# Charmonium event generators for PandaRoot

Vasily Mochalov, Alexey Luchinsky, Dmitry Morozov, Stanislav Poslavsky

Institute for High Energy Physics, Protvino, Russia

SRRC RF ITEP NRC Kurchatov Institute, Moscow Russia

2 Mar 2016

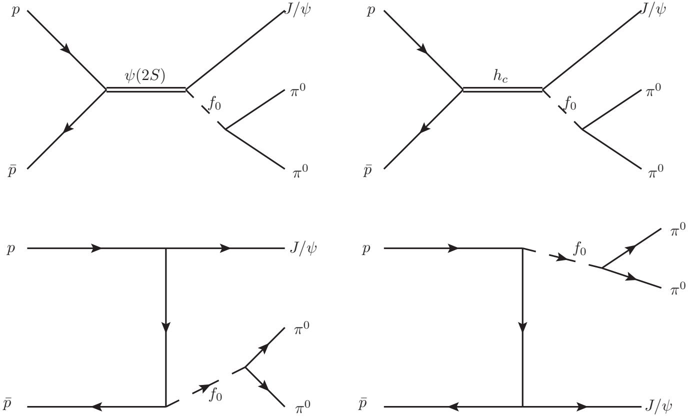
# Charmonium theory & event generators

- $h_c, \psi(2S)$ decays:
  - $p\bar{p} \to (h_c, \psi(2S)) \to J/\psi\, \pi^0 \pi^0$
  - $p\bar{p} \to (h_c, \psi(2S)) \to \eta_c \gamma$
- $\chi_c$ production and radiative decay:
  - $p\bar{p} \to \chi_c \to J/\psi\, \gamma$
  - $p\bar{p} \to \chi_c + X \to J/\psi\, \gamma + X$
- $X(3872)$ decays:
  - $p\bar{p} \to X(3872) \to J/\psi\, \rho \to J/\psi\, \pi^+ \pi^- \pi^0$
  - $p\bar{p} \to X(3872) \to J/\psi\, \omega \to J/\psi\, \pi^+ \pi^-$

- All these processes involve $\gamma$-quanta in final state, which are detected in EMC system

# Hadronic decays of $h_c$ and $\psi(2S)$

- Signal processes $p\bar{p} \to h_c, \psi(2S) \to J/\psi\pi^0\pi^0$
- Background process: $p\bar{p} \to J/\psi\pi^0\pi^0$
- Feynman diagrams:



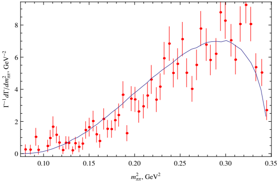
# Hadronic decays of $h_c$ and $\psi(2S)$

- Vertices

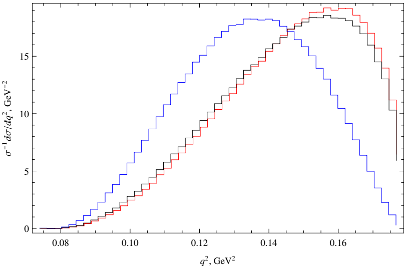
$$
\begin{aligned}
V_\mu^{p\bar{p}\psi'} &= g_{\psi'}^{p\bar{p}}\,\bar{v}\gamma_\mu u \\
V_{\mu\nu}^{\psi'\,J/\psi\,f_0} &= g_{f_0}^{\psi'\,J/\psi}\,g_{\mu\nu} \\
V_\mu^{p\bar{p}h_c} &= g_{h_c}^{p\bar{p}}\,\bar{v}\gamma_5\gamma_\mu u \\
V_{\mu\nu}^{h_c\,J/\psi\,f_0} &= g_{f_0}^{h_c\,J/\psi}\,e_{\mu\nu\alpha\beta}p_{J/\psi}^\alpha p_{h_c}^\beta \\
F_{\pi\pi}^{f_0}(q^2) &= q^2 + K(m_{\psi'}^2 - m_\psi^2)^2\left(1 + \frac{2m_\pi^2}{q^2}\right), \quad K \approx 0.15
\end{aligned}
$$

