Simulation Studies of $X(3872) \to Z^{\pm}(3730)\pi^{\mp}$ Transitions

Status Update

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Search for X$\longrightarrow$ Z Transitions at $\bar{\text{P}}$ANDA

Motivation and Physics Case

- Multiple exotic Z states observed in the $c\bar{c}$ sector
  - Including charged, non-$c\bar{c}$ states, possibly isospin multiplets
- Mass values of observed $Z_c(3885)$, $Z_c(3900)$ and $Z_c(4020)$ close to the $\bar{D}\,D^*$ and $\bar{D}^*\,D^*$ thresholds

$\Longrightarrow$ Expect similar resonances for $\bar{D}\,D$ system, with masses close to $M(\bar{D}D) = 3730\,\text{GeV}/c^2$ and $J^P = 0^+$
  - Still unobserved
- Observed transitions between $Y(4260) \to Z(3900)^- \pi^+$ and $Y(4260) \to X(3872)\,\gamma$
- Transitions between X and Z states still unobserved

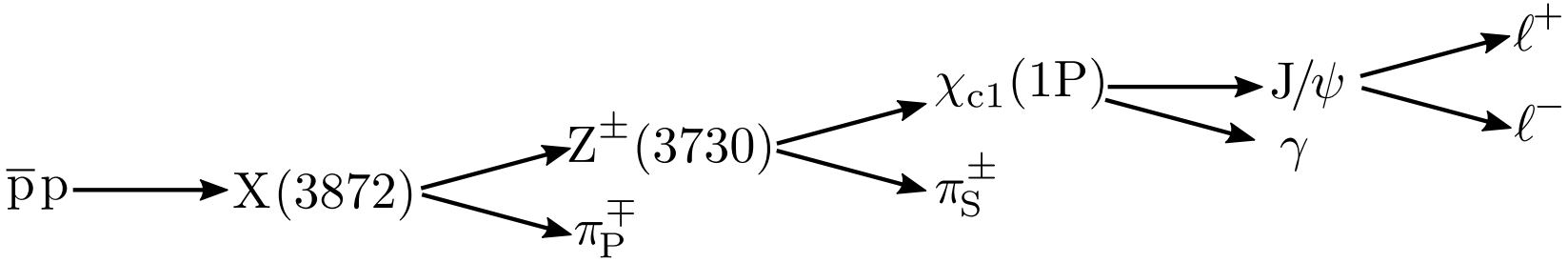
Search for X$\longrightarrow$ Z Transitions at $\bar{\text{P}}$ANDA

X$\longrightarrow$ Zπ Transitions

- Search for kinematically allowed but suppressed $X \leftrightarrow Z$ transitions such as X$\rightarrow$ Z π ($J^P = 1^+ \rightarrow 0^+0^-, \Delta L = 1$)
  - Competitive advantage of $\bar{\text{P}}$ANDA over $e^+ e^-$ experiments because of much higher X(3872) production rates
- Reconstruct Z(3730) from decays to $\chi_{c1}(1P)\pi$, considering both neutral and charged isospin partners
- Use large dataset from the planned $\bar{\text{P}}$ANDA run at $\sqrt{s} = 3.782$ GeV to study $X \leftrightarrow Z$ transitions without dedicated data run

Title

- Focus on:
  - Transitions w/ charged Z: X(3872) $\to$ Z(3730)$^{\pm}\pi^{\mp}$
  - Z(3730) $\to \chi_{c1}(1P)\pi^{\pm}$, $\chi_{c1} \to J/\psi\gamma$, $J/\psi \to \ell^+\ell^-$



- Goal: quantify potential to perform this study on the X(3872) line width scan dataset
  - $\mathcal{B}(Z \to \chi_{c1}(1P)\pi) \doteq \mathcal{B}(X \to Z\pi) \times \mathcal{B}(Z \to \chi_{c1}\pi)$ is unknown
  - Express sensitivity as lowest $\mathcal{B}(Z \to \chi_{c1}(1P)\pi)$ for which $\{3, 5\}\sigma$ can be obtained within a specified data-taking period
  - Study different scenarios varying $\mathcal{B}(Z \to \chi_{c1}(1P)\pi)$ and other free parameters of the analysis

Summary of Analysis Settings

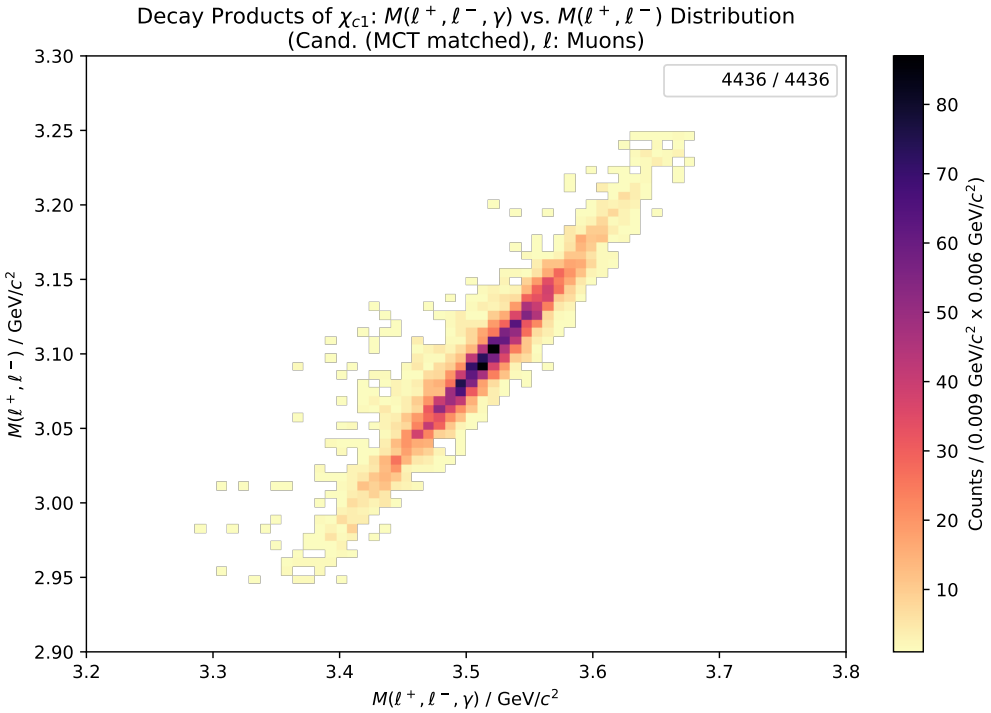
- PandaRoot version: release `feb17`
- 4 particles in the final state
  - ℓ^+, ℓ^- from J/ψ
  - γ from $\chi_{c1}(1P)$
  - π_S from $Z(3730)$
  - Not included in reconstruction: π_P from $X(3872)$
- PID criteria
  - `Best` PID
  - `pidSel = "PidAlgoIdeal{Charged}"`
- Preselection criteria
  - $0.1 < E_{CM}(\gamma) < 0.6\,\text{GeV}$
  - $p_T(\ell) > 0.4\,\text{GeV}/c$
  - $p_T(\pi_S) < 0.5\,\text{GeV}/c$
- Candidate choice criteria
  - If $N_{cand} > 1$, choose candidate with minimum $|M_{reco,\,PCA}(Z) - M_{PDG}(Z)|$

Decorrelated Mass Observables

- Alternative to Mass Constraint Fit to improve mass resolution while minimizing biasing background in signal region
- Build linear combination of components plus constant offset from nominal mass to obtain minimal (and maximal) correlation, similar to PCA (Principal Components Analysis) techniques

Decorrelated Mass Observables

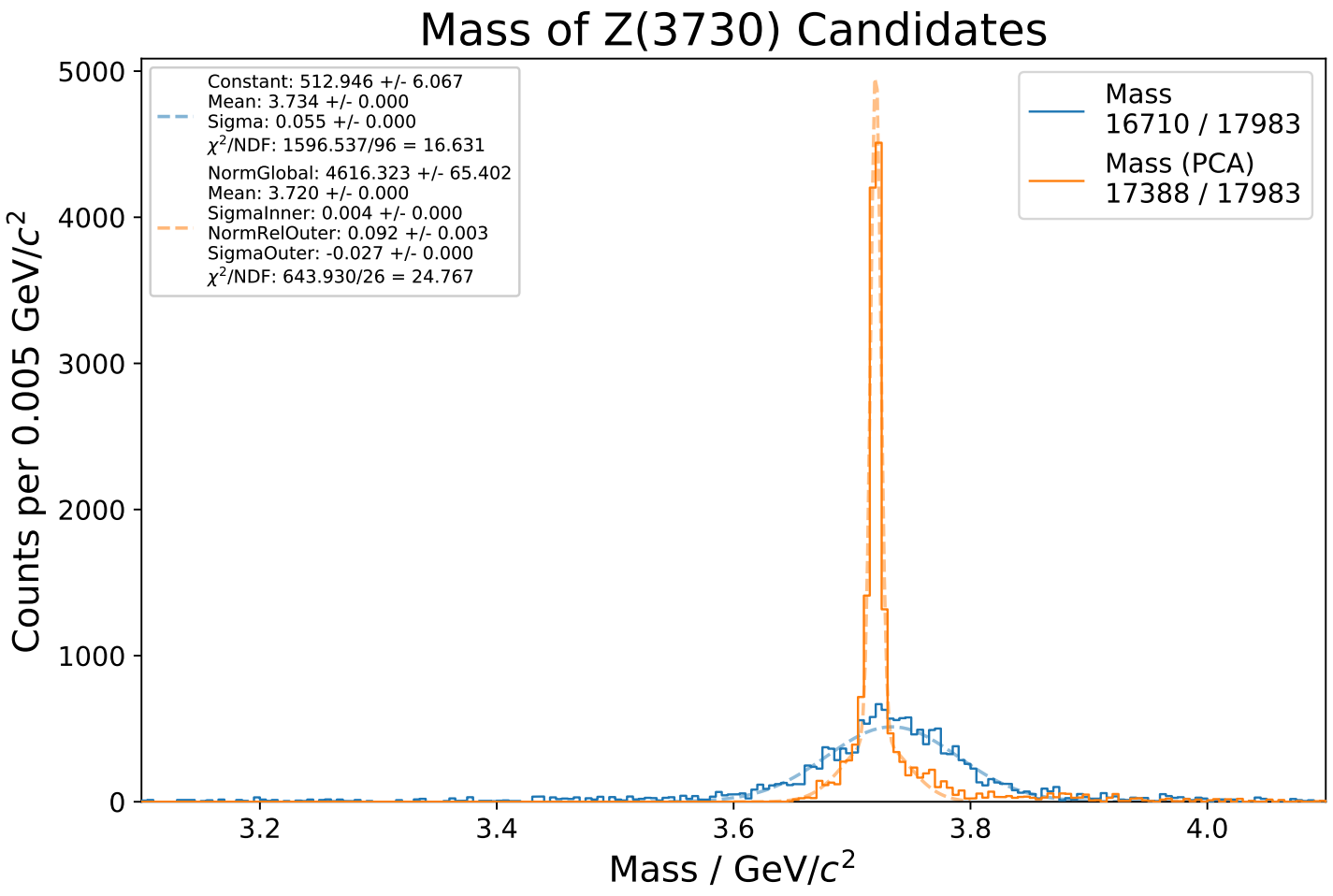
Example: $\chi_{c1}(1P)$ Mass



- $M_{\mathrm{PCA}}(\chi_{\mathrm{c1}}(1\mathrm{P})) = M(\gamma, \ell^+, \ell^-) - M(\ell^+, \ell^-) + (M_{\mathrm{PDG}}(\chi_{\mathrm{c1}}(1\mathrm{P})) - M_{\mathrm{PDG}}(\mathrm{J}/\psi))$
- $p_{4,\mathrm{PCA}}(\chi_{\mathrm{c1}}(1\mathrm{P})) = (p_3(\chi_{\mathrm{c1}}(1\mathrm{P})), M_{\mathrm{PCA}}(\chi_{\mathrm{c1}}(1\mathrm{P})))$

