Collider Probes for "4321" and Beyond

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"4321" gauge models in a nutshell

Di Luzio, Greljo, Nardecchia [1708.08450]
Bordone, et al [1712.01368]
Greljo, Stefanek [1802.04274]
Fornal, Gadam, Grinstein [1812.01603]

- Flavor non-universal model based on Pati-Salam group

$$\overbrace{SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)_X}^{U(1)_Y} \xrightarrow{\langle\Omega_{1,3,15}\rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\underbrace{SU(4)_3 \times SU(3)_{1+2}}_{SU(3)_c} \qquad \psi = (\psi_1 \; \psi_2 \; \psi_3)$$

$$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$
$$Z' \sim (\mathbf{1}, \mathbf{1}, 0)$$
$$G' \sim (\mathbf{8}, \mathbf{1}, 0)$$

$$SU(4) \sim \begin{pmatrix} G^a & U^\alpha \\ (U^\alpha)^* & Z' \end{pmatrix}$$

Vector Leptoquark + Coloron

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
q_L^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
u_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
d_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
ℓ_L^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
e_R^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
ψ_L	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
$\psi_R^\pm$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$
χ_L^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
χ_R^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
Ω_1	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
Ω_3	$\bar{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0

1st & 2nd families $i = 1, 2$

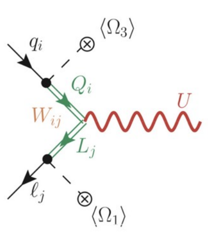
3rd family

$$\psi_L = \begin{pmatrix} q_L^3 \\ \ell_L^3 \end{pmatrix} \qquad \psi_R^+ = \begin{pmatrix} t_R \\ \nu_R \end{pmatrix} \qquad \psi_R^- = \begin{pmatrix} b_R \\ \tau_R \end{pmatrix}$$

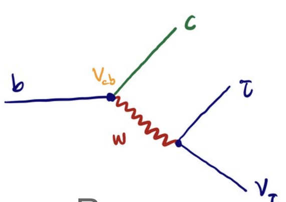
Vectorlike

$$\chi_i = \begin{pmatrix} Q_i \\ L_i \end{pmatrix}$$

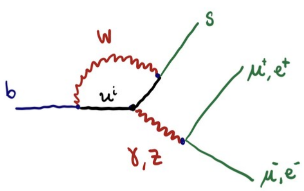
4321 SSB scalars



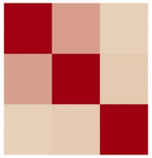
- Motivation: - LFUV (B-anomalies)
  - Flavor Puzzle

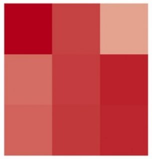


$R_{D^{(*)}}$



$R_{K^{(*)}}$


CKM


PMNS

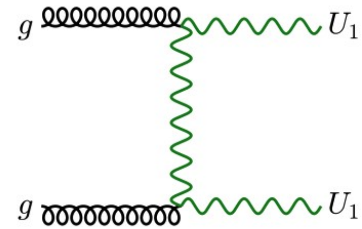
Vector Leptoquark $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

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

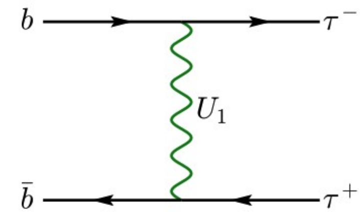
$$J_\mu^U = \beta_L^{i\alpha} \left(\bar{q}_L^i \gamma_\mu \ell_L^\alpha \right) + \beta_R^{i\alpha} \left(\bar{d}_R^i \gamma_\mu e_R^\alpha \right)$$

$$|\beta_L^{b\tau}| = 1 \gg |\beta_L^{s\tau, b\mu}| \gg |\beta_L^{d\tau, s\mu}|$$

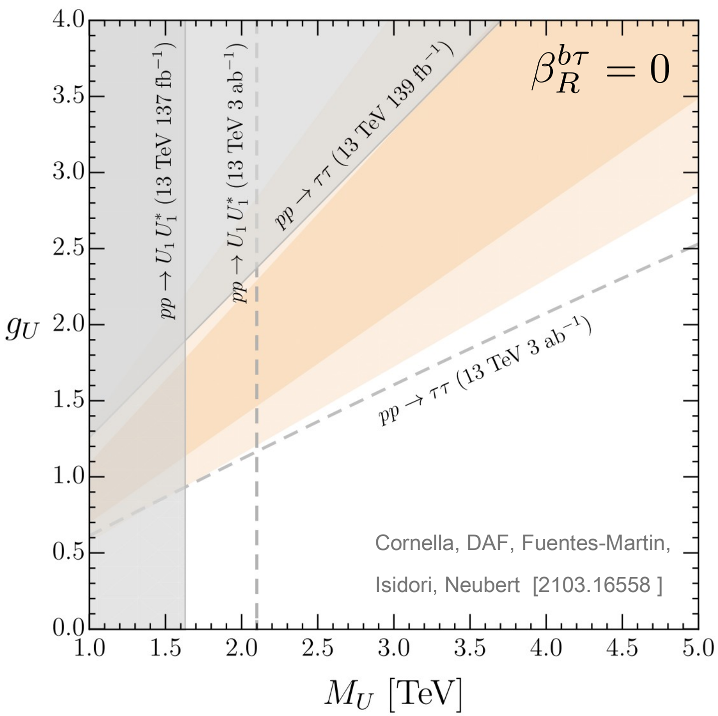
Approx, U(2)[5] symmetry

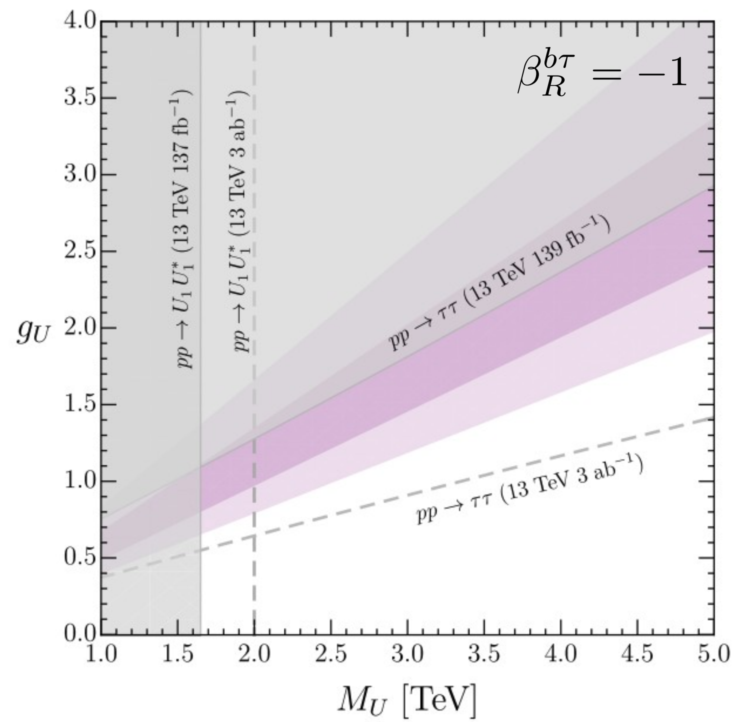


$$pp \to U_1 U_1 \to \begin{cases} b\tau\, b\tau \\ t\nu\, t\nu \\ b\tau\, t\nu \end{cases}$$



$$pp \to \tau^- \tau^+$$



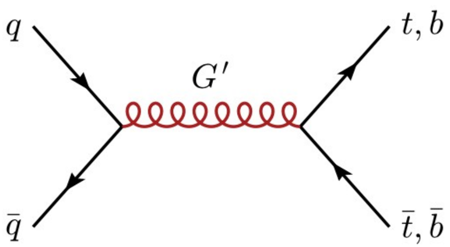


- Dedicated search by CMS! [CMS-PAS-HIG-21-001]

