

X(3872)-Scan Reloaded

Charmonium Exotics Meeting

18. 11. 15

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 $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ 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

Molecular Picture (Hanhart et al)

- Lineshapes from [Hanhart et al, PRD 76 (2007) 034007]
- Here only interested in $X(3872) \rightarrow J/\psi \pi^+ \pi^-$

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

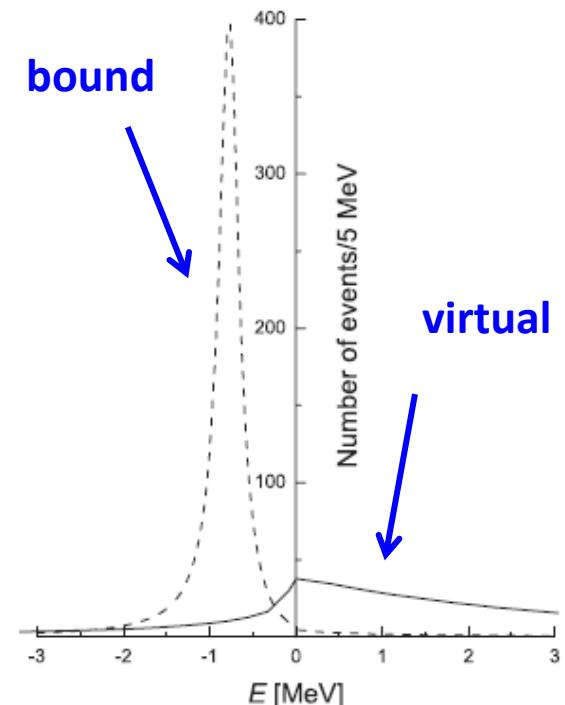
(assuming lineshape as in B decays)

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

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

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

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



Parameter E_f determines state to be bound or virtual

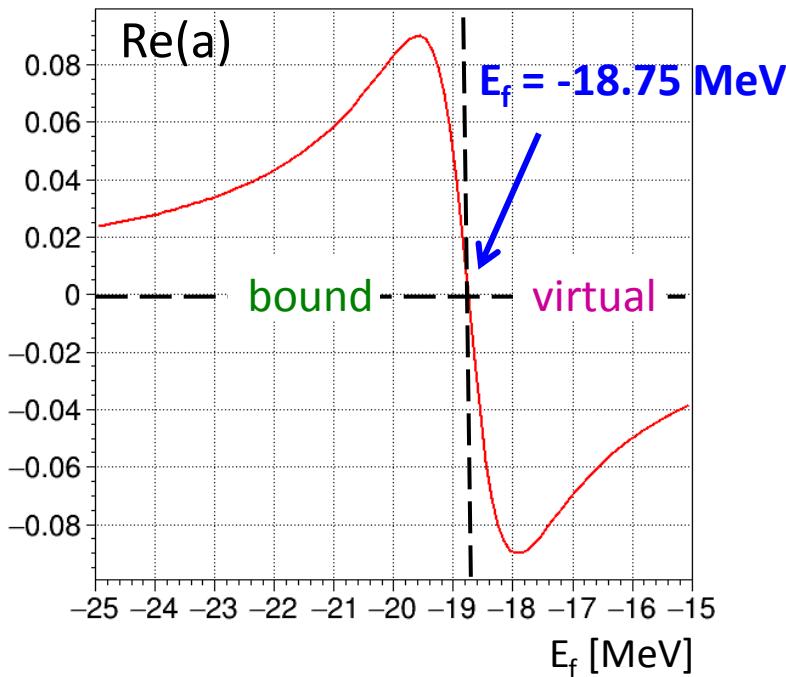
Lineshapes for different E_f

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

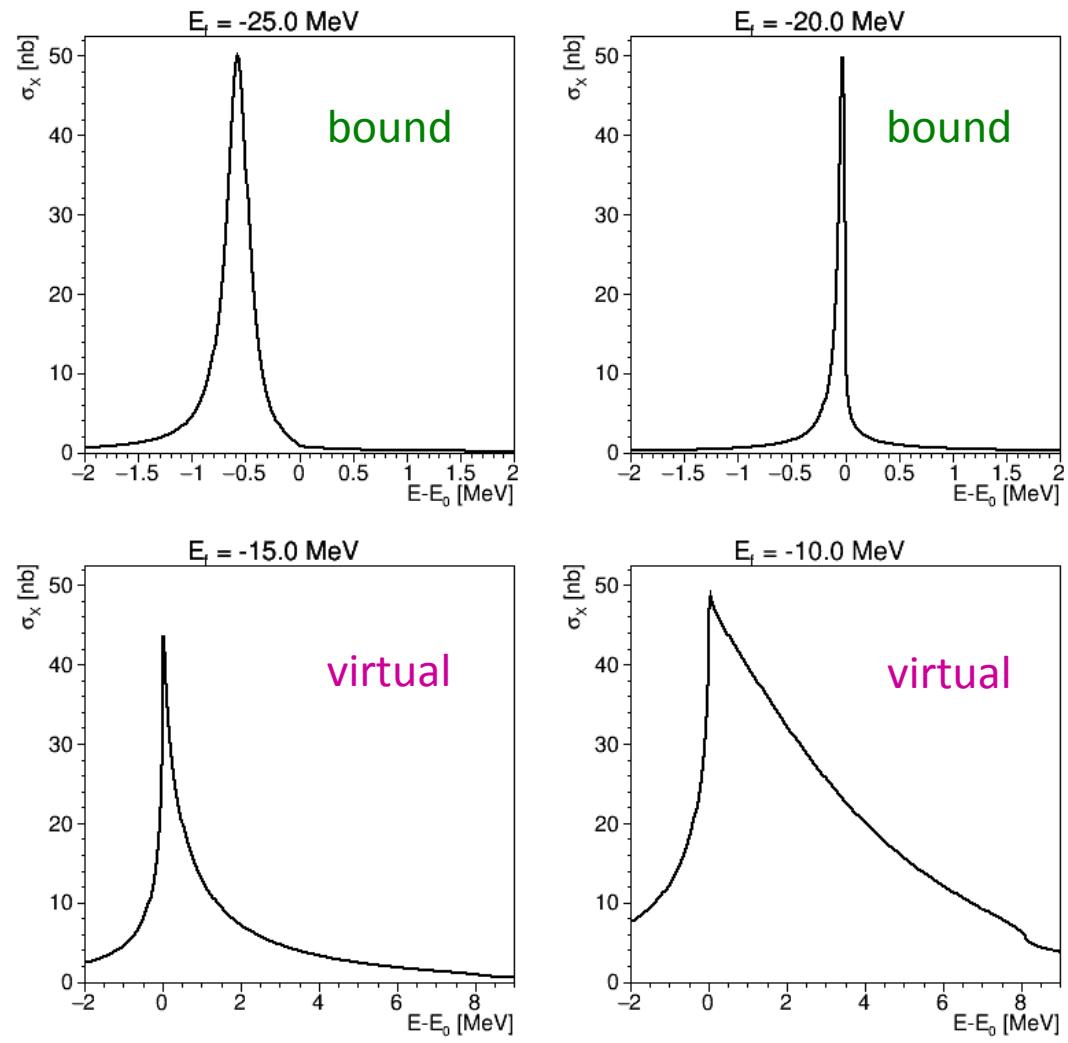
$$a = -\frac{\sqrt{2\mu_2\delta} + 2E_f/g + i\Gamma(0)/g}{(\sqrt{2\mu_2\delta} + 2E_f/g)^2 + \Gamma(0)^2/g^2}$$

$\text{Re}(a) > 0$: bound state

$\text{Re}(a) < 0$: virtual state



Always scaled to $f_{\max} = 50 \text{ nb}$ here!



Reconstruction Part

Parameters

Branching
Fractions

Cross sections

Luminosities

Resolutions

Parameter	Value
$\text{BR}(\text{J}/\psi \rightarrow e^+ e^-)$	5.97 %
$\text{BR}(\text{J}/\psi \rightarrow \mu^+ \mu^-)$	5.96 %
$\text{BR}(X \rightarrow \text{J}/\psi \rho^0)$	5 %
$\sigma(\bar{p}p \rightarrow X)$	50 nb
$\sigma(\bar{p}p \rightarrow \text{J}/\psi \pi^+\pi^- \text{ non-res})$	$\approx 1.2 \text{ nb}$ (<i>neglected</i>)
$\sigma(\bar{p}p \rightarrow \text{inelastic}) @ 3.872 \text{ GeV}$	46 mb
$L_{\text{HL}} @ 3.872 \text{ GeV}$	13683 (nb·d) ⁻¹
$L_{\text{HR}} @ 3.872 \text{ GeV}$	1368 (nb·d) ⁻¹
$L_{\text{HESRr}} @ 3.872 \text{ GeV}$	1170 (nb·d) ⁻¹
dE_{abs} (<i>absolute energy positioning</i>)	100 keV
dE_{rel} (<i>relative energy positioning</i>)	10 keV
$dE_{\text{beam}}(\text{HL})$	168 keV
$dE_{\text{beam}}(\text{HR/HESRr})$	67 keV

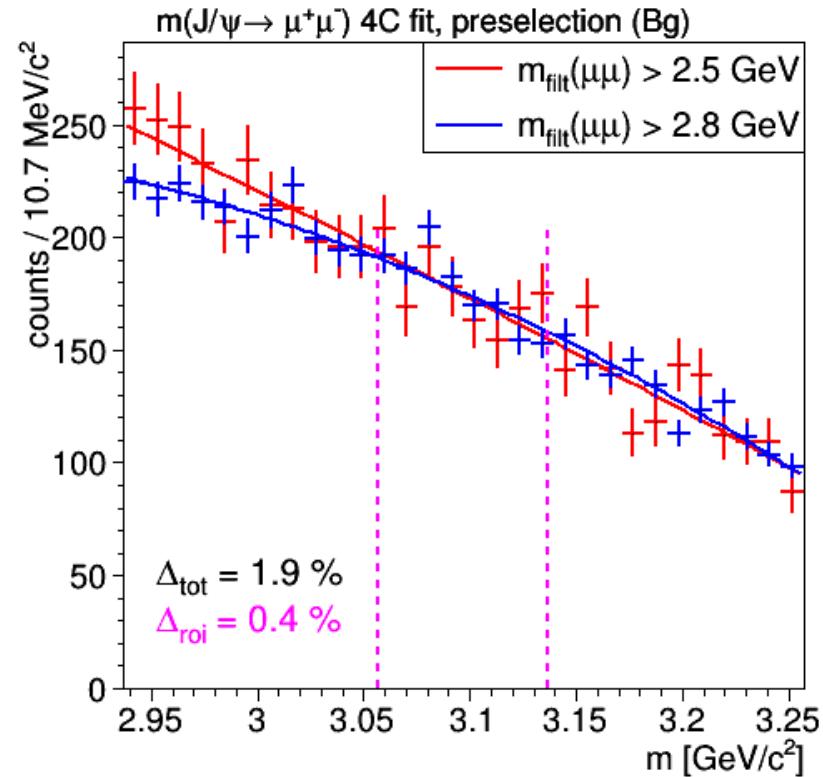
Software and Data

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

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
DPM ($J/\psi \rightarrow e^+ e^-$ prefilter)	$\approx 10M = 9.58G$ generated
DPM ($J/\psi \rightarrow \mu^+ \mu^-$ prefilter)	$\approx 10M = 8.87G$ generated

