中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

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# Search for dark matter in the events with missing transverse momentum in colliders

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IHEP,CAS

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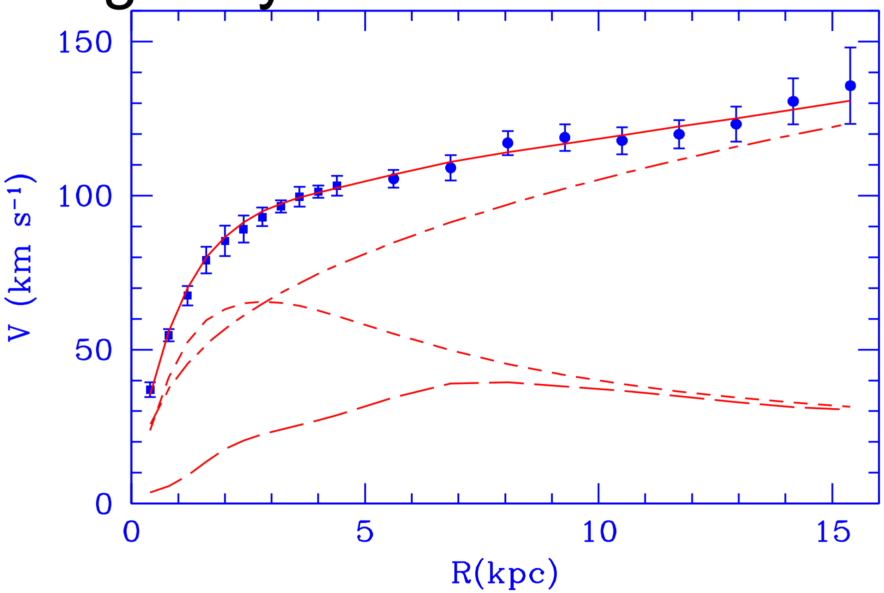
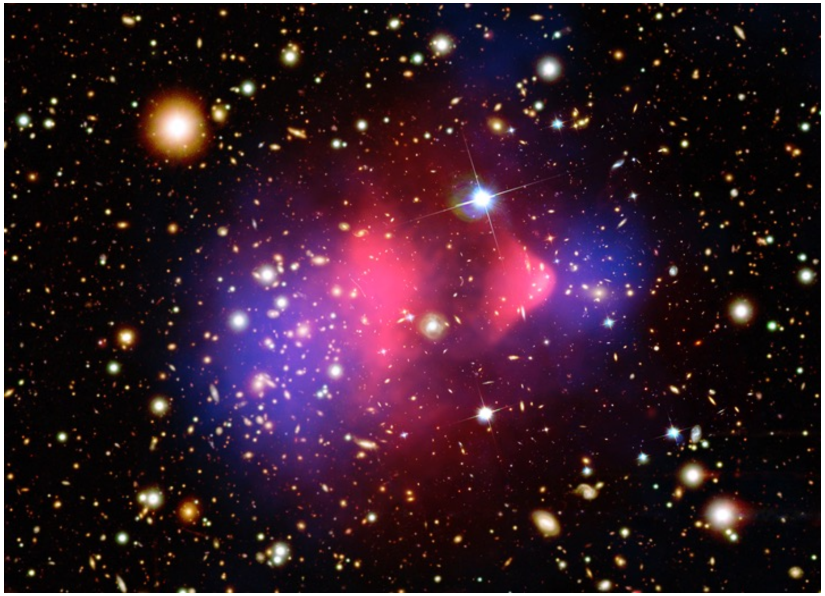
# Introduction

- Many astrophysical observations provide clear evidence for the existence of dark matter, such as rotation curve and galaxy cluster.




Rotation Curve of M33.

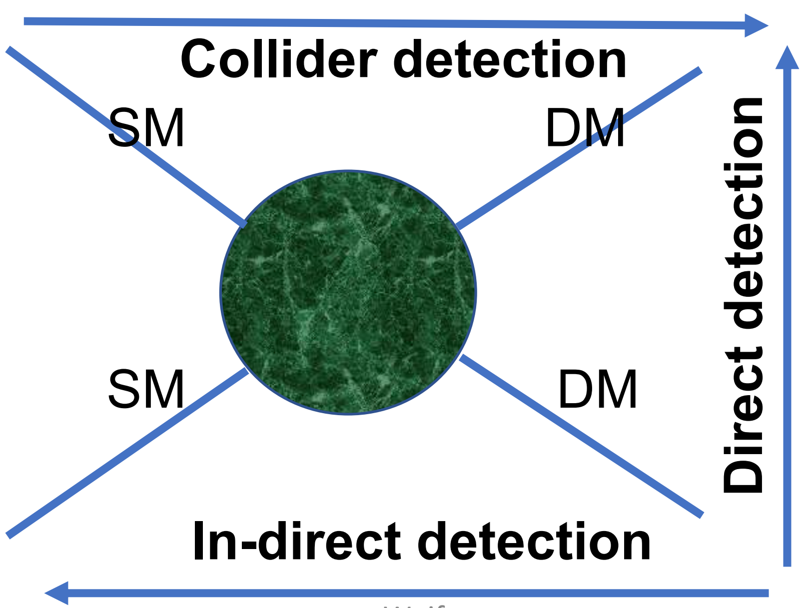


The galaxy cluster 1E 0657-56

- The dark matter accounts for 26.4% in the universe. PDG
- It is important to search for DM in particle physics experiment.

