Muon *g*-2 anomaly + SUSY (theory)

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KMI Nagoya University

Magnetic dipole moment (*g*-2)

- Definition of "spin *g*-factor"

$$\mathcal{L} = -\frac{eQ_\ell}{4m_\ell}\bar{\ell}\sigma_{\mu\nu}\ell F^{\mu\nu} - \frac{eQ_\ell}{4m_\ell}a_\ell\bar{\ell}\sigma_{\mu\nu}\ell F^{\mu\nu} = -\frac{eQ_\ell}{8m_\ell}(2+2a_\ell)\bar{\ell}\sigma_{\mu\nu}\ell F^{\mu\nu}$$

Equation of motion

tree level "$F_1(0)$" $\mathcal{L} = \bar{\ell}(i\not{D} - m_\ell)\ell$ radiative corrections "$F_2(0)$"

➡ spin *g*-factor $g_\ell = 2 + 2a_\ell$

g-2 : $a_\ell = \frac{g_\ell - 2}{2}$ ✔

➡ $\mathcal{H} = -\frac{eQ_\ell}{2m_\ell}g_\ell\vec{S}\cdot\vec{B} = -\vec{\mu}_\ell\cdot\vec{B}$

rest frame

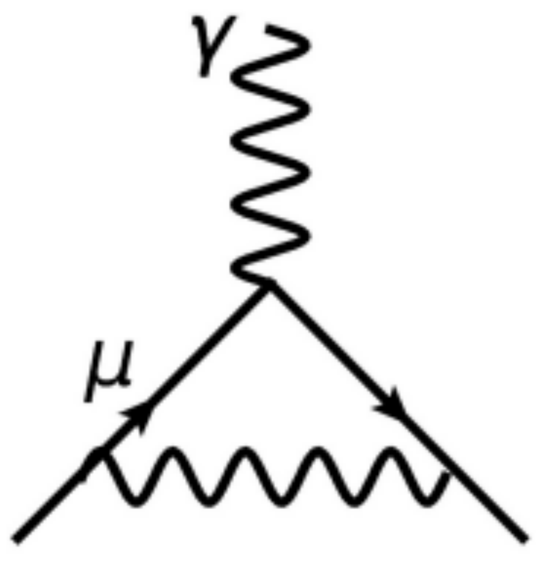
spin—magnetic interaction

spin magnetic moment:

$\vec{\mu}_\ell = g_\ell\frac{eQ_\ell}{2m_\ell}\vec{S}$ observable

The muon g-2

Theory (four *g*-2 contributions)

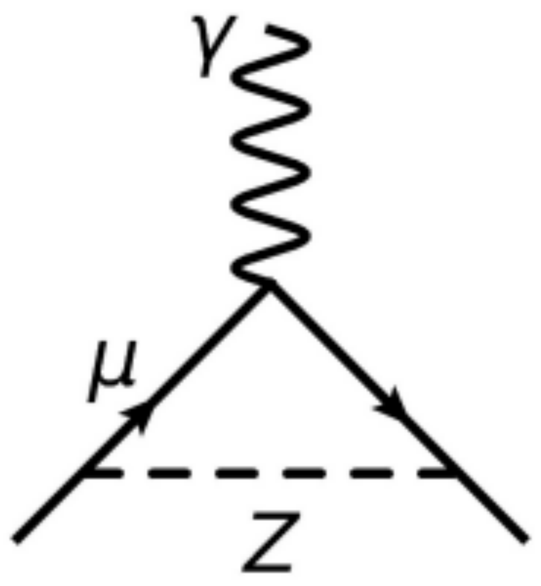


QED

4-loop analytic

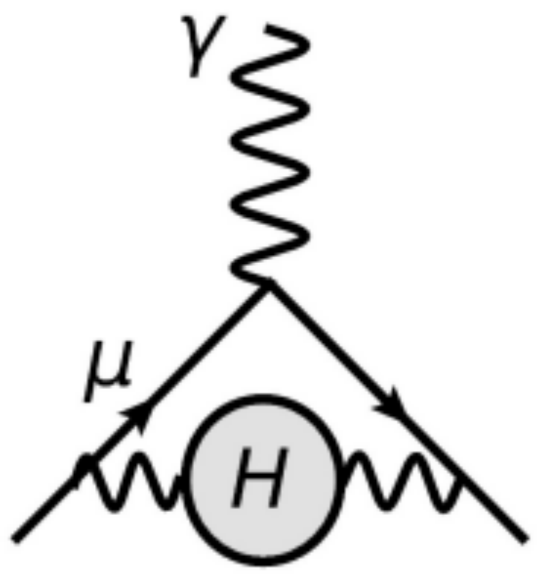
5-loop numeric

small disagreement here



EW

2-loop analytic

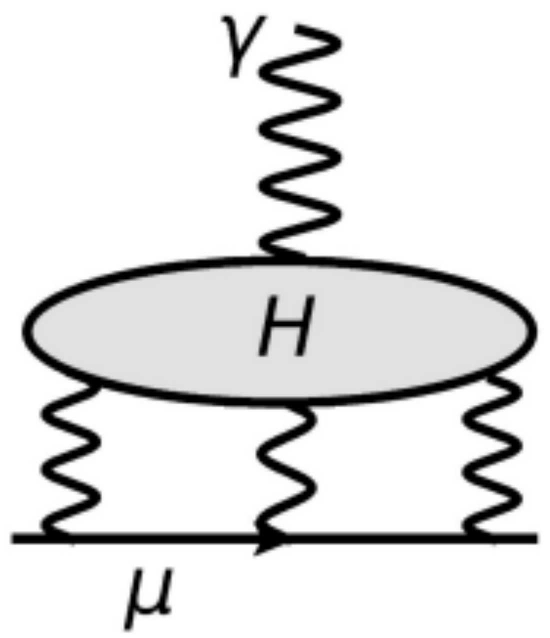


Hadronic vacuum polarization **(HVP)**

Phenomenological

Lattice

Problematic



Hadronic light-by-light **(HLbL)**

Pheno.

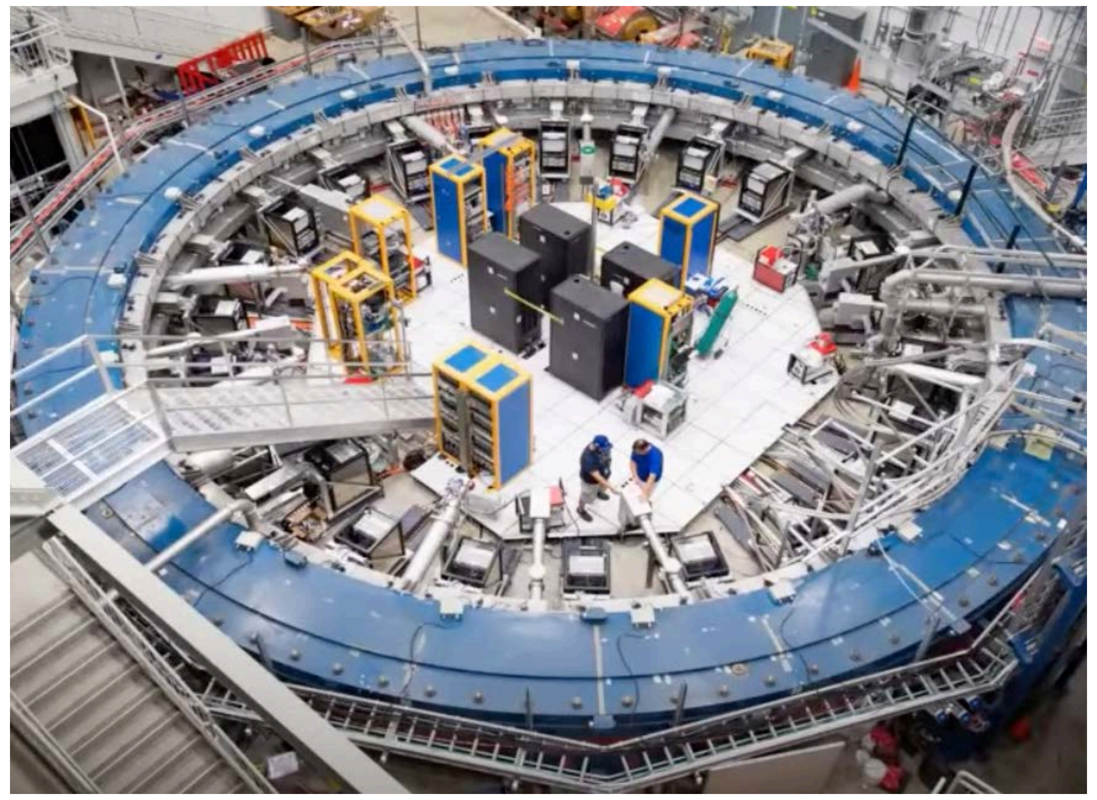
Lattice

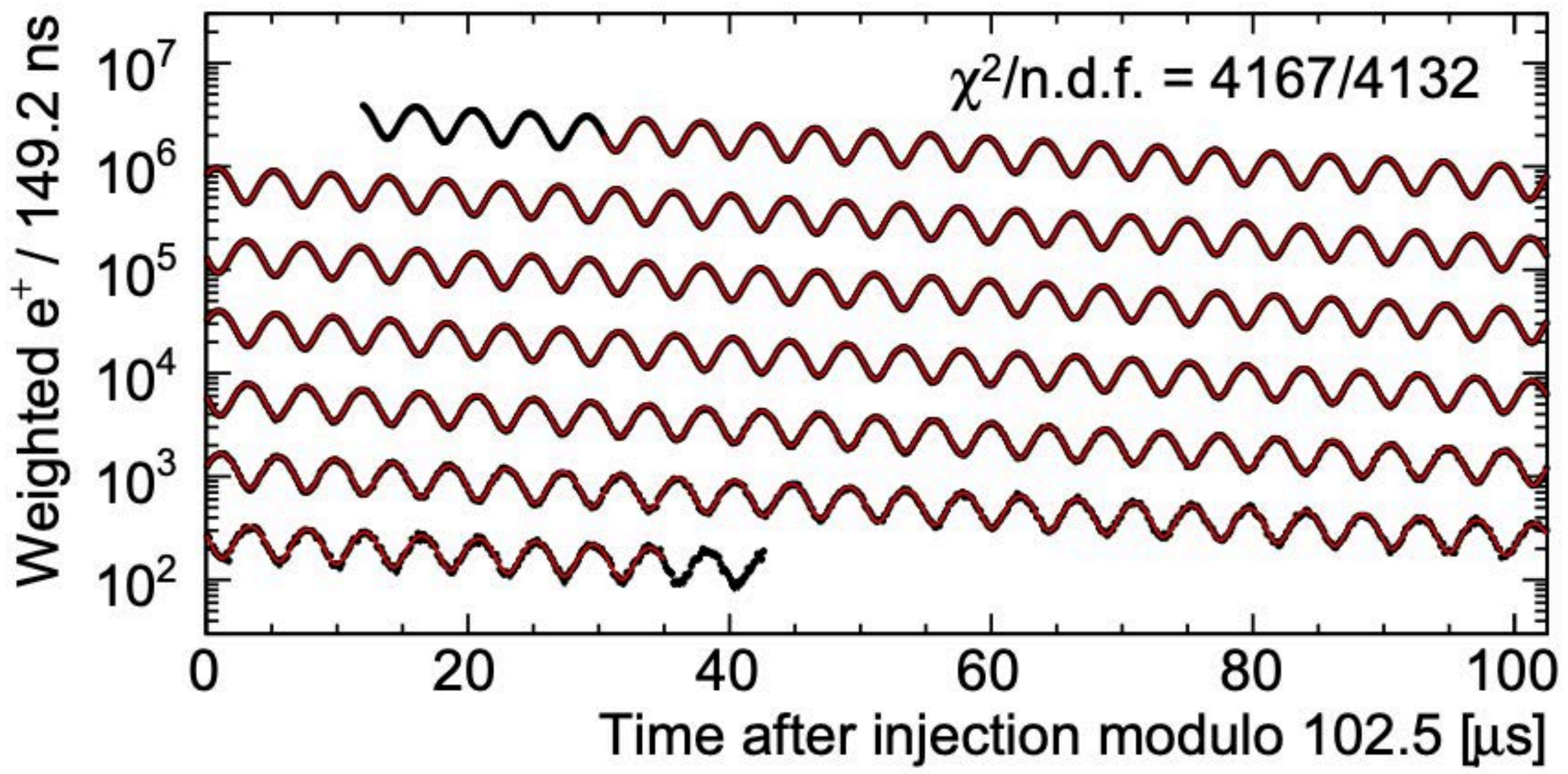
Exp.

BNL ’97-‘01

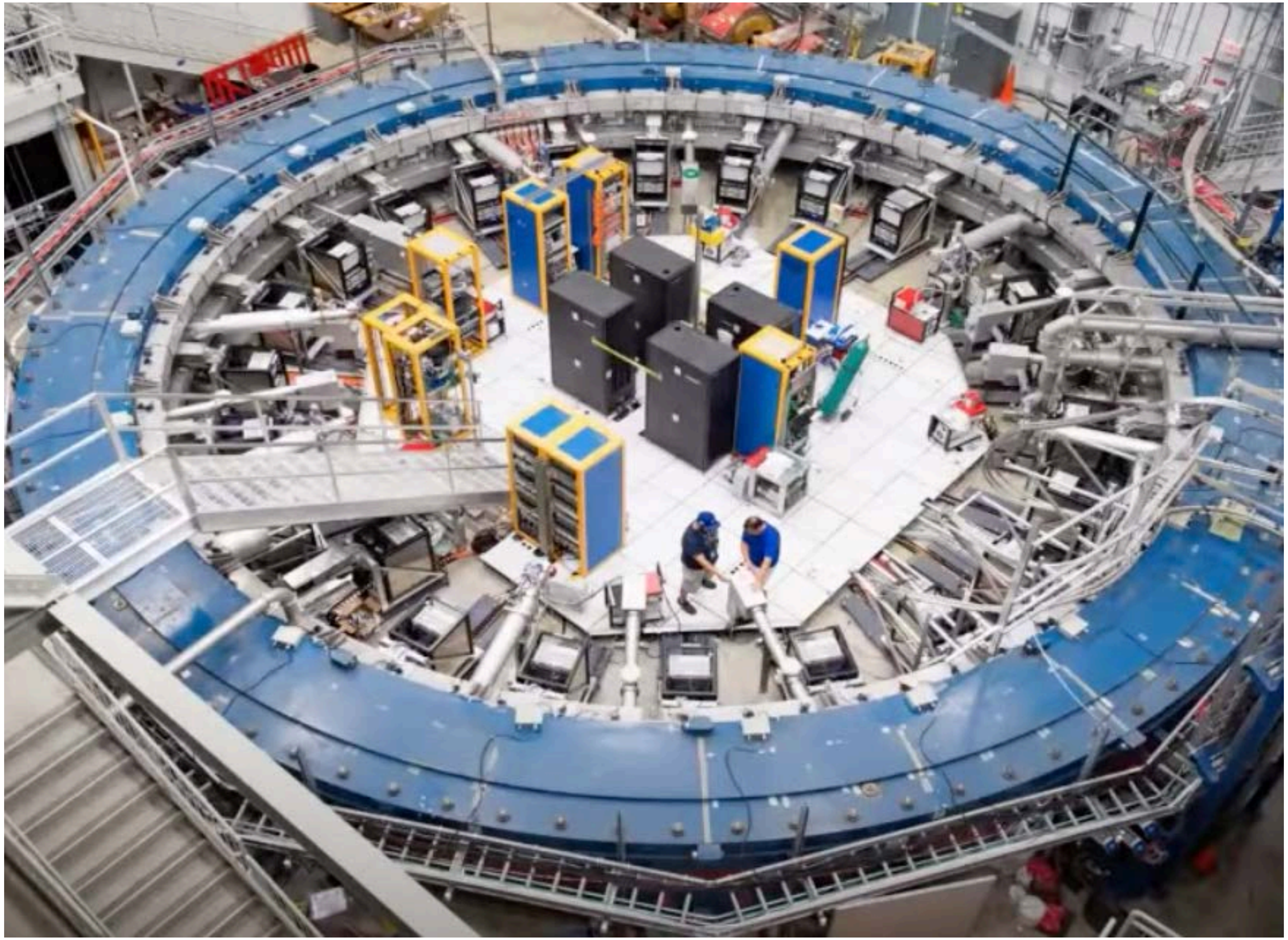
FNAL **Run4** was done

J-PARC near future

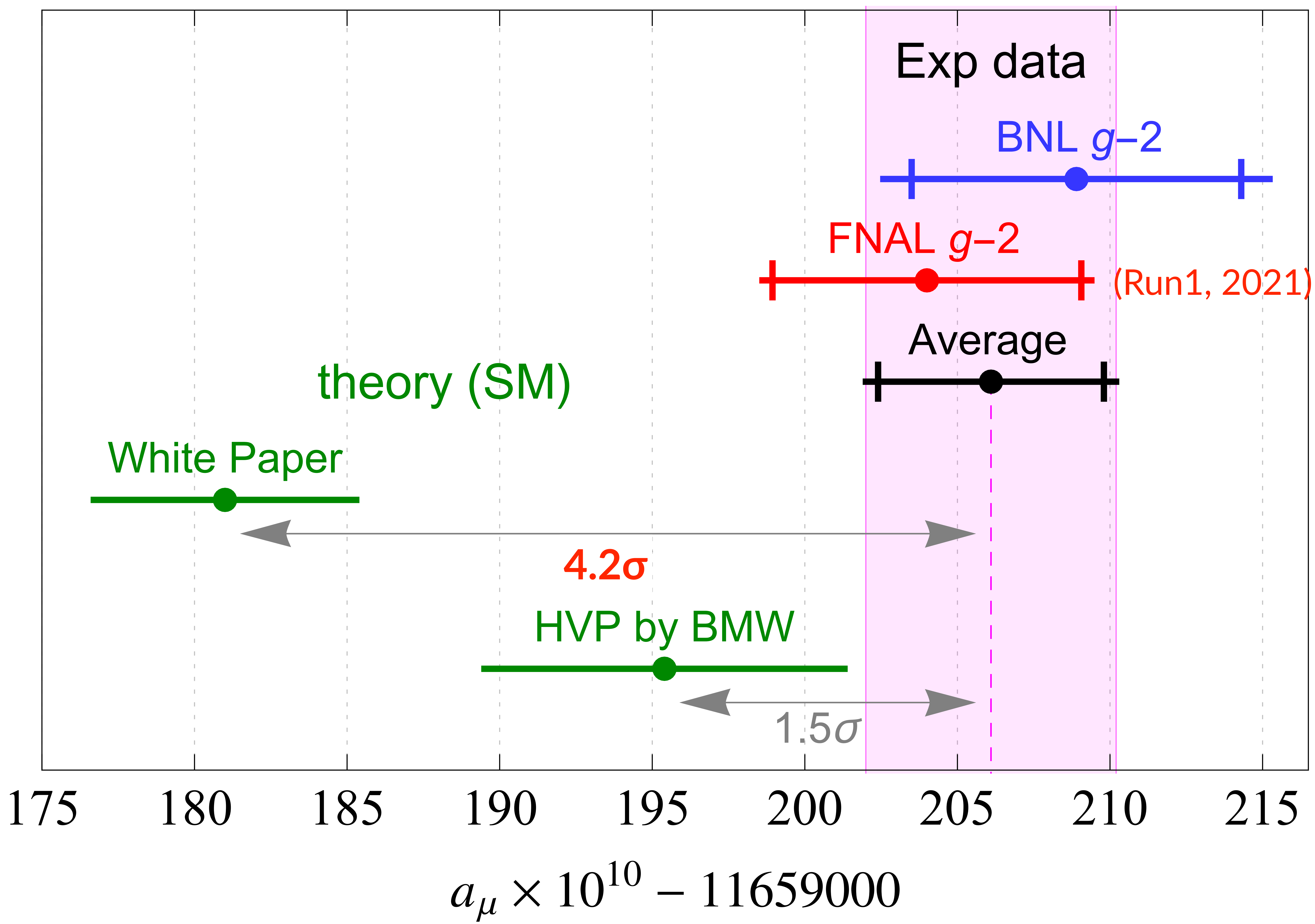




Current situation of muon g-2



[Endo, Iwamoto, TK, High Energy News, 2021]



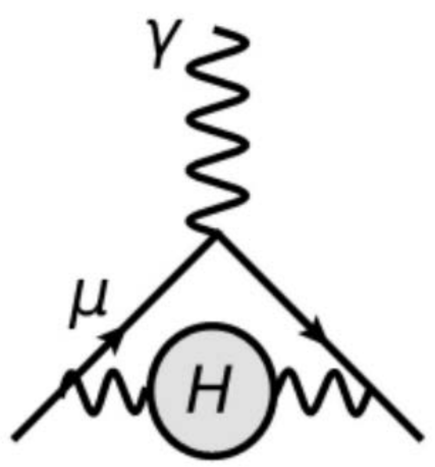
The BNL data was checked

The latest lattice result for HVP significantly reduces tension [BMW, Nature '21]

This leads to other tensions

Problematic

Status of HVP (1/2)



[Keshavarzi, Marciano, Passera, Sirlin, 2006.12666]

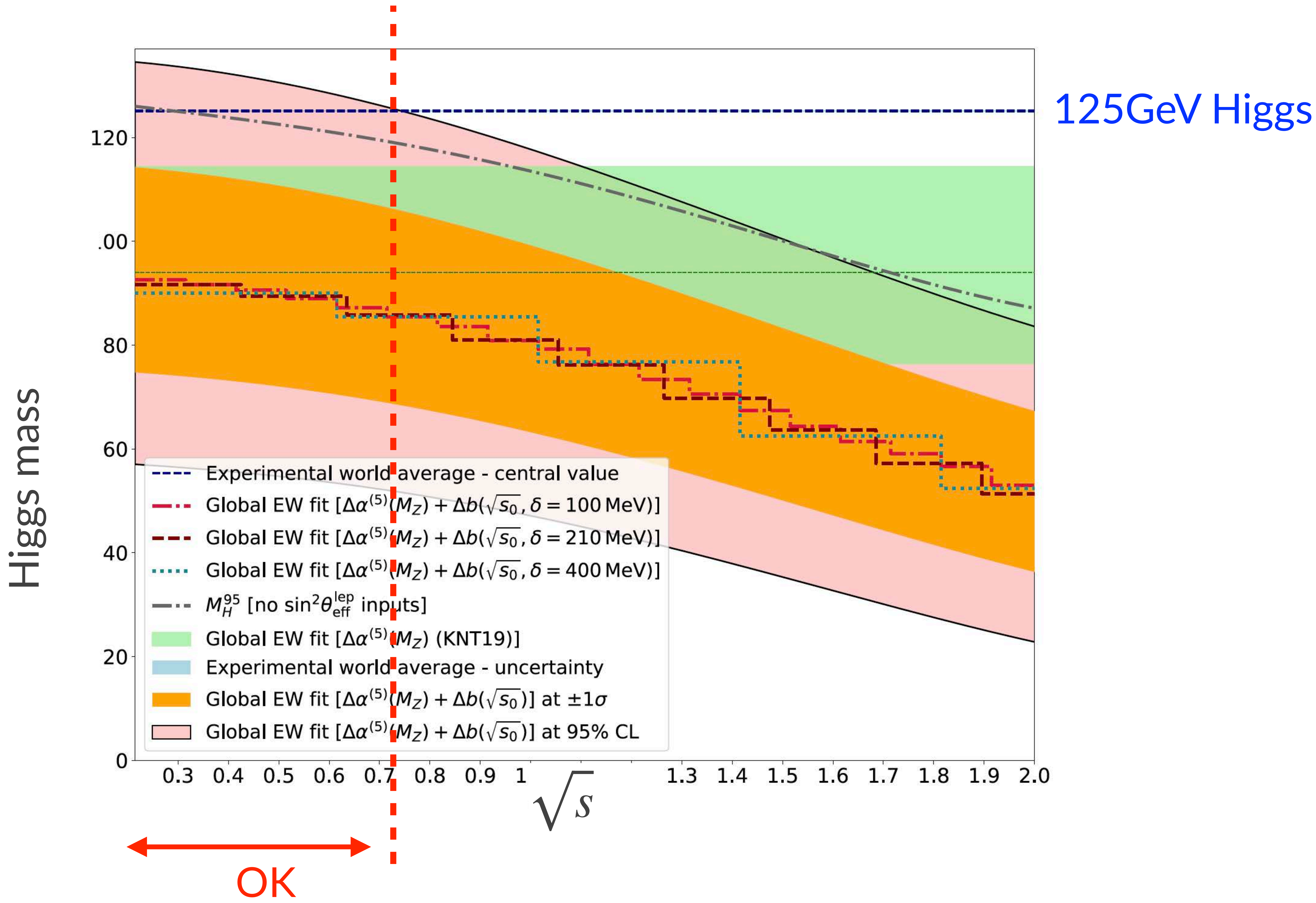
Logical possibility: is there unknown QCD contribution to HVP?

