Explore beyond the Standard Model of Particle Physics

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National Taiwan University

62±2 min. talk + $O(1)$ min. Q&A

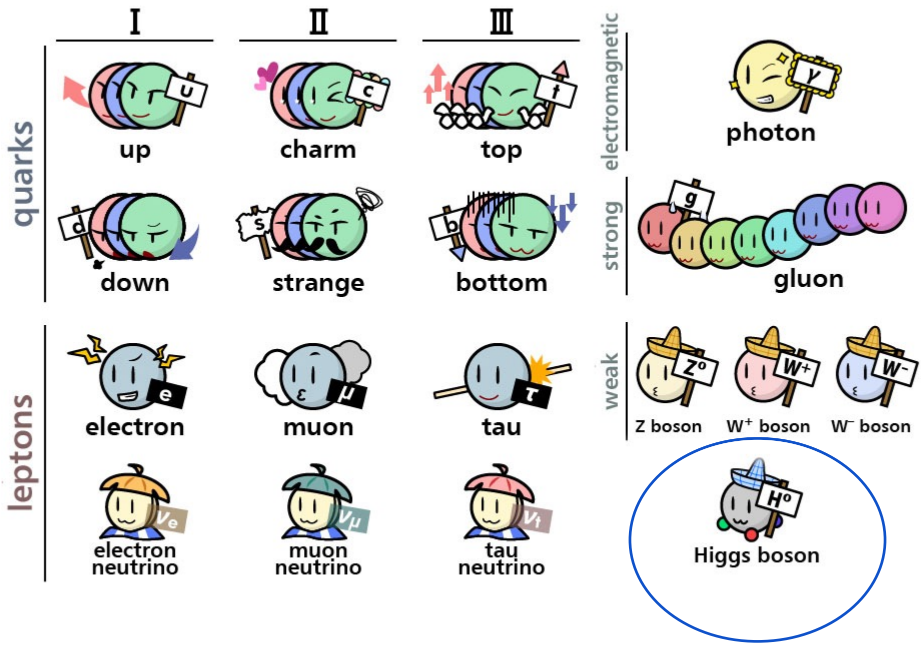
including your questions: **Feel free to ask questions whenever you want!** (speak / text chat)

This presentation file is available at: `https://bit.ly/iwamoto20211220`

Standard Model = quantum field theory with

- quarks and leptons,
- "gauge symmetry" $SU(3)\times\underbrace{SU(2)\times U(1)}_{\to\, U(1)}$,
- and Higgs boson *H*.

spontaneous symmetry breaking
induced by Higgs boson



	$SU(3)_{color}$	$SU(2)_{weak}$	$U(1)_Y$	
Q_L	3	2	1/6	$= (u_L, d_L)$
U_R	3		2/3	$= u_R$
D_R	3		−1/3	$= d_R$
L_L		2	−1/2	$= (\nu_L, e_L)$
E_R			−1	$= e_R$
B			✓	
W		✓		
g	✓			
H		2	1/2	

$B, W \to (W^+, W^-, Z) + \gamma$

discovered in 2012 at the LHC

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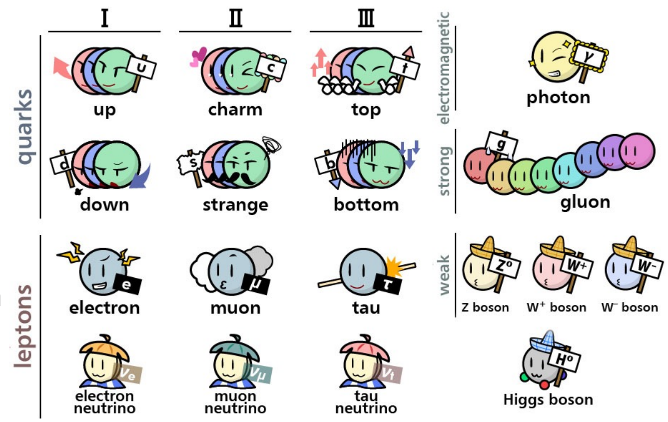
Figure courtesy of HiggsTan.com

■ Standard Model = quantum field theory with

- ➢ quarks and leptons,
- ➢ "gauge symmetry" SU(3)×$\underline{\text{SU(2)×U(1)}}$, → U(1)
  spontaneous symmetry breaking induced by Higgs boson
- ➢ and Higgs boson *H*.



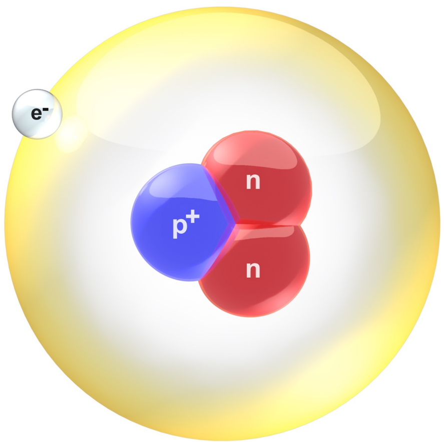
■ The SM explains...

- ✓ ingredients of 5% of the Universe,
- ✓ mechanism of three forces,
  [strong, weak, and electromagnetic forces]
- ✓ mechanism of {q, e, μ, τ, W, Z, H} mass,

and...

- ✓ many many more! → next page!

Example: Tritium



$$\longrightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

Figs. courtesy of HiggsTan.com and B. Blaus, Medical gallery of Blausen Medical

✓ Lepton magnetic moment

$$g_e(\text{SM}) = \begin{cases} 2.00231930436408(144) & (\text{Rb}) \\ 2.00231930436324(046) & (\text{Cs}) \end{cases}$$

[using α_{EM} from Rb/Cs interferometry]

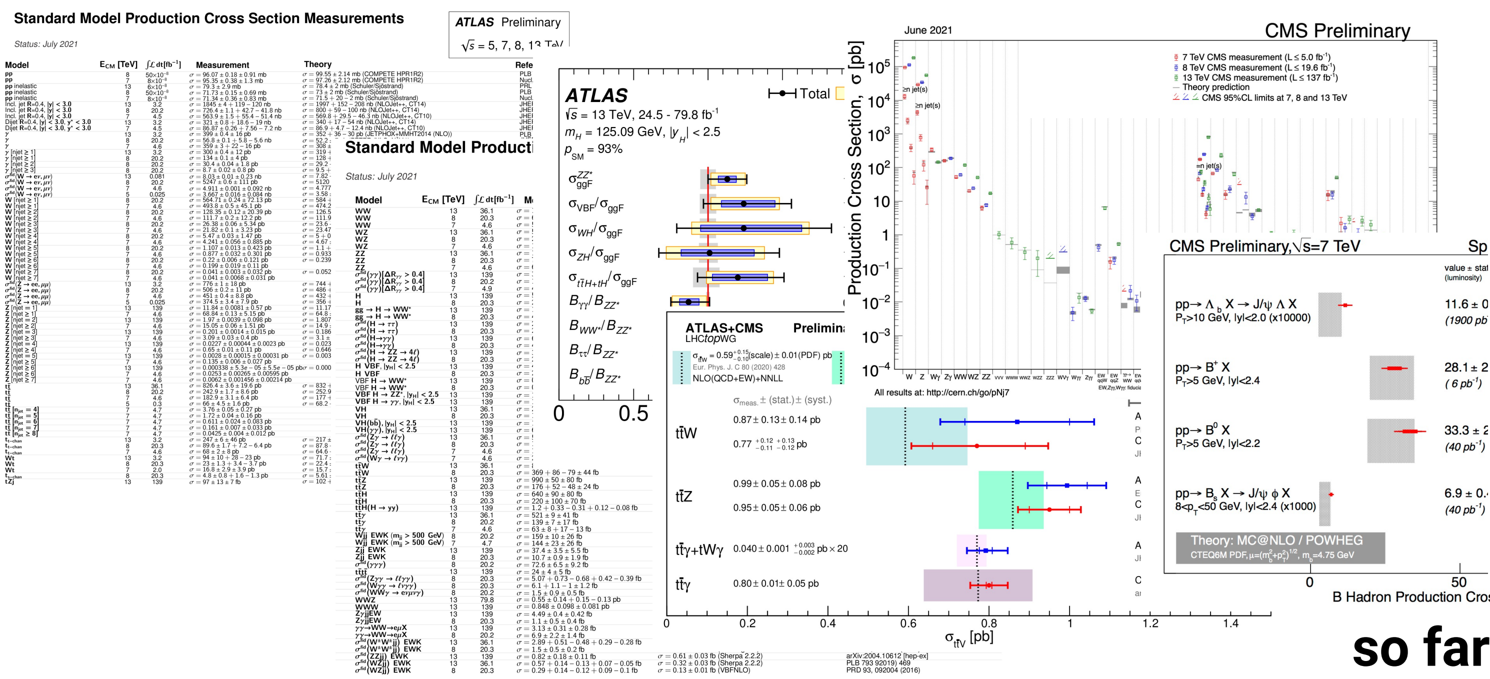
$$g_e(\text{meas}) = 2.00231930436146(056)$$

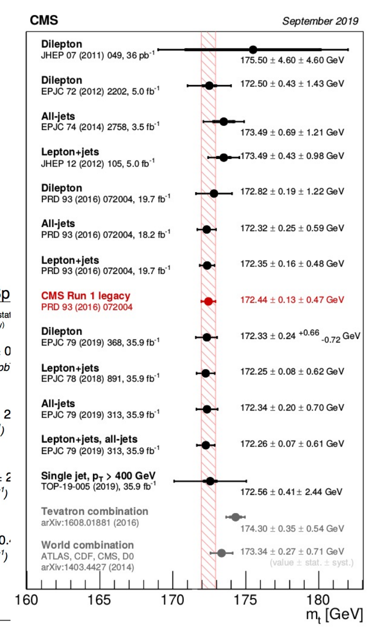
$$g_\mu(\text{SM}) = 2.0023318362 0(86)$$

$$g_\mu(\text{meas}) = 2.0023318412 2(82)$$

e) Keshavarzi, Marciano, Passera, Sirlin [2006.12666] and refs. therein.
μ) The White paper [2006.04822] for SM prediction,
hep-ex/0602035 (BNL) and 2104.03281 (FNAL) for measurements.

✓ Tremendous number of Results from the LHC





so far so good, but...

But Standard Model is not perfect. (1)

✓ Lepton magnetic moment

$$g_e(\text{SM}) = \begin{cases} 2.00231930436408(144) & \text{(Rb)} \\ 2.00231930436324(046) & \end{cases}$$

[using $\alpha_{\rm EM}$ from Rb/Cs interferometry]

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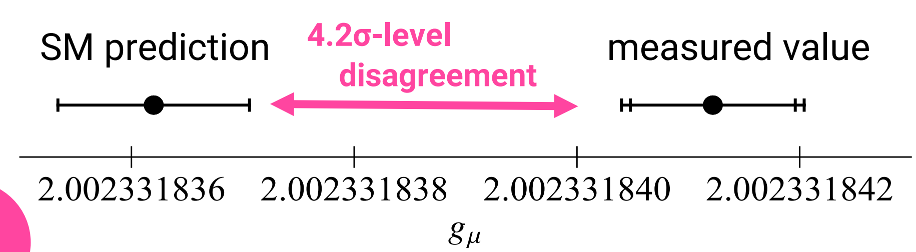
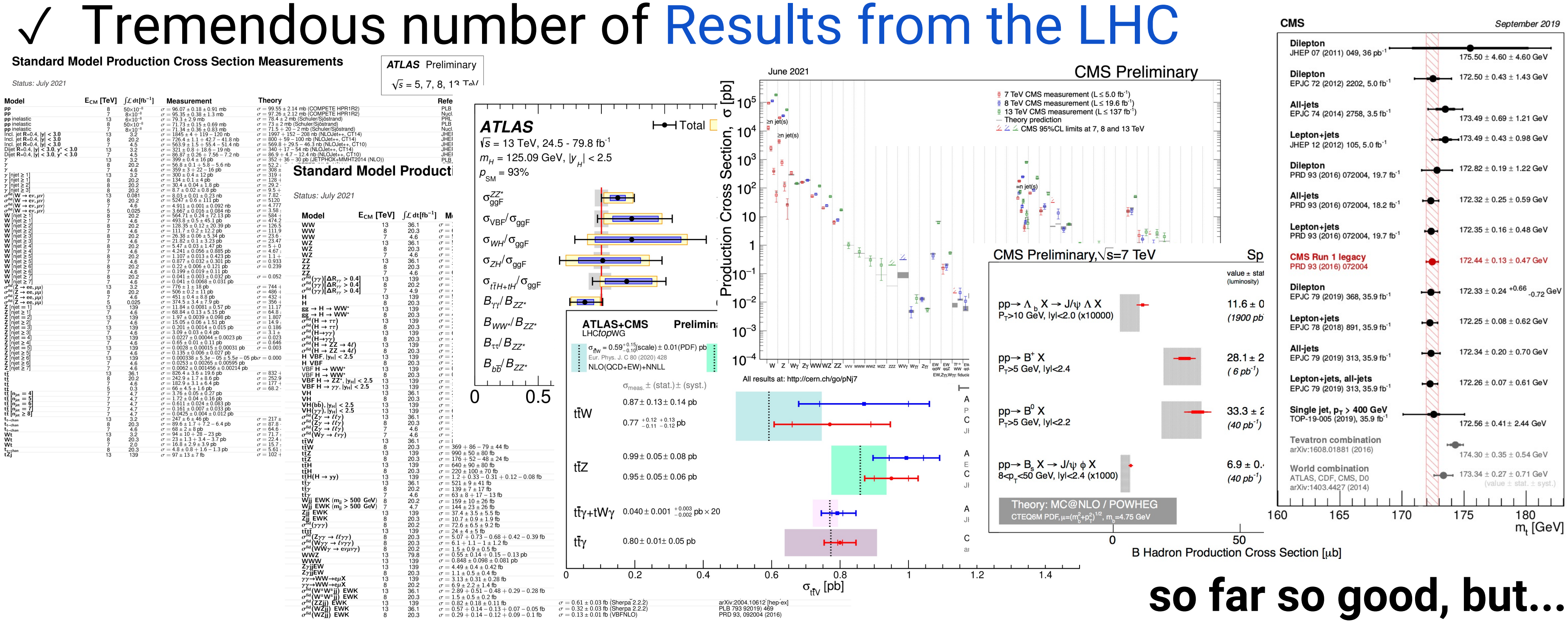


"muon g−2 anomaly" → 5 pages later

✓ Tremendous number of Results from the LHC



so far so good, but...

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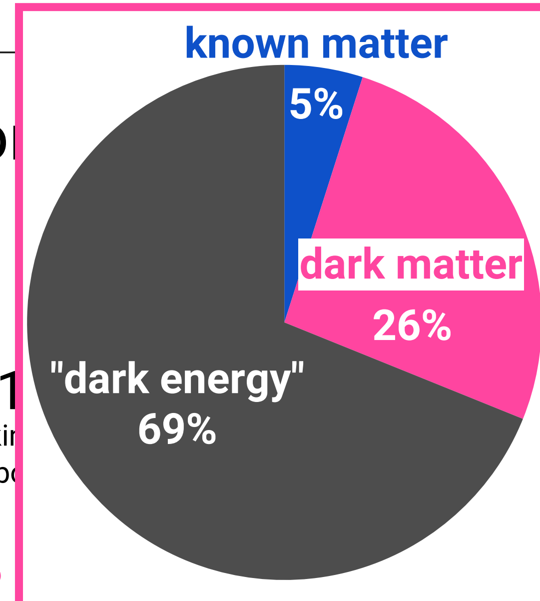
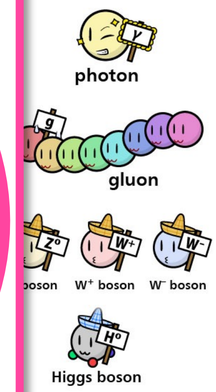


e.g., Planck 2018 Result [1807.06209]



- ■ The SM explains...
  - ✓ ingredients of 5% of the Universe, ← ? only 5%!?
  - ✓ mechanism of three forces, ? gravity?
    [strong, weak, and electromagnetic forces]
  - ✓ mechanism of {*q*, *e*, *μ*, *τ*, *W*, *Z*, *H*} mass,

and... ? mass of neutrinos (ν)?

  - ✓ many many more!

Figure courtesy of HiggsTan.com

Problems (and academic/phenomenological questions): They may be solved by BSM models.

!!! Dark matter

!!! Dark energy

!!! Gravity

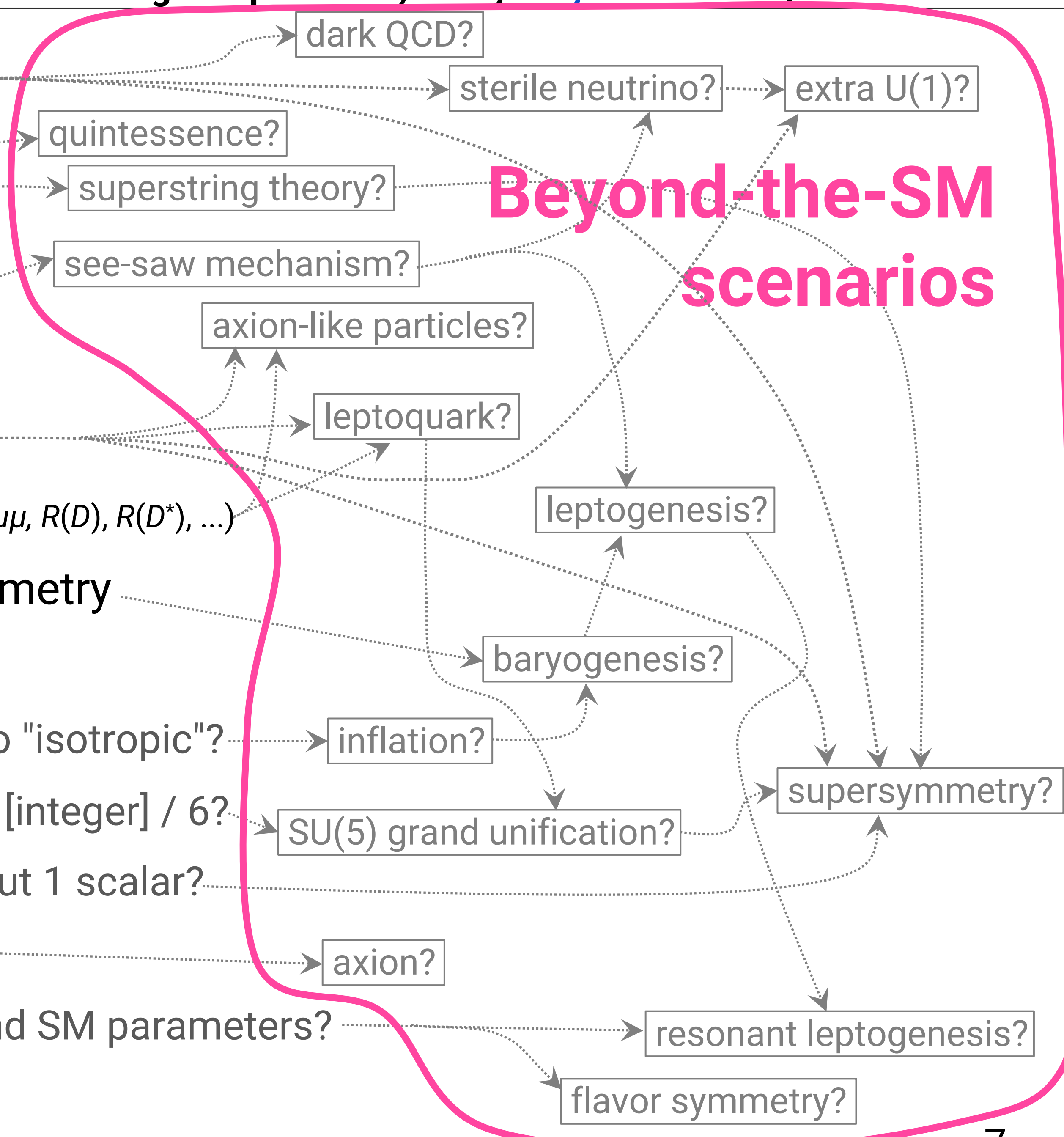
!!! Mechanism for neutrino mass

!? Muon $g-2$ anomaly

!? Flavor anomalies ($b \to s\mu\mu$, $R(D)$, $R(D^*)$, ...)

!? Origin of baryon asymmetry

- Why is the Universe so "isotropic"?
- Why are U(1)-charges [integer] / 6?
- Why many fermions but 1 scalar?
- Why θ_{QCD} so small?
- Any mechanism behind SM parameters?



My previous works have covered some of these topics.

- !!! Dark matter
- !!! Dark energy
- !!! Gravity
- !!! Mechanism for neutrino mass
- !? Muon $g-2$ anomaly
- !? Flavor anomalies ($b \to s\mu\mu$, $R(D)$, $R(D^*)$, ...)
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quintessence?

superstring theory?

see-saw mechanism?

axion-like particles?

leptoquark?

leptogenesis?

baryogenesis?

inflation?

SU(5) grand unification?

supersymmetry?

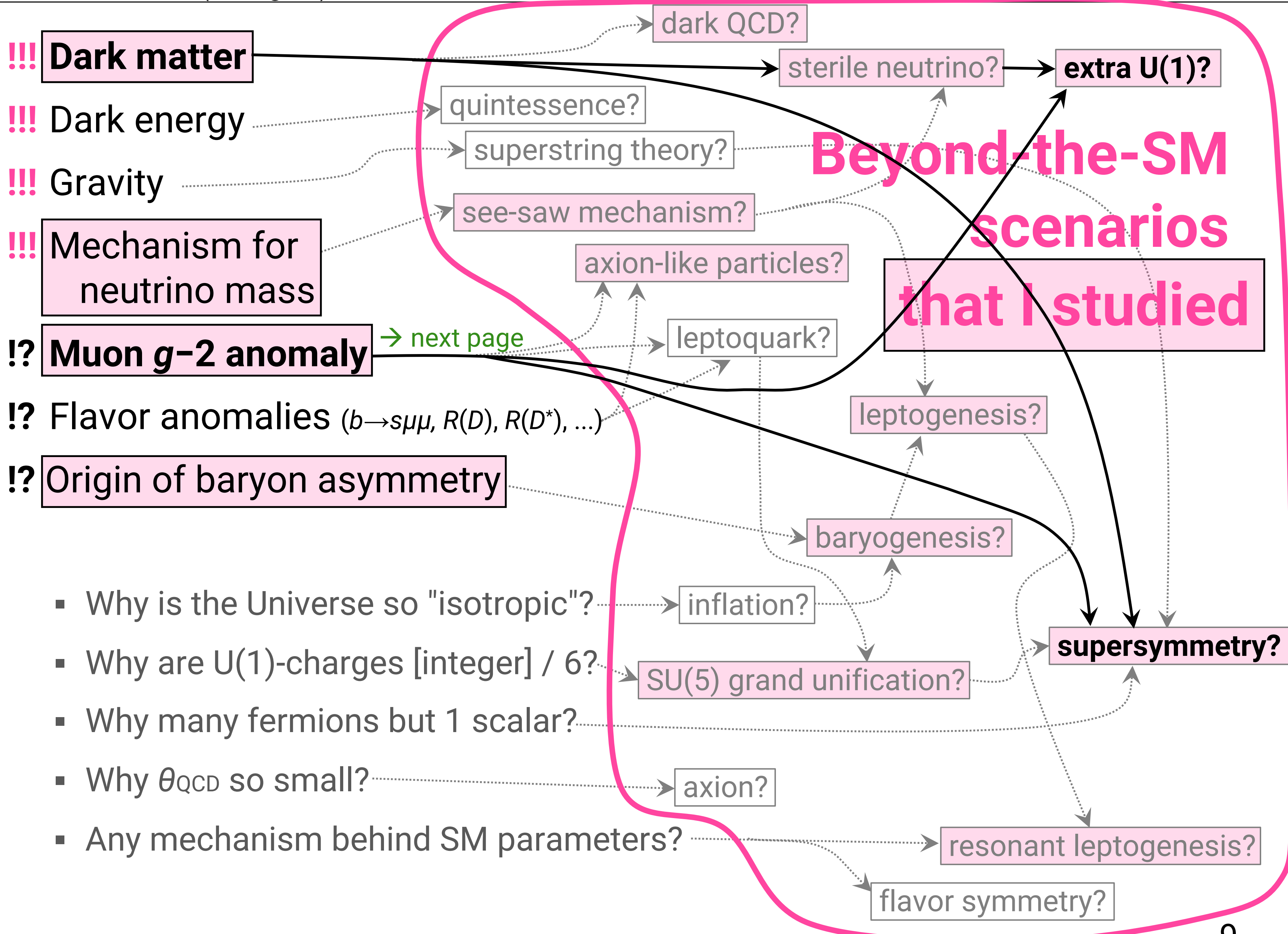
axion?

resonant leptogenesis?

flavor symmetry?

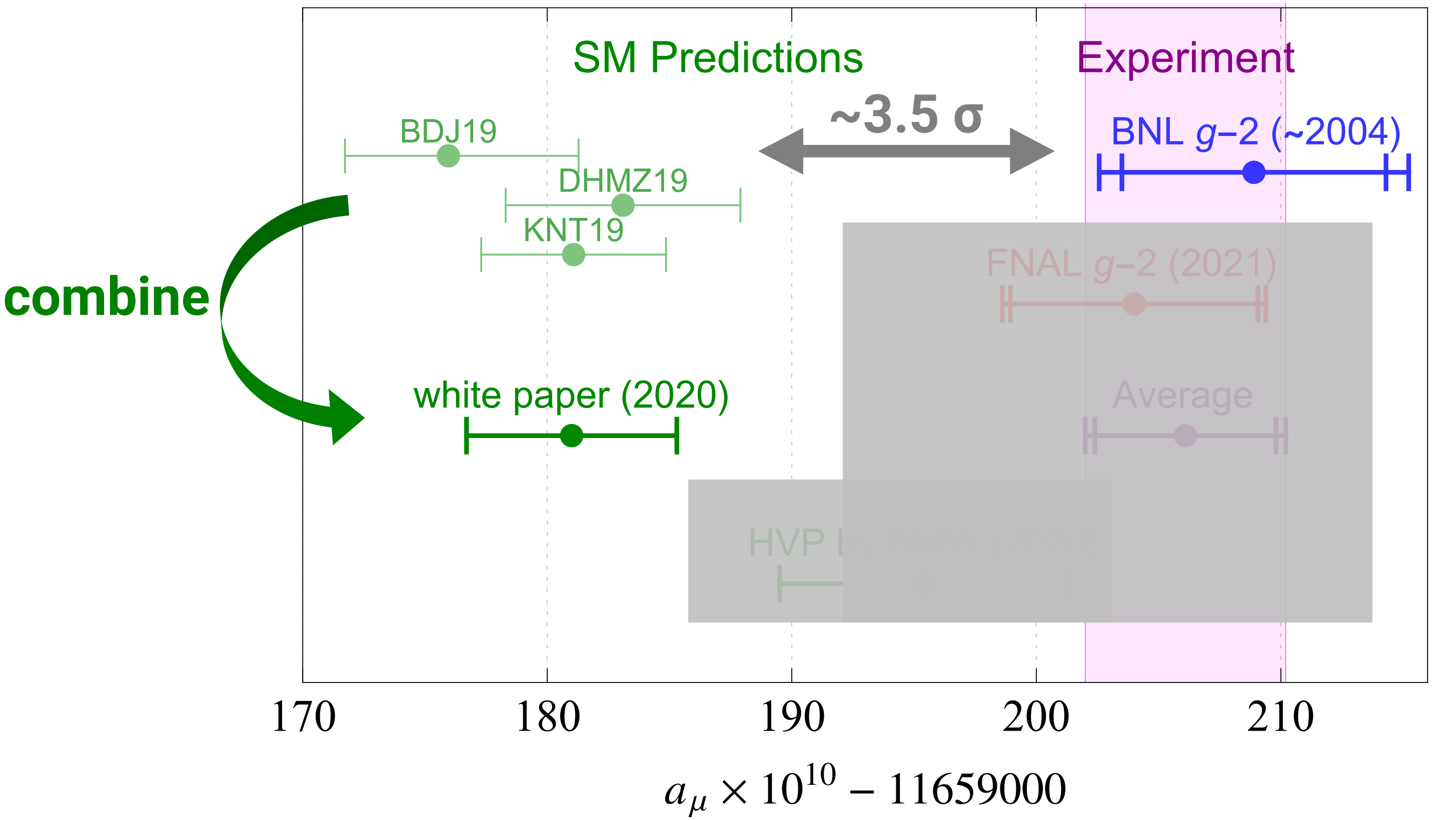
Beyond-the-SM scenarios that I studied

I will focus on (DM, *g*−2) + SUSY in this talk (and briefly on extra U(1) models).



$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

■ Pre-2021 situation



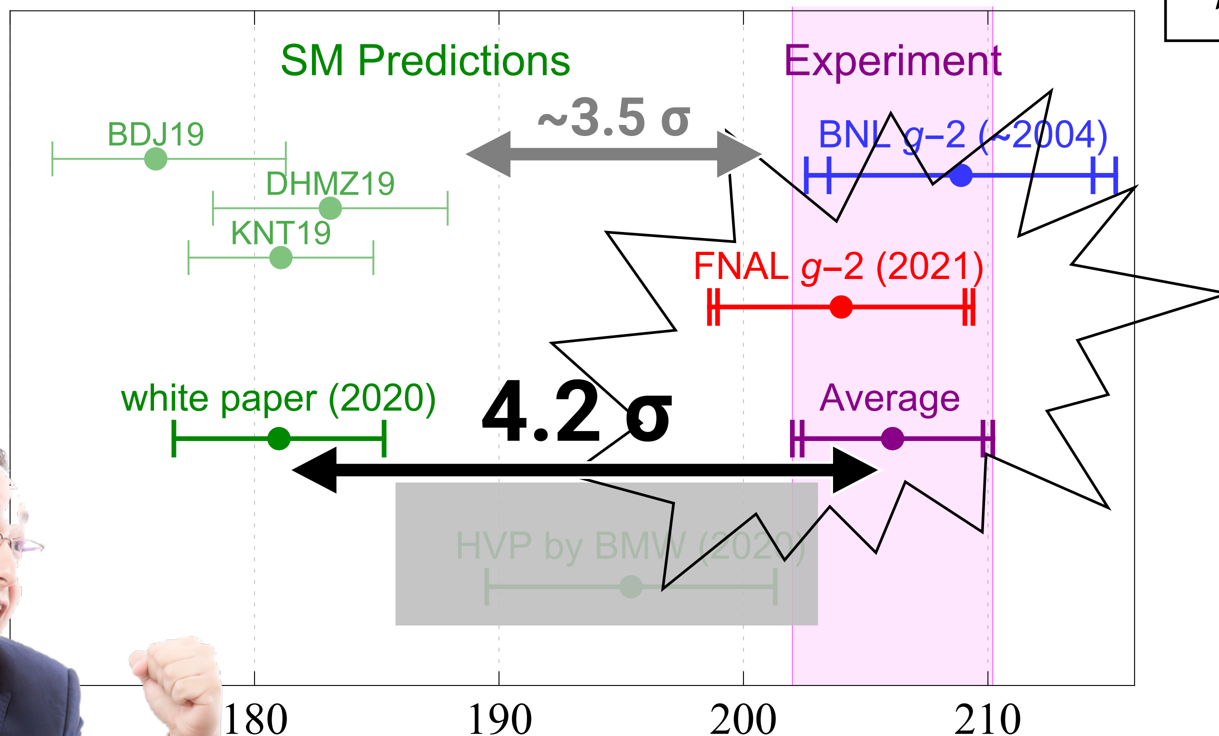
expm: Brookhaven Natl. Lab. [hep-ex/0602035]
Fermilab (Run1) [2104.03247]
SM: White paper [2006.04822]
HVP(lattice) by BMW [2002.12347v3]

old SM: BDJ19 [1903.11034]
DHMZ19 [1908.00921]
KNT19 [1911.00367]

The muon g−2 anomaly was confirmed in the latest measurement at Fermilab.

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

■ 7 April 2021



→ 32 arXiv preprints within 150 minutes

including:

Endo, Hamaguchi, **Iwamoto**, Kitahara [2104.03217],
Iwamoto, Yanagida, Yokozaki [2104.03223].

Fermilab (Run1) [2104.03247]
SM: White paper [2006.04822]
HVP(lattice) by BMW [2002.12347v3]

old SM: BDJ19 [1903.11034]
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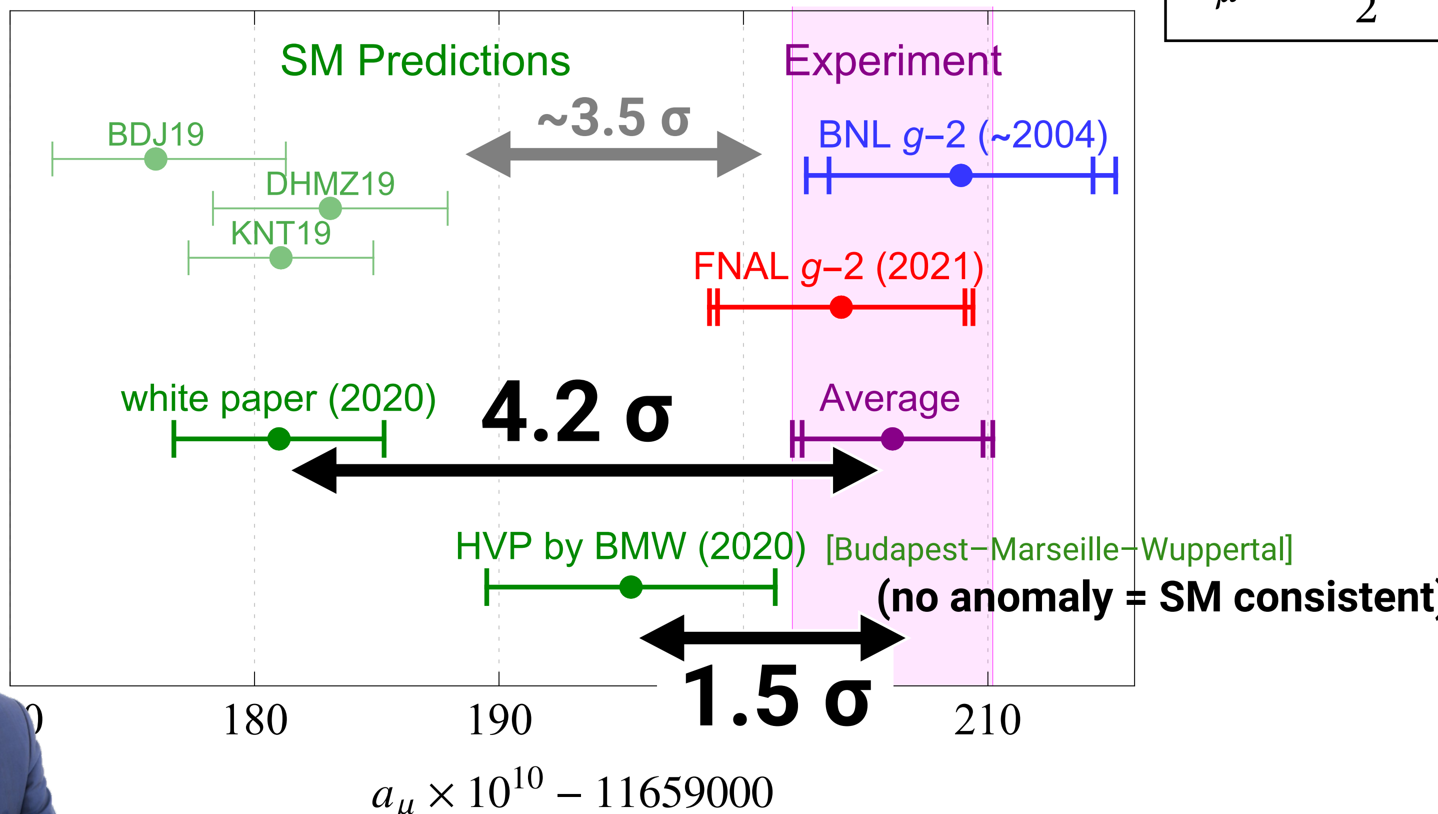
KNT19 [1911.00367]

Image courtesy of pakutaso.com

However, two "SM predictions" are reported. Which is correct? Discussions ongoing.

