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

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Nuclear and Particle Physics Seminar, Uppsala

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UPPSALA UNIVERSITET

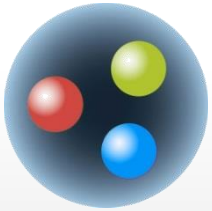
Outline

- Introduction
  - Configuration of (Exotic) Hadrons
  - XYZ states in the last two decades
  - What is this $\chi_{c1}(3872)$?
  - How to determine the nature?
- The PANDA Experiment at FAIR
  - Precision energy scans with antiprotons
- Simulation of measuring of the $\chi_{c1}(3872)$ line shape
  - Strategy
  - Results

Configuration of (Exotic) Hadrons

- Conventional hadrons are:

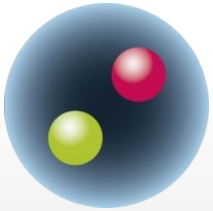
Baryons: qqq



e.g.

$p(uud), n(udd)$

Mesons: $q\bar{q}$



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$\pi^+(u\bar{d}), \eta_c(c\bar{c})$

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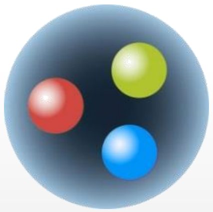

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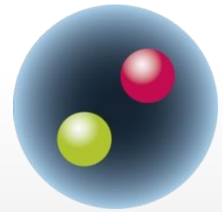
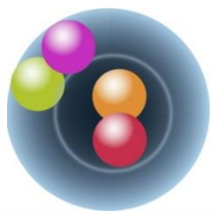


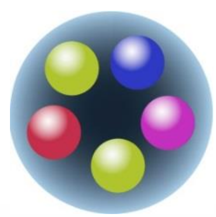
e.g.

$\pi^+(u\bar{d}), \eta_c(c\bar{c})$

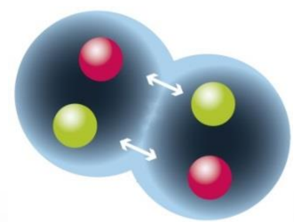
- Other color-neutral configurations called exotic hadrons

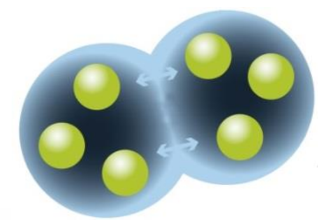
Multiquarks: $qq\bar{q}\bar{q}$, $qqqq\bar{q}$





Molecules: $(q\bar{q})(q\bar{q})$, $(qqq)(qqq)$



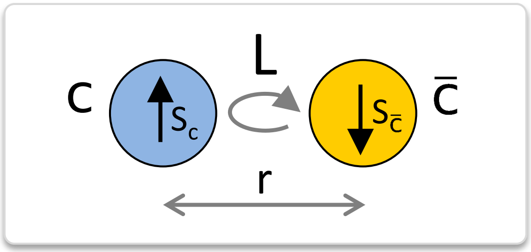


Hybrids: $q\bar{q}g$

Glueballs: ggg, gg

Potential Models

- **Charmonium**: Bound state of charm and anti-charm quarks

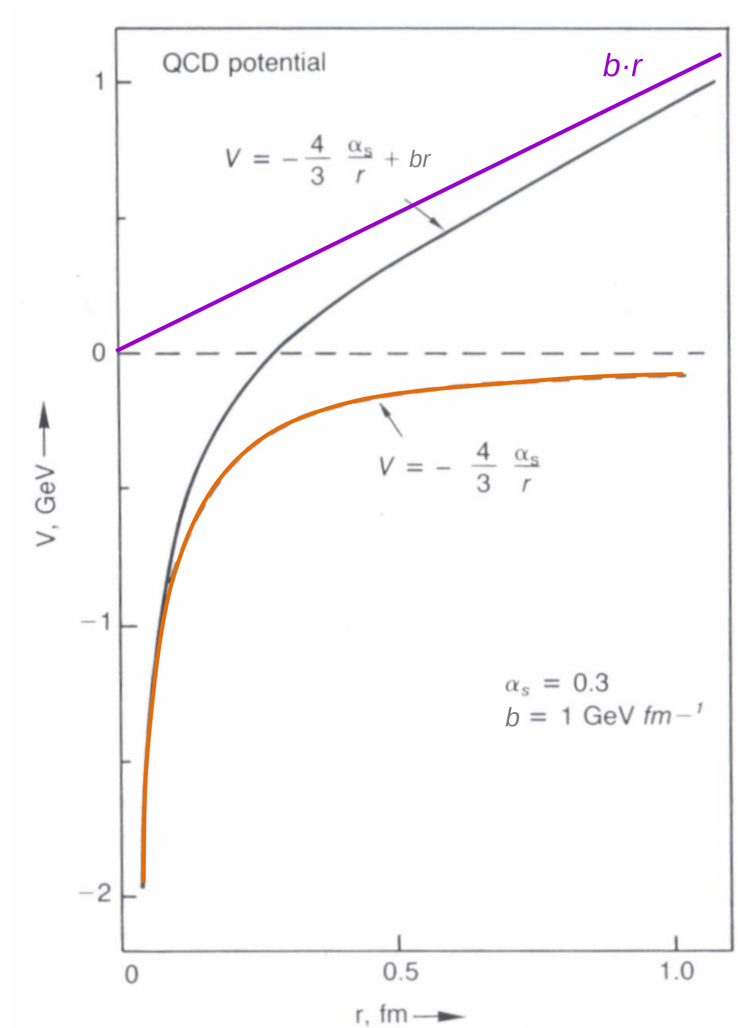


- Conventional approach for predictions:
  → Potential Models

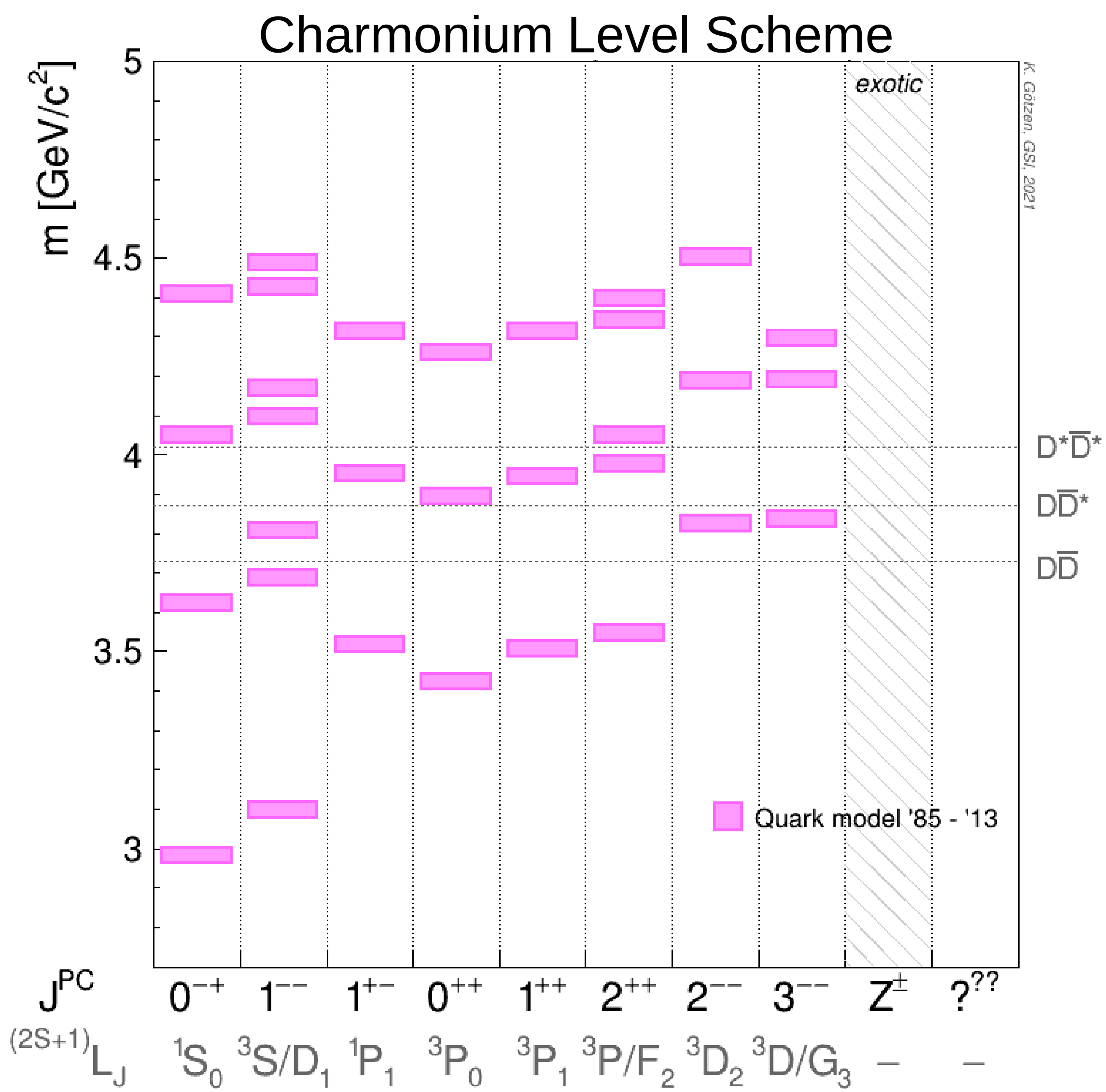
- Coulomb-like (asymptotic freedom, $r \to 0$)
  + linear (confinement, $r \to \infty$)
  + spin dependent terms

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\,\tilde{\delta}_\sigma(r)\,\vec{S}_c \cdot \vec{S}_{\bar{c}} + \ldots$$

[PRD 72 (2005) 054026]

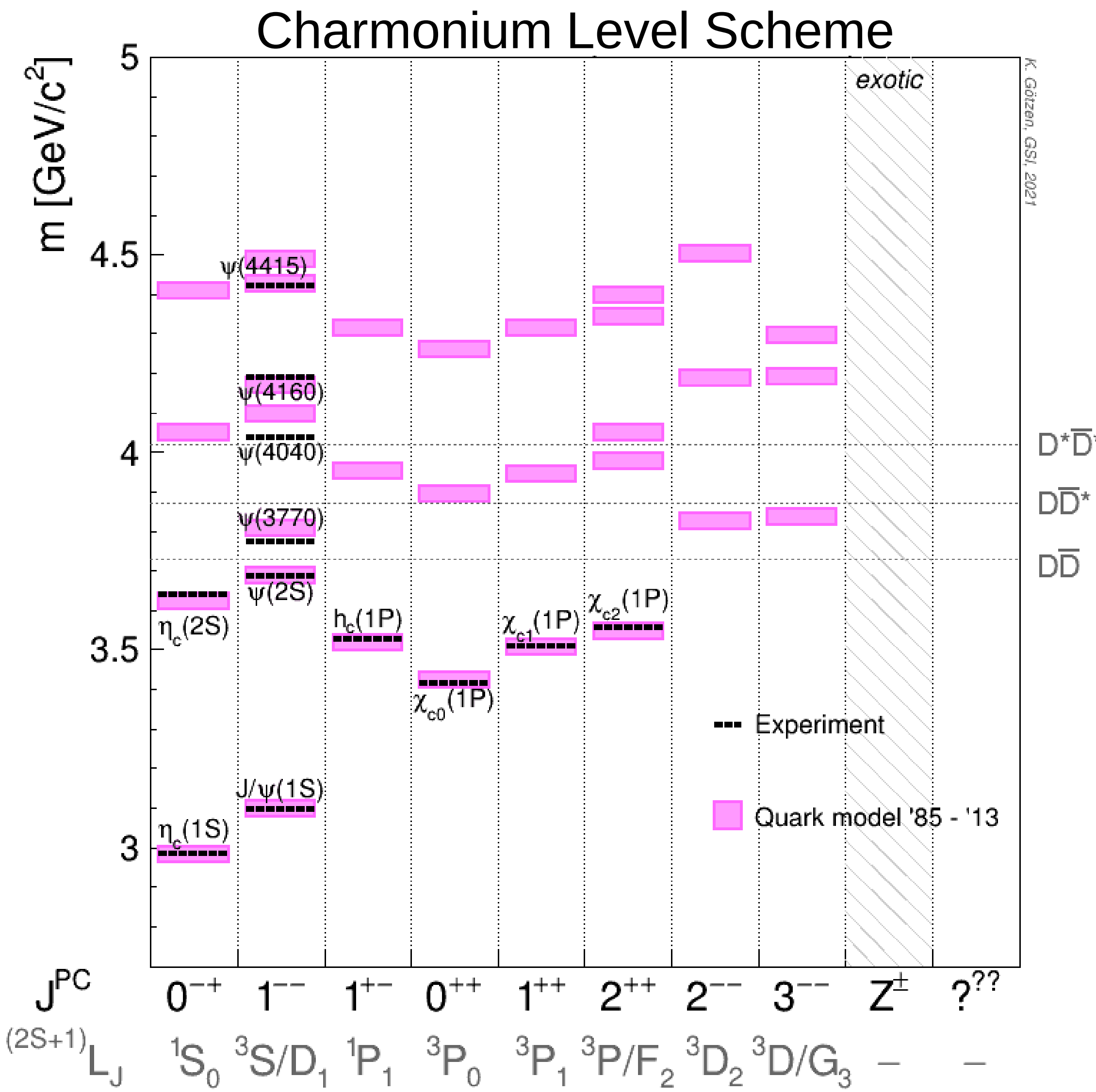


Charmonium: Theory ...