Background Prefilter QA

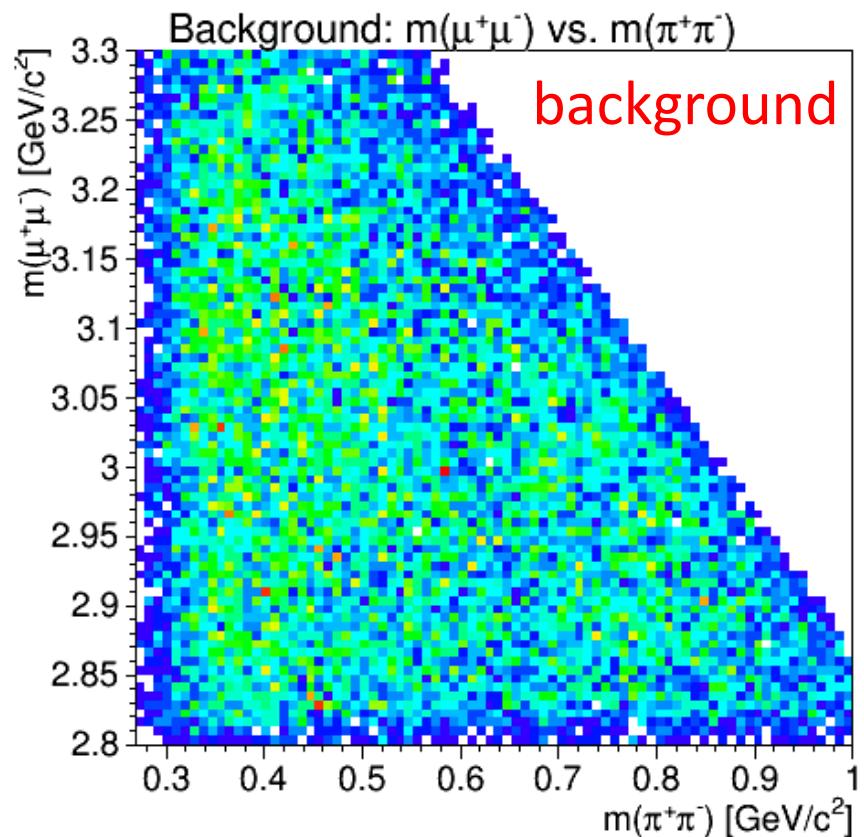
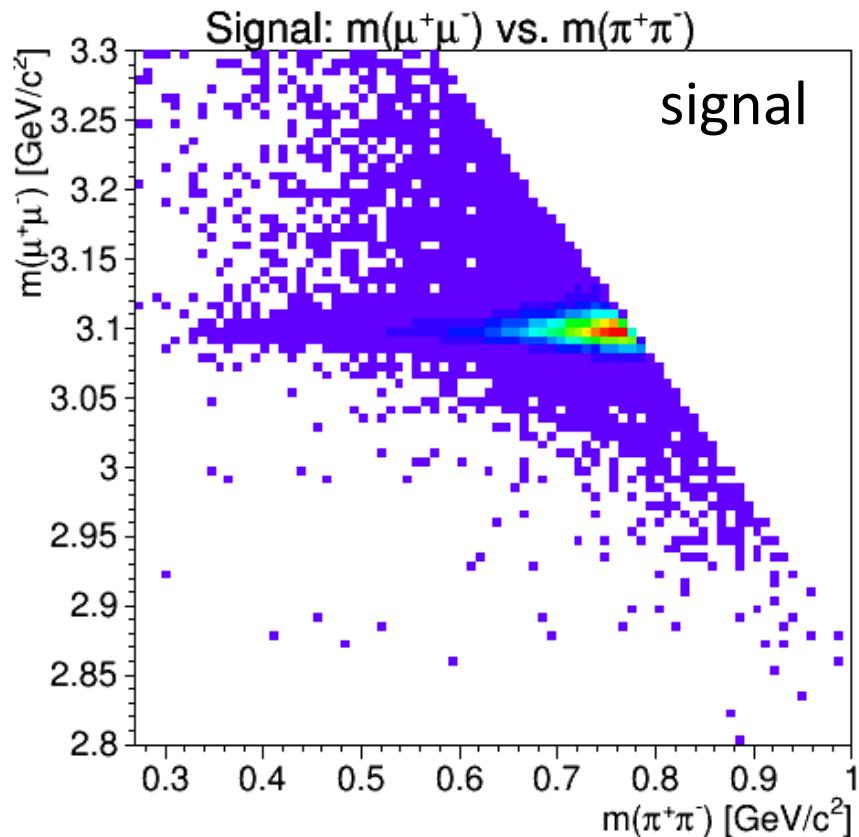
- Filtering criteria
 - Require 4 charged tracks
 - Require one 2-track combination : $m_{ee/\mu\mu} > 2.8 \text{ GeV}/c^2$
 - Suppression factor e^+e^- : $\approx 1/1000$
 - Suppression factor $\mu^+\mu^-$: $\approx 1/900$
 - Check filter bias ($\mu\mu$ only)
 - Cross check with criterium $m_{\mu\mu} > 2.5 \text{ GeV}/c^2$ ($10M \rightarrow 2.6G$)
 - Slight difference at lower edge of distribution
 - Total integral difference: 1.9%
 - Difference in J/ψ ROI: 0.4%
- ⇒ Negligible effect!



Signal Reconstruction

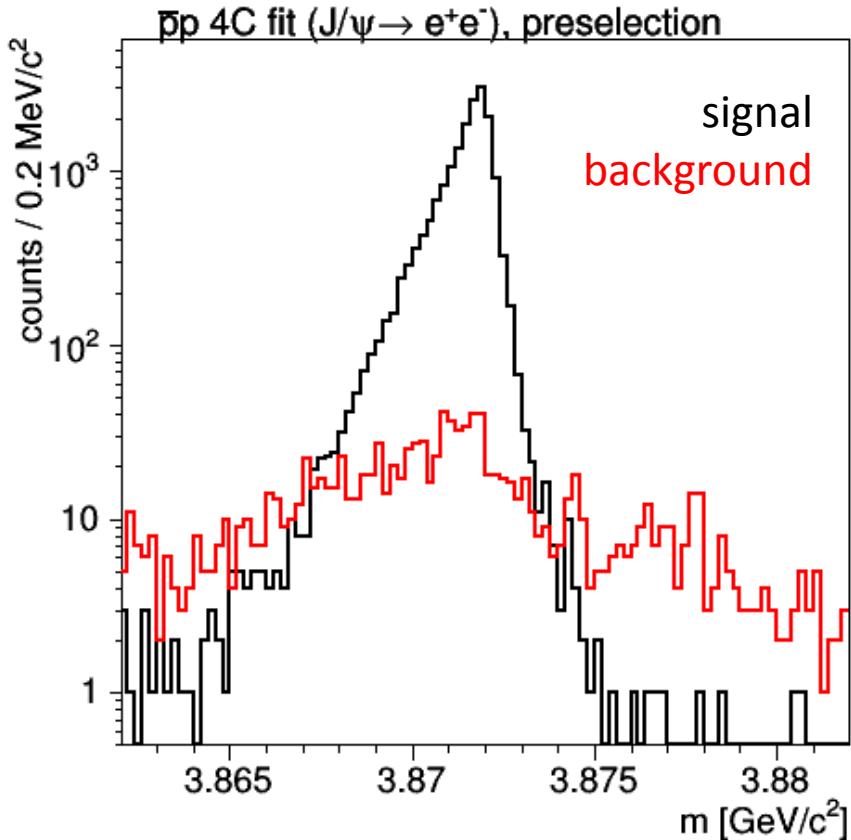
- Preselection e^+e^- :
 - Particle Identification : ElectronTight, PionAll
(PidAlgoEmcBayes;PidAlgoDrc;PidAlgoDisc;PidAlgoStt;PidAlgoMdtHardCuts)
 - $J/\psi \rightarrow e^+e^-$ mass window: $2.0 < m(e^+e^-) < 3.4 \text{ GeV}/c^2$
 - $\rho^0 \rightarrow \pi^+\pi^-$ mass window: $0.27 < m(\pi^+\pi^-) < 1.0 \text{ GeV}/c^2$
 - $\bar{p}p \rightarrow J/\psi \rho^0$ 4C fit : $\chi^2 < 200$
- Preselection $\mu^+\mu^-$:
 - Particle Identification : MuonTight, PionAll
(PidAlgoEmcBayes;PidAlgoDrc;PidAlgoDisc;PidAlgoStt;PidAlgoMdtHardCuts)
 - $J/\psi \rightarrow \mu^+\mu^-$ mass window: $2.5 < m(\mu^+\mu^-) < 3.4 \text{ GeV}/c^2$
 - $\rho^0 \rightarrow \pi^+\pi^-$ mass window: $0.27 < m(\pi^+\pi^-) < 1.0 \text{ GeV}/c^2$
 - $\bar{p}p \rightarrow J/\psi \rho^0$ 4C fit : $\chi^2 < 100$

Correlation $M(J/\psi)$ vs. $M(\rho^0)$

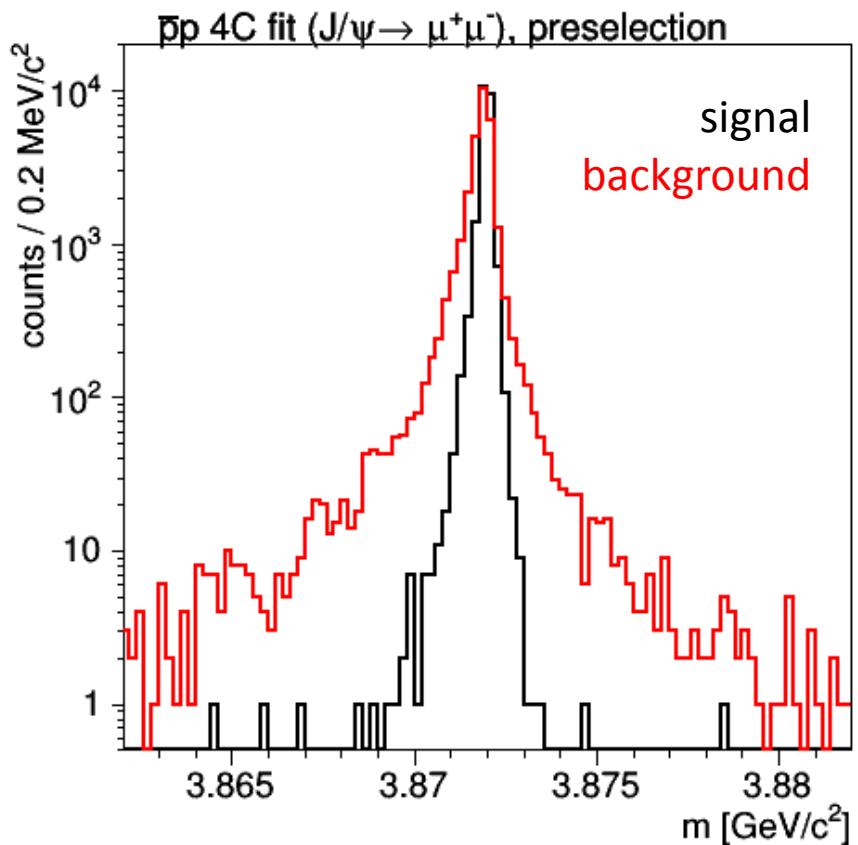


$\bar{p}p$ System after Preselection

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



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

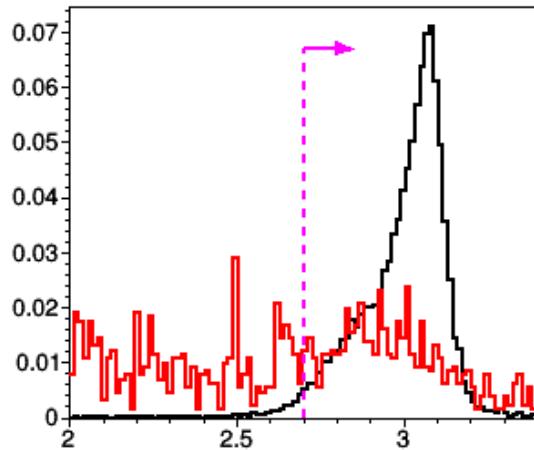


Final Selection Criteria

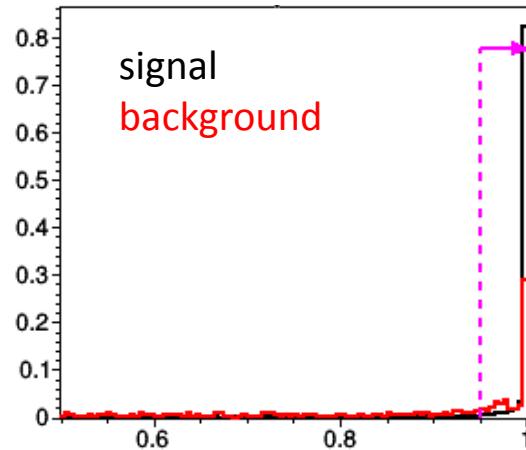
- Final selection e^+e^-
 - Electron PID(e^\pm) > 0.95
 - $m(e^+e^-) > 2.7 \text{ GeV}/c^2$
 - $p(e^+e^-) > 4.6 \text{ GeV}/c$
 - $p_{cm}(e^+e^-) < 0.66 \text{ GeV}/c$
 - $\not{\epsilon}(p_{e+}, p_{e-}) < 2 \text{ rad}$
- Final selection $\mu^+\mu^-$
 - Muon PID(μ^\pm) > 0.99
 - $p_{cm}(\mu^+\mu^-) < 0.32 \text{ GeV}/c$
 - $p_{cm}(\mu^\pm) > 1.37 \text{ GeV}/c$