# Introduction

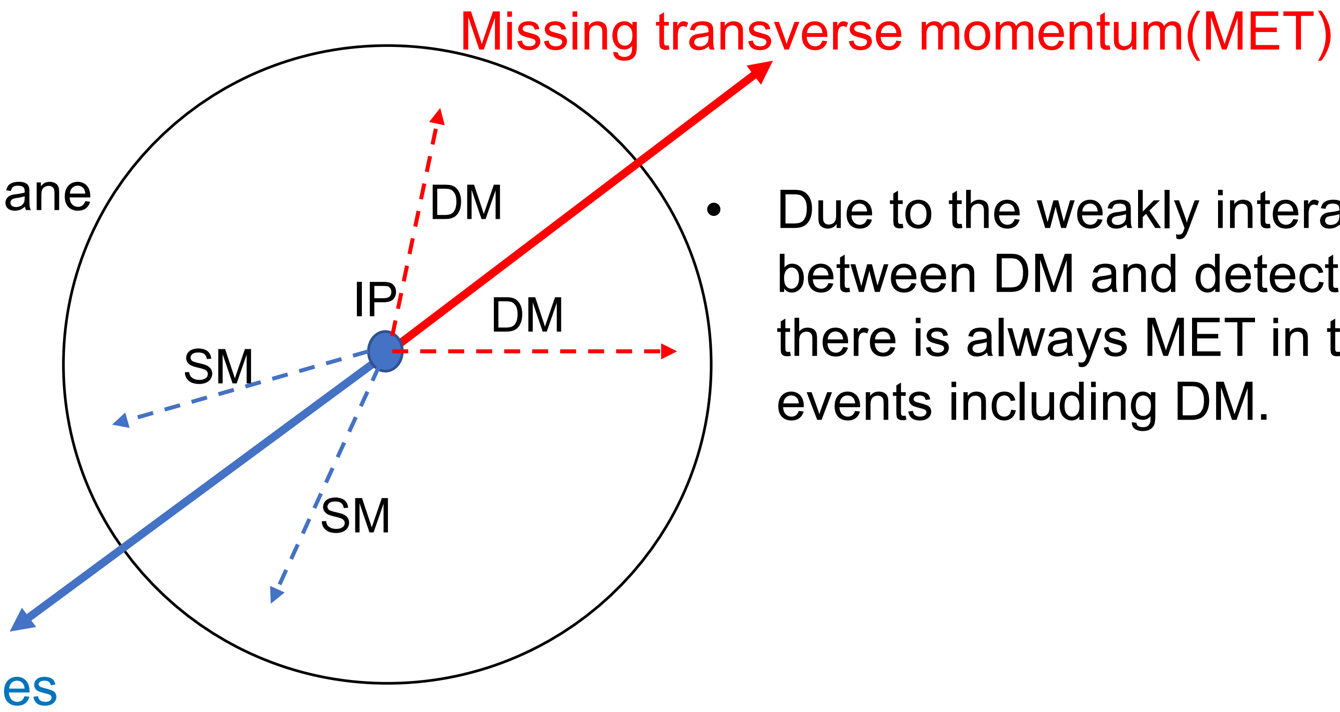
- There are 3 ways to detect the dark matter according to the different interactions between SM and DM.
  - **Direct detection**: Use the scatter between SM and DM.
  - **Indirect detection**: DM can decay or annihilate into SM particles. The decay/ annihilate products can be used to detect DM.
  - **Collider detection**: DM is produced in SM particle collisions.



# Introduction

- The collider detection has signature as MET + X(SM particles).

Transverse plane of detector.

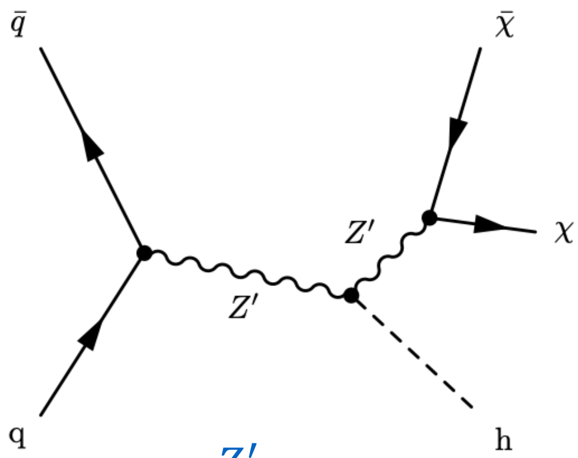



- Due to the weakly interaction between DM and detector, there is always MET in the events including DM.

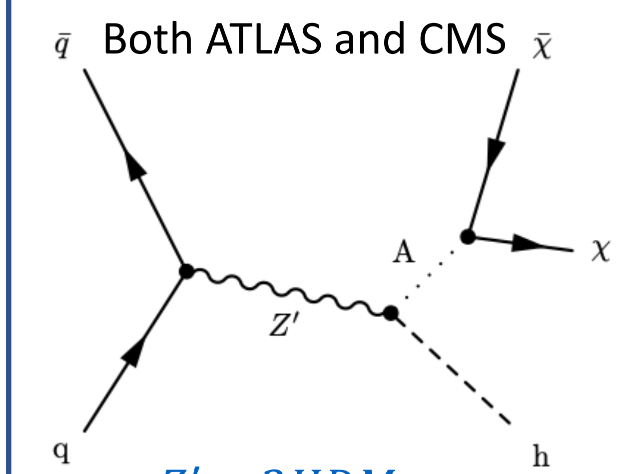
- The studies have been performed in many experiments, including ATLAS, CMS, BELLE II and BESIII etc.
- I will show some results(selected) in the following slides.

# $pp \to h(\gamma\gamma) + E_T^{miss}$ in LHC

- The $Z'_B$ and $Z'2HDM$ model are used in these studies. JHEP10(2021)013 JHEP10(2017)180




$Z'_B$




$Z' - 2HDM$

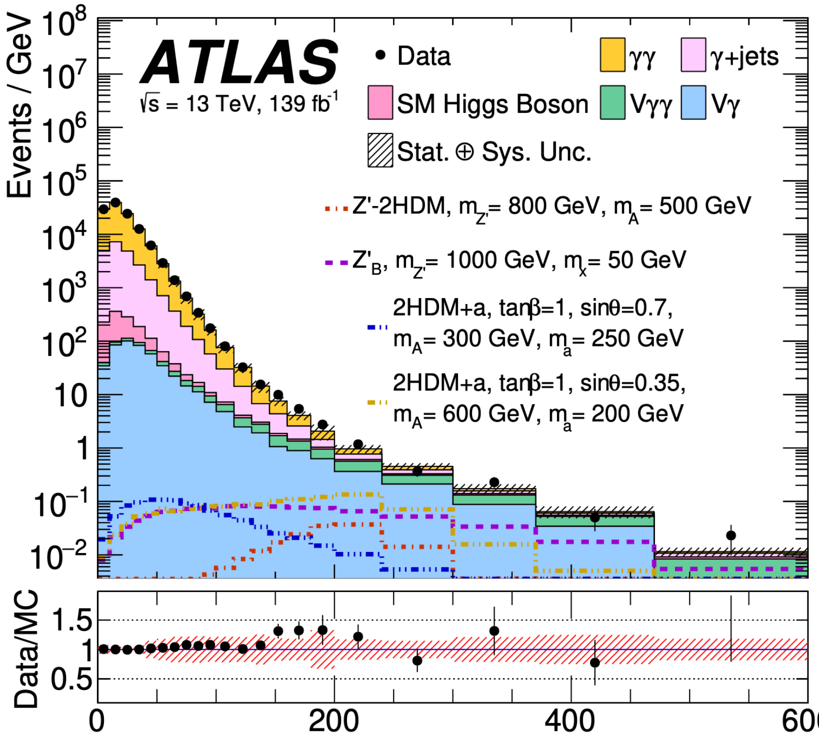
- $m_{Z'}$, the $Z'$ boson mass;
- $g_\chi$, the coupling of the $Z'$ boson to the DM particle $\chi$;
- $g_q$, the coupling of the $Z'$ boson to quarks;
- $g_{hZ'Z'}$, the coupling between the $Z'$ boson and the observed Higgs boson $h$;
- $\sin\theta$, the mixing angle between the baryonic Higgs boson and the observed Higgs boson; and
- $m_\chi$, the mass of the fermionic dark-matter candidate $\chi$.