4321 Coloron $G' = (\mathbf{8}, \mathbf{1}, 0)$

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

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



$pp \to G' \to t\bar{t}$

$pp \to G' \to b\bar{b}$

(broad resonances)

- Recast of dijet & ditop searches

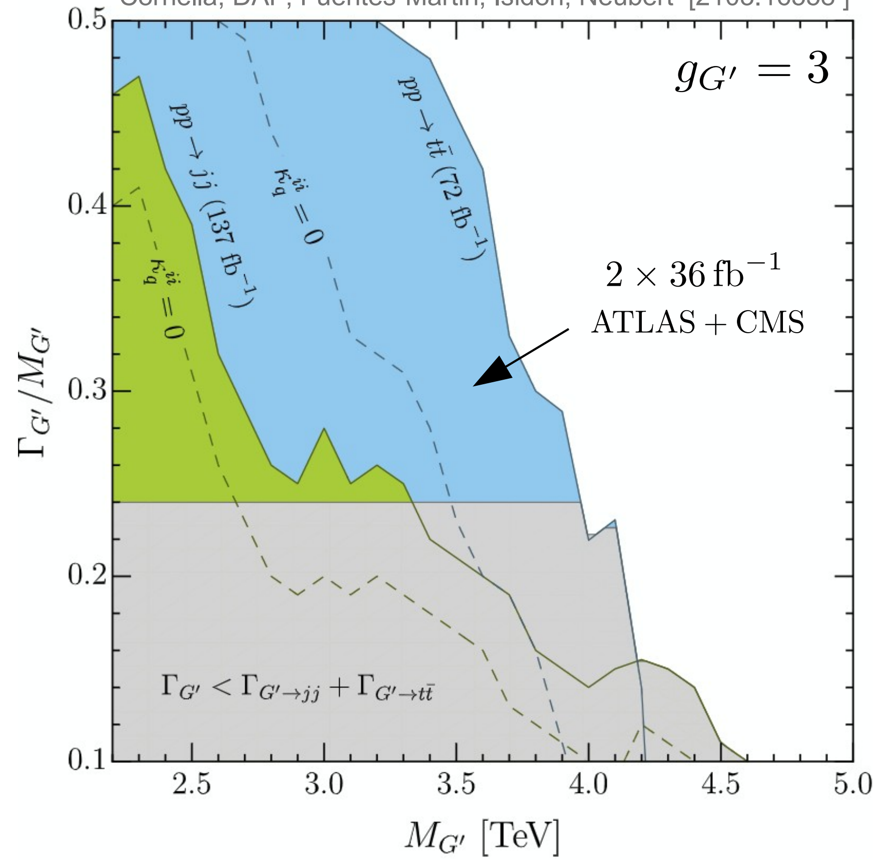
- broad $pp \to jj$ resonance

- Unfolded inv. Mass spectrum $d\sigma/dm_{t\bar{t}}$

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

Ditop searches provide the best direct limits on the scale of the 4321 model!

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



Vector-like fermions

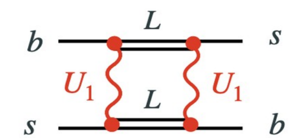
4321 vector-like fermion $\chi = (Q, L)^T \sim (\mathbf{4}, \mathbf{1}, \mathbf{2}, 0)$

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

Di Luzio et al. [1808.00942]

Important 4321 prediction:

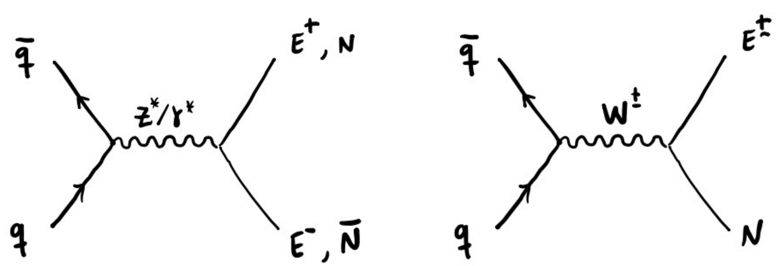
$m_L \sim 1 - 2\,\mathrm{TeV}$

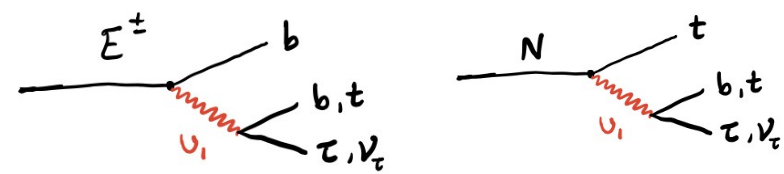


$B_s^0 - \overline{B_s^0}$

vector-like lepton needs to be light!

- These heavy leptons can be pair production at LHC via EW interactions $pp \to E^+E^-,\ N\bar{N},\ E^{\pm}N$





3-body decay modes into 3rd gen.

- Very rich LHC pheno!

$pp \to E^+E^- \to b\bar{b}b\bar{b}\,\tau\tau$

$pp \to E^+N \to t\bar{b}b\bar{b}\,\tau\tau$

$pp \to E^+E^- \to t\bar{t}b\bar{b}\,\nu\nu$

$pp \to N\bar{N} \to t\bar{t}b\bar{b}\,\tau\tau$

$pp \to N\bar{N} \to t\bar{t}t\bar{b}\,\tau\nu$

$pp \to N\bar{N} \to t\bar{t}t\bar{t}\,\nu\nu$

Multi-top Signatures

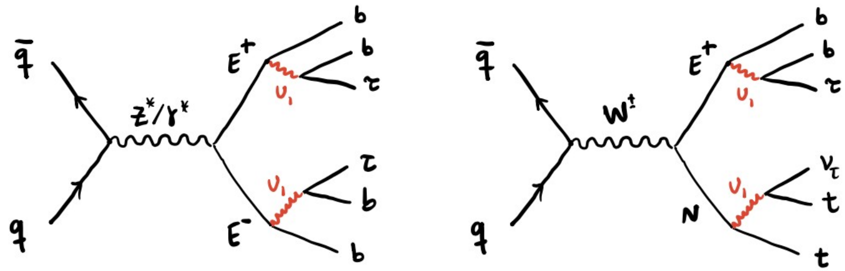
Search for 4321 vector-like leptons

Cormier, DAF, Fuentes-Martin, Mikuni [CMS-PAS-B2G-21-004]

