Charmonia modeling for the SPD NICA experiment using Pythia8 Monte Carlo generator and the SPDroot software packages

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Purpose and Goals

Main purpose – estimate charmonia prospectives for the SPD NICA experiment

Goals:

- Estimate charmonia cross-section

$$N = \sigma \cdot L \cdot t \cdot P,$$

- Charmonia signal modeling
- Obtain kinematic characteristics distributions:
  1. Invariant mass;

$$m_{12}{}^2 = E_{12}{}^2/c^4 - \boldsymbol{p}_{12}{}^2/c^2.$$

  2. Transverse momentum pT;

The component of the momentum that is transverse (i.e. perpendicular) to the beam

  3. Pseudorapidity η;

$$\eta = -\ln\left[\mathrm{tg}\left(\frac{\theta}{2}\right)\right]$$

  4. Azimuth angle φ;

Additional tasks:

- Bottomonia cross-section estimation and signal modeling
- Compare development and master versions of reconstruction algorithm

Spin Physics Detector

- Spin Physics Detector – the planned universal detector of the NICA collider, designed to study the spin structure of protons and deuterons

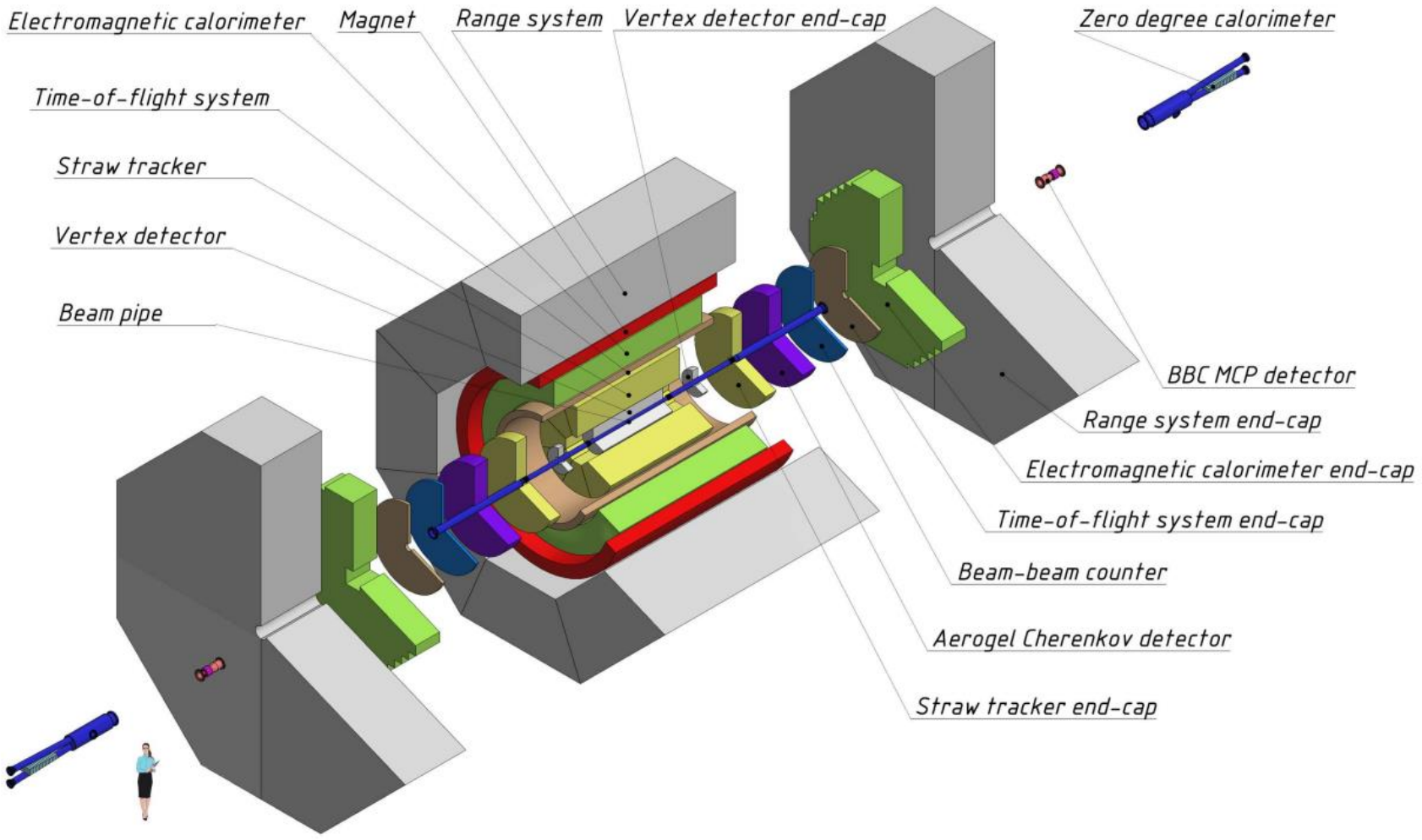


Figure 1. General layout of the SPD setup

Tentative operating plan of the SPD project.

The periods considered in the work:

1) The first stage of the experiment at $\sqrt{s} = 7.5$ GeV (Charmonia only)

2) The second stage of the experiment at $\sqrt{s} = 27$ GeV (Charmonia and bottomonia)

	Physics goal	Required time	Experimental conditions
	First stage		
1	Spin effects in p-p scattering dibaryon resonanses	0.3 year	$p_{L,T}$-$p_{L,T}$, $\sqrt{s}$ <7.5 GeV
	Spin effects in p-d scattering, non-nucleonic structure of deuteron, $\bar{p}$ yield	0.3 year	d_{tensor}-p, $\sqrt{s}$ <7.5 GeV
	Spin effects in d-d scattering hypernuclei	0.3 year	d_{tensor}-d_{tensor}, $\sqrt{s}$ <7.5 GeV
	Hyperon polarization, SRC, ... multiquarks	together with MPD	ions up to Ca
	Second stage		
2	Gluon TMDs, SSA for light hadrons	1 year	p_T-p_T, $\sqrt{s}$ =27 GeV
	TMD-factorization test, SSA, charm production near threshold, onset of deconfinment, $\bar{p}$ yield	1 year	p_T-p_T, 7 GeV< $\sqrt{s}$ <27 GeV (scan)
	Gluon helicity, ...	1 year	p_L-p_L, $\sqrt{s}$ =27 GeV
	Gluon transversity, non-nucleonic structure of deuteron, "Tensor porlarized" PDFs	1 year	d_{tensor}-d_{tensor}, $\sqrt{s_{NN}} = 13.5$ GeV or/and d_{tensor}-p_T, $\sqrt{s_{NN}} = 19$ GeV

Table 1. Tentative operating plan of the SPD project
[Technical Design Report of the Spin Physics Detector: arXiv:2404.08317 [hep-ex]]