- $m_A$, the pseudoscalar boson mass;
- $m_{Z'}$, the $Z'$ boson mass;
- $m_\chi$, the mass of the fermionic dark-matter candidate $\chi$;
- $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets;
- $g_{Z'}$ the coupling strength of the $Z'$ boson to quarks; and
- $\alpha$, the mixing angle between the two neutral scalars in the 2HDM model.

# $pp \to h(\gamma\gamma) + E_T^{miss}$ in LHC

➢ Analysis strategy(ATLAS):

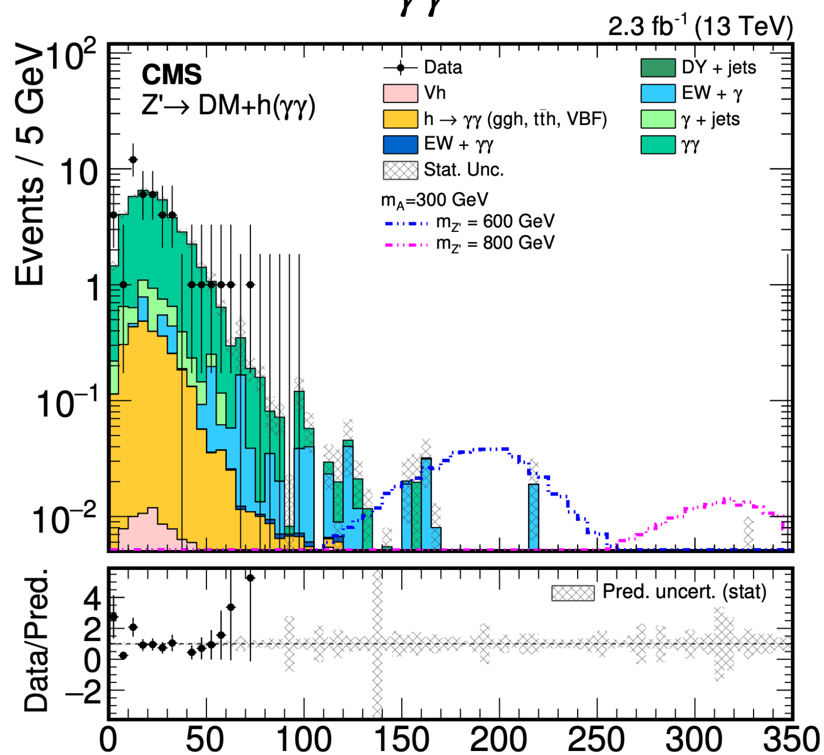
- $E_\gamma / m_{\gamma\gamma} > 0.35/0.25$,
- $E_T^{miss} > 90$ GeV,
- $\Delta E_T^{miss} < 30$ GeV,
- $105 < m_{\gamma\gamma} < 160$ GeV




[JHEP10(2021)013](JHEP10(2021)013)

➢ Analysis strategy(CMS):

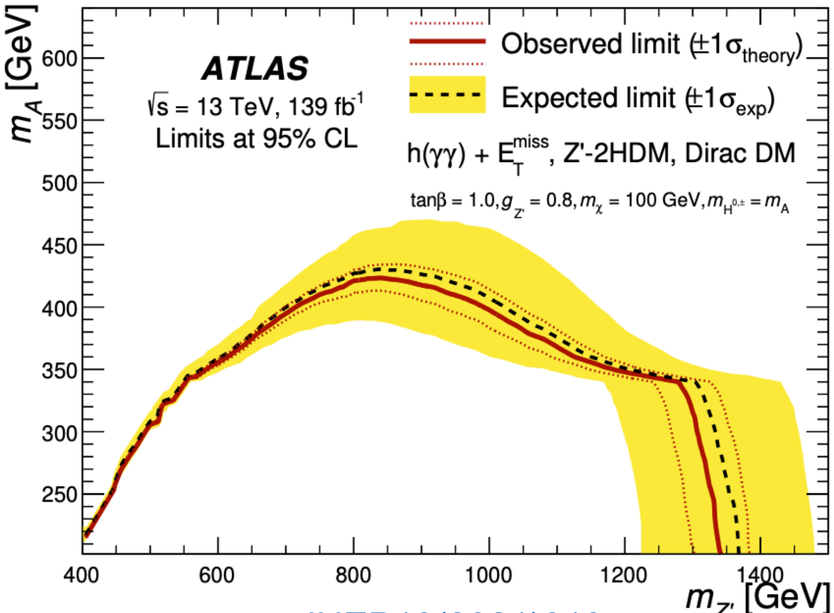
- $p_T / m_{\gamma\gamma} > 0.5/0.25$,
- $E_T^{miss} > 105$ GeV,
- $p_{T\gamma\gamma} > 90$ GeV,
- $105 < m_{\gamma\gamma} < 180$ GeV




JHEP10(2017)180

# $pp \to h(\gamma\gamma) + E_T^{miss}$ in LHC

➢ The 95% C.L. upper limits on the signal strength in the $m_{Z'}$ VS $m_A$ plane are shown as below.

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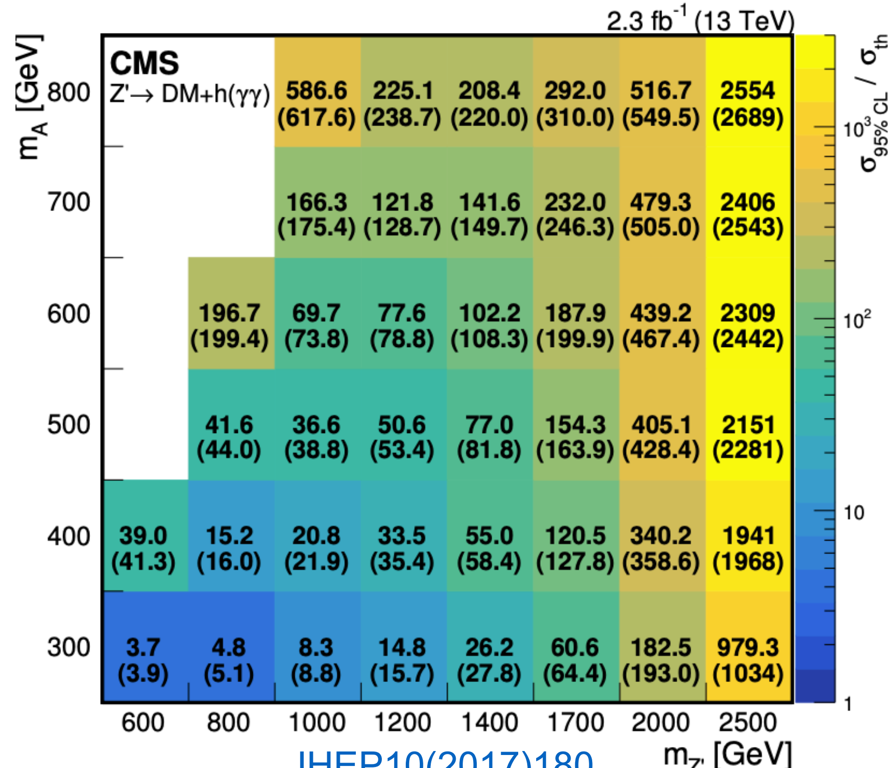


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- The maximum limit on $m_A$ reaches 420 GeV, when the limit on $m_{Z'}$ mass is 825 GeV.
- The exclusion power is not too high due to the low statistics.

