

# *A Guaranteed Discovery at Future Muon Colliders*

PITT PACC Workshop: Muon collider physics

University of Pittsburgh

02/Dec/2020

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Perimeter Institute for Theoretical Physics,  
and University of Toronto

**RC, David Curtin, Yonatan Kahn, Gordan Krnjaic, arXiv:2006.16277, arXiv:2012.xxxx**

# *Summary*

1. Muon g-2 anomaly: **If confirmed, what does that mean?**
2. A muon collider is in unique position: It collides the particles of the anomaly!
3. We analyze the *space of models* that can solve the g-2 anomaly, and we identify the **nightmare scenarios** i.e. models that maximize the BSM mass scale    If a muon collider can find these, you can find any scenario!
4. **This tells us what kind of collider do we need to guarantee a discovery!**
5. We found models with new singlets and models with new EW states.
6. A  $\sim$  TeV muon collider can probe all *singlet models* and a  $\sim$  10 TeV muon collider can probe the *EW models*.

# *Outline*

1. Muon Anomalous Magnetic Moment

2. Nightmare Scenarios

- Singlet Models
- Electroweak Models

3. Muon Collider

# *Outline*

## **1. Muon Anomalous Magnetic Moment**

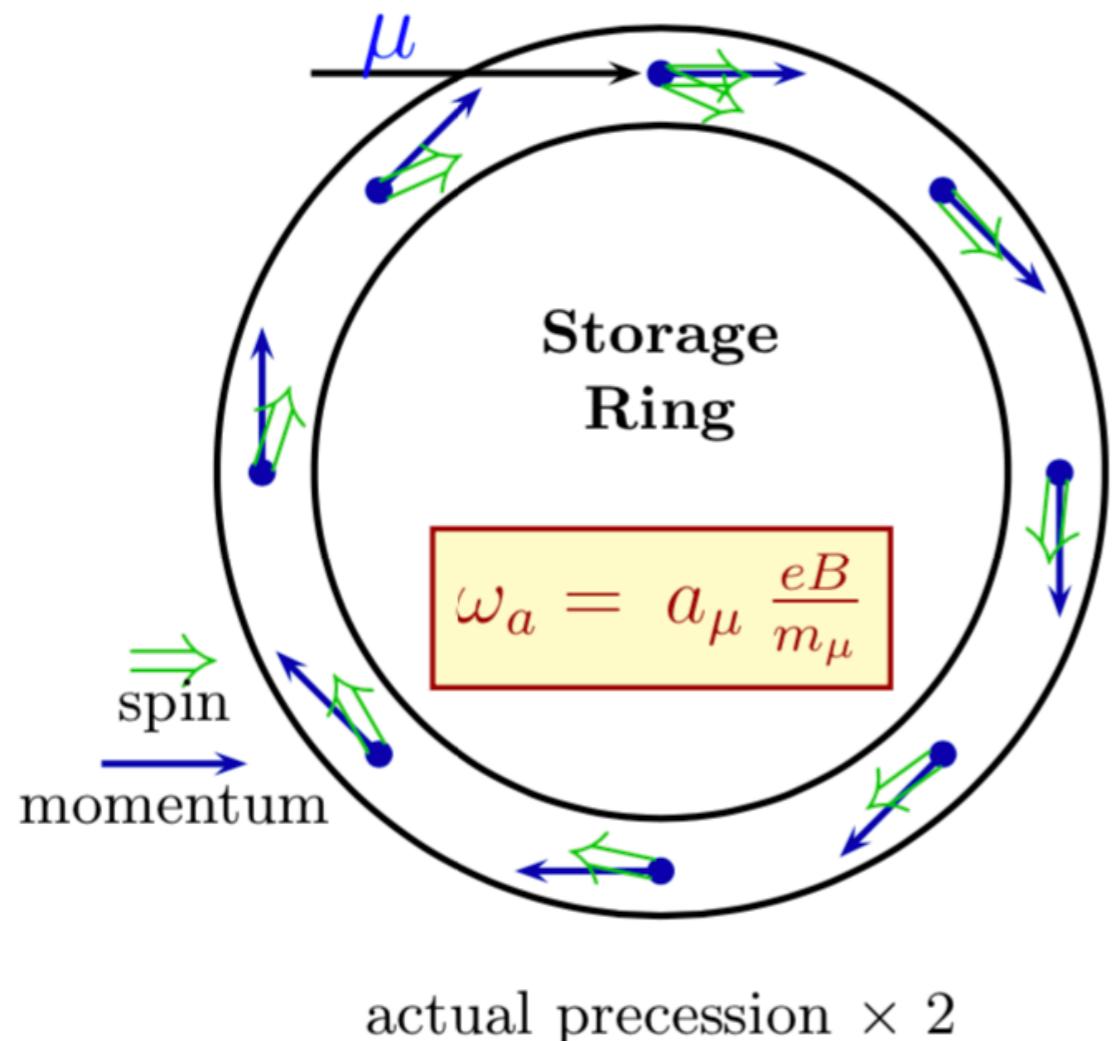
## 2. Nightmare Scenarios

- Singlet Models
- Electroweak Models

## 3. Muon Collider

# 1. Muon $g-2$

## Experiment

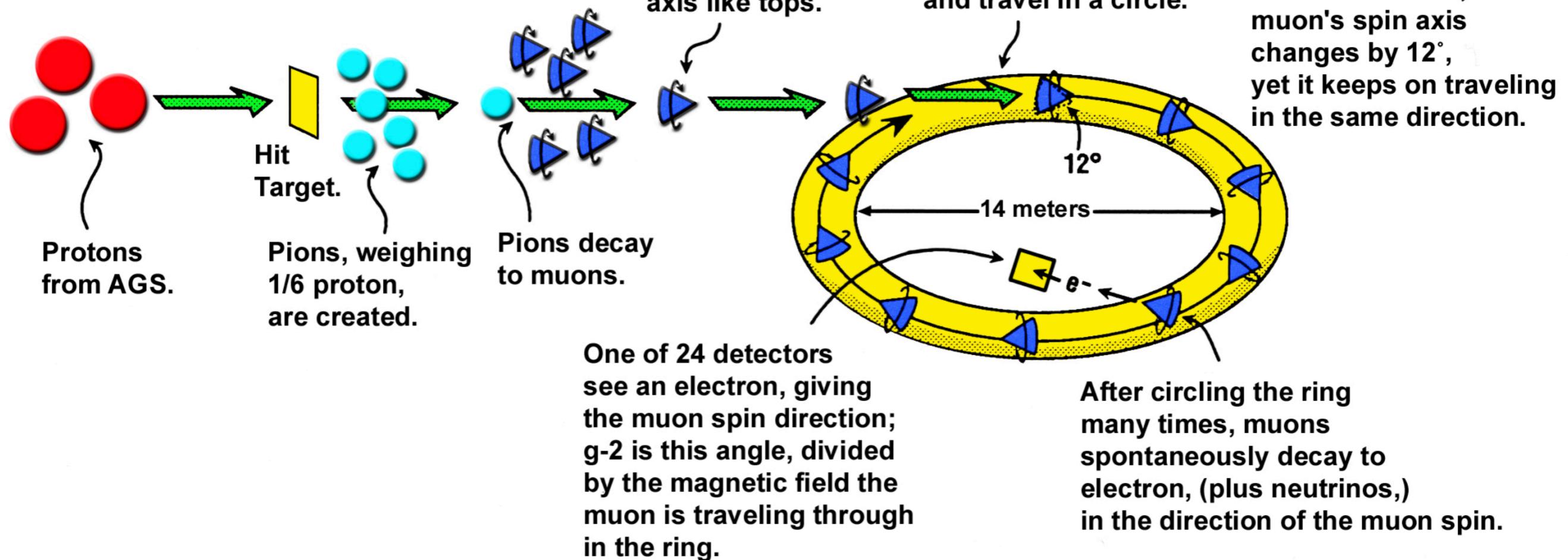


$$\vec{\omega}_a = \frac{e}{m_\mu} \left( a_\mu \vec{B} - \left[ a_\mu - \frac{1}{\gamma^2 - 1} \right] \vec{v} \times \vec{E} \right)$$

spin precession frequency

# 1. Muon $g-2$

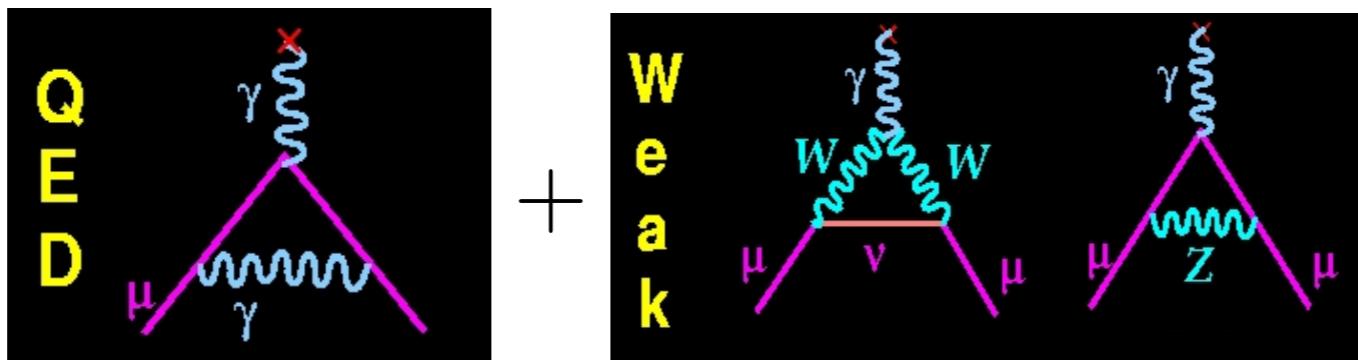
## LIFE OF A MUON: THE $g-2$ EXPERIMENT



# 1. Muon $g-2$

## Theory

Perturbative



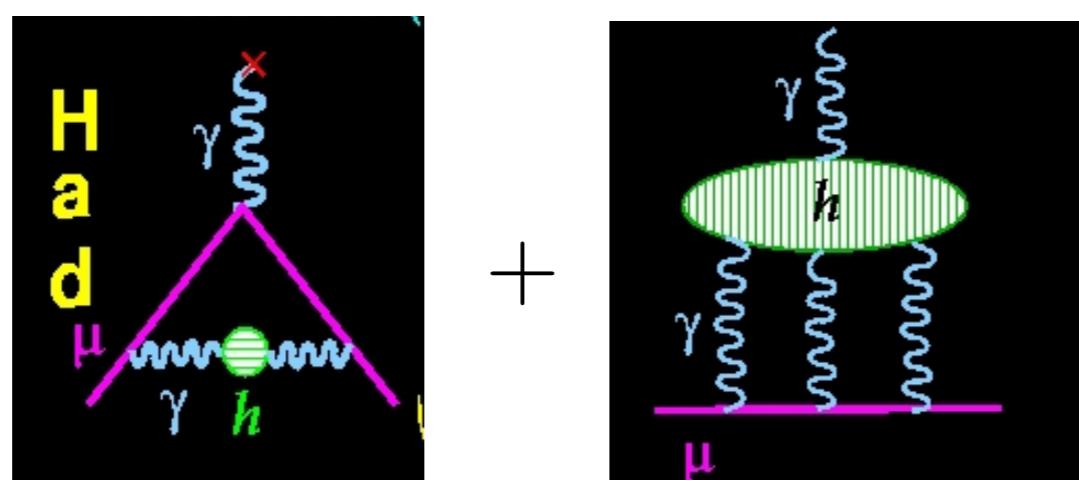
Aoyama et al, Phys.Rev.Lett. 109 (2012) 111808  
Aoyama et al, Phys.Rev. D85 (2012) 033007

