X(3872)-Scan Reloaded

PANDA CM Vienna

Charmonium Exotics Session

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Idea

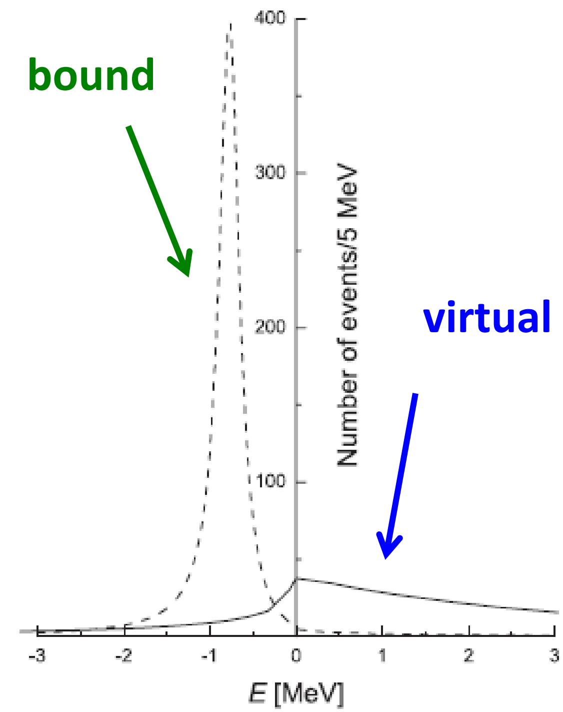
- Nature of X(3872)
  - Need lineshape and width to understand structure
- Approach at PANDA
  - Fine scan around nominal mass
    $\rightarrow$ energy dependent cross section
- Analysis goals
  - Sensitivity of Γ measurement (conventional BW)
  - Sensitivity for virtual/bound state (molecular picture)
- Analysis strategy
  - Analysis of $X(3872) \rightarrow J/\psi(\ell^+\ell^-)\ \rho^0(\pi^+\pi^-)$ channel only
  - Full sim/reco $\rightarrow$ 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 [Kalashnikova et al, Phys. Atom. Nucl. 73 (2010) 1592]
- Here only interested in X(3872) → J/ψ π⁺π⁻

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

(assuming lineshape as in B decays)



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

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

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

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

Parameter E_f determines state to be bound or virtual

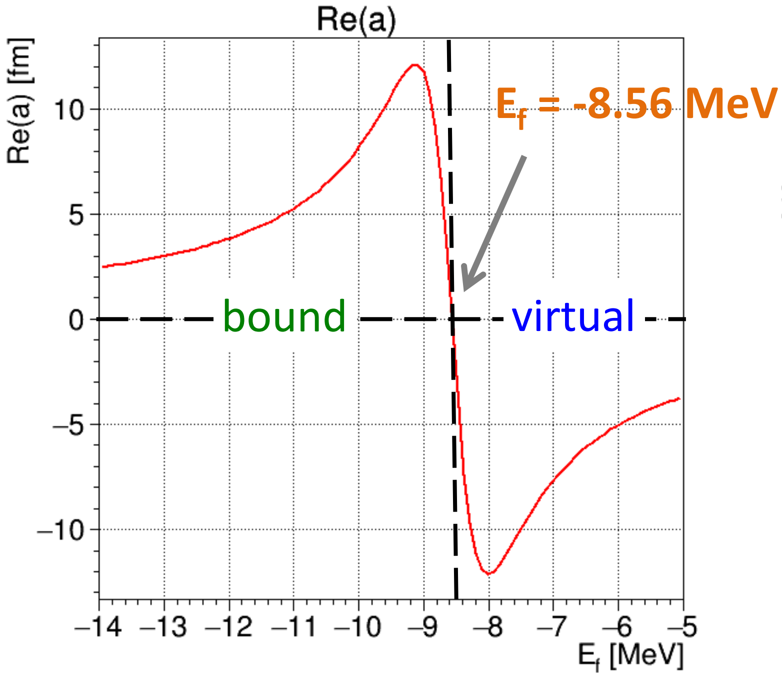
Lineshapes for different E_f

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

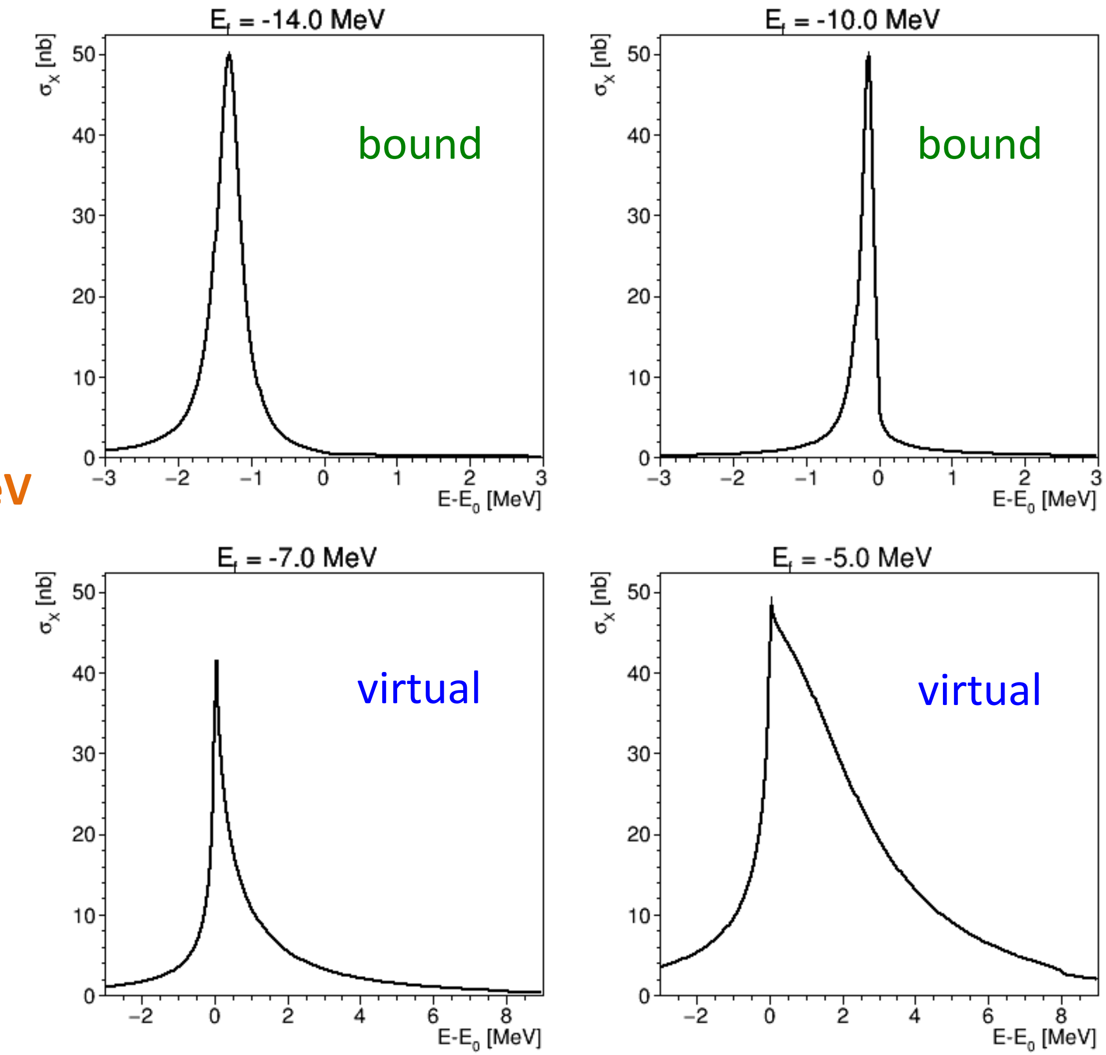
$$a = -\frac{\sqrt{2\mu_2\delta} + 2E_f/g + i\Gamma(0)/g}{(\sqrt{2\mu_2\delta} + 2E_f/g)^2 + \Gamma(0)^2/g^2}$$

Re(a) > 0 : bound state

Re(a) < 0 : virtual state



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



(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 %
	$BR(X \to J/\psi\ \rho^0)$	5 % (assumption)
Cross sections	$\sigma(\bar{p}p \to X)$	50 nb (assumption)
	$\sigma(\bar{p}p \to J/\psi\ \pi^+\pi^-$ 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_{HR} (3.872 GeV)	1368 $(nb \cdot d)^{-1}$
	L_{HESRr} (3.872 GeV)	1170 $(nb \cdot d)^{-1}$
Resolutions	$\sigma_{E,abs}$ *(absolute energy positioning)*	100 keV (assumption)
	$\sigma_{E,rel}$ *(relative energy positioning)*	10 keV (assumption)
	$\sigma_{E,beam}$(HL)	168 keV
	$\sigma_{E,beam}$(HR/HESRr)	67 keV

*[PRD 77 (2008) 097501]

Software and Data

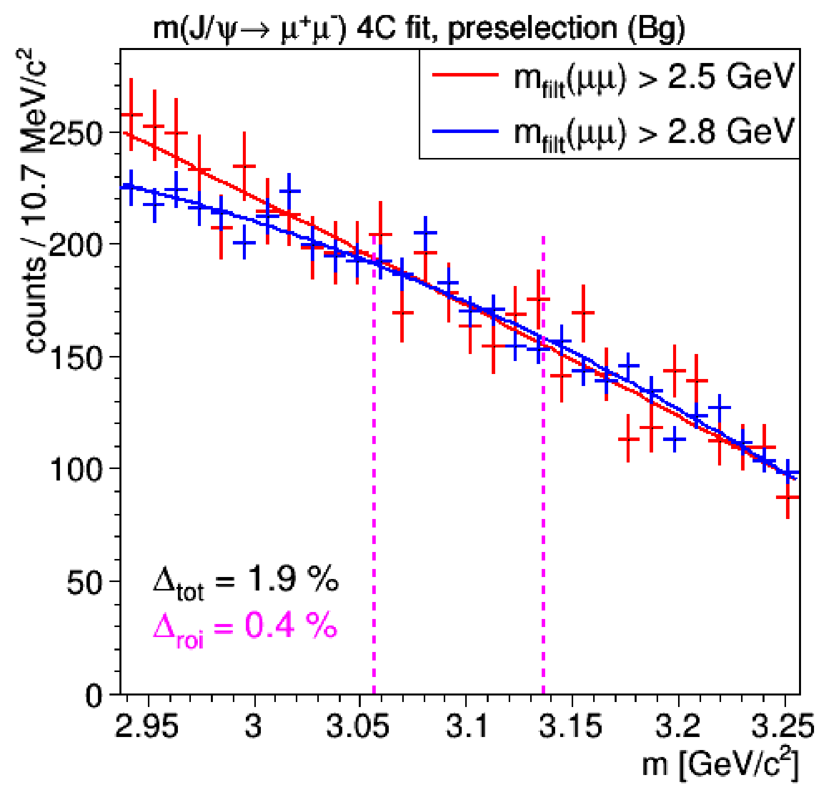
- Software
  - PandaRoot: Revision 28670
  - FairSoft: mar15p2
  - FairRoot: v15.03
- Data @ E_{cm} = 3.872 GeV

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%
  - Difference in J/ψ ROI: 0.4%

⇒ Negligible effect!

