Search for New Physics at BESIII

Liang Sun <sunl@whu.edu.cn>

Wuhan University

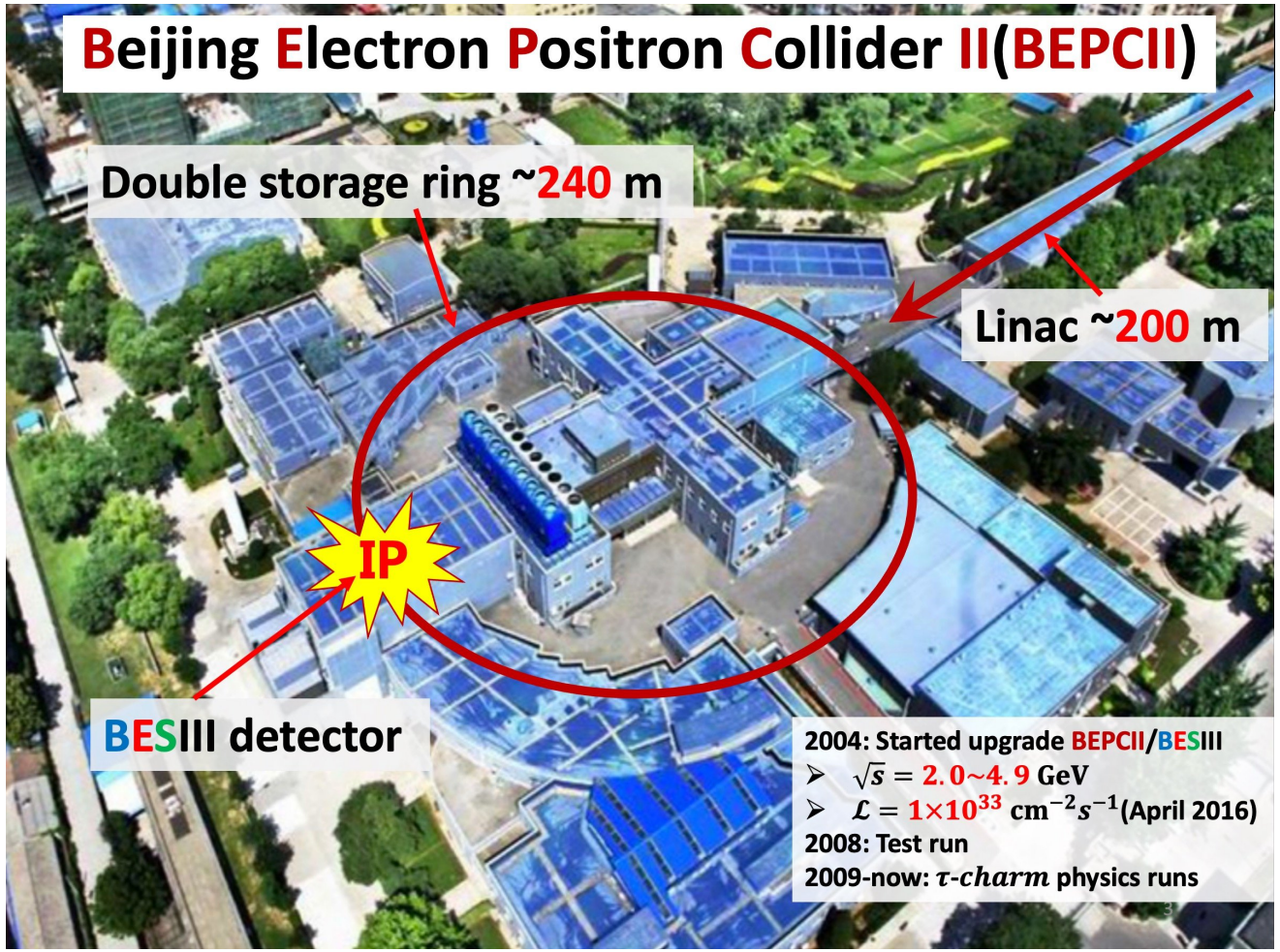
On behalf of BESIII collaboration

10/23/2024

Outline

- Introduction on BESIII experiment
- Datasets
- Highlights of recent searches on
  - Diphoton decays of an axionlike particle in radiative J/ψ decays [PRD 111 (2024) L031101]
  - Invisible decays of a dark photon using initial state radiation [PLB 839 (2023) 137785]
  - A muonphilic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^- +$ invisible decays [PRD 109 (2024) L031102]
  - A massless BSM particle in $\Sigma^+ \to p +$ invisible decay [PLB 852 (2024) 138614]
  - Week decays of J/ψ containing a D meson [PRD 111 (2024) 032020, JHEP 01(2024) 126]
  - Radiative decay of $J/\psi \to \gamma D^0 +$ c.c. [arXiv:2408.08826]
  - Decays of $D_s^+ \to h(h')e^+e^-$ [PRL 133 (2024) 121801]
  - LNV decays of $D_s^+ \to hh'e^+e^+$ [arXiv:2410.02421] New
- Summary and outlook

BEPCII & BESIII



Electromagnetic CsI(Tl) Calorimeter (EMC)

$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)

$\sigma_E/E < 5\%$ @ 1 GeV (end-caps)

Time-of-Flight (TOF)

$\sigma_t = 90$ ps (barrel)

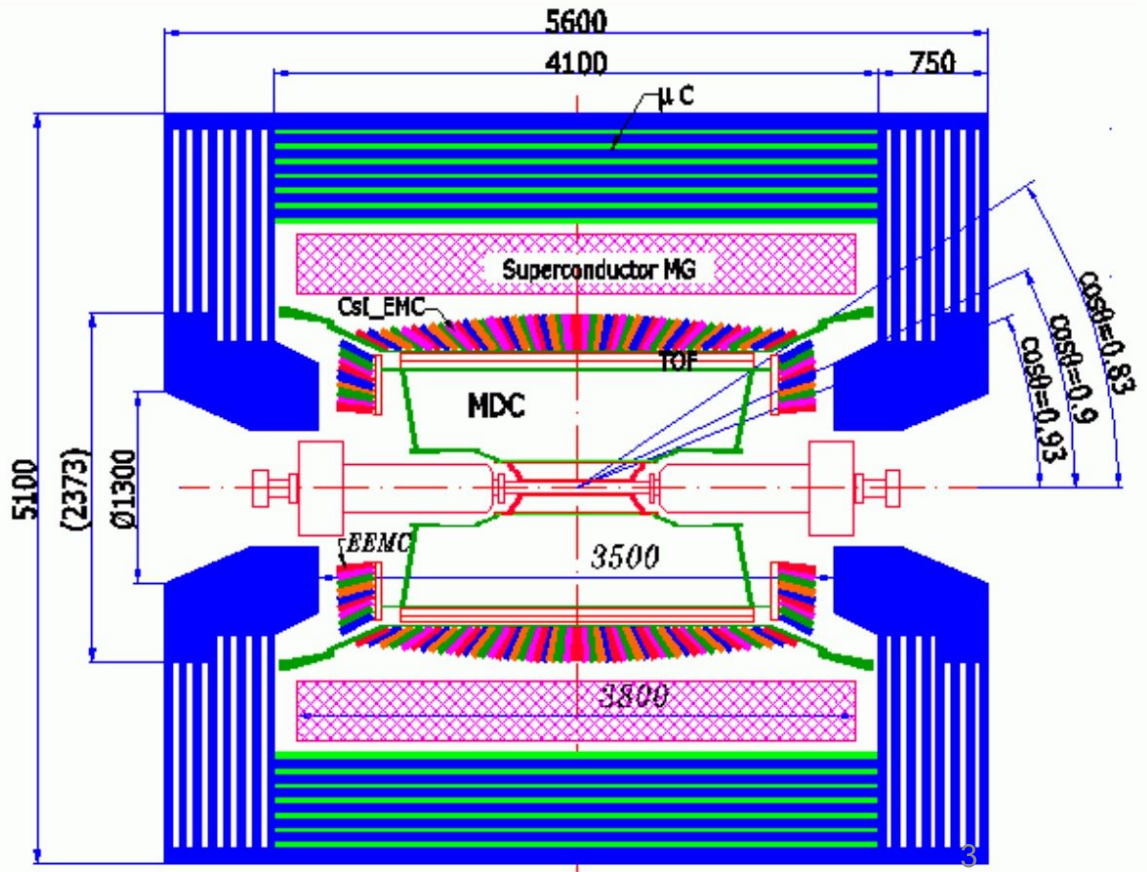
$\sigma_t = 120$ ps (end-caps)

Main Drift Chamber (MDC)

$\sigma_{r\phi} = 130$ μm (single wire)

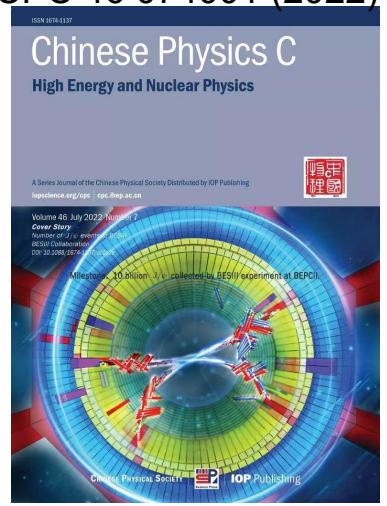
$\sigma_{p_t}/p_t = 0.5\%$ @ 1 GeV

Superconducting solenoid (1 Tesla)

