SEP. 23 - 27, 2019

Korea Institute for Advanced Study (KIAS)

1F Auditorium

Search for muon-philic new light gauge boson at Belle II

Seong Chan Park (Yonsei)

based on Yongsoo Jho, Yongjoon Kwon, SCP, Po-Yan Tseng, 1904.13053

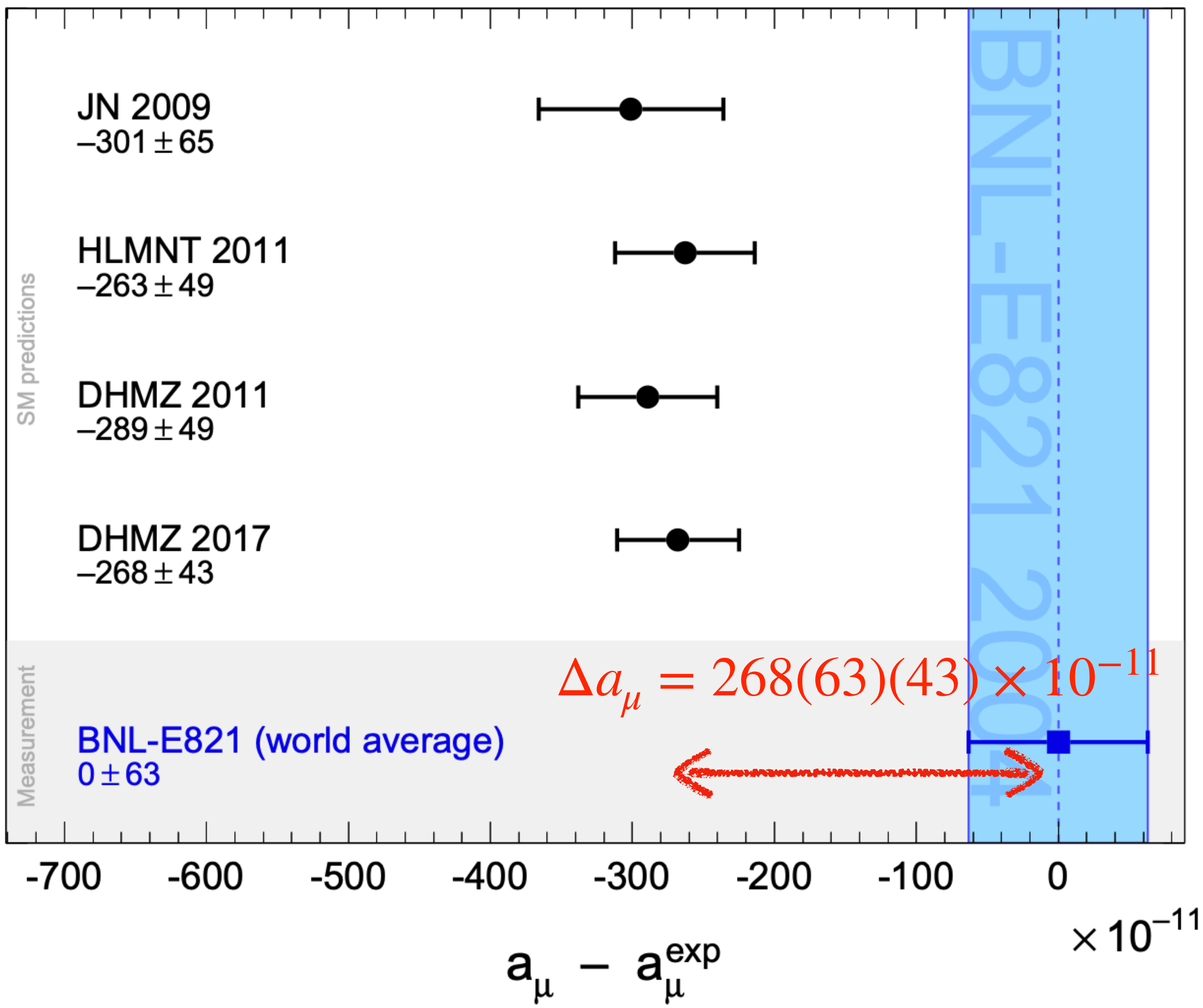
INTERNATIONAL WORKSHOP ON NEW PHYSICS AT THE LOW ENERGY SCALES

NEPLES-2019

outline

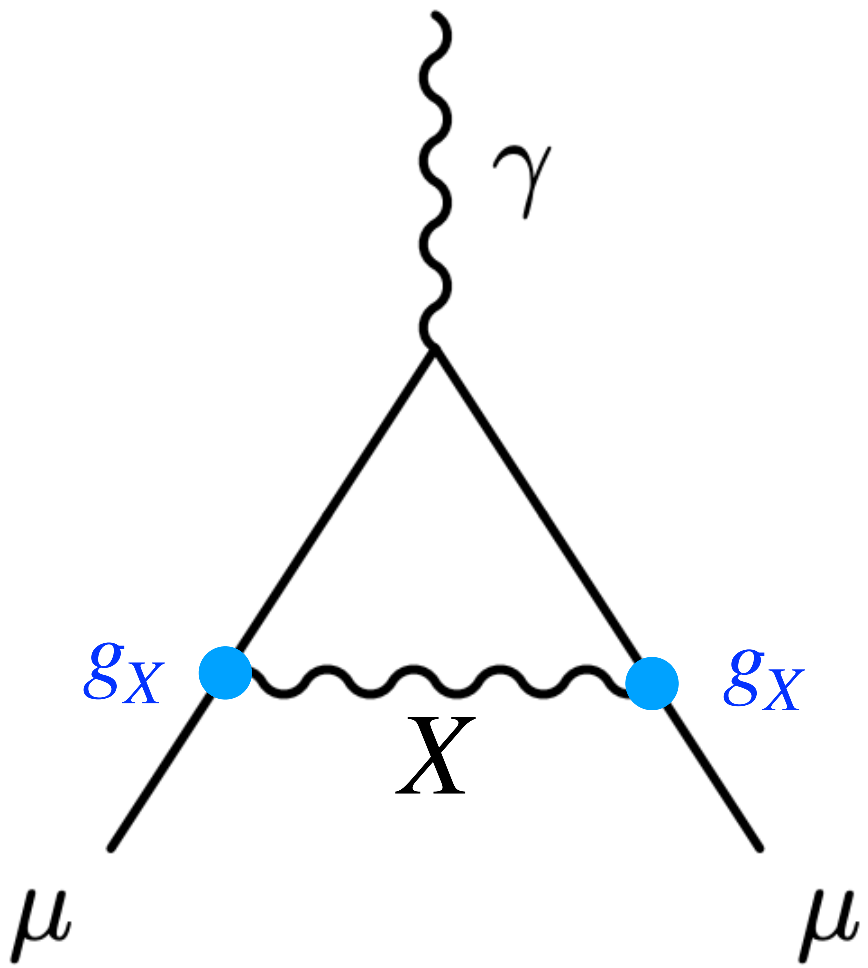
- Why μ-philic light boson?
- Constraints
- Search strategy at Belle-II
- Conclusion

Motivation



PDG

X contribution to $(g-2)_\mu$



$$\Delta a_\mu^X = \frac{g_X^2}{8\pi^2}\int_0^1 dz \frac{2z(1-z)^2}{(1-z)^2 + (m_X/m_\mu)^2 z}$$

$$\approx \begin{cases} 1 & \textbf{if } m_X \ll m_\mu \\ \frac{2}{3}\frac{m_\mu^2}{m_X^2} & \textbf{if } m_X \gg m_\mu \end{cases}$$

