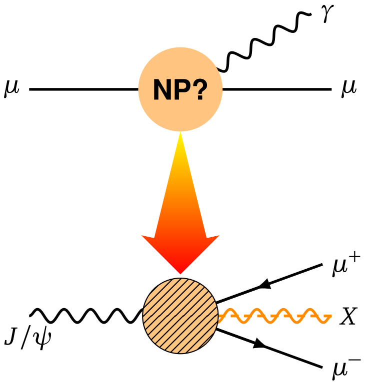
# Probing new physics explanations of muon $g-2$ at BESIII via $J/\psi$ decay

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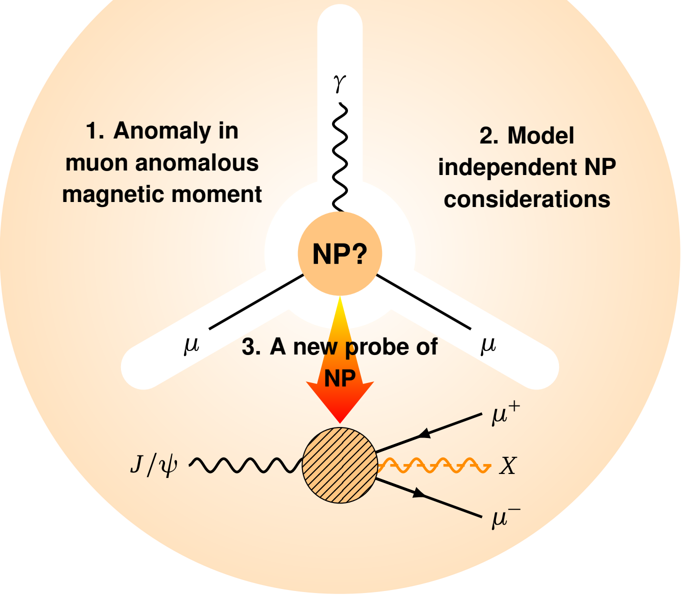
**arXiv:2004.03124 [hep-ph]**

with Gorazd Cvetič, C.S. Kim, and Donghun Lee

**ANOMALIES 2020**

12 September 2020

# Plan of the talk

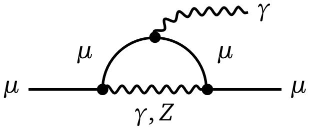


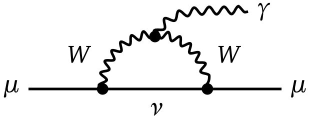
# Muon anomalous magnetic moment (what we know)

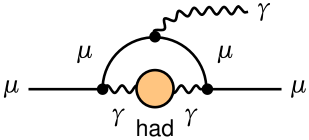
magnetic dipole moment — spin

$$\boldsymbol{\mu} = g_\mu \left(\frac{e}{2m_\mu}\right) \boldsymbol{S}$$

gyromagnetic ratio




- Dirac equation $\Rightarrow g_\mu = 2$
  ($\because \mu$ is an elementary fermion)
- Quantum loop effects $\Rightarrow g_\mu \approx 2$
- Anomalous magnetic moment

$$a_\mu \equiv \frac{1}{2}\left(g_\mu - 2\right)$$

- $a_\mu^{\text{SM}}$: precise prediction from SM

  $a_\mu^{\text{exp}}$: precise measurement from E821 experimet at BNL

$\therefore \Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} \Rightarrow$ probe NP

- $\Delta a_\mu = \left(261 \pm 63 \pm 48\right) \times 10^{-11}$

  63: experimental error; 48: theoretical error

**$3.3\sigma$ discrepancy**

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

# Muon anomalous magnetic moment (what we want to know)

**Q1. Is this discrepancy an indication of NP?**
We are not sure yet.

- Need more precise experimental result
  - E989 at Fermilab (ongoing)
    - Successor to E821 at BNL
    - 21 times more data (planned)
    - Improve precision of $a_\mu$ by a factor 4 (expected)
  - E34 at J-PARC (future)
- Need reduced theoretical uncertainties
  - Recent SM calculation puts the discrepancy at $\mathbf{3.7\sigma}$

arXiv:2006.04822 [hep-ph]

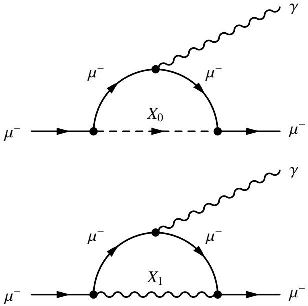
**Q2. What kind of NP can contribute?**
Plethora of possibilities.