Decorrelated Mass

*Reconstructed **Z(3730)** Candidates*



Bkg Studies: DPM

- Study of DPM background using entire sample `DPM3872` from $\bar{\text{P}}$ANDA centralized production campaign
- Features of sample:
  - $N_{\text{sim}} = 2.5 \times 10^8$
  - Prefilter factor $F = N_{\text{gen}}/N_{\text{sim}}$: ~ 170

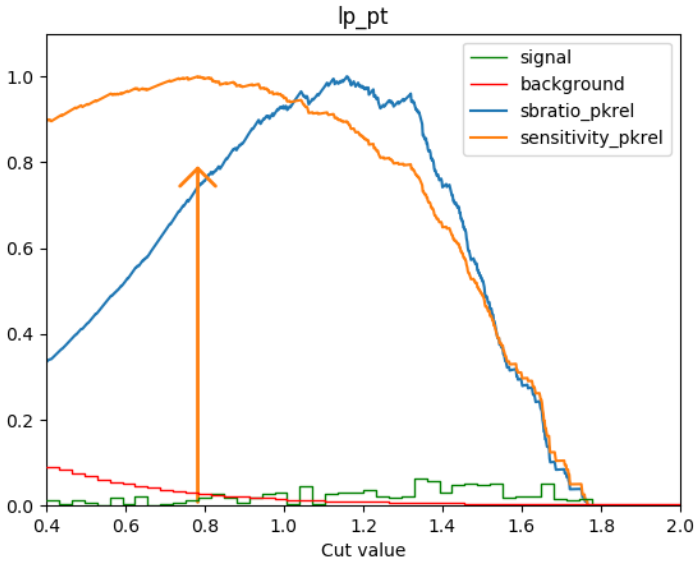
$\Longrightarrow$ $N_{\text{gen}} = 4.3 \times 10^{10}$

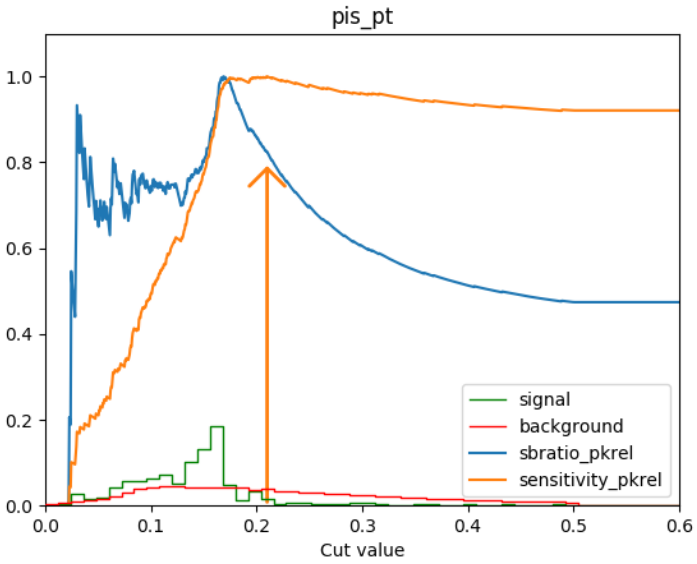
Bkg Studies: DPM

Cut Optimization

- Consider `sig` = $X(3872) \to Z^{\pm}(3730)\pi^{\mp}$, `bkg` = DPM
- Identify separating variables
- Vary 1D cuts in sequence so that figure of merit (significance $\Sigma = N_S/\sqrt{N_S + N_B}$) is maximized
- Study permutation of cut sequences:
  - Vary order in which cuts are applied
  - Measure shift of optimal cut value depending on cut order, verifying cut values are stable
  - Select combination which maximizes Σ
  - Verify that no bias is introduced in signal distributions

