Status of the hybrid charmonium candidate analysis

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October 27, 2021

Exotic Charmonium

- For hybrid charmonium states ($(c\bar{c})g$) the ground state is expected to be $J^{PC} = 1^{-+}$ spin-exotic [1]
- Lattice QCD calculations predict its mass to be around 4290 MeV with a width of 20 MeV
- One of its possible decay channel is used as a benchmark channel in the PANDA EMC TDR

[1] Nora Brambilla et al., Spin structure of heavy-quark hybrids, PRD 99, 014017 (2019)

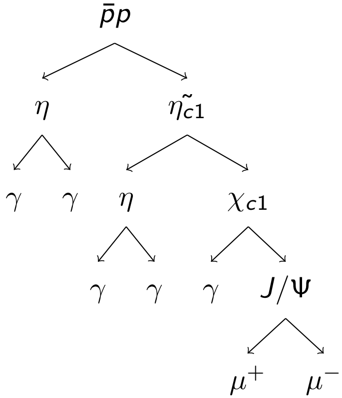
Possible decay channels

Table 1: Some possible experimentally accessible final states of J^{PC} exotic charmed hybrids and glueballs below $D^{**}D$ threshold. Note that open charm modes of ψ_g may be suppressed by a selection rule [4]. For hidden charm modes, the charmonia tend to have the same C as that of the parent ψ_g. The light hadron modes are expected to be enhanced for ψ_g with $C=+$. See the main text for details. Decays to $p\bar{p}\{\pi,\eta^{(\prime)},\omega,\rho,\phi\}$ are allowed for all states listed.

J^{PC}	Open charm	Hidden charm	Light hadrons
0^{+-}	Quantum numbers forbid $D^{(*)}D^{(*)}$	$J/\psi\{f_{\{0,1,2\}},(\pi\pi)_S\}$ $h_c\eta;\ \eta_c h_1$ $\chi_{c0}\omega$ $\chi_{c\{1,2\}}\{\omega,h_1,\gamma\}$	$a_{\{0,1,2\}}\rho;\ a_{\{1,2\}}\{b_1,\gamma\}$ $b_1\pi;\ h_1\eta^{(\prime)}$ $\{(\pi\pi)_S,f_0\}\{\omega,\phi\}$ $f_{\{1,2\}}\{\omega,h_1,\phi,\gamma\}$
0^{--}	D^*D	$h_c(\pi\pi)_S$ $J/\psi\{f_{\{1,2\}},\eta^{(\prime)}\}$ $\chi_{c0}h_1;\ \eta_c\{\omega,\phi\}$ $\chi_{c\{1,2\}}\{\omega,h_1,\gamma\}$	$a_{\{0,1,2\}}b_1;\ a_{\{1,2\}}\{\rho,\gamma\}$ $\rho\pi$ $f_0h_1;\ \eta^{(\prime)}\{\omega,\phi\}$ $f_{\{1,2\}}\{\omega,h_1,\phi,\gamma\}$
1^{-+}	$D^*D,\ D^*D^*$	$\chi_{c\{0,1,2\}}(\pi\pi)_S$ $\eta_c\{f_{\{1,2\}},\eta^{(\prime)}\}$ $\chi_{c\{1,2\}}\eta$ $\{h_c,J/\psi\}\{\omega,h_1,\phi,\gamma\}$	$a_{\{0,1,2\}}a_{\{0,1,2\}};\ a_{\{1,2\}}\pi$ $f_{\{0,1,2\}}f_{\{0,1,2\}};\ f_{\{1,2\}}\eta^{(\prime)}$ $\{\rho,\gamma\}\{\rho,b_1\};\ b_1b_1$ $\{\omega,h_1,\phi,\gamma\}\{\omega,h_1,\phi,\gamma\}$
2^{+-}	$D^*D,\ D^*D^*$	$\{h_c,J/\psi\}\{f_{\{0,1,2\}},(\pi\pi)_S\}$ $\{h_c,J/\psi\}\eta^{(\prime)}$ $\{\eta_c,\chi_{c\{0,1,2\}}\}\{\omega,h_1,\phi,\gamma\}$	$a_{\{0,1,2\}}\{\rho,b_1,\gamma\}$ $\{\rho,\gamma,b_1\}\pi$ $\{\eta^{(\prime)},f_{\{0,1,2\}}\}\{\omega,h_1,\phi,\gamma\}$

[1] Frank E. Close et al. Gluonic Hadrons and Charmless β Decays (1997)

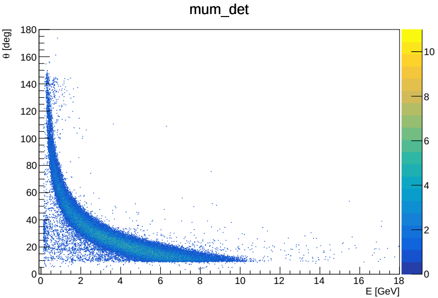
Decay Channel $\eta\chi_{c1}$



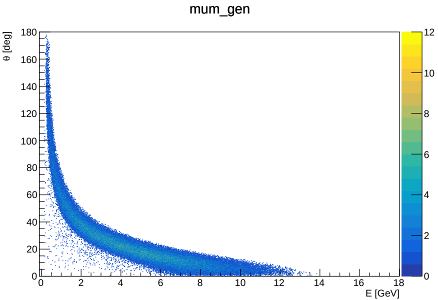
Detailed efficiency studies

- Detailed efficiency studies were performed
- 4 issues were found:
- Problems with charged particle reconstruction a low θ
- Some of the photons did pair production and can be recovered
- The photon efficiency is low (gap at $\theta \approx 20^{\circ}$)
- Mc matching numbers are inconsistent

