# Chasing Long-lived Scalars at the Future Lepton Colliders

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# Outline

**Based on: 2602.02308 (**Nandini Das, Dilip Kumar Ghosh, ***Nivedita Ghosh***, Ritesh K. Singh**)**

- Introduction to Long-lived Particle (LLP)
- Model
- LLP search at the future lepton colliders
  - ★ International Linear Collider (ILC)
  - ★ International Muon Collider Collaboration (IMCC)
- Summary

# Introduction to LLP

- Most of the conventional searches at the LHC assumes that the new BSM particles decay promptly.
- Is it really necessary to assume?

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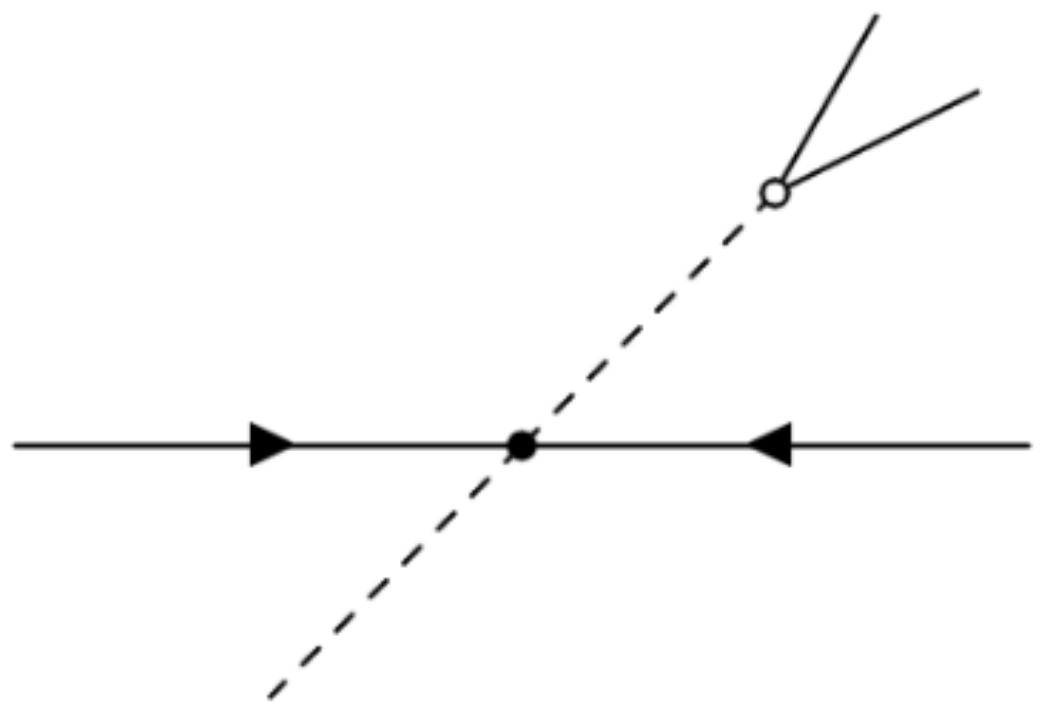


$$c\tau \geq \mathcal{O}(\mathrm{mm})$$

# Detecting the LLPs

**How it is produced ?**

- Production rate
- Boost factor ($\beta\gamma$)

**What are the decay Products?**

Proper decay length ($c\tau$)

