New physics interpretation of the muon *g*-2 anomaly

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Based on: Endo, Hamaguchi, Iwamoto, TK
[2001.11025] [2104.03217]

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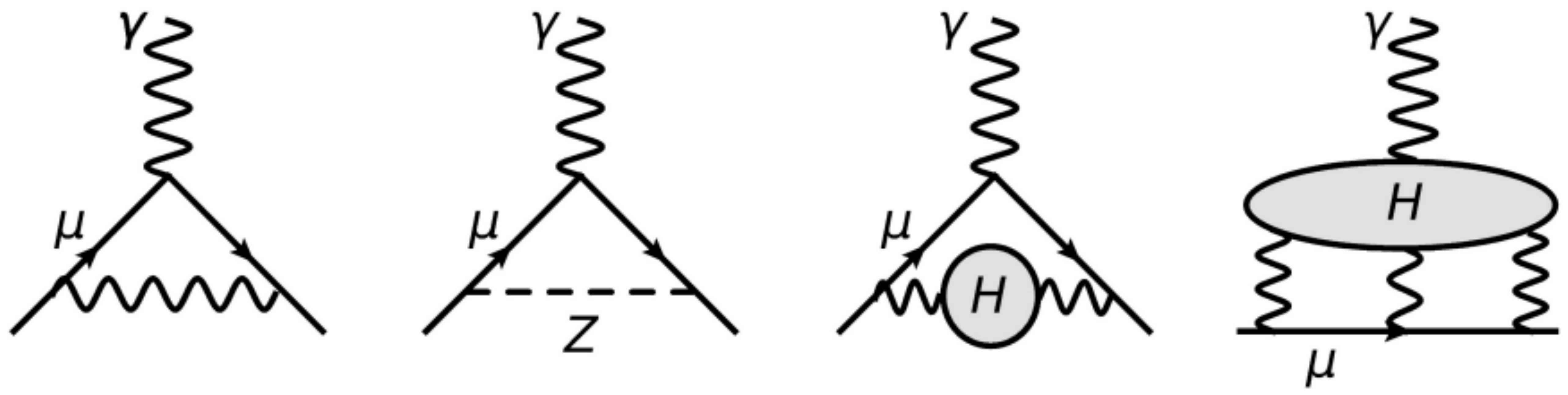
Muon g-2

Theory



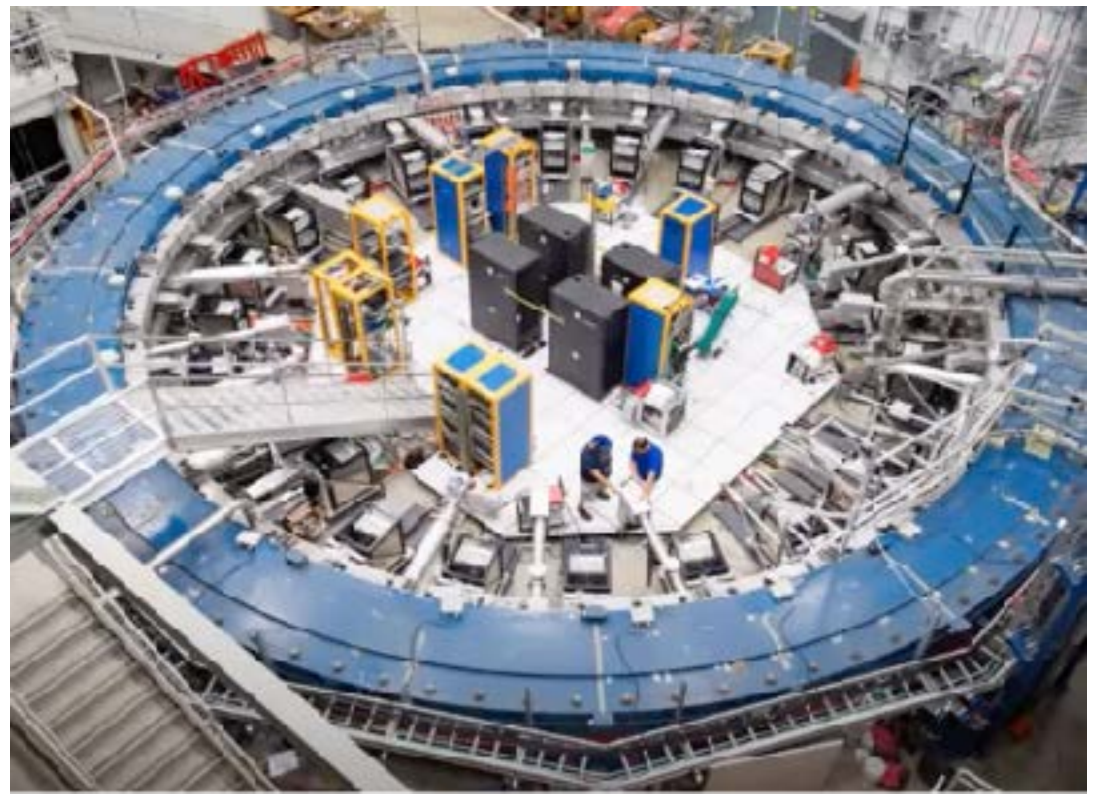
QED	EW	Hadronic vacuum polarization **(HVP)**	Hadronic light-by-light **(HLbL)**
		Phenomenological	Pheno.
Analytic	Analytic	Lattice	Lattice
		Problematic	

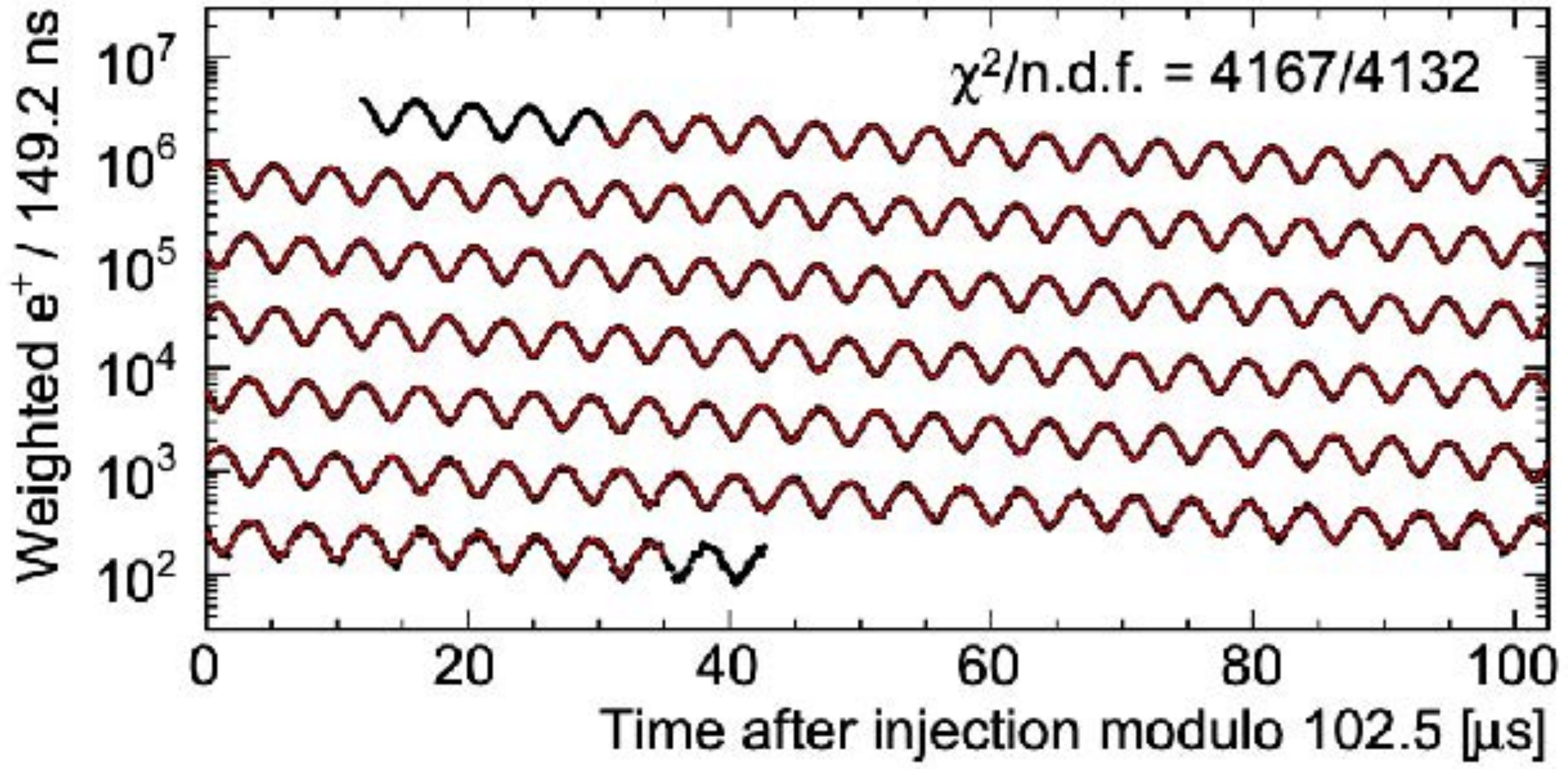
Exp.