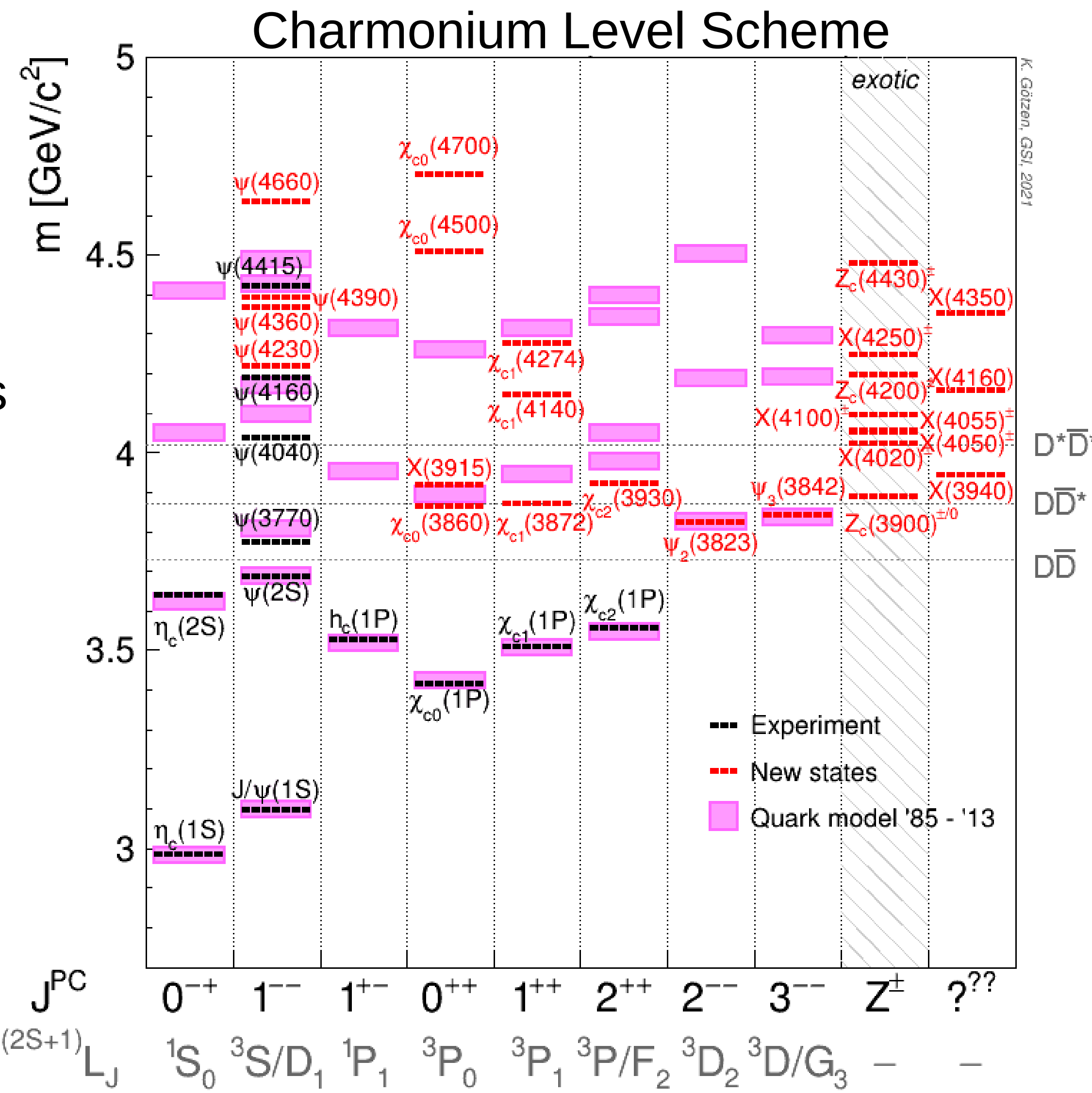
... and Experiment (until 2003)

- Charmonium predictions fitted well until 2003



... and Experiment (PDG 2021)

- Charmonium predictions fitted well until 2003
- Since 2003: >20 new charmonium-like states not fitting well the predictions



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- Charmonium predictions fitted well until 2003
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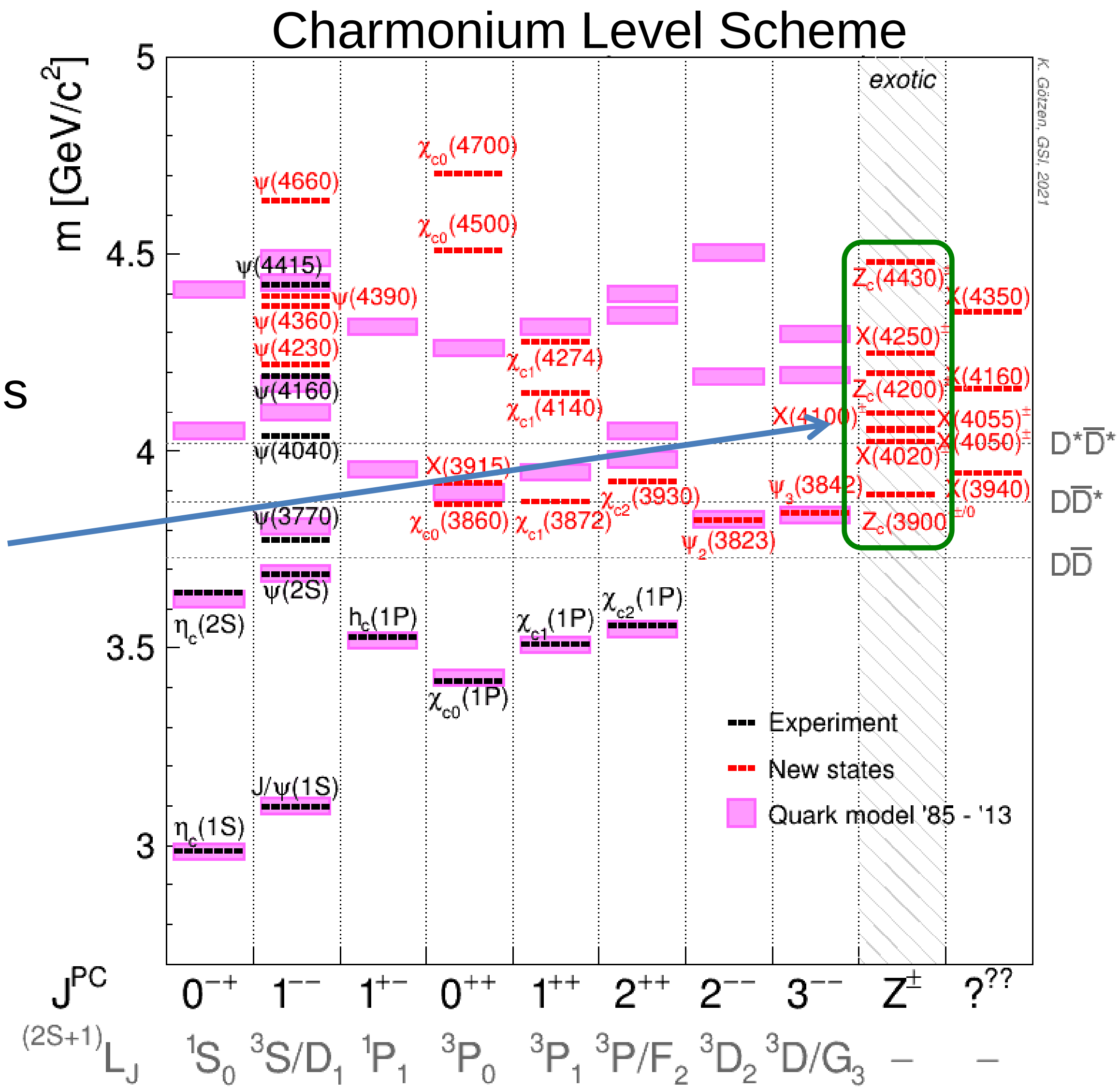
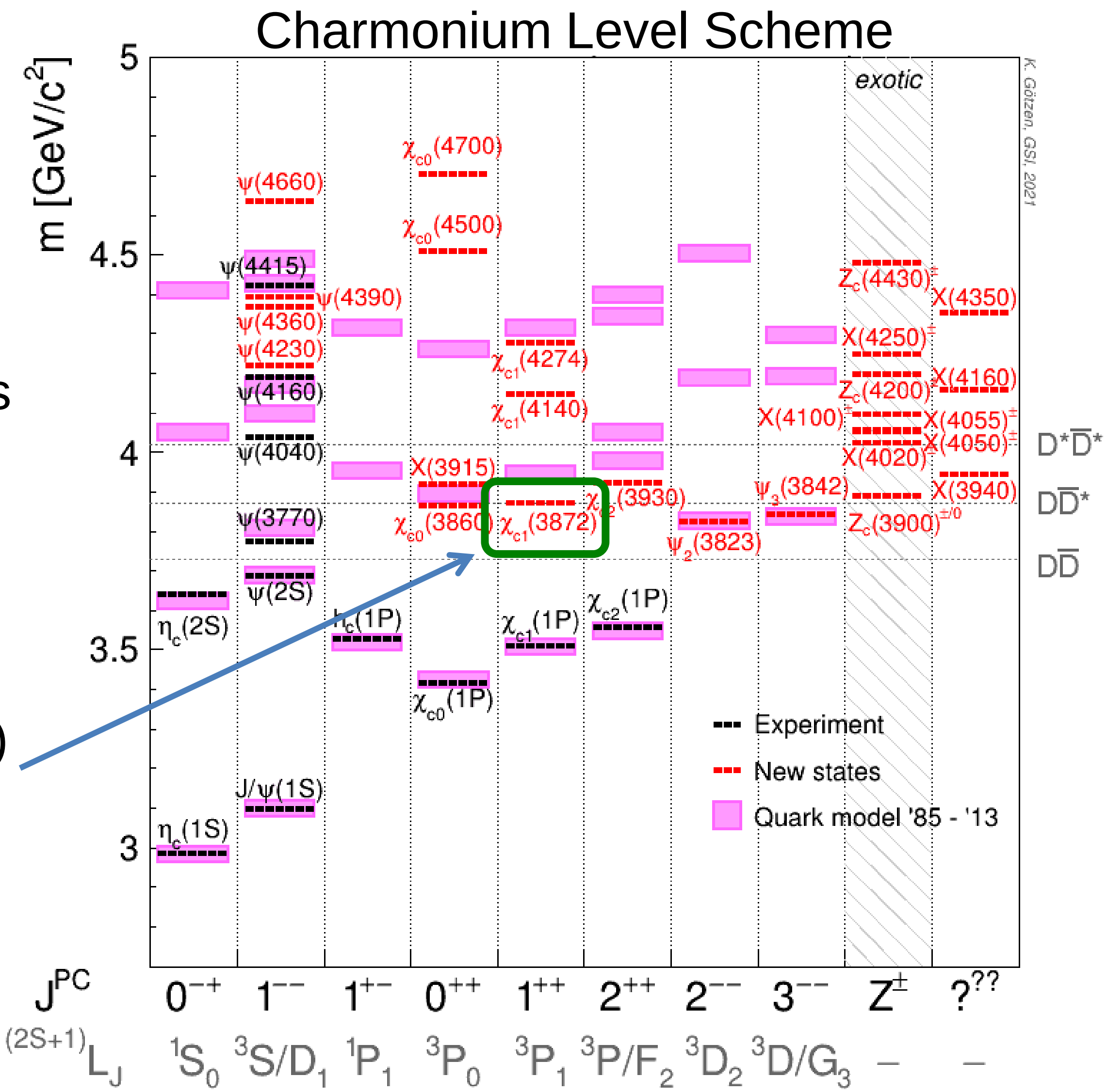
- Seven **charged states:** Z(3900)$^+$, ..., Z(4430)$^+$



… and Experiment (PDG 2021)

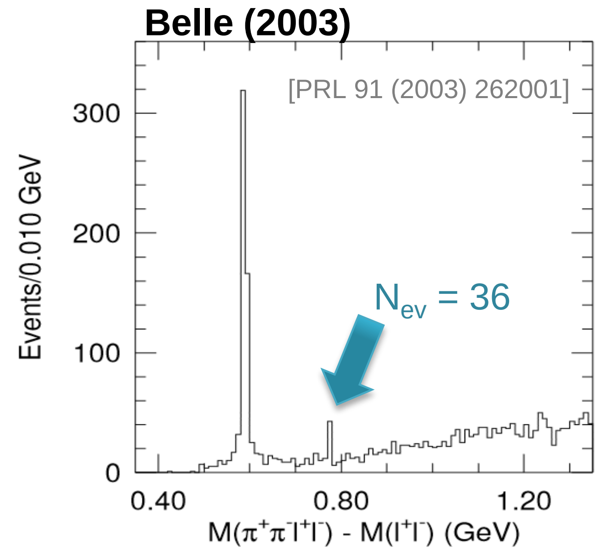
- Charmonium predictions fitted well until 2003
- Since 2003: >20 new charmonium-like states not fitting well the predictions
- Seven **charged states:** $Z(3900)^{+}$, …, $Z(4430)^{+}$
- Even first observation (2003) **$\chi_{c1}(3872)$ not resolved yet**



The *mysterious* $\chi_{c1}(3872)$ aka X(3872)

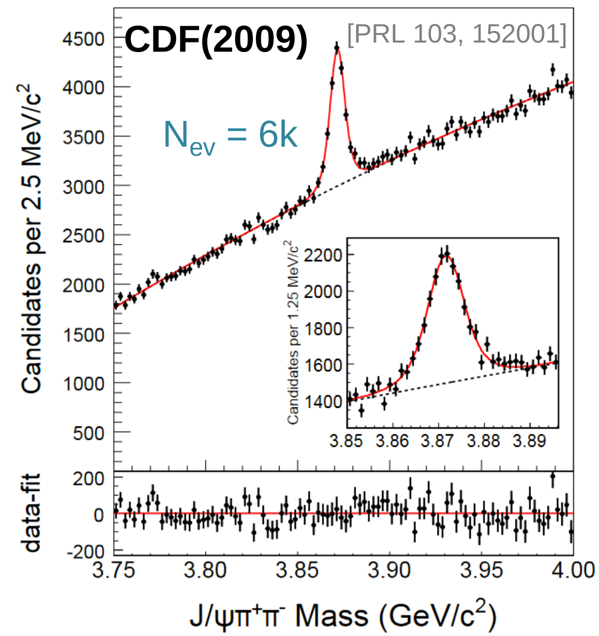
- Discovered at Belle (e^+e^-) 2003 in reaction $B^+ \rightarrow K^+X$, $X \rightarrow J/\psi\pi^+\pi^-$

- Seen by many experiments in 7 channels: $J/\psi\rho$, $J/\psi\omega$, $J/\psi\gamma$, $\psi'\gamma$, $\chi_{c0}\pi^0$, $D^0\bar{D}^0\pi^0$, $D^*\bar{D}$



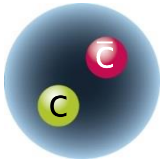
Properties

- Spin-parity quantum number $J^{PC} = 1^{++}$
- Strong isospin violation: $I_{J/\psi\rho} = 1$, $I_{J/\psi\omega} = 0$
- Quite narrow: $\Gamma = 1.2 \pm 0.2$ MeV
- Extremly close to $D^0\bar{D}^{0*}$ threshold: $E_B = m_X - (m_{D^0} + m_{\bar{D}^{0*}}) = -0.07 \pm 0.12$ MeV

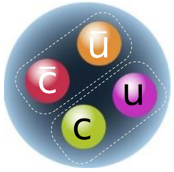


Possible Interpretation of $\chi_{c1}(3872)$

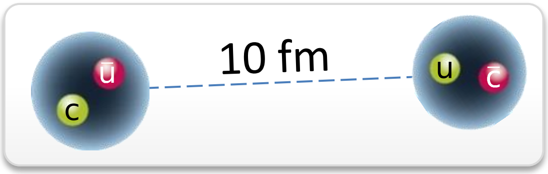
- **Conventional $c\bar{c}$ state χ_{c1}(2P)**
  - Assignment not likely, since 50-100 MeV/c² too light
  - Isospin violation!



