Reproducing the LHCb X(3872) Results
(and Possible Effect of Adding DD* Channel)

Oct 14, 2020

Klaus Götzen
GSI Darmstadt

Flatté Model Revisited

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

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

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

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

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

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

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

$$g_1 = g_2 = g$$

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

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

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

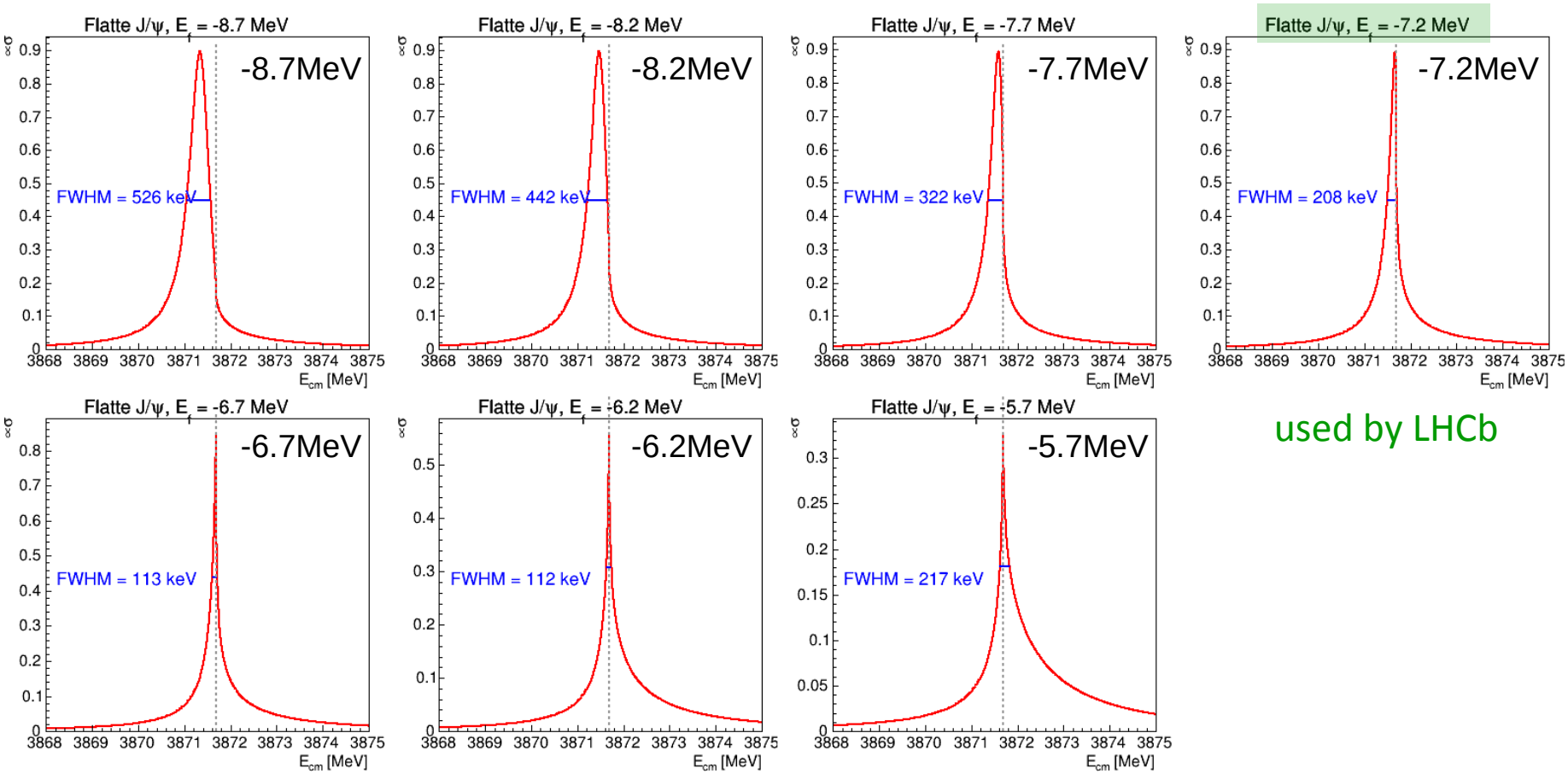
$$\Gamma_{\pi^+\pi^-\pi^0 J/\psi}(E) = f_\omega \int_{3m_\pi}^{M - m_{J/\psi}} \frac{dm}{2\pi} \frac{q(m)\Gamma_\omega}{(m - m_\omega)^2 + \Gamma_\omega^2/4},$$

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

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

- Lineshapes for various E_f



used by LHCb

LHCb Findings

- Breit Wigner fit

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

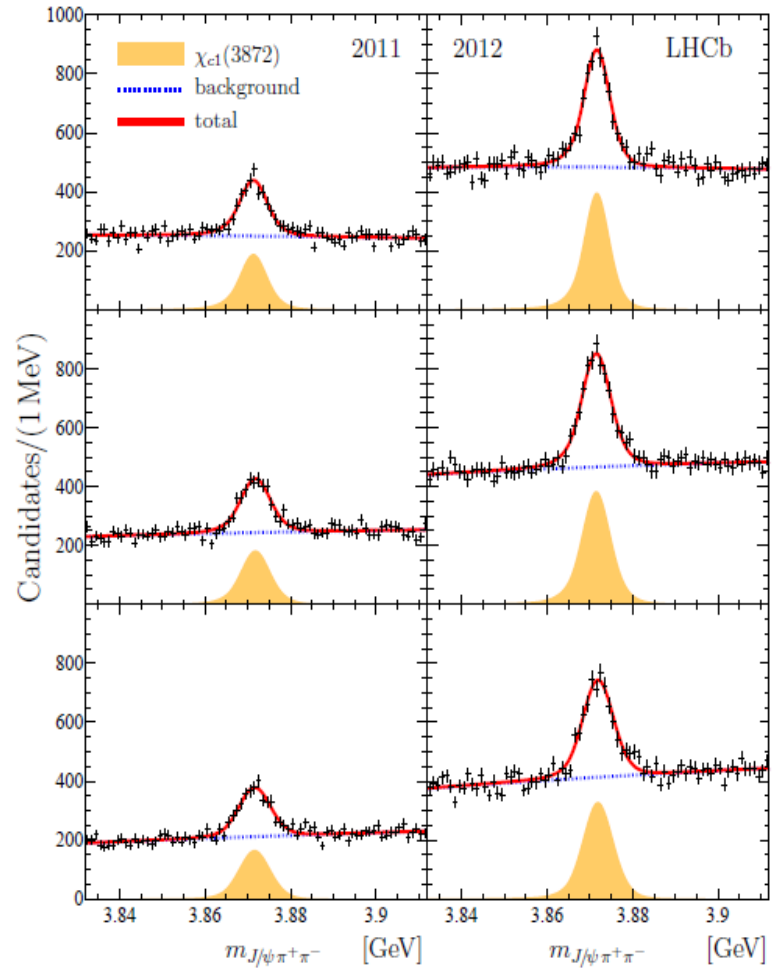
[old Belle result: Γ < 1.2 MeV (CL90)]

- 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)

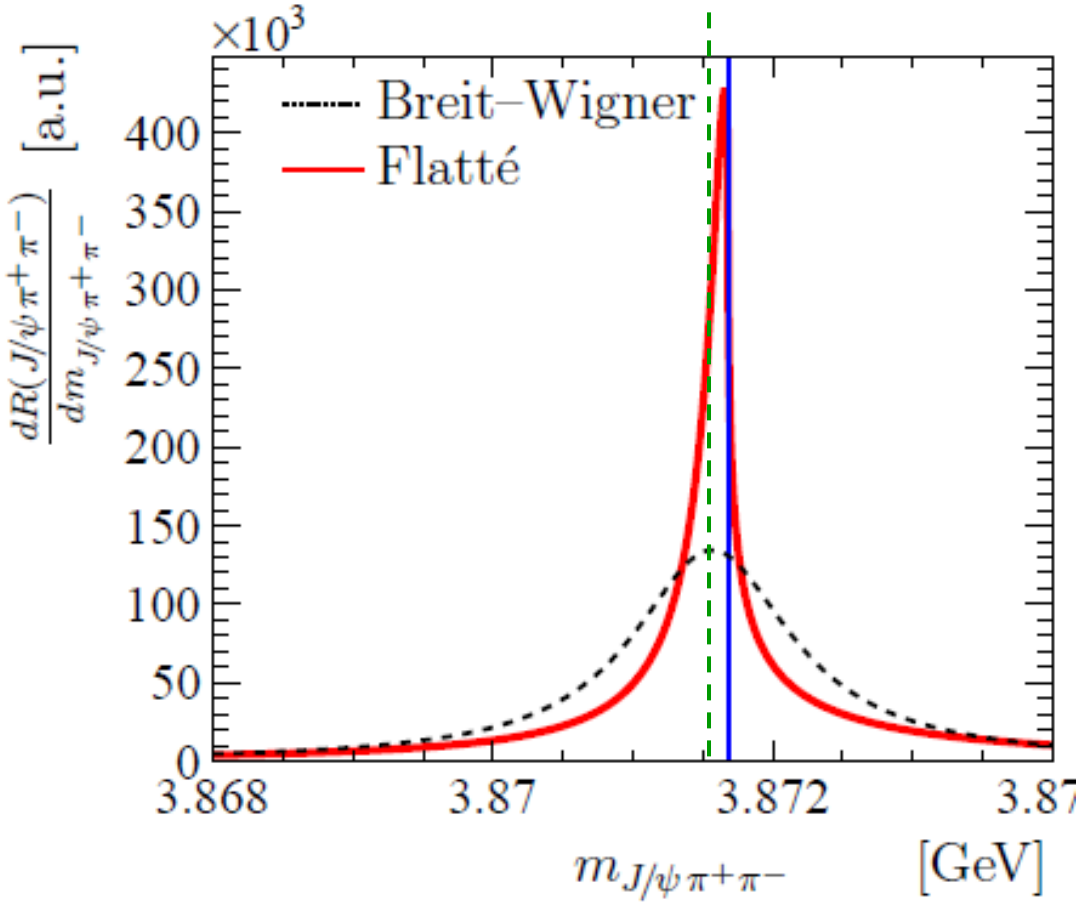
  - Dominant pole: Bound state
  - Virtual state allowed at 2 sigma level



LHCb Paper - Questions (1)

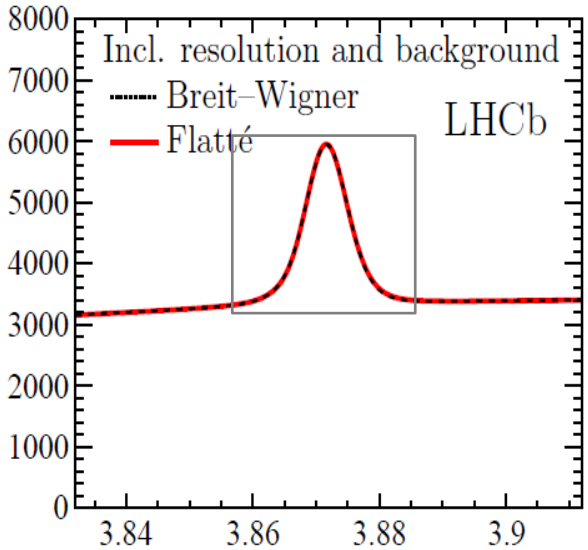
- Position of BW unclear (apparently not the fitted mass)

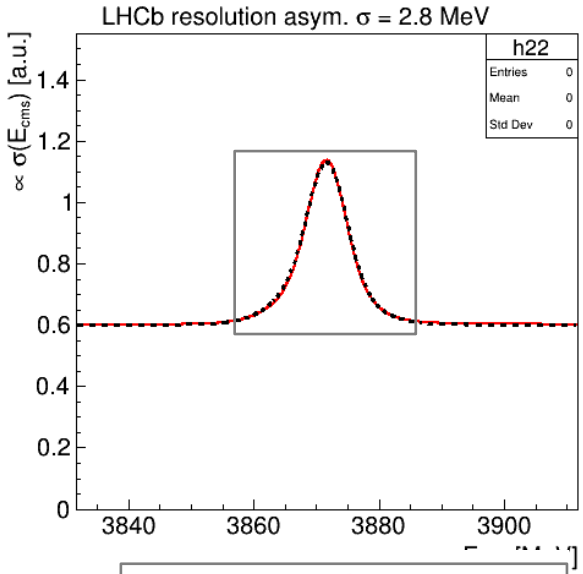
peak seems rather at 3871.5x MeV
instead of 3871.695 MeV found in BW fit

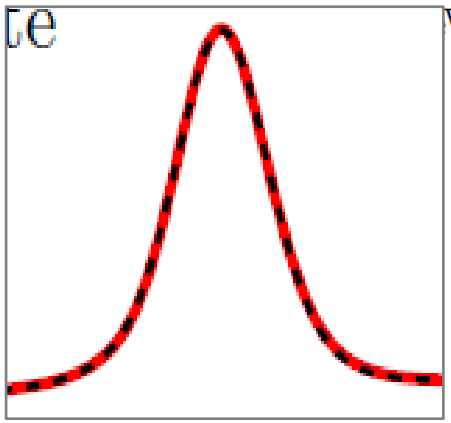


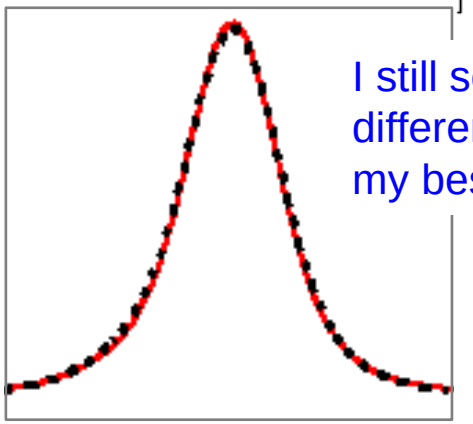
LHCb Paper - Questions (2)

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







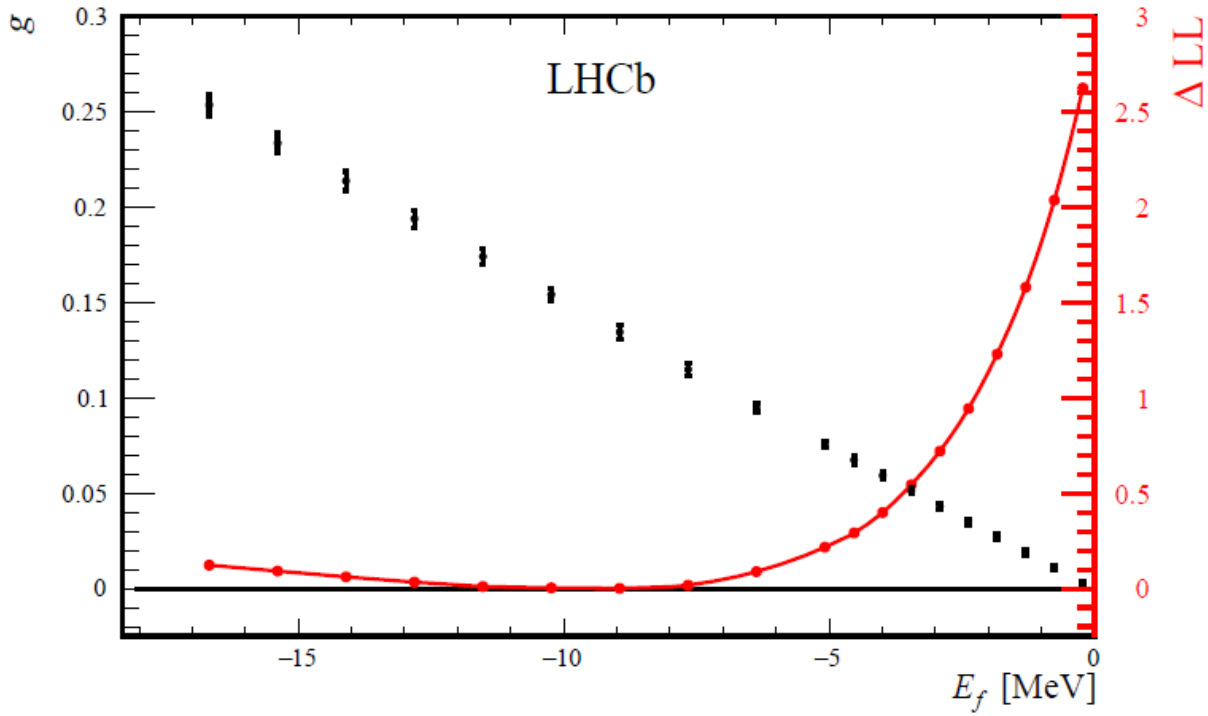


I still see differences after my best modelling ...