# $pp \to h(\gamma\gamma) + E_T^{miss}$ in LHC

➢ The upper limit on the spin-independent cross section of ATLAS result is shown.

$$\sigma_{N\chi}^{SI} = \frac{\mu_{N\chi}^2}{\pi A^2}[Zf_p + (A-Z)f_n]^2$$

- $\mu_{N\chi}$ : reduced mass of DM-nucleon system.
- Z/A : number of protons/nucleons in the considered nucleus.
- $f_p$ / $f_n$ : couplings between DM and protons/neutrons.

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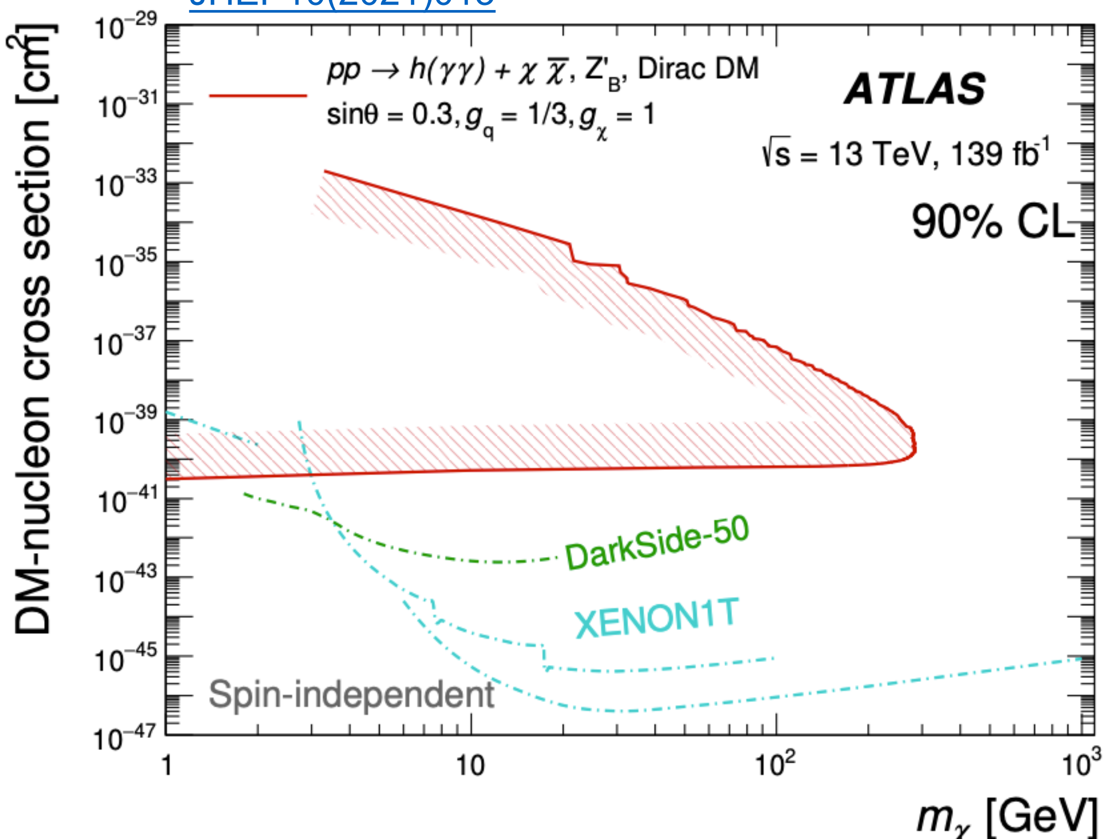
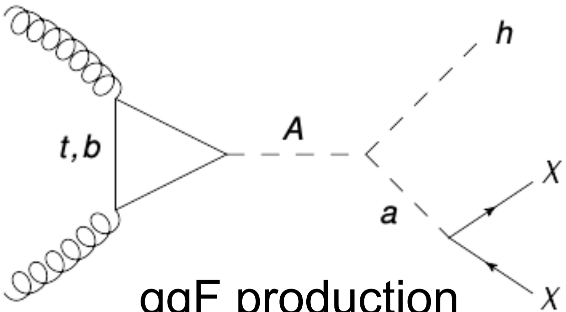



➢ The upper limit on the spin-independent cross section for $m_\chi$ < 2 GeV decreases by a factor of two.

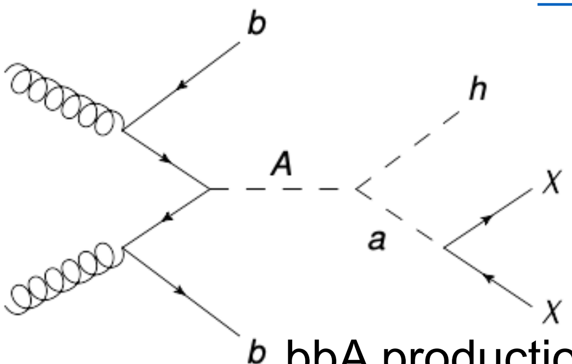
# $pp \rightarrow h(b\bar{b}) + E_T^{miss}$ in LHC

