Reproducing the LHCb X(3872) Results

(and Possible Effect of Adding DD* Channel)

Oct 28, 2020

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The LHCb Paper

[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

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

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

Large width would undermine the PANDA precision advantage...

LHCb Findings

- Breit Wigner fit

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

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

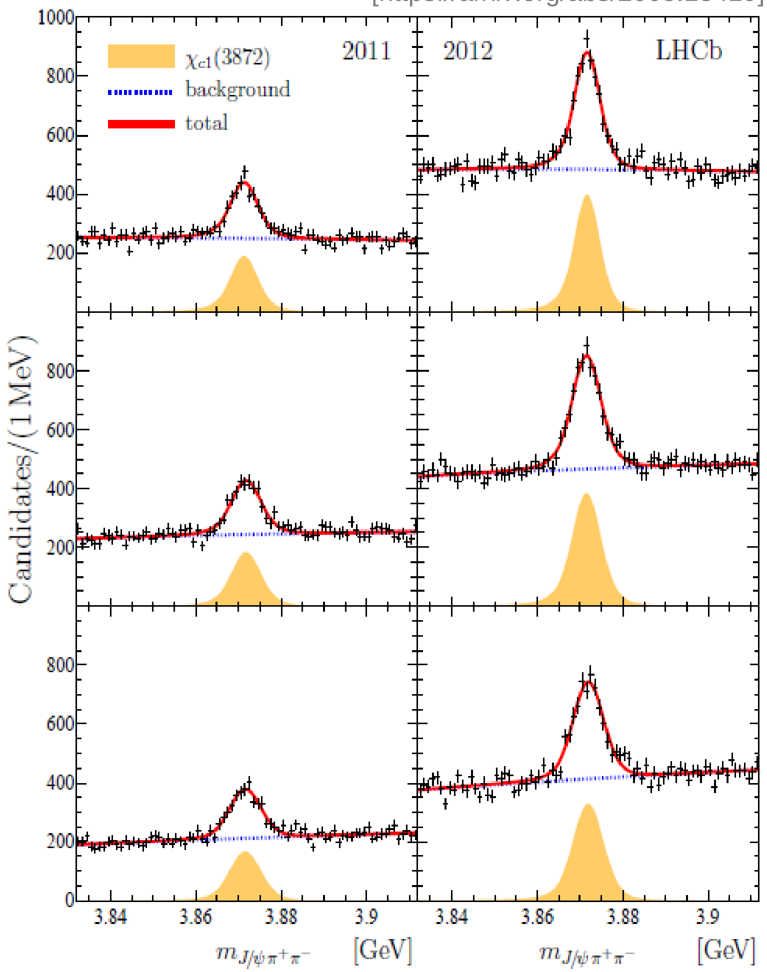
- Flatté model fit

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)

  - Dominant pole: Bound state
  - Virtual state allowed at 2 sigma level

[https://arxiv.org/abs/2005.13419]



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discrepancy?

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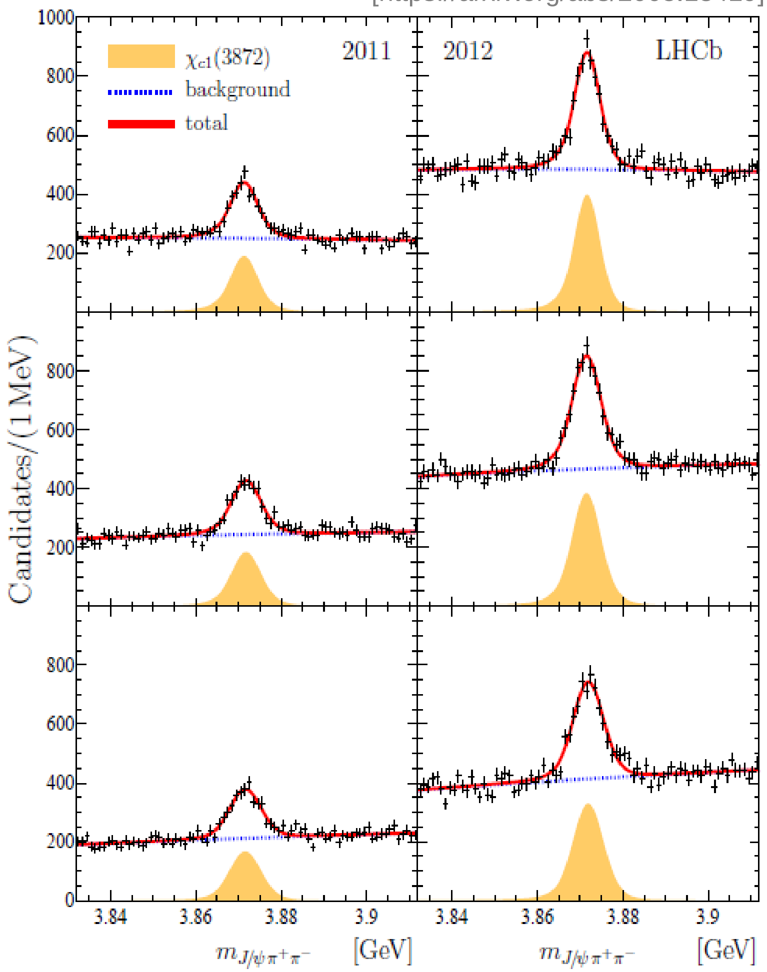


What we want to study

Idea: With given yield and resolution model of LHCb spectra:

- Can we reproduce the results from paper with Toy MC?

1. Bias of Breit-Wigner (BW) and Flatté FWHM
   - Paper: $\Gamma_{BW}/FWHM_{Flatté}$ = **6.3**

2. Distinguishing BW and Flatté line shape
   - Paper: "... **indistinguishable**."

3. Identification of nature given the Flatté-model is true
   - Paper: "... virtual state allowed at **2σ level**."

Flatté Model Revisited

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

$$\frac{dBr(B \to K D^0 \bar{D}^{*0})}{dE} = \mathcal{B}\frac{1}{2\pi}\frac{g k_1}{|D(E)|^2},$$

DD* lineshape

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

J/ψππ lineshape

with

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

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

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

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

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

$$g_1 = g_2 = g$$

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

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

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

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

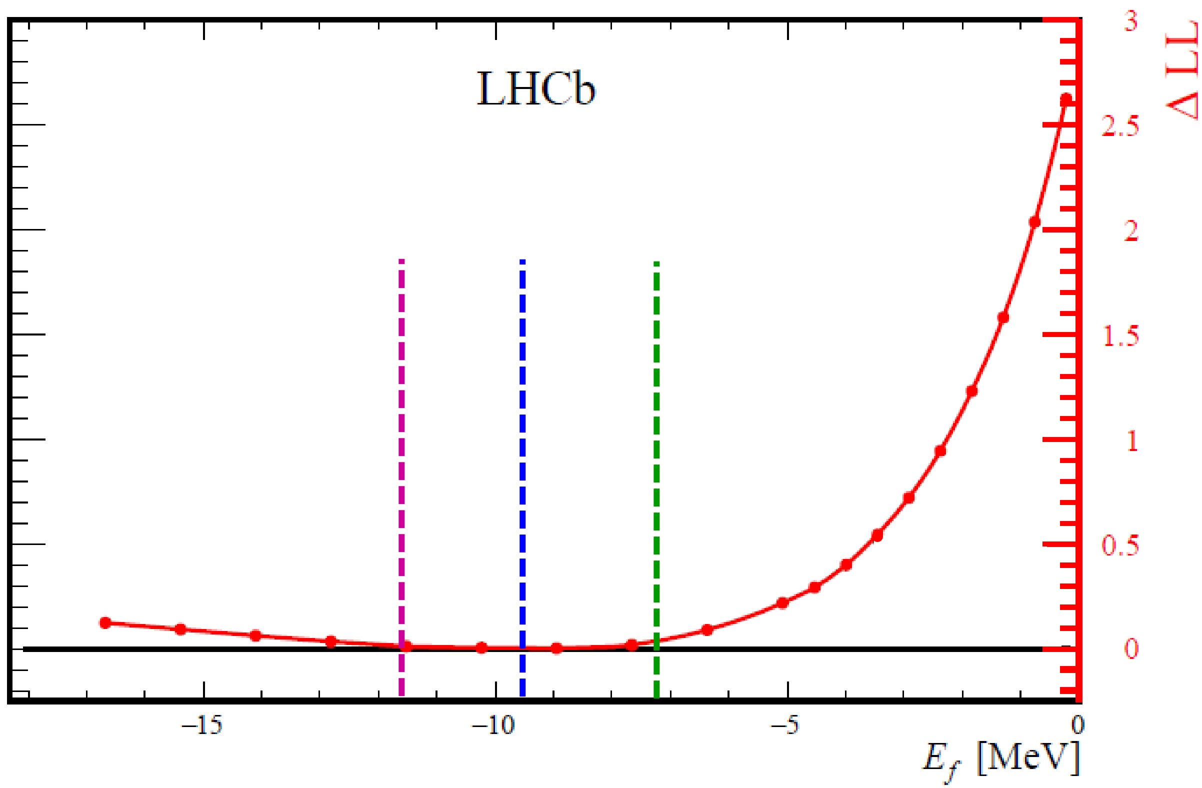
Param.	PANDA study	LHCb
g	0.137	0.108
Γ_0	1.0	1.4
f_ρ	0.007	0.0018
f_ω	0.036	0.01
$E_{f,thr}$	-8.56MeV	-6.82 MeV

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

(subject of publication)

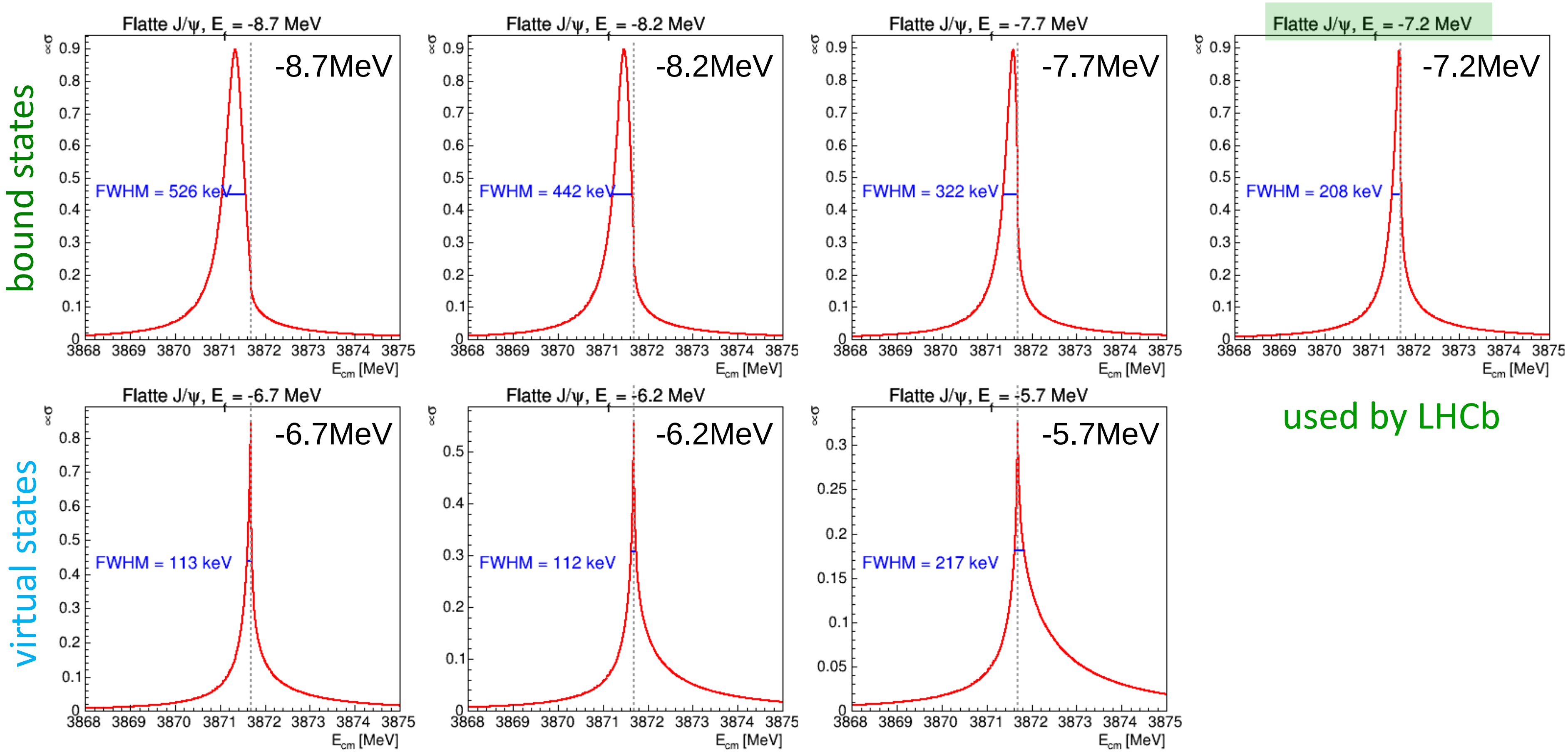
LHCb Paper - Parameter E_f

- ΔLL seems to indicate best $E_f \approx -10 \ldots -9$ MeV
- They quote minimum at $m_0 = 3860$ MeV
- Definition: $E_f = m_0 - (m_D + m_{D^*}) \rightarrow E_f = -11.68$ MeV
- They fix for further analysis $m_0 = 3864.5$ MeV / $E_f = -7.2$ MeV

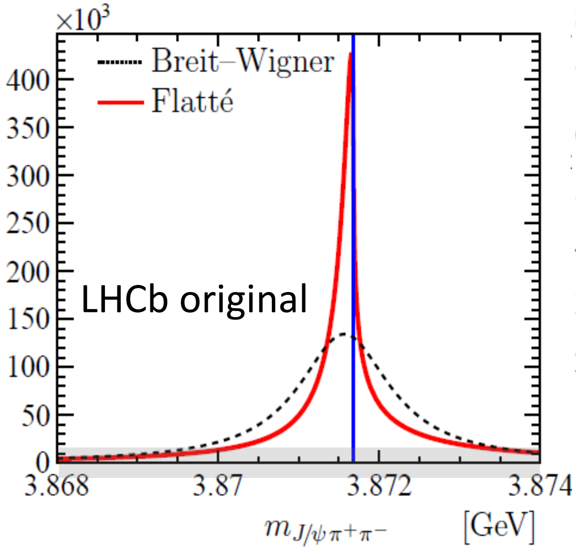


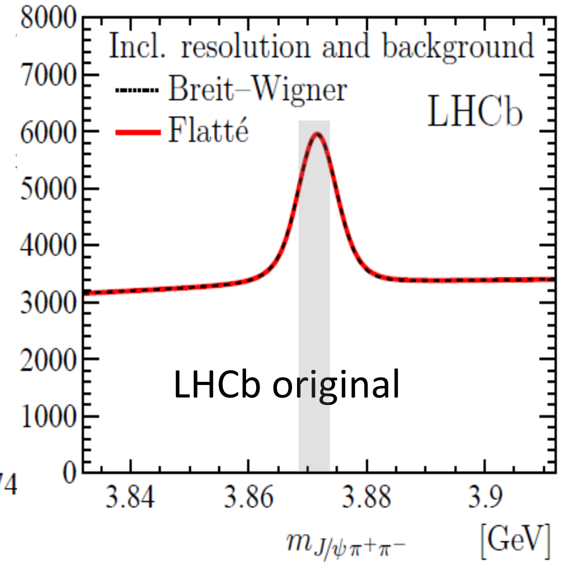
J/ψπ⁺π⁻ Lineshapes

- Lineshapes for various E_f



J/ψπ⁺π⁻ - LHCb Lineshapes (incl Resolution)





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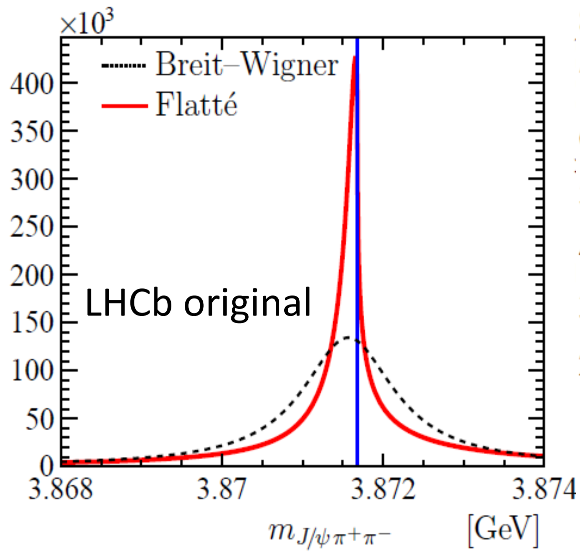