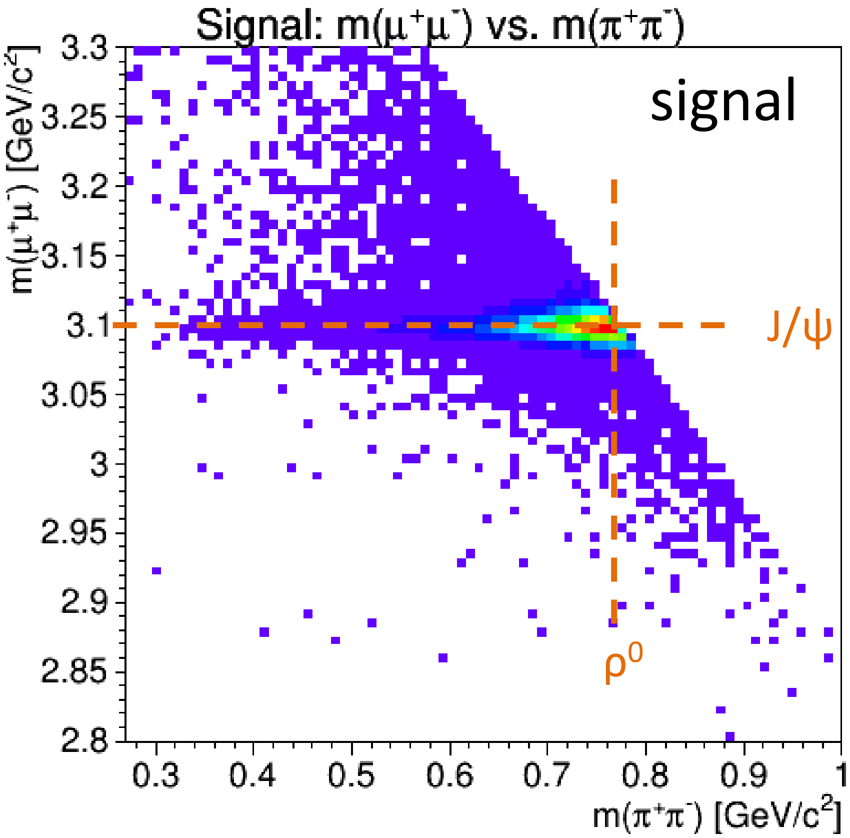


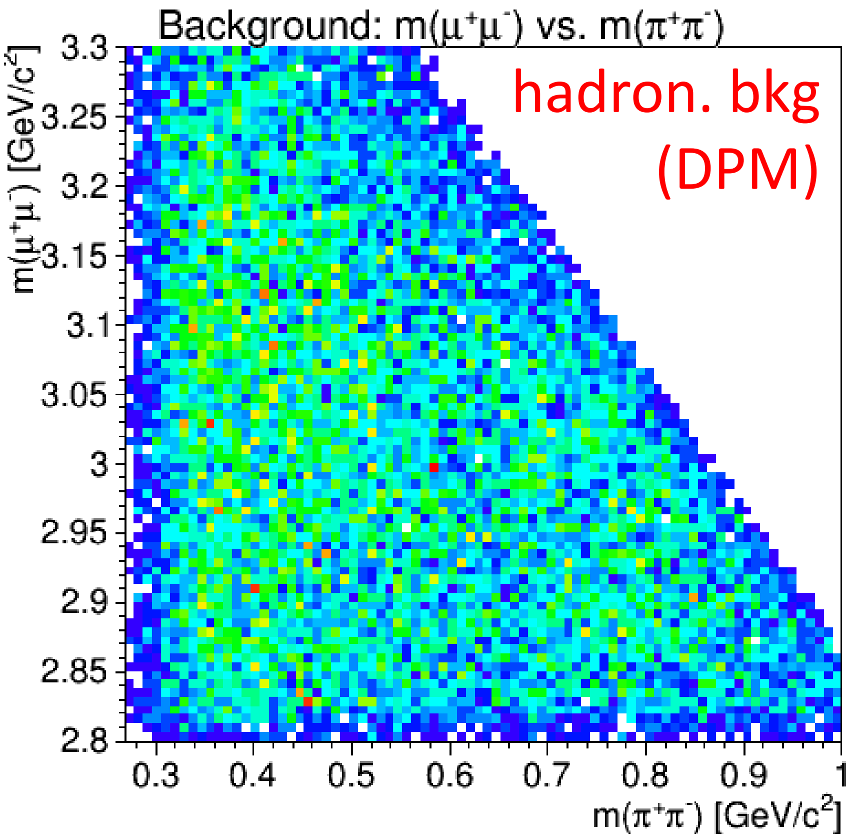
Signal Reconstruction

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

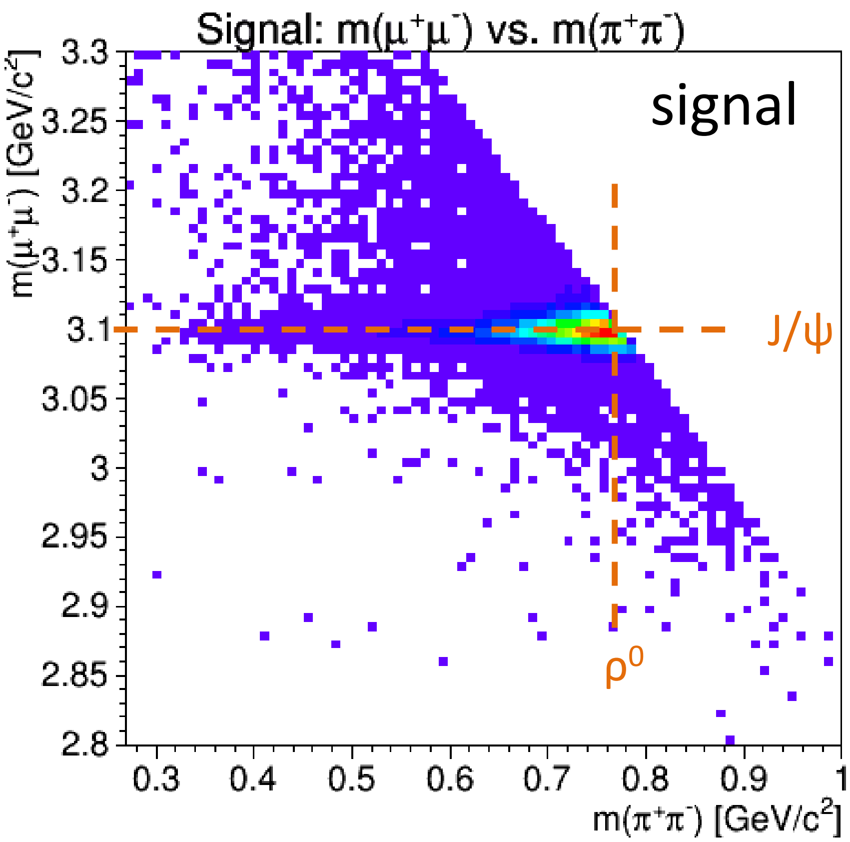
- Preselection $\mu^+\mu^-$:
  - Particle Identification : MuonTight, PionAll (PidAlgoEmcBayes;PidAlgoDrc;PidAlgoDisc;PidAlgoStt;PidAlgoMdtHardCuts)
  - $J/\psi \to \mu^+\mu^-$ mass window: $2.5 < m(\mu^+\mu^-) < 3.4$ GeV/c^2
  - $\rho^0 \to \pi^+\pi^-$ mass window: $0.27 < m(\pi^+\pi^-) < 1.0$ GeV/c^2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

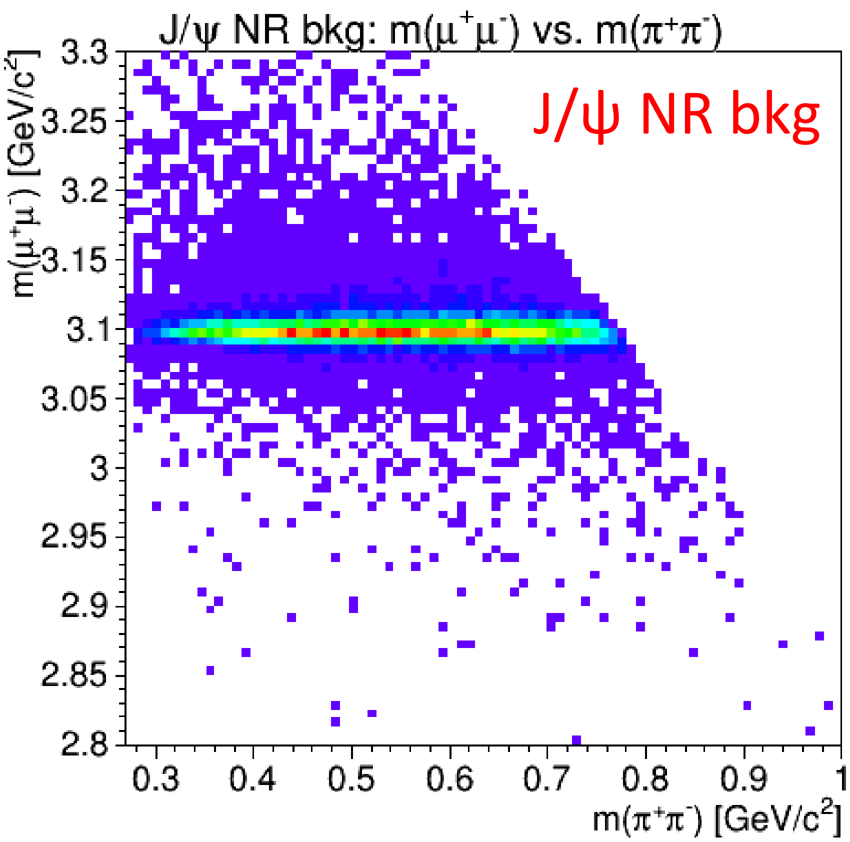
Correlation $M(\ell^+\ell^-)$ vs. $M(\pi^+\pi^-)$





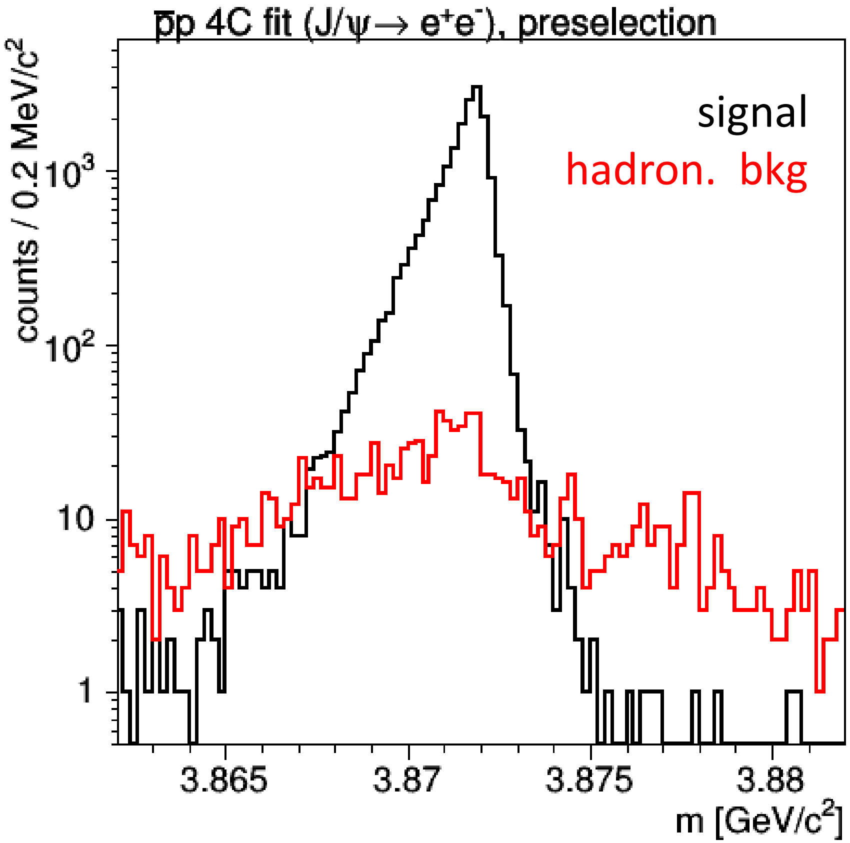
Correlation $M(\ell^+\ell^-)$ vs. $M(\pi^+\pi^-)$



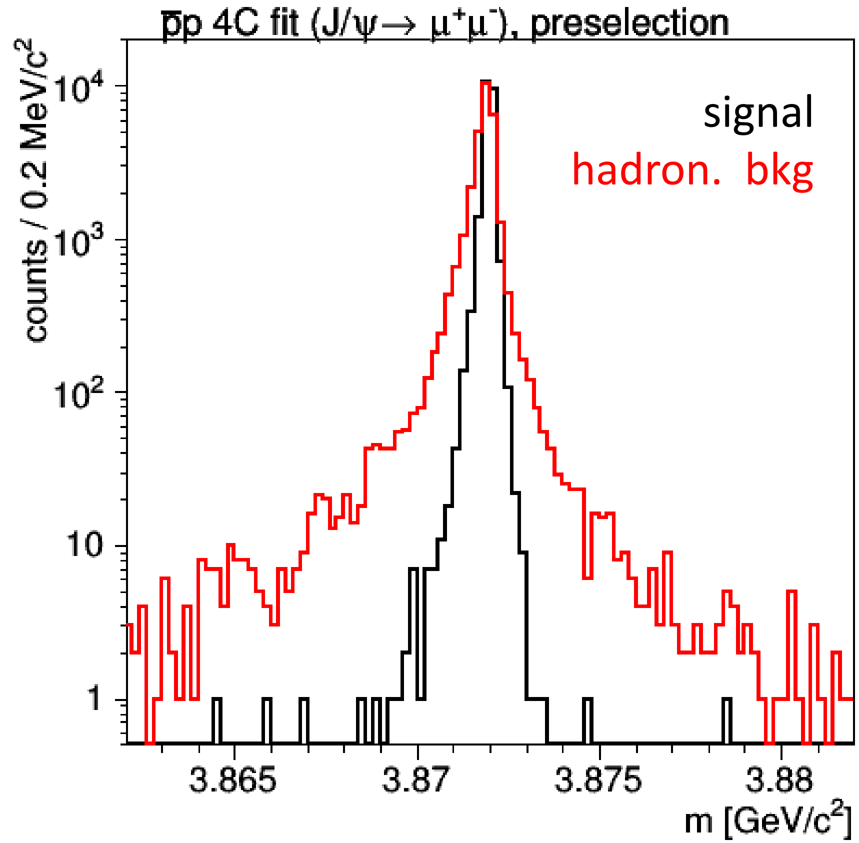


p̄p System after Preselection

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



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



Final Selection Criteria

- Final selection e^+e^-
  - Electron PID($e^\pm$) > 0.95
  - $m(e^+e^-)$ > 2.7 GeV/c^2
  - $p(e^+e^-)$ > 4.6 GeV/c
  - $p_{cm}(e^+e^-) < 0.38$ GeV/c
  - $\measuredangle(p_{e+},p_{e-}) < 2$ rad

- Final selection $\mu^+\mu^-$
  - Muon PID($\mu^\pm$) > 0.99
  - $p_{cm}(\mu^+\mu^-) < 0.32$ GeV/c
  - $p_{cm}(\mu^\pm)$ > 1.37 GeV/c

