# Collider probes of baryogenesis with maximal CP asymmetry

Keping Xie

Tsung-Dao Lee Institute & School of Physics and Astronomy,
Shanghai Jiao Tong University

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In collaboration with D. Borah, K. Cheng, A. Dasgupta, T. Han
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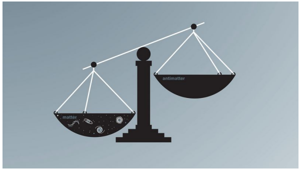
# Motivation: matter-antimatter asymmetry




- Baryon Asymmetry of the Universe (BAU) [Planck 2018, 1807.06209]:

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}.$$

- Sakharov conditions for a nonzero baryon asymmetry cannot be satisfied in the Standard Model $\Longrightarrow$ Beyond SM.
- Baryogenesis (BG) and leptogenesis are possible options.
- A typical BG at a high scale is out of reach of lab experiments.
- Low- and intermediate-scale baryogenesis can be tested via $n - \bar{n}$ oscillations or at colliders
- Proton decay strongly bounds on $\Delta(B-L) = 1$ process.
- Electroweak sphalerons can wash out $B + L$ but conserve $B - L$.
- New mechanism:

Dirac Baryogenesis

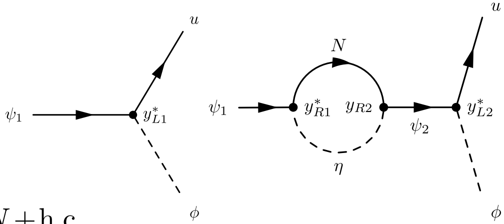
# Dirac Baryogenesis

- Similar to Dirac leptogenesis [9907562,0206177], equal and opposite CP asymmetries in the left- and right-chiral (mother) fermions
- CP asymmetries arise from the decays

$$A = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, \qquad \overset{(-)}{\Gamma} \sim \Gamma(\overset{(-)}{\psi} \to \overset{(-)}{u}\,\overset{(-)}{\phi})$$

- This can be only achieved through at least 1-loop interference
- We need at least two generations $\psi_{1,2}$, with a phase difference in the couplings
- $Z_4$ symmetry to avoid unwanted terms, also for cold dark matter

| Field | Spin | $SU(3)$ | $SU(2)_L$ | $U(1)_Y$ | $Z_4$ | $B$ |
|---|---|---|---|---|---|---|
| $\psi_{L,R}$ | 1/2 | 3 | 1 | 2/3 | $i$ | 1/3 |
| $\eta$ | 0 | 3 | 1 | 2/3 | $i$ | 1/3 |
| $N$ | 1/2 | 1 | 1 | 0 | 1 | 0 |
| $\phi$ | 0 | 1 | 1 | 0 | $i$ | 0 |




$$-\mathscr{L}_{\rm BSM} \supset y_L \bar{\psi}_L u_R \phi + y_R \bar{\psi}_R N \eta + M_\psi \bar{\psi}_L \psi_R + \frac{1}{2} M_N \bar{N}^c N + \text{h.c.}$$

# Asymmetry and branch fractions

$$A_u = \frac{\Gamma(\psi \to u\phi) - \Gamma(\bar{\psi} \to \bar{u}\bar{\phi})}{\Gamma(\psi \to u\phi) + \Gamma(\bar{\psi} \to \bar{u}\bar{\phi}) + \Gamma(\psi \to N\eta) + \Gamma(\bar{\psi} \to N\bar{\eta})} \sim \mathscr{B}^{(0)}(\psi \to u\phi)\delta_u$$

$$\delta_u = \frac{\Gamma(\psi \to u\phi) - \Gamma(\psi \to u\phi)}{\Gamma(\psi \to u\phi) + \Gamma(\psi \to u\phi)} \sim \sum_j 2\frac{\mathrm{Im}[y^*_{R1} y_{Rj} y_{Lj} y^*_{L1}]}{|y_{R_1}|^2 |y_{L1}|^2} \frac{\Gamma(\psi_1 \to N\eta) M_{\psi_j}(M^2_{\psi_1} - M^2_{\psi_j})}{(M^2_{\psi_1} - M^2_{\psi_j}) + M^2_{\psi_j}\Gamma^2_{\psi_j}}.$$

