Systematically testing (all) Singlet solutions of the muon g-2 anomaly

New Scientific Opportunities with the TRIUMF ARIEL e-linac

May/26/2022

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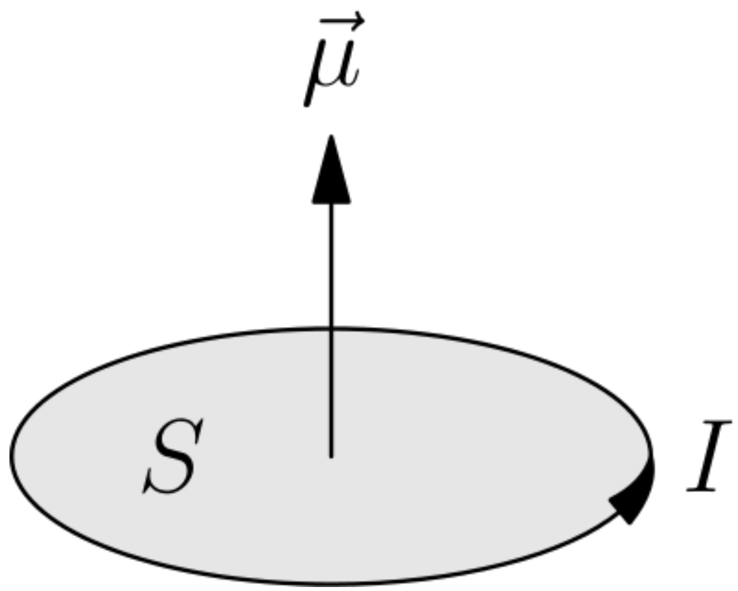
***RC**, David Curtin, Yonatan Kahn, Gordan Krnjaic,*
Phys. Rev. D 103 (2021) 7, 075028
Phys. Rev. D 105 (2022) 1, 015028
JHEP 04 (2022) 129

Outline

1. Muon Anomalous Magnetic Moment
    - Experiment Status
    - Theory Status
2. New Physics Explanations
    - Singlet Models
3. Summary

1. Muon Anomalous Magnetic Moment

- Magnetic moment (macroscopic)



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

- Possible to define for a fundamental particle

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

g-factor

- Relativistic quantum mechanics prediction

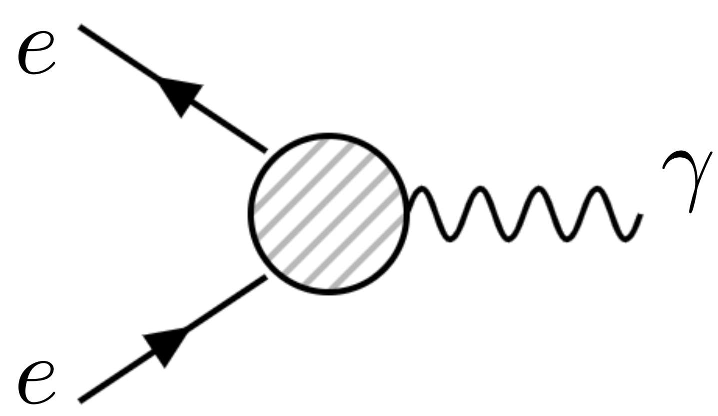
$$i\hbar\frac{\partial\phi}{\partial t} = \left[\frac{p^2}{2m} - \frac{\mu_B}{\hbar}(\vec{L} + 2\vec{S})\cdot\vec{B}\right]\phi$$

$g = 2$

- Anomalous Magnetic Moment

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

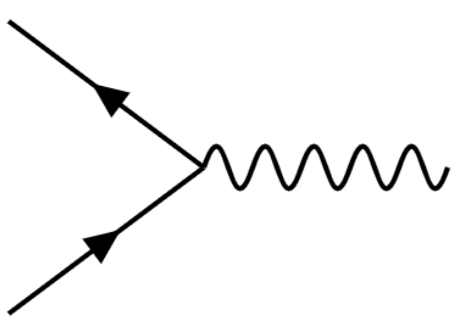
1. Muon *Anomalous Magnetic Moment*



two Letters to the Editor.[6] Subsequent to the publication of preliminary results of our experiments, Schwinger[7] has published results of theoretical investigation which indicate that the magnetic moment of the electron is, indeed, to be modified as the result of the interaction of the radiation field.

$$\sim \gamma_\mu F_1 + \frac{i\sigma_{\mu\nu}q^\nu}{2m}F_2 \rightarrow g = 2 + 2F_2(0) \qquad \boxed{a = F_2(0)}$$

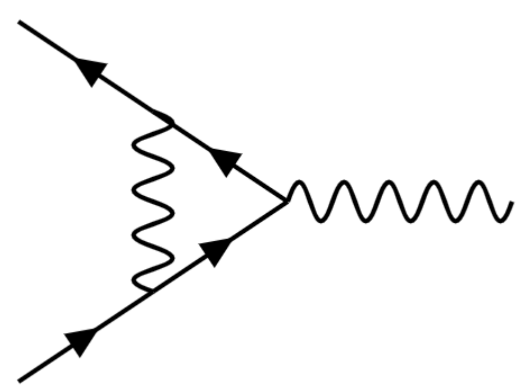
- Tree-level result



$$\boxed{\begin{array}{c} a = 0 \\ g = 2 \end{array}}$$

- QED (1st order) correction

J. Schwinger, Phys. Rev. **73**, 416 (1948)



$$\boxed{a = \frac{\alpha}{2\pi} \sim 0.0011614}$$

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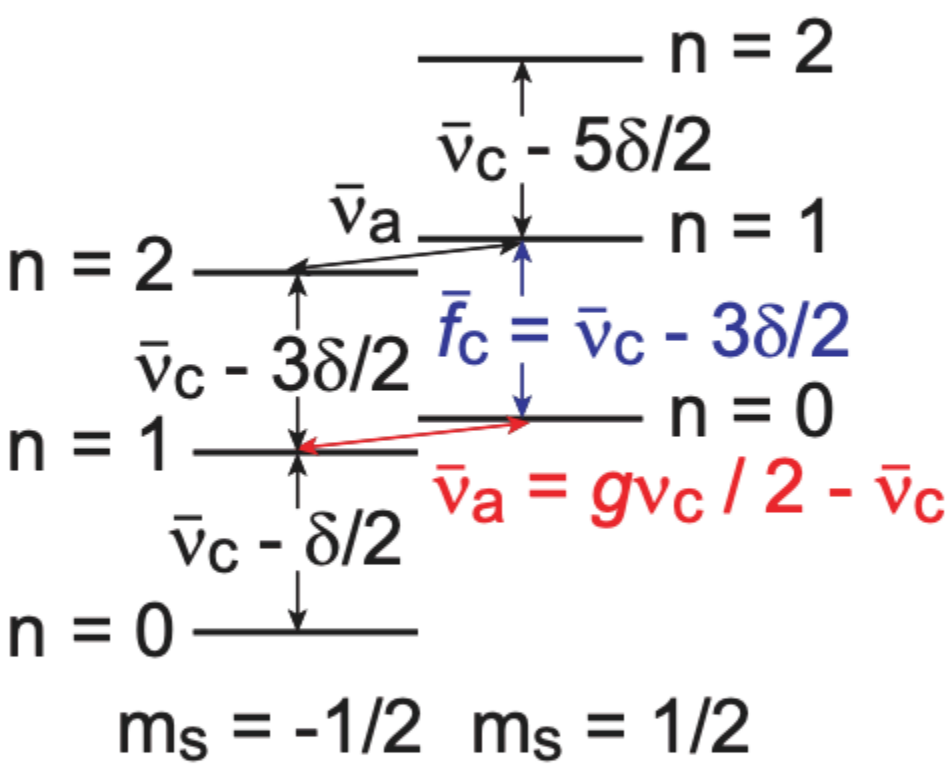
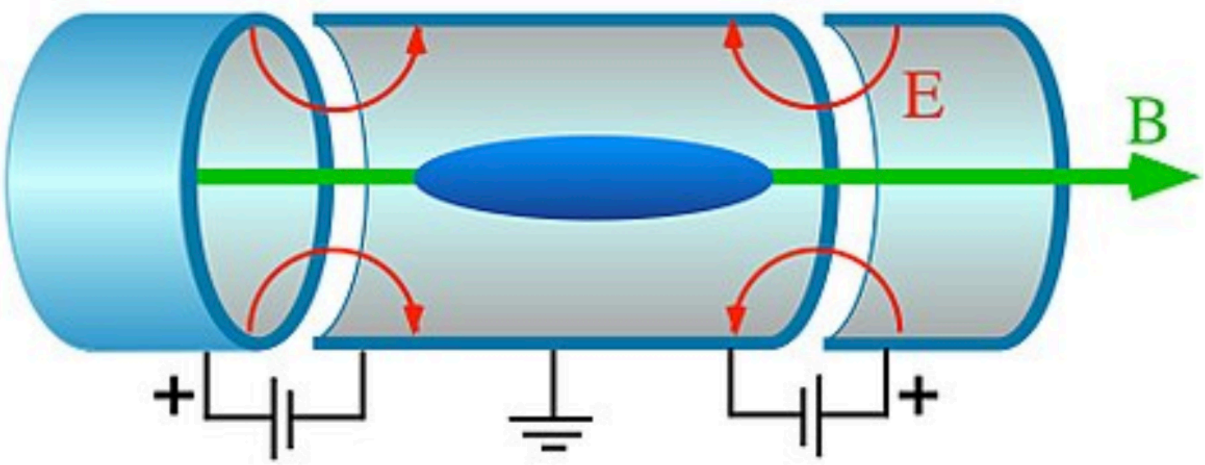
1. Muon Anomalous Magnetic Moment

- More recent experiments



Cyclotron and spin energy levels

Single-electron Penning Trap



$$\frac{g}{2} = \frac{\nu_s}{\nu_c} = 1 + \frac{\nu_s - \nu_c}{\nu_c}$$

D. Hanneke, S. Fogwell, G. Gabrielse, Phys. Rev. A **83**, 052122 (2011)

$$a_e(\text{exp}) = 1\,159\,652\,180.73\,(28) * 10^{-12} \;\; [0.28\,\text{ppt}]$$

1. Muon Anomalous Magnetic Moment

T. Aoyama et al, Phys. Rev. Lett. 109 (2012) 111807
T. Aoyama et al, Phys. Rev. D 85 (2012) 033007
T. Aoyama et al, Phys. Rev. D 91 (2015) 3, 033006
T. Aoyama et al, Phys. Rev. D 96 (2017) 1, 019901

- Theoretical prediction

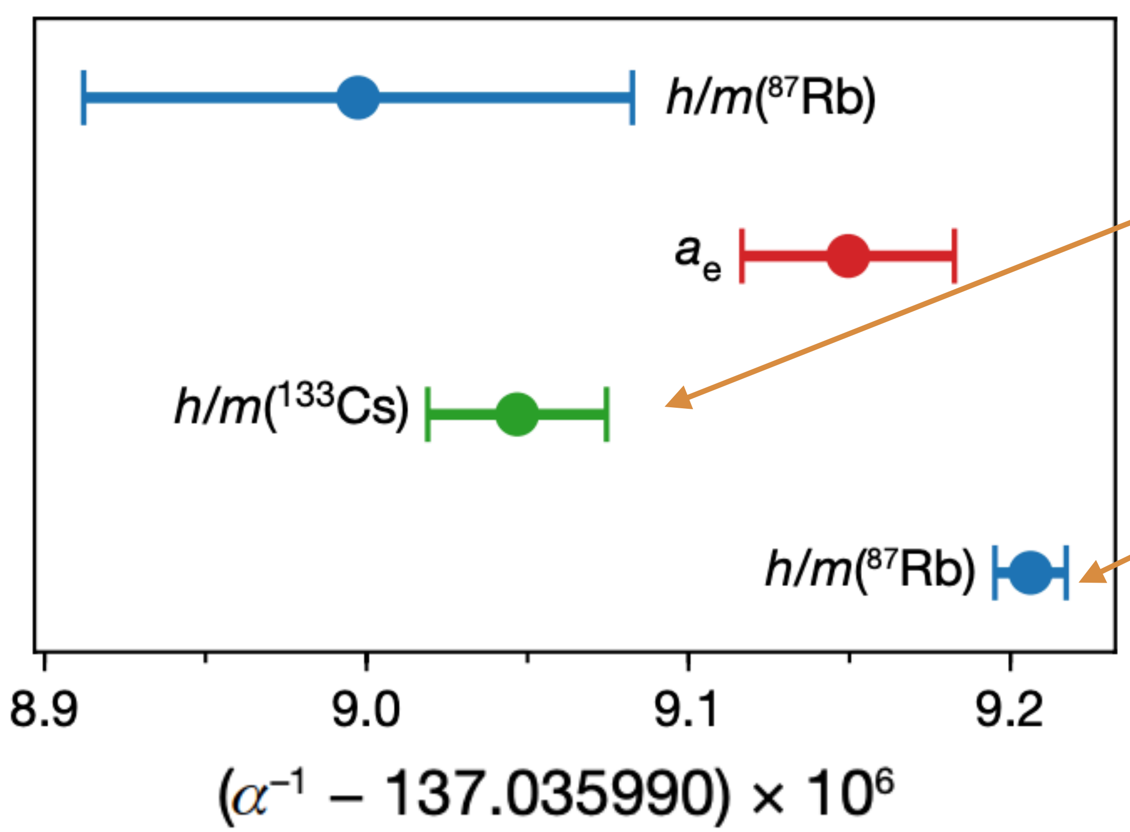
$$a_e(\text{the}) = 1\,159\,652\,182.031\,(15)\,(15)\,(720) * 10^{-12}$$

10th order calculation (as of 2017)

10th order term — Hadronic terms — Fine-structure constant

$$\alpha^{-1} = 137.035\,998\,996\,(85)$$

P. Mohr, D. Newell, B. Taylor, Rev. Mod. Phys. 88 (2016) 3, 035009



$$a_e(\text{exp}) - a_e(\text{the}) \sim -2.5\,\sigma$$

R. Parker et al., Science 360, 191–195 (2018)

$$a_e(\text{exp}) - a_e(\text{the}) \sim 1.6\,\sigma$$

L. Morel et al., Nature 588 (2020) 7836, 61-65

Outline

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   - **Experiment Status**
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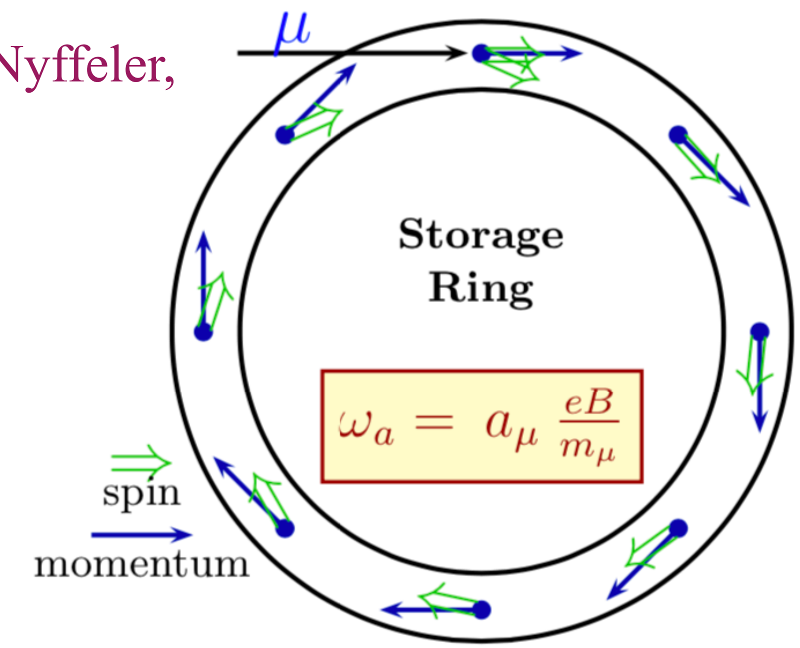
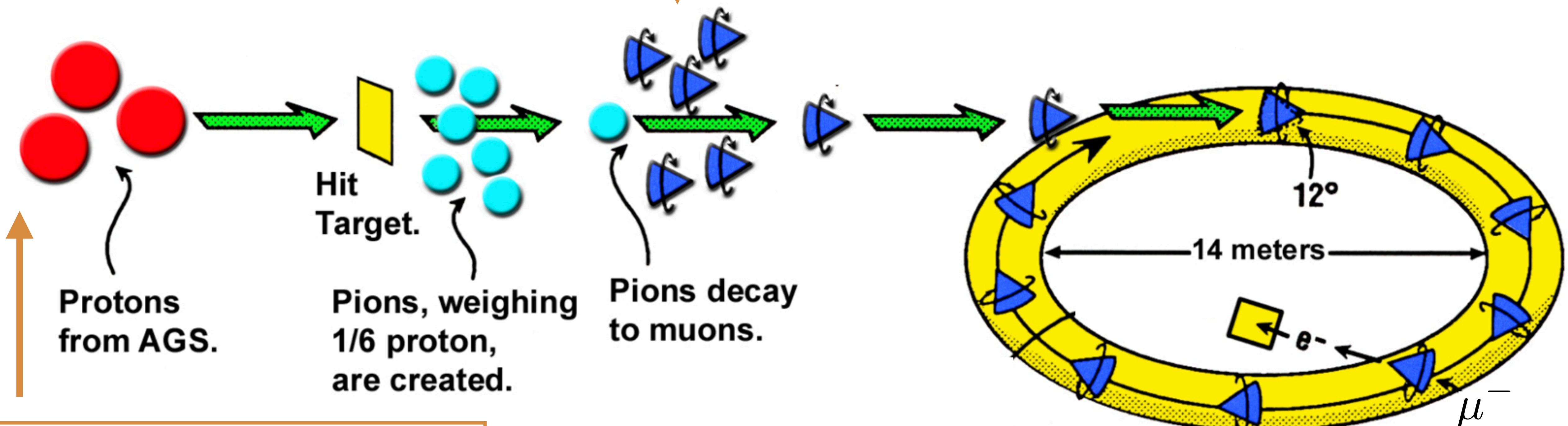
1. Experiment Status