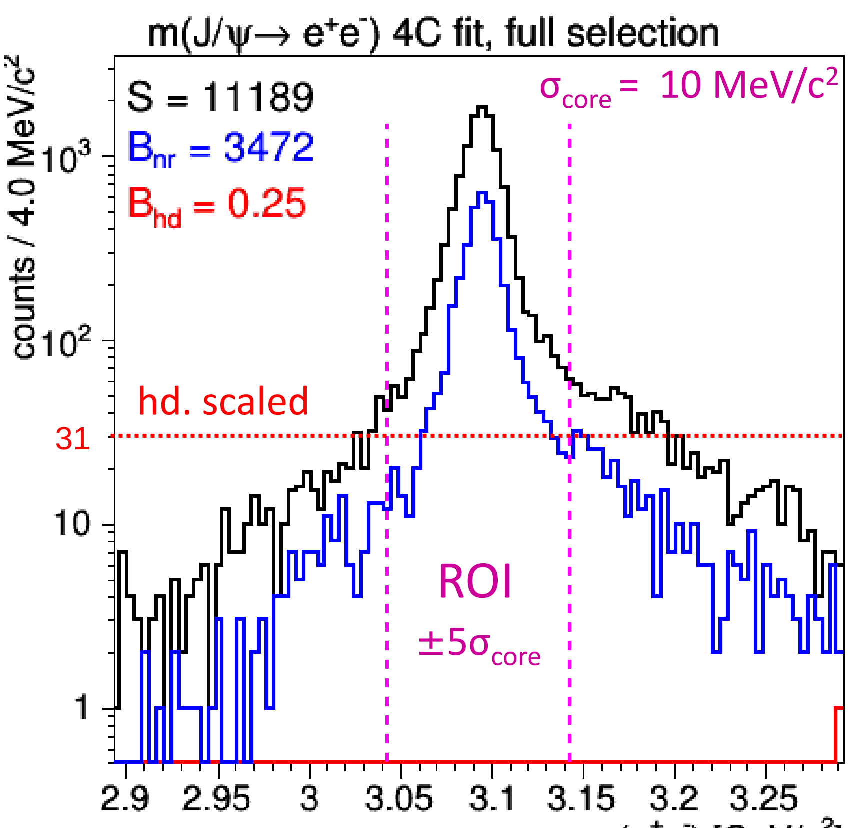
Final Selection Results

$J/\psi \rightarrow e^+e^-$

$\varepsilon_S = 11.4\%$

$\varepsilon_{B,nr} = 3.5\%$, $\varepsilon_{B,hd} = 2.6 \cdot 10^{-11}$

S:N = 4.6 : 1

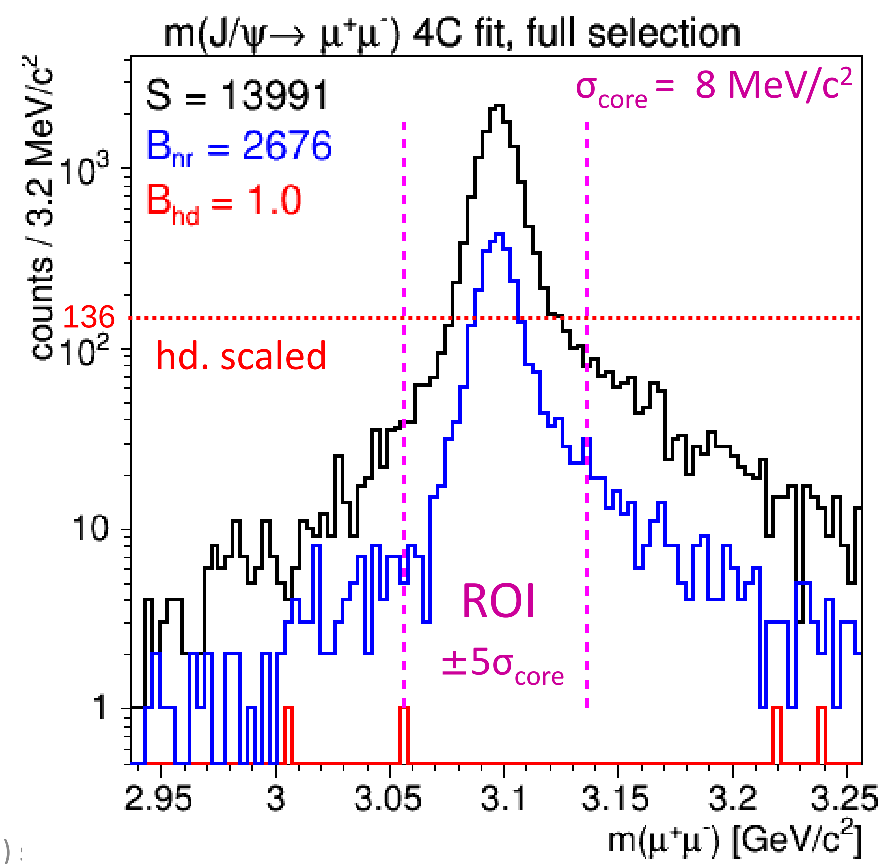


$J/\psi \rightarrow \mu^+\mu^-$

$\varepsilon_S = 14.0\%$

$\varepsilon_{B,nr} = 2.7\%$, $\varepsilon_{B,hd} = 1.1 \cdot 10^{-10}$

S:N = 3 : 1



Energy Scan Part

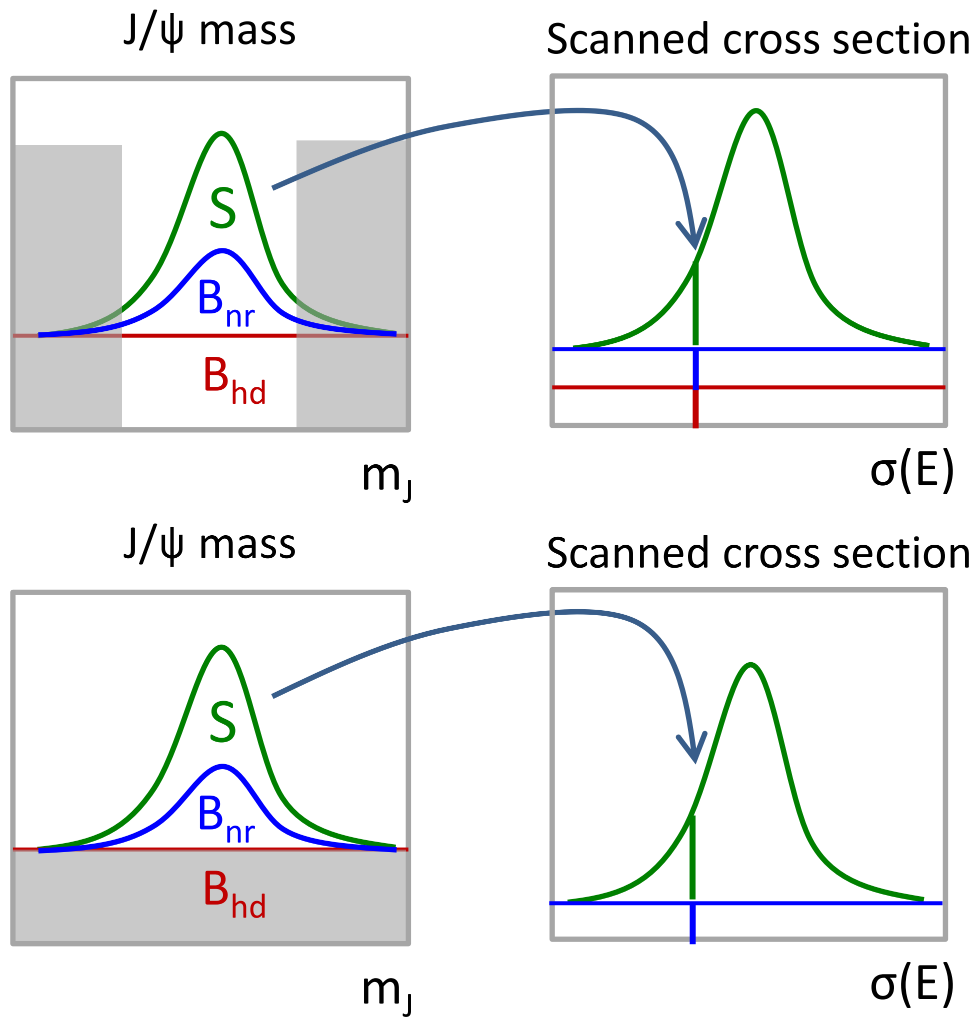
Possible Approaches

Two obvious approaches possible to extract lineshape:

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

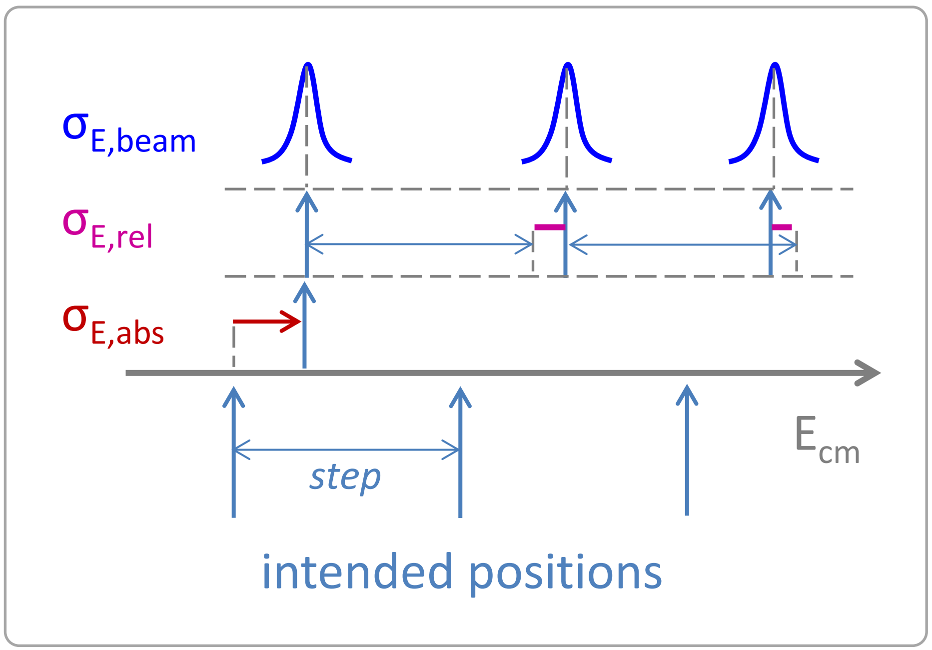
2. Fit signal in J/ψ mass
   - removes hadronic bkg
   - NR bkg still present

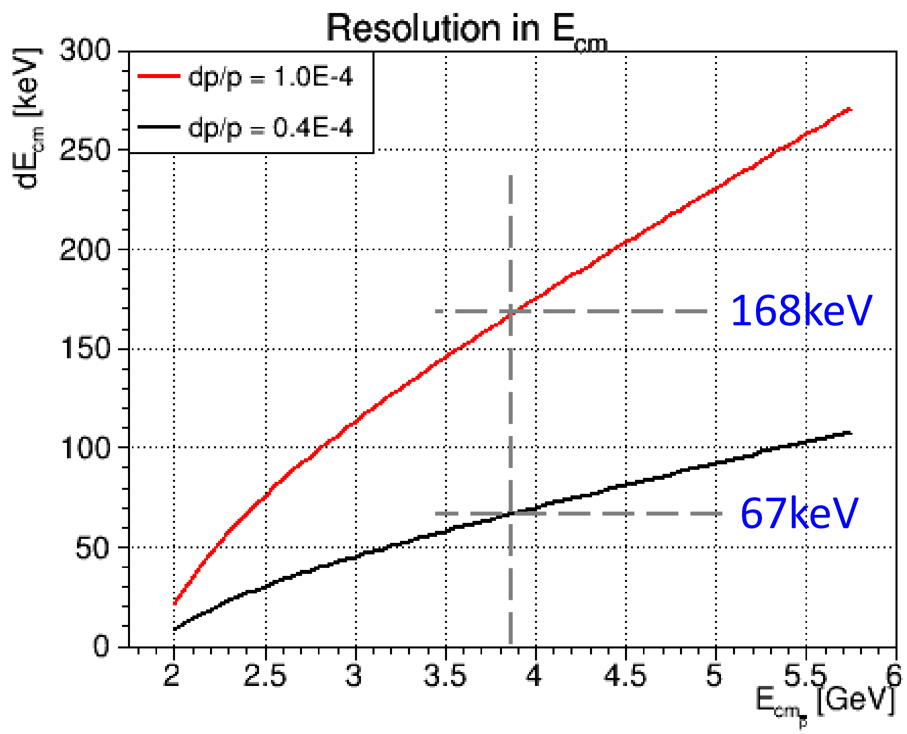
Show 2. method here
being slightly better than 1.



