The impact of **dark Higgs** on **dark photon** detection

Mengchao Zhang (张孟超)

2026-01-18

Cross-Strait 2026

Guangzhou - Zhujiang Hotel

Based on: *Phys.Rev.D 111 (2025) 3, 035005* Song Li, Jin Min Yang, MZ, Rui Zhu
arXiv: 2506.20208 Song Li, Jin Min Yang, Yang Zhang, MZ, Rui Zhu
arXiv: 260X.xxxxx Yi Li, MZ

Outline

I. Motivation: why dark Higgs must be considered?

II. Dark final state radiation (FSR) & dark merging

III. A case study at BaBar

IV. Conclusion

Outline

I. Motivation: why dark Higgs must be considered?

II. Dark final state radiation (FSR) & dark merging

III. A case study at BaBar

IV. Conclusion

Mass origin of dark photon

Dark photon A' is a popular NewPhysics assumption. It's a massive gauge boson of a hidden/dark $U(1)'$:

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \varepsilon e A'_\mu J^\mu_{EM}$$

A' couples to SM charge current via kinetic mixing ε .

A' is massive, with mass $m_{A'}$.

Mass origin of dark photon

Dark photon A' is a popular NewPhysics assumption. It's a massive gauge boson of a hidden/dark $U(1)'$:

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \varepsilon e A'_\mu J^\mu_{EM}$$

A' couples to SM charge current via kinetic mixing ε .

A' is massive, with mass $m_{A'}$.

If we assume A' to decay invisibly ($A' \to$ invis), then the property of dark photon is determined by 2 parameters: $\{m_{A'}, \varepsilon\}$.

Mass origin of dark photon

Dark photon A' is a popular NewPhysics assumption. It's a massive gauge boson of a hidden/dark $U(1)'$:

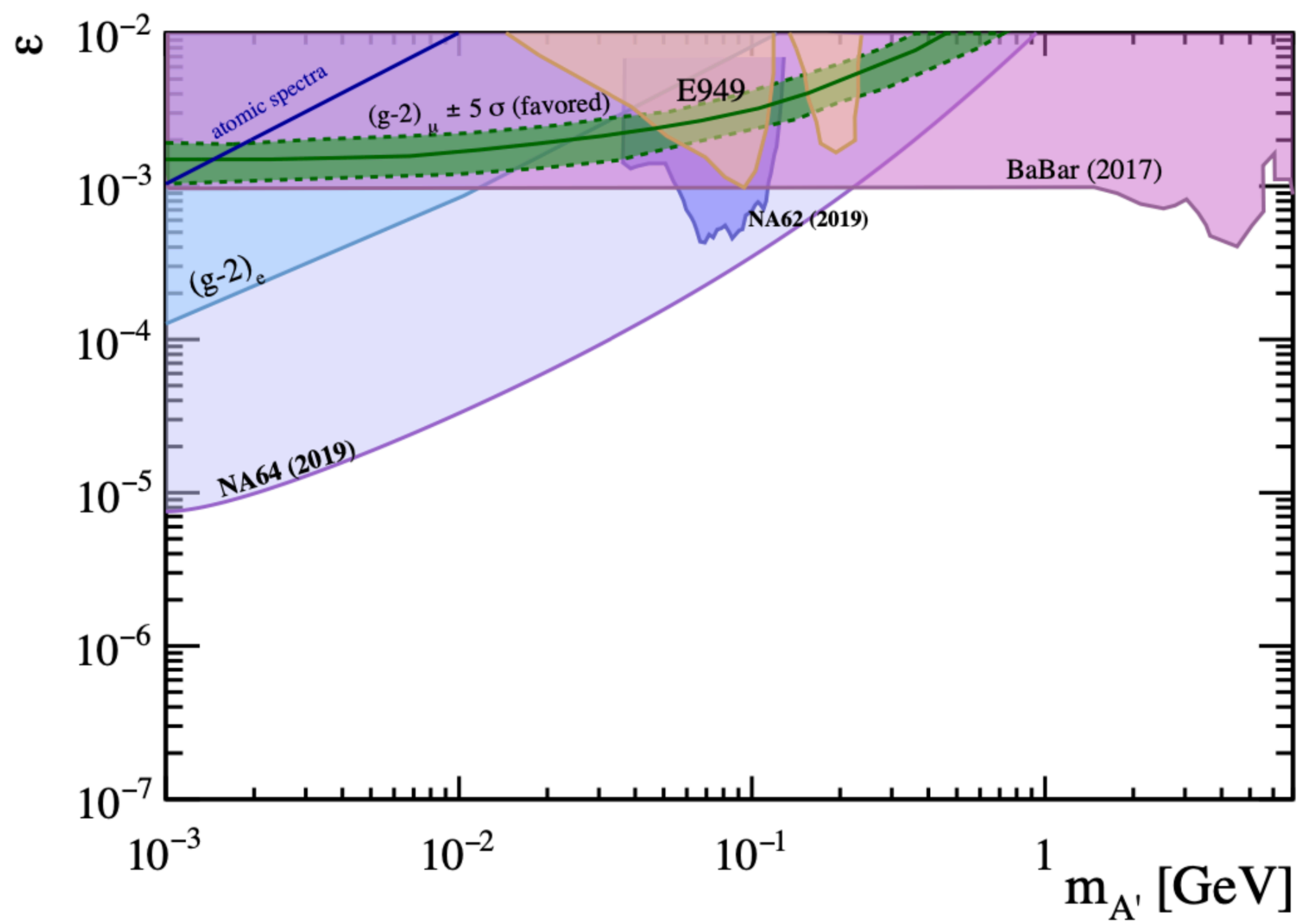
$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \varepsilon e A'_\mu J^\mu_{EM}$$

A' couples to SM charge current via kinetic mixing ε .

A' is massive, with mass $m_{A'}$.

If we assume A' to decay invisibly ($A' \to$ invis), then the property of dark photon is determined by 2 parameters: $\{m_{A'}, \varepsilon\}$.

Current limits:
BaBar + NA64



Mass origin of dark photon

But, what is the origin of dark photon? Where does $m_{A'}$ come from?

Mass origin of dark photon

But, what is the origin of dark photon? Where does $m_{A'}$ come from?

You might say Stueckelberg mechanism. But Stueckelberg mechanism is actually the heavy Higgs limit for Higgs mechanism.

Higgs very heavy

Higgs mechanism → Stueckelberg mechanism

Mass origin of dark photon

But, what is the origin of dark photon? Where does $m_{A'}$ come from?

You might say Stueckelberg mechanism. But Stueckelberg mechanism is actually the heavy Higgs limit for Higgs mechanism.

Higgs mechanism → (Higgs very heavy) → Stueckelberg mechanism

Consider a dark $U(1)'$ Higgs mechanism, with gauge coupling g', Higgs self-coupling λ and vev v. Then the mass ratio between dark Higgs and dark photon is

$$\frac{m_s^2}{m_{A'}^2} = \frac{\lambda v^2/2}{g'^2 v^2} = \frac{\lambda}{2g'^2}$$

Mass origin of dark photon

But, what is the origin of dark photon? Where does $m_{A'}$ come from?

You might say Stueckelberg mechanism. But Stueckelberg mechanism is actually the heavy Higgs limit for Higgs mechanism.

Higgs mechanism —(Higgs very heavy)→ Stueckelberg mechanism

Consider a dark $U(1)'$ Higgs mechanism, with gauge coupling g', Higgs self-coupling λ and vev v. Then the mass ratio between dark Higgs and dark photon is

$$\frac{m_s^2}{m_{A'}^2} = \frac{\lambda v^2/2}{g'^2 v^2} = \frac{\lambda}{2g'^2}$$

So Stueckelberg mechanism is only valid when $\lambda \gg g'^2$. Only in this case you can ignore dark Higgs and only consider 2 parameters $\{m_{A'}, \varepsilon\}$.

Mass origin of dark photon

Is the assumption $\lambda \gg g'^2$ okay?

Mass origin of dark photon

Is the assumption $\lambda \gg g'^2$ okay? Maybe not.

Mass origin of dark photon

Is the assumption $\lambda \gg g'^2$ okay? Maybe not.

We know from the perturbative unitarity that λ has an upper bound.
(You can calculate 2to2 scattering process in dark Higgs model with longitudinal dark photon)

$$\lim_{E_{\rm cm}\to\infty} \langle 0,0|M^{j=0}|0,0\rangle = \frac{1}{8\pi}\frac{m_s^2}{v_{\rm cl}^2}\left(\begin{array}{c|ccc} & A'_L A'_L & ss & A'_L s \\ \hline A'_L A'_L & -3 & 1 & 0 \\ ss & 1 & -3 & 0 \\ A'_L s & 0 & 0 & -2 \end{array}\right)$$

Mass origin of dark photon

Is the assumption $\lambda \gg g'^2$ okay? Maybe not.

We know from the perturbative unitarity that λ has an upper bound. (You can calculate 2to2 scattering process in dark Higgs model with longitudinal dark photon)

$$\lim_{E_{\rm cm}\to\infty} \langle 0,0|M^{j=0}|0,0\rangle = \frac{1}{8\pi}\frac{m_s^2}{v_{\rm cl}^2}\left(\begin{array}{c|ccc} & A'_L A'_L & ss & A'_L s \\ \hline A'_L A'_L & -3 & 1 & 0 \\ ss & 1 & -3 & 0 \\ A'_L s & 0 & 0 & -2 \end{array}\right)$$

$$\Rightarrow \quad m_s^2 < 2\pi v^2 \quad \Rightarrow \quad \lambda < 4\pi$$

Mass origin of dark photon

Is the assumption $\lambda \gg g'^2$ okay? Maybe not.

We know from the perturbative unitarity that λ has an upper bound. (You can calculate 2to2 scattering process in dark Higgs model with longitudinal dark photon)

$$\lim_{E_{\rm cm}\to\infty} \langle 0,0|M^{j=0}|0,0\rangle = \frac{1}{8\pi}\frac{m_s^2}{v_{\rm cl}^2}\left(\begin{array}{c|ccc} & A'_L A'_L & ss & A'_L s \\ \hline A'_L A'_L & -3 & 1 & 0 \\ ss & 1 & -3 & 0 \\ A'_L s & 0 & 0 & -2 \end{array}\right)$$

$\longrightarrow$ $m_s^2 < 2\pi v^2$ $\longrightarrow$ $\lambda < 4\pi$

So assumption $\lambda \gg g'^2$ is only valid when g' is very small.

Mass origin of dark photon

So assumption $\lambda \gg g'^2$ is only valid when g' is very small.

Can g' be that small?

Mass origin of dark photon

So assumption $\lambda \gg g'^2$ is only valid when g' is very small.

Can g' be that small? No.

Mass origin of dark photon

So assumption $\lambda \gg g'^2$ is only valid when g' is very small.

Can g' be that small? No.

For invisible dark photon decay, dark photon should decay to some light fermion χ via $U(1)'$ coupling:

$$\Gamma(A' \to \chi\bar{\chi}) \sim \alpha' m_{A'}$$

with $\alpha' \equiv \frac{g'^2}{4\pi}$.

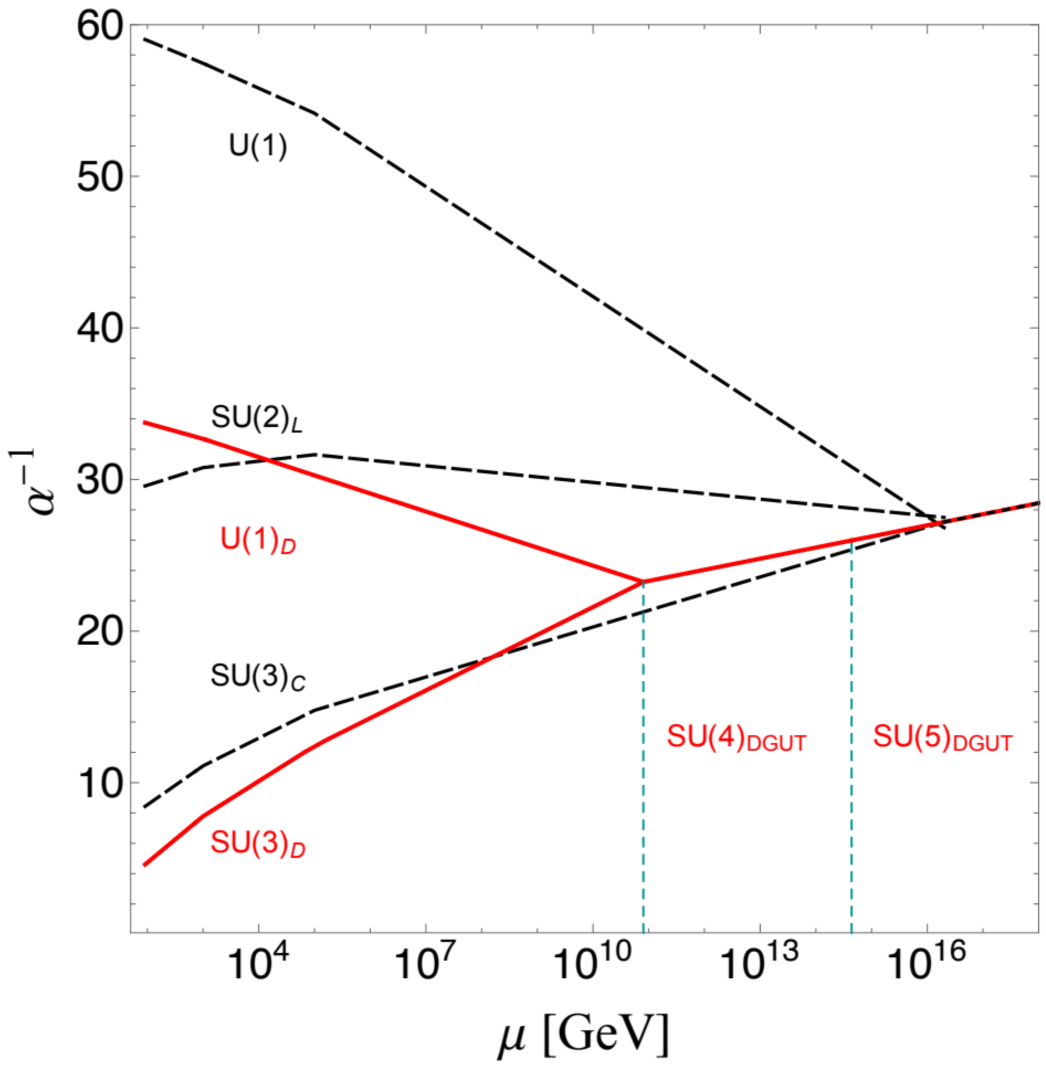
So, to make the invisible decay channel dominant, the g' can not be that small.

