Discovering the New Physics of (g–2)μ at Colliders

FNAL Online Theory Seminar

19/Aug/2021

Rodolfo Capdevilla
Perimeter Institute for Theoretical Physics
and University of Toronto

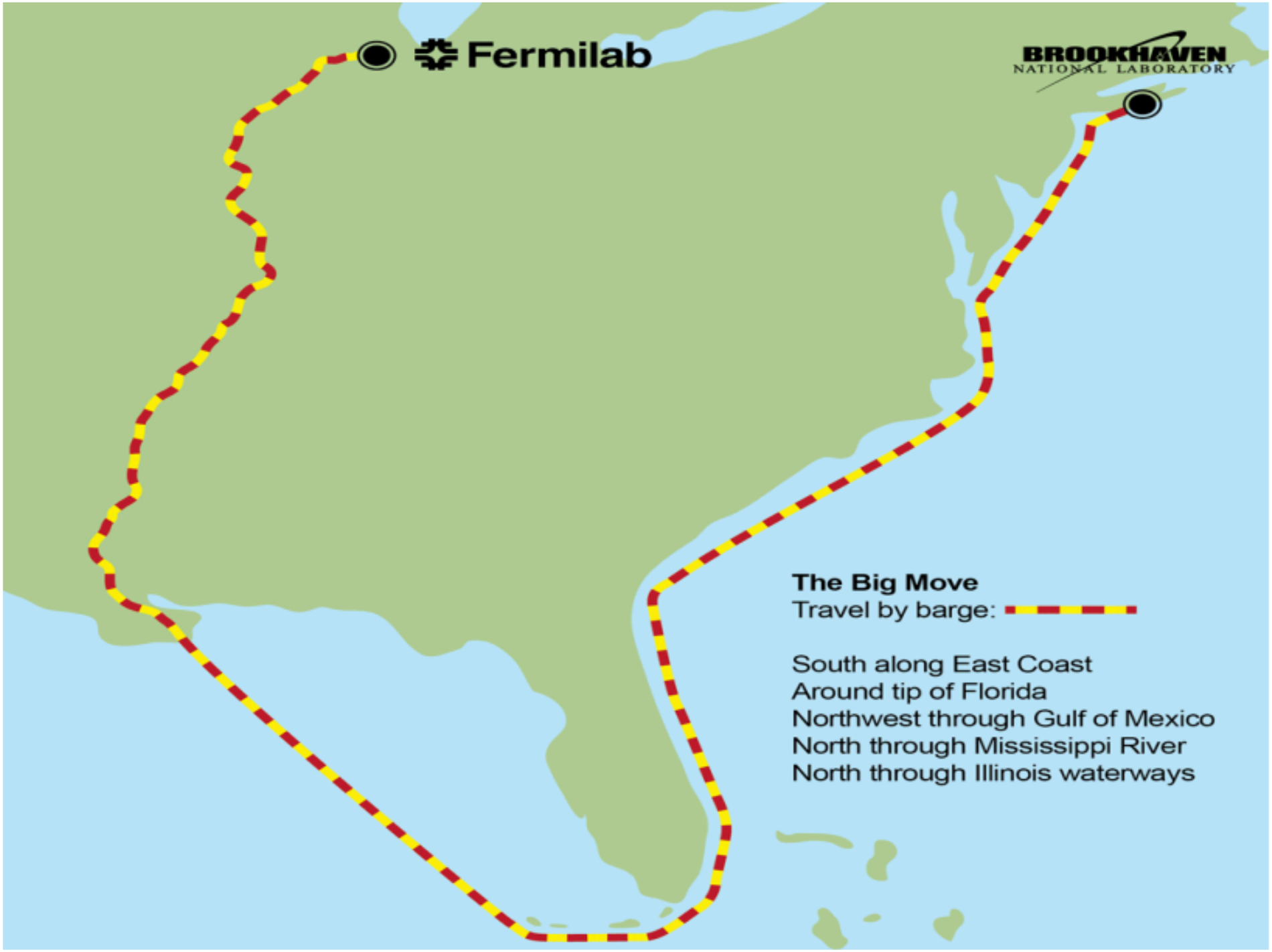


***RC**, David Curtin, Yonatan Kahn, Gordan Krnjaic,*
arXiv:2006.16277
arXiv:2101.10334
arXiv:2108.?????

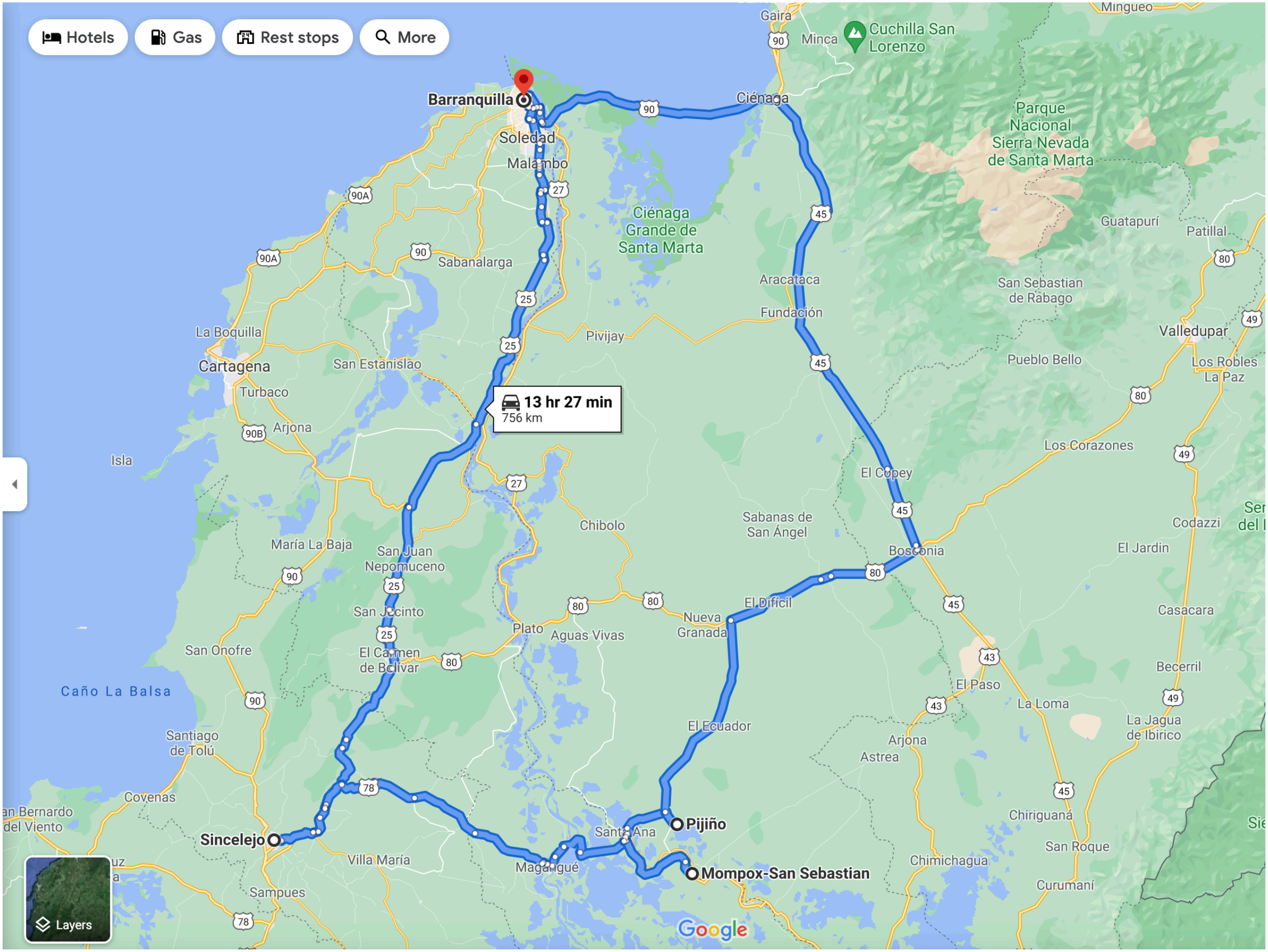
Outline

1. Muon Anomalous Magnetic Moment
2. BSM Physics of (g-2)μ at Muon Colliders (MuC)
3. Singlet Scenarios: Hadron colliders + EW Precision
4. Electroweak Scenarios: Indirect signals at a MuC
5. Summary

(An epic trip!)


Fermilab
BROOKHAVEN
NATIONAL LABORATORY
The Big Move
Travel by barge:
South along East Coast
Around tip of Florida
Northwest through Gulf of Mexico
North through Mississippi River
North through Illinois waterways

(An epic trip!)



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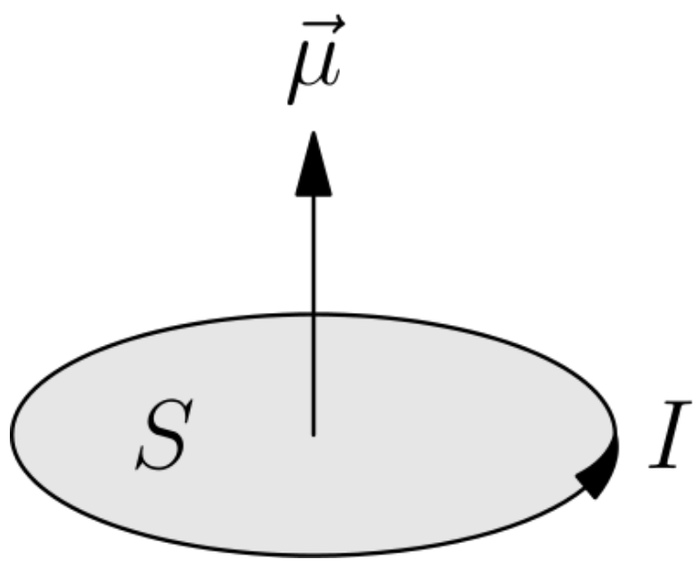
1. Muon Anomalous Magnetic Moment

- Magnetic moment (macroscopic)



$$U = -\vec{\mu} \cdot \vec{B}$$

- Anomalous Magnetic Moment

$$a = \frac{g-2}{2}$$

- Possible to define for a fundamental particle

$$\vec{\mu} = -g\frac{\mu_B}{\hbar}\vec{S}$$

g-factor

- Relativistic quantum mechanics prediction

$$i\hbar\frac{\partial\phi}{\partial t} = \left[\frac{p^2}{2m} - \frac{\mu_B}{\hbar}(\vec{L} + 2\vec{S}) \cdot \vec{B}\right]\phi$$

$$g = 2$$

1. Muon Anomalous Magnetic Moment

- State of affairs

T. Aoyama et al., Phys. Rept. 887 (2020) 1-166

Muon g − 2 Theory Initiative

Contribution	Value $\times 10^{11}$
Experiment (E821)	116 592 089(63)
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)
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)
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)

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"It now appears conclusive that the HLbL contribution cannot explain the current tension between theory and experiment for the muon g-2"

$$106.8(14.7)\ (\sim 14\%)$$

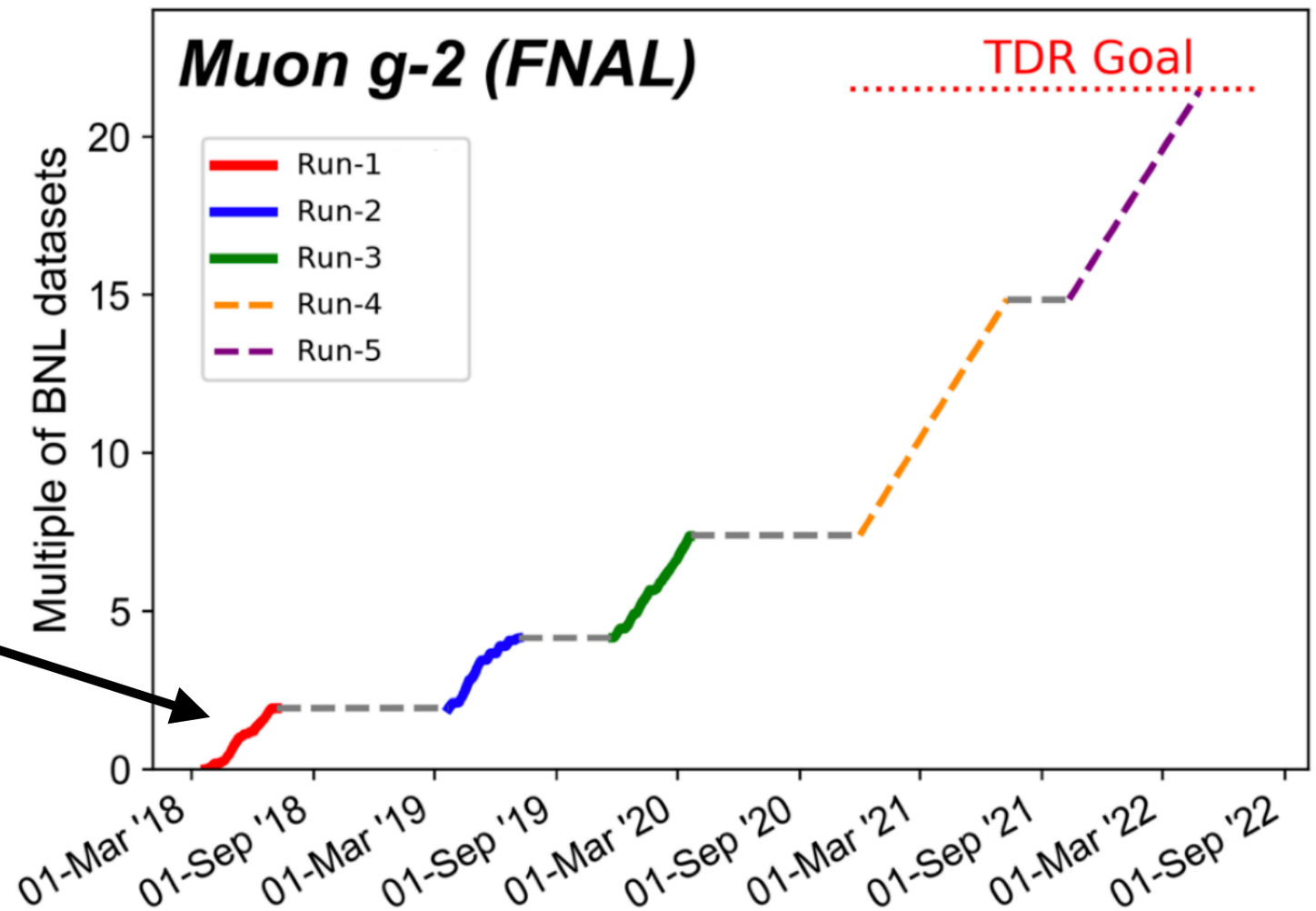
En-Hung Chao et al., e-Print: 2104.02632

$$\Delta a_\mu \sim 3.7\,\sigma$$

1. Muon Anomalous Magnetic Moment

- State of affairs

April's Announcement based on Run 1 (Data set comparable to BNL)



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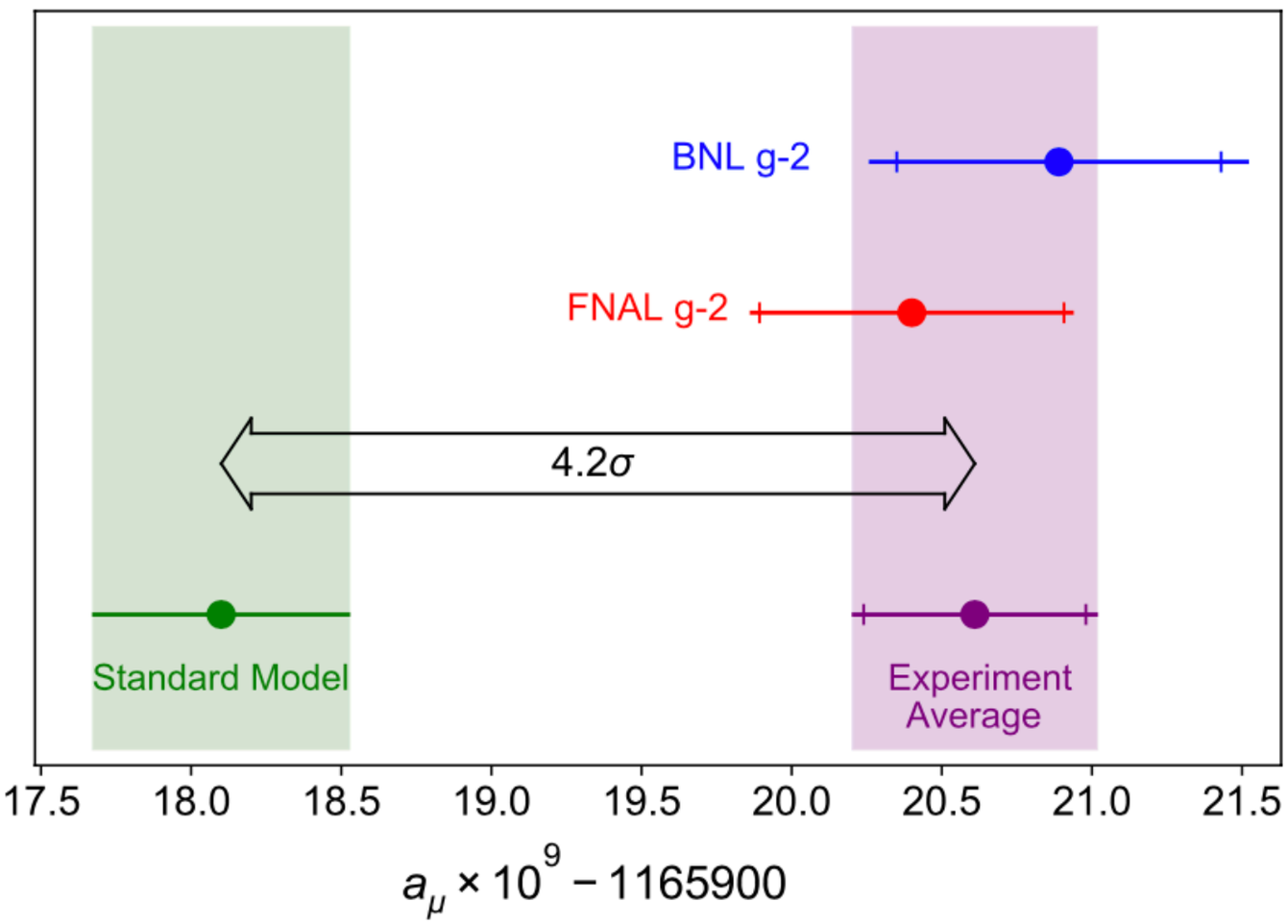

$$a_\mu(\text{exp}) = 116\,592\,061(41) \times 10^{-11}$$

Muon g-2 Collaboration (BNL), Phys. Rev. D 73 (2006) 072003

Muon g-2 Collaboration (FNAL), Phys. Rev. Lett. 126 (2021) 14, 141801

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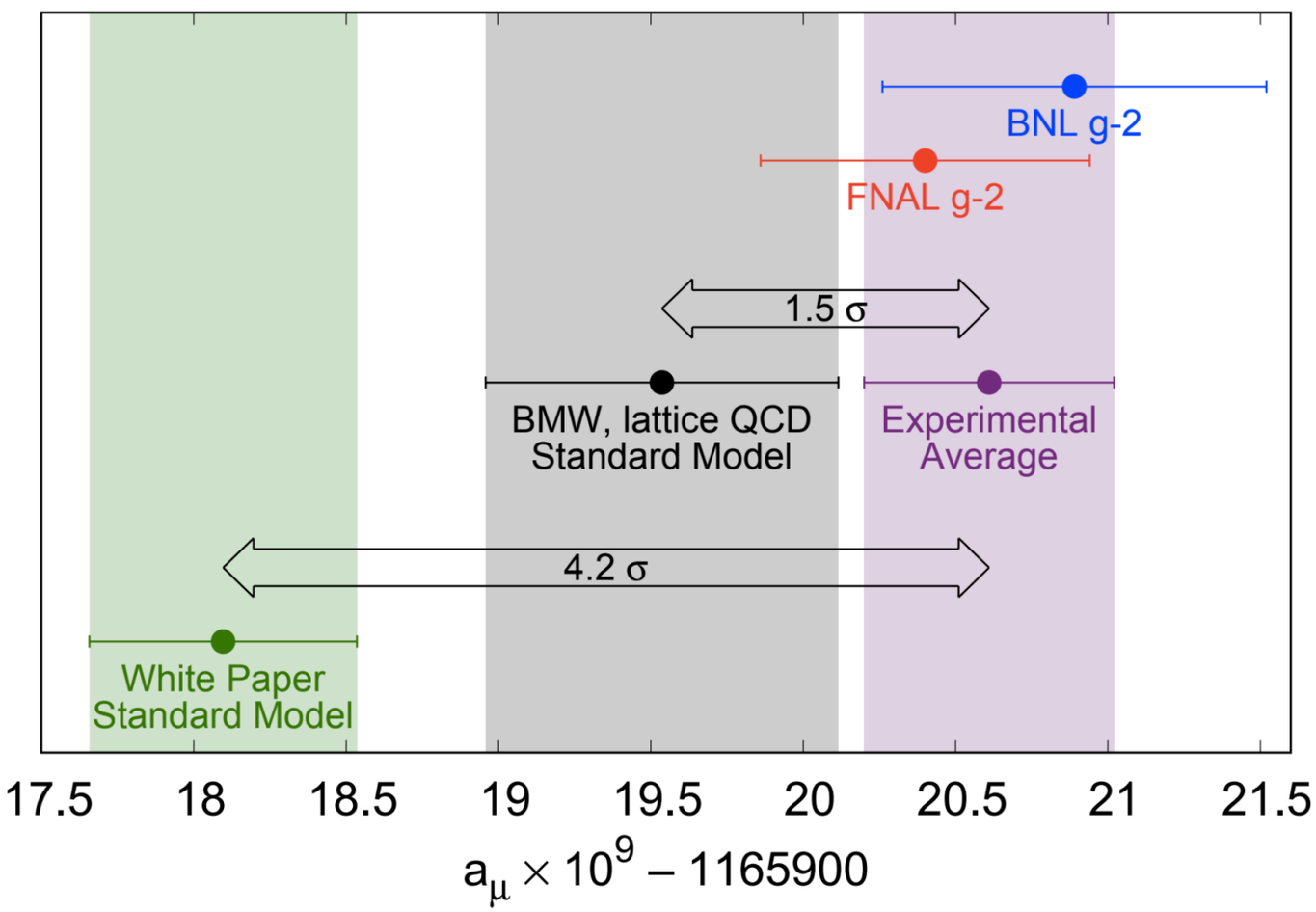
BMW collaboration, Nature 593 (2021) 7857, 51-55



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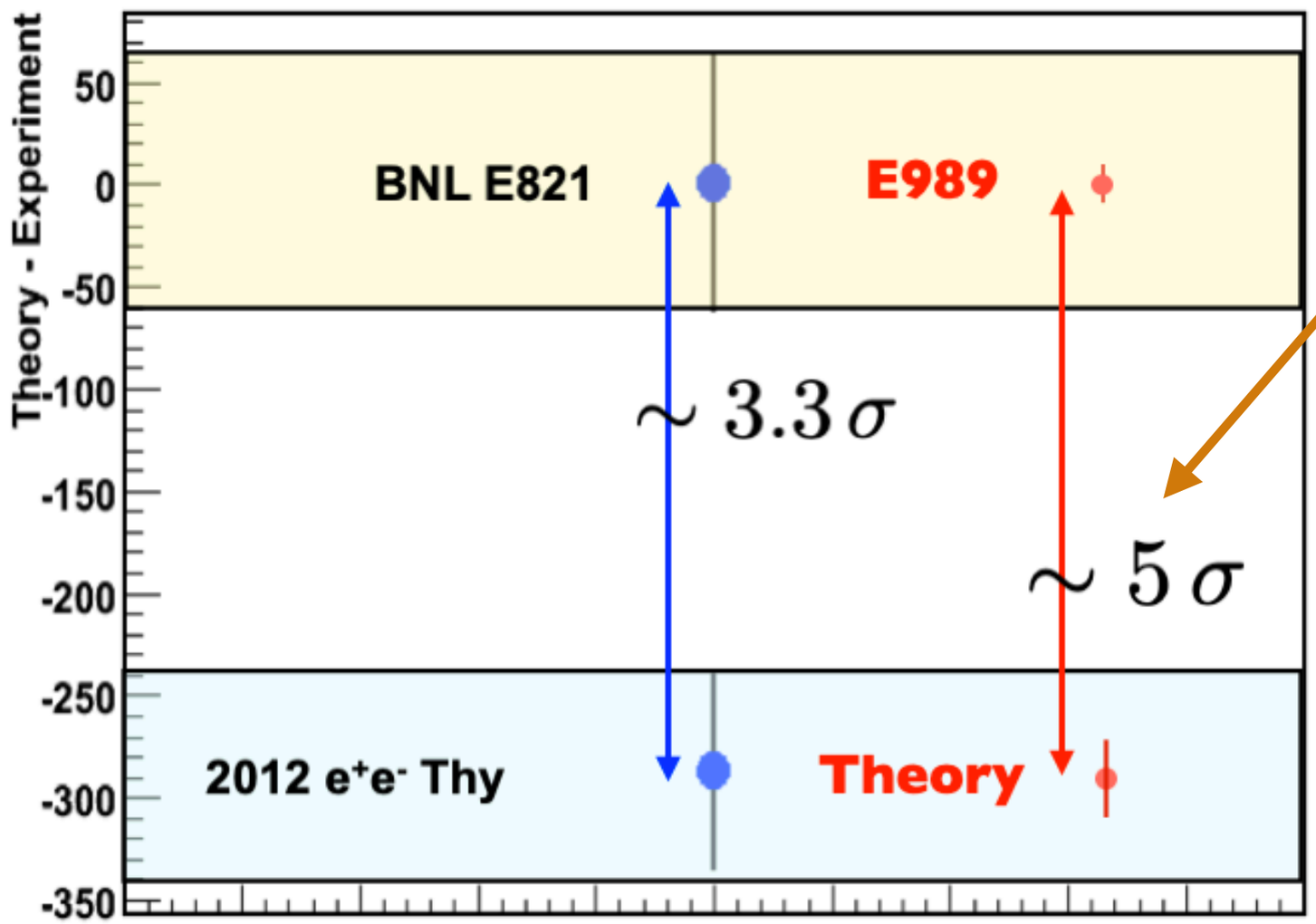
1. Muon Anomalous Magnetic Moment

- What if?

