Supersymmetric interpretation of the muon g-2 anomaly

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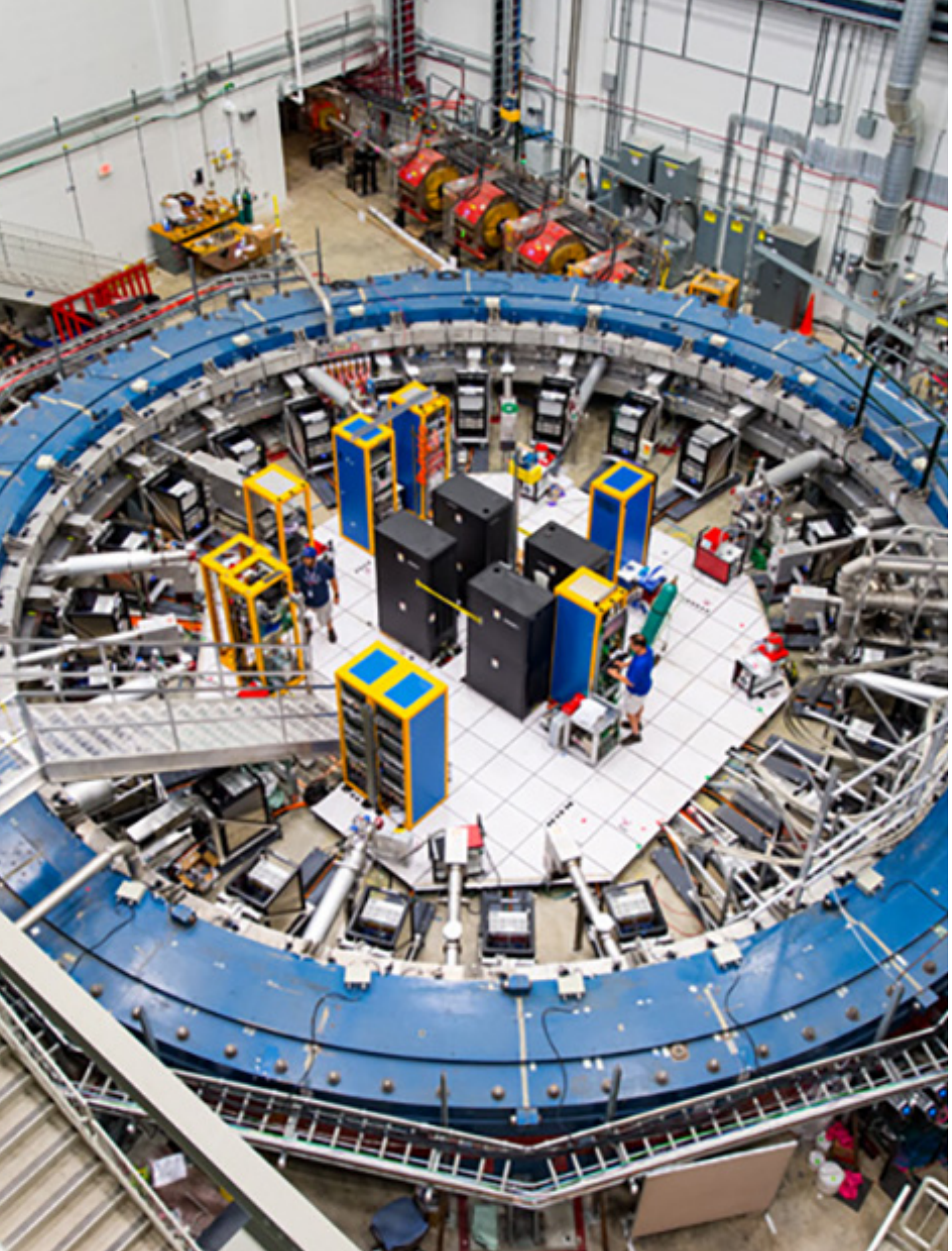
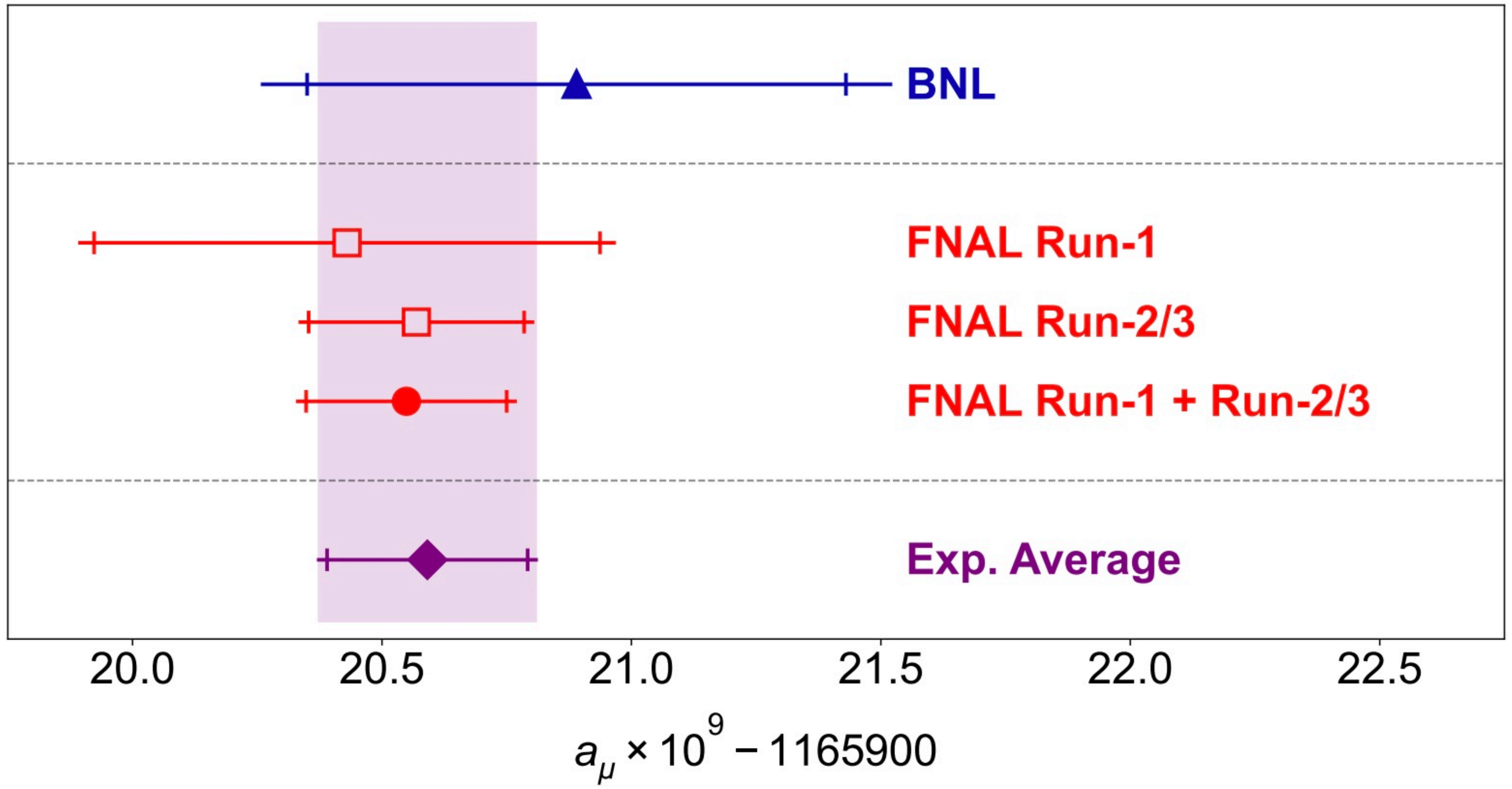


FNAL Run-2/3 data confirmed the previous results

Now, we know $a_\mu(\mathrm{Exp})$ very precisely

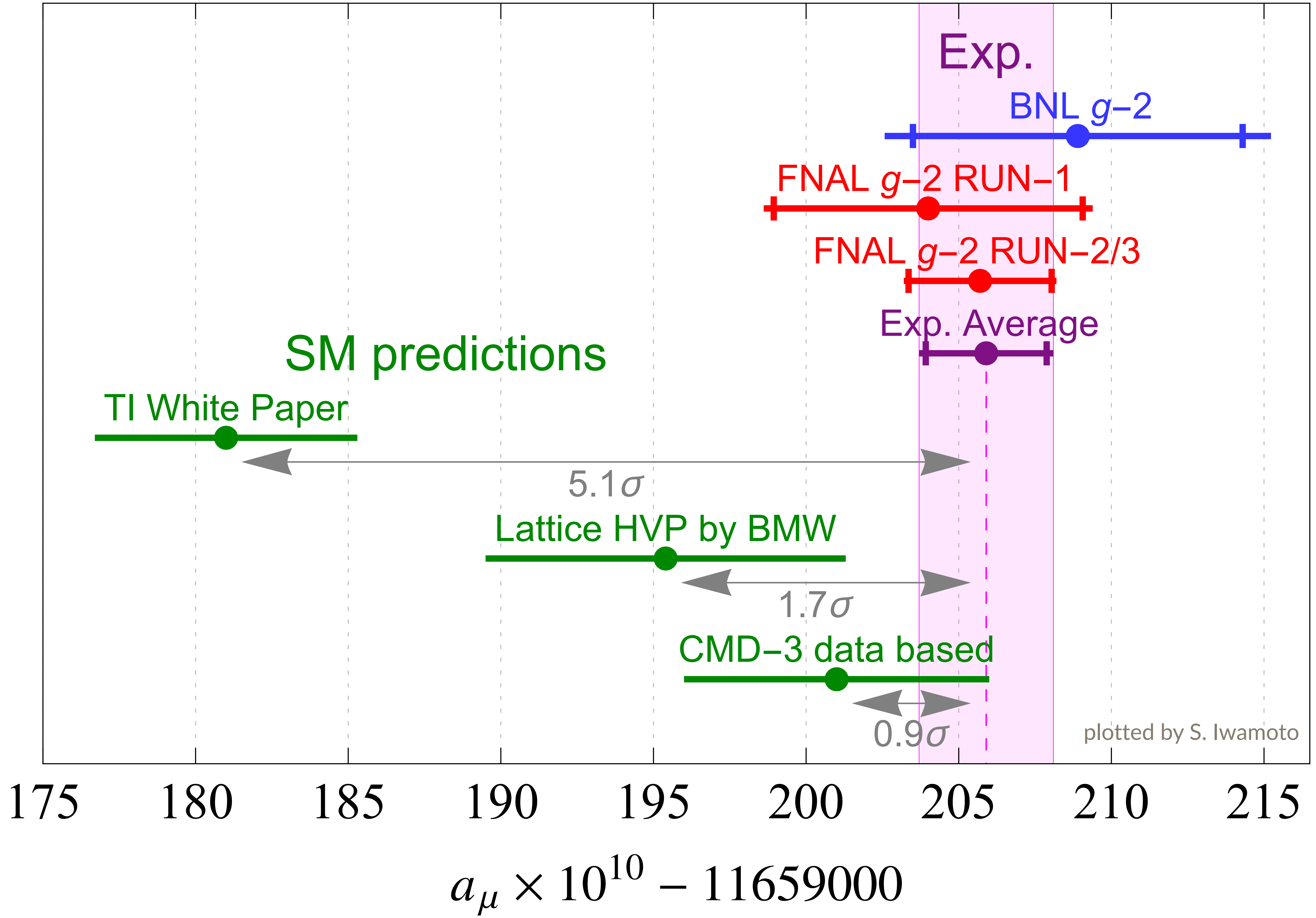
[Muon g-2 Collab. 2023, 2308.06230]

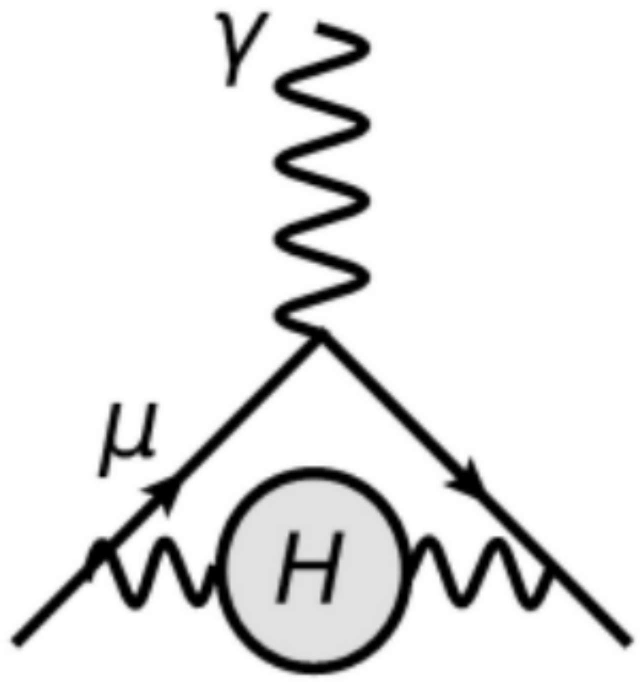


$$a_\mu(\mathrm{Exp}) = \frac{(g-2)_\mu}{2}(\mathrm{Exp}) = 116\,592\,059(22) \times 10^{-11}$$

