4321 at the LHC

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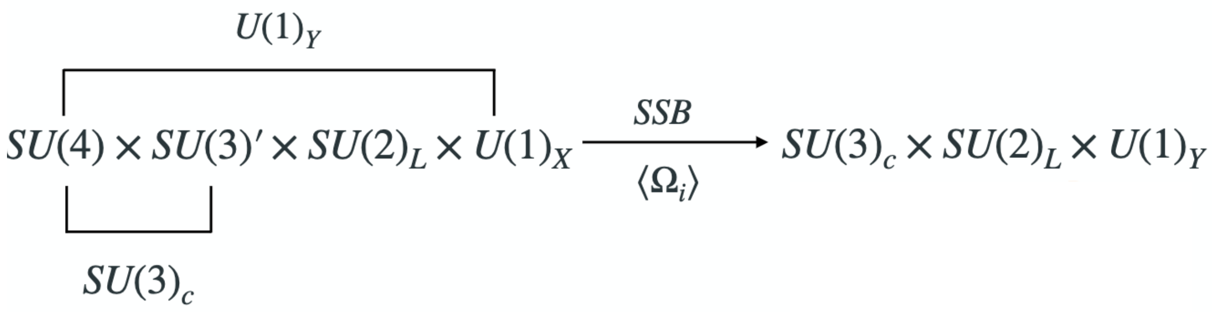
Physics of the Flavourful Universe, 21-24 September 2021

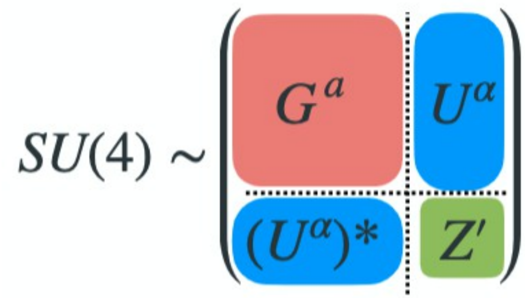
Portoroz, Slovenija

'4321' models

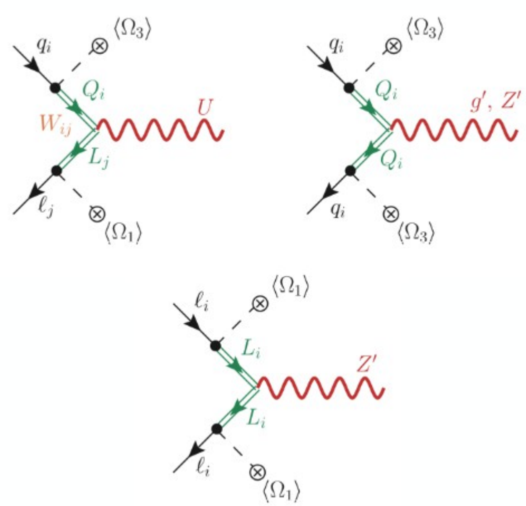
[See Claudia's talk *and refs within*]

Vector leptoquark $U_1^\mu \sim (\mathbf{3}, \mathbf{1})_{2/3}$





Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
q_L^i	**1**	**3**	**2**	1/6
u_R^i	**1**	**3**	**1**	2/3
d_R^i	**1**	**3**	**1**	−1/3
ℓ_L^i	**1**	**1**	**2**	−1/2
e_R^i	**1**	**1**	**1**	−1/2
$\chi_{L,R}^i$	**4**	**1**	**2**	0
H	**1**	**1**	**2**	1/2
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	−1/2
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	1/6
Ω_{15}	**15**	**1**	**1**	0



Rich Gauge
& fermion sector

4321 models lead to new states living at the TeV scale!
Generic prediction: new effects in 3rd generation final states

LHC ballpark!

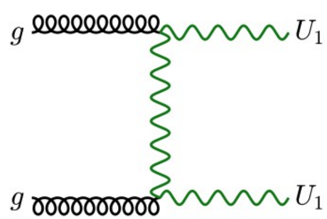
Vector leptoquark $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

$$\mathcal{L}_U^{\rm int} = \frac{g_U}{\sqrt{2}} (U_1^\mu J_\mu^U + {\rm h.c.})$$

$$J_\mu^U = \beta_L^{i\alpha} (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_R^{i\alpha} (\bar{d}_R^i \gamma_\mu e_R^\alpha)$$

Broken $U(2)^5$ flavor symmetry: $|\beta_L^{d\tau, s\mu}| \ll |\beta_L^{s\tau, b\mu}| \ll \beta_L^{b\tau} = 1$

- LQ pair production (QCD):

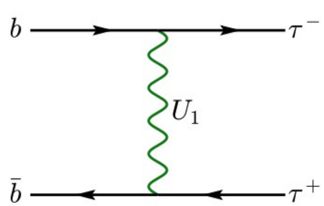


$U_1 \to b\tau^+, \, t\bar{\nu}$

${\rm Br}(U_1 \to b\tau) \approx 0.5$

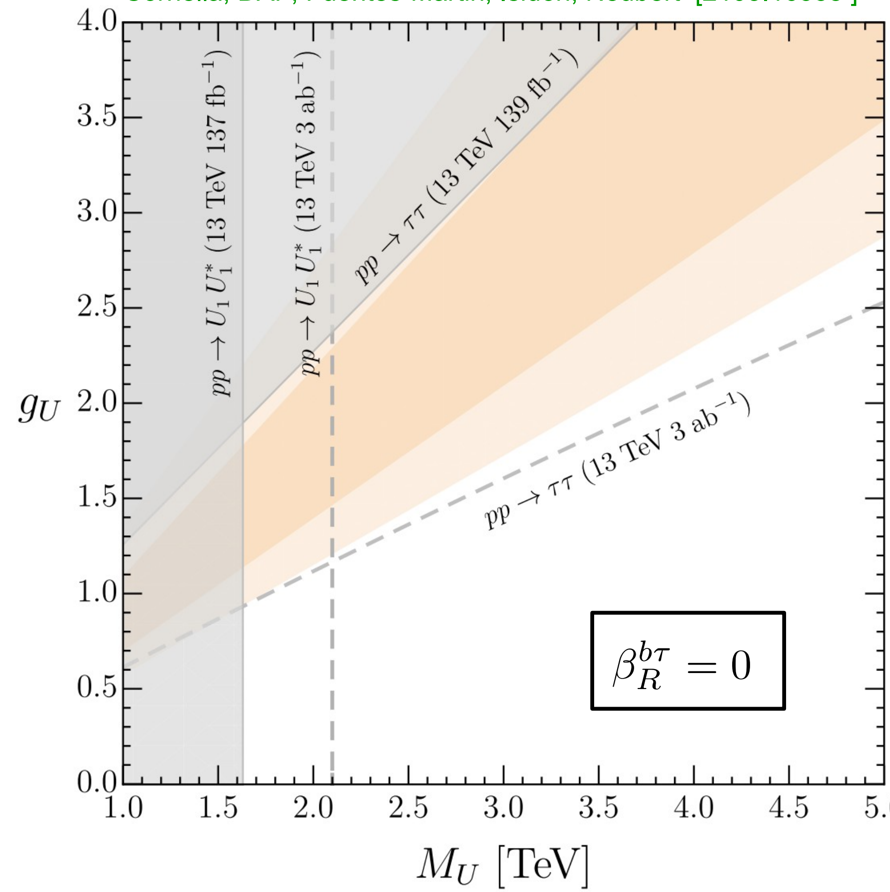
$pp \to U_1^+ U_1^- \to b\tau \, t\nu$ CMS 2012.04178

- Drell-Yan t-channel exchange: $\tau\tau$-tails



(Recast) ATLAS EXPERIMENT 2002.12223

Cornella, DAF, Fuentes-Martin, Isidori, Neubert [2103.16558]



Vector leptoquark $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

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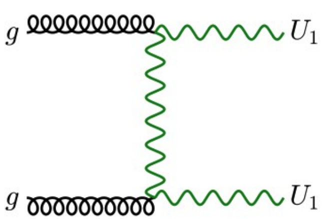

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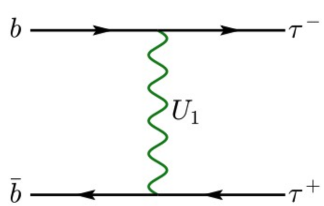