Charged particle reconstruction



Reconstructed mc matched μ distribution



Generated μ distribution

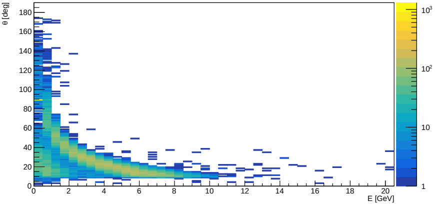
Charged particle reconstruction

- The problem was present in a customized dev version from December 2018
- Some features were taken from the later versions, but the tracking was unmodified
- Using the master from 30 April 2021 fixed the problem
- All reconstruction and analysis was rerun
- $\sim 38\%$ of the muon pairs were lost

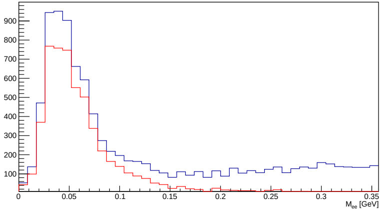
Pair production

- electrons and positrons detected
- Some of these photons can be reconstructed

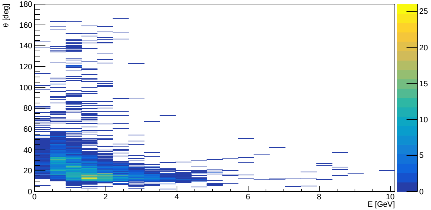
Pair production



Charged particles



Invariant mass of charged particle pairs



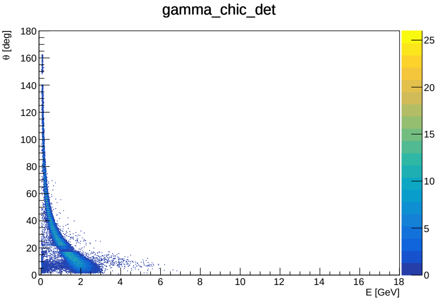
Reconstructed pair produced photons

Photon reconstruction

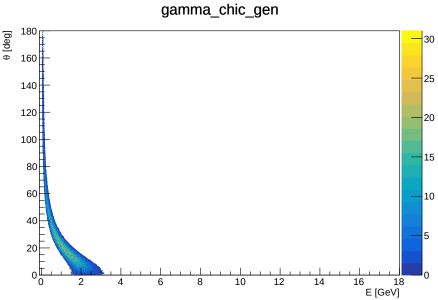
- The photon detection efficiency drops around 20°
- The overall 1γ efficiency is around 40-50%
- It effects all photons, but the $\chi_{c1} \to J/\Psi\gamma$ is the most effected
- The photons are not reconstructed (or not correctly mc matched) in the transition area between the forward endcap and the barrel
- The efficiency drops around 1 GeV, where we have the most photons in these decays

