Explore beyond the Standard Model of Particle Physics

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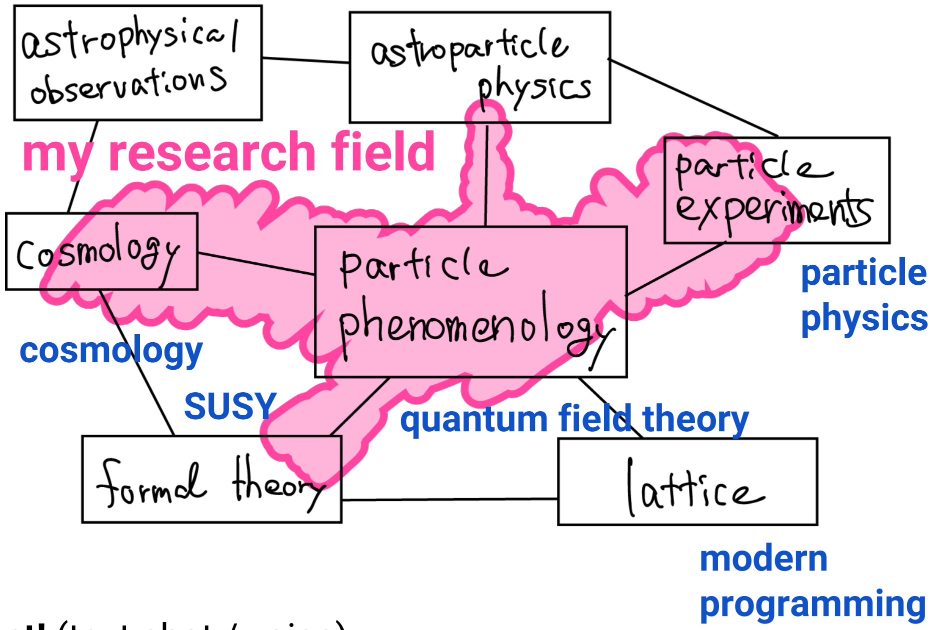
3 Mar. 2022
National Sun Yat-sen University



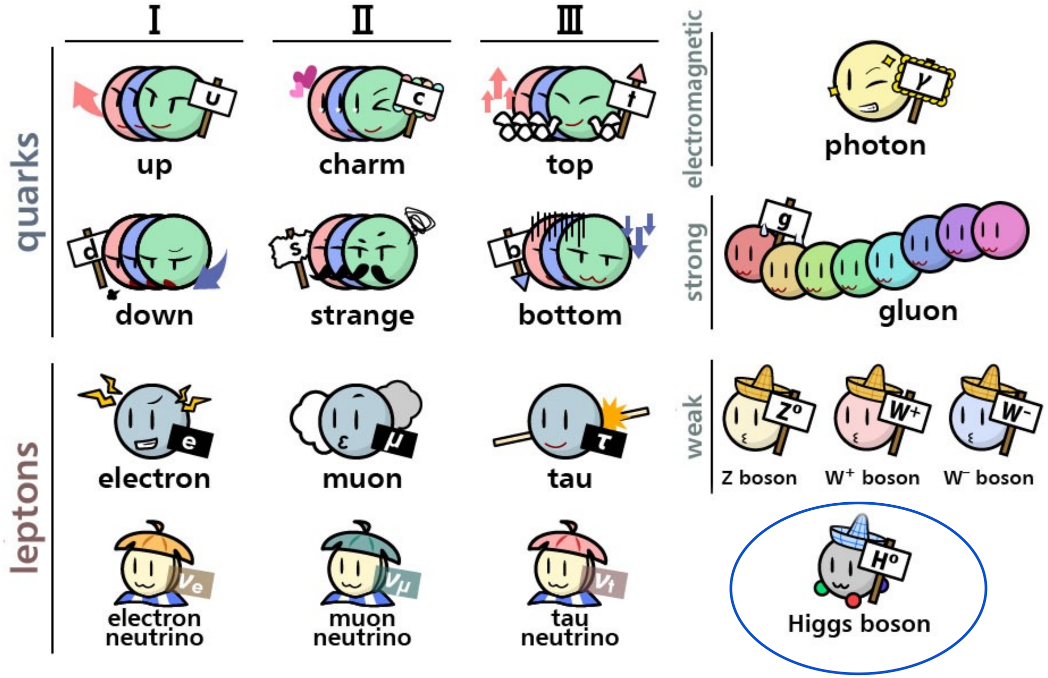
Please feel free to ask questions whenever you want! (text chat / voice)

This presentation file is available at: `https://bit.ly/iwamoto20220303`

Our civilization established the Standard Model of Particle Physics, a state-of-the-art theory.

- **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



discovered in 2012 at the LHC

	$SU(3)_{\text{color}}$	$SU(2)_{\text{weak}}$	$U(1)_Y$	
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			✓	$\to (W^+, W^-, Z) + \gamma$
W		✓		
g	✓			
H		2	1/2	

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Figure courtesy of HiggsTan.com

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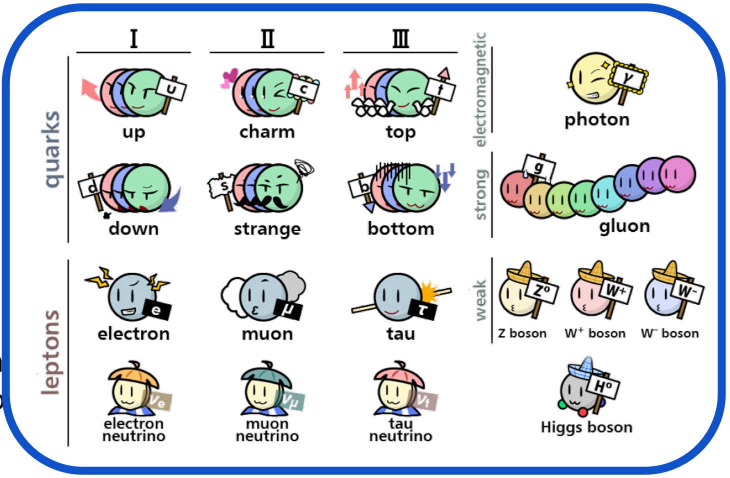

■ The SM explains...

- ✓ ingredients of 5% of the Universe,
- ✓ origin of three forces,
  [strong, weak, and electromagnetic forces]
- ✓ origin of {*q*, *e*, *μ*, *τ*, *W*, *Z*, *H*} mass,
- ✓ data from LHC (and other) experiments,
- ✓ electron *g*−2 (anomalous magnetic moment).

$$a_e(\text{meas}) = 0.00115965218072(28)$$

$$a_e(\text{SM}) = \begin{cases} 0.00115965218204(72) & \text{(Rb)} \\ 0.00115965218162(23) & \text{(Cs)} \end{cases}$$

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

but...

- ? only 5%!?
- ? gravity?
- ? mass of neutrinos?
- ? muon *g*−2?

$$a_\mu(\text{meas}) = 0.00116592061(41)$$

$$a_\mu(\text{SM}) = 0.00116591810(43)$$

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).

Figure courtesy of HiggsTan.com

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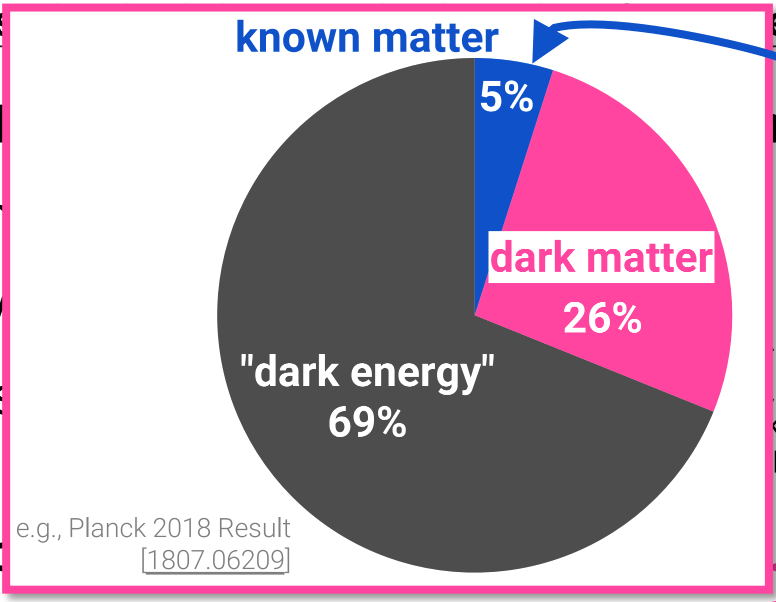
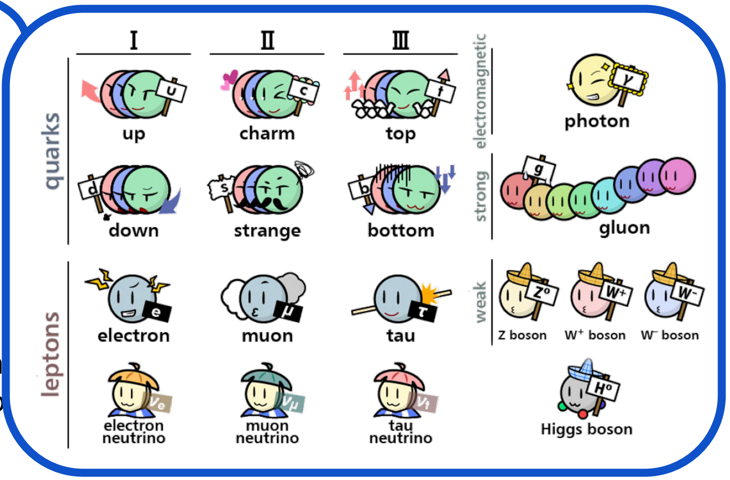


e.g., Planck 2018 Result [1807.06209]



- **Standard M**
  - ➢ quarks ar
  - ➢ "gauge sy
  - ➢ and Higgs

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1

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bo

- **The SM exp**

…

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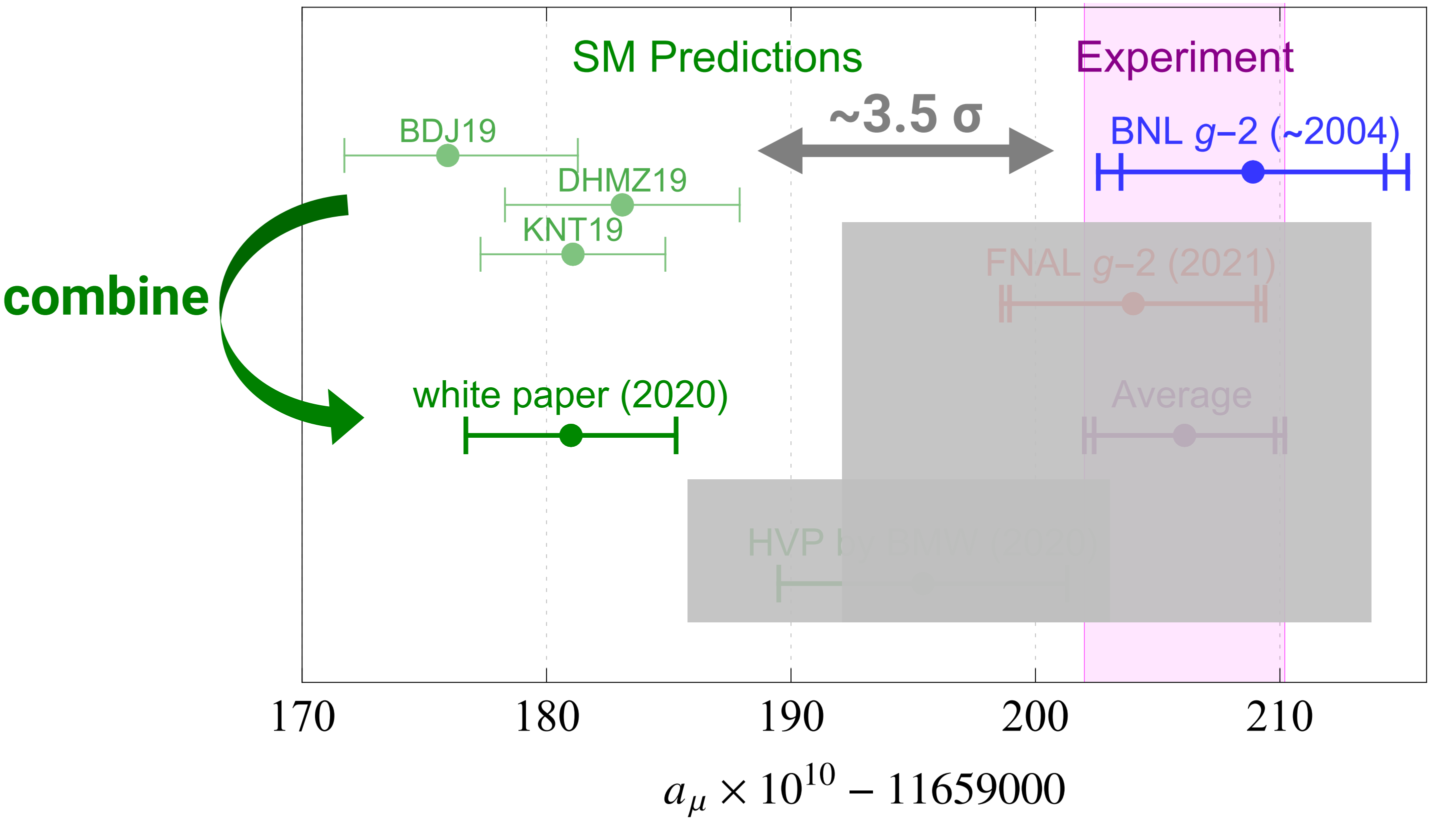
Figure courtesy of HiggsTan.com

3σ-level anomaly in **muon anomalous magnetic moment** has been known for more than 10 years.

■ Pre-2021 situation

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



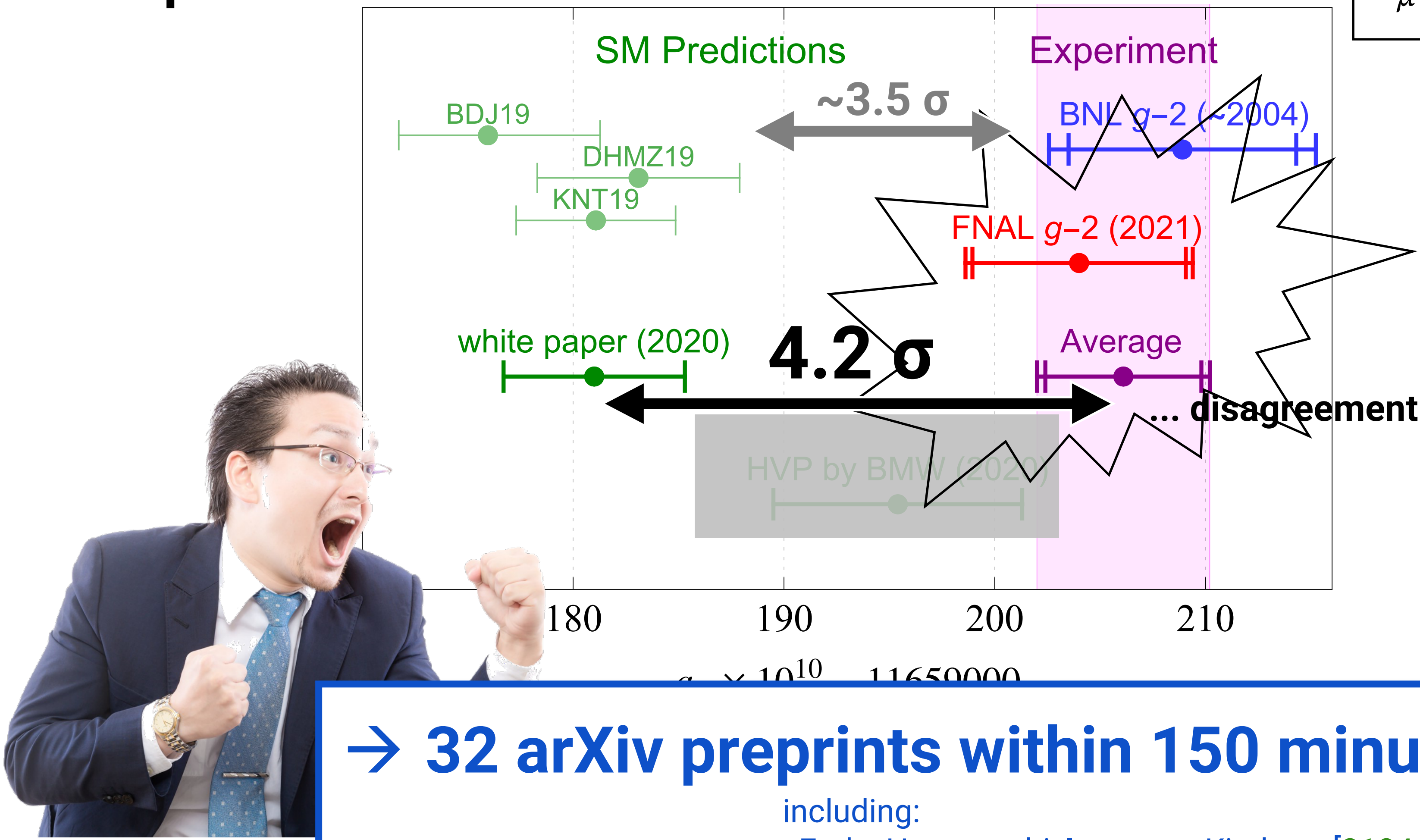
expm: Brookhaven Natl. Lab. [hep-ex/0602035]
Fermilab (Run1) [2104.03247]
SM: White paper [2006.04822]
HVP(lattice) by BMW [2002.12347v3]

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

Last year, the anomaly was confirmed by a new measurement at Fermilab.

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

- **7 April 2021**



... disagreement with SM!!!

→ **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]
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old SM: BDJ19 [1903.11034]
DHMZ19 [1908.00921]
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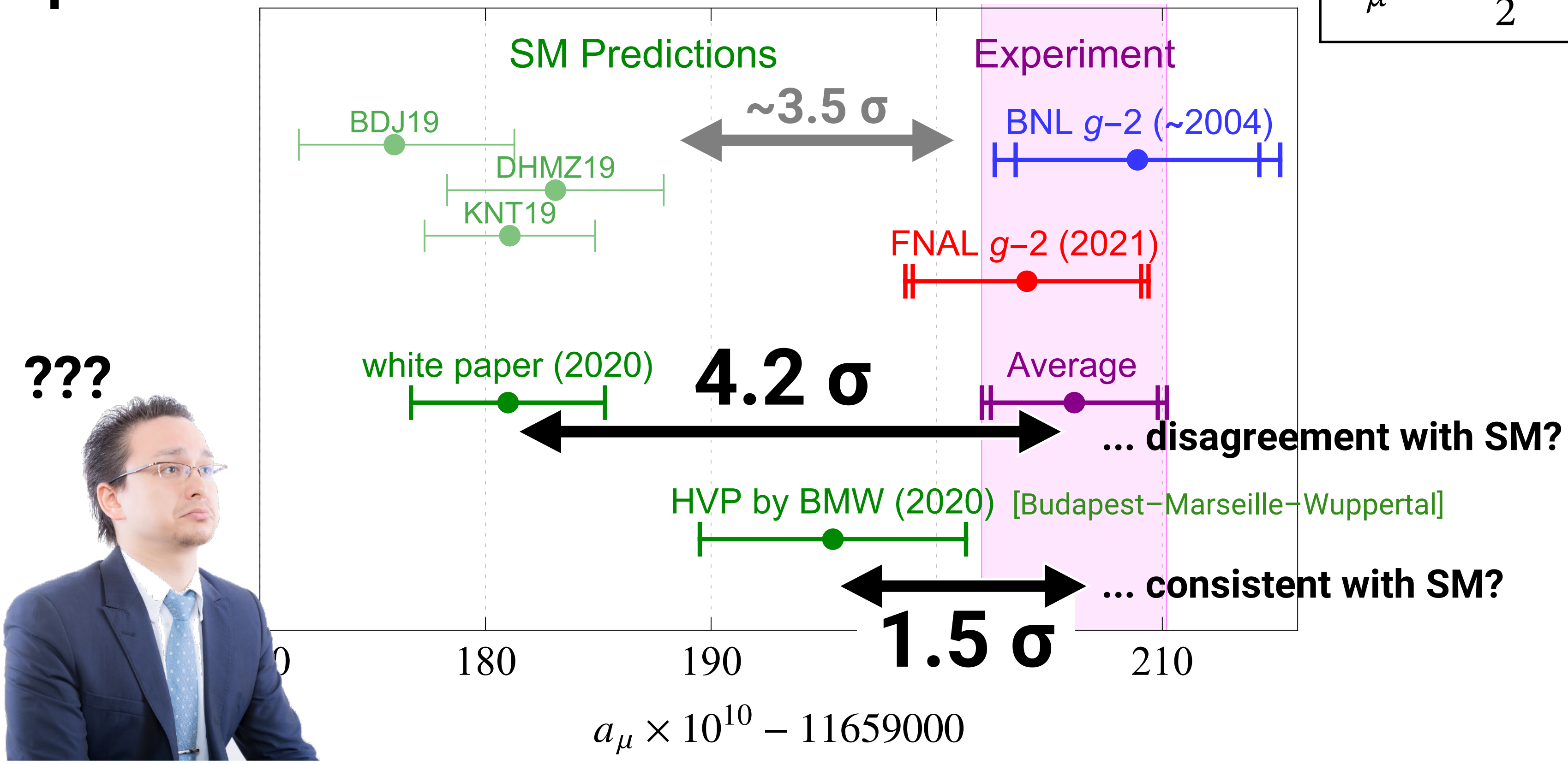
Image courtesy of pakutaso.com

Two "SM predictions" are reported. Which is correct? We will see in the near future...

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

■ 7 April 2021



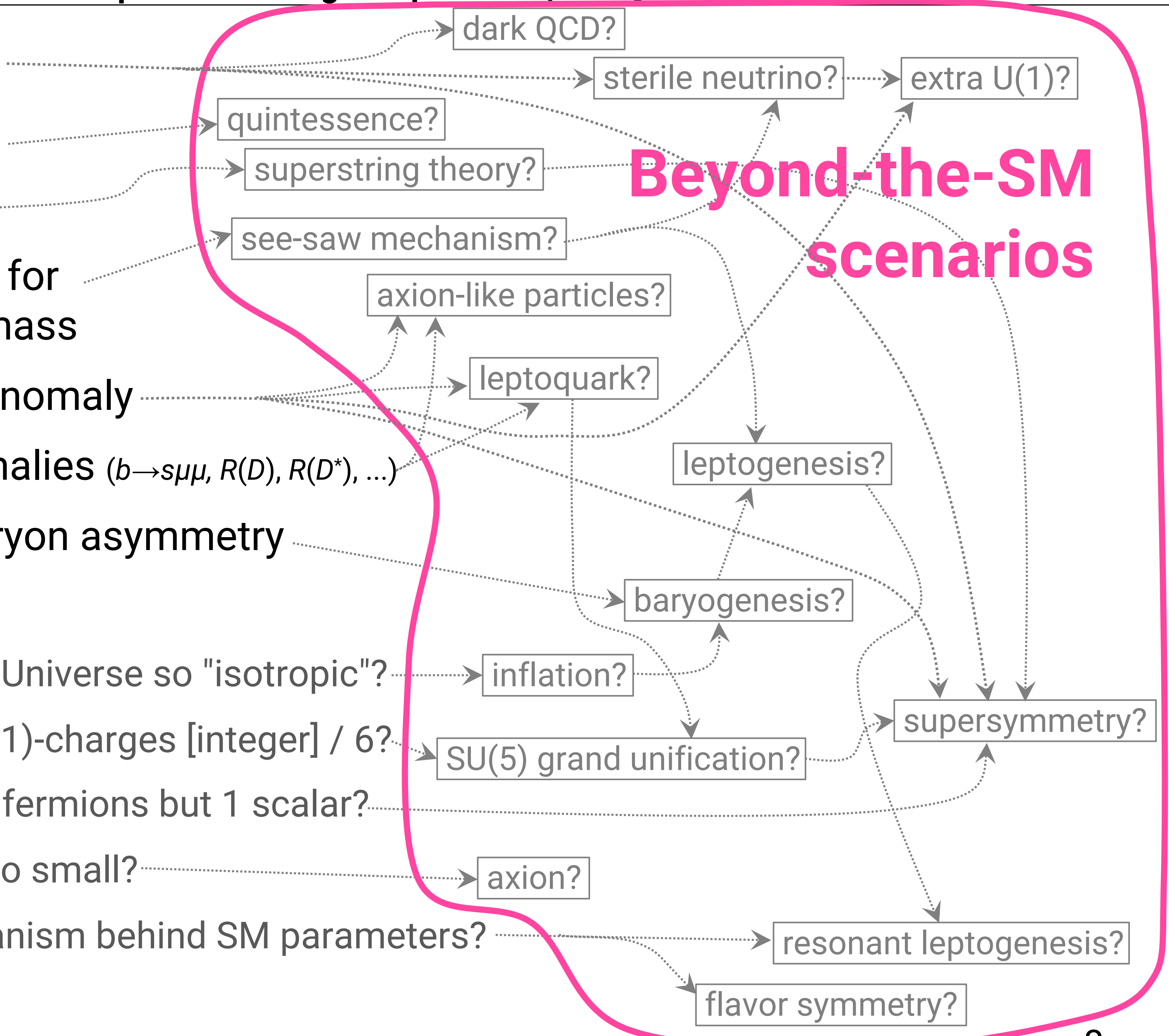
- ❖ Discussion ongoing over two SM predictions. [→ backup slides]
  - ▪ "Belle II" and "MUonE" experiments will give some hints.
- ❖ FNAL *g*−2 measurement is ongoing.