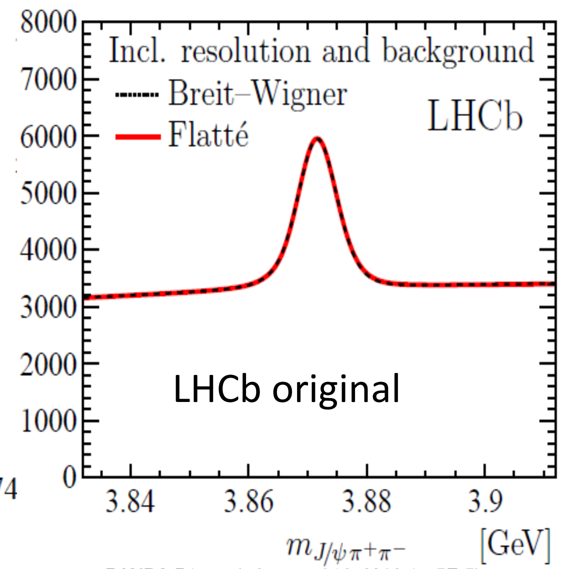

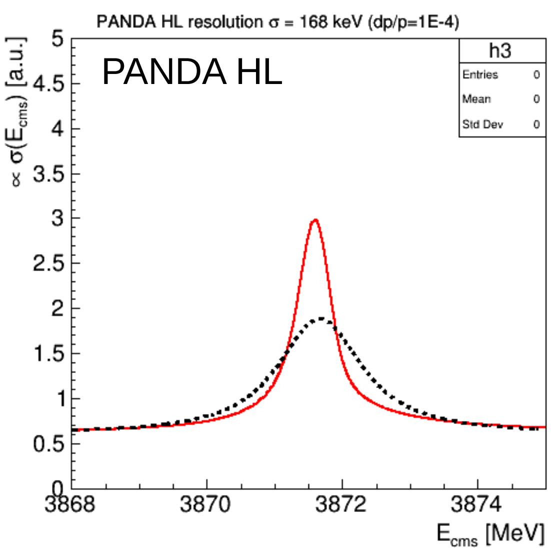

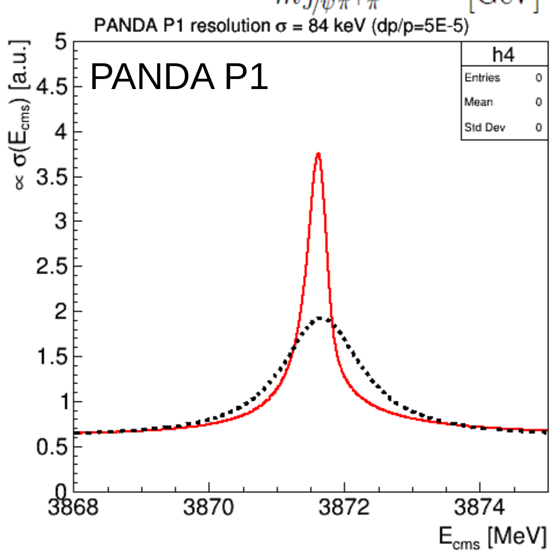

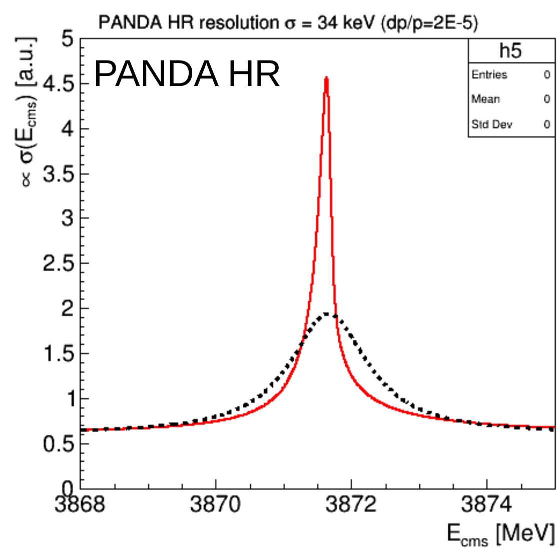

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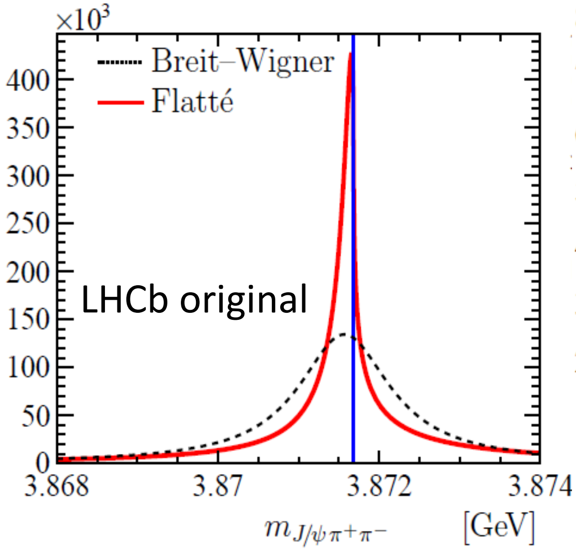
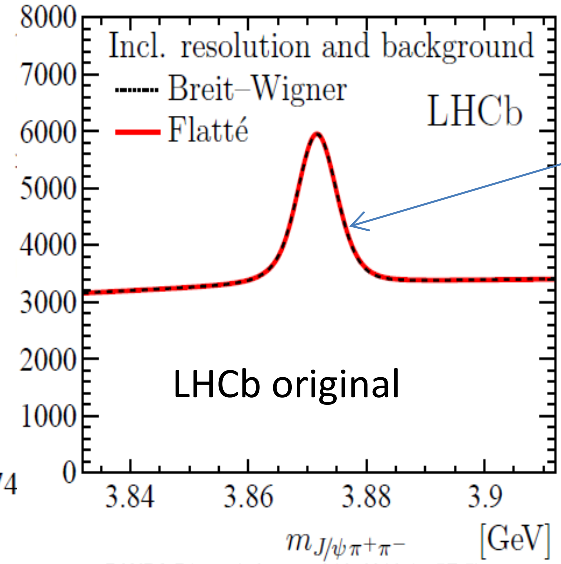
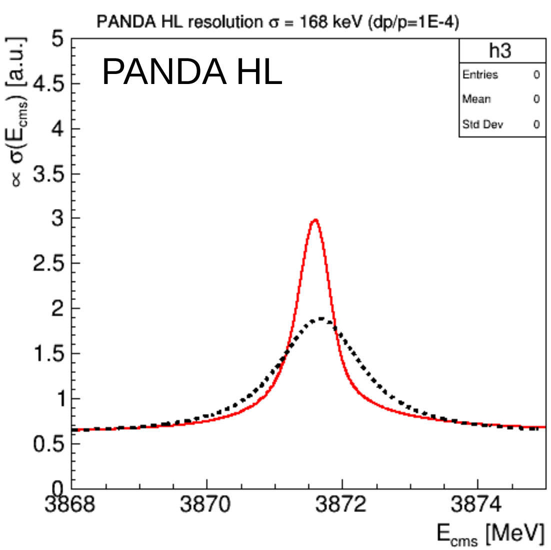
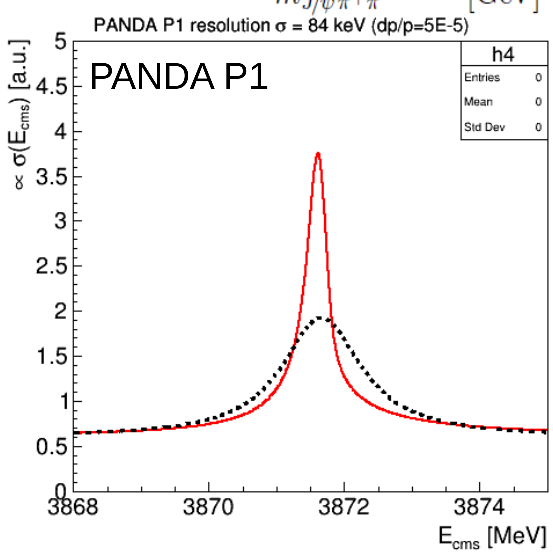
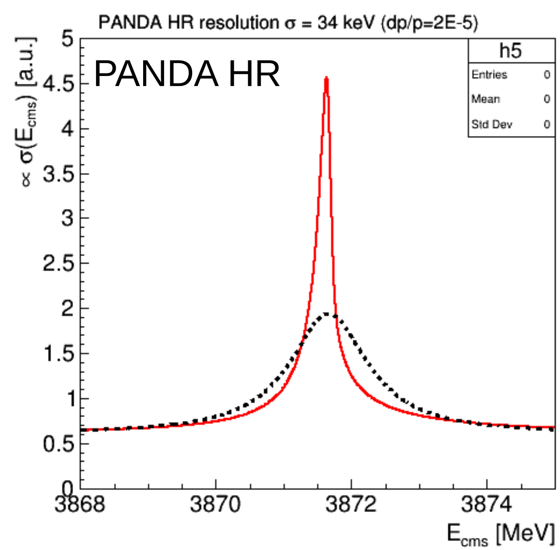




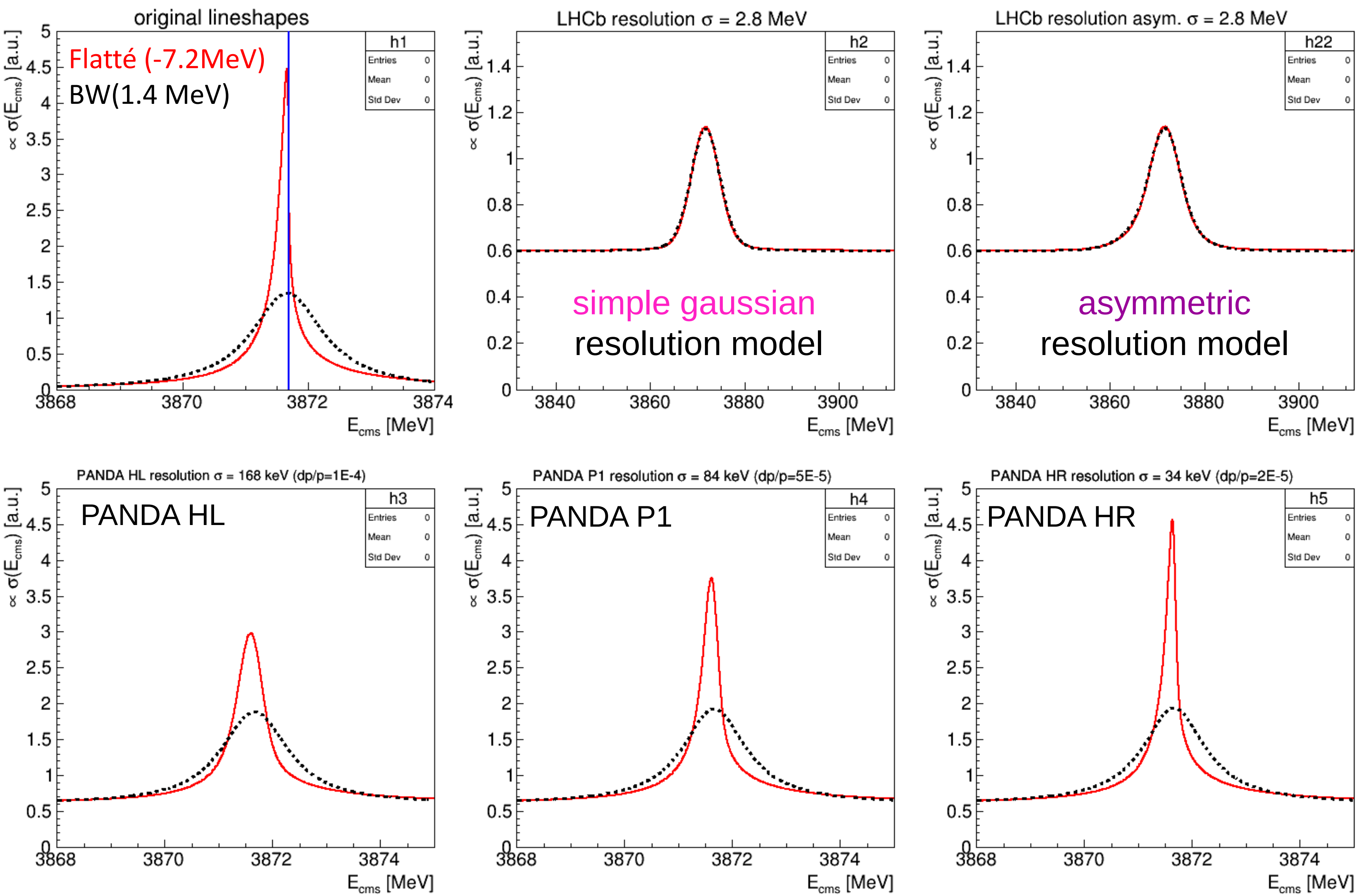
For Toy MC:
Resolution model not specified in LHCb publication
→ use two reasonable assumptions for toy MC here (Gaussian, asymmetric)



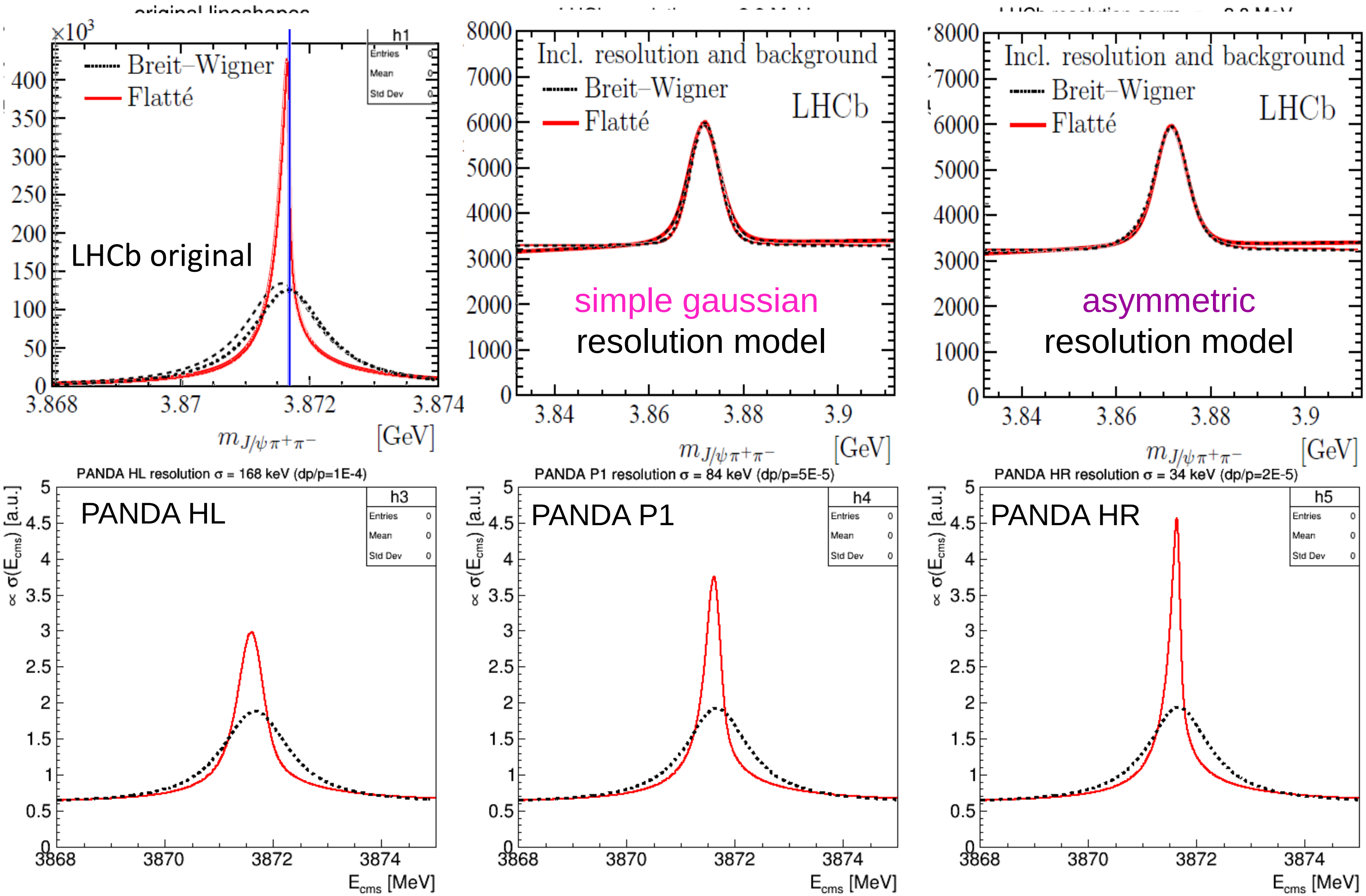




J/ψπ⁺π⁻ - Remodelling Resolution

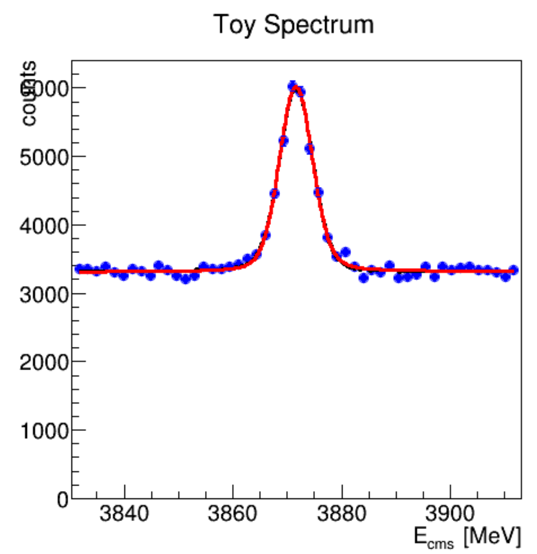


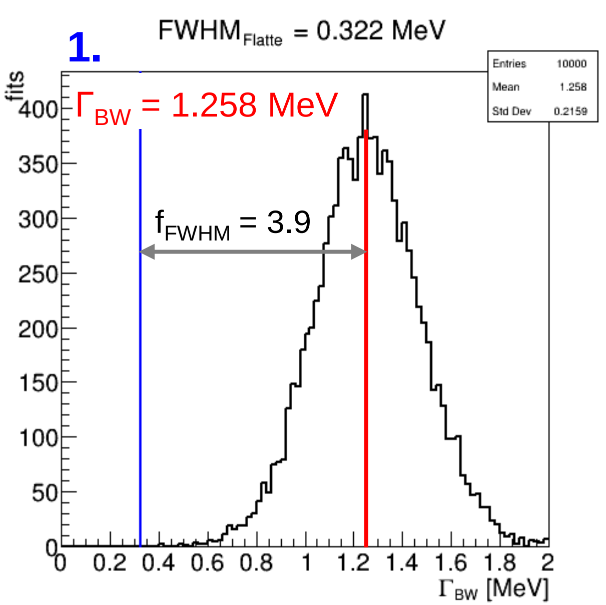
$J/\psi\pi^+\pi^-$ Lineshapes with Resolution