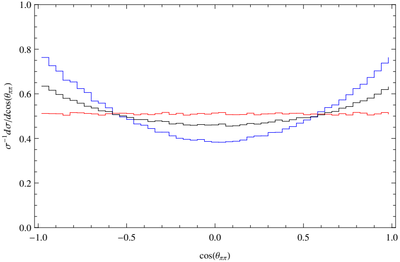
- $\psi'$ couplings can be determined using known decays width, while for $h_c$ can be only estimated (upper bound, *F. Murgia, Phys.Rev.D54 (1996) 3365 - 3373*).
- $f_0 \to \pi\pi$ form-factor is known experimentally

- Having analytical matrix elements, we've implemented these processes in `EvtGen`



# $h_c$ resonance production




Cross sections:

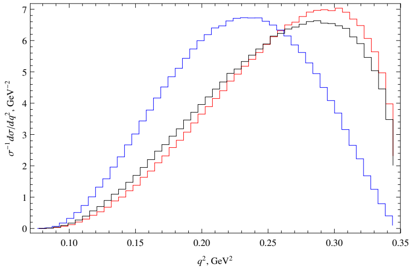
| $\psi(2S)$ | $h_c$ | $p\bar{p}$ |
|---|---|---|
| 0.004 *pb* | 93 *nb* | 0.8 *pb* |

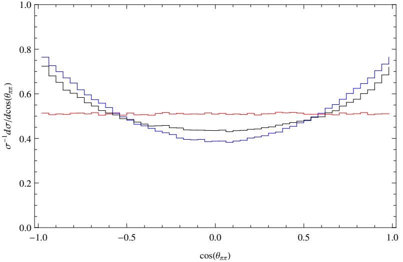
$$\frac{d\sigma_{h_c}}{d\,cos\theta_{\pi\pi}} \sim 1 + cos^2\theta_{\pi\pi}$$

Distribution parameters:
($\alpha_\pi$ is $p\pi$ angle, $\alpha_{\pi\pi}$ – $p(\pi\pi)$)

| | $\psi(2S)$ | $h_c$ | $p\bar{p}$ |
|---|---|---|---|
| $\langle m^2_{\pi\pi} \rangle$ | 0.15 | 0.13 | 0.14 |
| $\langle \delta m^2_{\pi\pi} \rangle$ | 0.02 | 0.02 | 0.02 |
| $\alpha_{\pi\pi}$ | 0 | 1 | 0.38 |
| $\alpha_\pi$ | 0 | 0.16 | 0.08 |

# $\psi'$ resonance production




Cross sections:

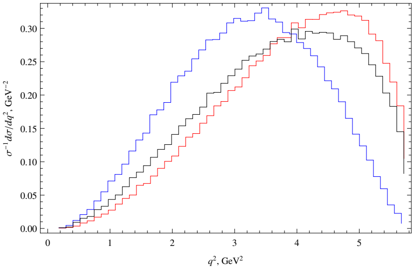
| $\psi(2S)$ | $h_c$ | $p\bar{p}$ |
|---|---|---|
| $0.5\,\mu b$ | $0.05\,pb$ | $12\,pb$ |

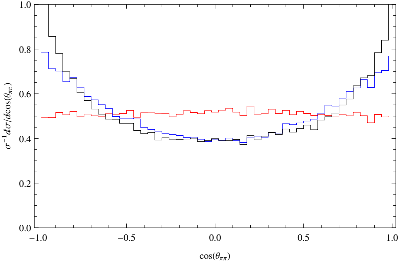
$$\frac{d\sigma_{\psi'}}{d\,cos\theta_{\pi\pi}} \sim const$$

Distribution parameters:
($\alpha_\pi$ is $p\pi$ angle, $\alpha_{\pi\pi}$ – $p(\pi\pi)$)

| | $\psi(2S)$ | $h_c$ | $p\bar{p}$ |
|---|---|---|---|
| $\langle m^2_{\pi\pi} \rangle$ | 0.25 | 0.22 | 0.25 |
| $\langle \delta m^2_{\pi\pi} \rangle$ | 0.05 | 0.05 | 0.05 |
| $\alpha_{\pi\pi}$ | 0 | 1 | 0.63 |
| $\alpha_\pi$ | 0 | 0.17 | 0.13 |