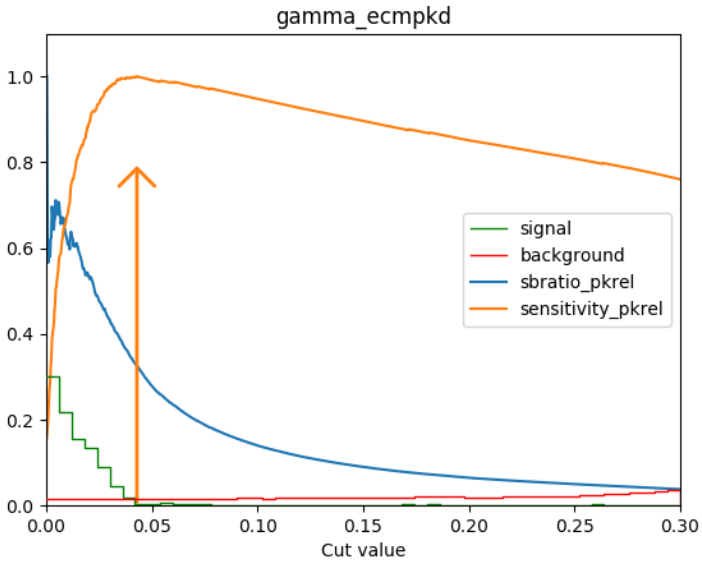
DPM Cut Optimization

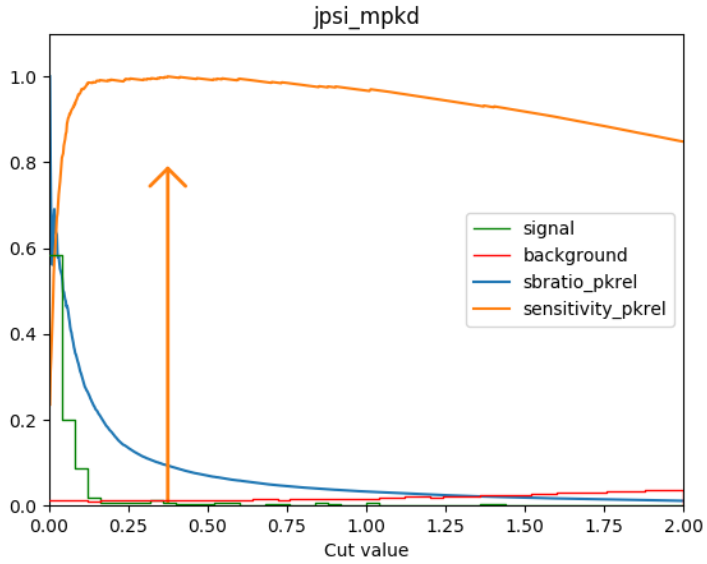




- Each cut applied independently

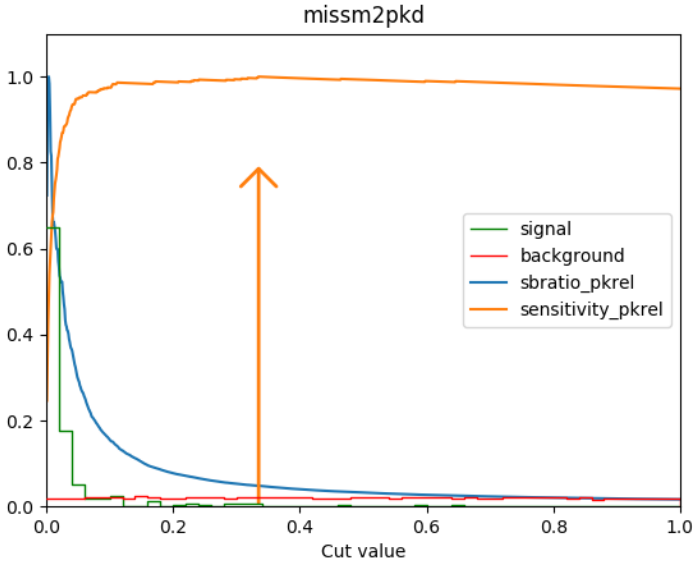
DPM Cut Optimization

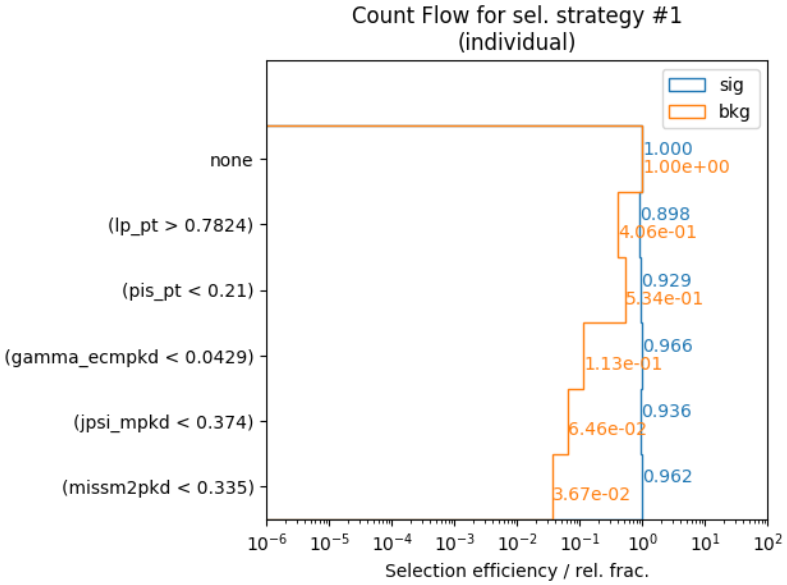




- Each cut applied independently

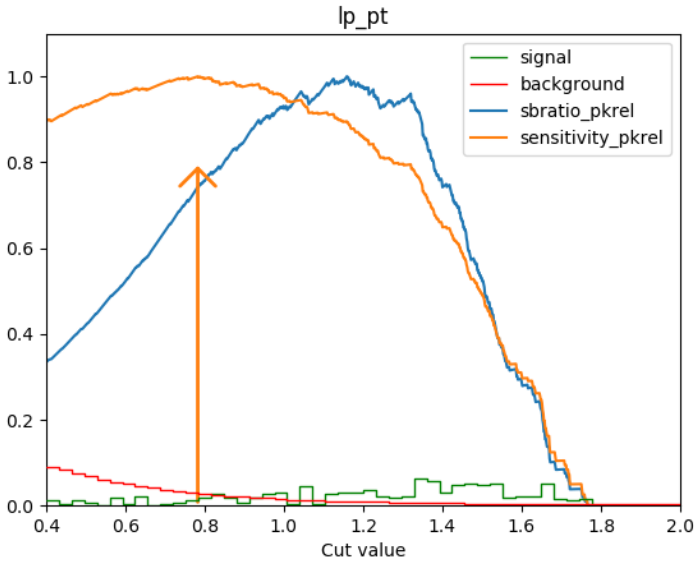
DPM Cut Optimization

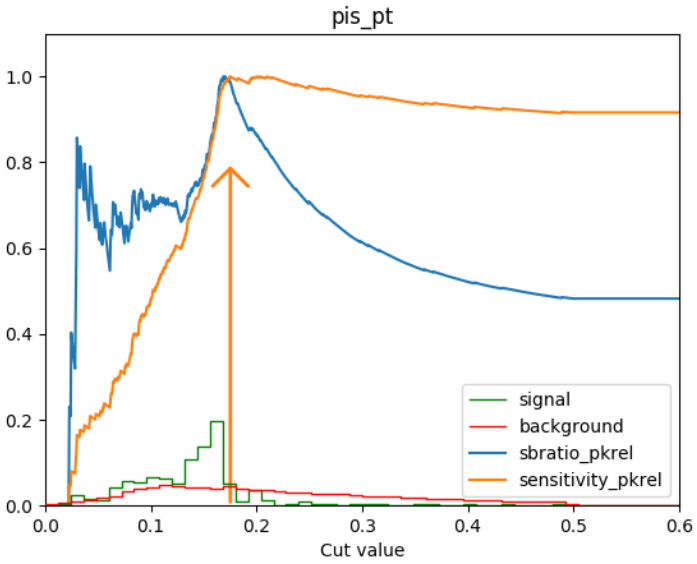




- Each cut applied independently
- Efficiencies relative to preselected samples

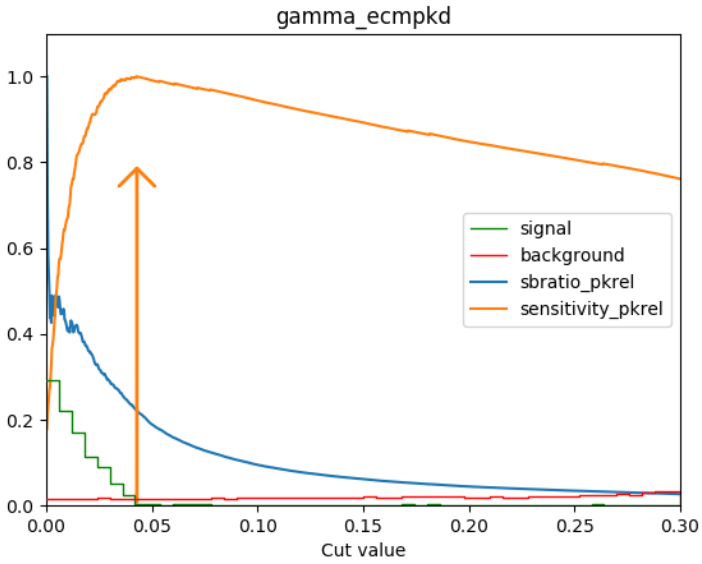
DPM Cut Optimization

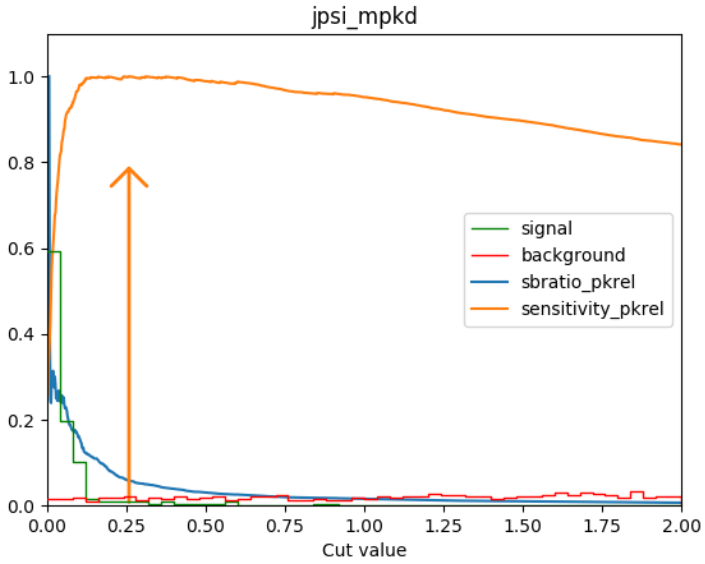




- Cuts applied cumulatively

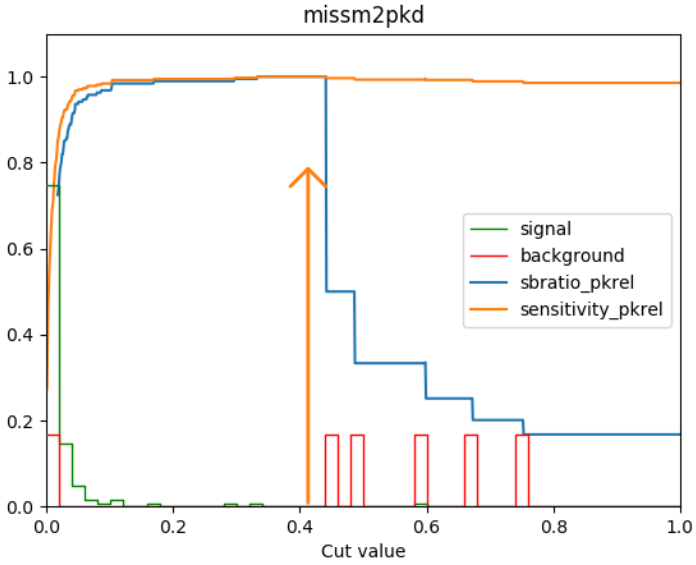
DPM Cut Optimization

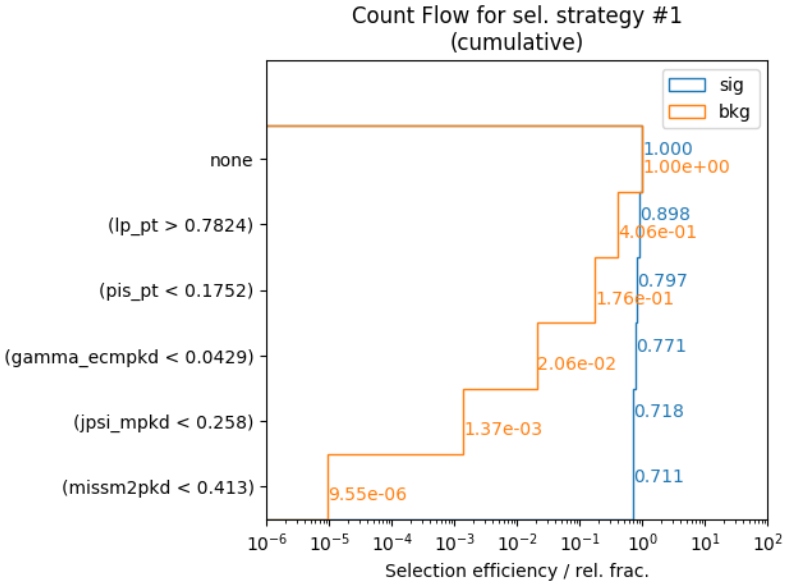




- Cuts applied cumulatively

DPM Cut Optimization





- Cuts applied cumulatively
- Efficiencies relative to preselected samples

DPM Study

Rate Calculation

- Bkg selection efficiency ε_B such that (down to) $N_{\text{DPM}} = 1$ events pass selection $\Longrightarrow$ high template uncertainty
- Calculate correspondence between size of simulated DPM sample and beamtime to quantify impact of this uncertainty on validity of estimates

$$N = \mathcal{L}t\sigma \Longrightarrow t = \frac{N}{\mathcal{L}\sigma}$$

- Using $\mathcal{L}_d = 0.864\,\text{pb}^{-1}\,\text{d}^{-1}$, $N_{\text{DPM}} = 4.3 \times 10^{10}$, $\sigma_{\text{DPM}} = 46\,\text{mb}$

$\Longrightarrow$ $t = 1.08\,\text{d}$

- Primary timeframe for this study is 2 days
- Large uncertainty on DPM background template acceptable considering expected event rate

Bkg Studies: Peaking

- Processes that have (at least) a real J/ψ in the final state
- $\sigma_{\mathrm{PK}} \ll \sigma_{\mathrm{DPM}}$, but
  - Separating power reduced since topology, kinematics closer to signal
  - Can become dominant when evaluating low values of $\mathcal{B}(Z \to \chi_{c1}(1P)\pi)$

