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Description of the LbOniaPairs package

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Abstract

The `LbOniaPairs` package is destined to produce quarkonia pairs in Gauss framework. Currently production of S-wave quarkonia pairs is implemented according to the color-singlet leading order calculation. In this note the description of configuration and examples of use are given. Some particular predictions for the LHCb acceptance are also included.

1 Intro

`LbOniaPairs` package is created to supplement standard PYTHIA [1] production in GAUSS [2] with production of quarkonia pairs. Its implementation is based on PYTHIA functionality, which allows to add external user processes to the event generation loop. The subroutines added are responsible for matrix element calculation and phase space sampling. The `OniaPairsProduction` production tool introduces a set of options to configure generation of these events in GAUSS framework.

Production of S-wave quarkonia pairs in single gluon-fusion subprocesses is currently implemented. The matrix element used [3] accounts production of quarkonia states from color-singlet (CS) $Q\bar{Q}$ configurations. The calculation is performed at leading order (LO) in α_s.

These assumptions stand on the solid-ground formalism of color-singlet approach [4], which has almost no free parameters. The expression for the partonic cross section depends only on α_s, m_Q, and on the value of the quarkonium wave function at origin.

Most of theoretical uncertainty dues to the dependence of α_s on the renormalization scale. Default choice is the LO running α_s at the scale equal to the transverse mass of one of the quarkonia produced. The choice of the heavy quark mass m_Q also adds some uncertainty, but it is not crucial for lowest quarkonia states, such as J/ψ. Half of the quarkonium mass is used. What concerns the value of the wave function at origin, for the color singlet contribution it is extracted directly from the dileptonic decay width of quarkonium, which is well measured. The values used in `LbOniaPairs` are:

$$\psi^{c\bar{c}}_{J/\psi}(r)|_{r=0} = 0.2115 \text{ GeV}^{3/2}, \quad (1)$$

$$\psi^{c\bar{c}}_{\psi(2S)}(r)|_{r=0} = 0.164 \text{ GeV}^{3/2}. \quad (2)$$

LO PDFs are used to obtain hadronic cross section from the partonic one. The default choice is to use CTEQ6L1 [5]. The factorization scale for PDFs is taken equal to the transverse mass of one of the quarkonia produced.

The final step towards the generation of realistic events is enabling primordial transverse momenta of partons and initial parton showers. Both of these tasks are fulfilled by PYTHIA with Perugia-2012 [6] tune applied. For the parton shower machinery PYTHIA needs to know the hard scale at which the interaction took place. Again one transverse mass of the quarkonium produced is used by default.

It is appropriate to mention here that LHCb detector allows to reconstruct J/ψ-mesons without limitation on the lowest transverse momentum. As a result prediction of double J/ψ production cross section virtually does not depend on the tune of initial showers and primordial transverse momenta of partons.

The CS LO contribution considered here is a nice starting point for quarkonia pair production studies as it should definitely exist. However other mechanisms can contribute to the same final states. Among them are feeddown from the P-wave quarkonium states, double parton scattering (DPS) [7, 8], and color-octet (CO) contribution [9]. Also NLO corrections can modify the predictions of the CS model [10]. That is why it is worth investigating discrepancies between CS LO prediction and the observed signal.

2 Parameters

In principle, working option files for `LbOniaPairs` should appear in `DecFiles`. However any Gauss user can add relevant lines to job-options file and get much more freedom in configuration.

First is to select `OniaPairsProduction` production tool:

```
from Configurables import Special
Generation().SampleGenerationTool = "Special"
Generation().addTool( Special )

from Configurables import OniaPairsProduction
Generation().Special.ProductionTool = "OniaPairsProduction"
Generation().Special.addTool( OniaPairsProduction )
```

The center of mass energy is taken from the beam momentum:

```
from Configurables import Gauss
from GaudiKernel import SystemOfUnits
Generation().Special.OniaPairsProduction.Ecm = 2 * Gauss().BeamMomentum /
    SystemOfUnits.GeV
```

Next is to select which quarkonia pairs to produce. For instance, J/ψ family:

```
Generation().Special.OniaPairsProduction.Psi1S1S = 1
Generation().Special.OniaPairsProduction.Psi1S2S = 1
Generation().Special.OniaPairsProduction.Psi2S2S = 1
```

$\Upsilon(1, 2, 3S)$-meson pairs are available under names "Ups1S1S" and so on. Any positive value turns corresponding process on. These values are also used as multipliers to the calculated cross sections. Thus they can be used to introduce K-factors, variate quarkonia wave function values or to tune feeddown.

