

Charmonium event generators for PandaRoot

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IHEP young scientists group

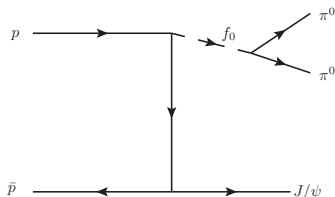
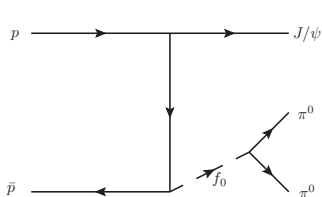
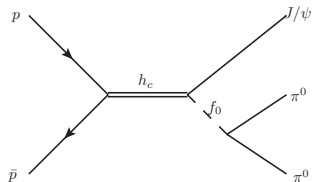
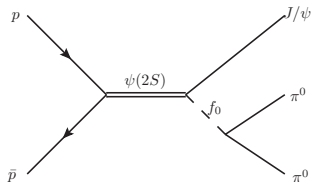
- Fair-Russia Research Center grant for young scientists
- Theory (Luchinsky & Poslavsky):
 - ▶ Charmonium theory
 - ▶ PandaRoot event generators
- Software (Morozov):
 - ▶ PandaRoot development (calorimetry)
 - ▶ Analysis algorithms
- Engineering: Forward Spectrometr Calorimeter (Ryzhikov & Bukreeva)
 - ▶ Slow control system
 - ▶ LED monitoring system

Charmonium theory & event generators

- $h_c, \psi(2S)$ decays:
 - ▶ $p\bar{p} \rightarrow (h_c, \psi(2S)) \rightarrow J/\psi \pi^0 \pi^0$
 - ▶ $p\bar{p} \rightarrow (h_c, \psi(2S)) \rightarrow \eta_c \gamma$
- χ_c production and radiative decay:
 - ▶ $p\bar{p} \rightarrow \chi_c \rightarrow J/\psi \gamma$
 - ▶ $p\bar{p} \rightarrow \chi_c + X \rightarrow J/\psi \gamma + X$
- $X(3872)$ decays:
 - ▶ $p\bar{p} \rightarrow X(3872) \rightarrow J/\psi \rho \rightarrow J/\psi \pi^+ \pi^- \pi^0$
 - ▶ $p\bar{p} \rightarrow X(3872) \rightarrow J/\psi \omega \rightarrow J/\psi \pi^+ \pi^-$
- All these processes involve γ -quanta in final state, which are detected in EMC system

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

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



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

- Vertices

$$V_{\mu}^{P\bar{P}\psi'} = g_{\psi'}^{P\bar{P}} \bar{v} \gamma_{\mu} u$$

$$V_{\mu\nu}^{\psi' J/\psi f_0} = g_{f_0}^{\psi' J/\psi} g_{\mu\nu}$$

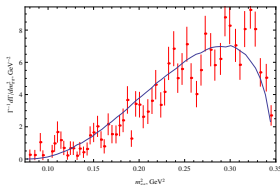
$$V_{\mu}^{P\bar{P}h_c} = g_{h_c}^{P\bar{P}} \bar{v} \gamma_5 \gamma_{\mu} u$$

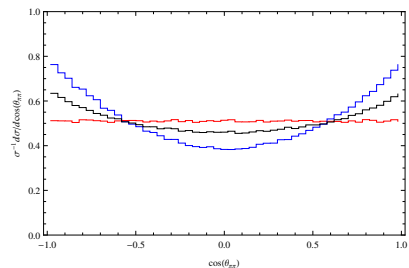
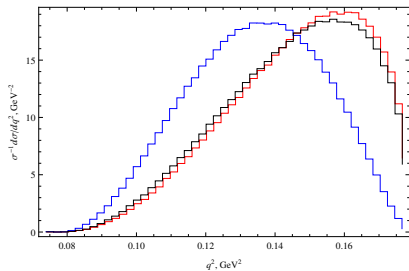
$$V_{\mu\nu}^{h_c J/\psi f_0} = g_{f_0}^{h_c J/\psi} e_{\mu\nu\alpha\beta} p_{J/\psi}^{\alpha} p_{h_c}^{\beta}$$

$$F_{\pi\pi}^{f_0}(q^2) = q^2 + K(m_{\psi'}^2 - m_{\psi}^2)^2 \left(1 + \frac{2m_{\pi}^2}{q^2}\right), \quad K \approx 0.15$$

