Collider pheno of MSSM4G

Sho IWAMOTO（岩本　祥）

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ATLAS internal meeting

Based on

Jonathan L. FENG, **SI**, Mohammad ABDULLAH, Benjamin LILLARD [1608.00283]
(UC Irvine) (Texas A&M) (UC Irvine)

- MSSM4G = MSSM + 4th (and 5th) generation

the well-known
SUSY particles

$\begin{pmatrix} T_4 \\ B_4 \end{pmatrix}$, t_4, τ_4 in QUE model

$\begin{pmatrix} T_4 \\ B_4 \end{pmatrix}$, b_4, τ_4, τ_5 in QDEE model

+ their SUSY partners

- "Minimum" set-up?
  - Dark matter : Bino-like neutralino $\tilde{\chi}^0$ → Overabundant problem
    $\Omega_{\mathrm{DM}} h^2 \gg 0.12$ (theory >> observed)
  - To solve the overabundance: τ_4 $\tilde{\tau}_4$

    extra vector-like lepton + slepton

    - Other particles are introduced to maintain GUT compatibility.

- MSSM4G = MSSM + 4th (and 5th) generation

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two "GUT-compatible" models

+ their SUSY partners

SU(2)-doublet quarks

SU(2)-singlet quark

SU(2)-singlet lepton(s)

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1. Extra VL-lepton τ_4 search

3. Extra VLQ search

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+ their SUSY partners $\tilde{\tau}_4$

2. Extra VL-slepton $\tilde{\tau}_4$ search

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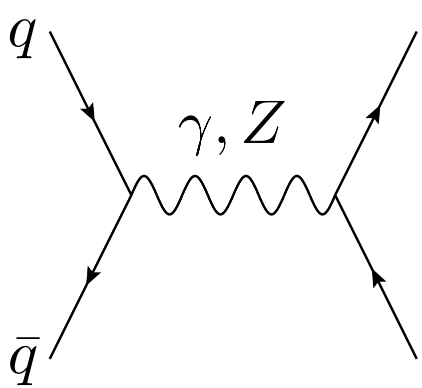
Vector-like lepton τ_4

- **Mass hierarchy** (to reduce DM) $\tilde{\tau}_4 \gtrsim \tilde{\chi}^0 > \tau_4$ (> LEP bounds) ~100 GeV
- **Production & Decay:**

$$pp \to \tau_4 \bar{\tau}_4, \quad \tau_4 \to W^- \nu_i,\ Z\, l_i^-,\ h\, l_i^-$$

"Drell-Yan" production



Decay through "SM-4G mixing"

$\mathcal{L} \ni \lambda_i'' H_\mathrm{d} L_i \bar{\tau}_4$ → τ_4-l_i mixing

If τ_4 is mixed with...

- mainly e : $\tau_4 \to W\nu_e,\ Ze,\ he$
  (i.e. $\lambda_1'' \gg \lambda_{2,3}''$)
- mainly μ : $\tau_4 \to W\nu_\mu,\ Z\mu,\ h\mu$
- mainly τ : $\tau_4 \to W\nu_\tau,\ Z\tau,\ h\tau$
- more than 2 gen. with a large extent
  → combinations of the above.
  (less motivated for flavor constraints)

(cf. SM Yukawa coupling $\mathcal{L}_\mathrm{SM} \ni (y_e)_{ij} H L_i \bar{E}_j$)

LHC is less sensitive... (yes, tau-tag...)

- a collider study: [1510.03456](1510.03456) (Kumer & Martin)

  "excluding any range of masses requires O(1000)/fb"

  $(\epsilon_\tau = 0.4,\ \epsilon_j = 0.001)$

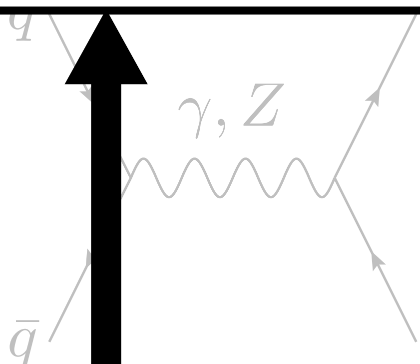
but testable at **Cherenkov Telescope Array (CTA).**

... observe gamma-ray from $\tilde{\chi}^0\tilde{\chi}^0 \to \tau_4\bar{\tau}_4 \to \tau\bar{\tau}$

~100 GeV

> LEP bounds)

$h\, l_i^-$



$\mathcal{L} \ni \lambda_i'' H_d L_i \tau$

You will see in LHC!

(next slides)

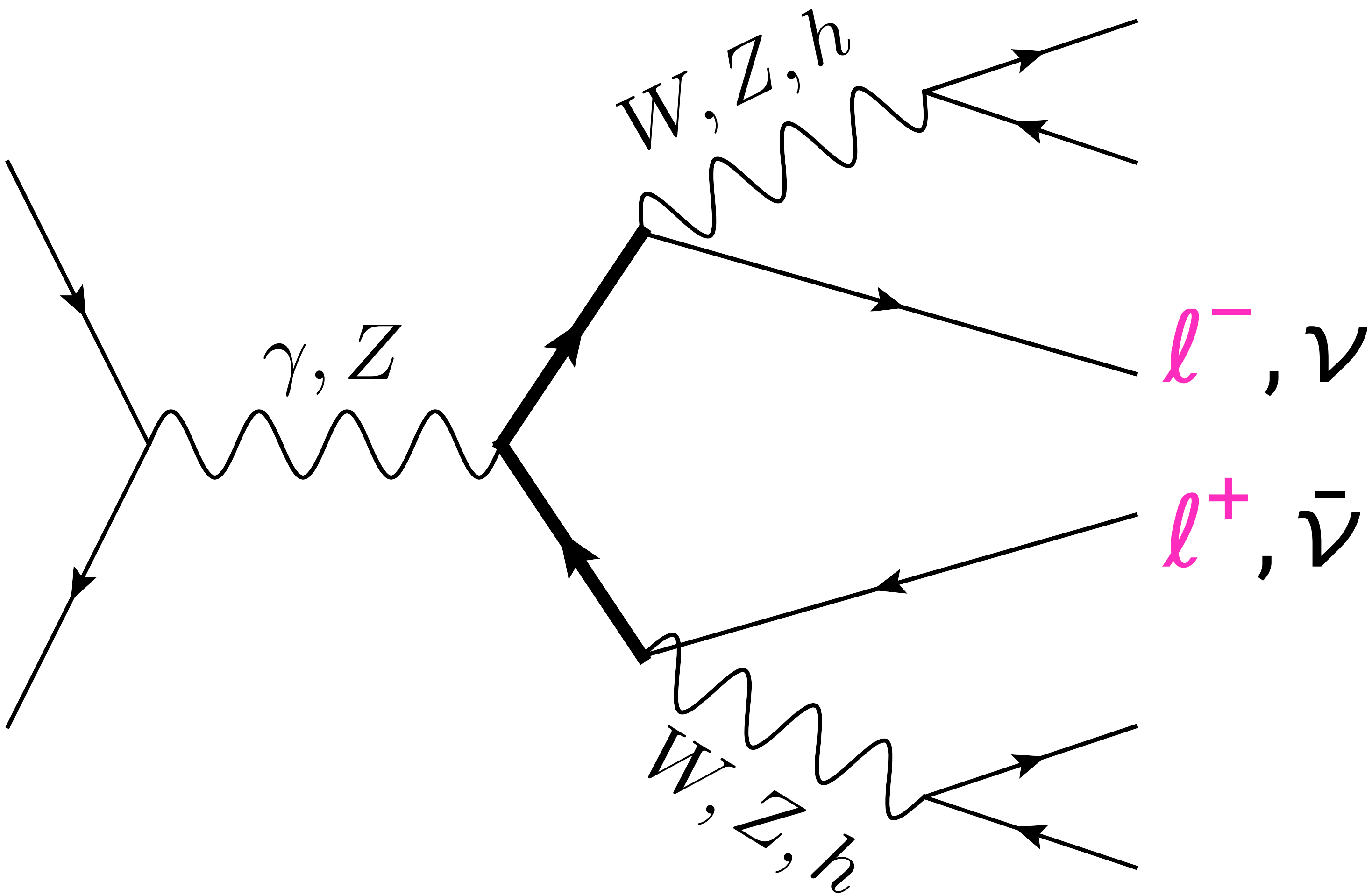
If τ_4 is mixed with....

- mainly e : $\tau_4 \to W\nu_e,\ Ze,\ he$
  (i.e. $\lambda_1'' \gg \lambda_{2,3}''$)
- mainly μ : $\tau_4 \to W\nu_\mu,\ Z\mu,\ h\mu$
- mainly τ : $\tau_4 \to W\nu_\tau,\ Z\tau,\ h\tau$
- more than 2 gen. with a large extent
  → combinations of the above.
  (less motivated for flavor constraints)

"Partially available" at LHC.
(down by the BR)

with l_i = (e or μ) $\equiv \ell$

- Vector-like lepton : $pp \to \tau_4 \bar{\tau}_4$, $\tau_4 \longrightarrow Z\, l_i^-,\ W^- \nu_i,\ h\, l_i^-$



How do you capture this signature?

with l_i = (e or μ) $\equiv \ell$

- Vector-like lepton : $pp \to \tau_4 \bar{\tau}_4$ $\quad \tau_4 \longrightarrow Z\, l_i^-,\ W^- \nu_i,\ h\, l_i^-$

  - Our "most basic" approach: **multi-$\ell^\pm$ (3−5$\ell^\pm$) search**

    → HL-LHC may exclude m_{τ_4} < 350 (425) GeV.

    QUE τ_4 QDEE τ_4&τ_5

    (same mass assumed)

$W\nu Z\ell \to 3\ell$ (1.3%)
$W\nu h\ell \to 3\ell$ (0.6%)
$h\ell Z\ell \to 3\ell$ (0.8%)
$h\ell h\ell \to 3\ell$ (0.8%)

$W\nu Z\ell \to 4^+\ell$ (0.4%)
$h\ell Z\ell \to 4^+\ell$ (1.0%)
$Z\ell Z\ell \to 4^+\ell$ (0.8%)
$h\ell h\ell \to 4^+\ell$ (0.2%)

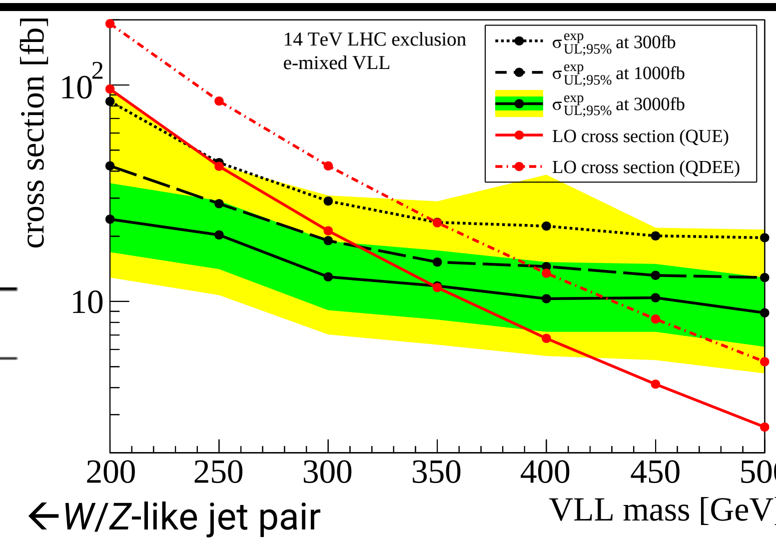
$3\ell \sim 4\%$ $\qquad$ $4\text{–}5\ell \sim 2\%$

	$WZ(j)$	$WZ(\ell)$	$ZZ(j)$	$ZZ(\ell)$
N_ℓ	≥ 3	≥ 4	≥ 4	≥ 5
N_j	≥ 2	< 2	≥ 2	—
$\lvert m_{jj} - m_W \rvert$	< 20 GeV	—	—	—
$\lvert m_{jj} - m_Z \rvert$	—	—	< 40 GeV	—
$\not{E}_T$	> 60 GeV	> 100 GeV	—	—
$N_{Z(\ell\ell)}$	—	—	≥ 1	≥ 1

←W/Z-like jet pair

←Large mET from ν&W

←Z-like lepton pair



- Snowmass BKG set is used.
  - MG5−Pythia−Delphes + NLO *K*-factor
  - di-boson + *tt* dominated
- Signal by FR−MG5aMC−Pythia−Delphes (LO)

- PT cut: $(\ell_1, \ell_2, \ell_i) > (120, 60, 20)\,\text{GeV}, \ (j) > 20\,\text{GeV}.$
- **tau-tag / b-tag not used (avoided)**
- Uncertainties = stat. + 20% syst.

with l_i = (e or μ) $\equiv \ell$

- Vector-like lepton : $pp \to \tau_4 \bar{\tau}_4$ $\quad \tau_4 \longrightarrow Z\, l_i^-,\ W^-\nu_i,\ h\, l_i^-$
  - ➢ Our "most basic" approach: **multi-$\ell^\pm$ (3−5$\ell^\pm$) search**

    → HL-LHC may exclude m_{τ_4} < 350 (425) GeV.

    QUE τ_4 QDEE τ_4 & τ_5 (same mass assumed)

$$\left\{\begin{array}{l} W\nu Z\ell \to 3\ell\ (1.3\%) \\ W\nu h\ell \to 3\ell\ (0.6\%) \\ h\ell Z\ell \to 3\ell\ (0.8\%) \\ h\ell h\ell \to 3\ell\ (0.8\%) \end{array}\right. \qquad \left\{\begin{array}{l} W\nu Z\ell \to 4^+\ell\ (0.4\%) \\ h\ell Z\ell \to 4^+\ell\ (1.0\%) \\ Z\ell Z\ell \to 4^+\ell\ (0.8\%) \\ h\ell h\ell \to 4^+\ell\ (0.2\%) \end{array}\right.$$

$3\ell \sim 4\%$ $\qquad$ 4–$5\ell \sim 2\%$

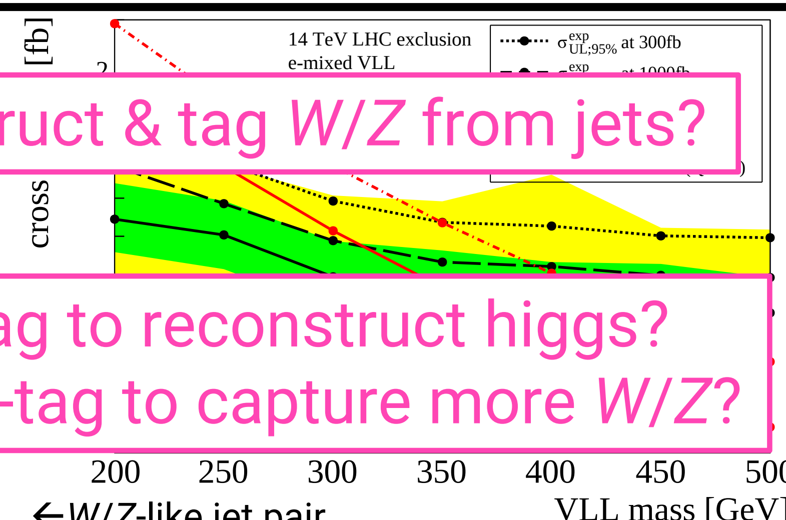
Reconstruct & tag *W/Z* from jets?

	$WZ(j)$	$WZ(\ell)$	$ZZ(j)$	
N_ℓ	≥ 3	≥ 4	≥ 4	
N_j	≥ 2	< 2	≥ 2	
$\lvert m_{jj} - m_W \rvert$	< 20 GeV	—	—	—
$\lvert m_{jj} - m_Z \rvert$	—	—	< 40 GeV	—
$\not{E}_T$	> 60 GeV	> 100 GeV	—	—
$N_{Z(\ell\ell)}$	—	—	≥ 1	$\geq$

←*W/Z*-like jet pair

←Large mET from ν&*W*

←Z-like lepton pair



b-tag to reconstruct higgs?
tau-tag to capture more *W/Z*?

- Snowmass BKG set is used.
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- Signal by FR−MG5aMC−Pythia−Delphes (LO)
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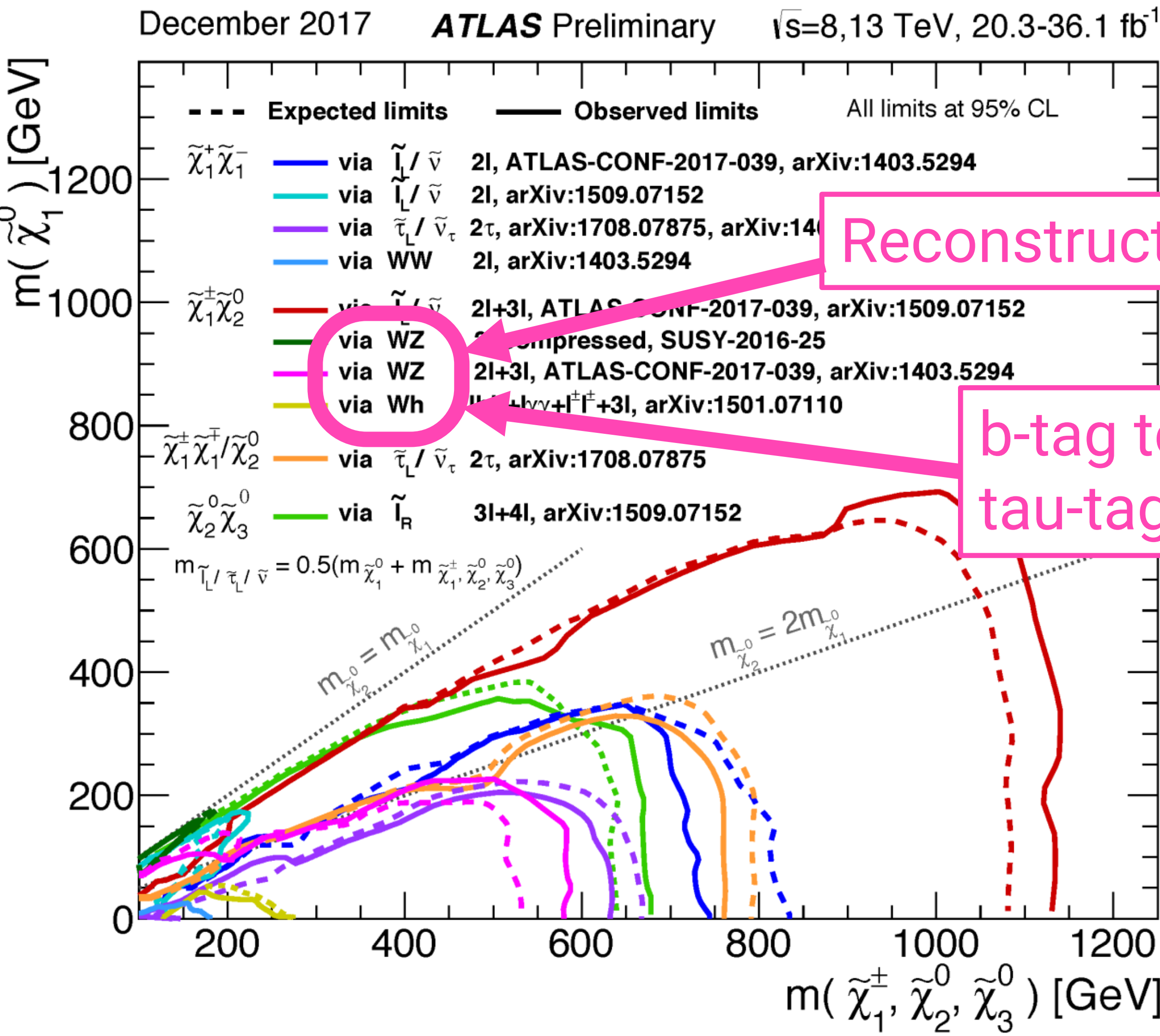
- Uncertainties = stat. + 20% syst.