- Various NP models
  - MSSM
  - Left-Right symmetric models
  - $B-L$
  - 2HDM
  - Neutrino mass models
  - Dark photon models
  - $L_\mu - L_\tau$ models etc.
- Model independent approaches
  - Spin-0 mediator
  - Spin-1 mediator

Phys. Rept. **731**, 1-82 (2018)

# Interesting model independent results for NP contributions to muon $g-2$

- Only conservation of electric charge and Lorentz invariance are considered.
- No new fermions and new mediator is neutral. $X_0$: scalar, $X_1$: vector




- Lagrangians (muon-philic interactions)

$$\mathcal{L}_0 = -g_0 X_0 \bar{\mu} \mu, \qquad \mathcal{L}_1 = -g_1 X_{1\alpha} \bar{\mu} \gamma^\alpha \mu.$$

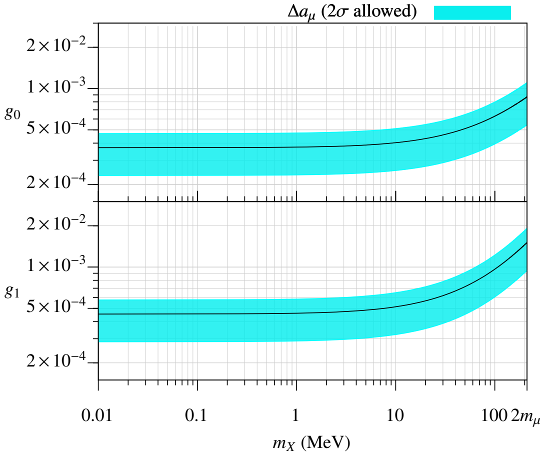
- 2 variable parameter space: $g_{0,1}$, $m_X$
- For $m_X \lesssim 2m_\mu$ we have

$$\Delta a_\mu^{\text{scalar}} = \frac{g_0^2}{8\pi^2} \int_0^1 dx \, \frac{m_\mu^2 (1-x)(1-x^2)}{m_\mu^2 (1-x)^2 + m_X^2 x},$$

$$\Delta a_\mu^{\text{vector}} = \frac{g_1^2}{8\pi^2} \int_0^1 dx \, \frac{2 m_\mu^2 \, x \, (1-x)^2}{m_\mu^2 (1-x)^2 + m_X^2 x}.$$

- Pseudo-scalar and axial-vector couplings $\Rightarrow a_\mu^{\text{th}}$ decreases
  $\Rightarrow \Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{th}}$ increases
  $\therefore$ only scalar and vector couplings considered. JHEP09 (2018) 153

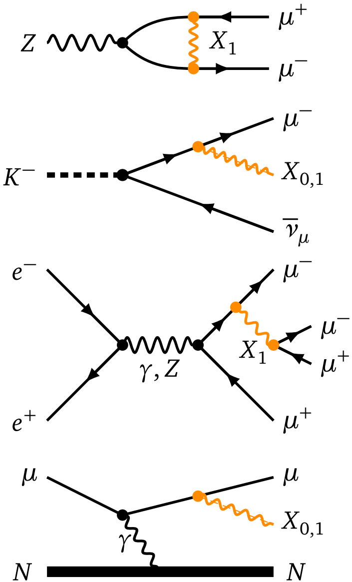
# Parameter space allowed by $\Delta a_\mu$




- errors added in quadrature
- $X_{0,1} \not\to \mu^-\mu^+$ ($\because m_X < 2m_\mu$)
- muon-philic $X$. $X_{0,1} \not\to e^-e^+$, $\nu_\ell\overline{\nu}_\ell$ (at tree level). Possible via loops only (suppressed).