→ **A very hot topic in 2020s!**

Image courtesy of pakutaso.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 $\theta_{\rm QCD}$ so small?
  - Any mechanism behind SM parameters?



Beyond-the-SM scenarios

dark QCD?

sterile neutrino?

extra U(1)?

quintessence?

superstring theory?

see-saw mechanism?

axion-like particles?

leptoquark?

leptogenesis?

baryogenesis?

inflation?

supersymmetry?

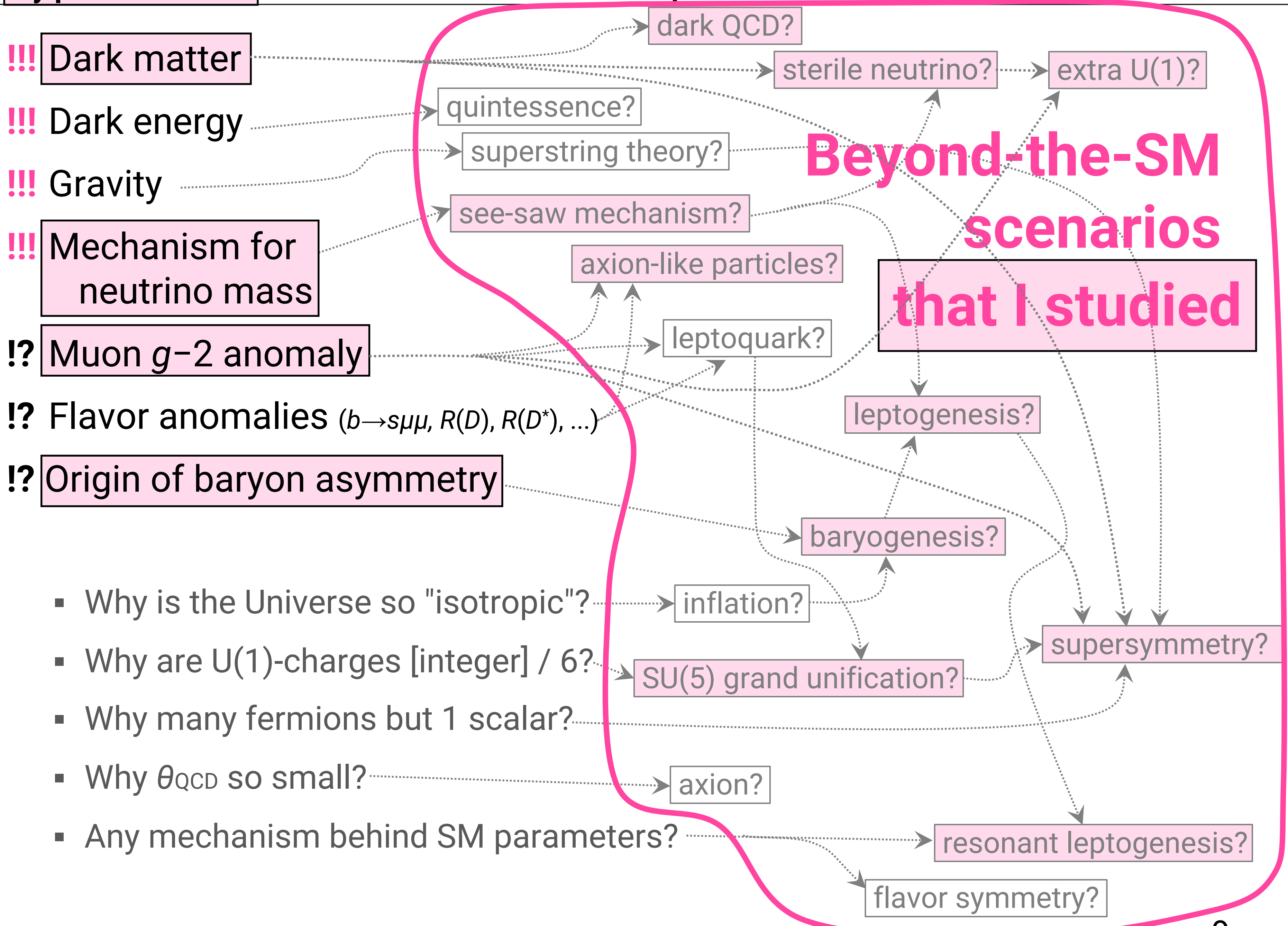
SU(5) grand unification?

axion?

resonant leptogenesis?

flavor symmetry?

My previous works have covered some of these topics.



!!! **Dark matter**

!!! Dark energy

!!! Gravity

!!! **Mechanism for neutrino mass**

!? **Muon $g-2$ anomaly**

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

!? **Origin of baryon asymmetry**

- Why is the Universe so "isotropic"?
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dark QCD?

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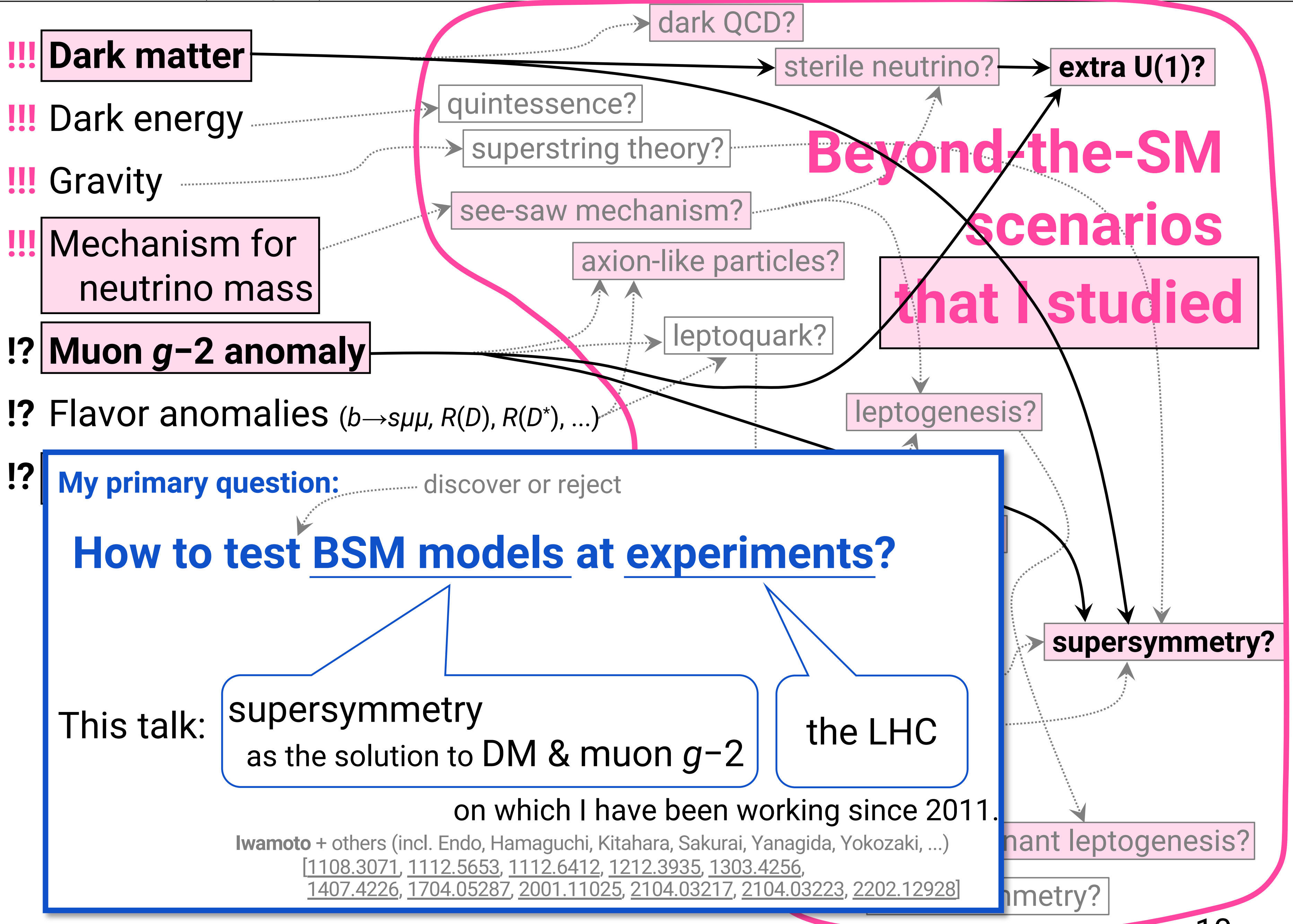
Beyond-the-SM scenarios that I studied

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



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leptogenesis?

supersymmetry?

nant leptogenesis?

mmetry?

Beyond-the-SM scenarios that I studied

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, Sakurai, Yanagida, Yokozaki, ...)
[1108.3071, 1112.5653, 1112.6412, 1212.3935, 1303.4256, 1407.4226, 1704.05287, 2001.11025, 2104.03217, 2104.03223, 2202.12928]

Theory has been introduced. Now the time for Experiments.

"How to test BSM models at experiments?"

1. Introduction
   - ✓ Standard Model
   - ✓ Muon $g-2$ anomaly: Needs to go Beyond the Standard Model
   - ➢ **"LHC"** : energy frontier of particle-physics experiments

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

3. Research plan
   - ➢ Energy frontier: LHC and more.
   - ➢ Intensity frontier: ILC, Belle II, and beam dump.

BSM scenarios = SM + new particle(s). Why are they "new?" Because Heavy or Elusive.

- $(g-2)_\mu$ → new particle(s) to give extra contribution to $(g-2)_\mu$.
- DM → a new particle for DM.

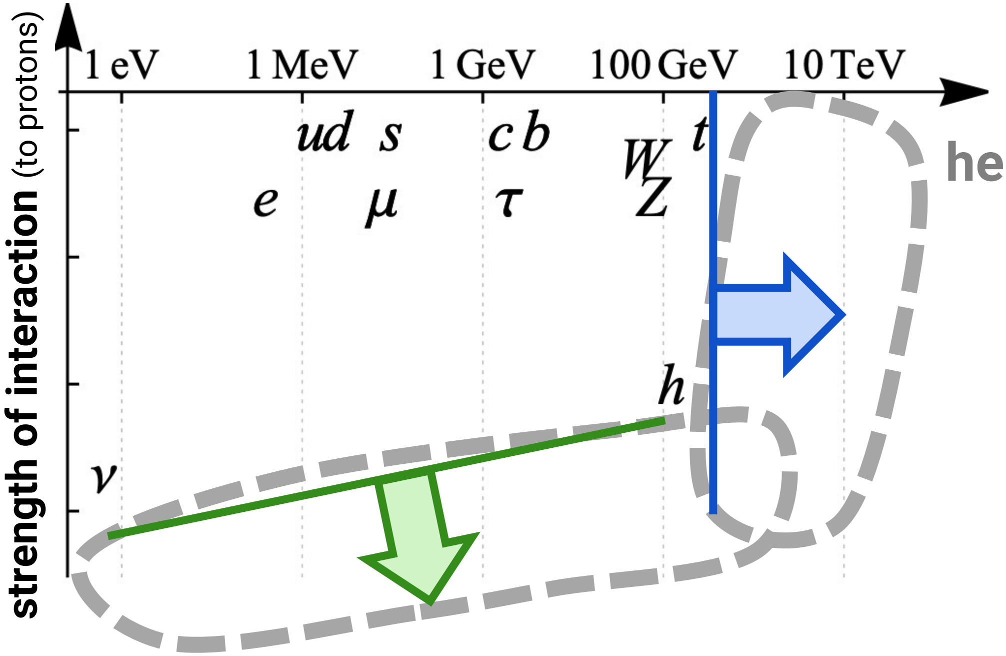
↳ **search targets at experiments**

(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"

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

weak and elusive? → We need more intensity!

"intensity frontier"

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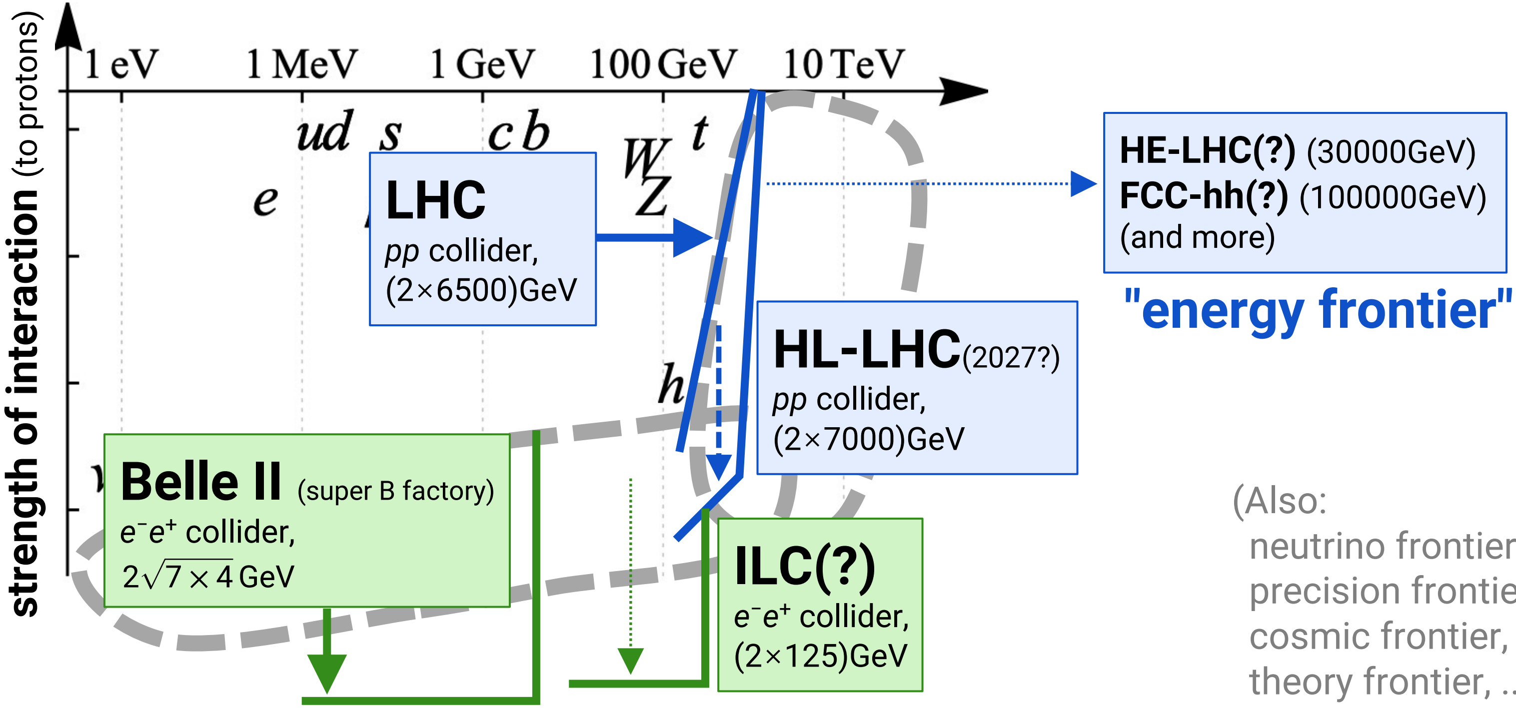


LHC
pp collider,
(2×6500)GeV

HE-LHC(?) (30000GeV)
FCC-hh(?) (100000GeV)
(and more)

HL-LHC(2027?)
pp collider,
(2×7000)GeV

Belle II (super B factory)
e⁻e⁺ collider,
$2\sqrt{7\times 4}$ GeV

ILC(?)
e⁻e⁺ collider,
(2×125)GeV

"energy frontier"

"intensity frontier"

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

The LHC is a proton-proton collider with several experiments. Its Run 3 is starting.

- Large Hadron Collider

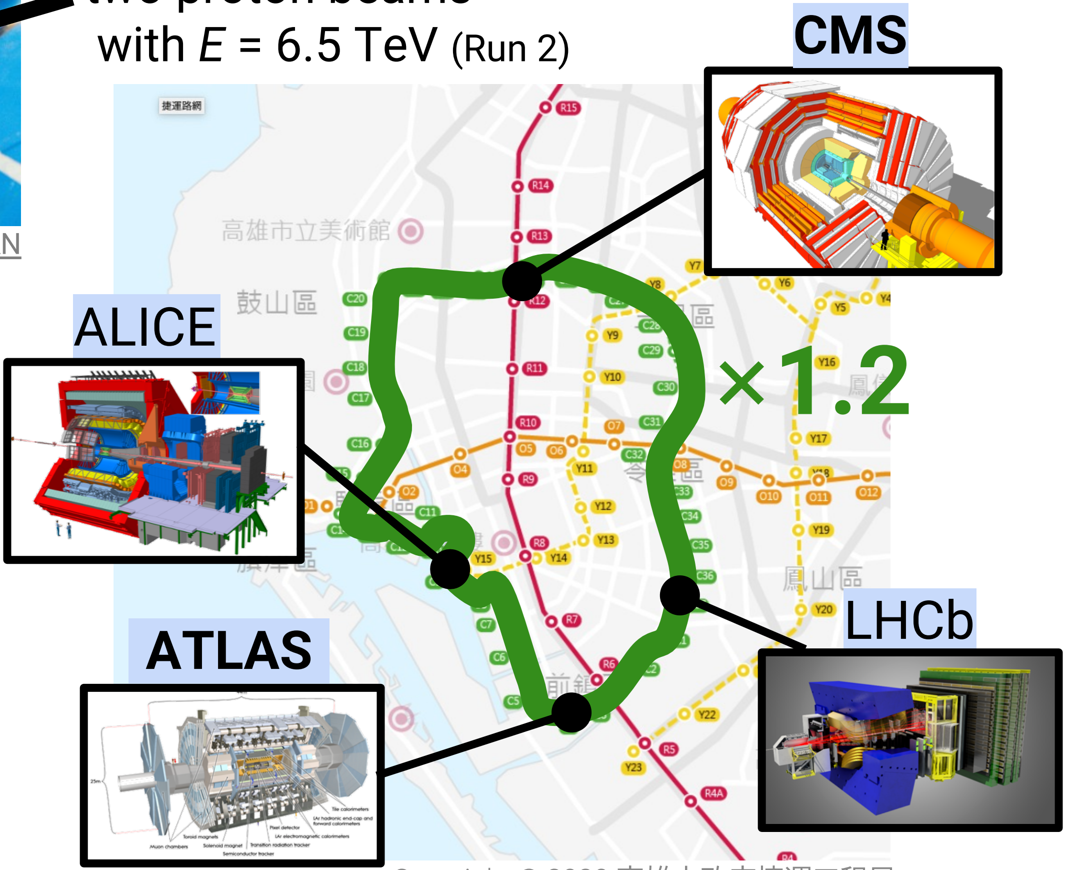
- Run 1 (2009–2013) ✓ (7–8 TeV)
- Run 2 (2015–2018) ✓ (13 TeV)
- Run 3 (2022–2024?) (13.6 TeV?)
- Run 4 +more? (2027?) [High Luminosity LHC] (14 TeV?)

©2014 CERN

two proton beams with E = 6.5 TeV (Run 2)

26659m ring ≃

©2021 Google, GeoBasis-De/BKG, Inst. Geogr. Nacional



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My previous researches: I like SUSY 🍣.

"How to test BSM models at experiments?"

1. Introduction

- ✓ Standard Model
- ✓ Muon $g-2$ anomaly: Needs to go Beyond the Standard Model
- ✓ "LHC" : energy frontier of particle-physics experiments

2. Supersymmetry (as the solution to **DM & muon *g*−2**) at the LHC

3. Research plan

- ➢ Energy frontier: LHC and more
- ➢ Intensity frontier: ILC, Belle II, and beam dump

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

超對稱 = **fermion** ⇔ **boson**

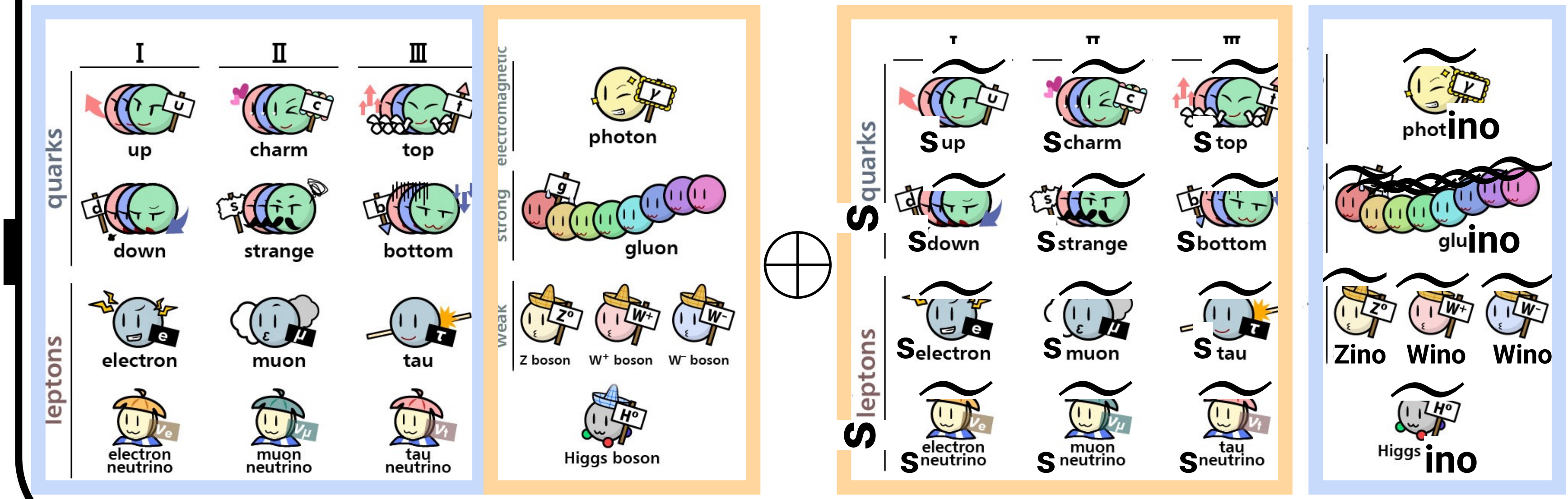
- quark ⇔ **s**quark
- lepton ⇔ **s**lepton
- higgs**ino** ⇔ higgs

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

(minimal) Supersymmetric Standard Model [MSSM]

Standard Model particles

SUSY partners (hypothetical particles)



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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.

recall:

try" SU(3)×SU(2)×U(1),

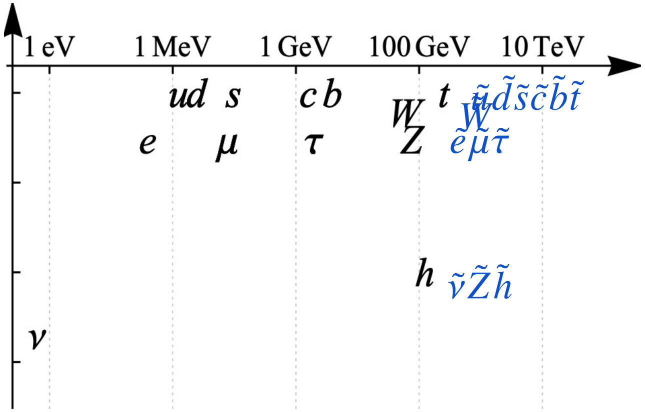
on *H*.

→U(1)

spontaneous symmetry breaking
induced by Higgs boson

Figure courtesy of HiggsTan.com

There are several reasons why I like SUSY.



Assume: SUSY particles at 100GeV−10TeV.

[1TeV = 1000GeV]

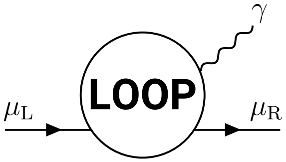
Why 100GeV−10 TeV?

