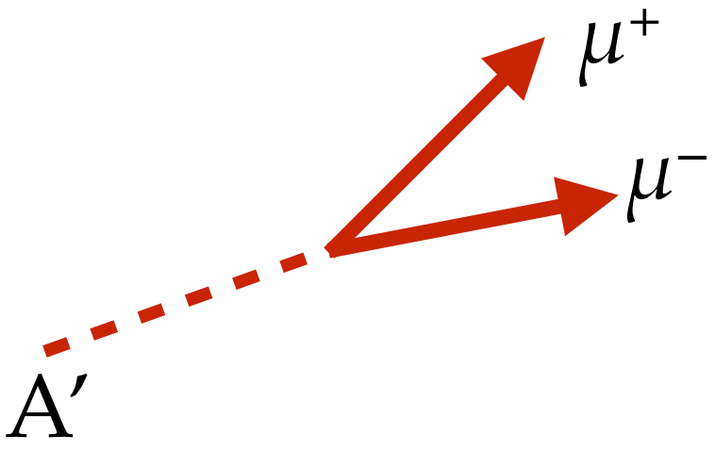
Exploring Dark Photons
from Colliders to Cosmos

Wei Xue

Dec 12, 2019
NCTS Annual Meeting

UF | UNIVERSITY of FLORIDA

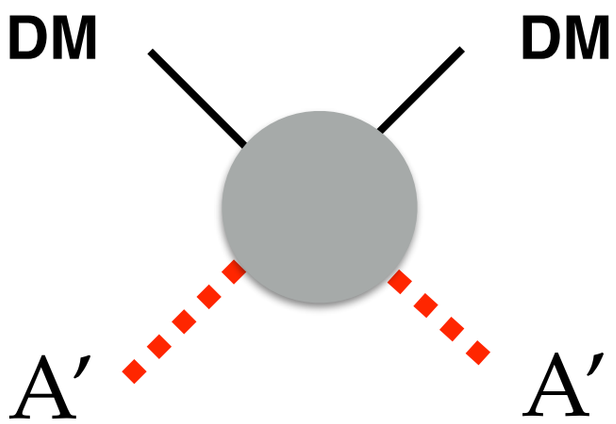
Plans



Colliders

dark photon searches with dimuon final states

and beyond dark photon



Cosmology, Galaxies and Stars

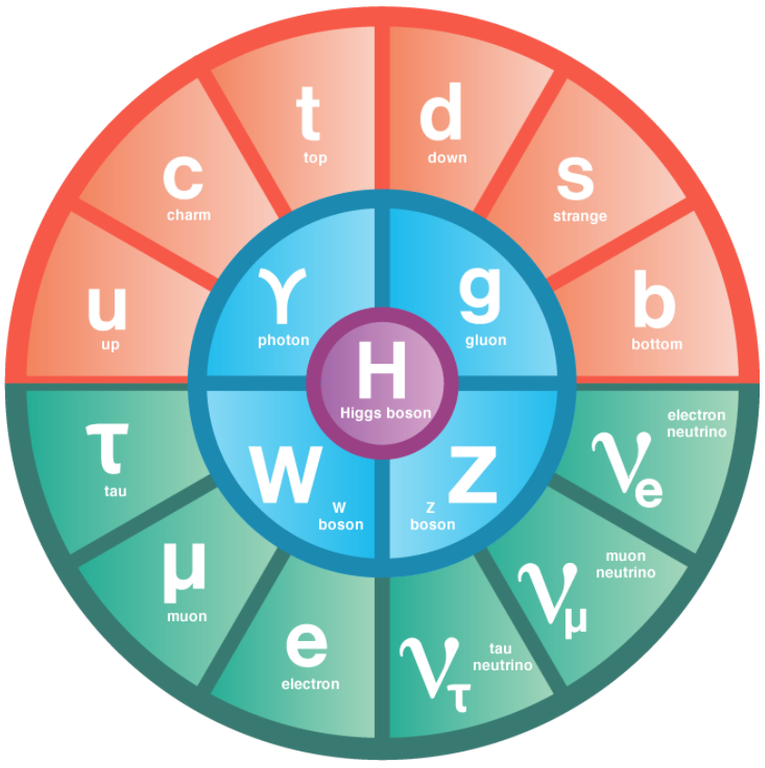
dark photon dark matter

production , small scale issues

detections

WIMP

weakly interacting massive particles



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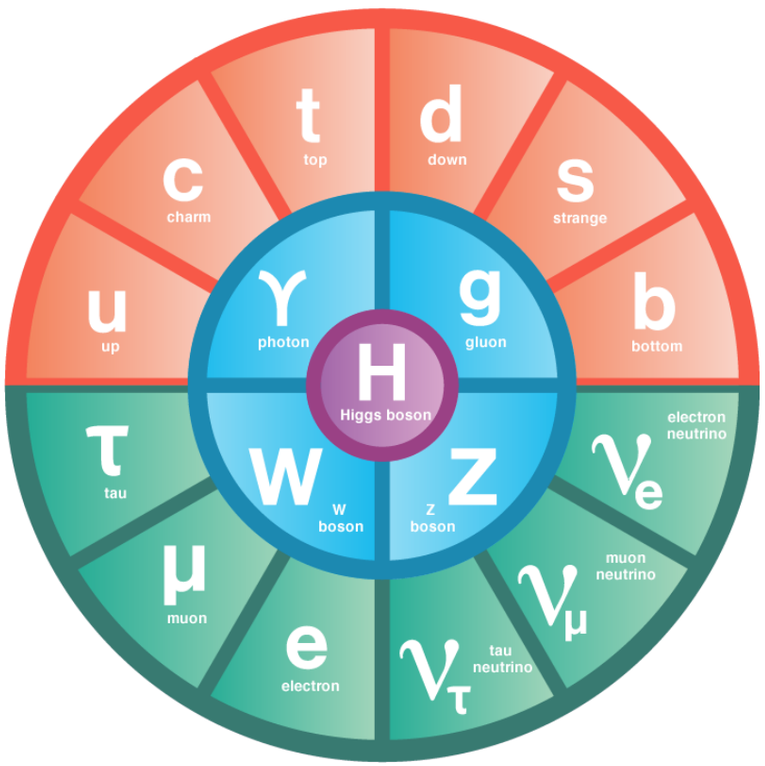
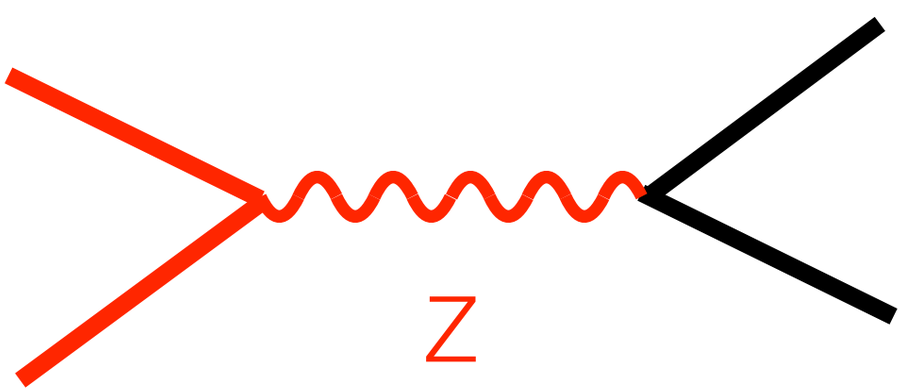
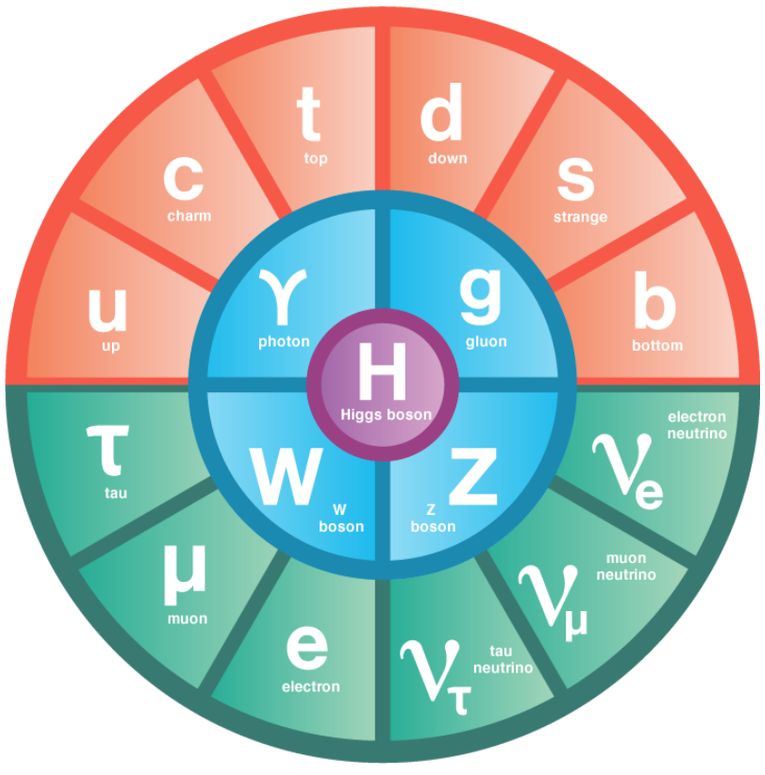
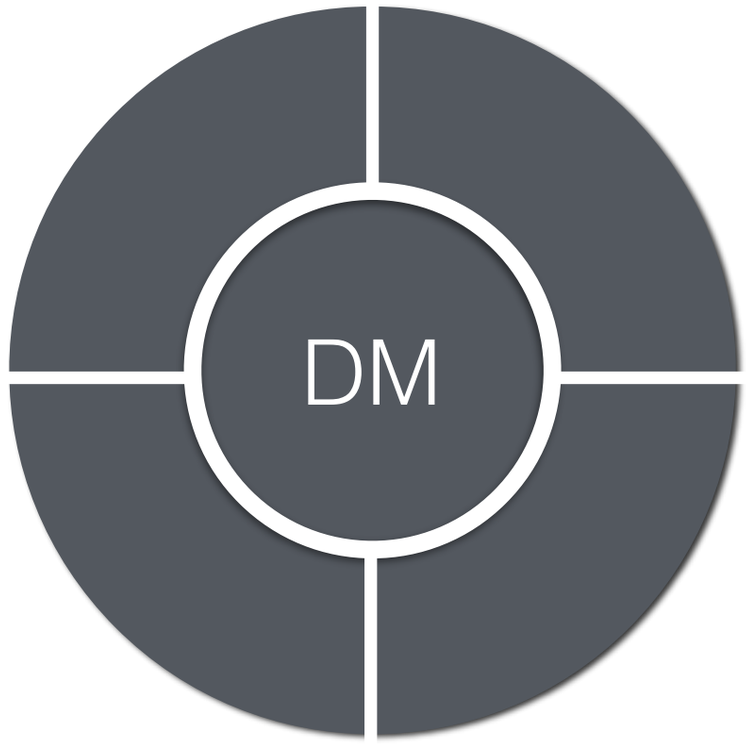




Dark Sector?

- analogous to the Standard Model
  dark sector can have rich structures





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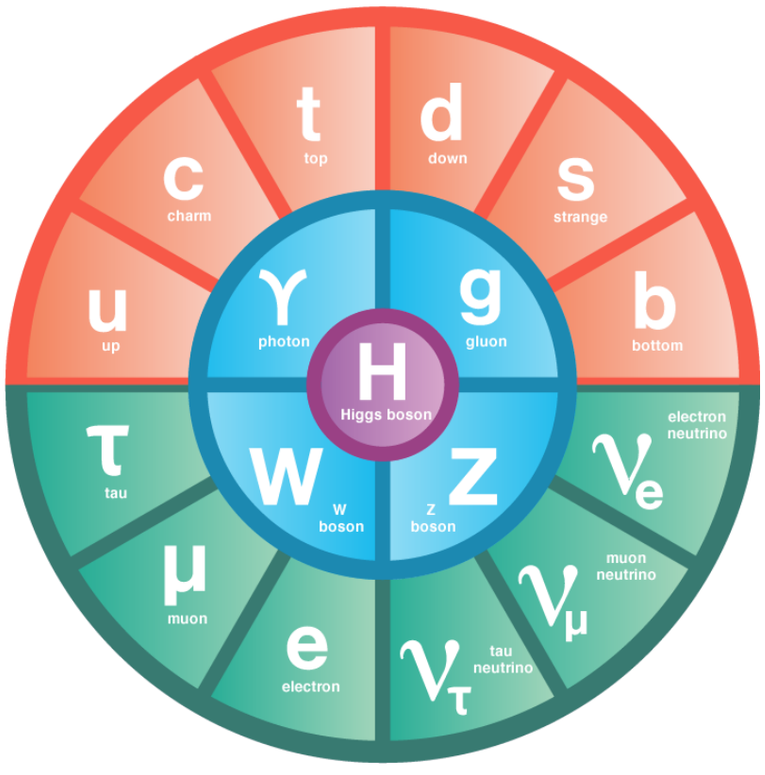

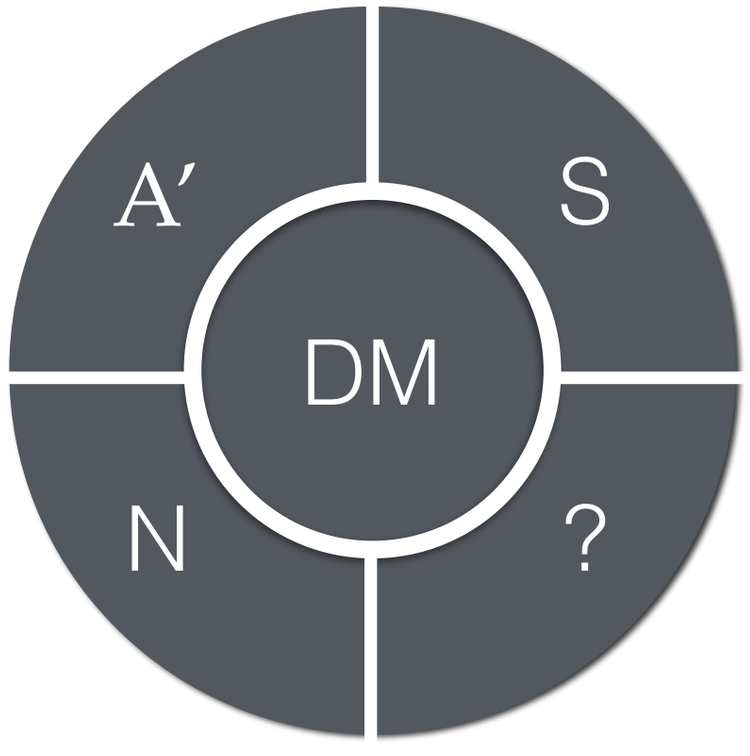

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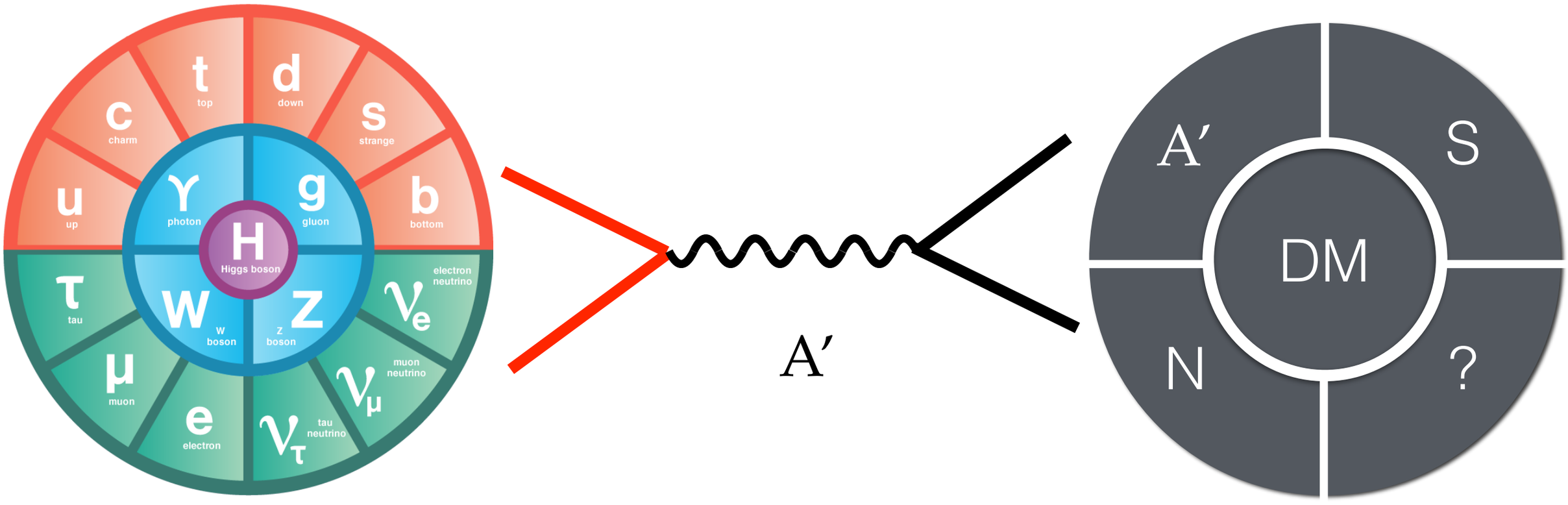
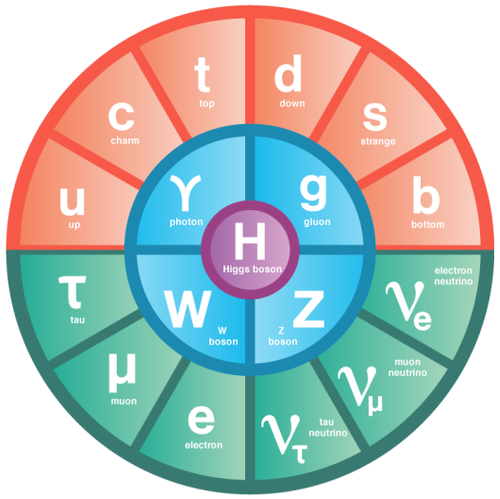


Dark Photons

- U(1)’ dark photon can kinetically mix with photon



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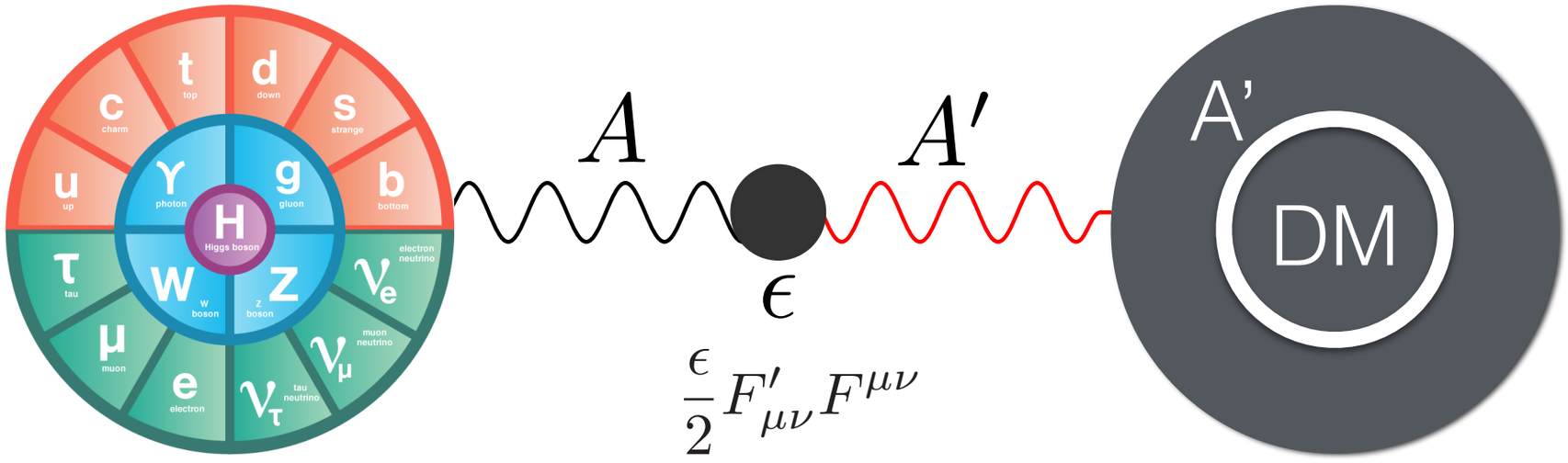