Final Selection $J/\psi \rightarrow e^+e^-$ Channel

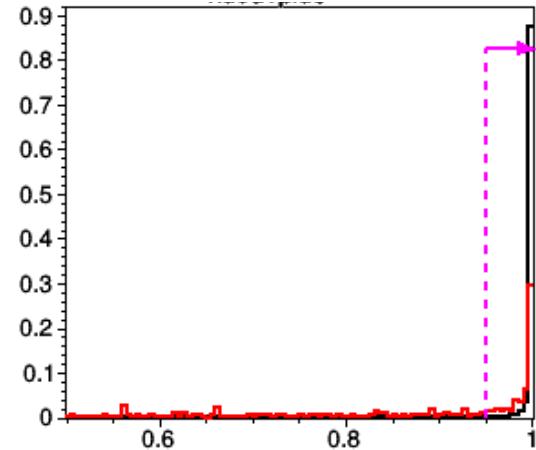
$m(e^+e^-) > 2.7 \text{ GeV}/c^2$



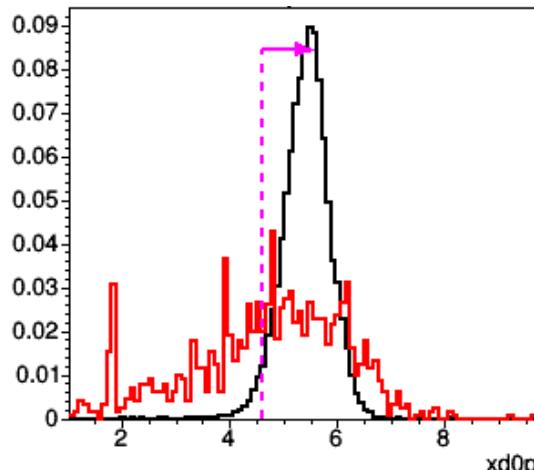
$\text{PID}(e^+) > 0.95$



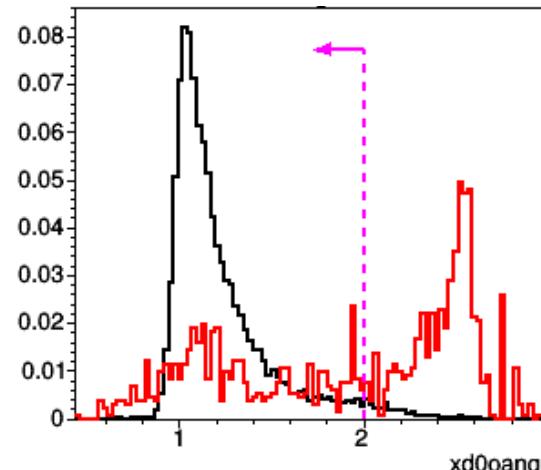
$\text{PID}(e^-) > 0.95$



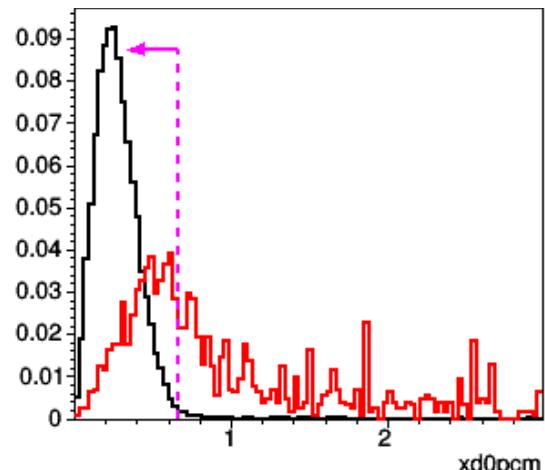
$p(e^+e^-) > 4.6 \text{ GeV}/c$



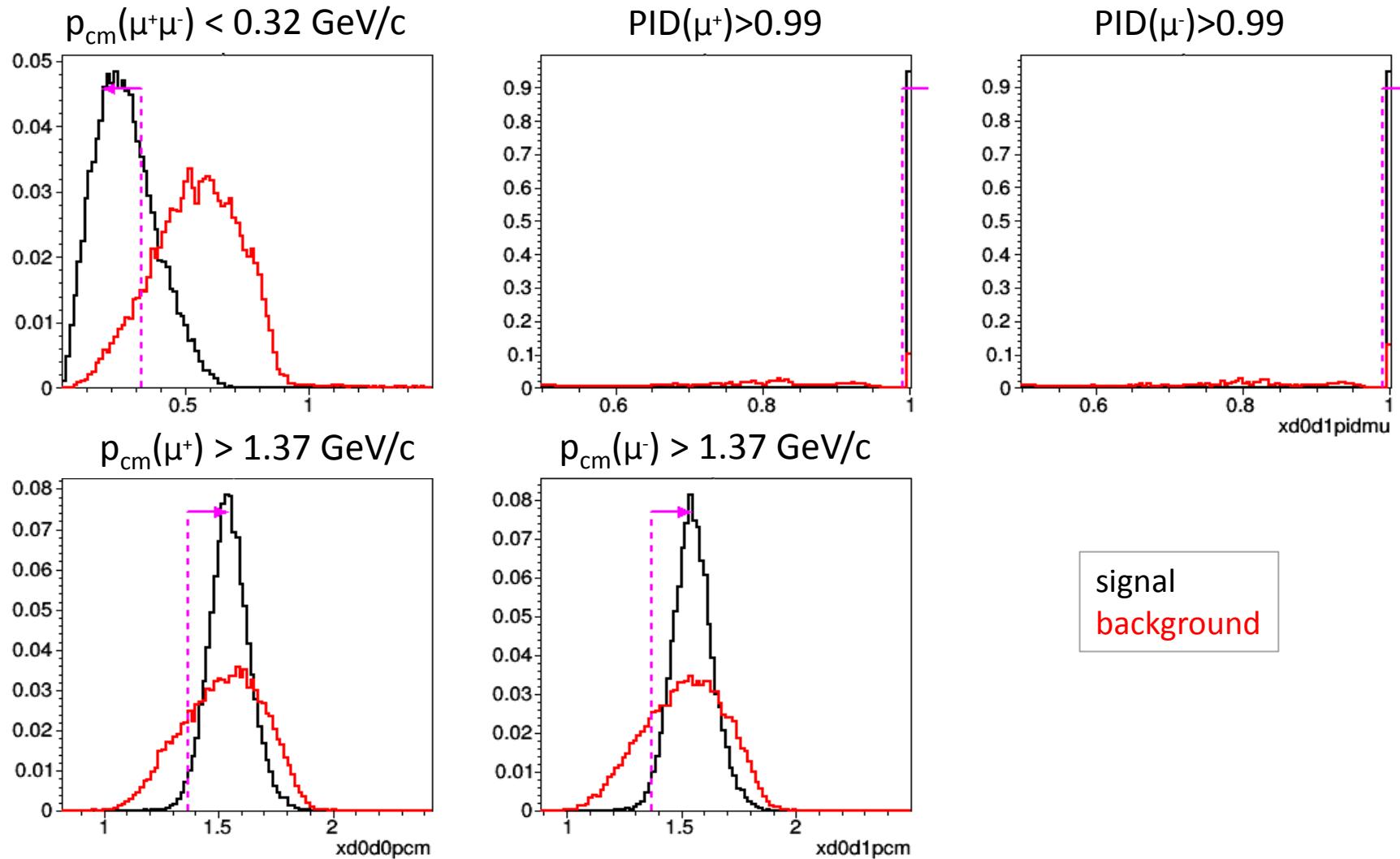
$\Delta\phi(p_{e+}, p_{e-}) < 2 \text{ rad}$