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."

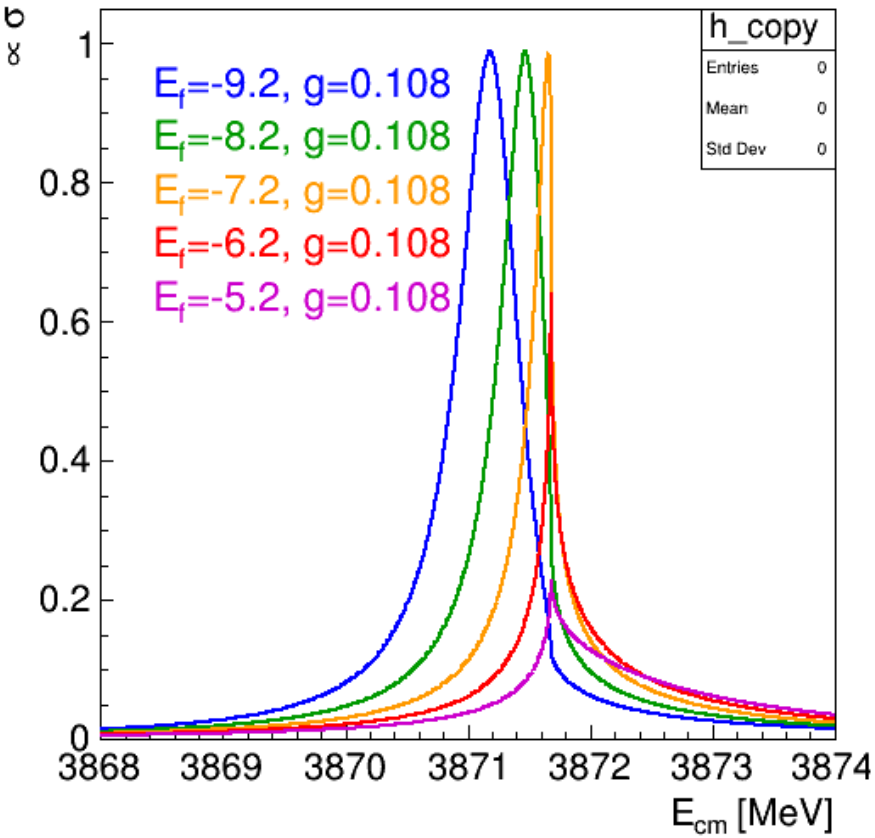
$$\frac{dg}{dE_f} = (-15.11 \pm 0.16)\ \mathrm{GeV}^{-1}$$



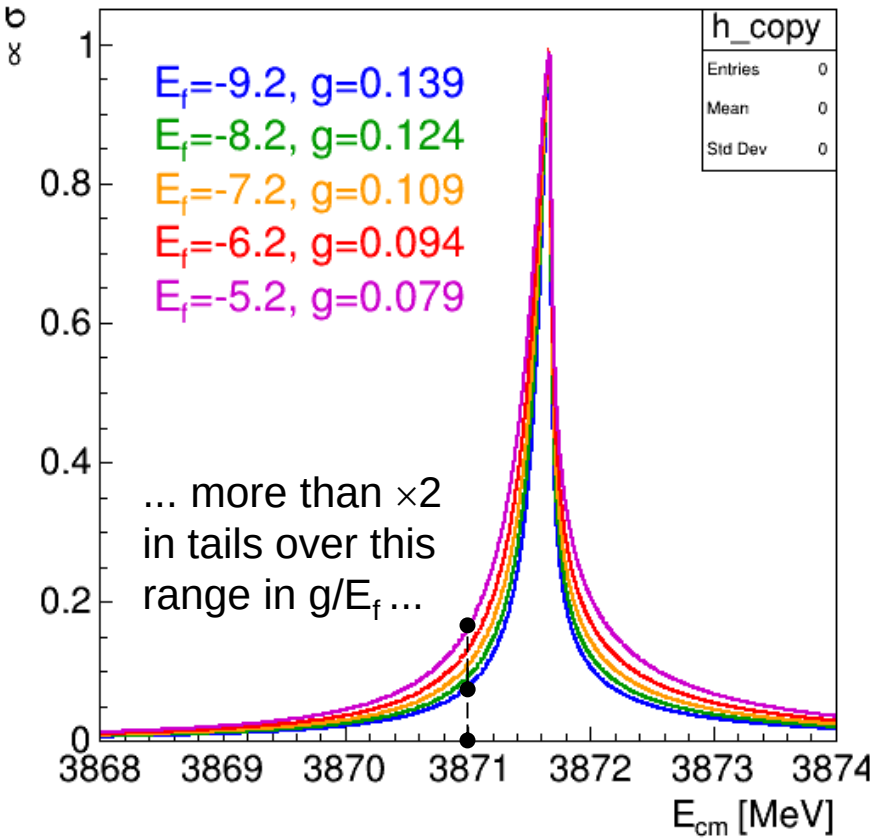
LHCb Paper - Questions (3)

- Example lineshapes

...with fixed coupling g

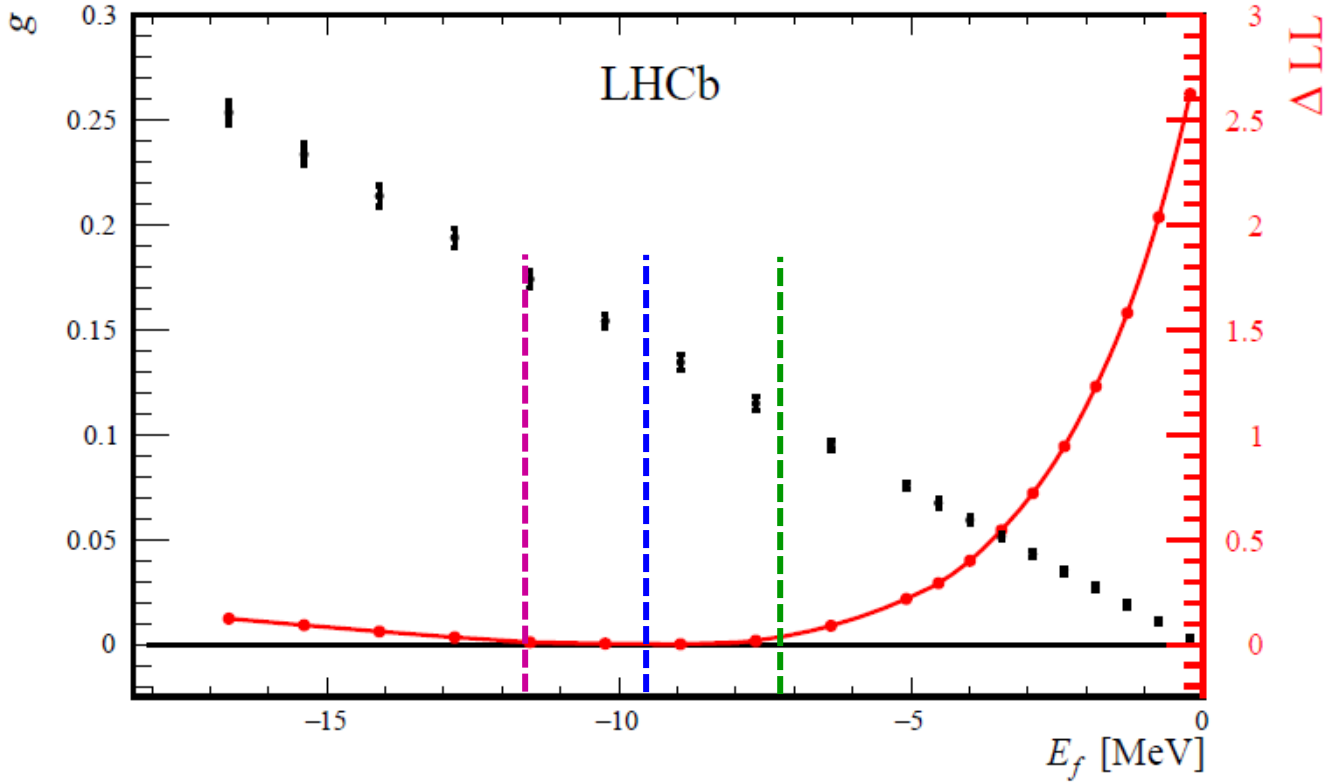


"almost identical"
...with scaled coupling g



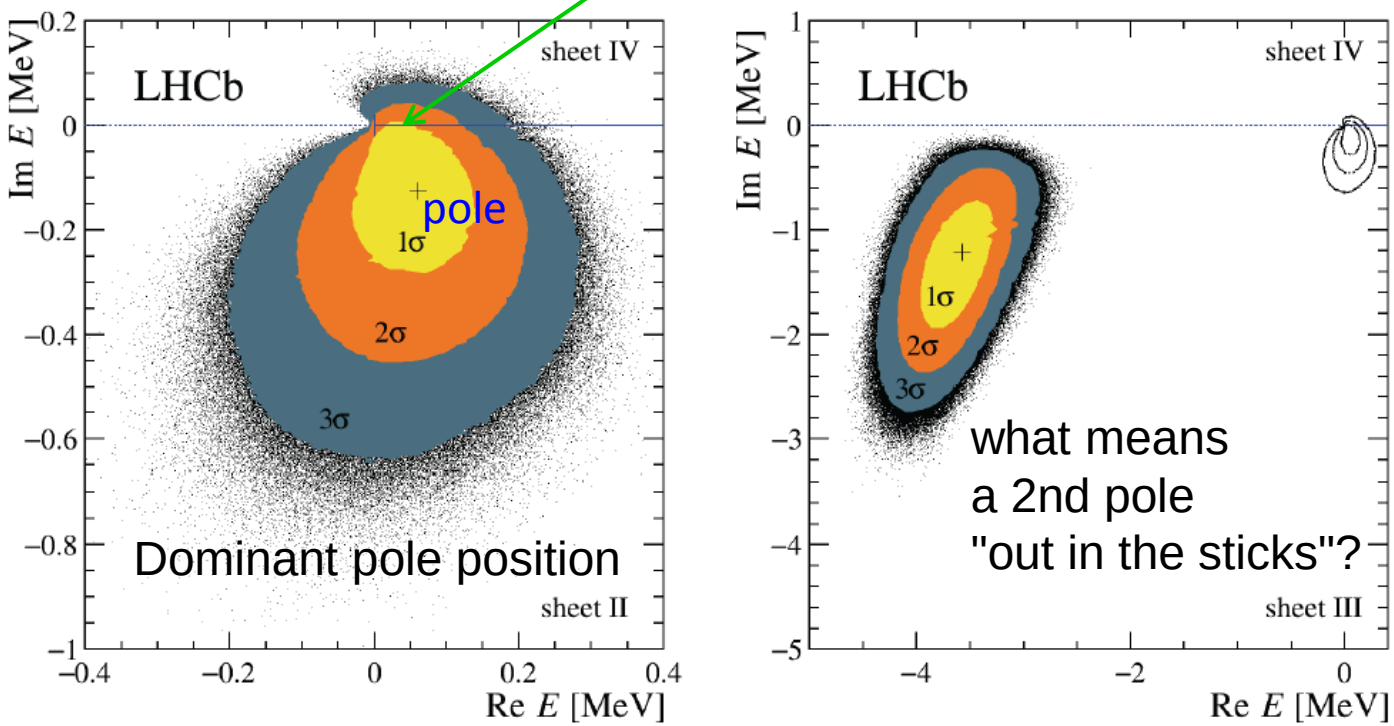
LHCb Paper - Questions (4)

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



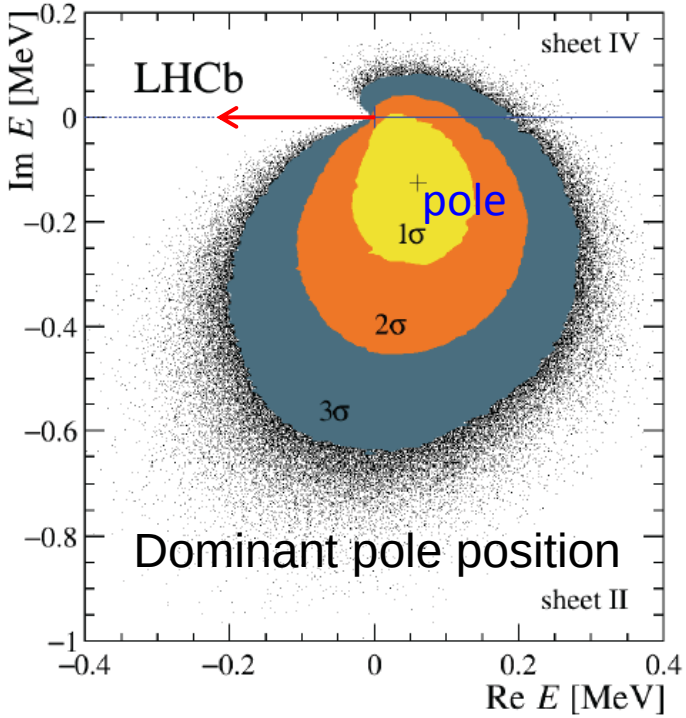
LHCb Paper - Questions (5)

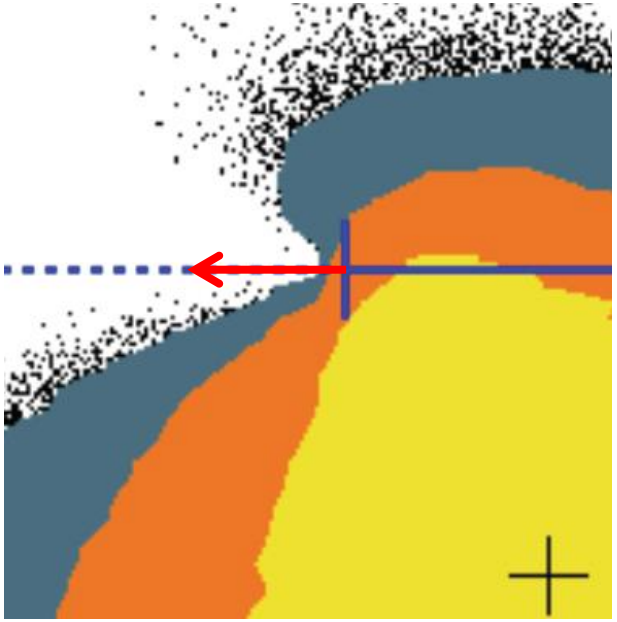
- Statement: Virtual state allowed(excluded?) at 2σ level
  - "While a pole location on sheet II is preferred by the data, a location on sheet IV is still allowed at the 2σ level."
- What I observe is the yellow 1σ area intersecting sheet IV; doesn't this mean, the virtual state is excluded by only 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



LHCb Paper - Questions (5)

- 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...