χ_{c1} photons

- det: detected and has an mc truth which has the right mothers up to a point

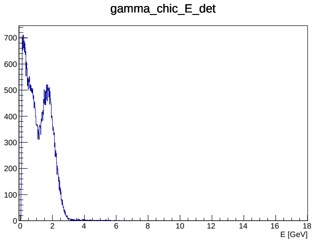


Reconstructed mc matched γ distribution

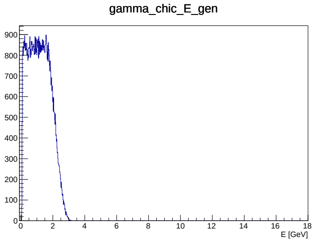


Generated γ distribution

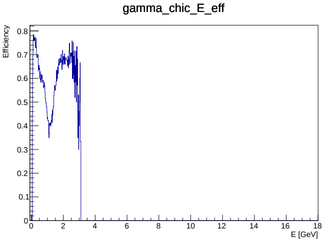
χ_{c1} photons



Reconstructed mc matched γ-s

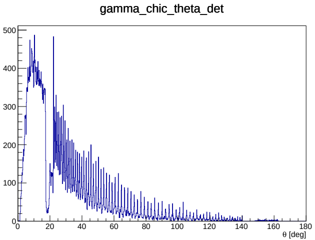


Generated γ distribution

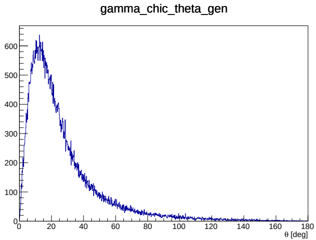


Efficiency

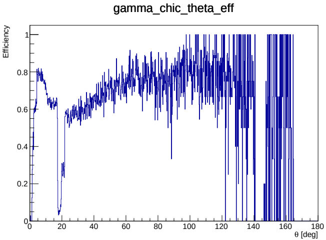
χ_{c1} photons



Reconstructed mc matched γ-s



Generated γ distribution



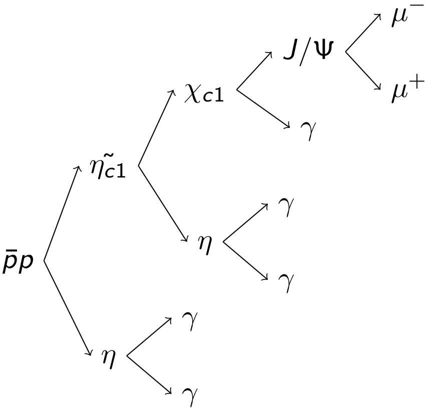
Efficiency

Inconsistencies in the mc efficiencies

- The missing mass peaks are not fully mc matched
- Single particle efficiencies should add up
- See J/Ψ as an example - with the wrong reconstruction
  - The muon efficiency is around 80% - $\sim$64%
  - Number of events in the peak - $\sim$52%
  - mc match level 0 - 52%
  - mc match level 1 or 2 - 34%
  - Has an mc truth - 0%
    (mc tracks which didn't interact with any sensitive material are deleted to save disk space)

New mc matching

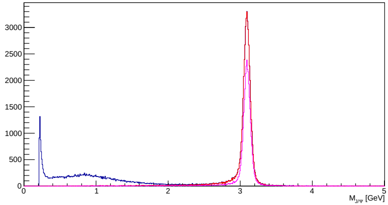
- Get the mc truths from the final state particles
- Check the PIDs by asking for the truth mothers going up in the decay tree
- Check if the mc mother object is the same for all "sisters"



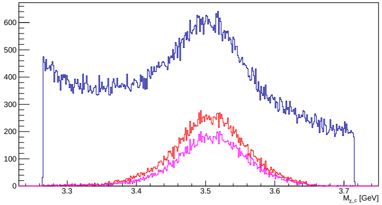
New mc matching

- This is implemented for each decay tree individually
- A general implementation based on linked trees - Gives same results as the individual implementations
- Tests should be performed before general release
- Will be added to PandaRoot

New mc matching



J/Ψ invariant mass



χ_{c1} invariant mass

Improvements

- Charged track reconstruction at low θ - rerun pid with newest release version
- $\gamma \rightarrow e^+e^-$ recovered
  - In $\sim 3\%$ of all events at least 1 photon did pair production
  - $\sim 33\%$ of these photons are recovered
- New mc matching

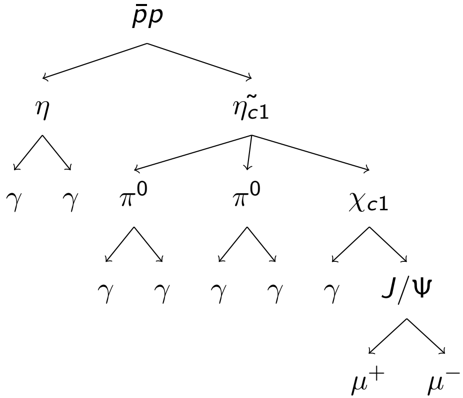
Efficiencies

	J/ψ	χ_{c1}	$\tilde{\eta_{c1}}$
Old reco mct	31%	18%	2.6%
New reco mct	63%	28%	4.1%
New reco new mct	93%	39%	6%

Analysis

- All previous channels were analyzed again with the new settings
- 2 additional channels with more charged final state particles were analyzed
- The cuts were optimized by a genetic algorithm
  - Mass cuts on η-s and π^0-s
  - Cuts on the probability of kinematic fits (mass constraint, 4C, ...)

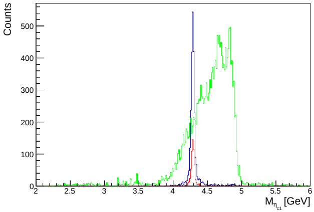
Decay channel $2\pi\chi_{c1}$



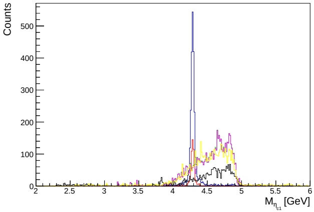
Simulations

- Antiproton momentum: 15 GeV
- 100000 signal events
- 1000000 dedicated background events
  - $\bar{p}p \to \chi_{c0}\pi^0\pi^0\eta$
  - $\bar{p}p \to \chi_{c1}\pi^0\pi^0\pi^0\eta$
  - $\bar{p}p \to \chi_{c1}\pi^0\eta\eta$
  - $\bar{p}p \to J/\Psi\pi^0\pi^0\pi^0\eta$
- 250000000 filtered DPM: at least 2 charged tracks with invariant mass 2.5-4.0 GeV using muon PID hypothesis