M. Tanabashi et al. (Particle Data Group),  
Phys. Rev. D 98, 030001 (2019)

$$a_{\mu}^{\text{QED}} = 116\,584\,718.92(0.03) \times 10^{-11}$$

$$a_{\mu}^{\text{EW}} = 153.6(1.0) \times 10^{-11}$$

Non-perturbative



Davier et al., Eur.Phys.J. C71(2011) 1515  
Aoyama et al, Phys.Rev. D85 (2012) 093013  
HP QCD collaboration, PoS LATTICE2016 (2016) 377  
RBC & UKQCD collaboration, EPJ Web Conf. 175 (2018) 01024

# 1. Muon $g-2$

Theory



From data

$$a_\mu^{\text{Had}}[\text{LO}] = \frac{1}{3} \left( \frac{\alpha}{\pi} \right)^2 \int_{m_\pi^2}^\infty ds \frac{K(s)}{s} R^{(0)}(s)$$

M. Tanabashi et al. (Particle Data Group),  
Phys. Rev. D 98, 030001 (2018) and 2019 update

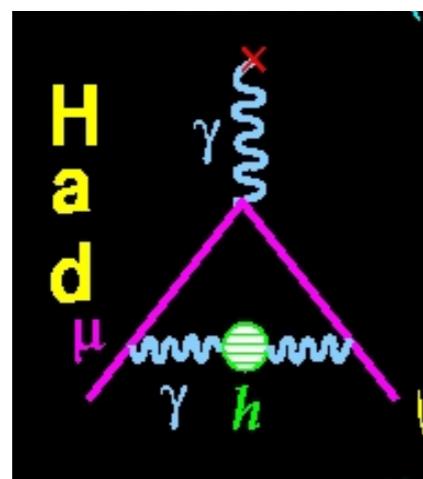
$$a_\mu^{\text{Had}}[\text{LO}] = 6939(39)(7) \times 10^{-11}$$

$$a_\mu^{\text{Had}}[\text{N(N)LO}] = 19(26) \times 10^{-11}$$

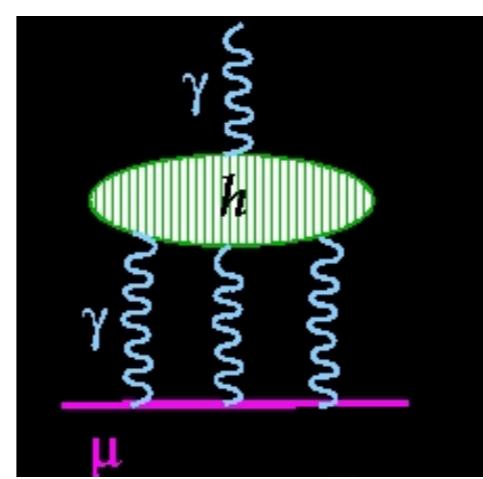
$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 261(63)(48) \times 10^{-11}$$

$\sim 3.3 \sigma$

Non-perturbative



+



Davier et al., Eur.Phys.J. C71(2011) 1515

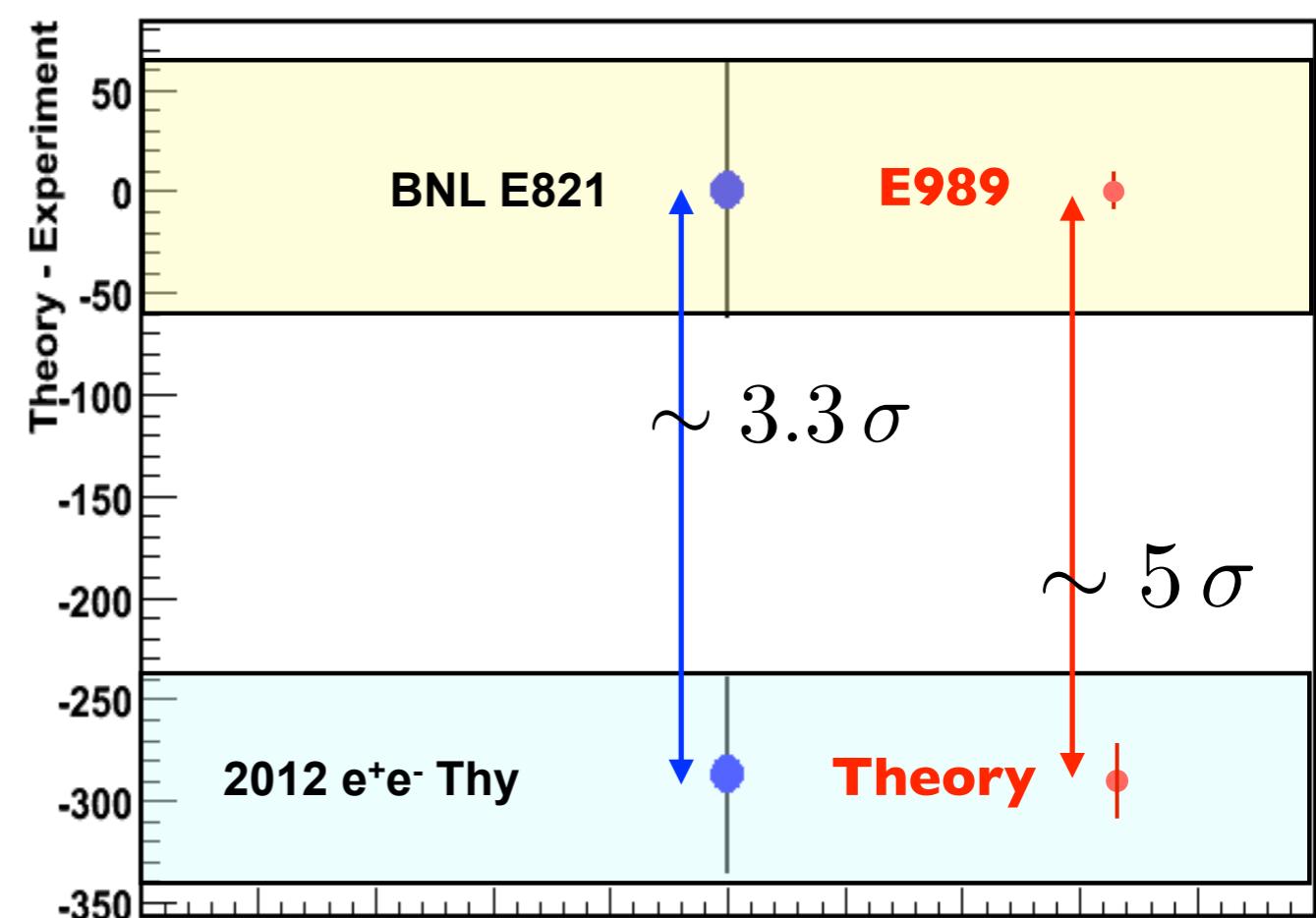
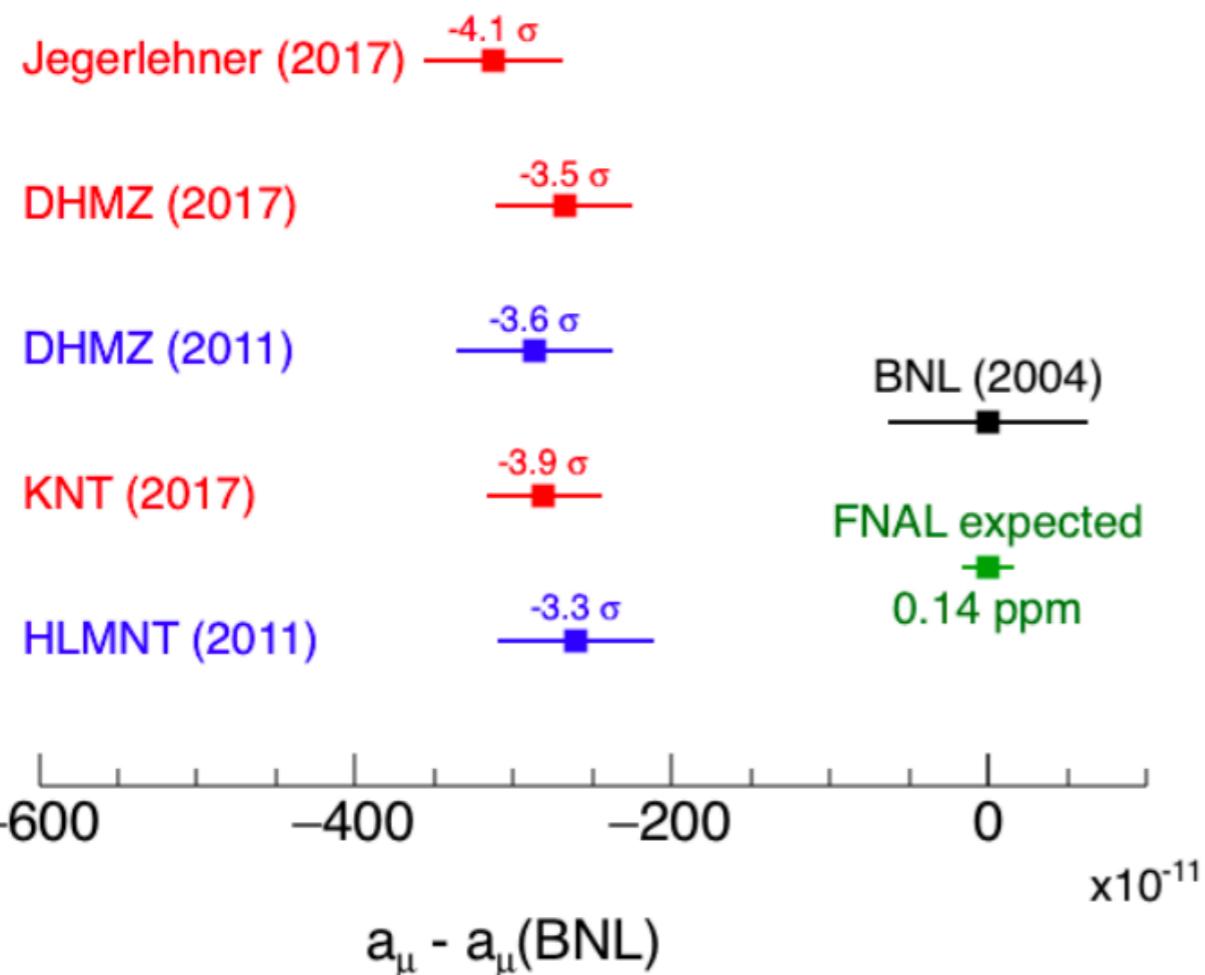
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# 1. Muon $g-2$

