

Lattice QCD: From Precision Tests to New-Physics Searches

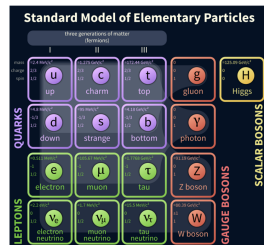
孟 雨 (Yu Meng)
郑州大学

@第六届中国格点量子色动力学研讨会(CLQCD2026), 深圳
2026.10.08-10.11

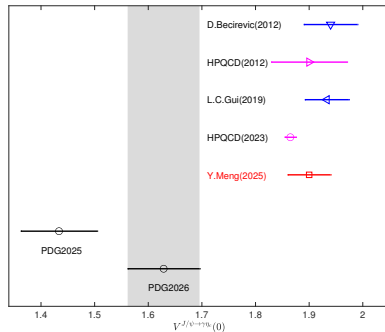
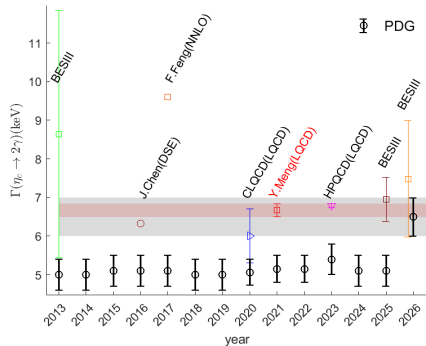
- Introduction
- Standard Model precision test
 - Charmonium decay puzzle
 - $D \rightarrow K^* l \nu_l$
- New physics constraints— A^0, A', a
 - $J/\psi \rightarrow \gamma A^0/a$
 - $\eta_c \rightarrow \gamma A'$
- Summary

Precision frontier and new physics search

- Standard model quantities
 - Direct observable, i.e. mass, branching fraction, ...
 - Combined with experiment
 - CKM matrix element $V_{cs(d)}$
- Search for new physics in collider
 - Invisible decay TO constrain dark matter properties
 - (a) CP-odd Higgs boson;
 - (b) Dark photon;
 - (c) Axion-like particle
 - Neutrino background



Precision test: charmonium decay puzzle



- $\mathcal{B}(J/\psi \rightarrow \gamma \eta_c) \times \mathcal{B}(\eta_c \rightarrow 2\gamma) = 5.23(26)(30) \times 10^{-6}$

BESIII, PRL134,181901(2025)

- $\mathcal{B}(J/\psi \rightarrow \gamma \eta_c) \times \mathcal{B}(\eta_c \rightarrow p\bar{p}) = 2.11(2)(7) \times 10^{-5}$

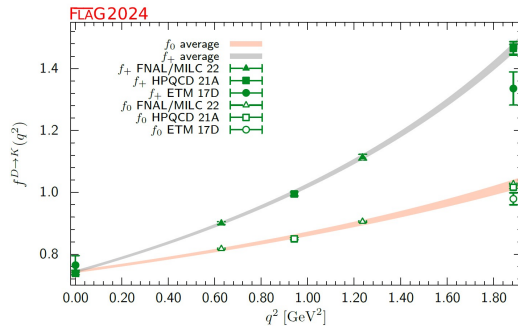
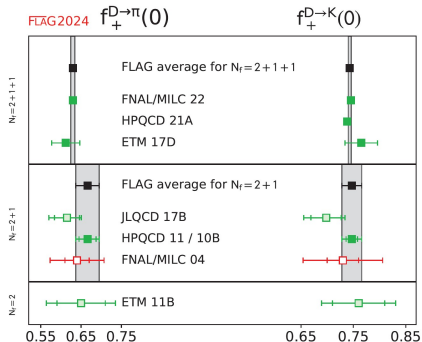
BESIII, PRL136,051901(2026)

- Absolute branching fraction $\mathcal{B}(\eta_c \rightarrow 2\gamma) = 2.45(48)(09) \times 10^{-4}$.

BESIII, PRL137,071802(2026)

Precision test: charm semileptonic decay

FLAG24: no results away from $q^2 = 0$ provided due to discrepancy among ETM17 and others.