- The asymmetry $\delta_u$ can be maximized with a closed degeneracy,

$$\frac{\Delta M^2_\psi}{M^2_\psi} \sim \frac{2\Delta M_\psi}{M_\psi} = \frac{\Gamma_\psi}{M_\psi}$$

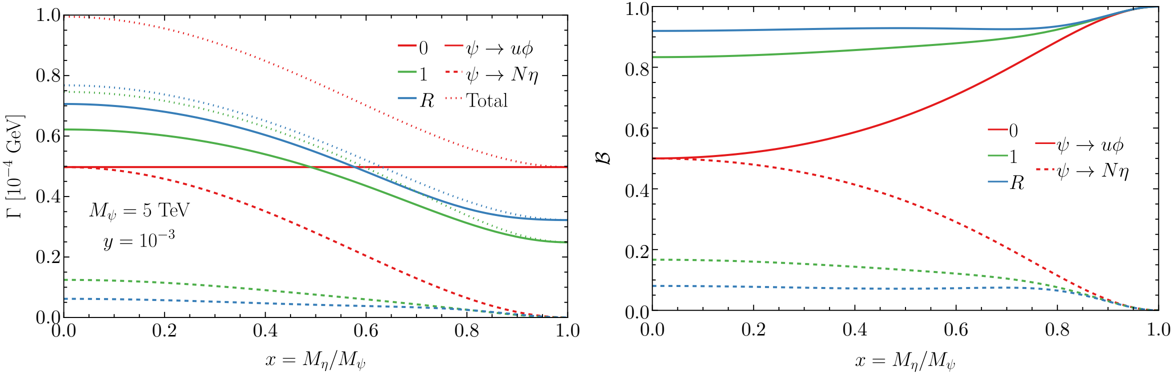
  which gives

$$\delta_u^{\max} \sim \frac{\mathrm{Im}[y^*_{R1} y_{Rj} y_{Lj} y^*_{L1}]}{|y_{R1}|^2 |y_{L1}|^2} \mathscr{B}^{(0)}(\psi_1 \to N\eta).$$

- For simplicity, we take $y_{L1} = y_{L2} = iy_{R1} = y_{R2} = y$, which gives

$$\delta_u \sim \mathscr{B}^{(0)}(\psi_1 \to N\eta),\ \delta_\eta \sim -\mathscr{B}^{(0)}(\psi_1 \to u\phi).$$

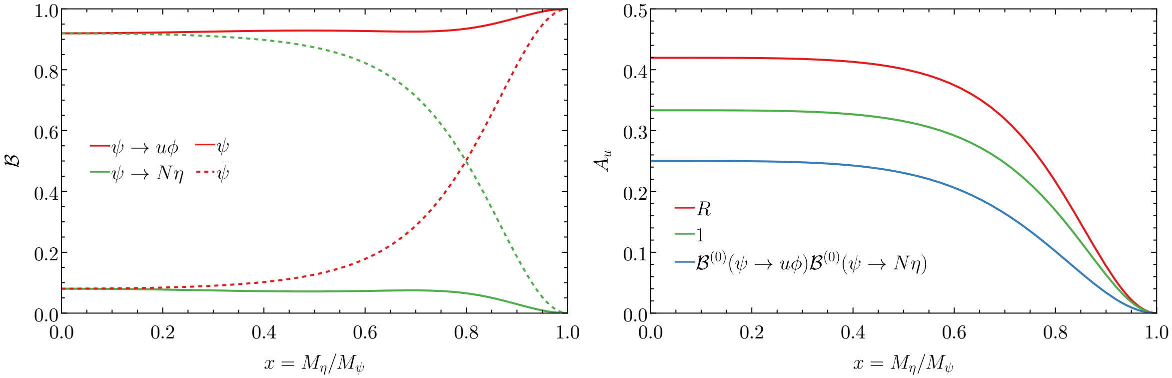
# High-order corrections to decay width and branch fraction