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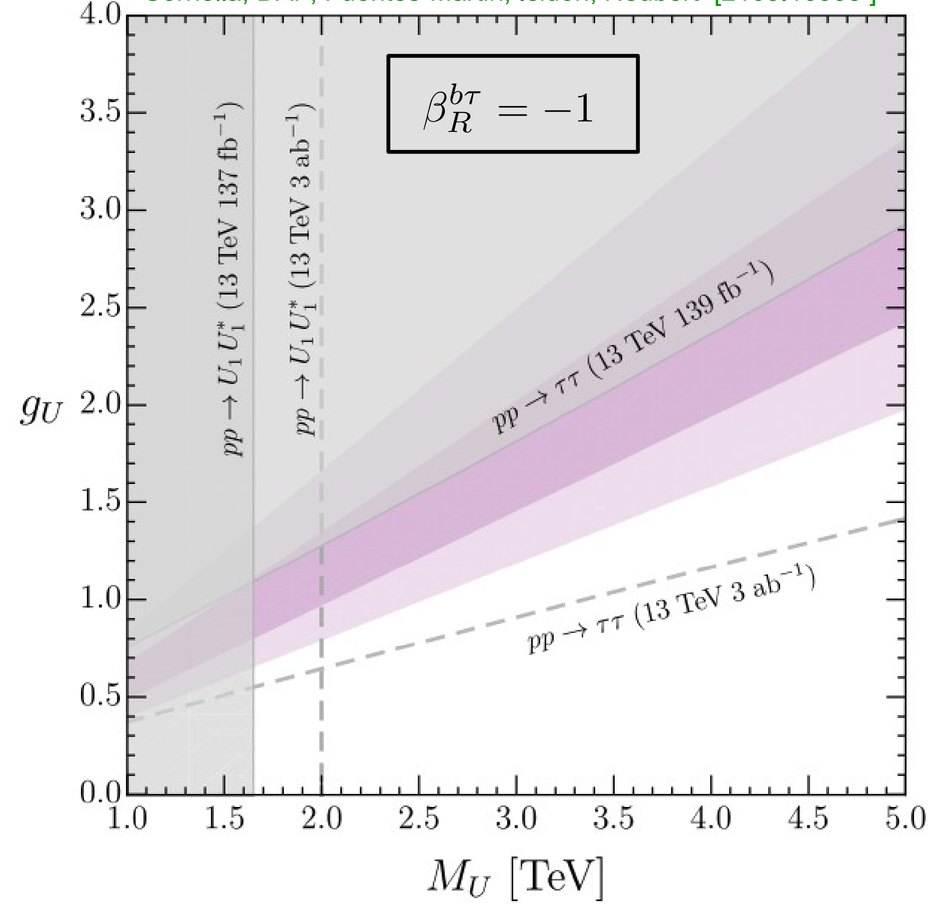


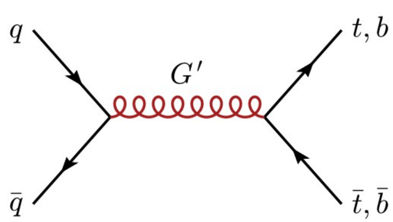
Coloron $G' = (\mathbf{8}, \mathbf{1}, 0)$

Di Luzio et al. [1808.00942]
Baker et al. [1901.10480]
Cornella et al. [2103.16558]

$$\mathcal{L}^{\rm int}_{G'} = g_{G'}\, G'^{\,a\,\mu} \left(\kappa_q^{ij}\, \bar{q}_L^i\, T^a \gamma_\mu\, q_L^j + \kappa_u^{ij}\, \bar{u}_R^i\, T^a \gamma_\mu\, u_R^j + \kappa_d^{ij}\, \bar{d}_R^i\, T^a \gamma_\mu\, d_R^j \right)$$

$g_{G'} \approx g_U$

(approx) flavor diagonal $\quad \kappa^{33}_{q,u,d} = 1 \quad \kappa^{11}_{u,d} = \kappa^{22}_{u,d} = -\dfrac{g_s^2}{g_{G'}^2} \quad \kappa^{11}_q = \kappa^{22}_q = \sin^2\theta_Q - \dfrac{g_s^2}{g_{G'}^2}$



Valence quarks dominate production

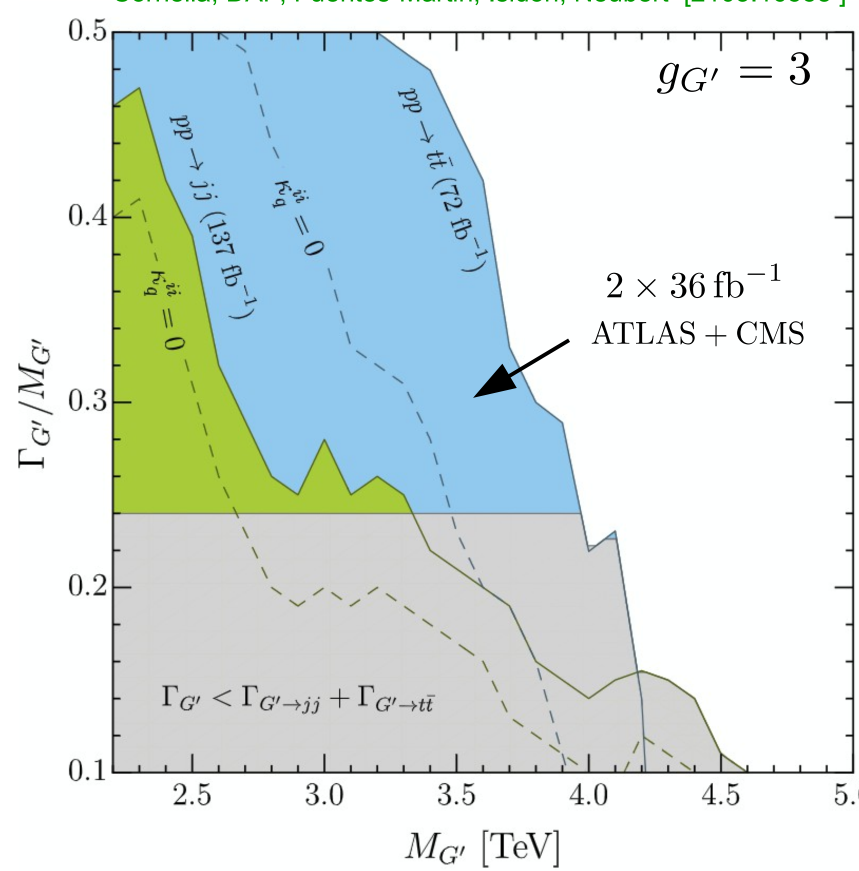
- Recast of dijet & ditop searches

- broad $pp \to jj$ resonance
- $d\sigma/dm_{t\bar{t}}$ measurment

CMS-PAS-TOP-18-013
[1801.02052]
[1906.0320]

Decay width taken as free param

Cornella, DAF, Fuentes-Martin, Isidori, Neubert [2103.16558]



Best high-pT limits on the 4321 model!

Vector-like fermions

4321 fermion bi-fundamental $\Psi = (Q, L)^T \sim (\mathbf{4}, \mathbf{1}, \mathbf{2}, 0)$

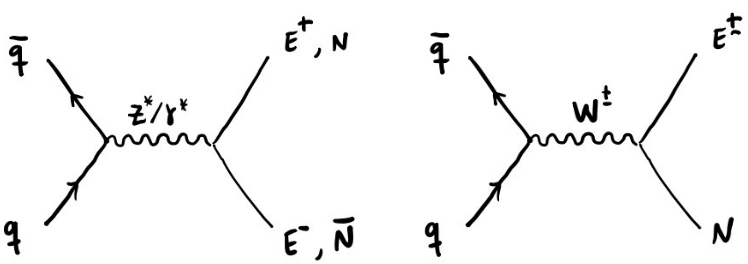
$$\begin{cases} Q \sim (\mathbf{3}, \mathbf{2}, 1/6) & Q = \begin{pmatrix} U \\ D \end{pmatrix} \\ L \sim (\mathbf{1}, \mathbf{2}, -1/2) & L = \begin{pmatrix} N \\ E^{\pm} \end{pmatrix} \end{cases}$$

vector-like lepton can't be too heavy! $m_L \sim 1\,\text{TeV}$

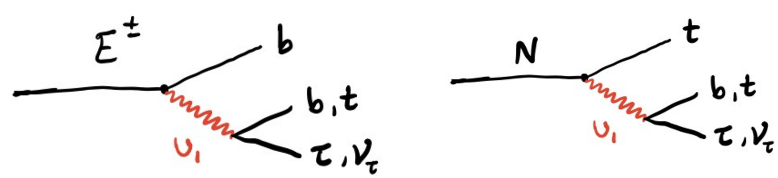
$$\mathcal{L}_U^{\text{int}} \supset \frac{g_U}{\sqrt{2}} U_\mu \left[\beta_L^{QL} (\bar{Q}_L \gamma^\mu L_L) + \beta_R^{QL} (\bar{Q}_R \gamma^\mu L_R) + \beta_L^{Q\tau} (Q_L \gamma^\mu \ell_L^3) + \beta_L^{3L} (q_L^3 \gamma^\mu L_L) \right] + \text{h.c.}$$

$$\mathcal{L}_{Z'}^{\text{int}} \supset -\frac{3 g_{Z'}}{2\sqrt{6}} Z'_\mu \left[\zeta_L^{LL} (\bar{L}_L \gamma_\mu L_L) + \zeta_R^{LL} (\bar{L}_R \gamma_\mu L_R) \right]$$