Mass origin of dark photon

So assumption $\lambda \gg g'^2$ is only valid when g' is very small.

Can g' be that small? No.

If you believe GUT and embed dark $U(1)'$ into it. Then g' can not be too smaller than the SM gauge couplings.



RGE running in GUT model tells you that g' should be around g_{EW}.

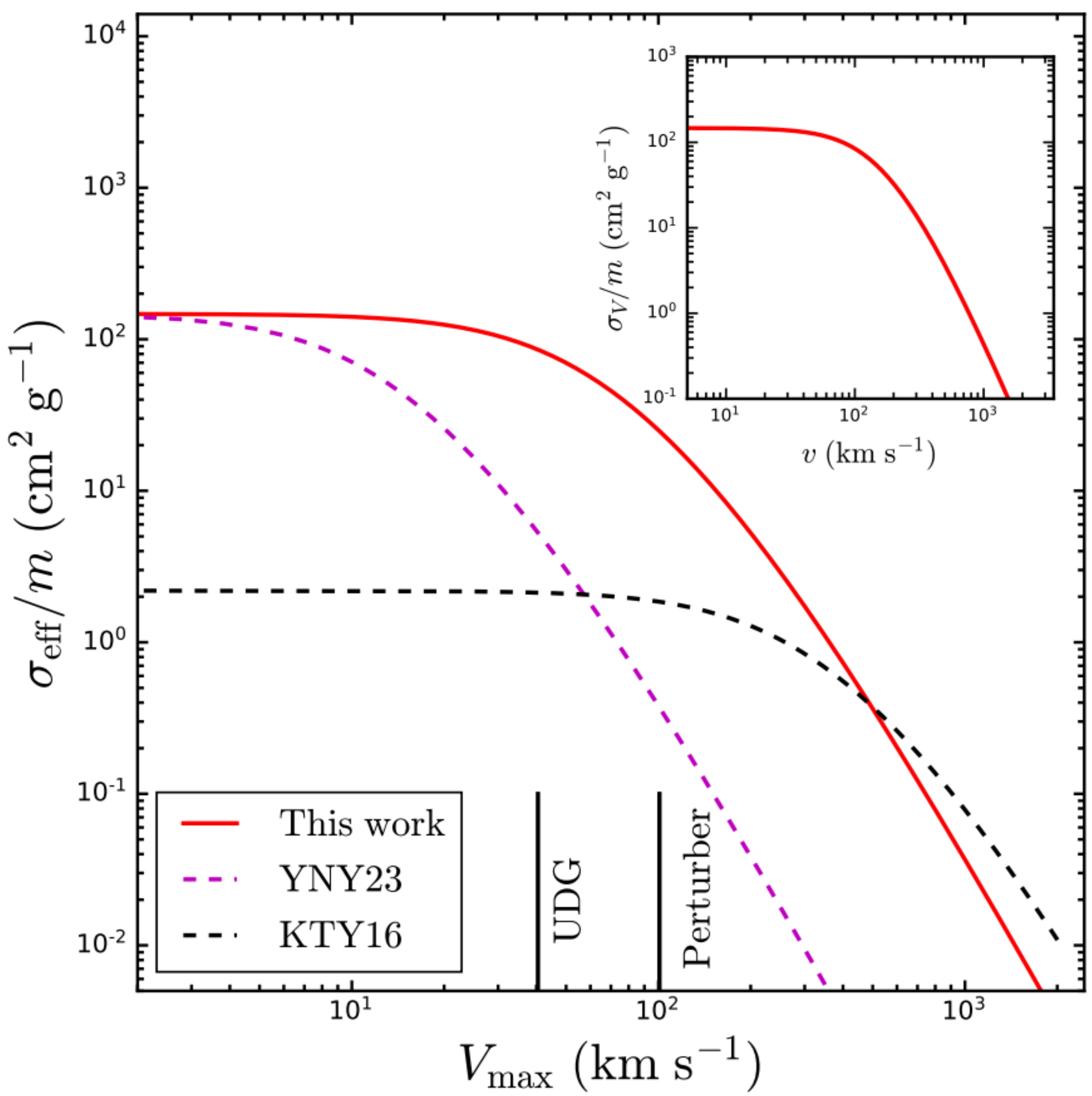
PRD (2019) "Baryon-Dark Matter Coincidence in Mirrored Unification"

Mass origin of dark photon

So assumption $\lambda \gg g'^2$ is only valid when g' is very small.

Can g' be that small? No.

If you want to solve the "diversity problem" of dark matter, then the gauge coupling in the dark sector can not be small.



"Diversity" of dark matter halo observation require strong self-interaction in the dark sector.

Astrophys.J.Lett. (2023) *"A Self-interacting Dark Matter Solution to the Extreme Diversity of Low-mass Halo Properties"*

Mass origin of dark photon

So assumption $\lambda \gg g'^2$ is only valid when g' is very small.

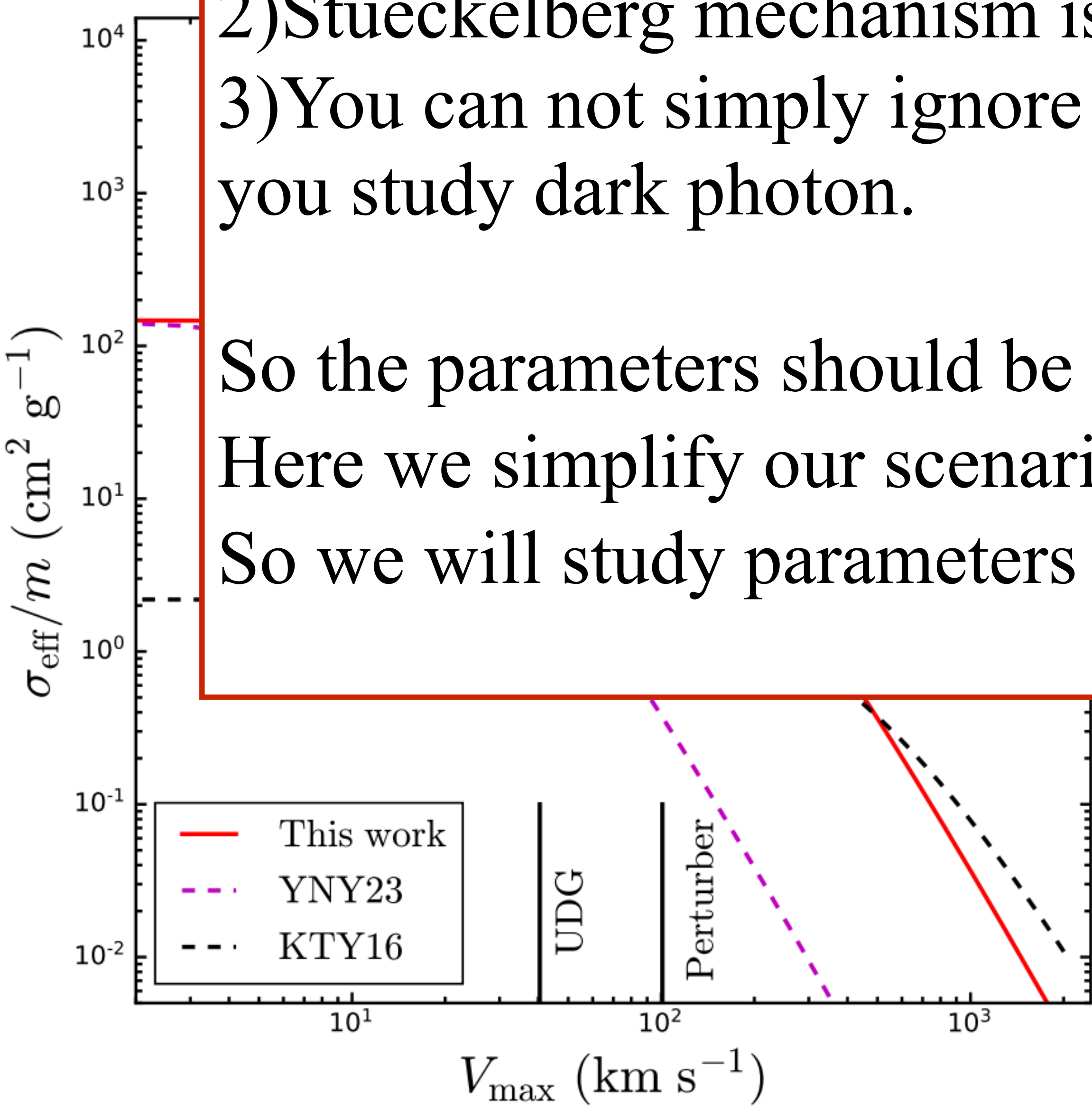
Can g' be that small? No.

If you … uge
coupl …

So we conclude:
1) $\lambda \gg g'^2$ generally can not happen.
2) Stueckelberg mechanism is generally invalid.
3) You can not simply ignore dark Higgs (labeled by s) when you study dark photon.

So the parameters should be $\{m_{A'}, m_s, \varepsilon, \alpha'\}$.
Here we simplify our scenario by equating 2 masses: $m_{A'} = m_s$.
So we will study parameters : $\{m_{A'} = m_s, \varepsilon, \alpha'\}$.

… eraction



Dark Matter Solution to the Extreme Diversity of Low-mass Halo Properties”

Outline

I. Motivation: why dark Higgs must be considered?

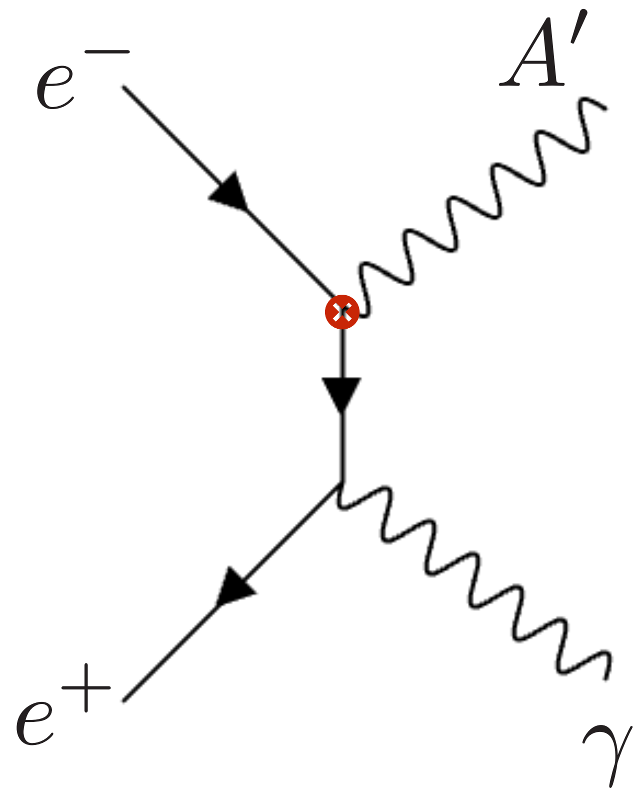
II. Dark final state radiation (FSR) & dark merging

III. A case study at BaBar

IV. Conclusion

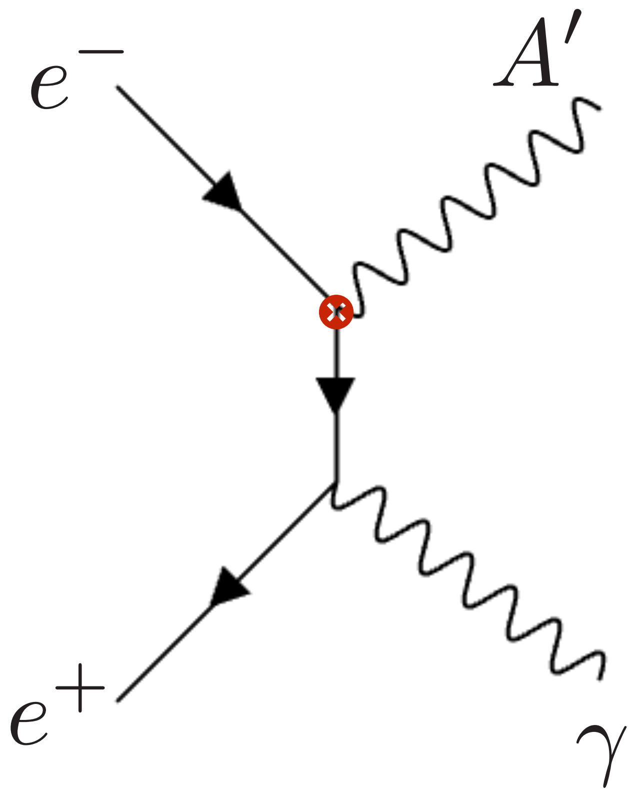
Dark final state radiation (D-FSR)

For the search of dark photon at ep collider, the process is just $e^- e^+ \to \gamma A'$.