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

■ 7 April 2021



???

expm: Brookhaven Natl. Lab. [hep-ex/0602035]
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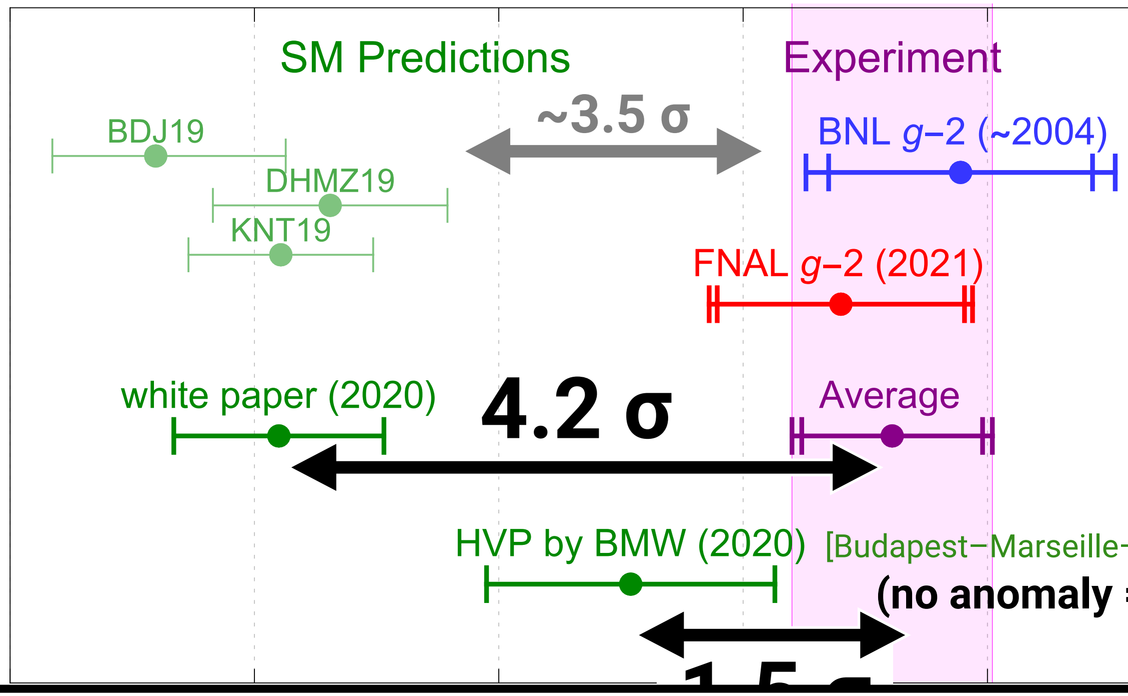
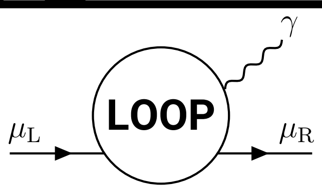
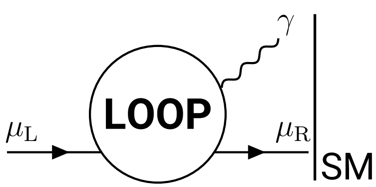
- **7 April 2021**

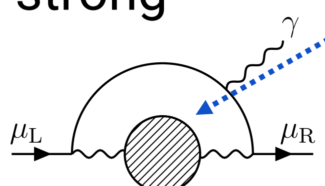
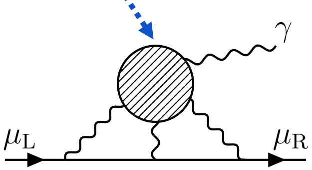


- Theory Predictions = calculate (and sum) **all** of  diagrams.

- 

= "EM" + "weak" + "strong"

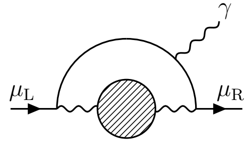
contributions from strong force

$\simeq$ "EM" + "weak" +  + 

Hadronic Vacuum Polarization

Hadronic Light-by-Light

The difference comes from the evaluation of HVP diagrams, in which all hadrons contributes.

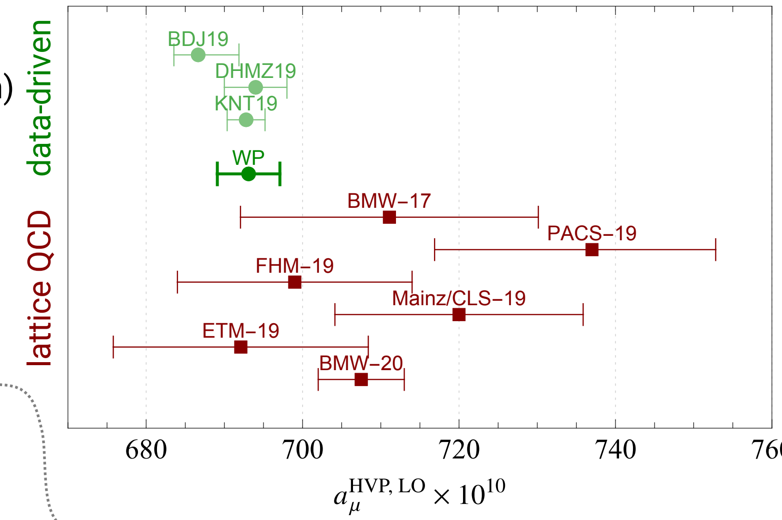
- Two methods for  (hadronic vacuum polarization)

  - White paper: **data-driven approach**

    Optical theorem says:

    HVP = sum of all "$e^+e^- \to$ hadrons" cross sections

    ← Attack: Did you include ALL processes? Are all cross-section data valid and consistent?



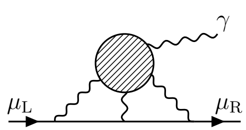
$$a_\mu^{\text{HVP, LO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} \mathrm{d}s\, K(s)\sigma_{e^+e^-\to\text{hadrons}}(s)$$

$\sigma(s)$: cross section with collision energy s

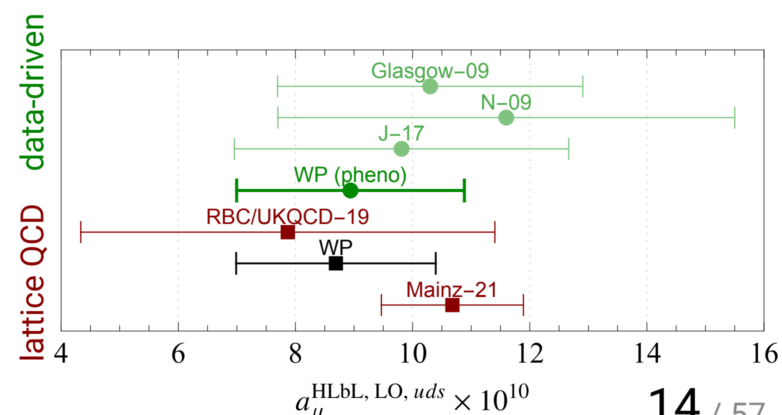
$K(s)$: known analytic function

  - BMW collaboration: **lattice QCD**

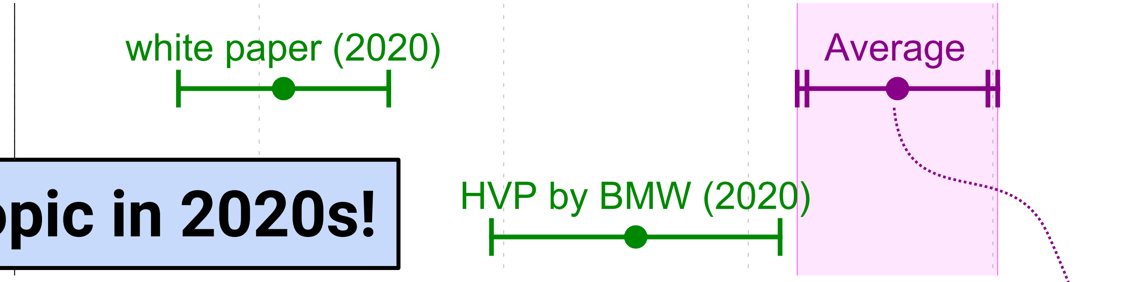
    ← Attack: Are the extrapolations safe? (especially: lattice spacing $a \to 0$)

- Two methods for  (hadronic light-by-light)

  → consistent results.



The muon g−2 anomaly will be one of the hottest 🌶 topics in 2020s.



A very hot topic in 2020s!

- The battle of HVP:
  - data-driven?
    ← Attack: Did you include ALL processes?
    Are all cross-section data valid and consistent?
  - lattice QCD?
    ← Attack: Are the extrapolations safe? (especially: lattice spacing $a \to 0$)
- More supporting data
  e.g. Belle II ($e^+e^- \to \pi^+\pi^-\gamma$ etc.), MUonE ($\mu^\pm e^- \to \mu^\pm e^-$), Electroweak precision tests.
- More precise measurement at Fermilab:

[An important note: I like very hot dishes.]

In this talk, I will assume "BSM solves 4.2σ anomaly."

This is the situation of the Standard Model as of 2021.

- !!! **Dark matter**
- !!! Dark energy
- !!! Gravity
- !!! Mechanism for neutrino mass
- !? **Muon g−2 anomaly**
- !? Flavor anomalies ($b \to s\mu\mu$, $R(D)$, $R(D^*)$, ...)
- !? Origin of baryon asymmetry

- Why is the Universe so "isotropic"?
- Why are U(1)-charges [integer] / 6?
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- Any mechanism behind SM parameters?

dark QCD?
sterile neutrino?
extra U(1)?
quintessence?
superstring theory?
see-saw mechanism?
axion-like particles?
leptoquark?
leptogenesis?
baryogenesis?
inflation?
supersymmetry?
SU(5) grand unification?
axion?
resonant leptogenesis?
flavor symmetry?

I am interested in experimental verifications of the BSM scenarios.

dark QCD?
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!!! **Dark matter**

!!! Dark energy

!!! Gravity

!!! Mechanism for neutrino mass

!? **Muon *g*−2 anomaly**

!? Flavor anomalies ($b\to s\mu\mu$, $R(D)$, $R(D^*)$, ...)

!?

My primary question: discover or reject

How to test BSM models at experiments?

This talk: supersymmetry as the solution to DM & muon $g-2$ | the LHC

on which I have been working since 2011.

Iwamoto + others (incl. Endo, Hamaguchi, Kitahara, Yanagida, Yokozaki, ...)
[1108.3071, 1112.5653, 1112.6412, 1212.3935, 1303.4256, 1407.4226, 1704.05287, 2001.11025, 2104.03217, 2104.03223]

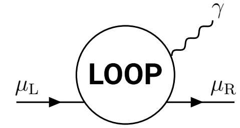
"How to test BSM models at experiments?"

1. Standard Model
   - ✓ Success
   - ✓ Issues: Dark matter, muon $g{-}2$ anomaly, ...

2. Frontiers of experiments

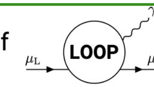
3. Supersymmetry (as the solution to DM & muon $g{-}2$) at the LHC

4. A few other topics

- $(g-2)_\mu$ → new particle(s) to give extra contribution of 

- DM → a new particle for DM

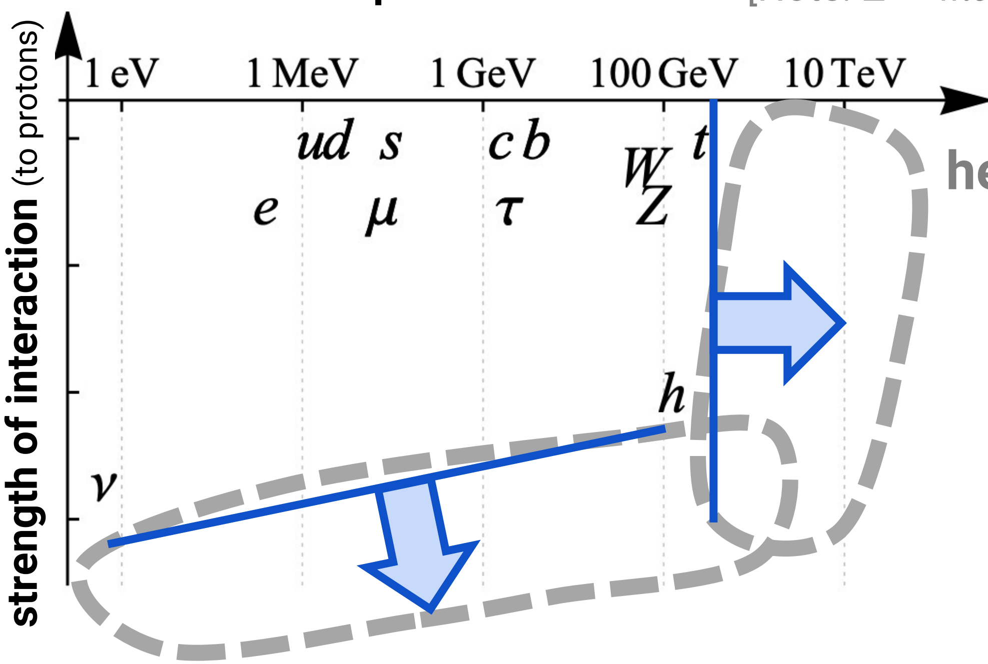
search targets at experiments

remember:
- Theory Predictions = calculate (and sum) **all** of  diagrams.

(We will assume these problems are solved by BSM.)

■ "new" = not discovered. But Why?

particle mass [Note: $E = mc^2$, $1\,\mathrm{GeV} = 1.8\times10^{-24}\,\mathrm{g} \simeq$ proton mass]



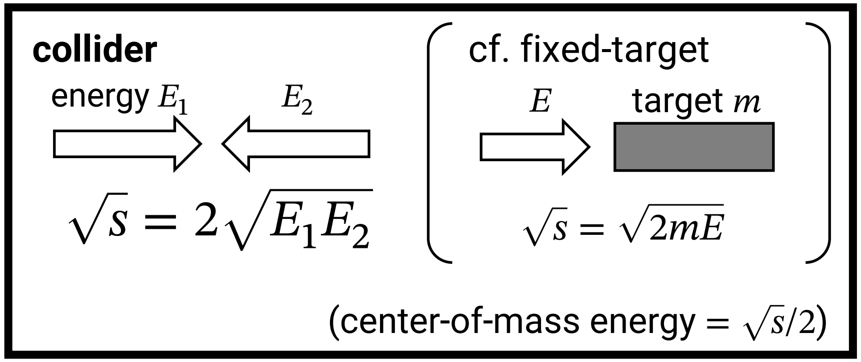
heavy?
→ We need more energy!
"energy frontier"

weak and elusive? → We need more intensity!
"intensity frontier"

(Also:
neutrino frontier,
precision frontier,
cosmic frontier,
theory frontier, ...)

- Particle physics experiments:

  collider experiments,
  fixed-target experiments [NA64, NA42, KOTO, ...],
  DM direct detection [XENON, LUX, ...],
  neutrino [DayaBay, Super-K, ...],
  astro-particle observations [Fermi, AMS-02, ...],
  ...,
  ...,



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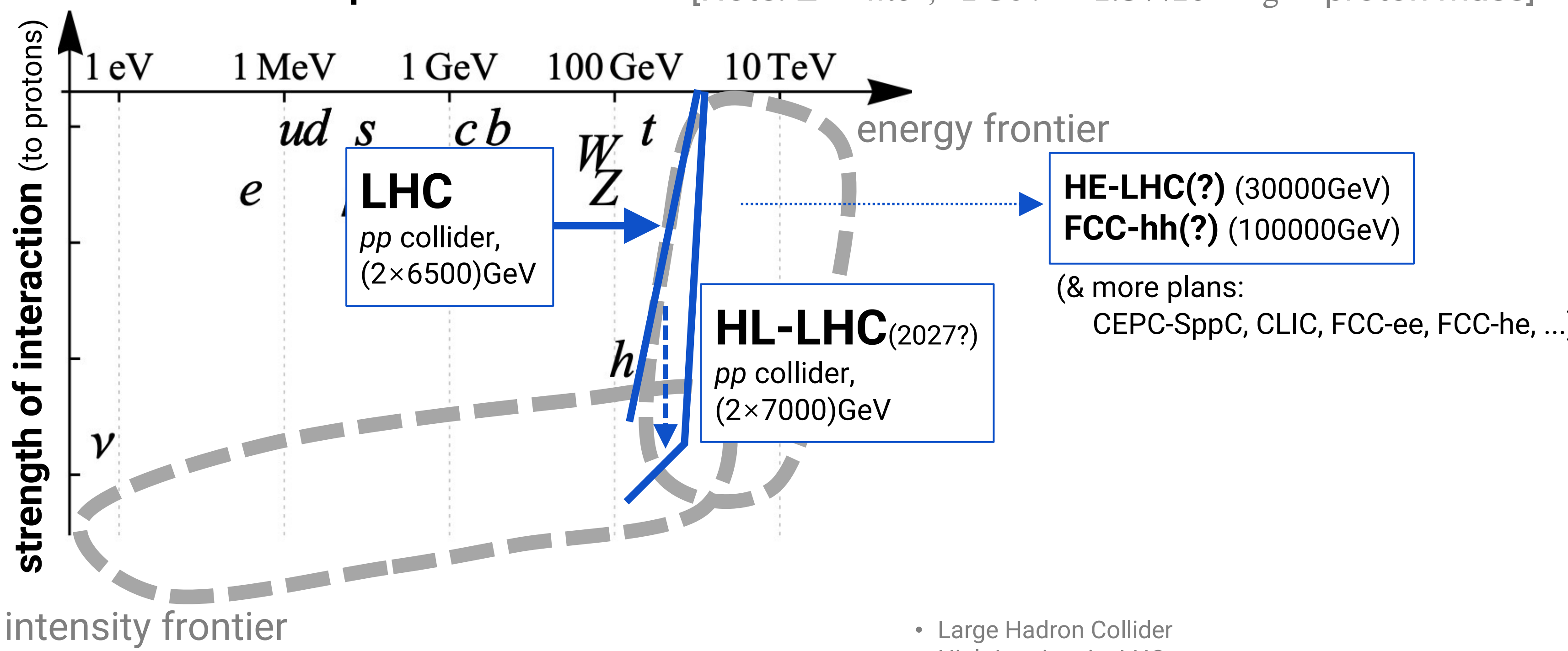

- Large Hadron Collider
- High-Luminosity LHC
- High-Energy LHC
- Future Circular Collider: hadron-hadron

- Particle physics experiments:

  collider experiments,
  fixed-target experiments [NA64, NA42, KOTO, ...],
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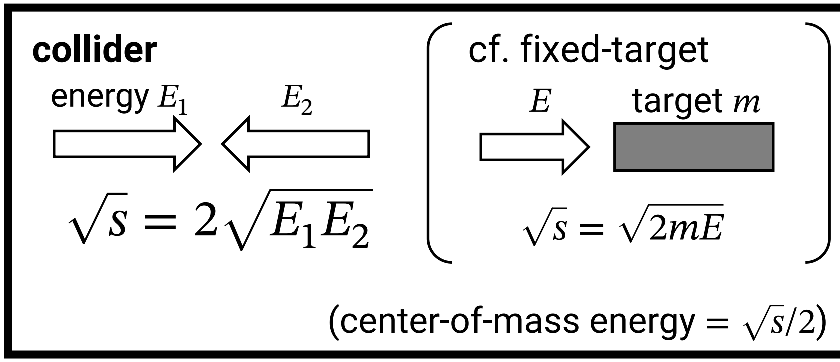

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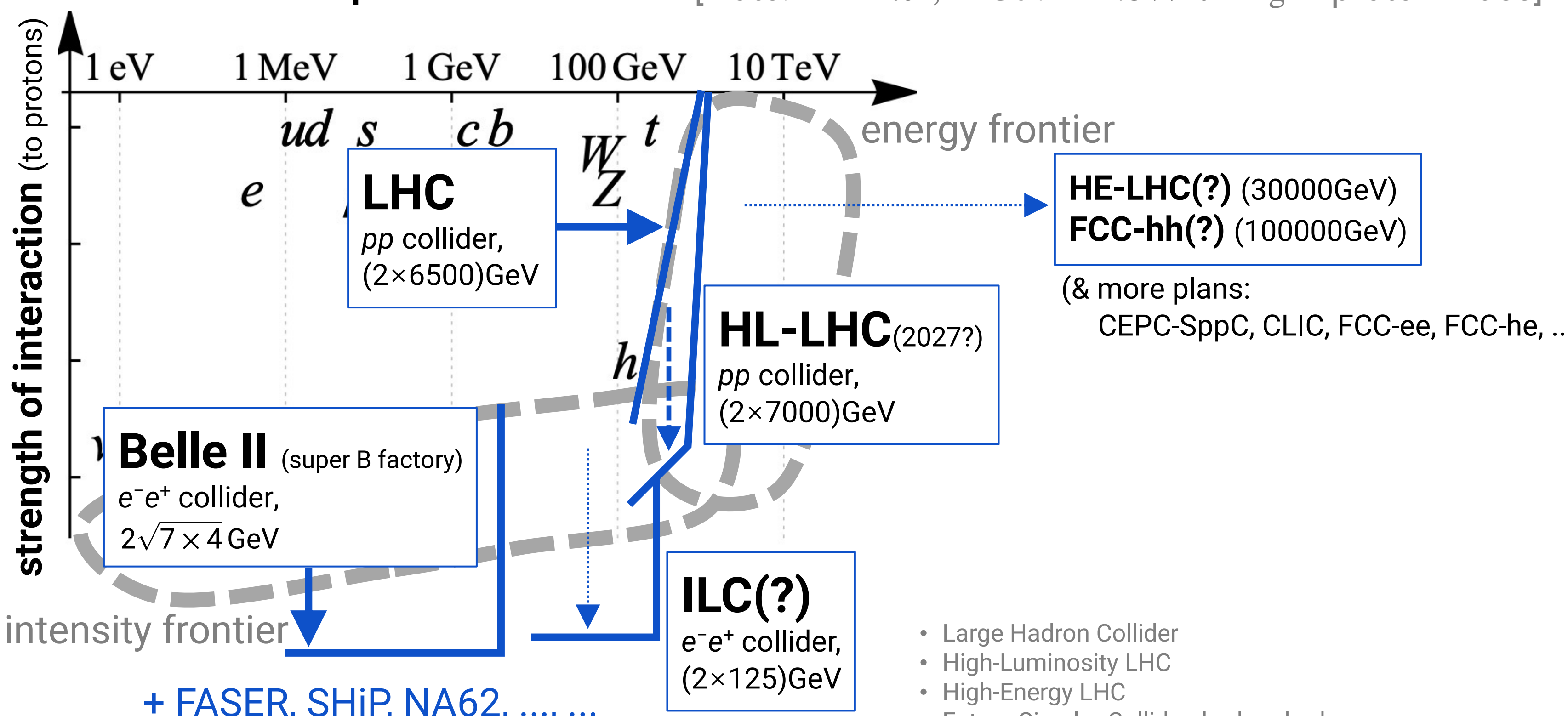

+ FASER, SHiP, NA62, ..., ...

- Large Hadron Collider
- High-Luminosity LHC
- High-Energy LHC
- Future Circular Collider: hadron-hadron
- International Linear Collider

The LHC is a proton-proton collider with several experiments.

■ Large Hadron Collider

©2014 CERN

two proton beams with $E = O(1)$ TeV

collider

energy E_1 $\quad\rightarrow\quad\leftarrow\quad$ E_2

$$\sqrt{s} = 2\sqrt{E_1 E_2}$$

26659m ring $\simeq$

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©2014 Taipei Metro

- Large Hadron Collider

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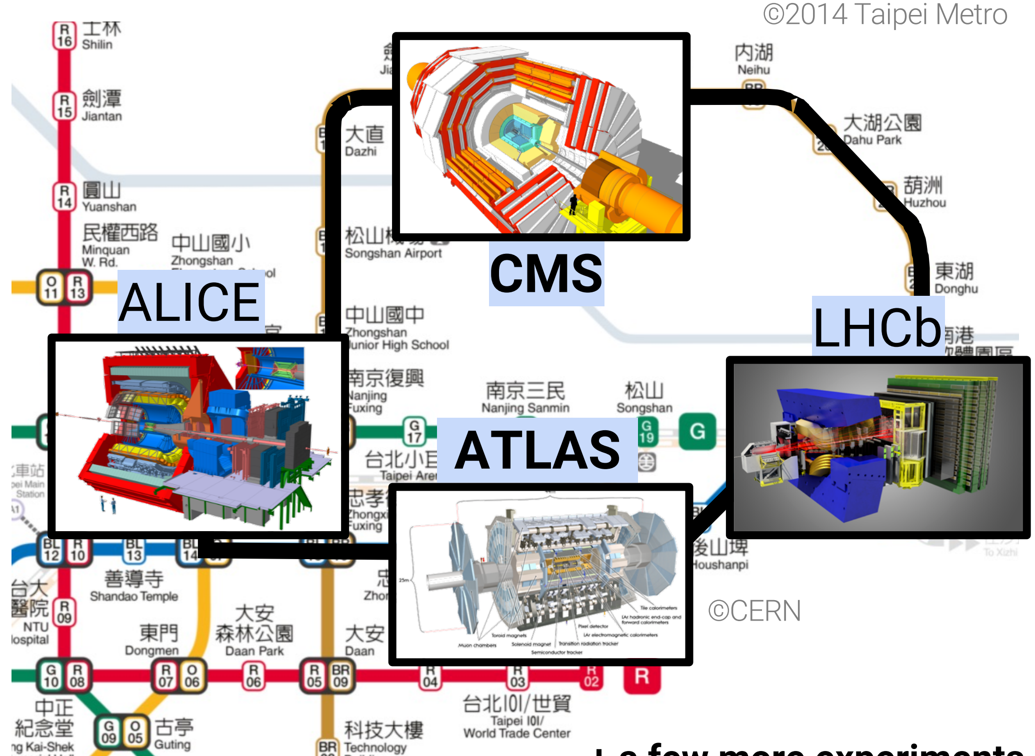


+ a few more experiments

■ Large Hadron Collider

	[2×(beam energy)] $\sqrt{s}$	[integrated luminosity] $\int L$ (approx.)
Run 1 (2009–2013) ✓	7–8 TeV	5 + 20 fb^{-1}
Run 2 (2015–2018) ✓	13 TeV	135 fb^{-1}
Run 3 (2022–2024?)	13.6 TeV?	160 fb^{-1}?
Run 4 +more? (2027?) [High Luminosity LHC]	14 TeV?	3000 fb^{-1}?

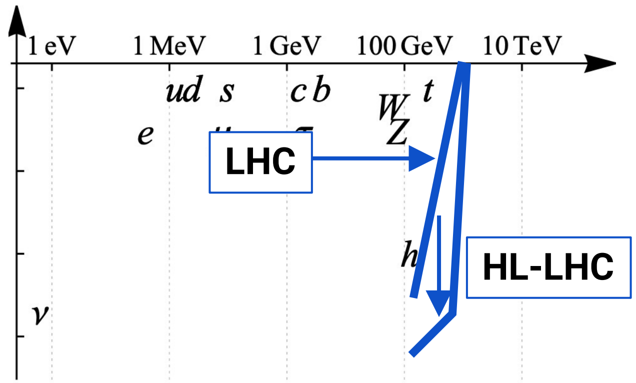
~10^{16} *pp* collisions (excl. pile-up)

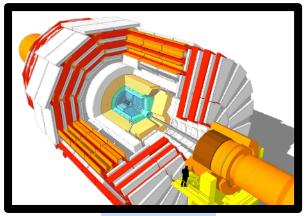
[Note: 1yr ~ 10^7s]

collider

energy E_1 E_2

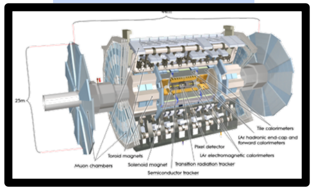
$$\sqrt{s} = 2\sqrt{E_1 E_2}$$





CMS

ATLAS



©CERN

Note for experts:
We here refer only to proton–proton collisions; the LHC also operates as a proton–Pb and Pb–Pb collider (and more).

"How to test BSM models at experiments?"

1. Standard Model
   - ✓ Success
   - ✓ Issues: Dark matter, muon $g-2$ anomaly, ...
2. Frontiers of experiments
   - ✓ Energy frontier, Intensity frontier
   - ✓ (HL-)LHC
3. Supersymmetry (as the solution to DM & muon $g-2$) at the LHC
4. Two other topics at intensity (+ cosmic & neutrino) frontier

Supersymmetry (SUSY) is a hypothetical symmetry of fermion ⇔ boson.

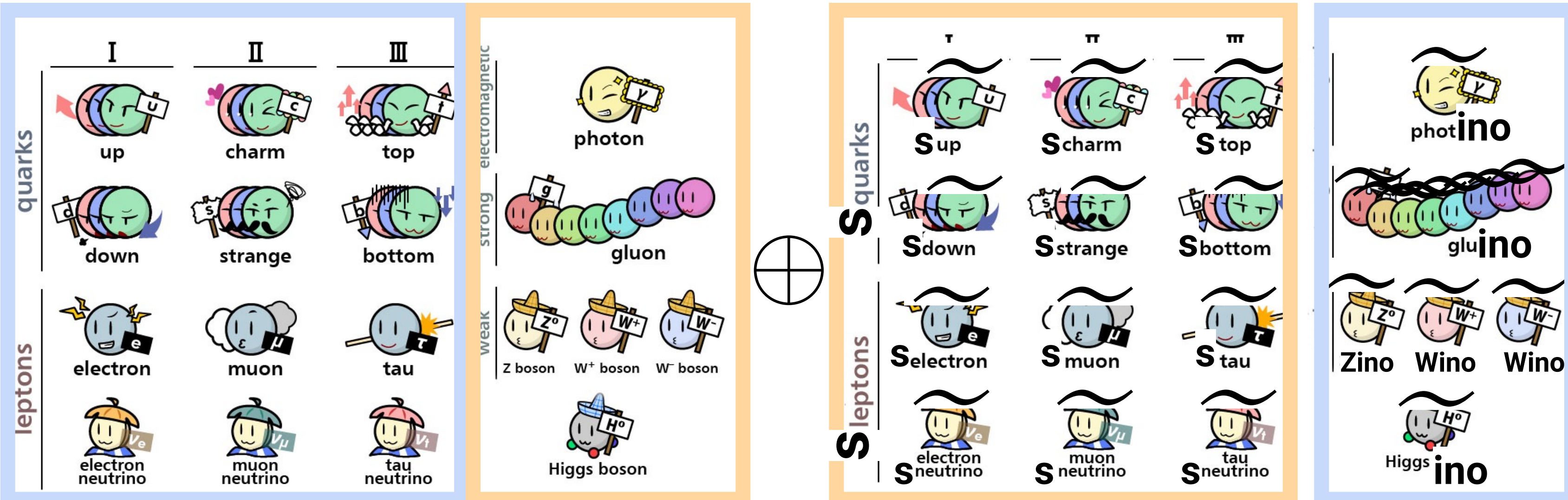
超對稱 = **fermion** ⇔ **boson**

- quark ⇔ **s**quark
- lepton ⇔ **s**lepton
- higgs**ino** ⇔ higgs

Supersymmetry (SUSY) is a hypothetical symmetry of fermion ⇔ boson.

(minimal) Supersymmetric Standard Model [MSSM]

Standard Model particles — SUSY partners (hypothetical particles)



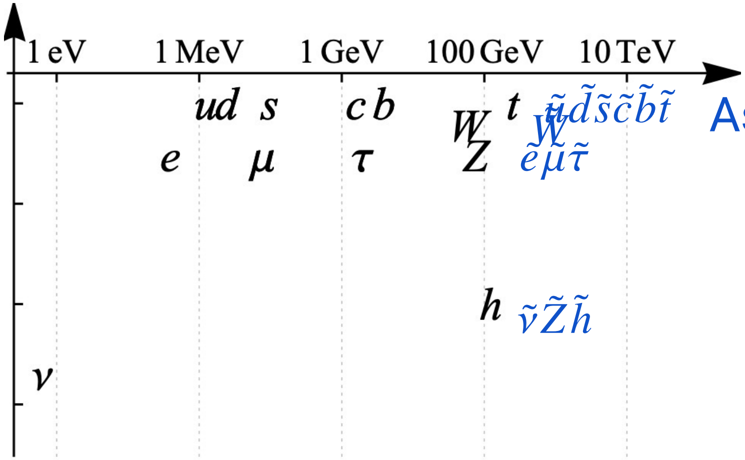
If the Universe *were* supersymmetric:

$m_{\text{slepton}} = m_{\text{lepton}}$, $m_{\text{squark}} = m_{\text{quark}}$, … → contradiction!

→ We *assume*:
SUSY is spontaneously-broken so that
SUSY particles have 100–1000 GeV mass.

son
rk
on

remember:
try" SU(3)×SU(2)×U(1),
on *H*.
→U(1)
spontaneous symmetry breaking
induced by Higgs boson



Assume: SUSY particles at 100GeV−10TeV.