$p_{\text{cm}}(e^+e^-) < 0.66 \text{ GeV}/c$



Final Selection $J/\psi \rightarrow \mu^+\mu^-$ channel

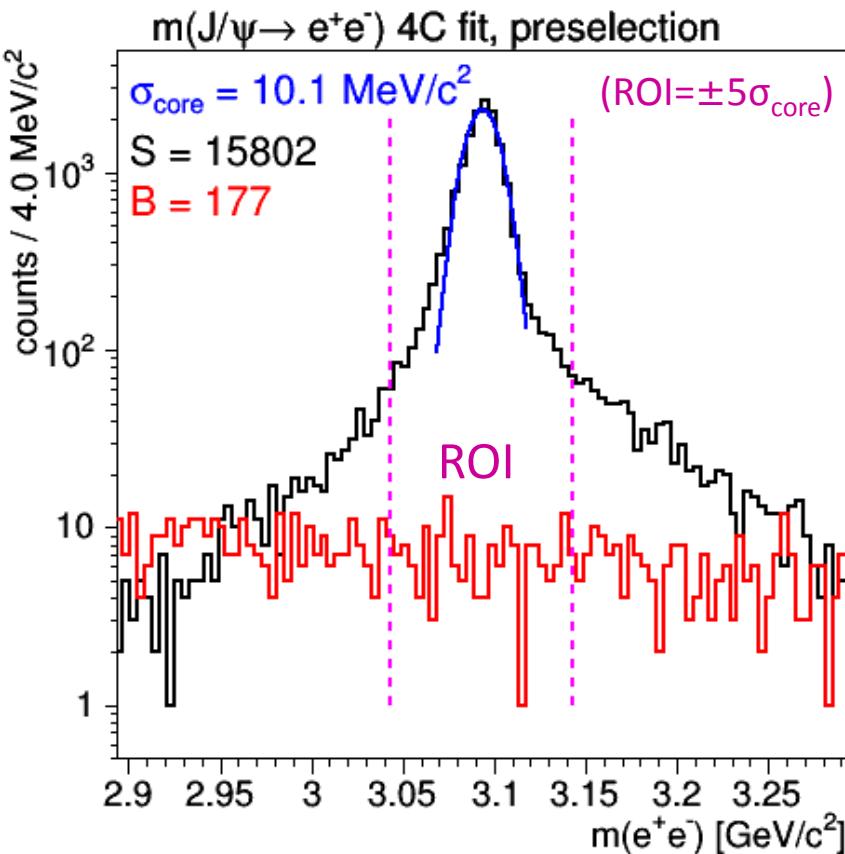


Final Selection $J/\psi \rightarrow e^+e^-$ Channel

Preselection

$\epsilon_S = 16.12\%$, $\epsilon_B = 1.8 \cdot 10^{-8}$

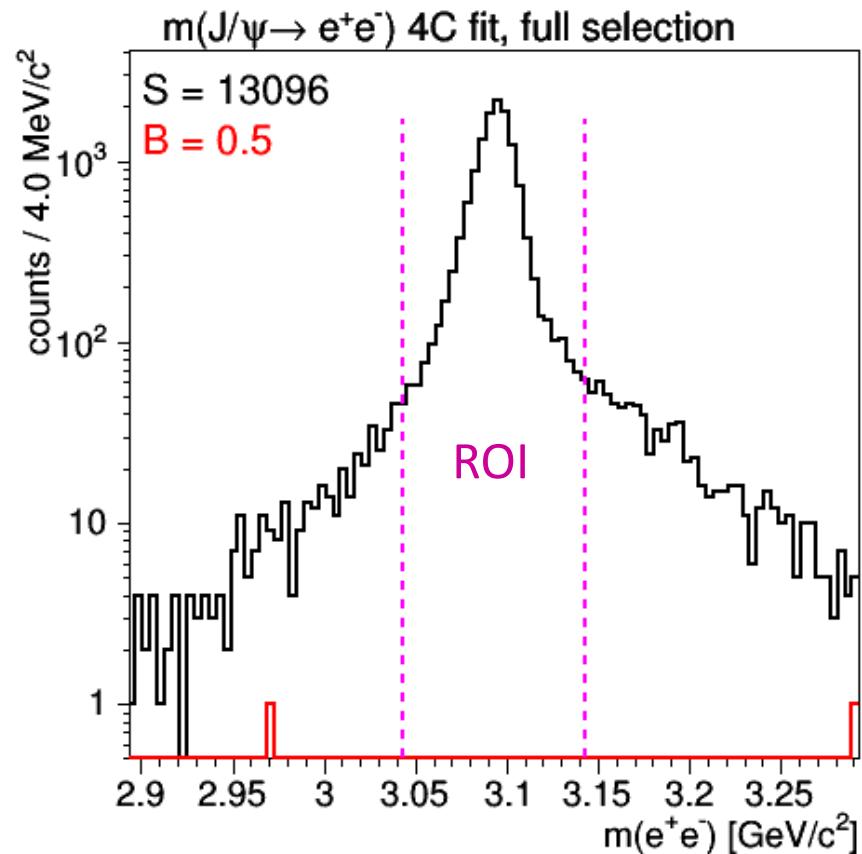
S/N = 1 : 34



Final Selection

$\epsilon_S = 13.4\%$, $\epsilon_B = 5.2 \cdot 10^{-11}$

S/N = 8 : 1

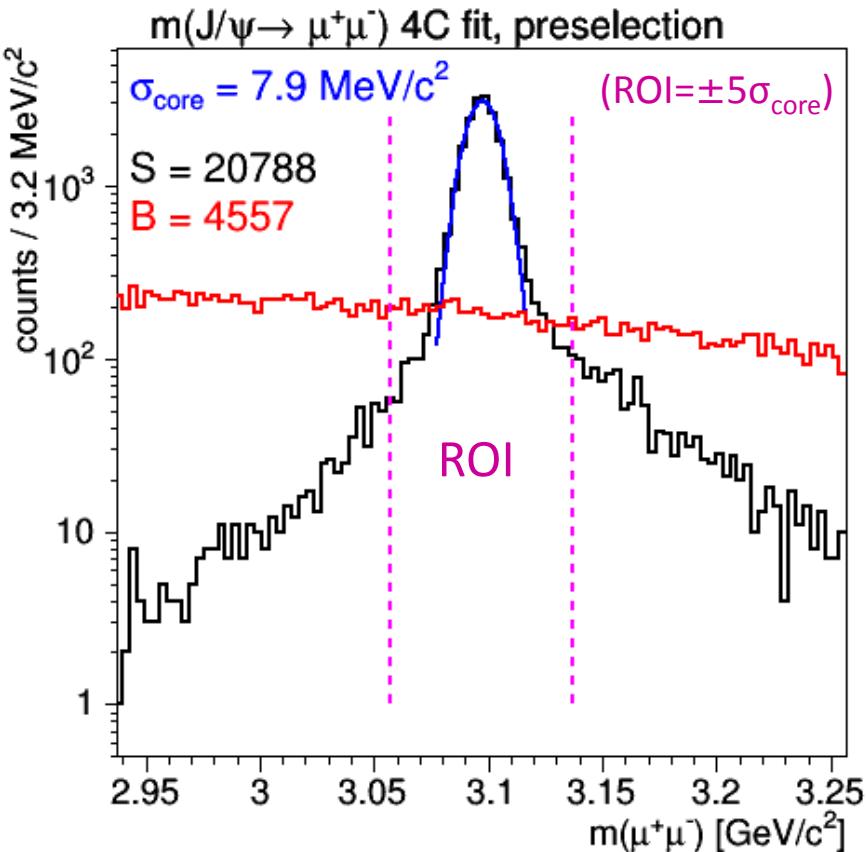


Final Selection $J/\psi \rightarrow \mu^+\mu^-$ channel

Preselection

$\epsilon_S = 20.79\%$, $\epsilon_B = 5.1 \cdot 10^{-7}$

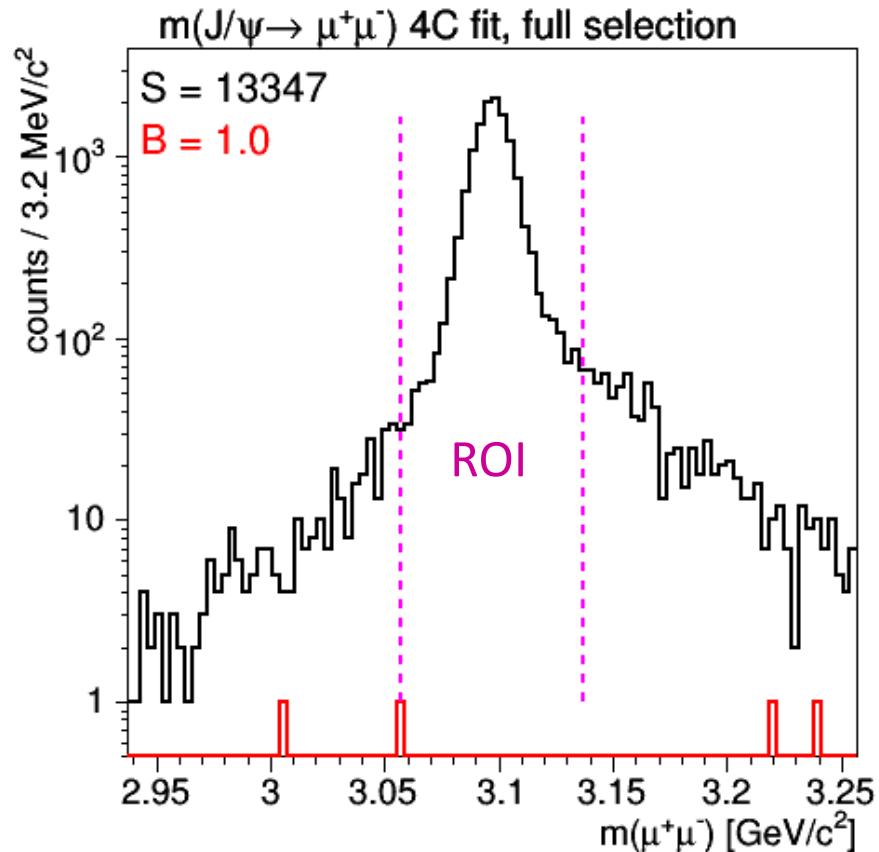
S/N = 1 : 750



Final Selection

$\epsilon_S = 13.3\%$, $\epsilon_B = 1.1 \cdot 10^{-10}$

S/N = 4 : 1



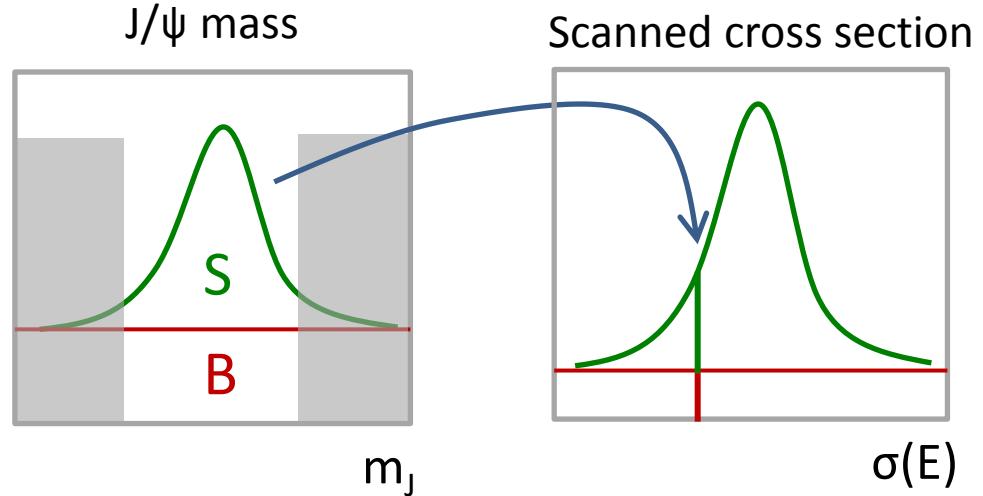
Energy Scan Part

Possible Approaches

- Two obvious approaches possible to extract lineshape:

1. Cut on J/ψ and count

- simple + robust
- background still in scanned lineshape

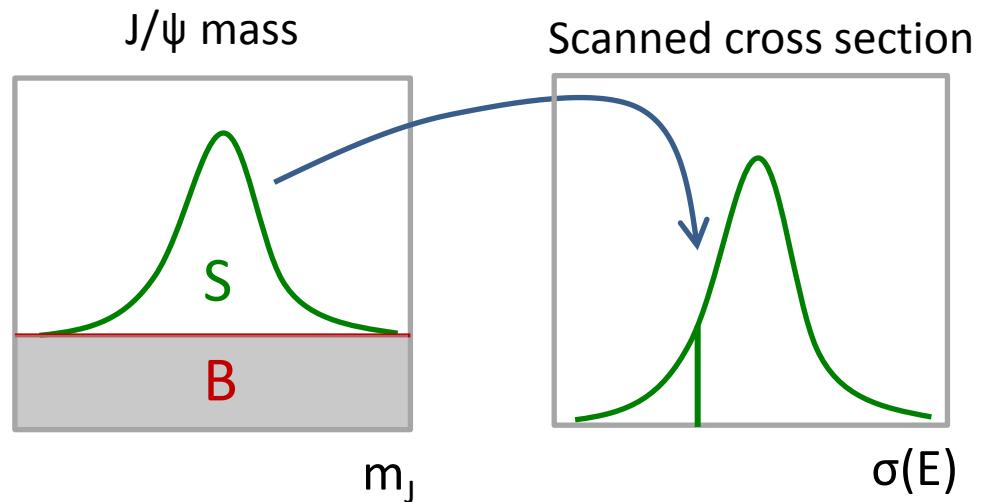


2. Fit signal in J/ψ mass

- removes hadronic bkg
- fit on sparse signals
might be problem

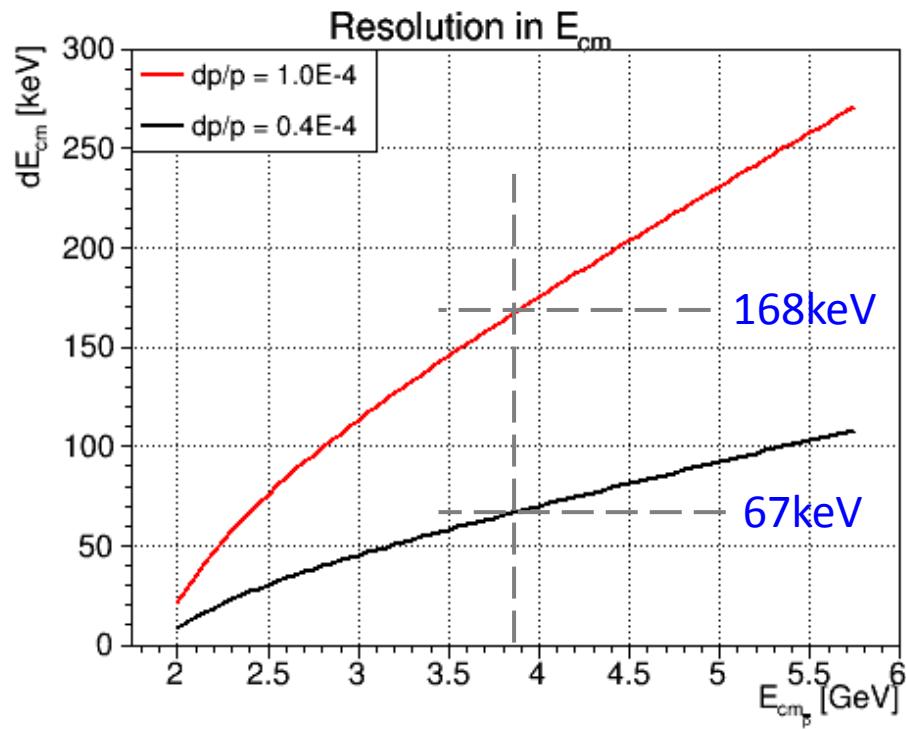
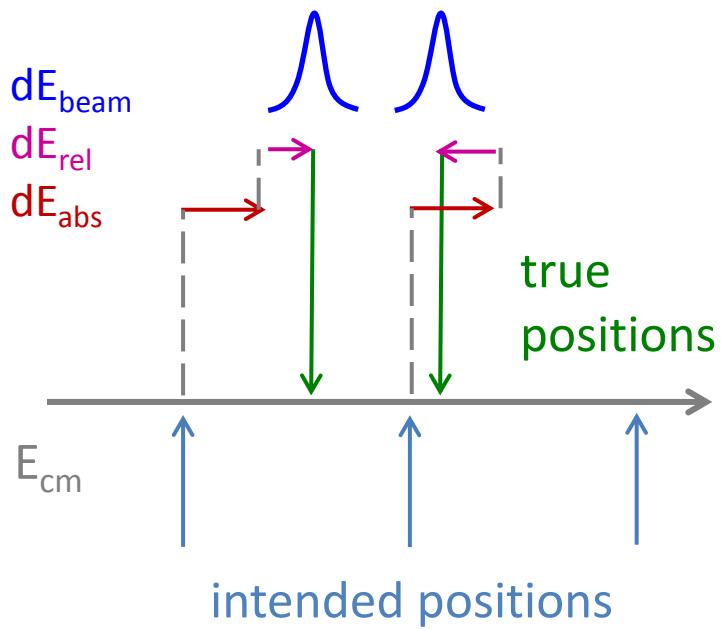
Show 1. method here

(2. method in preparation)



Uncertainties for Scan

- Absolute positioning resolution: $dE_{abs} = 100 \text{ keV}$ (shift)
- Relative positioning resolution: $dE_{rel} = 10 \text{ keV}$
- Beam related energy resolution: $dE_{beam} = 67(\text{HR}) / 168(\text{HL}) \text{ keV}$



Procedure for Individual Scan

- **Scan procedure**
 - Set parameters in signal function (Molecule or BW)
 - Fix scan region, number of points, L_{int} / point
 - Scale unfolded function $\sigma_S(E)$ to $\sigma_{S,max} = 50\text{nb}$ and adapt convoluted function $\sigma_S'(E) \rightarrow \sigma_{S',max} \leq 50\text{nb}$
 - For each energy scan point E
 - Modify energy $E_{cm} \rightarrow E_{cm}'$ due to dE_{abs} , dE_{rel}
 - Compute expected S_0 and B_0 based on $\sigma_S'(E_{cm}')$ and σ_B
 - Generate randomly $S = \text{Poisson}(S_0)$, $B = \text{Poisson}(B_0)$
 - Fill $N = S+B$ (error = \sqrt{N}) in scan graph at position E_{cm}
 - Fit graph with signal + background function → parameter P
- Repeat N times to determine uncertainty & bias of P

Investigated Scenarios

- Luminosity modes ($E_{\text{cm}} = 3.872 \text{ GeV}$): $N_L = 3$

Mode	HL	HR	HESRr
$L_{\text{int}} [(\text{nb} \cdot \text{d})^{-1}]$	13683	1368	1170

- Parameter settings: $N_P = 6 / \text{mode}$

BW	$\Gamma [\text{keV}]$	50	70	100	250	500	800
Molecule	$E_f [\text{MeV}]$	-25	-22	-20	-18	-15	-12

