Dial M for Muons

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+Gustavo Marques-Tavares, Diego Redigolo, Kohsaku Tobioka
1902.07715 *Phys.Rev.Lett.* (2020)

+Yonatan Kahn, Nhan Tran, Andrew Whitbeck
1804.03144 *JHEP* (2018)

+Rodolfo Capdevilla, David Curtin, Yonatan Kahn
2101.10334, 2006.16277 *Phys.Rev.D* (2021)

APEC Seminar June, 9 2021

Overview

Current Status of g-2

Singlet Models

Electroweak Models

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Singlet Models

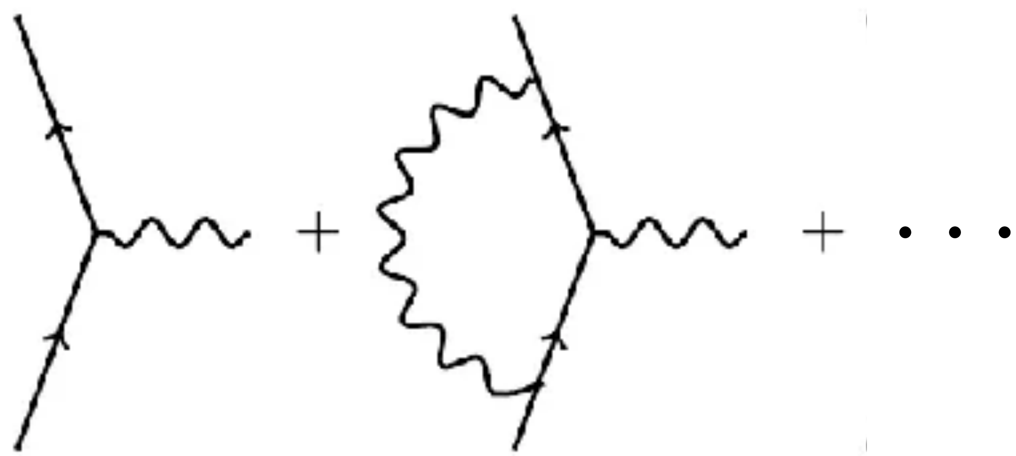
Electroweak Models

Muon Anomalous Magnetic Moment

Lepton dipole moment $\vec{\mu}_\ell = \pm g_\ell \frac{e}{2m_\ell}\vec{S}$ $a \equiv \frac{g-2}{2}$

Tree level QED prediction: $a = 0$

Quantum loop corrections: $a \neq 0$



$$\rightarrow g = 2 + \frac{\alpha}{2\pi} + \cdots$$

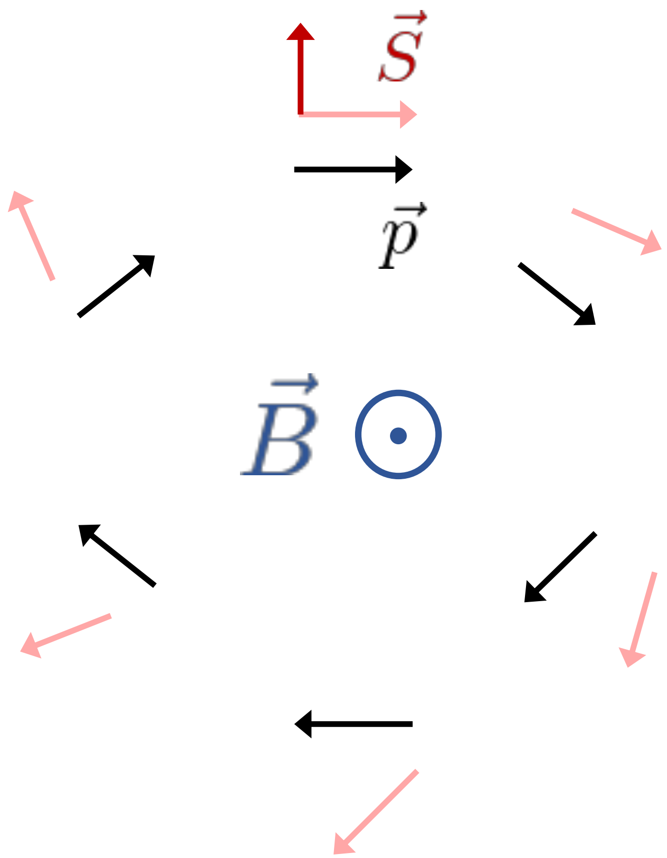
Sensitive to all known ***and unknown*** particles coupled to leptons

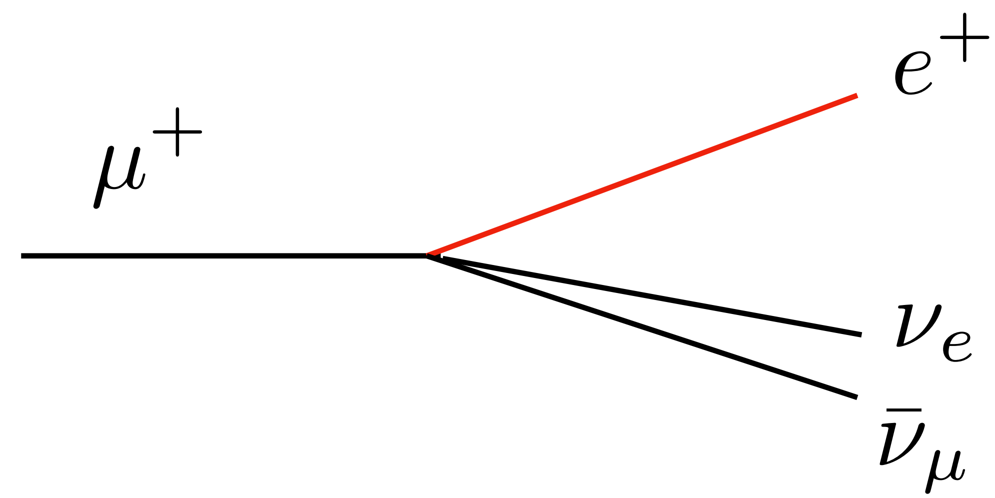
For electrons agrees SM to ~ 12 decimals, best prediction in history

Spin precession in a uniform B field

$$\omega_a = a_\mu \frac{eB}{2m_\mu}$$

Lab Frame





$$\frac{d\Gamma}{dE} = A\left[1 - B(\vec{s}\cdot\vec{p})\right] \qquad \vec{s}\cdot\vec{p} \propto \cos\omega_a t$$

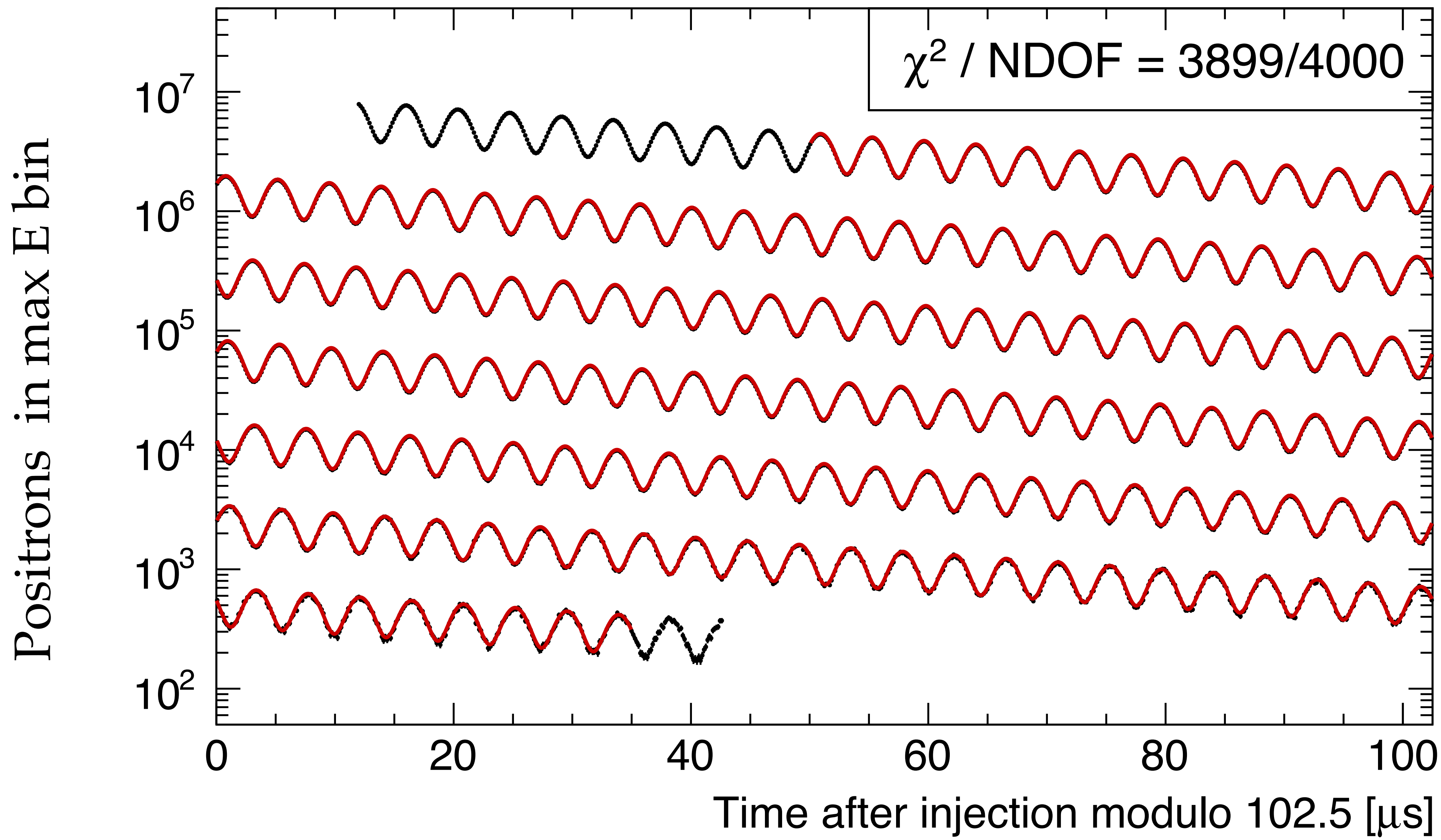
Upon $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay e^+ emitted preferentially along $\vec{S}$

Asymmetry in e^+ energy distribution measures ω_a

Graphic: Ryan Janish

Spin precession in a uniform B field

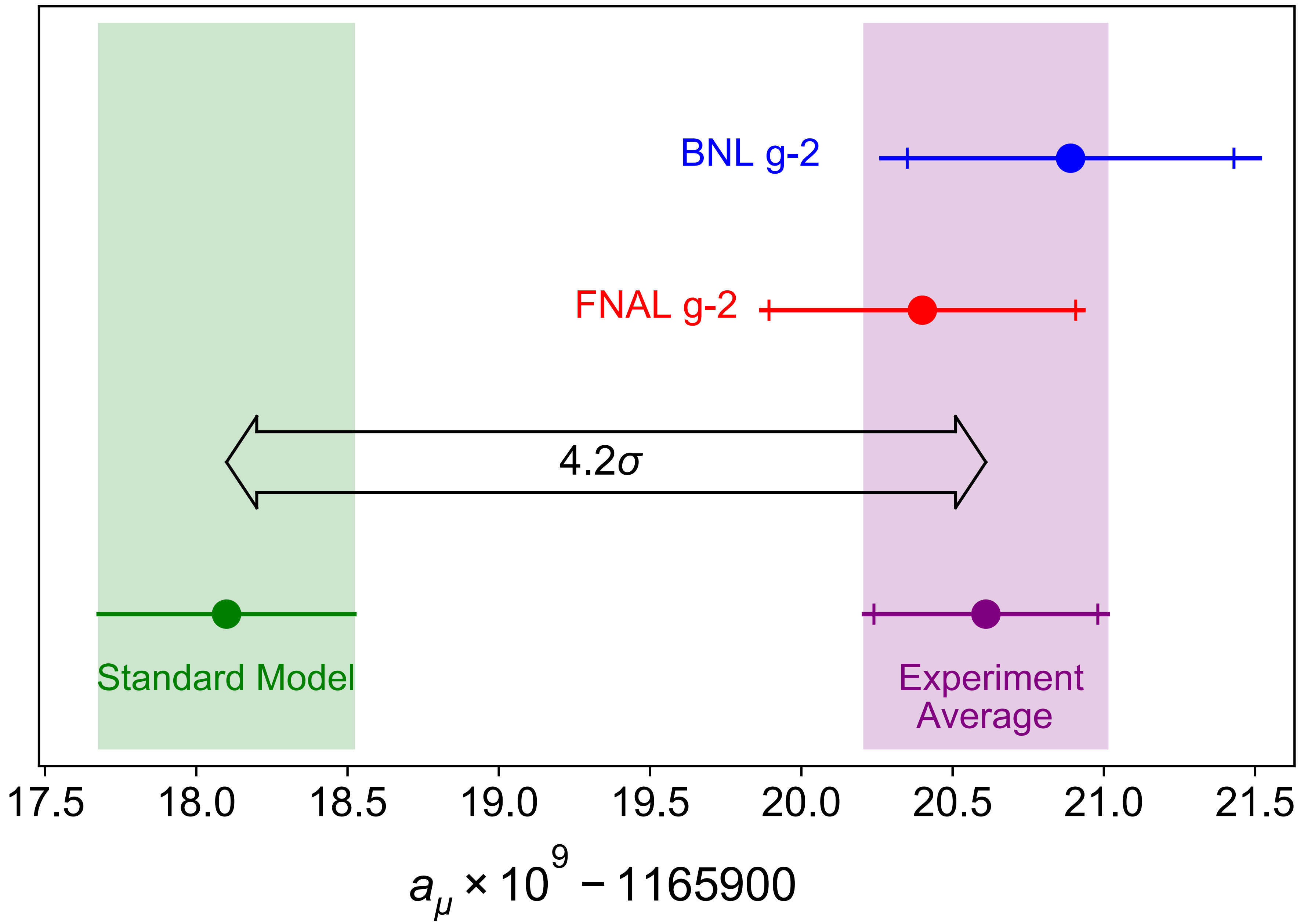
$$\omega_a = a_\mu \frac{eB}{2m_\mu}$$



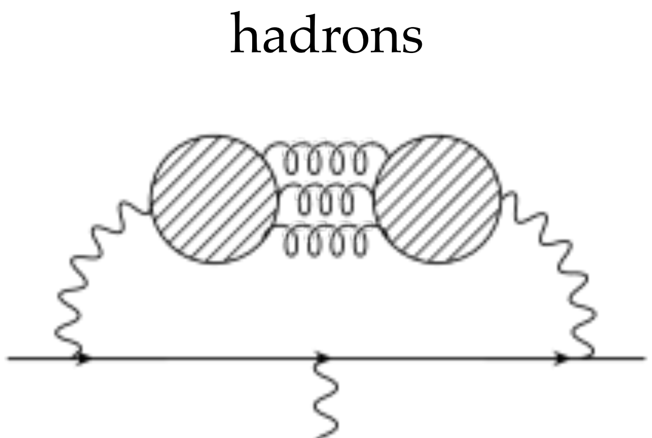
$$N_e(t) \propto e^{-t/\tau_\mu}\,(1 + B' \cos \omega_a t)$$

g-2 collaboration 2104.03247

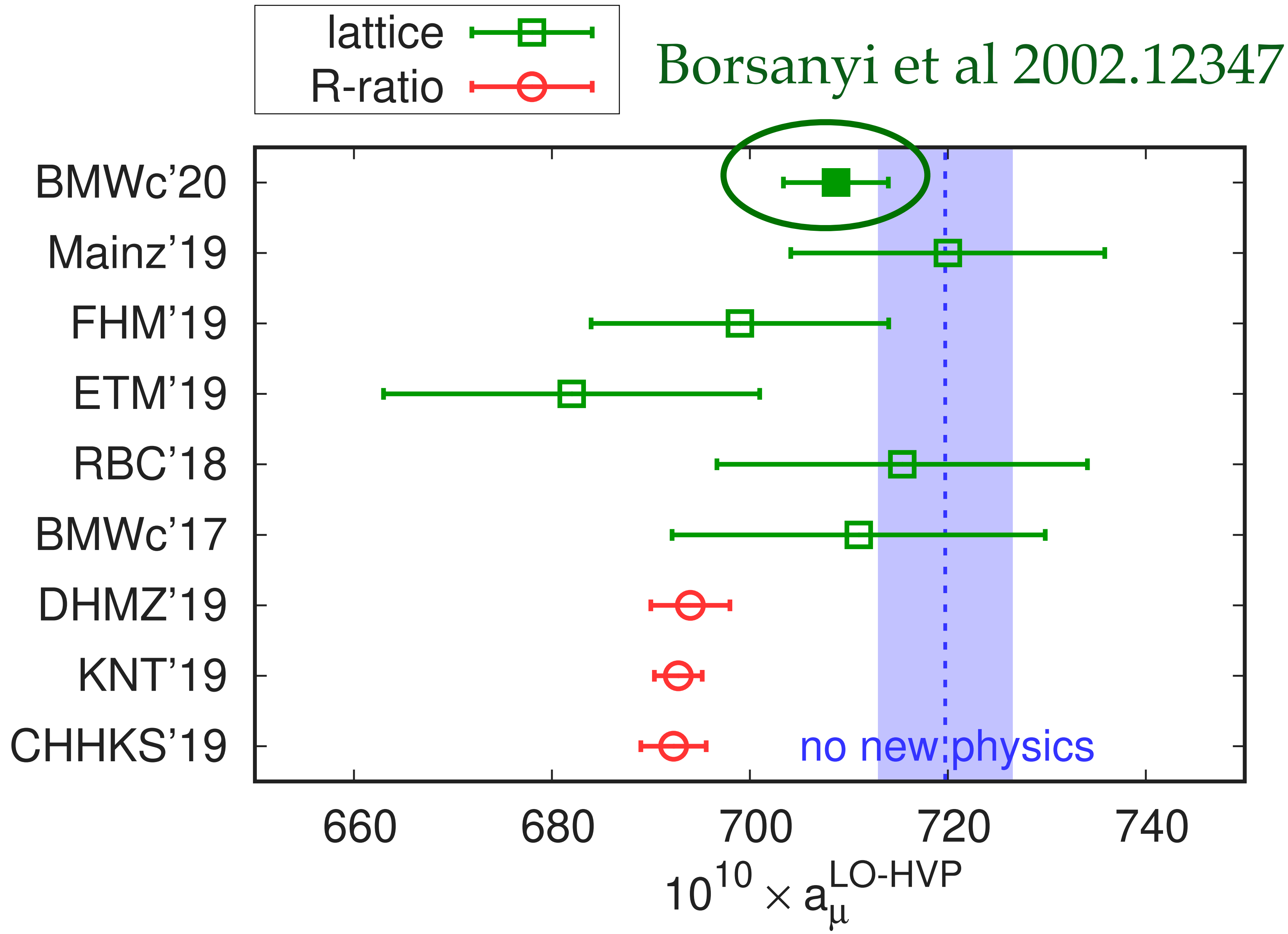
Theory vs. Experiment



Theory uncertainty driven by
non-perturbative QCD corrections



Comparing SM Theory Calculations

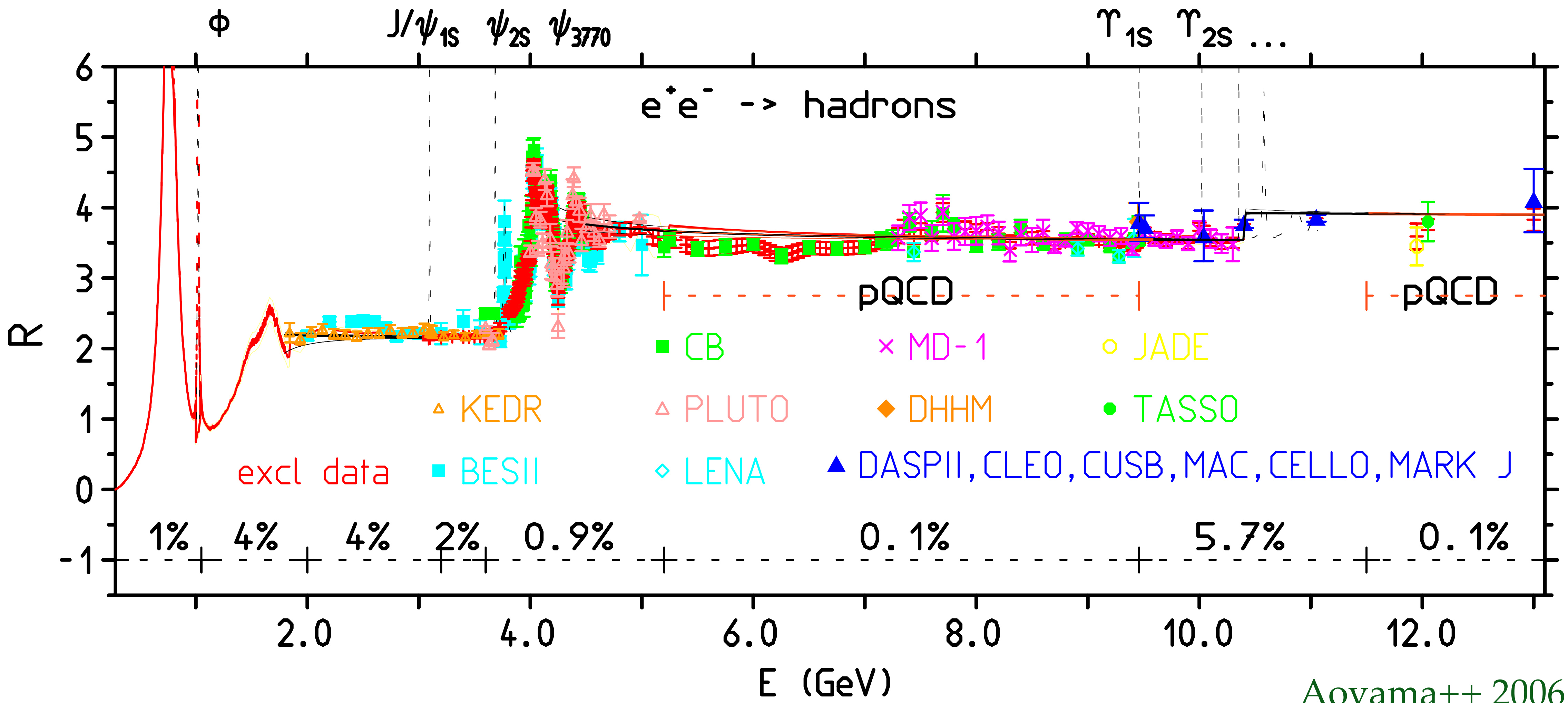


Recent lattice BMWc result in tension with data driven R-ratio method

… but it's closer to experiment

R-Ratio Calculations

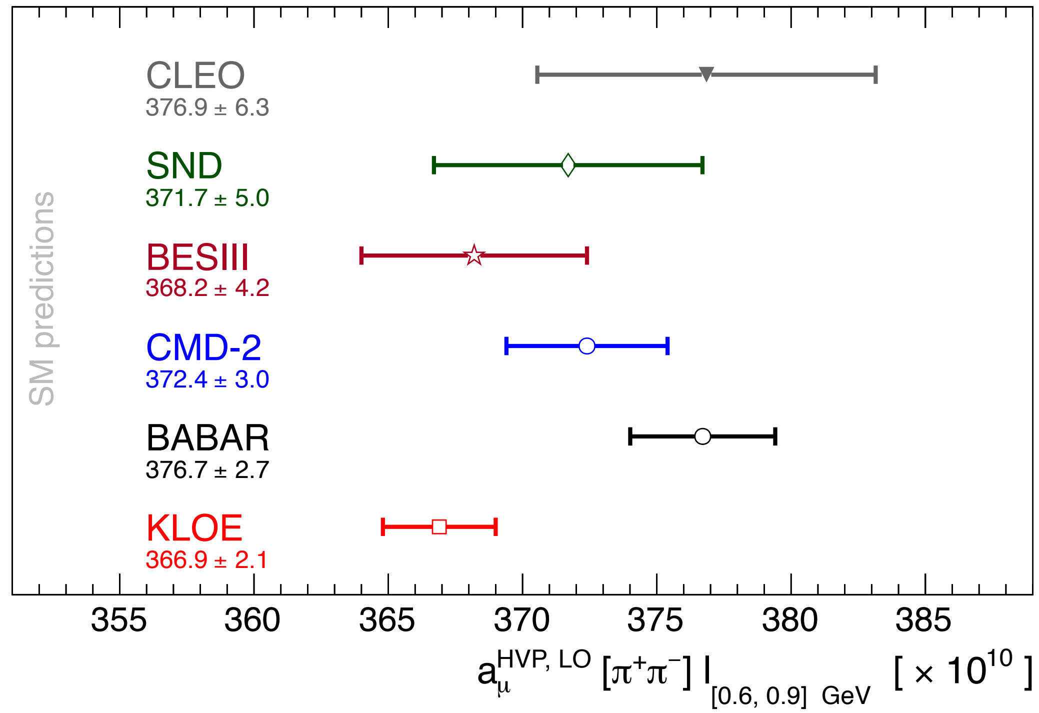
Hadronic contributions can be extracted from $e^+e^- \to \text{hadrons}$ data



