Simulation Study of the Width and Lineshape of the X(3872)

PANDA CM Bochum

Charmonium Exotics Session

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K. Götzen
GSI Darmstadt

Idea

- Nature of X(3872)
  - Need lineshape and width to understand structure
- Approach at PANDA
  - Fine scan around nominal mass
    → energy dependent cross section
- Analysis goals
  - Sensitivity of Γ measurement (conventional BW)
  - Sensitivity for virtual/bound state (molecular picture)
- Analysis strategy
  - Analysis of $X(3872) \rightarrow J/\psi(\ell^+\ell^-)\ \rho^0(\pi^+\pi^-)$ channel only
  - Full sim/reco → signal + background efficiencies ε_S and ε_B
  - Toy MC scan simulation with assumption for cross sections, integrated luminosities, BRs

Note ready for Review

Simulation Study of the Width and Line Shape of the X(3872)

Klaus Götzen*[,1], Ralf Kliemt[1,3], Frank Nerling[1,2], Klaus Peters[1,2]

[1]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt
[2]Goethe Universität Frankfurt
[3]Helmholtzinstitut Mainz

primary author

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Contents

Symbol R in talk indicates material "Proposed for Release"

Molecular Picture (Hanhart et al)

- Lineshapes from [Kalashnikova et al, Phys. Atom. Nucl. 73 (2010) 1592]
- Here only interested in X(3872) → J/ψ $\pi^+\pi^-$

$$\sigma(E) = C \cdot \frac{\Gamma_{\pi^+\pi^- J/\psi}(E)}{|D(E)|^2}$$

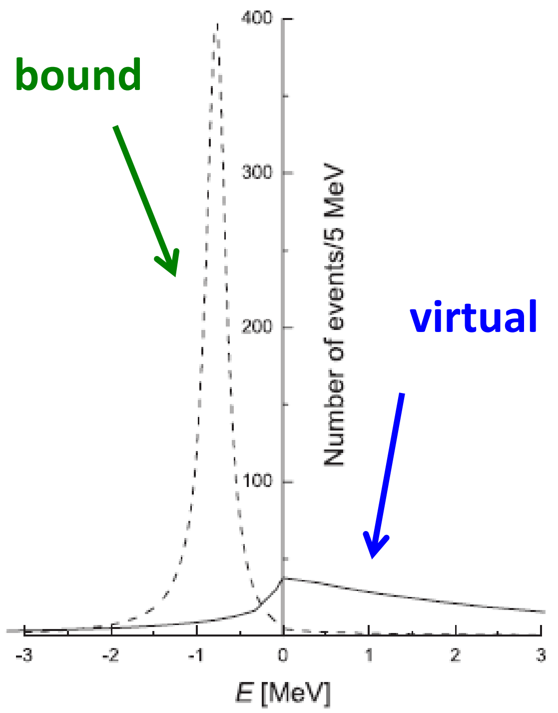
(assuming lineshape as in B decays)

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

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

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

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



Parameter E_f determines state to be bound or virtual

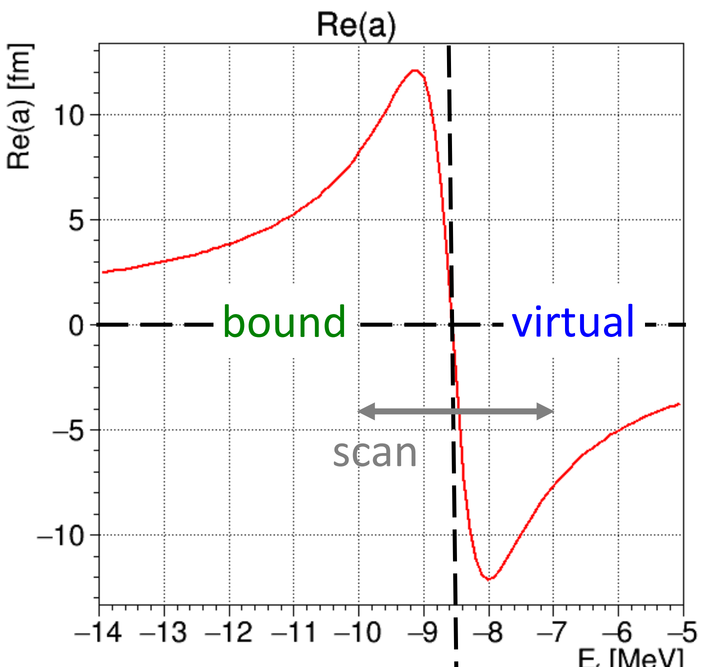
Lineshapes for different E_f

Scattering length D^0D^{0*}:

$$a = -\frac{\sqrt{2\mu_2\delta} + 2E_f/g + i\Gamma(0)/g}{(\sqrt{2\mu_2\delta} + 2E_f/g)^2 + \Gamma(0)^2/g^2}$$

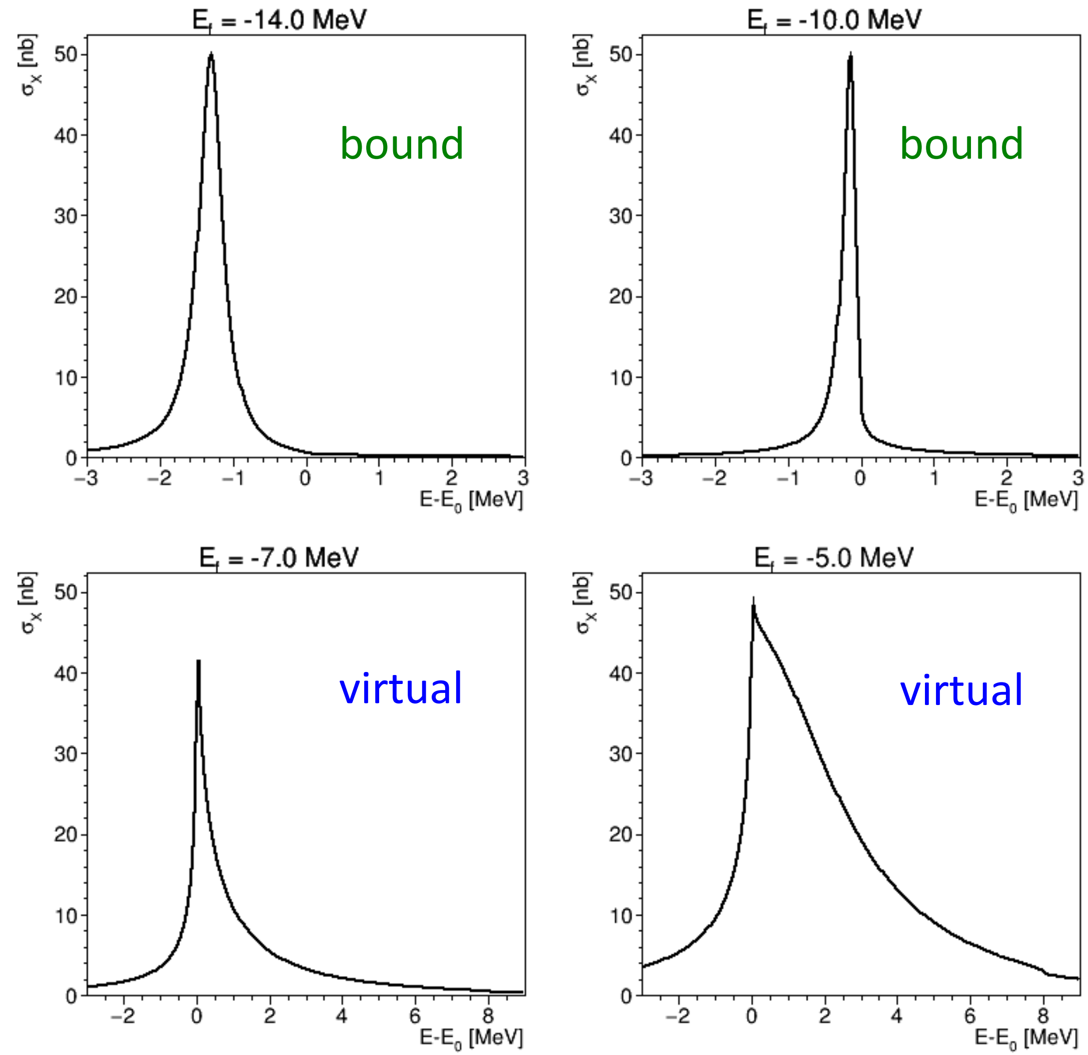
Re(a) > 0 : bound state

Re(a) < 0 : virtual state



$E_{f,th}$ = -8.56 MeV

Always scaled to same f_{max}



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

Reconstruction Part

Parameters

	Parameter	Value
Branching Fractions	$BR(J/\psi \to e^+ e^-)$	5.97 %
	$BR(J/\psi \to \mu^+ \mu^-)$	5.96 %
	$BR(\rho^0 \to \pi^+ \pi^-)$	100%
	$BR(X \to J/\psi\ \rho^0)$	5 % (UL: 6.6%)
Cross sections	$\sigma_{peak}(\bar{p}p \to X)$	100 nb (UL: 169nb)
	$\sigma(\bar{p}p \to J/\psi\ \pi^+\pi^-$ non-res)	1.2 nb* (theory)
	$\sigma(\bar{p}p \to$ inelastic) @ 3.872 GeV	46 mb
Luminosities	L_{HL} (3.872 GeV)	13683 $(nb \cdot d)^{-1}$ **
	L_{HESRr} (3.872 GeV)	1170 $(nb \cdot d)^{-1}$ **
Resolutions	ΔE_{abs} *(energy prec. w/ calibration)*	168 keV ($dp/p = 10^{-4}$)
	ΔE_{rel} *(relative energy positioning)*	1.7 keV ($dp/p = 10^{-6}$)
	ΔE_{mom} (HL)	168 keV ($dp/p = 10^{-4}$)
	ΔE_{mom} (HESRr)	84 keV ($dp/p = 5 \cdot 10^{-5}$)

* [PRD 77 (2008) 097501]
** [IN-IDE-2015-002 (2015)]

Signal Cross Section - Remarks

[Eur. Phys. J. C73 (2013) 2462]
[arXiv:0910.3138v2 (2009)]

- LHCb: $B(X\rightarrow \bar{p}p) <$ **0.002**$\cdot$ $B(X\rightarrow J/\psi\ \pi\ \pi)$ (CL95)
- Review paper + PDG: **2.6%** $<$ $B(X\rightarrow J/\psi\ \pi\ \pi) <$ **6.6%** (CL90)
- Crossing Symmetry (or detailed balance) gives at peak

$$\sigma_{\mathrm{peak},\bar{p}p\rightarrow X} = \underbrace{\frac{12\pi}{M_X^2 - 4m^2}}_{k} \cdot B(X\rightarrow \bar{p}p) < \underbrace{2.56\mu b}_{k\cdot(197.3\ \mathrm{MeV\cdot fm})^2\cdot 0.01\ \mathrm{b/fm}^2\cdot 0.002} \cdot B(X\rightarrow J/\psi\pi^+\pi^-)$$

2.6% 5% 6.6%

$\Rightarrow$ $\boldsymbol{\sigma_{\text{peak, }p\bar{p}\rightarrow X}} <$ 67 nb ... 128 nb ... **169 nb** *@ CL95 · CL90*

↖ product of LL and UL not an UL!