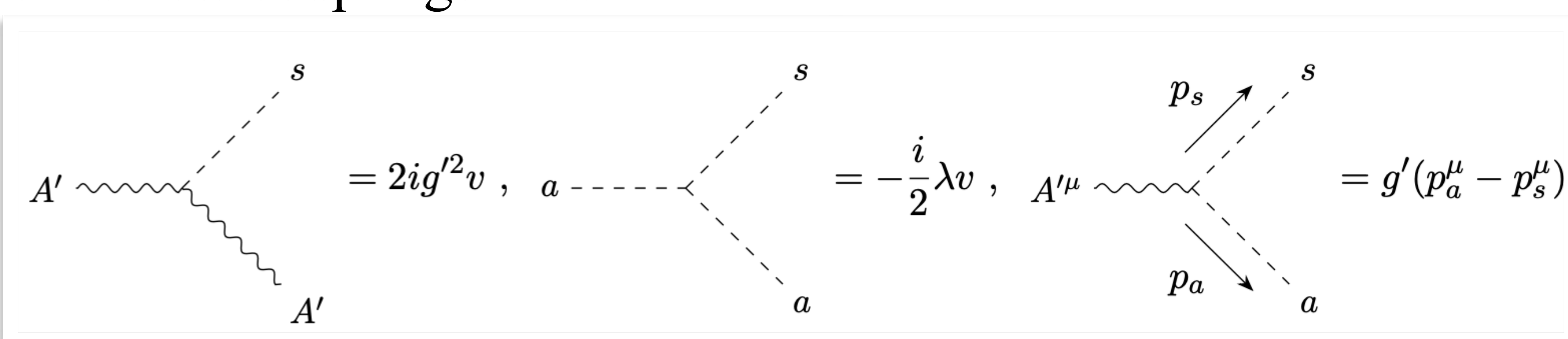


Dark final state radiation (D-FSR)

For the search of dark photon at ep collider, the process is just
$e^-e^+ \to \gamma A'$.



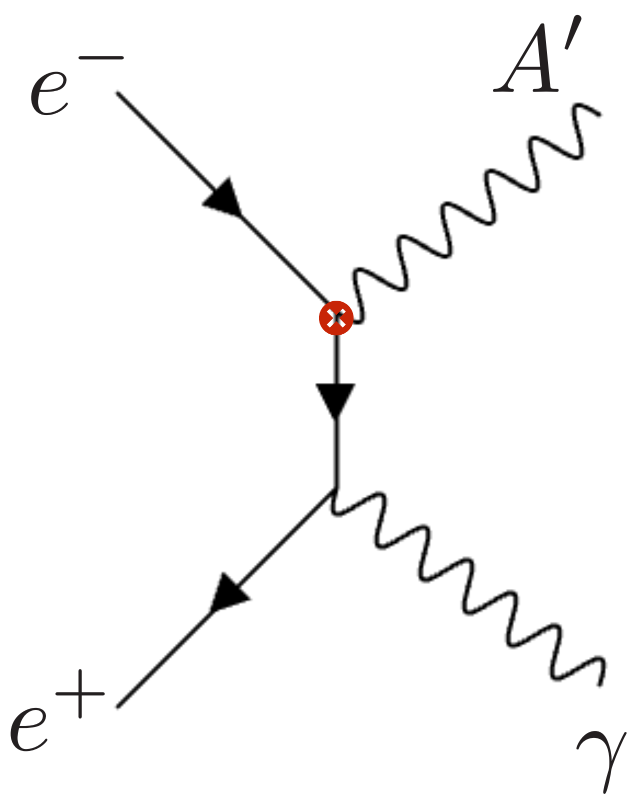
If dark Higgs is considered, then the pheno of dark photon will be richer.
There are new couplings like:

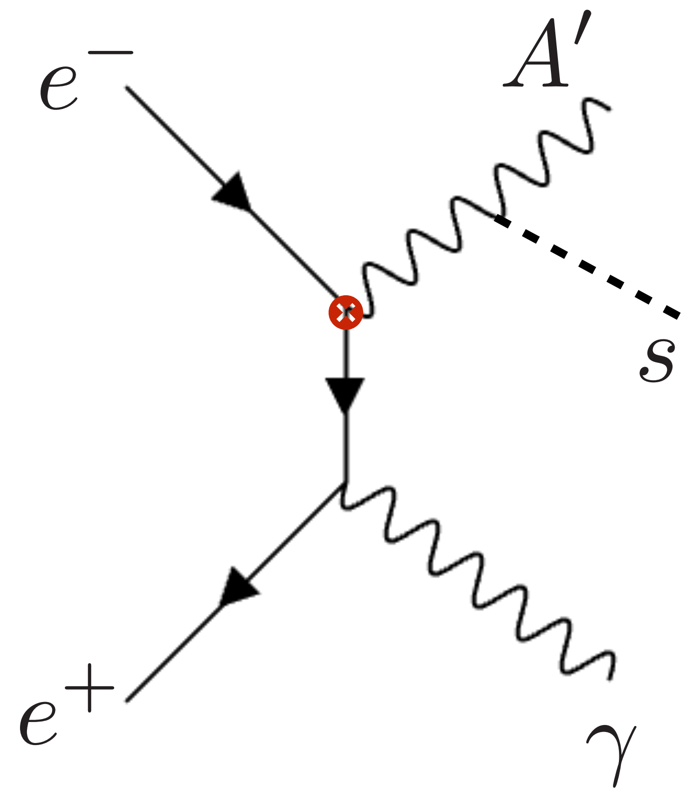


Here a is the Goldstone (longitudinal A').

Dark final state radiation (D-FSR)

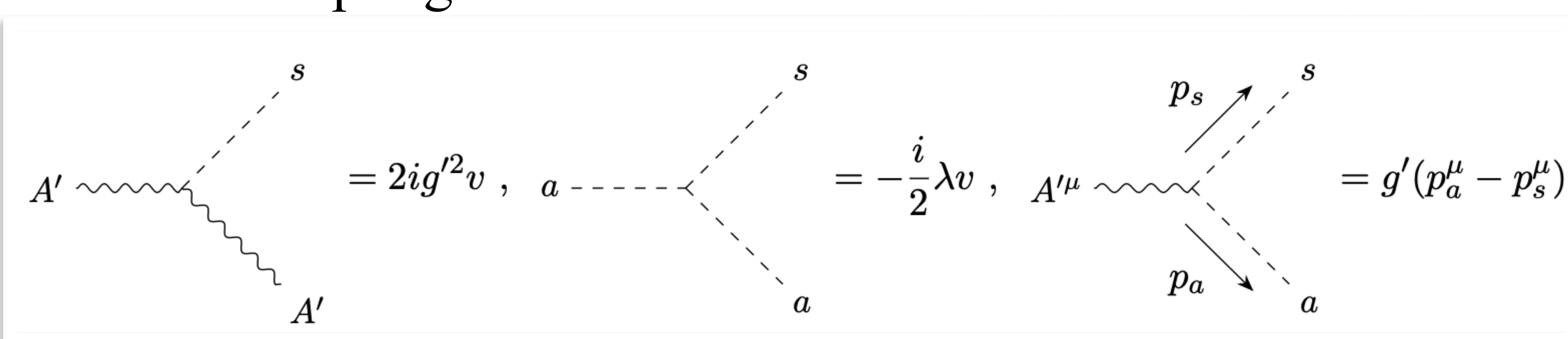
For the search of dark photon at ep collider, the process is just $e^- e^+ \to \gamma A'$.





NLO process
$e^- e^+ \to \gamma A' s$

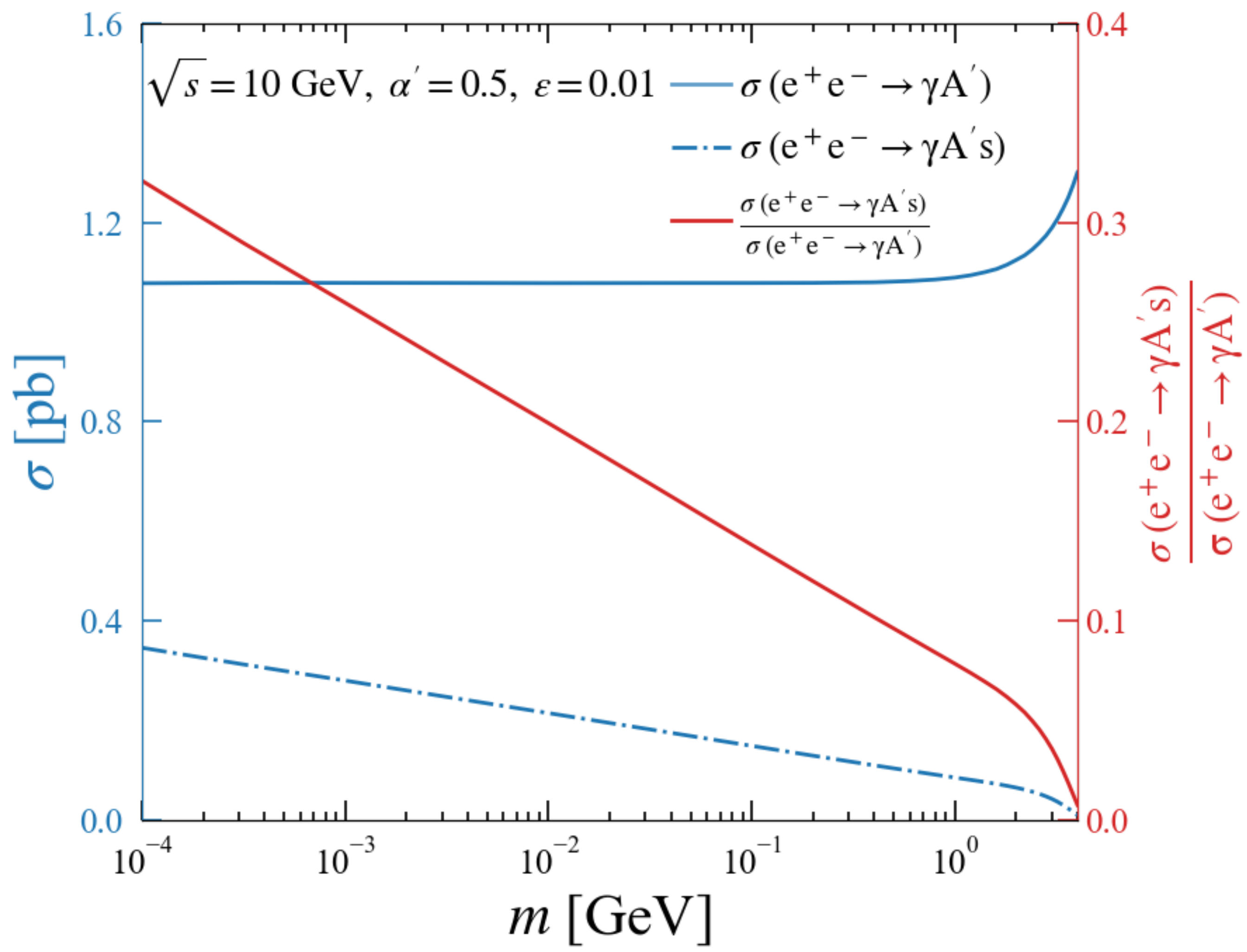
If dark Higgs is considered, then the pheno of dark photon will be richer. There are new couplings like:



Here a is the Goldstone (longitudinal A').