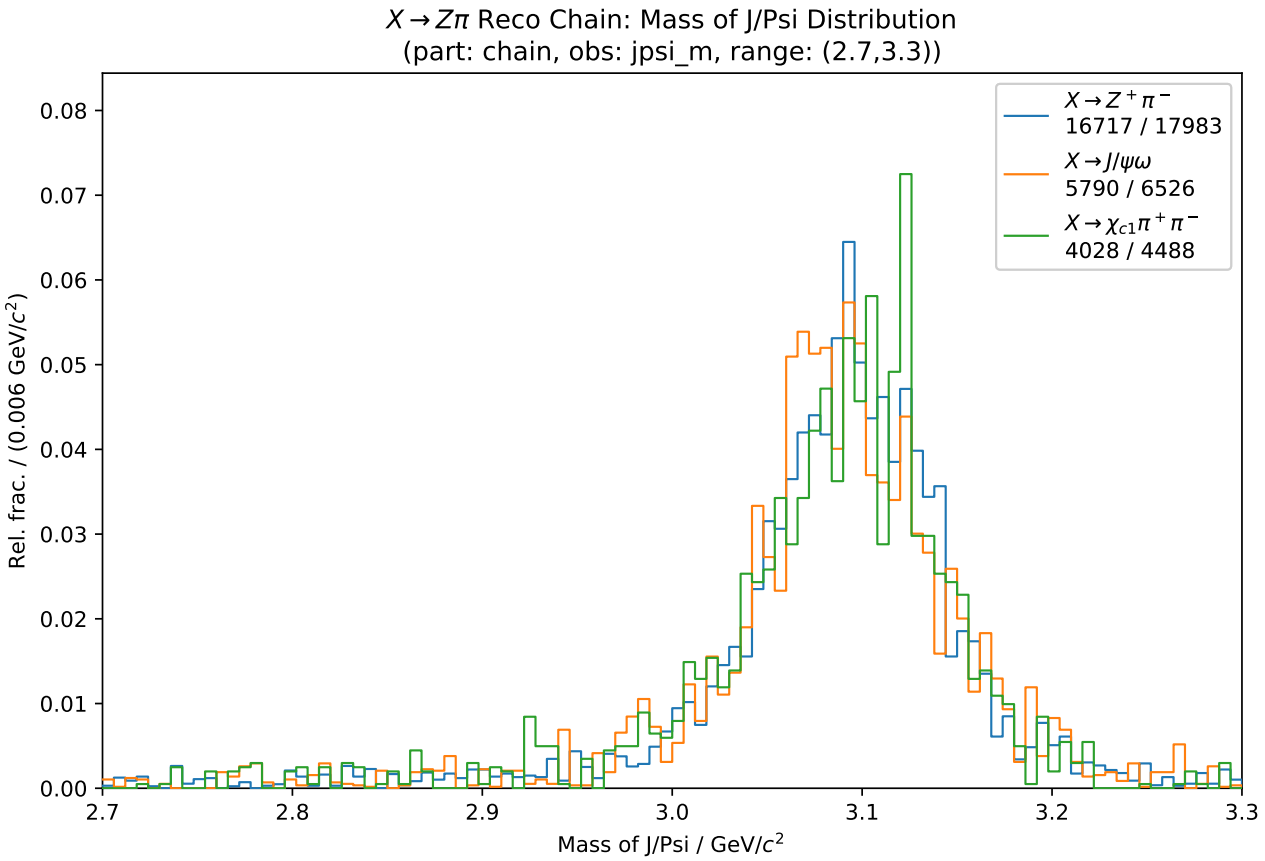
Peaking Bkg

Exploratory Studies

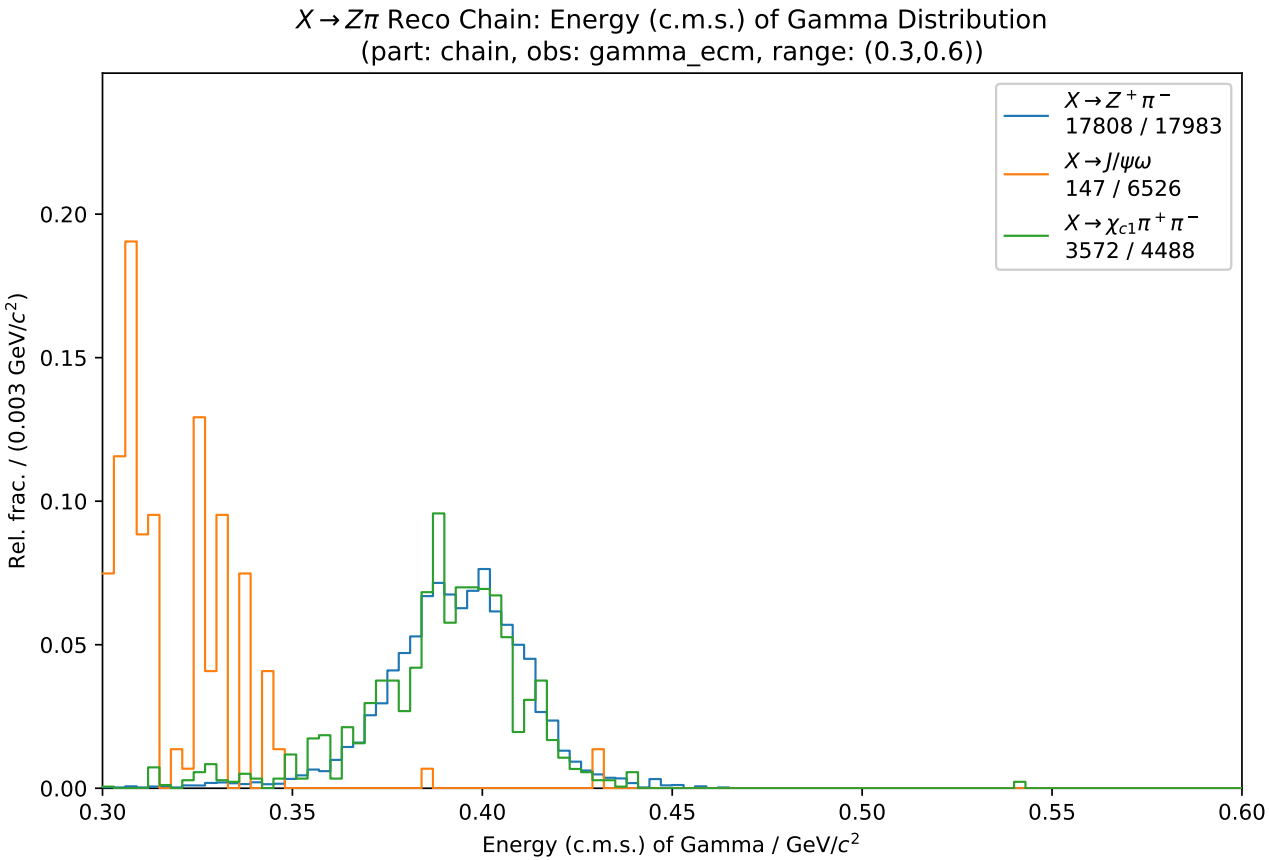
- Exploratory study of peaking bkg processes

  Processes considered:
- $\bar{\mathrm{p}}\mathrm{p} \to \mathrm{J}/\psi\omega, \mathrm{J}/\psi \to \ell^+\ell^-, \omega \to \pi^+\pi^-\pi^0$
  - π^0 reconstructed as γ
  - No separation in J/ψ observables
- $\bar{\mathrm{p}}\mathrm{p} \to \chi_{\mathrm{c1}}(1\mathrm{P})\pi^+\pi^-, \chi_{\mathrm{c1}}(1\mathrm{P}) \to \mathrm{J}/\psi\gamma, \mathrm{J}/\psi \to \ell^+\ell^-$
  - Closest match to signal topology
  - No separation in both $\chi_{\mathrm{c1}}(1\mathrm{P})$ and J/ψ observables
  - Dalitz plot studies analyzing $\chi_{\mathrm{c1}}(1\mathrm{P})$, π_{P} (as missing particle, $\tilde{P}$), π_{S}

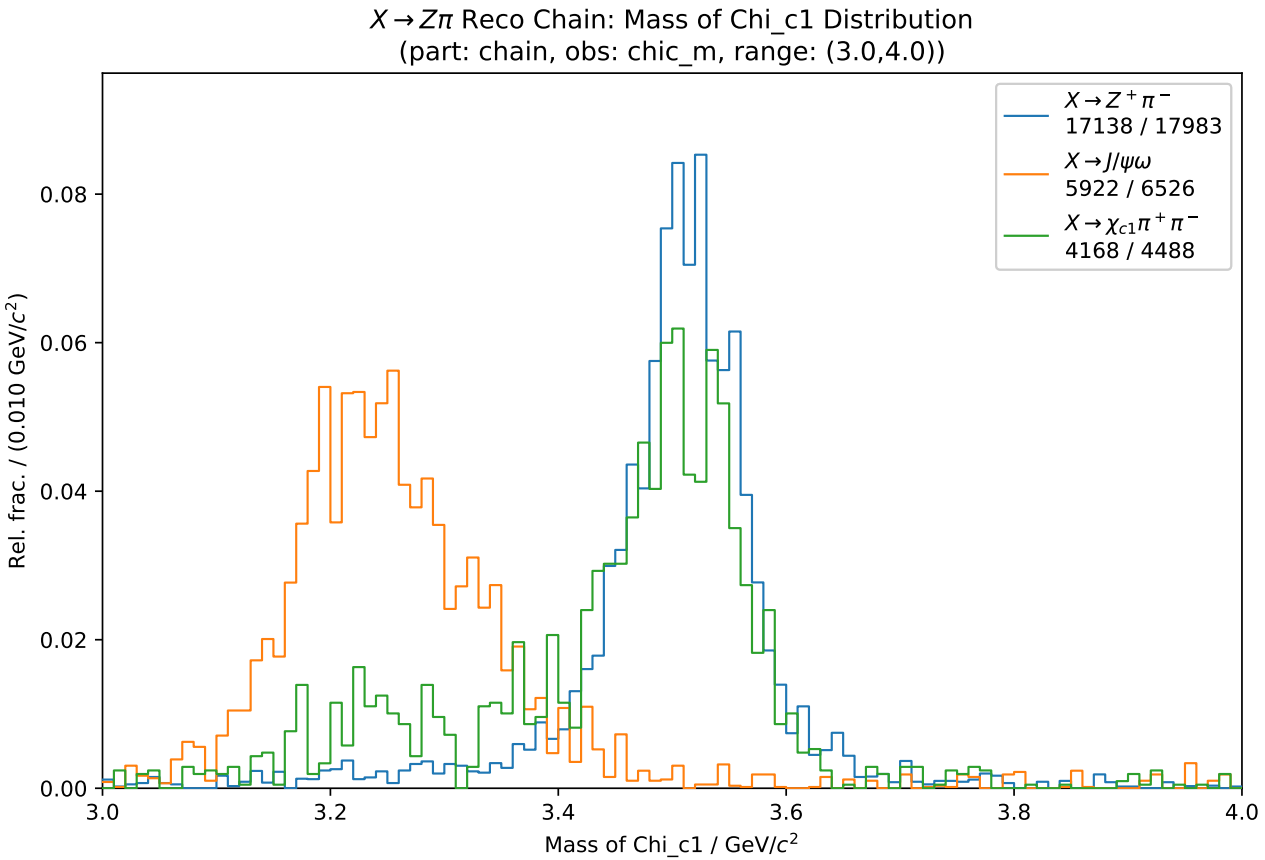
Peaking Bkg



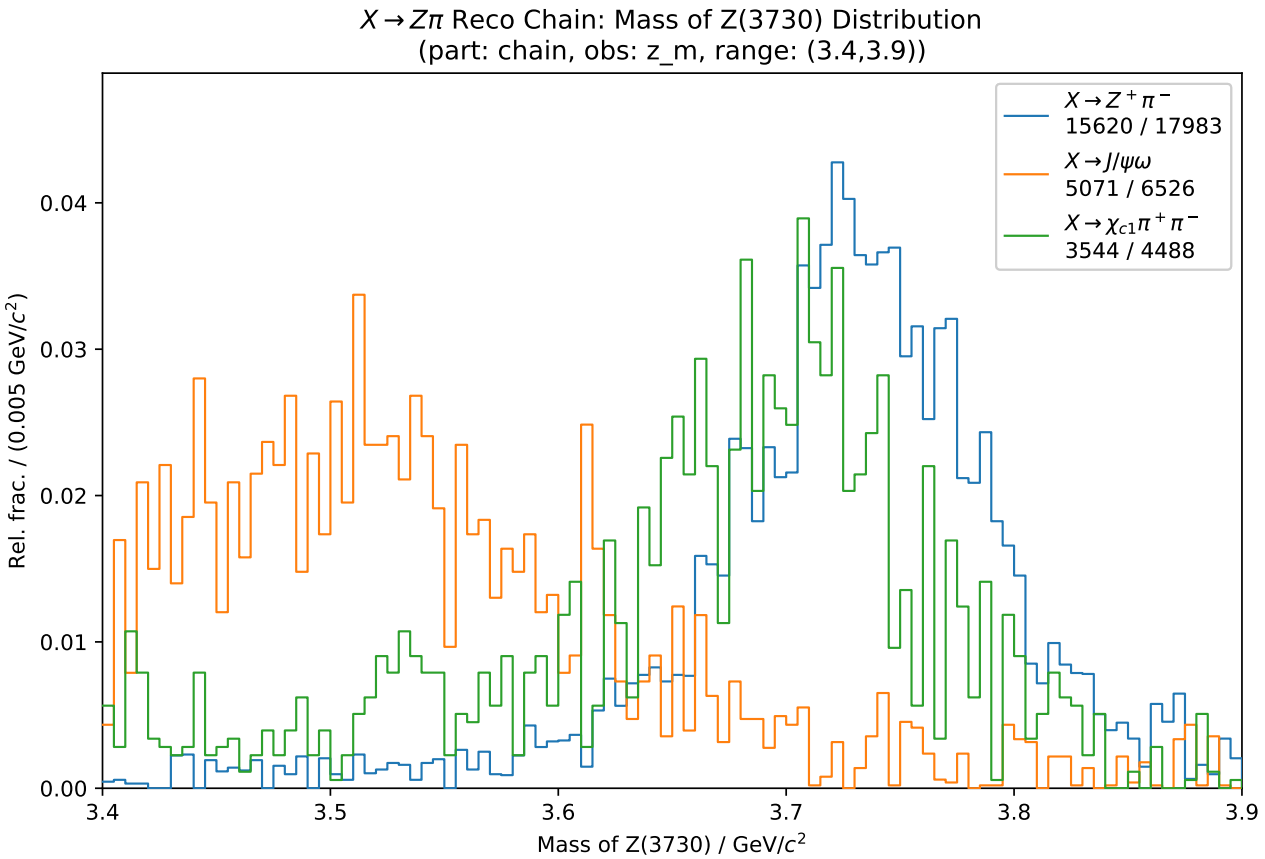
Peaking Bkg


$X \to Z\pi$ Reco Chain: Energy (c.m.s.) of Gamma Distribution
(part: chain, obs: gamma_ecm, range: (0.3,0.6))
$X \to Z^+\pi^-$
17808 / 17983
$X \to J/\psi\omega$
147 / 6526
$X \to \chi_{c1}\pi^+\pi^-$
3572 / 4488
Rel. frac. / (0.003 GeV/c^2)
0.00
0.05
0.10
0.15
0.20
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Energy (c.m.s.) of Gamma / GeV/c^2