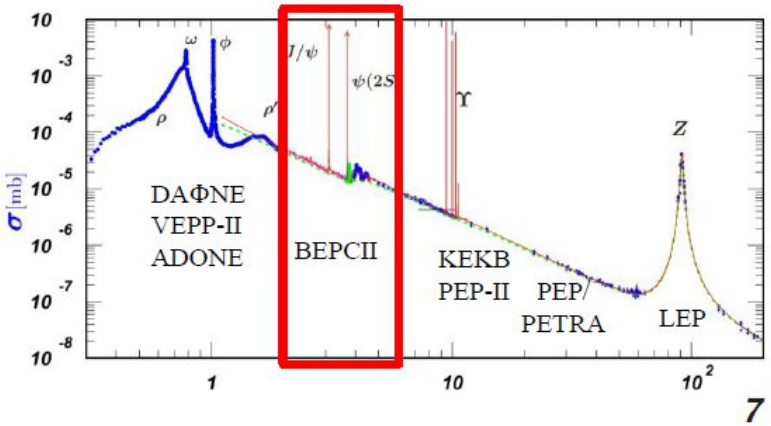


M. Ablikim *et al.* (BESIII Collaboration), Nucl. Instr. Meth. A614, 345 (2010)

CPC 46 074001 (2022)

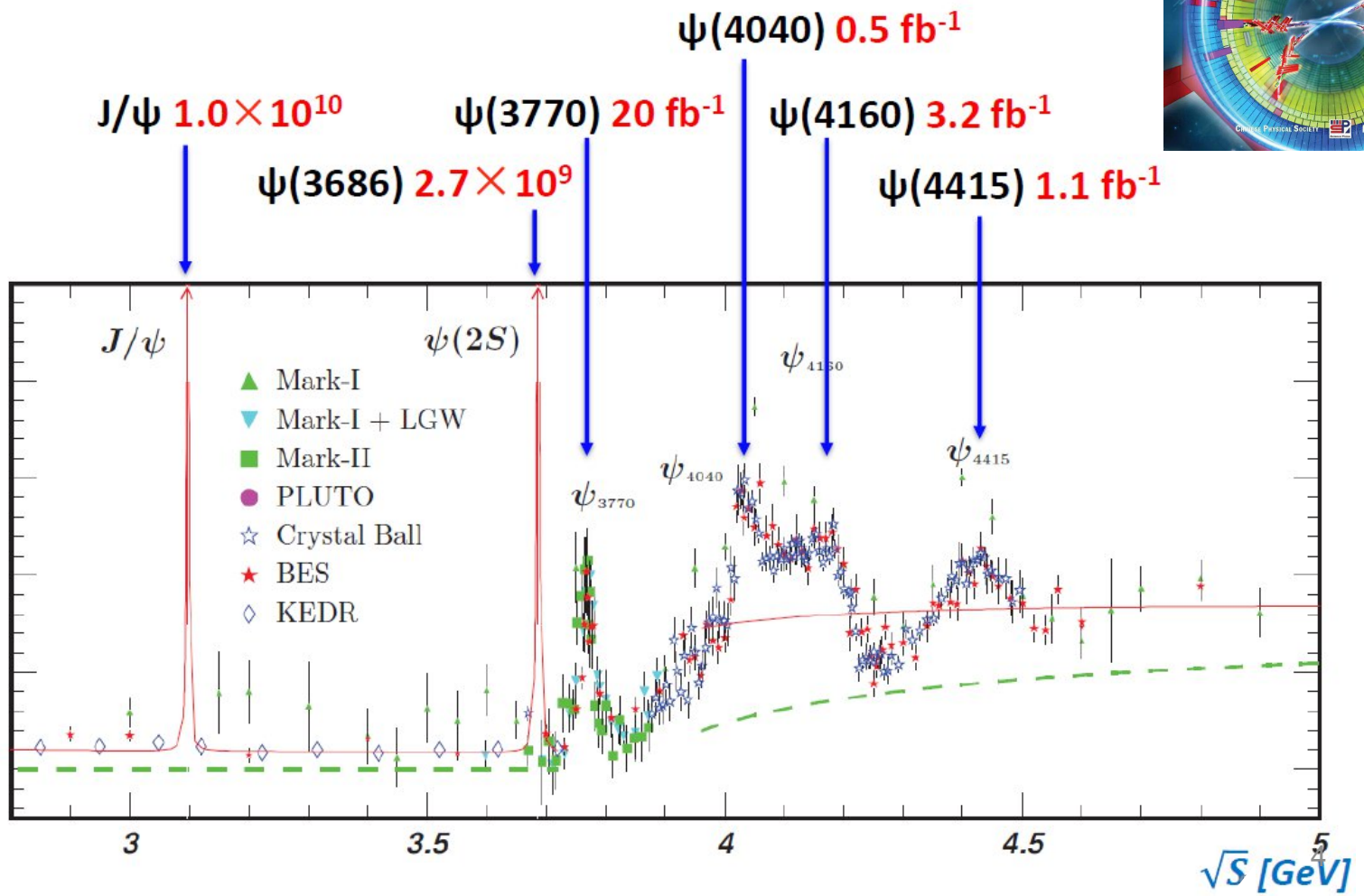


BESIII charmonium datasets



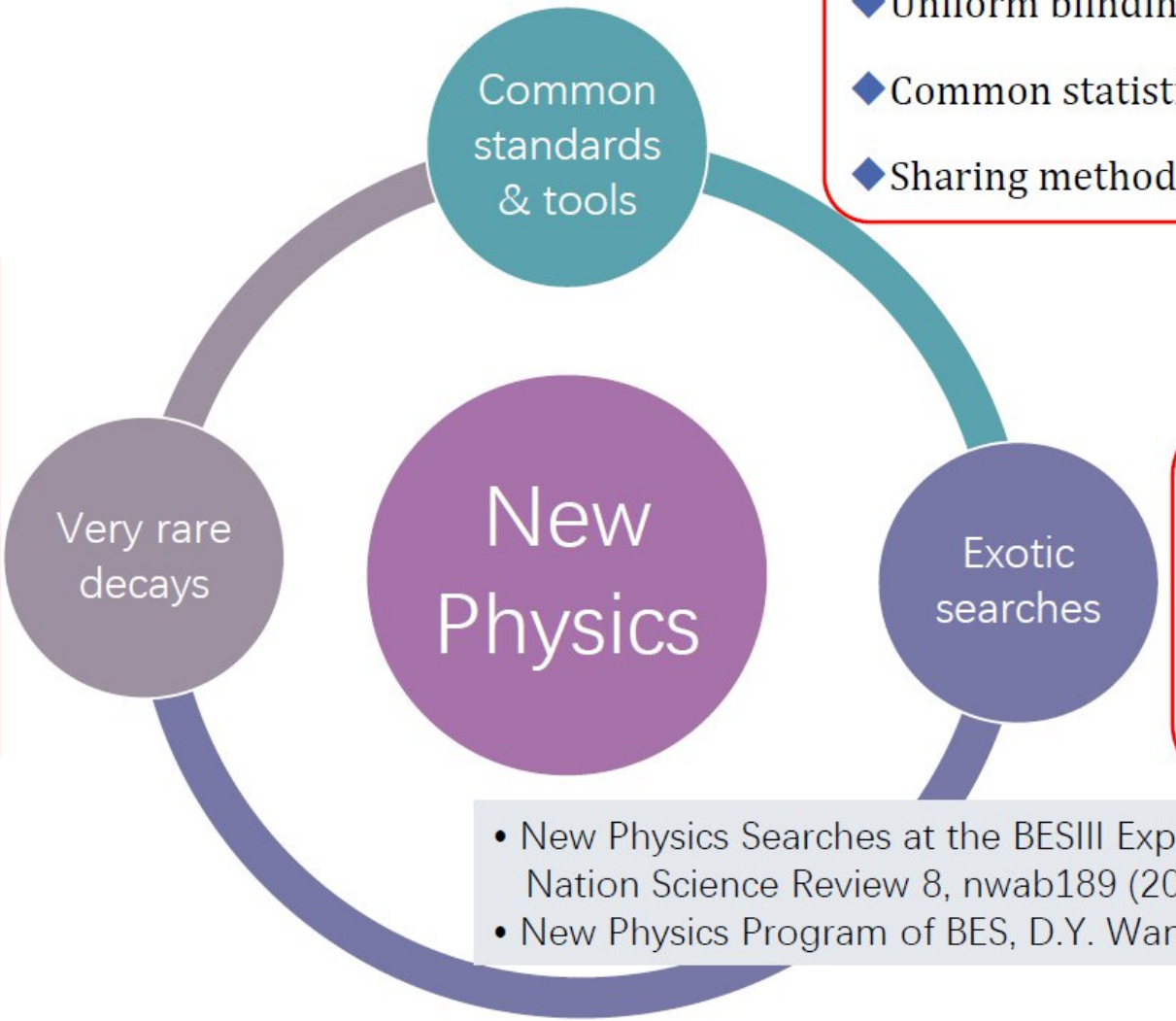
10 Billion J/ψ collected!

- BESIII has collected the largest J/ψ & $\psi(3686)$ data samples on threshold
- $> 20\ \text{fb}^{-1}$ above 4.0 GeV in total



New physics searches @ BESIII

- Charmonium weak decays
- FCNC processes
- LNV processes
- BNV & LNV processes
- LFV processes
- Other processes



- Uniform blinding strategy and datasets
- Common statistic and standards
- Sharing methods, tools and codes

Exotic

- Dark photon
- Invisible signatures
- Light Higgs, Z'
- Exotic resonances

- New Physics Searches at the BESIII Experiment, S.J. Chen and S. Olsen, Nation Science Review 8, nwab189 (2021), arXiv: 2102.13290
- New Physics Program of BES, D.Y. Wang, in "30 Years of BES Physics"

Exotic searches:

- Axion-like particles
  - $J/\psi \to \gamma a(\to \gamma\gamma)$
- Invisible massive dark photon
  - ISR process $e^+e^- \to \gamma\gamma'$
- Muonphilic scalar X_0 or vector X_1
  - $J/\psi \to \mu^+\mu^-$ + invisible
- Other exotics with invisible signature
  - $\Sigma^+ \to p$ + invisible

Axion-like particle in radiative J/ψ decay

- Data sample: 10 B J/ψ events
- Strategy: search for $J/\psi \to \gamma a$, $a \to \gamma\gamma$ with on-threshold J/ψ data
  - Contribution from non-resonant $e^+e^- \to \gamma a$ is calculated to be 4.4% and subtracted (interference ignored)
  - The BF is related to coupling constant $g_{a\gamma\gamma}$:

$$\frac{\mathcal{B}(J/\psi \to \gamma a)}{\mathcal{B}(J/\psi \to e^+e^-)} = \frac{m_{J/\psi}^2}{32\pi\alpha} g_{a\gamma\gamma}^2 \left(1 - \frac{m_a^2}{m_{J/\psi}^2}\right)^3$$