If new physics is confirmed, what comes next?



	E821	E989
Number of positrons	9×10^{9}	2×10^{11} (x 20 BNL)
Statistical Uncertainty	480 ppb	100 ppb
Systematic Uncertainty	248 ppb	100 ppb
Total Uncertainty	540 ppb	140 ppb

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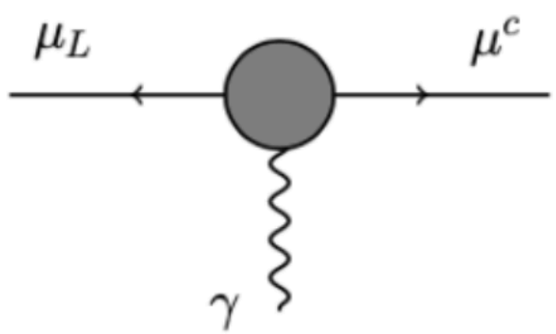
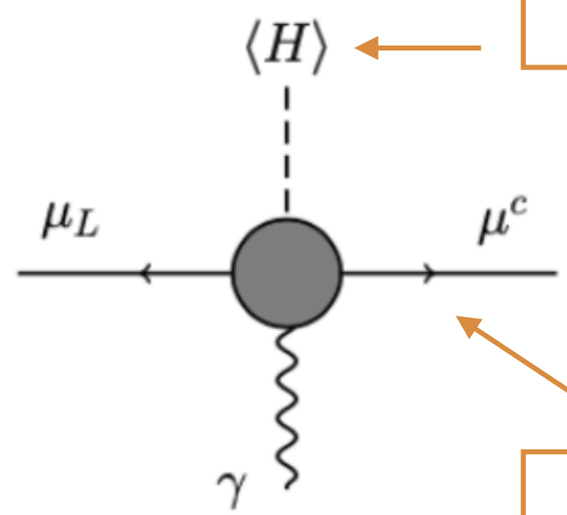
2. BSM Physics of (g-2)μ at MuC

- Ingredients for (g-2)μ

Assumptions	$\Delta a_\mu = a_\mu^{\rm obs}$ $U(1)_{em}$ gauge invariance	$\Delta a_\mu = a_\mu^{\rm obs}$ SM gauge invariance
$(g-2)_\mu$ diagram		
How to predict new signatures	$\frac{1}{M}(\mu_L \sigma^{\nu\rho} \mu^c) F_{\nu\rho}$	$\frac{1}{M^2} H^\dagger (L \sigma^{\nu\rho} \mu^c) F_{\nu\rho}$

EW breaking insertion!

Chiral flip insertion!

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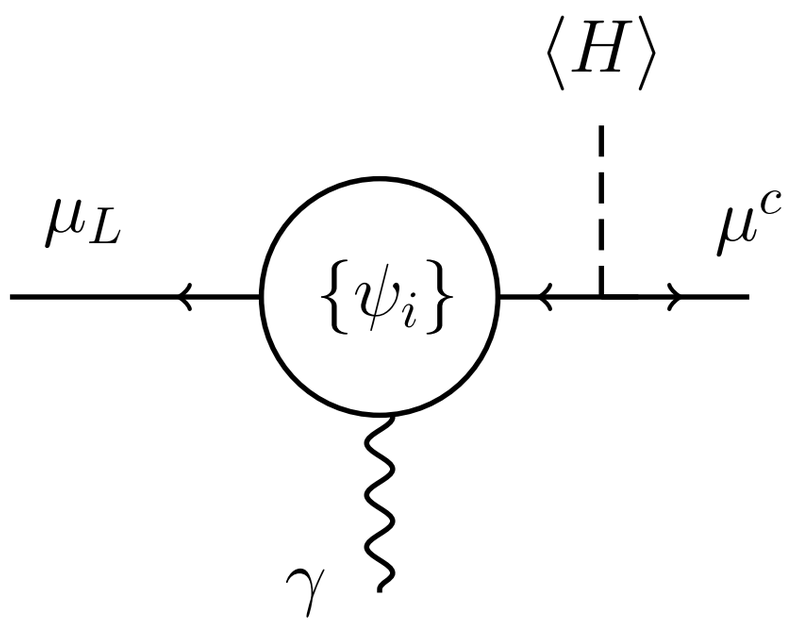
2. BSM Physics of (g-2)μ at MuC

Capdevilla, Curtin, Kahn, Krnjaic,
ArXiv:2006.16277
ArXiv:2101.10334

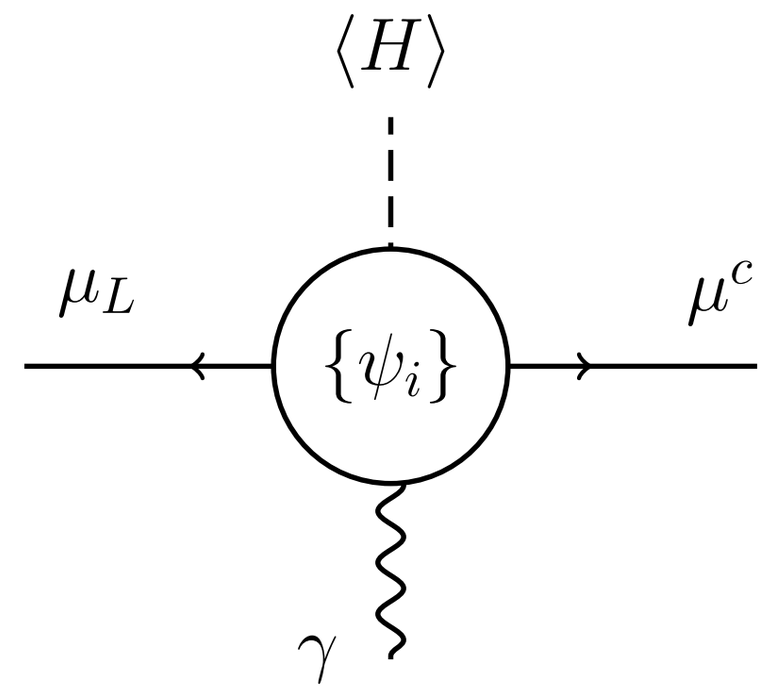
- Singlet and EW Scenarios



"Singlet scenarios"
(Introduce only SM singlets into the loop)

- Simple Models
- Phenomenology can be tricky

Produce singlets - Muon coupling



"Electroweak scenarios"
(Introduce at least one new charged state)

- Complicated Models
- Easy Phenomenology

Focus lightest charged state!

2. BSM Physics of (g-2)μ at MuC

Capdevilla, Curtin, Kahn, Krnjaic,
ArXiv:2006.16277
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- Singlet and EW Scenarios

Particularly relevant for a Muon Collider:

- For singlet scenarios, can couple to singlet via same coupling that makes g-2
- For EW scenarios, can reach high energies and discover "all" charged particles with masses < Ecm/2

"Singlet scenarios"
(Introduce only SM singlets into the loop)

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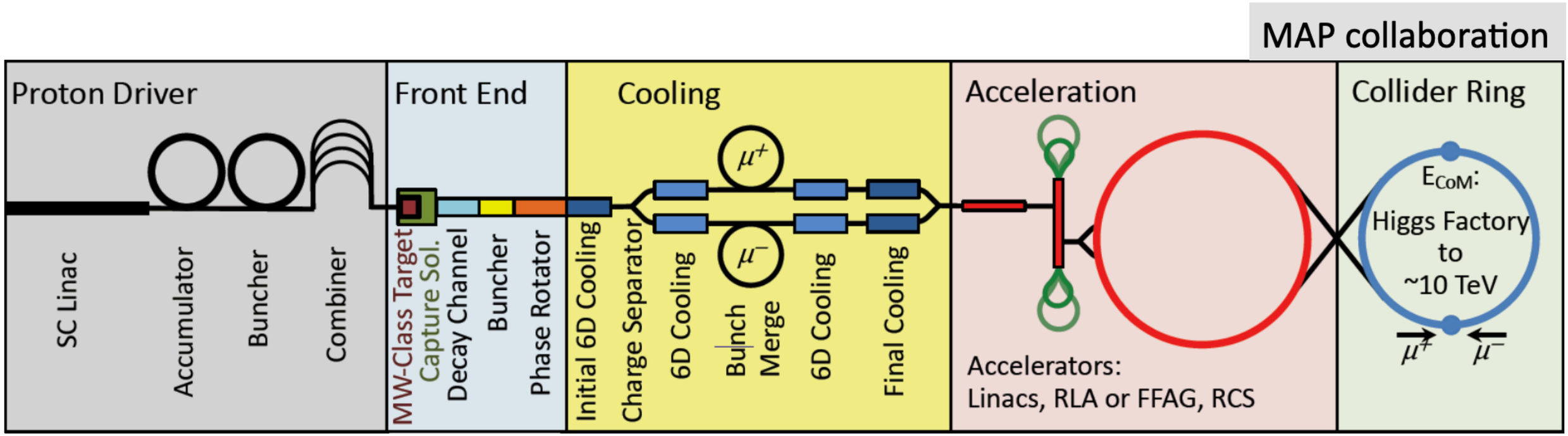
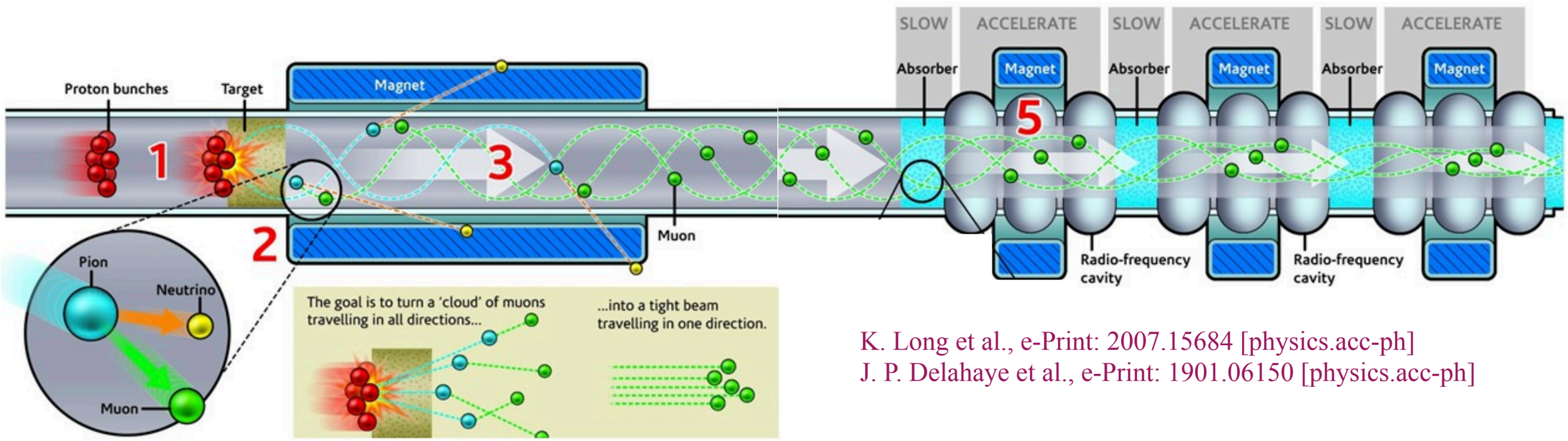




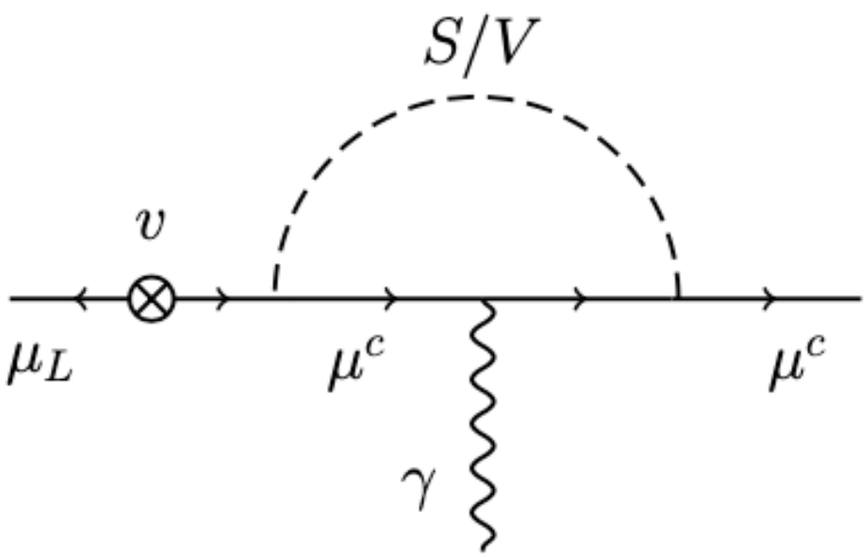
K. Long et al., e-Print: 2007.15684 [physics.acc-ph]
J. P. Delahaye et al., e-Print: 1901.06150 [physics.acc-ph]

Cooling - Proof of concept!

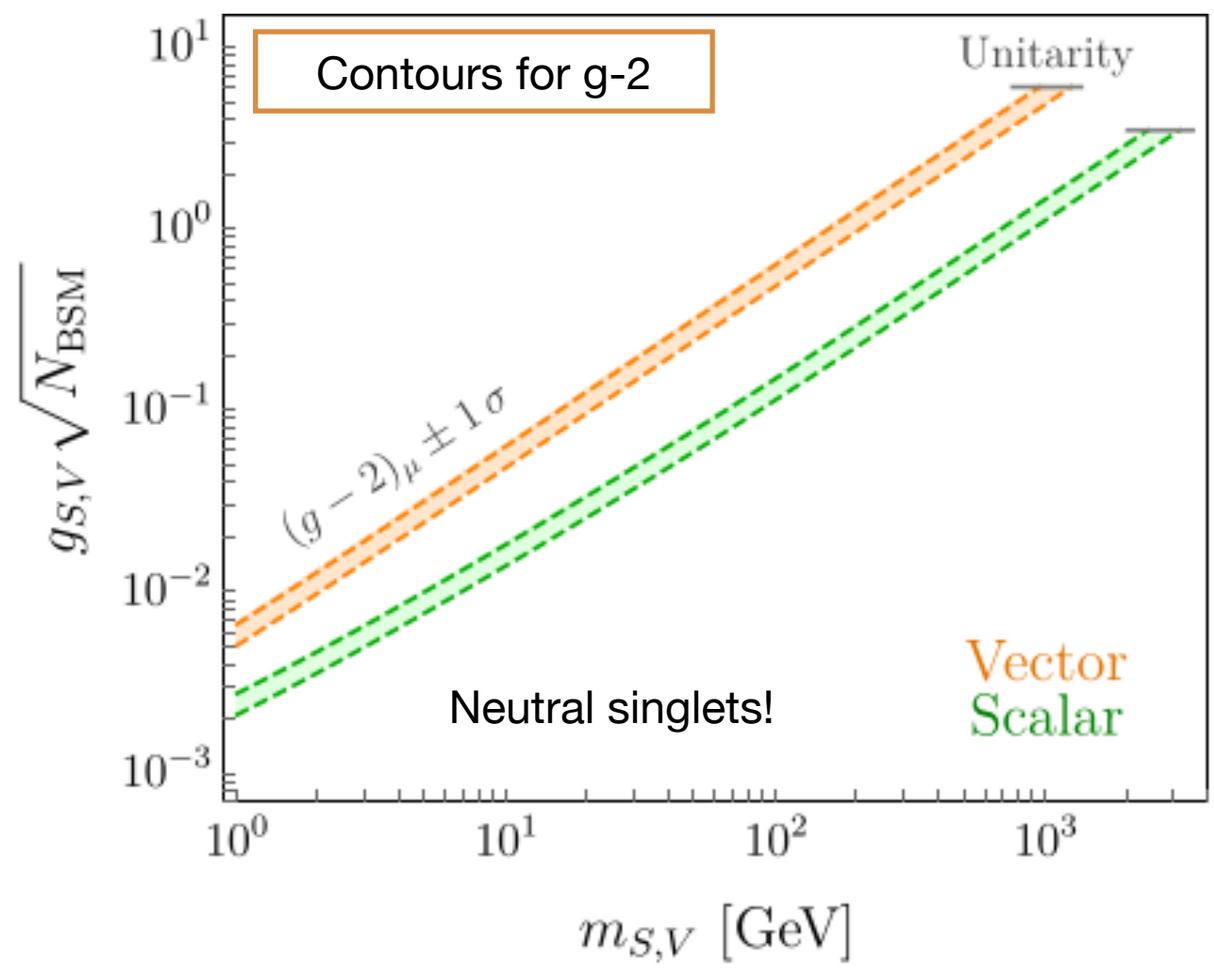
MICE Collaboration, PoS EPS-HEP2019 (2020) 025
MICE Collaboration, Nature 578 (2020) 7793, 53-59
MAP and MICE Collaborations, EPJ Web Conf. 95 (2015) 03019

2. BSM Physics of (g-2)μ at MuC

- Singlet scenarios



$$\Delta a_\mu \sim N_{BSM} \frac{g^2}{4\pi^2} \frac{m_\mu^2}{M^2} C_{\text{loop}}$$



Perturbative Unitarity

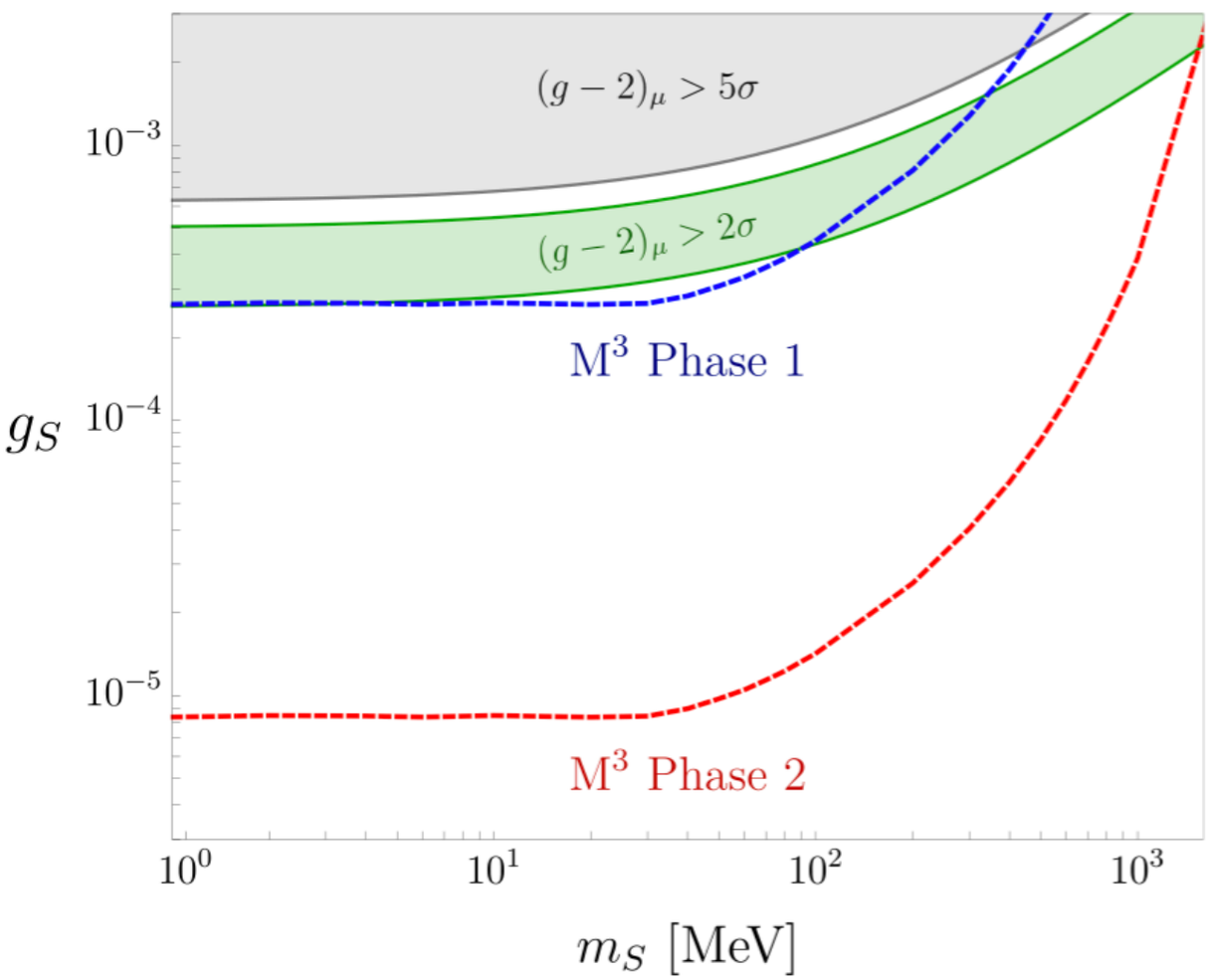
$$g_S^2 \leq \frac{4\pi}{N_{\text{BSM}}} \qquad g_V^2 \leq \frac{12\pi}{N_{\text{BSM}}}$$