- dark matter, → appendix
- grand unification, → appendix
- muon g−2.

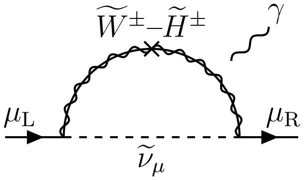
Lightest SUSY Particle can be **stable** (=**DM**).

~100GeV LSP with "freeze-out" can naturally explain why DM is 26%.

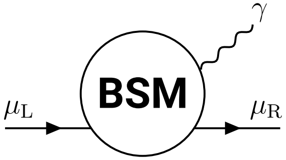
$$a_\mu = \frac{(g-2)_\mu}{2} =$$



e.g.,



$$\Delta a_\mu =$$



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

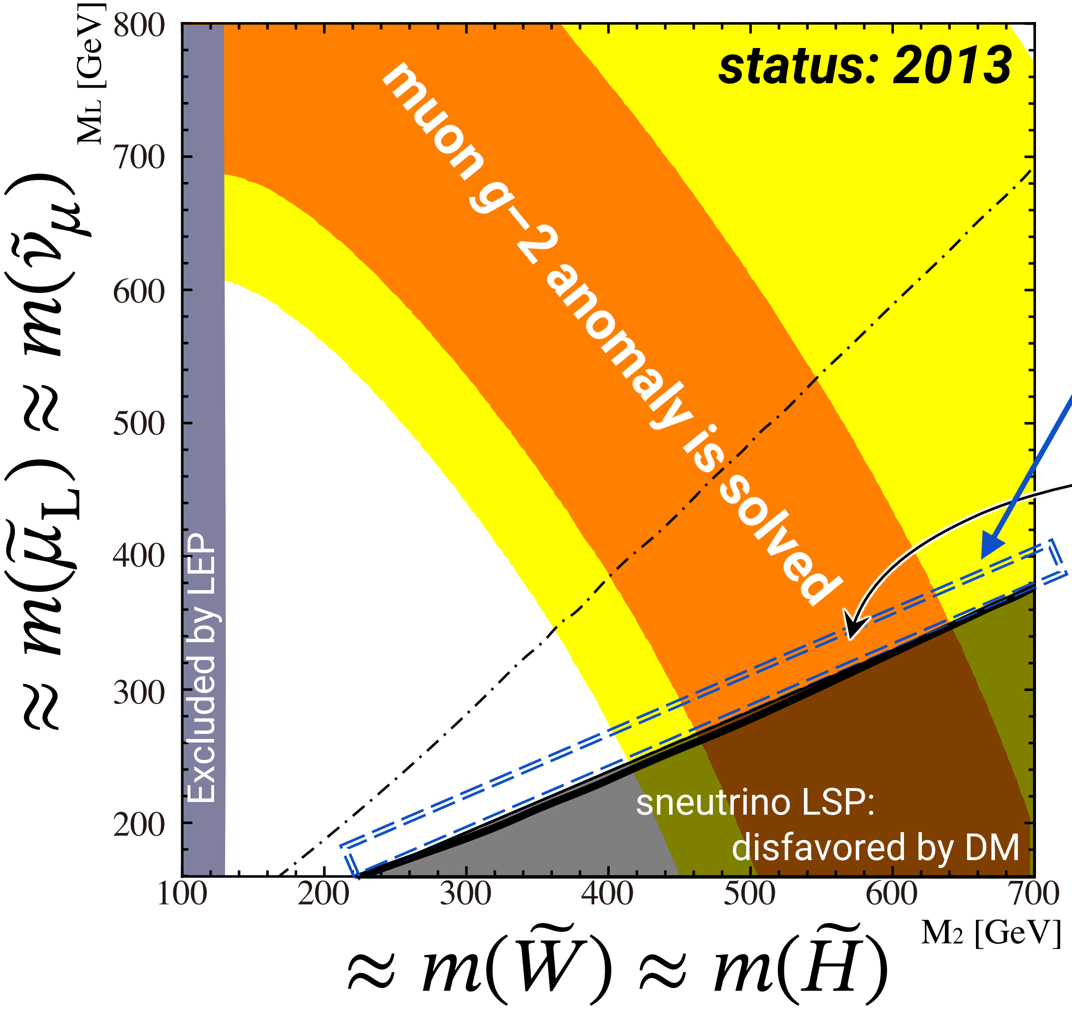
measurements

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

quantum field theory

An example of the motivated parameter space.

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



DM density is explained.
(bino−smuon coannihilation)

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

theory detail

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

$m_{\tilde E} \gg 1\,\mathrm{TeV}, \quad m(\mathrm{stau}) \gg 1\,\mathrm{TeV},$

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

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

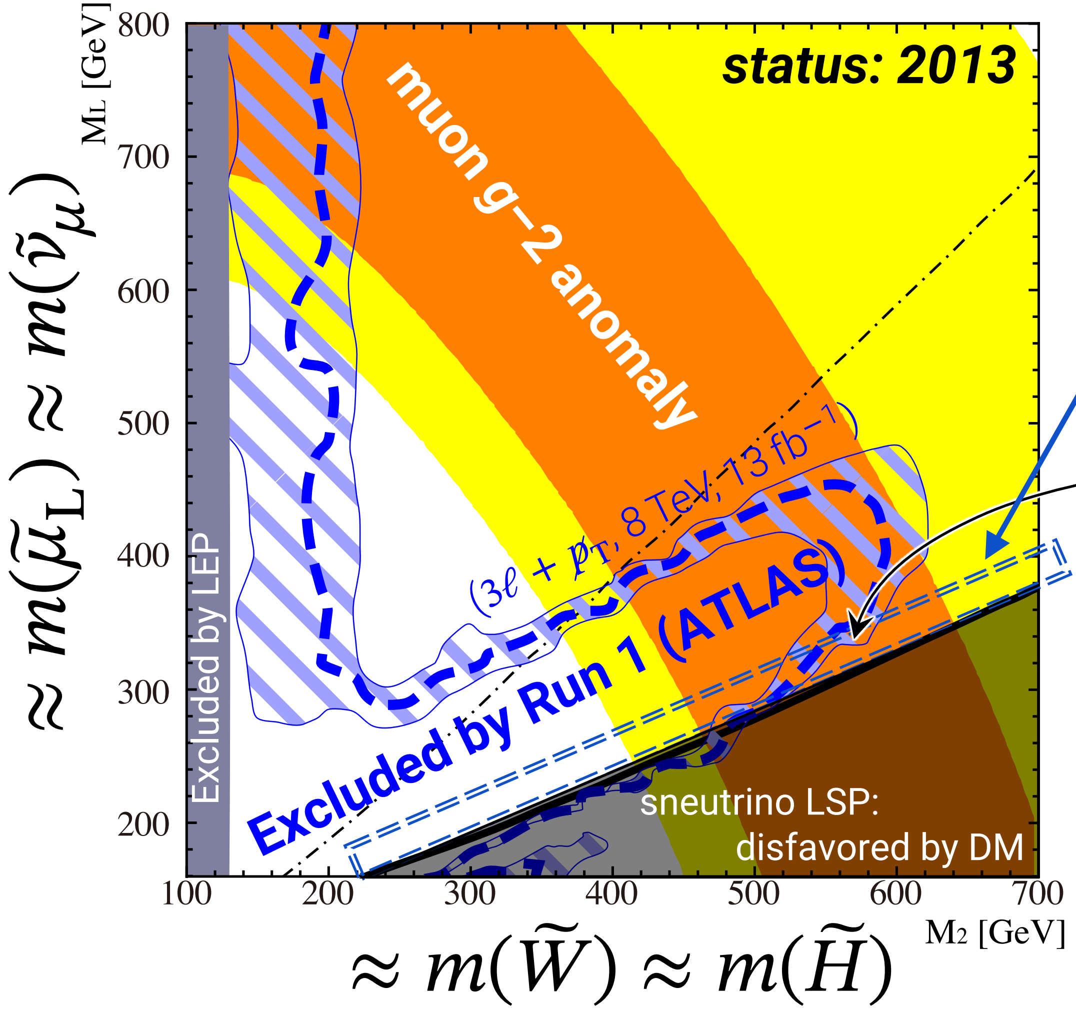
~~SUSY~~-parameters set at 500 GeV

"How can we explore this parameter space?"

→ Monte Carlo simulation (emulation of the LHC).

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

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



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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)

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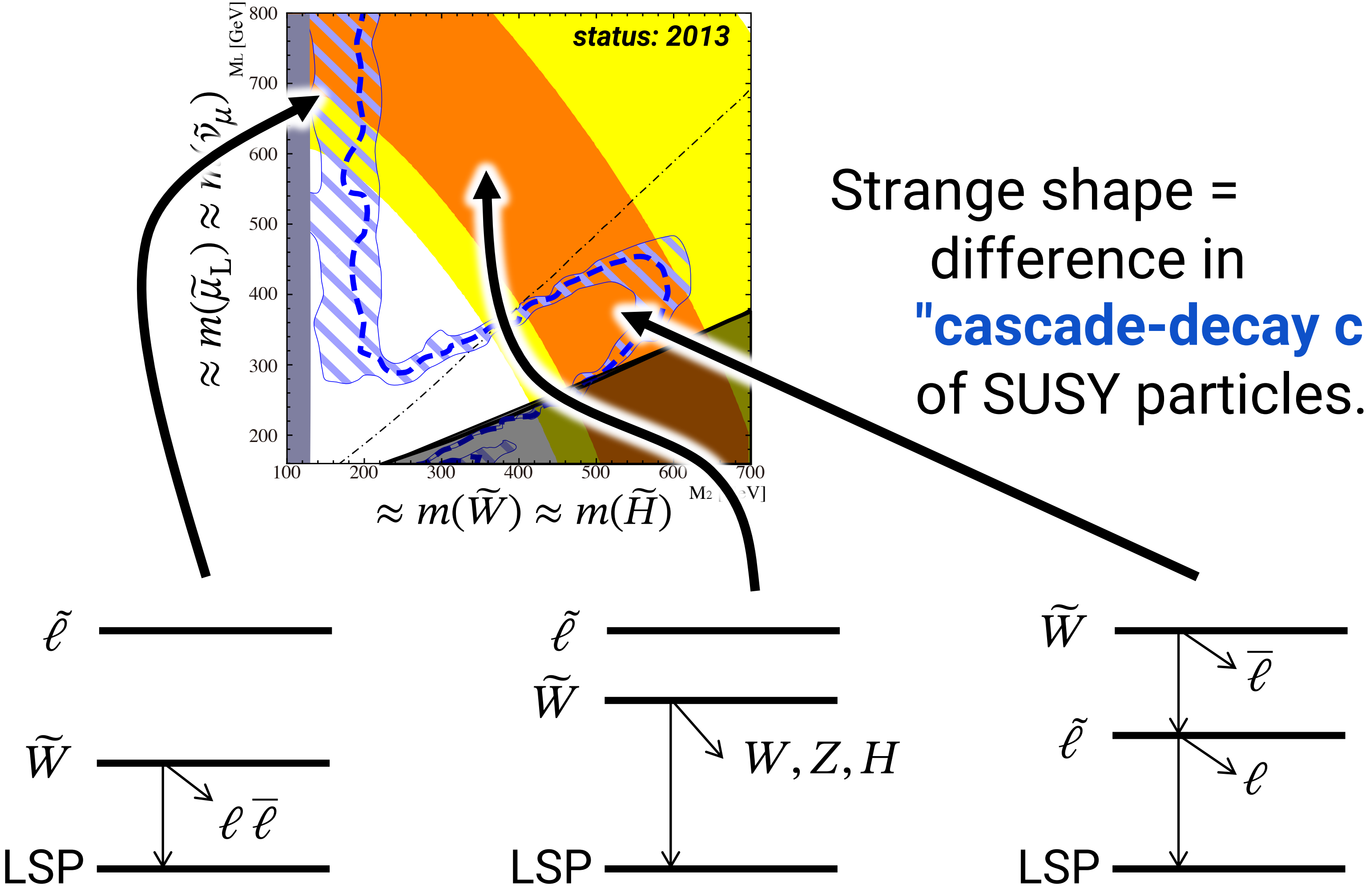
Endo, Hamaguchi, **Iwamoto**, Yoshinaga
[1303.4256]



Strange shape =
difference in
"cascade-decay chains"
of SUSY particles.

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

$$pp \to \widetilde{W}^+\widetilde{W}^0 \to W^+Z + \not{p}_T \text{ or } W^+H + \not{p}_T$$

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

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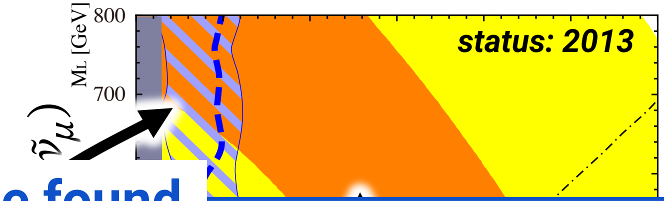
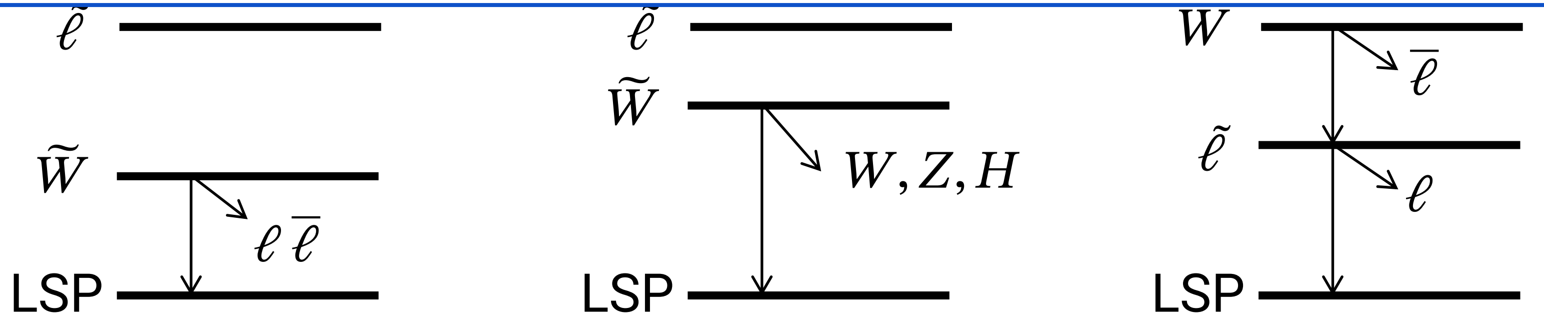


What we found

- LHC Run 1 already rejects some of "*g*−2 SUSY".
  - ➢ If SUSY provides $3\ell + \not{p}_{\mathrm{T}}$ signature, likely to be rejected.
- LHC Run 2 target would be "$WZ + \not{p}_{\mathrm{T}}$ and $WH + \not{p}_{\mathrm{T}}$" signature.

→ They did!
(with citing our work ☺)



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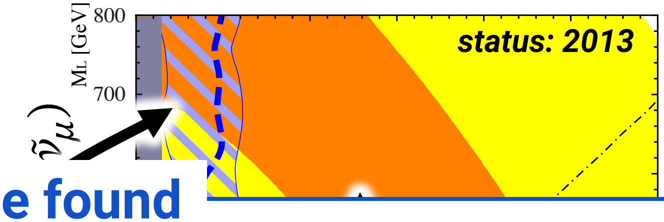

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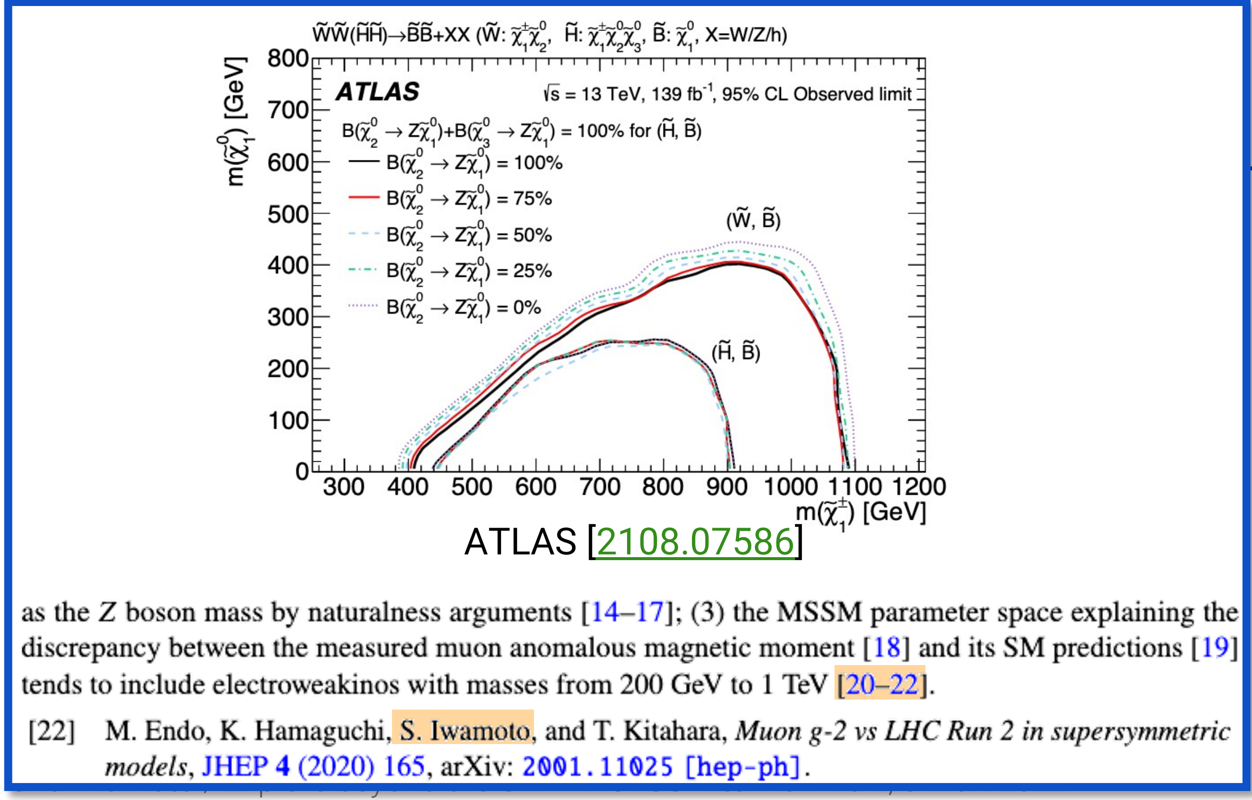
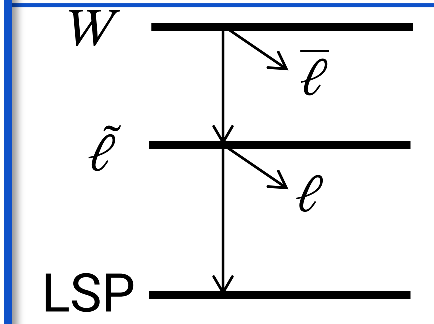


ATLAS [2108.07586]

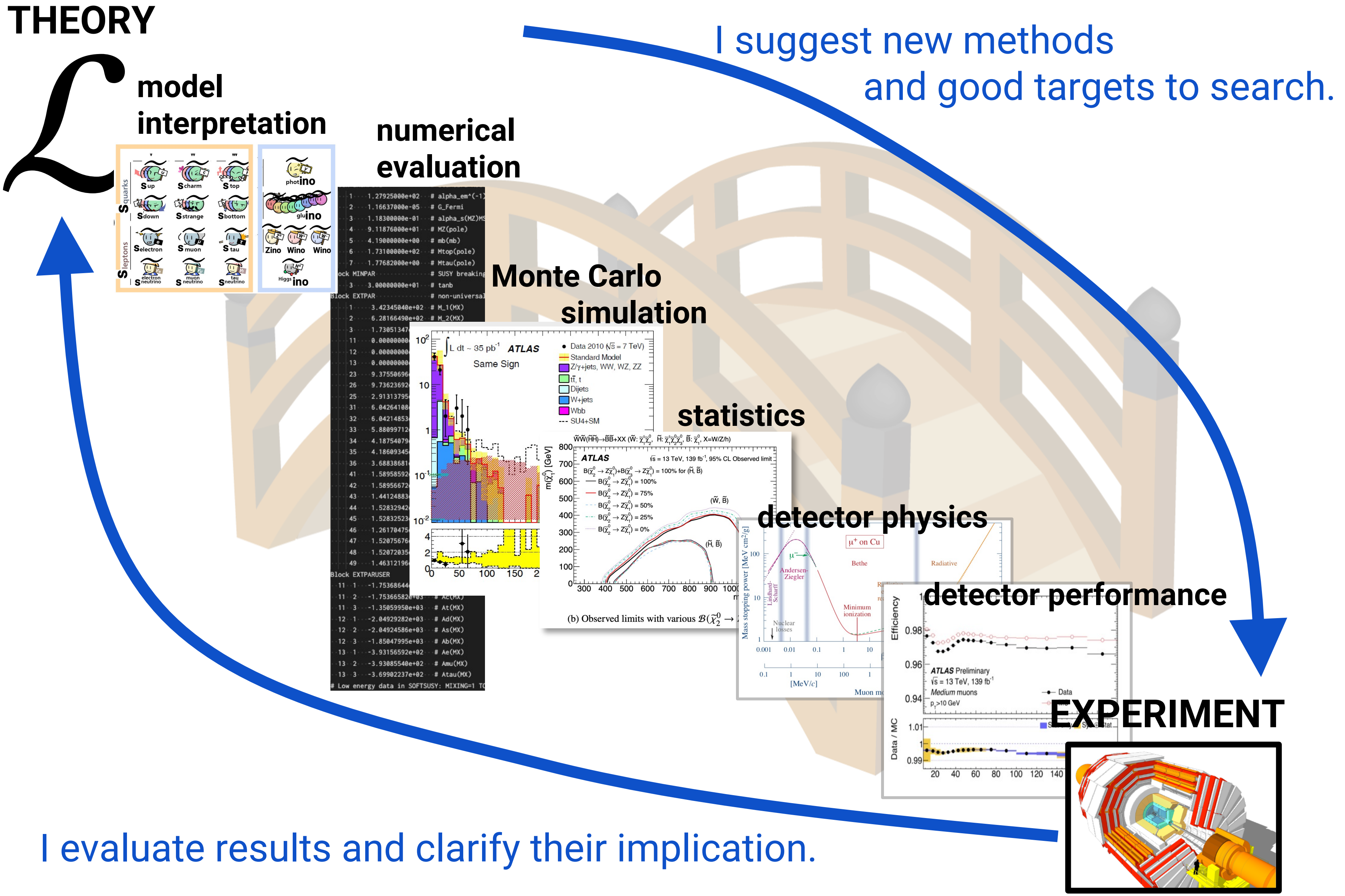
as the *Z* boson mass by naturalness arguments [14–17]; (3) the MSSM parameter space explaining the discrepancy between the measured muon anomalous magnetic moment [18] and its SM predictions [19] tends to include electroweakinos with masses from 200 GeV to 1 TeV [20–22].

[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].



$$pp \to \widetilde{W}^+\widetilde{W}^0$$
$$\to 3\ell + \not{p}_{\mathrm{T}}$$

I have worked as a **bilingual bridge** between theorists and experiment collaborations.



THEORY

EXPERIMENT

I suggest new methods
and good targets to search.

I evaluate results and clarify their implication.

model interpretation

numerical evaluation

Monte Carlo simulation

statistics

detector physics

detector performance

```
  1    1.27925000e+02   # alpha_em^(-1)
  2    1.16637000e-05   # G_Fermi
  3    1.18300000e-01   # alpha_s(MZ)MS
  4    9.11876000e+01   # MZ(pole)
  5    4.19000000e+00   # mb(mb)
  6    1.73100000e+02   # Mtop(pole)
  7    1.77682000e+00   # Mtau(pole)
ock MINPAR               # SUSY breaking
  3    3.00000000e+01   # tanb
Block EXTPAR             # non-universal
  1     3.42345040e+02  # M_1(MX)
  2     6.28166490e+02  # M_2(MX)
  3     1.73051347
  11    0.00000000
  12    0.00000000
  13    0.00000000
  23    9.37550696
  26    9.73623692
  25    2.91313795
  31    6.04264108
  32    6.04214853
  33    5.88099712
  34    4.18754079
  35    4.18609345
  36    3.68838681
  41    1.58958592
  42    1.58956672
  43    1.44124883
  44    1.52832942
  45    1.52832523
  46    1.26170475
  47    1.52075676
  48    1.52072035
  49    1.46312196
Block EXTPARUSER
 11  1   -1.75368644
 11  2   -1.75366582e+03   # Ac(MX)
 11  3   -1.35059950e+03   # At(MX)
 12  1   -2.04929282e+03   # Ad(MX)
 12  2   -2.04924586e+03   # As(MX)
 12  3   -1.85047995e+03   # Ab(MX)
 13  1   -3.93156592e+02   # Ae(MX)
 13  2   -3.93085540e+02   # Amu(MX)
 13  3   -3.69902237e+02   # Atau(MX)
# Low energy data in SOFTSUSY: MIXING=1 TO
```

Image courtesy of らいとりぃ and CERN

I have worked as a bilingual bridge between theorists and experiment collaborations.