Iteratively determine the corrections to decay width $\Gamma(\psi \to u\phi)$

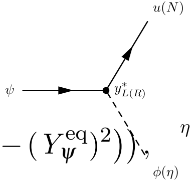
- The leading (0-th) order: $\Gamma^{(0)} = \frac{|y_{Li}|^2}{32\pi} M_\psi$
- Next-to-leading (1-th) order correction: $\Gamma^{(1)} = \frac{5}{4}\Gamma^{(0)}$
- Resummation to all orders: $\Gamma^{(R)} \sim 1.420\Gamma^{(0)}$

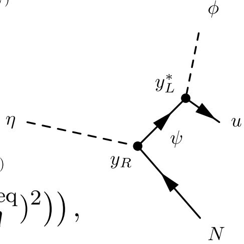
# Higer-order corrected asymmetry




- Largely, $\psi \to u\phi$, while $\bar{\psi} \to N\bar{\eta}$
- A sizable asymmetry can be achieved around $A_u \sim 0.42$.

# Bayron asymmetry evolution

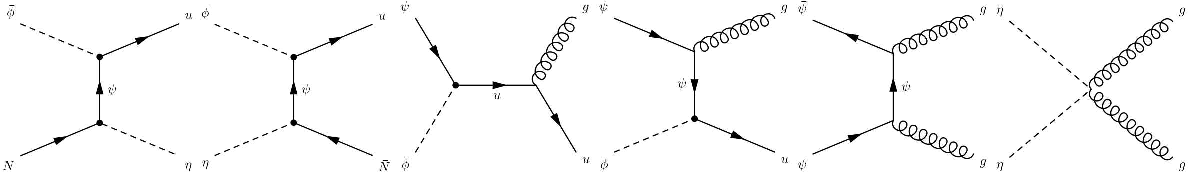


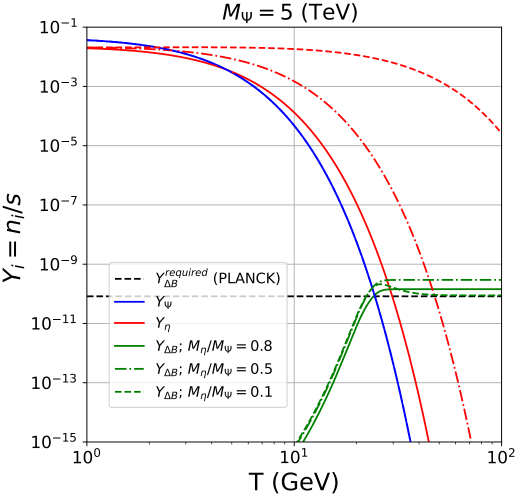

$$\frac{dY_\psi}{dz} = -\frac{1}{Hz}\left(\langle\Gamma_{\text{total}}\rangle(Y_\psi - Y_\psi^{\text{eq}}) + s\langle\sigma(\psi\bar{\psi}\to gg)v\rangle\left(Y_\psi^2 - (Y_\psi^{\text{eq}})^2\right)\right),$$

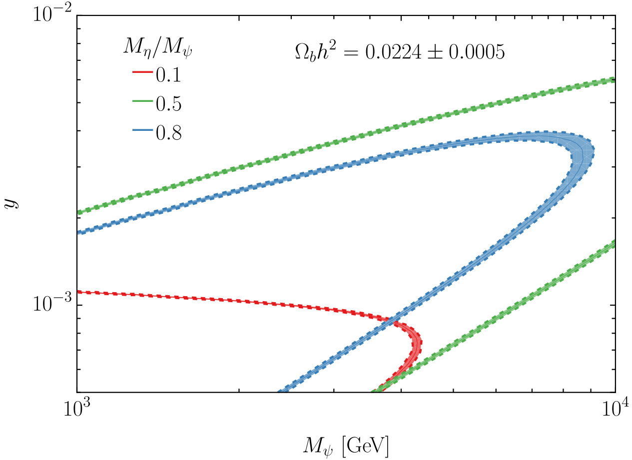
$$\frac{dY_\eta}{dz} = -\frac{1}{Hz}\left(\langle\Gamma(\eta\to u\phi N)\rangle(Y_\eta - Y_\eta^{\text{eq}}) + s\langle\sigma(\eta\bar{\eta}\to gg)v\rangle\left(Y_\eta^2 - (Y_\eta^{\text{eq}})^2\right)\right),$$