Motivation

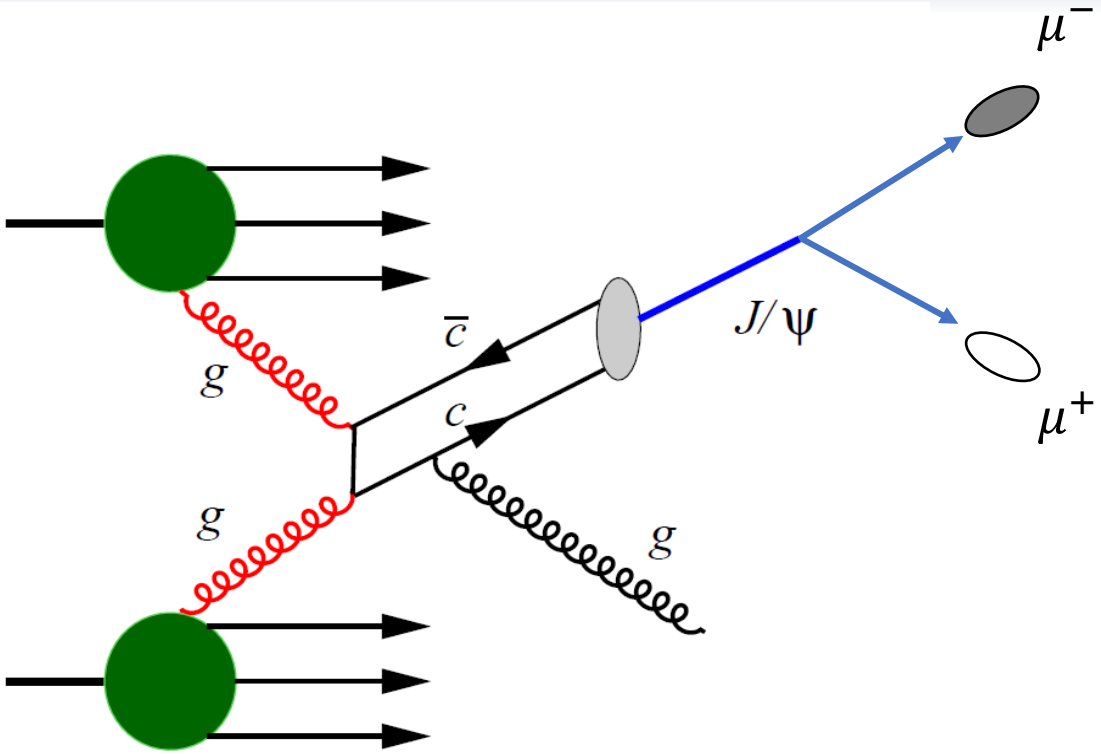


Figure 2. J/ψ-meson production and muon channel decay

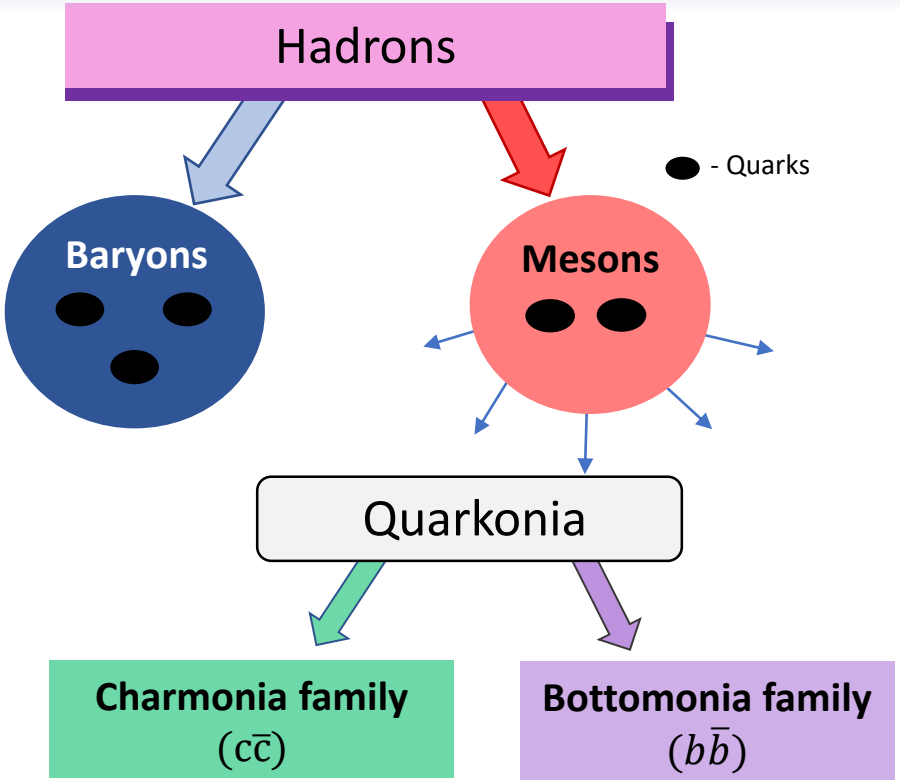


Figure 3. Charmonia and bottomonia classification

Studying the hadron structure is an important task for hadron physics. Investigation of the characteristics of quarkonia produced in gluon fusion may help to refine the gluon parton distribution functions (gPDF).

Used tools

- Pythia8 is a program for generating collision events in high energy physics, using the Monte Carlo method to generate events.

  Used version: PYTHIA 8.240

- SPDroot – open source software packages developed by the SPD working group specifically for modeling processes in SPD detectors

  Used version : SPD ROOT v. 4.1.5 & Development version

Results

	J/ψ		χ_c	Υ	
	Muon channel $\mu^+\mu^-$	Electron channel e^+e^-	$\gamma + J/\psi$	Muon channel $\mu^+\mu^-$	Electron channel e^+e^-
In Pythia8, the cross-sections and number of events are calculated	+	+	-	+	+
In Pythia8, distributions of the number of events by kinematic characteristics (M,pT,η,φ) were obtained	+	+	-	+	+
SPDRoot signal modeling	+	+	-		
SPDRoot Development-ver. signal modeling	+	+	+		

1st step – Pythia8 events generation and cross-sections
Muon channel

Cross-section:	$1{,}608 * 10^{-7} \pm 4{,}831 * 10^{-10}$ mb (0,16 nb)	J/ψ	1st stage
Events (time = 0,3 year)	$N = 2{,}88 * 10^{3}$		
Production is impossible due to lack of energy :	$\sqrt{s} = 7{,}5$ GeV $M_{\Upsilon} = 9{,}46$ GeV	ϒ	
Cross-section:	$6{,}538 * 10^{-5} \pm 1{,}246 * 10^{-7}$ mb (65 nb)	J/ψ	2nd stage
Events (time = 1 year)	$N = 3{,}9 * 10^{6}$		
Cross-section:	$3{,}080 * 10^{-8} \pm 1{,}851 * 10^{-11}$ mb (0,03 nb)	ϒ	
Events (time = 1 year)	$N = 750$		

1st step – Pythia8 events generation and cross-sections
Electron channel

Cross-section: Events (time = 1 year)	$6{,}555 * 10^{-5} \pm 3{,}953 * 10^{-7}$ mb (65 nb) $N = 3{,}9 * 10^{6}$	J/ψ	2nd stage – Electron
Cross-section: Events (time = 1 year)	$3{,}783 * 10^{-7} \pm 2{,}262 * 10^{-10}$ mb (0,03 nb) $N = 1{,}6 * 10^{4}$	ϒ	
Cross-section: Events (time = 1 year)	$6{,}538 * 10^{-5} \pm 1{,}246 * 10^{-7}$ mb (65 nb) $N = 3{,}9 * 10^{6}$	J/ψ	2nd stage – Muon
Cross-section: Events (time = 1 year)	$3{,}080 * 10^{-8} \pm 1{,}851 * 10^{-11}$ mb (0,03 nb) $N = 750$	ϒ	

1st step – Pythia8 events generation and cross-sections
Comparison to real cross-sections in SPD energy range

Generator *J/ψ -> μμ*

(2nd stage SPD -> $\sqrt{s} = 27$GeV)

Pythia8 cross-section:

$65 \pm 0{,}12\ nb$

~100-250 nb lack

Experimental *J/ψ -> μμ* cross-sections[1]:

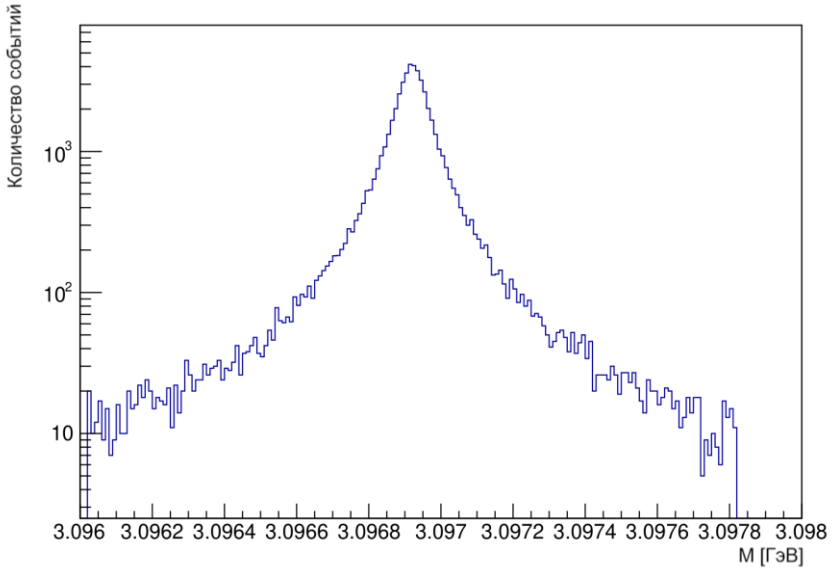
E444 ($\sqrt{s} = 20$ GeV) σ = 166 ± 23 (nb/nucleon)

E595 ($\sqrt{s} = 27.4$ GeV) σ = 306 ± 18 (nb/nucleon)

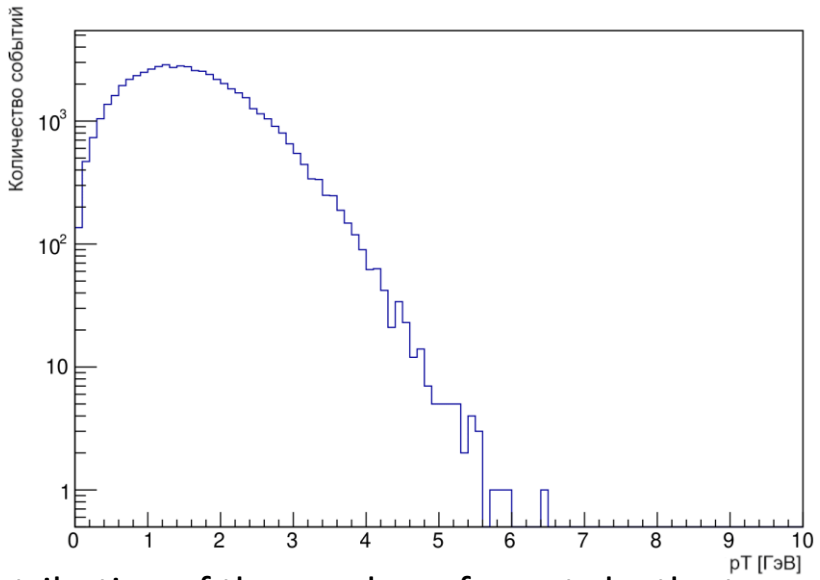
NA50 ($\sqrt{s} = 29.1$ GeV) σ = 325 ± 67 (nb/nucleon)

[1] Maltoni, Fabio ; Spengler, J. ; Bargiotti, M. ; Bertin, A. ; Bruschi, M. ; et. al. *Analysis of charmonium production at fixed-target experiments in the NRQCD approach.* In: *Physics Letters. Section B: Nuclear, Elementary Particle and High-Energy Physics*, Vol. B638, p. 202-208 (2006) http://hdl.handle.net/2078/31058 -- DOI : 10.1016/j.physletb.2006.05.010

Kinematic characteristics distibutions (J/ψ, 2nd stage)