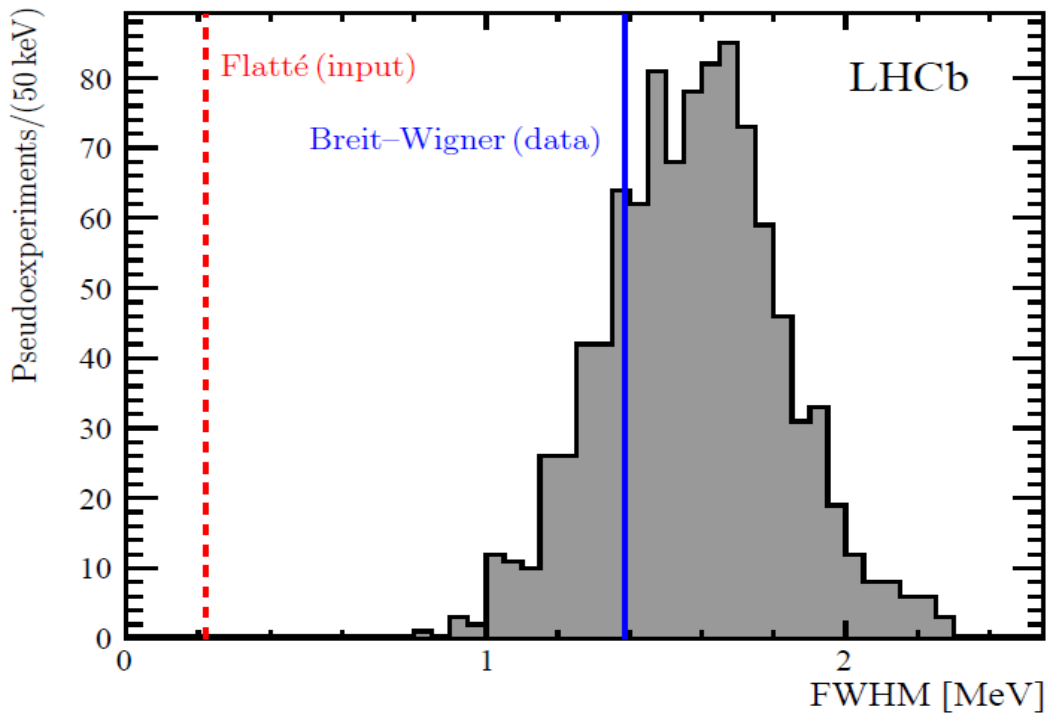


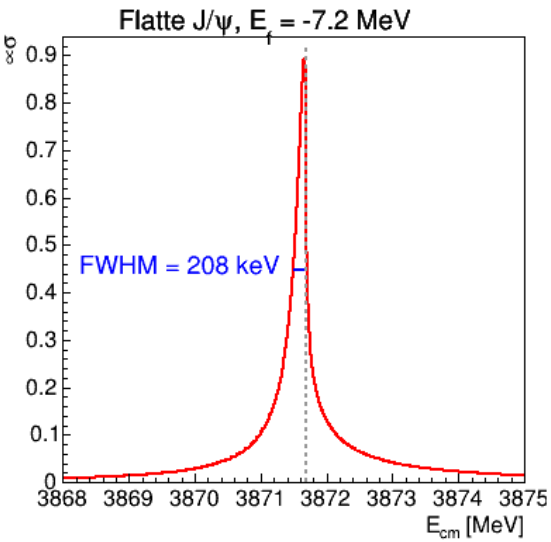


LHCb Paper - Questions (6)

- Input Flatté FWHM seems different then what I get

LHCb FWHM = 220(?) keV

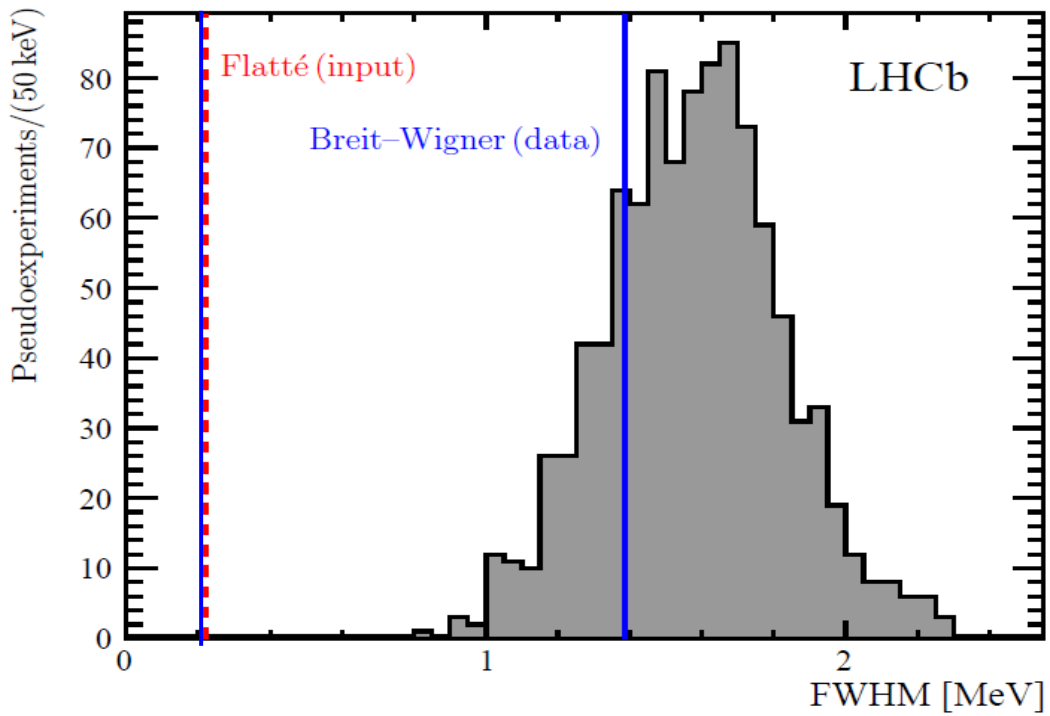


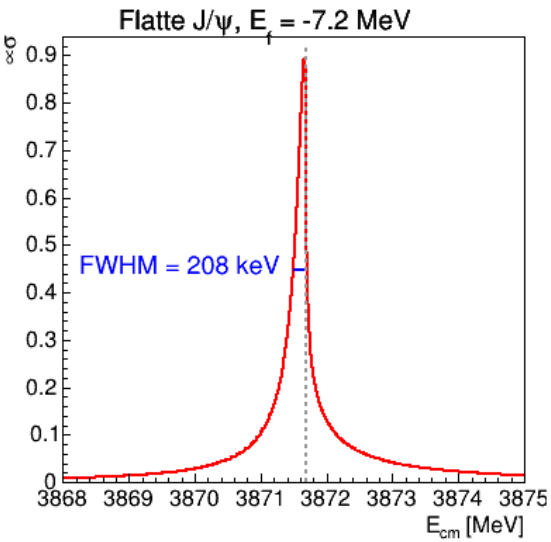


LHCb Paper - Questions (6)

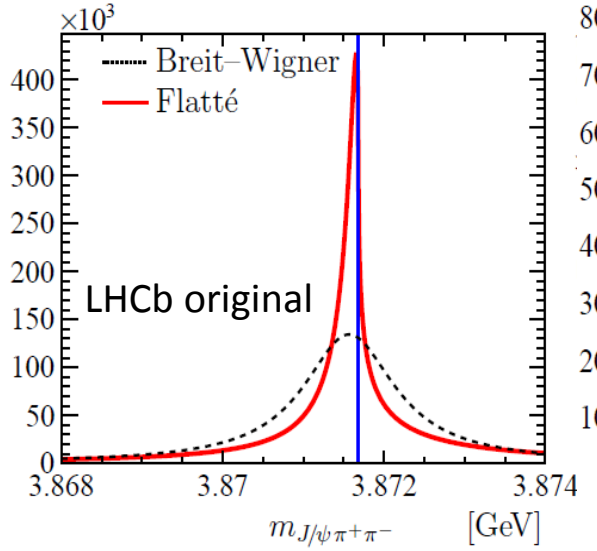
- Input Flatté FWHM seems different then what I get

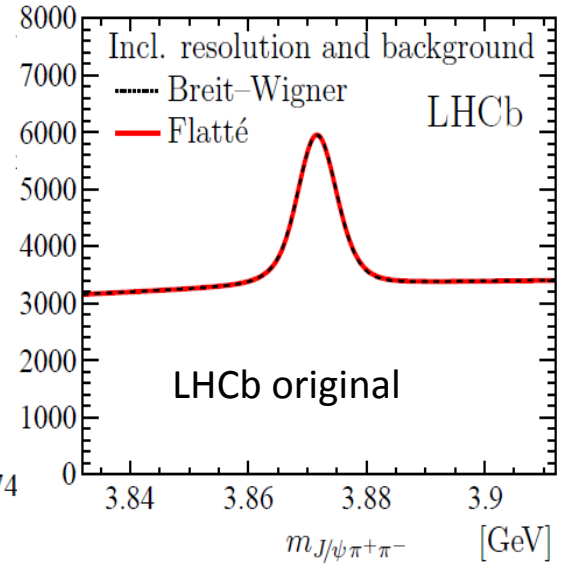
LHCb FWHM = 220(?) keV
My FWHM = 208 keV



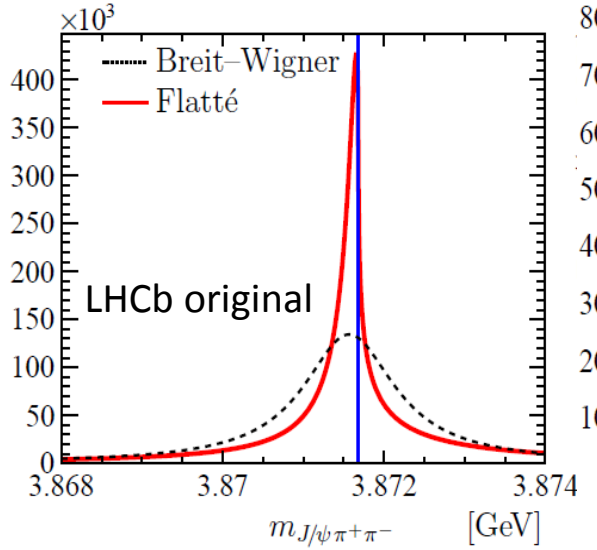


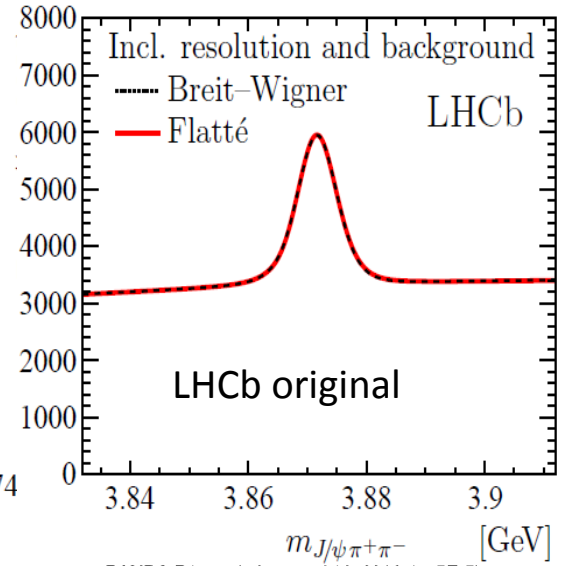
$J/\psi\pi^+\pi^-$ Lineshapes with Resolution