- Use $\boldsymbol{\sigma_{\text{peak,}p\bar{p}\rightarrow X}}$ **= 100 nb** instead previous 50 nb

(BESIII uses $B(X\rightarrow J/\psi 2\pi) = 5\%$ in some paper $\Rightarrow$ $\sigma_{p\bar{p}\rightarrow X} < 128\mathrm{nb}$)

- NB: $\sigma_{p\bar{p}\rightarrow X} \cdot B(X\rightarrow J/\psi 2\pi)$ = 100nb · 5% (new) = 50nb · 10% (M. Galuska) = 5nb *(same!)*

Software and Data

- Software
  - PandaRoot: Revision 28670
  - FairSoft: mar15p2
  - FairRoot: v15.03
- Data @ E_{cm} = 3.872 GeV

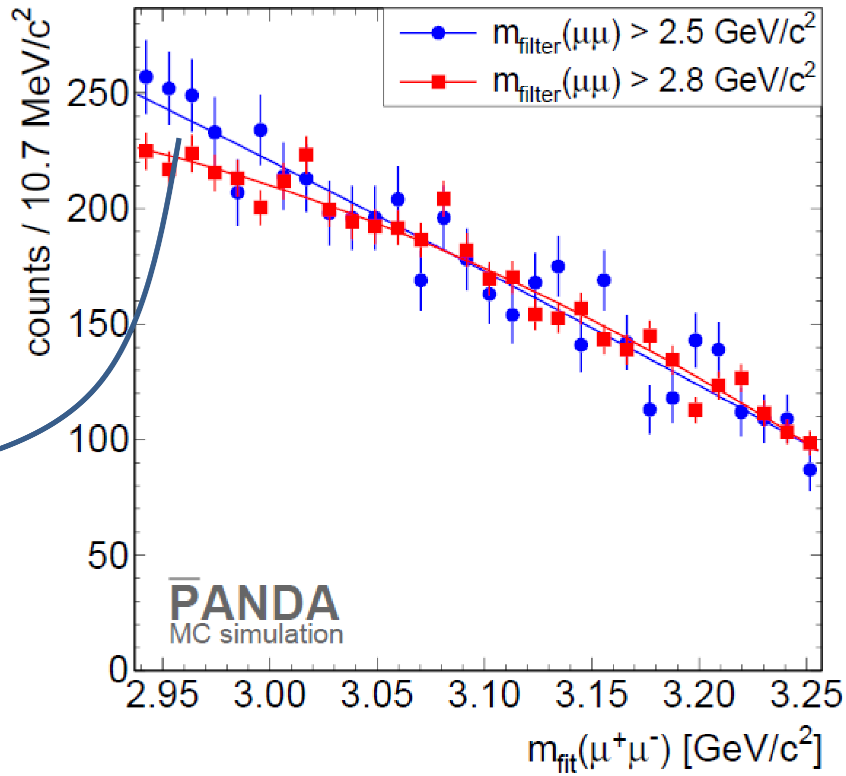
Channel	#Events
$\bar{p}p \rightarrow J/\psi\ \rho^0 \rightarrow e^+e^-\ \pi^+\pi^-$	98k
$\bar{p}p \rightarrow J/\psi\ \rho^0 \rightarrow \mu^+\mu^-\ \pi^+\pi^-$	100k
$\bar{p}p \rightarrow J/\psi\ (\rightarrow e^+e^-)\ \pi^+\pi^-$ (NR)	100k
$\bar{p}p \rightarrow J/\psi\ (\rightarrow \mu^+\mu^-)\ \pi^+\pi^-$ (NR)	99k
DPM ($J/\psi \rightarrow e^+ e^-$ prefilter)	≈10M = 9.58G generated
DPM ($J/\psi \rightarrow \mu^+ \mu^-$ prefilter)	≈10M = 8.87G generated

Background Prefilter QA

- Filtering criteria
  - Require 4 charged tracks
  - Require one 2-track combination : $m_{ee/\mu\mu} > 2.8$ GeV/c^2
  - Suppression factor e^+e^- : ≈1/1000
  - Suppression factor $\mu^+\mu^-$: ≈1/900

- Check filter bias (μμ only)
  - Cross check with criterion $m_{\mu\mu} > 2.5$ GeV/c^2 (10M → 2.6G)
  - Slight difference at lower mass edge
  - Total integral difference: 1.9%

⇒ Negligible effect!

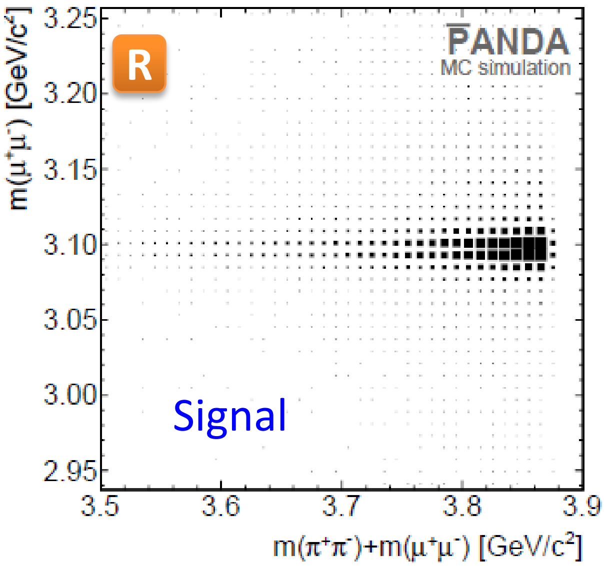


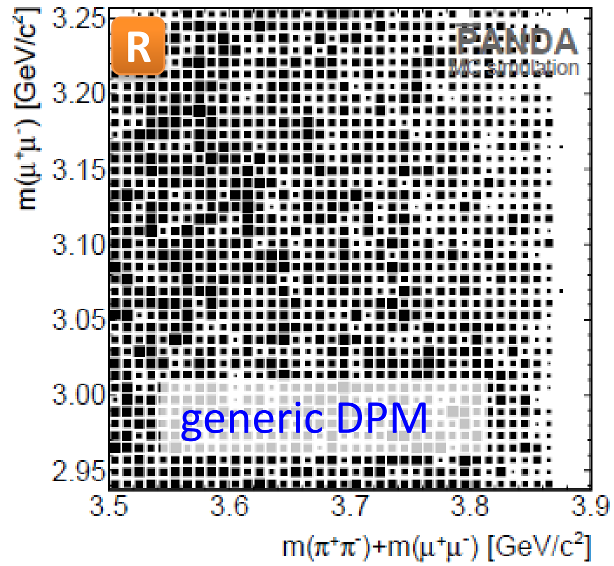
Signal Reconstruction & Pre-Selection

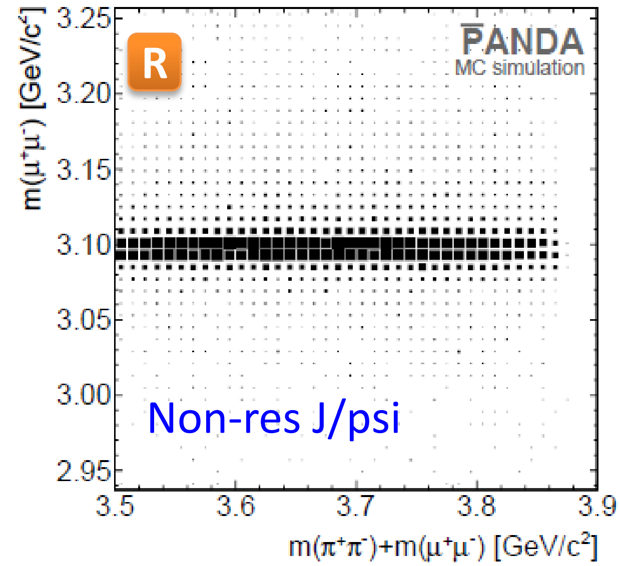
- Preselection e^+e^- :
  - Particle Identification : ElectronTight, PionAll (PidAlgoEmcBayes;PidAlgoDrc;PidAlgoDisc;PidAlgoStt;PidAlgoMdtHardCuts)
  - $J/\psi \rightarrow e^+e^-$ mass window: $2.0 < m(e^+e^-) < 3.4$ GeV/c^2
  - $\rho^0 \rightarrow \pi^+\pi^-$ mass window: $0.27 < m(\pi^+\pi^-) < 1.0$ GeV/c^2
  - $\bar{p}p \rightarrow J/\psi\, \rho^0$ 4C fit : $\chi^2 < 200$

- Preselection $\mu^+\mu^-$:
  - Particle Identification : MuonTight, PionAll (PidAlgoEmcBayes;PidAlgoDrc;PidAlgoDisc;PidAlgoStt;PidAlgoMdtHardCuts)
  - $J/\psi \rightarrow \mu^+\mu^-$ mass window: $2.5 < m(\mu^+\mu^-) < 3.4$ GeV/c^2
  - $\rho^0 \rightarrow \pi^+\pi^-$ mass window: $0.27 < m(\pi^+\pi^-) < 1.0$ GeV/c^2
  - $\bar{p}p \rightarrow J/\psi\, \rho^0$ 4C fit : $\chi^2 < 100$