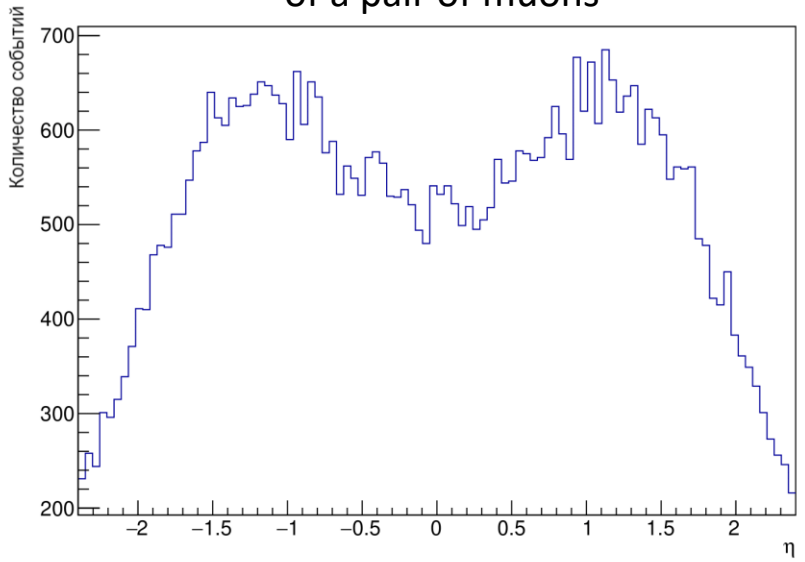


Distribution of the number of events by the invariant mass of a pair of muons

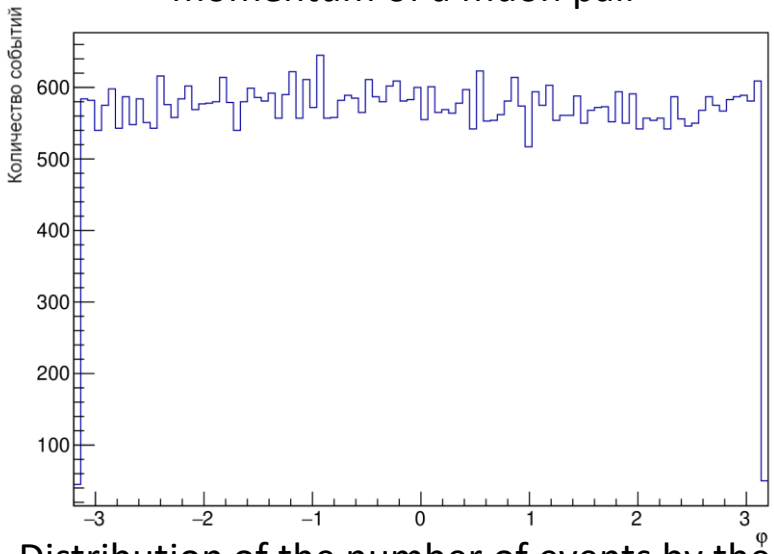


Distribution of the number of events by the transverse momentum of a muon pair

Pythia8
Events generated: 10k

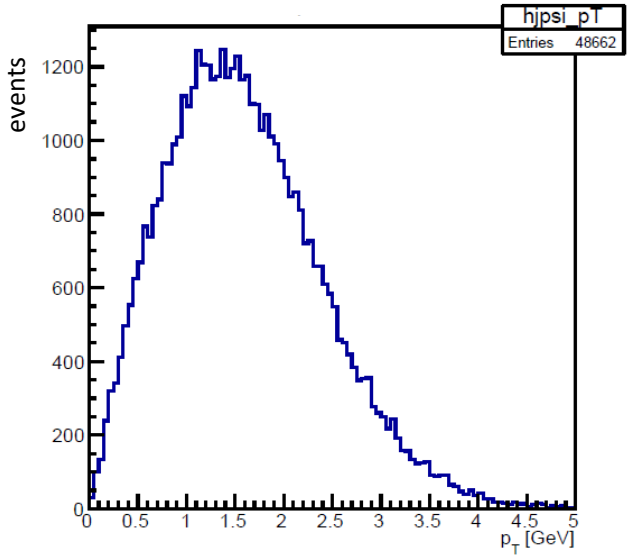


Distribution of the number of events by the pseudorapidity of a pair of muons

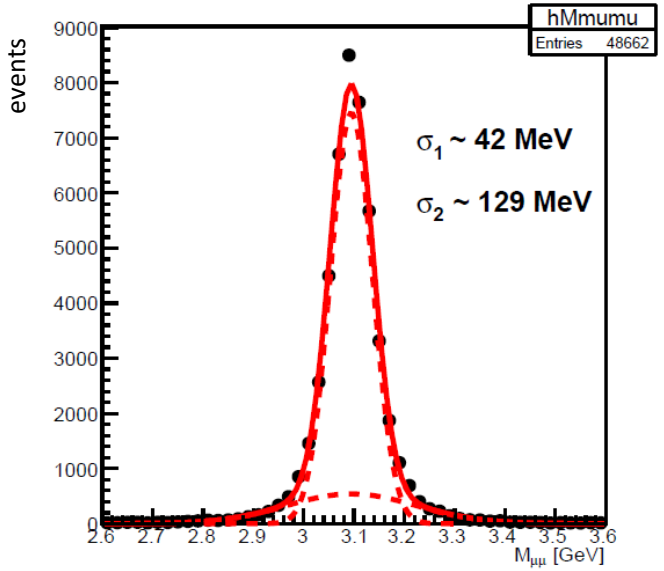


Distribution of the number of events by the azimuthal angle of a pair of muons

SPD ROOT J/ψ modeling – dimuon mode

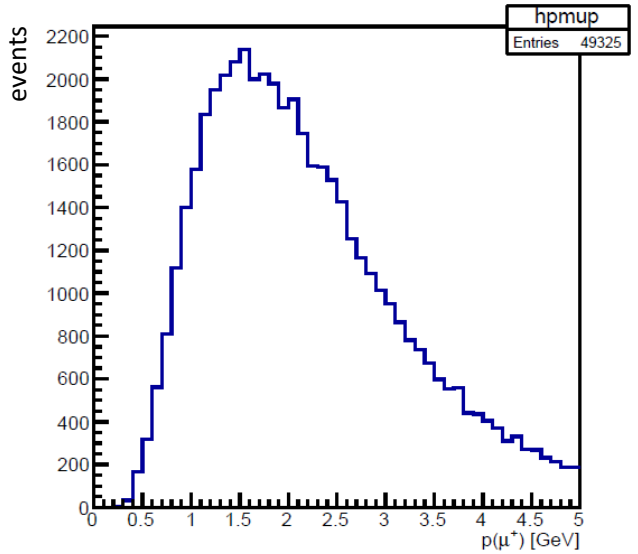


Distribution of the number of events by the transverse momentum of muons

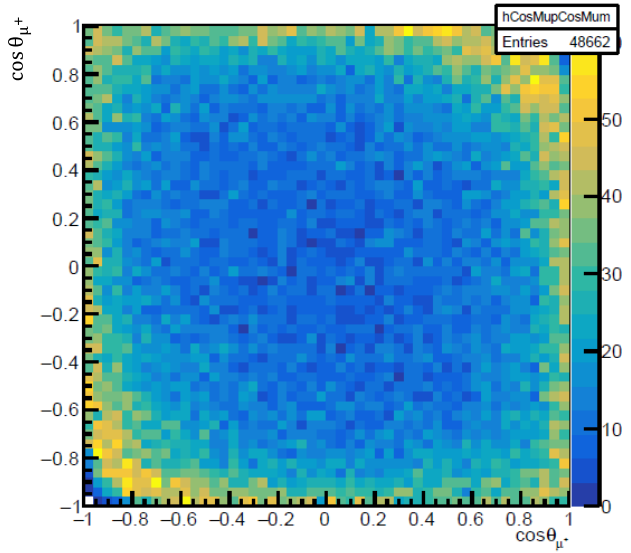


Distribution of the number of events by the invariant mass of muon pair

Master-version
Events
generated:50k

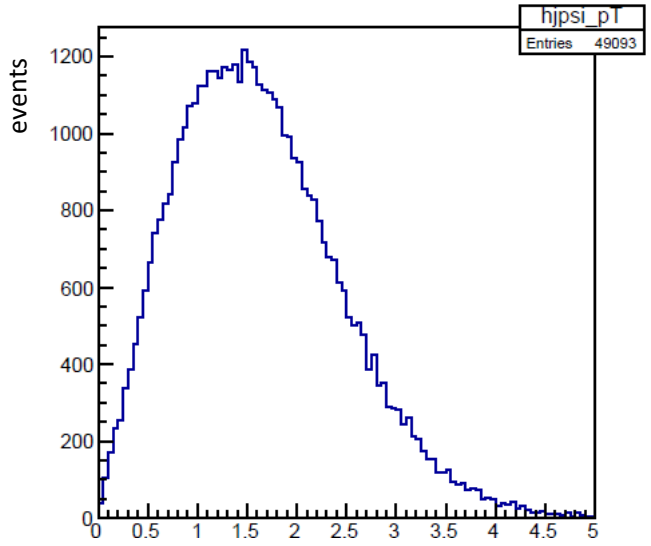


Distribution of the number of events by the muon momentum (μ+)

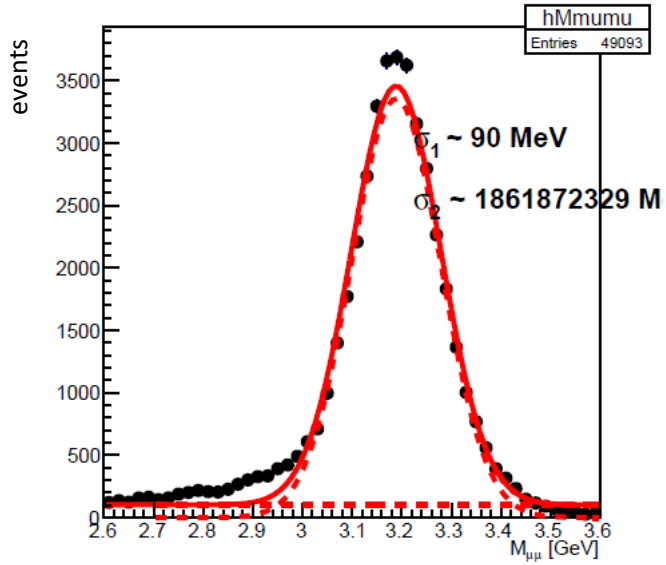


A two-dimensional distribution where the X and Y axes represent the cosθ of positively and negatively charged muons, respectively