BNL ’97-‘01

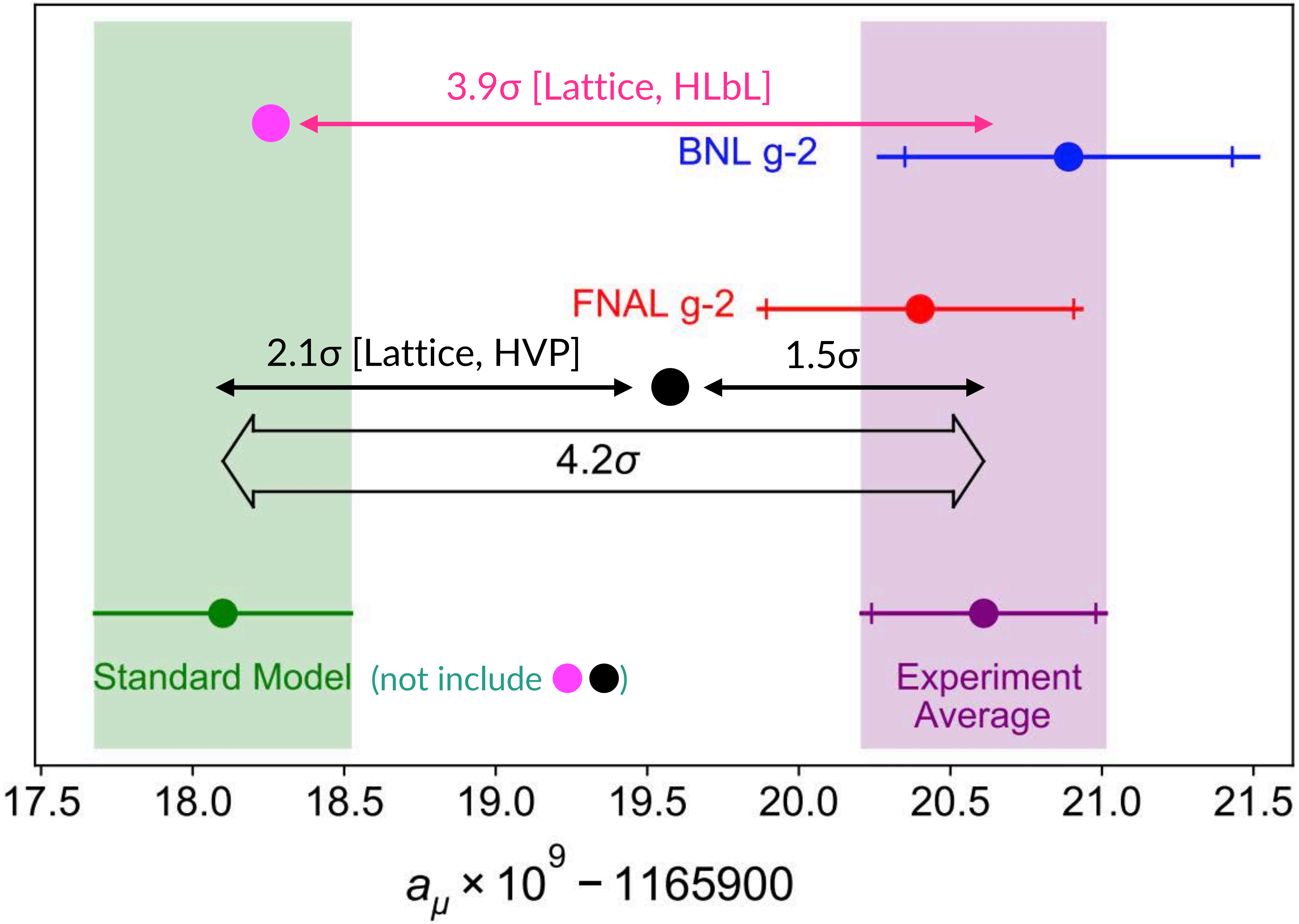
FNAL ongoing

J-PARC
near future





Based on [FNAL Muon g-2, PRL2021]



comments

Stat errors dominated

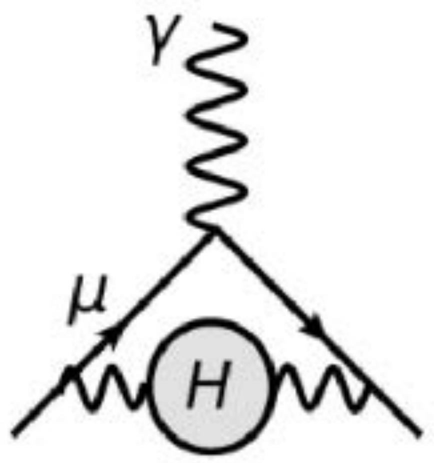
Almost no correlation between BNL and FNAL syst errors

The latest lattice result for HLbL slightly reduces tension [Mainz group, 2104.02632]

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

→ next slide

Status of HVP

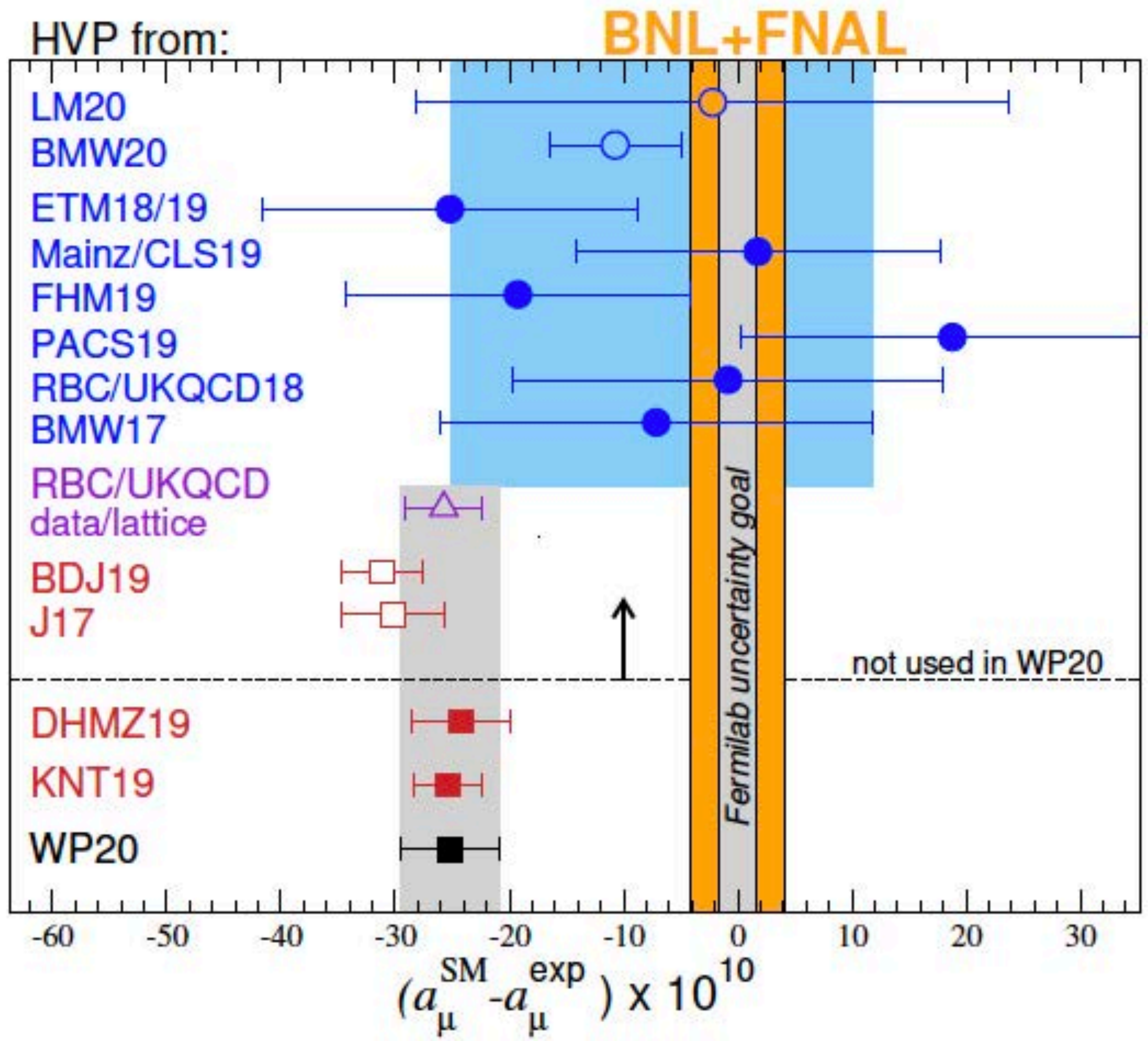


[Lehner, KEK-PH2021]