Data distributions

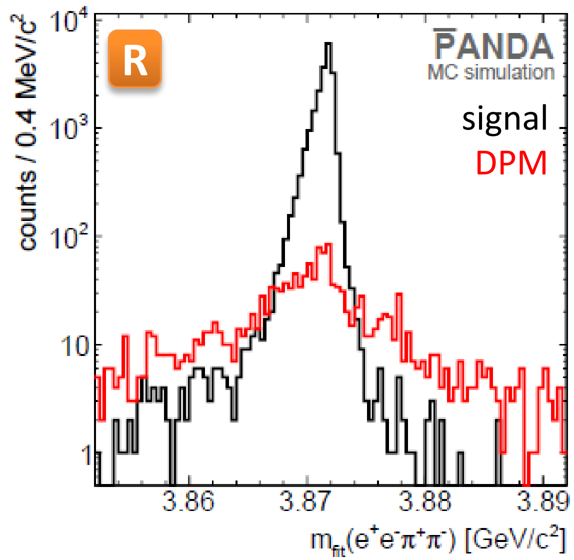




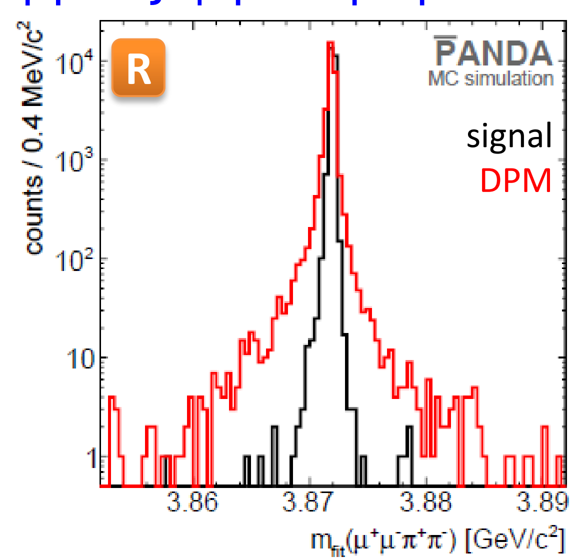


Fitted four particle masses

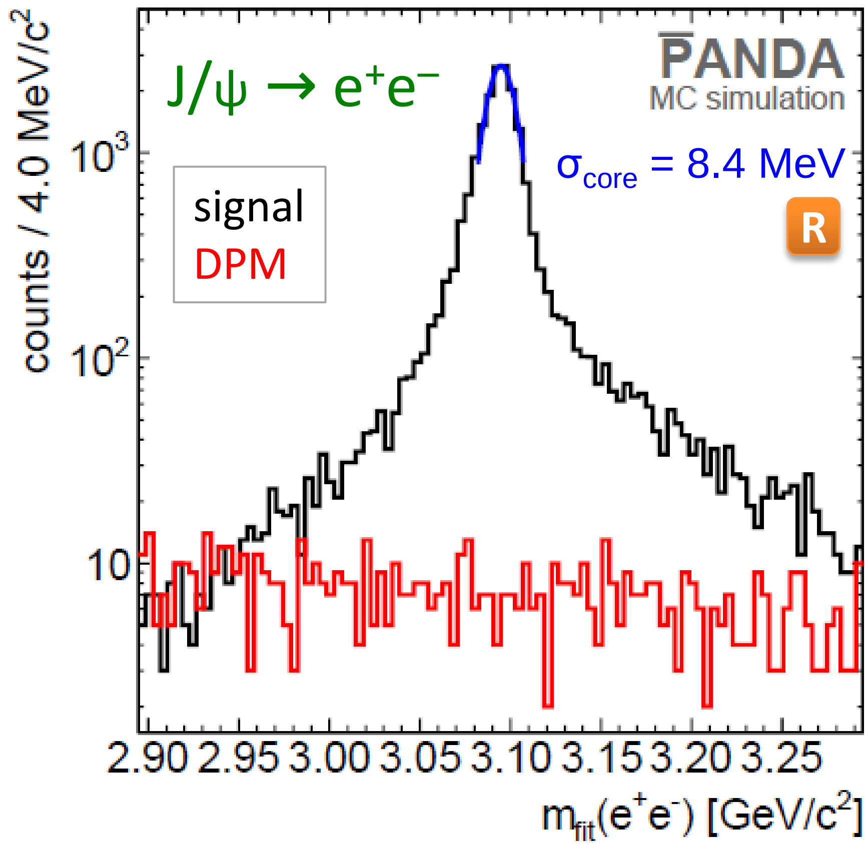
$\bar{p}p \to J/\psi\ \rho^0 \to e^+ e^- \pi^+ \pi^-$

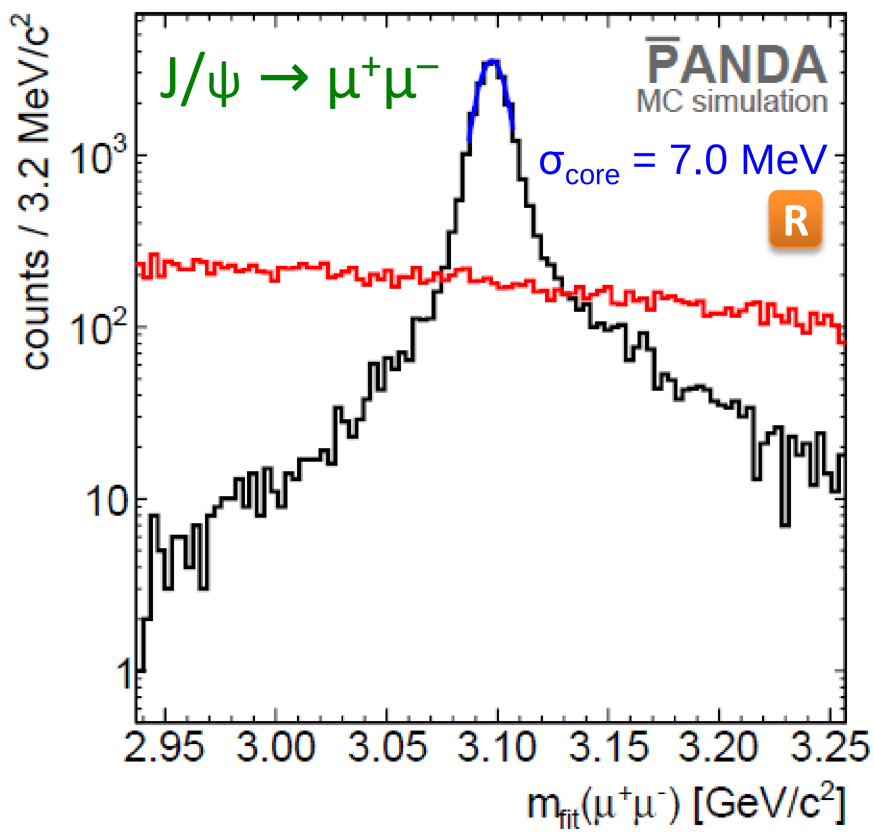


$\bar{p}p \to J/\psi\ \rho^0 \to \mu^+ \mu^- \pi^+ \pi^-$



Pre-selection Results





R

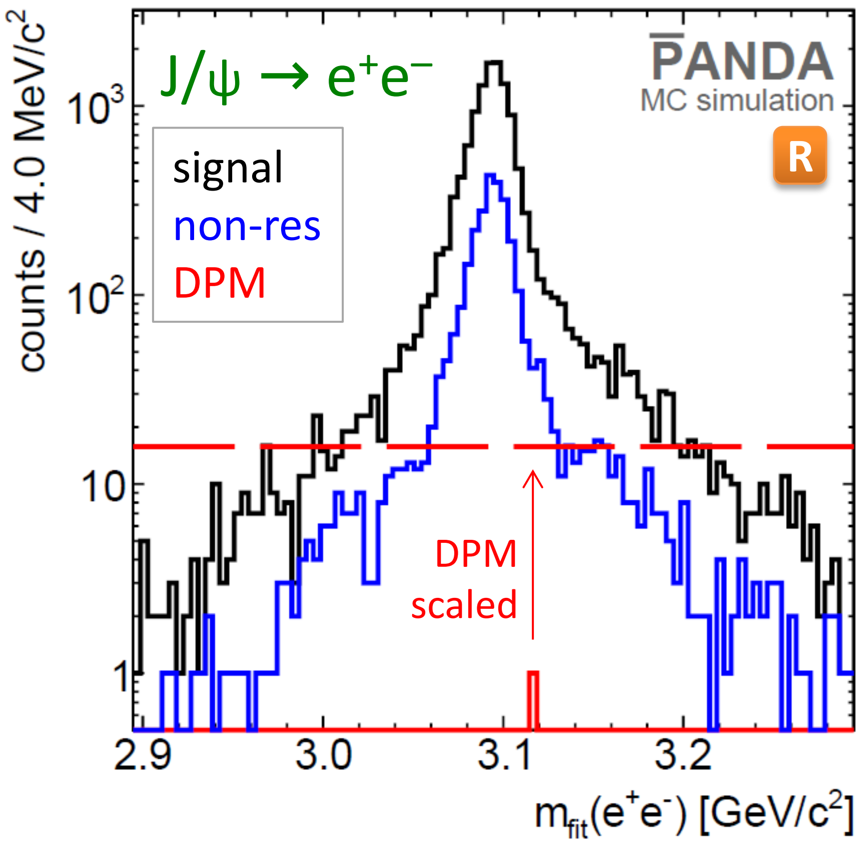
	$J/\psi \to e^+e^-$			$J/\psi \to \mu^+\mu^-$			
Efficiency	ε_S [%]	ε_{DPM} [10^{-10}]	ε_{NR} [%]	ε_S [%]	ε_{DPM} [10^{-10}]	ε_{NR} [%]	$S:N_{comb}$
Pre-select.	19.1	1150	17.3	24.2	29300	21.8	1 : 1087
Final select.	12.2	1.0	2.8	15.2	4.5	3.0	2.7 : 1
Final(±3σ)	10.1	0.13	2.3	13.1	0.56	2.6	10.4 : 1

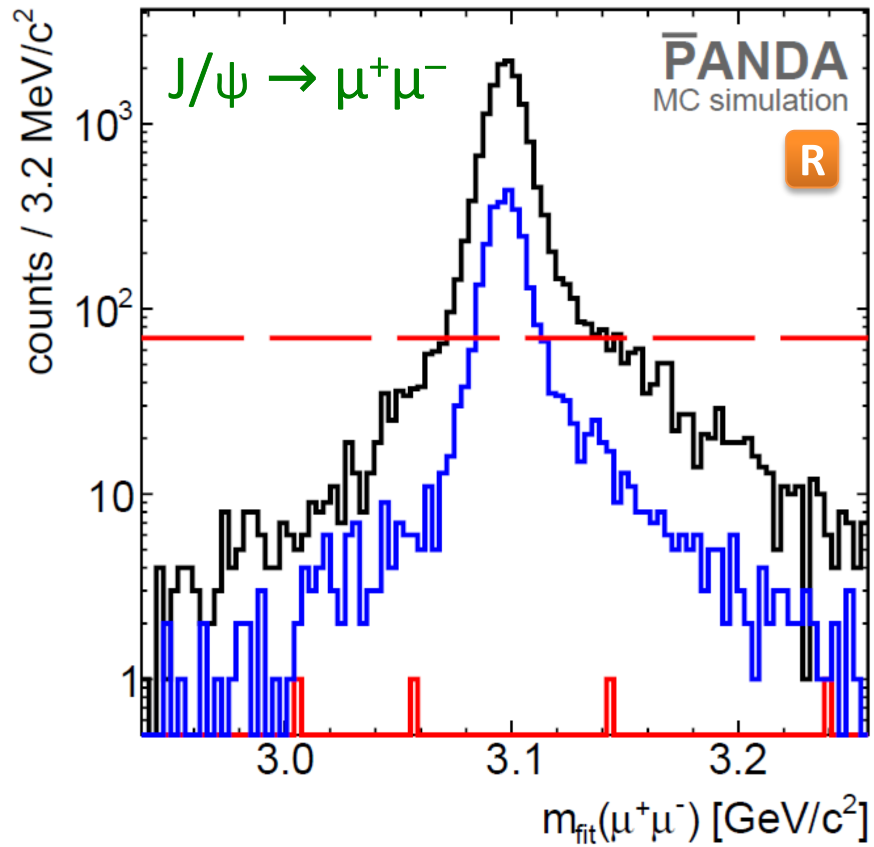
Final Selection Criteria

- Final selection e^+e^-
  - Electron PID($e^\pm$) > 0.95
  - $m_{fit}(e^+e^-) + m_{fit}(\pi^+\pi^-) > 3.77$ GeV/c^2
  - 3.867 GeV/c^2 < $m_{fit}(e^+e^- \pi^+\pi^-)$ < 3.874 GeV/c^2
  - $p_{cm}(e^+e^-) < 0.4$ GeV/c
  - $\measuredangle(p_{e+},p_{e-}) < 2.1$ rad

- Final selection $\mu^+\mu^-$
  - Muon PID($\mu^\pm$) > 0.99
  - $m_{fit}(\mu^+\mu^-) + m_{fit}(\pi^+\pi^-) > 3.78$ GeV/c^2
  - $\measuredangle(p_{\mu+},p_{\mu-}) < 1.4$ rad
  - Sphericity $S<0.11$