- **Compact tetraquark state** $([cu][\bar{c}\bar{u}] - [cd][\bar{c}\bar{d}])/\sqrt{2}$
  - Unlikely, since tuned so closely to $D^0\bar{D}^{0*}$ threshold



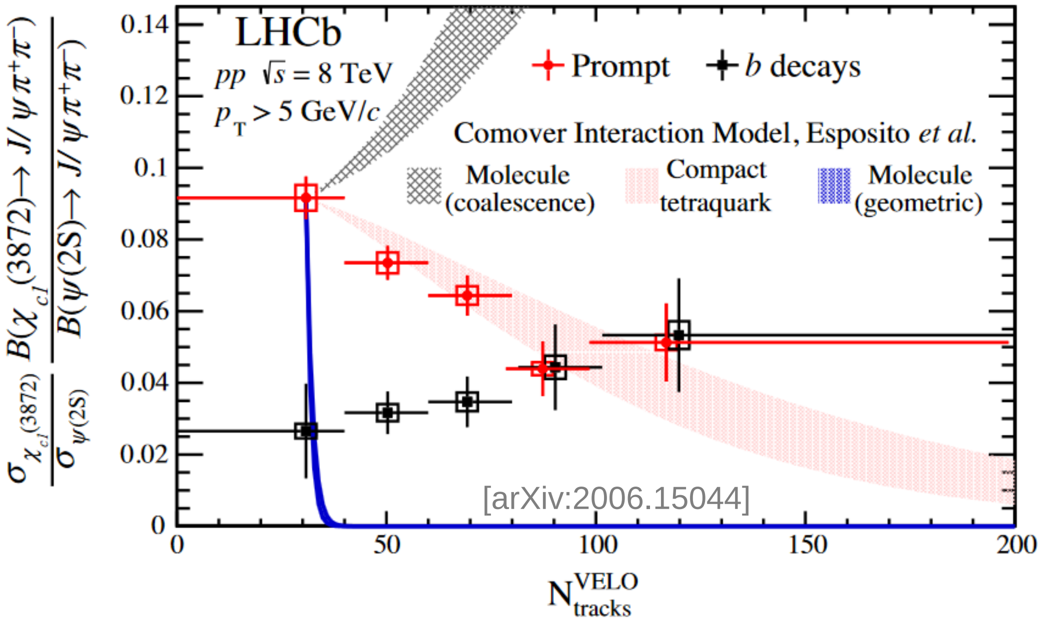
- **Molecule** (most favoured interpretation)
  - Shallow bound state: $E_B < 20$ MeV [Rev. Mod. Phys. 90(2018)015004]
  - We see $E_B < 200$ keV → huge size ≳10 fm
  - How to re-arrange quarks to form $c\bar{c}$ ρ^0?
  - Why is loosely bound state produced so frequently in TeV reactions?



- **Other ...?**

χ_{c1} Production Rate [PRL 126 (2021)092001]

- Large molecule should be affected by production environment
- Production rate: Prompt and from b-decays (χ_{c1} vs. ψ(2S))
- Inconsistent results for molecule (both coalescence and geometric)
- Seems to favour compact tetraquark in spite of closeness to DD* thresh.



Molecule geometric: destruction only by comoving particles

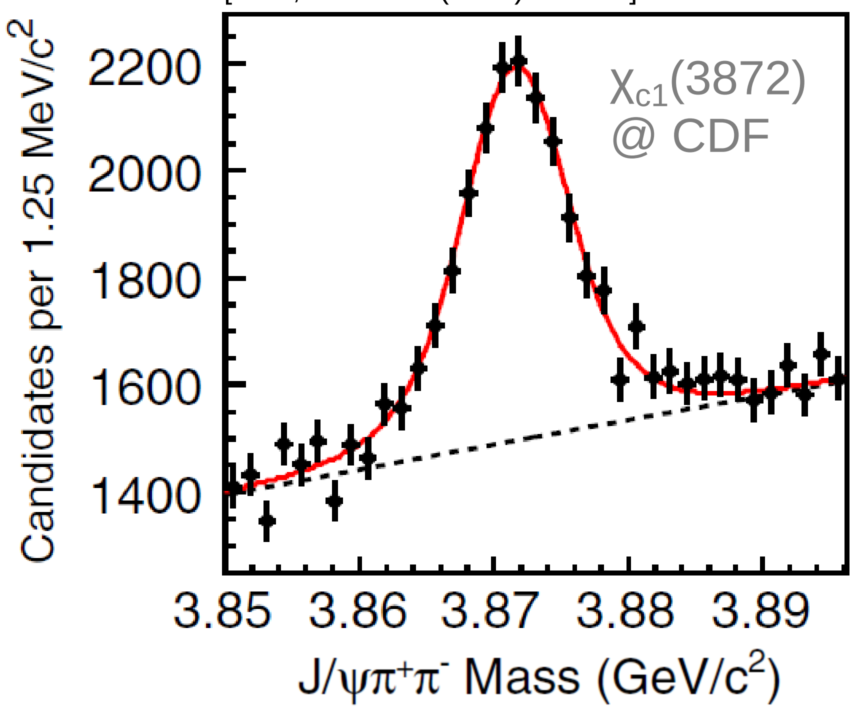
Molecule coalescence: destruction and recombination by comovers

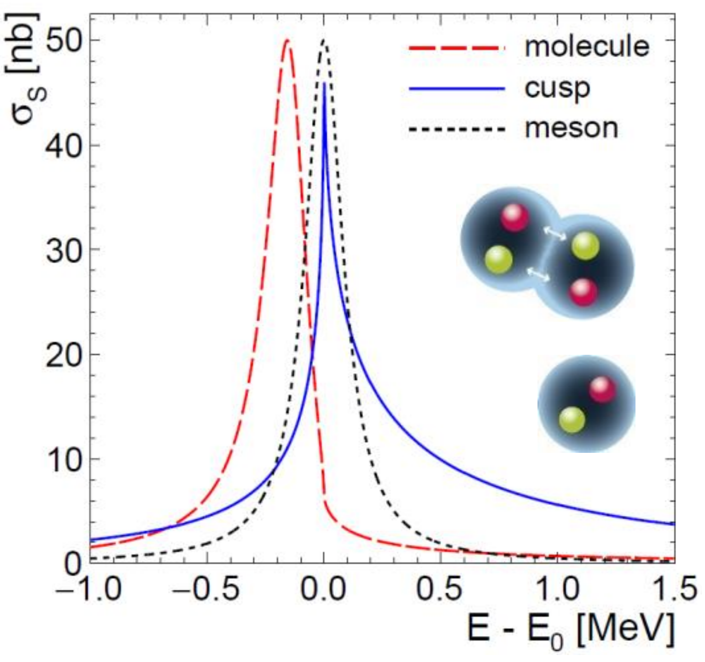
- Alternative measurements to reveal nature?

Line Shape Measurements

- Different internal structure → different production/decay dynamics
- Idea: Line shape of resonance reveals nature!

[CDF, PRL 103 (2009) 152001]

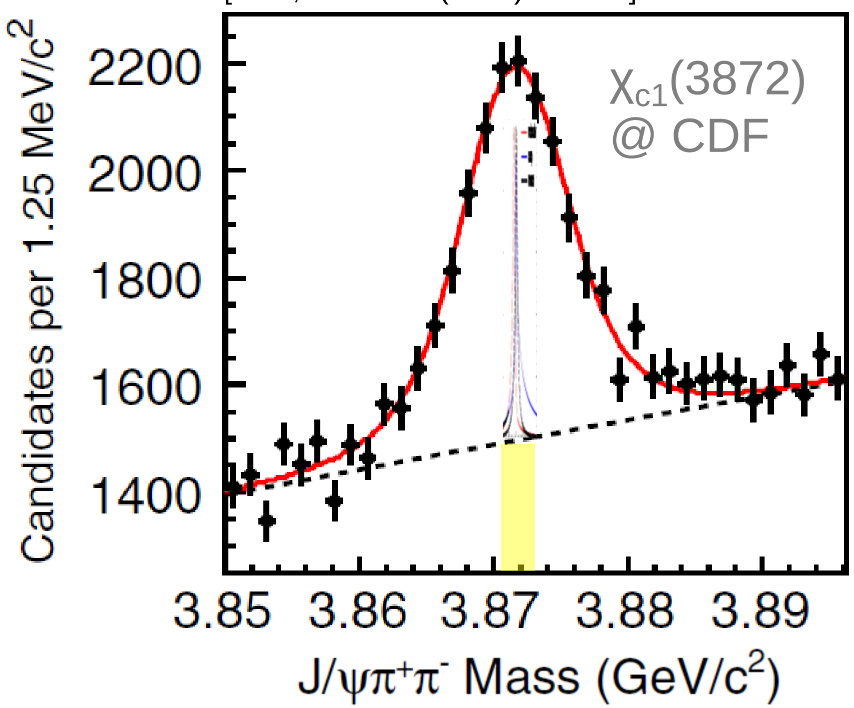


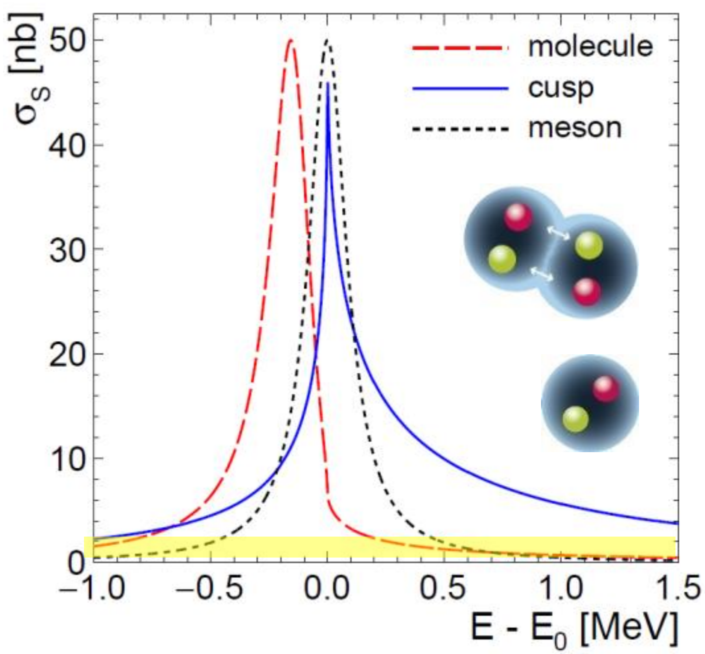


Line Shape Measurements

- Different internal structure → different production/decay dynamics
- Idea: Line shape of resonance reveals nature!
- Challenge: High resolution needed to resolve structures!

[CDF, PRL 103 (2009) 152001]





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 $3\,\mathrm{fb}^{-1}$ 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

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

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.

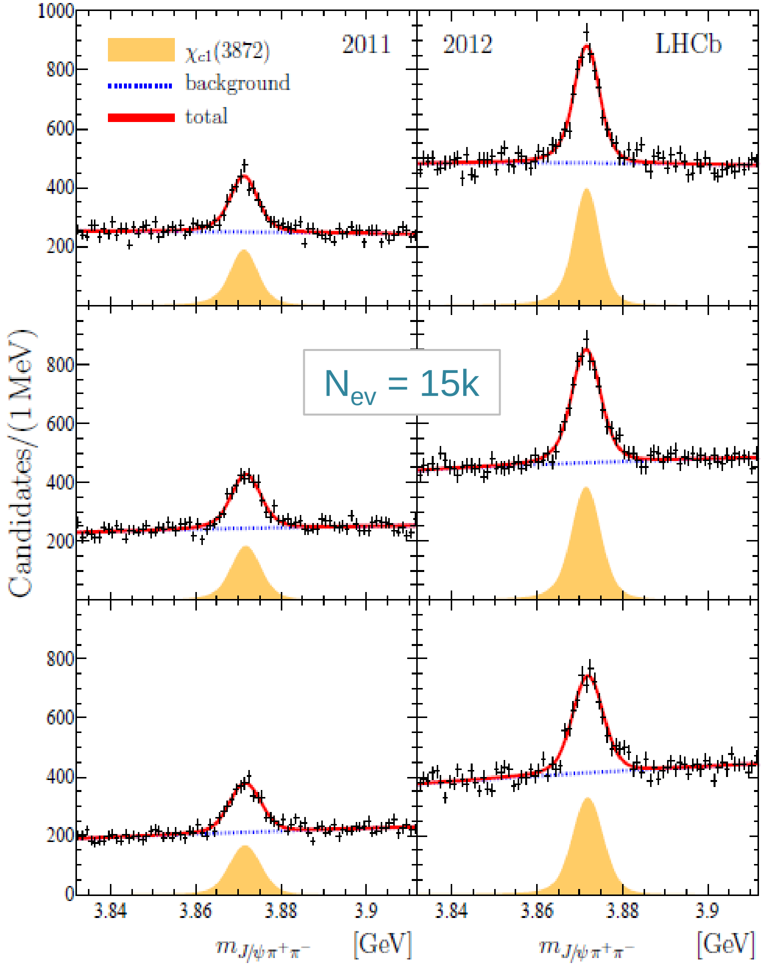
LHCb Findings

- Breit Wigner fit

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

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

[PRD 102 (2020) 9, 092005]