For instance, $J/\psi + \psi(2S)$ production can be used as only a feeddown source for the $J/\psi + J/\psi$ final state. For this purpose one should force $\psi(2S) \to J/\psi + X$ decay in the dk-file and decrease $J/\psi + \psi(2S)$ production by its branching. Analogously $\psi(2S) + \psi(2S)$ production should be decreased by the branching of this decay squared:

```
Generation().Special.OniaPairsProduction.Psi1S1S = 1
Generation().Special.OniaPairsProduction.Psi1S2S = 0.59
Generation().Special.OniaPairsProduction.Psi2S2S = 0.35
```

At the same time the following lines should be added to the dk-file:

```
Decay psi(2S)
        0.655           J/psi           pi+             pi-             PHSP;
        0.345           J/psi           pi0             pi0             PHSP;
Enddecay
```

On the other hand, one can study $J/\psi + \psi(2S)$ production separately by forcing both charmonia to decay into $\mu^+\mu^-$ and switching off other processes.

Dependence on scales can be studied by varying them independently in α_s, PDFs, and Pythia showers:

```
Generation().Special.OniaPairsProduction.ScaleFactorInAlpS = 1
Generation().Special.OniaPairsProduction.ScaleFactorInPDF  = 1
Generation().Special.OniaPairsProduction.ScaleFactorInShowers = 1
```

The corresponding scale is taken equal to the transverse mass of quarkonium multiplied by the factor set here.

For some combinations of scales choice and PDFs `LbOniaPairs` underestimates maximum weight for events. To avoid this an extra multiplier for the estimated maximum event weight can be introduced:

```
Generation().Special.OniaPairsProduction.MaxWeightMultiplier = 1.5
```

By default `LbOniaPairs` configures Pythia with Perugia-2012 (P12) tune. This tune can be overridden by pushing a command vector in a customary format. The following command disables the default tune and allows to reconfigure raw Pythia by hand:

```
Generation().Special.OniaPairsProduction.PyCommVec += [ "pypars mstp 5 0" ]
```

For instance, by adding the following command one can switch to MSTW2008lo PDFs

```
Generation().Special.OniaPairsProduction.PyCommVec += [ "pypars mstp 52 2" ,
                                                        "pypars mstp 51 21000" ]
```

It is probably better not to change PDFs separately, but to switch to some Pythia tune, which uses desired PDF set. For MSTW2008lo there is a recent Perugia-2012 tune (P12-M8LO):

```
Generation().Special.OniaPairsProduction.PyCommVec += [ "pypars mstp 5 378" ]
```

Perugia-2011 with CTEQ5L PDFs, which were used in `LbOniaPairs` previously, can be selected by the following command:

```
Generation().Special.OniaPairsProduction.PyCommVec += [ "pypars mstp 5 350" ]
```

Other tunes and their descriptions can be found in Pythia update notes.

`FullGenEventCut` cut tool is used to ensure both J/ψ are in LHCb acceptance. The following lines allow to configure it from the options file:

```
Generation().Special.CutTool = ""
from Configurables import LoKi__FullGenEventCut
Generation().addTool( LoKi__FullGenEventCut, "PsiPairInAcc" )
Generation().FullGenEventCutTool = "LoKi::FullGenEventCut/PsiPairInAcc"
Generation().PsiPairInAcc.Code = " count ( isPsi & inY & isGood ) > 1.5 "
Generation().PsiPairInAcc.Preambulo += [
    "isPsi        = GDECTREE ( ' Meson  => mu+ mu- ' ) & ( 'J/psi(1S)' == GID ) " ,
    "inY          = in_range ( 2. , GY , 4.5 ) " ,
    "Bancestors   = GNINTREE ( GBEAUTY , HepMC.ancestors ) " ,
    "notFromB     = 0 == Bancestors " ,
    "isGood       = ( 3 != GSTATUS ) & notFromB "
    ]
```

3 Generation

Let us briefly go through the output of generation phase of GAUSS. With `LbOniaPairs` it can be executed by a command like this:

```
> gaudirun.py $GAUSSOPTS/Gauss-Job.py $GAUSSOPTS/Gauss-2011.py
    $GAUSSOPTS/GenStandAlone.py $LBONIAPAIRSOPTS/opts.py
    $LBPYTHIAROOT/options/Pythia.py
```