Final Selection Results





	$J/\psi \to e^+e^-$			$J/\psi \to \mu^+\mu^-$			
Efficiency	ε_S [%]	ε_{DPM} [10^{-10}]	ε_{NR} [%]	ε_S [%]	ε_{DPM} [10^{-10}]	ε_{NR} [%]	$S:N_{comb}$
Pre-select.	19.1	1150	17.3	24.2	29300	21.8	1 : 1087
Final select.	12.2	1.0	2.8	15.2	4.5	3.0	2.7 : 1
Final(±3σ)	10.1	0.13	2.3	13.1	0.56	2.6	10.4 : 1

Energy Scan Part

Parameters

- All relevant parameters used for scan

Symbol	Value	Description
$B(X \to J/\psi\rho^0) = B_X$ [%]	5	branching fraction of $X(3872)$ decay
$B(J/\psi \to e^+e^-) = B_{ee}$ [%]	5.971	branching fraction of the J/ψ decay
$B(J/\psi \to \mu^+\mu^-) = B_{\mu\mu}$ [%]	5.961	branching fraction of the J/ψ decay
$B(\rho^0 \to \pi^+\pi^-)$ [%]	100	branching fraction of the ρ^0 decay
$\sigma_{S,\mathrm{max}}$ [nb]	100	peak production cross section of $X(3872)$
$\sigma_{B,\mathrm{gen}}$ [mb]	46	cross section of generic background
$\sigma_{B,\mathrm{NR}}$ [nb]	1.2	cross section of non-resonant $J/\psi\pi^+\pi^-$ prod.
$\bar{L}_{\mathrm{HL}}$ [1/(nb·d)]	13683	HL average luminosity
$\bar{L}_{\mathrm{HESRr}}$ [1/(nb·d)]	1170	HESRr average luminosity
ΔE_{HL} [keV]	167.8	center-of-mass energy spread in HL mode
ΔE_{HR} [keV]	83.9	center-of-mass energy spread in HESRr mode
t_{scan} [d]	80	total scan time
N_{scan}	40	number of scan points
Γ_X [keV]	[50, 70, 100, 130, 180, 250, 500]	parameter range Breit-Wigner study
E_f [MeV]	$-$[10.0, 9.0, 8.8, 8.3, 8.0, 7.5, 7.0]	parameter range molecule line shape study

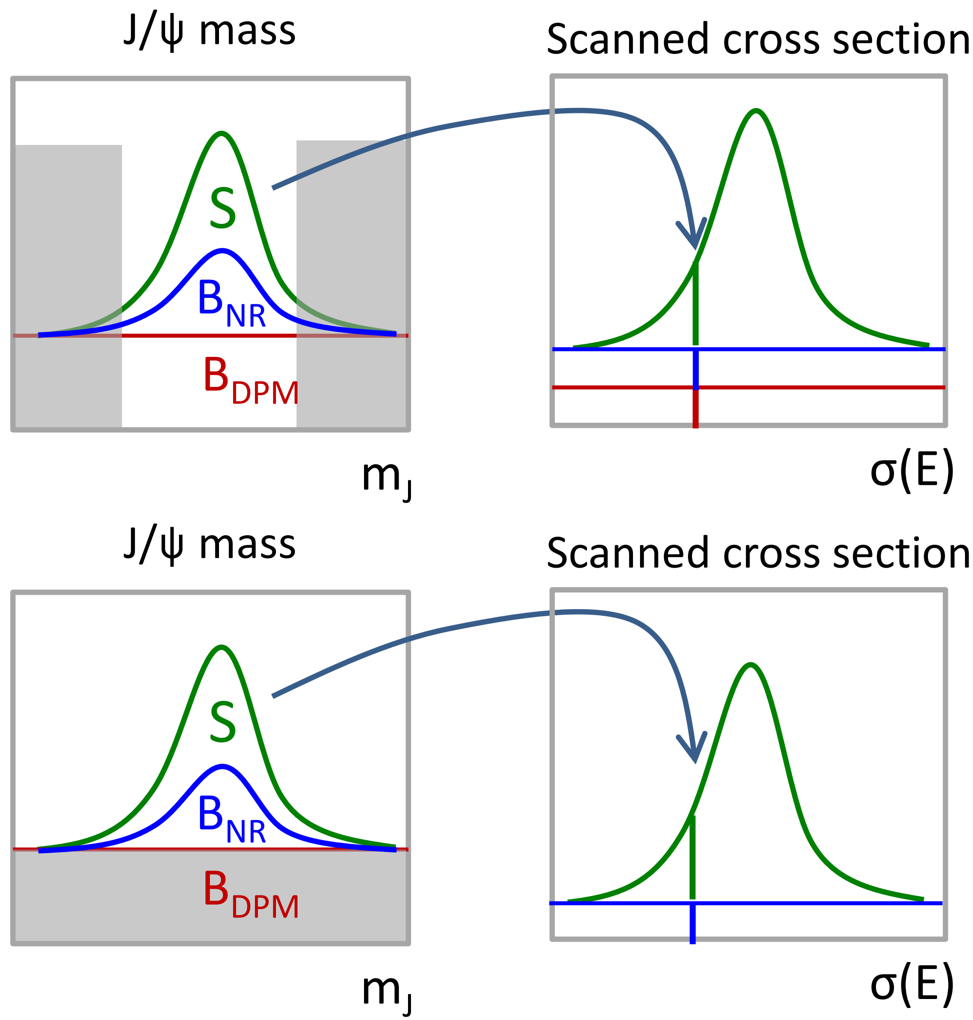
Possible Approaches

Two obvious approaches possible to extract lineshape:

1. Cut on J/ψ and count
   - simple + robust
   - both backgrounds still in scanned lineshape

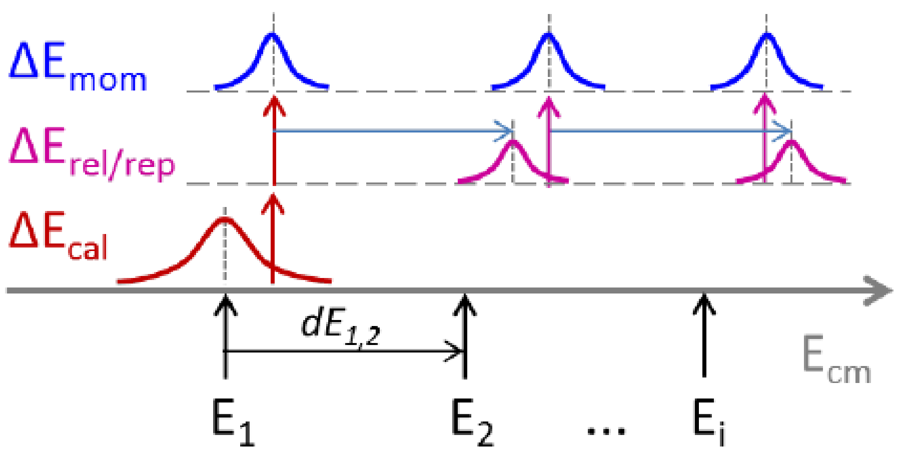
2. Fit signal in J/ψ mass
   - removes DPM bkg
   - NR bkg still present

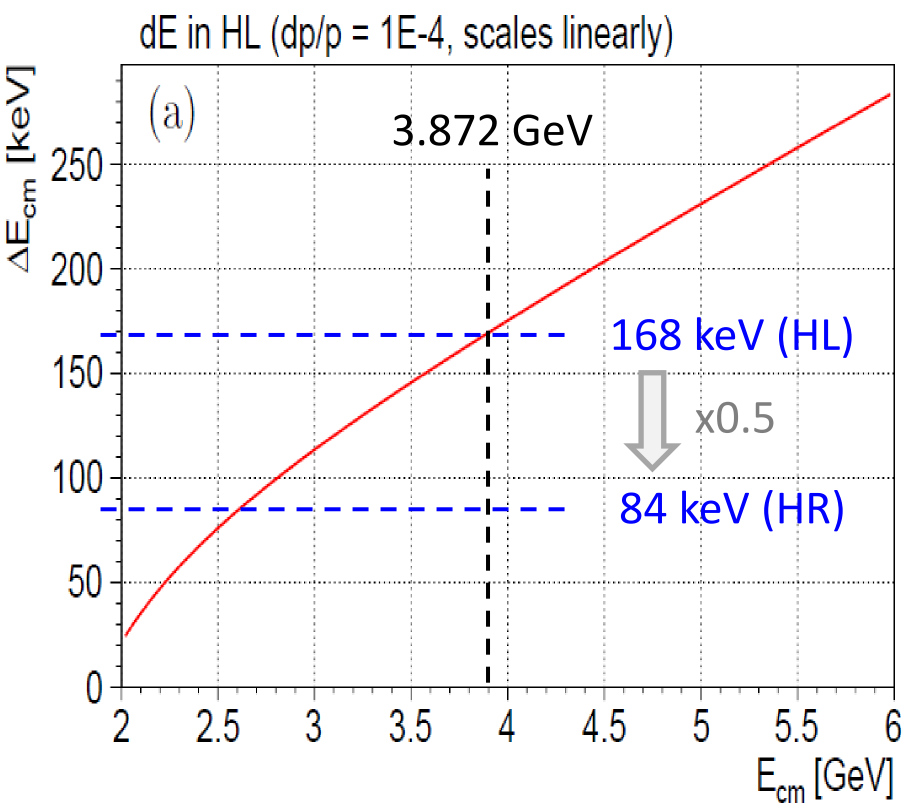
Use 2. method here!



Uncertainty Assumptions for Scan

- Beam related energy resolution: ΔE_{mom} = 84 (HESRr) / 168(HL) keV
- Absolute positioning (calibration): ΔE_{cal} = 167 keV (shift)
- Relative positioning resolution: ΔE_{rel} = 1.7 keV (negligible!)