similar for a scalar

1804.0314

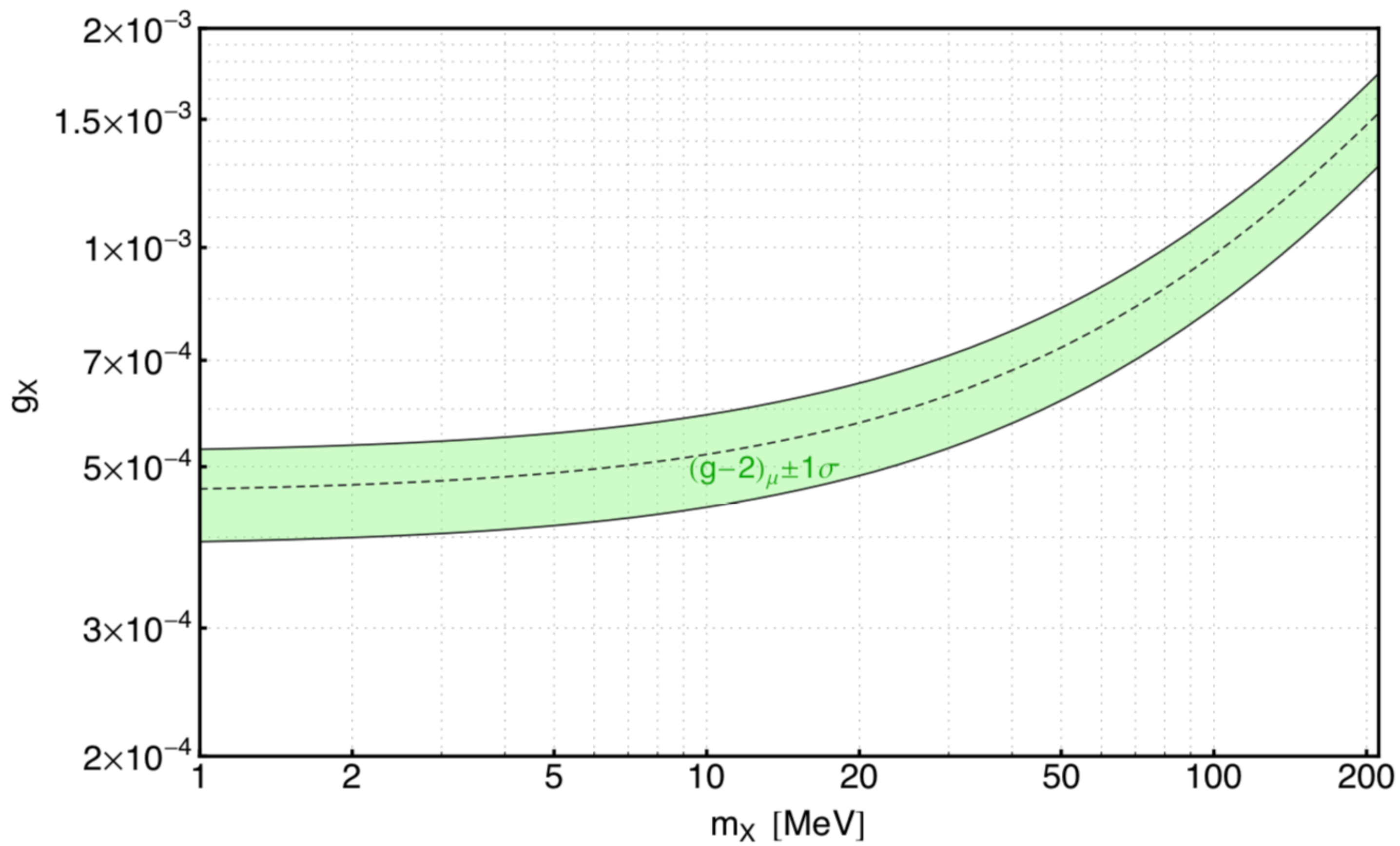
‘Heavy’ : $m_X \gg m_\mu$

$$\Delta a_\mu^X = \frac{g_X^2}{8\pi^2}\int_0^1 dz \frac{2z(1-z)^2}{(1-z)^2 + (m_X/m_\mu)^2 z} \approx \frac{g_X^2}{12\pi^2}\frac{m_\mu^2}{m_X^2}$$