## Comparison of SM & BNL Measurement



# *Outline*

1. Muon Anomalous Magnetic Moment

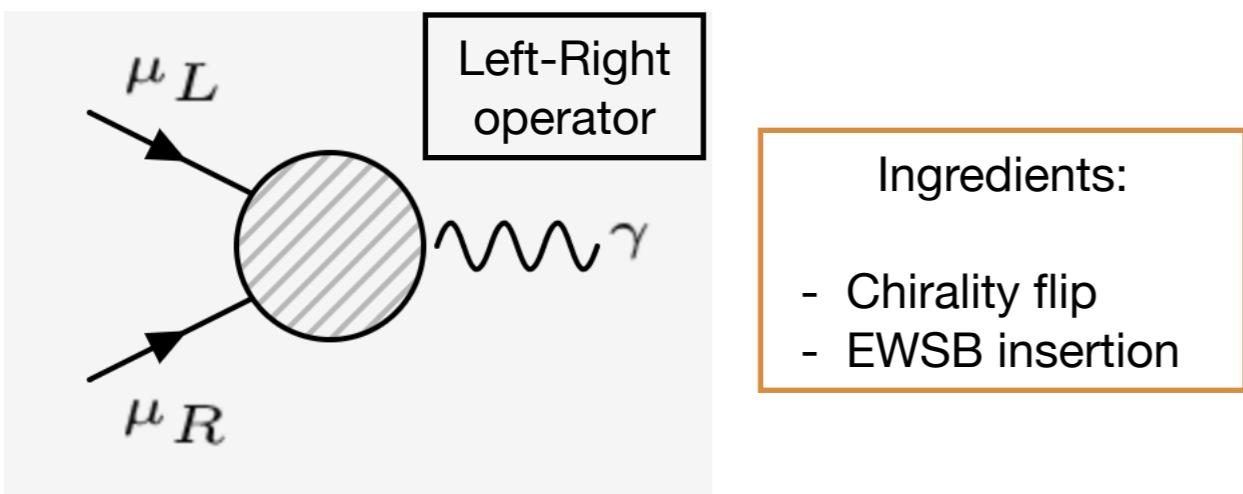
## **2. Nightmare Models for g-2**

- Singlet Models
- Electroweak Models

3. Muon Collider

## 2. Nightmare Scenarios

### Theory

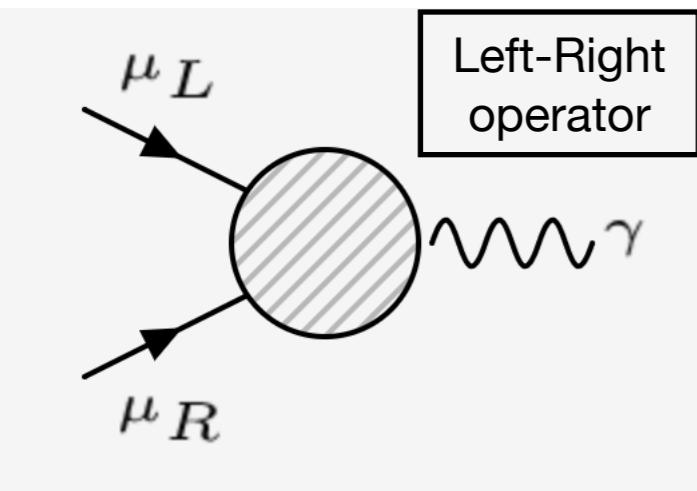


$$\mathcal{L} = \frac{em_\mu C_\mu}{8\pi^2 \Lambda^2} (\bar{\mu}_R \sigma_{\alpha\beta} \mu_L) F^{\alpha\beta} + \text{h.c.}$$

$$\Delta a_\mu = \frac{1}{2\pi^2} \frac{m_\mu^2}{\Lambda^2} \text{Re}(C_\mu)$$

## 2. Nightmare Scenarios

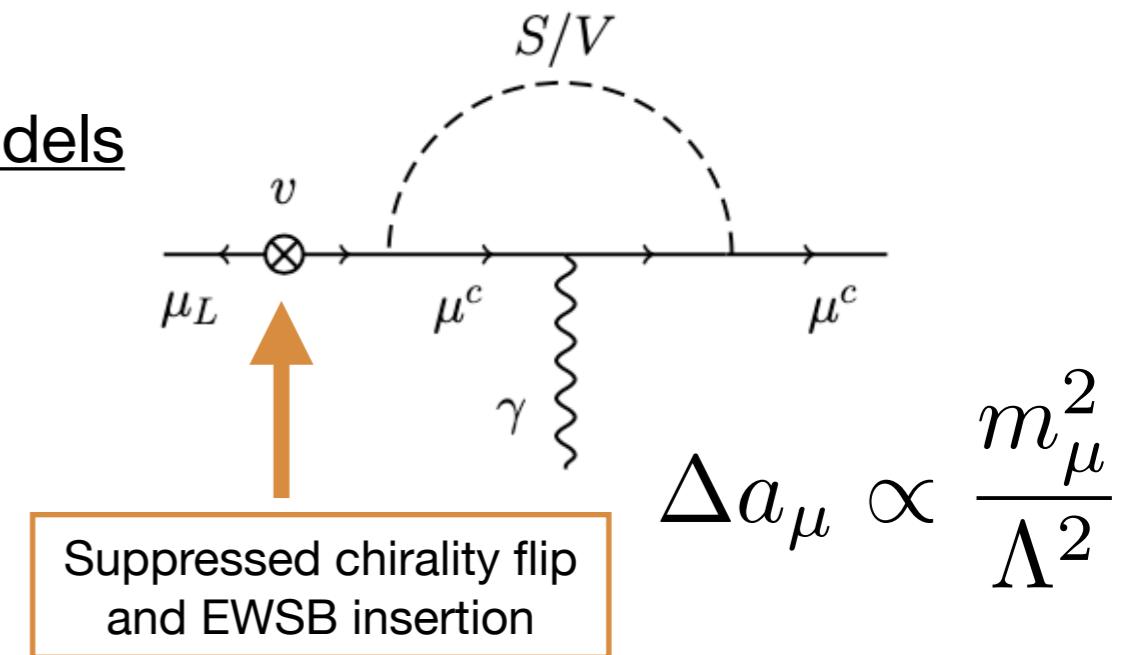
### Theory



Ingredients:

- Chirality flip
- EWSB insertion

- Singlet Models

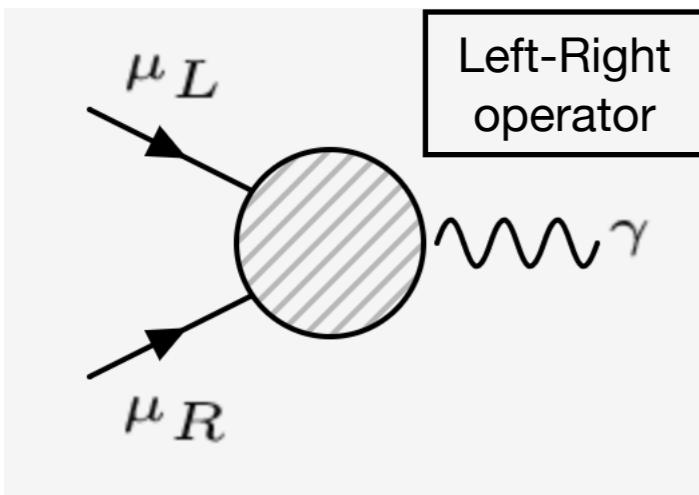


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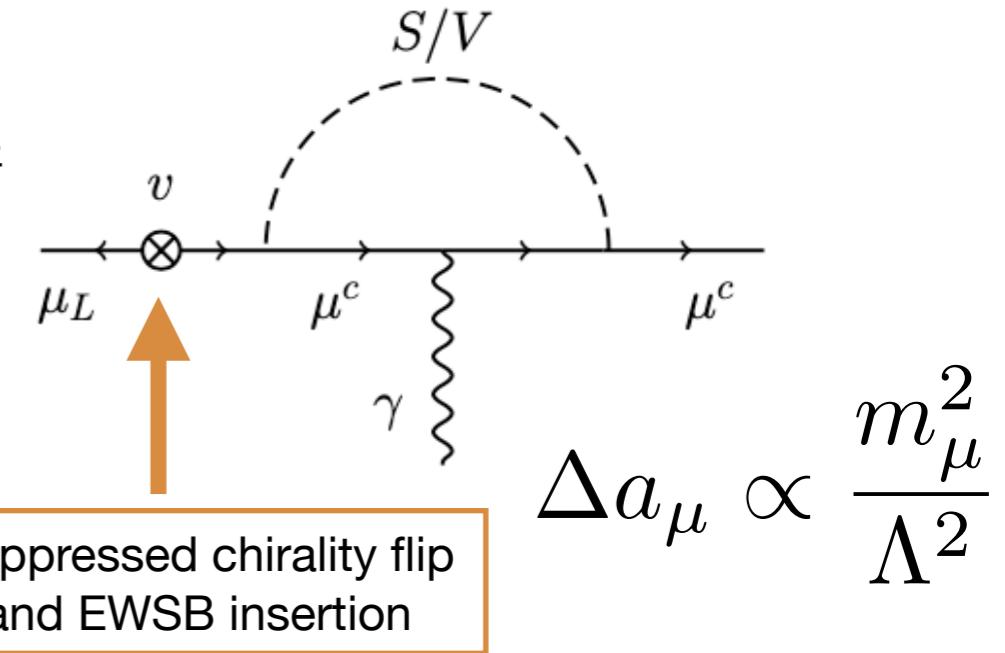
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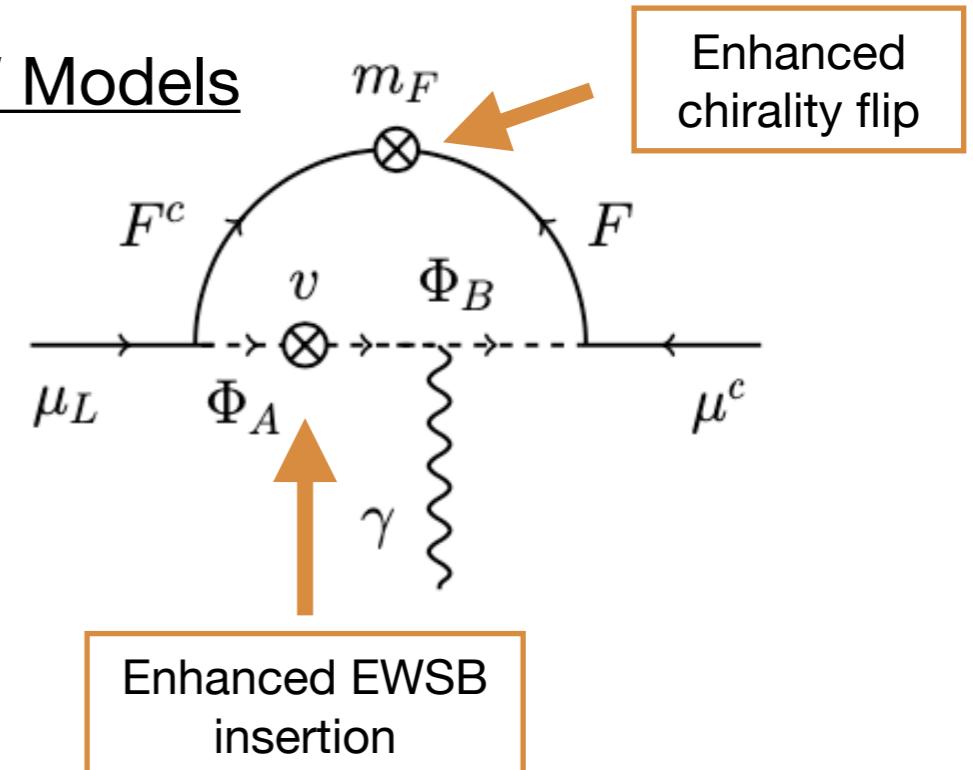