Scalar Vector

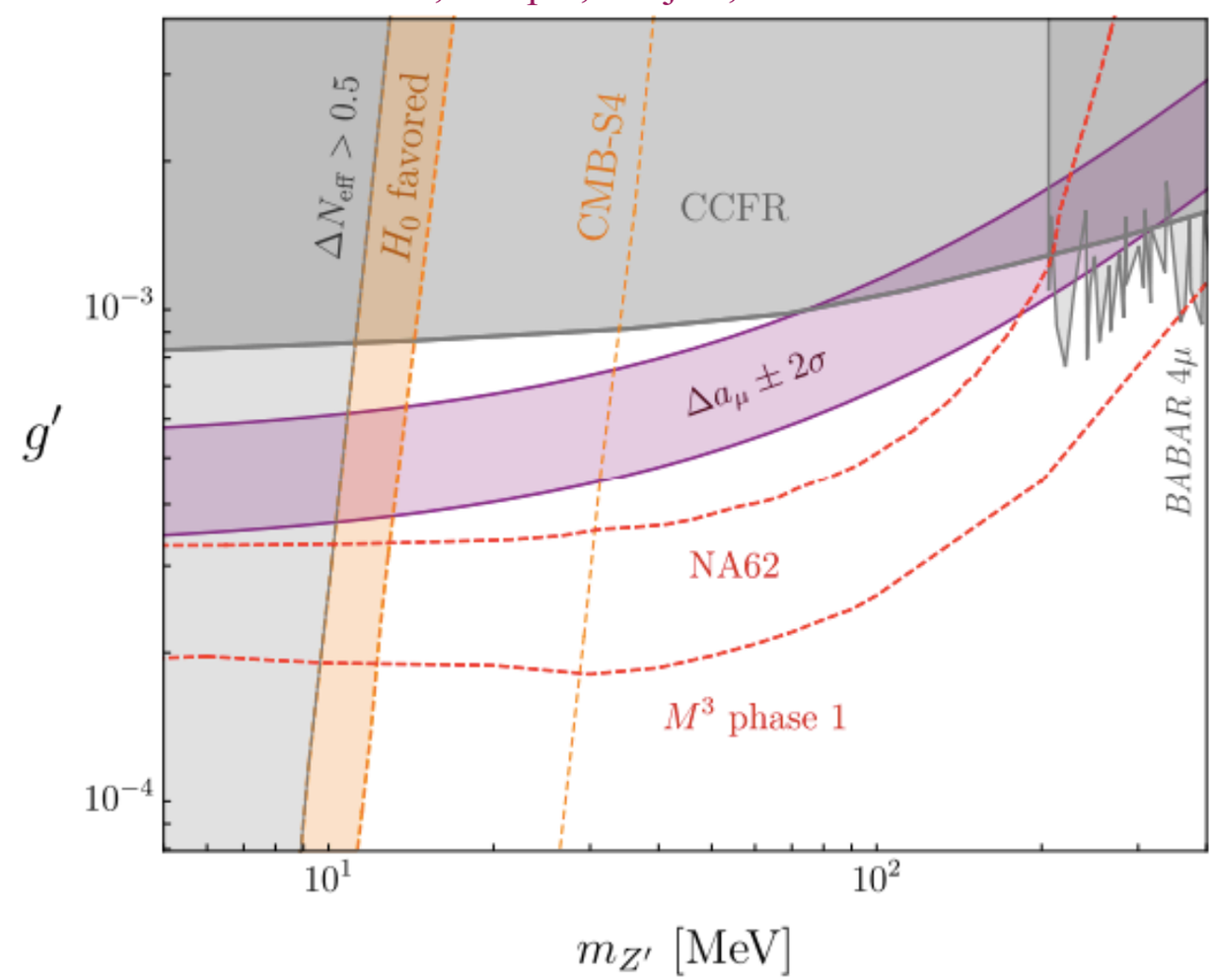
2. BSM Physics of (g-2)μ at MuC

- Singlet scenarios

Kahn, Krnjaic, Tran, Whitbeck, JHEP 09 (2018) 153



Holst, Hooper, Krnjaic, ArXiv: 2107.09067



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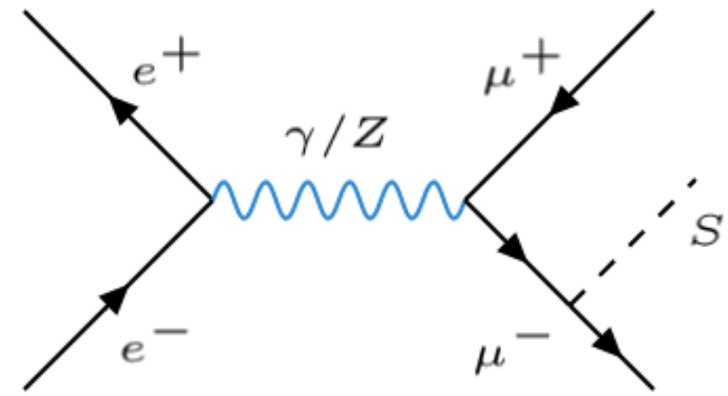
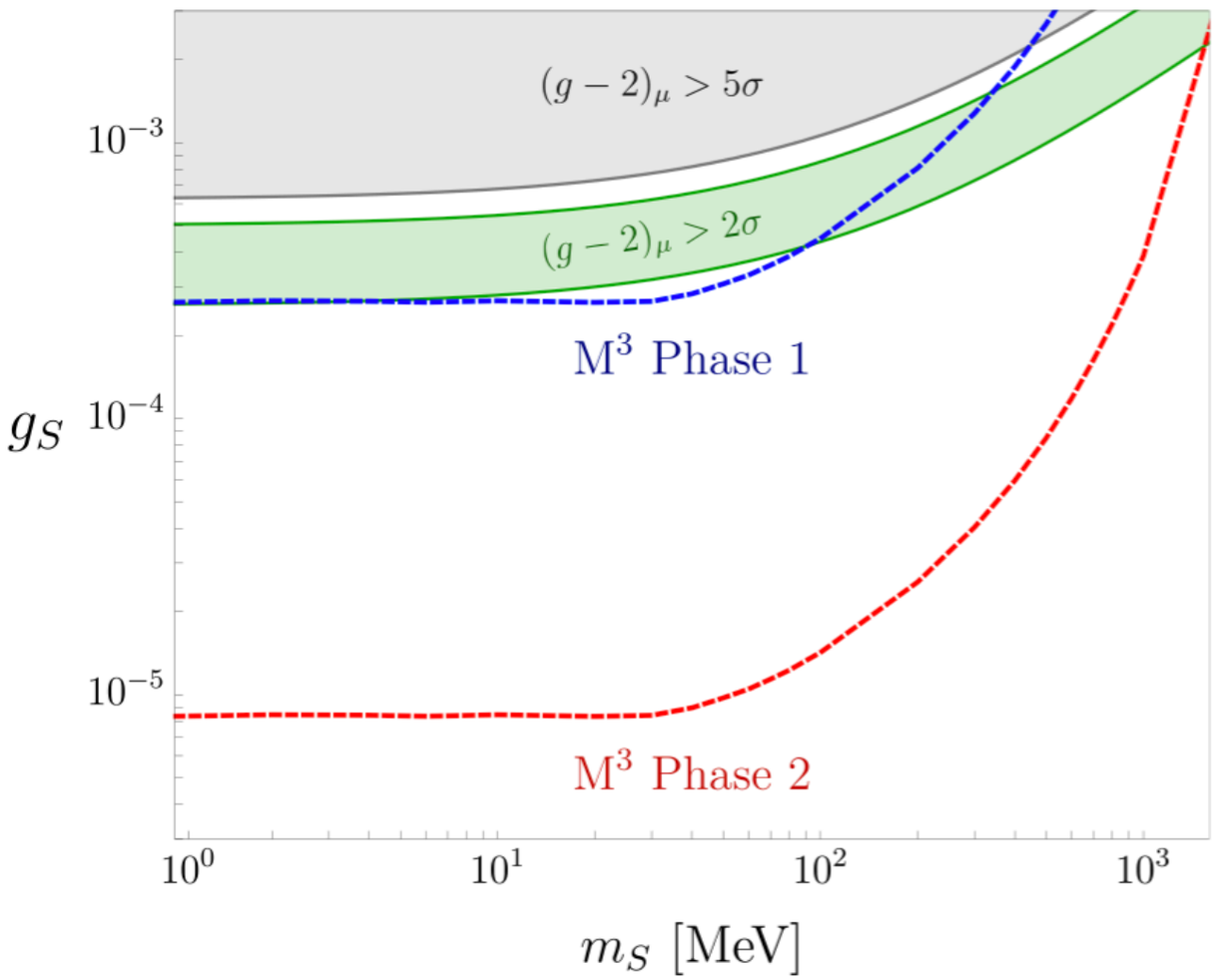
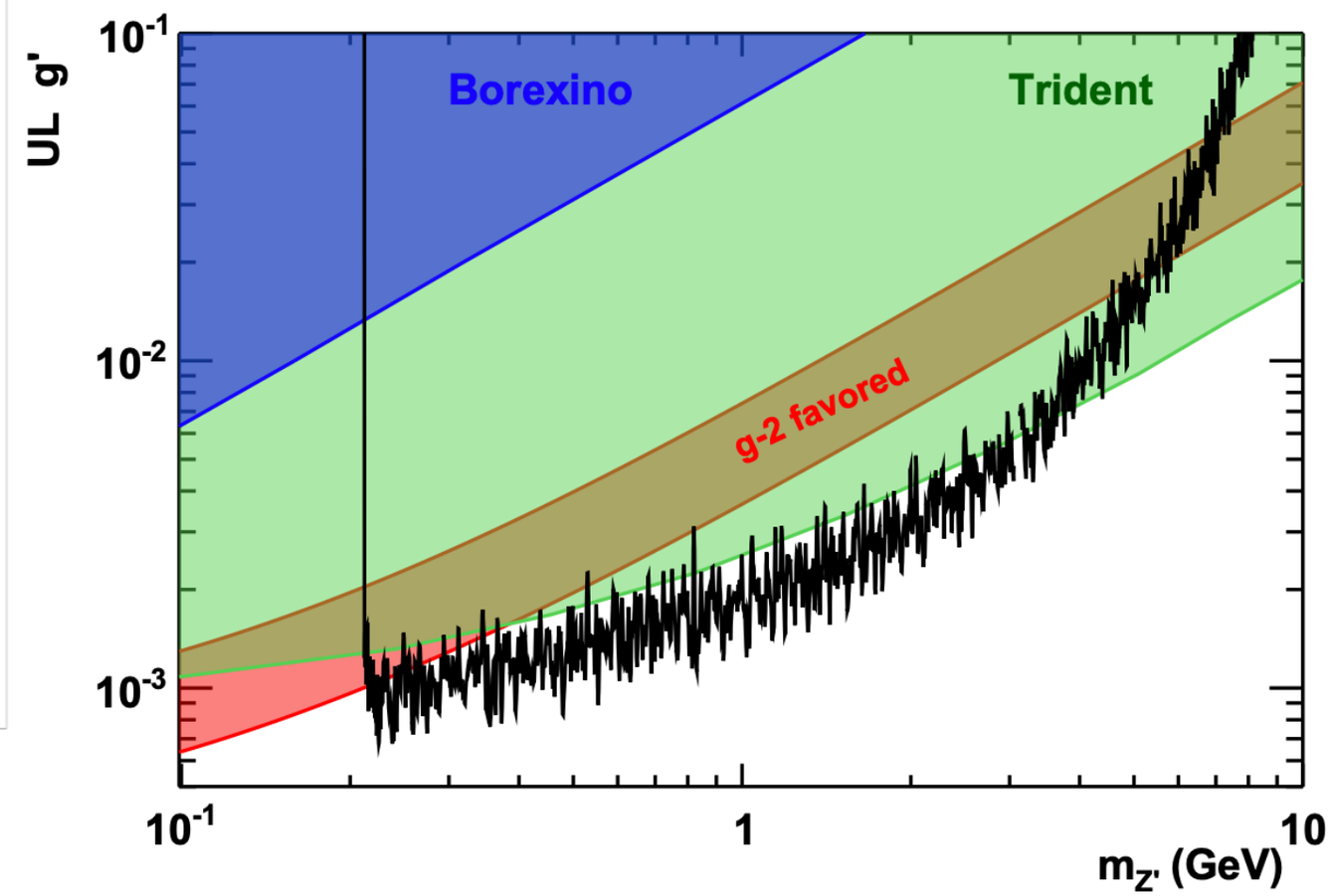


Kahn, Krnjaic, Tran, Whitbeck, JHEP 09 (2018) 153



BaBar Collaboration, Phys. Rev. D 94 (2016) 1, 011102



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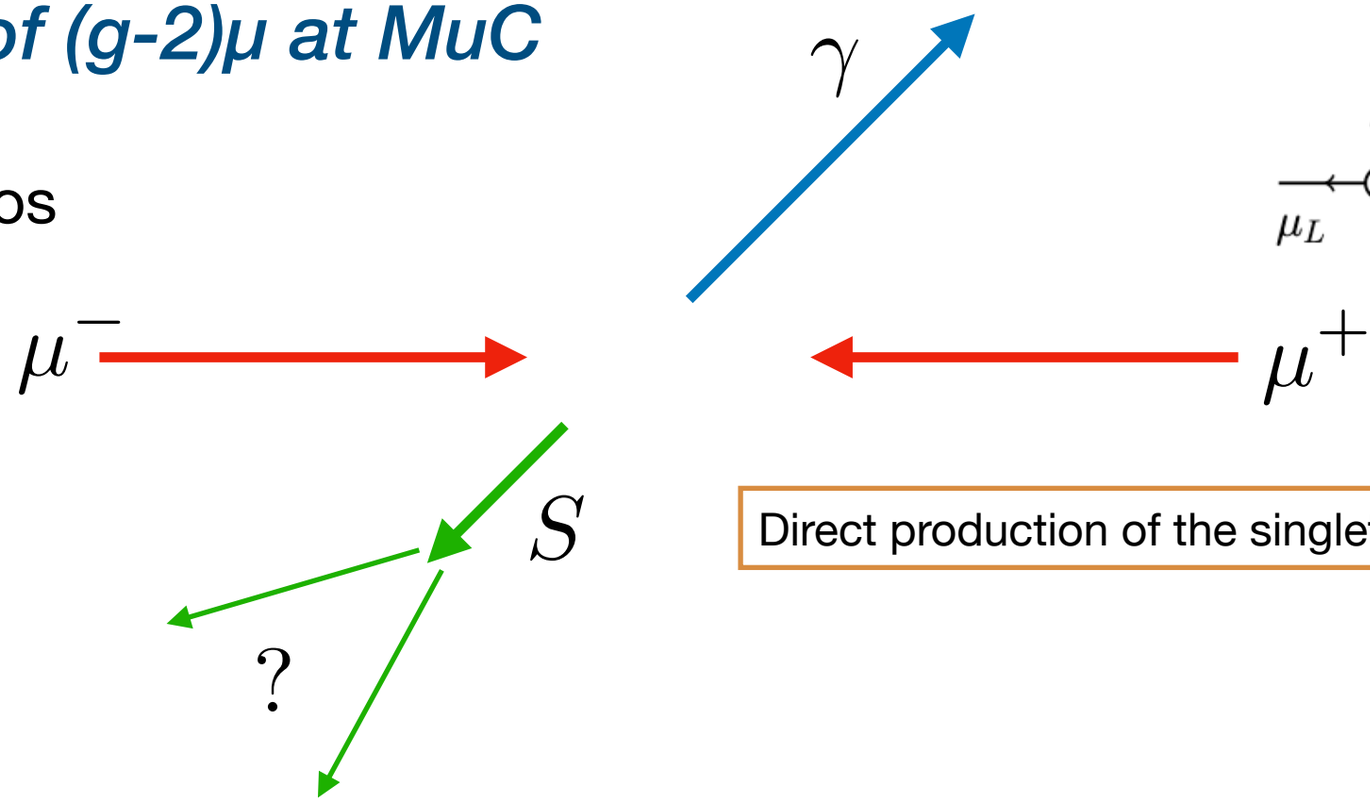
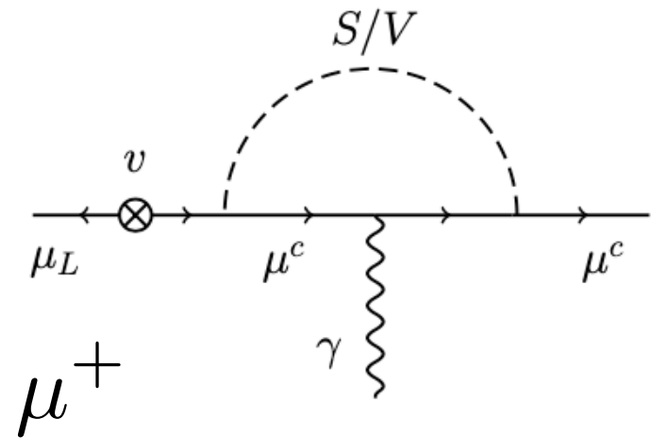
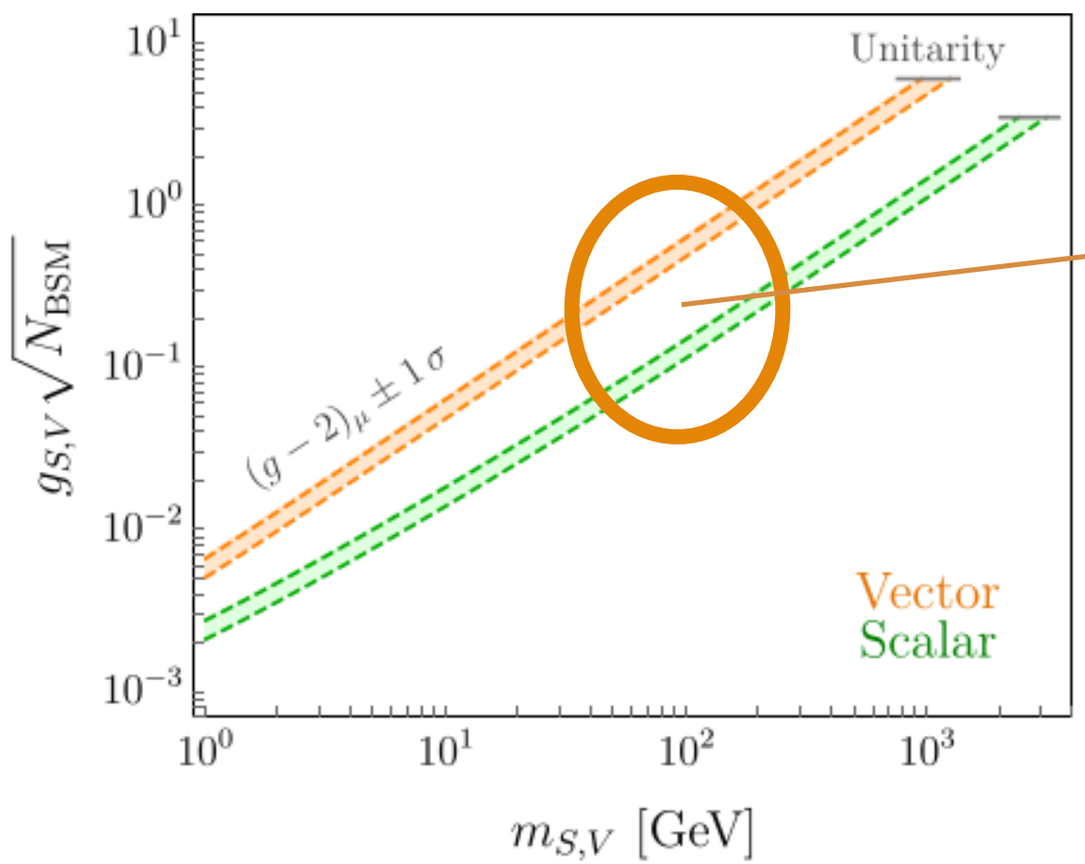
- Singlet scenarios





Direct production of the singlet



$$m_S \gtrsim 100\,\text{GeV}$$

$$g \gtrsim 0.1$$

Reasonable to assume ?

$$S \to \mu^+\mu^-$$

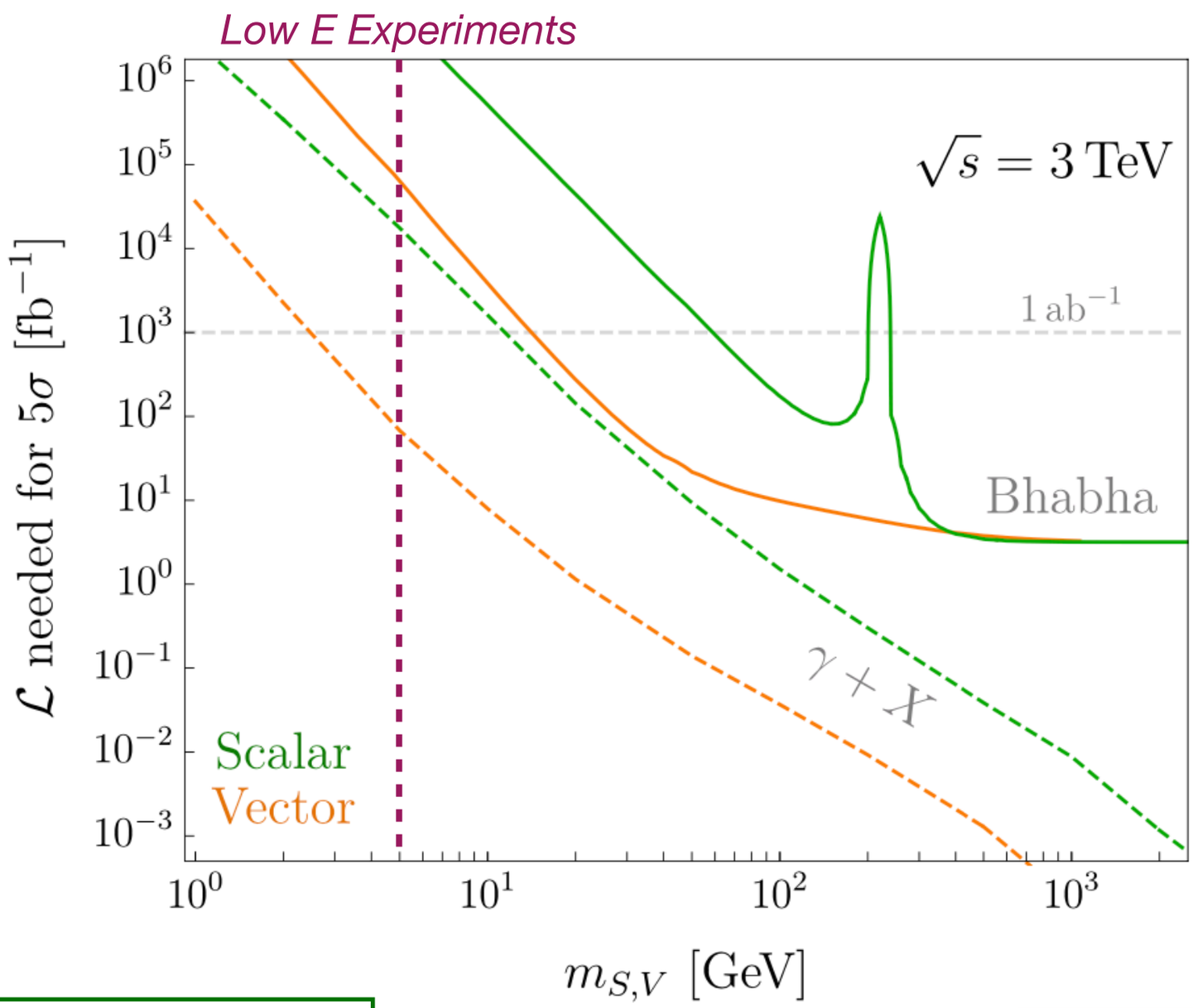
Dominant decay mode

2. BSM Physics of (g-2)μ at MuC

"Singlet scenarios"

A 3 TeV Muon Collider can probe all Singlet explanations for g-2

Capdevilla, Curtin, Kahn, Krnjaic,
ArXiv:2006.16277
ArXiv:2101.10334



Luminosity goal for a 3 TeV MuC

$$g_S S \mu_L \mu^c$$

Scalar Singlets

$$g_V(\mu_L^\dagger \bar{\sigma}^\nu \mu_L + \mu^c \sigma^\nu \mu^{c\dagger}) V_\nu$$

Vector Singlets

2. BSM Physics of (g-2)μ at MuC

Capdevilla, Curtin, Kahn, Krnjaic,
ArXiv:2006.16277
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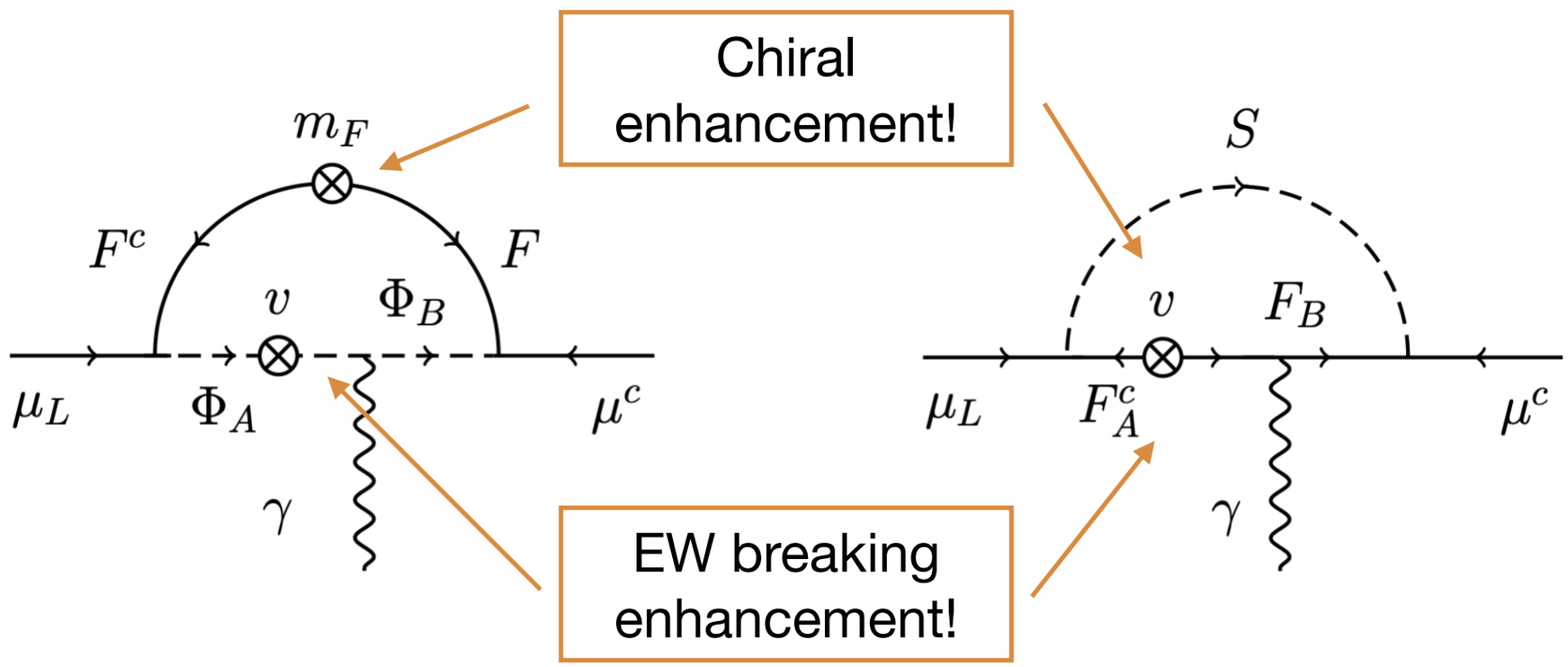
- Is it possible to discover all BSM solutions to the (g–2)μ anomaly?