THEORY

$\mathcal{L}$

model interpretation

numerical evaluation

I suggest new methods and good targets to search.

A few simple examples

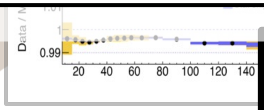
Researchers in ATLAS experiment

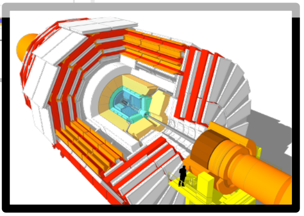
- Asai, Azuma, Endo, Hamaguchi, **Iwamoto** [1103.1881]
  "Kinked tracks" were useful (in LHC Run 1) to search for gauge-mediation SUSY.
- Feng, **Iwamoto**, Shadmi, Tarem [1505.02996]
  FCC-hh (planned 100TeV collider) is capable to explore SuperWIMP scenario, where the radiative energy loss of muons will be utilized for background rejection.

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

My effective supervision of student

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





I evaluate results and clarify their implication.

Image courtesy of らいとりぃ and CERN

My previous researches: I like SUSY 🍣.

"How to test BSM models at experiments?"

1. Introduction

- ✓ Standard Model
- ✓ Muon $g-2$ anomaly: Needs to go Beyond the Standard Model
- ✓ "LHC" : energy frontier of particle-physics experiments

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

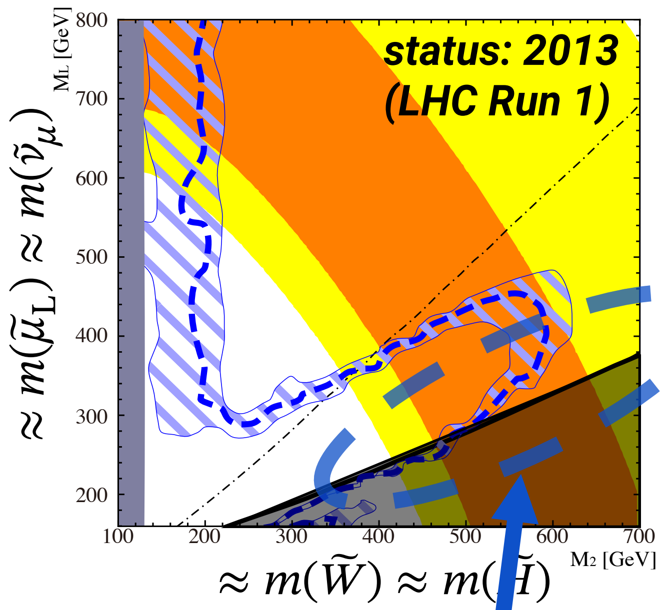
2*. (extra) **Five** simplified scenarios for DM & muon $g-2$

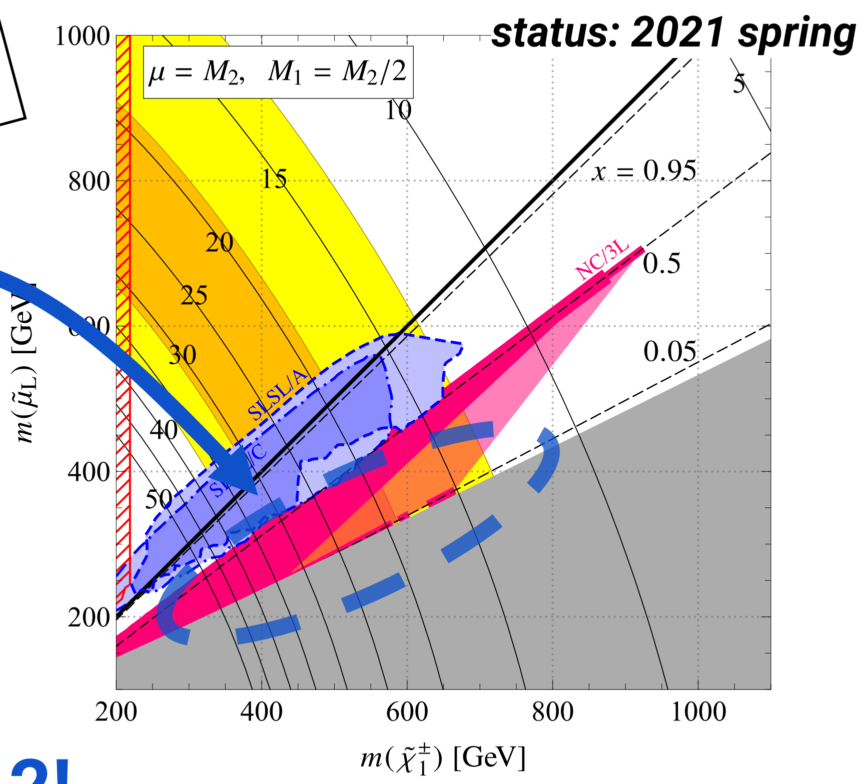
3. Research plan

- ➢ Energy frontier: LHC and more
- ➢ Intensity frontier: ILC, Belle II, and beam dump

The parameter space motivated by DM and $g\!-\!2$ are mostly excluded in this scenario.

Endo, Hamaguchi, **Iwamoto**, Yoshinaga
[1303.4256]
Endo, Hamaguchi, **Iwamoto**, Kitahara
[2001.11025] [2104.03217]



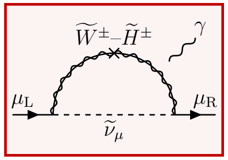


- ✓ coupling unification,
- ✓ Bino DM,
- ✓ muon $g\!-\!2$.

... but almost excluded by LHC Run 2!

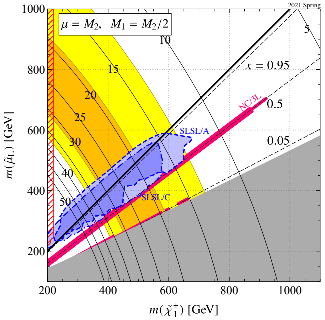
But there are four more simplified SUSY scenarios that solve DM & $g-2$.

WHL



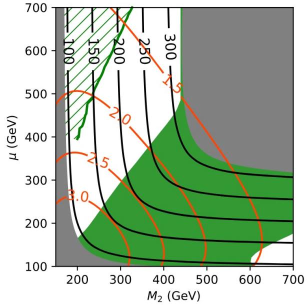
Bino-DM (coannhilation):

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

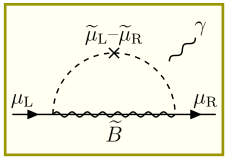


Wino / Higgsino-DM:

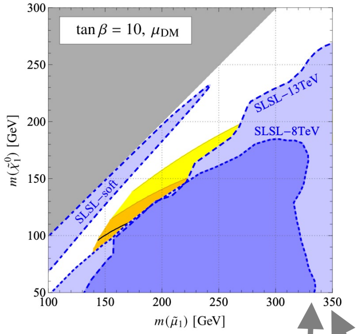
Iwamoto, Yanagida, Yokozaki [2104.03223]



BLR



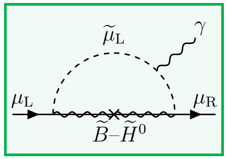
Bino-DM (coannhilation)



LHC

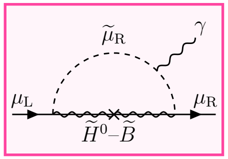
- $3\ell + \not{p}_T$
- $(H|Z)W + \not{p}_T$
- $2\ell + \not{p}_T$
- disappearing track
- $2\tau + \not{p}_T$

BHL



Bino-DM (coannhilation)

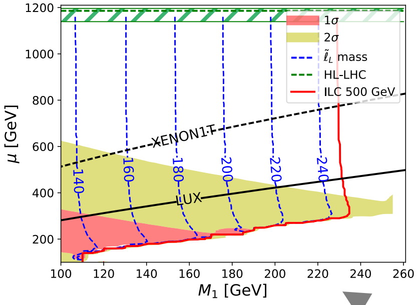
BHR

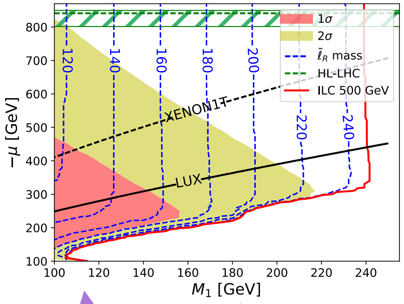


Bino-DM (coannhilation)

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

with old values; needs update





DM direct detection (XENON1T, LUX, ...)

ILC-500

I analyzed ✓collider experiments (LHC & ILC),
✓DM detection experiments,
✓DM cosmology for **all** the simplified scenarios.

Research plans (1) SUSY at the energy frontier.

✓completed : Simplified SUSY models for DM and muon $g-2$.

1. *"LHC will go on."*
   - watch LHC & update our "status plots"
   - contribute to future-collider planning

   to assist HEP-expm community.

2. DM or muon $g-2$?
3. More general models?

Somebody needs to do, and I can do.

(but less important than "and" scenario...)

with **ATLAS researchers in Japan**,
CMS researchers in Taiwan,
and **theorists** *(in Taiwan: NTU, NCTS, ...)*.

(**current** or *potential/intended* collaborators)

My previous researches: I like SUSY 🍣.

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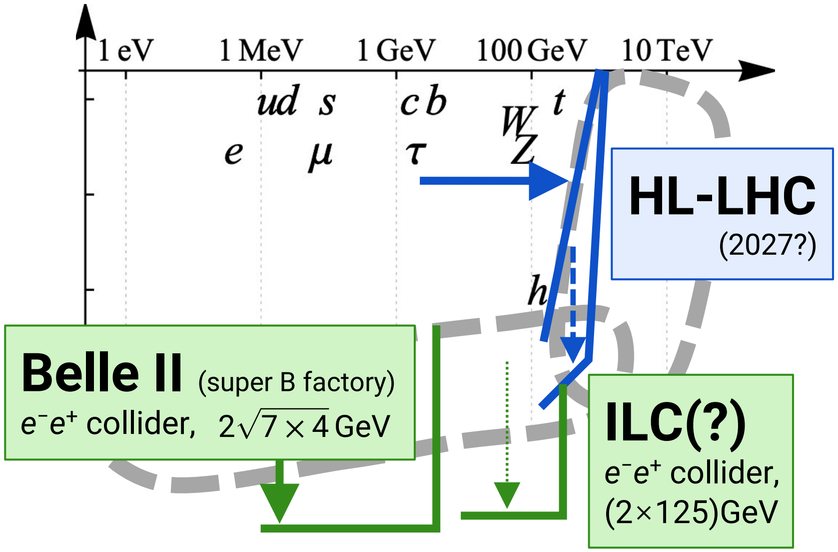
2*. (extra) Five simplified scenarios for DM & muon $g-2$

3. Research plan

- ✓ Energy frontier: LHC and more
- ➢ **Intensity frontier:** ILC, Belle II, and beam dump

I have started working around the intensity frontier.

■ BSM at intensity frontier



Hypotheses with sub-GeV new particles:

- ❖ axion-like particles
  [→ flavor anomaly, $g-2$]
- ❖ extra U(1) symmetry
  [→ DM, $g-2$, ν mass]
- ❖ extra neutrinos
  [→ DM, ν mass]
- ❖ ...

■ Recent works

- ➢ proved that *"SM + extra U(1) + extra 3 lepton + extra scalar-boson"* can explain the current DM density (26%).

  (cosmology × intensity frontier) **Iwamoto**, Seller, Trócsányi [2104.11248]

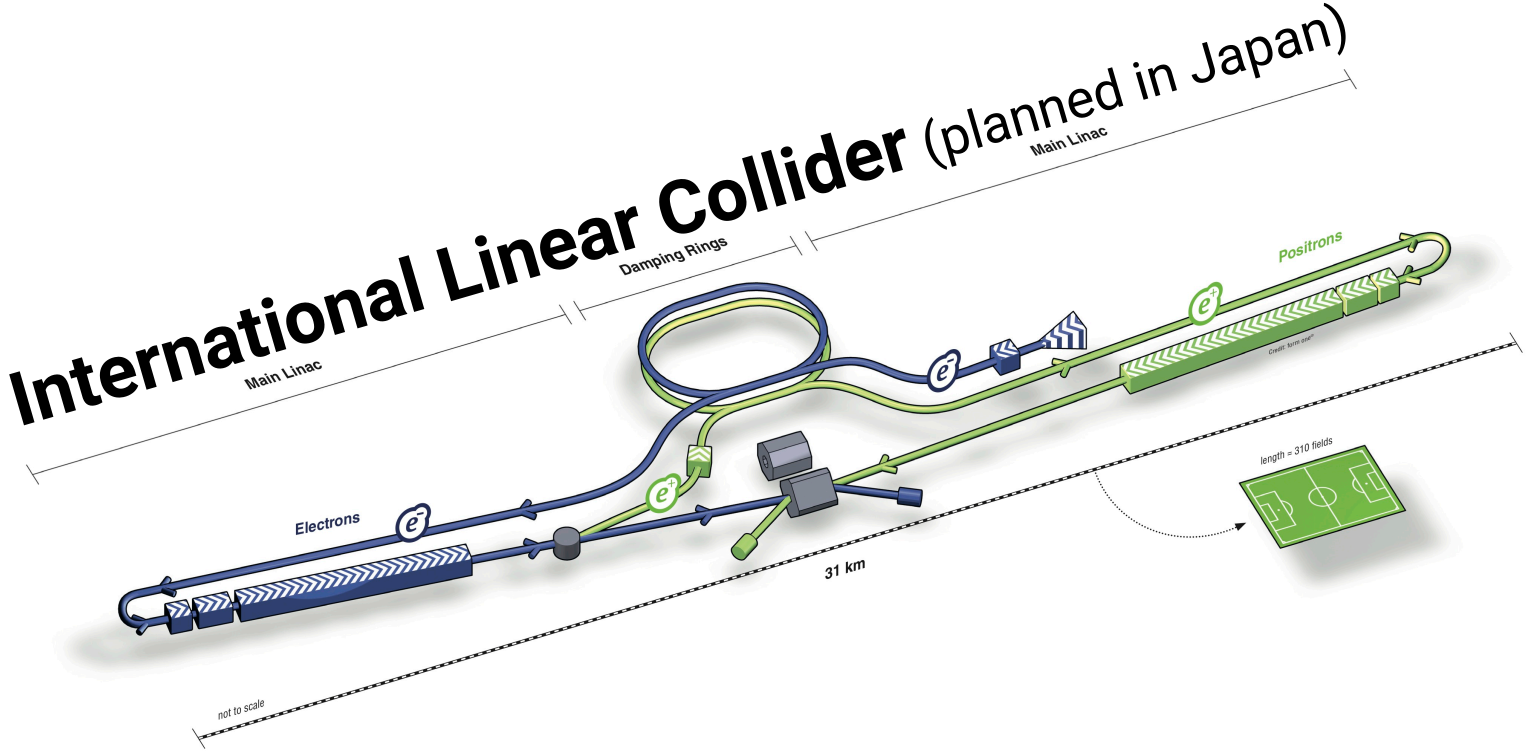
  My effective supervision of student

- ➢ analyzed **feasibility of ILC positron beam dump** experiment.

  (contribution to planning in intensity frontier) Asai, **Iwamoto**, Sakaki, Ueda [2105.13768]

We analyzed the potential of ILC positron beam-dump experiment.

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

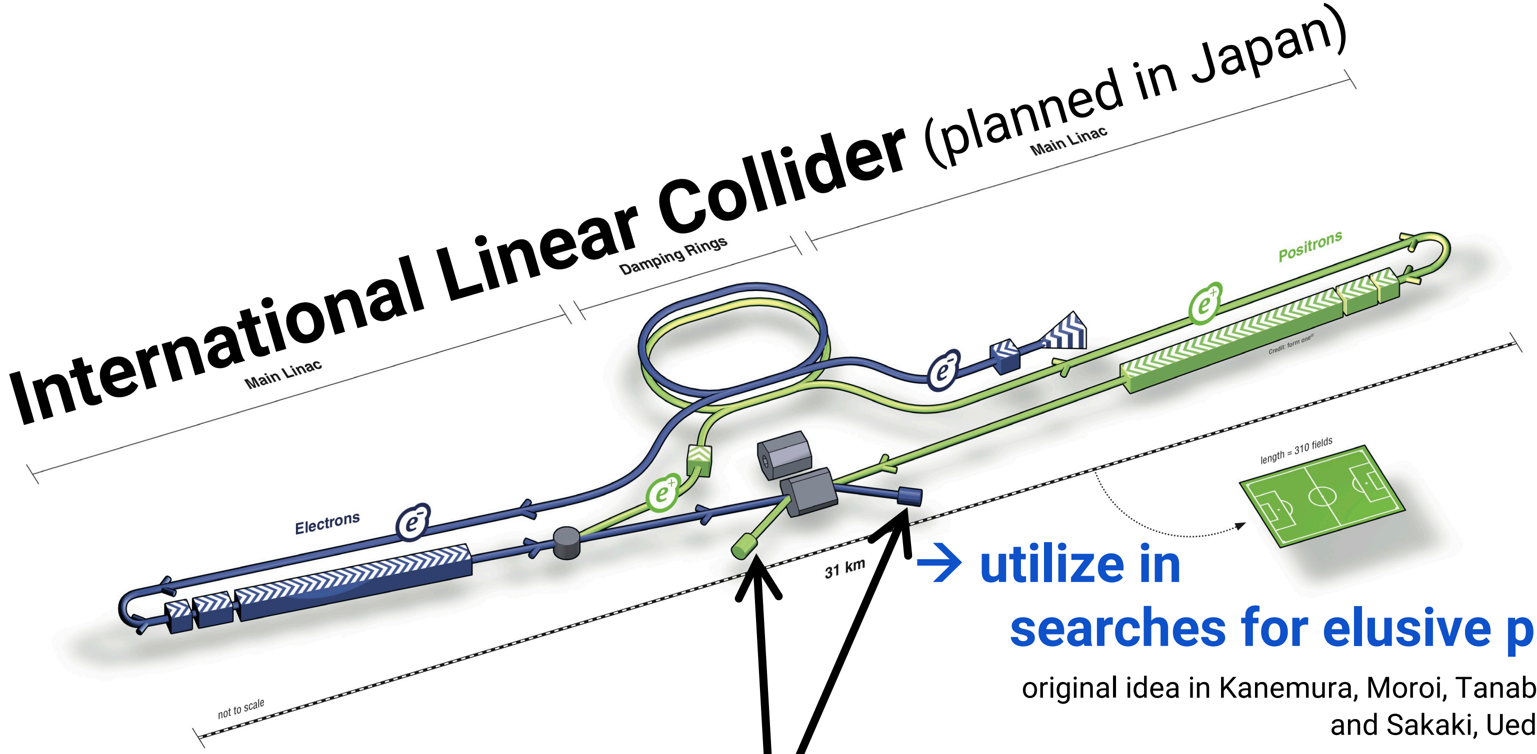


International Linear Collider (planned in Japan)

Image courtesy of ILC News Line

We analyzed the potential of ILC positron beam-dump experiment.

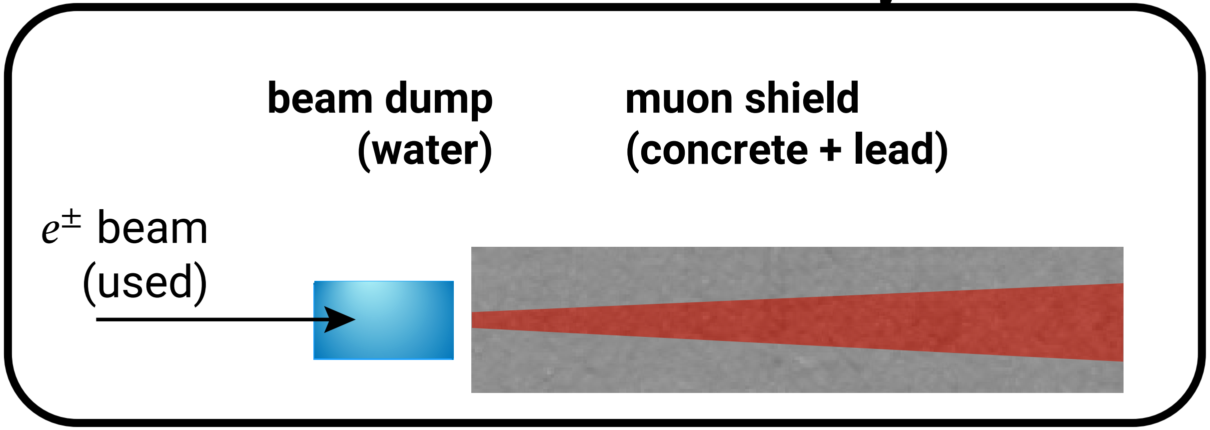
Asai, **Iwamoto**, Sakaki, Ueda [2105.13768]



International Linear Collider (planned in Japan)

→ **utilize in searches for elusive particles!**

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



beam dump (water)

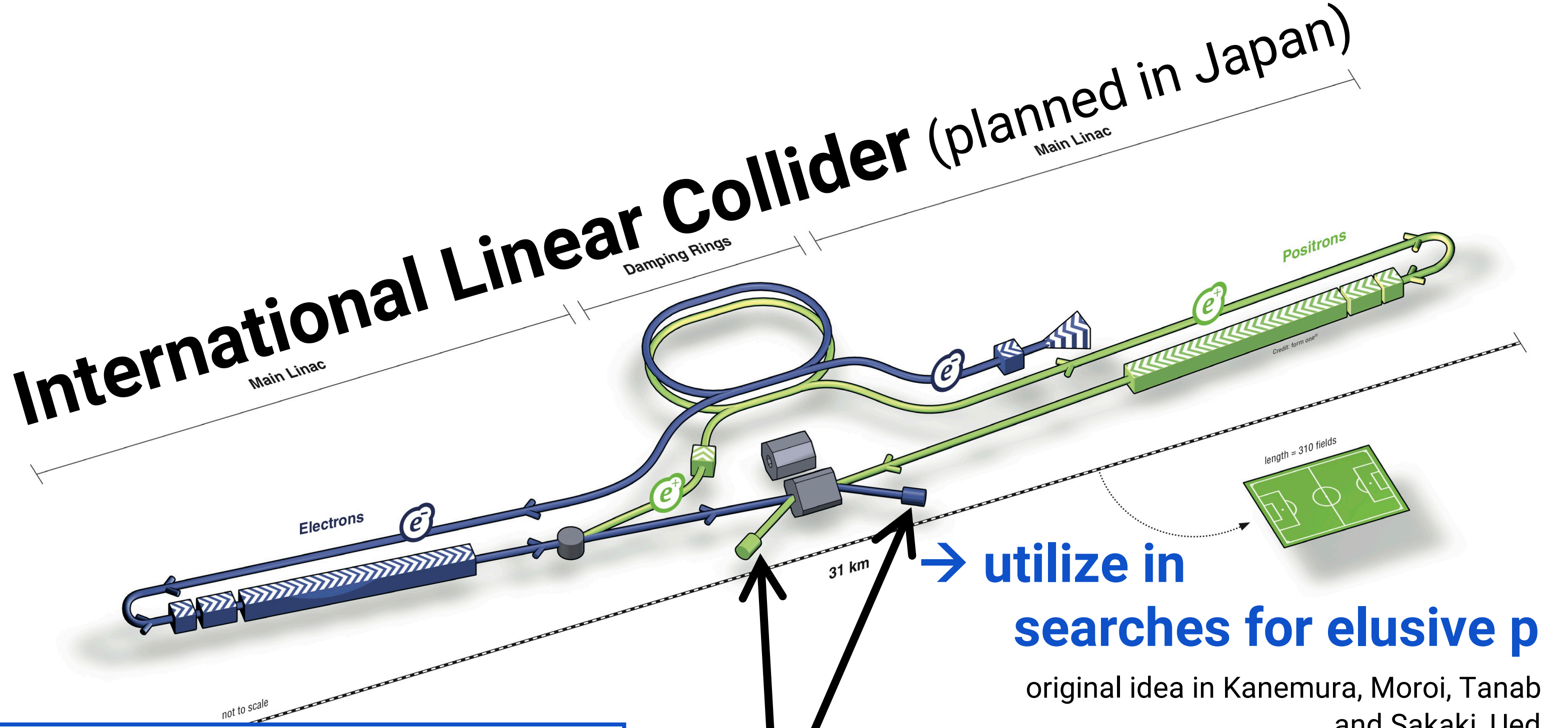
muon shield (concrete + lead)

$e^{\pm}$ beam (used)

Image courtesy of ILC News Line

We analyzed the potential of ILC positron beam-dump experiment.