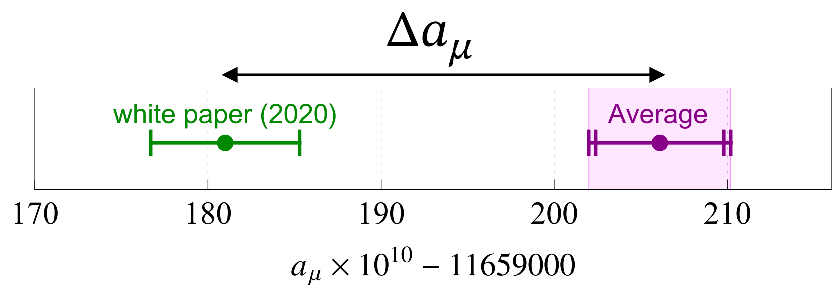
[1TeV = 1000GeV]

■ Why SUSY at 100GeV−10 TeV?

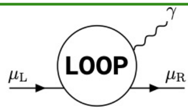
- ❖ "superstring theory" ...? (but it requires only "below 10^{19} GeV", not TeV-scale.)
- ❖ naturalness of Higgs mass,
- ❖ dark matter, → appendix →
- ❖ grand unification, → appendix
- ❖ muon g−2. → next page

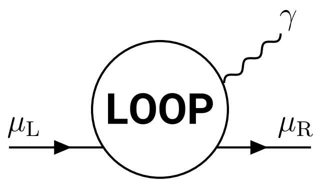
- **Lightest SUSY Particle can be DM.**
- ~100GeV LSP with "freeze-out" can naturally explain why DM is 26%.

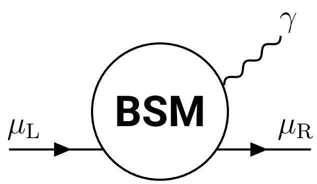
Motivation for TeV-scale SUSY (3) We can explain the muon g−2 anomaly.



remember:

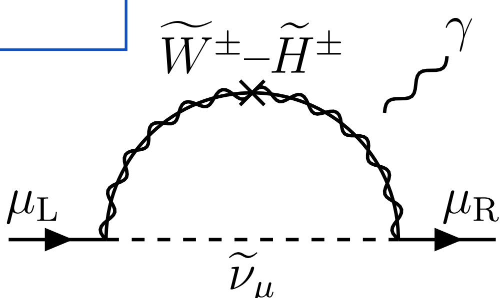
- Theory Predictions = calculate (and sum) **all** of  diagrams.

$a_\mu = \dfrac{(g-2)_\mu}{2} =$ 

$\Delta a_\mu =$  $\approx \dfrac{m_\mu^2}{16\pi^2} \dfrac{(\text{new particle coupling})^2}{(\text{new particle mass})^2} = 25 \times 10^{-10}$

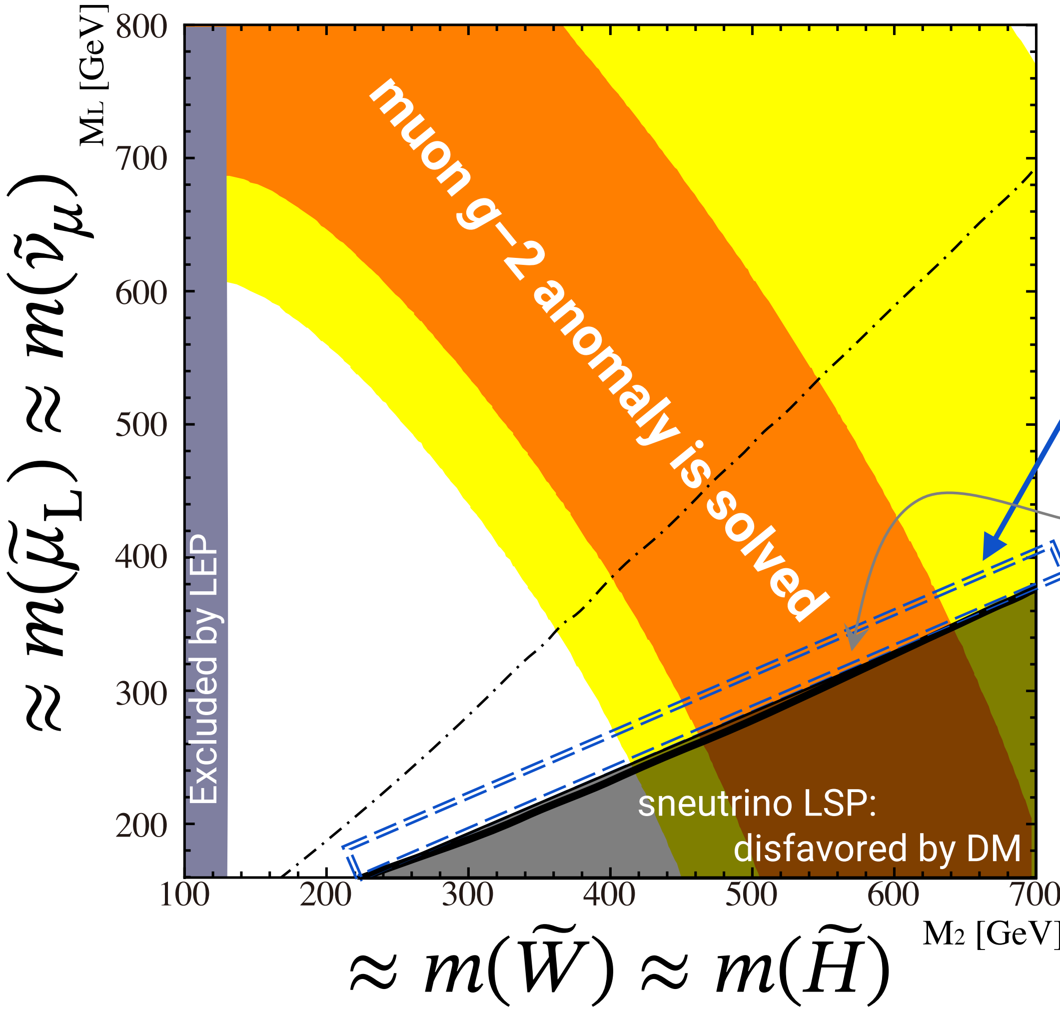
$$\boxed{\frac{(\text{new particle mass})}{(\text{new particle coupling})} \approx 200\,\text{GeV}}$$

Δa_μ may come from, e.g.,



An example of the motivated parameter space (from my old work).

Endo, Hamaguchi, **Iwamoto**, Yoshinaga [1303.4256]



Note: This plot was drawn in 2013.
Obsolete values are used.

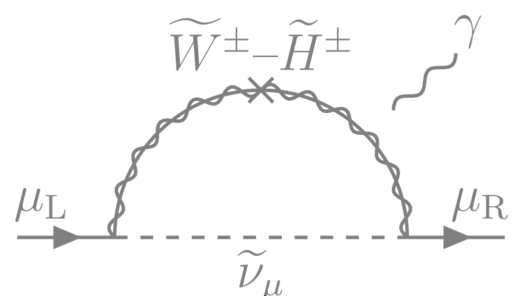
DM density is explained.
(bino−smuon coannihilation)

✓ dark matter,
✓ coupling unification,
✓ muon *g*−2.

theory detail

$\mu = M_2$, $\tan\beta = 40$,
$m_{\tilde{E}} \gg 1\,\mathrm{TeV}$, $m(\mathrm{stau}) \gg 1\,\mathrm{TeV}$,
$2M_1 = M_2 \ll M_3$, $m(\mathrm{squark}) \gg 1\,\mathrm{TeV}$,
$m_A \gg 1\,\mathrm{TeV}$, $A_l = 0$,
~~SUSY~~-parameters set at 500 GeV

Δa_μ may come from, e.g.,



To compare with experiment, theory equations should be converted to "real" numbers.

THEORY

$$\{Q^A_\alpha, \bar{Q}_{\dot\beta B}\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu \delta^A_B$$

$$\mathcal{L} = \left[\Phi_i^* [\mathrm{e}^{2gV t^a_\Phi}]_{ij}\Phi_j\right]_{\theta^4} + \{[\mathcal{W}^a\mathcal{W}^a]_{\theta^2} + [W(\Phi_i)]_{\theta^2} + \text{H.c.}\} + D$$

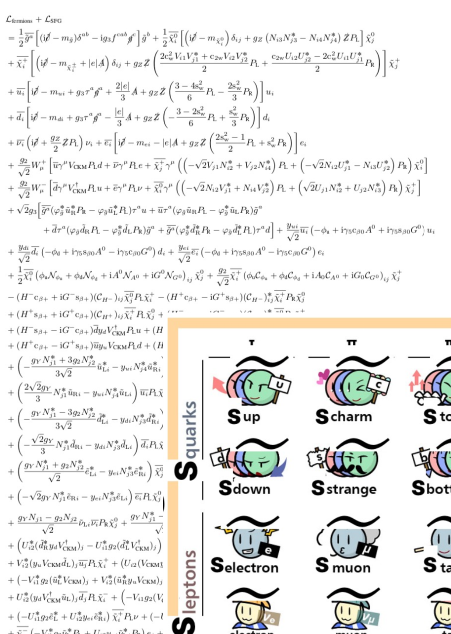
$$W_{\rm RPC} = \mu H_{\rm u} H_{\rm d} - y_{{\rm u}ij} U^{\rm c}_i H_{\rm u} Q_j + y_{{\rm d}ij} D^{\rm c}_i H_{\rm d} Q_j + y_{{\rm e}ij} E^{\rm c}_i H_{\rm d} L_j,$$

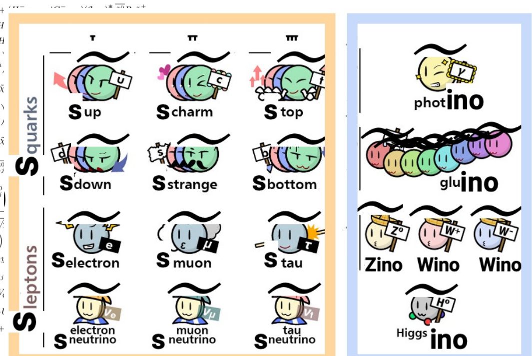
$$W_{\rm RPV} = -\kappa_i L_i H_{\rm u} + \frac{1}{2}\lambda_{ijk} L_i L_j E^{\rm c}_k + \lambda'_{ijk} L_i Q_j D^{\rm c}_k + \frac{1}{2}\lambda''_{ijk} U^{\rm c}_i D^{\rm c}_j D^{\rm c}_k,$$

$$\mathcal{L}_{\cancel{\rm SUSY}} = -\frac{1}{2}\left(M_3\tilde g_0 \tilde g_0 + M_2 \tilde w\tilde w + M_1 \tilde b\tilde b + \text{H.c.}\right) - V_{\cancel{\rm SUSY}};$$

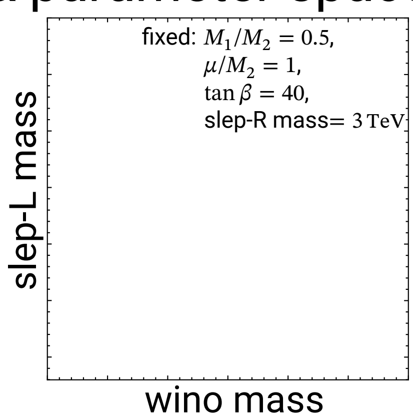
$$V^{\rm RPC}_{\cancel{\rm SUSY}} = \left(\tilde q^*_{\rm L} m^2_Q \tilde q_{\rm L} + \tilde l^*_{\rm L} m^2_L \tilde l_{\rm L} + \tilde u^*_{\rm R} m^2_{U^{\rm c}} \tilde u_{\rm R} + \tilde d^*_{\rm R} m^2_{D^{\rm c}} \tilde d_{\rm R} + \tilde e^*_{\rm R} m^2_{E^{\rm c}} \tilde e_{\rm R} + m^2_{H_{\rm u}}|h_{\rm u}|^2 + m^2_{H_{\rm d}}|h_{\rm d}|^2\right) + \left(-\tilde u^*_{\rm R} h_{\rm u} a_{\rm u} \tilde q_{\rm L} + \tilde d^*_{\rm R} h_{\rm d} a_{\rm d} \tilde q_{\rm L} + \tilde e^*_{\rm R} h_{\rm d} a_{\rm e} \tilde l_{\rm L} + b H_{\rm u} H_{\rm d} + \text{H.c.}\right)$$

expand & interpret

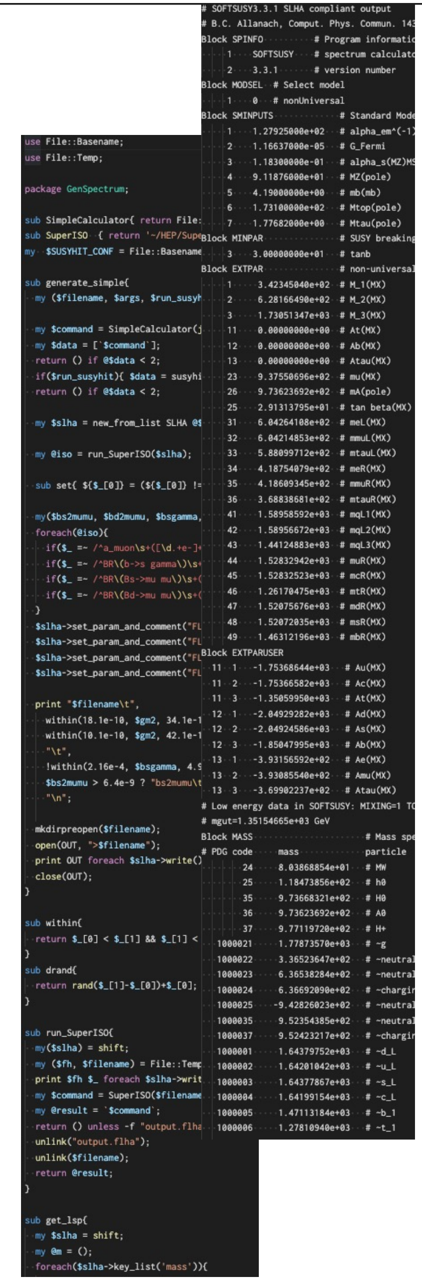




choose meaningful scenarios & parameter space



calculate everything



draw

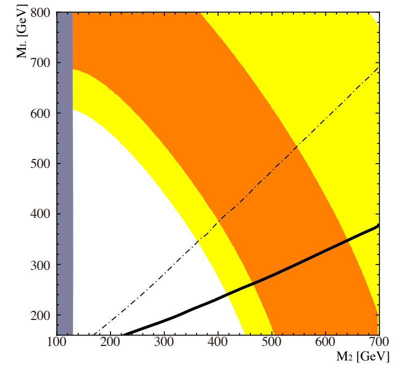
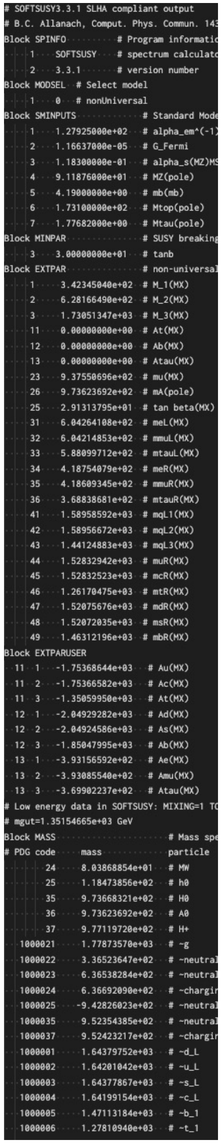
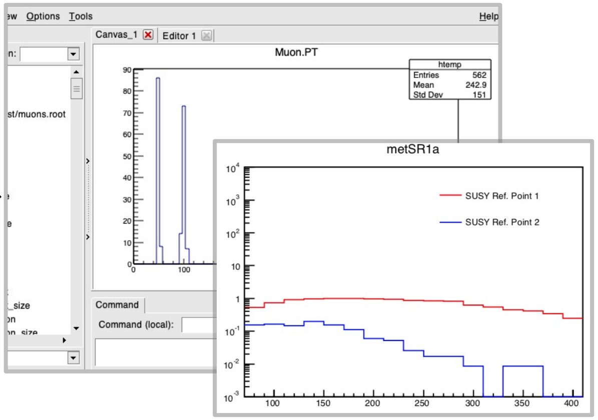


Figure courtesy of HiggsTan.com

Understanding the experiment (and its detectors) is necessary as well for my goal.

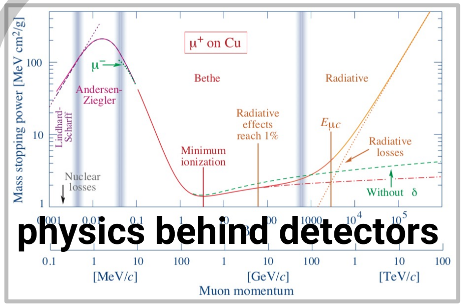


Monte Carlo simulation



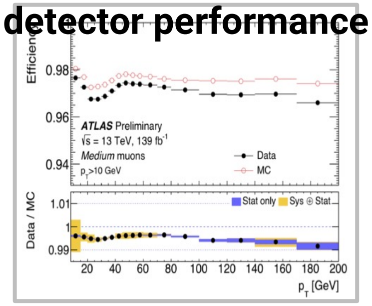
statistical analysis

next page

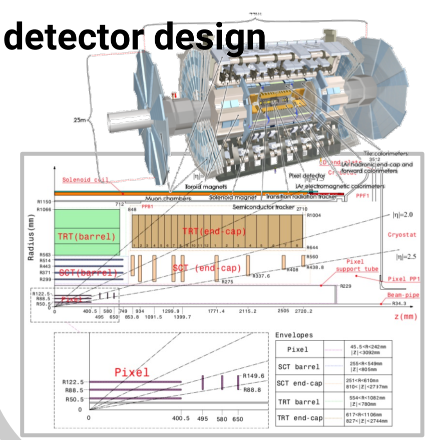


physics behind detectors

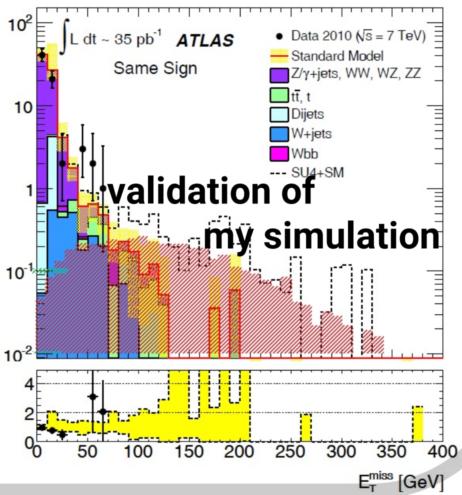
detector performance



detector design



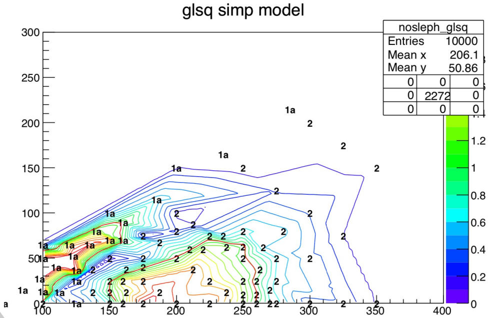
© CERN



validation of my simulation

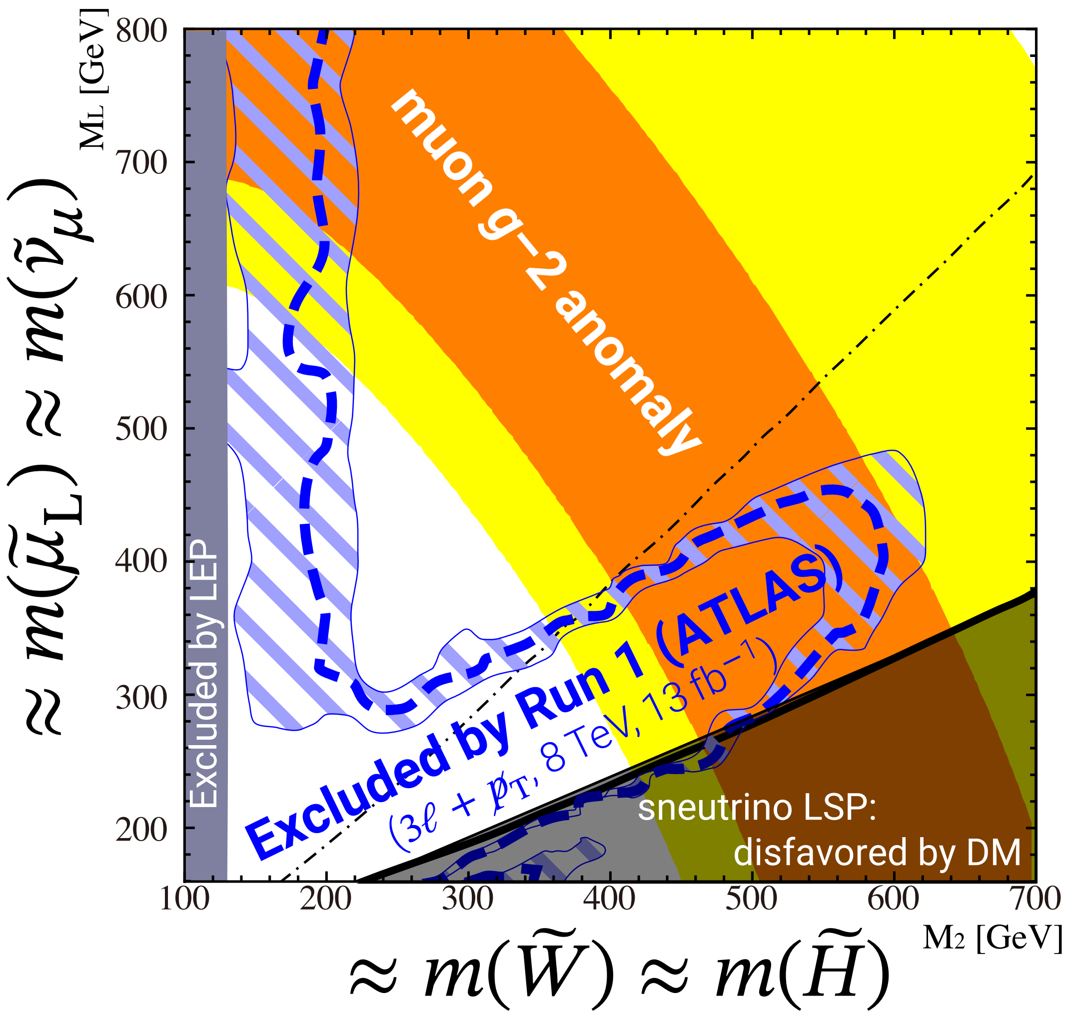
	background cross section [fb]				N_{UL}		
	di-boson	tri-boson	top	total	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
$N_\ell \geq 3$	222	5.1	13.4	249	—	—	—
$WZ(j)^-$	0.071	0.013	0.082	0.166	25.1	70.4	200
$WZ(j)^Z$	0.643	0.071	0.183	0.898	111	359	1060
$WZ(\ell)^-$	0.014	0.025	0.017	0.056	11.9	27.4	71.1
$WZ(\ell)^Z$	< 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

glsq simp model



We calculated the LHC constraints on this parameter space ("WHL scenario").

Endo, Hamaguchi, **Iwamoto**, Yoshinaga [1303.4256]



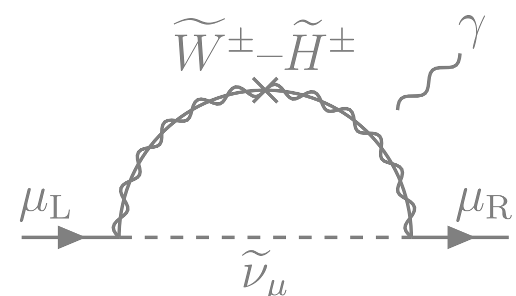
Note: This plot was drawn in **2013**.
Obsolete values are used.

theory detail

$\mu = M_2$, $\tan\beta = 40$,
$m_{\tilde{E}} \gg 1\,\mathrm{TeV}$, $m(\mathrm{stau}) \gg 1\,\mathrm{TeV}$,
$2M_1 = M_2 \ll M_3$, $m(\mathrm{squark}) \gg 1\,\mathrm{TeV}$,
$m_A \gg 1\,\mathrm{TeV}$, $A_l = 0$,
~~SUSY~~-parameters set at 500 GeV

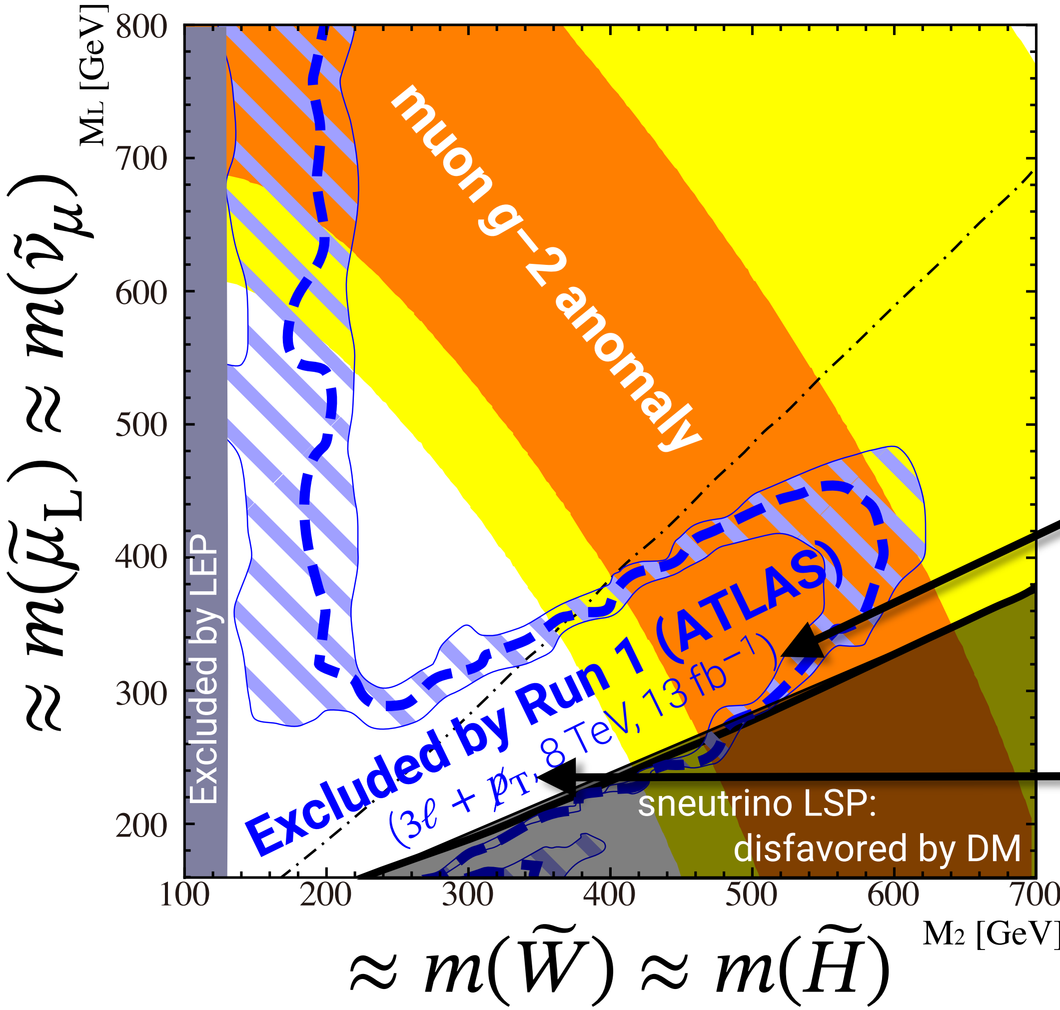
Expm/MC detail

Based on ATLAS-CONF-2012-154 (8TeV, 13/fb)
Pythia: ATLAS MC09 tune + CTEQ6L1
Delphes: default ATLAS card + FASTJET (anti-Kt, 0.4)
Lepton-eff. from ATLAS performance 2010
SR: mpT75+3L10 with SFOS(>12 but Z-unlike)
NLO K-factor 1.2 (sys unc 30% = blue shaded)



What does this mean? A message to theory community, and another to experiment community.

Endo, Hamaguchi, **Iwamoto**, Yoshinaga [1303.4256]



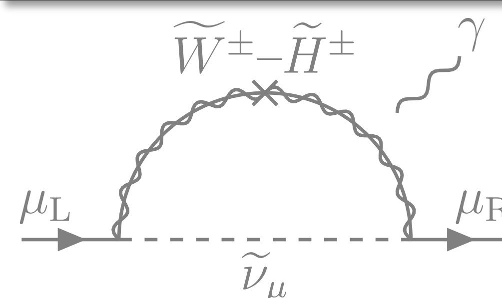
Note: This plot was drawn in **2013**.
Obsolete values are used.

We found that...

Some of "***g*−2 SUSY**" was already excluded at LHC Run 1 (2012)!
[→ theory]

$\left(pp \to \widetilde{W}^0 \widetilde{W}^+ \to 3\ell + \not{p}_T\right)$

"$3\ell + \not{p}_T$" signal is the best in this case.
[→ expm]



theory detail

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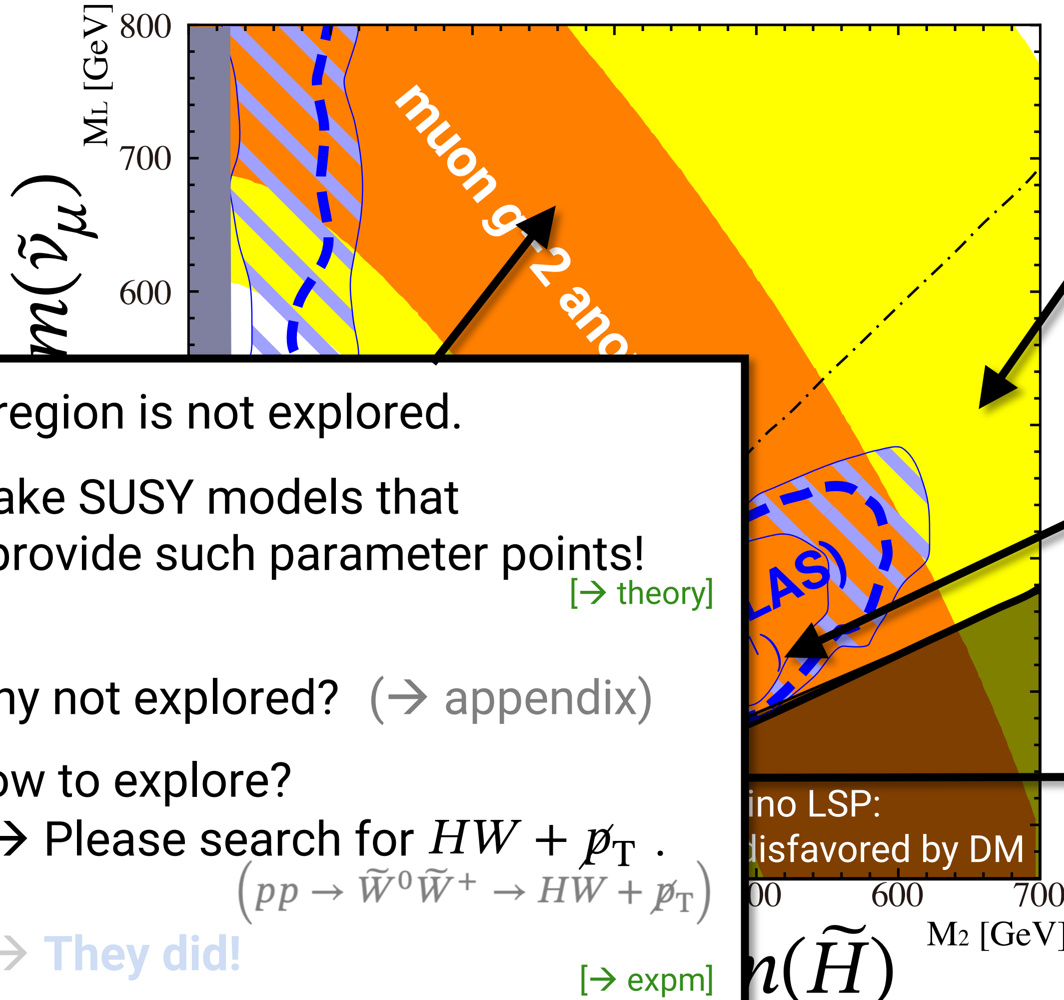
NLO K-factor 1.2 (sys unc 30% = blue shaded)

We proposed that they should search for *HW* + missing-energy signature (and a few more channels).

Endo, Hamaguchi, **Iwamoto**, Yoshinaga [1303.4256]



This region is not explored.

- Make SUSY models that provide such parameter points! [→ theory]
- Why not explored? (→ appendix)
- How to explore?
  → Please search for $HW + \not{p}_{\mathrm{T}}$.
  $\left(pp \to \widetilde{W}^0\widetilde{W}^+ \to HW + \not{p}_{\mathrm{T}}\right)$
  → They did!
  [→ expm]

This region will soon be explored by $3\ell + \not{p}_{\mathrm{T}}$.

We found that...