- $X$ is most-likely stable, electrically neutral and invisible.
- **To decipher the nature of $X$, it is imperative to study other relevant processes.**

# Other independent searches for such NP




- $Z$ pole precision measurement (LEP) $\dfrac{\Delta\Gamma(Z \to \mu^-\mu^+)}{\Gamma(Z \to \mu^-\mu^+)}$
- Rare kaon decay (beam-dump experiments, e.g. NA62, NA64$\mu$)
  PRL **124**, no.4, 041802 (2020)
  JPG **47**, no.1, 010501 (2020)
- $4\mu$ channel search (BaBar)
  PRD **94**, no.1, 011102 (2016)
- Search for $e^+e^- \to \mu^-\mu^+X$ with "invisible" $X$ (Belle II)
  JHEP10 (2019) 168
- Muon missing momentum search ($M^3$ at Fermilab)
  JHEP09 (2018) 153

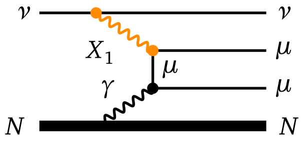
# Other independent searches for such NP

- Additional interaction with neutrino(s) are sometimes considered, e.g. as in $U(1)_{L_\mu - L_\tau}$ models:

$$\mathscr{L} \supset \mathscr{L}_{\rm SM} - \frac{1}{4} X_1^{\alpha\beta} X_{1\alpha\beta} + \frac{m_X^2}{2} X_1^{\alpha} X_{1\alpha} - X_{1\alpha} J^{\alpha}_{\mu-\tau},$$

with

$$X_{1\alpha\beta} = \partial_\alpha X_{1\beta} - \partial_\beta X_{1\alpha},$$
$$J^{\alpha}_{\mu-\tau} = g_1 \left( \overline{\mu}\gamma^\alpha \mu - \overline{\tau}\gamma^\alpha \tau + \overline{\nu}_\mu \gamma^\alpha P_L \nu_\mu - \overline{\nu}_\tau \gamma^\alpha P_L \nu_\tau \right).$$




- Neutrino trident production cross-section (CCFR)
  PRL **66**, 3117-3120 (1991)

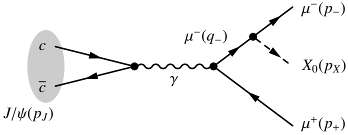
- Big-bang nucleosynthesis (BBN) constraints: deviation of effective neutrino number $\Delta N_{\rm eff}$ due to the decays $X \to \nu\overline{\nu}$
  PRD **92**, no.11, 113004 (2015)

# A new search strategy involving $J/\psi$ decay

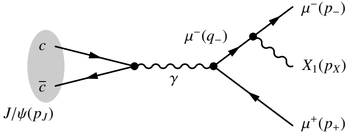
- Process: $J/\psi(p_J) \to \mu^-(p_-)\,\mu^+(p_+)\ \underbrace{X(p_X)}_{\text{“missing”}}$

- Feynman diagrams:

Scalar case




Vector case




- $0 \leqslant m_X \leqslant m_J - 2m_\mu = 2885.58$ MeV.

# A new search strategy involving $J/\psi$ decay
## Kinematics

- Three invariant mass-squares

$$s = (p_+ + p_-)^2 = (p_J - p_X)^2\,,$$
$$t = (p_+ + p_X)^2 = (p_J - p_-)^2 \equiv q_+^2,$$
$$u = (p_- + p_X)^2 = (p_J - p_+)^2 \equiv q_-^2.$$

- Note:

$$4m_\mu^2 \leqslant s \leqslant (m_J - m_X)^2\,,$$
$$\left(m_\mu + m_X\right)^2 \leqslant t \leqslant \left(m_J - m_\mu\right)^2,$$
$$\left(m_\mu + m_X\right)^2 \leqslant u \leqslant \left(m_J - m_\mu\right)^2.$$

- $\because s + t + u = m_J^2 + m_X^2 + 2m_\mu^2 \implies$ only two variables are independent.