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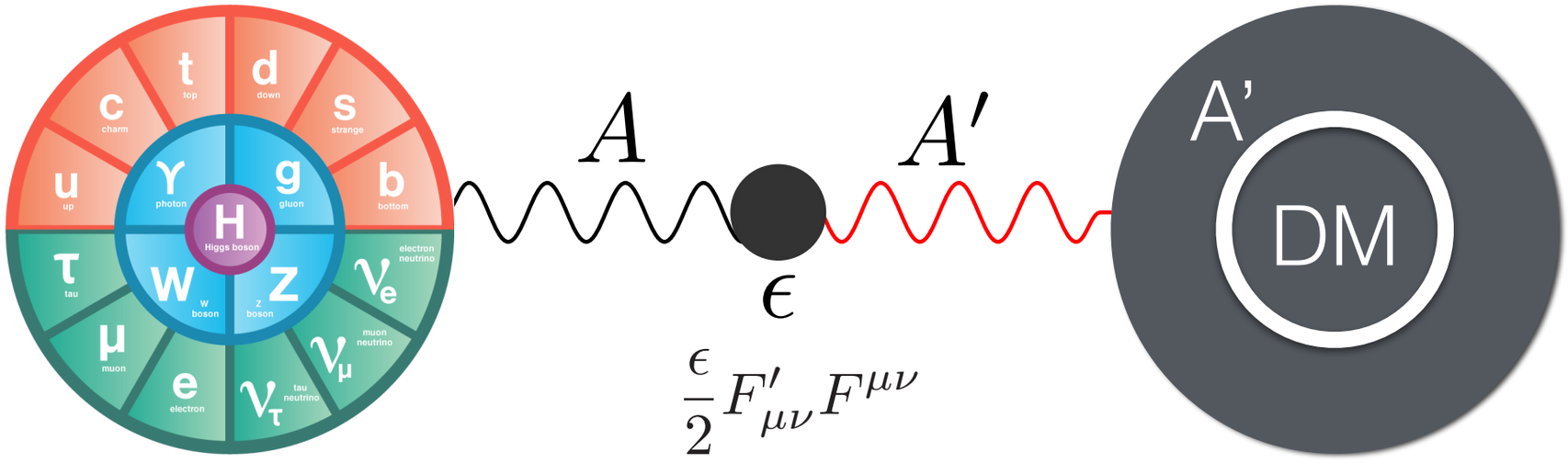

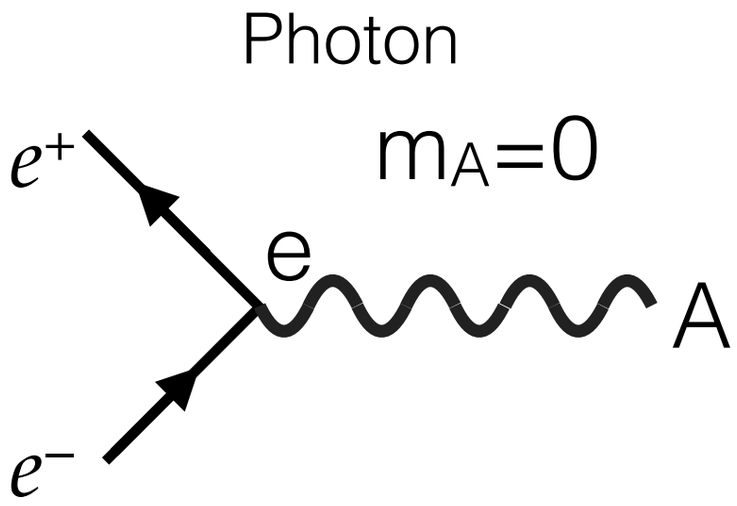

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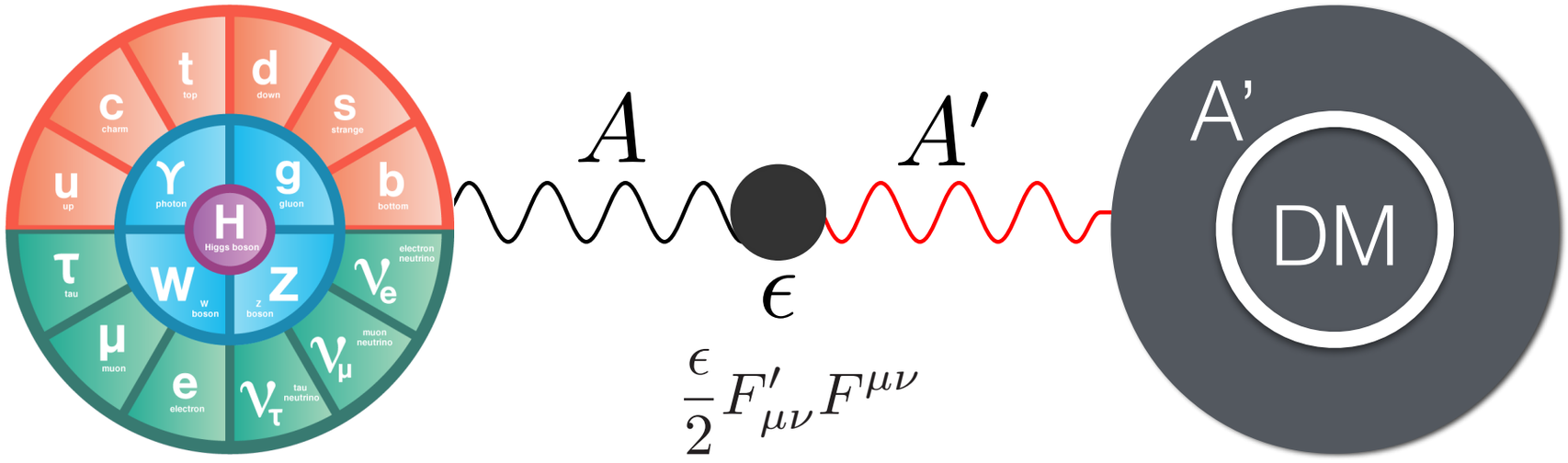
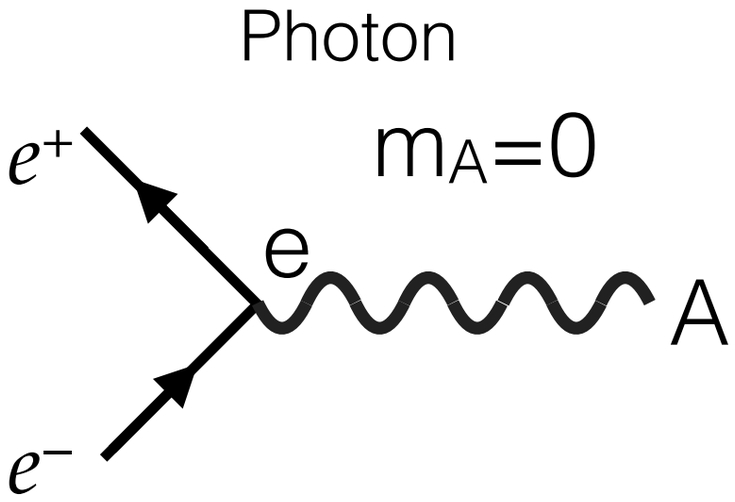
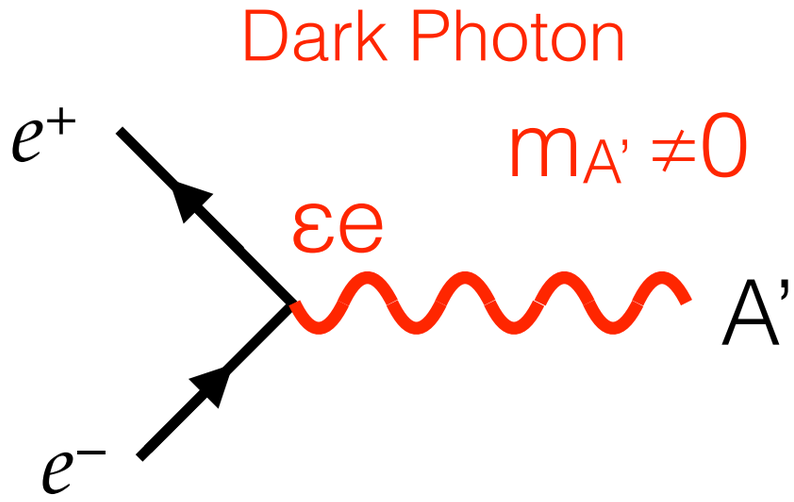
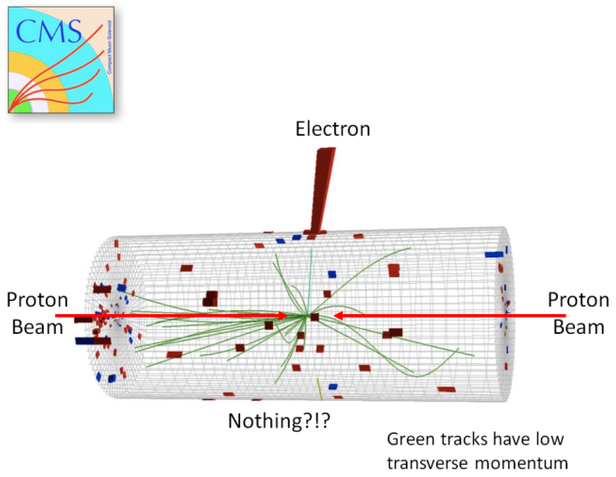
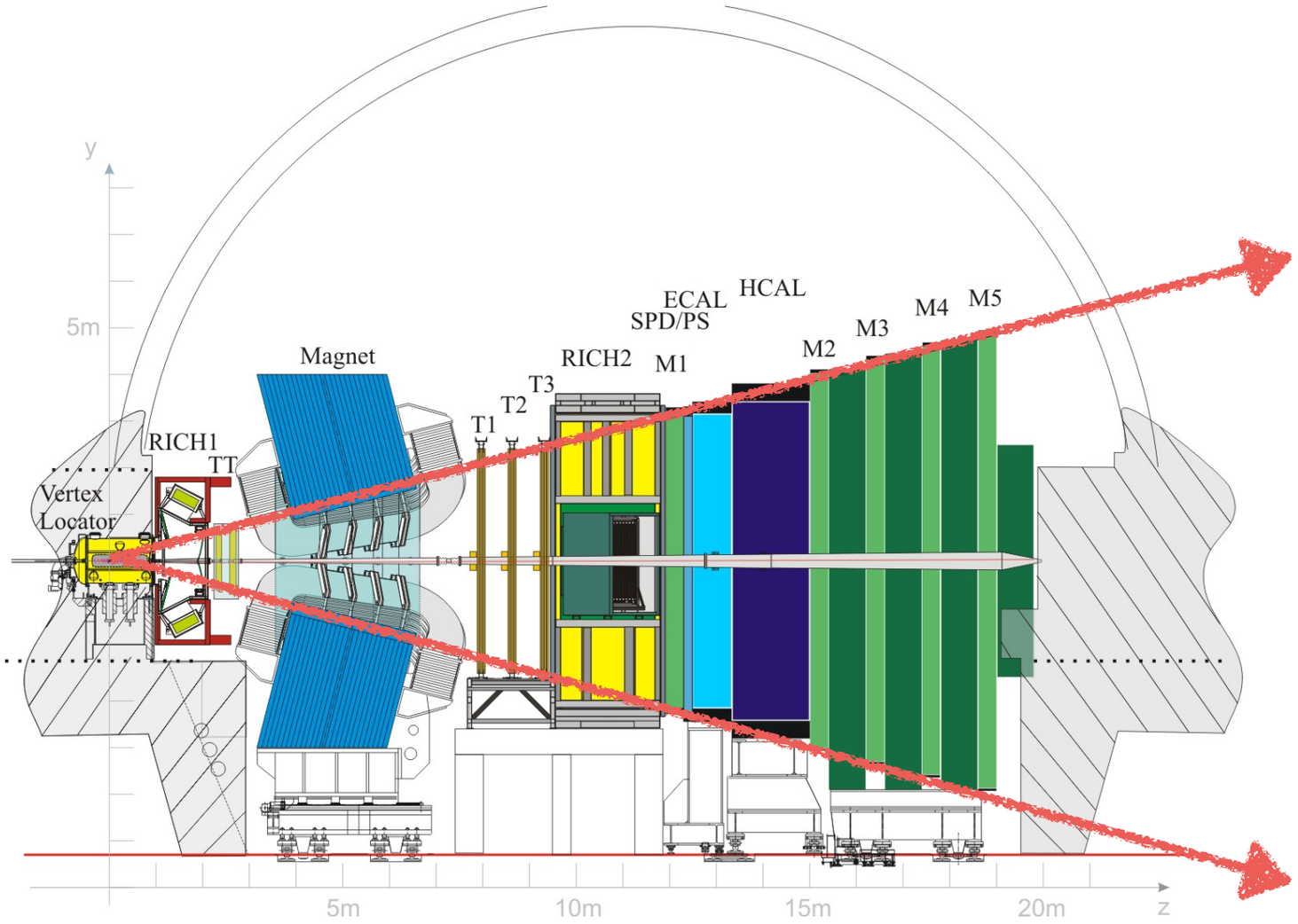






How about LHCb?





LHCb

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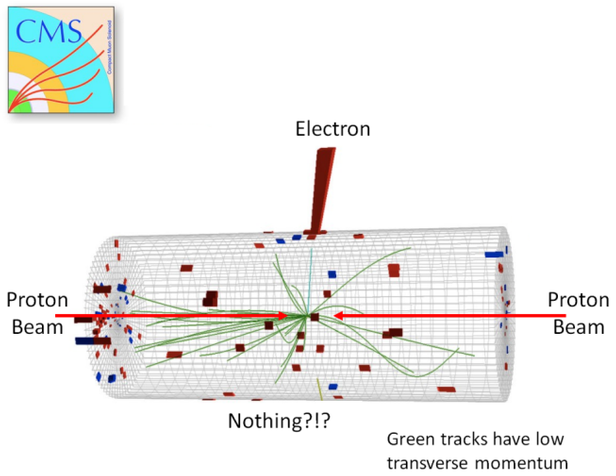
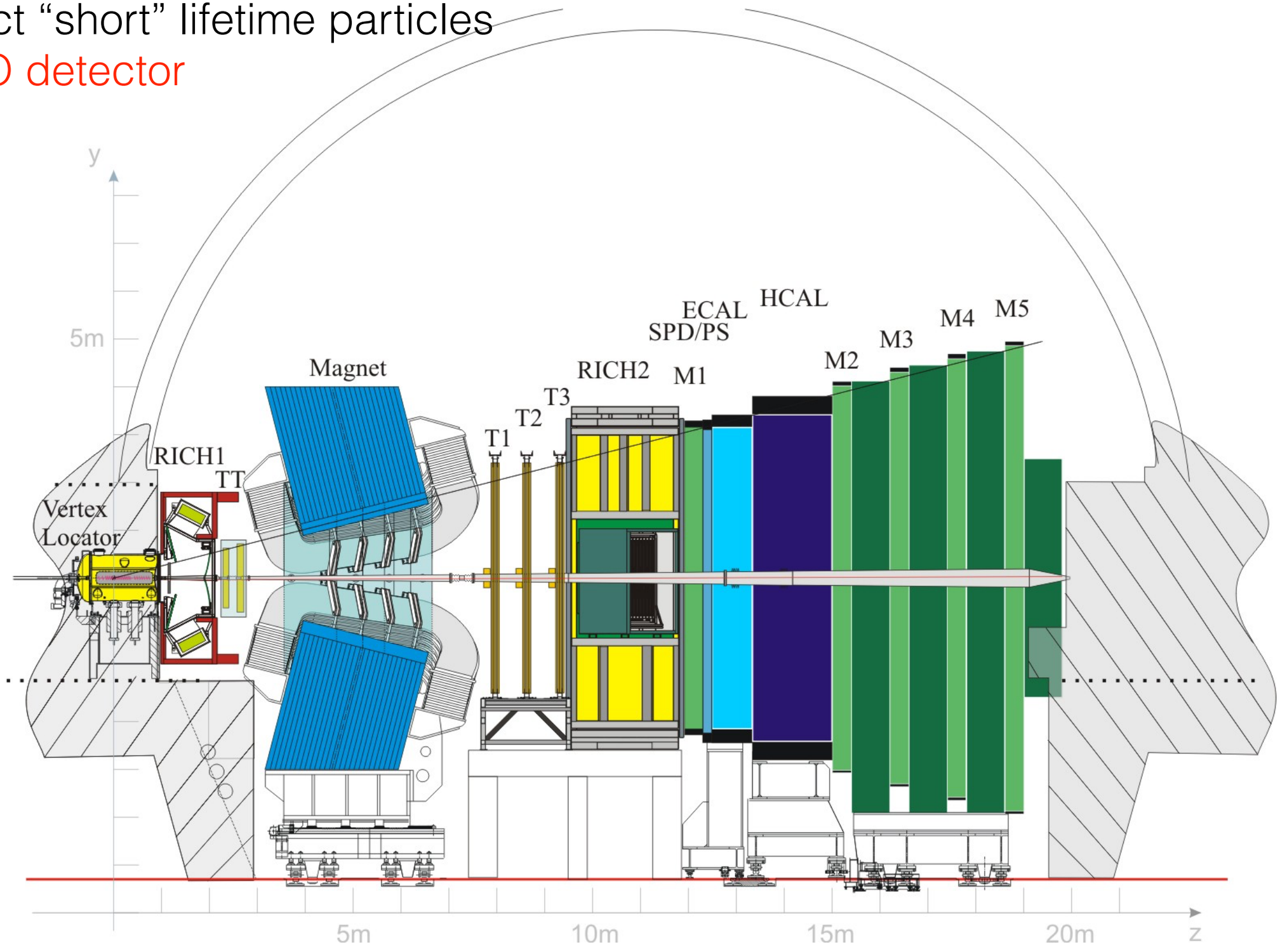


???

LHCb

Why LHCb?