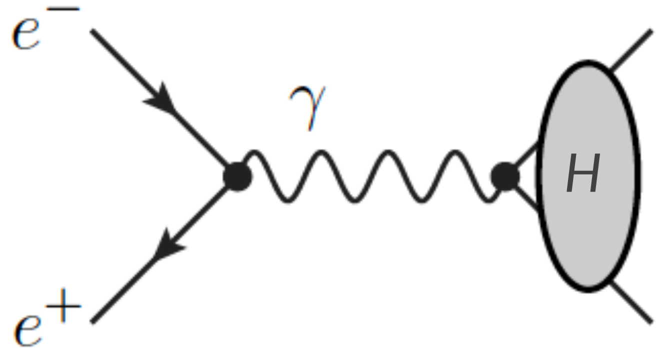
factor of two improved

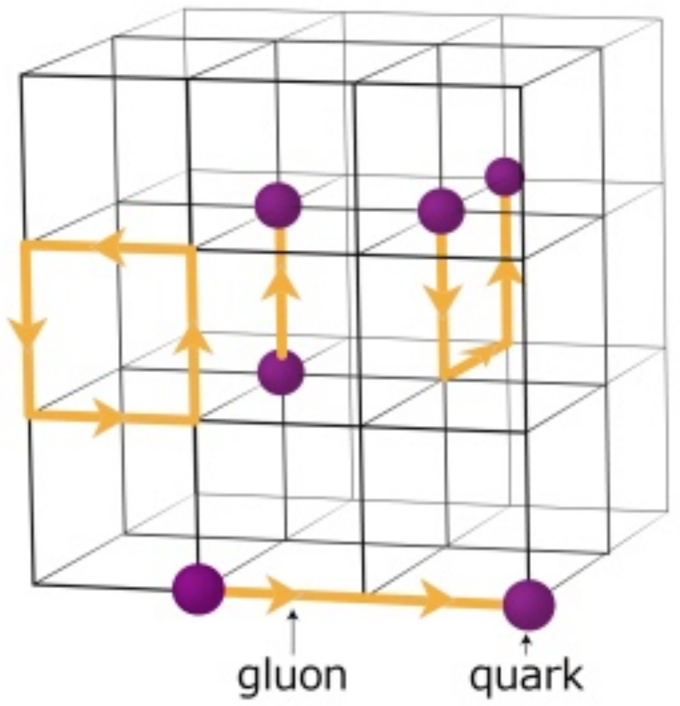
Current status of a_μ(Exp) vs a_μ(SM)





Hadronic-vacuum polarization



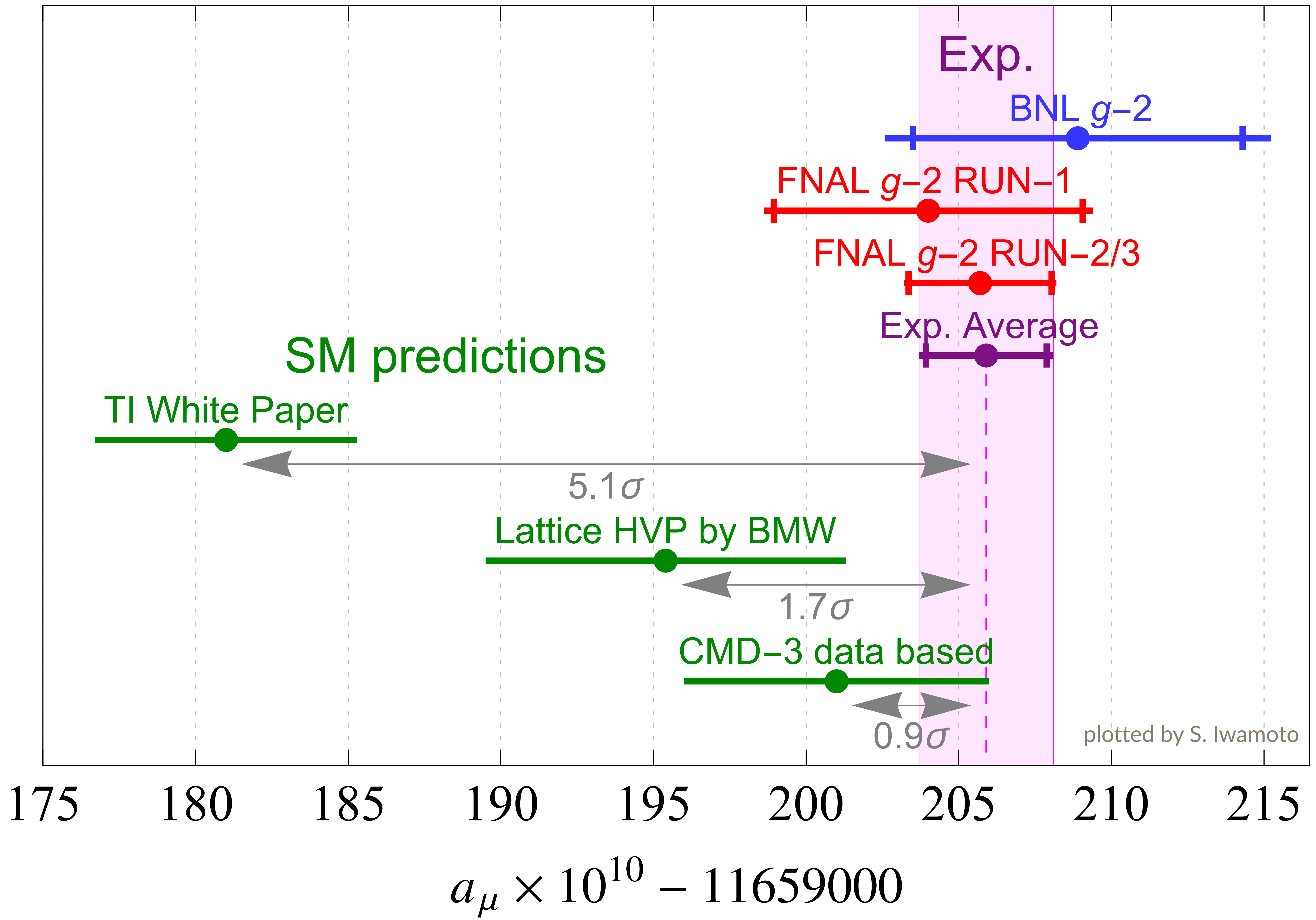


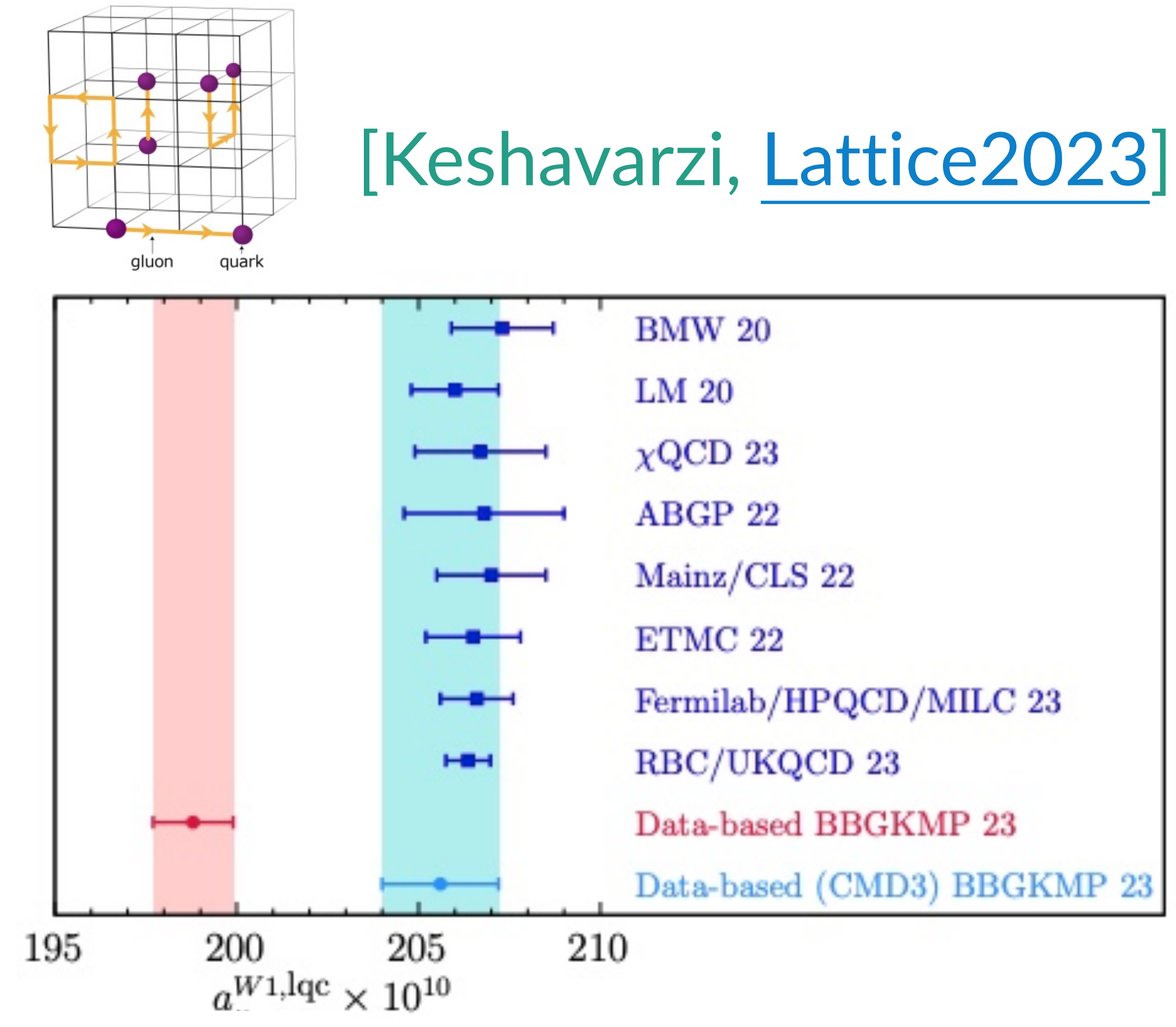
Data-driven

Lattice from [Bi, et al]

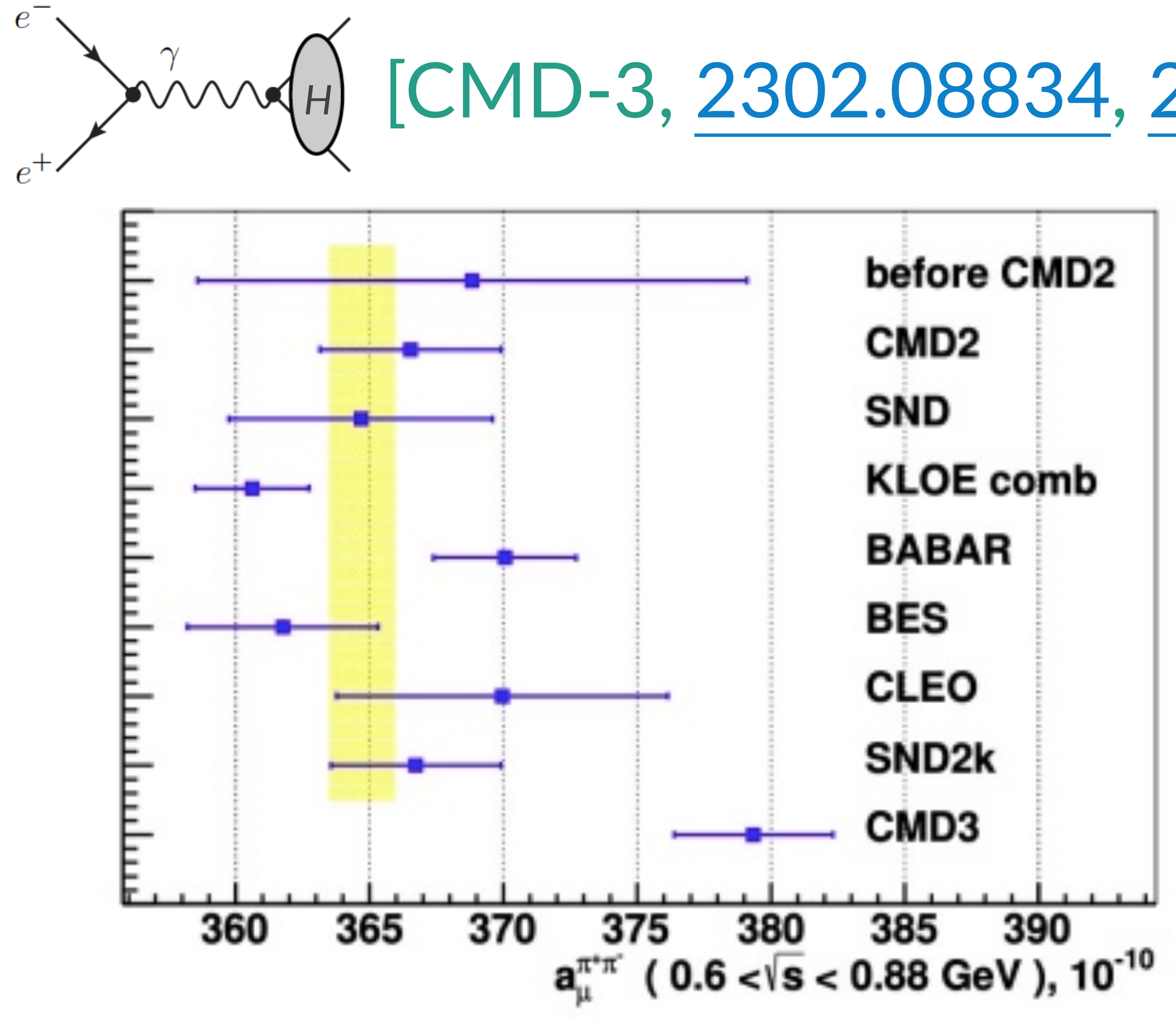
[BMW, 2002.12347]

Current status of $a_\mu(\mathrm{Exp})$ vs $a_\mu(\mathrm{SM})$





[Keshavarzi, Lattice2023]