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



→ utilize in searches for elusive particles!

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.)

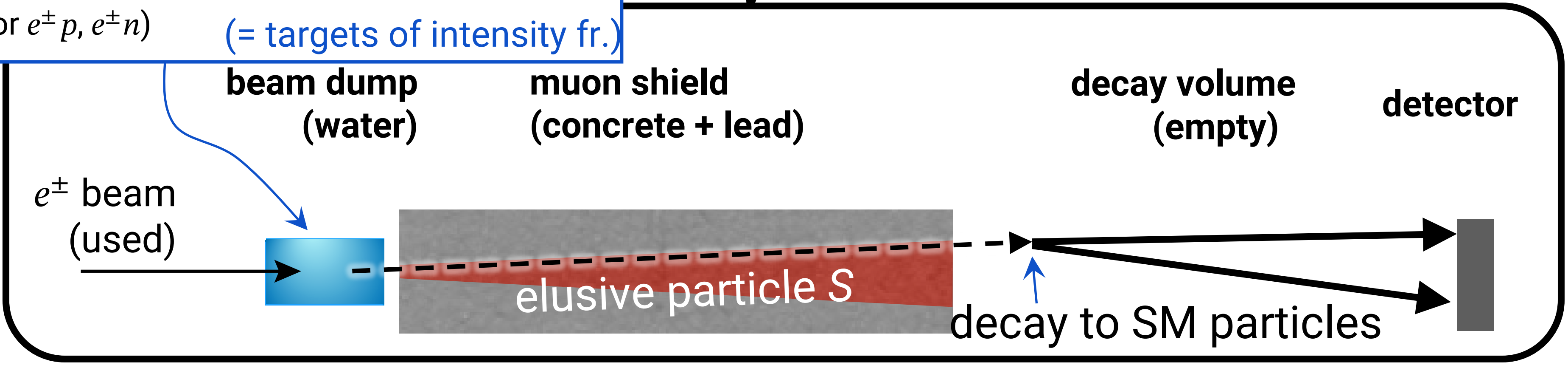


Image courtesy of ILC News Line

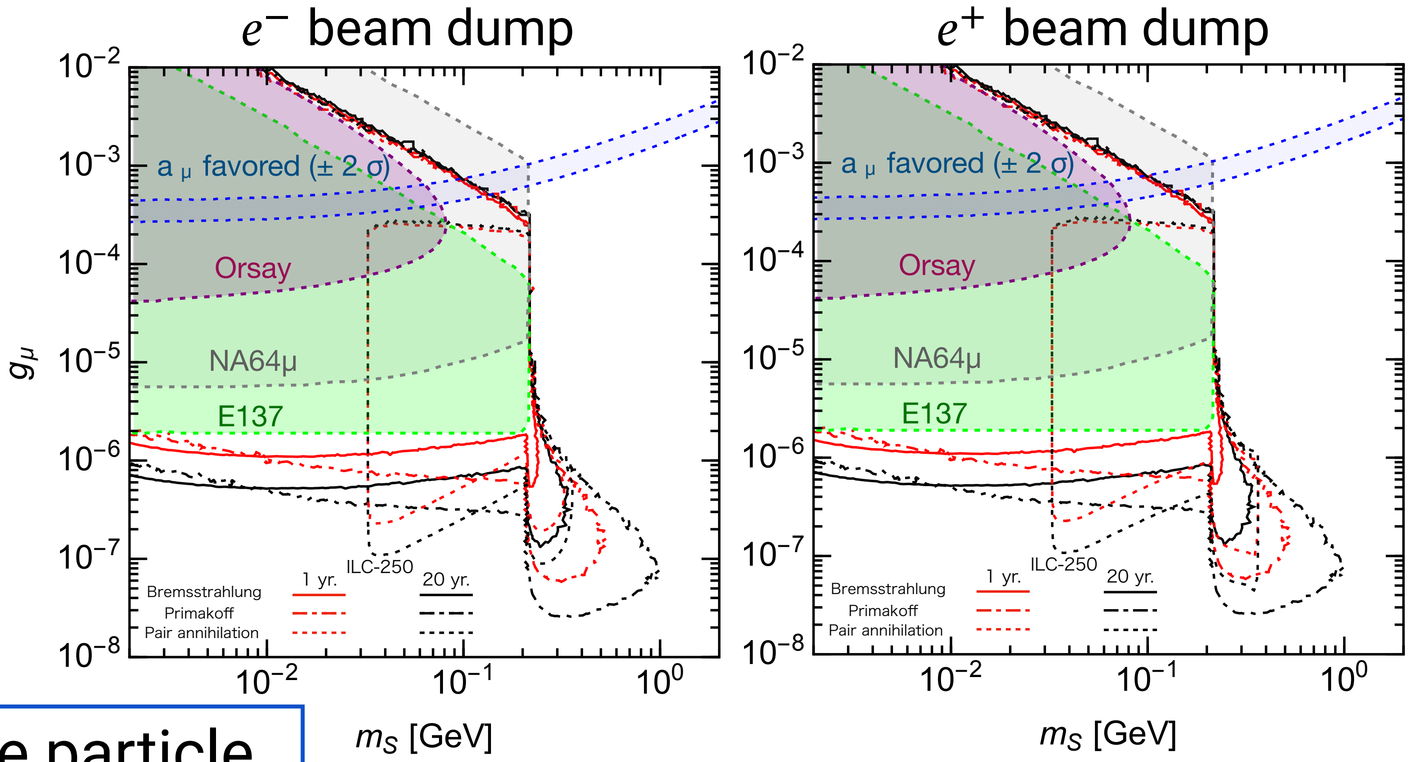
We found that positron beam dump is (only a bit) better than electron beam dump.

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

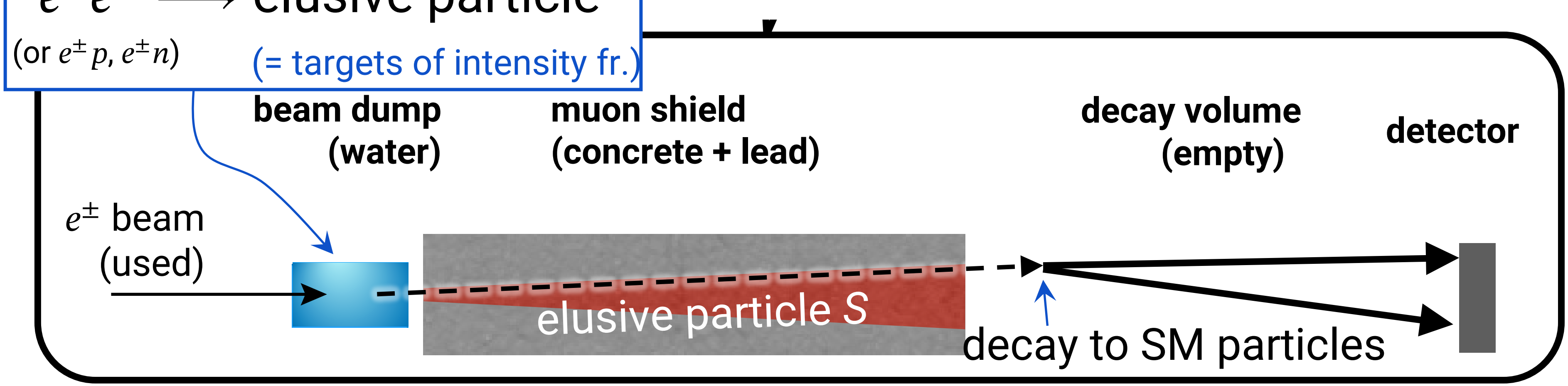
benchmark model:
extra singlet S

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

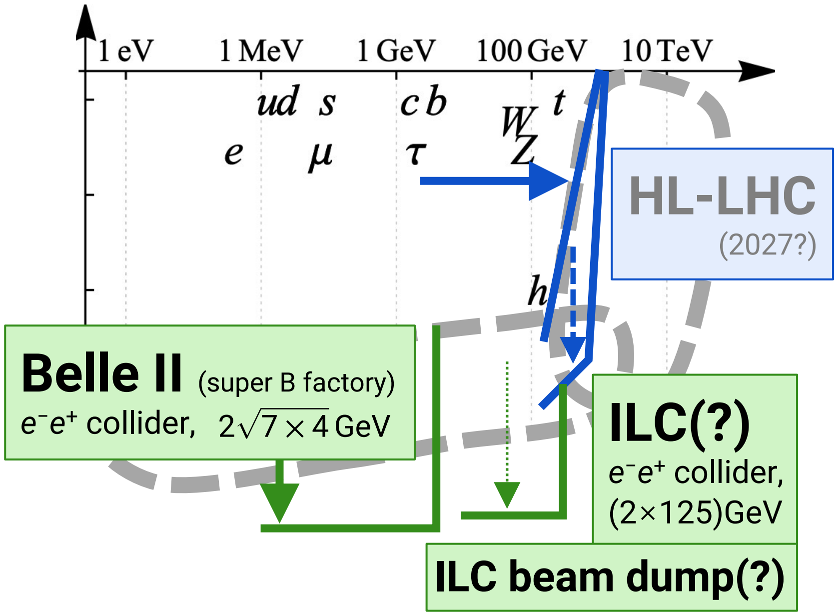
$$\left(\frac{g_e}{m_e} = \frac{g_\mu}{m_\mu} = \frac{g_\tau}{m_\tau}\right)$$



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



Research plans (2) BSM searches at the intensity frontier.



HL-LHC
(2027?)

Belle II (super B factory)
e^-e^+ collider, $2\sqrt{7 \times 4}\,\text{GeV}$

ILC(?)
e^-e^+ collider,
(2×125)GeV

ILC beam dump(?)

Hypotheses with sub-GeV new particles:

- axion-like particles
  [→ flavor anomaly, $g-2$]
- extra U(1) symmetry
  [→ DM, $g-2$, ν mass]
- extra neutrinos
  [→ DM, ν mass]
- …

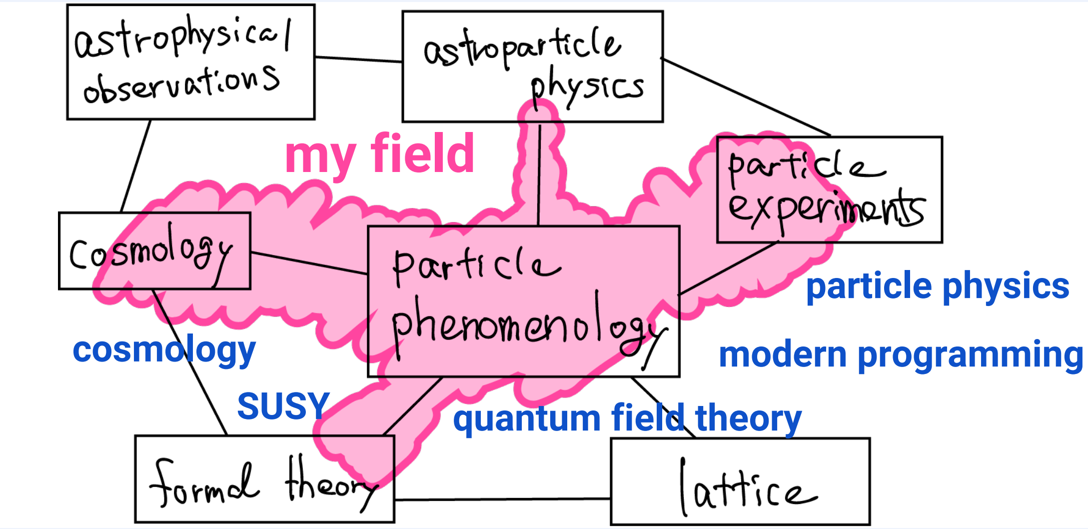
■ My research orientation

- sub-GeV BSM search @ Belle II
  ("theory-side assistant")
- Contribute to ILC planning

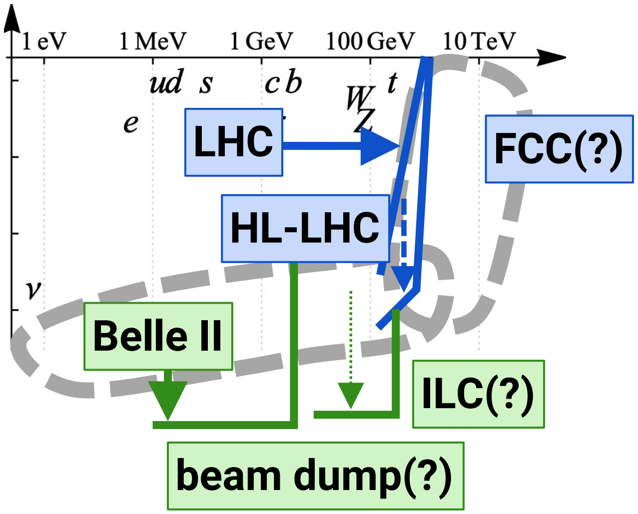
with **ILC researcher in Japan**/*Taiwan*,
Belle II researcher in Japan/Taiwan,
theorists,
and *graduate students in NSYSU*.

(**current** or *potential/intended* collaborators)

Conclusion: "Big Picture" and Plans



(future topics)



(**current** or *potential/intended* collaborators)

- **Energy frontier**
  - ➢ SUSY@LHC & FCC (Europe)

    "theory-side assistant" for LHC people

with **ATLAS researchers in Japan**,
CMS researchers in Taiwan,
and **theorists** *(in Taiwan: NTU, NCTS, ...)*.

- **Intensity frontier**
  - ➢ sub-GeV BSM search @ Belle II

    ("theory-side assistant")
  - ➢ Contribute to ILC planning

with **ILC researcher in Japan**/*Taiwan*,
Belle II researcher in Japan/Taiwan,
theorists,
and *graduate students in NSYSU*.

- **Open-source tools** for particle physics

  (calculator, data handling, statistics, ...)

with *students in NSYSU*.
https://github.com/misho104
https://misho104.github.io/FeynLecture/

Extra 0) More on $g-2$

Derivation of lepton anomalous magnetic moment

($Q = -1$ for electron/muon)

- Quantum Mechanics $g = 2$

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

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

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

$$\mathcal{L}_{\mathrm{QED}} = \overline{\psi}(\mathrm{i}\not{D} - m)\psi \supset -Q|e|\overline{\psi}\not{A}\psi$$

$$\xrightarrow{\text{equations of motion (Gordon decomposition)}} \frac{-\mathrm{i}Q|e|A^\mu}{2m}\left(\overline{\psi}\partial_\mu\psi - (\partial_\mu\overline{\psi})\psi\right) - \underline{\frac{Q|e|}{2m}A_\mu\partial_\nu(\overline{\psi}\sigma^{\mu\nu}\psi)}$$

$$= \frac{-Q|e|}{4m}F_{\mu\nu}\overline{\psi}\sigma^{\mu\nu}\psi$$

$$\downarrow$$

$$\frac{Q|e|}{2m}2\boldsymbol{S}\cdot\boldsymbol{B}$$

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

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

- Quantum corrections

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

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

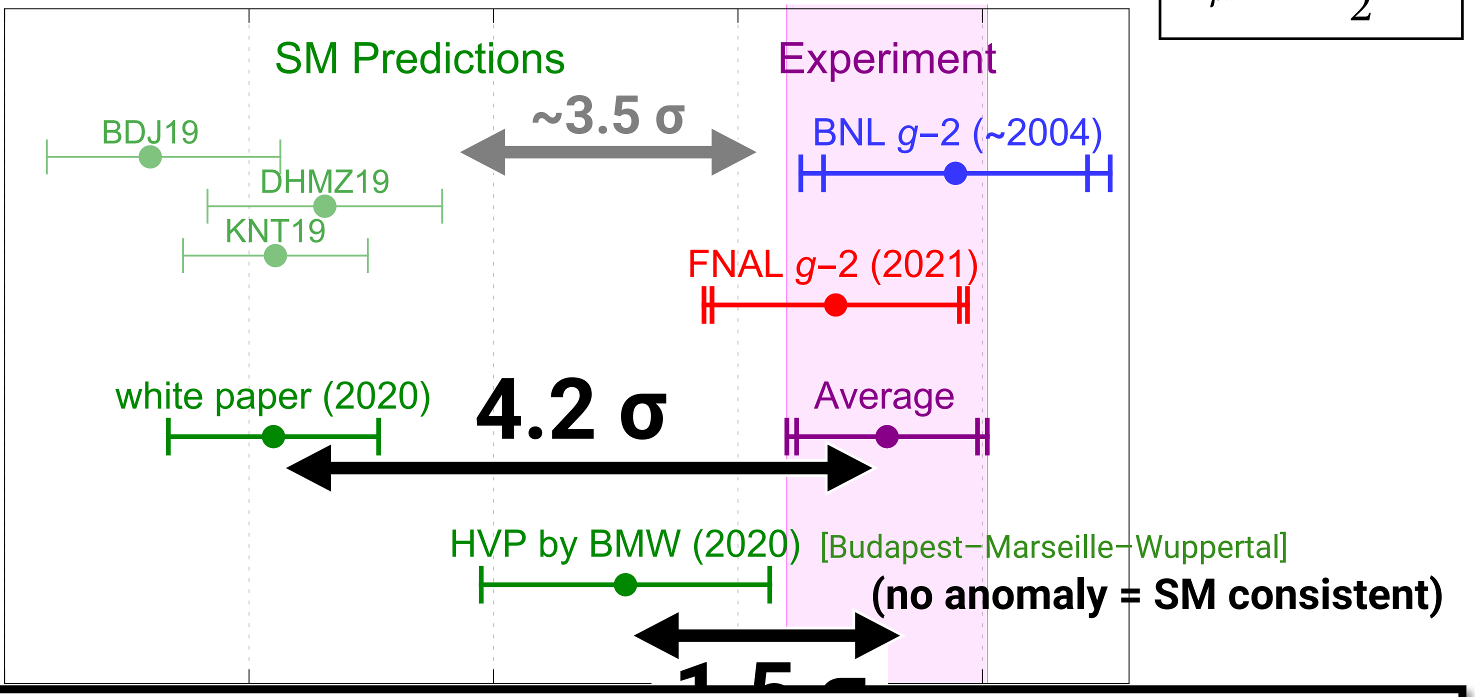
$$\to \frac{\sigma^{\mu\nu}(-\partial_\nu A_\mu)}{2m} = \frac{\sigma^{\mu\nu}F_{\mu\nu}}{4m} \sim -\frac{2\boldsymbol{S}\cdot\boldsymbol{B}}{2m}\quad (\times -Q|e|)$$

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

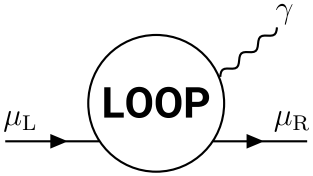
Two "SM predictions" are reported. Which is correct? Discussions ongoing.

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

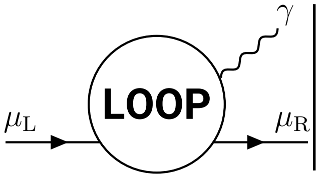
■ 7 April 2021



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

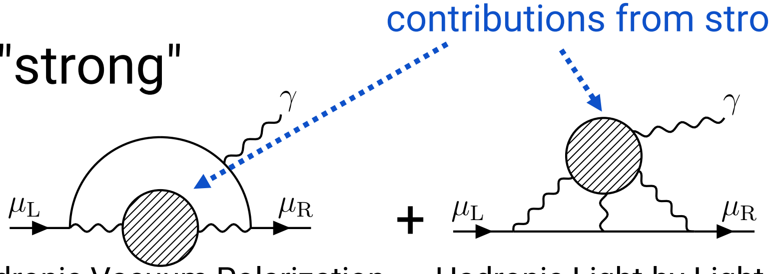


diagrams.

- 

|SM = "EM" + "weak" + "strong"

≃ "EM" + "weak" +



contributions from strong force

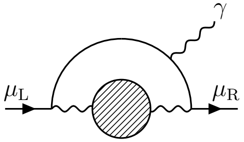
Hadronic Vacuum Polarization

Hadronic Light-by-Light

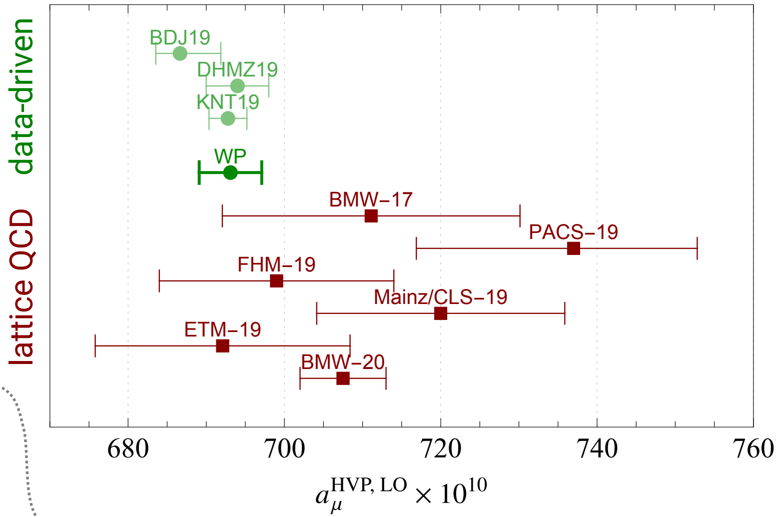
Image courtesy of pakutaso.com

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^- → hadrons" cross sections

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

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

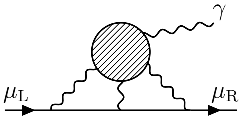
$K(s)$: known analytic function

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

➢ BMW collaboration: **lattice QCD**

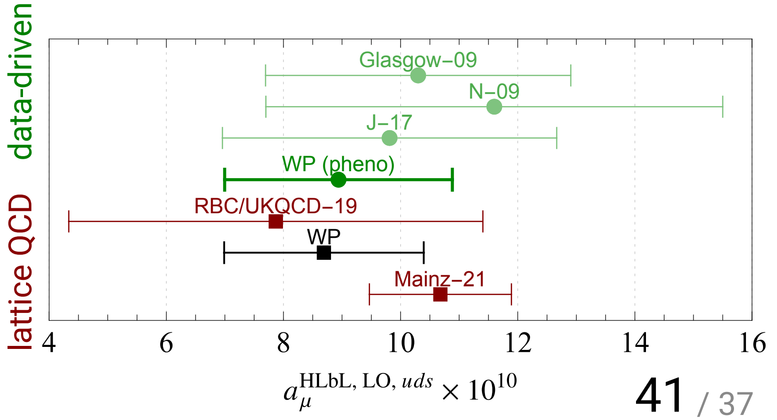
← Attack: Are the extrapolations safe? (especially: lattice spacing $a \to 0$)

- Two methods for

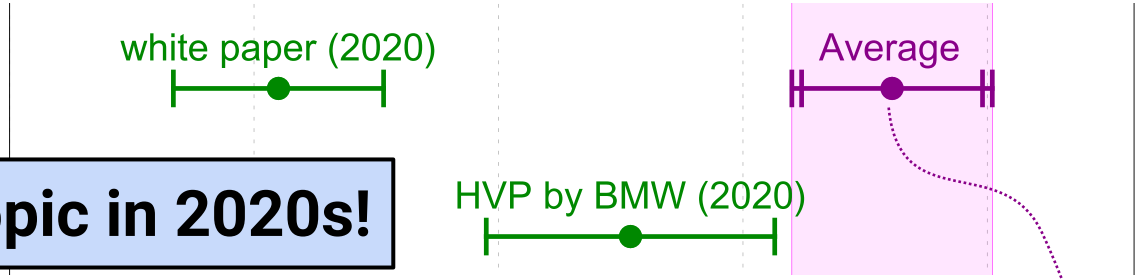


(hadronic
light-by-light)

→ consistent results.



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



A very hot topic in 2020s!