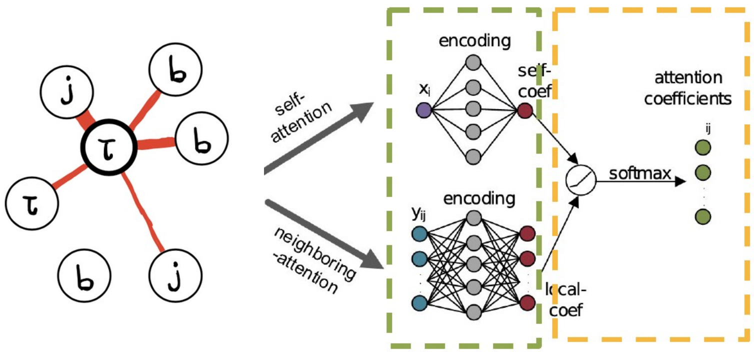
- Targets all-hadronic modes $t \to bqq,\ \tau \to qq\nu_\tau$

Event selection:

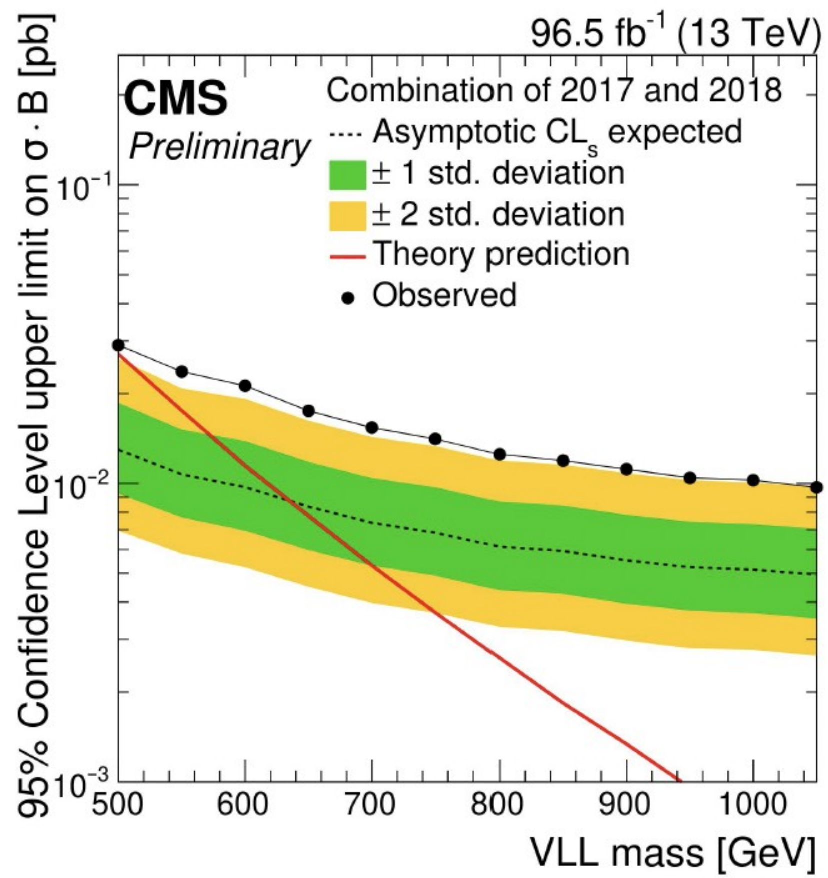
- 3 or more b-tagged jets
- 0,1 or 2 tau-tagged jets
- cut in missing transverse energy



- Analysis using Graph neural network (GNN)



Attention-based Cloud Network (ABCNet)



- LHC limits of **10-30 fb** on EW production xsection

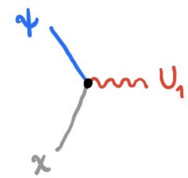
$$\boxed{M_L \sim 500\ \mathrm{GeV}}$$

Beyond '4321' - Majorana DM

Extend with Dark Sector: Baker, DAF, Trifinopoulos [2109.08689]

- $\mathbb{Z}_2$ odd states: $\begin{cases} X \sim (\mathbf{4}, \mathbf{1}, \mathbf{1}, +1/2) \\ S_R \sim (\mathbf{1}, \mathbf{1}, \mathbf{1}, 0) \end{cases}$ $X = \begin{pmatrix} \psi \\ \chi \end{pmatrix}$ Colored partner (ψ), DM (χ)

Heavy fermion singlet

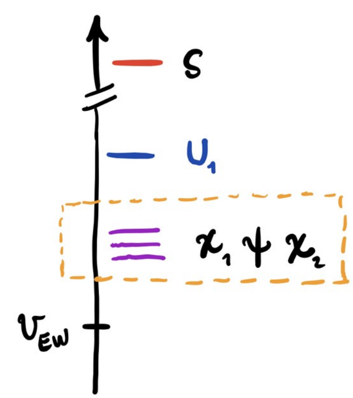


$$\mathcal{L}^{DS} = \overline{X}(i\not{D} - m_X)X + i\overline{S_R}\not{\partial}S_R - \left(\frac{M_S}{2}\overline{S_R^c}S_R + \lambda_R\,\overline{S_R^c}\Omega_1^T X_R + \lambda_L\,\overline{X}_L\Omega_1^* S_R + \text{h.c.}\right)$$

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

Integrate S out : $\overline{X}_L\,\Omega_1^*\Omega_1^T X_R \quad \overline{X_R^c}\,\Omega_1\Omega_1^T X_R \quad \overline{X_L}\,\Omega_1^*\Omega_1^\dagger X_L^c$ dim-5 operators

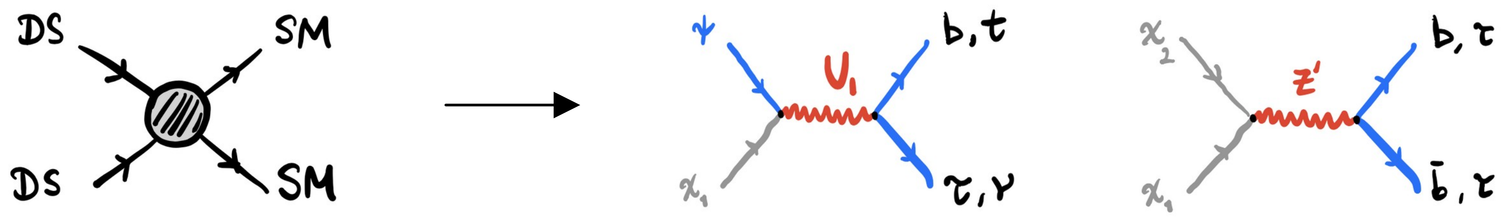
Pseudo-Dirac Pair: $\begin{cases} m_{\chi_2} \simeq m_\psi + (\lambda_L + \lambda_R)^2 \dfrac{\langle\Omega_1\rangle^2}{4M_S} \\ m_{\chi_1} \simeq m_\psi - (\lambda_L - \lambda_R)^2 \dfrac{\langle\Omega_1\rangle^2}{4M_S} \end{cases}$