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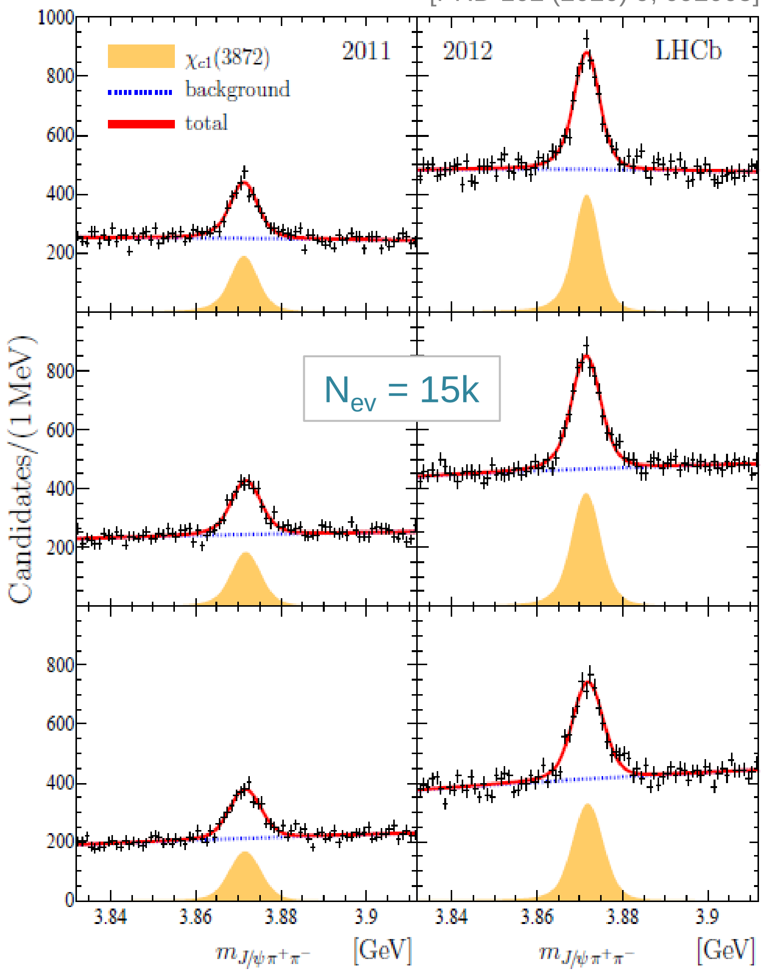

- Alternative Flatté model fit

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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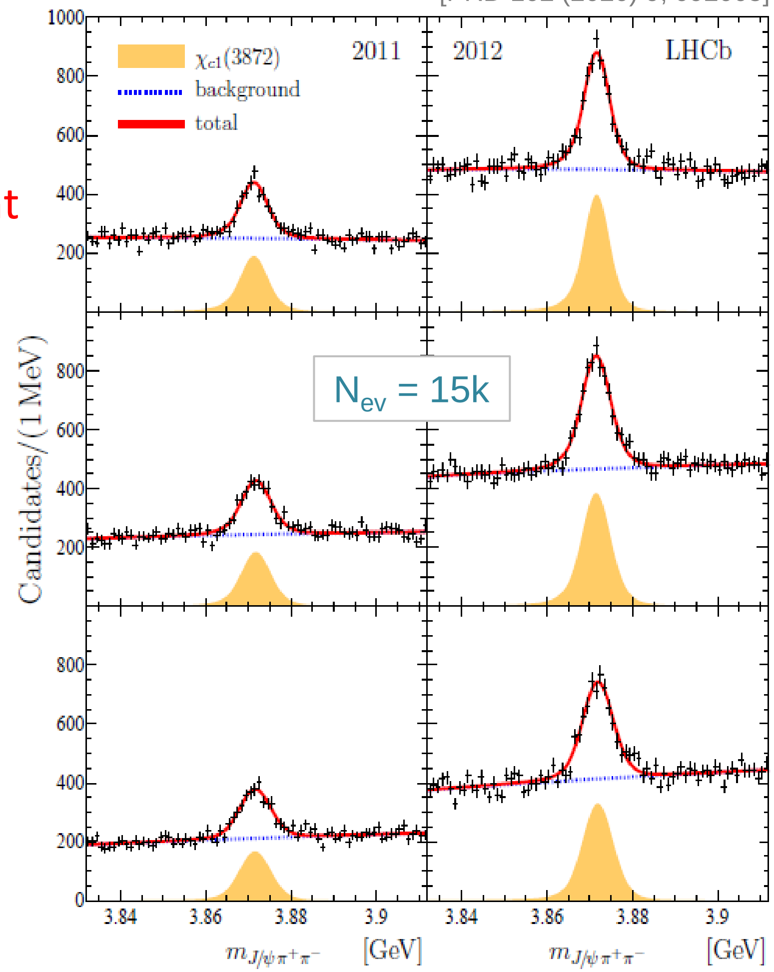
(Flatté energy E_f = -7.2 MeV)

→ Need to fix the model!

[PRD 102 (2020) 9, 092005]



Flatté Model (Hanhart et al.)

[PRD 76 (2007) 034007]

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

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

with (Flatté Energy: E_f)

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

$$k_1 = \sqrt{2\mu_1 E}, \qquad \mu_1 = \frac{m_{D^0} m_{D^{*0}}}{(m_{D^0} + m_{D^{*0}})}$$

$$\kappa_1 = \sqrt{-2\mu_1 E}, \qquad \mu_2 = \frac{m_{D^+} m_{D^{*-}}}{(m_{D^+} + m_{D^{*-}})}$$

$$k_2 = \sqrt{2\mu_2(E - \delta)} \qquad \delta = 8.2\,\text{MeV}$$

$$\kappa_2 = \sqrt{2\mu_2(\delta - E)}$$

$$g_1 = g_2 = g \quad \text{(isospin conservation)}$$

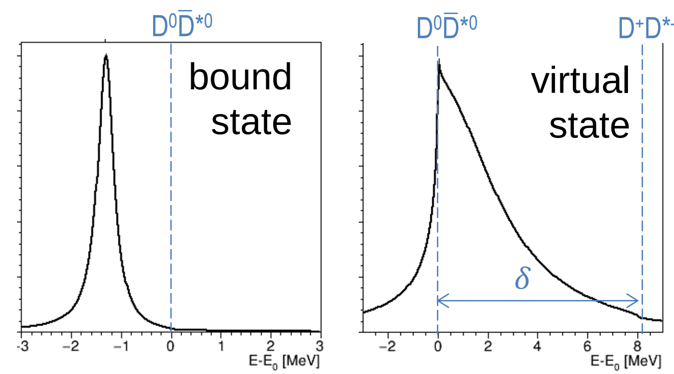
$$\Gamma(E) = \Gamma_{\pi^+\pi^- J/\psi}(E) + \Gamma_{\pi^+\pi^-\pi^0 J/\psi}(E) + \Gamma_0,$$

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

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

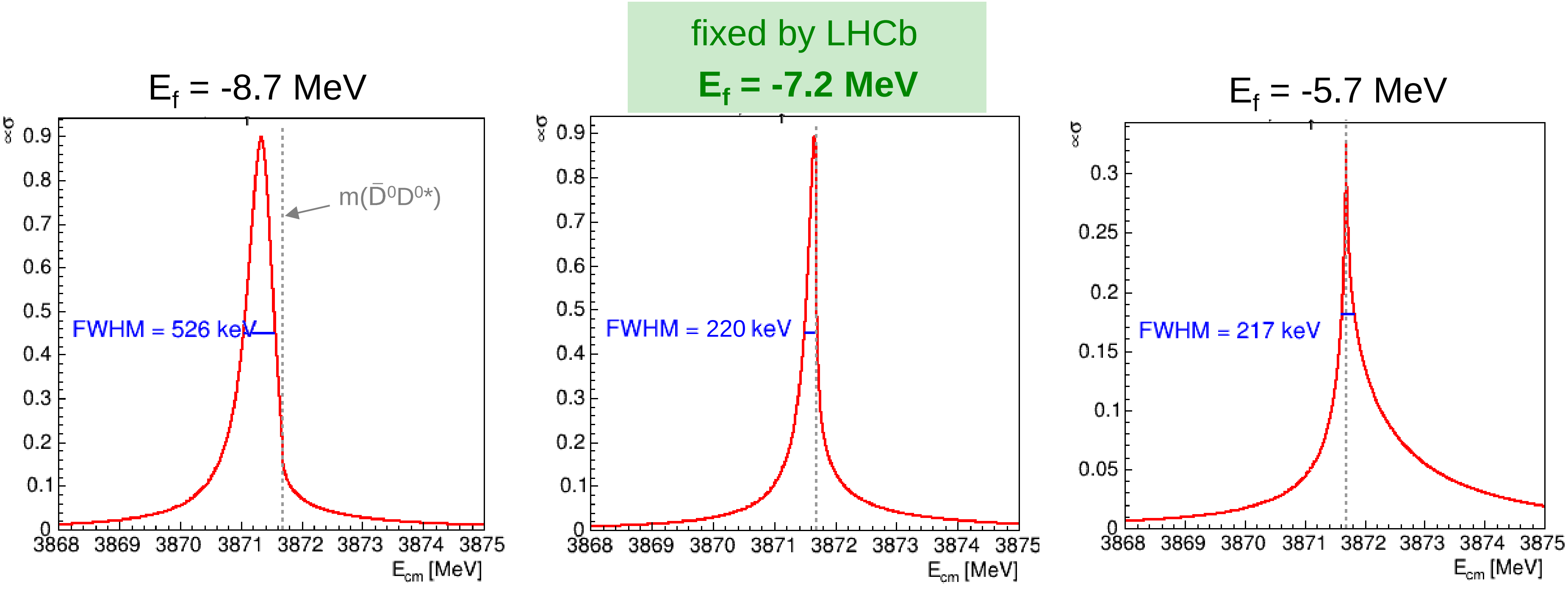
$$E_{f,thr} = -g\sqrt{\mu_2\delta/2}$$

threshold for bound/virtual



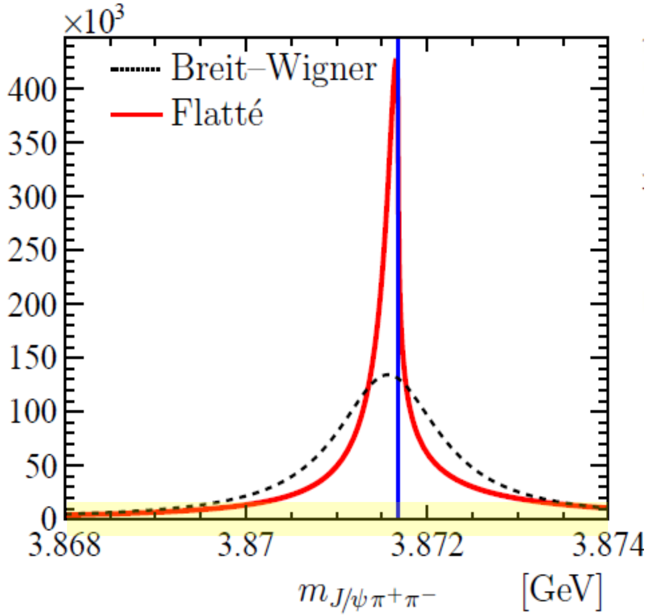
$J/\psi\pi^+\pi^-$ Lineshapes

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

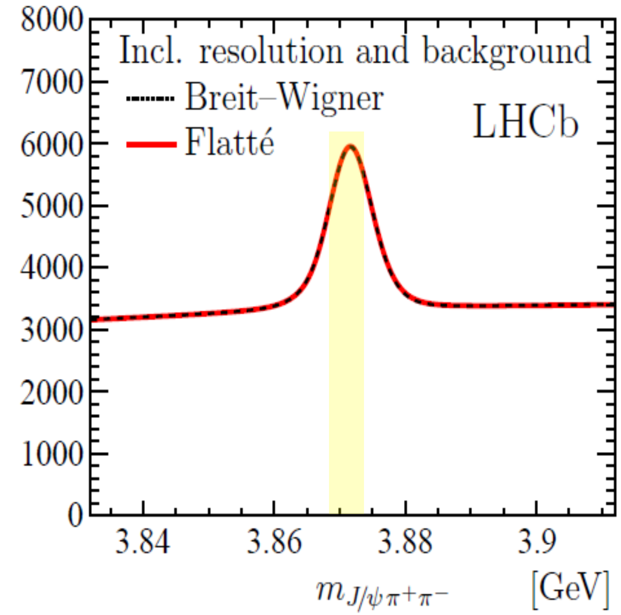


LHCb Lineshapes (incl Resolution)

Original lineshapes



Lineshapes with resolution



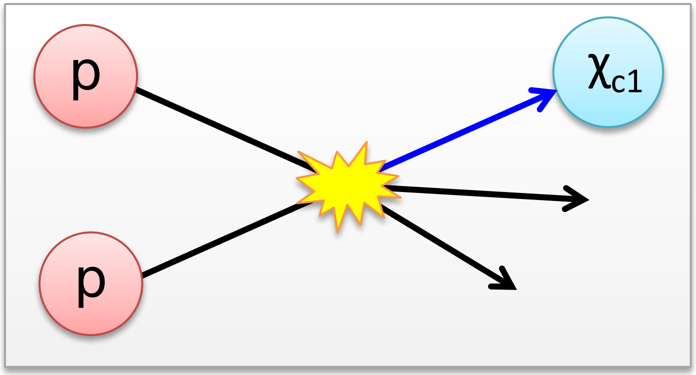
- Quote LHCb:

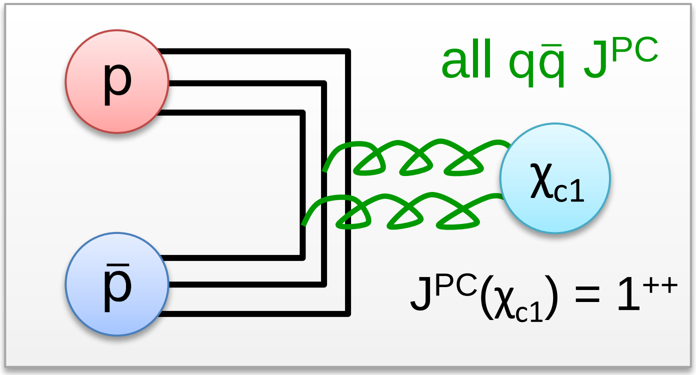
7.3 Comparison between Breit–Wigner and Flatté lineshapes

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.