Some of "***g*−2 SUSY**" was already excluded at LHC Run 1 (2012)! [→ theory]

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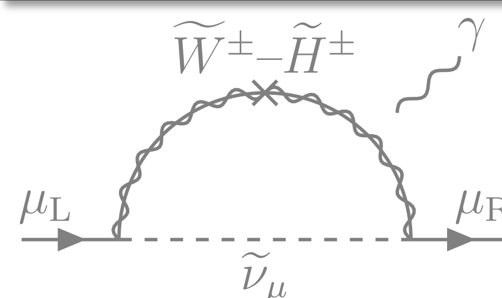

theory detail

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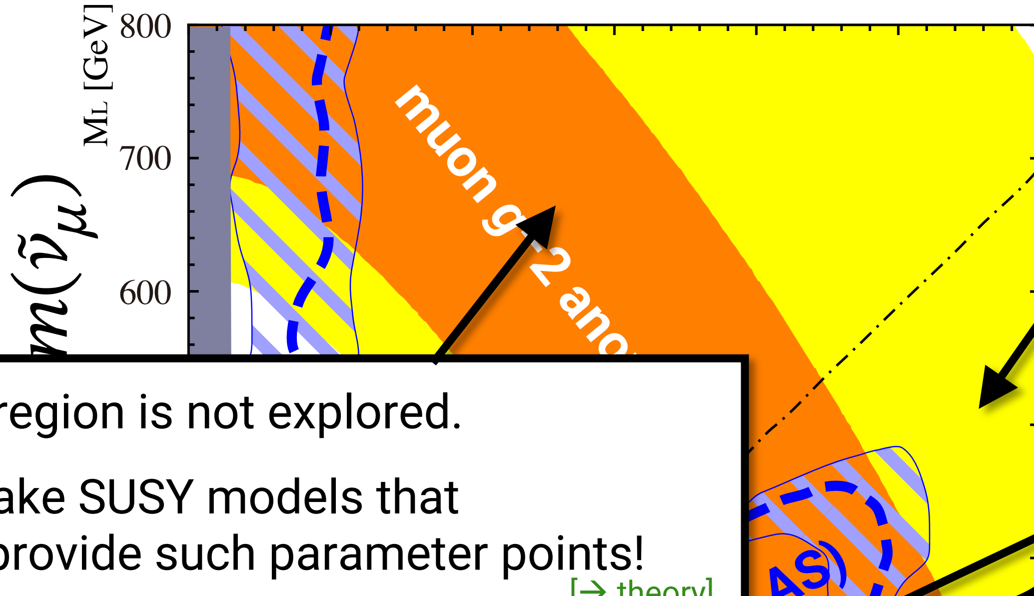


This region will soon be explored by $3\ell + \not{p}_{\mathrm{T}}$.

We found that...

Some of "***g*−2 SUSY**" was already excluded at LHC Run 1 (2012)!
[→ theory]

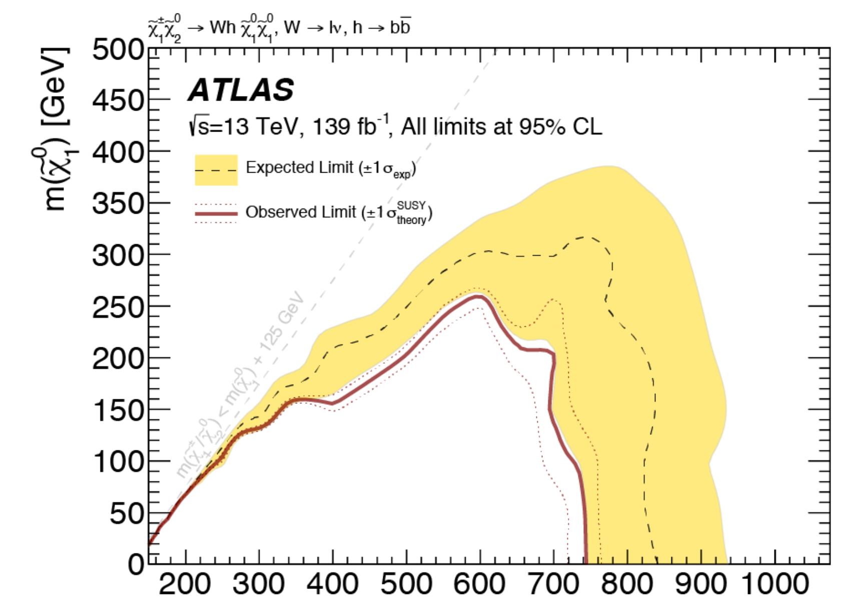
This region is not explored.

- Make SUSY models that provide such parameter points!
[→ theory]

- Why not explored? (→ appendix)

- How to explore?
  → Please search for $HW + \not{p}_{\mathrm{T}}$.
  $\left(pp \to \widetilde{W}^0\widetilde{W}^+ \to HW + \not{p}_{\mathrm{T}}\right)$

  → **They did!**
[→ expm]



ATLAS [1909.09226]

theory detail

$\mu = M_2$, $\tan\beta = 40$,
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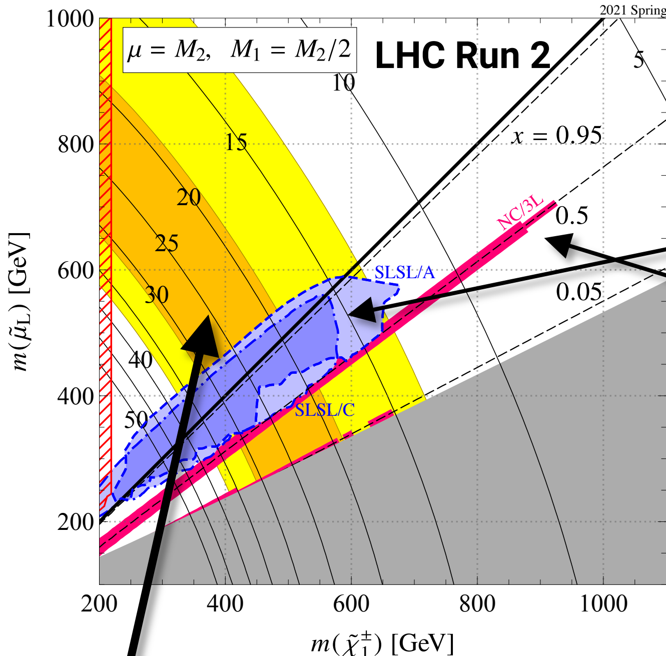
SR: mpT75+3L10 with SFOS(>12 but Z-unli
NLO K-factor 1.2 (sys unc 30% = blue shade

LHC Run 2 excludes the lower-right region as expected. How to proceed to the upper-left?

Endo, Hamaguchi, **Iwamoto**, Kitahara [2001.11025] [2104.03217]



$m(\widetilde{\mu}) \approx m(\widetilde{W})$ is covered by $2\ell + \not{p}_T$.

$\left(pp \to \tilde{\ell}^+\tilde{\ell}^- \to 2\ell + \not{p}_T\right)$

" $3\ell + \not{p}_T$ " excludes most of $m(\widetilde{\mu}) < m(\widetilde{W})$.

$\left(pp \to \widetilde{W}^0\widetilde{W}^+ \to 3\ell + \not{p}_T\right)$

$m(\widetilde{\mu}) > m(\widetilde{W})$ is still alive after LHC Run 2. **Why!?**

theory detail

$\mu = M_2, \quad \tan\beta = 40,$

$m_{\tilde{E}} \gg 1\,\mathrm{TeV}$ (flavor universal),

$2M_1 = M_2 \ll M_3, \quad m(\text{squark}) \gg 1\,\mathrm{TeV},$

$m_A \gg 1\,\mathrm{TeV}, \quad A_l = 0,$

Tree-level SUSY masses are used

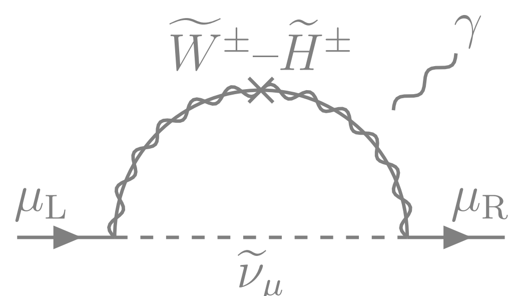
Expm detail

NC/3L: 1709.05406 (CMS, 36/fb), 1803.02762 (ATLAS, 36/fb)

SLSL: 1908.08215 (ATLAS, 139/fb), 2012.08600 (CMS, 139/fb)

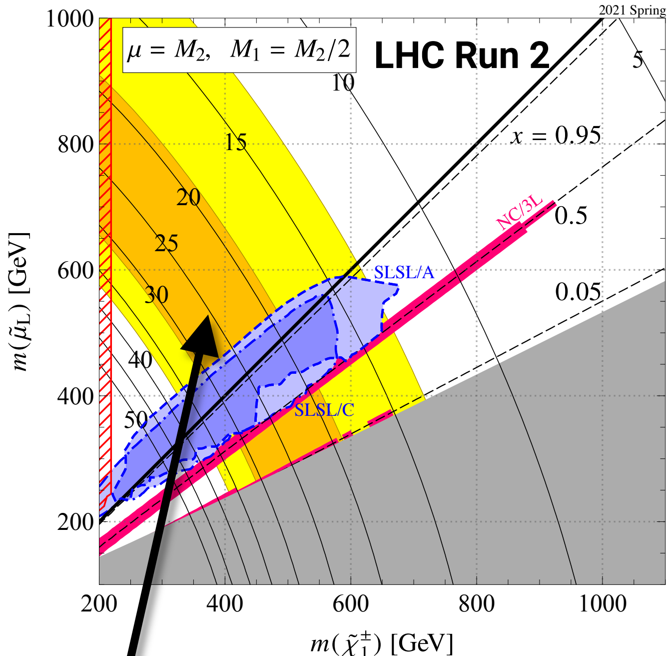
CC/WW & NC/HW: 1909.09226 (ATLAS, 139/fb)

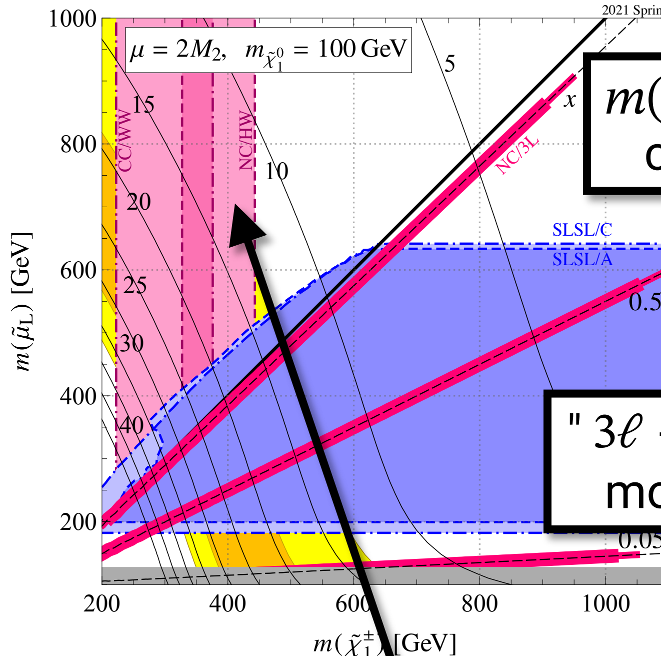
(+15 papers are analyzed but we found they give no constraints.



We proposed that they should combine *"HW + missing"* with *"ZW + missing"* for upper-left.

Endo, Hamaguchi, **Iwamoto**, Kitahara [2001.11025] [2104.03217]





$m(\tilde{\mu}) \approx m(\widetilde{W})$ is covered by $2\ell + \not{p}_T$.

$(pp \to \tilde{\ell}^+\tilde{\ell}^- \to 2\ell + \not{p}_T)$

" $3\ell + \not{p}_T$ " excludes most of $m(\tilde{\mu}) < m(\widetilde{W})$.

$(pp \to \widetilde{W}^0\widetilde{W}^+ \to 3\ell + \not{p}_T)$

$m(\tilde{\mu}) > m(\widetilde{W})$ is still alive after LHC Run 2. **Why!?**

In a similar parameter plane, $HW + \not{p}_T$ works to exclude $m(\tilde{\mu}) > m(\widetilde{W})$.

Why not in the left panel?

→ Need to combine two allowed decay channels:

$$pp \to \widetilde{W}^0\widetilde{W}^+ \longrightarrow HW + \not{p}_T$$
$$\searrow ZW + \not{p}_T$$

→ **They did!** (and cited our work ☺)

theory detail

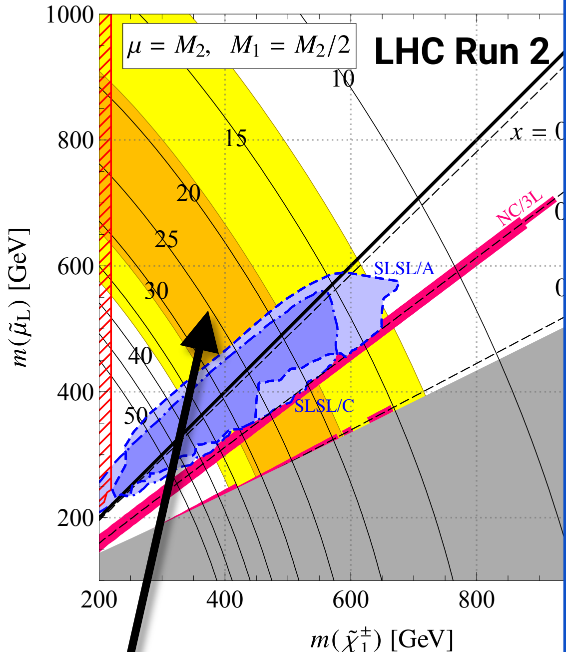
$\mu = M_2, \quad \tan\beta = 40,$
$m_{\tilde{E}} \gg 1\,\mathrm{TeV}$ (flavor universal),
$2M_1 = M_2 \ll M_3, \quad m(\mathrm{squark}) \gg 1\,\mathrm{TeV},$
$m_A \gg 1\,\mathrm{TeV}, \quad A_l = 0,$
Tree-level SUSY masses are used

Expm detail

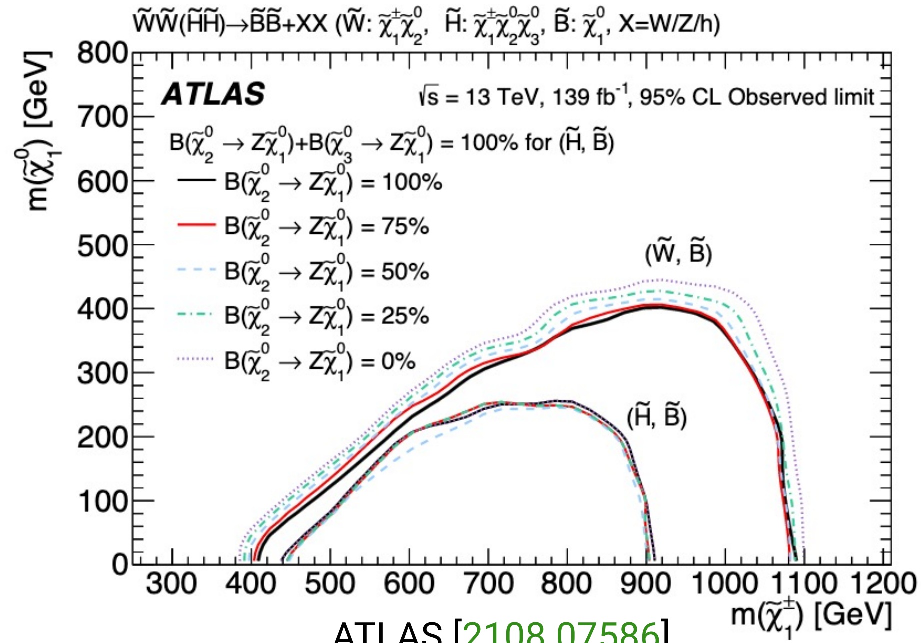
NC/3L: 1709.05406
SLSL: 1908.08215
CC/WW & NC/HW:
(+15 papers are an

ATLAS acknowledges our work as one among three representative works on this topic.

Endo, Hamaguchi, **Iwamoto**, Kitahara [2001.11025] [2104.03217]



$m(\tilde{\mu}) > m(\widetilde{W})$ is still alive after LHC Run 2. **Why!?**



ATLAS [2108.07586]

as the Z boson mass by naturalness arguments [14–17]; (3) the MSSM parameter space explaining the discrepancy between the measured muon anomalous magnetic moment [18] and its SM predictions [19] tends to include electroweakinos with masses from 200 GeV to 1 TeV [20–22].

[22] M. Endo, K. Hamaguchi, S. Iwamoto, and T. Kitahara, *Muon g-2 vs LHC Run 2 in supersymmetric models*, JHEP **4** (2020) 165, arXiv: 2001.11025 [hep-ph].

→ Need to combine two allowed decay channels:

$$pp \to \widetilde{W}^0\widetilde{W}^+ \longrightarrow HW + \not{p}_T$$
$$\searrow ZW + \not{p}_T$$

→ They did! (and cited our work ☺)

theory detail

$\mu = M_2, \quad \tan\beta = 40,$
$m_{\tilde{E}} \gg 1\,\mathrm{TeV}$ (flavor universal),
$2M_1 = M_2 \ll M_3, \quad m(\text{squark}) \gg 1\,\mathrm{TeV},$
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Tree-level SUSY masses are used

Expm detail

NC/3L: 1709.05406
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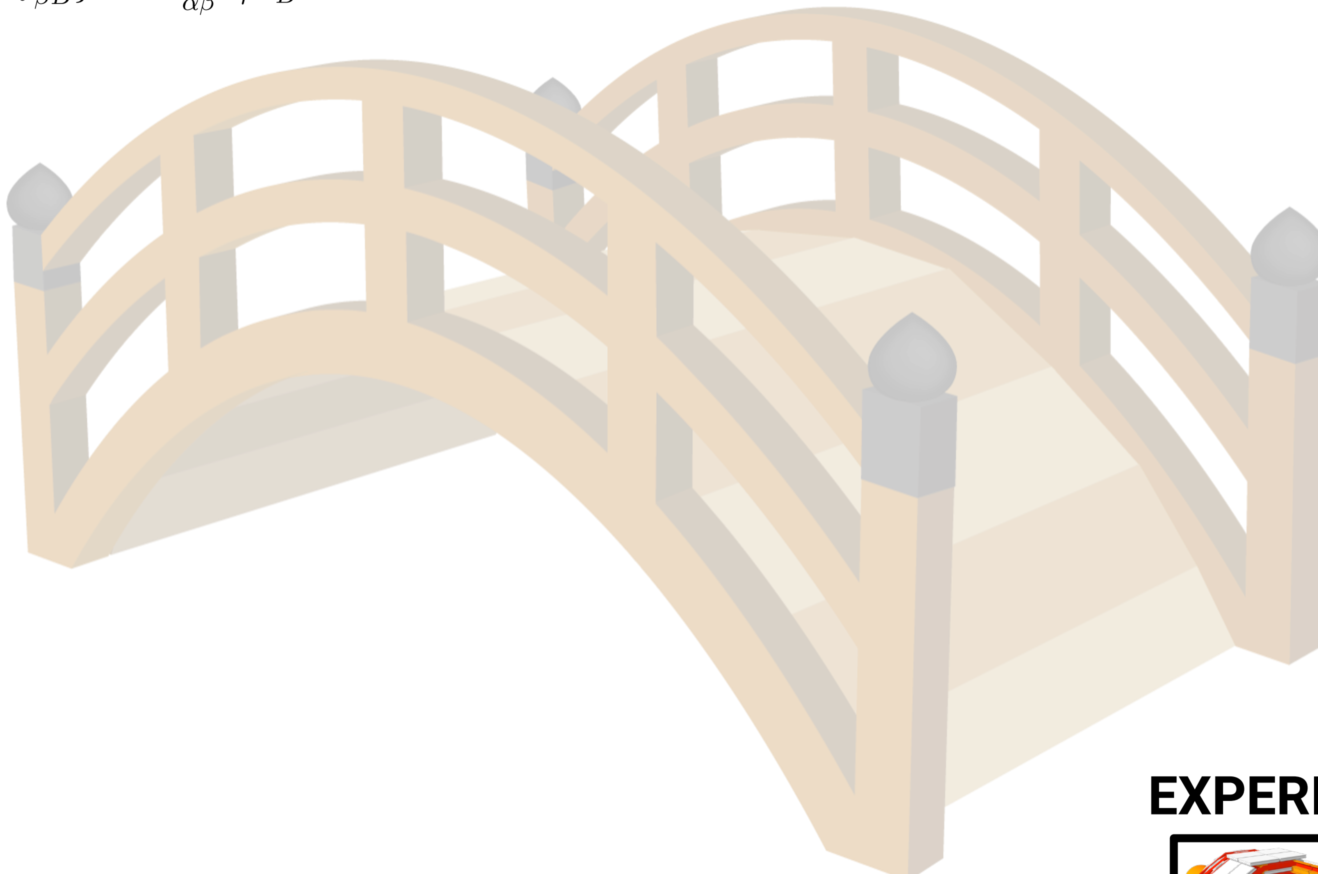
CC/WW & NC/HW:
(+15 papers are an

THEORY

$$\mathcal{L}$$

$$\mathcal{L} = \Big[\Phi_i^*[\mathrm{e}^{2gVt_\Phi^a}]_{ij}\Phi_j\Big]_{\theta^4} + \{[\mathcal{W}^a\mathcal{W}^a]_{\theta^2} + [W(\Phi_i)]_{\theta^2} + \mathrm{H.c.}\} + D$$

$$\{Q_\alpha^A, \bar{Q}_{\dot\beta B}\} = 2\sigma^\mu_{\alpha\dot\beta}P_\mu\delta^A_B$$



EXPERIMENT

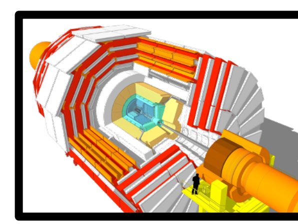
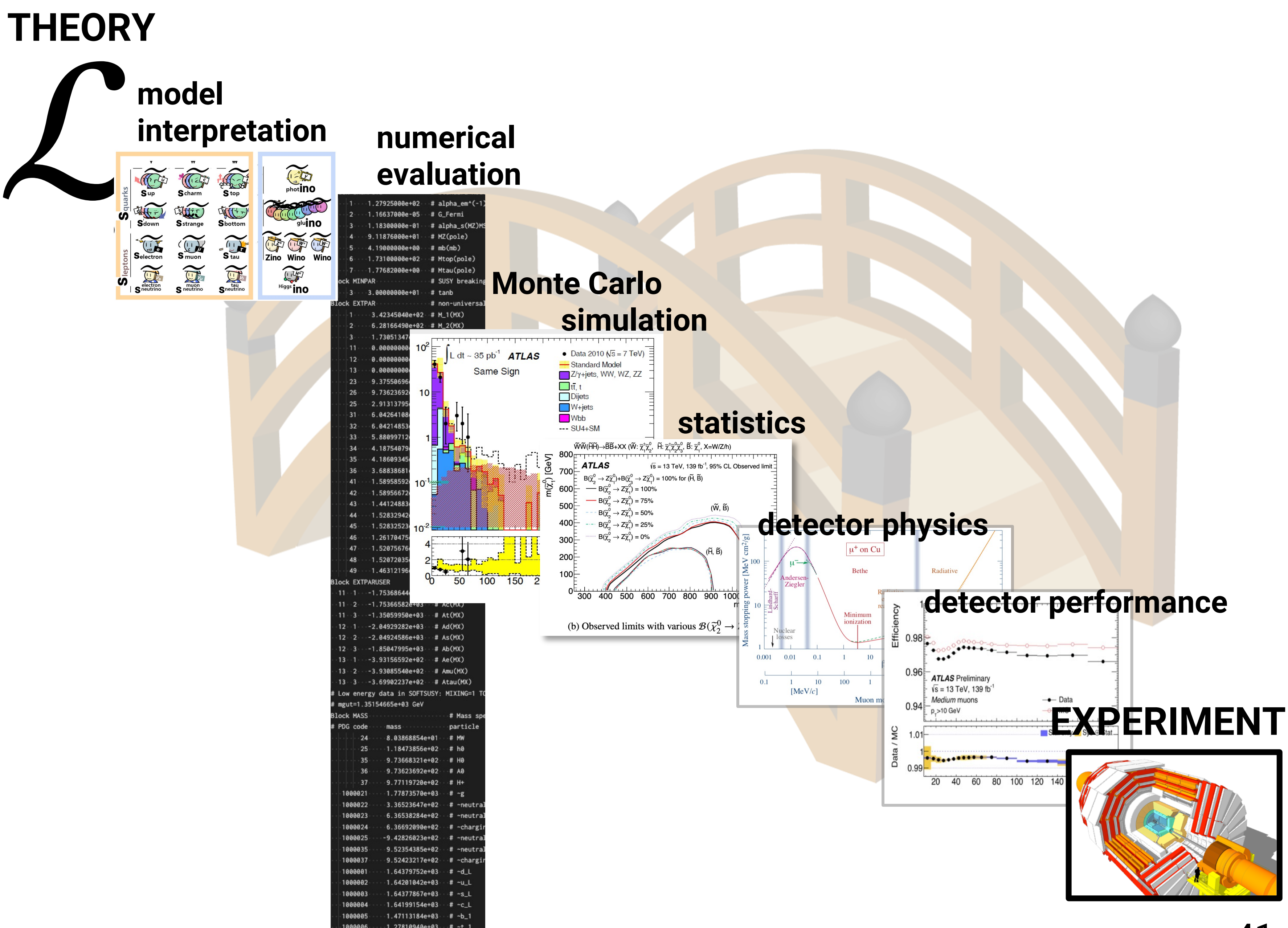


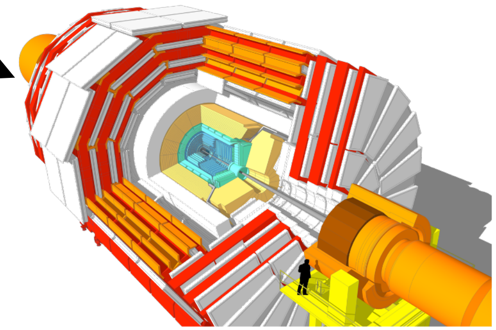
Image courtesy of らいとりぃ and CERN

Particle-physics phenomenology as a bridge between theorists and experiment collaborations.



Suggest new methods / next targets.

$$\mathcal{L}$$



Evaluate LHC results and tell their implications.

A few simple examples

Researchers in ATLAS experiment

- Asai, Azuma, Endo, Hamaguchi, **Iwamoto** [1103.1881]
  "Kinked tracks" were useful (in LHC Run 1) to search for gauge-mediation SUSY.

- Feng, **Iwamoto**, Shadmi, Tarem [1505.02996]
  FCC-hh (planned 100TeV collider) is capable to explore SuperWIMP scenario, where the radiative energy loss of muons will be utilized for background rejection.

  → Accepted in a physics report for FCC-hh planning [1606.00947].

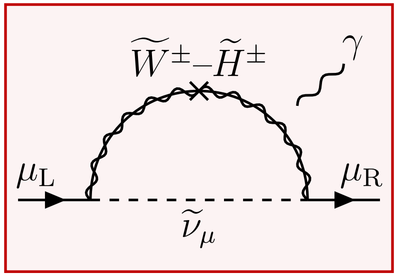
- **Iwamoto**, Lee, Shadmi, Weiss [1703.05748]
  LHC *c*-quark tagging will be useful in discrimination of SUSY models.

Image courtesy of acworks and CERN

"How to test BSM models at experiments?"

1. Standard Model
   - ✓ Success
   - ✓ Issues: Dark matter, muon $g{-}2$ anomaly, ...
2. Frontiers of experiments
   - ✓ Energy frontier, Intensity frontier
   - ✓ (HL-)LHC
3. Supersymmetry (as the solution to DM & muon $g{-}2$) at the LHC
   - ✓ WHL-scenario and LHC
   - ➢ **(extra)** Four simplified scenarios for DM + $g{-}2$
4. A few other topics at intensity (+ cosmic & neutrino) frontier

In fact, MSSM has four simplified scenarios to explain muon $g-2$ anomaly.

WHL


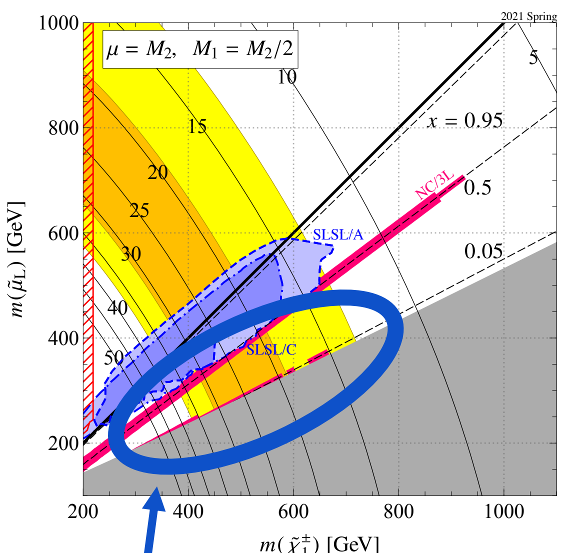
BLR

BHL

BHR

Bino-DM (coannhilation): ← **We have discussed.**

Endo, Hamaguchi, **Iwamoto**, Kitahara [2001.11025] [2104.03217]

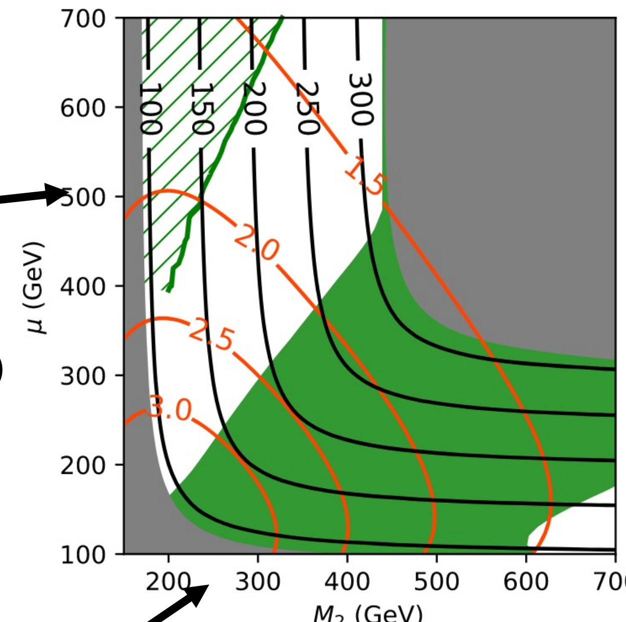


- ✓ coupling unification,
- ✓ Bino DM,
- ✓ muon $g-2$.

… but nearly excluded!

Wino / Higgsino-DM:

Iwamoto, Yanagida, Yokozaki [2104.03223]

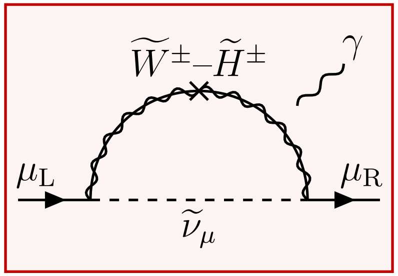


Wino DM:
constrained by LHC
(disappearing track, $2\ell + \not{p}_T$)

Higgsino DM:
disfavored by DM direct detection

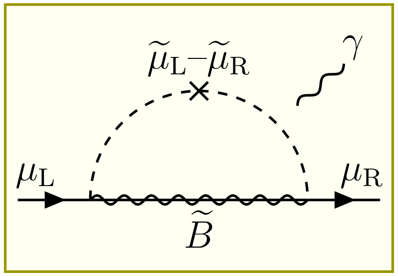
I have analyzed all the simplified scenarios.

WHL



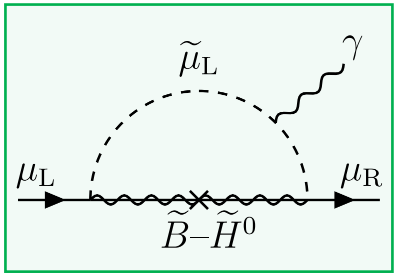
Bino-DM (coannhilation):

BLR



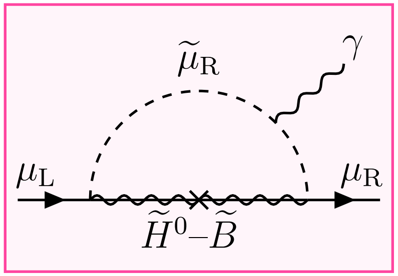
Bino-DM (coannhilation)

BHL



Bino-DM (coannhilation)

BHR



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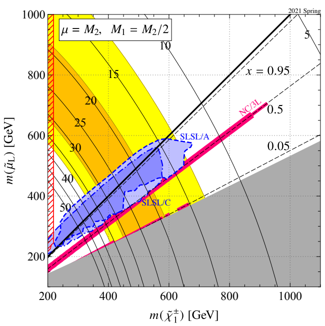
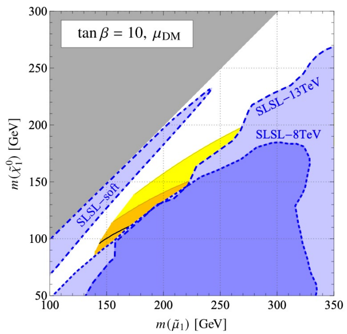
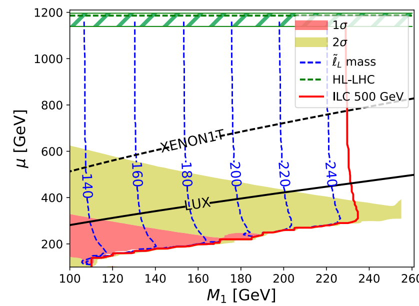
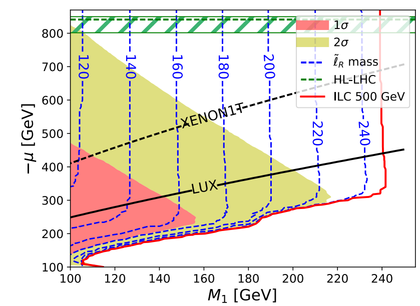
Endo, Hamaguchi, **Iwamoto**, Yanagi [1704.05287]

with old values; needs update









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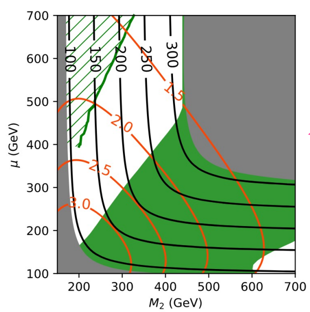


LHC

- $3\ell + \not{p}_{\mathrm{T}}$
- $(H|Z)W + \not{p}_{\mathrm{T}}$
- $2\ell + \not{p}_{\mathrm{T}}$
- disappearing track
- $2\tau + \not{p}_{\mathrm{T}}$

dark matter direct detection (XENON1T, LUX, ...)