Uncertainty Assumptions for Scan

- Beam related energy resolution: $\sigma_{E,beam}$ = 67(HR) / 168(HL) keV
- Absolute positioning resolution: $\sigma_{E,abs}$ = 100 keV (shift)
- Relative positioning resolution: $\sigma_{E,rel}$ = 10 keV (~ error in E_{cm})





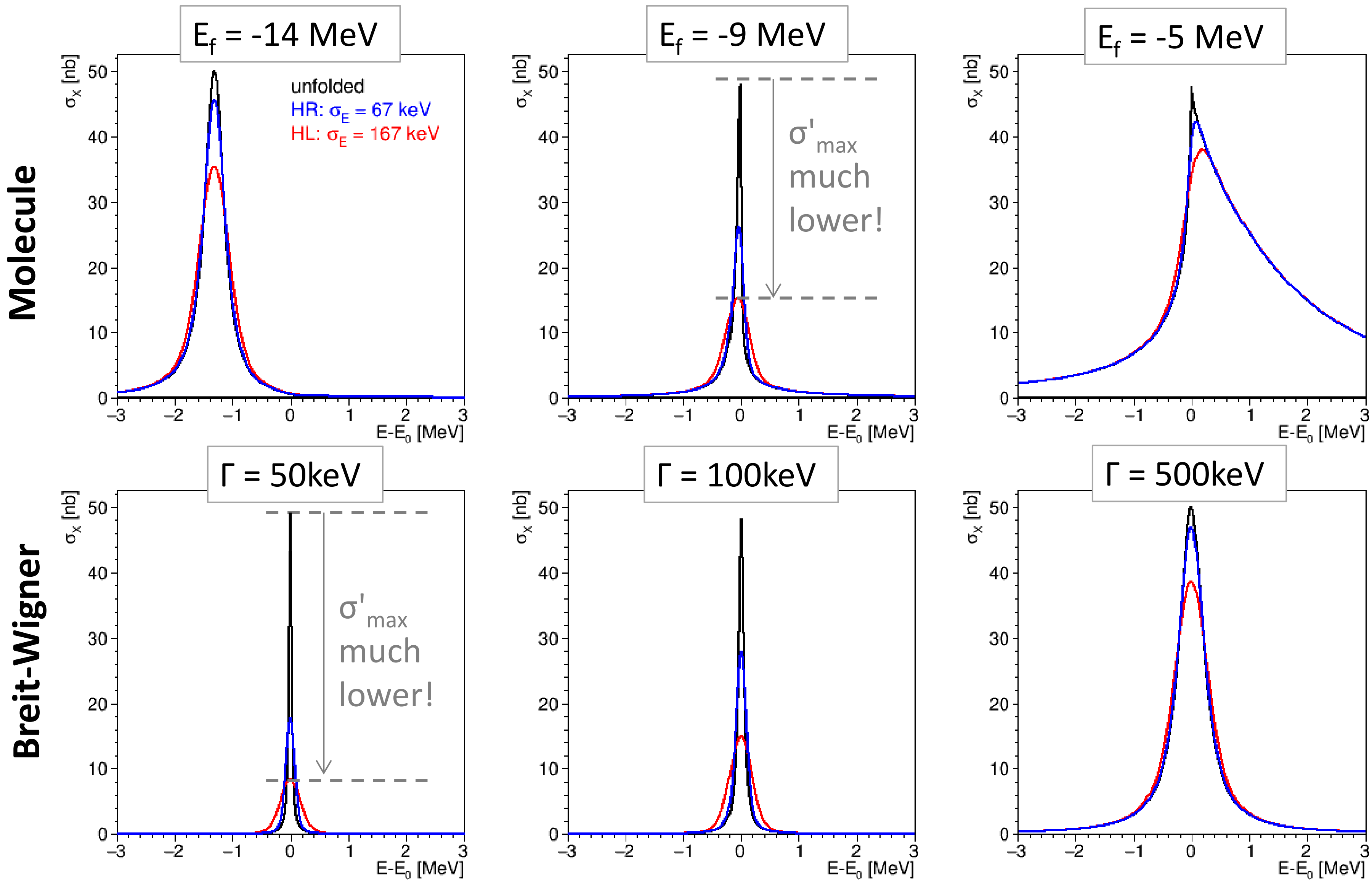
Procedure for Individual Scan

- **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 $\sigma_{S,max}$ = 50nb and adapt convoluted function $\sigma_S'(E) \rightarrow \sigma_S'_{,max} \leq$ 50nb
  - For each energy scan point (E_{cm})

    1. Modify energy $E_{cm} \rightarrow E_{cm}'$ due to $\sigma_{E,abs}$ and $\sigma_{E,rel}$
       (Uncertainty for i-th scan point $\Delta E_{cm,i} = \sqrt{i} \cdot \sigma_{E,rel}$)
    2. Compute expected S_0 / $B_{hd,0}$ / $B_{nr,0}$ based on $\sigma_S'(E_{cm}')$ / $\sigma_{B,hd}$ / $\sigma_{B,nr}$
    3. Generate Poissonians S / B_{hd} / B_{nr} from expected numbers
    4. Generate J/ψ data with S+B_{nr} signal and B_{hd} 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

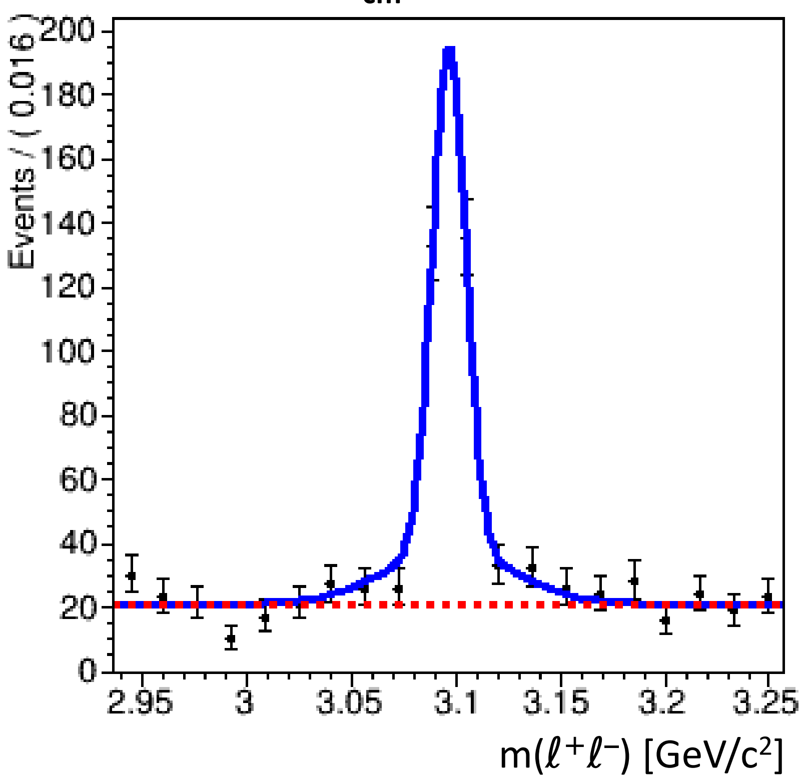
Lineshape Examples



Generated J/ψ Plots Examples

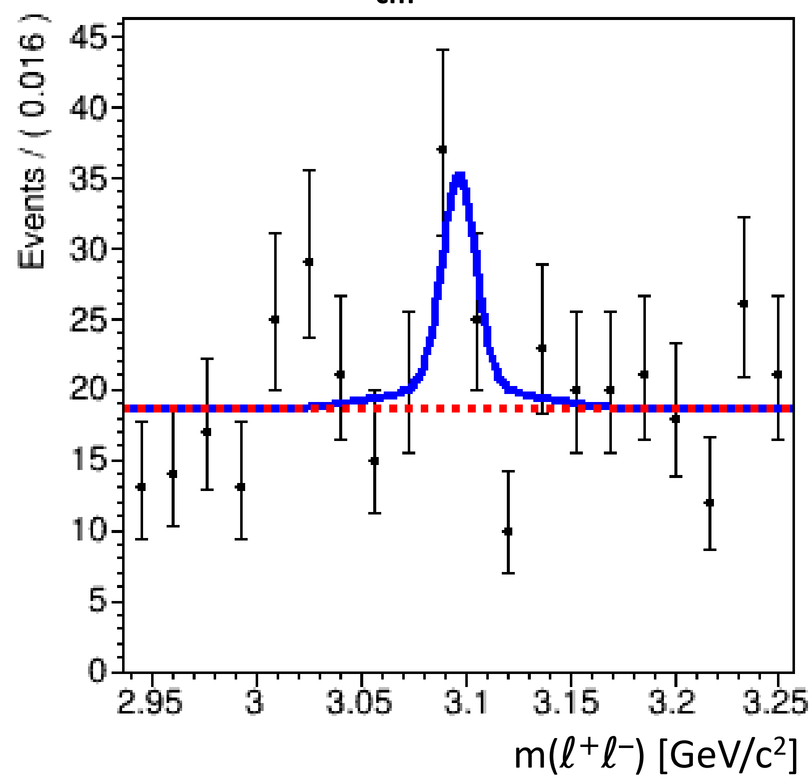
- Signal pdf like in true reco; hadr. background flat
- Scale efficiencies from ROI to full window width ($\varepsilon_S \times 1.1$, $\varepsilon_B \times 4$)

E_{cm} in peak



$$S = 275.8 \,^{+16.8}_{-16.7}$$

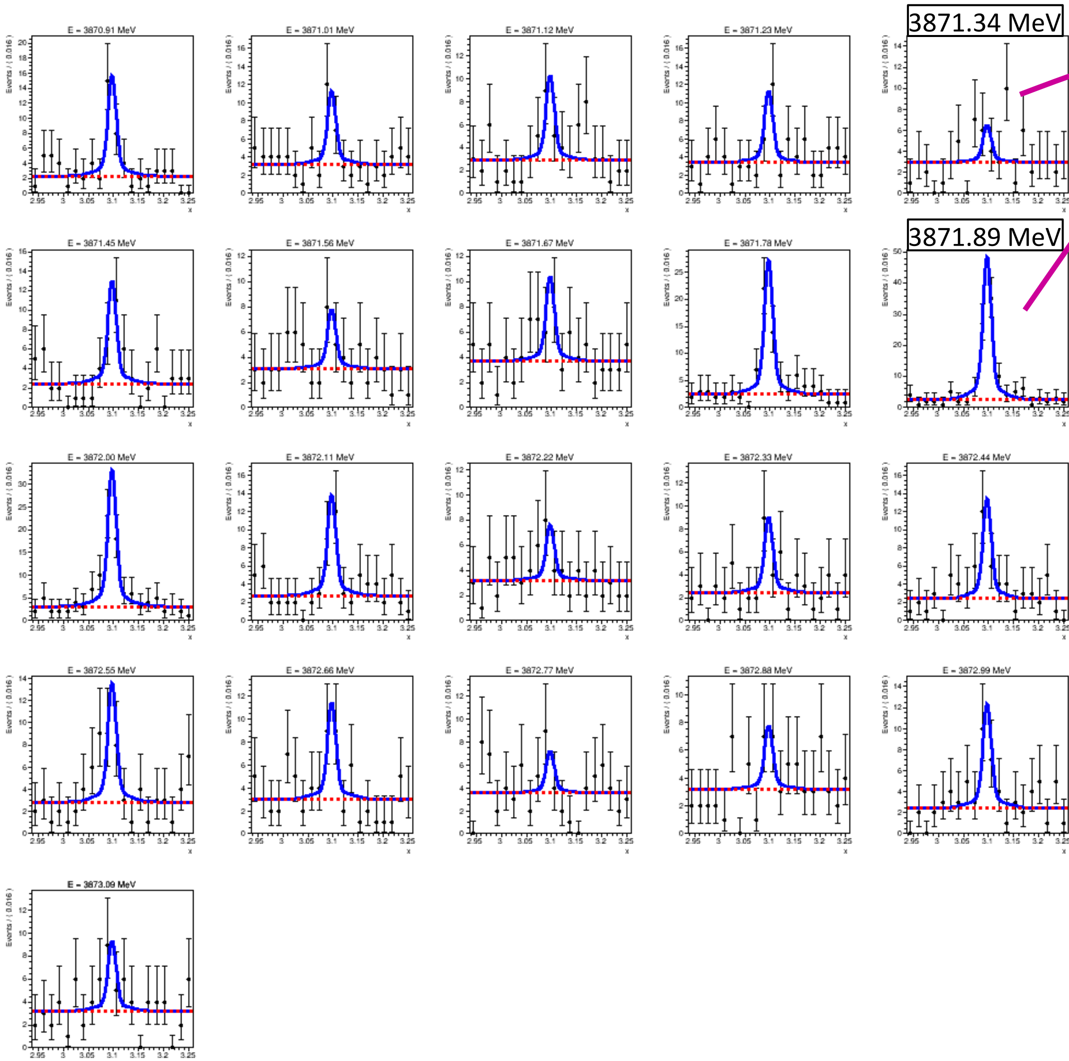
E_{cm} in tail

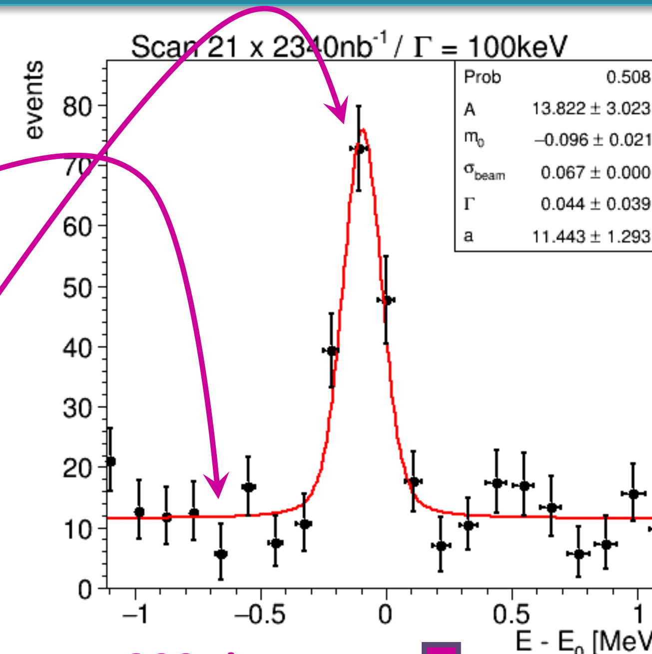


$$S = 26.1 \,^{+9.7}_{-9.0}$$

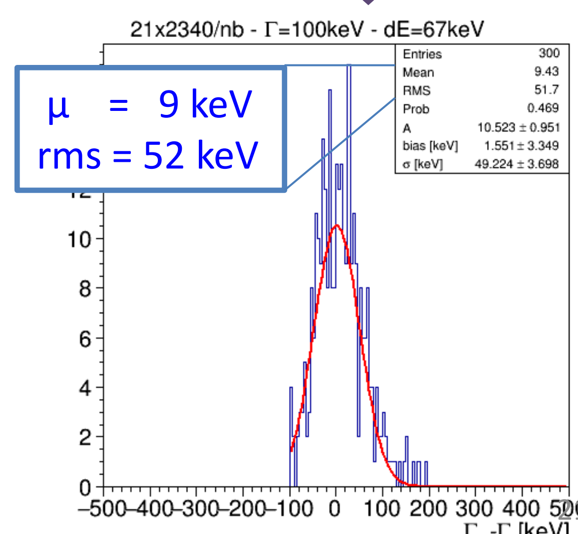
Illustration for Scan

BW, 21 x 2d in HESRr mode





300 times ...