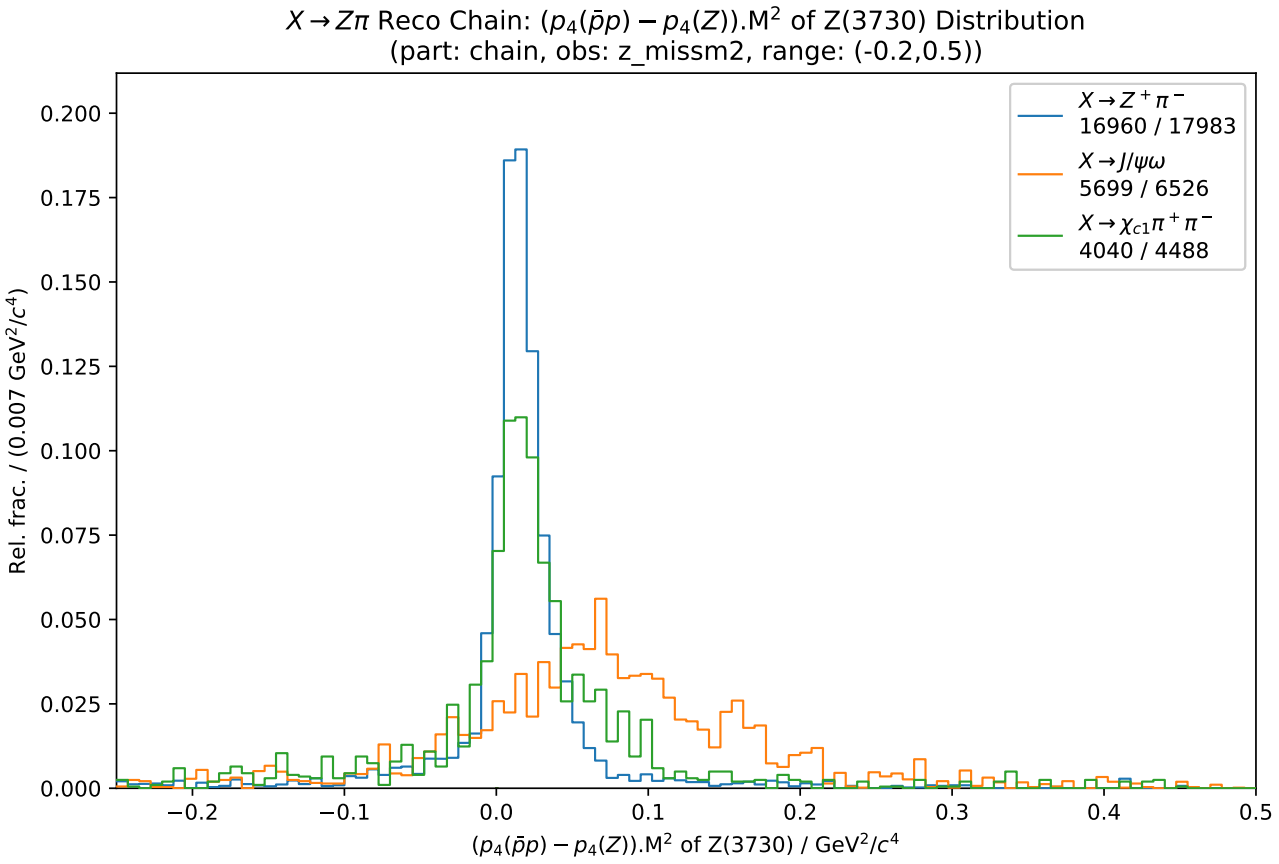
Peaking Bkg



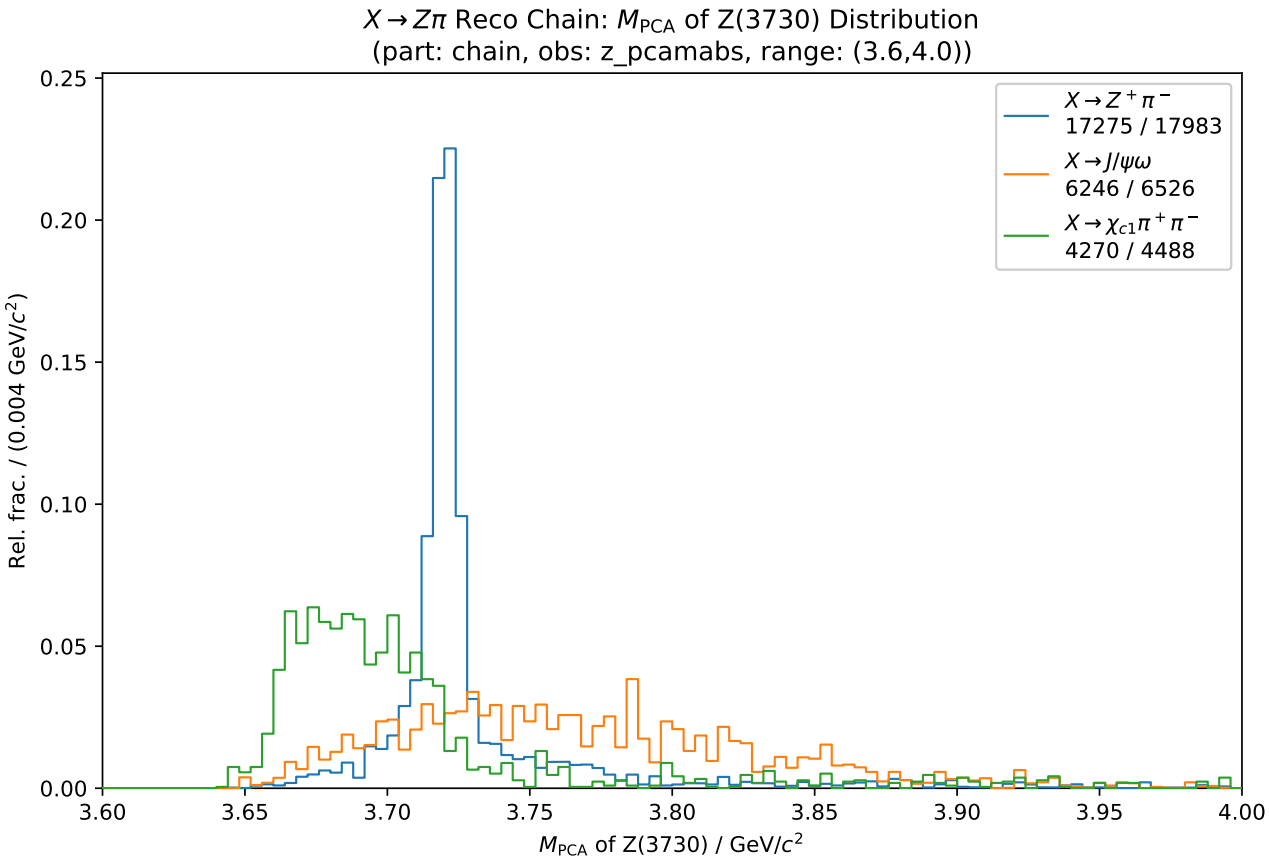
Peaking Bkg


$X \to Z\pi$ Reco Chain: Mass of Z(3730) Distribution
(part: chain, obs: z_m, range: (3.4,3.9))
$X \to Z^+\pi^-$
15620 / 17983
$X \to J/\psi\omega$
5071 / 6526
$X \to \chi_{c1}\pi^+\pi^-$
3544 / 4488
Rel. frac. / (0.005 GeV/c^2)
0.00
0.01
0.02
0.03
0.04
3.4
3.5
3.6
3.7
3.8
3.9
Mass of Z(3730) / GeV/c^2