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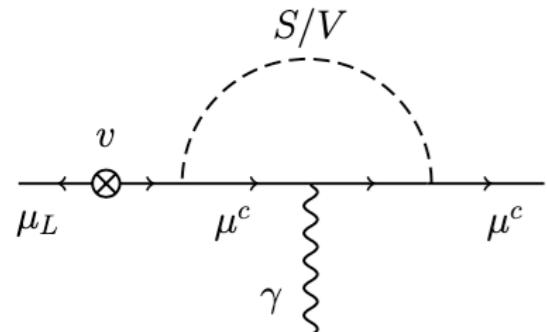
$$\Delta a_\mu = \frac{1}{2\pi^2} \frac{m_\mu^2}{\Lambda^2} \text{Re}(C_\mu)$$

- High-Scale EW Models

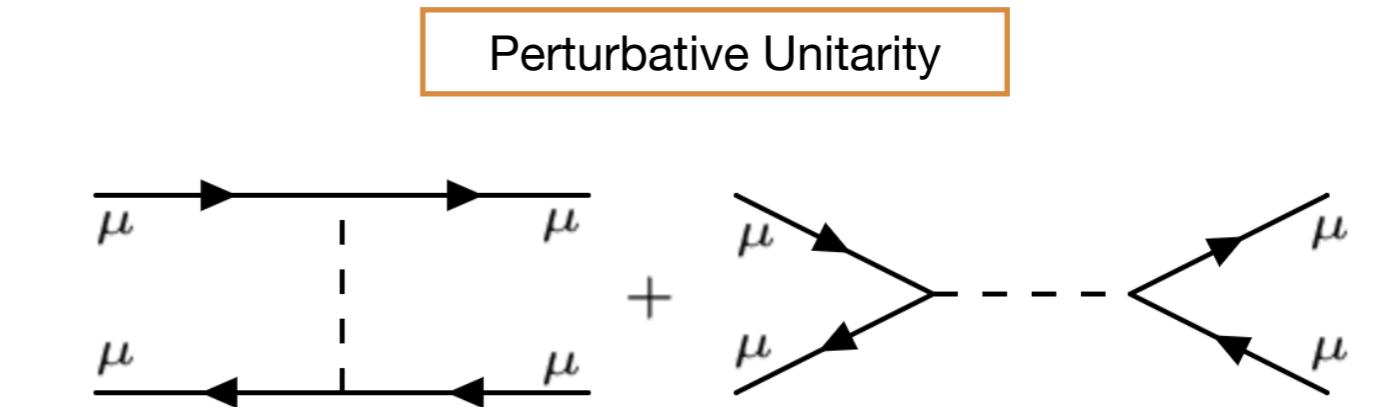
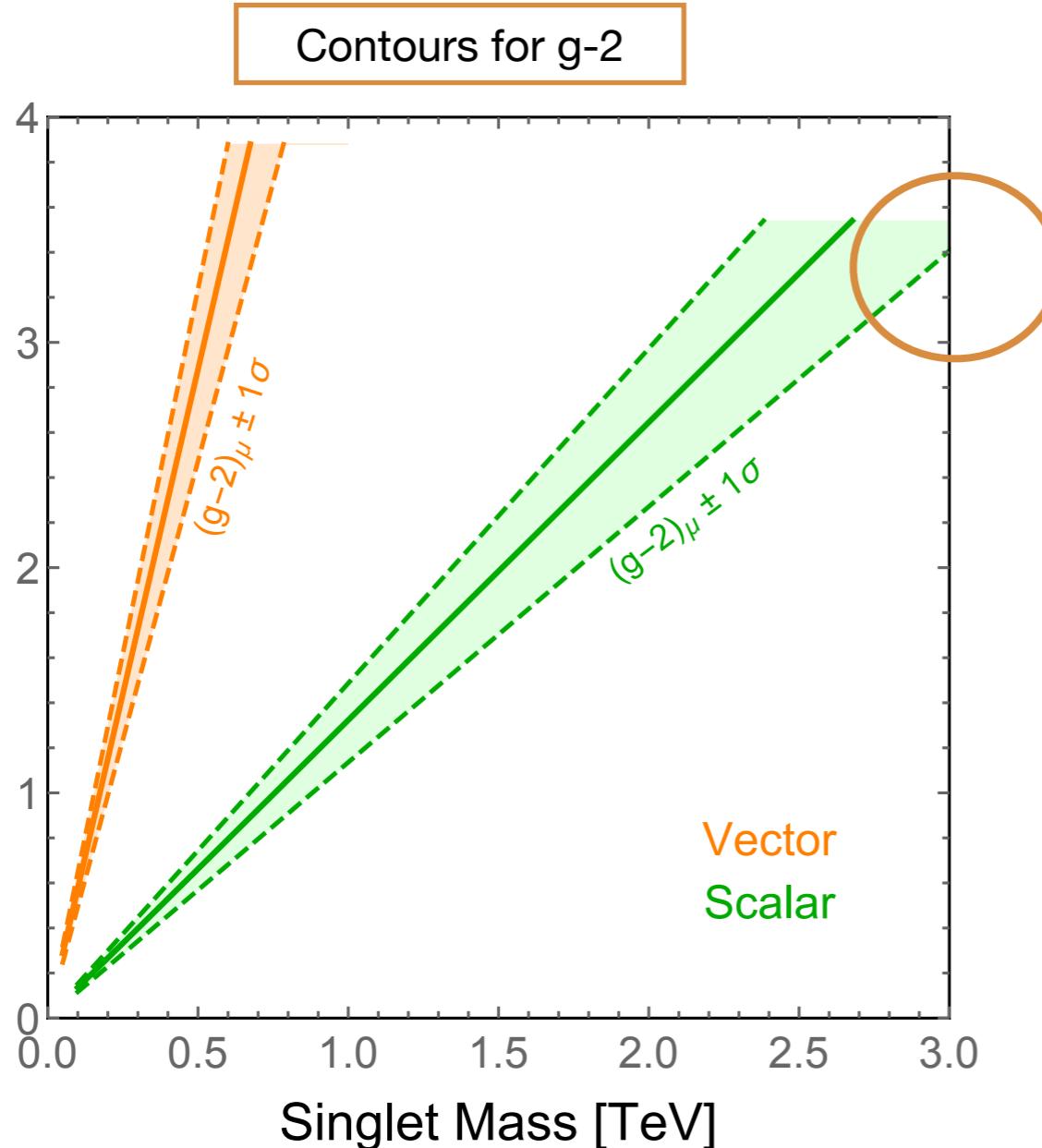
$$\Delta a_\mu \propto \frac{m_\mu m_F}{\Lambda^2}$$



## 2. Nightmare Scenarios: Singlet Models



$$a_\mu = \frac{y^2}{4\pi^2} \frac{m_\mu^2}{M^2} C_{\text{loop}}$$



$$\mathcal{M}_{if}(\theta) = 8\pi \sum_{j'} (2j' + 1) T_{if}^{j'} d_{\lambda_f \lambda_i}^{j'}(\theta)$$

$$\beta_i \beta_f |T_{if}^j|^2 \leq 1$$

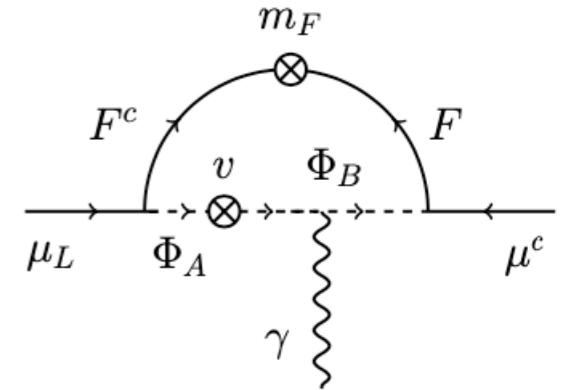
$$\frac{y_S^2}{8\pi} \leq \frac{1}{2}$$

Scalar

$$\frac{5g_V^2}{48\pi} \leq \frac{1}{2}$$

Vector

## 2. Nightmare Scenarios: Electroweak Models



$$\mathcal{L} \supset -\bar{F}(aP_L + bP_R)eS^* + h.c.$$

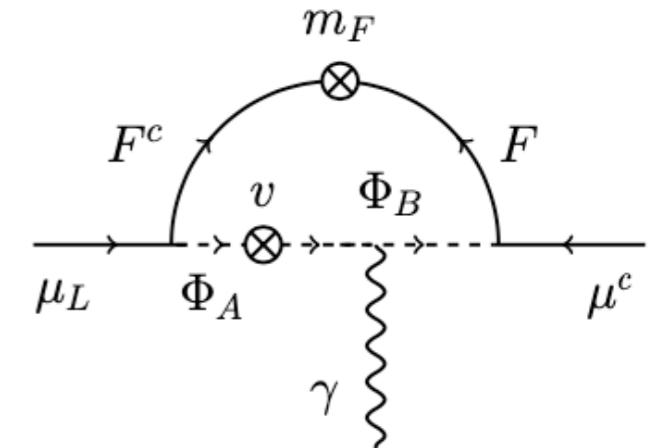
$$\Delta a_\mu = -\frac{m_\mu m_F}{8\pi^2 m_S^2} \left\{ Q_F \left[ \text{Re}(a^*b) I_F(\epsilon, x) + (|a|^2 + |b|^2) \frac{m_\mu}{m_F} \tilde{I}_F(\epsilon, x) \right] - Q_S \left[ \text{Re}(a^*b) I_S(\epsilon, x) + (|a|^2 + |b|^2) \frac{m_\mu}{m_F} \tilde{I}_S(\epsilon, x) \right] \right\}$$

Perturbative Unitarity

$$\frac{|a_1|^2 + |a_2|^2}{32\pi} \leq \frac{1}{2} \quad \quad \quad \frac{|b_1|^2 + |b_2|^2}{32\pi} \leq \frac{1}{2}$$

$$|\text{Re}(a_0)| \leq \frac{1}{2} \quad \quad \quad a_0 = -\frac{1}{32\pi} \left\{ A_{eff} \sqrt{1 - \frac{4m_1^2}{s}} + B_{eff} \log \left[ \frac{m_h^2}{m_h^2 + (s - 4m_1^2)} \right] \right\}$$