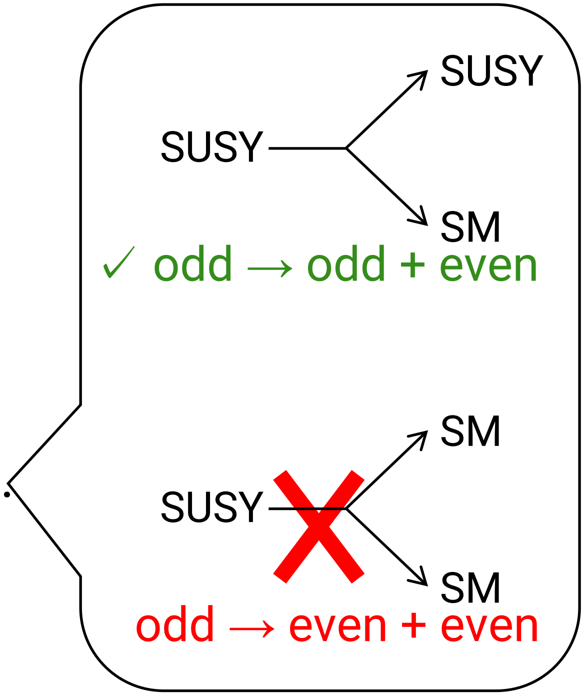
- The battle of HVP:
  - data-driven?
    ← Attack: Did you include ALL processes?
    Are all cross-section data valid and consistent?
  - lattice QCD?
    ← Attack: Are the extrapolations safe? (especially: lattice spacing $a \to 0$)
- More supporting data
  e.g. Belle II ($e^+e^- \to \pi^+\pi^-\gamma$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

Extra 1) SUSY-DM and freeze-out

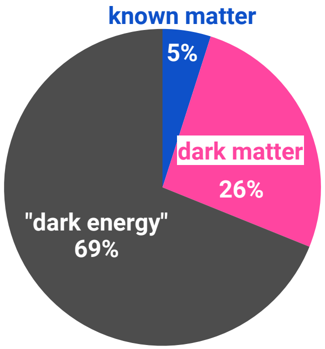
Motivation for TeV-scale SUSY (2) We can easily explain why DM = 26%.

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

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

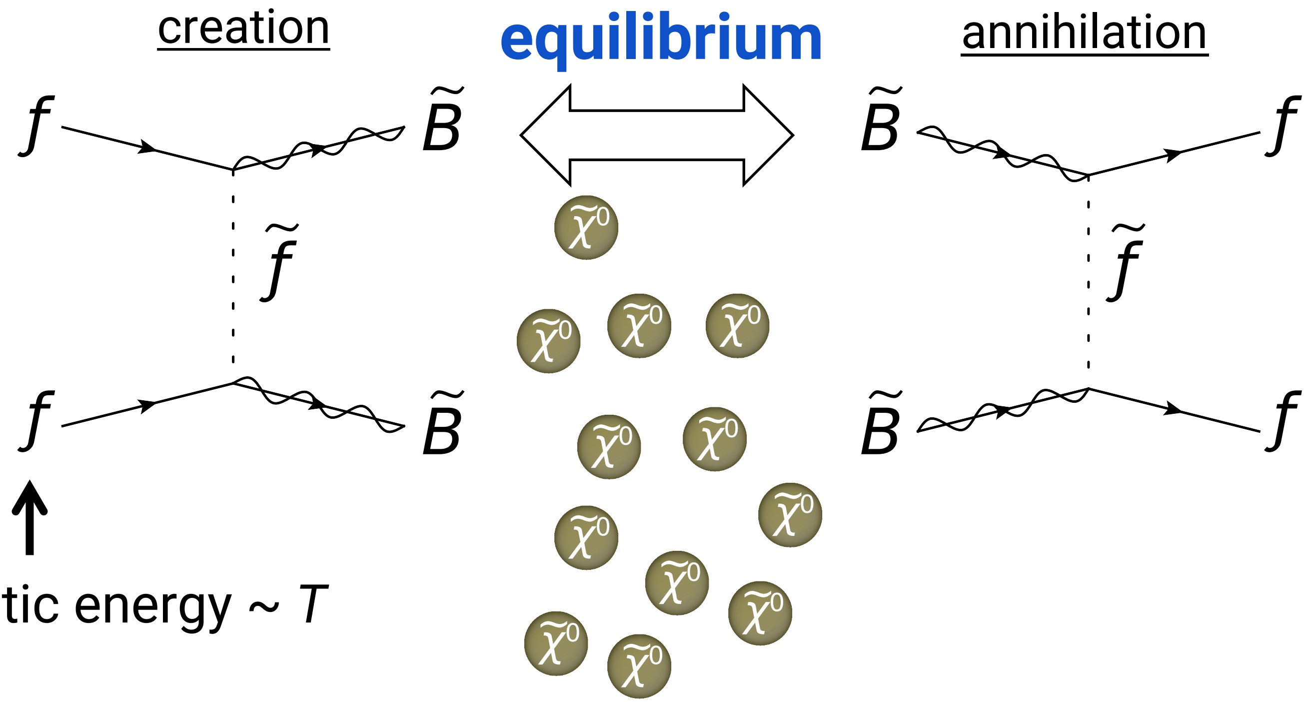


- ➢ Particles can decay to lighter particle.
  → The lightest SUSY particle **(LSP)** cannot decay.
  = DM candidate.
- ➢ If LSP ~ 100 GeV, we can explain why DM is "26%".



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

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



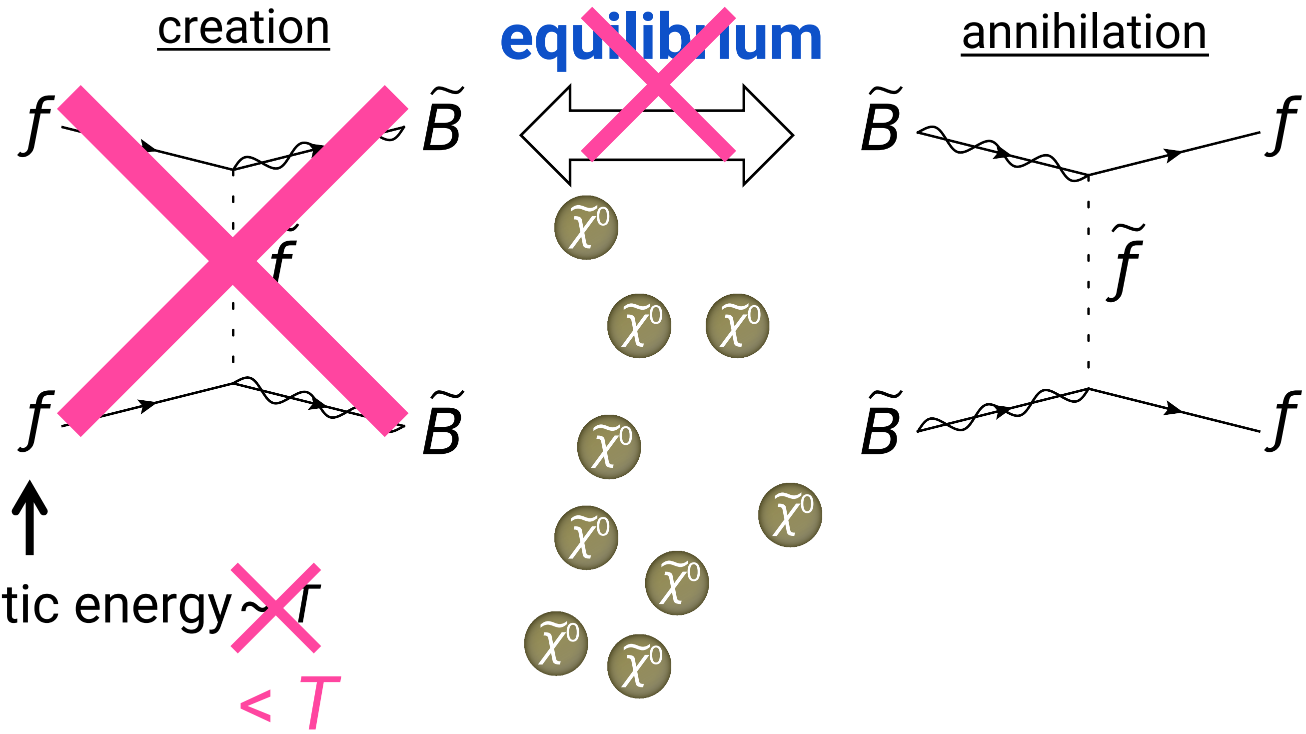
creation

equilibrium

annihilation

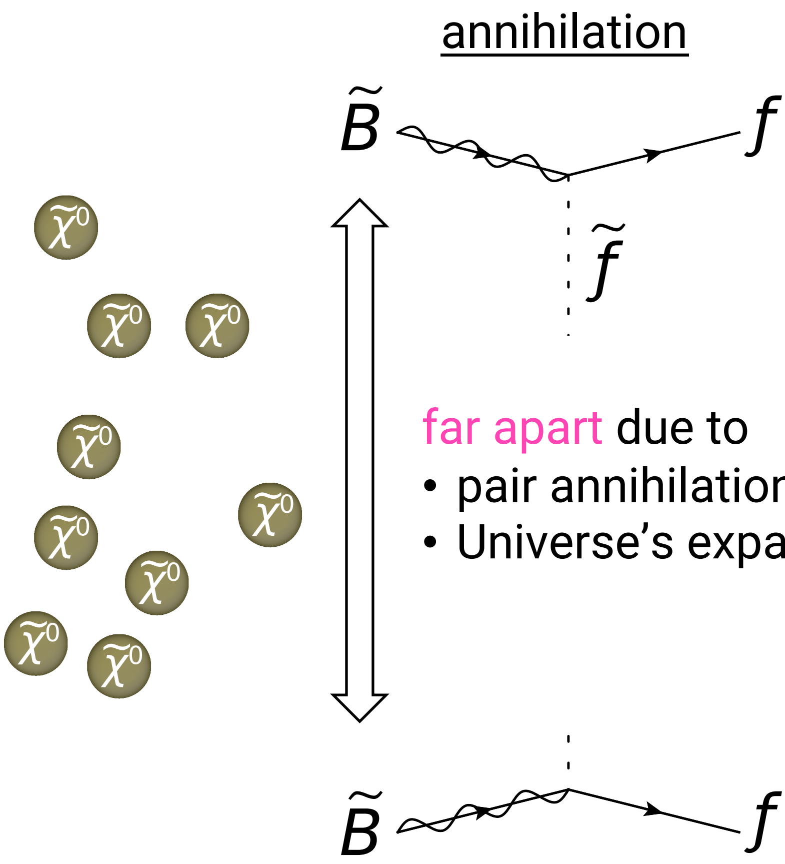
with kinetic energy ~ T

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



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

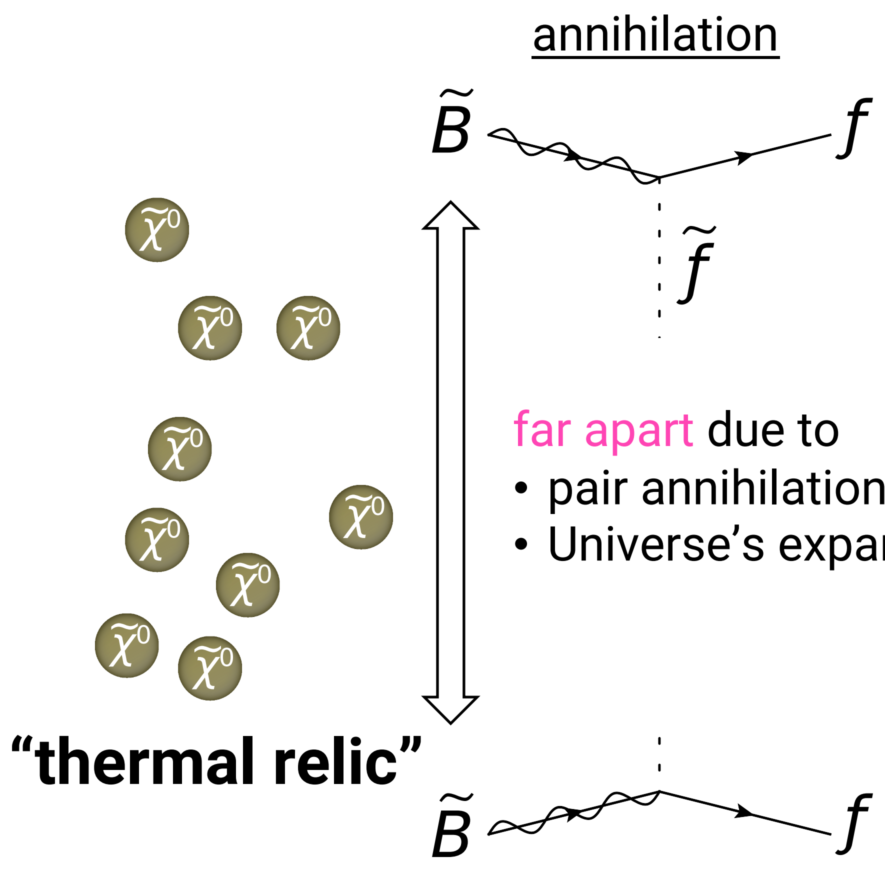
- Early Universe with $T \lesssim m_{\widetilde{B}}/20$



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

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

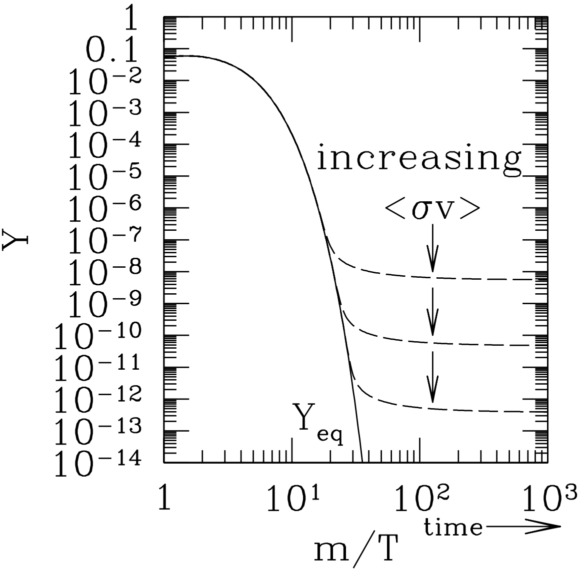
- Early Universe with $T \lesssim m_{\widetilde{B}}/20$



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

“thermal relic”

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

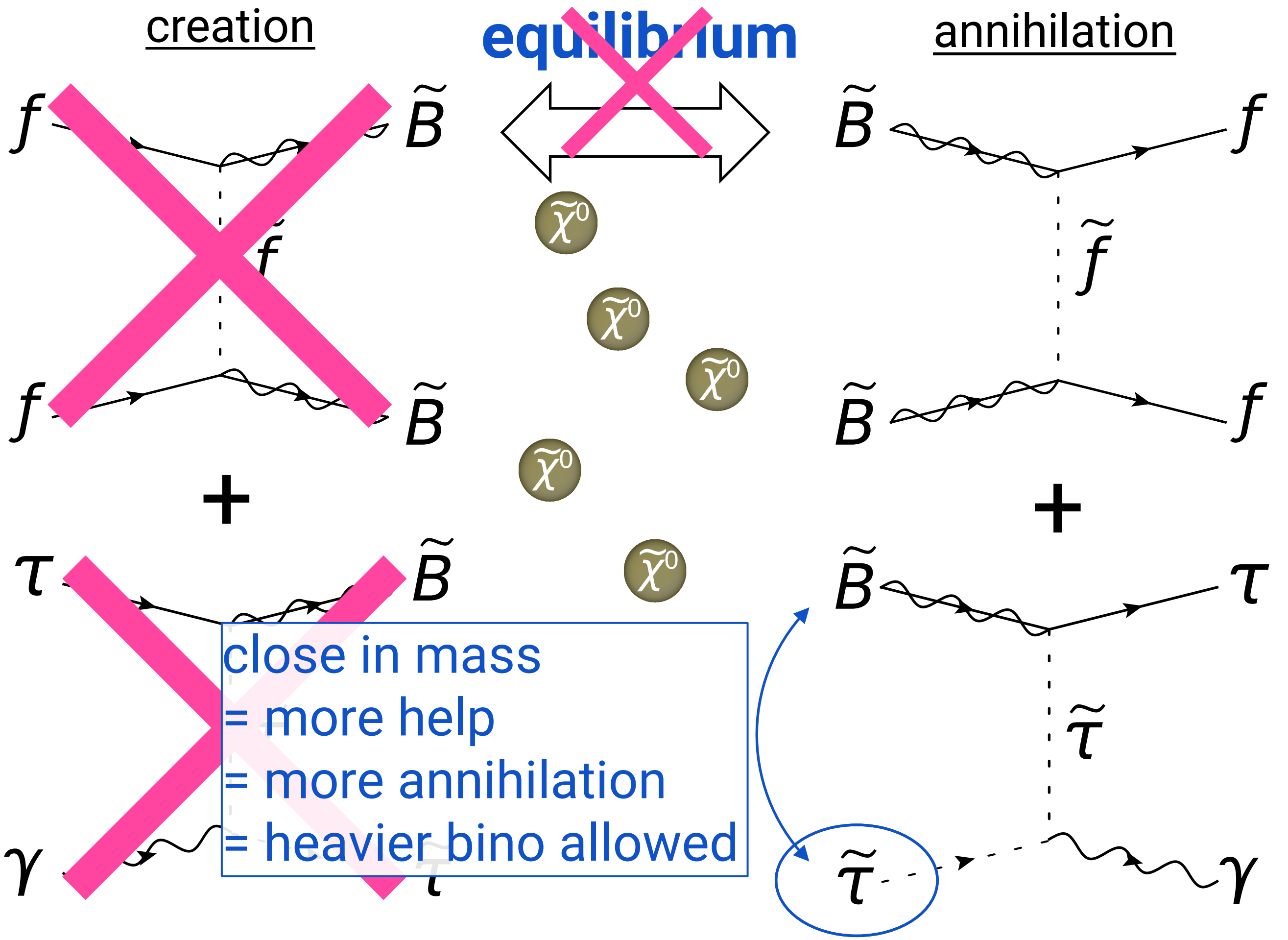


Gelmini and Gondolo, 1009.3690

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

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

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



close in mass
= more help
= more annihilation
= heavier bino allowed

annihilation helper!

cf. Edsjö, Schelke, Ullio, Gondolo, hep-ph/0301106

MSSM: DM & *g*−2 ... possible?

- *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

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

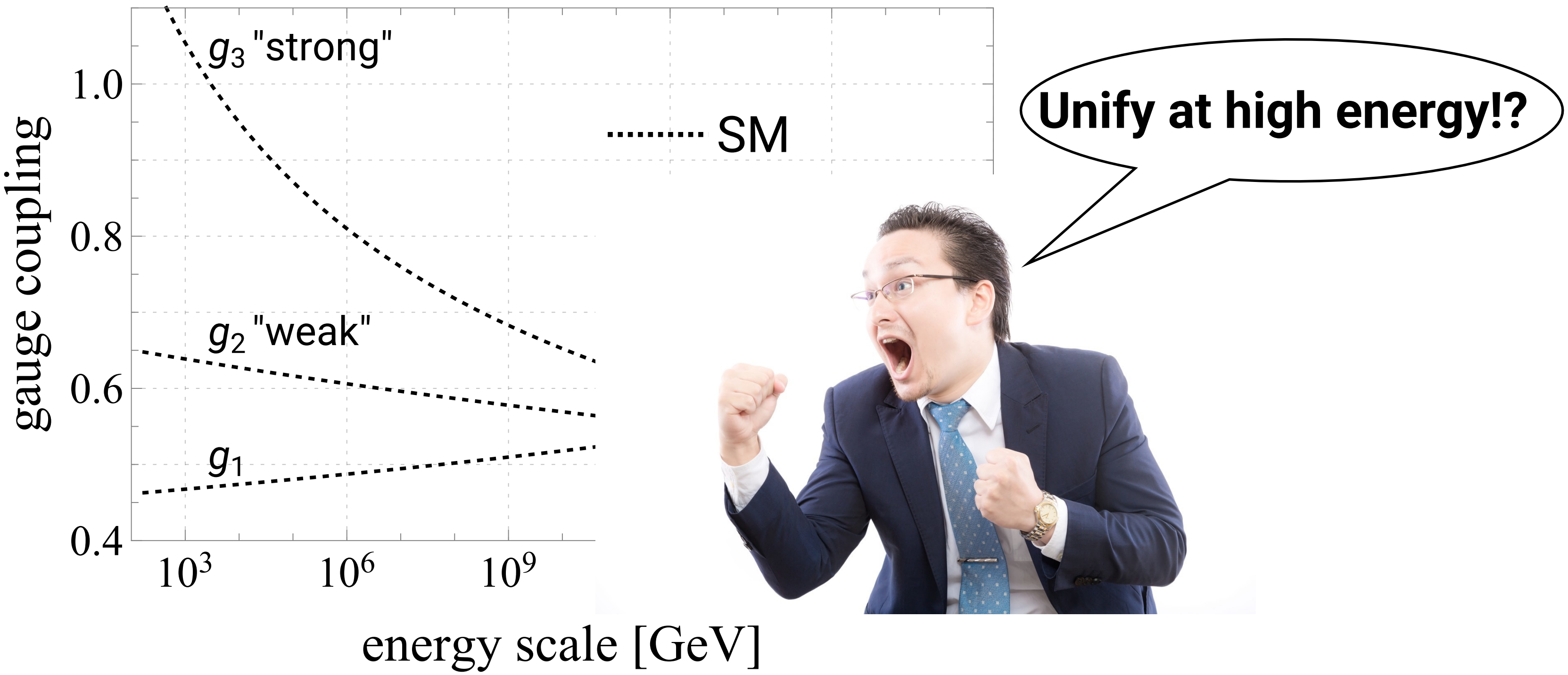
- ➢ bino-like DM → $m_{\mathrm{LSP}} < 100$ GeV
- ➢ higgsino-like DM → $m_{\mathrm{LSP}} \sim 1$ TeV
- ➢ wino-liike DM → $m_{\mathrm{LSP}} \sim 3$ TeV

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

Extra 2) Coupling Unification

Motivation for TeV-scale SUSY (2) It helps the grand unification.

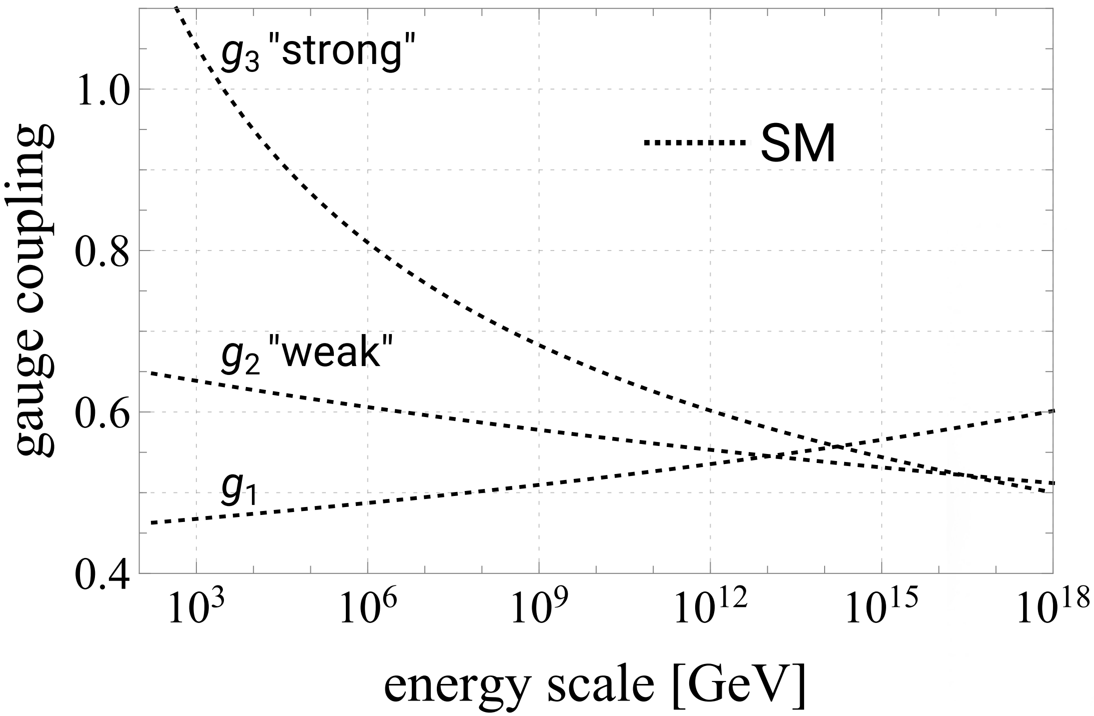
- Strengths of 3 forces depend on energy scale:



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

Image courtesy of pakutaso.com

- Strengths of 3 forces depend on energy scale:

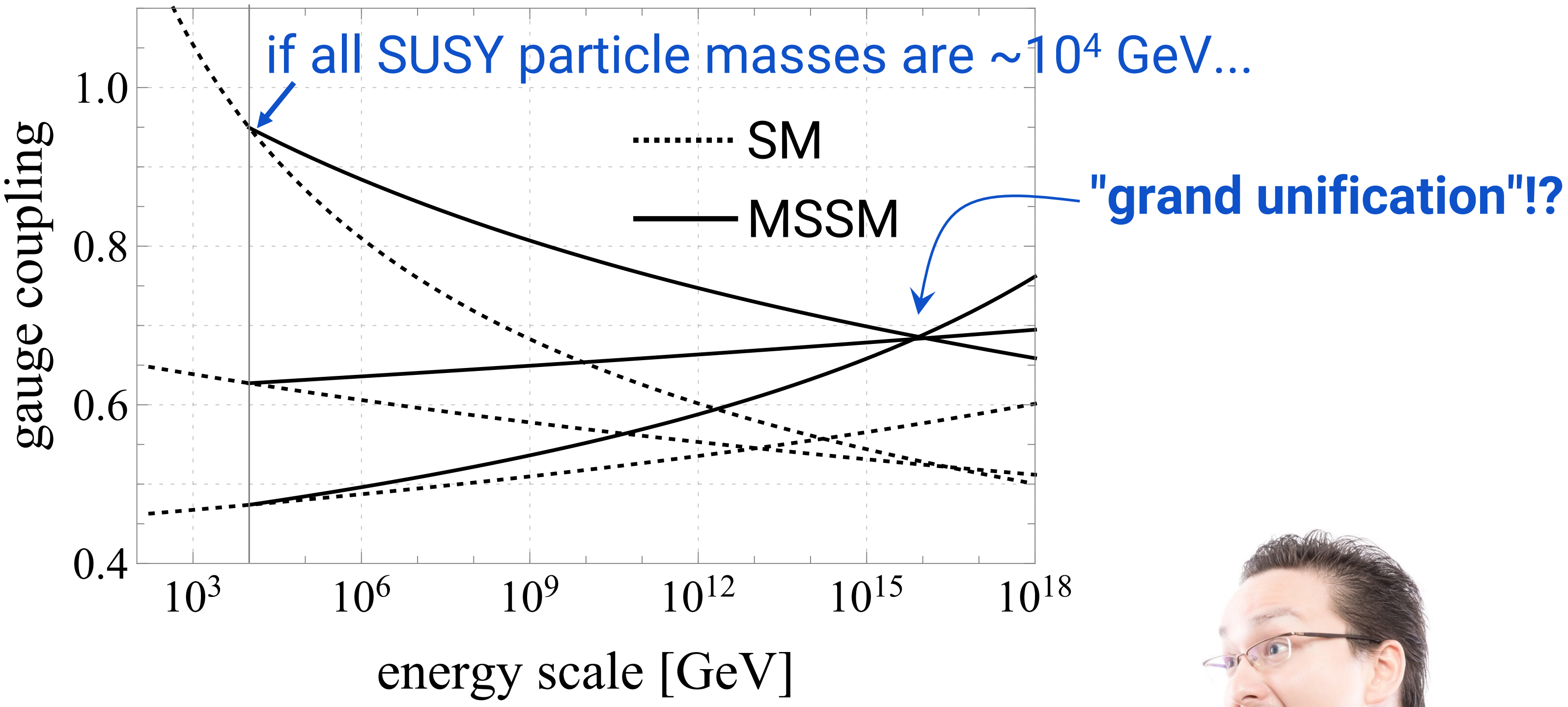


- ❖ dark matter,
- ➢ **grand unification,**
- ❖ muon $g-2$.