- More lattice QCD calculations on $D \rightarrow K$. in progress
- Independent determination on CKM matrix element from other channels, i.e. $P \rightarrow V$

Why $P \rightarrow V$ semileptonic decay?

- For $P' \rightarrow P$:

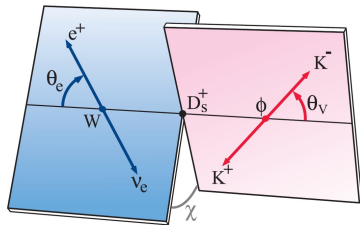
$$\frac{d\Gamma(P' \rightarrow P e \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |\vec{p}|^3 |V_{xy}|^2 |f_+(q^2)|^2$$

for example, $D \rightarrow \pi$ and $D \rightarrow K$

- For $P \rightarrow V$:

$$\frac{d\Gamma(P \rightarrow V e \nu)}{dq^2 d\chi d\cos\theta_\ell d\cos\theta_V} = \frac{G_F^2 |V_{xy}|^2 |\vec{p}| q^2}{12(2\pi)^4 M^2} W(q^2, \theta_V, \theta_\ell, \chi)$$

- Independent** determination of the CKM matrix element
- Stronger test** with abundant polarization information



$P \rightarrow V$ semileptonic decay

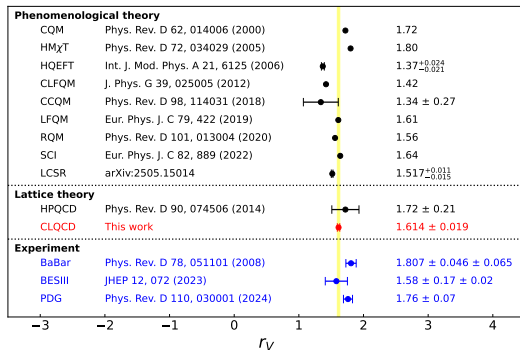
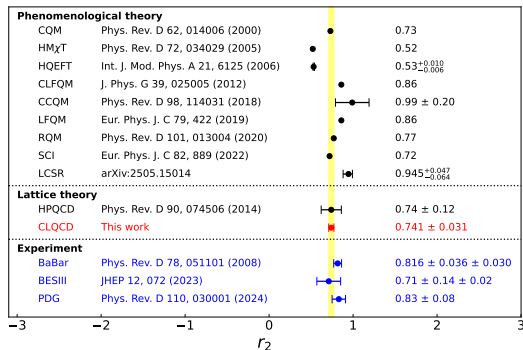
- Experiments:

Channels	r_V	r_2	Refs
$D^0 \rightarrow K^*(892)$			
(μ)	$1.37 \pm 0.09 \pm 0.03$	$0.76 \pm 0.06 \pm 0.02$	PRL134,011803(2025)
(μ)	$1.46 \pm 0.11 \pm 0.04$	$0.71 \pm 0.08 \pm 0.03$	PRL135,111803(2025)
(e)	$1.48 \pm 0.05 \pm 0.02$	$0.70 \pm 0.04 \pm 0.02$	JHEP03,197(2025)
LQCD	$1.48(12) \& 1.46(11) \rightarrow 1.44(28)$	$0.6(3) \& 1.0(2) \rightarrow 1.5(6)$	NPB119,625(2003)
$D_s \rightarrow \phi$			
(μ)	$1.58 \pm 0.17 \pm 0.02$	$0.71 \pm 0.14 \pm 0.02$	JHEP12,072(2023)
(e)	$1.807 \pm 0.046 \pm 0.065$	$0.816 \pm 0.036 \pm 0.030$	PRD78,051101(2008)
LQCD	$1.72(21)$	$0.74(12)$	PRD90,074506(2014)
$D^0 \rightarrow \rho^- e^+ \nu_e$	$1.695 \pm 0.083 \pm 0.051$	$0.845 \pm 0.056 \pm 0.039$	PRL122,062001(2019)

- $D_s \rightarrow \phi$ in CLQCD25, continuous progress in $D \rightarrow K^*(892)$ in CLQCD26.

