Status of the hybrid charmonium candidate analysis

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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	$h_c(\pi\pi)_S$ $J/\psi\{f_{\{1,2\}}, \eta^{(\prime)}\}$ $\chi_{c0}h_1;\ \eta_c\{\omega, \phi\}$ $\chi_{c\{1,2\}}\{\omega, h_1, \gamma\}$	$a_{\{0,1,2\}}b_1;\ a_{\{1,2\}}\{\rho, \gamma\}$ $\rho\pi$ $f_0 h_1;\ \eta^{(\prime)}\{\omega, \phi\}$ $f_{\{1,2\}}\{\omega, h_1, \phi, \gamma\}$
1^{-+}	$D^*D,\ D^*D^*$	$\chi_{c\{0,1,2\}}(\pi\pi)_S$ $\eta_c\{f_{\{1,2\}}, \eta^{(\prime)}\}$ $\chi_{c\{1,2\}}\eta$ $\{h_c, J/\psi\}\{\omega, h_1, \phi, \gamma\}$	$a_{\{0,1,2\}}a_{\{0,1,2\}};\ a_{\{1,2\}}\pi$ $f_{\{0,1,2\}}f_{\{0,1,2\}};\ f_{\{1,2\}}\eta^{(\prime)}$ $\{\rho, \gamma\}\{\rho, b_1\};\ b_1 b_1$ $\{\omega, h_1, \phi, \gamma\}\{\omega, h_1, \phi, \gamma\}$
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)

The 4 most probable decay modes are 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

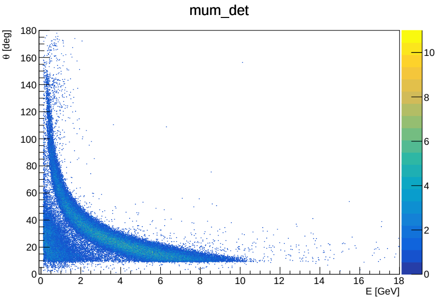
Previous findings

- Problems with charged particle reconstruction a low θ - or low p_T?
- Recovered pair-produced photons - Is it an improvement?
- The photon efficiency is low (gap at $\theta \approx 20^\circ$) - new GEM geometry?
- New MC matching

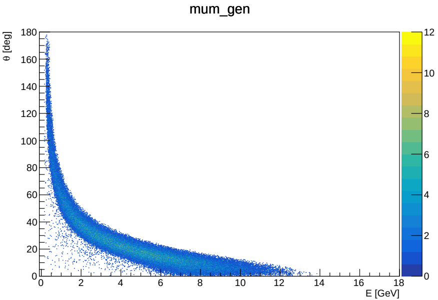
Other suggestions

- Refit final Voigt fits with background
- Best candidate implementation
- Solve compatibiliy issues with Virgo - all solved
  - Problems with eventfilter - bug fixed
  - Corrupted fairsoft installaton installation on cvmfs - the documentation is now updated to the correct paths
  - Problems with exporting PATH - adjustments to the mechanism used to start the containers on virgo