- The study is performed with 2HDM+a model. EPJC 79, 280 (2019) JHEP11(2021)209

Both ATLAS and CMS




ggF production

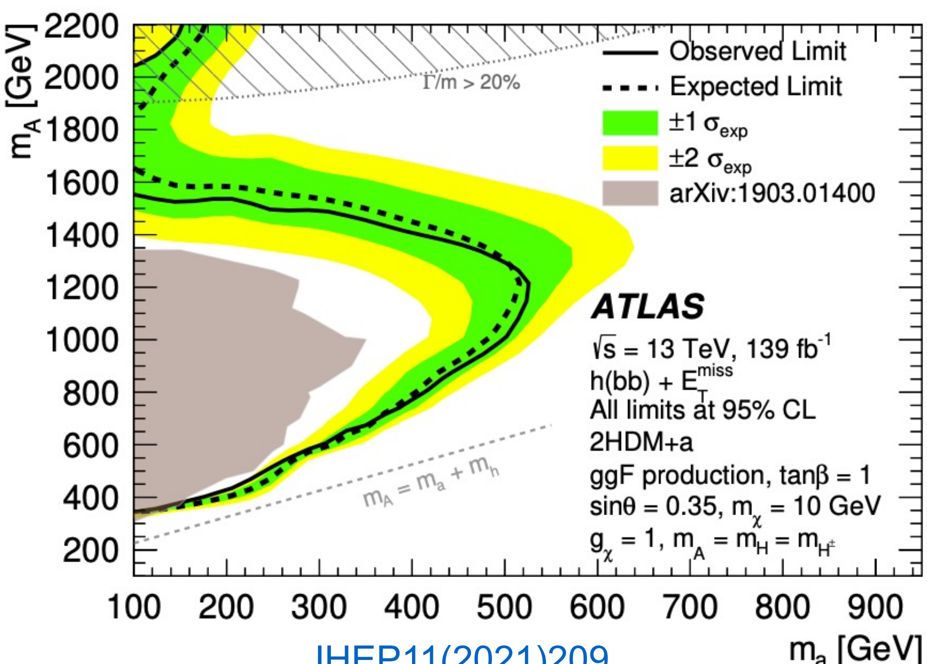



bbA production

- 2HDM+a model : the extension of 2HDM model with a simplified pseudoscalar mediator.
  - The pseudoscalar mediator $a$ couples to SM fermions and DM particles $\chi$.
  - $tan\beta$ is the ratio of vacuum expectation values of the two Higgs doublets.
    - Low $tan\beta$ ~ ggF production, high $tan\beta$ ~ bbA production.

# $pp \to h(b\bar{b}) + E_T^{miss}$ in LHC

- The 95% C.L. upper limits in the $m_A$ VS $m_a$ plane are shown as below.

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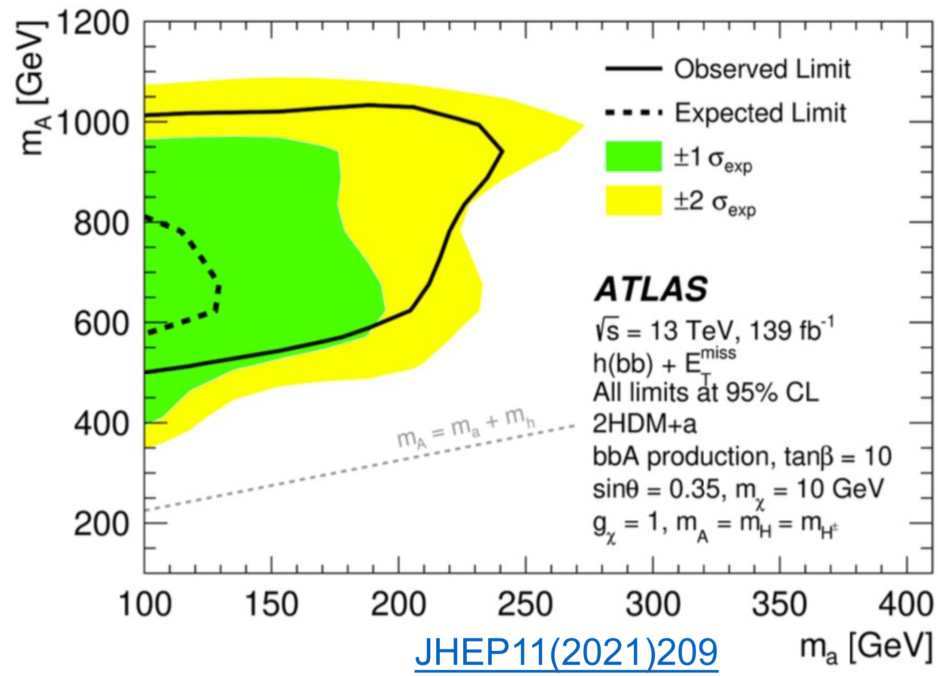


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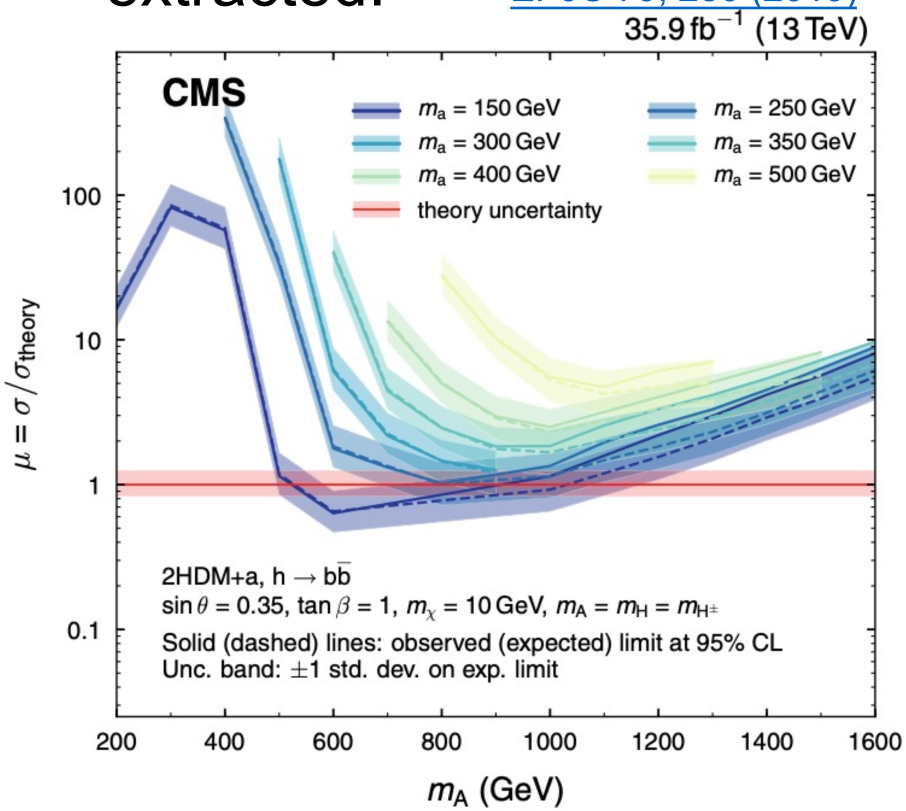
- The exclusion boundaries extend up to $m_a$ = 520 GeV for $m_A$ = 1.25 TeV in ggF production case.

- The exclusion limits extend up to $m_a$ = 240 GeV for $m_A$ = 900 GeV in bbA production case.

# $pp \to h(b\bar{b}) + E_T^{miss}$ in LHC

- The 95% C.L. upper limits on the signal strength are extracted.