↓

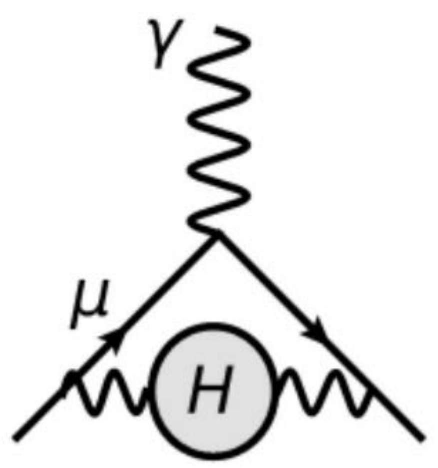
This possibility is severely constrained by the electroweak (EW) fit (right figure)

↓

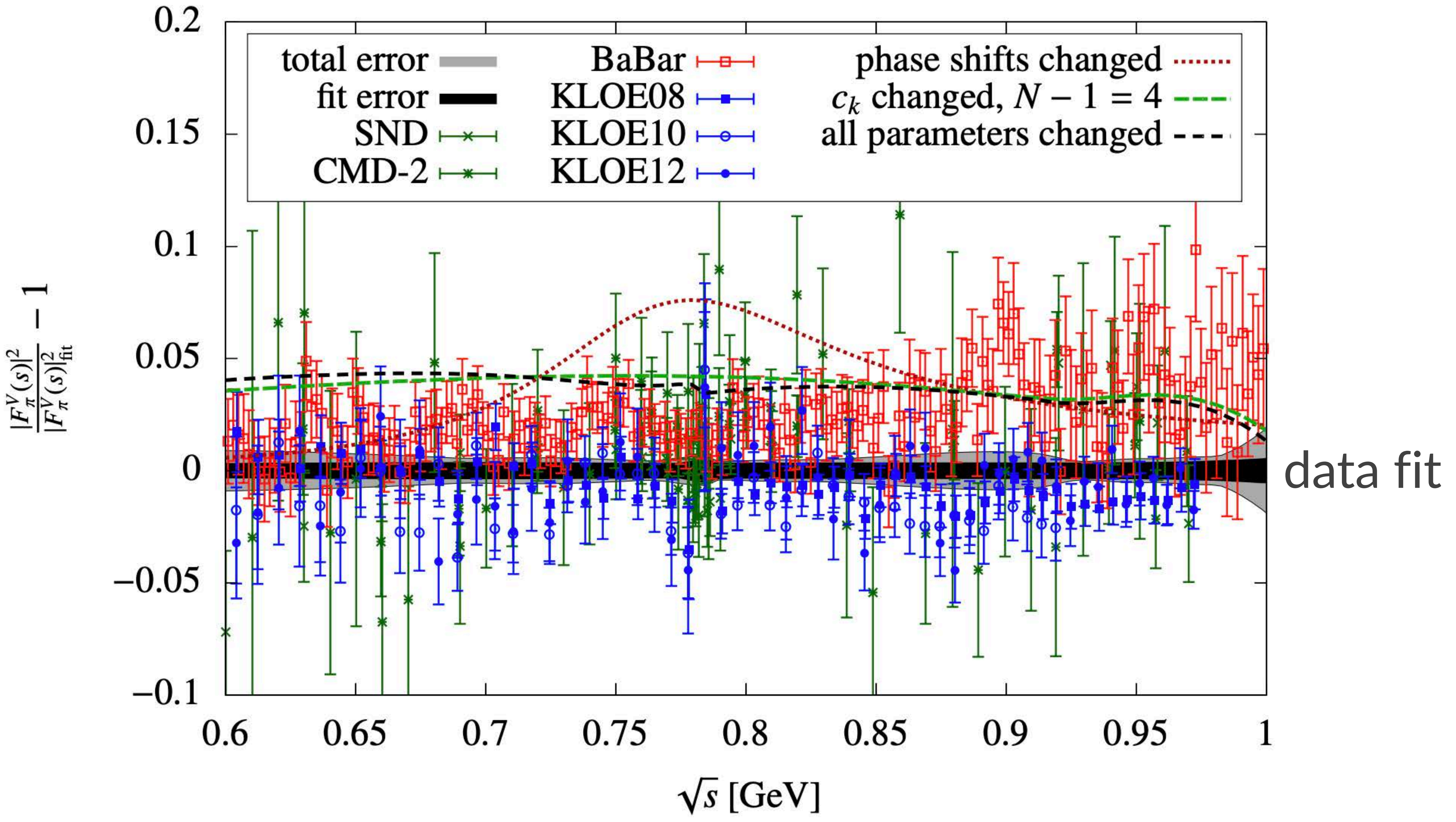
EW fit could be no problem, only when the low energy region of $e^+e^- \to \mathrm{hadrons}$ ($\sqrt{s} \lesssim 0.7\,\mathrm{GeV}$) are modified by unknown QCD.



Status of HVP (2/2)



◆ Focus on $e^+e^- \to$ hadrons $\sqrt{s} \lesssim 0.7\,\mathrm{GeV}$ [Colangelo, Hoferichter, Stoffer, 2010.07943]



When one considers that the lattice value can be explained by the unknown QCD effects ($\sqrt{s} \lesssim 0.7\,\mathrm{GeV}$),

then there is additional tension:

8% change of $e^+e^- \to \rho$ resonance (········),

or

4% change of $e^+e^- \to 2\pi$ data (- - - - -).

But, data fit has **only 1% error** [Keshavarzi, Nomura, Teubner, 1911.00367]

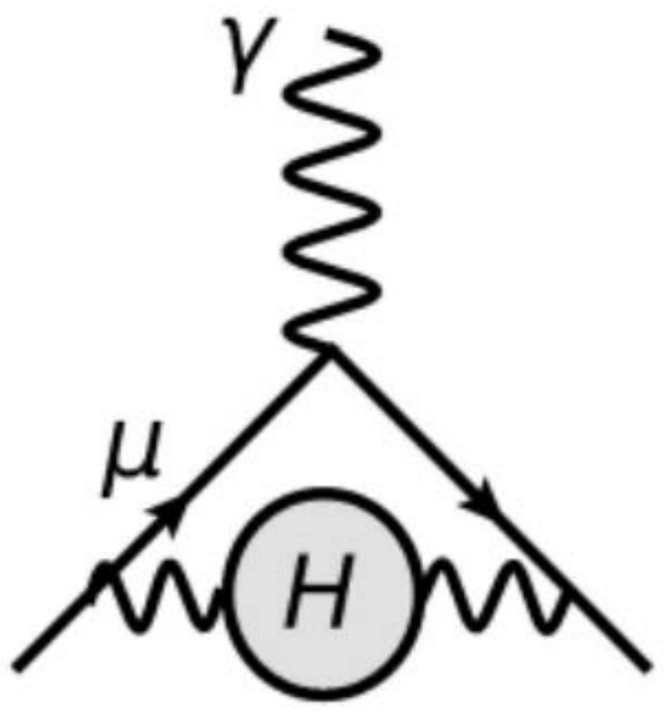
Updated lattice (**RBC-UKQCD**) will be presented near future.

Updated data will be provided by **Belle II experiment.**

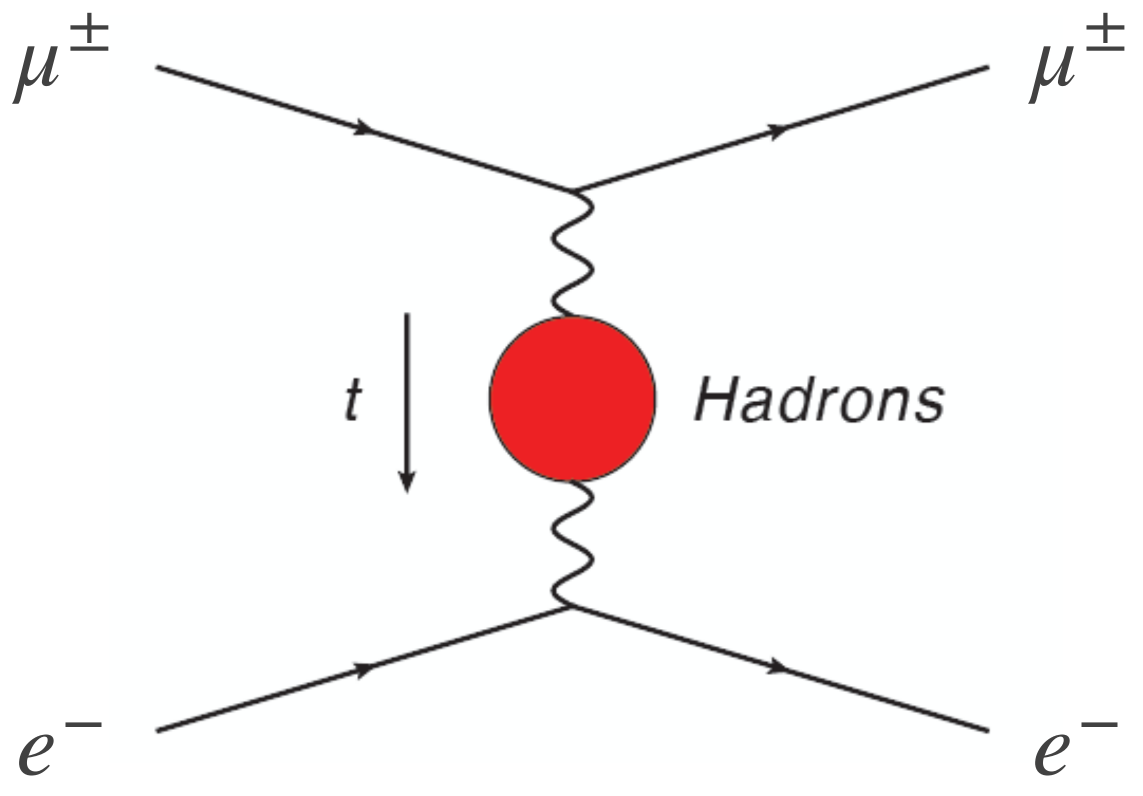
MUonE experiment

- The MUonE experiment at CERN can directly and precisely prove HVP [MUonE collaboration, 2004.13663]
- Use $\mu^{\pm}$ + fixed $e^{-} \rightarrow \mu^{\pm} e^{-}$ elastic scattering
- Test run was approved for 2021.

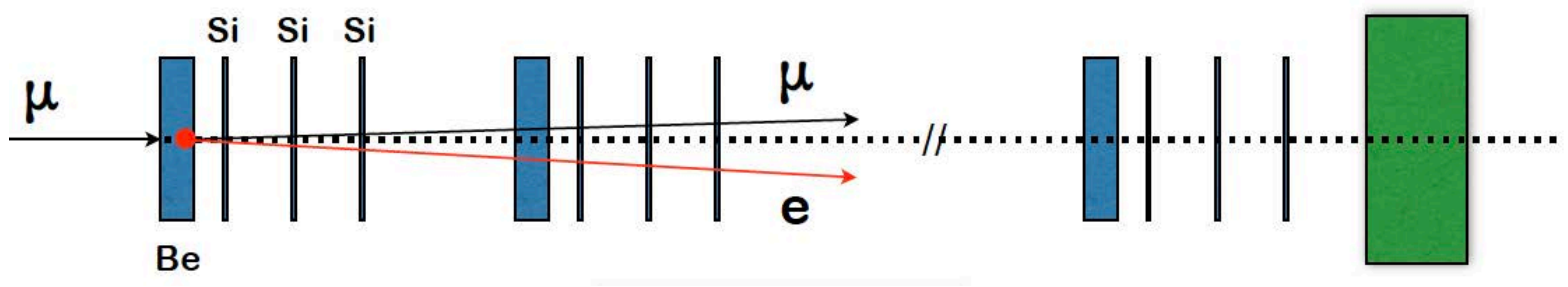
[Passera, KEK-PH2021]



HVP



MUonE process

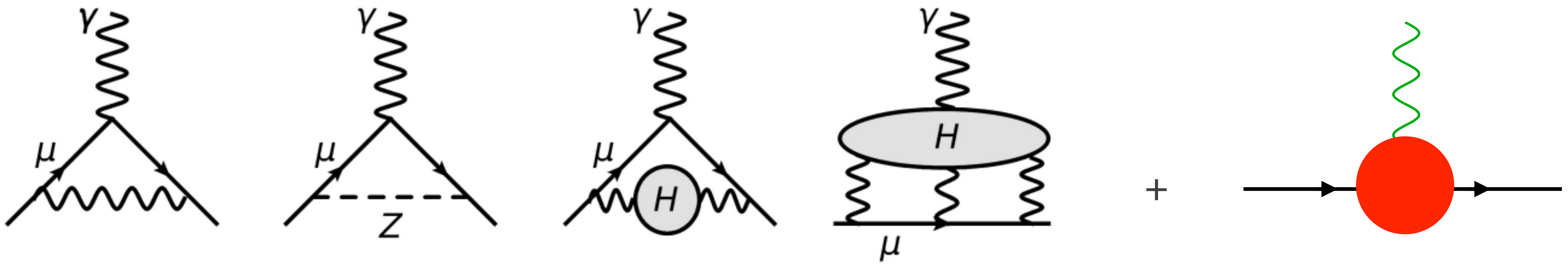


By using 3 years data, statistical sensitivity is $0.3\,\%$ on $a_{\mu}^{\mathrm{HVP-LO}}$ (curent *tension* is $2\,\%$ on $a_{\mu}^{\mathrm{HVP-LO}}$)

For theoretical uncertainties, NLO corrections were ready and NNLO is close to completion.

[Budassi et al., 2109.14606]

Naive NP energy scale (1/2)



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

- Muon g-2 anomaly implies that NP mass scale is around the electroweak scale.

$$\Delta a_\mu \equiv a_\mu^{\mathrm{BNL+FNAL}} - a_\mu^{\mathrm{SM}} = (25.1 \pm 5.9) \times 10^{-10} \quad (4.2\sigma)$$

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

Naive NP energy scale (2/2)

muon g-2 anomaly → $$M_{\rm NP} \sim g_{\rm NP} \times 150\,{\rm GeV}$$

- NP scale $M_{\rm NP}$ is determined by size of the NP couplings to muon $g_{\rm NP}$
  - Large $g_{\rm NP}$ by certain mechanisms (*e.g.*, "$\tan\beta$ enhancement", chiral enhancement)

    → TeV scale NP models (*e.g.*, **Supersymmetry**)
  - Small $g_{\rm NP}$ (*e.g.*, $g \sim 10^{-3}$)

    → MeV scale NP models

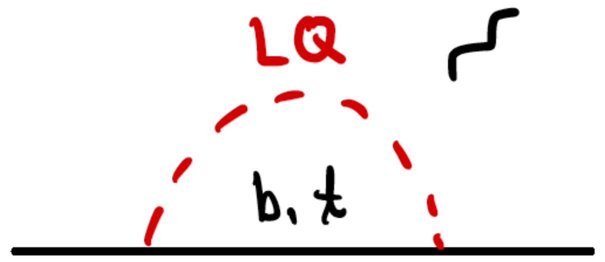
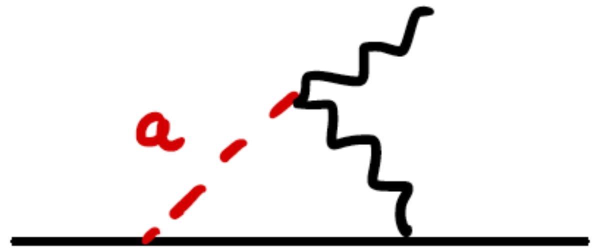
Point: MeV scale NP search is difficult at the LHC
because of so much QCD background noise

New physics models

https://publicdomainq.net/

New physics interpretations

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

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

New physics interpretations

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

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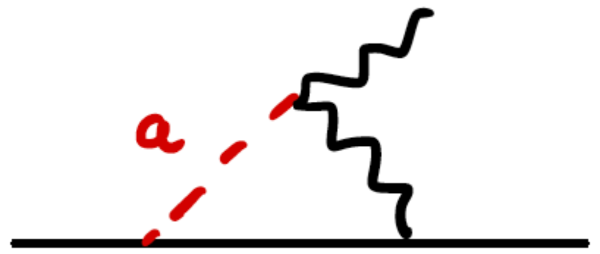
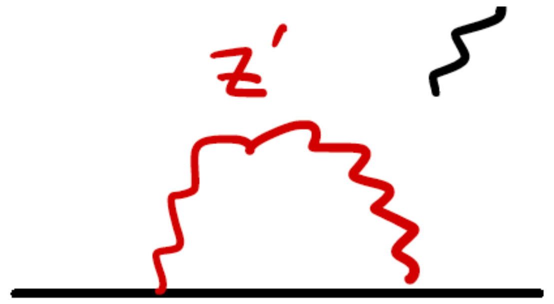
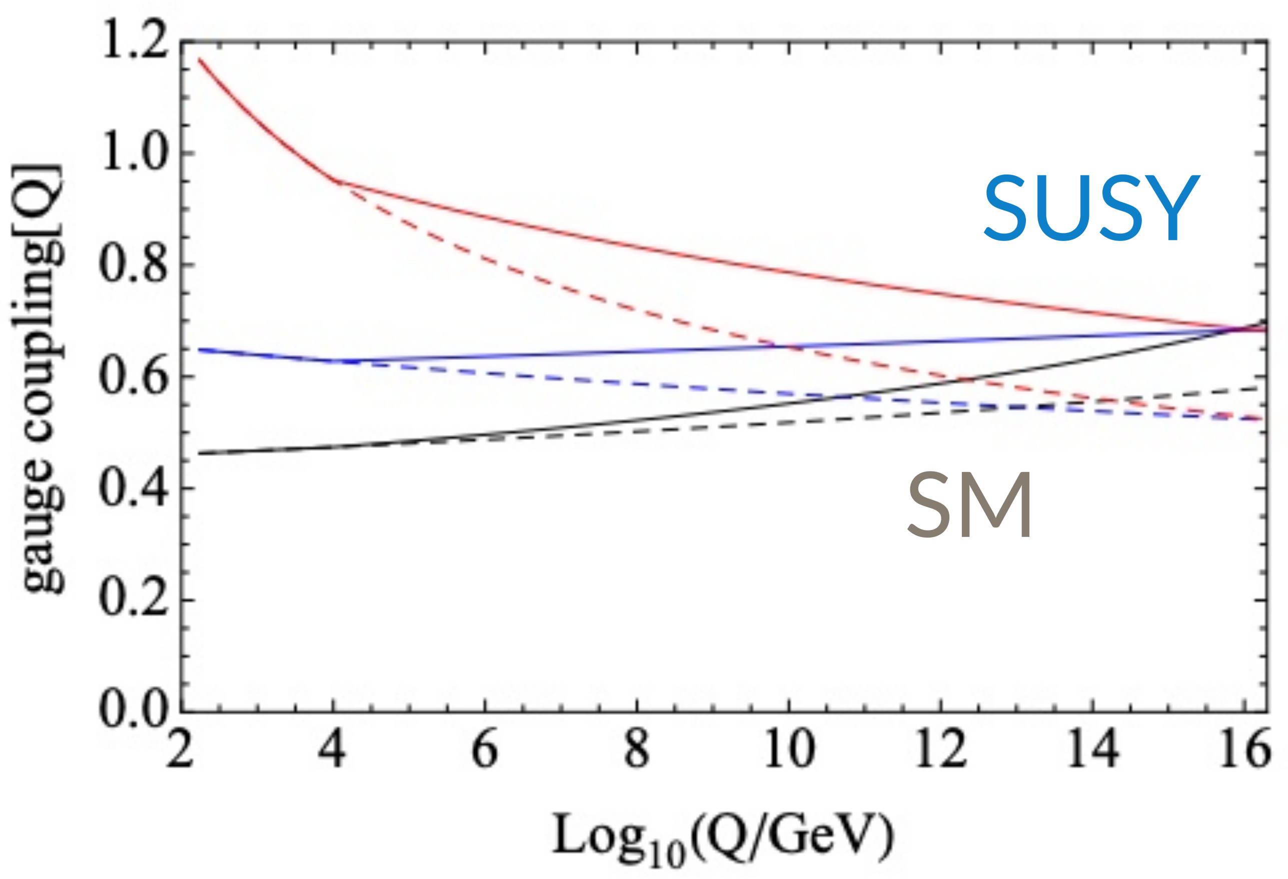
Axion-like particle		40 MeV〜200 GeV	$e^+e^- \to \gamma a \to 3\gamma$
U(1) Lμ-Lτ		10〜200 MeV	$e^+e^- \to \mu^+\mu^- Z'$ $K \to \mu\nu Z'$, $\mu e \to \mu e Z'$