Charged particle reconstruction



Reconstructed mc matched μ distribution

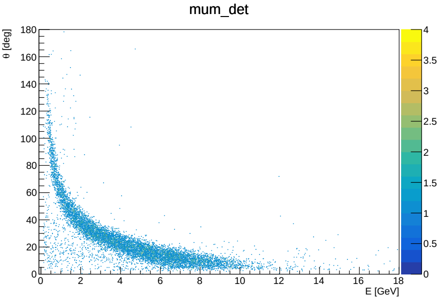


Generated μ distribution

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

Charged particle reconstruction - newer version



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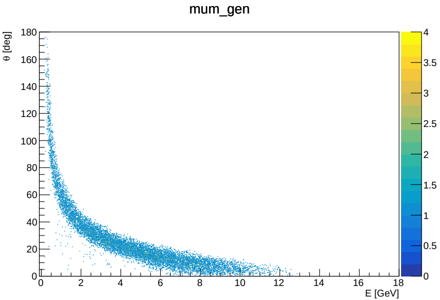
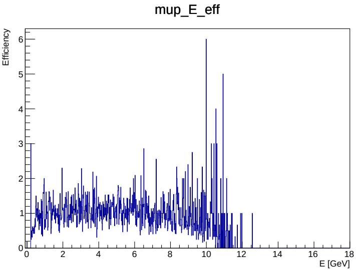
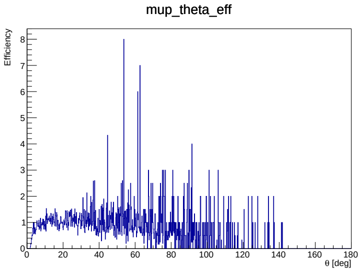
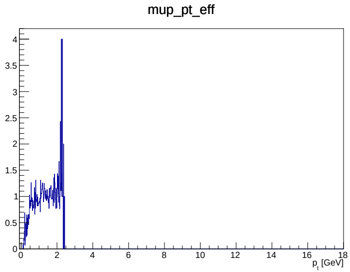


Generated μ distribution

Muon efficiencies - newer version



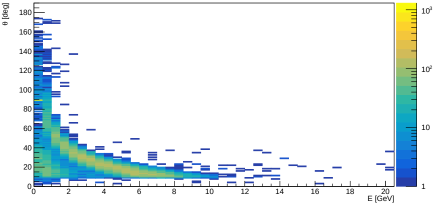




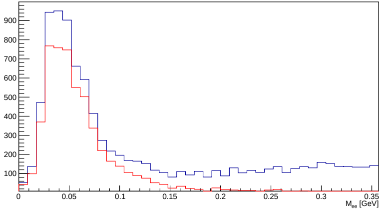
Pair production

- Electrons and positrons detected
- Some of these photons can be reconstructed
- During reconstruction combine electron-positron pairs with invariant mass below 0.1 to photons

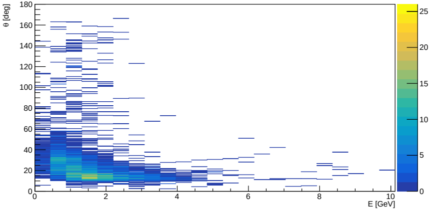
Pair production



Charged particles



Invariant mass of charged particle pairs (red:$\gamma \rightarrow$ee MCT, blue: all)



Reconstructed MCT pair produced photons

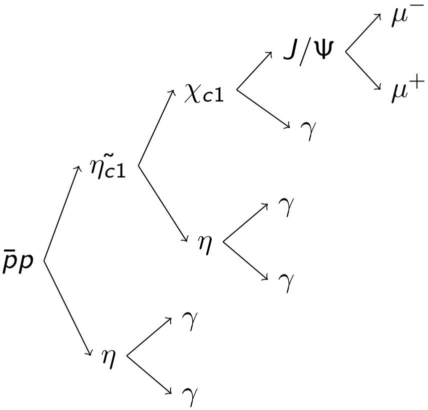
Effect of this recovery

Channel	Φ	ω	$\eta\chi_{c1}$
Significance with rec	90.5	18.7	7.1
Significance without rec	90.7	25.8	9.5
Significance with (only signal)	92.5	25.5	19.5
Significance without (only signal)	91.3	31.0	23.6

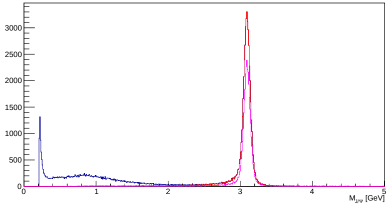
- It improves the efficiency
- But it reduces the overall significance

New mc matching

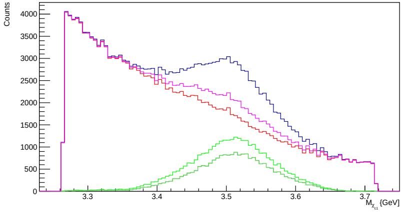
- Get the mc truths from the final state particles
- Check the PIDs by asking for the truth mothers going up in the decay tree
- Check if the mc mother object is the same for all "sisters"



New mc matching



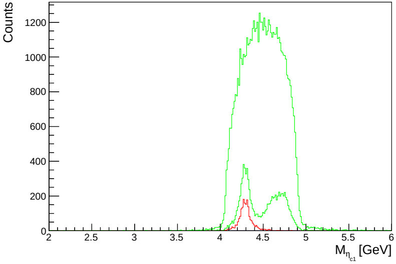
J/Ψ invariant mass



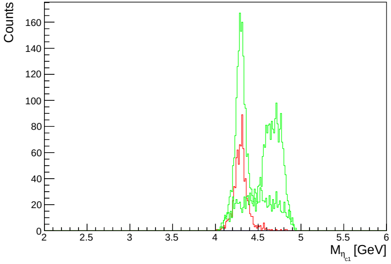
χ_{c1} invariant mass

blue - all, red - new mct, purple - default mct, green - new mct, dark green - default mct