"Electroweak scenarios"

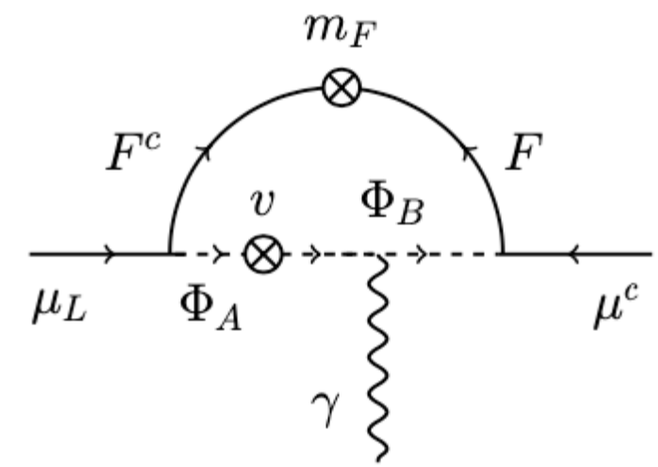


SM gauge invariance:

$$\mathbf{1} \subset R^A \otimes R \otimes \mathbf{2}$$
$$R^B = \bar{R}$$
$$Y^A = -\frac{1}{2} - Y$$
$$Y^B = -1 - Y,$$

can just list off all such representations up to some maximum Q (we take Q <= 2)

2. BSM Physics of (g-2)μ at MuC

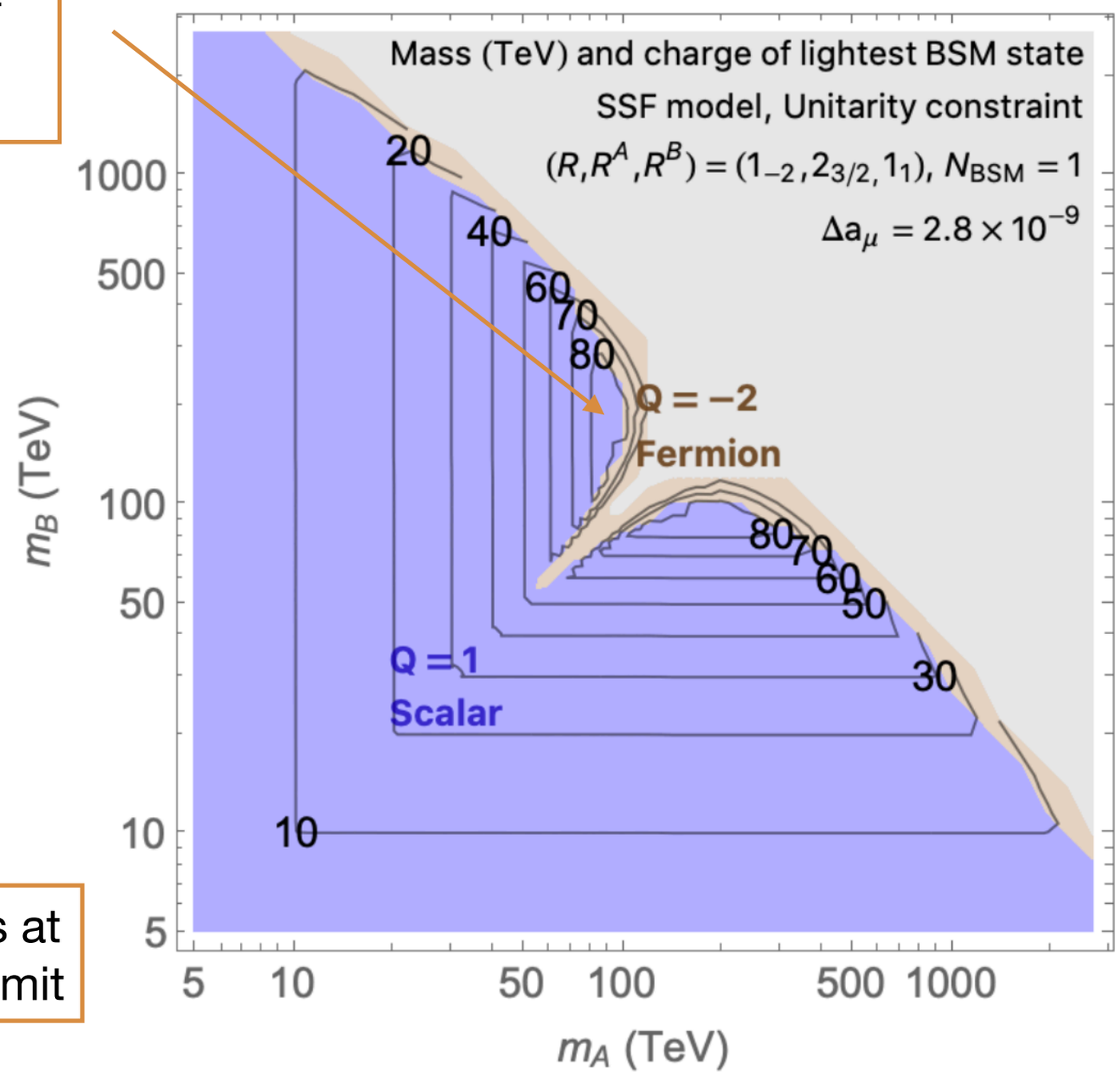


If only perturbative unitarity

Heaviest states at

$\sim 100\,\mathrm{TeV}$

Unitarity only

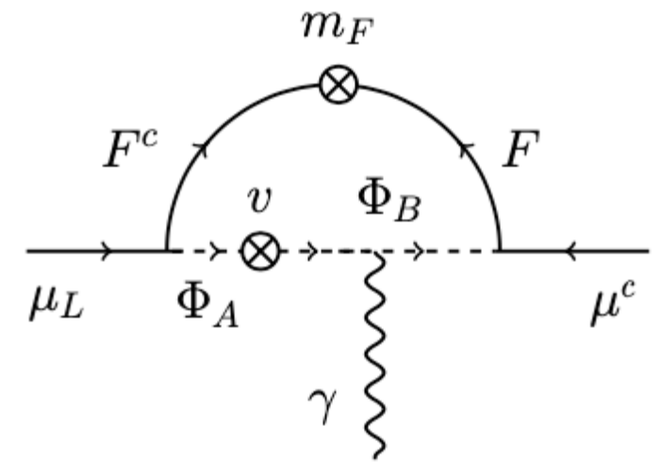


- EW representations up to **3**
- Models with charged scalars up to Q = 2
- BSM number of flavours up to 10

N_{BSM}

Maximal couplings at the perturbativity limit

2. BSM Physics of (g-2)μ at MuC



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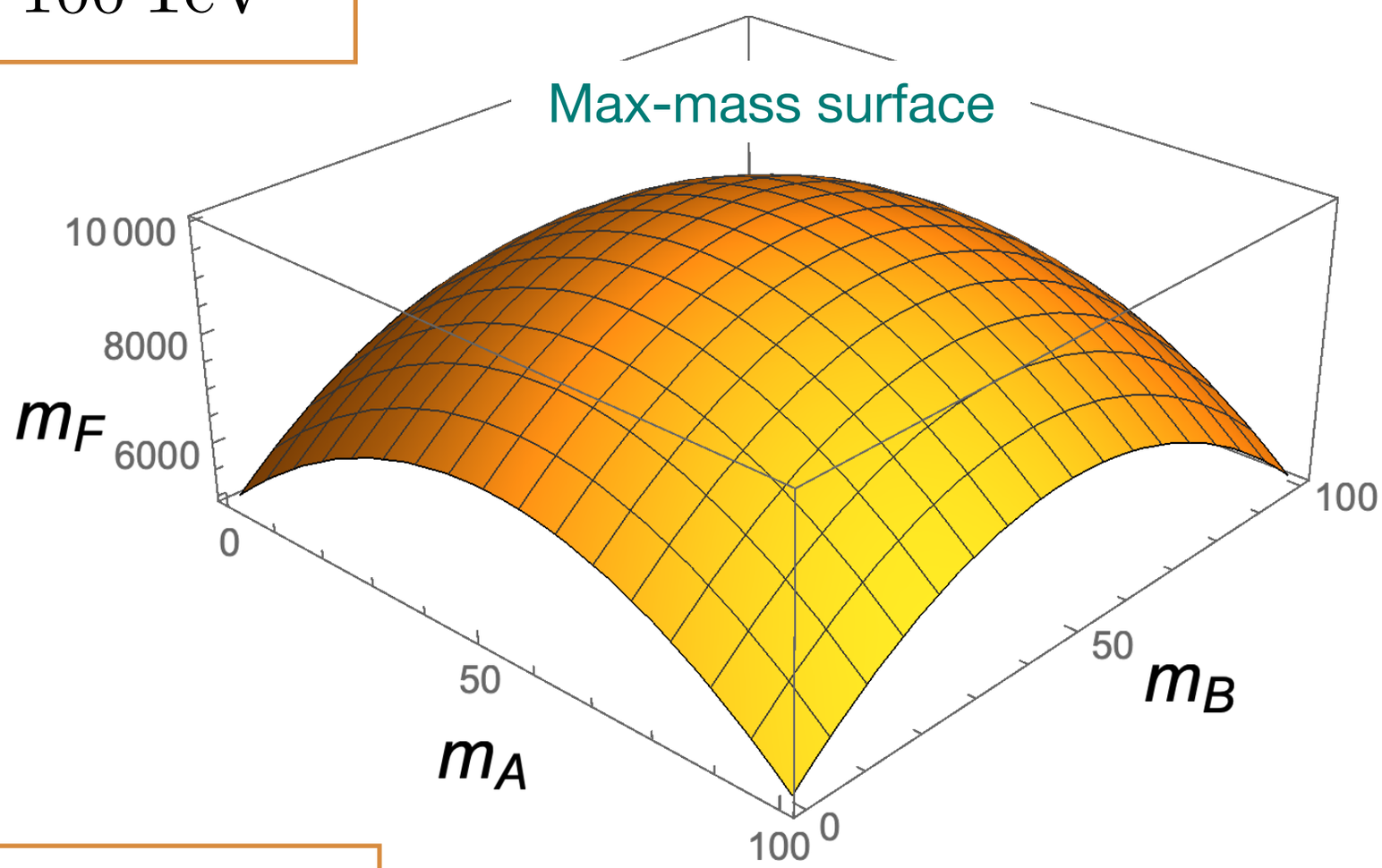

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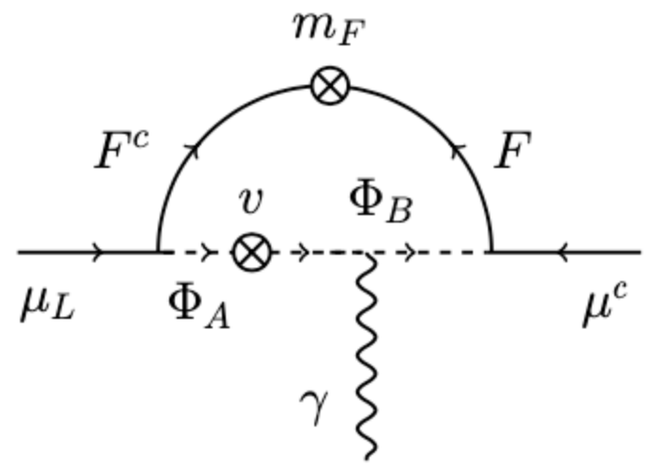
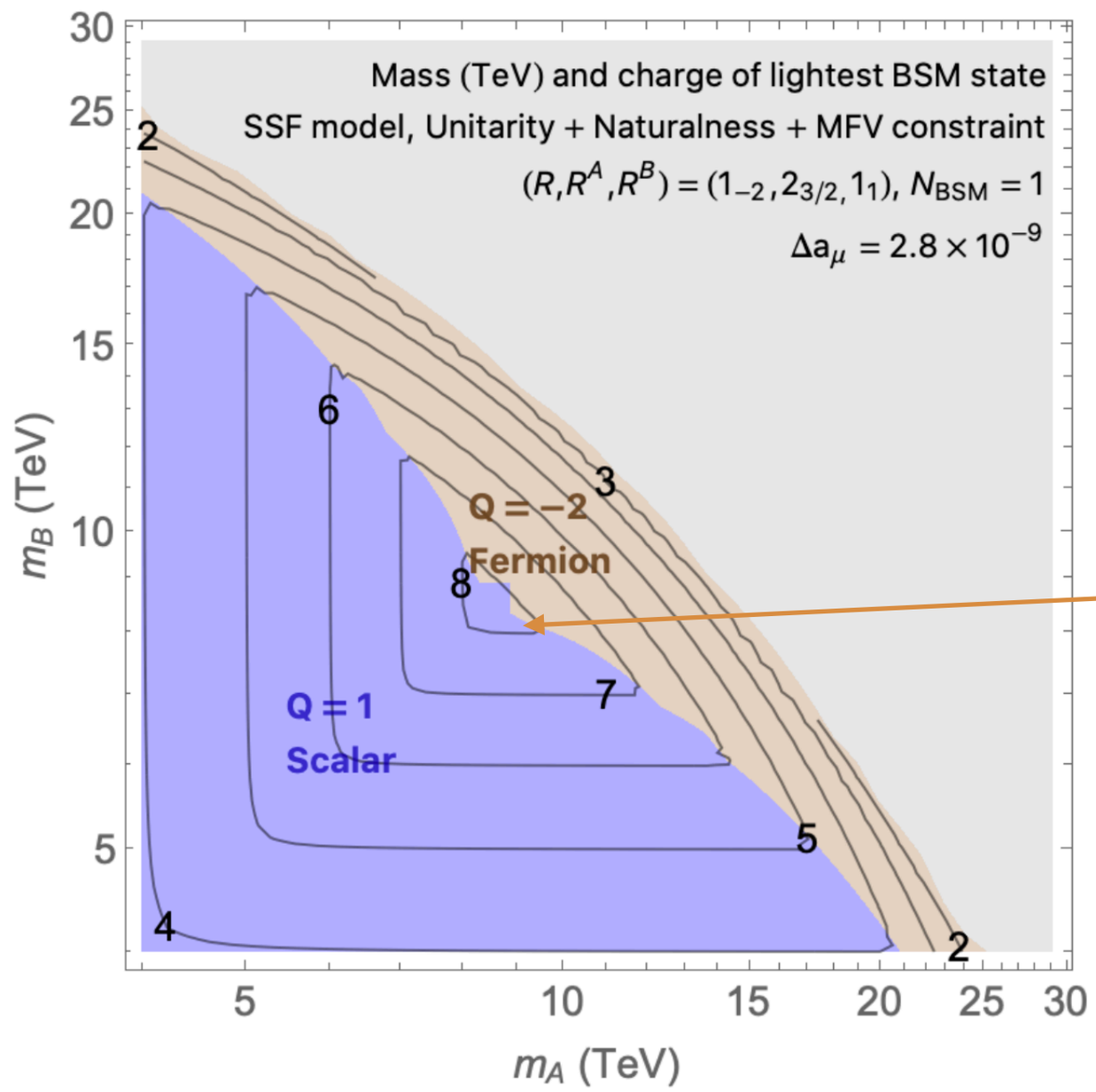


"Electroweak scenarios"

A 20 TeV Muon Collider can probe Electroweak scenarios under the assumptions of MFV and Naturalness

Capdevilla, Curtin, Kahn, Krnjaic,
ArXiv:2006.16277
ArXiv:2101.10334



Unitarity
Naturalness
MFV

Heaviest states at
$\sim 10\,\mathrm{TeV}$

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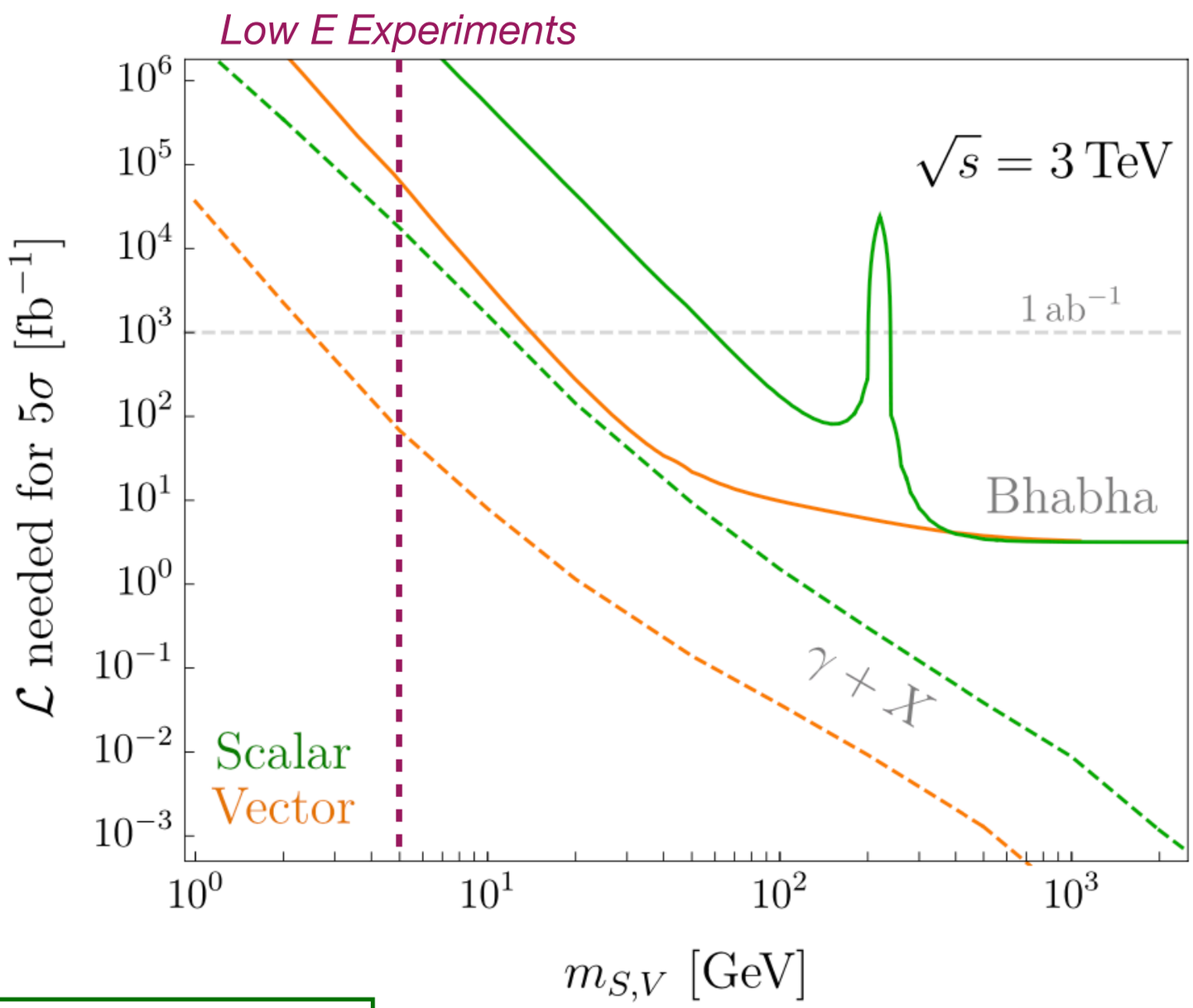