$$\frac{dY_{\Delta B}}{dz} = \frac{1}{Hz}\left[A_u\langle\Gamma(\psi\to u\phi)\rangle(Y_\psi - Y_\psi^{\text{eq}}) - Y_{\Delta B}\frac{Y_\psi^{\text{eq}}}{Y_{\Delta B}^{\text{eq}}}\left(\langle\Gamma(\psi\to u\phi)\rangle + s\langle\sigma(\psi\phi\to gu)v\rangle\right)\right.$$
$$\left. - Y_{\Delta B}\frac{Y_\eta^{\text{eq}}}{Y_{\Delta B}^{\text{eq}}}\left(\langle\Gamma(\eta\to u\phi N)\rangle + s\langle\sigma(\eta\phi\to Nu)v\rangle + s\langle\sigma(\eta N\to\phi u)v\rangle\right)\right].$$



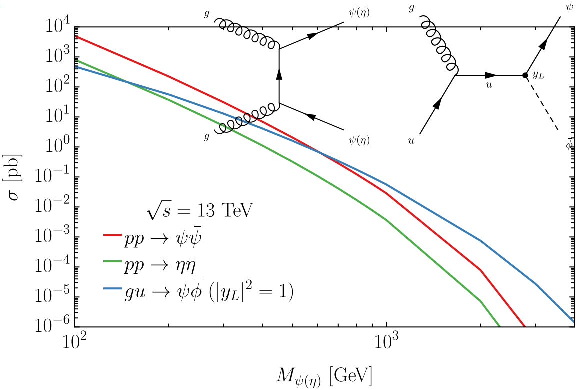
# Observed baryon asymmetry

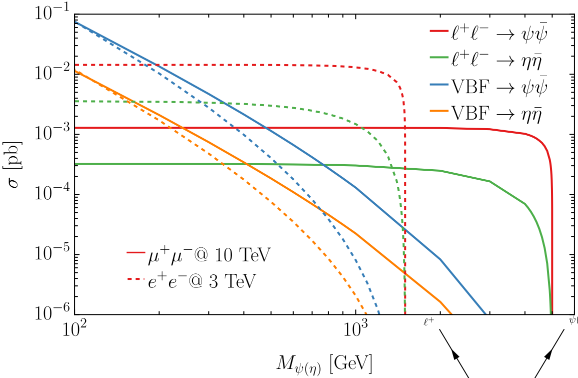


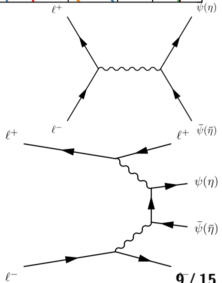




- For a demonstration, we fix $M_\psi = 5$ TeV and $M_\eta/M_\psi = 0.1, 0.5, 0.8$.
- The required $M_\psi$ can be lower down to TeV scale, with Yukawa coupling around $y \sim 10^{-3}$