## 2. Nightmare Scenarios: Electroweak Models

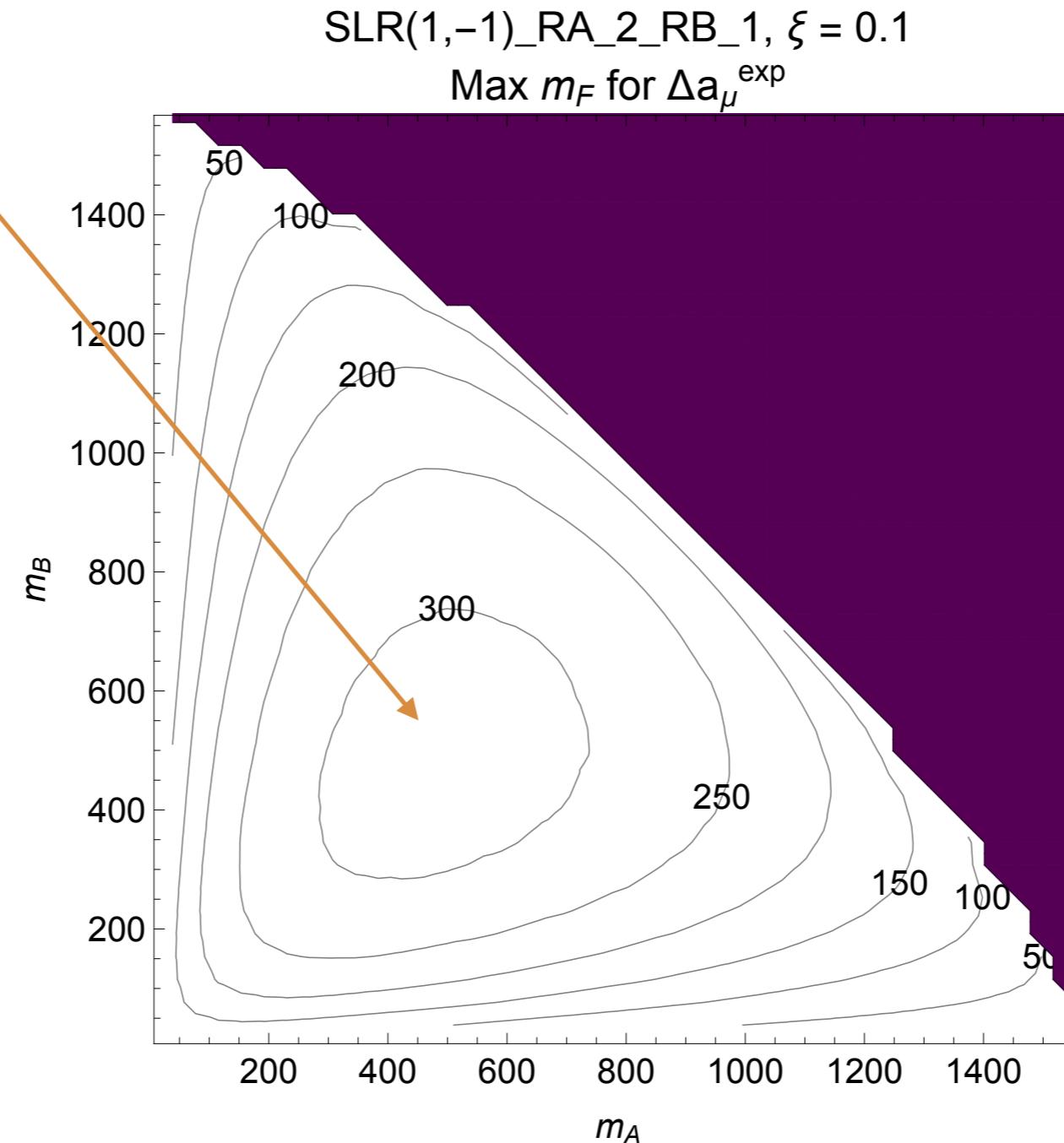


If only perturbative unitarity

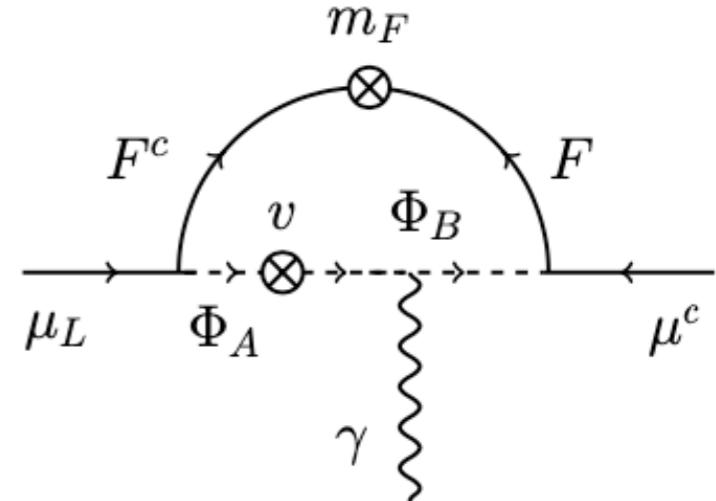
Heaviest states at  
~ 100 TeV

Heaviest states from  
nightmare scenario!

Maximal couplings at the  
perturbativity limit



## 2. Nightmare Scenarios: Electroweak Models



Consider extra ingredients:

- Couplings  $\mathcal{O}(1)$



$$M_{BSM} \sim 30 \text{ TeV}$$

- Minimal Flavor Violation

$$(y_1)_i \ell_L^i F^c \Phi_A^* + (y_2)_i \ell_i^c F \Phi_B$$

$$\frac{(y_{1,2})_\tau}{(y_{1,2})_\mu} \sim \frac{(y_{SM})_\tau}{(y_{SM})_\mu}$$

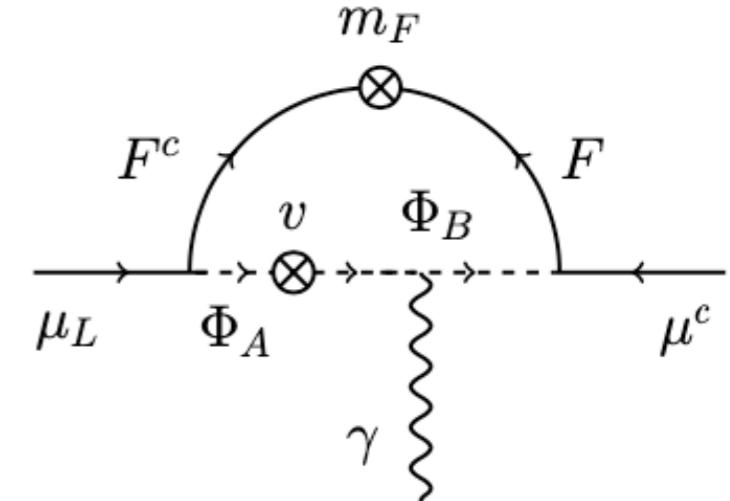


$$M_{BSM} < 10 \text{ TeV}$$

- Fine tuning in both, Higgs and muon mass!

## 2. Nightmare Scenarios: Electroweak Models

Consider extra ingredients:



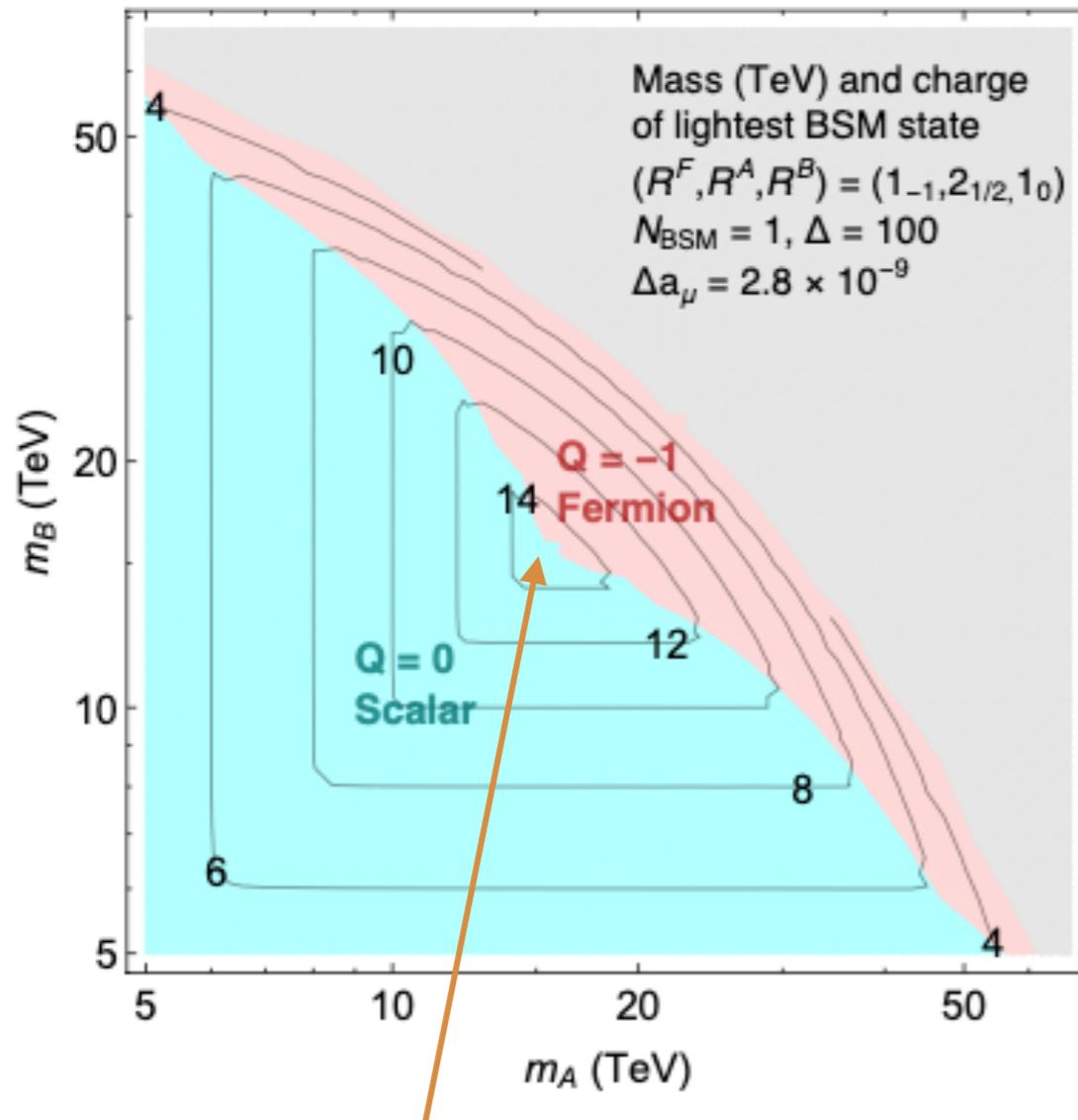
$$H - \text{---} \begin{array}{c} \nearrow \Phi_B \\ \searrow \Phi_A \end{array} \text{---} H \rightarrow \Delta\mu_H^2 \sim \frac{\kappa^2}{16\pi^2} C'_{\text{loop}}$$

$$H - \text{---} \begin{array}{c} \nearrow \Phi_B \\ \searrow \Phi_A \end{array} \text{---} \begin{array}{l} \mu^c \\ \oplus \\ \mu_L \end{array} \rightarrow \Delta y_\mu \sim \frac{y_1 y_2 m_F \kappa}{16\pi^2 M_{A/B}^2} C_{\text{loop}}$$

- Fine tuning in both, Higgs and muon mass!