- Boson (*W*/*Z*/h)-tag is desired also in **SUSY EWKino** searches.

muon *g*−2 anomaly "predicts" ≲1TeV EWKino.

→ cf. works by Endo, Hamaguchi, Iwamoto, Kitahara, Yanagi, Yoshinaga [1303.4256] [1309.3065] [1704.05287]



Reconstruct & tag *W*/*Z* from jets?

b-tag to reconstruct higgs?
tau-tag to capture more *W*/*Z*?

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    (theory >> observed)
  - To solve the overabundance: τ_4 $\tilde{\tau}_4$
    extra vector-like lepton + slepton
    - Other particles are introduced to maintain GUT compatibility.

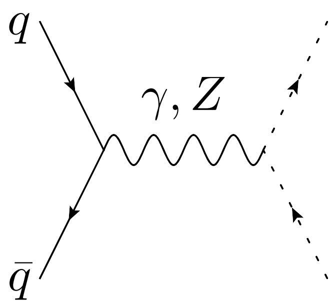
■ Vector-like slepton $\tilde{\tau}_4$

- **Mass hierarchy** (to reduce DM) $\tilde{\tau}_4 \gtrsim \tilde{\chi}^0 > \tau_4$ (> LEP bounds ~100 GeV)
- **Production & Decay:**

$$pp \to \tilde{\tau}_4 \tilde{\tau}_4^*, \qquad \tilde{\tau}_4 \to \tilde{\chi}^0\, l_i^-$$

* All the other channels are kinematically closed.

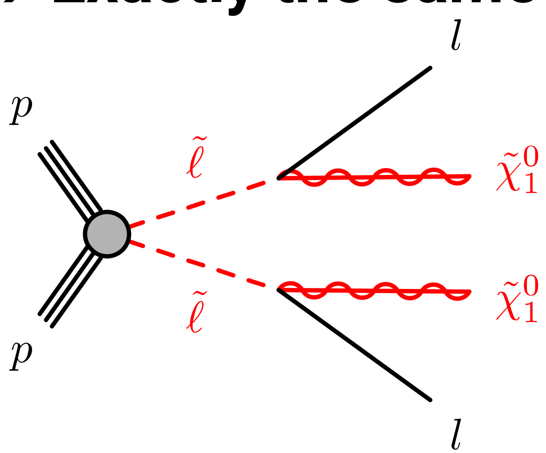
"Drell-Yan" production

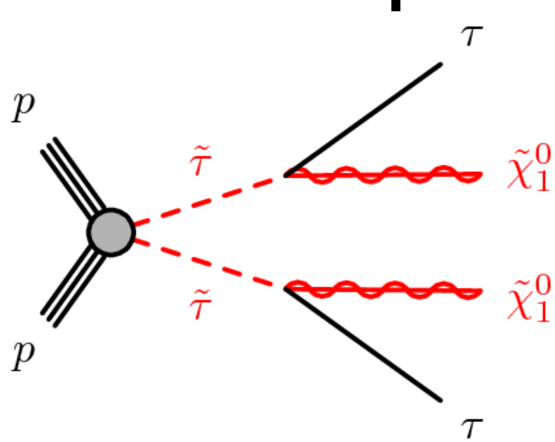


(again) Decay through "SM-4G mixing"

* $\tilde{\tau}_4$ has the same mixing pattern as τ_4 (in QUE model).

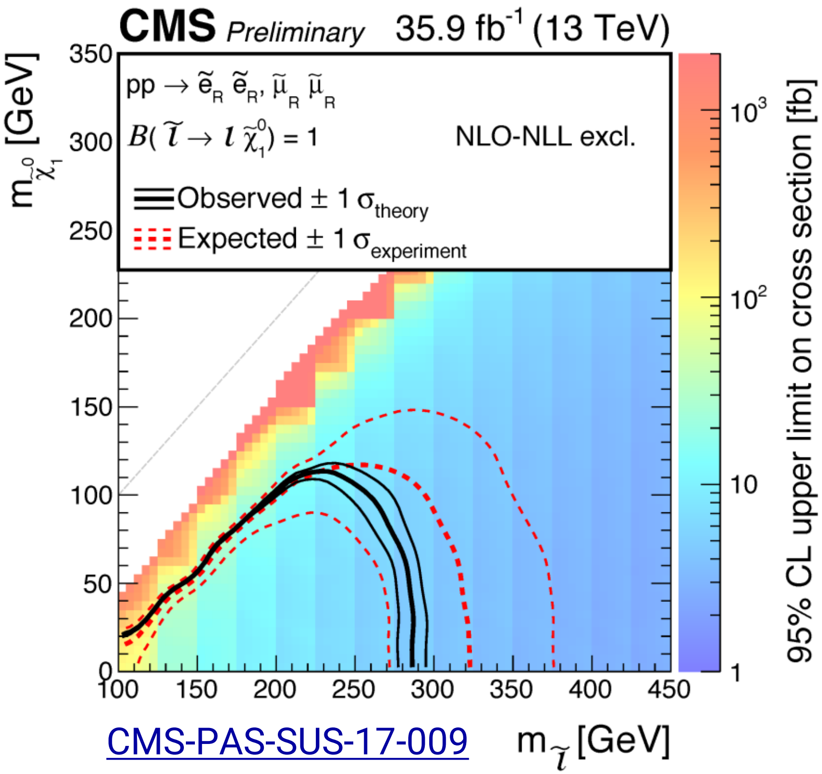
→ Exactly the same as MSSM slepton $\tilde{l}_R$





- Vector-like slepton $pp \to \tilde{\tau}_4 \tilde{\tau}_4^*$, $\tilde{\tau}_4 \to l_i \tilde{\chi}^0$

$l_i =$ e or μ : CMS result

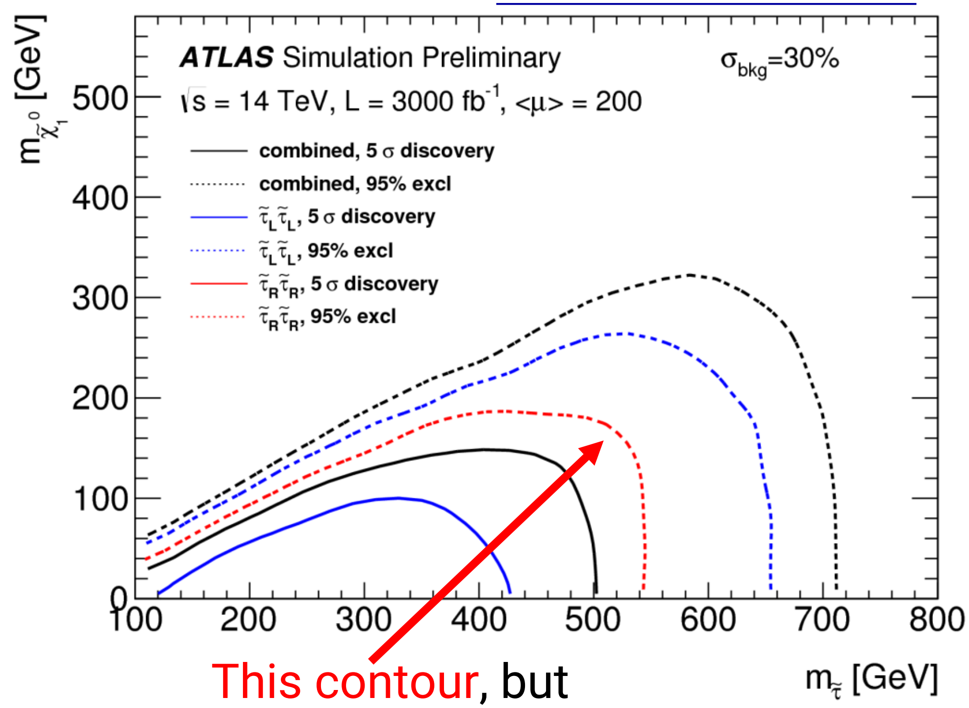


CMS-PAS-SUS-17-009

(But x1 (x2) production x.s. expected for QUE (QDEE) model.)

$l_i = \tau$: ATLAS HL-LHC simulation

ATL-PHYS-PUB-2016-021



This contour, but with x2 (x4) production x.s. for QUE (QDEE) model.

Nothing to add; thanks for your work & please continue!

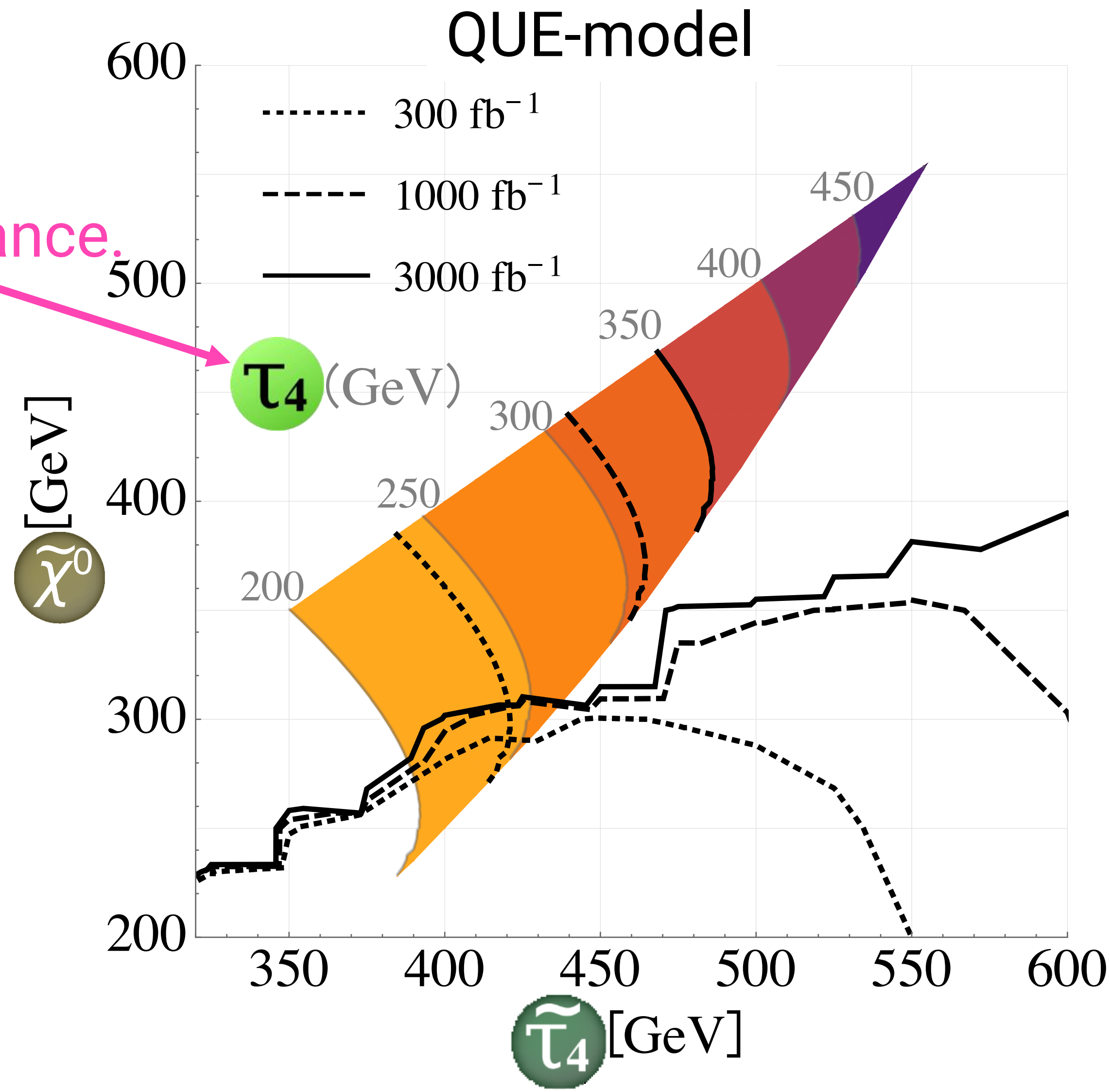
- DM overabundant problem if bino-like $\tilde{\chi}^0$ is DM.
- A solution: **MSSM4G = 4th-gen. vector-like (s)lepton τ_4 $\tilde{\tau}_4$.**
  - τ_4 : multi-lepton + multi-(Z/W/h) signature → dedicated searches.
  - $\tilde{\tau}_4$: 2-lepton + mET signature = MSSM slepton searches.

  ... **Decays through mixing** : if with (e or μ) → sensitive @ LHC
  τ → less sensitive... rather at CTA.

  - **Long-lived** if mixing is tiny.
    → Long-lived charged (τ_4 $\tilde{\tau}_4$) & colored (VLQ) particle searches.

- if 4G is mixed with *e* or *μ*:

Fixed by DM abundance.



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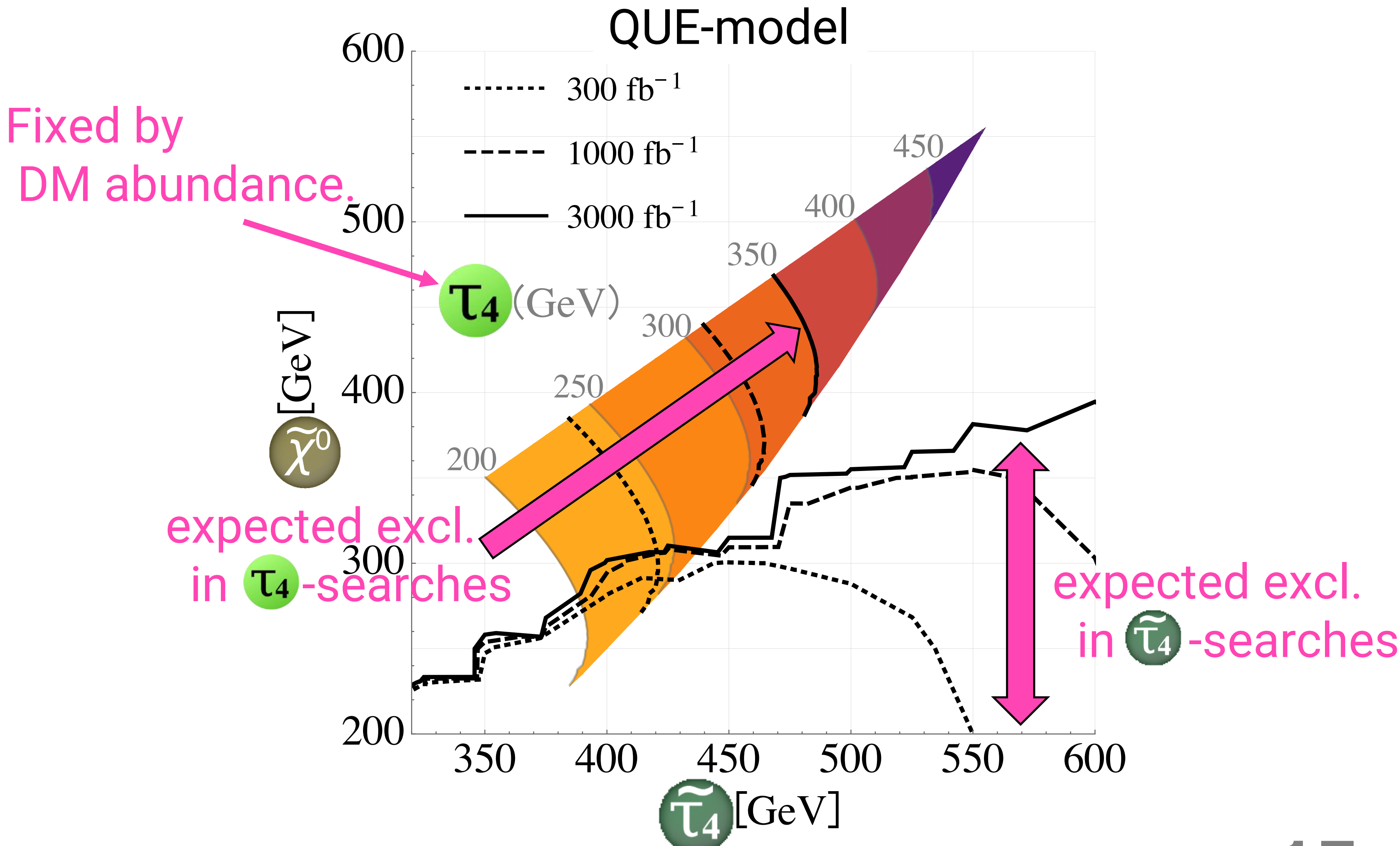

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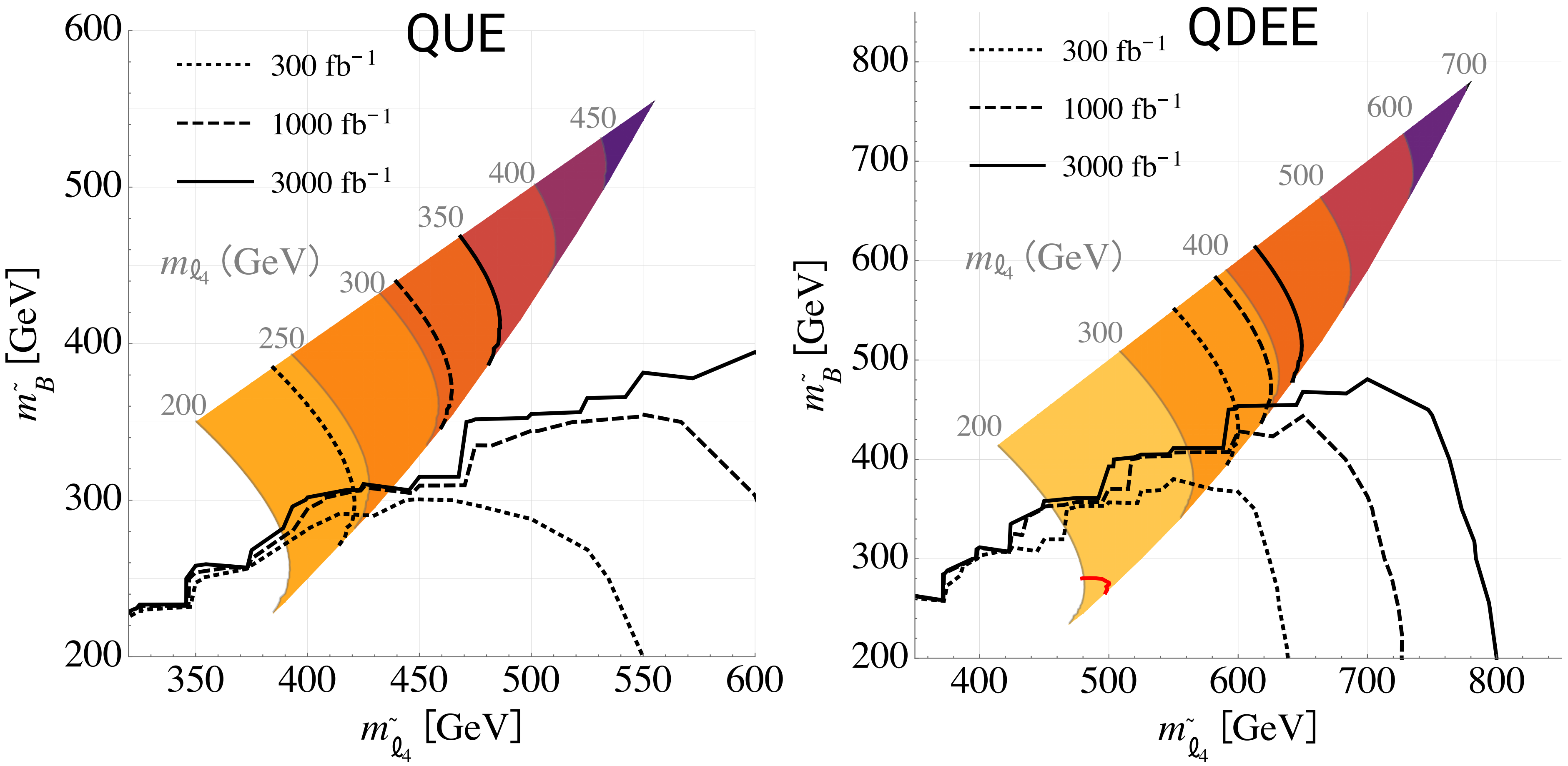