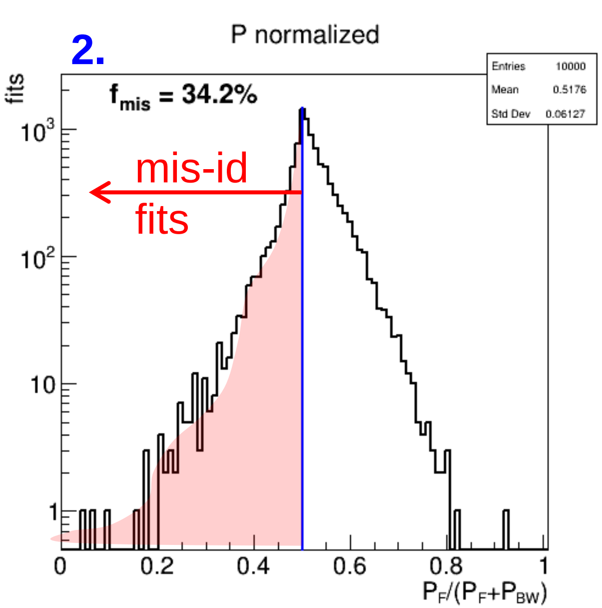


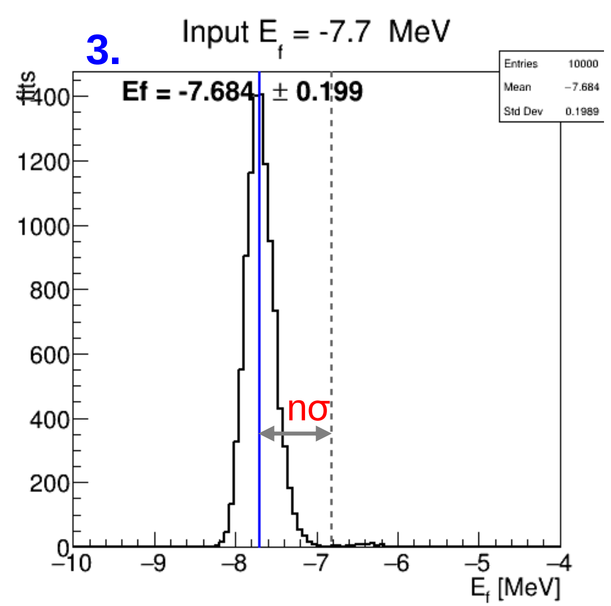
Reproduce LHCb with Toy MC

- Generate and fit many Flatté toy MC spectra
- Determine
  1. Width Γ_{BW} compared to Flatté FWHM
  2. Prob. to confuse Flatté with BW ($P_{fit,BW} > P_{fit,Flatte}$)
  3. Significance to determine nature (Flatté)
     $|E_{f,fit}-E_{f,thresh}|/\sigma_{Ef}$ from many Flatté fits
- In addition: Compare to PANDA P1, HR, HL modes



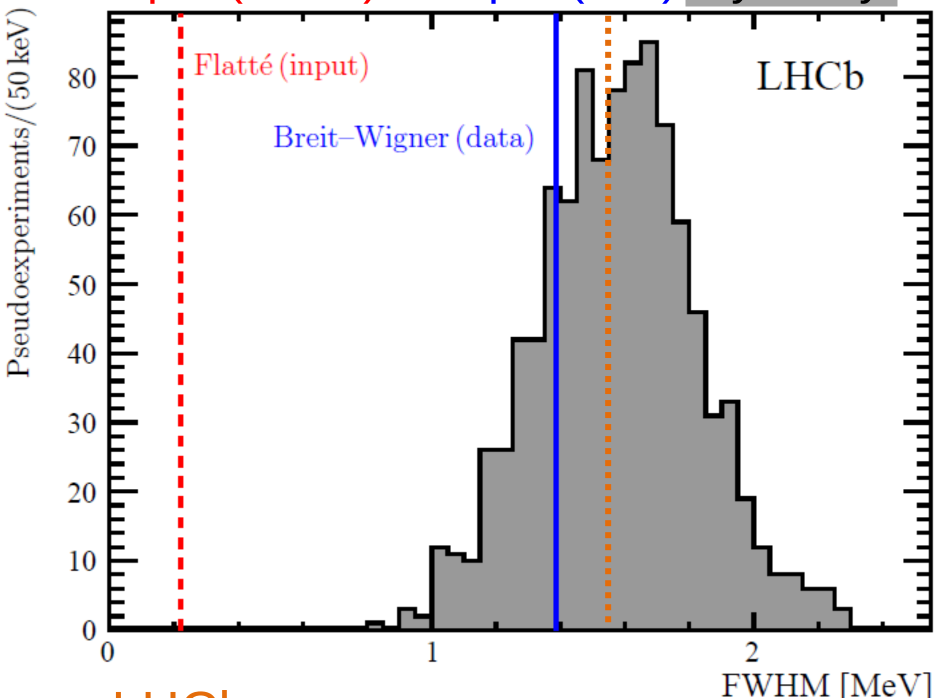


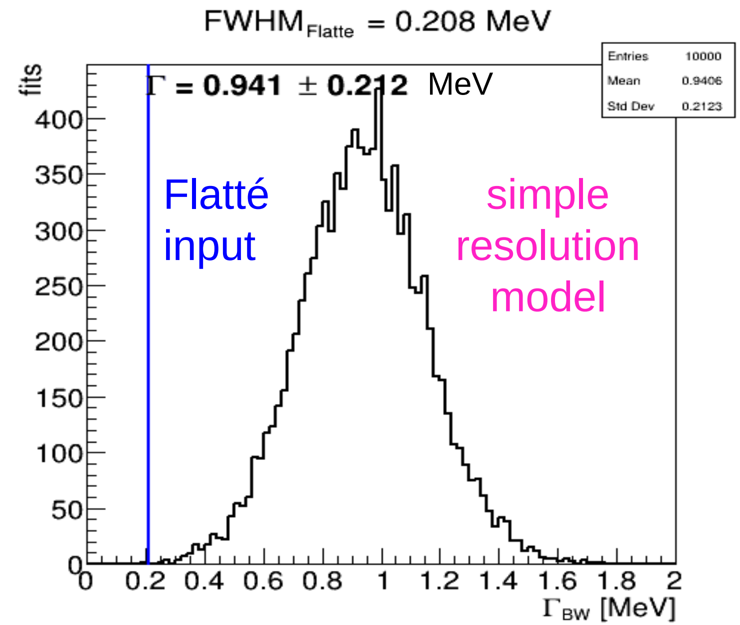


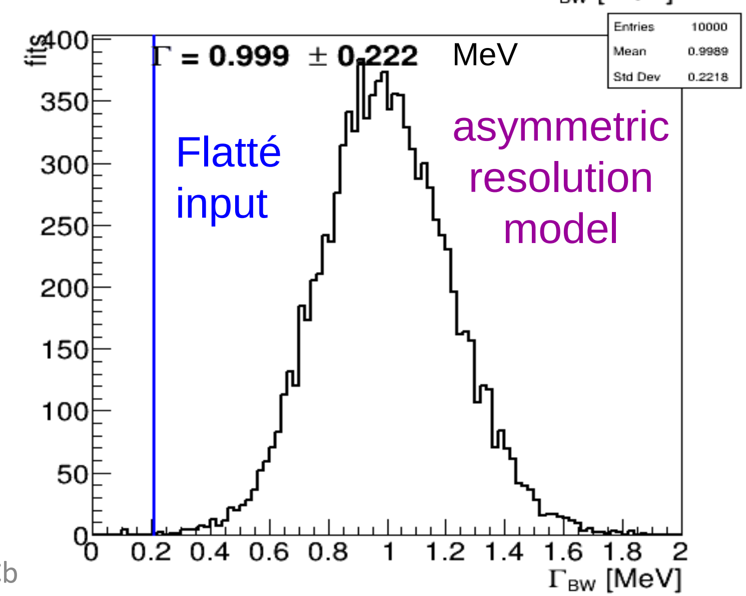


Toy Study Comparison with Paper: Width

Input (Flatté) - output (BW) toy study







LHCb paper:

$\Gamma_{BW,toy} \approx 1.55 \pm 0.3$ MeV

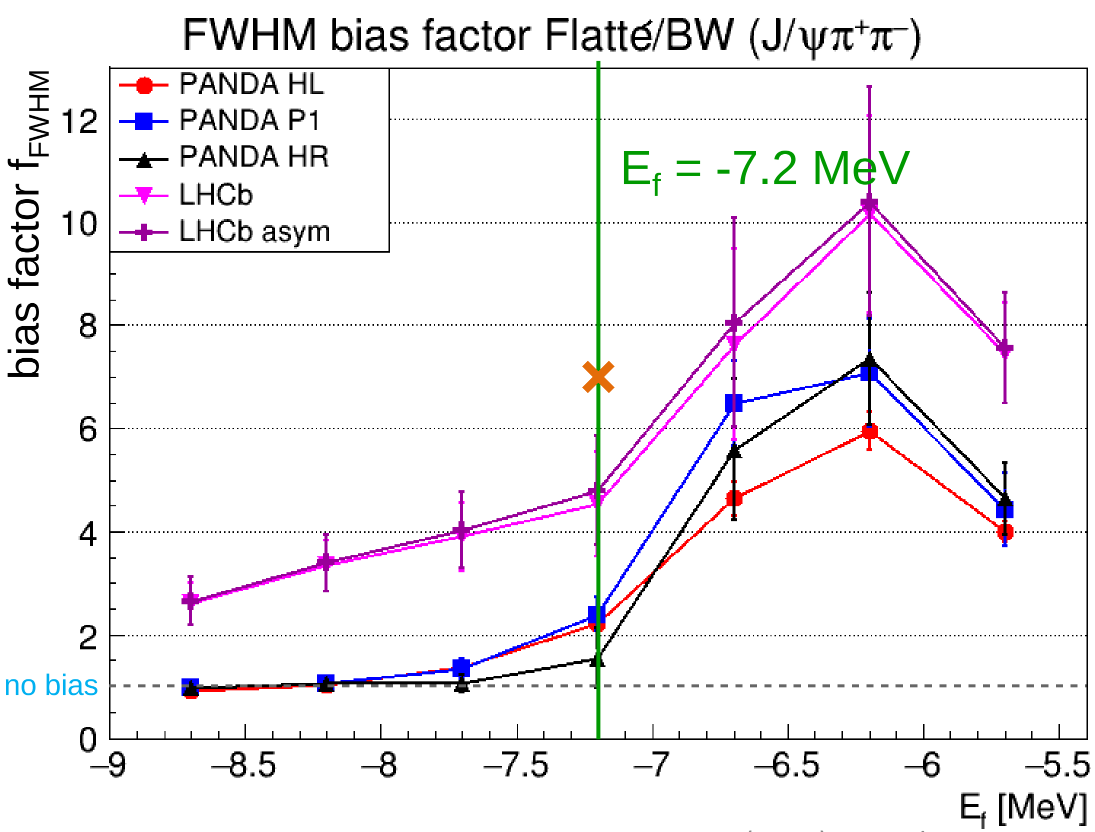
This study:

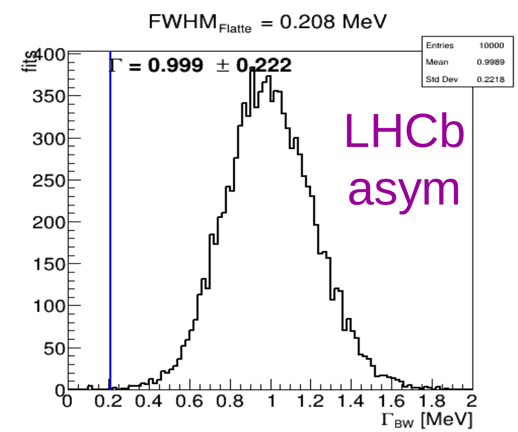
$\Gamma_{BW,toy} \approx 0.94 \pm 0.21$ MeV (simple)

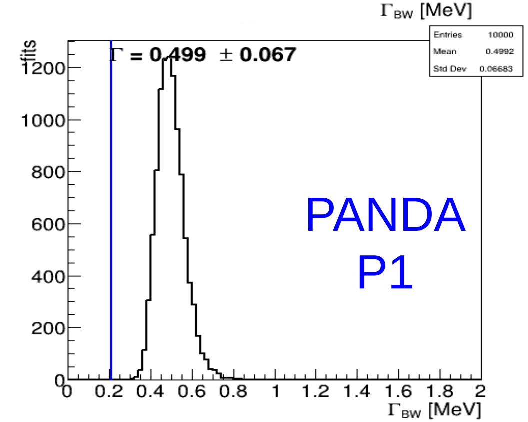
$\Gamma_{BW,toy} \approx 0.99 \pm 0.22$ MeV (asym)

Width Bias Factor from Breit-Wigner Fit

- LHCb paper: f_{FWHM} = 1.55 (BW) / 0.22 (Flatté) = 7.0
- This study:
  - LHCb toy: $f_{FWHM} \approx$ 4.5 ... 4.7 in ROI
  - PANDA toy: $f_{FWHM} \approx$ 1.5 (HR) ... 2.2(HL) ... 2.4 (P1) in ROI