Aoyama++ 2006.04822

$$a_\mu^{\text{HVP, LO}} = \frac{\alpha^2}{3\pi^2}\int_{M_\pi^2}^{\infty} \frac{K(s)}{s} R(s)\, ds \qquad R(s) \propto \sigma(e^+e^- \to \text{hardons})$$

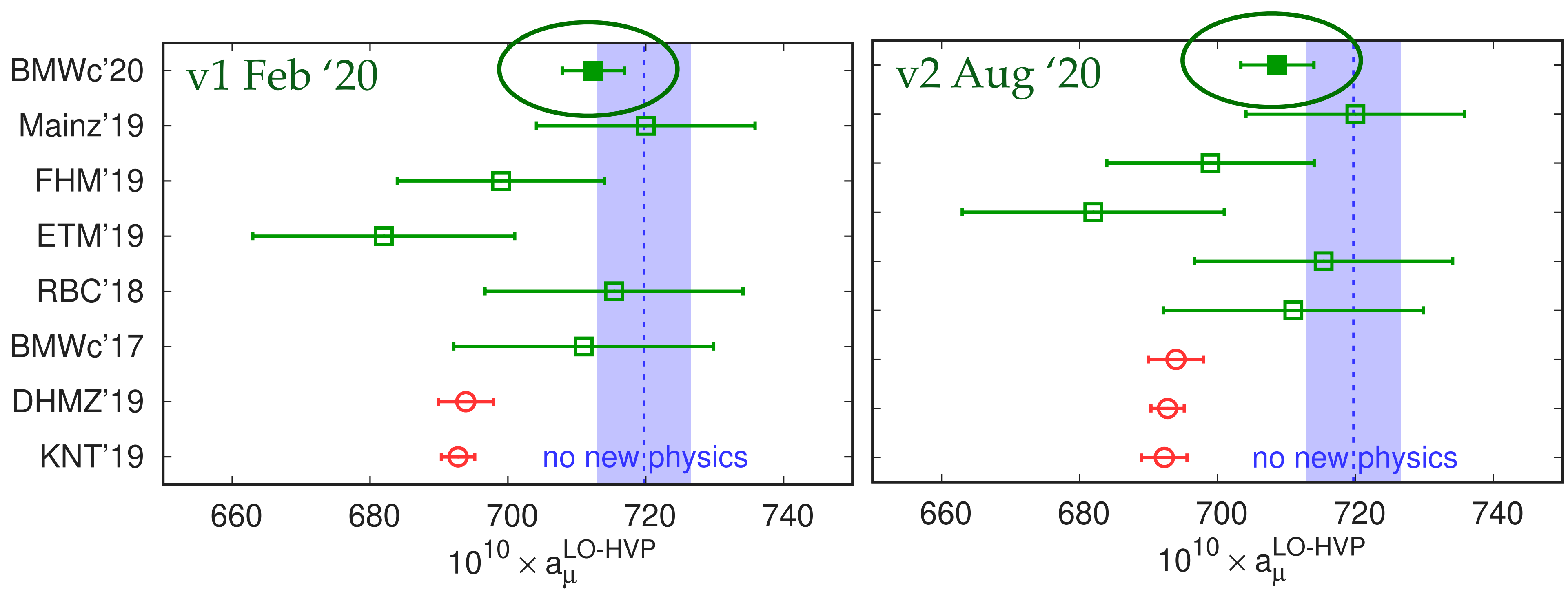
R-Ratio Possible issue of internal consistency across full data set?



Aoyama++ 2006.04822

Borsanyi++ 2002.12347

Lattice



Possible issue of extrapolating to continuum limit?

BMW also makes electroweak fit worse and in tension with $e^+e^- \to \pi\pi$

What should we believe?

1) Issue with with R-ratio calculations?

Possible, but nothing obvious (maybe tension in data?)

2) Issue with lattice calculations?

Also possible, need confirmation from other groups

3) R-ratio correct, but unknown experimental systematic?

After new data, this is extremely unlikely

This is the main new thing we have learned

4) New BSM particles contributing to loops?

Overview

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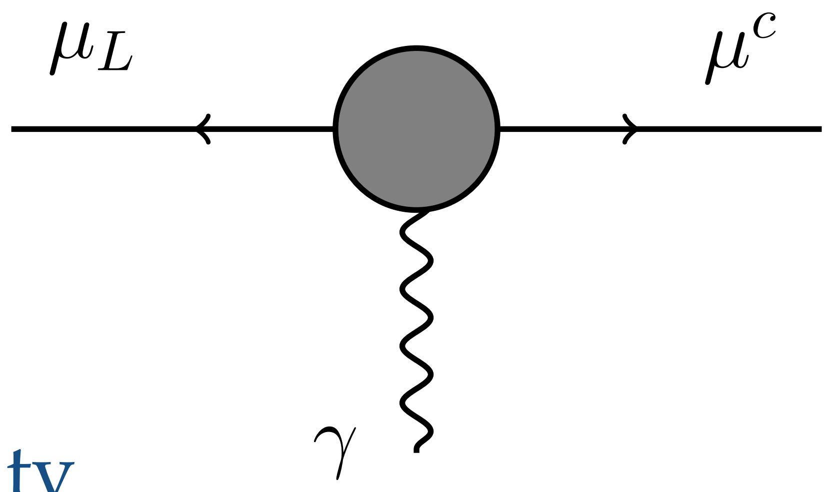
Effective Operator Analysis

Generic interaction to g-2 can be written as

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda} \left(\mu_L \sigma^{\nu\rho} \mu^c\right) F_{\nu\rho}$$



In 2 component notation: arrows track chirality

Arrows point in **opposite** direction **(chiral flip)**

but like with Yukawas, this is not gauge invariant

$$\mathcal{L}_{\text{mass}} = y_\mu H^\dagger L \mu^c \;\rightarrow\; y_\mu v \mu_L \mu^c \equiv m_\mu \, \mu_L \mu^c$$

… so also need an **EWSB insertion**

$$\psi_{\text{dirac}} = \begin{pmatrix} \mu_L \\ \mu^{c\dagger} \end{pmatrix}$$

Effective Operator Analysis

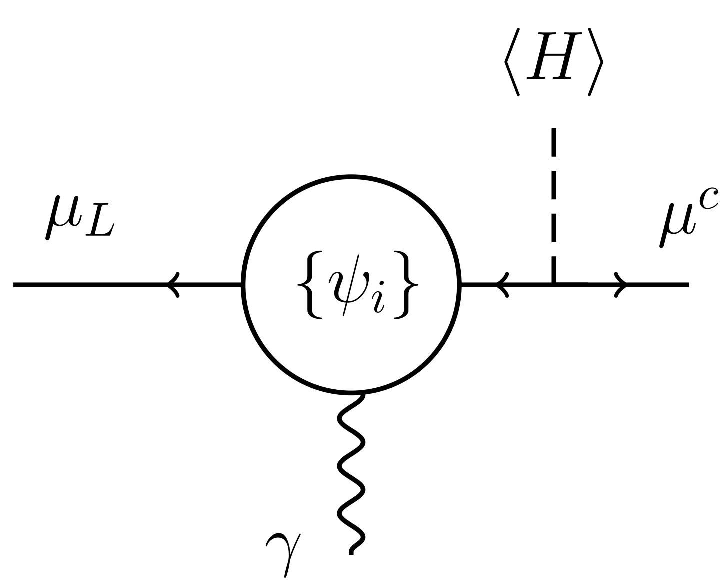
$$\mathcal{L}_{\text{eff}} = C_{\text{eff}} \frac{v}{M^2} (\mu_L \sigma^{\nu\rho} \mu^c) F_{\nu\rho} + \text{h.c.}$$

Do EWSB + chiral flip come from muon mass insertion?

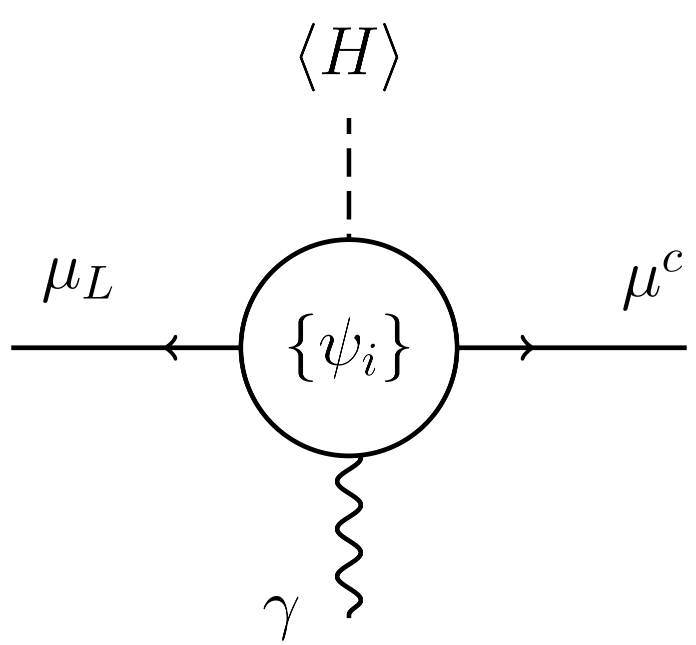
YES

NO

Singlet Models

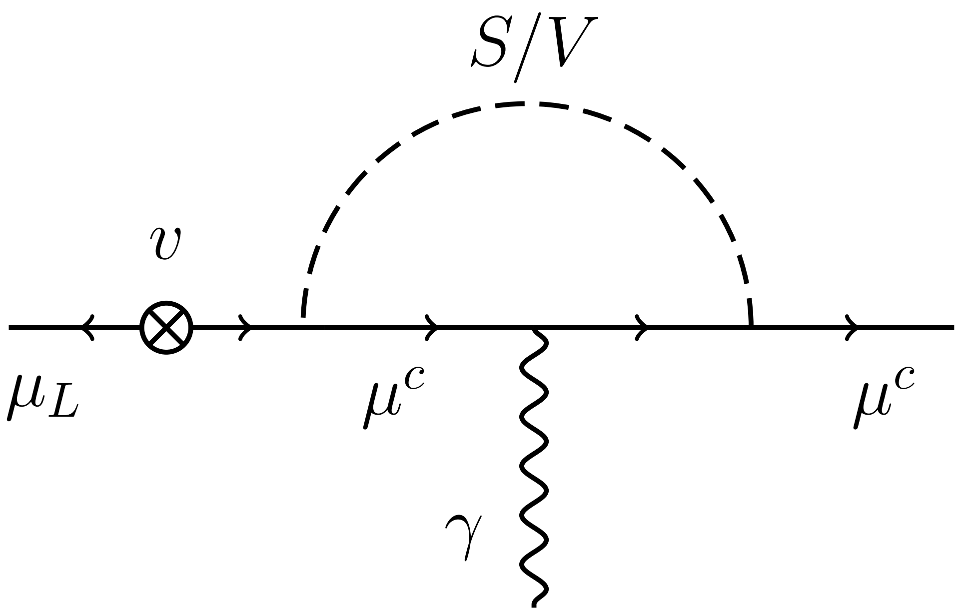


Electroweak Models



Singlet Models

Chiral flip and EWSB on muon line



Simple BSM Landscape

Must be scalar (S) or vector (V)

Must be SM gauge singlet

Must be MeV-TeV (BBN / unitarity)

$$\Delta a_\mu^V = \frac{g_V^2}{4\pi^2}\int_0^1 dz \frac{m_\mu^2 z(1-z)^2}{m_\mu^2(1-z)^2 + m_V^2\, z} \simeq 1.3\times 10^{-10}\left(\frac{g_V}{10^{-4}}\right)^2 \quad (m_V \ll m_\mu)$$

Pospelov 0811.1030

Pseudo scalar or axial vector make g-2 worse

Options For Singlets

1) Mix S/V with neutral SM bosons

2) Couple S/V to heavy states that mix with the muon

3) V is the gauge boson of a new U(1) SM extension

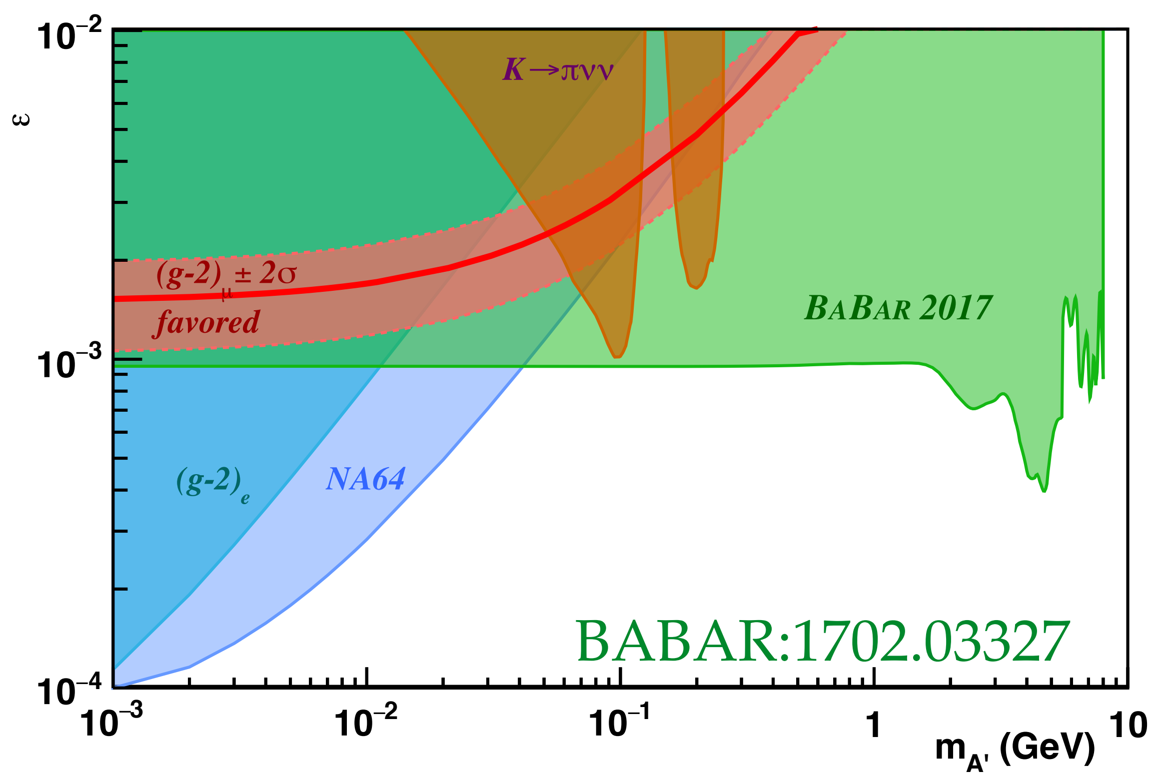
Options For Singlets

1) Mix S/V with neutral SM bosons

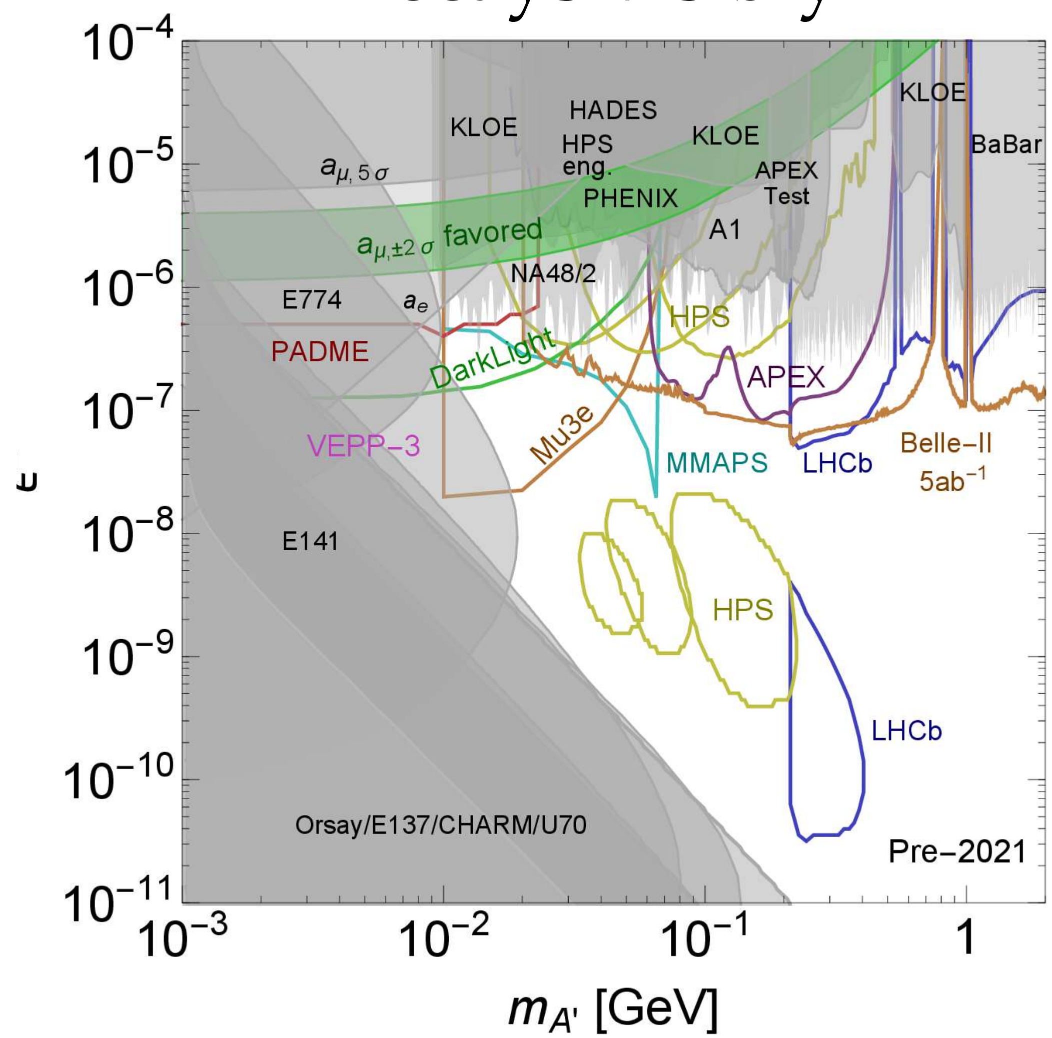
Kinetically mixed dark photon *A′* ruled out

$$\mathcal{L}_{\rm int} = \epsilon e A'_\mu J^\mu_{\rm EM}$$

Decays invisibly



Decays visibly



See Mohlabeng for semi-visible decays 1809.07768

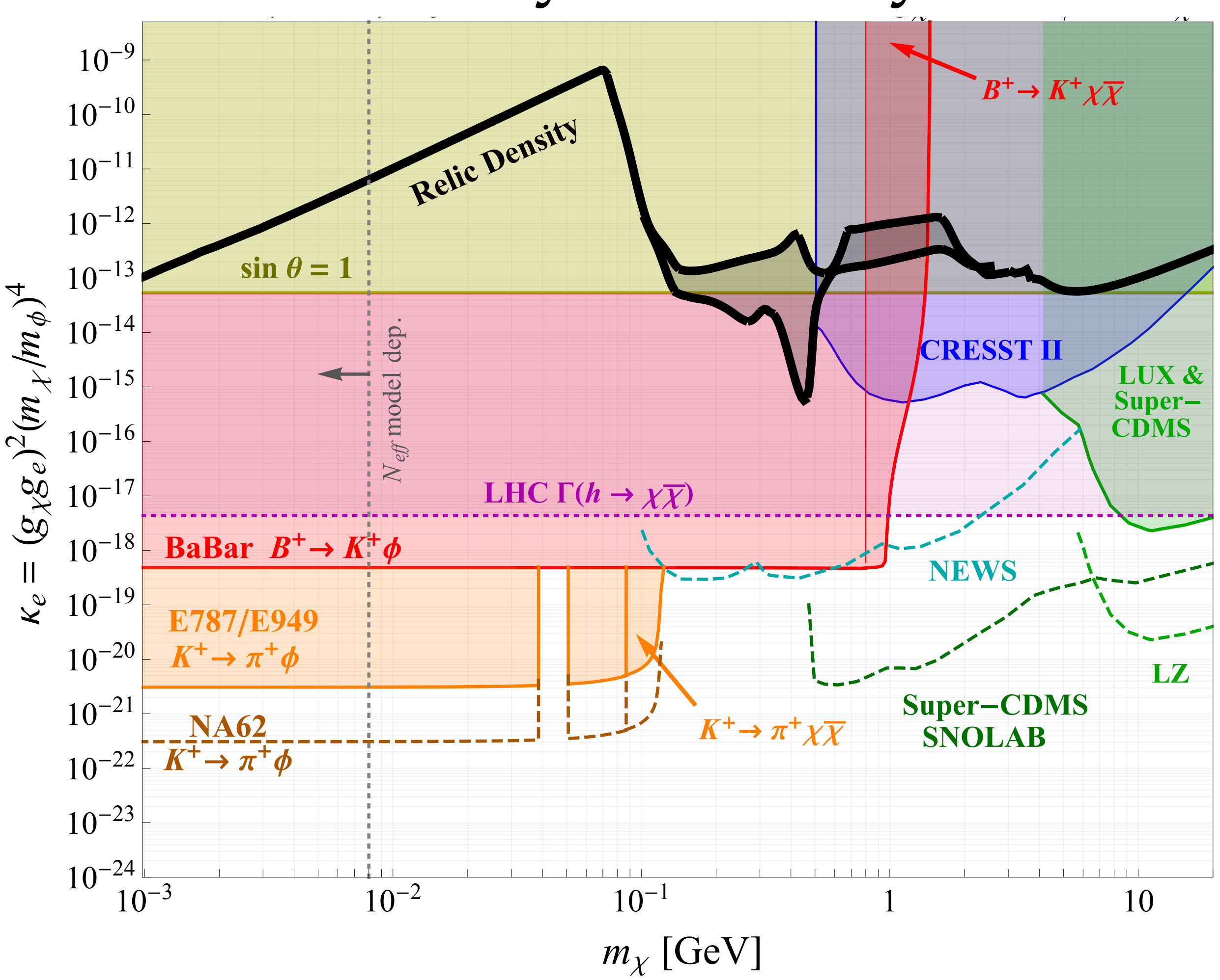
1707.04591

Options For Singlets

1) Mix S/V with neutral SM bosons

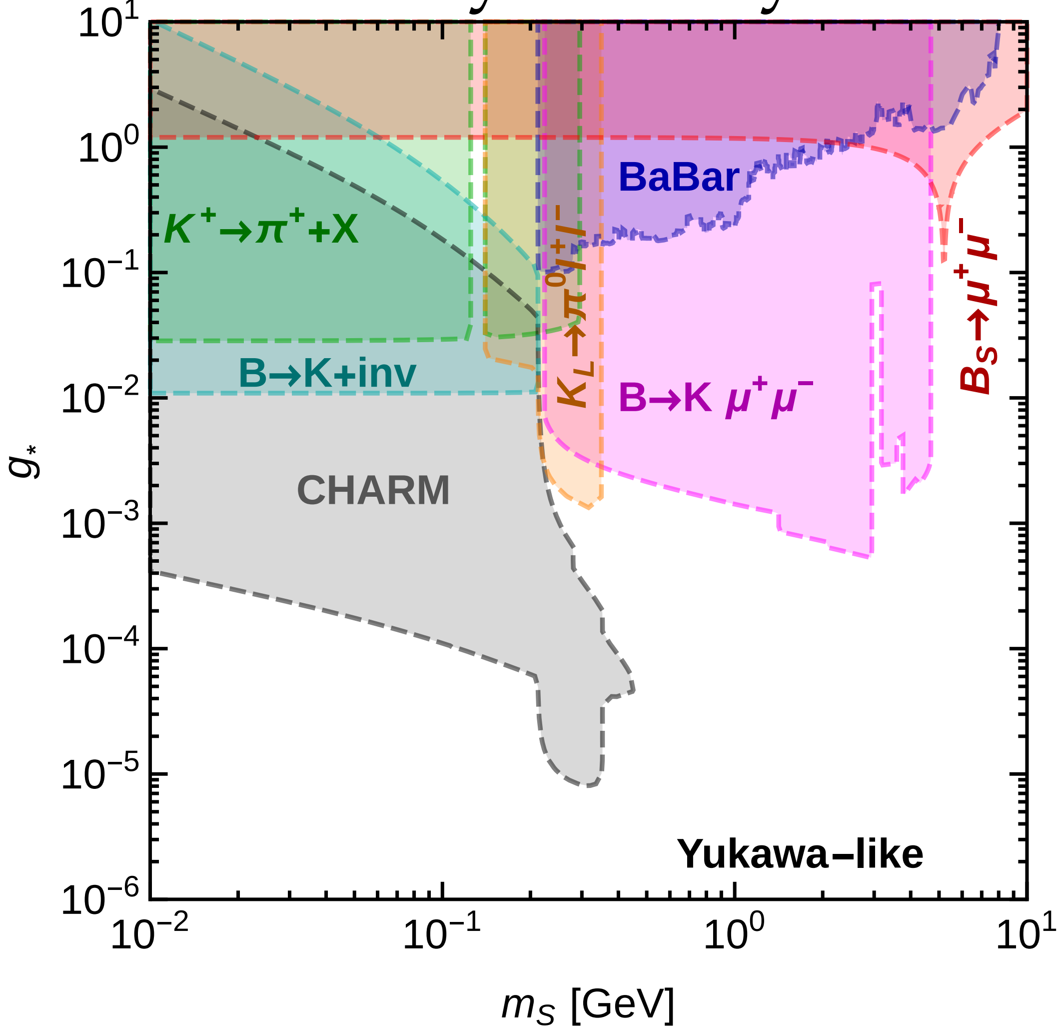
Higgs mixed scalar ϕ ruled out $\quad \mathcal{L}_{\rm int} = \sin\theta\, \phi\, \frac{m_f}{v} \bar{f} f$