Image courtesy of pakutaso.com

Motivation for TeV-scale SUSY (2) It helps the grand unification.

- 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.

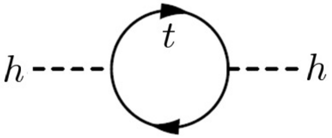
quantum correction

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

physical mass 10^4 GeV^2

Λ (cutoff) ~ Planck or GUT scale

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



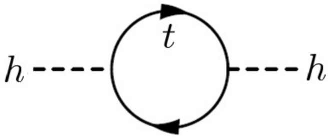
"naturalness problem"
"hierarchy problem"

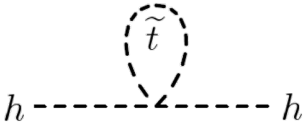
before 2012

- ➢ 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!

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

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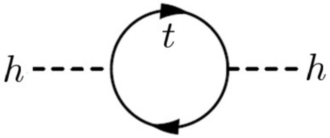
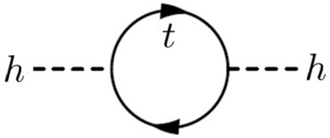


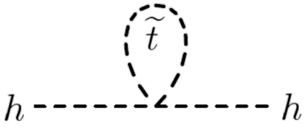
"naturalness problem"
"hierarchy problem"

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!

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

Kitano, Nomura [hep-ph/0602096]

■ However....

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

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

"Log divergence"

➢ if scalar-top mass is
$300\,\mathrm{GeV}:\quad 10^5 + (-10^5) \rightsquigarrow 10^4 \quad [10\%]$ ☺️ natural
$1000\,\mathrm{GeV}:\quad 10^6 + (-10^6) \rightsquigarrow 10^4 \quad [1\%]$ 😕
$3000\,\mathrm{GeV}:\quad 10^7 + (-10^7) \rightsquigarrow 10^4 \quad [0.1\%]$ 👿 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?????**

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

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

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

ral

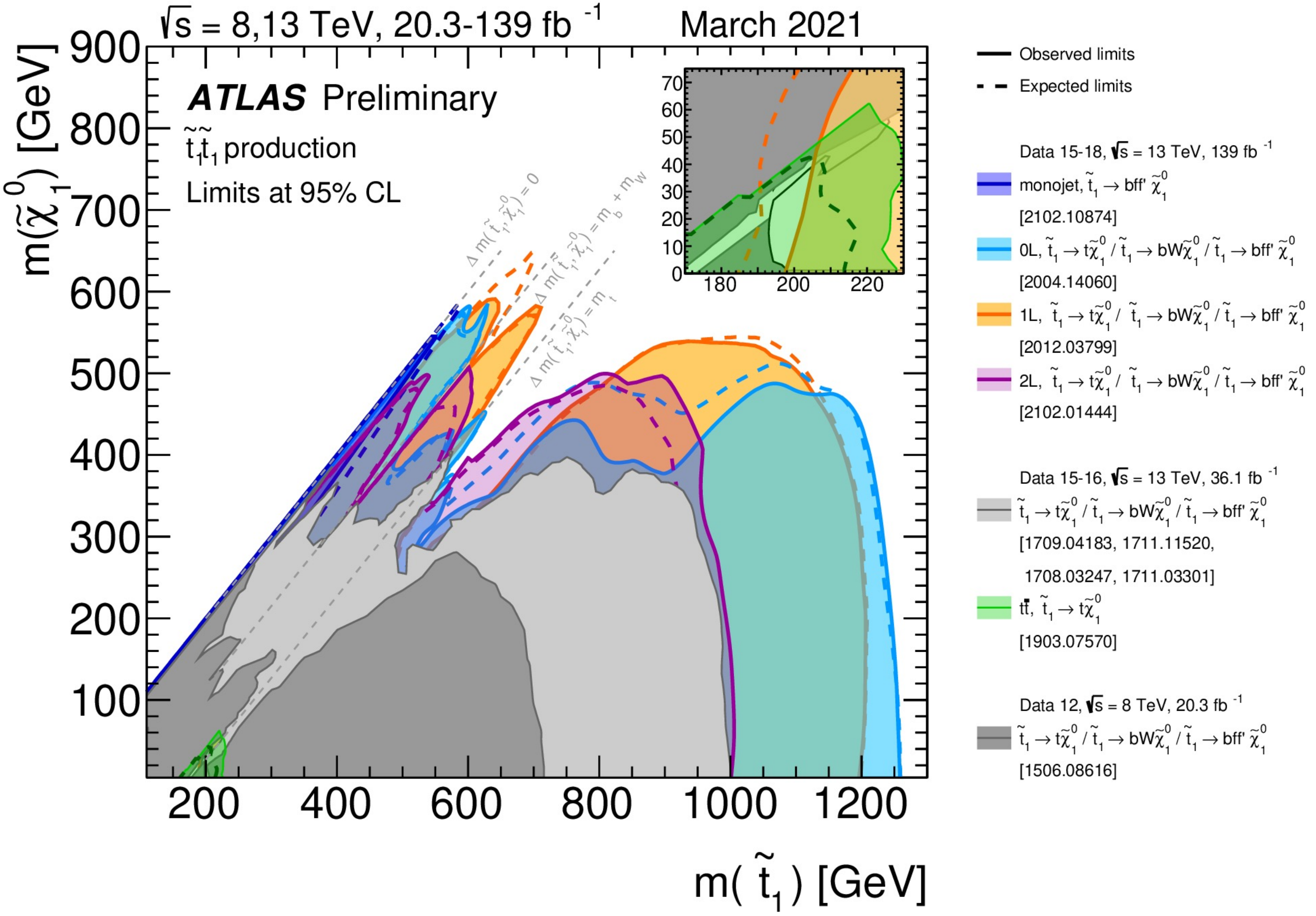
pinion)

After 2018 (LHC Run 2)

- ➢ **No SUSY yet.** Strong constraints on ~300 GeV squarks. [→ later]
- ➢ **SUSY fails to solve the hierarchy problem?????**

ATLAS scalar-top search summary

ATLAS, SUSY March 2021 Summary Plot



Extra 4) dark photon & Lmu–Ltau

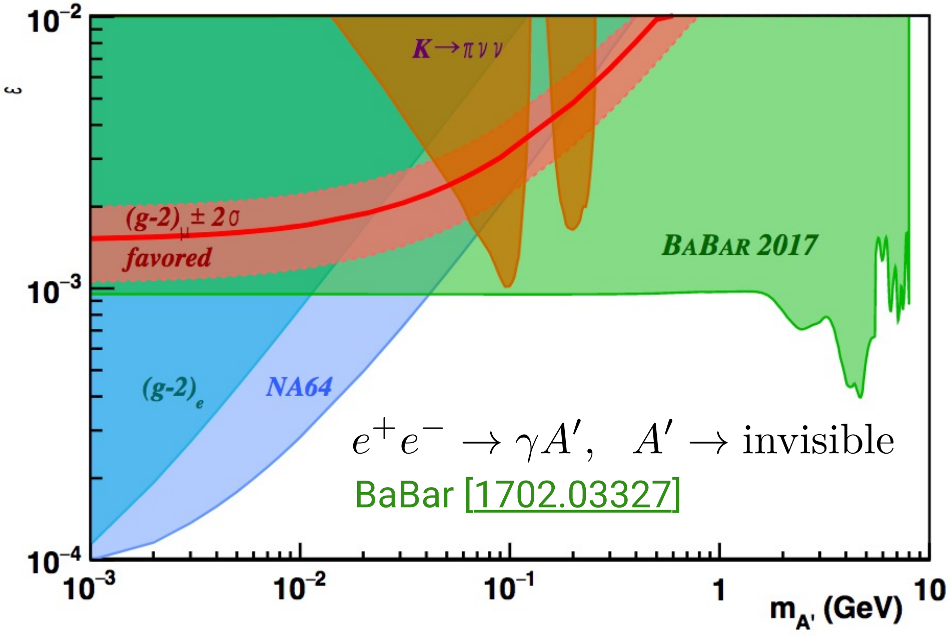
Muon g−2 anomaly : Other possibilities

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

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

- 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



$e^+e^- \to \gamma A', \quad A' \to \text{invisible}$

BaBar [1702.03327]

⇨ **excluded (as a Δa_μ solution)**

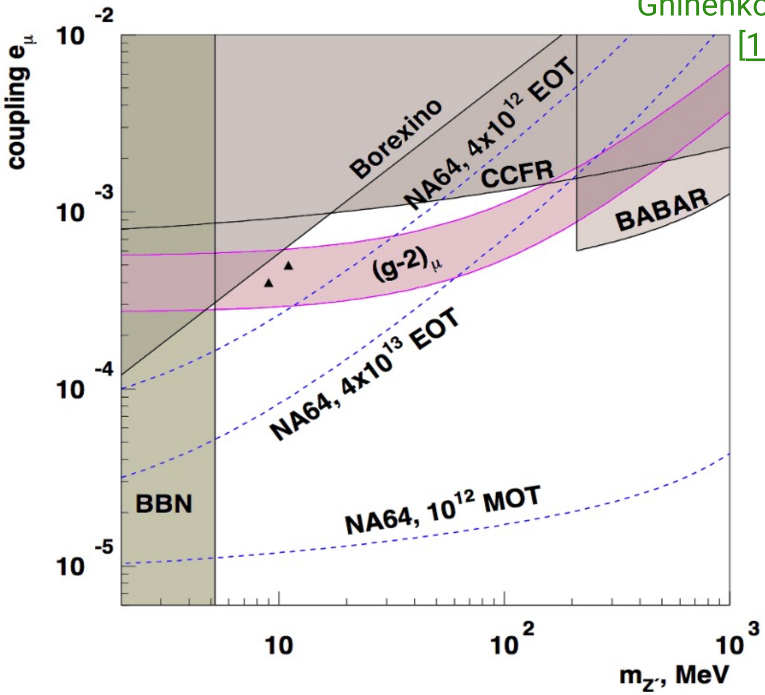
Muon $g-2$ anomaly : Other possibilities

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

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

- 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]

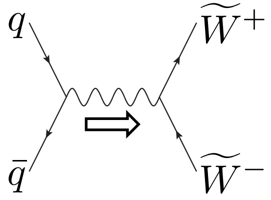
⇨ **another valid solution**

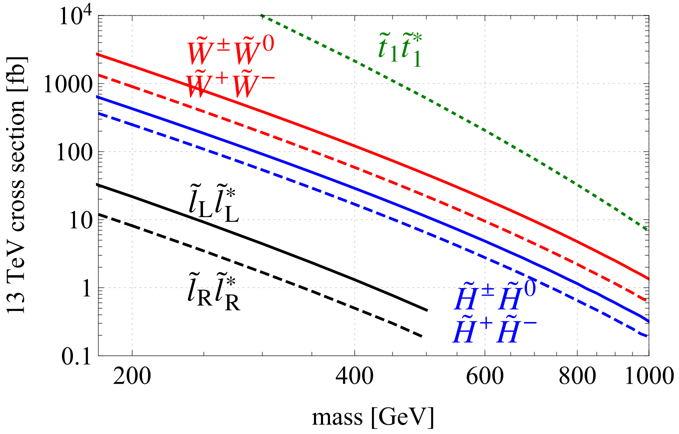
$$L_{Z'} = e_\mu Z'_\nu[\bar\mu\gamma^\nu\mu - \bar\tau\gamma^\nu\tau + \bar\nu_\mu\gamma^\nu\nu_\mu - \bar\nu_\tau\gamma^\nu\nu_\tau]$$

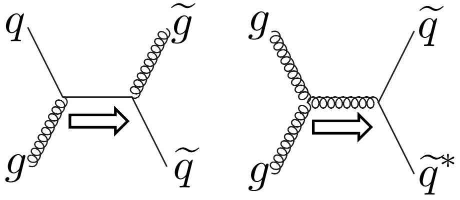
Extra 5) LHC Non-colored SUSY

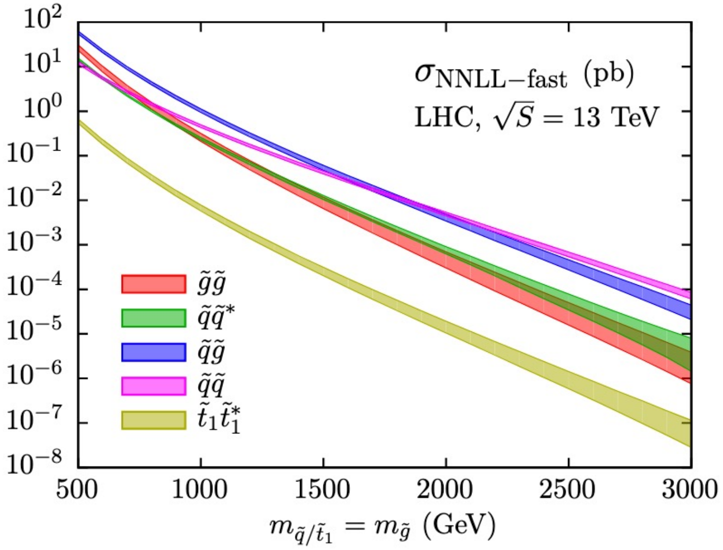
Non-colored particles have smaller production cross section.

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









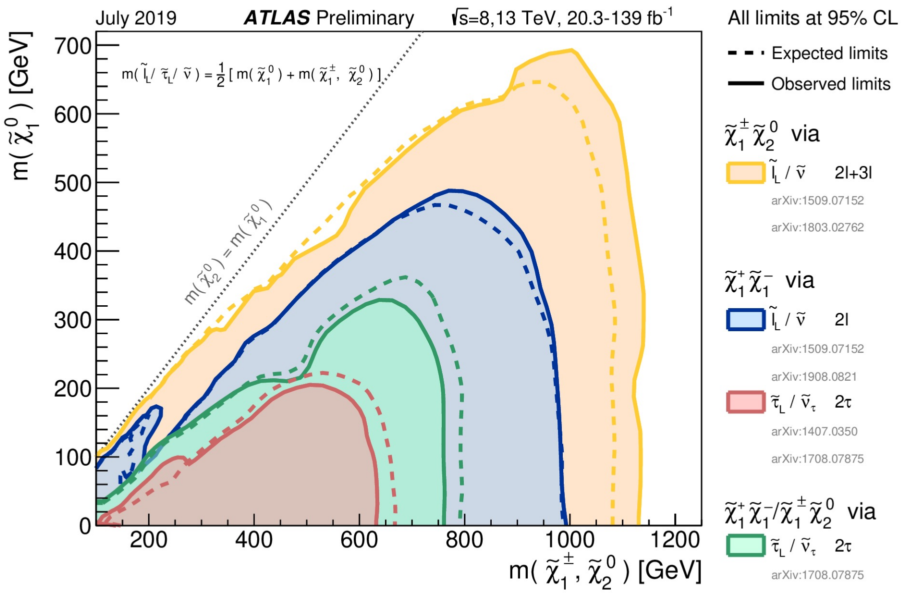
Beenakker, Borschensky, et al. [1607.07741]

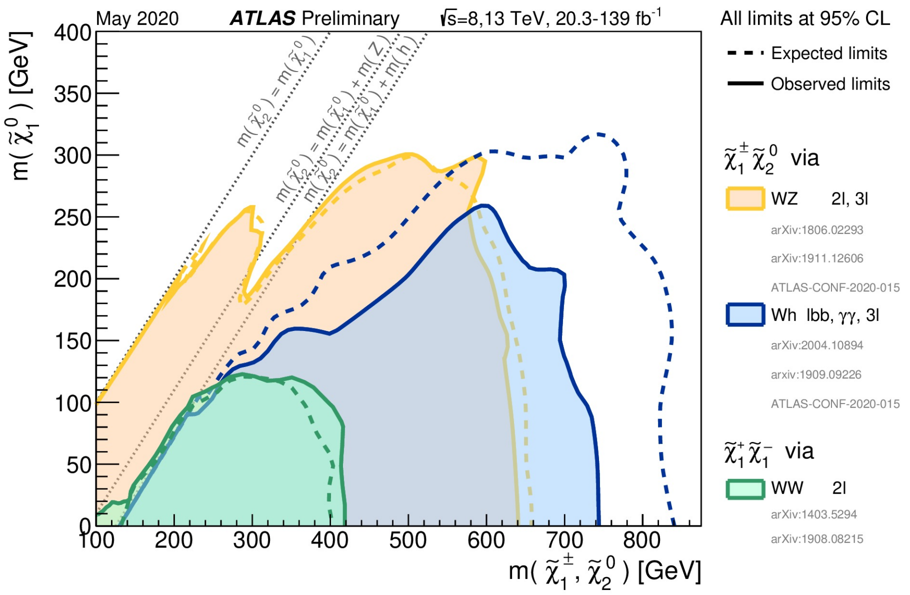
- ➢ Non-colored XS is smaller because
  - Smaller couplings
  - *s*-channel only
  - Needs anti-quark from *p*

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

ATLAS neutralino-chargino search summary

ATLAS, SUSY March 2021 Summary Plot



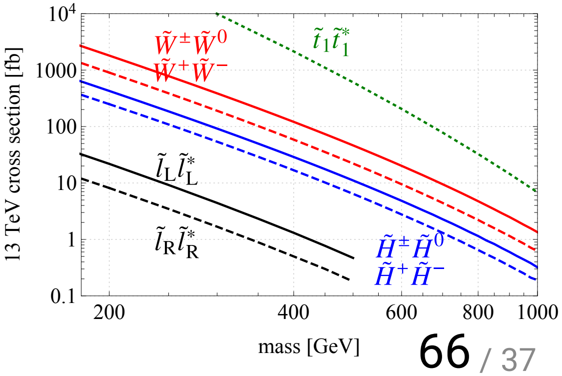


(slepton-mediated: NC/3L)

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

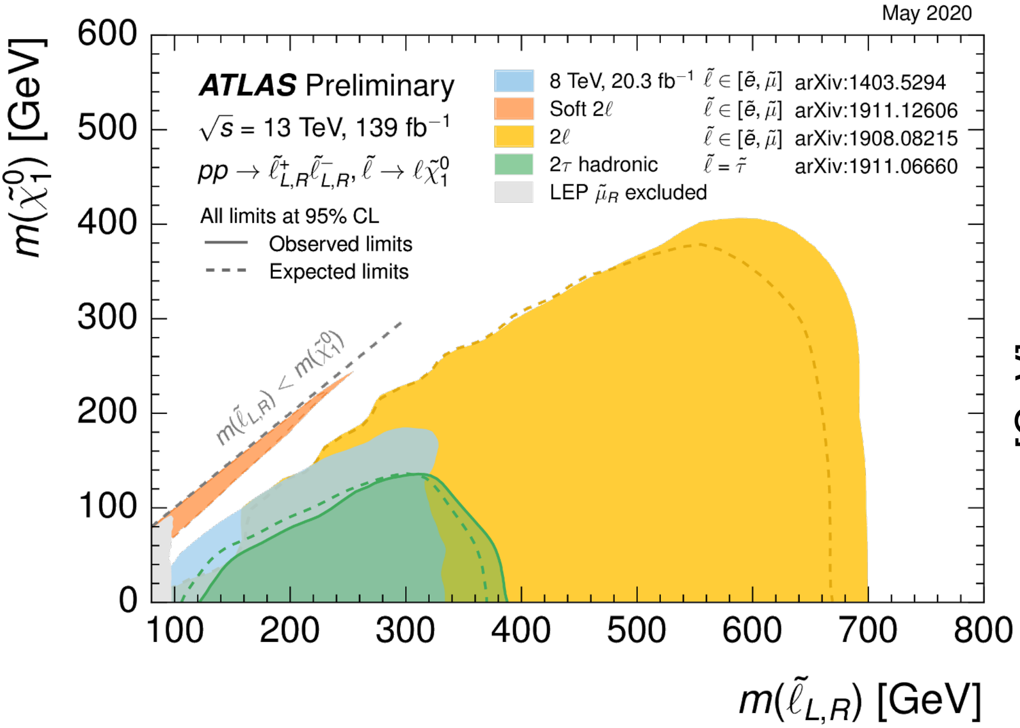
(They usually assume $\tilde\chi^0_2\equiv\widetilde{W}^0,\,\tilde\chi^+_1\equiv\widetilde{W}^+$.)