ILC-500

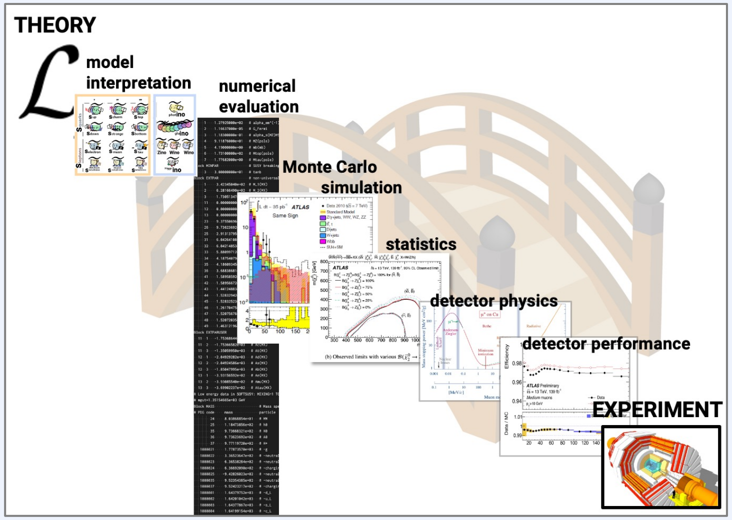
Supersymmetry (as the solution to DM and/or muon g−2)

- Simplified models: all done.
  - ➢ **LHC will go on:** Continue theory ⇄ experiment iteration.
  - ➢ **Future colliders:** Contribute to their planning.

- Analyze "not-simplified" models
  - ➢ There are various models (WHL+BHL, Gravitino-LSP, R-parity violation, ...)

    but usually less motivated.

    → **Explore with prioritization.**



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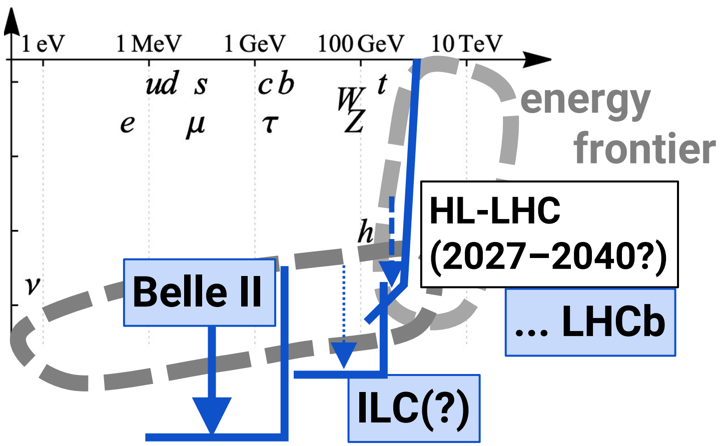
   - ✓ WHL-scenario and LHC
   - ✓ **(extra)** Four simplified scenarios for DM + $g\!-\!2$
4. A few other topics at **intensity** **(+ cosmic & neutrino)** **frontier**

- Previous section: SUSY at the LHC
  BSM / energy frontier

- Recent works of mine (2017–): **BSM at intensity frontier**
  (incl. neutrino frontier).
  - Experiments

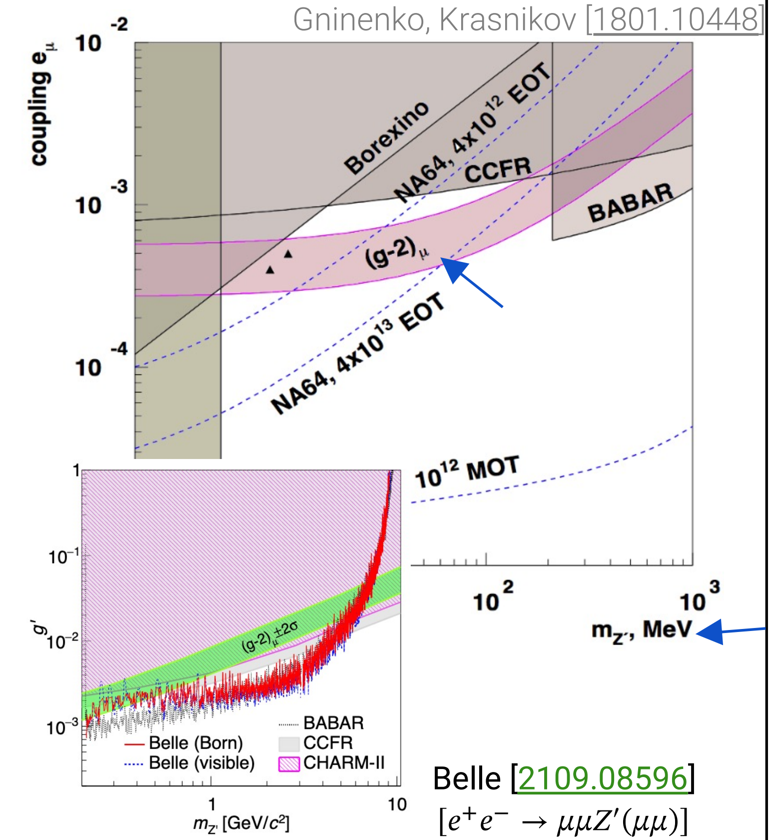


+ FASER, NA62, NA64, ...

  - Theory
    - extra neutrinos,
    - axion-like particles,
    - extra U(1) symmetry,
    - ..., ...

example) vector boson of U(1) $L_\mu - L_\tau$

Gninenko, Krasnikov [1801.10448]



Belle [2109.08596]
$[e^+e^- \to \mu\mu Z'(\mu\mu)]$

Iwamoto, Seller, Trócsányi [2104.11248]

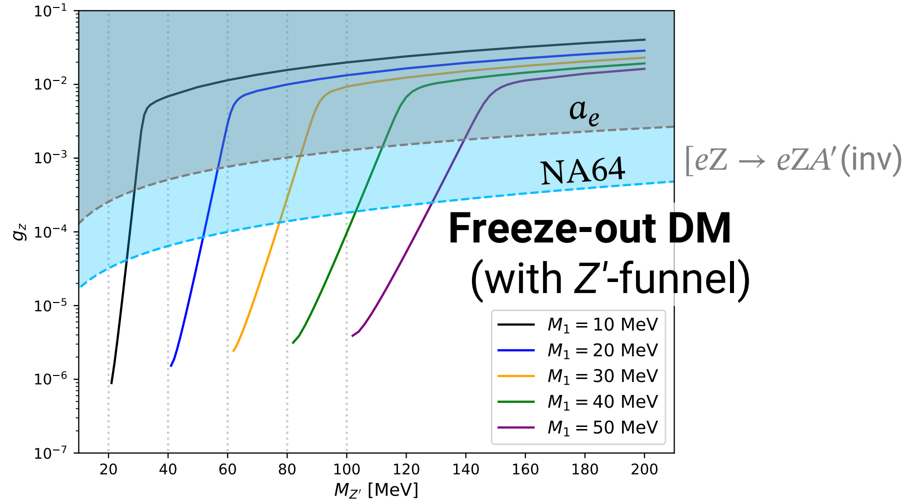
His first paper!

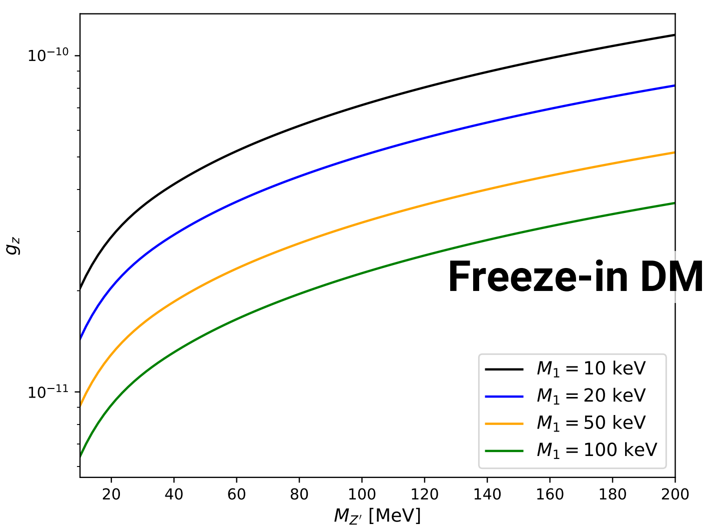
Model: SM + extra U(1)
+ 3 right-handed neutrinos → **DM candidate**
+ 1 extra Higgs boson

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_y$	$\mathrm{U}(1)_z$
Q_L	**3**	**2**	$1/6$	$1/6$
U_R	**3**	**1**	$2/3$	$7/6$
D_R	**3**	**1**	$-1/3$	$-5/6$
l_L	**1**	**2**	$-1/2$	$-1/2$
N_R	**1**	**1**	0	$1/2$
e_R	**1**	**1**	-1	$-3/2$
ϕ	**1**	**2**	$1/2$	1
χ	**1**	**1**	0	-1

	freeze out	**freeze in**
coupling	$\sim 10^{-5}$	$\sim 10^{-11}$
m_DM	$\mathcal{O}(10)\,\mathrm{MeV}$	$\mathcal{O}(10)\,\mathrm{keV}$
$m_{Z'}$	$\simeq 2m_\mathrm{DM}$	$\mathcal{O}(100)\,\mathrm{MeV}$

→ explains why DM is 26%.





Asai, **Iwamoto**, Sakaki, Ueda [2105.13768]

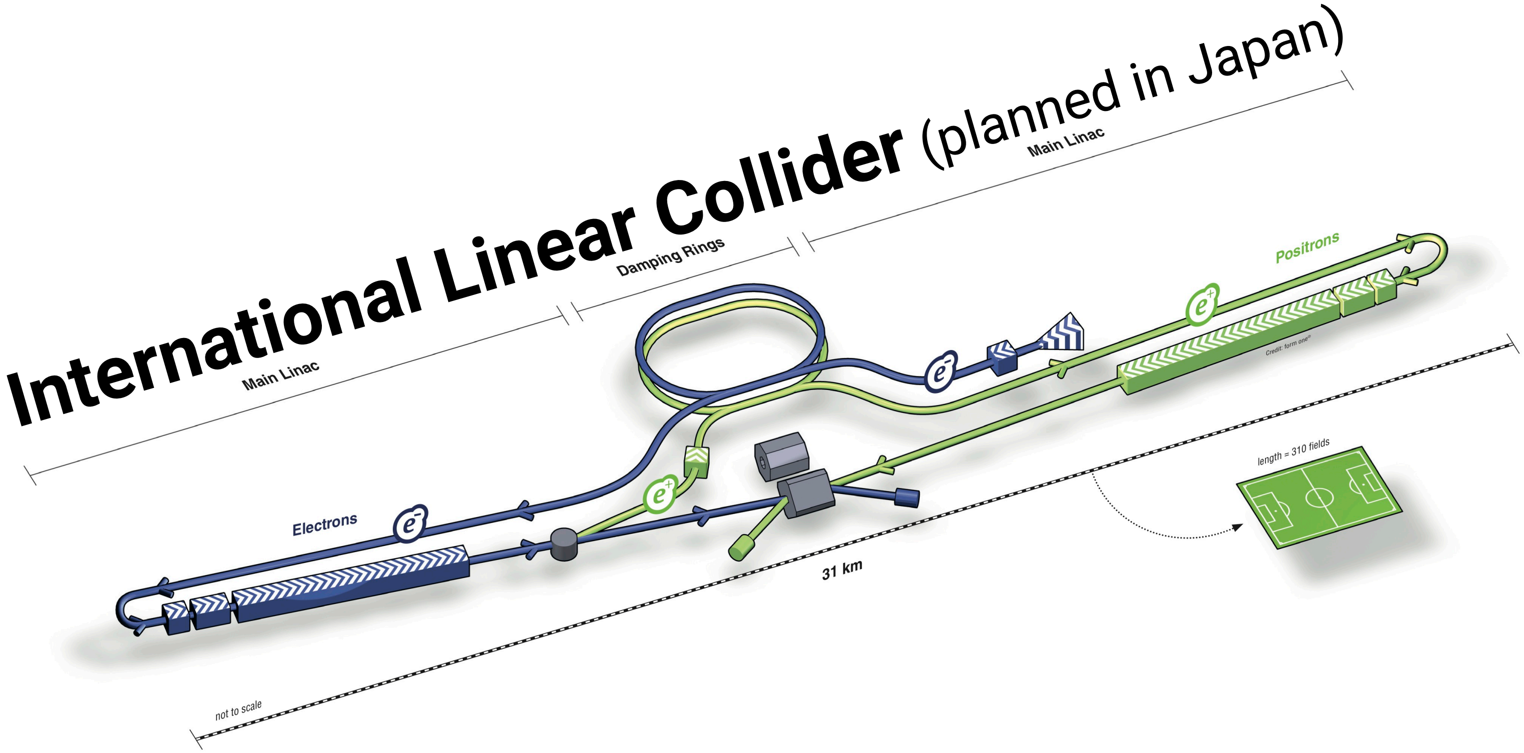
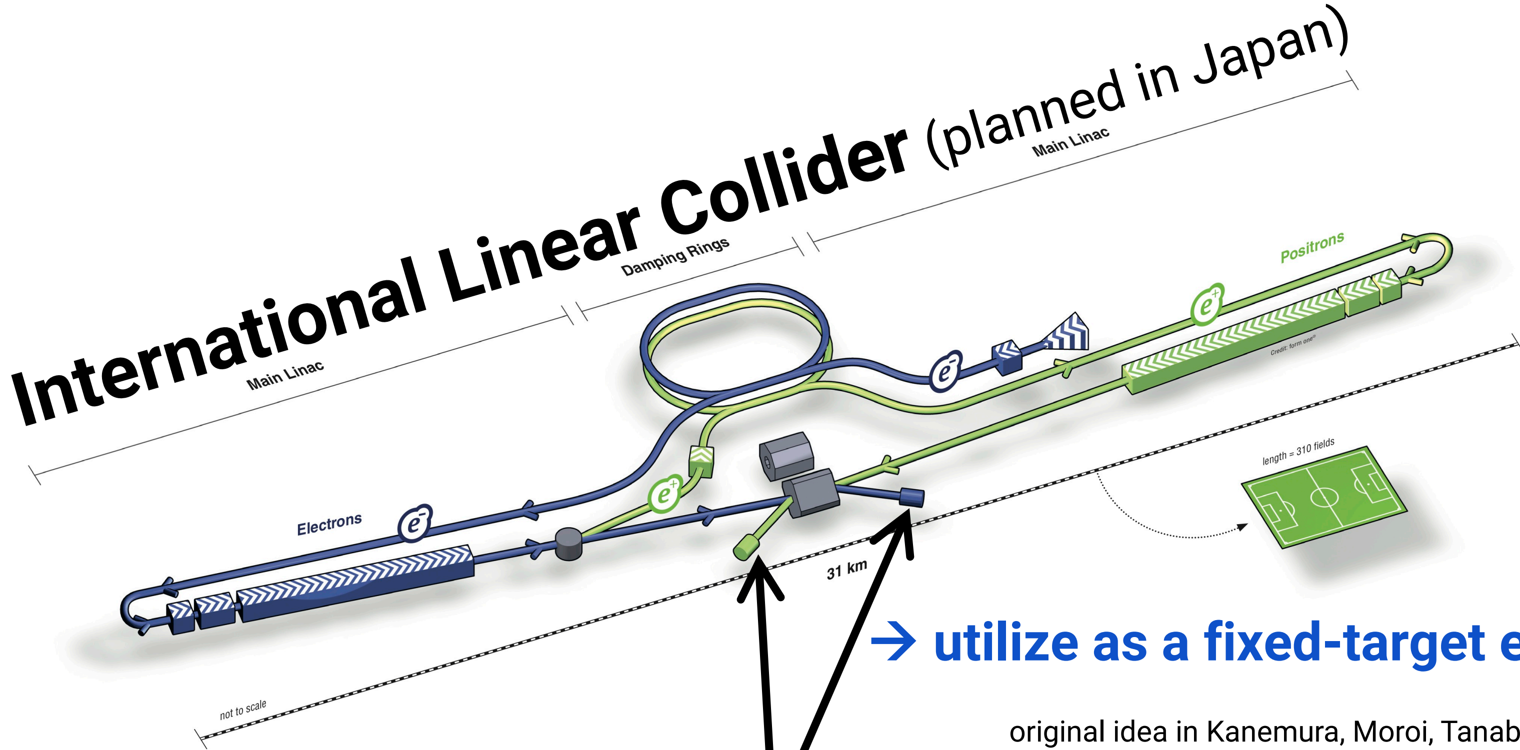


Image courtesy of ILC News Line

Asai, **Iwamoto**, Sakaki, Ueda [2105.13768]



→ **utilize as a fixed-target expm!**

original idea in Kanemura, Moroi, Tanabe [1507.02809]
and Sakaki, Ueda [2009.13790]

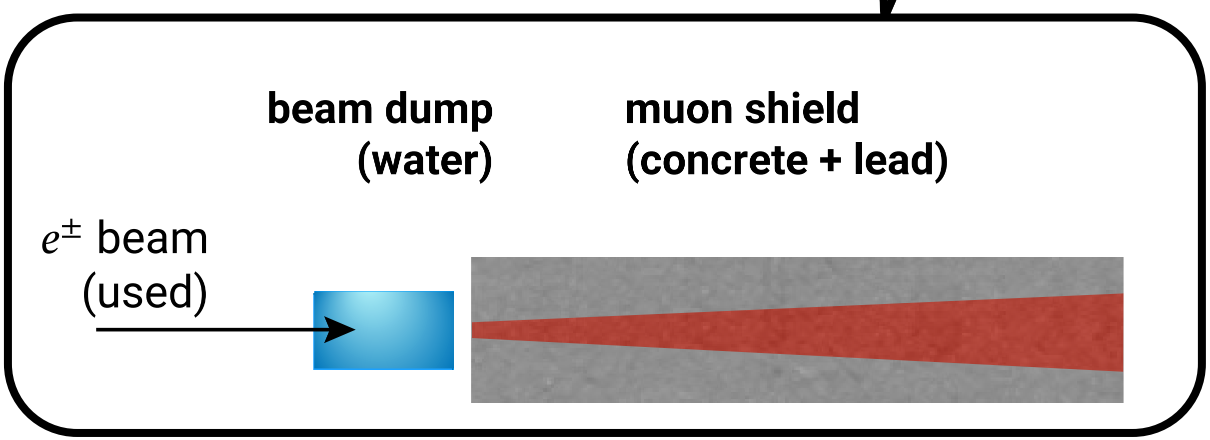
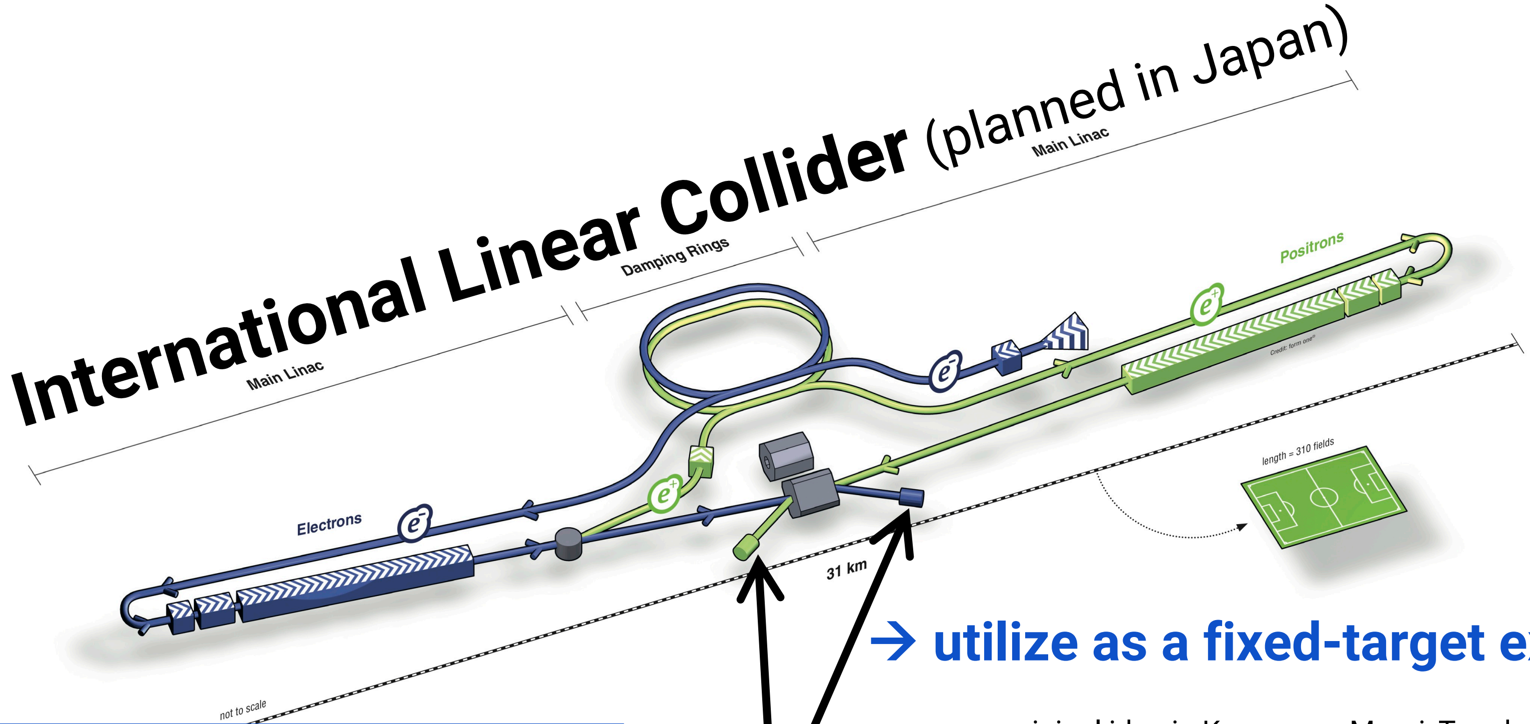


Image courtesy of ILC News Line

My recent work 2) Beam dump experiments at the ILC [experiment proposal in intensity frontier]

Asai, **Iwamoto**, Sakaki, Ueda [2105.13768]



→ utilize as a fixed-target expm!

original idea in Kanemura, Moroi, Tanabe [1507.02809]
and Sakaki, Ueda [2009.13790]

$e^{\pm}e^{\mp} \longrightarrow$ elusive particle
(or $e^{\pm}p$, $e^{\pm}n$) (= targets of intensity fr.)

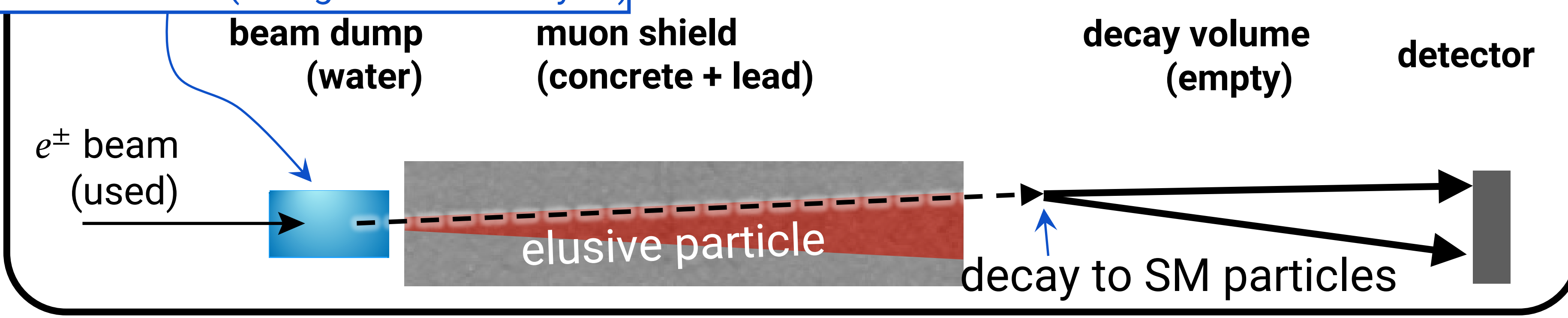


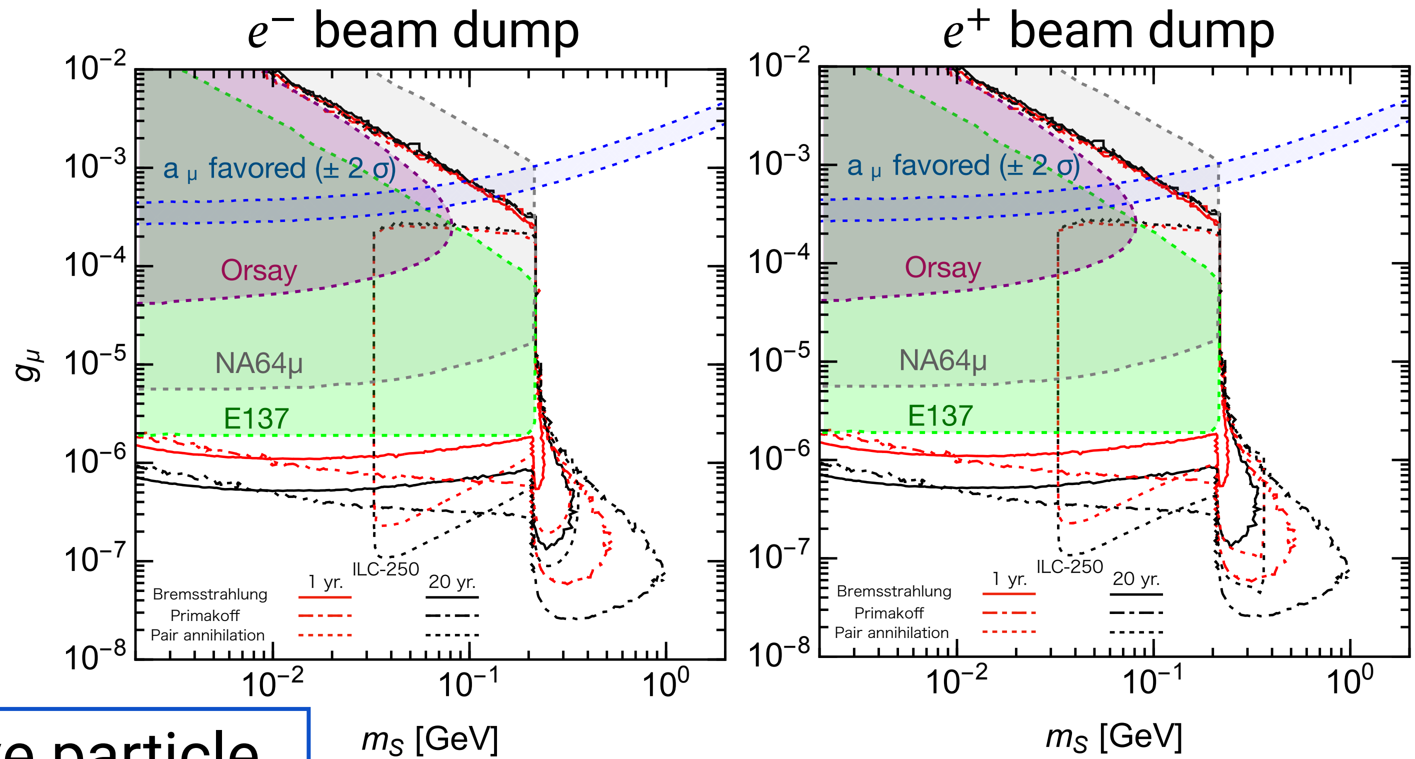
Image courtesy of ILC News Line

Asai, **Iwamoto**, Sakaki, Ueda [2105.13768]

benchmark model:
extra singlet S

$$\mathcal{L} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \sum_{\ell=e,\mu,\tau} g_\ell S\bar{\ell}\ell - \frac{1}{4}g_{S\gamma\gamma}SF_{\mu\nu}F^{\mu\nu}$$

$$\left(\frac{g_e}{m_e} = \frac{g_\mu}{m_\mu} = \frac{g_\tau}{m_\tau}\right)$$



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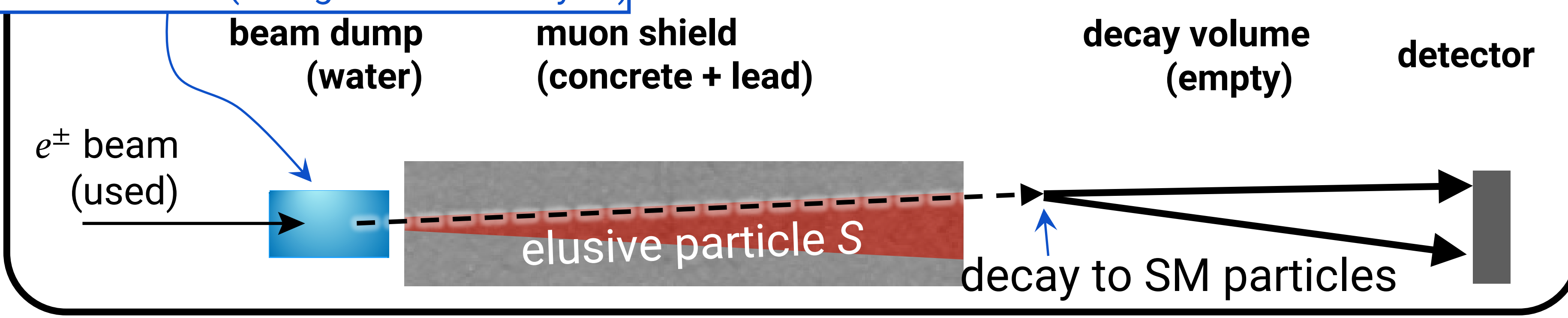


Brdar, Helmboldt, **Iwamoto**, Schmitz [1905.12634]

- Higgs potential $V = \lambda|H|^4 - \mu^2|H|^2$

  $\mu \sim \underline{100\,\mathrm{GeV}}$ so that $m_h = 125\,\mathrm{GeV}$

  Any mechanism behind this value?

- Right-handed neutrinos *N* can solve

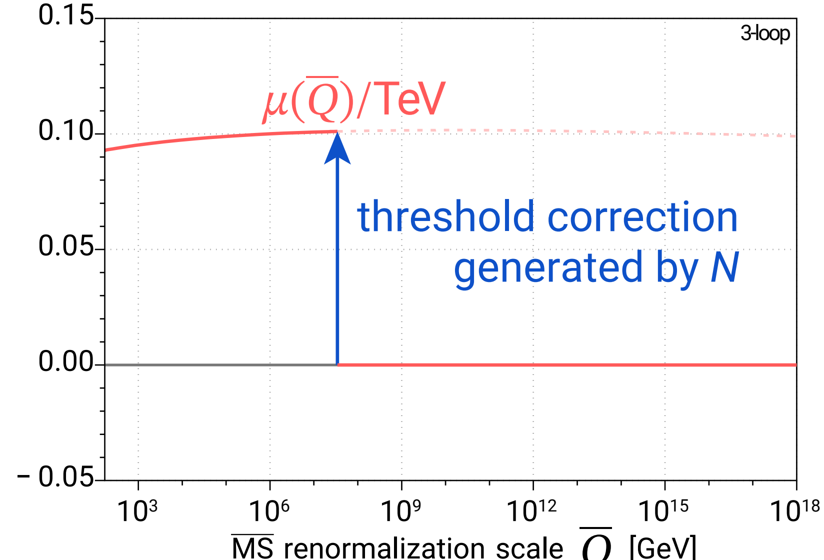
  a) Neutrino mass & mixings
  [see-saw mechanism]

  b) Baryon asymmetry of Universe
  [leptogenesis] if Mass ≫ TeV,

  c) Dark matter
  [sterile neutrino] if Mass ~ keV,

  d) The origin of μ ~ 100 GeV
  [neutrino option] if Mass ~ PeV.

Brivio, Trott [1703.10924]



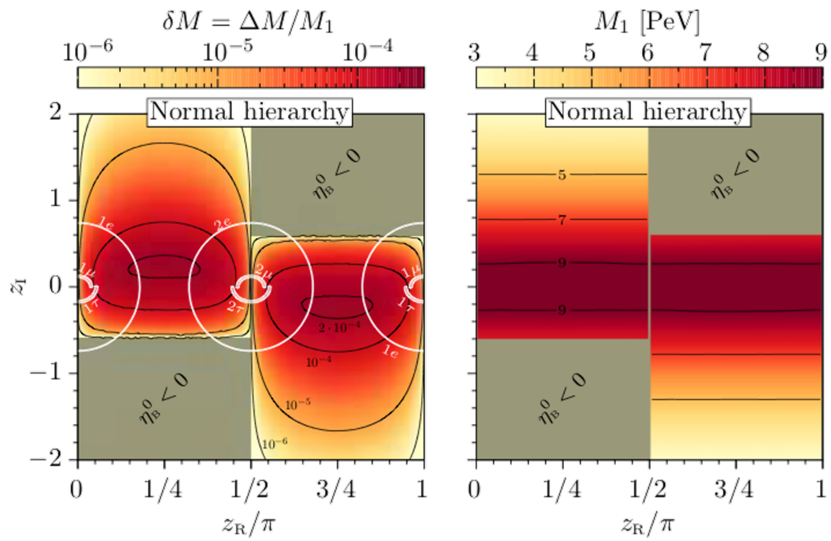
$$\left(\Delta\mu^2 \approx \frac{\mathrm{Tr}(yy^\dagger)}{16\pi^2} M_N^2\right)$$

Brdar, Helmboldt, **Iwamoto**, Schmitz [1905.12634]

Question: Can we do a) b) c) d) together? → **Yes!**

- N_1 ~ keV → **sterile neutrino DM** ✓**c**
- N_2 & N_3 ~ 10^8 GeV with $\Delta M \sim 10^4$ GeV → **resonant leptogenesis** ✓**b & d**

under the conditions for ✓**a.**



■ Right-handed neutrinos N can s

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[see-saw mechanism]

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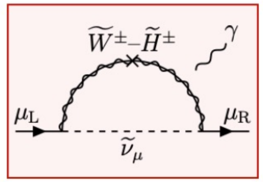
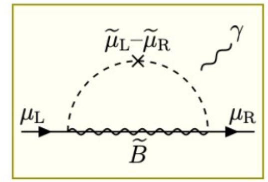
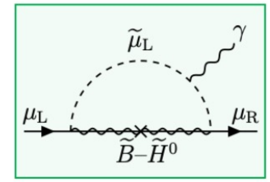
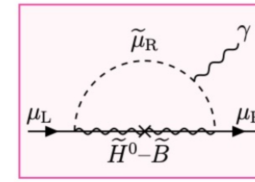
$\left(\Delta\mu^2 \approx \frac{\cdots}{16\pi^2} M_N^2\right)$

Physics summary

- !!! **Dark matter** → **TeV-scale SUSY: simplified scenarios**
- !!! Dark energy
- !!! Gravity
- !!! Mechanism for neutrino mass
- !? **Muon g−2 anomaly**
- !? Flavor anomalies ($b \to s\mu\mu$, $R(D)$, $R(D^*)$, ...)
- !? Origin of baryon asymmetry
  - Why is the Universe so "isotropic"?
  - Why are U(1)-charges [integer] / 6?
  - Why many fermions but 1 scalar?
  - Why $\theta_{\rm QCD}$ so small?
  - Any mechanism behind SM parameters?

