Rare η and η' decays

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Based on:
R. Escribano, S. González-Solís, R. Jora and E. Royo, Phys.Rev.D 102 (2020) 3, 034026;
R. Escribano and E. Royo, arXiv: 2007.12467

See also: L. Gan, B. Kubis, E. Passemar and S. Tulin, arXiv:2007.00664

Introduction

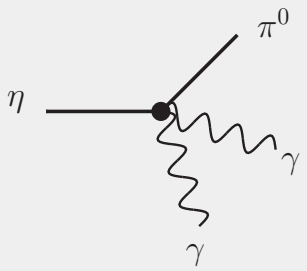
- η and η' decays offer **fantastic opportunities** to:
  - test low-energy QCD
  - search for New Physics beyond SM
- **High priority** $\eta^{(\prime)}$ decays for experiment and theory
  (L. Gan, B. Kubis, E. Passemar and S. Tulin, 2007.00664)

Decay channel	Standard Model	Discrete symmetries	BSM particles
$\eta^{(\prime)} \to \pi^+\pi^-\pi^0$	light quark masses	C/CP violation	scalar bosons
$\eta^{(\prime)} \to \gamma\gamma$	η-η' mixing, width	—	—
$\eta^{(\prime)} \to \ell^+\ell^-\gamma$	$(g-2)_\mu$	—	Z', dark photon
$\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$	higher-order χPT, scalar dynamics	—	$U(1)_B$ boson, scalar boson
$\eta^{(\prime)} \to \mu^+\mu^-$	$(g-2)_\mu$, precision tests	CP violation	—
$\eta^{(\prime)} \to \pi^0\ell^+\ell^-$	—	C violation	scalar bosons
$\eta^{(\prime)} \to \pi^+\pi^-\ell^+\ell^-$	$(g-2)_\mu$	—	ALP, dark photon
$\eta^{(\prime)} \to \pi^0\pi^0\ell^+\ell^-$	—	C violation	ALP

- **Important** experimental activities: A2, Belle-II, BESIII, KLOE-II, GlueX, WASA-at-COSY
- **Forthcoming** experiments: JLab Eta Factory (JEF) and REDTOP
  (see next talks by A. Mazzacane and L. Gan)

$\eta \to \pi^0\gamma\gamma$ DECAYS: THEORETICAL MOTIVATION

- **SM motivations**:
  - Tree level contributions at $\mathcal{O}(p^2)$ and $\mathcal{O}(p^4)$ vanish
  - First non-vanishing contribution comes from $\mathcal{O}(p^4)$ loops
  - First sizable contribution comes at $\mathcal{O}(p^6)$, but LEC's are not well known
  - To test ChPT and a wide range of chiral models, *e. g.* VMD and LσM



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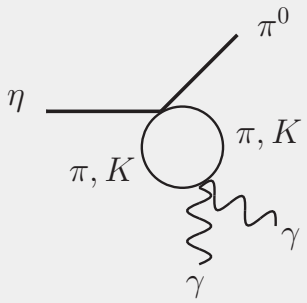
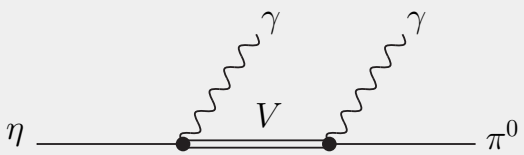
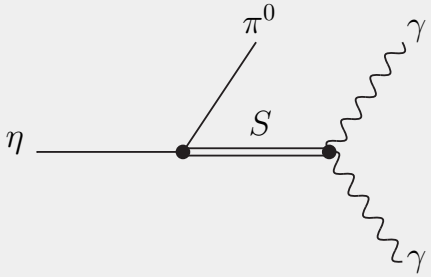