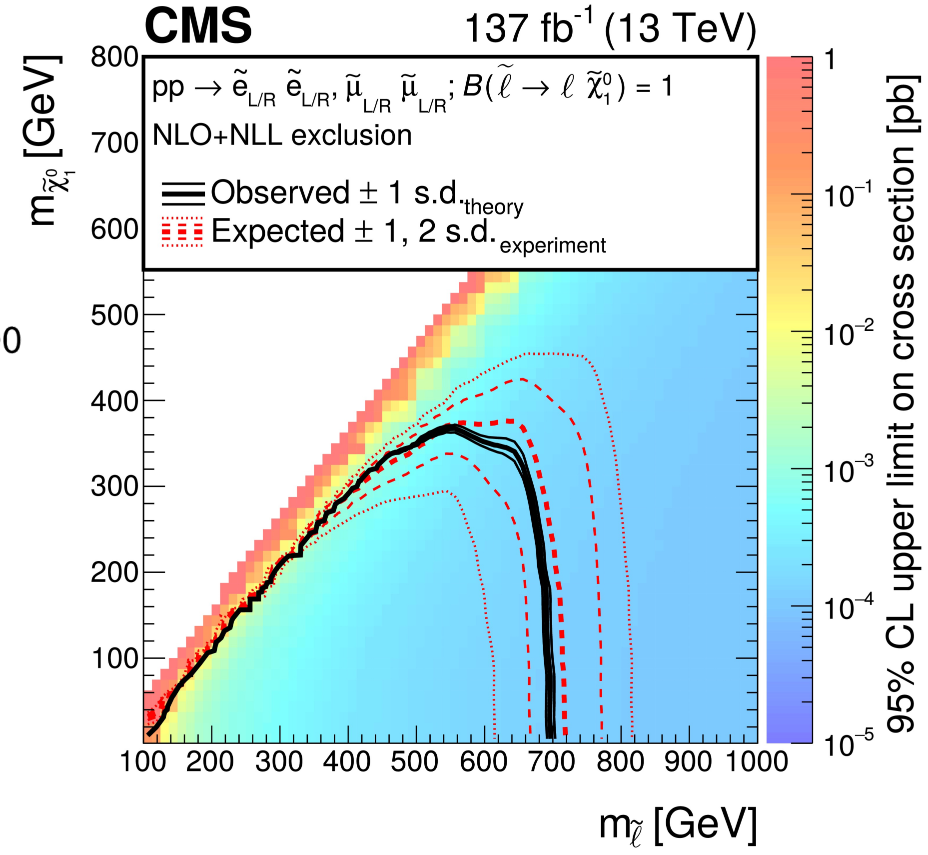
$$\begin{aligned}
\mathrm{Br}(Z\to\mathrm{had}) &= 69.911(56)\% \\
\mathrm{Br}(Z\to b\bar b) &= 15.12(5)\% \\
\mathrm{Br}(Z\to e,\mu,\tau) &\simeq 10.10\% \\
\mathrm{Br}(Z\to\mathrm{inv}) &= 20.000(55)\% \\
\mathrm{Br}(W\to\mathrm{had}) &= 67.41(27)\%
\end{aligned}$$



LHC scalar-lepton search summary

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

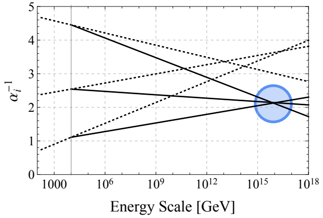




Extra 6) ~~SUSY~~ and 2104.03223

Iwamoto, Yanagida, Yokozaki [2104.03223]

Constrained MSSM: an old "consensus" for benchmark parameter set



■ **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]

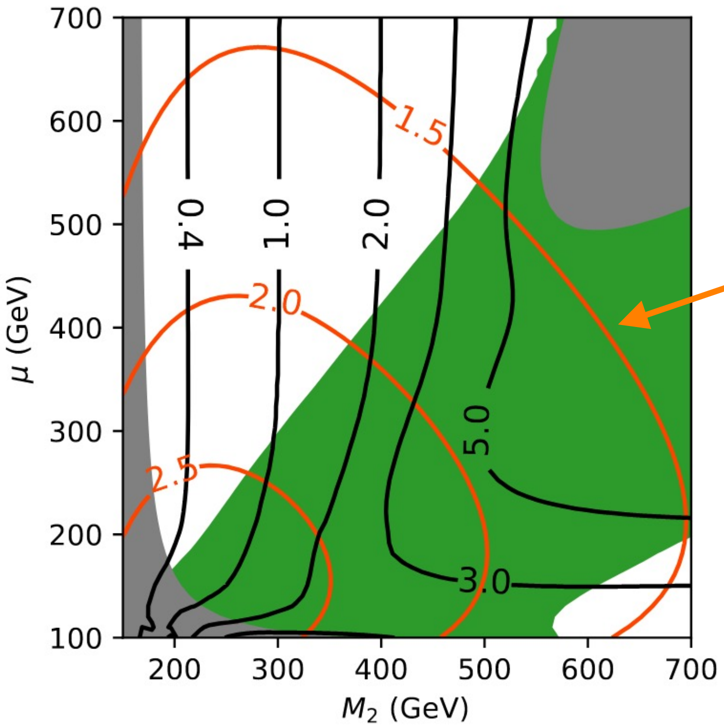
■ **NUGM + NUHiggsM** scenario

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

→ We provide a benchmark plane.

Benchmark parameter plane

Iwamoto, Yanagida, Yokozaki [2104.03223]



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

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

excluded by XENON1T

$m_0 = 0$

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

$\mu = 100\text{–}700\,\mathrm{GeV}$

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

$M_2 = 150\text{–}700\,\mathrm{GeV}$

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

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

$A_{d,e} = 0$

$\tan\beta = 40$

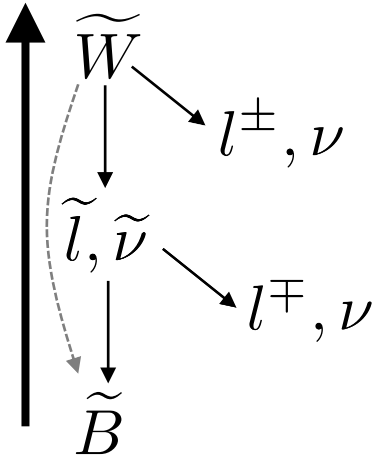
$\mathrm{sgn}\,\mu = +$

- *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

We need to think the decay patterns....

■ Wino > sleptons



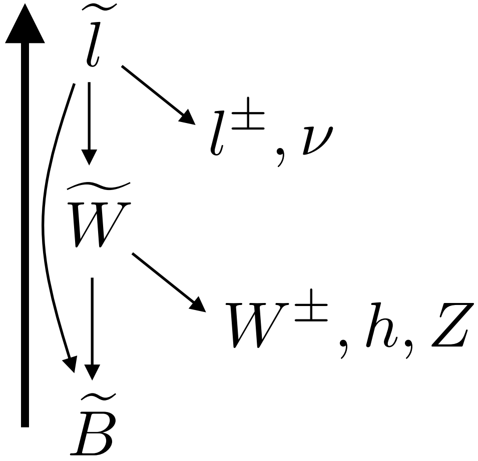
$$\widetilde{W}^{+}\widetilde{W}^{0} \to (l^{+}\nu\widetilde{B})(l^{-}l^{+}\widetilde{B}) = 3\ell + \not{E}_{\mathrm{T}}$$

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

➢ 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]

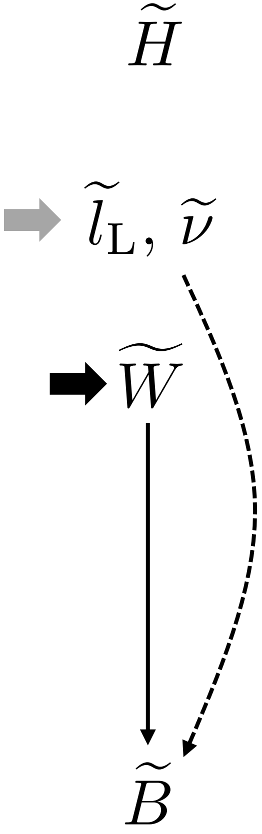
➢ Search targets:

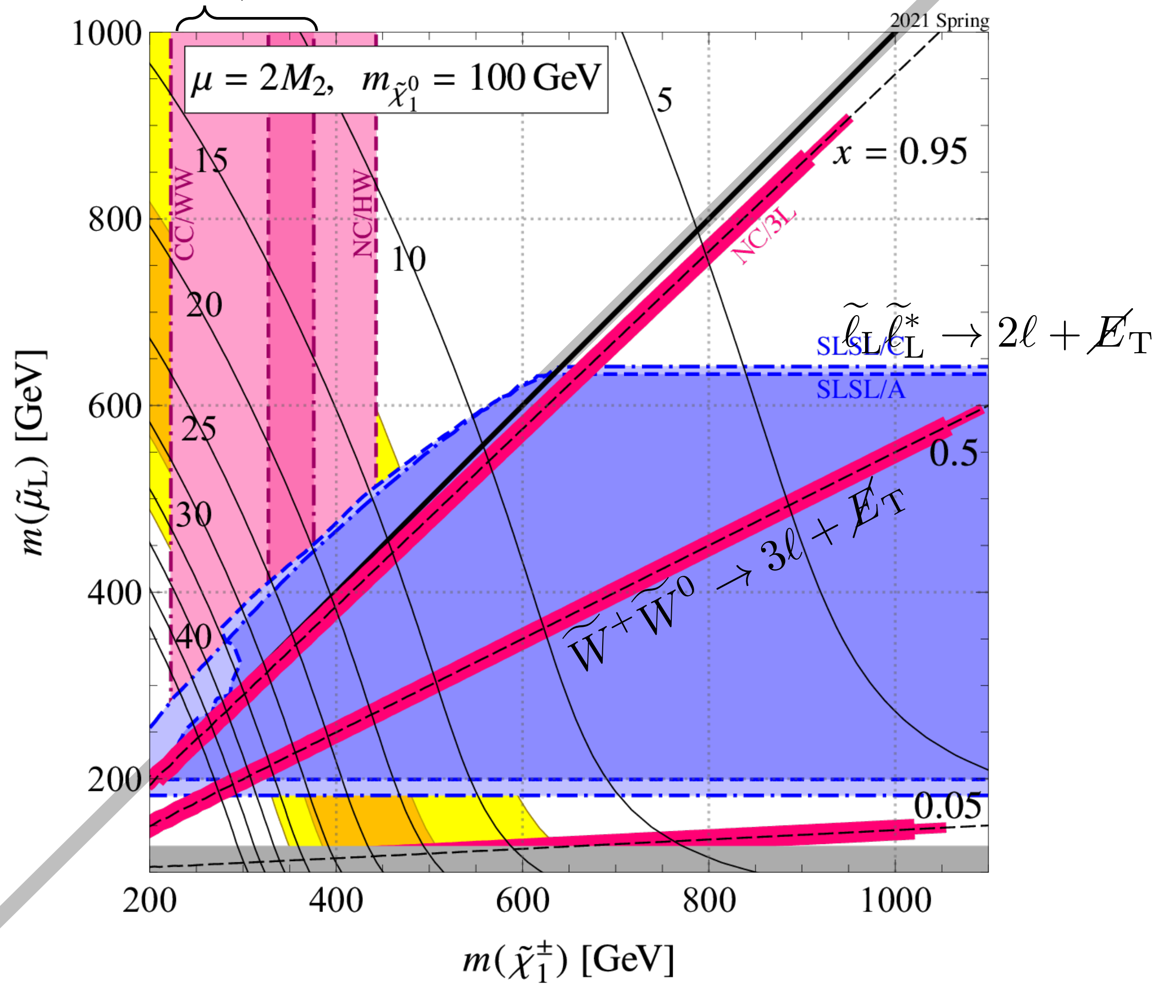
- Wino pair → WZ + mET
- Wino pair → Wh + mET

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

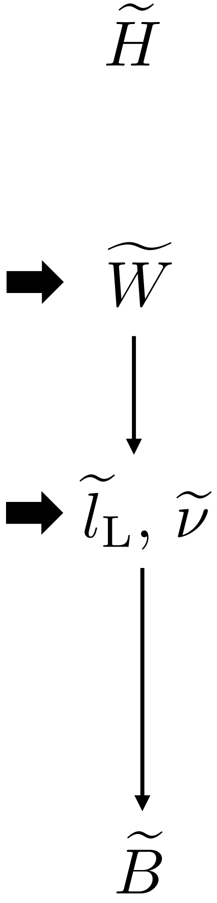
$\widetilde{W}^0\widetilde{W}^+ \to hW + \not{E}_\mathrm{T}$

$\widetilde{W}^+\widetilde{W}^- \to WW + \not{E}_\mathrm{T}$





↑ Wino



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.

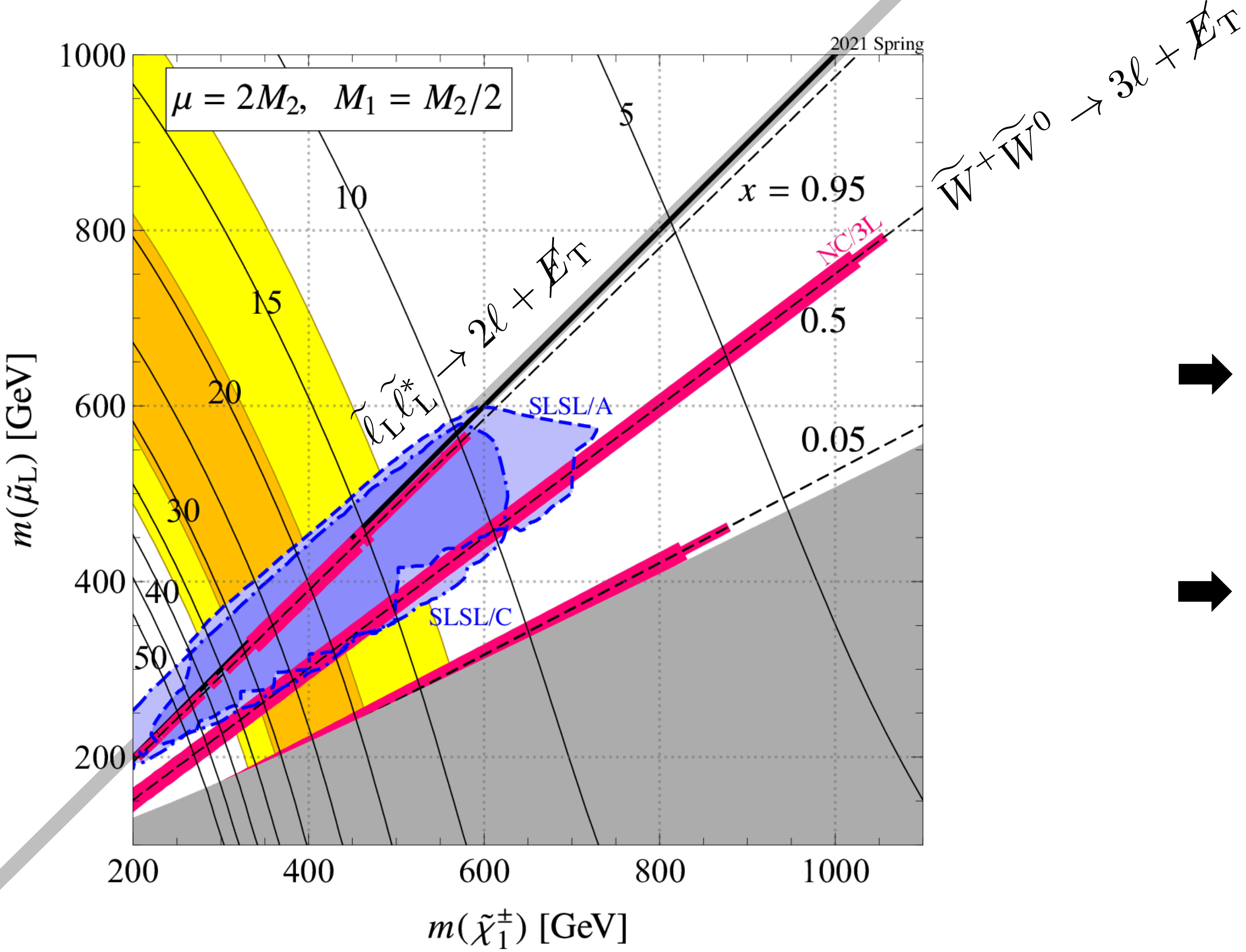
$\widetilde{H}$

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

$\widetilde{W}$

$\downarrow$

$\widetilde{B}$



↑ Wino

$\widetilde{H}$

$\widetilde{W}$

$\downarrow$

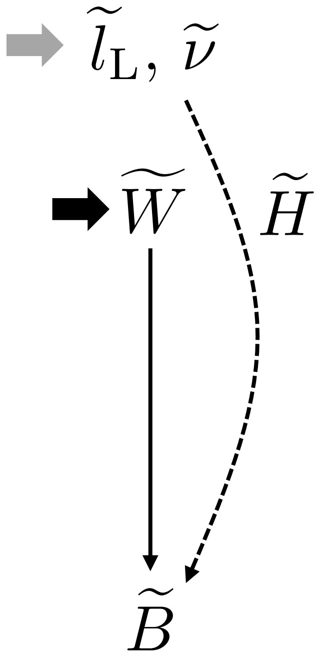
$\widetilde{l}_{\rm L},\ \widetilde{\nu}$

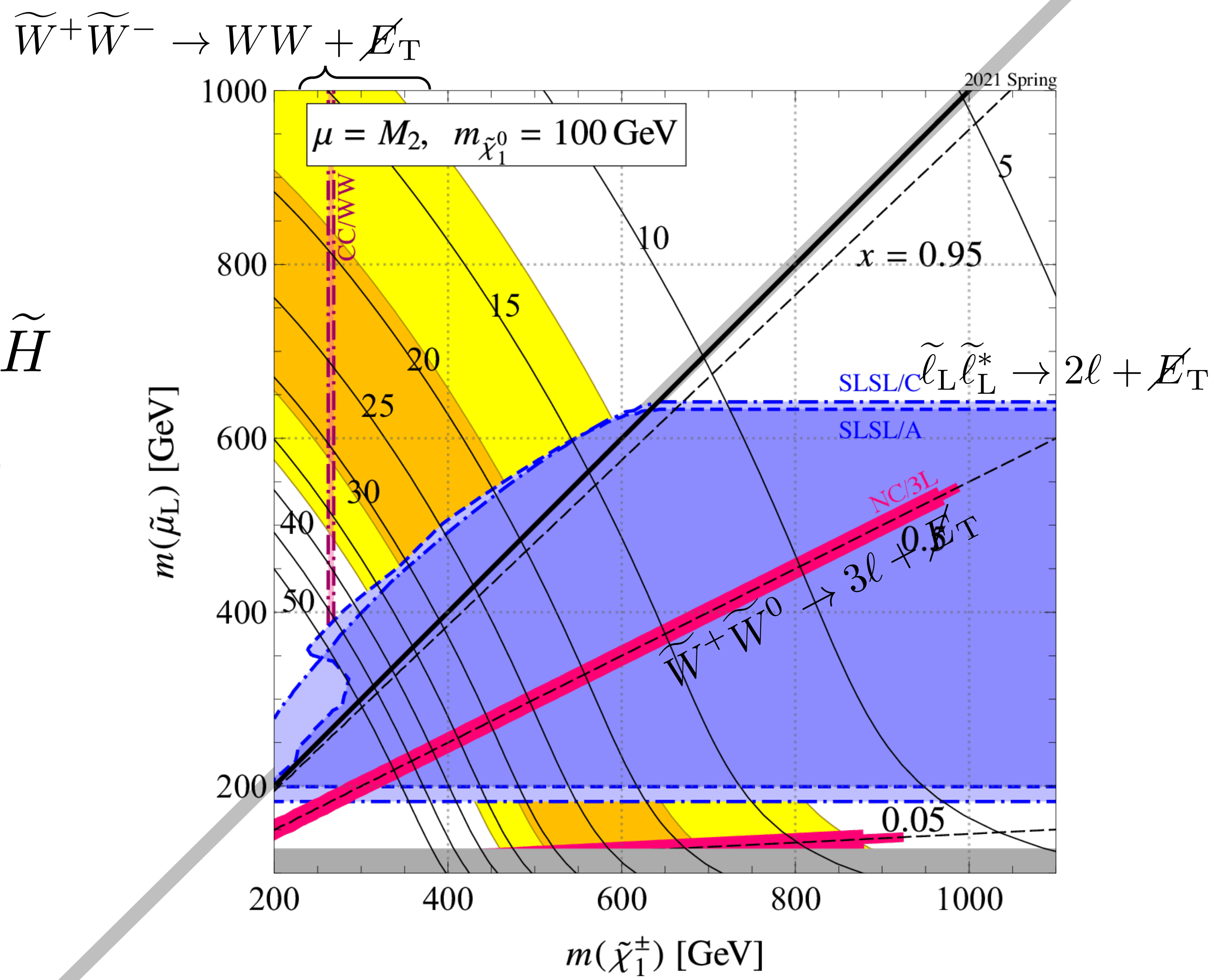
$\downarrow$

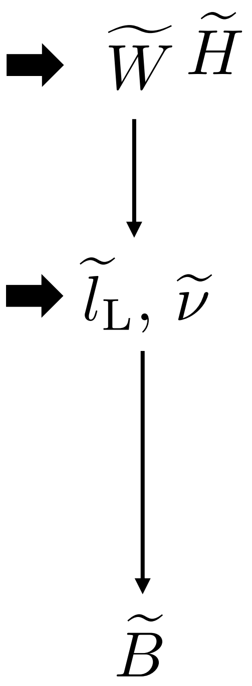
$\widetilde{B}$

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

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



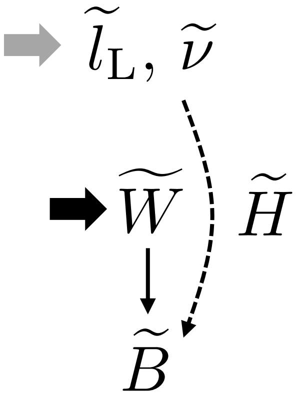


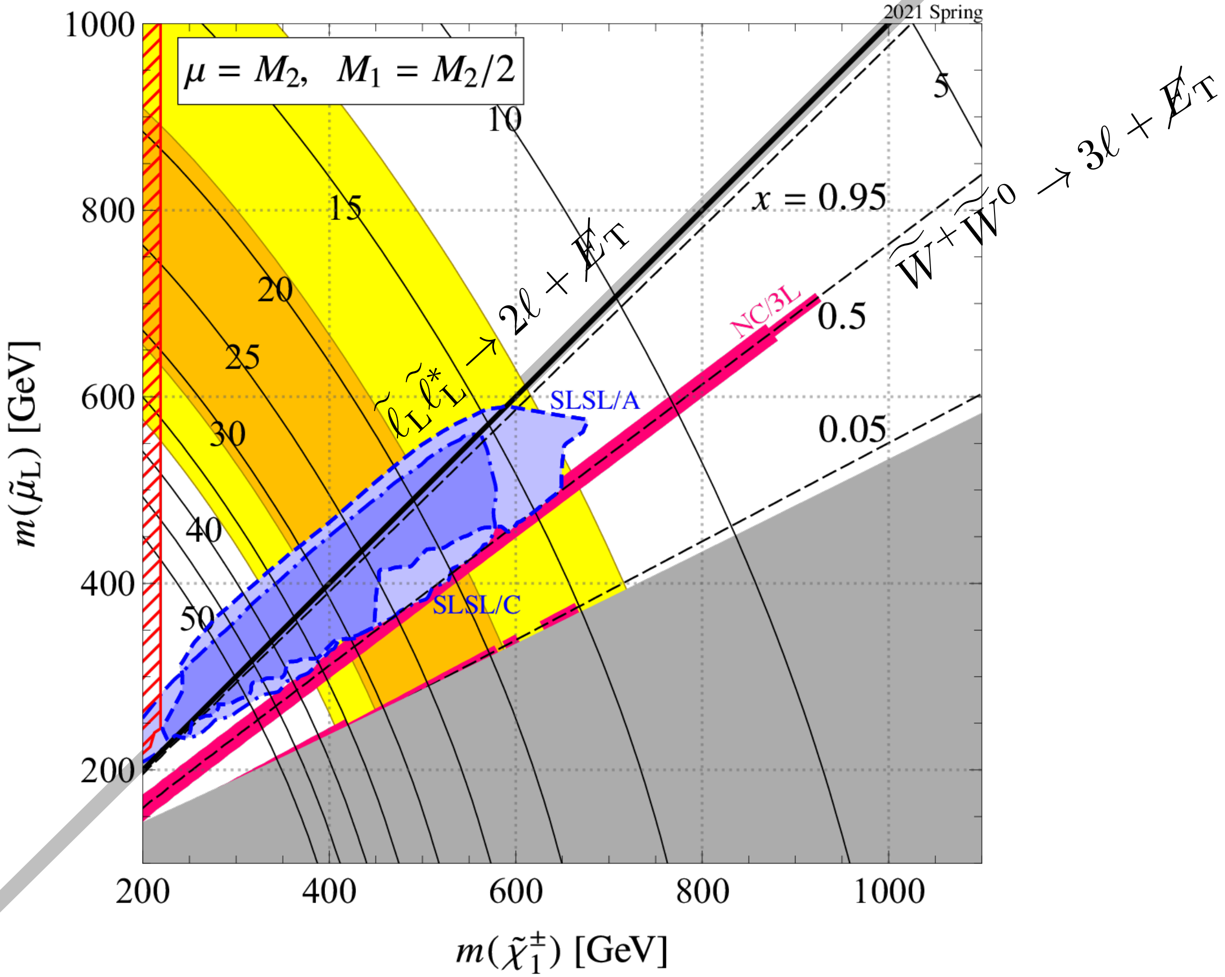


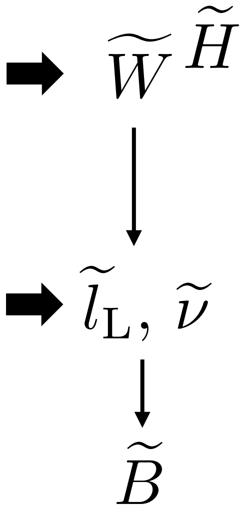
↑ Wino/Higgsino mixed

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

[D] LSP = (M2/2) bino, with Higgsino/Wino mixing. Smaller neutralino-chargino production XS.







↑ Wino/Higgsino mixed

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