- detect “short” lifetime particles
  VELO detector



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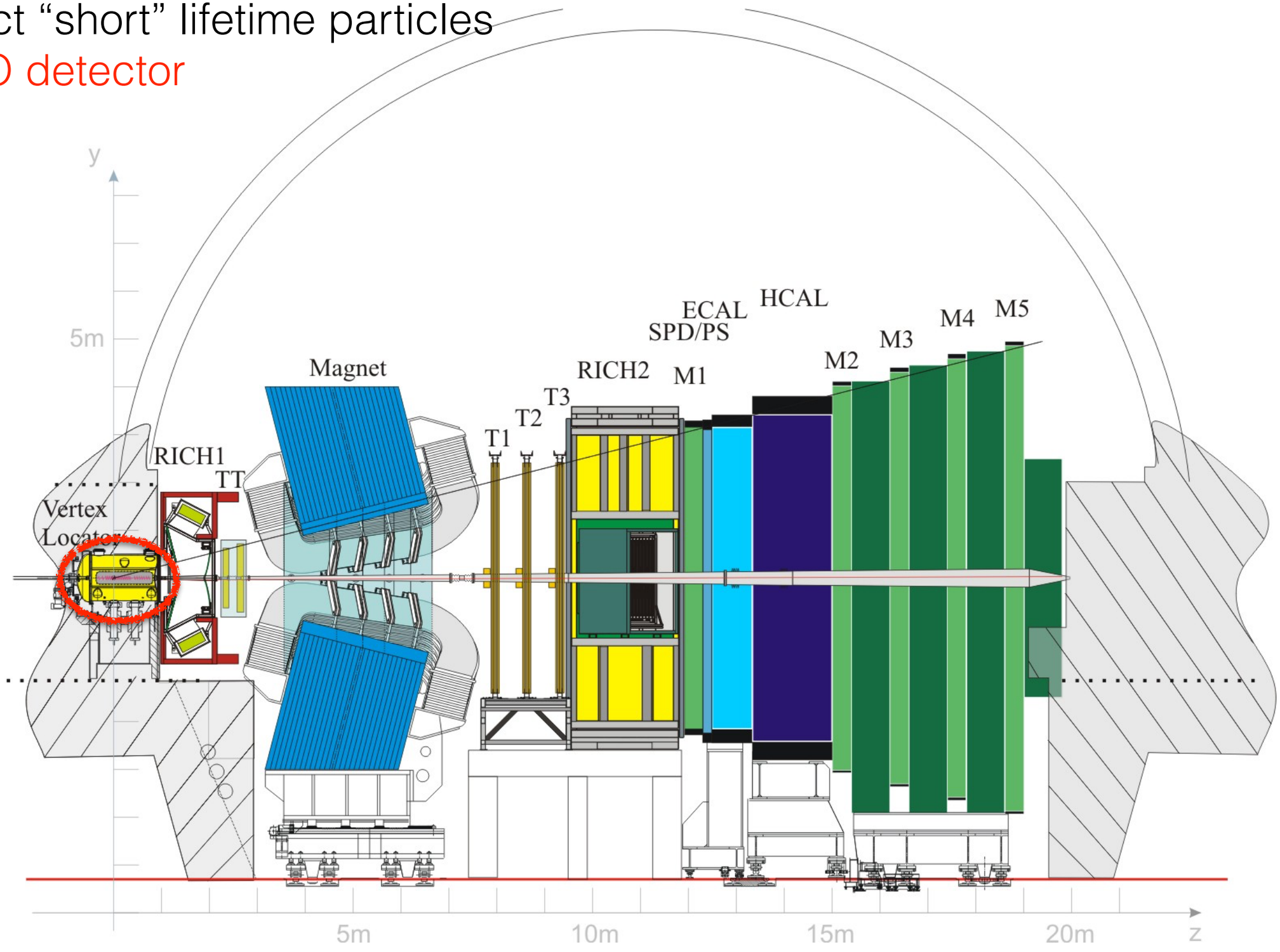

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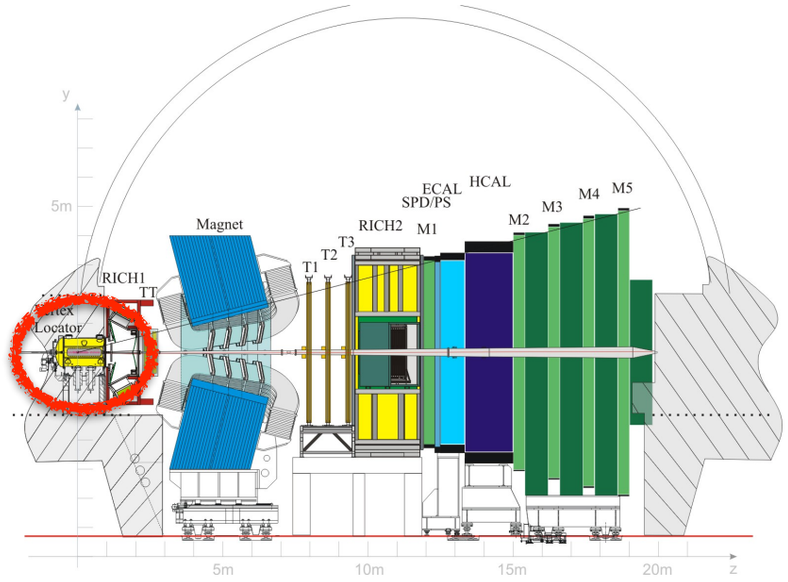

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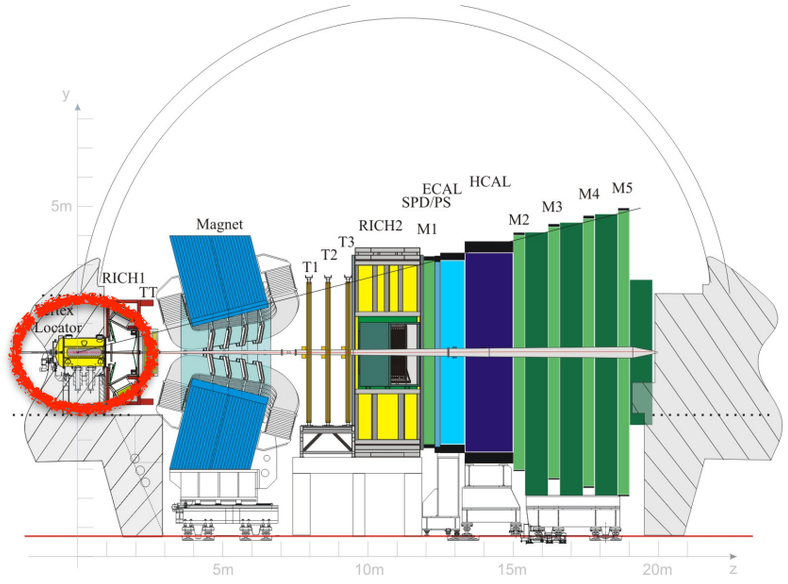

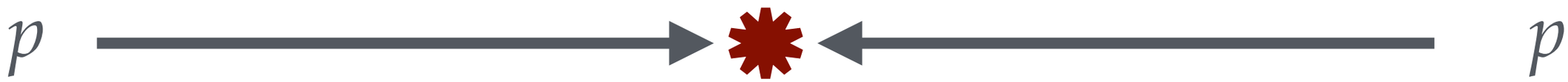

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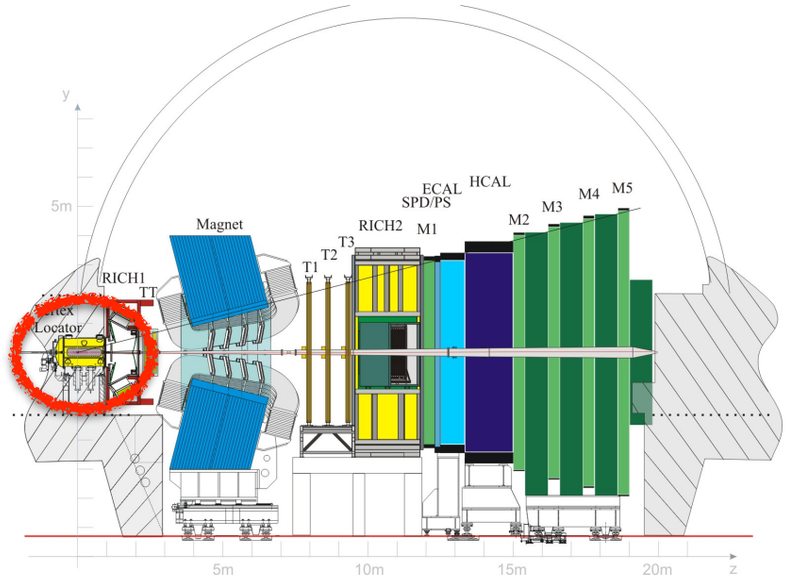

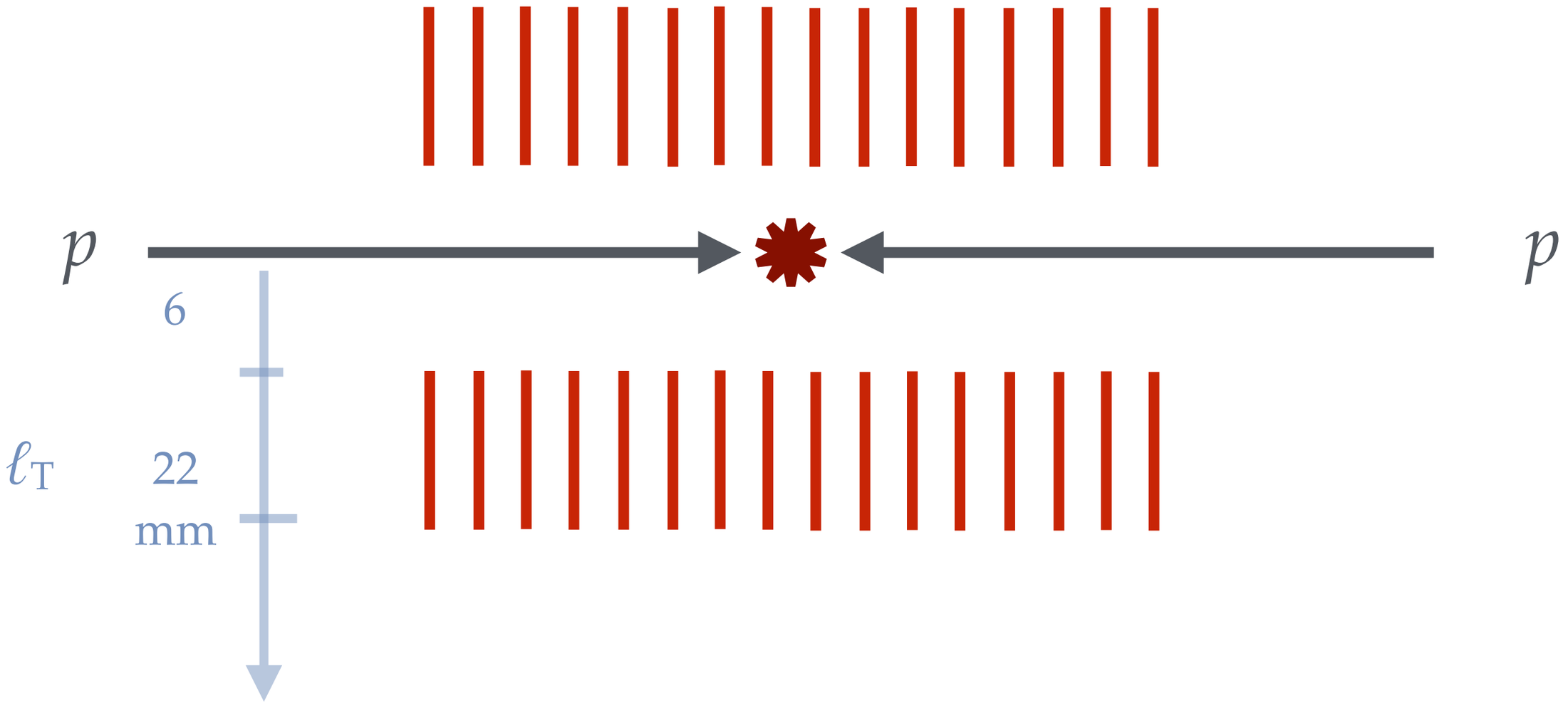

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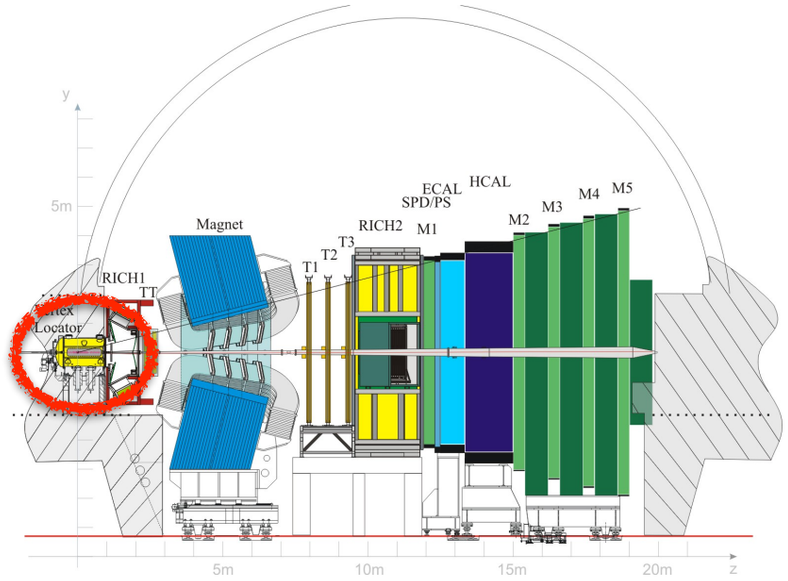