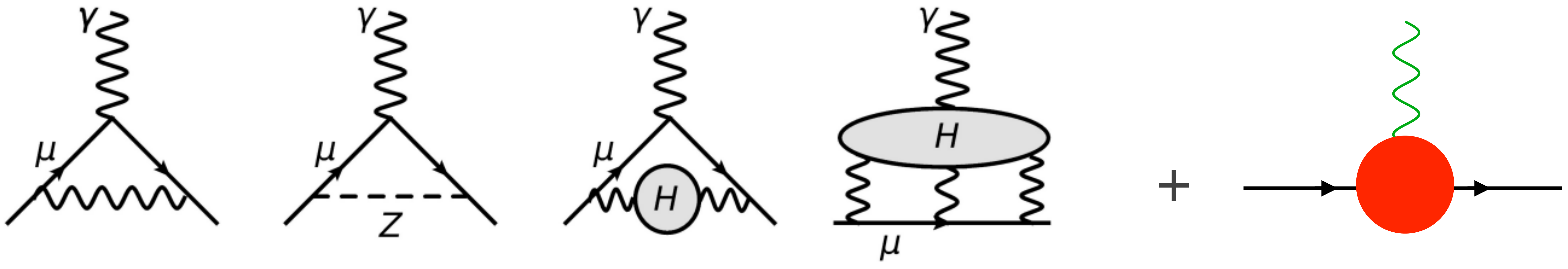
[CMD-3, 2302.08834, 2309.12910]

Prospects of $a_\mu(\mathrm{Th})$

[see details, Statement of the Muon g-2 Theory Initiative]

- Long-distance contribution to HVP (BMW) has not been cross-checked by other lattice
  - The intermediate window observables (⅓ of the total HVP) have been cross-checked well
- CMD-2, CMD-3 and SND collaborations are using the same facility, but only CMD-3 provides the different result of the $\pi^+\pi^-$ cross section
  - New analysis of **BaBar** (in 2024), update analysis of **SND**, update and new analysis of **BES III**, update and new blind analysis of **KLOE**, and **Belle II** result (in 2025) of the $\pi^+\pi^-$ cross sections will be reported in near future
- Next theory consensus value will be announced in near future
- MUonE (space-like HVP) final-goal result will be announced in LHC Run 4 (~2030)

Naive new physics mass scale



QED | EW | Hadronic vacuum polarization **(HVP)** | Hadronic light-by-light **(HLbL)** | New physics (NP)

$$\Delta a_\mu \equiv a_\mu(\mathrm{Exp}) - a_\mu^{WP}(\mathrm{SM}) = (24.9 \pm 4.8) \times 10^{-10}\ (5.1\sigma)$$

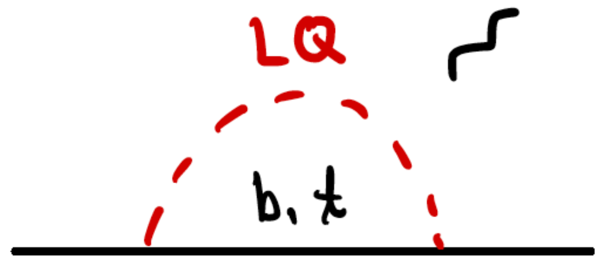
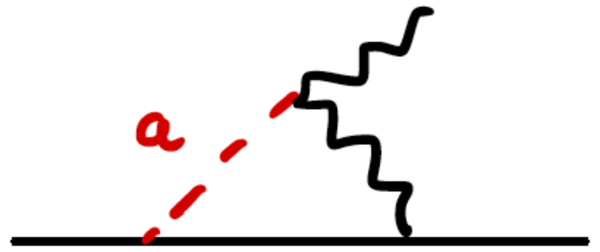
$$= \frac{m_\mu^2}{16\pi^2}\frac{g_{\rm NP}^2}{M_{\rm NP}^2} \Rightarrow M_{\rm NP} \approx g_{\rm NP} \times 150\,\mathrm{GeV}$$

- TeV scale NP (*e.g.*, **Supersymmetry**) with large $g_{\rm NP}$ (*e.g.*, $\tan\beta$ enhancement, chiral enhancement)
- MeV scale NP with small $g_{\rm NP}$ (*e.g.*, $g_{\rm NP} \sim 10^{-3}$)

New physics scenarios on market

New physics interpretations

See [Endo, Iwamoto, TK, High Energy News, 2021] for details

NP type	diagrams	mass range	probe	
Supersymmtery		200〜500 GeV	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (h\tilde{\chi}_1^0)\,(W^\pm\tilde{\chi}_1^0)$ $pp \to \gamma\gamma \to \widetilde{\ell\ell^*}$	Heavy NP
Leptoquark		1.5〜2.1 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$ $Z \to \mu^+\mu^-$	Heavy NP
Vector-like lepton		100 GeV〜1 TeV	$h \to \mu^+\mu^-$ $Z \to \mu^+\mu^-$	Heavy NP
Scalar extensions		10〜100 GeV (A), 150〜300 GeV (H)	$Z \to \tau^+\tau^-$ $pp \to HA \to 4\tau$	Heavy NP
Axion-like particle		40 MeV〜200 GeV	$e^+e^- \to \gamma a \to 3\gamma$	Light NP
U(1) L_μ-L_τ		10〜200 MeV	$e^+e^- \to \mu^+\mu^- Z'$ $K \to \mu\nu Z'$, $\mu e \to \mu e Z'$	Light NP

New physics interpretations

See [Endo, Iwamoto, TK, High Energy News, 2021] for details

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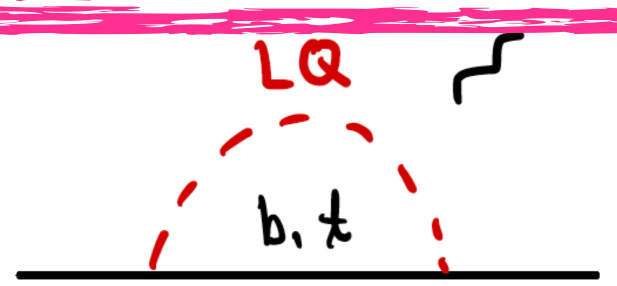
Leptoquark		1.5〜2.1 TeV	$pp \to \mathrm{LQLQ}$ $Z \to \mu^+\mu^-$
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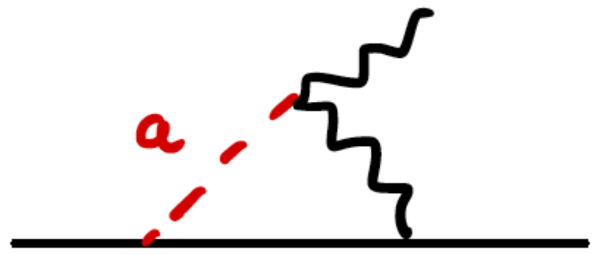
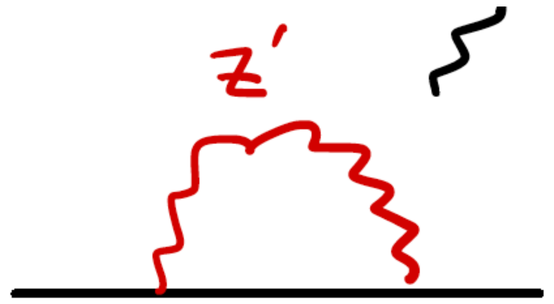
Axion-like particle		40 MeV〜200 GeV	$e^+e^- \to \gamma a \to 3\gamma$
U(1) Lμ-Lτ		10〜200 MeV	$e^+e^- \to \mu^+\mu^- Z'$ $K \to \mu\nu Z',\ \mu e \to \mu e Z'$

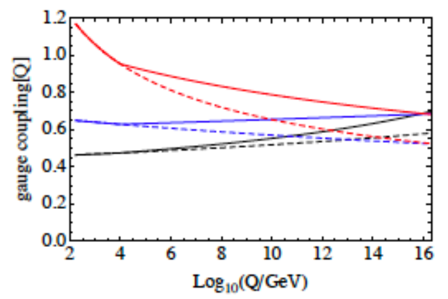
WIMP DM!!

Heavy NP

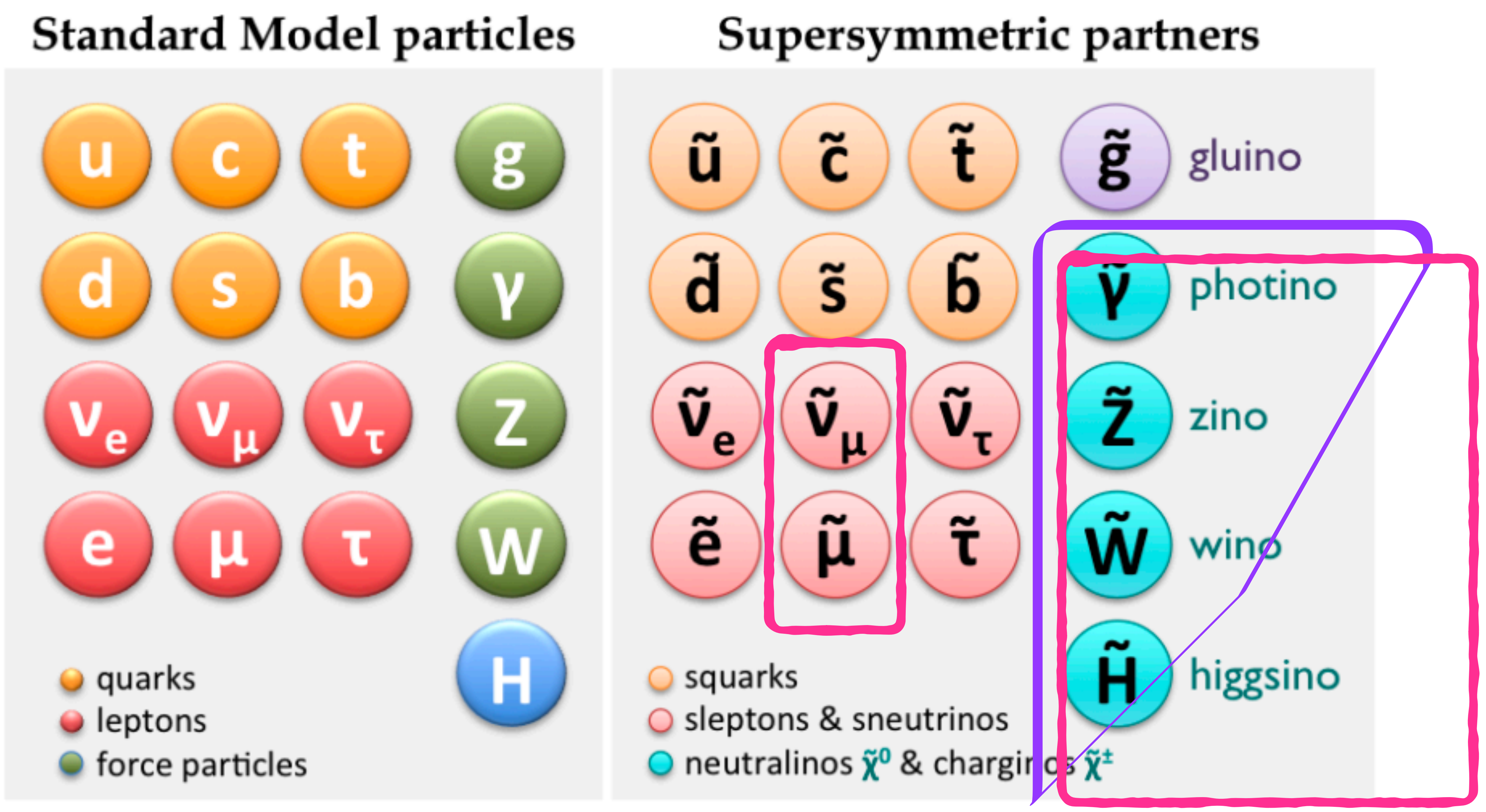
Light NP

Supersymmetry and WIMP DM

- Fundamental motivation of Supersymmetry (SUSY): **hierarchy problem**, **vacuum stability, gauge coupling unification**



- Extra advantages: there are natural parameter regions for **WIMP dark matter** and **muon g-2**



Lightest SUSY particle is a WIMP dark matter candidate

Large muon g-2 contribution

https://ific.uv.es/sct/physics_susy

$\tan\beta$ enhancement

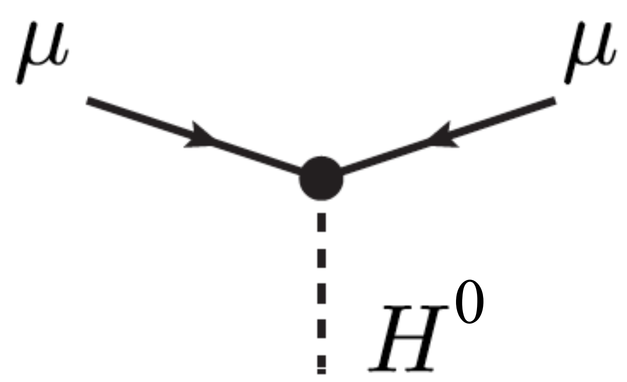
- $\tan\beta \equiv v_u/v_d$ is a free parameter with $v_{\rm SM} = \sqrt{v_u^2 + v_d^2}$

SM

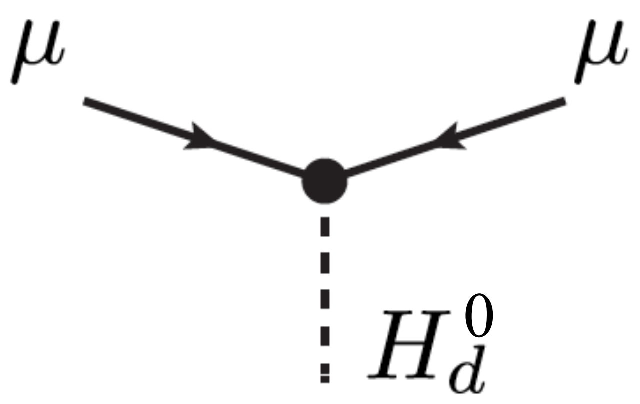
$$\begin{pmatrix} H^+ \\ v + H^0 \end{pmatrix}_{\rm SM} \rightarrow \begin{pmatrix} H_u^+ \\ v_u + H_u^0 \end{pmatrix}, \begin{pmatrix} v_d + H_d^0 \\ H^- \end{pmatrix}_{\rm SUSY}$$