Decays invisibly



GK 1512.04119

Decays visibly



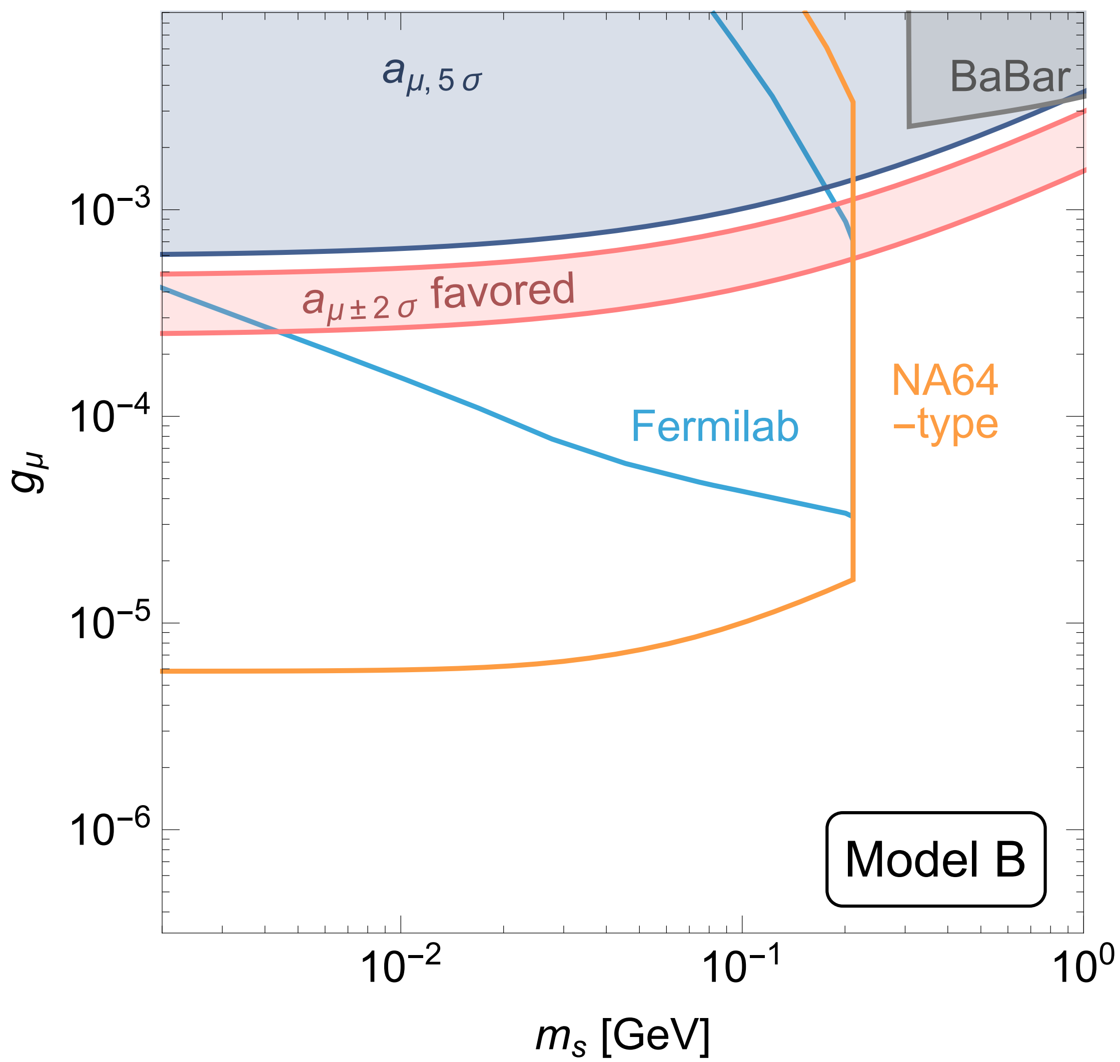
SHiP collab 1504.04855

Options For Singlets

2) Couple S to heavy states that mix with the muon

$$\mathcal{L} \supset -\frac{1}{2} m_S^2 - \left(y_\mu H^\dagger L \mu^c + \frac{c_s}{M} S H^\dagger L \mu^c \right) \rightarrow \mathcal{L}_{\rm eff} = g_\mu S \mu \mu^c$$

$S \rightarrow \gamma\gamma$ via muon loop



Muon only coupling

Decays through loop

… or decays invisibly

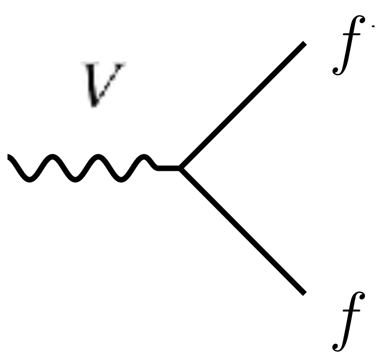
Chen, Pospelov, Zhong, 1701.07437
Batell, Freitas, Ismail, McKeen 1712.10022

Options For Singlets

3) V is the gauge boson of a new U(1) SM extension

SM particles now carry a new gauge quantum number

$$\mathcal{L} \supset g V_\mu J^\mu_{\rm SM} \quad , \quad J^\mu_{\rm SM} \equiv \sum_f Q_f \bar{f} \gamma^\mu f$$



Only anomaly free possibilities:

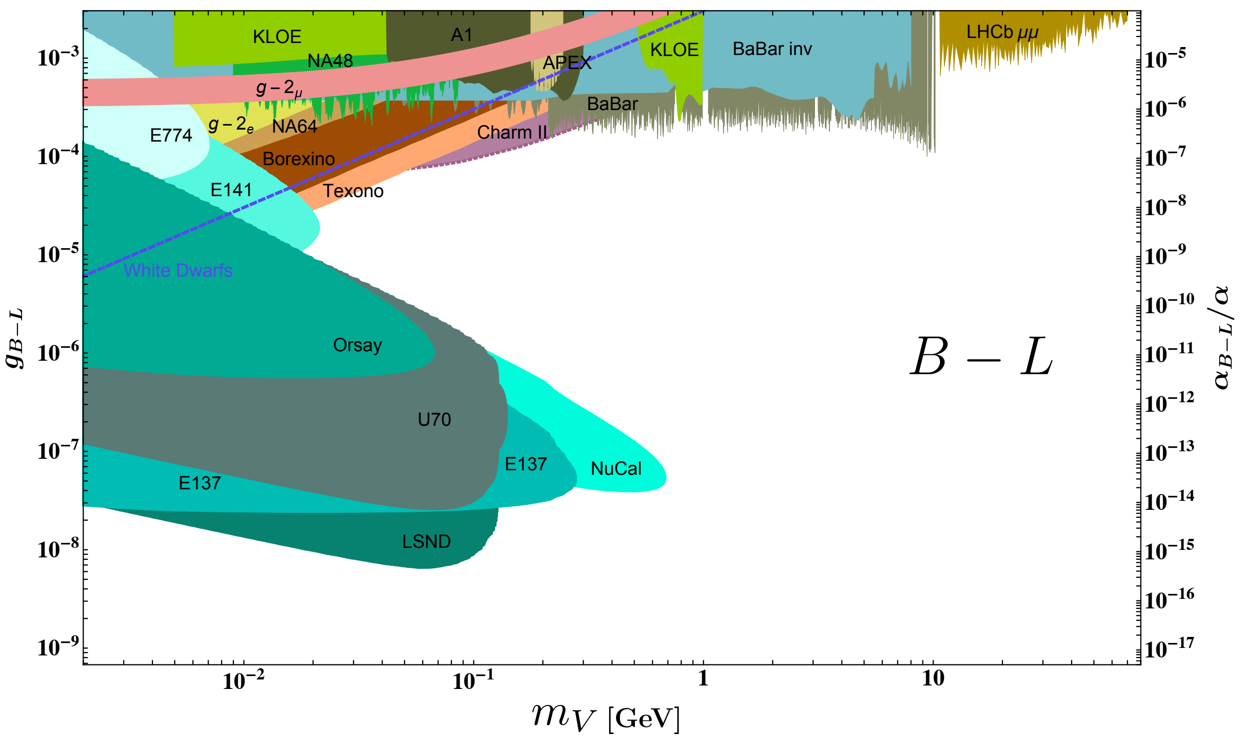
$$U(1)_{B-L} \ , \ U(1)_{L_i - L_j} \ , \ U(1)_{B-3L_i}$$

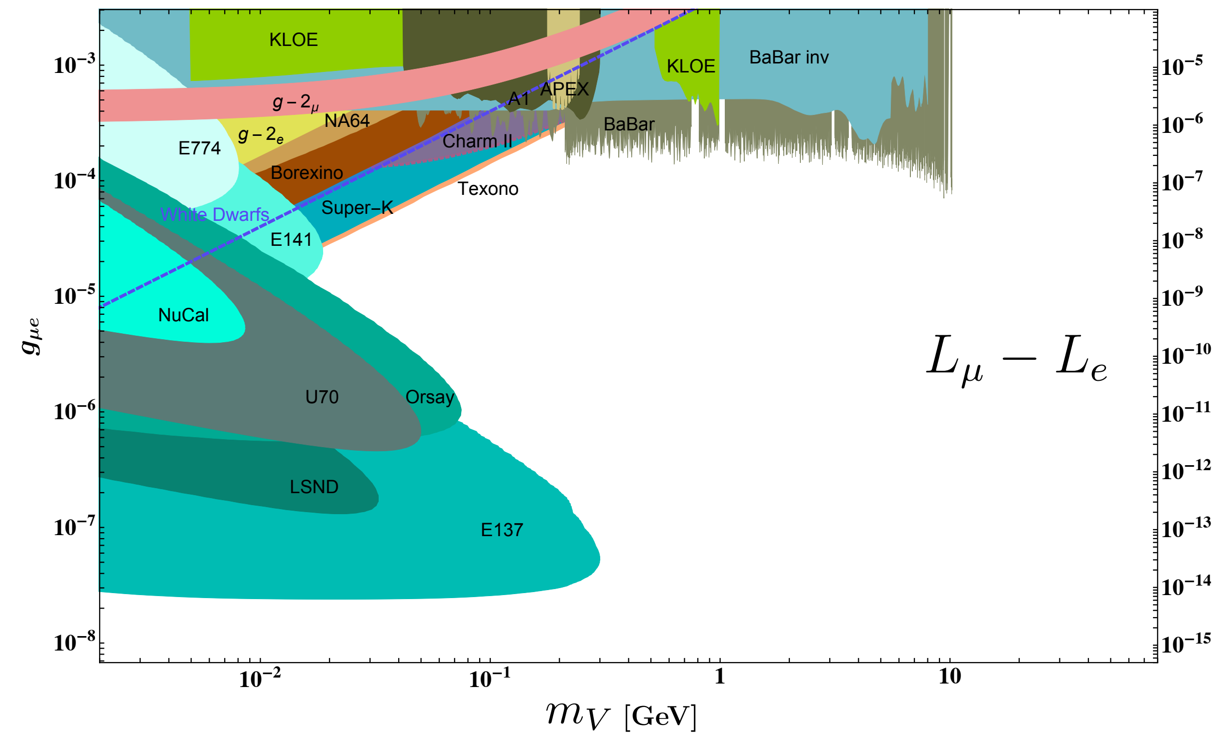
All similar, but some differences in bounds

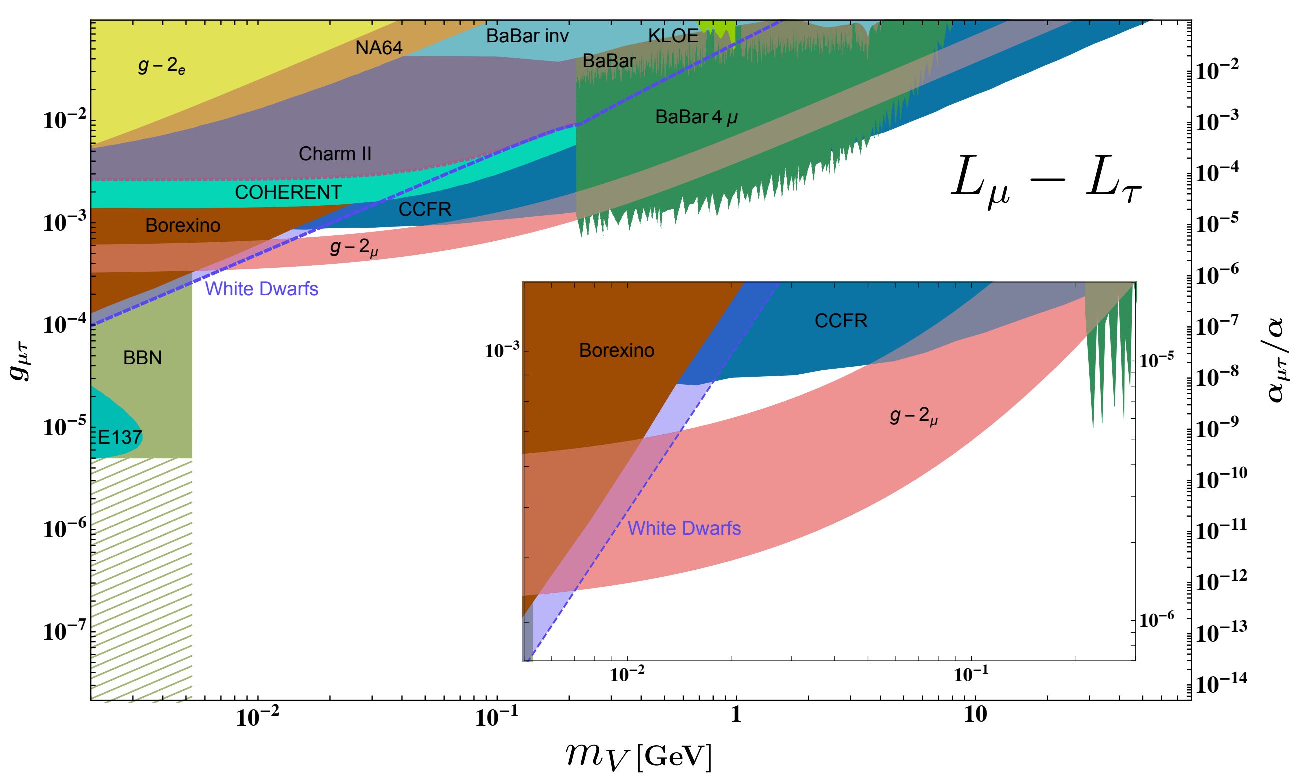
Two parameter family of models: $\{g, m_V\}$

Options For Singlets

3) V is the gauge boson of a new U(1) SM extension



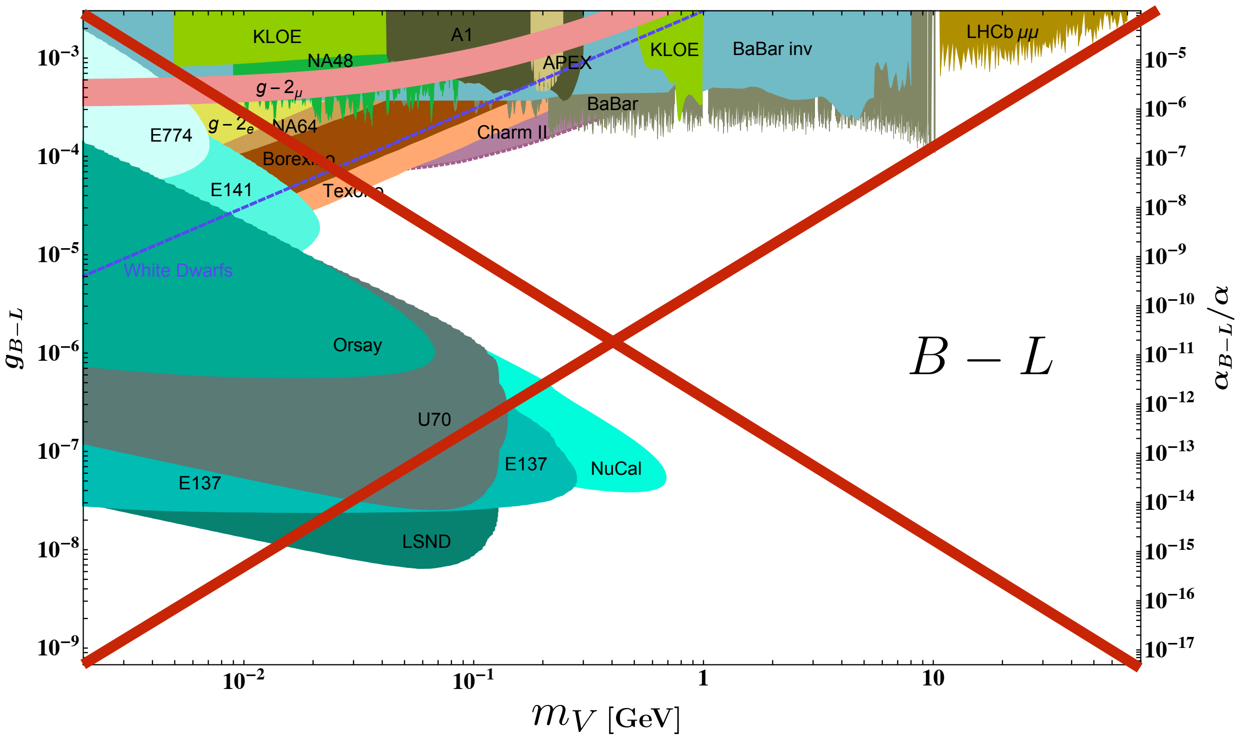


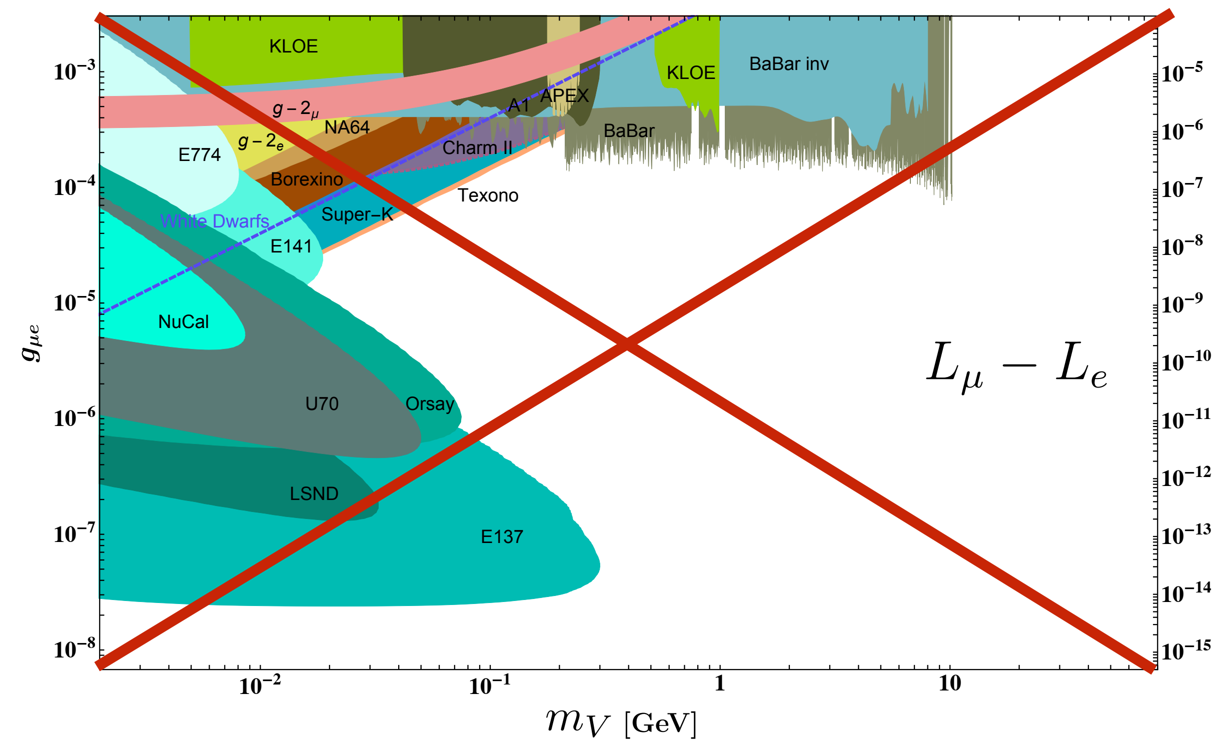


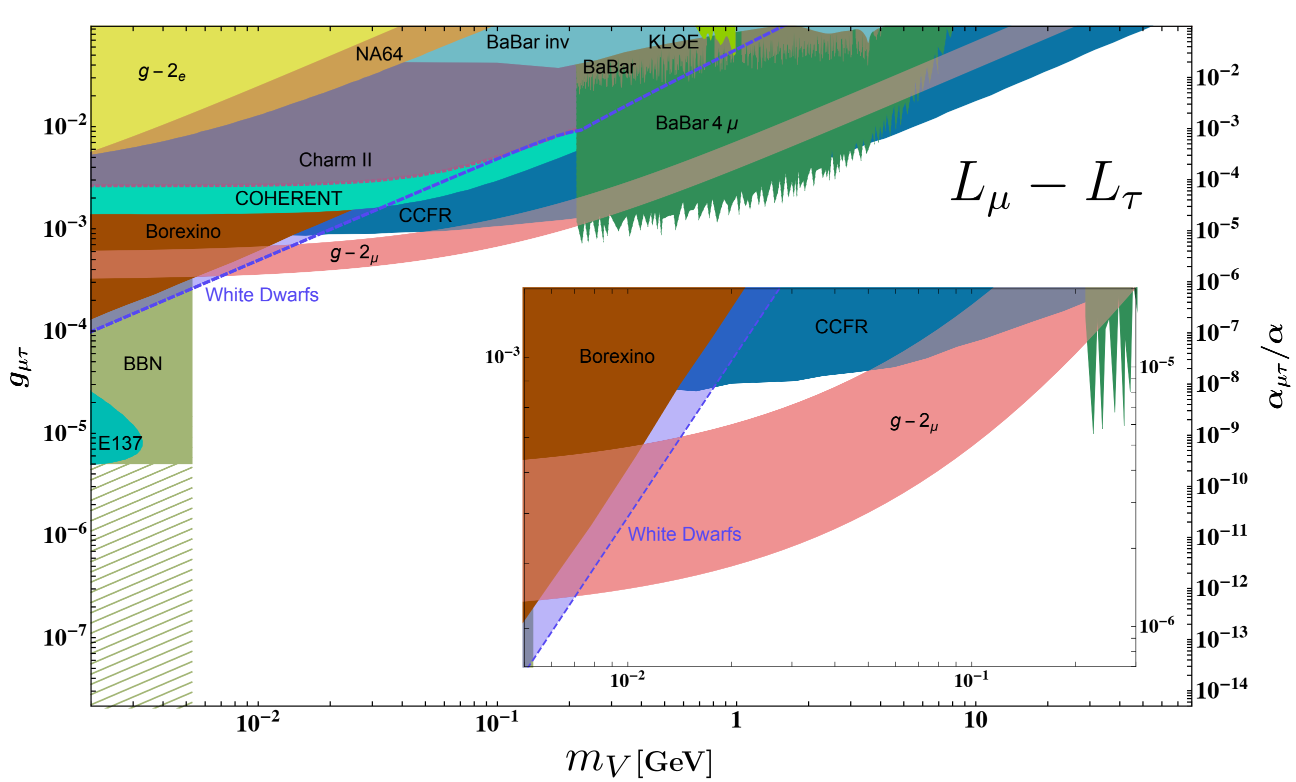
Bauer, Foldenauer, Jaeckel, 1803.05466

Options For Singlets

3) V is the gauge boson of a new U(1)