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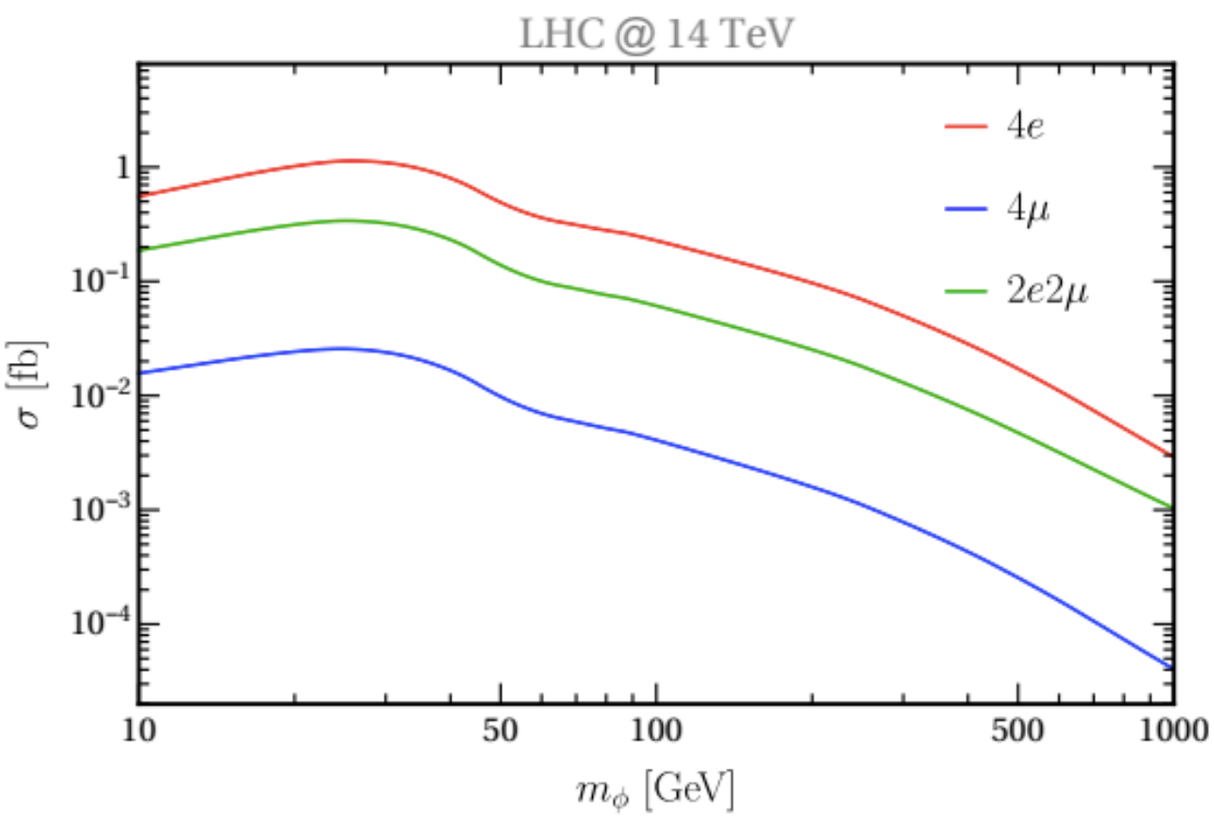
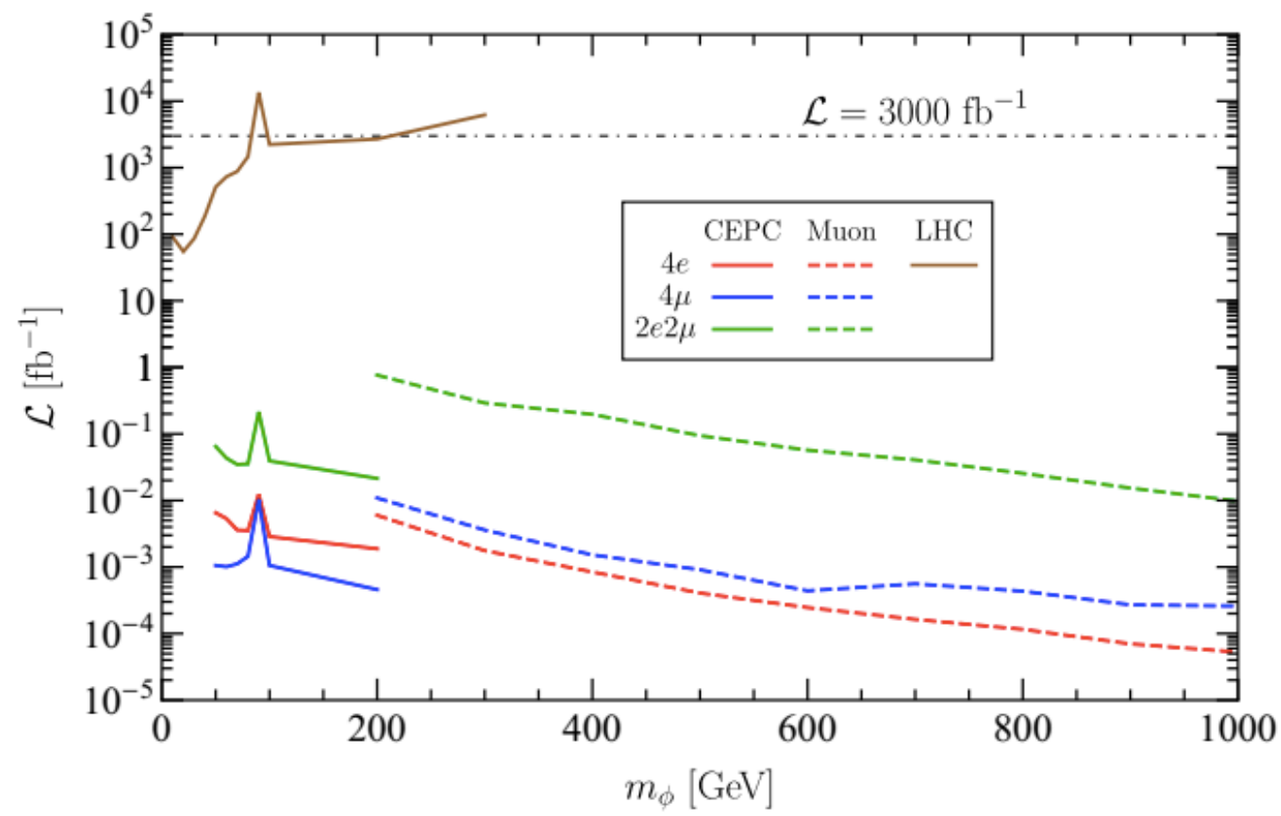
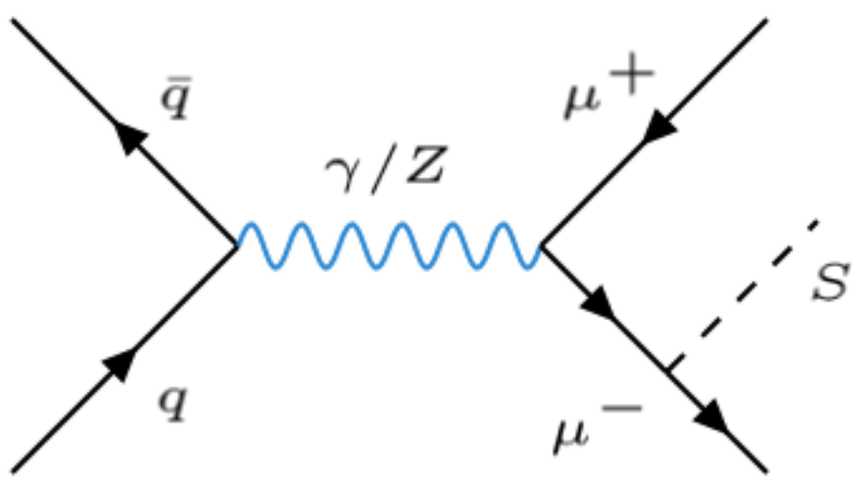
3. Singlets: Hadron colliders + EW Precision

Chen, Wang, Yao, ArXiv:2102.05619

How about LHC?

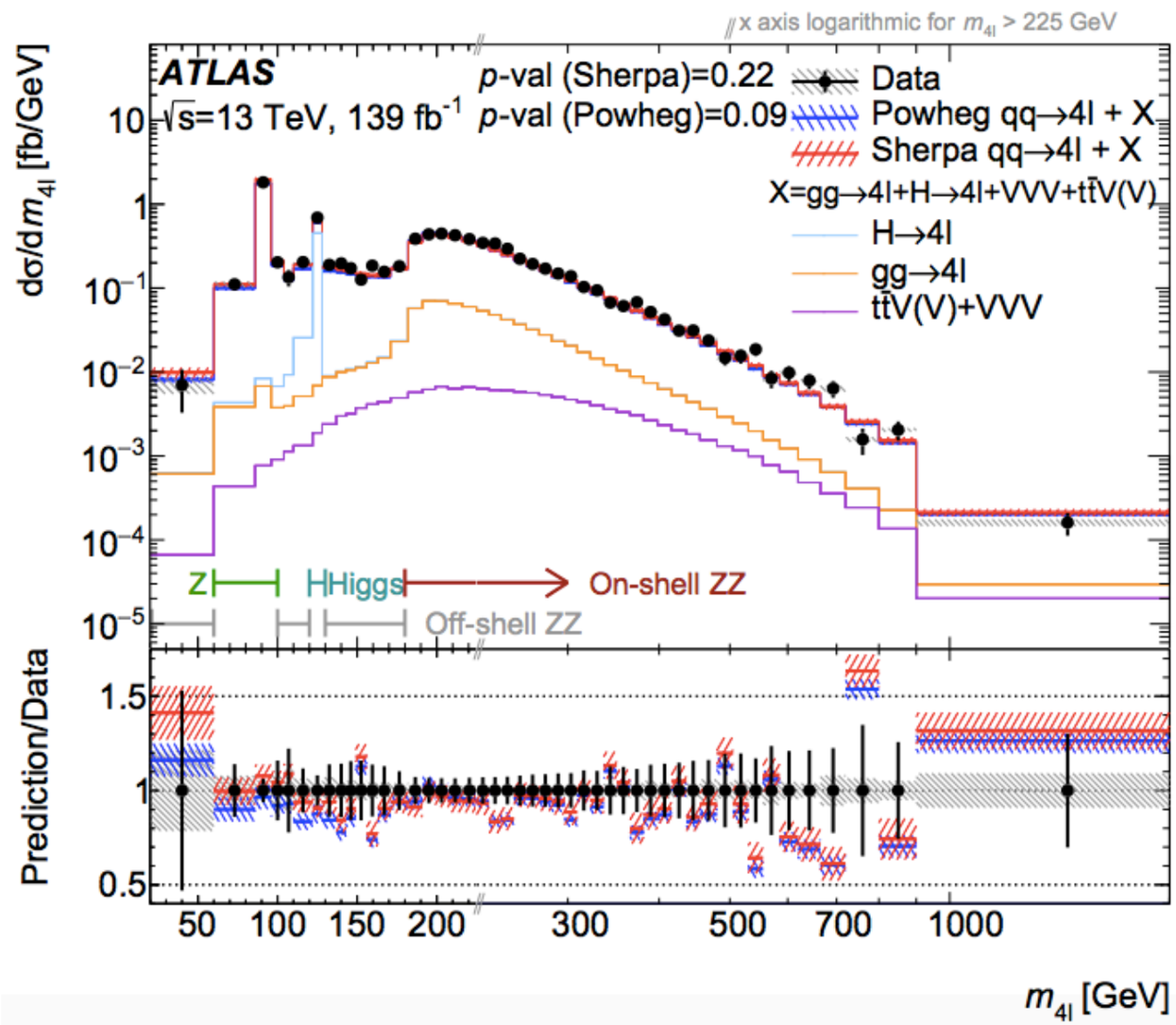






3. Singlets: Hadron colliders + EW Precision

ATLAS Collaboration, JHEP 07 (2021) 005



Four-muon search loose cuts:

$$p_T^\mu > 20\,\mathrm{GeV}$$
$$p_T^\mu > 15\,\mathrm{GeV}$$
$$p_T^\mu > 10\,\mathrm{GeV}$$
$$p_T^\mu > 5\,\mathrm{GeV}$$

Leading muon!

$$\Delta R_{\mu\mu} > 0.1$$

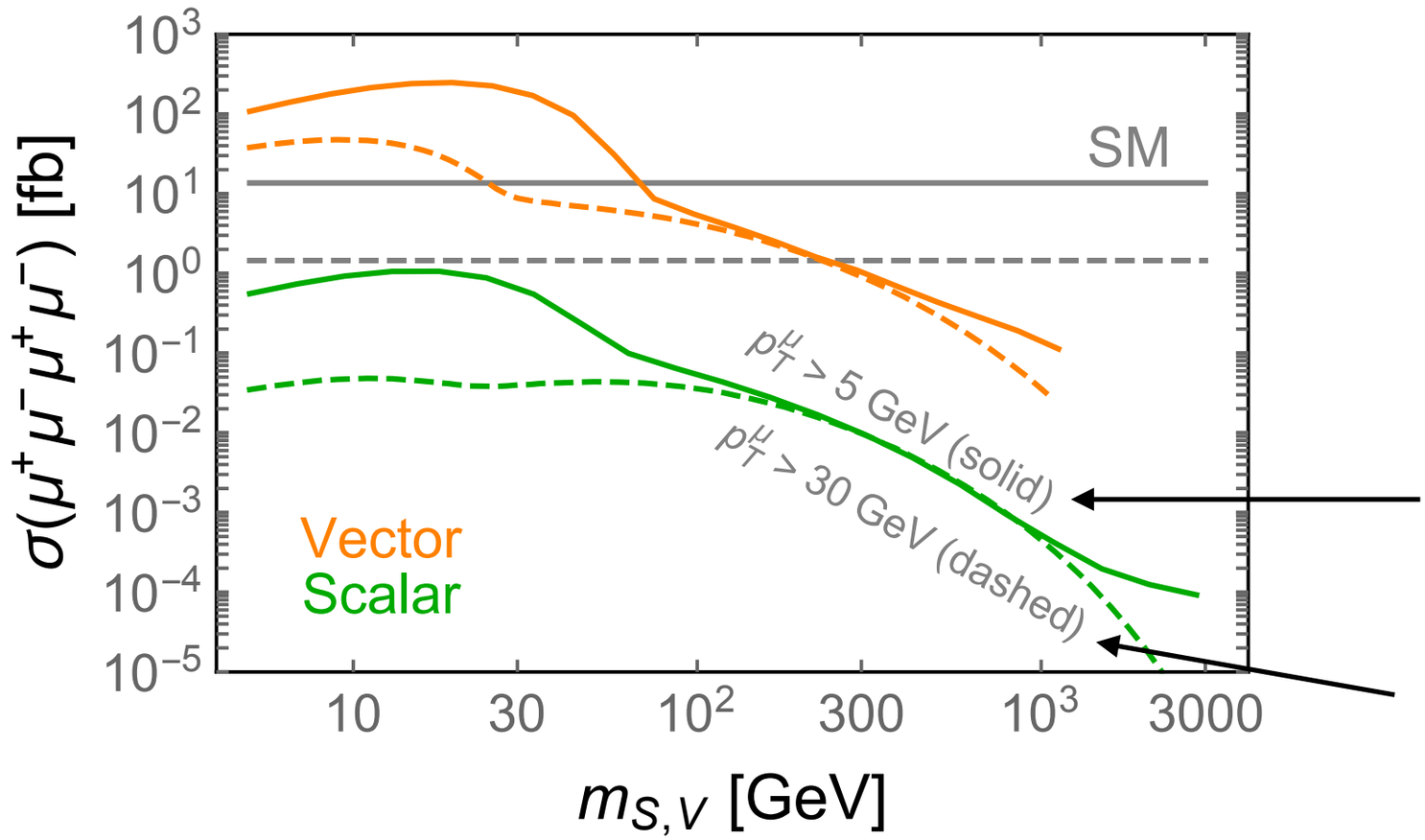
For boosted Z

$$m_{\mu^+\mu^-} > 5\,\mathrm{GeV}$$

Exclude leptons from quarkonia

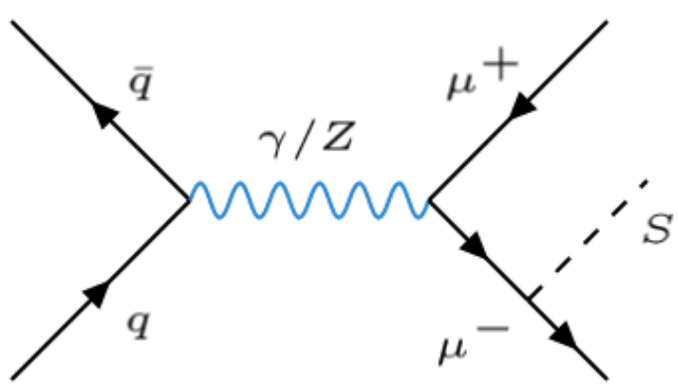
3. Singlets: Hadron colliders + EW Precision

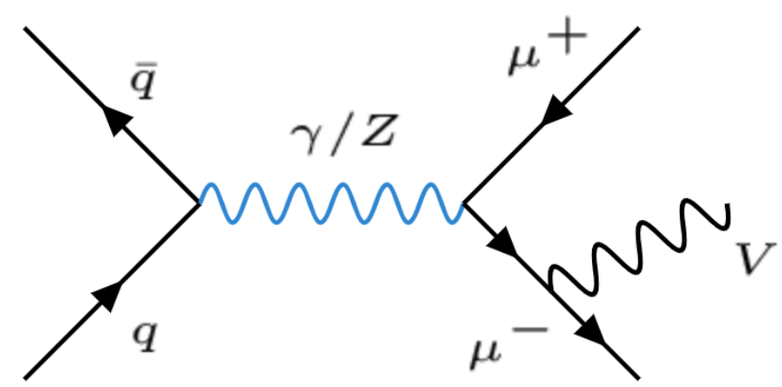
How about LHC?



Loose cuts

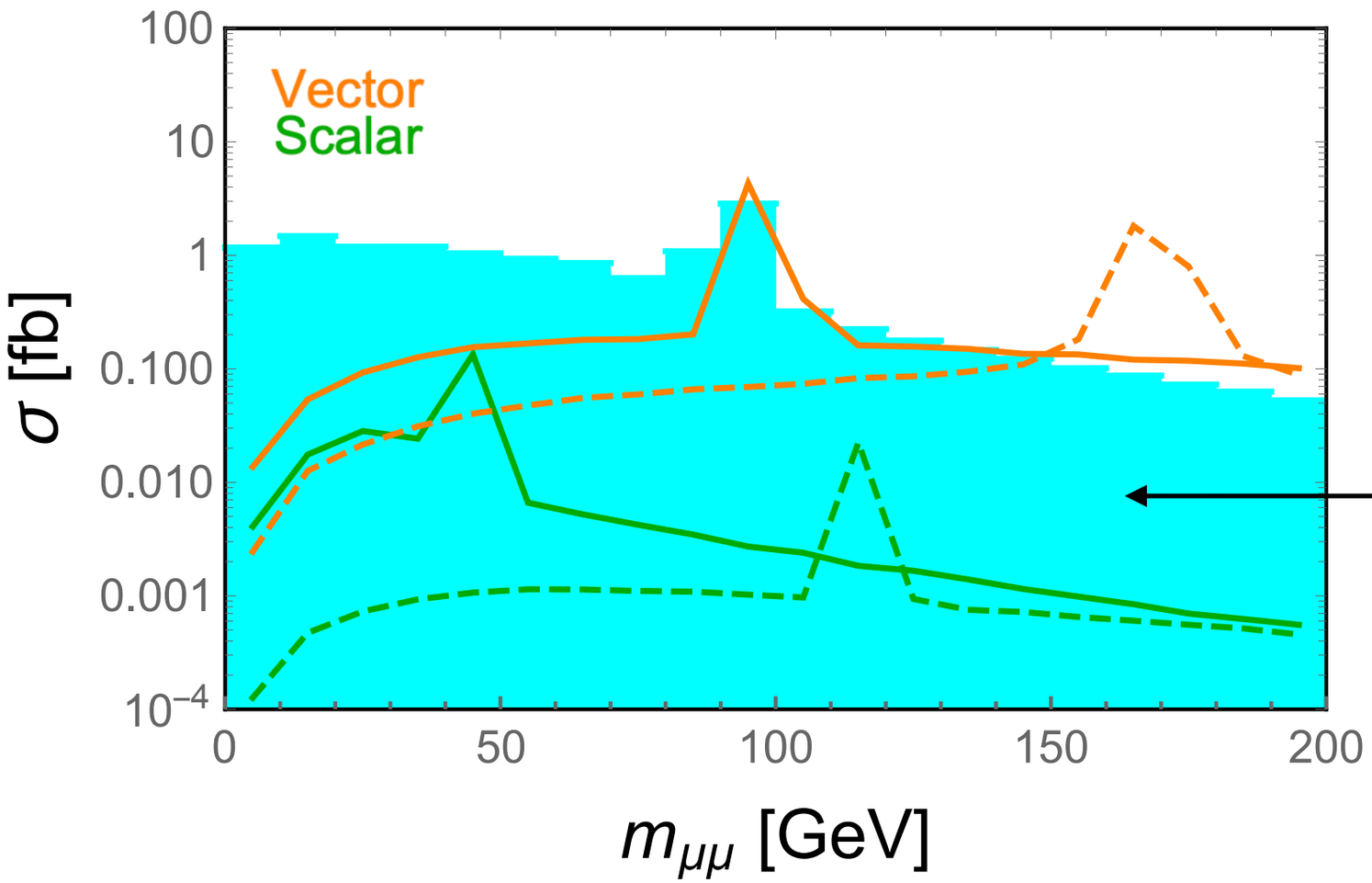
Tight cuts





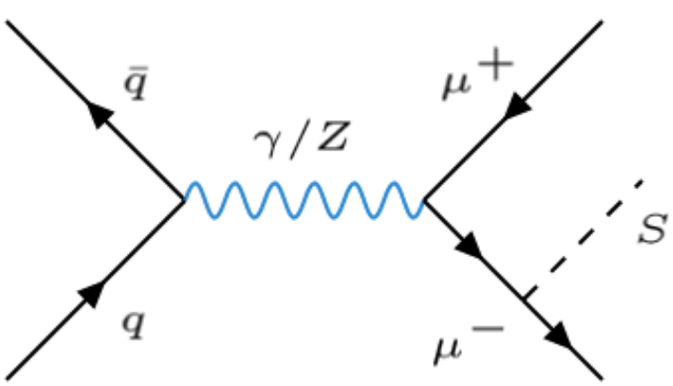
3. Singlets: Hadron colliders + EW Precision

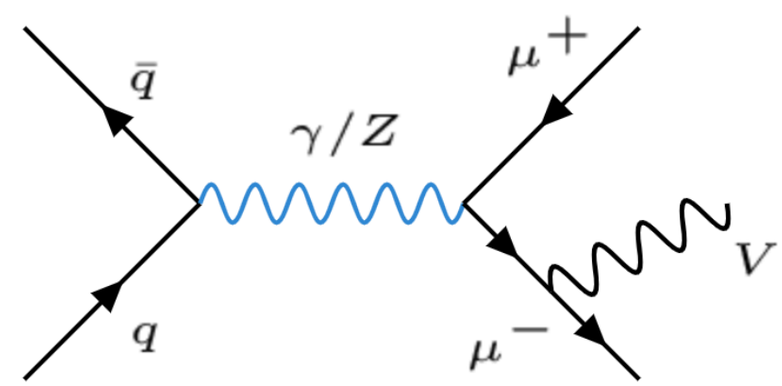
How about LHC?



SM background!

Invariant mass of mu+ mu- pairs

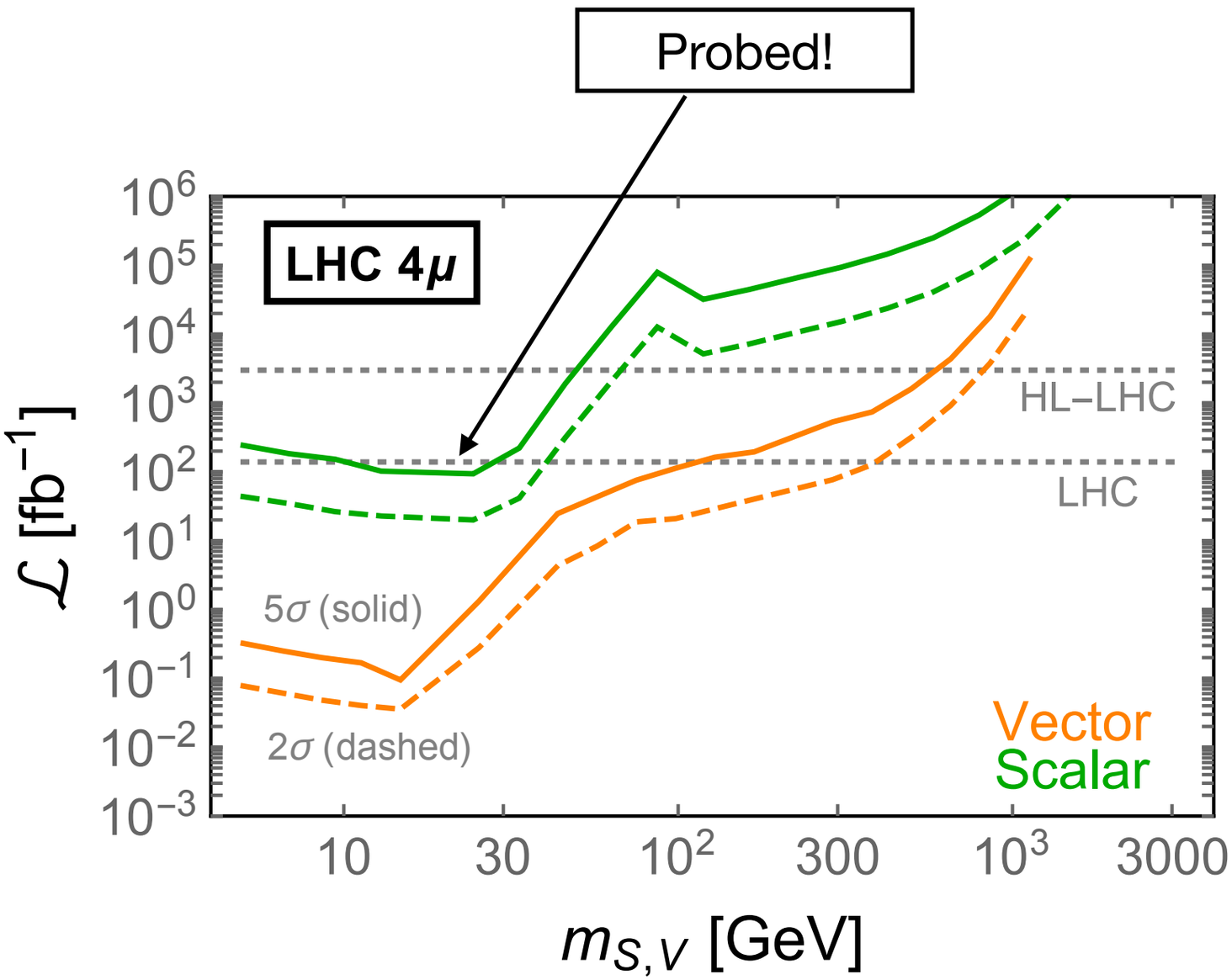




3. Singlets: Hadron colliders + EW Precision

Preliminary!