# Production at colliders: LHC and muon colliders

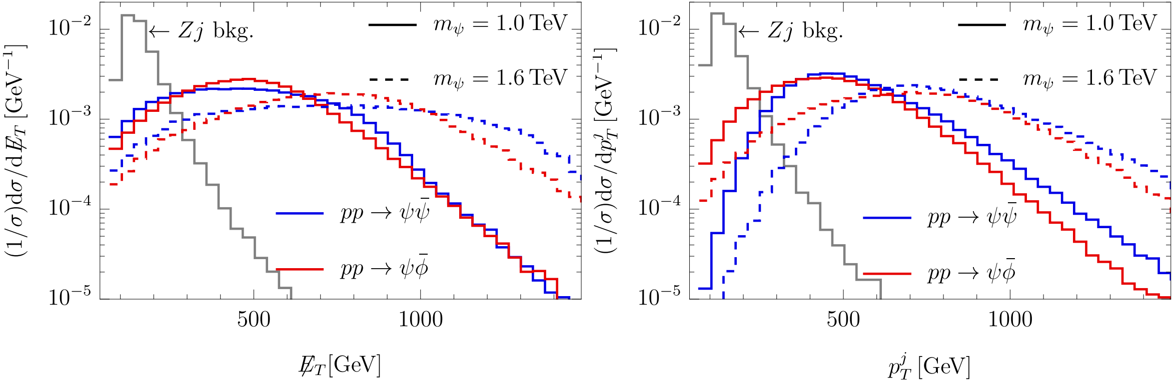


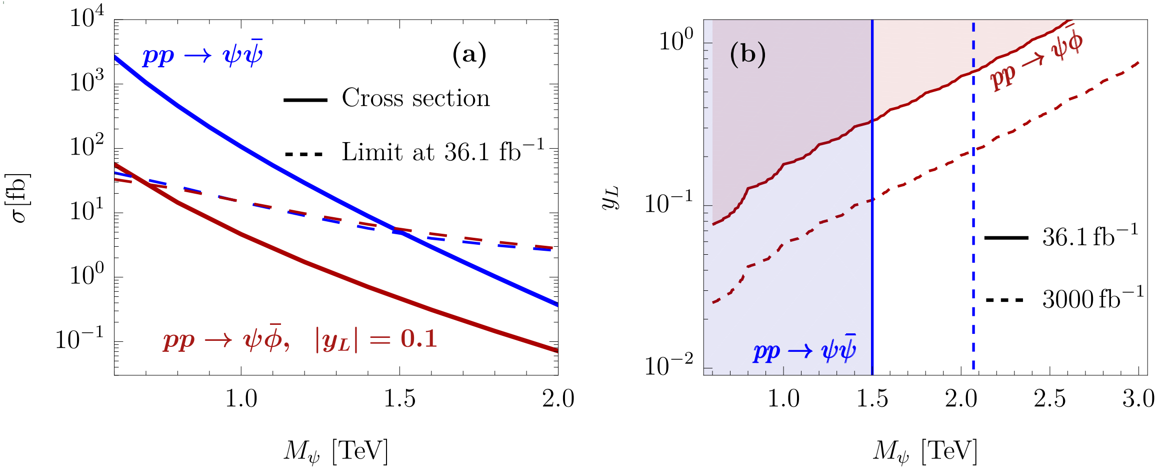
- Both $\psi$ and $\eta$ can be produced at the LHC and muon colliders.
- At the LHC, we have pair and single production of the $\psi$.
- At the MuC, we have annihilation and Vector-boson fusion.

# A LHC signal: monon-jet



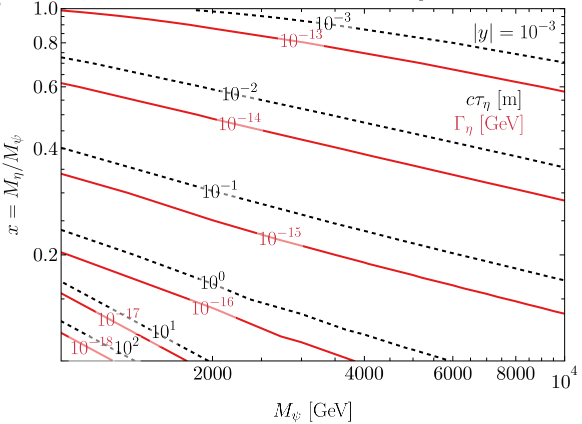

- Either through a single $\psi$ production or $\psi\bar{\psi}$ production with $\bar{\psi} \to N\bar{\eta}$ decay.
- Background mainly comes from $(Z \to \nu\bar{\nu})j$.
- Signal populates at high $\not{E}_T$ or $p_T^j$.

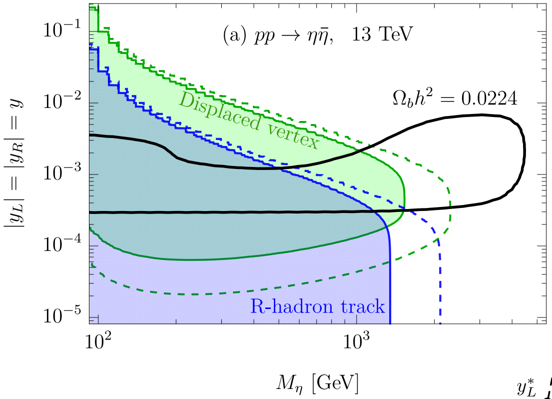
# Constraints on the parameter space

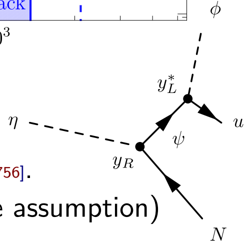



- LHC searches for an energetic jet with missing $\not{E}_T$ [ATLAS, 1711.03301, 2102.10874]
- We take the same pre-selection cuts with the same histogram binning [ATLAS, 2102.10874]
- Constraints on $M_\psi$ (pair production) as well as coupling $y$ (single production).