Only one possibility left

Viable between $\text{MeV} - 2m_\mu$

$<$ MeV spoils BBN

$> 2m_\mu$ decays to muons

Bauer, Foldenauer, Jaeckel, 1803.05466

Summary of Singlet Models

Experimental bounds require muon-philic forces

Scalar model

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - \sum_{\ell = e,\mu,\tau} g_\ell S \bar{\ell}\ell,$$

Generically need $g_{e,q} \ll g_\mu$

Need extra SM charged fields in UV

Model dependent decays — **invisible = safest**

Vector model

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

$$\mathcal{L} \supset \frac{m_V^2}{2} V_\alpha V^\alpha + g_V V_\alpha J^\alpha_{\mu-\tau}$$

$$J^\alpha_{\mu-\tau} \equiv \bar{\mu}\gamma^\alpha \mu + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu - (\mu \to \tau)$$

For viable mass range < 200 MeV, V always* decays invisibly

Overview

Current Status of g-2

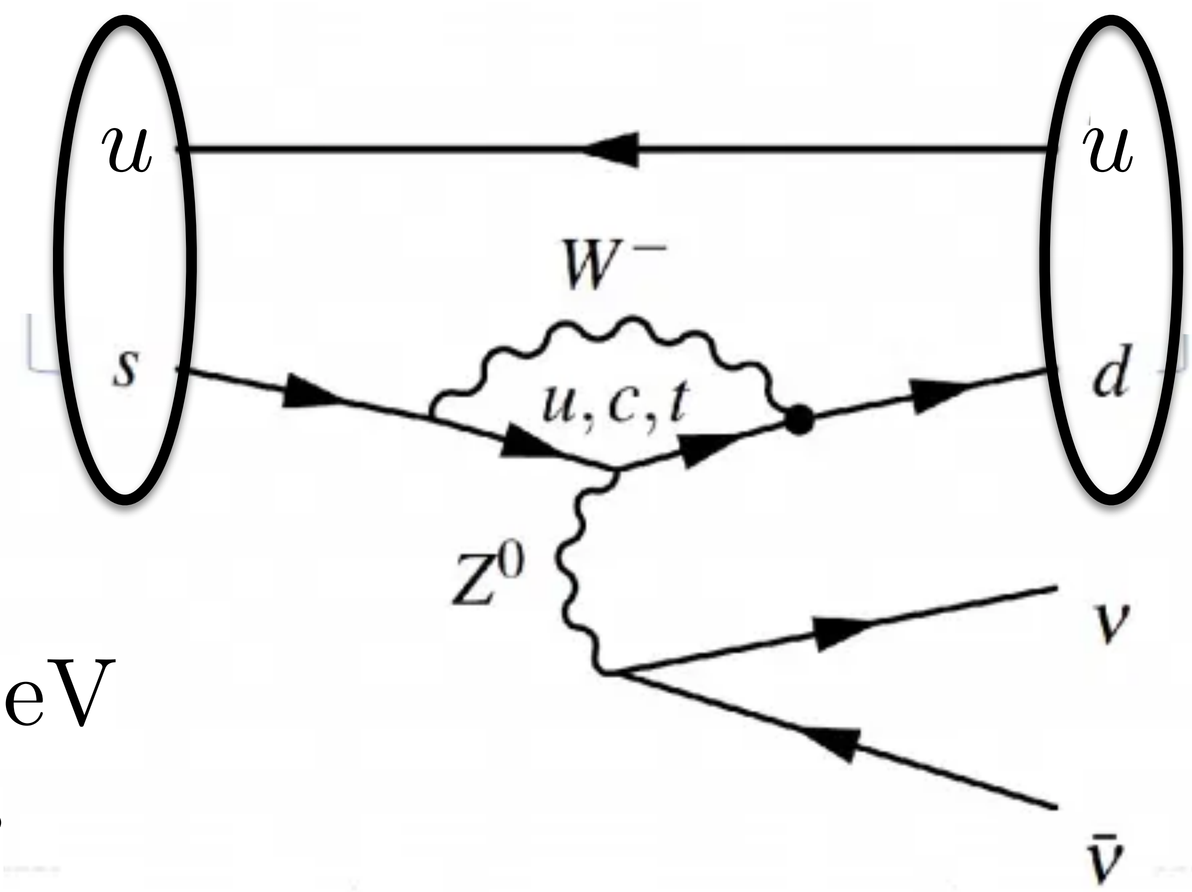
***Discovering* Singlet Models**

NA62 Experiment

Electroweak Models

NA62 Physics Goals

Designed to measure rare SM kaon decays



$E_{K^+} \approx 75\,\mathrm{GeV}$

$N_{K^+} \sim 10^{13}$

$$m^2_{\mathrm{miss}} = (p_\nu + p_{\bar{\nu}})^2 = (p_K - p_\pi)^2$$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5}{}_{stat.} \pm 0.3_{syst.}) \times 10^{-11}$$

First NA62 observation announced at ICHEP, August 2020

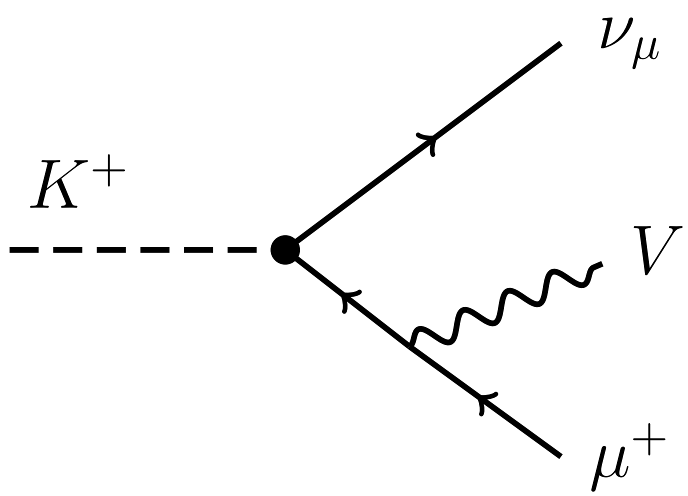
https://indico.cern.ch/event/868940/contributions/3815641/

Invisible New Particles @ NA62

Step 1: define process & observables

Dominant decay channel $\mathrm{BR}(K^+ \to \mu^+ \nu_\mu) = 0.64$

Our proposed strategy: $K^+ \to \mu^+ \nu_\mu V, \text{ then } V \to \nu\bar{\nu}$



Construct observable

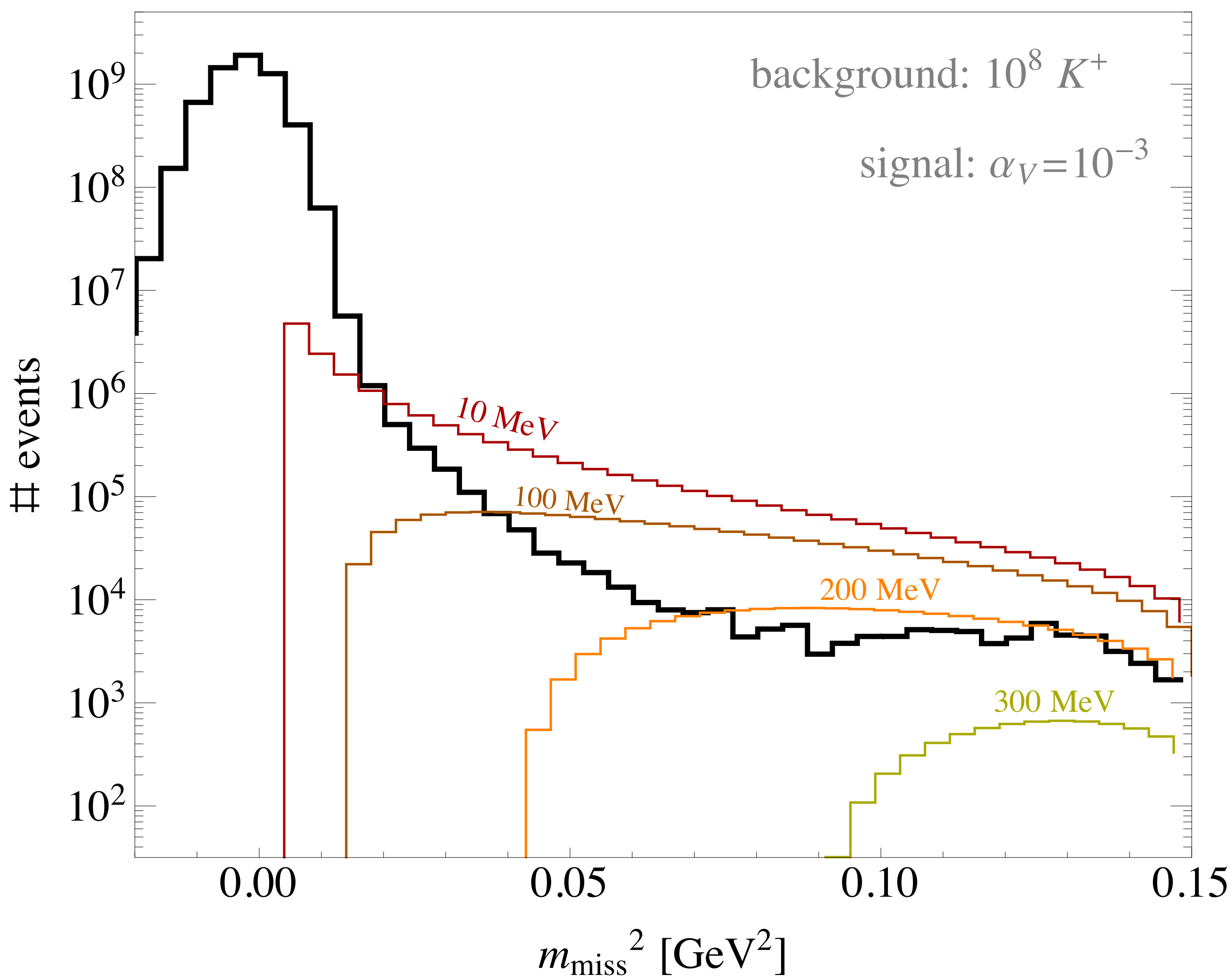
$$m^2_{\text{miss}} = (p_{\nu_\mu} + p_V)^2 = (p_K - p_\mu)^2$$

$$\frac{d\Gamma(K^+ \to \mu^+ \nu X)}{dm^2_{\text{miss}}} = \frac{1}{256\pi^3 m_K^3} \int \sum |\mathcal{M}|^2 dm^2_{\mu X}$$

GK, Marques-Tavares, Redigolo, Tobioka 1902.07715

Invisible New Particles @ NA62

Step 2: define cuts from BG distribution



Proposed analysis cut

$$m^2_{\rm cut} > 0.05\,{\rm GeV}^2$$

Minimizes BG from

$K^+ \to \mu^+ \nu \gamma$ (E_γ<10 MeV)
$K^+ \to \mu^+ \nu \gamma$ (E_γ>10 MeV)
$K^+ \to \mu^+ \nu (\gamma)$ (upstream)
$K^+ \to \pi^+ \pi^+ \pi^-$

NA62 currently keeps only 1/400 single muon evts. (bandwidth)

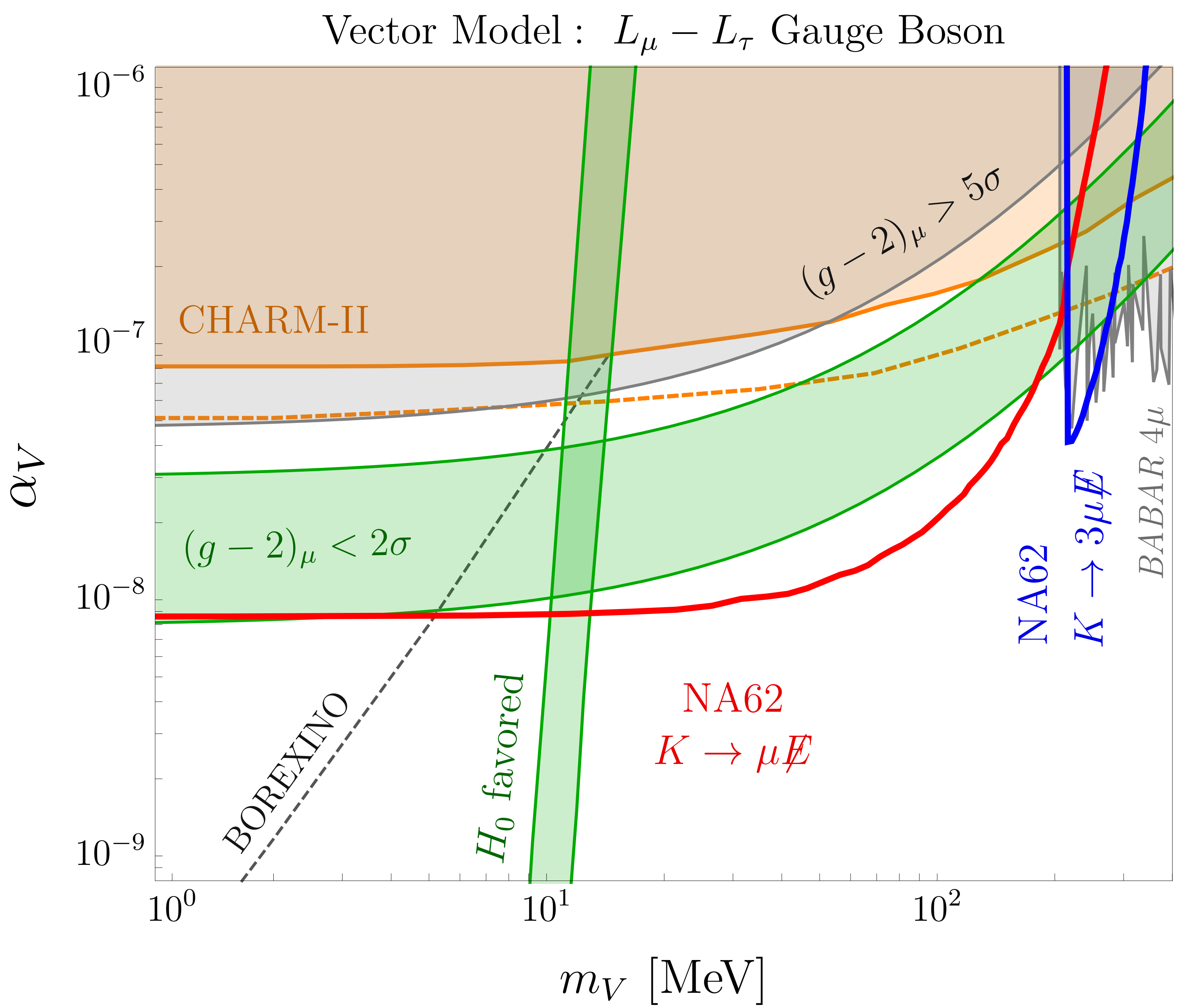
$$S = \frac{N_{K^+}\mathcal{A}}{\Gamma_{K^+}} \int_{m^2_{\rm cut}}^{m^2_{\rm max}} dm^2_{\rm miss} \frac{d\,\Gamma_{K^+\to\mu^+\nu X}}{dm^2_{\rm miss}}$$

acceptance $\mathcal{A} = 0.35$

BG from NA62 1712.00297

Invisible New Particles @ NA62

Step 3: calculate reach

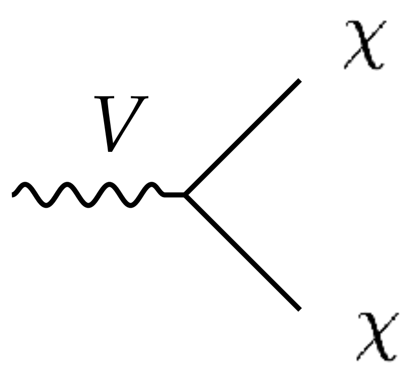


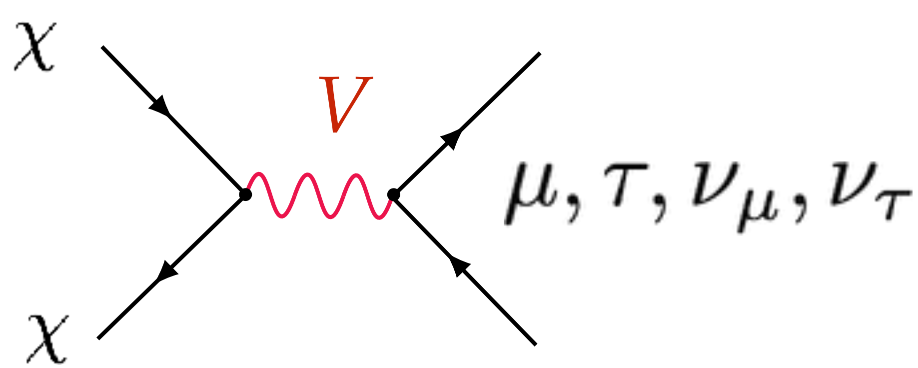
NA62 is doing this analysis now https://na62.web.cern.ch/Documents/SPSC-SR-266.pdf