$D_s \rightarrow \phi$ form factors

$$r_2 \equiv A_2(0)/A_1(0), \quad r_V \equiv V(0)/A_1(0)$$



- Precision improved by up to an order of magnitude

G.-F.Fan, Y.M, C.Liu, Z.-F Liu, T.-X Wang, T.-H Shen, K.-Z Zhang, and L.Zhang, arXiv:2510.14478

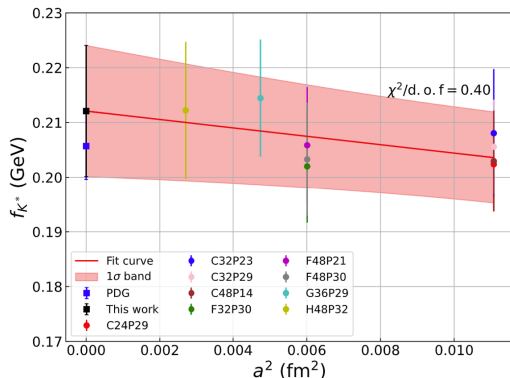
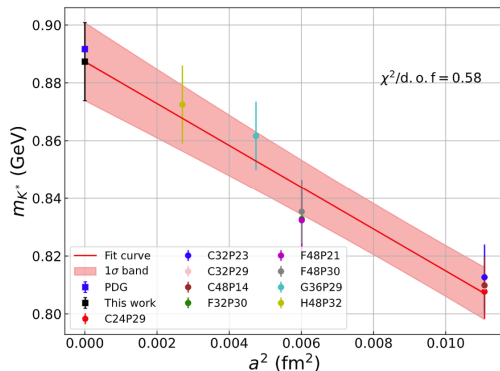
Gauge ensembles in $D \rightarrow K^*(892)$

Configuration	Volume	a/fm	m_π/MeV	$N_{\text{conf}} \times N_t \times N_s$
C24P29	$24^3 \times 72$	0.10524(05)	292.3(1.0)	$450 \times 72 \times 2$
C32P29	$32^3 \times 64$	0.10524(05)	293.1(0.8)	$397 \times 64 \times 2$
C32P23	$32^3 \times 64$	0.10524(05)	227.9(1.2)	$333 \times 64 \times 3$
C48P14	$32^3 \times 64$	0.10524(05)	136.4(1.7)	$180 \times 96 \times 16$
F32P30	$32^3 \times 96$	0.07753(03)	300.4(1.2)	$360 \times 96 \times 2$
F48P30	$48^3 \times 96$	0.07753(03)	302.9(1.9)	$166 \times 96 \times 4$
F48P21	$48^3 \times 96$	0.07753(03)	207.5(1.1)	$241 \times 48 \times 4$
G36P29	$36^3 \times 108$	0.06887(12)	297.2(0.9)	$300 \times 54 \times 2$
F48P32	$48^3 \times 144$	0.05199(08)	316.6(1.0)	$300 \times 72 \times 2$

- Four lattice spacings $[0.052 - 0.105]$ fm $\rightarrow$ continuum limit
- $m_\pi = 136 - 317$ MeV $\rightarrow$ physical pion masses
- C24P29 vs C32P29 and F32P30 vs F48P30 $\rightarrow$ finite-volume effect

$K^*(892)$: mass and decay constant

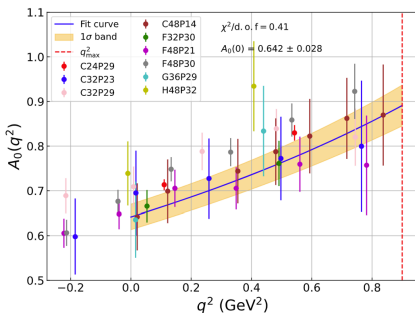
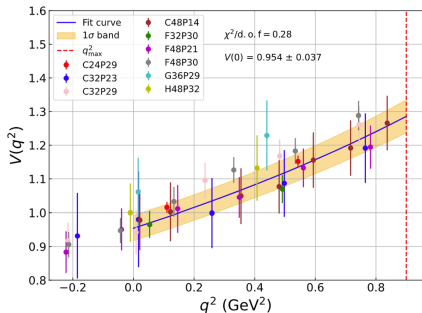
$$m, f_{K^*} = c + da^2 + f(m_\pi^2 - m_{\pi,\text{phy}}^2) + ge^{-m_\pi L}$$