F. Jegerlehner, A. Nyffeler,
e-Print: 0902.3360



- Good old BNL E821

~ 10^4 mu+ stored per fill



- 24 GeV beam
- 10^12 protons per bunch

$$\mathrm{R} = N_\mu\, e^{-\frac{\tau\omega}{64.4}} \left(\frac{1}{24\,\mathrm{Detectors}}\right)\left(\frac{1}{64.4\,10^{-6}s}\right)\epsilon_d \;\sim 10^6 s^{-1}$$

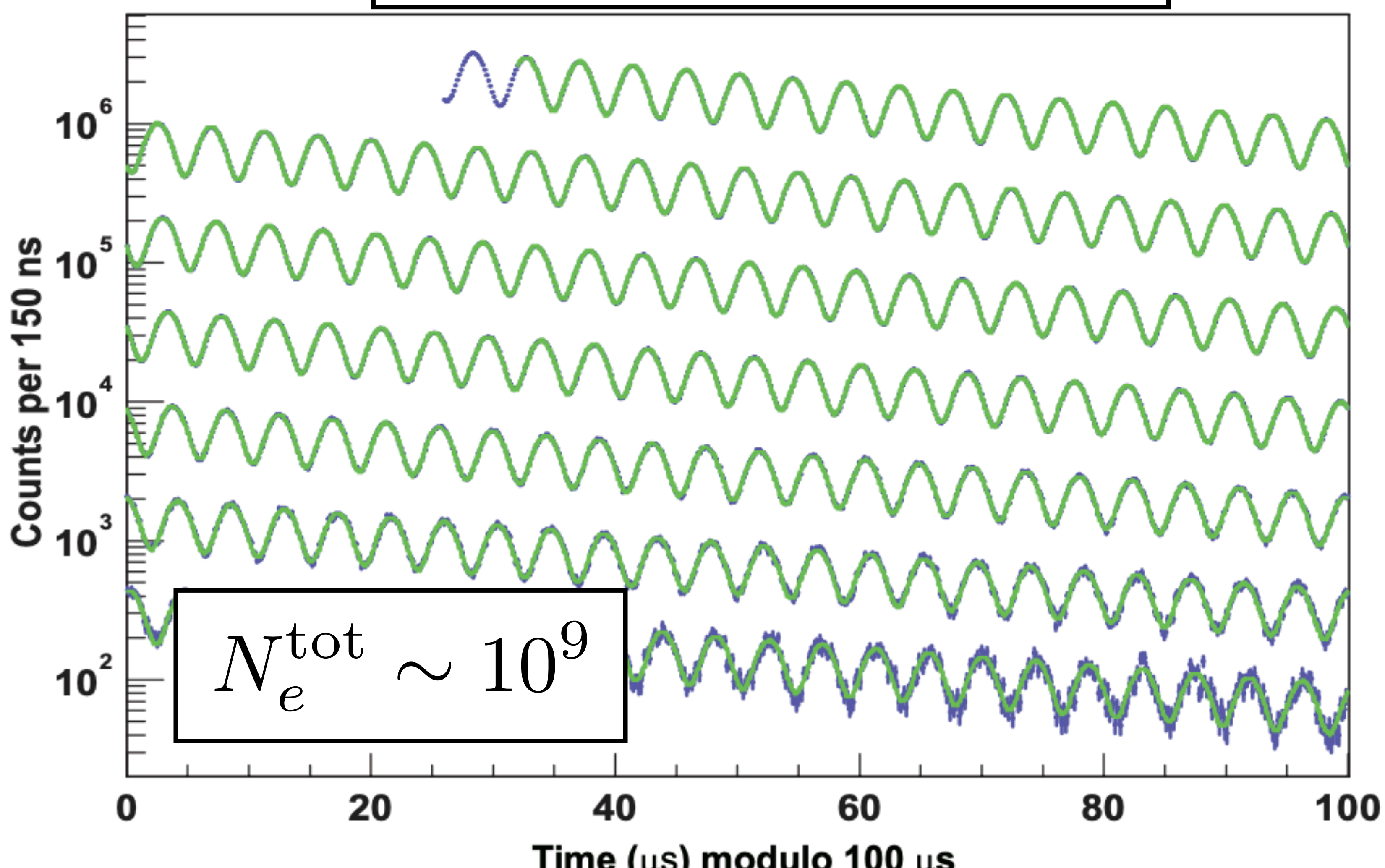
1. Experiment Status

- Good old BNL E821

$$N(t, E_{th}) = N_0(E_{th}) e^{-t/\gamma\tau}[1 + A(E_{th}) \cos(\omega_a t + \phi(E_{th}))]$$

Number of electrons above the energy threshold

$E_{\rm th} = 1.8\,\mathrm{GeV}$



$N_e^{\rm tot} \sim 10^9$

F. Jegerlehner, A. Nyffeler, e-Print: 0902.3360

1. Experiment Status

- Systematic effects

$$\vec{\omega}_a = -\frac{q}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta}\right]$$

1) E-field correction — 2) Pitch correction

1) The presence of E-field contributes to the precession

- Run the experiment at the "magic momentum"
- This cancels the E-field correction to first order

2) Not a perfect trajectory

- Need to understand B field to a high precision

1. Experiment Status

- Other systematic effects

	BNL E821	FNAL 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

  - Effects from e/m

$$\omega_a \propto \frac{q}{m_\mu}$$

  - Systematics due to phase(t)

$$N(t, E_{\rm th}) \propto \cos(\omega_a t + \phi(t, E_{\rm th}))$$

  - B measurements

  - E measurements

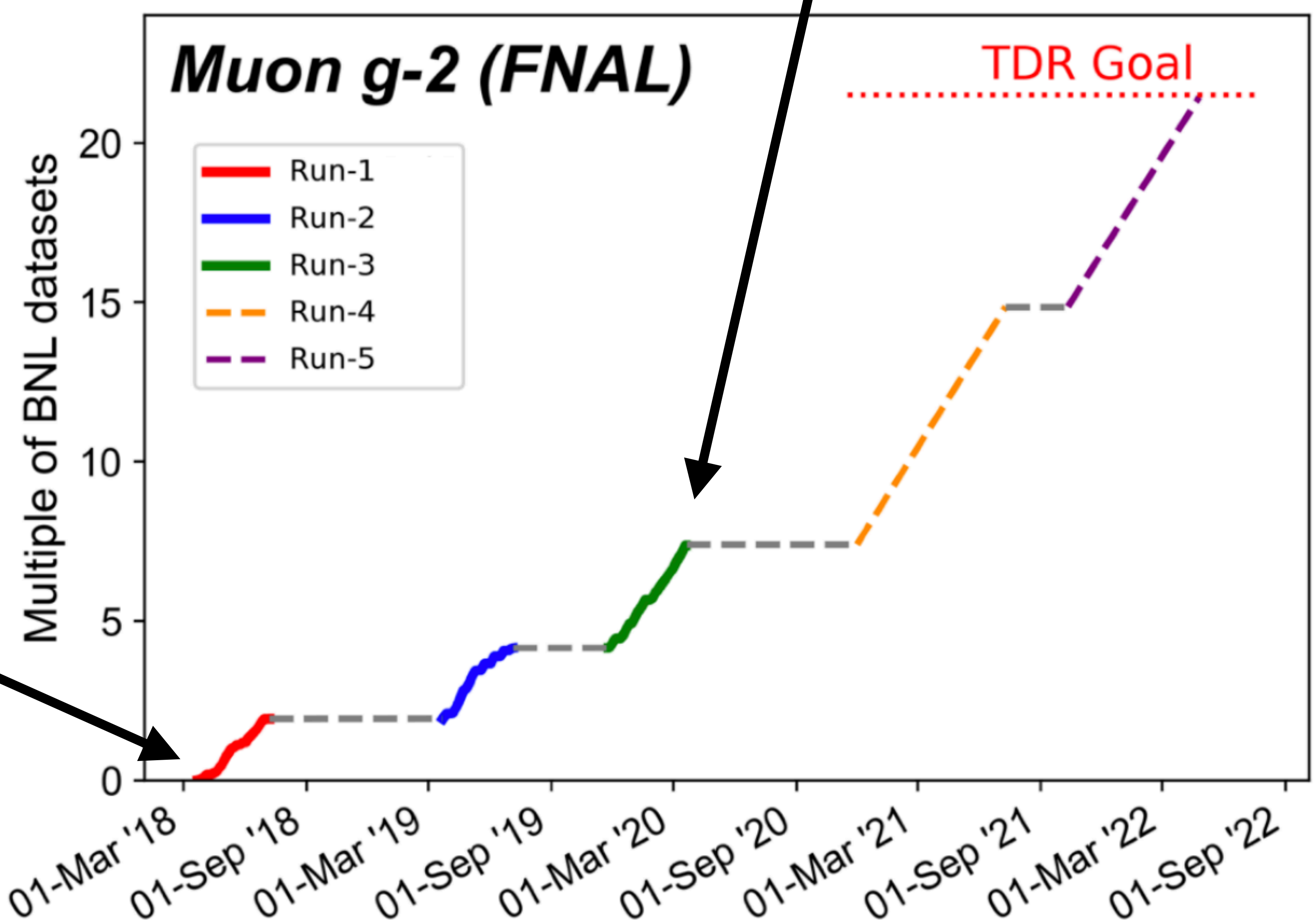
Muon g-2 Collaboration, e-Print: 1501.06858
Muon g-2 Collaboration, e-Print: 2104.03240

1. Experiment Status

- FNAL E989

Three runs completed so far!

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



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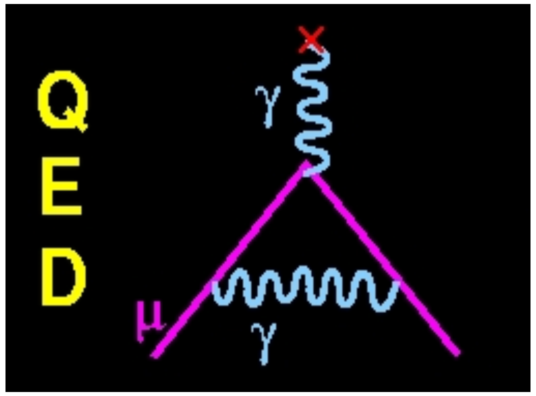
1. Theory Status

- Perturbative

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

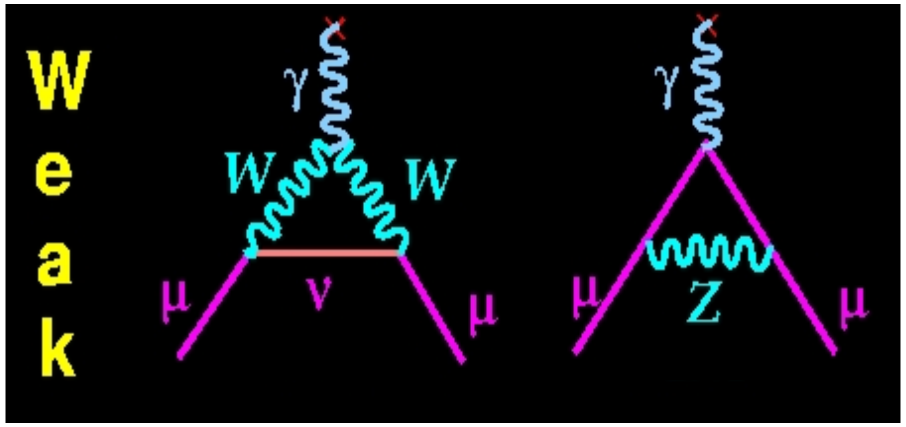
Muon g − 2 Theory Initiative



Five loops

$$a_\mu^{\text{QED}} = 116584718.931(104) \times 10^{-11}$$

T. Aoyama, T. Kinoshita, M. Nio, Atoms 7, 28 (2019)



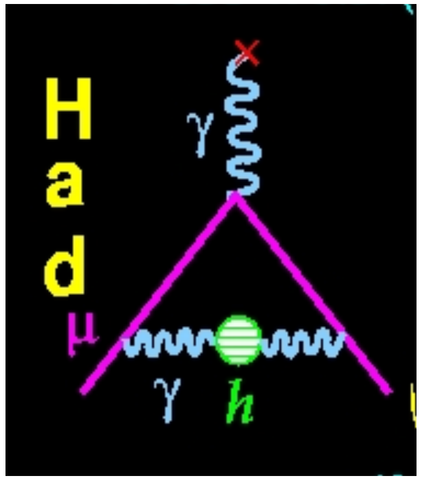
Two loops

$$a_\mu^{\text{EW}} = 153.6(1.0) \times 10^{-11} \quad (\sim 0.7\,\%)$$

A. Czarnecki at al., Phys. Rev. D 67, 073006 (2003)
A. Czarnecki at al., Phys. Rev. D 73, 119901 (2006)
C. Gnendiger et al., Phys. Rev. D 88, 053005 (2013)

1. Theory Status

- Non-perturbative



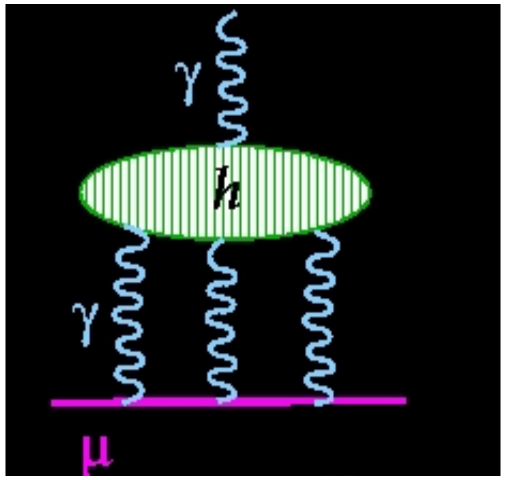
NNLO

$$a_\mu^{\mathrm{HVP}} = 6845(40) \times 10^{-11} \quad (\sim 0.6\,\%)$$

M. Davier et al., Eur. Phys. J. C 77 (2017) 12, 827

M. Hoferichter et al., JHEP 08 (2019) 137

A. Kurz et al., Phys. Lett. B 734 (2014) 144-147



NLO

$$a_\mu^{\mathrm{HLbL}} = 106.8(14.7) \times 10^{-11} \quad (\sim 14\%)$$

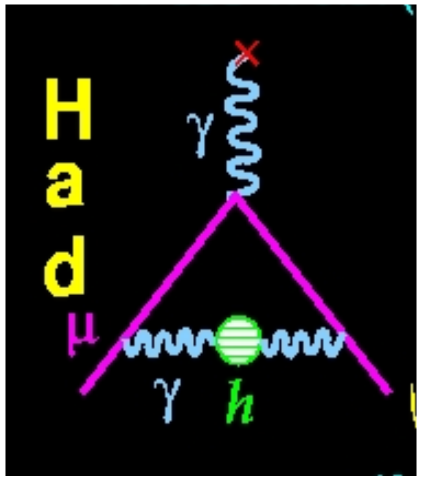
En-Hung Chao et al., e-Print: 2104.02632

V. Pauk, M. Vanderhaeghen, Eur. Phys. J. C 74 (2014) 8, 3008

T. Blum et al., Phys. Rev. Lett. 124 (2020) 13, 132002

1. Theory Status

- Non-perturbative



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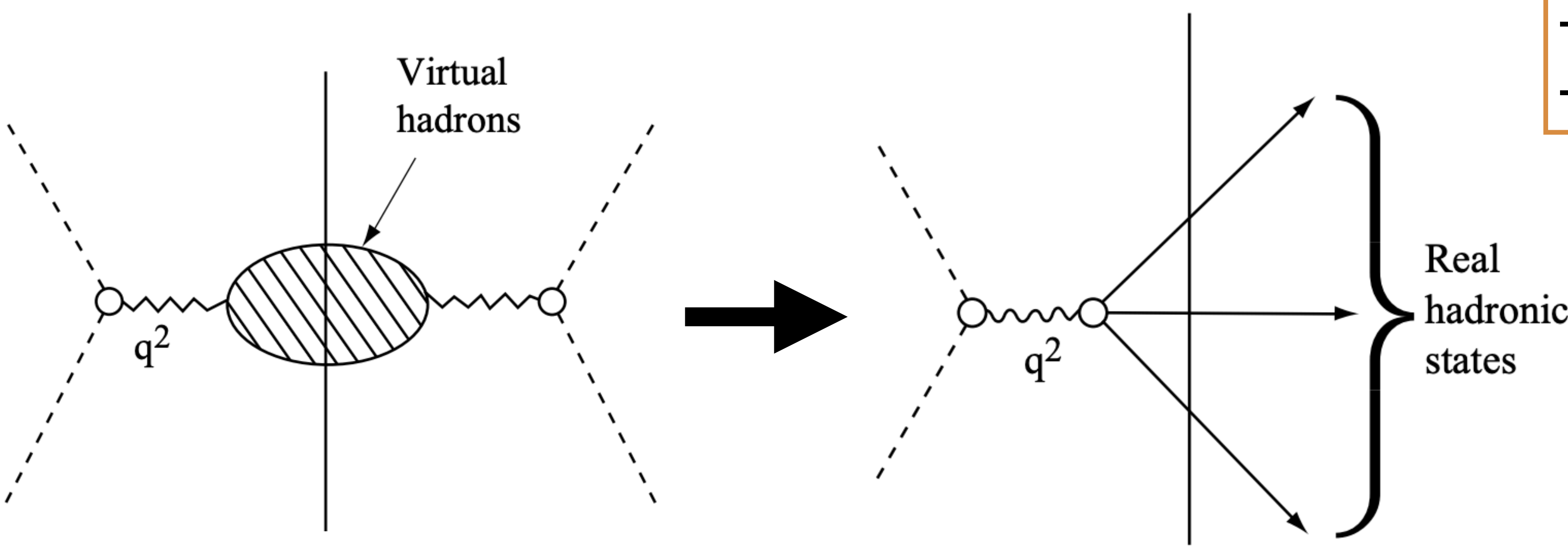
M. Hoferichter et al., JHEP 08 (2019) 137

