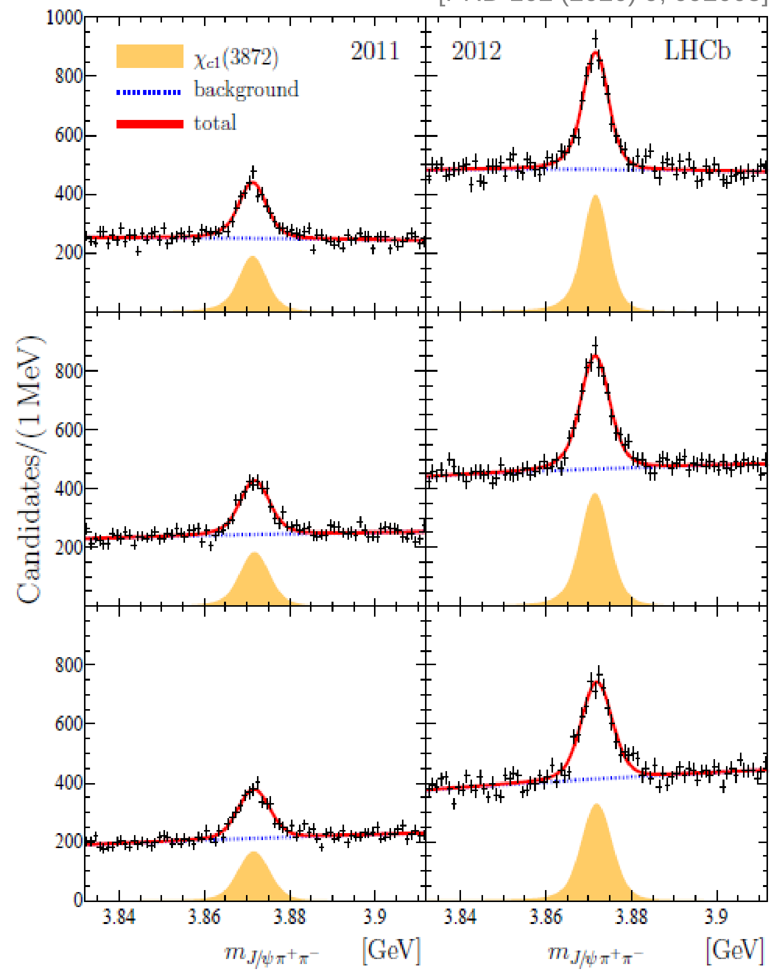
LHCb Findings

- Breit Wigner fit

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

[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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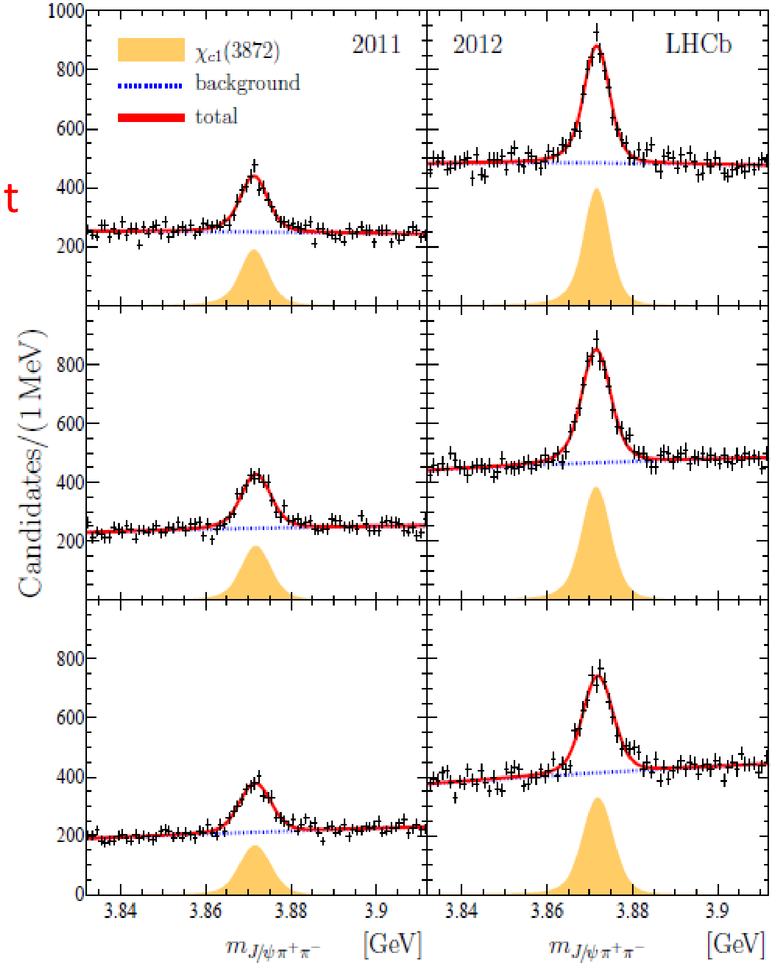
(Flatté energy E_f = -7.2 MeV)