• $m_{K^*} = 887(14)\text{MeV}$, $f_{K^*} = 212(12)\text{MeV}$, both consistent with PDG.

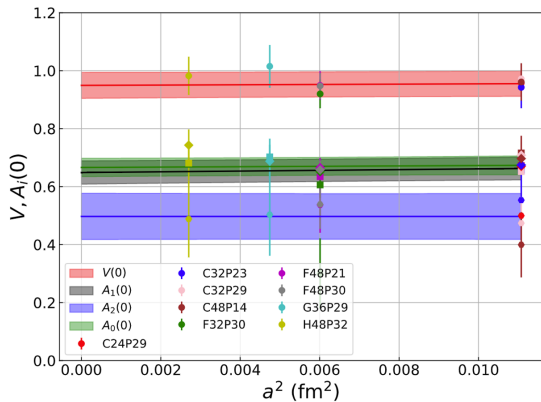
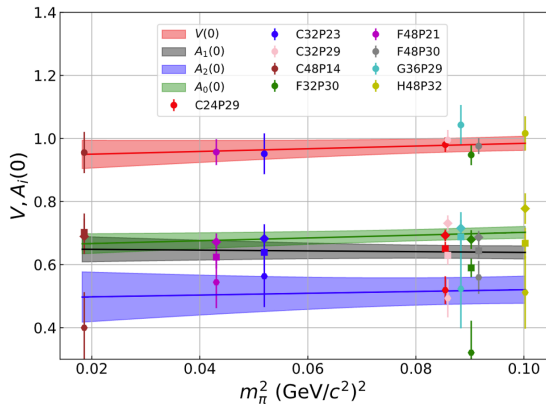
$D \rightarrow K^*$ form factors

$$\begin{aligned} \langle K^*(p) | V_\mu - A_\mu | D(p') \rangle &= \varepsilon_\nu^* \epsilon_{\mu\nu\alpha\beta} p'_\alpha p_\beta \frac{2V}{m+M} + (M+m) \varepsilon_\mu^* A_1 \\ &+ \frac{\varepsilon^* \cdot q}{M+m} (p+p')_\mu A_2 - 2m \frac{\varepsilon^* \cdot q}{q^2} q_\mu (A_0 - A_3) \end{aligned}$$



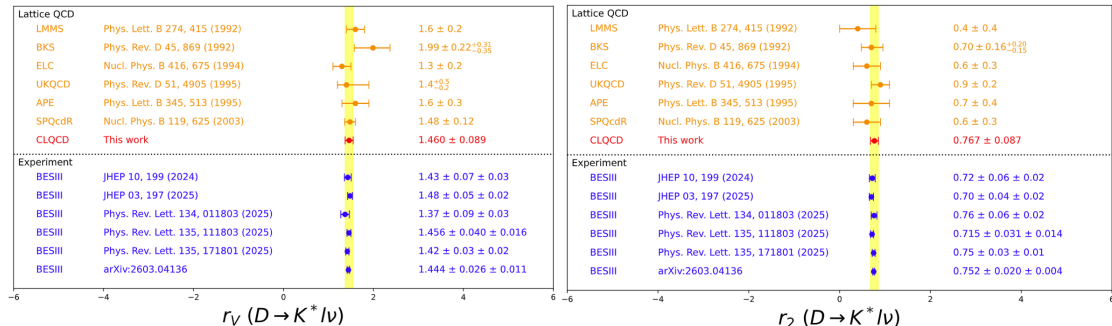
- Physical pion mass, continuum limit, and infinite volume in z -expansion scheme.