A. Kurz et al., Phys. Lett. B 734 (2014) 144-147

Unitarity

$$\mathrm{Im(HVP)} \propto \sigma(\gamma^* \to \mathrm{hadrons})$$

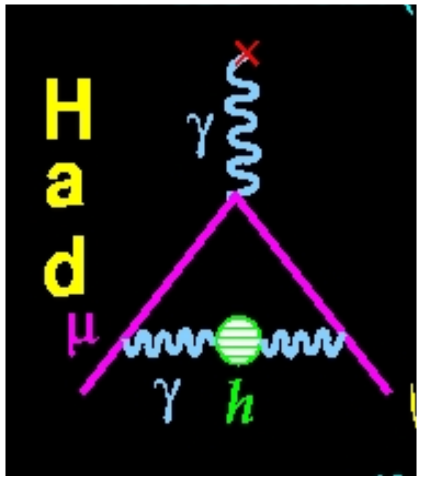
Include:
- All modes
- ISR
- FSR



F. Farley, Y. Semertzidis, Prog. Part. Nucl. Phys. 52 (2004) 1-83

1. Theory Status

- Non-perturbative



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M. Hoferichter et al., JHEP 08 (2019) 137
A. Kurz et al., Phys. Lett. B 734 (2014) 144-147

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

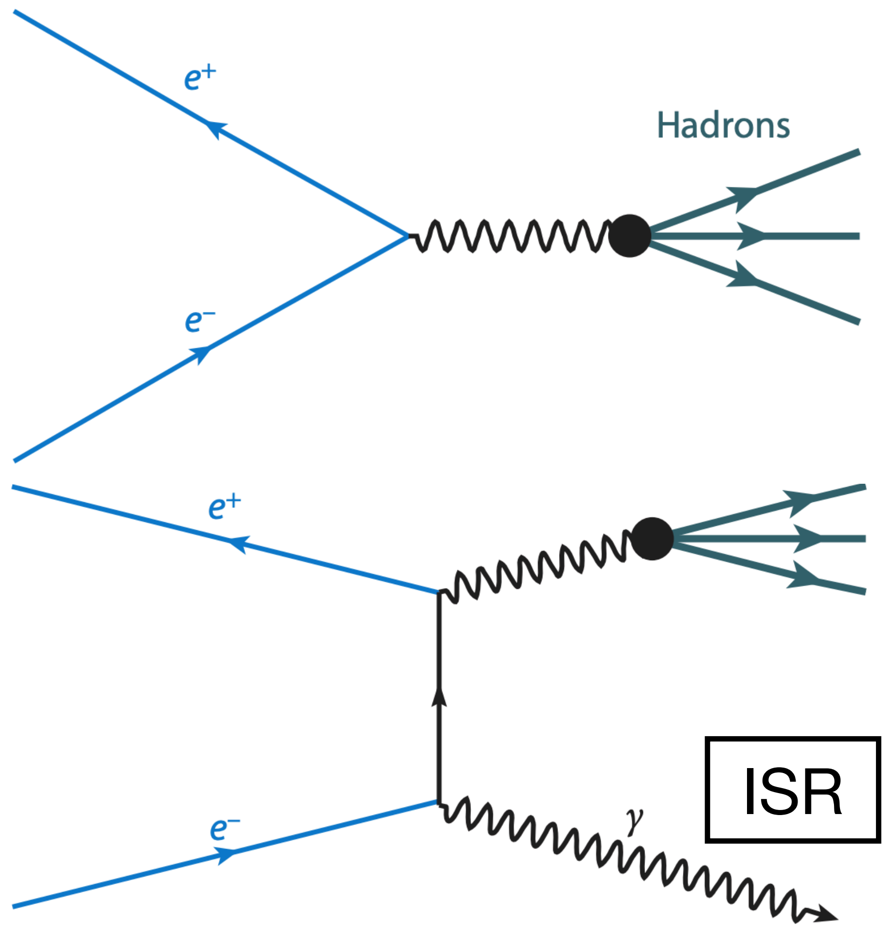
Extract from data

$$R(s) = \frac{\sigma^0(e^+e^- \to {\rm hadrons}(+\gamma))}{\sigma_{\rm pt}} \qquad \sigma_{\rm pt} = \frac{4\pi\alpha^2}{3s}$$

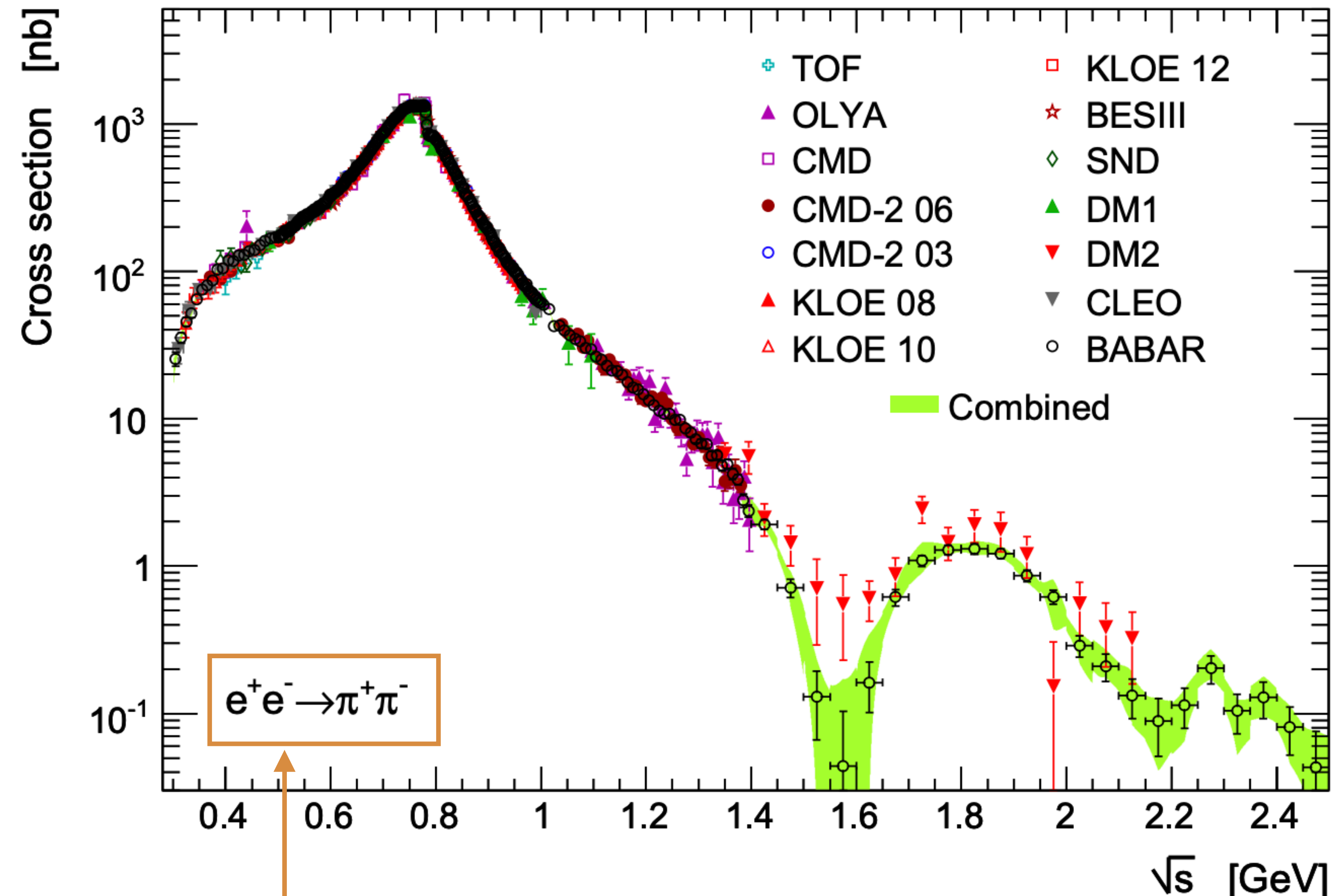
Hadronic R-ratio

1. Theory Status

- Non-perturbative



M. Davier, Ann. Rev. Nucl. Part. Sci. 63, 407 (2013)

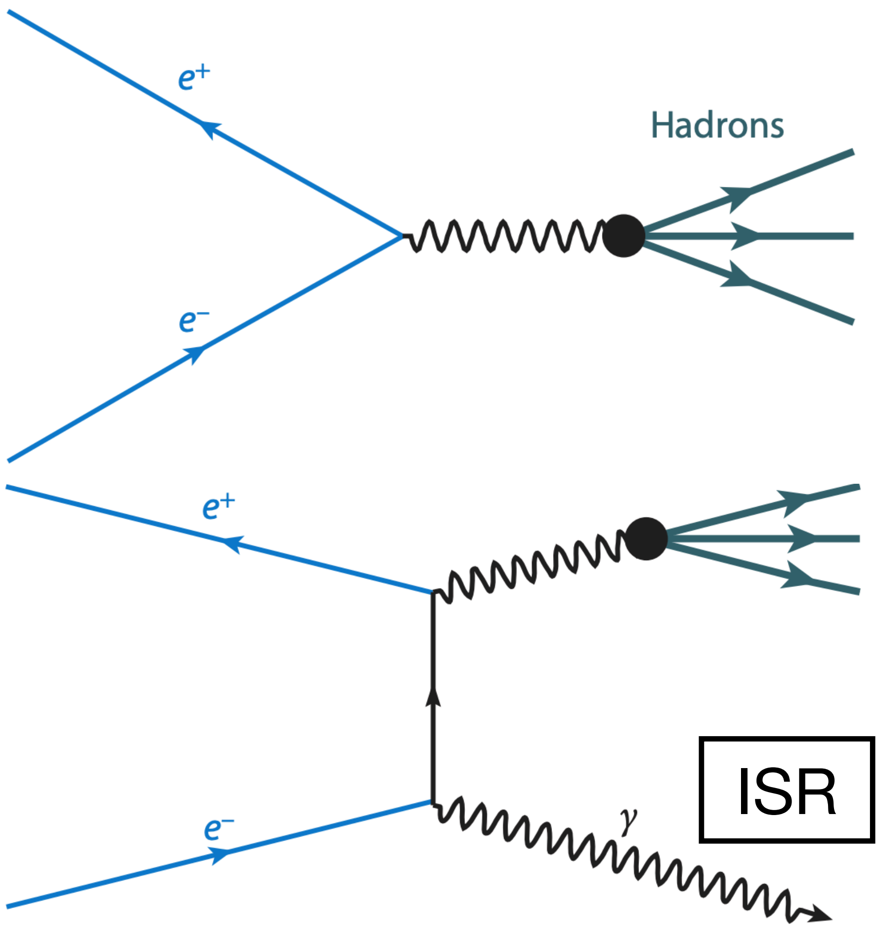


M. Davier et al., Eur. Phys. J. C80 (2020) 3, 241
T. Xiao et al., Phys. Rev. D 97, 032012 (2018)

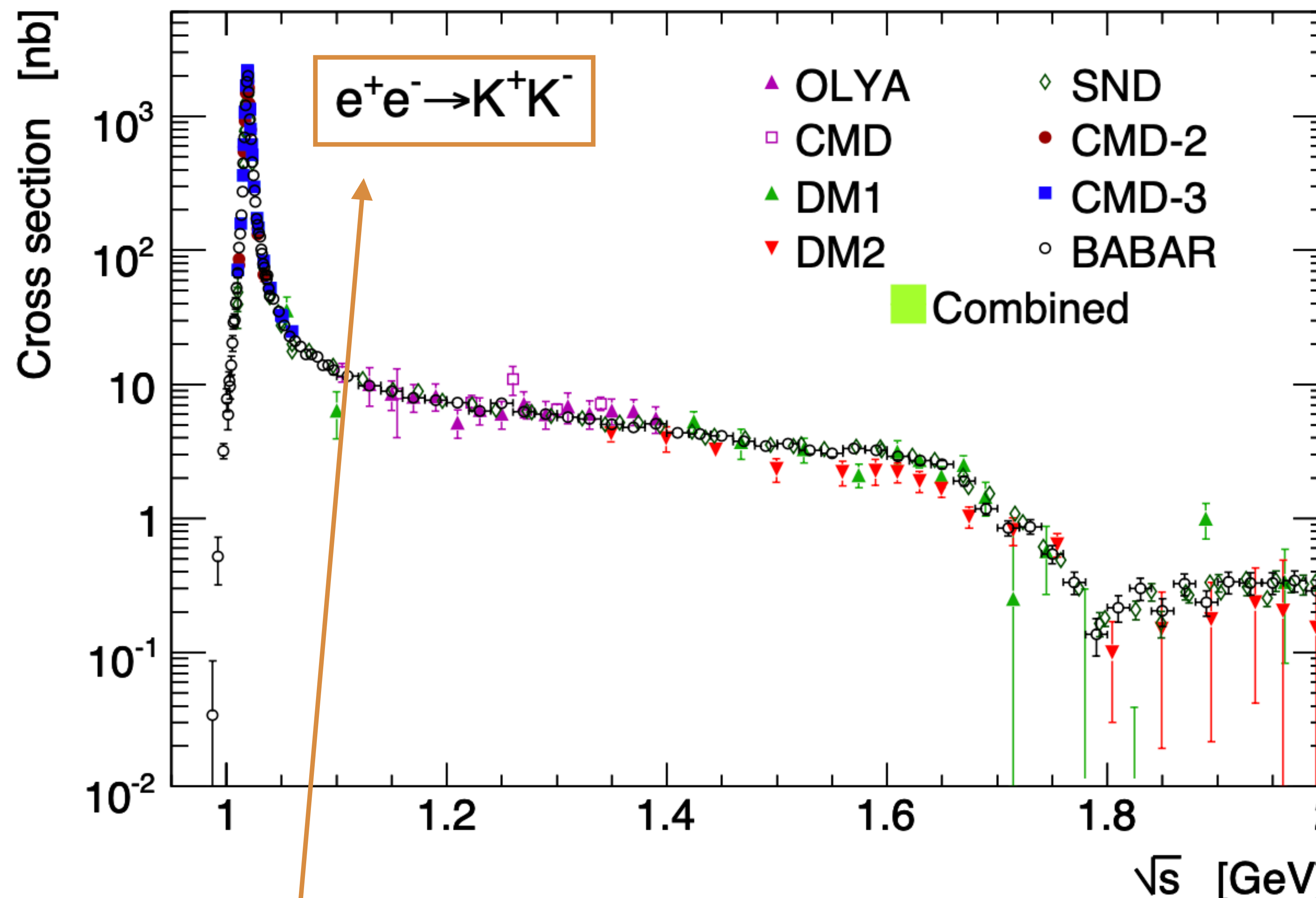
Contributes to $a_\mu^{\rm HVP}[\rm LO]$ by ~73%

1. Theory Status

- Non-perturbative



M. Davier, Ann. Rev. Nucl. Part. Sci. 63, 407 (2013)



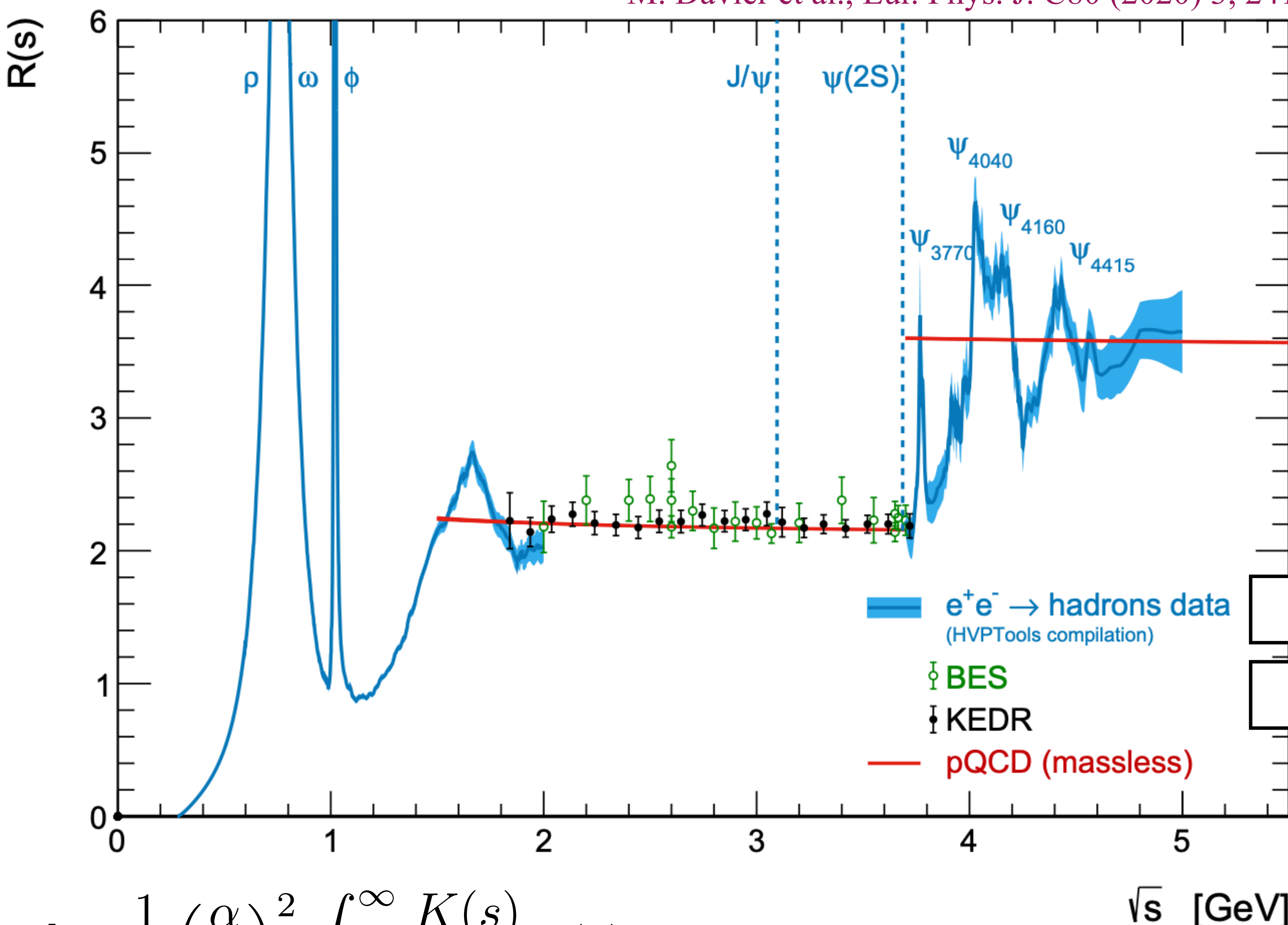
T. Aoyama et al., Phys. Rept. 887 (2020) 1-166