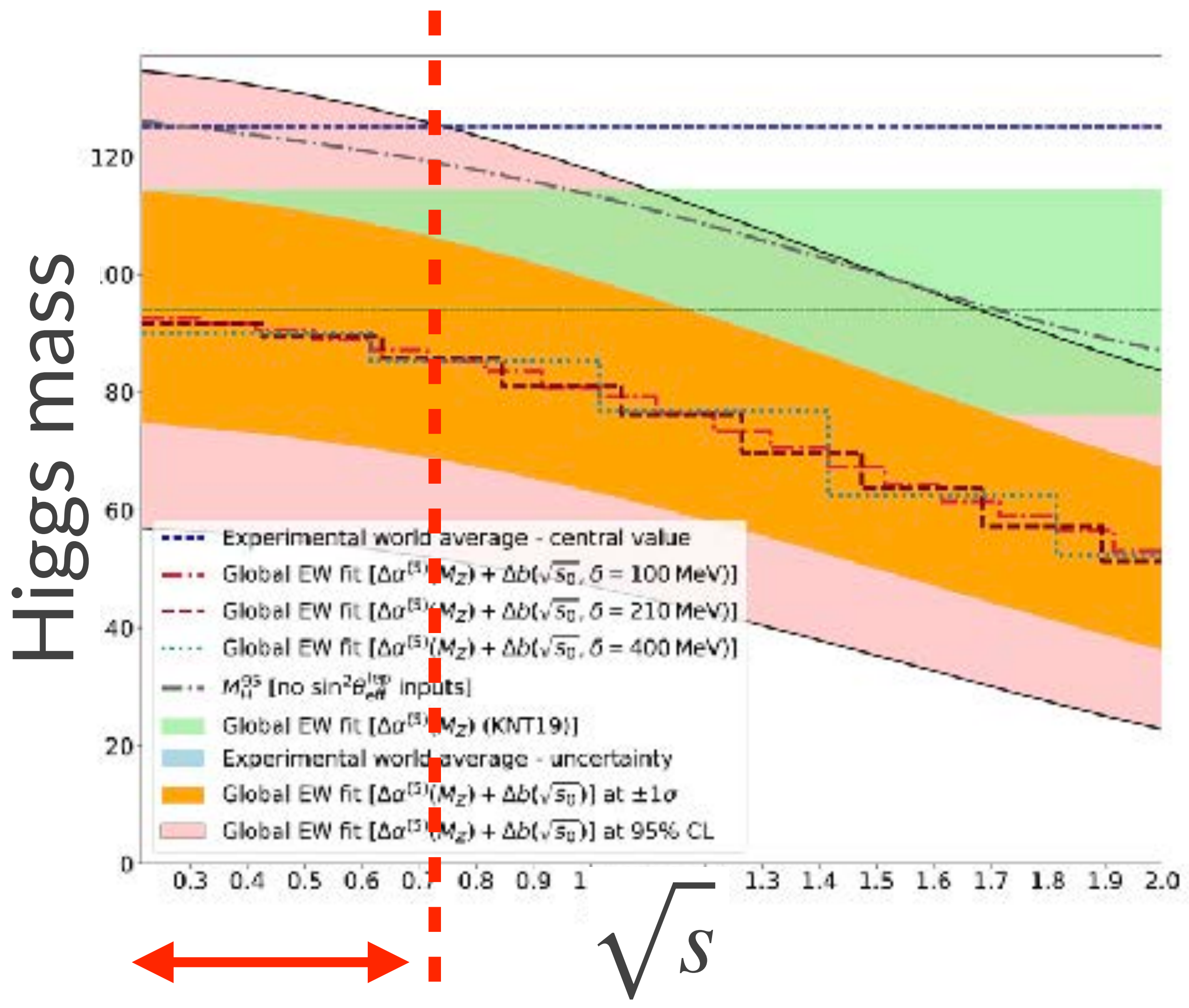
lattice

hybrid

$e^+e^- \to$ hadrons



[Keshavarzi et al, 2006.12666]



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

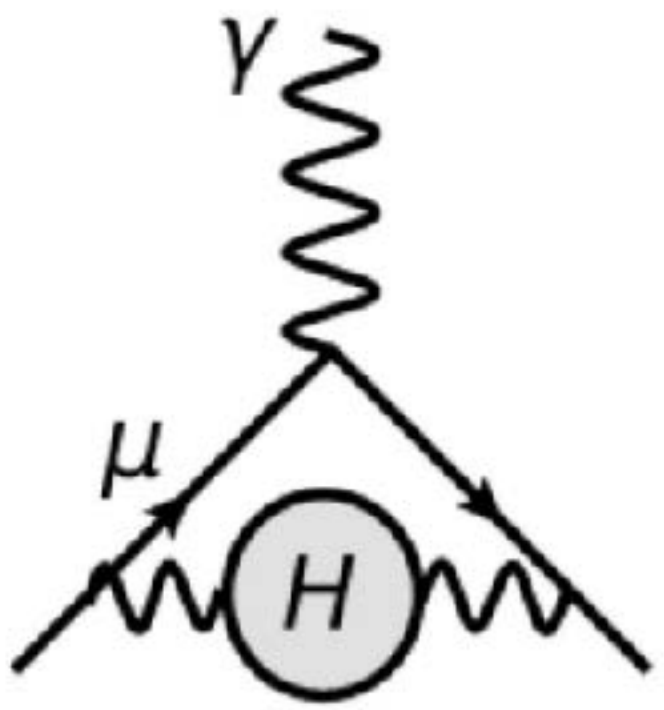
Then, there is additional tension:
8% change of $e^+e^- \to \rho$ resonance, or
4% change of $e^+e^- \to 2\pi$ data, see *e.g.*,
[Colangelo et al, 2010.07943]

But, data fit is 1% error [Nomura et al, 1911.00367]

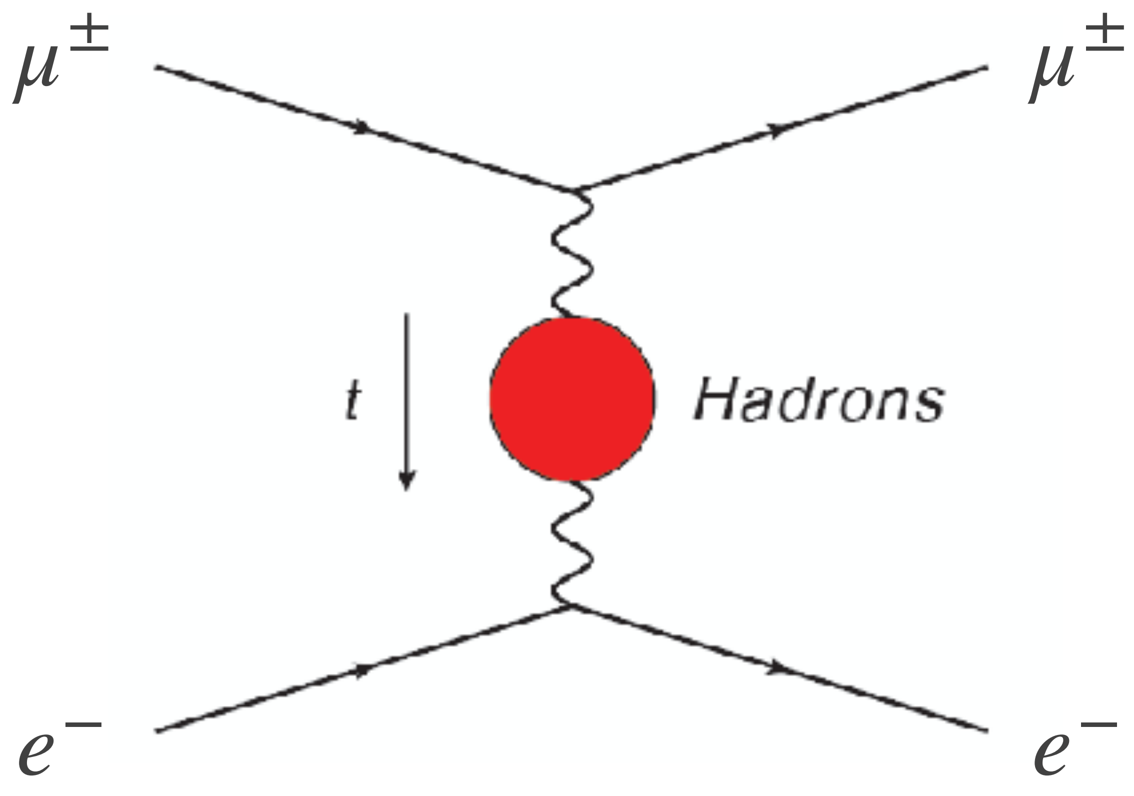
Updated RBC/UKQCD18 will be presented near future