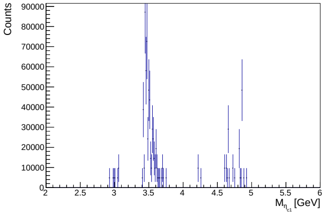
Final results



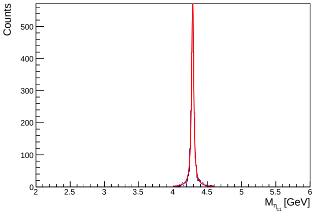
Signal and background



Signal and background

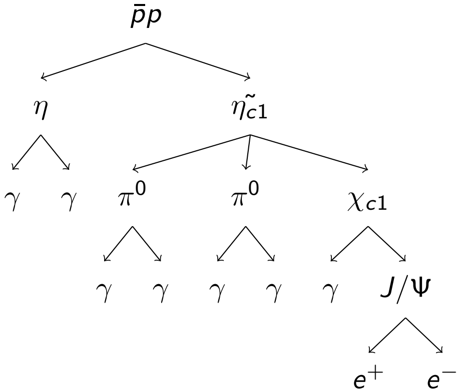


DPM background



Final Voigt fit

Decay channel $2\pi\chi_{c1}$ - e^+e^-



Simulations

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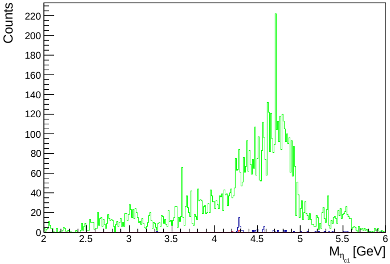
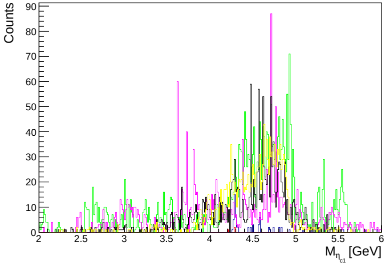
  - $\bar{p}p \to \chi_{c0}\pi^0\pi^0\eta$
  - $\bar{p}p \to \chi_{c1}\pi^0\pi^0\pi^0\eta$
  - $\bar{p}p \to \chi_{c1}\pi^0\eta\eta$
  - $\bar{p}p \to J/\Psi\pi^0\pi^0\pi^0\eta$
- Bremsstrahlung corrected electrons are used during the reconstruction

Final results

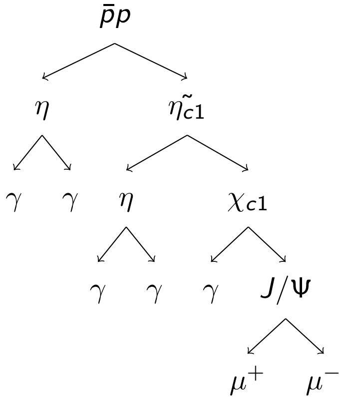


Signal and background



Signal and background

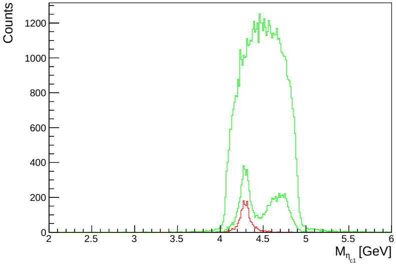
Decay channel $\eta\chi_{c1}$



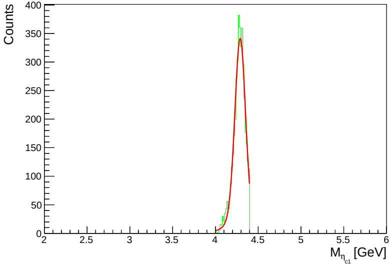
Simulations

- 100000 signal events
- 500000 dedicated background events
  - $\bar{p}p \to \chi_{c1}\eta\eta$
  - $\bar{p}p \to J/\psi\eta\eta\pi^0$

Final results

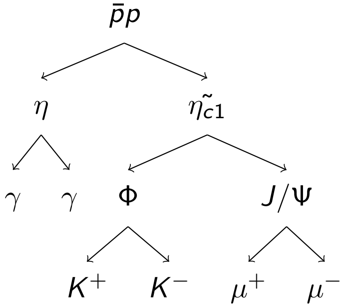


Signal and background



Final Voigt fit

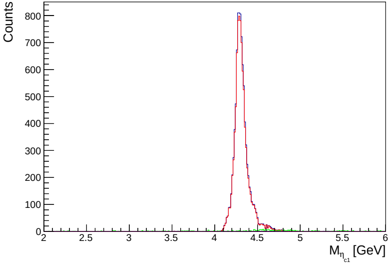
Decay channel $\Phi J/\Psi$



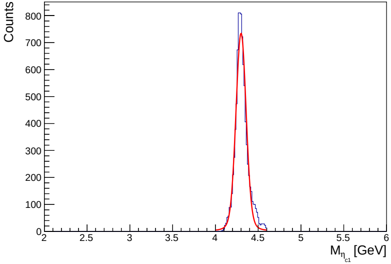
Simulations

- 100000 signal events
- 1000000 dedicated background events
  - $\bar{p}p \rightarrow \eta\Phi J/\Psi$