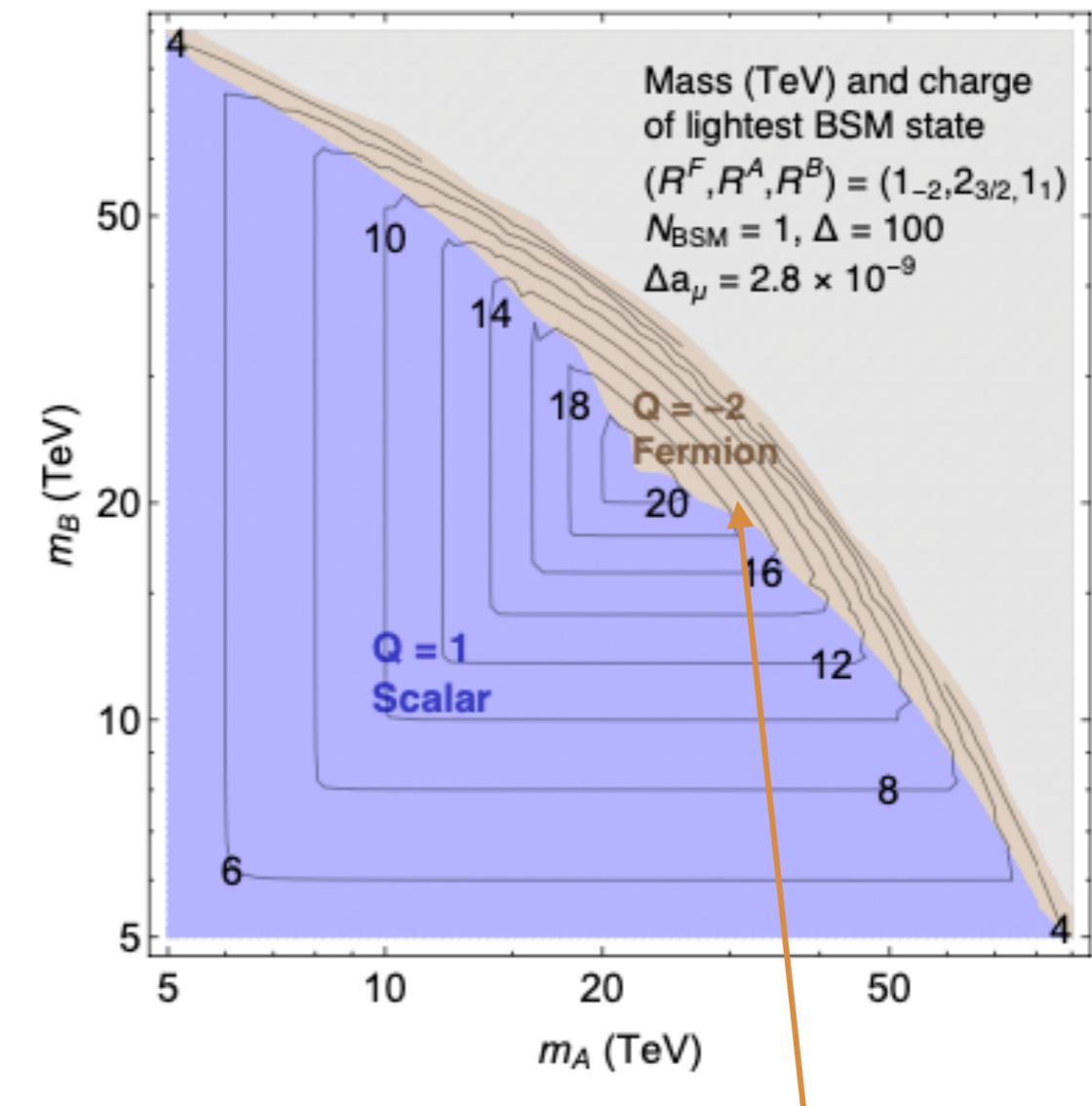
Muon mass  
technically  
unnatural !!!

## 2. Nightmare Scenarios: Electroweak Models



Neutral lightest states:  $\sim 15$  TeV

Worse case scenario if  $E_{\text{coll}} < M_{\text{BSM}}$



Charged lightest states:  $\sim 25$  TeV



Look for indirect signatures from EFT (\*)

NOTE: (other gauge charge choices for BSM states do not give heavier masses)

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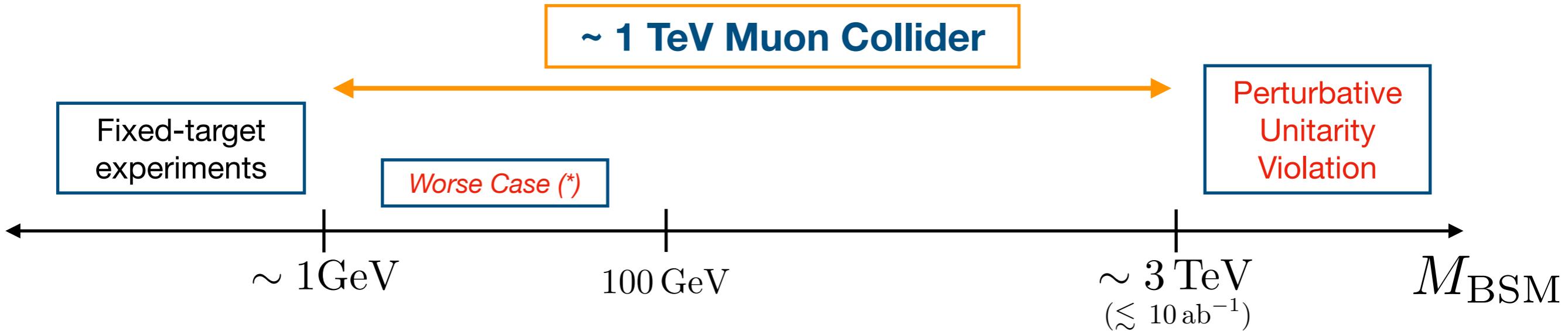
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- Singlet Models
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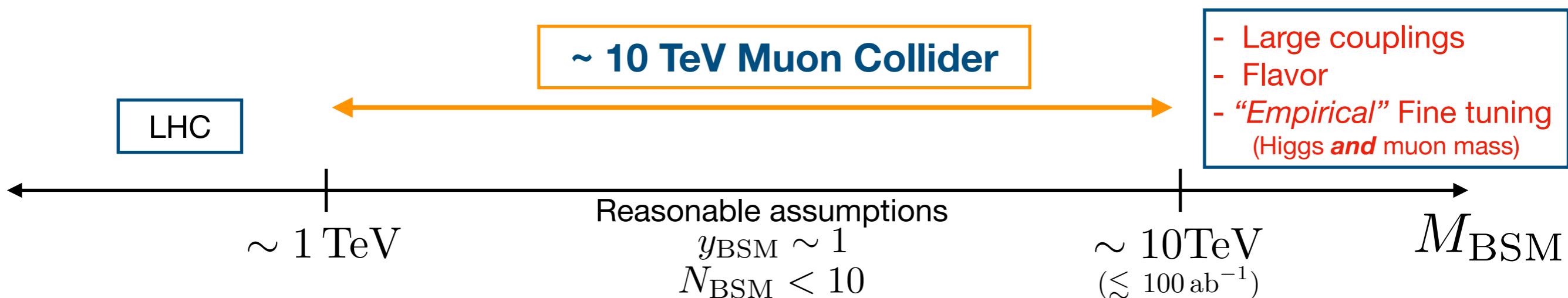
**3. Muon Collider**