MUonE experiment

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

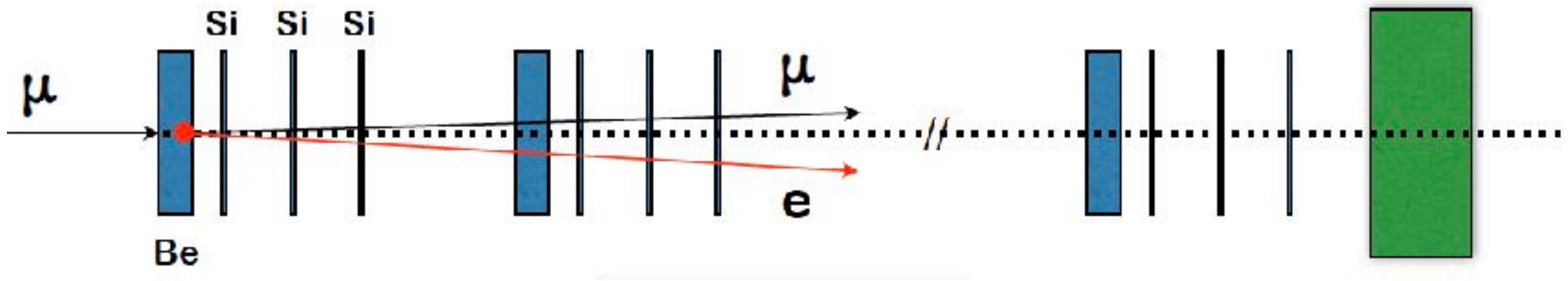


HVP



MUonE process

[Passera, KEK-PH2021]



By using 3 years data, statistical sensitivity is $0.3\,\%$ on a_μ^{HLO} (curent *tension* is $2\,\%$ on a_μ^{HLO})

For theoretical uncertainties, NLO corrections were ready and NNLO is close to completion muon g-2 anomaly = physics beyond the SM?

Naive NP energy scale

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

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

$$= \frac{m_\mu^2}{16\pi^2} \frac{g_{\rm NP}^2}{M_{\rm NP}^2}$$

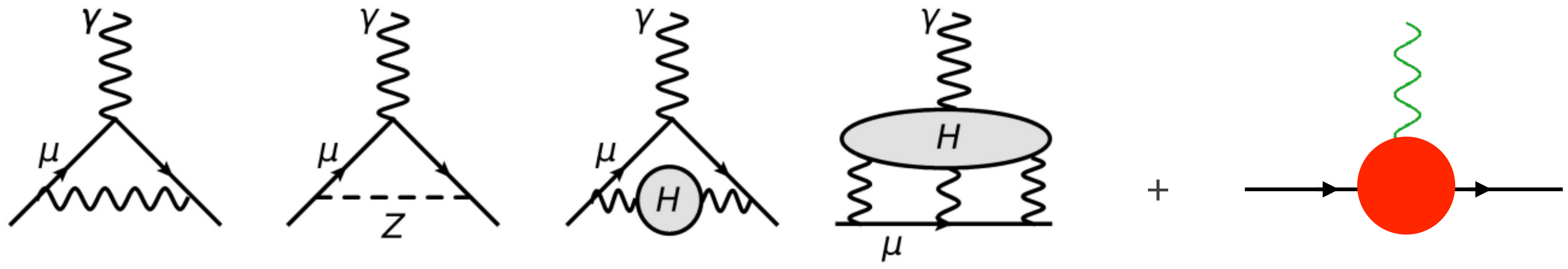
→

$$M_{\rm NP} \sim g_{\rm NP} \times 150\,{\rm GeV}$$

$M_{\rm NP}$ is determined by size of the NP couplings to muon

Large $g_{\rm NP}$ by certain mechanisms
→ TeV scale NP

Small $g_{\rm NP}$ → MeV NP

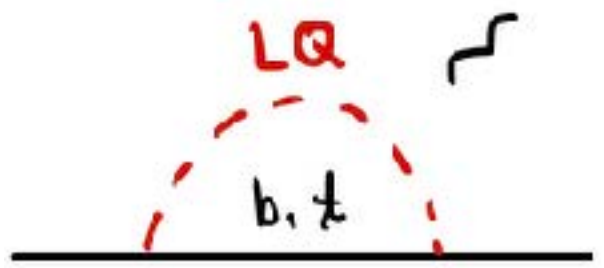


QED EW Hadronic vacuum polarization **(HVP)** Hadronic light-by-light **(HLbL)** NP

Positiveness ($\Delta a_\mu > 0$) sets a strong constraint on light CP-odd scalar scenarios

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
Supersymmetry		200〜500 GeV	$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to (h\tilde{\chi}_1^0)\,(W^\pm \tilde{\chi}_1^0)$ $pp \to \gamma\gamma \to \widetilde{\ell\ell^*}$
Scalar extensions		20〜100 GeV, 150〜250 GeV	$Z \to \tau^+\tau^-$ $h \to AA$
Axion-like particle		40 MeV〜6 GeV	$e^+e^- \to \gamma a, a \to \gamma\gamma$
Leptoquark		1.5〜2 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$ $Z \to \mu^+\mu^-$
U(1) μ-τ		10〜200 MeV	$e^+e^- \to \mu^+\mu^- Z'$ $K^- \to \mu^-\bar{\nu}Z'$
Vector-like lepton		< 7 TeV	$h, Z \to \mu^+\mu^-$

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[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	
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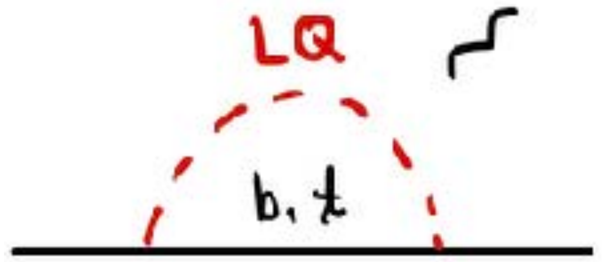
テラスケール	Leptoquark		1.5〜2 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$ $Z \to \mu^+\mu^-$	テラスケール
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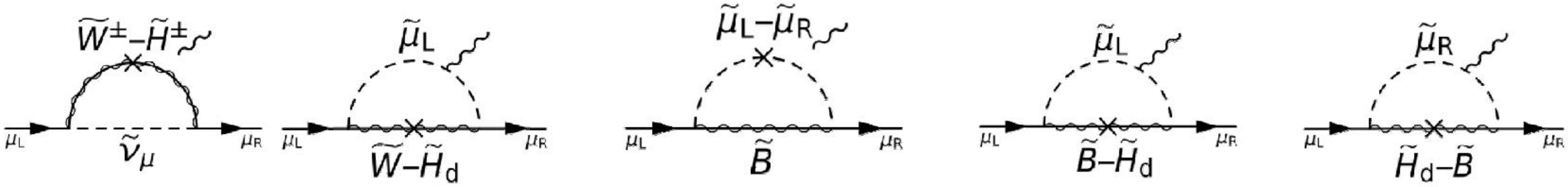
Supersymmetry (SUSY)

- Theoretical motivation **other than** muon g-2 anomaly; → SUSY is the most attractive scenario.
  - gauge hierarchy problem, gauge coupling unification, and dark matter (DM)
- Under SUSY, slepton/squark (s=0), gaugino (s=1/2), and higgsino (s=1/2) are required
- Four types of one-loop diagrams are responsible to explain the anomaly:

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



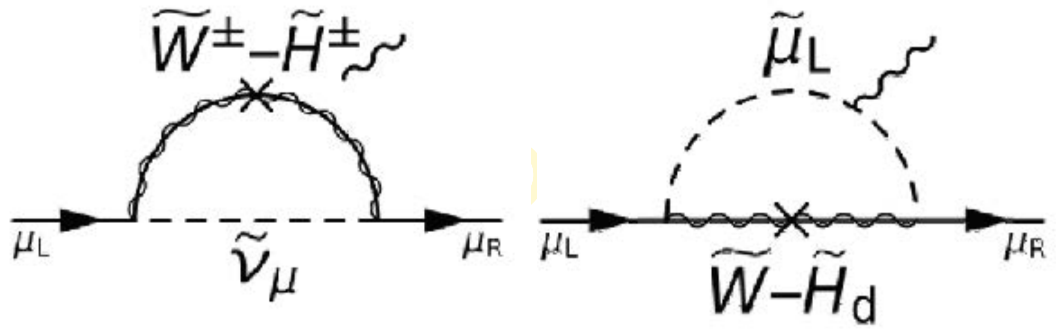
$SU(2)_L$

These diagrams are proportional to $\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle \sim 1 - 60$ → TeV scale NP

3, BHL and 4, BHR are constrained from DM direct detection (XENON1T)

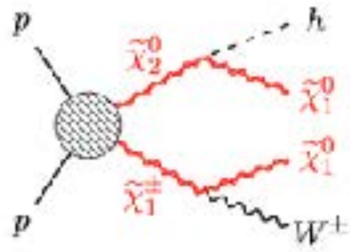
[Endo et al, 1704.05287, Baum et al, 2104.03302]