Somewhere in the output the initialization lines of `OniaPairsProduction` tool should appear:

```
Generation.Special         INFO Generating Special events.
Generation.Special.On...SUCCESS ==================================================
Generation.Special.On...SUCCESS Using as production engine  OniaPairsProduction
Generation.Special.On...SUCCESS ==================================================
LbOniaPairsProduction: Hello from OniaPairs!
                       ONIAPAIRS_UPINIT: First call
                       Initialization for  7000.GeV pp-collisions.
                       ONIAPAIRS_UPEVNT: First call
```

Before generating events PYTHIA estimates maximum weight for the processes turned on:

```
LbOniaPairsProduction: ONIAPAIRS_UPINIT: Determining maximum weights for subprocesses:
                       XMAXUP[  1(  1)] =  45334.75272
                       XMAXUP[  2(  2)] =   3375.71557
                       XMAXUP[  3(  3)] =  24916.13246
```

Then information on generation of events should appear in the output:

```
GaussGen INFO Evt 1, Run 1082, Nr. in job = 1 with seeds [1082, 1, 2119103972, 0]
GaussGen INFO Evt 2, Run 1082, Nr. in job = 2 with seeds [1082, 2, 1474865432, 0]
GaussGen INFO Evt 3, Run 1082, Nr. in job = 3 with seeds [1082, 3, 645125023, 0]
...
```

Sometimes warnings about the excess of maximum weight can appear:

```
LbOniaPairsProduction: ONIAPAIRS_UPEVNT: Warning: XWGTUP 1.234 times grater than
    XMAXUP.
```

The reason for this is the way the phase space is sampled. When $\hat{s} \gg m_Q^2$ and $\hat{t}$ happen to obtain some particular values, which are close to thresholds, the $\hat{t}$-dependence of the matrix element squared is not under control of the weight function used. However the convolution of the matrix element squared with PDFs decreases rapidly with growth of $\hat{s}$ and the weight function takes account of it. As a result these special regions in the $(\hat{s}, \hat{t})$ parameter space give negligible contribution. Normally not more than 1 event from 10^6 has exceeded weight. The situation can change if one uses PDFs, which differ significantly from CTEQ LO. Setting a proper multiplier for maximum event weight can amend this situation.

The successive event generation is followed by a summary. For 7 TeV center of mass energy and Perugia-2012 tune it looks like

```
LbOniaPairsProduction: Cross-section summary:
                       *----------- Process # 1 --  Cross-section  =   15.847 nb
                       | Corresponding number of unweighted events =  442863.
                       | Generator level efficiency                =  0.31634
                       | Fraction of events with excessive weight  =  0.00000
                       *----------- Process # 2 --  Cross-section  =    1.159 nb
                       | Corresponding number of unweighted events =   32416.
                       | Generator level efficiency                =  0.29758
                       | Fraction of events with excessive weight  =  0.00000
                       *----------- Process # 3 --  Cross-section  =    8.516 nb
                       | Corresponding number of unweighted events =  237796.
                       | Generator level efficiency                =  0.30241
                       | Fraction of events with excessive weight  =  0.00000
                       Please note, these cross-sections do not account any cuts.
                       No reasons to worry if fraction of events with excessive weight
     it is not far above 0.01.
LbOniaPairsProduction: Goodbye from OniaPairs!
```

Cross sections here correspond to the total 4π solid angle. To get cross section in the LHCb acceptance one should know the fraction of events in which both quarkonia are in the LHCb rapidity range. Thanks to the `FullGenEventCutTool` all the requested events fit this criteria. In the above example 10^5 events were requested. Thus the J/ψ-pair production cross section in the LHCb range can be evaluated as follows:

$$\sigma^{\mathrm{LHCb,P12}}_{pp\to J/\psi\, J/\psi+X} = \frac{10^5\cdot(15.847+1.159+8.516)}{442863+32416+237796}\,\mathrm{nb} = 3.6\,\mathrm{nb}.$$

This value is less than those obtained previously with CTEQ5L PDFs. With CTEQ5L PDFs one got

$$\sigma^{\mathrm{LHCb,\ CTEQ5L}}_{pp\to J/\psi\, J/\psi+X} = \frac{10^5\cdot(18.351+1.278+9.494)}{445424+31067+229742}\,\mathrm{nb} = 4.1\,\mathrm{nb}.$$

4 Results

With standard Perugia-2012 tune LO CS cross section of double J/ψ production at 7 TeV energy of pp-collisions in LHCb fiducial region is found to be

$$\sigma^{\mathrm{LHCb,7\,TeV}}_{pp\to J/\psi\, J/\psi+X} \approx 3.6\,\mathrm{nb}.$$