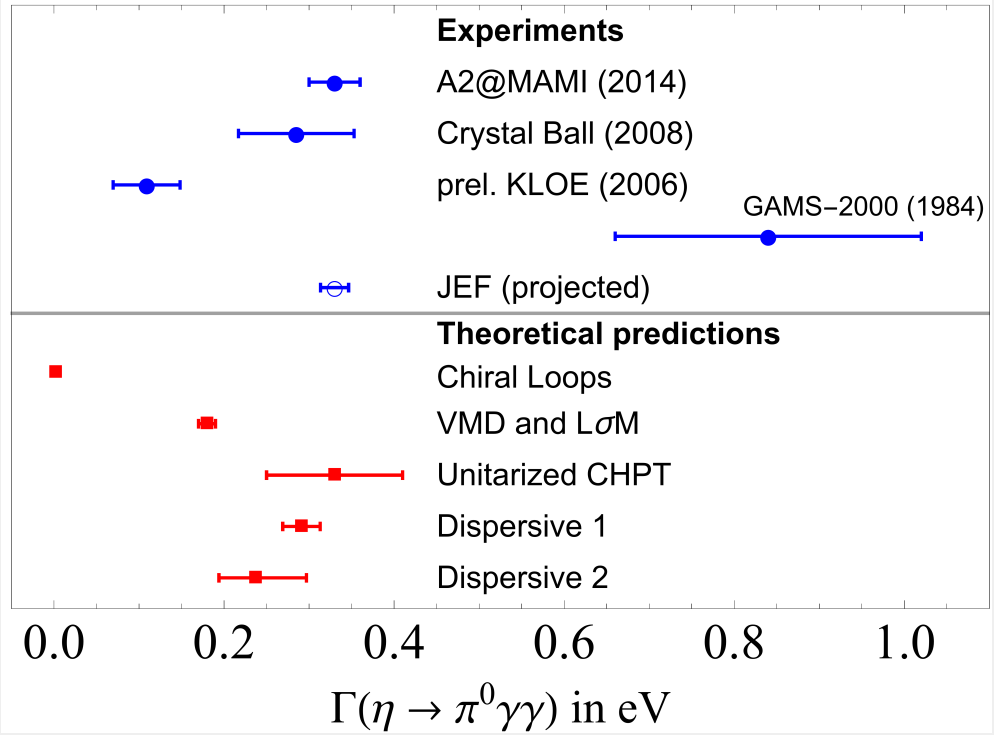




- **BSM motivation**: search for a B boson via $\eta \to \gamma B, B \to \gamma\pi^0$

$\eta \to \pi^0\gamma\gamma$ DECAYS: EXPERIMENTAL MOTIVATION

- KLOE-II final measurement is forthcoming
- JEF experiment:
  - BR and Dalitz distribution with $\sim 5\%$ precision
  - Improved understanding of the interplay of meson resonances
  - $\mathcal{O}(p^6)$ LEC's determination



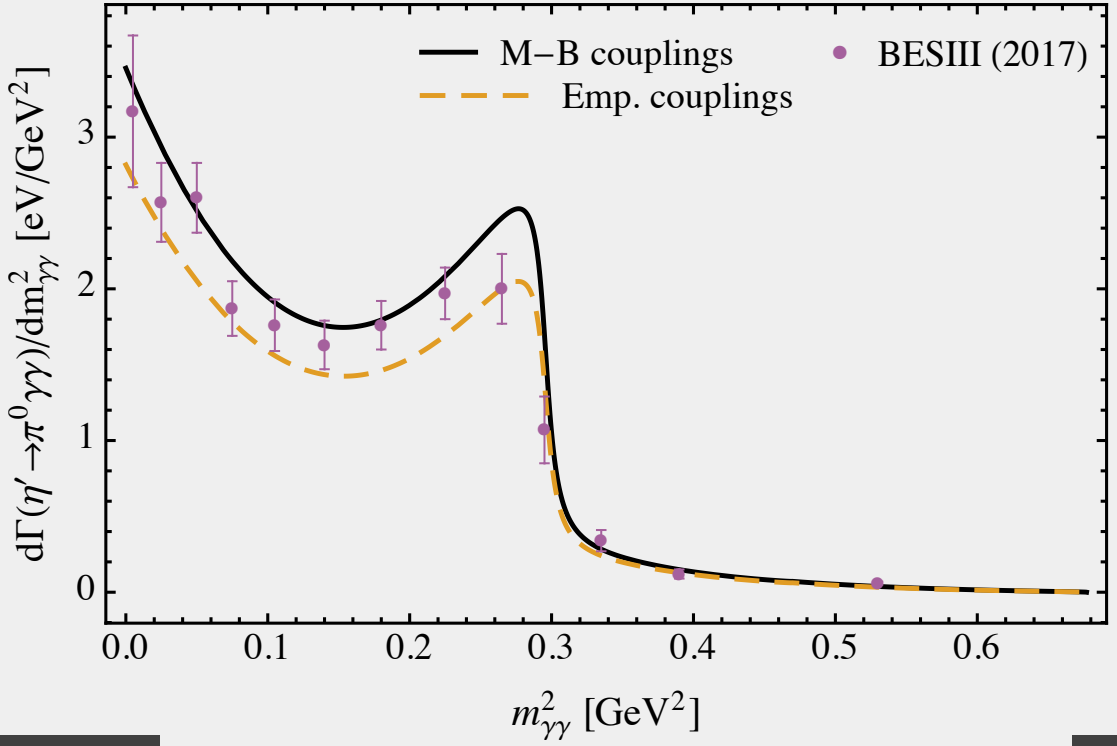
Chiral Loops: Ametller *et al.* Phys.Lett. B 276, 185 (1992); VMD and LσM: Escribano *et al.* Phys.Rev.D 102 (2020) 3, 034026;

