

# Generation of millicharged particles at the LHC

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## 1 Introduction

In this document we discuss the MC generation of millicharged particles ( $\zeta$ ) in  $pp$  collisions at the LHC in the central rapidity region. Except for Drell-Yan (DY), this is done in a few steps

1. Generate in various ways SM particles ( $A$ ) that can decay as  $A \rightarrow X\zeta^+\zeta^-$
2. Keep track of the cross-section for SM production of  $A$ .
3. Calculate the branching ratio for  $A \rightarrow X\zeta^+\zeta^-$  for millicahрге  $Q = 1$ . For different charges, it is easy to scale the branching ratio as  $Q^2$ .
4. Generate the  $A \rightarrow X\zeta^+\zeta^-$  decay with proper kinematics.
5. Save the “event” for further processing in a root file.

## 2 Special (simplest) case: Drell-Yan

The Drell-Yan process  $pp \rightarrow \zeta^+\zeta^-$  is generated with the external model interface in MadGraph. Note: we cannot use the SM  $pp \rightarrow \ell^+\ell^-$  because the couplings of the  $Z$  to  $\zeta$ 's and leptons are different, since in our model  $\zeta$ 's are weak isoaspin singlet.

**Status of this: this was done by Itay in MadGraph4, Golf is porting it to Madgraph5, but he has some bugs to fix.**

### 3 List of non-DY processes

The main processes for  $A \rightarrow e^+e^-X$  at the LHC are:

- $\pi^0 \rightarrow e^+e^-\gamma$  (BR=1.17%, Dalitz decay)
- $\eta \rightarrow e^+e^-\gamma$  (BR=0.7%, Dalitz decay)
- $\eta' \rightarrow e^+e^-\gamma$  (BR=5e-4, Dalitz decay)
- $\omega \rightarrow \pi^0 e^+e^-$  (BR=8e-4, Dalitz decay)
- $\eta' \rightarrow \omega e^+e^-$  (BR=2e-4, Dalitz Decay)
- $\eta' \rightarrow \pi^+\pi^-e^+e^-\gamma$  (BR=2e-3, sort of Dalitz, skip for now)
- $V \rightarrow e^+e^-$  ( $V = \text{onia}, \phi, \rho, \omega$ )

Note that if we are only interested on  $\zeta$  masses above 100 MeV, Dalitz decays of  $\pi^0$  and decays of  $\eta'$  into  $\omega$  do not contribute. In all cases the BR for  $A \rightarrow \zeta^+\zeta^-X$  can be obtained by rescaling  $A \rightarrow e^+e^-X$  by a factor of  $Q^2$  times an additional mass-dependent factor. In general this factor consists of a phase space piece  $\sqrt{1 - (2m_\zeta/m_A)^2}$  plus an additional piece that arises from the matrix element.

### 4 Branching Ratios of non-DY processes (Q=1).

#### 4.1 Dalitz BR

The partial width for  $A \rightarrow e^+e^-\gamma$  can be written as[1, 2]:

$$\frac{d\Gamma}{dq^2} = \frac{2\alpha}{3\pi q^2} \left(1 + \frac{2m_e^2}{q^2}\right) \sqrt{1 - \frac{4m_e^2}{q^2}} \left(1 - \frac{q^2}{m_A^2}\right)^3 |F(q^2)|^2 \Gamma(A \rightarrow \gamma\gamma) \quad (1)$$

where  $m_A$  is the mass of  $A$ ,  $q^2$  is the mass-squared of the  $e^+e^-$  pair, and  $F(q^2)$  is a form factor. This form factor is such that  $F(0) = 1$  and for pions is usually parametrized near  $q^2 = 0$  as  $F(q^2) = 1 + a \frac{q^2}{m_\pi^2}$  with  $a \approx 0.03$ . The form factor can also be estimated in the Vector Dominance Model (VDM) as

$$|F(q^2)|^2 = \frac{m_\rho^4 + m_\rho^2 \Gamma_\rho^2}{(m_\rho^2 - q^2)^2 + m_\rho^2 \Gamma_\rho^2} \quad (2)$$

where  $m_\rho$  and  $\Gamma_\rho$  are the mass and width of the  $\rho$  meson. The VDM model assumes that the decay proceeds through  $\pi^0 \rightarrow \gamma V^*$ ,  $V^* \rightarrow e^+e^-$  and  $V = \rho$  or  $\omega$ ; equation 2 neglects the difference between  $\rho$  and  $\omega$ .