Investigated Scenarios

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

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

- Parameter settings: $N_P = 8$

BW	Γ [keV]	50	70	100	130	180	250	500	800
Molecule	$-E_f$ [MeV]	14	12	10	9	8	7	6	5

- Investigated scenarios: $N_S = 5$

Mainly show results for this one

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

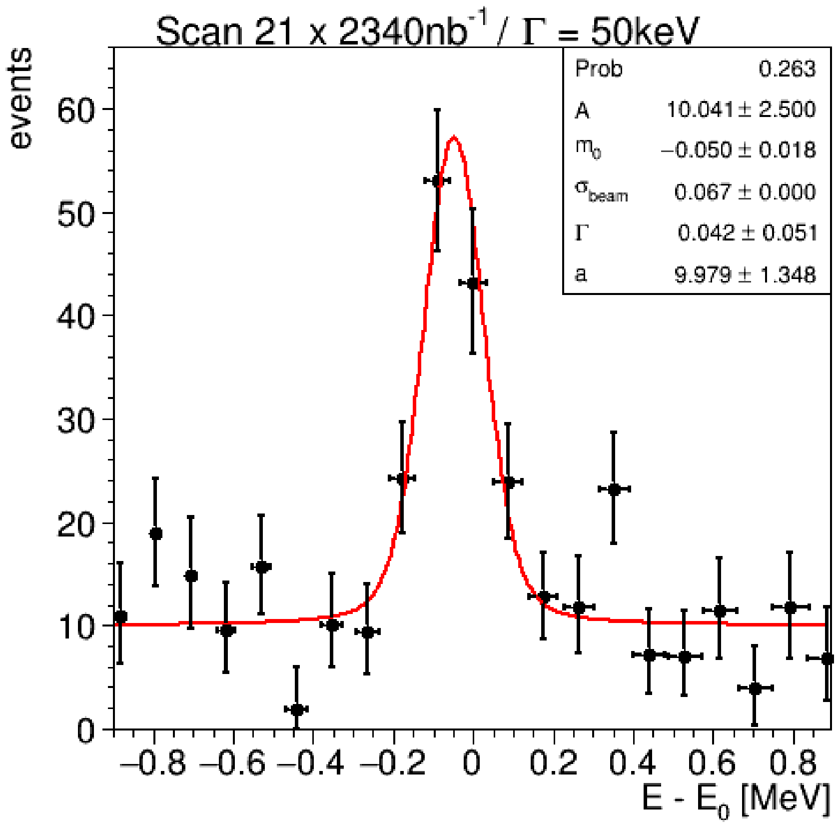
- Toy MC fits: N_{MC} = 100 ... 300 ($N_{tot} \approx 50000$)

Physics mode	Breit-Wigner Γ	Molecule E_f
Number of fits	150 ... 300 / setup	100 / setup