✓ dark matter,
✓ coupling unification,
✓ muon g−2.

TeV-scale SUSY: simplified scenarios

WHL	BLR	BHL	BHR
			
Bino-DM (coannhilation):	Bino-DM (coannhilation):	Bino-DM (coannhilation):	Bino-DM (coannhilation):

Endo, Hamaguchi, **Iwamoto**, Kitahara [2001.11025] [2104.03217]

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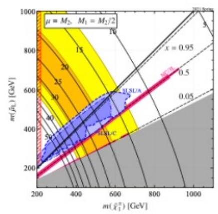
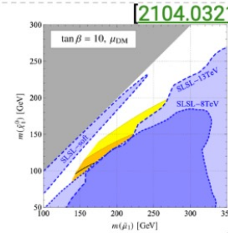
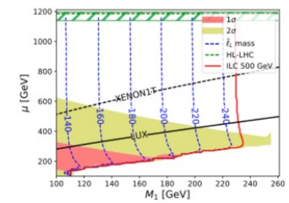
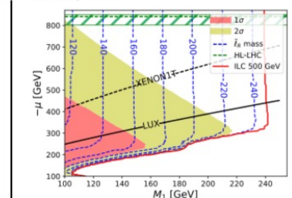
with old values; needs update









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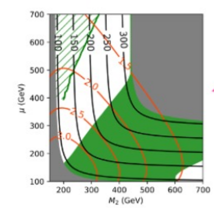


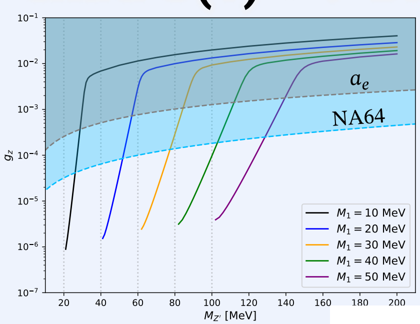
LHC

- $3\ell + \not{p}_{\rm T}$
- $(H|Z)W + \not{p}_{\rm T}$
- $2\ell + \not{p}_{\rm T}$
- disappearing track
- $2\tau + \not{p}_{\rm T}$

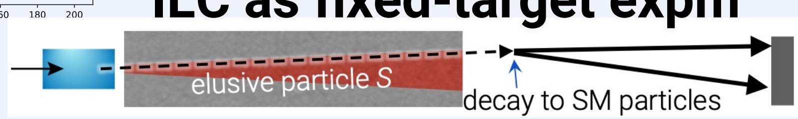
dark matter direct detection (XENON1T, LUX, ...)

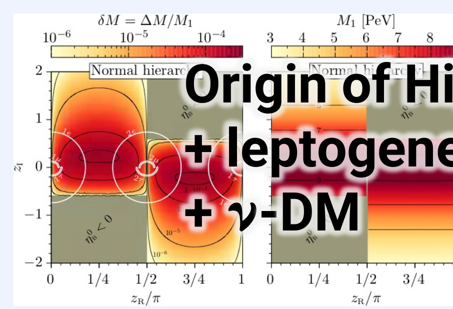
ILC-500

extra U(1) + ν-DM

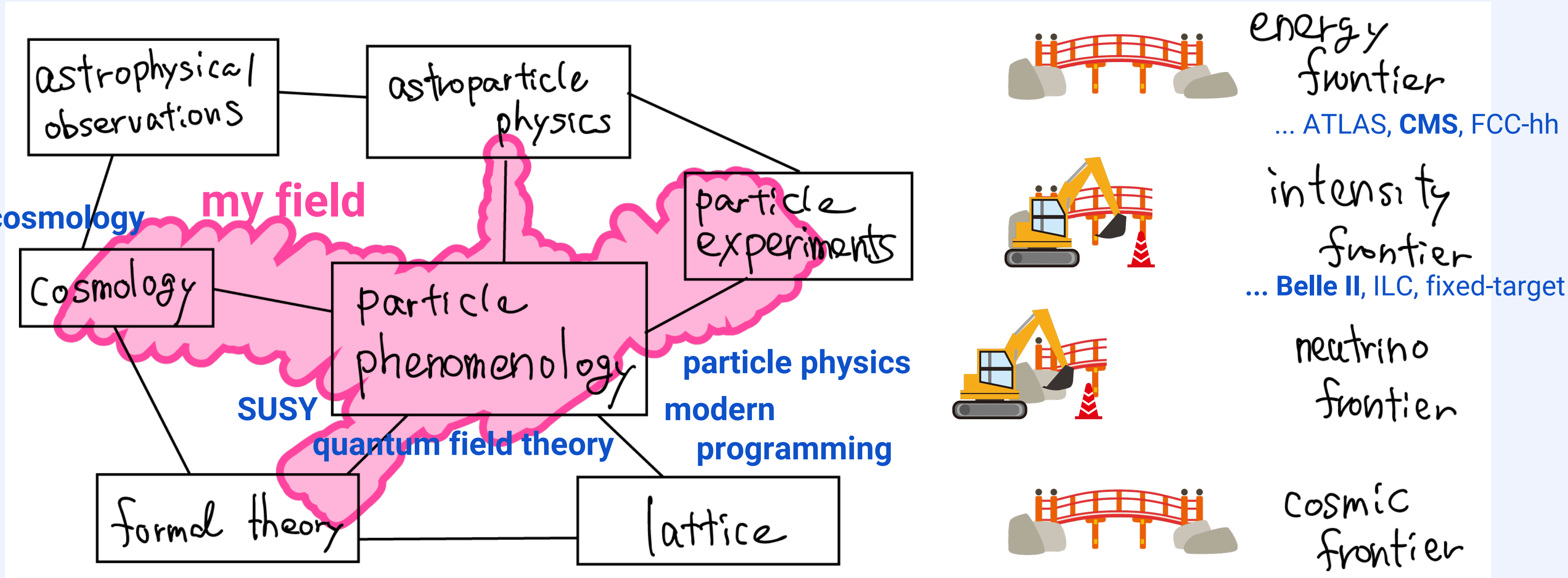


ILC as fixed-target expm





Origin of Higgs mass + leptogenesis + ν-DM



Energy frontier: Continue my job "theory ⇄ expm" for LHC & future plans.

Other frontiers:

- BSM searches at the intensity frontier
- Neutrinos and its cosmology (see-saw, leptogenesis, DM)

- Open-source tools for particle physics
  (calculator, data handling, statistics, tutorials, ...) https://github.com/misho104

Extra 0) Magnetic moment Basic

- Quantum Mechanics $g = 2$

$$\boldsymbol{\mu} = \frac{Q|e|}{2m}(\boldsymbol{L} + 2\boldsymbol{S}), \ \ H = -\boldsymbol{\mu}\cdot\boldsymbol{B}$$

$$\left(\begin{array}{c} D_\mu = \partial_\mu + \mathrm{i}Q|e|A_\mu \ \ \text{so that} \\ E \supset Q|e|\phi \sim Q|e|\overline{\psi}\gamma^0 A^0\psi \\ \text{is contained in } -\mathcal{L}. \end{array} \right)$$

- Quantum Field Theory: Tree-level $g = 2$

$$\mathcal{L}_{\mathrm{QED}} = \overline{\psi}(\mathrm{i}\not{D} - m)\psi \supset -Q|e|\overline{\psi}\not{A}\psi \longrightarrow \frac{-\mathrm{i}Q|e|A^\mu}{2m}\left(\overline{\psi}\partial_\mu\psi - (\partial_\mu\overline{\psi})\psi\right) - \underline{\frac{Q|e|}{2m}A_\mu\partial_\nu(\overline{\psi}\sigma^{\mu\nu}\psi)}$$

equations of motion (Gordon decomposition)

$$= \frac{-Q|e|}{4m}F_{\mu\nu}\overline{\psi}\sigma^{\mu\nu}\psi \ \downarrow \ \frac{Q|e|}{2m}2\boldsymbol{S}\cdot\boldsymbol{B}$$

$$\boxed{\begin{array}{l} A^\mu = (\phi, \boldsymbol{A}), \quad \boldsymbol{S} = (S^{23}, S^{31}, S^{12}), \quad S^{\mu\nu} = \sigma^{\mu\nu}/2 \\ \longrightarrow \ F_{\mu\nu}\sigma^{\mu\nu} = 2F_{\mu\nu}S^{\mu\nu} = -4\boldsymbol{B}\cdot\boldsymbol{S} \end{array}}$$

$$\Longrightarrow \quad \mathcal{H}_{\mathrm{int}} = -\mathcal{L}_{\mathrm{int}} \supset -\left(\frac{Q|e|}{2m}2\boldsymbol{S}\right)\cdot\boldsymbol{B}$$

- Quantum corrections

$$\left\langle \psi(p+q) \middle| J^\mu_{\mathrm{EM}} \middle| \psi(p) \right\rangle = \overline{\psi}(p+q)\Gamma^\mu(q)\psi(p),$$

$$\rightarrow \frac{\sigma^{\mu\nu}(-\partial_\nu A_\mu)}{2m} = \frac{\sigma^{\mu\nu}F_{\mu\nu}}{4m} \sim -\frac{2\boldsymbol{S}\cdot\boldsymbol{B}}{2m} \ (\times - Q|e|)$$

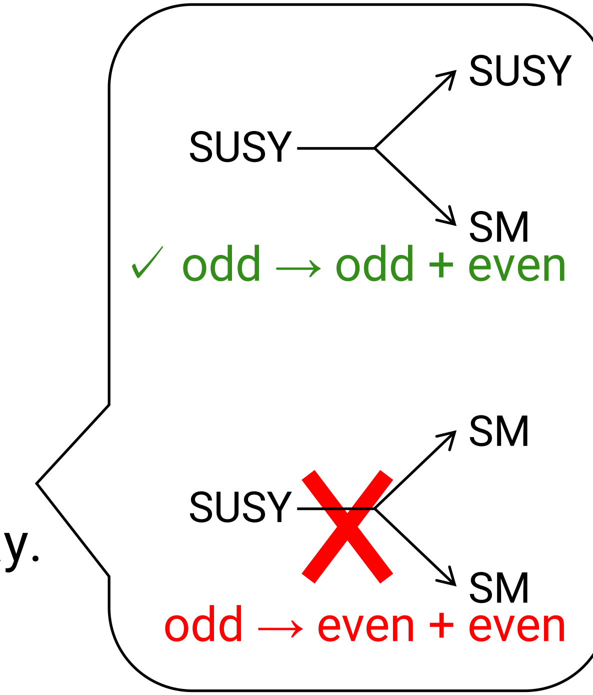
$$\Gamma^\mu(q) \overset{\mathrm{CP}}{=} F_1(q^2)\gamma^\mu + F_2(q^2)\frac{\mathrm{i}\sigma^{\mu\nu}q_\nu}{2m} \xrightarrow{q\to 0} \gamma^\mu + F_2(0)\frac{\sigma^{\mu\nu}(\overleftarrow{\partial} + \overrightarrow{\partial})_\nu}{2m}$$

$$\left(\ \mathrm{i}\partial_\nu\psi \sim -\mathrm{i}\partial_\nu\overline{\psi} \sim p_\nu \right) \quad \Longrightarrow \quad g = 2 + 2F_2(0) \Longleftrightarrow F_2(0) = \frac{g-2}{2}$$

Extra 1) SUSY-DM and freeze-out

- In MSSM, we usually impose "*R*-parity" (to avoid proton-decay problem).

	R ($\cong Z_2$)
SM particles	even
SUSY particles	odd

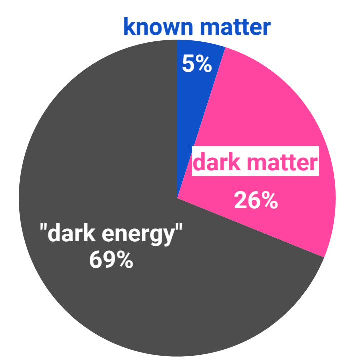


- Particles can decay to lighter particle.

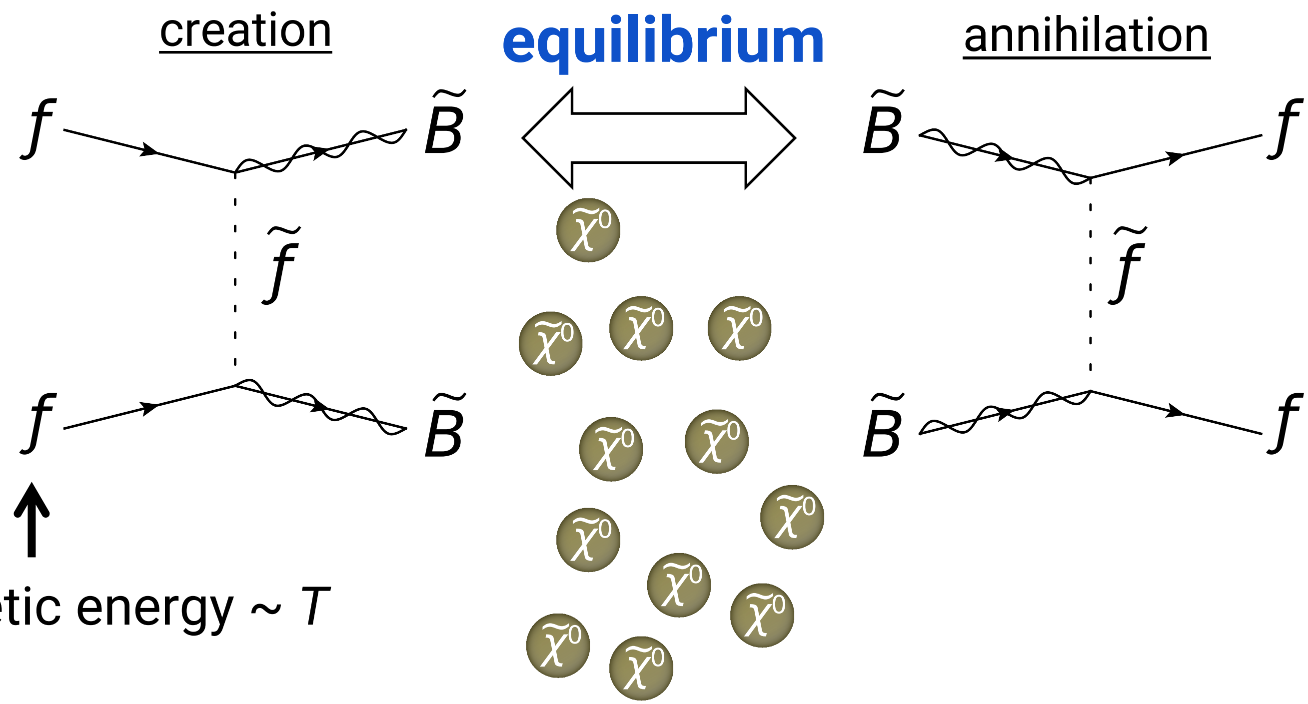
  → The lightest SUSY particle **(LSP)** cannot decay.

  = DM candidate.

- If LSP ~ 100 GeV, we can explain why DM is "26%".

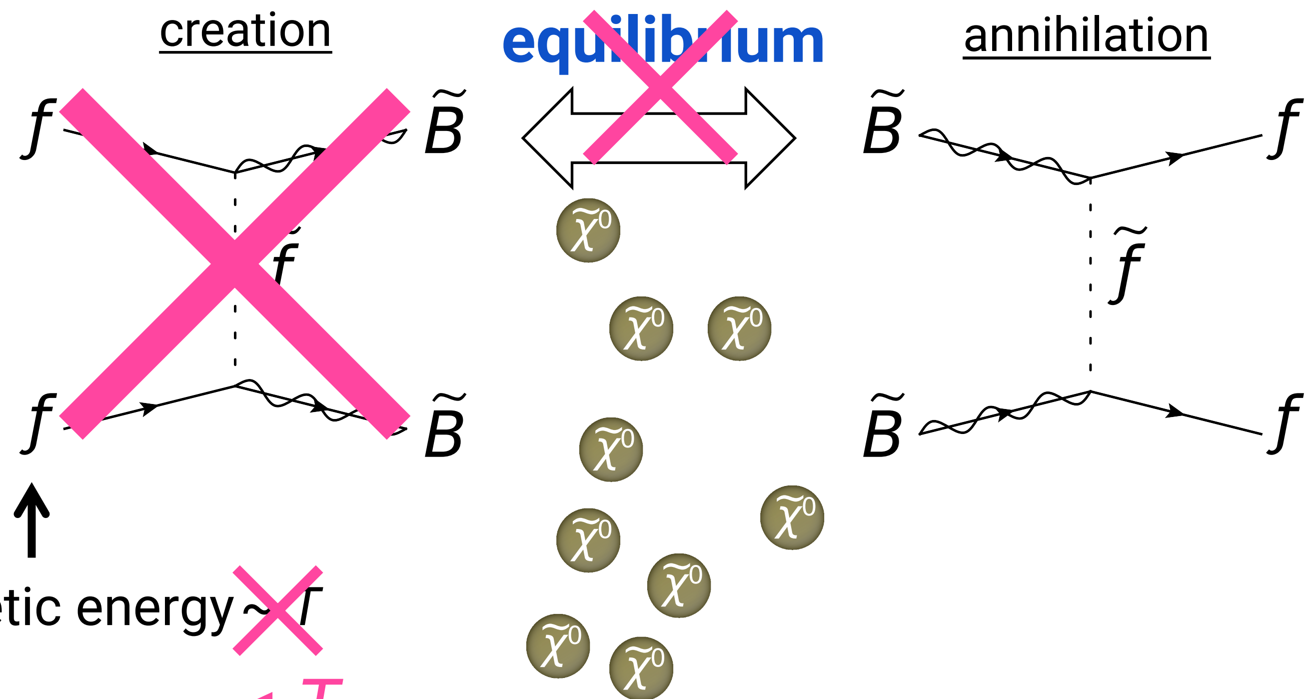


■ Early Universe with $T > m_{\widetilde{B}}$



with kinetic energy ~ T

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



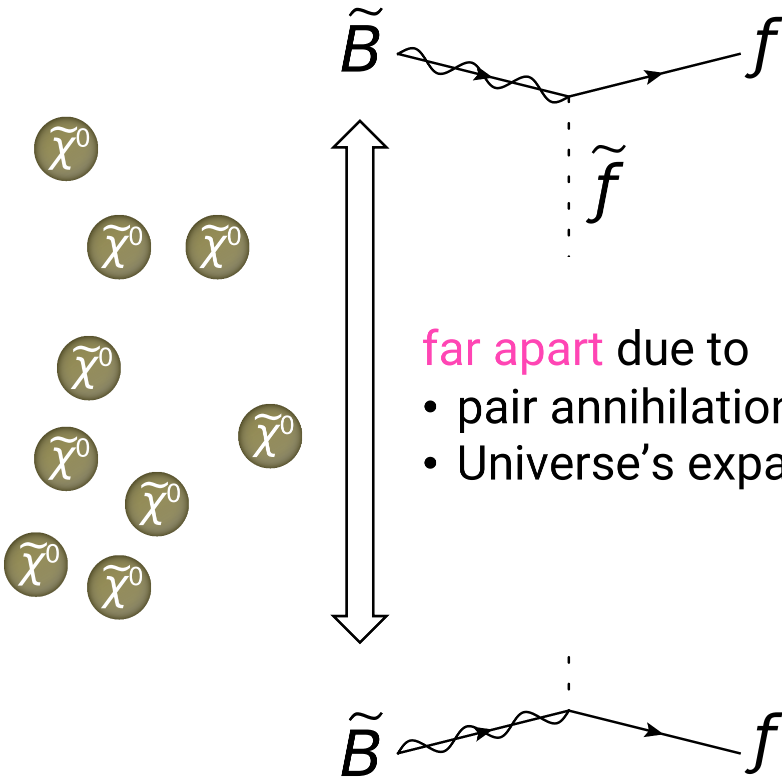
with kinetic energy ~~$\sim T$~~

$< T$

■ Early Universe with $T \lesssim m_{\widetilde{B}}/20$

<u>creation</u>

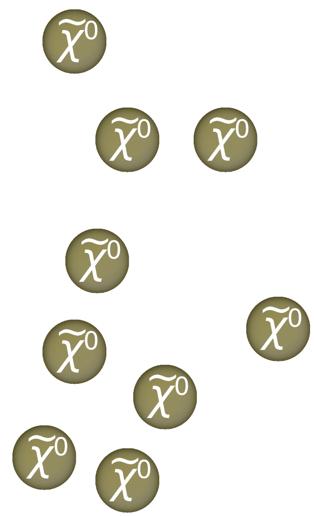
<u>annihilation</u>



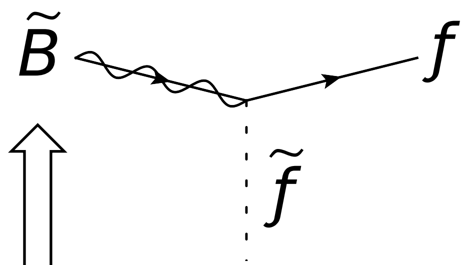
far apart due to
- pair annihilation
- Universe's expansion

■ Early Universe with $T \lesssim m_{\widetilde{B}}/20$

creation

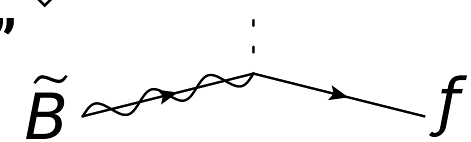


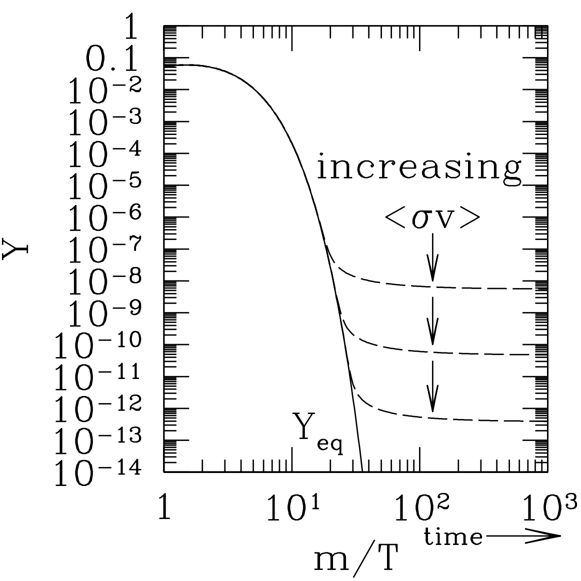
annihilation



far apart due to
- pair annihilation
- Universe's expansion

"thermal relic"





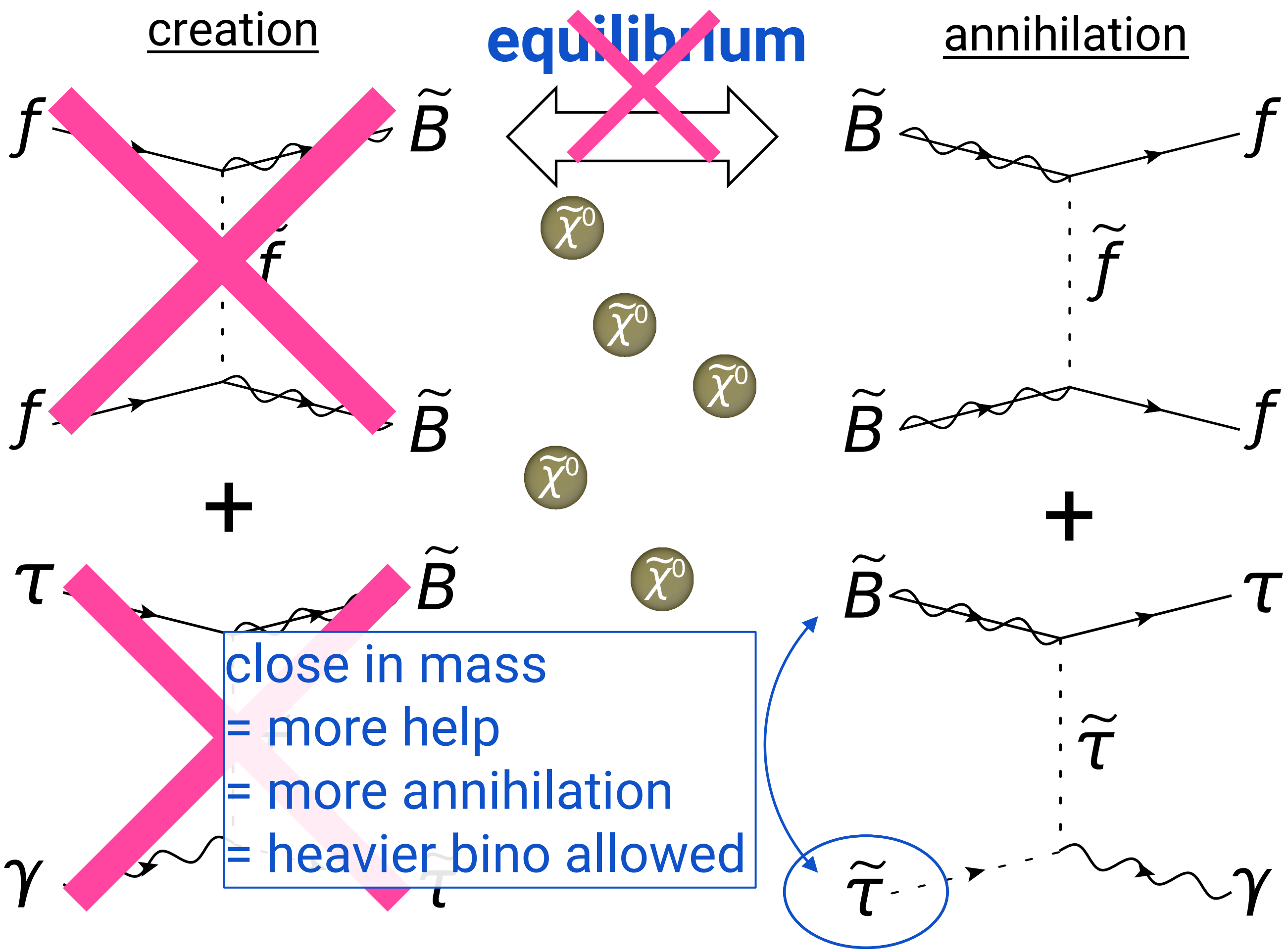
... too much for ~100GeV bino-like DM.

$$\Omega_{\mathrm{DM}} h^2 \approx \frac{1.1\times 10^9 \cdot x_{\mathrm{f}}}{\sqrt{g_*} M_{\mathrm{pl}} \langle \sigma v\rangle \cdot \mathrm{GeV}} \approx 0.1 \cdot \frac{15}{\sqrt{g_*}} \frac{x_{\mathrm{f}}}{30} \frac{3\times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle \sigma v\rangle} \quad \text{with } x_{\mathrm{f}} = m_{\mathrm{DM}}/T_{\mathrm{fo}}.$$

Gelmini and Gondolo, 1009.3690

Freeze-out of Bino DM = overabundance in standard thermal history.

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



annihilation helper!

cf. Edsjö, Schelke, Ullio, Gondolo, [hep-ph/0301106](hep-ph/0301106)

- g−2 motivates SUSY mass of 100−1000 GeV.
  - **bino**-like DM with ~100 GeV = **overabundance.**
    - non-standard thermal history?
    - with helpers for annihilation?

      too heavy = too small annihilation

      → co-annihilation: Binetruy, Girardi, Salati (1984), Griest, Seckel (1991)
      vectorlike leptons: Abdullah, Feng [1510.06089], Abdullah, Feng, Iwamoto, Lillard [1608.00283]
  - **wino-** or **higgsino**-like DM with ~100 GeV = **underabundance.**
    - non-standard thermal history?
    - extra particles for DM?

      too light = too much annihilation
  - **bino-higgsino** mixture = strong constraints from DM direct detections.

    "well-tempered scenario" ... not talking today

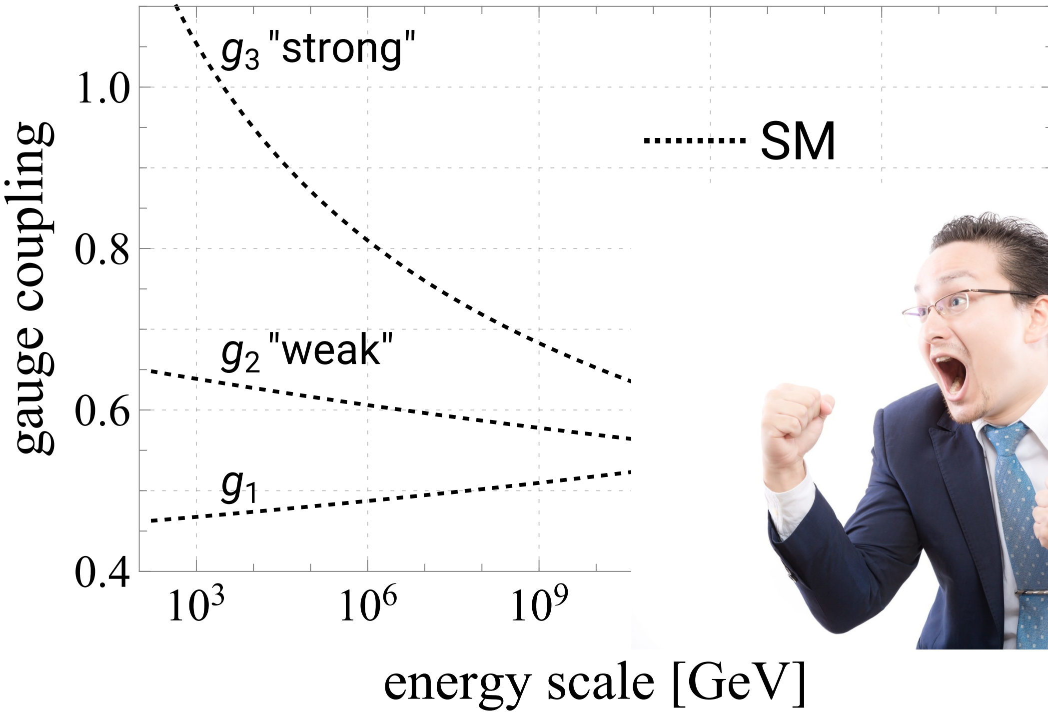
| by freeze-out mechanism
under "standard" thermal history of Universe:

- bino-like DM → $m_{\mathrm{LSP}} < 100$ GeV
- higgsino-like DM → $m_{\mathrm{LSP}} \sim 1$ TeV
- wino-liike DM → $m_{\mathrm{LSP}} \sim 3$ TeV

Cf. Hisano, Matsumoto, et al. [ph/0610249]
Farina, Pappadopulo, Strumia [1303.7244]

Extra 2) Coupling Unification

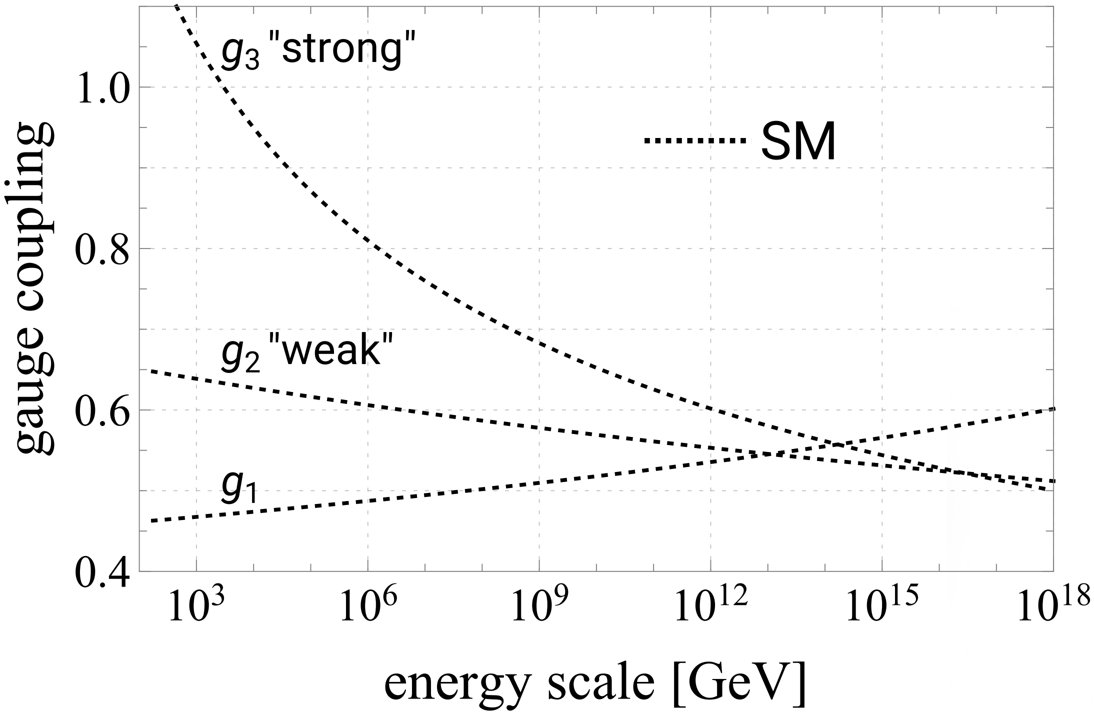
■ Strengths of 3 forces depend on energy scale:



- ❖ dark matter,
- ➢ **grand unification,**
- ❖ muon $g-2$.