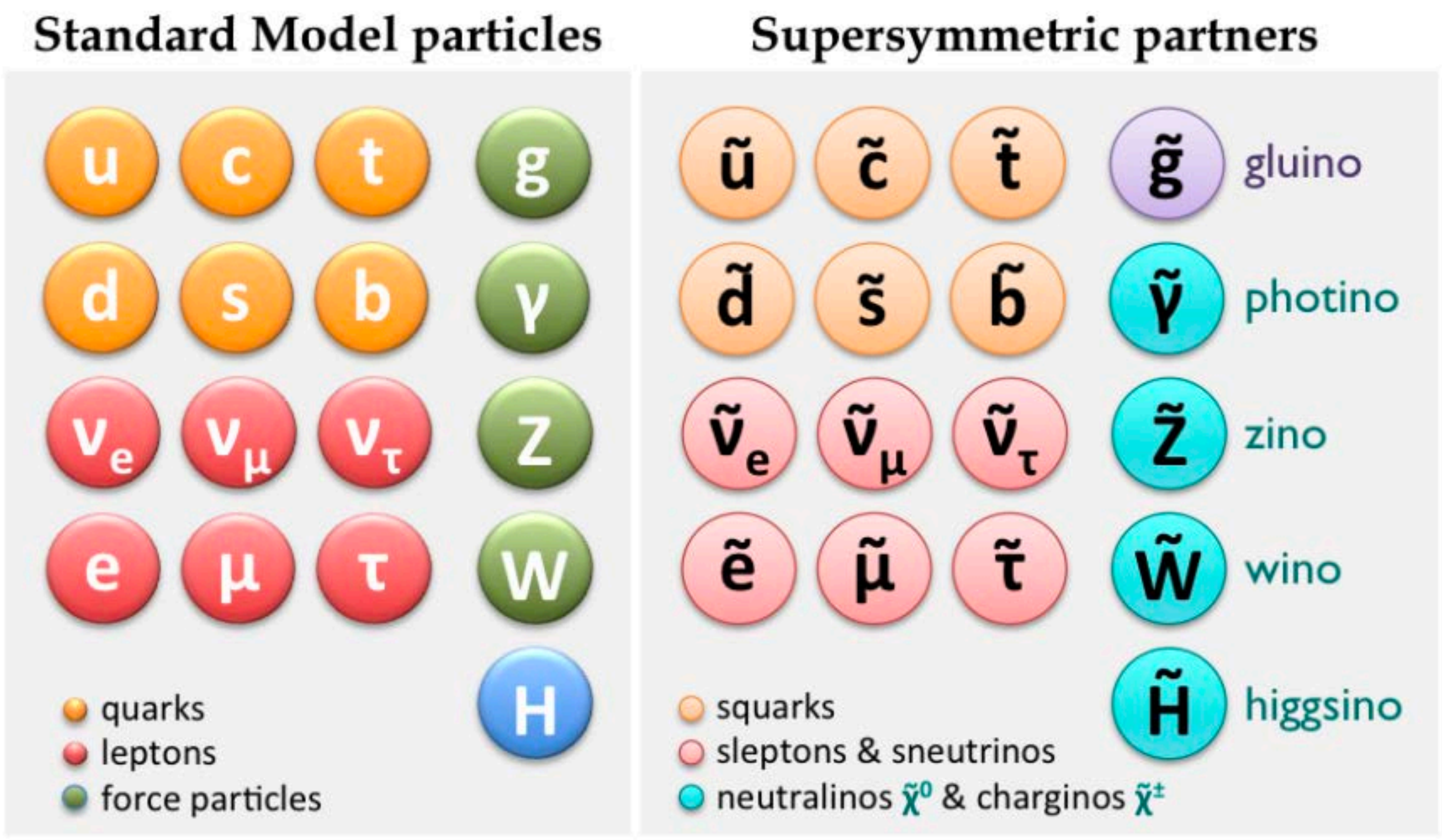
Supersymmetry (SUSY)

- Many motivations: **gauge hierarchy problem**, **gauge coupling unification,** and **dark matter**



- Under SUSY, slepton/squark (s=0), gaugino (s=1/2), and higgsino (s=1/2) are required

SUSY = symmetry between fermion and boson



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

Supersymmetric (SUSY) Interpretation

- Crucial: SM owns one Higgs-doublet, while the minimal SUSY requires **two** Higgs/Higgsino-doublet
  ← **Holomorphy of superpotential** and **gauge anomaly cancelation**
- So, the electroweak symmetry breaking must occur **by two Higgs VEVs**

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

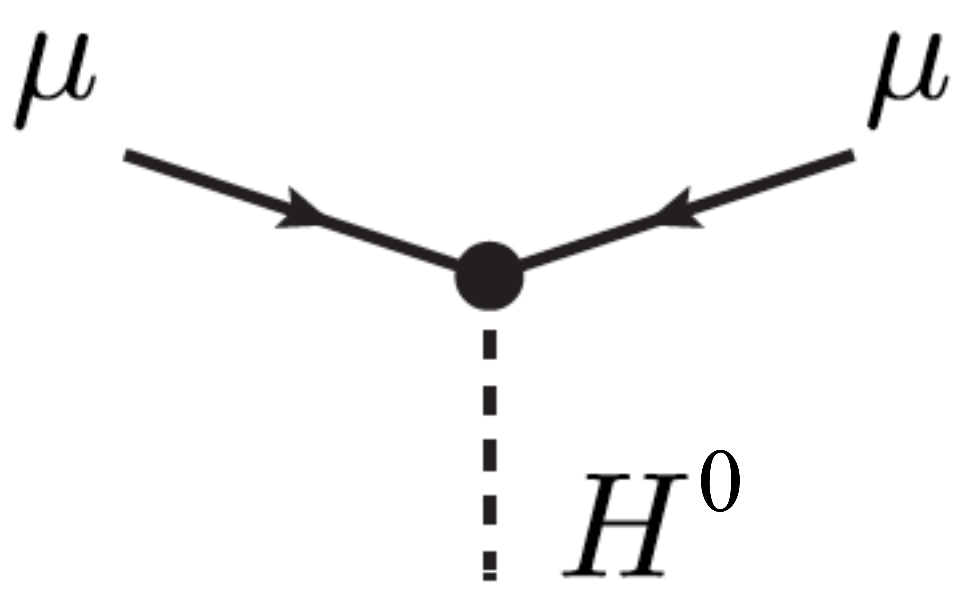
+ two Higgsino doublets

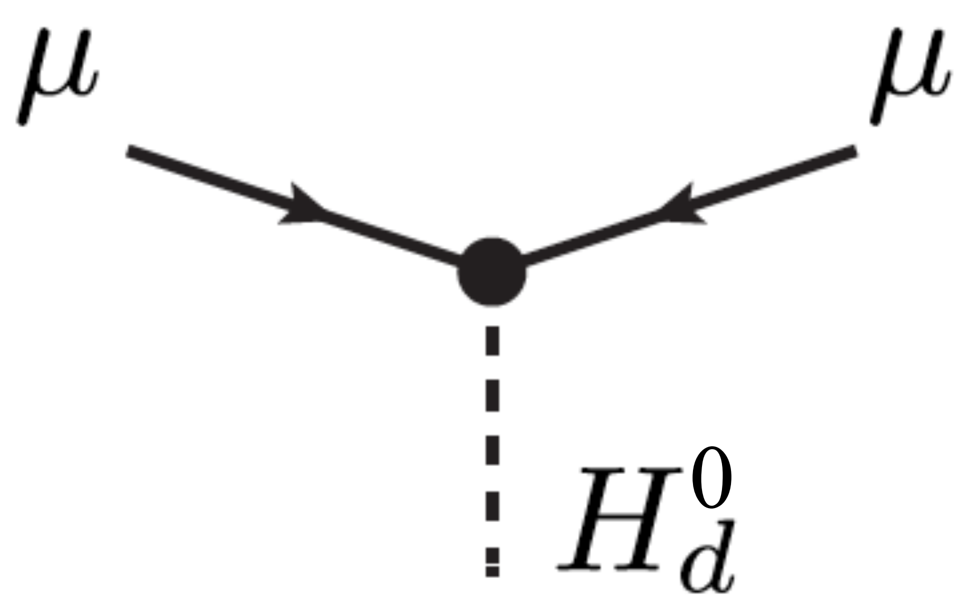
- **Then,** $\tan\beta \equiv v_u/v_d$ **is a free parameter, where** $v_{\rm SM} = \sqrt{v_u^2 + v_d^2}$

“$\tan\beta$ enhancement”

- “$\tan\beta$ enhancement” stems from the muon-Yukawa interaction

SM





SUSY

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

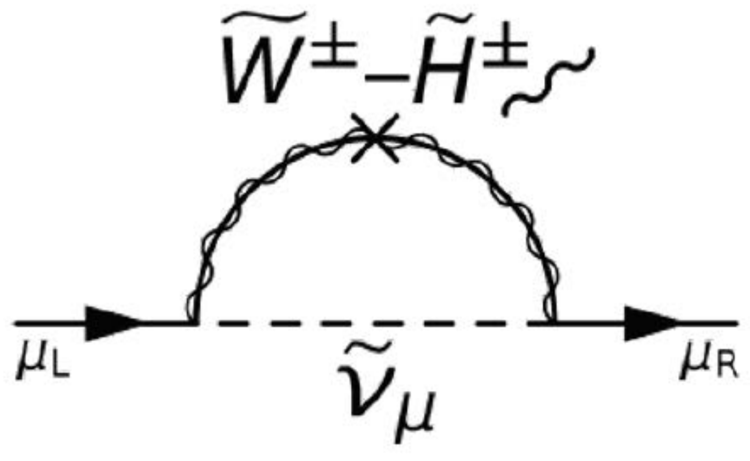
$$m_\mu = m_\mu \;\Rightarrow\; y_\mu^{\rm SUSY} = y_\mu^{\rm SM}\frac{v}{v_d} = y_\mu^{\rm SM}\frac{1}{\cos\beta} \simeq y_\mu^{\rm SM}\tan\beta$$

- When $v_d \ll v = \sqrt{v_u^2 + v_d^2} \leftrightarrow \tan\beta \gg 1$, the SUSY muon Yukawa is enhanced by $\tan\beta \sim \mathcal{O}(10)$

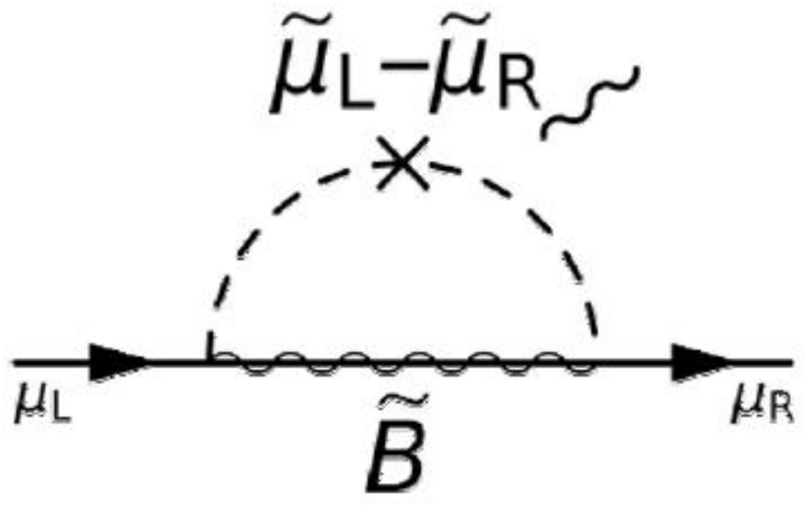
Supersymmetric Interpretation

- Four types of one-loop diagrams are responsible to explain the anomaly:

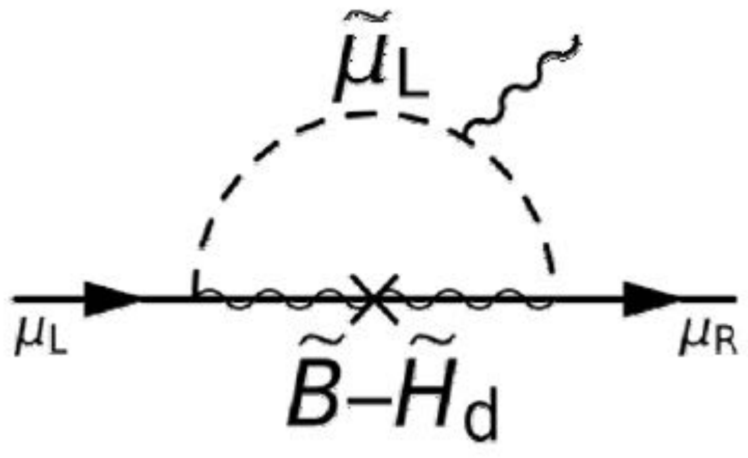
1, WHL scenario



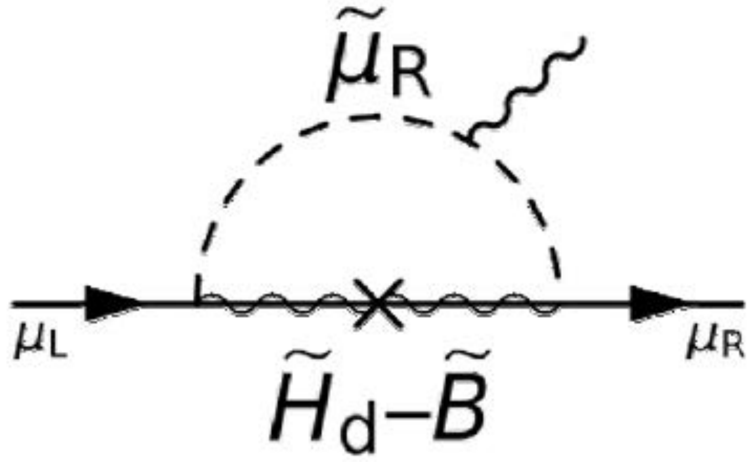
2, BLR scenario



3, BHL scenario



4, BHR scenario



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

- 1, WHL and 2, BLR $\to$ next slide

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

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

[Endo, Hamaguchi, Iwamoto, TK, 2104.03217]

1, Wino-Higgsino-LH slepton (WHL) scenario

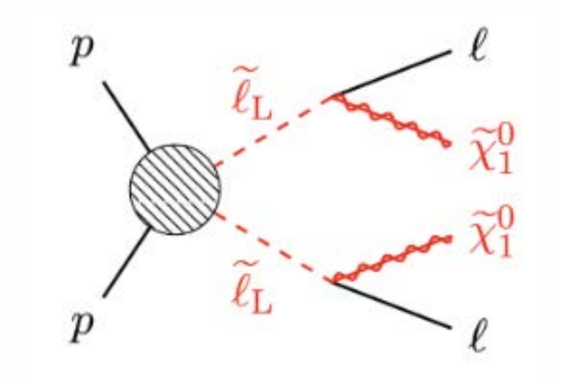
$m(\tilde{\chi}_1^{\pm}) = 500\mathrm{GeV}$ light EWkino ⟵ / ⟶ light slepton

Benchmark point

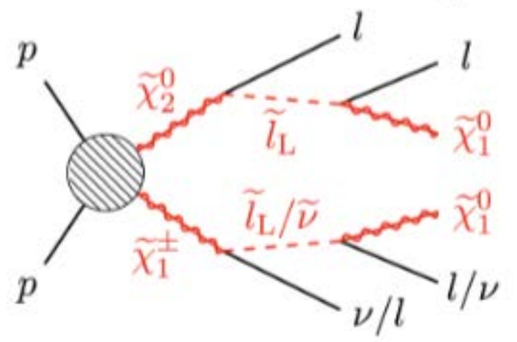
$$M_1 : M_2 : \mu = 1 : 2 : 4$$
$$\tan\beta = 40$$

strong bound from:

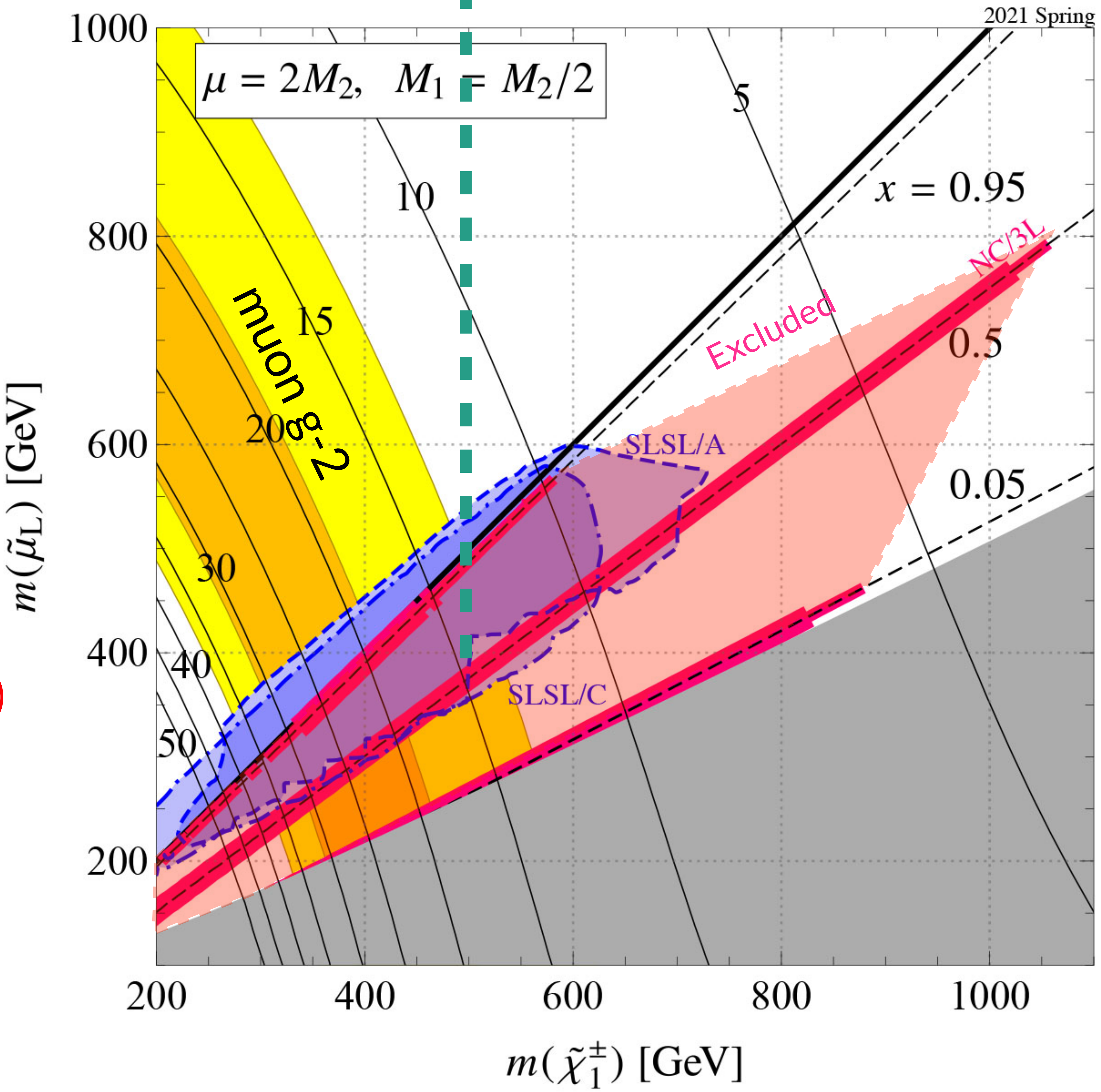
$\tilde{\ell}_L \tilde{\ell}_L^* \to (\ell \tilde{\chi}_1^0)\,(\bar{\ell}\tilde{\chi}_1^0)$



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

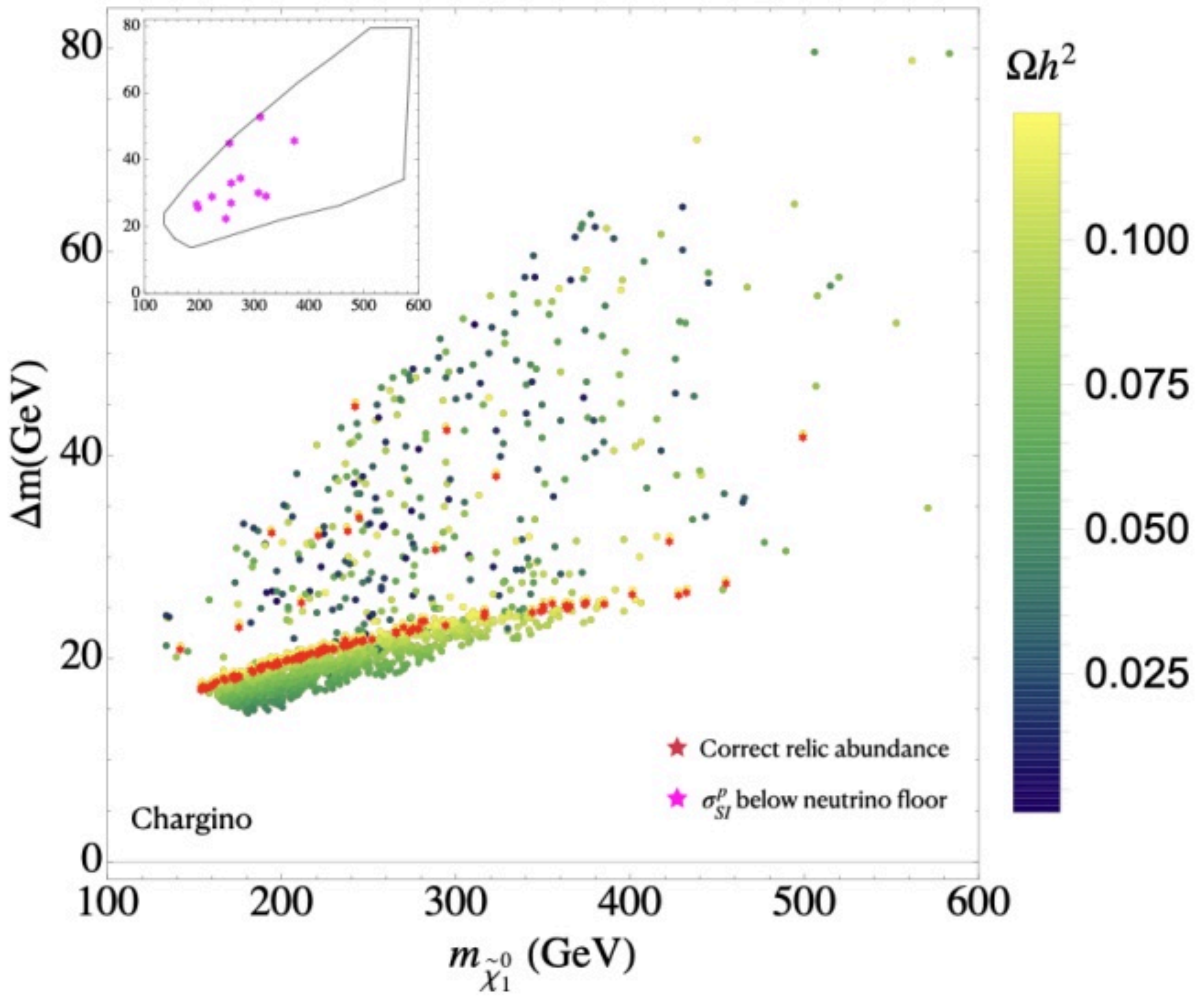


ILC1TeV can probe these arrowed regions



Bino-Wino coannihilation can explain the DM relic density

[Chakraborti, Heinemeyer, Saha, Schappacher, 2112.01389]