Best candidate per event - decay channel $\eta\chi_{c1}$



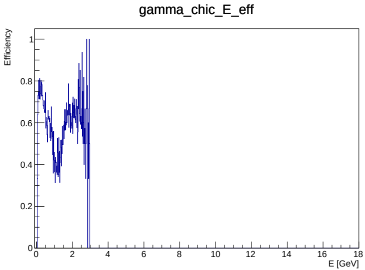
Signal (green, red-mct) and background (dark green)

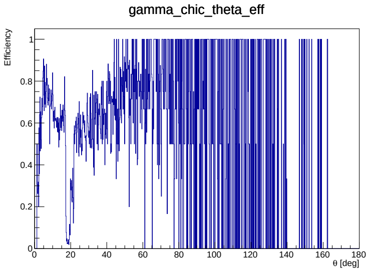


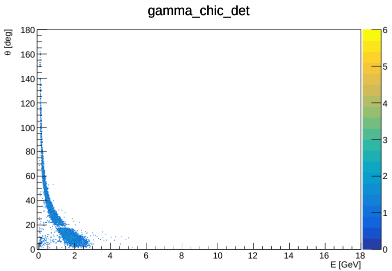
Signal (green-mct) and background (dark green) with best cand

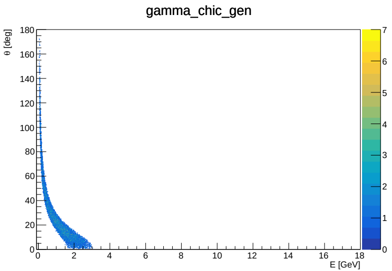
- ∼66% less mct events
- The dedicated background is highly reduced

Photon efficiencies - GEM or MCT?









Summary

- Pair-produced photon recovery is not a clear improvement - removed
- New Voigt fits with background
- Best candidate implementation
- New mc matching - planned to be added to PandaRoot
- Low photon efficiency - due to GEM geometry or MCT?

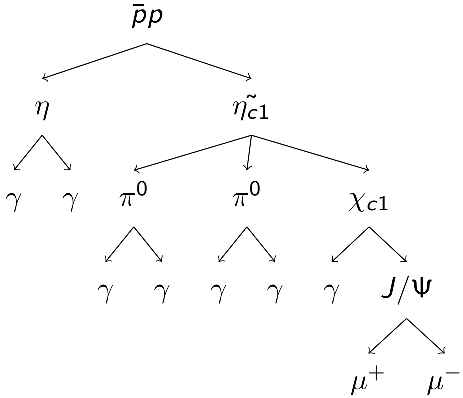
- 4 decay channels analised with optimalised cuts (using genetic algorythm)
- Beam time assumptions - feasable, but pre-pandaroot studies showed better efficiencies
- More DPM? (250000000 filtered - 0-10 events after the cuts)

Detailed results - already presented

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, ...)