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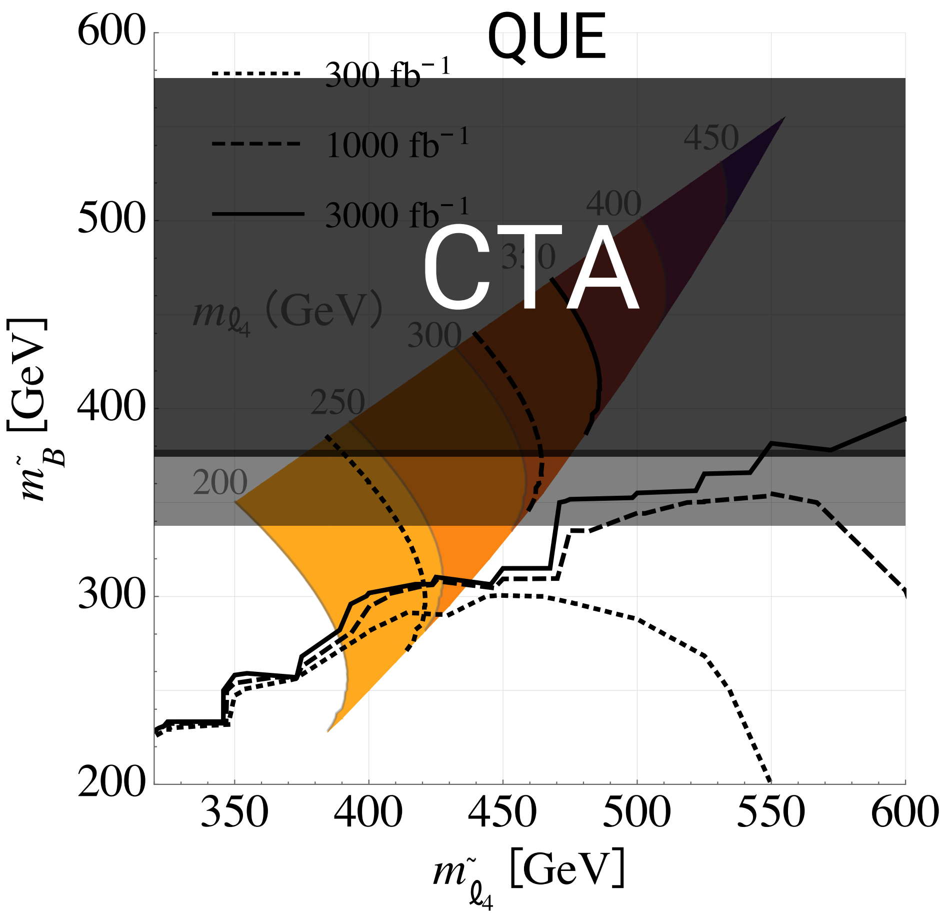
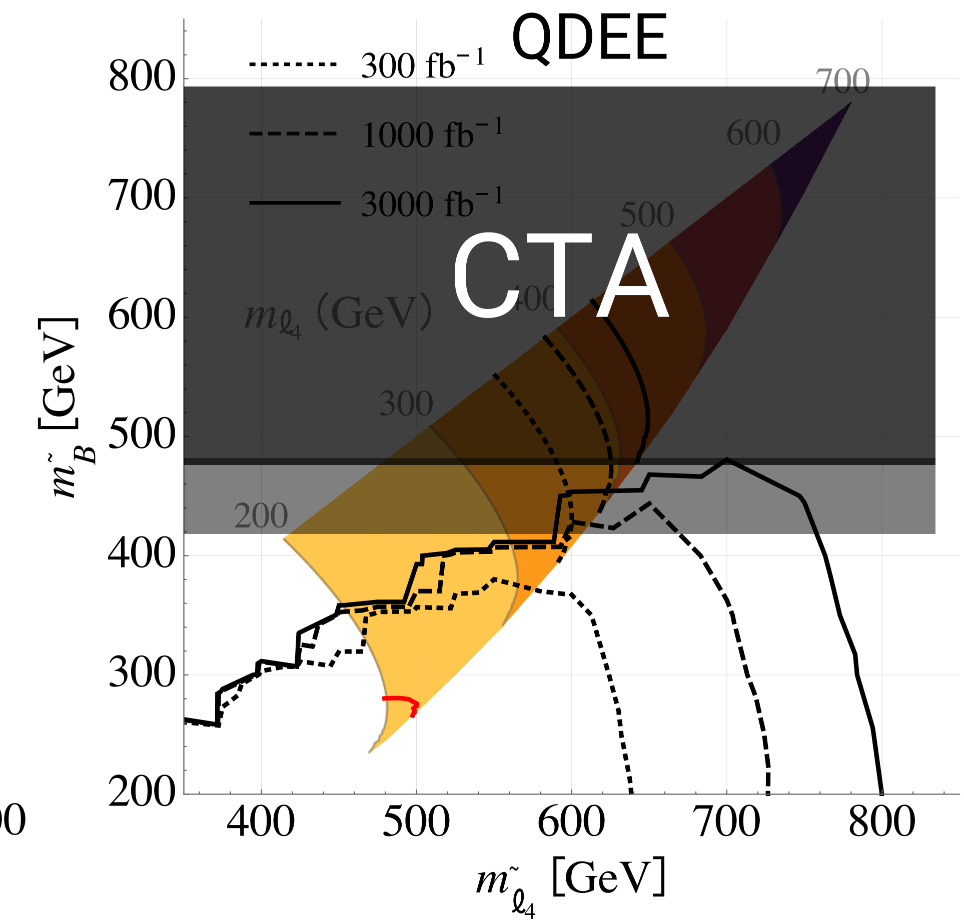
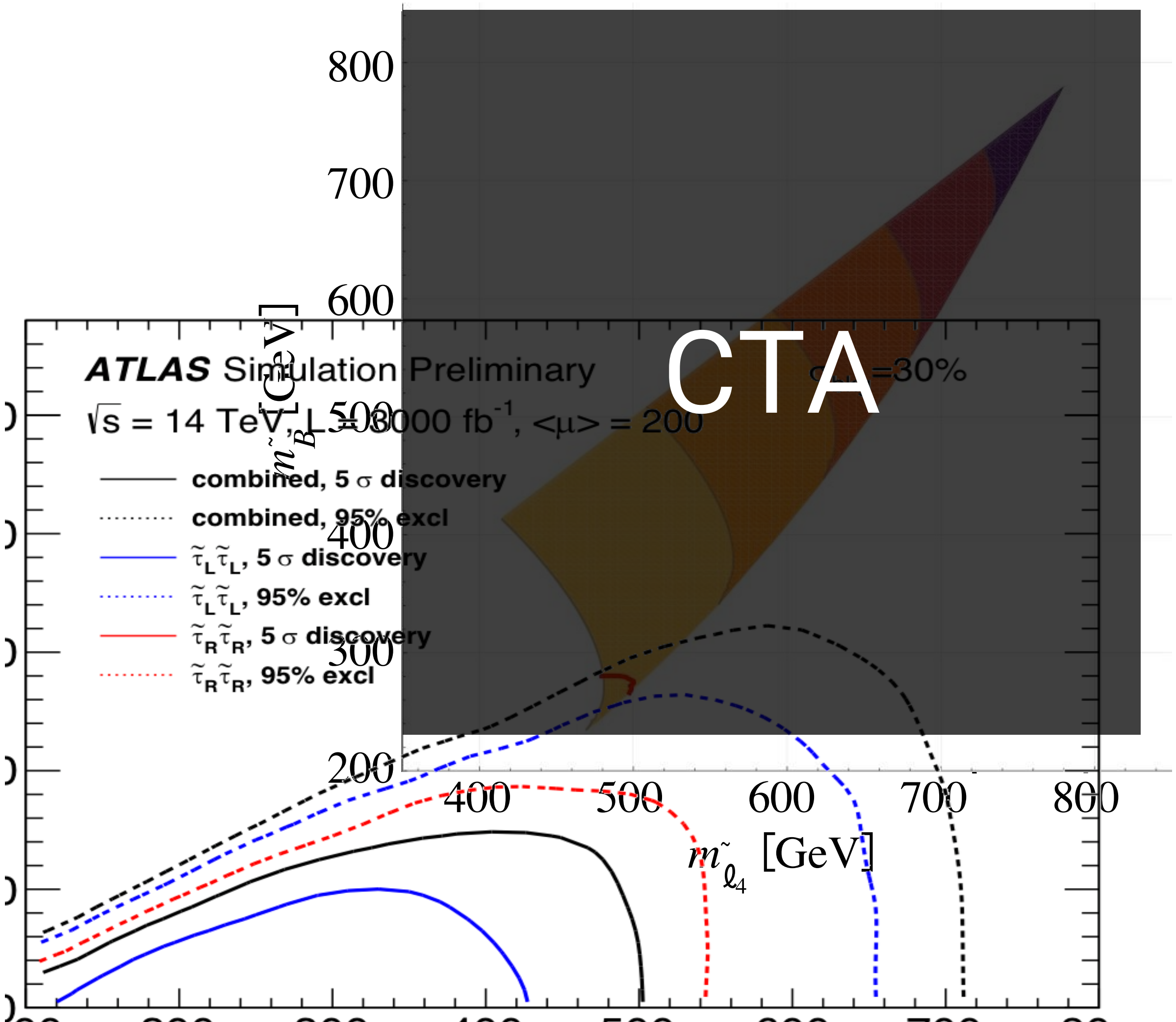




LHC + CTA cover the whole region!

- if 4G is mixed with τ:

QDEE (but similar for QUE)



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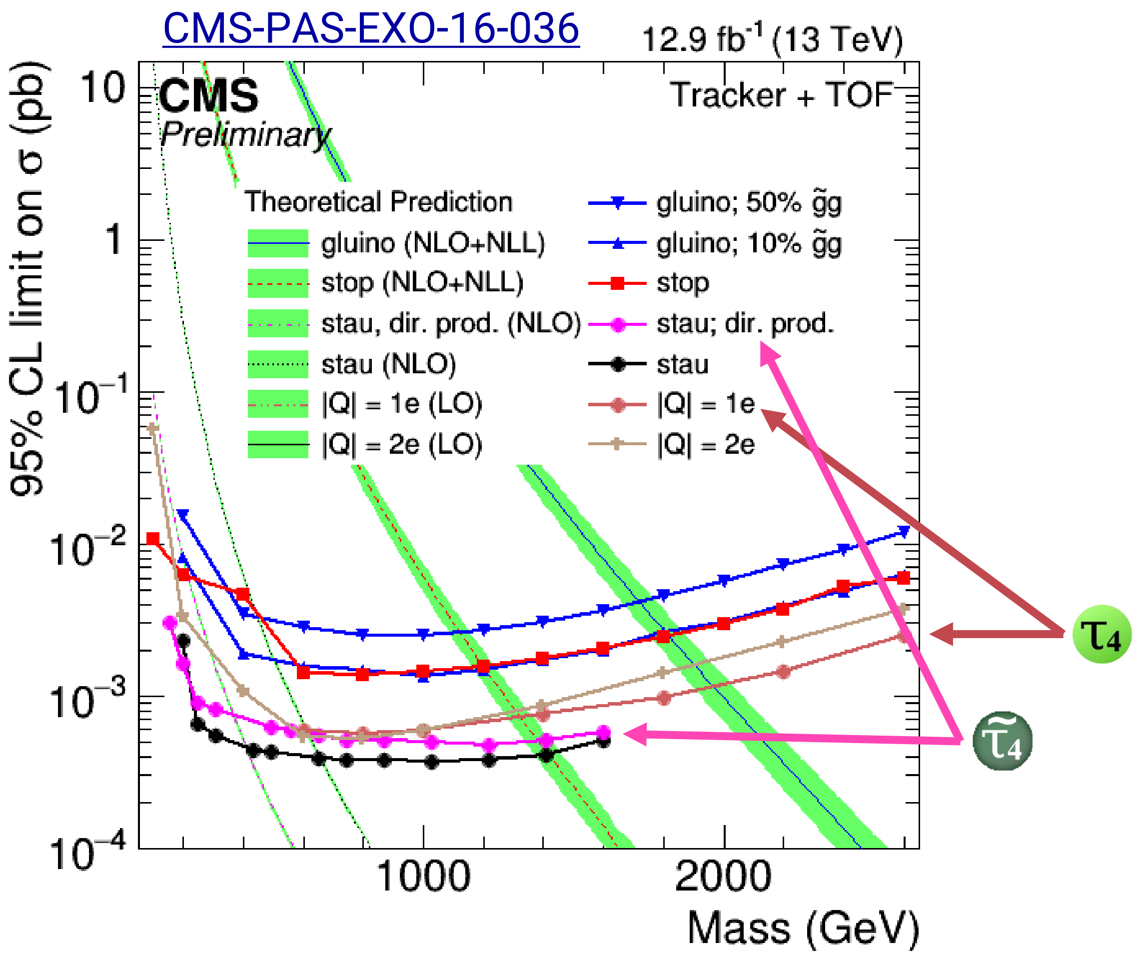

(but theoretical production is not the same; x1—4 depending on models.)

* "displaced jets / leptons" are also possible.

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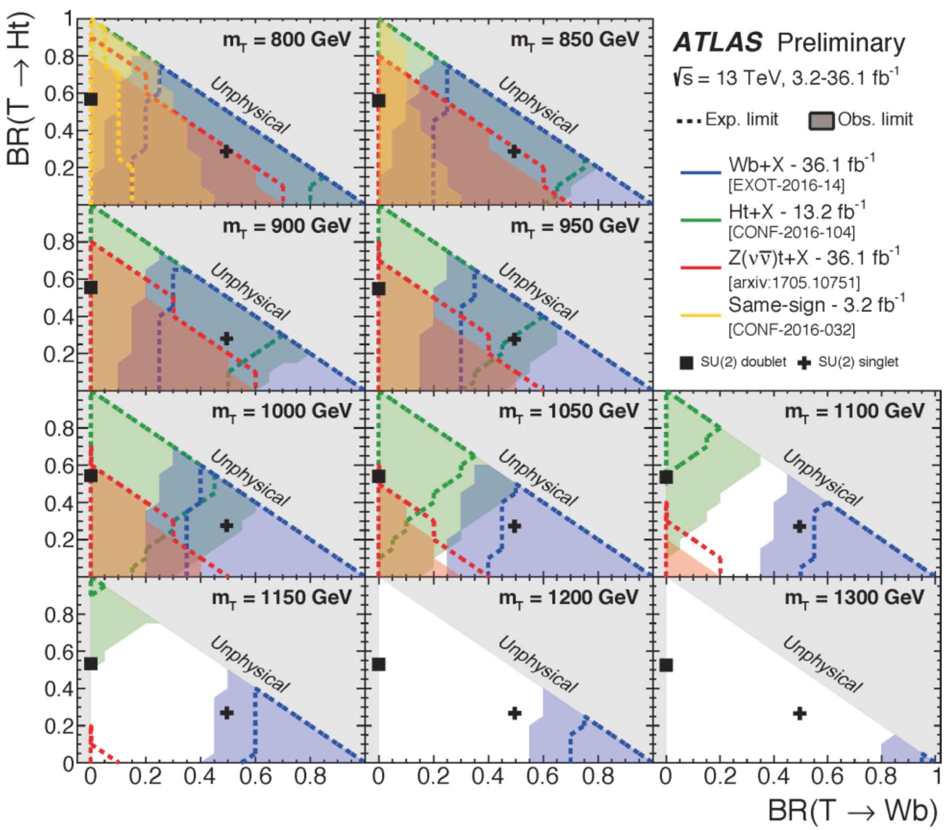
$$pp \to b_4\bar{b}_4, \; b_4 \to Wq, Zq, hq$$

Production: similar to top-quark

Decay: similar to τ_4 ("through mixing")

- Assuming mixing w. 3rd-gen. only,



[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults]

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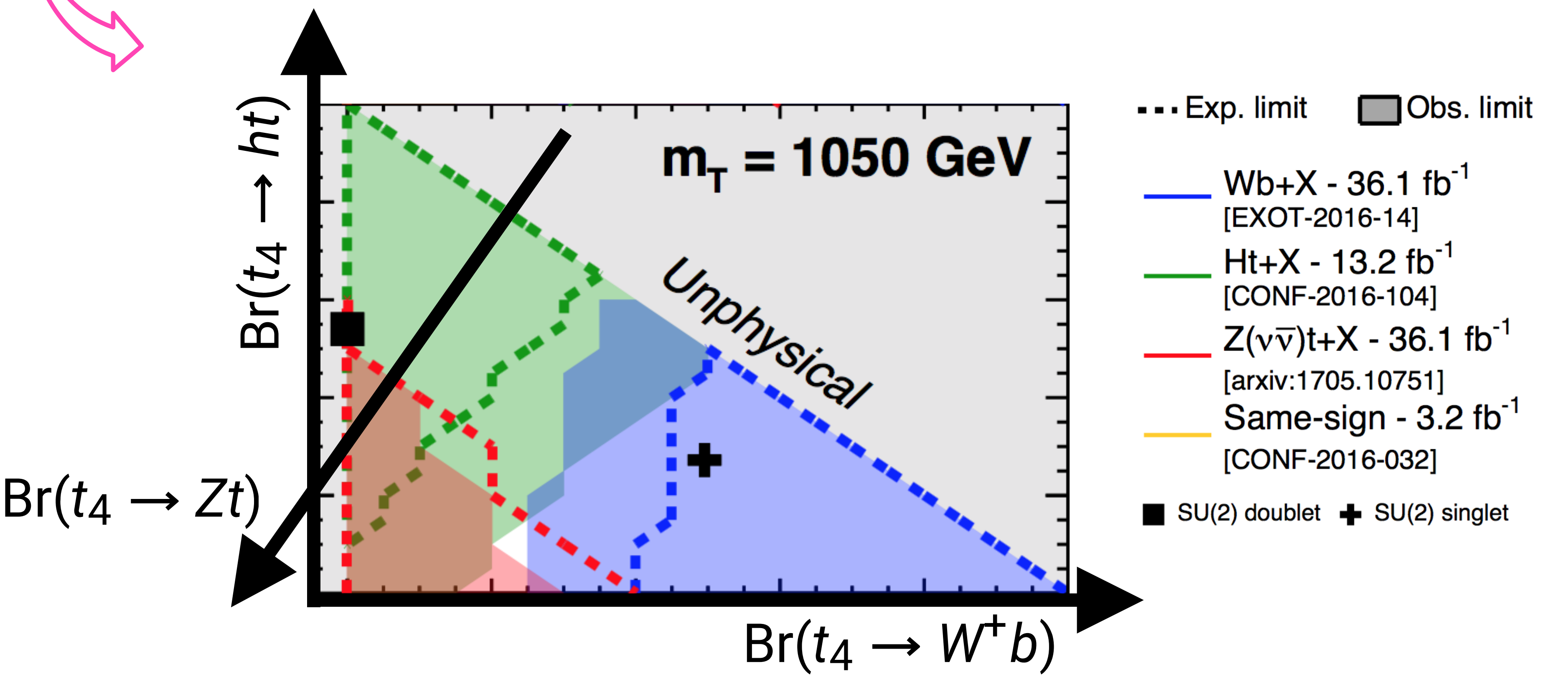