[Endo, Hamaguchi, Iwamoto, TK, 2104.03217]

1, Wino-Higgsino-LH slepton (WHL) scenario

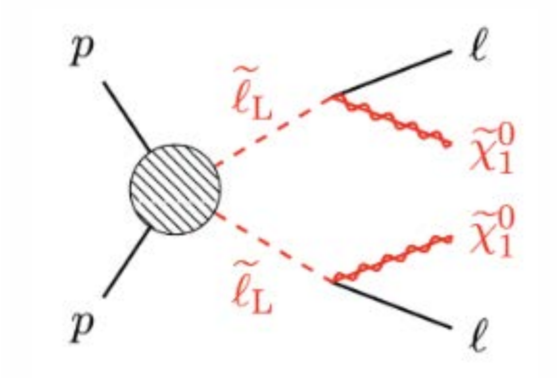
$m(\tilde{\chi}_1^{\pm}) = 500\mathrm{GeV}$ light EWkino ⇦ / ⇨ light slepton

Benchmark point

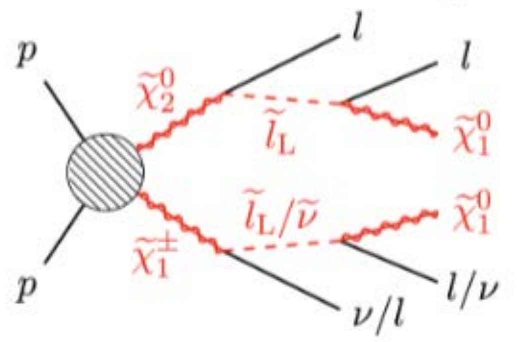
$$M_1 = 100\mathrm{GeV}$$
$$\tan\beta = 40$$

strong bound from:

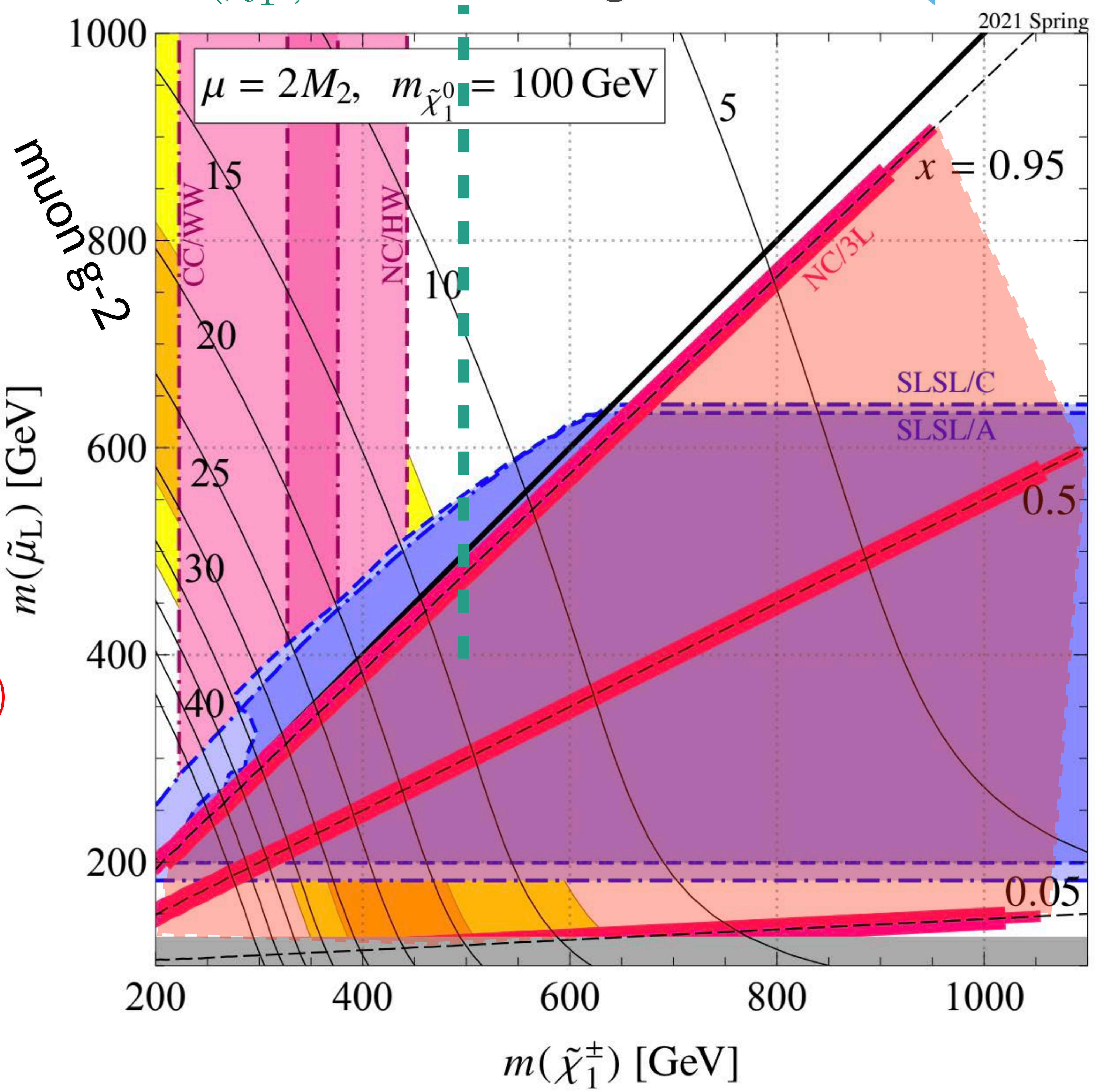
$\tilde{\ell}_L \tilde{\ell}_L^* \to (\ell\tilde{\chi}_1^0)\,(\bar{\ell}\tilde{\chi}_1^0)$



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

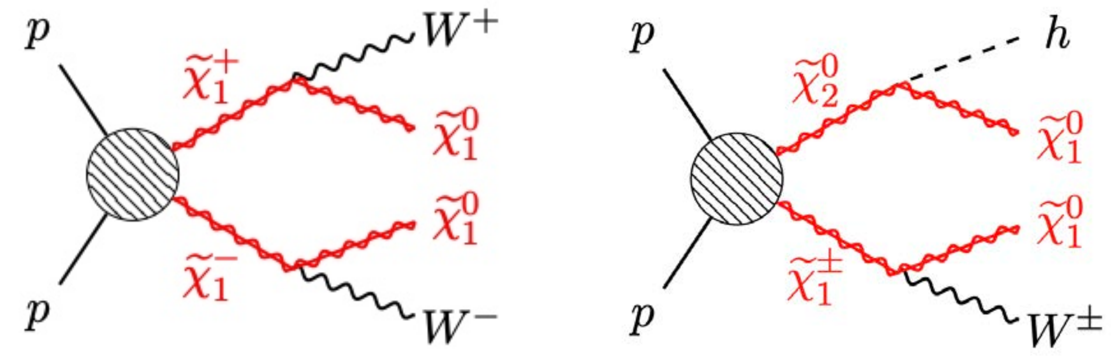


ILC1TeV can probe these arrowed regions



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

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

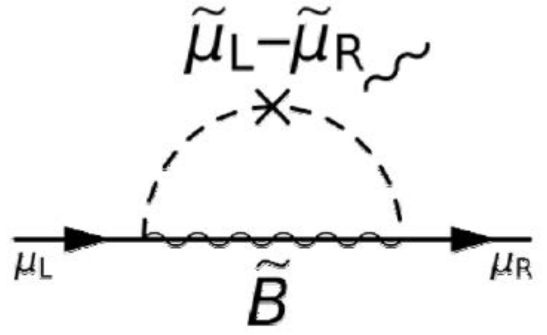


Point: $\tilde{W}^0$ decays into *h*. In general, $\mathrm{Br}\left(\chi_2^0 \to \chi_1^0 Z\right) \sim O(0.1)$

Light bino scenario is severely constrained

[Endo, Hamaguchi, Iwamoto, TK, 2104.03217]

2, Bino-LH-RH sleptons (BLR) scenario



Benchmark point

Bino-stau coannihilation **with correct Ω_{DM}**

+ universal slepton mass

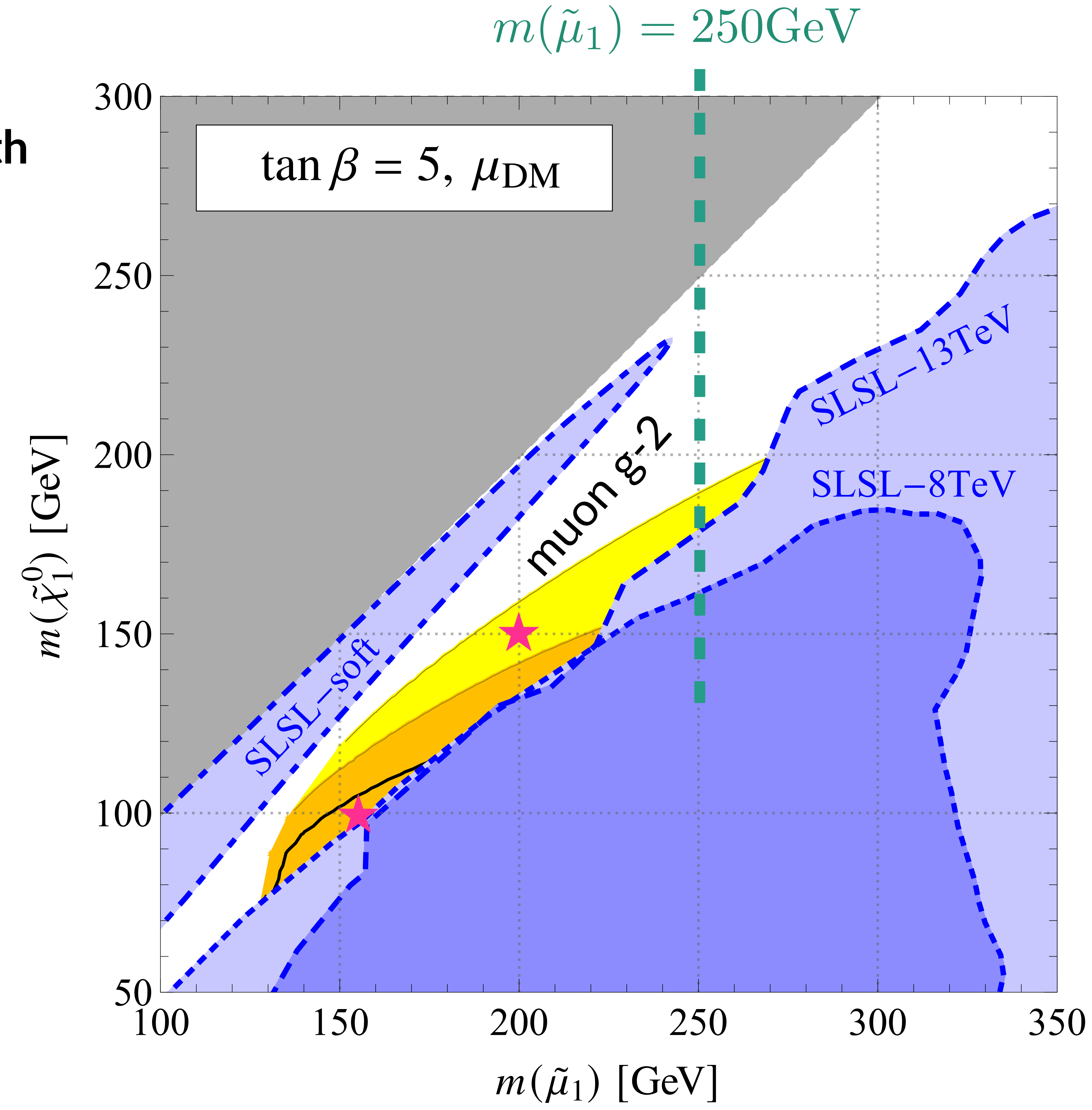
Large μ with small tan β is favored in this study

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**



Benchmark points

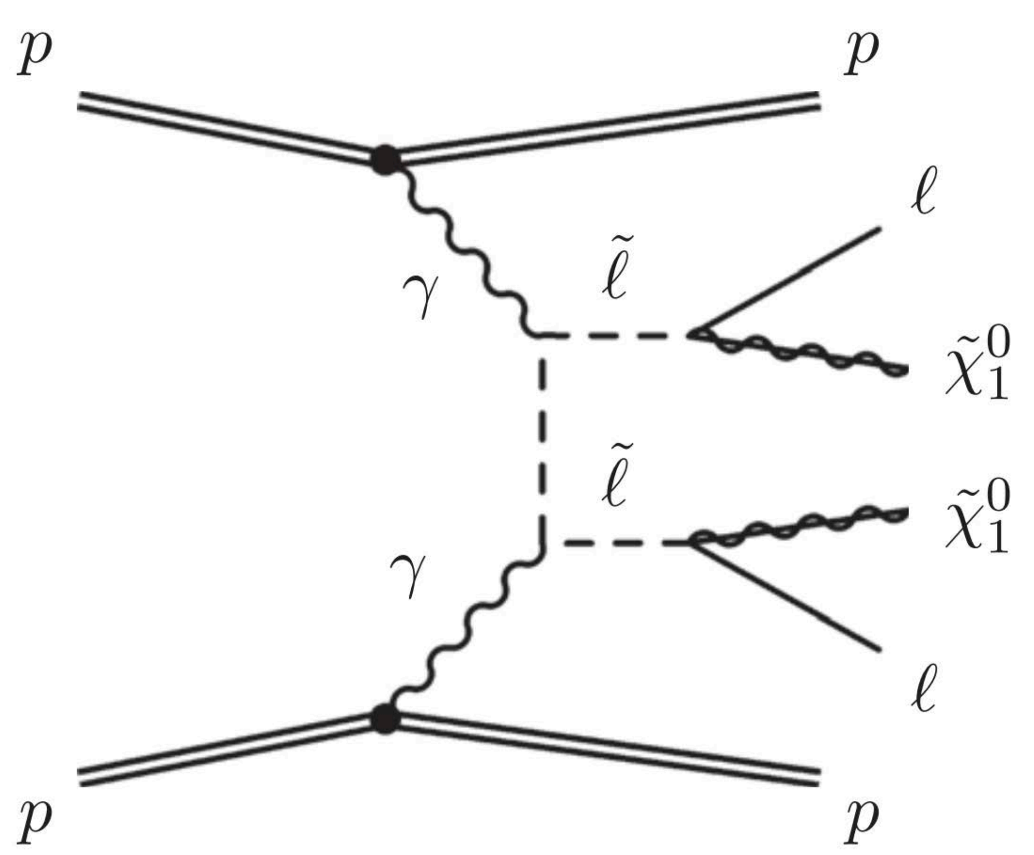
	BLR1	BLR3
M_1	100	150
$m_L = m_R$	150	200
$\tan\beta$	5	5
μ	1323	1922
$m_{\tilde{\mu}_1}$	154	202
$m_{\tilde{\mu}_2}$	159	207
$m_{\tilde{\tau}_1}$	113	159
$m_{\tilde{\tau}_2}$	190	242
$m_{\tilde{\nu}_{\mu,\tau}}$	137	190
$m_{\tilde{\chi}_1^0}$	99	150
$m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_1^\pm}$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

XENONnT (DM direct detection) can probe this scenario

Slepton search via photon collision

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

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



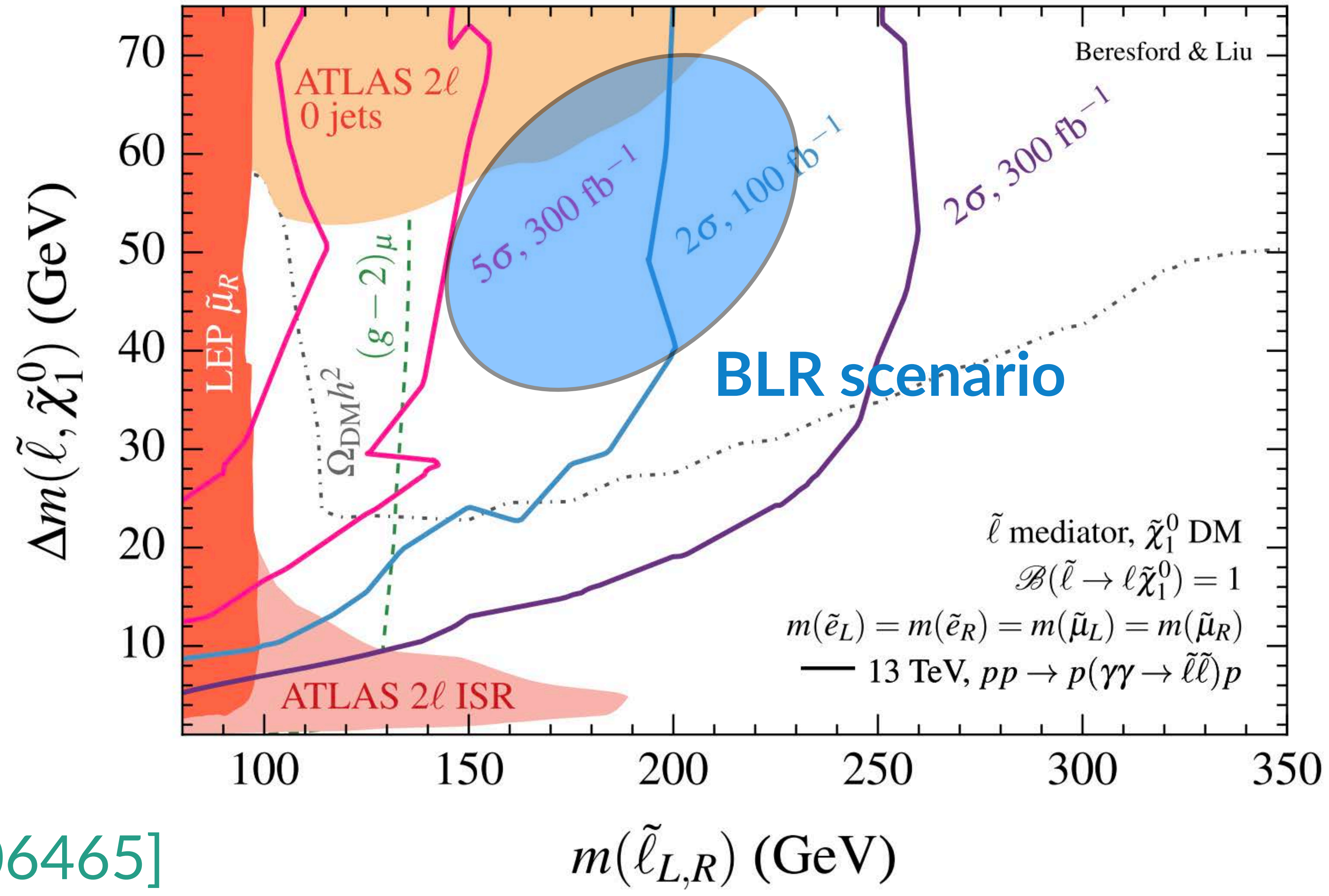
nearly on-shell photons

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

2, measure lepton four-momentum

3, reconstruct missing momentum four-vector

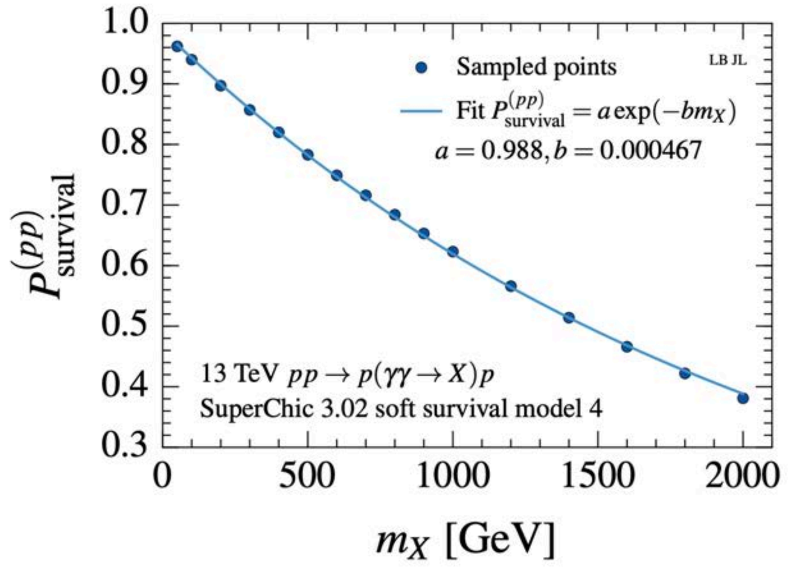
Slepton mass gap could be covered.

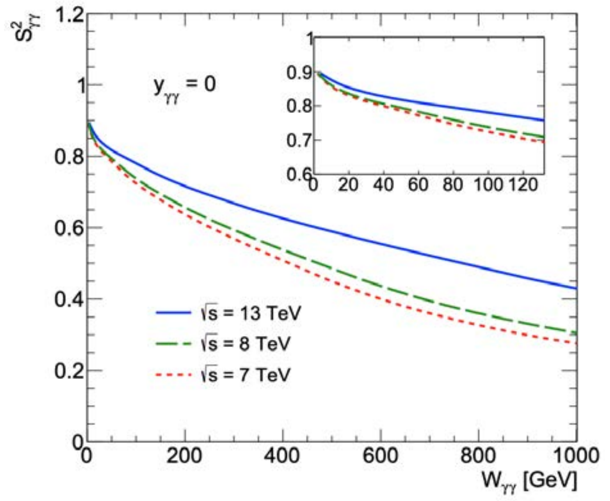


Proton soft survival probability is crucial

Slightly optimistic?