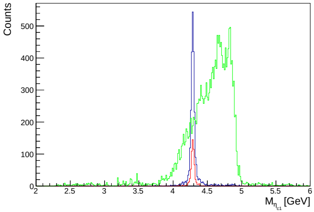
Decay channel $2\pi\chi_{c1}$



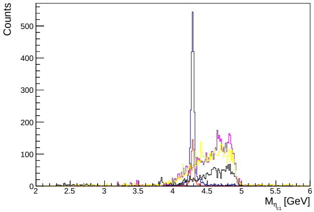
Simulations

- 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

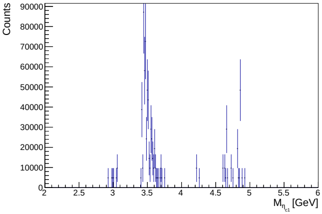
Final results



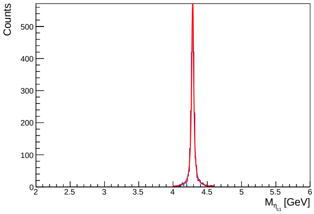
Signal and background



Signal and background

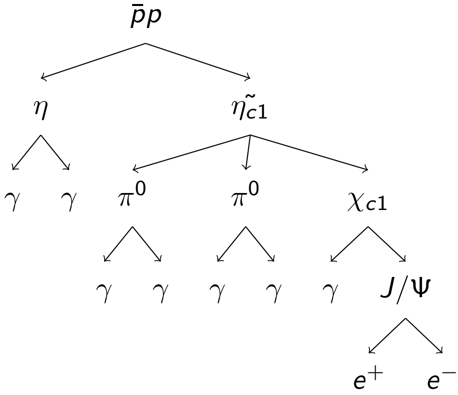


DPM background



Final Voigt fit

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



Simulations

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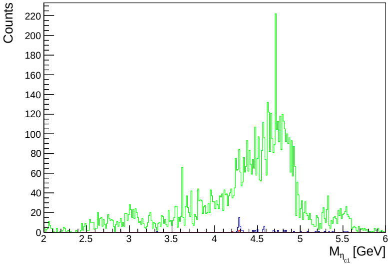
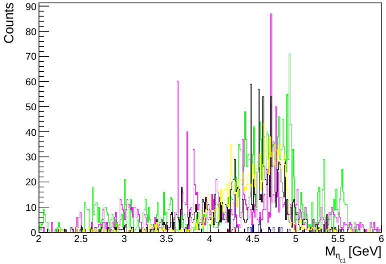
- 1000000 dedicated background events
  - $\bar{p}p \to \chi_{c0}\pi^0\pi^0\eta$
  - $\bar{p}p \to \chi_{c1}\pi^0\pi^0\pi^0\eta$
  - $\bar{p}p \to \chi_{c1}\pi^0\eta\eta$
  - $\bar{p}p \to J/\Psi\pi^0\pi^0\pi^0\eta$
- Bremsstrahlung corrected electrons are used during the reconstruction