Scan Examples Breit Wigner

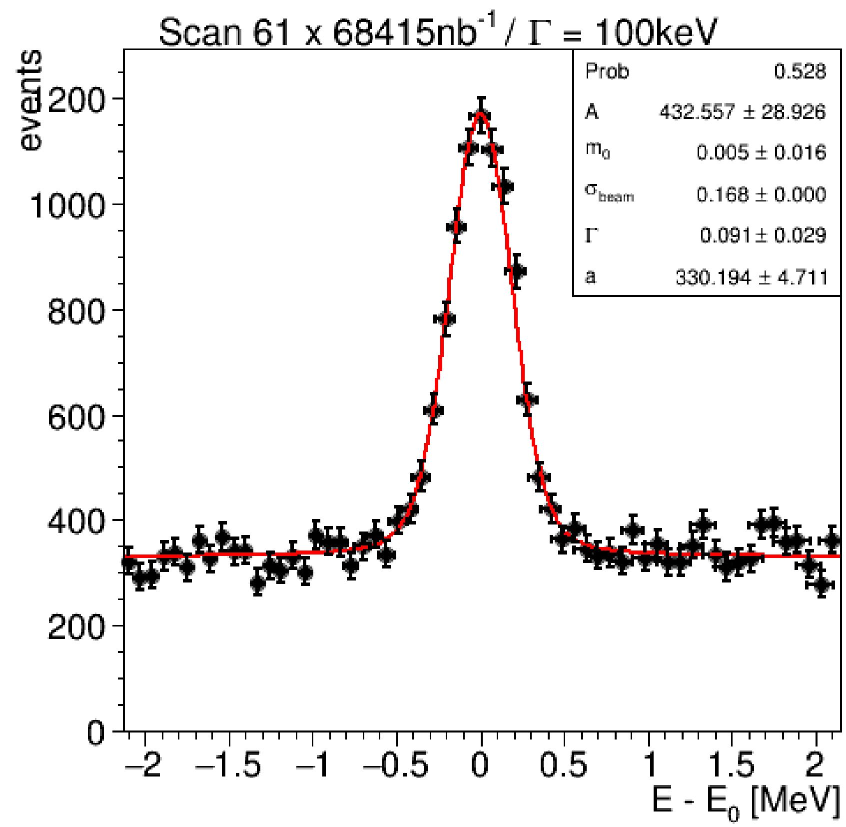
HESRr: 21 x 2 days

Γ = 50 keV



HL: 61 x 5 days

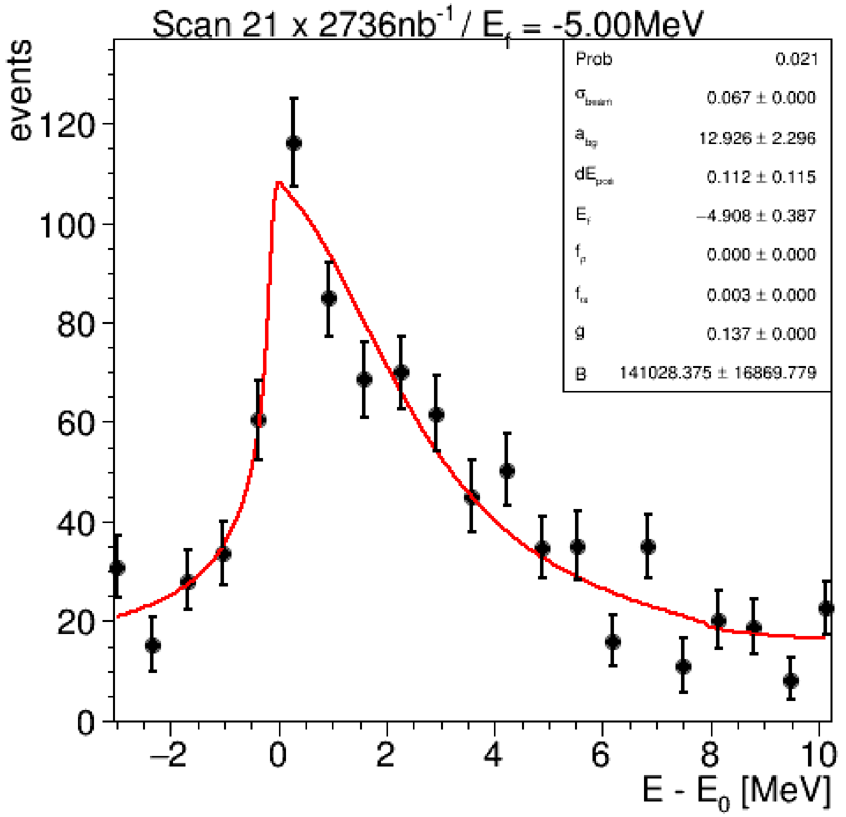
Γ = 100 keV



Scan Examples Molecule Lineshape

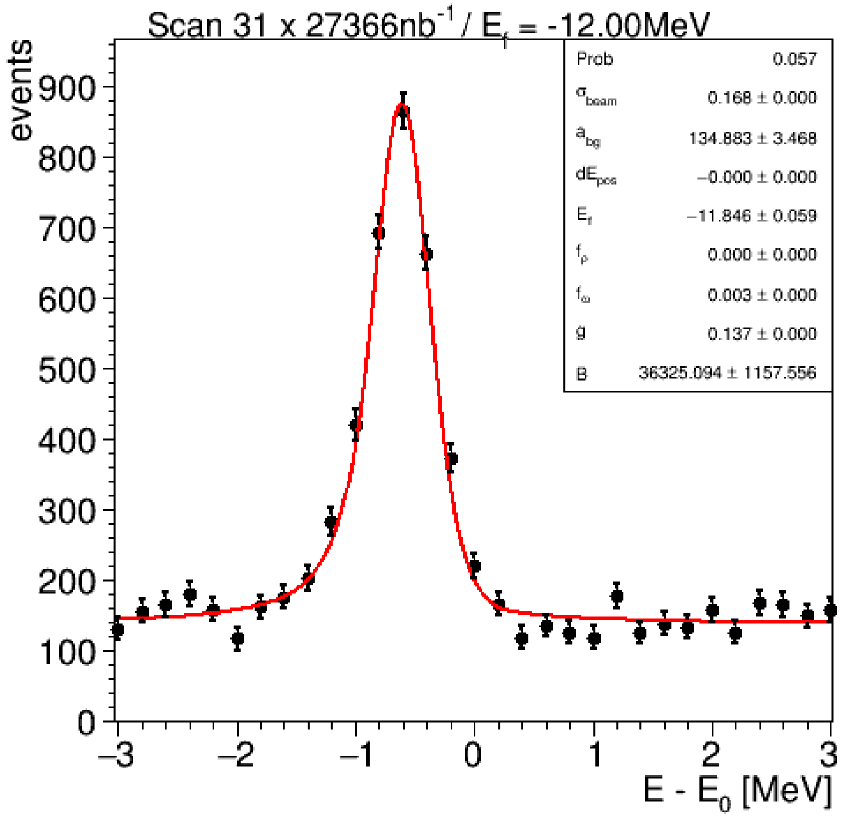
HR: 21 x 2 days

E_f = -5 MeV



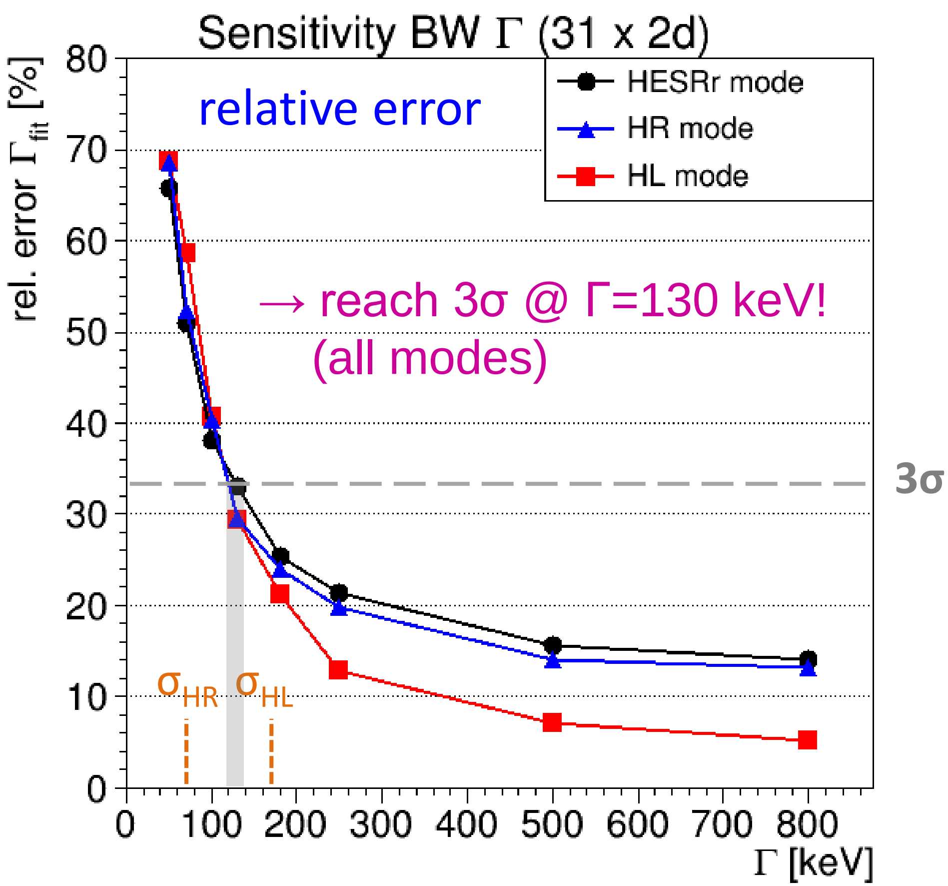
HL: 31 x 2 days

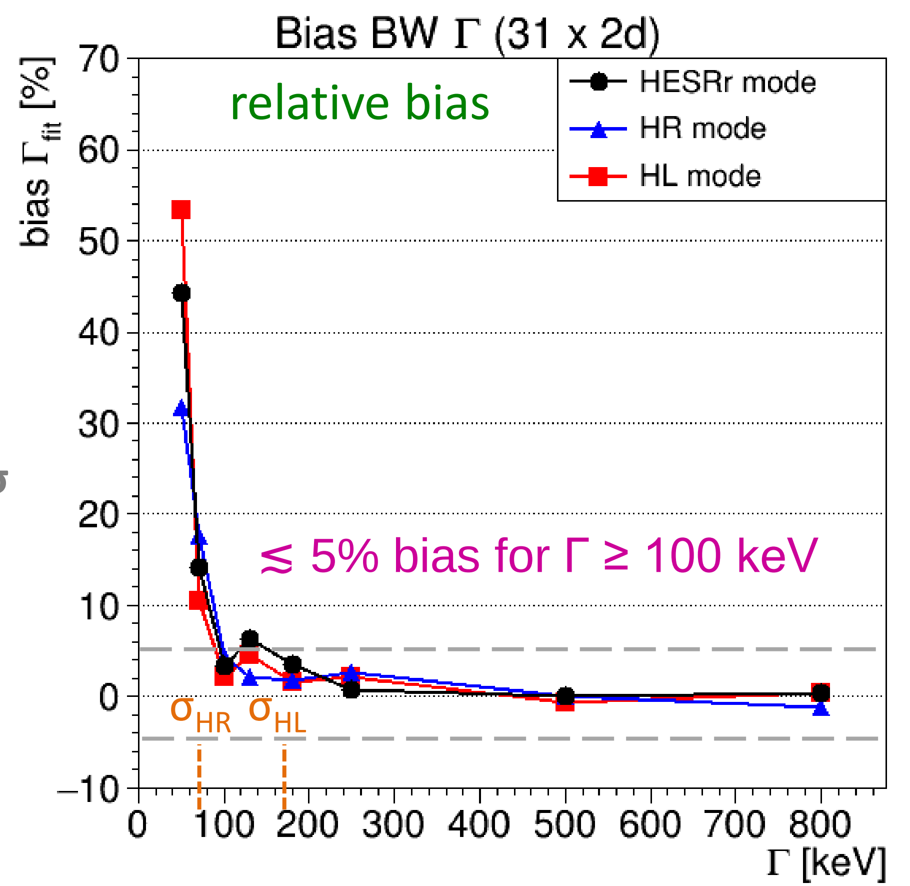
E_f = -12 MeV



Sensitivities Breit-Wigner Γ (31 x 2d)

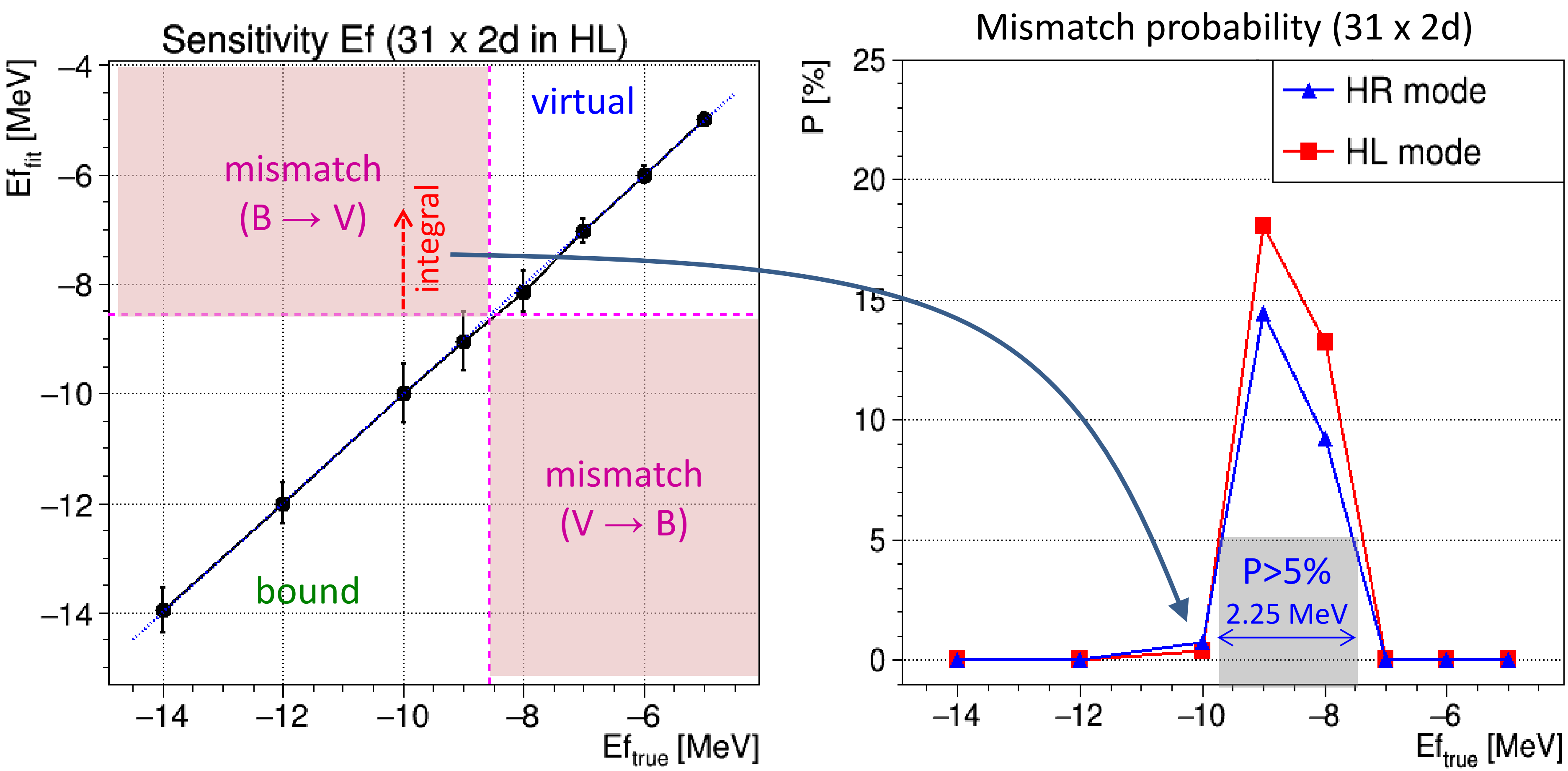
- Extract standard deviation and bias from toy MC fits (ML)
- Show relative error $rms_{fit}/\bar{\Gamma}_{fit}$ and bias $(\bar{\Gamma}_{fit} - \Gamma)/\Gamma$ in [%]





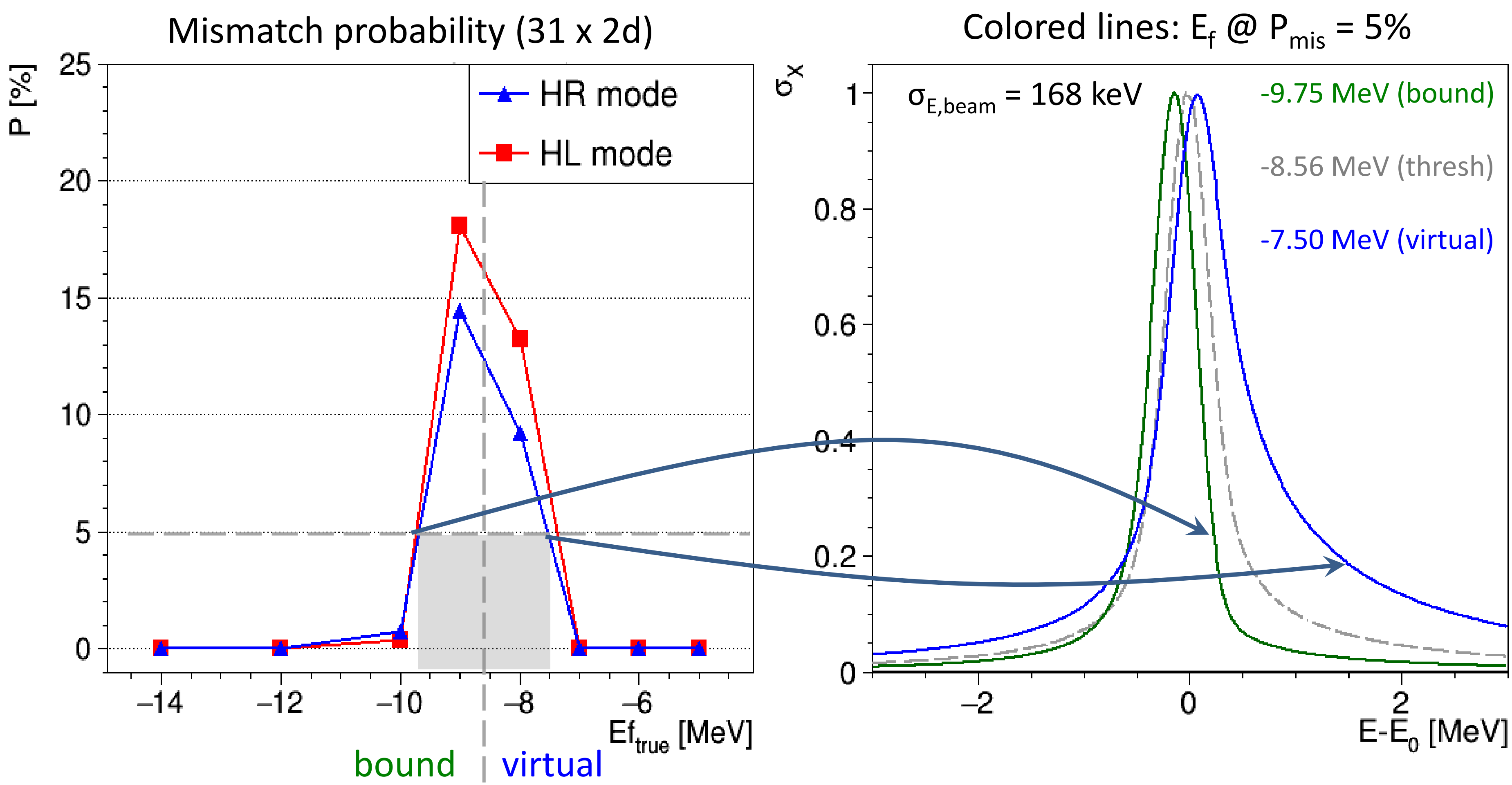
Sensitivities Molecule Lineshapes (31 x 2d)

- Extract standard deviation and bias from toy MC fits
- How well can virtual and bound state be distinguished?
- Uncertainty = $\sigma_{Gaussian}$ → Integrate in mismatch region



Probability of Mismatch (31x2d)

- How do the lineshapes look like?