# Long-lived features of $\eta$

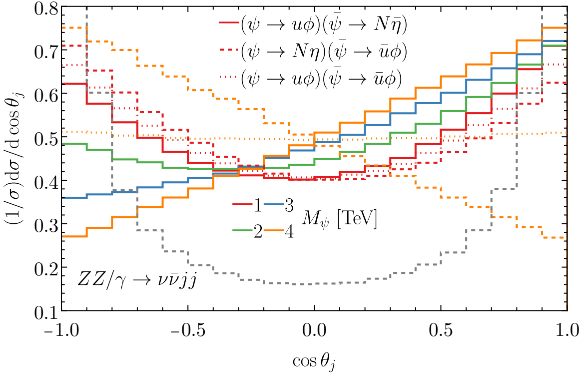


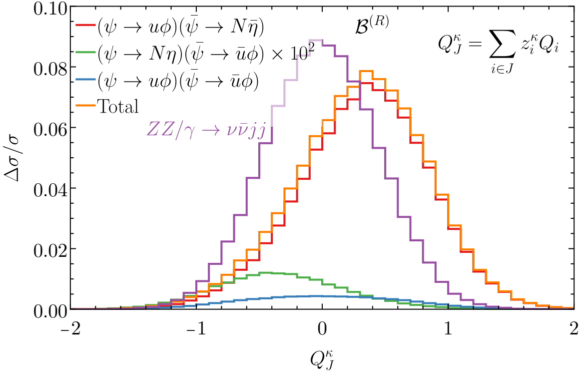




- 3-body decay of $\eta$: $\Gamma_\eta \sim |y|^2 M_\eta^3 / M_\psi^2 \to$ long-lived.
- Searches for displaced vertex as well as the colored tracks R-hadron [1008.2756].
- 5-event constraints on the $M_\eta$ as well as the coupling (a background-free assumption)

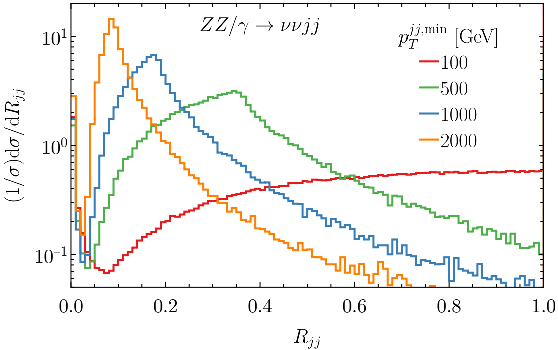
# A smoking gun signal at muon colliders: asymmetry

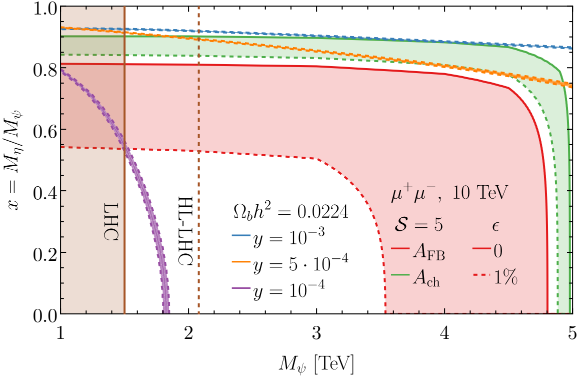



- A backward-forward asymmetry $A_{\mathrm{FB}}$ will be generated through the $Z$ coupling
- The asymmetry $\delta_u$ will generate a charge asymmetry $A_{\mathrm{ch}}$, if we can measure the jet charge.