EPJC 79, 280 (2019)

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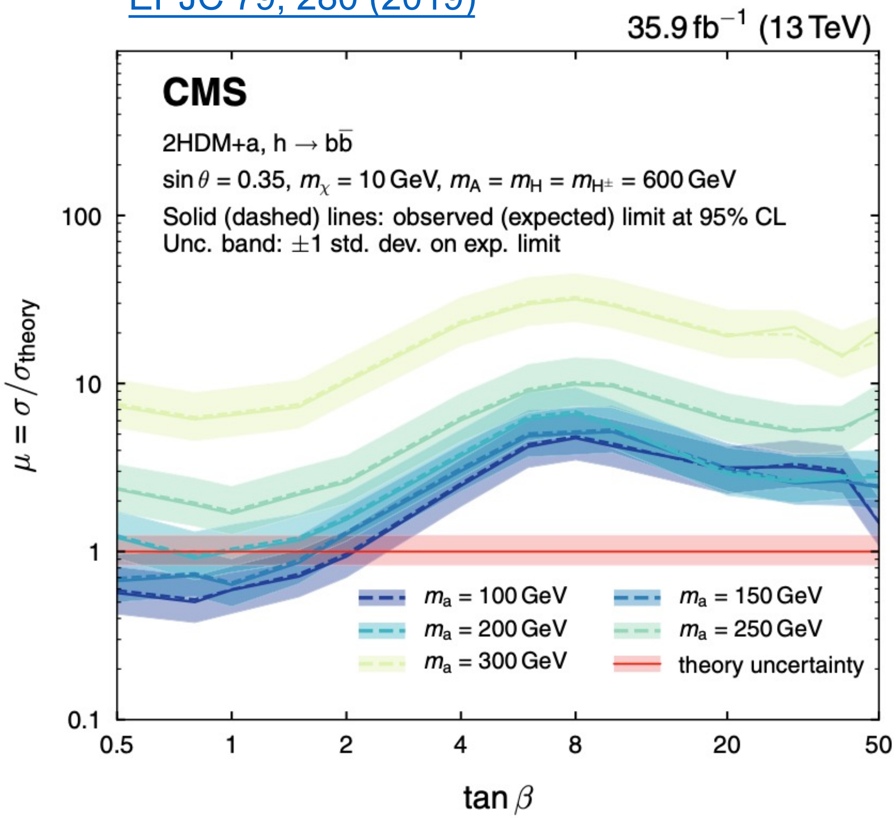



- $m_A$ masses are excluded between 500 and 900 GeV for the configuration in figure.

- No significant excess is observed.
- $tan\beta$ between 0.5 and 2.0 is excluded for $m_a$ = 100 GeV.

# $e^+e^- \to \mu^+\mu^- + invisible$ in Belle II

- The decay process is $e^+e^- \to \mu^+\mu^- Z', Z' \to \chi\bar{\chi}$ .
  - Vector boson, $Z'$, only couples to SM $\mu$, $\tau$, $\nu_\mu$ and $\nu_\tau$.
  - $Z'$ can decay to dark matter particles $\chi\bar{\chi}$.
  - $g'$ : coupling between $Z'$ and SM $\mu$, $\tau$, $\nu_\mu$ and $\nu_\tau$.
  - $g'_D$ : coupling between $Z'$ and $\chi$.

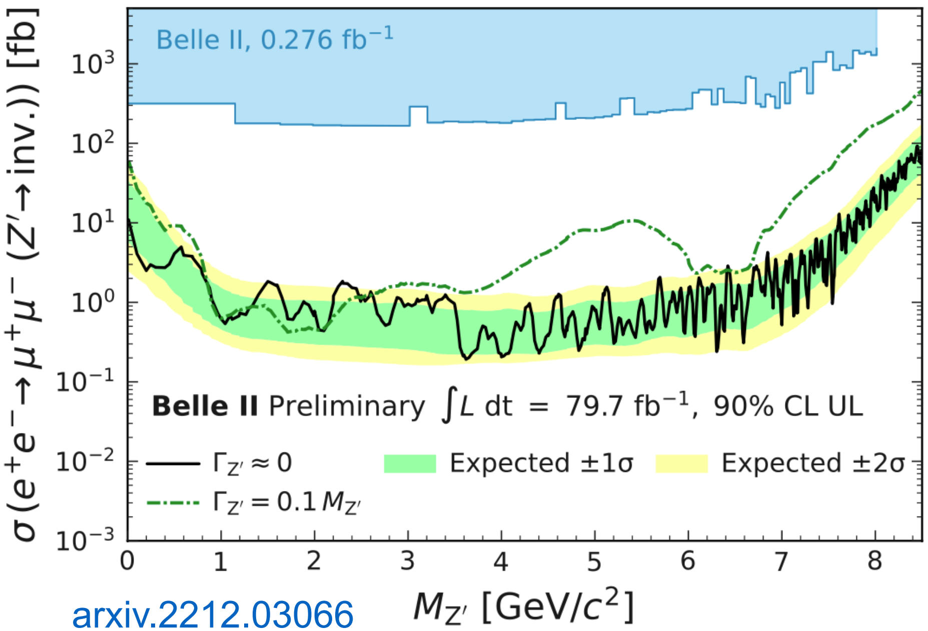
- The dominant background :
  - $e^+e^- \to \mu^+\mu^- + \gamma$ , photon is not detected.
  - $e^+e^- \to \tau^+\tau^- + \gamma$, $\tau$ decays to muon and neutrinos.
  - $e^+e^- \to e^+e^-\mu^+\mu^-$, electrons outside the detector.

- An artificial neural network is employed to select the event candidates.
  - Four kinematic variables are used.

arxiv.2212.03066 PhysRevD.89.113004

# $e^+e^- \to \mu^+\mu^- + invisible$ in Belle II

- The 90% C.L. upper limits on the $\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to invisible)$ and $g'$ are shown as below.

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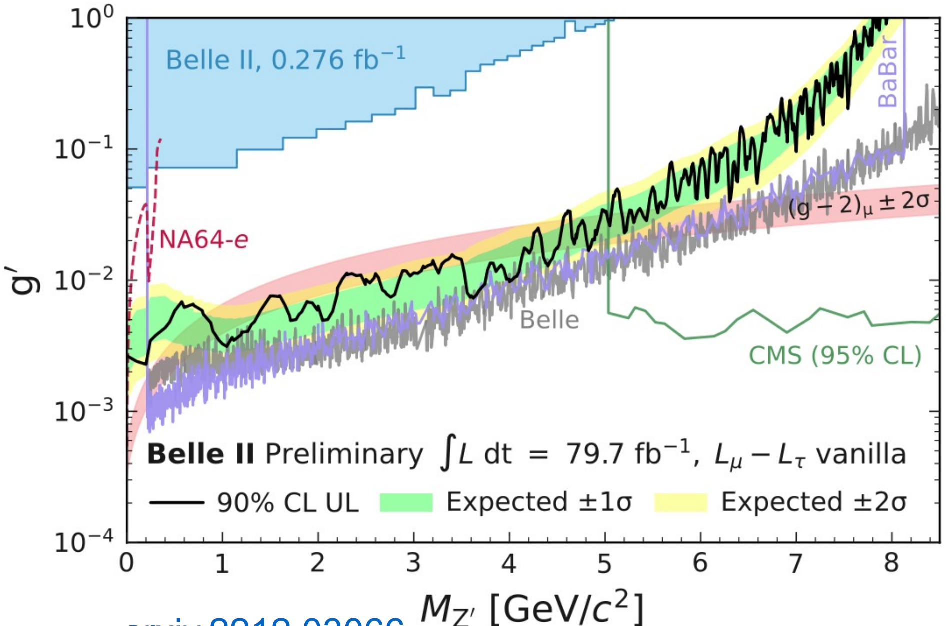



arxiv.2212.03066

- The upper limit of $\sigma$ is set as small as 0.2 fb .
- No significant excess is observed.