For now, we only focus on electroweak pair production at LHC... $pp \to E^+ E^-,\, N\bar{N},\, E^{\pm} N$



3rd gen decays

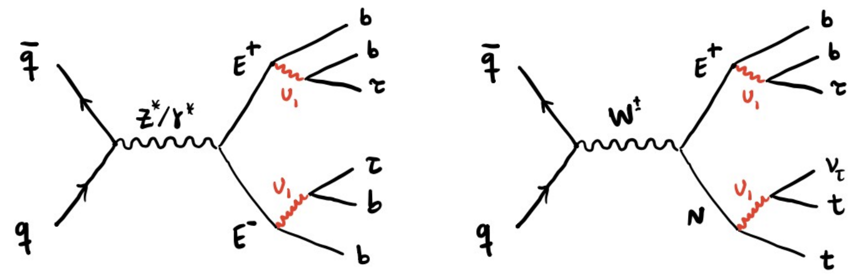


Currently no searches for heavy lepton decaying into 3rd generation

See Di Luzio et al. [1808.00942]
for more details

New search for vector-like leptons

K. Cormier, DAF, J. Fuentes-Martin, V. Mikuni [work in progress]



- Fairly generic search for pair produced heavy Lepton doublet decaying into 3rd gen fermions

- signal categories:

tau multiplicity	production + decay mode	final state
$0\,\tau$	$EE \to b(t\nu_\tau)b(t\nu_\tau)$	$4b+4j+2\nu$
	$EN \to b(t\nu_\tau)t(t\nu_\tau)$	$4b+6j+2\nu$
	$NN \to t(t\nu_\tau)t(t\nu_\tau)$	$4b+8j+2\nu$
$1\,\tau$	$EE \to b(b\tau)b(t\nu)$	$4b+2j+\tau+\nu$
	$EN \to b(t\nu_\tau)t(b\tau)$	$4b+4j+\tau+\nu$
	$EN \to b(b\tau)t(t\nu_\tau)$	$4b+4j+\tau+\nu$
	$NN \to t(b\tau)t(t\nu_\tau)$	$4b+6j+\tau+\nu$
$2\,\tau$	$EE \to b(b\tau)b(b\tau)$	$4b+2\tau$
	$EN \to b(b\tau)t(b\tau)$	$4b+2j+2\tau$
	$NN \to t(b\tau)t(b\tau)$	$4b+4j+2\tau$

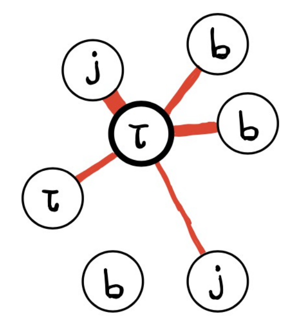
Event selection:

- Light lepton veto
- $p_T(j_1, j_2, j_3, j_4) > (80, 65, 50, 50)\,\mathrm{GeV}$
- $N_b \geq 3$
- $H_T > 400\,\mathrm{GeV}$

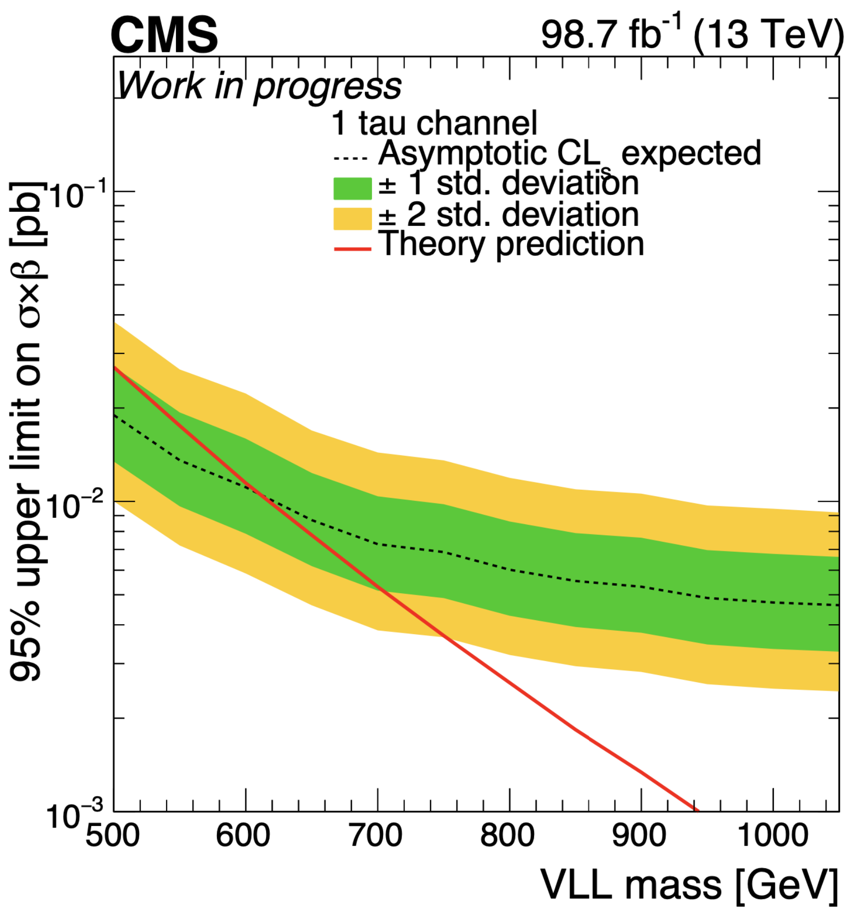
Main backgrounds: top-pairs and fake-taus

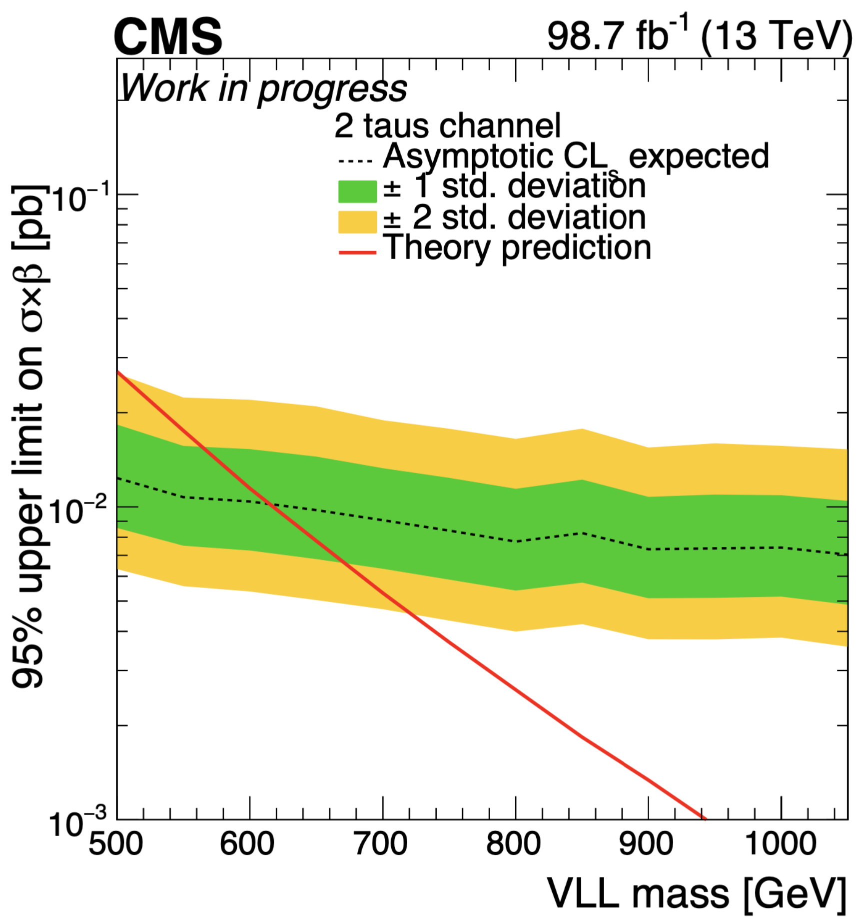
- Analysis using Graph neural network (GNN): Attention-based Cloud Network (ABCNet) [2001.05311]