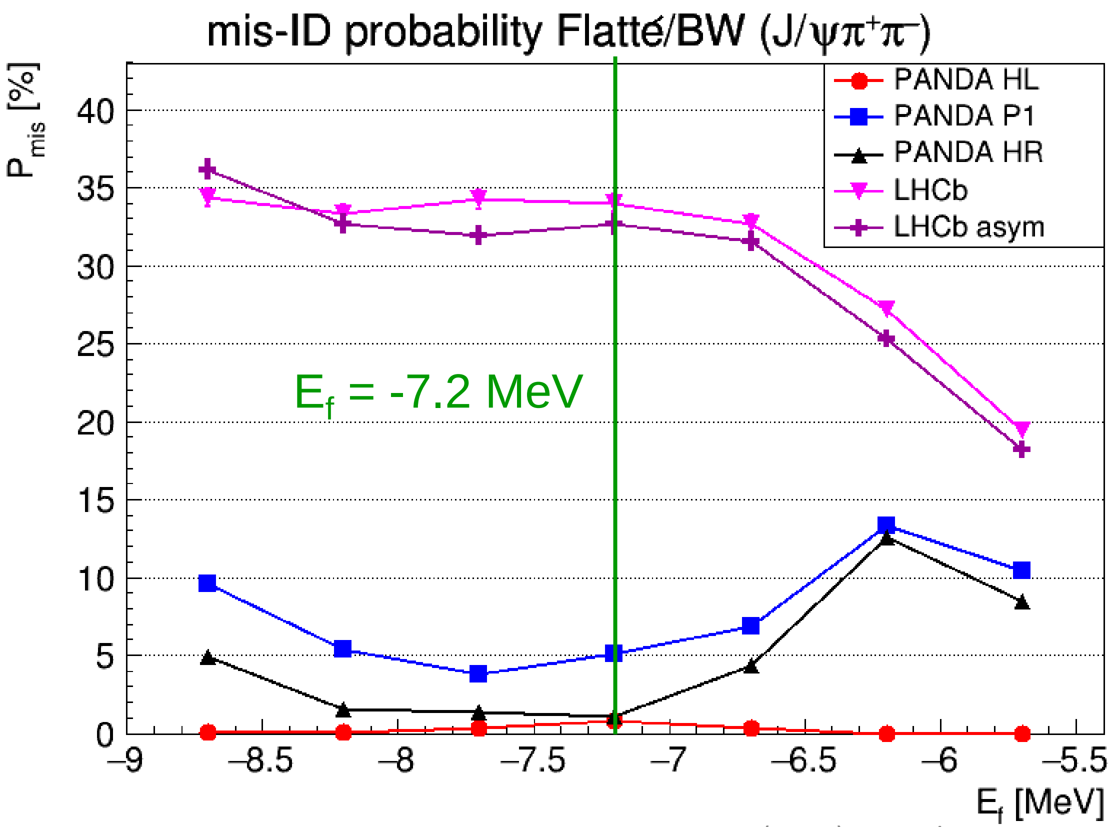


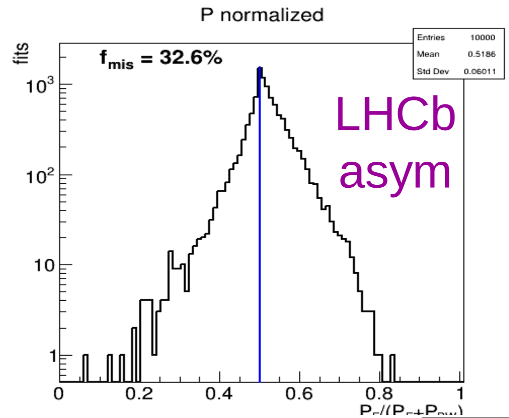


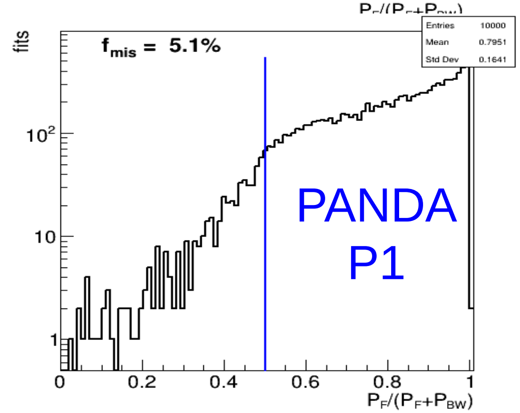


Distinguish Flatté from Breit-Wigner

- LHCb paper: BW and Flatté distributions "... indistinguishable."
- This study:
  - LHCb toy: $P_{mis} \approx 33\%$ in region of interest (at E_f = -7.2 MeV)
  - PANDA toy: $P_{mis} \approx 1\%$ (HR/HL) ... 5% (P1) in ROI

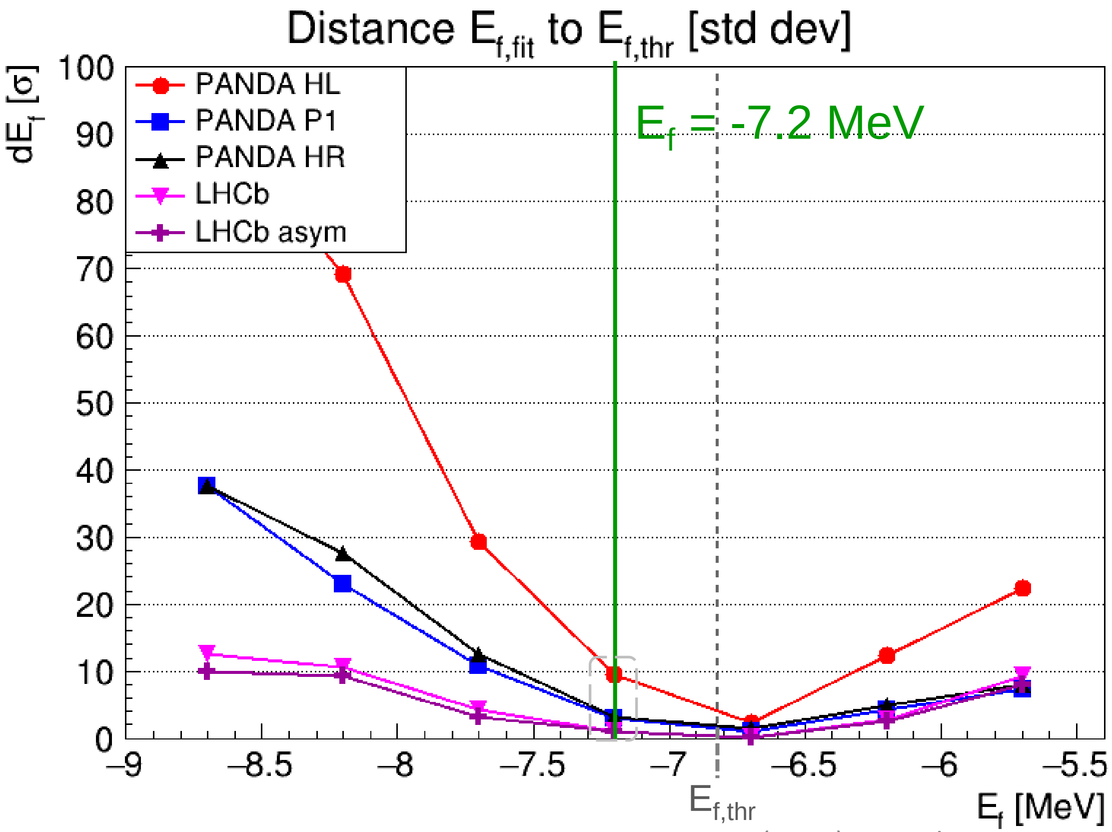


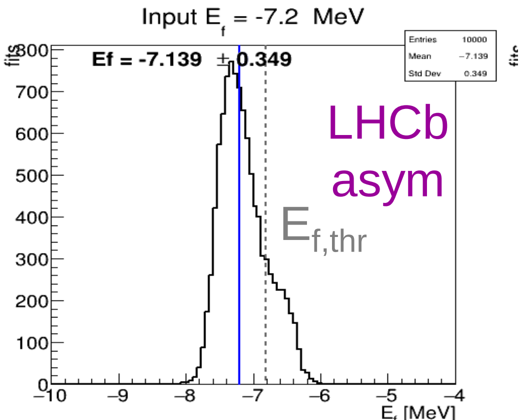


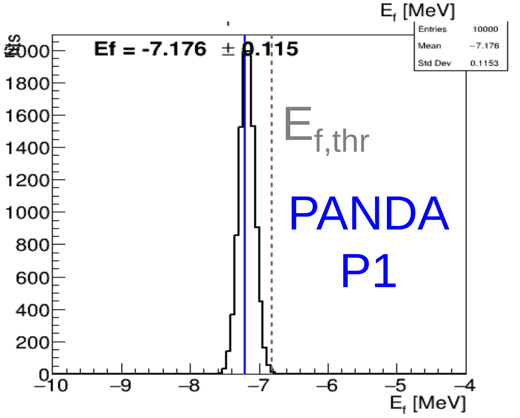


Distinguish Nature in #std. dev.

- LHCb paper: "..virtual state allowed at 2σ level."
- This study with $dE_f = (E_{f,fit} - E_{f,thr})/\sigma_{Ef,fit}$:
  - LHCb toy: $dE_f \approx 0.9\sigma$ ... 1.0σ in ROI
  - PANDA toy: $dE_f \approx 3.0\sigma$ (P1) ... 3.1σ (HR) ... 9.5σ (HL) in ROI







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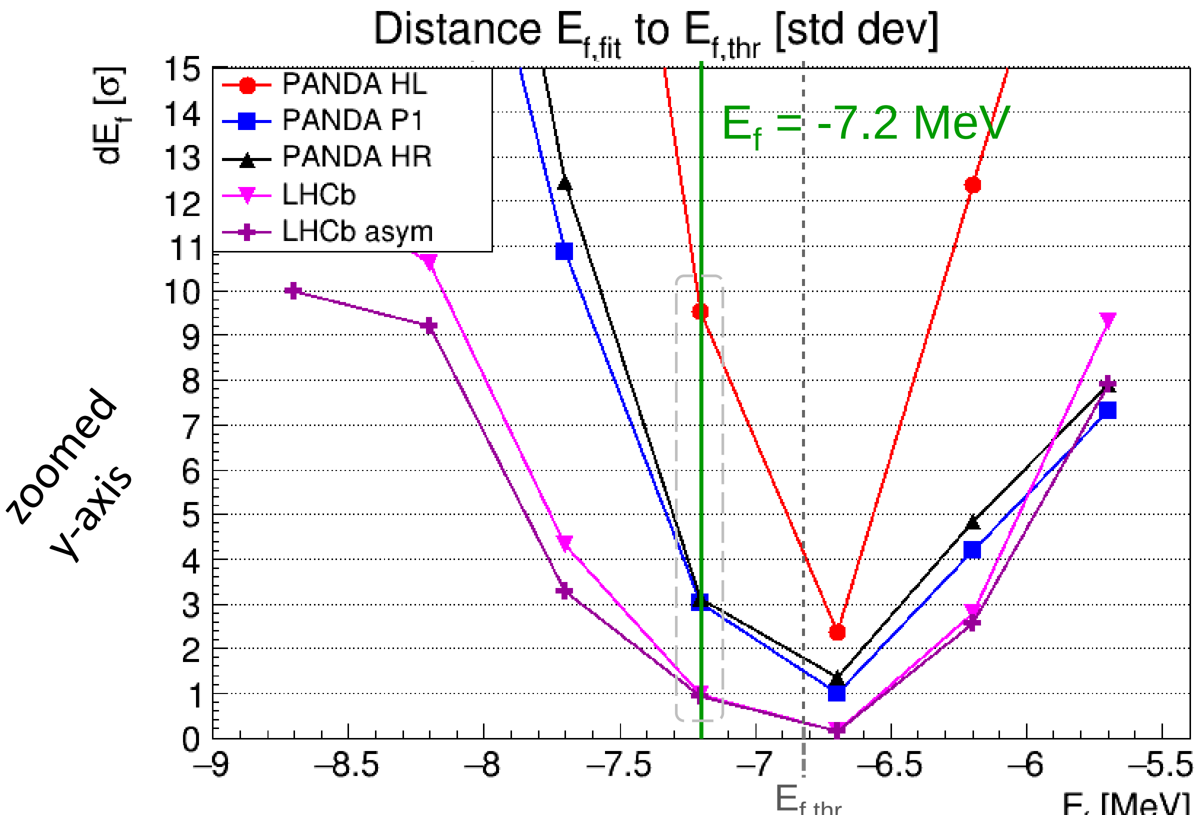
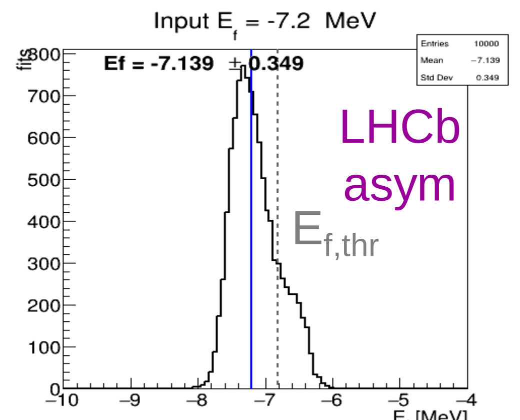
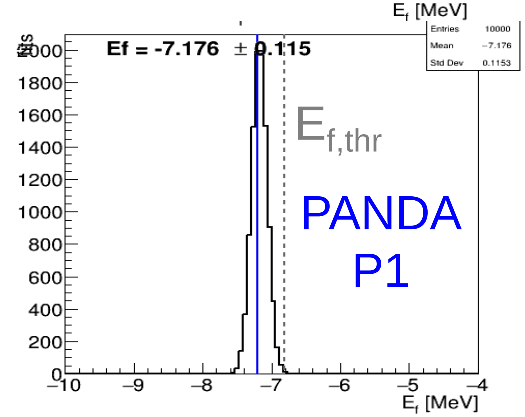






Summary - What we found

1. Bias factor of Breit-Wigner (BW) vs Flatté FWHM
   – Pub: **6.3**; LHCb toy: **~4.5**; PANDA: **1.5 - 2.4**

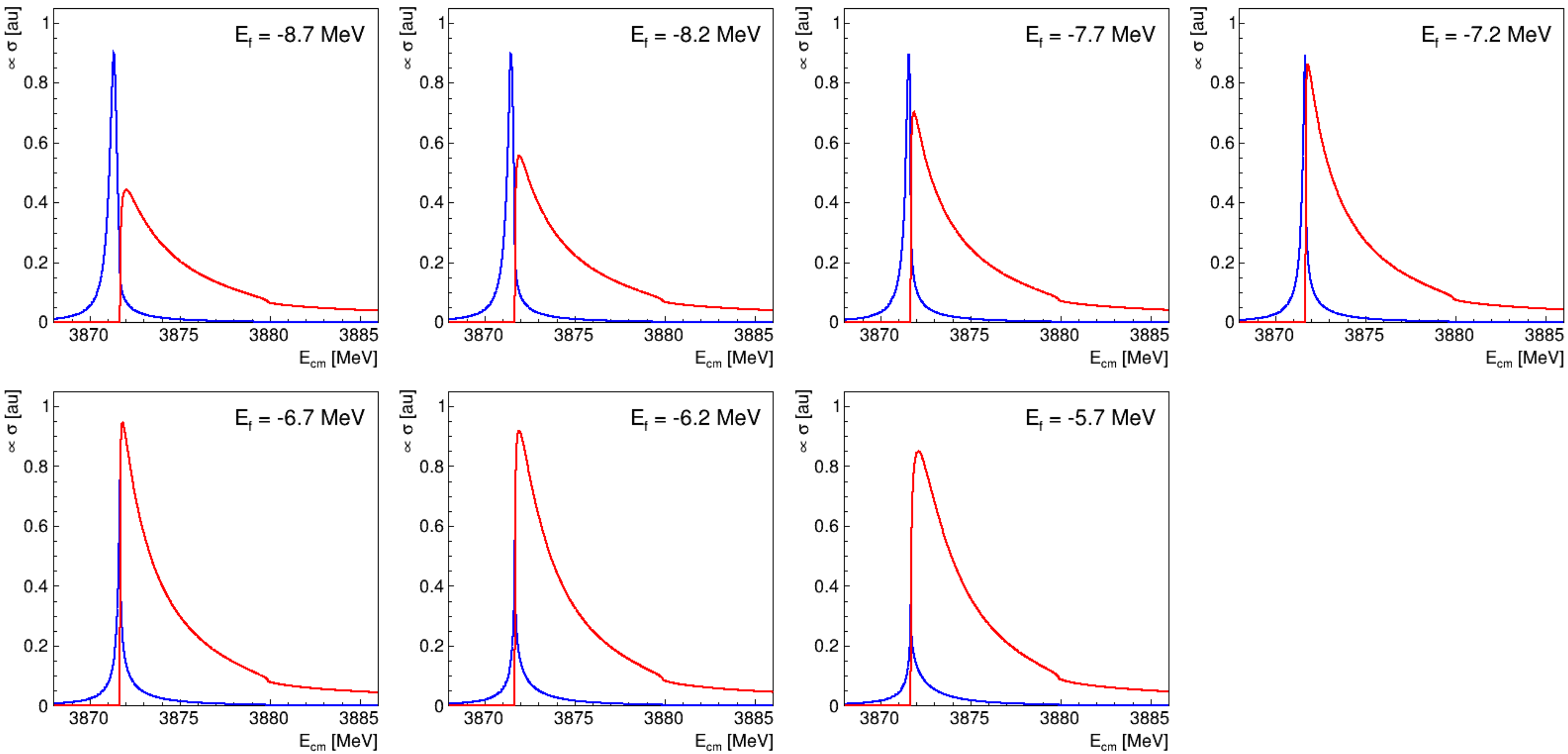
2. Distinguishing BW and Flatté line shape
   – Pub: **~50%**; LHCb toy: **33%**; PANDA: **1% - 5%**

3. Identification of nature given the Flatté-model is true
   – Pub: ~**2σ**; LHCb toy: **1σ**; PANDA: **>3σ**

Aspects of DD* channel

DD* Lineshapes

- LHCb plans simultanous analysis with DD*
- How much could DD* help to increase sensitivity for LHCb/PANDA?
- DD* lineshapes compared to J/ψππ