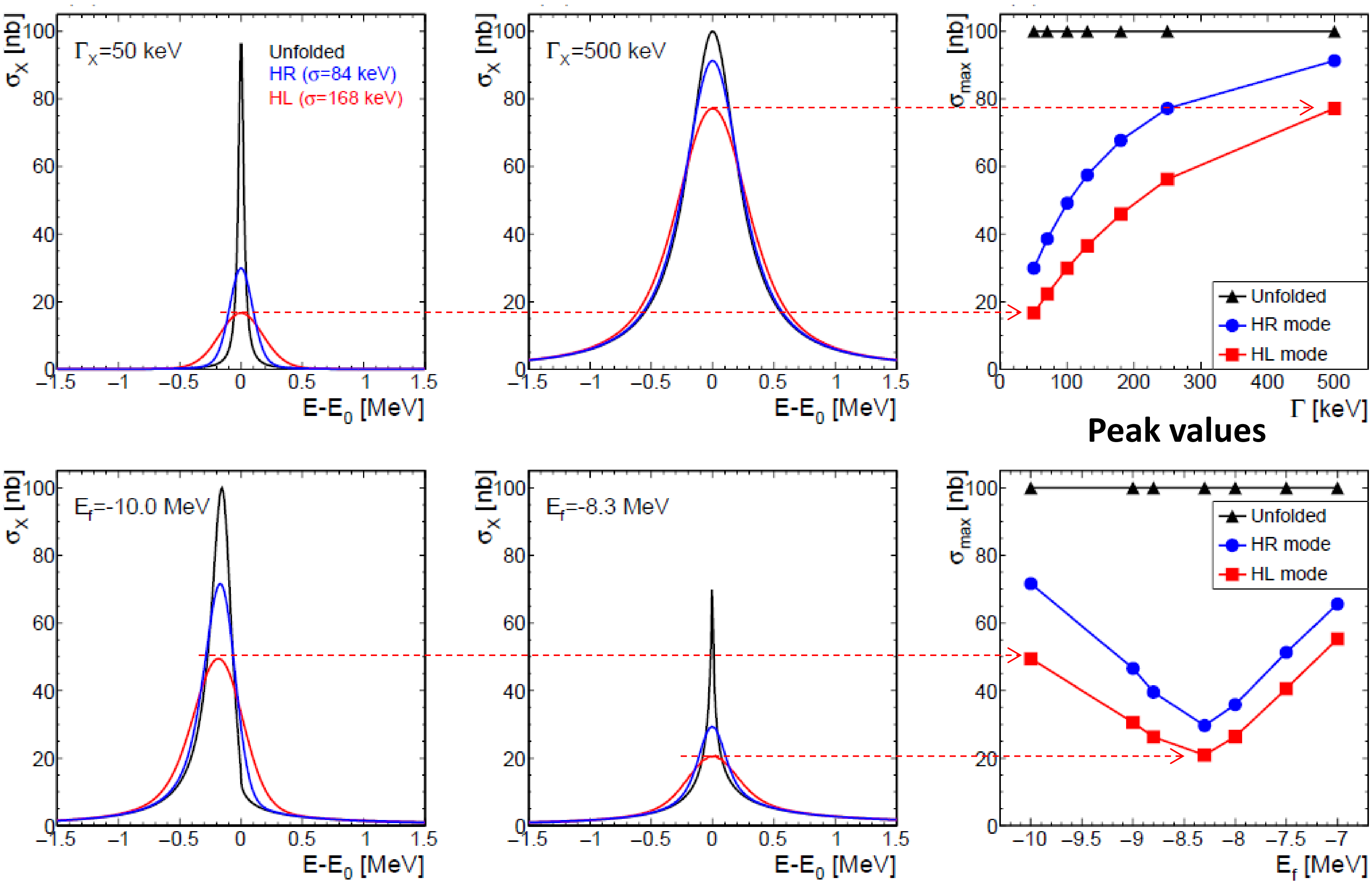




Procedure for Individual Scan

- **Scan procedure**
  - Set parameter P (Γ or E_f) in signal function
  - Define scan region, number of points, L_{int} / point
  - Scale unfolded function $\sigma_S(E)$ to $\sigma_{S,max}$ = 100nb and adapt convoluted function $\sigma^*_S(E) \rightarrow \sigma^*_{S,max} \leq$ 100nb
  - For each energy scan point (E_{cm})
    1. Modify energy $E_{cm} \rightarrow E_{cm}'$ according to ΔE_{cal}
    2. Compute expected S_0 / $B_{DPM,0}$ / $B_{NR,0}$ based on $\sigma^*_S(E_{cm}')$ / σ_{DPM} / σ_{NR}
    3. Generate Poisson random num. S / B_{DPM} / B_{NR} from expected ones
    4. Generate J/ψ data with S+B_{NR} signal and B_{DPM} background events
    5. Do unbinned ML fit to extract $N_{J/\psi}{}^{+\Delta N_{hi}}_{-\Delta N_{lo}}$ $\rightarrow$ Scan graph at E_{cm}
  - Fit graph with signal + background function $\rightarrow$ parameter P
- Repeat N times to determine root-mean-square & bias of P

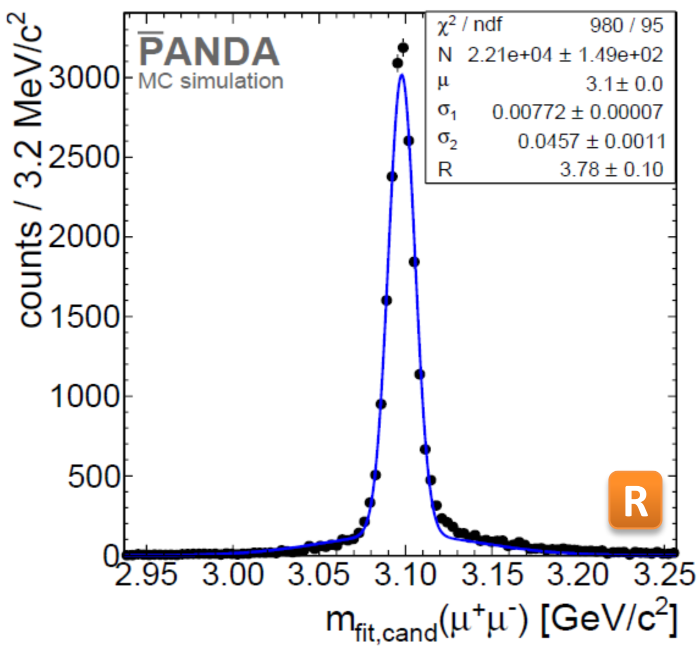
Lineshape Examples



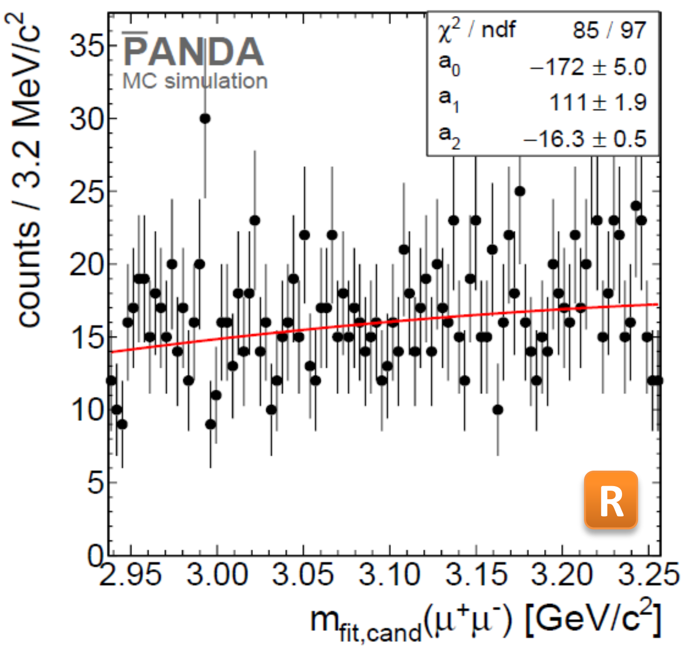
Signal/Background PDF for ML fits

- Softened selection for $\mu^+\mu^-$
  - Muon PID($\mu^\pm$) > 0.8
  - $m_{fit}(\mu^+\mu^-) + m_{fit}(\pi^+\pi^-) > 3.65$ GeV/c^2
- Signal: Double-Gauss
- Background: Parabola