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



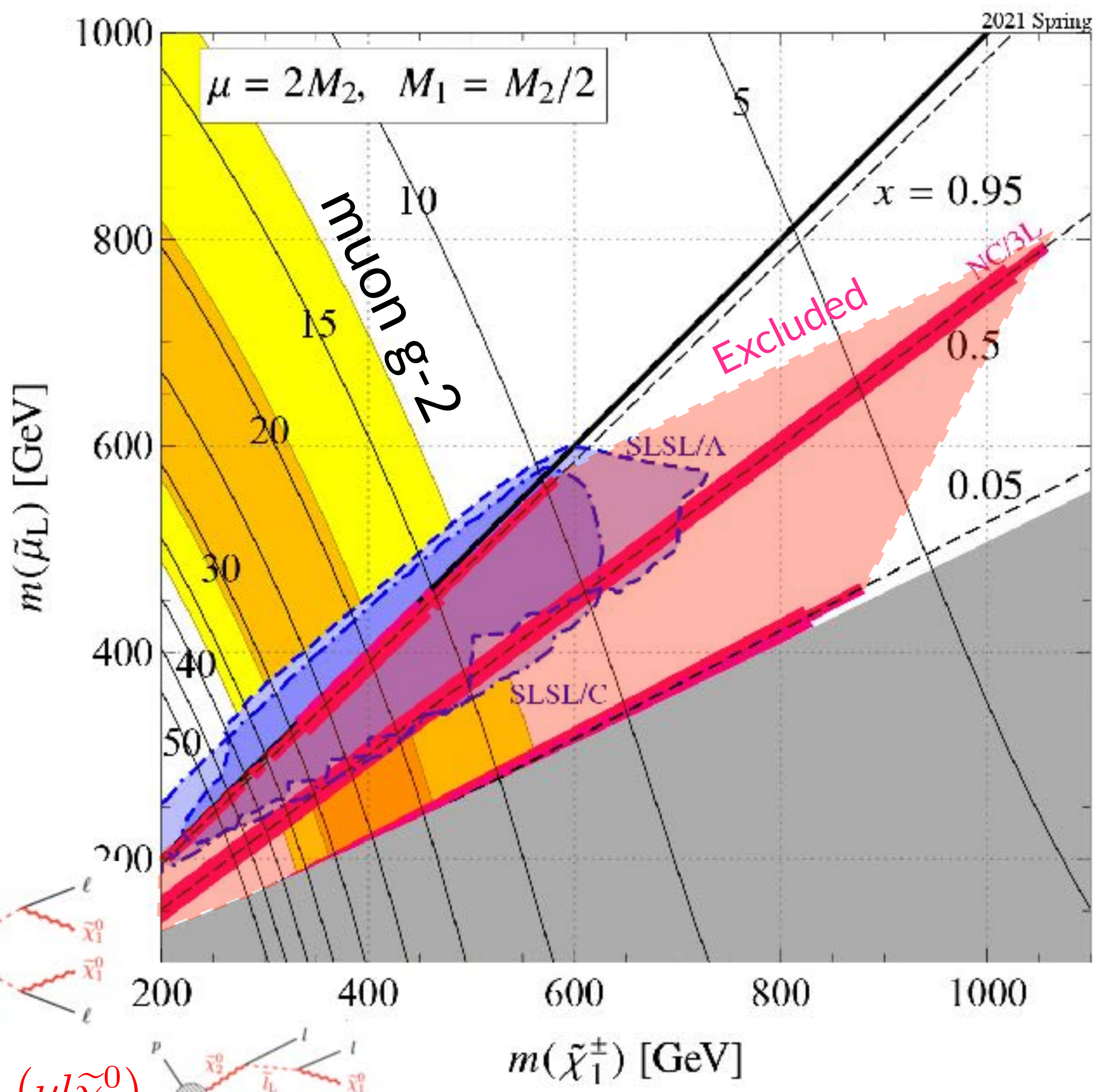
When bino is the lightest SUSY particle (LSP), regions of $m_{\tilde{\mu}} < m_{\tilde{\chi}^{\pm}}$ are severely constrained from the LHC.

DM relic abundance can be explained by bino/wino coannihilation [Saha et al, 2104.03287]

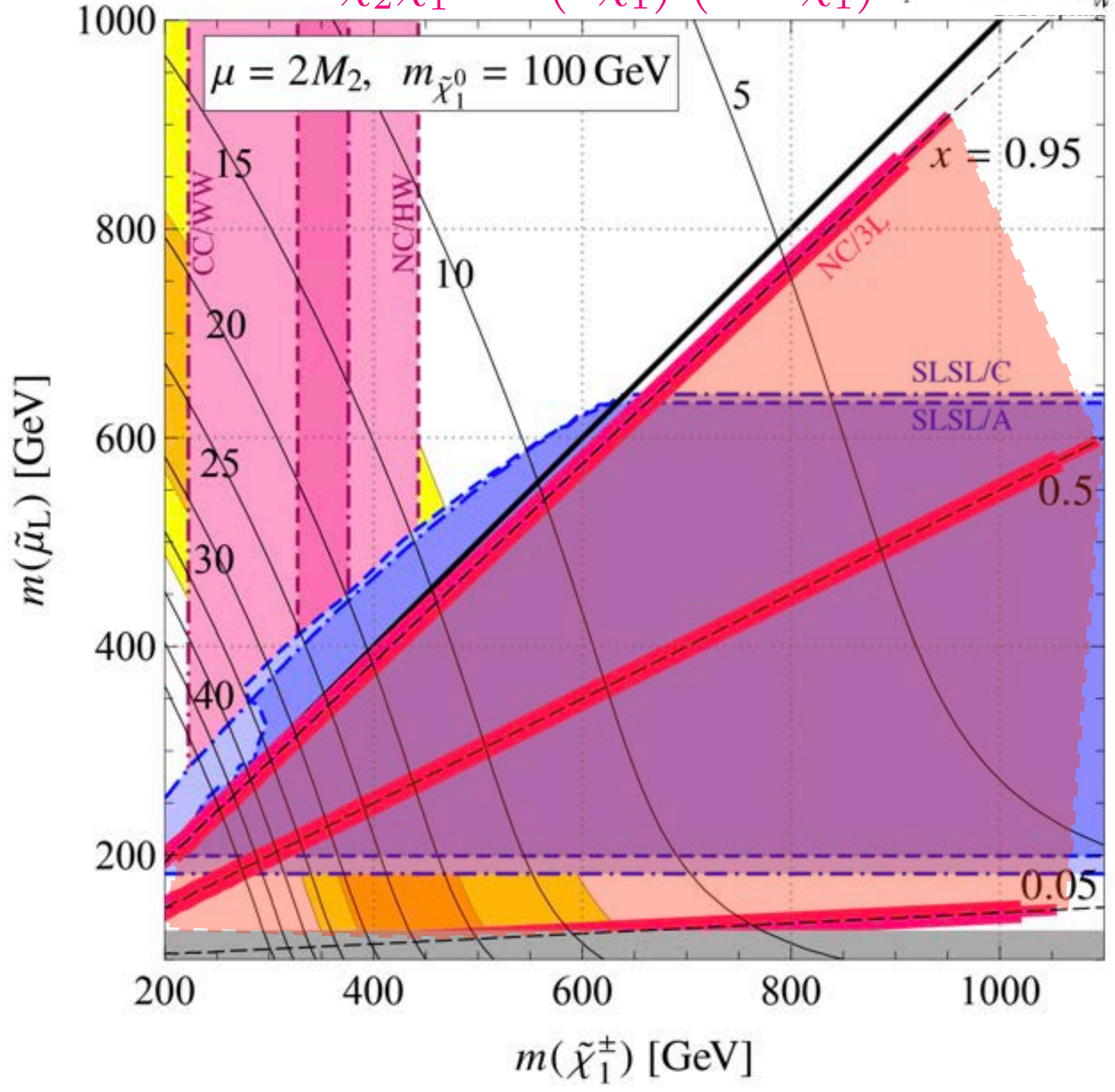


$\tilde{\chi}_2^0\tilde{\chi}_1^{\pm} \to (h\tilde{\chi}_1^0)\,(W^{\pm}\tilde{\chi}_1^0)$ will be able to probe.