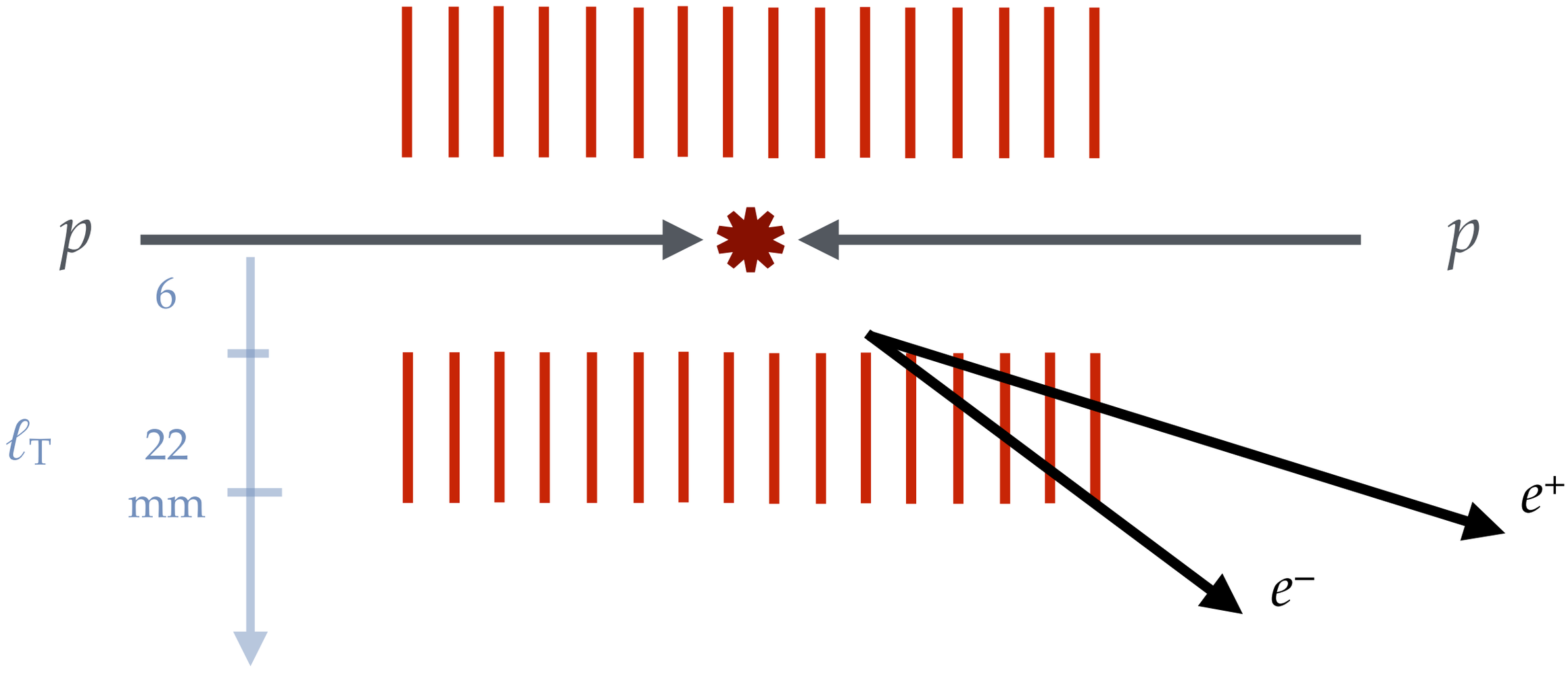

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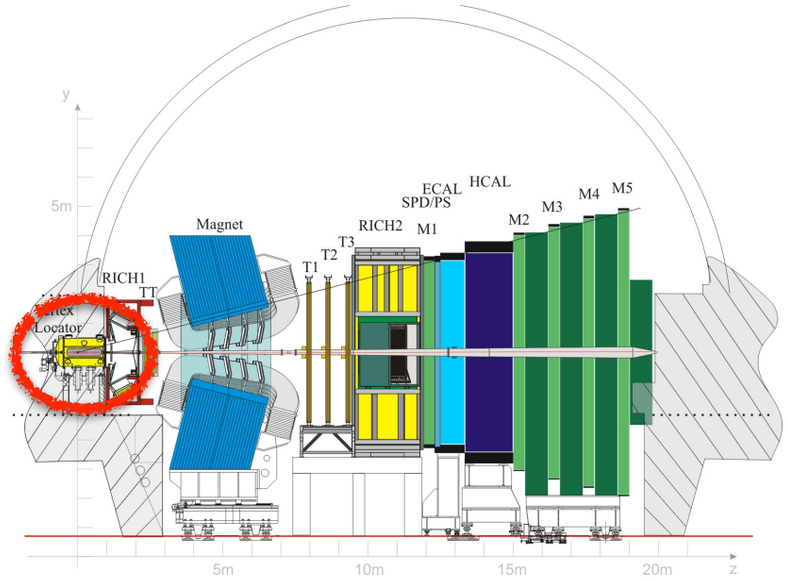
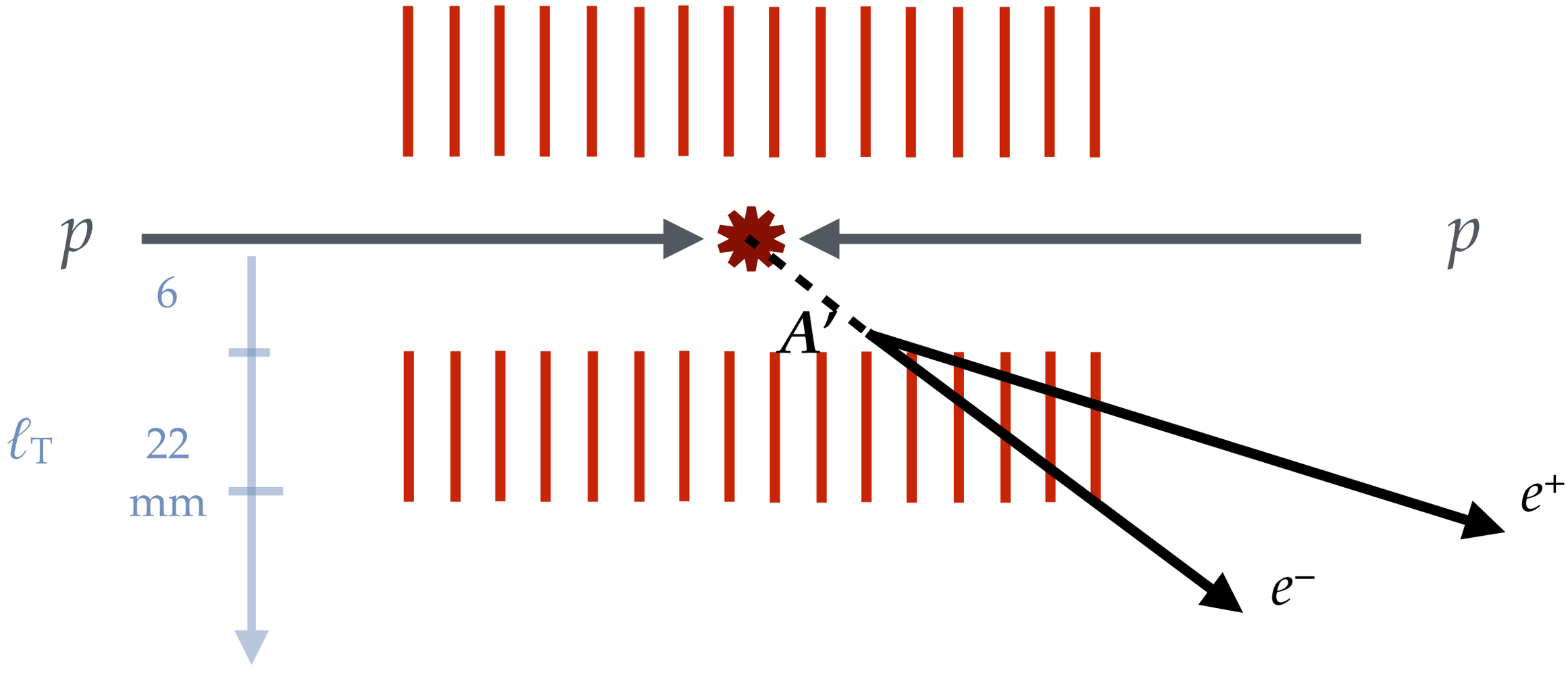
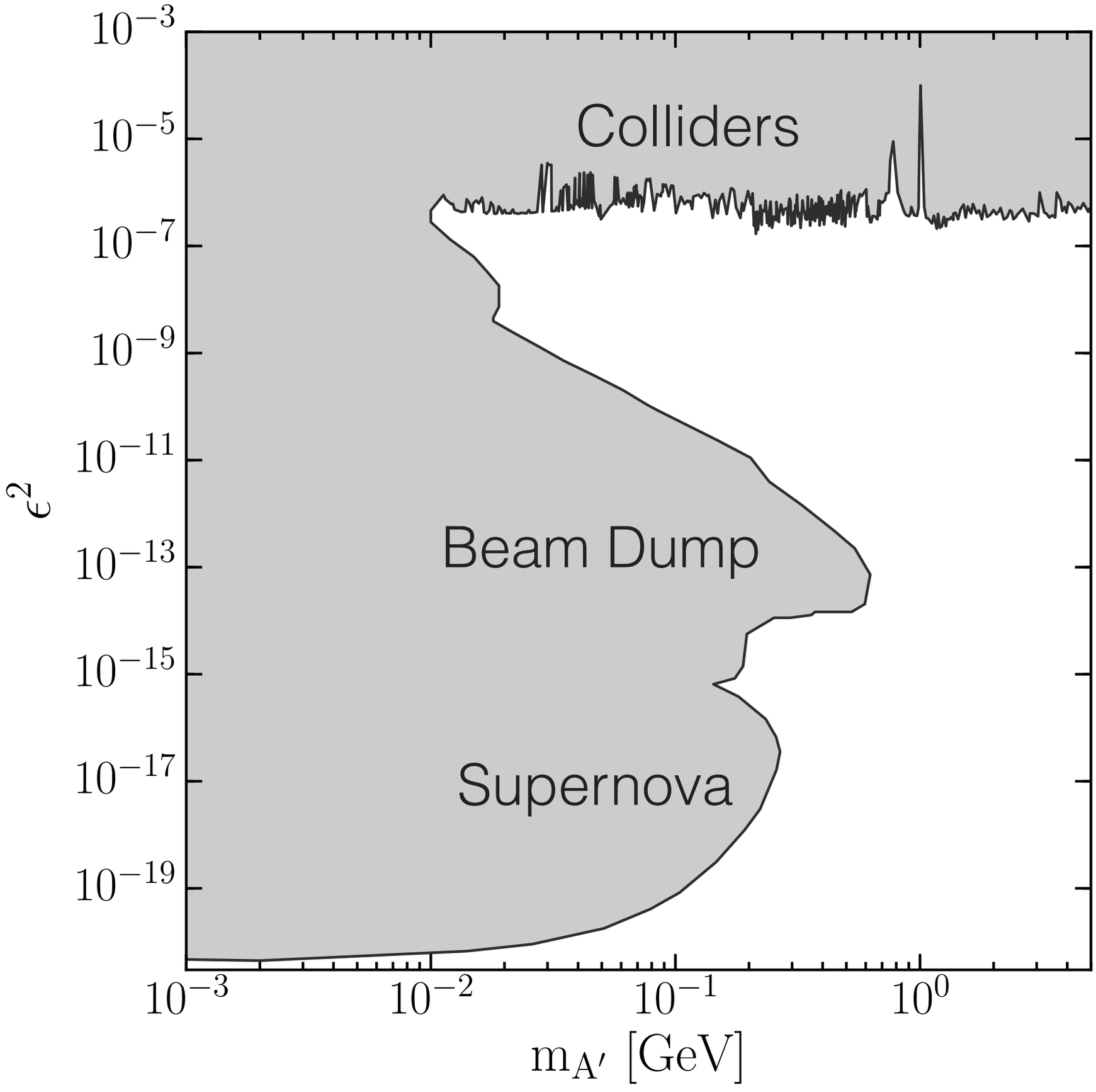
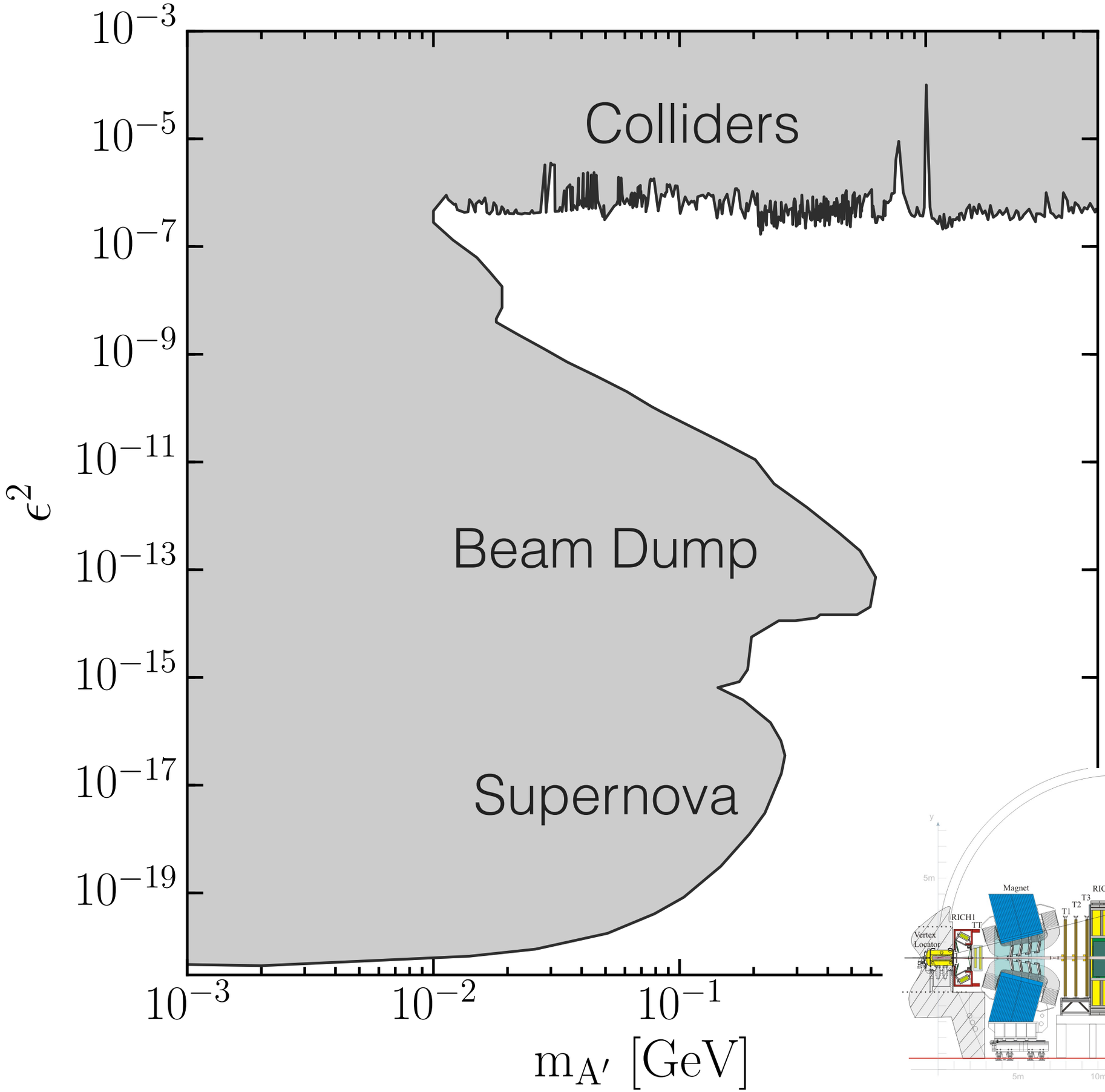





Colliders
Beam Dump
Supernova
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
ϵ^2
10^{-3}
10^{-2}
10^{-1}
10^{0}
$m_{A'}$ [GeV]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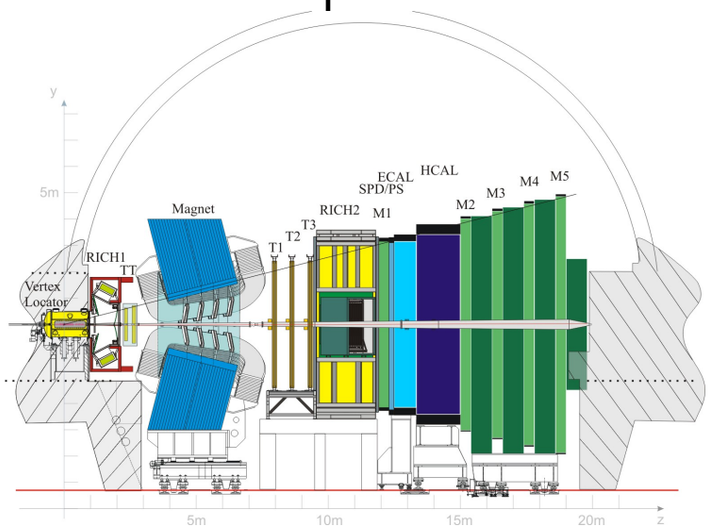
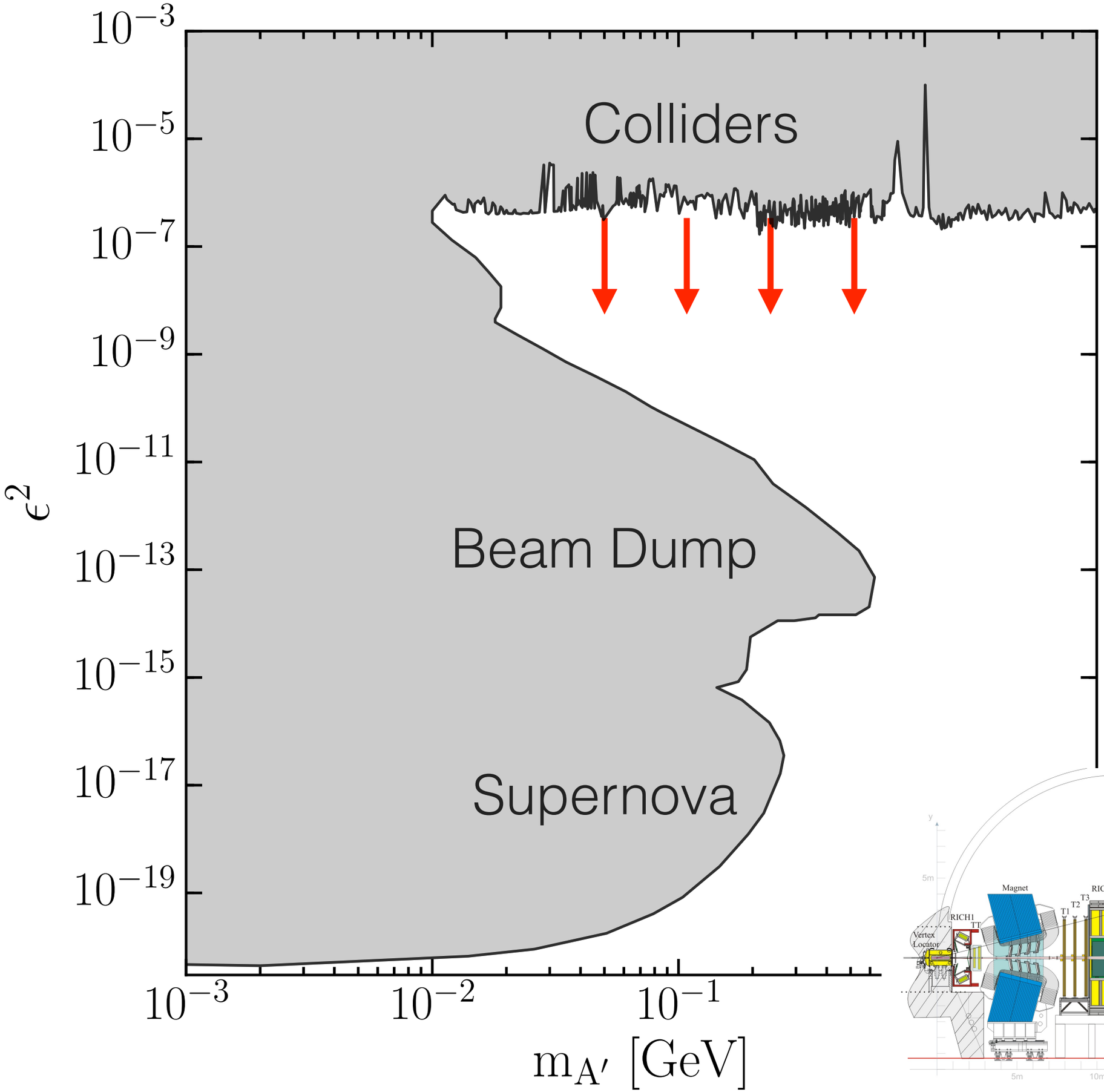

y
5m
Magnet
RICH2
ECAL
HCAL
SPD/PS
M1
M2
M3
M4
M5
T1
T2
T3
RICH1
TT
Vertex Locator
5m
10m
15m
20m
z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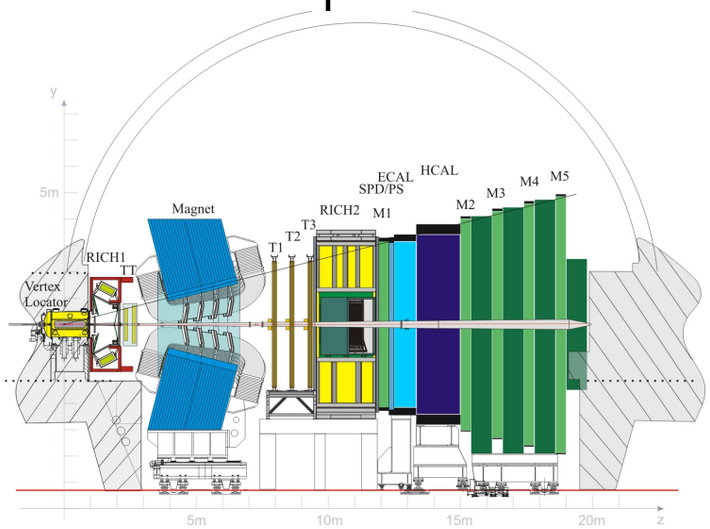
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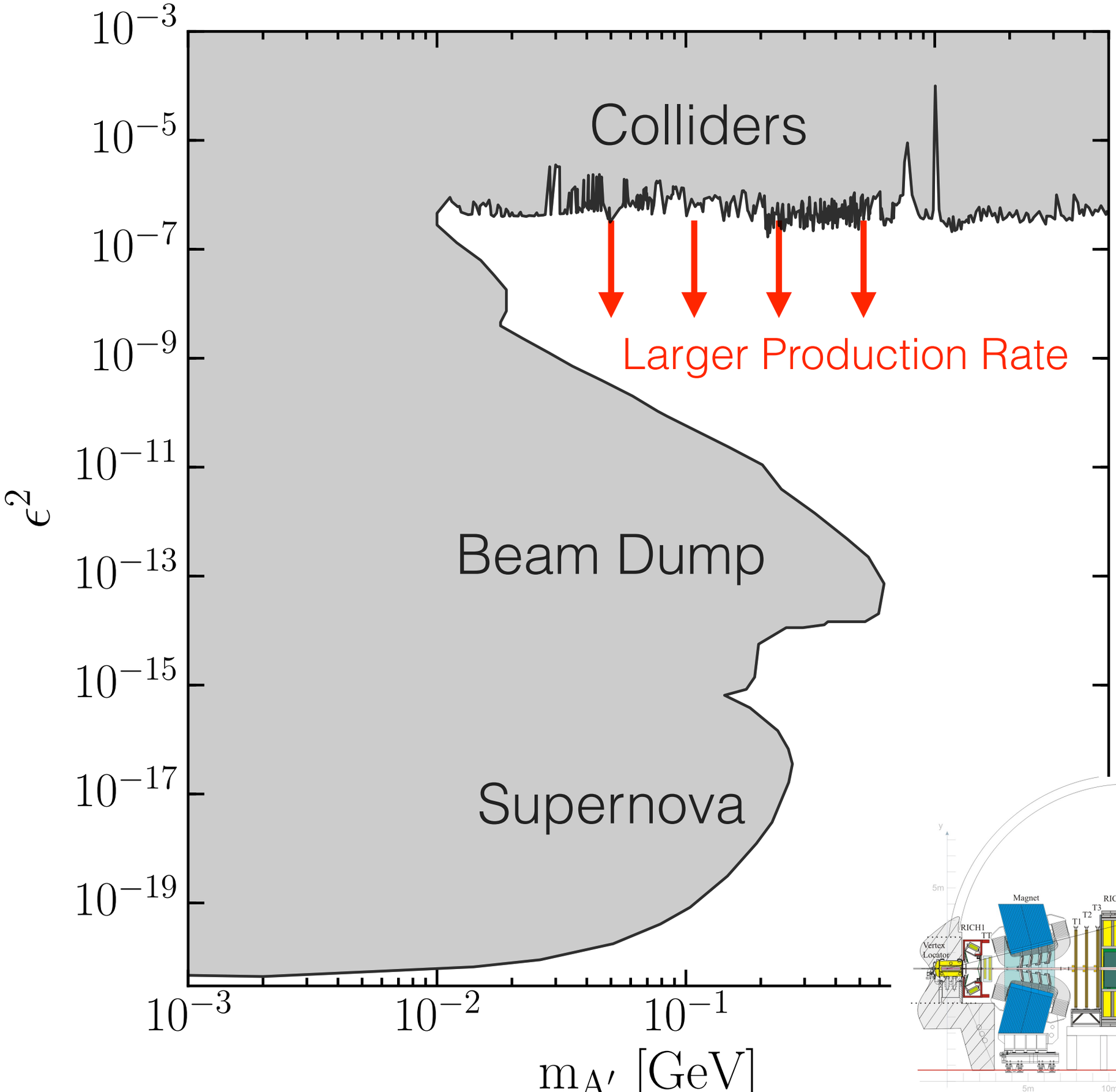
Colliders
Larger Production Rate
Beam Dump
Supernova
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
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ϵ^2
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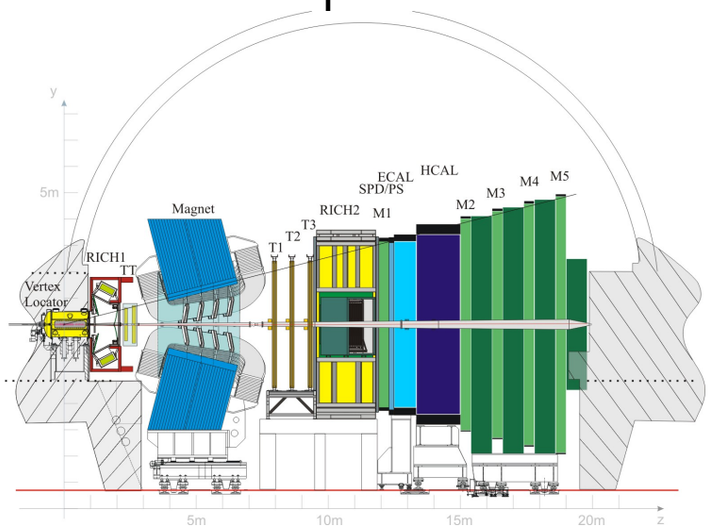
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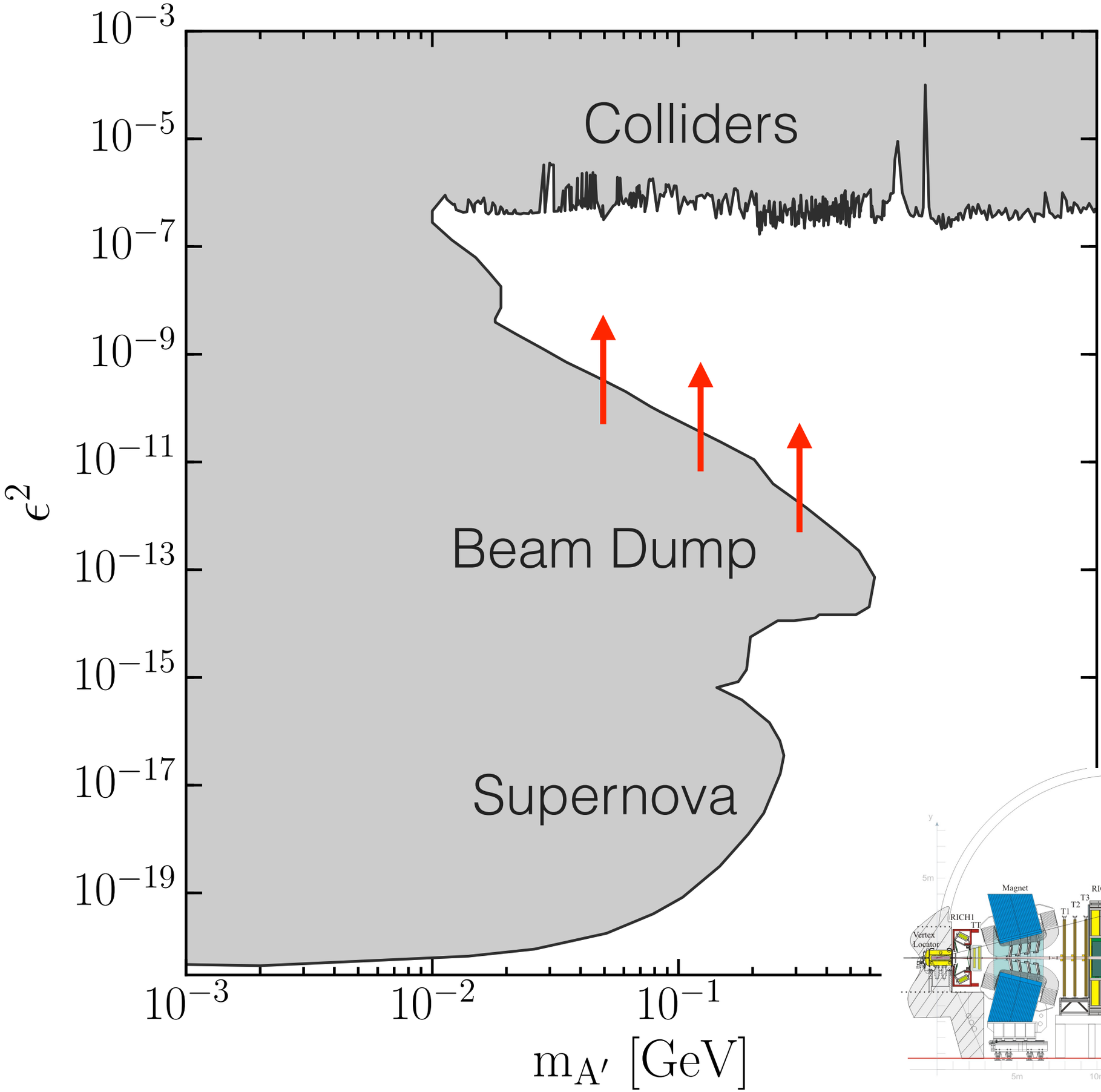
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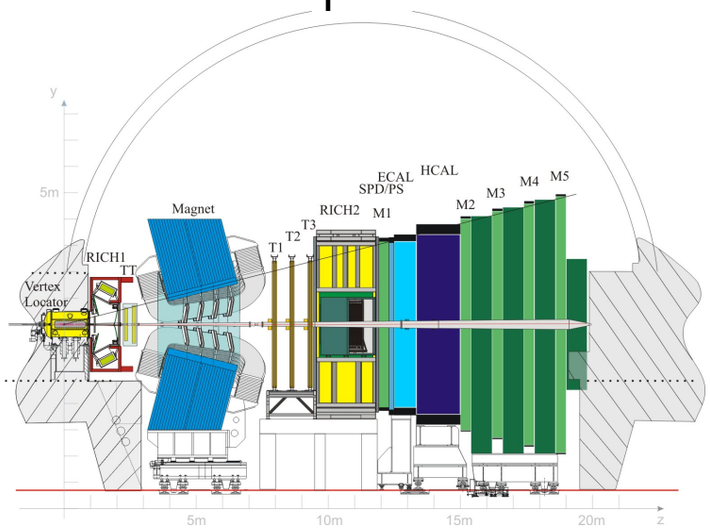
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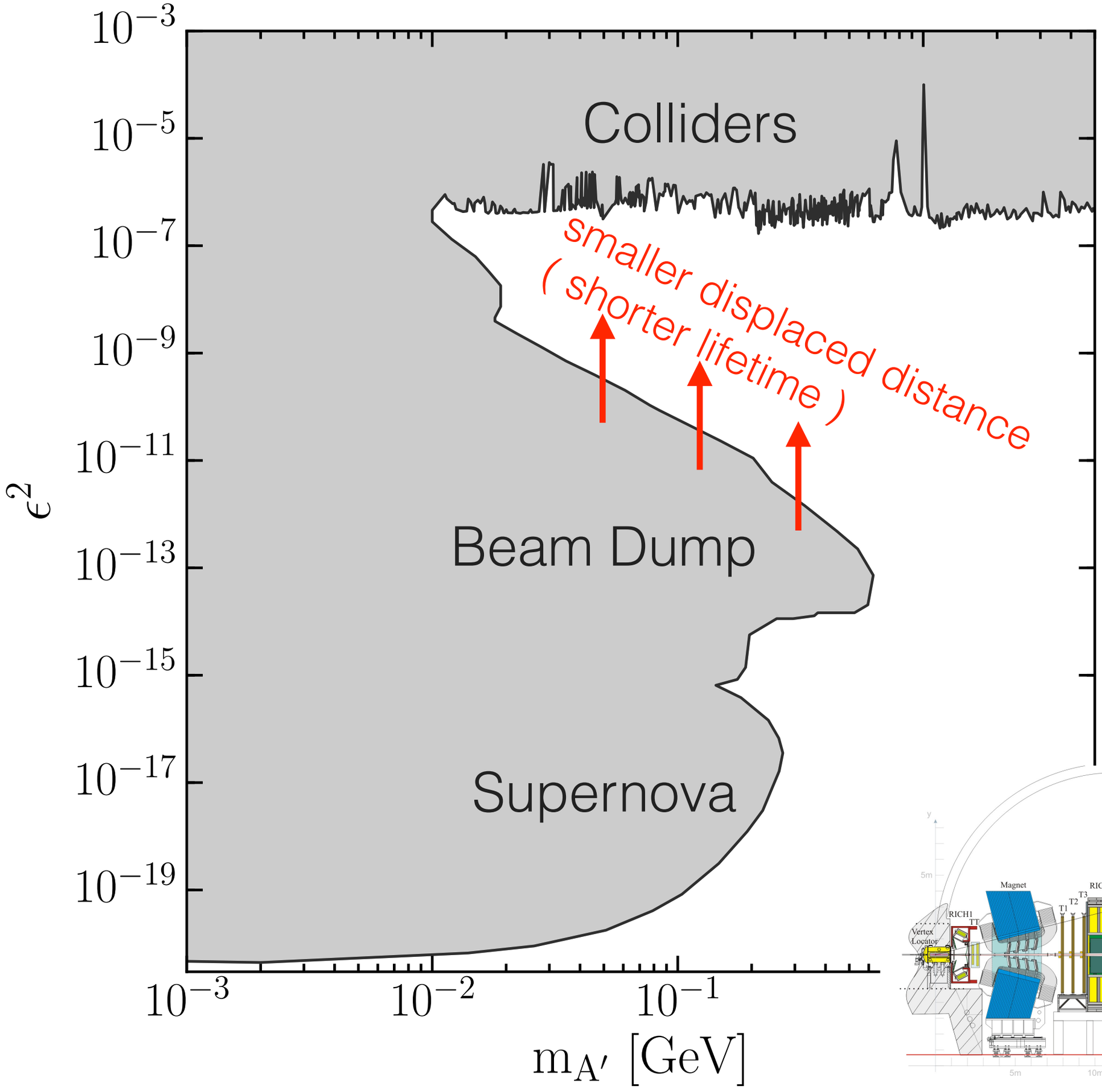
Colliders
smaller displaced distance
(shorter lifetime)
Beam Dump
Supernova
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
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ϵ^2
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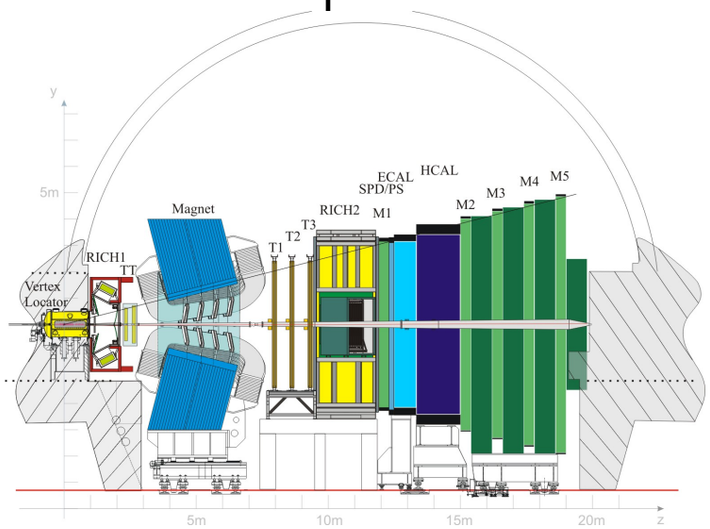
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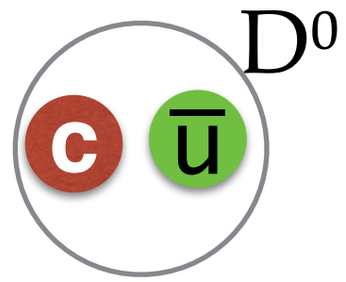
20m
z