In the case of  $A \rightarrow e^+e^-X$ , when  $X$  is not  $\gamma$ , the partial width can be written as

$$\begin{aligned} \frac{d\Gamma}{dq^2} = & \frac{\alpha}{3\pi q^2} \left(1 + \frac{2m_e^2}{q^2}\right) \sqrt{1 - \frac{4m_e^2}{q^2}} \cdot \\ & \left[ \left(1 + \frac{q^2}{m_A^2 - m_X^2}\right)^2 - \frac{4m_A^2 q^2}{(m_A^2 - m_X^2)^2} \right]^{3/2} |F_{AX}(q^2)|^2 \Gamma(A \rightarrow X\gamma) \end{aligned} \quad (3)$$

where  $m_X$  is the mass of  $X$ , and the transition form factor  $F_{AX}$  can also be approximated as in equation 2.

For millicharged particles, Dalitz decays branching ratios can be obtained by integrating equation 1 or 3 from  $q^2 = 4m_\zeta^2$  to the kinematical limit, substituting  $m_\zeta$  for  $m_e$ , and rescaling by  $Q^2$ . Some numerical results, for  $Q = 1$  are given in Table 1. Note the sharp drop in branching ratios with mass, especially for the  $\pi^0$ . The calculations with the electron and muon masses are in good agreement with the PDG.

## 4.2 Vector meson branching ratios

At lowest order the SM decay rate for  $V \rightarrow \ell\ell$  is given by the Van Royen-Weisskopf formula[3, 4]:

$$\Gamma(V \rightarrow \ell\ell) = 4\pi\alpha^2 \frac{f_V^2}{m_V} Q_q^2 (1 - 4x_\ell^2)^{1/2} (1 + 2x_\ell^2) \quad (4)$$

where  $f_V$  is the vector decay constant,  $m_V$  is the vector mass,  $Q_q$  is the charge of the quark that makes up the meson,  $x_\ell = m_\ell/m_V$ , and  $m_\ell$  is the lepton mass.

Thus the ratio of BR for  $V \rightarrow \zeta\zeta$  to  $V \rightarrow ee$  is given by

$$\frac{\Gamma(V \rightarrow \zeta\zeta)}{\Gamma(V \rightarrow ee)} = Q^2 \frac{(1 - 4x_\zeta^2)^{1/2} (1 + 2x_\zeta^2)}{(1 - 4x_\ell^2)^{1/2} (1 + 2x_\ell^2)} \quad (5)$$

where  $x_\zeta = m_\ell/m_V$ , and  $m_\zeta$  is the mass of  $\zeta$ .