How about LHC?



$$g_S S \mu_L \mu^c$$

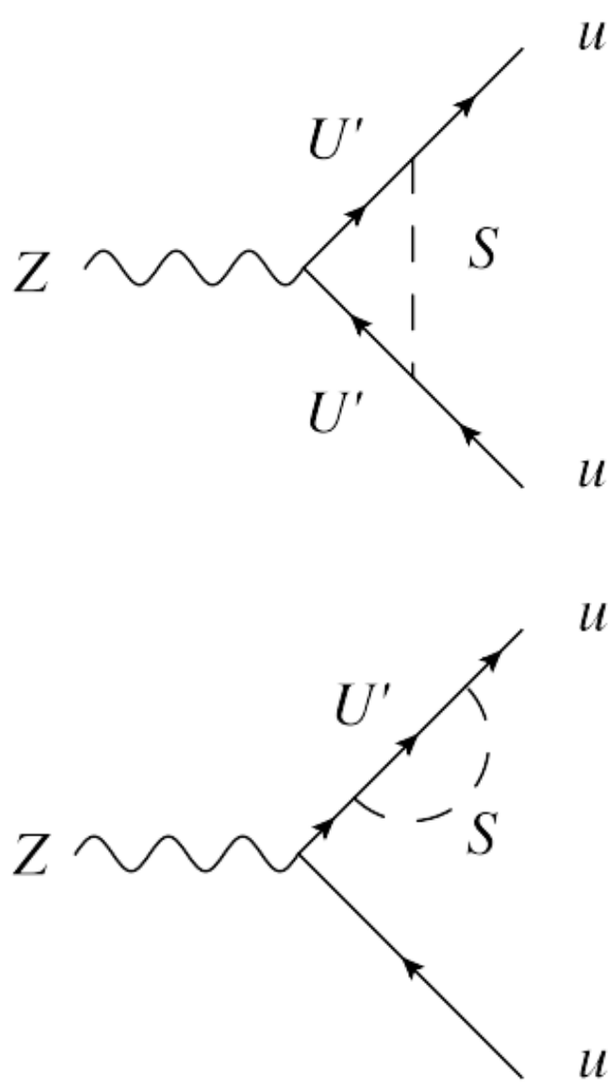
Scalar Singlets

$$g_V(\mu_L^\dagger \bar{\sigma}^\nu \mu_L + \mu^c \sigma^\nu \mu^{c\dagger}) V_\nu$$

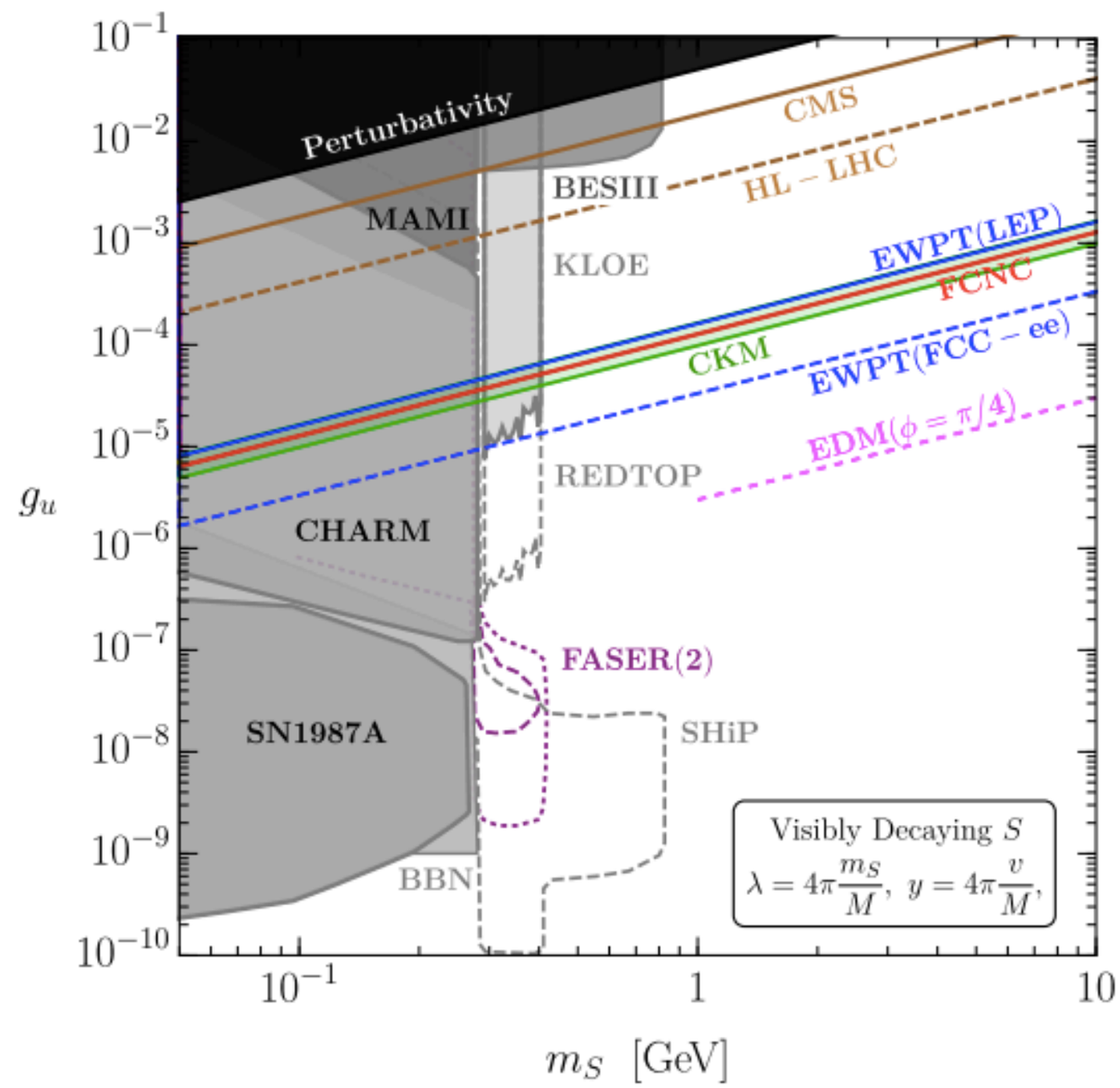
Vector Singlets

3. Singlets: Hadron colliders + EW Precision

Batell, Freitas, Ismail, ArXiv:2107.08059



How about EW Precision?



3. Singlets: Hadron colliders + EW Precision

$$g_S S \mu_L \mu^c$$

Scalar Singlets

Need UV completions!

$$\mathcal{L}_\chi \supset -y_1 L H^\dagger \chi^c - y_2 \mu^c \chi S$$

$$\mathcal{L} \supset -y_1 L \Psi^c S - y_2 \mu^c H^\dagger \Psi$$

$$\mathcal{L} \supset -y L \Phi^\dagger \mu^c - \kappa S H^\dagger \Phi$$

$$\mathcal{O} \sim \frac{y_1 y_2}{M} H^\dagger L \mu^c S \quad \rightarrow \quad g_S = \frac{y_1 y_2 v_h}{M}$$

$$\mathcal{O} \sim \frac{y\kappa}{M^2} H^\dagger L \mu^c S \quad \rightarrow \quad g_S = \frac{y\kappa v_h}{M^2}$$

3. Singlets: Hadron colliders + EW Precision

$$g_S S \mu_L \mu^c$$

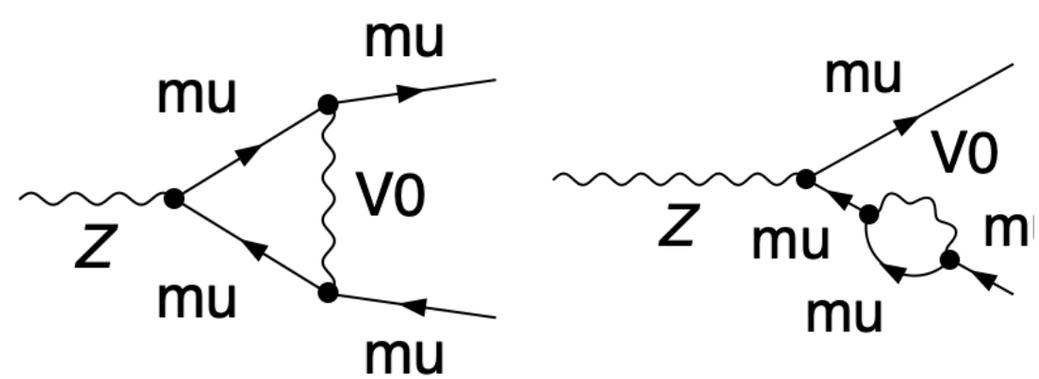
Scalar Singlets

$$g_V (\mu_L^\dagger \bar{\sigma}^\nu \mu_L + \mu^c \sigma^\nu \mu^{c\dagger}) V_\nu$$

Vector Singlets

$$\mathcal{L}_\chi \supset -y_1 L H^\dagger \chi^c - y_2 \mu^c \chi S$$

Mixing!



$$R_{\mu e} = \frac{\Gamma(Z \to \mu\mu)}{\Gamma(Z \to ee)} \longrightarrow \delta R_{\mu e}$$

$$\delta R_{\mu e} \propto \frac{y_1^2 v_h^2}{M^2}$$

$$\delta R_{\mu e} \propto \frac{g_V^2}{16\pi^2} \frac{m_Z^2}{m_V^2} C_{\text{loop}}$$

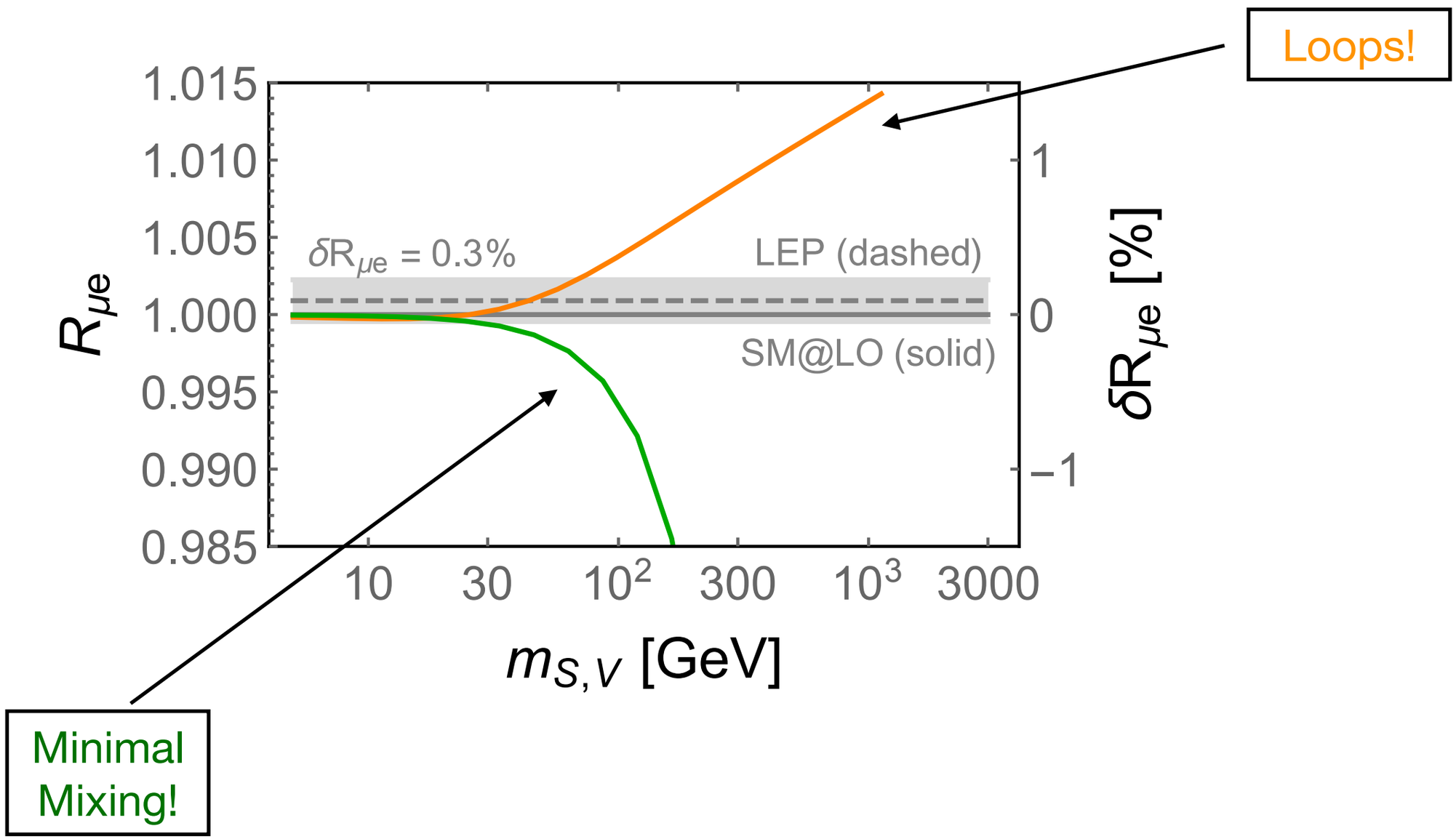
3. Singlets: Hadron colliders + EW Precision

$$g_S S \mu_L \mu^c$$

Scalar Singlets

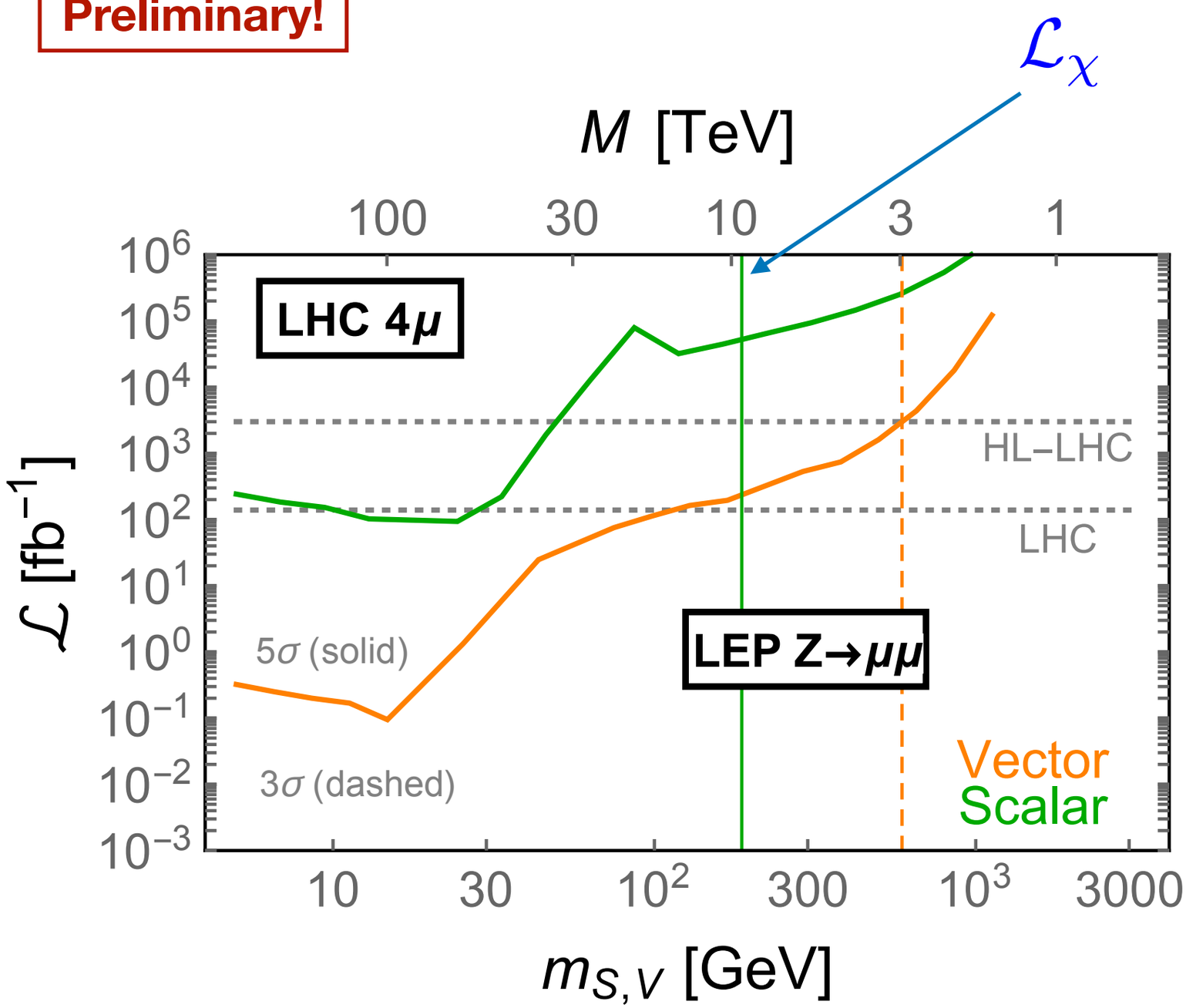
$$g_V(\mu_L^\dagger \bar{\sigma}^\nu \mu_L + \mu^c \sigma^\nu \mu^{c\dagger}) V_\nu$$

Vector Singlets



3. Singlets: Hadron colliders + EW Precision

Preliminary!



Top-left exclusion regions will increase at higher energy hadron colliders like FCC-hh

Improved measurement of Z decay modes at FCC-ee will move the vertical lines to the left!

$$g_S S \mu_L \mu^c$$

Scalar Singlets

$$g_V(\mu_L^\dagger \bar{\sigma}^\nu \mu_L + \mu^c \sigma^\nu \mu^{c\dagger}) V_\nu$$

Vector Singlets

Rodolfo Capdevilla, Perimeter Institute and University of Toronto

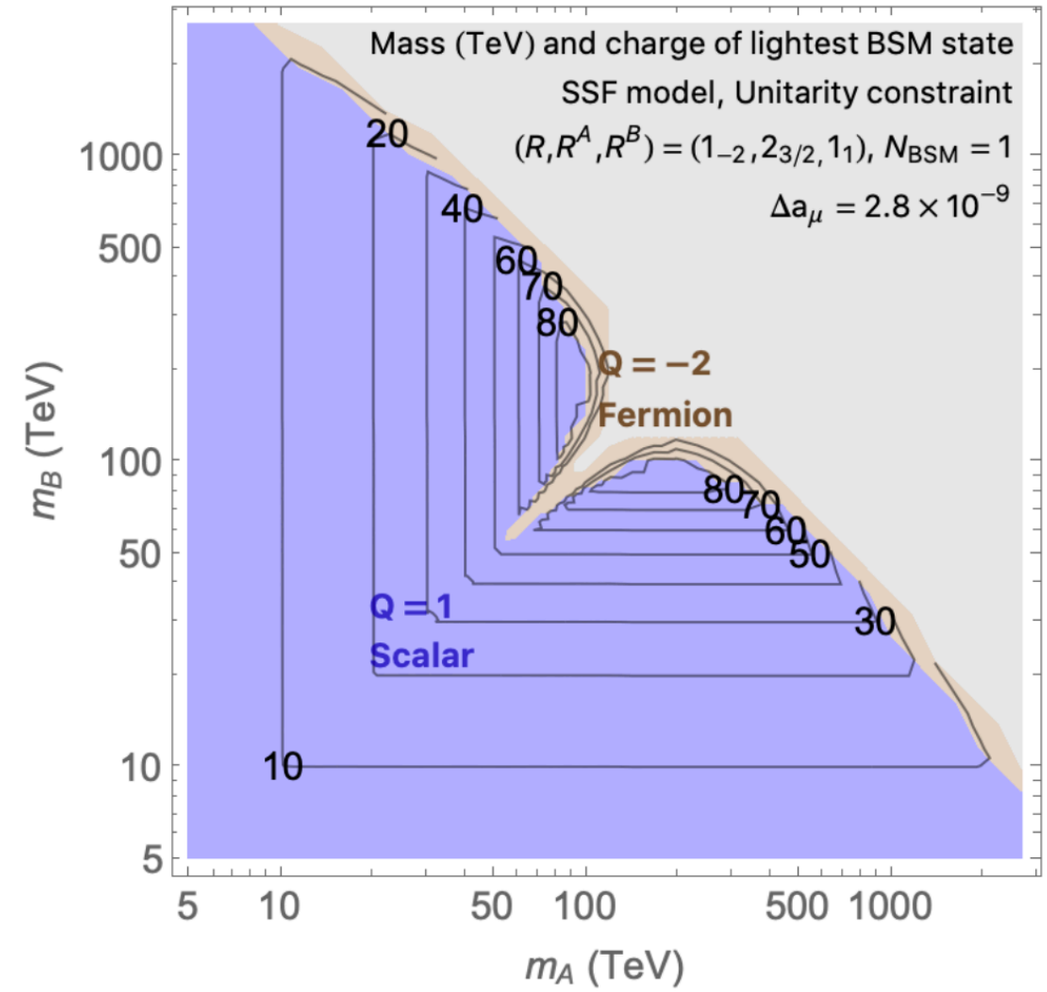
Outline

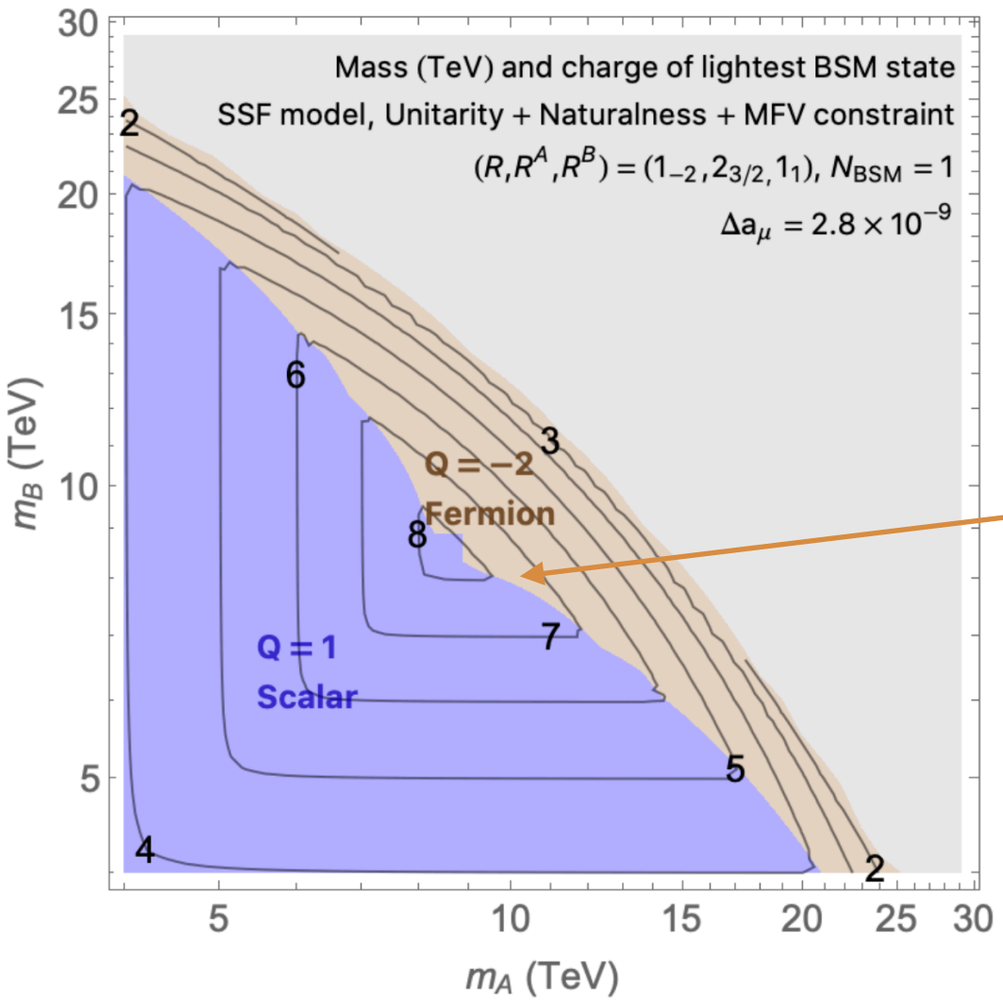
1. Muon Anomalous Magnetic Moment
2. BSM Physics of (g-2)μ at Muon Colliders (MuC)
3. Singlet Scenarios: Hadron colliders + EW Precision
4. **Electroweak Scenarios: Indirect signals at a MuC**
5. Summary

"Electroweak scenarios"

A 20 TeV Muon Collider can probe Electroweak scenarios under the assumptions of MFV and Naturalness

Capdevilla, Curtin, Kahn, Krnjaic,
ArXiv:2006.16277
ArXiv:2101.10334





Unitarity
Naturalness
MFV

Heaviest states at
$\sim 10\,\mathrm{TeV}$

4. EW Scenarios: Indirect signals at a MuC

Buttazzo and Paradisi, ArXiv:2012.02769

$$\mathcal{L} = \frac{C^{\ell}_{eB}}{\Lambda^2}\left(\bar{\ell}_L \sigma^{\mu\nu} e_R\right) H B_{\mu\nu} + \frac{C^{\ell}_{eW}}{\Lambda^2}\left(\bar{\ell}_L \sigma^{\mu\nu} e_R\right) \tau^I H W^I_{\mu\nu}$$

$$\Delta a_\ell \simeq \frac{4 m_\ell v}{e\sqrt{2}\Lambda^2}\left(C^{\ell}_{e\gamma} - \frac{3\alpha}{2\pi}\frac{c_W^2 - s_W^2}{s_W c_W} C^{\ell}_{eZ} \log\frac{\Lambda}{m_Z}\right)$$

Fixed by the (g-2)μ measurement!