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

DM candidate

DM Relic abundance



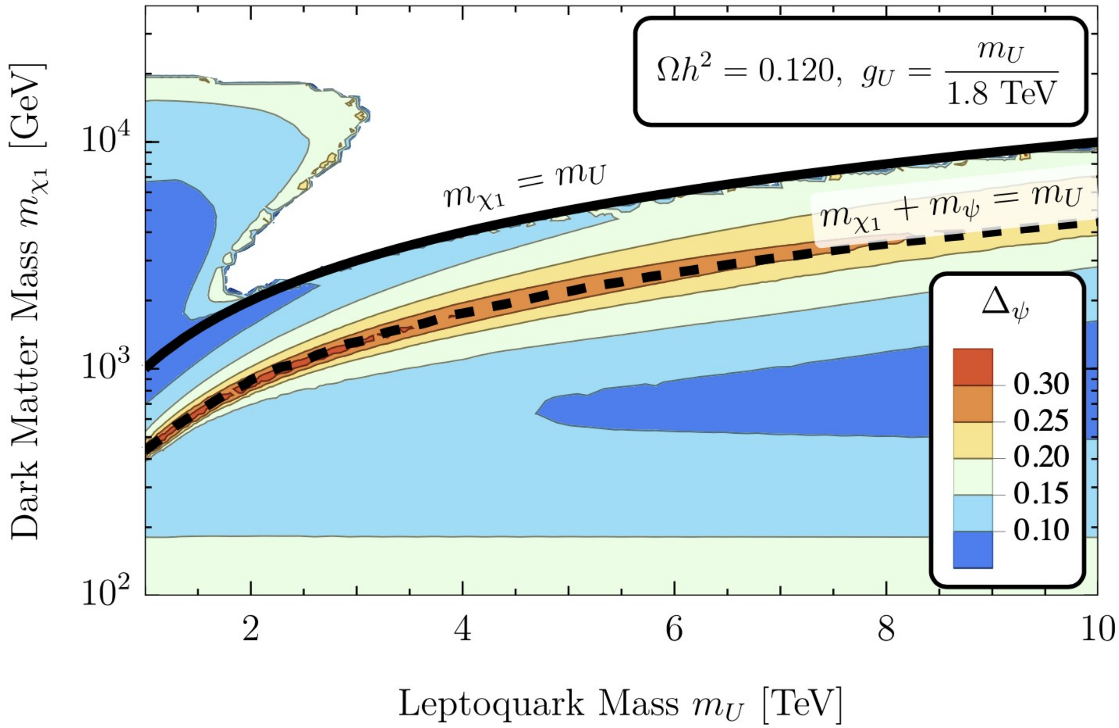
- Co-annihilation into 3rd gen SM: $\begin{cases} \chi_1\ \psi \to \mathrm{SM}_3\ \mathrm{SM}_3 \\ \chi_1\ \chi_2 \to \mathrm{SM}_3\ \mathrm{SM}_3 \end{cases}$ U₁ leptoquark portal dominates!

- Observed relic abundance fixes the mass splitting

$$\Delta_\psi = \frac{m_\psi - m_{\chi_1}}{m_{\chi_1}}$$

$$\boxed{\begin{array}{l} \Delta_\psi < 30\% \\ m_{\chi_1} \approx m_\psi \approx m_{\chi_2} \end{array}}$$

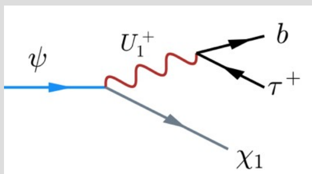
compressed spectrum!



Co-annhilation partner at the LHC

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

- The co-annhilation partner hadronizes!



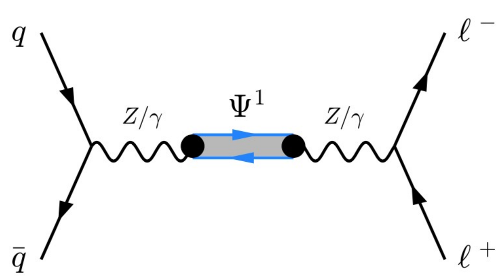
$$\Gamma \sim 10^{-6} \left(\frac{m_\psi}{\text{TeV}}\right)^5$$

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

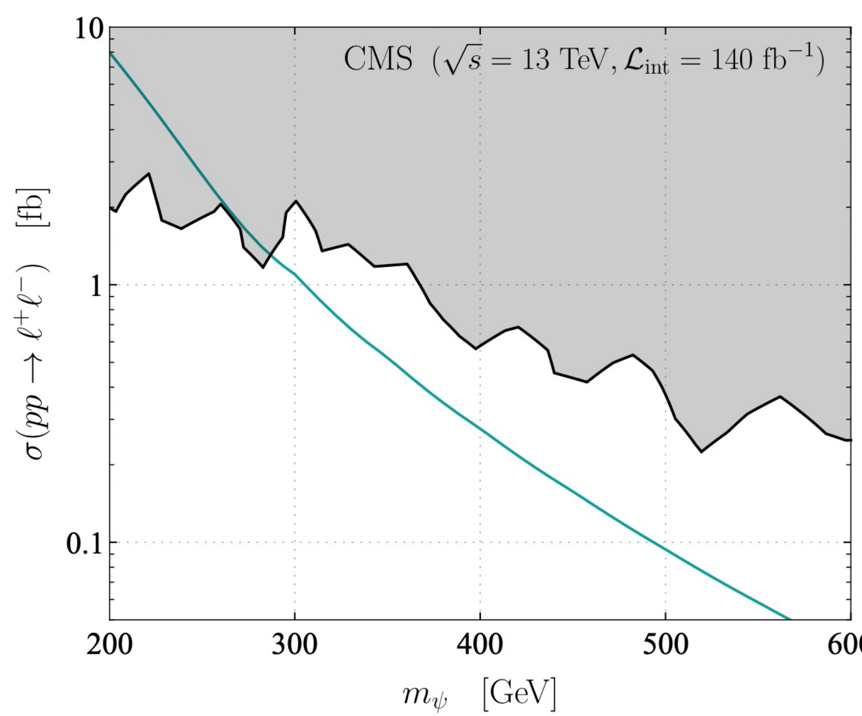
similar to QCD Quarkonia states

- *Psionium* production at LHC:

EW



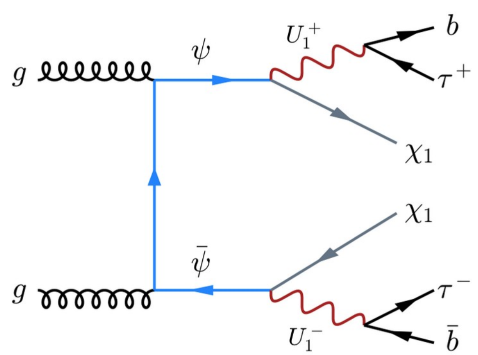
Dilepton resonance



Model independent limit on DM mass:

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

- Pair production $pp \to \psi\bar{\psi}$

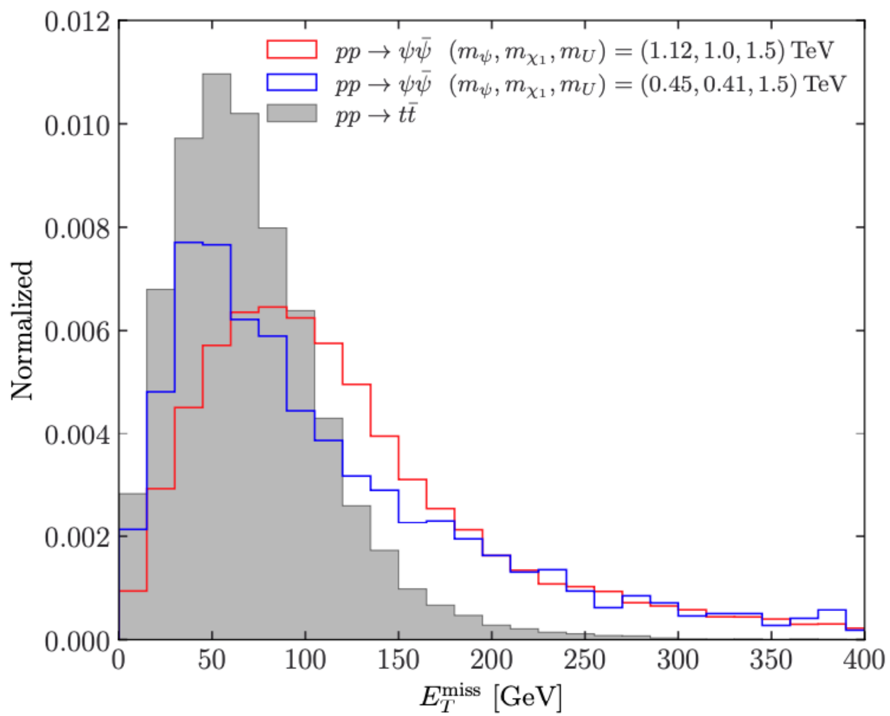


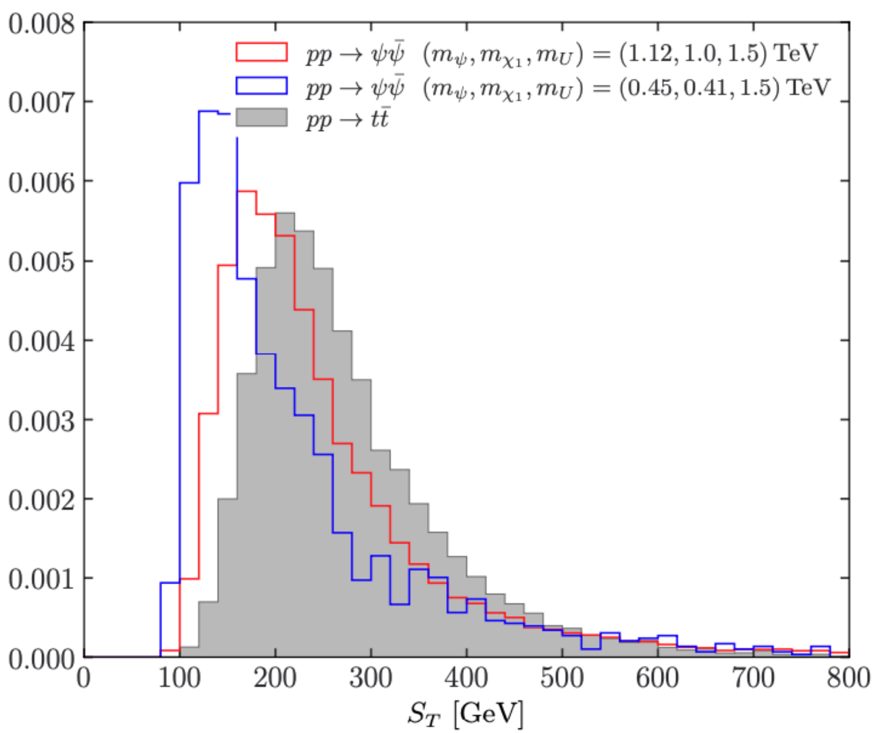
Challenging sigature:

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

Because of small mass splitting $m_\psi \approx m_{\chi_1}$

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

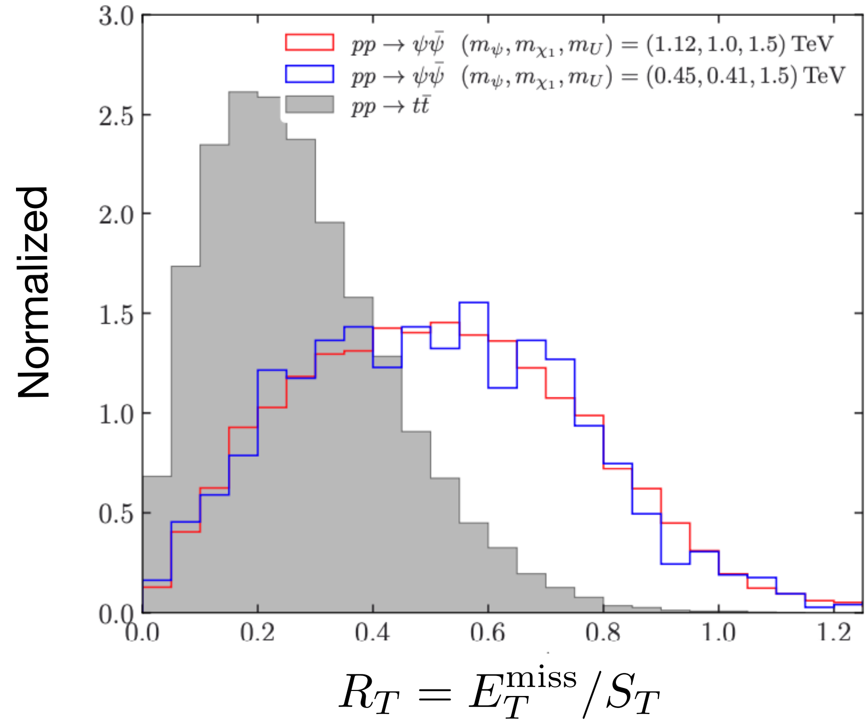




$$S_T = p_T(j_1) + p_T(j_2) + p_T(\tau_{\text{had}}) + p_T(\tau_\ell)$$

Define the ratio between invisible and visible energies:

$$\boxed{R_T = \frac{E_T^{\text{miss}}}{S_T}}$$



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

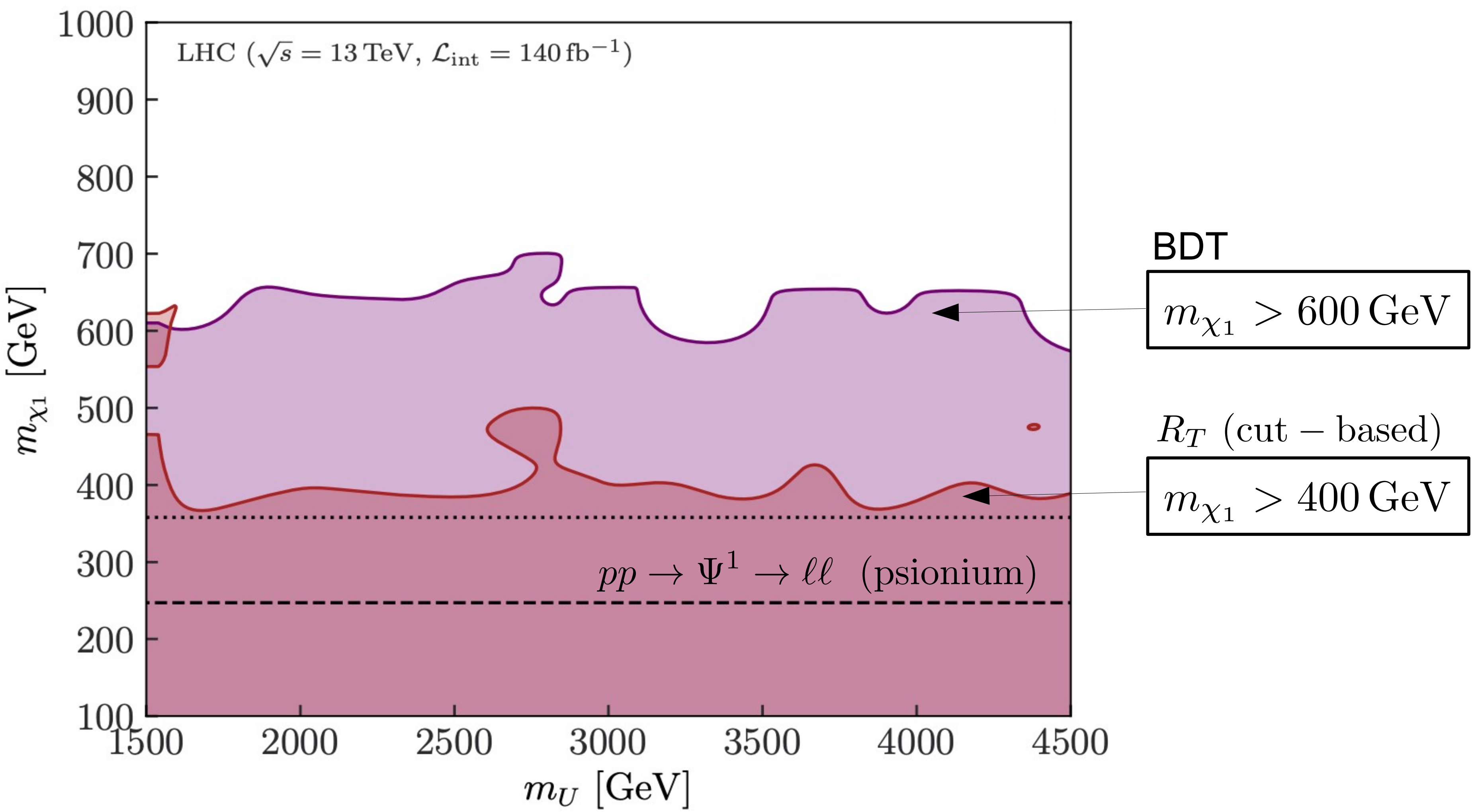
  "soft" pre-selection: $p_T(j, \tau_{had}) > 20\,\text{GeV} \qquad p_T(\ell) > 5\,\text{GeV}$

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

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

LHC Limits for 4321 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 most at HL-LHC.

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

- LHC is already probing the fermion sector of 4321

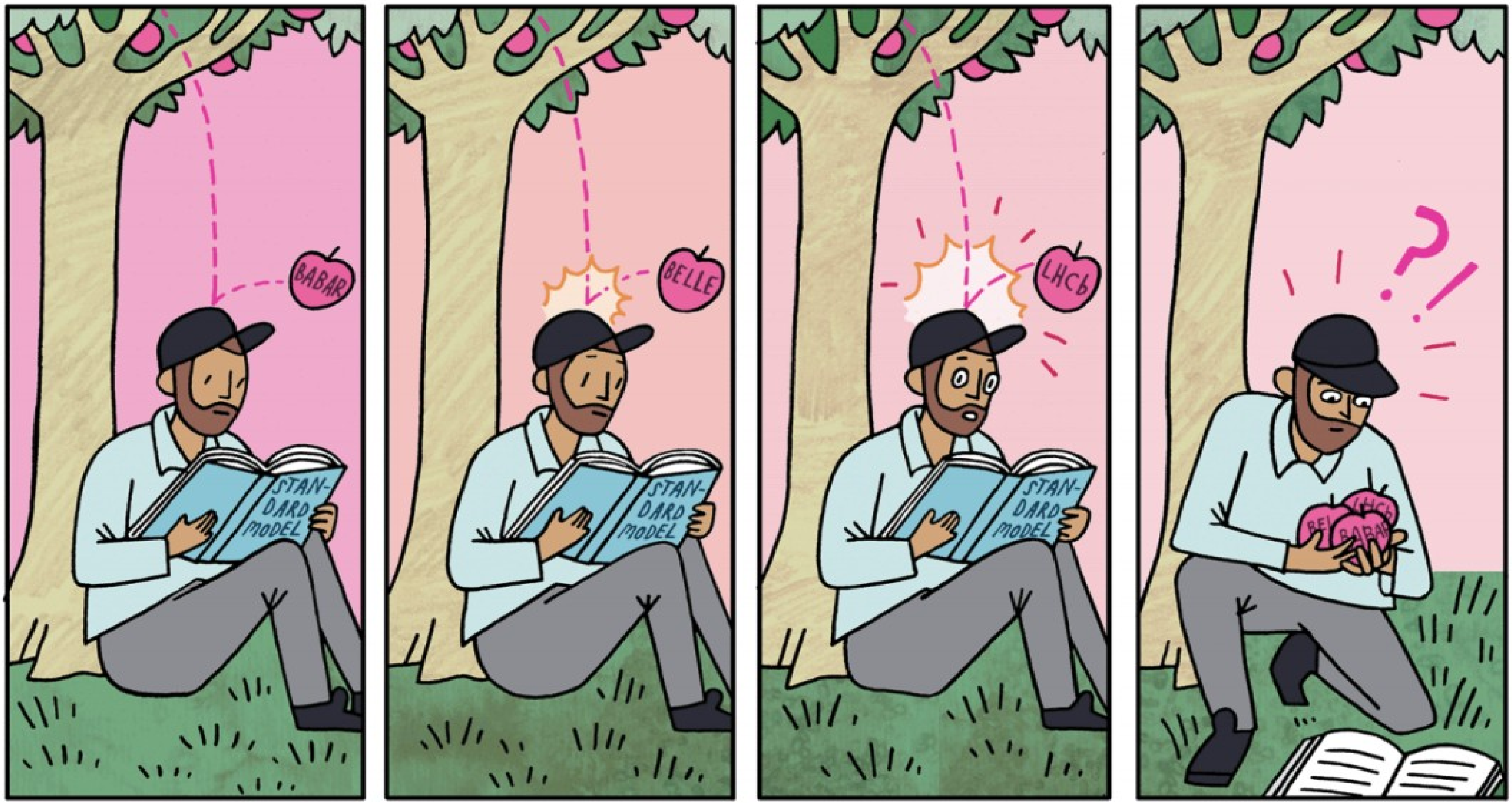
  We showed first limits on the **vector-like lepton** mass $m_L > 700\,\mathrm{GeV}$