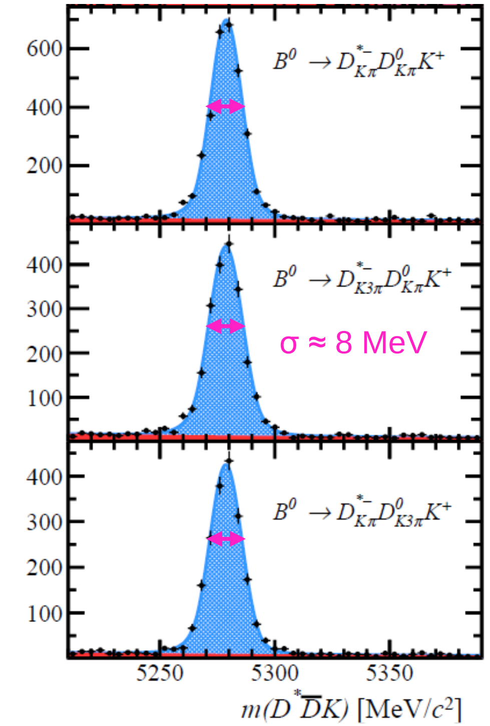
LHCb: Estimate DD* Yields

- Estimate yield from $B^0 \to D^{*-}D^0 K^+$ reco (Runs 1+2, 9 fb^{-1})

Mode	Run 1 N	Run 1 $N^{\rm corr}$ (10^6)	Run 2 N	Run 2 $N^{\rm corr}$ (10^6)
$B^0 \to D^{*-}_{K\pi} D^0_{K\pi} K^+$	605 ± 26	1196 ± 52	2409 ± 52	3495 ± 76
$B^0 \to D^{*-}_{K3\pi} D^0_{K\pi} K^+$	321 ± 20	949 ± 57	1706 ± 44	3541 ± 92
$B^0 \to D^{*-}_{K\pi} D^0_{K3\pi} K^+$	331 ± 20	1105 ± 64	1544 ± 41	3812 ± 104

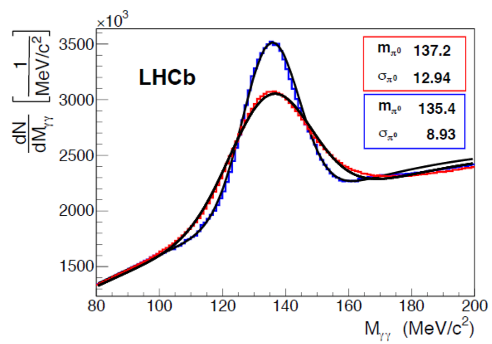
N_{tot} = 6916

[https://arxiv.org/abs/2005.10264]



- Factors to estimate yield:
  - Ratio $r_{BR} = \frac{BR(B^0 \to D^{*0}\overline{D^0}K^0 + c.c.)}{BR(B^0 \to D^{*-}D^0K^+)} = \frac{1.1 \cdot 10^{-3}}{2.47 \cdot 10^{-3}} = 0.45$
  - $BR(K_S^0 \to \pi^+\pi^-) = 0.69$
  - $BR(D^{*0} \to \text{all})/BR(D^{*+} \to D^0\pi^+) = 1.0/0.68 = 1.47$
  - Assumed efficiency factor $f_{\pi 0/\gamma}$ (from D^{*0} decay) = 0.7

[https://arxiv.org/abs/1412.6352]



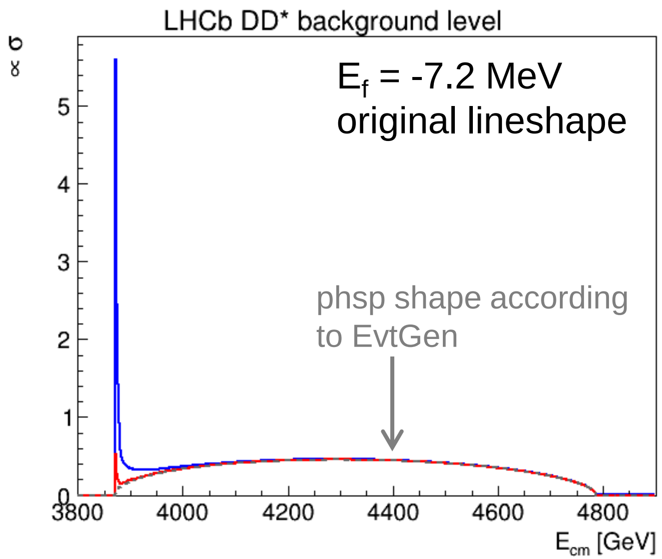
- Yield N = 6916 × 0.45 × 0.69 × 1.47 × 0.7 = 2210 (full PHSP)
- Resolution $\sigma = \sqrt{\sigma_B^2 + \sigma_{\pi^0}^2} = \sqrt{8^2 + 8.93^2} = 12$ MeV
- Investigate: N, N×20, N×100, N×1000 and σ, σ/2

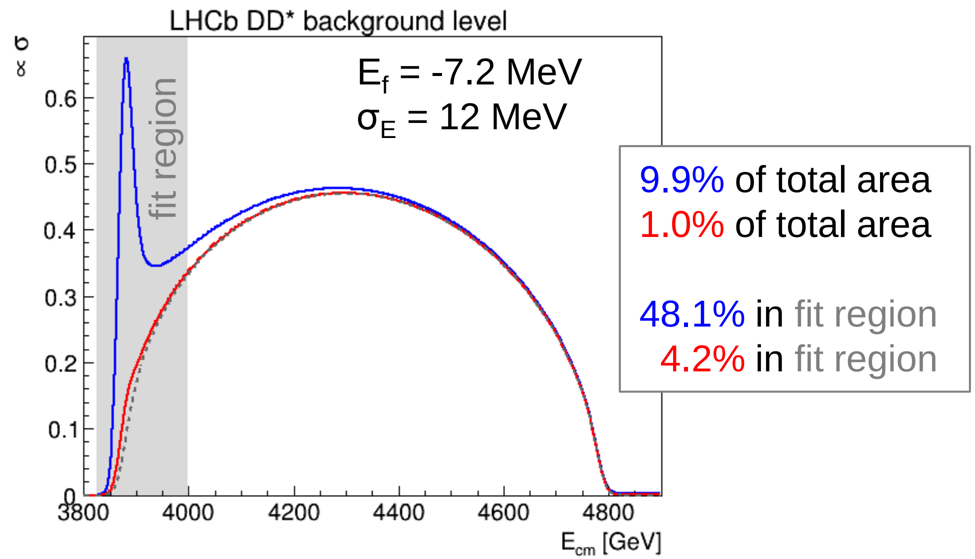
LHCb DD*: Expected S/B Level

- For channels $B \to X(3872)\,K$, background comes from non-res. decays
- PDG live info (Sep. 4, 2020) (incl. c.c.):

Decay	BR
BR_0 : $B^0 \to D^0 \underline{D^{0*}} K^0$	$(1.1 \pm 0.5) \cdot 10^{-3}$
$BR_{X,0}$: $B^0 \to X(3872) K^0 \to D^0 \underline{D^{0*}} K^0$	$(1.2 \pm 0.4) \cdot 10^{-4}$
BR_+ : $B^+ \to D^0 \underline{D^{0*}} K^+$	$(8.56 \pm 0.84) \cdot 10^{-3} = [(2.26 \pm 0.23) + (6.3 \pm 0.5)] \cdot 10^{-3}$
$BR_{X,+}$: $B^+ \to X(3872) K^+ \to D^0 \underline{D^{0*}} K^+$	$(8.5 \pm 2.6) \cdot 10^{-5}$

- $BR_{X,0}/BR_0 = 0.109$, $BR_{X,+}/BR_+ = 0.01 \to$ use B^0 scenario





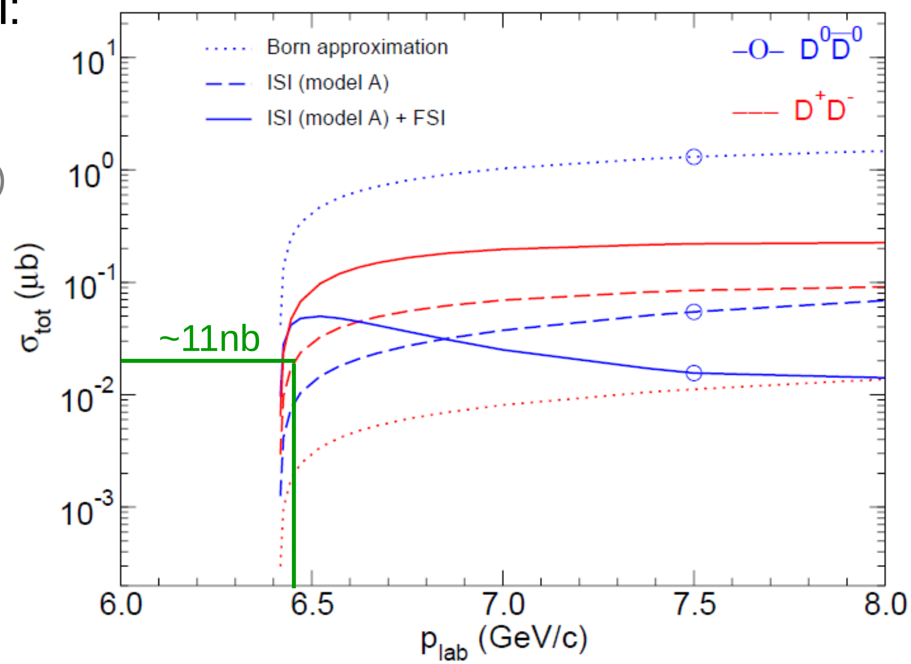
DD* Expected Background Levels PANDA

- PANDA background from non-resonant DD* production around threshold

- Non-resonant $D^0\underline{D}^0$ from Haidenbauer et al:

  $\sigma_{D0\underline{D0}}$(3740MeV) ≈ 11 nb (12 MeV above thresh.)
  $\sigma_{D0\underline{D0*}}$(3884MeV) $\overset{?}{\approx}$ 11 nb (assume same number)

[https://arxiv.org/abs/1010.5324v1]



- Assumptions for signal cross section
  - $\sigma_{X(3872)}$ = 50nb
  - BR(X →J/ψπ⁺π⁻) = 5%
  - BR(X → DD*)/BR(X → J/ψπ⁺π⁻) = 9
    BR(X → DD*) = 45%
  - $\sigma_{X(3872) \to DD^*}$ = 50nb · 0.45 = 22.5 nb

  - Need to estimate efficiency ε for yield calculation N(E) = σ(E) × $\mathcal{L}$ × BR × ε

DD* Efficiency Estimate for PANDA

- Assumptions for exclusive DD* reconstruction:
  - ε_{trk} = 85%, ε_γ = 75%, additional (arbitrary) efficiency reduction factor ε_r = 0.3
  - Reco. 6 D^0 decays, both D^{0*} decays ($D^0\pi^0$, $D^0\gamma$) and form all 6×12 = 72 combinations

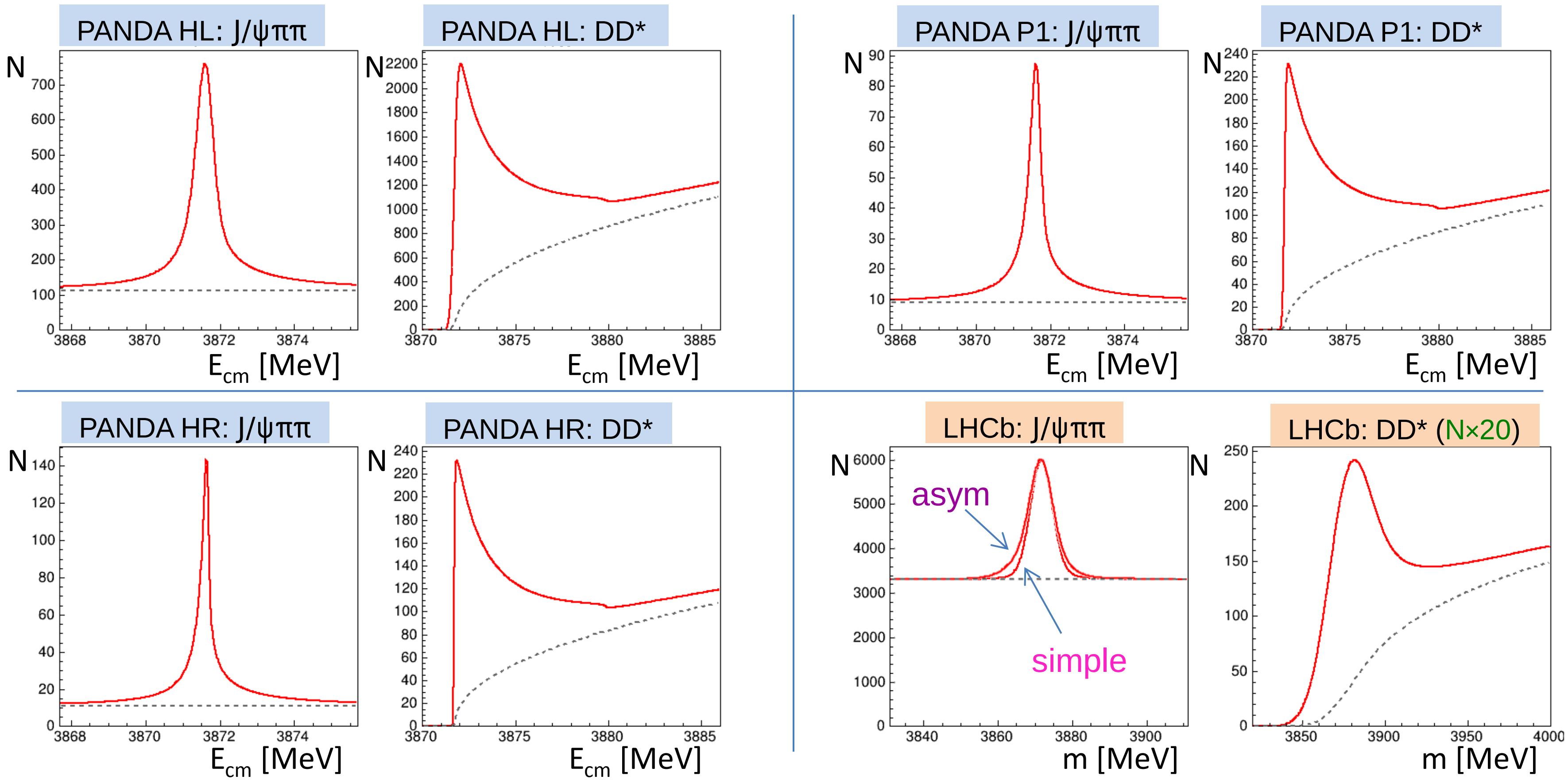
		D^0		$D^{0*}(\pi^0)$	$D^{0*}(\gamma)$	D0		$D^{0*}(\pi^0)$		$D^{0*}(\gamma)$	
Channel	BR(D^0)	trk	neut	neut	neut	ε	ε × BR	ε	ε × BR	ε	ε × BR
Kπ	0,0393	2	0	2	1	0,723	0,028	0,406	0,010	0,542	0,008
Kπππ	0,0188	4	0	2	1	0,522	0,010	0,294	0,004	0,461	0,003
$K\pi\pi^0$	0,1430	2	2	4	3	0,406	0,058	0,229	0,021	0,305	0,015
$K_S\pi\pi$	0,0285	4	0	2	1	0,522	0,015	0,294	0,005	0,392	0,004
$K_S\pi\pi\pi^0$	0,0520	4	2	4	3	0,294	0,015	0,165	0,006	0,220	0,004
$K\pi\pi\pi\pi^0$	0,0420	4	2	4	3	0,294	0,012	0,165	0,004	0,220	0,003

sum all products

  - Individual efficiency: $\varepsilon = (\varepsilon_{trk})^{n_{trk}} \cdot (\varepsilon_{neut})^{n_{neut}}$
  - Total reconstruction fraction: $f_{rec} = \sum_{i,j} (\varepsilon_{D^0,i} \cdot BR_{D^0,i}) \cdot (\varepsilon_{D^{0*},j} \cdot BR_{D^{0*},j}) \cdot \varepsilon_r = 0.37\%$
  - Total BR: $BR_{tot} = \left(\sum_i BR_{D^0,i}\right)^2 = (0.3236)^2 = 10.5\%$
  - Effective efficiency: $\varepsilon_{eff} = f_{rec}/BR_{tot} = 3.45\%$
  - Compare to: $BR_{tot,J/\psi} = 12\%,\ \varepsilon_{eff,J/\psi} = 13.5\% \ \rightarrow\ f_{rec,J/\psi} = 1.6\%$

Simultaneous Fit

- LHCb: Assume various scale factors/resolutions in DD* spectrum
- PANDA: Compute expected yield based on given estimates
- Generate spectra and perform simultaneous fit for E_f to both channels