Contributes to $a_\mu^{\rm HVP}[\rm LO]$ by ~ 3%

1. Theory Status

- Non-perturbative

M. Davier et al., Eur. Phys. J. C80 (2020) 3, 241



Exclusive

Inclusive

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

1. Theory Status

- Combined

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: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	279(76)

1. Theory Status

- Combined

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

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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"

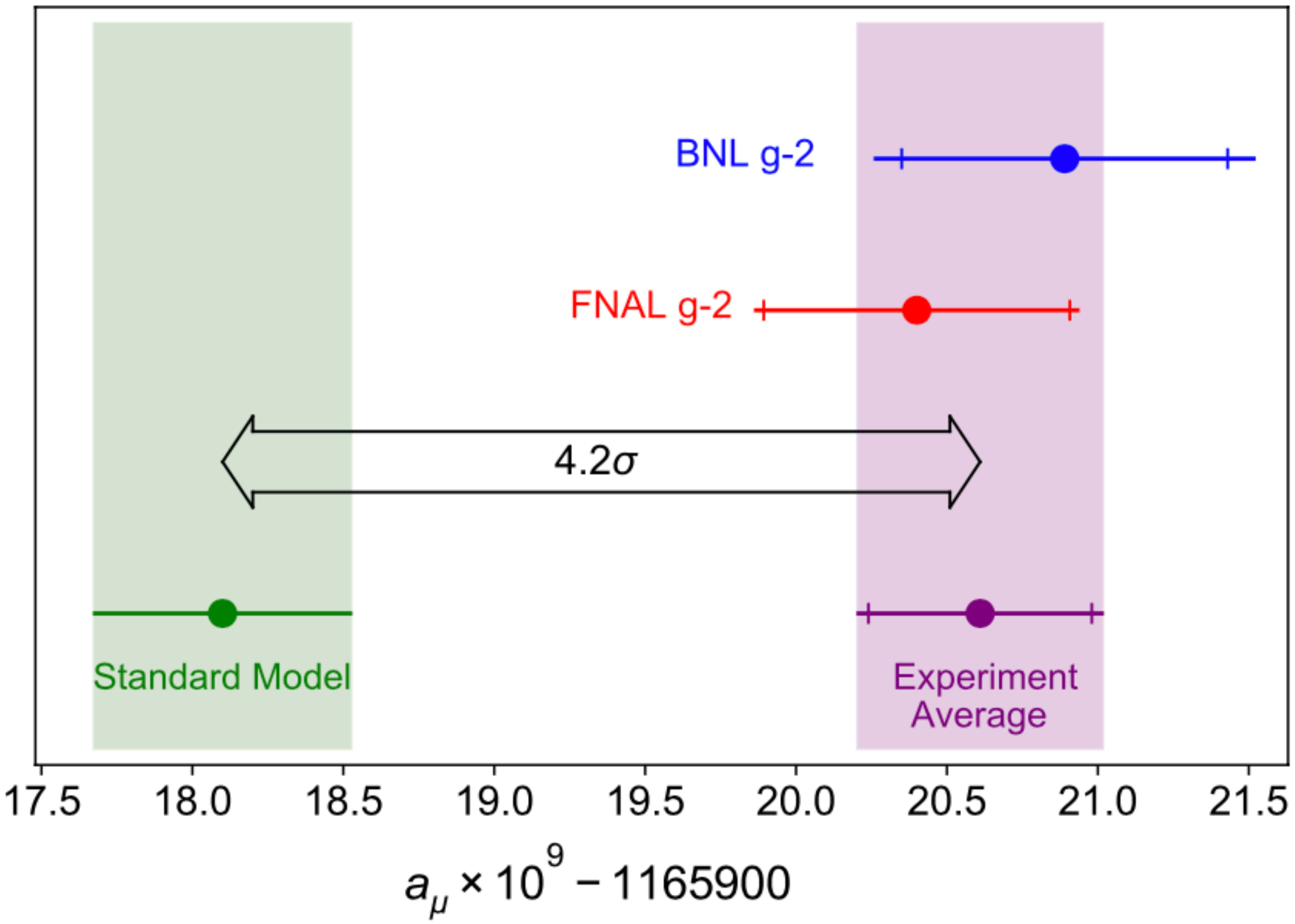
$106.8(14.7)\ (\sim 14\%)$

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

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

1. Theory Status

- State of affairs



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

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

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

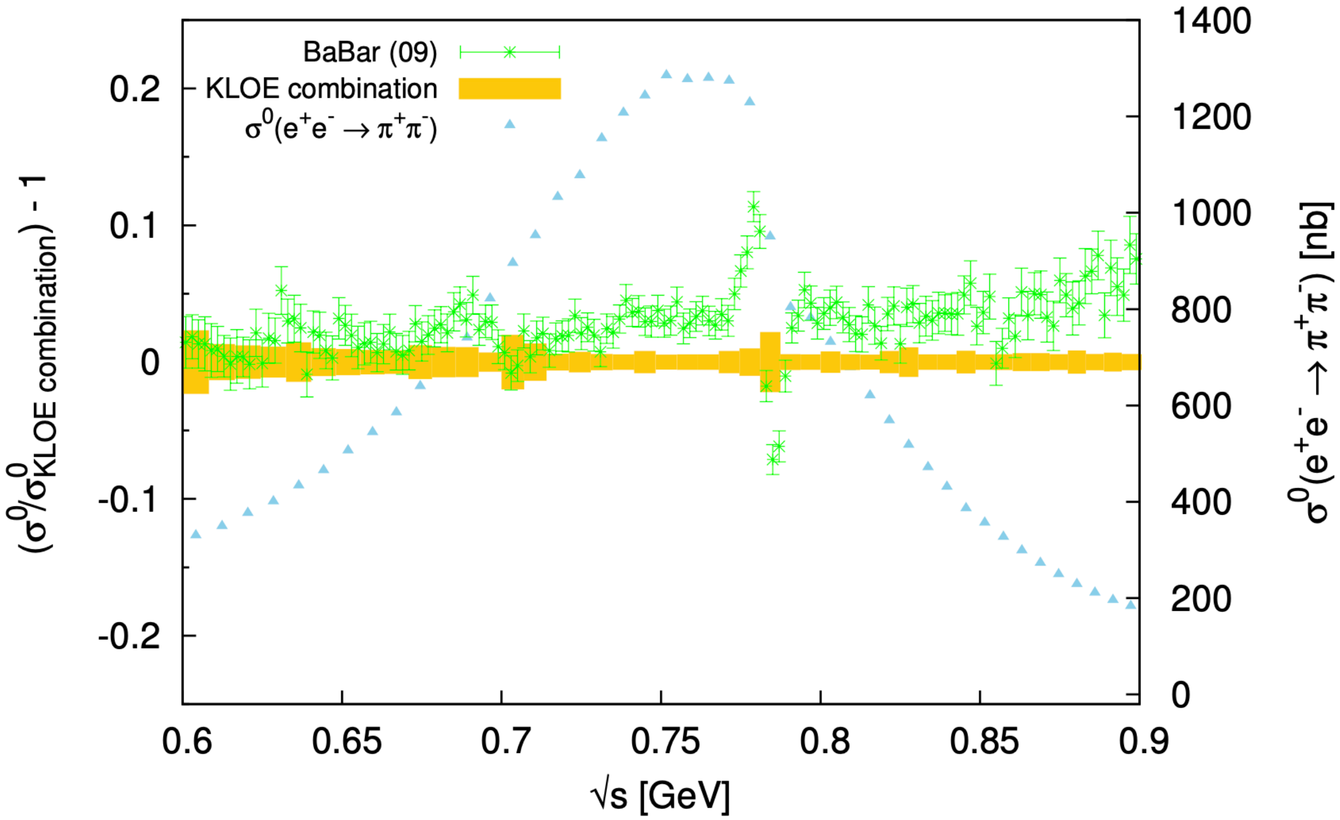
$$a_\mu(\text{the}) = 116\,591\,810(43) \times 10^{-11}$$

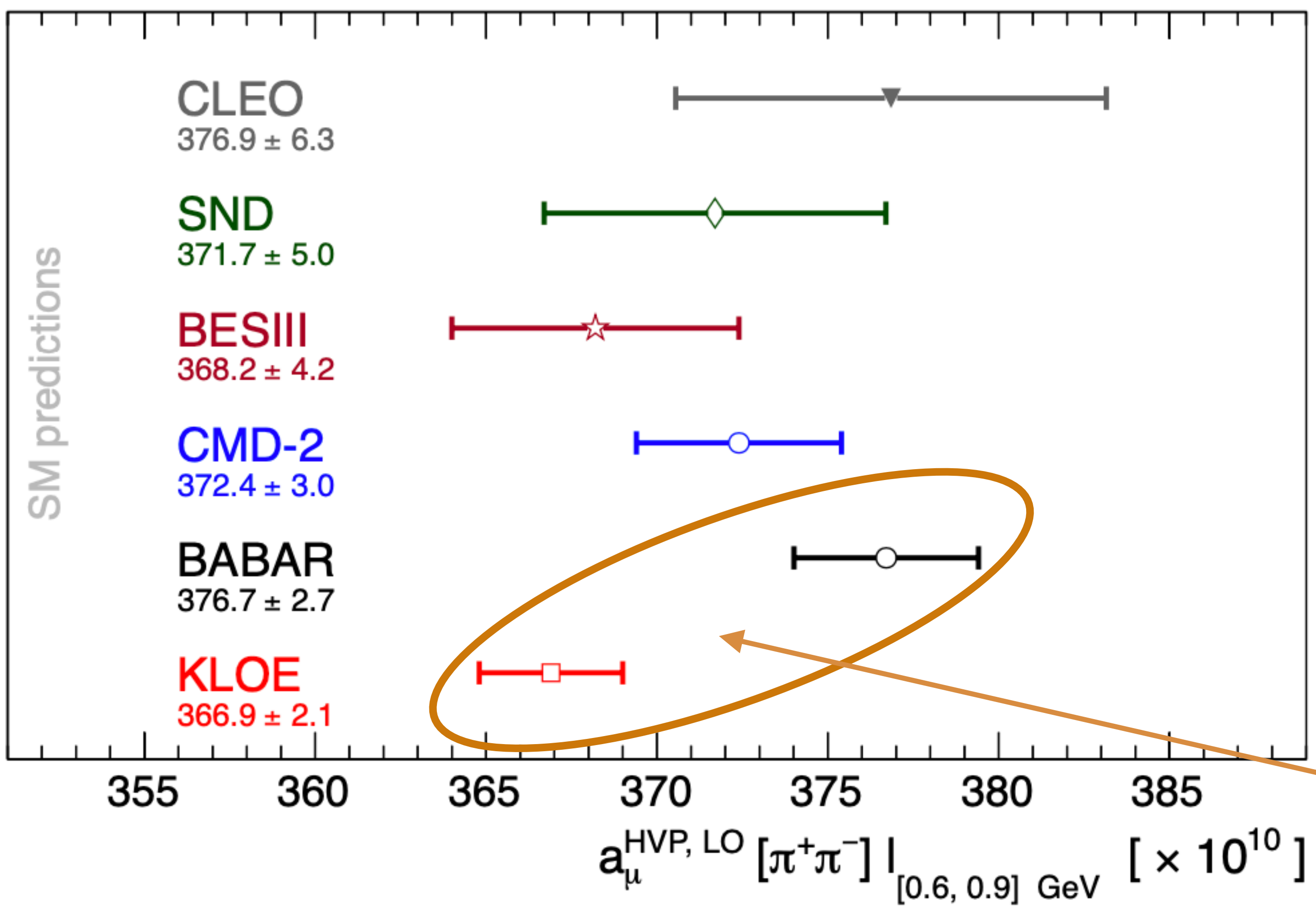
Muon g-2 Theory Initiative, Phys. Rept. 887 (2020) 1-166

1. Theory Status

- Challenges 1:

  Tension in Hadronic Data





$(\sim 4\sigma)$

Can g-2 be ok, and NP is here?

DiLuzio, Masiero, Paradisi, Passera, arXiv:2112.08312 — NO!

Darme, Grilli, Nardi, arXiv:2112.09139 — YES!

1. Theory Status

- Challenges 2:

  Lattice Calculations

Contribution	Value $\times 10^{11}$
Experiment (E821)	116 592 089(63)
HVP LO (e^+e^-)	6931(40)
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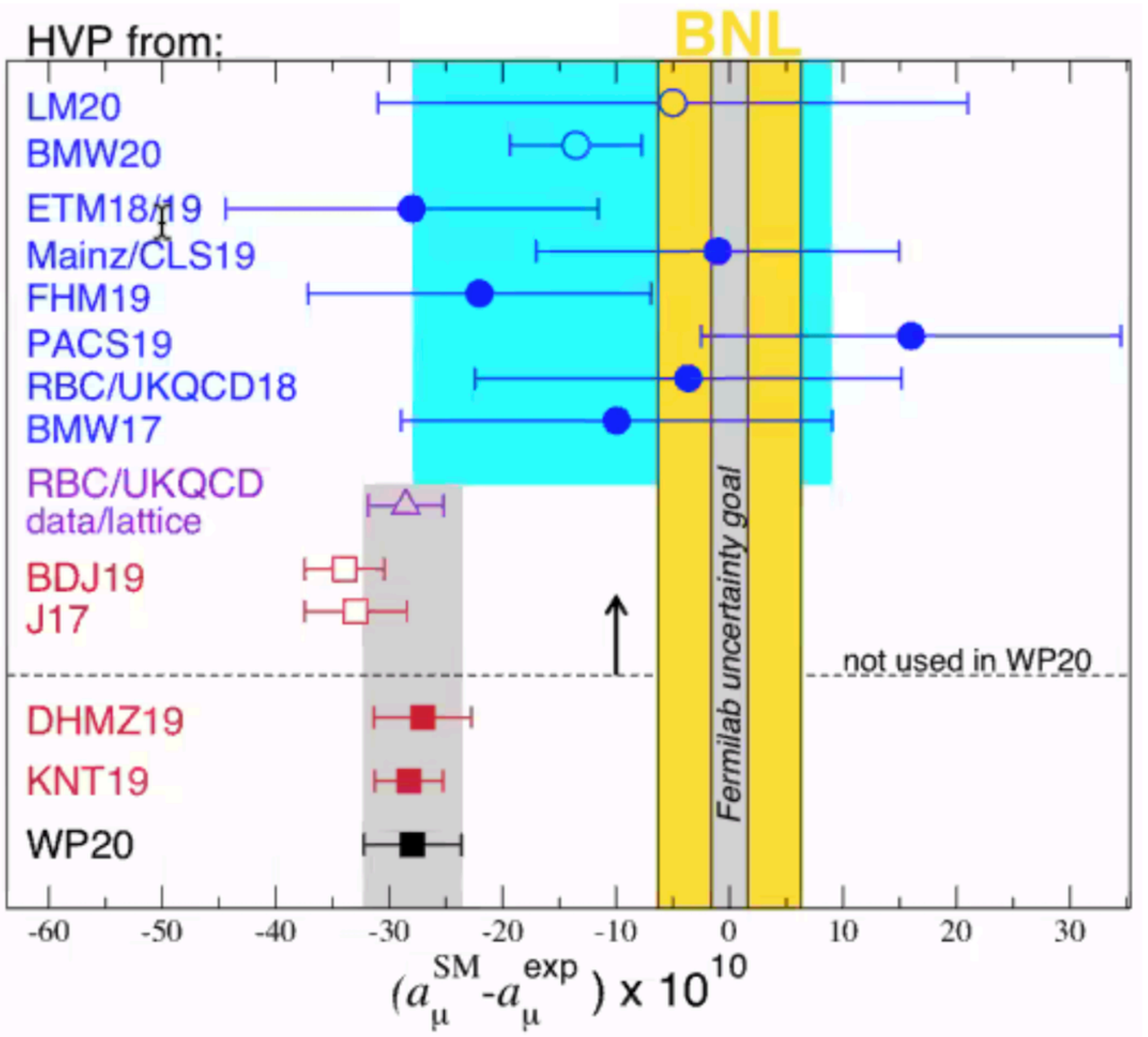
T. Aoyama et al., Phys. Rept. 887 (2020) 1-166