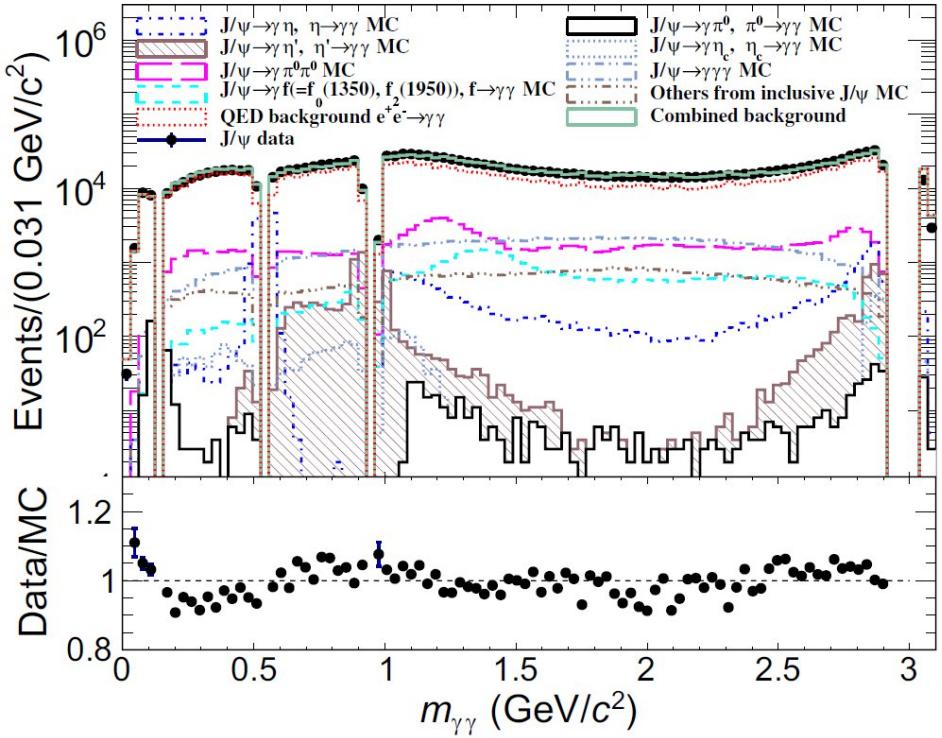


TABLE I. The fit intervals of $m_{\gamma\gamma}$ for various m_a points.

m_a range (GeV/c^2)	$m_{\gamma\gamma}$ fit interval (GeV/c^2)	Polynomial function order
0.180–0.420	0.16, 0.46	Fourth
0.421–0.490	0.39, 0.51	Fifth
0.610–0.880	0.59, 0.90	Fifth
1.020–1.099	1.00, 1.20	Fifth
1.100–2.770	$m_a - 0.10$, $m_a + 0.10$	Third
2.772–2.850	2.70, 2.88	Fourth

Signal extractions with fits to $m_{\gamma\gamma}$ (3 combinations per event) at different m_a points

[PRD 111 (2024) L031101]

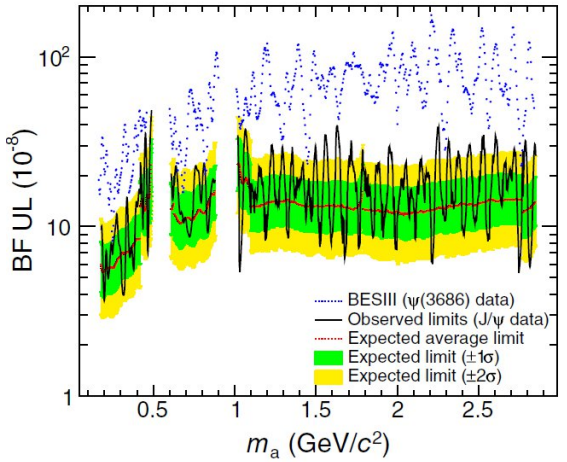
Axion-like particle in radiative J/ψ decay

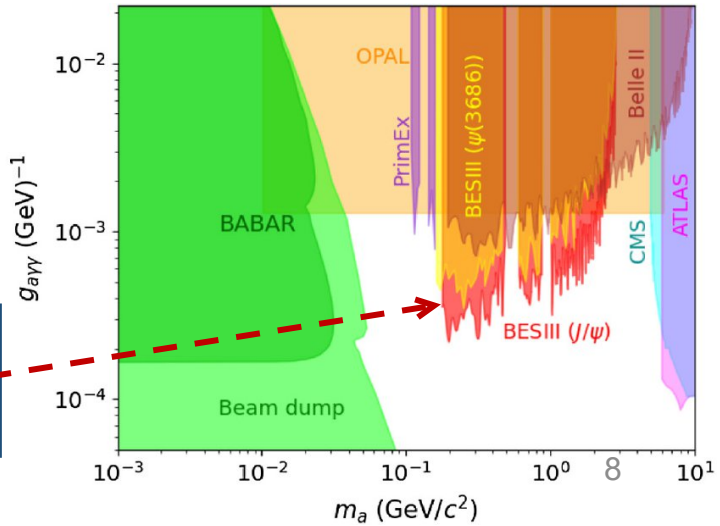
- Data sample: 10 B J/ψ events
- Strategy: search for $J/\psi \to \gamma a$, $a \to \gamma\gamma$ with on-threshold J/ψ data
  - Contribution from non-resonant $e^+e^- \to \gamma a$ is calculated to be 4.4% and subtracted (interference ignored)
  - The BF is related to coupling constant $g_{a\gamma\gamma}$:

$$\frac{\mathcal{B}(J/\psi \to \gamma a)}{\mathcal{B}(J/\psi \to e^+e^-)} = \frac{m_{J/\psi}^2}{32\pi\alpha} g_{a\gamma\gamma}^2 \left(1 - \frac{m_a^2}{m_{J/\psi}^2}\right)^3$$

Most stringent constraints to date for $0.18 < m_a < 2.85$ GeV

Replacing previous BESIII results using $\psi(3686)$ data

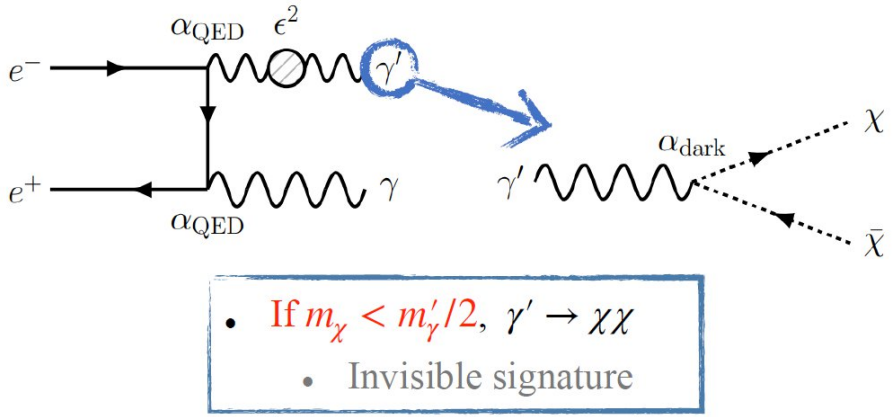




[PLB 839 (2023) 137785]

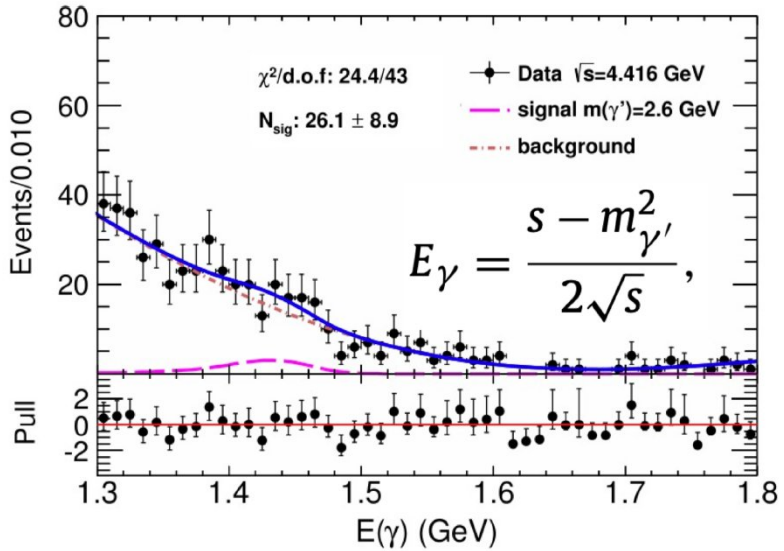
Massive dark photon in $e^+e^- \to \gamma\gamma'$

- Data sample: 14.9 fb^{-1} e^+e^- annihilation data at $\sqrt{s}$ = 4.13 ~ 4.60 GeV
- Search for single photon signals in $1.3 < E(\gamma) < 1.8$ GeV corresponding to $1.5 < m_{\gamma'} < 2.9$ GeV with high trigger efficiency
- Signal extraction via fit to $E(\gamma)$ spectrum:



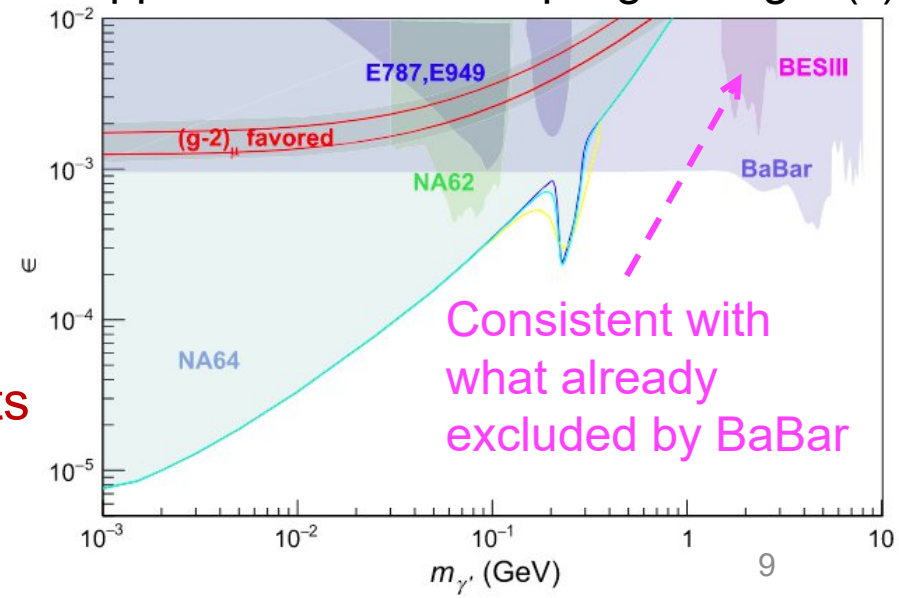
- If $m_\chi < m_{\gamma'}/2$, $\gamma' \to \chi\chi$
  - Invisible signature

Maximum global significance 2.2σ



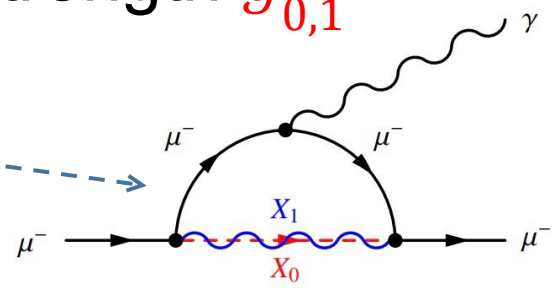
Recent 20.3 fb^{-1} BESIII data @ 3.773 GeV will lead to more competitive results

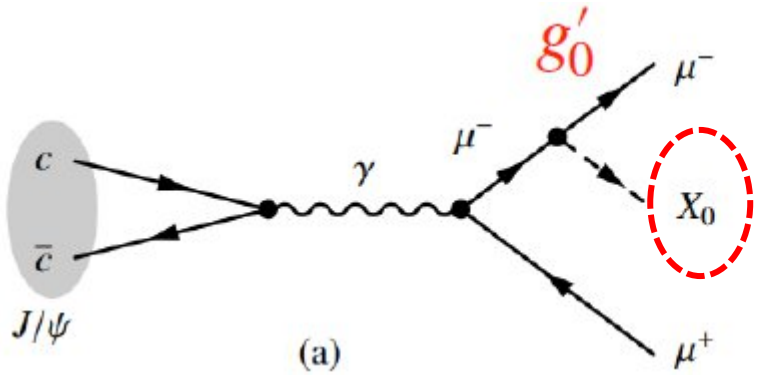
Upper limit on the coupling strength (ϵ)

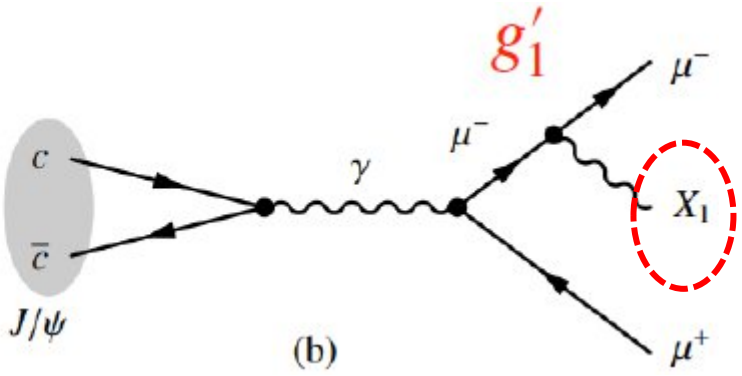


Muonphilic scalar X_0 or vector X_1

- An extra U(1) group is added as minimal extension to SM
- The outcome: new massive scalar (X_0) or vector (X_1) boson that only couples to 2nd or 3rd gen leptons with coupling strength $g'_{0,1}$
  - May help to explain $(g-2)_\mu$ anomaly
- Can be accessible via $J/\psi \to \mu^+\mu^- + \text{invisible}$





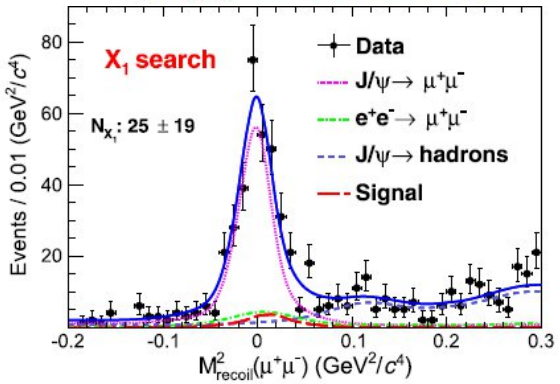


[PRD 109 (2024) L031102]

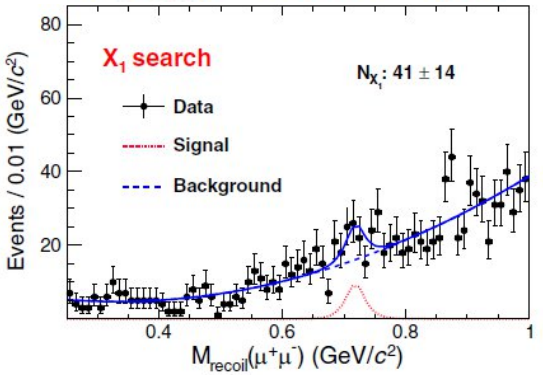
Muonphilic $X_{0,1}$ via $J/\psi \to \mu^+\mu^- +$ invisible

- Data sample: 9 B J/ψ events
- Signal extraction via fit to $M^2_{\text{recoil}}(\mu^+\mu^-)$ (low mass) or $M_{\text{recoil}}(\mu^+\mu^-)$ (high mass) for a series of $M(X_{0,1})$ values
- No sign of $X_{0,1}$ signals, constraints on coupling $g'_{0,1}$ are set

$M(X_{0,1}) = 120$ MeV/c^2



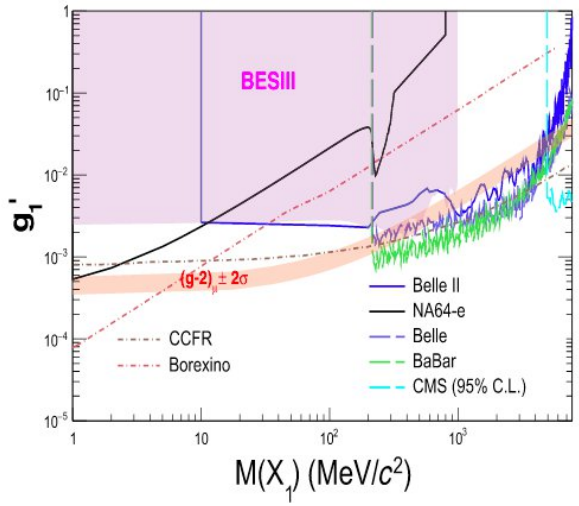
$M(X_{0,1}) = 720$ MeV/c^2



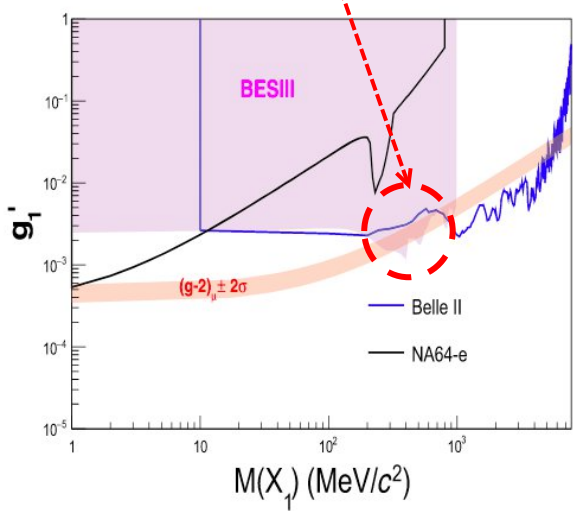
Better sensitivity!

First constraint!