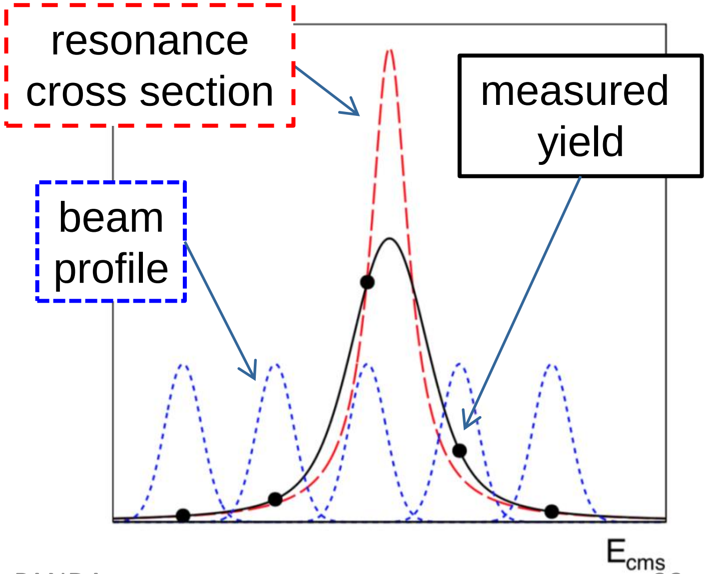
Overcome Detector Resolution with Formation

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



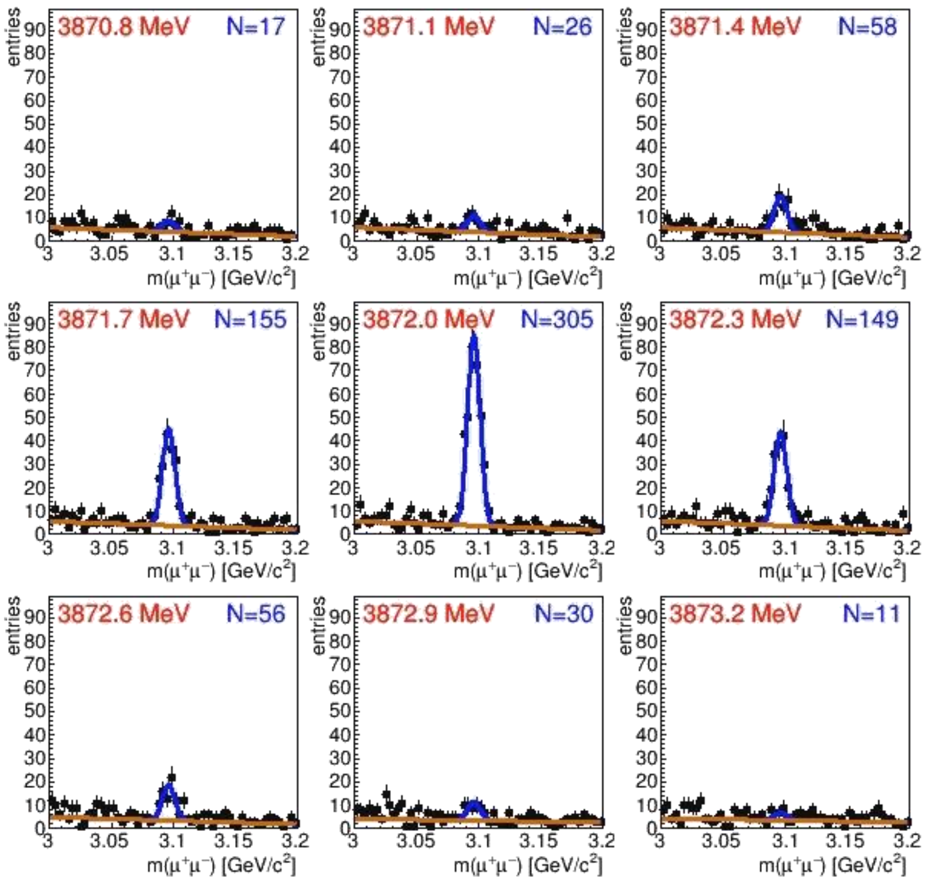


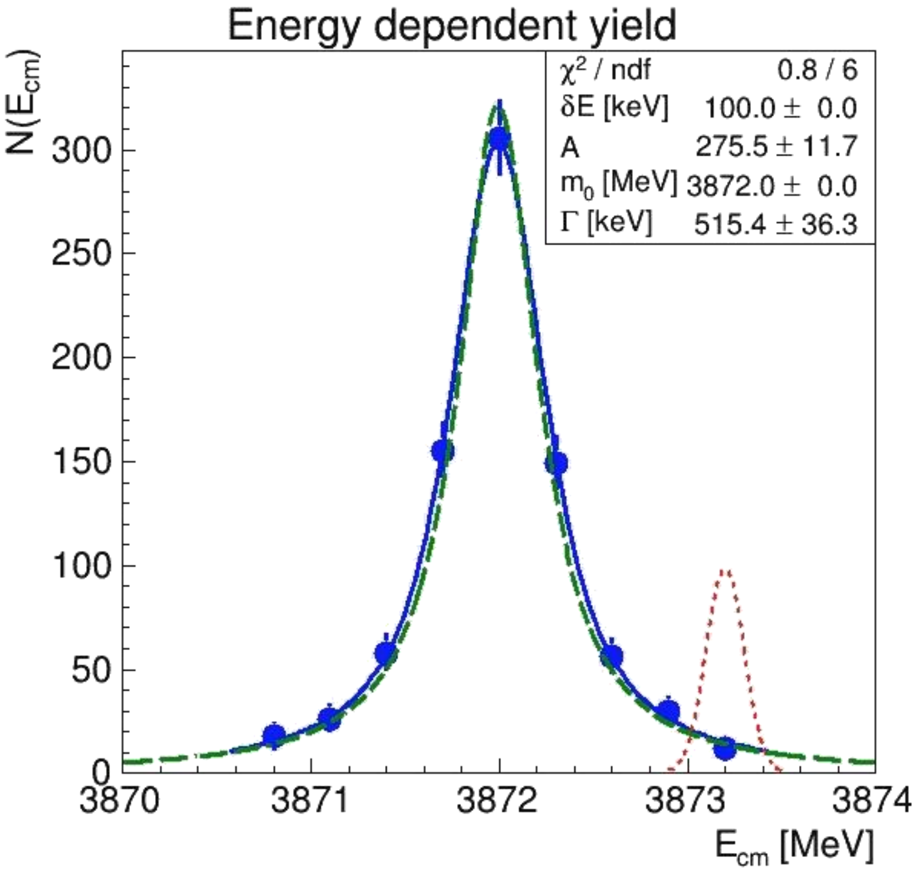
- Beam energy spread → resolution
- Measure yield at different E_{cms}