SPD ROOT J/ψ modeling – dielectron mode

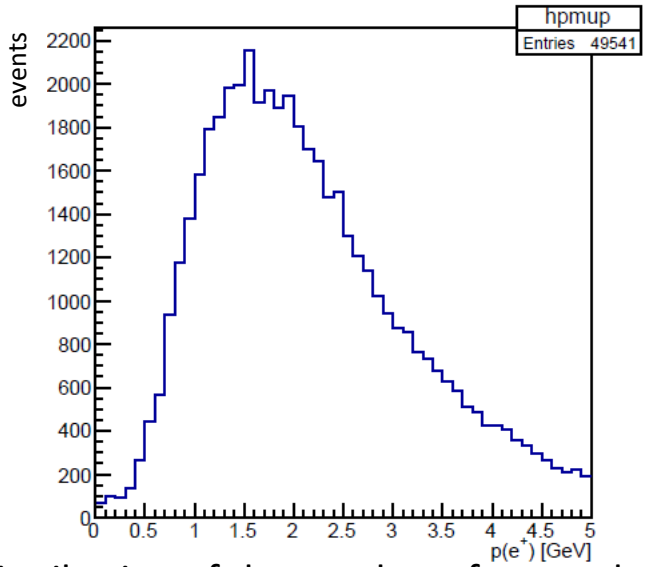


Distribution of the number of events by the transverse momentum of electrons

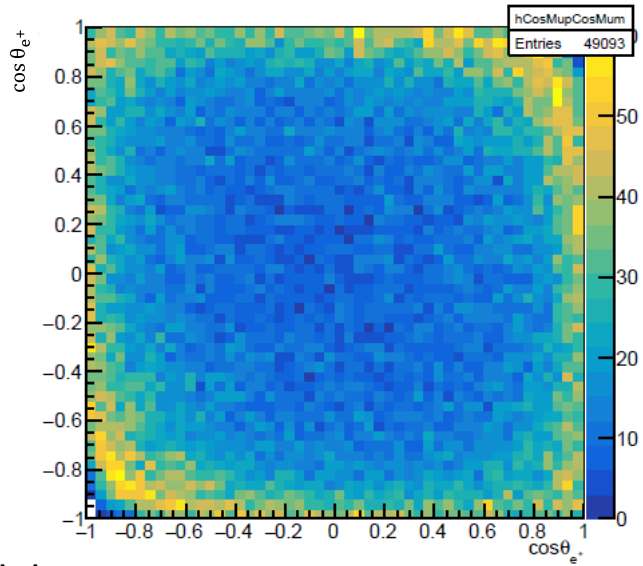


Distribution of the number of events by the invariant mass of electron pair

Master-version
Events generated:50k

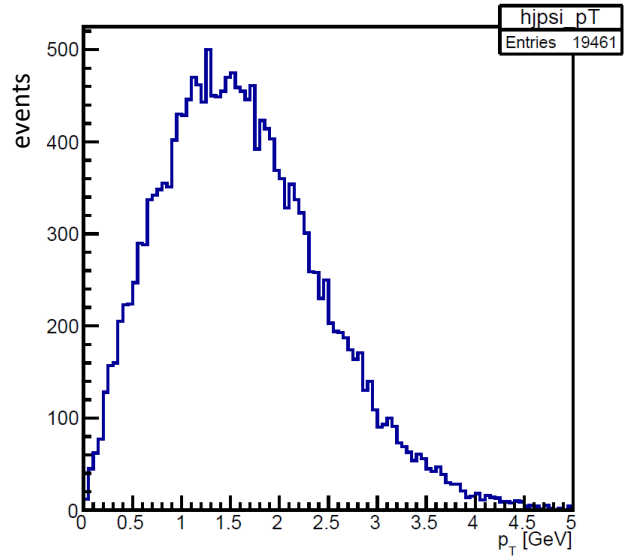


Distribution of the number of events by the positron momentum (μ+)

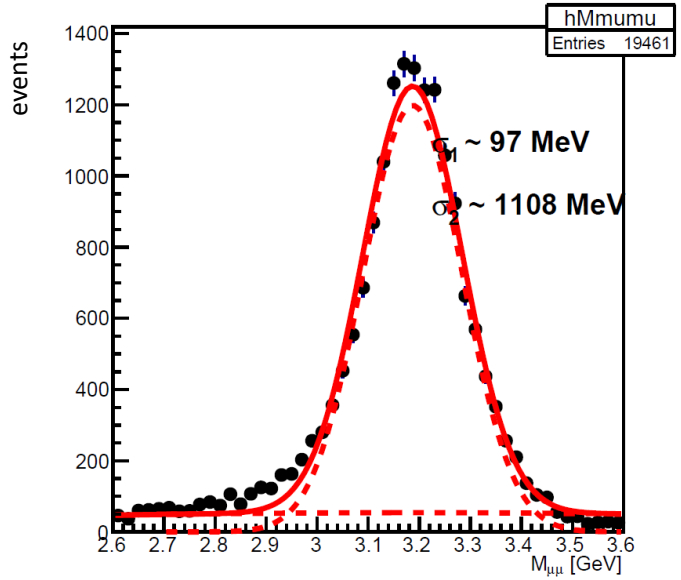


A two-dimensional distribution where the X and Y axes represent the cosθ of positively and negatively charged electrons, respectively

SPD ROOT J/ψ modeling – dielectron mode

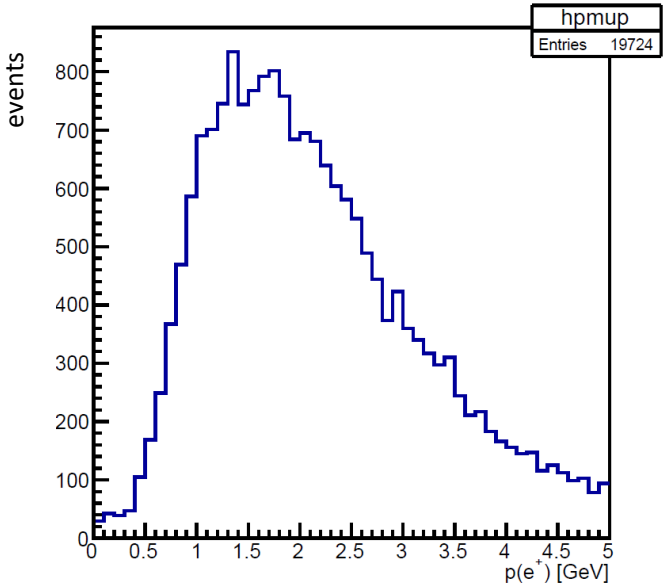


Distribution of the number of events by the transverse momentum of electrons

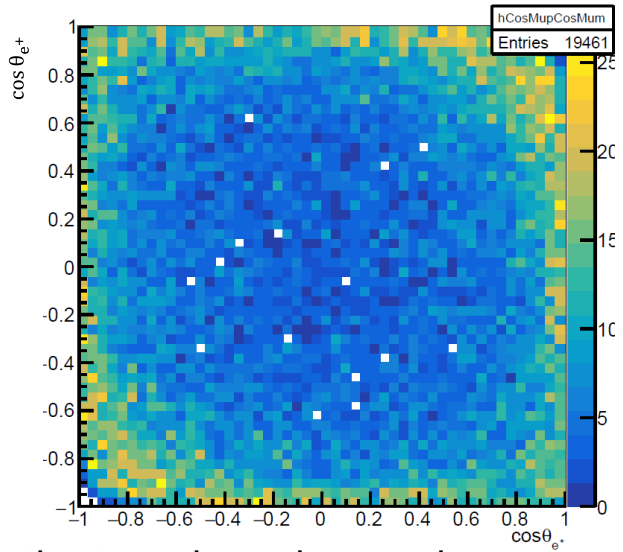


Distribution of the number of events by the invariant mass of electron pair

Master-version Events generated:20k



Distribution of the number of events by the positron momentum (μ+)



A two-dimensional distribution where the X and Y axes represent the cosθ of positively and negatively charged electrons, respectively

Primary vertex

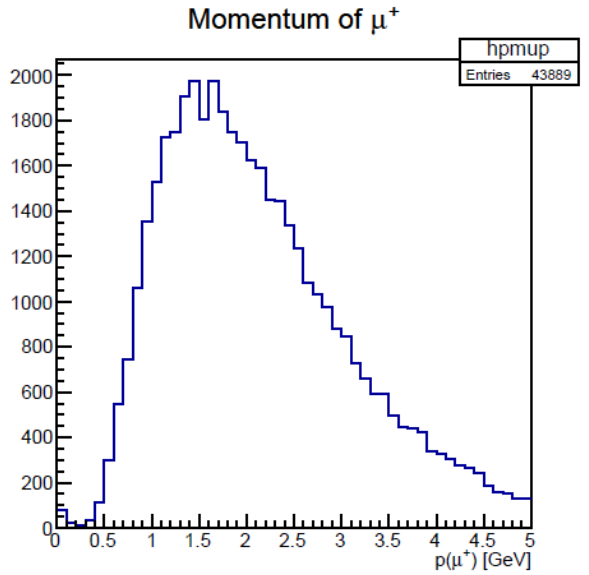
- Simulations were performed in SPD ROOT. The new algorithm takes into account the primary interaction vertex