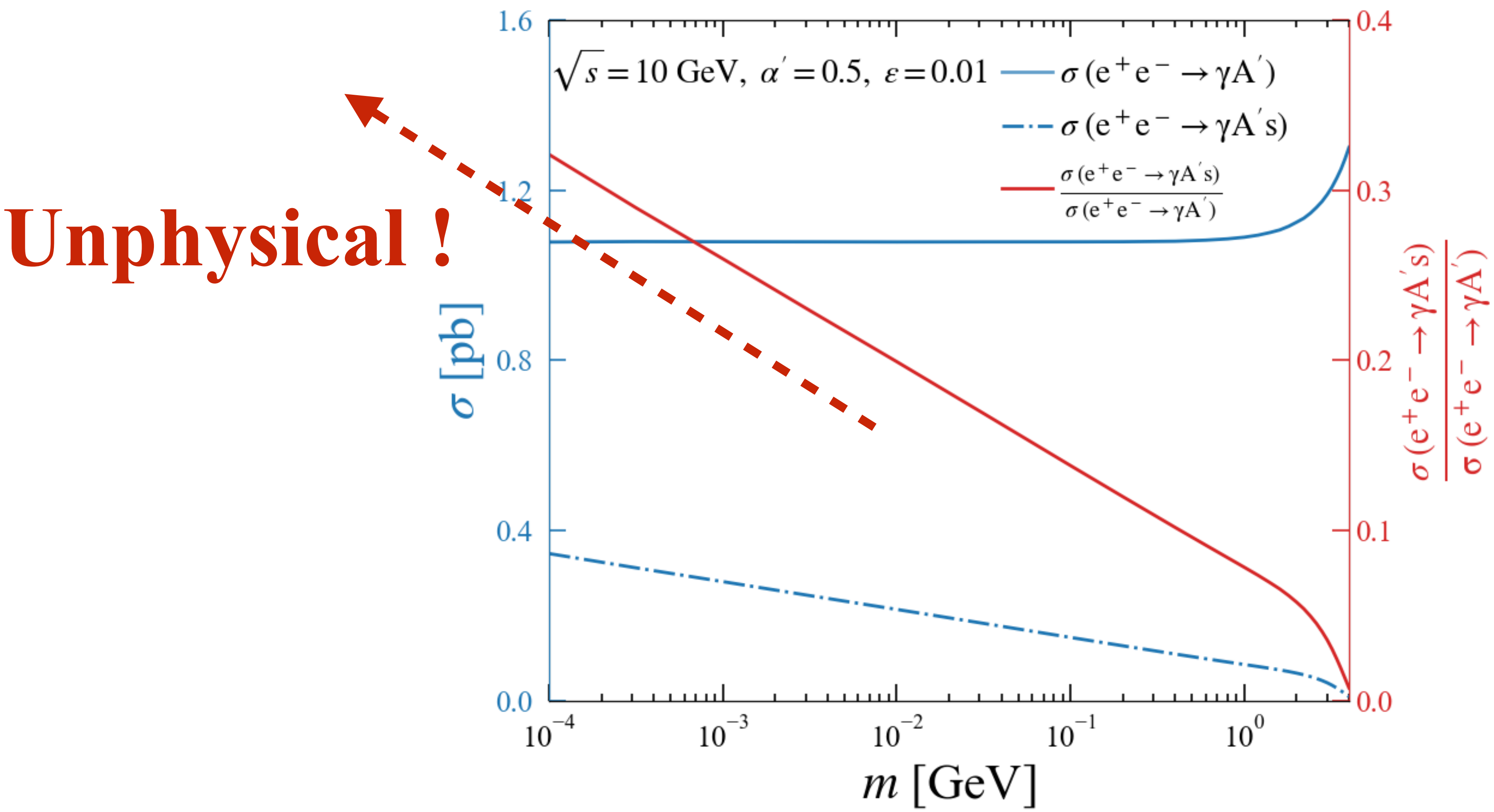
Dark final state radiation (D-FSR)

NLO process $e^- e^+ \to \gamma A's$ will face some problem when the mass become very small ($m_{A'}, m_s \ll \sqrt{s}$).



Dark final state radiation (D-FSR)

NLO process $e^-e^+ \to \gamma A's$ will face some problem when the mass become very small ($m_{A'}, m_s \ll \sqrt{s}$).



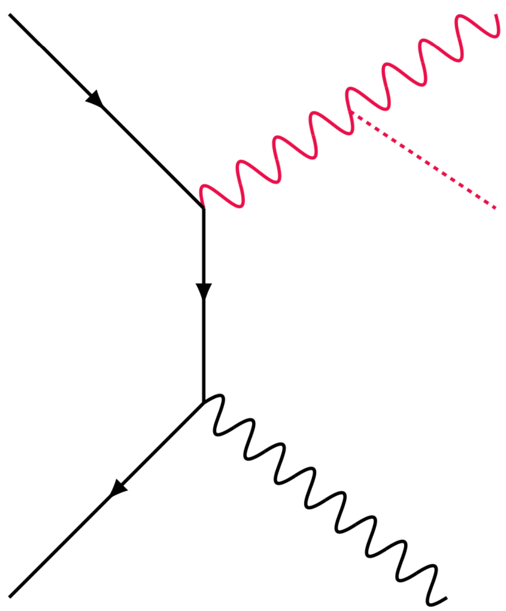
The unphysical behavior of the $\sigma(e^-e^+ \to \gamma A's)$ comes from the "collinear divergence", which means that the fixed-order calculation is not valid for "dark final state radiation" $A' \to A's$ when dark particles are too light.

Dark final state radiation (D-FSR)

We learn from the QFT textbook that the IR divergence in the real emission will be canceled by the IR divergence in the virtual/vertex correction.
This is promised by the KLN theorem.

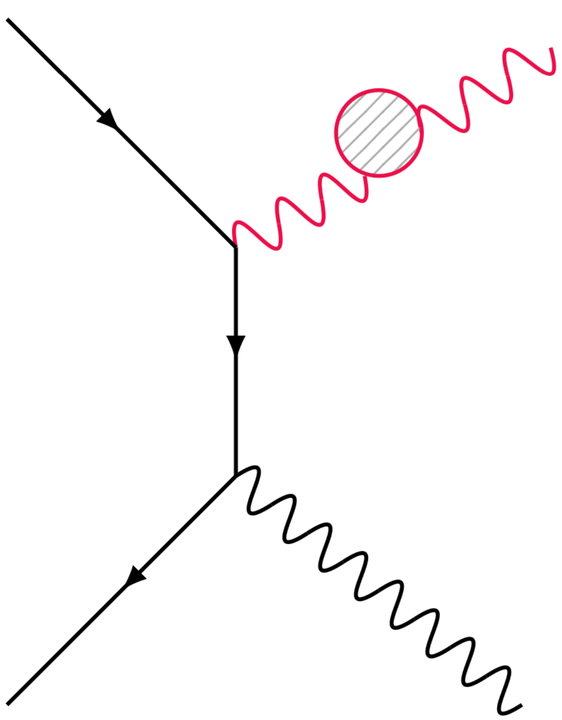
Dark final state radiation (D-FSR)

We learn from the QFT textbook that the IR divergence in the real emission will be canceled by the IR divergence in the virtual/vertex correction.
This is promised by the KLN theorem.



$m_{A'} \to 0$

$$\frac{-16\, m_e^4\, s + s^3 - 2\sqrt{-4m_e^2 + s}\,\left[s^{5/2} - 8\, m_e^4 s^{1/2} + 4\, m_e^2 s^{3/2}\right] \operatorname{arctanh}\left(\sqrt{1 - \frac{4m_e^2}{s}}\right) \cdot \log m_{A'}}{48\,\pi^3\, s^{5/2}\,(-4m_e^2 + s)^{3/2}}$$

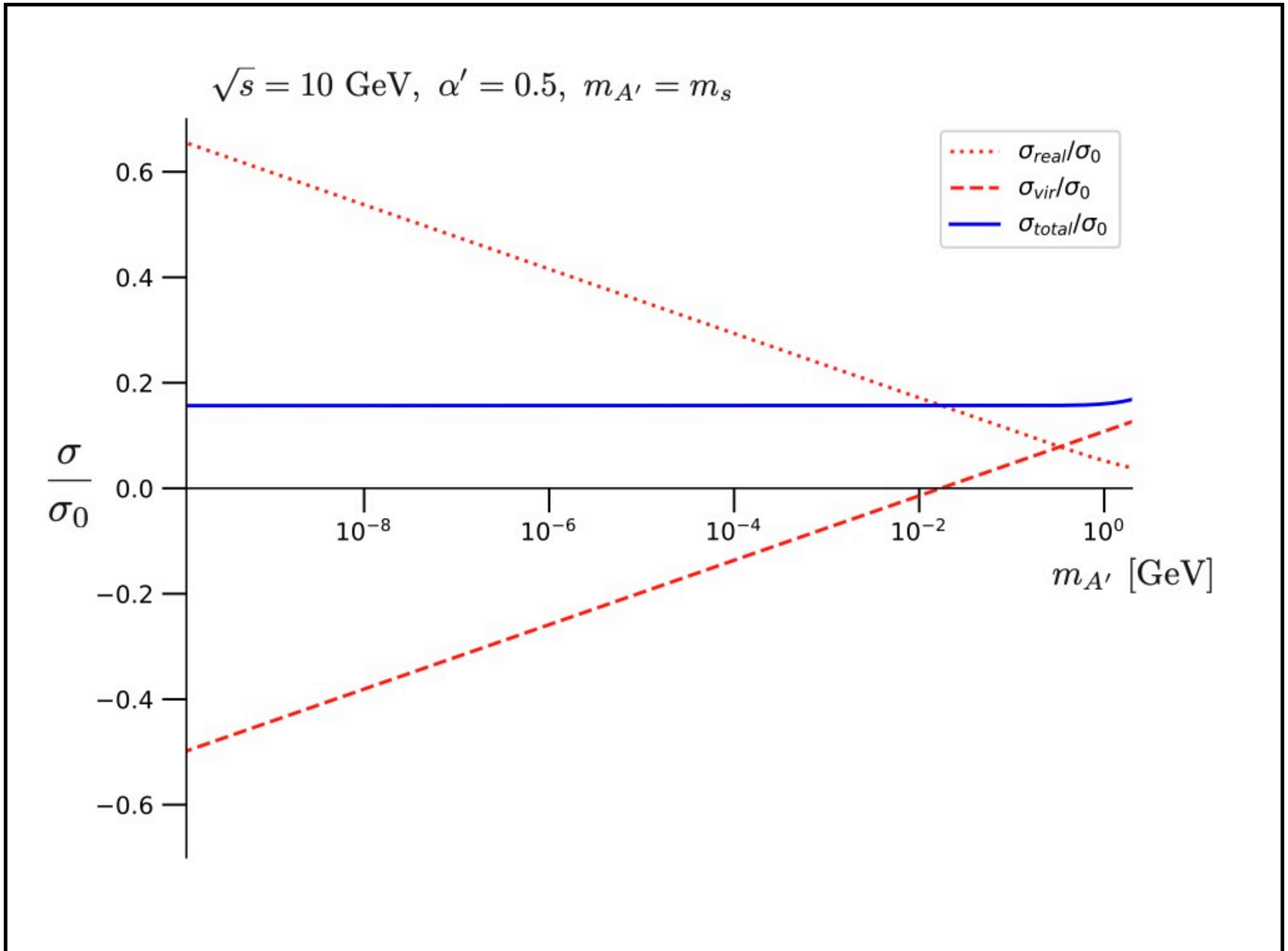


$m_{A'} \to 0$

$$\frac{\ln\left(m_{A'}^2\right)\left[s\left(4m_e^2 + s\right) - 2\sqrt{\frac{s}{s-4m_e^2}}\left(-8m_e^4 + 4m_e^2 s + s^2\right)\tanh^{-1}\left(\sqrt{1 - \frac{4m_e^2}{s}}\right)\right]}{96\,\pi^3\sqrt{s^5(s - 4m_e^2)}}$$

Dark final state radiation (D-FSR)

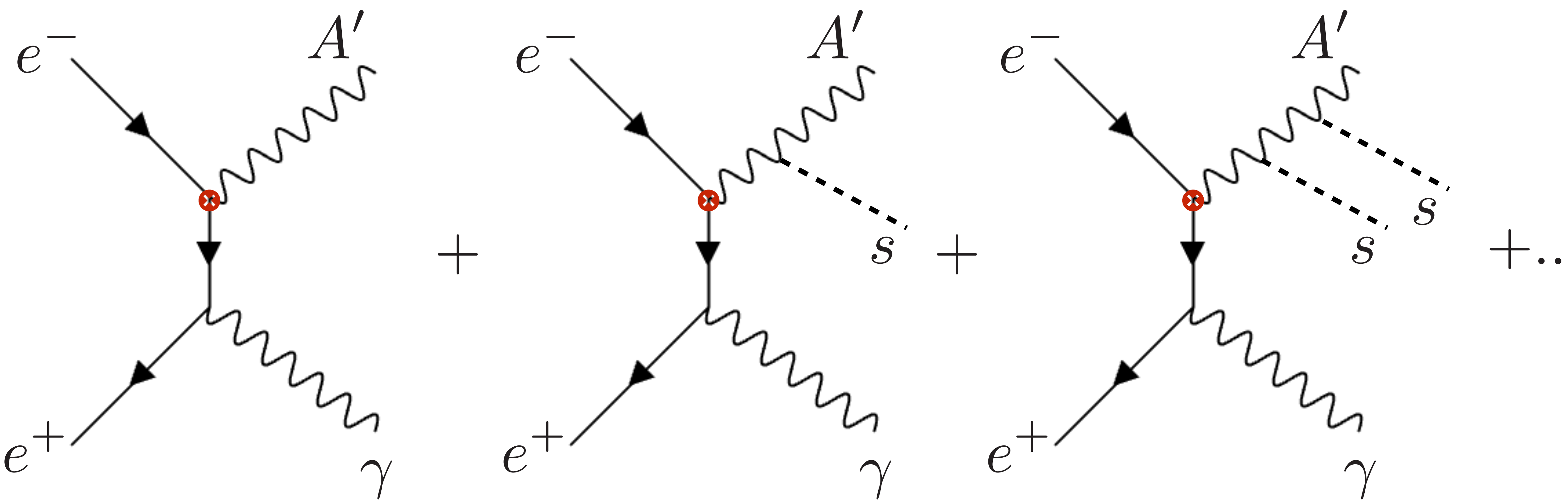
We learn from the QFT textbook that the IR divergence in the real emission will be canceled by the IR divergence in the virtual/vertex correction. This is promised by the KLN theorem.