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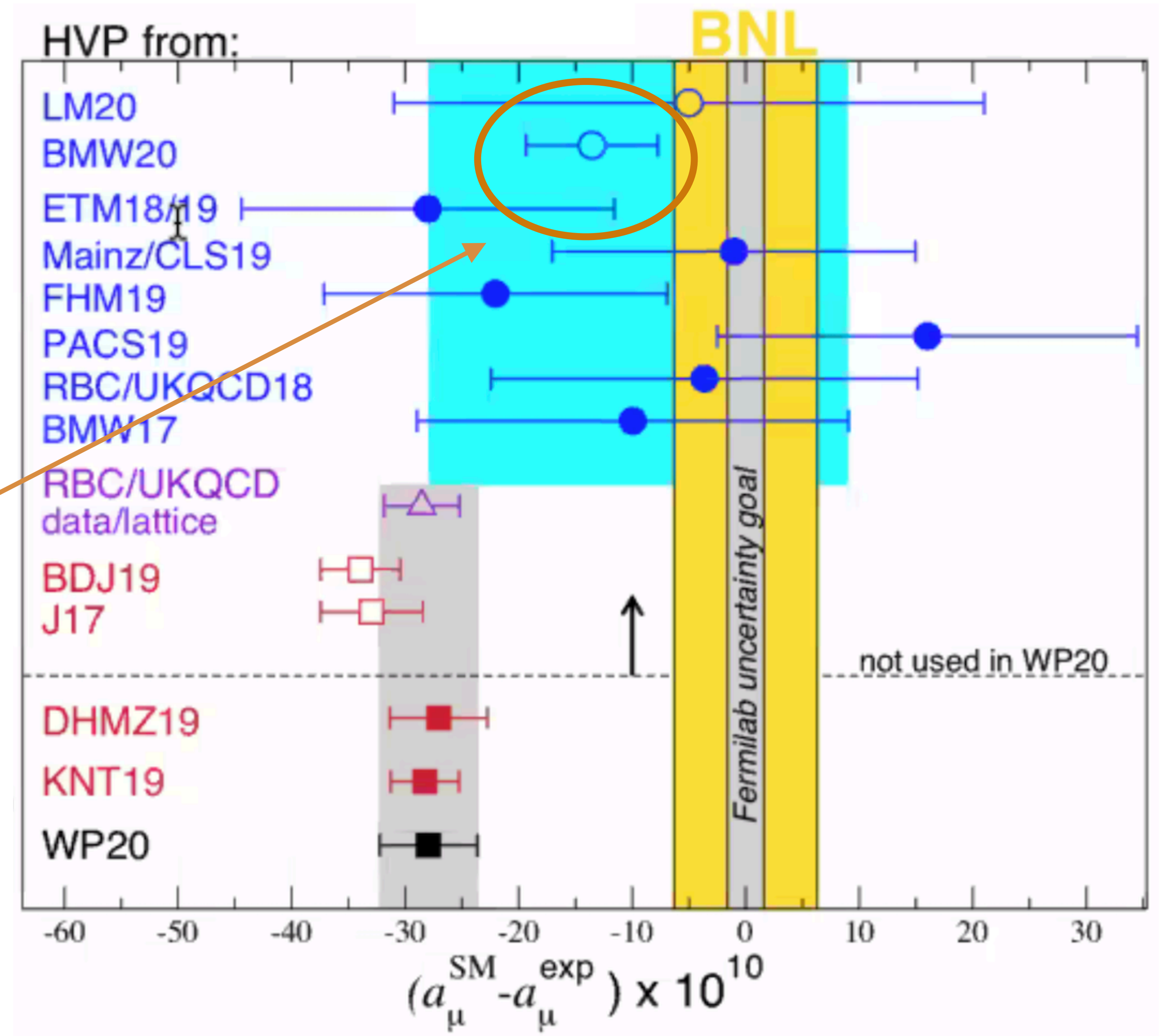
1. Theory Status

- Challenges 2:

  Lattice Calculations

The one evaluation with small uncertainties comparable to the R-ratio method



Article | Published: 07 April 2021

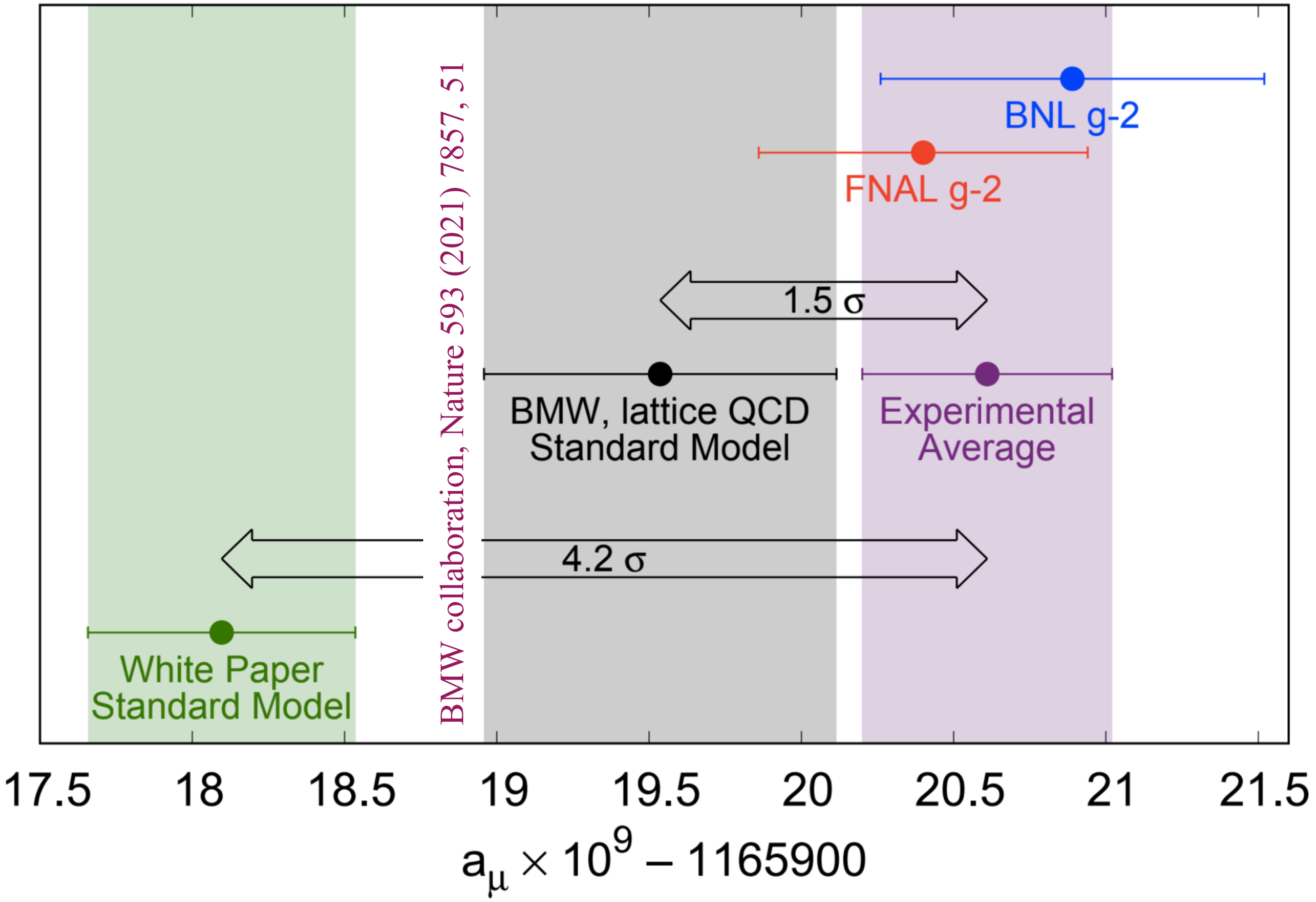
Leading hadronic contribution to the muon magnetic moment from lattice QCD

Sz. Borsanyi, Z. Fodor, J. N. Guenther, C. Hoelbling, S. D. Katz, L. Lellouch, T. Lippert, K. Miura, L. Parato, K. K. Szabo, F. Stokes, B. C. Toth, Cs. Torok & L. Varnhorst

simulations to compute the LO-HVP contribution. We reach sufficient precision to discriminate between the measurement of the anomalous magnetic moment of the muon and the predictions of dispersive methods. Our result favours the experimentally measured value over those obtained using the dispersion relation. Moreover, the methods used and

1. Theory Status

- State of affairs



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

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

$$a_\mu(\text{the}) = 116\,591\,810(43) \times 10^{-11}$$

Muon g-2 Theory Initiative, Phys. Rept. 887 (2020) 1-166

1. Theory Status

- Challenges 3:

  EW Precision fit

However, issues with EW data fits:

A. Keshavarzi et al., Phys.Rev.D 102 (2020) 3, 033002

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

$$R(s) = \frac{\sigma^0(e^+e^- \to \mathrm{hadrons}(+\gamma))}{\sigma_{\mathrm{pt}}}$$

$$\Delta a_\mu \sim 4.2\sigma$$

1. Theory Status

- Challenges 3:

  EW Precision fit

However, issues with EW data fits:

A. Keshavarzi et al., Phys.Rev.D 102 (2020) 3, 033002

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$$R(s) = \frac{\sigma^0(e^+e^- \to \mathrm{hadrons}(+\gamma))}{\sigma_{\mathrm{pt}}}$$

→

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi} \int_0^1 dx\,(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

$$\Delta\alpha_{\mathrm{had}}^{(5)}(M_Z^2) = 0.02722(41)$$ EW fit

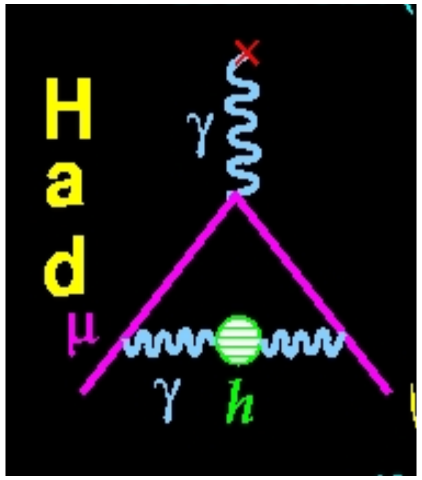
$$\Delta\alpha_{\mathrm{had}}^{(5)}(M_Z^2) = 0.02761(11)$$ Dispersion approach

$$\Delta a_\mu \sim 0$$

?

$$M_W\,,\ \sin\theta_W\,,\ M_H\,,\ a_e$$

1. Theory Status



- Prospects:

MUonE Experiment Carloni, Passera, Trentadue, Venanzoni, Phys. Lett. B 746 (2015) 325

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

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

C. Calame et al., Phys. Lett. B 746 (2015) 325

$$t(x) = \frac{x^2 m_\mu^2}{x-1}$$

Momentum transfer

$$\alpha(t) = \frac{\alpha(0)}{1-\Delta\alpha(t)}$$

Fine-structure constant

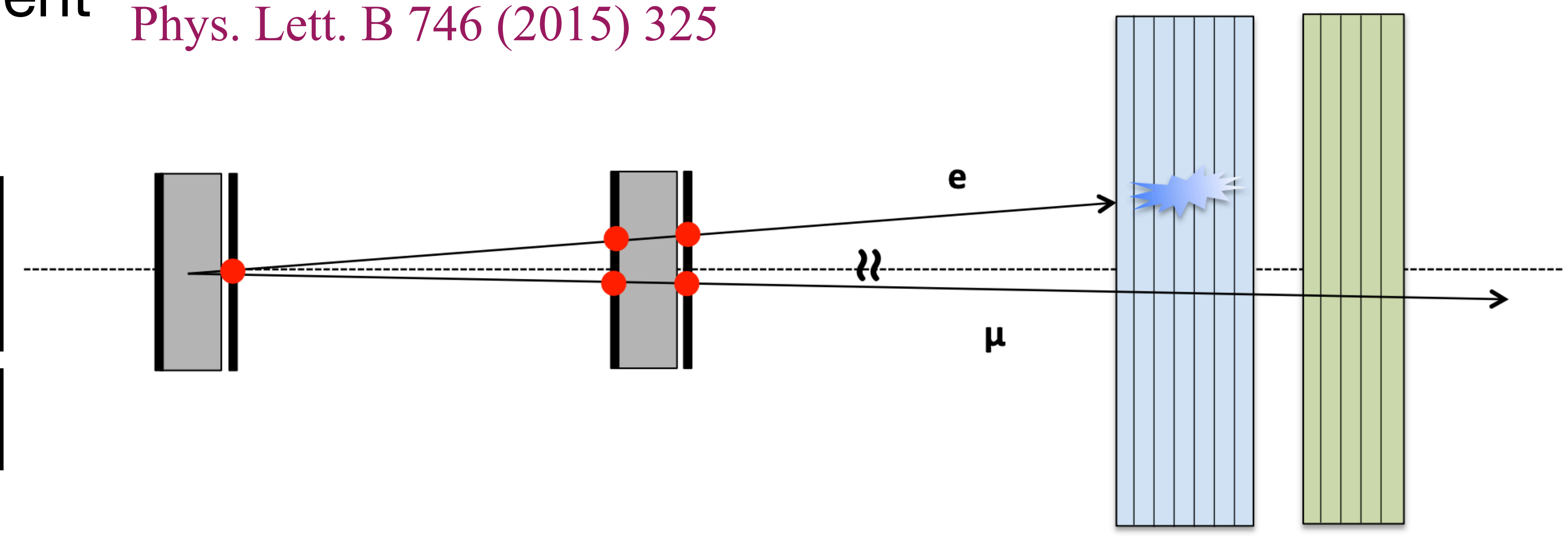
1. Theory Status

- Prospects:

MUonE Experiment Carloni, Passera, Trentadue, Venanzoni, Phys. Lett. B 746 (2015) 325

150 GeV Muon beam!

10^7 mu/s

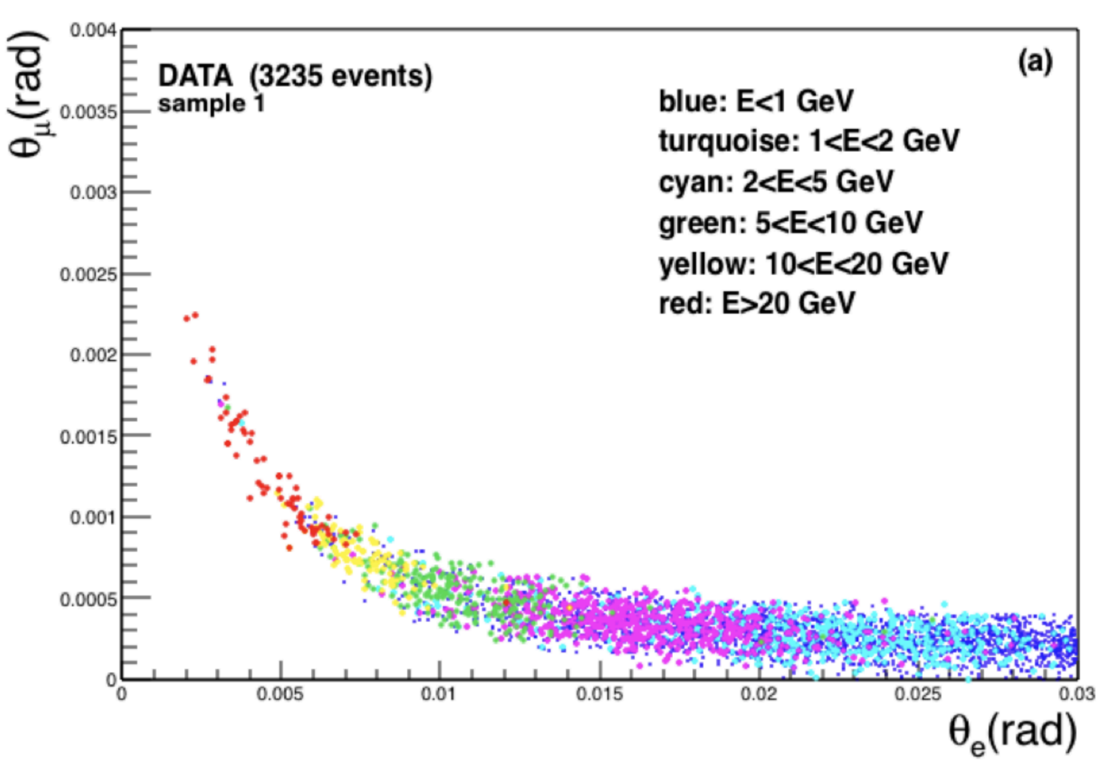


- Measure the running of alpha $\alpha(t)$
- Get $\Delta\alpha(t)$
- Subtract purely leptonic contribution

$\Delta\alpha_{\text{lep}}$ (calculated in perturbation theory!)

Stat. uncertainty ~0.3%

2y of data taking!