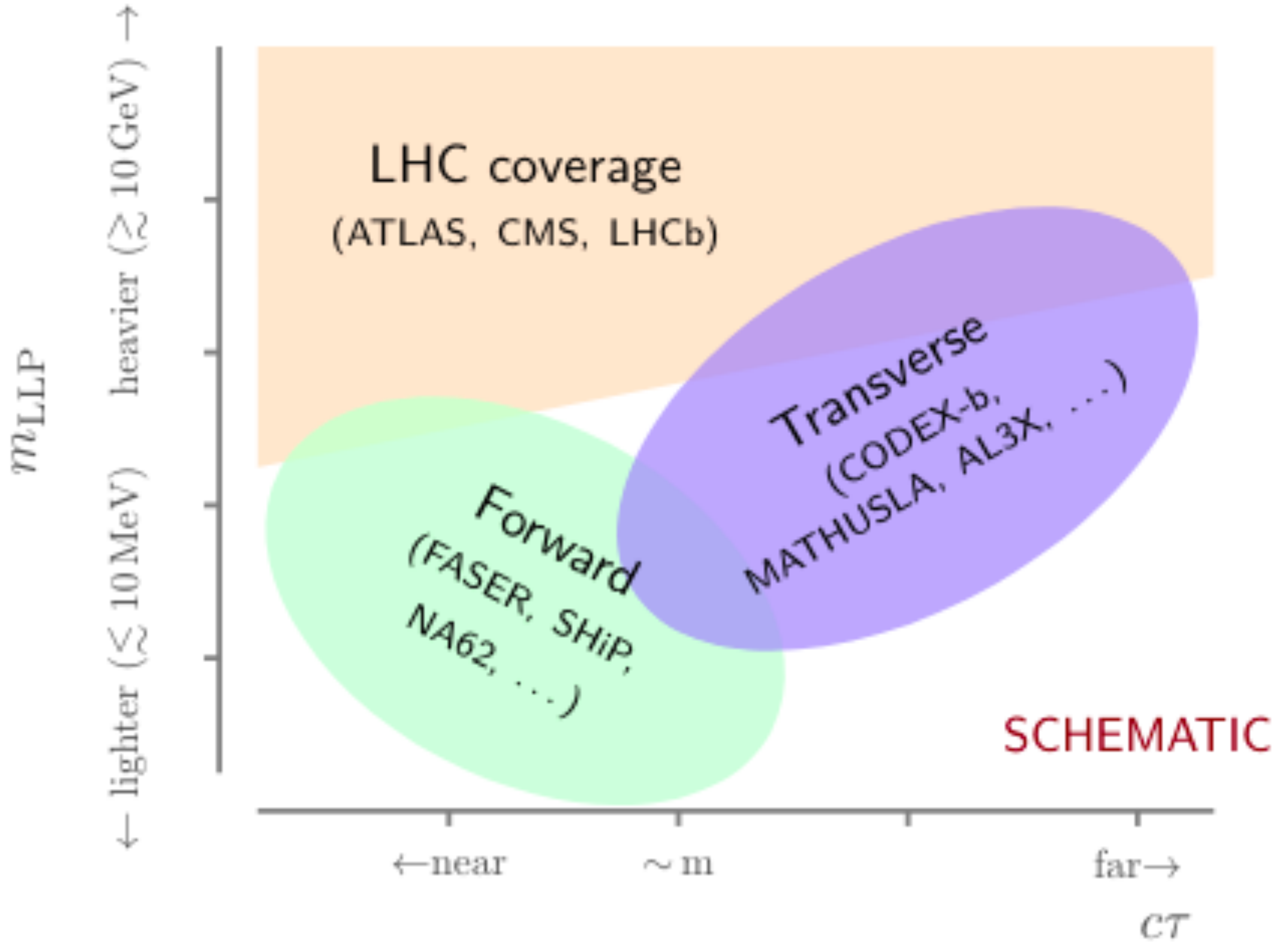
decay products

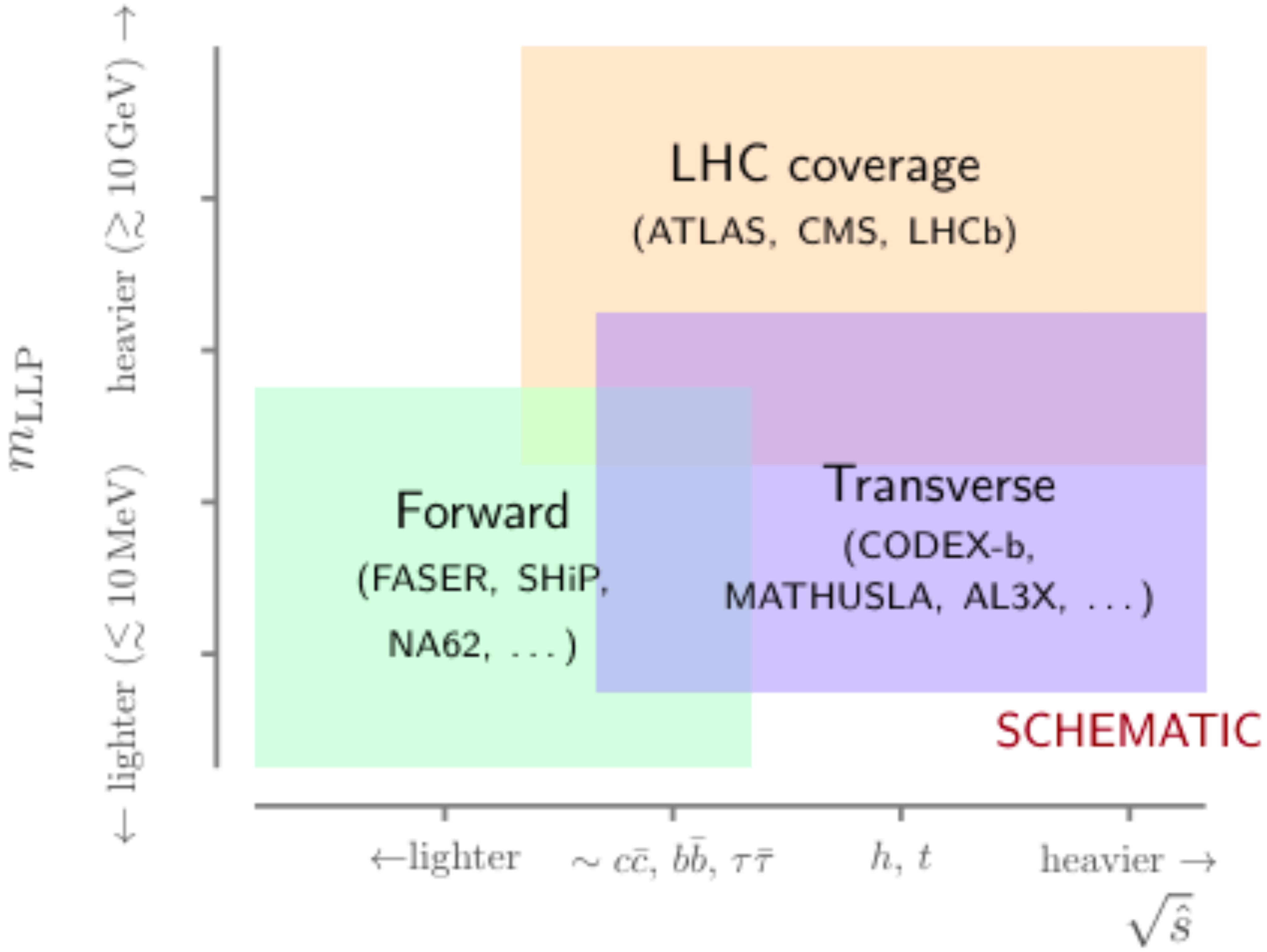
**Where does it decay?**

d= $\beta\gamma c\tau$

# Reach and Coverage of LLP experiments

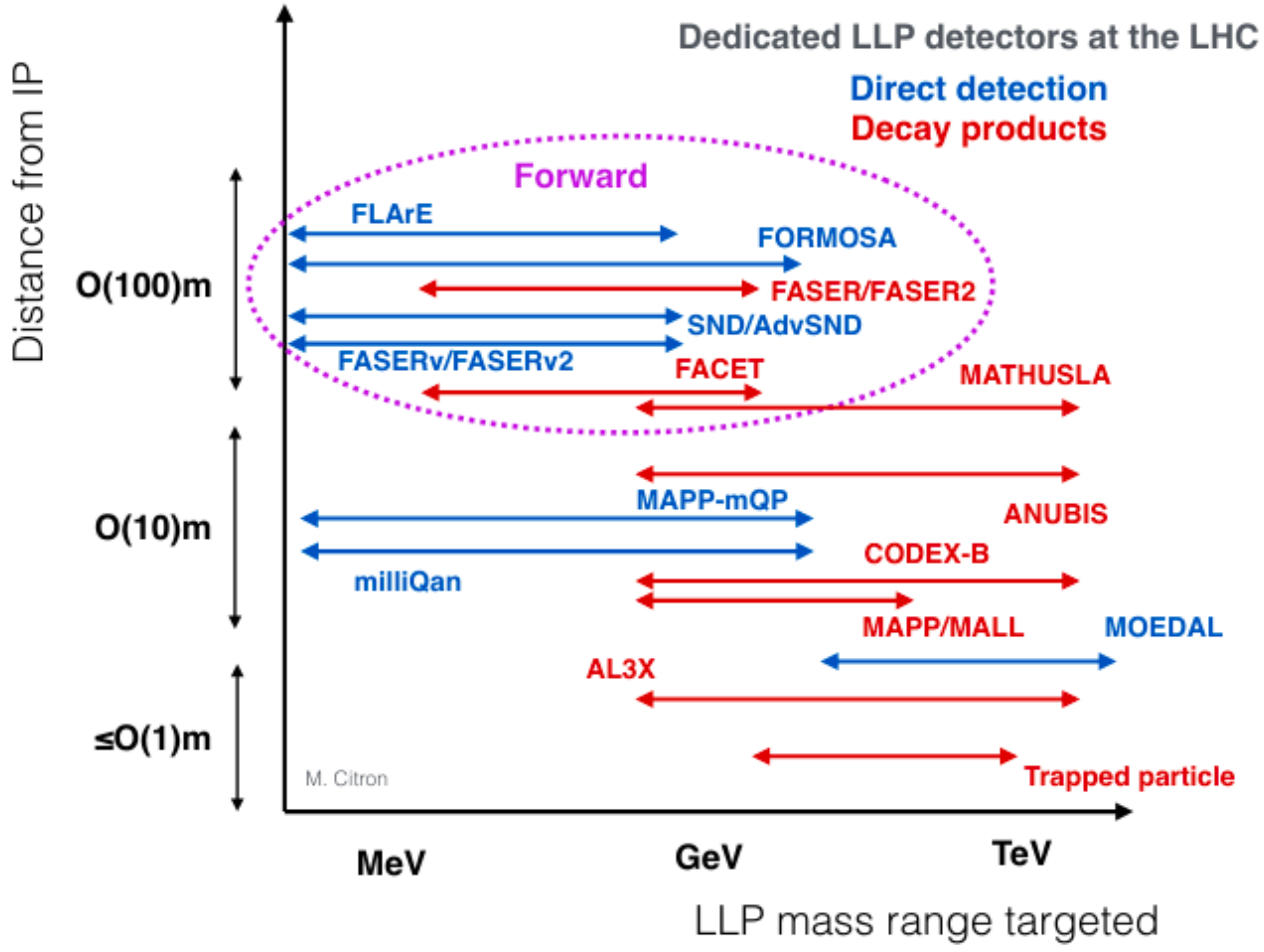
[1911.00481]



# Dedicated Detectors for LLP

[2209.13128]



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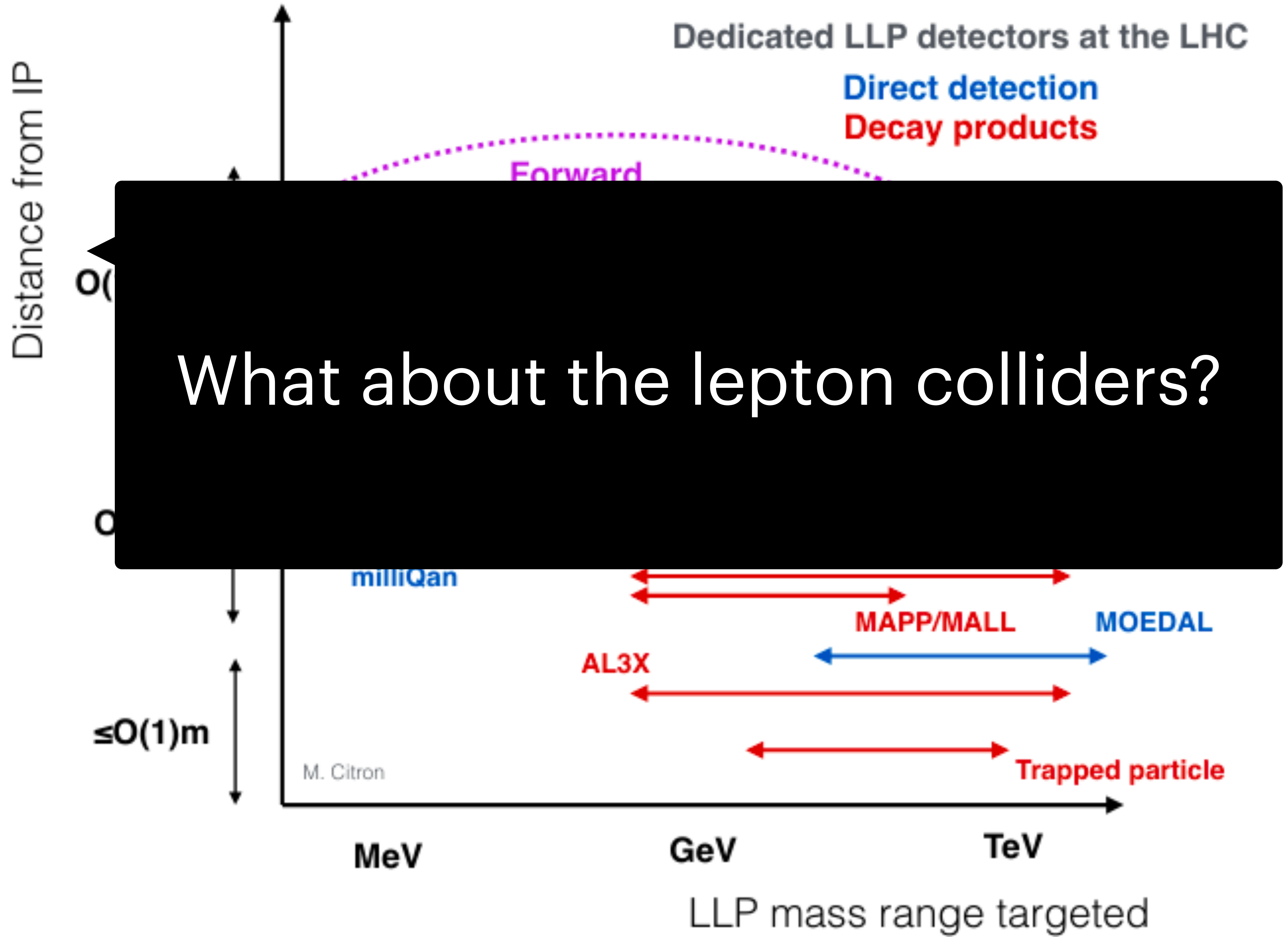


What about the lepton colliders?