Holomorphy and gauge anomaly

SUSY



$m_\mu = y_\mu^{\rm SM} v$ $\rightarrow$



$m_\mu = y_\mu^{\rm SUSY} v_d$

$m_\mu = m_\mu$ $\rightarrow$

$$y_\mu^{\rm SUSY} = y_\mu^{\rm SM}\frac{v}{v_d} = y_\mu^{\rm SM}\frac{1}{\cos\beta} \simeq y_\mu^{\rm SM}\tan\beta$$

- When $v_d \ll v_u \leftrightarrow \tan\beta \gg 1$, the SUSY muon Yukawa $y_\mu^{\rm SUSY}$ is enhanced by $\tan\beta = \mathcal{O}(10)$

SUSY interpretations

- Four types of diagrams are responsible to explain *g-2* (three particles must be light):

1, WHL scenario 2, BLR scenario 3, BHL scenario 4, BHR scenario

- All diagrams are proportional to $\tan\beta = \mathcal{O}(10) \to$ effectively large $g_{NP} \to$ TeV scale

- 1, WHL and 2, BLR → Good candidate

- 3, BHL and 4, BHR are constrained from dark matter direct detection (XENON1T)

[Endo, Hamaguchi, Iwamoto, Yanagi, 1704.05287; Baum, Carena, Shah, Wagner, 2104.03302]

BLR + bino-stau coannihilation

[Endo, Hamaguchi, Iwamoto, TK, 2104.03217]

Benchmark point

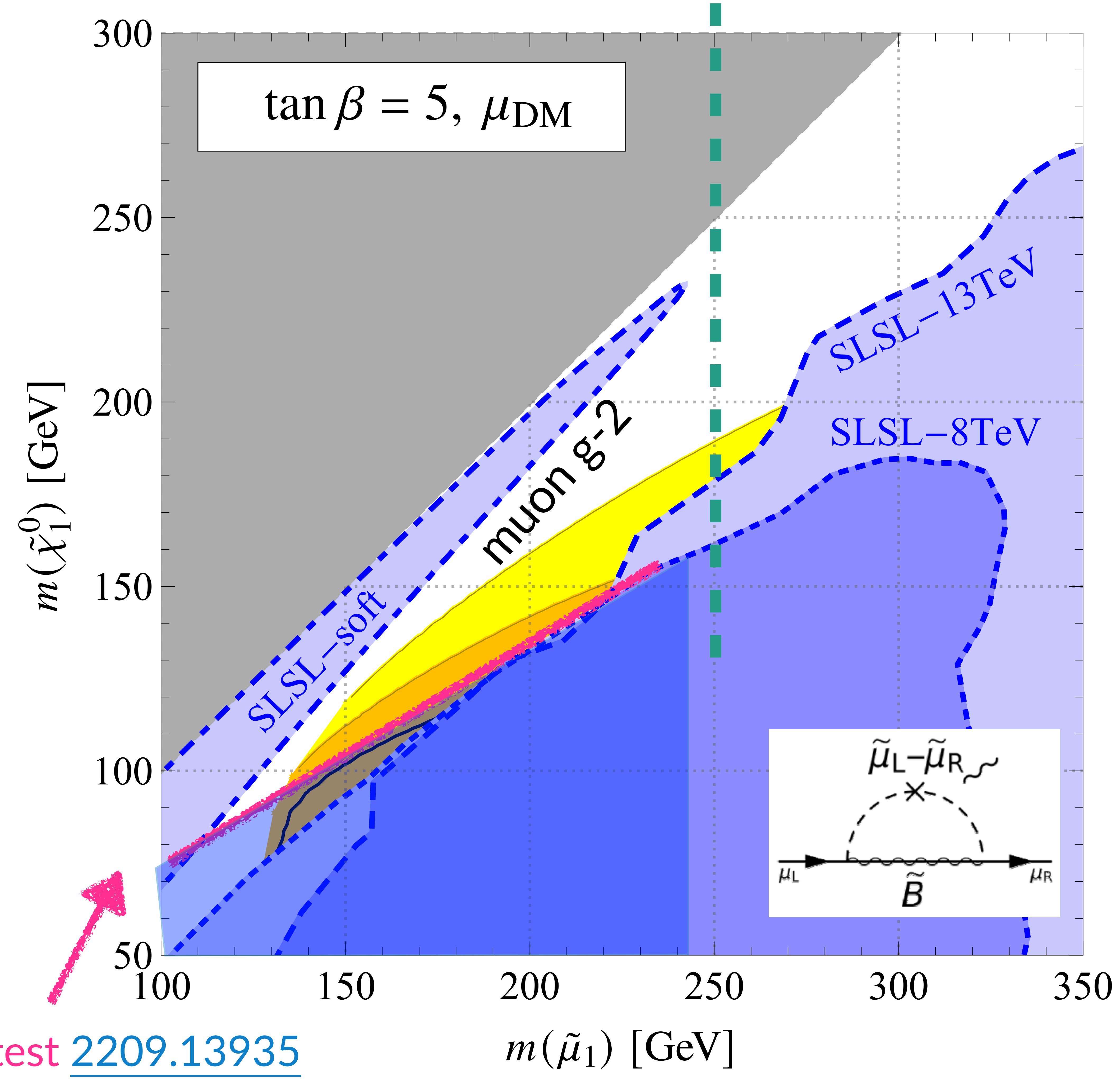
Bino-stau coannihilation
with correct Ω_{DM}
+ universal slepton mass

Large μ with small $\tan\beta$ is favored in this study
(BHR gives negative contribution)

strong bound from:

$$\tilde{\ell}\tilde{\ell}^* \to (\ell\tilde{\chi}_1^0)\,(\bar{\ell}\tilde{\chi}_1^0)$$

stau mass < 200 GeV
→ good target for **ILC500**



ATLAS the latest 2209.13935

Benchmark points

	BLR1	BLR3
M_1	100	150
$m_{\mathrm{L}} = m_{\mathrm{R}}$	150	200
$\tan\beta$	5	5
μ	1323	1922
$m_{\tilde{\mu}_1}$	154	202
$m_{\tilde{\mu}_2}$	159	207
$m_{\tilde{\tau}_1}$	113	159
$m_{\tilde{\tau}_2}$	190	242
$m_{\tilde{\nu}_{\mu,\tau}}$	137	190
$m_{\tilde{\chi}_1^0}$	99	150
$m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_1^\pm}$	1323–1324	1922–1923
$a_\mu^{\mathrm{SUSY}} \times 10^{10}$	27	17
$\Omega_{\mathrm{DM}} h^2$	0.120	0.120
$\sigma_p^{\mathrm{SI}} \times 10^{47}$ [cm^2]	1.7	0.8
$\mu_{\gamma\gamma}$	1.01	1.01

XENONnT (DM direct detection) can probe this scenario

WHL scenario (without DM)

[Endo, Hamaguchi, Iwamoto, TK, 2001.11025]

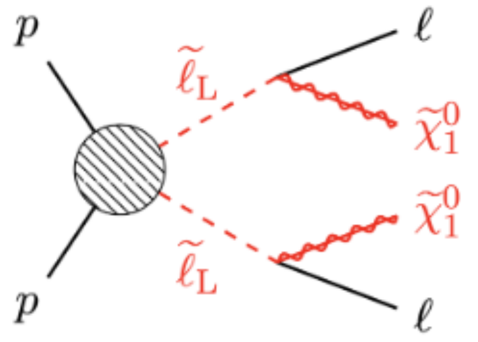
$m(\tilde{\chi}_1^\pm) = 500\text{GeV}$ light EWkino ⟵ / ⟶ light slepton

Benchmark point

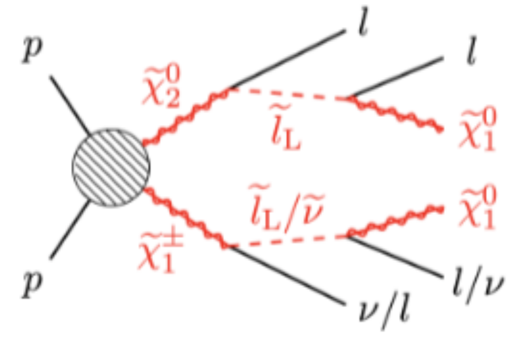
$$M_1 : M_2 : \mu = 1 : 2 : 4$$
$$\tan\beta = 40$$

strong bound from:

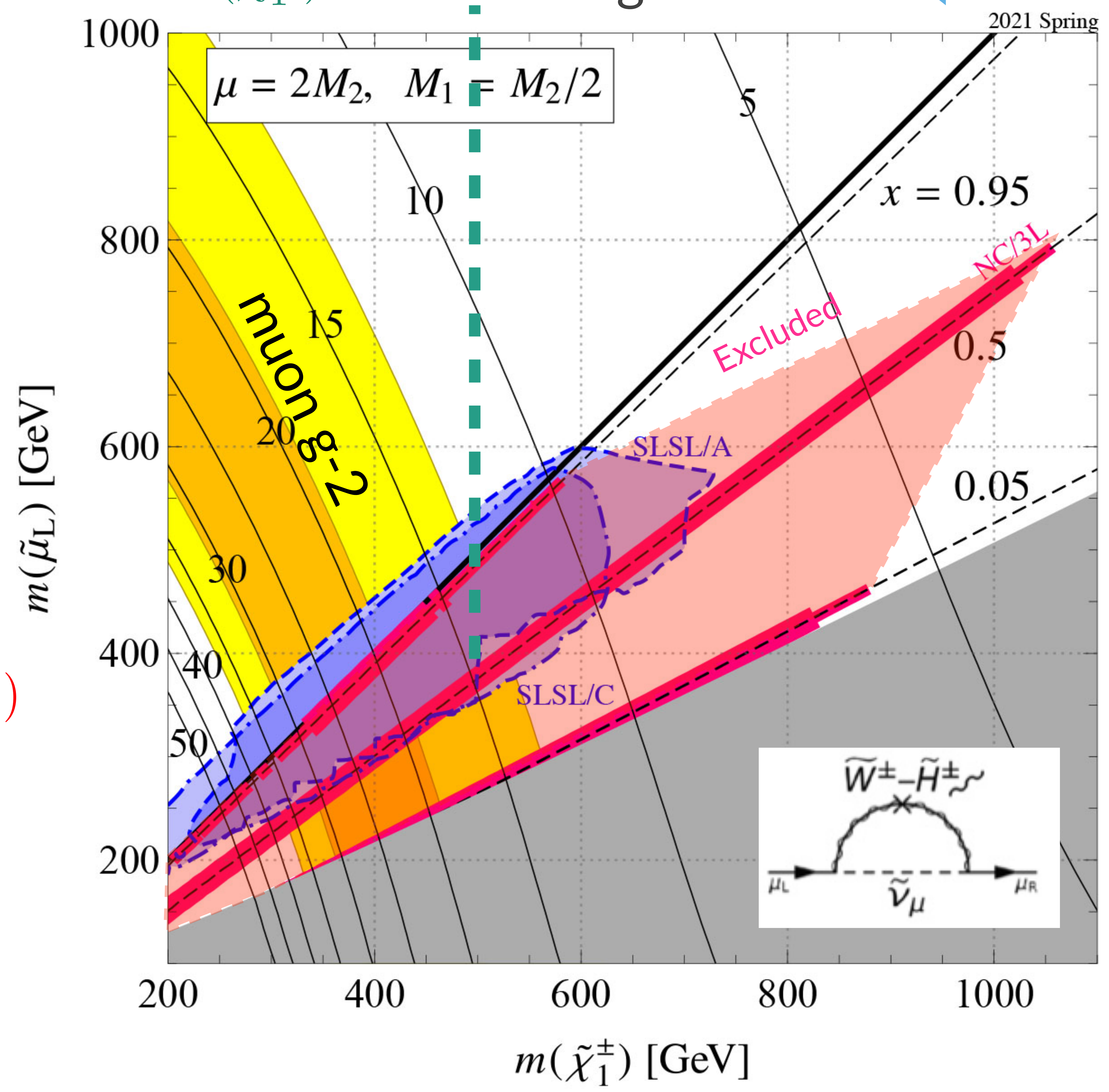
$\tilde{\ell}_L \tilde{\ell}_L^* \to (\ell\tilde{\chi}_1^0)\,(\bar{\ell}\tilde{\chi}_1^0)$



$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to \left(l\tilde{l}_L\right)\left(\nu\tilde{l}_L\right) \to (ll\tilde{\chi}_1^0)\,(\nu l\tilde{\chi}_1^0)$



ILC1TeV can probe these arrowed regions



For WIMP dark matter, bino-wino coannihilation can explain the DM relic density

[Chakraborti, Heinemeyer, Saha, Schappacher, 2112.01389; Baum, Carena, Ou, Rocha, Shah, Wagner, 2303.01523]

WHL scenario (without DM)

[Endo, Hamaguchi, Iwamoto, TK, 2001.11025]