# A new search strategy involving $J/\psi$ decay

## Differential decay rates

- Scalar case

$$\frac{d^2\Gamma(J/\psi \to \mu^-\mu^+X_0)}{dT\,dU} = \frac{\alpha^2 g_0^2 f_J^2}{27\,\pi\,m_J^5}\frac{1}{Y}\Big(\left(T^2+U^2\right)\left(4m_\mu^2-m_X^2\right)\left(2m_\mu^2+m_J^2\right) + TU\,(T+U)\left(T+U+2\left(4m_\mu^2-m_X^2\right)\right) + TU\left(\left(4m_\mu^2-m_X^2\right)^2-m_X^2\left(4m_\mu^2-m_X^2\right)+8m_J^2m_\mu^2\right)\Big).$$

- Vector case

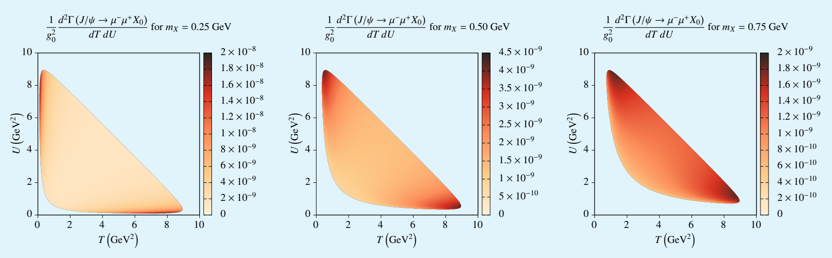
$$\frac{d^2\Gamma(J/\psi \to \mu^-\mu^+X_1)}{dT\,dU} = \frac{2\,\alpha^2 g_1^2 f_J^2}{27\,\pi\,m_J^5}\frac{1}{Y}\Big(\left(T^2+U^2\right)\left(TU-\left(m_J^2+2m_\mu^2\right)\left(m_X^2+2m_\mu^2\right)\right) - 2M^2\,TU\left(T+U-M'^2\right)\Big).$$

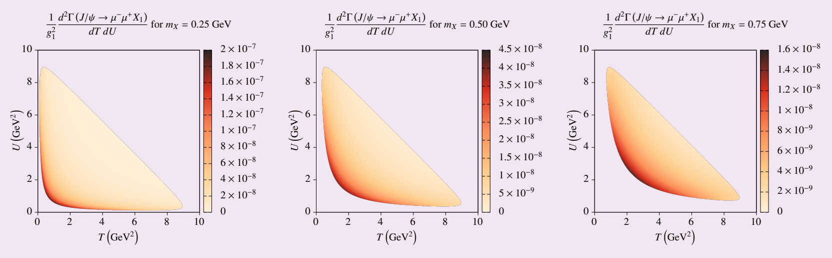
- Here, $f_J = 0.407$ GeV is the decay constant of $J/\psi$ and

$$T = t-m_\mu^2, \quad U = u-m_\mu^2, \quad Y = \left(T^2+m_\mu^2\Gamma_\mu^2\right)\left(U^2+m_\mu^2\Gamma_\mu^2\right),$$
$$M^2 = m_J^2+m_X^2+2m_\mu^2, \quad M'^2 = m_J^2+m_X^2-2m_\mu^2$$

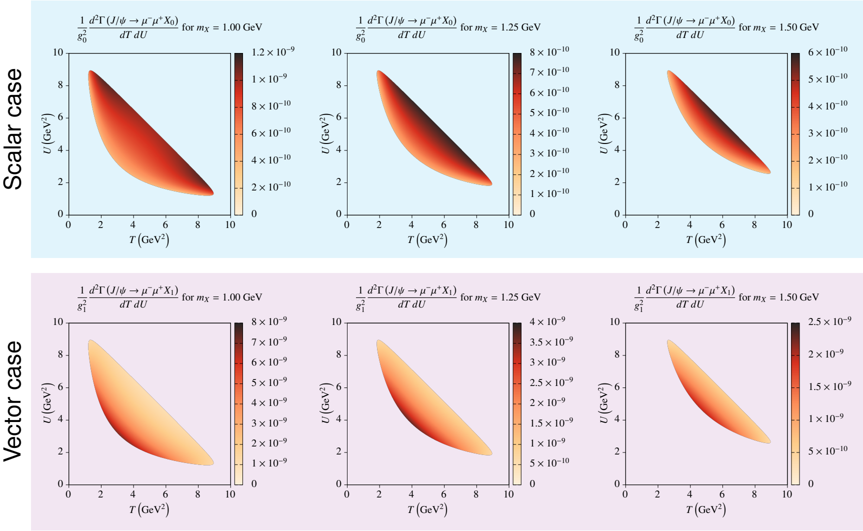
# A new search strategy involving $J/\psi$ decay