Image courtesy of pakutaso.com

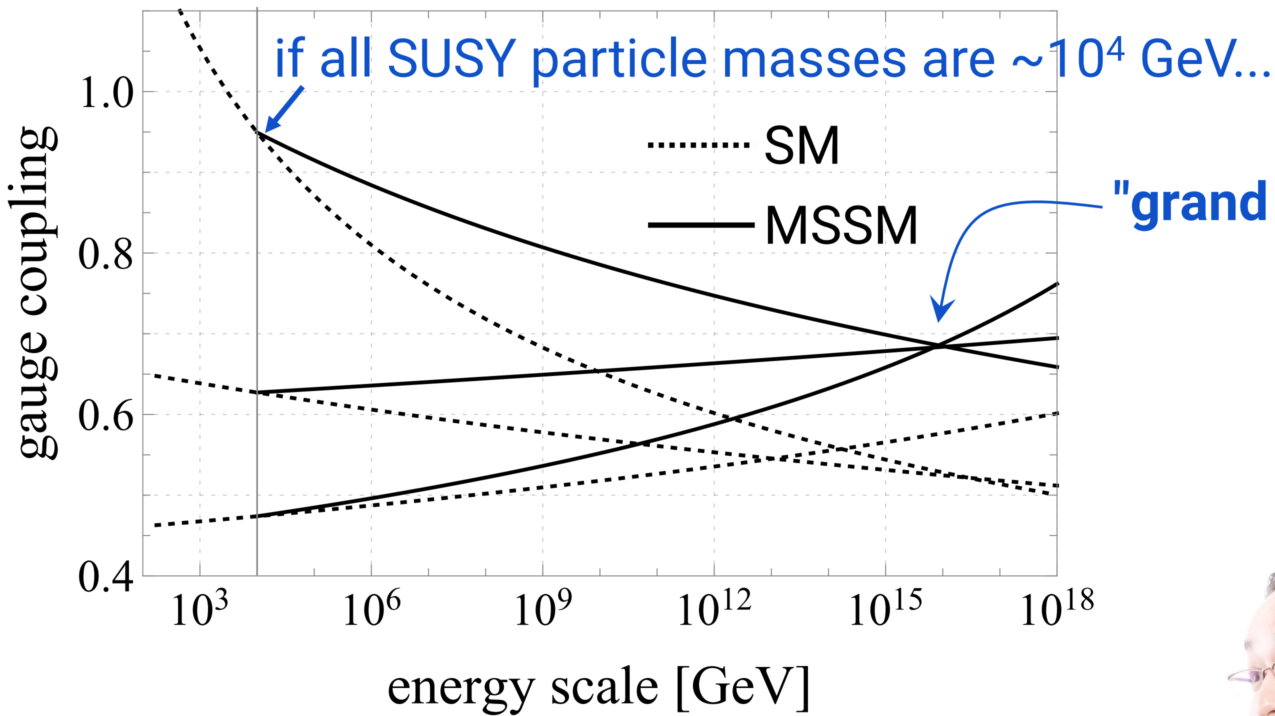
■ Strengths of 3 forces depend on energy scale:



- ❖ dark matter,
- ➢ **grand unification,**
- ❖ muon $g-2$.

Image courtesy of pakutaso.com

■ SUSY particles can modify the lines.



- ❖ dark matter,
- ➢ **grand unification,**
- ❖ muon $g-2$.

Image courtesy of pakutaso.com

Extra 3) SUSY naturalness

Motivation for MSSM (0) "Naturalness" was the primary motivation for SUSY.

■ Higgs mass is unnatural.

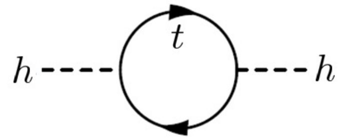
quantum correction

$$m_h^2 \simeq m_{\text{bare}}^2 + \Delta m_h^2$$

physical
mass
10^4 GeV^2

Λ (cutoff) ~ Planck or GUT scale

$$\text{SM:}\quad \Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2}\Lambda^2 + \cdots$$



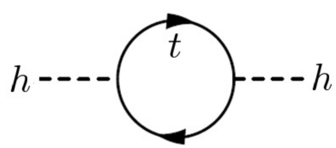
"naturalness problem"
"hierarchy problem"

<u>before 2012</u>

➢ No Higgs? (e.g., technicolor, extra dim., gauge-Higgs unif., ...)

➢ SUSY?

$$\text{MSSM:}\quad \Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2}\Lambda^2 + \underline{\frac{3y_t^2}{4\pi^2}\Lambda^2} + \cdots$$



"scalar top $\tilde{t}$ " contribution

"Quadratic divergence" is cancelled out: Power of symmetry!

■ Higgs mass is unnatural.

quantum correction

$$m_h^2 \simeq m_{\text{bare}}^2 + \Delta m_h^2$$

physical
mass
$10^4\ \mathrm{GeV}^2$

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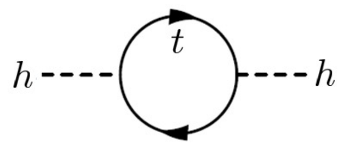
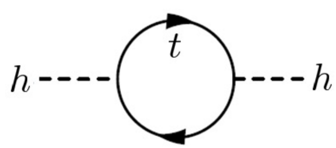


"naturalness problem"
"hierarchy problem"

4 July 2012: Higgs discovery

- ~~No Higgs? (e.g., technicolor, extra dim., gauge-Higgs unif., ...)~~

- **SUSY!!!!** $$\text{MSSM:}\quad \Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2}\Lambda^2 + \underline{\frac{3y_t^2}{4\pi^2}\Lambda^2} + \cdots$$



"scalar top $\tilde{t}$ " contribution

"Quadratic divergence" is cancelled out: Power of symmetry!

Kitano, Nomura [hep-ph/0602096]

■ However....

$$\text{MSSM:}\quad \Delta m_h^2 \sim \cancel{-\frac{3y_t^2}{4\pi^2}\Lambda^2 + \frac{3y_t^2}{4\pi^2}\Lambda^2} + \underline{\cdots}$$

$$\sim \boxed{-\frac{3y_t^2}{4\pi^2}\underline{m_{\tilde t}^2}\log\frac{\Lambda}{m_{\tilde t}} + \cdots}$$

"Log divergence"

➢ if scalar-top mass is

$$\begin{aligned} 300\,\mathrm{GeV}:&\quad 10^5 + (-10^5) \rightsquigarrow 10^4 \quad [10\%] \\ 1000\,\mathrm{GeV}:&\quad 10^6 + (-10^6) \rightsquigarrow 10^4 \quad [1\%] \\ 3000\,\mathrm{GeV}:&\quad 10^7 + (-10^7) \rightsquigarrow 10^4 \quad [0.1\%] \end{aligned}$$

☺️ natural

😕

👿 unnatural

(my subjective opinion)

- **We expected scalar quark at $\mathcal{O}$(0.1–1) TeV.** (motivation for 14 TeV LHC!)

After 2018 (LHC Run 2)

➢ **No SUSY yet.** Strong constraints on ~300 GeV squarks. [→ later]

➢ **SUSY fails to solve the hierarchy problem?????**

Kitano, Nomura [hep-ph/0602096]

■ Ho

Note

MSSM condition for EWSB:

$$\frac{m_Z^2}{2} = -\mu^2 + \frac{m_{H_\mathrm{d}}^2 - m_{H_\mathrm{u}}^2 \tan^2\beta}{\tan^2\beta - 1}$$

(little hierarchy problem on Higgsino mass μ)

Requirements for "natural SUSY"

Papucci, Ruderman, Weiler [1110.6926]

Higgsino mass

$$|\mu| \lesssim 200\,\mathrm{GeV}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

scalar-top mass

$$\sqrt{m_{\tilde t_1}^2 + m_{\tilde t_2}^2} \lesssim 600\,\mathrm{GeV}\frac{\sin\beta}{\sqrt{1+\alpha^2}}\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

gluino mass

$$m_{\tilde g} \lesssim 900\,\mathrm{GeV}\cdot\sin\beta\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

ural

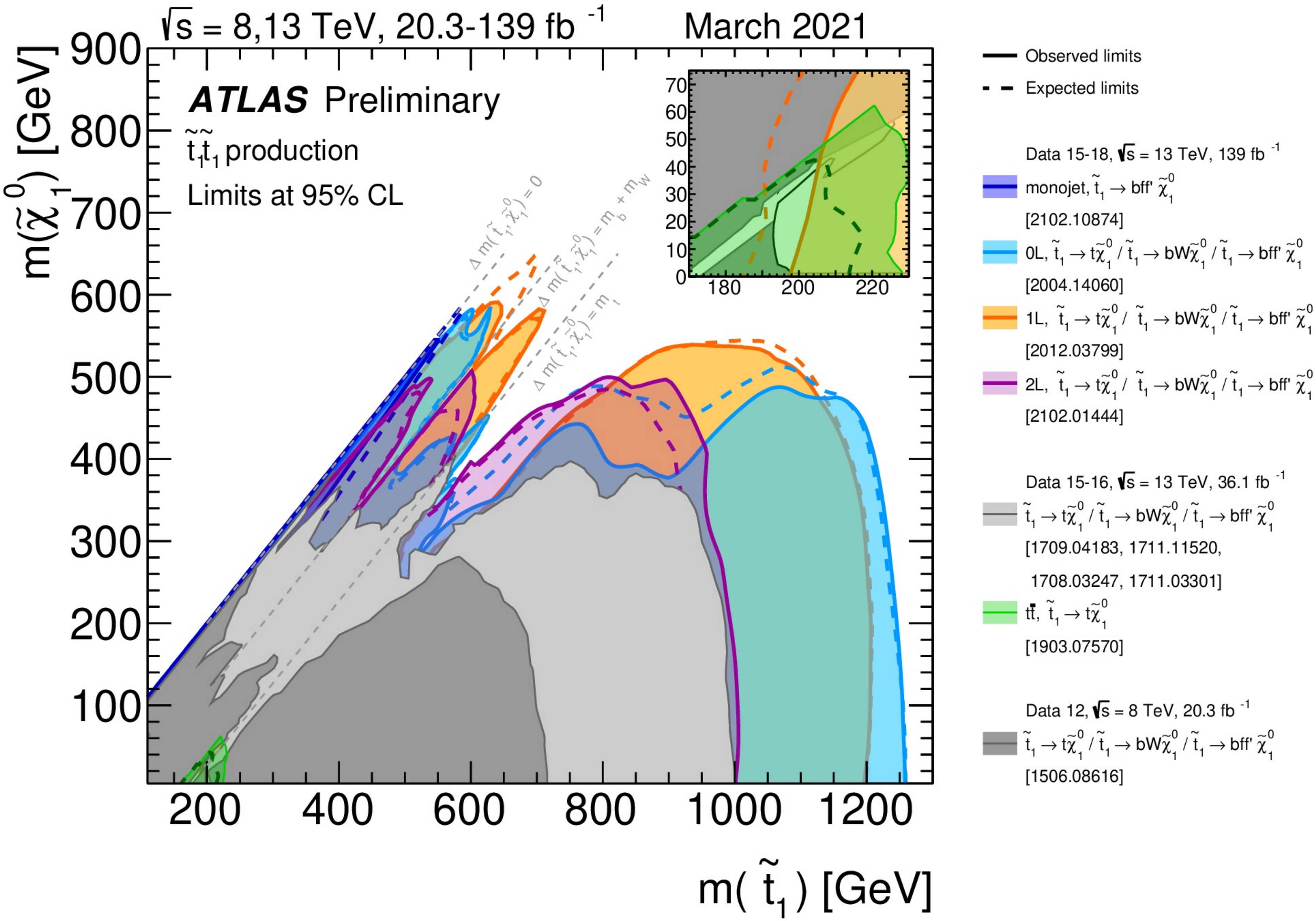
pinion)

After 2018 (LHC Run 2)

➢ **No SUSY yet.** Strong constraints on ~300 GeV squarks. [→ later]

➢ **SUSY fails to solve the hierarchy problem?????**

ATLAS, SUSY March 2021 Summary Plot



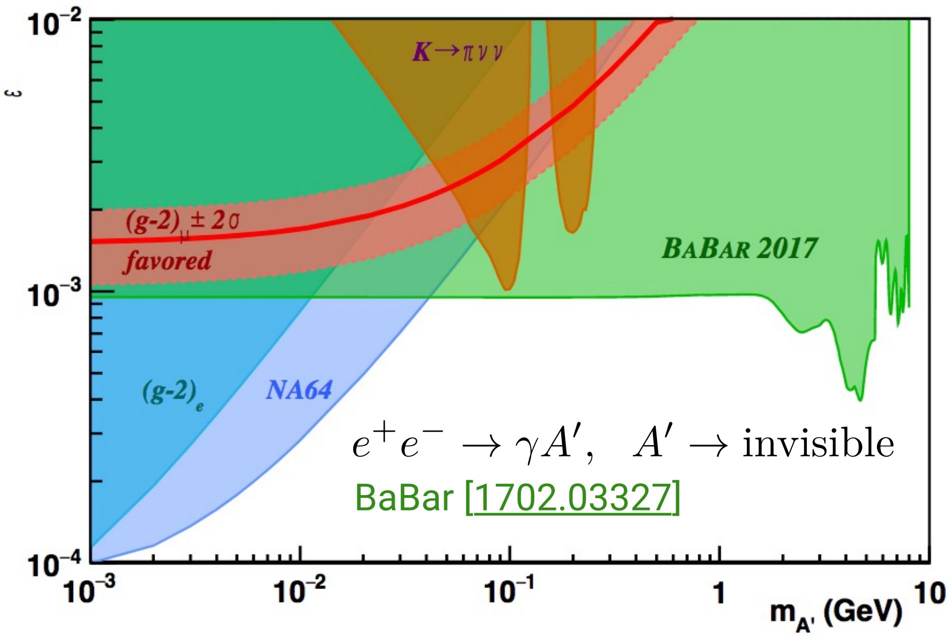
Extra 4) dark photon & Lmu−Ltau

$$a_\mu^{\rm NP} \sim \frac{m_\mu^2}{16\pi^2}\frac{(\text{new coupling})^2}{(\text{new mass})^2} \Rightarrow \frac{\text{mass}}{\text{coupling}} \sim 150\,\text{GeV}$$

$$a_\mu(\text{expm}) = (11\,659\,208.9 \quad \pm 6.3 \quad) \times 10^{-10}$$
$$a_\mu(\text{SM}) = (11\,659\,181.0 \quad \pm 4.3 \quad) \times 10^{-10}$$
$$\boldsymbol{\Delta a_\mu = (\quad 27.9 \quad \pm 7.6 \quad) \times 10^{-10}}$$

- MSSM: (coupling, mass) ~ (1, 200GeV)
- light Z' models: (coupling, mass) ~ (tiny, tiny)

	U(1)$_Y$	"dark photon"
Q_L	1/6	(1/6)ε
U_R	2/3	(2/3)ε
D_R	−1/3	(−1/3)ε
L_L	−1/2	(−1/2)ε
E_R	−1	(−1)ε
B	✓	
A'		✓
H	1/2	(1/2)ε



⇨ **excluded (as a Δa_μ solution)**

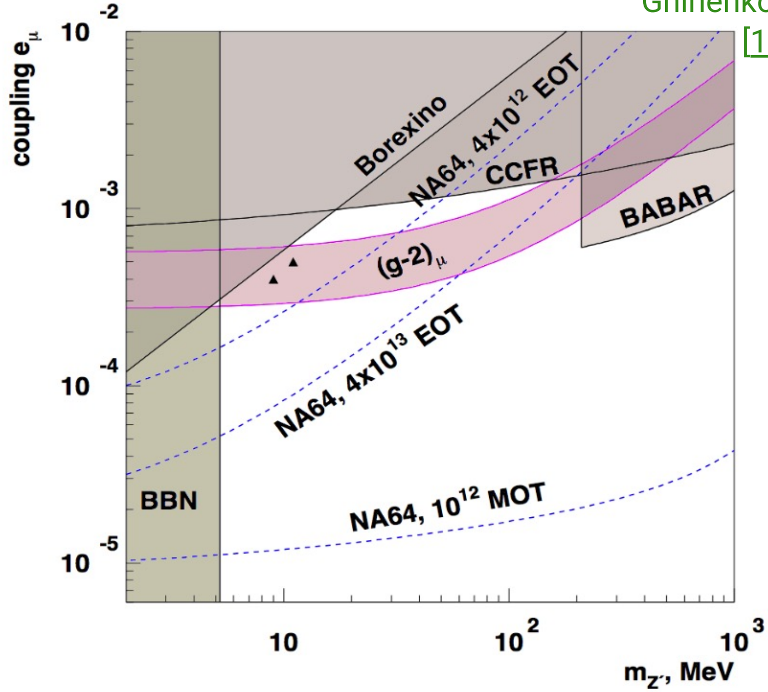
$$a_\mu^{\rm NP} \sim \frac{m_\mu^2}{16\pi^2}\frac{(\text{new coupling})^2}{(\text{new mass})^2} \Rightarrow \frac{\text{mass}}{\text{coupling}} \sim 150\,\text{GeV}$$

$$\begin{aligned} a_\mu(\text{expm}) &= (11\,659\,208.9 \quad \pm 6.3 \quad) \times 10^{-10} \\ a_\mu(\text{SM}) &= (11\,659\,181.0 \quad \pm 4.3 \quad) \times 10^{-10} \\ \hline \Delta a_\mu &= (\quad 27.9 \quad \pm 7.6 \quad) \times 10^{-10} \end{aligned}$$

- MSSM: (coupling, mass) ~ (1, 200GeV)
- light Z' models: (coupling, mass) ~ (tiny, tiny)

	$U(1)_Y$	"$L_\mu - L_\tau$"		
Q_L	1/6	0		
U_R	2/3	0		
D_R	−1/3	0		
L_L	−1/2	0	ε	−ε
E_R	−1	0	ε	−ε
B	✓			
Z'		✓		
H	1/2	0		

Gninenko, Krasnikov [1801.10448]



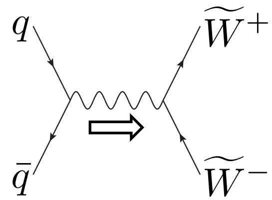
⇨ **another valid solution**

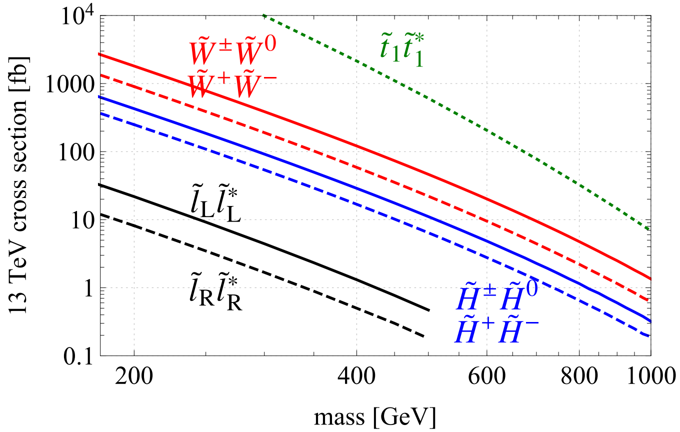
$$L_{Z'} = e_\mu Z'_\nu[\bar\mu\gamma^\nu\mu - \bar\tau\gamma^\nu\tau + \bar\nu_\mu\gamma^\nu\nu_\mu - \bar\nu_\tau\gamma^\nu\nu_\tau]$$

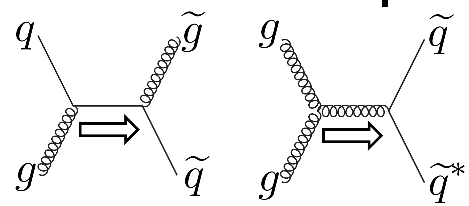
Extra 5) LHC Non-colored SUSY

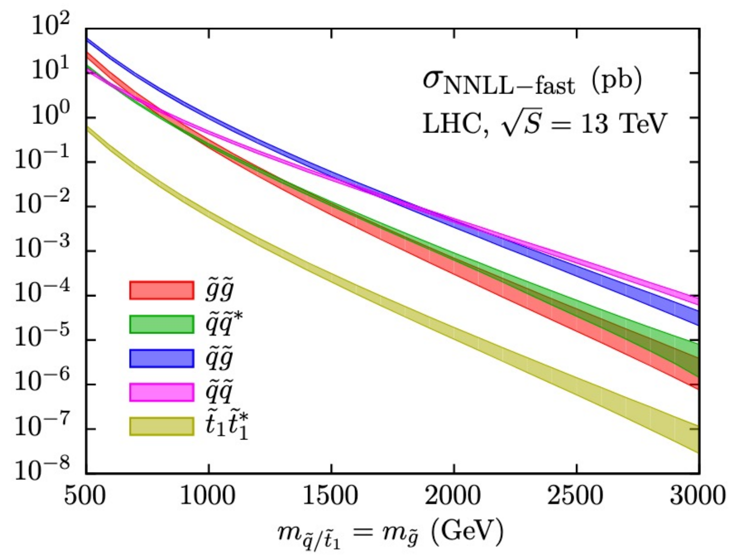
Non-colored particles have smaller production cross section.

■ Non-colored SUSY production **vs.** Colored SUSY production







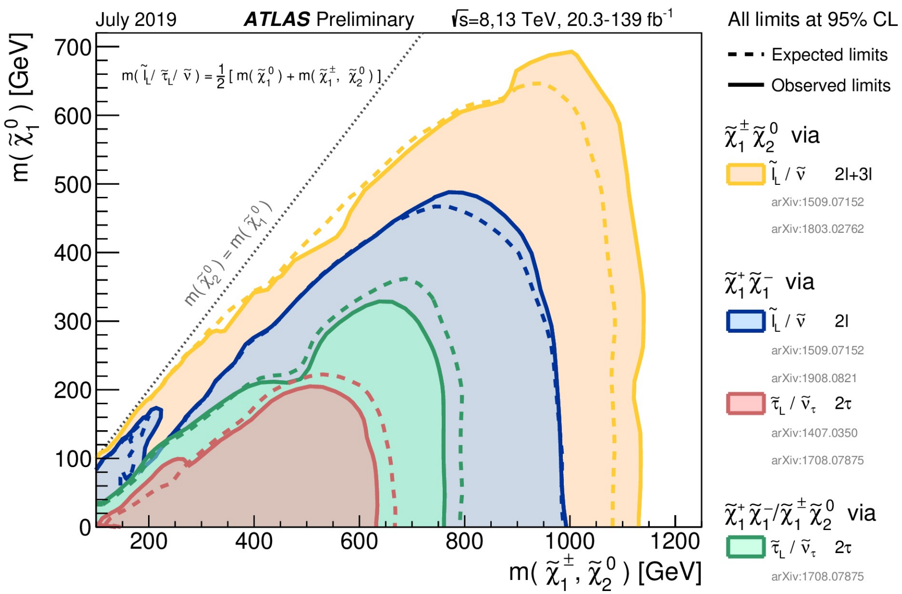


Beenakker, Borschensky, et al. [1607.07741]

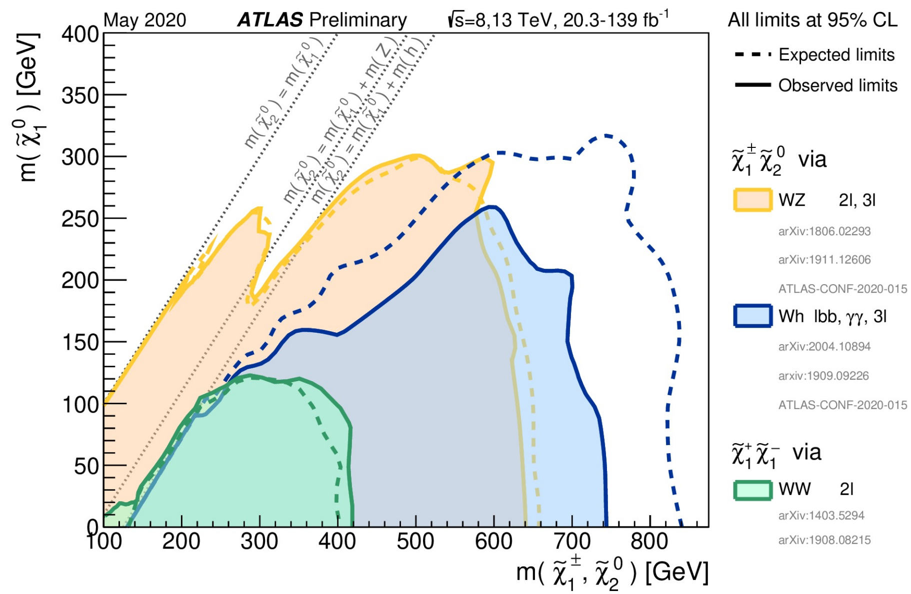
➢ Non-colored XS is smaller because

- Smaller couplings
- *s*-channel only
- Needs anti-quark from *p*

➢ $\tilde{g} \simeq \tilde{q} \gg \tilde{t} \simeq \tilde{b} \gg \widetilde{W} > \widetilde{H} \gg \tilde{l}_{\mathrm{L}} > \tilde{l}_{\mathrm{R}}$ if similar mass



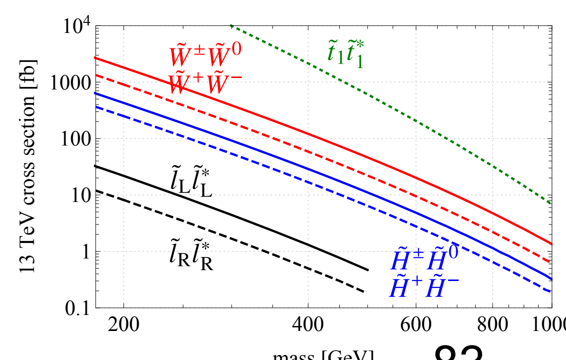
(slepton-mediated: NC/3L)



(direct-to-LSP: NC/ZW, NC/HW, CC/WW)

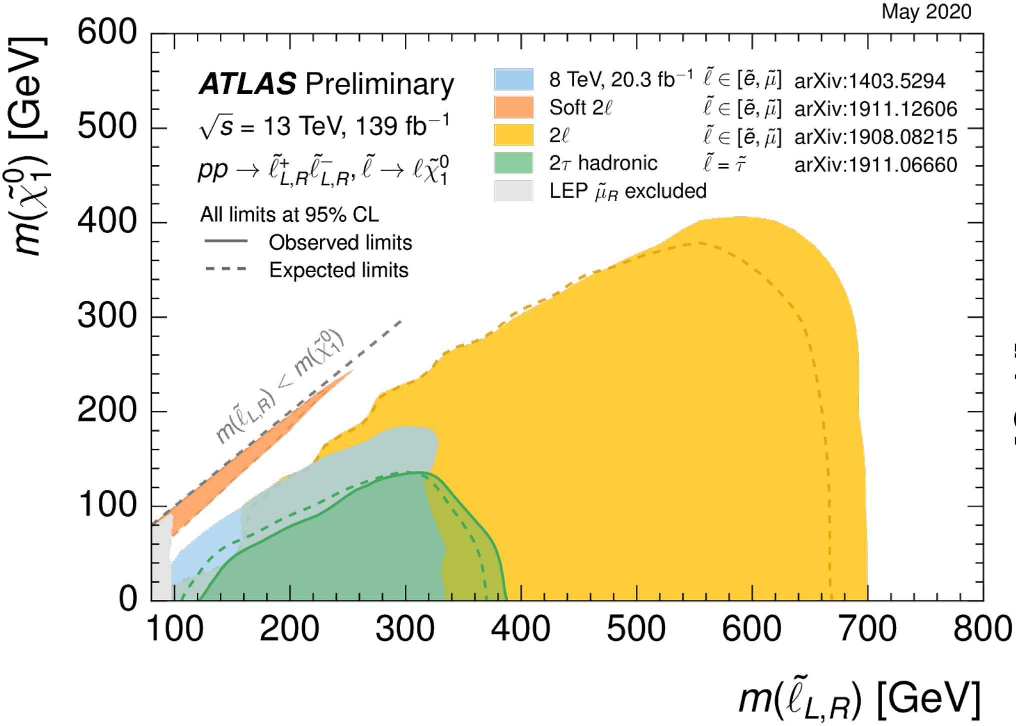
(They usually assume $\tilde\chi_2^0 \equiv \widetilde{W}^0$, $\tilde\chi_1^+ \equiv \widetilde{W}^+$.)

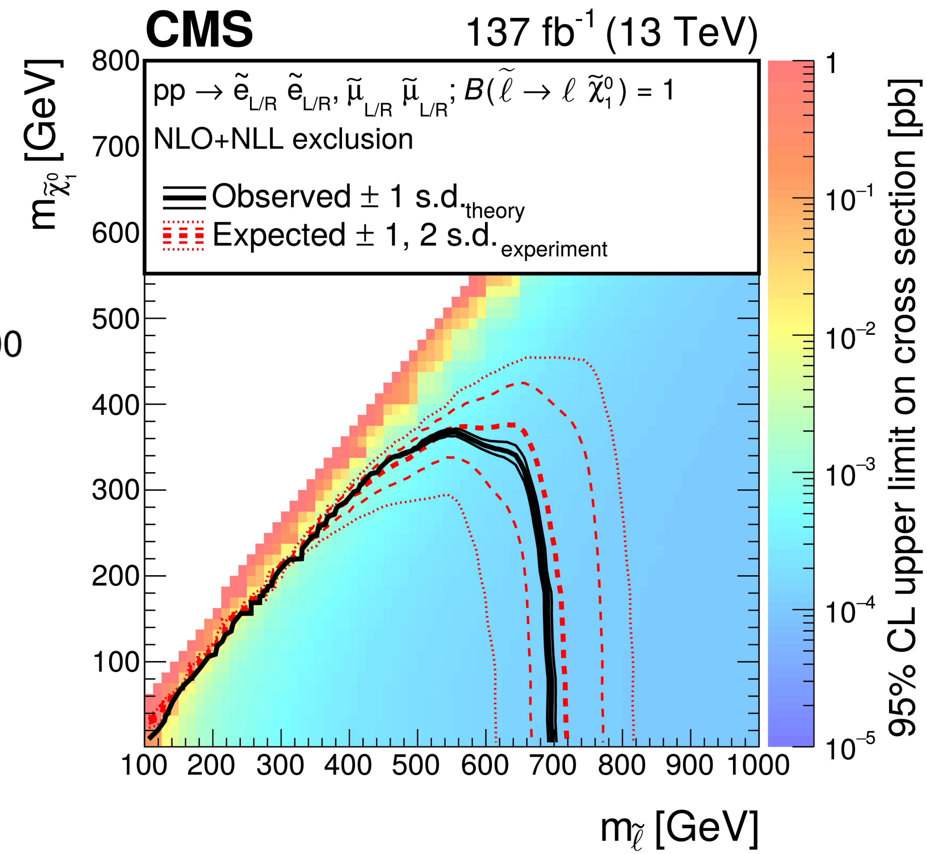
$$
\begin{aligned}
\mathrm{Br}(Z \to \mathrm{had}) &= 69.911(56)\% \\
\mathrm{Br}(Z \to b\bar b) &= 15.12(5)\% \\
\mathrm{Br}(Z \to e, \mu, \tau) &\simeq 10.10\% \\
\mathrm{Br}(Z \to \mathrm{inv}) &= 20.000(55)\% \\
\mathrm{Br}(W \to \mathrm{had}) &= 67.41(27)\%
\end{aligned}
$$



LHC scalar-lepton search summary

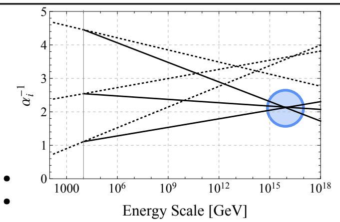
ATLAS, SUSY March 2021 Summary Plot & CMS [2012.08600]





Extra 6) ~~SUSY~~ and 2104.03223

Iwamoto, Yanagida, Yokozaki [2104.03223]



CMSSM (mSUGRA)

- an assumption that ~~SUSY~~ is controlled by only 5 parameters:

$$(m_0, M_{1/2}, A_0, \tan\beta, \mathrm{sgn}\,\mu) \quad @ \quad \text{"GUT scale"} \quad \sim 10^{16}\,\mathrm{GeV}$$

common gaugino mass

common sfermion mass

- cannot explain muon g−2 anomaly. Ghilencea, Lee, Park [1203.0569]

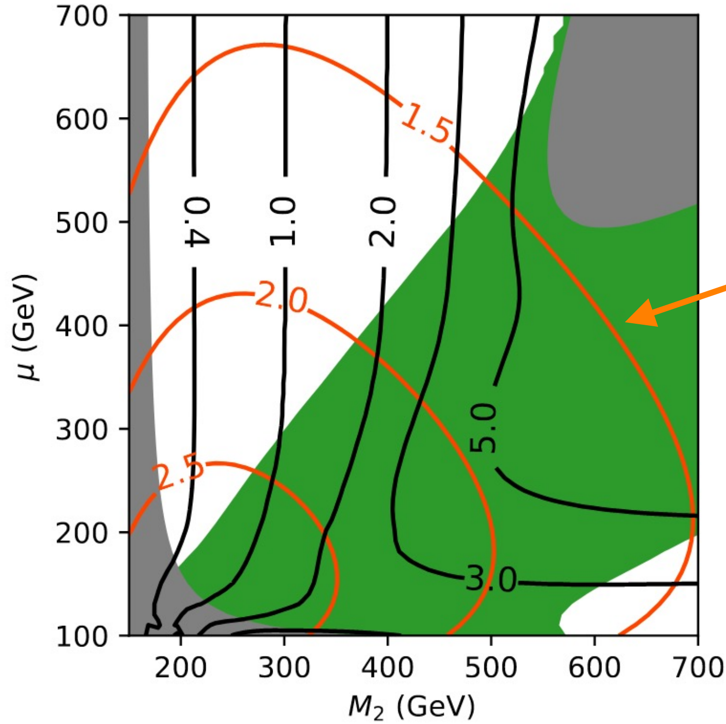
Non-Universal Gaugino Mass scenario

- $(m_0, \underbrace{M_1, M_2, M_3,}_{\text{bino/wino/gluino mass taken different}} A_0, \tan\beta, \mathrm{sgn}\,\mu)$
- can explain muon g−2 anomaly. Ghilencea, Lee, Park [1203.0569]

NUGM + NUHiggsM scenario

- $(m_0, m_{H_\mathrm{u}}, m_{H_\mathrm{d}}, M_1, M_2, M_3, A_0, \tan\beta, \mathrm{sgn}\,\mu)$

→ We provide a benchmark plane.



(a) $\Omega_{\mathrm{LSP}}/\Omega_{\mathrm{CDM}}$ [%]

$a_\mu^{\mathrm{NP}} \times 10^9$

excluded by XENON1T

$m_0 = 0$

$m_A = 2000\,\mathrm{GeV}$

$\mu = 100\text{–}700\,\mathrm{GeV}$

$M_1 = 3800\,\mathrm{GeV}$

$M_2 = 150\text{–}700\,\mathrm{GeV}$

$M_3 = 2500\,\mathrm{GeV}$

$A_u = -1000\,\mathrm{GeV}$

$A_{d,e} = 0$

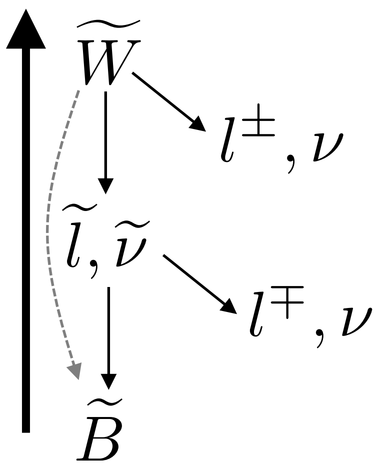
$\tan\beta = 40$

$\mathrm{sgn}\,\mu = +$

- *g*−2 + Wino/Higgsino DM only explains ~1% of DM.
- Higgsino DM is disfavored by DM direct detection.
- (Wino DM is disfavored by LHC searches.)