[1811.06465]

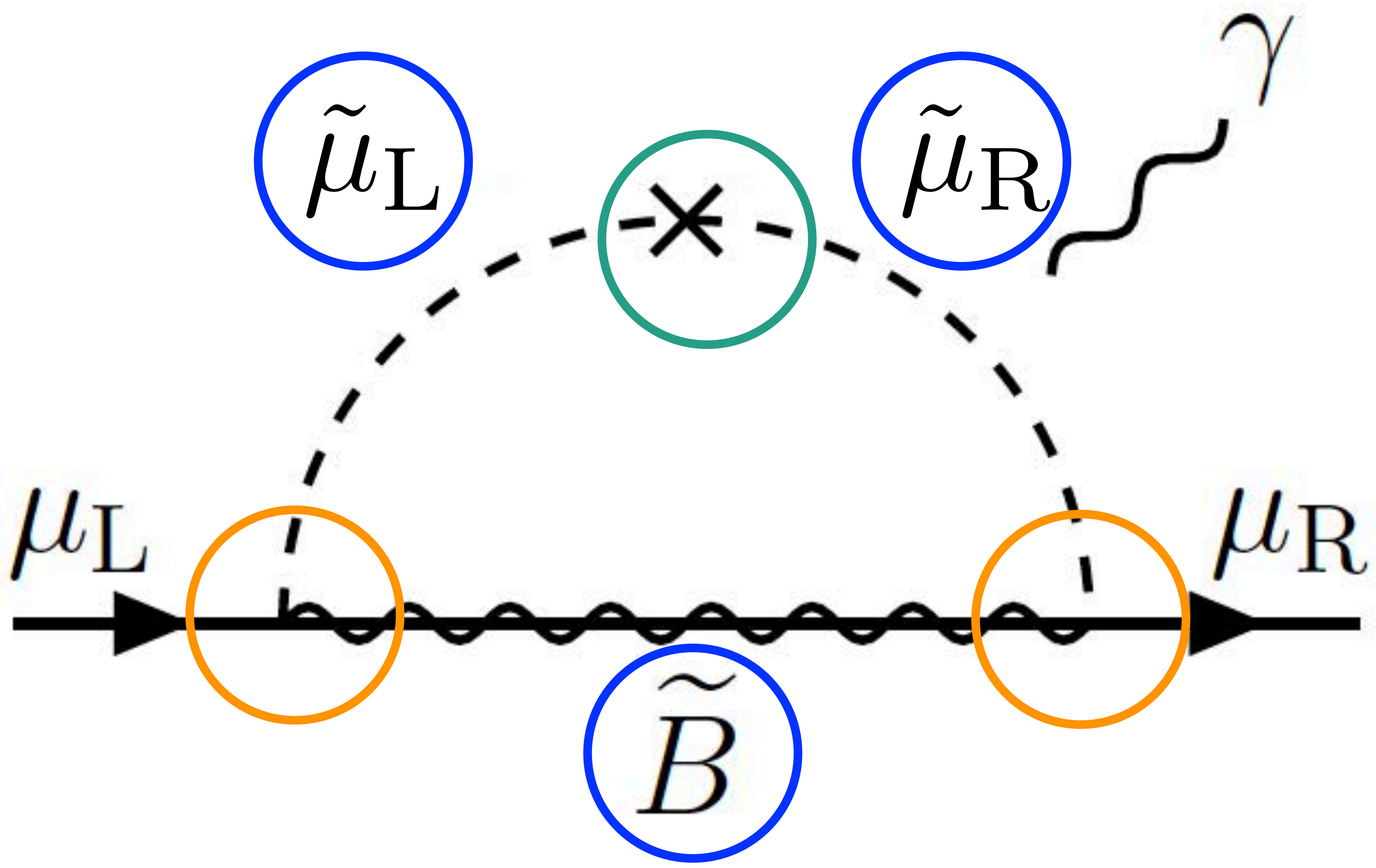




ATLAS first result [ATLAS, 2009.14537] agrees on [Dyndal et al, 1410.2983]

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

- Statement: 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] → see NEXT talk by **Kawada-san**



Based on ~ **SPS1a' model-point study** [Berggren *et al.*, 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%

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

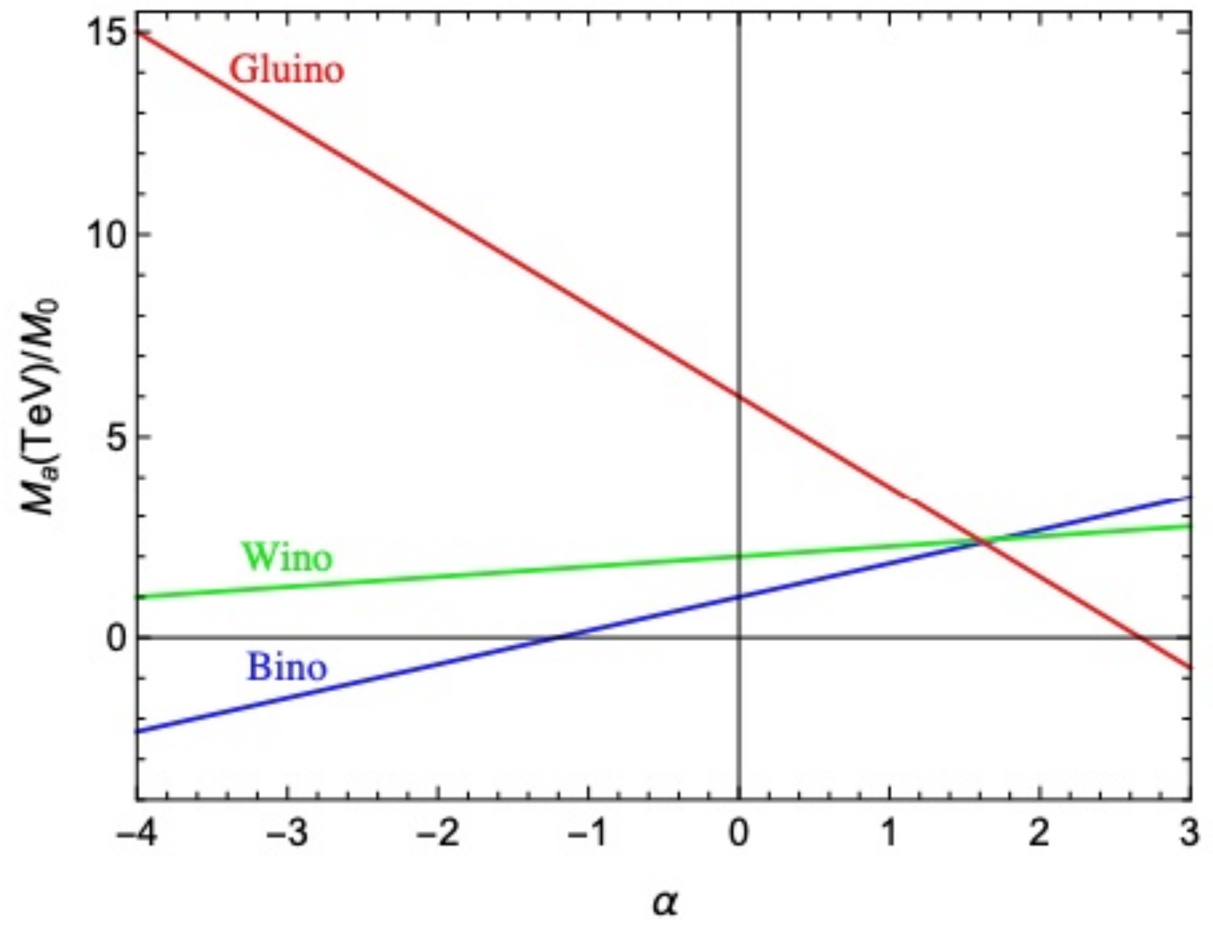
UV model

- 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

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



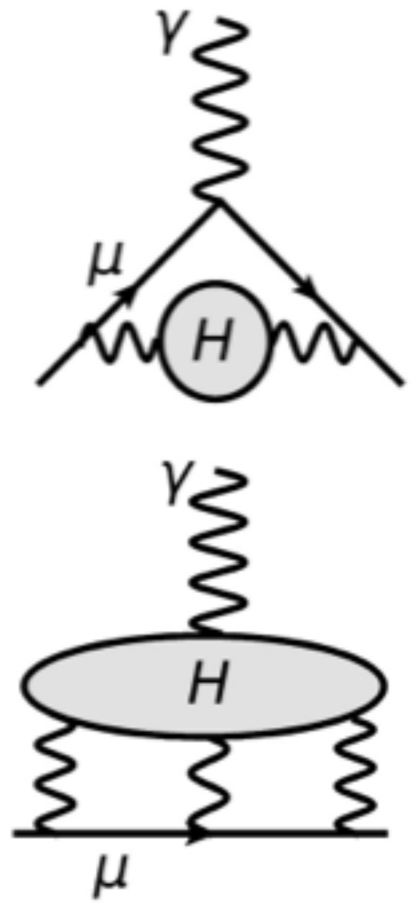
Summary

- Fermilab Muon g-2 collaboration confirmed the BNL muon g-2 data (**4.2σ anomaly**).
- The standard model prediction is still controversial. Other lattice group results / Belle II data / MUonE data will shed light on **the HVP contributions**.
- Several TeV—MeV scale new physics models have been suggested by muon g-2 anomaly.
- SUSY models can still explain the muon g-2 anomaly
- **ILC can probe SUSY** (motivated by muon g-2 anomaly)
  - ILC 500GeV → Bino-LH-RH sleptons (BLR) scenario
  - ILC 1TeV → Wino-Higgsino-LH slepton (WHL) scenario
- **ILC can reconstruct SUSY contributions to muon g-2**

Backup

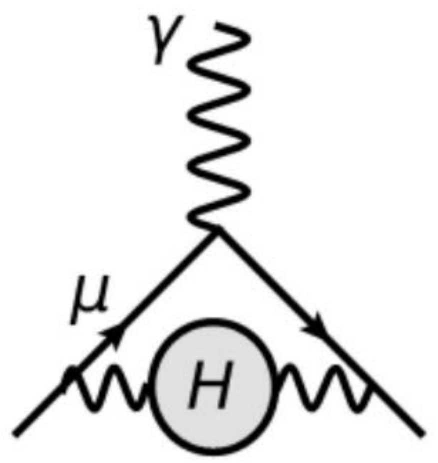
White paper average

[Muon g-2 theory initiative, 2006.04822]



Contribution	Value $\times 10^{11}$	
Experiment (E821)	116 592 089(63)	BNL value
HVP LO (e^+e^-)	6931(40)	
HVP NLO (e^+e^-)	−98.3(7)	
HVP NNLO (e^+e^-)	12.4(1)	
HVP LO (lattice, *udsc*)	7116(184)	← this error shrinks
HLbL (phenomenology)	92(19)	
HLbL NLO (phenomenology)	2(1)	
HLbL (lattice, *uds*)	79(35)	
HLbL (phenomenology + lattice)	90(17)	
QED	116 584 718.931(104)	5-loop!
Electroweak	153.6(1.0)	
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)	
HLbL (phenomenology + lattice + NLO)	92(18)	
Total SM Value	116 591 810(43)	
Difference: $\Delta a_\mu := a_\mu^{\rm exp} - a_\mu^{\rm SM}$	279(76)	3.7σ tension in the end

Status of HVP

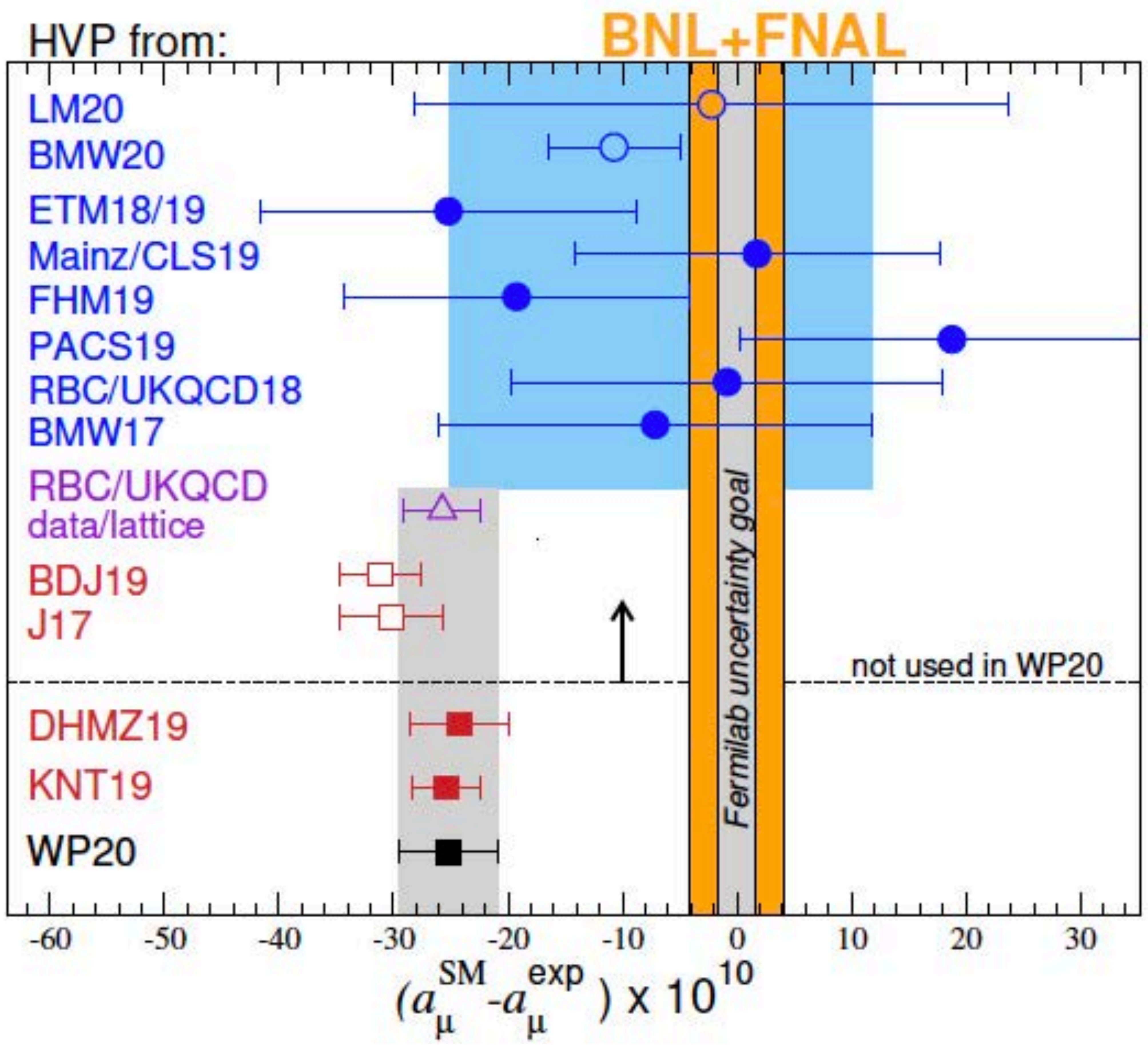


[Lehner, KEK-PH2021]

lattice

hybrid

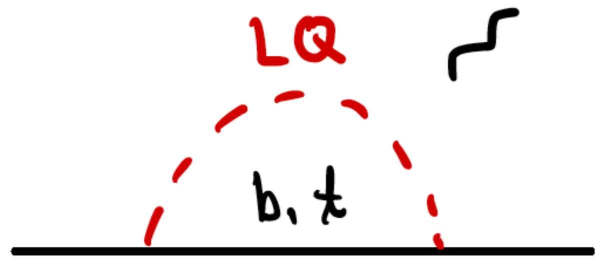
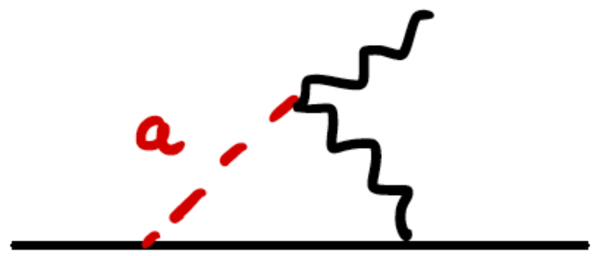
$e^+e^- \to$ hadrons



2.1σ tension between data-driven value (WP20) and BMW20

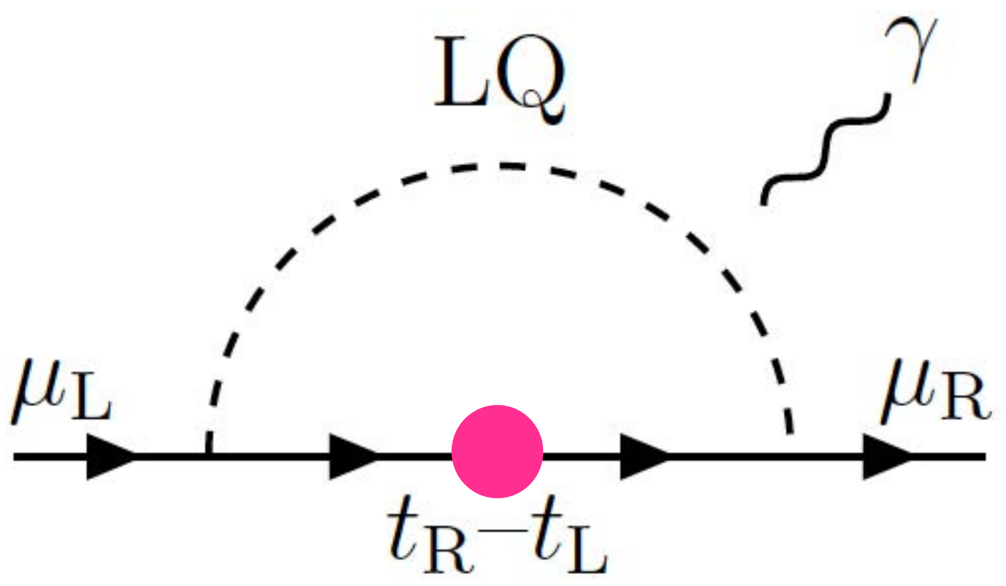
New physics interpretations

[Refs: Athron et al, 2104.03691; Buen-Abad et al, 2104.03267; Krnjaic et al, 1902.07715; Dermisek et al, 2103.05645]

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

Leptoquark models

- TeV-scale scalar/vector leptoquark can also explain muon g-2 anomaly.



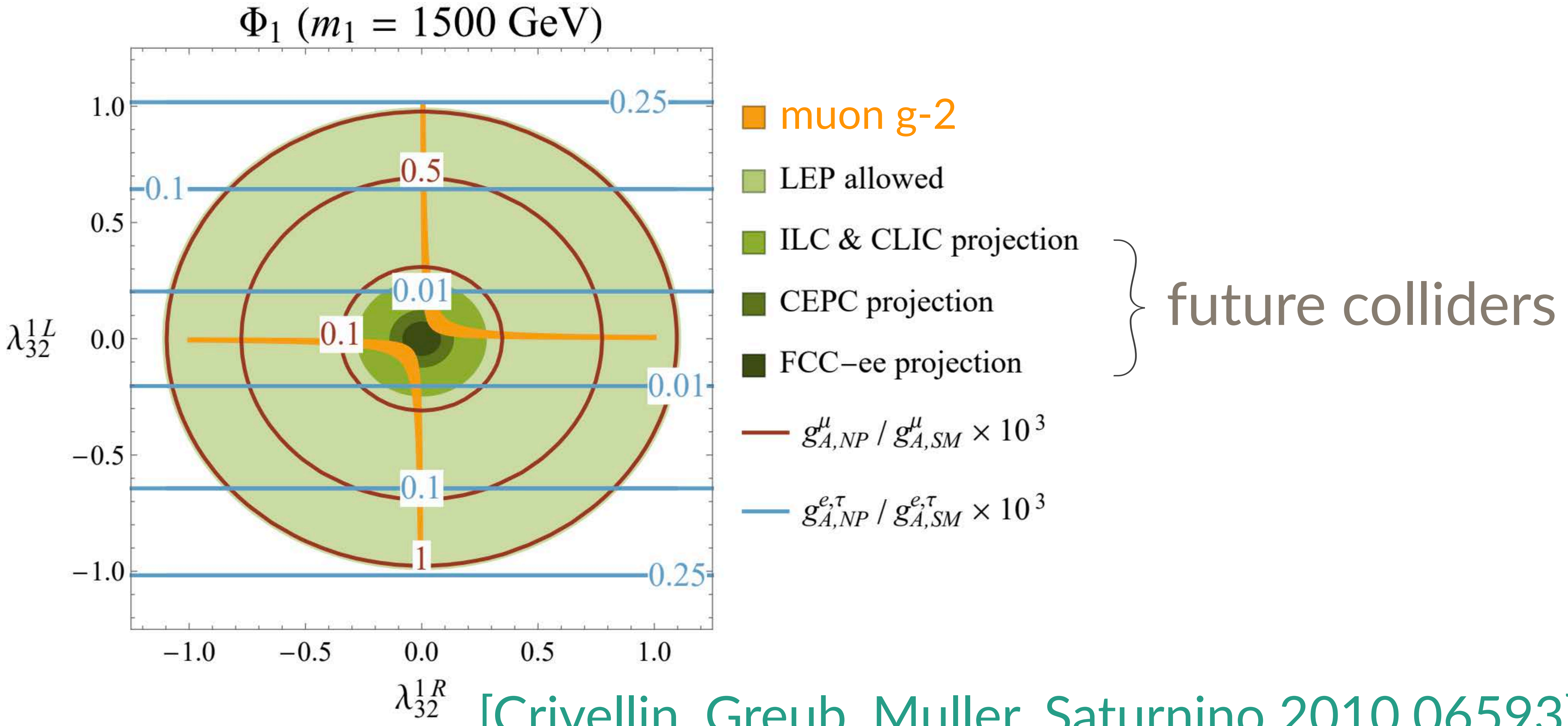
e.g., Low scale Pati-Salam model (SU(4) x SU(2)$_L$ x SU(2)$_R$) predicts TeV-scale leptoquark.