Dark final state radiation (D-FSR)

We learn from the QFT textbook that the IR divergence in the real emission will be canceled by the IR divergence in the virtual/vertex correction.
This is promised by the KLN theorem.

But, the KLN theorem only give you a physical total cross-section, not a physical distribution for $e^-e^+ \to \gamma A's$.
The physical distribution can be obtained by resummation.



Dark final state radiation (D-FSR)

Resummation of the multiple real emission can be performed by "parton shower" (can be called "dark shower" in this model):

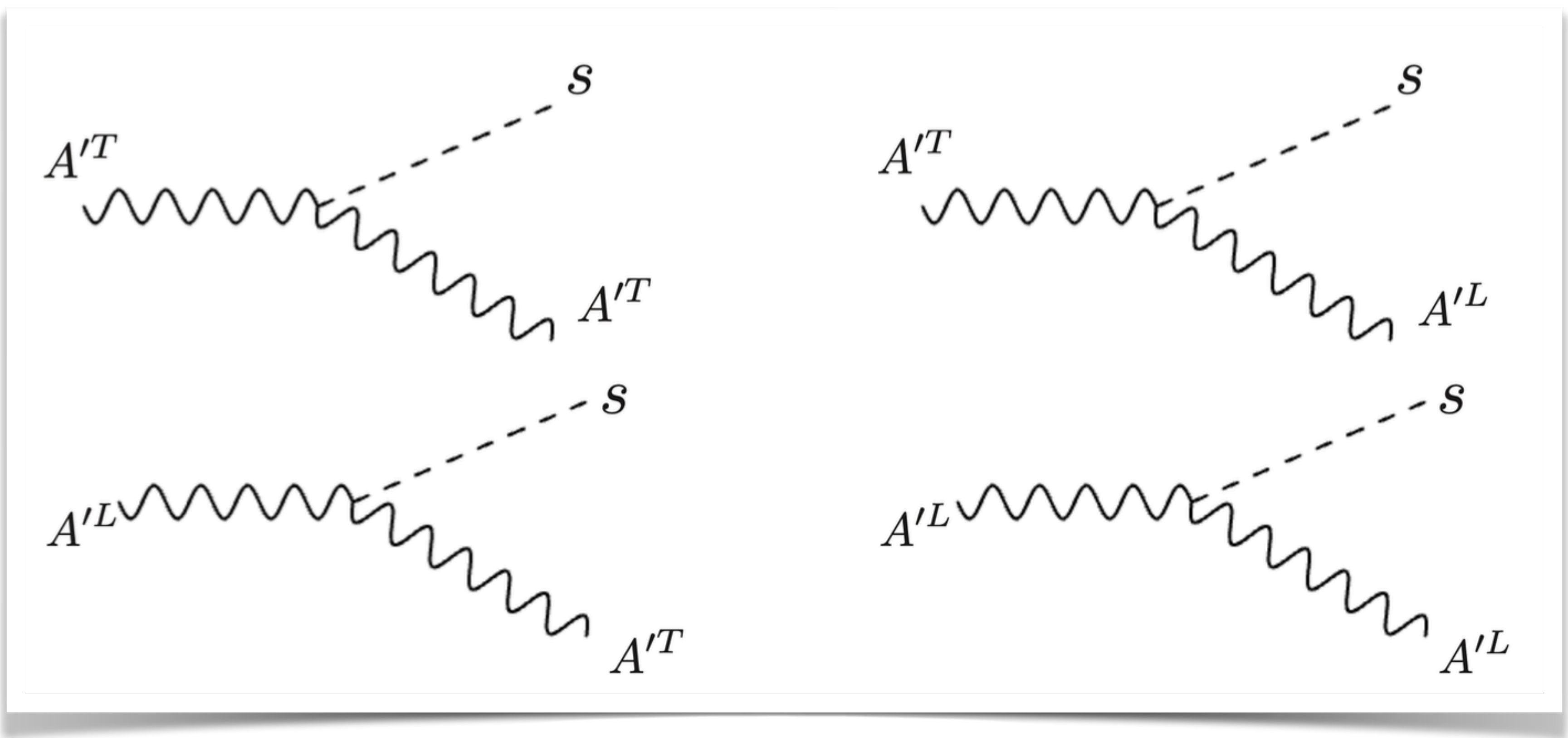
$$d\sigma(X \to Y + A' + s) \simeq d\sigma(X \to Y + A') \times d\mathcal{P}(A' \to A' + s)$$

Dark final state radiation (D-FSR)

Resummation of the multiple real emission can be performed by "parton shower" (can be called "dark shower" in this model):

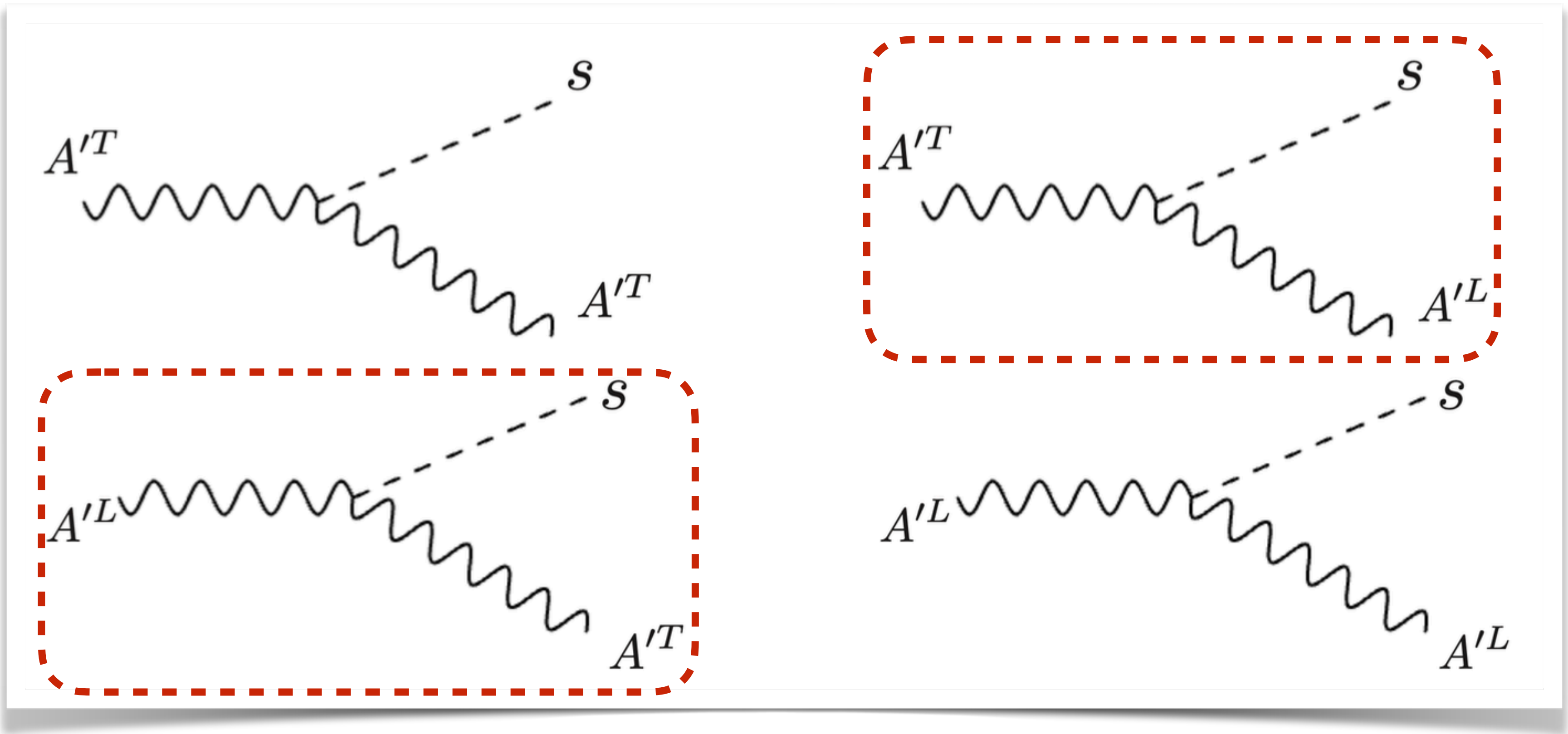
$$d\sigma(X \to Y + A' + s) \simeq d\sigma(X \to Y + A') \times d\mathcal{P}(A' \to A' + s)$$

The kernel of dark shower is the splitting function, which correspond to 4 sub-process:



We need to distinguish "longitudinal A'" and "transverse A'", because they behaviors are very different.

Dark final state radiation (D-FSR)



We need to distinguish “longitudinal A'” and “transverse A'”, because they behaviors are very different.
We find that, the most important splitting processes are “polarization flip” process:

$$\frac{d\mathcal{P}}{dz dk_T^2}(A'_T \to s + A'_L) = \frac{\alpha'}{2\pi} z\bar{z} \frac{p_T^2}{\tilde{p}_T^4},$$

$$\frac{d\mathcal{P}}{dz dk_T^2}(A'_L \to s + A'_T) = \frac{\alpha'}{2\pi} \frac{2z}{\bar{z}} \frac{p_T^2}{\tilde{p}_T^4}.$$

Here $\tilde{p}_T^2 \equiv p_T^2 + \bar{z} m_s^2 + z m_{A'}^2 - z\bar{z} m_{A'}^2$ and $\bar{z} \equiv 1 - z$.

Dark final state radiation (D-FSR)

It should be emphasized that the dark shower can only by used to describe collinear region when dark particles' masses are very small. But when dark particles' masses are not that small, or splitting angle is large, then NLO result is right.

Dark final state radiation (D-FSR)

It should be emphasized that the dark shower can only by used to describe collinear region when dark particles' masses are very small. But when dark particles' masses are not that small, or splitting angle is large, then NLO result is right.
So, we need to do what we learned from the MadGraph winter school:

Merging !