$m(\tilde{\chi}_1^\pm) = 500\text{GeV}$ light EWkino ⟵ / ⟶ light slepton

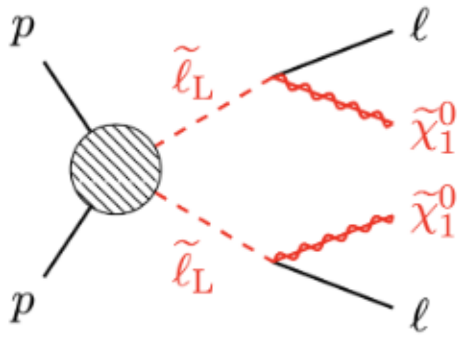
Benchmark point

$M_1 = 100\text{GeV}$ ⟵

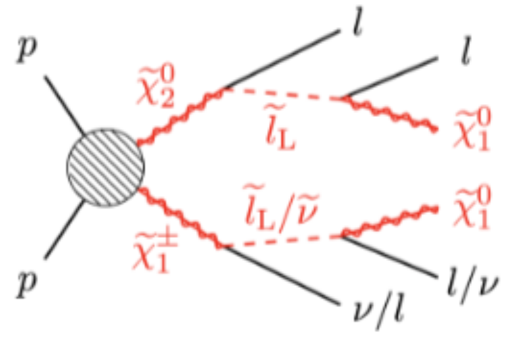
$\tan\beta = 40$

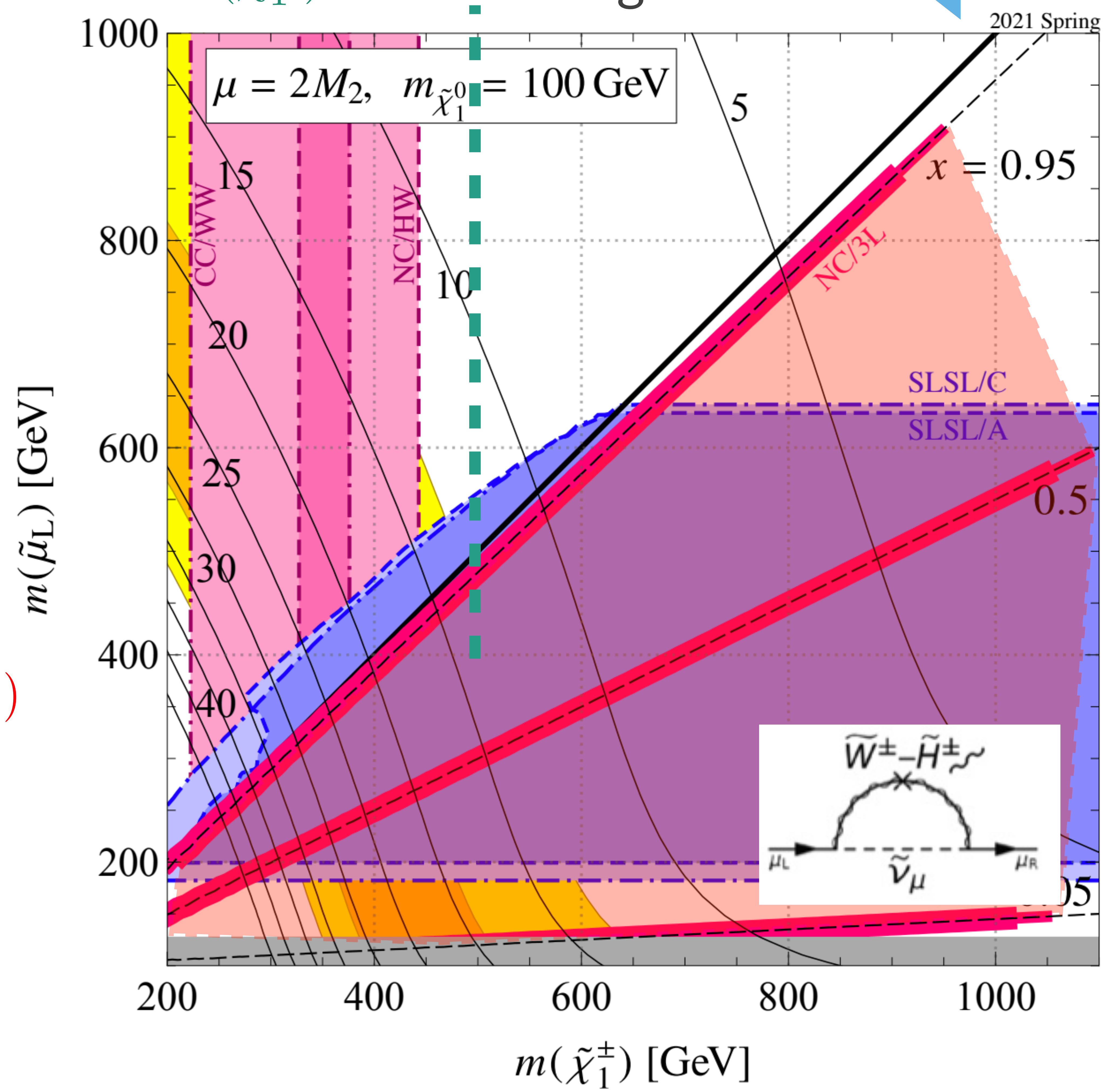
strong bound from:

$\tilde{\ell}_L \tilde{\ell}_L^* \to (\ell \tilde{\chi}_1^0)\,(\bar{\ell}\tilde{\chi}_1^0)$



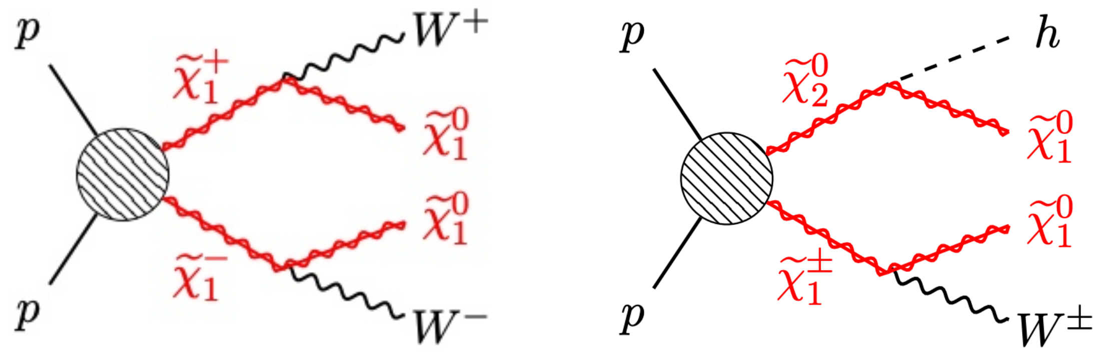
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to (l\tilde{l}_L)\,(\nu\tilde{l}_L) \to (ll\tilde{\chi}_1^0)\,(\nu l \tilde{\chi}_1^0)$





$\tilde{\chi}_1^+ \tilde{\chi}_1^- \to (W^+ \tilde{\chi}_1^0)\,(W^- \tilde{\chi}_1^0)$

$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to (h\tilde{\chi}_1^0)\,(W^\pm \tilde{\chi}_1^0)$



Point: $\tilde{W}^0$ decays into h. In general, $\text{Br}\left(\chi_2^0 \to \chi_1^0 Z\right) \sim O(0.1)$

Light bino scenario is severely constrained

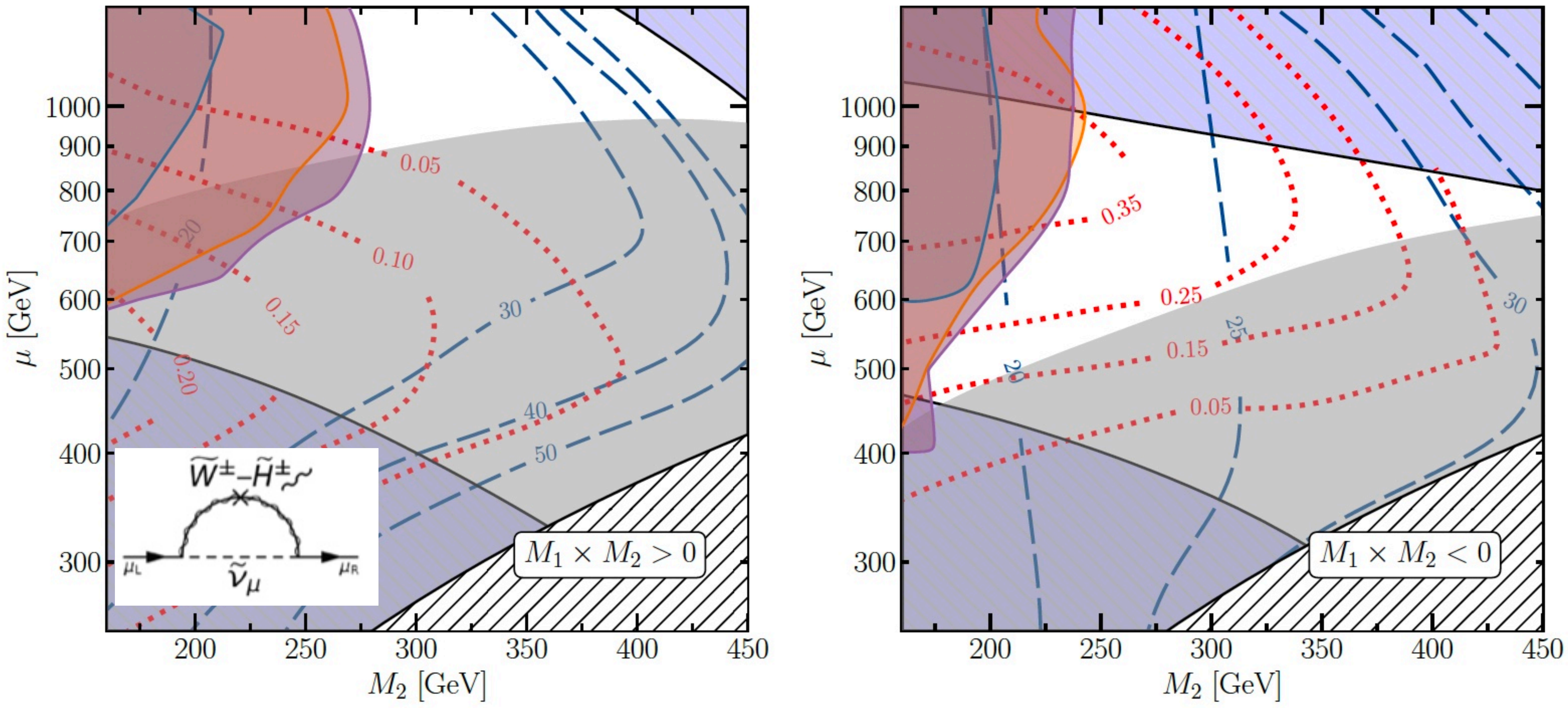
WHL + bino-wino coannihilation scenario

[Baum, Carena, Ou, Rocha, Shah, Wagner, 2303.01523]

- Bino mass M_1 is fixed by the relic abundance; bino-wino coannihilation

$$m_{\tilde{\mu}_L} = m_{\tilde{\mu}_L} = 500\,\mathrm{GeV} \ \text{and} \ \tan\beta = 50$$

excluded by soft slepton searches



Δa_μ within 2σ

$(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$ [GeV]

$\sigma_{\rm DD} \times (\Omega_{\tilde{\chi}_1^0} h^2/0.12)$ Excluded

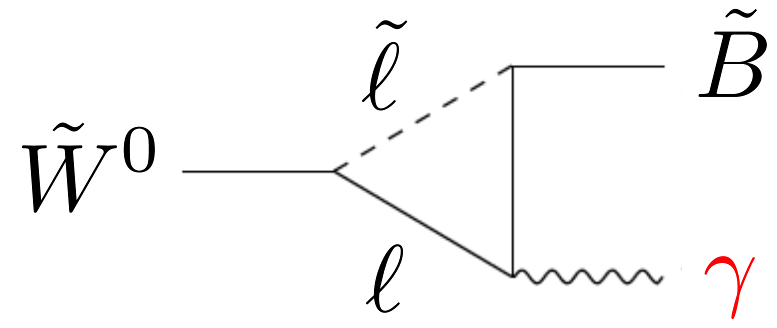
$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma)$

$M_1 \times M_2 < 0$ case is interesting

1. Direct detection is weakened
   "blind spot ($M^{\rm SI} = 0$)"

$$\mathcal{M}^{\rm SI} \propto 2\frac{(M_1 + 2\mu/\tan\beta)}{m_h^2} + \frac{\mu\tan\beta}{m_H^2}$$