Charm Mesons

very promising channel



- $D^{0*} \rightarrow D^0 + \gamma$

  large production rate
  less backgrounds

Charm Mesons

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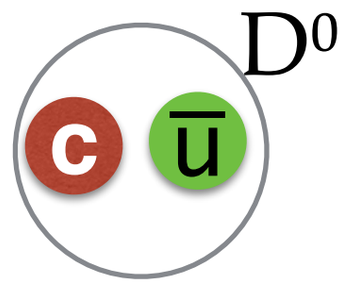

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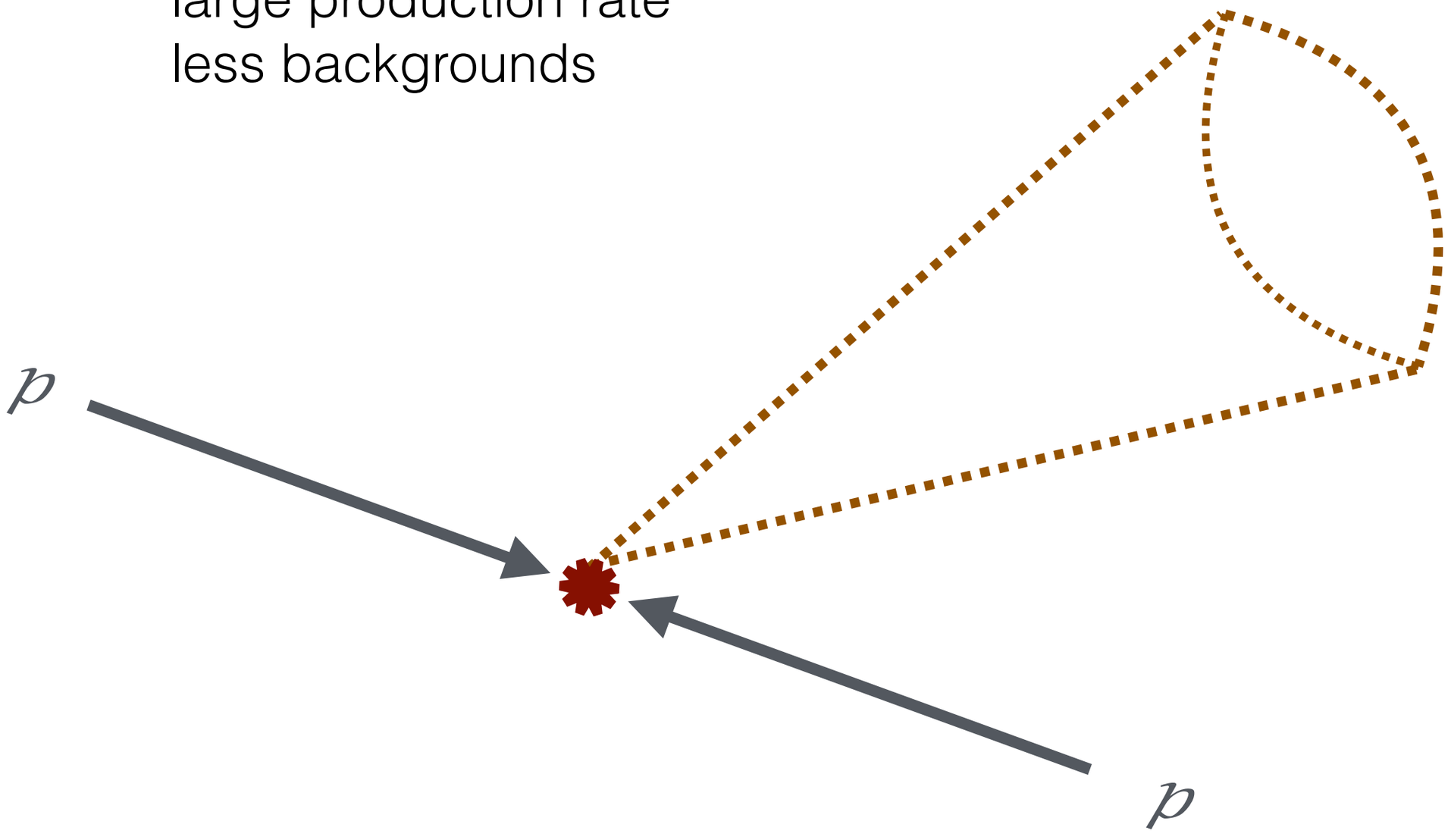

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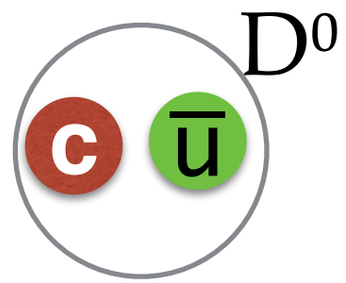

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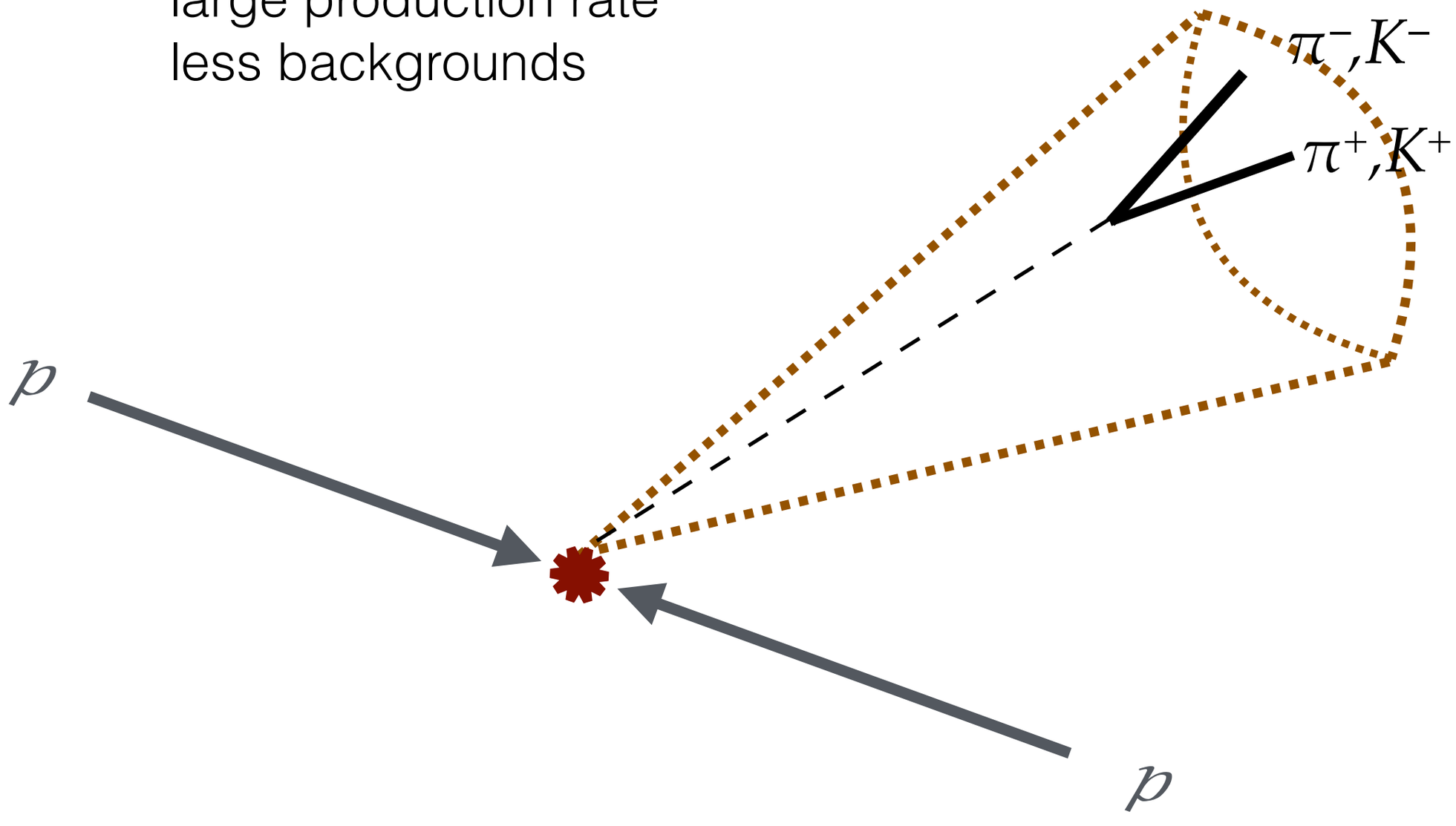

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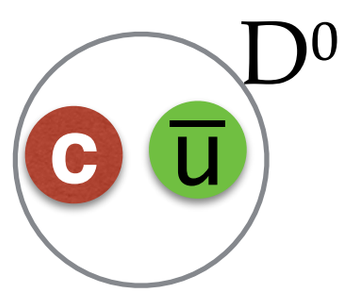

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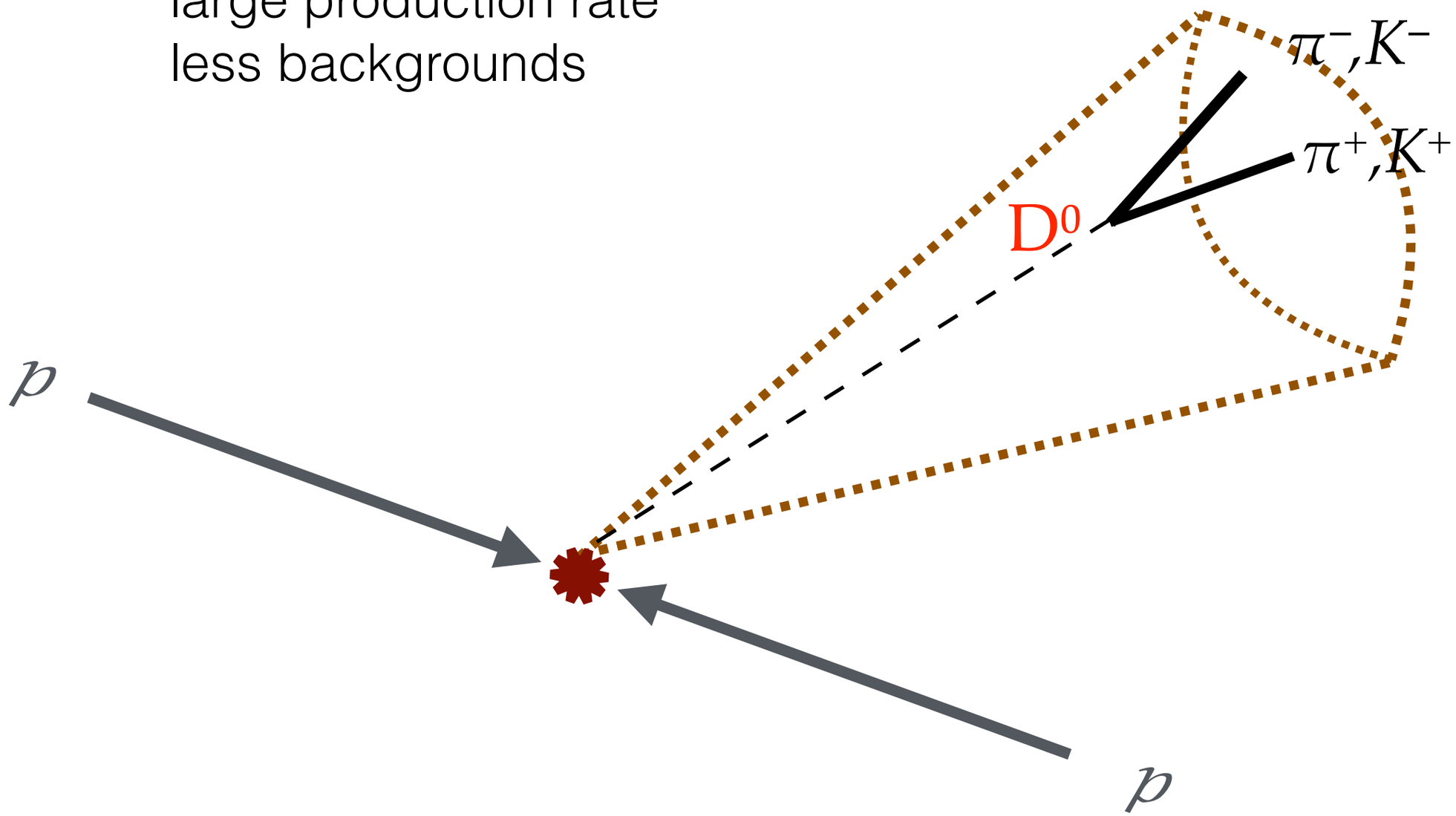