# Model

$$\Delta = \frac{\sigma^i}{\sqrt{2}}\Delta_i = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}, \quad \Delta_1 = (\delta^{++}+\delta^0)/\sqrt{2},\ \Delta_2 = i(\delta^{++}-\delta^0)/\sqrt{2},\ \Delta_3 = \delta^+$$

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$$\mathcal{L} = \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{Kinetic}} - V(\Phi, \Delta),$$

$$\begin{aligned} \mathcal{L}_{\text{kinetic}} &= (D_\mu\Phi)^\dagger (D^\mu\Phi) + \text{Tr}\left[(D_\mu\Delta)^\dagger (D^\mu\Delta)\right], \\ \mathcal{L}_{\text{Yukawa}} &= \mathcal{L}_{\text{Yukawa}}^{\text{SM}} - (Y_\Delta)_{ij} L_i^\top C i\sigma_2 \Delta L_j + \text{h.c.}\,. \end{aligned}$$

$$D_\mu\Delta = \partial_\mu\Delta + i\frac{g}{2}[\sigma^a W_\mu^a, \Delta] + ig' B_\mu\Delta \qquad (a = 1, 2, 3).$$

# Model

$$V(\Phi,\Delta) = -m_\Phi^2(\Phi^\dagger\Phi) + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + M_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \left(\mu\Phi^\mathsf{T} i\sigma_2\Delta^\dagger\Phi + \mathrm{h.c.}\right) + \lambda_1(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}(\Delta^\dagger\Delta)^2 + \lambda_4\Phi^\dagger\Delta\Delta^\dagger\Phi.$$

# Model

$$V(\Phi,\Delta) \;=\; -m_\Phi^2(\Phi^\dagger\Phi)+\frac{\lambda}{4}(\Phi^\dagger\Phi)^2+M_\Delta^2\mathrm{Tr}(\Delta^\dagger\Delta)+\Big(\mu\Phi^\mathsf{T} i\sigma_2\Delta^\dagger\Phi+\mathrm{h.c.}\Big)+$$
$$\lambda_1(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta)+\lambda_2\Big[\mathrm{Tr}(\Delta^\dagger\Delta)\Big]^2+\lambda_3\mathrm{Tr}(\Delta^\dagger\Delta)^2+\lambda_4\Phi^\dagger\Delta\Delta^\dagger\Phi.$$

$$m_\Phi^2=\lambda\frac{v_d^2}{4}-\sqrt{2}\mu v_t+\frac{(\lambda_1+\lambda_4)}{2}v_t^2\,,$$

$$M_\Delta^2=\frac{\mu v_d^2}{\sqrt{2}v_t}-\frac{\lambda_1+\lambda_4}{2}v_d^2-(\lambda_2+\lambda_3)v_t^2\,,$$

# Model

$$V(\Phi,\Delta) = -m_\Phi^2(\Phi^\dagger\Phi) + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + M_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \left(\mu\Phi^\mathsf{T} i\sigma_2\Delta^\dagger\Phi + \mathrm{h.c.}\right) + \lambda_1(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}(\Delta^\dagger\Delta)^2 + \lambda_4\Phi^\dagger\Delta\Delta^\dagger\Phi.$$

$$m_\Phi^2 = \lambda\frac{v_d^2}{4} - \sqrt{2}\mu v_t + \frac{(\lambda_1+\lambda_4)}{2}v_t^2\,,$$

$$M_\Delta^2 = \frac{\mu v_d^2}{\sqrt{2}v_t} - \frac{\lambda_1+\lambda_4}{2}v_d^2 - (\lambda_2+\lambda_3)v_t^2\,,$$

$$v = \sqrt{v_d^2 + 2v_t^2} = 246\ \mathrm{GeV}.$$

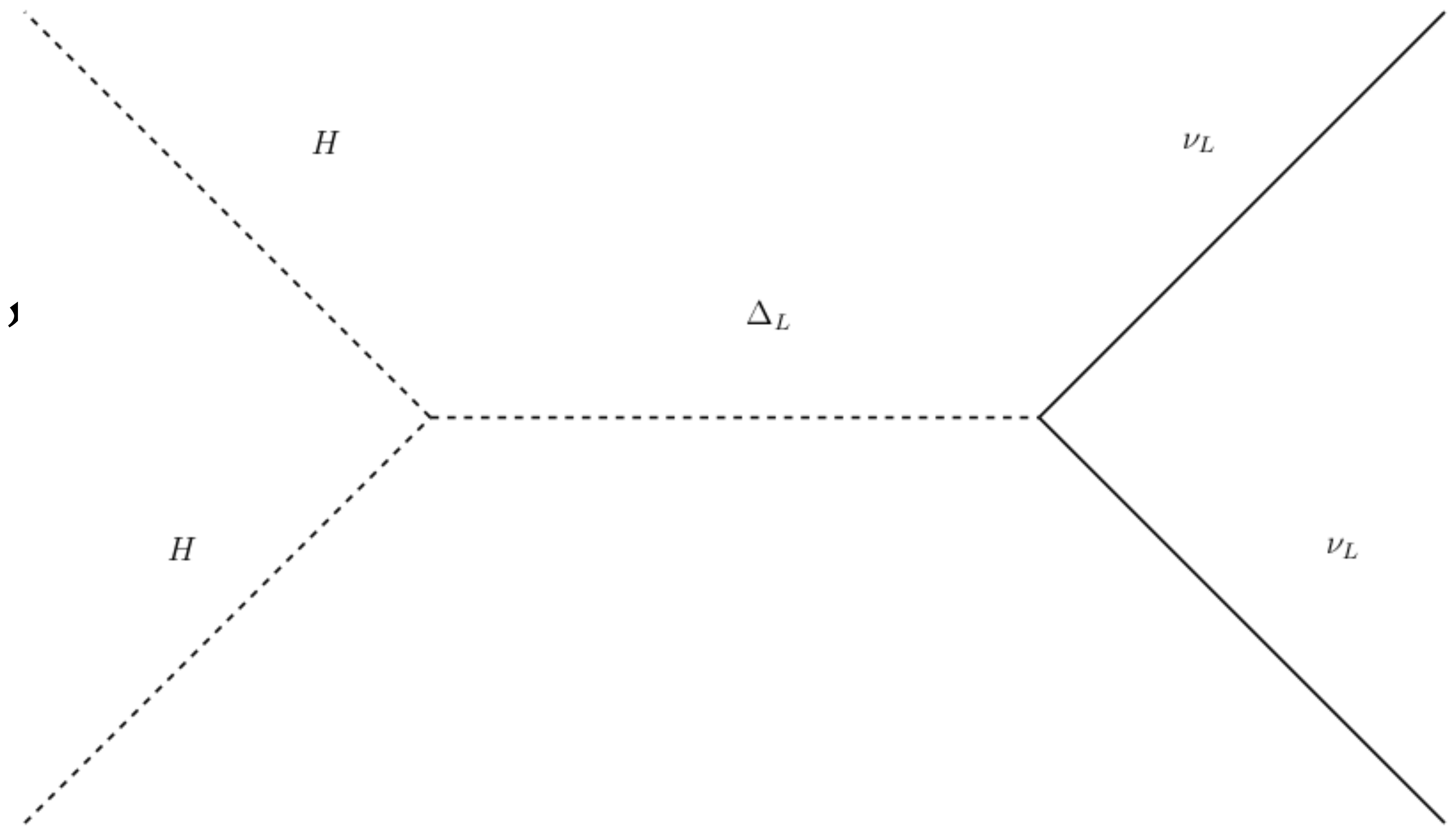
# Model

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = \frac{1+\frac{2v_t^2}{v_d^2}}{1+\frac{4v_t^2}{v_d^2}}.$$

- $\rho$ parameter close to unity→ upper bound on $v_t < 2$ GeV[1811.03476]

$$M_\nu = \sqrt{2} v_t Y_\Delta.$$

- For $v_t \sim \mathcal{O}($ GeV), the Yukawa coupling must be small, whereas an order-one neutrino Yukawa coupling $(Y_\Delta \sim \mathcal{O}(1))$ requires $v_t < \mathcal{O}(10^{-2}$ eV).