Unitarized ChPT: Oset *et al.* Phys.Rev.D 77, 073001 (2008); Dispersive 1: Danilkin *et al.* Phys.Rev.D 96, 114018 (2017);

Dispersive 2: Lu and Moussallam, Eur.Phys.J.C 80, 436 (2020)

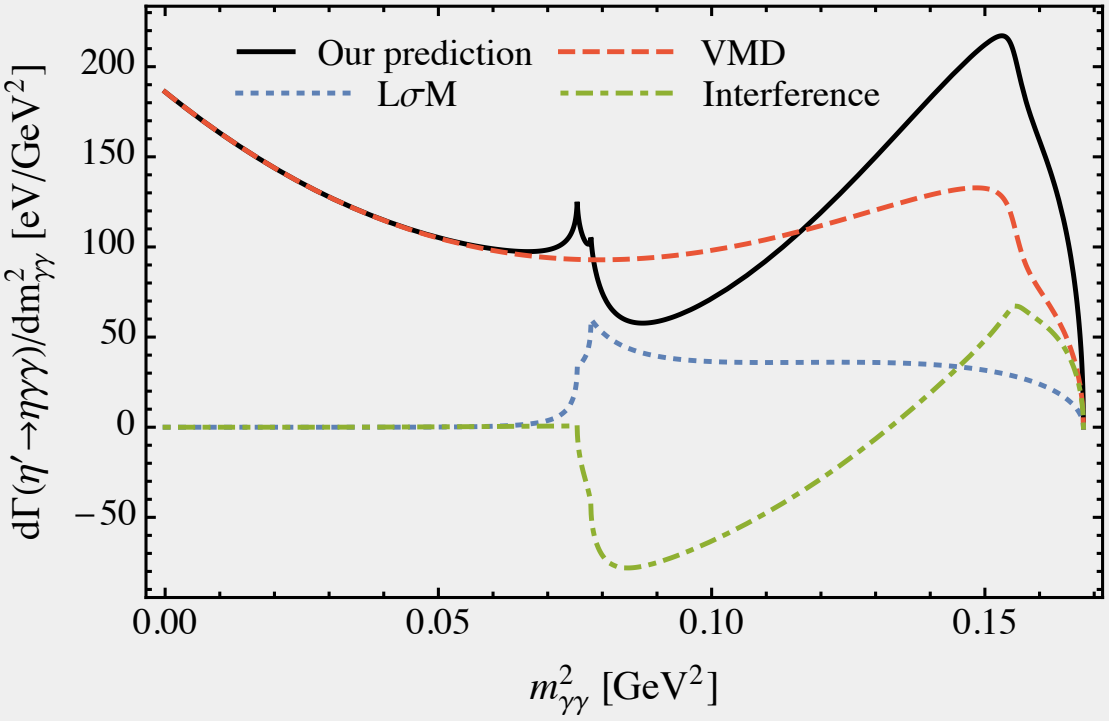
$\eta' \to \pi^0\gamma\gamma$ DECAYS

- First time $m_{\gamma\gamma}$ invariant mass distribution by the BESIII coll.; $BR = 3.20(7)(23) \times 10^{-3}$ (Ablikim *et al.* Phys.Rev.D 96, 012005 (2017))
- Our theoretical predictions $BR = [2.91(21), 3.57(25)] \times 10^{-3}$ (R. Escribano, S. G-S, R. Jora, E. Royo, Phys.Rev.D 102, 034026 (2020))
  - VMD completely dominates:
  - ω: 78% of the signal
  - ρ: 5% of the signal
  - ϕ: 0% of the signal
  - interference: 17%



$\eta' \to \eta\gamma\gamma$ DECAYS

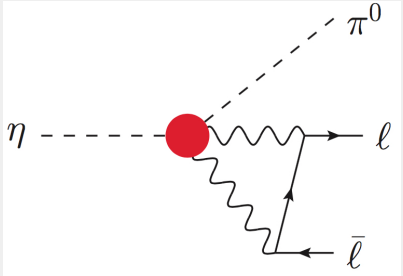
- 1st BR measurement by BESIII, $BR = 8.25(3.41)(0.72) \times 10^{-5}$ or $BR < 1.33 \times 10^{-4}$ at 90% C.L. (Ablikim *et al.* Phys.Rev.D 100, 052015 (2019))
- Our theoretical predictions $BR = [1.07(7), 1.17(8)] \times 10^{-4}$ (R. Escribano, S. G-S, R. Jora, E. Royo, Phys.Rev.D 102, 034026 (2020))
  - VMD predominates (91% of the signal)
  - Substantial scalar meson effects (16%)
  - Interference between scalar and vector mesons (7%)