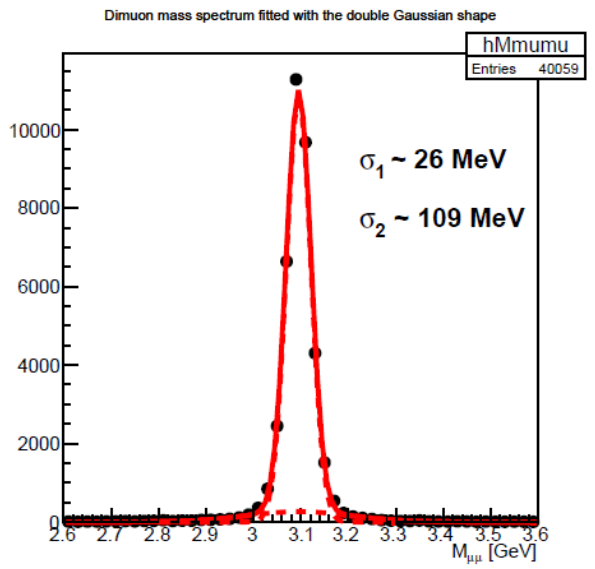
Full simulation

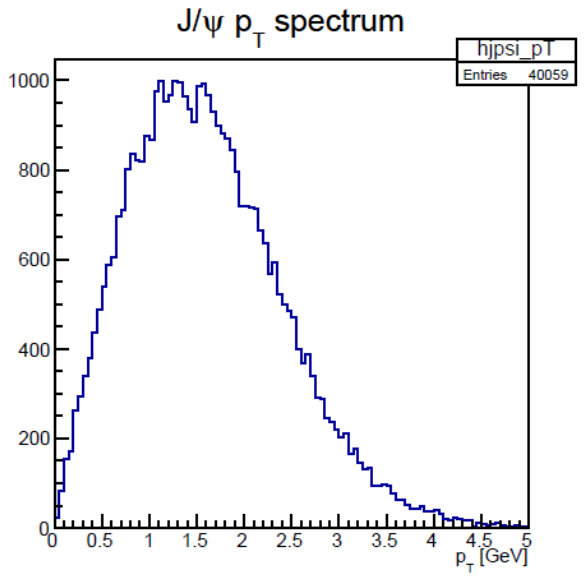
(J/ψ, dimuon mode)

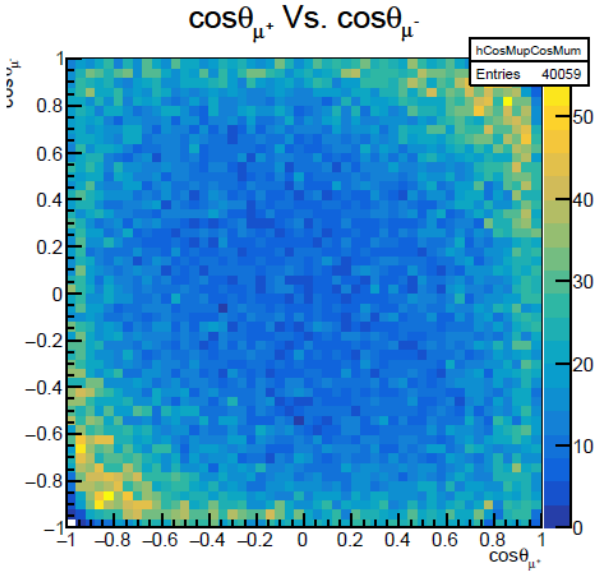
50k events

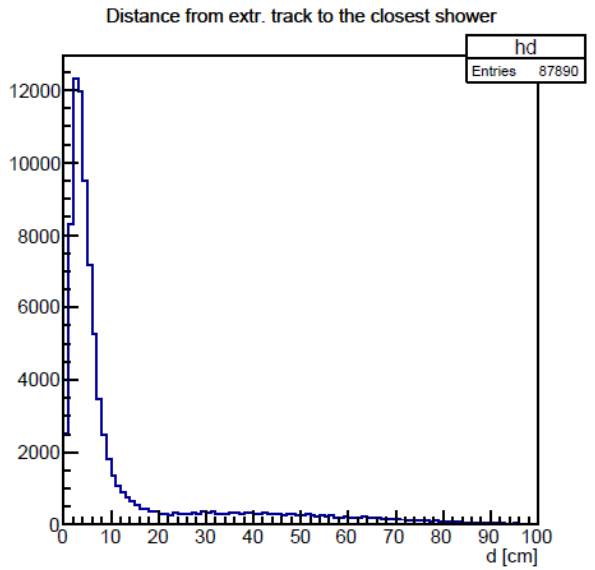
Development-Ver.

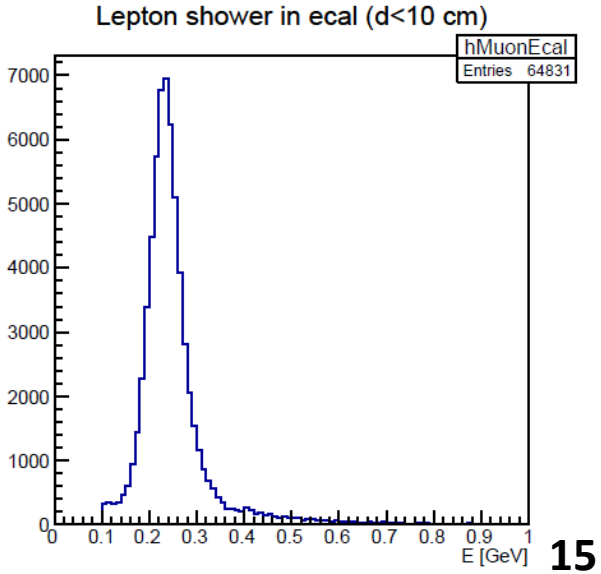












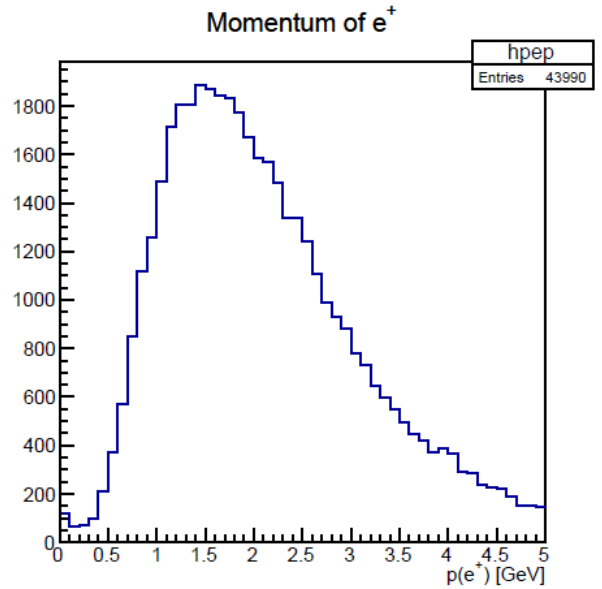
Primary vertex

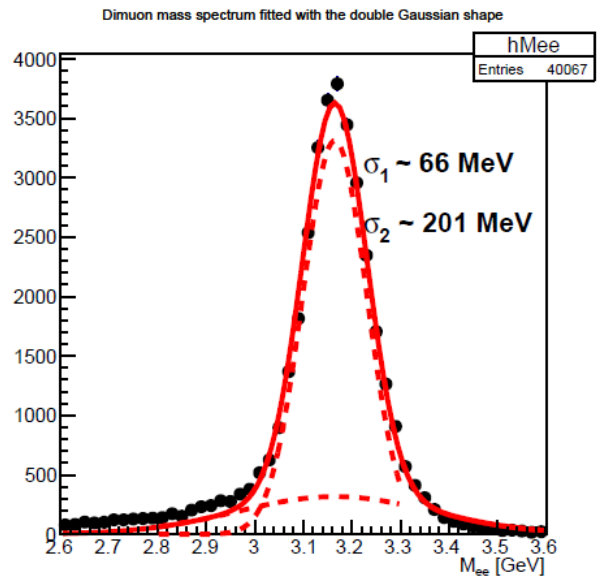
Full simulation

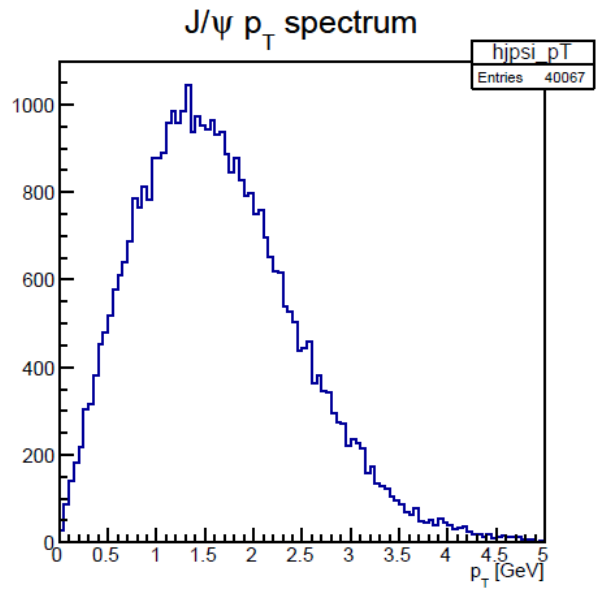
(J/ψ, dielectron mode)