$V(0)$ and $A_i(0)$



$$r_2 \equiv A_2(0)/A_1(0), \quad r_V \equiv V(0)/A_1(0)$$

$D \rightarrow K^*$ form factors



- First **un-quenched** lattice QCD calculation.
- First **physical point**: a^2 , m_π^2 , and $e^{-m_\pi L}$ extrapolation

Gaofeng Fan, Chuan Liu, Zhaofeng Liu, and Y.M, in preparation

Cuttent status of the dark matter search on the collider

- Remarkable candidates
 - **Dark photon A'** : coupling to the photon through the kinetic mixing $\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$, free parameters are $m_{A'}$ and ϵ
 - **CP-odd Higgs Boson A^0** : m_{A^0} and $g_{aq\bar{q}}$
 - **Axion-like particle a** : m_a and $g_{aq\bar{q}}$
- Dark matter can be produced on the collider
 - **Direct production: $e^+e^- \rightarrow \gamma X$**
BABAR,PRL119,131804(2017) BESIII,PLB839,137785(2023)
 - **Resonant production: $e^+e^- \rightarrow J/\psi/\Upsilon(1S) \rightarrow \gamma + X$**
CLEO,PRD81,091101(2010) BABAR,PRL107,021804(2011)
Belle,PRL122,011801(2019) Belle,PRL128,081804 (2022)
BESIII,PRD101,112005(2020) BESIII,PRD105,012008(2022)
BESIII,PLB838,137698(2023)

Light dark matter search at the collider

CLEO 2010

PHYSICAL REVIEW D 81, 091101(R) (2010)
Search for the decay $J/\psi \rightarrow \gamma + \text{invisible}$
(CLEO Collaboration)

$J/\psi \rightarrow \gamma + X$
invisible to detector
light dark matter?

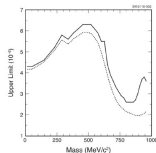


FIG. 4. The 90% confidence level upper limits for $J/\psi \rightarrow \gamma X$, where X is invisible to the detector. The dashed line shows the results for statistical uncertainties alone, and the solid line includes systematic and statistical uncertainties.

The upper limit corresponding to $m_X = 0$
is 4.3×10^{-6} at the 90% confidence level

BESIII

PHYSICAL REVIEW D 101, 112005 (2020)
Search for the decay $J/\psi \rightarrow \gamma + \text{invisible}$

Upper bound $B \sim 7.0 \times 10^{-7}$

PHYSICAL REVIEW D 105, 012008 (2022)
Search for a CP-odd light Higgs boson in $J/\psi \rightarrow \gamma A^0$

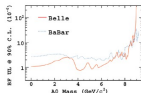
Upper bound $B(J/\psi \rightarrow \gamma A^0) \times B(A^0 \rightarrow \mu^+ \mu^-) \sim (1.2 - 778.0) \times 10^{-9}$

BABAR
Belle

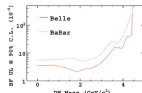
$\Upsilon(1S) \rightarrow \gamma + X$

PRL 107, 021804 (2011)
Search for Production of Invisible Final States in Single-Photon Decays of $\Upsilon(1S)$
(BABAR Collaboration)

PRL 122, 011801 (2019)
Search for a Light CP-odd Higgs Boson and Low-Mass Dark Matter at the Belle Exper
(Belle Collaboration)



$B(\Upsilon \rightarrow \gamma A^0) \times B(A^0 \rightarrow \text{invisible})$



$B(\Upsilon(1S) \rightarrow \gamma \chi\chi)$

PHYSICS LETTERS B 838, 137698 (2023)
Search for an axion-like particle in radiative J/ψ decays