Invisible New Particles @ NA62

Now let's couple V to dark matter χ

If V is sufficiently heavy $m_V > 2m_\chi$



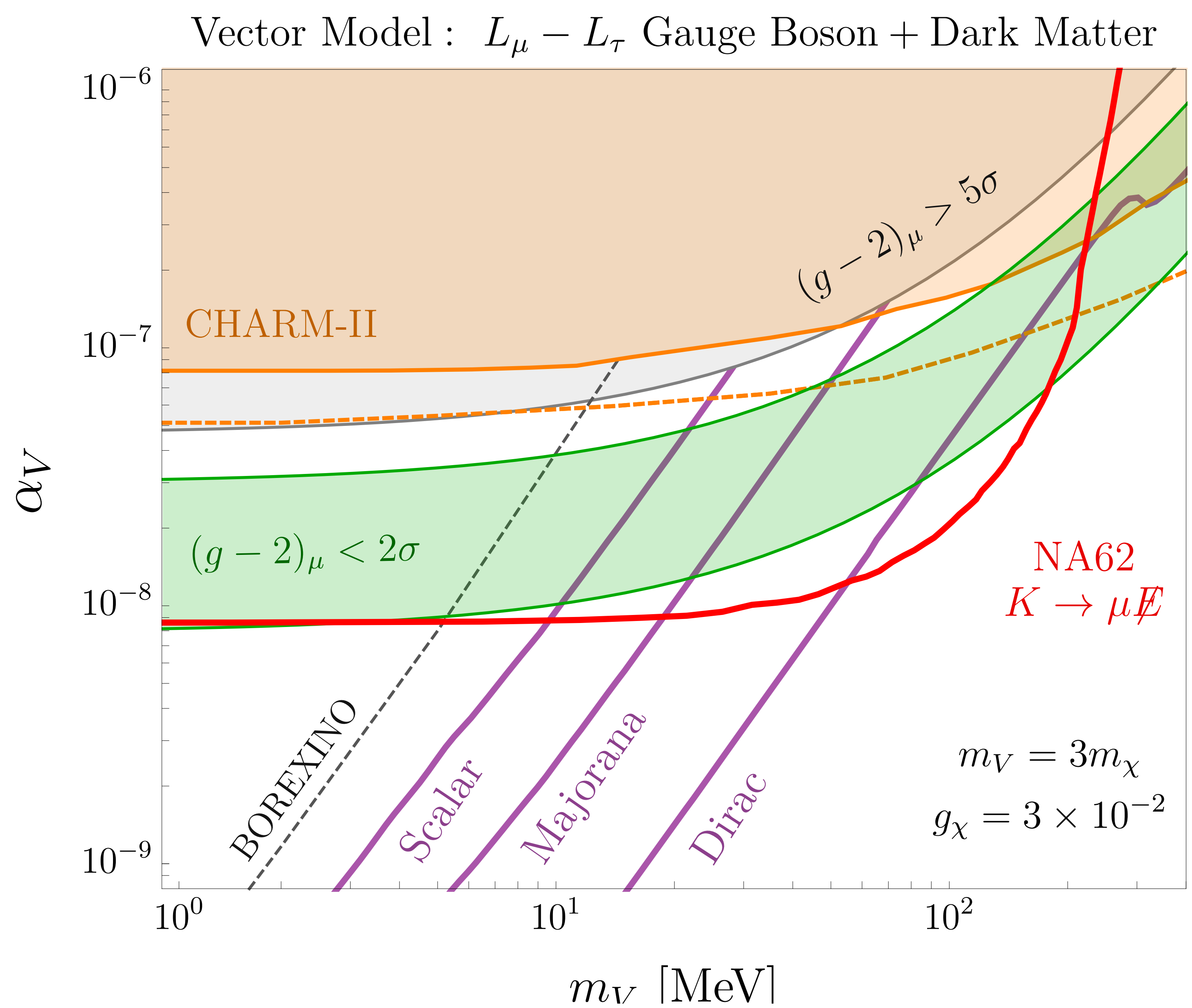


It can decay to DM
in the laboratory

… and mediate DM freeze-out
in the early universe

DM annihilation is s-channel and rate depends on V-SM coupling

Invisible New Particles @ NA62

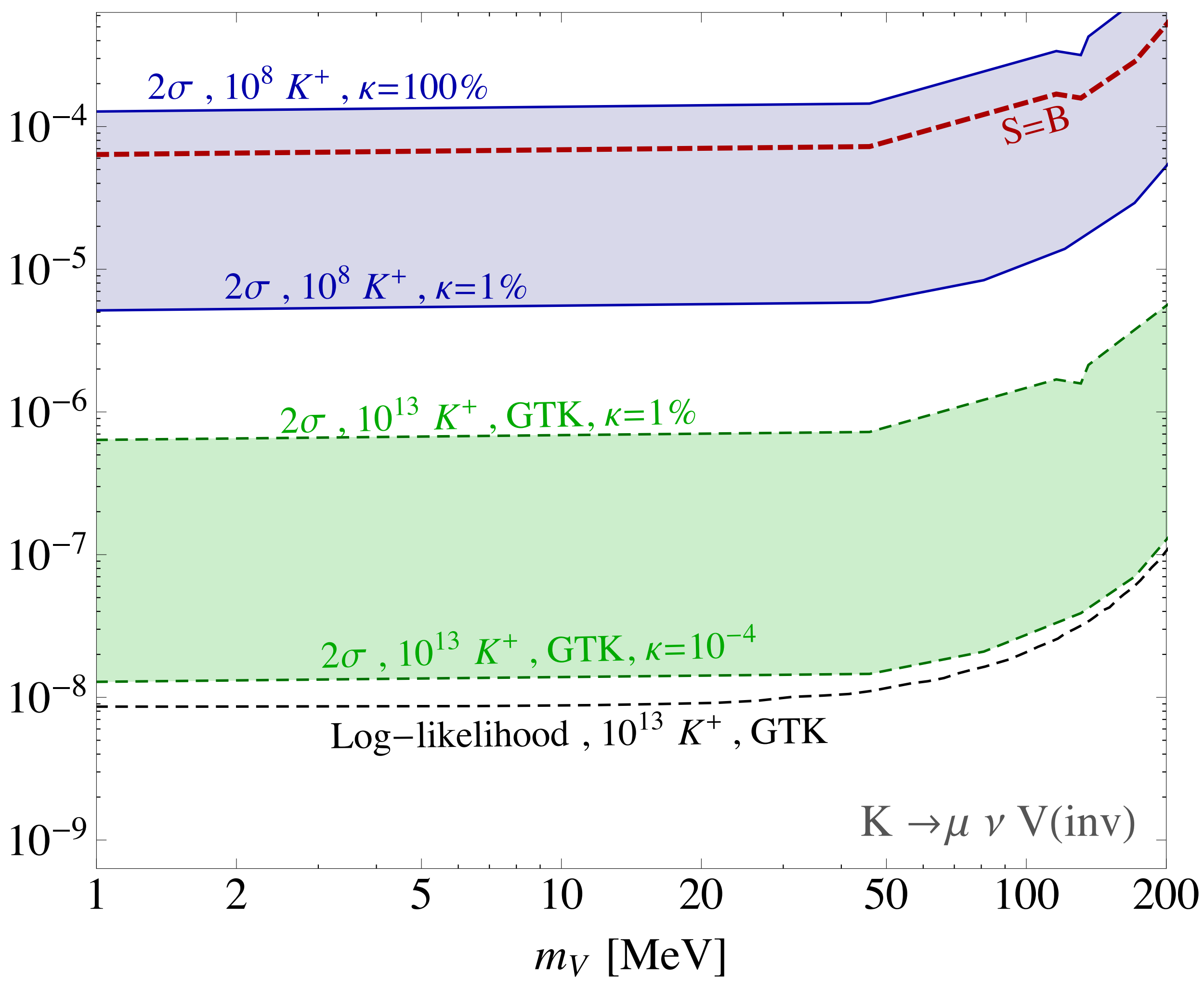


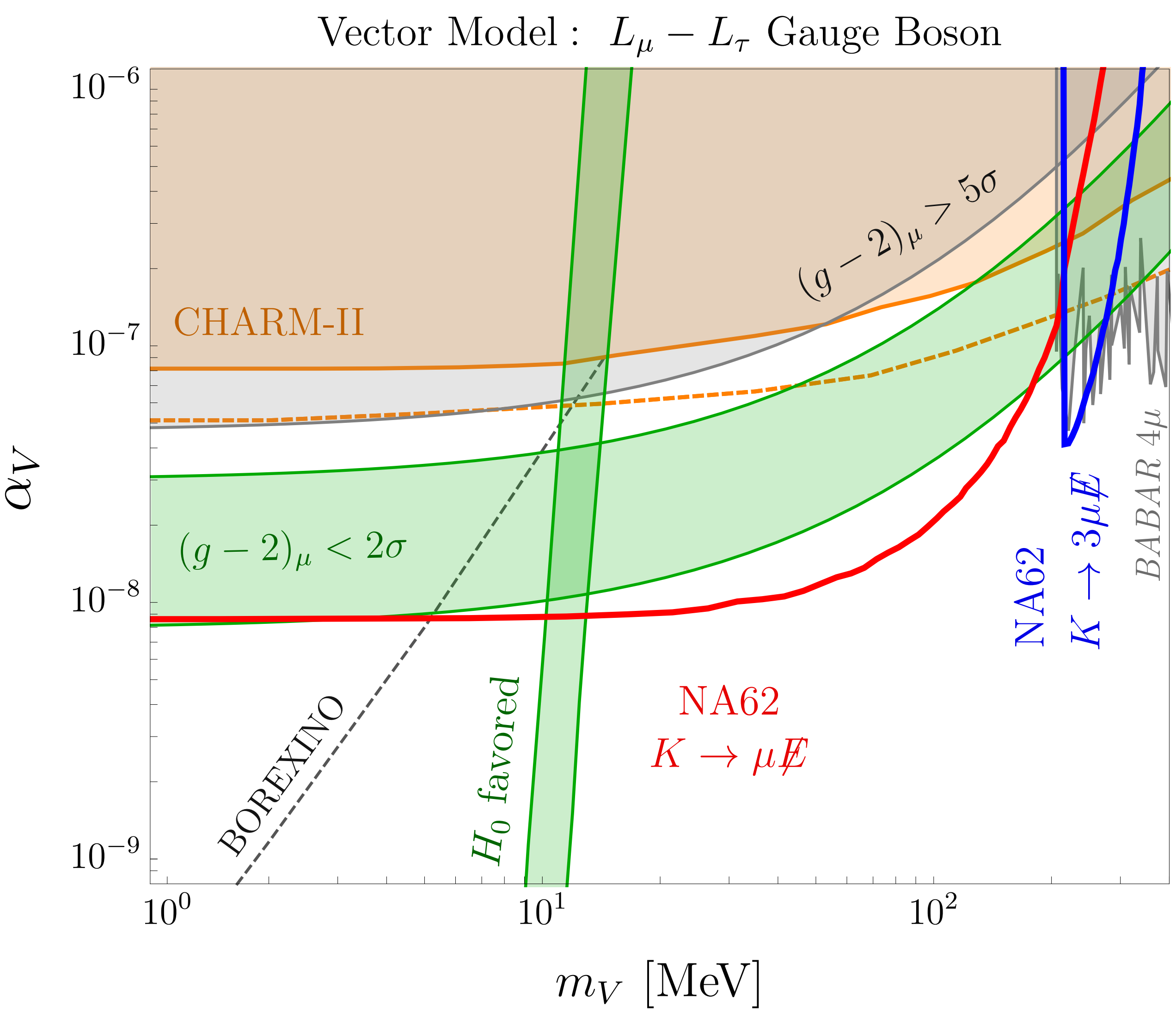
Same analysis as before

NA62 covers DM and g-2 parameter space

Invisible New Particles @ NA62

Caution!





Vary systematics

A lot depends on currently unknown systematics for this search

Stay tuned… but can we do better in principle?

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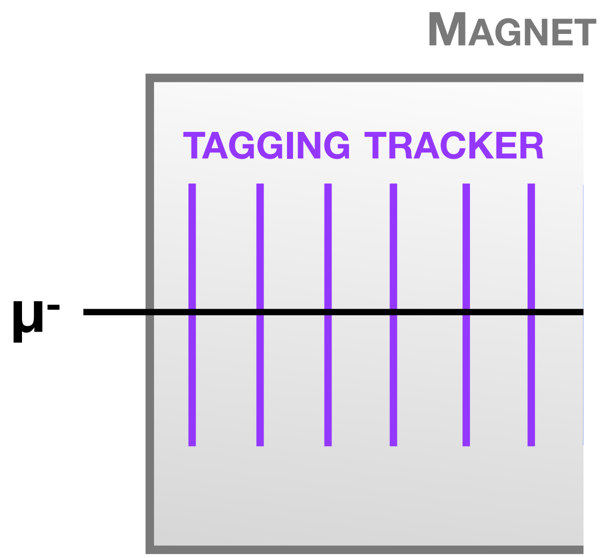
***Discovering* Singlet Models**

Muon Missing Momentum M^3

Electroweak Models

Muon Missing Momentum Concept

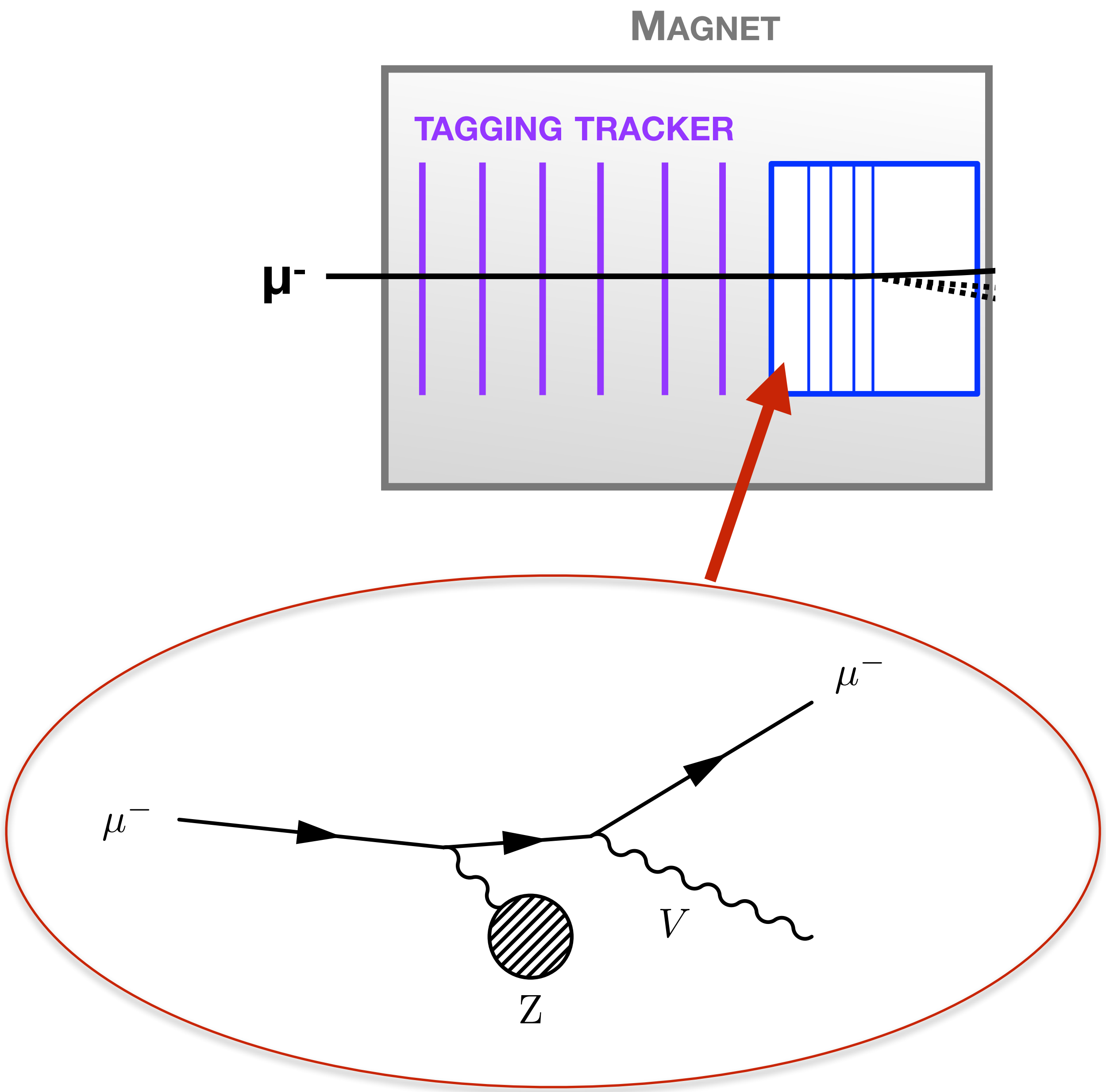


$$E_{\rm in} \sim 15\,{\rm GeV}$$
$$N_\mu \sim 10^{10} - 10^{13}$$
Low current beam

1) Measure Ein with tracker

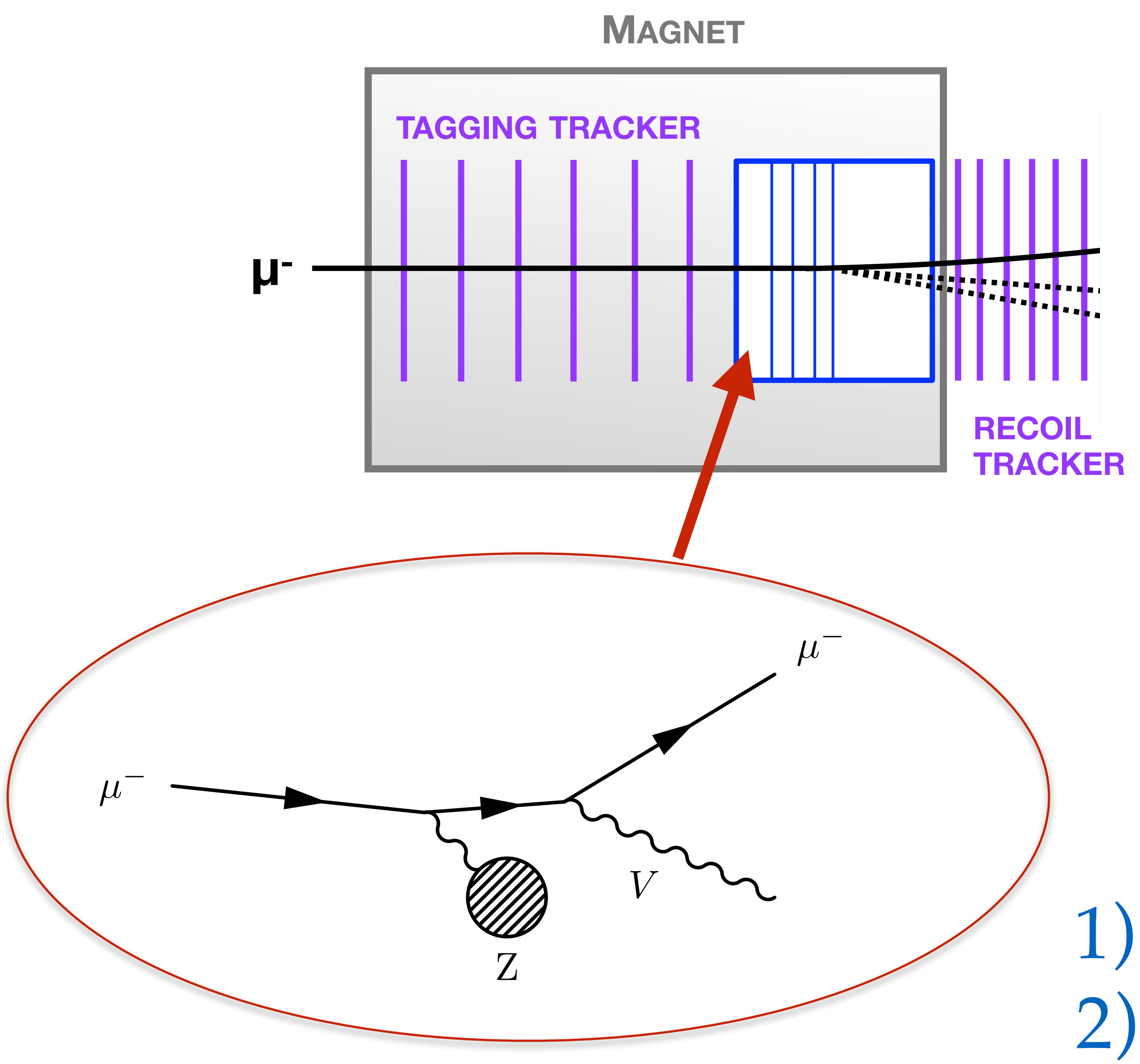
Kahn, GK, Tran, Whitbeck 1804.03144 (JHEP 2018)

Muon Missing Momentum Concept



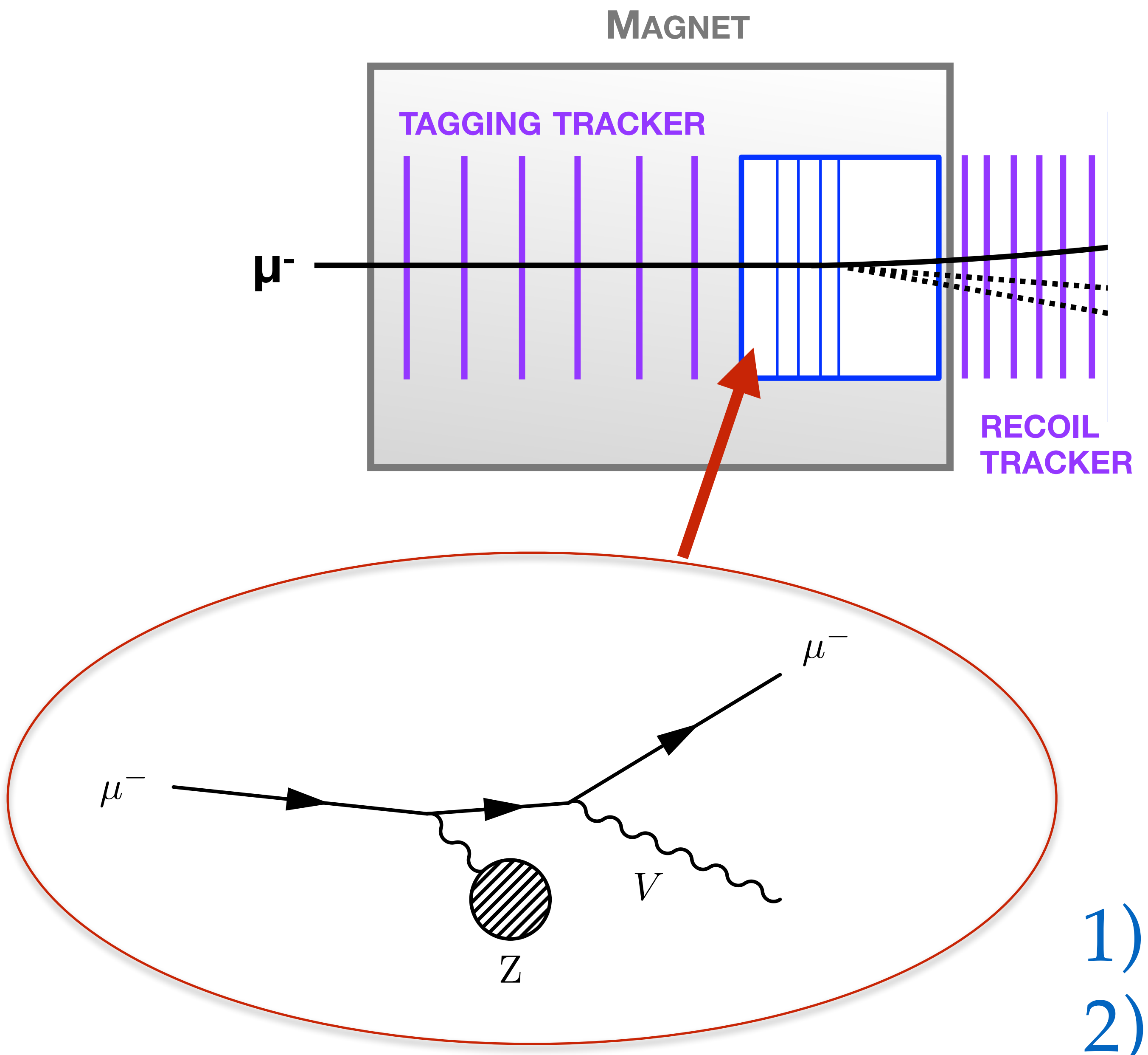
1) Measure Ein with tracker
2) Pass beam through target

Muon Missing Momentum Concept



1) Measure Ein with tracker
2) Pass beam through target
3) Measure Eout with tracker