$m_\zeta$ (MeV)	$\pi^0 \rightarrow \zeta\zeta\gamma$	$\eta \rightarrow \zeta\zeta\gamma$	$\eta' \rightarrow \zeta\zeta\gamma$	$\eta' \rightarrow \zeta\zeta\omega$	$\omega \rightarrow \zeta\zeta\pi^0$
0.511 ( $=m_e$ ) PDG for $ee$	1.17 e-2 (1.17 $\pm$ 0.04)e-2	6.6 e-3 (6.9 $\pm$ 0.4)e-4	4.6 e-4	1.8 e-4 (2.0 $\pm$ 0.4)e-4	7.6 e-4 (7.7 $\pm$ 0.6)e-4
10	2.8 e-3	2.9 e-3	2.5 e-4	5.7 e-5	3.7 e-4
30	3.5 e-4	1.6 e-3	1.8 e-4	1.7 e-5	2.3 e-4
50	1.2 e-5	1.0 e-3	1.4 e-4	4.3 e-6	1.6 e-4
60	2.7 e-7	8.2 e-4	1.3 e-4	1.7 e-6	1.4 e-4
90		4.3 e-4	1.0 e-4		9.2 e-5
105.7 ( $=m_\mu$ ) PDG for $\mu\mu$		3.0 e-4 (3.1 $\pm$ 0.4) e-4	9.2 e-5 (1.1 $\pm$ 0.3) e-4		7.4 e-5 (1.3 $\pm$ 0.2) e-4
150		8.9 e-5	6.8 e-5		3.7 e-5
200		1.2 e-5	4.8 e-5		1.5 e-5
250		1.0 e-7	3.2 e-5		3.6 e-6
400			5.6 e-7		

Table 1: Branching ratios for different Dalitz decay modes as a function of  $m_\zeta$  for  $Q = 1$  calculated based on equations 1, 2, and 3. When possible we compare with the values from the 2019 PDG.

As a sanity check, we use equation 5 and  $\text{BR}(\psi(2S) \rightarrow ee) = 7.93\text{e-}3$  to predict  $\text{BR}(\psi(2S) \rightarrow \tau\tau) = 3.1\text{e-}3$ , in agreement with the PDG value of  $(3.1 \pm 0.4)\text{e-}3$ .

## 5 Generation of SM particles decaying into $\zeta^+\zeta^-$

The key features of our approach are the following

- Use theory or published data, or some MC to generate  $P_T$  distributions for SM particles saved as histograms in ROOT files (Drell Yan is an exception, as discussed previously).
- Sample the ROOT histograms to generate SM particles of a given  $P_T$
- Pick azimuthal angles  $\phi$  and pseudorapidity  $\eta$  in a limited range, matched to the acceptance of milliquan.

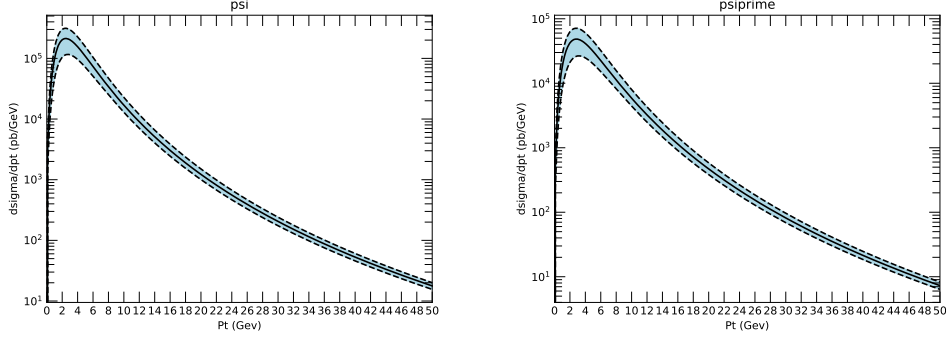


Figure 1: Transverse momentum distributions of  $J/\psi$  (left) and  $\psi'$  from bottom quark decays. Note: this is from a single  $b$ , multiply by two to include  $\bar{b}$ . The units are pb/GeV and the distributions are integrated over  $|\eta| < 1.0$ .

- Decay the SM particles into milliCharged particles (this step is described in a separate note).
- When possible, keep track of theoretical uncertainties.
- In general it is sufficient to generate SM particles at low and moderate  $P_T$  since that is where the cross-section is largest.