# Model

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\chi_d^+ \\ v_d + h_d + i\eta_d \end{pmatrix} \qquad \Delta = \frac{1}{\sqrt{2}}\begin{pmatrix} \delta^+ & \sqrt{2}\delta^{++} \\ v_t + h_t + i\eta_t & -\delta^+ \end{pmatrix}.$$

- 7 physical Higgs bosons, namely two doubly charged $H^{\pm\pm}$, two singly charged $H^{\pm}$, two CP-even neutral (h,H) and a CP-odd (A) scalar.[1711.06062]

$$\tan\beta' = \frac{\sqrt{2}v_t}{v_d}, \quad \tan\beta = \frac{2v_t}{v_d} \equiv \sqrt{2}\tan\beta'$$

$$\text{and} \quad \tan 2\alpha = \frac{2\mathcal{B}}{\mathcal{A}-\mathcal{C}},$$

$$\text{where,} \quad \mathcal{A} = \frac{\lambda}{2}v_d^2, \qquad \mathcal{B} = v_d[-\sqrt{2}\mu + (\lambda_1+\lambda_4)v_t], \quad \mathcal{C} = \frac{\sqrt{2}\mu v_d^2 + 4(\lambda_2+\lambda_3)v_t^3}{2v_t}.$$

# Model

$$\lambda = \frac{2}{v_d^2}(c_\alpha^2 m_h^2 + s_\alpha^2 m_H^2),$$

$$\lambda_1 = \frac{4m_{H^\pm}^2}{v_d^2 + 2v_t^2} - \frac{2m_A^2}{v_d^2 + 4v_t^2} + \frac{\sin 2\alpha}{2v_d v_t}(m_h^2 - m_H^2),$$

$$\lambda_2 = \frac{1}{v_t^2}\left[\frac{1}{2}\left(s_\alpha^2 m_h^2 + c_\alpha^2 m_H^2\right) + \frac{1}{2}\frac{v_d^2 m_A^2}{v_d^2 + 4v_t^2} - \frac{2v_d^2 m_{H^\pm}^2}{v_d^2 + 2v_t^2} + m_{H^{\pm\pm}}^2\right],$$

$$\lambda_3 = \frac{1}{v_t^2}\left[\frac{2v_d^2 m_{H^\pm}^2}{v_d^2 + 2v_t^2} - m_{H^{\pm\pm}}^2 - \frac{v_d^2 m_A^2}{v_d^2 + 4v_t^2}\right],$$

$$\lambda_4 = \frac{4m_A^2}{v_d^2 + 4v_t^2} - \frac{4m_{H^\pm}^2}{v_d^2 + 2v_t^2},$$

$$\mu = \frac{\sqrt{2}v_t m_A^2}{v_d^2 + 4v_t^2},$$

# Theoretical and Experimental Constraints

- ***Vacuum Stability:*** The scalar potential has to be bounded from below [1105.1925]

$$
\begin{aligned}
\lambda &\geq 0\,, \\
\lambda_2 + \lambda_3 &\geq 0\,, \\
\lambda_2 + \frac{\lambda_3}{2} &\geq 0, \\
\lambda_1 + \sqrt{\lambda(\lambda_2 + \lambda_3)} &\geq 0\,, \\
\lambda_1 + \sqrt{\lambda\left(\lambda_2 + \frac{\lambda_3}{2}\right)} &\geq 0, \\
\lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \lambda_3)} &\geq 0\,, \\
\lambda_1 + \lambda_4 + \sqrt{\lambda\left(\lambda_2 + \frac{\lambda_3}{2}\right)} &\geq 0.
\end{aligned}
$$

# Theoretical and Experimental Constraints

- ***Perturbative Unitarity :*** The tree-level unitarity demands the eigenvalues to be bounded from above [1105.1925]

$$
\begin{aligned}
|\lambda_1 + \lambda_4| &\leq 16\pi\,, \\
|\lambda_1| &\leq 16\pi\,, \\
|2\lambda_1 + 3\lambda_4| &\leq 32\pi\,, \\
|\lambda| &\leq 32\pi\,, \\
|\lambda_2| &\leq 8\pi\,, \\
|\lambda_2 + \lambda_3| &\leq 8\pi\,, \\
|\lambda + 4\lambda_2 + 8\lambda_3 \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2}| &\leq 64\pi\,, \\
|3\lambda + 16\lambda_2 + 12\lambda_3 \pm \sqrt{(3\lambda - 16\lambda_2 - 12\lambda_3)^2 + 24(2\lambda_1 + \lambda_4)^2}| &\leq 64\pi\,, \\
|2\lambda_1 - \lambda_4| &\leq 16\pi\,, \\
|2\lambda_2 - \lambda_3| &\leq 16\pi.
\end{aligned}
$$

# Theoretical and Experimental Constraints

- ***Electroweak Precision Test:*** The strongest bound comes from the T-parameter, which imposes a strict limit on the mass splitting between the doubly and singly charged scalars, $\Delta M \equiv | m_{H^{\pm\pm}} - m_{H^{\pm}} | \equiv | m_{H^{\pm}} - m_H/m_A |$ which should be $\lesssim 40$ GeV [1209.1303]

- ***Higgs Signal Strength:*** Higgs to di-photon signal strength is within $2\sigma$ limit of the current experimental bound $1.13 \pm 0.09$ [2207.00043].

# Theoretical and Experimental Constraints

- ***Experimental bound on scalar masses:*** The direct search on the singly charged scalar in LEP II places a limit on $m_{H^\pm} \geq 80$ GeV [1301.6065]
  LHC has also searched for the decay of $t \rightarrow H^+ b$ [2412.17584] and $H^+ \rightarrow t\bar{b}$[2411.03969].

  Non-standard neutral Higgs searches have also been done in detail at the LHC [1710.01123,2009.14791].

  The search for doubly charged Higgs in the multi-lepton final state is done in ATLAS [2211.07505] assuming that the doubly charged Higgs decays promptly and masses $\in [300:1080]$ GeV have been excluded. There is also a bound on doubly-charged Higgs from the production of same-sign W-boson pairs $\in [200:220]$GeV [1808.01899]. CMS has also searched for the doubly-charged scalar at 13 TeV[1709.05822,2104.04762].

***However, all searches assume that the scalar decays promptly.***

# Long-lived Doubly Charged Scalar

If $v_t < 10^{-4}$ GeV, pair of di-leptons , else it goes to pair of di-bosons

In the crossover region, $H^{\pm\pm} \Rightarrow W^{\pm}(W^{\pm})^{*} \Rightarrow W^{\pm} f f'$

By appropriately tuning $v_t$ and $m_{H^{\pm\pm}}$, the total decay width $\Gamma \lesssim 10^{-14}$ GeV$^{-1}$ ➡ $c\tau \gtrsim$ O(mm).

For $m_{H^{\pm\pm}} \in [89, 200]$ GeV and $v_t \in [10^{-4}, 10^{-3}]$ GeV, a region of parameter space remains unconstrained.

| | $H^{\pm\pm}$ (GeV) | $v_t$ (GeV) | $c\tau$ (mm) |
|---|---|---|---|
| BP1 | 100 | $9.0 \times 10^{-4}$ | 26.2 |
| BP2 | 120 | $5.0 \times 10^{-4}$ | 8.6 |
| BP3 | 180 | $1.6 \times 10^{-4}$ | 0.14 |