The uncertainty associated with this value dues mainly to the dependence of α_s on the hard scale and can amount to factor of 2. The cross section at 8 TeV center of mass energy is slightly larger due to the larger flux of gluons with corresponding low x values. The predicted value is

$$\sigma^{\mathrm{LHCb,8\,TeV}}_{pp\to J/\psi\, J/\psi+X} \approx 4.0\,\mathrm{nb}.$$

The ratio of 8 and 7 TeV cross sections is expected to be virtually unaffected by α_s uncertainties and equals

$$\sigma^{\mathrm{LHCb,8\,TeV}}_{pp\to J/\psi\, J/\psi+X}/\sigma^{\mathrm{LHCb,7\,TeV}}_{pp\to J/\psi\, J/\psi+X} \approx 1.1.$$

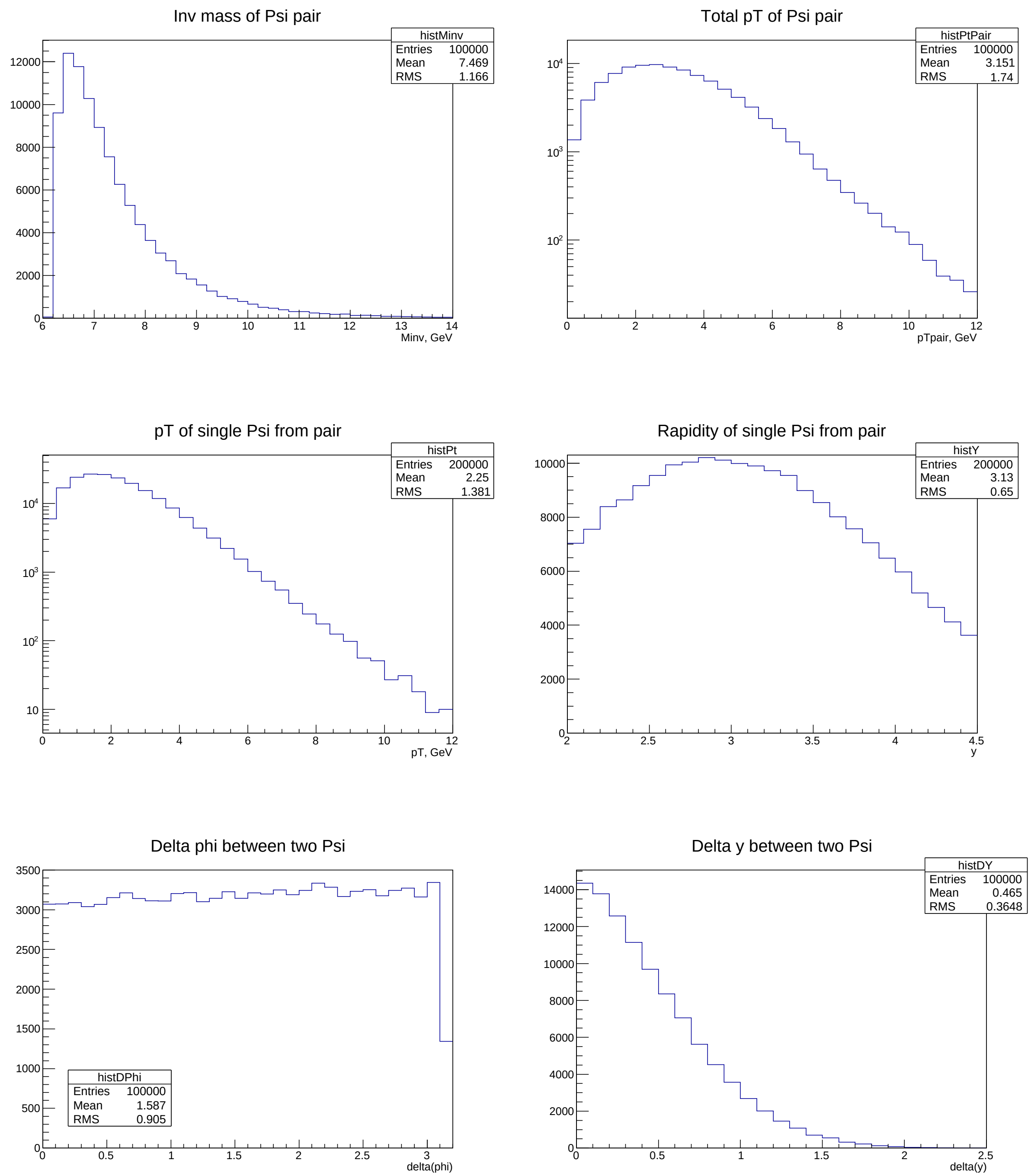

Figure 1: Kinematic distributions for double J/ψ production via gluon fusion process in 7 TeV pp collisions in LHCb rapidity window.