Final results

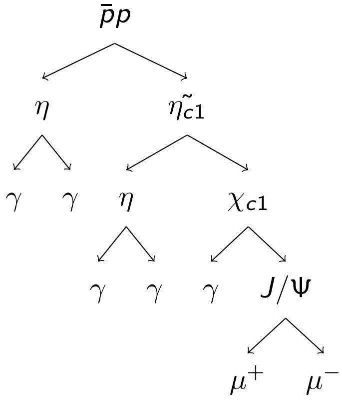


Signal and background



Signal and background

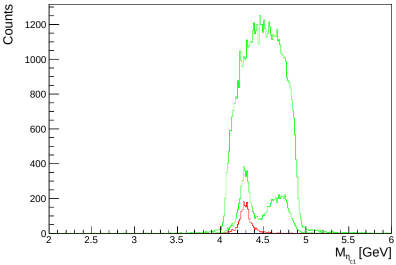
Decay channel $\eta\chi_{c1}$



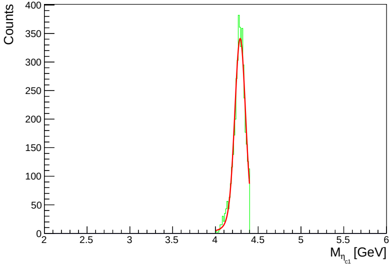
Simulations

- 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

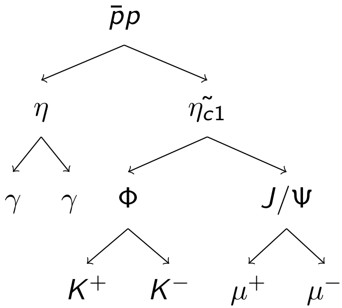


Signal and background



Final Voigt fit

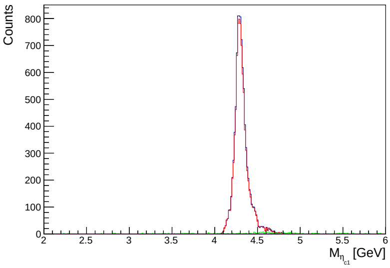
Decay channel $\Phi J/\Psi$



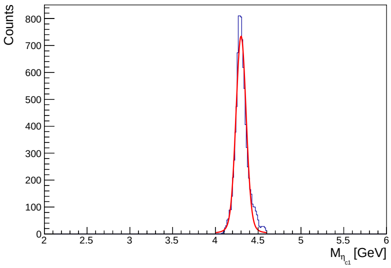
Simulations

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

Results

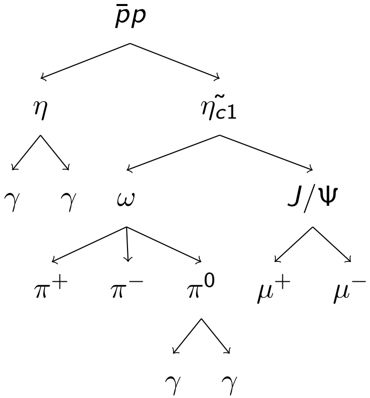


Signal and background



Final Voigt fit

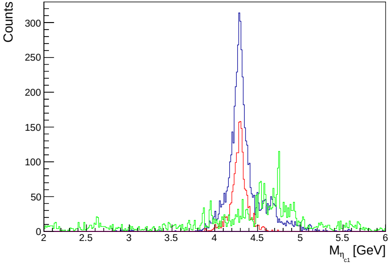
Decay channel $\omega J/\Psi$



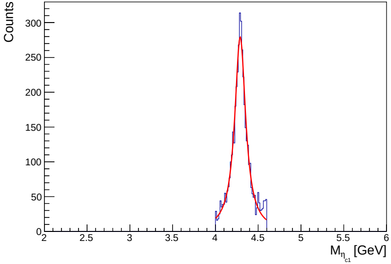
Simulations

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

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

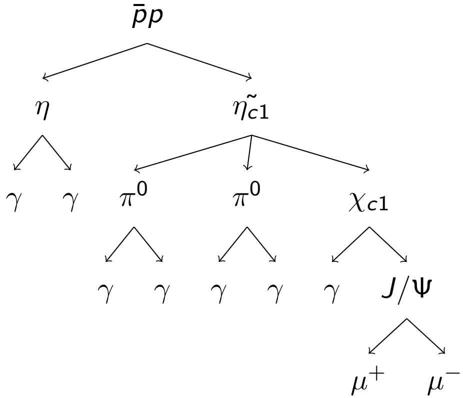
[1] Agnes Lundborg, Exotic charmonium hybrids at PANDA (2004)

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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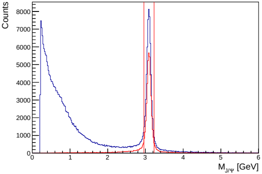
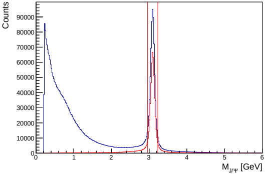
  - $\bar{p}p \rightarrow \chi_{c1}\pi^0\pi^0\pi^0\eta$
  - $\bar{p}p \rightarrow \chi_{c1}\pi^0\eta\eta$
  - $\bar{p}p \rightarrow J/\Psi\pi^0\pi^0\pi^0\eta$
- 250000000 filtered DPM: at least 2 charged tracks with invariant mass 2.5-4.0 GeV using muon PID hypothesis