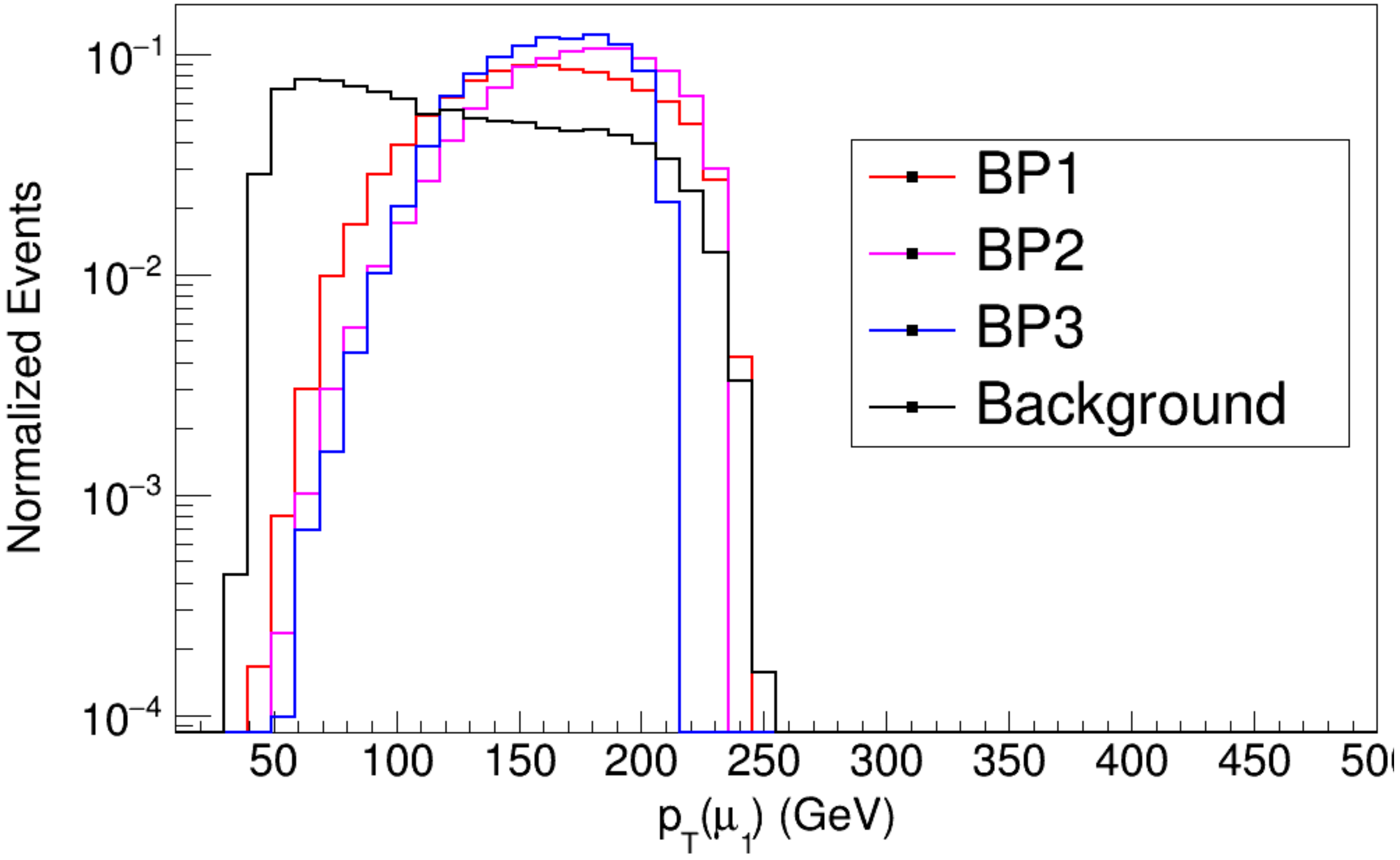
# Pair Production of the Doubly-Charged at the ILC ($\sqrt{s} = 500$ GeV)

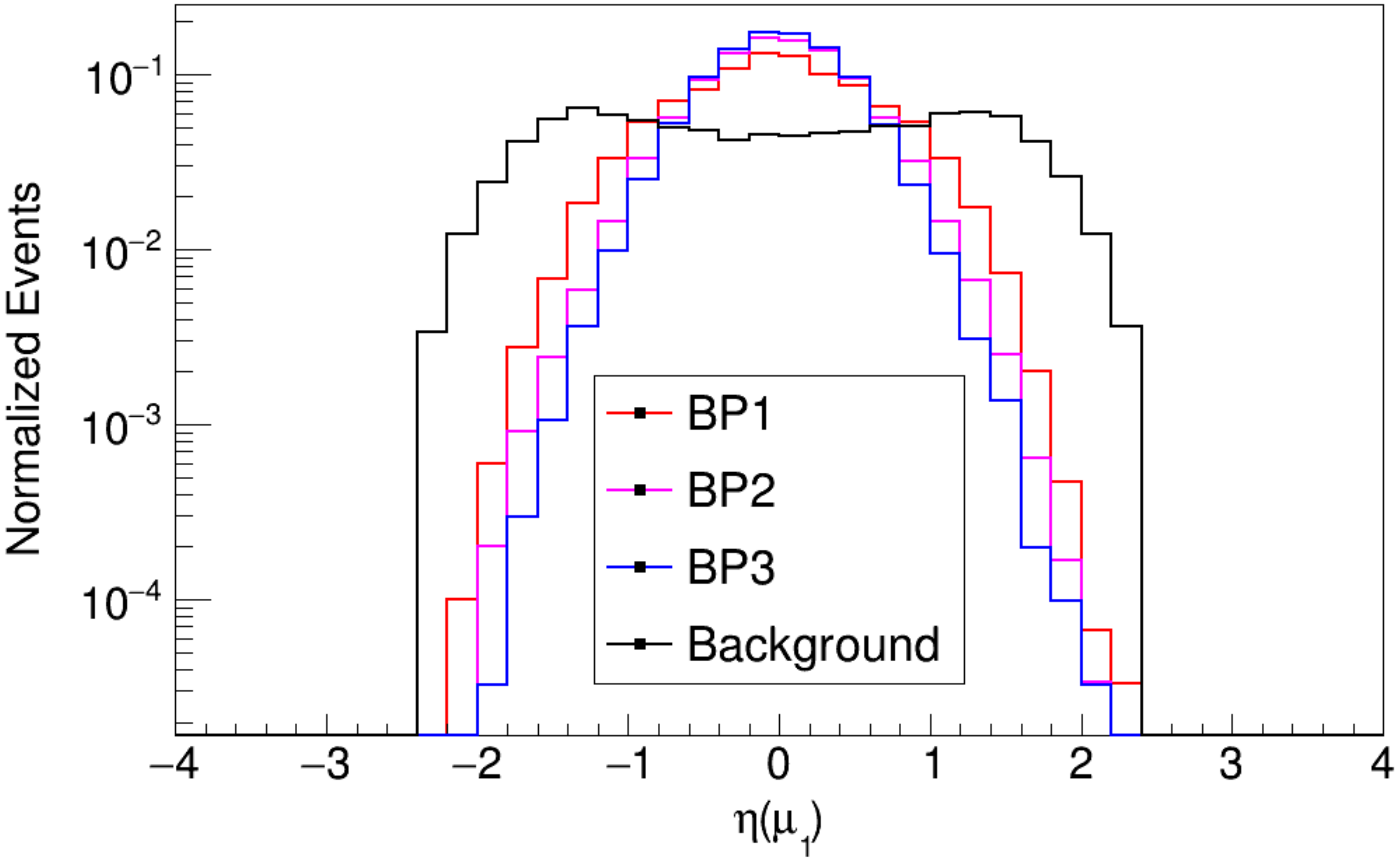
$$e^+e^- \to H^{++}H^{--}, H^{\pm\pm} \to \mu^\pm\mu^\pm$$

The SM background comes from the di-boson final state.

$$|\eta(\ell)| < 2.5; \quad \mathrm{p_T}(\ell) > 10\ \mathrm{GeV}; \quad \Delta\mathrm{R}_{\ell\ell} \geq 0.4$$

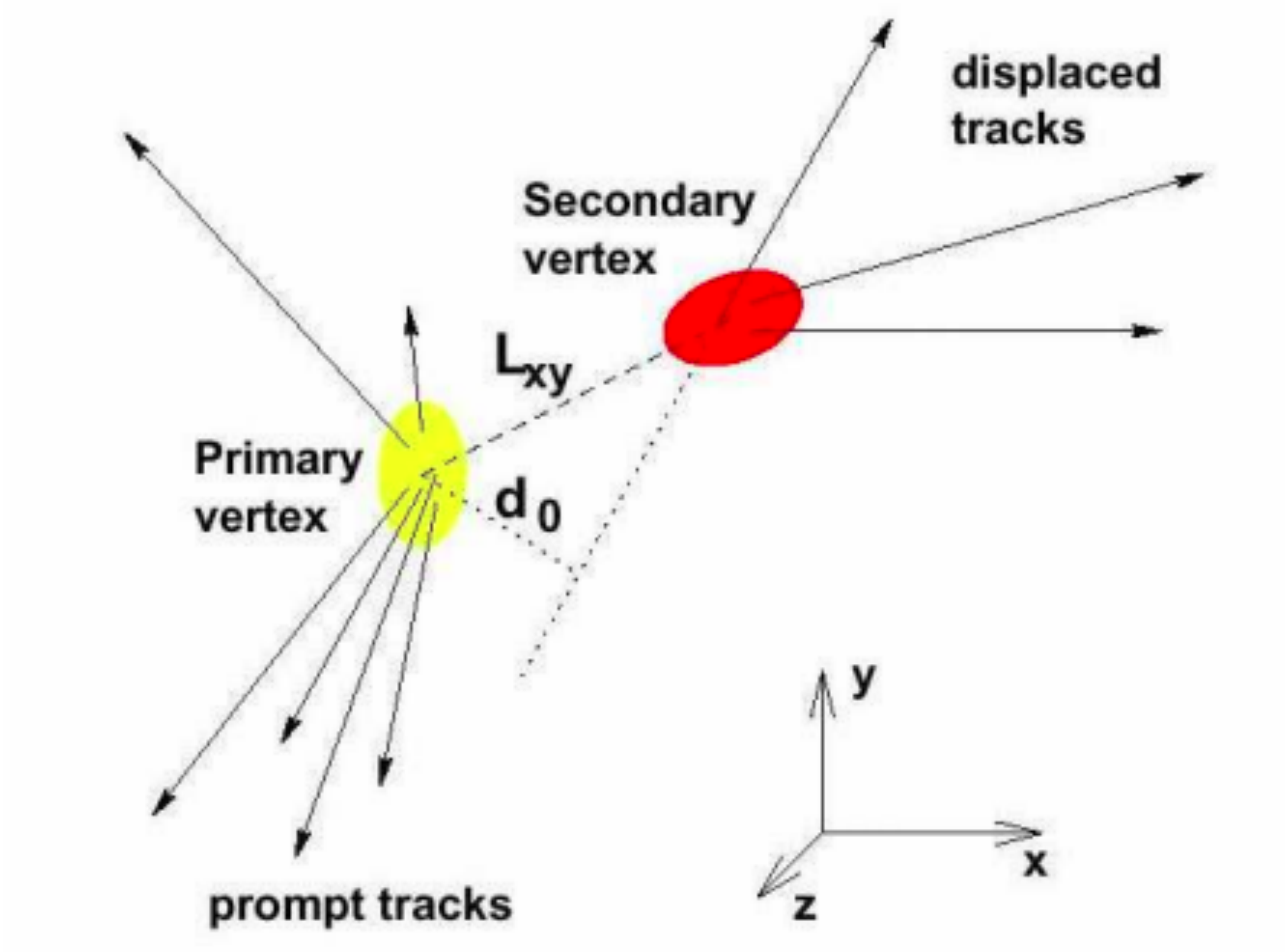
| $\sigma_{\text{ILC}}$ | BP1 | BP2 | BP3 | SM Bkgd |
|---|---|---|---|---|
| (fb) | 12.18 | 7.18 | 0.62 | 0.64 |