- Trained on low level observables $\log(p_T)$, η, ϕ, Q



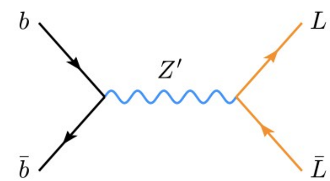
Expected limits (EW prod. only)





Combining all channels: $m_L > 700\,\mathrm{GeV}$

Limits will become more stringent once we include Z'



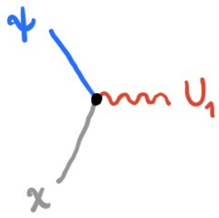
Majorana Dark Matter & B-anomalies

Baker, DAF, Trifinopoulos 2109.08689

- Setup: $G_{\rm NP} \xrightarrow{\langle\Omega\rangle} G_{\rm SM} \otimes \mathbb{Z}_2$ ------- or any other stabilizing symmetry

  - Gauge sector: $U_1\,, Z'\,, ...$ $\quad U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$ (mediates B-anomalies)
  - Dark sector: $\mathbb{Z}_2$ odd vector-like fermion multiplet

$$X = \chi \oplus \psi \oplus ... \quad \begin{cases} \chi \sim (\mathbf{1}, \mathbf{1}, 0) & \text{dark mater candidate} \\ \psi \sim (\mathbf{3}, \mathbf{1}, 2/3) & \text{coloured partner} \end{cases}$$



- Dark sector Lagrangian for Majorana DM:

$$\mathcal{L}_{\rm eff}^{\rm DS} = \overline{X}(i\not{D} - m_X)X - \sum_n \frac{c_n^5}{\Lambda}\mathcal{O}_n^5$$

- d=5 operators: $\overline{X} F X\,,\; \overline{X}^c F' X$ where F, F' : d=2 operators in Ω

- Λ fermion number breaking scale $\Lambda^2 \gg \langle F \rangle\,, \langle F' \rangle\,, m_X^2$

For 4321 + Dirac DM see Guadagnoli, Reboud, Stangl [2005.10117]

- After spontaneous symmetry breaking:

$$\mathcal{L}^{\rm DS}_{\rm mass} = -m_\psi \overline{\psi}\psi - m_\chi \overline{\chi}\chi - \frac{1}{2}\left(m_L\, \overline{\chi^c_L}\chi_L + m_R\, \overline{\chi^c_R}\chi_R + \text{h.c.}\right)$$

small Majorana masses: $m_L,\, m_R \sim \langle F' \rangle / \Lambda \ll m_\chi \sim m_\psi$

- Mass eigenstates: “Pseudo-Dirac” fermion pair

$$\begin{cases} \chi_1 \simeq \dfrac{i}{\sqrt{2}}(\chi - \chi^c)\,, & m_{\chi_1} \simeq m_\chi - \dfrac{m_L + m_R}{2} \\ \chi_2 \simeq \dfrac{1}{\sqrt{2}}(\chi + \chi^c)\,, & m_{\chi_2} \simeq m_\chi + \dfrac{m_L + m_R}{2} \end{cases}$$

$m_\psi \approx m_{\chi_1} \approx m_{\chi_2}$
quasi-degenerate

χ_1 lightest state is a Majorana DM candidate

ψ becomes a (coloured) coannhiliation partner when computing the relic abundance

Majorana DM in a '4321' Model

Baker, DAF, Trifinopoulos 2109.08689

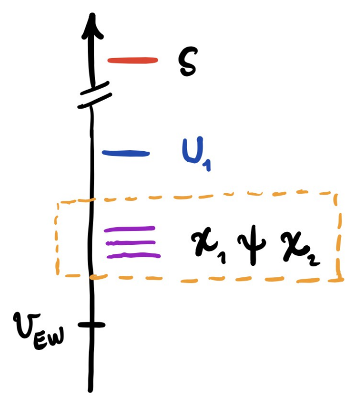
- $G_{4321} \xrightarrow{\langle \Omega_{1,3} \rangle} G_{\rm SM} \qquad \Omega_1 \sim (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{1}, -1/2)$

- $\mathbb{Z}_2$ odd states: $\begin{cases} X \sim (\mathbf{4}, \mathbf{1}, \mathbf{1}, +1/2) \qquad X = \begin{pmatrix} \psi \\ \chi \end{pmatrix} \\ S_R \sim (\mathbf{1}, \mathbf{1}, \mathbf{1}, 0) \end{cases}$ heavy RH fermion singlet

$$\mathcal{L}^{DS} = \overline{X}(i\not{D} - m_X)X + i\overline{S_R}\not{\partial}S_R - \left(\frac{M_S}{2}\overline{S^c_R}S_R + \lambda_R \overline{S^c_R}\Omega_1^T X_R + \lambda_L \overline{X}_L \Omega_1^* S_R + \text{h.c.} \right)$$

Integrate out: dim-5 ops: $\overline{X^c_R}\,\Omega_1\Omega_1^T X_R \qquad \overline{X_L}\,\Omega_1^*\Omega_1^\dagger X_L^c \qquad \overline{X}_L\,\Omega_1^*\Omega_1^T X_R$

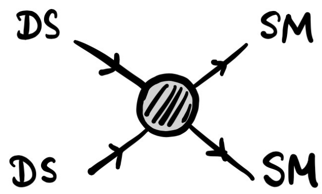
Spectrum: $\begin{cases} m_{\chi_2} \simeq m_\psi + (\lambda_L + \lambda_R)^2 \dfrac{\langle \Omega_1 \rangle^2}{4M_S} \\ m_{\chi_1} \simeq m_\psi - (\lambda_L - \lambda_R)^2 \dfrac{\langle \Omega_1 \rangle^2}{4M_S} \end{cases}$