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



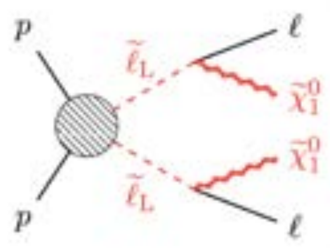
$\tilde{\chi}_2^0\tilde{\chi}_1^{\pm} \to (h\tilde{\chi}_1^0)\,(W^{\pm}\tilde{\chi}_1^0)$



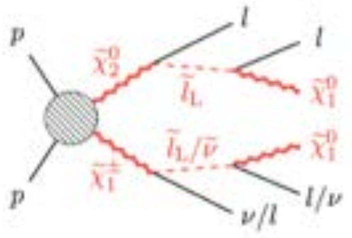
[Endo, Hamaguchi, Iwamoto, TK, 2001.11025, 2104.03217]

strong bound from:

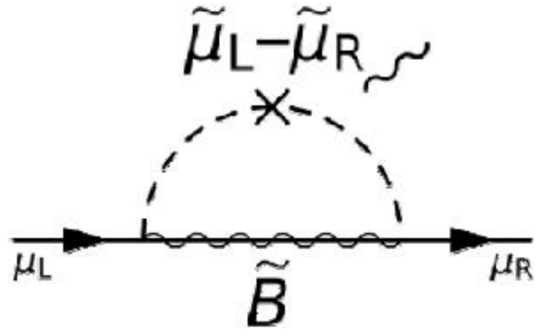
$\tilde{\ell}_L\tilde{\ell}_L^* \to (\ell\tilde{\chi}_1^0)\,(\bar{\ell}\tilde{\chi}_1^0)$



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



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



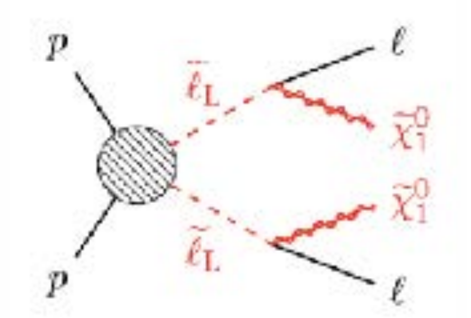
The bino/slepton coannihilation scenario still works.

We found the heavy μ and small $\tan\beta$ are favored in this study (under the vacuum decay condition)

XENONnT (DM direct detection) can probe this scenario

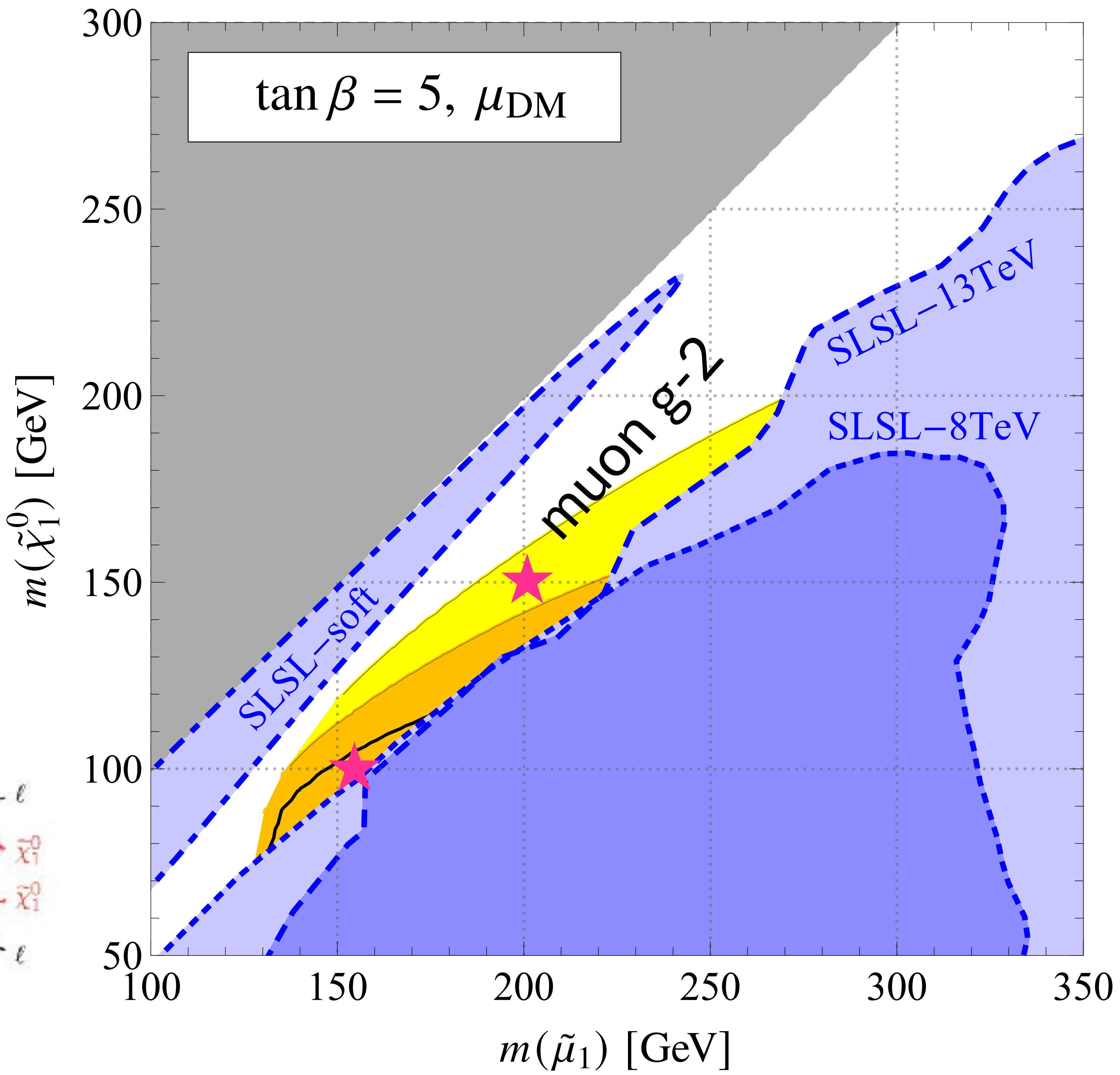
strong bound from:

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



pure-bino contribution **with correct Ω_{DM}**

with universal slepton mass



[Endo, Hamaguchi, TK, Yoshinaga 1309.3065; Endo, Hamaguchi, Iwamoto, TK, 2104.03217]

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

stau mass < 200 GeV → good target for ILC500?

"Reconstruction" of muon g-2 by LHC500 is studied [Endo, Hamaguchi, Iwamoto TK, Moroi 1310.4496]

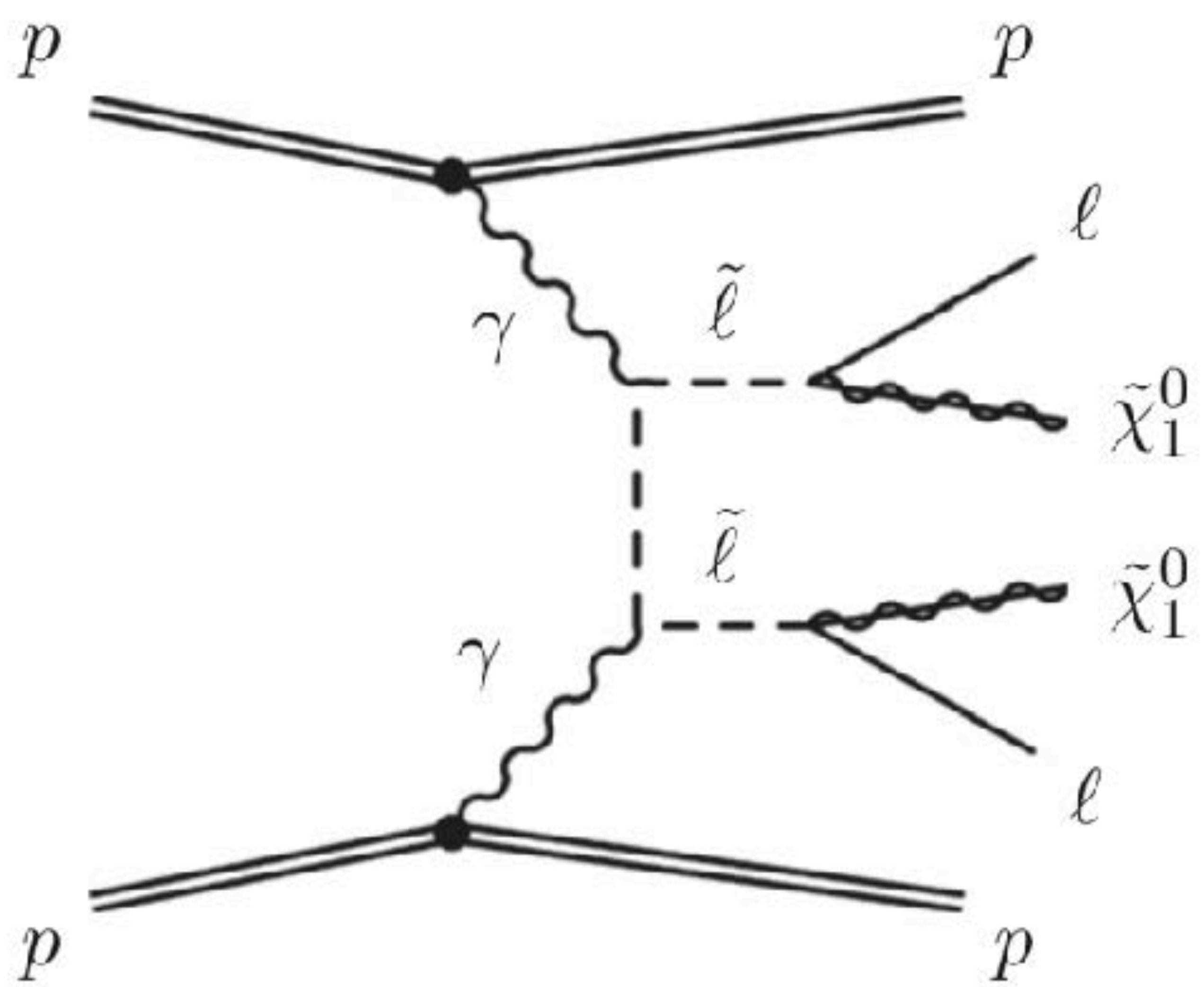
Slepton search via photon collision

See also, Kawade-san talk page 25-

- Novel (?) idea that slepton can be probed via photon collision in the LHC [Beresford, Liu 1811.06465]