Results

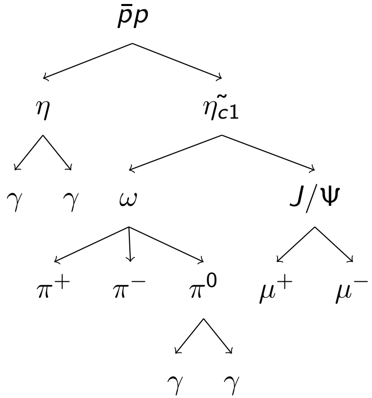


Signal and background



Final Voigt fit

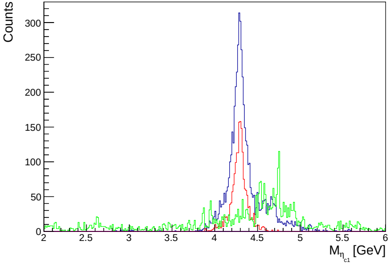
Decay channel $\omega J/\Psi$



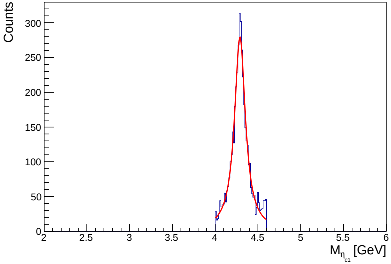
Simulations

- 100000 signal events
- 1000000 dedicated background events
  - $\bar{p}p \to \eta\omega J/\Psi$

Results



Signal and background



Final Voigt fit

Voigt fits

	$2\pi\chi_{c1}$	$\eta\chi_{c1}$	$\Phi J/\Psi$	$\omega J/\Psi$	Input
Constant	33±1	61±1	117±1	68±1	-
Mass [MeV]	4287±6	4289±1	4299.6±0.7	4290±1	4290
σ [MeV]	2e-4±6e-6	55±3	55±1	0.4±2	-
Γ [MeV]	35±1	37±5	21±2	15±4	20

Cross-section estimation

Reaction	$\sigma^{max}_{p\bar{p}\to m\Psi}$ [pb]	E^{max}_{cm} [GeV]	A_D [GeV^4]
$p\bar{p}\to\pi^0 J/\psi$	420 ± 40	4.28	9.265
$p\bar{p}\to\eta J/\psi$	1520 ± 140	4.57	4.520
$p\bar{p}\to\rho^0 J/\psi$	<450	4.80	2.114
$p\bar{p}\to\omega J/\psi$	1900 ± 400	4.80	2.053
$p\bar{p}\to\eta' J/\psi$	3300 ± 1500	4.99	0.765
$p\bar{p}\to\phi J/\psi$	280 ± 90	5.06	0.452
$p\bar{p}\to\pi^0\psi'$	55 ± 8	5.14	30.500
$p\bar{p}\to\eta\psi'$	33 ± 8	5.38	20.984
$p\bar{p}\to\rho^0\psi'$	38 ± 17	5.59	14.953
$p\bar{p}\to\omega\psi'$	46 ± 22	5.60	14.778
$p\bar{p}\to\phi\psi'$	<28	5.84	9.118

- The previously used 33 pb was taken from here
- The other feasability study[2] used 130 pb (measured for J/Ψ)
- Estimate it to be 100 pb

[1] A.Lundborg, T.Barnes and U.Wiedner, Charmonium production in $p\bar{p}$ annihilation:Estimating cross sections from decay widths (2005)

[2] Agnes Lundborg, Exotic charmonium hybrids at PANDA (2004)

Beam time assumptions

- $p\bar{p} \to \eta\tilde{\eta_{c1}}$ cross-section is 100 pb
- $\tilde{\eta_{c1}}$ to ... BR is 100%

Channel	$2\pi\chi_{c1}$	$\eta\chi_{c1}$	$\Phi J/\Psi$	$\omega J/\Psi$
days/event (rec.)	56	9.5	1.65	64
Efficiency (det. + cut)	0.866%	1.909%	8.857%	1.837%
Efficiency (det.)	1.788%	4.246%	17.028%	5.862%

- The detector efficiency of the 2 pion channel in PANDA before PandaRoot was estimated to be 7.5%[1] - photon reconstruction problem

[1] Agnes Lundborg, Exotic charmonium hybrids at PANDA (2004)

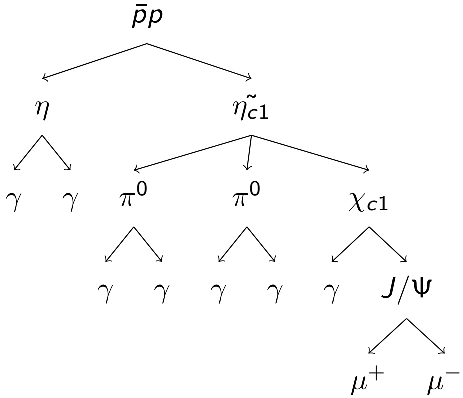
Summary

- With the corrected issues and increased cross-section estimates the detection of the hybrid charmonium seems more feasible
- The 4 most probable decay modes were investigated:
  - $2\pi\chi_{c1}$ - Theoretically most probable, poor efficiency - 7γ
  - $\eta\chi_{c1}$ - Better efficiency, bit worse background rejection
  - $\Phi J/\Psi$ - Very clean, good efficiency, possibly lower BR
  - $\omega J/\Psi$ - Similar to $\eta\chi_{c1}$, but with lower estimated BR
- Comparison with previous feasibility studies
  - More detailed background studies - it is manageable in most cases
  - DPM studies - very good suppression
  - Worse efficiency - gap in photon detection
  - $J/\Psi \to \mu^+\mu^-$ is better than $J/\Psi \to e^+e^-$