- Investigated scenarios: $N_S = 5$ Will show results for these

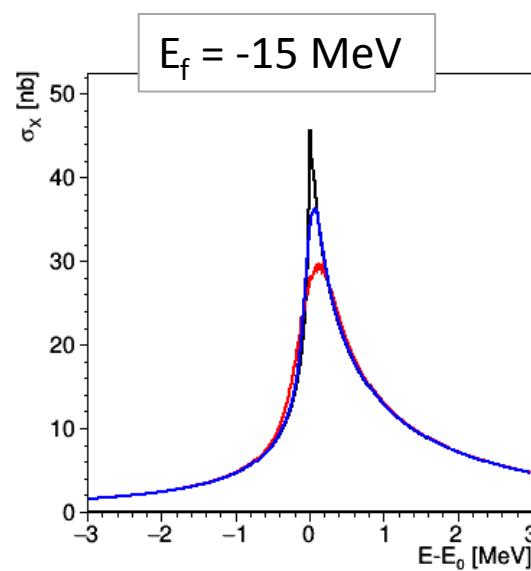
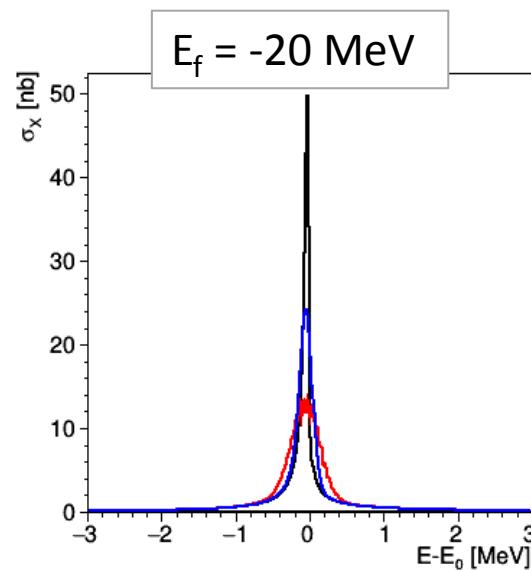
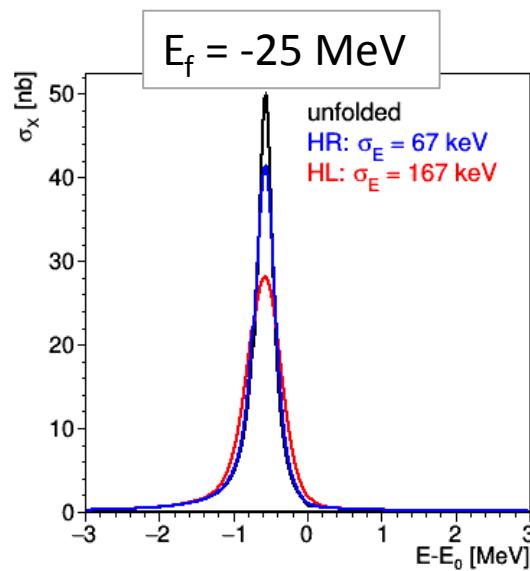
Scan time [month]	1.5	2	2	2	10
Points \times days	21 \times 2	21 \times 3	31 \times 2	61 \times 1	61 \times 5

- Toy MC fits: $N_{\text{MC}} = 500/100$ ($N_{\text{tot}} = N_L \cdot 2N_P \cdot N_S \cdot N_{\text{MC}} > 50000$)

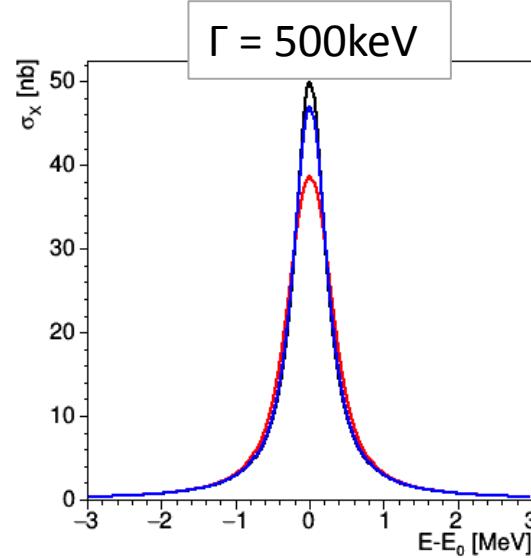
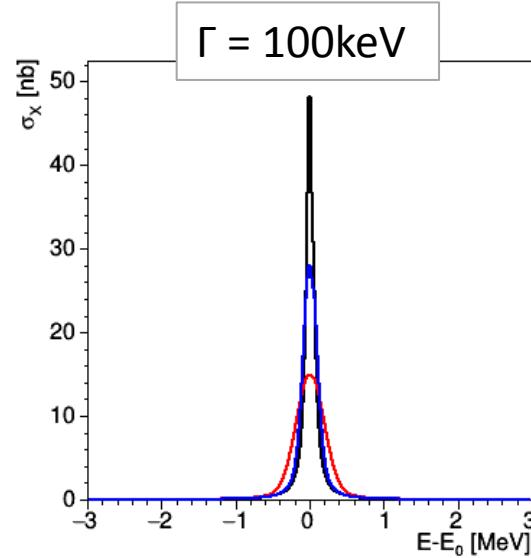
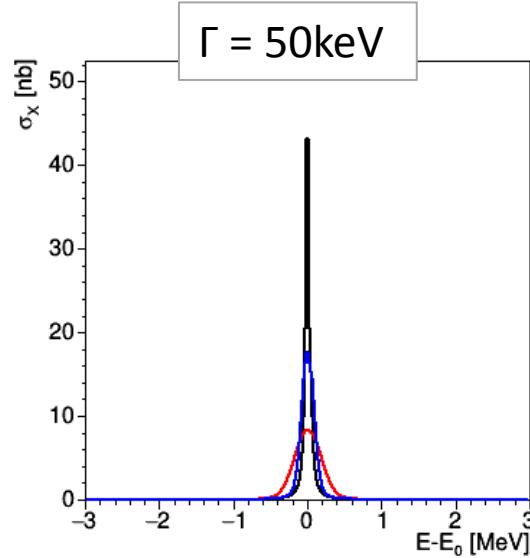
Physics mode	Breit-Wigner Γ	Molecule E_f
Number of fits	500 / setup	100 / setup