The charm, strange (2nd gen.) couplings are strongly constrained by flavor precision constraints. [Kowalska, Sessolo, Yamamoto 1812.06851]

- Top quark are preferred for the muon g-2 anomaly because chirality enhancement is significant
  $m_t/m_\mu \sim 1600$ → TeV scale leptoquark is possible

- LQ also gives radiative muon mass. No tuning leads to $m_{LQ} < 2.1$ TeV [2104.03691]

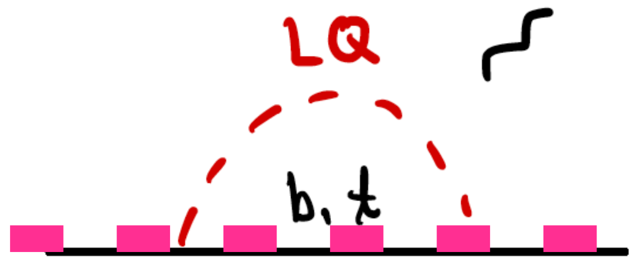
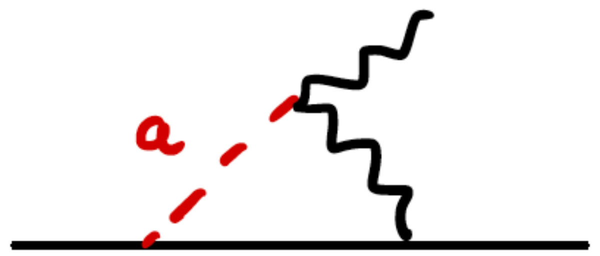
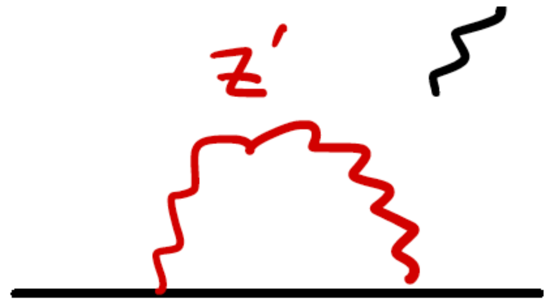
- $Z \to \mu^+\mu^-$ can be probed by **ILC**



[Crivellin, Greub, Muller, Saturnino 2010.06593]

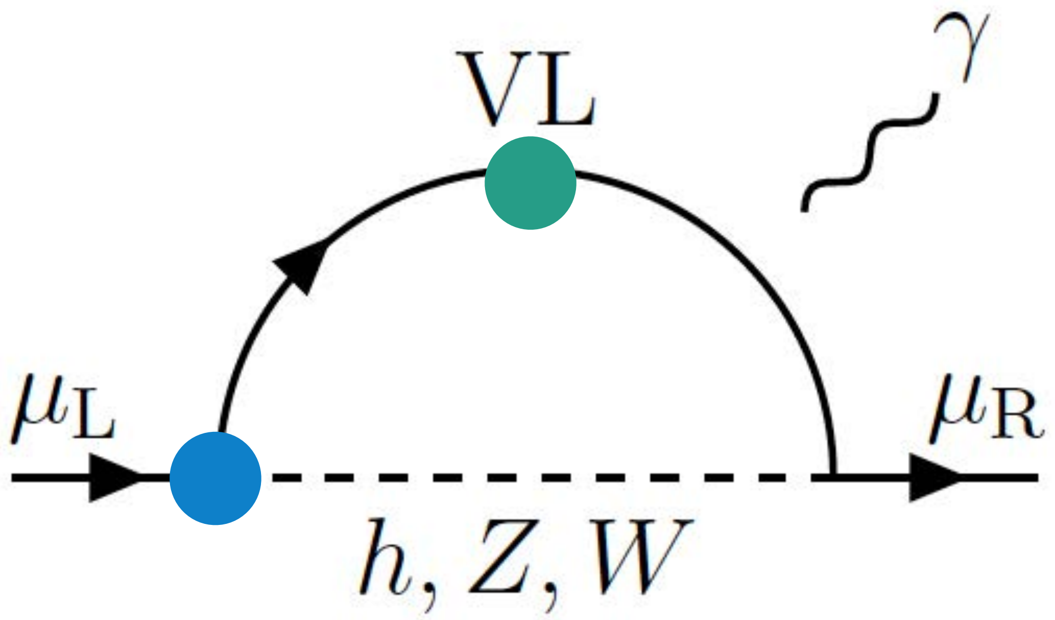
New physics interpretations

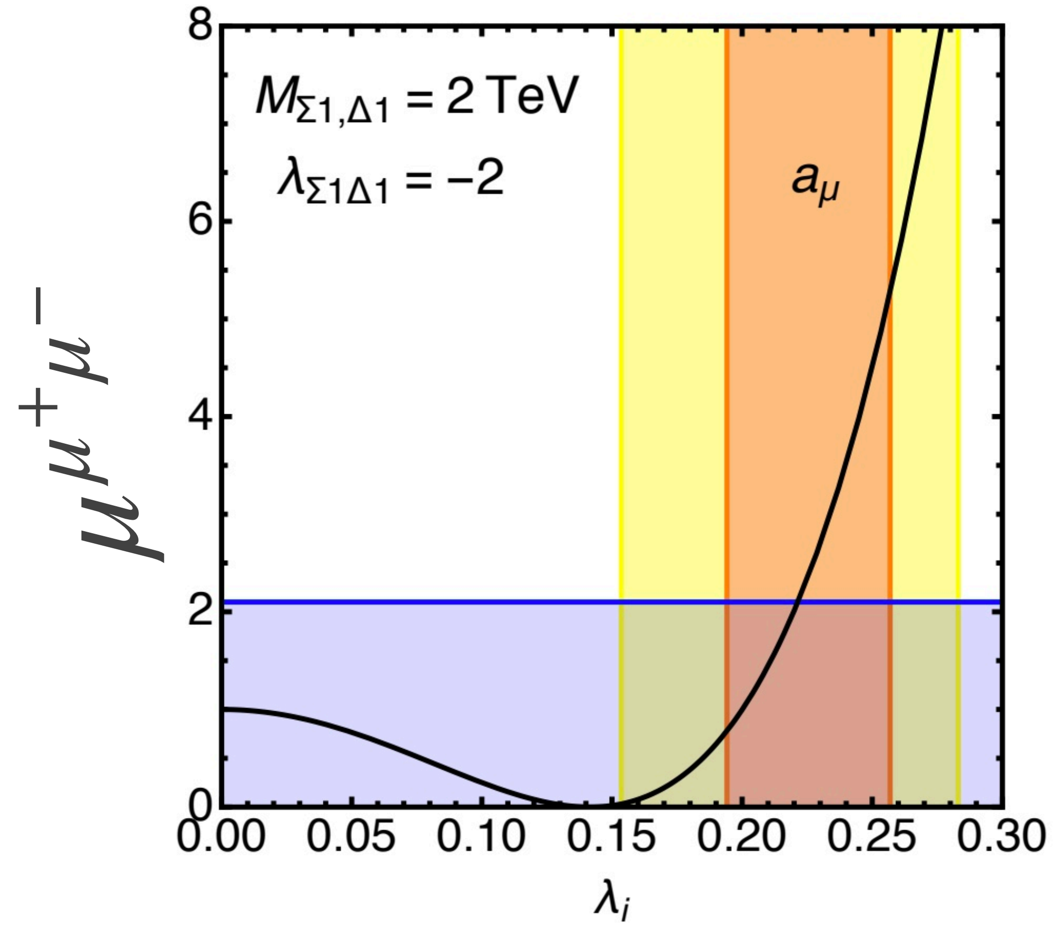
[Refs: Athron et al, 2104.03691; Buen-Abad et al, 2104.03267; Krnjaic et al, 1902.07715; Dermisek et al, 2103.05645]

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

Vector-like lepton

- Extra vector-like leptons can provide significant contribution to muon *g*-2





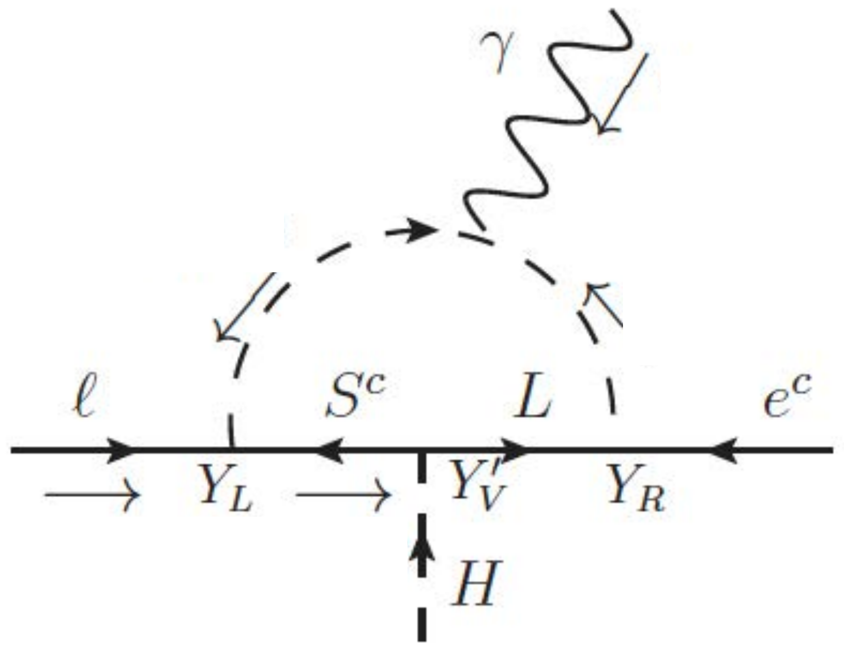
- Enhancement occurs from large Yukawa coupling and large chirality flip
- $m_{\rm VL}$< 100GeV was excluded by LHC Run 1. Run 2 would exclude $m_{\rm VL} \lesssim \mathcal{O}(500)$ GeV region [ATLAS 2008.07949]
- There is a robust correlation with $h \to \mu^+\mu^-$ (SM is $\mu^{\mu^+\mu^-} = 1$ in the left figure) [Endo, Mishima 2005.03933]
- ILC has ~ 10% sensitivity for $\mu^{\mu^+\mu^-}$ measurement

Novel theoretical finding: Violation of Wilsonian (1/2)

[Arkani-Hamed, Harigaya, 2106.01373]

- Using **a vector-like lepton model**, the authors discover "violation of Wilsonian naturalness" following from "total derivative phenomenon"
- Two vector-like leptons are introduced: SU(2)$_L$ doublet L and singlet S **(motivation: $h\mu^+\mu^-$ is SM-like)**
- Dimension-six one-loop contributions are canceled out without symmetry reason, independently of mass spectrum! The reason is that the loop function is "total derivative"

Σ



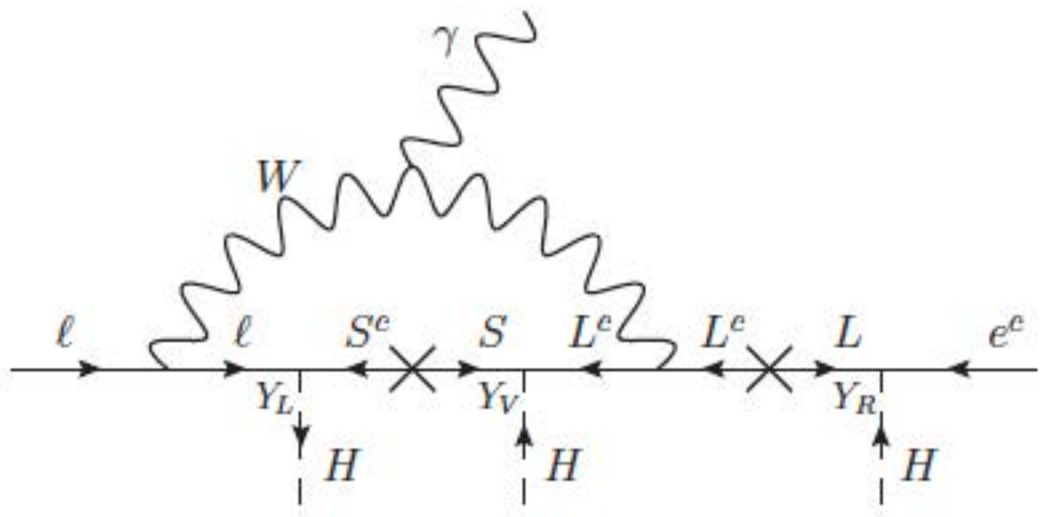
etc. $= 0$

total derivative!

No UV div.

$$\propto \int_0^\infty dk^2 f'(k^2) = 0 \text{ with } f(\infty) = f(0) = 0$$

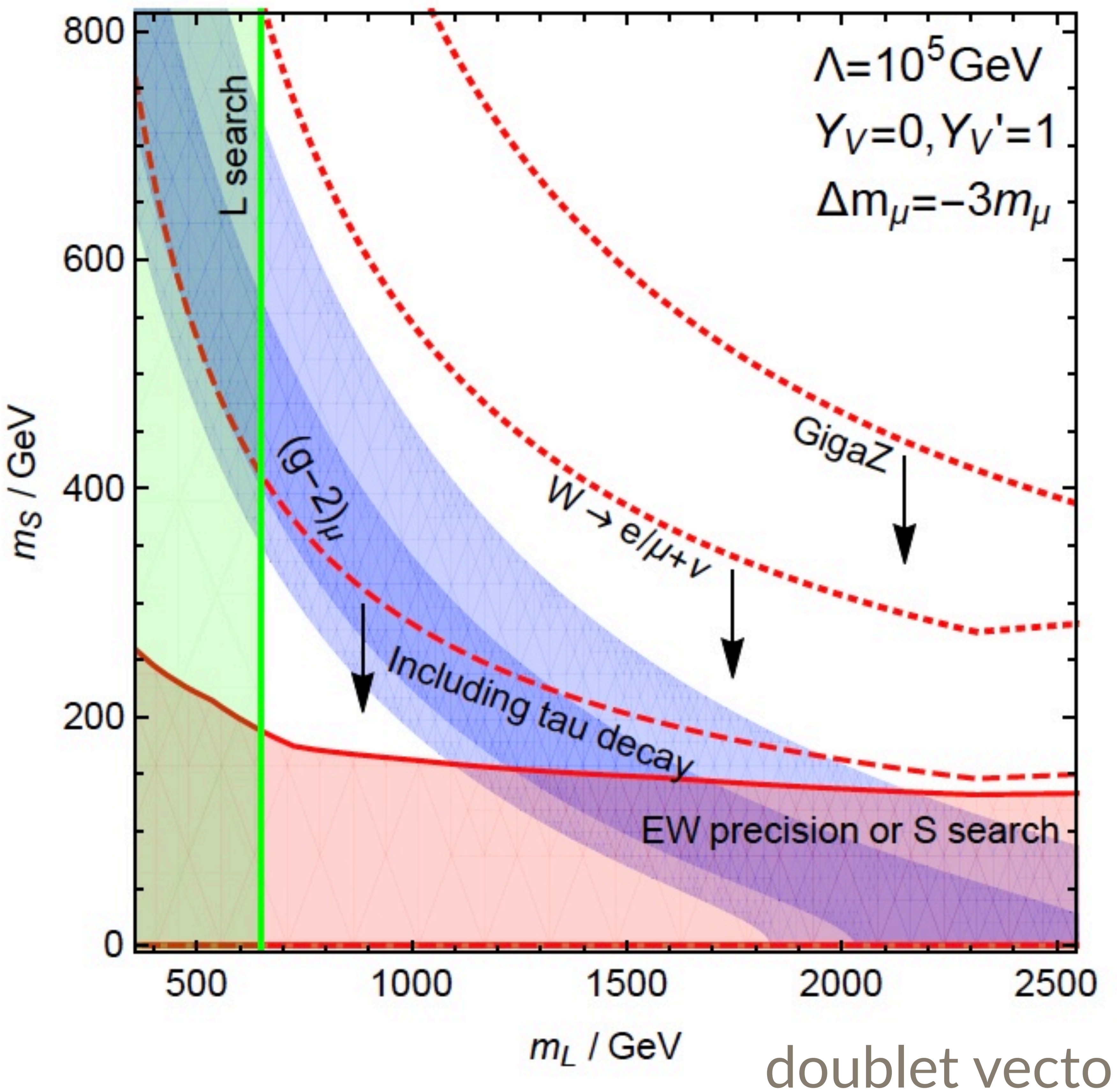
- Leading contribution comes from dimension-eight one-loop



Novel theoretical finding: Violation of Wilsonian (2/2)

- Prediction. Viable parameter space will be fully proved by future lepton colliders.

Excluded by LHC search



singlet vector-like lepton mass

doublet vector-like lepton mass

[Arkani-Hamed, Harigaya, 2106.01373]

$Z \to \mu^+\mu^-$

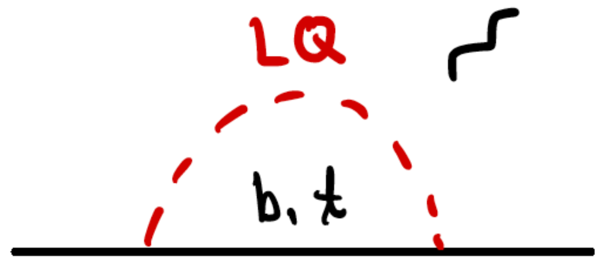
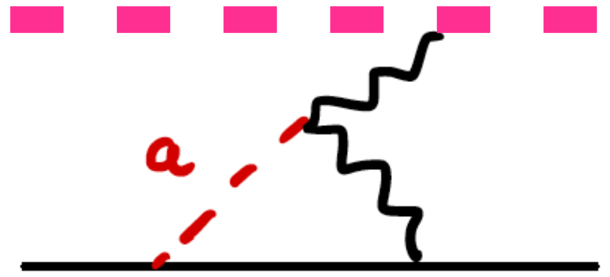
$W \to \mu\bar{\nu}$

$\tau \to \mu\nu\bar{\nu}$

Excluded by electroweak fit

New physics interpretations

[Refs: Athron et al, 2104.03691; Buen-Abad et al, 2104.03267; Krnjaic et al, 1902.07715; Dermisek et al, 2103.05645]

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

Leptophilic scalar extensions

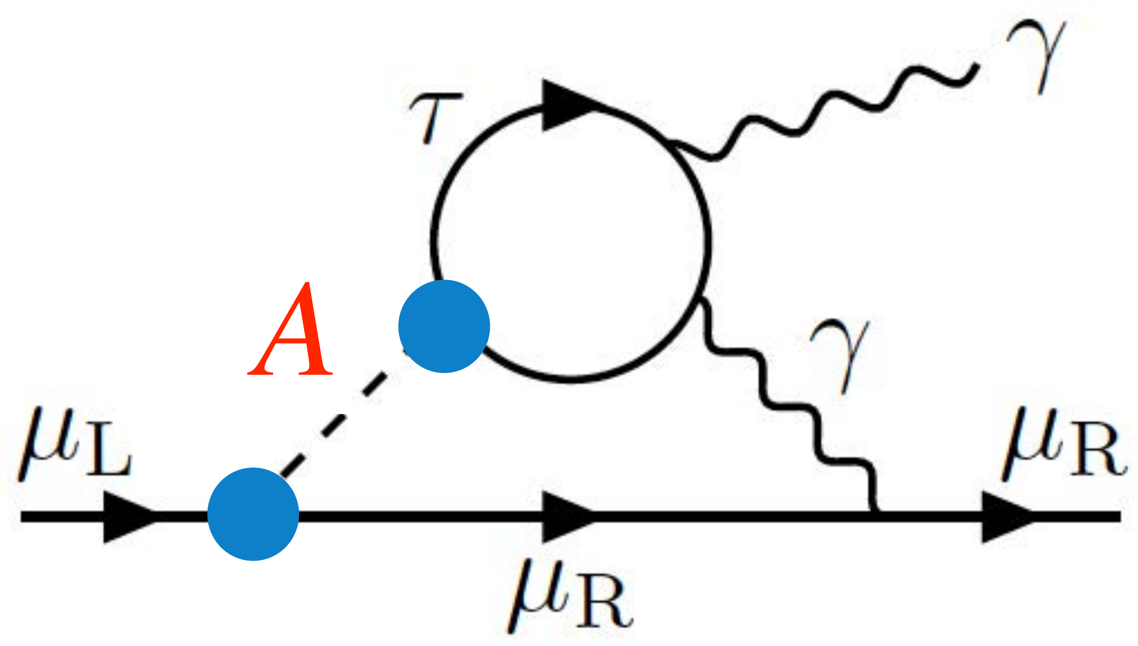
- **Type-X 2HDM** is a leptophilic scalar extension model
- Two-loop Barr-Zee diagram is proportional to $(\tan\beta)^2$
- Bounds from $B_s \to \mu^+\mu^-, Z \to \tau^+\tau^-, \tau \to \mu\nu\bar{\nu}$, EW fit, and LHC
- Still allowed: [Athron et al, 2104.03691]

$$20\ \text{GeV} \lesssim m_A \lesssim 40\ \text{GeV},$$
$$150\ \text{GeV} \lesssim m_{H,H^\pm} \lesssim 250\ \text{GeV}$$