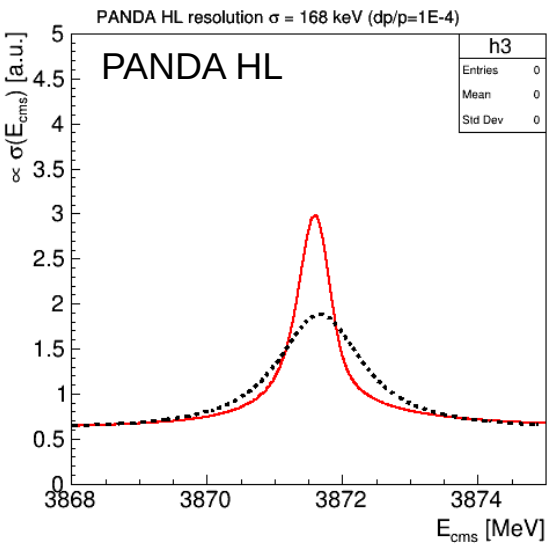


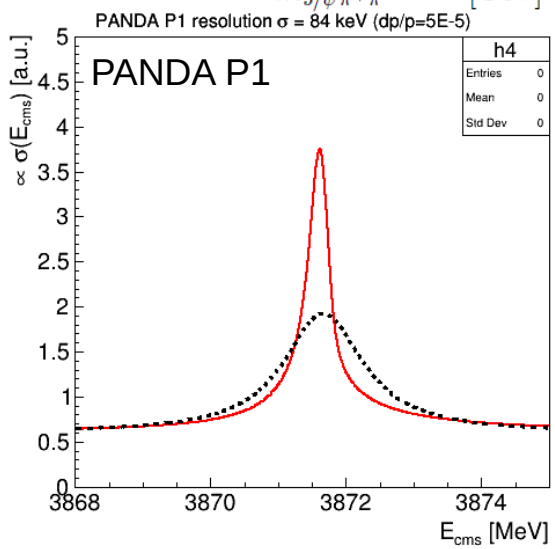


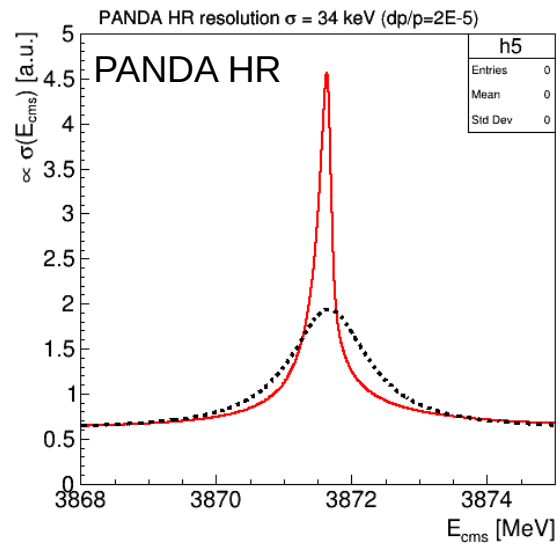
$J/\psi\pi^+\pi^-$ Lineshapes with Resolution



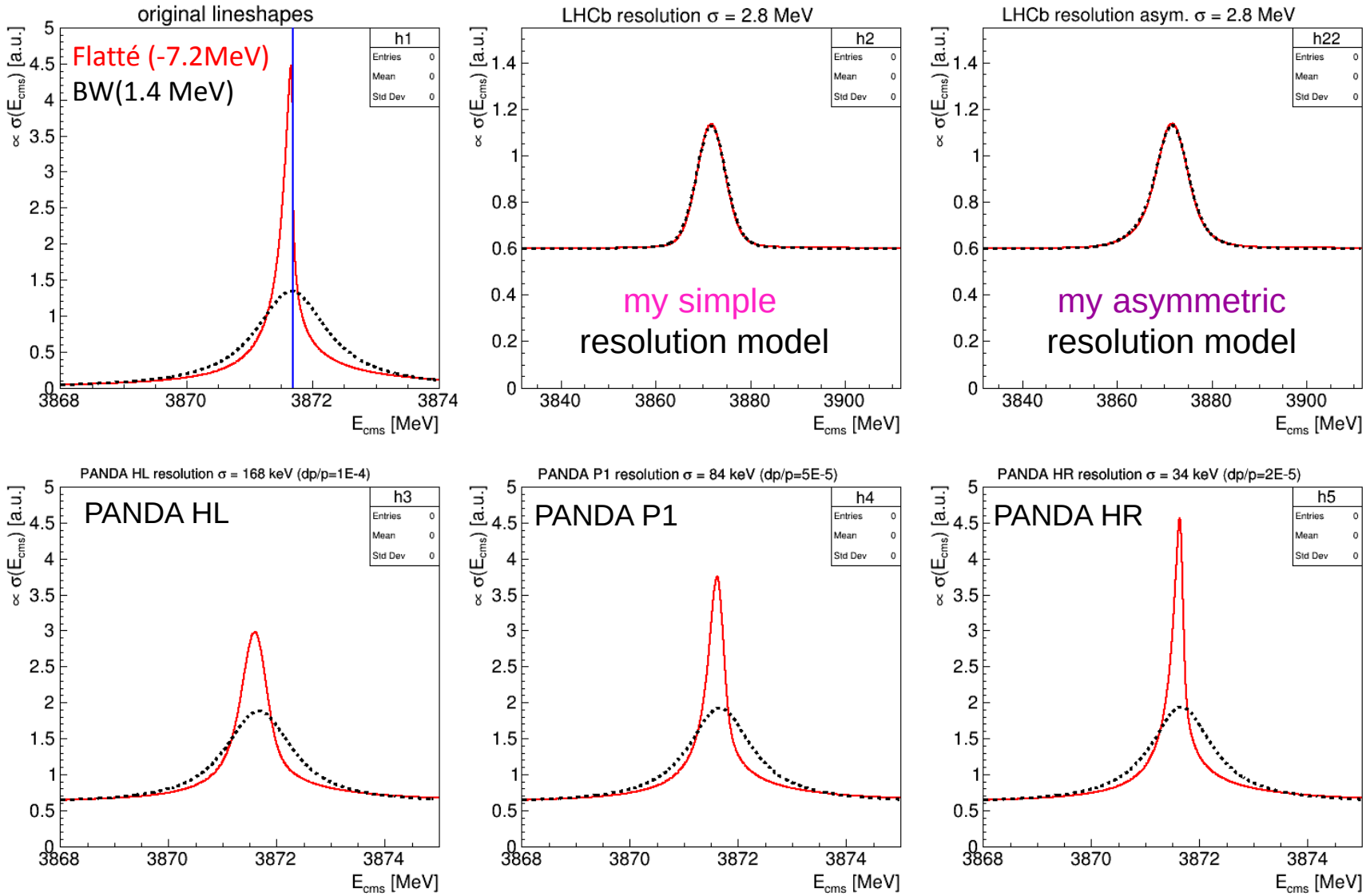




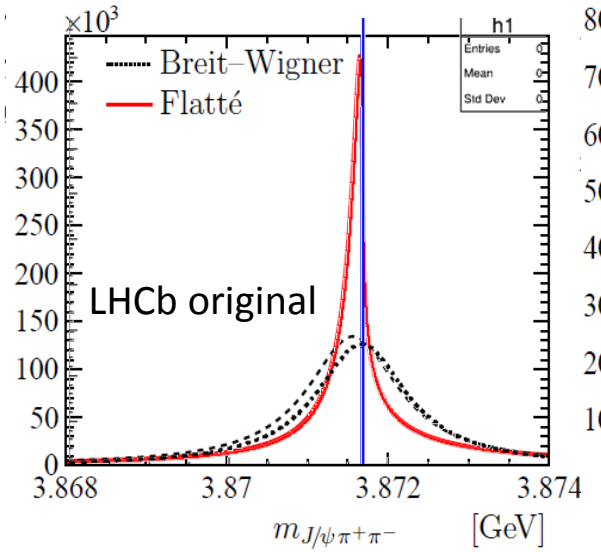


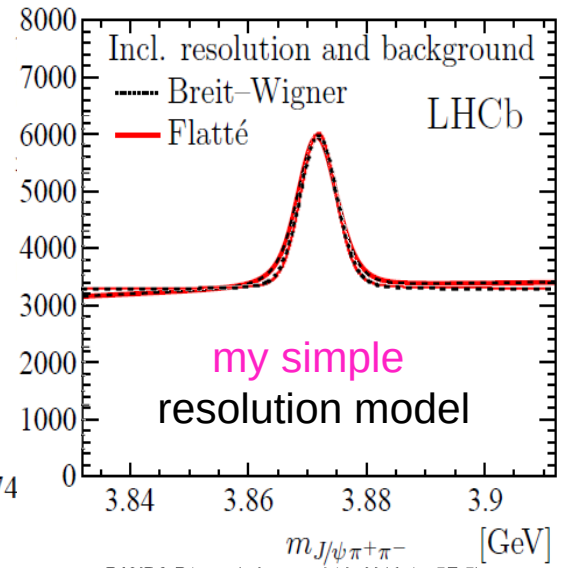


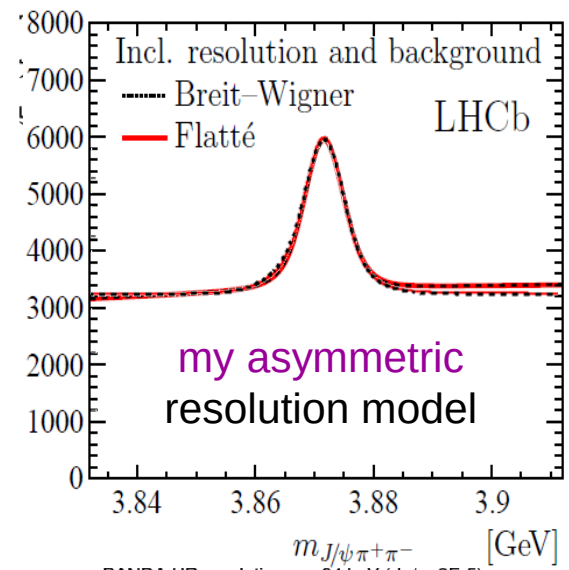
$J/\psi\pi^+\pi^-$ Lineshapes with Resolution

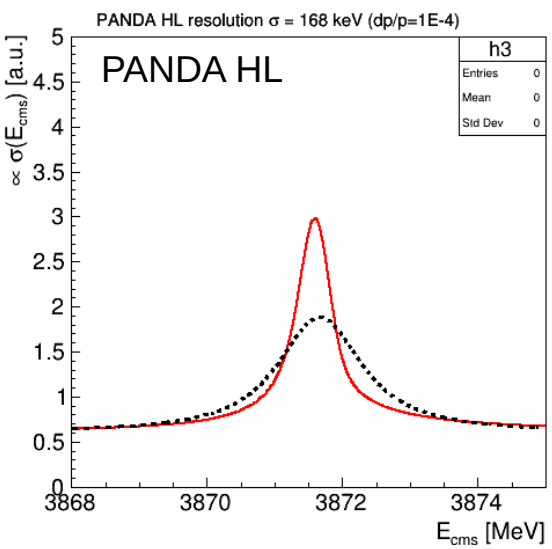


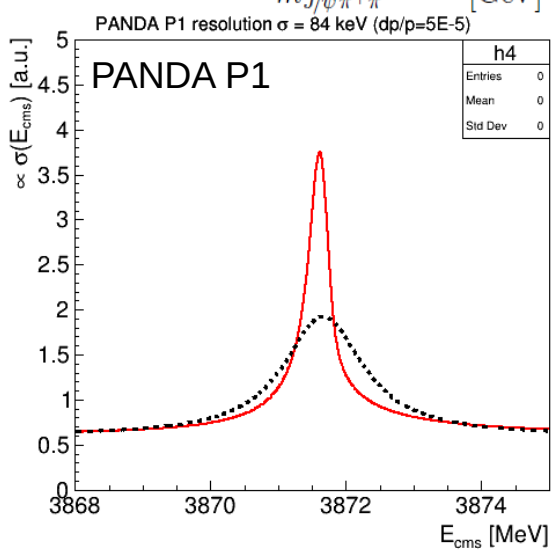
$J/\psi\pi^+\pi^-$ Lineshapes with Resolution

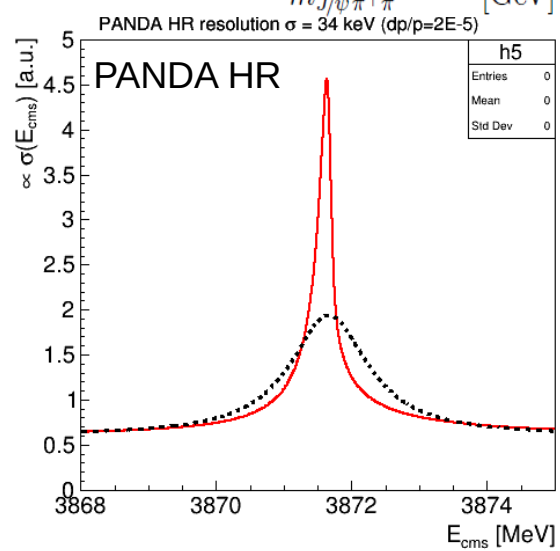






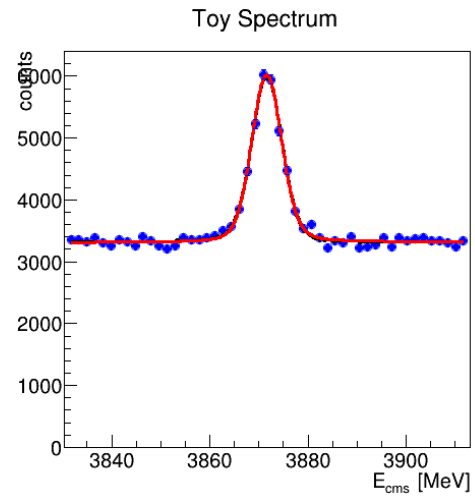


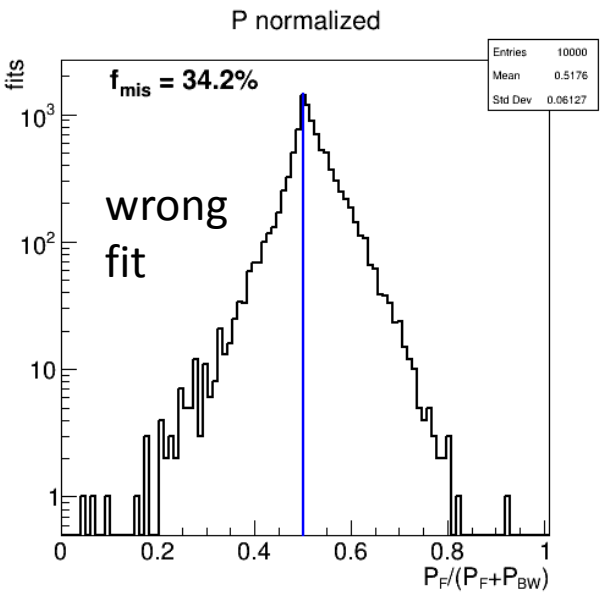


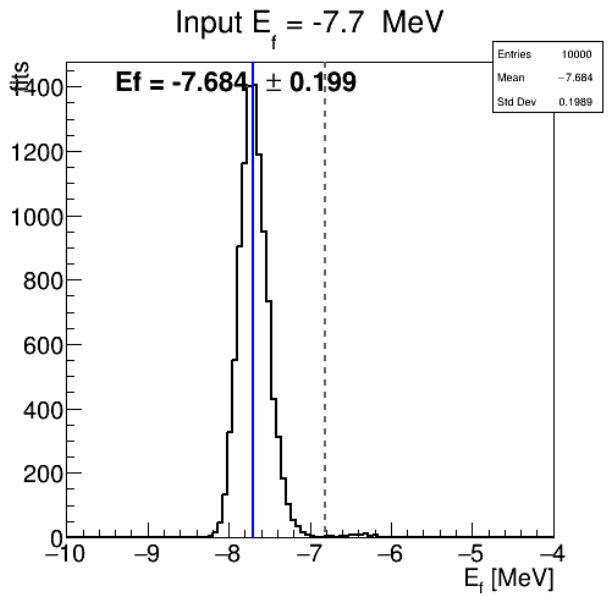


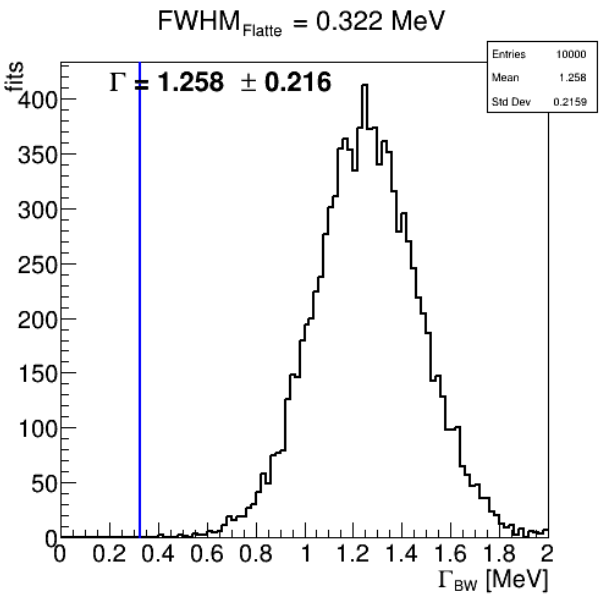
Reproduce LHCb with Toy MC

- Generated and fit many Flatté toy MC spectra
- Goal: Determine
  - Fraction to mix up BW with Flatté ($P_{fit,BW} > P_{fit,Flatte}$)
  - Distance to $E_{f,thresh}$ in terms of σ_{Ef} for Flatté fit
  - Bias factor of Γ_{BW} compared to Flatté FWHM
- In addition: Compare to PANDA P1, HR, HL modes