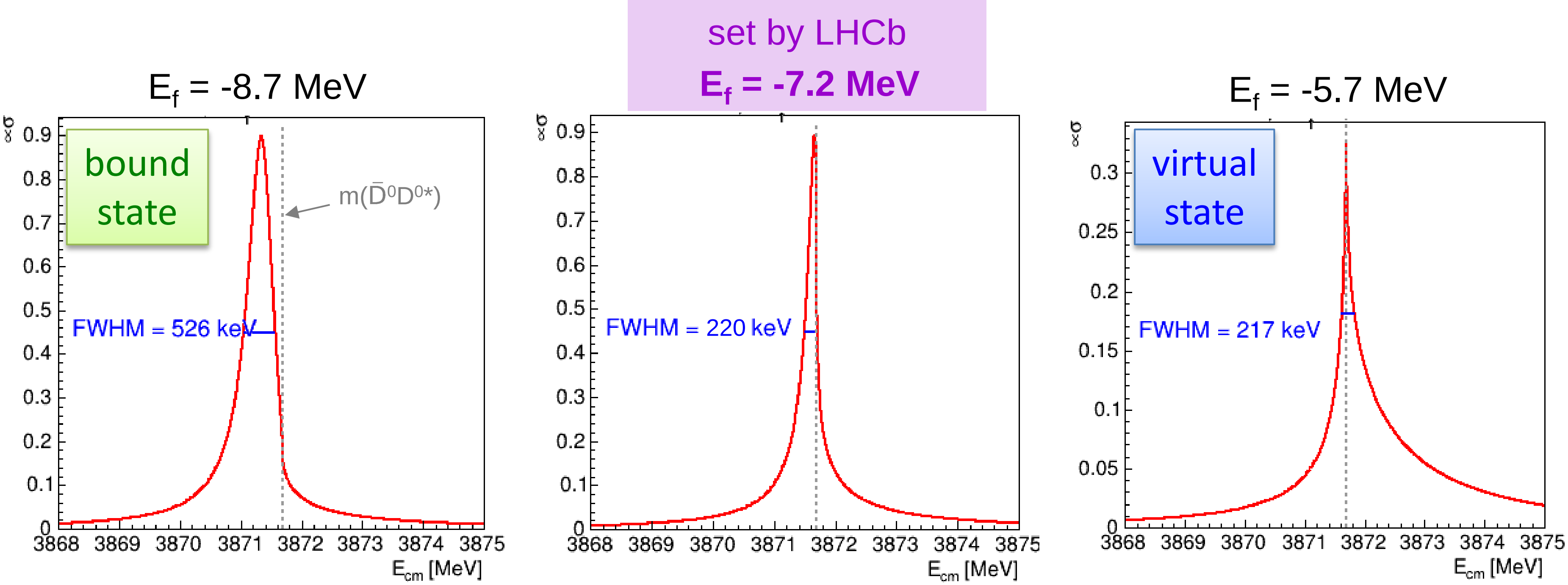
→ Need to discriminate models!

[PRD 102 (2020) 9, 092005]



J/ψπ⁺π⁻ Lineshapes

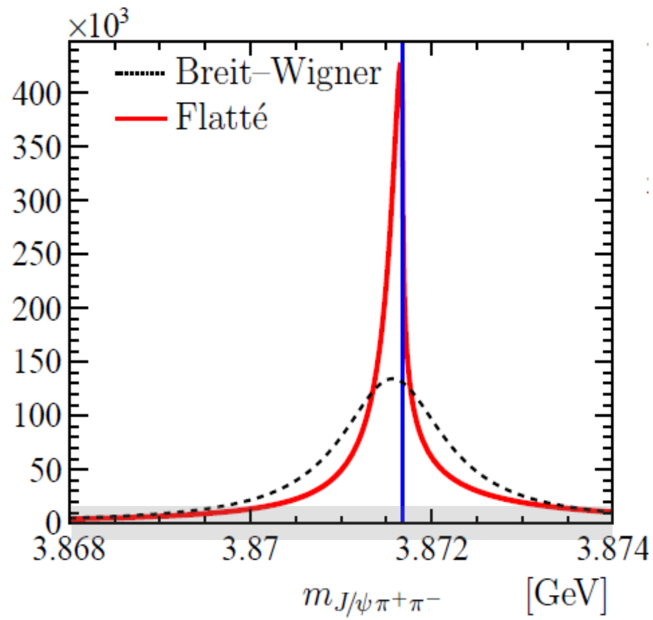
- Flatté Model with LHCb setting
  ⇒ Slight changes in E_f range



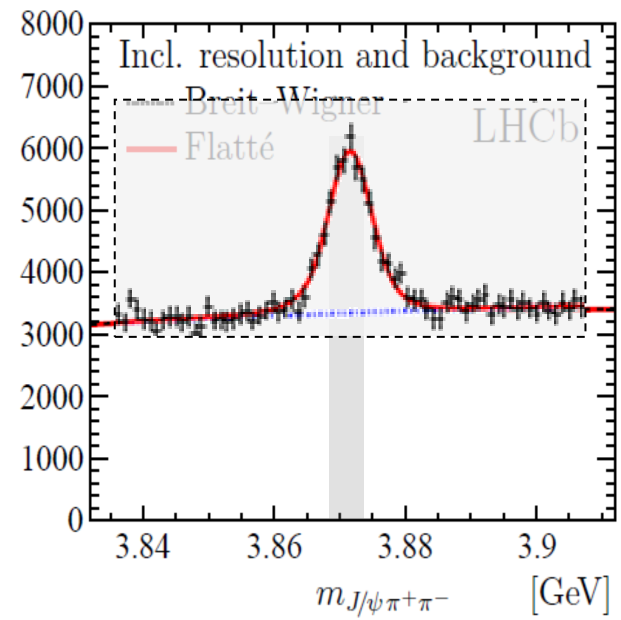
[Hanhart et al, PRD 76 (2007) 034007]

LHCb Lineshapes (incl Resolution)

Original lineshapes



Lineshapes with resolution (~2.6 MeV)



- 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.