## Distinguishing scalar and vector cases using Dalitz plot



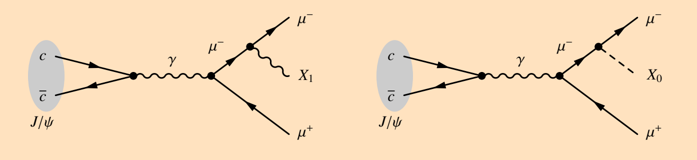



# A new search strategy involving $J/\psi$ decay
## Distinguishing scalar and vector cases using Dalitz plot

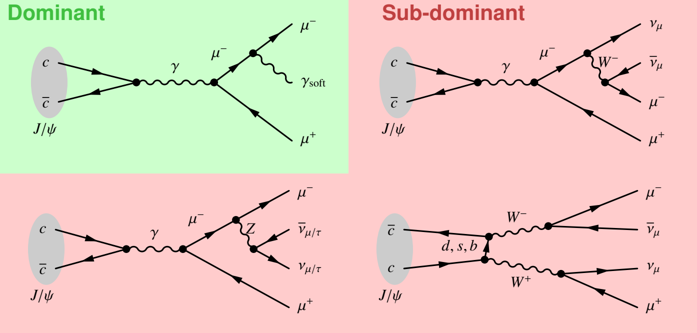


# A new search strategy involving $J/\psi$ decay
## Identifying the background processes

Signal




Background



# A new search strategy involving $J/\psi$ decay

## BESIII seems to be the ideal place for doing this study.

- Advantages of the decay $J/\psi \to \mu^-\mu^+X$ over the similar continuum process $e^+e^- \to \mu^-\mu^+X$ (which can be probed at Belle II and BaBar):

  - $\begin{pmatrix} \text{Resonant enhancement in} \\ e^+e^- \to J/\psi \to \mu^-\mu^+X \end{pmatrix} \Longrightarrow \begin{pmatrix} \text{more } J/\psi \text{ events} \\ \text{than continuum} \end{pmatrix}$

  - cross-section $\sigma \propto 1/s$. $\because \sqrt{s} \approx 10$ GeV for Belle II and BaBar, while $\sqrt{s} \approx 3$ to 4 GeV for BESIII, the continuum process is suppressed.

  - $\Gamma_J = 92.9$ keV (very narrow width)
    $\Rightarrow$ unlike continuum case, the ISR can be safely ignored
    $\Rightarrow$ only soft FSR (energy $< 20$ MeV at BESIII) constitutes background
    $\Rightarrow$ easy to remove as missing mass for background is centered at zero.

# A new search strategy involving $J/\psi$ decay
## Numerical study in context of BESIII

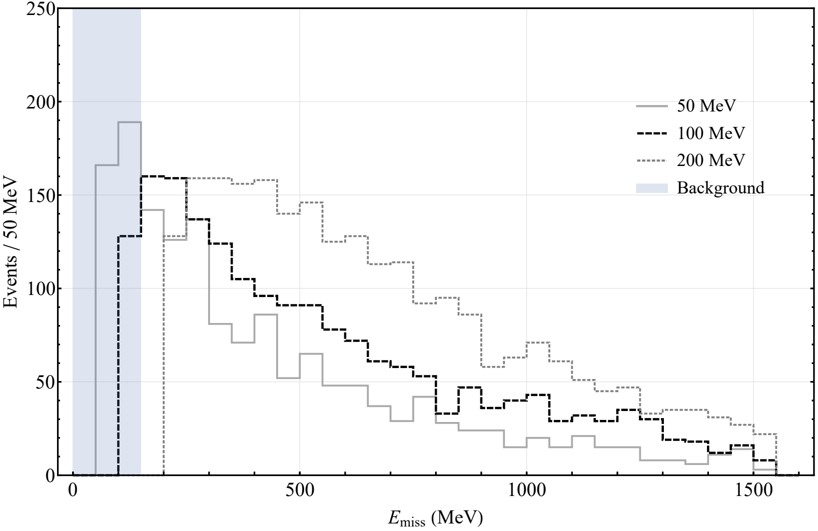
- We have considered
  - $N_J = 10^{11}$ (already $10^{10}$ $J/\psi$ events have been accumulated at BESIII),
  - Uncertainty in momentum measurement: $\sigma_p = 15$ MeV which provides a reasonably bigger momentum uncertainty than $\sigma_p = 0.01p$ in the kinematic region under consideration,
  - Photons with energy $E_\gamma > 20$ MeV are detected.