## 5.1 $J/\psi$ and $\psi'$ from b-decays

We use the tool available in

<http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html>

to generate histograms of  $P_T$  distributions (cross-sections) for charmonium from bottom decays, including theoretical uncertainties[6, 7]. See Figure 1

## 5.2 Direct onia production

### 5.2.1 Direct bottonium

There have been many measurement of the  $P_T$  spectra of  $\Upsilon$  in  $pp$  collisions at the LHC by CMS [8, 9, 10, 11], Atlas [12, 13], and LHCb [14, 15, 16, 17, 18]. The LHCb measurements are in the forward region. The only measurement

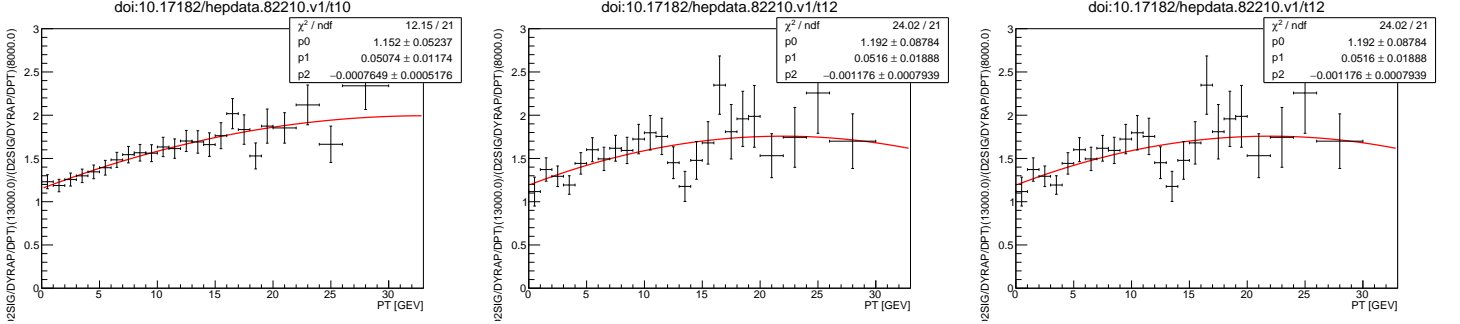


Figure 2: Ratio of 13 to 7 GeV  $\Upsilon$  cross-section for  $2.0 < |\eta| < 2.5$  from LHCb [14]. From left to right: 1S, 2S, 3S. The quadratic fits are ours.

at 13 TeV in the central region is from CMS [11]. Unfortunately, it is limited to  $P_T > 20$  GeV.

Due to the lack of 13 TeV data, initially we planned to use theoretical predictions as a basis of the  $\Upsilon$  event generation. We contacted the theorists [19] that provided the state-of-the art calculations used to confront the data in Reference [11]. We asked them to extend their predictions to lower  $P_T$ , unfortunately they claim that these are unreliable below 15 GeV.

As a result we decided to use 7 TeV data for  $P_T < 20$  GeV and the CMS 13 TeV data at higher  $P_T$ . A key ingredient is the ratio of 13 and 7 GeV  $\Upsilon$  production cross-sections. These have been measured for  $P_T > 20$  GeV and  $|\eta| < 1.2$  by CMS, see Figure 2 of Reference [11]. The ratios are about 1.7 at  $P_T = 20$  GeV, irrespective of  $\Upsilon$  state (1S, 2S, or 3S), and increase slowly to about 2 at  $P_T = 40$  GeV. The ratios have also been measured by LHCb [14] all the way down to zero  $P_T$  for  $2.0 < |\eta| < 2.5$ , see Figure 2. These ratios in the 20-30 GeV region are in agreement with the central ratios measured by CMS.

We rescale the measured 7 GeV central low  $P_T$   $\Upsilon$  spectra to 13 TeV using the fitted curves of Figure 2; we combine these with the 13 TeV measured central high  $P_T$  spectra to obtain an inclusive 13 TeV spectrum. The 7 TeV data is from Atlas [13], and the 13 TeV spectrum is from CMS [11]. We demonstrate in Figure 3 that the matching of the Atlas and CMS cross-sections works well. The combined spectrum to be used in the event generation is in Figure 4.