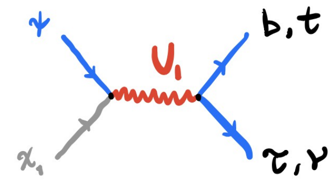


$m_{\chi_1} < m_\psi < m_{\chi_2}$

DM Relic Abundance

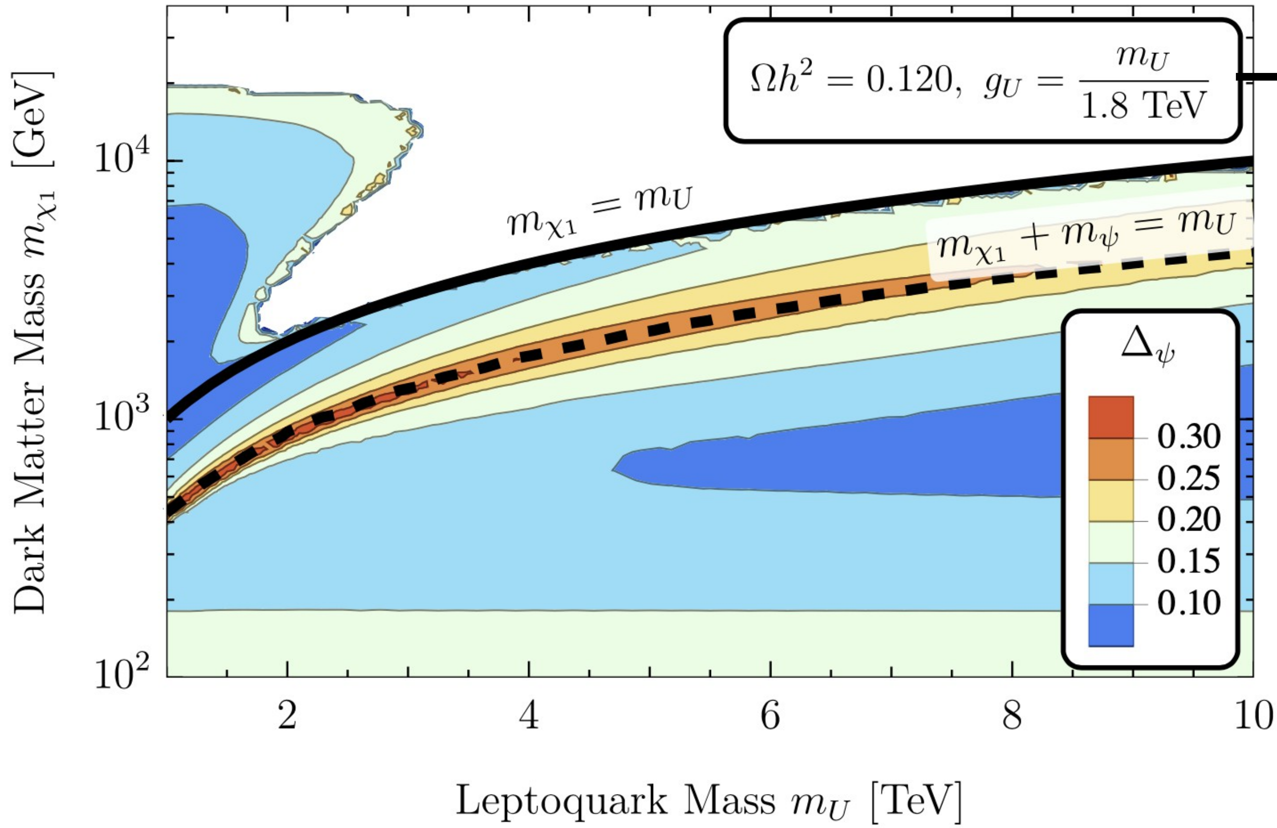
$$\Omega_{\rm DM} h^2 = \frac{1}{\langle v\sigma_{\rm ann}\rangle}$$





Coannihilation into LQ

- Observed relic abundance fixes the mass splitting $\Delta_\psi = \dfrac{m_\psi - m_{\chi_1}}{m_{\chi_1}}$



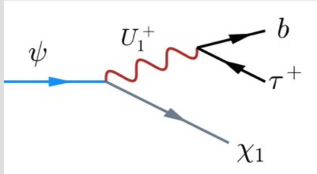
B-anomalies

$\Delta_\psi < 30\%$

Coloured coannhiliation partner @ LHC

We can probe the DM mass at the LHC by searching for the colored partner.

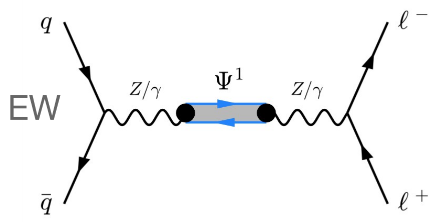
- Because of the compressed spectrum the coannhilation partner can hadronize!



$$\Gamma \sim 10^{-6} \left(\frac{m_\psi}{\text{TeV}}\right)^5$$

$$\begin{cases} \text{'psionium'} & \Psi^0, \Psi^1 = (\psi\bar{\psi}) \\ \text{'open-psi'} & \Psi_q = (\psi q) \end{cases}$$

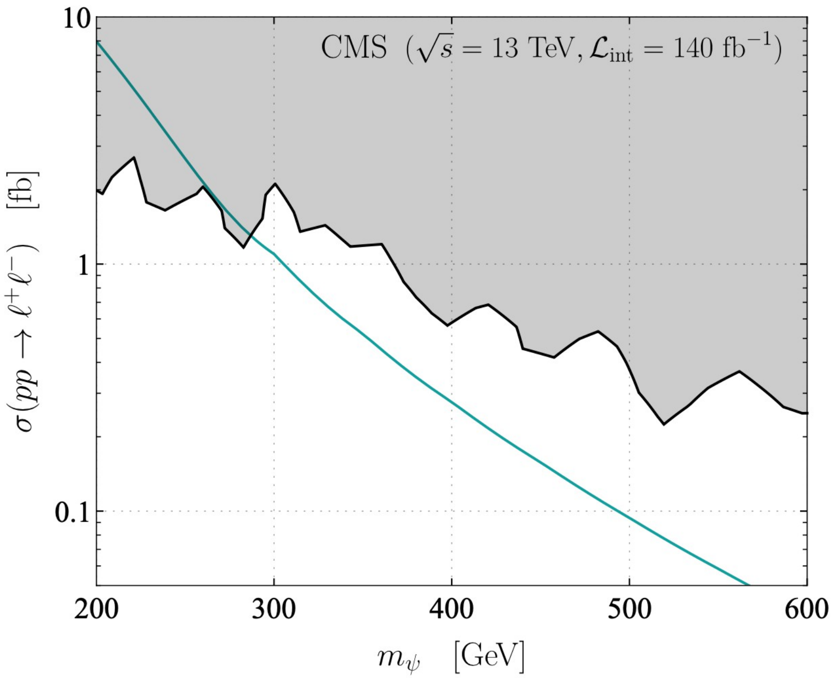
- 'psionium' production at LHC



Dilepton resonance

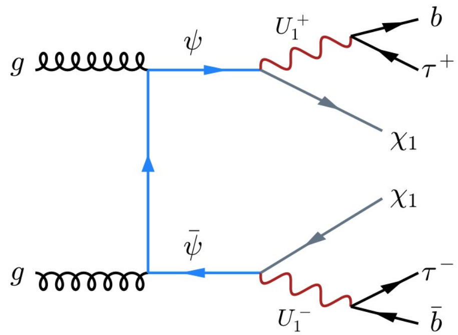
Model independent limit on DM mass:

$$m_\psi > 280\,\text{GeV} \implies m_{\chi_1} > 250\,\text{GeV}$$



Coloured coannhiliation partner @ LHC

$pp \to \psi\bar{\psi}$

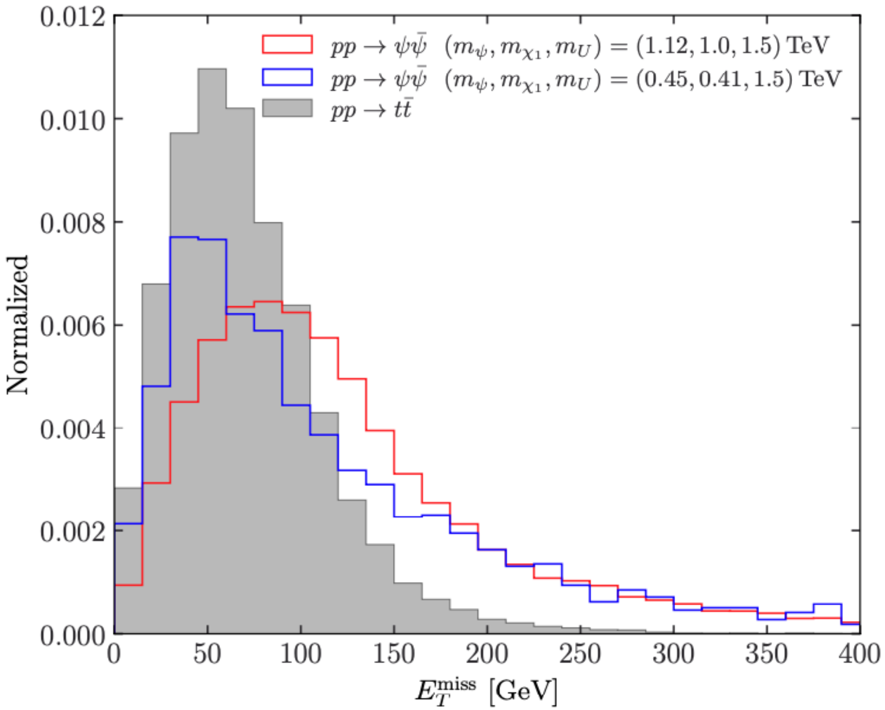


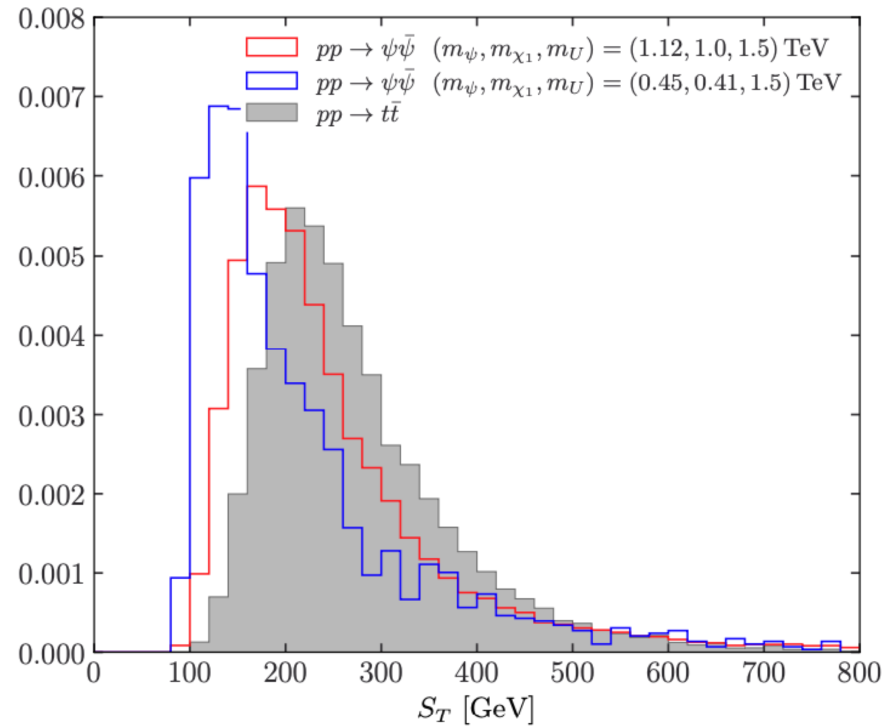
Challenging sigature:

$2b + 2\tau + E_T^{\rm miss} \implies$ soft

Because of small mass splitting $\Delta_\psi < 30\%$

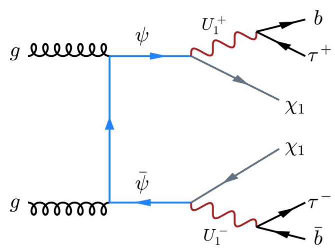
Currently, no LHC searches for this scenario....





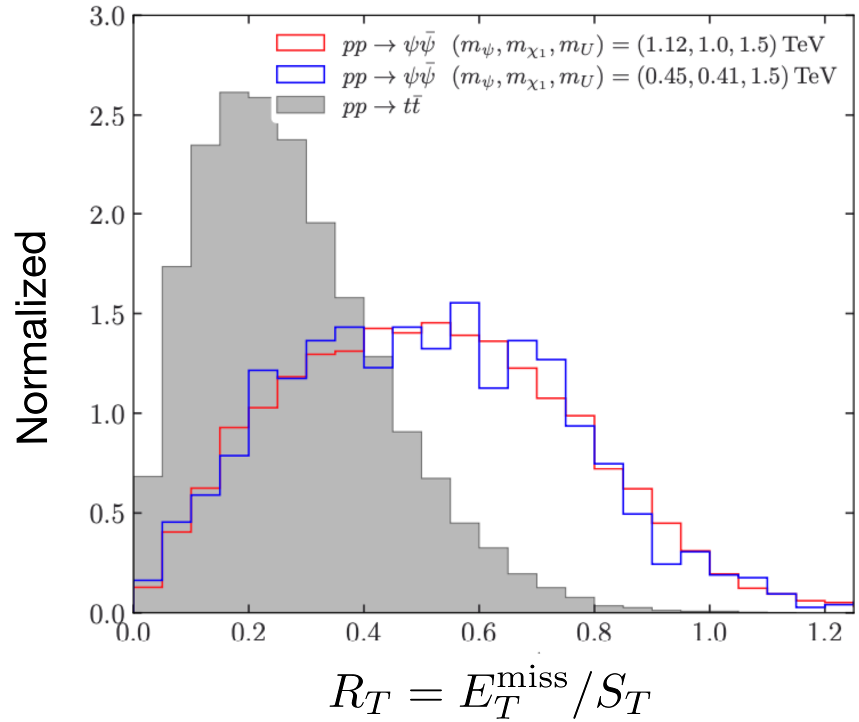
$$S_T = p_T(j_1) + p_T(j_2) + p_T(\tau_{\rm had}) + p_T(\tau_\ell)$$

$pp \to \psi\bar{\psi}$



Define the ratio between invisible and visible energies:

$$R_T = \frac{E_T^{\rm miss}}{S_T}$$



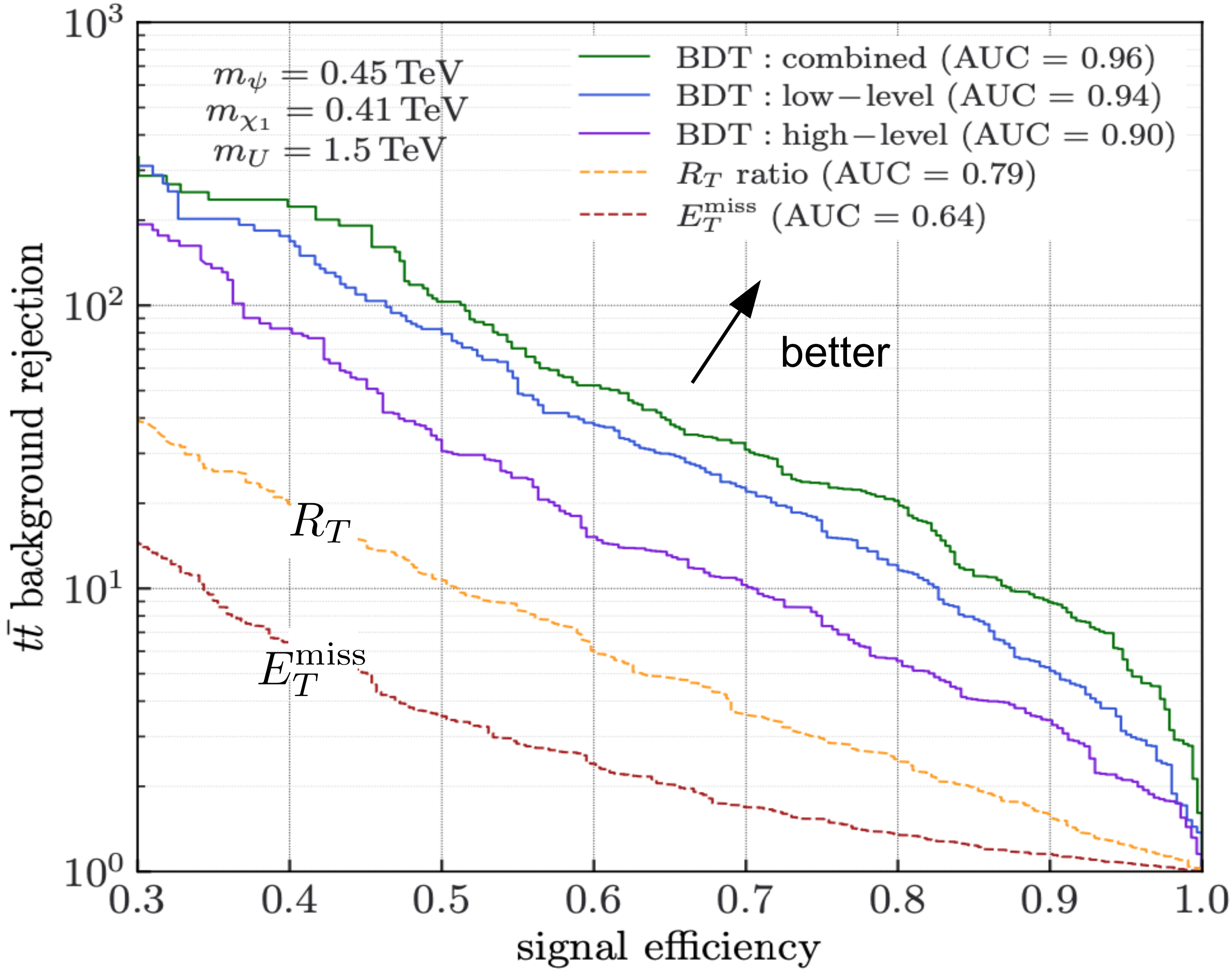
- Search strategies: $2j_b + \tau_{\rm had}\tau_\ell + E_T^{\rm miss}$