- Analysis note is in preparation

Backup slides

Decay channel $2\pi\chi_{c1}$



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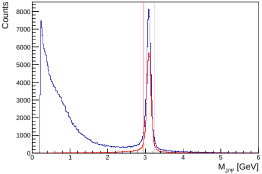
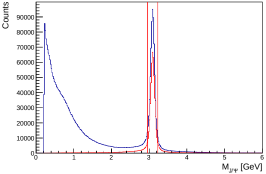
  - $\bar{p}p \rightarrow J/\Psi\pi^0\pi^0\pi^0\eta$
- 250000000 filtered DPM: at least 2 charged tracks with invariant mass 2.5-4.0 GeV using muon PID hypothesis

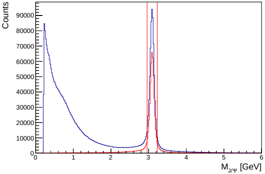
J/Ψ invariant mass



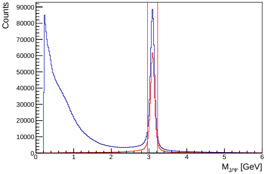
Signal



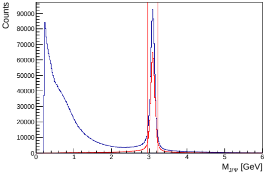
Background 1



Background 2

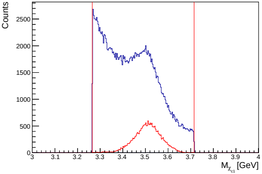


Background 3

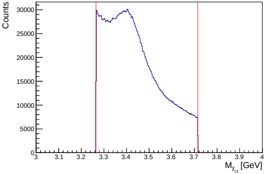


Background 4

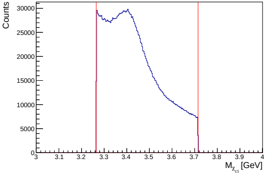
χ_{c1} invariant mass



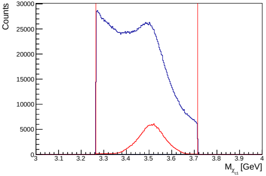
Signal



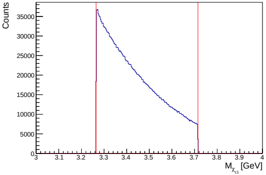
Background 1



Background 2

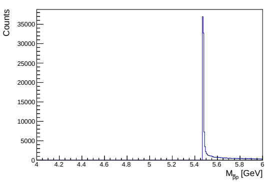


Background 3

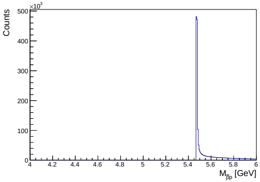


Background 4

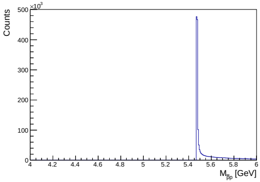
$\bar{p}p$ invariant mass



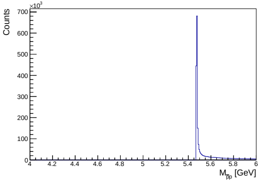
Signal



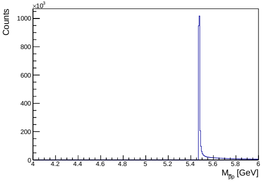
Background 1



Background 2

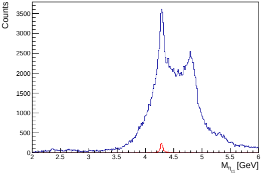


Background 3

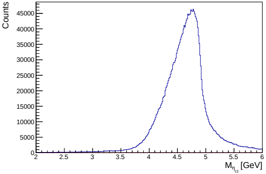


Background 4

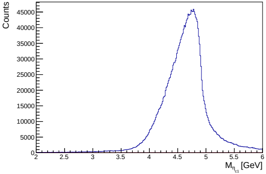
$\tilde{\eta}_{c1}$ invariant mass



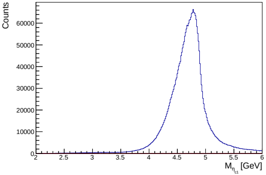
Signal



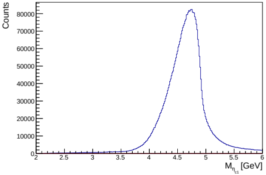
Background 1



Background 2

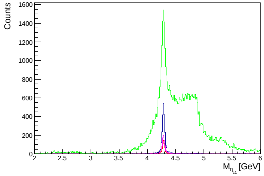


Background 3

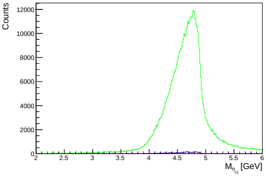


Background 4

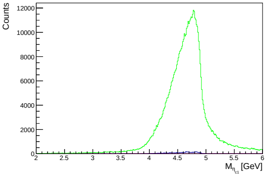
$\tilde{\eta_{c1}}$ invariant mass after the mass and all 6 prob. cuts