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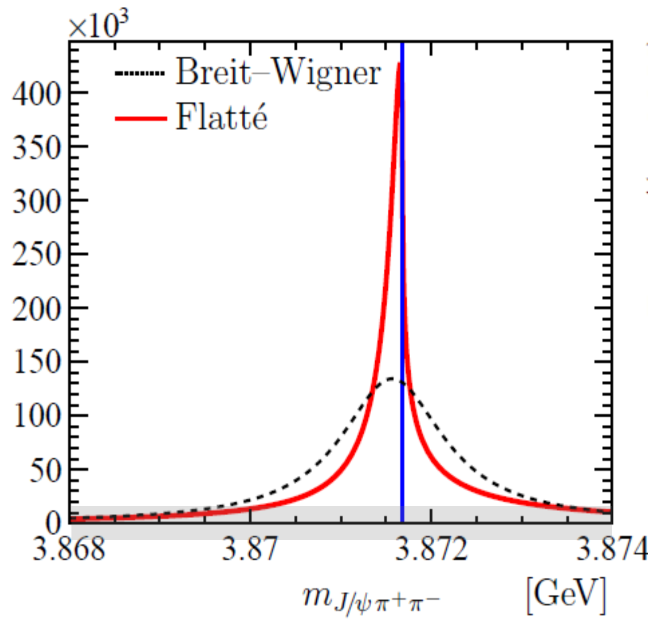

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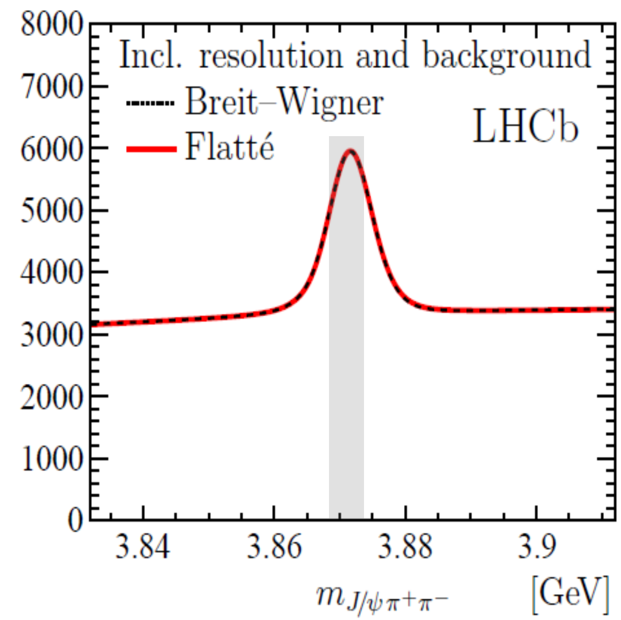

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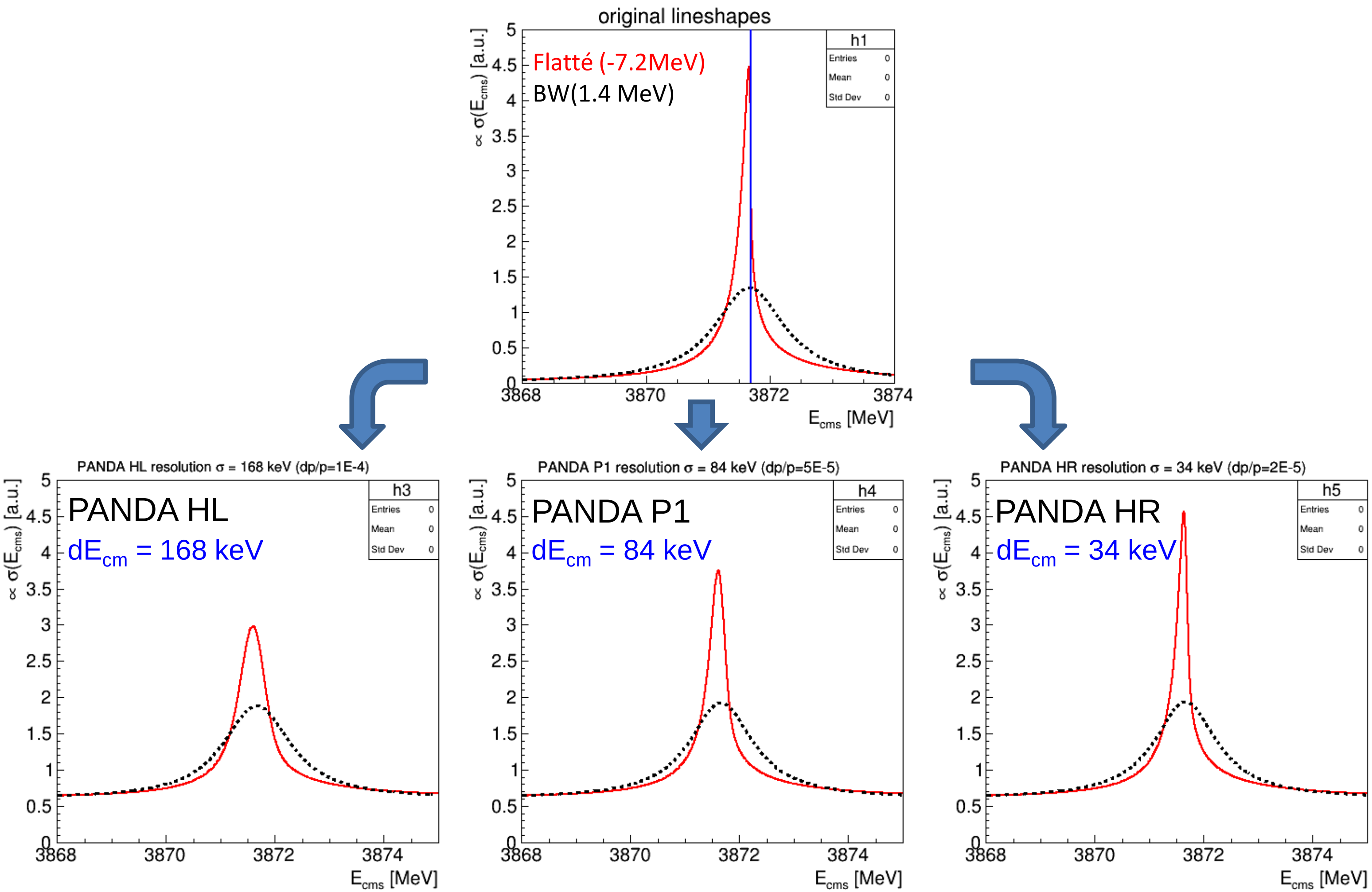
PANDA@HESR Beam Resolution