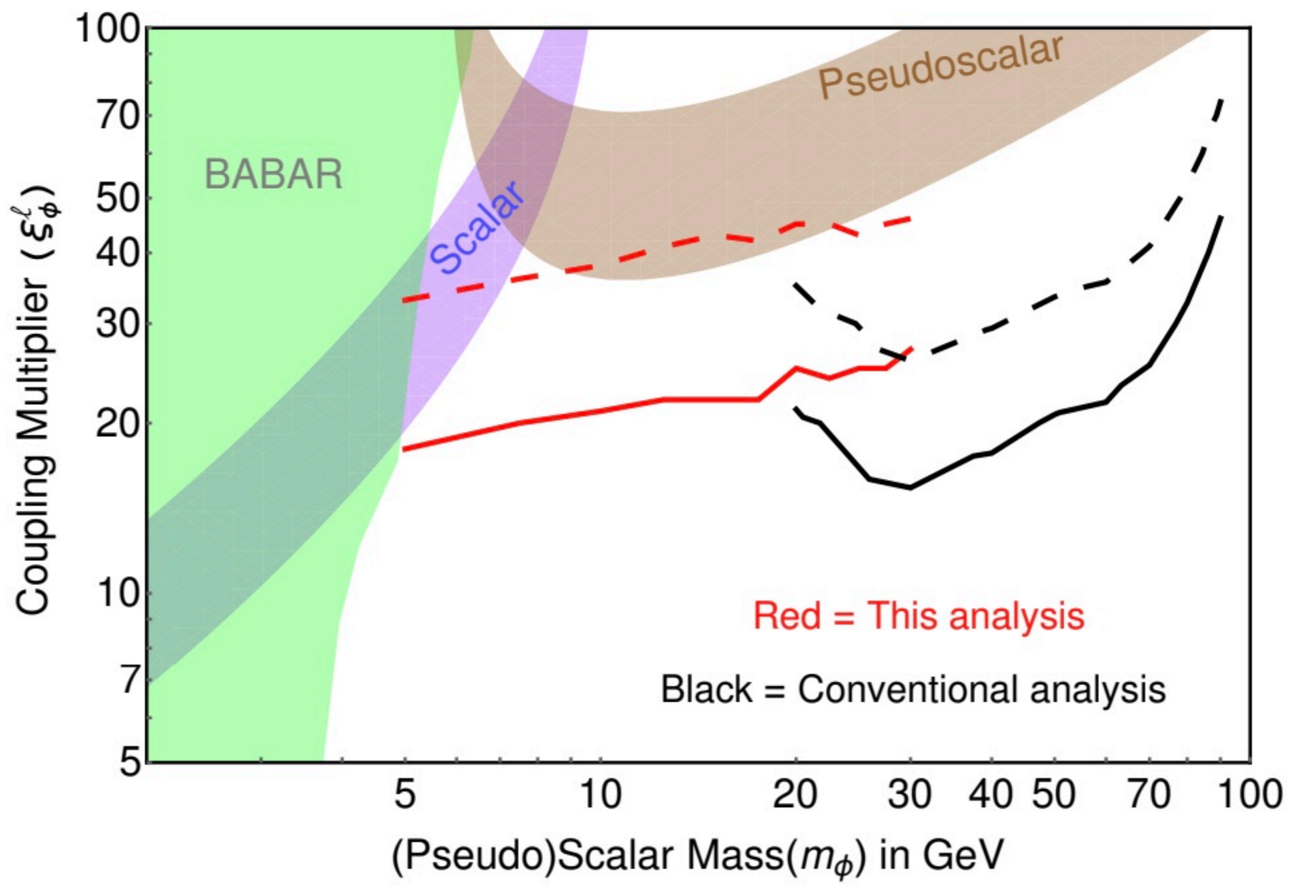
- ILC250 can probe via

$$e^+e^- \to \tau^+\tau^- A \to \tau^+\tau^+\tau^-\tau^-$$

collimated $\mu^+\mu^-$ (from τ)/ 4τ search

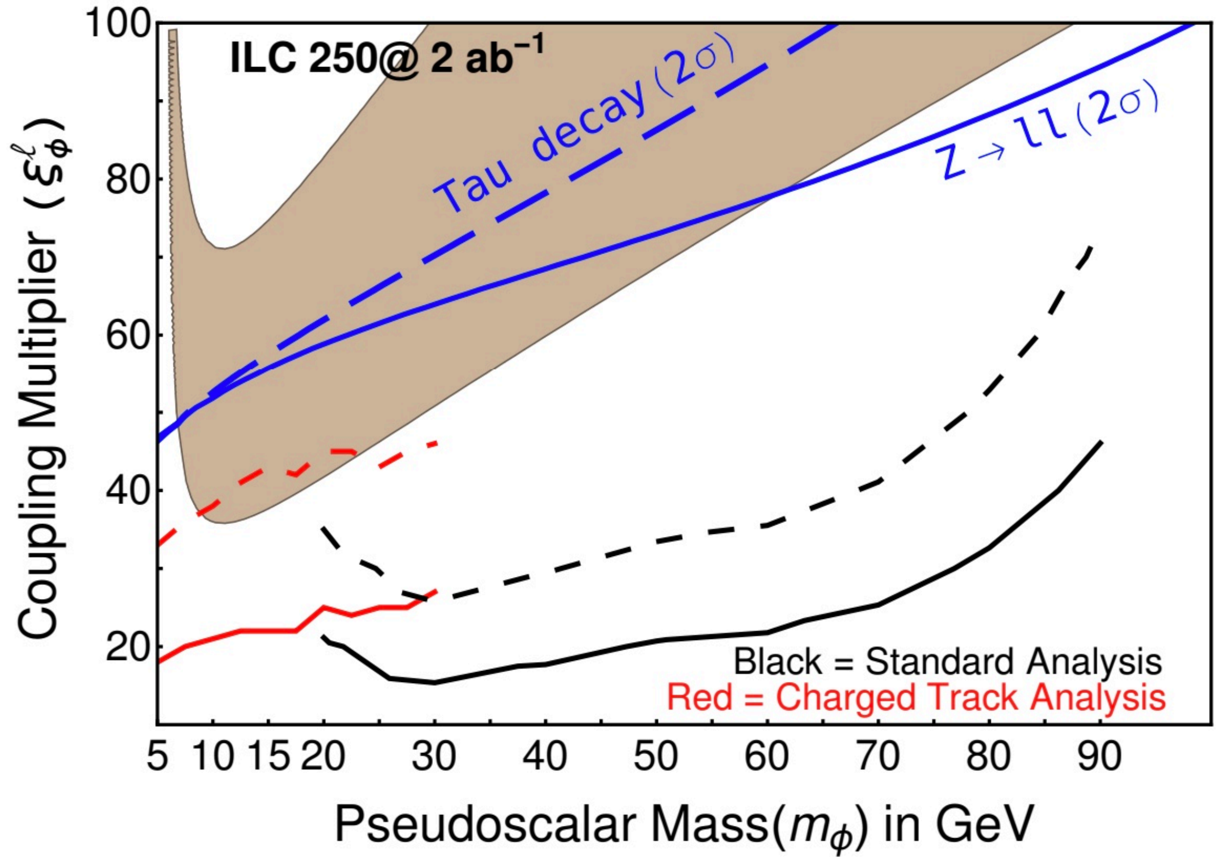


Type-X 2HDM



2σ (dashed), 5σ (solid)

2HDM + A



[Chun, Mondal, 2104.03701]

New physics interpretations

[Refs: Athron et al, 2104.03691; Buen-Abad et al, 2104.03267; Krnjaic et al, 1902.07715; Dermisek et al, 2103.05645]

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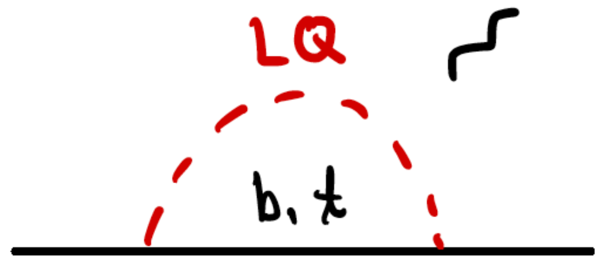
Leptoquark		1.5〜2.1 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$ $Z \to \mu^+\mu^-$
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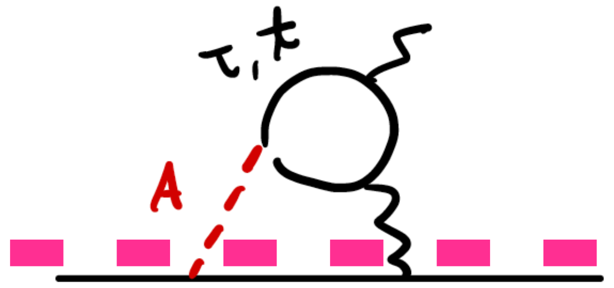
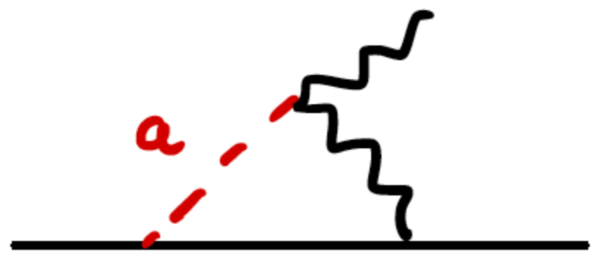
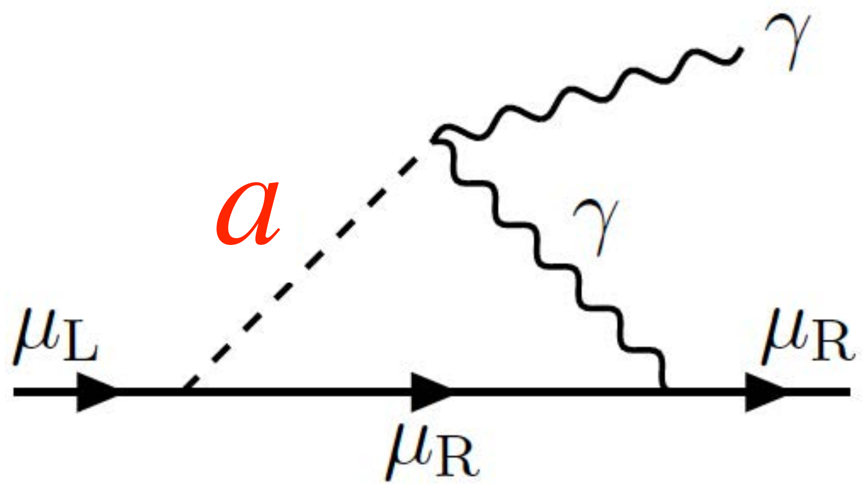
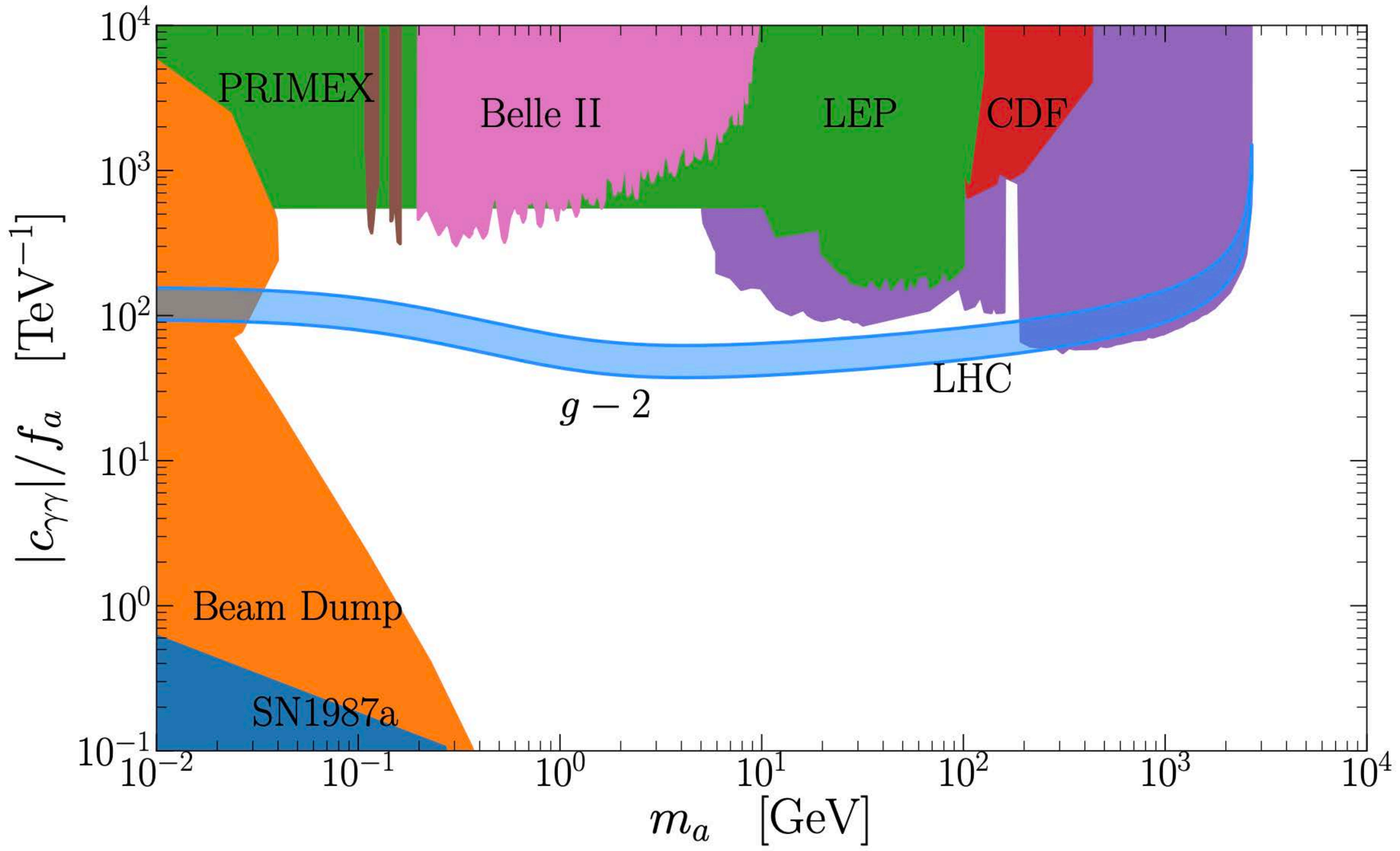
Scalar extensions		10〜100 GeV (A), 150〜300 GeV (H)	$Z \to \tau^+\tau^-$ $pp \to HA \to 4\tau$
Axion-like particle		40 MeV〜200 GeV	$e^+e^- \to \gamma a \to 3\gamma$
U(1) Lμ-Lτ		10〜200 MeV	$e^+e^- \to \mu^+\mu^- Z'$ $K \to \mu\nu Z'$, $\mu e \to \mu e Z'$

Axion-like particle

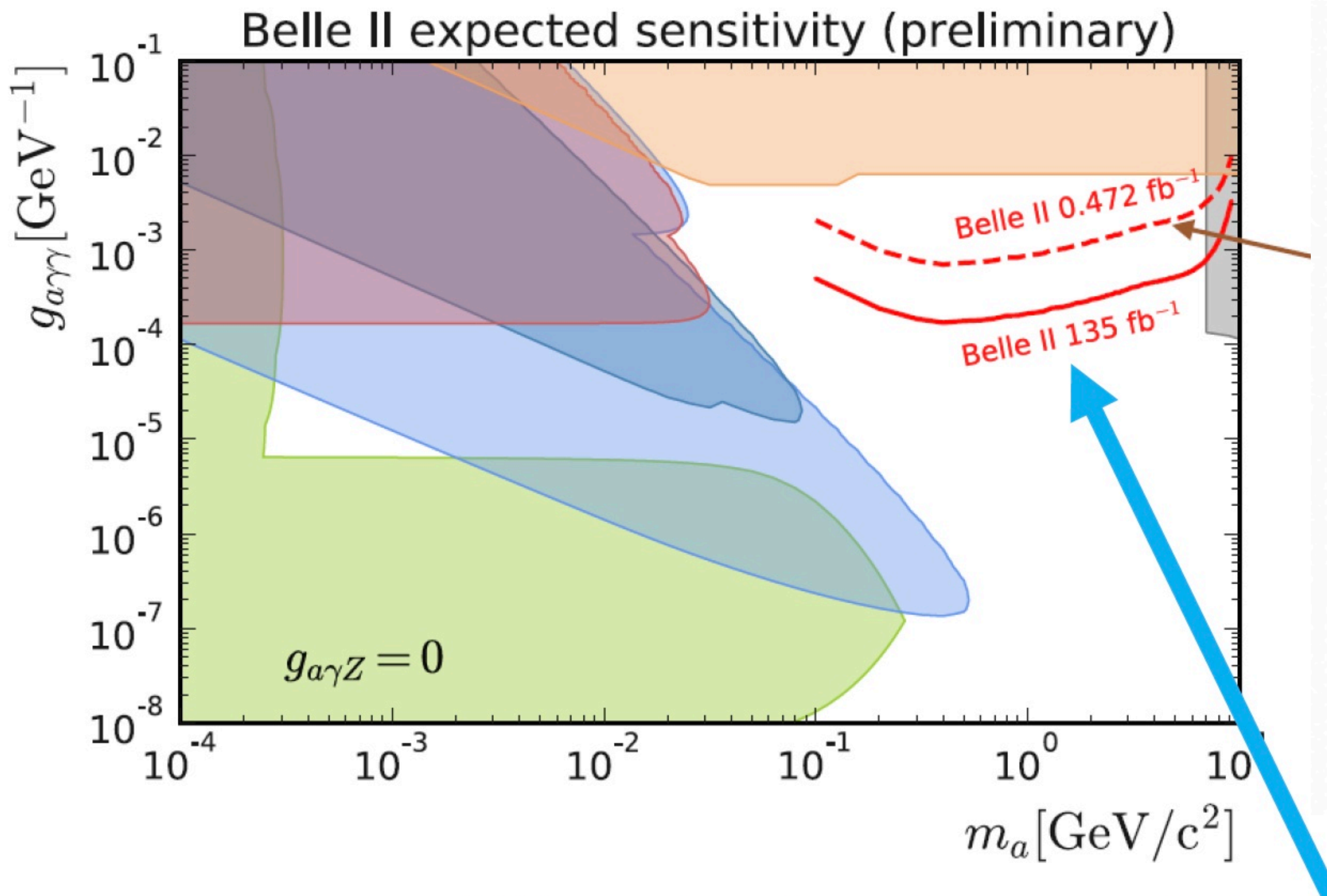
- Axion-like particle (ALP) would be pseudo-NG boson of UV symmetry, and hence mass has to be light



[Buen-Abad, Fan, Reece, Sun 2104.03267]

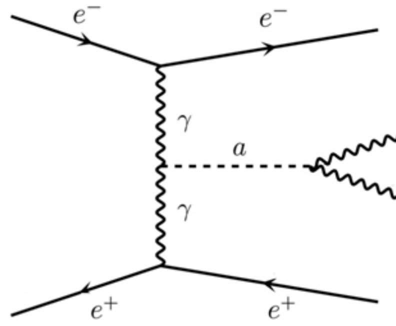


$$e^+e^- \to \gamma a \to 3\gamma$$

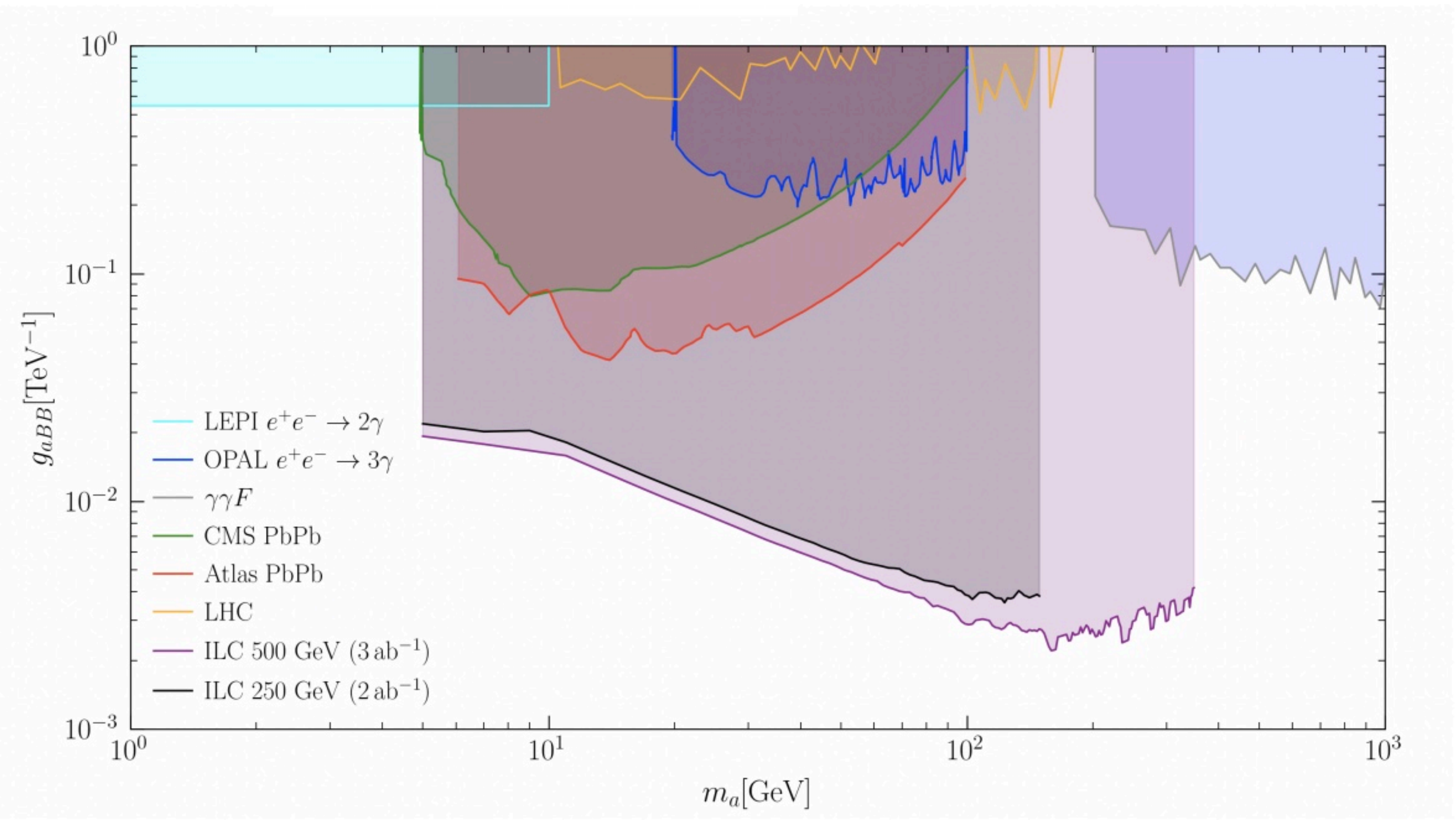


This region is only accessible with Belle II.