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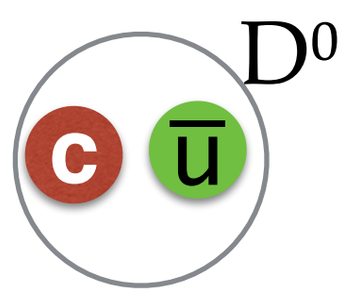
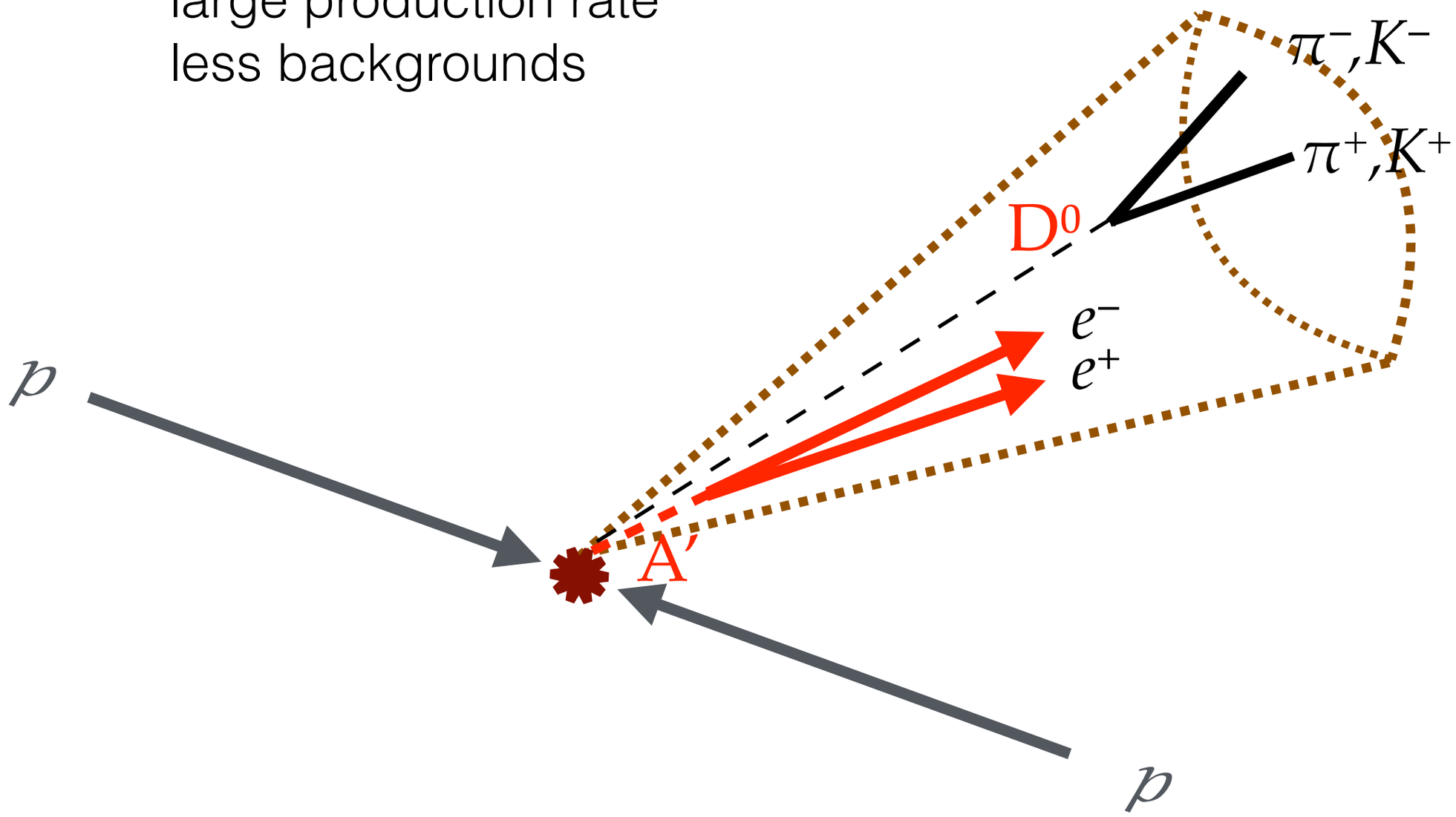
very promising channel



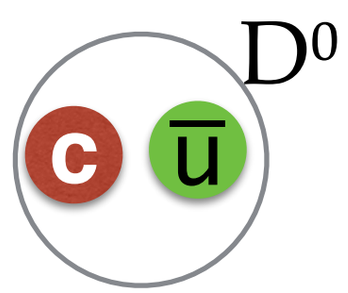
- $D^{0*} \rightarrow D^0 + \gamma$

  large production rate
  less backgrounds



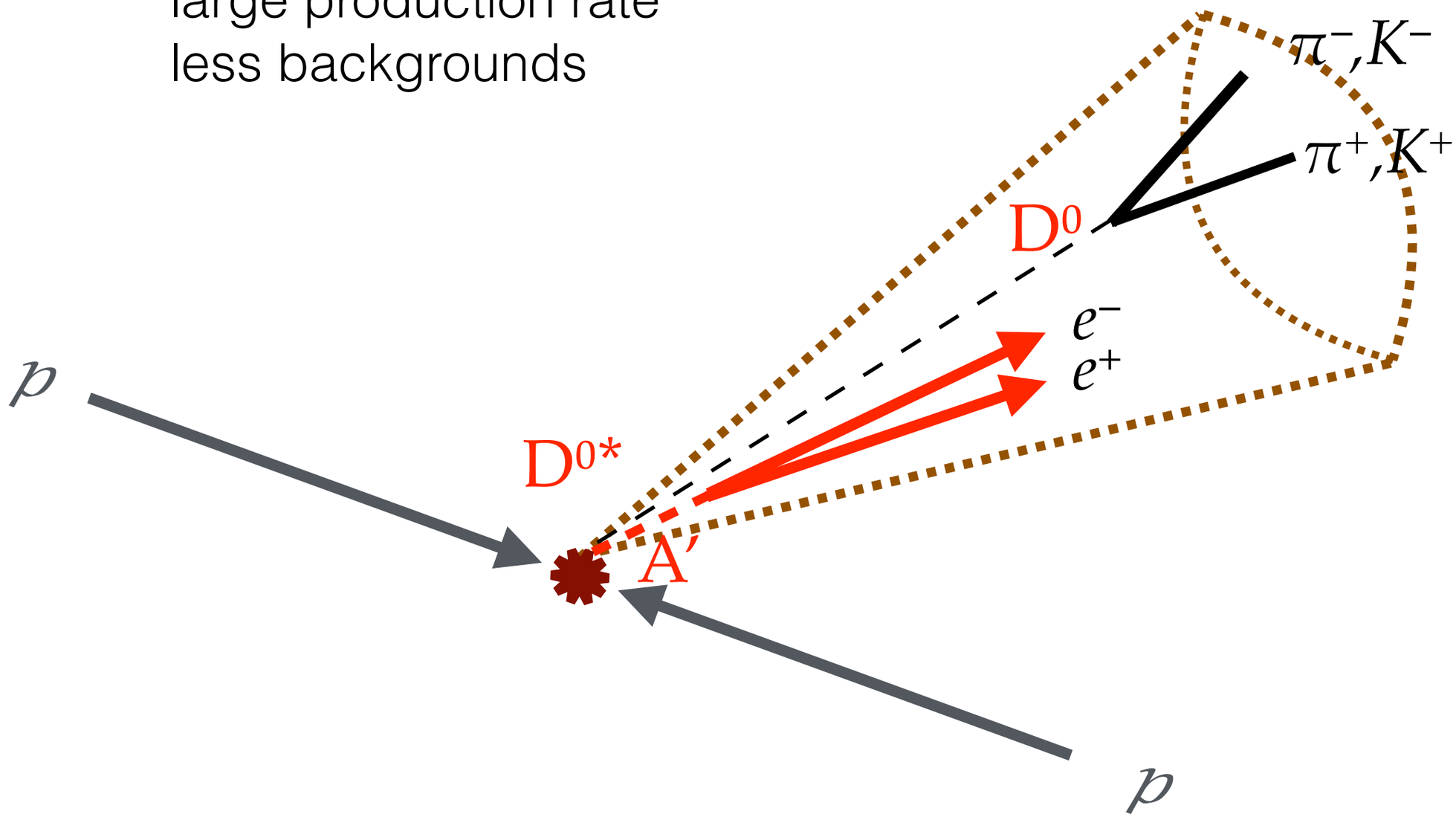
Charm Mesons

very promising channel



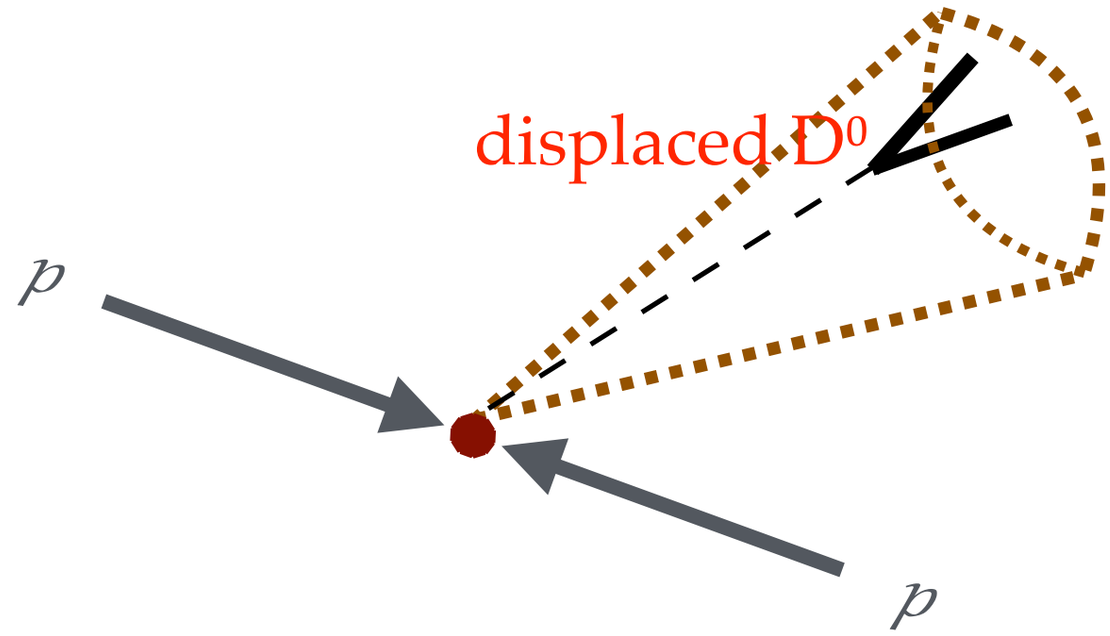
- $D^{0*} \rightarrow D^0 + \gamma$

  large production rate
  less backgrounds



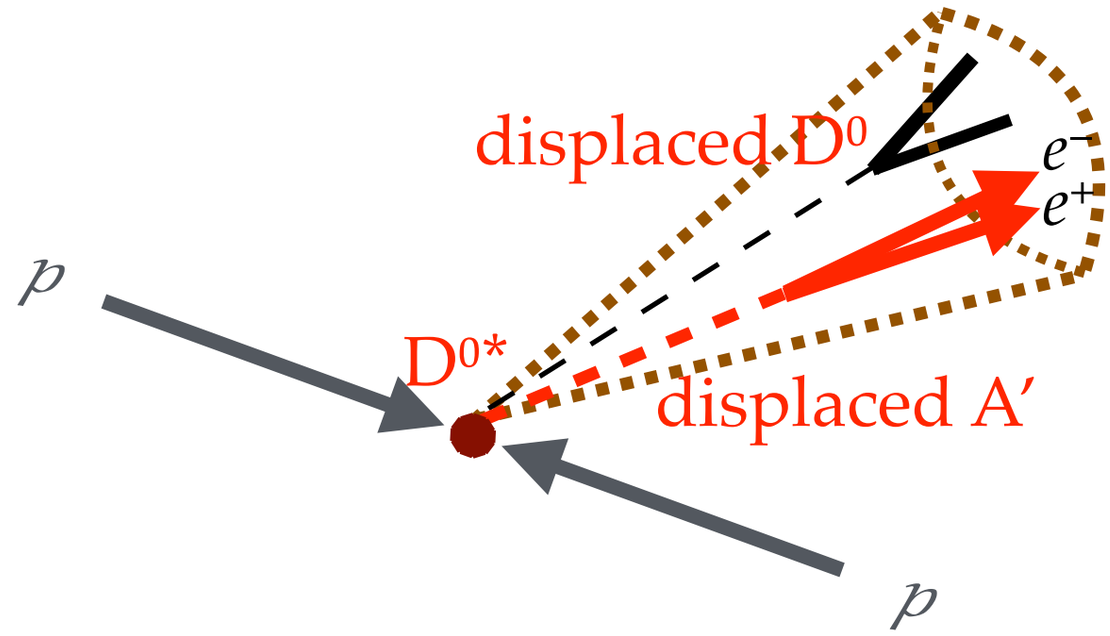
Displaced Search

- displaced D^0 and displaced A’



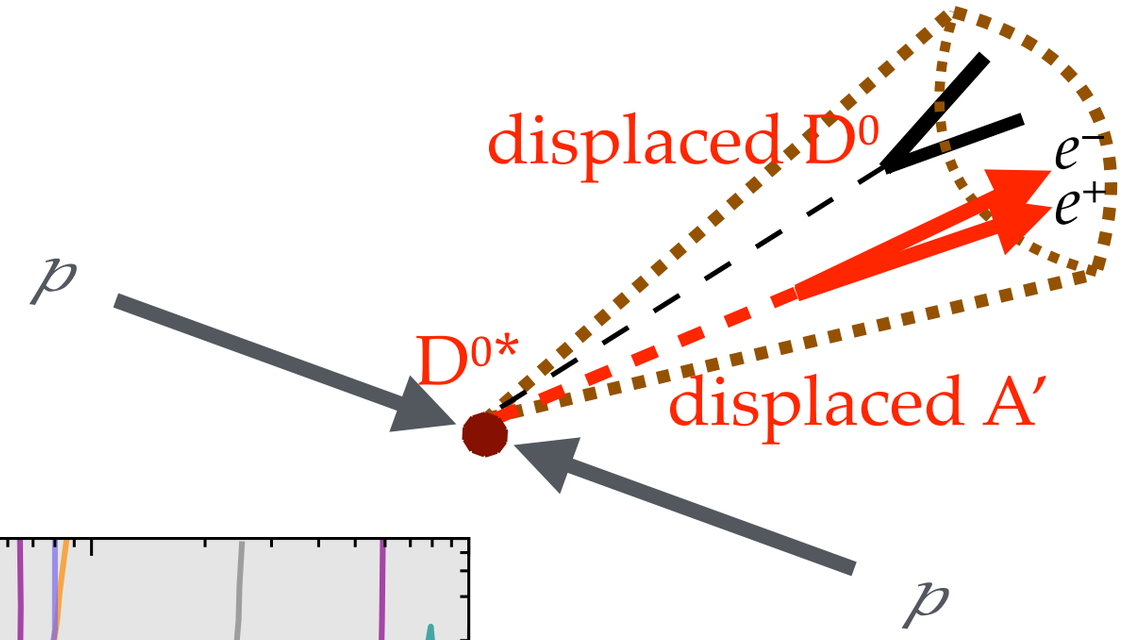
Displaced Search

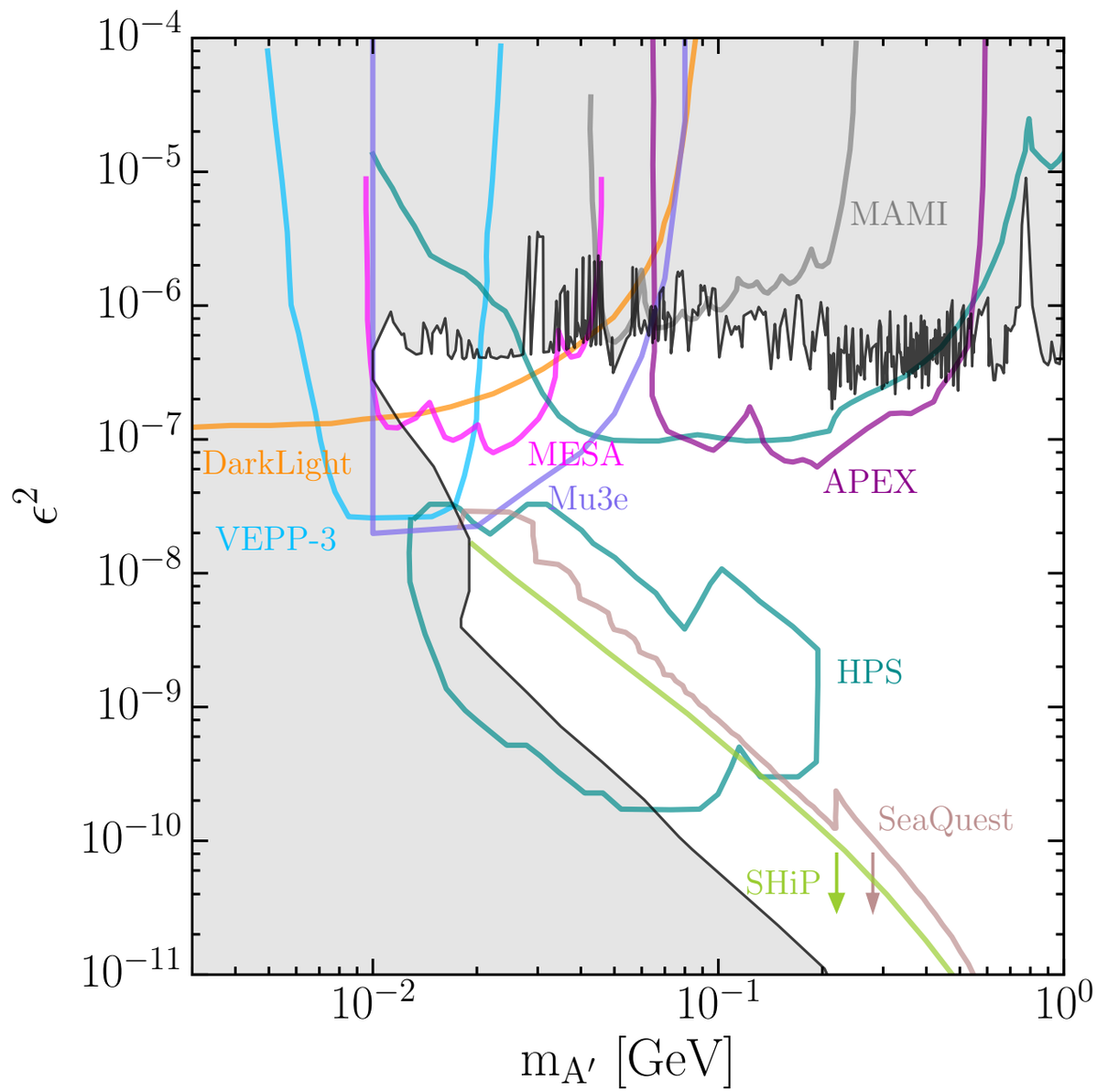
- displaced D^0 and displaced A’