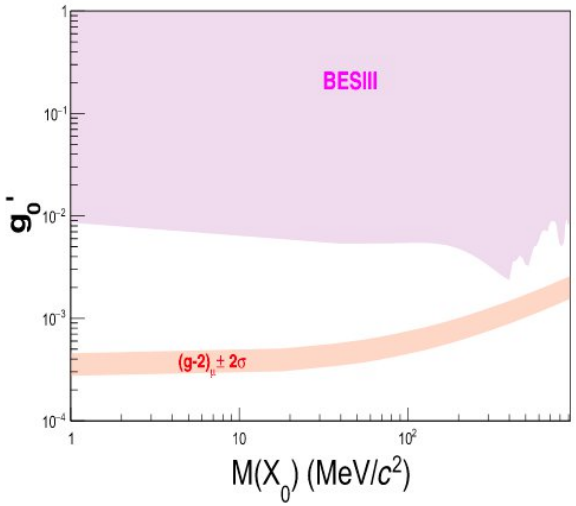
"vanilla" $L_\mu - L_\tau$ model



"invisible" $L_\mu - L_\tau$ model



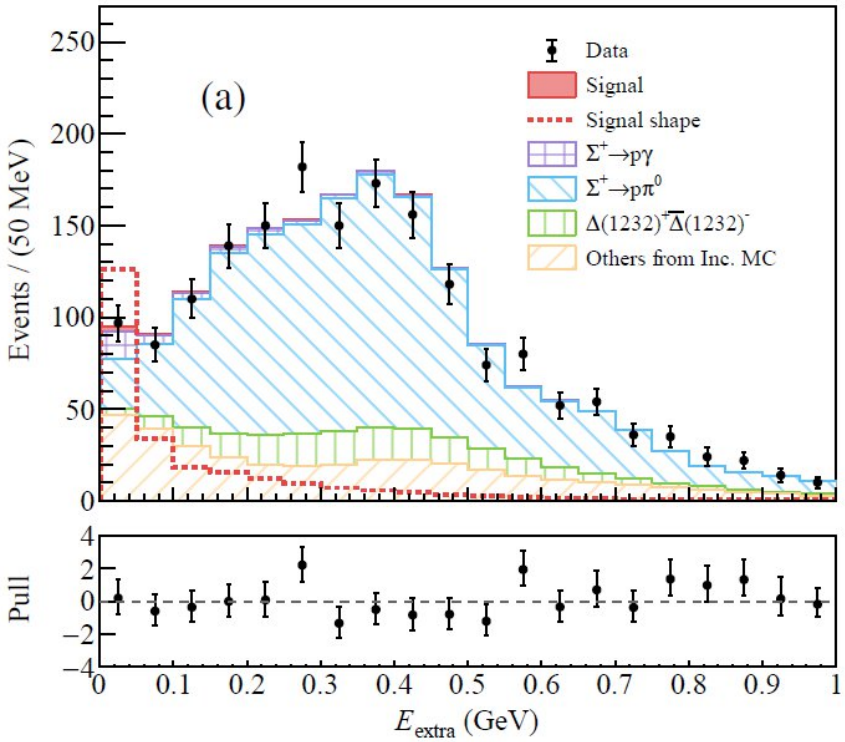
"scalar" $U(1)$ model

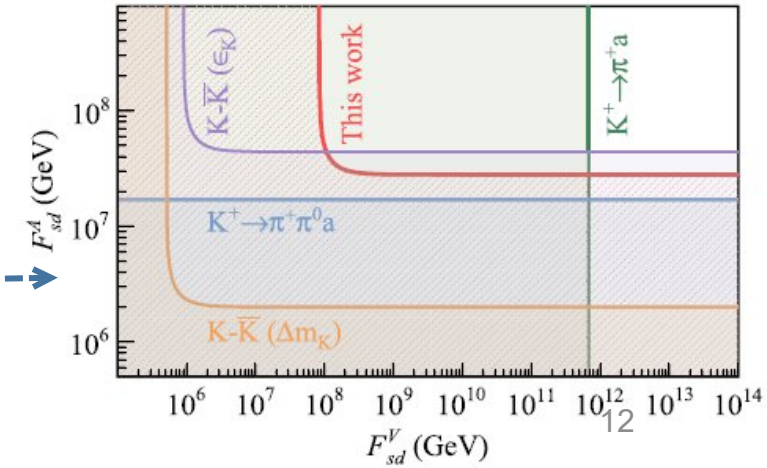


[PLB 852 (2024) 138614]

$\Sigma^+ \to p +$ invisible

- $s \to d\nu\bar{\nu}$ processes highly suppressed in SM
- New invisible particles such as massless dark photon or QCD axion could contribute to the $s \to d$ FCNC transition and enhance the decay BF
- Using ~10^7 $\Sigma^+\bar{\Sigma}^-$ pairs from 10 B J/ψ data
- Fully reconstructing $\bar{\Sigma}^- \to \bar{p}\pi^0$ at the tag side
- First upper limit is set:
  - $B\left(\Sigma^+ \to p + \text{invisible}\right) < 3.2 \times 10^{-5}$
- 90% CL exclusion limit of $s \to d$ axion-fermion effective decay constant is set



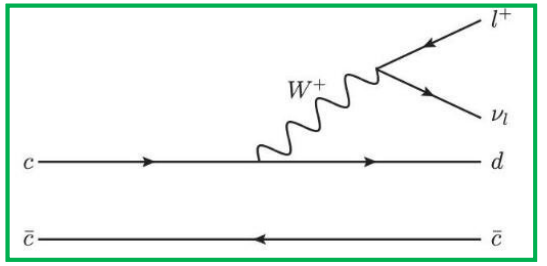


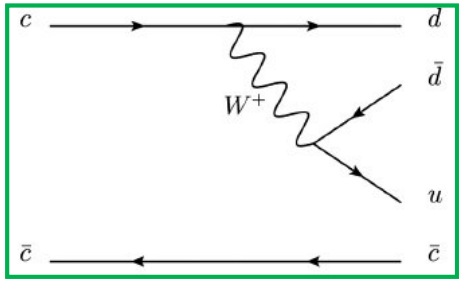
Search for rare decays:

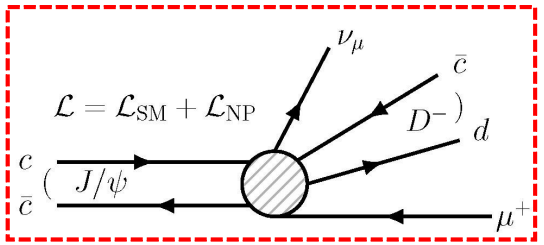
- Charmonium weak decay
  - $J/\psi \to D^- \mu^+ \nu_\mu + \text{c.c.}$
  - $J/\psi \to \bar{D}^0 h^0 + c.c.,\ h = \pi,\rho,\eta$ and $J/\psi \to D^- h^+ + c.c.,\ h = \pi,\rho$
- FCNC related
  - $J/\psi \to \gamma D^0 + \text{c.c.}$
  - $D_s^+ \to h^+ e^+ e^-,\ h = \pi,\rho$, and $D_s^+ \to h^+ h^0 e^+ e^-$
- LNV
  - $D_s^+ \to h^- h^0 e^+ e^+$

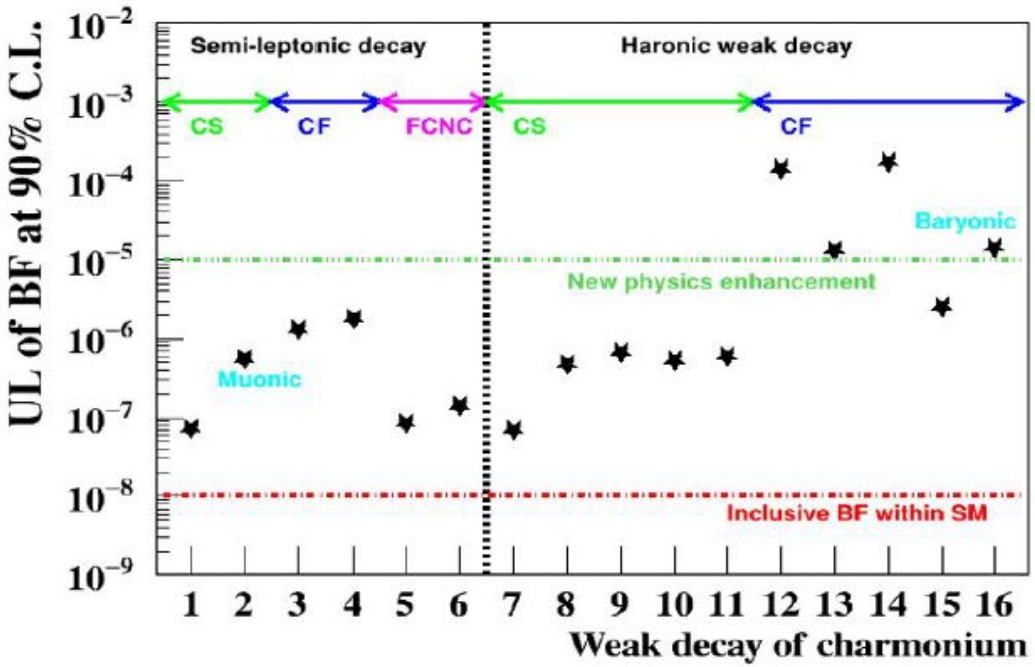
Weak decays of J/ψ

- BFs of J/ψ decays containing a D meson expected to be up to $O(10^{-8})$ in the SM
- These BFs could be significantly enhanced by some new physics models









1: $J/\psi \to D^- e^+ \nu_e$ + c.c.
2: $J/\psi \to D^- \mu^+ \nu_\mu$ + c.c.
3: $J/\psi \to D_s^- e^+ \nu_e$ + c.c.
4: $J/\psi \to D_s^{*-} e^+ \nu_e$ + c.c.
5: $J/\psi \to D^0 e^+ e^-$ + c.c.
6: $\psi(2S) \to D^0 e^+ e^-$ + c.c.
7: $J/\psi \to D^- \pi^+$ + c.c.
8: $J/\psi \to D^0 \pi^0$ + c.c.
9: $J/\psi \to D^0 \eta$ + c.c.
10: $J/\psi \to D^0 \rho^0$ + c.c.
11: $J/\psi \to D^- \rho^+$ + c.c.
12: $J/\psi \to D_s^- \pi^+$ + c.c.
13: $J/\psi \to D_s^- \rho^+$ + c.c.
14: $J/\psi \to D^0 K^0$ + c.c.
15: $J/\psi \to D^0 K^{*0}$ + c.c.
16: $\psi(2S) \to \Lambda_c^+ \bar{\Sigma}^-$ + c.c.