  "soft" pre-selection: $p_T(j, \tau_{had}) > 20\,{\rm GeV}$ $\quad p_T(\ell) > 5\,{\rm GeV}$

  i) Cut-based analysis: $R_T > 0.5$

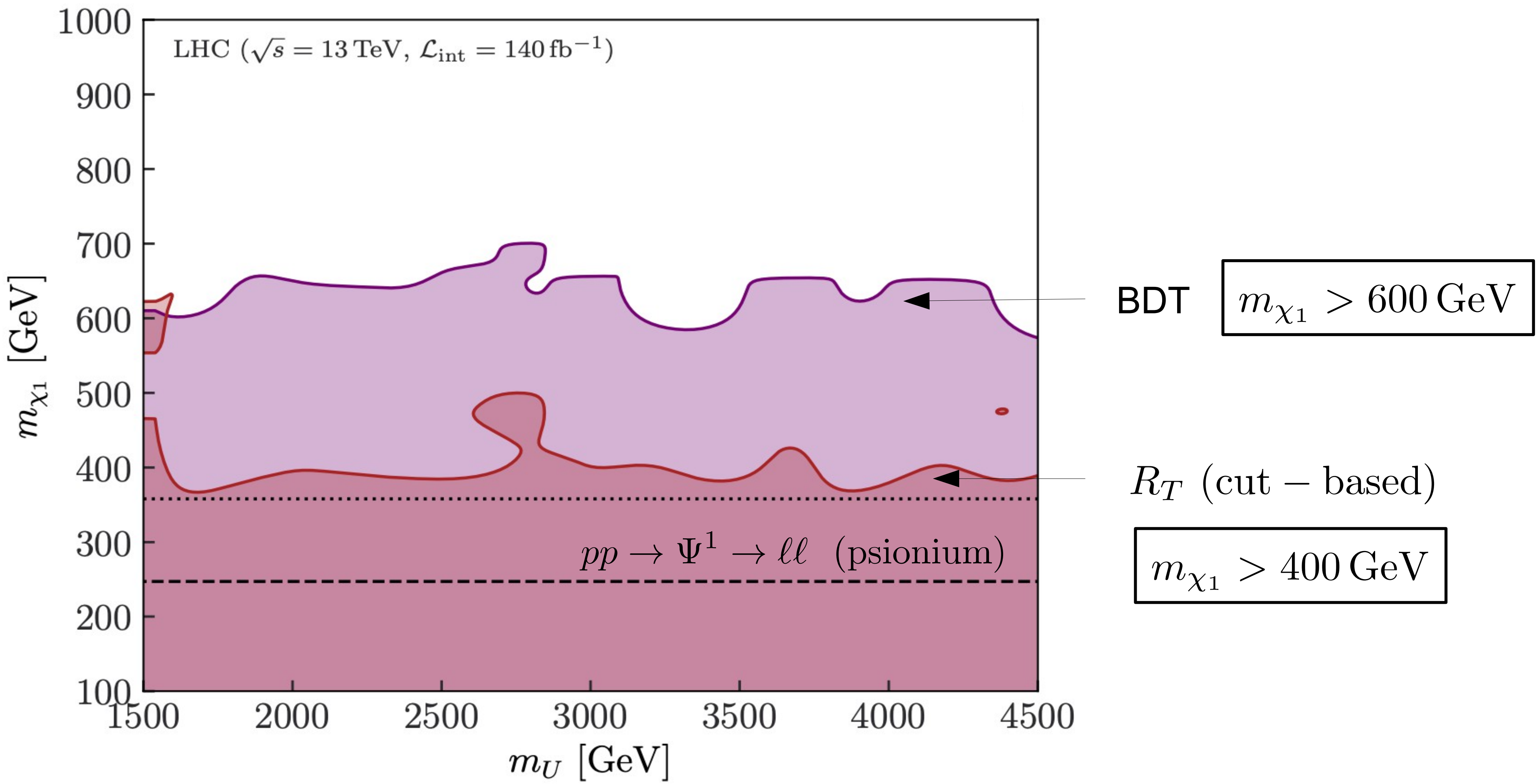
  ii) Multivariate: Boosted Decision Tree (BDT)
  - Low-level obs (p_T, η, ϕ)
  - High-level obs $(S_T, E_T^{\rm miss}, R_T, ...)$
  - Combination of Low and High obs.

ROC curves: $m_\psi = 450\,\text{GeV}\ ,\quad \Delta_\psi \approx 10\%$



LHC limits for DM

95% CL excl. Limits at current lumis (140/fb)



Conclusions

- LHC can efficiently test several crucial predictions from 4321 models:

  $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$ we should see deviations in ditau tails at the LHC.

  $G' = (\mathbf{8}, \mathbf{1}, 0)$ we should see a resonance in the high-mass ttbar spectrum.

- LHC will is starting to probe the fermion sector of 4321!

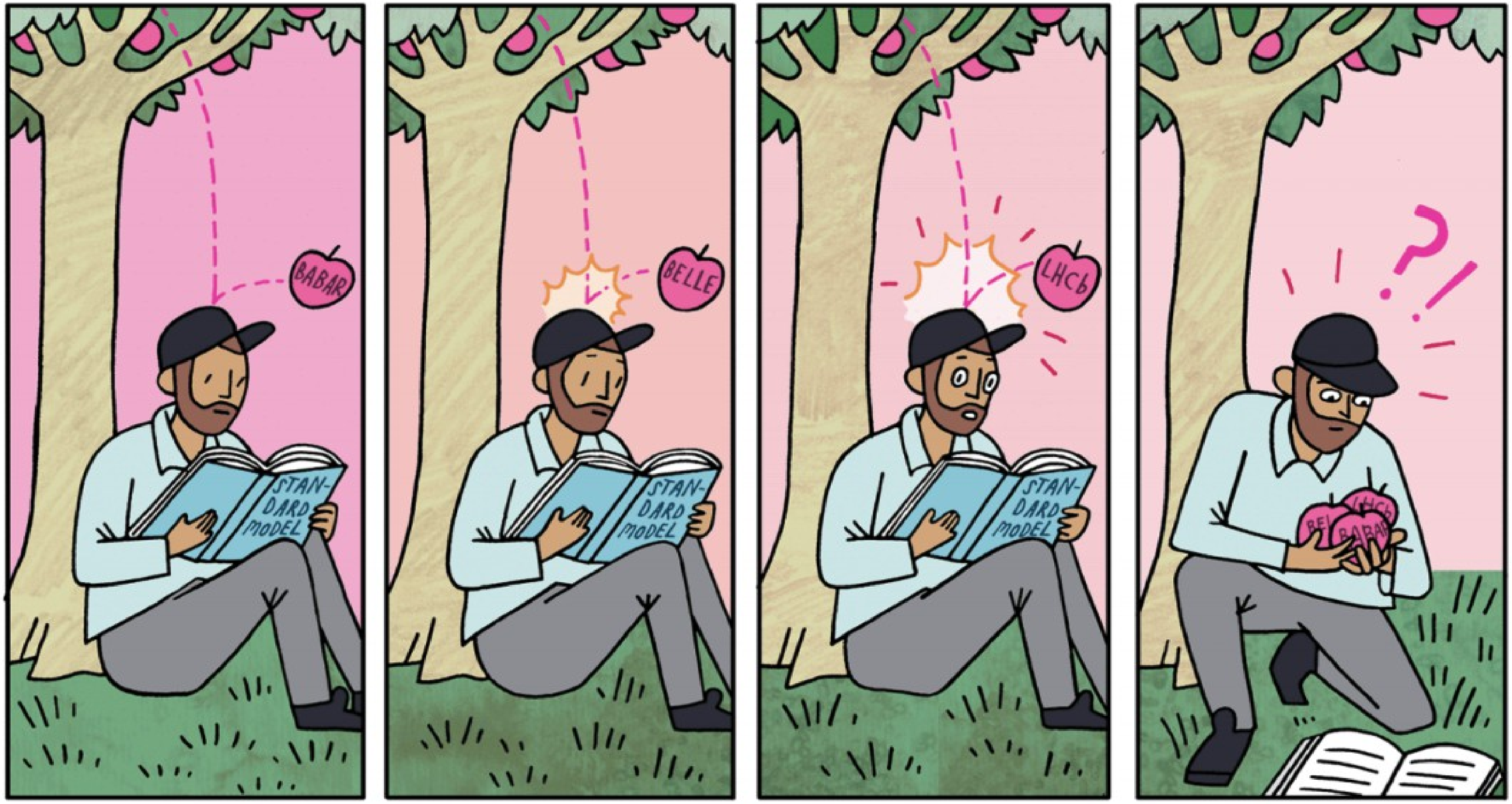
  We provided first limits on the **vector-like lepton** mass $m_L > 700\,\mathrm{GeV}$

- LHC can also probe Dark sector extensions of 4321 with Majorana DM.