We search for an axion-like particle (ALP) a through the process $\psi(3686) \rightarrow \pi^+ \pi^- J/\psi$, $J/\psi \rightarrow \gamma a$, $a \rightarrow \gamma\gamma$ in a data sample of $(2.71 \pm 0.01) \times 10^9 \psi(3686)$ events collected by the BESIII detector. No significant ALP signal is observed over the expected background, and the upper limits on the branching fraction of the decay $J/\psi \rightarrow \gamma a$ and the ALP-photon coupling constant $g_{a\gamma\gamma}$ are set at 95% confidence level in the mass range of $0.165 \leq m_a \leq 2.84 \text{ GeV}/c^2$. The limits on $B(J/\psi \rightarrow \gamma a)$ range from 8.3×10^{-8} to 1.8×10^{-6} over the search region, and the constraints on the ALP-photon coupling are the most stringent to date for $0.165 \leq m_a \leq 1.468 \text{ GeV}/c^2$.

Dark matter properties in charmonium sector

- Axion-like particle— a

$$\delta\mathcal{L}_{eff}^a = i\frac{a}{f_a}c_c m_c \bar{c}\gamma_5 c$$

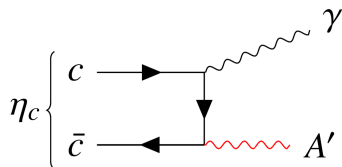
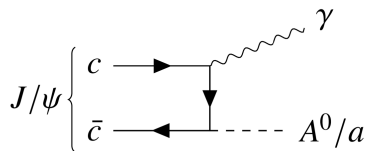
- CP-odd Higgs boson— A^0

$$\delta\mathcal{L}_{eff}^{A^0} = -\frac{m_c c_p}{v}i\bar{c}\gamma_5 c A^0$$

- Dark photon— A'

$$\delta\mathcal{L}_{eff}^{A'} = \epsilon i e \bar{c}\gamma_\mu c A'_\mu, m_{A'} \neq 0$$

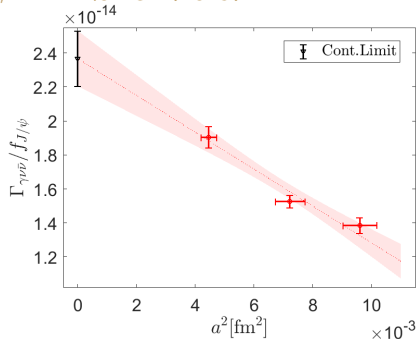
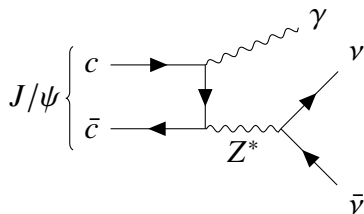
- **SM background** in $J/\psi \rightarrow \gamma X$ and $\eta_c \rightarrow \gamma X$ must be estimated.



Neutrino background in $J/\psi \rightarrow \gamma A^0/a$ and $\eta_c \rightarrow \gamma A'$

- $J/\psi \rightarrow \gamma \nu \bar{\nu}$

- $\text{Br}[J/\psi \rightarrow \gamma \nu \bar{\nu}] = 1.04(7)(8) \times 10^{-10}$ **YM et al, PRD114,014524(2026)**



- $\eta_c \rightarrow \gamma \nu \bar{\nu}$, $\text{Br} \sim 10^{-14}$ **Dao-Neng Gao, PRD 90,077501(2014)**

- Completely ignored in current experiment

$$J/\psi \rightarrow \gamma A^0$$

- Parameterization

$$\langle A^0(p) | J_\mu^{em} | J/\psi(\epsilon^{J/\psi}, p') \rangle = \frac{2F_{\gamma A^0}(q^2)}{M} \epsilon_{\mu\nu\alpha\beta} \epsilon_\nu^{J/\psi} p_\alpha p'_\beta$$

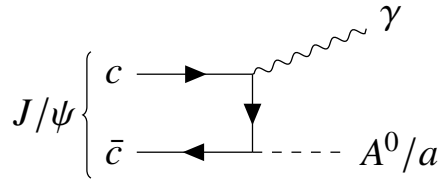
- Decay width

$$\Gamma(J/\psi \rightarrow \gamma A^0) = \frac{16\alpha_{em}}{27} \frac{|\vec{p}|^3}{M^2} \left(\frac{m_c c_p}{v} \right)^2 F_{\gamma A^0}^2(0)$$