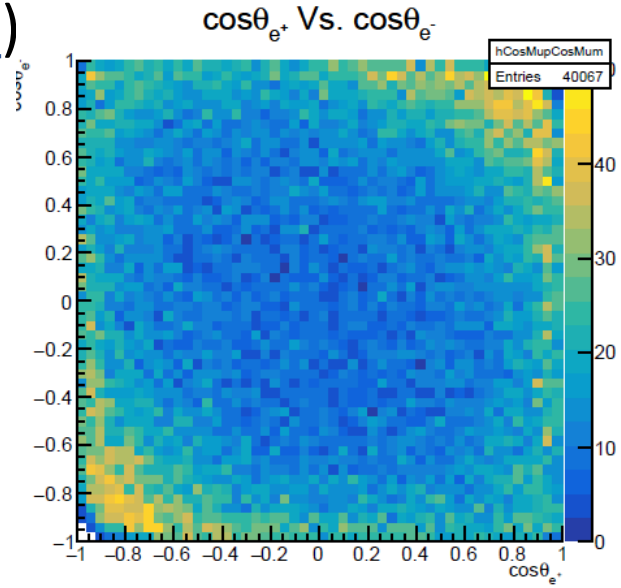
50k events

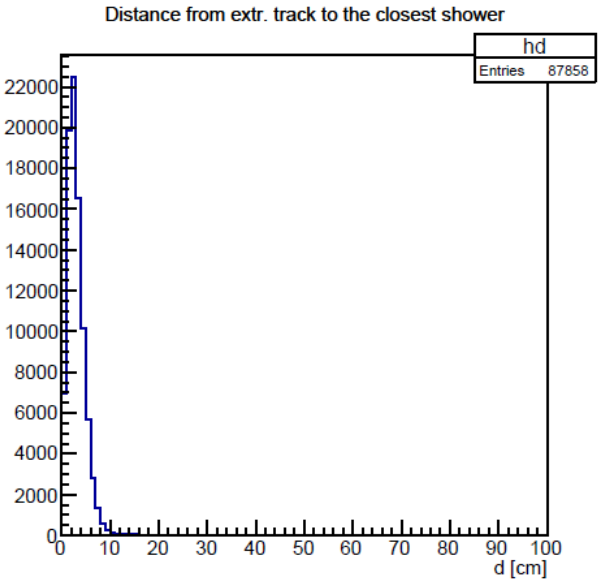
Development-Ver.