- We look forward to the release of the $m_{\gamma\gamma}$ spectrum

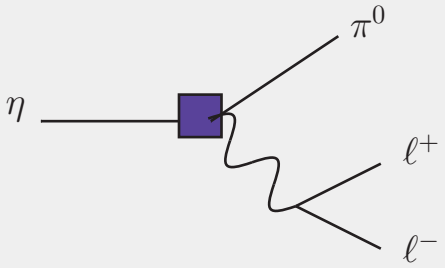
$\eta^{(\prime)} \to \{\pi^0, \eta\}\ell^+\ell^-$ DECAYS ($\ell = e, \mu$)

- In the SM:
  - $\eta \to \pi^0\gamma^* \to \pi^0\ell^+\ell^-$ forbidden by *C* and *CP*
  - $\eta \to \pi^0\ell^+\ell^-$ proceed via *C*-conserving two-photon intermediate state



Decay channel	$BR_{\rm th}$ (Escribano&Royo 2007.12467)	$BR_{\rm exp}$ (pdg)
$\eta \to \pi^0 e^+e^-$	$2.1(1)(2) \times 10^{-9}$	$< 7.5 \times 10^{-6}$ (CL=90%)
$\eta \to \pi^0 \mu^+\mu^-$	$1.2(1)(1) \times 10^{-9}$	$< 5 \times 10^{-6}$ (CL=90%)
$\eta' \to \pi^0 e^+e^-$	$4.6(3)(7) \times 10^{-9}$	$< 1.4 \times 10^{-3}$ (CL=90%)
$\eta' \to \pi^0 \mu^+\mu^-$	$1.8(1)(2) \times 10^{-9}$	$< 6.0 \times 10^{-5}$ (CL=90%)
$\eta' \to \eta e^+e^-$	$3.9(3)(4) \times 10^{-10}$	$< 2.4 \times 10^{-3}$ (CL=90%)
$\eta' \to \eta \mu^+\mu^-$	$1.6(1)(2) \times 10^{-10}$	$< 1.5 \times 10^{-5}$ (CL=90%)

- Background for BSM searches, *e.g.* *C*-violating virtual photon exchange or new scalar mediators
- REDTOP can improve the experimental state



Other interesting η and η' decays

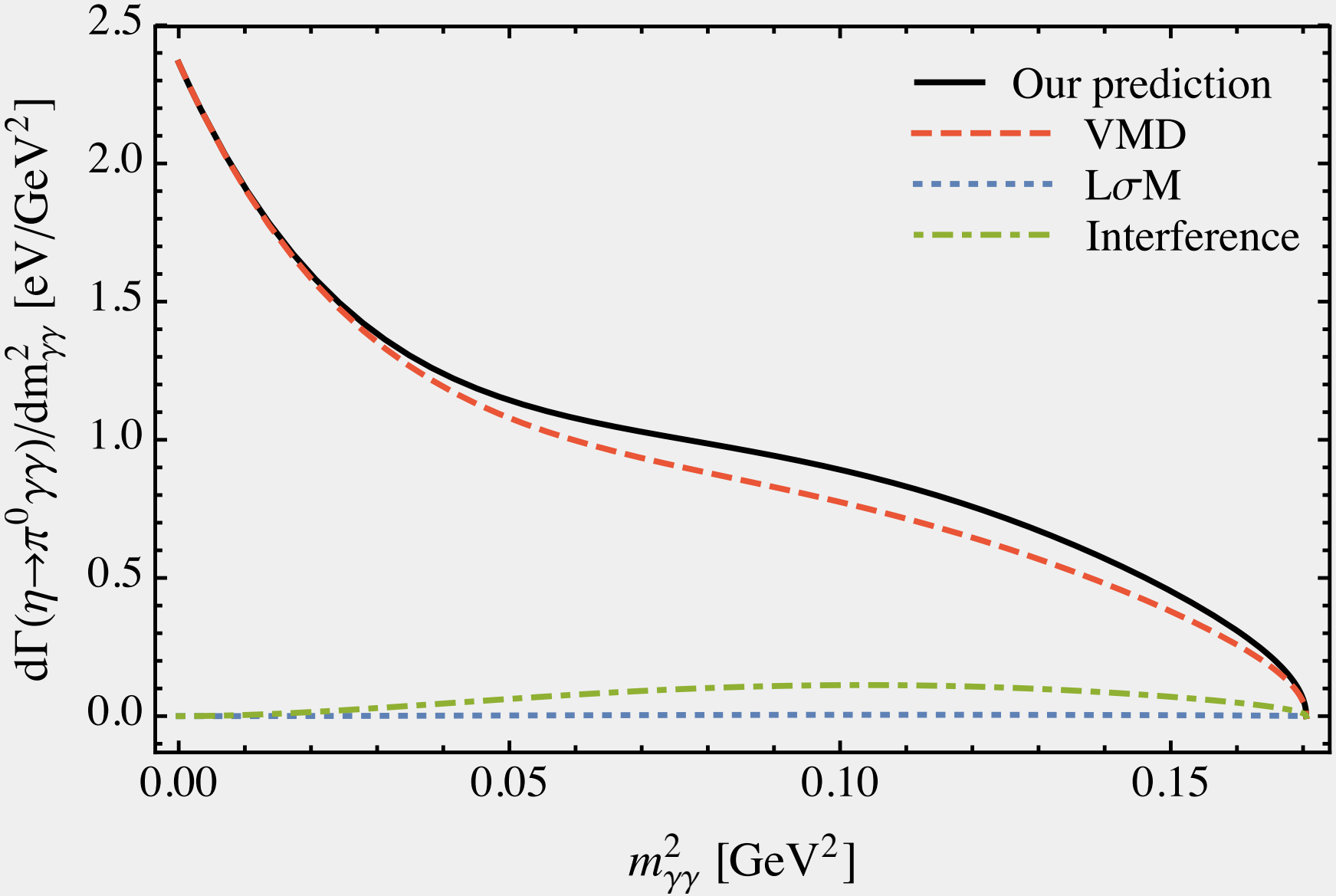
- Standard Model decays:
  - $\eta \to 3\pi$: Dalitz plot measurements with improved precision (GlueX, REDTOP) $\Rightarrow$ more precise extraction of Q
  - $\eta' \to 3\pi$: theoretical advances $\Rightarrow$ extraction of Q also possible
  - $\eta^{(\prime)} \to \pi^+\pi^-\ell^+\ell^-$: detailed differential information $\Rightarrow$ access to the doubly-virtual transition form factors $\Rightarrow (g-2)_\mu$
- Discrete symmetry tests:
  - $\eta \to \mu^+\mu^-$: high-precision experimental test (REDTOP) can probe *CP* violation
  - $\eta^{(\prime)} \to \pi\pi$: improved experimental bounds are welcome
  - $\eta^{(\prime)} \to \pi^0\pi^0\ell^+\ell^-$: test of *C*-violation
- New light BSM particles:
  - dark photon appears as a resonance in $\eta^{(\prime)} \to \ell^+\ell^-\gamma$ (REDTOP)
  - Axion-like particles searches in $\eta^{(\prime)}$ decays, *e.g.* $\eta^{(\prime)} \to 2\pi a$