[PRD 111 (2024) 032020, JHEP 01(2024) 126]

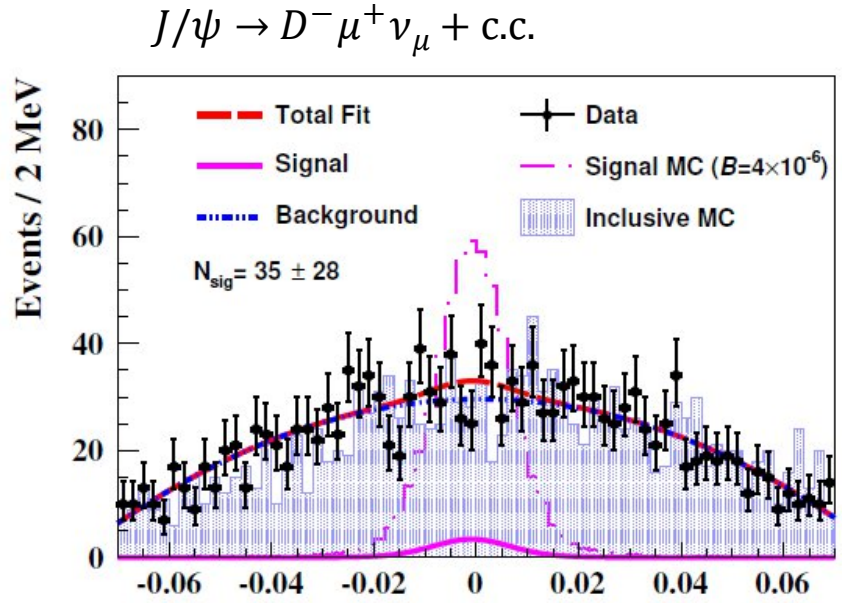
Weak decays of J/ψ

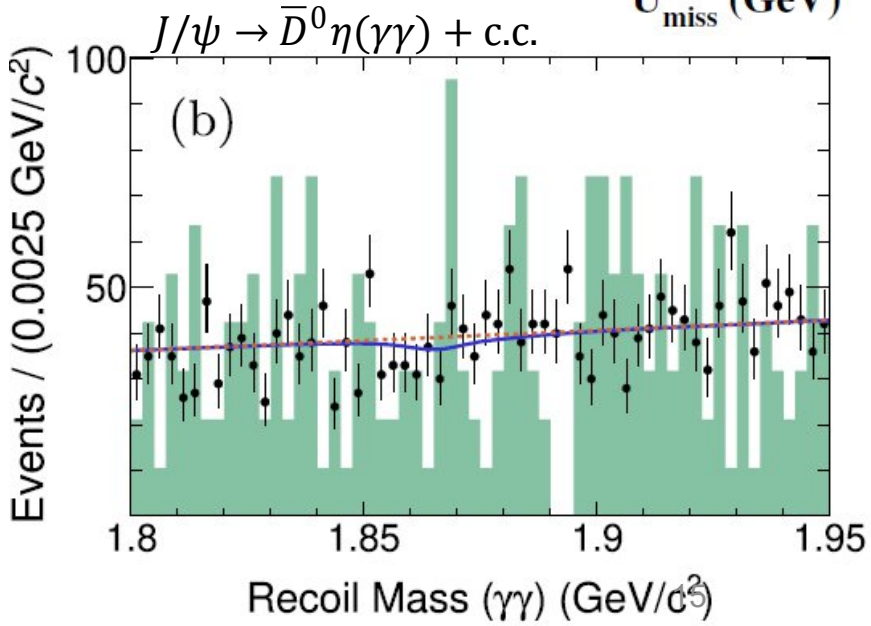
- Data samples: 10 B J/ψ
- For $J/\psi \to D^- \mu^+ \nu_\mu + \text{c.c.}$:
  - Reconstructing $D^- \to K^+ \pi^- \pi^-$
  - First upper limit @90% CL:

$$\mathcal{B}(J/\psi \to D^- \mu^+ \nu_\mu) < 5.6 \times 10^{-7}$$

- for $J/\psi \to \bar{D} h + \text{c.c.}$
  - Reconstructing $\bar{D}^0 \to K^+ e^- \bar{\nu}_e$ and $D^- \to K_S^0 e^- \bar{\nu}_e$
  - First upper limits or world's best

Mode	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}$ (90% CL)
$J/\psi \to \bar{D}^0 \pi^0$	-49.5 ± 69.3	<68.8	$<4.7 \times 10^{-7}$
$J/\psi \to \bar{D}^0 \eta$	-28.9 ± 34.5	<32.9	$<6.8 \times 10^{-7}$
$J/\psi \to \bar{D}^0 \rho^0$	2.0 ± 37.1	<59.9	$<5.2 \times 10^{-7}$
$J/\psi \to D^- \pi^+$	-4.3 ± 10.3	<14.4	$<7.0 \times 10^{-8}$
$J/\psi \to D^- \rho^+$	18.6 ± 26.2	<51.4	$<6.0 \times 10^{-7}$



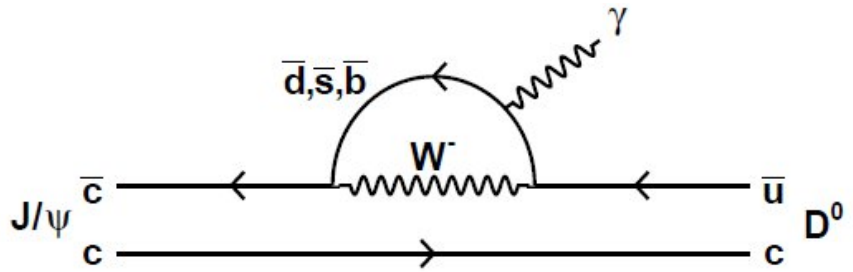


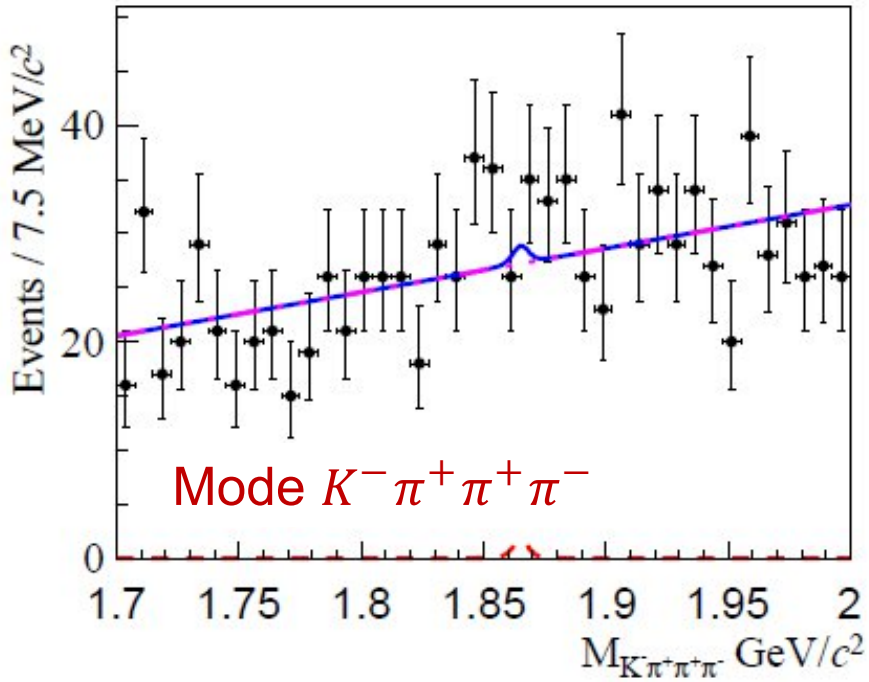
[arXiv:2408.08826]

$J/\psi \to \gamma D^0$+ c.c.

- FCNC $c \to u\gamma$ process, highly suppressed in SM
- Could be significantly enhanced by NP
- Data samples: 10 B J/ψ
- Reconstruct D^0 in 3 modes: $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$
- The first upper limit @ 90% CL:

$$\mathcal{B}(J/\psi \to \gamma D^0 + c.c.) < 9.1 \times 10^{-8}$$





[PRL 133 (2024) 121801]
[arXiv:2410.02421]

Searches for $D_s^+ \to hh'ee$ decays

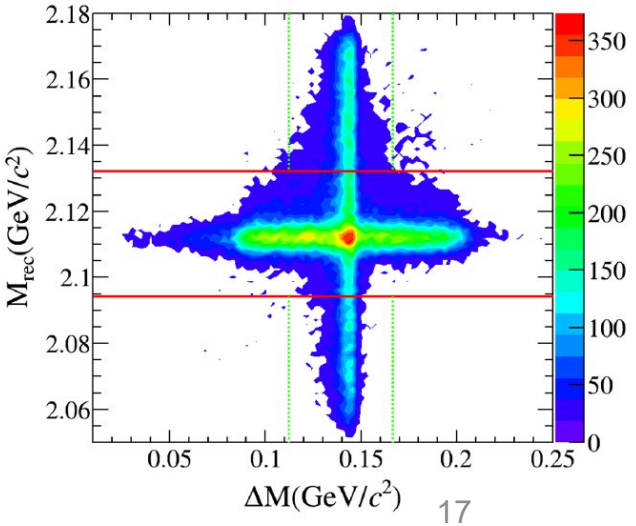
- First searches for four-body D_s^+ decays to an electron pair
- Using 7.33 fb^{-1} data @ 4.128-4.226 GeV
- D_s^+ mainly from $e^+e^- \to D_s^{*\pm}D_s^{\mp}$, with total number of $N_{D_s^{\pm}D_s^{\mp}} = (64.7 \pm 0.3) \pm 10^5$
- Single-tag method, the BF for a given channel is given by:

$$\mathcal{B}(D_s^+ \to h^+(h^0)e^+e^-) = \frac{N_{\rm sig}}{2 \cdot N_{D_s^{*\pm}D_s^{\mp}} \cdot \epsilon \cdot \mathcal{B}_{\rm inter}}$$