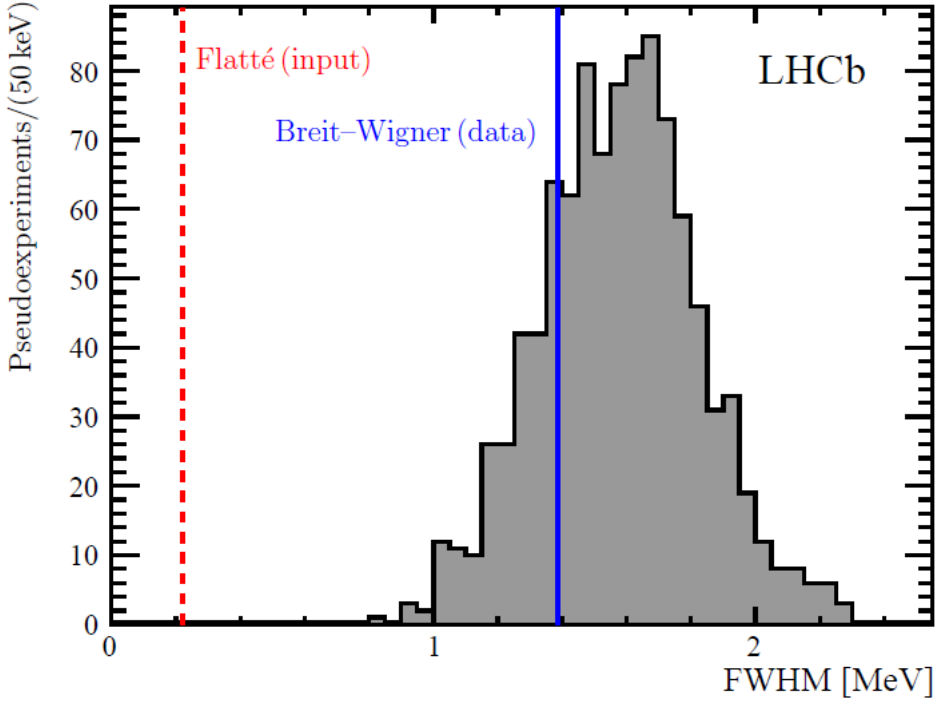


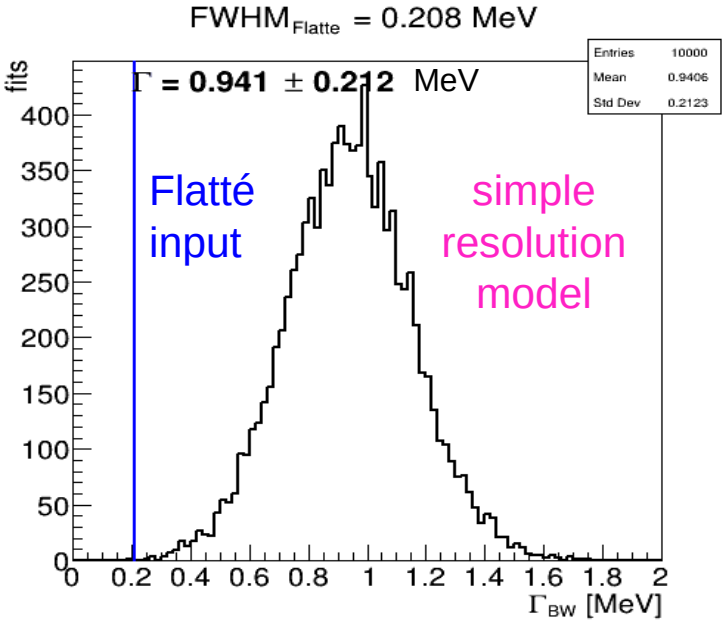


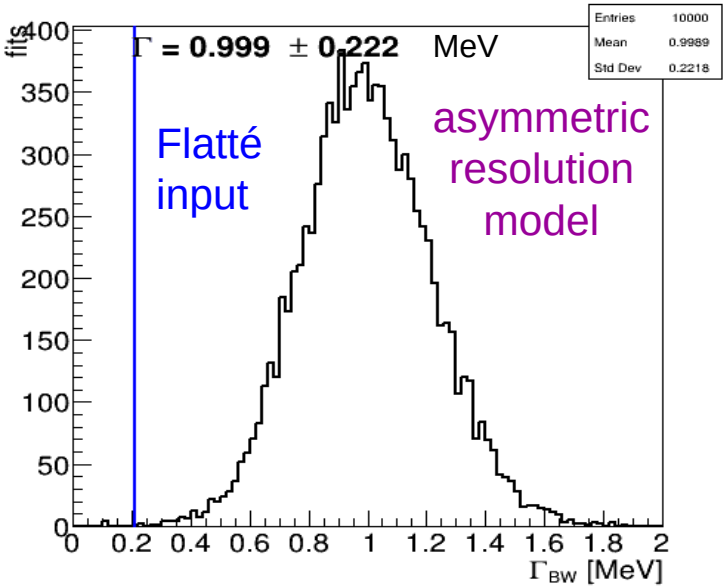




Comparison with Paper: FWHM







LHCb paper:

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

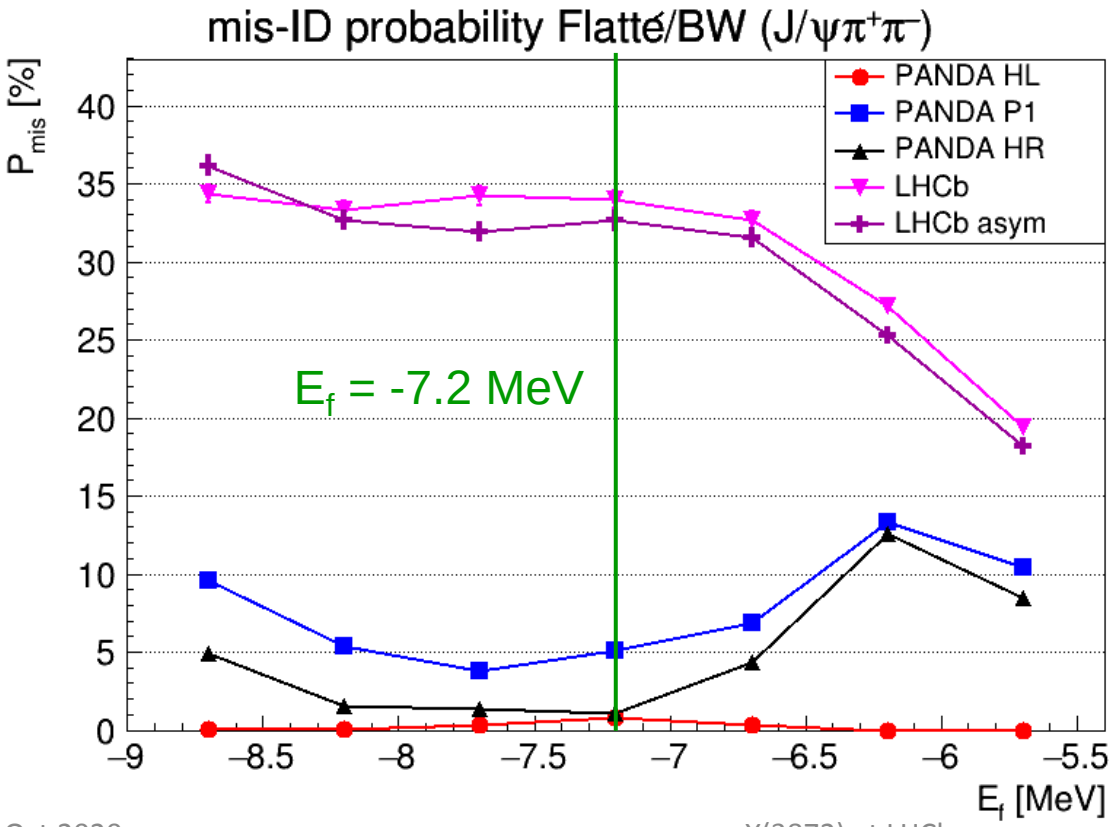
This study:

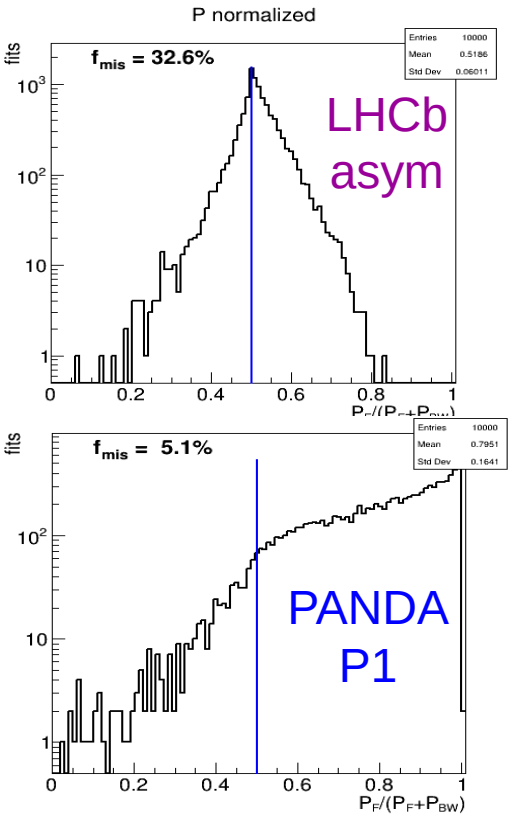
$\Gamma_{BW,toy} \approx 0.94 \pm 0.21$ MeV (simple)

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

Mis-ID Breit-Wigner vs. Flatté

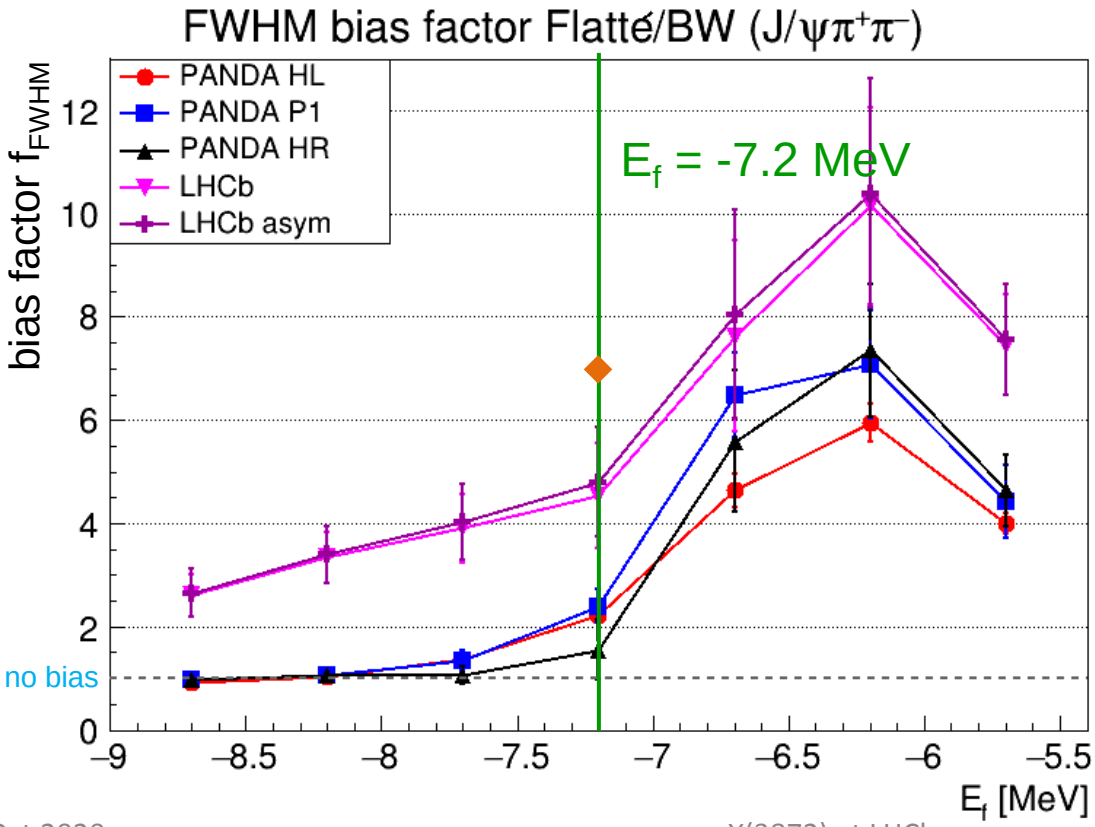
- LHCb paper: BW and Flatté distributions "... indistinguishable."
- This study:
  - LHCb toy: $P_{mis} \approx 33\%$ in region of interest (at E_f = -7.2 MeV)
  - PANDA toy: $P_{mis} \approx 1\%$ (HR/HL) ... 5% (P1) in ROI