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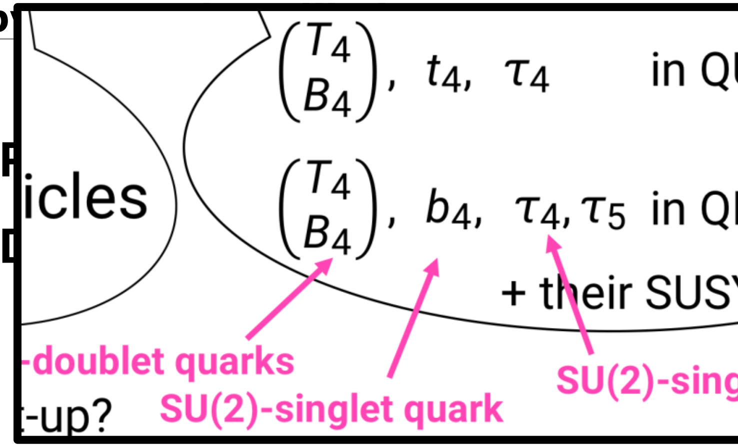

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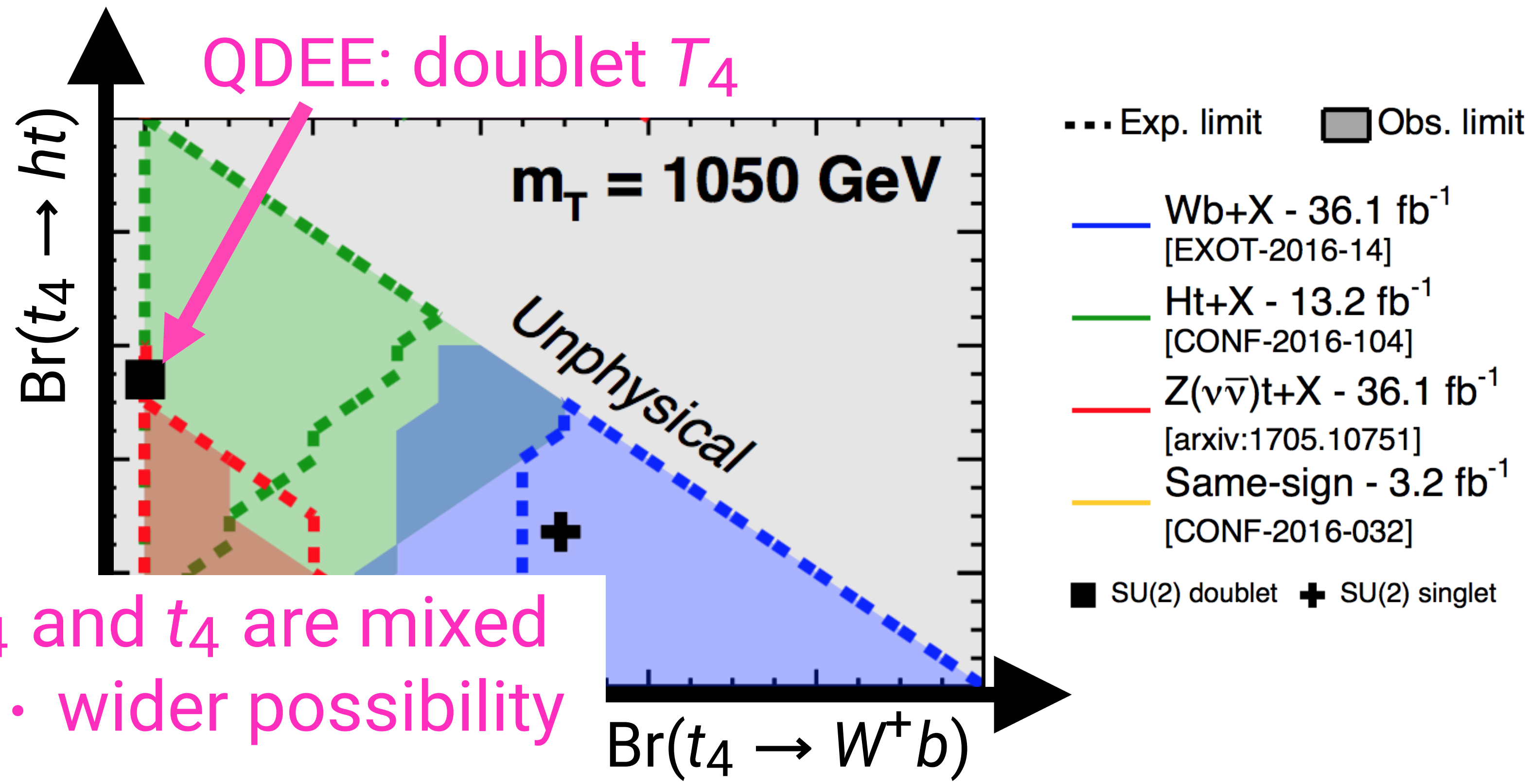
  - Assuming mixing w. 3[rd]-gen. only,

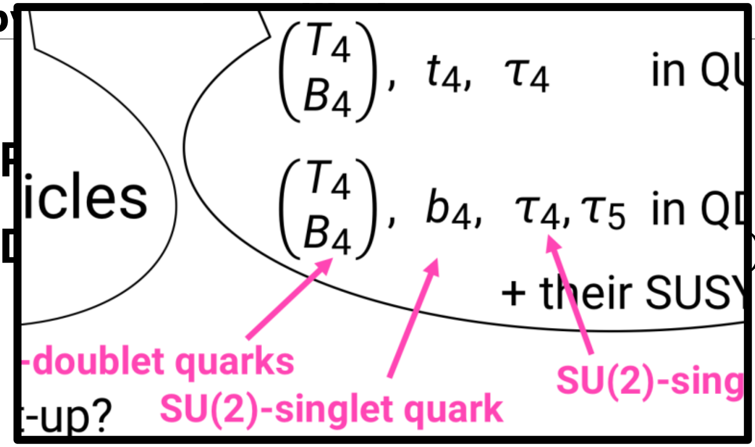
QDEE: doublet T_4



QUE: T_4 and t_4 are mixed

$\cdots$ wider possibility

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults]



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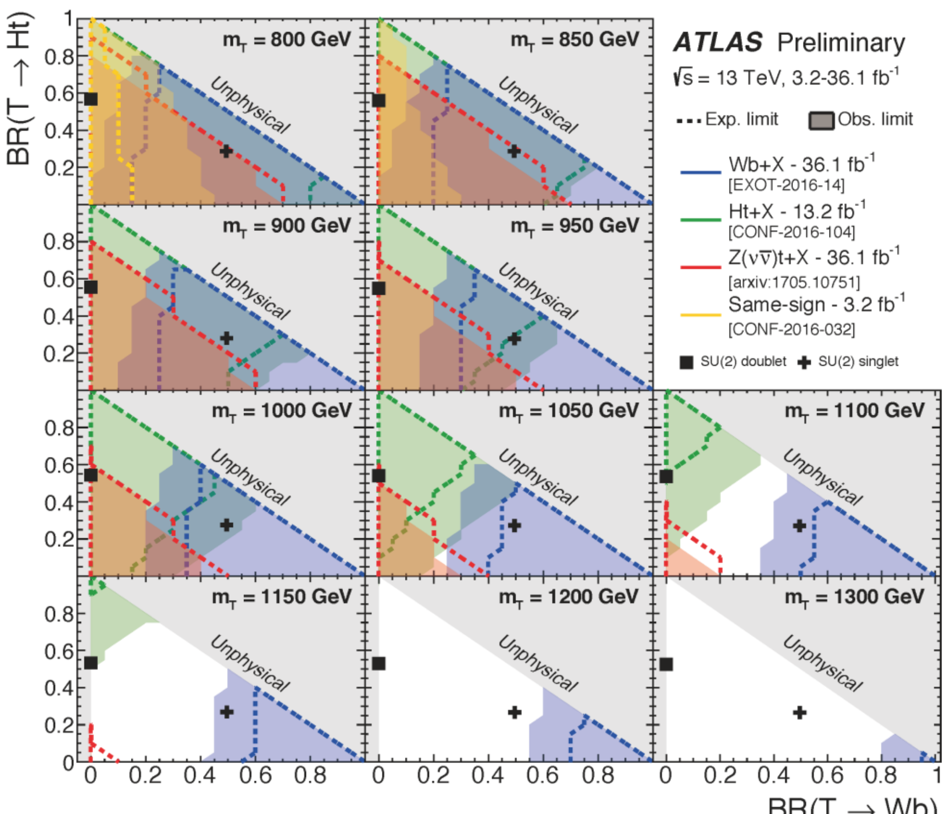

✓ **Very impressive to me;**
no comments/requests from me.
thank you so much.

✓ Less-motivated possibilities:

- mixing with 1st/2nd gen.
- mixing with multiple gen.
  ... flavor constraints

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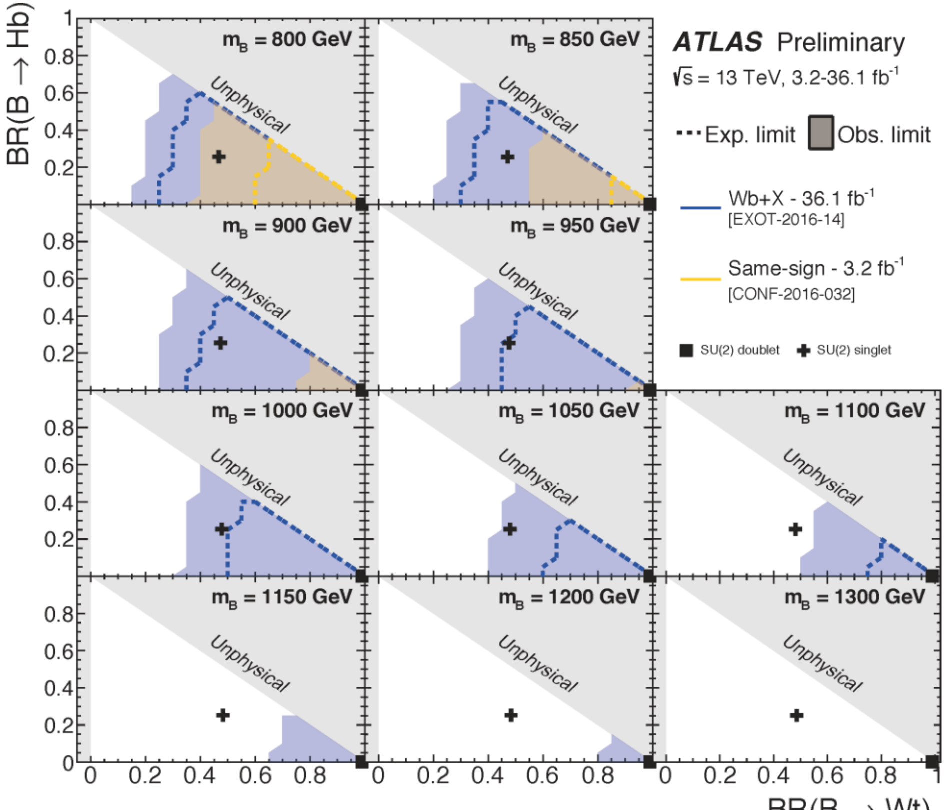

$b_4 \bar{b}_4 \to (W^- t)(W^+ \bar{t})$: done

$(Zb)(Z\bar{b})$

$(hb)(h\bar{b})$

... Z/h-tagging?

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- A solution: **MSSM4G = 4th-gen. vector-like (s)lepton τ_4 $\tilde{\tau}_4$.**
  - τ_4 : multi-lepton + multi-(Z/W/h) signature → dedicated searches.
  - $\tilde{\tau}_4$: 2-lepton + mET signature = MSSM slepton searches.

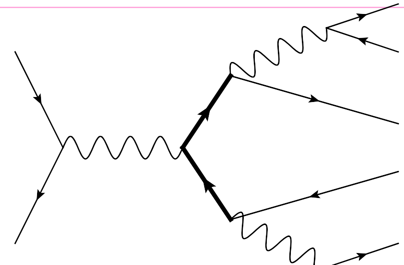
  ... Decays through mixing : if with (e or μ) → sensitive @ LHC
  τ → less sensitive... tau-tagging!

  - **Long-lived** if mixing is tiny.
    → Long-lived charged (τ_4 $\tilde{\tau}_4$) & colored (VLQ) particle searches.
- We can further make GUT-compatible : adding VLQ.
  - $(T', B'), t', b'$ → VLQ-searches done by ATLAS.

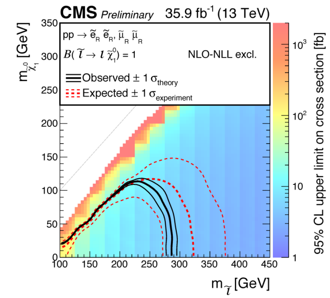
✓ Most channels are covered! Thanks for your work!

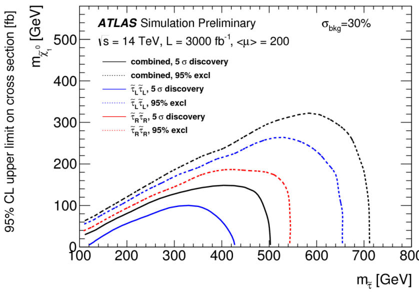
$(g-2)_\mu \Rightarrow m \lesssim 1\,\text{TeV}$

✓ This is also expected from SUSY EWKino.
→ Interesting! Improvements by "boson-tagging"?



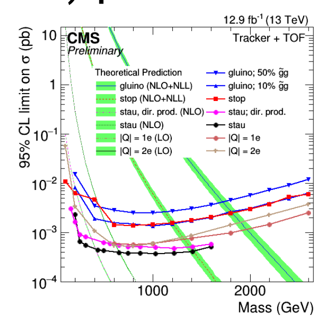
multi-lepton + multi-(Z/W/h) signature



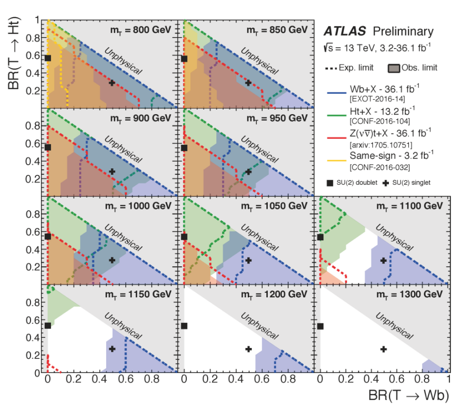


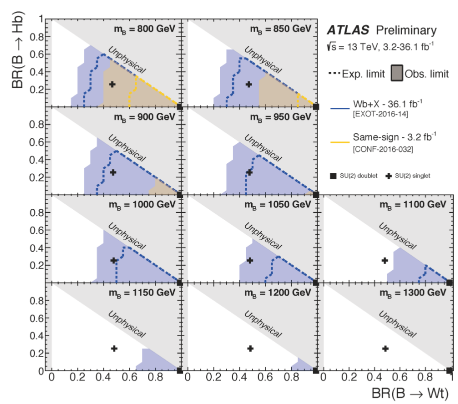
MSSM slepton searches.

Long-lived charged (τ_4 $\tilde{\tau}_4$) & colored (VLQ) particle searches.



VLQ-searches





More data from VLL search

TABLE IV: Selection flow of the background events in the vector-like lepton search. Upper bounds on the number of events in each SR, $N_{\rm UL}$, are shown for three values of integrated luminosity, where systematic uncertainty of 20% as well as statistical uncertainty is included.

	background cross section [fb]				$N_{\rm UL}$		
	di-boson	tri-boson	top	total	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
$N_\ell \geq 3$	222	5.1	13.4	249	—	—	—
$WZ(j)^-$	0.071	0.013	0.082	0.166	25.1	70.4	200
$WZ(j)^Z$	0.643	0.071	0.183	0.898	111	359	1060
$WZ(\ell)^-$	0.014	0.025	0.017	0.056	11.9	27.4	71.1
$WZ(\ell)^Z$	< 0.001	0.005	0.003	0.008	5.1	7.9	14.5
$ZZ(j)^0$	0.194	0.016	0.058	0.268	37.2	111	321
$ZZ(j)^J$	0.064	0.007	0.022	0.093	16.4	41.8	114
$ZZ(j)^L$	0.182	0.012	0.024	0.218	31.2	91.7	263
$ZZ(j)^Z$	0.020	0.004	0.019	0.043	10.2	22.2	55.7
$ZZ(j)^{JL}$	0.060	0.005	0.009	0.075	14.2	35.3	94.3
$ZZ(j)^{JZ}$	0.008	0.001	0.008	0.017	6.7	11.9	25.6
$ZZ(j)^{LZ}$	0.020	0.004	0.019	0.043	10.2	22.2	55.9
$ZZ(j)^{JLZ}$	0.008	0.001	0.008	0.017	6.7	11.9	25.5
$ZZ(\ell)$	< 0.001	0.005	< 0.001	0.005	4.7	6.8	11.5
$ZZ(\ell)^{<2}$	< 0.001	0.003	< 0.001	0.004	4.2	5.8	9.2
$ZZ(\ell)^{<1}$	< 0.001	0.001	< 0.001	0.001	3.6	4.5	6.3

Z-flag for $WZ(j)$: a Z-like $\ell\ell$ (SFOS, $|m_{\ell\ell} - m_Z| < 10\,\mathrm{GeV}$)
Z-flag for $WZ(\ell)$: a Z-like $\ell\ell$ in 3^+rd-leading leptons
J-flag for $ZZ(j)$: a Z-like jj (10 GeV)
L-flag for $ZZ(j)$: a Z-like $\ell\ell$ in 2^+nd-leading leptons
Z-flag for $ZZ(j)$: leading-lepton does NOT form Z-like pairs
$ZZ(\ell)$ divided by number of jets

TABLE V: Selection flow of the signal events in searches for the e- or μ-mixed τ_4 in the QUE model, displayed as a signal cross section in fb. SRs marked with $*$, † and ‡ are the most sensitive for exclusion at $\mathcal{L} = 300$, 1000, and 3000 fb^{-1}, respectively.