Summary

- Investigation of X(3872)-Scan at PANDA in various scenarios
- Determined sensitivity for BW width measurement
  - Reach $\Gamma/\sigma_\Gamma > 3$ at $\Gamma \gtrsim 130$ keV (2 months data)
  - For $\Gamma \geq 100$keV bias $\Delta\Gamma/\Gamma \leq 5\%$ (")
  - HL mode superior for $\Gamma > 180$ keV
- Determined sensitivity for molecular lineshape measurement
  - Possible to distinguish bound/virtual state
  - Outside $\Delta E_f = 2.25$ MeV trans. region $P > 95\%$ for correct id.
  - HL and HR modes seem comparable
- Further steps
  - Improve suppression of $J/\psi\, \pi^+\pi^-$ NR background
  - Start writing analysis document

BACKUP

Background Prefilter

- Reasonable S/N sensitivity: need huge amount of BG

- Example calculation:
  - Signal: σ_S = 50 nb, $BR_{J/\psi}$ = 0.06, BR_X = 0.05, ε_S = 20%
  - 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

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

Preselection

$\varepsilon_S = 16.6\%$

$\varepsilon_{B,nr} = \varepsilon_S$, $\varepsilon_{B,hd} = 1.7 \cdot 10^{-8}$

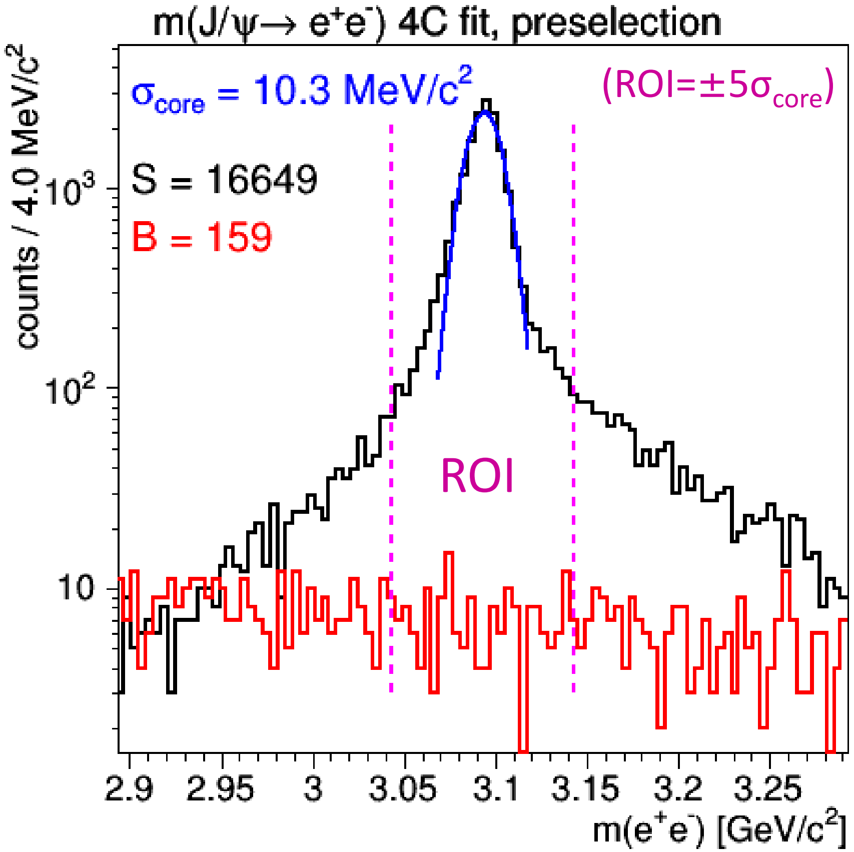
S:N = 1 : 32

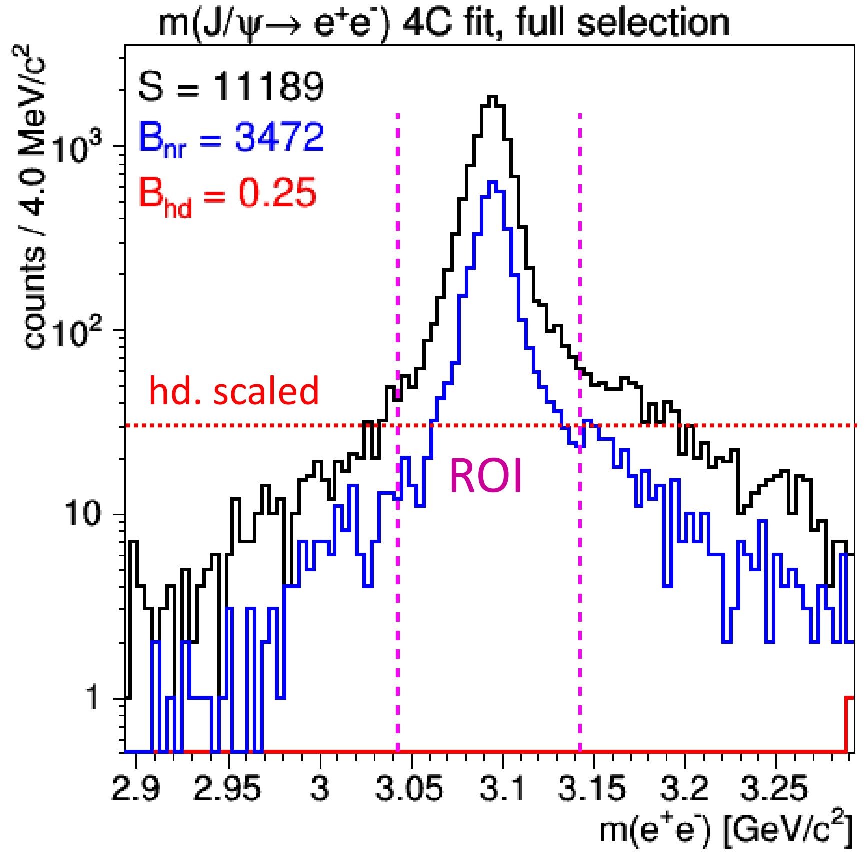
Final Selection

$\varepsilon_S = 11.4\%$

$\varepsilon_{B,nr} = 3.5\%$, $\varepsilon_{B,hd} = 2.6 \cdot 10^{-11}$

S:N = 4.6 : 1





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

Preselection

ε_S = 21.8%

$\varepsilon_{B,nr} = \varepsilon_S$, $\varepsilon_{B,hd} = 4.8 \cdot 10^{-7}$

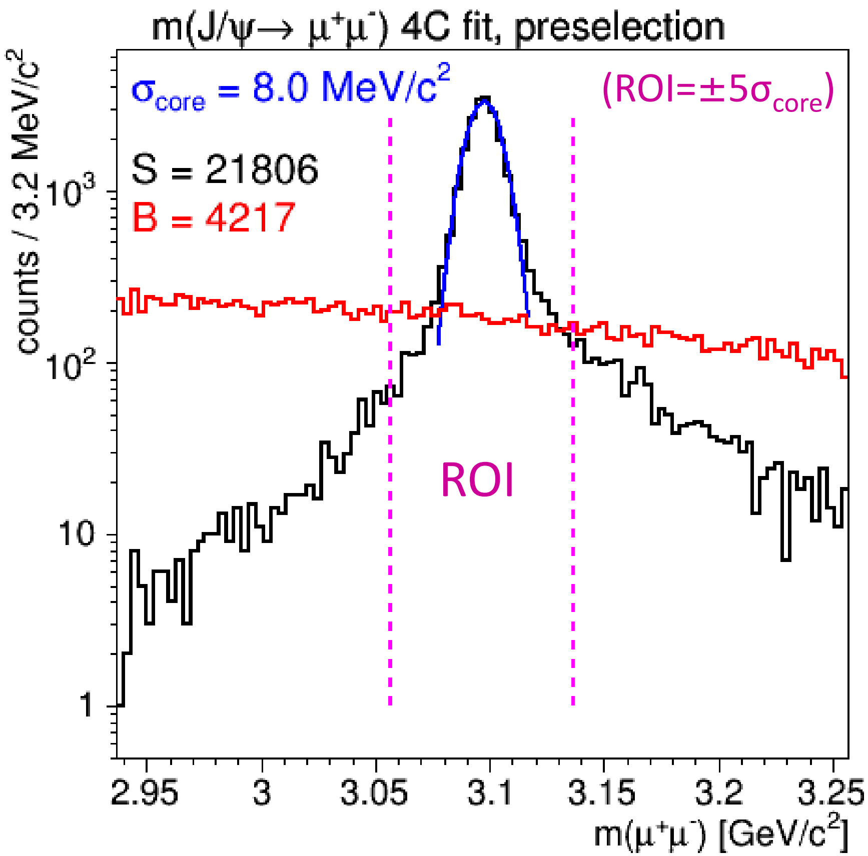
S:N = 1 : 670

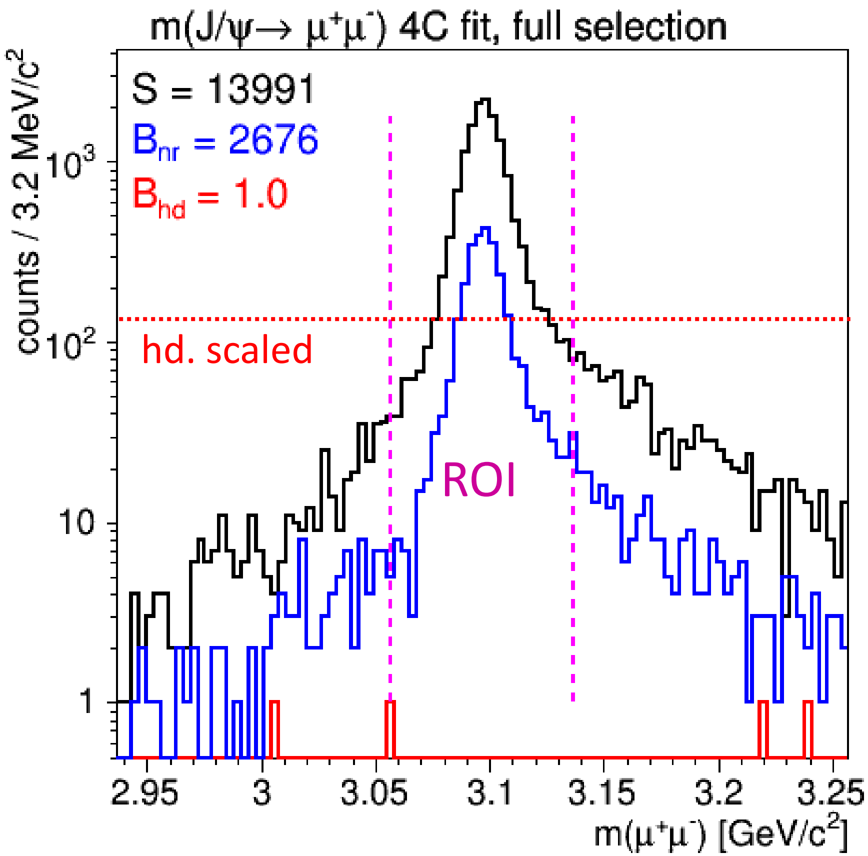
Final Selection

ε_S = 14.0%

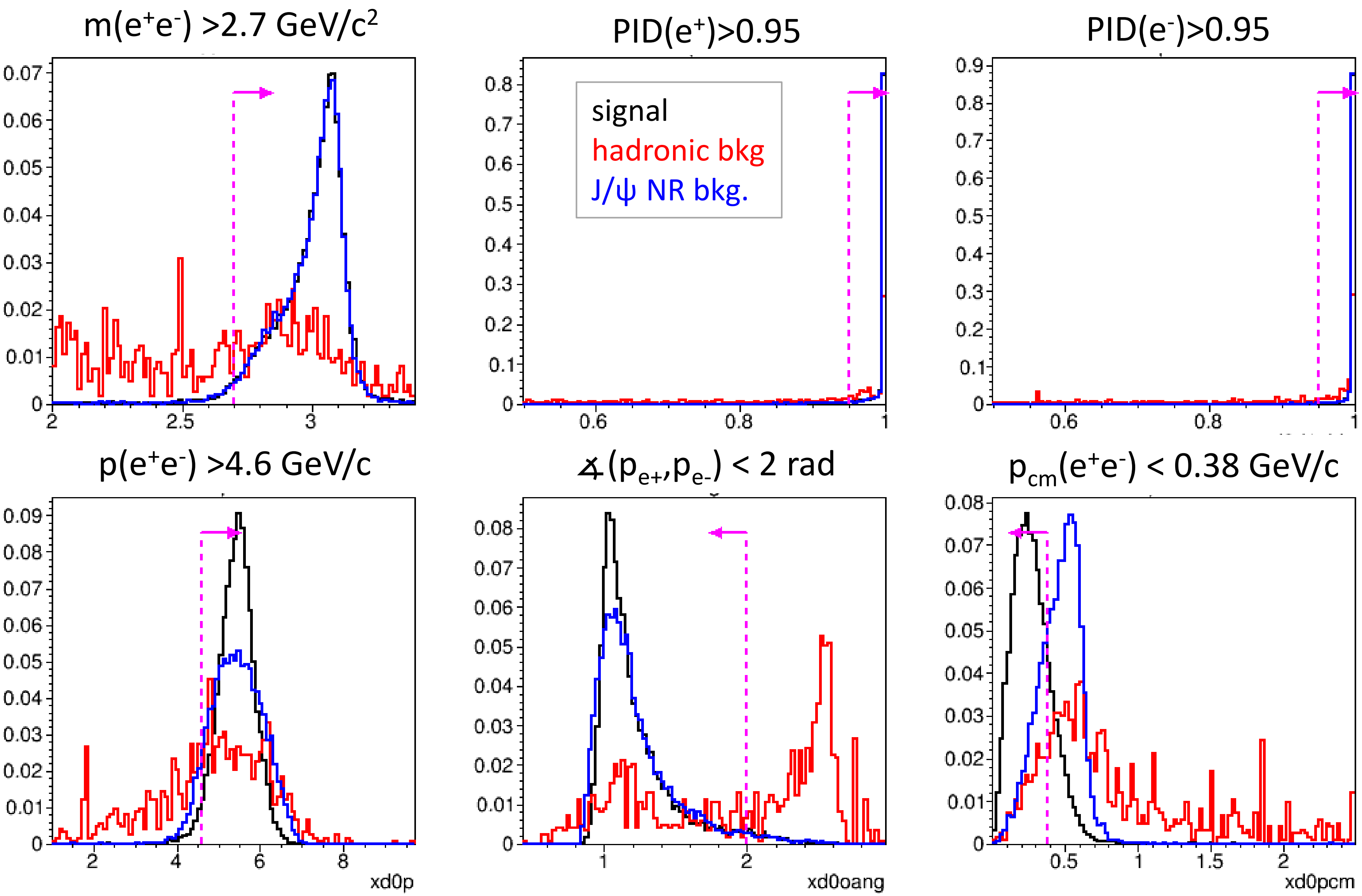
$\varepsilon_{B,nr}$ = 2.7%, $\varepsilon_{B,hd} = 1.1 \cdot 10^{-10}$