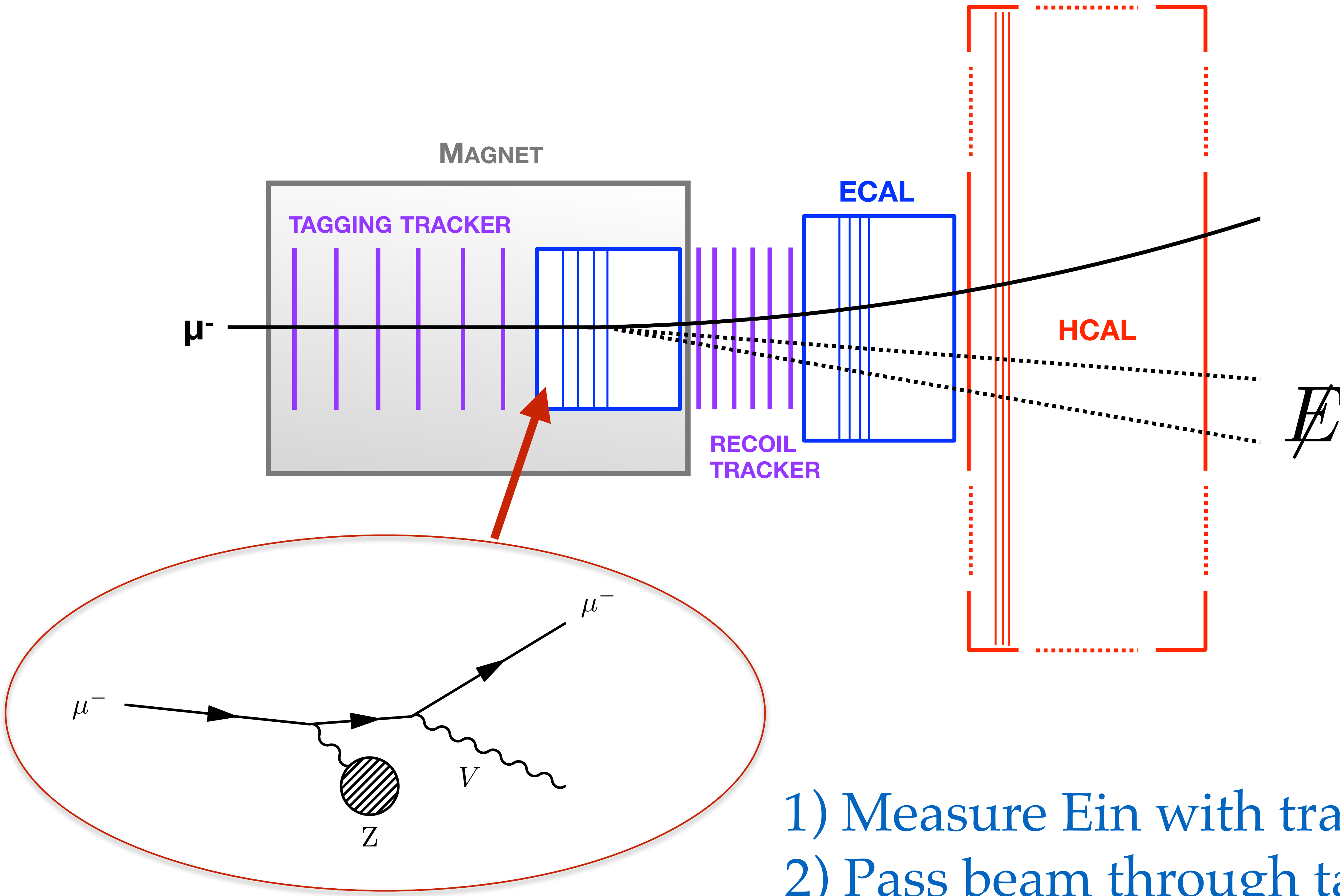
Muon Missing Momentum Concept



Demand $E_{\text{out}} < 9\,\text{GeV}$

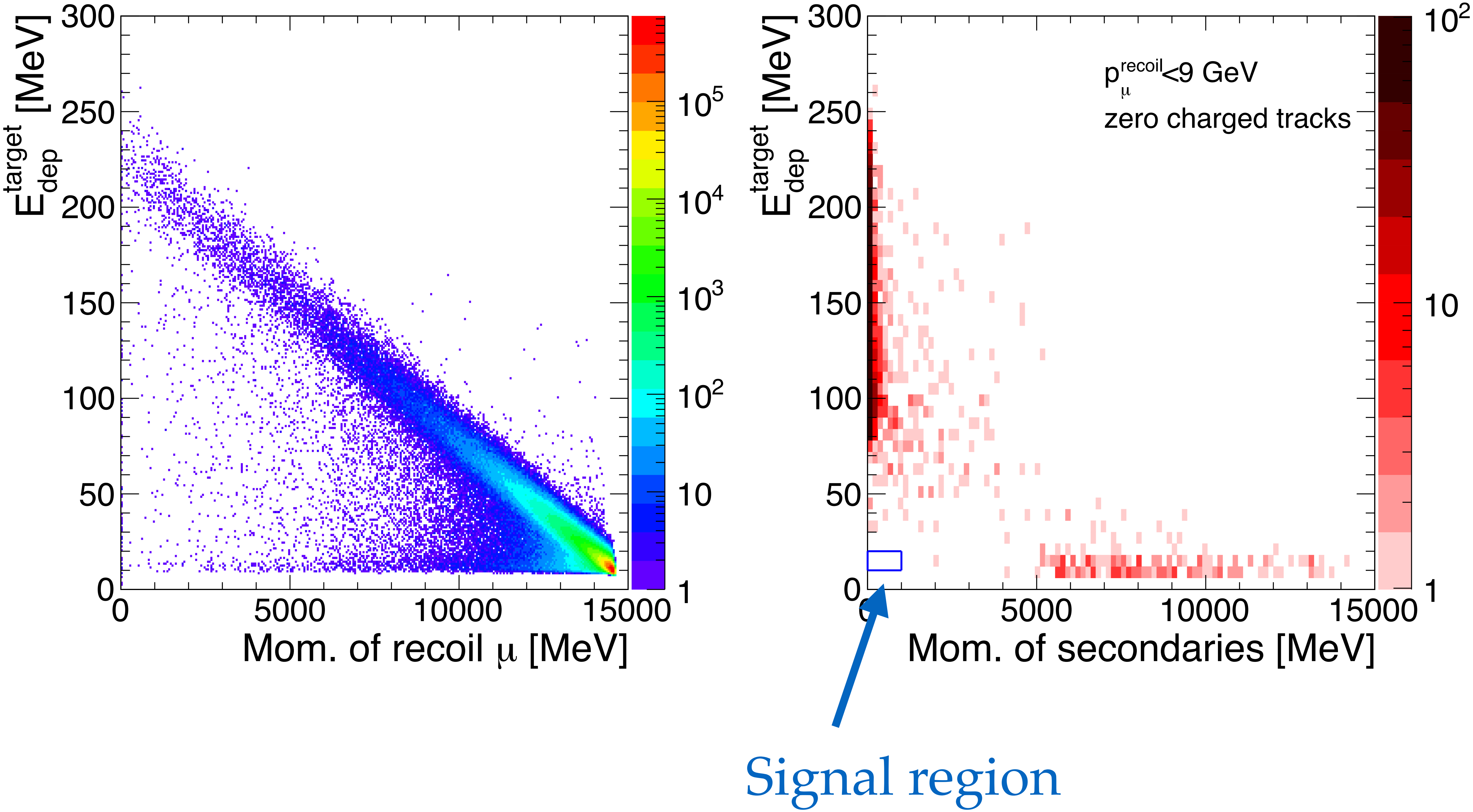
1) Measure Ein with tracker
2) Pass beam through target
3) Measure Eout with tracker
4) Trigger on missing energy

Muon Missing Momentum Concept

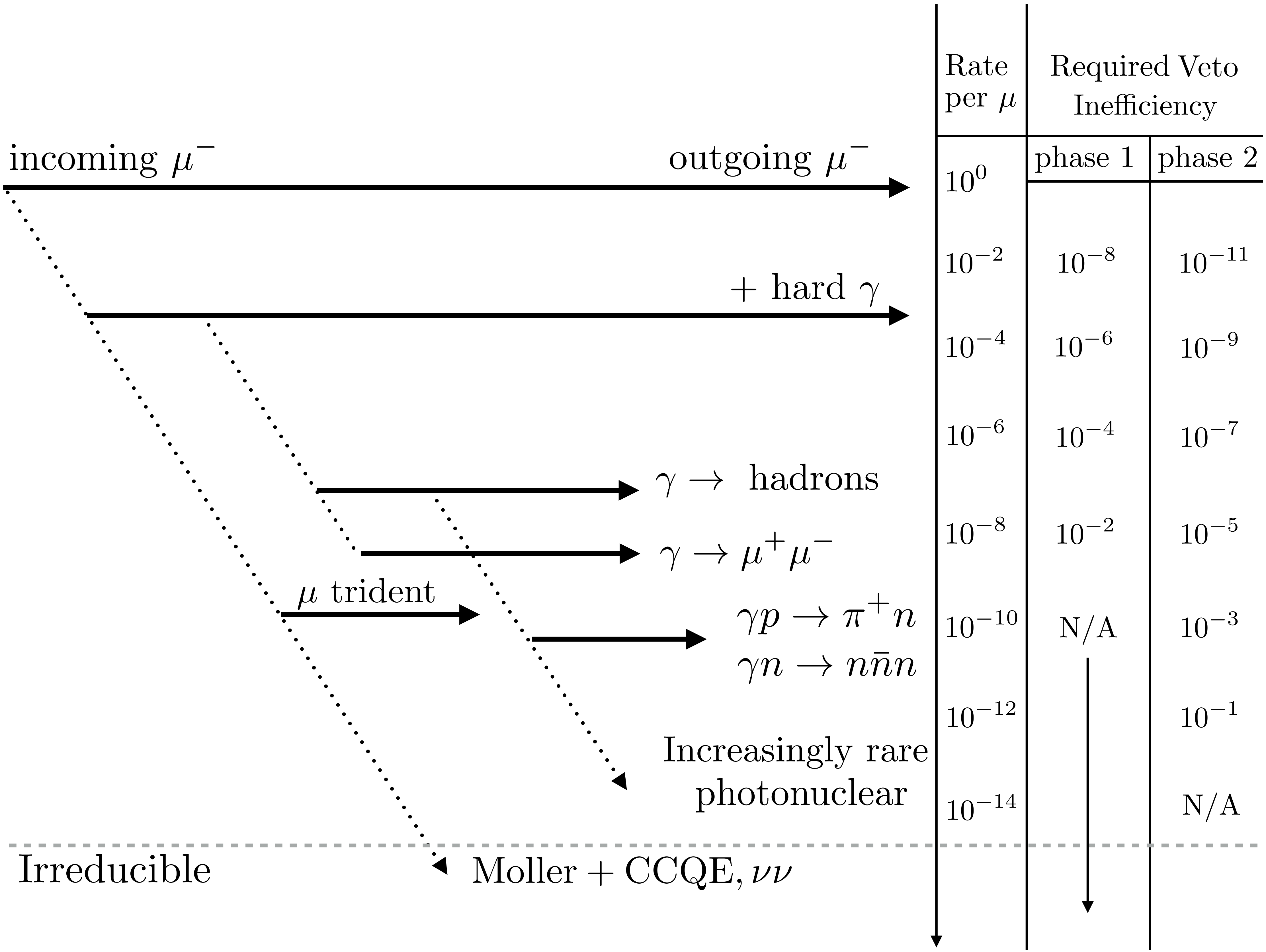


1) Measure Ein with tracker
2) Pass beam through target
3) Measure Eout with tracker
4) Trigger on missing energy
5) Veto additional SM activity

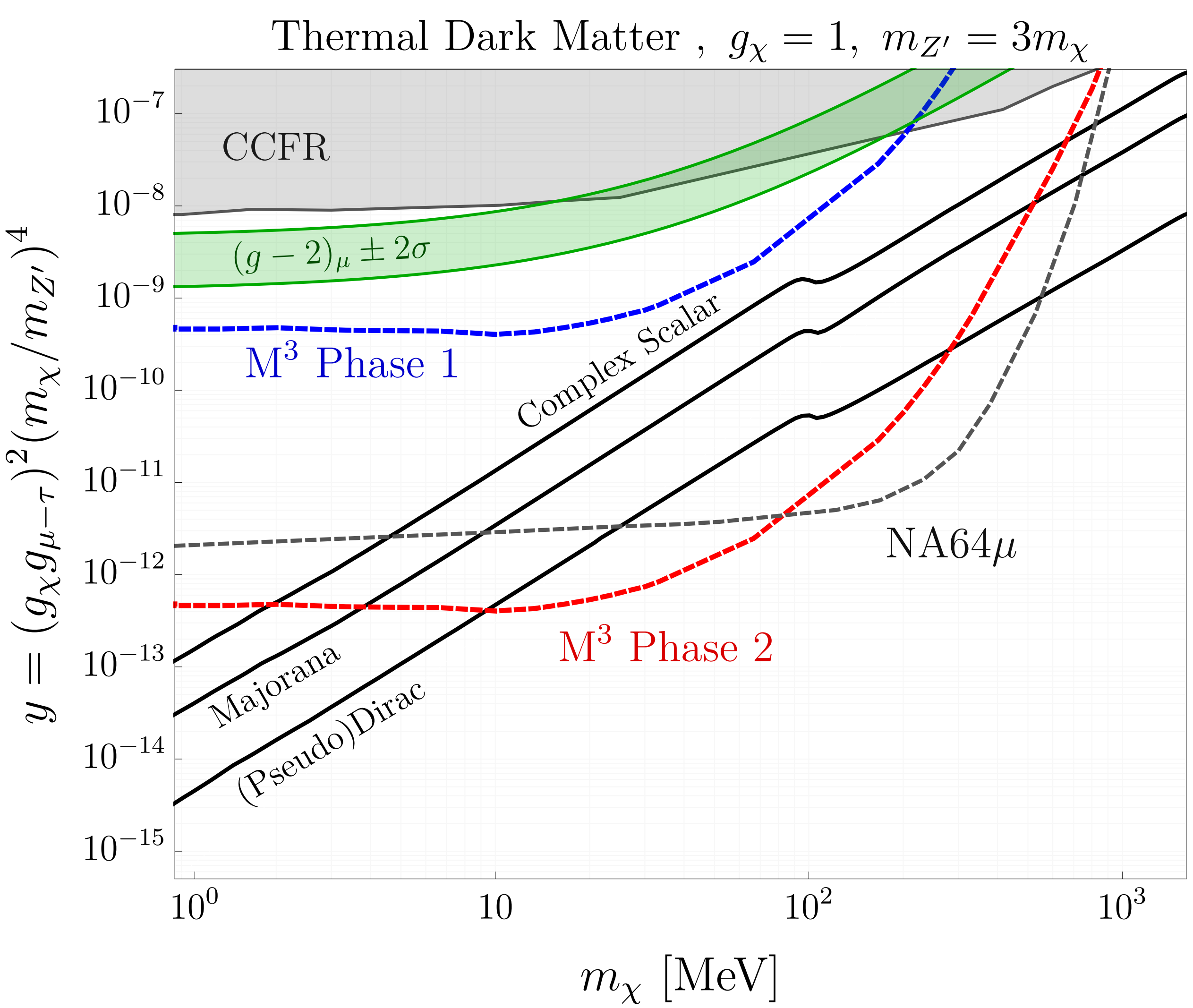
GEANT Simulation

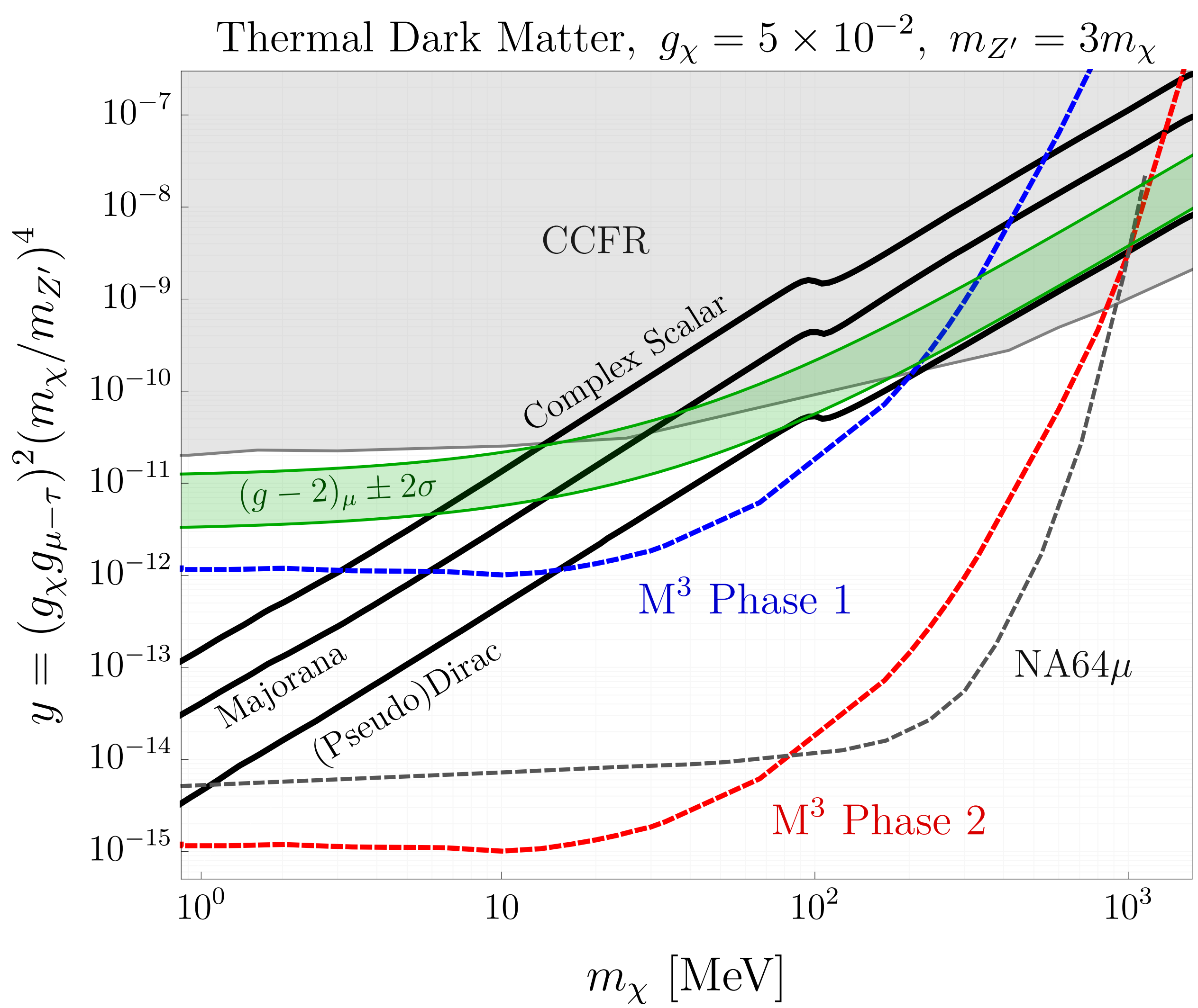


Background Rates

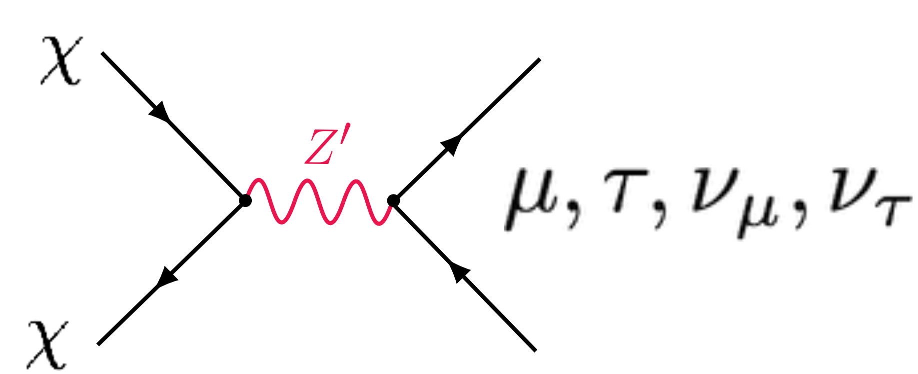


Comprehensive Coverage





Gauged $L_\mu - L_\tau$ Interaction



Also resolve muon g-2 with light physics

Compatible parameter space for freeze-out

Phase 1,2: 1e10, 1e13 muons

Overview

Current Status of g-2

Singlet Models

Electroweak Models

Effective Operator Analysis

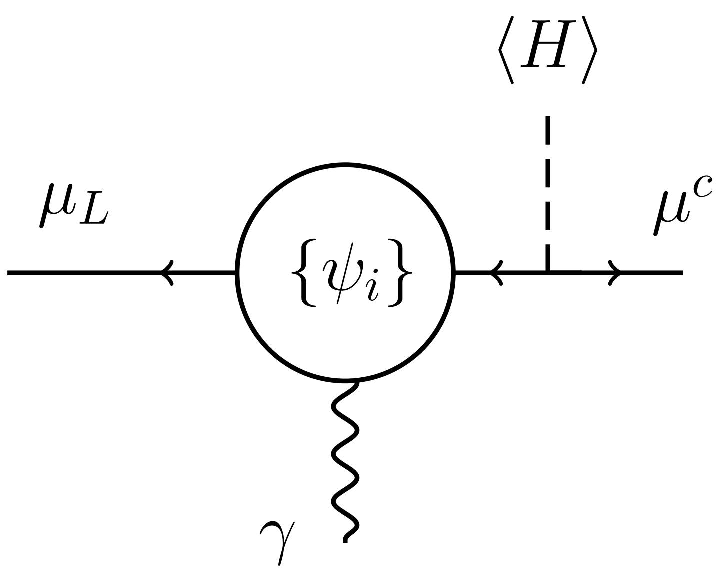
$$\mathcal{L}_{\text{eff}} = C_{\text{eff}} \frac{v}{M^2} (\mu_L \sigma^{\nu\rho} \mu^c) F_{\nu\rho} + \text{h.c.}$$

Do EWSB + chiral flip come from muon mass insertion?