- ψ' 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*).
- $f_0 \rightarrow \pi\pi$ form-factor is known experimentally

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



h_c resonance production

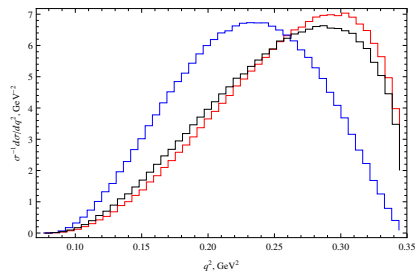
Cross sections:

$\psi(2S)$	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:

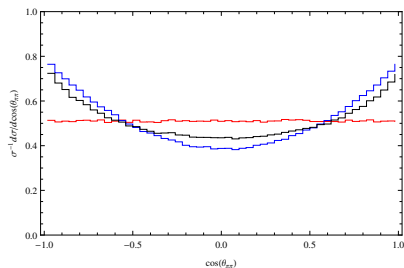
	$\psi(2S)$	h_c	$p\bar{p}$
$\langle m_{\pi\pi}^2 \rangle$	0.15	0.13	0.14
$\langle \delta m_{\pi\pi}^2 \rangle$	0.02	0.02	0.02
$\alpha_{\pi\pi}$	0	1	0.38
α_{π}	0	0.16	0.08

ψ' resonance production

Cross sections:

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

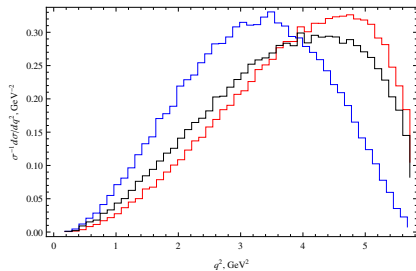
$$\frac{d\sigma_{\psi'}}{d \cos\theta_{\pi\pi}} \sim const$$



Distribution parameters:

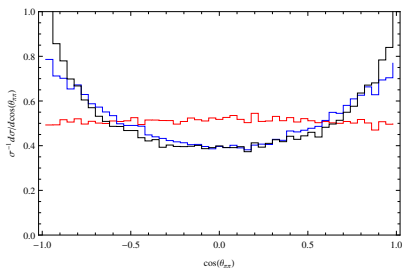
	$\psi(2S)$	h_c	$p\bar{p}$
$\langle m_{\pi\pi}^2 \rangle$	0.25	0.22	0.25
$\langle \delta m_{\pi\pi}^2 \rangle$	0.05	0.05	0.05
$\alpha_{\pi\pi}$	0	1	0.63
α_{π}	0	0.17	0.13

$$\sqrt{s} = 5.5 \text{ GeV}$$



Cross sections:

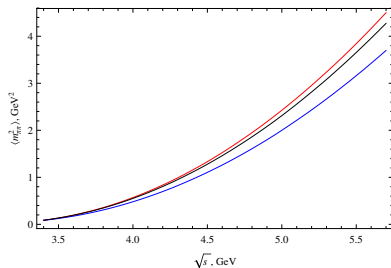
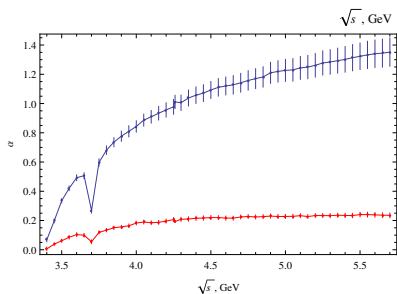
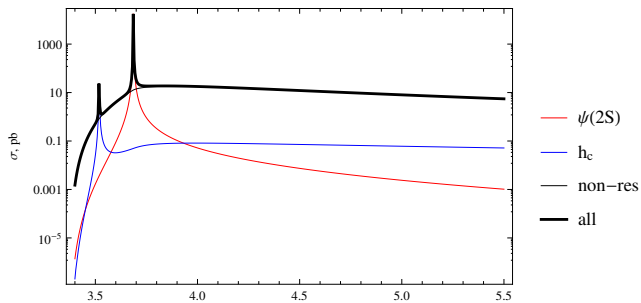
$\psi(2S)$	h_c	$p\bar{p}$
0.001 pb.	0.05 pb	5.5 pb