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

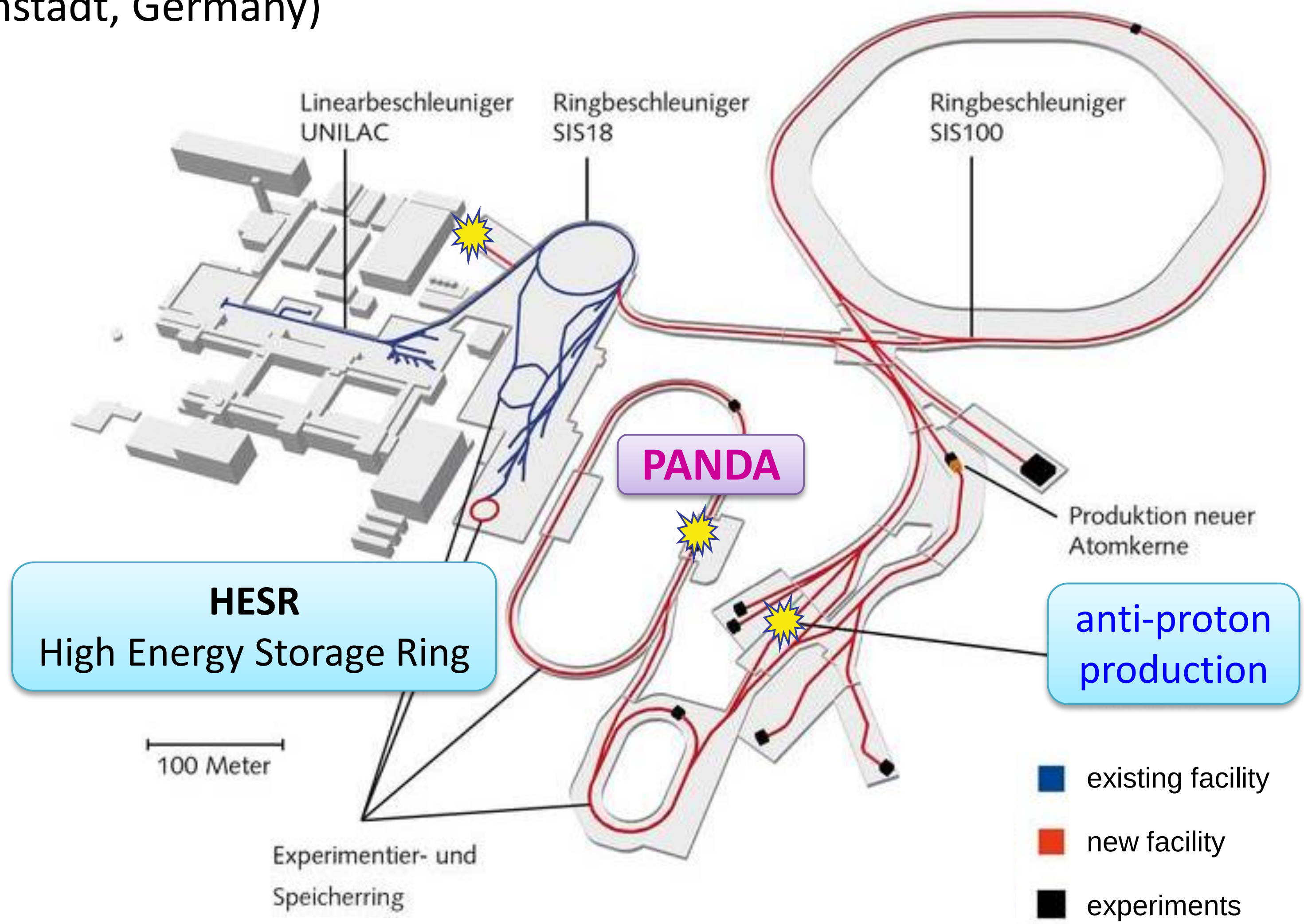
Lineshape Scan Example Animation





PANDA at FAIR

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



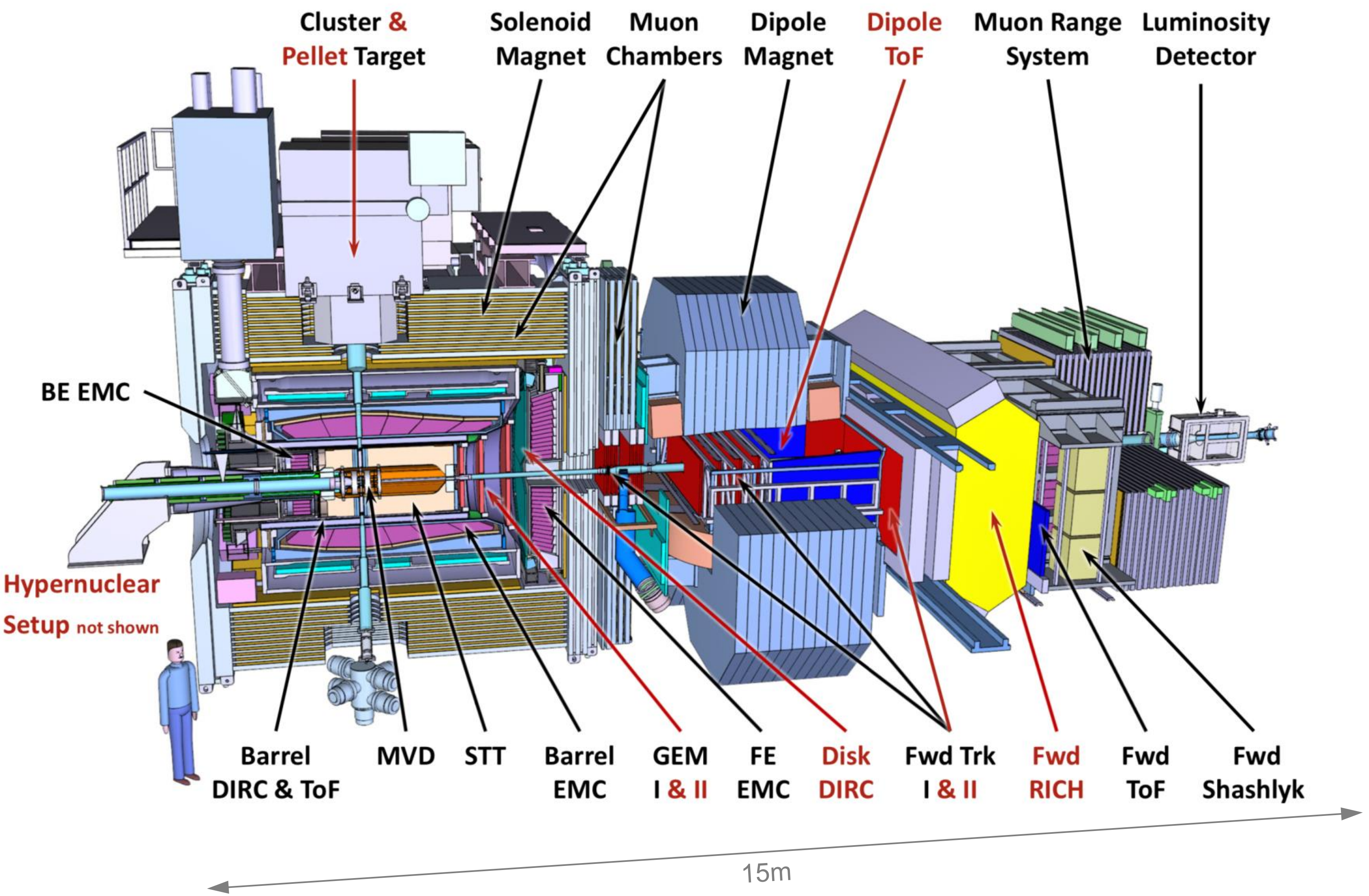
FAIR Construction Site

Good progress despite pandemic

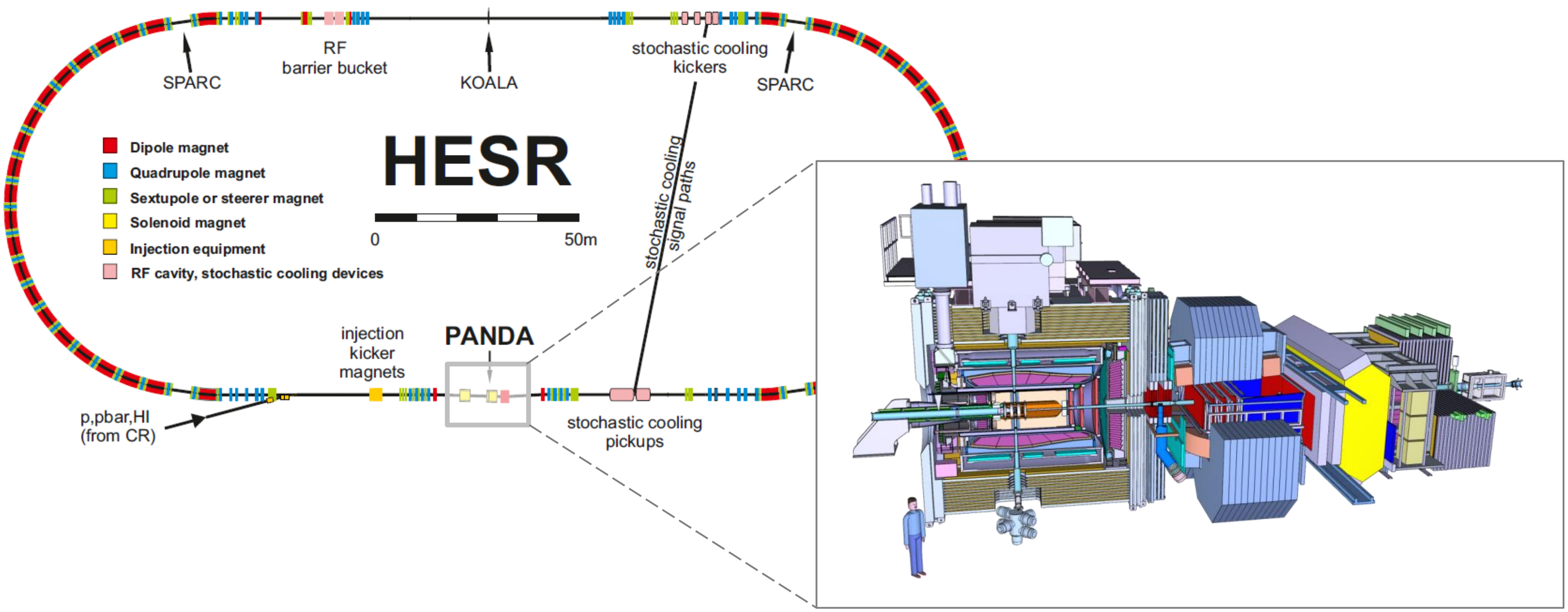
FAIR Construction Site

Good progress despite pandemic

The PANDA Detector



PANDA and HESR



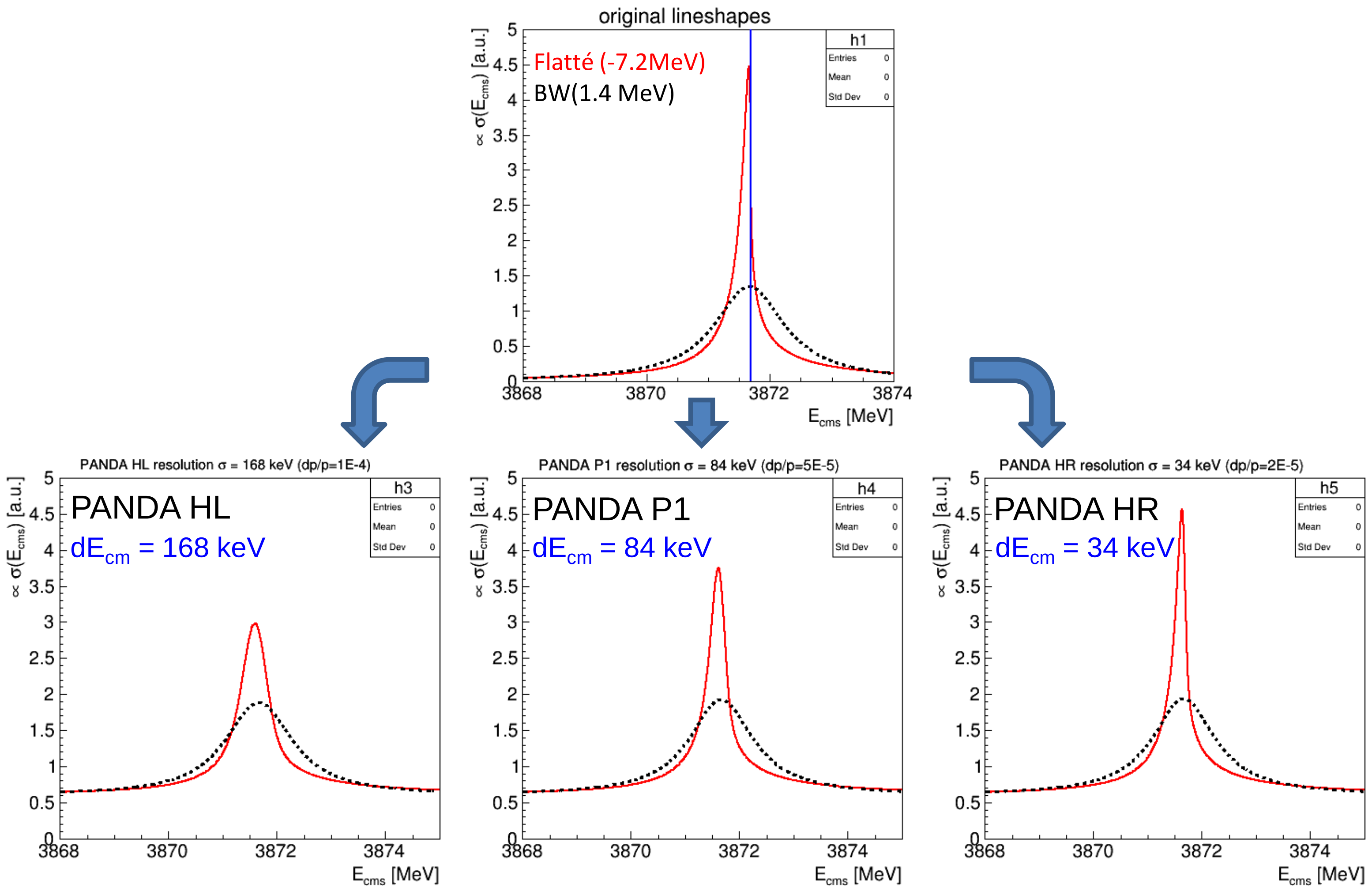
HESR mode	d*p*/*p*	L_{max} [1/cm²·s]	dE_{cm} [keV]
High Luminosity (HL)	$1 \cdot 10^{-4}$	$2.0 \cdot 10^{32}$	168
High Resolution (HR)	$2 \cdot 10^{-5}$	$2.0 \cdot 10^{31}$	34
Phase 1 Mode (P1)	$5 \cdot 10^{-5}$	$2.0 \cdot 10^{31}$	84

@ E_{cm} = 3872 MeV

What can PANDA do?

Due to precise beam resolution

→ Breit-Wigner and Flatté-model are distinguishable



Strategy

Toy MC Simulation of Energy Scan

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

Precision resonance energy scans with the PANDA experiment at FAIR

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

- Use parameters (σ, L, $\mathcal{B}$, ε_{reco}, ...) from above study of

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

- Energy scan simulation: Estimate the expected energy dependent yield

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

➢ Investigate **separation power** between **Flatté & Breit-Wigner** lineshapes

Total data taking time: **$T = 40 \times 2d$** **= 80 d**

Cross section assumption: **$\sigma_{peak}(\bar{p}p \rightarrow \chi_{c1})$** **= 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_{BW}** = [100, 150, 200, 250, 300, ... , 550] keV

Procedure

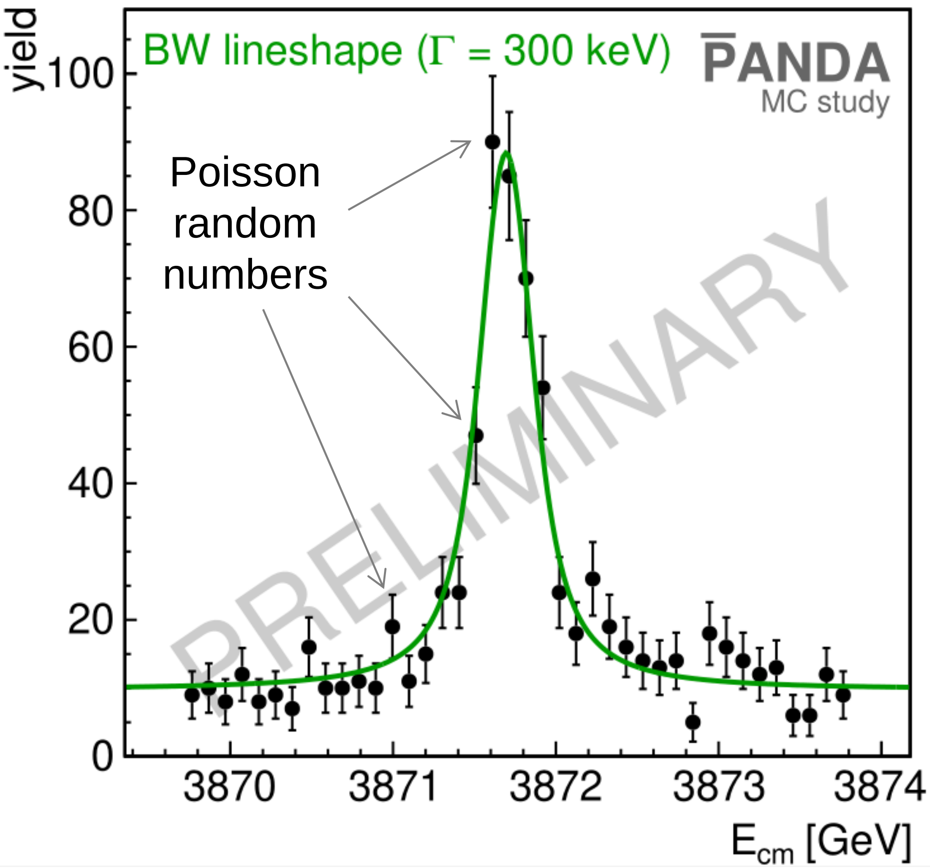
We use the following approach:

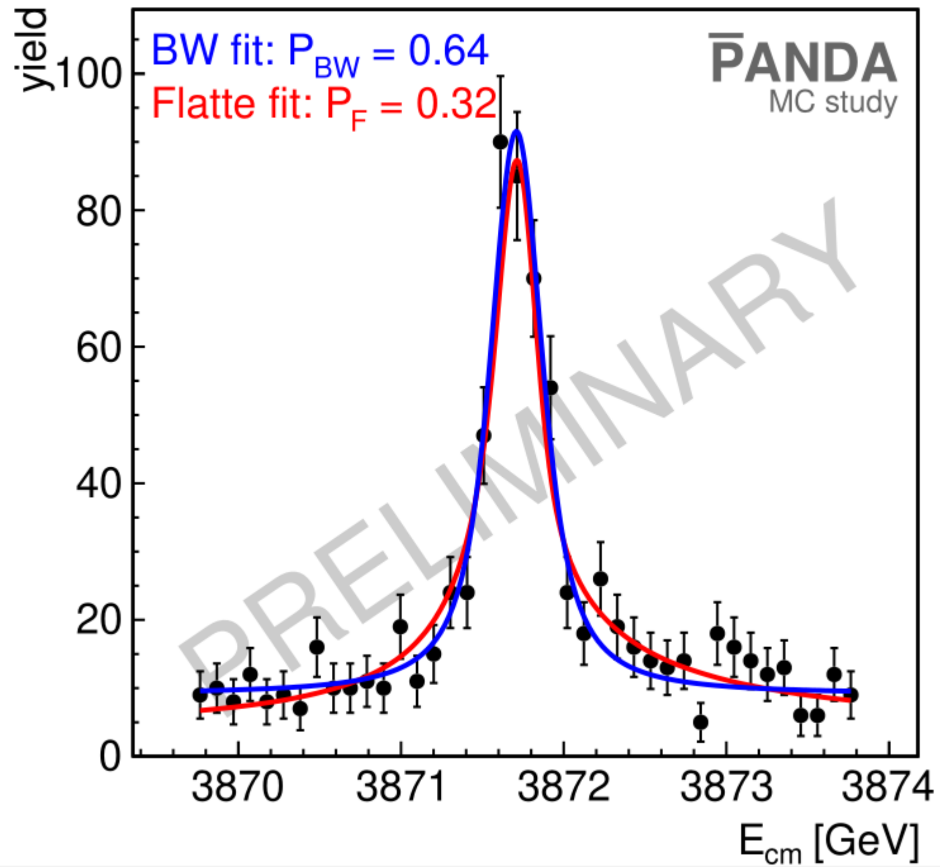
1. Use key parameters from EPJ A 55 (2019) 42
2. Generate many (toy) spectra for Flatté (BW) model
3. Fit both BW and Flatté to each generated distribution and determine fit probabilities P_{BW} and P_F
4. Identification considered correct, if $P_F > P_{BW}$ ($P_{BW} > P_F$)
5. Count fraction of incorrect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

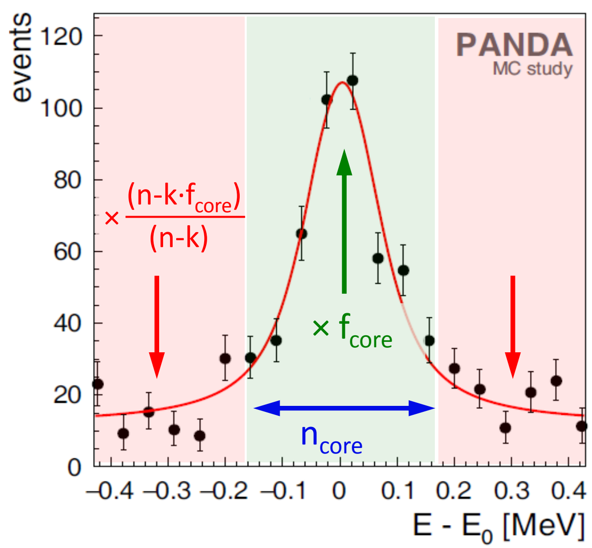
Scan Time Optimisation

- 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})