$$g_X \sim 1, \;\; m_X \sim 330 \text{ GeV}$$

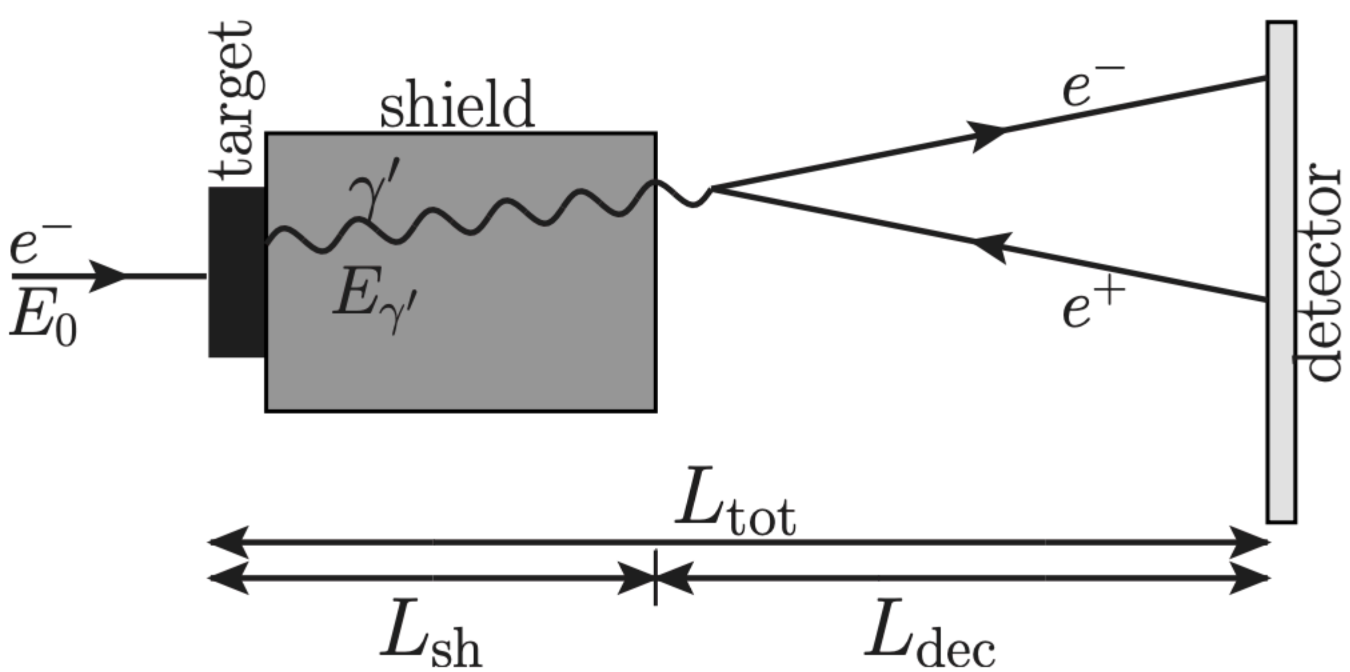
ruled out by LHC

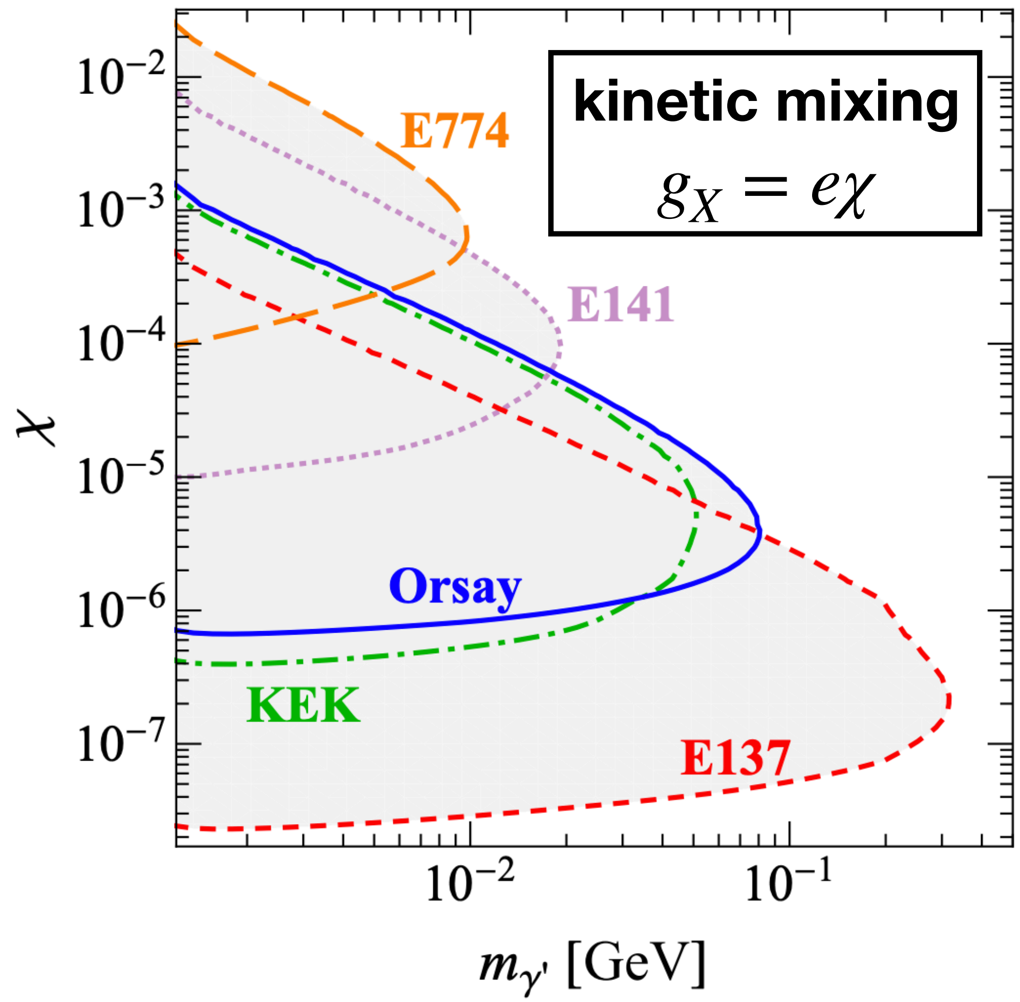
‘Light’: $m_X \leq 2m_\mu$



Ball park: $g_X \sim 5 \times 10^{-4}, m_X \sim 10 \text{ MeV}$

Light, flavor universal X:
Beam dump $e^+e^- \to \gamma X(e^+e^-)$

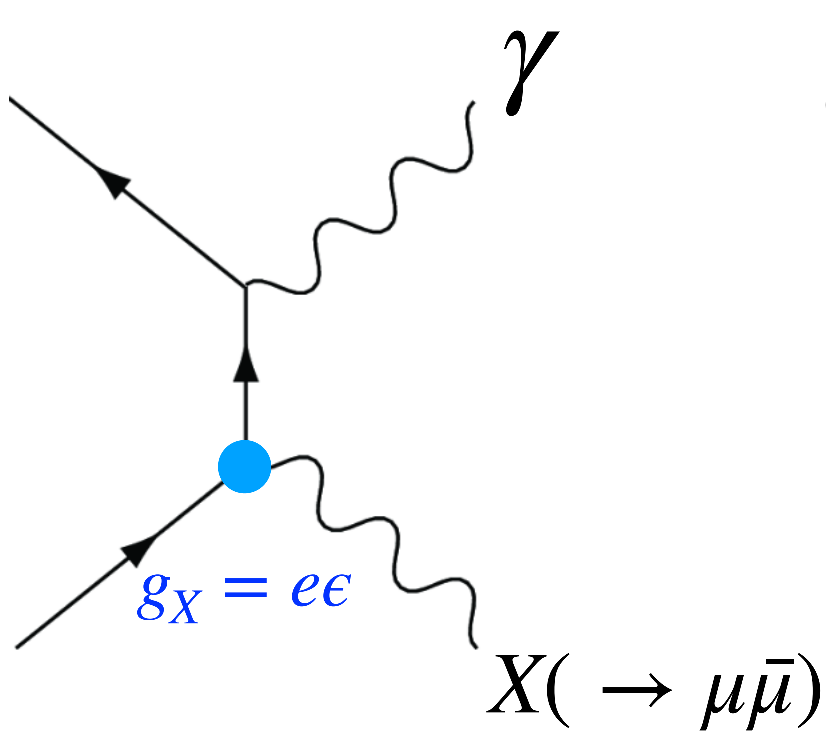


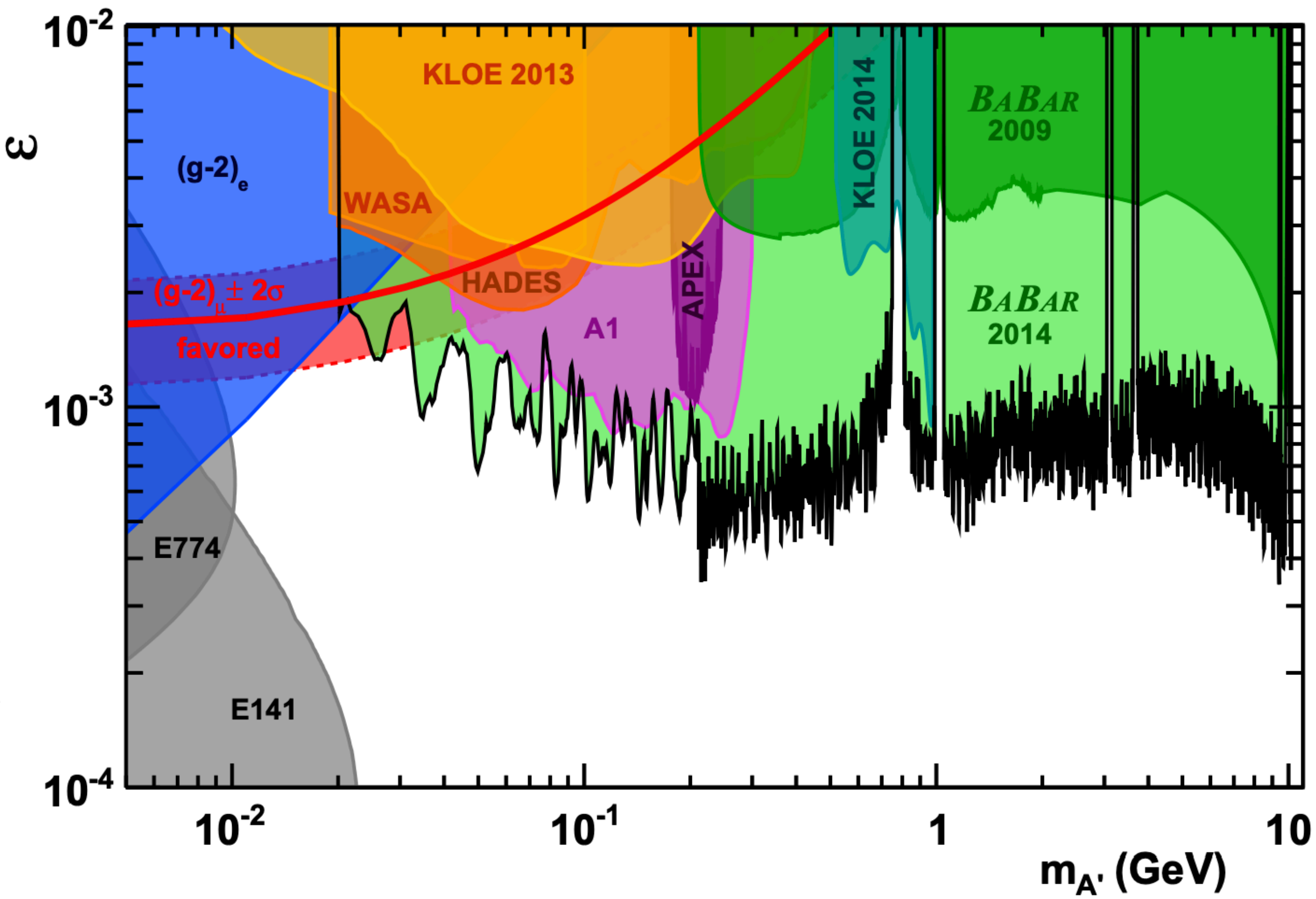


Sarah Andreas, Carsten Niebuhr, and Andreas Ringwald, 1209.6083

Light, flavor universal case:

BarBar $e^+e^- \to \gamma X(X \to \mu^+\mu^-)$





BarBar 1406.2980

No interesting parameter for $(g-2)_\mu$ anomaly exists for light, flavor universal X

~~No~~ interesting parameter for $(g-2)_\mu$

anomaly exists for ~~flavor universal~~ X

$\mu - philic$

e.g. $U(1)_{L_\mu}, U(1)_{L_\mu - B_i}, U(1)_{L_\mu - L_\tau}$

L_μ

- Lepton numbers (L_e, L_μ, L_τ) are accidental symmetries of the SM.

- Anomalous

- WZW contribution:
  $$g_X \epsilon^{\mu\nu\rho\sigma} X_\mu (g'^2 B_\nu \partial_\rho B_\sigma + g^2 W_\nu^a \partial_\rho W_\sigma^a + \frac{g^2}{3} \epsilon^{abc} W_\nu^a W_\rho^b W_\sigma^c)$$
  induce $Z \to X\gamma, B \to KX, B \to \pi X$ …

- highly constrained

$$L_\mu - B_{i=1,2,3}$$

- Anomaly free
- Has additional hadronic interactions
- highly constrained

$L_\mu - L_\tau$

- The differences $(L_i - L_j), i \neq j$ are anomaly free in the SM.
- Economical extension of the SM: $G_{SM} \times U(1)_{L_i - L_j}$ does not need any exotic fermion.
- $L_\mu - L_\tau$ explains $(g-2)_\mu$: our X-boson!

Model Lagrangian

Only two free parameters

$$\mathscr{L}_{\text{minimal}} \ni -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}m_X^2 X^\mu X_\mu - g_X X_\mu J_X^\mu$$

$$J_X^\mu = \bar{\mu}\gamma^\mu\mu - \bar{\tau}\gamma^\mu\tau + \bar{\nu}_\mu\gamma^\mu\nu_{\mu L} - +\bar{\nu}_\tau\gamma^\mu\nu_{\tau L}$$

(possible)
Extension with dark sector

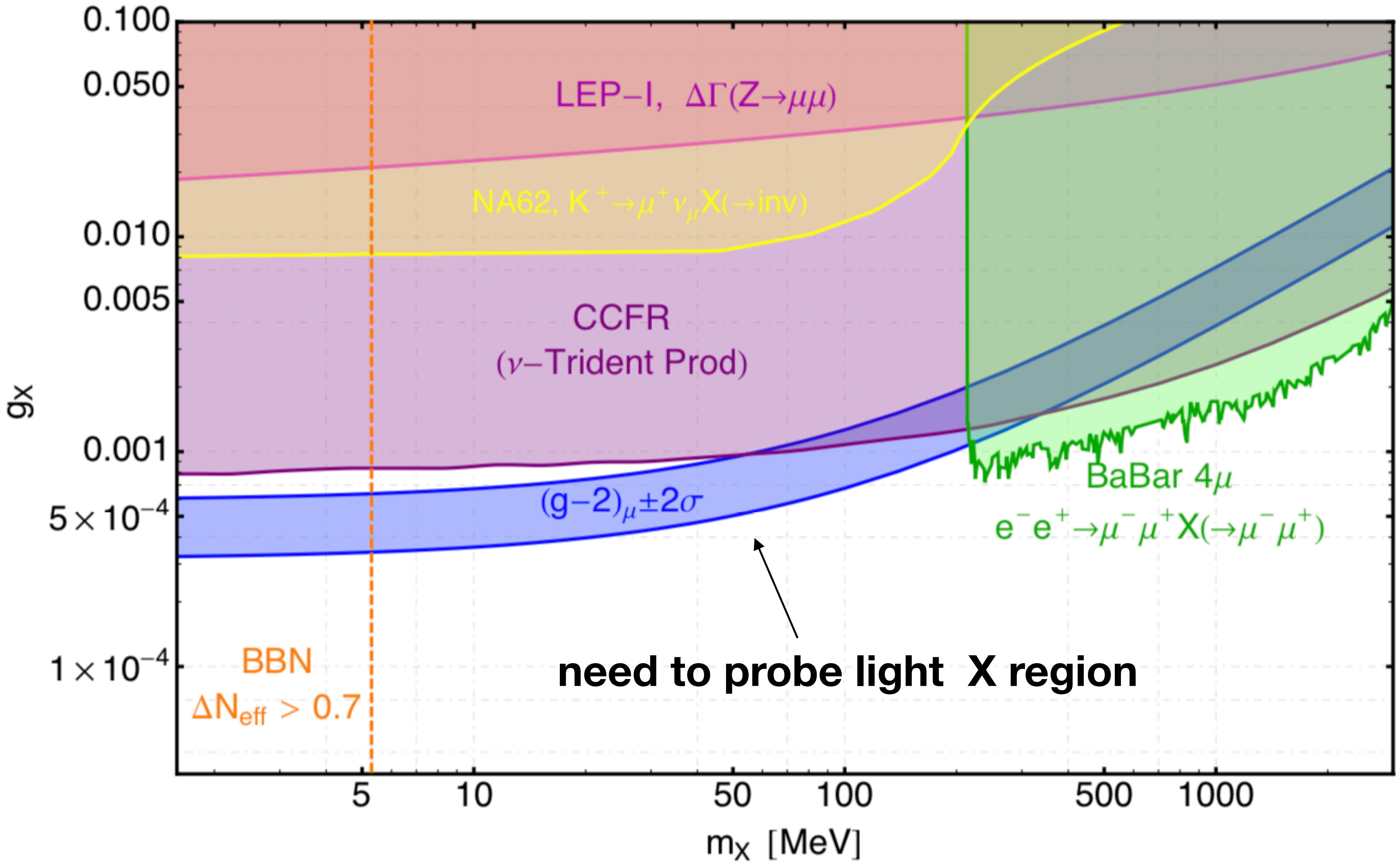
$$\mathscr{L} = \mathscr{L}_{\text{minimal}} + \sum_{i=1}^{N_\chi} \left[\bar{\chi}_i (i\gamma^\mu \partial_\mu - m_{\chi_i})\chi_i - g_D(\bar{\chi}_i \gamma^\mu \chi_i) X_\mu \right]$$