Distribution parameters:

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

Energy dependence

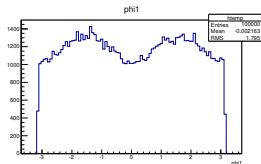
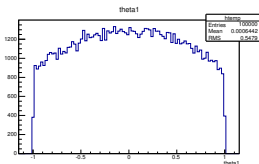
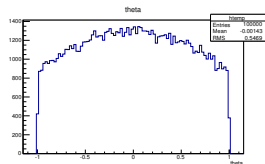
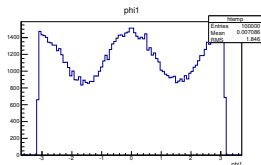
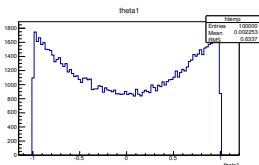
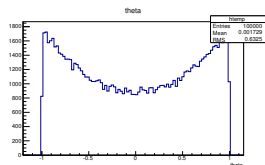
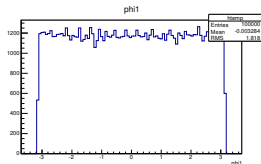
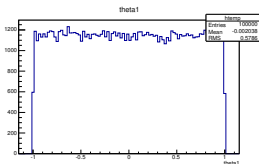
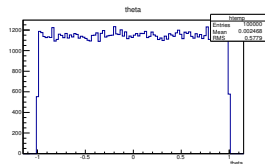


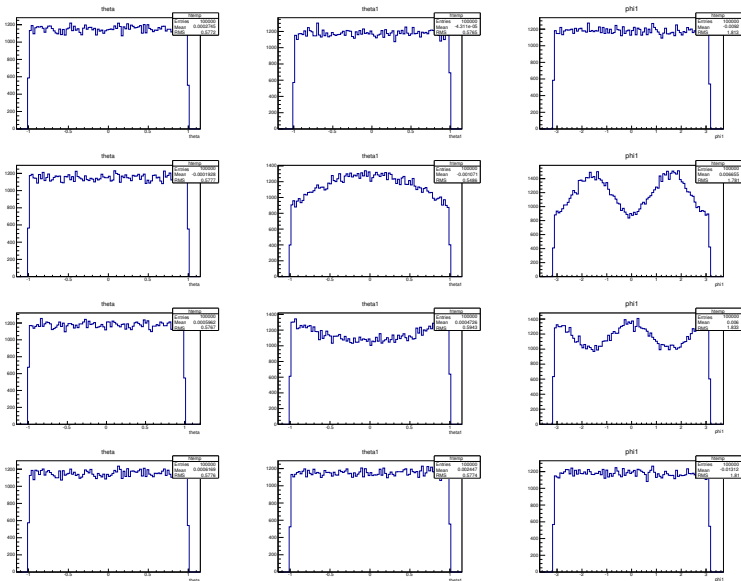
Radiative decays of $h_c, \chi_{c1,2}$

- Standard matrix elements:

$$\begin{aligned}
 V^{h_c \eta_c \gamma} &= g_{h_c}^{\eta_c \gamma} M_{h_c} \left(g^{\mu\nu} - \frac{k^\mu p^\nu}{(kp)} \right) \epsilon_\mu^{(h_c)} \epsilon_\mu^{(\gamma)} \\
 V^{\chi_{c1} J/\psi \gamma} &= g_{\chi_{c1}}^{J/\psi \gamma} e^{\mu\nu\alpha\beta} k_\mu \epsilon_\nu^{(\chi_{c1})} \epsilon_\alpha^{(J/\psi)} \epsilon_\beta^{(\gamma)} \\
 V^{\chi_{c2} J/\psi \gamma} &= g_{\chi_{c2}}^{J/\psi \gamma} p^\mu \epsilon_{\alpha\beta}^{(\chi_{c2})} \epsilon_\alpha^{(J/\psi)} \left(k_\mu \epsilon_\beta^{(\gamma)} - k_\beta \epsilon_\mu^{(\gamma)} \right)
 \end{aligned}$$