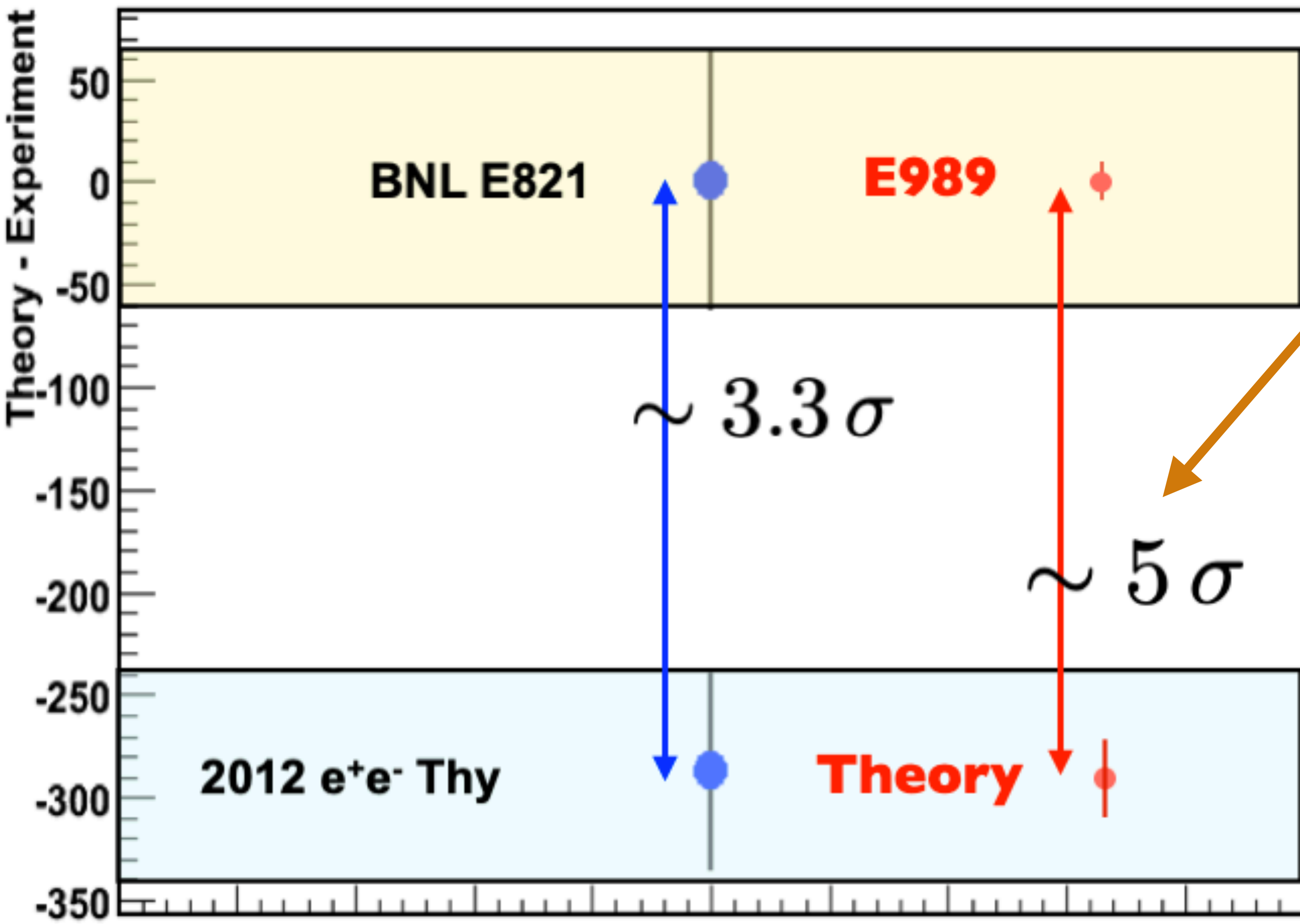


Abbiendi, Ballerini, Banerjee, Bernhard, Bonanomi, JINST 16 (2021) 06, P06005

1. Theory Status

- What if?

If new physics is confirmed, what comes next?



	BNL E821	FNAL 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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Outline

1. Muon Anomalous Magnetic Moment
    - Experiment Status
    - Theory Status
2. **New Physics Explanations**
    - Singlet Models
3. Summary

2. New Physics Explanations

- Ingredients for (g-2)μ

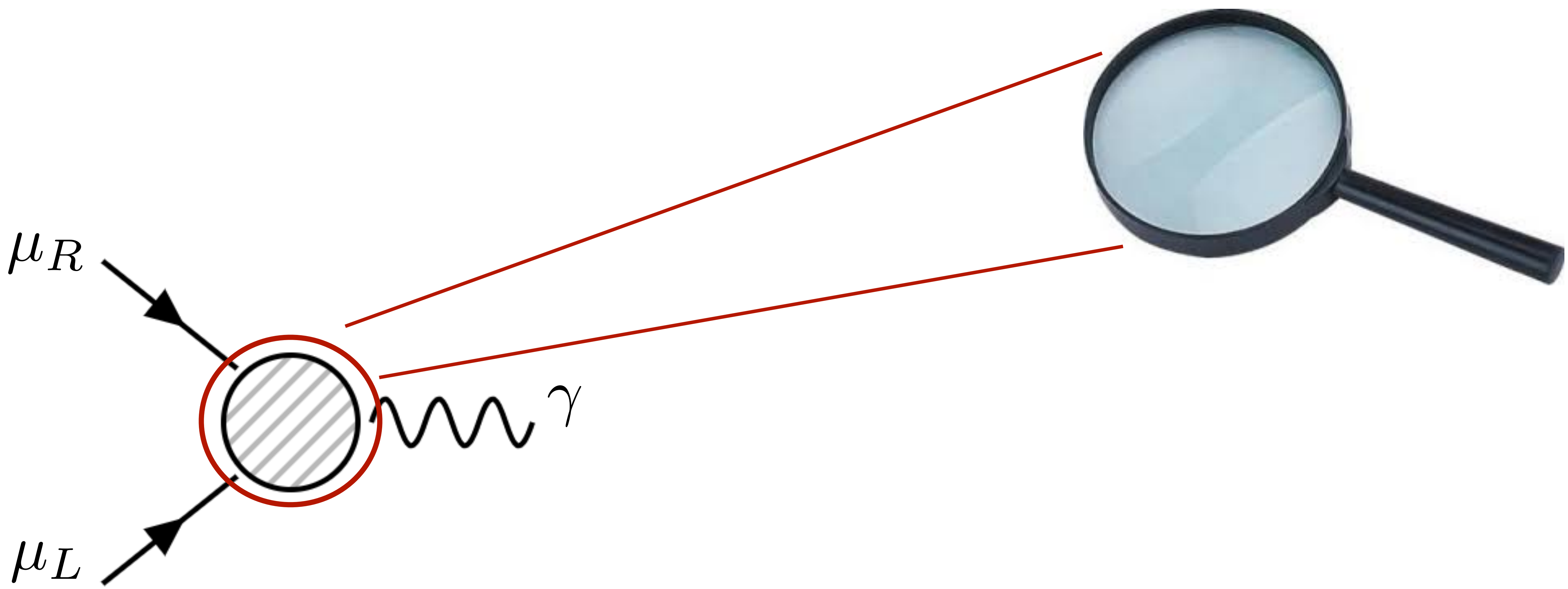
(Chiral flip - LR operator)

$$H^\dagger L \sigma_{\alpha\beta} \mu_R F^{\alpha\beta}$$

(Higgs insertion)

(Photon field strength tensor)

Dipole Operator



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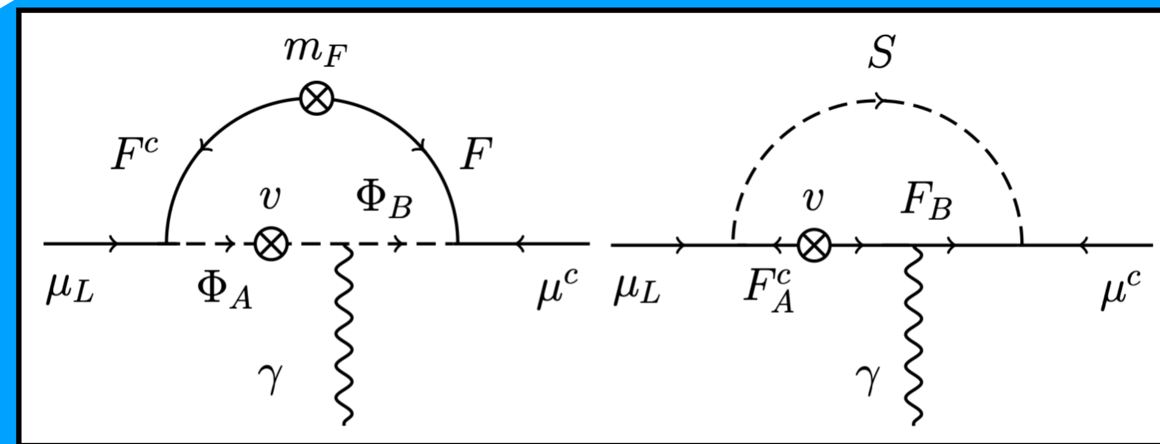
2. New Physics Explanations

Heavy

- Theory Space

Electroweak Models



Leptoquarks

2HDM + VLL

MSSM

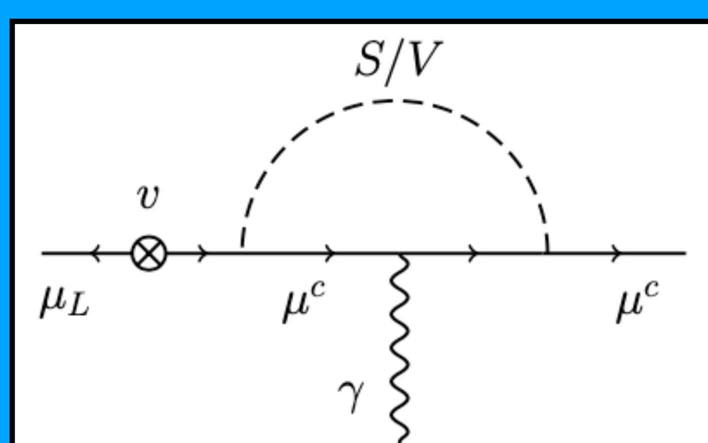
B-L

ALPs

Heavy Neutral Leptons

Vector-Like Leptons

Lmu - Ltau



SM+S

Bridge Topologies

2HDM+S

Two-loops

Light

Singlet Models

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   - **Singlet Models**
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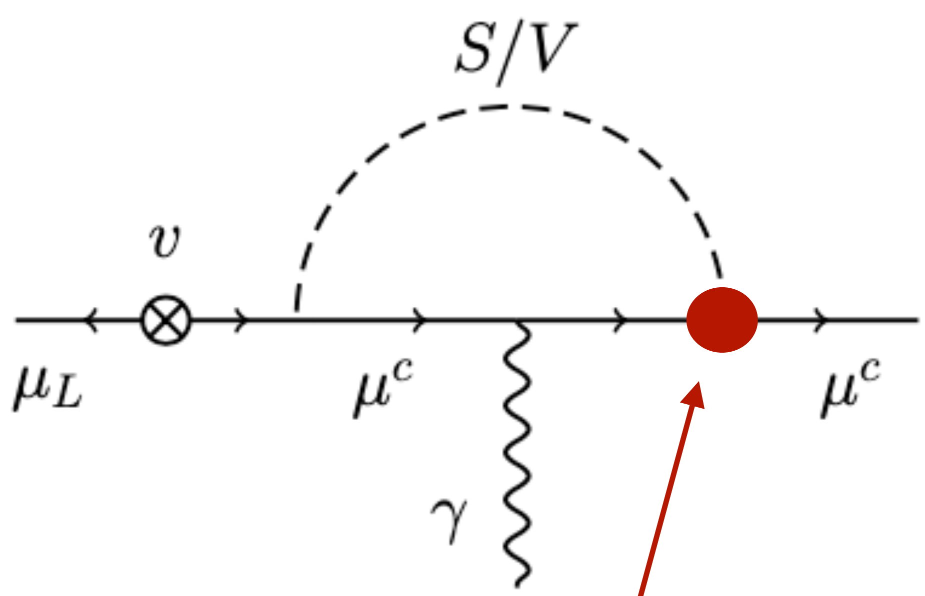
2. Singlet Models

- What range of masses makes sense?



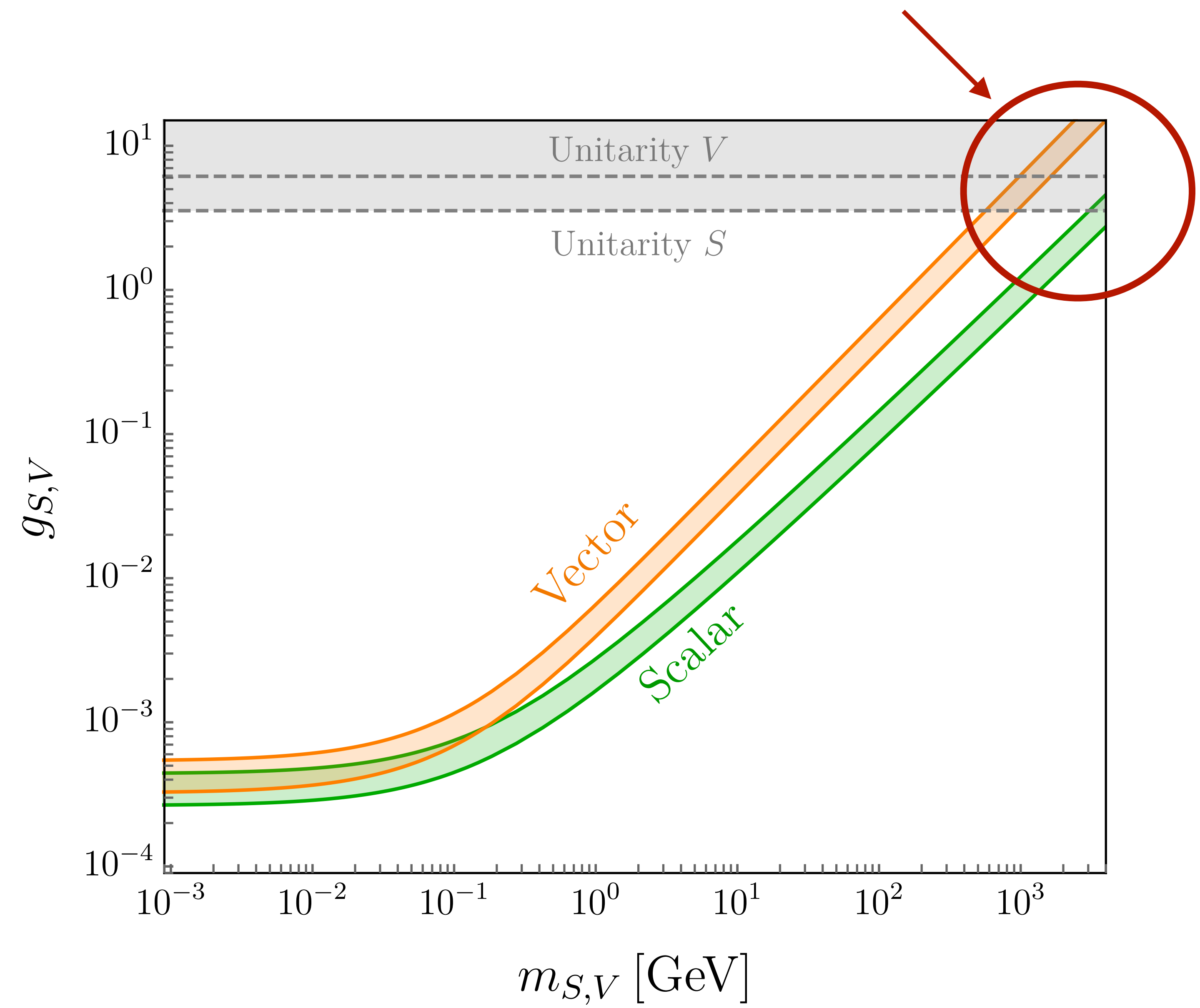
$$\Delta a_\mu \sim N_{\rm BSM} \frac{m_\mu^2}{4\pi^2} \frac{g_{S,V}^2}{m_{S,V}^2} C_{\rm loop}$$

We would like:

$$\Delta a_\mu = 279$$

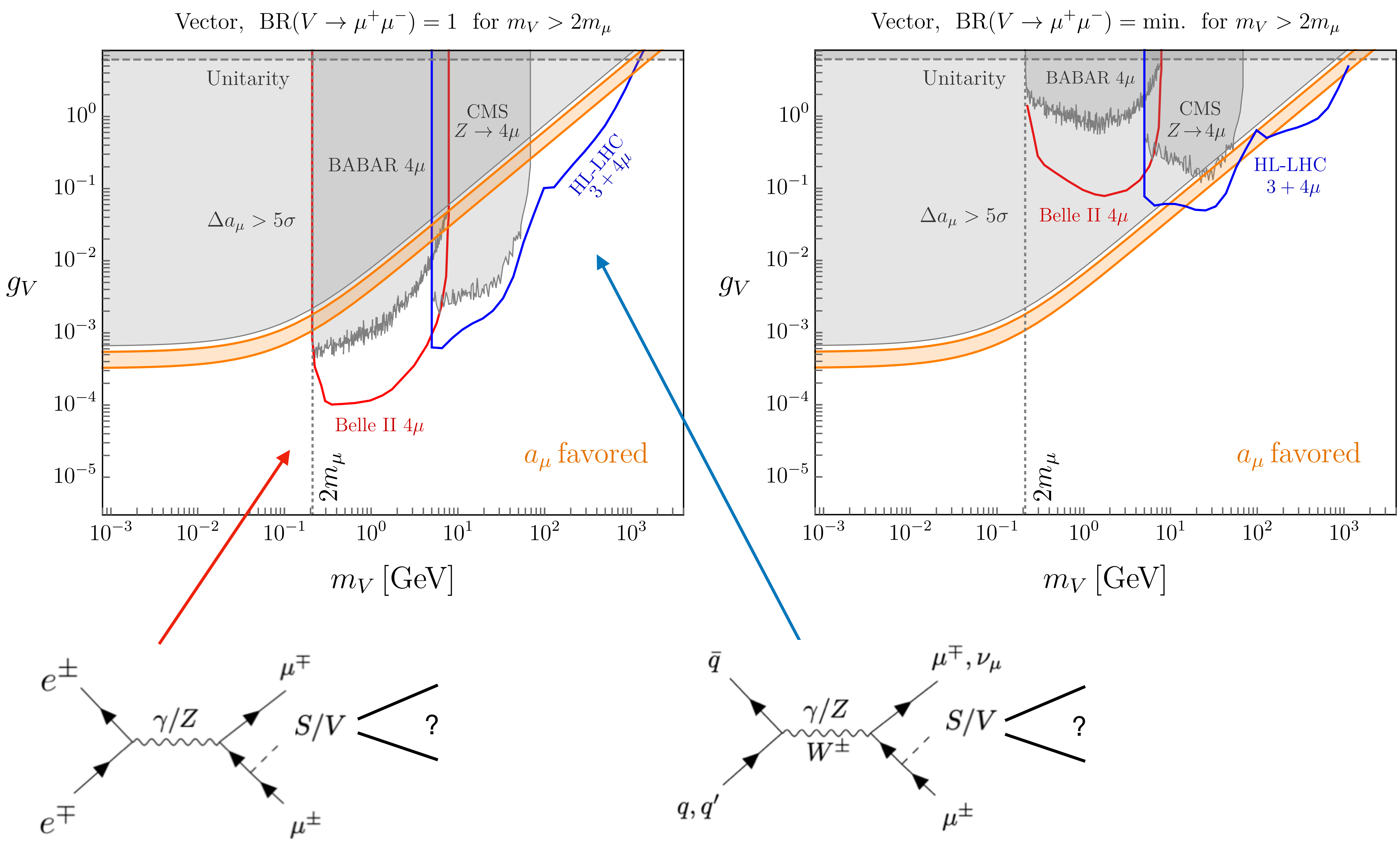
To explain the anomaly!