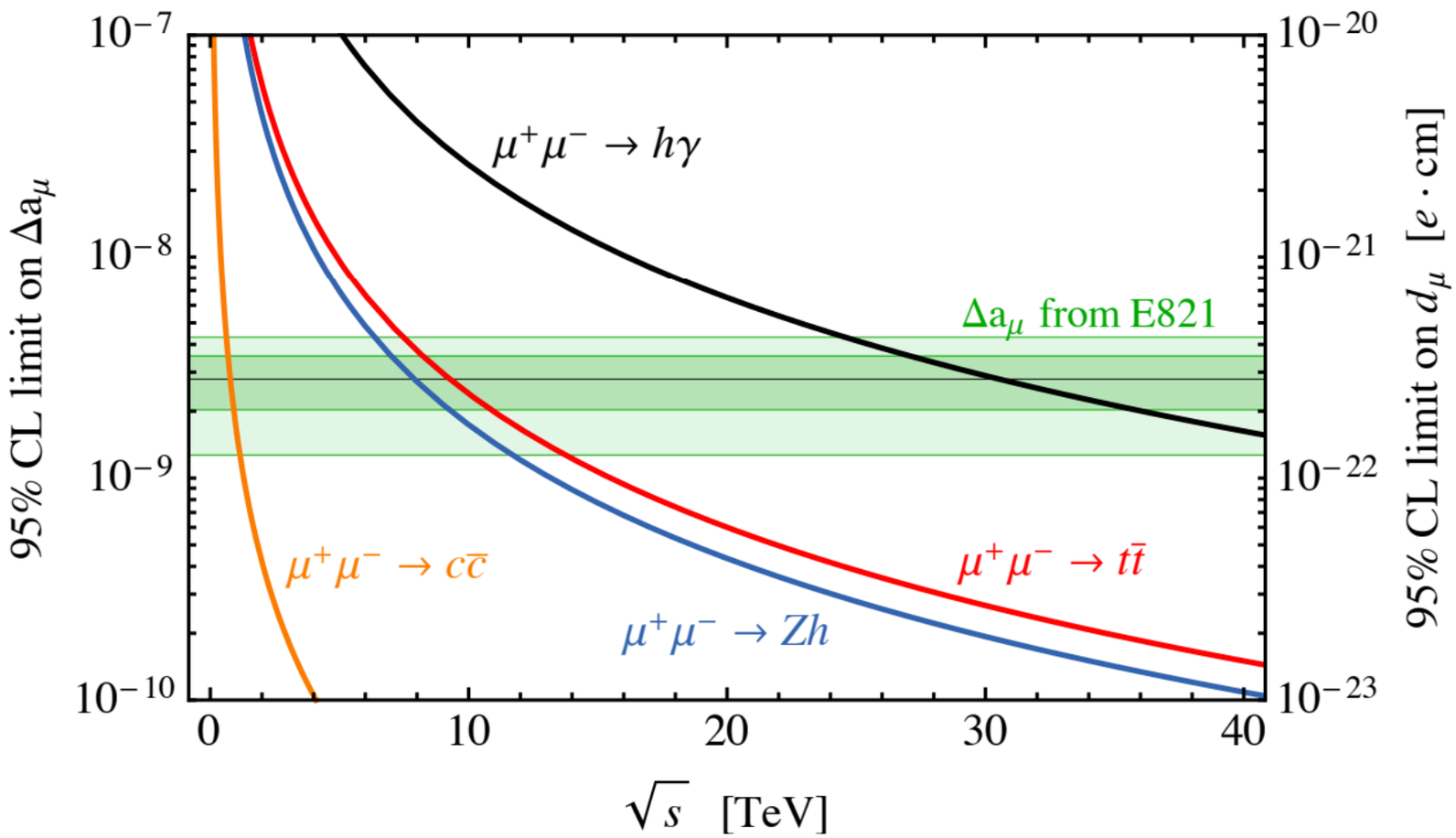
$$\frac{d\sigma_{\mu\mu\to h\gamma}}{d\cos\theta} = \frac{|C^{\mu}_{e\gamma}(\Lambda)|^2}{\Lambda^4}\frac{s}{64\pi}(1-\cos^2\theta)$$

4. EW Scenarios: Indirect signals at a MuC

Buttazzo and Paradisi, ArXiv:2012.02769

$$\sigma_{\mu\mu\to h\gamma} = \frac{s}{48\pi}\frac{|C^{\mu}_{e\gamma}(\Lambda)|^2}{\Lambda^4}$$

$$\approx 0.7\,\mathrm{ab}\left(\frac{\sqrt{s}}{30\,\mathrm{TeV}}\right)^2\left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2$$



$$\sigma^{\mathrm{cut}}_{\mu\mu\to h\gamma} \approx 0.53\,\mathrm{ab}\left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2$$

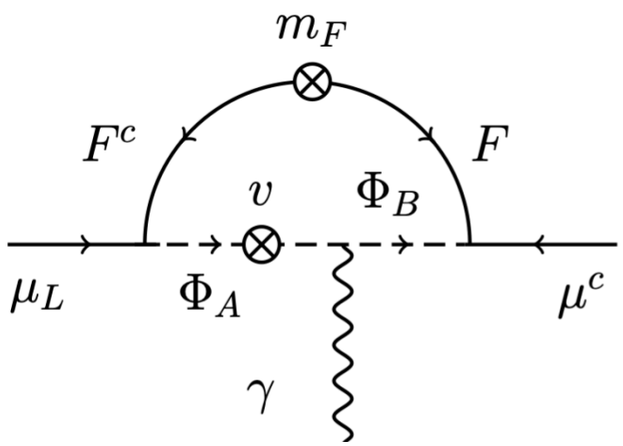
$$\sigma^{\mathrm{cut}}_{\mu\mu\to Z\gamma} \approx 82\,\mathrm{ab}$$

$$|\cos\theta| \lesssim 0.6$$

a 30 TeV collider would be able to reach a sensitivity to the electromagnetic dipole operator comparable to the present value of Δaμ

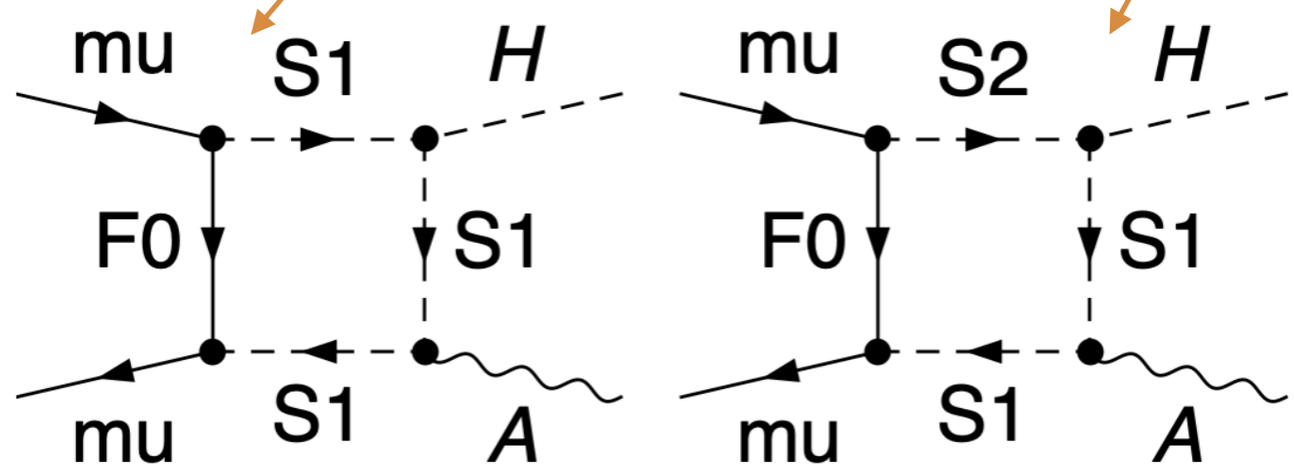
4. EW Scenarios: Indirect signals at a MuC

"Electroweak scenarios"



$$\mathcal{L}_{\rm SSF} \supset -y_1 F^c L_{(\mu)} \Phi_A^* - y_2 F \mu^c \Phi_B - \kappa H \Phi_A^* \Phi_B$$

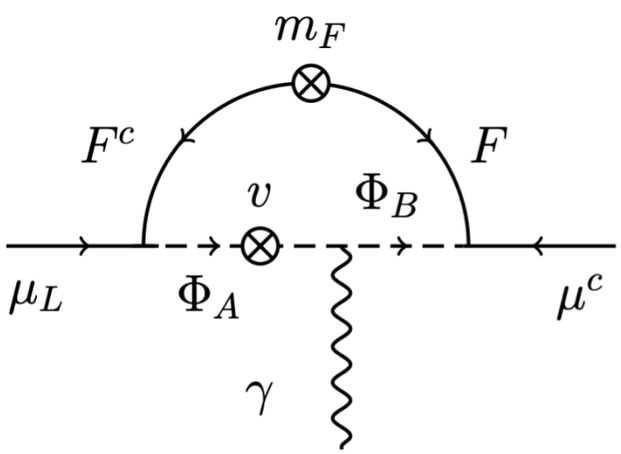
$\mathcal{M} \supset$



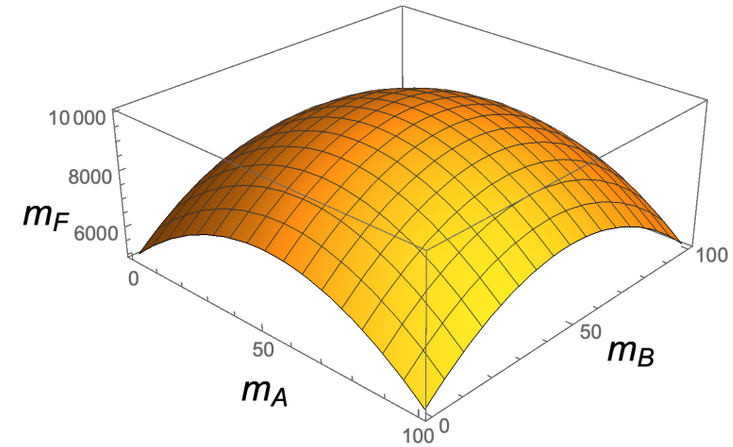
The LR piece maps into the dipole operator!

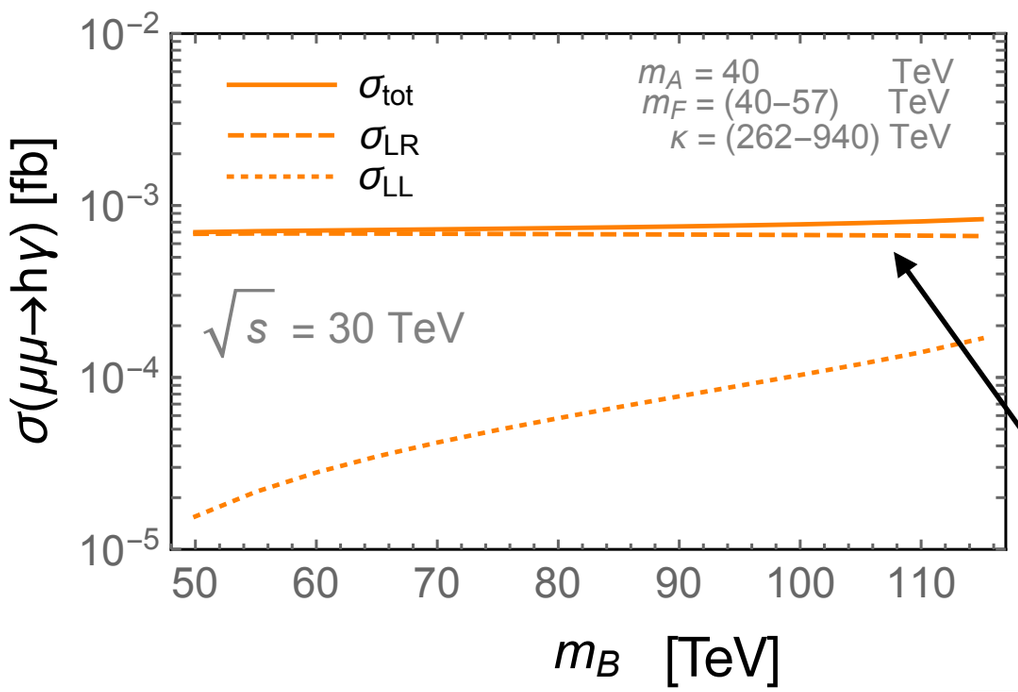
$$\mathcal{M}_{LR} \leftrightarrow \mathcal{O}_{\rm dipole}$$

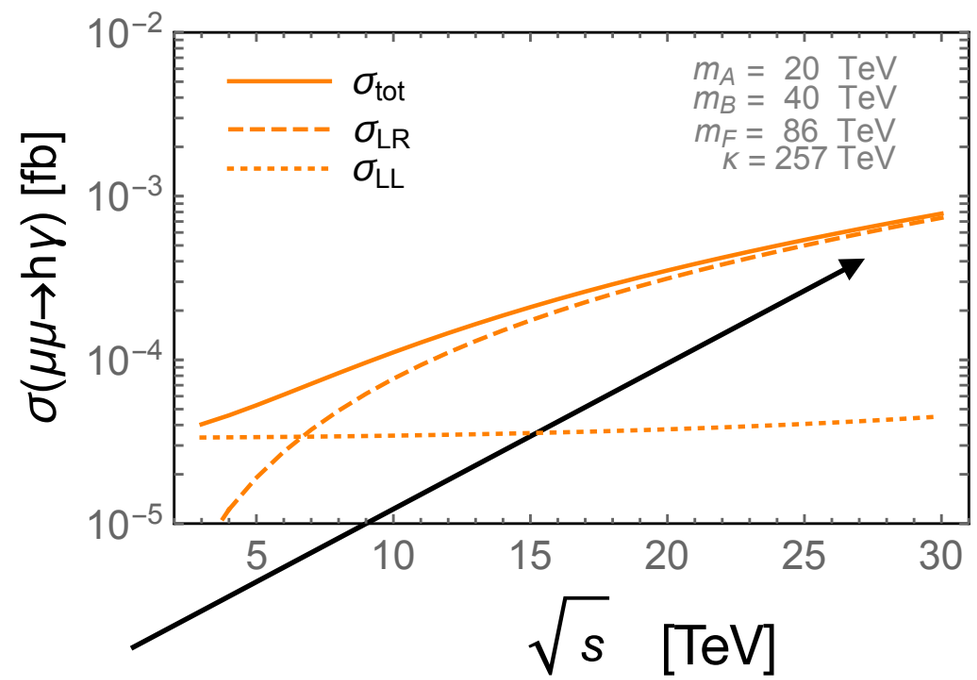
4. EW Scenarios: Indirect signals at a MuC



"Electroweak scenarios"



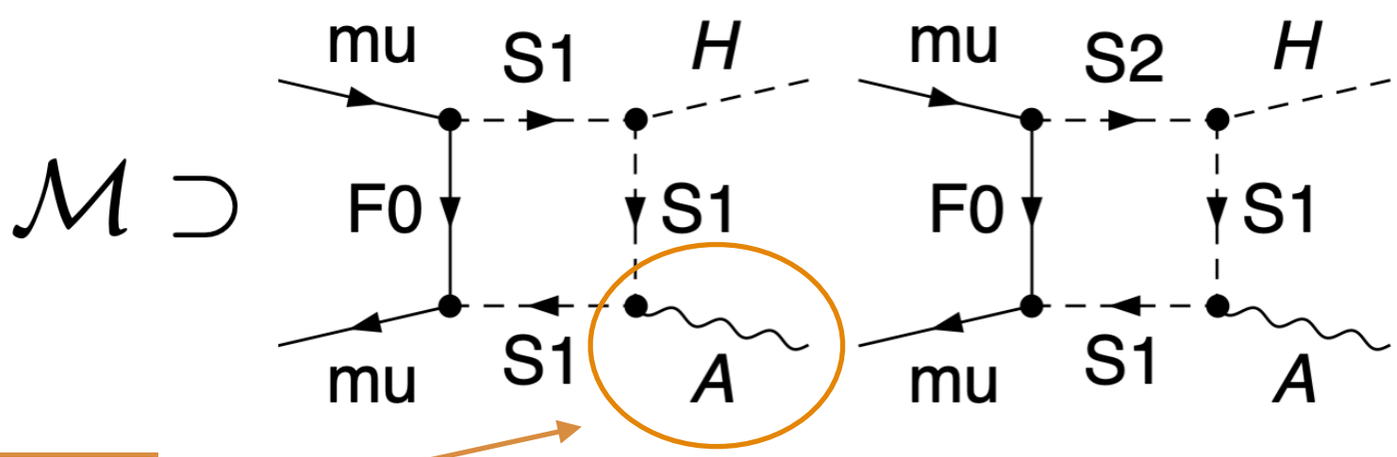




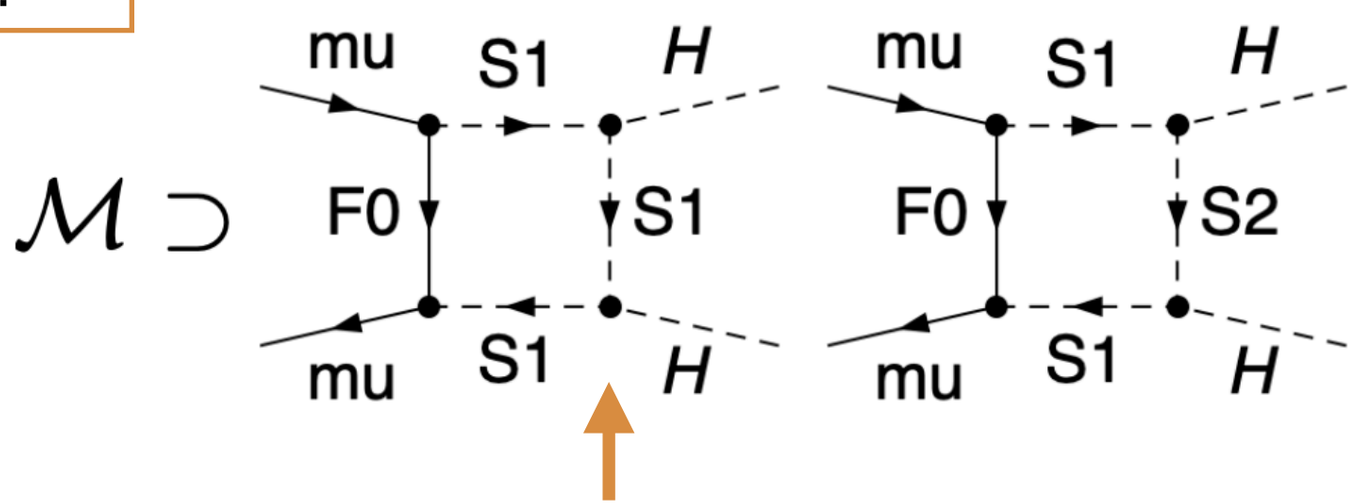
Cross section at
ECOM = 30 TeV
~ 0.7 ab

4. EW Scenarios: Indirect signals at a MuC

"Electroweak scenarios"

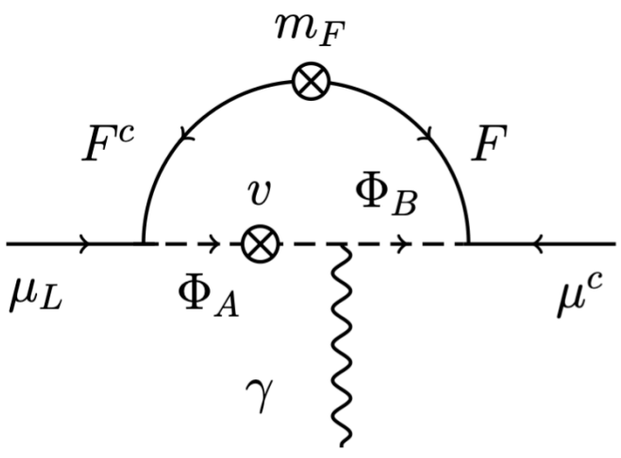


Replace the photon by another Higgs!

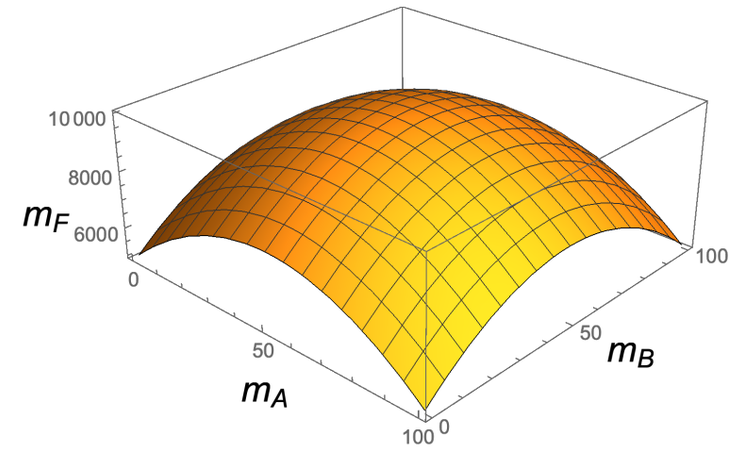


This replaces a factor of alpha by a factor of kappa^2 in the cross section!