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



Distinguish Breit-Wigner from Flatté

- Extension of our previous study:
  Investigate separation power between Flatté & BW lineshapes

- Take (ε_{reco}, $\mathcal{B}$, σ, L, ...) to estimate expected yields from study

$$N_{exp}(E_{cms}) = \sigma^*(E_{cms}) \cdot L \cdot t \cdot BR_X \cdot BR_{J/\psi} \cdot \varepsilon_{reco}$$

- Adapted Parameters:

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

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

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

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

Procedure

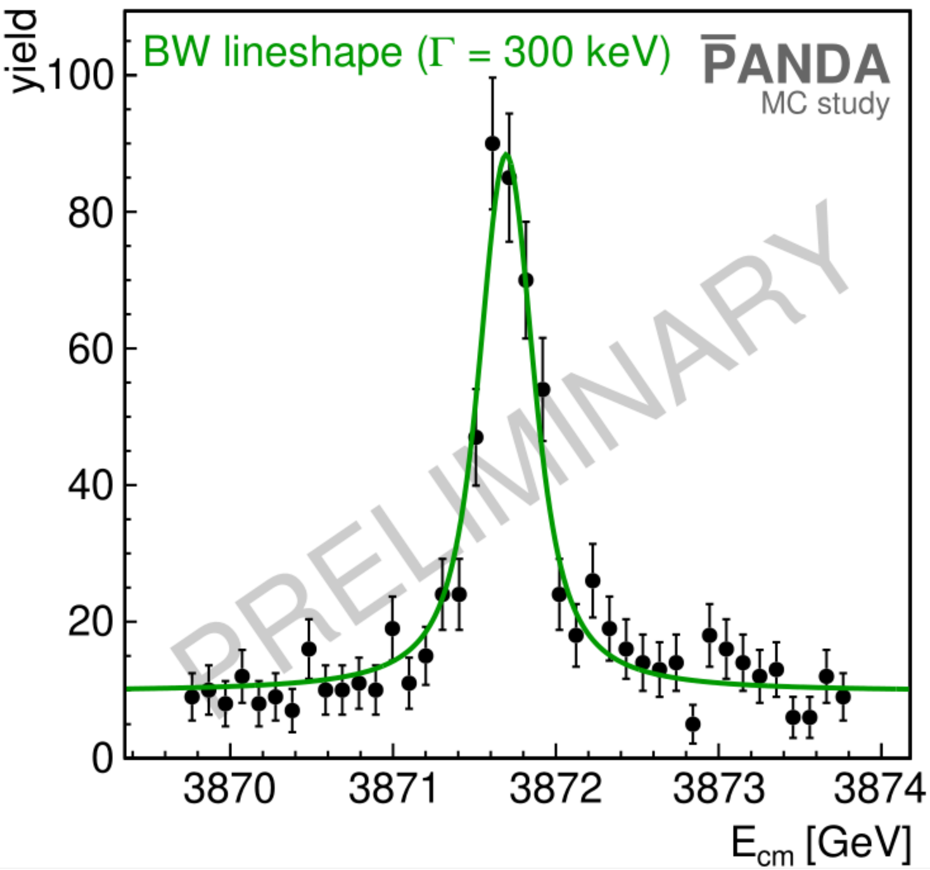
We use the following approach:

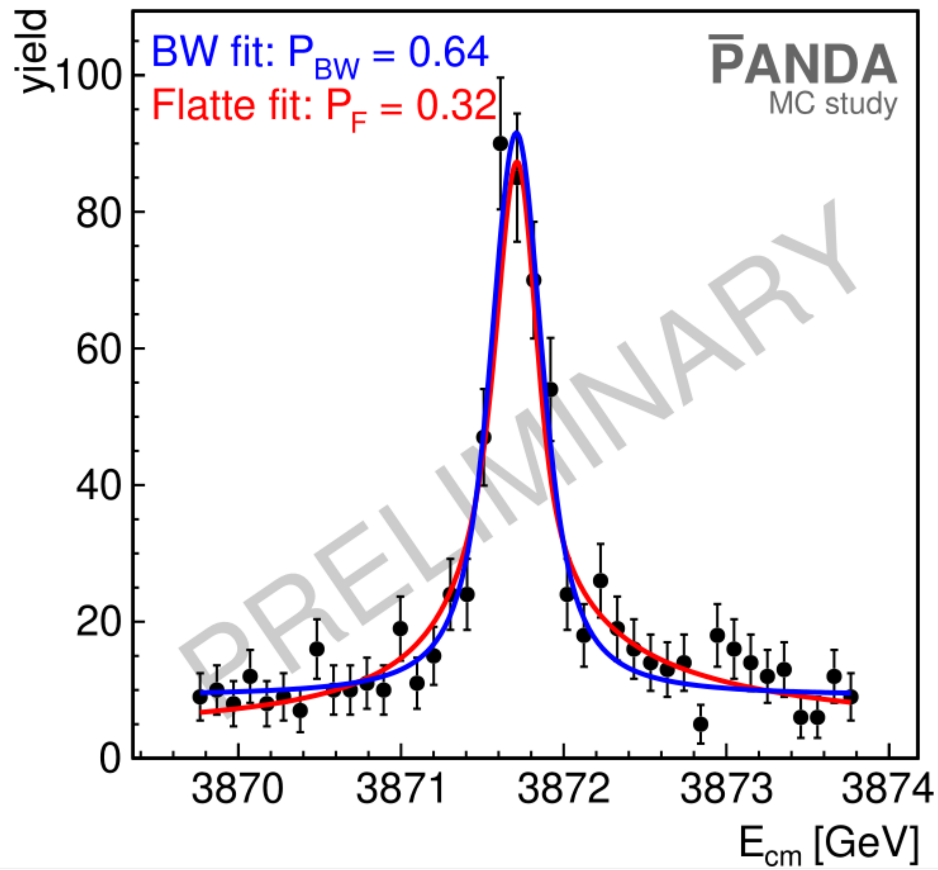
1. Use key parameters from EPJ A 55 (2019) 42
2. Generate many (toy) spectra for Flatté (BW) model
3. Fit both BW and Flatté to each generated distribution and determine fit probabilities P_{BW} and P_F
4. Identification considered correct, if $P_F > P_{BW}$ ($P_{BW} > P_F$)
5. Count fraction of incorrect 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. Fit lineshapes to extract fit probabilities P_{BW} and P_F