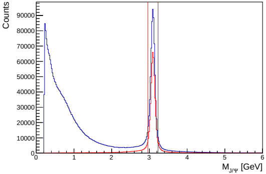
J/Ψ invariant mass



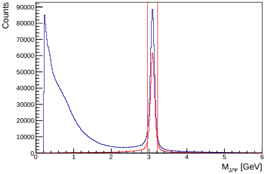
Signal



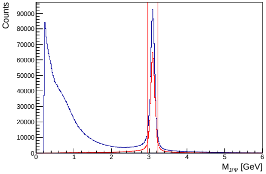
Background 1



Background 2

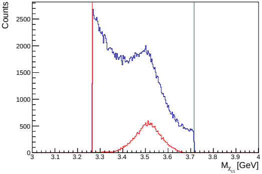


Background 3

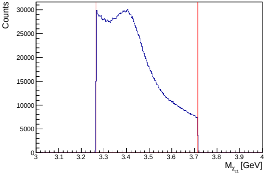


Background 4

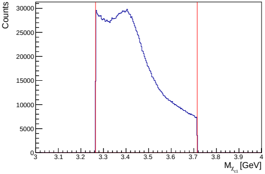
χ_{c1} invariant mass



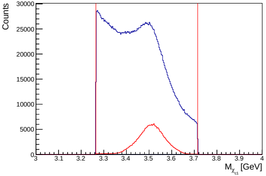
Signal



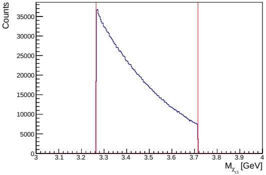
Background 1



Background 2

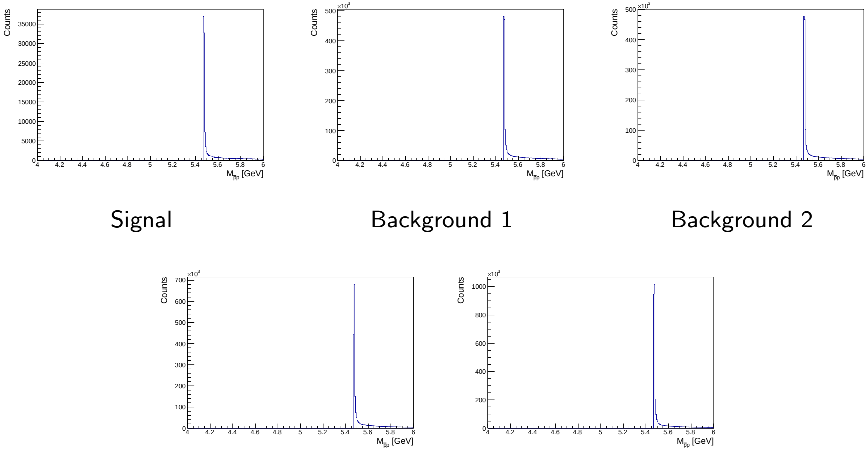


Background 3



Background 4

$\bar{p}p$ invariant mass



Signal

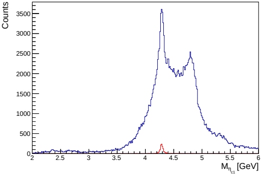
Background 1

Background 2

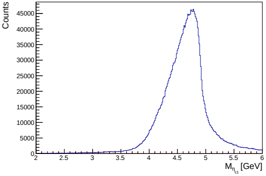
Background 3

Background 4

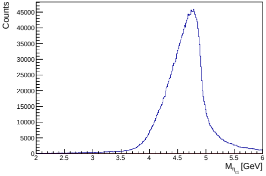
$\tilde{\eta_{c1}}$ invariant mass



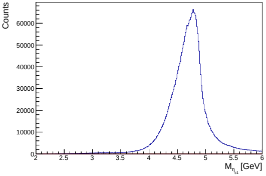
Signal



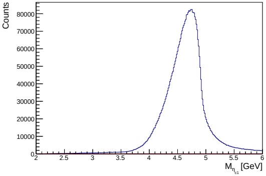
Background 1



Background 2

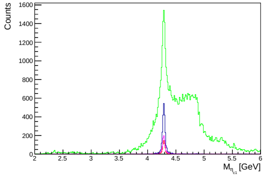


Background 3

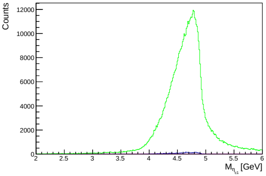


Background 4

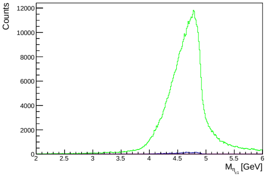
$\tilde{\eta}_{c1}$ invariant mass after the mass and all 6 prob. cuts



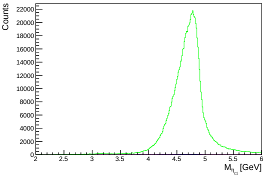
Signal



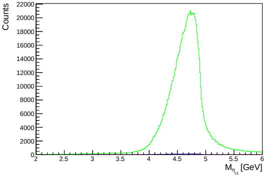
Background 1



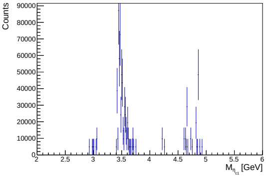
Background 2



Background 3

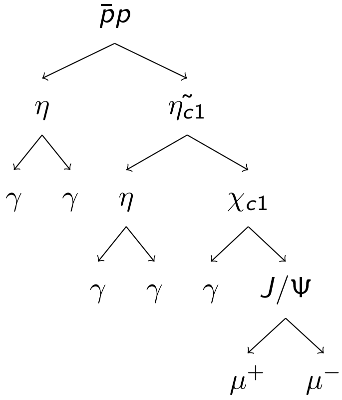


Background 4



DPM (upscaled)