Displaced Search

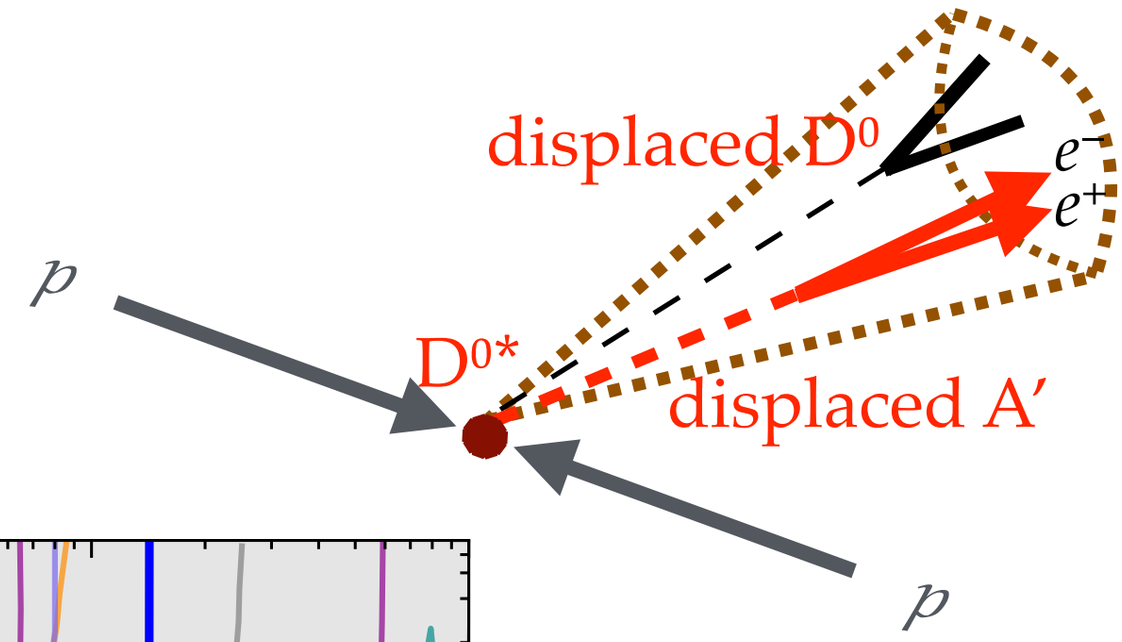
- displaced D^0 and displaced A'

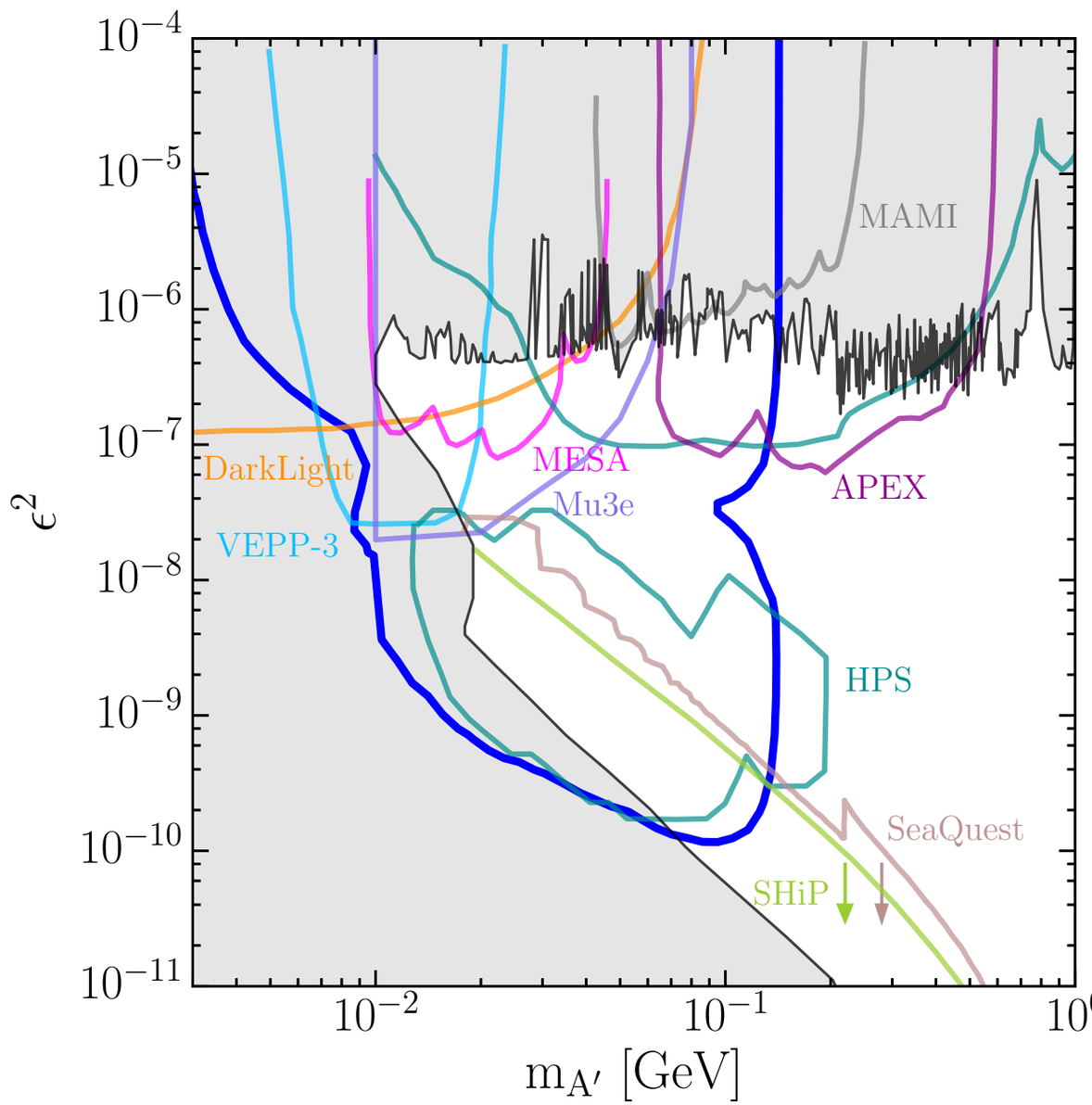




Displaced Search

- displaced D^0 and displaced A'

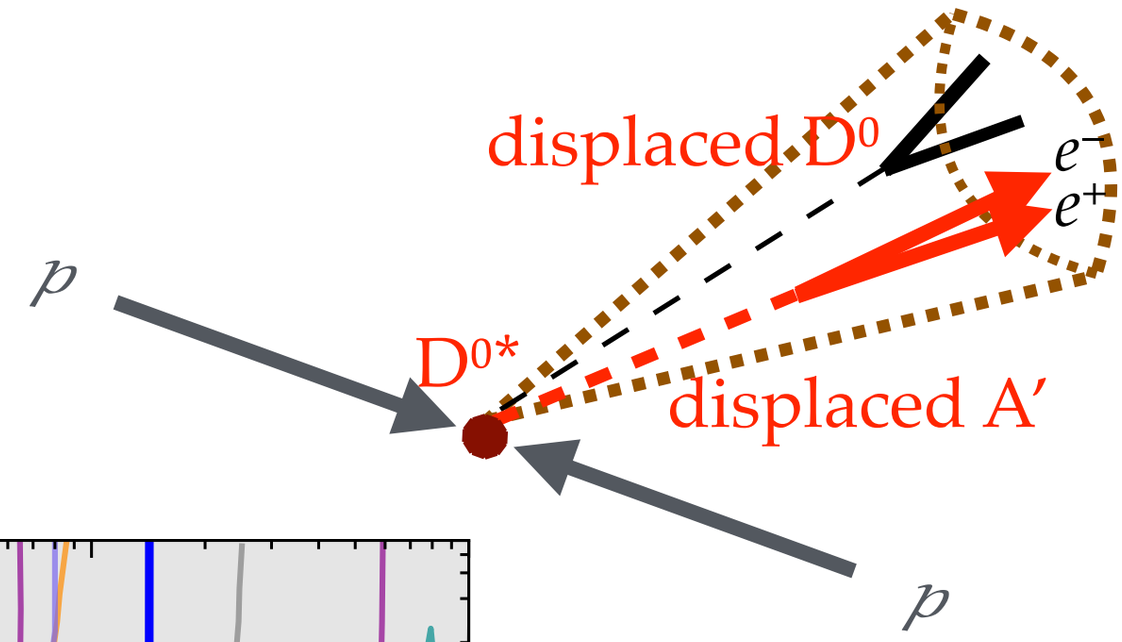


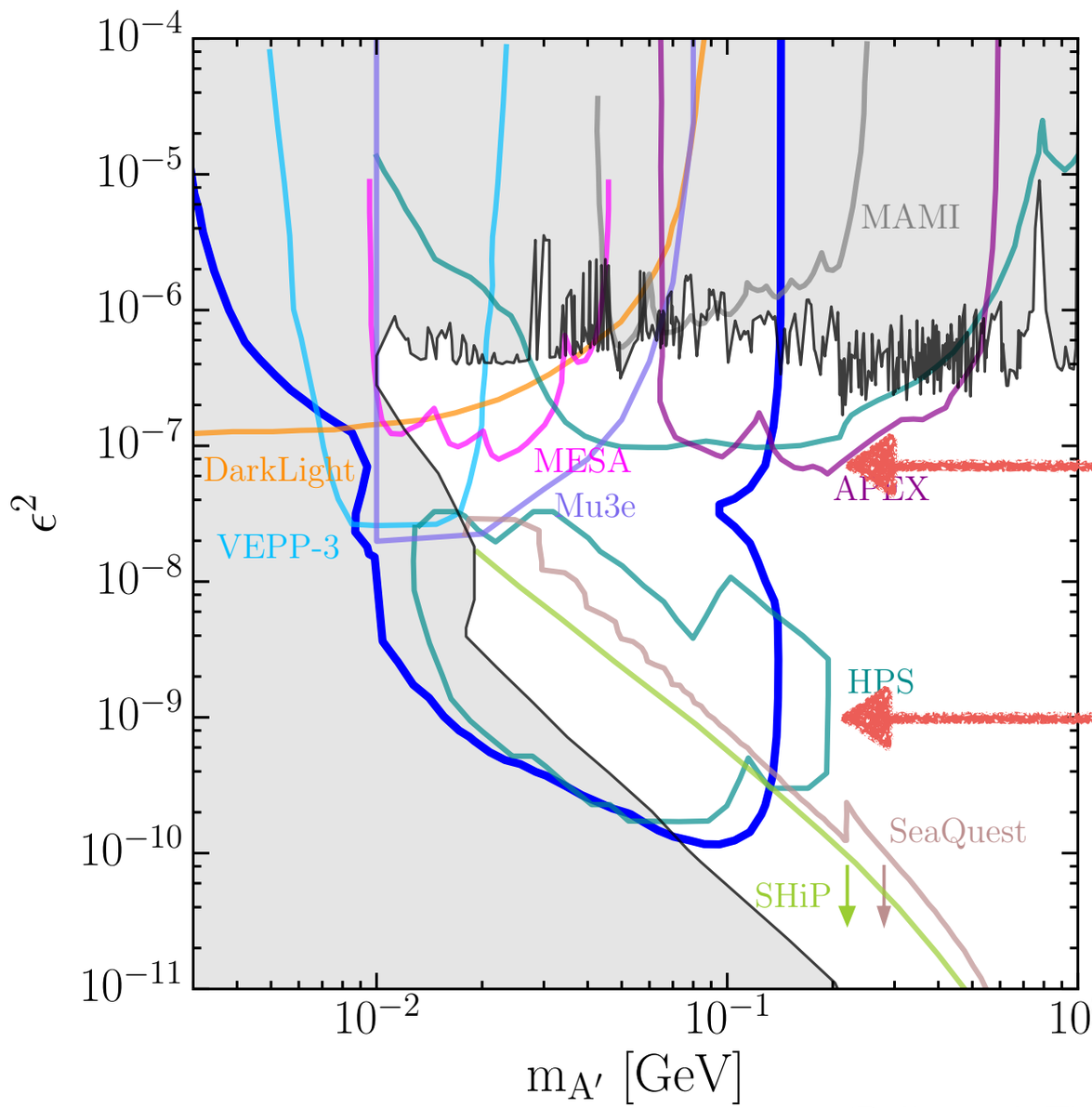


*[P. Ilten, J. Thaler, M. Williams, **WX** (2015)]*

Displaced Search

- displaced D^0 and displaced A'

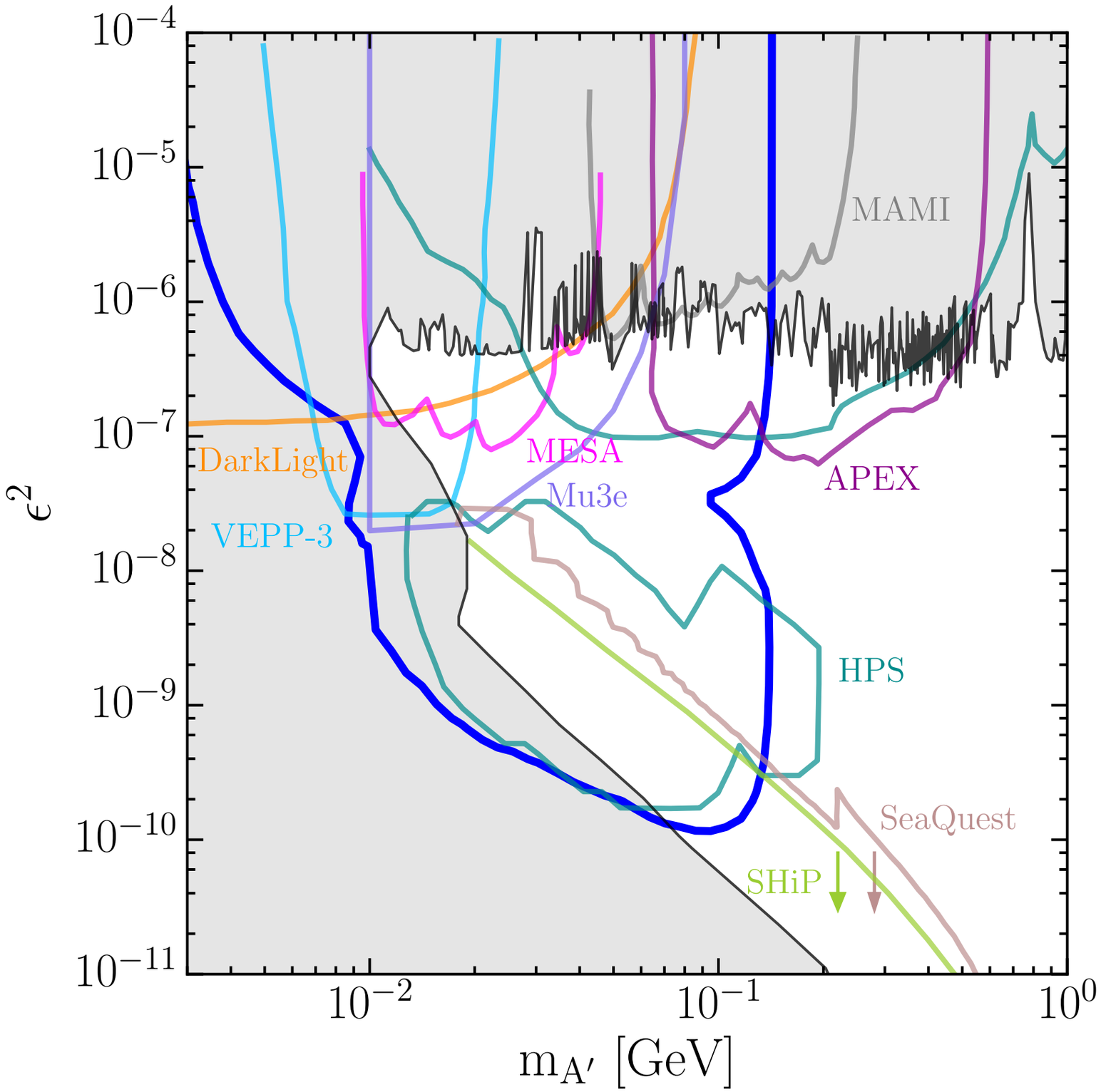




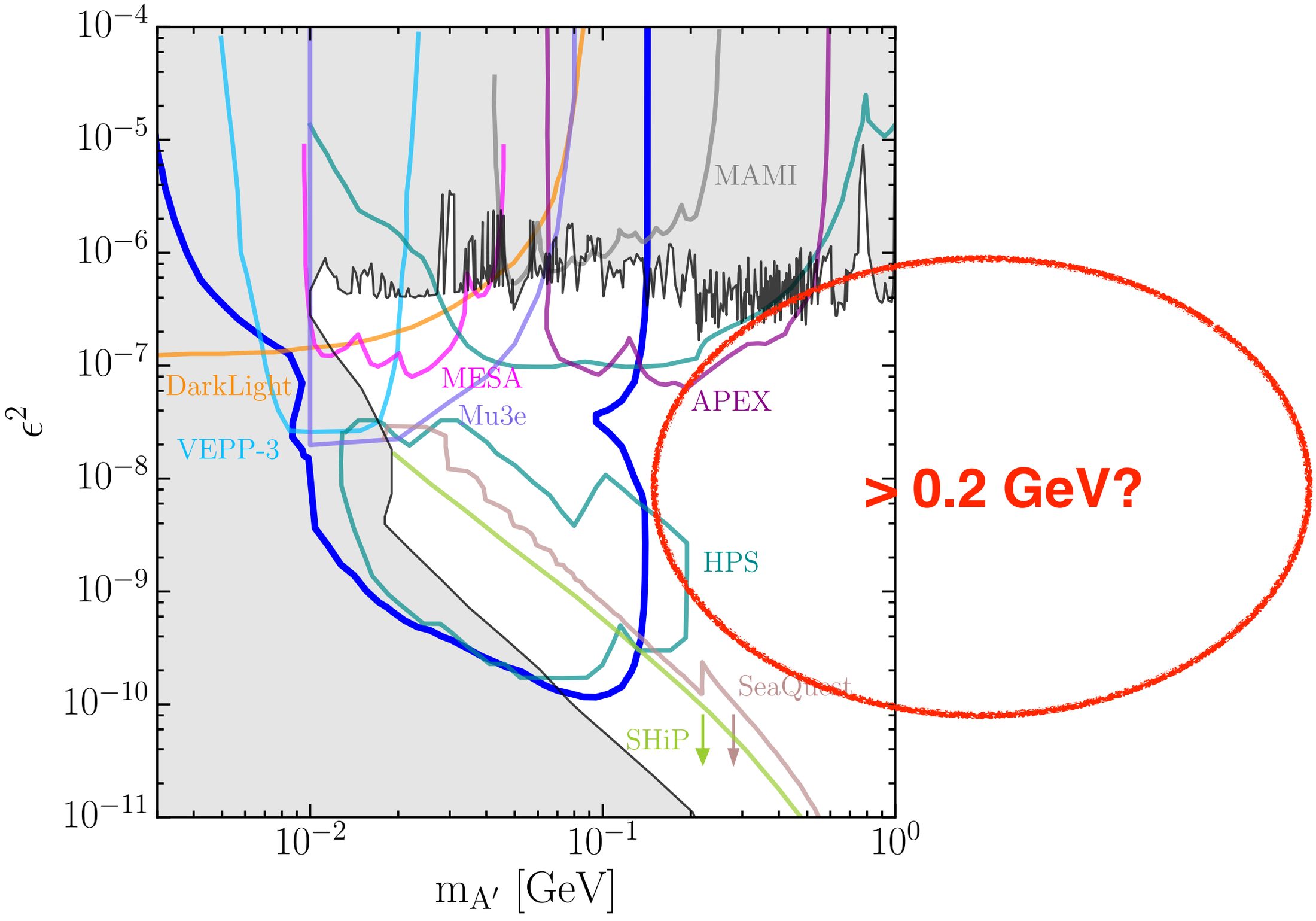
resonant

displaced

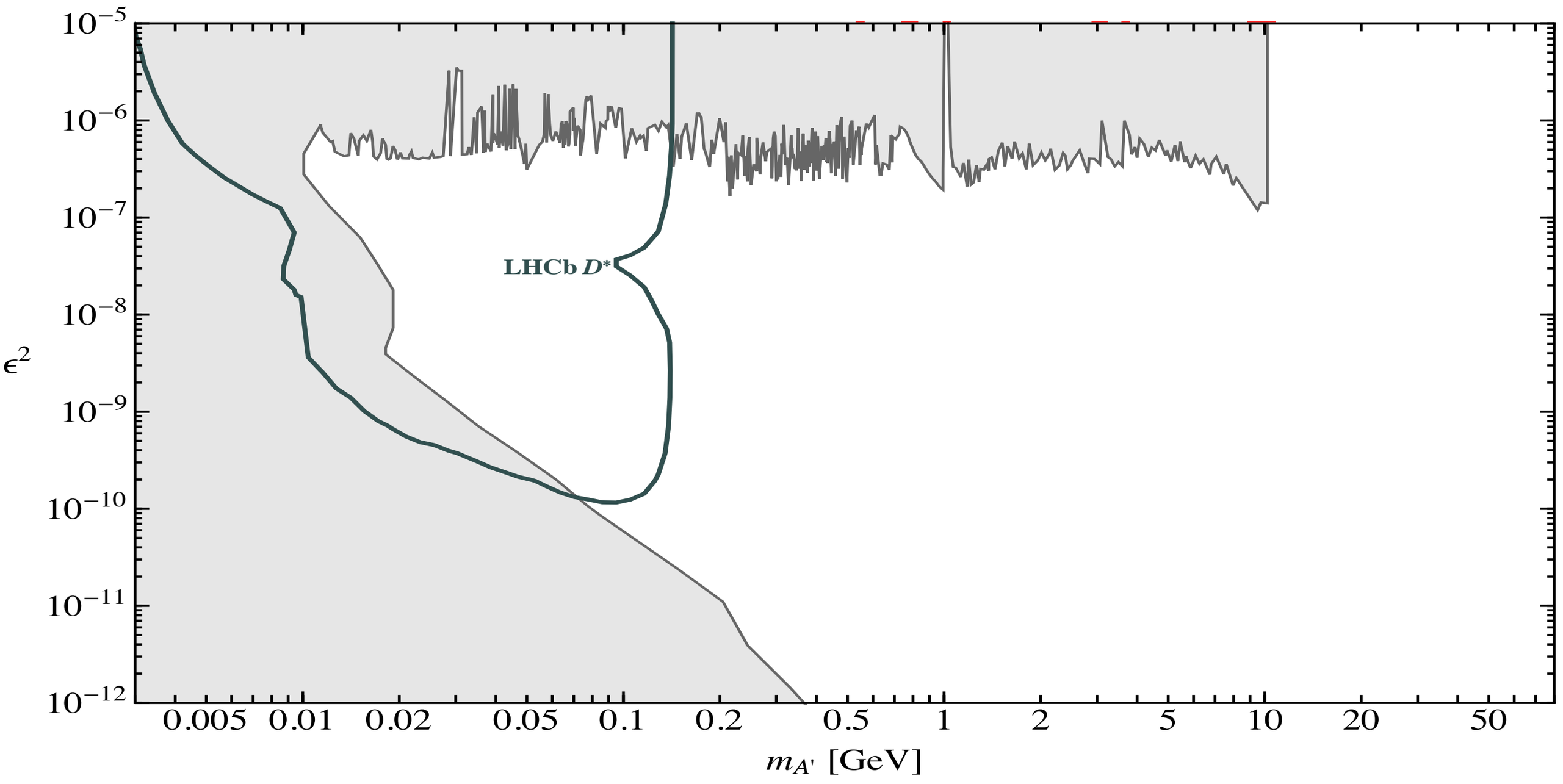
*[P. Ilten, J. Thaler, M. Williams, **WX** (2015)]*