χ_i : **dark sector fermions**

$$\Gamma_{X,\textbf{total}} = (1 + \delta_{\text{NM}}) \cdot \Gamma_{\text{Minimal}}$$ **:enhanced decay width**

$$\delta_{\text{NM}} = \sum_{i=1}^{N_\chi} \frac{g_D^2}{g_X^2} ((1 + \frac{m_{\chi_i}^2}{m_X^2})) \sqrt{1 - 4\frac{m_{\chi_i}^2}{m_X^2}}$$

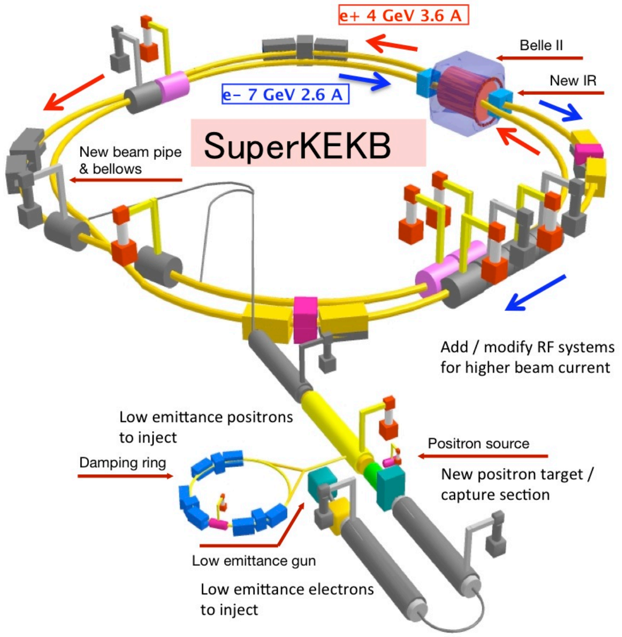
Known constraints

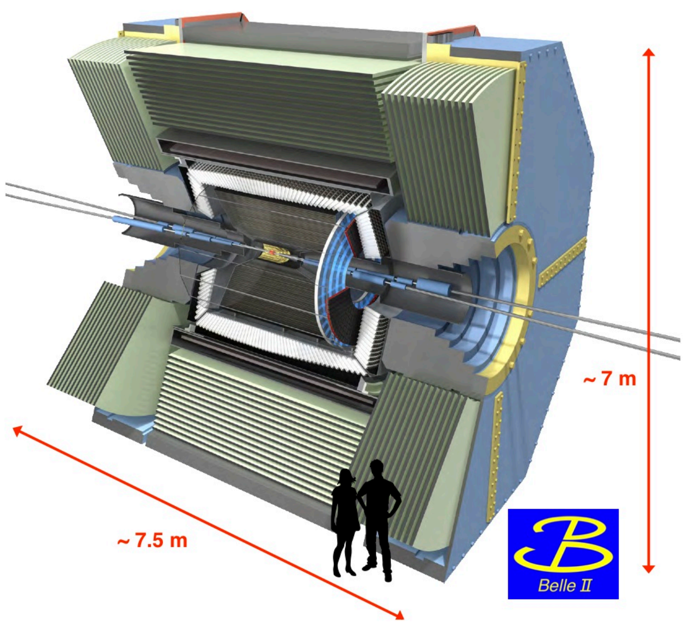


Ball park: $g_X \sim 5\times10^{-4}, m_X \sim 10\ \text{MeV}$

Jho, Kwon, SCP, Tseng 1904.13053

Belle-II($50\mathrm{ab}^{-1}$) = 50 Belle
:an ideal place to look for a light-X





$i)\ \epsilon(p_{\mu^\pm} > 0.6\mathrm{GeV}/c) = 0.9$ at KLM(K_L, μ) detector **Excellent muon detector**

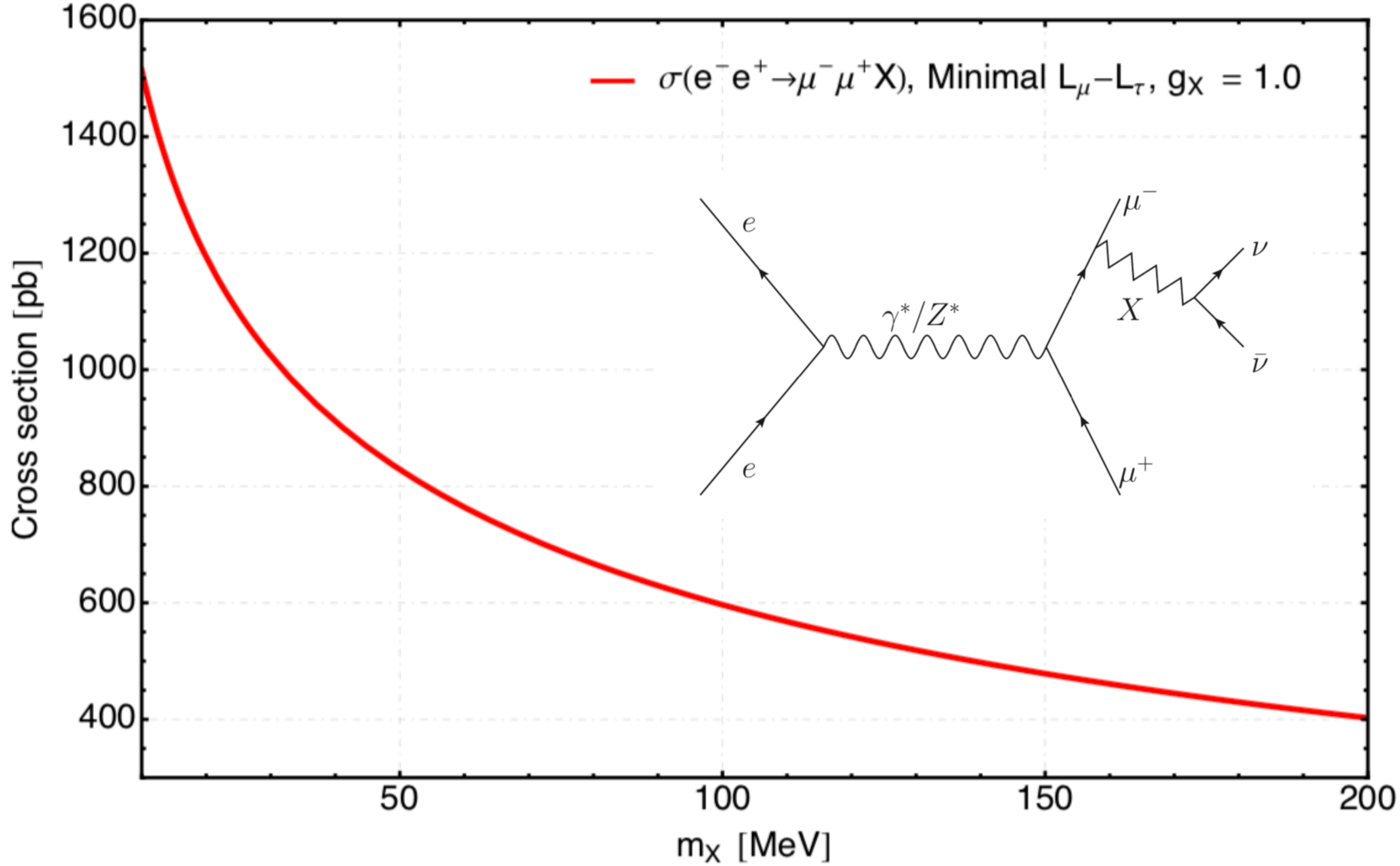
$\sigma_{p_{\mu^\pm}}/p_{\mu^\pm} = 0.0011 p_{\mu^\pm}[\mathrm{GeV}] \oplus 0.0025/\beta$ **Excellent muon tracker (Central Drift Chamber)**

$ii)\ 1 - \epsilon_\gamma = 10^{-6}$ Low intrinsic probability of missing the photon detection inside the ECL crystals

+KLM detectability (end cap region) **Excellent photon detector for background rejection**