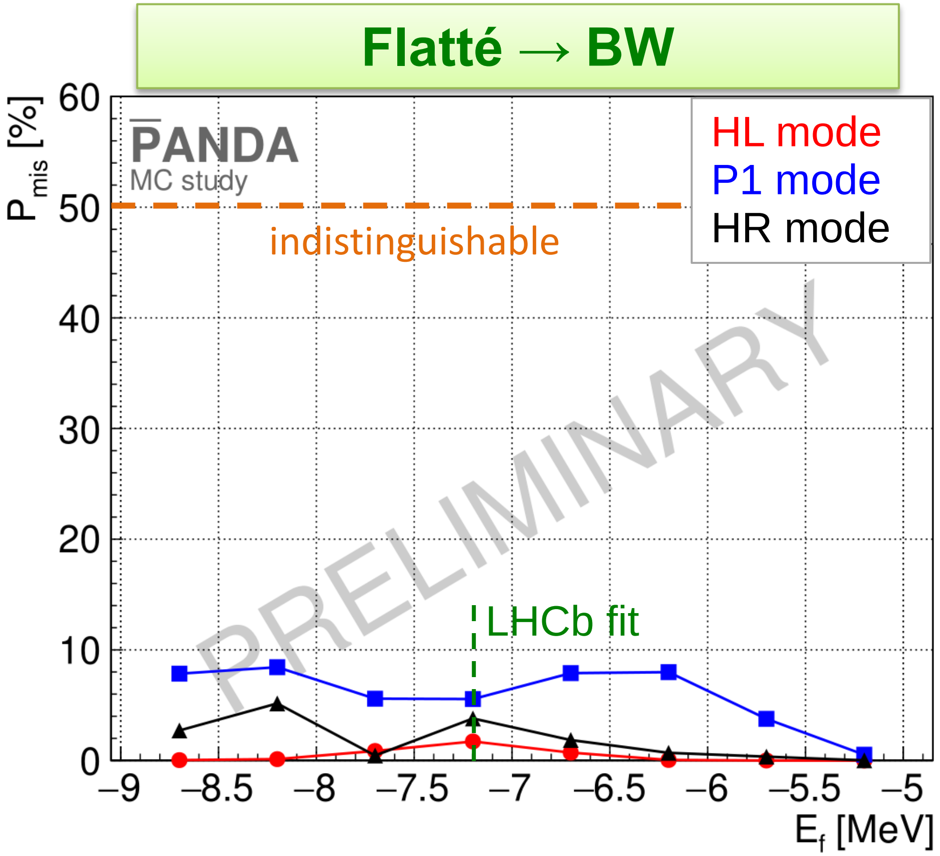




RESULTS

Parameter Dependent Performance

- Performance across Flatté energy E_f range

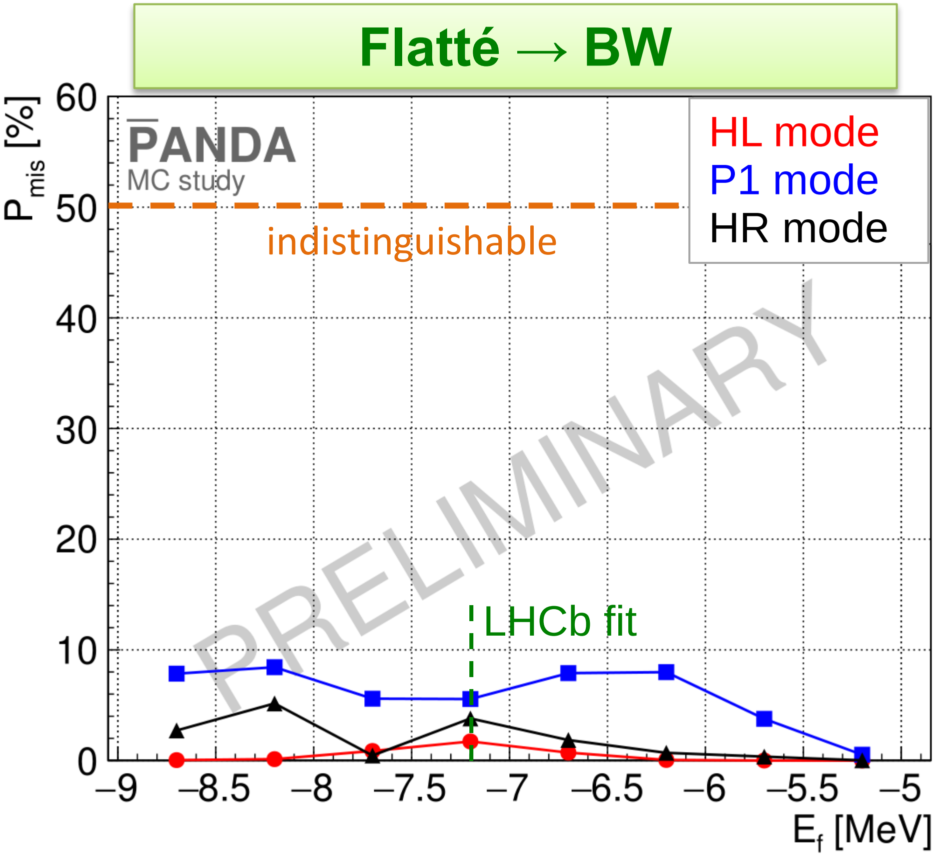


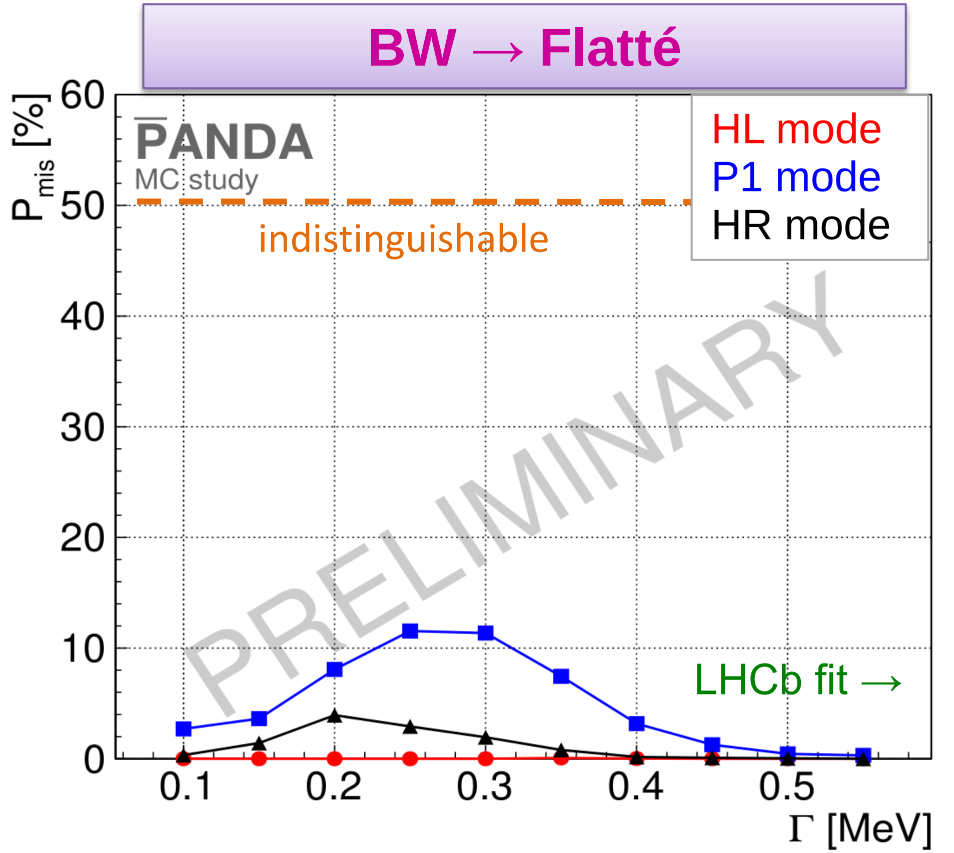
For Mis-match of Flatté as BW we see

- 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