  Nucl. Instrum. Meth. A **614**, 345-399 (2010)

- To separate the signal events from soft-photon background events we utilize the following quantities:
  - missing mass squared: $m^2_{\text{miss}} = p^2_{\text{miss}} = (p_J - p_+ - p_-)^2$,
  - missing energy: $E_{\text{miss}} = m_J - E_+ - E_-$.

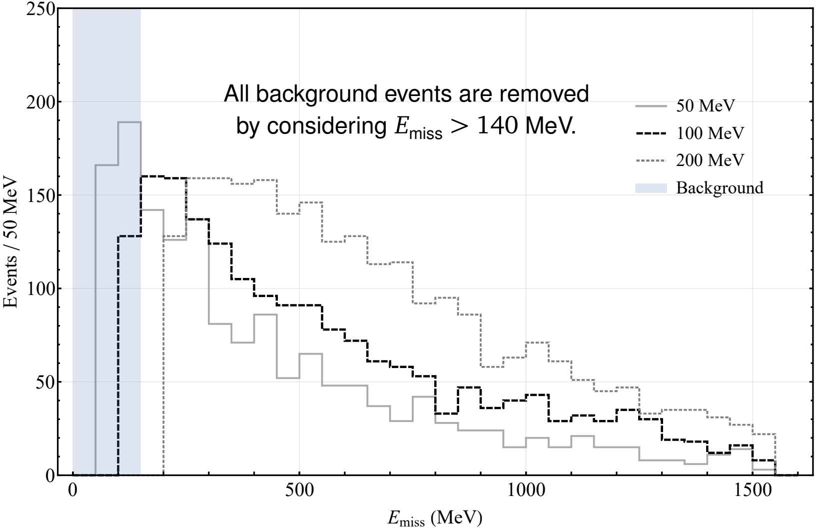
# A new search strategy involving $J/\psi$ decay

## Missing energy distribution (vector case)



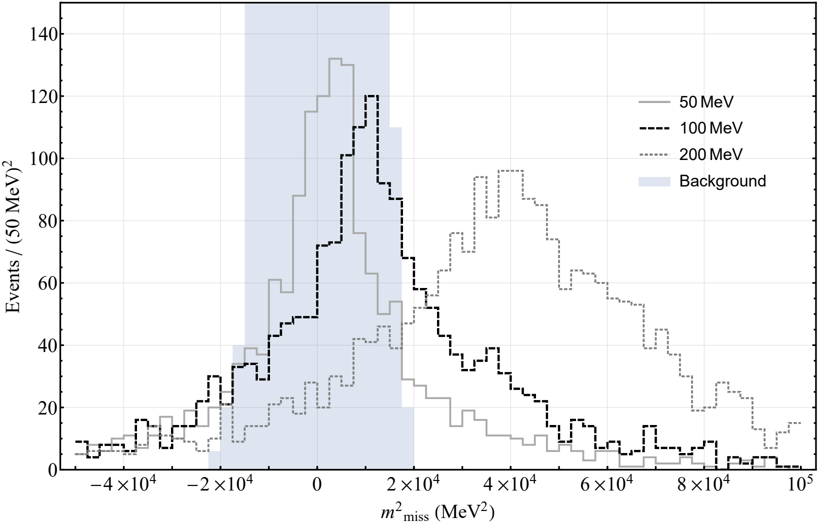
# A new search strategy involving $J/\psi$ decay