Lineshape Examples

Molecule

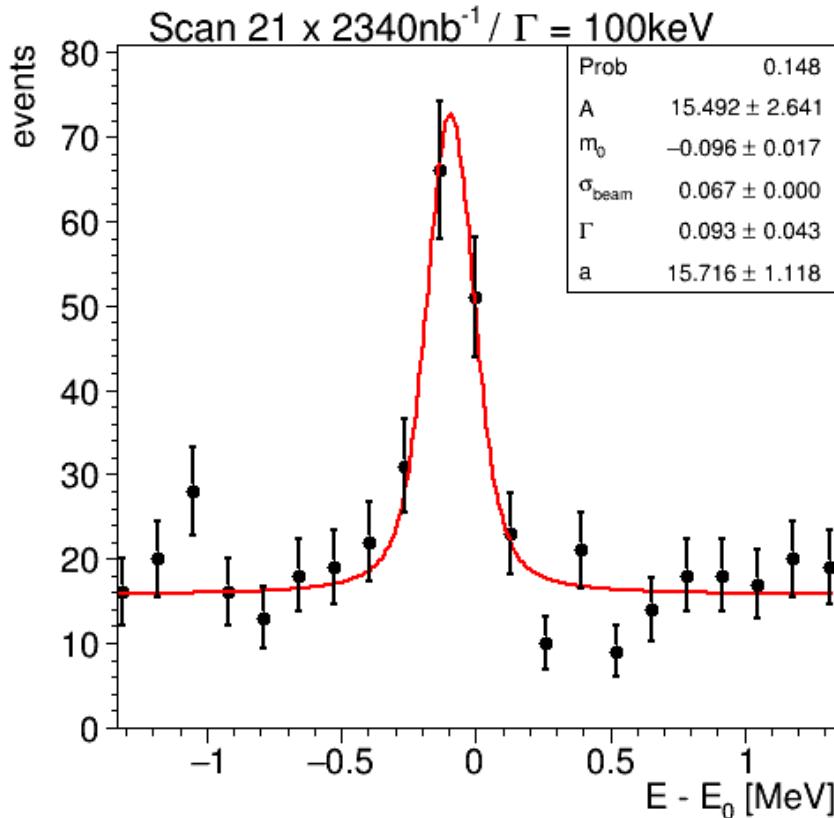


Breit-Wigner

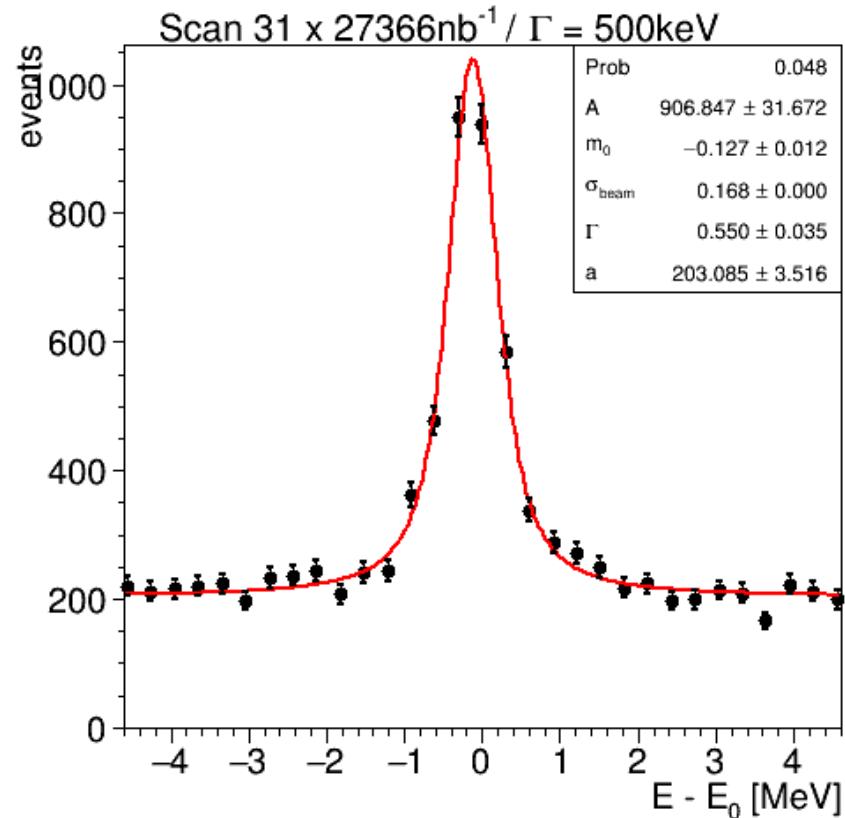


Scan Examples Breit Wigner

HESRr: 21×2 days
 $\Gamma = 100$ keV



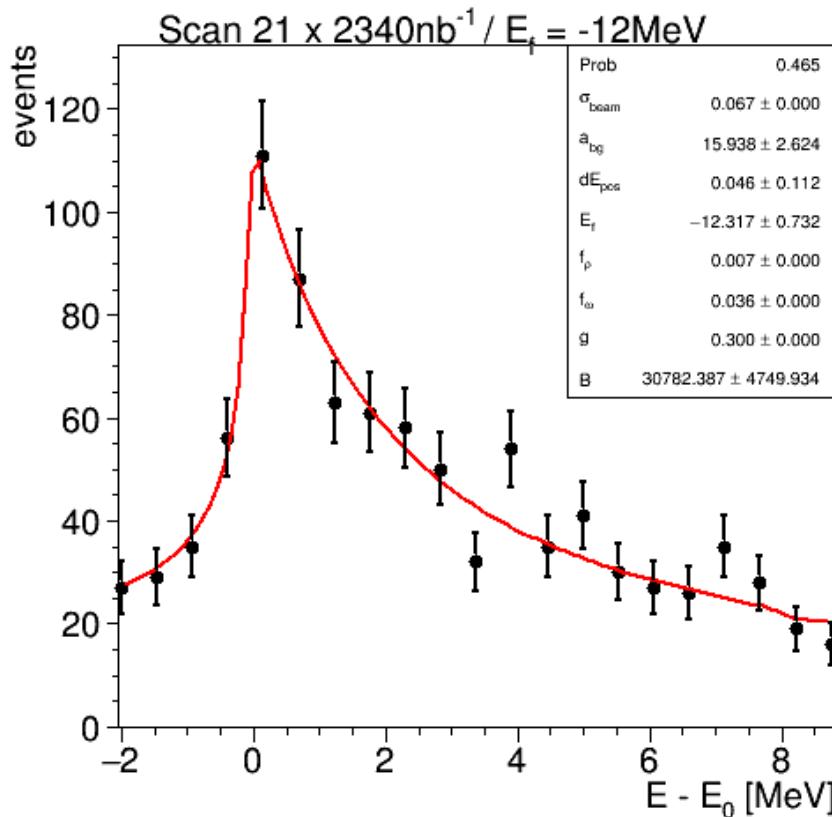
HL: 31×2 days
 $\Gamma = 500$ keV



Scan Examples Molecule Lineshape

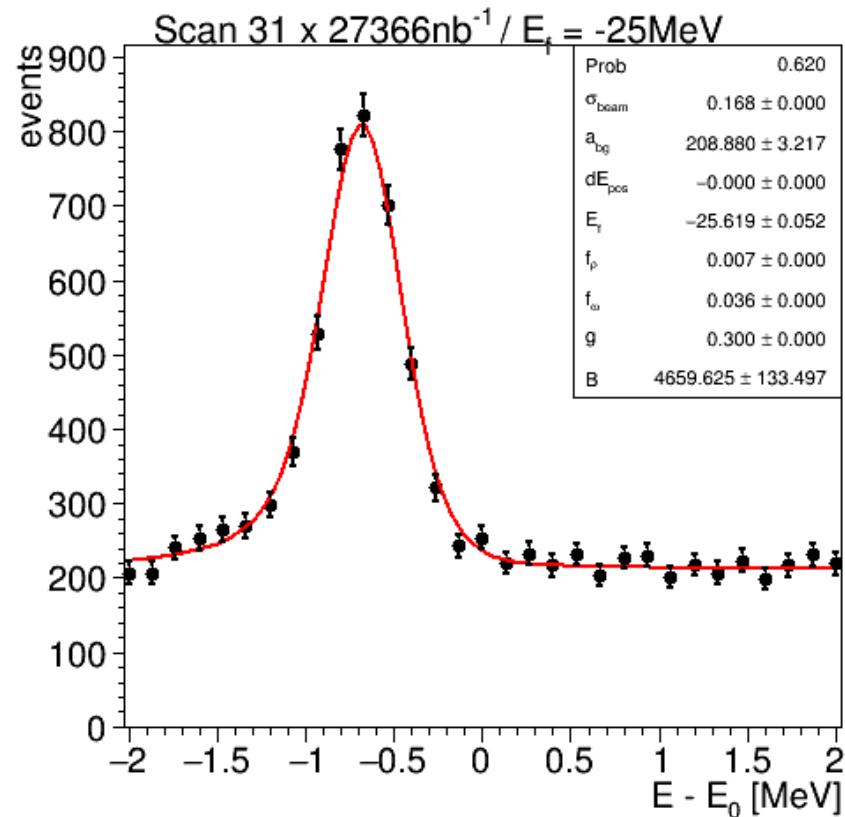
HESRr: 21×2 days

$E_f = -12$ MeV



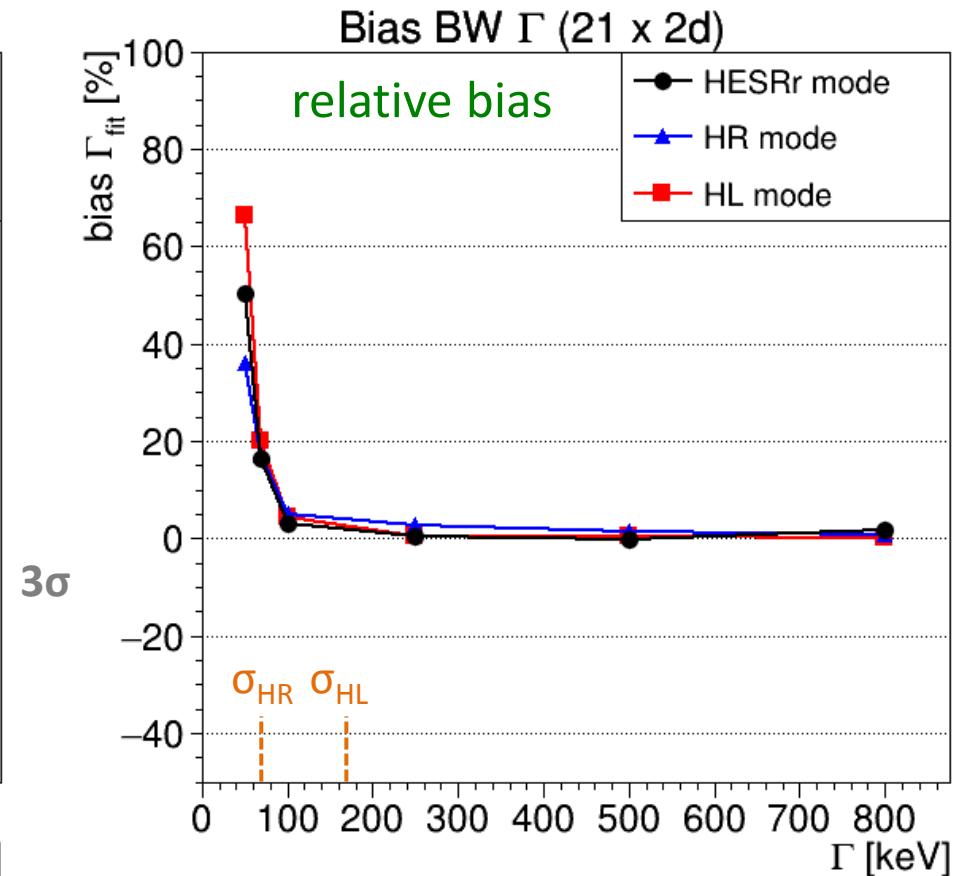
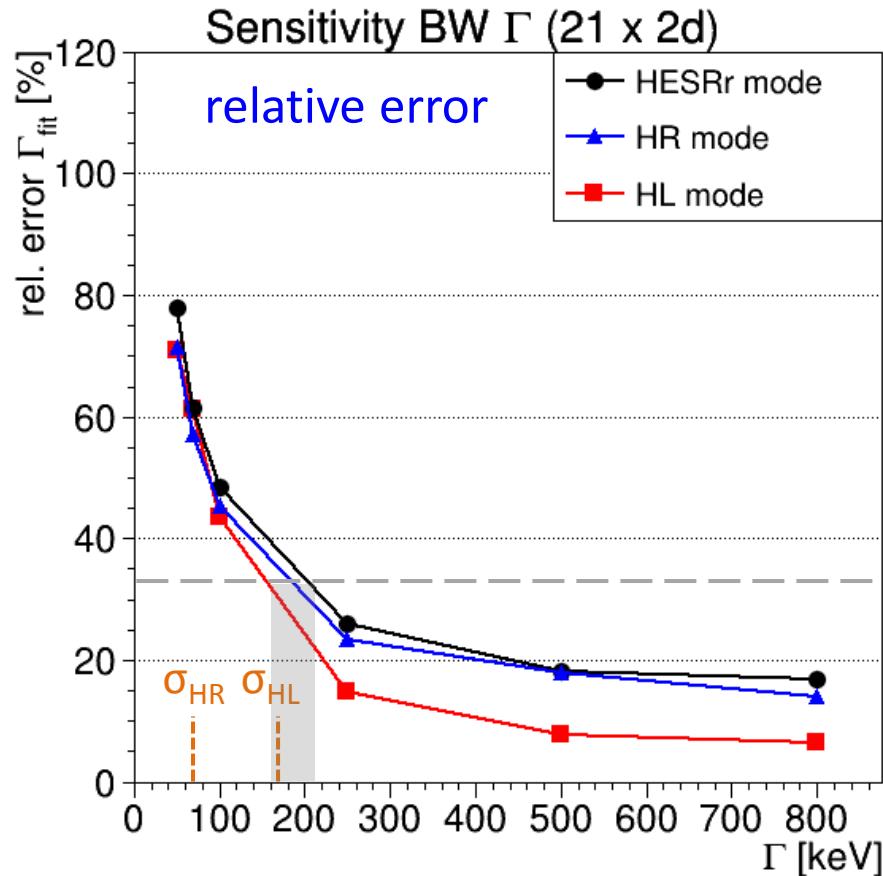
HL: 31×2 days

$E_f = -25$ MeV



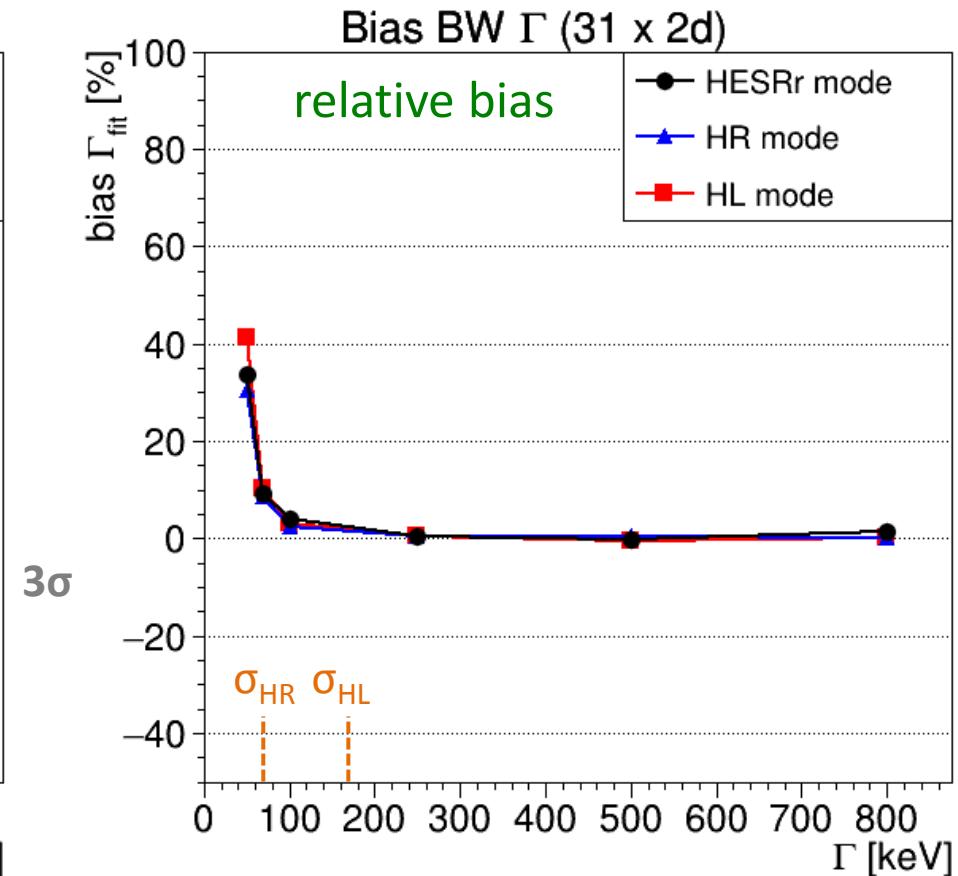
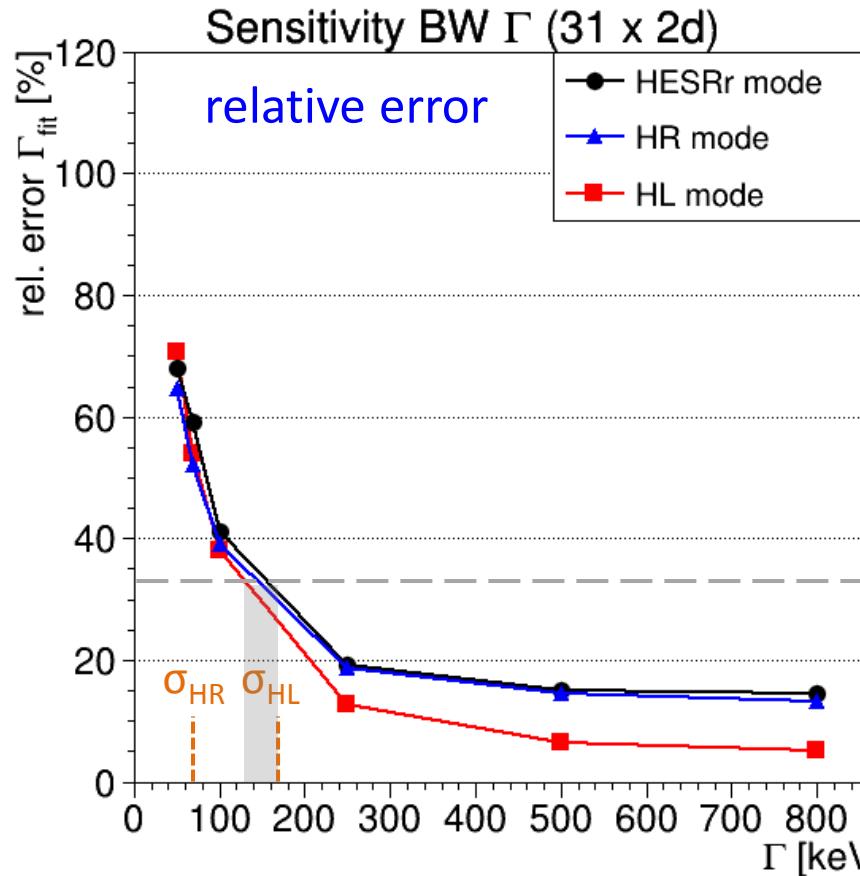
Sensitivities Breit-Wigner Γ (21 x 2d)

- Extract standard deviation and bias from toy MC fits
- Show relative error $\sigma_{\text{fit}}/\Gamma_{\text{fit}}$ and bias $(\Gamma_{\text{fit}} - \Gamma)/\Gamma$ in [%]