m_τ [GeV], mixing	200, e	200, μ	300, e	300, μ	400, e	400, μ
total	95.7	96.0	21.2	21.2	6.76	6.74
$N_\ell \geq 3$	2.23	2.42	0.634	0.671	0.231	0.230
$WZ(j)^-$	0.018	0.022	0.020	0.024	0.011	0.012
$WZ(j)^Z$	0.049	0.063	0.034	0.036	0.014	0.014
$WZ(\ell)^Z$	0.012	0.014	$0.008^‡$	0.008	0.003	$0.004^‡$
$ZZ(j)^0$	0.066	0.065	0.035	0.044	0.015	0.015
$ZZ(j)^J$	0.035	0.033	0.018	0.023	0.008	0.007
$ZZ(j)^L$	0.045	0.048	0.026	0.031	0.011	0.012
$ZZ(j)^Z$	0.039^*	0.042^*	$0.025^{*†}$	$0.029^†$	0.010^*	$0.012^†$
$ZZ(j)^{JL}$	0.025	0.025	0.013	0.016	0.006	0.006
$ZZ(j)^{JZ}$	0.021	0.022	0.013	$0.015^‡$	0.005	0.006
$ZZ(j)^{LZ}$	0.039	0.042	0.025	0.029^*	$0.010^†$	0.012^*
$ZZ(j)^{JLZ}$	0.021	0.022	0.013	0.015	0.005	0.006
$ZZ(\ell)$	$0.015^{†‡}$	$0.014^{†‡}$	0.005	0.007	$0.003^‡$	0.002
$ZZ(\ell)^{<2}$	0.010	0.009	0.003	0.004	0.002	0.001
$ZZ(\ell)^{<1}$	0.004	0.003	0.001	0.002	8×10^{-4}	6×10^{-4}

Z-flag for $WZ(j)$: a Z-like $\ell\ell$ (SFOS, $|m_{\ell\ell} - m_Z| < 10$ GeV)
Z-flag for $WZ(\ell)$: a Z-like $\ell\ell$ in 3^+rd-leading leptons
J-flag for $ZZ(j)$: a Z-like jj (10 GeV)
L-flag for $ZZ(j)$: a Z-like $\ell\ell$ in 2^+nd-leading leptons
Z-flag for $ZZ(j)$: leading-lepton does NOT form Z-like pairs
$ZZ(\ell)$ divided by number of jets

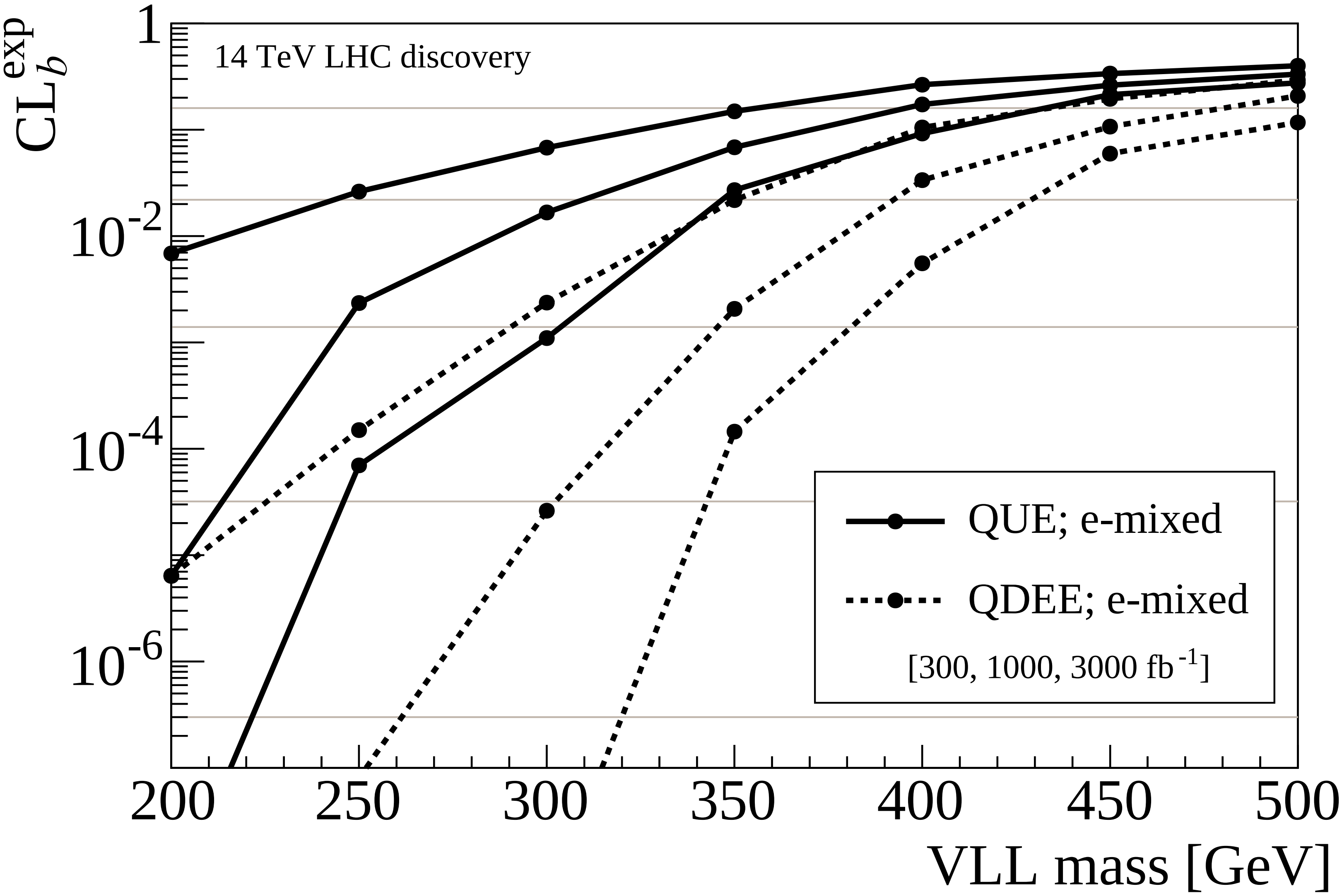

14 TeV LHC discovery
CL_b^{exp}
1
10^{-2}
10^{-4}
10^{-6}
200
250
300
350
400
450
500
VLL mass [GeV]
QUE; e-mixed
QDEE; e-mixed
[300, 1000, 3000 fb^{-1}]

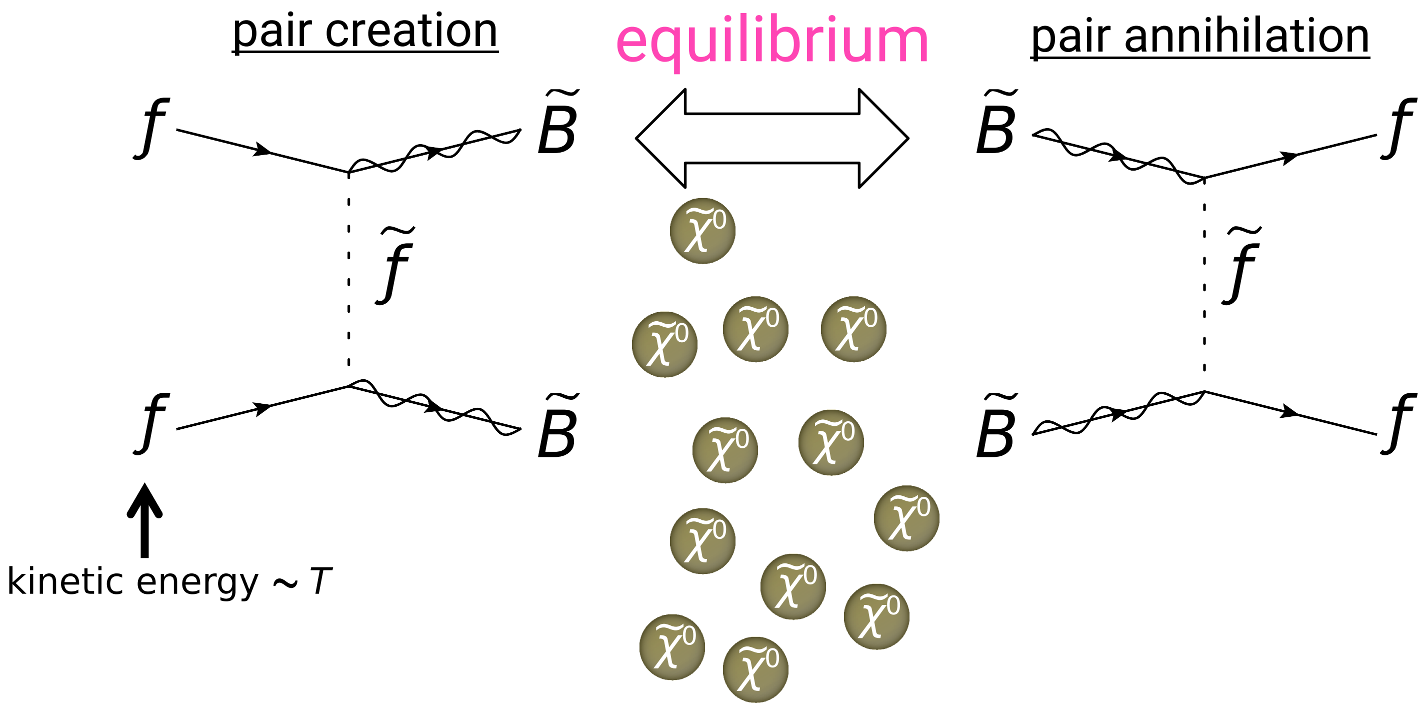
TABLE II: Future prospects for searches for vector-like leptons at the 14 TeV LHC for three values of integrated luminosity. The first table is for the QUE models, and the second for the QDEE models. We consider vector-like leptons with a mass $m_{\ell_4} \geq 200$ GeV; the expressions 0^{+250} GeV etc. show that the central value of exclusion or discovery limit is below our model points and we may achieve the limit of 250 GeV with 1σ statistical fluctuation. In the dashed entries the upper limit is less than 200 GeV even with 1σ statistical fluctuation. The CL_s method is used for statistical treatment, where the statistical uncertainty and a 20% systematic uncertainty for the background contribution are taken into account, while the theoretical uncertainty on the signal cross section as well as the NLO correction are not considered. See Appendix B for further details.

QUE model		$300\,\mathrm{fb}^{-1}$	$1000\,\mathrm{fb}^{-1}$	$3000\,\mathrm{fb}^{-1}$
95% CL exclusion	e-mixed	240^{+60} GeV	310^{+50}_{-60} GeV	350^{+40}_{-40} GeV
	μ-mixed	270^{+50} GeV	330^{+40}_{-60} GeV	370^{+40}_{-40} GeV
3σ discovery	e-mixed	0^{+250} GeV	250^{+60}_{-40} GeV	300^{+50}_{-50} GeV
	μ-mixed	0^{+280} GeV	260^{+70}_{-60} GeV	320^{+50}_{-40} GeV
5σ discovery	e-mixed	—	0^{+210} GeV	220^{+20}_{-20} GeV
	μ-mixed	—	0^{+210} GeV	240^{+20}_{-20} GeV

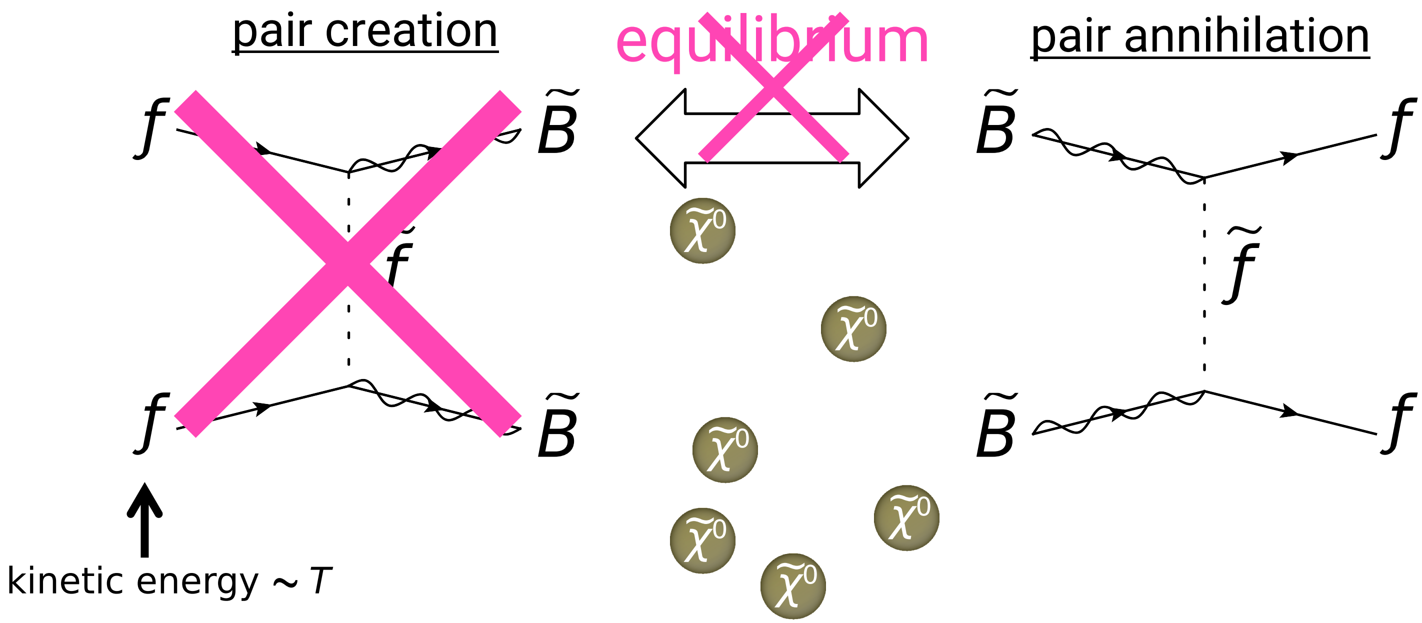
QDEE model		$300\,\mathrm{fb}^{-1}$	$1000\,\mathrm{fb}^{-1}$	$3000\,\mathrm{fb}^{-1}$
95% CL exclusion	e-mixed	350^{+40}_{-50} GeV	390^{+40}_{-40} GeV	430^{+40}_{-40} GeV
	μ-mixed	360^{+40}_{-40} GeV	400^{+40}_{-40} GeV	440^{+40}_{-40} GeV
3σ discovery	e-mixed	290^{+60}_{-70} GeV	340^{+60}_{-40} GeV	380^{+50}_{-40} GeV
	μ-mixed	310^{+60}_{-50} GeV	360^{+40}_{-30} GeV	400^{+40}_{-30} GeV
5σ discovery	e-mixed	0^{+200} GeV	260^{+40}_{-50} GeV	310^{+20}_{-30} GeV
	μ-mixed	0^{+260} GeV	280^{+30}_{-30} GeV	320^{+40}_{-20} GeV

Bino overabundance

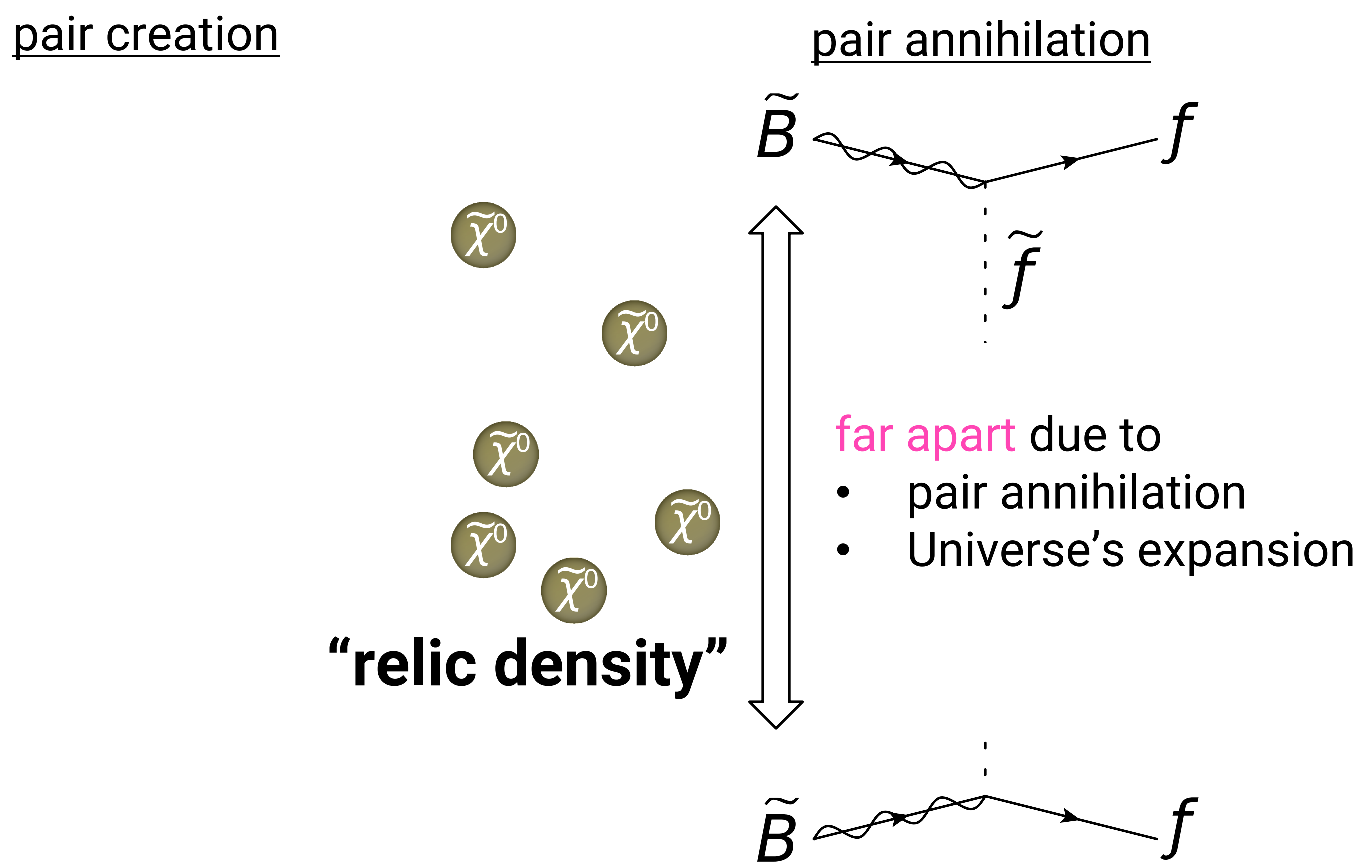
- Early Universe with $T > m_{\tilde{B}}$