[Ishikawa, PPP2021]



@ ILC



ILC could probe the heavy mass region $m_a \gtrsim 5$ GeV

[Steinberg, 2108.11927, 2101.00520]

New physics interpretations

[Refs: Athron et al, 2104.03691; Buen-Abad et al, 2104.03267; Krnjaic et al, 1902.07715; Dermisek et al, 2103.05645]

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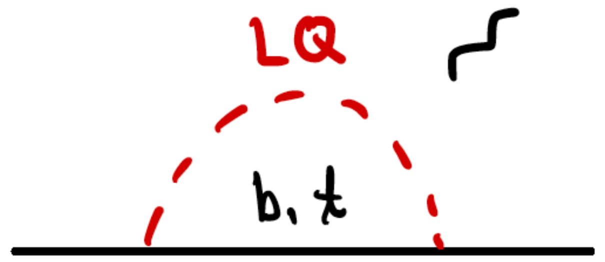
Leptoquark		1.5〜2.1 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$ $Z \to \mu^+\mu^-$
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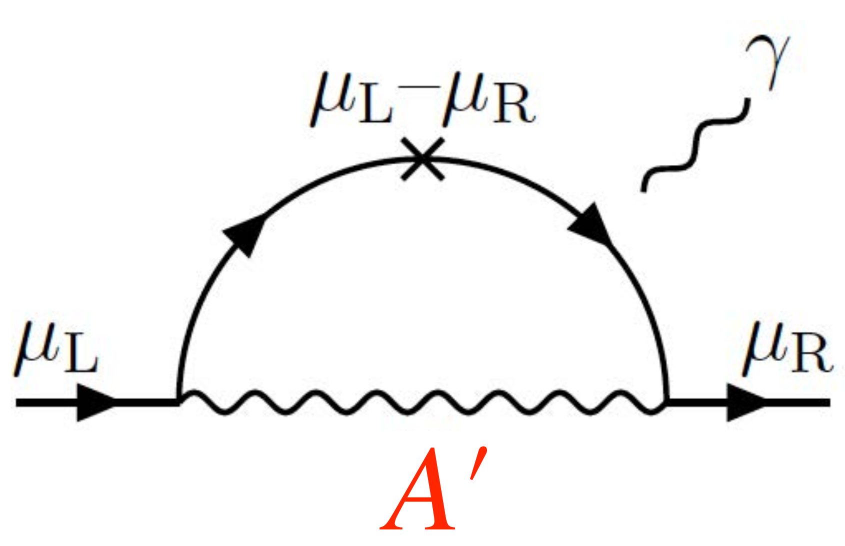
U(1) L_μ-L_τ		10〜200 MeV	$e^+e^- \to \mu^+\mu^- Z'$ $K \to \mu\nu Z',\ \mu e \to \mu e Z'$

Excluded: dark-photon model

◆ Dark-photon (hidden-photon) model: SM + massive U(1) gauge

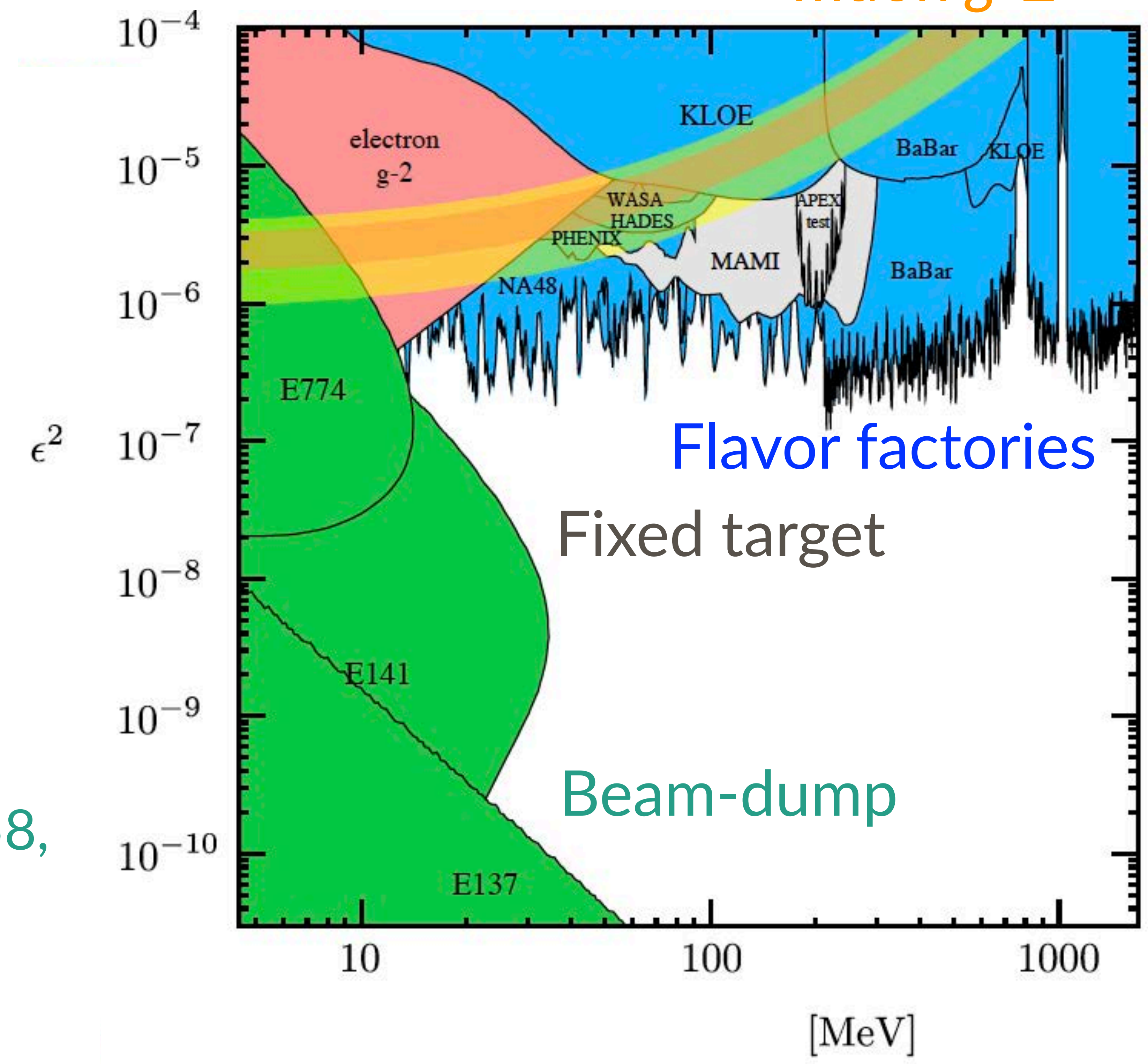
$$\mathcal{L}_V = -\frac{1}{4}F^V_{\mu\nu}F^{V\,\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}F^V_{\mu\nu}B^{\mu\nu}$$

$\sim \epsilon^2$



electron g-2

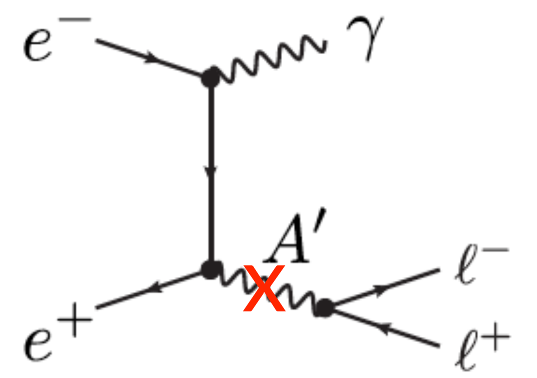
muon g-2



[Endo, Hamaguchi, Mishima, 1209.2558, updated]

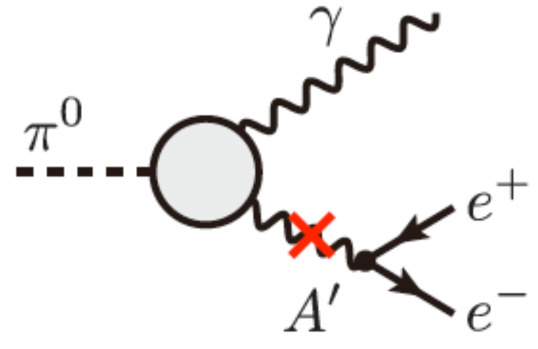
BaBar

$e^+e^- \to \gamma A', \quad A' \to \ell^+\ell^-$



NA48

$\pi^0 \to \gamma A', \; A' \to e^+e^-$



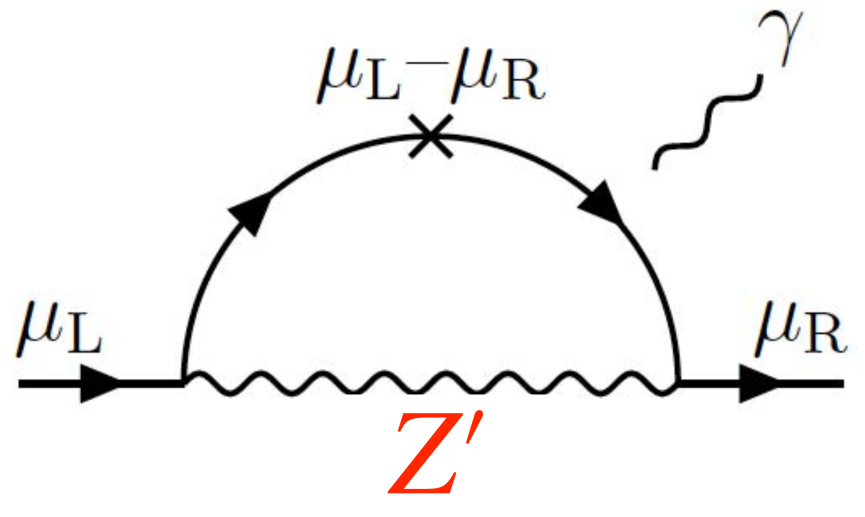
Dark-photon model is very simple and motivative.

Unfortunately, all parameter region that explains the muon g-2 anomaly has been excluded.

U(1)$_{L_\mu - L_\tau}$ gauge symmetry (vector muonic force)

- Electron coupling/mode gives severe bounds
- $L_\mu - L_\tau$ U(1) gauge symmetry (muon number and tau number are gauged including neutrino)
    - No electron direct interaction, and bounds are week
    - gauge anomaly-free
    - Motivative: neutrino mass, Leptogenesis [e.g., Asai, Hamaguchi, Nagata, Tseng 2005.01039]

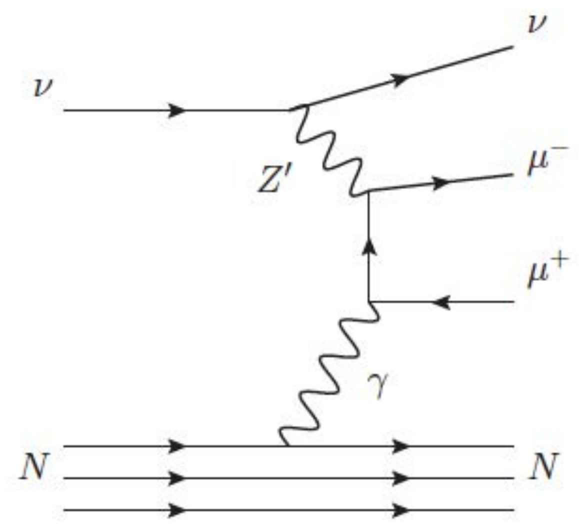
$$\mathcal{L} = -\frac{1}{4}Z'_{\alpha\beta}Z'^{\alpha\beta} + \frac{1}{2}m_{Z'}^2 Z'_\alpha Z'^\alpha + g' Z'_\alpha \left(\bar{\ell}_2\gamma^\alpha\ell_2 - \bar{\ell}_3\gamma^\alpha\ell_3 + \bar{\mu}_R\gamma^\alpha\mu_R - \bar{\tau}_R\gamma^\alpha\tau_R\right)$$



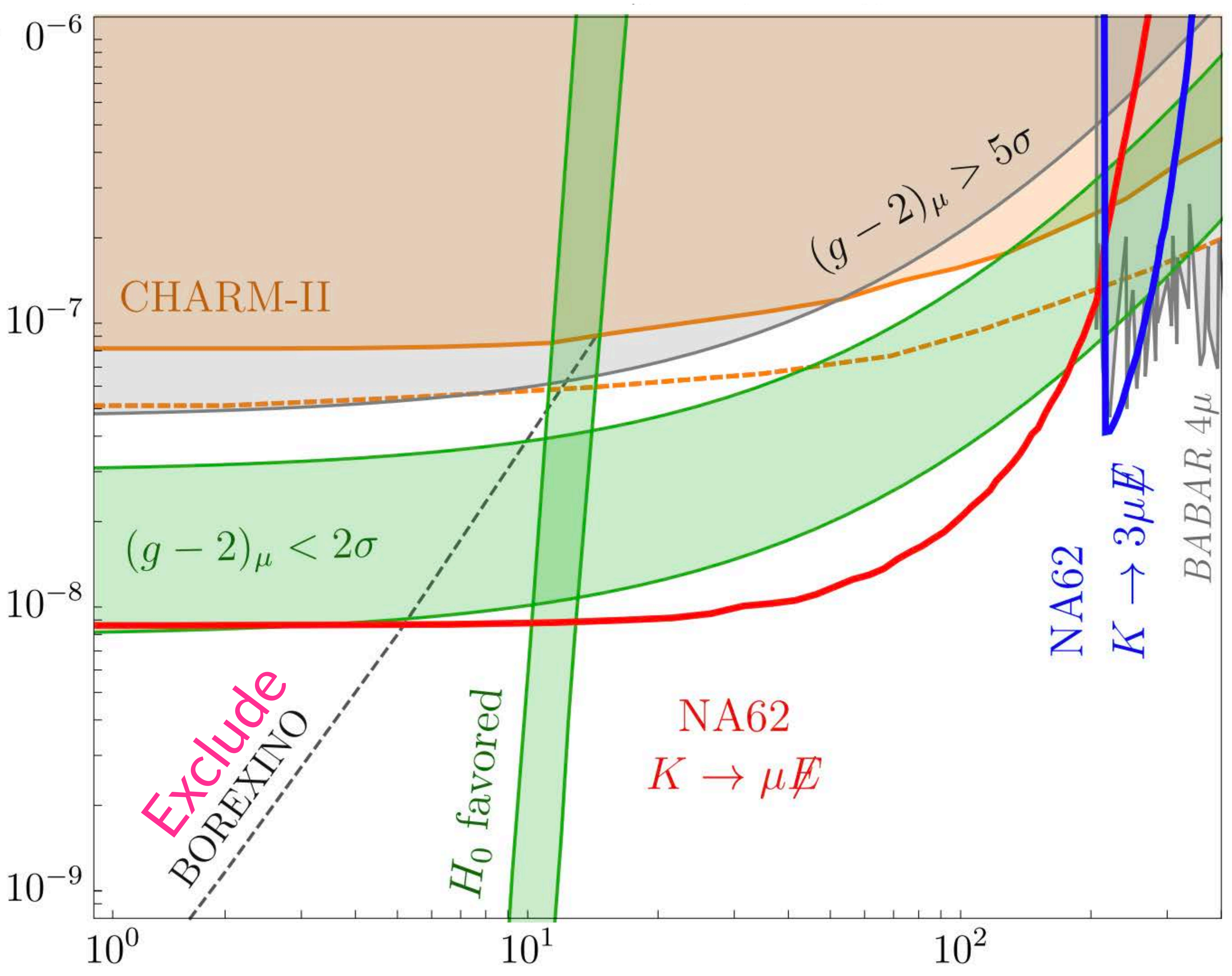
$\sim (g')^2$

U(1)$_{L_\mu - L_\tau}$ gauge symmetry

neutrino-trident bound



$(g')^2/4\pi$

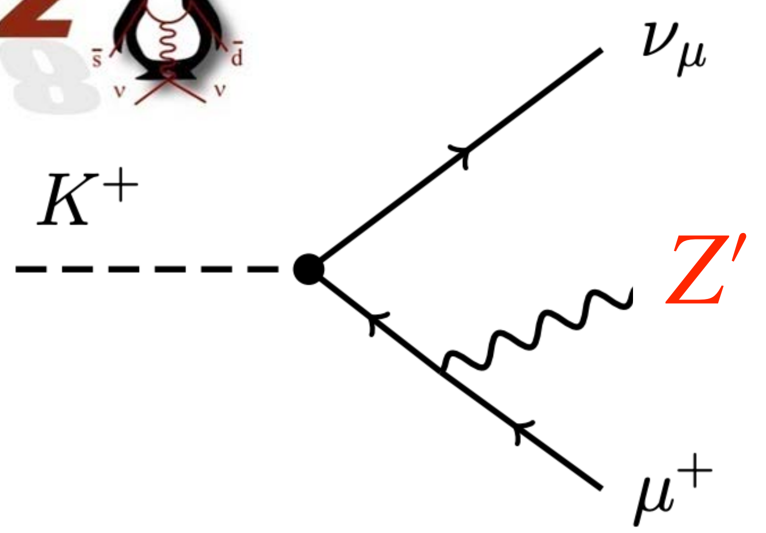


Solar neutrino measurement

$m_{Z'}$ [MeV]

[Krnjaic, Marques-Tavares, Redigolo, Tobioka 1902.07715]

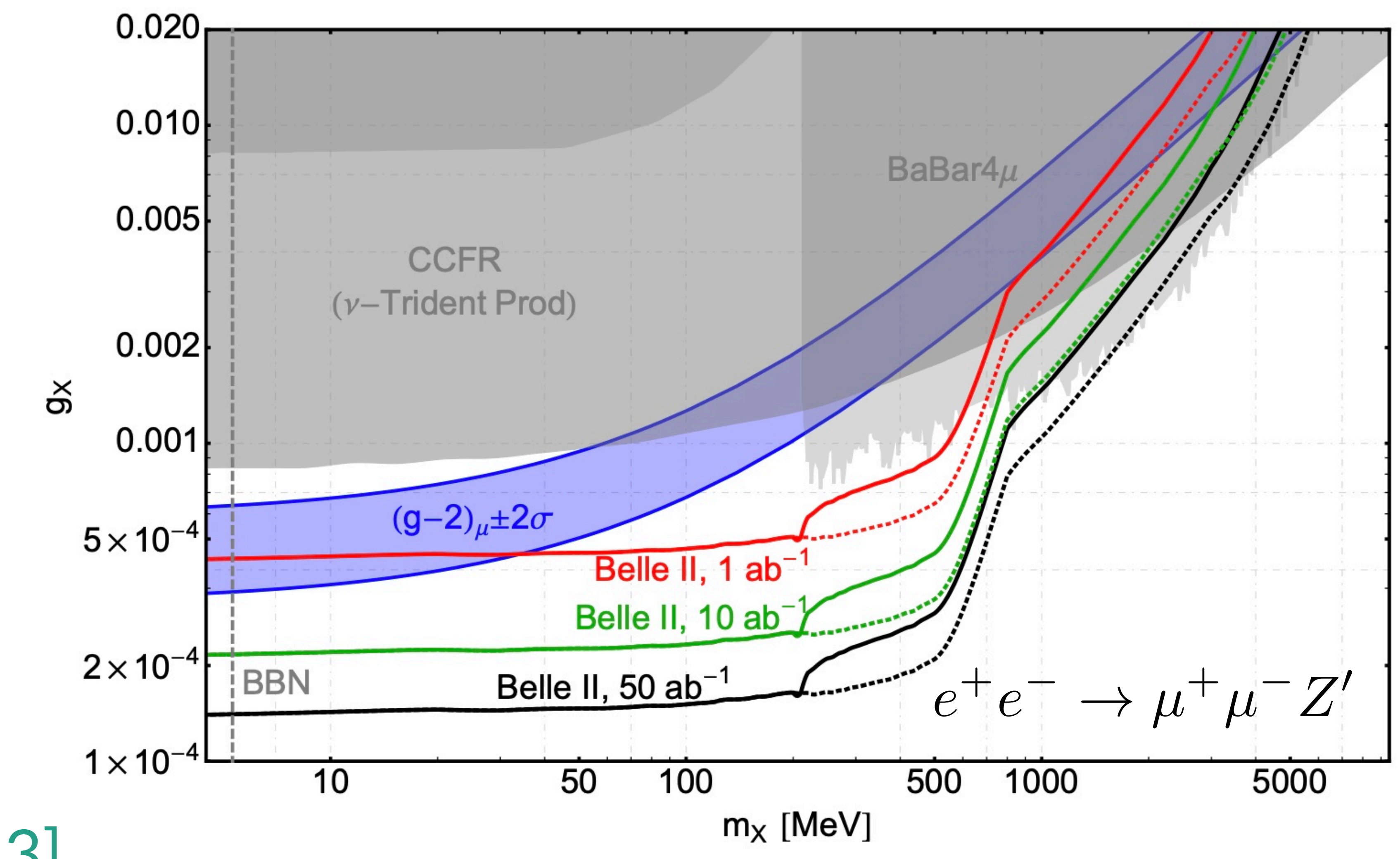
NA62 (K^+ beam) exp can probe all parameter region by



decay into $\nu\bar{\nu}$

$\mu\bar{\mu}$ is kinematically forbidden

Belle II

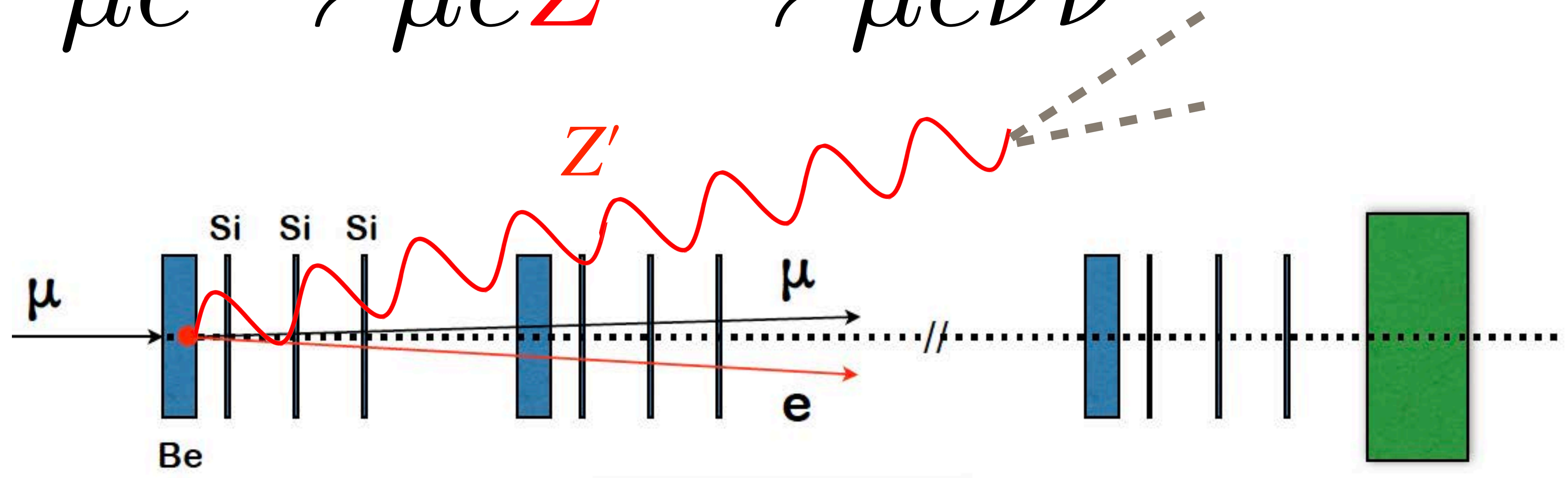


[Jho, Kwon, Park, Tseng, 1904.13053]

MUonE experiment vs. muonic force

- MUonE experiment could probe U(1)$_{L_\mu - L_\tau}$ model completely [Asai, Hamaguchi, Nagata, Tseng, Wada 2109.10093]

$$\mu e \to \mu e Z' \to \mu e \nu \bar{\nu}$$



$\sqrt{s} \sim 400$ MeV