# $\sqrt{s} = 5.5$ GeV



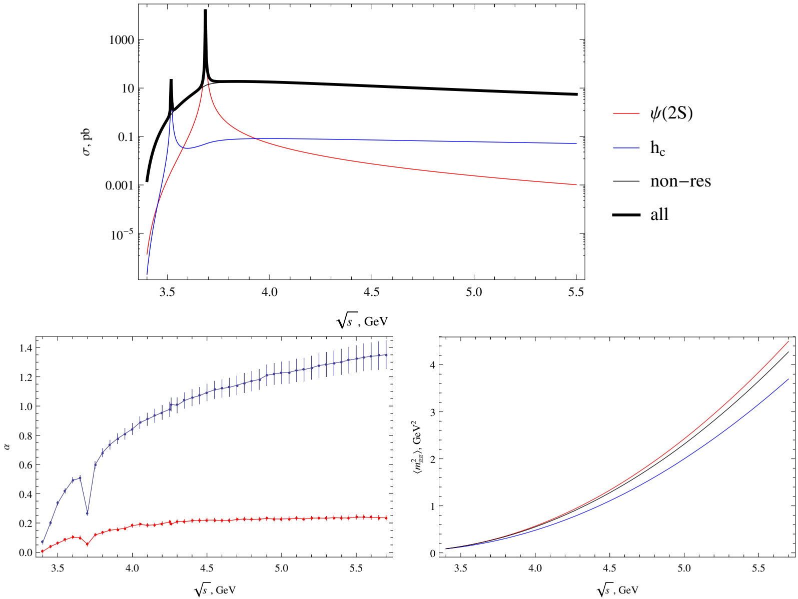

Cross sections:

| $\psi(2S)$ | $h_c$ | $p\bar{p}$ |
|---|---|---|
| 0.001 *pb.* | 0.05 *pb* | 5.5 *pb* |

Distribution parameters:
($\alpha_\pi$ is $p\pi$ angle, $\alpha_{\pi\pi}$ – $p(\pi\pi)$)

| | $\psi(2S)$ | $h_c$ | $p\bar{p}$ |
|---|---|---|---|
| $\langle m^2_{\pi\pi} \rangle$ | 3.8 | 3.1 | 3.6 |
| $\langle \delta m^2_{\pi\pi} \rangle$ | 1.2 | 1.1 | 1.2 |
| $\alpha_{\pi\pi}$ | 0 | 1 | 1.3 |
| $\alpha_\pi$ | -0.01 | 0.14 | 0.22 |

# Energy dependence



# Radiative decays of $h_c, \chi_{c1,2}$

- Standard matrix elements:

$$V^{h_c \eta_c \gamma} = g_{h_c}^{\eta_c \gamma} M_{h_c} \left( g^{\mu\nu} - \frac{k^\mu p^\nu}{(kp)} \right) \epsilon_\mu^{(h_c)} \epsilon_\mu^{(\gamma)}$$

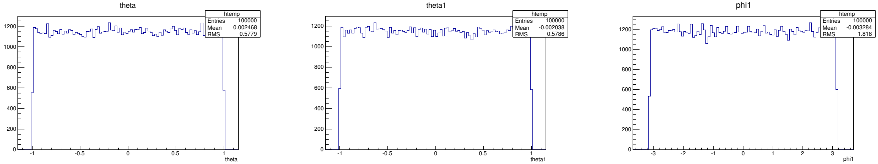
$$V^{\chi_{c1} J/\psi \gamma} = g_{\chi_{c1}}^{J/\psi \gamma} e^{\mu\nu\alpha\beta} k_\mu \epsilon_\nu^{(\chi_{c1})} \epsilon_\alpha^{(J/\psi)} \epsilon_\beta^{(\gamma)}$$

$$V^{\chi_{c2} J/\psi \gamma} = g_{\chi_{c2}}^{J/\psi \gamma} p^\mu \epsilon_{\alpha\beta}^{(\chi_{c2})} \epsilon_\alpha^{(J/\psi)} \left( k_\mu \epsilon_\beta^{(\gamma)} - k_\beta \epsilon_\mu^{(\gamma)} \right)$$