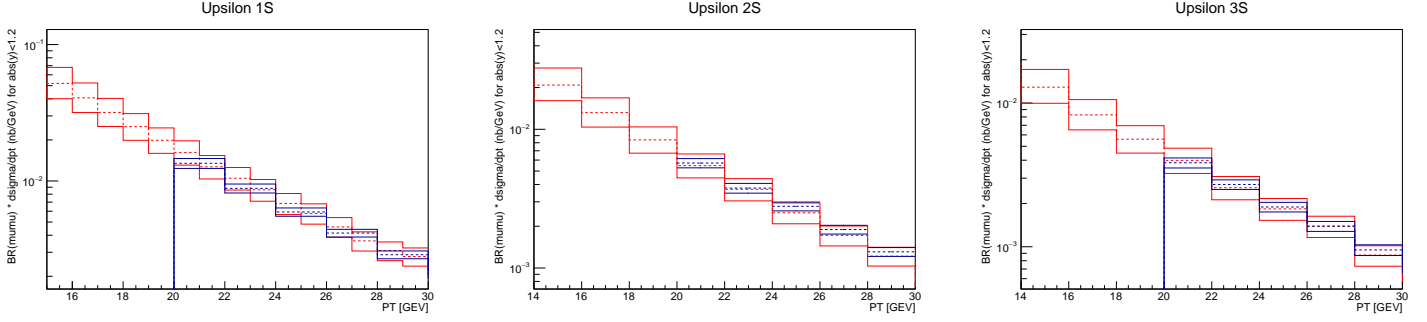


Figure 3: Comparison of the rescaled 7 GeV Atlas  $\Upsilon$  spectra (red) with the 13 GeV CMS spectra (blue) in the neighborhood of 20 GeV, where the matching of the two spectra takes place. From left to right: 1S, 2S, 3S. The dashed lines represent the central values, the solid lines cover the uncertainty range. This is  $\mathcal{B}(\Upsilon \rightarrow \mu\mu) \cdot d\sigma/dP_T$  in nb/GeV integrated over  $|\eta| < 1.2$ .

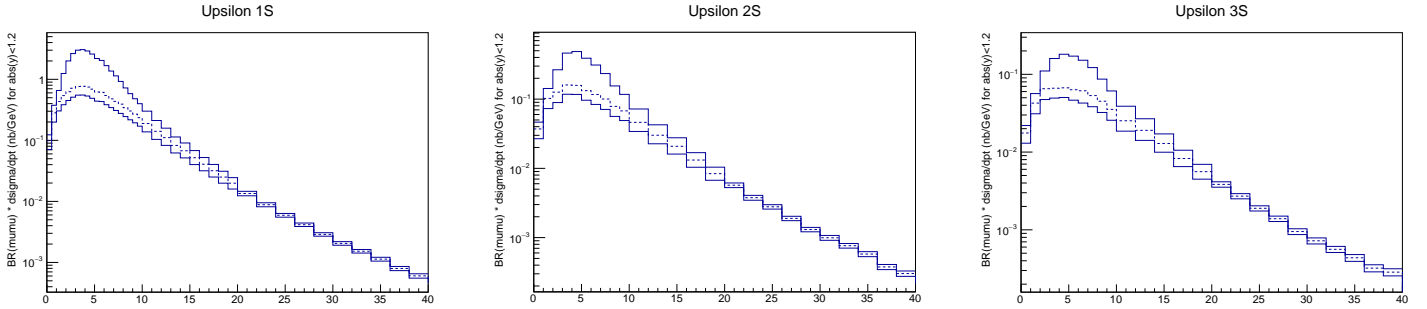


Figure 4: Combined Atlas 7 TeV, CMS 13 TeV  $\Upsilon$  spectra. From left to right: 1S, 2S, 3S. The dashed line represent the central value, the solid lines cover the uncertainty range. This is  $\mathcal{B}(\Upsilon \rightarrow \mu\mu) \cdot d\sigma/dP_T$  in nb/GeV integrated over  $|\eta| < 1.2$ .