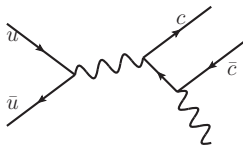
- Again, χ_c couplings can be determined from known widths, while h_c can be only estimated
- $p\bar{p} \rightarrow J/\psi, \psi(2S) \rightarrow \eta_c \gamma$ and backgrounds for h_c : $p\bar{p} \rightarrow h_c \rightarrow \eta_c \pi_0$, $p\bar{p} \rightarrow \eta_c \pi_0$ are also implemented
- Angular distributions in the radiative decay of χ_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 χ_{c1})

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

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

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

- Production of $\chi_{c1,2}$ is a main source of J/ψ mesons in PANDA
- Theoretical background: *Luchinsky and Poslavsky, Phys.Rev. D85 (2012) 074016*
 - the dominated partonic subprocess: $u + \bar{u} \rightarrow \chi_c + g$
 - 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: 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 $\bar{3}_c \rightarrow 3_c 3_c$
- ⇒ 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

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

- ▶ 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 $u + \bar{u} \rightarrow \chi_c + g$

2 Hadronizes color remnants using Pythia8 :

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

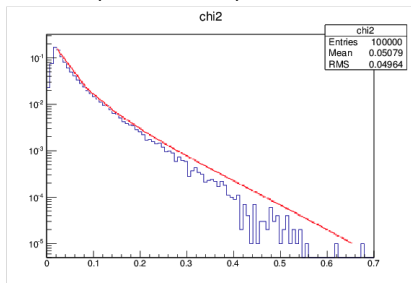
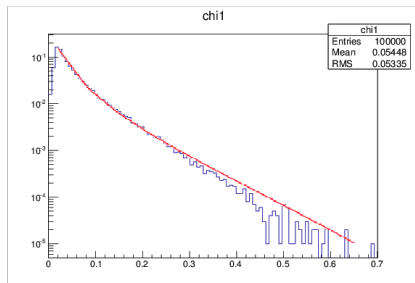
3 Use EvtGen for radiative decays

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

4 Pass all final particles to PandaRoot

Inclusive channel: test generator kinematics etc.

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



$$\sqrt{s} = 5.5 \text{ GeV}$$

- The distributions over common kinematical variables (p_T , y , η 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>

Conclusions

- List of implemented processes:

$$p\bar{p} \rightarrow (h_c, J/\psi, \psi(2S)) \rightarrow \eta_c \gamma$$

$$p\bar{p} \rightarrow \eta_c \gamma$$

$$p\bar{p} \rightarrow \eta_c \pi^0$$

$$p\bar{p} \rightarrow \gamma \pi^0$$

$$p\bar{p} \rightarrow (h_c, \psi(2S)) \rightarrow J/\psi \pi^0 \pi^0$$

$$p\bar{p} \rightarrow J/\psi \pi^0 \pi^0$$

$$p\bar{p} \rightarrow J/\psi \eta_c \pi^0$$

$$p\bar{p} \rightarrow (\chi_{c1}, \chi_{c2}, X(3872)) \rightarrow J/\psi \gamma$$

$$p\bar{p} \rightarrow (\chi_{c1}, \chi_{c2}, X(3872)) + X \rightarrow J/\psi \gamma + X$$

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

$$p\bar{p} \rightarrow X(3872) \rightarrow J/\psi \pi^+ \pi^-$$

$$p\bar{p} \rightarrow X(3872) \rightarrow J/\psi \pi^+ \pi^- \pi^0$$