X-boson at Belle II

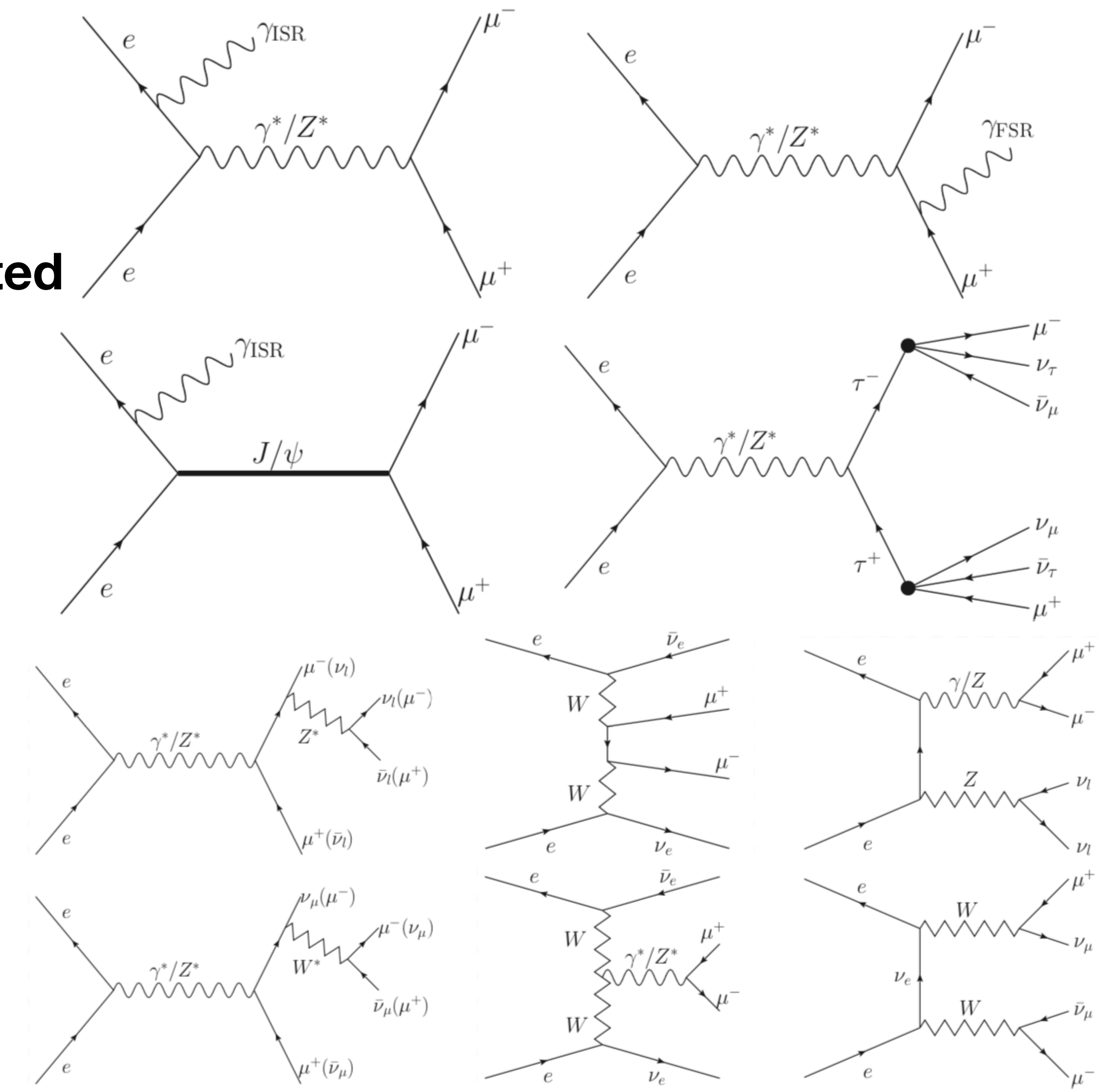
$$e^+e^- \to \mu^+\mu^- X(\to \nu\bar{\nu})$$



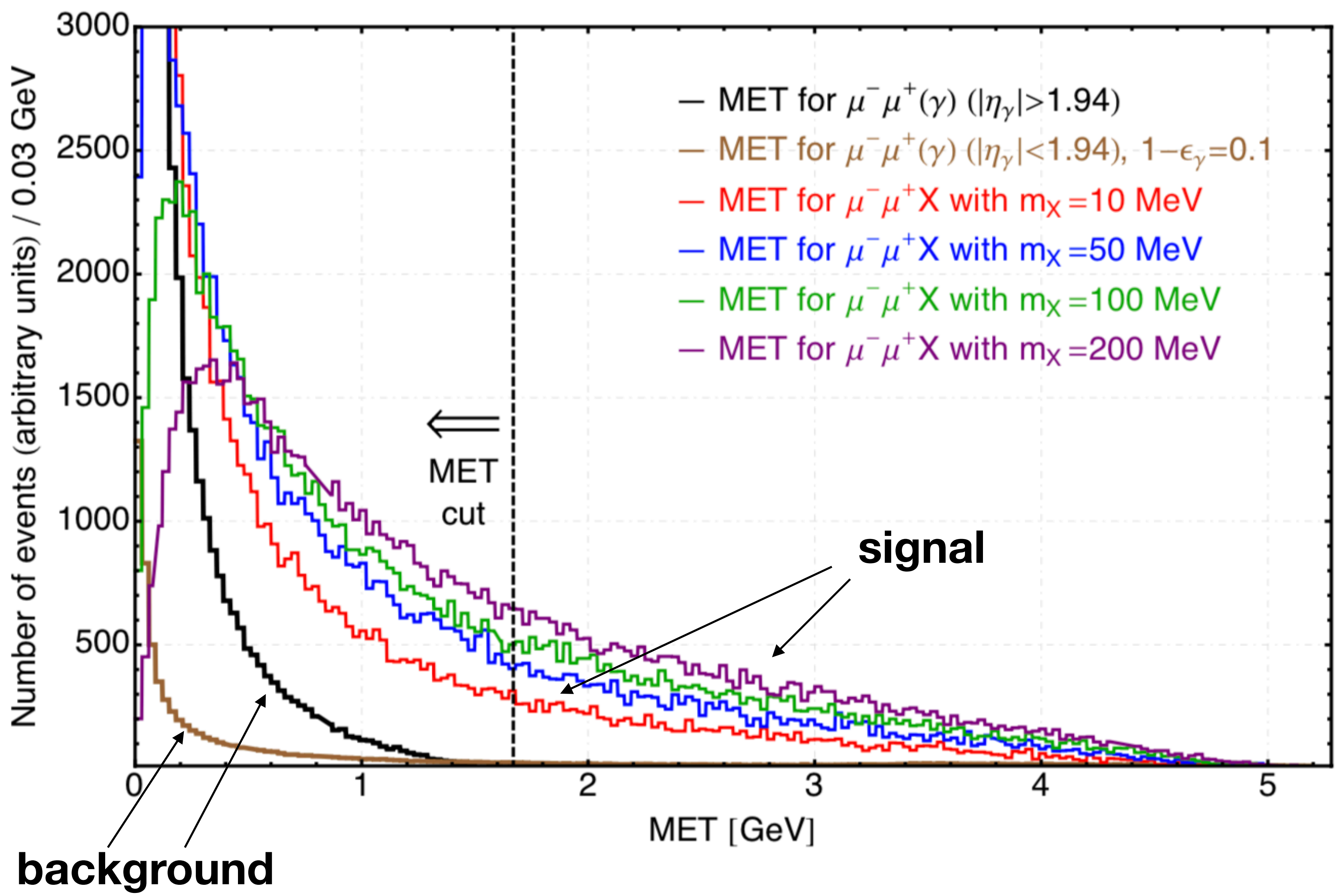
MadGraph5 aMC@NLO, FeynRules

SM background: $\mu^+\mu^- + MET$

- $e^-e^+ \to \mu^-\mu^+(\gamma_{\rm ISR,FSR})$ **: soft γ not detected**
- $e^-e^+ \to \tau^-\tau^+ \to \mu^-\mu^+\nu_\mu\bar{\nu}_\mu\nu_\tau\bar{\nu}_\tau$
- $e^-e^+ \to \mu^-\mu^+\nu_l\bar{\nu}_l$ by off-shell W and Z