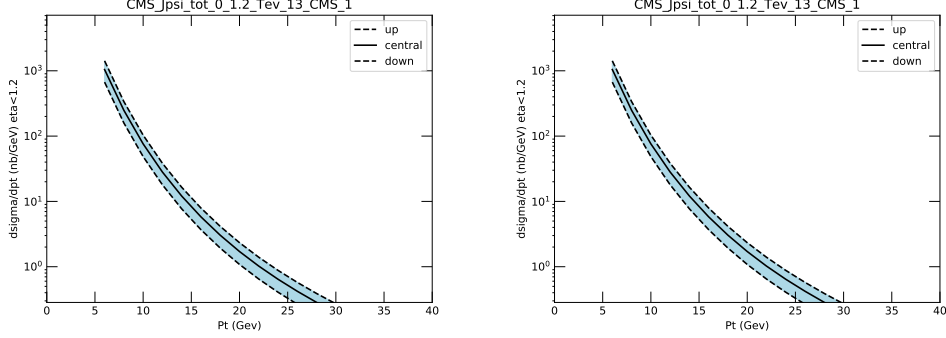


Figure 5: Transverse momentum distributions of  $J/\psi$  (left) and  $\psi'$  from direct production. The units are nb/GeV and the distributions are integrated over  $|\eta| < 1.2$ .

### 5.2.2 Direct charmonium

We take the charmonium spectra from theory [20, 21], see Figure 5. **NOTE: THESE ONLY GO DOWN TO 6 GEV BUT THE THEORISTS WILL PROVIDE CALCULATIONS TO LOWER PTs.**

### 5.3 $\pi^0$ , $\eta$ , $\eta'$ , $\phi$ , $\rho$ , and $\omega$

We generate these from Pythia. The measurement of the  $\pi^\pm$   $P_T$  spectrum from CMS[22] is in good agreement with Pythia 8 Minimum Bias at low momentum. We use this MC for all mesons. We do not attempt to use QCD  $2 \rightarrow 2$  at very low  $P_T$  since the process is infrared divergent. Note that Pythia `SoftQcd:nonDiffractive` includes all hard QCD processes[23] so in principle this is all that is needed. However, one runs out of statistics at high  $P_T$ . So at high  $P_T$  we stitch together the minimum bias distributions with distributions obtained from QCD  $2 \rightarrow 2$  at moderate  $P_T$ .

Eventually we will generate Pythia events in “standalone” mode to be independent of CMS software. For now we use existing CMS Monte Carlos for Minimum Bias and for QCD. The CMS QCD samples are “ $P_T$ -binned”, (15-30 GeV, 30-50 GeV, and 50-80 GeV). The Minimum Bias cross-section is taken to be 78.4 mb. Then the stitching procedure is the following:

- The QCD samples are first normalized to their LO cross-sections.



- next, we estimate a “qcd-minbias scale factor” by integrating over some region where the ratio is roughly flat
- the QCD samples are renormalized by this scale factor
- the samples are then stitched together by visually picking the  $P_t$  where the curves cross each other.

The resulting  $P_T$  curves are shown in Figure 6. It is not clear what kind of uncertainties we should assign. Let’s first see how important these are at the end of the day before going crazy.