NP masses upper bound!



2. Singlet Models

- Probes?



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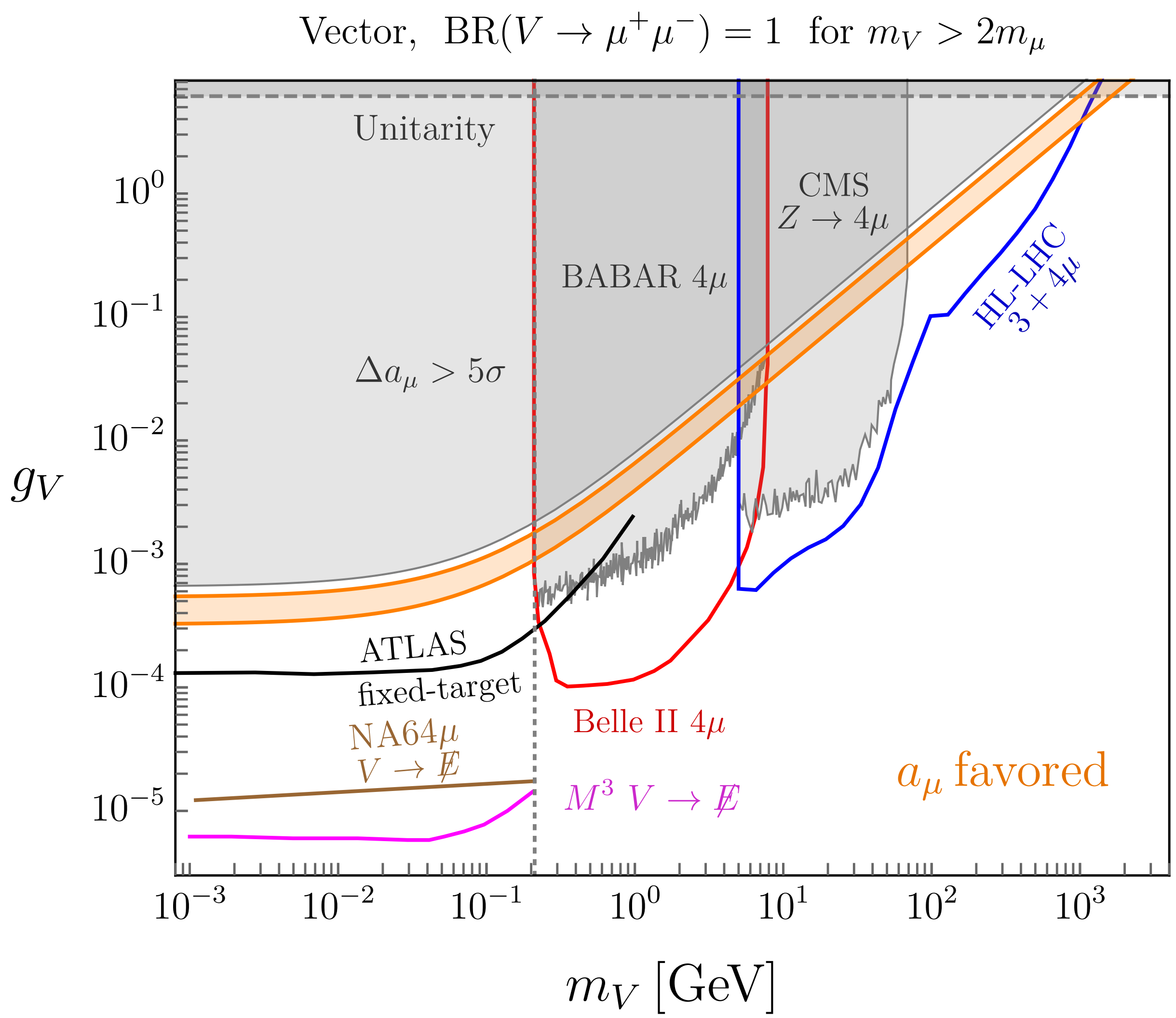
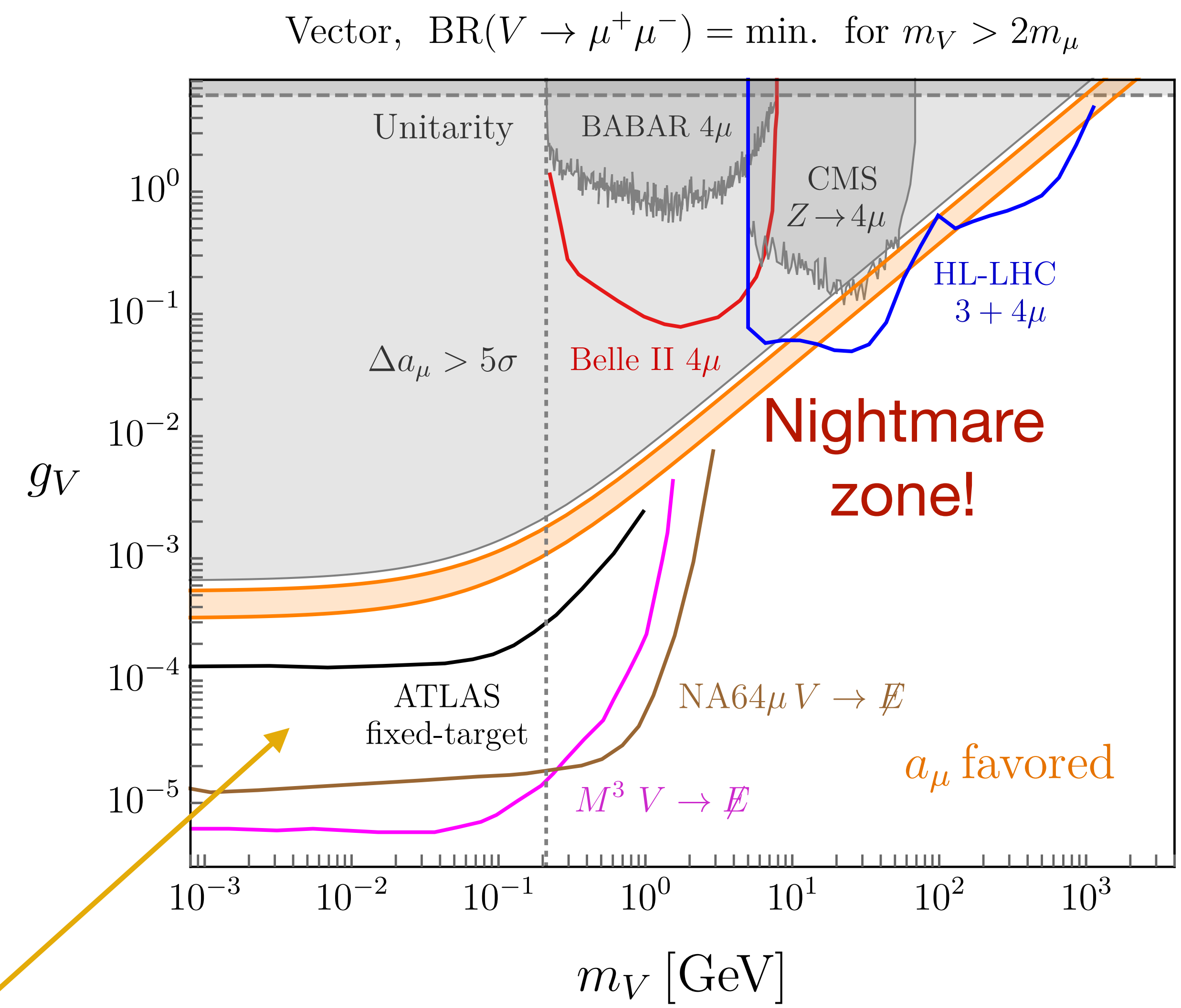
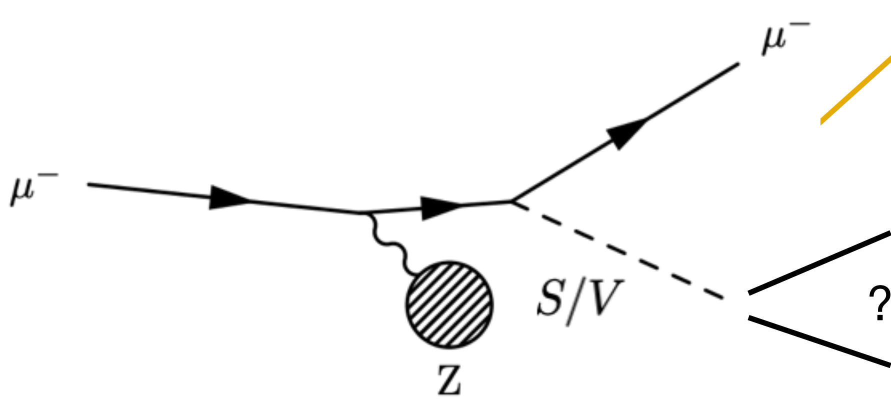
2. Singlet Models

- Probes?







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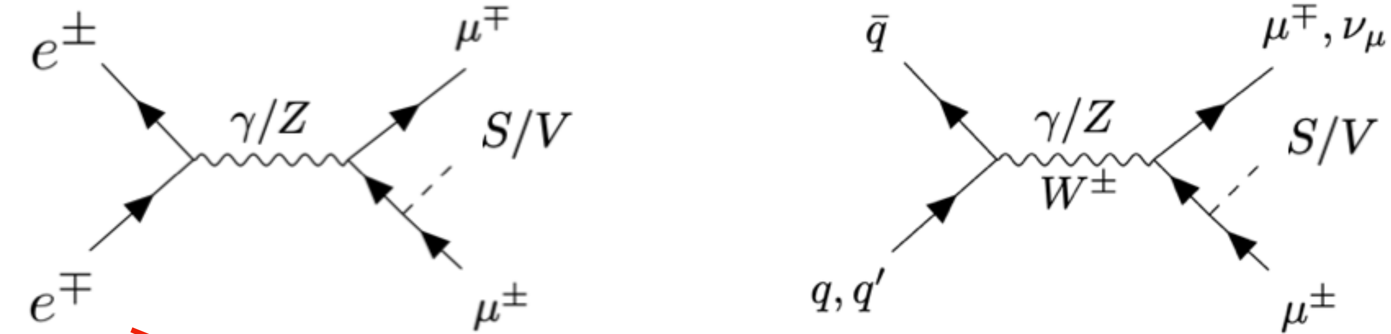
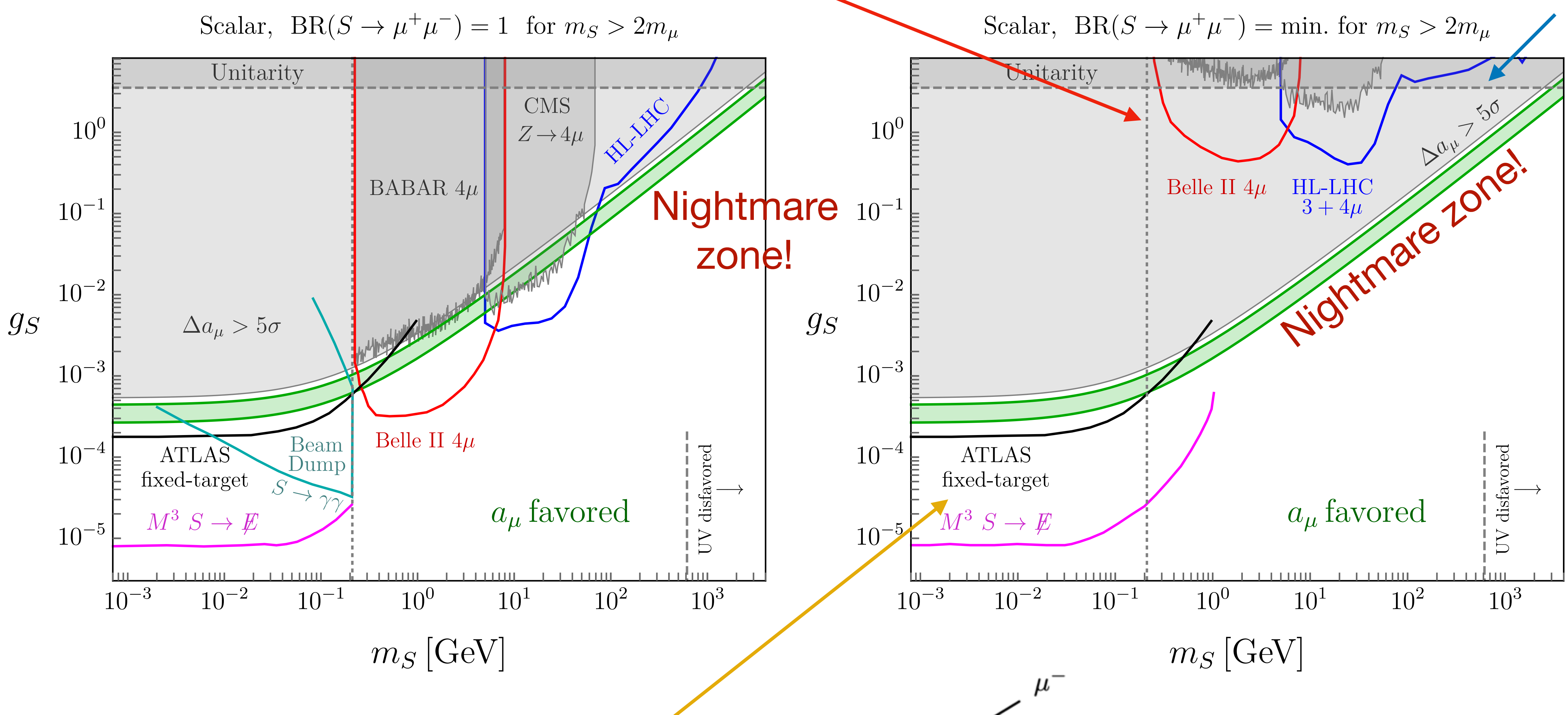
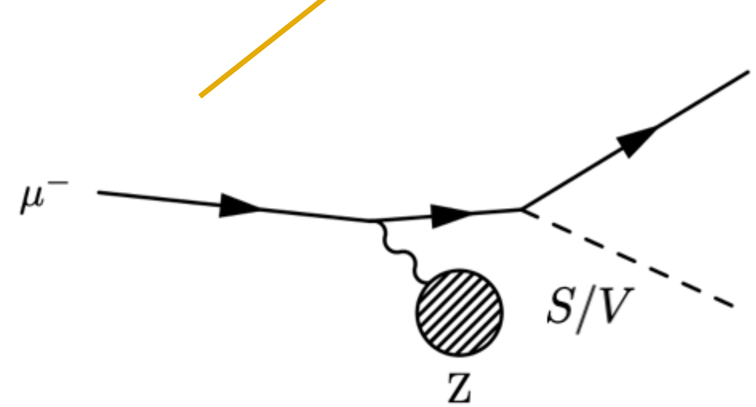
2. Singlet Models

- Probes?







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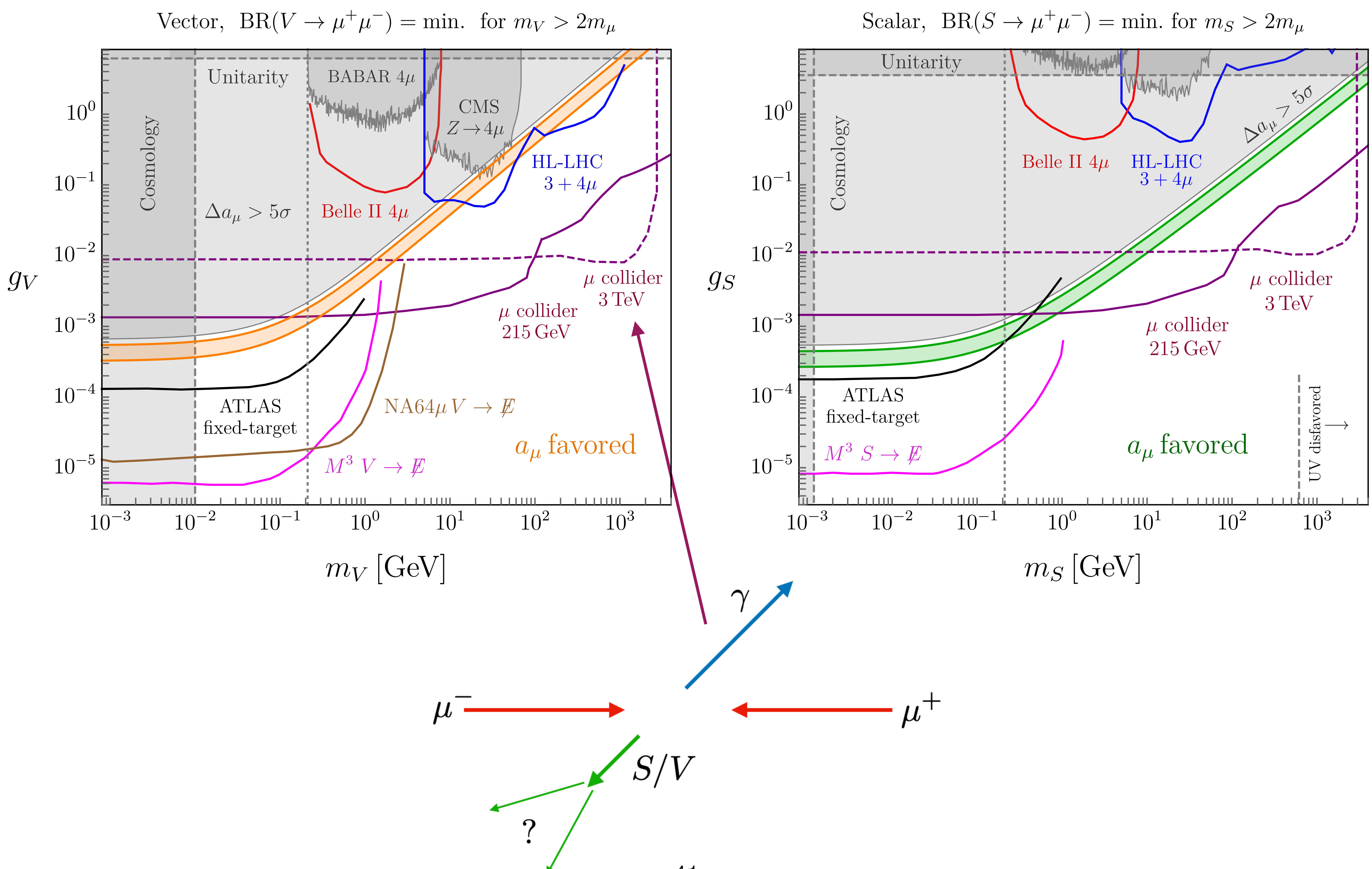
2. Singlet Models

- Probes?