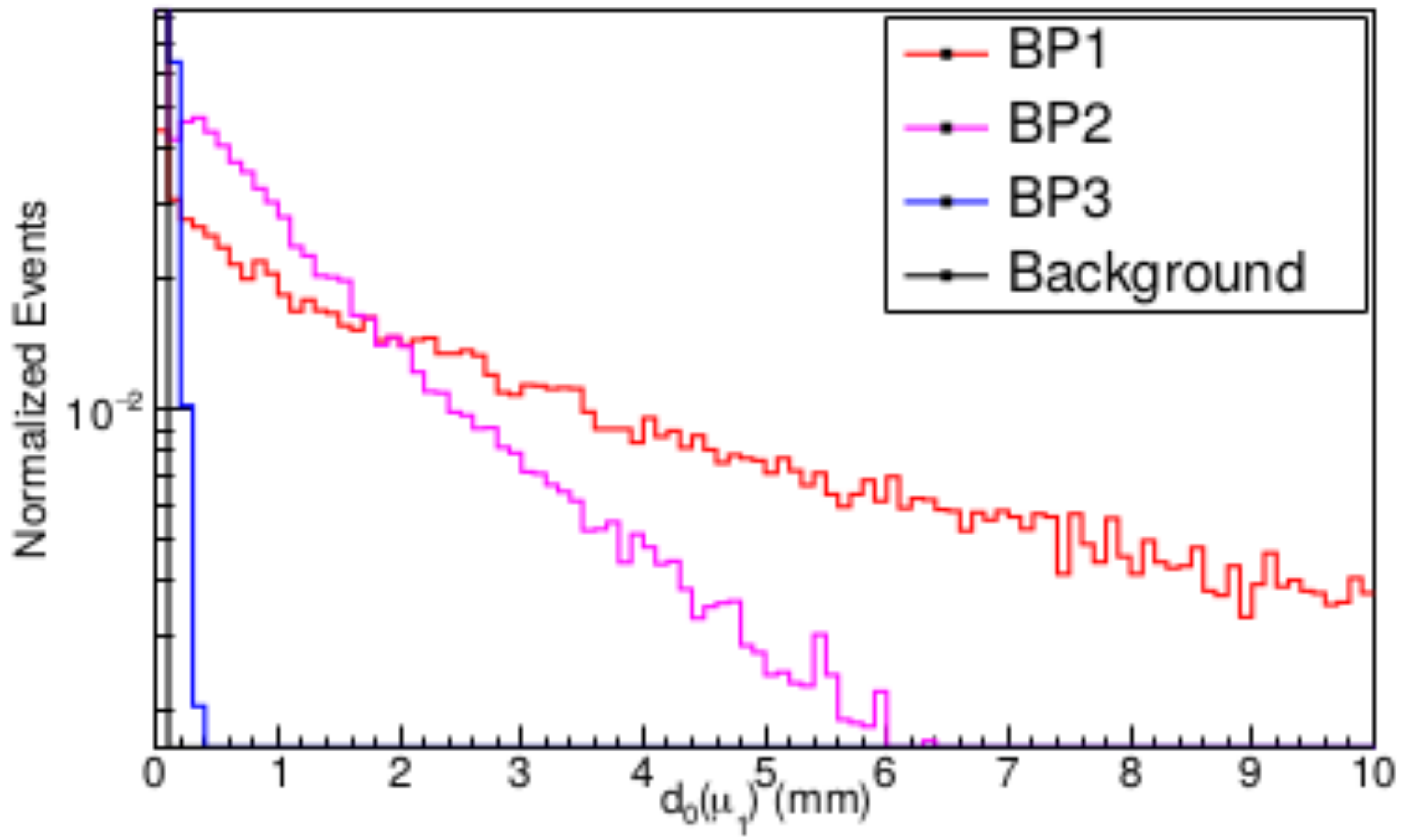


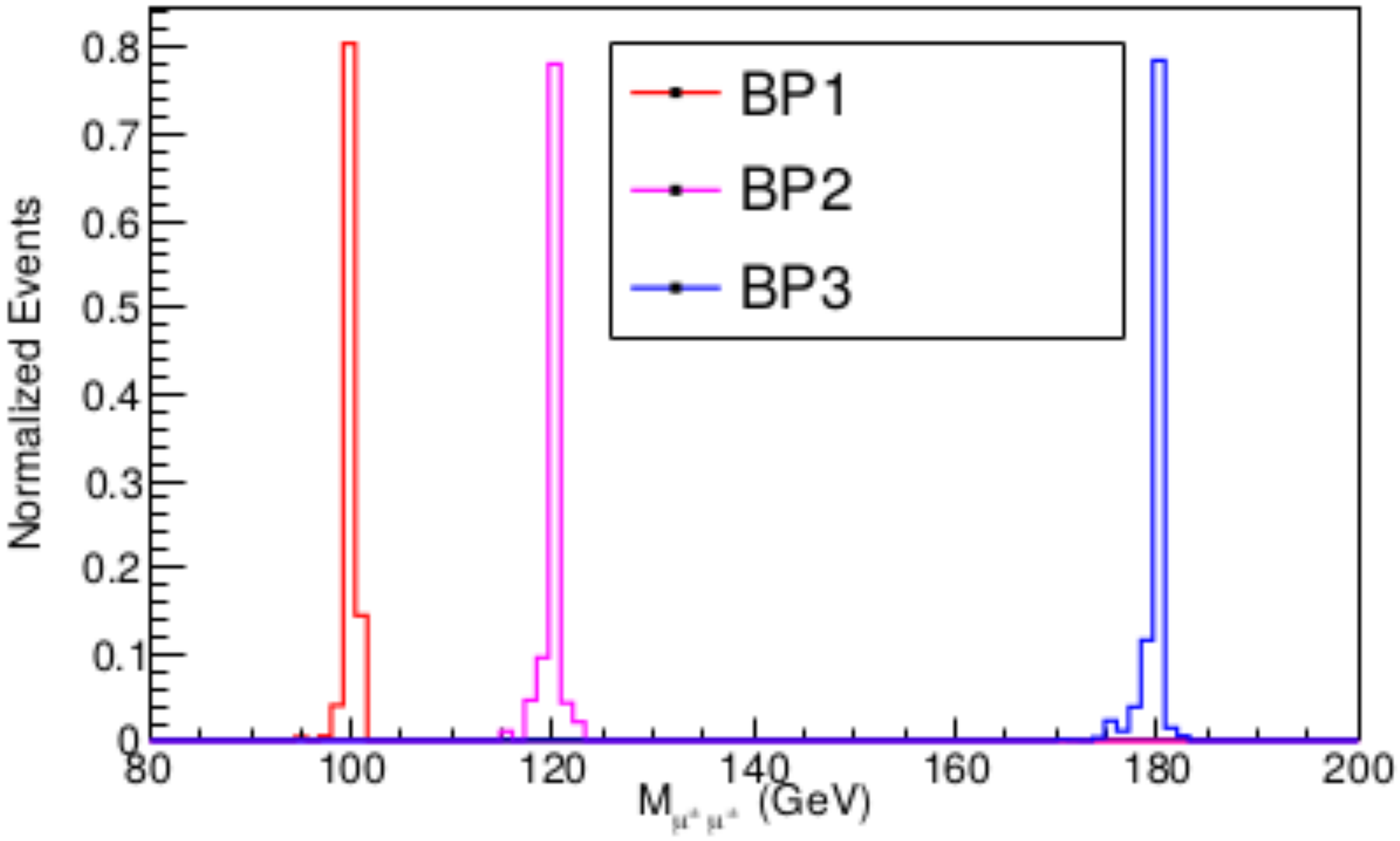

- $p_T(\ell) > 30$ GeV
- $|\eta_\ell| < 2.0$

Borrowed from [hep-ph/0508097]