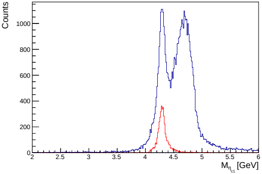
Decay channel $\eta\chi_{c1}$



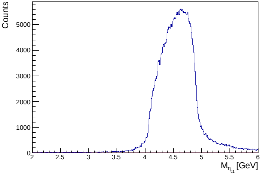
Simulations

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

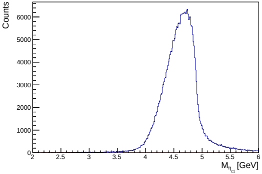
$\eta_{c1}^{\sim}$ invariant mass



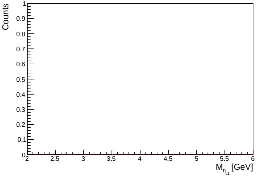
Signal



Background 1

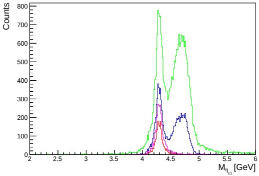


Background 2

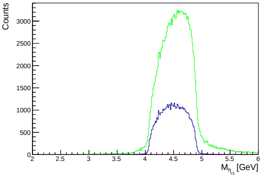


DPM

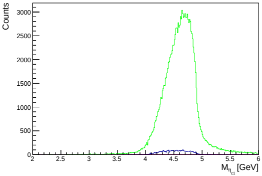
$\tilde{\eta}_{c1}$ invariant mass after the mass and all prob. cuts