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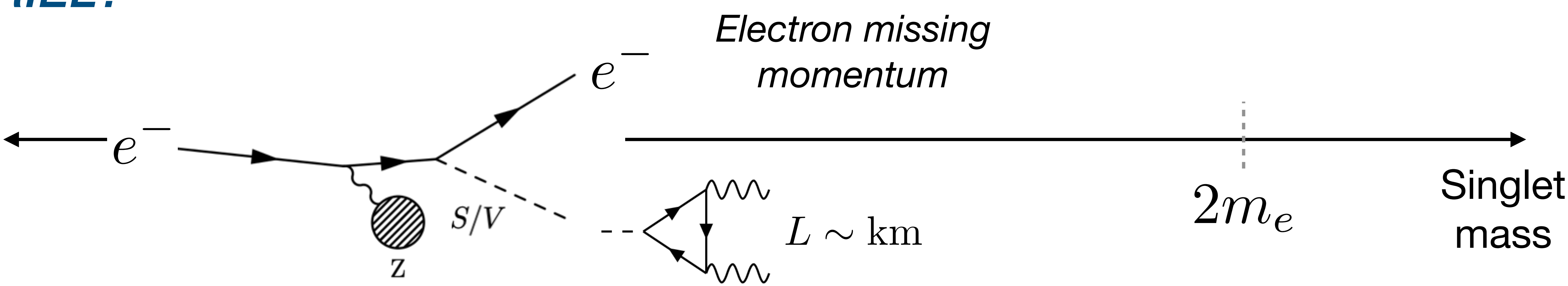
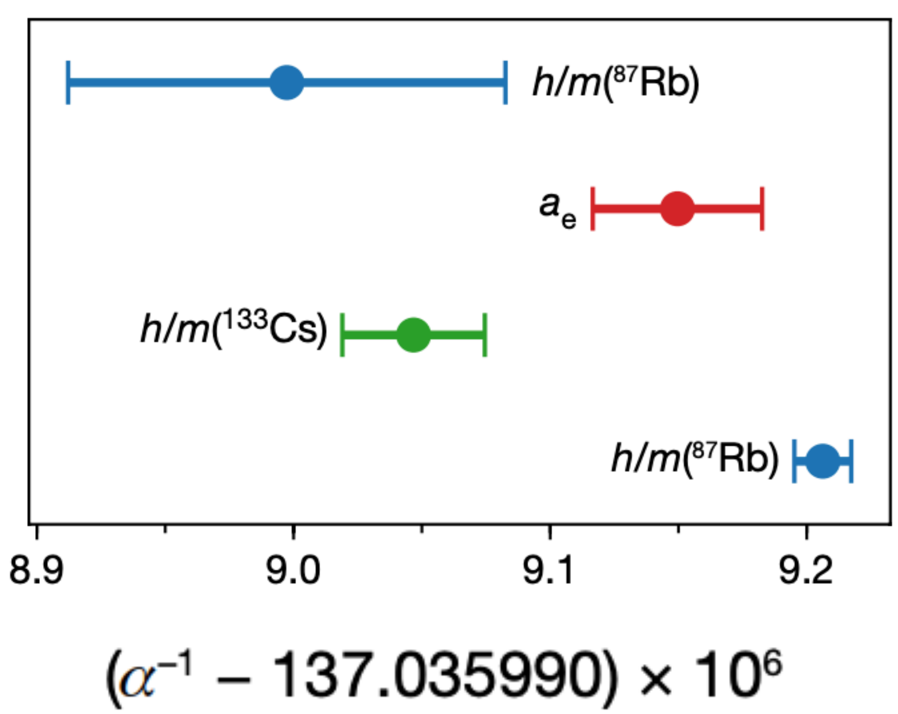
ARIEL?

ARIEL?



Motivation from electron g-2 (?)



$$a_e(\text{exp}) - a_e(\text{the}) \sim -2.5\,\sigma$$
$$a_e(\text{exp}) - a_e(\text{the}) \sim 1.6\,\sigma$$

?

Issues with Cosmology (?)

$$\Gamma_{S,V} \sim g_{S,V}^2 T$$

$$T \gtrsim \frac{1.66\sqrt{g_\star}}{g_{S,V}^2 M_{\text{Pl}}} \approx 1\,\text{eV}\left(\frac{5\times 10^{-4}}{g_{S,V}}\right)^2$$

$$\Delta N_{\text{eff}} \qquad ?$$

$$m_V \gtrsim 10\,\text{MeV} \quad , \quad m_S \gtrsim 1\,\text{MeV}$$

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Summary

1. Measurements of the anomalous magnetic moment of fundamental particles are important laboratories for high precision tests of the SM. In the incoming years, progress in theory as well as in current and new experiments will shed light to the muon (g-2)μ anomaly.

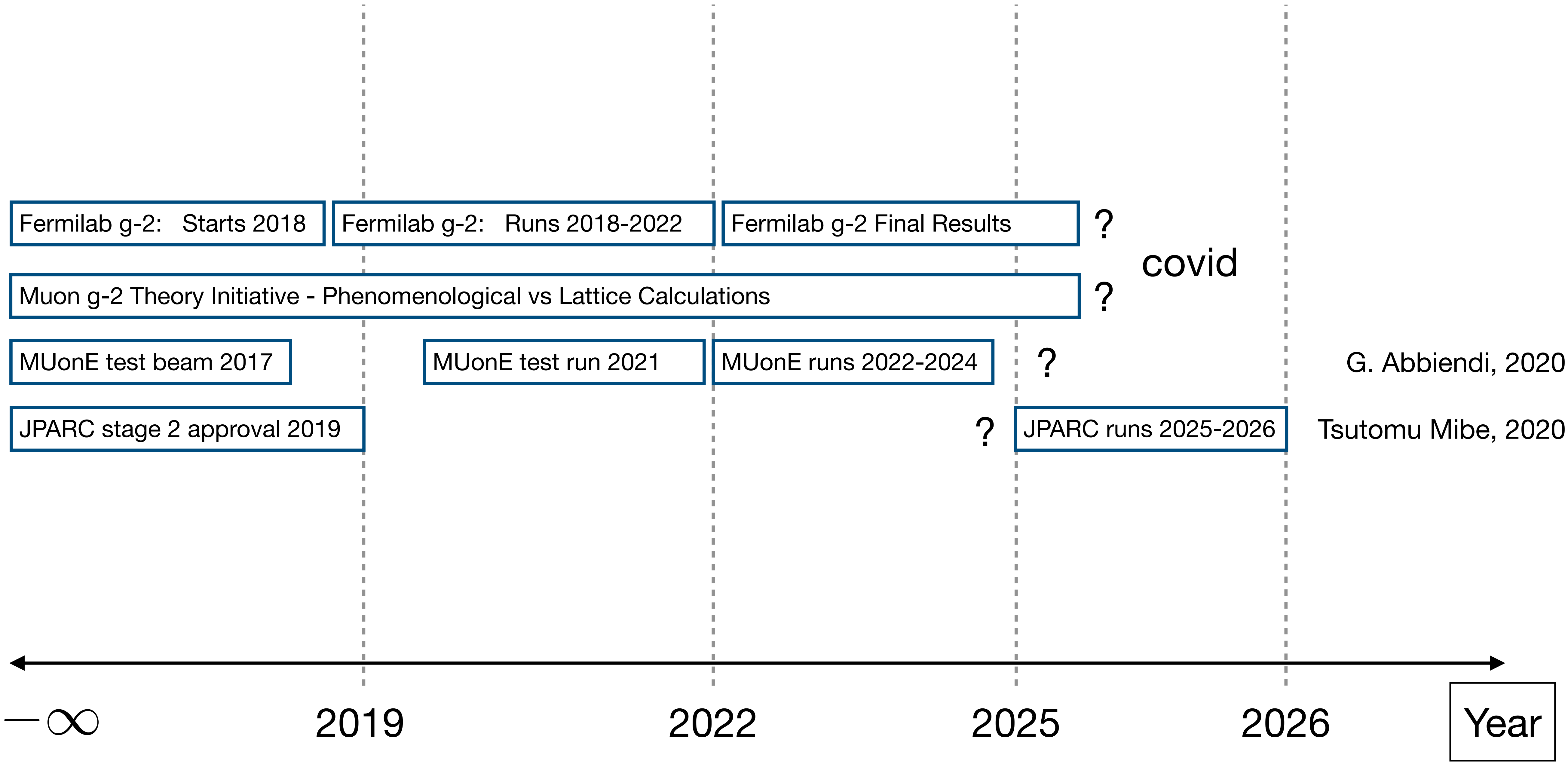
2. Simple new physics models aiming to explain the anomaly predict new states in the range MeV-TeV (**Singlet Models**).

3. A combination of **Low Energy Experiments and High Energy Colliders** can probe the parameter space of new physics for (g-2)μ in the context of **Singlet Models**.

Thanks!

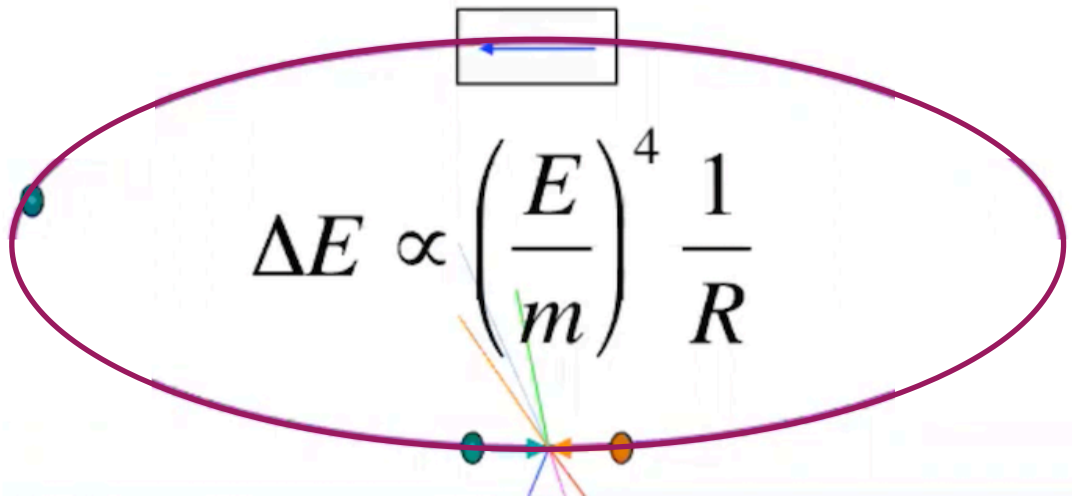
1. Experiment Status

- Timeline



2. Muon Colliders?

- Circular colliders: Multi-pass! ➔ Bad for ee, ok for pp

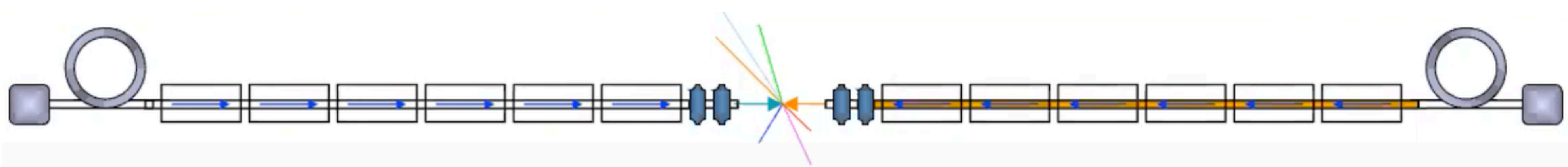


$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

~~Electrons~~

Protons
Energy frontier

- Linear colliders: Only one pass ➔ high lumi = high Power



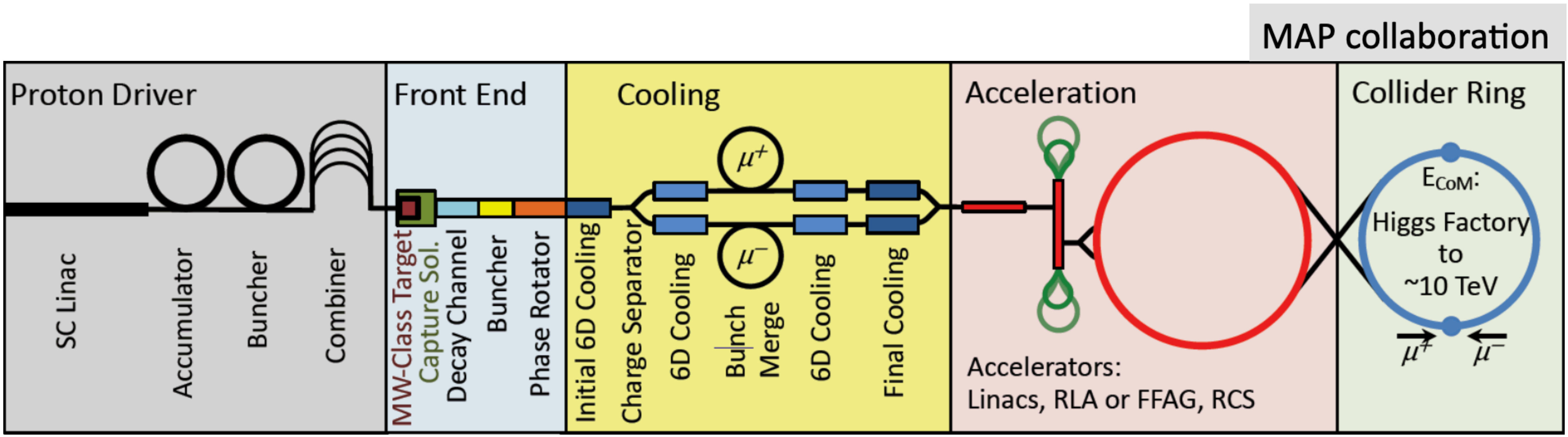
- Circular muon colliders?

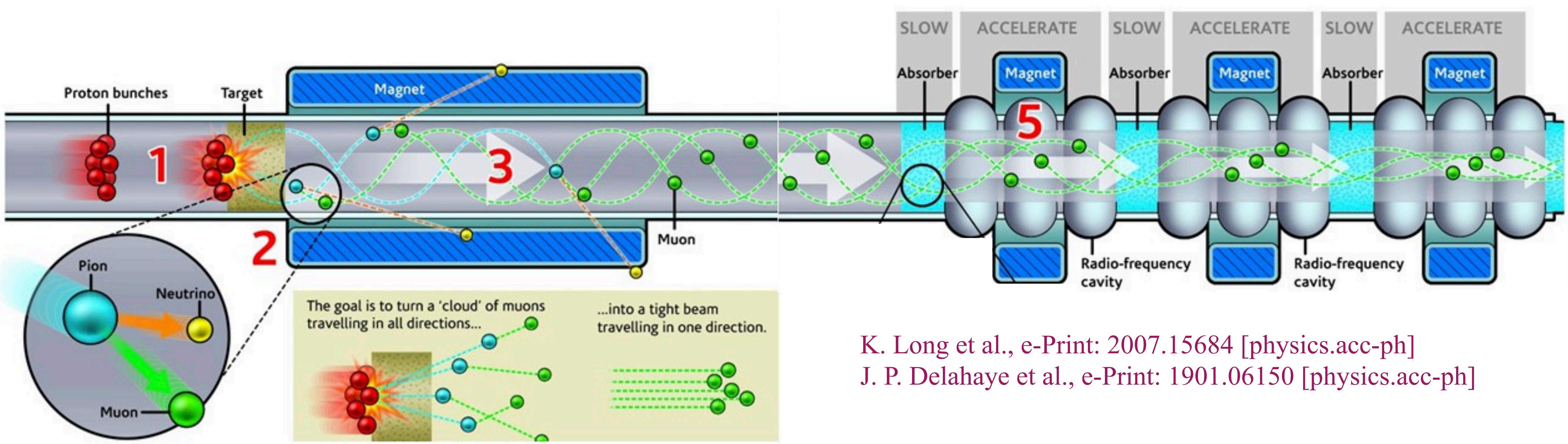
High energy!

High luminosity!

Clean?

2. Muon Colliders?





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

Aspirational Timeline