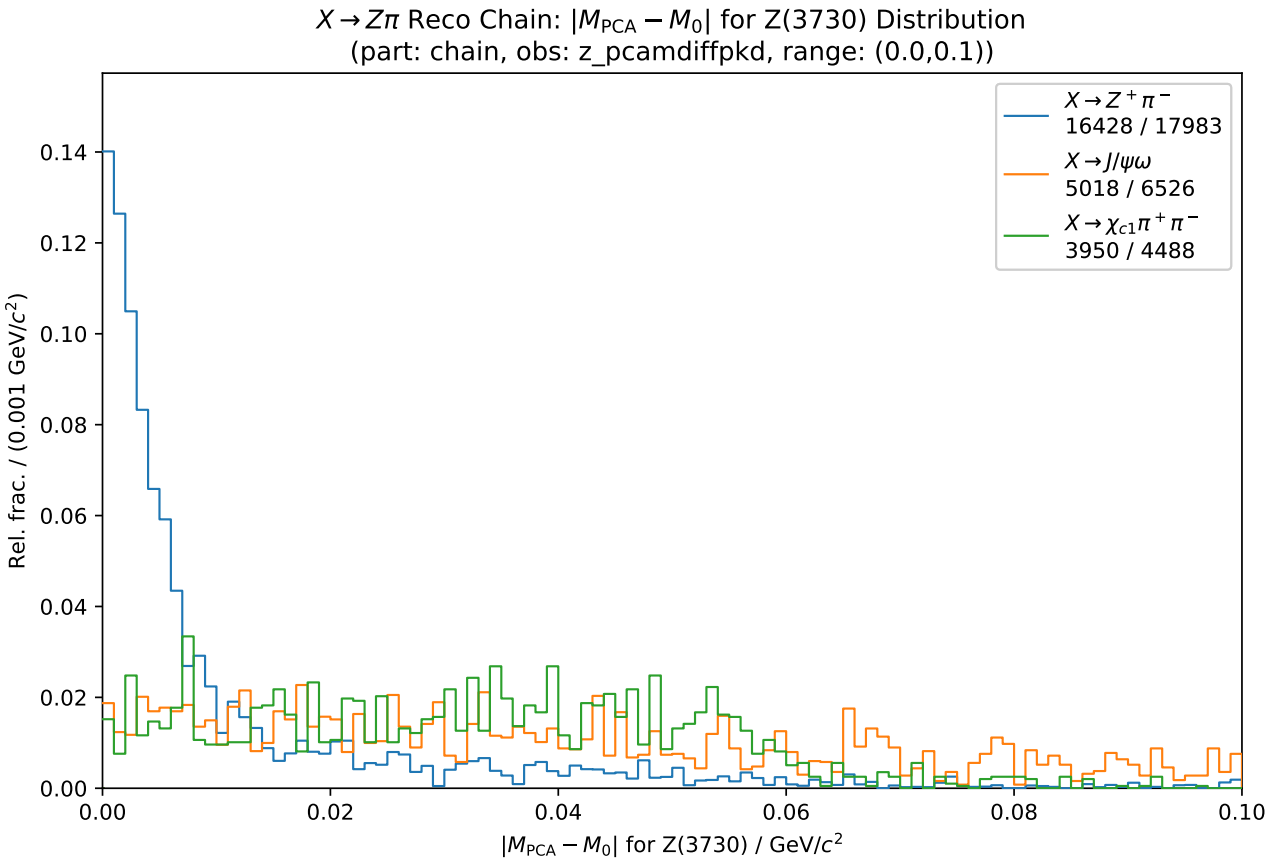
Peaking Bkg


$X \to Z\pi$ Reco Chain: $(p_4(\bar{p}p) - p_4(Z))$.M^2 of Z(3730) Distribution
(part: chain, obs: z_missm2, range: (-0.2,0.5))
$X \to Z^+\pi^-$
16960 / 17983
$X \to J/\psi\omega$
5699 / 6526
$X \to \chi_{c1}\pi^+\pi^-$
4040 / 4488
Rel. frac. / (0.007 GeV$^2/c^4$)
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5
$(p_4(\bar{p}p) - p_4(Z))$.M^2 of Z(3730) / GeV$^2/c^4$

Peaking Bkg

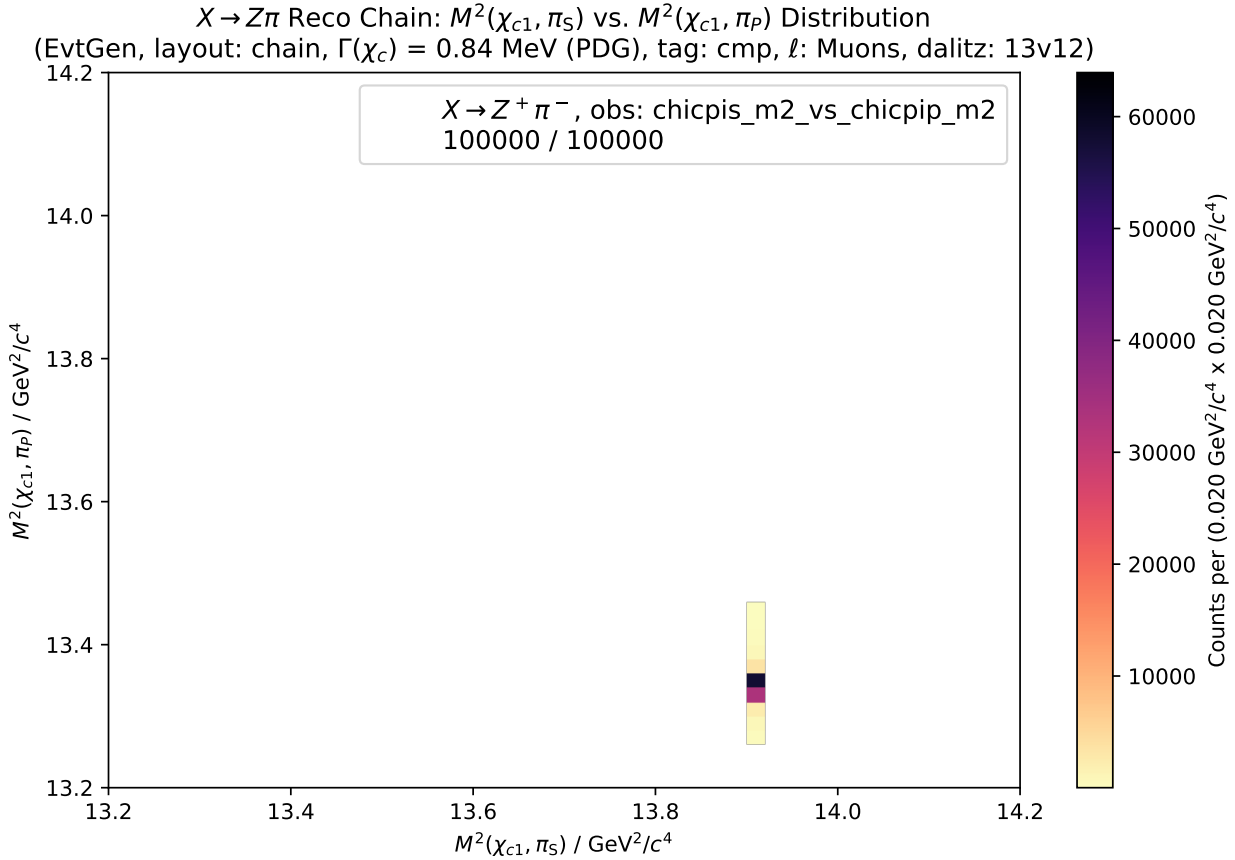


Peaking Bkg


$X \to Z\pi$ Reco Chain: $|M_{PCA} - M_0|$ for Z(3730) Distribution
(part: chain, obs: z_pcamdiffpkd, range: (0.0,0.1))
$X \to Z^+\pi^-$
16428 / 17983
$X \to J/\psi\omega$
5018 / 6526
$X \to \chi_{c1}\pi^+\pi^-$
3950 / 4488
Rel. frac. / (0.001 GeV/c^2)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.00
0.02
0.04
0.06
0.08
0.10
$|M_{PCA} - M_0|$ for Z(3730) / GeV/c^2

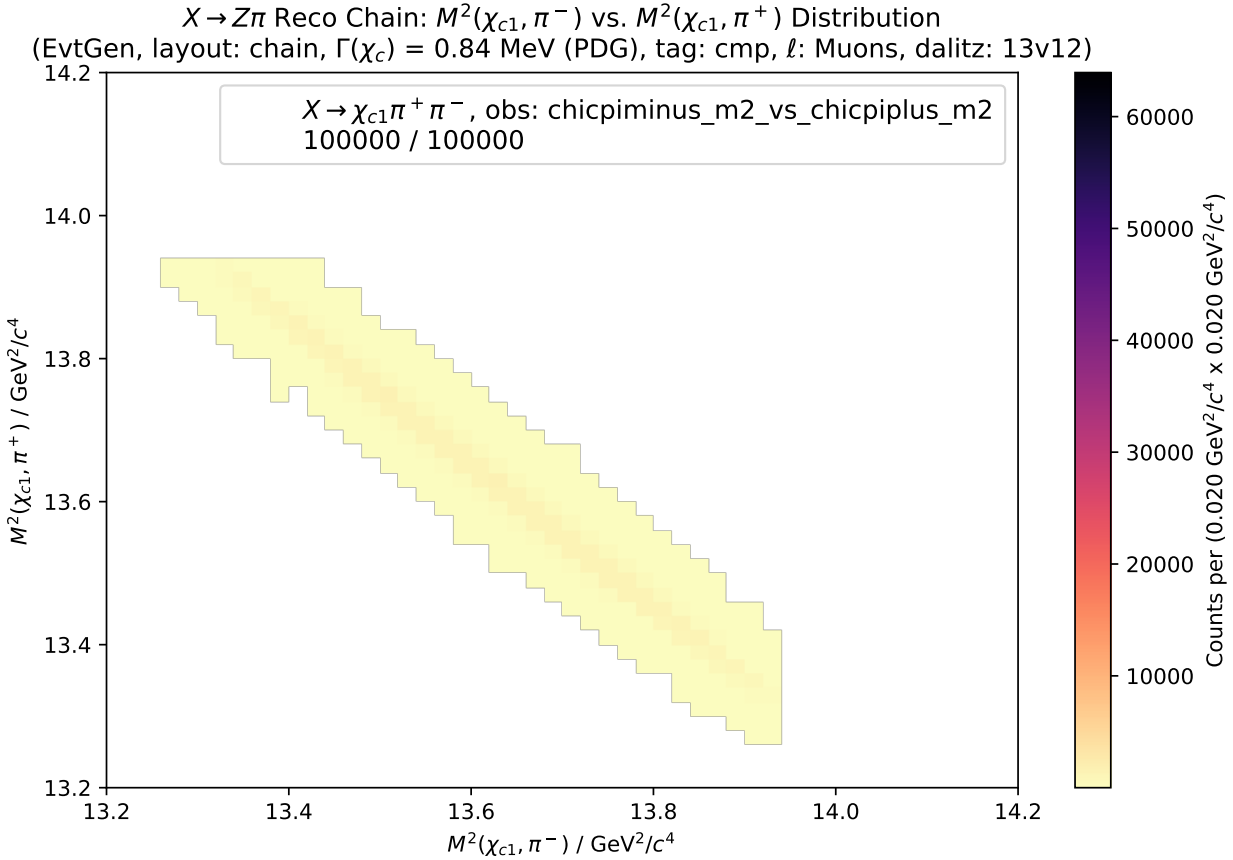
Dalitz Studies for $\bar{p}p \to \chi_{c1}(1P)\pi^+\pi^-$

0



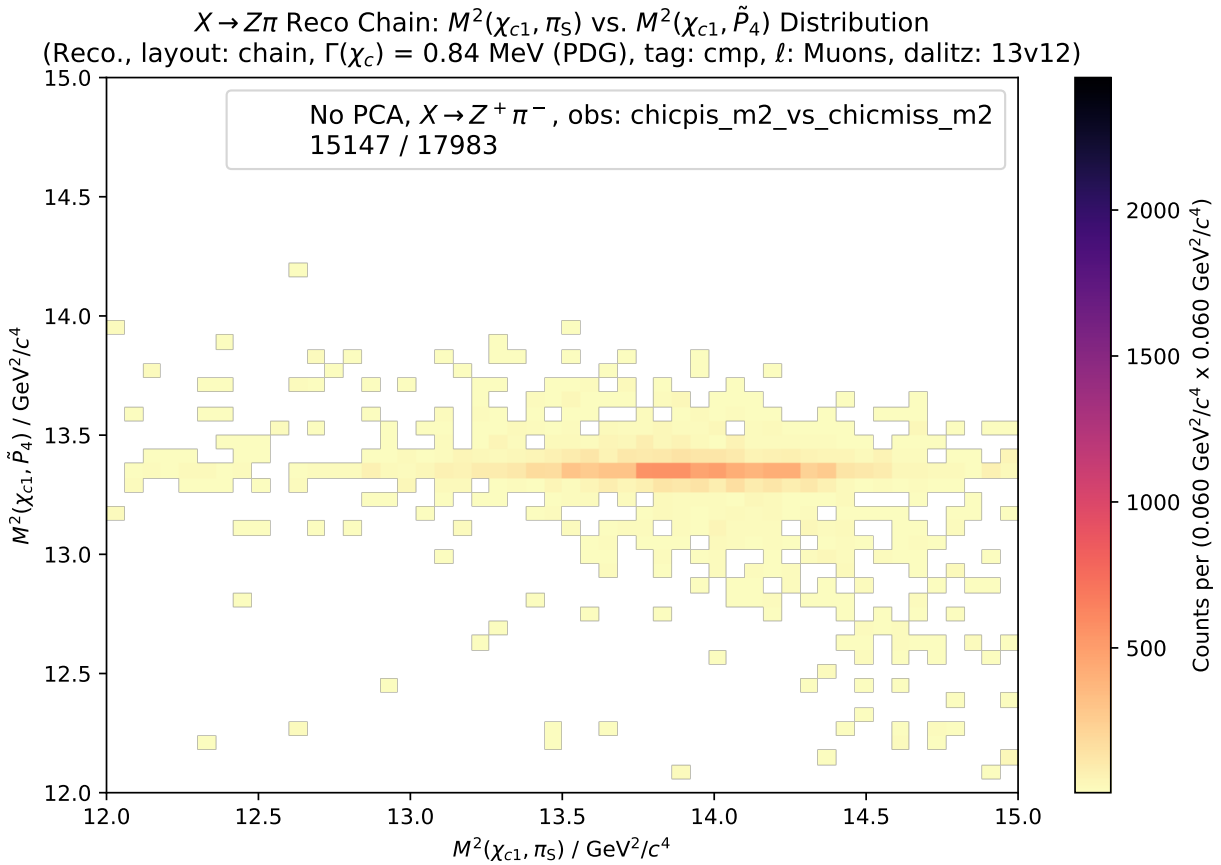
Dalitz Studies for $\bar{p}p \rightarrow \chi_{c1}(1P)\pi^+\pi^-$