Extra 7) WHL in details

■ Wino > sleptons



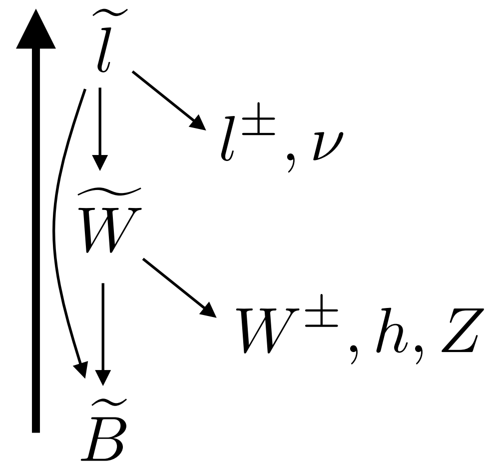
$$\widetilde{W}^{+}\widetilde{W}^{0} \to (l^{+}\nu\widetilde{B})(l^{-}l^{+}\widetilde{B}) = 3\ell + \not{E}_{\mathrm{T}}$$

$$\widetilde{l}\widetilde{l}^{*} \to (l^{-}\widetilde{B})(l^{+}\widetilde{B}) = 2\ell + \not{E}_{\mathrm{T}}$$

➢ Search targets:

- Wino pair → 2–3 lepton + mET
- slepton pair → 2 lepton + mET

■ Wino < sleptons



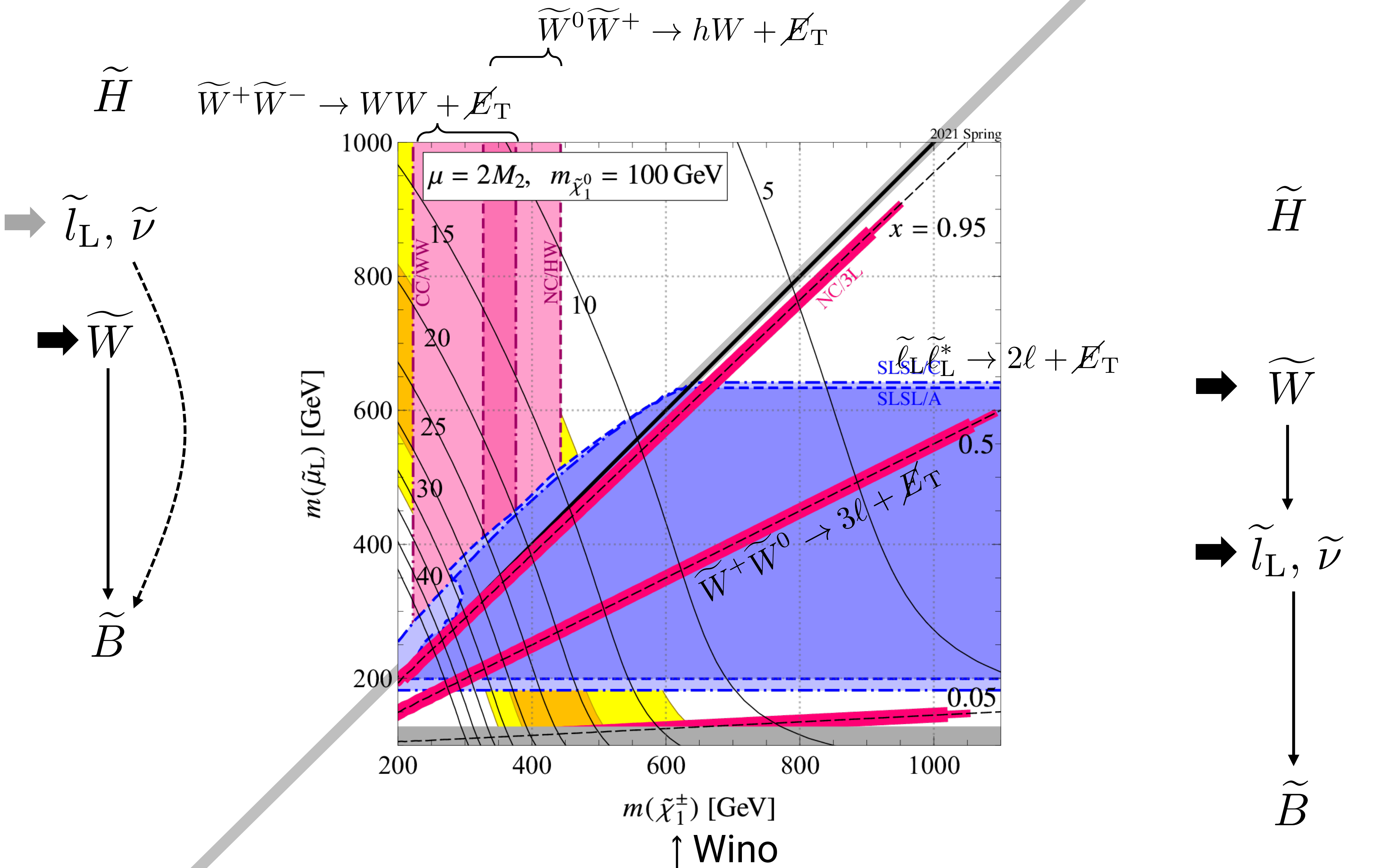
$$\widetilde{W}^{+}\widetilde{W}^{0} \to (W^{+}\widetilde{B})([Z \text{ or } h]\widetilde{B})$$

[no need to rely on slepton production]

➢ Search targets:

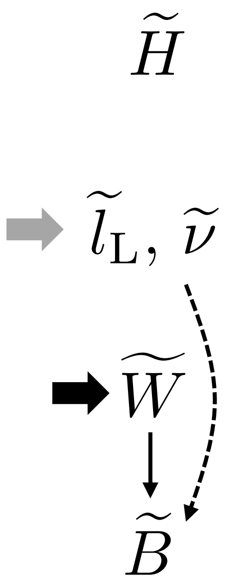
- Wino pair → WZ + mET
- Wino pair → Wh + mET

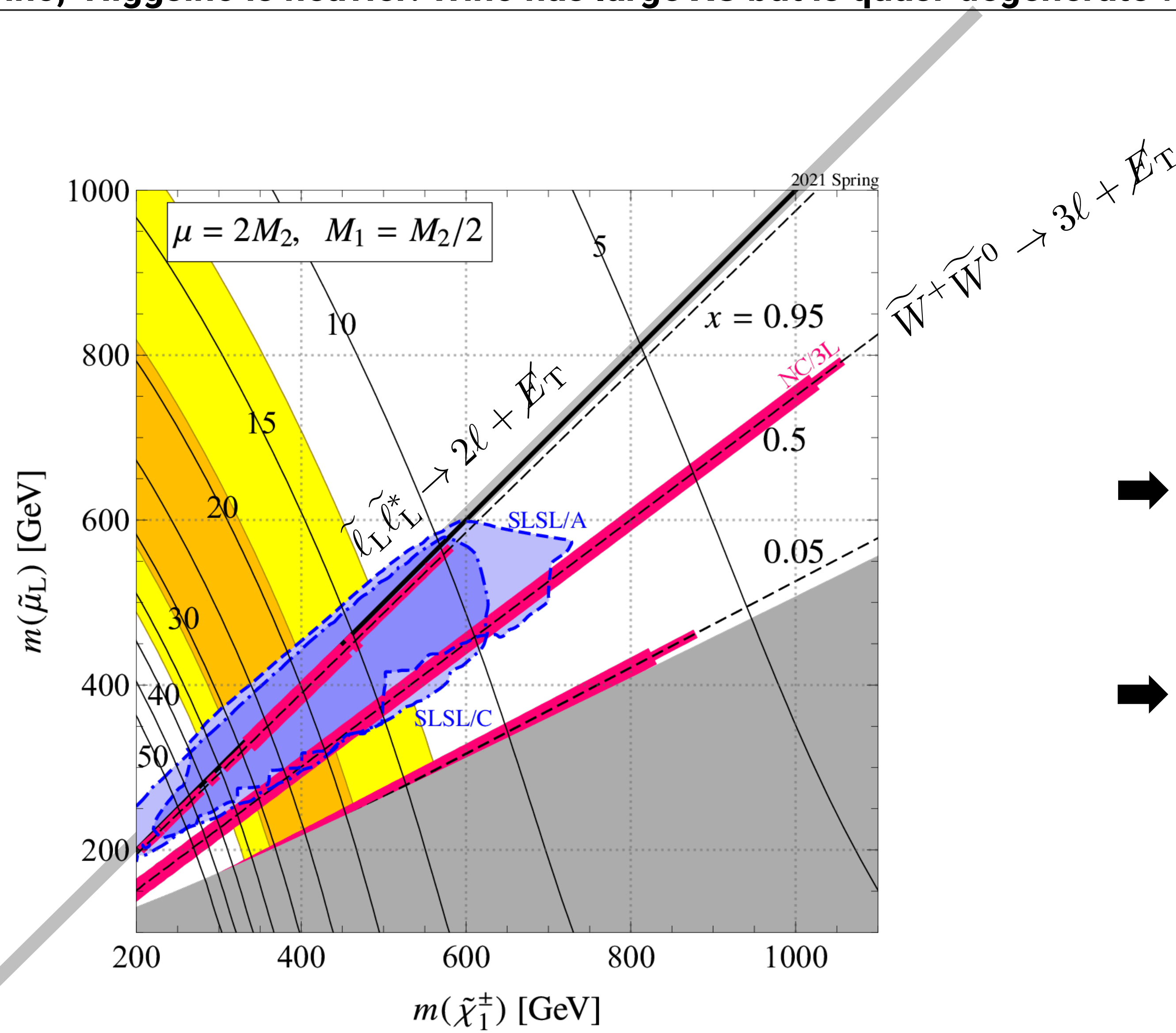
[A] LSP = 100GeV bino, Higgsino is heavier. Large wino XS helps LHC searches.



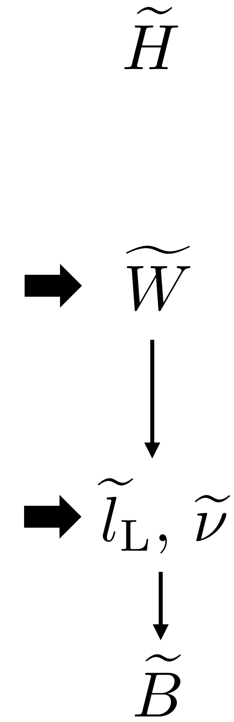
Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025][2104.03217]

[B] LSP = (M2/2) bino, Higgsino is heavier. Wino has large XS but is quasi-degenerate with Bino.



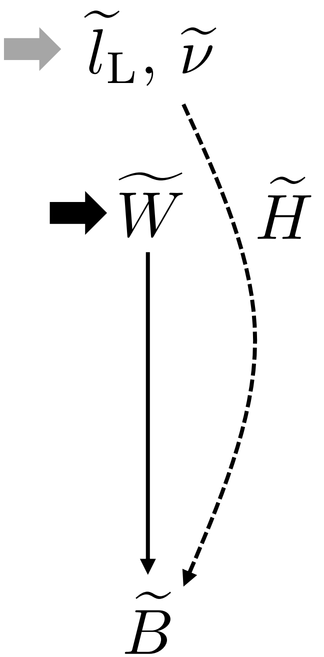


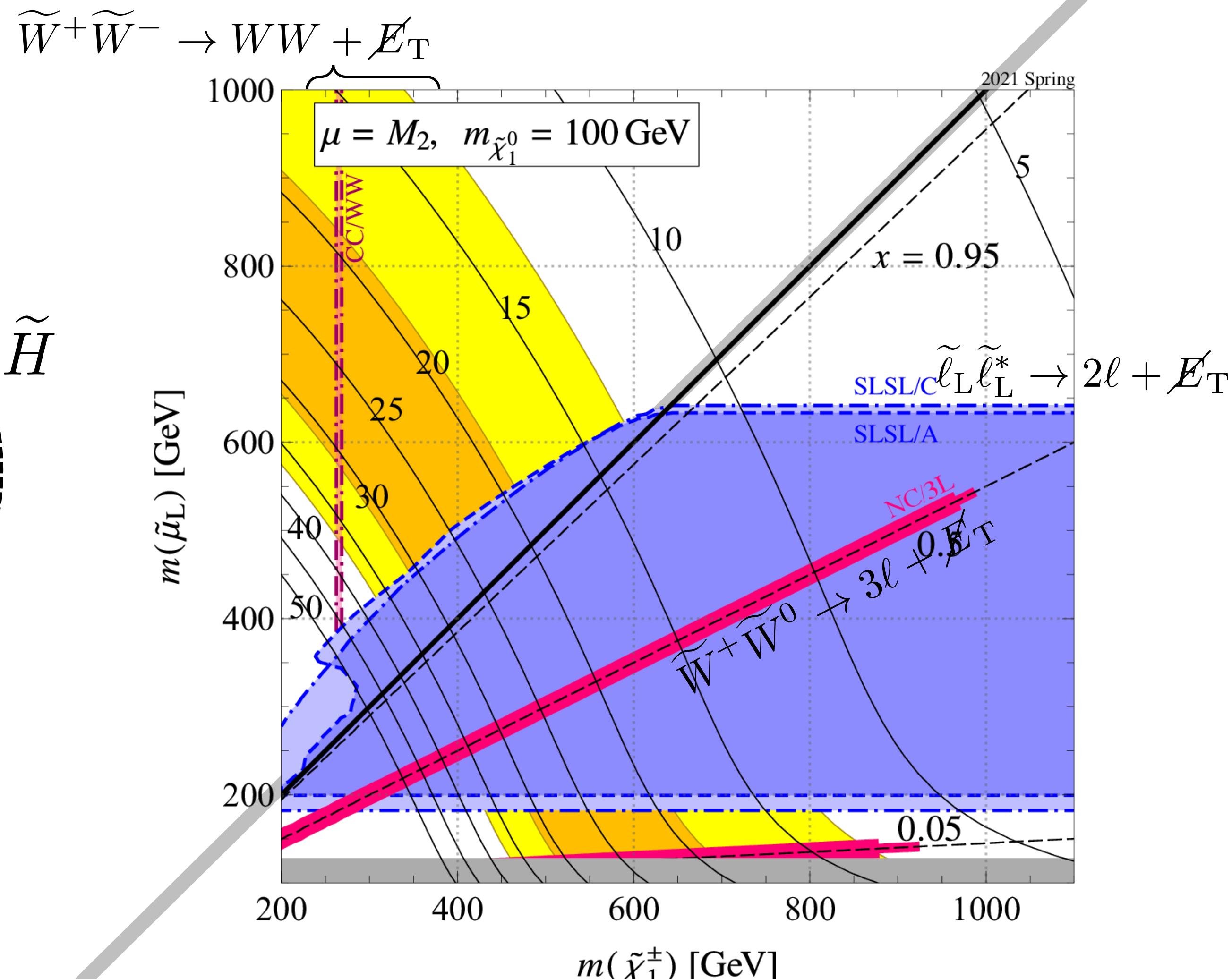
↑ Wino

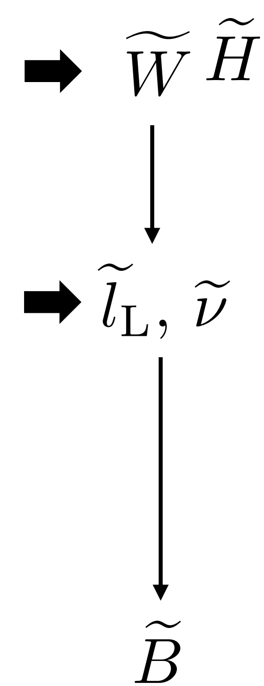


Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025][2104.03217]

[C] LSP = 100GeV bino, with Higgsino/Wino mixing. Smaller neutralino-chargino production XS.







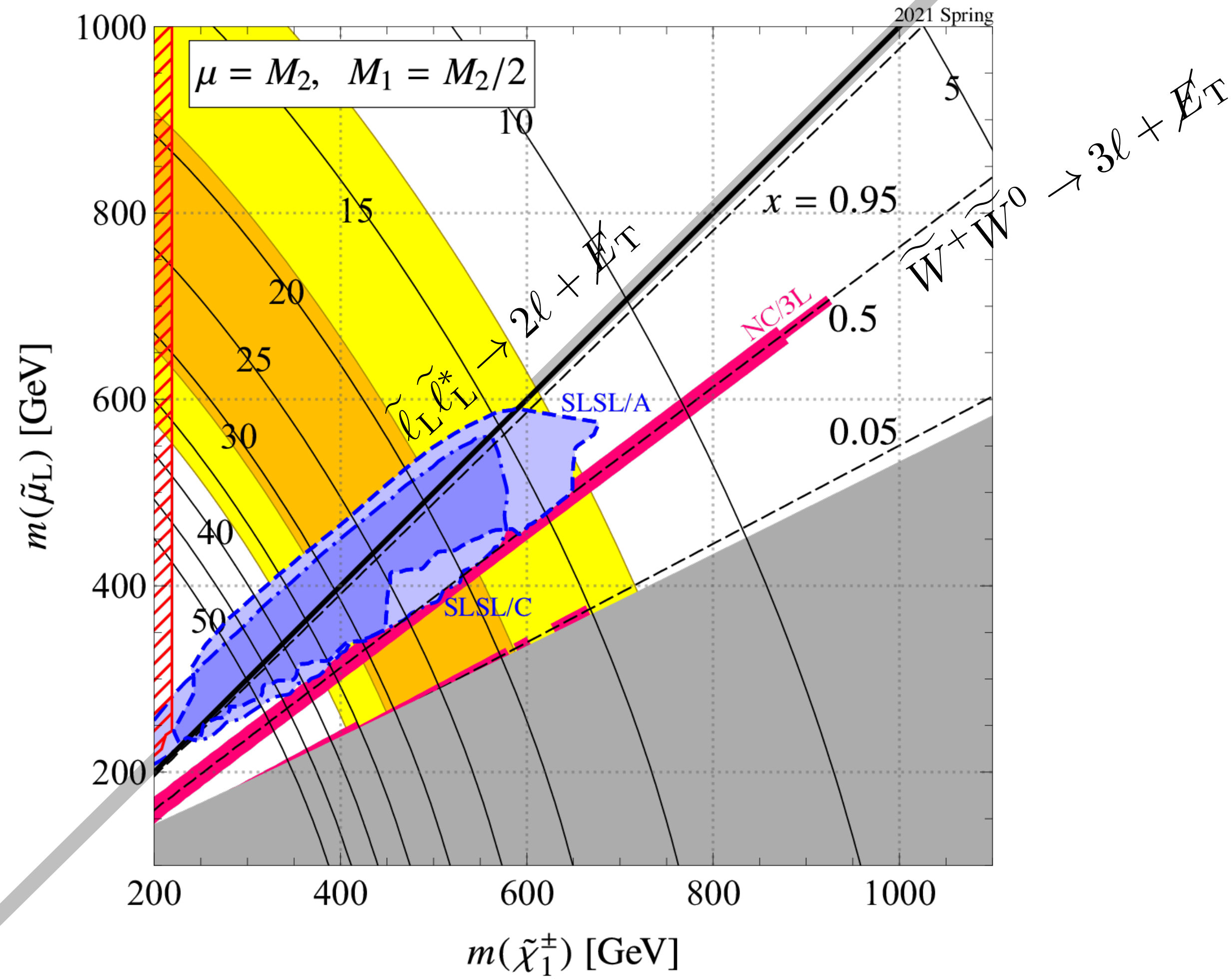
↑ Wino/Higgsino mixed

Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025][2104.03217]

➡ $\widetilde{l}_{\rm L},\ \widetilde{\nu}$

➡ $\widetilde{W}$ $\widetilde{H}$

$\widetilde{B}$



↑ Wino/Higgsino mixed

➡ $\widetilde{W}$ $\widetilde{H}$

➡ $\widetilde{l}_{\rm L},\ \widetilde{\nu}$

$\widetilde{B}$

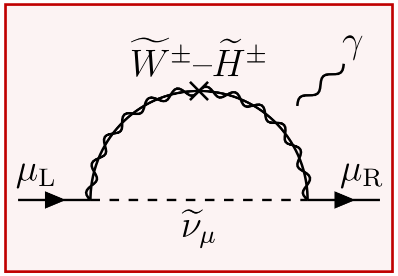
Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025][2104.03217]

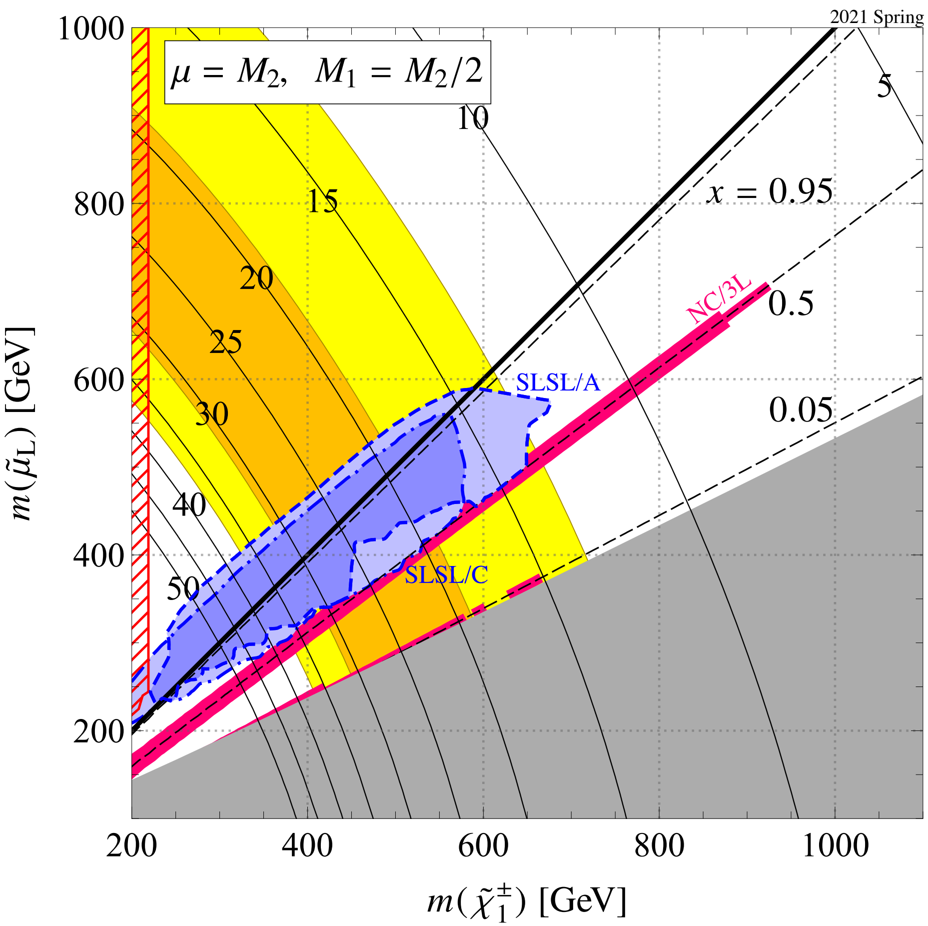
Extra 8) Big figures

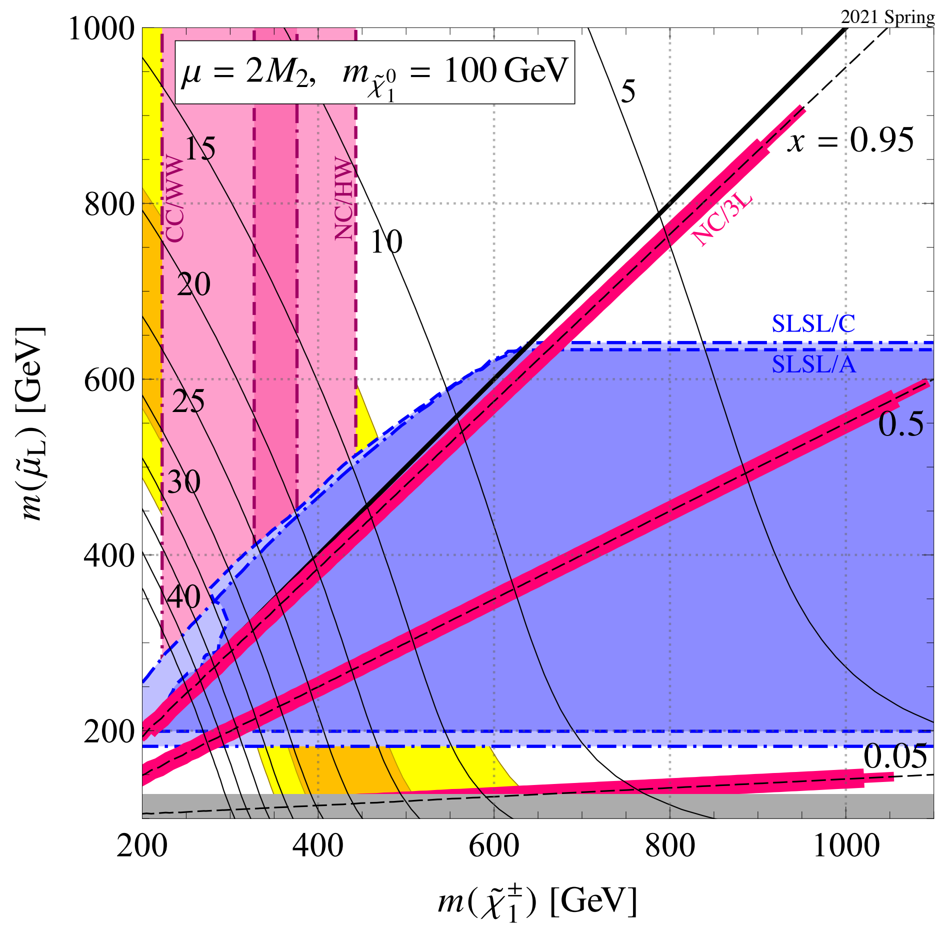
I have analyzed all the simplified scenarios.

WHL

Endo, Hamaguchi, **Iwamoto**, Kitahara [2001.11025] [2104.03217]

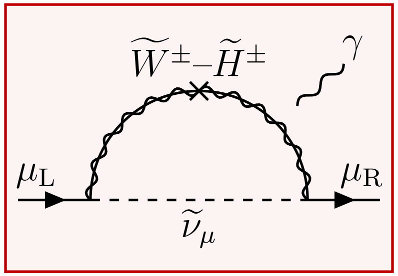




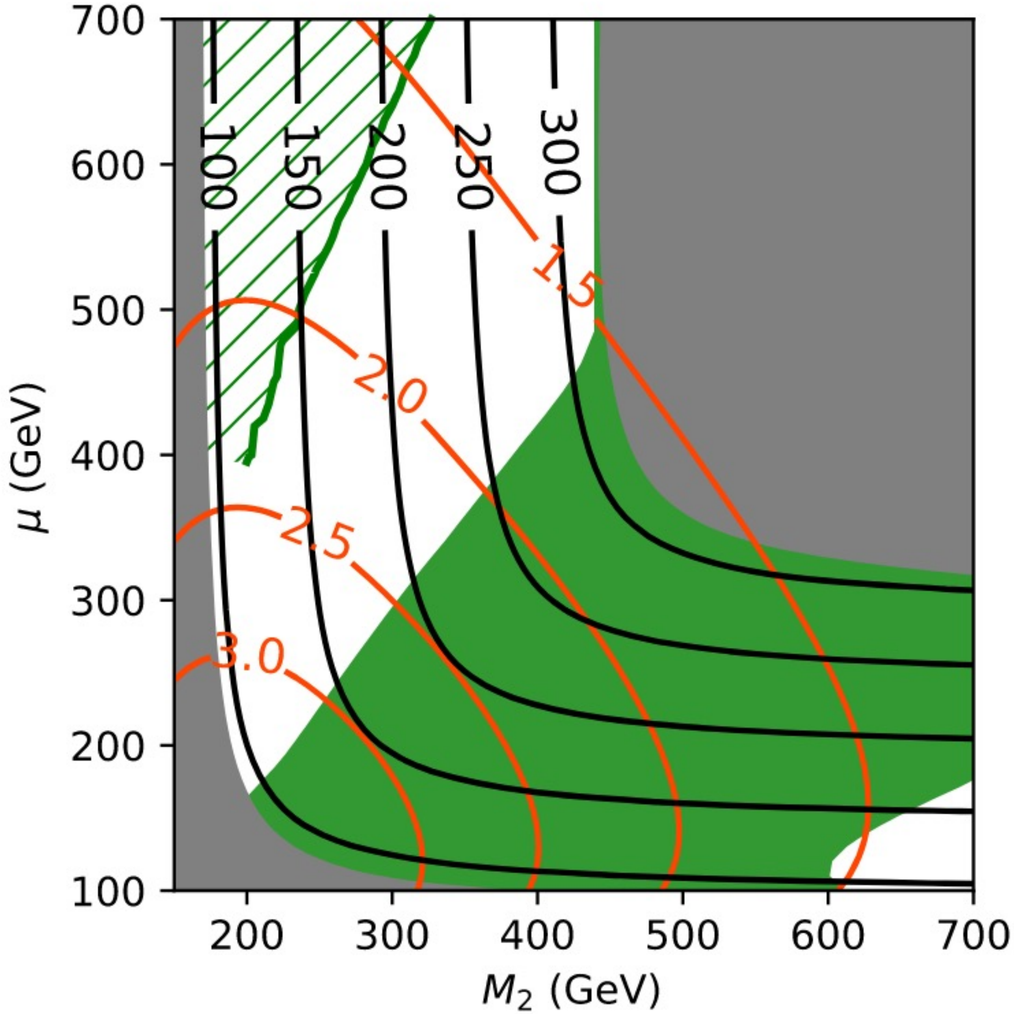


I have analyzed all the simplified scenarios.

WHL

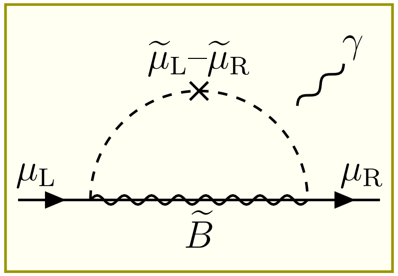


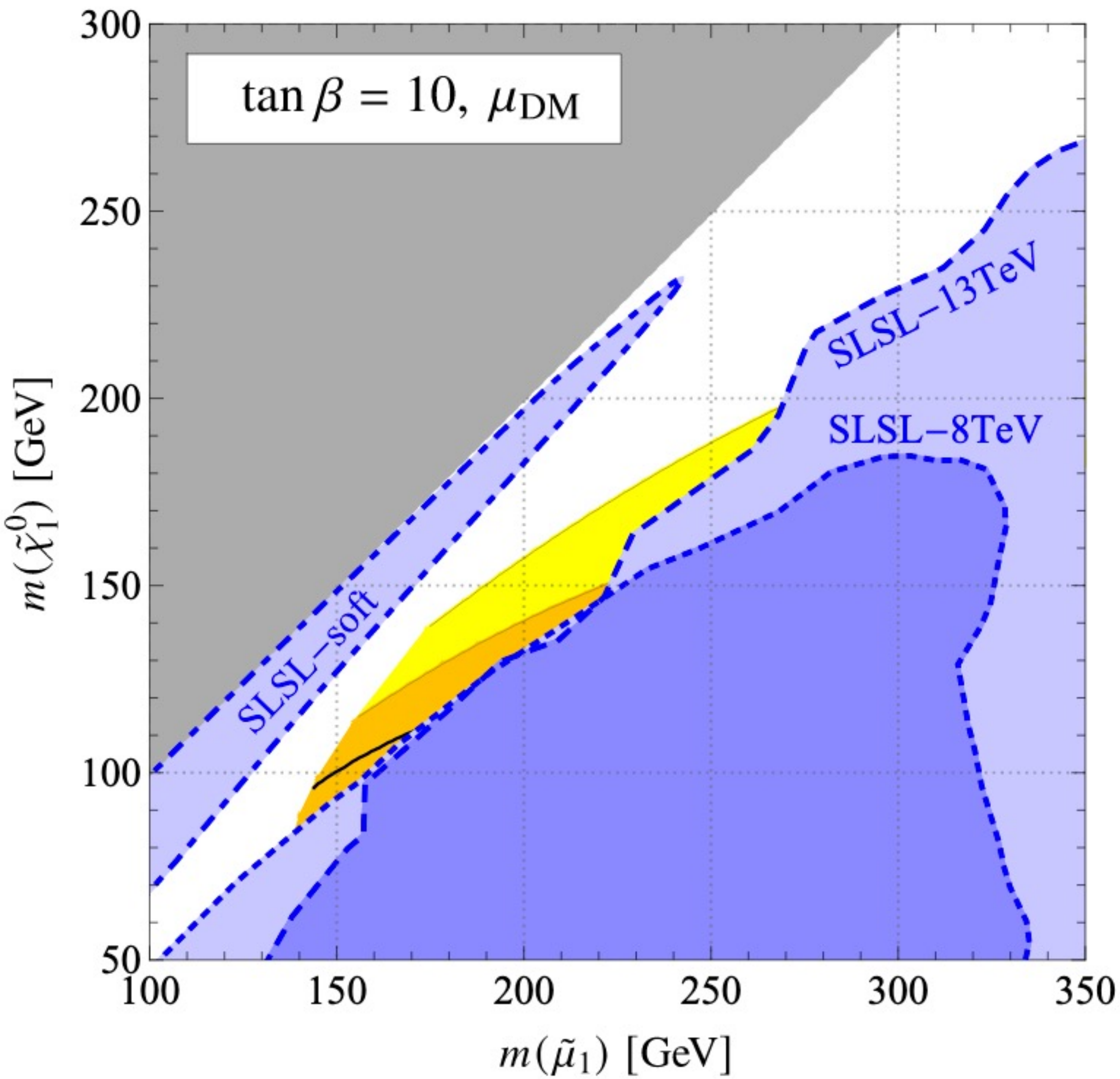
Iwamoto, Yanagida, Yokozaki [2104.03223]



BLR

Endo, Hamaguchi, **Iwamoto**, Kitahara [2001.11025] [2104.03217]

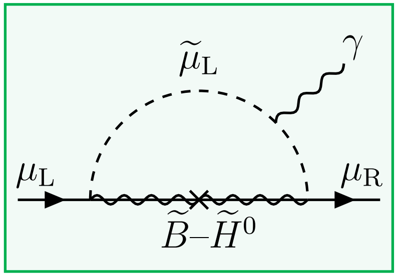




Endo, Hamaguchi, **Iwamoto**, Yanagi [1704.05287]

with old values; needs update

BHL



BHR