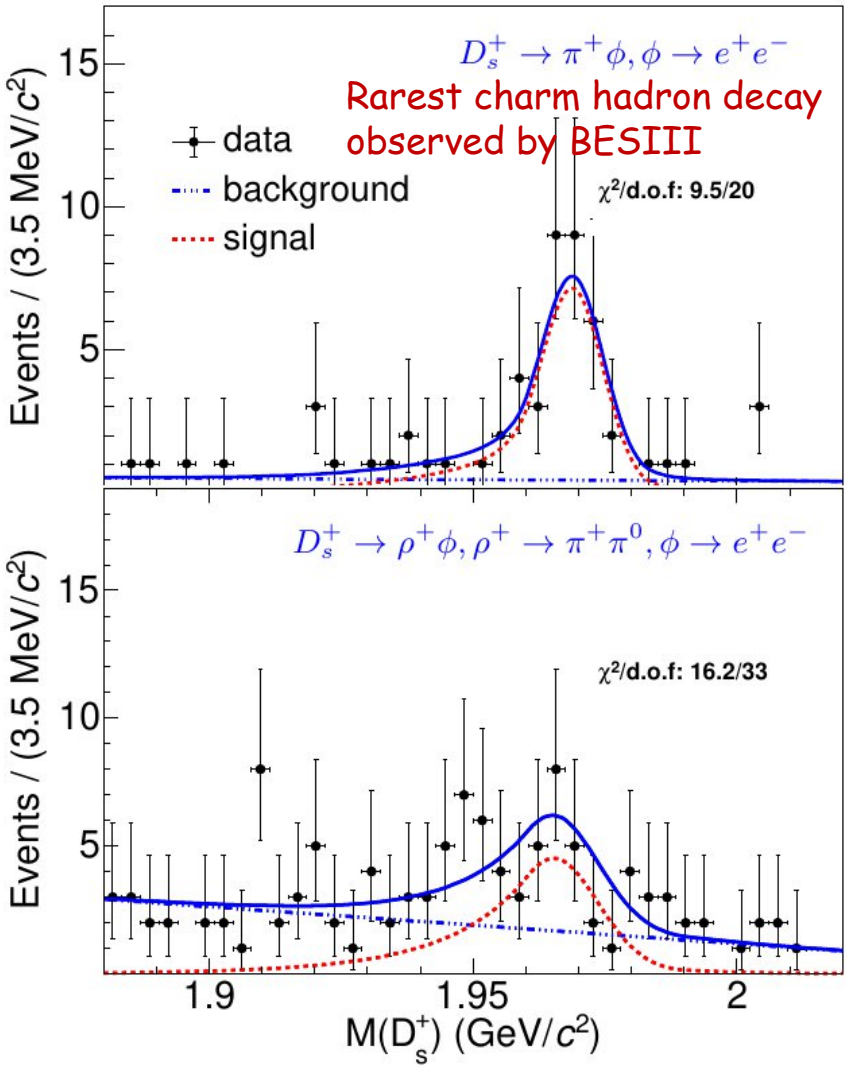
- 2D optimization of requirements on M_{rec} vs. ΔM

$$M_{\rm rec} = \sqrt{\left(E_{\rm cm} - \sqrt{|\vec{P}_{D_s^+}|^2 + m^2_{D_s^+}}\right)^2 - |P_{D_s^+}|^2},$$
$$\Delta M = M(D_s^+\gamma) - M(D_s^+),$$

PRD 104, 012016 (2021)



Results on $D_s^+ \to h(h^0)\phi(e^+e^-)$



- $M(e^+e^-) \in [0.98,1.04]\ \mathrm{GeV}/c^2$
- $M(\pi^+\pi^0) \in [0.60,0.95]\ \mathrm{GeV}/c^2$
- Unbinned maximum likelihood fits to the $M(D_s^+)$ distributions

Decay	N_{sig}	ϵ (%)	$\mathcal{B}$ ($\times 10^{-5}$)
$D_s^+ \to \pi^+\phi, \phi \to e^+e^-$	$38.2^{+7.8}_{-6.8}$	25.1	$1.17^{+0.23}_{-0.21} \pm 0.03$
$D_s^+ \to \rho^+\phi, \phi \to e^+e^-$	$37.8^{+10.3}_{-9.6}$	12.1	$2.44^{+0.67}_{-0.62} \pm 0.16$

7.8σ for $D_s^+ \to \pi^+\phi, \phi \to e^+e^-$ — improved by a factor of three

4.4σ for $D_s^+ \to \rho^+\phi, \phi \to e^+e^-$ — first evidence

NB: Using $D_{(s)}^+ \to \pi^+\phi$, LHCb measured

$$R_{\phi\pi} = 1.022 \pm 0.012\,(\mathrm{stat}) \pm 0.048\,(\mathrm{syst})$$

[JHEP 05 (2024) 293]

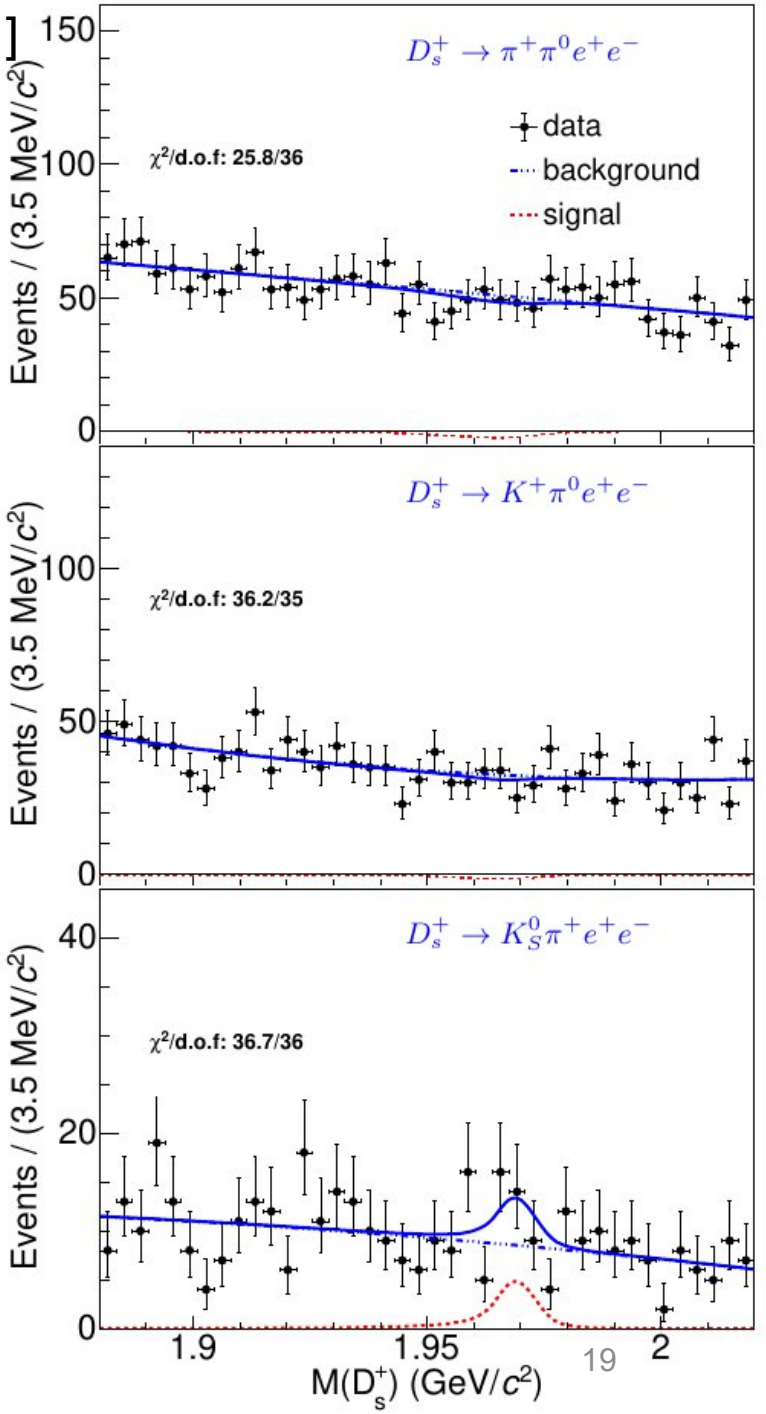
[PRL 133 (2024) 121801]

Upper limits on $D_s^+ \to hh'e^+e^-$

- FCNC $c \to ue^+e^-$ process, highly suppressed in SM
- Exclusion of events with $M(e^+e^-) \in [0.96, 1.05]$ GeV for mode $\pi^+\pi^0e^+e^-$
-

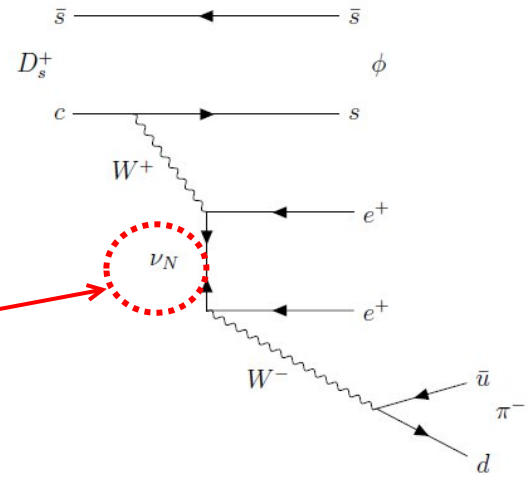
Decay	$N_{\rm sig}$	ϵ (%)	$\mathcal{B}$ ($\times 10^{-5}$)
$D_s^+ \to \pi^+\pi^0e^+e^-$	...	7.4	< 7.0
$D_s^+ \to K^+\pi^0e^+e^-$	...	5.3	< 7.1
$D_s^+ \to K_S^0\pi^+e^+e^-$	...	6.7	< 8.1

All first upper limits!