- On-shell form factor

$$F_{\gamma A^0} = -\frac{1}{4} \int d^4x e^{Et} \frac{j_1(|\vec{p}||\vec{x}|)}{|\vec{p}||\vec{x}|} \epsilon_{\mu\nu\alpha 0} x_\alpha \mathcal{H}_{\mu\nu}(\vec{x}, t)$$

$$\text{with } E = (M^2 + m_{A^0}^2)/(2M), |\vec{p}| = (M^2 - m_{A^0}^2)/(2M)$$



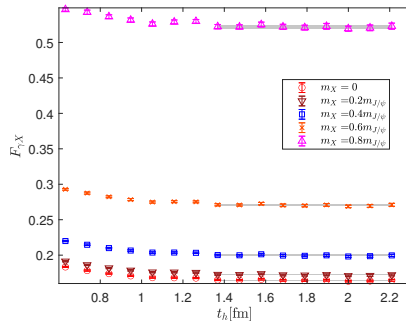
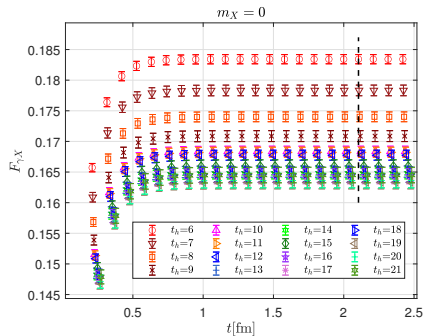
Method for:

$$\eta_c \rightarrow 2\gamma, J/\psi \rightarrow \gamma \eta_c, D_s^* \rightarrow D_s \gamma,$$

$$J/\psi \rightarrow D_{(s)} l \nu_l, \dots$$

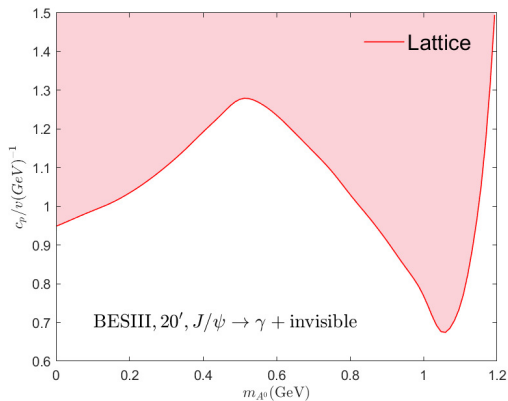
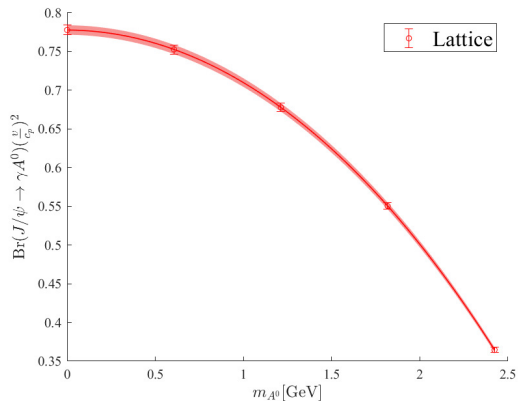
Form factor $F_{\gamma A^0}$

- A single ensemble with $a = 0.105$ fm and $m_\pi = 292$ MeV



- Note: $X = A^0/a$, $m_X = [0, 0.2, 0.4, 0.6, 0.8] * m_{J/\psi}$ for mass dependence study

Constraint on A^0 properties



- Assuming $A^0 \rightarrow \text{invisible}$.

YM, Chuan Liu, and Zhaofeng Liu, in progress.