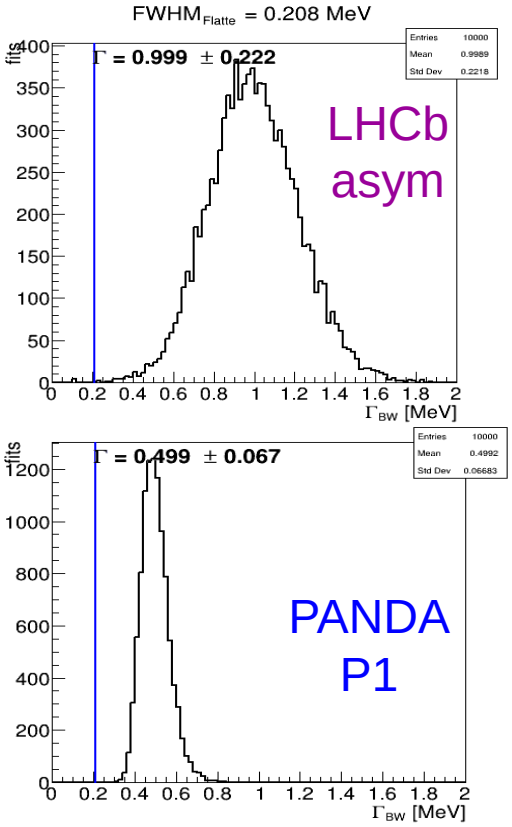




FWHM Bias Factor from Breit-Wigner Fit

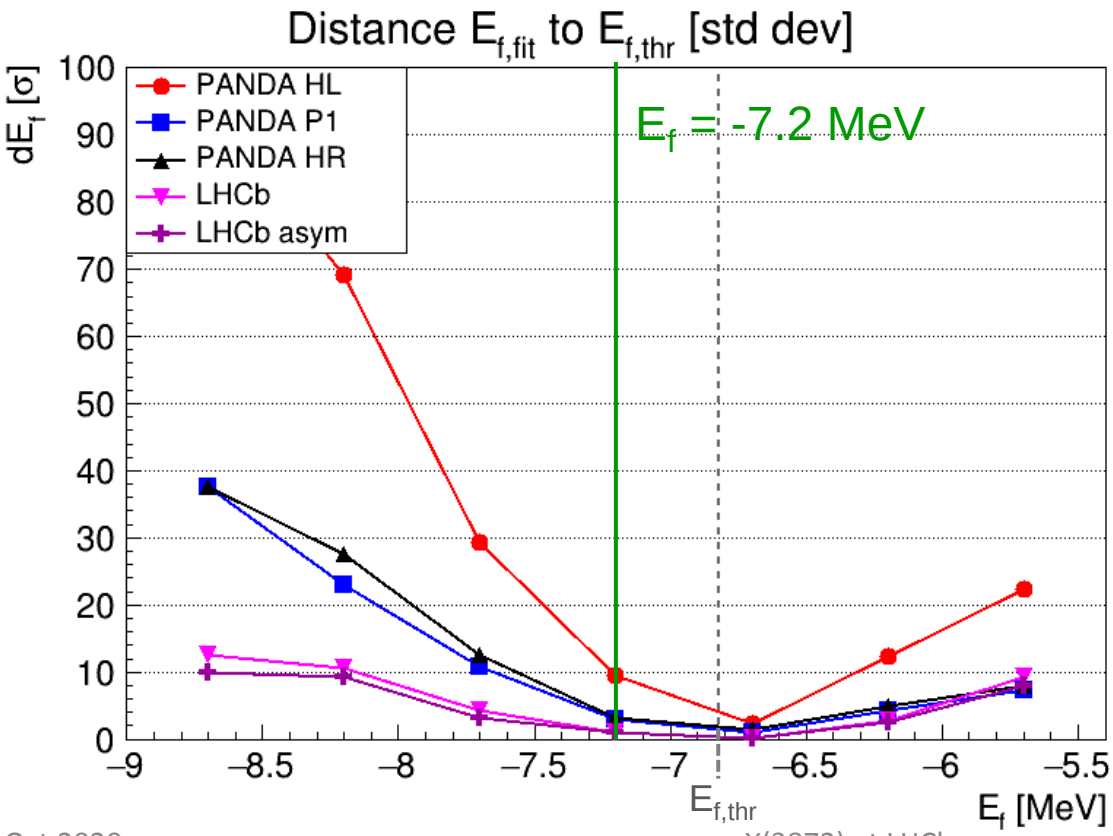
- LHCb paper: f_{FWHM} = 1.55 (BW) / 0.22 (Flatté) = 7.0
- This study:
  - LHCb toy: $f_{FWHM} \approx$ 4.5 ... 4.7 in ROI
  - PANDA toy: $f_{FWHM} \approx$ 1.5 (HR) ... 2.2(HL) ... 2.4 (P1) in ROI

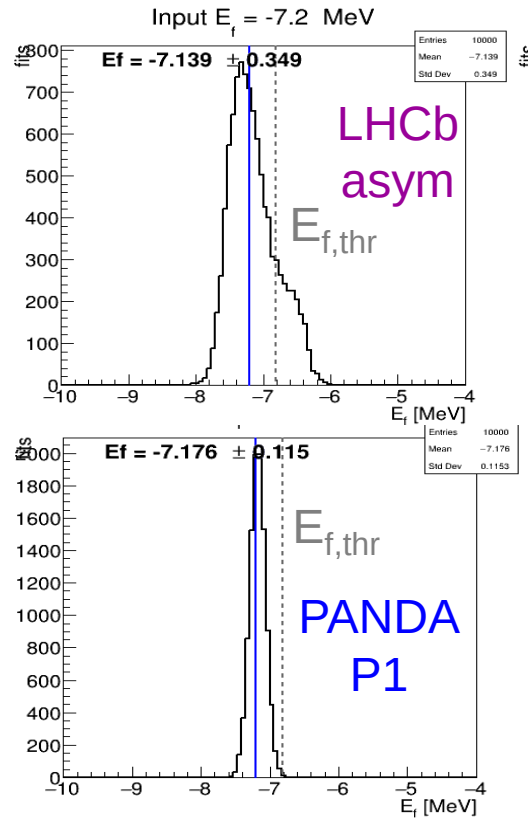




Distinguish Nature in #std. dev.

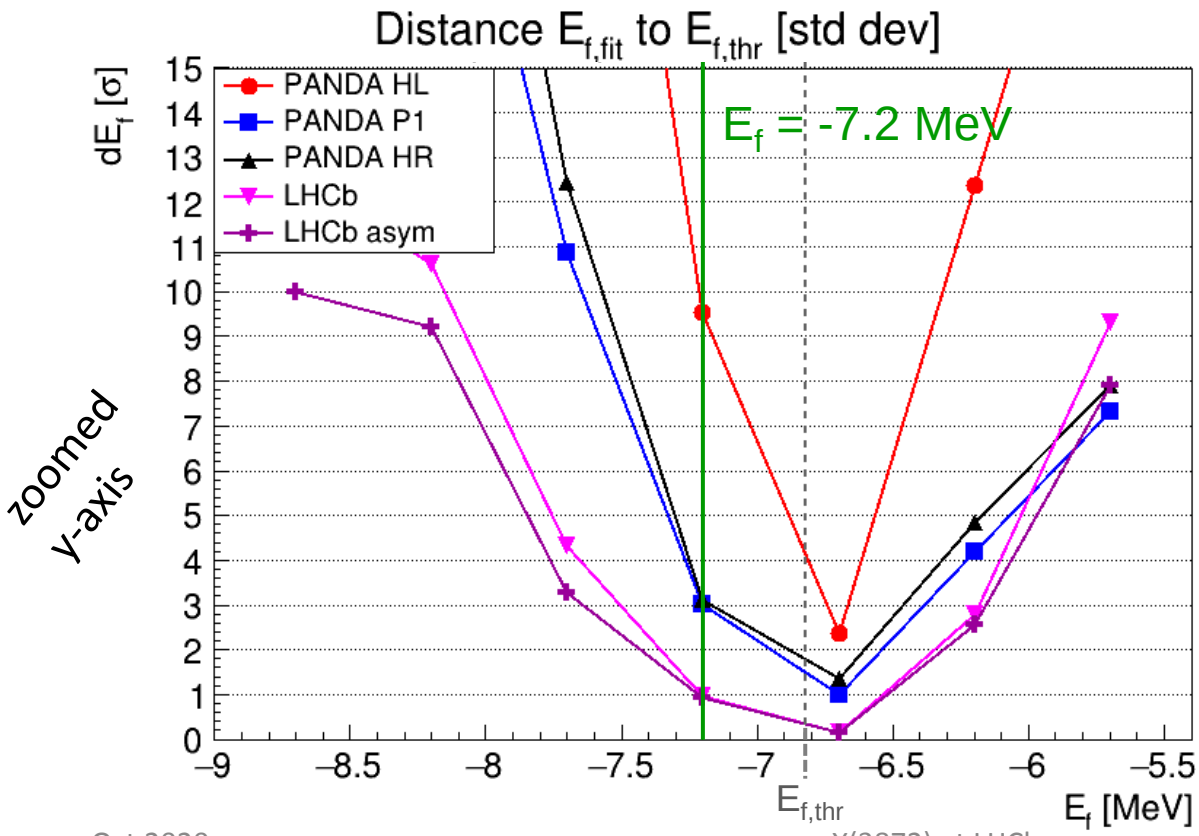
- LHCb paper: "..virtual state allowed at 2σ level." (see issue #3)
- This study with $dE_f = (E_{f,fit} - E_{f,thr})/\sigma_{Ef,fit}$:
  - LHCb toy: $dE_f \approx 0.9\sigma$ ... 1.0σ in ROI
  - PANDA toy: $dE_f \approx 3.0\sigma$ (P1) ... 3.1σ (HR) ... 9.5σ (HL) in ROI

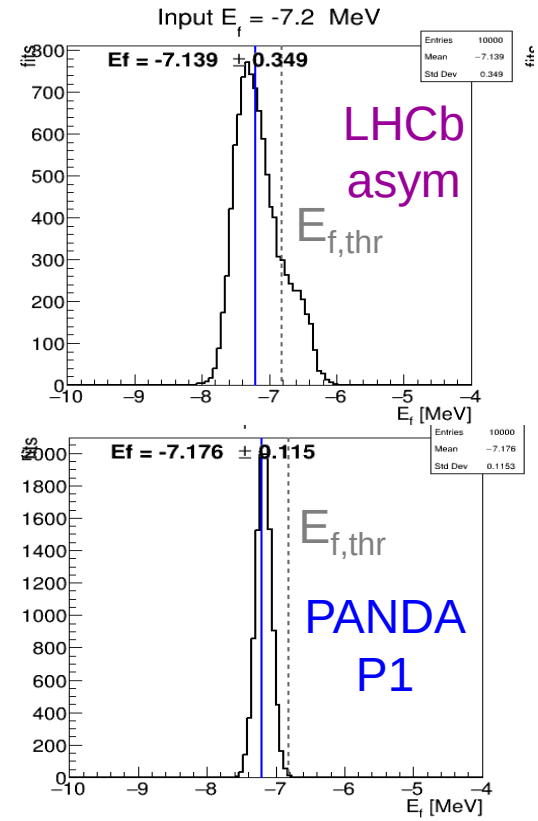




Distinguish Nature in #std. dev.

- LHCb paper: "..virtual state allowed at 2σ level." (see issue #3)
- 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