[arXiv:2410.02421]

$D_s^+ \to h^- h^0 e^+ e^+$

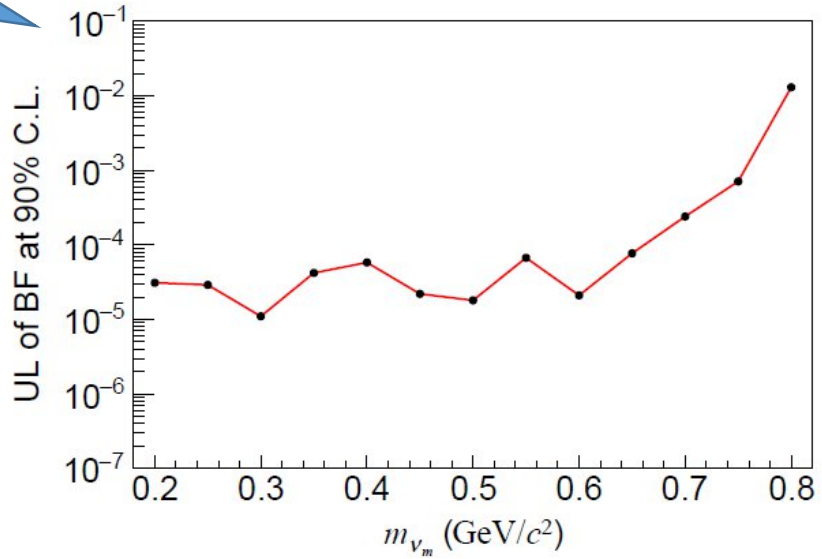


- LNV ($\Delta L = 2$) process could be mediated by a single Majorana neutrino
- First upper limits @ 90% CL:

New

Decay channel	ϵ (%)	$\mathcal{B}_{\rm UL}$ ($\mathcal{B}_{\rm UL}^{\rm expected}$)
$D_s^+ \to \phi\pi^- e^+ e^+$	3.0 ± 0.1	$6.9\ (3.5) \times 10^{-5}$
$D_s^+ \to \phi K^- e^+ e^+$	1.8 ± 0.1	$9.9\ (10.8) \times 10^{-5}$
$D_s^+ \to K_S^0 \pi^- e^+ e^+$	6.4 ± 0.1	$1.3\ (2.4) \times 10^{-5}$
$D_s^+ \to K_S^0 K^- e^+ e^+$	4.0 ± 0.1	$2.9\ (2.3) \times 10^{-5}$
$D_s^+ \to \pi^- \pi^0 e^+ e^+$	6.4 ± 0.1	$2.9\ (2.7) \times 10^{-5}$
$D_s^+ \to K^- \pi^0 e^+ e^+$	5.1 ± 0.1	$3.4\ (3.9) \times 10^{-5}$

$D_s^+ \to \phi\pi^- e^+ e^+$ (CF)



Scanning over a range of sub-GeV neutrino mass

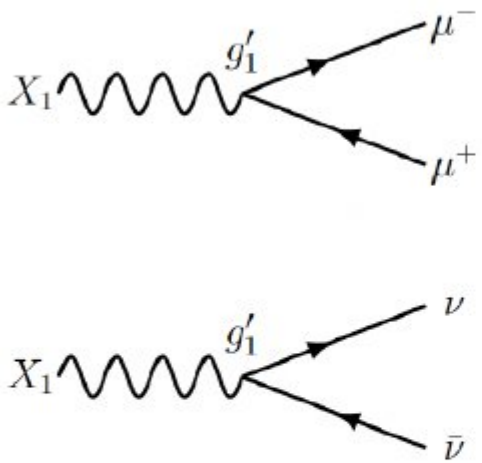
Summary & outlook

- BESIII has accumulated world's largest on-threshold J/ψ and $\psi(3686)$ data
- BESIII data has enabled a wide range of searches on exotic states such as ALP, dark photon, etc., with many of the first or offering best limits
- Also BESIII has searched for a number of rare decays of J/ψ and charm hadrons for the first time
- Not covered today: searches for light Higgs, LFV and BNV processes, etc
- A lot of analyses are still in the pipeline, and BESIII has recently collected 20.3 fb^{-1} of $\psi(3770)$ data
  - Stay tuned for more exciting result!

Backup Slides

Three cases of muonphilic particles

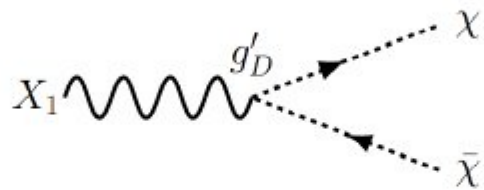
"vanilla" $L_\mu - L_\tau$ model



X_1 only couples with SM particles

- $\mathcal{B}(X_1 \to \nu\bar{\nu}) = 33 \sim 100\,\%$

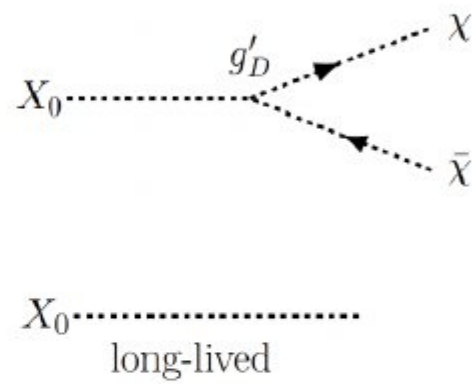
"invisible" $L_\mu - L_\tau$ model



X_1 couples with DM particle χ with coupling $g_{D'}$

- $m_\chi < m_{X_1}/2$
- $g_{D'} \gg g_{1'}$
- $\mathcal{B}(X_1 \to \chi\chi) \sim 100\,\%$

"scalar" $U(1)$ model



- Assume the X_0 is long lived or only decay to invisible final states

Search for X_0, X_1 via $J/\psi \to \mu^+\mu^- X_{0,1}$ with $X_{0,1}$ is invisible

Invisible decays

Search for the invisible decays of V(=ω , ϕ) mesons in J/ψ → Vη decays	Phys. Rev. D 98, 032001 (2018)
Search for J/ψ → γ + invisible via ψ'→ π+π- J/ψ	Phys. Rev. D 101, 112005(2020)
Search for the invisible decay of Λ baryon	Phys. Rev. D 105, L071101 (2022)
Search for Λ_C → P+ invisible	Phys. Rev. D 106, 072008 (2022)
Search for invisible dark photon decays using initial state radiation	Phys. Lett. B 839, 137785 (2023)
Search for a muonphilic scalar X0 or vector X1 via J/ψ → mu+mu- + invisible decays	Phys. Rev. D 109, L031102 (2024)
Search for BSM particles via Sigma+ to p invisible	Phys. Lett. B 852 (2024) 138614

Visible decays

Search for a light CP-odd Higgs boson in radiative decays of J/ψ	Phys. Rev. D 93, 052005 (2016)
Dark photon search in the mass range between 1.5 and 3.4 GeV/c^2	Phys. Lett. B 774, 252 (2017)
Study of the Dalitz decay J/ψ → e+e-η and probing the dark photon	Phys. Rev. D 99, 012006 (2019)
Probe dark photon via J/ψ → η'e+e-	Phys. Rev. D 99, 012013 (2019)
Search for light Higgs A^0 in radiative decays of J/ψ	Phys. Rev. D 105, 012008 (2022)
Search for axion-like particles via J/ψ → aγ	Phys. Lett. B 838, 137698 (2023)
Search for an Axion-like particle with J/ψ data	Phys. Rev. D 110, L031101 (2024)

Charmonium weak decays

Search for the rare decays J/ψ → Ds-ρ+ and J/ψ → D0K*0	Phys. Rev. D 89, 071101(2014)
Search for the weak decays J/ψ → Ds(*)-e+νe+c.c	Phys. Rev. D 90, 112014(2014)
Search for the rare decay J/ψ→ D-e+νe	JHEP157(2021)
Search for the Rare Decay ψ(2s) → Λc+ anti-Σ-	Chinese Phys. C 47 013002 (2023)
Search for the semi-muonic charmonium decay J/ψ → D+μ-νμ	JHEP 01 126 (2024)
Search for J/psi weak decays containing D meson	Phys. Rev. D 110, 032020 (2024)

FCNC processes

Search for the rare decays J/ψ → D0e+e- + c.c. and ψ(3686) → D0e+e- + c.c.	Phys. Rev. D 96, 111101(2017)
Search for the rare decays D → h(h(′))e+e-	Phys. Rev. D 97, 072015(2018)
Search for the rare decays of ψ(3686) → Λc+pe+e-	Phys. Rev. D 97, 091102(2018)
Search for the FCNC process D0→ Pi0νν	Phys. Rev. D 105, L071102 (2022)
Searching for D_s+ → h(h')e+e-	arxiv:2404.05973
Search for J/ψ → γD	arxiv:2408.08826

Charged lepton flavour violation

Search for the lepton flavor violation process $J/\psi \to e\mu$	Phys. Rev. D87, 112007(2013)
Search for the charged lepton flavor violating decay $J/\psi \to e\tau$	Phys. Rev. D 103, 112007 (2021)
Search for $J/\psi \to e\mu$	Sci. China-Phys. Mech. Astron. 66, 221011 (2023)

Lepton number violation

Search for $D0 \to K-\pi-e+e+$ and $D+ \to K\pi e+e+$	Phys. Rev. D 99, 112002(2019)
Search for $\Sigma- \to pe-e-$	Phys. Rev. D 103, 052011(2021)
Search for LNV process phi→PiPie-e- via J/ψ→etaphi	arXiv:2308.05490

Baryon number violation

Search for $J/\psi \to \Lambda c+e-$ + c.c.	Phys. Rev. D 99, 072006(2019)
Search for $D+ \to \Lambda/\Sigma e+$ and $D+ \to \Lambda/\Sigma e+$	Phys. Rev. D 101, 031102(2020)
Search for BNV and LNV decay $D0 \to pe$	Phys. Rev. D 105, 032006 (2022)
Search for $D+ \to ne+$ and $D- \to ne-$	Phys. Rev. D 106, 112009 (2022)
Search for $\Lambda\Lambda$ oscillation via $J/\psi \to pK-\Lambda$	Phys. Rev. Lett. 131, 121801 (2023)
Search for BNV and LNV decays of $\Xi 0 \to K+e-/K-e+$	Phys. Rev. D 108, 012006 (2023)

Other rare decays

Search for $J/\psi \to \phi e+e-$ via $\psi' \to \pi+\pi+J/\psi$	Phys. Rev. D 99, 052010(2019)
Study of EM Dalitz Decay $\psi(3686) \to e+e-\eta c$	Phys. Rev. D 106, 112002 (2022)
Search for hyperon $\Delta S=\Delta Q$ violating decay $\Xi 0 \to \Sigma ev$	Phys. Rev. D 107, 012002 (2023)
Measurement of $J/\psi \to 4$ leptons via $\psi' \to \pi+\pi-J/\psi$	Phys. Rev. D 109 (2024) 052006
Search for $\Delta S=2$ nonleptonic hyperon decays $\Omega- \to \Sigma 0Pi-$, nK-	JHEP 05 141 (2024)