- Early Universe with $T \lesssim m_{\widetilde{B}}$

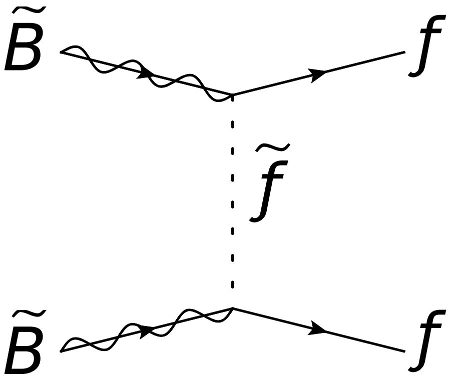


- Early Universe with $T \lesssim m_{\tilde{B}}/20$



- "observed" relic density Ωh^2

⇐ "proper" crosssection $\langle \sigma v \rangle$ of (DM)(DM)→SM



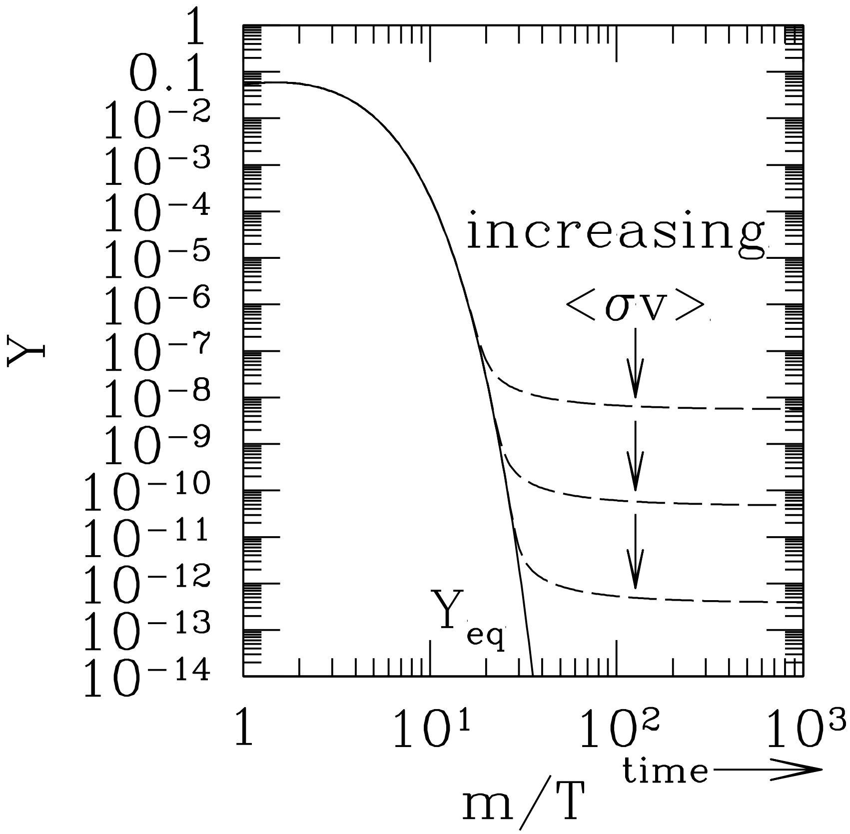
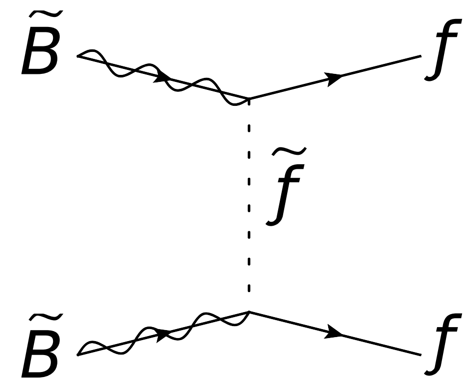


Figure from Gelmini and Gondolo, 1009.3690

- "observed" relic density Ωh^2

  ⇦ "proper" crosssection $\langle \sigma v \rangle$ of (DM)(DM)→SM



- pure $\tilde{B}$-DM (i.e., LSP $\tilde{\chi}^0$ is $\tilde{B}$-like)
  - $\langle \sigma v \rangle$ strongly depends on $m_{\tilde{f}}$

  ↳ $m_{\tilde{f}}$ should be ~100 GeV

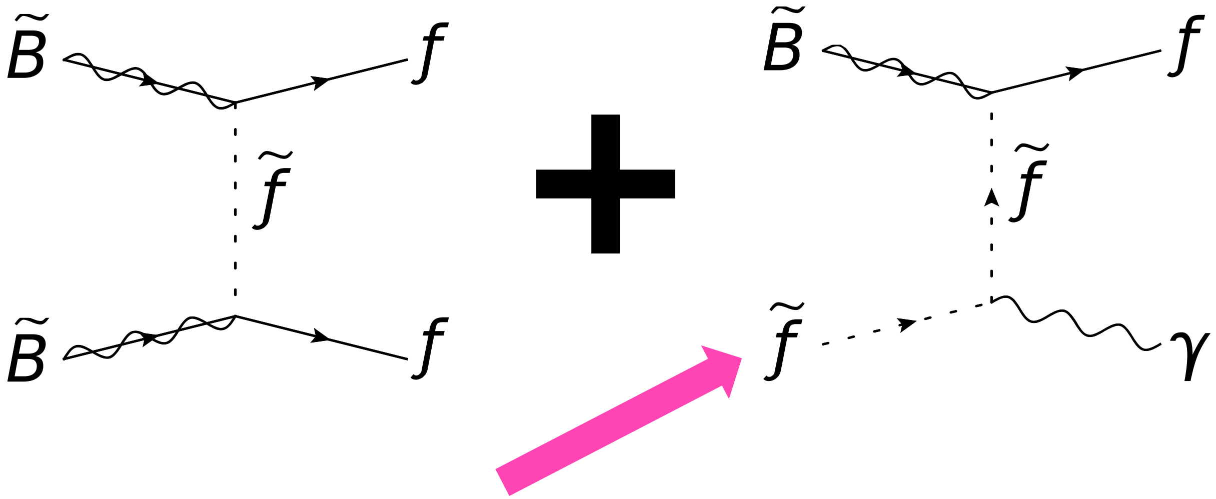
$$m_{\tilde{f}} \gg 100\ \text{GeV} \Longrightarrow \langle \sigma v \rangle \text{ too small}$$

$$\Longrightarrow \text{"overabundant" problem}$$

(i.e., $m_{\tilde{B}\text{-DM}} \lesssim$ 100 GeV)

Coannihilation & MSSM4G

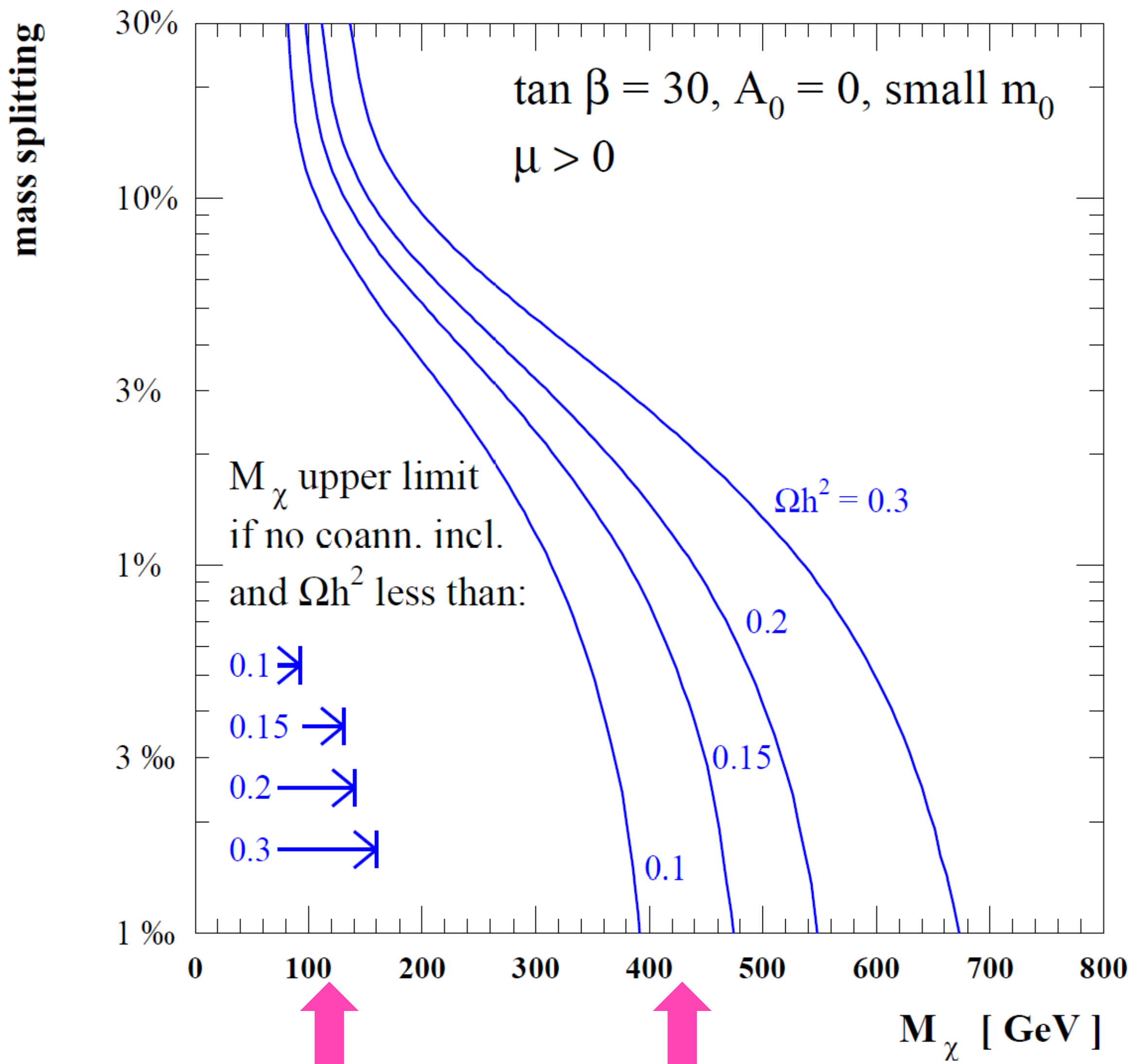
- An old solution to increase $\langle \sigma v \rangle$: "co-annihilation"



mass splitting $\dfrac{m_{\tilde{f}} - m_{\tilde{B}}}{m_{\tilde{B}}} \ll 1$

■ An c[...]on"

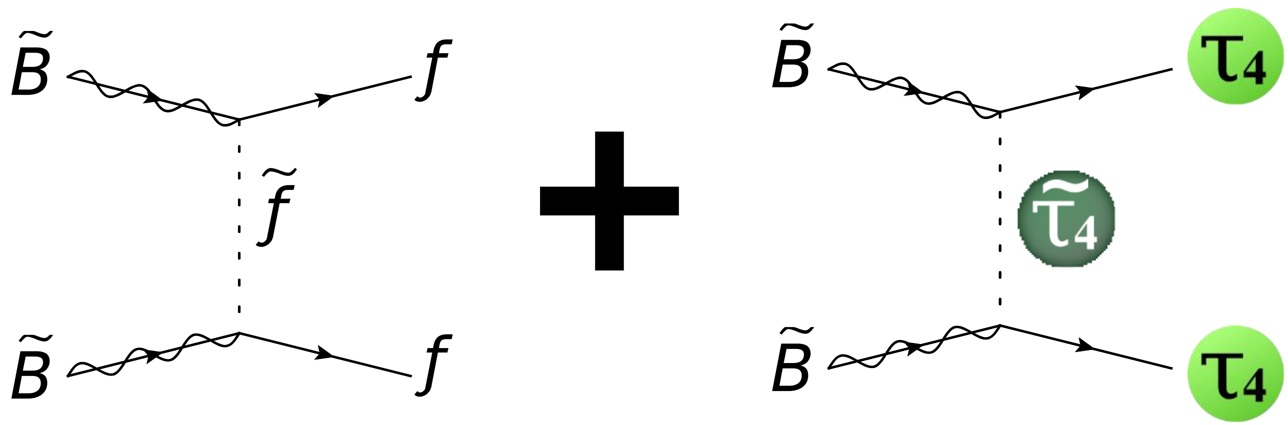
An example in CMSSM with $\tilde{\tau}$-coann.:



f
γ

Figure from Edsjö, Schelke, Ullio, Gondolo, hep-ph/0301106

- A new solution to increase $\langle \sigma v \rangle$: MSSM4G



extra annihilation channel
→ larger $\langle \sigma v \rangle$
→ "proper" Ωh^2

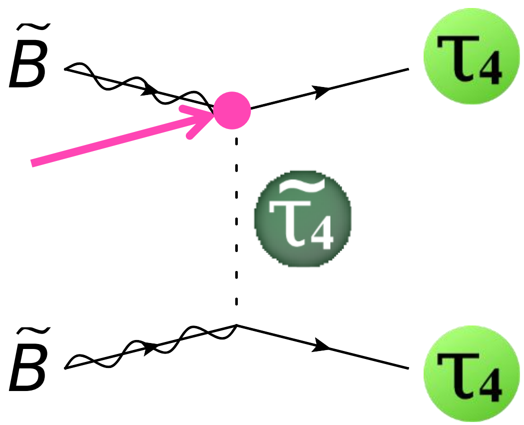
if $\tilde{\tau}_4 \gtrsim \tilde{B} > \tau_4$

$$\langle \sigma v \rangle_{s\text{-wave}} = \frac{g_Y^4 (Y_{\mathrm{L}}^2 + Y_{\mathrm{R}}^2)^2}{8\pi} \frac{m_f^2}{m_{\tilde{B}}} \frac{\sqrt{m_{\tilde{B}}^2 - m_f^2}}{(m_{\tilde{B}}^2 + m_{\tilde{f}}^2 - m_f^2)^2}$$

$$(Q_i, \bar{U}_i, \bar{D}_i, L_i, \bar{E}_i) + (H_{\rm u}, H_{\rm d})$$ [MSSM]

$(i = 1 \dots 3)$

$$+(E_4, \bar{E}_4)$$ [MSSM4G]



$\Longrightarrow \langle \sigma v \rangle \propto Y^4$

	$SU(3)_{\rm color}$	$SU(2)_{\rm weak}$	$U(1)_Y$
Q_i	$\mathbf{3}$	$\mathbf{2}$	$1/6$
$\bar{U}_i$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$
$\bar{E}_i$	$\mathbf{1}$	$\mathbf{1}$	1
$\bar{D}_i$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$H_{\rm u}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
$H_{\rm d}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$\bar{E}_4$	$\mathbf{1}$	$\mathbf{1}$	1
E_4	$\mathbf{1}$	$\mathbf{1}$	-1

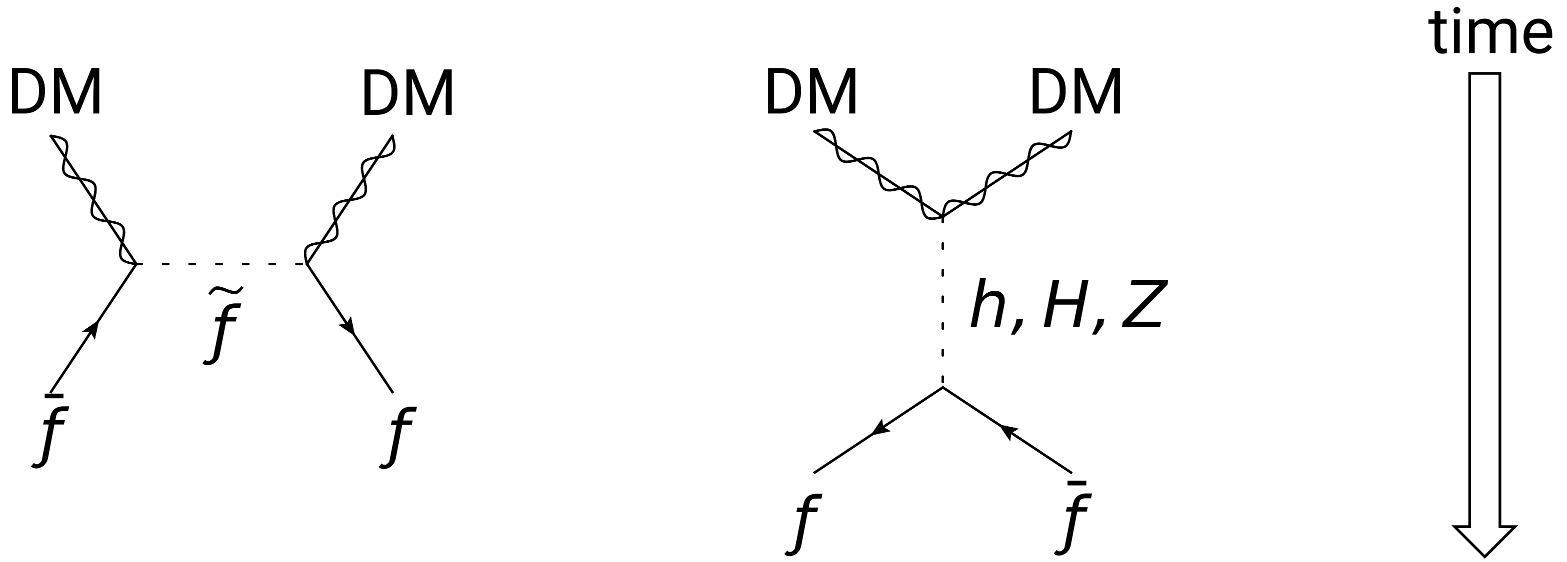
$$W = Y_{\rm u} H_{\rm u} Q \bar{U} + Y_{\rm d} H_{\rm d} Q \bar{D} + Y_{\rm e} H_{\rm d} L \bar{E}$$

$$+ M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_{\rm d} L_i \bar{E}_4$$

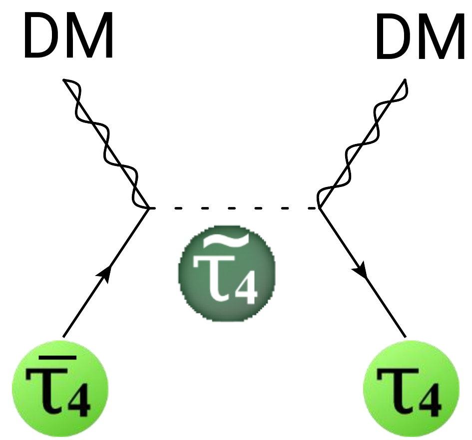
[vector-like mass] [mixing with SM leptons]

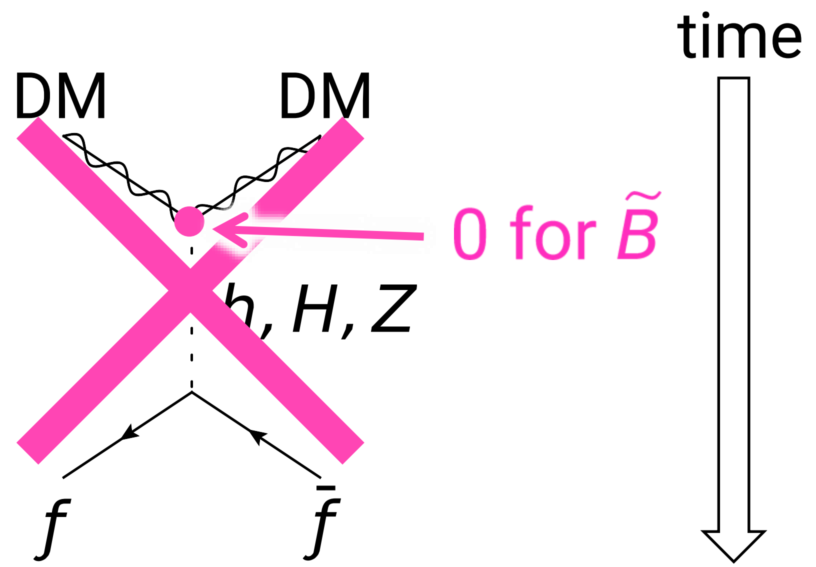
Cosmic-ray constraint

- DM indirect detection (= searches for DM annihilation)