### 3. Muon Collider

- Singlet Models



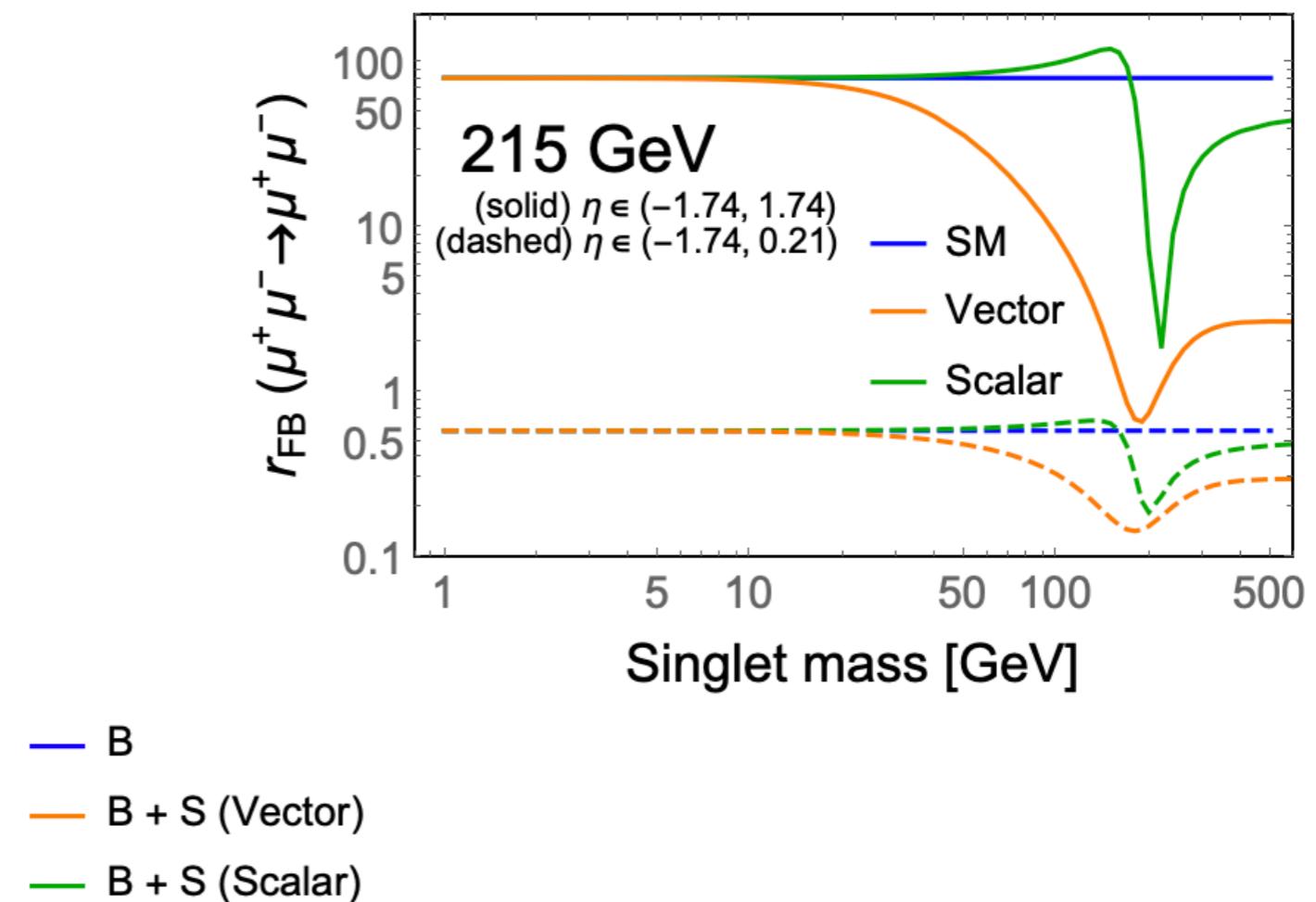
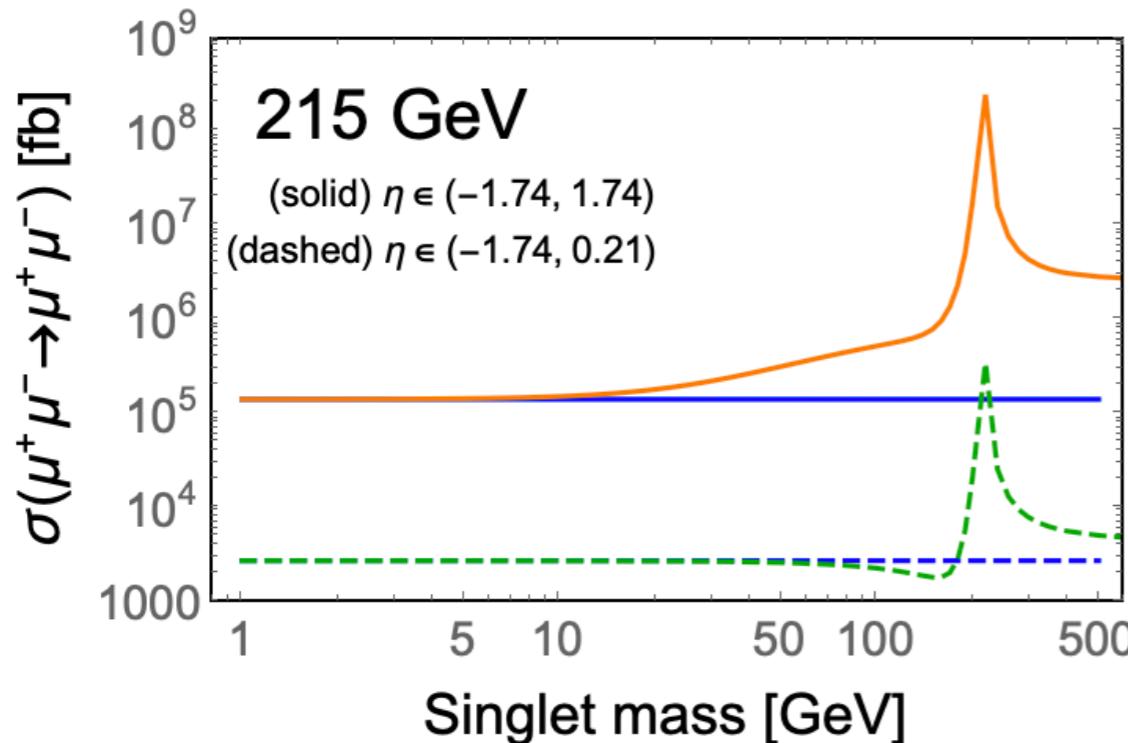
- High-Scale EW Models



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- Singlet Models

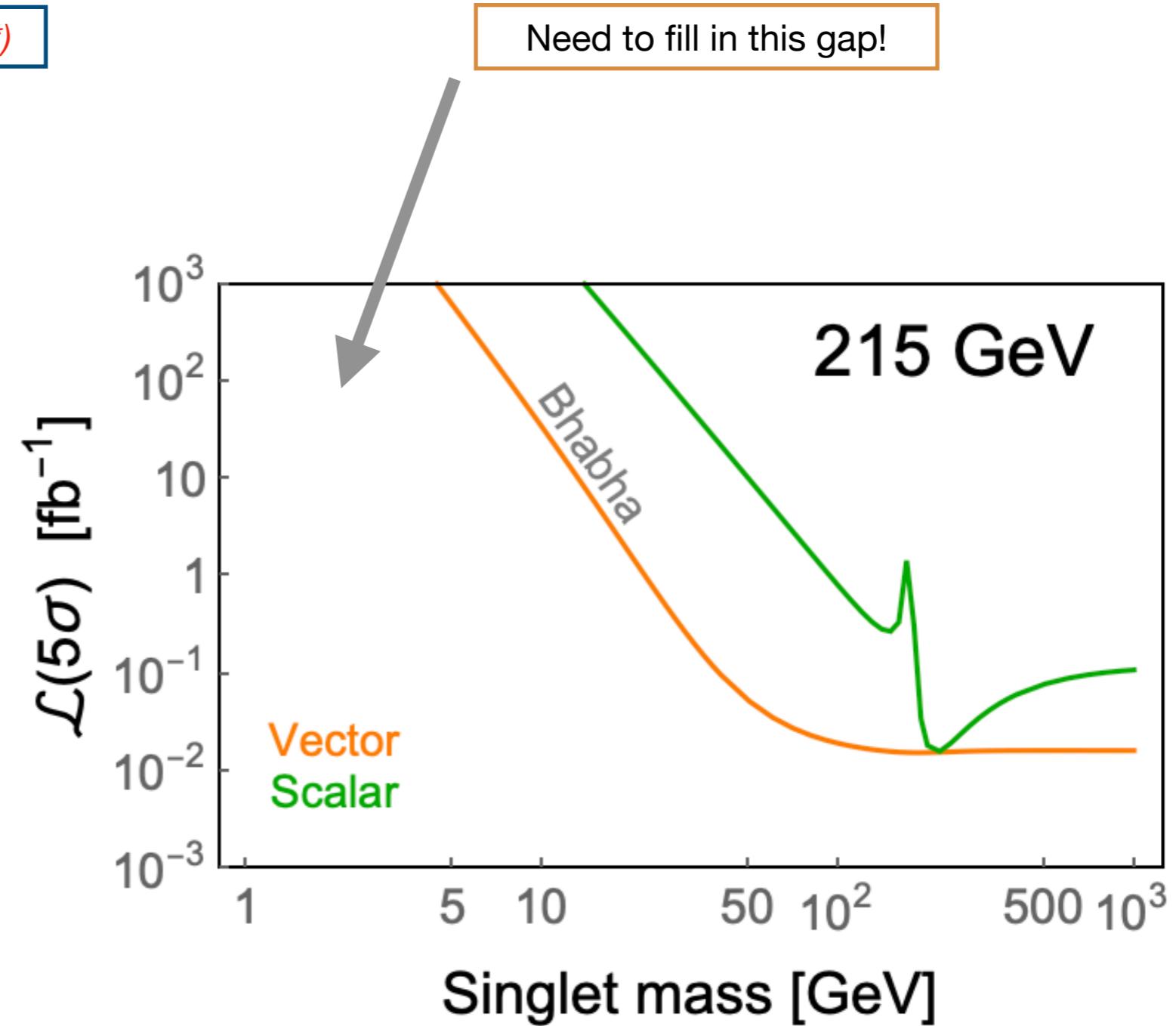
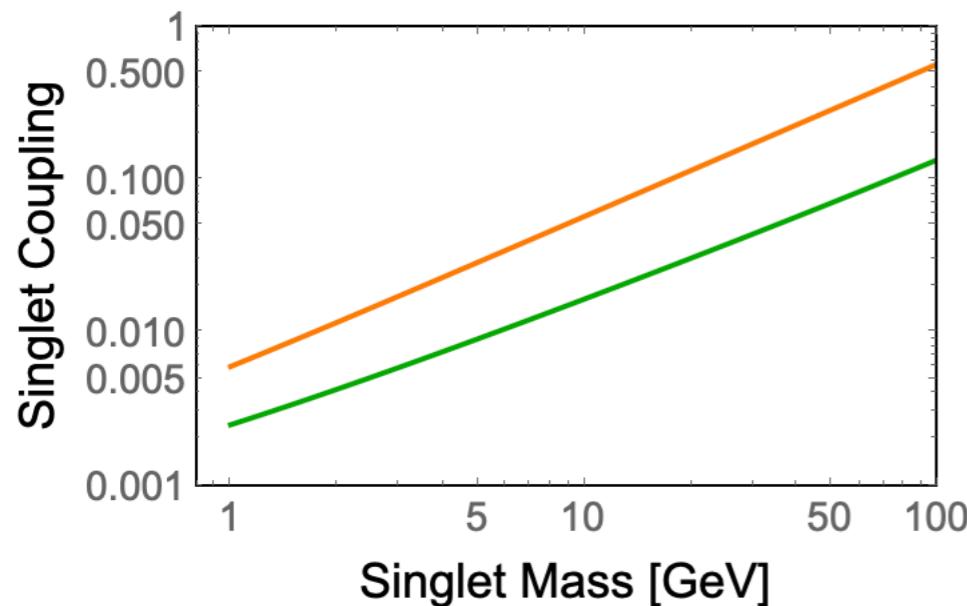
*Worse Case (\*)*