Signal PDF

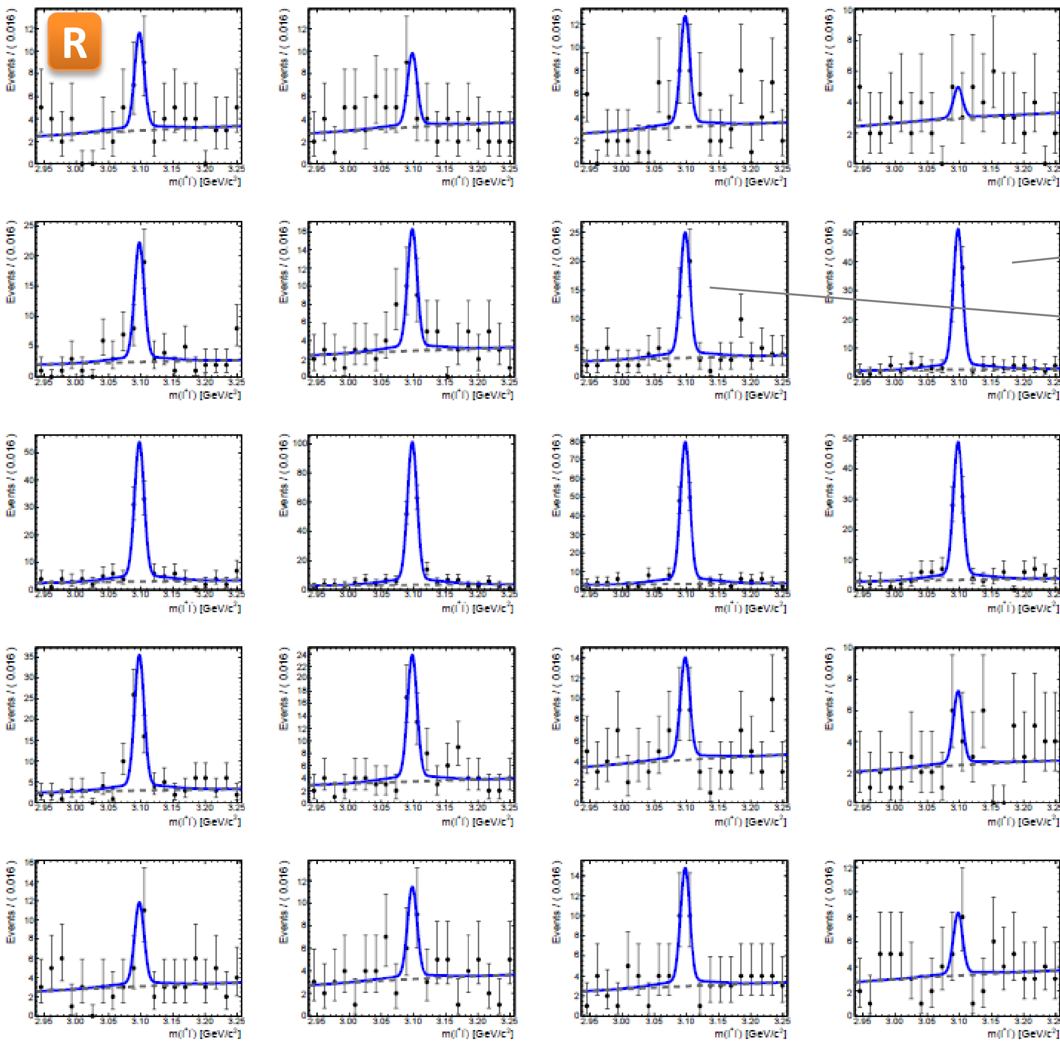


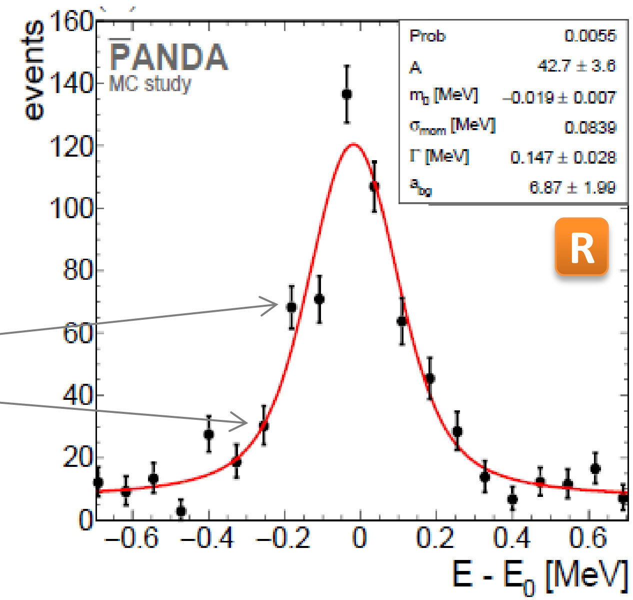
Background PDF

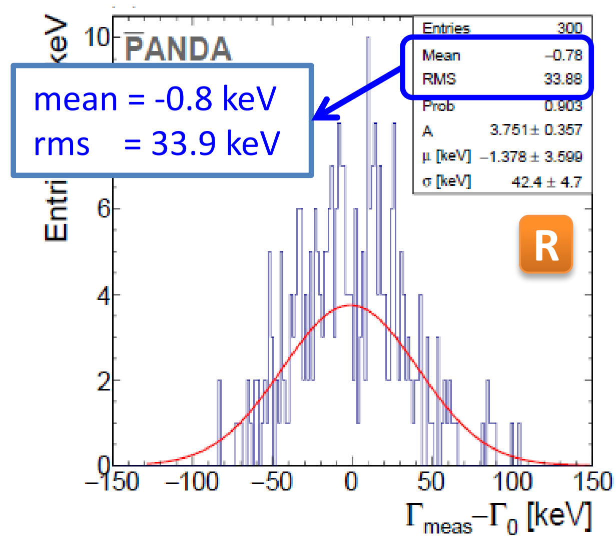


Scan Procedure Example

- BW Example: Γ = 130 keV, 20 points



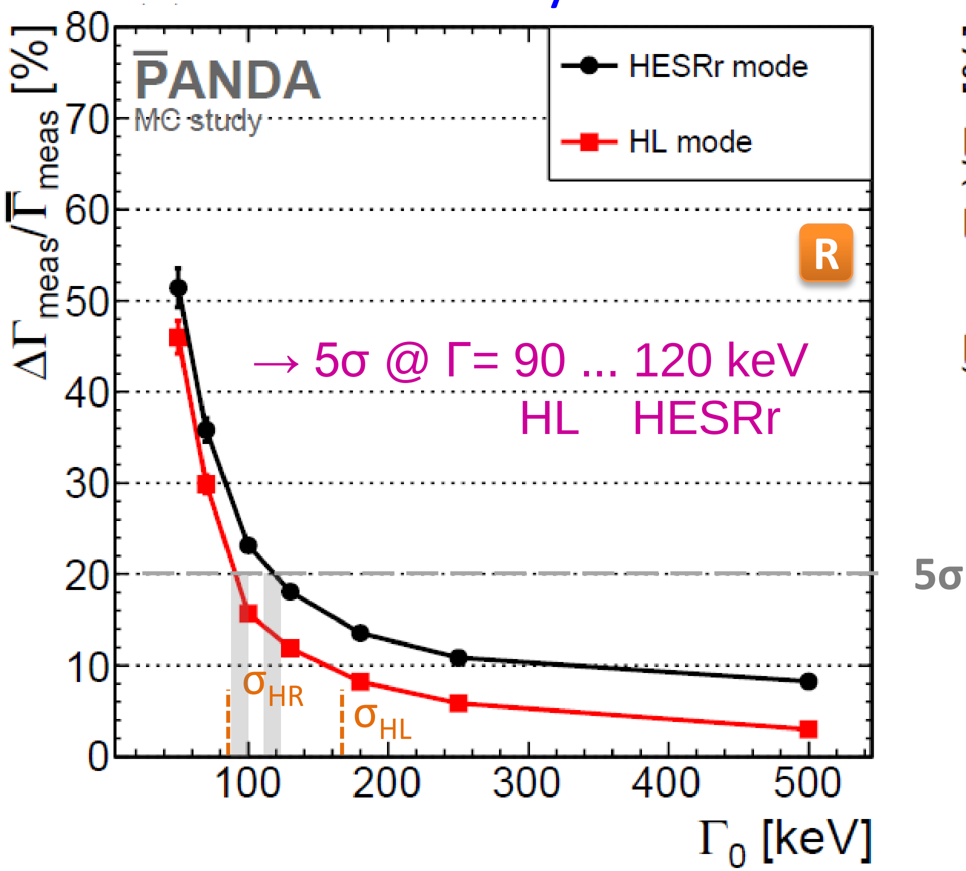




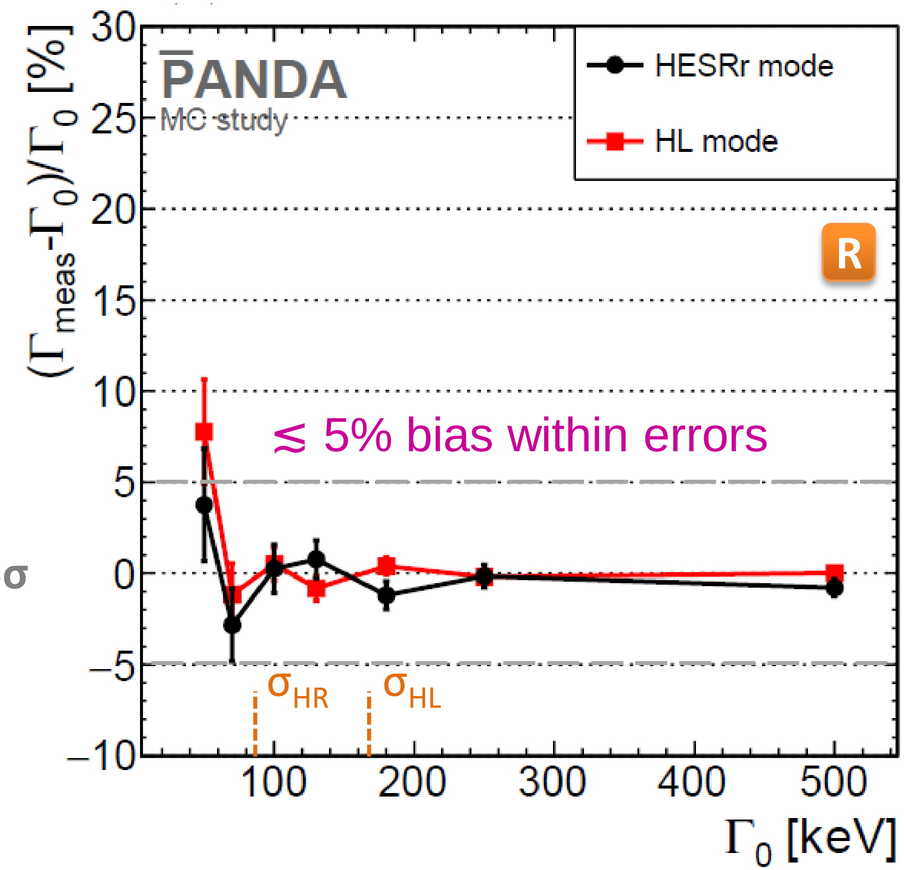
Sensitivities Breit-Wigner Γ (40 x 2d)

- Extract standard deviation and bias from toy MC fits
- Show relative error $rms_{fit}/\bar{\Gamma}_{fit}$ and bias $(\bar{\Gamma}_{fit} - \Gamma_0)/\Gamma_0$ in [%]