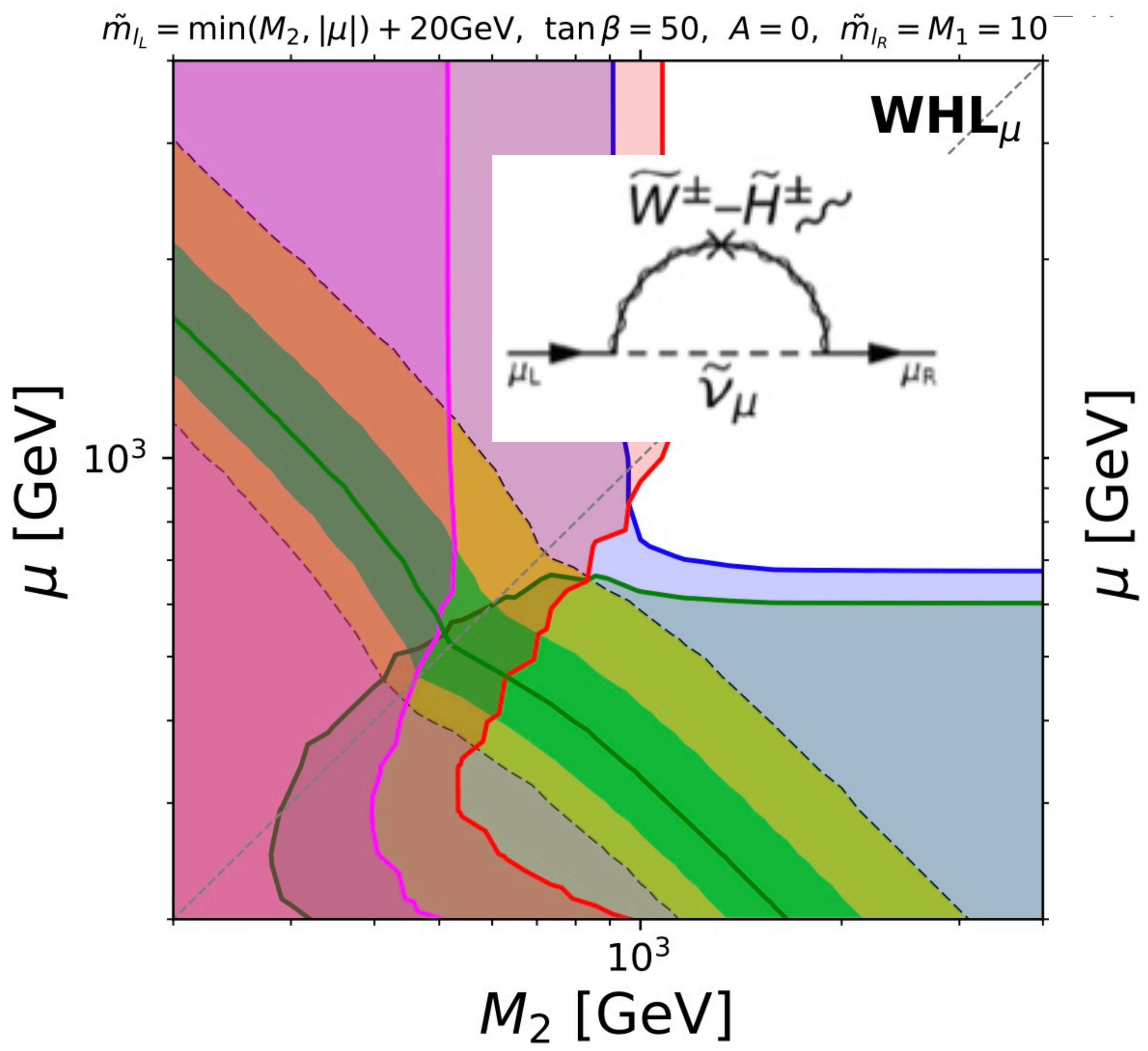
2. radiative decay BR is large



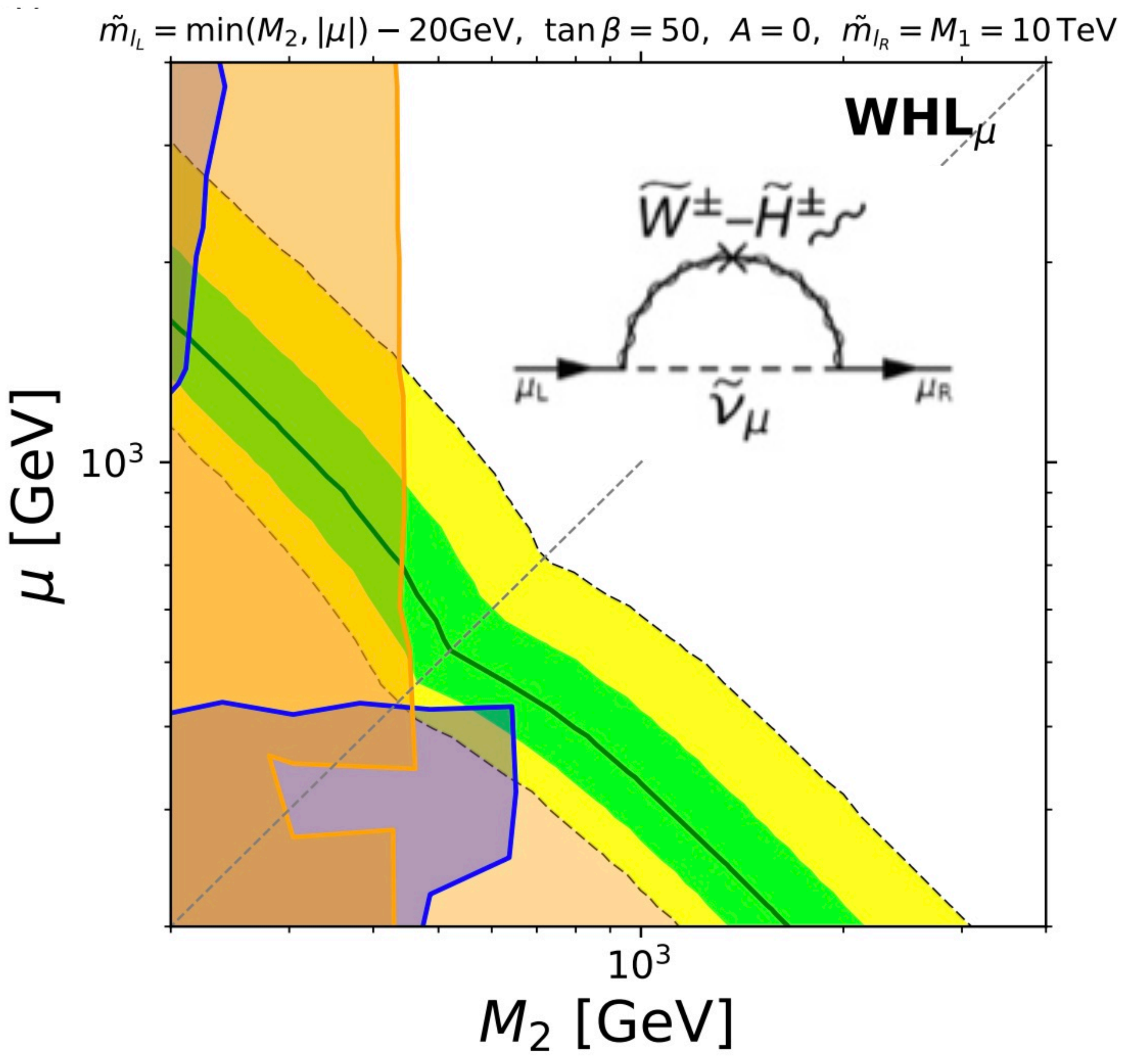
MSSM + Gravitino (GMSB)

[Chakraborti, Iwamoto, Kim, Masełek, 2202.12928]

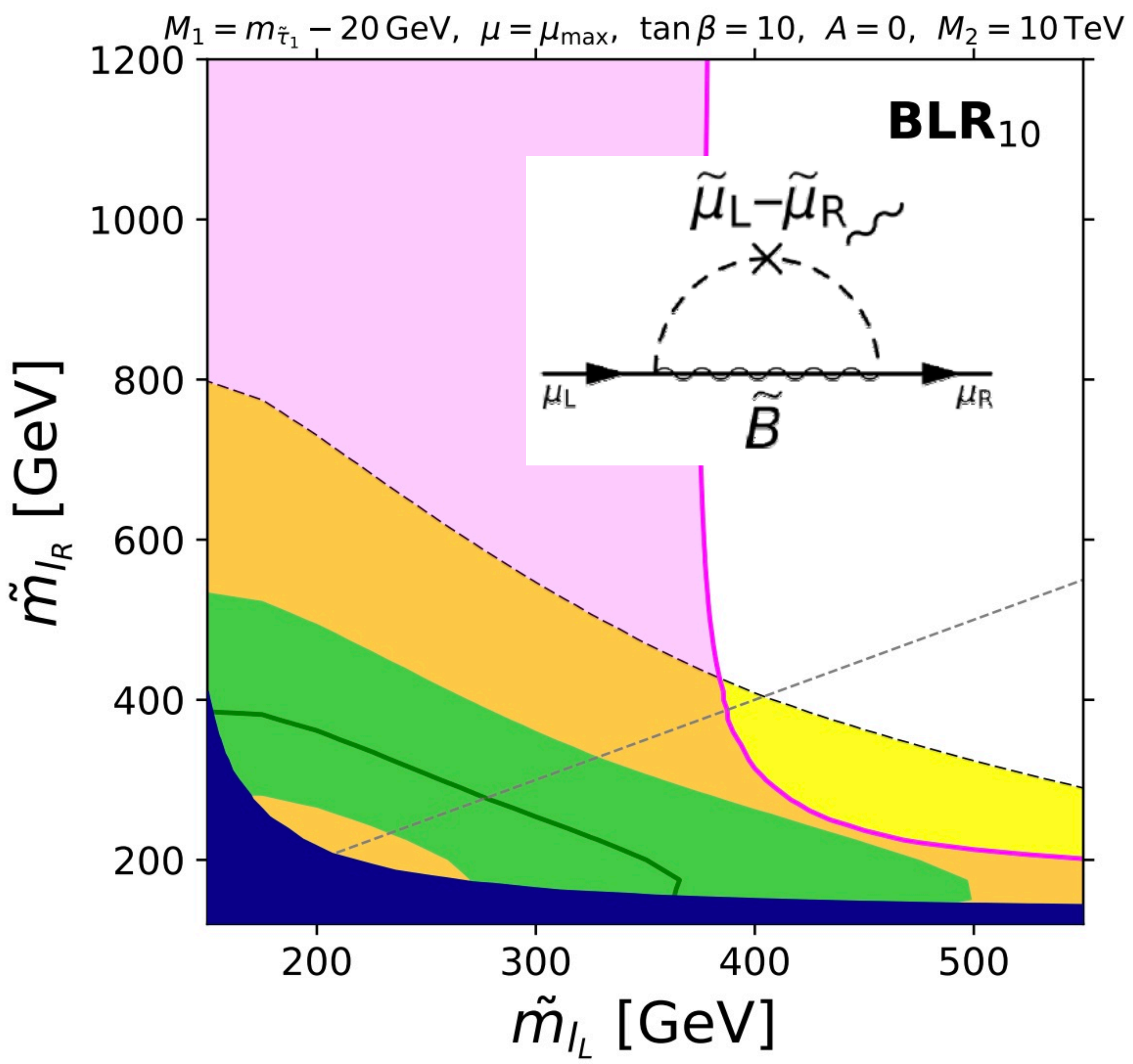
- In the gauge-mediation SUSY breaking, the lightest neutralino promptly decays into (~massless) gravitino $+\gamma/Z/h$, and no bound from DM direct detection