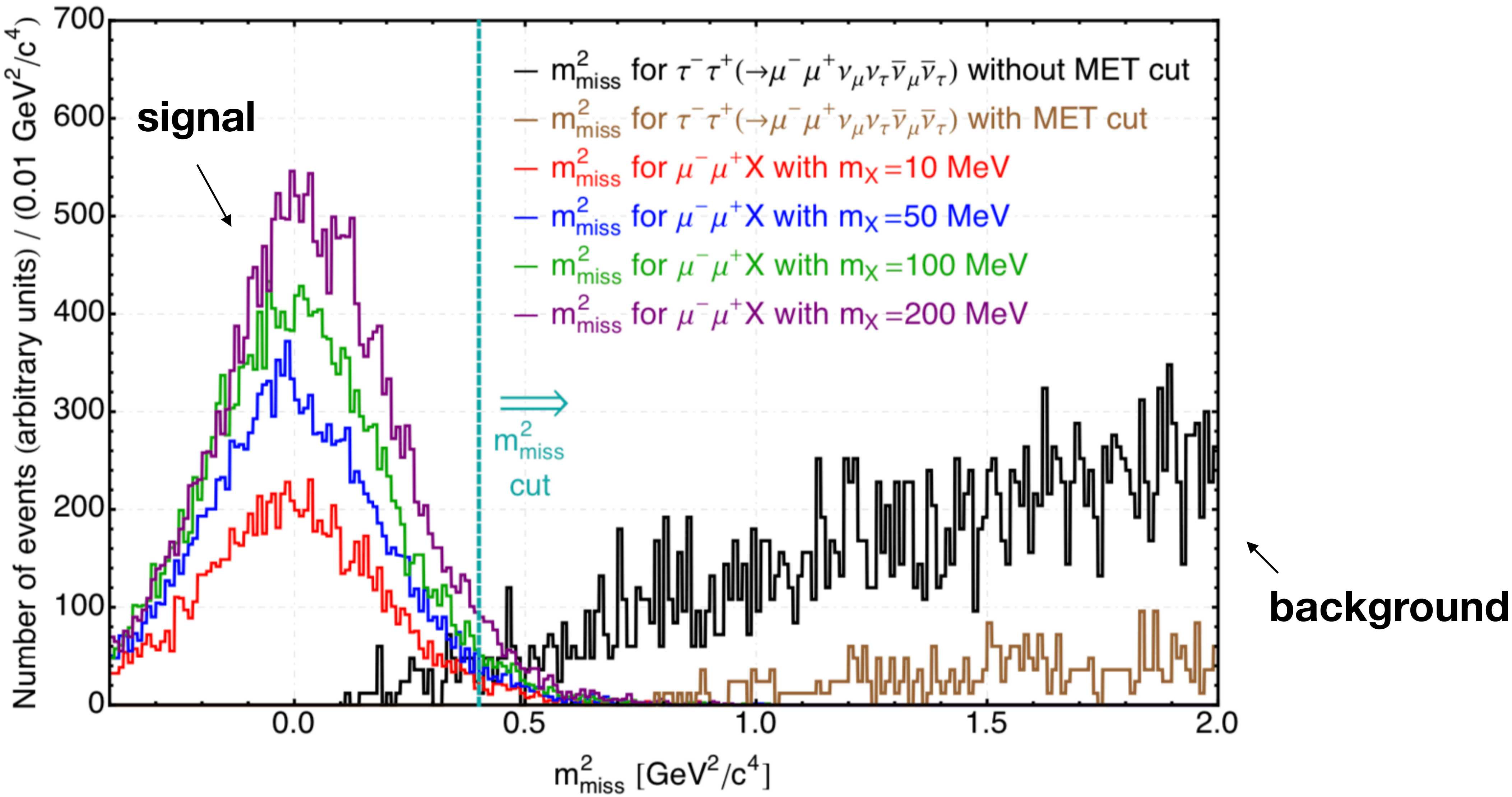


MET cut



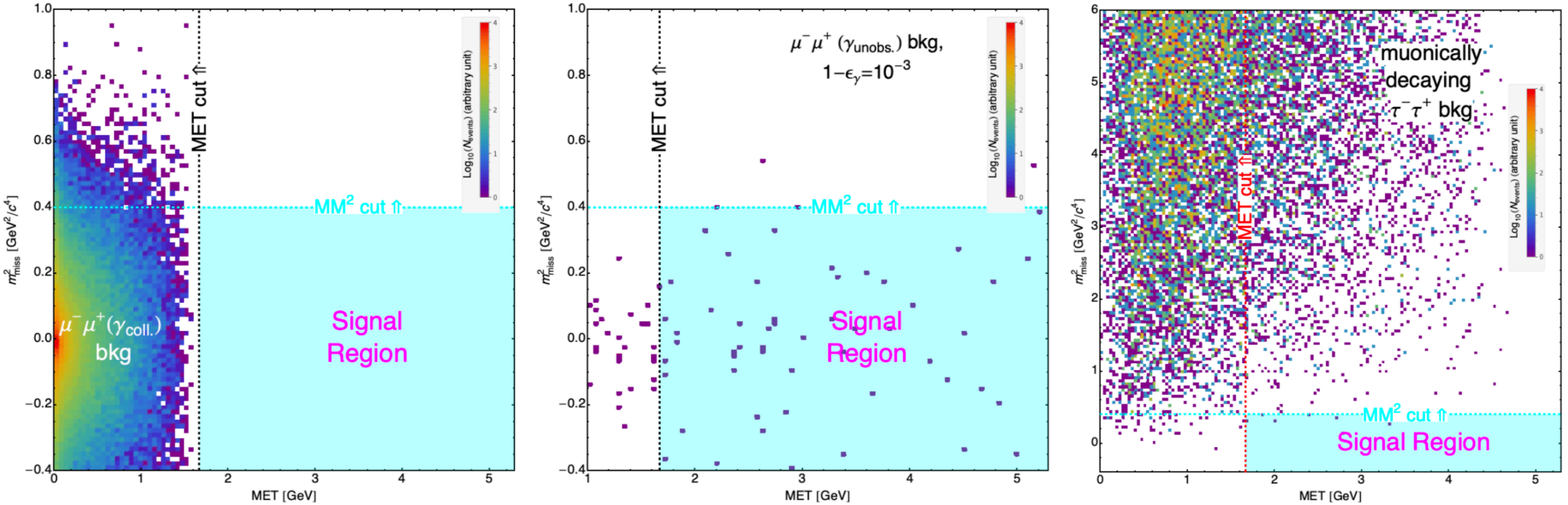
MadGraph5 aMC@NLO

Missing mass cut



MadGraph5 aMC@NLO

Cutting background



(a) $\mu^-\mu^+\gamma$ with $|\eta^*_\gamma| > 1.94$

photon to beam pipe

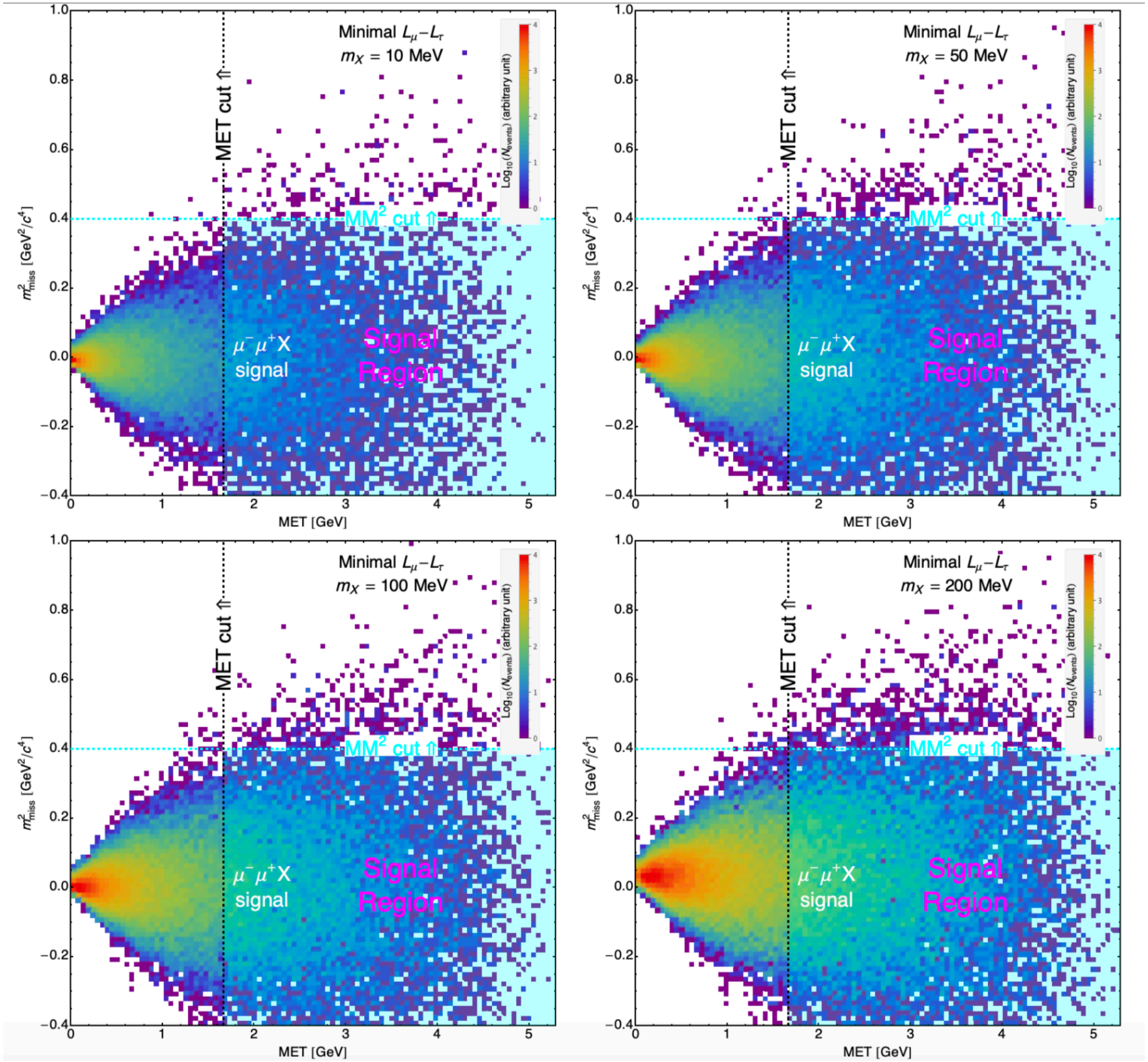
(b) $\mu^-\mu^+\gamma$ with $|\eta^*_\gamma| < 1.94$

(c) $\tau^-\tau^+(\to \mu^-\mu^+\nu\nu\bar{\nu}\bar{\nu})$

$i)\ \not{E}_T > 1.67$ GeV,

$ii)\ m^2_{\text{miss}} < 0.4\ \text{GeV}^2/c^4$

Signal



Minimal $L_\mu - L_\tau$
m_X = 10 MeV
m_X = 50 MeV
m_X = 100 MeV
m_X = 200 MeV
MET cut ⇑
MM² cut ⇑
$\mu^-\mu^+X$ signal
Signal Region
m^2_{miss} [GeV²/c⁴]
MET [GeV]
$Log_{10}(N_{events})$ (arbitrary unit)

Signal/background

$$\mathcal{S} = \left[\int_{\not{E}_T^{\rm cut}}^{\sqrt{s}/2} d\not{E}_T \int_{(m^2_{\rm miss})^{\rm min}_{\rm cut}}^{(m^2_{\rm miss})^{\rm max}_{\rm cut}} dm^2_{\rm miss}\ [\epsilon(p_{\mu^\pm})]^2\ \frac{d^2\sigma^{\rm signal}_{\mu\mu X}(s)}{d\not{E}_T dm^2_{\rm miss}}\right] \cdot \int \mathcal{L}\ dt,$$

$$\mathcal{B} = \left[\int_{\not{E}_T^{\rm cut}}^{\sqrt{s}/2} d\not{E}_T \int_{(m^2_{\rm miss})^{\rm min}_{\rm cut}}^{(m^2_{\rm miss})^{\rm max}_{\rm cut}} dm^2_{\rm miss}\ [\epsilon(p_{\mu^\pm})]^2\ \frac{d^2\sigma^{\rm background}_{\mu\mu\gamma,\tau\tau,W^*/Z^*}(s)}{d\not{E}_T dm^2_{\rm miss}}\right] \cdot \int \mathcal{L}\ dt,$$