- The invisible $Z'$ boson as an explanation of $(g-2)_\mu$ anomaly is excluded in $0.8 < M_{Z'} < 5.0$ GeV.

# $e^+e^- \to \gamma + invisible$ in BaBar and BESIII

- Search for dark photon in BaBar and BESIII.
  - A $U(1)_D$ gauge boson $\gamma'$(dark photon) is introduced, which mediate a new force between dark sector and SM.
  - The $\gamma'$ can mix with SM photon kinetically, and $\epsilon$ is the mixing strength.
  - $\epsilon \sim 10^{-3}$ when the mass of $\gamma'$ is in the GeV range.

- The decay process to search.
  - $e^+e^- \to \gamma\gamma', \gamma' \to invisible$.

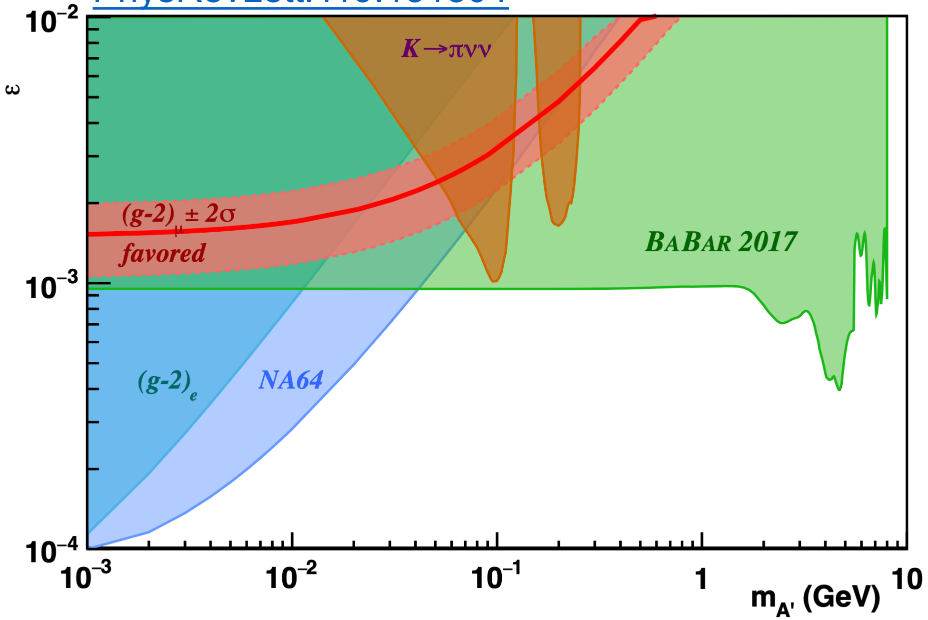
- The dominant background:
  - $e^+e^- \to \gamma\gamma, \gamma\gamma\gamma$ : some photons are not detected.

PhysRevLett.119.131804 Arxiv.2209.13893

# $e^+e^- \to \gamma + E_T^{miss}$ in BaBar and BESIII

- 90% C.L. upper limit on the $\epsilon$ is shown as below.

PhysRevLett.119.131804

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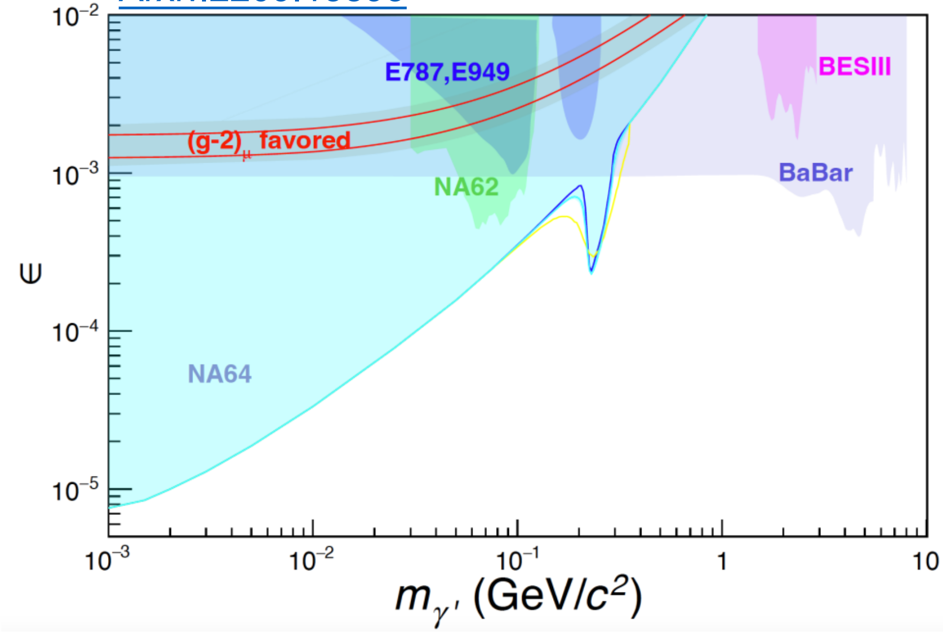



- The BaBar result rules out the dark-photon coupling as the explanation for the $(g-2)_\mu$ anomaly.
- The BESIII results is higher than BaBar results.
- The BESIII exclusion limits are below the $(g-2)_\mu$ anomaly.

# Summary

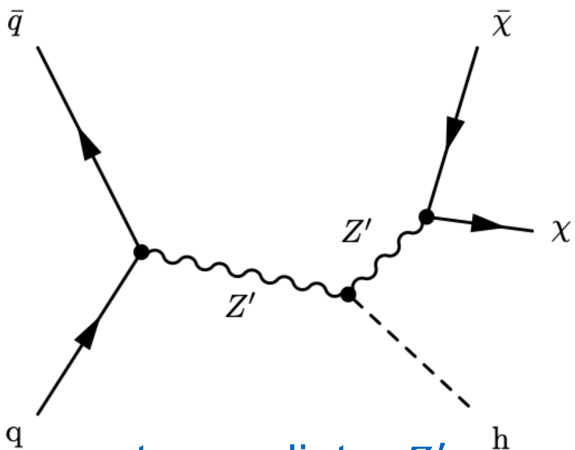
- Currently no evidence of DM is observed in particle physics experiments.
- Many measurements improve the existing constraints.
- Many searches are performed in collider experiments.
    - Including ATLAS, CMS, BaBar, BELLE II, BES III etc.
- Look forward the CEPC to get more results on the DM search.