1



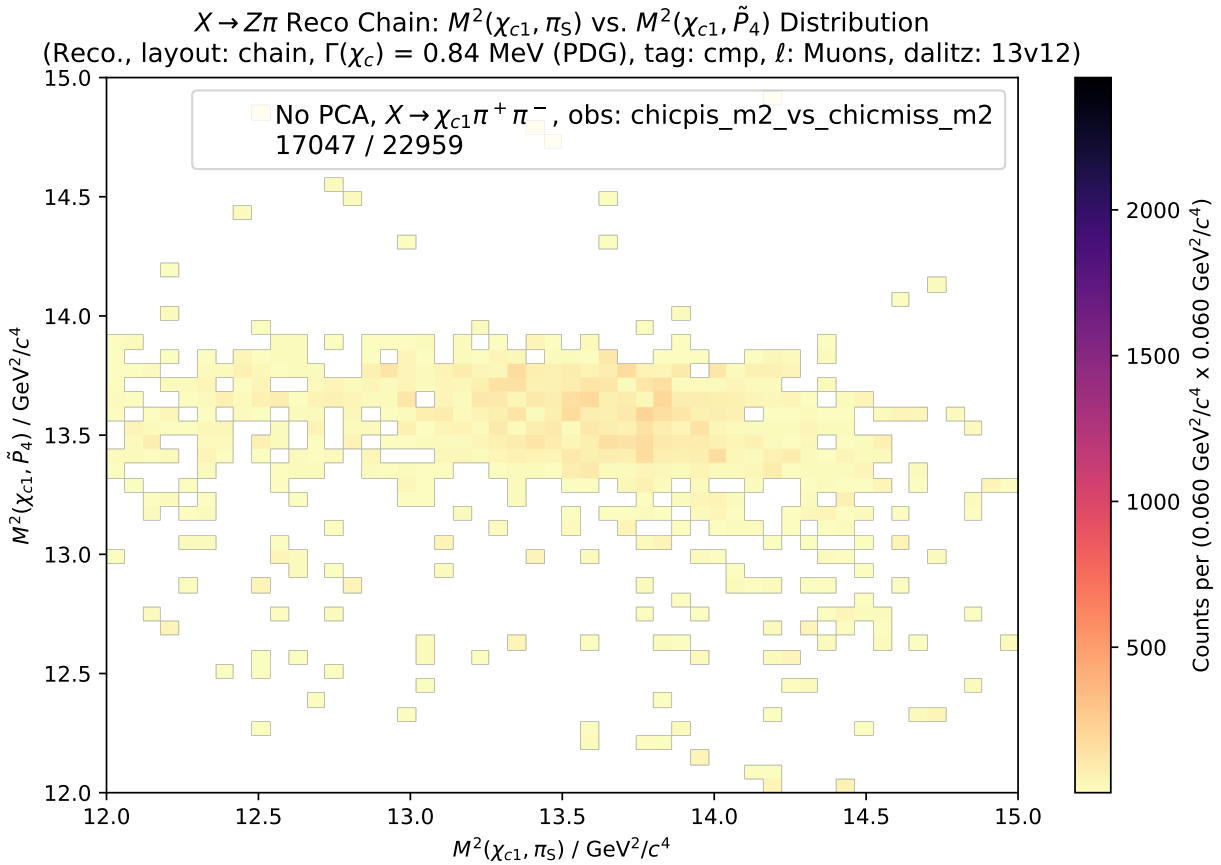
Dalitz Studies for $\bar{p}p \to \chi_{c1}(1P)\pi^+\pi^-$

0



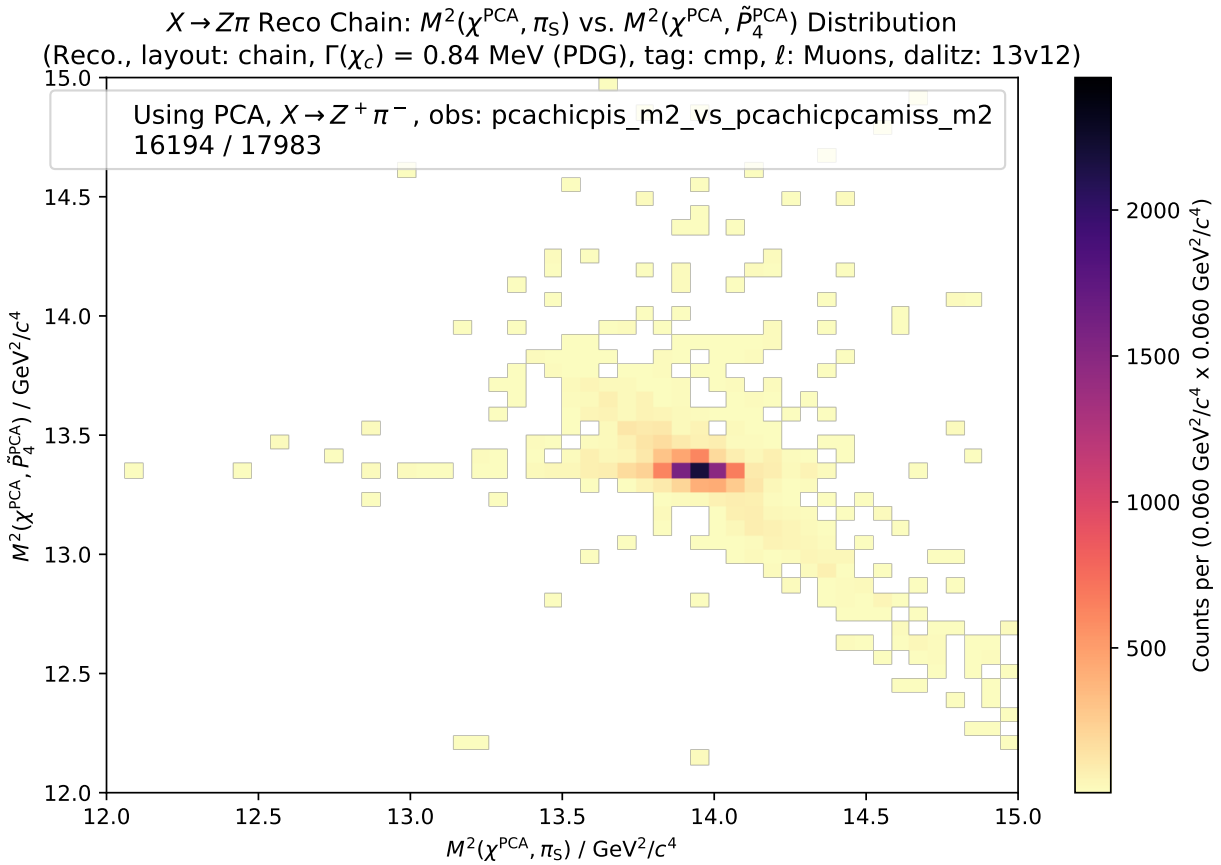
Dalitz Studies for $\bar{p}p \to \chi_{c1}(1P)\pi^+\pi^-$

1



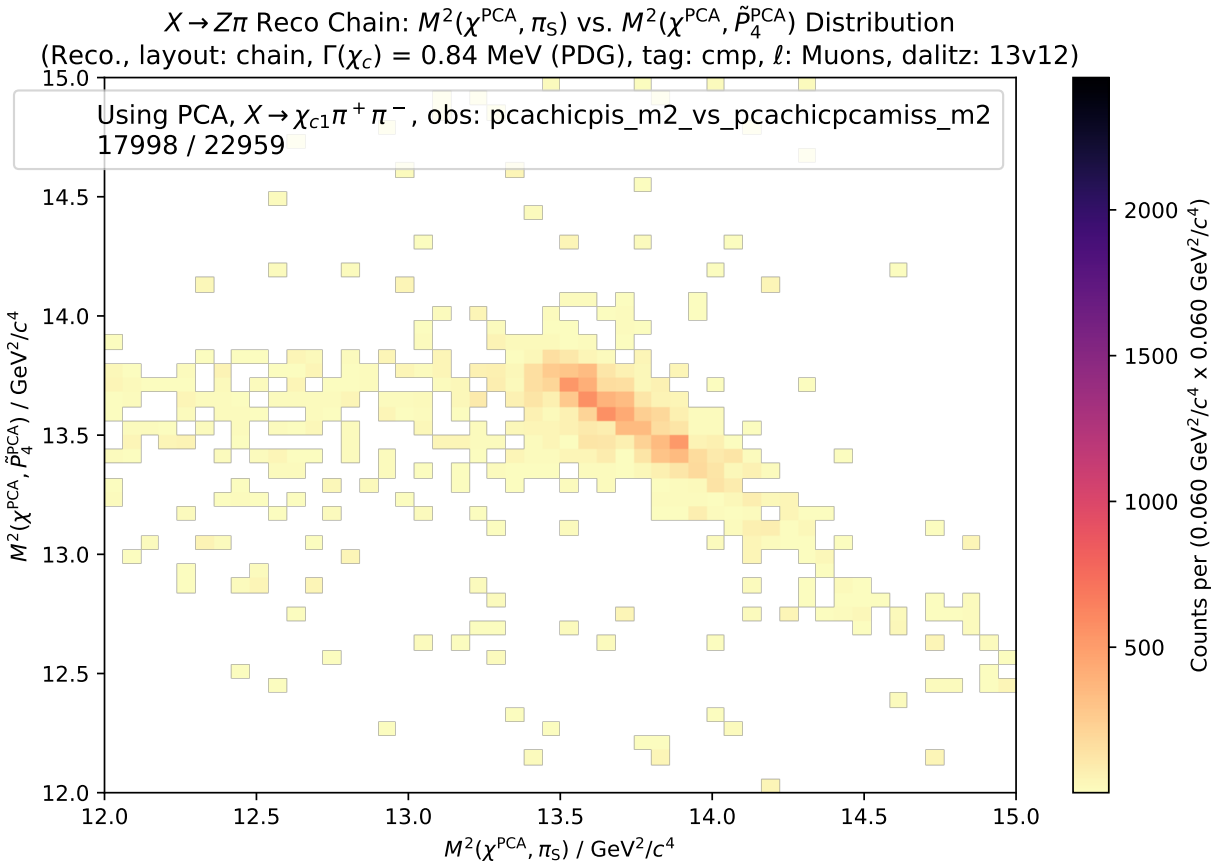
Dalitz Studies for $\bar{p}p \rightarrow \chi_{c1}(1P)\pi^+\pi^-$