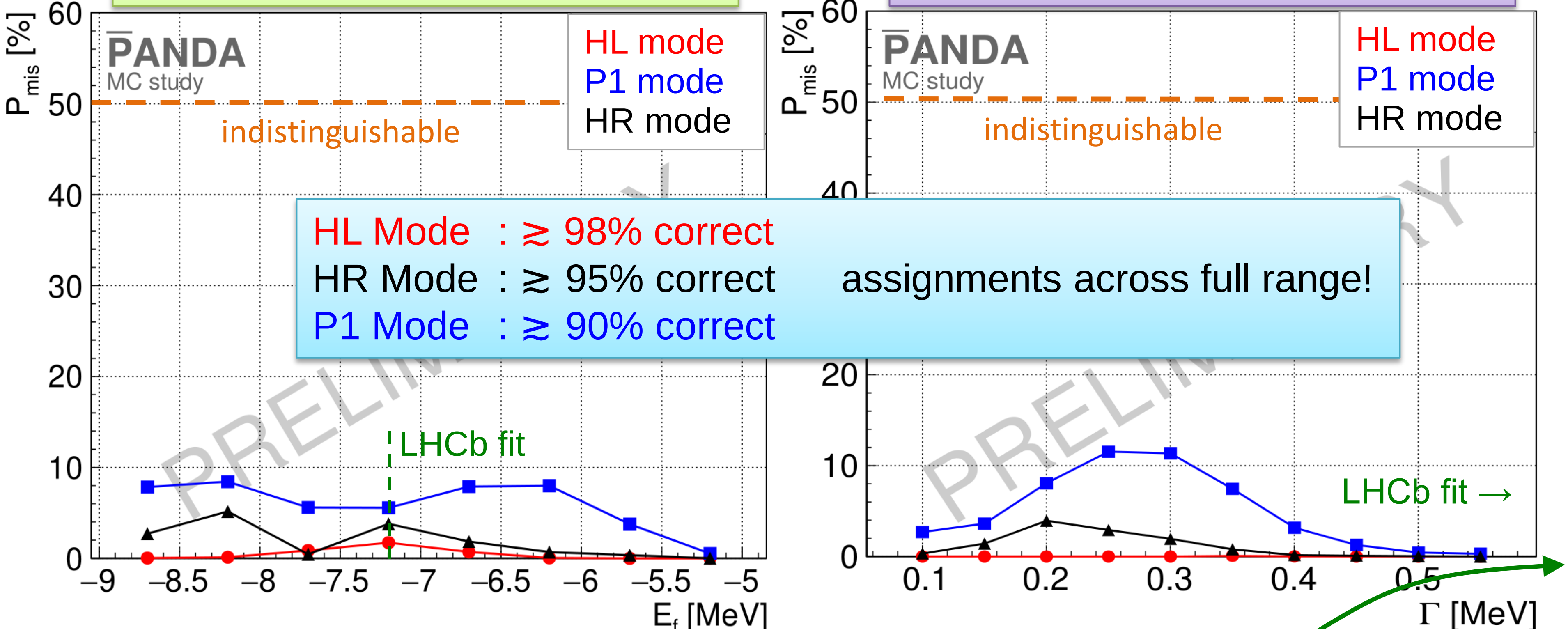




Parameter Dependent Performance

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

Flatté → BW | **BW → Flatté**



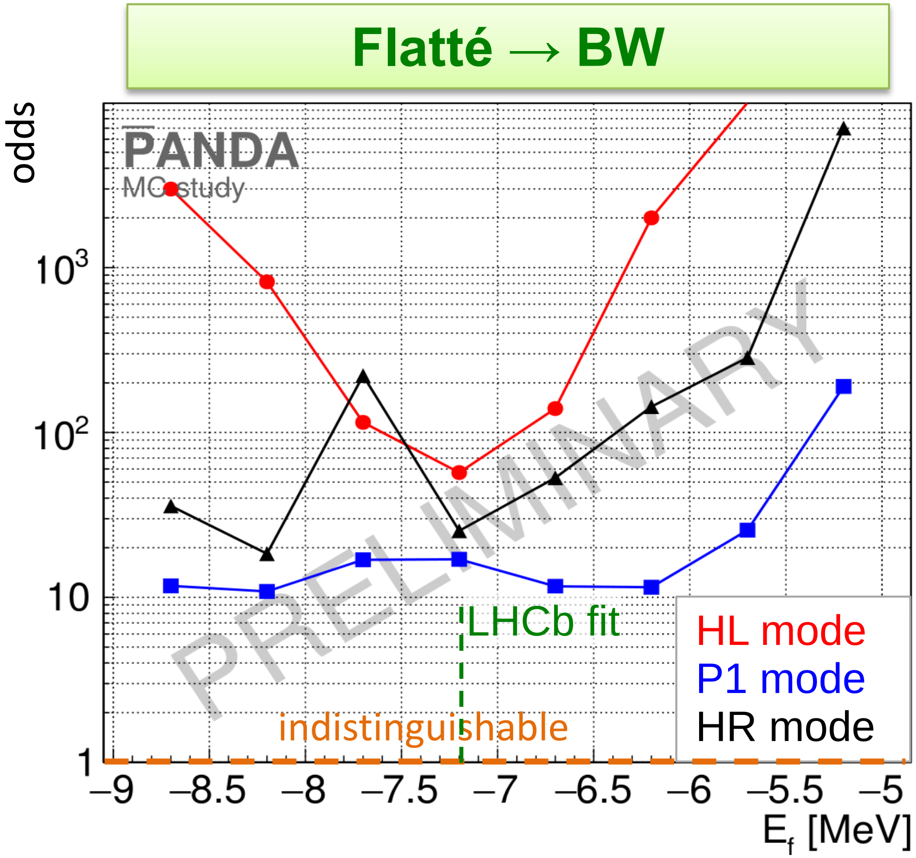
HL Mode : ≳ 98% correct
HR Mode : ≳ 95% correct
P1 Mode : ≳ 90% correct
assignments across full range!