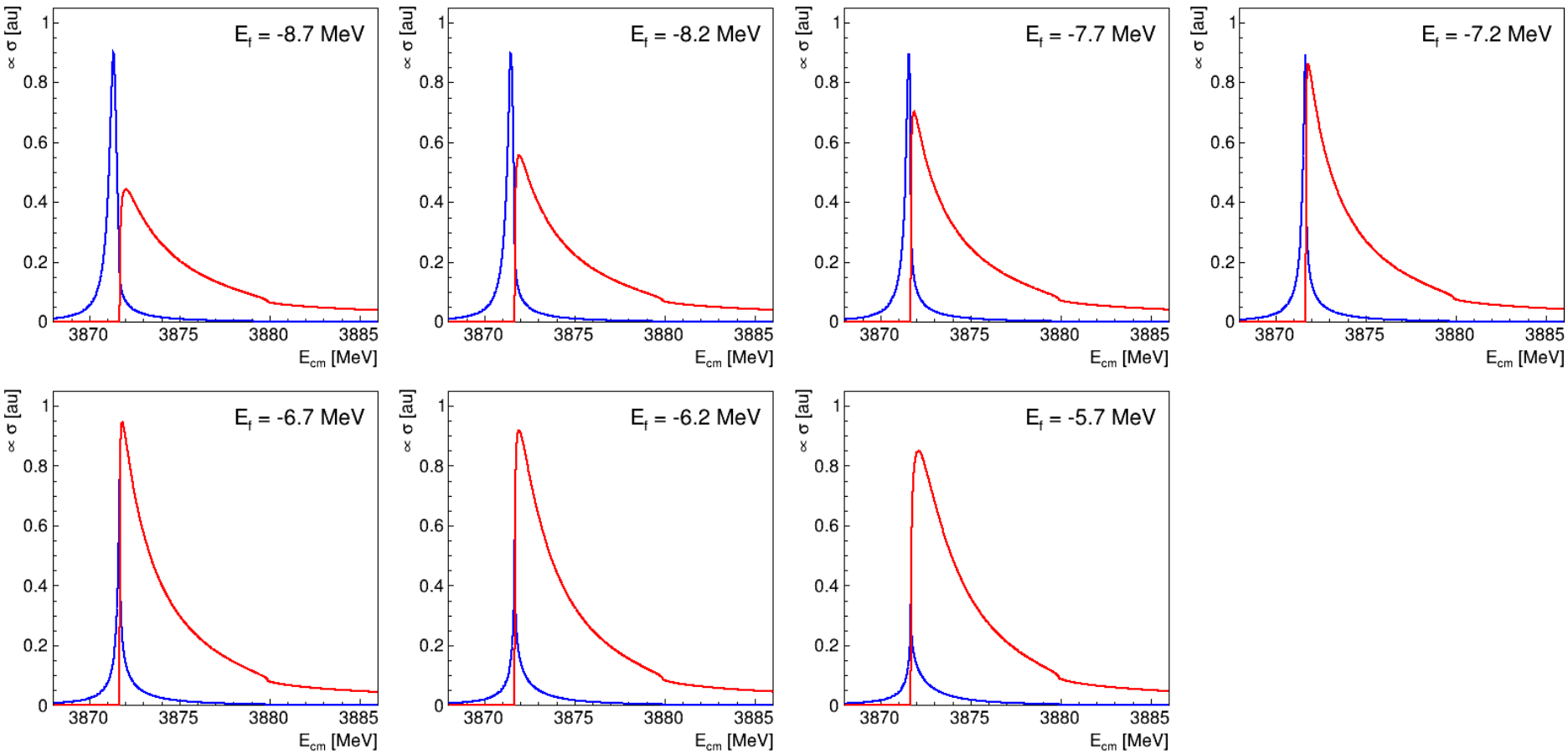




Aspects of DD* channel

DD* Lineshapes

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

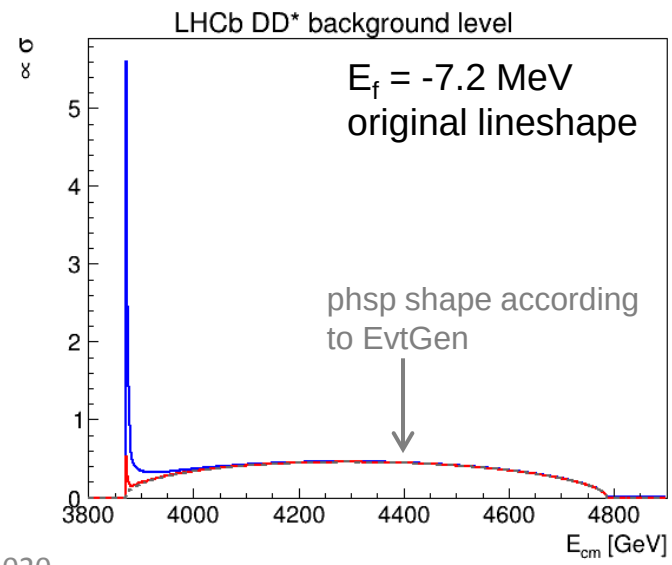


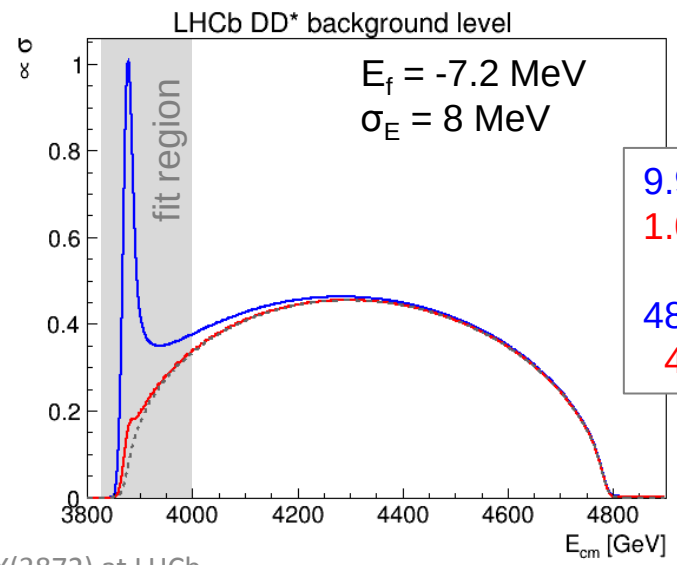
DD* Expected Background Levels LHCb

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

Decay	BR
BR_1: $B^0 \to D^0\ \underline{D^{0*}}\ K^0$	$(1.1 \pm 0.5) \cdot 10^{-3}$
BR_2: $B^+ \to D^0\ \underline{D^{0*}}\ K^+$	$(8.56 \pm 0.84) \cdot 10^{-3} = [(2.26 \pm 0.23) + (6.3 \pm 0.5)] \cdot 10^{-3}$
BR_3: $B^0 \to X(3872)\ K^0 \to D^0\ \underline{D^{0*}}\ K^0$	$(1.2 \pm 0.4) \cdot 10^{-4}$
BR_4: $B^+ \to X(3872)\ K^+ \to D^0\ \underline{D^{0*}}\ K^+$	$(8.5 \pm 2.6) \cdot 10^{-5}$

- $BR_3/BR_1 = 0.109$, $BR_4/BR_2 = 0.01$ → use B^0 scenario
- Further assumptions: $N_{max} = 5000$, $\sigma_E = 8$ MeV





9.9% of total area
1.0% of total area

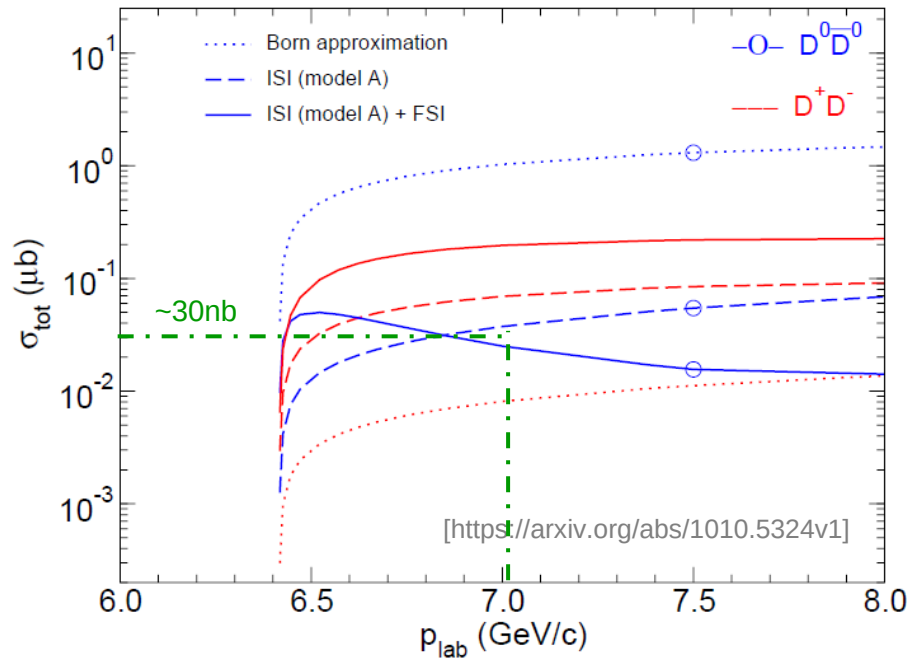
48.7% in fit region
4.3% in fit region

DD* Expected Background Levels PANDA

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

- Non-resonant from Haidenbauer et al:

  $\sigma_{D0\underline{D0}}(3884\text{MeV}) \approx 30$ nb
  $\sigma_{D0\underline{D0^*}}(3884\text{MeV}) \overset{?}{\approx} 20$ nb *(assume less DD*)*



- Assumptions for signal cross section
  - $\sigma_{X(3872)} = 50$nb
  - $BR(X \to J/\psi\pi^+\pi^-) = 5\%$
  - $BR(X \to DD^*)/BR(X \to J/\psi\pi^+\pi^-) = 9$
    $BR(X \to DD^*) = 45\%$
  - $\sigma_{X(3872) \to DD^*} = 50\text{nb} \cdot 0.45 = 22.5$ nb

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

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

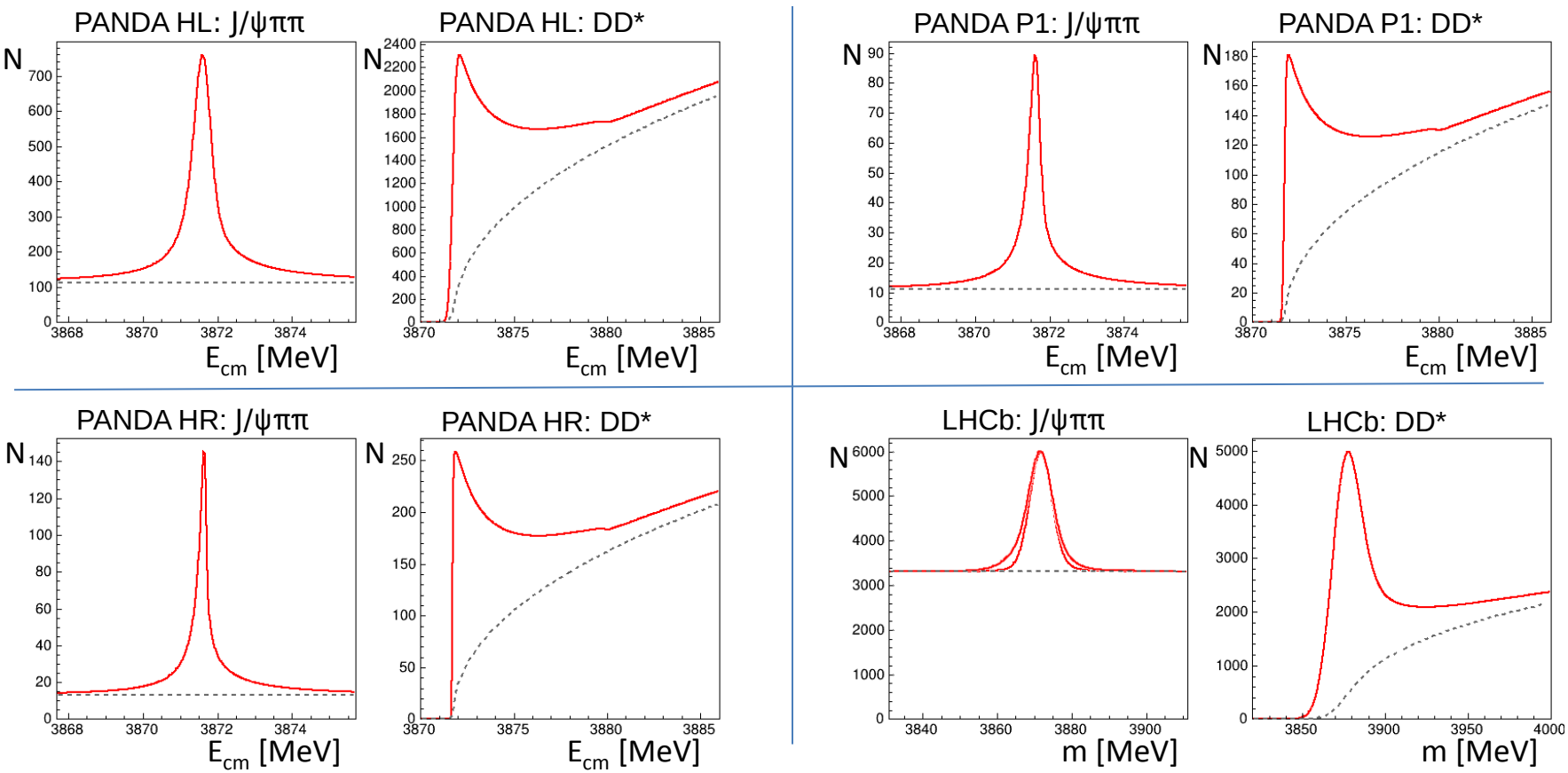
		D^0		$D^{0*}(\pi^0)$	$D^{0*}(\gamma)$	D0		$D^{0*}(\pi^0)$		$D^{0*}(\gamma)$	
Channel	BR(D^0)	trk	neut	neut	neut	ε	ε × BR	ε	ε × BR	ε	ε × BR
$K\pi$	0,0393	2	0	2	1	0,723	0,028	0,406	0,010	0,542	0,008
$K\pi\pi\pi$	0,0188	4	0	2	1	0,522	0,010	0,294	0,004	0,461	0,003
$K\pi\pi^0$	0,1430	2	2	4	3	0,406	0,058	0,229	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: $BR_{tot,J/\psi} = 12\%$, $\varepsilon_{eff,J/\psi} = 13.5\% \rightarrow f_{rec,J/\psi} = 1.6\%$