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

  We presented a dedicated search strategy and extracted limits.

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

Much Obliged!



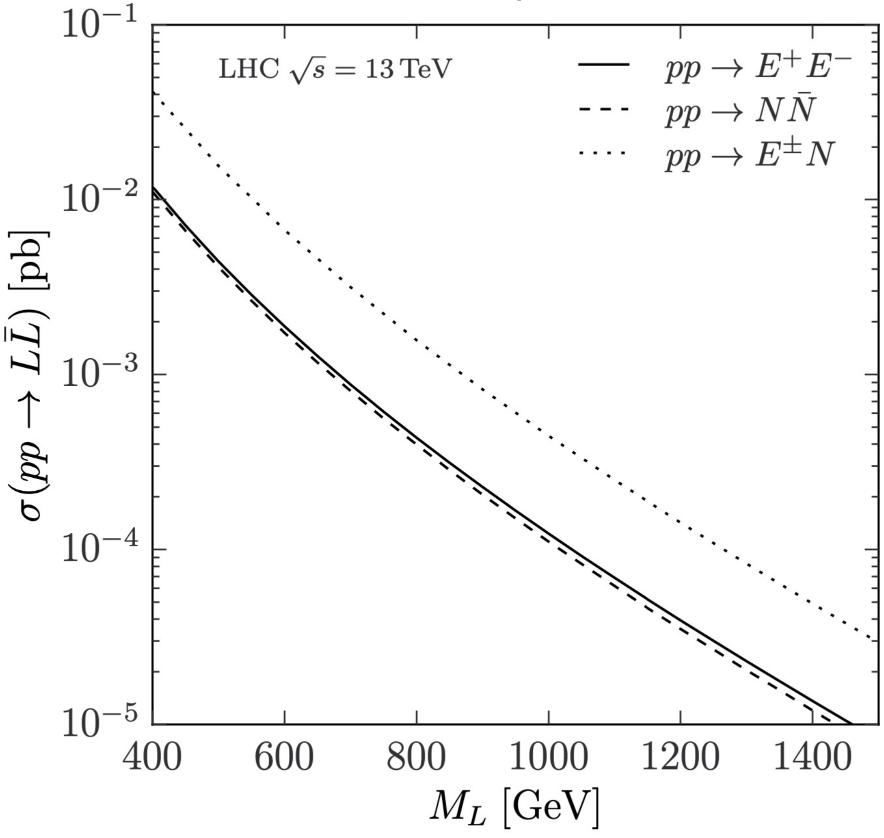
Artwork by Sandbox Studio, Chicago with Corinne Mucha

- Bonus Slides -

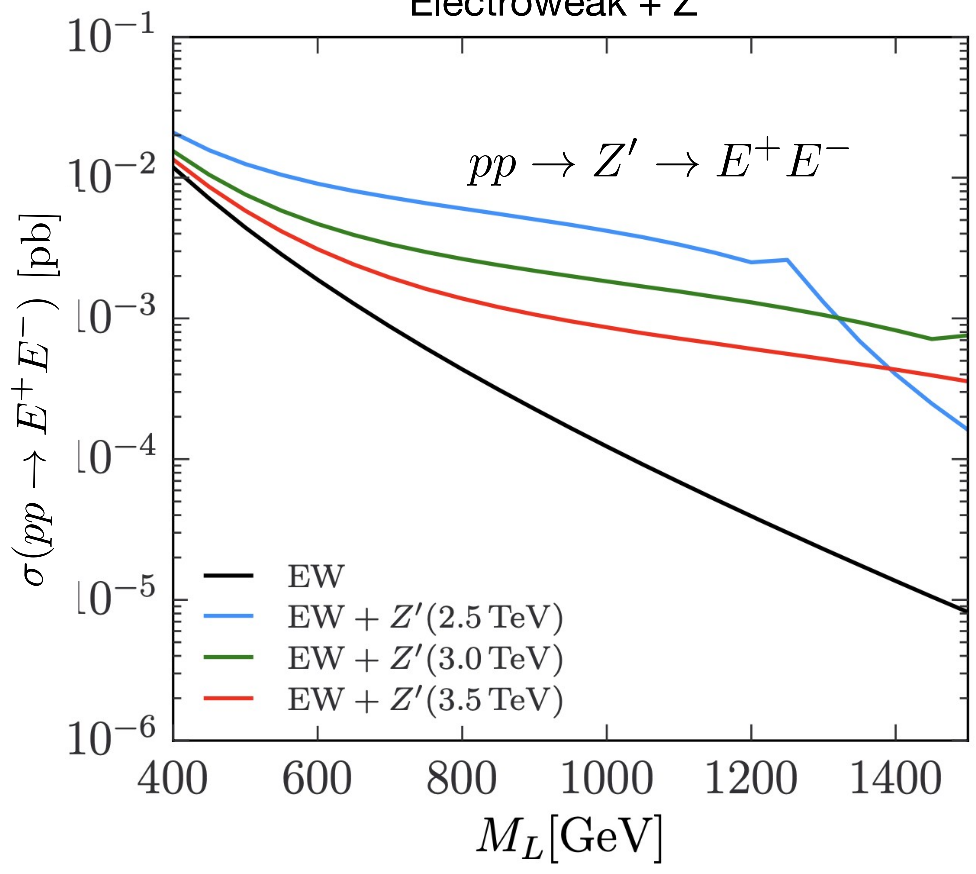
Vector-like leptons

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

Electroweak production



Electroweak + Z'