Figures 1 and 2 demonstrate kinematic distributions obtained by analyzing events generated at 7 and 8 TeV center of mass energy respectively. Shapes of these distributions are virtually insensible to this energy difference.

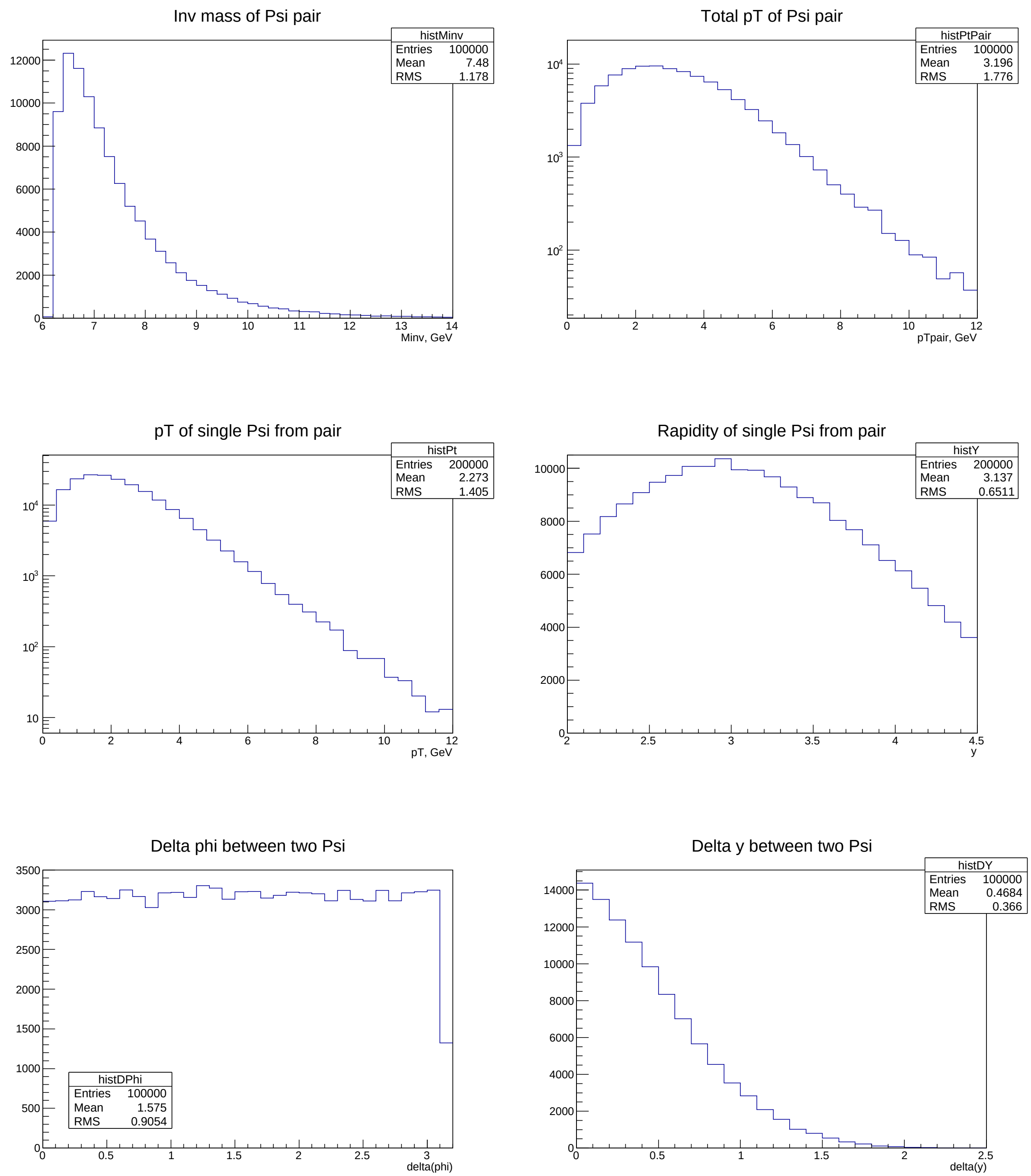

Figure 2: Kinematic distributions for double J/ψ production via gluon fusion process in 8 TeV pp collisions in LHCb rapidity window.