- Demanding 4 muons with $|d_0| > 0.1$ mm, we can see 16984, 7014 and 18 events for BP1, BP2 and BP3 respectively at 4 $ab^{-1}$ luminosity.




| Benchmark Points | Luminosity required for 5 events after $\|d_0\| > 0.1$mm cut ($\mathcal{L}_5$) (fb$^{-1}$) |
|---|---|
| BP1 | 1.1 |
| BP2 | 2.9 |
| BP3 | 1111.1 |

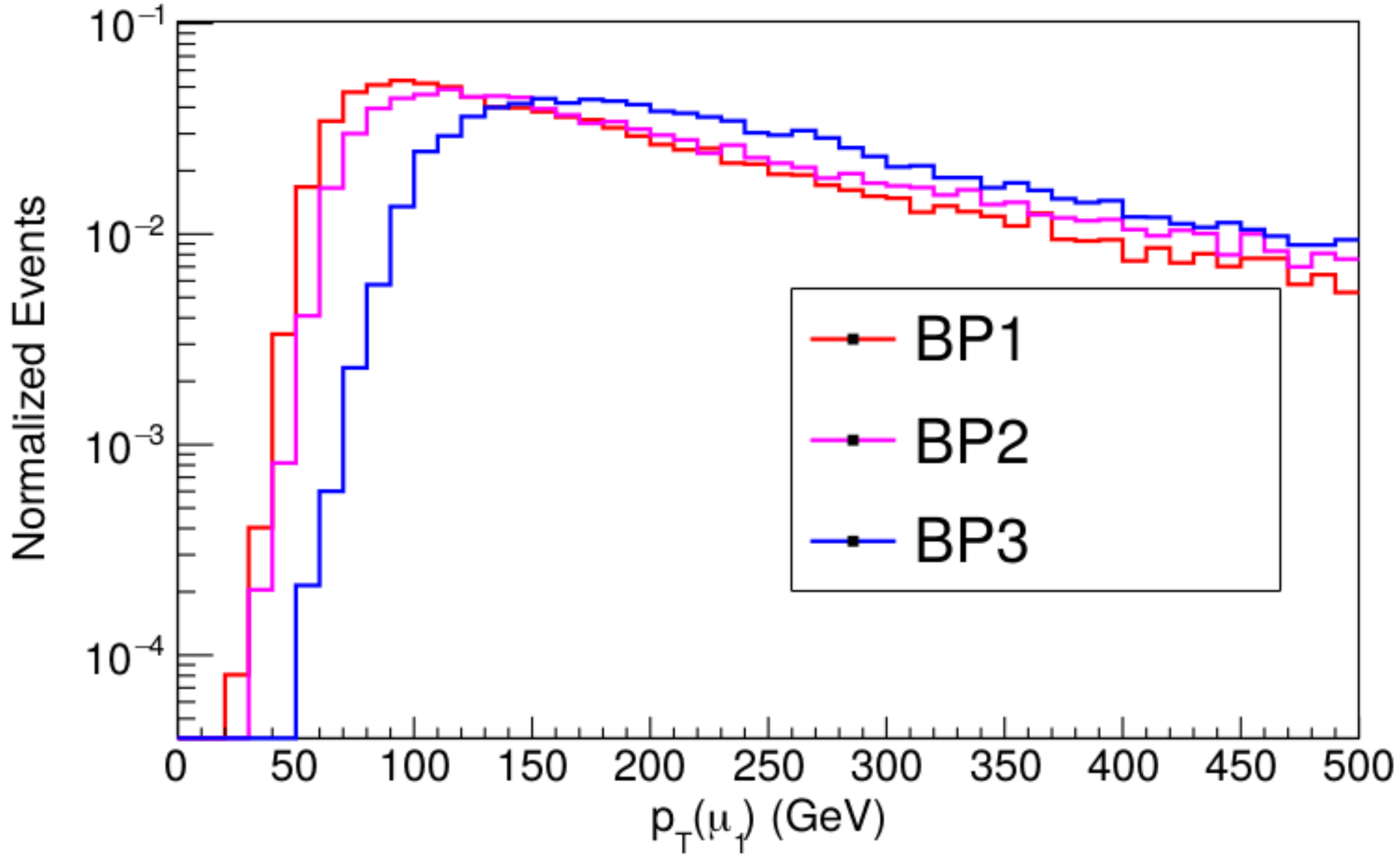
# Pair Production of the Doubly Charged Higgs at the Muon Collider with $\not{E}_T$ ($\sqrt{s} = 10$ TeV)

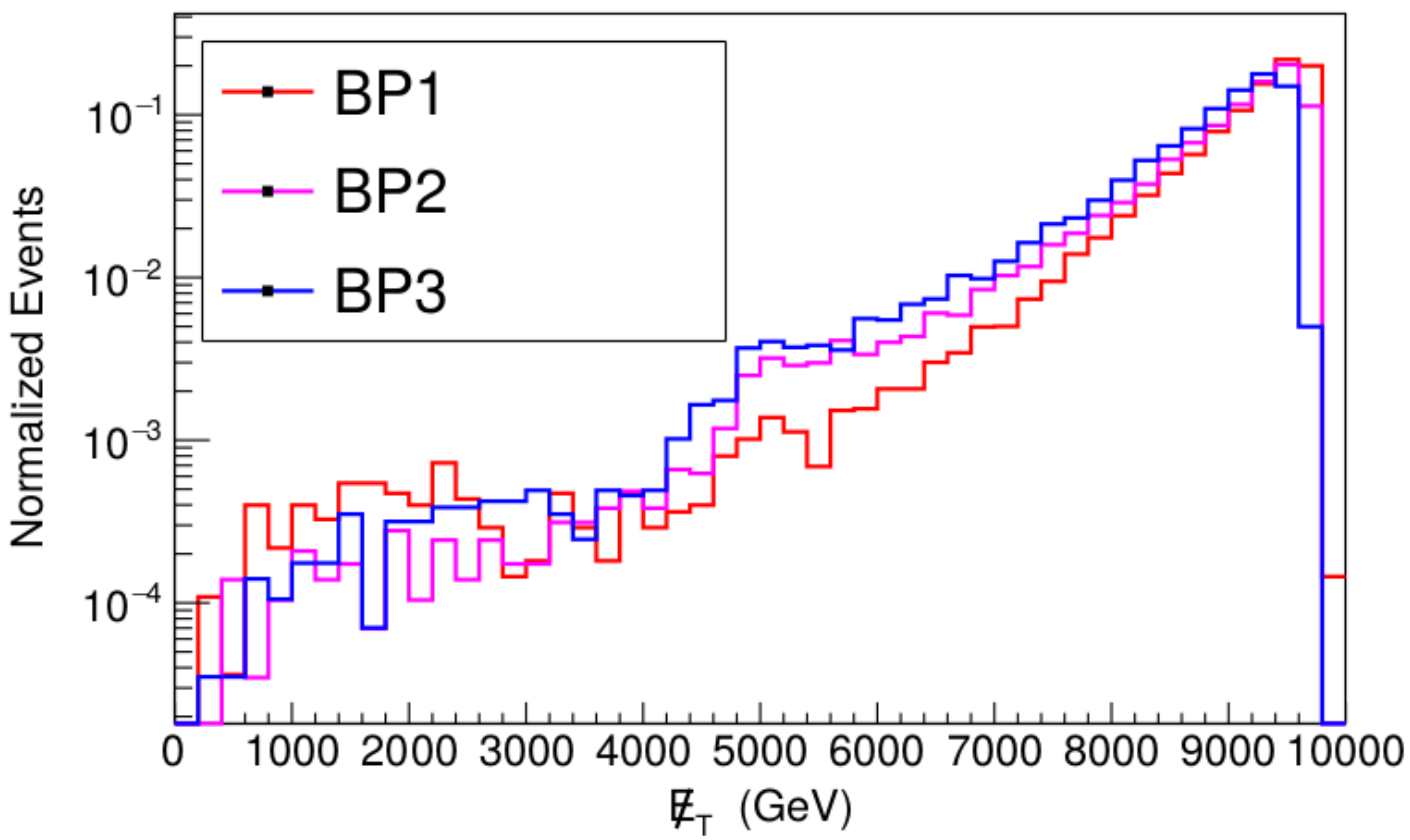
$$\mu^+\mu^- \to H^{++}H^{--}x\ y, H^{\pm\pm} \to \mu^\pm\mu^\pm$$

where $\{x, y = \mu^\pm, \nu_\ell\}$.