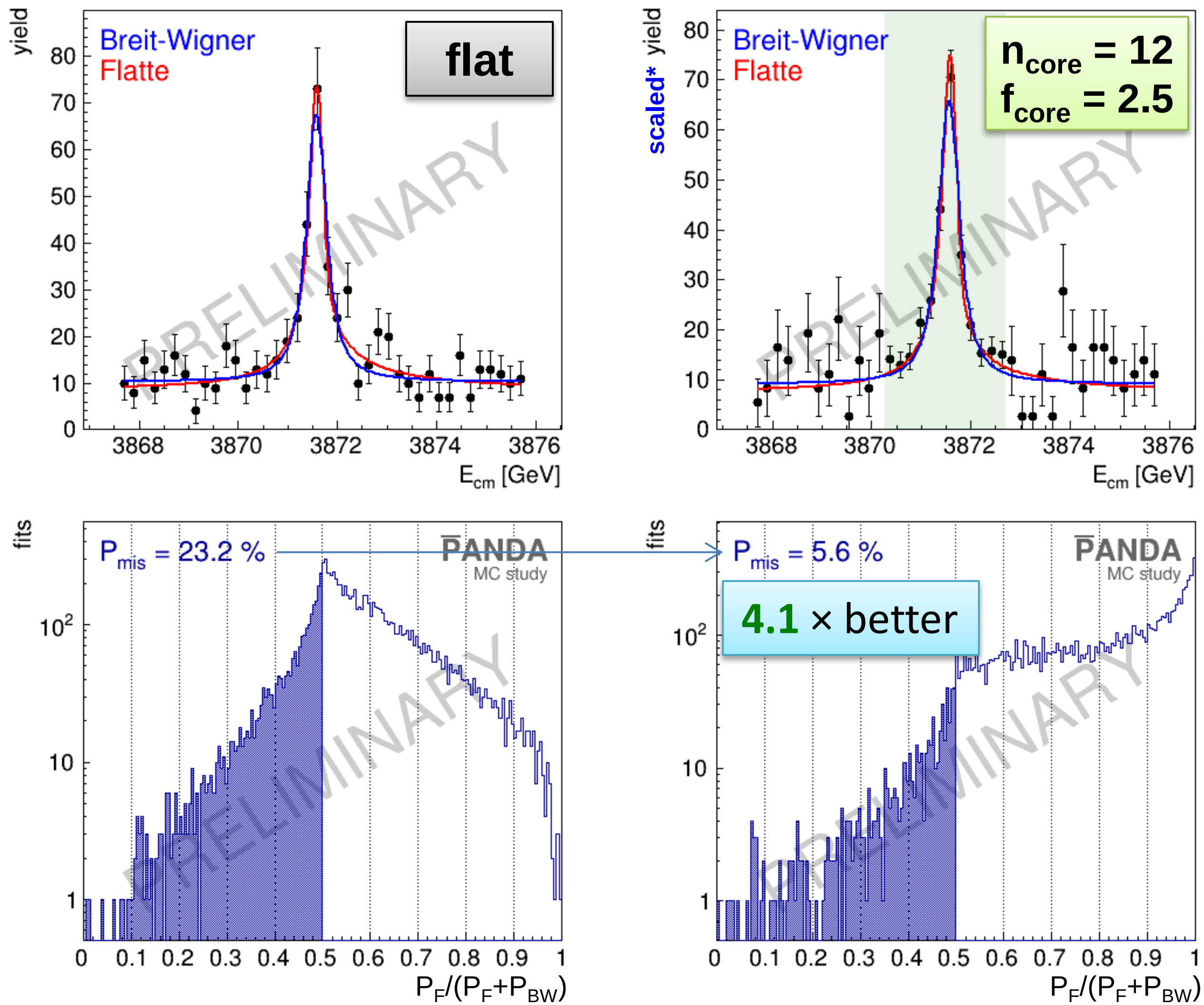


Scan Optimisation Example (P1)