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

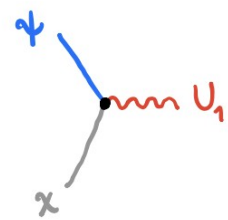
Majorana Dark Matter & LFUV

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

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



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

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

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

$\left\{ \begin{array}{l} \chi_1 \text{ lightest state is a Majorana DM candidate} \\ \psi \text{ becomes a (coloured) coannhiliation partner when computing the relic abundance} \end{array} \right.$

DM relic abundance

- Dark sector interactions:

$$\boxed{\begin{aligned}\mathcal{L}_U^{\rm int} &\supset \frac{g_U}{\sqrt{2}} U_\mu \left(\beta_{D_1}\,\overline{\chi 1}\gamma_\mu\psi + \beta_{D_2}\,\overline{\chi 2}\gamma_\mu\psi\right)\\ \mathcal{L}_{Z'}^{\rm int} &\supset \frac{g_{Z'}}{2\sqrt{6}} Z'_\mu \left(\zeta_\psi\,\overline{\psi}\gamma_\mu\psi + \zeta_\chi\,\overline{\chi 1}\gamma_\mu\chi_2\right)\end{aligned}}$$

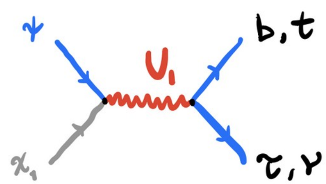
Field	Type	SM QN	$\mathbb{Z}_2$
χ_1	Majorana	$(\mathbf{1},\mathbf{1},0)$	-1
χ_2	Majorana	$(\mathbf{1},\mathbf{1},0)$	-1
ψ	Dirac	$(\mathbf{3},\mathbf{1},2/3)$	-1
Z'	Gauge	$(\mathbf{1},\mathbf{1},0)$	$+1$
U_1	Gauge	$(\mathbf{3},\mathbf{1},2/3)$	$+1$

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

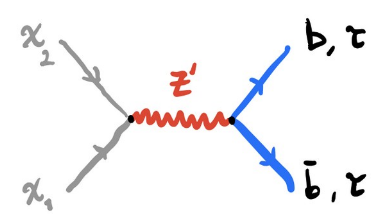
Model parameters: m_ψ, m_{χ_1}, m_U $\quad$ $g_U = (1.1 \pm 0.2) \times \left(\frac{m_U}{2\text{TeV}}\right)$ B-anomalies fit

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

$$\Omega_{\rm DM}h^2 = \frac{1}{\langle v\sigma_{\rm ann}\rangle} \quad \left\{\begin{array}{l}\chi_1\psi \to \text{SM SM}\\ \psi\psi \to \text{SM SM}\\ \\ \chi_1\chi_2 \to \text{SM SM}\\ \cancel{\chi_1\chi_1 \to \text{SM SM}}\end{array}\right.$$

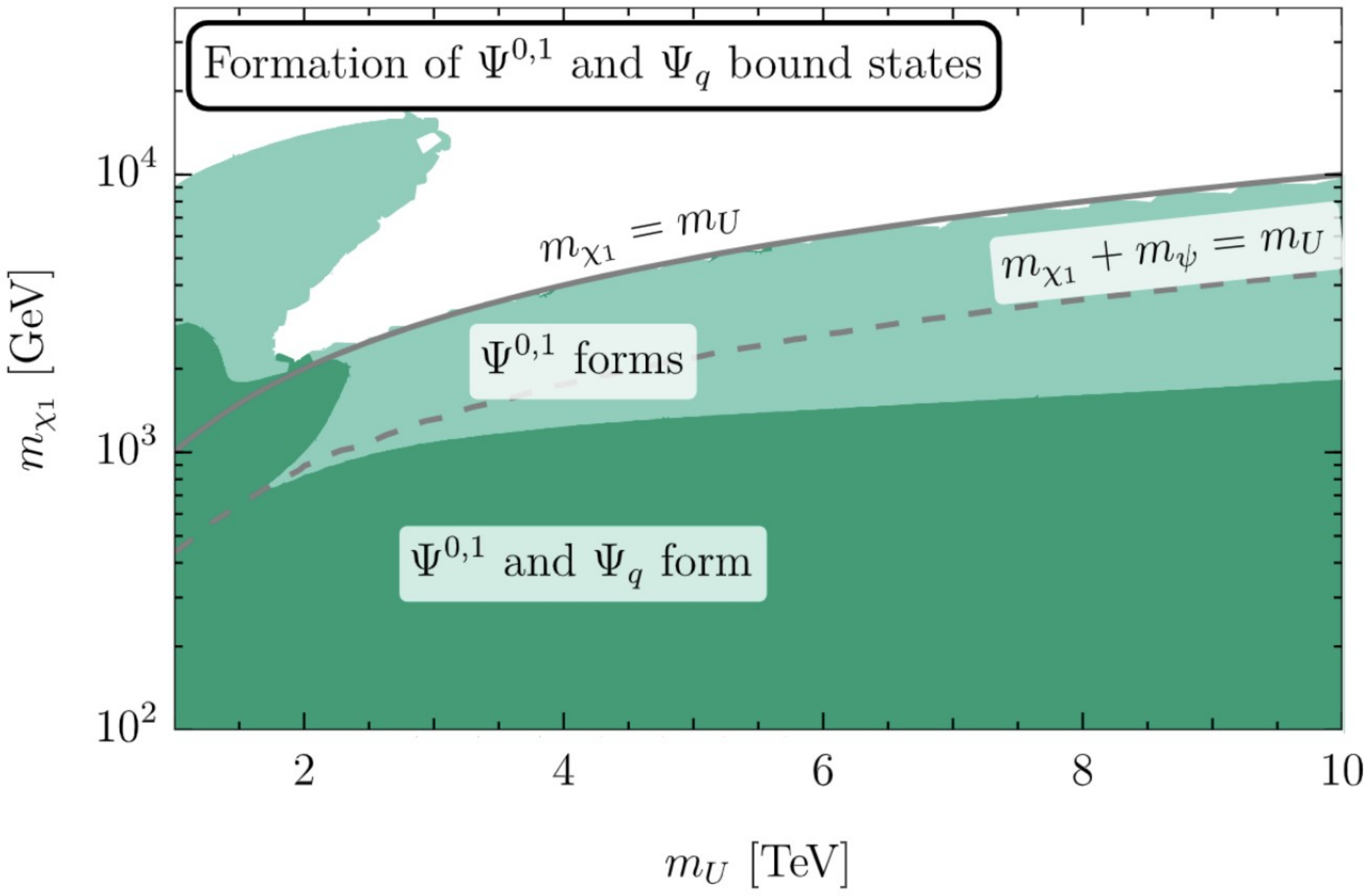


Most efficient channels



subleading

Psionium



Formation of $\Psi^{0,1}$ and Ψ_q bound states
$m_{\chi_1} = m_U$
$m_{\chi_1} + m_\psi = m_U$
$\Psi^{0,1}$ forms
$\Psi^{0,1}$ and Ψ_q form
10^4
10^3
10^2
m_{χ_1} [GeV]
2
4
6
8
10
m_U [TeV]

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