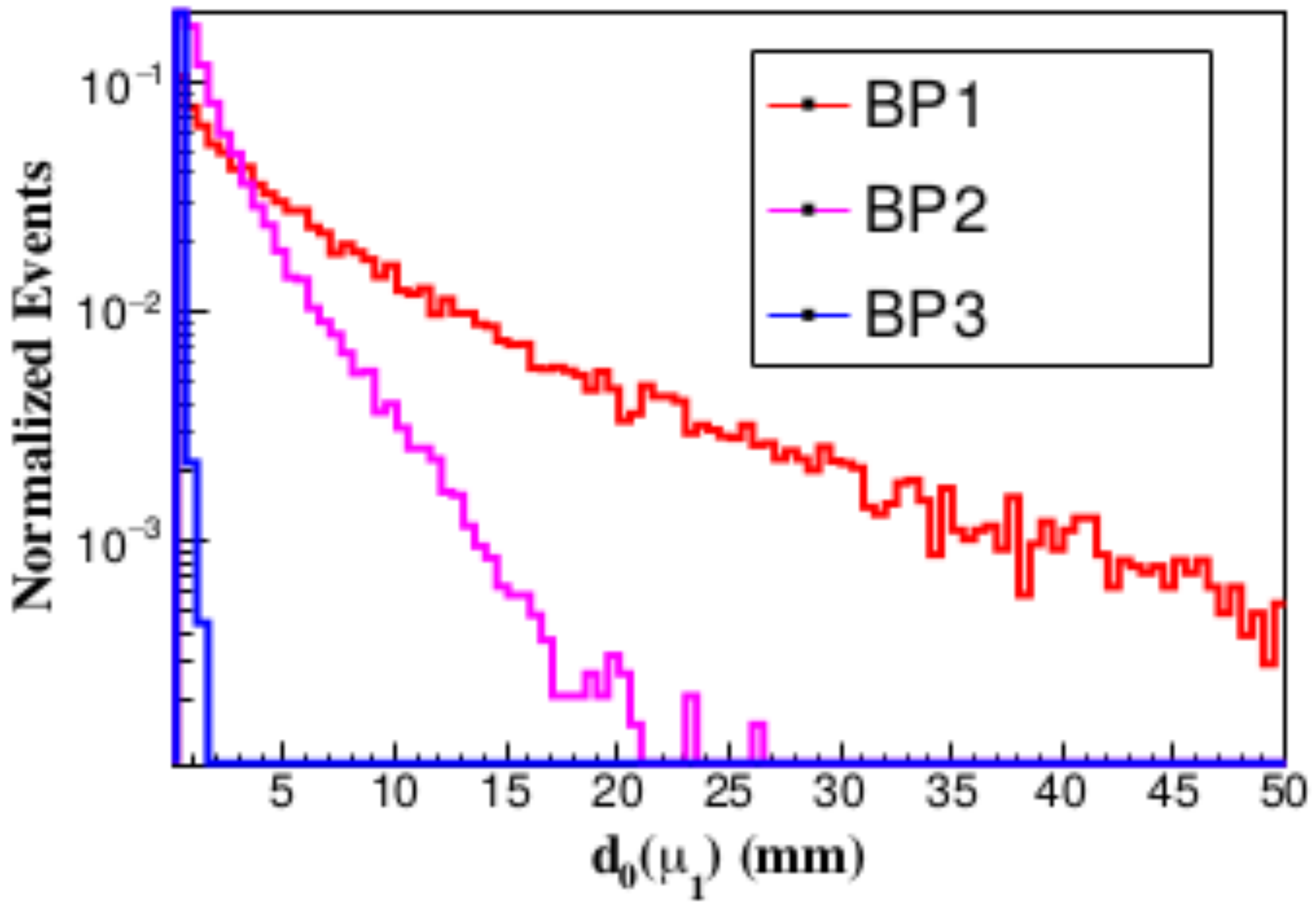
$$|\eta(\ell)| < 3.0; \quad \mathrm{p_T}(\ell) > 10\ \mathrm{GeV}; \quad \Delta\mathrm{R}_{\ell\ell} \geq 0.2.$$

| σ IMCC | BP1 | BP2 | BP3 |
|---|---|---|---|
| (fb) | 0.09 | 0.06 | 0.006 |

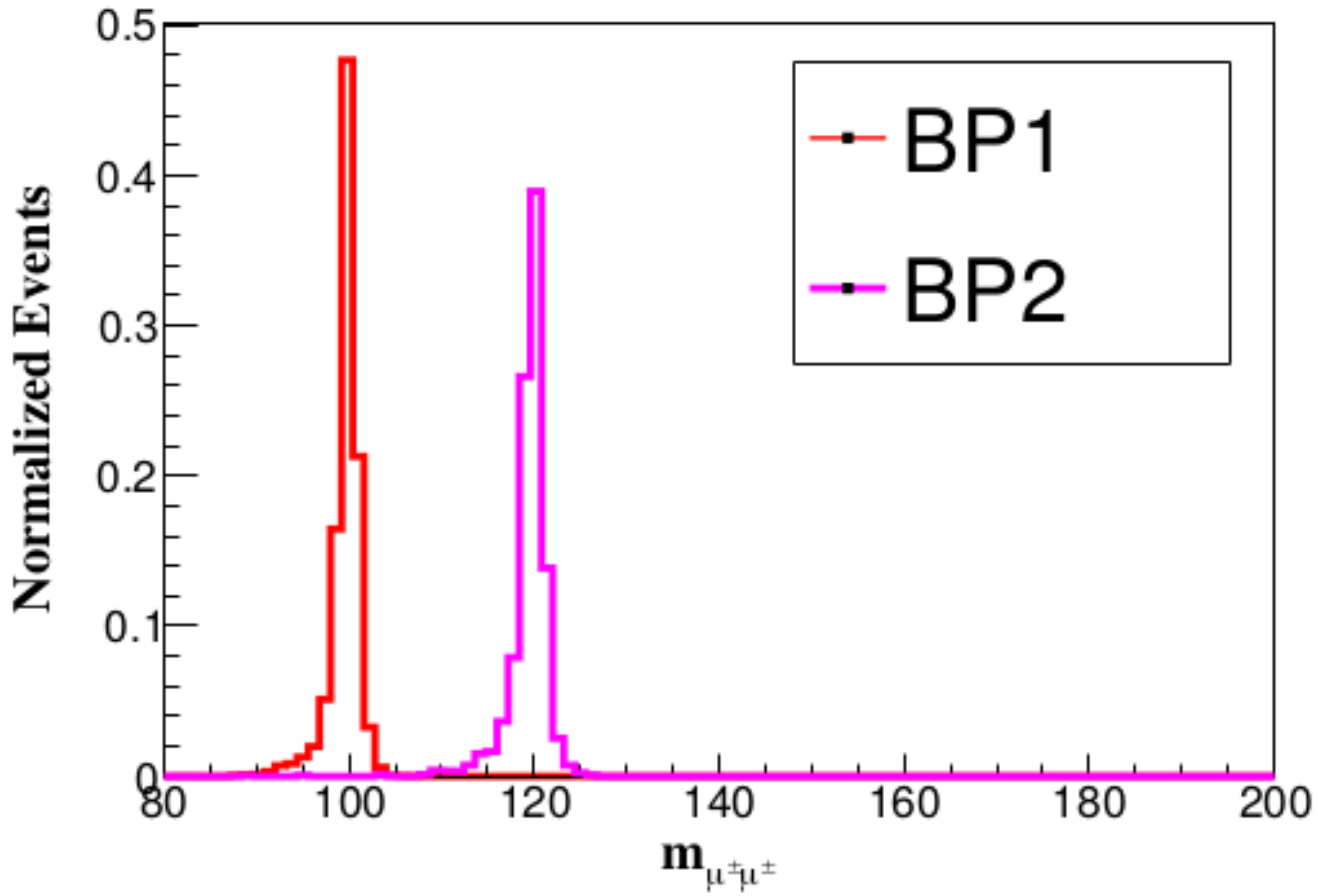



- $p_T(\ell_1) > 30$ GeV
- $\not{E}_T > 30$ GeV




- Demanding 4 muons with $|d_0| > 0.1$ mm, we can see 323 and 195 events for BP1 and BP2 respectively at 10 $ab^{-1}$ luminosity.




| Benchmark Points | $\mathcal{L}_{\rm int}$ required to see 5 events after $\lvert d_0\rvert > 0.1$mm cut ($\text{fb}^{-1}$) |
|---|---|
| BP1 | 155 |
| BP2 | 256 |

# Summary

- We investigate the discovery prospects of long-lived doubly charged scalars at future lepton colliders within the framework of the Type-II seesaw model.
- We focus on a parameter region where the doubly charged scalar behaves as a long-lived particle, satisfy all current theoretical and experimental constraints and are accessible at the ILC and a high-energy muon collider.
- Standard Model backgrounds can be effectively suppressed by exploiting displaced vertex information through a cut on the impact parameter $d_0$.
- The clean experimental environment of lepton colliders enables efficient mass reconstruction from same-sign di-muon pairs, significantly enhancing the discovery potential.
- The unique capability of future lepton colliders to explore long-lived particle signatures provides a compelling physics case for their role in probing extended scalar sectors beyond the SM.


thank you