## Missing energy distribution (vector case)



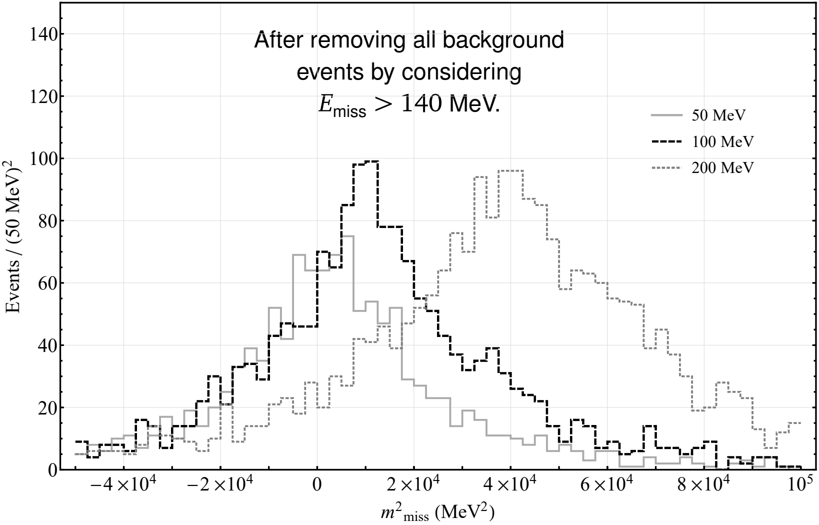
# A new search strategy involving $J/\psi$ decay

## Missing mass squared distribution (vector case)



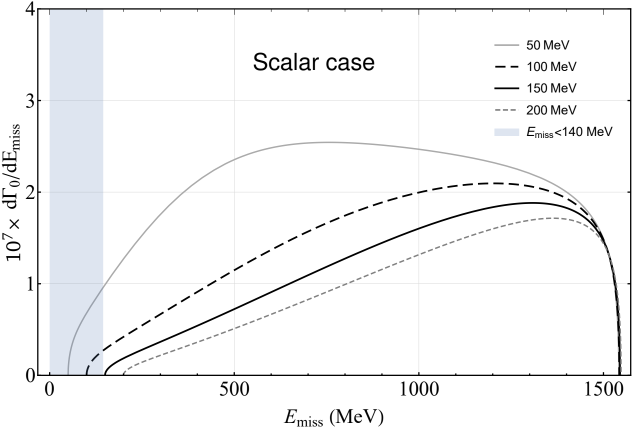
# A new search strategy involving $J/\psi$ decay

## Missing mass squared distribution (vector case)



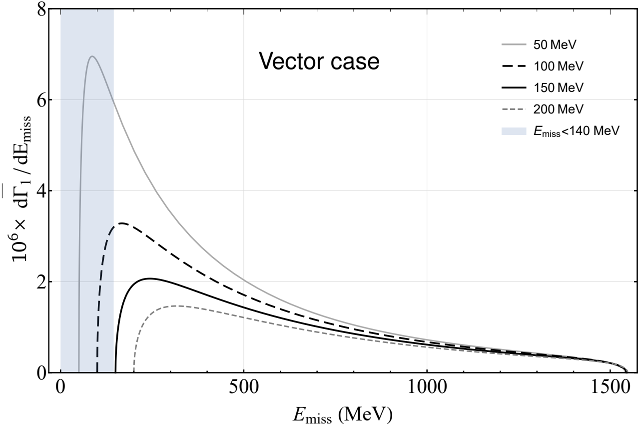
# A new search strategy involving $J/\psi$ decay