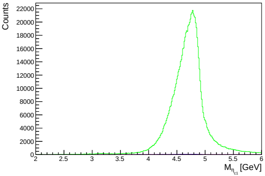
Signal



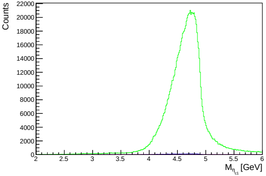
Background 1



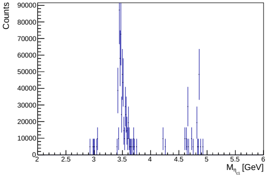
Background 2



Background 3

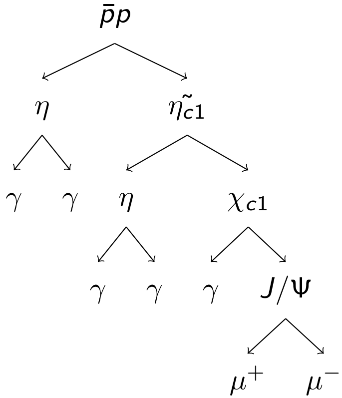


Background 4



DPM (upscaled)

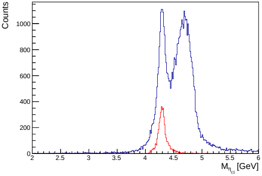
Decay channel $\eta\chi_{c1}$



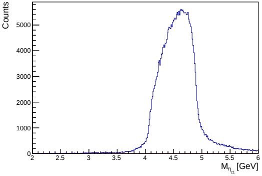
Simulations

- 100000 signal events
- 500000 dedicated background events
  - $\bar{p}p \to \chi_{c1}\eta\eta$
  - $\bar{p}p \to J/\psi\eta\eta\pi^0$

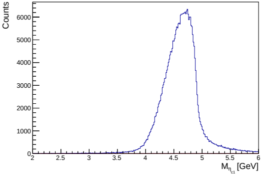
$\tilde{\eta_{c1}}$ invariant mass



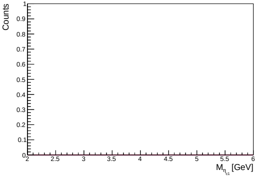
Signal



Background 1

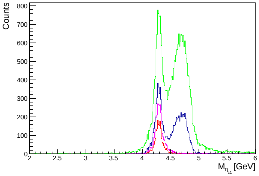


Background 2

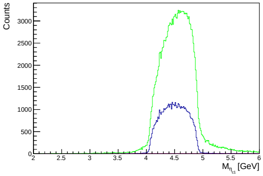


DPM

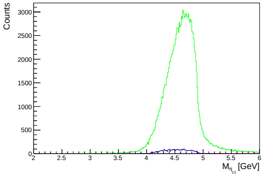
$\tilde{\eta_{c1}}$ invariant mass after the mass and all prob. cuts



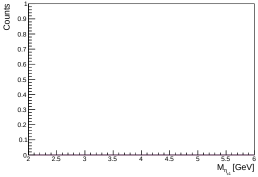
Signal



Background 1

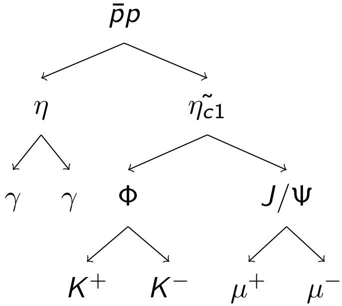


Background 2



DPM

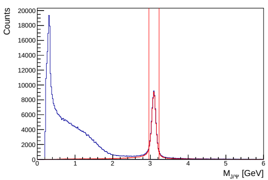
Decay channel Φ



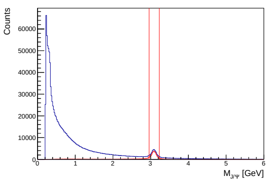
Simulations

- 100000 signal events
- 1000000 dedicated background events
  - $\eta \Phi J/\Psi$