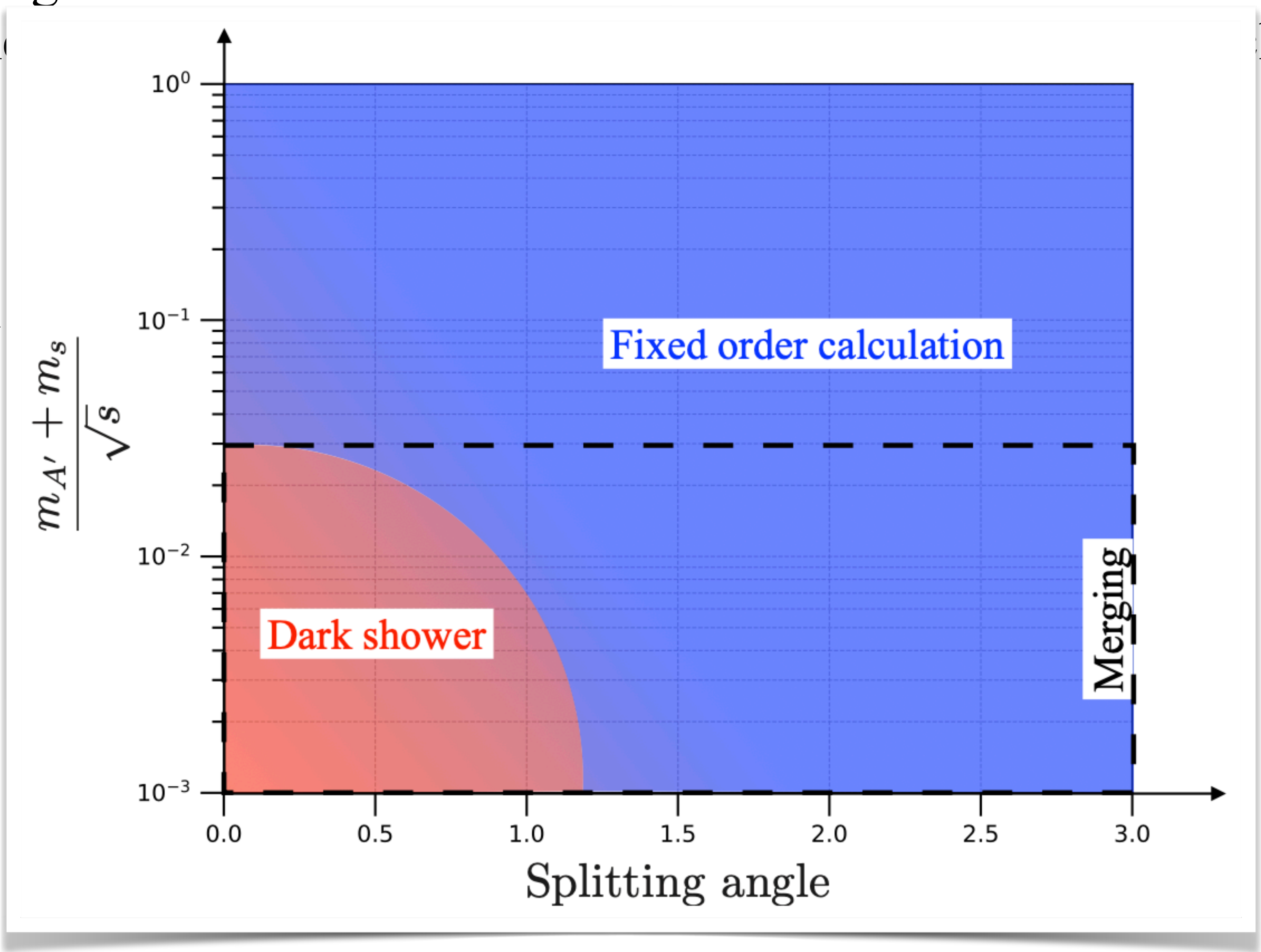
We need to merging the NLO process with the dark shower.

Dark final state radiation (D-FSR)

It should be emphasized that the dark shower can only by used to describe collinear region when dark particles' masses are very small. But when dark particles' masses are not that small, or splitting angle is large, then NLO result is right.

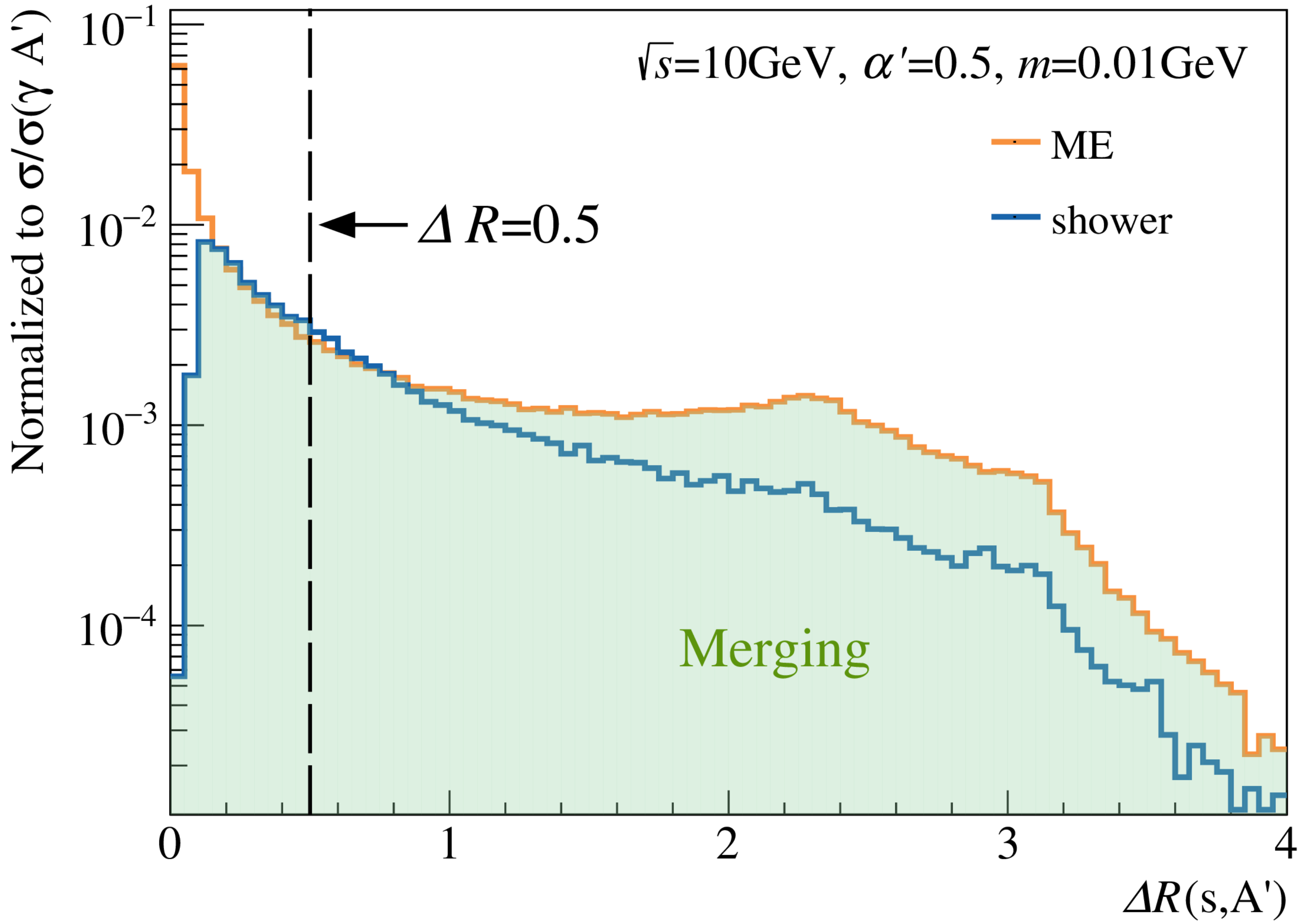
So, we n[…]hool:

We need



Merging in the dark sector

Here I show you some concrete result.
We do simulation by using the "veto algorithm" implemented in Pythia8.



Merging gives you the physical distribution.

Outline

I. Motivation: why dark Higgs must be considered?

II. Dark final state radiation (FSR) & dark merging

III. A case study at BaBar

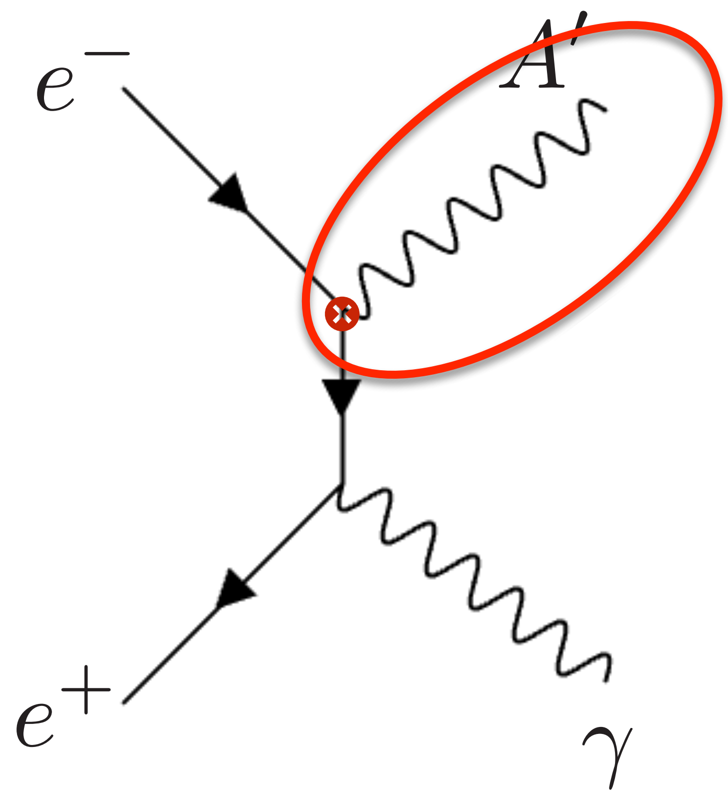
IV. Conclusion

Invisible dark photon search at BaBar

BaBar search for invisible dark photon by missing mass square from $e^-e^+ \to \gamma A'$ process:

$$M_X^2 = s - E_\gamma^* \sqrt{s}$$

which is just the invariant mass square of dark photon.

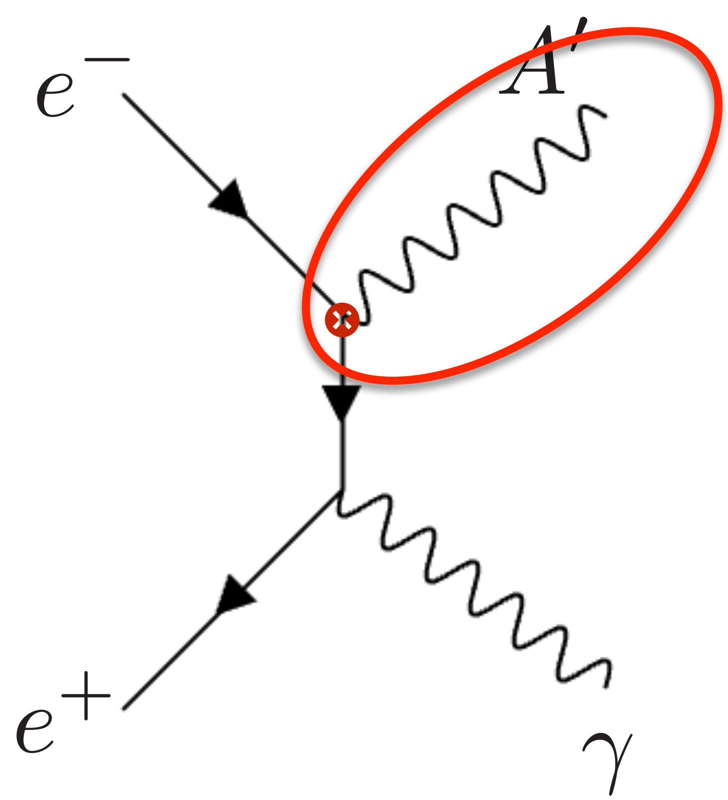


Invisible dark photon search at BaBar

BaBar search for invisible dark photon by missing mass square from $e^-e^+ \to \gamma A'$ process:

$$M_X^2 = s - E_\gamma^* \sqrt{s}$$

which is just the invariant mass square of dark photon.



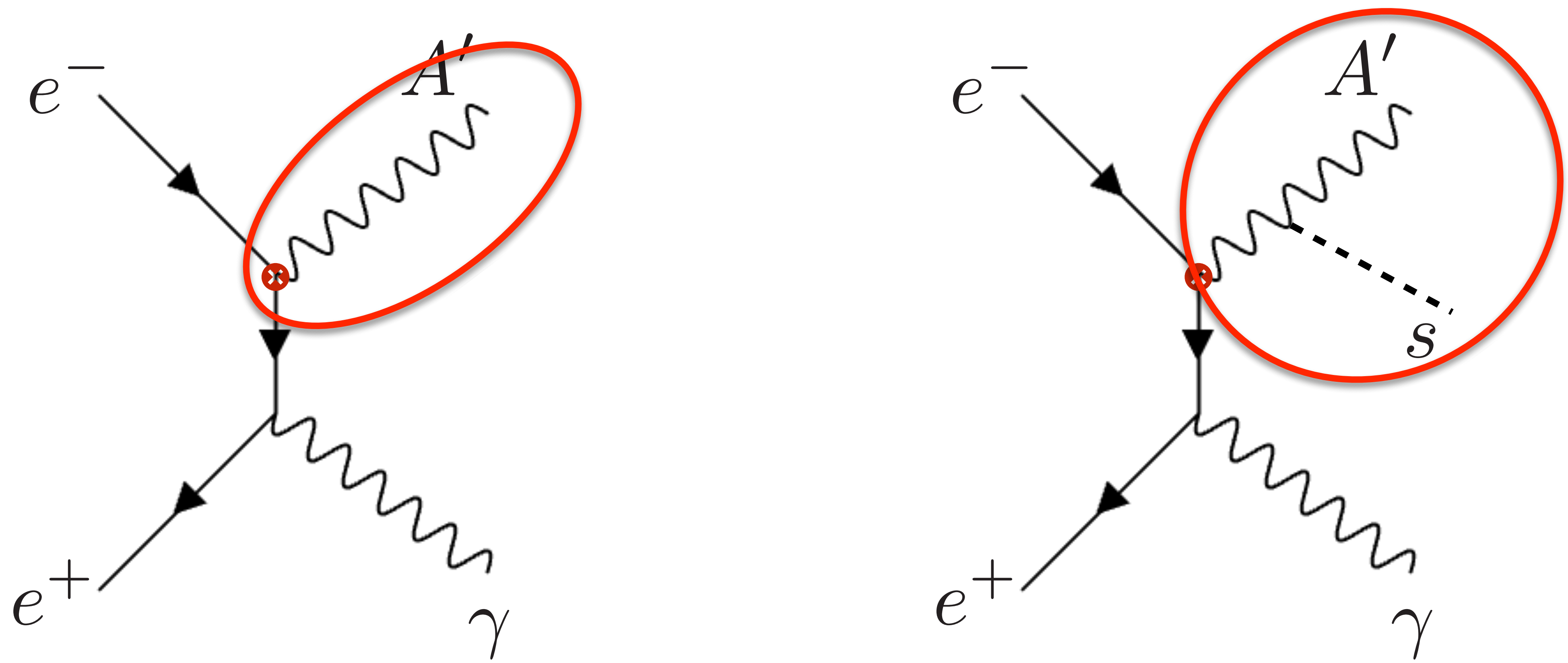
If you consider dark FSR, then M_X^2 will be invariant mass square of multiple particle system (composed by dark photon and dark Higgs).