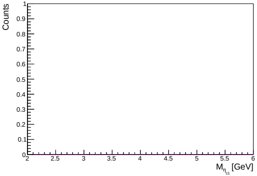
Signal



Background 1

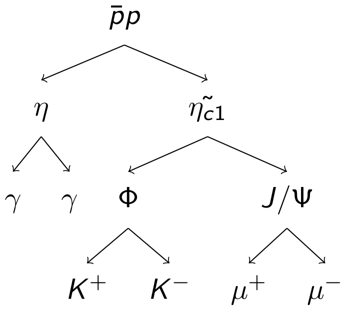


Background 2



DPM

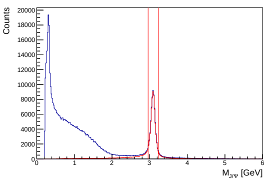
Decay channel Φ



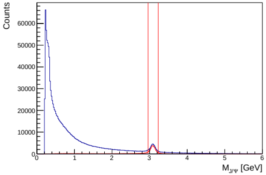
Simulations

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

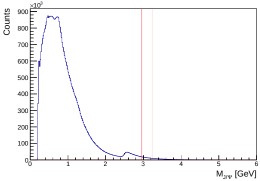
J/Ψ invariant mass



Signal

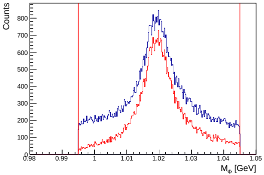


Background

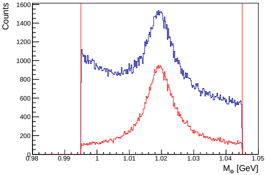


DPM

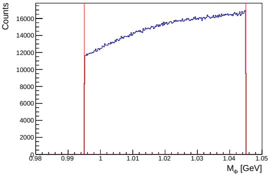
Φ invariant mass



Signal

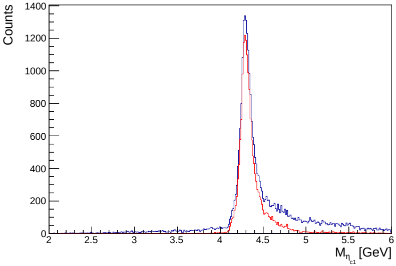


Background

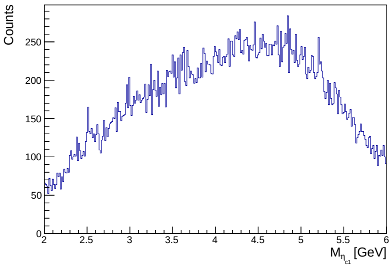


DPM

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

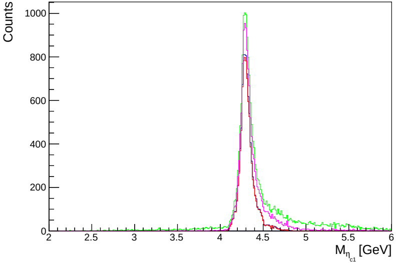


Signal

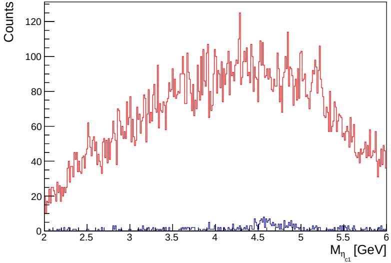


Background

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

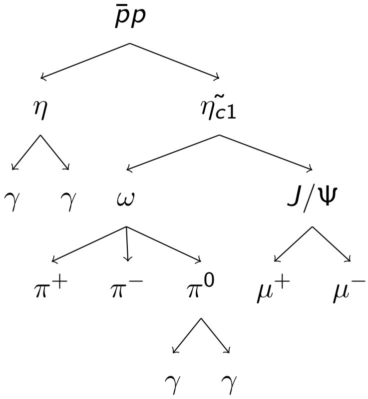


Signal



Background

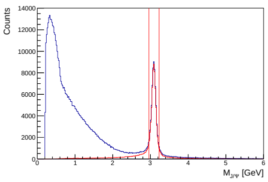
Decay channel ω



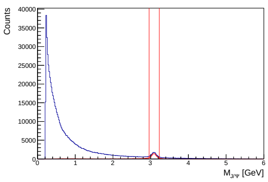
Simulations

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

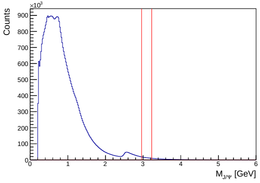
J/Ψ invariant mass



Signal

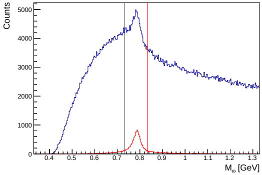


Background

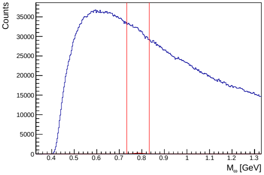


DPM

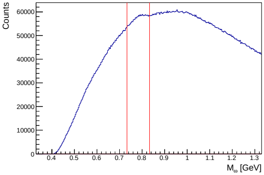
ω invariant mass



Signal

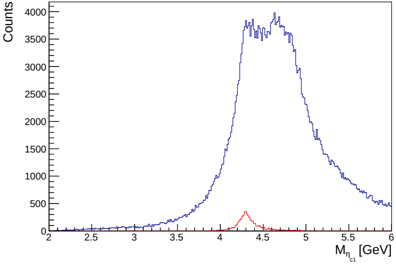


Background

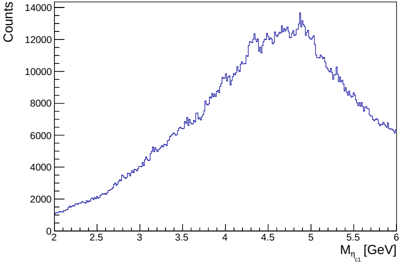


DPM

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

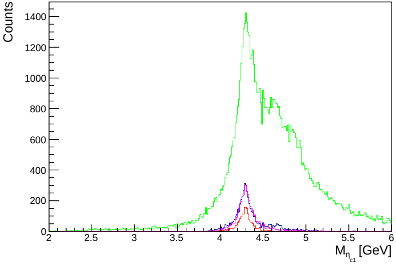


Signal

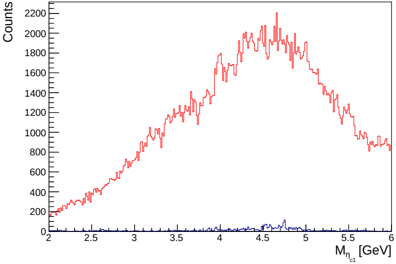


Background

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



Signal



Background