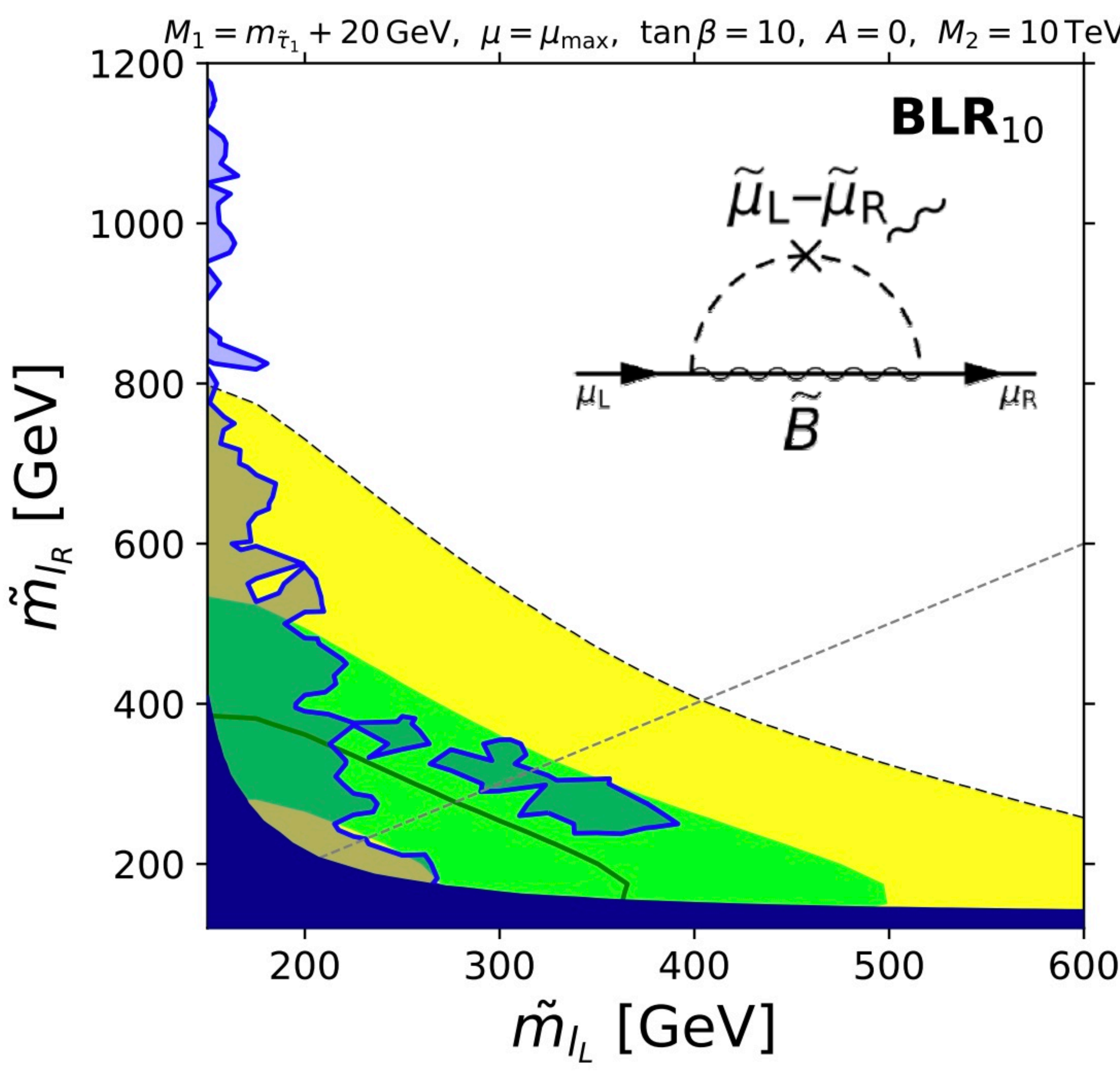
Neutralino NLSP



Slepton NLSP



Neutralino NLSP

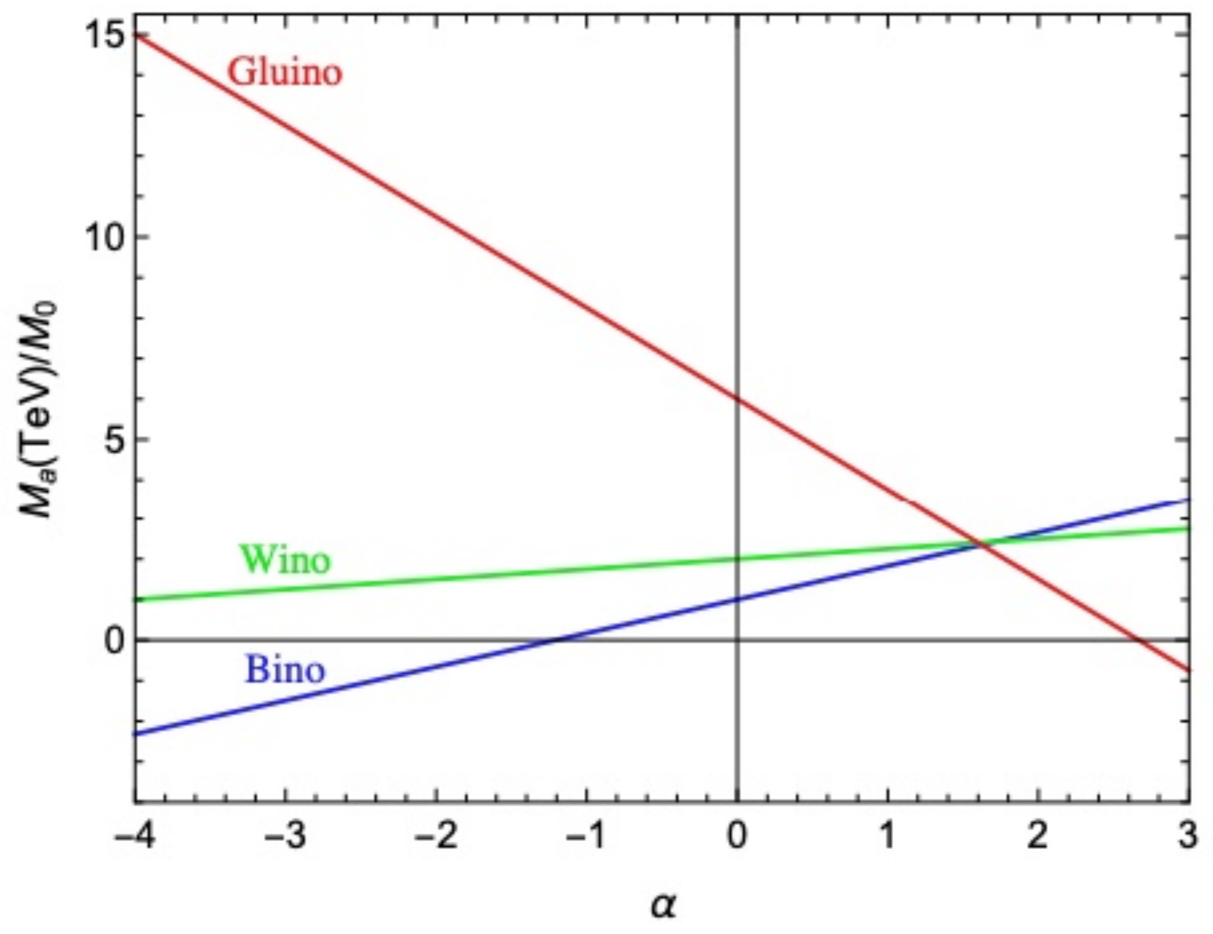


Slepton NLSP

UV model

- For muon g-2 anomaly, light slepton and light electroweakino are required $< \mathcal{O}(500)$GeV
- Under the GUT relation $M_1 : M_2 : M_3 \simeq 1 : 2 : 6$, a large portion of the parameter space is constrained by **direct gluino searches**
- Several theories can predict $M_1, M_2 \ll M_3$
  - a UV completion: mirage/mixed modulus-anomaly mediation
    [Jeong, Kawamura, Park,2106.04238]

$$M_1 : M_2 : M_3 \simeq (1 + 0.83\alpha) : (2 + 0.25\alpha) : (6 - 2.25\alpha)$$



α is a rational number determined by underlying string compactification

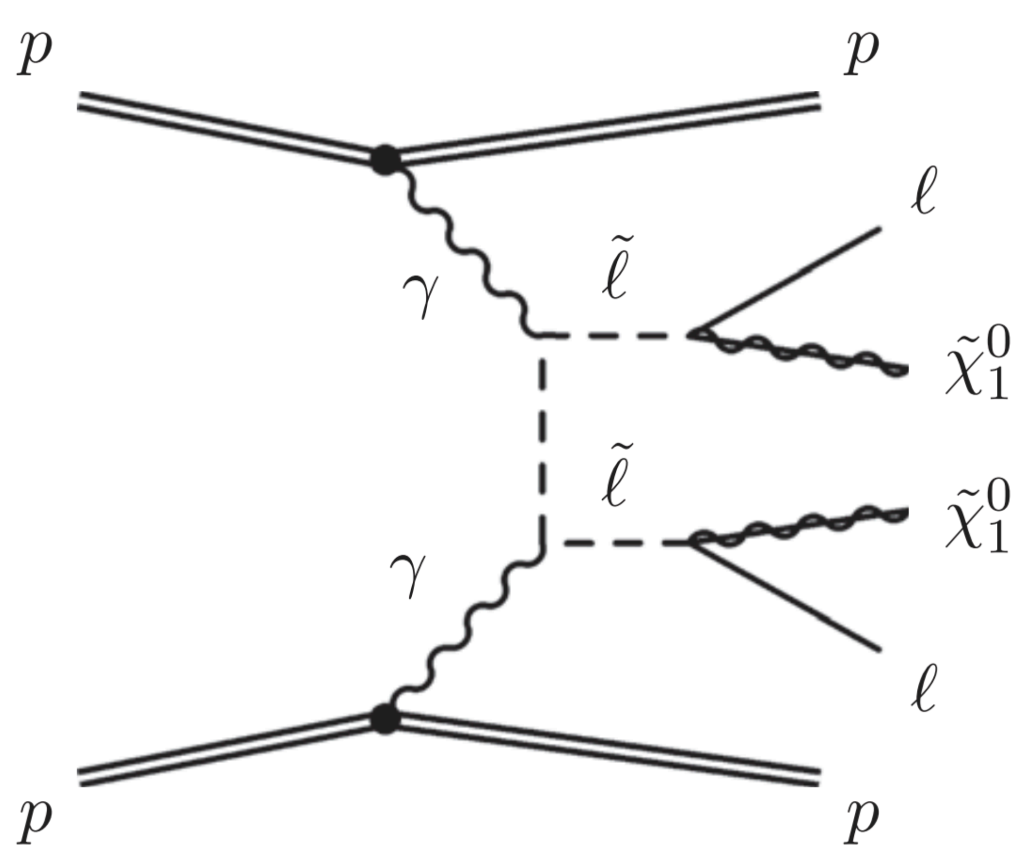
$$\alpha = -2 \to M_1 : M_2 : M_3 \simeq 1 : -2 : -16$$

Slepton search via photon collision

- Novel idea: slepton can be probed via photon collision in the LHC [Beresford, Liu, 1811.06465]

$pp \to \gamma\gamma pp \to \tilde{\ell}\tilde{\ell}^* \to (\ell\tilde{\chi}_1^0)\,(\bar{\ell}\tilde{\chi}_1^0)$

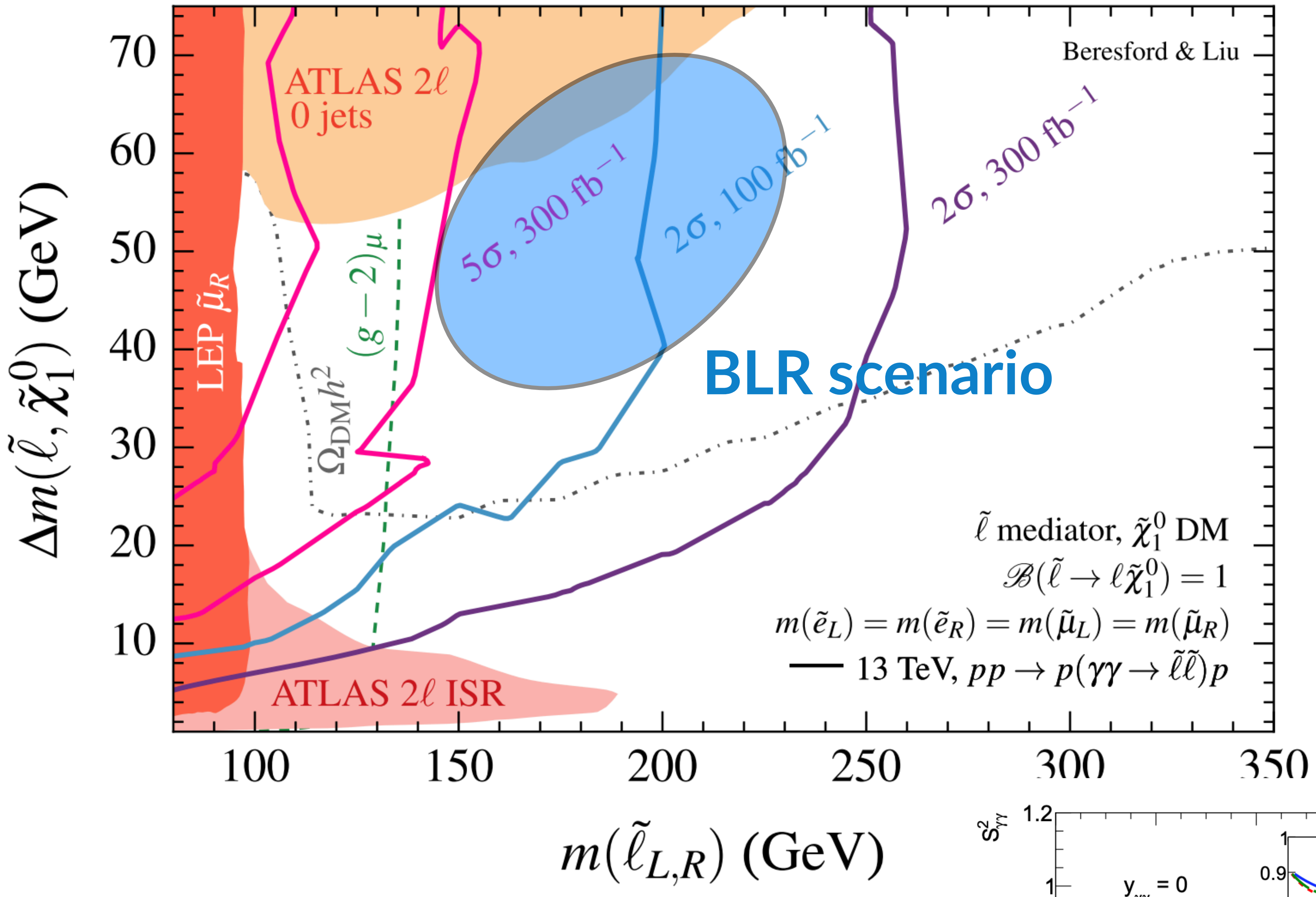
Slepton mass gap could be covered.