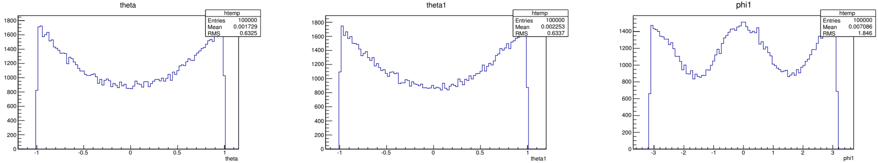
- Again, $\chi_c$ couplings can be determined from known widths, while $h_c$ can be only estimated
- $p\bar{p} \to J/\psi, \psi(2S) \to \eta_c \gamma$ and backgrounds for $h_c$ ($p\bar{p} \to \eta\gamma$, $p\bar{p} \to \eta\pi_0$) are also implemented
- Angular distributions in the radiative decay of $\chi_c$ provides information on the multipole structure of decay
- Polarized decays are also implemented
- $X(3872)$-decays are also implemented with the assumption that $X(3872)$ is $1^{++}$ $P$-wave quarkonia (as $\chi_{c1}$)

# Angular distributions of polarised decays $p\bar{p} \to \chi_{c1} \to J/\psi\gamma \to \mu^+\mu^-\gamma$

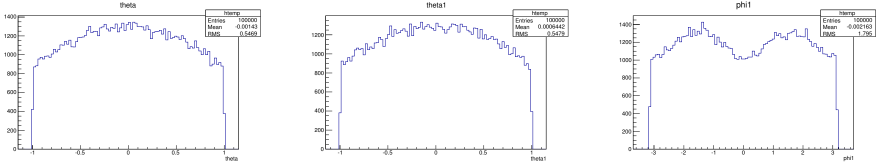
## Unpolarazed




## helicity = 0

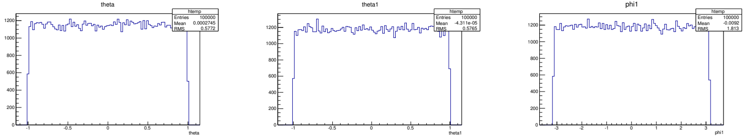



## helicity = ±1

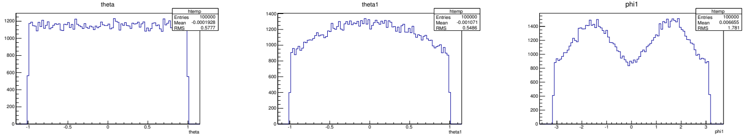


# Angular distributions of polarised decays $p\bar{p} \to \chi_{c2} \to J/\psi\gamma \to \mu^+\mu^-\gamma$

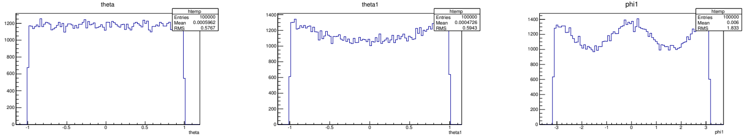
unpolarized



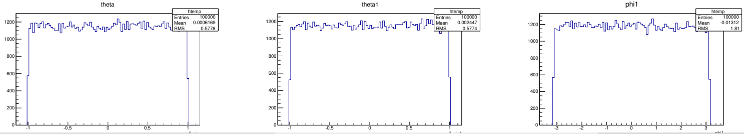

helicity $= 0$




helicity $= +1$

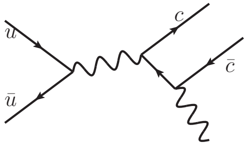



helicity $= +2$



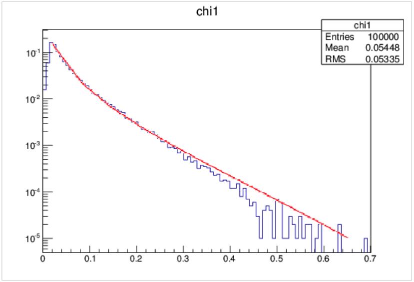
# Inclusive production of $\chi_{c1,2}$

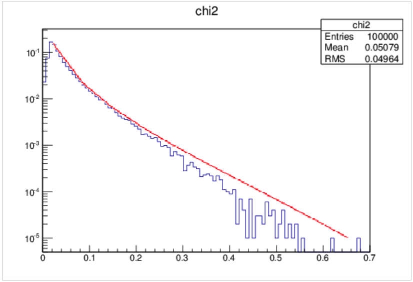
- Production of $\chi_{c1,2}$ is a main source of $J/\psi$ mesons in PANDA
- Theoretical background: *Luchinsky and Poslavsky, Phys.Rev. D85 (2012) 074016*
  - the dominated partonic subprocess: $u + \bar{u} \to \chi_c + g$
  - other subprocesses ($g + g$, $d + \bar{d}$, $g + u$ etc.) are suppressed due to small partonic distributions at large $x$
  - $c\bar{c}$ pair in $P$-wave mainly forms in color singlet combination *(Likhoded, Luchinsky and Poslavsky, Phys.Rev. D86 (2012) 074027)*
  - so, we can consider only one Feynman diagram