Outlook

- η-η' physics is a very **rich field** to:
  - **test low-energy QCD**: higher-order ChPT, precision tests, light-quark masses, scalar dynamics, $(g-2)_\mu$, η-η' mixing
  - **look for discrete symmetry violations**: C and CP violation
  - **search for New Physics BSM**: scalar bosons, Z', dark photon, Axion-like particles, $U(1)_B$ boson
- **Important experimental activities**: A2, Belle-II, BESIII, KLOE-II, GlueX, WASA
- The contribution of **new experiments** to $\eta^{(\prime)}$ physics, *e.g.* JEF and REDTOP, will be very welcome
- A lot of **interesting physics** to be done in the η-η' sector

$\eta \to \pi^0\gamma\gamma$ DECAYS

R. Escribano, S. Gonzàlez-Solís, R. Jora, E. Royo; Phys.Rev.D 102 (2020) 3, 034026; arXiv:1812.08454



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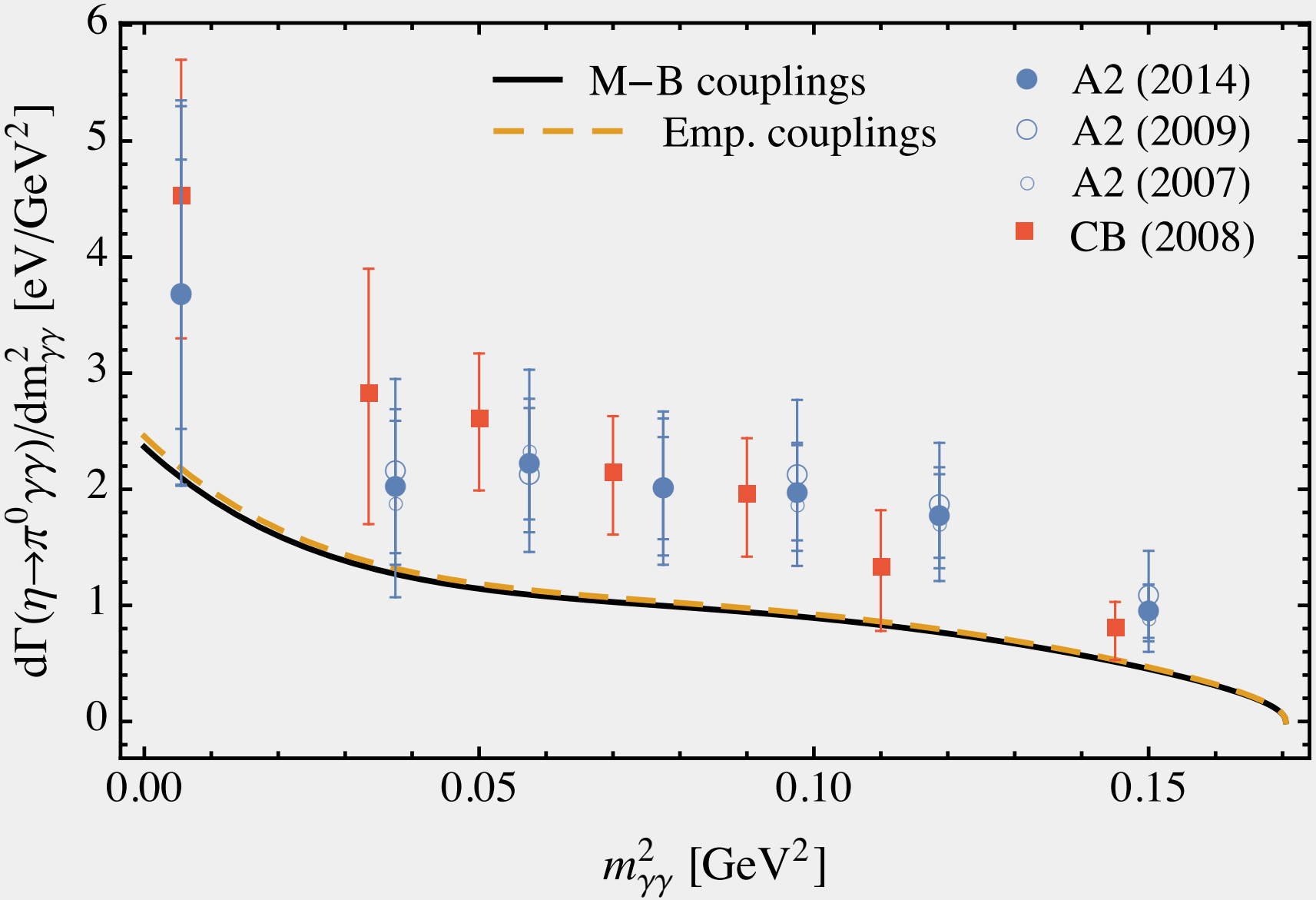
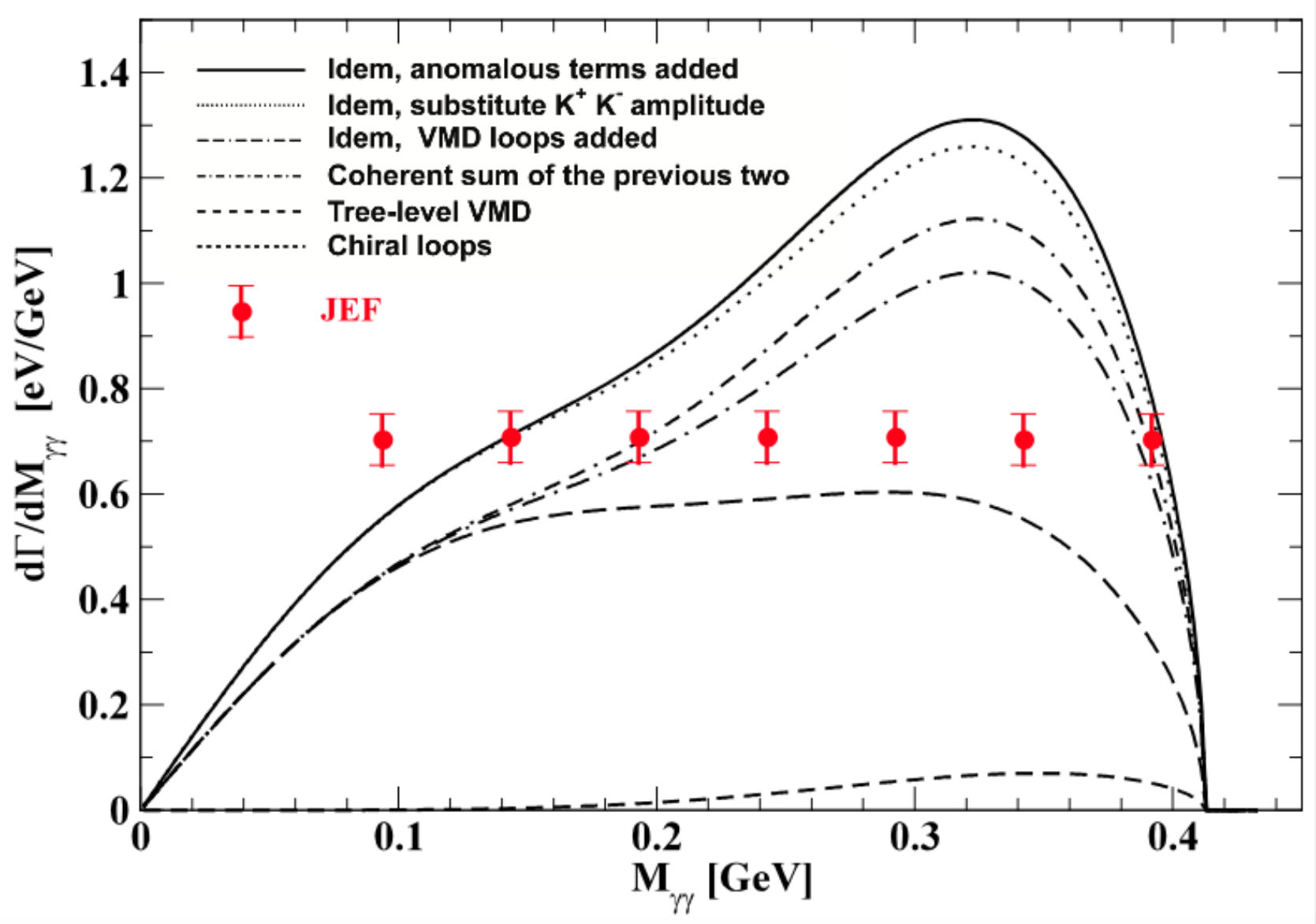
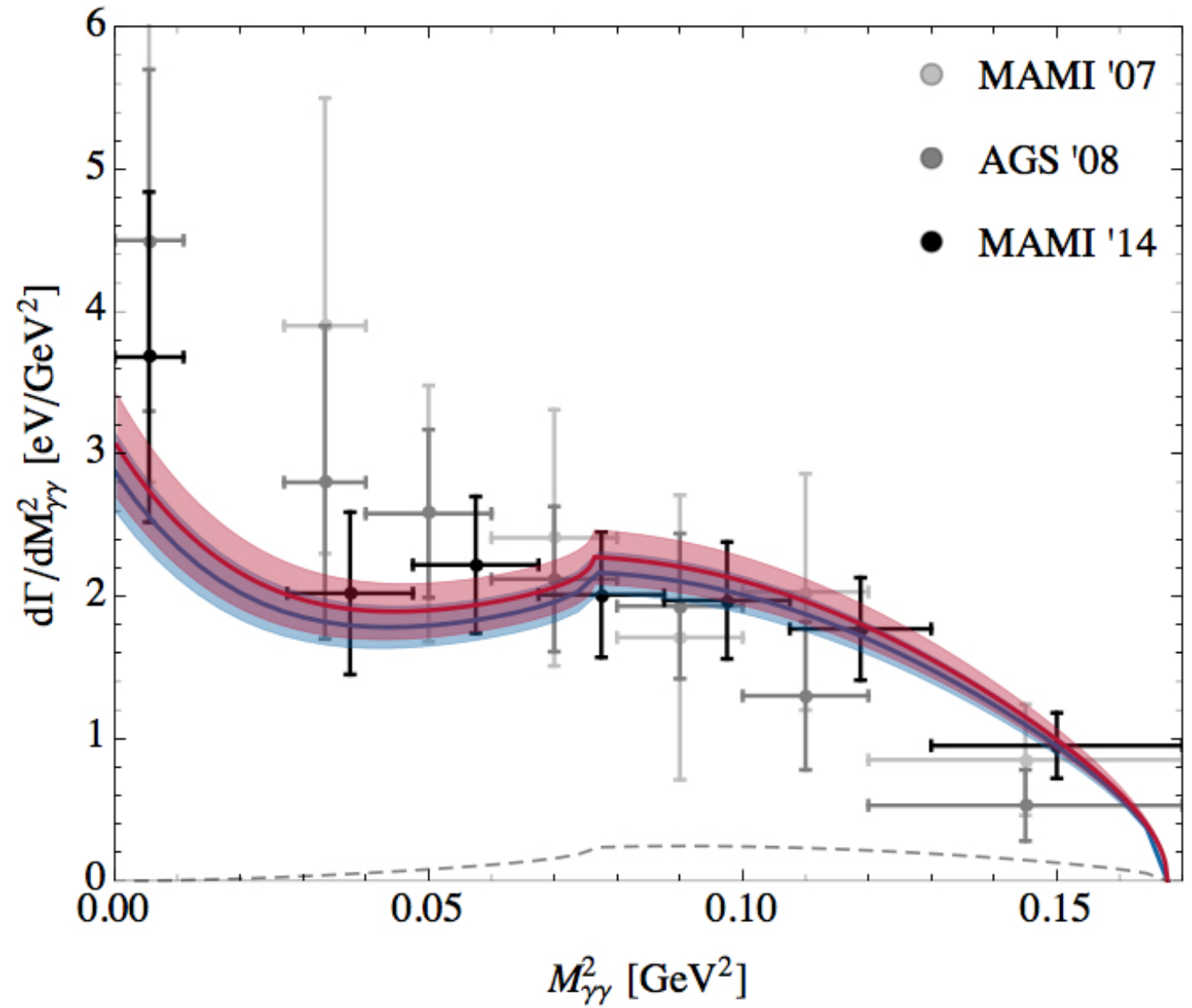