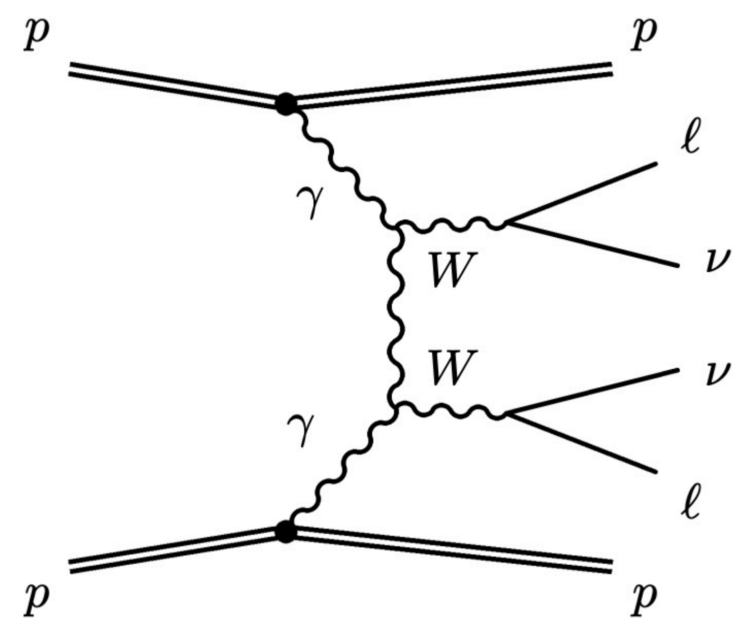
1, measure **outgoing proton** E_p by forward detector

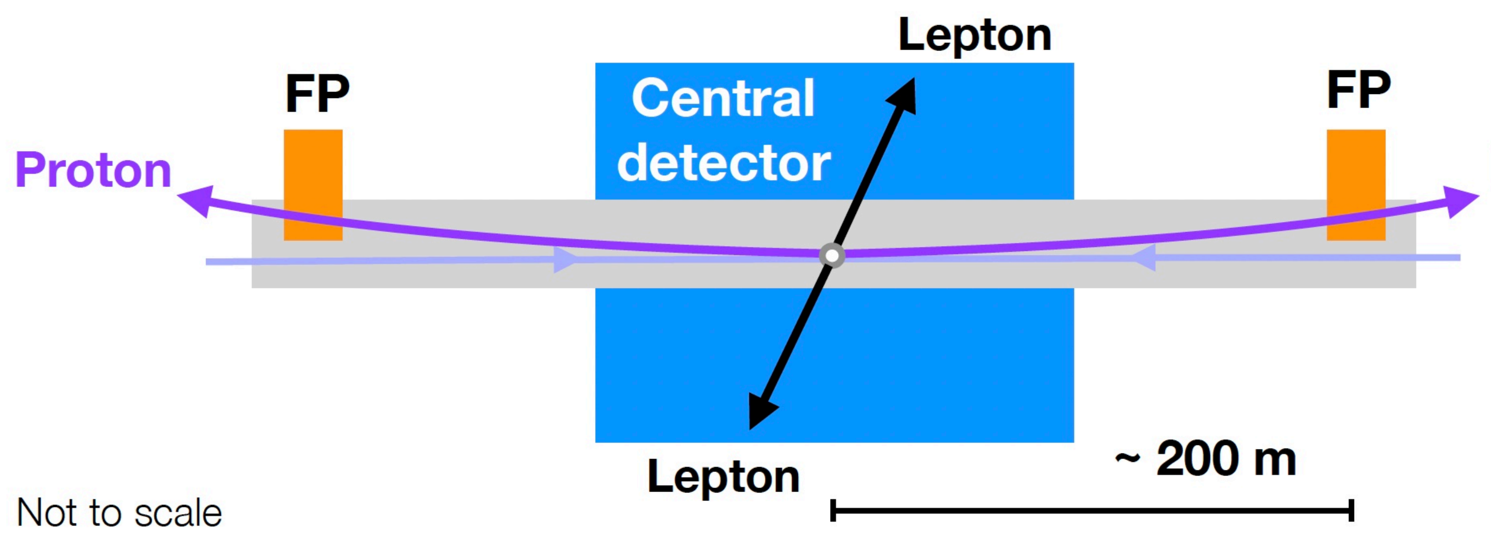
2, measure lepton four-momentum

3, reconstruct missing momentum



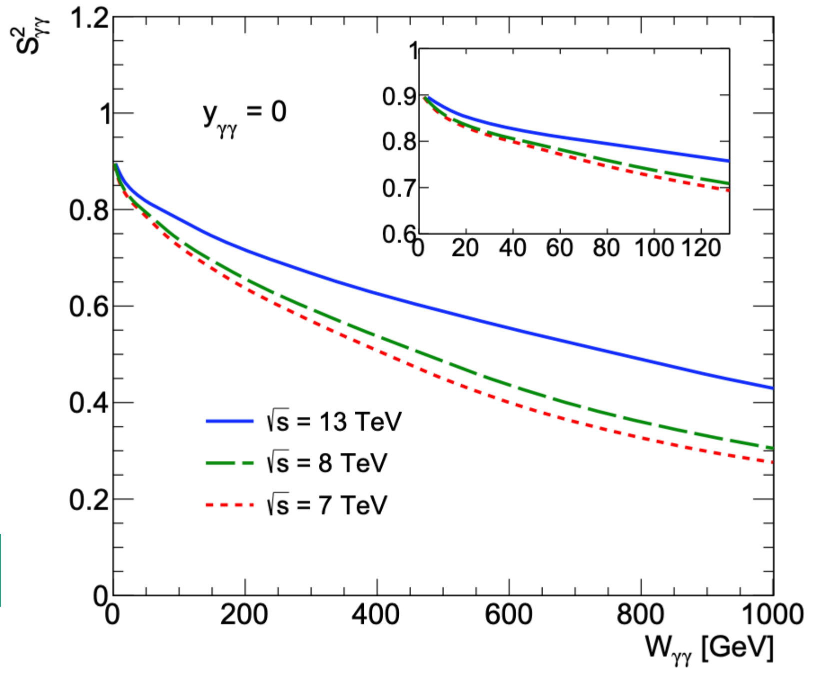
Bkg





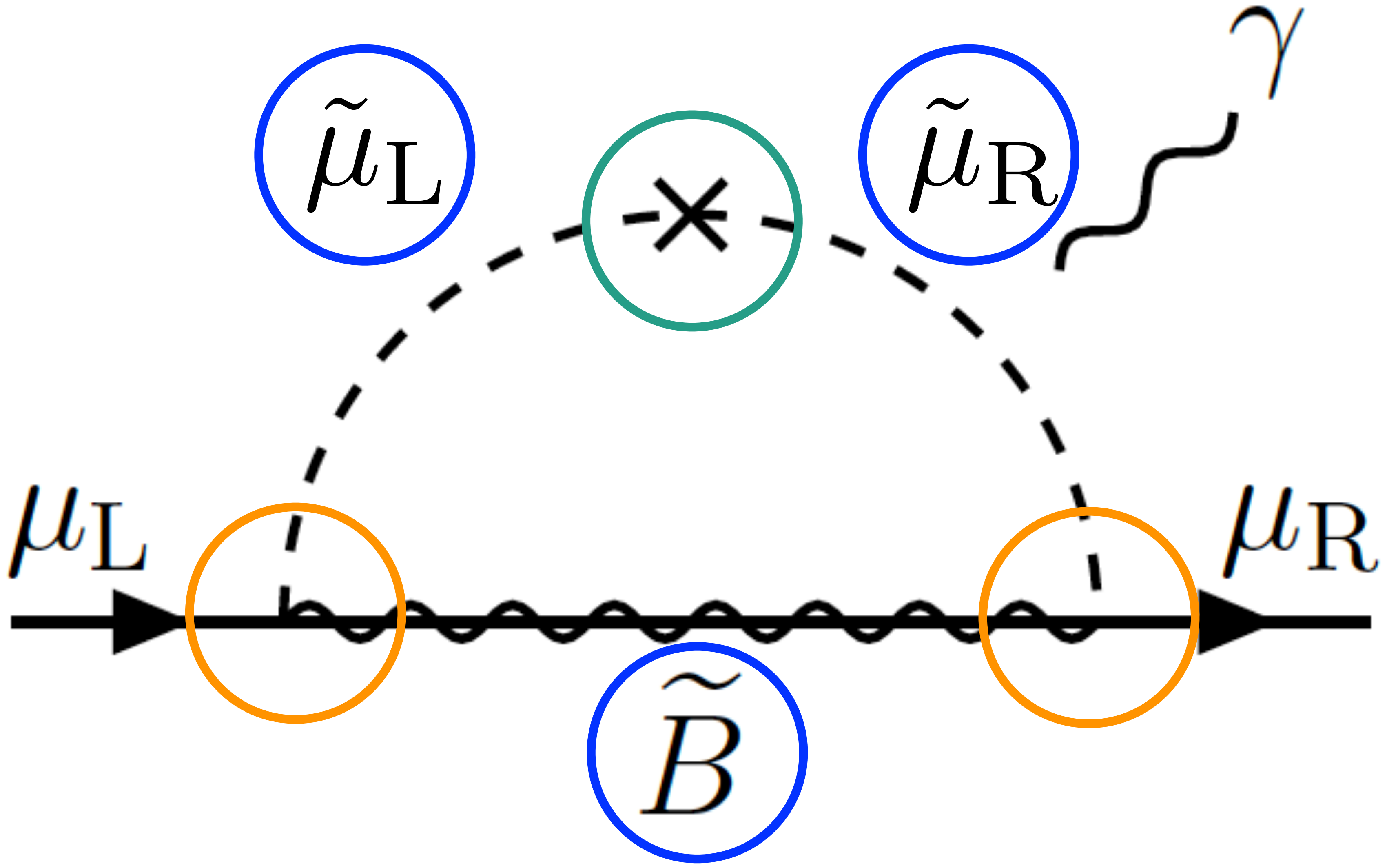
Proton soft survival probability

ATLAS first result [ATLAS 2009.14537] agrees on [Dyndal et al, 1410.2983]



Reconstruction $a_\mu^{\rm SUSY}$ from ILC measurements

- When *all charged-sleptons are measured* in the **ILC500**, one can reconstruct SUSY contribution to the muon g-2 [Endo, Hamaguchi, Iwamoto, TK, Moroi, 1310.4496 + Kawada, Suehara, 2203.07056]



Note: $\tilde{g}_{1,{\rm L/R}}$ would deviate at O(1-10)% from U(1)$_Y$ gauge coupling due to several SUSY contributions

Based on **SPS1a' model-point study** [0902.2434]

parameters	processes	precisions
$m_{\tilde{\mu}_{\rm L}},\, m_{\tilde{\mu}_{\rm R}},\, m_{\tilde{\chi}_1^0}$	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$	O(0.1)%
$\tilde{\mu}_{\rm L}$-$\tilde{\mu}_{\rm R}$ mixing	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$	12%
$\tilde{g}_{1,{\rm L}},\, \tilde{g}_{1,{\rm R}}$	$e^+e^- \to \tilde{e}^+\tilde{e}^-$	O(1)%
$a_\mu^{\rm reconst.}$	—	**13%**
$a_\mu^{\rm th\, error}$	if $m_{\tilde{\chi}_1^\pm} > 1\,{\rm TeV}$	< 4%

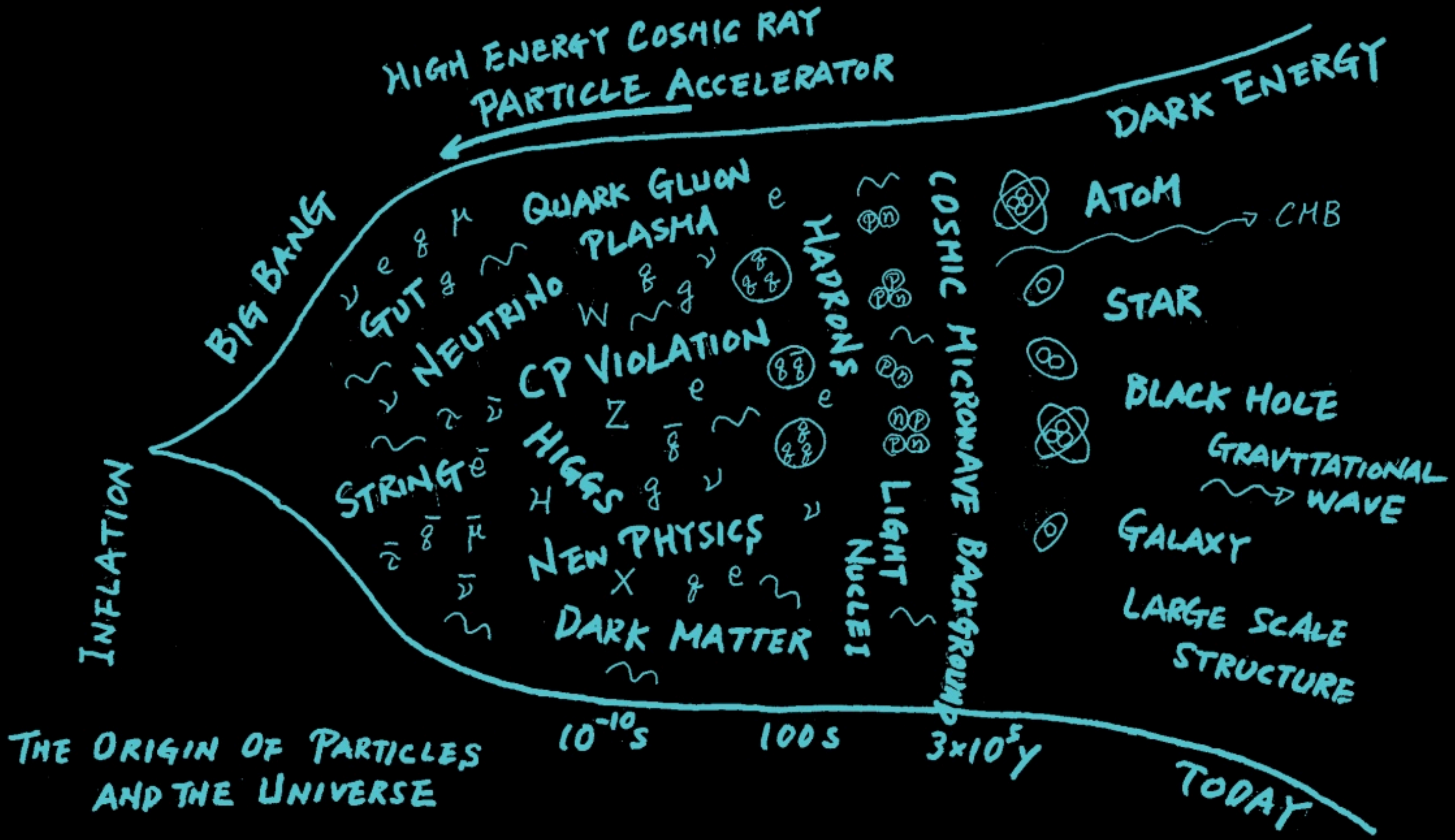
Summary

- Standard model prediction of the muon g-2 is currently controversial, but the consensus prediction provides 5.1σ tension
  - Other lattice group results/ BaBar, KLOE, BES III, SND, Belle II new results/ MUonE result will shed light on **the HVP contributions**
- SUSY interpretations of the muon g-2 with WIMP dark matter still work (only the following two region in MSSM)
  - Wino-Higgsino-LH slepton (WHL) contribution to muon g-2 with bino-wino coannihilation

    < ILC 1TeV
  - Bino-LH-RH sleptons (BLR) contribution to muon g-2 with bino-stau coannihilation

    < ILC 500GeV
- ILC can reconstruct a SUSY contribution to muon *g*-2

Backup slides



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