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

Fit Example

mis-ID from 10000 fits

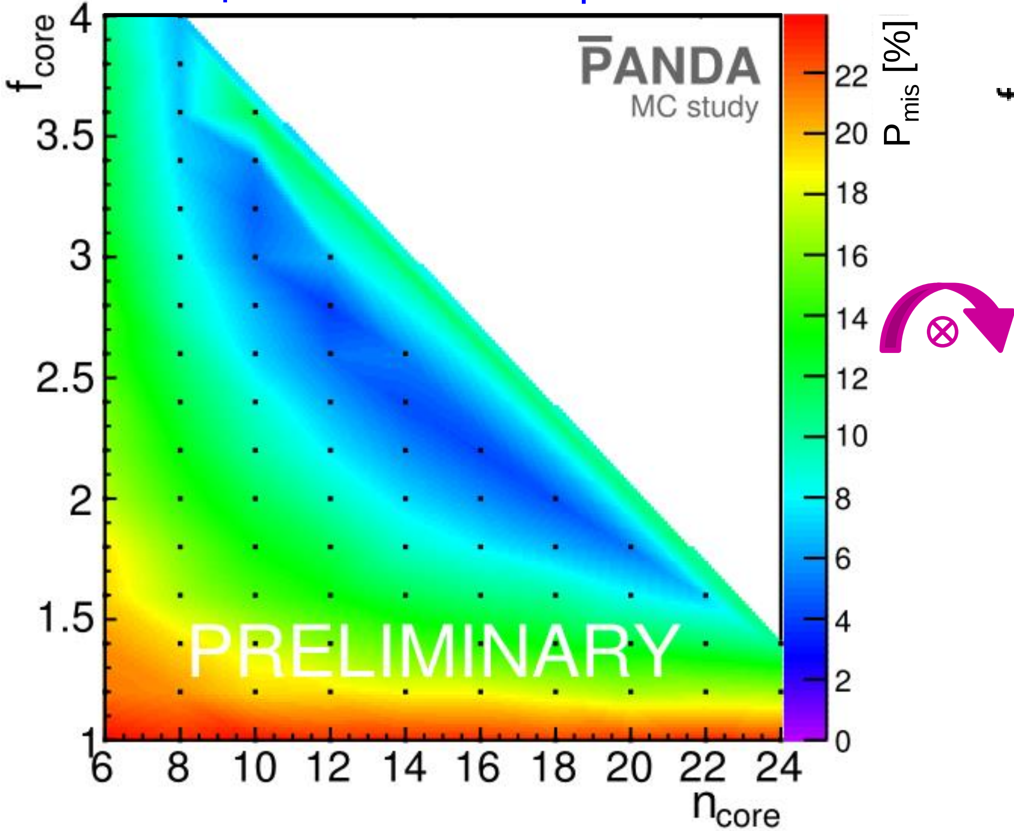


* yields scaled, errors adapted

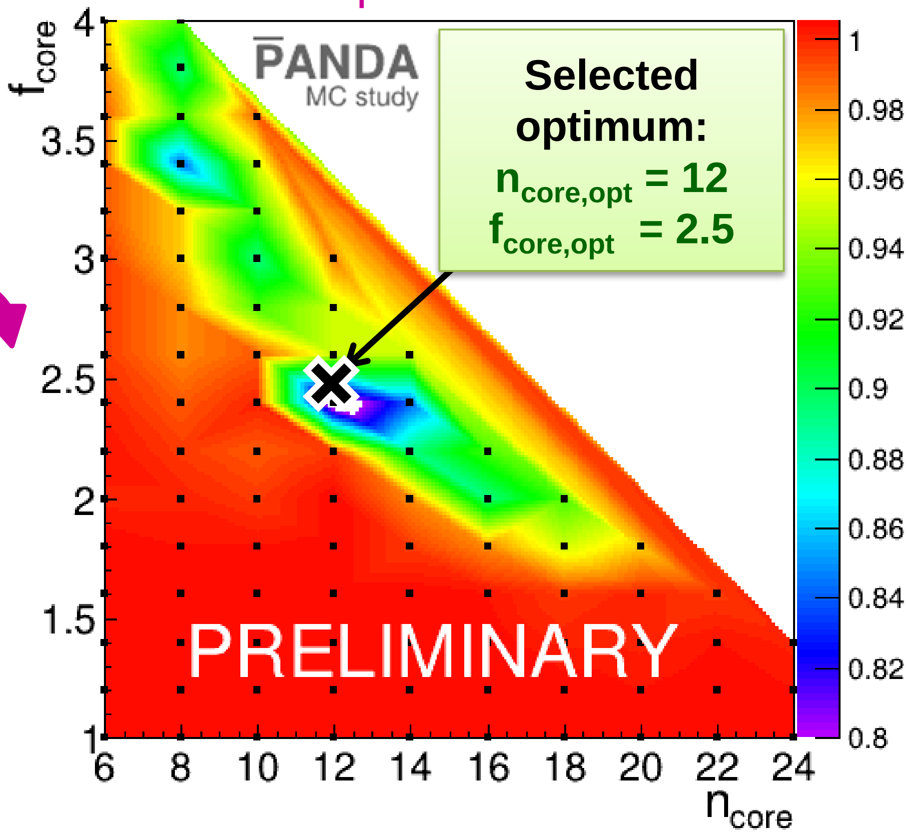
Overall Optimisation

- 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

Example scenario: **P1**, **E_f = -7.2 MeV**



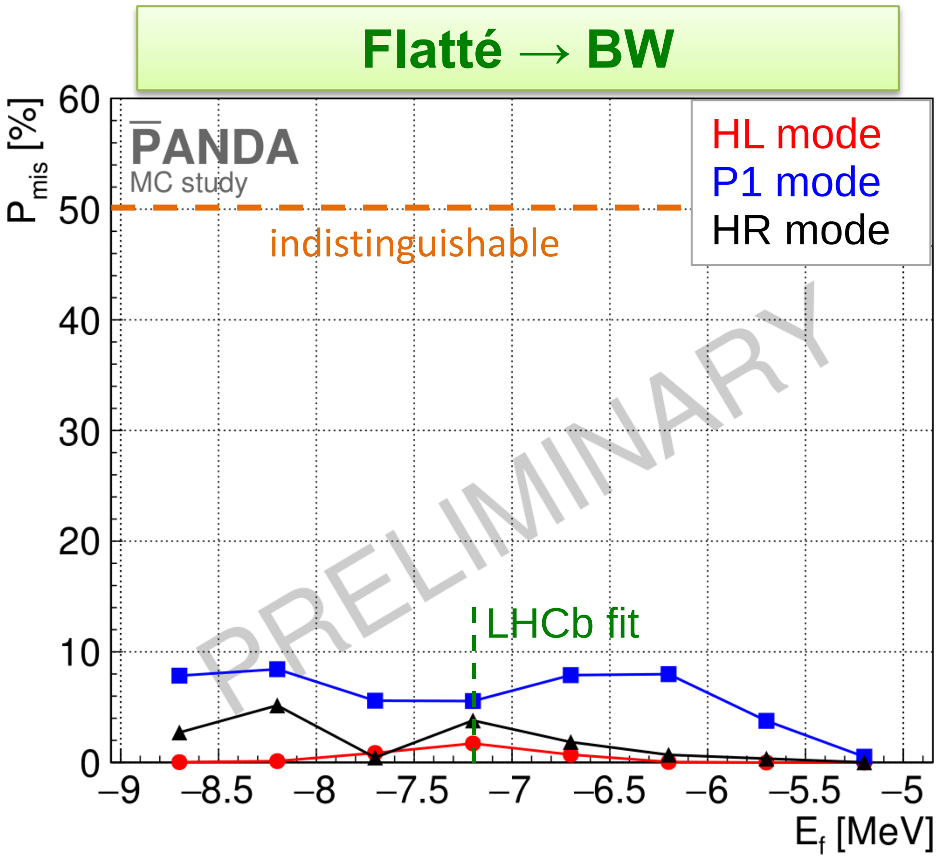
Combined plot of 15 scenarios



RESULTS

Parameter Dependent Performance

- Performance across Flatté energy E_f range

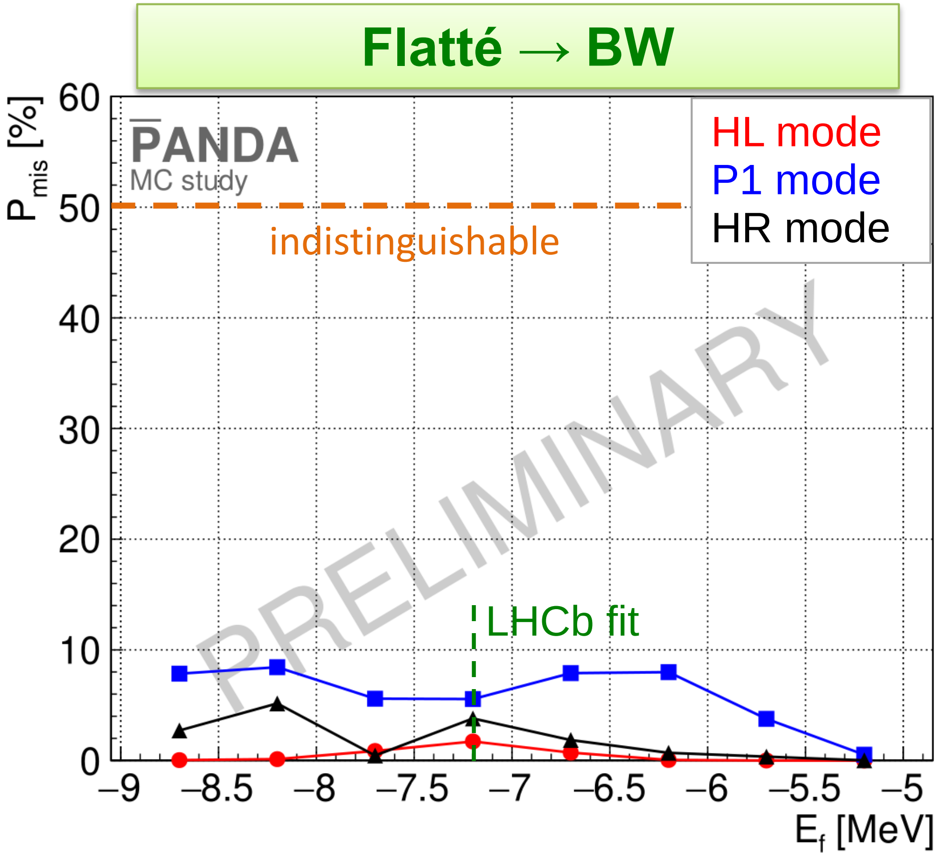


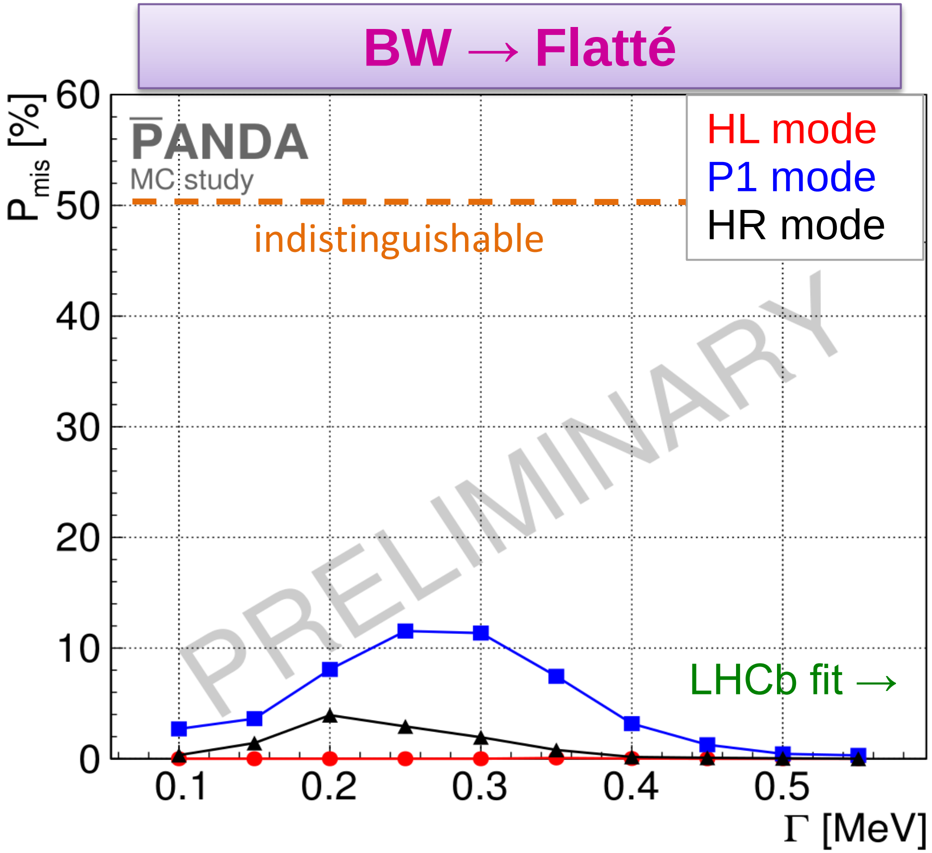
For Mis-match of Flatté as BW we see

- 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

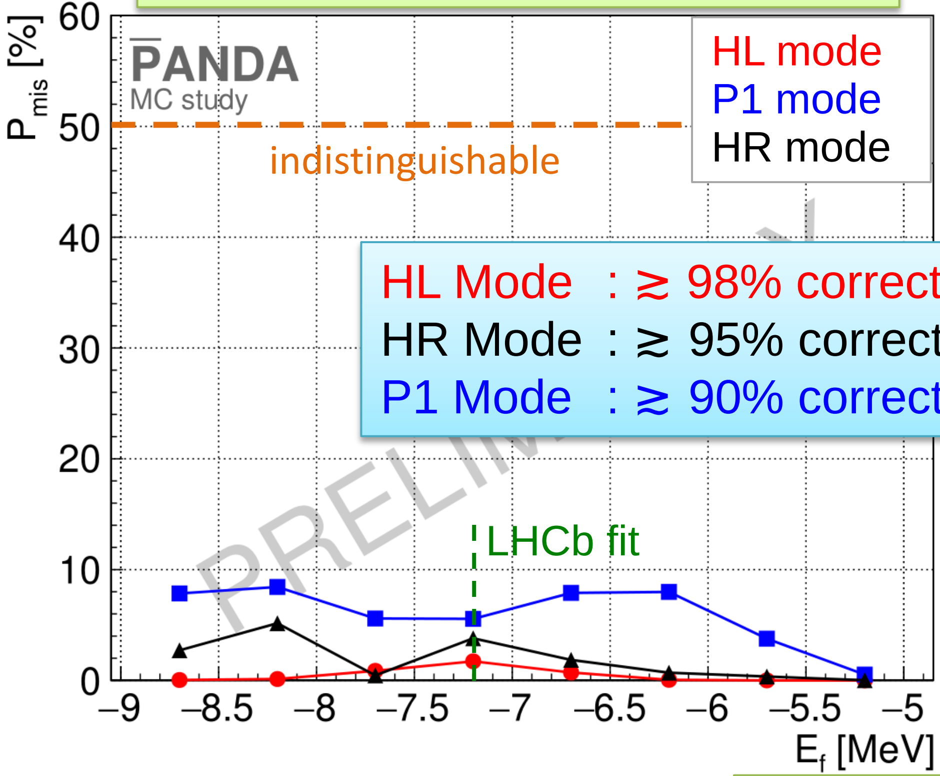




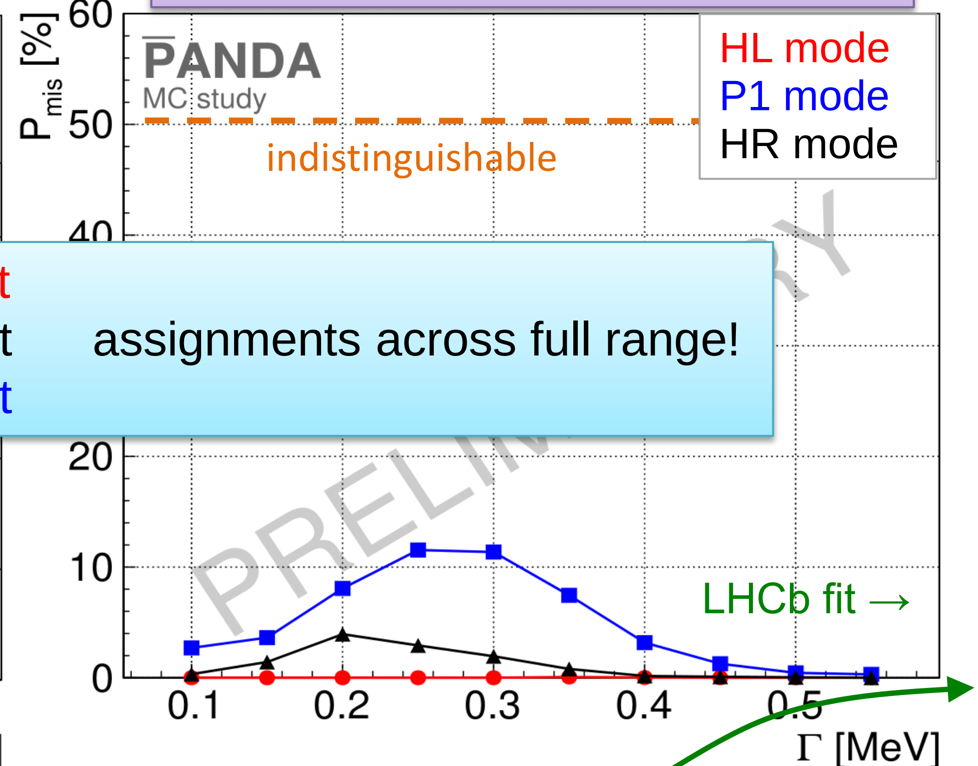
Parameter Dependent Performance

- 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

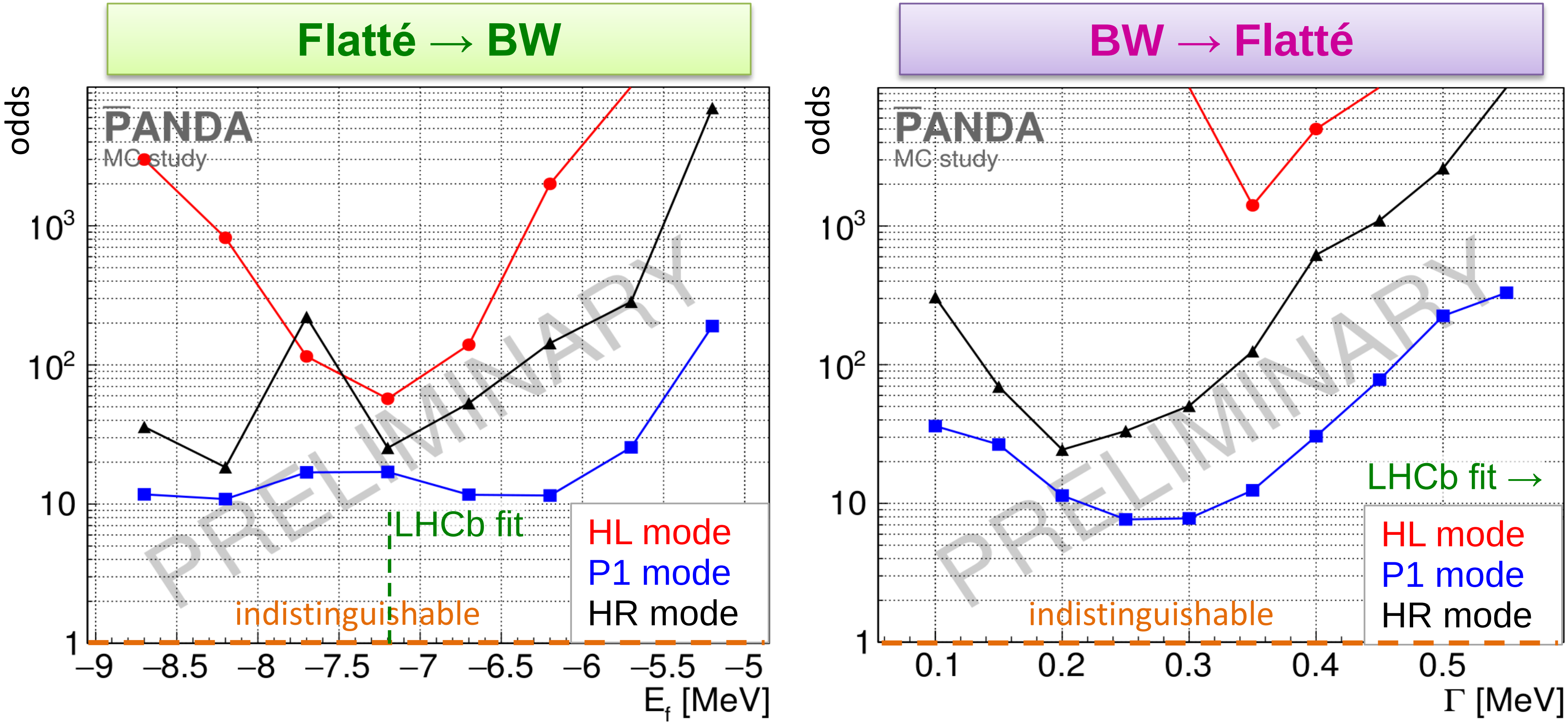
assignments across full range!

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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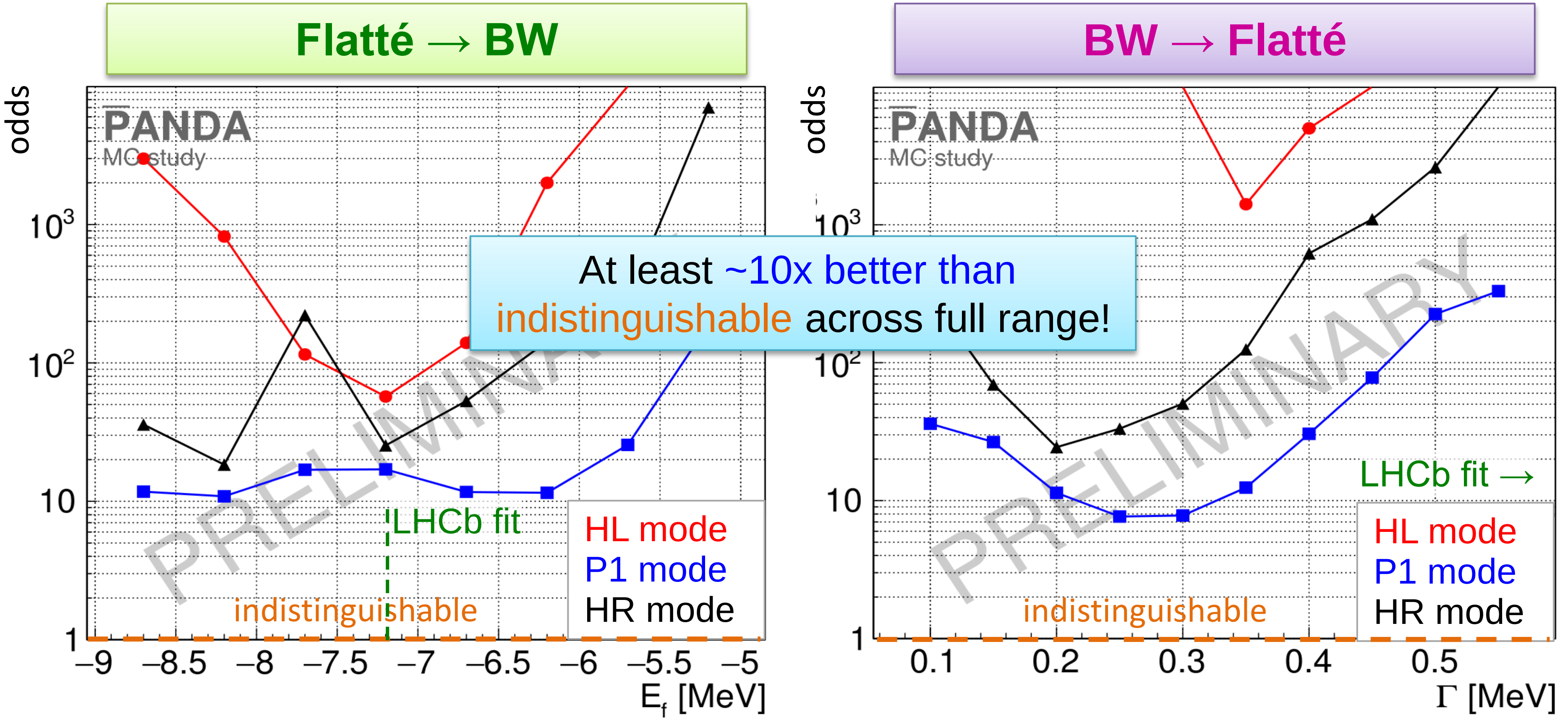

Summary and Conclusion

- 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
- At least ~10x higher odds to identify correct model than LHCb
- First attempt of scan optimization shows further potential

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Thank you very much for your attention!