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

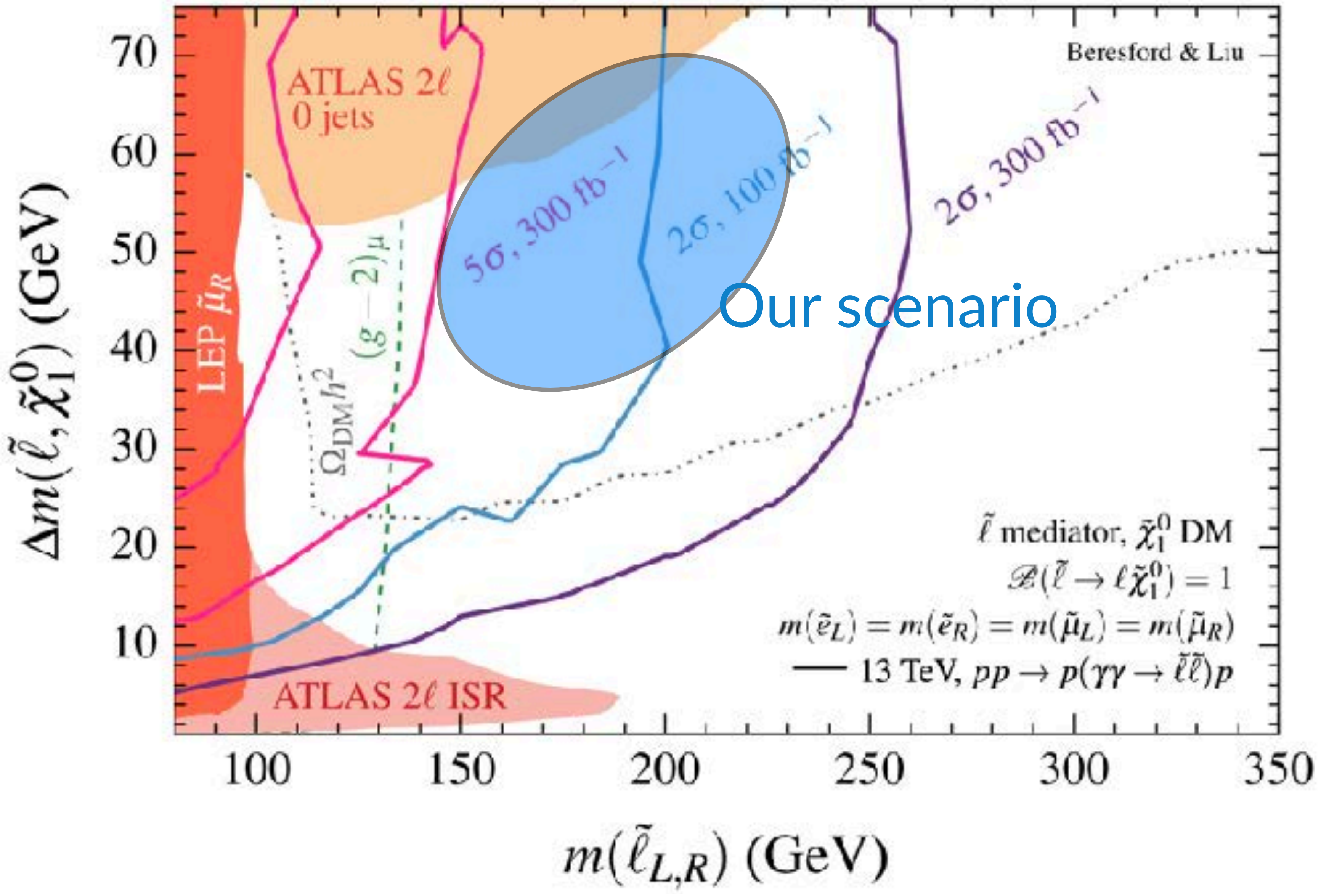
Slepton mass gap could be covered.



1, measure outgoing proton E_p by forward detector

2, measure lepton 4-momentum

3, reconstruct missing momentum 4-vector



Proton soft survival probability they used.

Slightly optimistic?

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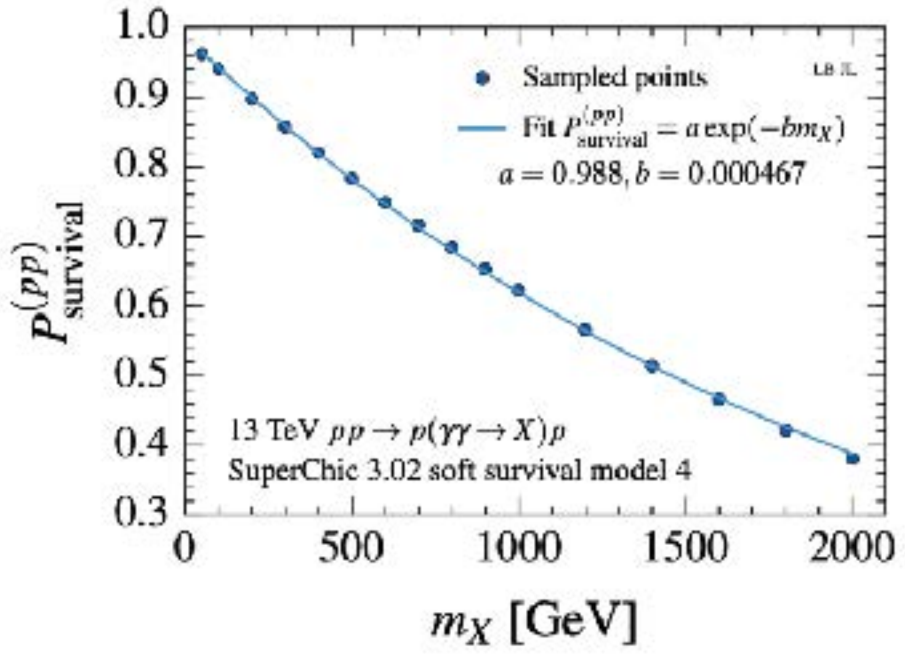
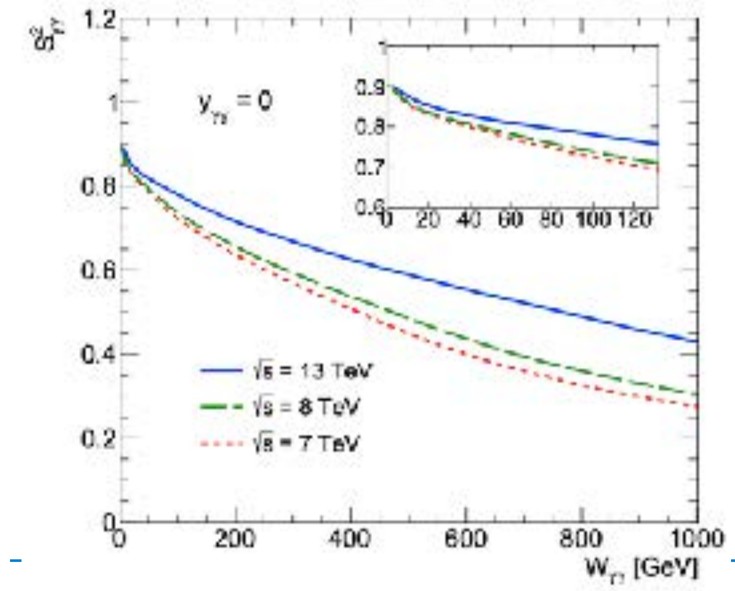
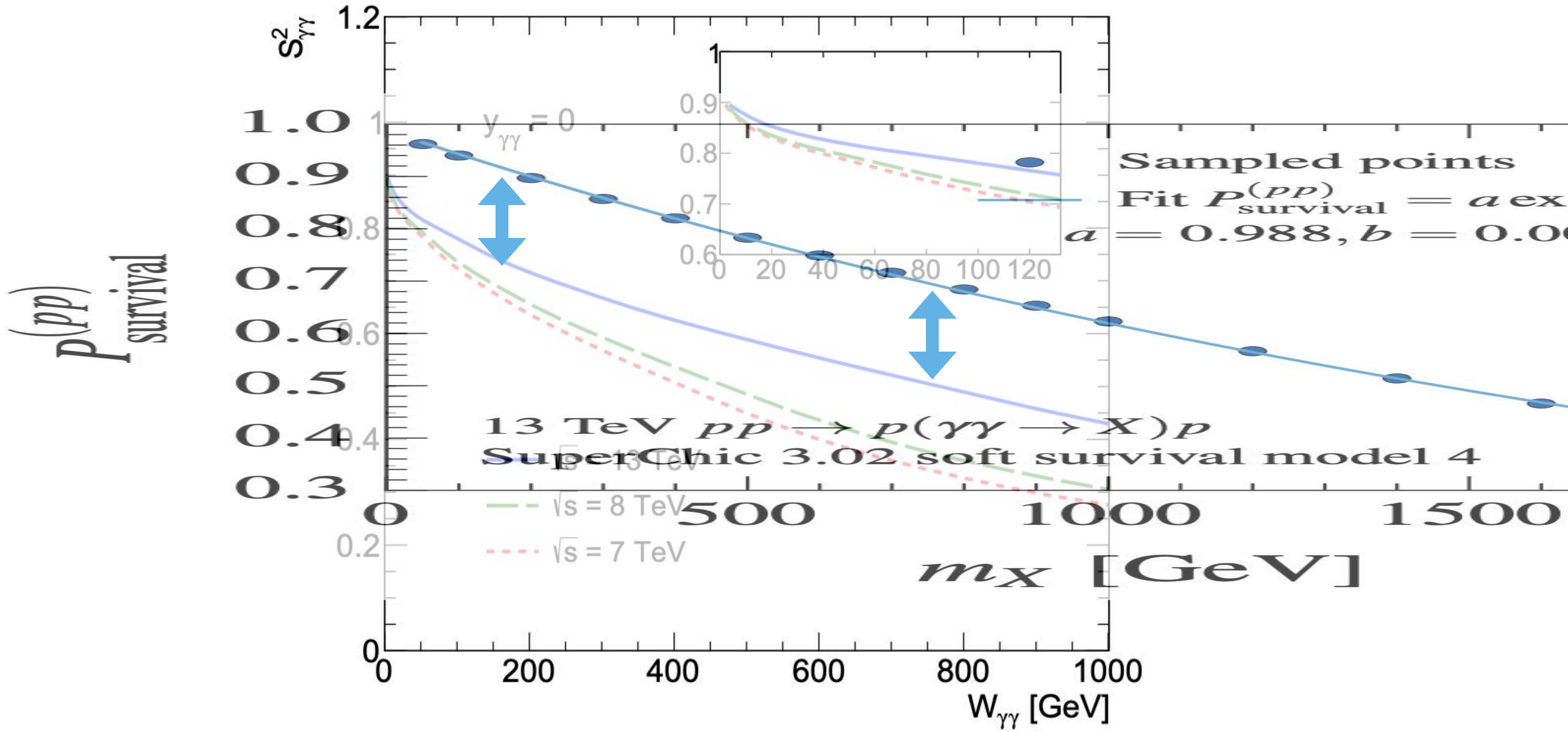