S:N = 3 : 1



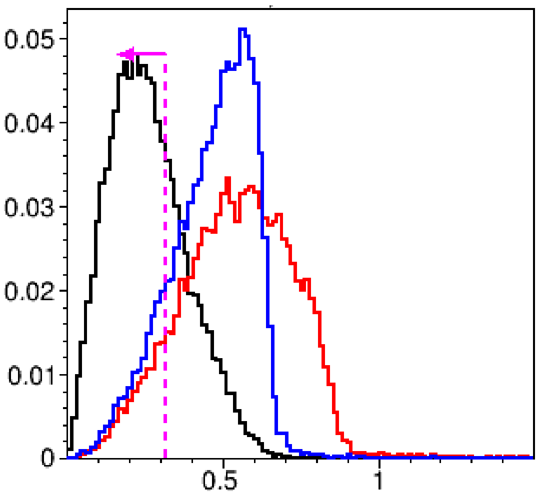


Criteria for J/ψ → e⁺e⁻ Channel

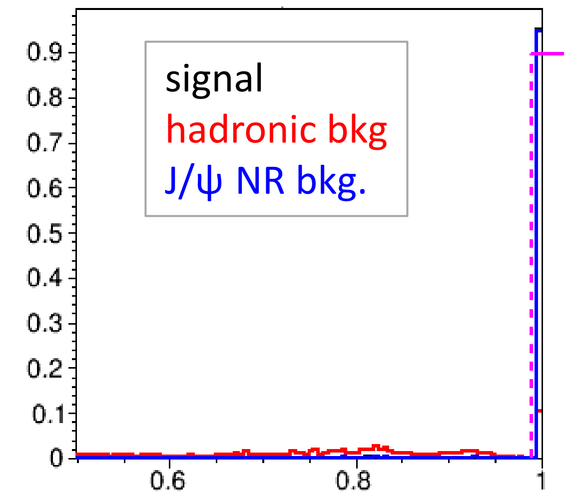


Criteria for $J/\psi \to \mu^+\mu^-$ Channel

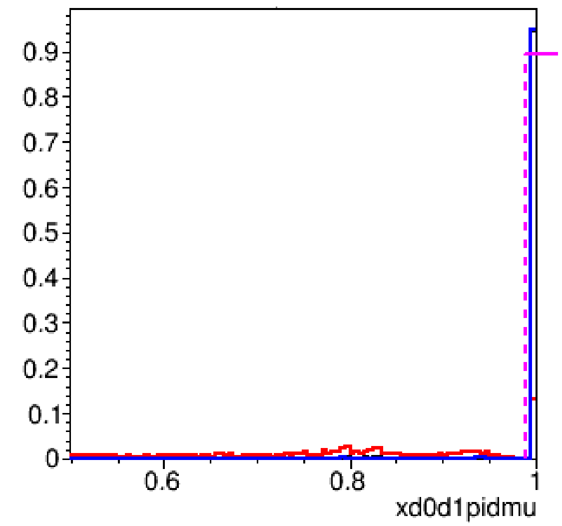
$p_{cm}(\mu^+\mu^-) < 0.32$ GeV/c



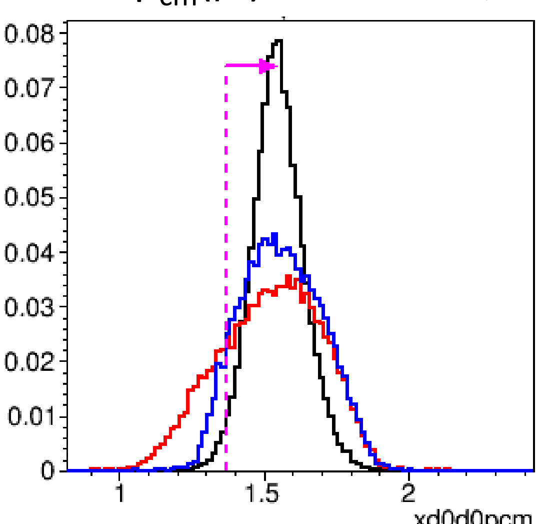
PID(μ^+)>0.99



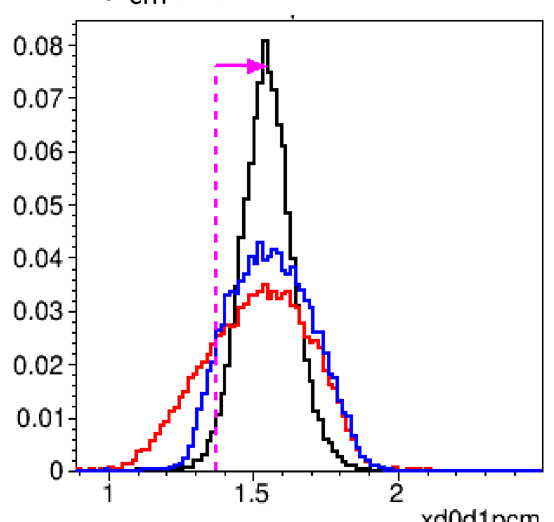
PID(μ^-)>0.99



$p_{cm}(\mu^+) > 1.37$ GeV/c



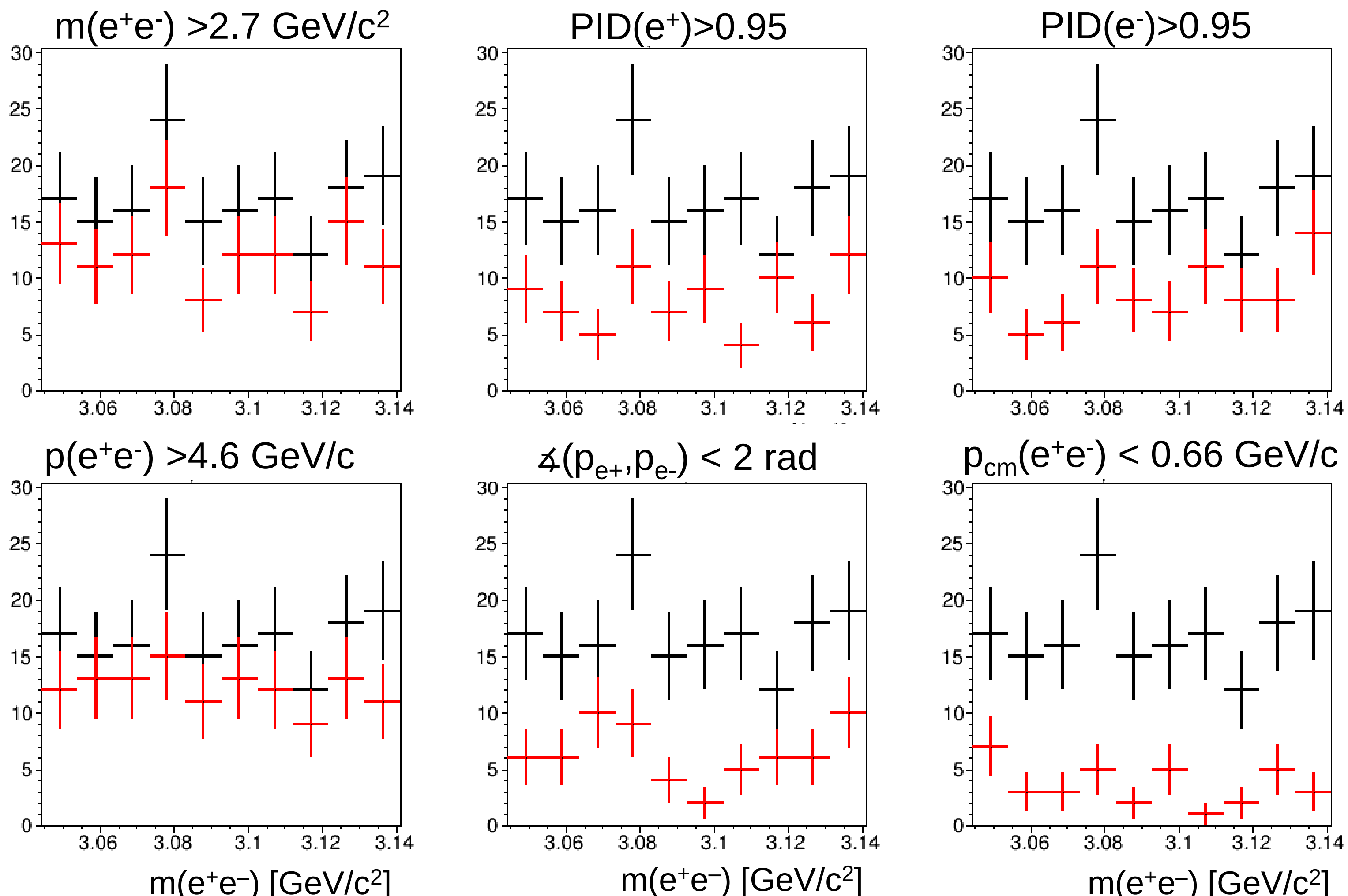
$p_{cm}(\mu^-) > 1.37$ GeV/c



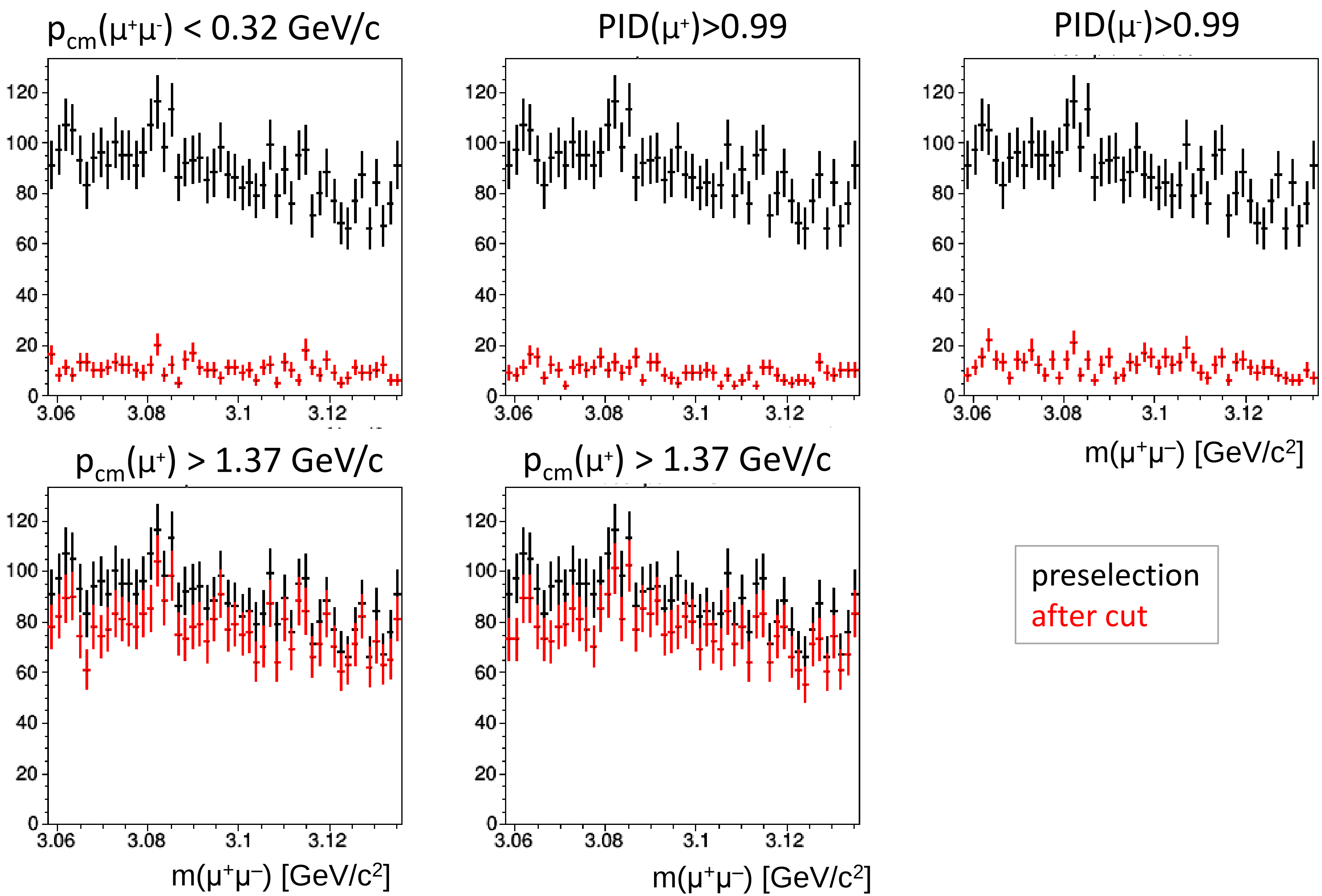
Flatness Check of Cuts

- We want to interpolate background in ROI
  - Cuts should not distort background shape!

preselection
after cut



Flatness Check of Cuts



Sensitivities Molecule Lineshapes (31 x 2d)

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