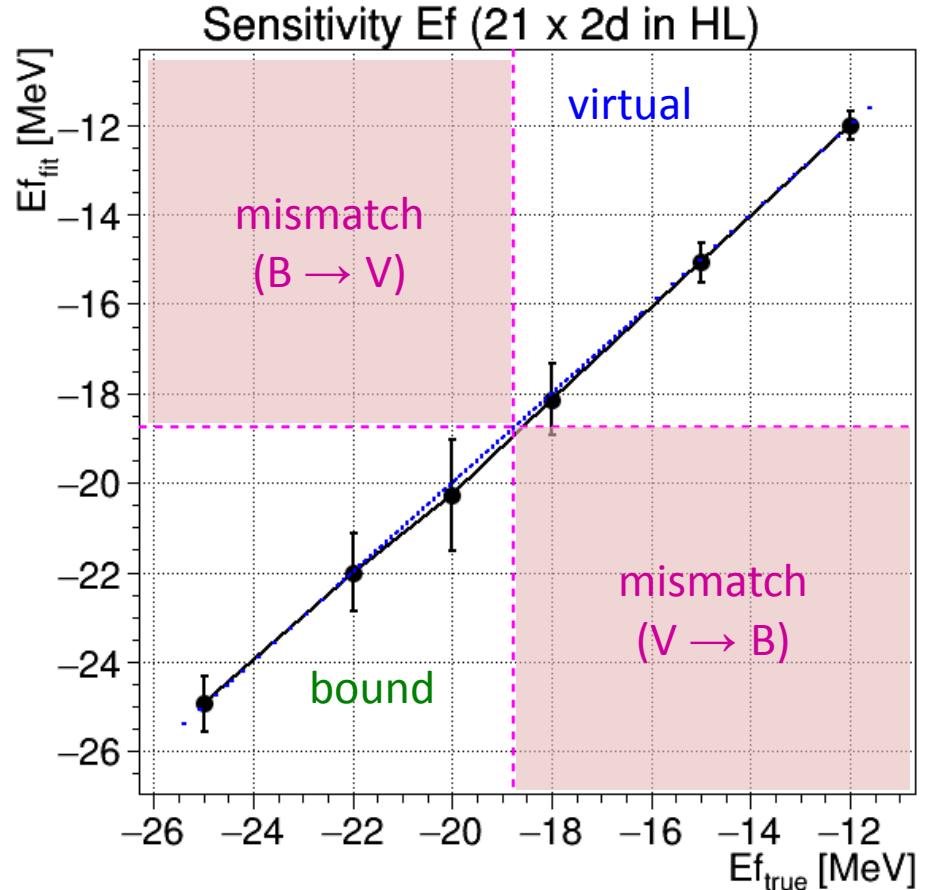
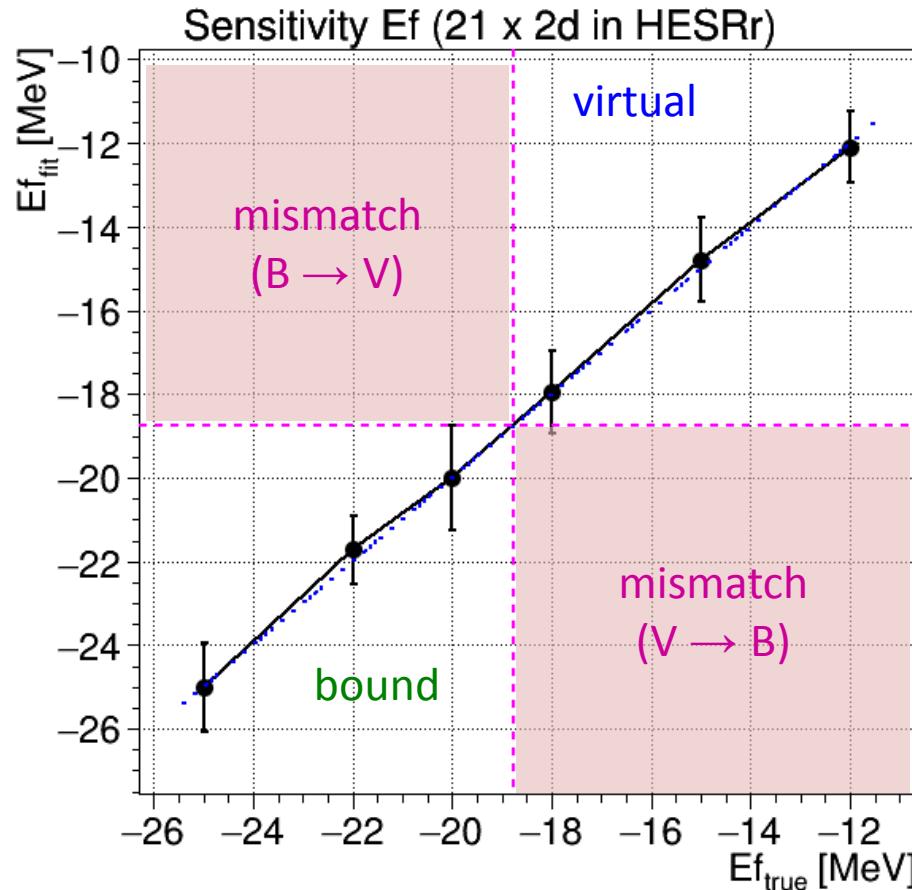
Sensitivities Breit-Wigner Γ (31 x 2d)

- Extract standard deviation and bias from toy MC fits
- Show relative error $\sigma_{\text{fit}}/\Gamma_{\text{fit}}$ and bias $(\Gamma_{\text{fit}} - \Gamma)/\Gamma$ in [%]



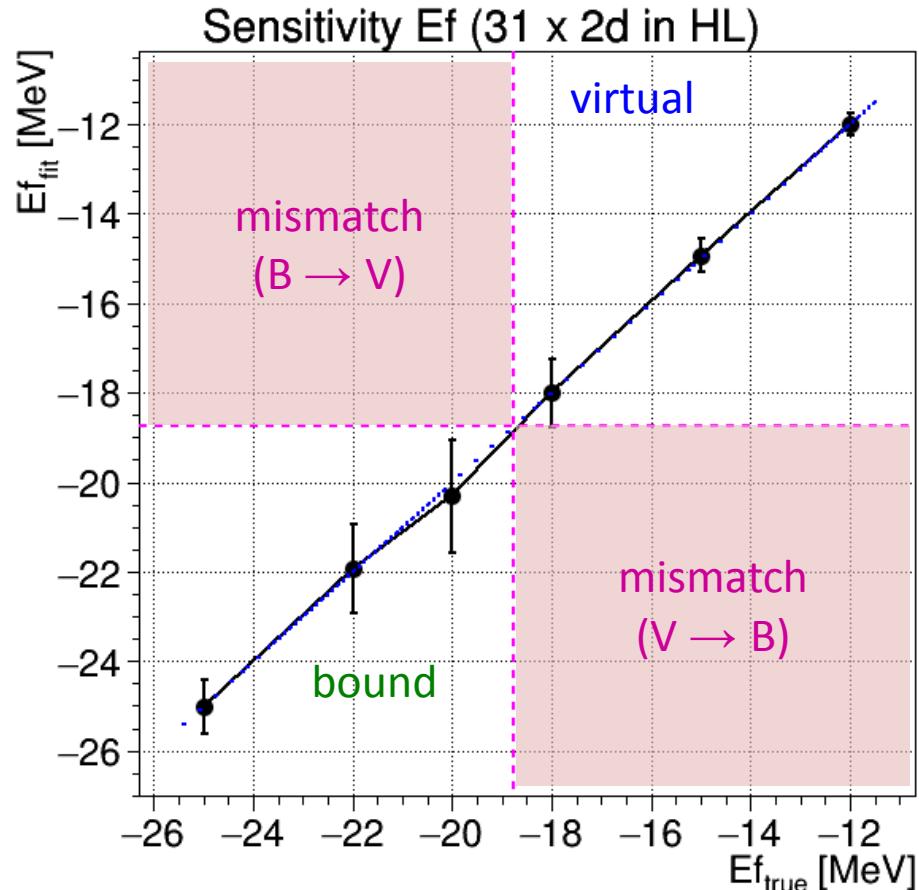
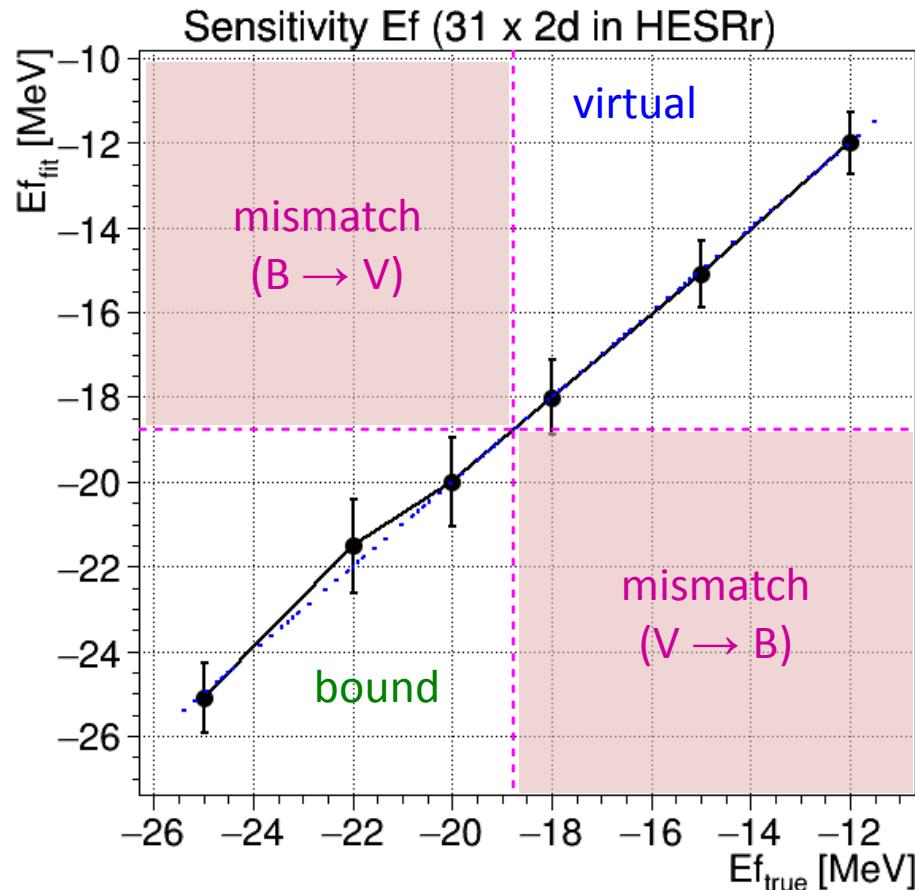
Sensitivities Molecule Lineshapes (21 x 2d)

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



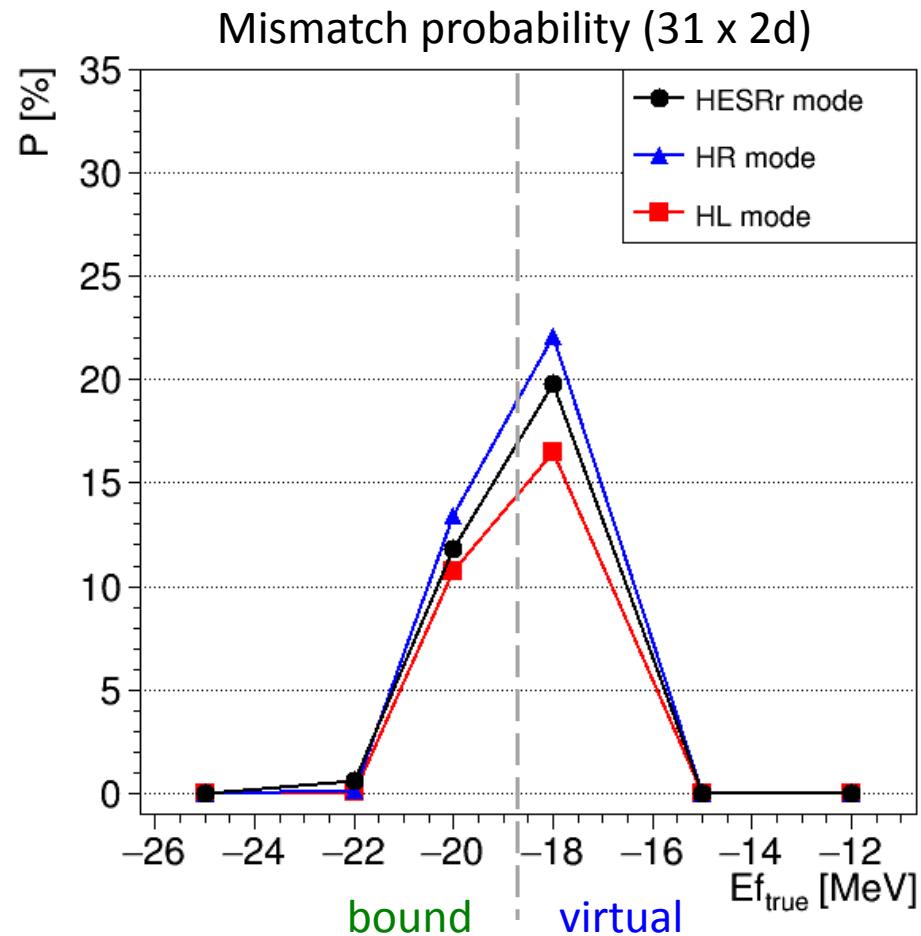
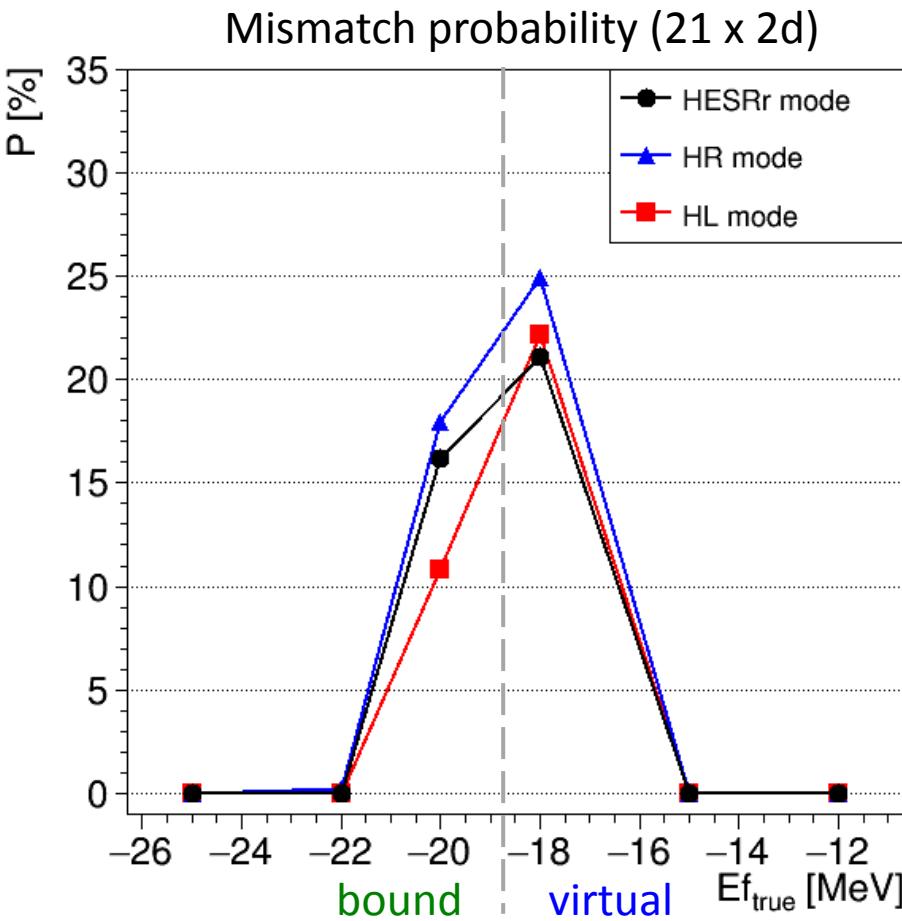
Sensitivities Molecule Lineshapes (31 x 2d)