$\eta \to \pi^0 \gamma\gamma$ DECAYS



$\eta \to \pi^0\gamma\gamma$ DECAYS

Danilkin *et al.* Phys.Rev.D 96, 114018 (2017)



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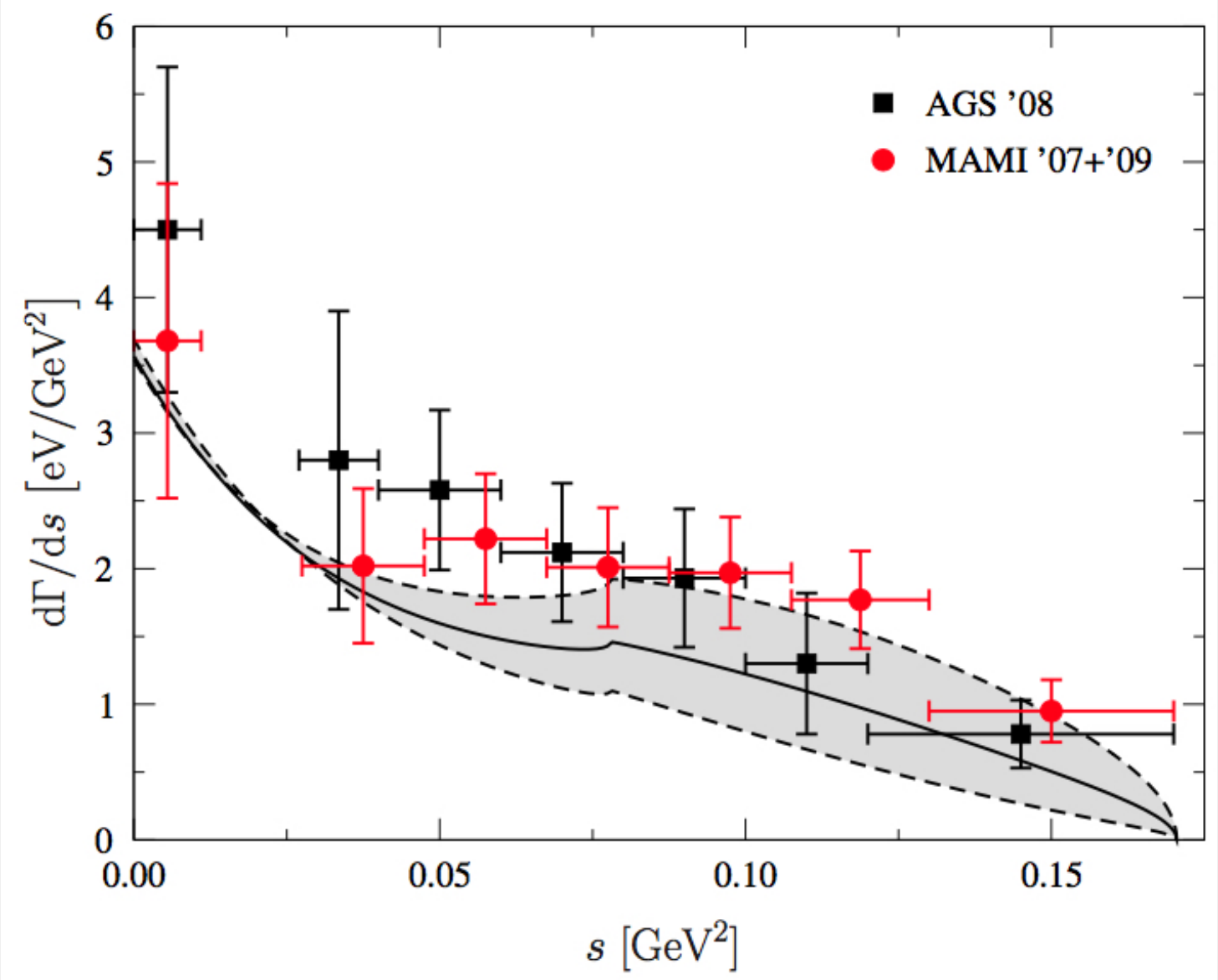
Lu and Moussallam, Eur.Phys.J.C 80, 436 (2020)



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