ATLAS first result [ATLAS, 2009.14537] agrees on [Dyndal et al, 1410.2983]

Comparison of proton survival probabilities



Leptoquark models

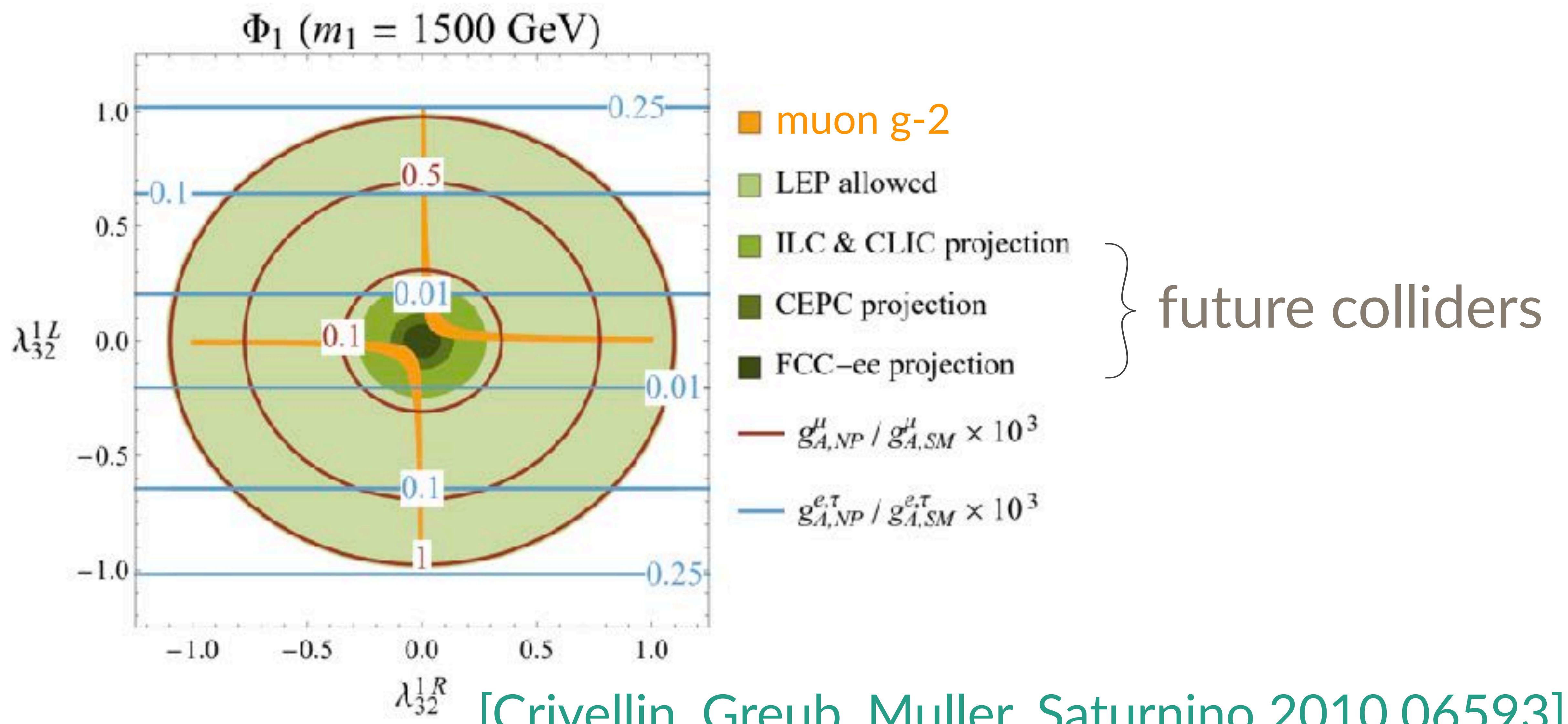
- TeV-scale scalar/vector leptoquark can also explain muon g-2 anomaly.

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 generation-philic) couplings are strongly constrained by flavor precision constraints. [Kowalska, Sessolo, Yamamoto 1812.06851]

Top are preferred for the muon g-2 anomaly because chirality enhancement is significant $m_t/m_\mu \sim 2000$ → TeV scale leptoquark is possible

Correlation with $Z \to \mu^+\mu^-$ can be probed by future colliders.



[Crivellin, Greub, Muller, Saturnino 2010.06593]

B anomaly + muon g-2 anomaly = ?

(B + muon g-2) anomaly =?

- 5 (and more) examples on arXiv

Refs	particles	solve	mass scale
Arcadi et al, 2104.03228	Vector-like fermion + scalars	muon g-2, R(K), DM	0.1〜1 TeV VL
Nomura, Okada 2104.03248	Scalar LQs	muon g-2, R(K), m_ν	〜5 TeV LQ
Bhattacharya et al, 2104.03947	ALP	muon g-2, $K\pi$ puzzle	〜140 MeV ALP
Marzocca, Trifinopoulos, 2104.05730	Scalar LQ + scalar	muon g-2, R(K), R(D), CAA	〜5 TeV LQ
Du et al, 2104.05685; Ban et al, 2104.06656	Vector LQ	muon g-2, R(K), R(D)	〜2 TeV LQ

Summary

- Fermilab collaboration confirmed the BNL muon g-2 data.
- The standard model prediction is still controversial. Other lattice group's result or MUonE experiment at CERN will shed light on the HVP contributions.

- Several TeV scale or MeV scale new physics models have been suggested.
- Supersymmetric solutions are still survived.
    - But, mass spectrum would be not attractive (or we don't know such a SUSY breaking), *e.g.*, gaugino masses.
    - Can the slepton search from photon collisions be possible in the LHC Run3?
- *B* anomalies can be correlated with several TeV new physics models.