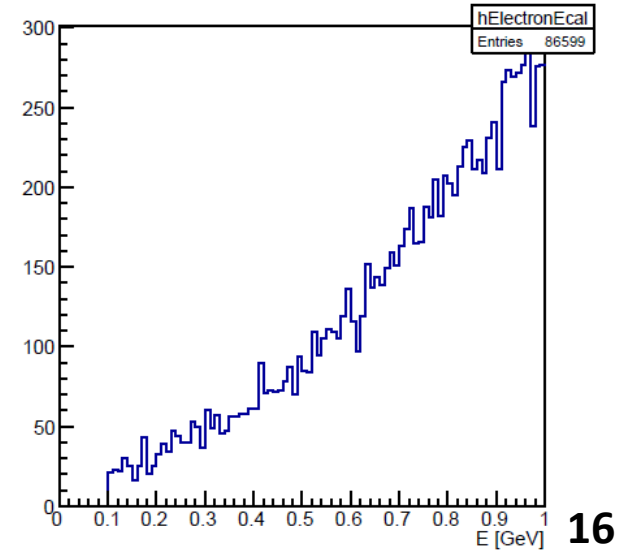




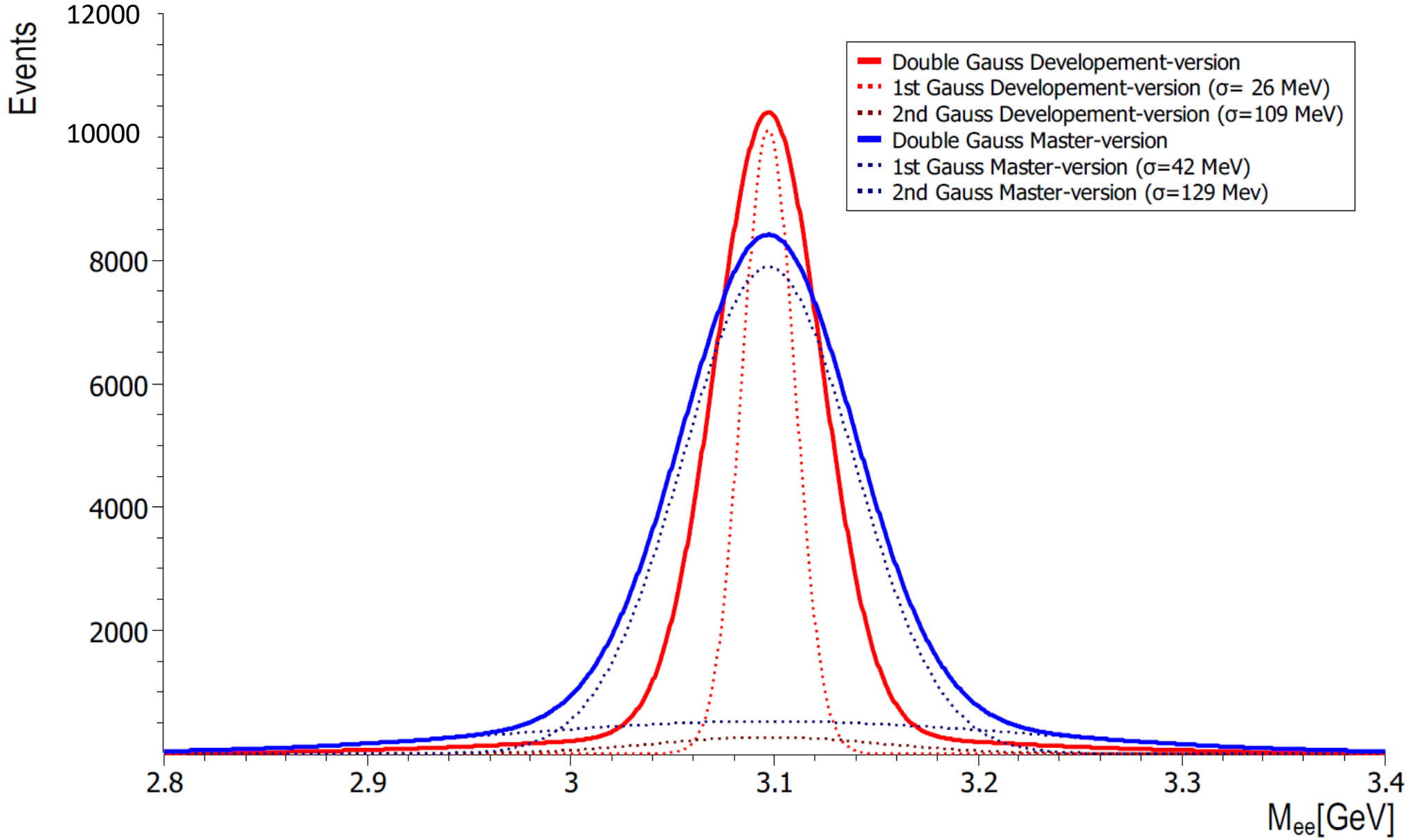






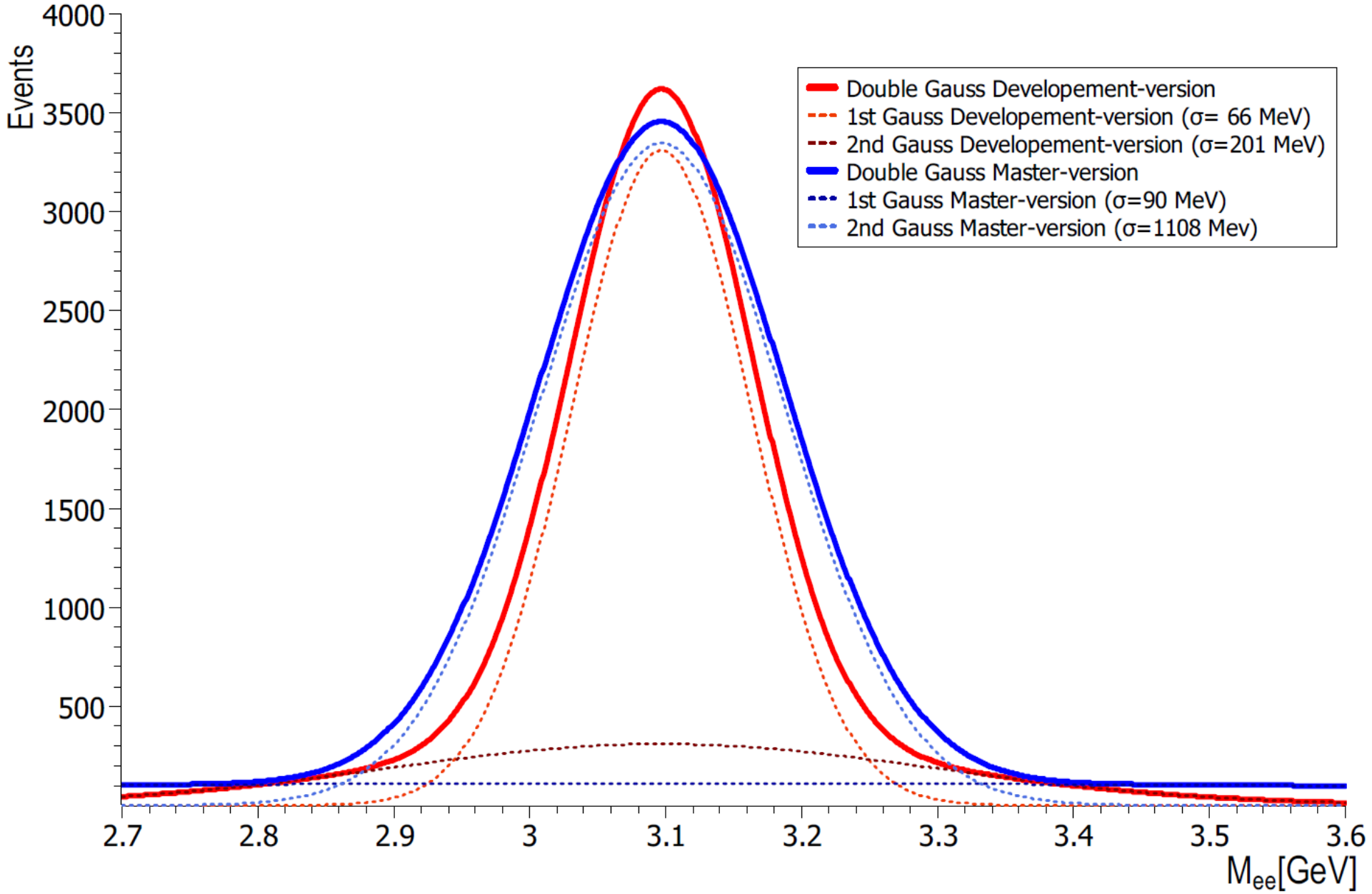


J/ψ decay in dimuon mode



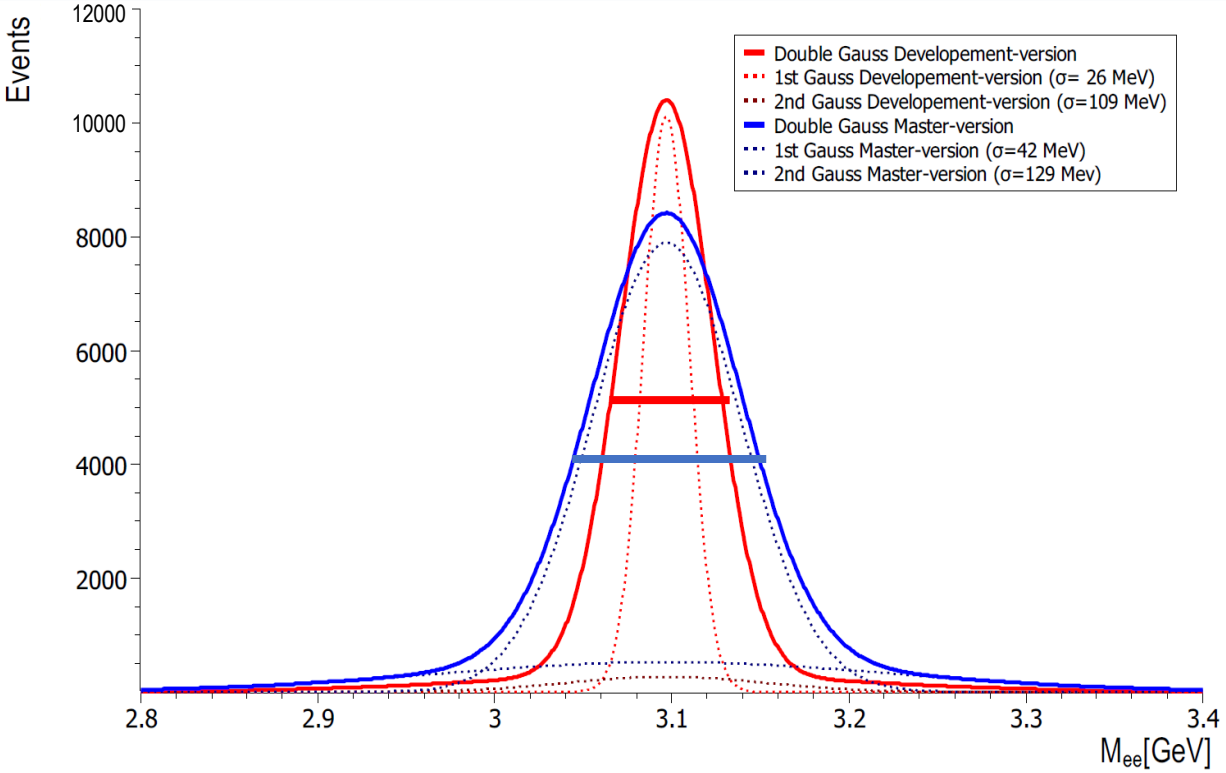
Events generated:50k

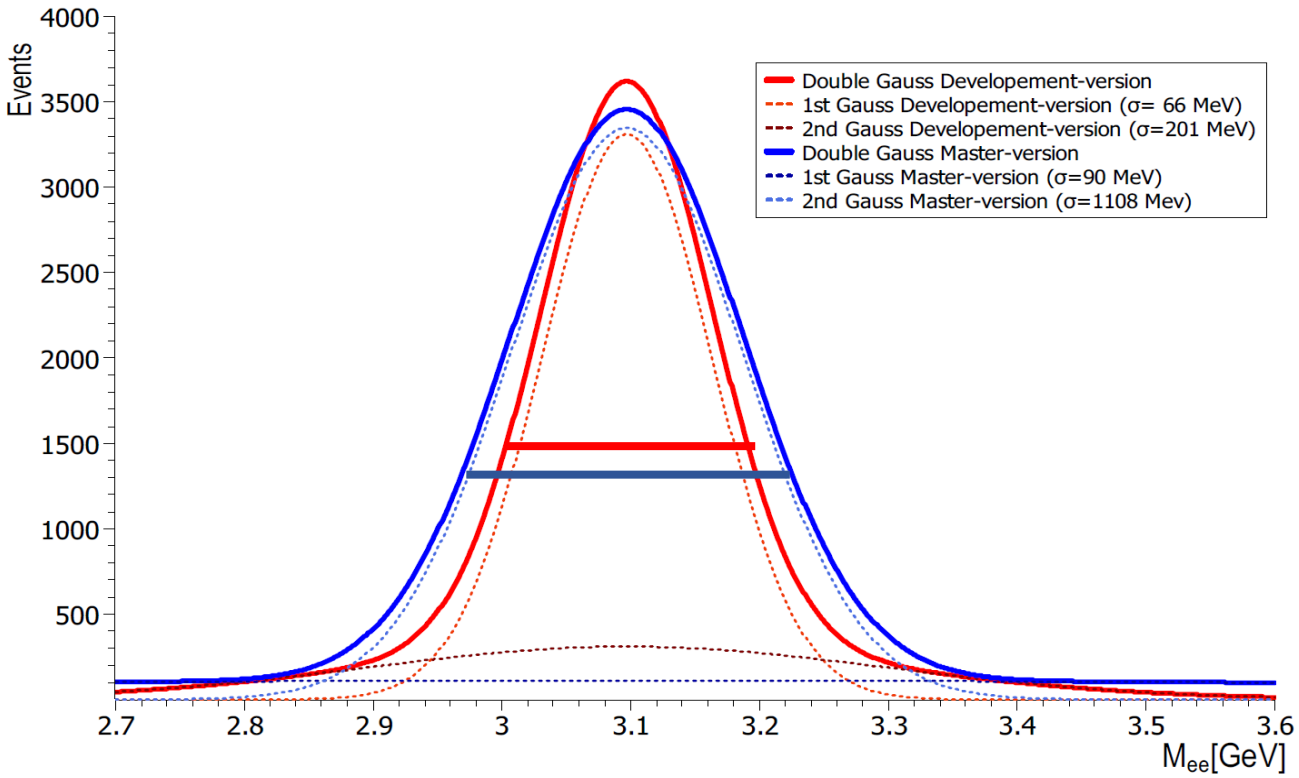
J/ψ decay in dielectron mode



Events generated:20k

Primary vertex - improvement





full width at half maximum has improved by 34.7% (98 MeV to 64 MeV)

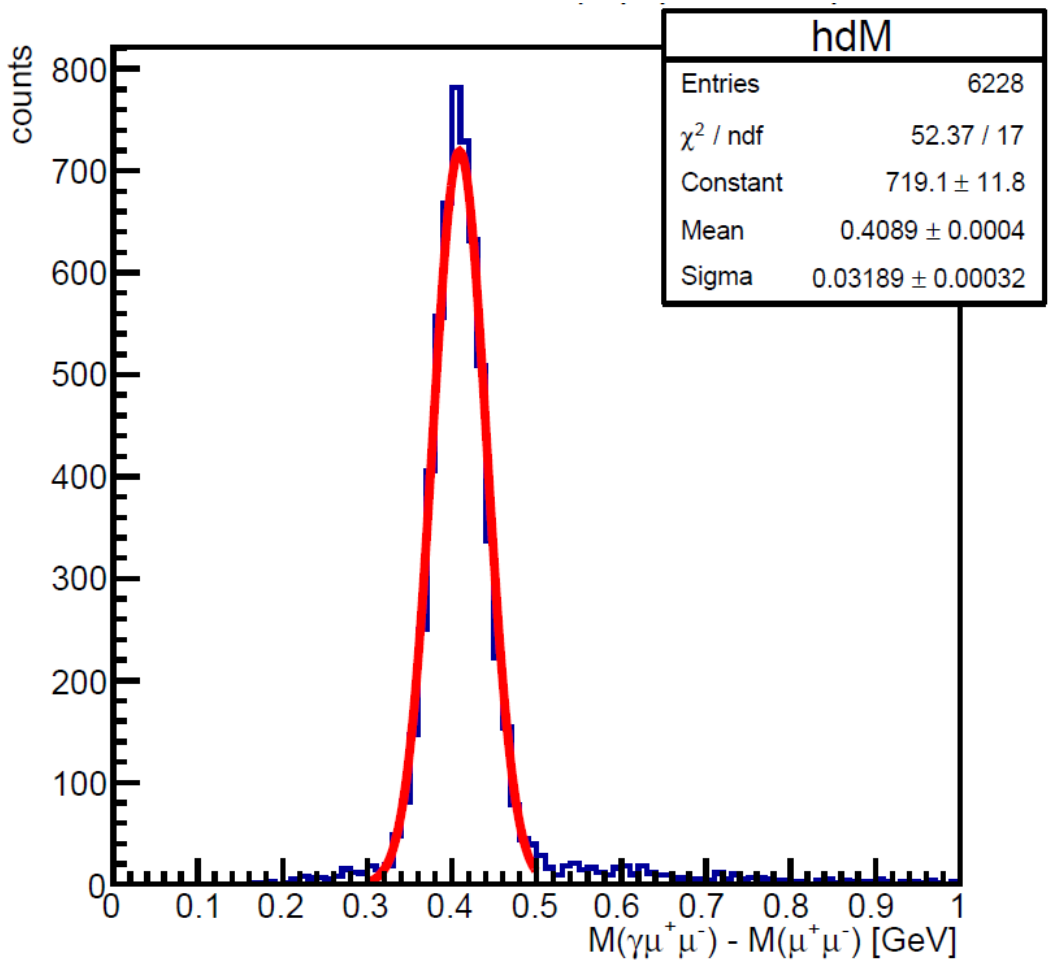
full width at half maximum has improved by 24.3% (222 MeV to 168 MeV)