Invisible dark photon search at BaBar

BaBar search for invisible dark photon by missing mass square from $e^-e^+ \to \gamma A'$ process:

$$M_X^2 = s - E_\gamma^* \sqrt{s}$$

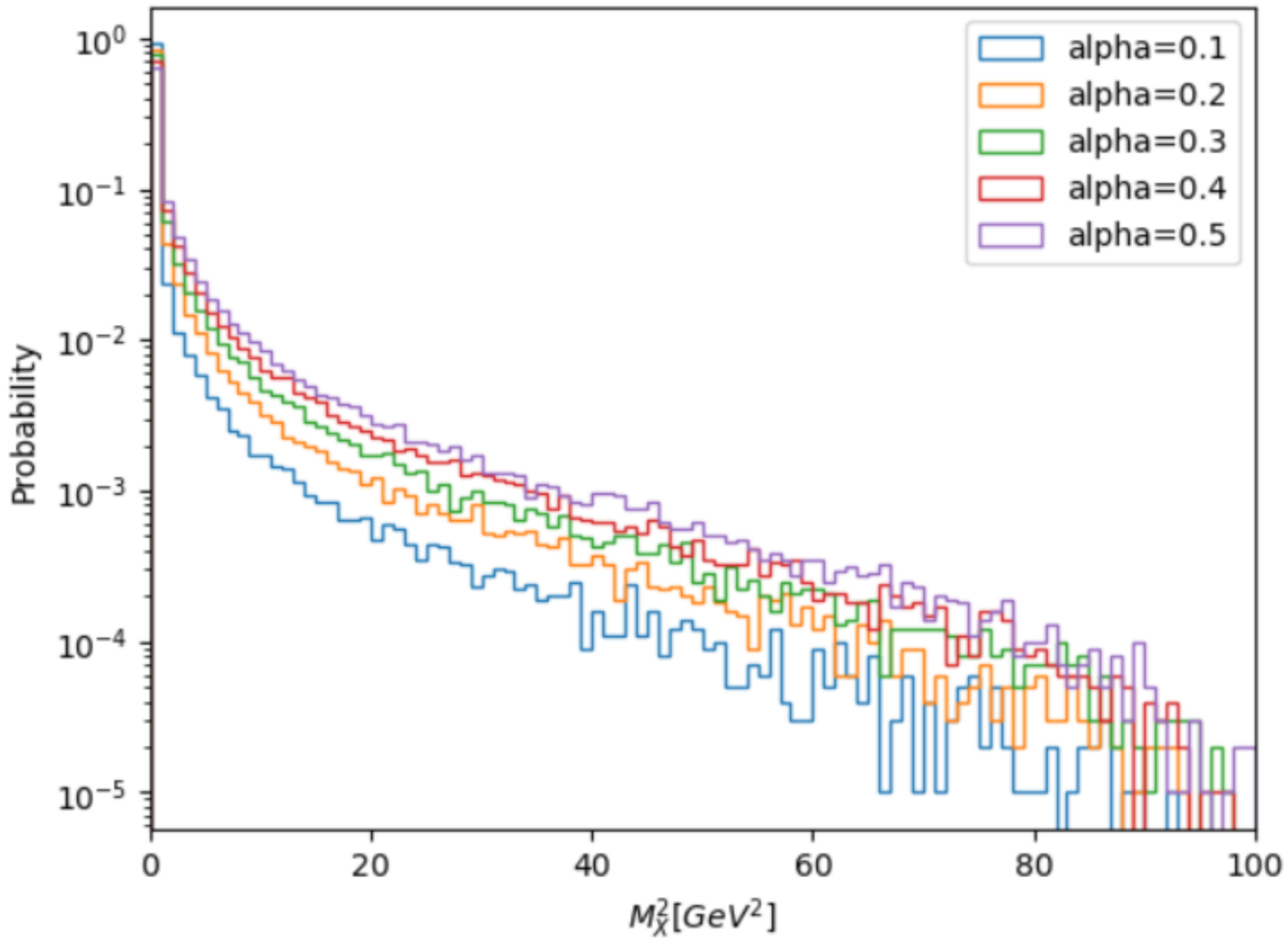
which is just the invariant mass square of dark photon.



If you consider dark FSR, then M_X^2 will be invariant mass square of multiple particle system (composed by dark photon and dark Higgs). So you expect to see a broader M_X^2 distribution.

Invisible dark photon search at BaBar

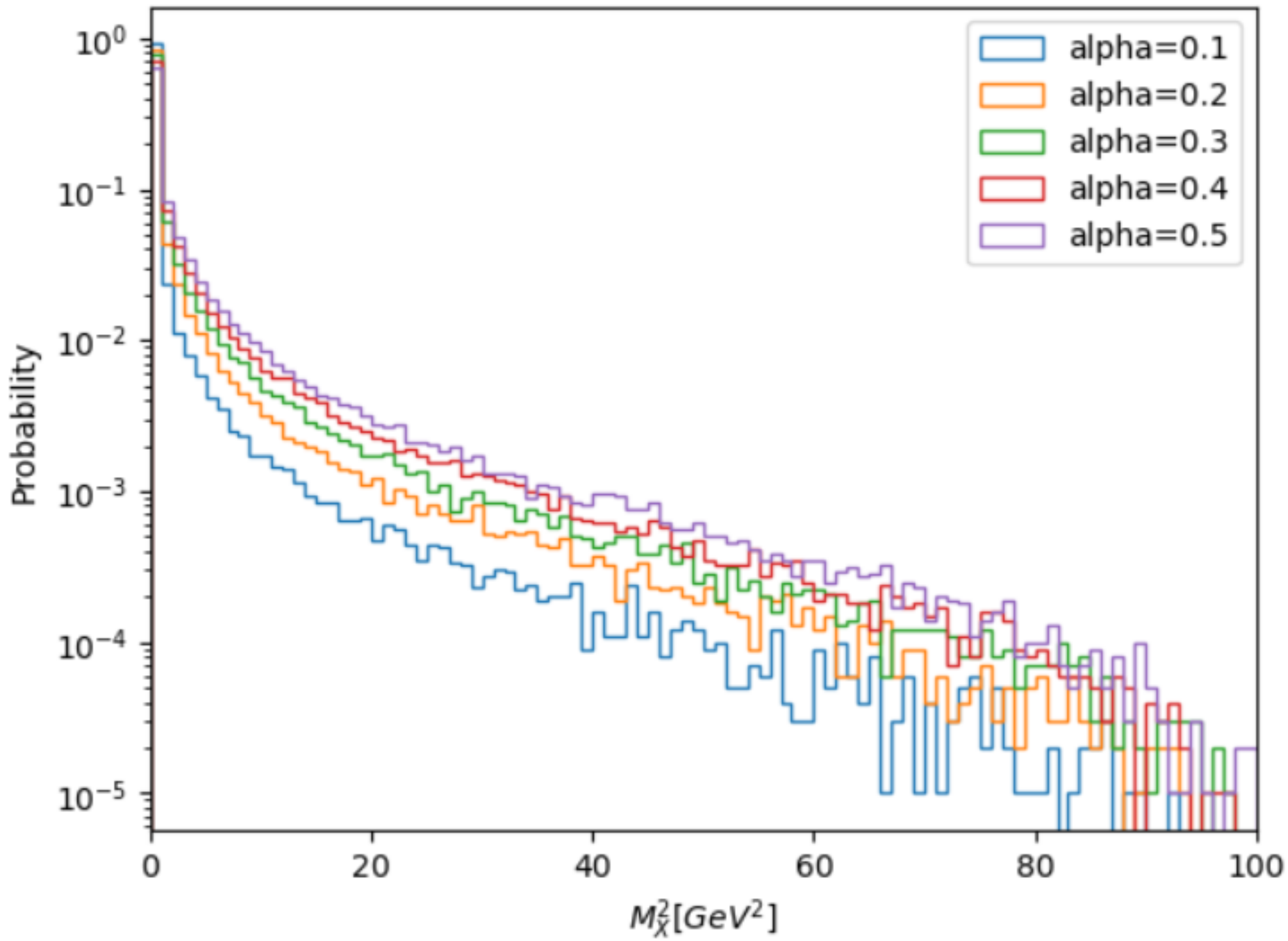
Simulation result is like (for $m_{A'} \ll 1$ GeV):



Dark Higgs will give you a "tail" in the M_X^2 distribution. If we can see the tail, we can say there is a dark Higgs.

Invisible dark photon search at BaBar

Simulation result is like (for $m_{A'} \ll 1$ GeV):

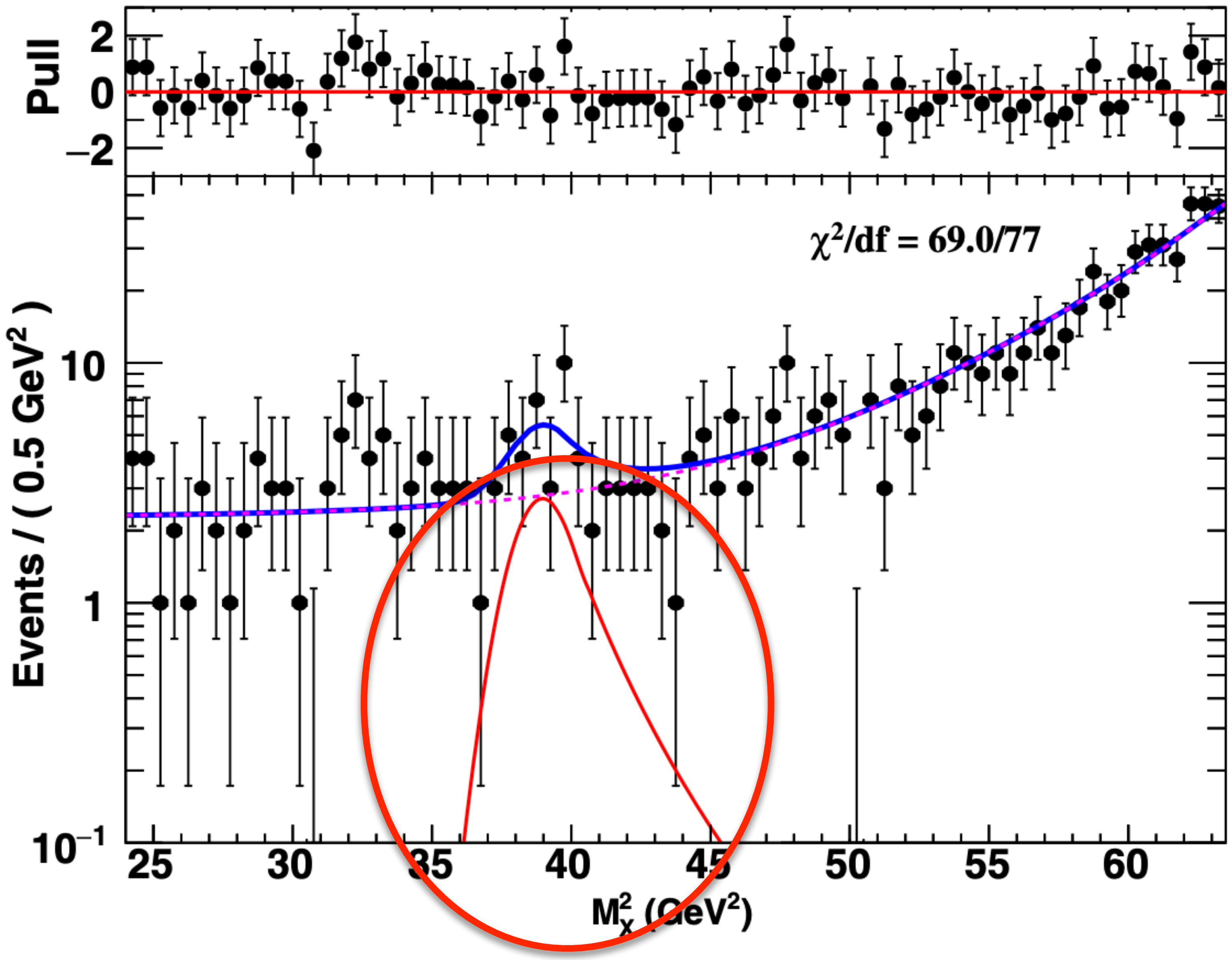


Dark Higgs will give you a "tail" in the M_X^2 distribution. If we can see the tail, we can say there is a dark Higgs.