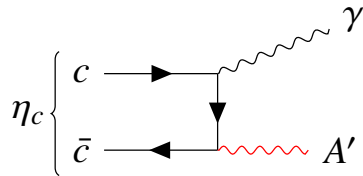
$$\eta_c \rightarrow \gamma A'$$

- Parameterization

$$\begin{aligned} H_{\mu\nu}(p, p') &= \int dt e^{Et} d^3\vec{x} e^{-i\vec{p}\cdot\vec{x}} \langle 0 | T \{ j'_\mu(x) j_\nu(0) \} | \eta_c(p') \rangle \\ &\equiv \epsilon_{\mu\nu\alpha\beta} p_\alpha p'_\beta F_{A'\gamma}(q^2) \end{aligned}$$

- Decay width

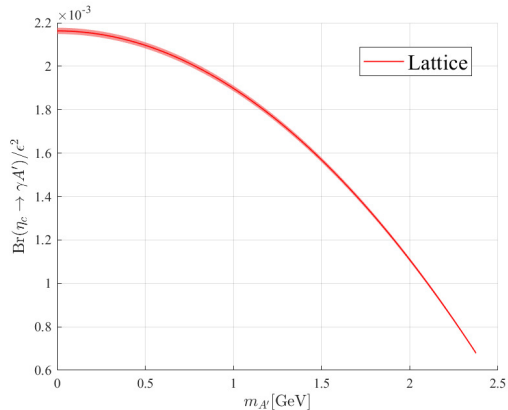
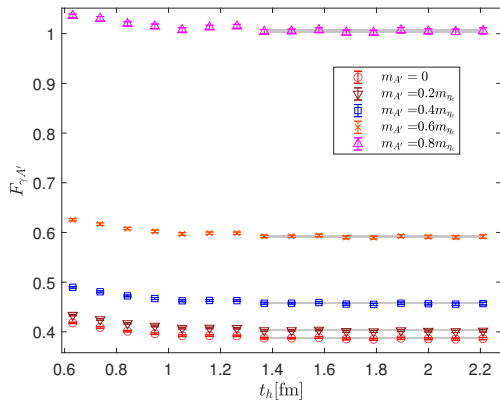
$$\Gamma(\eta_c \rightarrow A' \gamma) = \epsilon^2 \frac{64\pi}{81} \alpha_{\text{em}}^2 |\vec{p}|^3 F_{A'\gamma}^2(0)$$



- On-shell form factor

$$F_{A'\gamma}(q^2) = -\frac{1}{2M} \int d^4x e^{Et} \frac{j_1(|\vec{p}| |\vec{x}|)}{|\vec{p}| |\vec{x}|} \epsilon_{\mu\nu\alpha 0} x_\alpha \langle 0 | T \{ j'_\mu(x) j_\nu(0) \} | \eta_c(p') \rangle$$

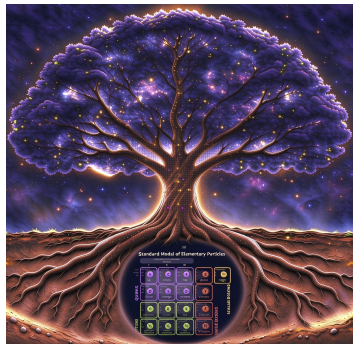
Form factor and branching fraction of $\eta_c \rightarrow \gamma A'$



- $m_{A'} = [0, 0.2, 0.4, 0.6, 0.8] * m_{\eta_c}$ for mass dependence study.
- Branching ratio upper limit $\text{Br}(\eta_c \rightarrow \gamma + \text{invisible})$ is needed to constrain ϵ and $m_{A'}$
- Extend to $\eta/\eta' \rightarrow \gamma A'$, vs HHaS experiment(expected) $\text{Br} = 10^{-8} \sim 10^{-9}$.

SM precision test TO new physical constraint

- Precision test
 - $D \rightarrow K^* l \nu$ at physical point
 - $D \rightarrow K l \nu$
- Dark matter constraint
 - $J/\psi \rightarrow \gamma \nu \bar{\nu}$
 - $J/\psi \rightarrow \gamma A^0/a, \eta_c \rightarrow \gamma A'$
 - Extrapolated to physical point
 - $\eta/\eta' \rightarrow \gamma A'$



Thank you!