J/ψ decay width
93.2±2.1 keV

$\chi_c \rightarrow \gamma + J/\psi$

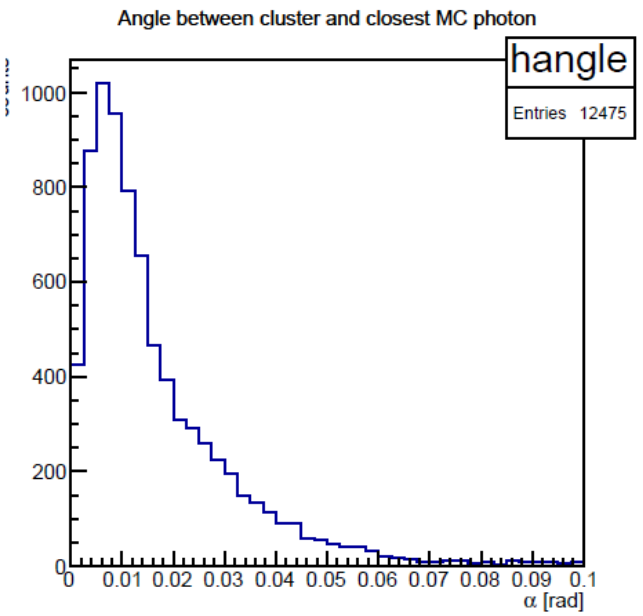
Tasks:

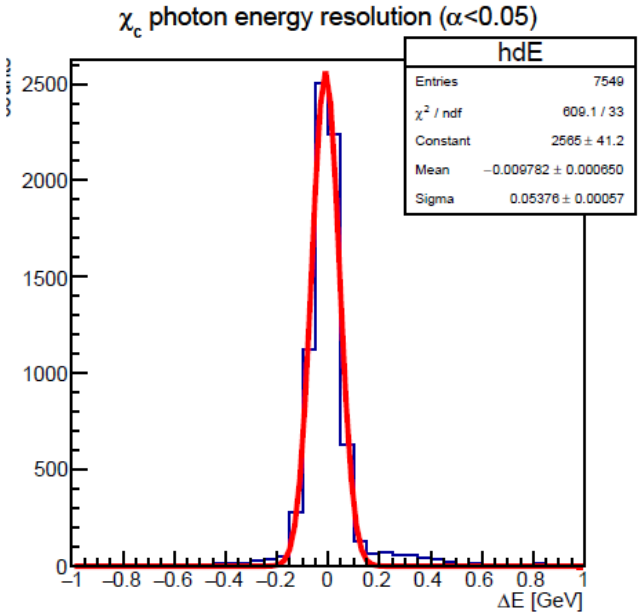
1. Check current resolution for $M(\gamma\ \mu^+\mu^-) - M(\mu^+\mu^-)$ ▣
2. Recover events with conversion $\gamma \rightarrow e^+ e^-$ ☐
3. Find a way to select electrons ☐

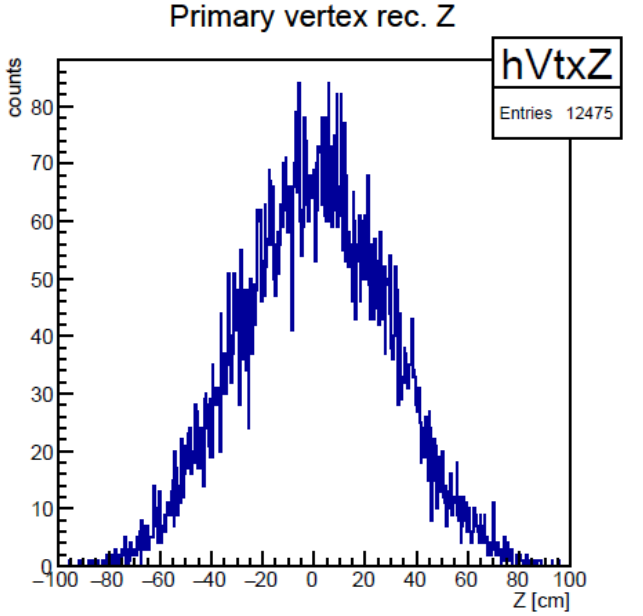


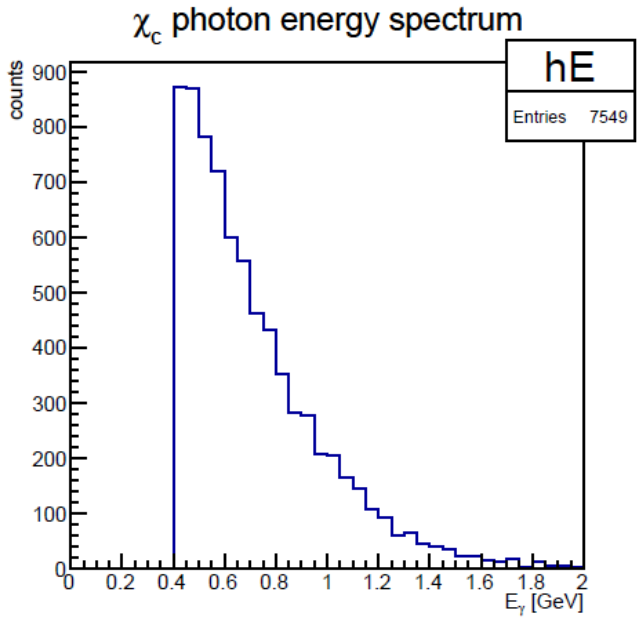
Development-ver.
Events generated:50k

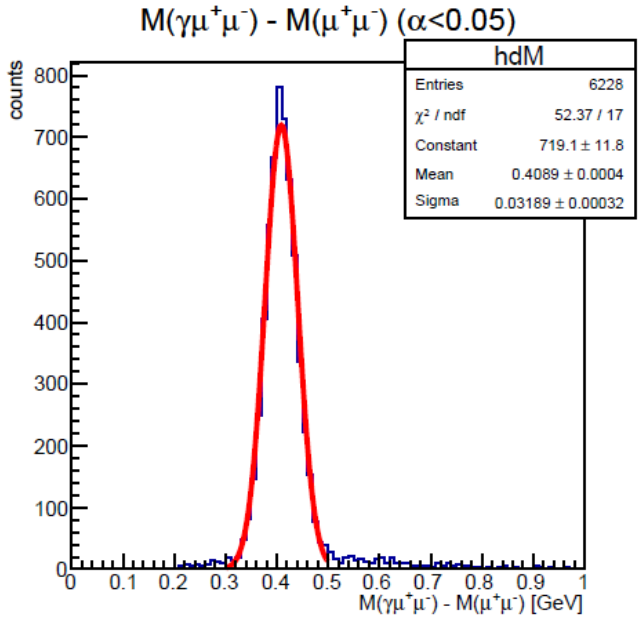
$\chi_c \rightarrow \gamma + J/\psi$

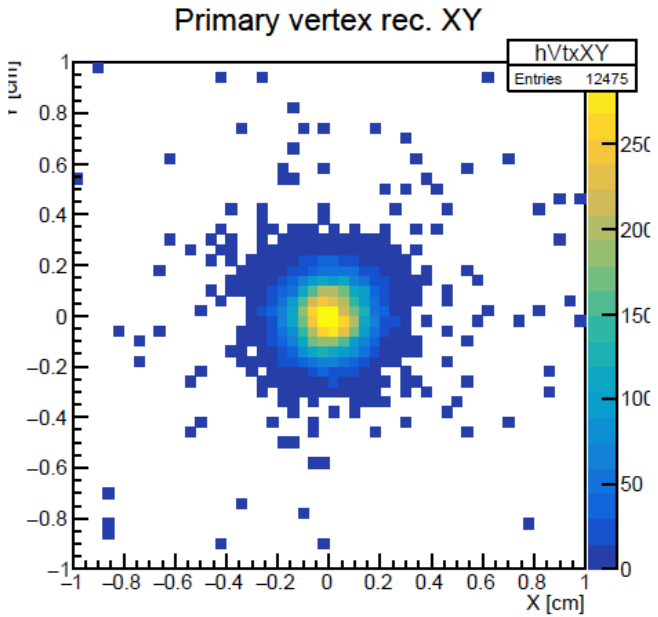












Development-ver.
Events generated:50k

Conclusion

Results:

- Cross-sections were obtained and the expected number of events was estimated using the Monte Carlo method
- Distributions of kinematic values of pairs of muons produced during meson decay were obtained
- A modeling of the J/ψ signal in the dimuon and dielectron modes has been performed
- A comparison of the algorithms' performance with and without taking into account the primary interaction vertex was carried out

Planned:

- Perform a full simulation of the ϒ signal in the dimuon and dielectron modes (in master & dev versions)
- To compare different reconstruction algorithms in SPD ROOT in the phi meson as an example
- Perform signal/background simulation for J/ψ decay, obtain 2D distribution $pT_{\mu+}\ Vs\ pT_{\mu-}$ for J/ψ decay
- Analize the decay $\chi_c \to \gamma + J/\psi$

Conclusions from the data obtained:

- The simulation results showed that the production cross section and the expected number of events of J/ψ-mesons are 3 orders of magnitude higher than those of ϒ-mesons.
- After modeling background muons (produced, for example, by pions), we can estimate whether the signal from J/ψ- and ϒ-mesons will be suppressed by the background.