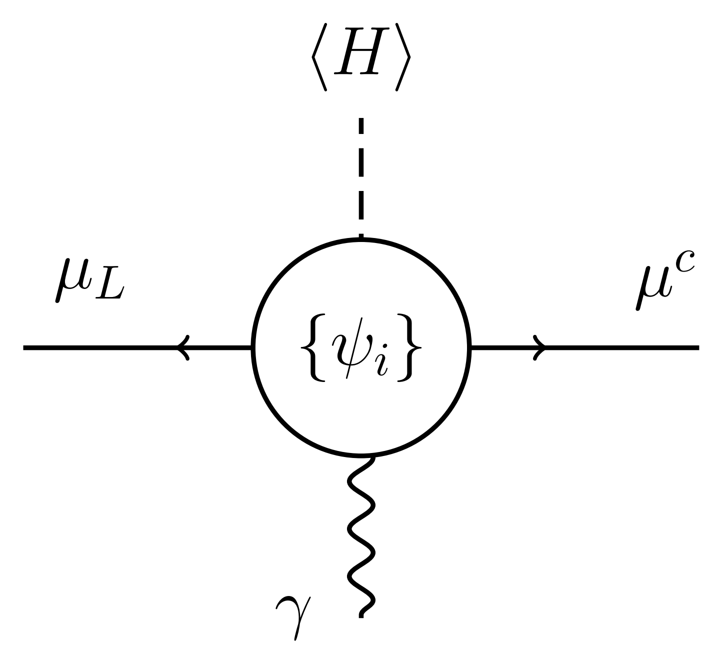
YES

NO

Singlet Models

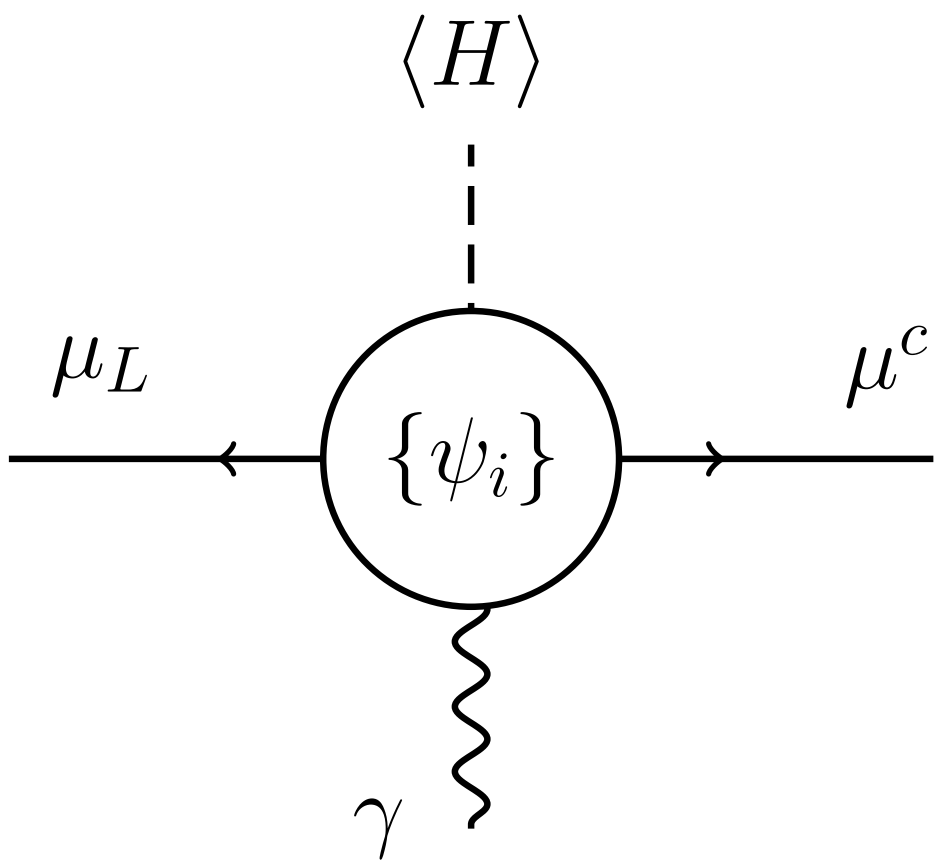


Electroweak Models



Electroweak Models

Chiral flip and EWSB on BSM lines



Hard to fully catalog BSM

Most new EW stuff will work
M > 100 GeV from LEP limits

Many free params (eg MSSM)
Many models testable @ LHC

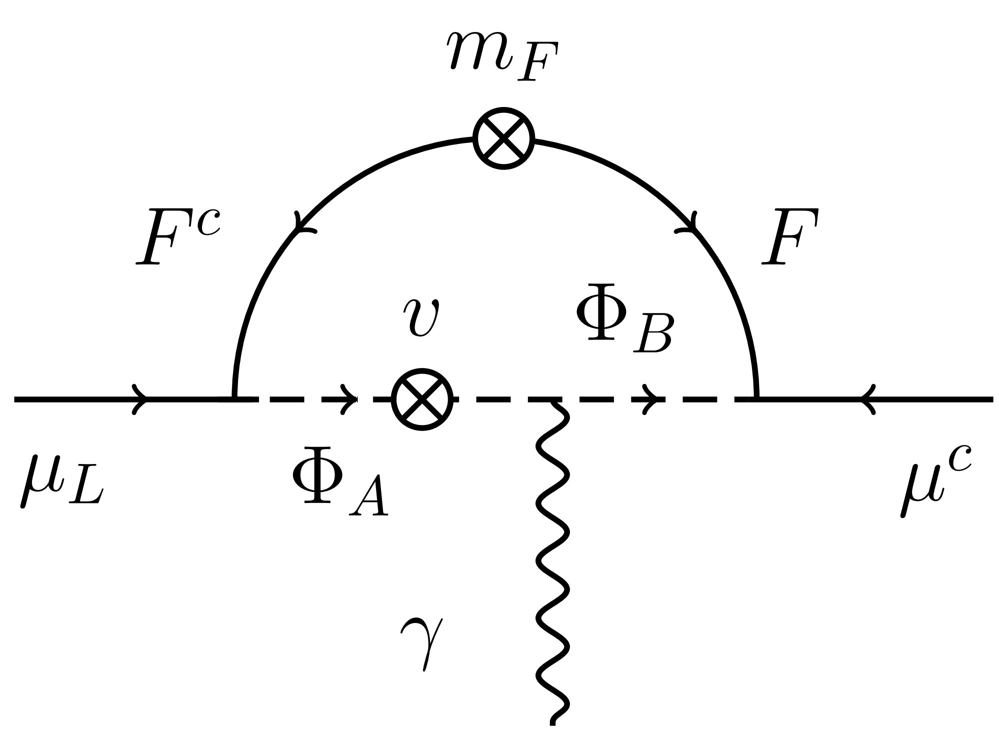
"Nightmare" Heavy BSM

Muon-philic~100 TeV & O(1) couplings
Need *muon* collider to fully test these

Capdevilla, Curtin, Kahn, GK 2006.16277,2101.10334

Electroweak Models

Reprsentative ultra-heavy model



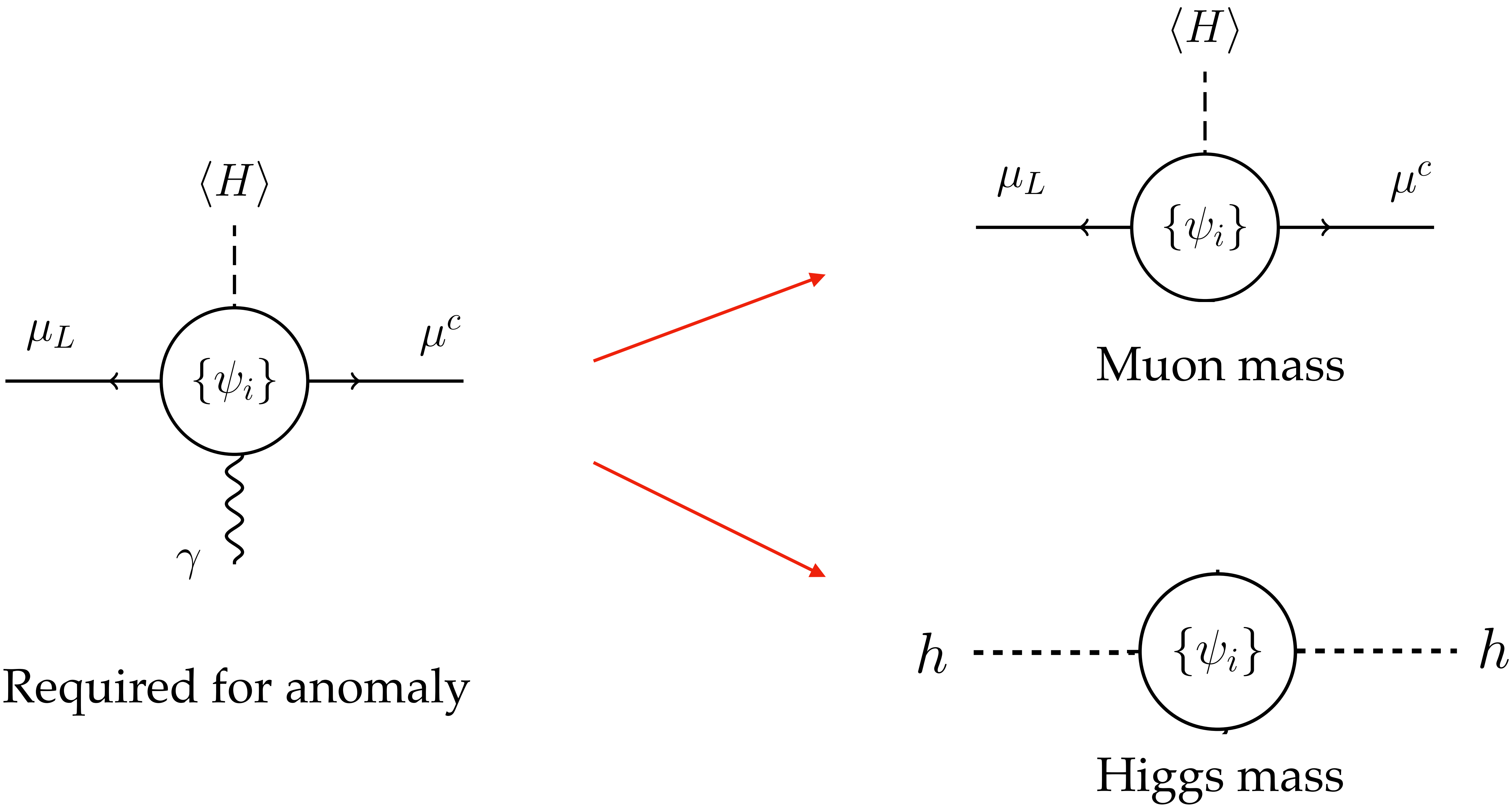
$$\mathcal{L}_{\rm SSF} \supset -y_1 F^c L_{(\mu)} \Phi_A^* - y_2 F \mu^c \Phi_B - \kappa H \Phi_A^* \Phi_B$$
$$-m_A^2 |\Phi_A|^2 - m_B^2 |\Phi_B|^2 - m_F F F^c + \text{h.c.} \ .$$

What is maximum mass of the *lightest* charged particle?

Model	R	R_A	R_B	Highest possible mass (TeV) of lightest charged BSM state — Unitarity only, N_{BSM}: 1	10
SSF	1_{-1}	$2_{1/2}$	1_0	65.2	241
	1_{-2}	$2_{3/2}$	1_1	85.9	321
	1_0	$2_{-1/2}$	1_{-1}	46.2	176
	1_1	$2_{-3/2}$	1_{-2}	81.8	302
	$2_{-1/2}$	3_0	$2_{-1/2}$	21.4	107
	$2_{-3/2}$	3_1	$2_{1/2}$	83.7	308
	$2_{1/2}$	3_{-1}	$2_{-3/2}$	95.5	356
	$2_{-1/2}$	1_0	$2_{-1/2}$	65.2	241
	$2_{-3/2}$	1_1	$2_{1/2}$	85.9	321
	$2_{1/2}$	1_{-1}	$2_{-3/2}$	44.8	155
	3_{-1}	$2_{1/2}$	3_0	95.4	359
	3_0	$2_{-1/2}$	3_{-1}	39.4	144
FFS	1_{-1}	$2_{1/2}$	1_0	37.3	118
	1_{-2}	$2_{3/2}$	1_1	67.3	213
	1_0	$2_{-1/2}$	1_{-1}	59.1	187
	1_1	$2_{-3/2}$	1_{-2}	73.2	231
	$2_{-1/2}$	3_0	$2_{-1/2}$	40	126
	$2_{-3/2}$	3_1	$2_{1/2}$	56.3	178
	$2_{1/2}$	3_{-1}	$2_{-3/2}$	82.3	260
	$2_{-1/2}$	1_0	$2_{-1/2}$	37.3	118
	$2_{-3/2}$	1_1	$2_{1/2}$	67.3	213
	$2_{1/2}$	1_{-1}	$2_{-3/2}$	46.2	146
	3_{-1}	$2_{1/2}$	3_0	71	225
	3_0	$2_{-1/2}$	3_{-1}	23.4	75
$M^{\mathrm{max}}_{\mathrm{BSM,charged}}$ (max in each column)				**95.5**	**359**

This seems pretty bad, but …

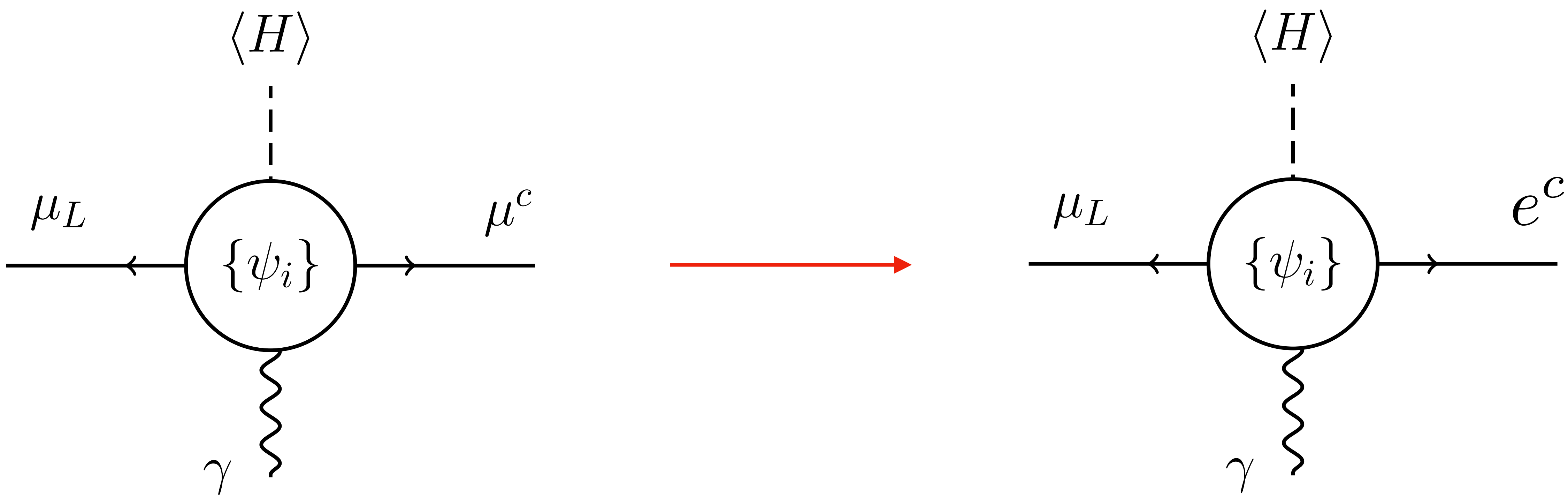
Makes the hierarchy problem real



Finite calculable ~ 100 TeV corrections to Higgs/muon masses

NOT like LHC and SUSY!

Important connection to flavor physics



Required for anomaly

$$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

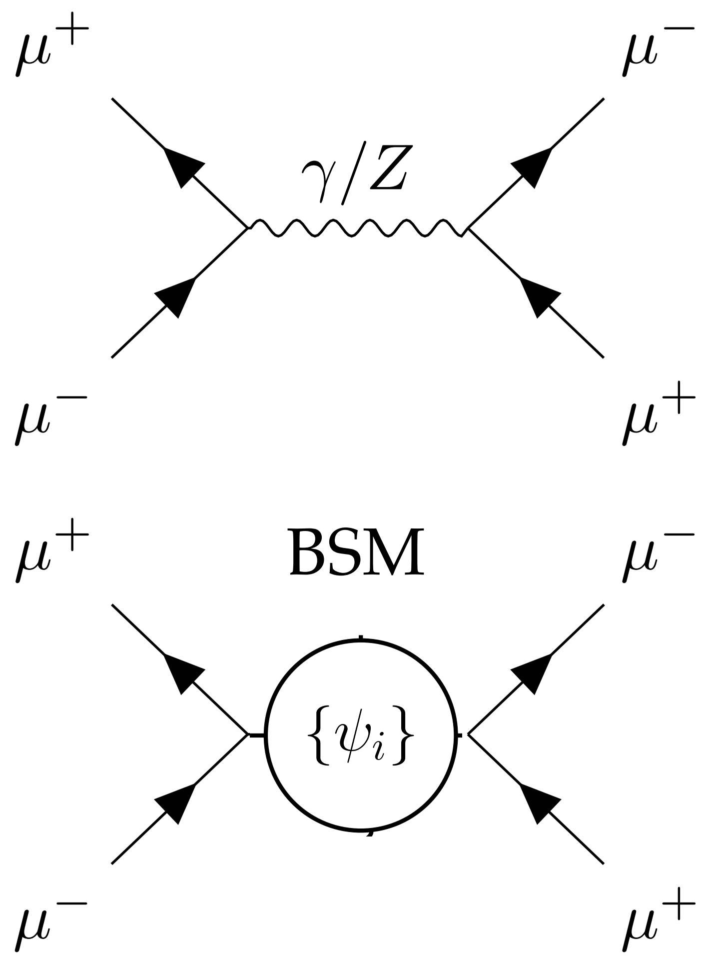
$$\mathrm{Br}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

Dangerous FCNC without MFV or tuning

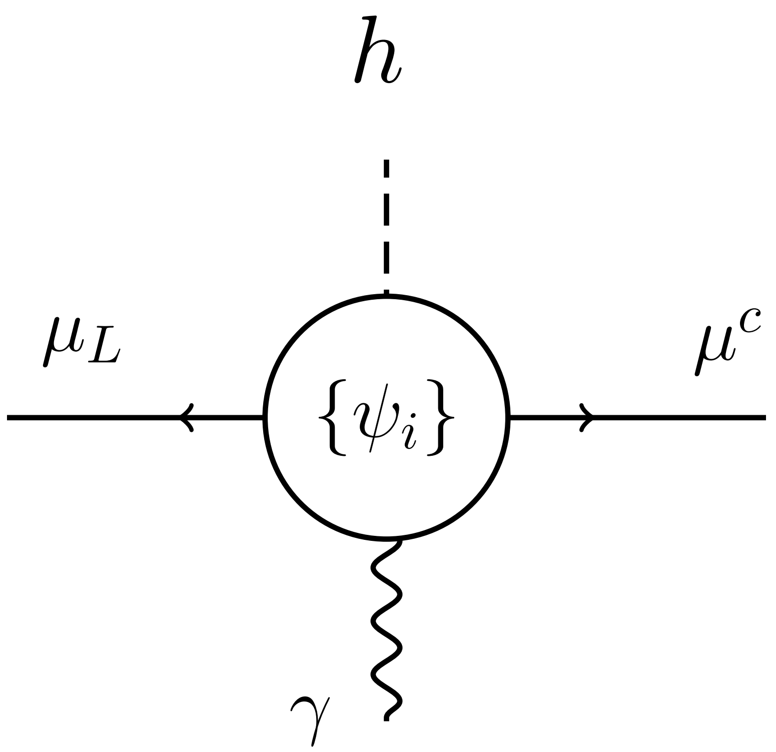
Model	R	R_A	R_B	Highest possible mass (TeV) of lightest charged BSM state: Unitarity only, $N_{\rm BSM}$: 1	Unitarity only, $N_{\rm BSM}$: 10	Unitarity + MFV, $N_{\rm BSM}$: 1	Unitarity + MFV, $N_{\rm BSM}$: 10	Unitarity + Naturalness, $N_{\rm BSM}$: 1	Unitarity + Naturalness, $N_{\rm BSM}$: 10	Unitarity + Naturalness + MFV, $N_{\rm BSM}$: 1	Unitarity + Naturalness + MFV, $N_{\rm BSM}$: 10
SSF	1_{-1}	$2_{1/2}$	1_0	65.2	241	12.9	47.1	11.5	11.5	6.54	10.1
	1_{-2}	$2_{3/2}$	1_1	85.9	321	18.1	64.8	19.2	19.2	8.41	12.3
	1_0	$2_{-1/2}$	1_{-1}	46.2	176	9.41	34.1	15.6	17.5	5.93	8.56
	1_1	$2_{-3/2}$	1_{-2}	81.8	302	17.1	63.7	19.3	19.3	8.38	12.1
	$2_{-1/2}$	3_0	$2_{-1/2}$	21.4	107	4.2	15.5	7.47	8.99	3.23	5.0
	$2_{-3/2}$	3_1	$2_{1/2}$	83.7	308	16.6	60.7	13.4	13.4	7.06	10.6
	$2_{1/2}$	3_{-1}	$2_{-3/2}$	95.5	356	18.3	67.8	15.6	15.6	7.75	11.3
	$2_{-1/2}$	1_0	$2_{-1/2}$	65.2	241	12.9	47.1	11.5	11.5	6.54	10.1
	$2_{-3/2}$	1_1	$2_{1/2}$	85.9	321	18.1	64.8	19.2	19.2	8.41	12.3
	$2_{1/2}$	1_{-1}	$2_{-3/2}$	44.8	155	8.8	32.3	10.9	10.9	5.64	8.56
	3_{-1}	$2_{1/2}$	3_0	95.4	359	19.4	73	20.1	30	7.75	11.5
	3_0	$2_{-1/2}$	3_{-1}	39.4	144	7.82	28.6	10.8	15.1	4.14	6.08
FFS	1_{-1}	$2_{1/2}$	1_0	37.3	118	8.87	28	12.3	18.7	4.6	7.04
	1_{-2}	$2_{3/2}$	1_1	67.3	213	15.8	50	13.5	18.8	4.86	6.93
	1_0	$2_{-1/2}$	1_{-1}	59.1	187	13.2	41.8	12.4	17.2	4.02	6.28
	1_1	$2_{-3/2}$	1_{-2}	73.2	231	17.4	55	13.9	19.7	5.04	7.25
	$2_{-1/2}$	3_0	$2_{-1/2}$	40	126	9.38	29.7	8.0	11.5	2.88	4.34
	$2_{-3/2}$	3_1	$2_{1/2}$	56.3	178	13.6	42.9	11.8	16.2	4.26	6.1
	$2_{1/2}$	3_{-1}	$2_{-3/2}$	82.3	260	19.2	60.6	13.6	19	4.93	7.0
	$2_{-1/2}$	1_0	$2_{-1/2}$	37.3	118	8.87	28	12.3	18.7	4.6	7.04
	$2_{-3/2}$	1_1	$2_{1/2}$	67.3	213	15.8	50	13.5	18.8	4.86	6.93
	$2_{1/2}$	1_{-1}	$2_{-3/2}$	46.2	146	11.2	35.4	9.83	13.8	3.49	5.18
	3_{-1}	$2_{1/2}$	3_0	71	225	17	53.6	13.1	18.1	4.04	6.97
	3_0	$2_{-1/2}$	3_{-1}	23.4	75	5.29	16.9	7.3	7.69	2.73	4.03
$M^{\rm max}_{\rm BSM,charged}$ (max in each column)				**95.5**	**359**	**19.4**	**73**	**20.1**	**30**	**8.41**	**12.3**

~ 10 TeV within scope of muon collider studies [Delahaye et al 1901.06150]

Guaranteed BSM at Muon Colliders



Bhabha scattering



Higgs photon production

Capdevilla, Curtin, Kahn, GK 2006.16277

Buttazzo Paradisi 2012.02769

Concluding Remarks

Exciting time for g-2 , new results soon!

If anomaly is due to SM singlets

Must be muon-philic scalar or vector

New searches for invisibly decaying "worst case" scenario

NA62 search in progress, M^3 concept being studied

Same S/V for g-2 can couple to dark matter

Common parameters for anomaly + freeze out

Searches can cover much of overlap regions

If anomaly is due to EW BSM

Unitarity < 100 TeV, but ~ 10s TeV from naturalness / flavor

Muon collider yields guaranteed discovery of new BSM

$$M^{\max}_{\text{BSM,charged}} \equiv \max_{\substack{\text{BSM theory space} \\ \Delta a_\mu = \Delta a_\mu^{\text{obs}}}} \left\{ \min_{i \,\in\, \text{BSM spectrum}} \left(m^{(i)}_{\text{charged}} \right) \right\}$$

Backup Slides

Constraints: Big Bang Nucleosynthesis

V is in chemical equilibrium with SM in early universe

$$n_V \propto \begin{cases} T^3 & (T \gg m_V) \\ e^{-m/T} & (T \ll m_V) \end{cases}$$

When T < *m*, the V decays transfer entropy to SM particles
Must happen before neutrinos decouple from photons

$$m \gtrsim T_{\nu,\mathrm{dec}} \approx 2\,\mathrm{MeV}$$

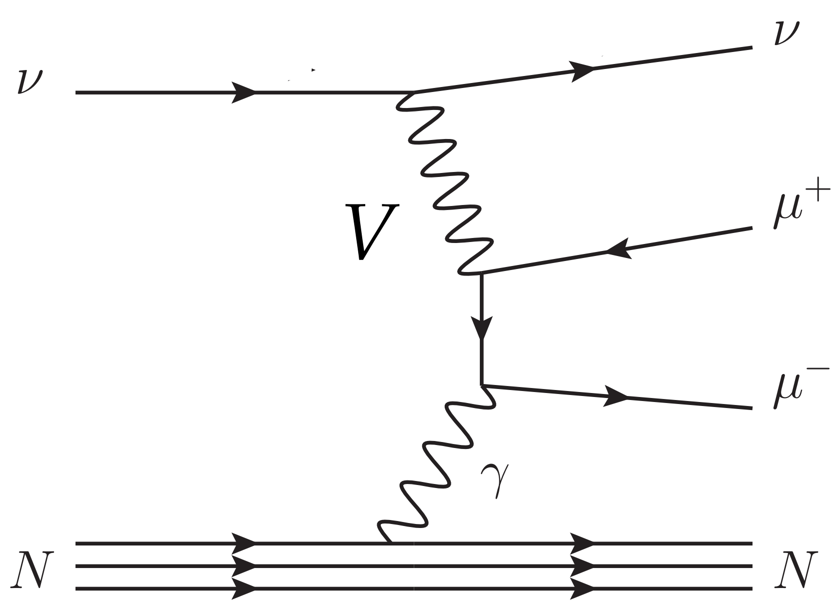
Otherwise V decays heat neutrinos not CMB $\rightarrow \Delta N_{\mathrm{eff}} \gtrsim 0.5$