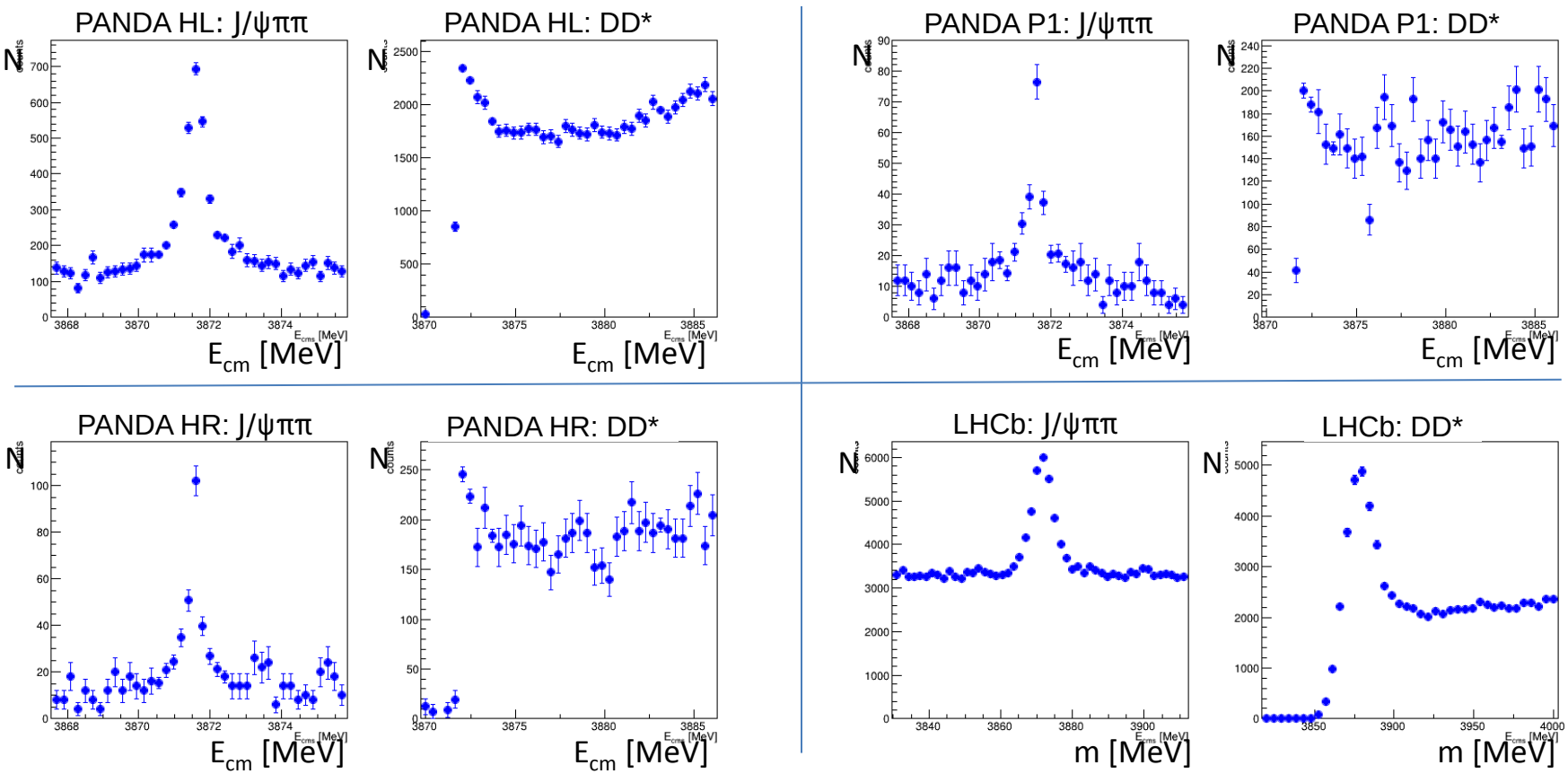
Simultaneous Fit

- LHCb: Assume 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



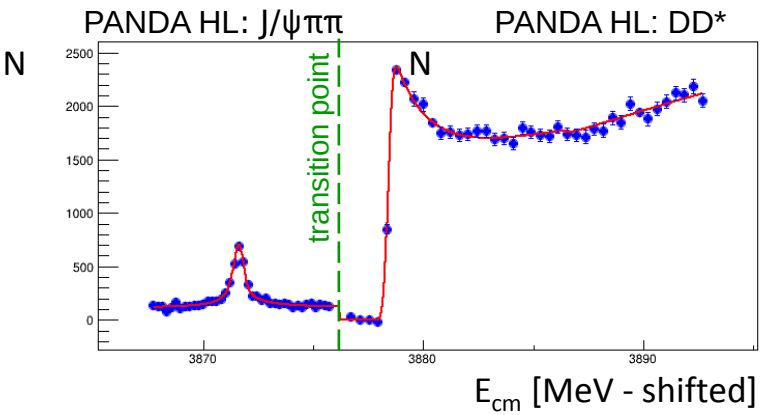
Simultaneous Fit

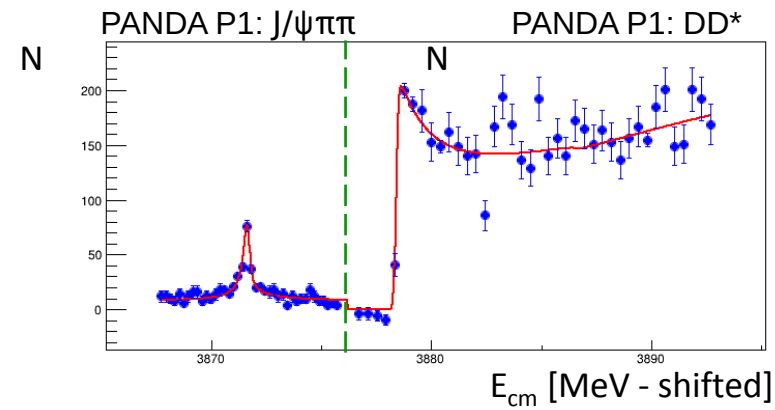
- LHCb: Assume N_{max} = 5000 in DD* spectrum (arbitrary)
- PANDA: Compute expected yield based on previous estimates
- Generate spectra and perform simultaneous fit for E_f to both channels

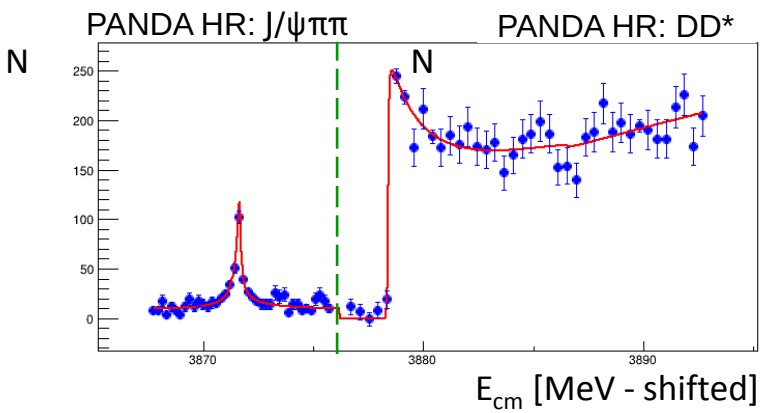


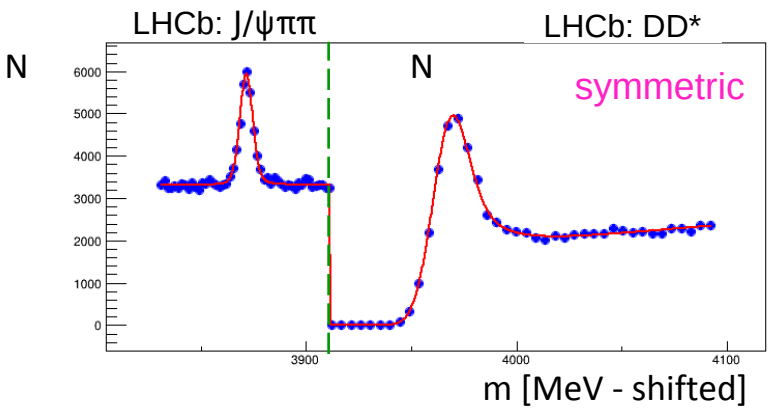
Simultaneous Fit

- 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



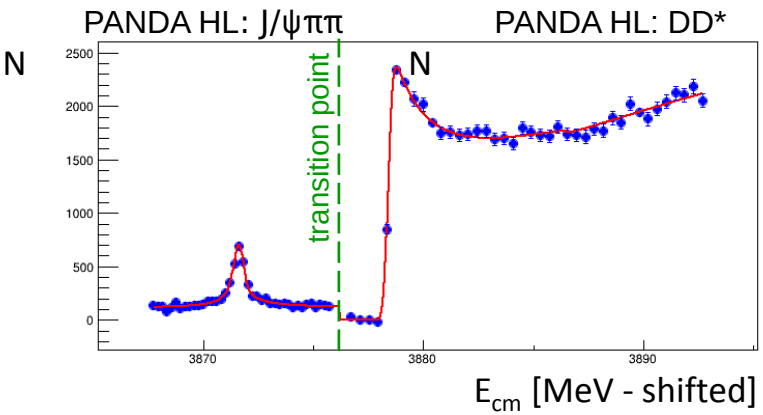


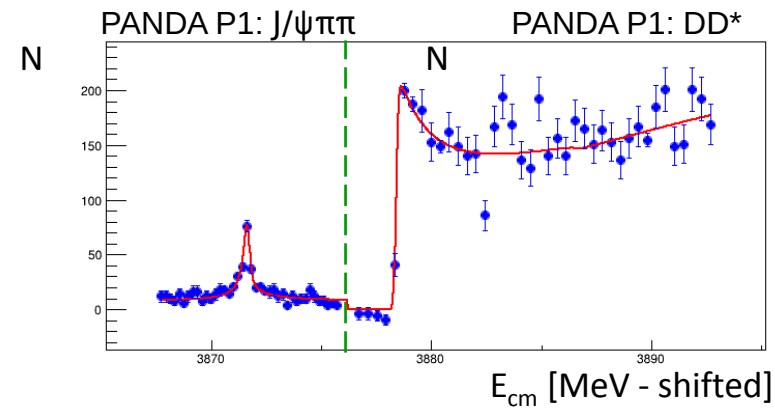


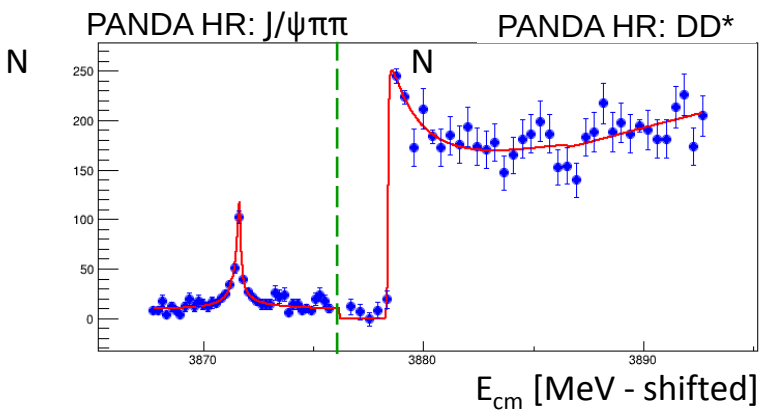


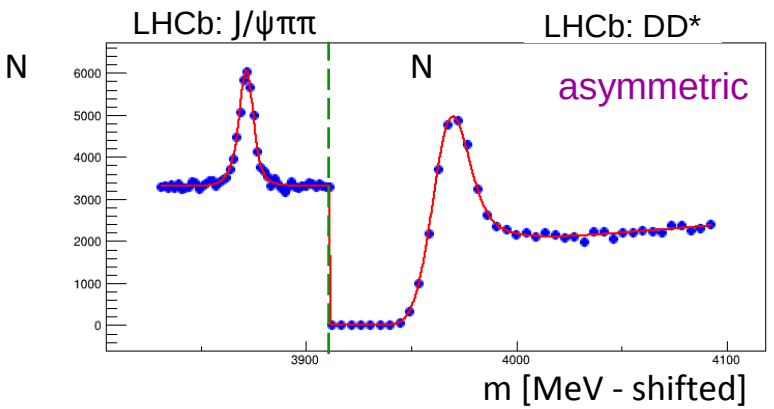
Simultaneous Fit

- 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



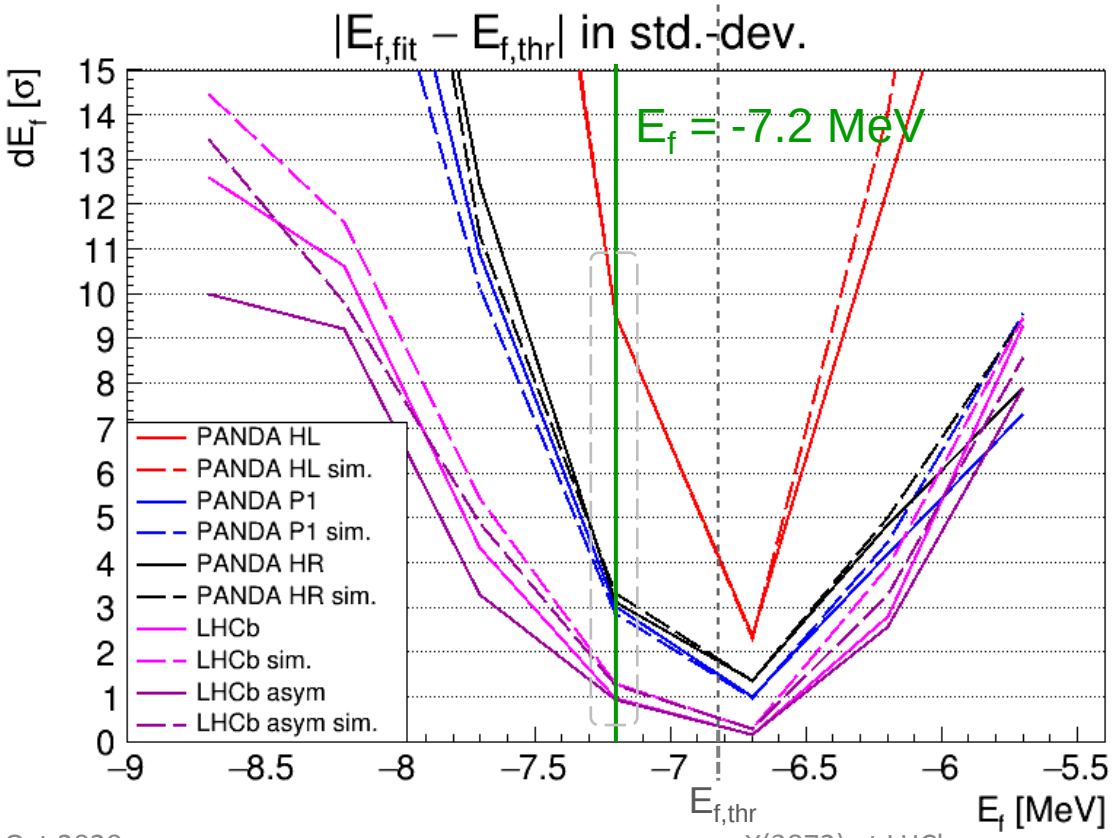


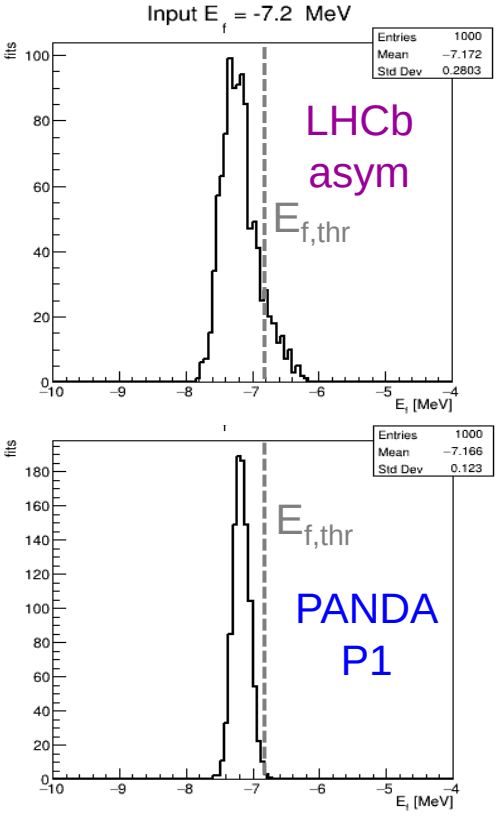




Distinguish Nature in #std. dev. (Simul. Fit)

- 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: $dE_f \approx 0.9 \ldots 1.0\ \sigma \rightarrow 1.3\sigma$ in ROI: +34% ... +38%
  - PANDA toy: almost no improvement





Conclusion

- Partially able to reproduce LHCb results
- Found 6 questions, where LHCb paper is not perfectly clear
- Investigated possible DD* simultaneous fit (with some rather arbitrary assumptions)

- In comparison to PANDA the results are (for E_f = -7.2 MeV) *(to be taken with a grain of salt)*

Measurement	LHCb	P1	HR	HL
Probability to confuse BW and Flatté case	33%	5%	1%	1%
FWHM bias factor fitting BW to Flatté	4.8 / 7.0	2.4	1.5	2.2
Significance to identify nature (bound/virtual)	1.0σ	3.0σ	3.1σ	9.5σ
Significance to identify nature incl. DD* channel*	1.3σ	2.8σ	3.3σ	9.5σ

*under certain assumptions made here