Sensitivity

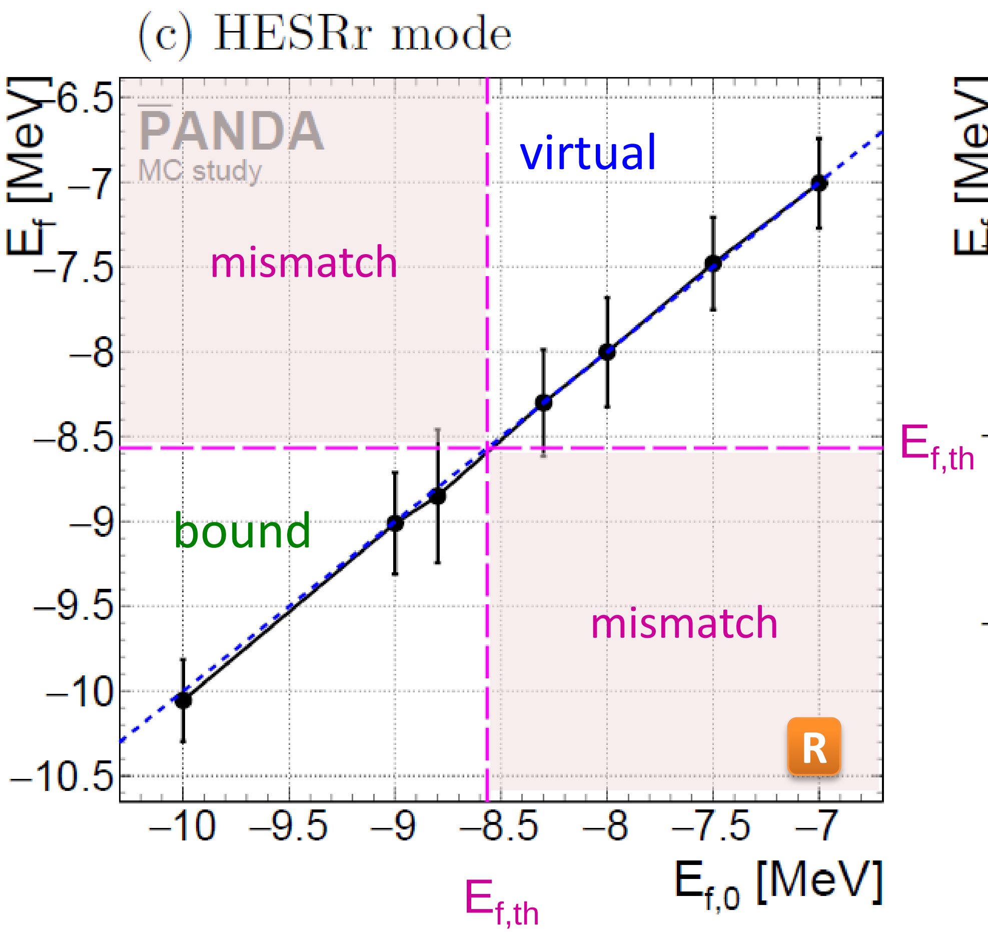


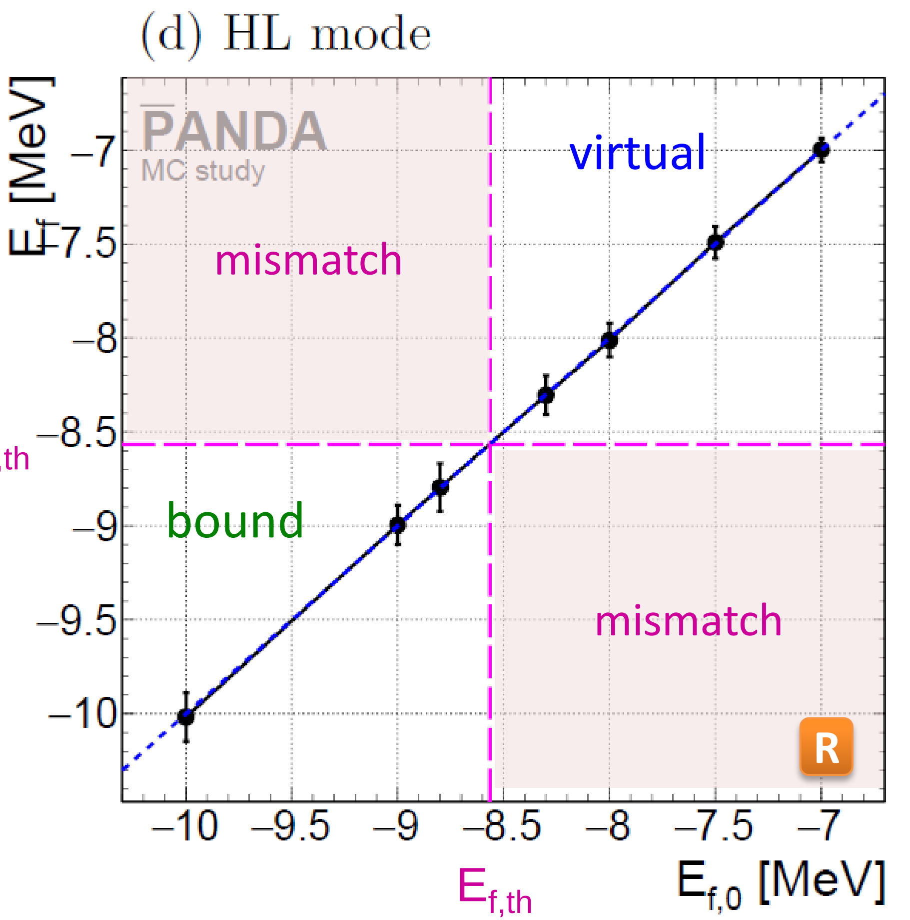
Relative Bias



Sensitivities Lineshapes (40 x 2d)

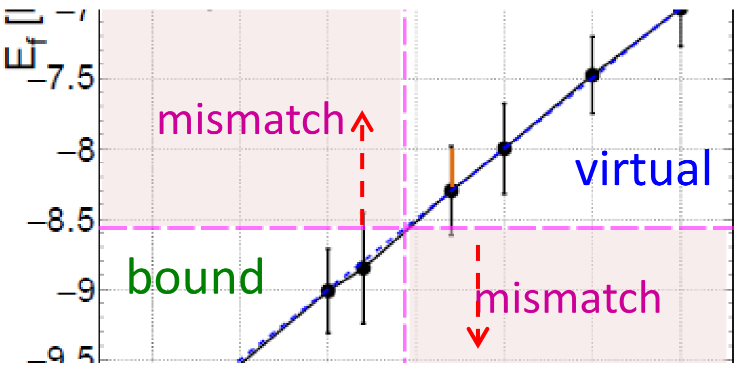
- Extract standard deviation and bias from toy MC fits
- How well can virtual and bound state be distinguished?

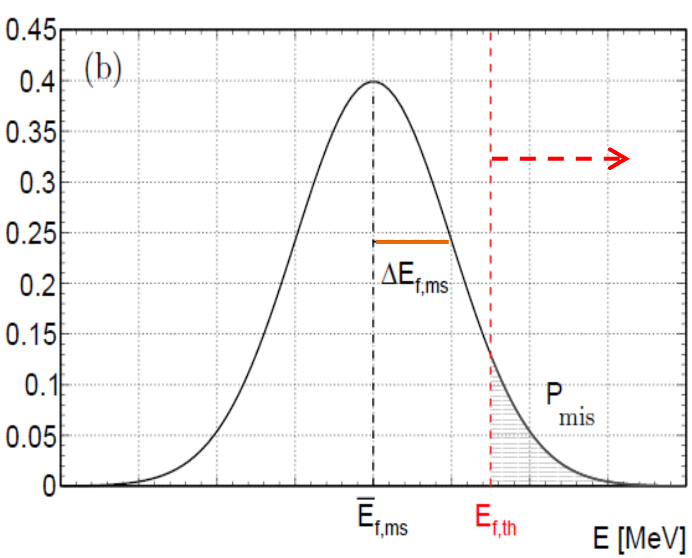




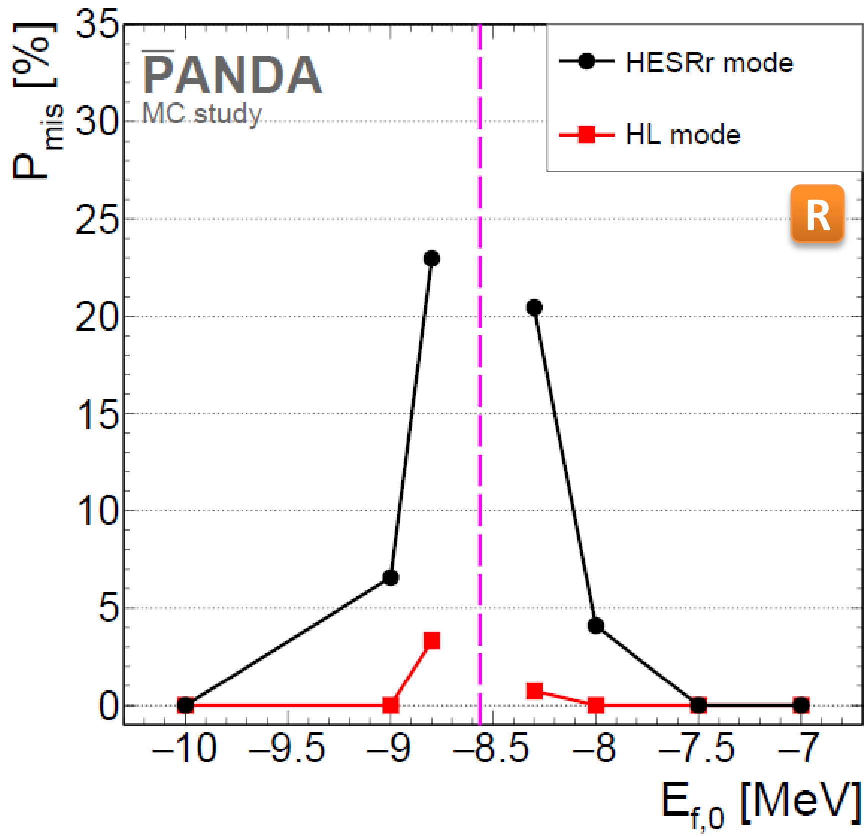
Mis-Identification Probability

- Take uncertainty as $\sigma_{Gaussian}$ → Integrate in mismatch region





Mis-Identification Probability

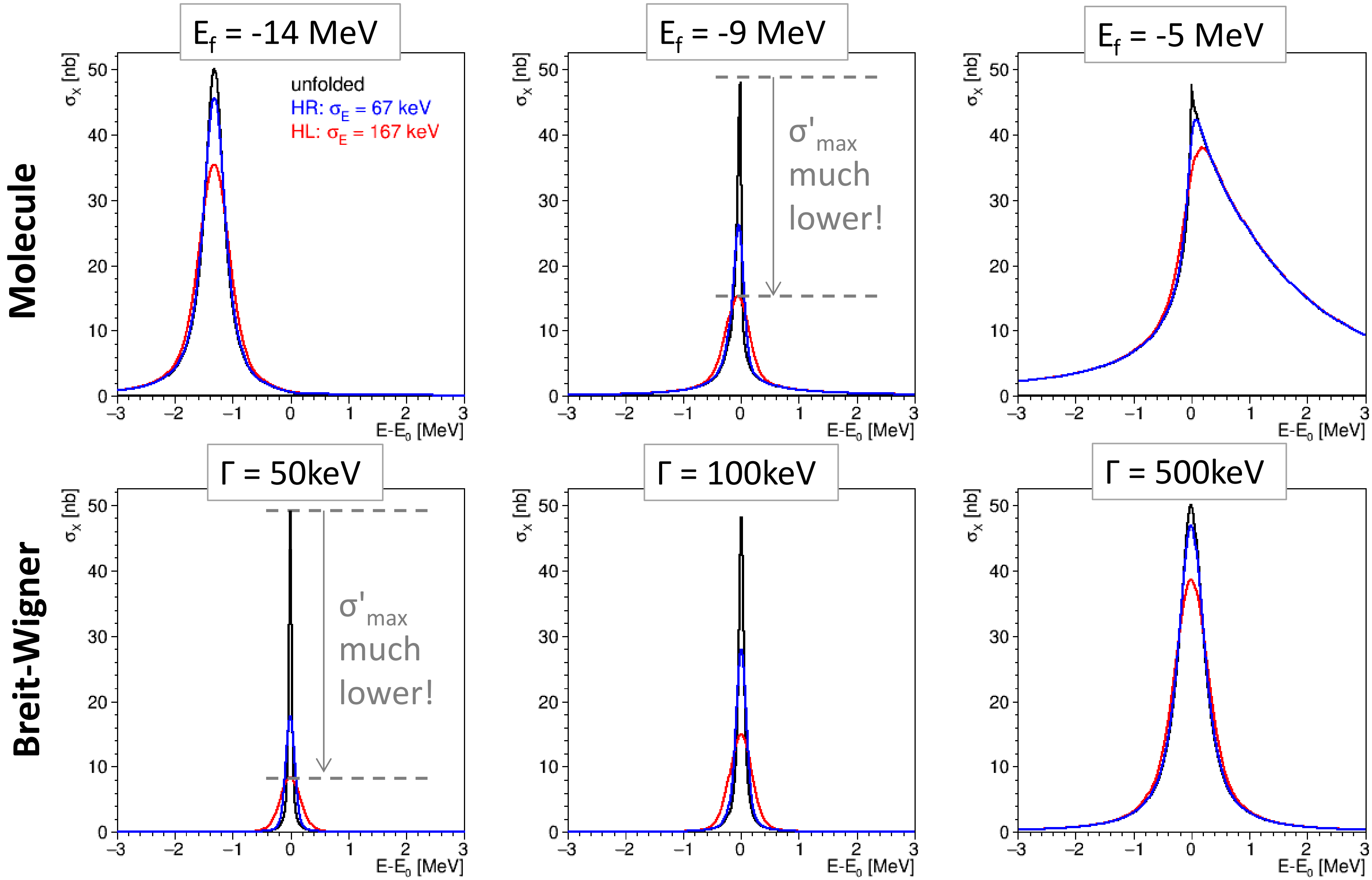


Summary

- Investigation of X(3872)-Scan at PANDA
- Main scenario: 40 x 2d data taking
- Determined sensitivity for BW width measurement
  – Sensitivity $\Gamma/\Delta\Gamma > 5$ at $\Gamma \gtrsim 90 ... 120$ keV
  – Bias $(\Gamma - \Gamma_0)/\Gamma_0$ no problem over full range
  – HL mode superior over investigated range
- Determined sensitivity for molecular lineshape measurement
  – Possible to distinguish bound/virtual state
  – $P_{HL} > 95\%$ (all investigated settings)
  – $P_{HESRr} > 95\%$ for $|E_f - E_{f,th}| \gtrsim 750$ keV
  – HL mode superior over investigated range
- Release note ready for review