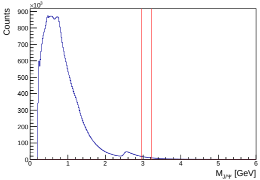
J/Ψ invariant mass



Signal

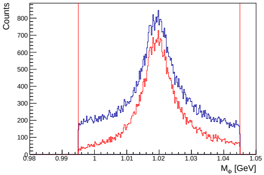


Background

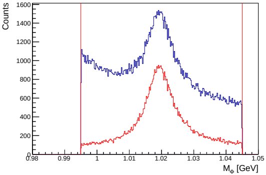


DPM

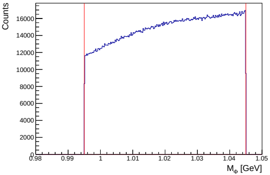
Φ invariant mass



Signal

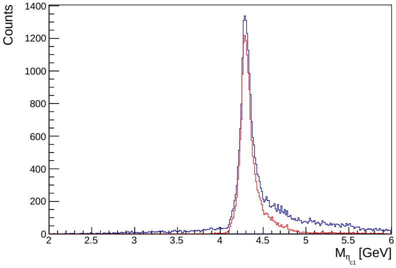


Background

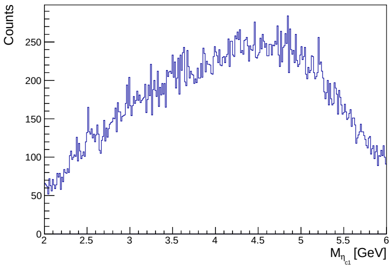


DPM

$\tilde{\eta_{c1}}$ invariant mass

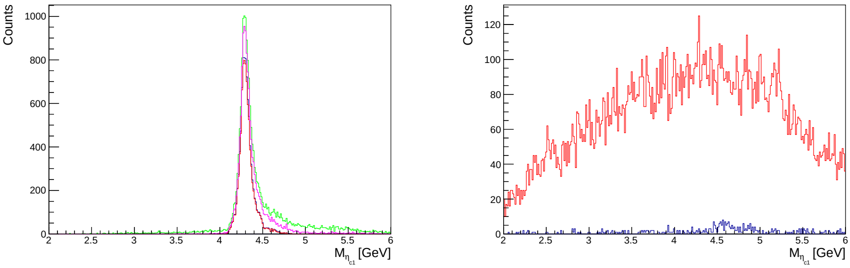


Signal



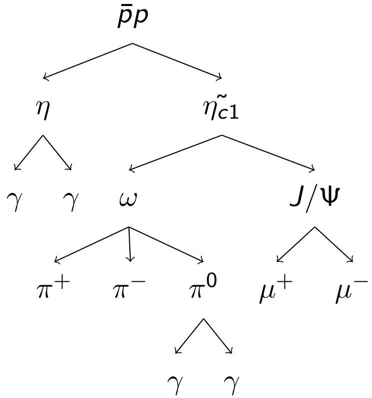
Background

$\tilde{\eta_{c1}}$ invariant mass after the mass and all prob. cuts



Signal Background

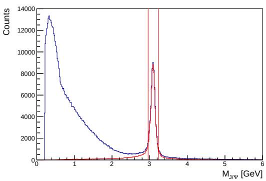
Decay channel ω



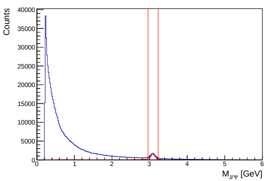
Simulations

- 100000 signal events
- 1000000 dedicated background events
  - $\eta\omega J/\Psi$

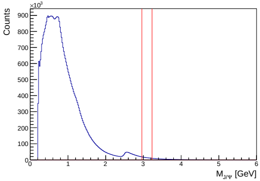
J/Ψ invariant mass



Signal

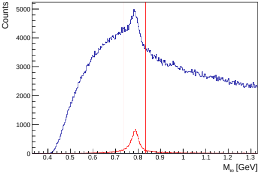


Background

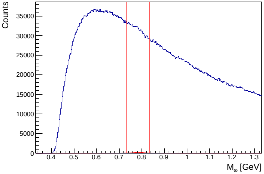


DPM

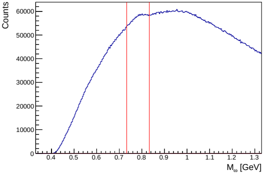
ω invariant mass



Signal

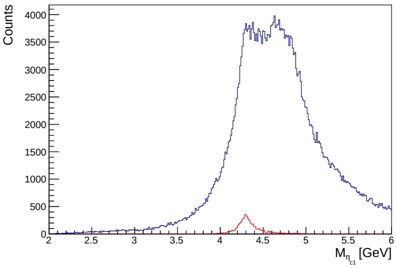


Background

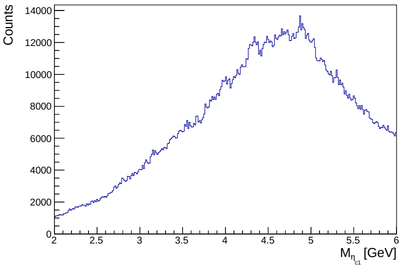


DPM

$\tilde{\eta_{c1}}$ invariant mass

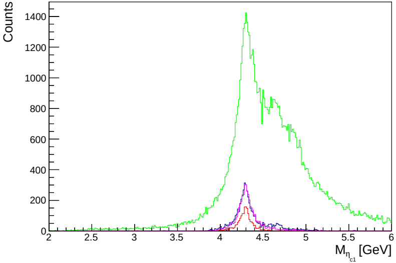


Signal

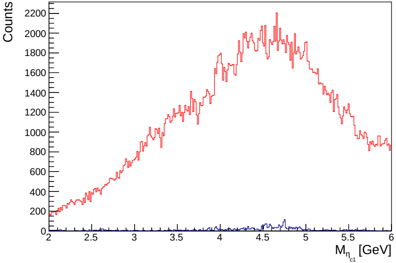


Background

$\tilde{\eta_{c1}}$ invariant mass after the mass and all prob. cuts



Signal



Background