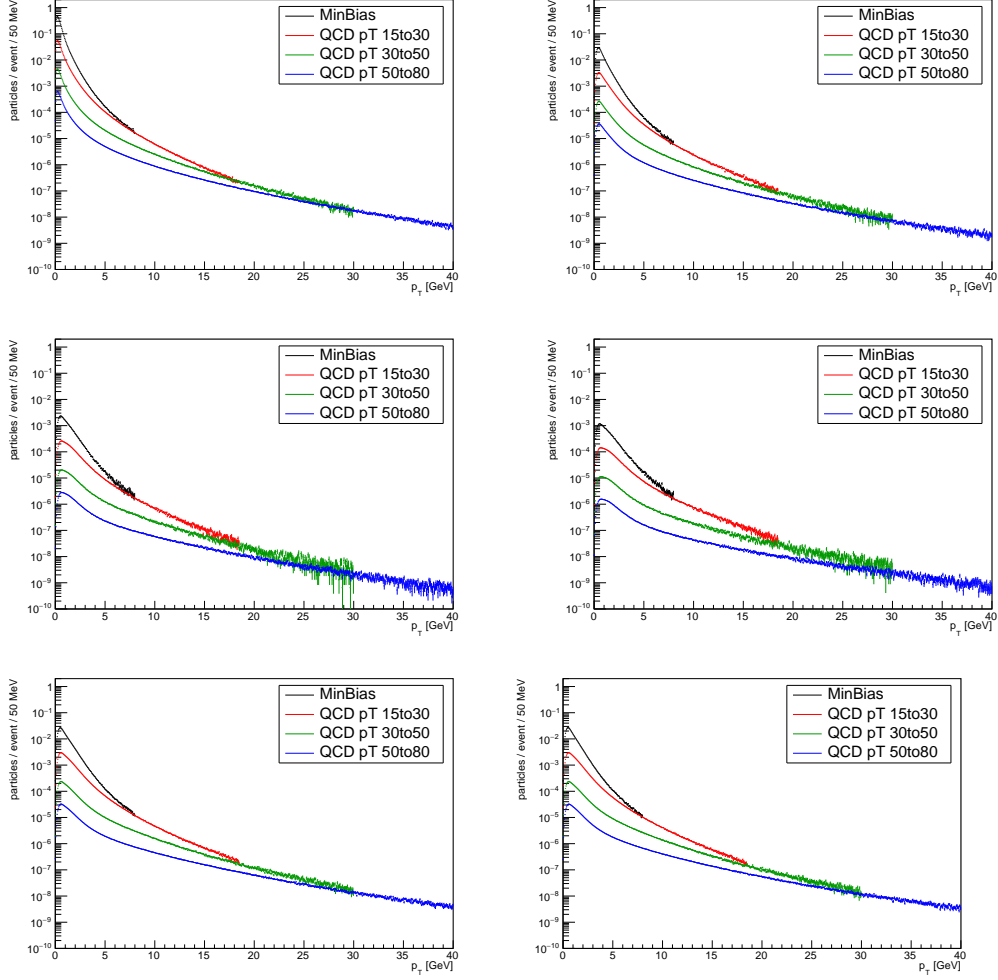


Figure 6: Transverse momentum distributions of  $\pi^0$ ,  $\eta$ ,  $\eta'$ ,  $\phi$ ,  $\rho$ , and  $\omega$ , top left to bottom right, for  $|\eta| < 1$ .