  We provided a dedicated search strategy and extracted limits.

  $m_{\mathrm{DM}} > 600\,\mathrm{GeV}$

Thank You!



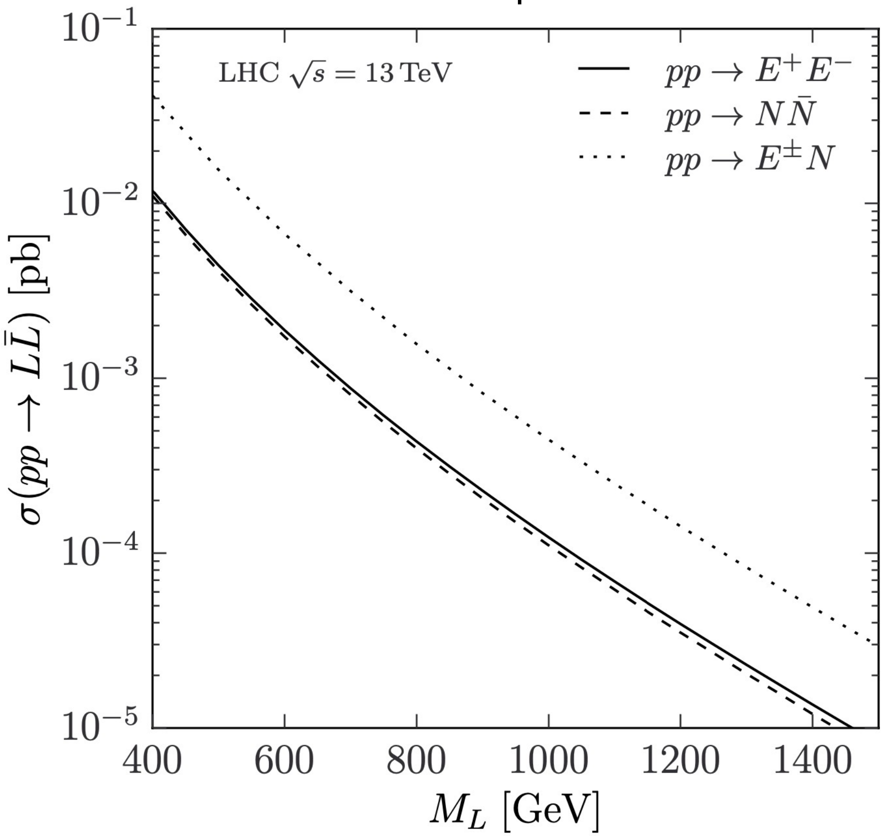
Artwork by Sandbox Studio, Chicago with Corinne Mucha

- extra slides -

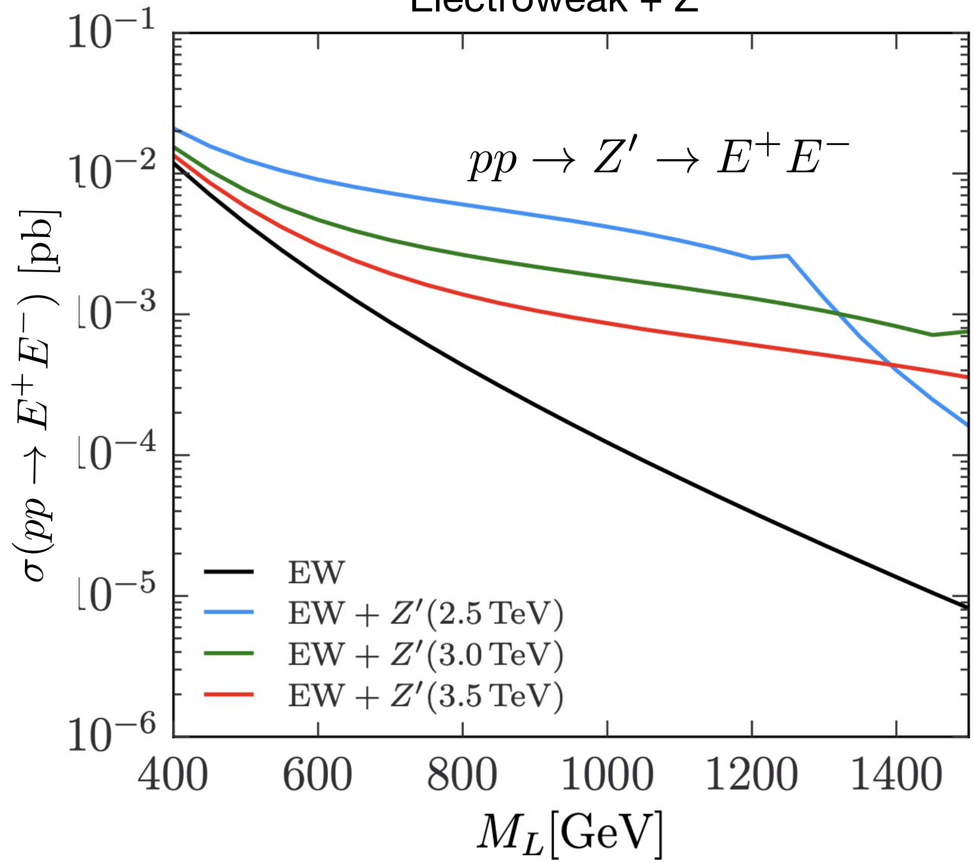
Vector-like leptons

$$L = \begin{pmatrix} N \\ E^{\pm} \end{pmatrix}$$

Electroweak production



Electroweak + Z'



Looks promising, but currently no heavy lepton search by ATLAS or CMS

DM relic abundance

- Dark sector interactions:

$$\mathcal{L}_U^{\rm int} \supset \frac{g_U}{\sqrt{2}} U_\mu \left(\beta_{D_1}\,\overline{\chi_1}\gamma_\mu\psi + \beta_{D_2}\,\overline{\chi_2}\gamma_\mu\psi\right)$$

$$\mathcal{L}_{Z'}^{\rm int} \supset \frac{g_{Z'}}{2\sqrt{6}} Z'_\mu \left(\zeta_\psi\,\overline{\psi}\gamma_\mu\psi + \zeta_\chi\,\overline{\chi_1}\gamma_\mu\chi_2\right)$$

Field	Type	SM QN	$\mathbb{Z}_2$
χ_1	Majorana	$(\mathbf{1},\mathbf{1},0)$	-1
χ_2	Majorana	$(\mathbf{1},\mathbf{1},0)$	-1
ψ	Dirac	$(\mathbf{3},\mathbf{1},2/3)$	-1
Z'	Gauge	$(\mathbf{1},\mathbf{1},0)$	$+1$
U_1	Gauge	$(\mathbf{3},\mathbf{1},2/3)$	$+1$

$\bar{\chi}_1\gamma^\mu\chi_1$ currents vanish because $\bar{\chi}_i\gamma^\mu\chi_j = -\bar{\chi}_j\gamma^\mu\chi_i$

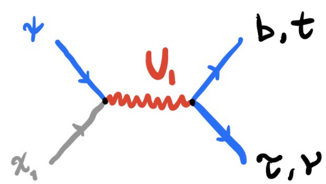
Model parameters: m_ψ, m_{χ_1}, m_U $\quad g_U = (1.1\pm 0.2)\times\left(\frac{m_U}{2\mathrm{TeV}}\right)$ B-anomalies fit

- DM relic abundance: $\mathrm{DS\,DS}\to\mathrm{SM\,SM}$

$$\Omega_{\rm DM}h^2 = \frac{1}{\langle v\sigma_{\rm ann}\rangle}$$

$\chi_1\psi \to \mathrm{SM\,SM}$

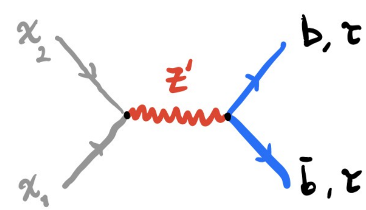
$\psi\psi \to \mathrm{SM\,SM}$



Most efficient channels

$\chi_1\chi_2 \to \mathrm{SM\,SM}$

~~$\chi_1\chi_1 \to \mathrm{SM\,SM}$~~



subleading

DM relic abundance