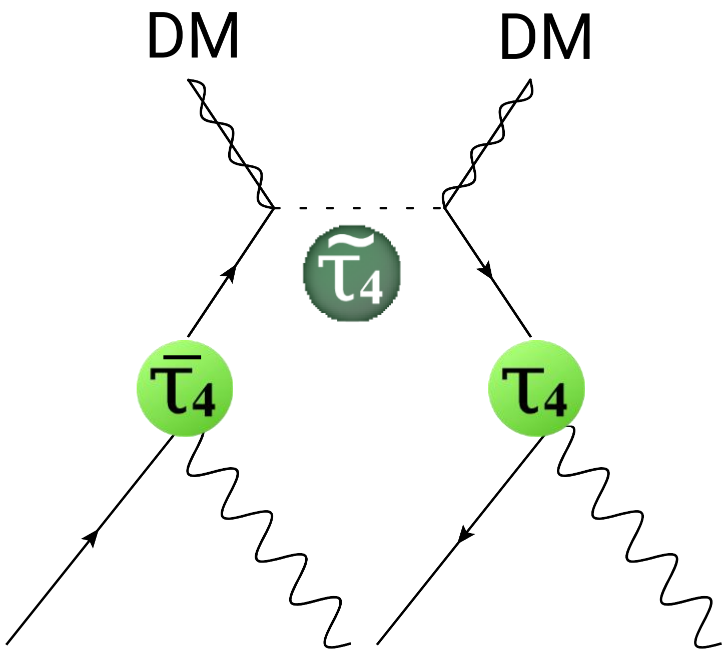
- DM indirect detection (= searches for DM annihilation)





$$\langle \sigma v \rangle_{s\text{-wave}} = \frac{g_Y^4 (Y_L^2 + Y_R^2)^2}{8\pi} \frac{m_f^2}{m_{\widetilde{B}}} \frac{\sqrt{m_{\widetilde{B}}^2 - m_f^2}}{(m_{\widetilde{B}}^2 + m_{\widetilde{f}}^2 - m_f^2)^2}$$

- DM indirect detection (= searches for DM DM $\to \tau_4 \bar{\tau}_4$)



$$\tau_4 \longrightarrow \begin{cases} W + \nu \\ Z + l \\ h + l \end{cases} \quad \begin{pmatrix} \nu = \nu_e, \nu_\mu, \nu_\tau \\ l = e, \mu, \tau \end{pmatrix}$$

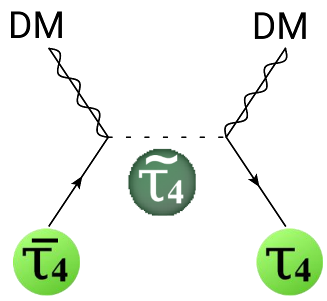
$$W\nu : Zl : hl \sim 2 : 1 : 1$$

$$W \ni Y_{\rm e} H_{\rm d} L \bar{E}$$
$$+ M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_{\rm d} L_i \bar{E}_4$$

[vector-like mass] [mixing with SM leptons]

- DM indirect detection

$$W \ni Y_e H_d L \bar{E} + M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_d L_i \bar{E}_4$$



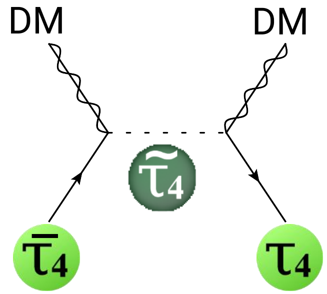
$W\nu : Zl : hl \sim 2:1:1$

	DM DM→
$\tau_{4(5)}$ mixes with e	W^+W^- ZZ hh $\nu\bar{\nu}$ e^+e^-
$\tau_{4(5)}$ mixes with μ	W^+W^- ZZ hh $\nu\bar{\nu}$ $\mu^+\mu^-$
$\tau_{4(5)}$ mixes with τ	W^+W^- ZZ hh $\nu\bar{\nu}$ $\tau^+\tau^-$

- DM indirect detection

$$W \ni Y_e H_d L \bar{E} + M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_d L_i \bar{E}_4$$

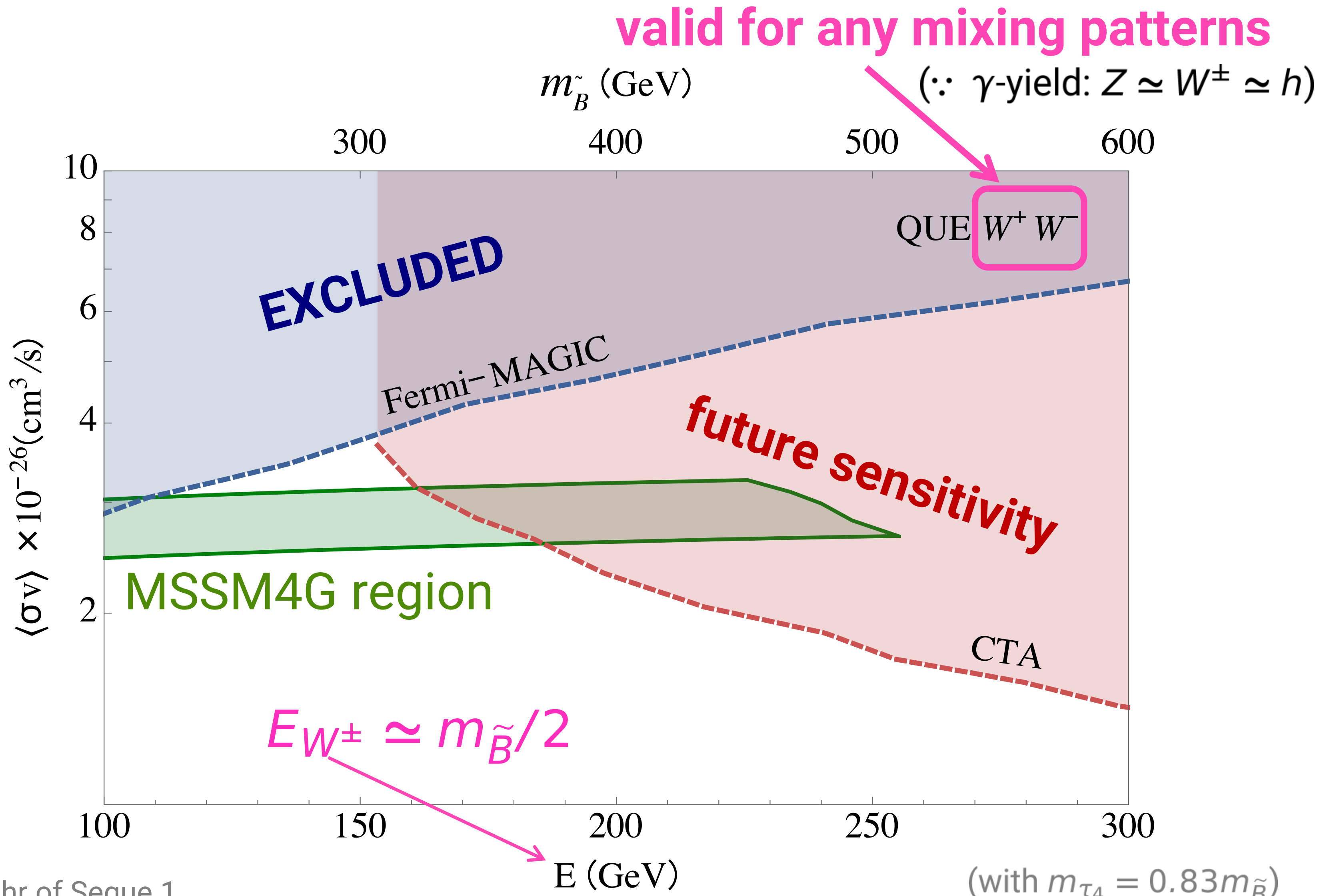
$W\nu : Zl : Hl \sim 2 : 1 : 1$



	DM DM→			insensitive (IceCube)	less sensitive / large BKG uncertainty
$\tau_{4(5)}$ mixes with e	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	e^+e^-
$\tau_{4(5)}$ mixes with μ	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	$\mu^+\mu^-$
$\tau_{4(5)}$ mixes with τ	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	$\tau^+\tau^-$

W^+W^-, ZZ, hh $\rightarrow \cdots \rightarrow \gamma$

$\tau^+\tau^-$ $\rightarrow \pi^0 \rightarrow \gamma$



(with $m_{\tau_4} = 0.83 m_{\tilde{B}}$)

MAGIC: 158 hr of Segue 1

Fermi-LAT: 6 yr of 15 dSph (incl. Segue 1)

DM profile: NFW

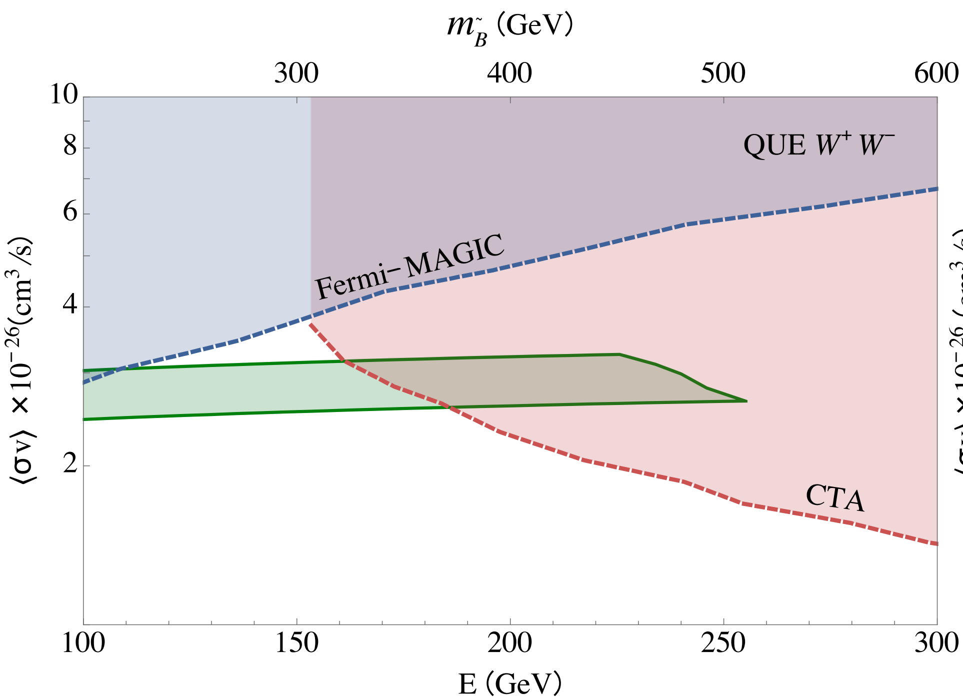
Fermi-LAT dominates MAGIC in almost all *E*-range.

CTA prospect : 500hr of Milky Way

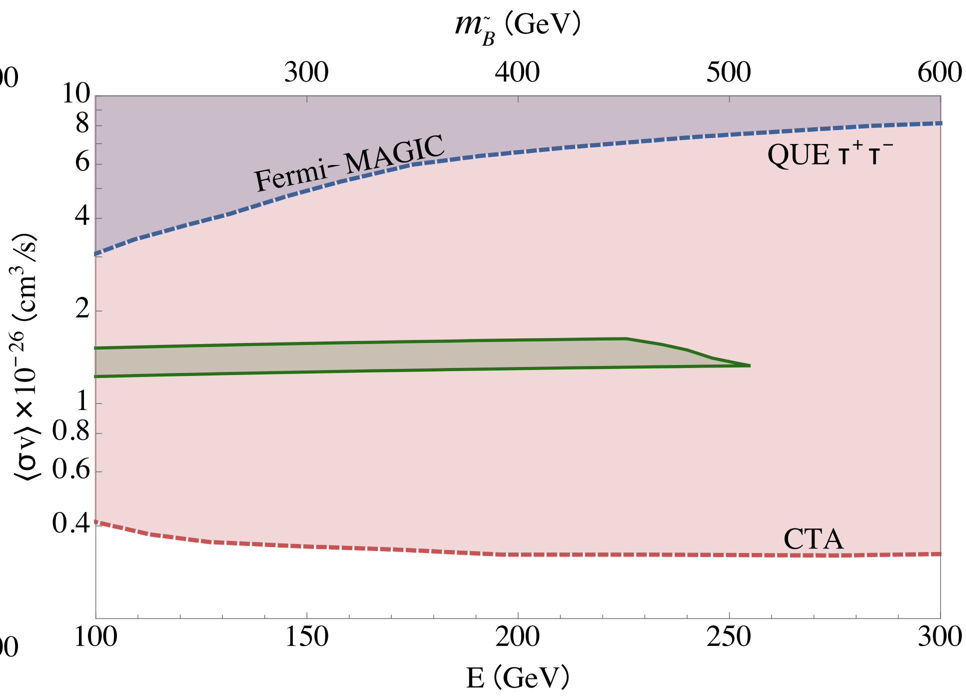
DM profile: Einasto

No syst. unc. (stat only)

WW (any mixing pattern)



ττ (only for τ-mixing cases)



✓ τ-mixing fully covered
✓ e/μ-mixing with $m_{\tilde{B}}$ > 340−380 GeV covered

MAGIC: 158 hr of Segue 1

Fermi-LAT: 6 yr of 15 dSph (incl. Segue 1)

DM profile: NFW

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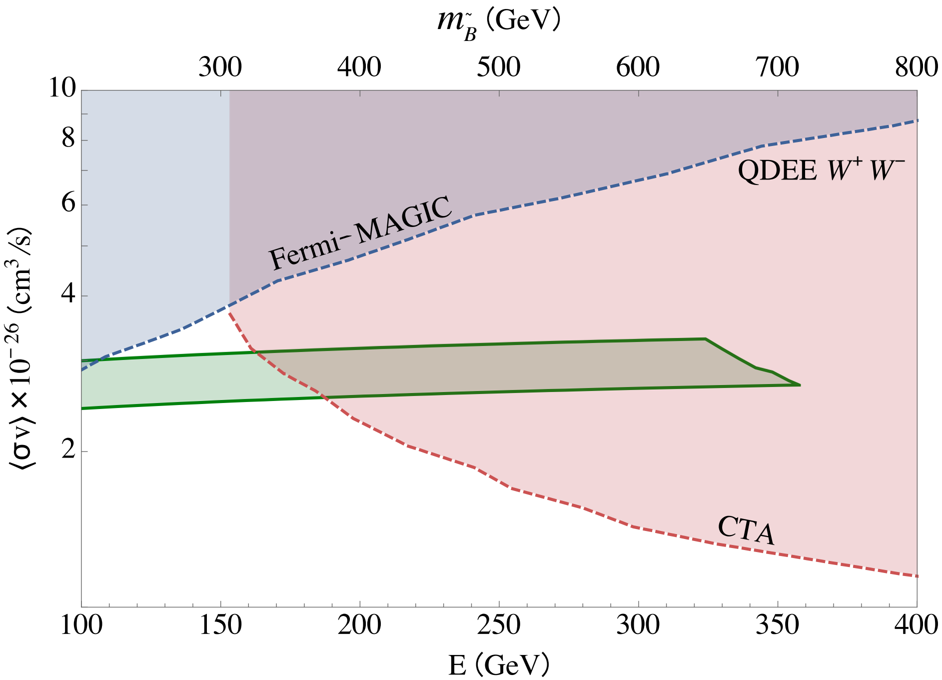
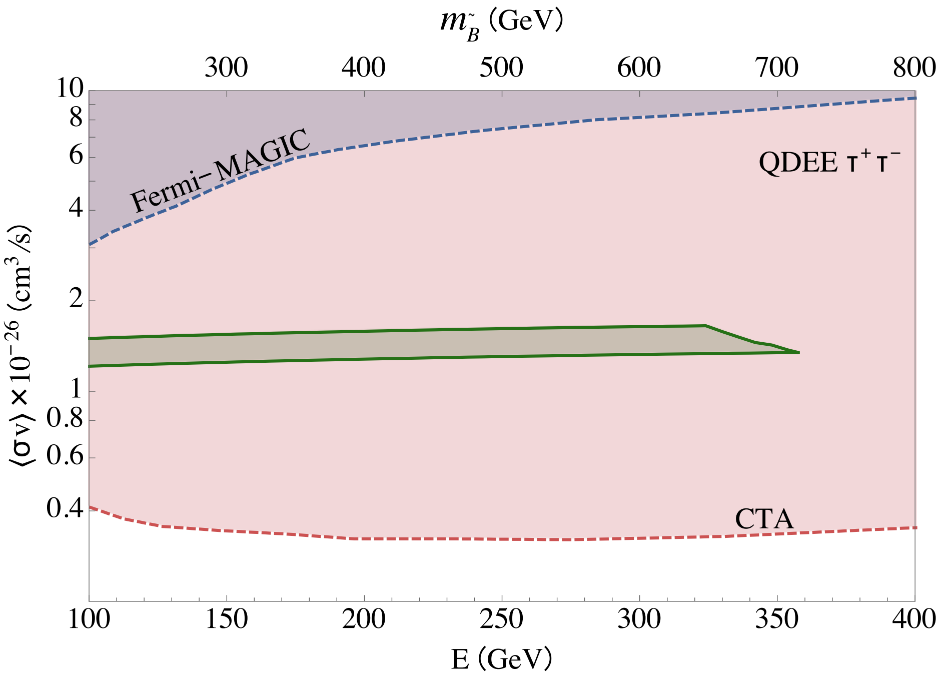


ττ (only for τ-mixing cases)



- ✓ τ-mixing fully covered
- ✓ e/μ-mixing with $m_{\tilde{B}} > 340-380$ GeV covered

MAGIC: 158 hr of Segue 1

Fermi-LAT: 6 yr of 15 dSph (incl. Segue 1)

DM profile: NFW

Fermi-LAT dominates MAGIC in almost all *E*-range.