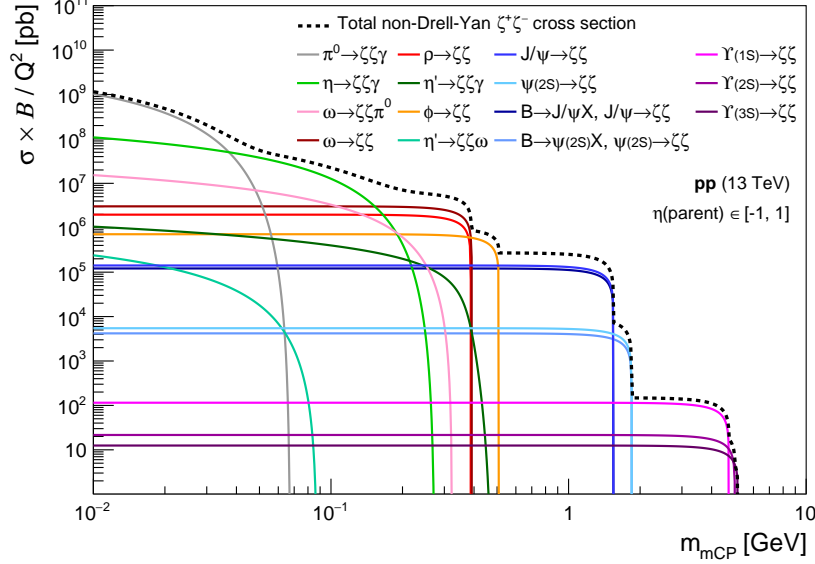


Figure 7: Cross-section times branching ratios for various decays into  $\eta^+\eta^-$  pairs, excluding DY. The contribution from direct charmonium is not complete yet.

## 6 Putting cross-sections and BR together

The total cross-section for millicharged particle production (excluding DY) is shown in Fig. 7.

## 7 Generation of the decays

We provide functions that take as input the lab frame 4-vector of either pseudoscalar ( $P$ ) or vector ( $V$ ) meson, and return the 4 vectors of the two  $\zeta$ 's from the decay. We assume that the  $V$ 's are unpolarized.

### 7.1 Generation of Dalitz decays

The implementation goes as follows (this should also work for the Dalitz decay of the  $\omega$  as long as the  $\omega$  is unpolarized):

- Rotate the 4-vector of  $P$  from the lab frame into frame  $S_1$  such that  $P$  is traveling in the  $z$ -direction.
- Boost along  $z$  into frame  $S_2$  where  $P$  is at rest.
- Pick a  $q^2$  according to equation 1.
- Generate a decay  $P \rightarrow X\gamma^*$  where  $\gamma^*$  is a particle of  $m^2 = q^2$ . The  $\gamma^*$  direction is random in  $\phi$  and random in  $\cos\theta$ .
- Rotate the  $\gamma^*$  4-vector into a frame  $S_3$  such that the  $\gamma^*$  is traveling in the  $z$ -direction.
- Boost along  $z$  into frame  $S_4$  where  $\gamma^*$  is at rest.
- Generate a decay  $\gamma^* \rightarrow \zeta^+\zeta^-$  such that the angle  $\phi$  of the  $\zeta^+$  is random and  $\cos\theta$  is picked according to [5]

$$\frac{dN}{d\cos\theta} = 1 + \cos^2\theta + \frac{4m_\zeta^2}{q^2} \sin^2\theta \quad (6)$$

- Set the 3-vector of the  $\zeta^-$  to be back-to-back with the  $\zeta^+$ .
- Boost the 4-vectors of the  $\zeta$ 's from  $S_4$  to  $S_3$ .
- Rotate the 4-vectors of the  $\zeta$ 's from  $S_3$  to  $S_2$ .
- Boost the 4-vectors of the  $\zeta$ 's from  $S_2$  to  $S_1$ .
- Rotate the 4-vectors of the  $\zeta$ 's from  $S_1$  to the lab frame.

## 7.2 Generation of vector decays

The procedure is the following:

- Rotate the 4-vector of  $V$  from the lab frame into frame  $S_1$  such that  $V$  is traveling in the  $z$ -direction.
- Boost along  $z$  into frame  $S_2$  where  $V$  is at rest.
- Generate a decay  $V \rightarrow \zeta^+\zeta^-$  such that both the angle  $\phi$  and the  $\cos\theta$  of the  $\zeta^+$  are random.

- Set the 3-vector of the  $\zeta^-$  to be back-to-back with the  $\zeta^+$ .
- Boost the 4-vectors of the  $\zeta$ 's from  $S_2$  to  $S_1$ .
- Rotate the 4-vectors of the  $\zeta$ 's from  $S_1$  to the lab frame.

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QCD on the left panel.