# Backup

# $pp \to h(\gamma\gamma) + E_T^{miss}$ in LHC

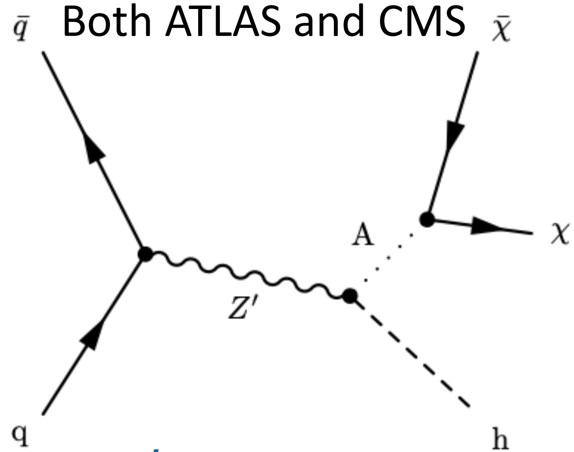
- Models to search.

JHEP10(2021)013
JHEP10(2017)180

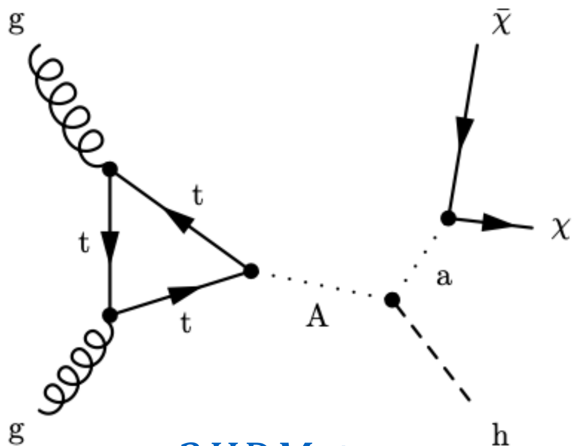



vector mediator $Z'$

Both ATLAS and CMS




$Z' - 2HDM$




$2HDM + a$

# Backup

➢ Parameters of $Z'_B$ model.

- $m_{Z'}$, the $Z'$ boson mass;
- $g_\chi$, the coupling of the $Z'$ boson to the DM particle $\chi$;
- $g_q$, the coupling of the $Z'$ boson to quarks;
- $g_{hZ'Z'}$, the coupling between the $Z'$ boson and the observed Higgs boson $h$;
- $\sin\theta$, the mixing angle between the baryonic Higgs boson and the observed Higgs boson; and
- $m_\chi$, the mass of the fermionic dark-matter candidate $\chi$.

# Backup

➢ Parameters of $Z'2HDM$ model.

- $m_A$, the pseudoscalar boson mass;
- $m_{Z'}$, the $Z'$ boson mass;
- $m_\chi$, the mass of the fermionic dark-matter candidate $\chi$;
- $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets;
- $g_{Z'}$ the coupling strength of the $Z'$ boson to quarks; and
- $\alpha$, the mixing angle between the two neutral scalars in the 2HDM model.

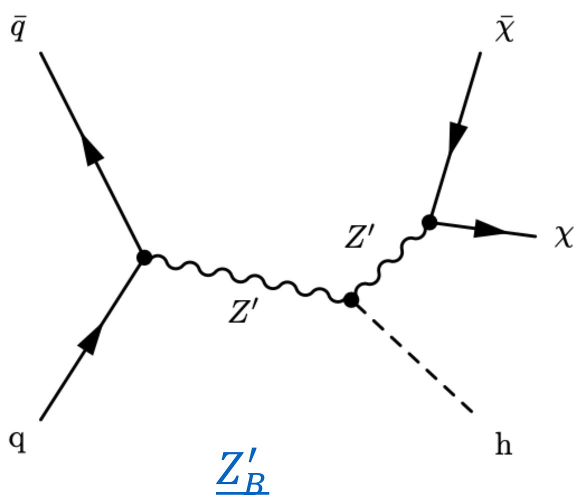
# Backup

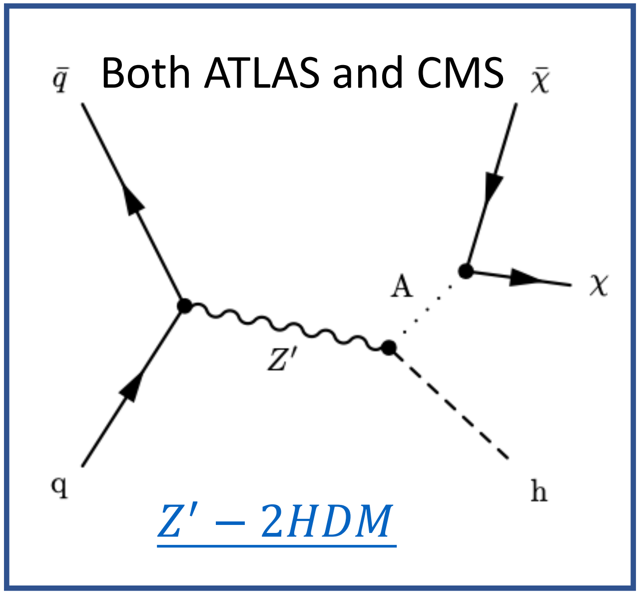
➢ Parameters of 2HDM+a model.

- $m_A$ and $m_a$, the pseudoscalar particle masses;
- $m_H$ and $m_h$, the scalar particle masses;
- $m_{H^\pm}$, the mass of the charged Higgs bosons;
- $m_\chi$, the fermionic DM particle mass;
- $y_\chi$, the DM Yukawa coupling;
- $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets;
- $\alpha$, the mixing angle between the two neutral scalars in the 2HDM model;
- $\theta$, the mixing angle between the two pseudoscalars; and
- $\lambda_3$, the quartic coupling of the Higgs potential, and $\lambda_{1P}$ and $\lambda_{2P}$, the quartic couplings of the pseudoscalar potentials.

# $pp \to h(\gamma\gamma) + E_T^{miss}$ in LHC

- The $Z'_B$ and $Z'2HDM$ model are used in these studies. JHEP10(2021)013 JHEP10(2017)180




- Analysis strategy(ATLAS):
  - $E_\gamma/m_{\gamma\gamma}$ > 0.35/0.25,
  - $E_T^{miss}$ > 90 GeV,
  - $\Delta E_T^{miss}$ < 30 GeV,
  - $105 < m_{\gamma\gamma} < 160$ GeV

- Analysis strategy(CMS):
  - $p_T/m_{\gamma\gamma}$ > 0.5/0.25,
  - $E_T^{miss}$ > 105 GeV,
  - $p_{T\gamma\gamma}$ > 90 GeV,
  - $105 < m_{\gamma\gamma} < 180$ GeV