2



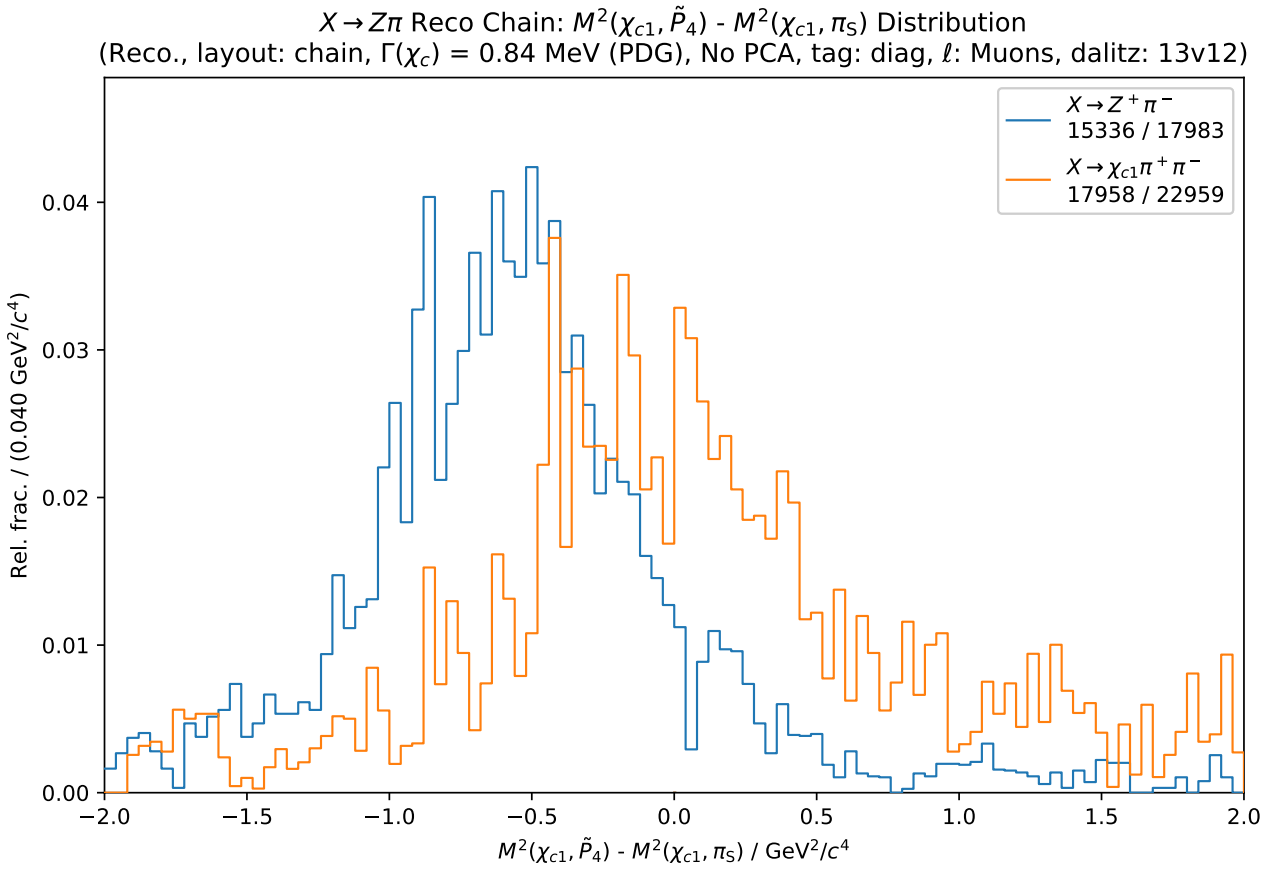
Dalitz Studies for $\bar{p}p \to \chi_{c1}(1P)\pi^+\pi^-$

3



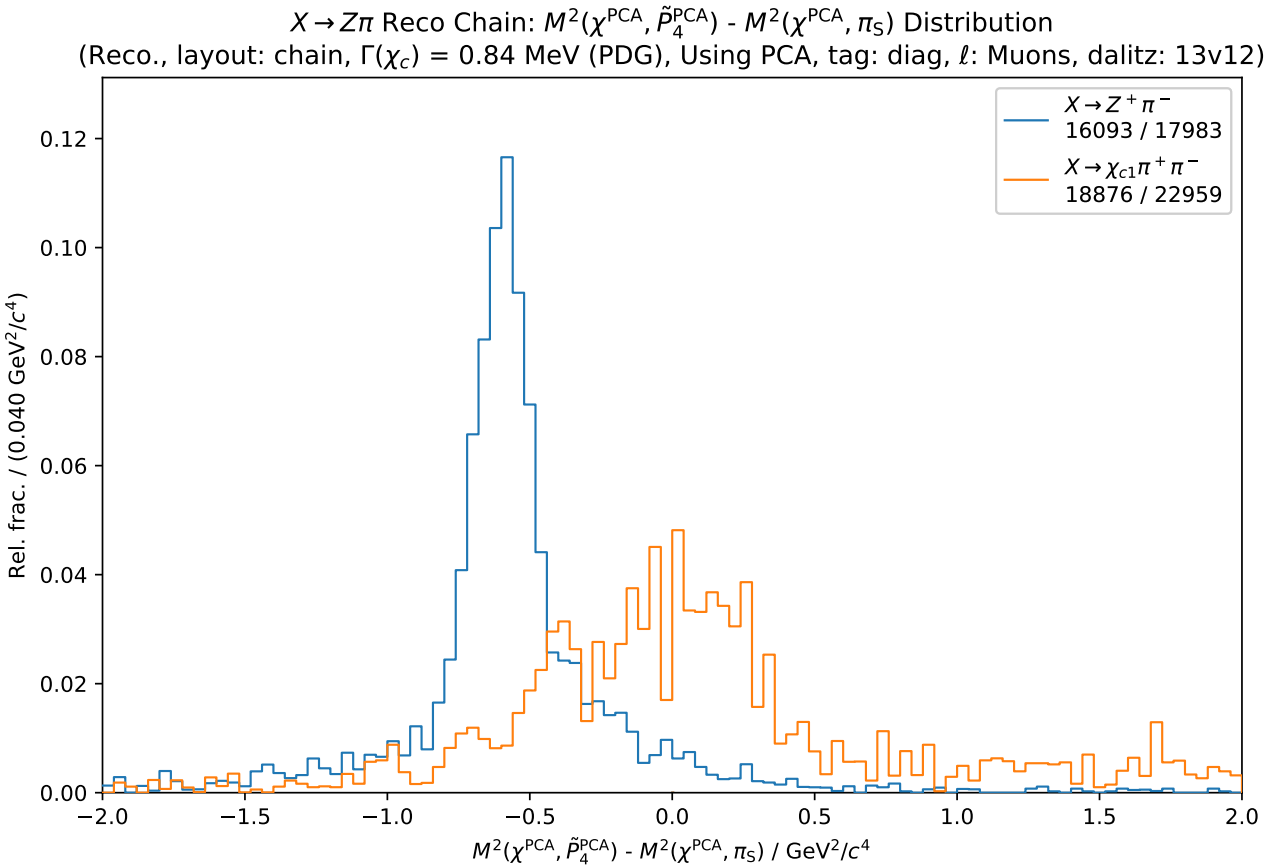
Dalitz Studies for $\bar{p}p \to \chi_{c1}(1P)\pi^+\pi^-$

2



Dalitz Studies for $\bar{p}p \to \chi_{c1}(1P)\pi^+\pi^-$

1



Peaking Bkg

Determination of Absolute Normalization

- Setting appropriate normalization requires knowing both σ and BR for each process P_i
- Assumption #1: since we're running at $\sqrt{s} = M(\mathrm{X}(3872))$, assume $\sigma(\bar{\mathrm{p}}\mathrm{p} \to P_i) \equiv \sigma(\bar{\mathrm{p}}\mathrm{p} \to \mathrm{X}(3872) \to P_i)$
- No BR measured for P_i under exam: from most recent PDG data,
  - Upper limits quoted for $\mathrm{X}(3872) \to \mathrm{J}/\psi\,\omega$, $\mathrm{X}(3872) \to \psi(2\mathrm{S})\,\gamma$
  - $\mathrm{X}(3872) \to \chi_{\mathrm{c1}}(1\mathrm{P})\ \pi^+\,\pi^-$ mentioned as "not seen"
- Possible assumptions for BRs:
  - Treat $\mathcal{B}(P_i) > x \equiv \mathcal{B}(P_i) = x$ if $\mathcal{B}(P_i)$ in PDG
  - If $\mathcal{B}(P_i)$ "not seen" in PDG, normalize to fixed arbitrary small amount, *or* set $\mathcal{B}(P_i) \equiv \mathcal{B}(\mathrm{Z} \to \chi_{\mathrm{c1}}(1\mathrm{P})\pi)$

Summary & Outlook

- Cut optimization study on DPM events
  - High rejection factor can be reached
  - Limited statistics of DPM sample cause large template uncertainty, but acceptable for our purposes
- Exploratory study on peaking bkg processes
  - Identification of possible discriminating variables
  - Dalitz plot study for $\bar{p}p \to \chi_{c1}(1P)\pi^+\pi^-$
- First draft of release note completed

48 pages written...

Feasibility studies for the $\bar{p}p \to Z(3730)^+\pi^-$ process at $\overline{\text{P}}$ANDA at FAIR.

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Elisabetta Prencipe, Forschungszentrum Jülich (Germany),
James Ritman, Forschungszentrum Jülich (Germany)
on behalf of the charmonium-exotics group.

Abstract

The copious number of observations in the sector of charmonium(-like) spectroscopy, that do not fit the quark potential model, strongly motivates the idea of building a $\bar{p}p$ machine for better understanding their nature, by measuring their rates, branching fractions, precision mass and width measurements. Prominent examples are the so called Z charged states and their neutral partners, which were first observed at the Belle and BES III experiments three years ago, and some of them recently confirmed by LHCb. The $\overline{\text{P}}$ANDA detector at FAIR aims to conduct an antiproton-proton experiment with a very high rate capability, up to 10^7 interactions/s. Measurements in $\bar{p}p$ annihilation are complementary to what has been achieved in this sector by the past e^+e^- colliders, or running experiments in pp collisions. In this short report, we present some new ideas about the presence of ad-

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  - Identification of possible discriminating variables
  - Dalitz plot study for $\overline{\mathrm{p}}\mathrm{p} \to \chi_{c1}(1P)\pi^+\pi^-$
- First draft of release note completed

In progress:

- Determination of procedure for normalization of all bkg processes
- Final collective bkg studies
- Estimate of sensitivity for different scenarios/parameters