BACKUP

Lineshape Examples



Background Prefilter

- Reasonable S/N sensitivity: need huge amount of BG
- Example calculation:
  - Signal: σ_S = 100 nb, $BR_{J/\psi}$ = 0.06, BR_X = 0.05, ε_S = 10%
  - Background: σ_B = 46 mb (inelastic @ E_{cm} = 3.872 GeV)

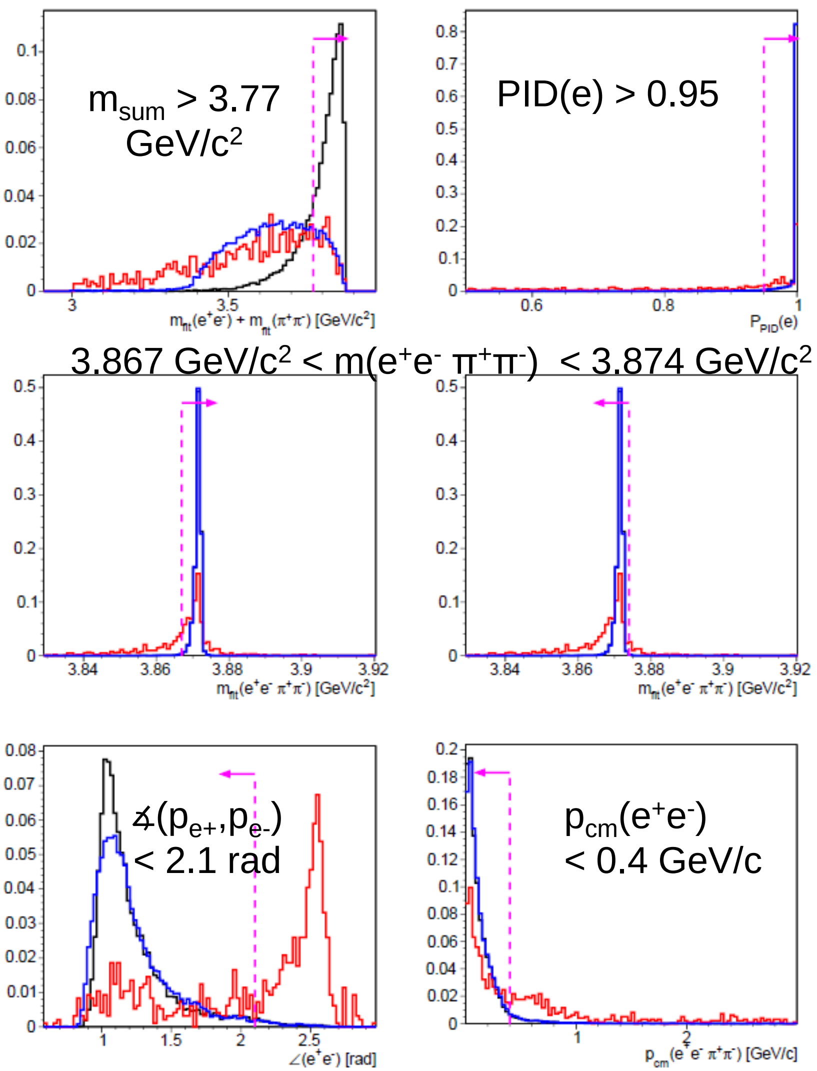
$$\frac{S}{N} = \frac{\sigma_S \cdot \varepsilon_S}{\sigma_B \cdot \varepsilon_B} \cdot BR_{J/\psi} \cdot BR_X \overset{!}{\geq} 1$$

$$\Rightarrow \varepsilon_B < \frac{\sigma_S \cdot \varepsilon_S}{\sigma_B} \cdot BR_{J/\psi} \cdot BR_X = 6.5 \cdot 10^{-10}$$

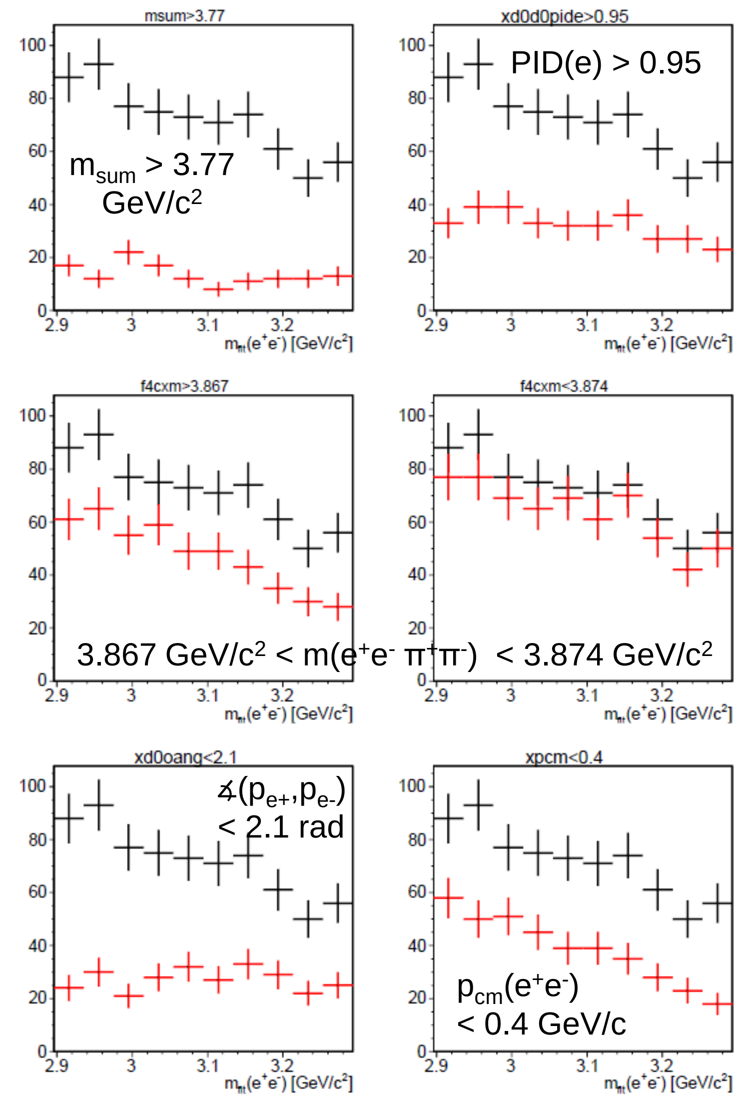
$$\Rightarrow N_B > 1/\epsilon_B = 1.5 \cdot 10^9$$

  - Neither feasible nor efficient to simulate completely
  - Use FairFilteredPrimaryGenerator to filter already at generator level

QA Plots for J/ψ → e^+e^- Channel

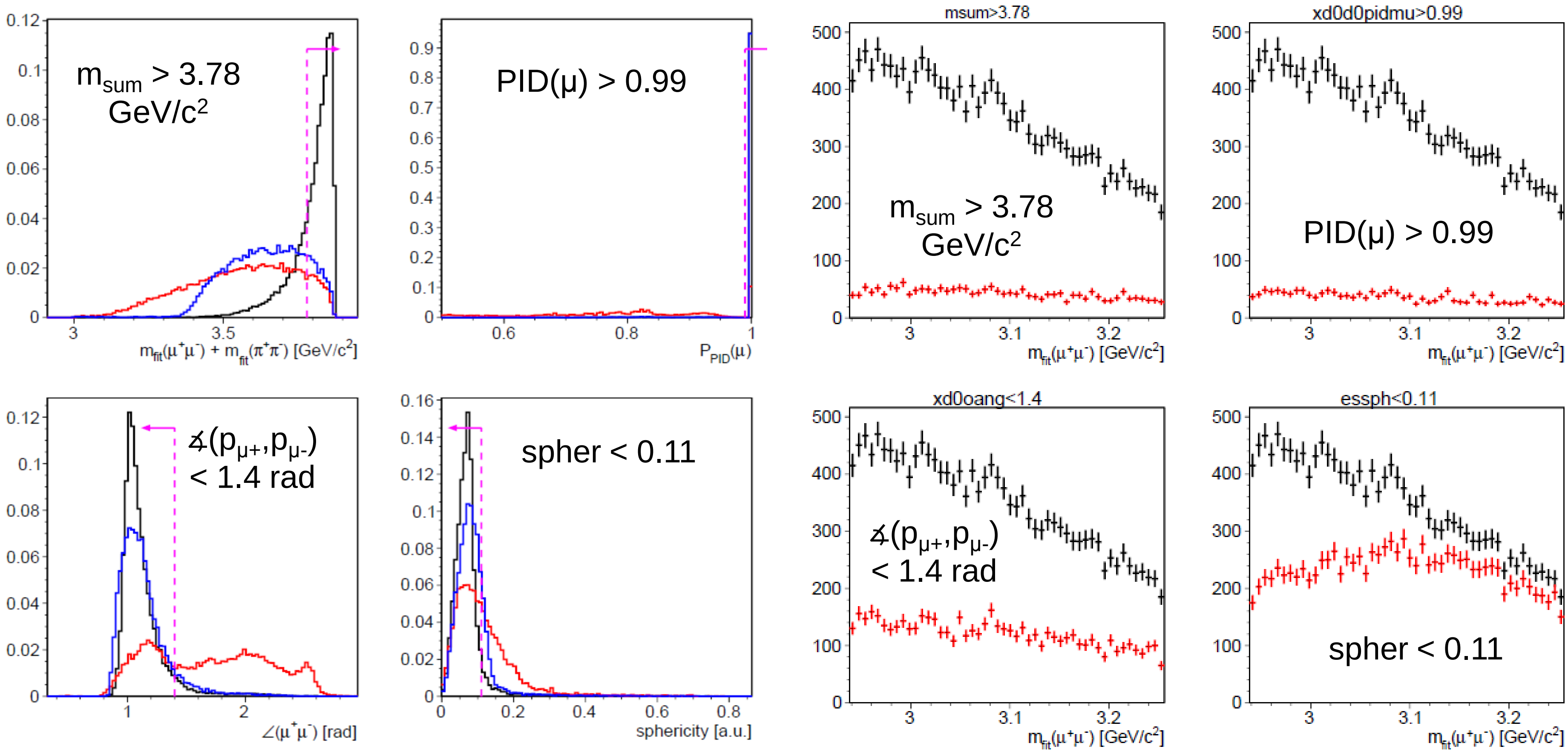


signal - hadronic bkg - J/ψ NR bkg.



preselection - after cut

QA Plots for J/ψ → $\mu^+\mu^-$ Channel



signal - hadronic bkg - J/ψ NR bkg.

preselection - after cut

Comparison to Previous Analysis

- Settings similar to 2009 study:
  - ΔE_{mom} (HESRr) = 33.6 keV (dp/p = $2 \cdot 10^{-5}$)
  - N_{scan} = 20 (2d per position)
  - ⇒ Compatible sensitivity, bias different

Fit with Constant Plus Convolution of Breit-Wigner and Gaussian	
χ^2/ndf	30.91/15
$m_{X(3872)}$	3.872 GeV ± 5.263 keV
$\Gamma_{X(3872)}$	86.9 ± 16.8 keV
Background Level	24.51 ± 1.80
$\Delta(\sqrt{s})$	fixed @ 33.568 keV