## Comparing scalar and vector cases

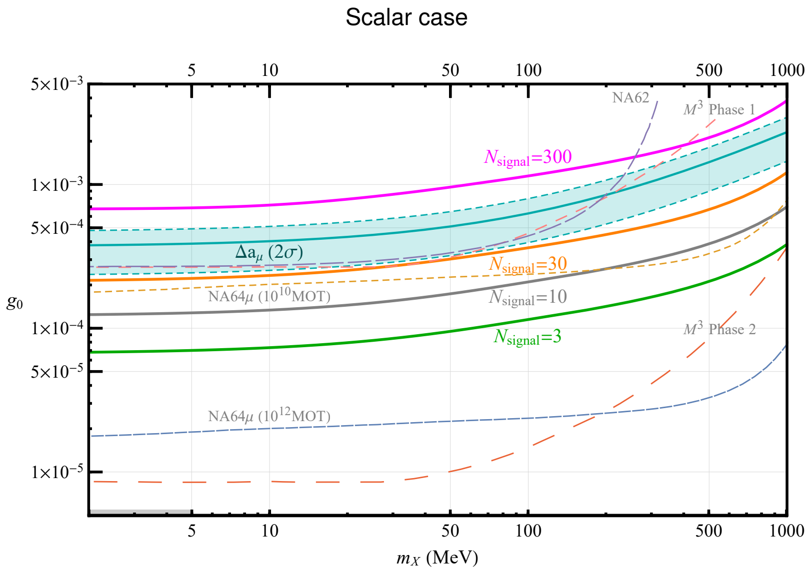


# A new search strategy involving $J/\psi$ decay

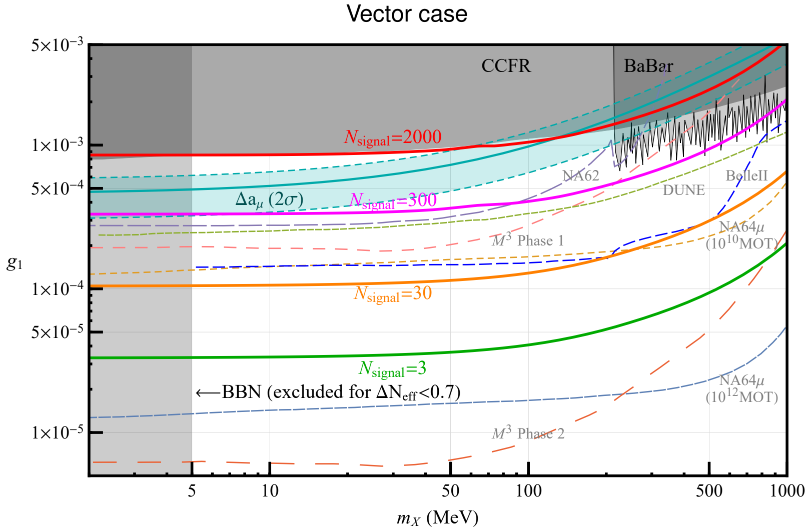
## Comparing scalar and vector cases



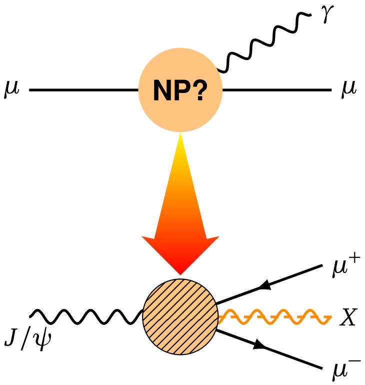
# Comparison of our approach with other proposals



# Comparison of our approach with other proposals



# Conclusion




- Scalar and vector type NP can alleviate the discrepancy in $\Delta a_\mu$.
- The new particle $X$ with mass $m_X \lesssim 2m_\mu$ has interesting phenomenology.
- The decay $J/\psi \to \mu^-\mu^+X$ can probe the existence of $X$, as well as determine whether $X$ is scalar or vector.
- The BESIII experiment is well suited for this study.

**Thank You**

# Backup slides

- Comparison of canonical branching ratios ($\overline{\mathrm{Br}}$) for scalar and vector cases:

| $m_X\,[\mathrm{MeV}]$ | $\overline{\mathrm{Br}}_{\mathrm{scalar}}$ | $\overline{\mathrm{Br}}_{\mathrm{vector}}$ |
|---|---|---|
| 50 | 0.0033254 | 0.032505 |
| 100 | 0.0022872 | 0.022285 |
| 150 | 0.0017978 | 0.016889 |
| 200 | 0.0014913 | 0.010947 |

$\overline{\mathrm{Br}} = \mathrm{Br} \times g_{0,1}^{-2}$, with Br = branching ratio of $J/\psi \to \mu^-\mu^+X_{0,1}$.

- Vector case:

| $m_X\,[\mathrm{MeV}]$ | $\overline{\mathrm{Br}}$ | $N_{\mathrm{signal}}$ | $N_{\mathrm{signal}}^{\mathrm{cut}}$ |
|---|---|---|---|
| 50 | 0.032505 | 1546 | 1236 |
| 100 | 0.022285 | 1840 | 1747 |
| 150 | 0.016889 | 2127 | 2127 |
| 200 | 0.010947 | 2378 | 2378 |

$N_{\mathrm{signal}}$ = number of signal events before applying missing energy cut,

$N_{\mathrm{signal}}^{\mathrm{cut}}$ = number of signal events after applying missing energy cut.