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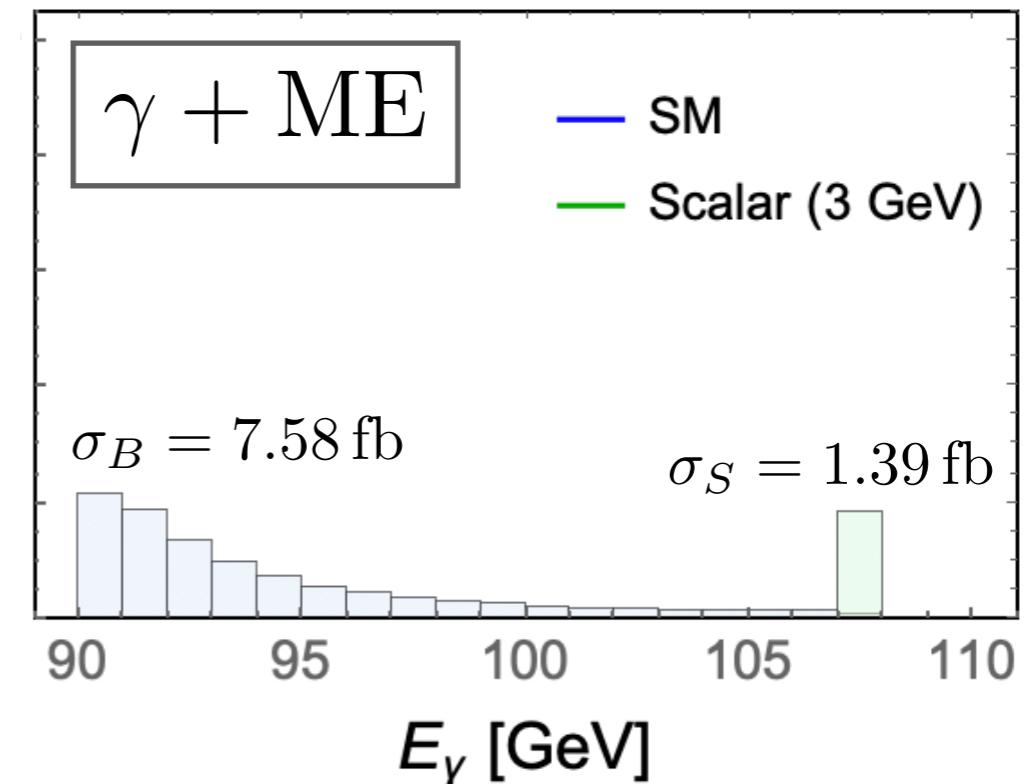
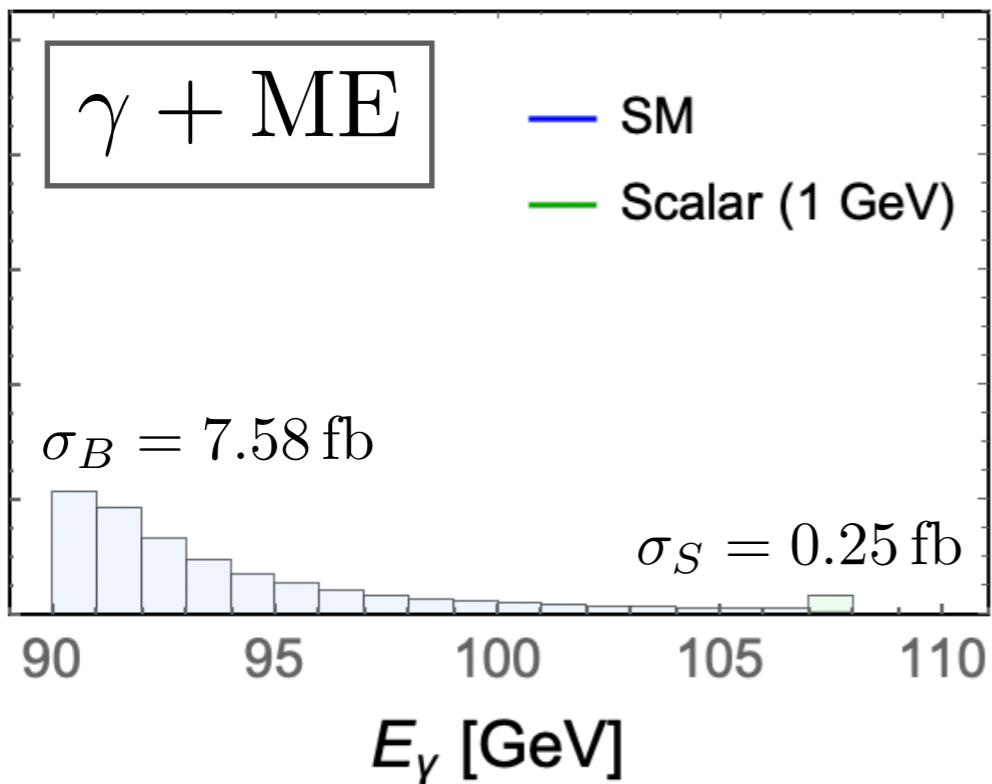
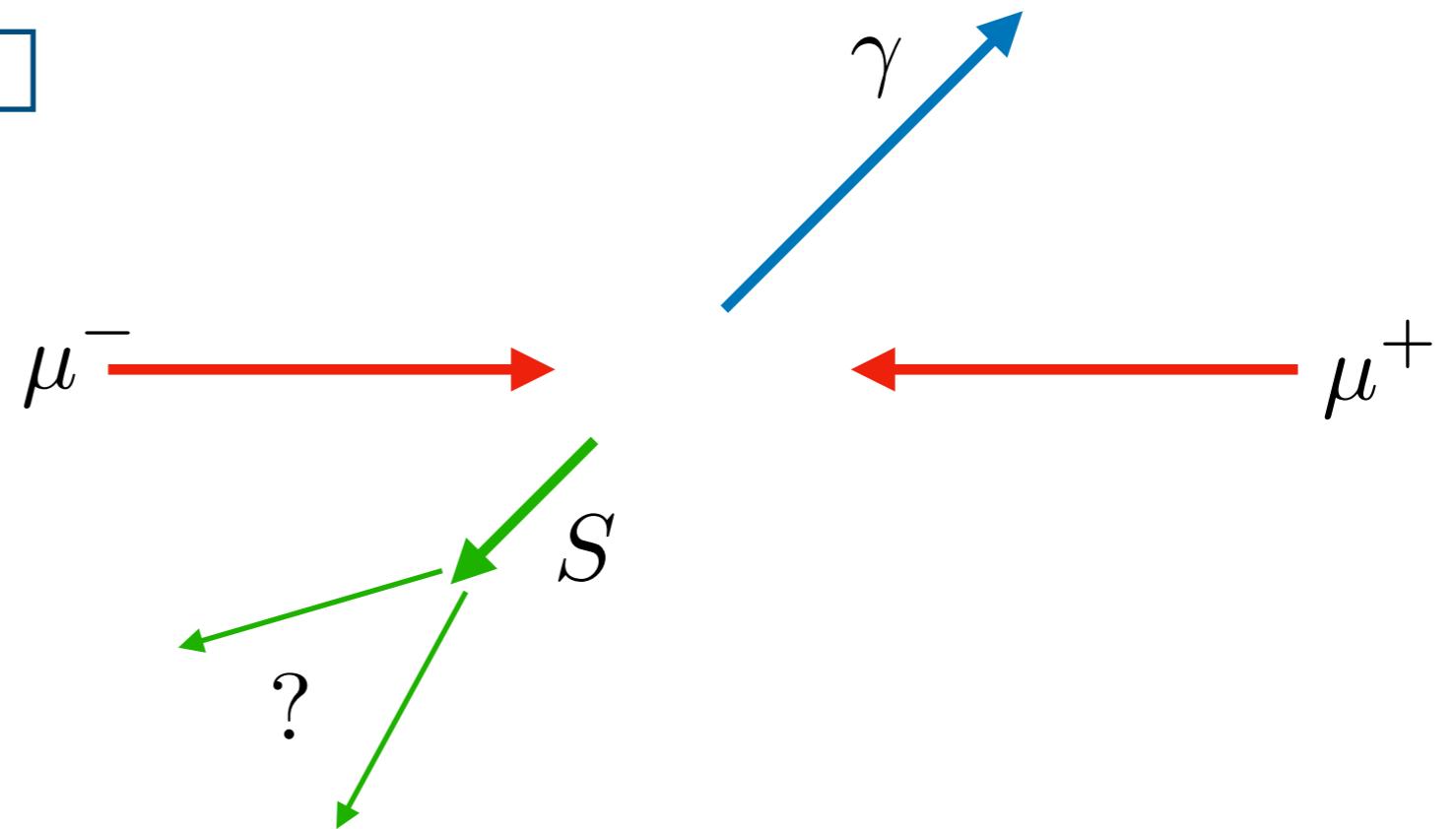


### 3. Muon Collider

- Singlet Models

*Worse Case (\*)*

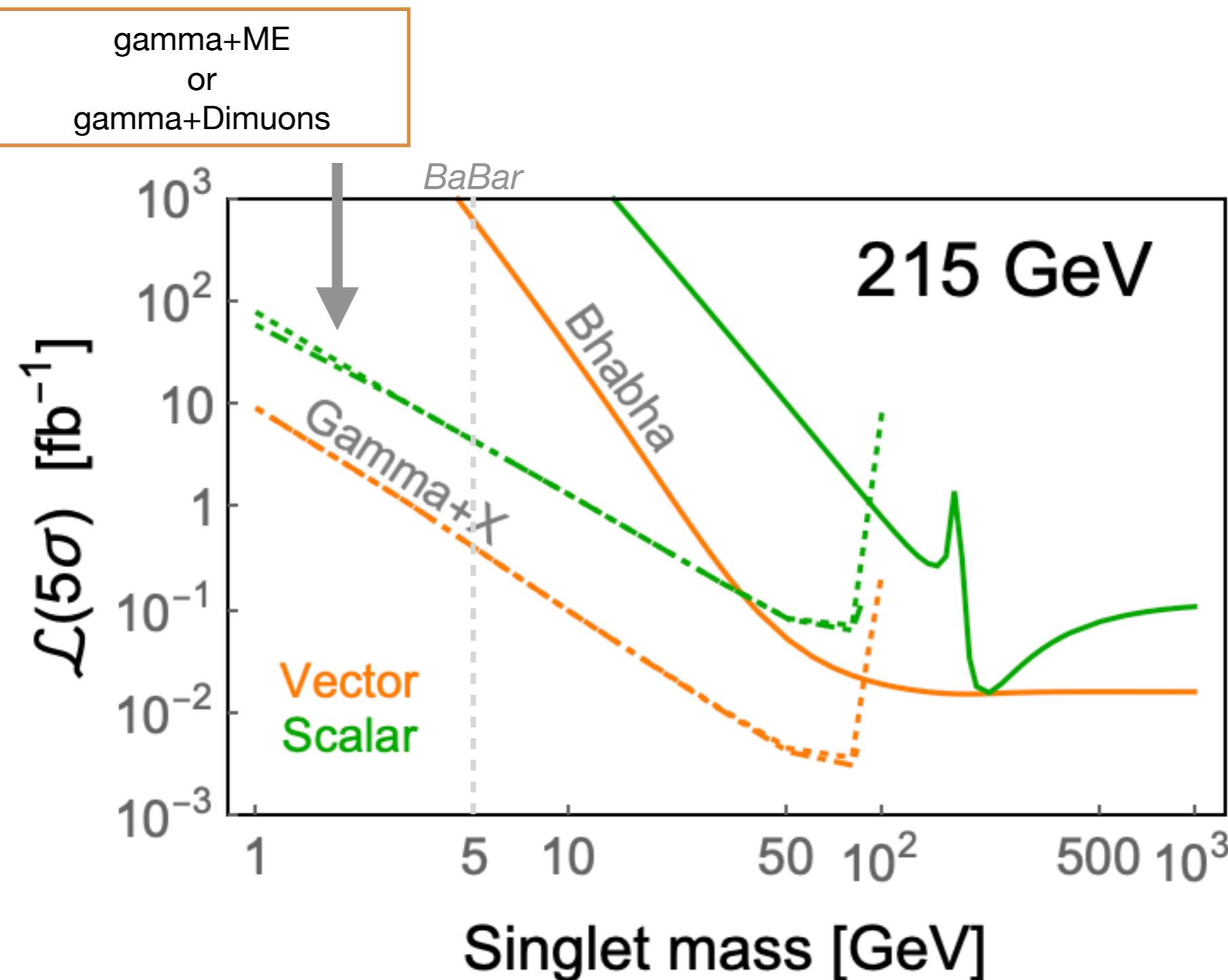
To fill in the gap, look for  
gamma+X



### 3. Muon Collider

- Singlet Models

*Worse Case (\*)*



## ~~Summary~~ Conclusions

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6. A ~ TeV muon collider can probe all *singlet models* and a ~10 TeV muon collider can probe the *EW models*.

# *Thanks!*