Simultaneous Fit

- LHCb: Assume various scale factors/resolutions in DD* spectrum
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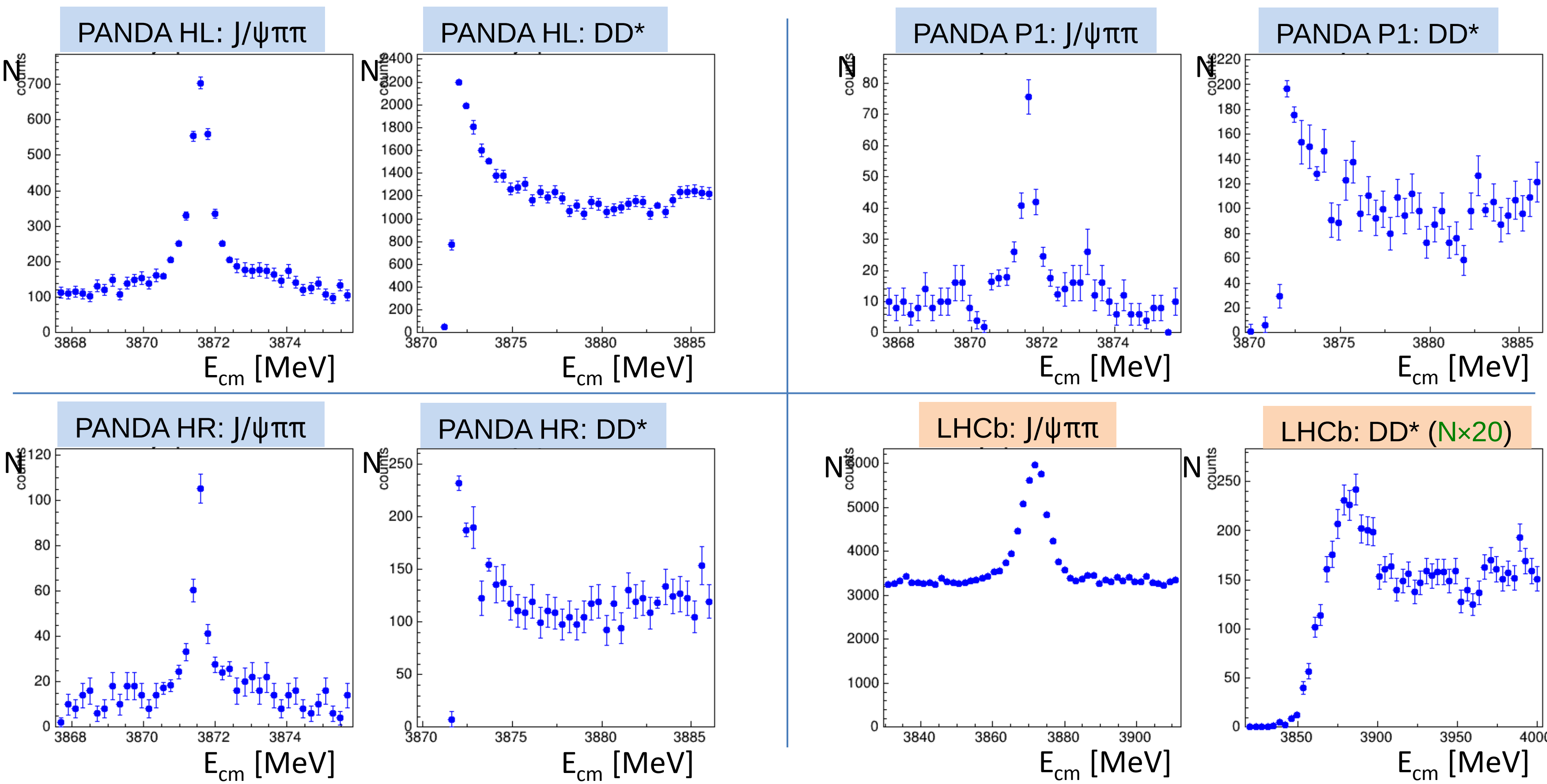

Simultaneous Fit

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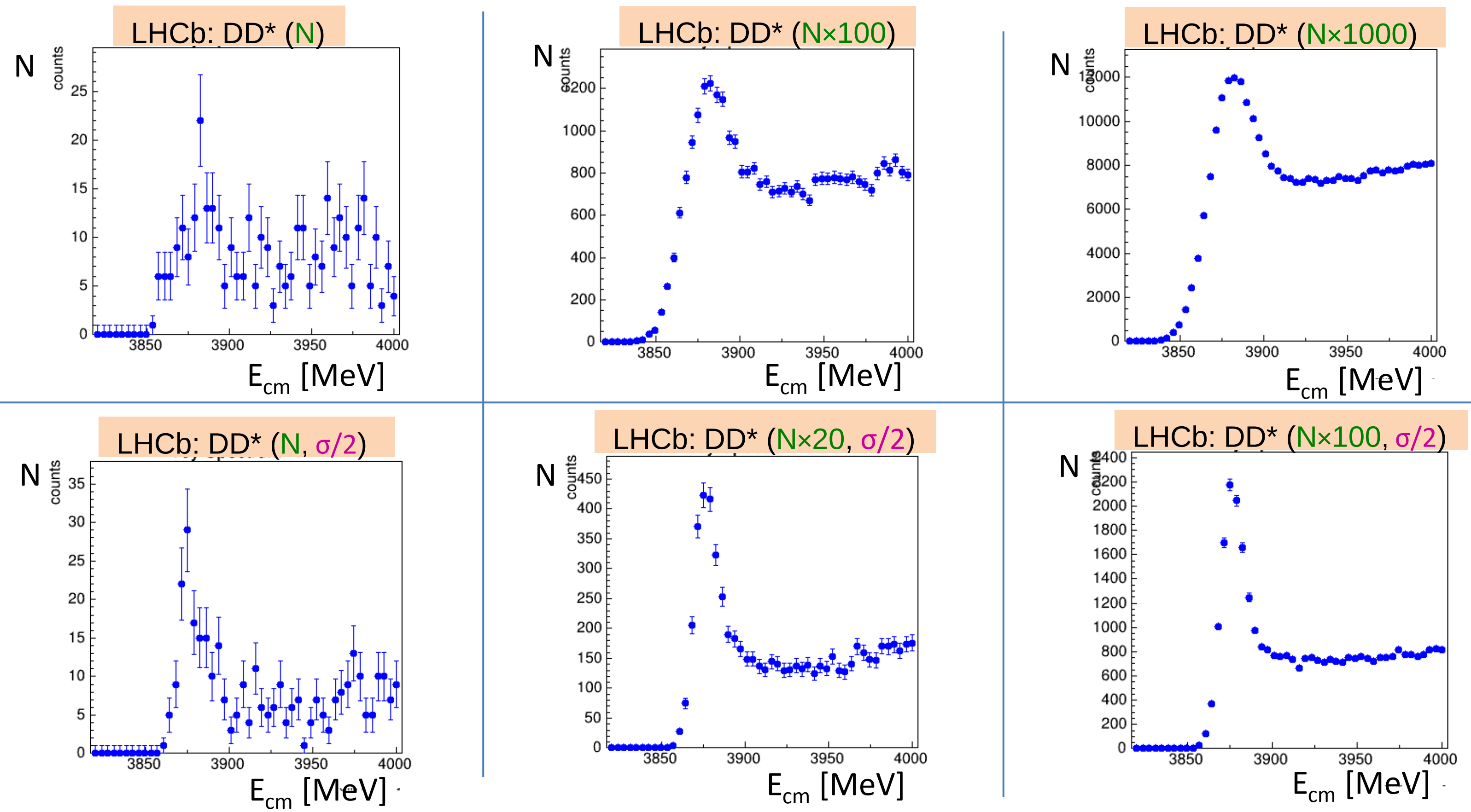
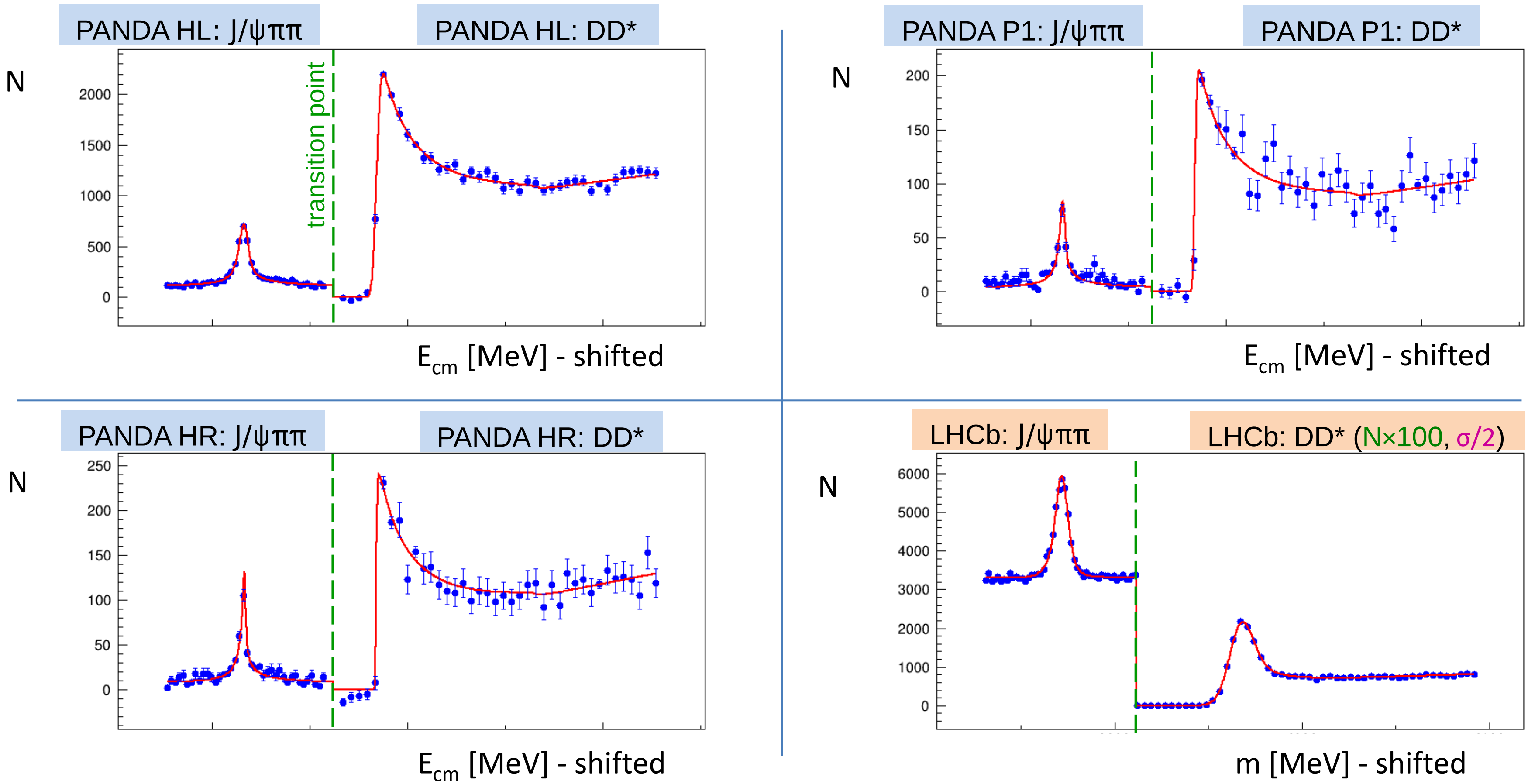


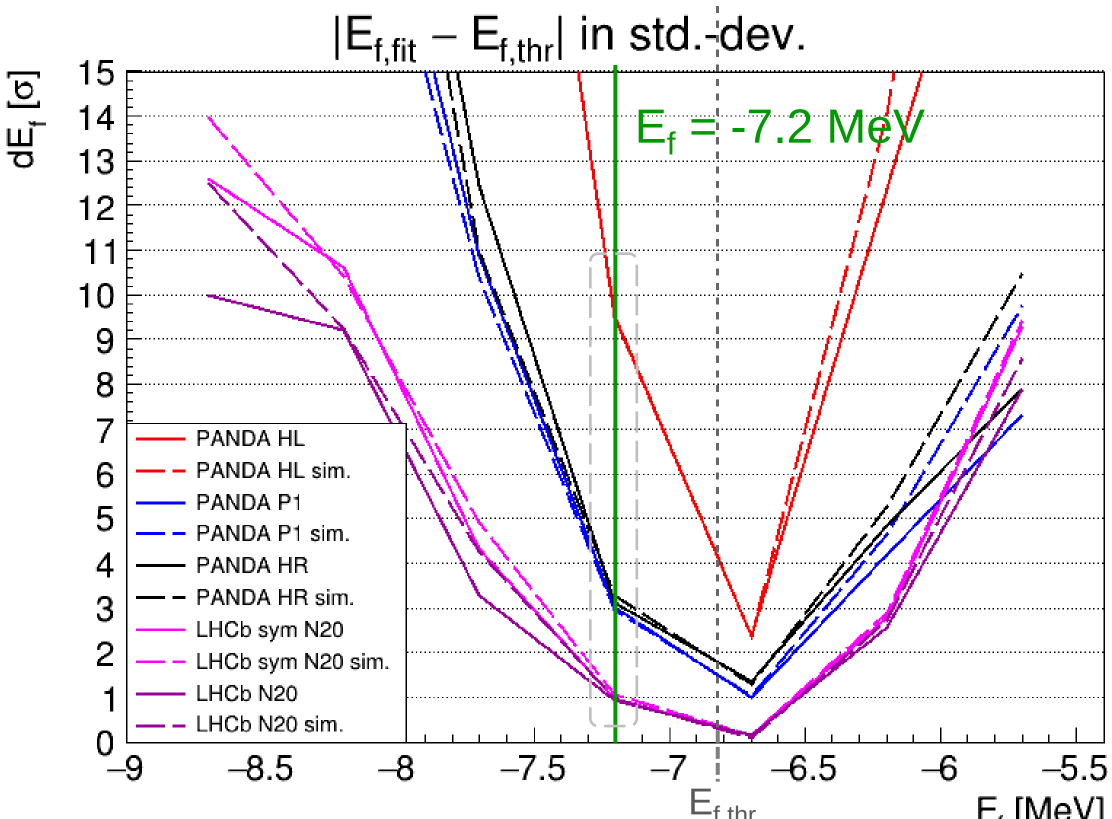
Simultaneous Fit

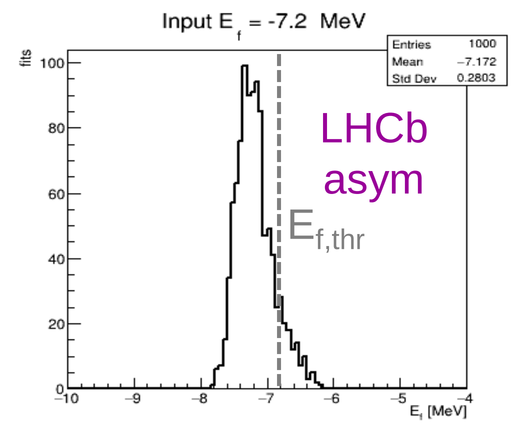
- LHCb: Assume various scale factors/resolutions in DD* spectrum
- PANDA: Compute expected yield based on given estimates
- Hand-made simultaneous fit for E_f → to fit two fctns, E shifted in between

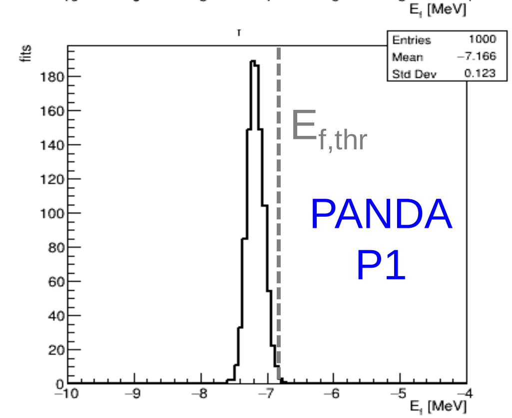


Distinguish Nature in #std. dev. (incl DD*)

- Improvement by adding the DD* channel (dashed vs. solid lines)
- Again with $dE_f = (E_{f,fit} - E_{f,thr})/\sigma_{Ef,fit}$:
  - LHCb toy: no improvement in ROI
  - PANDA toy: no improvement in ROI