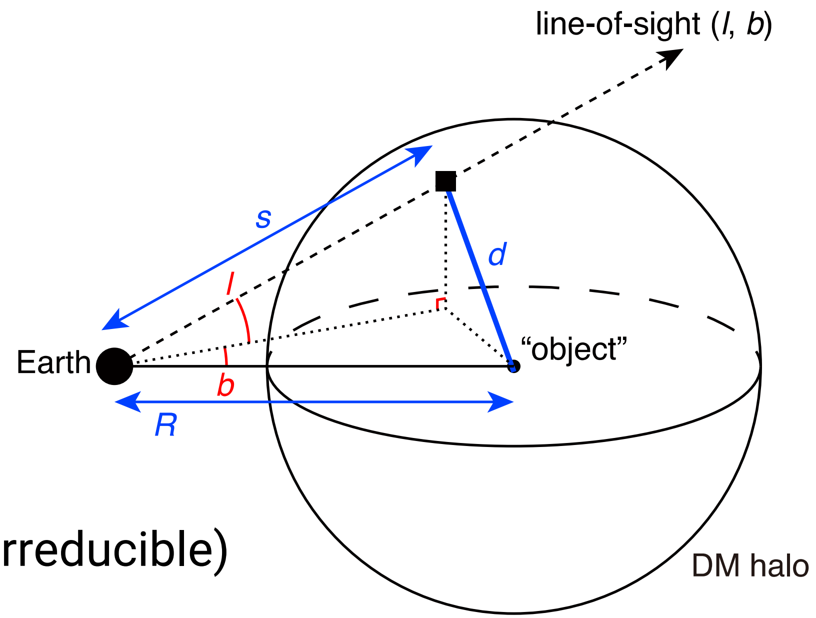
(with $m_{\tau_4} = 0.83 m_{\tilde{B}}$)

CTA prospect : 500hr of Milky Way

DM profile: Einasto

No syst. unc. (stat only)

- charged particles → diffusion
  - e : ~ 1 kpc are observable
  - P : ~ O(10) kpc ~ Milky Way
- neutral particles
  - from (neighbor of) galactic center
    - larger density, huge BKG (miss-ID & irreducible)
    - J ~ 10^{22} GeV^2/cm^5 (NFW; cuspy)
  - from dwarf spheroidals (mini-galaxies near MW)
    - DM rich, less baryon → low BKG
    - J < 10^{19-20} GeV^2/cm^5 (smaller profile dependence)



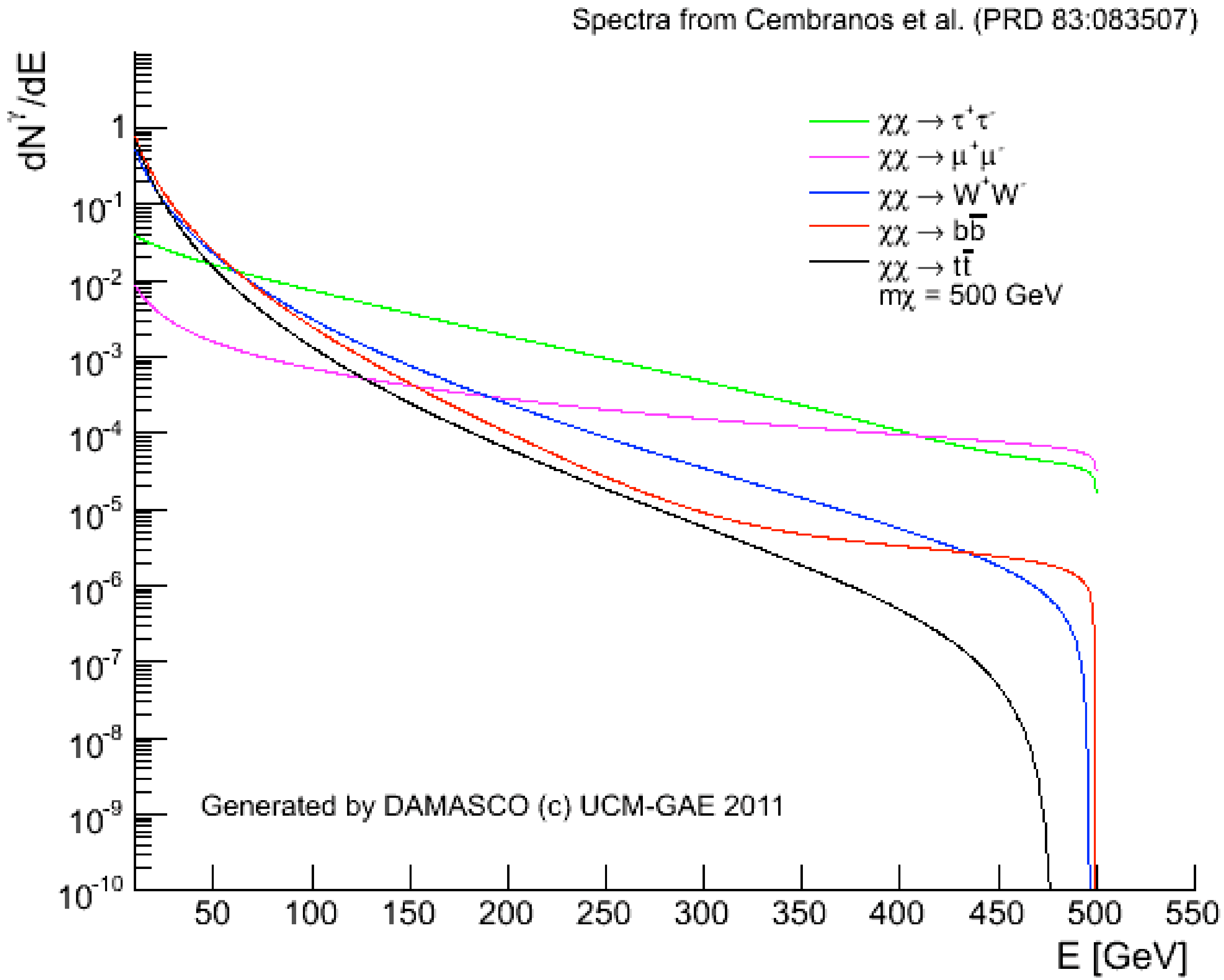
$$J = \int \mathrm{d}\Omega_{l,b} \int_0^\infty \mathrm{d}s\, \rho(d)^2$$

$$\left(d^2 = s^2 + R^2 - 2Rs \cos b \cos l\right)$$

- < 100 GeV : satellites
  - full-sky, ~1m^2, 5–10% energy resolution
  - Fermi-LAT (2008) : gamma-ray to electron conversion

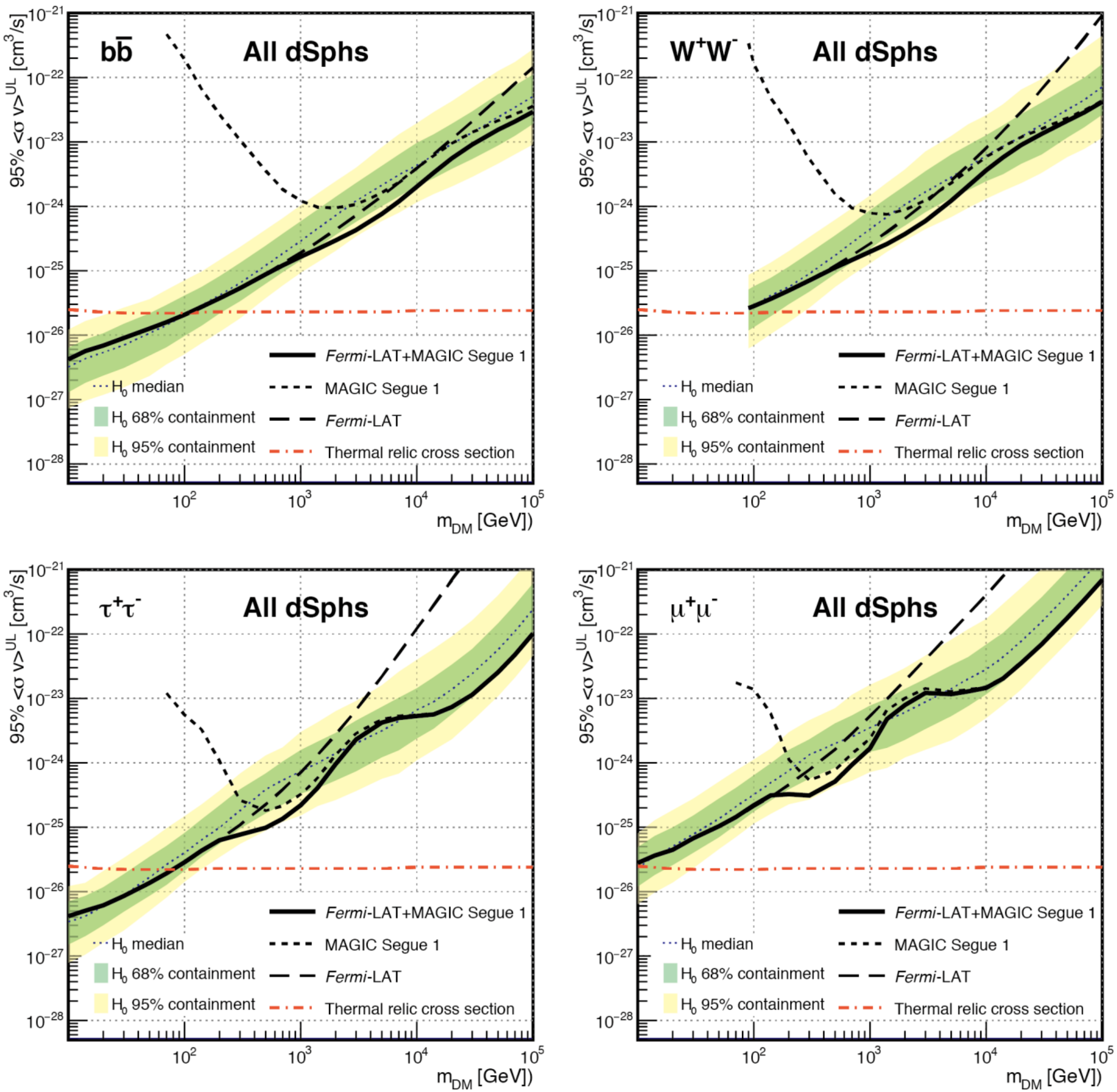
- > 100 GeV : ground-based Air Cherenkov Telescopes
  - several degree, 10^{5-6} m^{2,} ~20% energy resolution
  - VERITAS : 4x12m telescopes, Crab 36σ/√hr = 1%Crab in 35h
  - MAGIC : 2x17m telescope, 19σ/√hr = 2.2%Crab in 50h
  - HESS : 4x12m + 28m telescopes, 43σ/√hr

- > 10 TeV : ground-based Water Cherenkov
  - HAWC : 2/3-sky, effective area similar to ACT but worse resolution


Spectra from Cembranos et al. (PRD 83:083507)
dN^γ/dE
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
χχ → τ⁺τ⁻
χχ → μ⁺μ⁻
χχ → W⁺W⁻
χχ → bb̄
χχ → tt̄
mχ = 500 GeV
Generated by DAMASCO (c) UCM-GAE 2011
50
100
150
200
250
300
350
400
450
500
550
E [GeV]

Original data of Fermi-MAGIC constraints

Ahnen et al. [1601.06590]

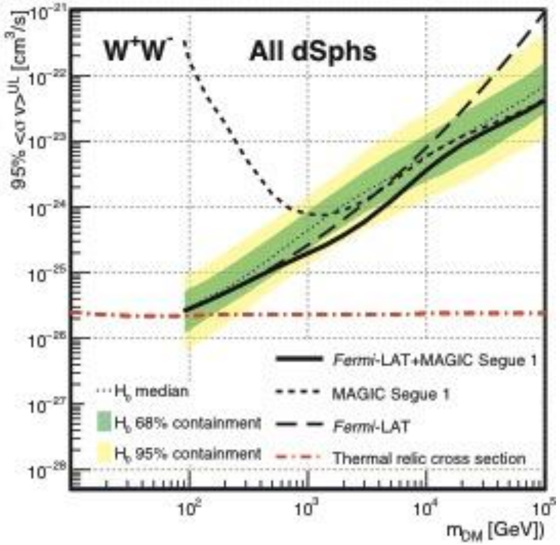


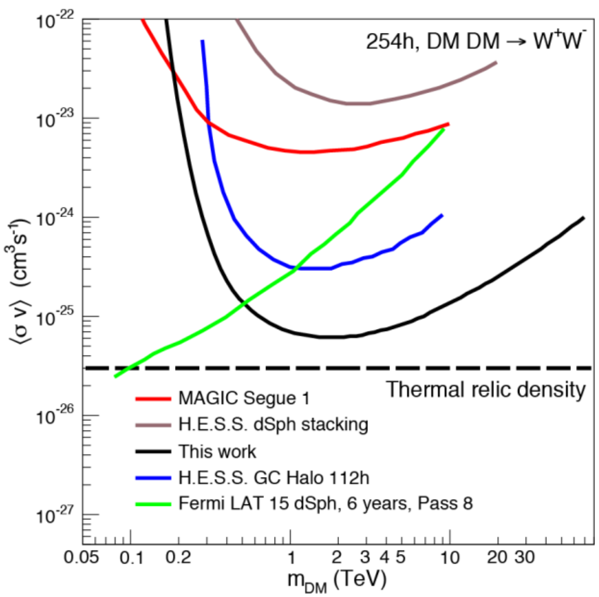
MAGIC:
158 hr of Segue 1

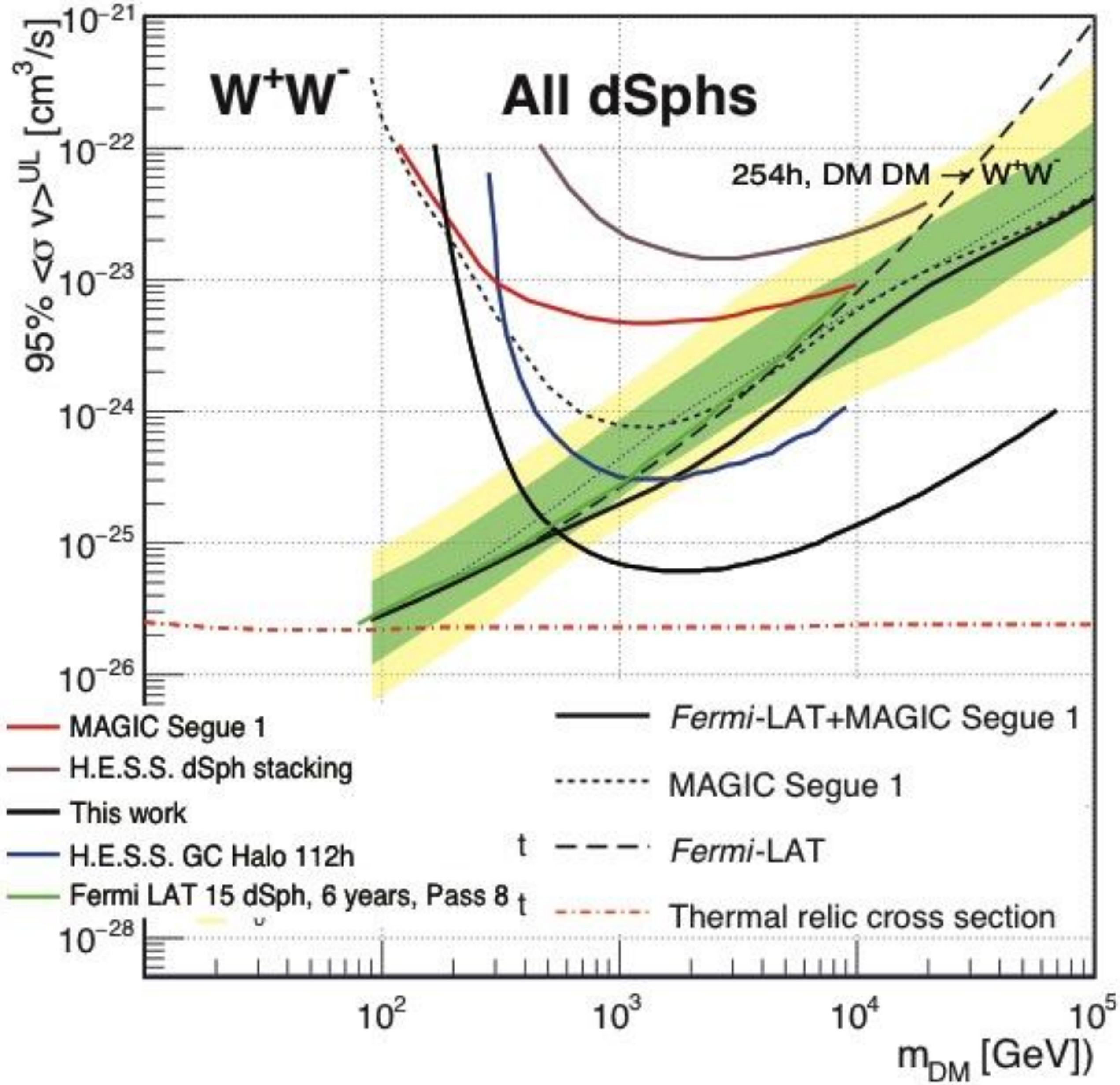
Fermi-LAT:
6 yr of 15 dSph
(incl. Segue 1)

DM profile: NFW

 Ahnen et al. [1601.06590] v.s. Lefranc, Mourin [1608.08453]







HESS assumes Einasto profile; for NFW weaker by factor ~2.

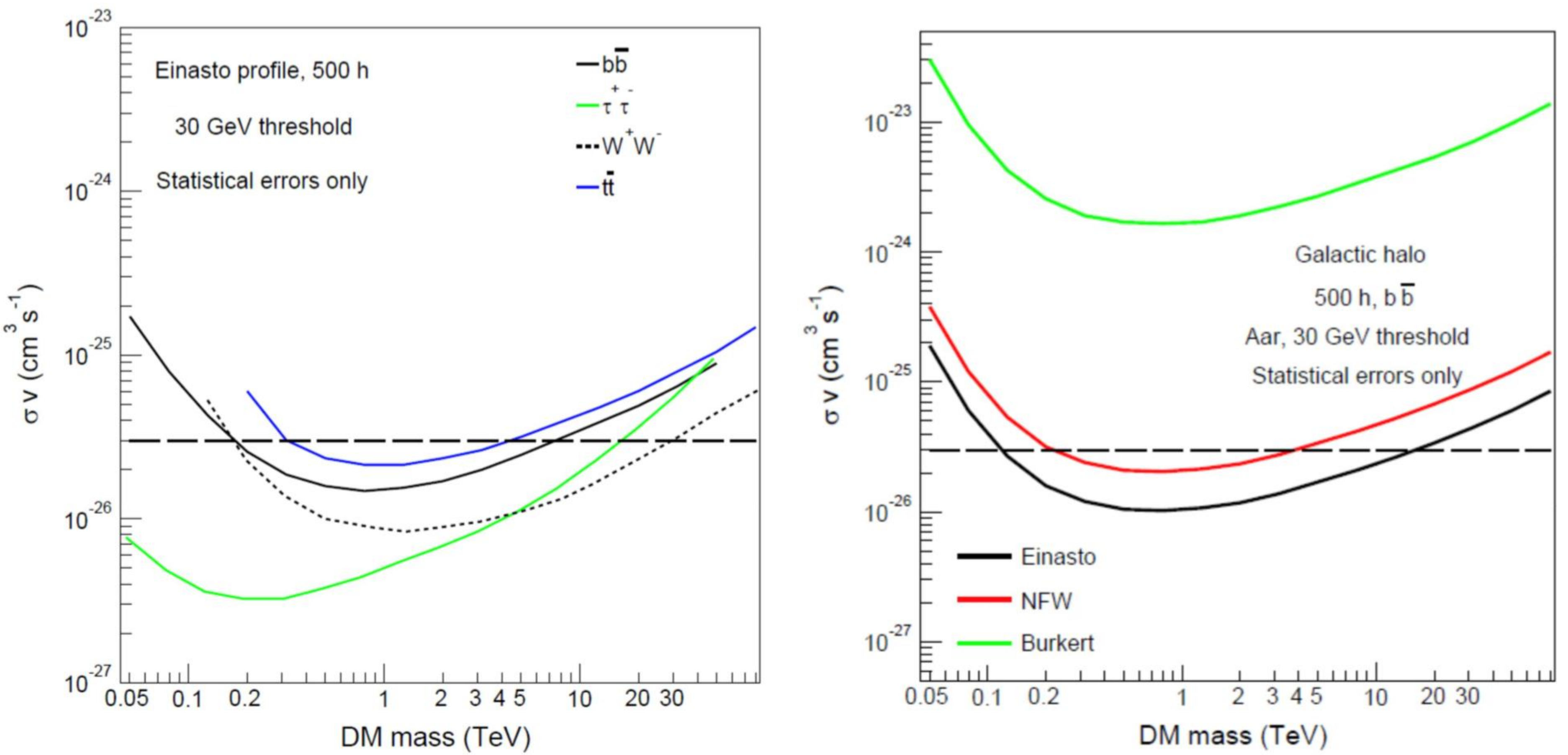


Figure1. Left: Sensitivity for σ v from observation on the Galactic Halo with Einsasto dark matter profile and for different annihilation modes as indicated. **Right**: for cuspy (NFW, Einasto) and cored (Burkert) dark matter halo profiles. For both plots only statistical errors are taken into account. The dashed horizontal lines indicate the level of the thermal cross-section of 3×10^{-26} cm^3 s^{-1}.