# Faked background and sensitivity




- A faked background can be generated through $(Z \to \nu\bar{\nu})(Z/\gamma \to jj)$ when the visible two jets become collimated due to the large boost (behaving as 1 jet)
- The background will not give $A_{\rm FB}$ nor $A_{\rm ch}$.
- Sensitivity measure $\mathscr{S} = \frac{N_+ - N_-}{\sqrt{N_{\rm tot} + \epsilon^2 N_{\rm tot}^2}} = 2(5)$ where $N_{\rm tot} = N_+ + N_- + N_{\rm SM}$.

# Summary

- We have proposed a Dirac Baryogenesis model, which can be tested at colliders.
- Equal and opposite CP asymmetries in the left- and right-chiral (mother) fermions
- CP asymmetries arise from the $\psi$ and $\bar{\psi}$ decays (at least two generations)
- We have parameter space around $M_\psi \sim$ a few TeV and coupling $y \sim 10^{-3}$, which can explain the observed baryon asymmetry
- It gives a mono-jet signal, which can be tested at the LHC
- The daughter colored particle $\eta$ can be searched through displaced vertices and colored tracks (R-hadron)
- Forward-background asymmetry and charged asymmetry can be directly tested at future muon colliders.

# The interference for the nearly degenerate resonance

A small mass splitting $\Delta M_\psi = \alpha\Gamma$ where $\alpha \sim 1/2$

- Single production

$$\sum_i \sigma(ug \to \psi_i \phi \to u\phi\phi) = 2\left(1 + \frac{1}{1+\alpha^2}\right)\sigma(ug \to \psi\phi \to u\phi\phi),$$

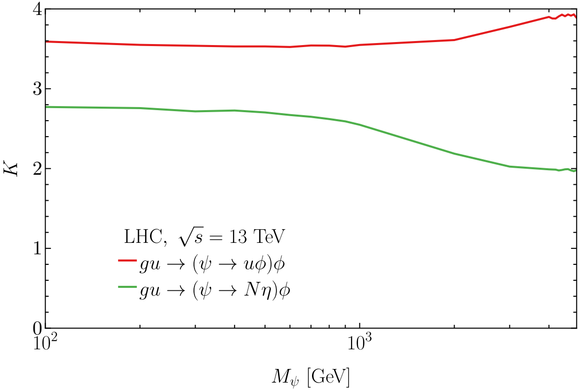
$$\sum_i \sigma(ug \to \psi_i \phi \to N\eta\phi) = 2\left(1 + \frac{\alpha}{1+\alpha^2}\right)\sigma(ug \to \psi\phi \to N\eta\phi).$$

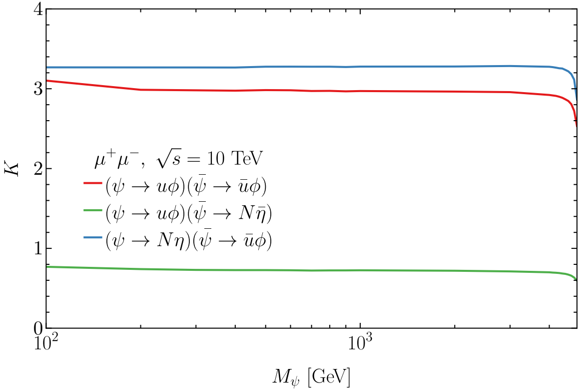
- Pair production

$$\sum_{i=1,2} \sigma(\psi_i(\to u\phi)\bar{\psi}_i(\to N\bar{\eta})) = 2\left(1 - \frac{2\alpha}{(1+\alpha^2)^2}\right)\sigma(\psi(\to u\phi)\bar{\psi}(\to N\bar{\eta})),$$

$$\sum_{i=1,2} \sigma(\psi_i(\to N\eta)\bar{\psi}_i(\to \bar{u}\phi)) = 2\left(1 + \frac{2\alpha}{(1+\alpha^2)^2}\right)\sigma(\psi(\to N\eta)\bar{\psi}(\to \bar{u}\bar{\phi})).$$

# Numerical test




- Single production $K \simeq 3.6$ and 2.8;
- double production $K \simeq 0.72$ and 3.28.