# Inclusive channel: test generator kinematics etc.

- Comparison of simulated data and theory predictions ($p_T$-spectrum):




$\sqrt{s} = 5.5$ GeV

  - The distributions over common kinematical variables ($p_T$, $y$, $\eta$ etc.) are same as theory predicts
  - Other obvious checks (energy/momentum conservation etc.) are also ok

- More documentation can be found at:

https://panda-wiki.gsi.de/foswiki/bin/view/Computing/ChiGen

# Conlusions

- List of implemented processes:

$$
\begin{aligned}
p\bar{p} &\rightarrow (h_c, J/\psi, \psi(2S)) \rightarrow \eta_c\gamma \\
p\bar{p} &\rightarrow \eta_c\gamma \\
p\bar{p} &\rightarrow \eta\pi^0 \\
p\bar{p} &\rightarrow \gamma\pi^0 \\
p\bar{p} &\rightarrow (h_c, \psi(2S)) \rightarrow J/\psi\pi^0\pi^0 \\
p\bar{p} &\rightarrow J/\psi\pi^0\pi^0 \\
p\bar{p} &\rightarrow J/\psi\eta\pi^0 \\
p\bar{p} &\rightarrow (\chi_{c1}, \chi_{c2}, X(3872)) \rightarrow J/\psi\gamma \\
p\bar{p} &\rightarrow (\chi_{c1}, \chi_{c2}, X(3872)) + X \rightarrow J/\psi\gamma + X
\end{aligned}
$$

- All `EvtGen` models and generators are in PandaRoot repository
- On road:

$$
\begin{aligned}
p\bar{p} &\rightarrow X(3872) \rightarrow J/\psi\,\pi^+\pi^- \\
p\bar{p} &\rightarrow X(3872) \rightarrow J/\psi\,\pi^+\pi^-\pi^0
\end{aligned}
$$

- Later the same for X(3940) and X(4160)

BACKUP

## Inclusive channel: implementation features

Problems using `Pythia8` :

- `Pythia8` does not work at energies lower than 10 GeV (in PANDA $\sqrt{s} \sim 5.6$ GeV in production mode)
- Even if we adjust `Pythia8` and make it works with low energies (by modifying `BeamParameters.xml`, `PhaseSpaceCuts.xml`, etc), it produces baryons in final state, which is crucial for charmonium production:

$$M_p + M_p + M_{\chi_c} \approx 5.5\,\text{GeV}$$

  - this is a consequence of `Pythia8` underlying quark-diquark model of proton and theory tells that this should happen nearly in a half of events

- In terms of `Pythia8` color flow it is impossible to describe $0_c \rightarrow 3_c 3_c 3_c$ and $\bar{3}_c \rightarrow 3_c 3_c$

$\Rightarrow$ We cannot use `Pythia8` in the usual way

- So we need to implement generator "from scratch"
- We can use `Pythia8` just for hadronization of color remnants

# Inclusive channel: the workflow

`ChiGen` workflow:

1 MC simulation on partonic level

$$p + \bar{p} \to (uud) + (\bar{u}\bar{u}\bar{d}) \to \chi_c + g + (ud) + (\bar{u}\bar{d})$$

- set kinematics and colors for all partons (neglect quark-diquark structure of proton)
- the momentums of $u$ and $\bar{u}$ are chosen using PDF's, while the momentums of remnants are randomly distributed
- calculate distribution of $u + \bar{u} \to \chi_c + g$

2 Hadronizes color remnants using `Pythia8` :

$$g + (ud) + (\bar{u}\bar{d}) \to X$$

3 Use `EvtGen` for radiative decays

$$\chi_{cJ} \to J/\psi + \gamma \to e^+ + e^- + \gamma$$

4 Pass all final particles to `PandaRoot`