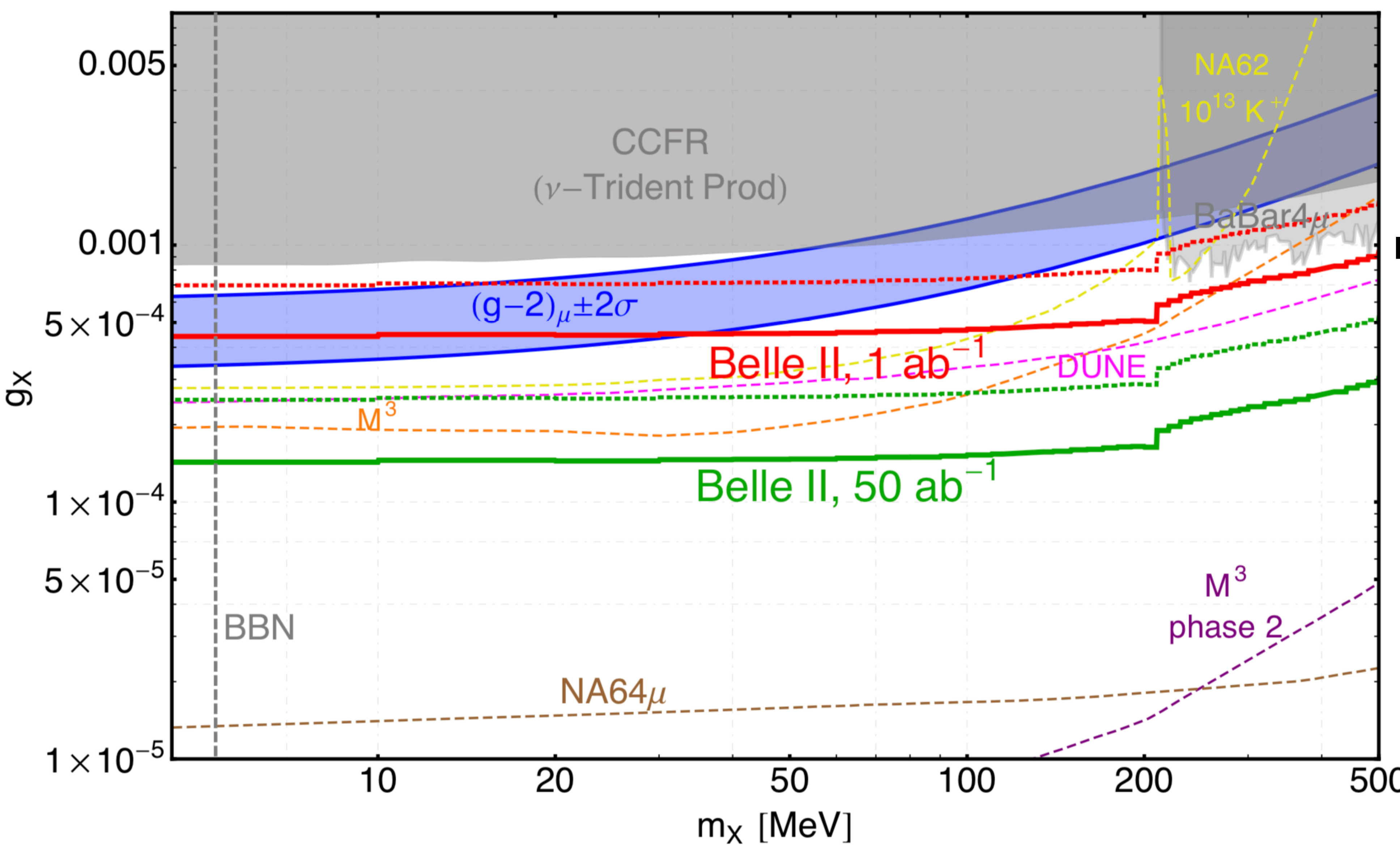
$i)$ $\not{E}_T > 1.67$ GeV,

$ii)$ $m^2_{\rm miss} < 0.4$ GeV$^2/c^4$

$iii)$ $\epsilon(p_{\mu^\pm} > 0.6{\rm GeV}/c) = 0.9$ at KLM(K_L, μ) detector

Sensitivity limit:

$$S/\sqrt{S+B} = 3$$

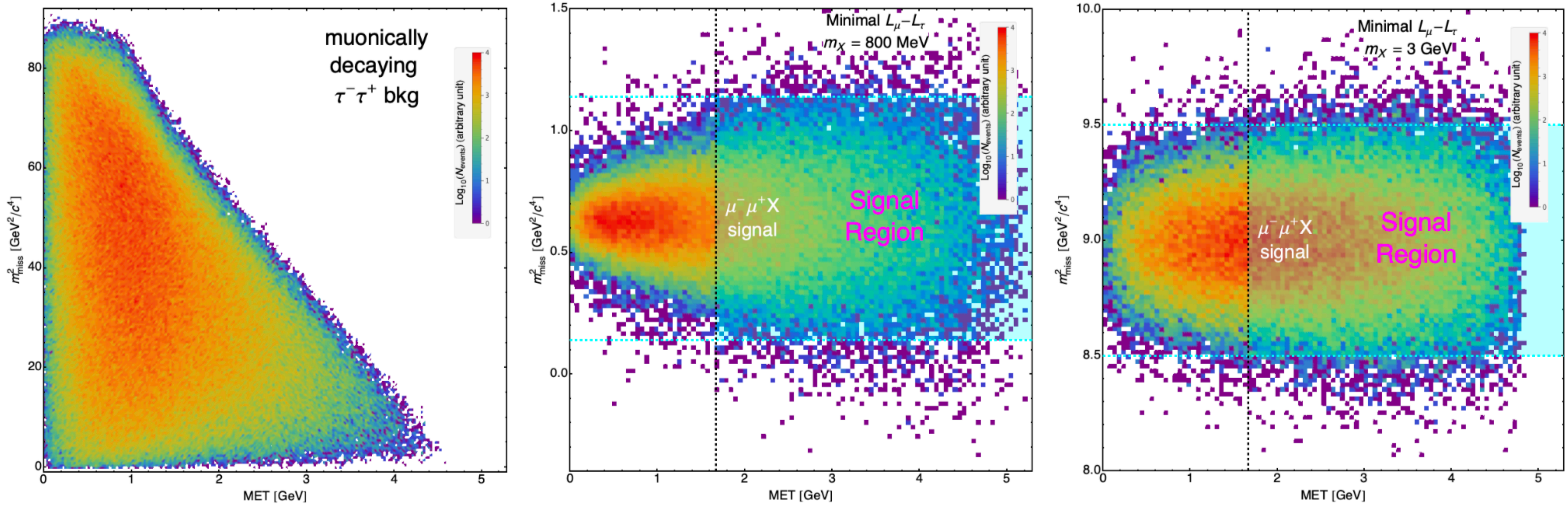


missing
γ-detection
rate@ Belle2

$1-\epsilon_\gamma = 10^{-5}$

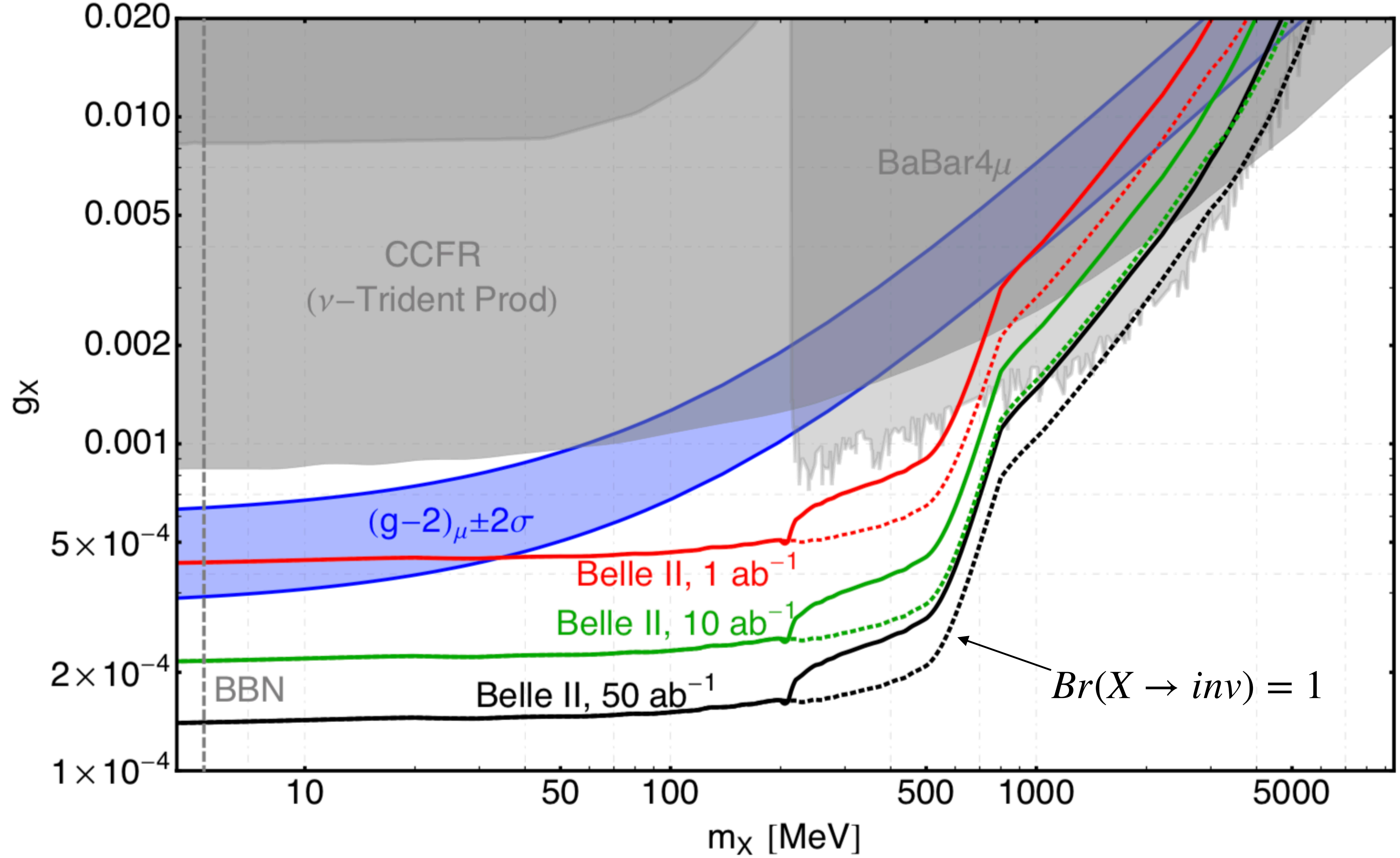
$1-\epsilon_\gamma = 10^{-6}$

For heavier X ($m_X > 2m_\mu$)