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



Probability of Mismatch

- Take uncertainty as gaussian sigma
- Integrate part of gaussian leaking into mismatch region



Summary

- Investigation of X(3872)-Scan at PANDA in various scenarios
- Determined sensitivity for BW width measurement
 - Reach $\Gamma/\sigma_\Gamma > 3$ at $\Gamma \gtrsim 150$ keV (2 months data)
 - For $\Gamma \geq 70$ keV bias $\Delta\Gamma/\Gamma \leq 10\%$ ("")
 - HL mode superior for $\Gamma > 150$ keV
- Determined sensitivity for molecular lineshape measurement
 - Possible to distinguish bound/virtual state
 - In transition region $P \lesssim 20 - 25\%$ for mismatch
 - HL seems slightly better than HR modes
- Further steps
 - 2nd approach to extract lineshape (J/ψ yield per scan point)
 - Prepare update for CM Vienna

BACKUP

Background Prefilter

- Reasonable S/N sensitivity: need huge amount of BG
- Example calculation:
 - Signal: $\sigma_S = 50 \text{ nb}$, $BR_{J/\psi} = 0.06$, $BR_X = 0.05$, $\varepsilon_S = 20\%$
 - Background: $\sigma_B = 46 \text{ mb}$ (inelastic @ $E_{cm} = 3.872 \text{ GeV}$)

$$\frac{S}{N} = \frac{\sigma_S \cdot \varepsilon_S}{\sigma_B \cdot \varepsilon_B} \cdot BR_{J/\psi} \cdot BR_X \stackrel{!}{\geq} 1$$
$$\Rightarrow \varepsilon_B < \frac{\sigma_S \cdot \varepsilon_S}{\sigma_B} \cdot BR_{J/\psi} \cdot BR_X = 6.5 \cdot 10^{-10}$$

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

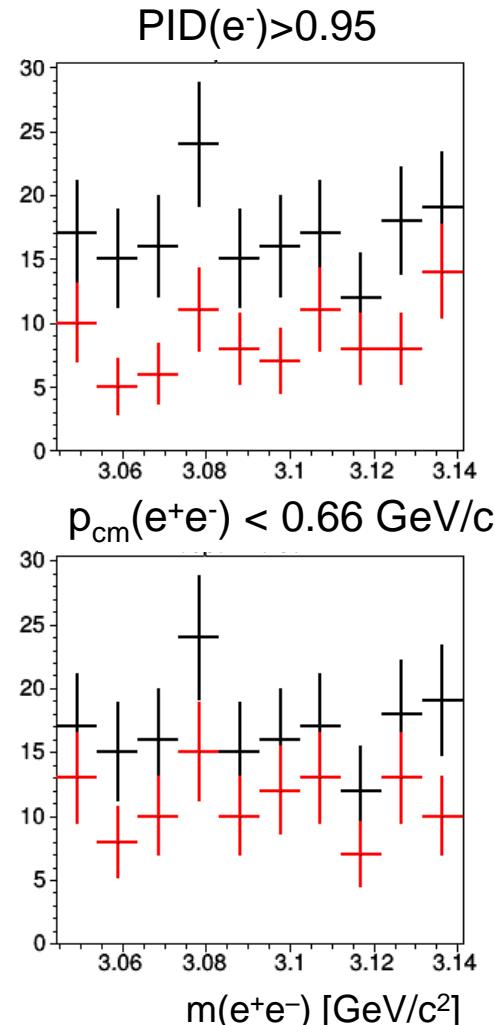
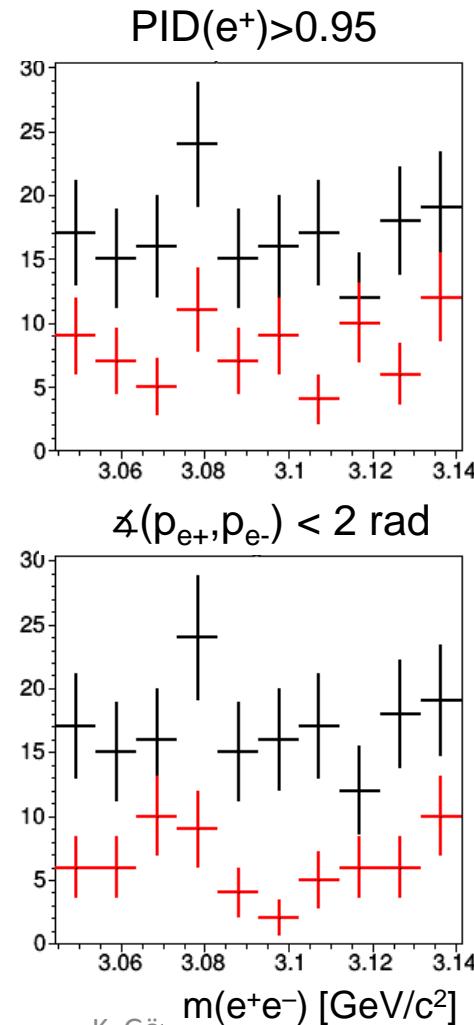
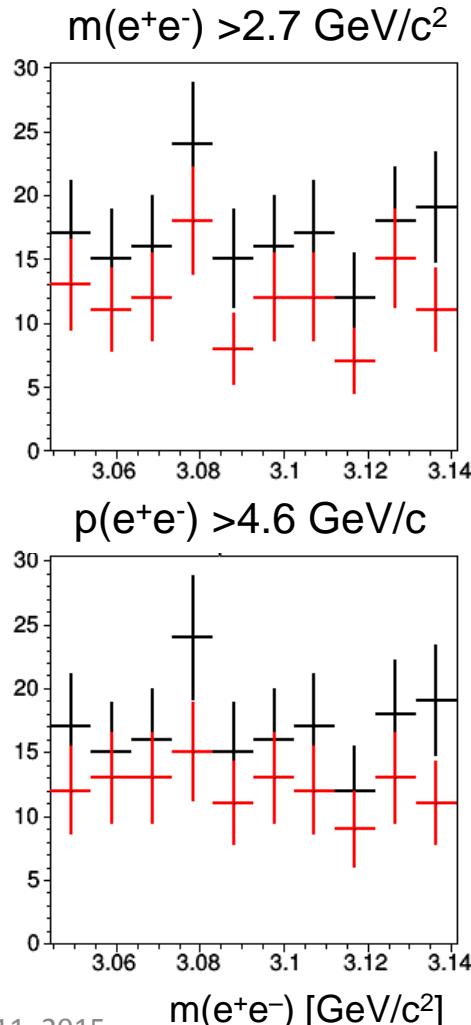
- Neither feasible nor efficient to simulate completely
- Use `FairFilteredPrimaryGenerator` to filter already at generator level

Flatness Check of Cuts

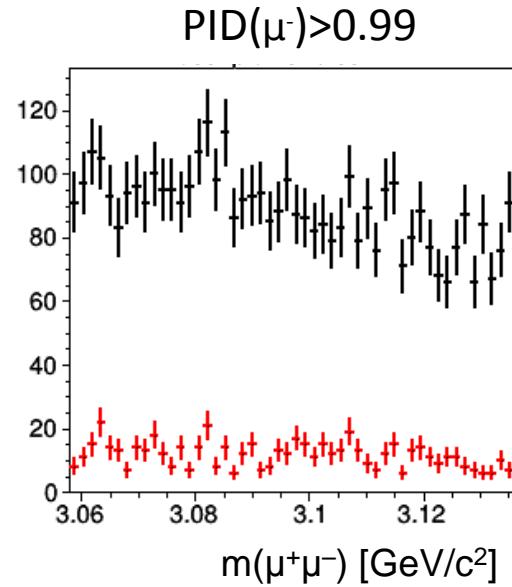
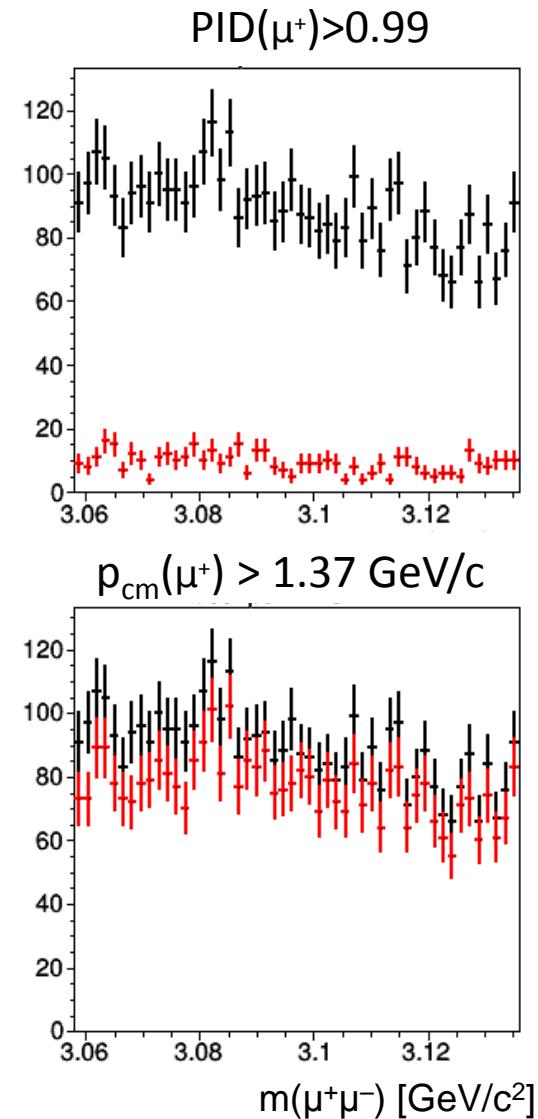
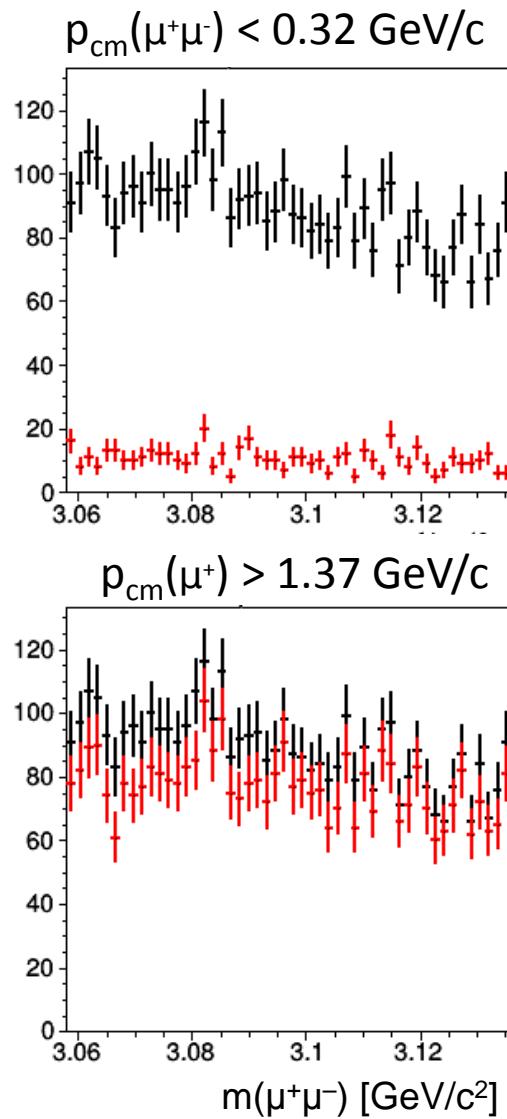
- We want to interpolate background in ROI

– Cuts should not distort background shape!

preselection
after cut



Flatness Check of Cuts



preselection
after cut

Energy Scan Principles

- Energy scan → residual cross section after some selection
- Principle contributions in this measurement:
 - Signal $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ (50 nb)
 - Non resonant $J/\psi \pi^+ \pi^-$ production ($\sim 1\text{nb}$, neglected)
 - Non resonant light hadron background (59mb)