The estimation for the cross section at 14 TeV energy is

$$\sigma^{\mathrm{LHCb,14\,TeV}}_{pp\to J/\psi\, J/\psi+X} \approx 6.4\,\mathrm{nb}.$$

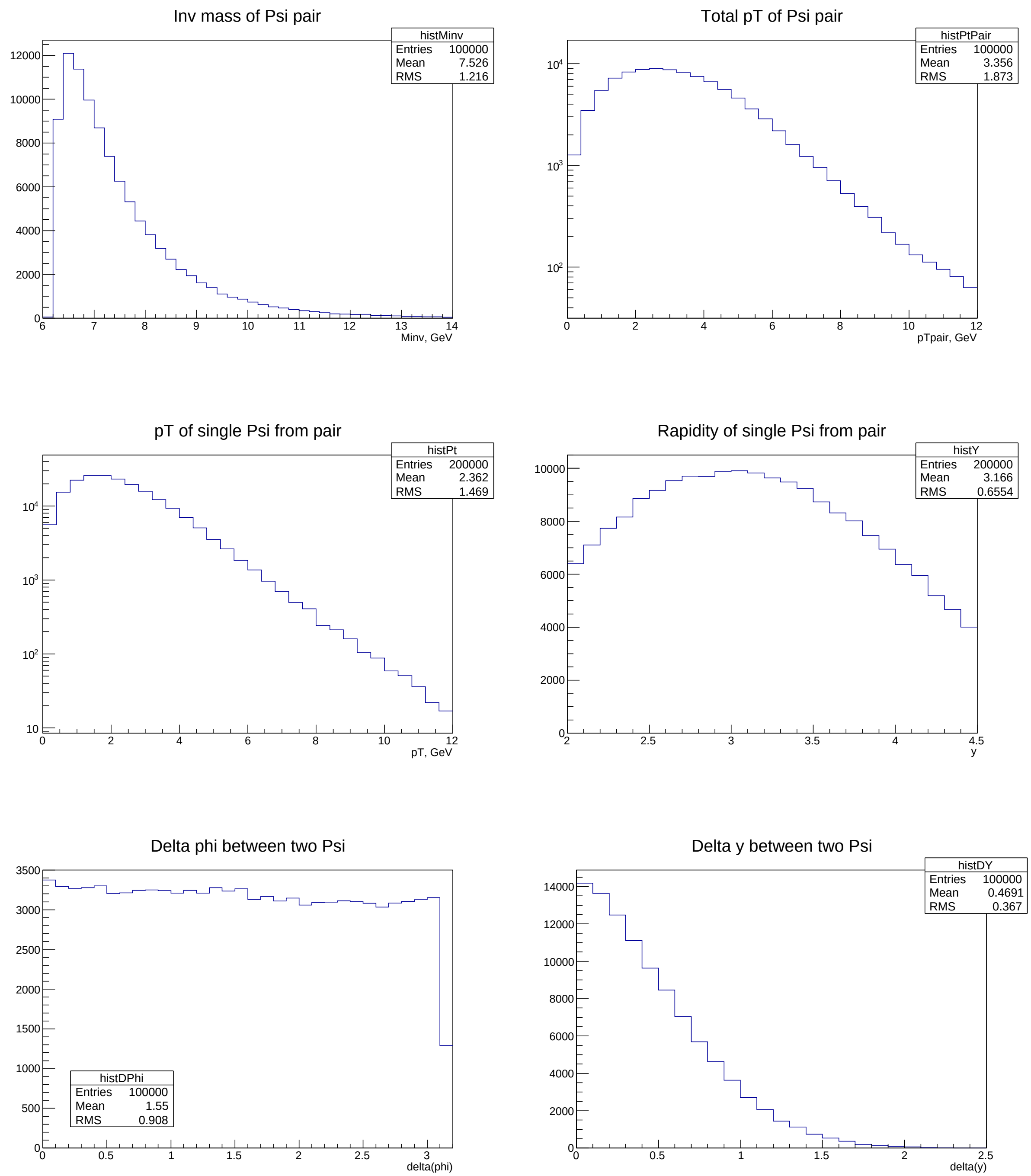

Figure 3: Kinematic distributions for double J/ψ production via gluon fusion process in 14 TeV pp collisions in LHCb rapidity window.

It is approximately 1.8 times larger than at 7 TeV. Kinematic distributions at 14 TeV collision energy are presented in Figure 3.

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