But, be careful, this distribution is "particle level" distribution, not "detector level" distribution.

Invisible dark photon search at BaBar

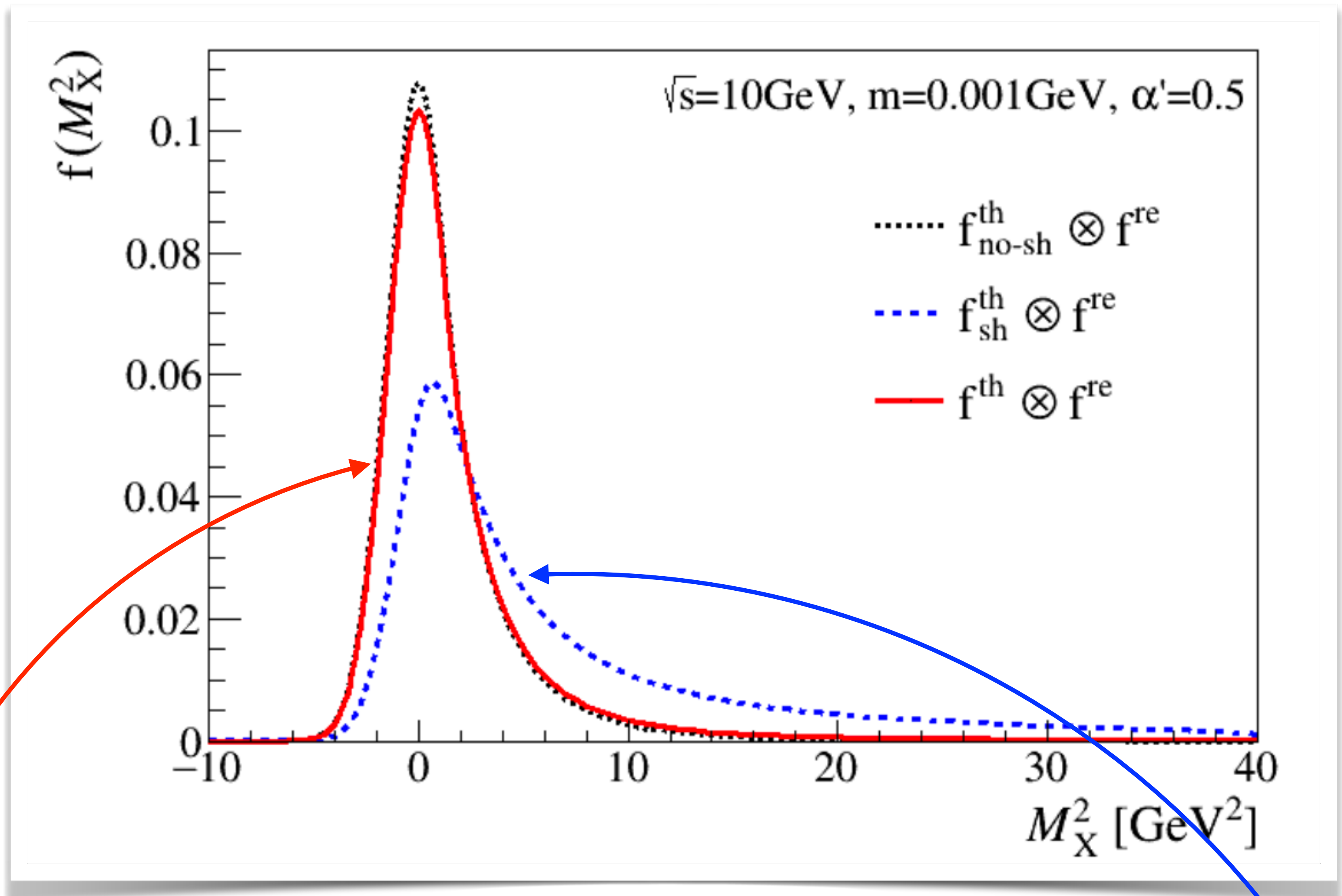
Detector effect at BaBar promote the narrow "spike" into a "Crystalball":



A Crystalball with width 5 GeV^2

Invisible dark photon search at BaBar

So, to include the detector effect, we need to dress up the “particle level” distribution by this Crystalball function. Then….

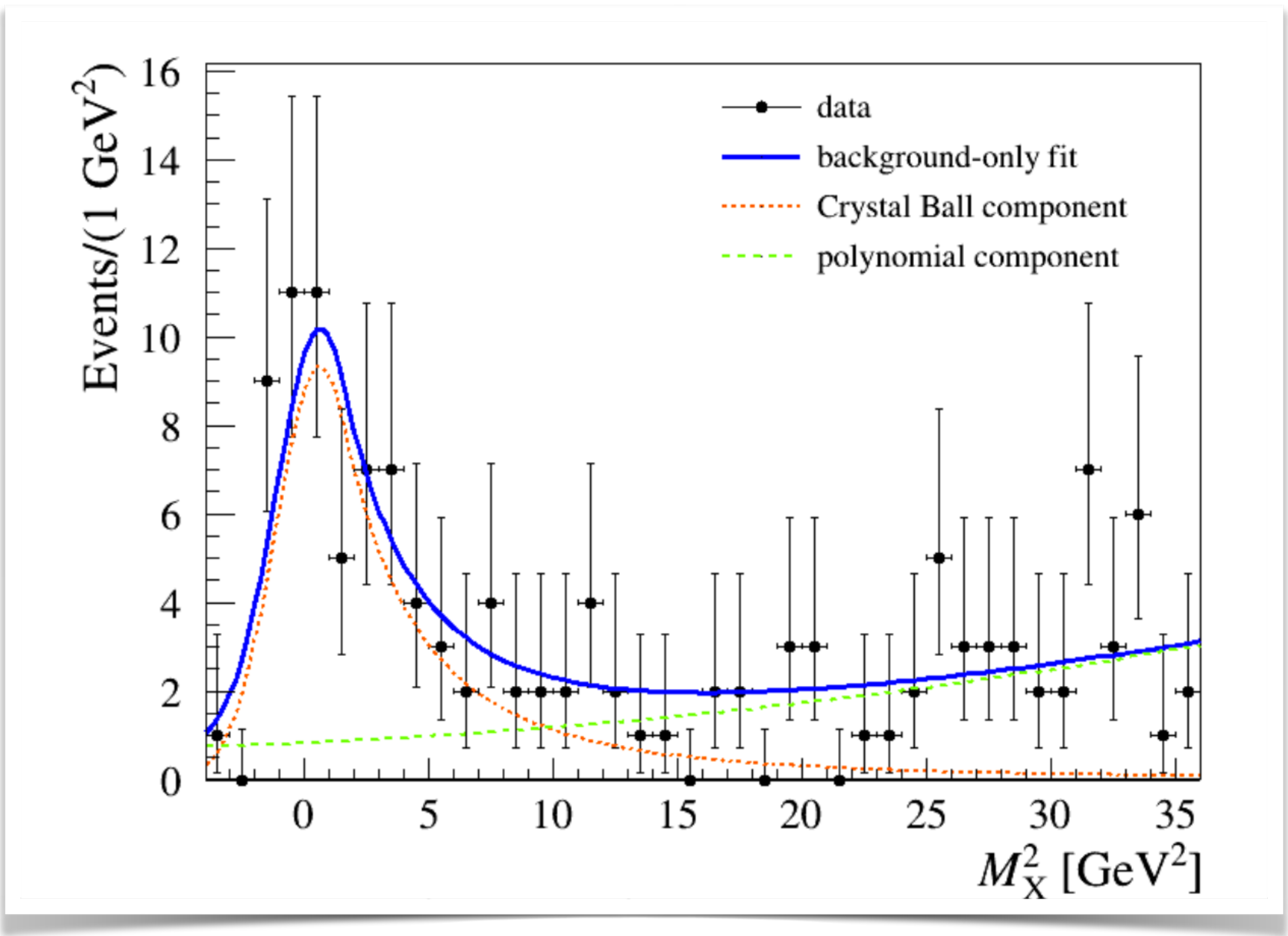


without dark shower

with dark shower

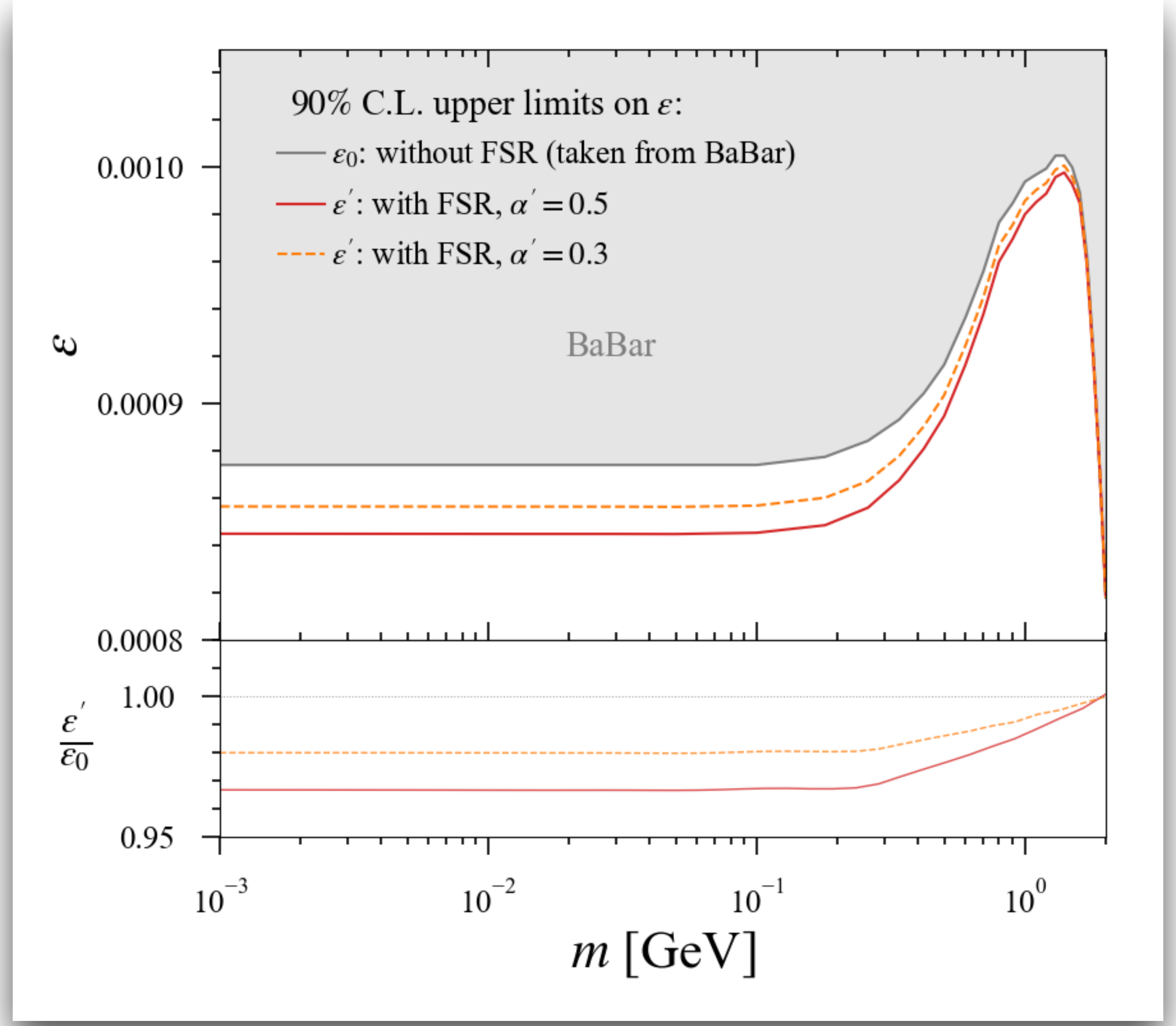
Invisible dark photon search at BaBar

Even the detector effect makes the impact from dark Higgs weak, but we can still perform a bin-by-bin fit to update the Babar limit.
Thanks to the detailed information given by BaBar report.



Invisible dark photon search at BaBar

Even the detector effect makes the impact from dark Higgs weak, but we can still perform a bin-by-bin fit to update the Babar limit.
Thanks to the detailed information given by BaBar report.



Conclusion

Generally speaking, we need to consider dark Higgs (s) when we study dark photon (A').

For invisible dark photon search at ep collider, we can consider NLO process $e^- e^+ \to \gamma A' s$.

But the Dark FSR process $A' \to A' s$ needs to be described by dark shower when s and A' are very light.

Merging is required to obtain correct distribution.

Detector effect at BaBar make the impact of dark Higgs very weak.

For CEPC

(1) What is the single-photon BKG estimation at CEPC?

(real detector simulation is required)

(2) What is the resolution of squared missing mass at CEPC?