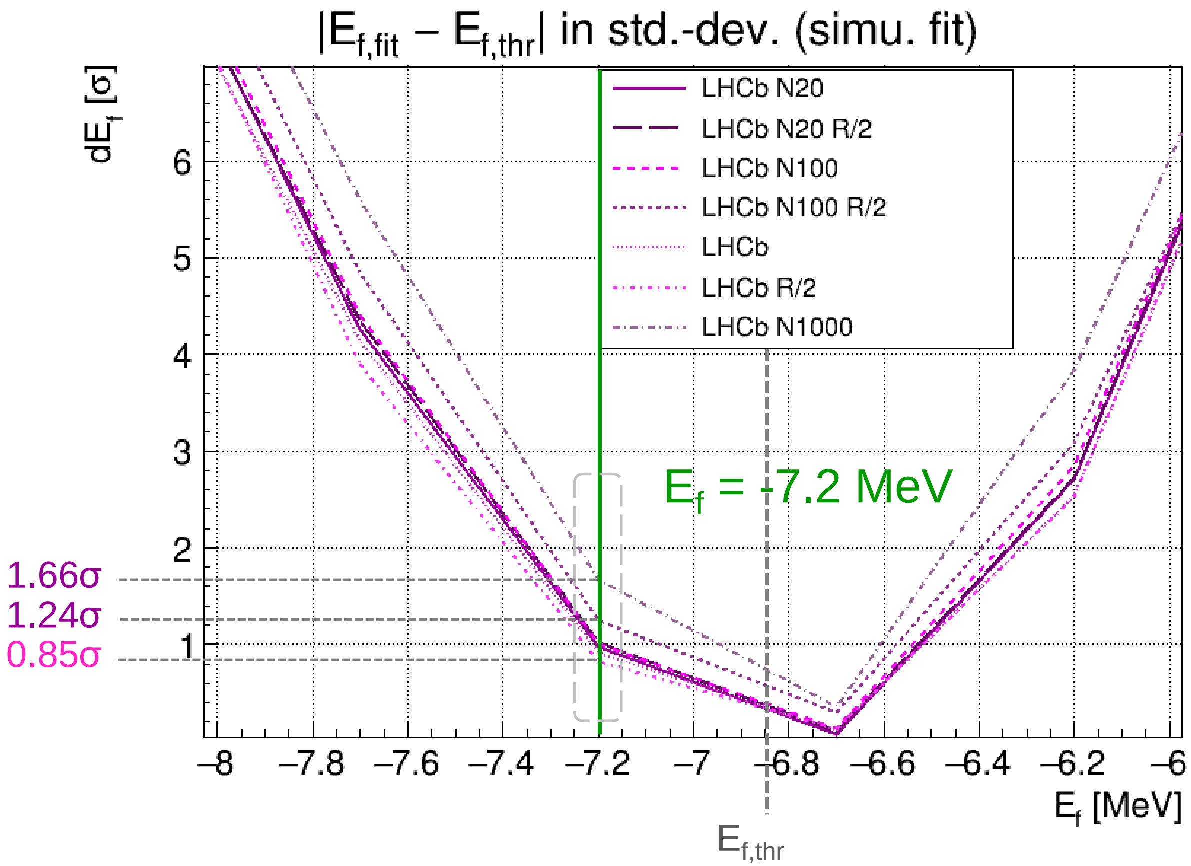






Variations of LHCb Yield Scenario

- Investigate: N, N×20, N×100, N×1000 and σ, σ/2
- Realistic estimates (N): no improvement in ROI
- Even for N×100 + σ/2 or N×1000: $dE_f \approx 1.2 \ldots 1.7\sigma$



Summary / Conclusion

- LHCb results mostly reproduced
- Investigated possible DD* simultaneous fit
- In comparison to PANDA the results are (for E_f = -7.2 MeV)
  (with grain of salt due to simplistic modelling)

Measurement	Pub	LHCb	P1	HR	HL
FWHM bias factor fitting BW to Flatté	7.0	4.6	2.4	1.5	2.2
Probability to confuse BW and Flatté case	50%	33%	5%	1%	1%
Significance to identify nature (bound/virtual)	~2σ	1.0σ	3.0σ	3.1σ	9.5σ
Significance to identify nature incl. DD* channel*		<1.7σ	3.0σ	3.3σ	9.5σ

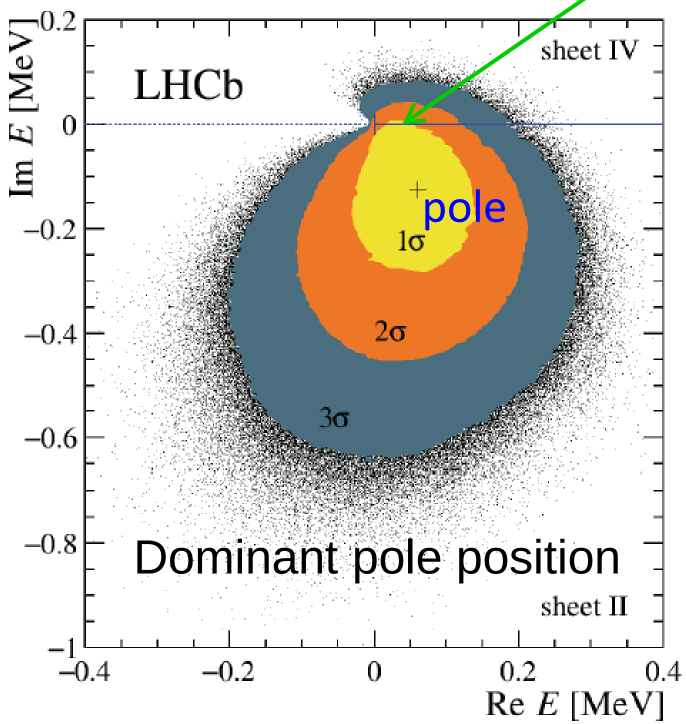
*under certain assumptions made here

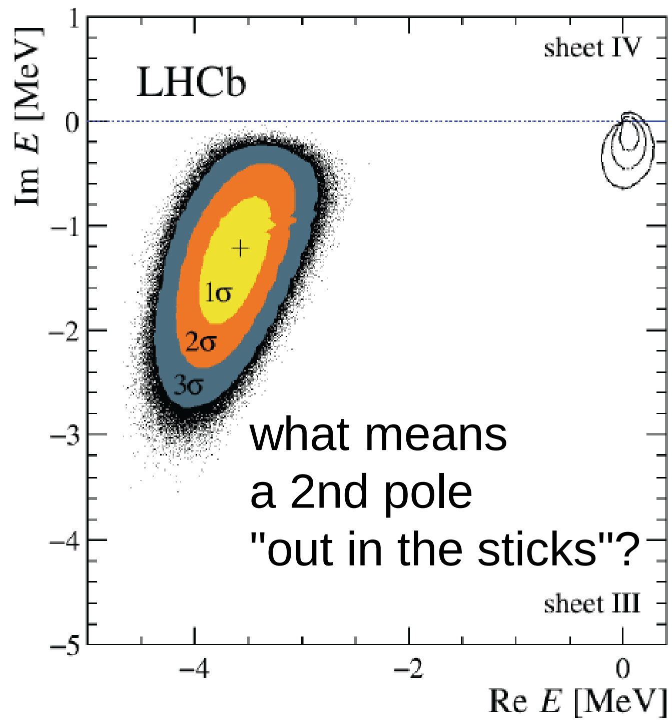
- Even adding DD*, LHCb seems not be able to identify nature ≥3σ
- PANDA superior in all aspects w/o considering DD*

BACKUP

LHCb Paper - Open Questions (2)

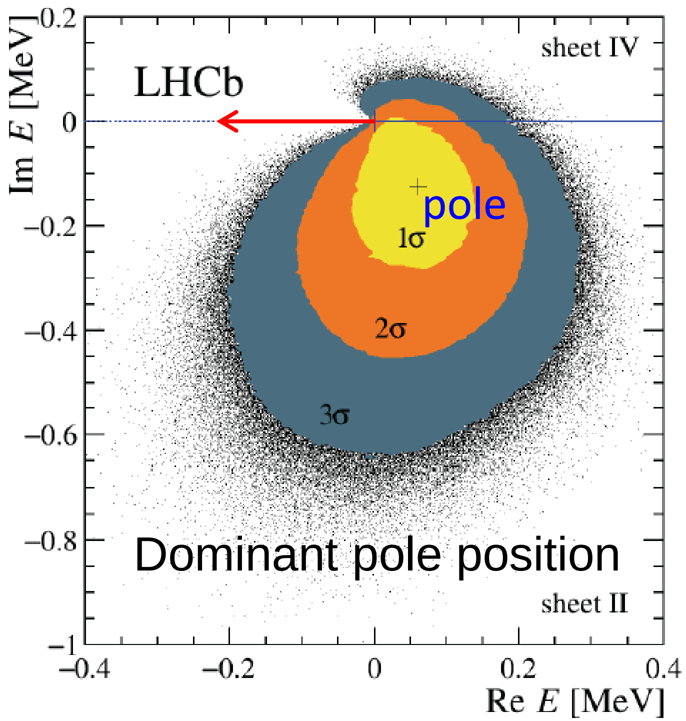
- Statement: Virtual state allowed(excluded?) at 2σ level
  - "While a pole location on sheet II is preferred by the data, a location on sheet IV is still allowed at the 2σ level."
- What I observe is the yellow 1σ area intersecting sheet IV; doesn't this mean, the virtual state is excluded by only <1σ?

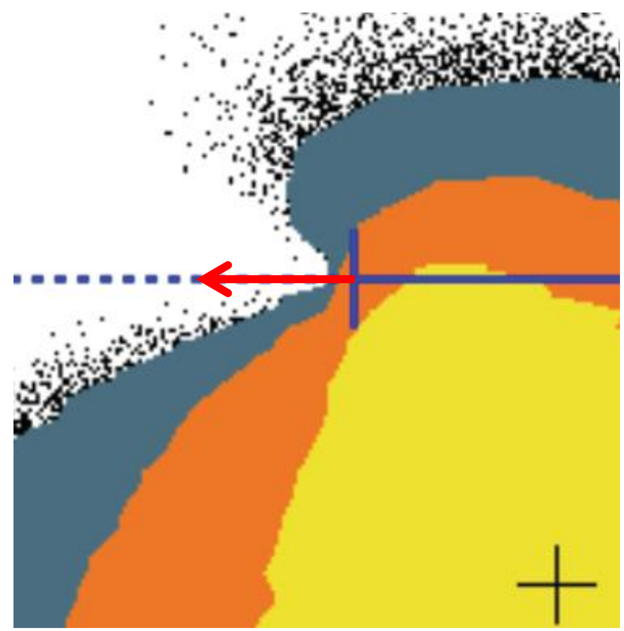




LHCb Paper - Open Questions (2)

- Statement: Virtual state allowed(excluded?) at 2σ level
  - "While a pole location on sheet II is preferred by the data, a location on sheet IV is still allowed at the 2σ level."
- What I observe is the yellow 1σ area intersecting sheet IV; doesn't this mean, the virtual state is excluded by only <1σ?
- Or does it refer to real axis Re E<0? which is still 1 to 2σ...

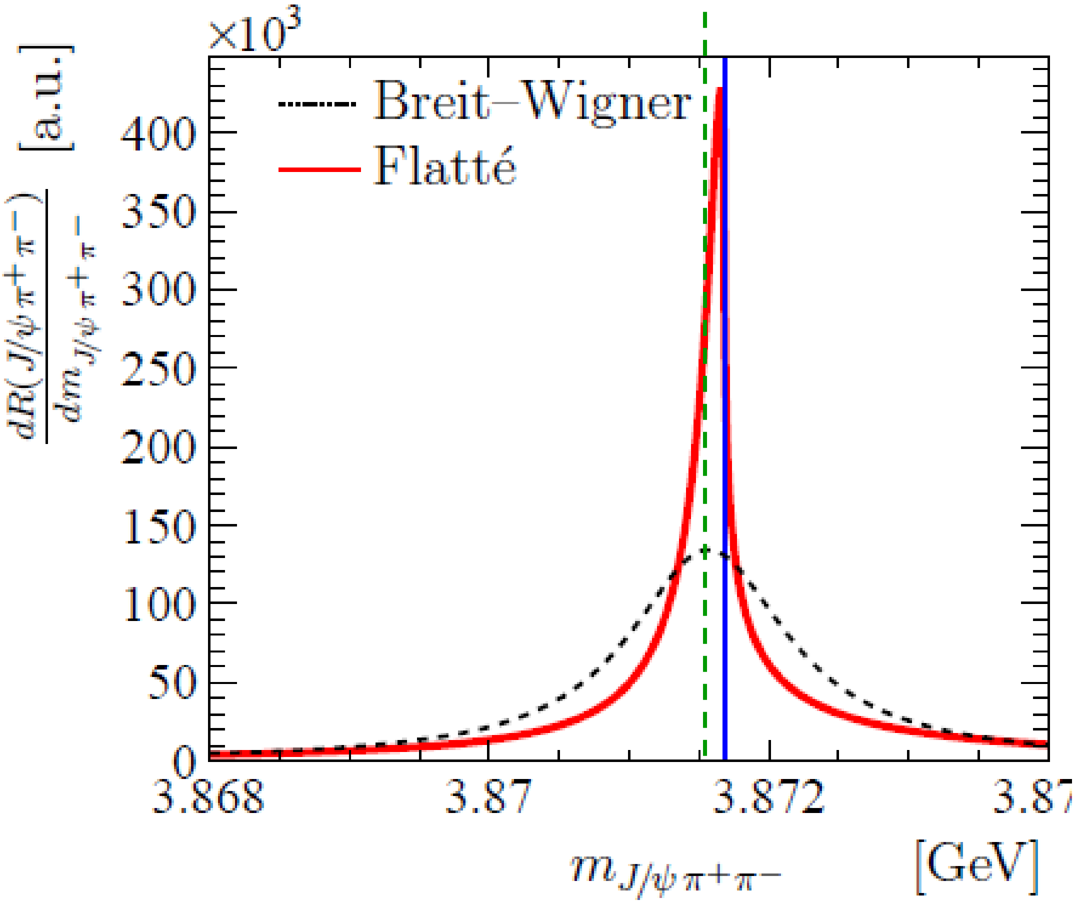




LHCb Paper - Questions (1)

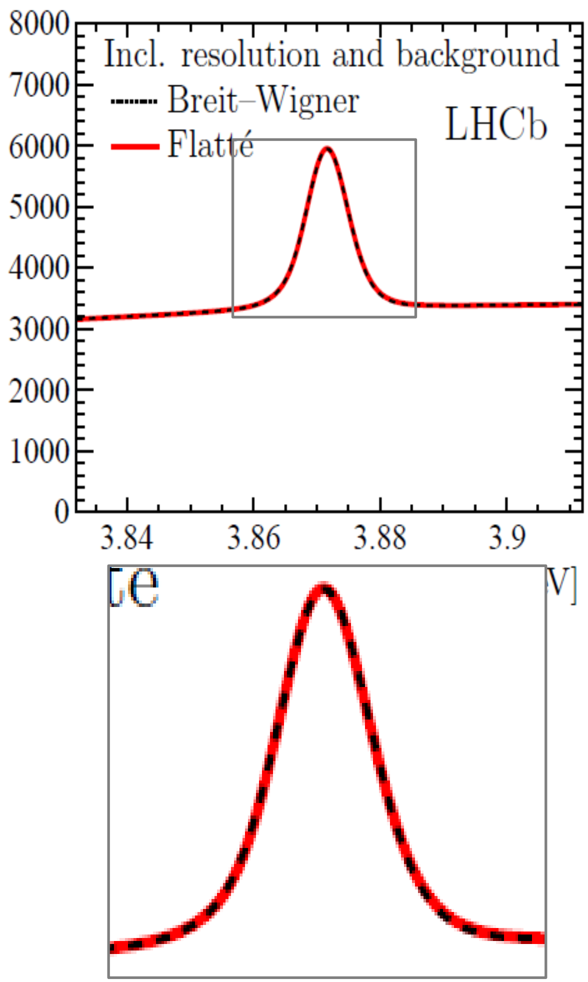
- Position of BW unclear (apparently not the fitted mass)

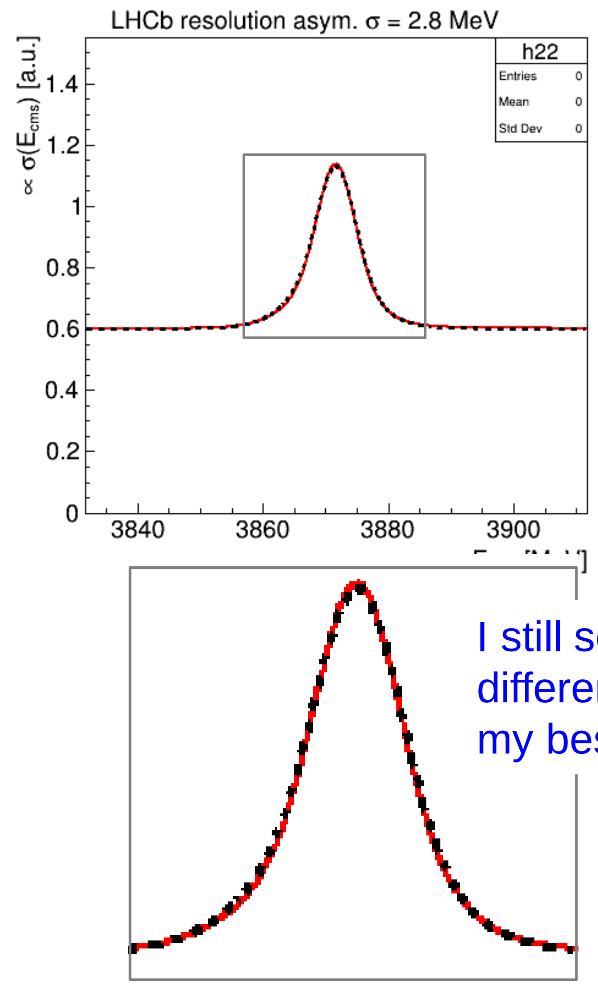
peak seems rather at 3871.5x MeV
instead of 3871.695 MeV found in BW fit



LHCb Paper - Questions (2)

- "However, after folding with the resolution function and adding the background, the observable distributions are indistinguishable."