(a) $\tau^-\tau^+(\to \mu^-\mu^+\nu\nu\bar{\nu}\bar{\nu})$ (b) $\mu^-\mu^+X$, $m_X = 800$ MeV (c) $\mu^-\mu^+X$, $m_X = 3$ GeV

Sensitivity bound: $S/\sqrt{S+B} = 3$ with & without dark matter

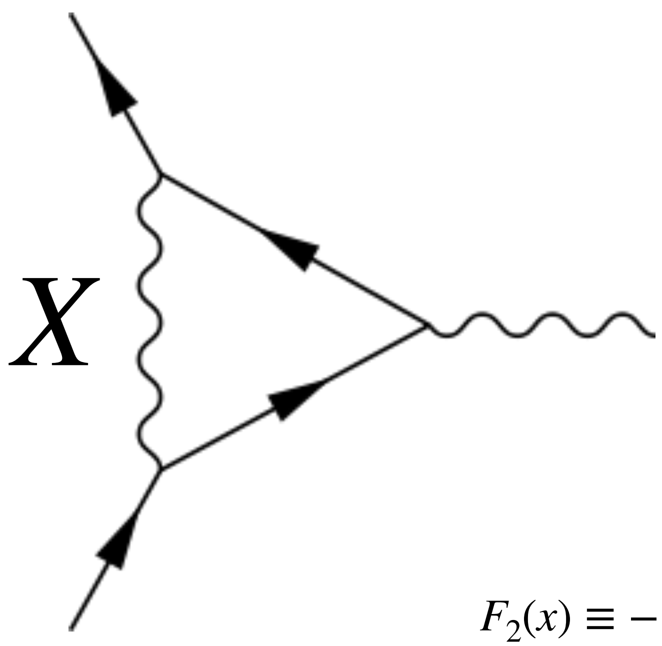


Summary

- The gauged $L_\mu - L_\tau$ can explain $(g-2)_\mu$ anomaly with $g_X \sim 10^{-4}$ and $m_X \sim 10\ \mathrm{MeV}$.
- Belle-2 with 50/ab will completely cover the preferred range in $\mu^+\mu^- + MET$ channel
- Possible extension with dark matter can be also interesting
- Stay tuned!

Back up

$Z - \mu\bar{\mu}$



$$\frac{\Delta\Gamma(Z \to \mu^-\mu^+)}{\Gamma(Z \to \mu^-\mu^+)} = \frac{g_X^2}{16\pi^2} F_2\left(\frac{m_X^2}{m_Z^2}\right)$$

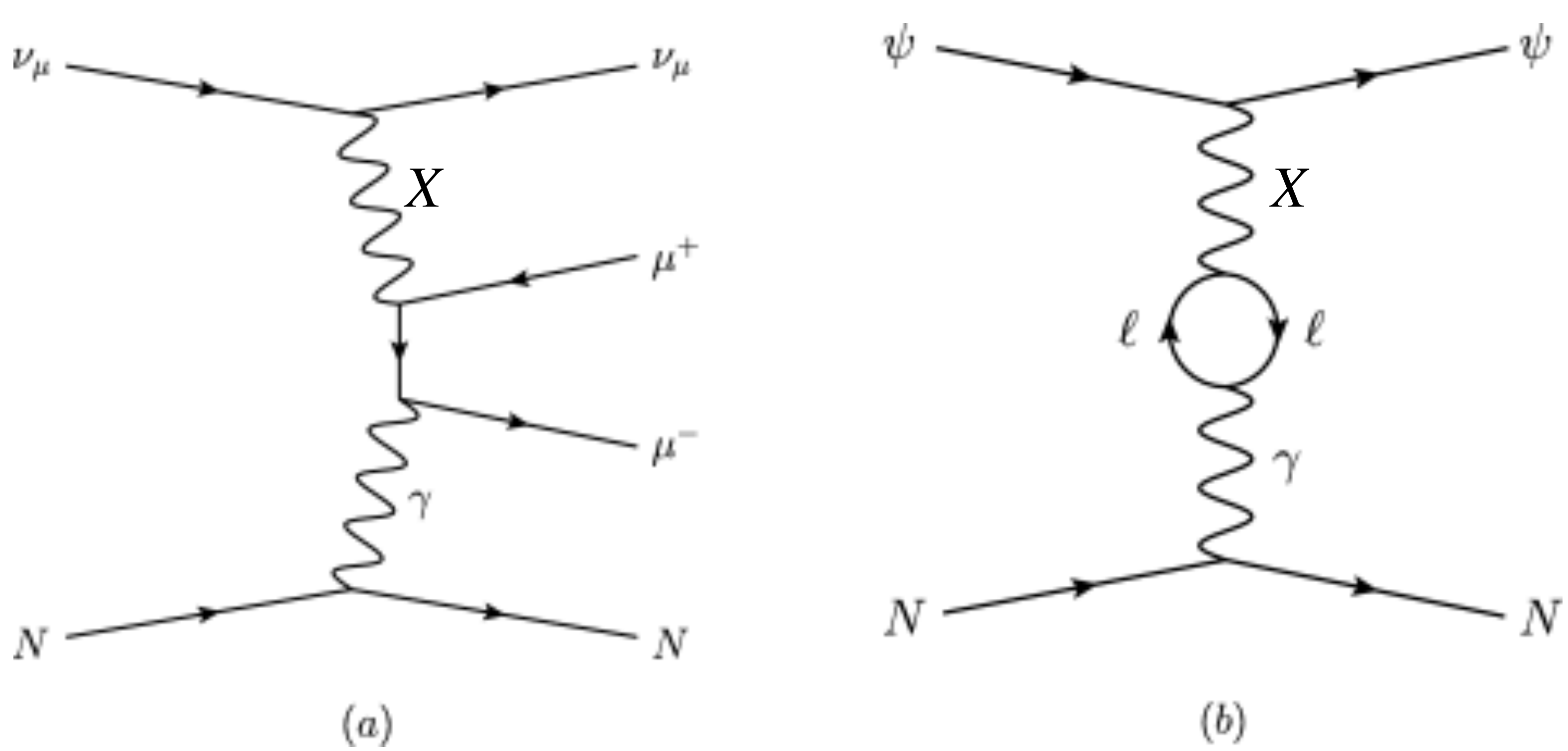
$$F_2(x) \equiv -2\left\{\frac{7}{4} + x + \left(x + \frac{3}{2}\right)\ln x + (1+x)^2\left[\mathbf{Li}_2\left(\frac{x}{1+x}\right) + \frac{1}{2}\ln^2\left(\frac{x}{1+x}\right) - \frac{\pi^2}{6}\right]\right\}$$

$$\left|\frac{g_X^2}{16\pi^2} F_2\left(\frac{m_X^2}{m_Z^2}\right)\right| < \left|\frac{\Gamma(Z \to \mu^-\mu^+)}{\Gamma(Z \to e^-e^+)} - 1\right|$$

$$\mathbf{Br}(Z \to e^-e^+) = 3.3632 \pm 0.0042\,\%\,,$$
$$\mathbf{Br}(Z \to \mu^-\mu^+) = 3.3662 \pm 0.0066\,\%$$

PDG

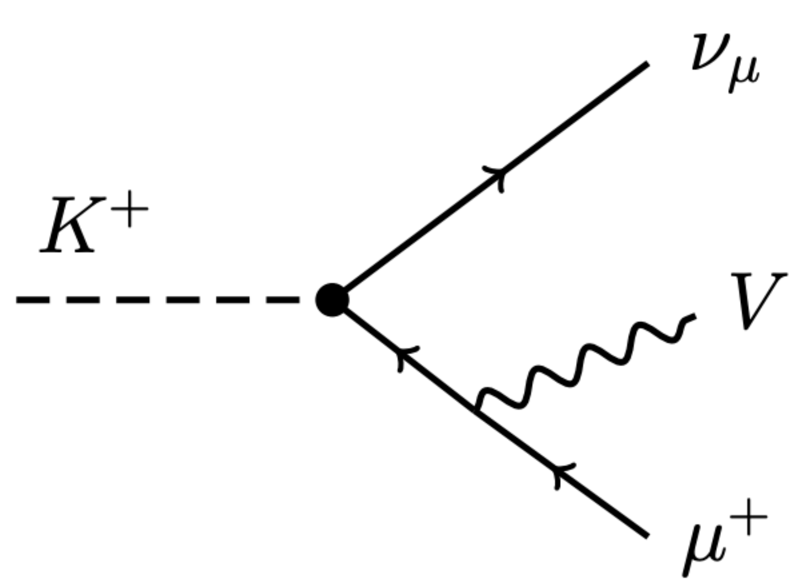
Neutrino trident
($\nu N \to \nu N \mu^+ \mu^-$)



$$\sigma_{\mathrm{CCFR}}/\sigma_{\mathrm{SM}} = 0.82 \pm 0.28 \qquad E_\mu = 160 \text{ GeV}$$

CCFR colla., PRL 1991

NA62



1902.07715