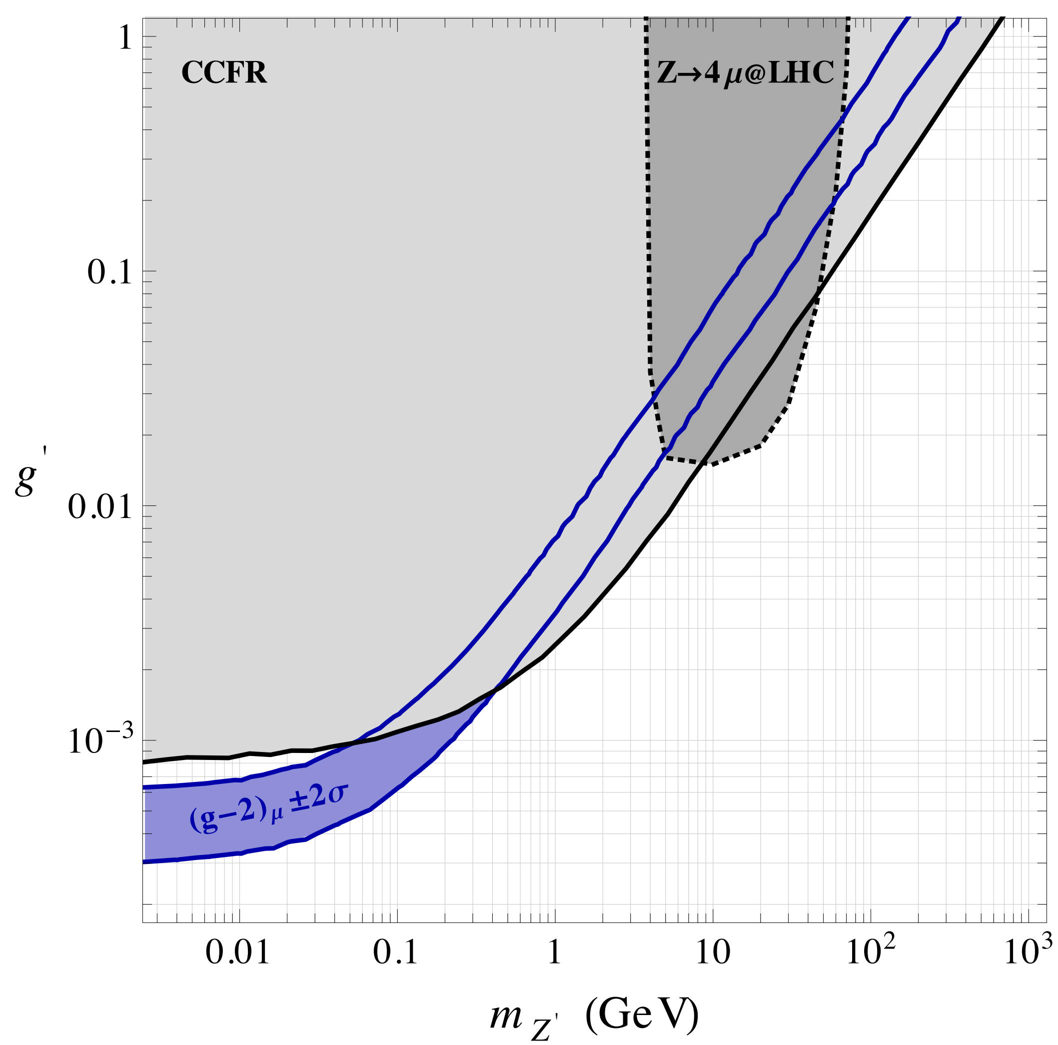
Spoils BBN element yields

*mild contribution for *m*~ few MeV may reduce Hubble tension

Escudero, Hooper, GK, Pierre, 1902.02010

Constraints: Neutrino Tridents, CCFR + CHARM II



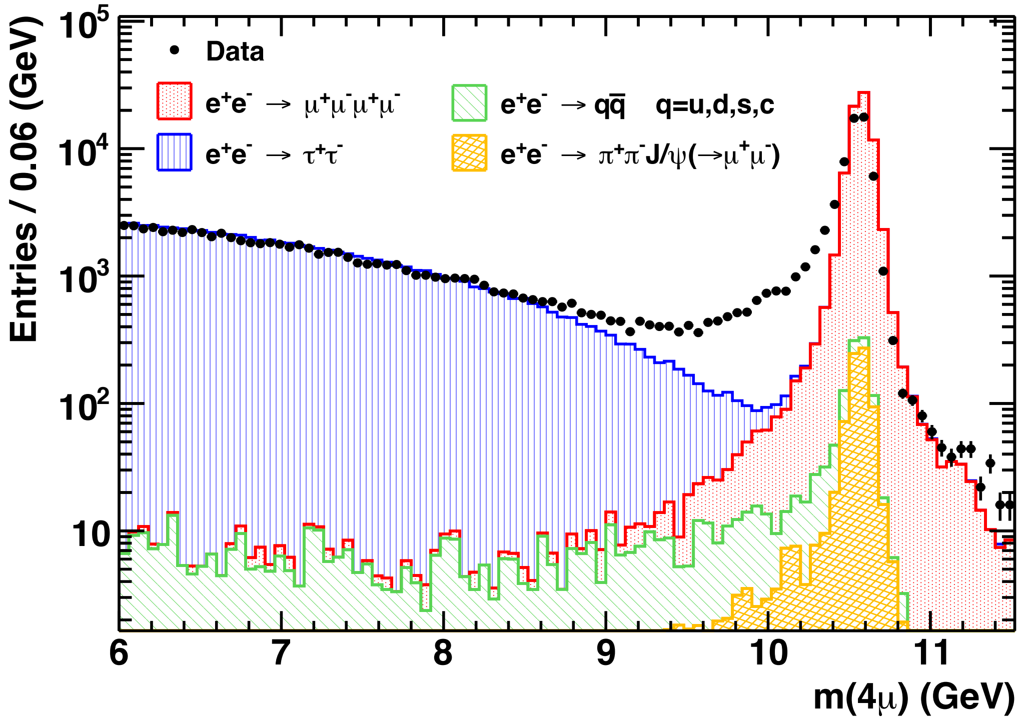


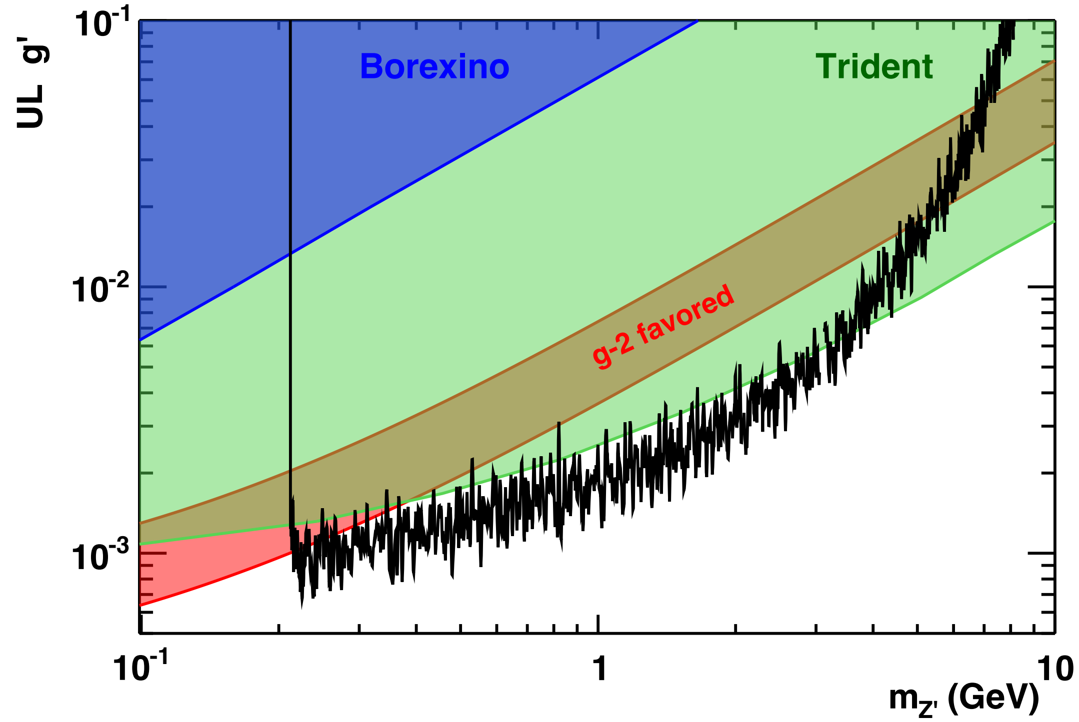
$$\frac{\sigma^{\mathrm{CCFR}}}{\sigma^{\mathrm{SM}}} = 0.82 \pm 0.28.$$

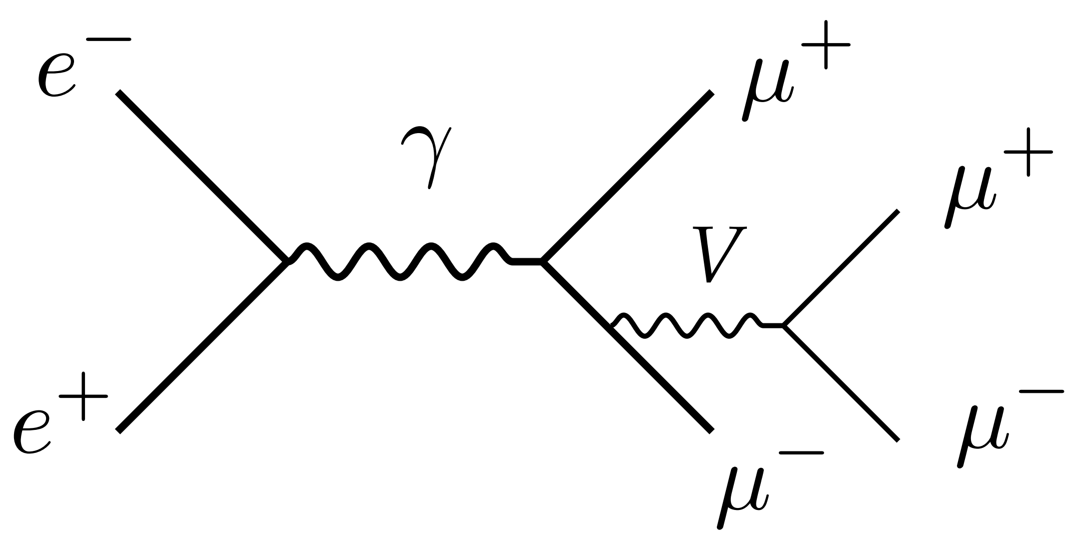
S. Mishra et al. (CCFR Collaboration), Phys.Rev.Lett. 66, 3117 (1991)

Altmanshoffer, Pospelov, Gori, Yavin 1406.2332

Constraints: BABAR Experiment





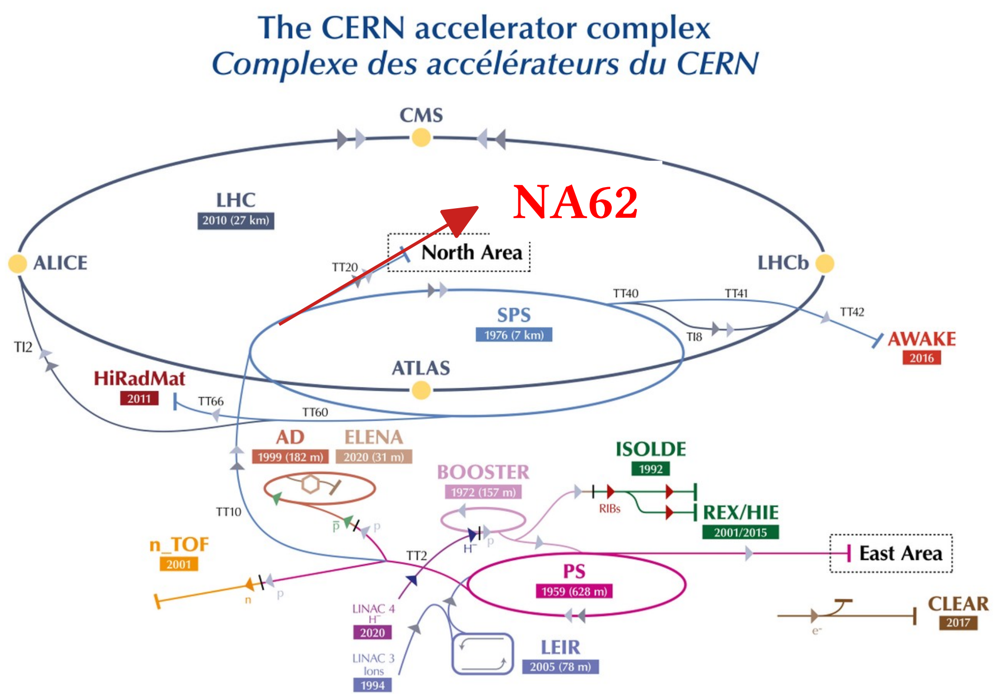


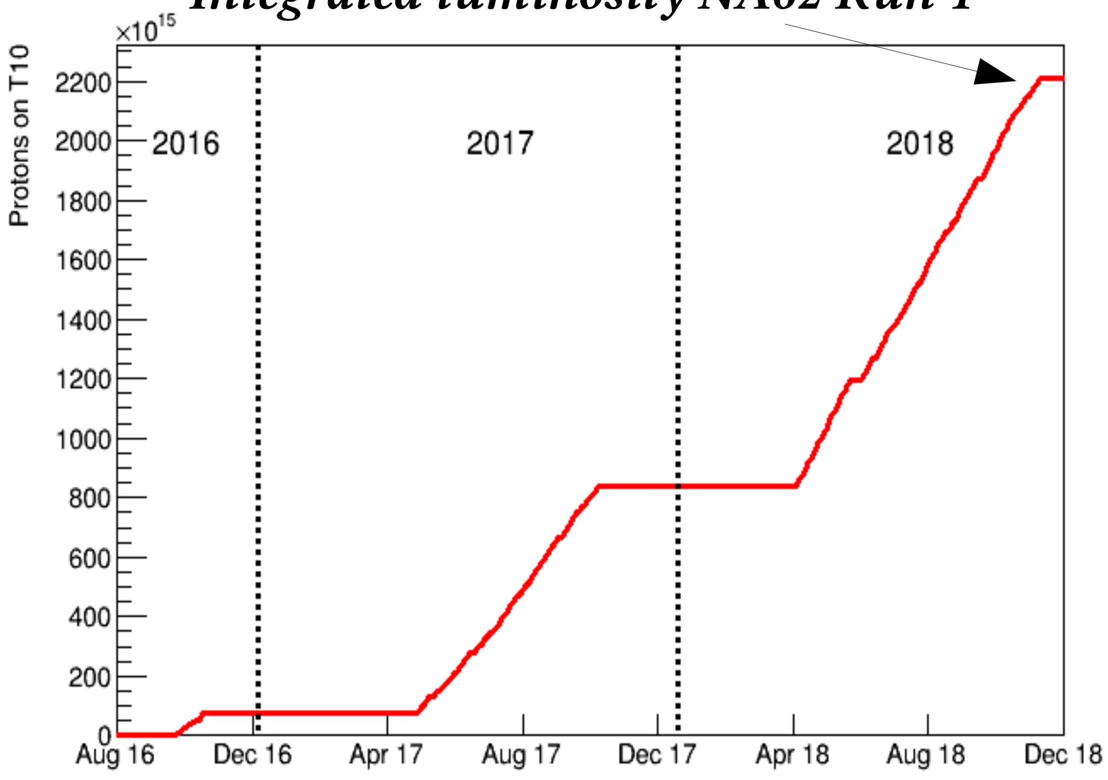
Search for 4 muon excess

Excludes g-2 for $m > 200$ MeV

BABAR Collaboration 1606.03501

State-of-the-art $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ experiments





- **Past experiments (E787/E949 @ BNL)**
  - Kaon decay-at-rest technique

    $$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

    Phys. Rev. D 79, 092004 (2009)

    Phys. Rev. D 77, 052003 (2008)

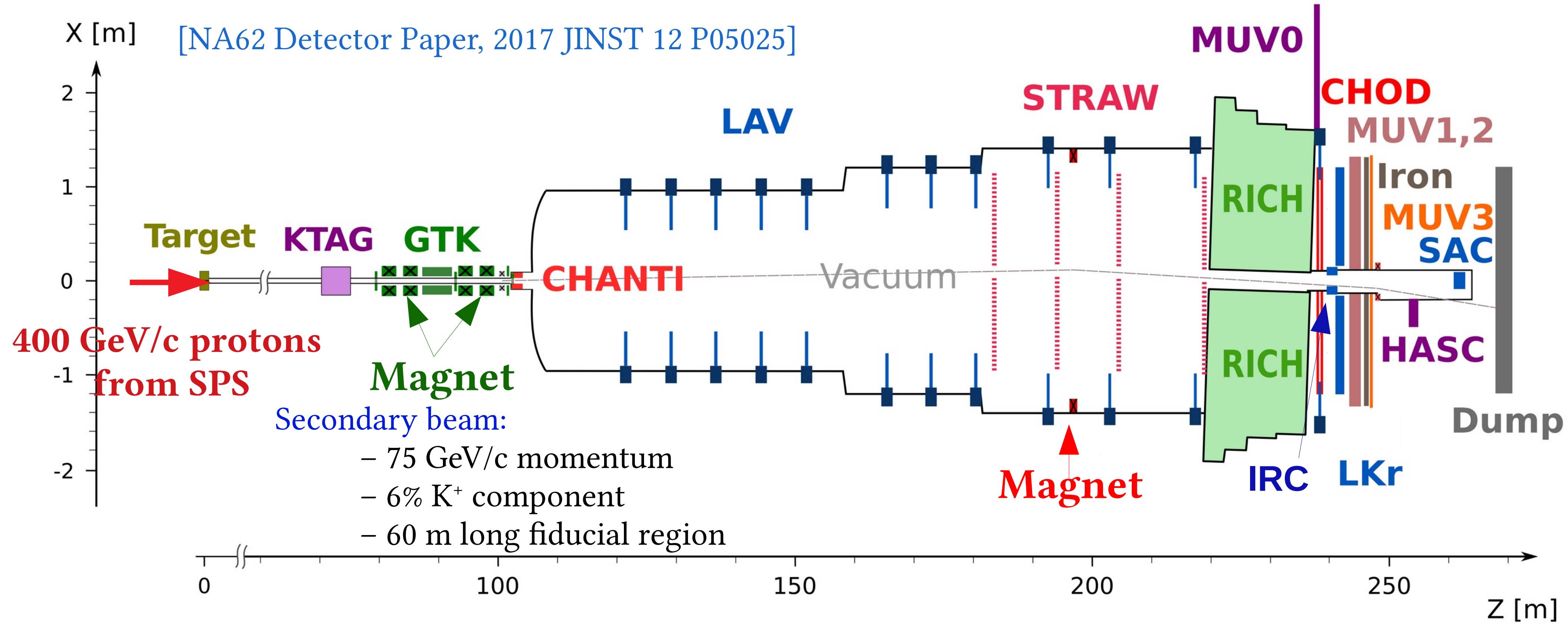
- **Present state-of-the-art $K^+ \rightarrow \pi^+ \nu\nu$ experiments**
  - Kaon decay-in-flight technique
  - NA62 experiment (this talk)

Run 1 statistics

1.9×10^{12} proton per spill on target

~ 2.2×10^{18} POT collected in Run 1

NA62 detector



- Upstream detectors (K^+):
  - **KTAG:** Differential Cherenkov counter for K^+ ID
  - **GTK:** Si pixel beam tracker
  - **CHANTI:** Anti-counter for inelastic beam-GTK3 interactions
- Decay Region detectors (π^+):
  - **STRAW:** track momentum spectrometer
  - **CHOD:** Scintillator hodoscopes
  - **LKr/MUV1/MUV2** : Calorimetric system
  - **RICH:** Cherenkov counter for $\pi/\mu/e$ ID
  - **LAV/SAC/IRC:** Photon veto detectors
  - **MUV3:** Muon veto

Invisible New Particles @ NA62

Step 2: calculate matrix element

$$m_{ij} \equiv (p_i + p_j)^2 \qquad\qquad \lambda_\mu \equiv 2 G_F f_K \, m_\mu V_{us} \simeq 8.7 \times 10^{-8}$$

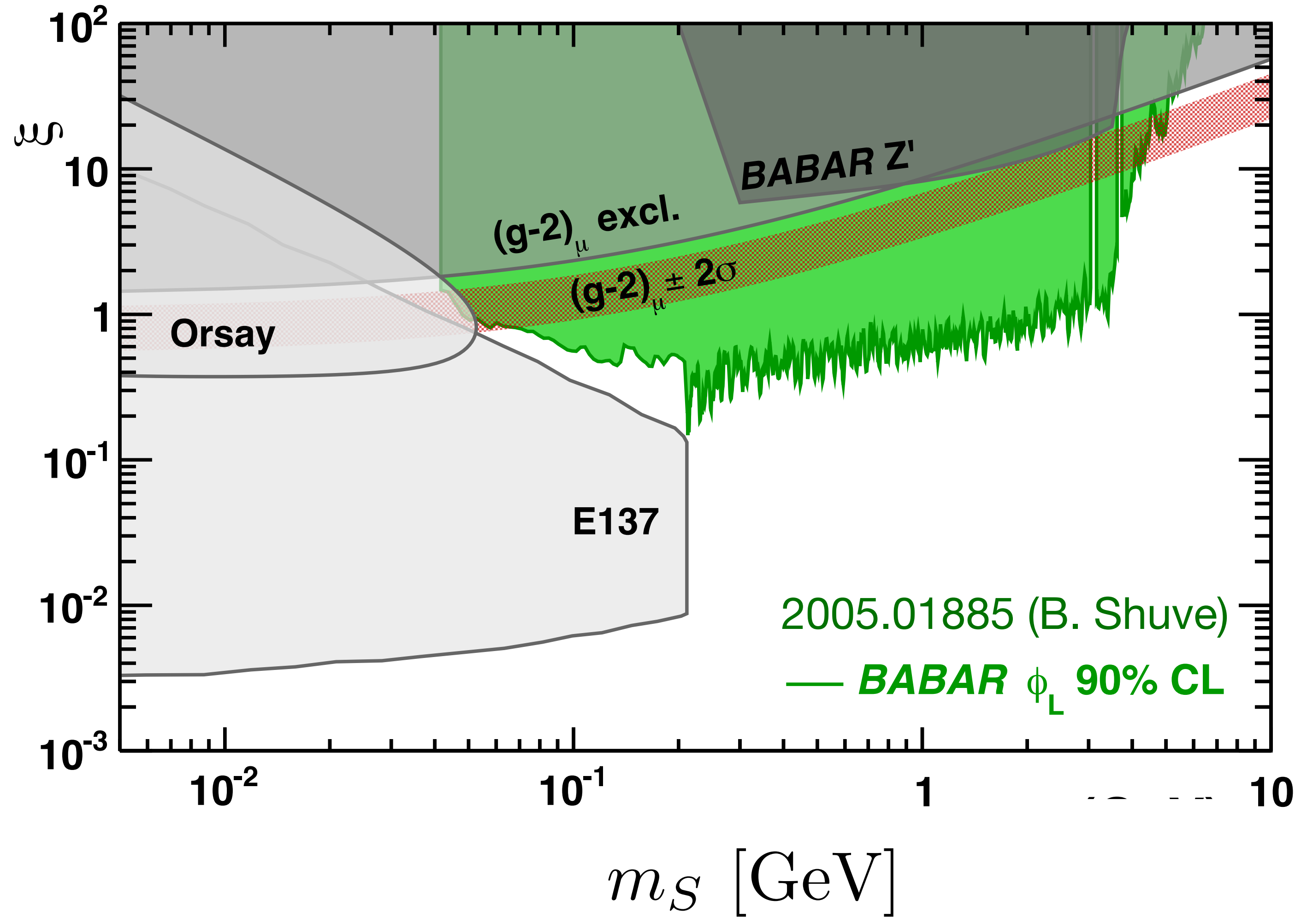
$$|\mathcal{M}_V|^2 = g_V^2 \lambda_\mu^2 \Bigg[2 + \frac{(m_{12}^2 + 2m_\mu^2 - 2m_K^2)}{m_{23}^2 - m_\mu^2} - \frac{(m_K^2 - m_\mu^2)(m_V^2 + 2m_\mu^2)}{(m_{23}^2 - m_\mu^2)^2} + 2\frac{(m_K^2 - m_\mu^2)^2 + m_V^2 m_\mu^2}{m_{12}^2 (m_{23}^2 - m_\mu^2)} - \frac{m_V^2 (m_K^2 - m_\mu^2)}{m_{12}^4} + \frac{(m_{23}^2 + m_\mu^2 - 2m_K^2)}{m_{12}^2} \Bigg]$$

Options For Singlets

Fun variation: mix S with neutral BSM bosons

Leptophilic scalar
(eg mix with 2HDM)

$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\ell S$$



LHC *probably* excludes > 10 GeV region… or will soon 1808.03684