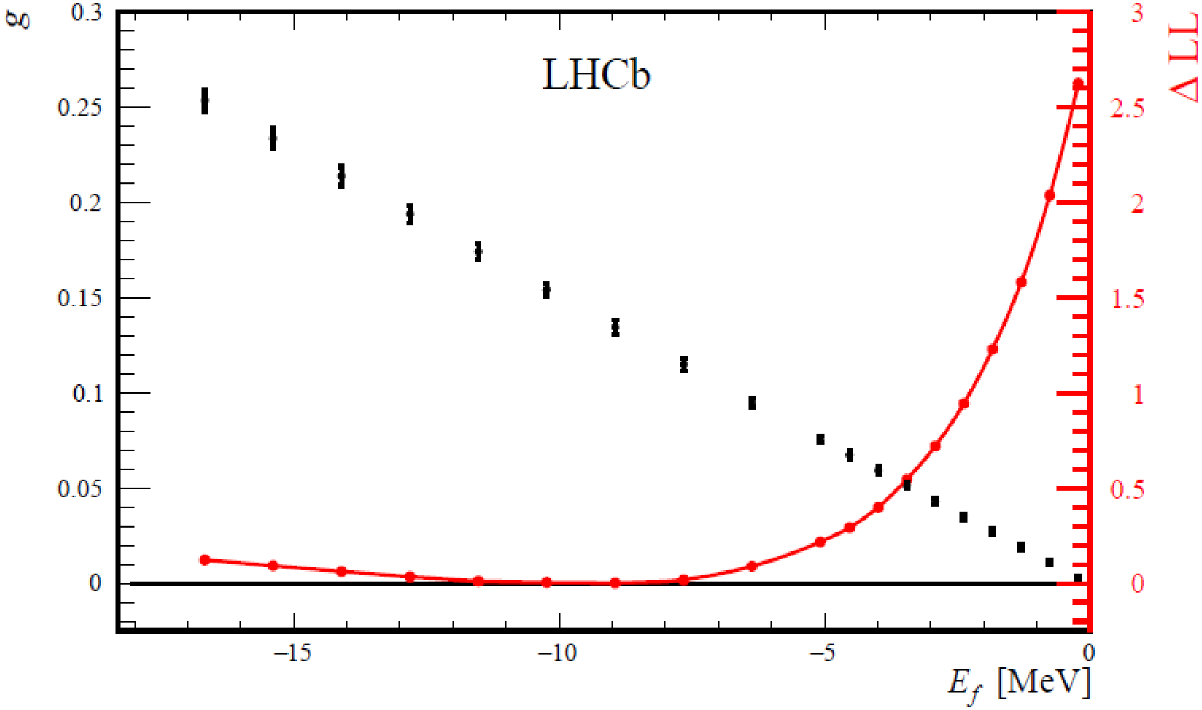


I still see differences after my best modelling ...

LHCb Paper - Questions (3)

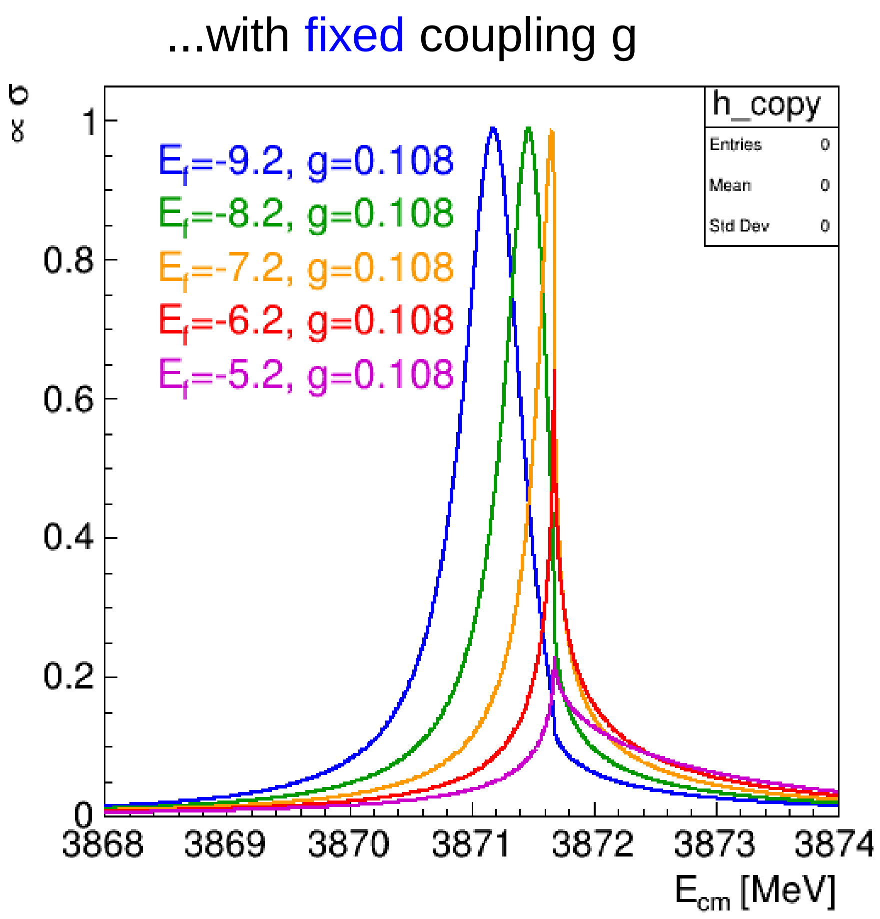
- Parameter correlation of g and E_f
- "Almost identical lineshapes are obtained when the parameters E_f, g, f_ρ and Γ_0 are scaled appropriately. In particular, it is possible to counterbalance a lower value of E_f with a linear increase in the coupling to the DD* channels g."

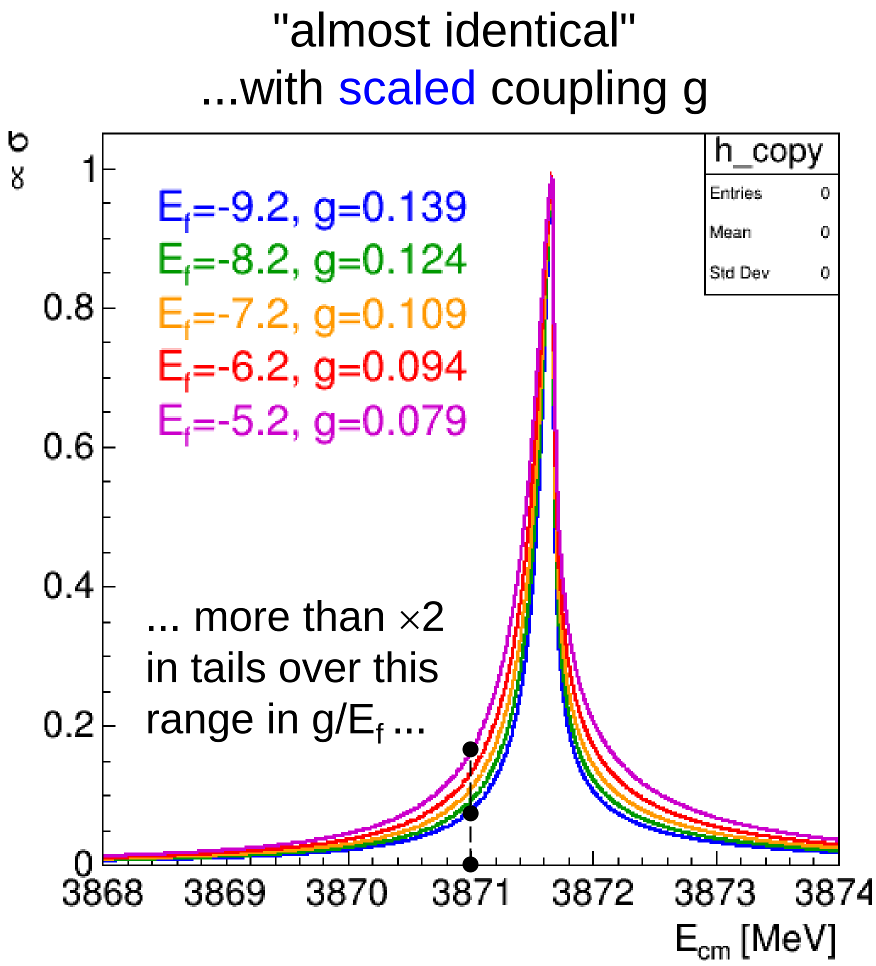
$$\frac{dg}{dE_f} = (-15.11 \pm 0.16)\ \mathrm{GeV}^{-1}$$



LHCb Paper - Questions (3)

- Example lineshapes

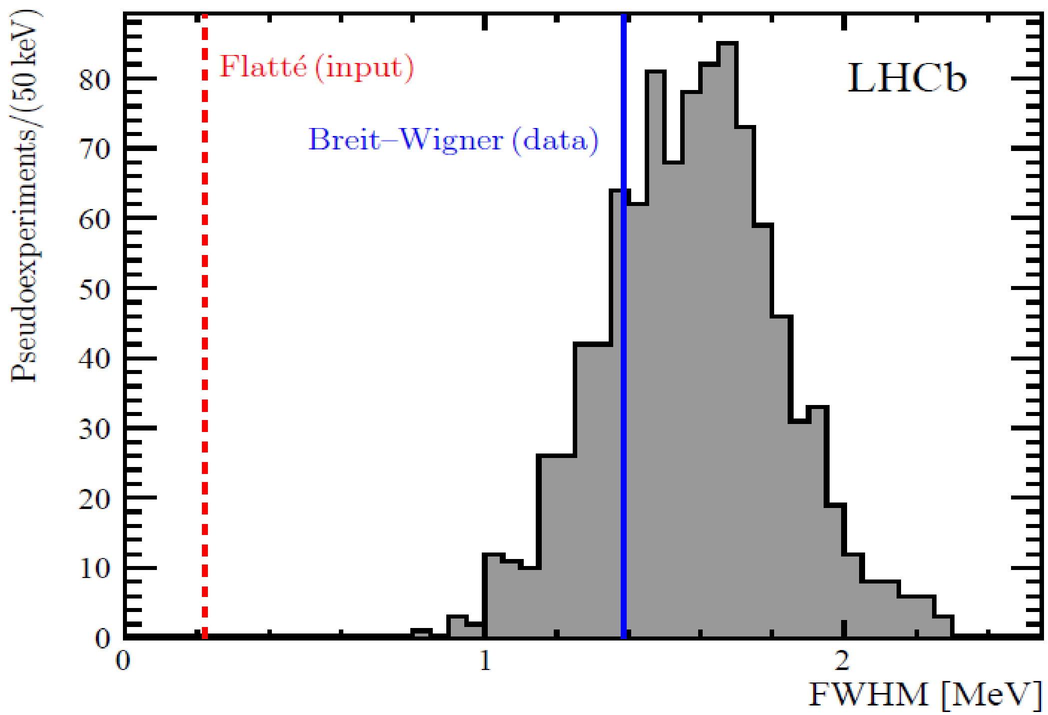


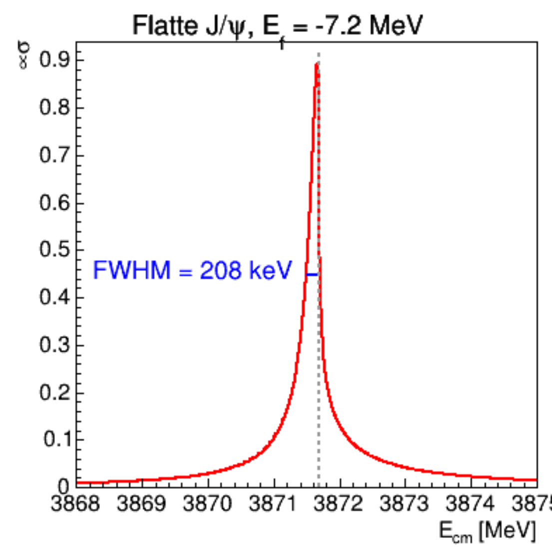


LHCb Paper - Questions (6)

- Input Flatté FWHM seems different then what I get

LHCb FWHM = 220(?) keV

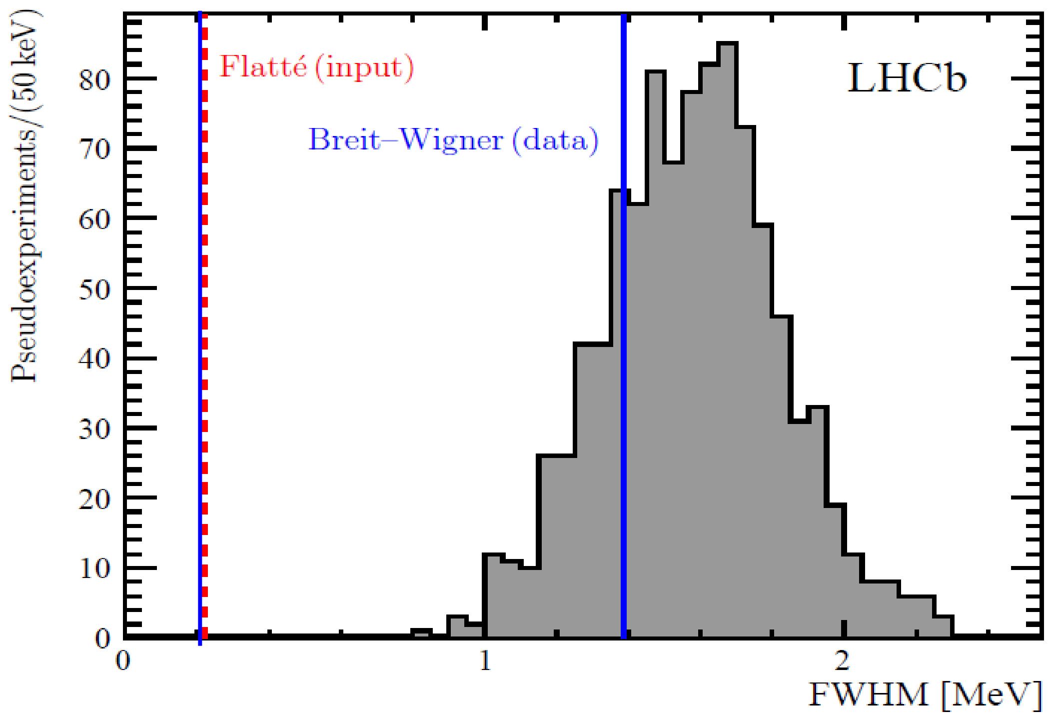


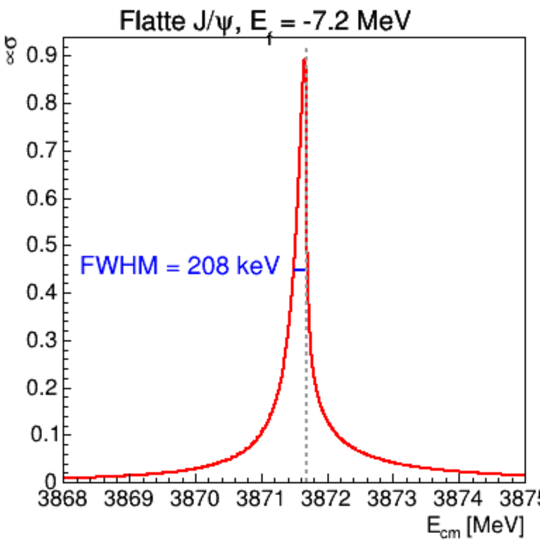


LHCb Paper - Questions (6)

- Input Flatté FWHM seems different then what I get

LHCb FWHM = 220(?) keV
My FWHM = 208 keV





Simultaneous Fit

- LHCb: Assume N_{max} = 5000 in DD* spectrum (arbitrary)
- PANDA: Compute expected yield based on previous estimates
- Generate spectra and perform simultaneous fit for E_f to both channels