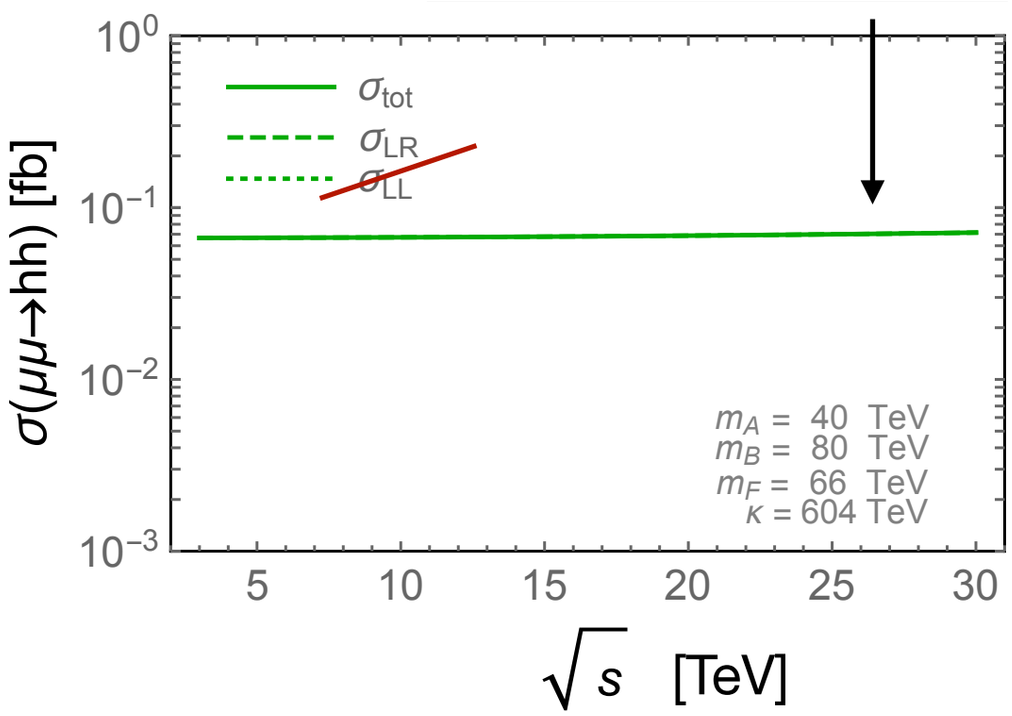
4. EW Scenarios: Indirect signals at a MuC



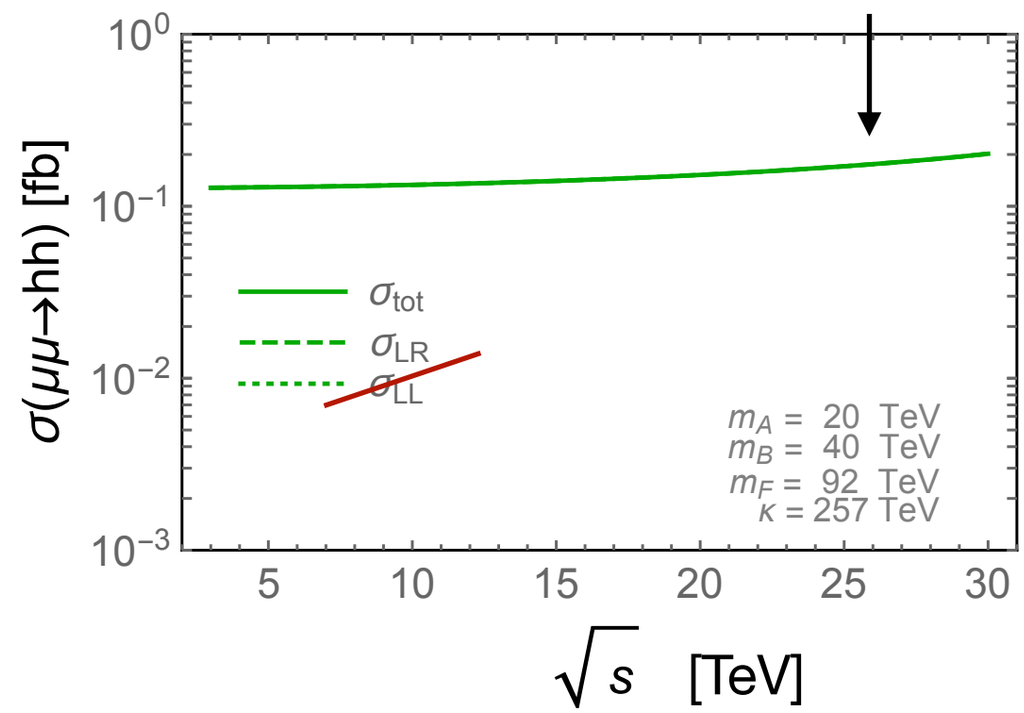
"Electroweak scenarios"



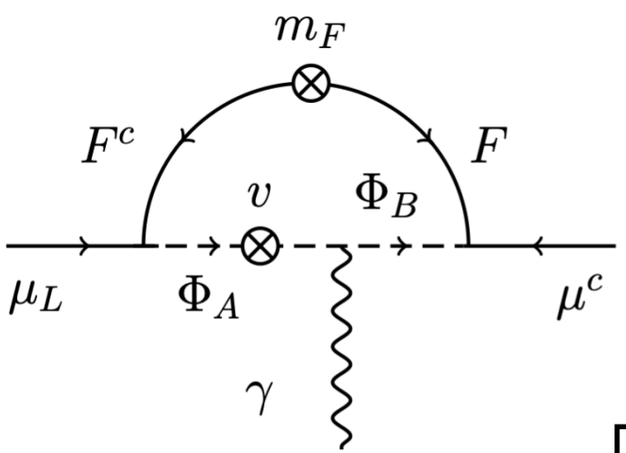
Flat in energy for larger masses



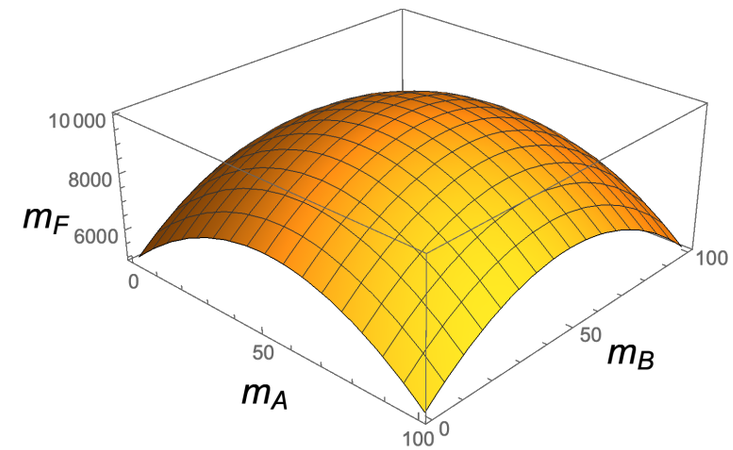
Slightly grows for smaller masses



4. EW Scenarios: Indirect signals at a MuC

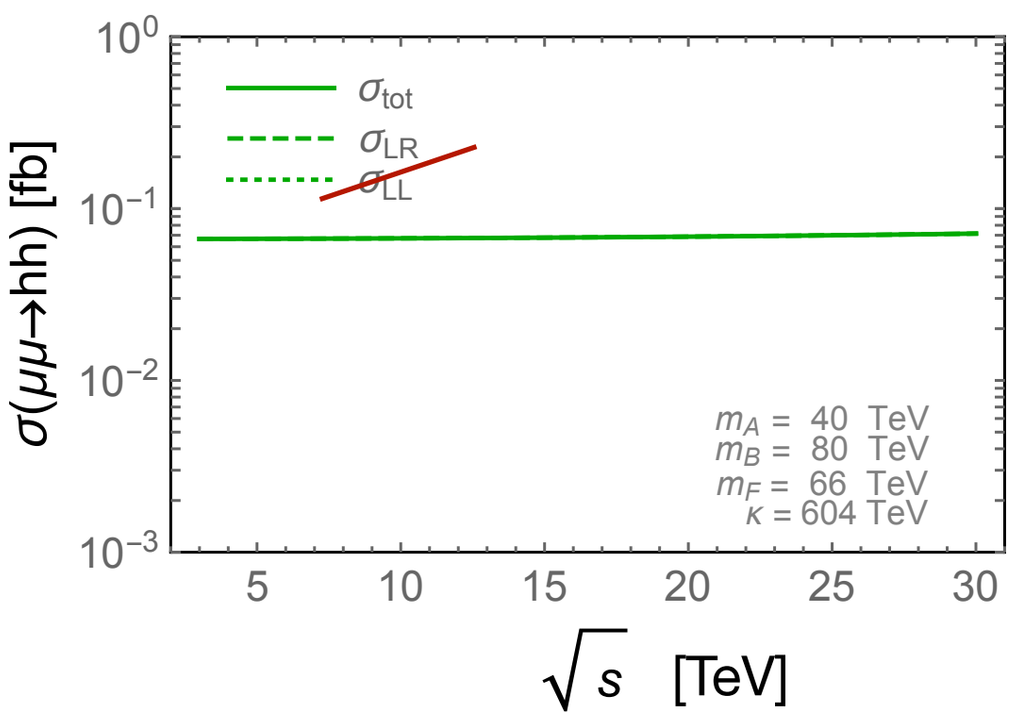


"Electroweak scenarios"



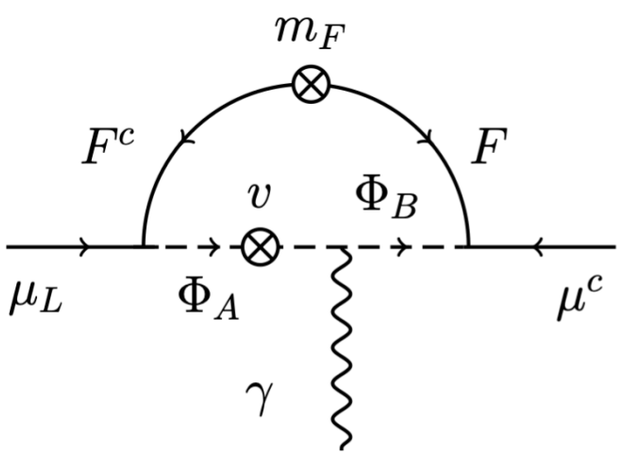
Signal competes with background from VBF processes!

Costantini, DeLillo, Maltoni, Mantani, Mattelaer, Ruizb, Zhaob, arXiv:2005.10289

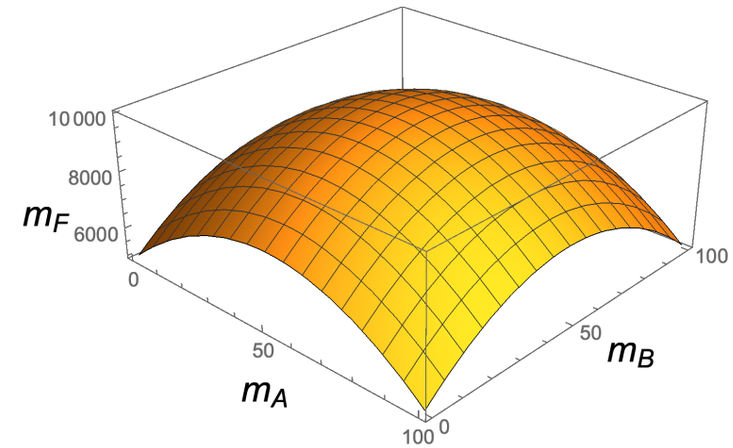


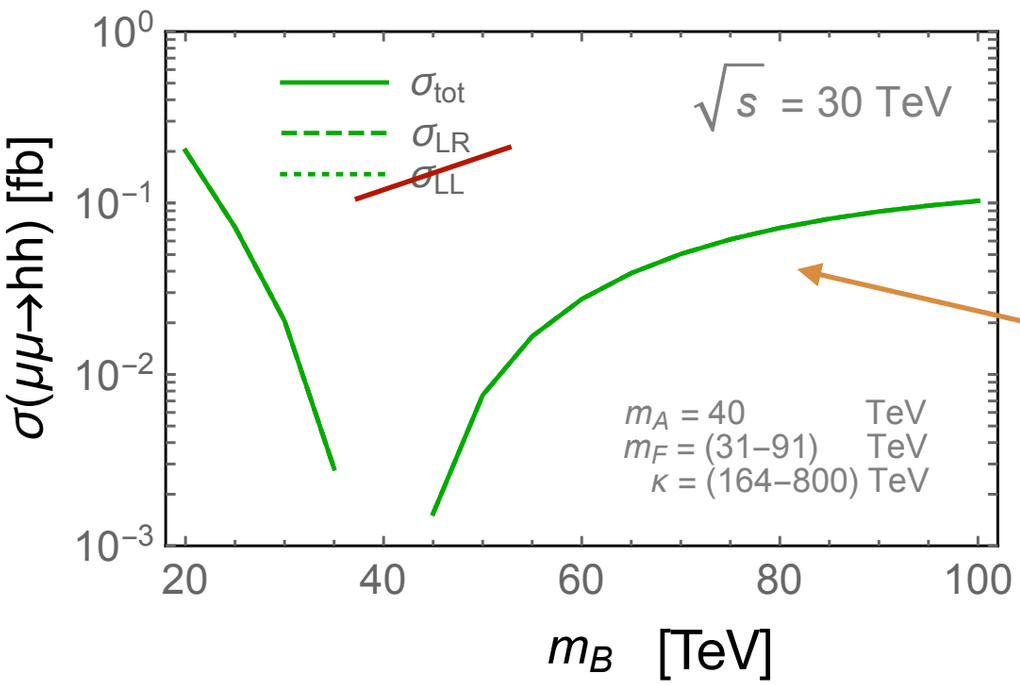
σ [fb]	$\sqrt{s} = 1$ TeV	$\sqrt{s} = 3$ TeV
$t\bar{t}$	$1.0 \cdot 10^{-1}$	$1.1 \cdot 10^{0}$
$t\bar{t}Z$	$1.2 \cdot 10^{-4}$	$6.7 \cdot 10^{-3}$
$t\bar{t}H$	$5.3 \cdot 10^{-5}$	$2.8 \cdot 10^{-3}$
H	$1.5 \cdot 10^{1}$	$3.8 \cdot 10^{1}$
HH	$5.0 \cdot 10^{-3}$	$7.3 \cdot 10^{-2}$
HHH	$3.6 \cdot 10^{-7}$	$3.1 \cdot 10^{-5}$
HWW	$3.5 \cdot 10^{-3}$	$1.4 \cdot 10^{-1}$
HZZ	$2.5 \cdot 10^{-5}$	$4.9 \cdot 10^{-4}$
WW	$2.2 \cdot 10^{1}$	$1.4 \cdot 10^{2}$
ZZ	$1.2 \cdot 10^{-1}$	$4.0 \cdot 10^{-1}$

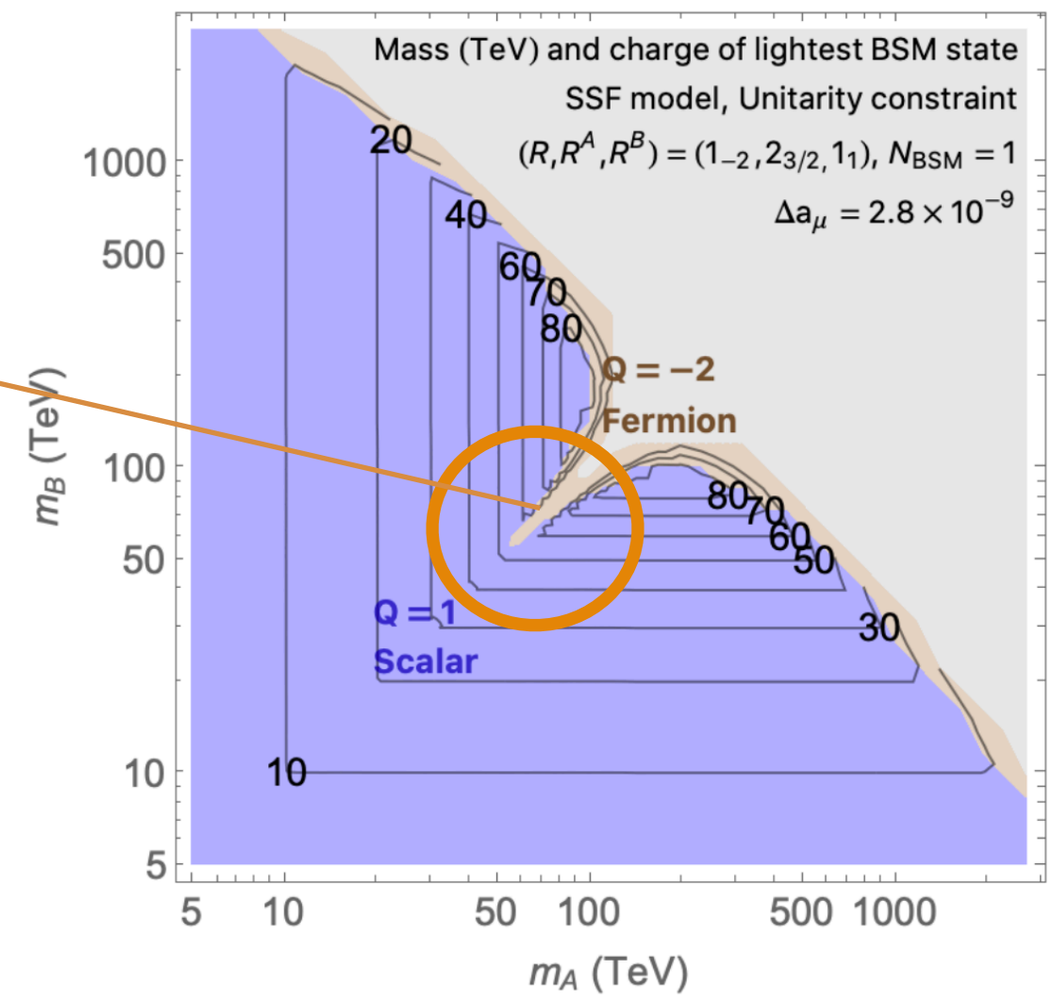
4. EW Scenarios: Indirect signals at a MuC



"Electroweak scenarios"



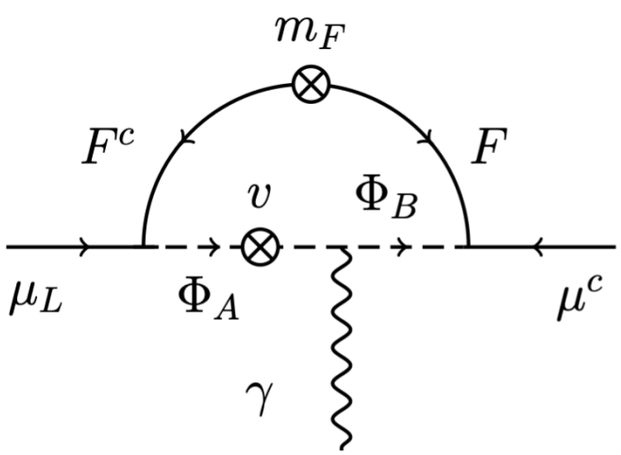




Small complication!

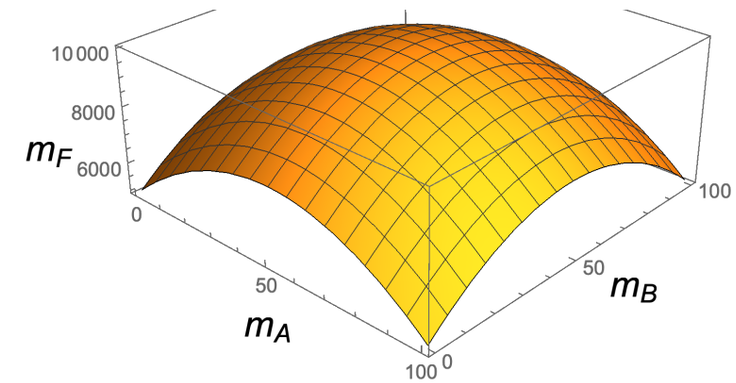
kappa is small
at the dip

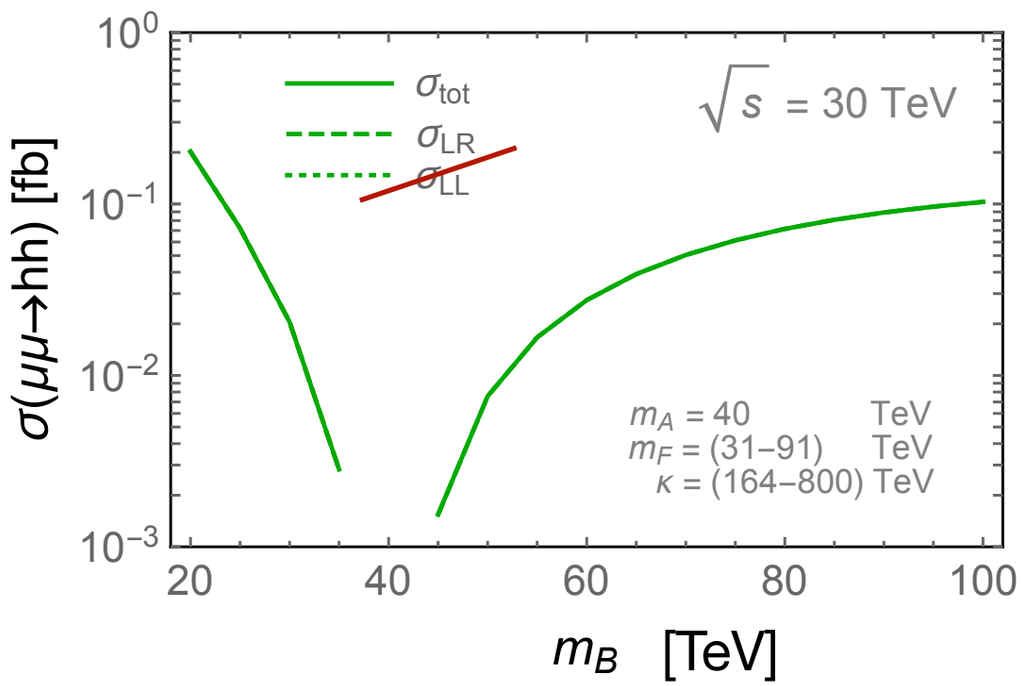
4. EW Scenarios: Indirect signals at a MuC

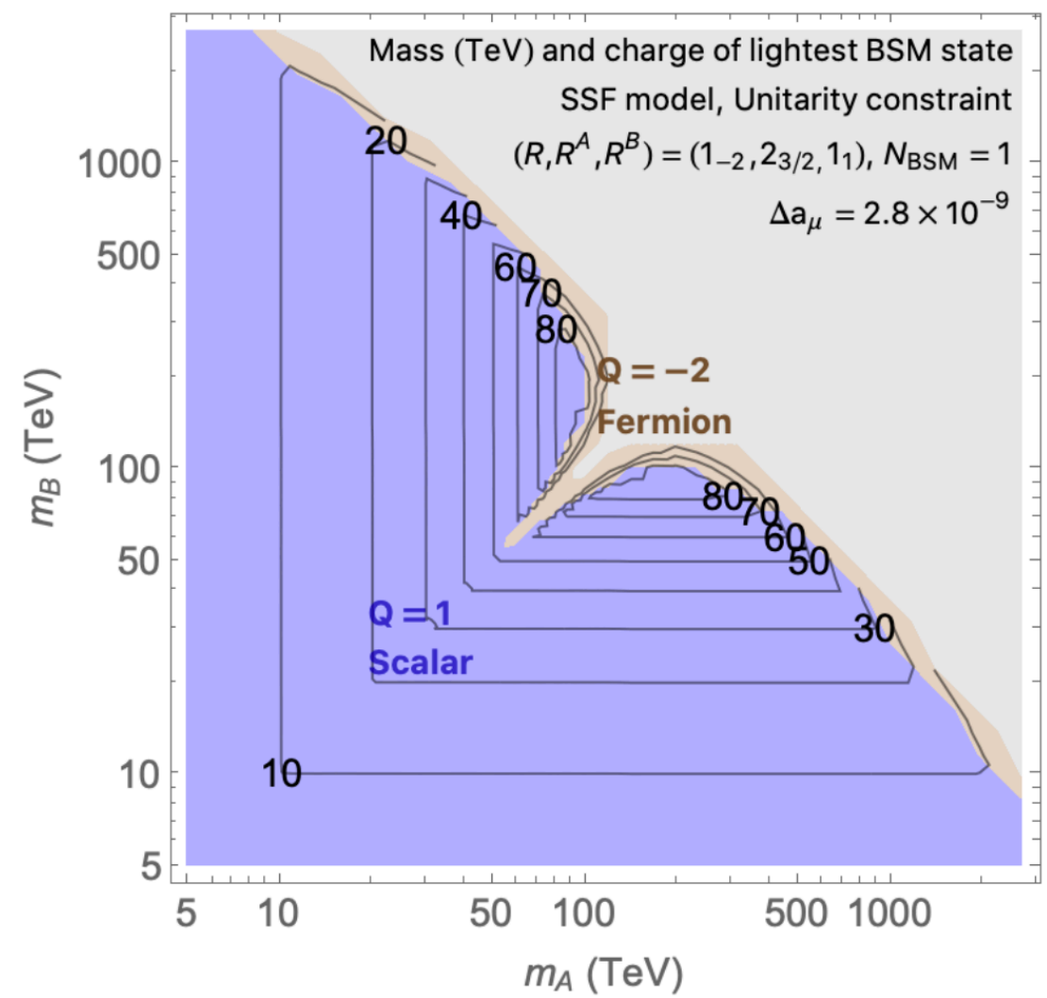


"Electroweak scenarios"

Max-mass surface







Reducing the couplings reduces the max-mass surface. How small the masses mA, mB, mF should be in order to suppress the HH signal?

Can a 30 TeV muon collider produce both indirect and direct signals from the BSM physics of (g-2)μ?

Rodolfo Capdevilla, Perimeter Institute and University of Toronto

Outline

1. Muon Anomalous Magnetic Moment
2. BSM Physics of (g-2)μ at Muon Colliders (MuC)
3. Singlet Scenarios: Hadron colliders + EW Precision
4. Electroweak Scenarios: Indirect signals at a MuC
5. **Summary**

Summary

1. Measurements of the anomalous magnetic moment of fundamental particles are important laboratories for high precision tests of the SM. The **most perverse** BSM scenarios point at a scale of **M ~100 TeV**.

2. A muon collider is in a privileged position: It collides the particles of the anomaly and it can reach high COM energies. A **30 TeV muon collider** is guaranteed to detect deviations in H+gamma from the BSM physics of (g-2)μ.

3. A combination of **hadron colliders** and **precision EW measurements** can probe the parameter space for (g-2)μ in the context of **Singlet Scenarios**. Alternatively, a 3 TeV muon collider can also probe this parameter space.

4. A 10 TeV muon collider can probe the **max-mass surface** in the parameter space of the Electroweak Scenarios via HH production. (*Is a 30 TeV muon collider guaranteed to produce both indirect and direct signals from the BSM physics of (g-2)μ?*)

Thanks!