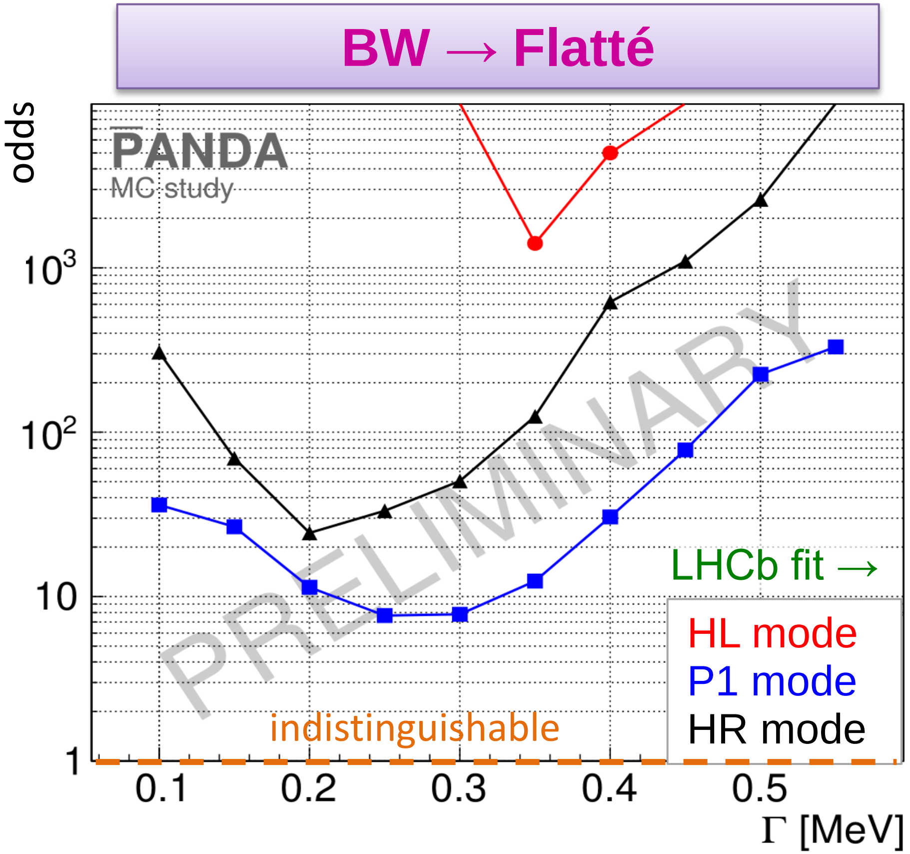
N.B.: For BW **Γ = 1.4 MeV** we find 0% mis-ID in all modes...

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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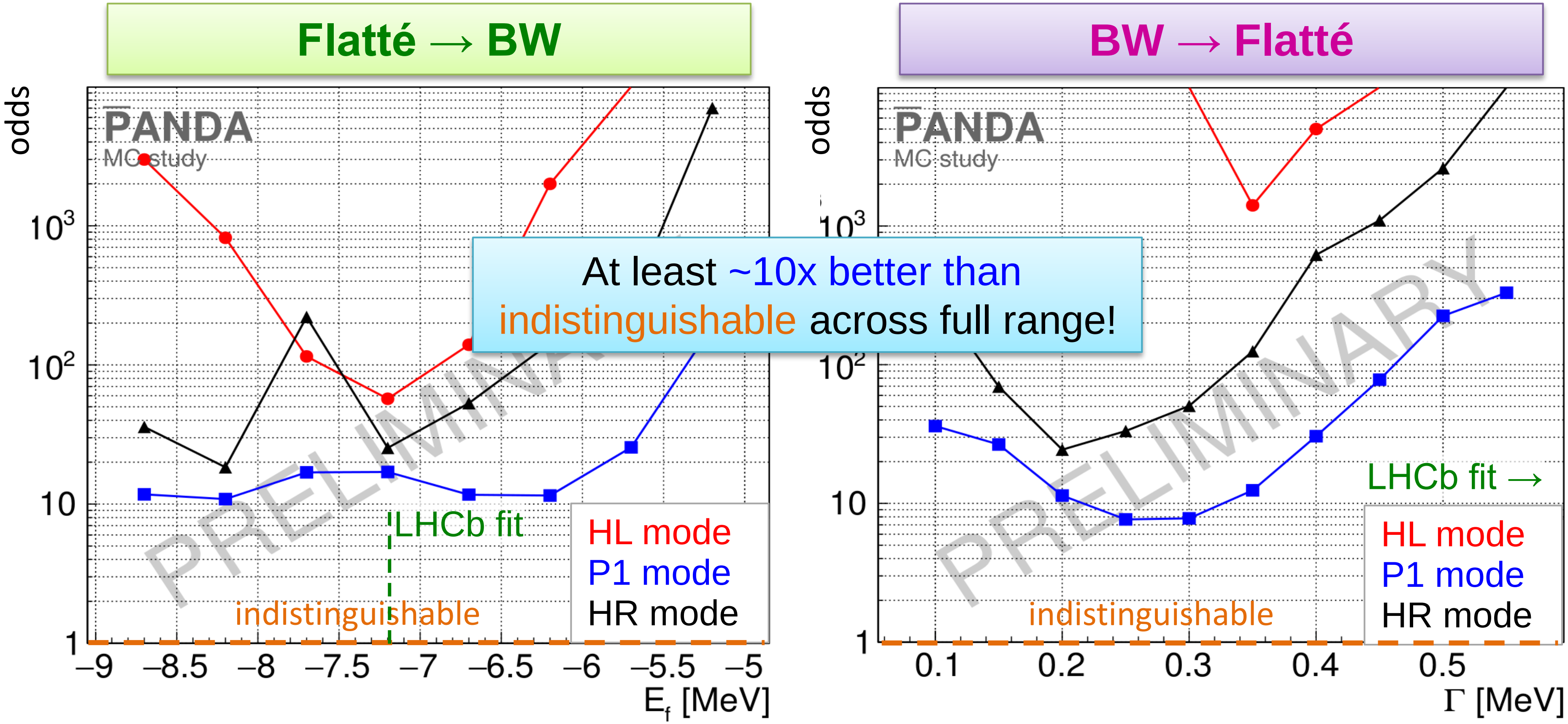

Summary and Conclusion

- 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
- At least **~10x higher odds** to identify correct model than LHCb

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- Line shape measurement of $\chi_{c1}(3872)$ at **PANDA**
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Thank you very much for your attention!