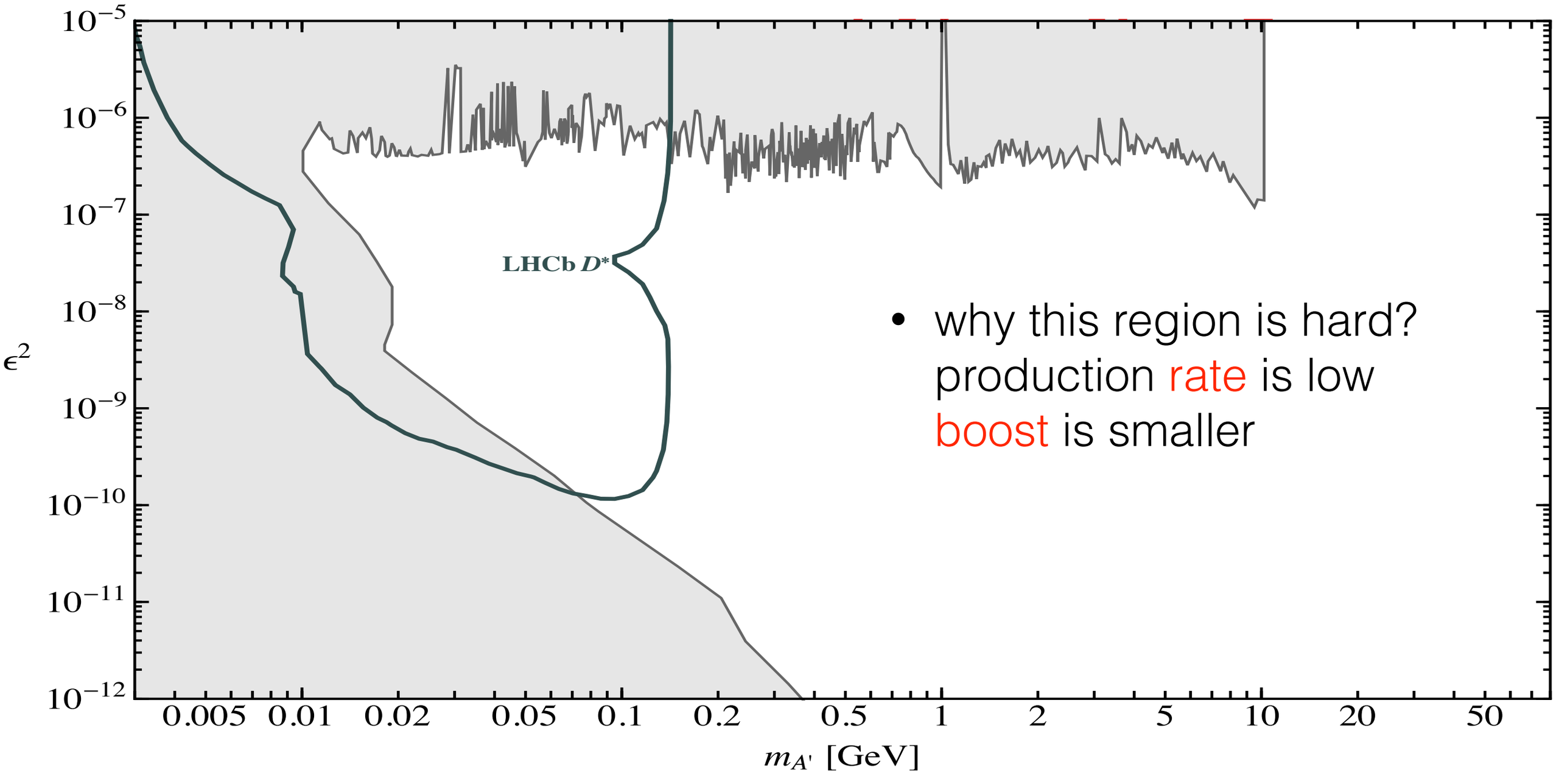


*[P. Ilten, J. Thaler, M. Williams, **WX** (2015)]*

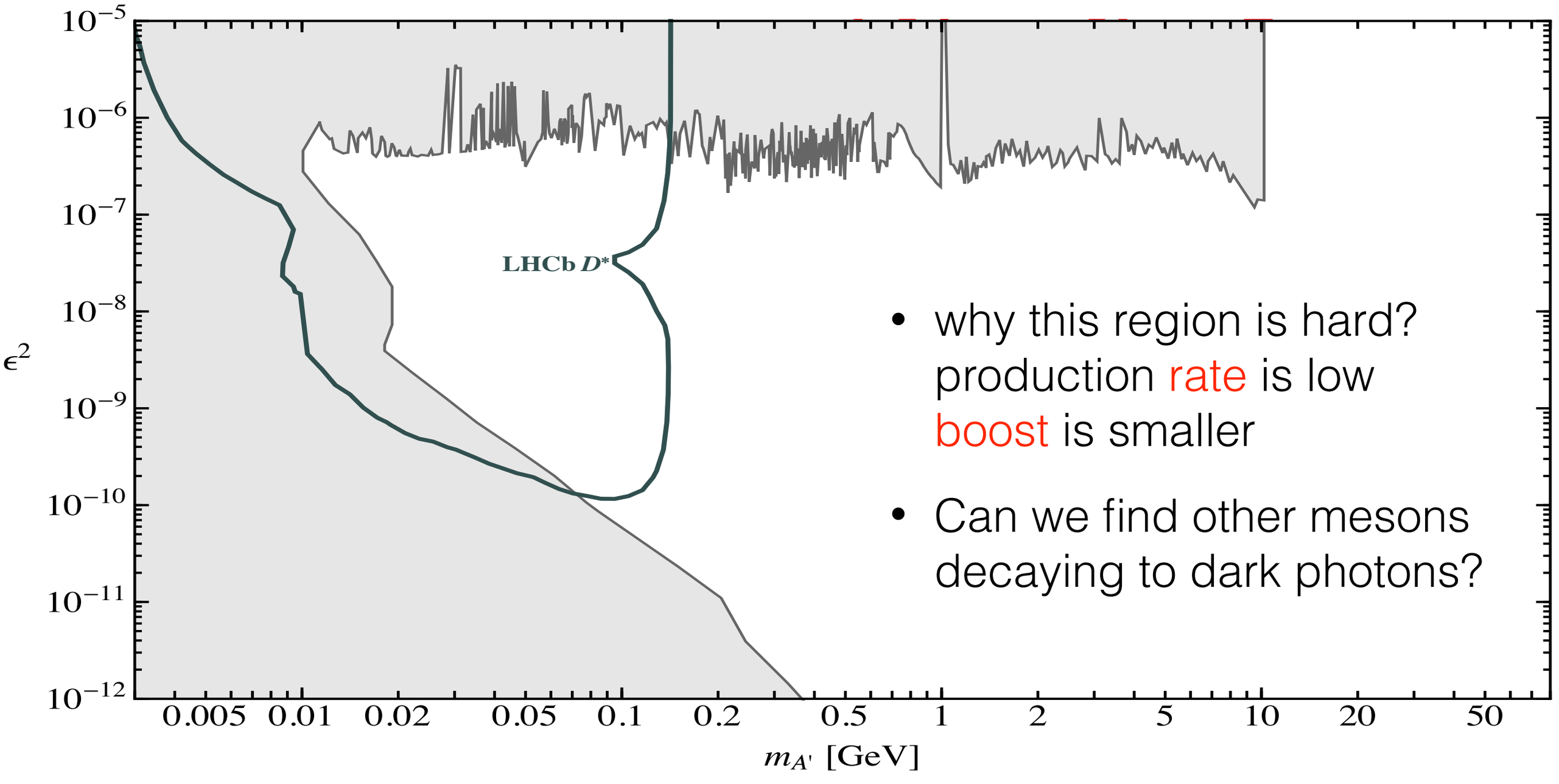


*[P. Ilten, J. Thaler, M. Williams, **WX** (2015)]*


LHCb D^*
ϵ^2
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1
2
5
10
20
50
$m_{A'}$ [GeV]



- why this region is hard?
  production rate is low
  boost is smaller



- why this region is hard?
  production rate is low
  boost is smaller
- Can we find other mesons decaying to dark photons?

Can we combine all the channels?

- channels we can use
  - Bremsstrahlung /Drell-Yan process
  - meson decays

- challenges:
  what is the signal rate?
  many potential sources of dark photons
  with uncertain production rates

Can we combine all the channels?

- channels we can use
  - Bremsstrahlung /Drell-Yan process
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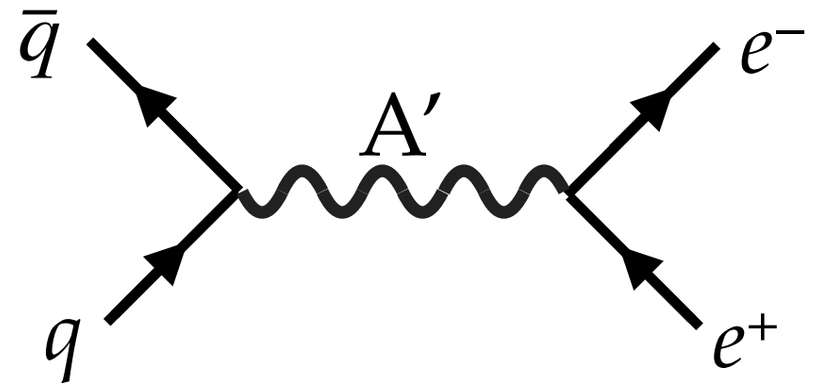

- challenges:
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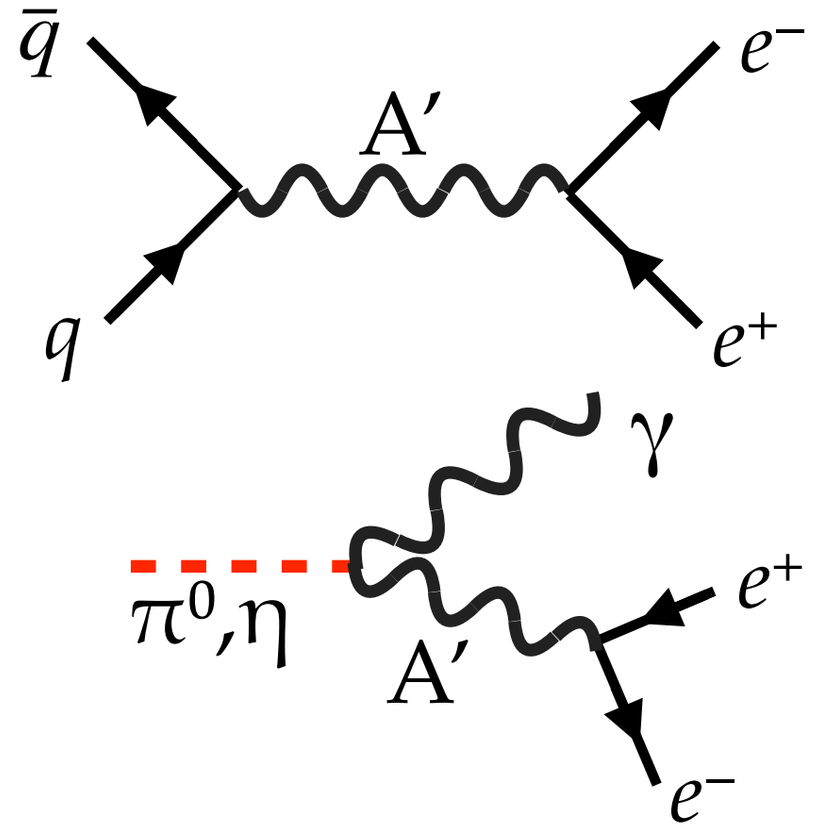

- challenges:
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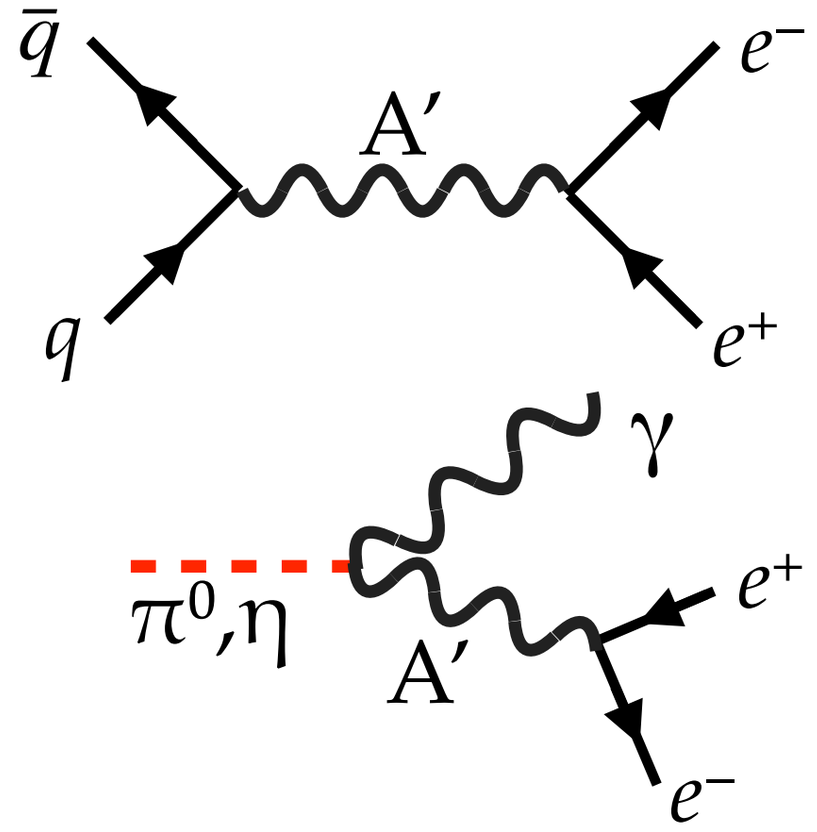
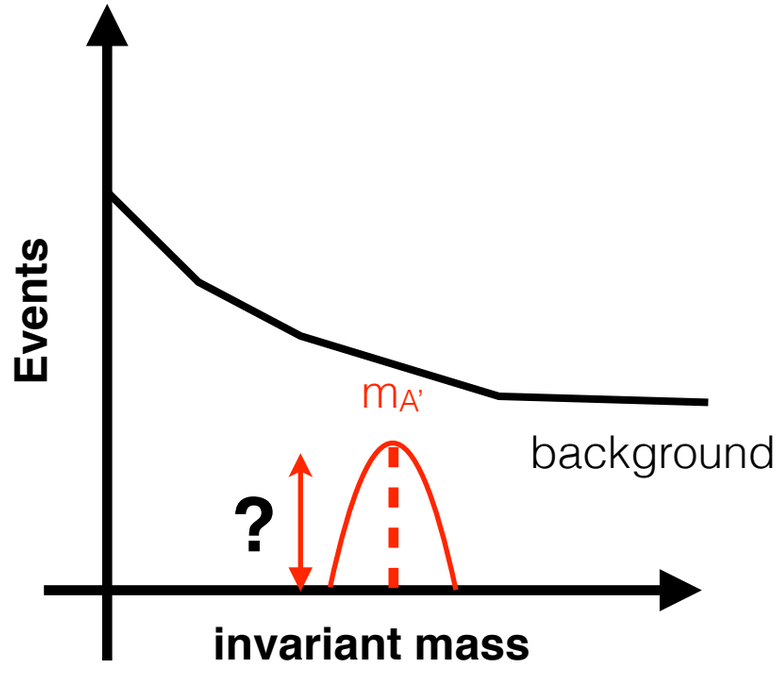
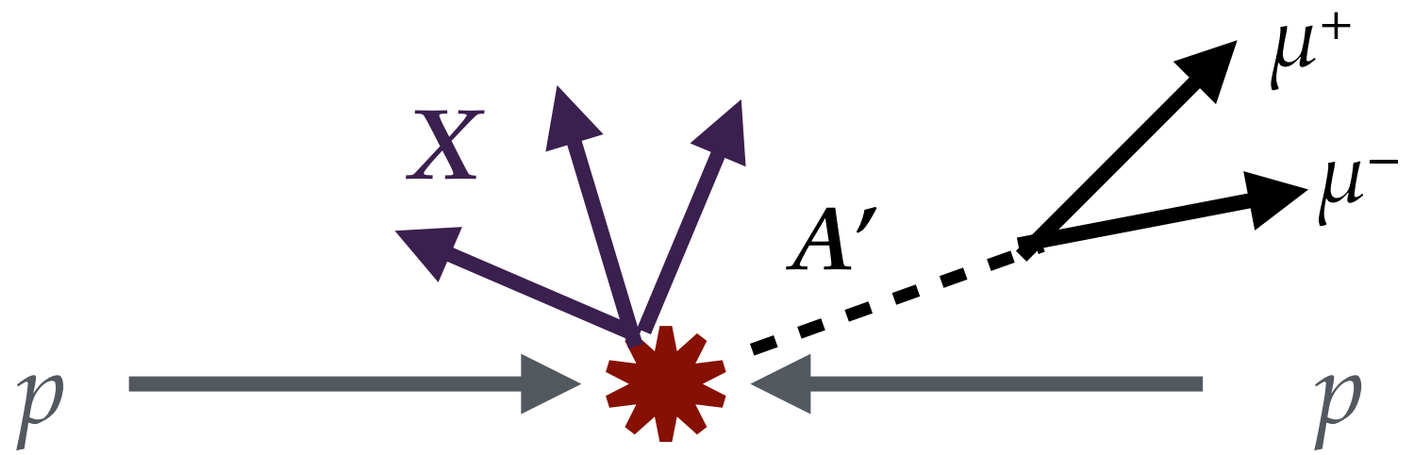


- challenges:
  what is the signal rate?
  many potential sources of dark photons
  with uncertain production rates

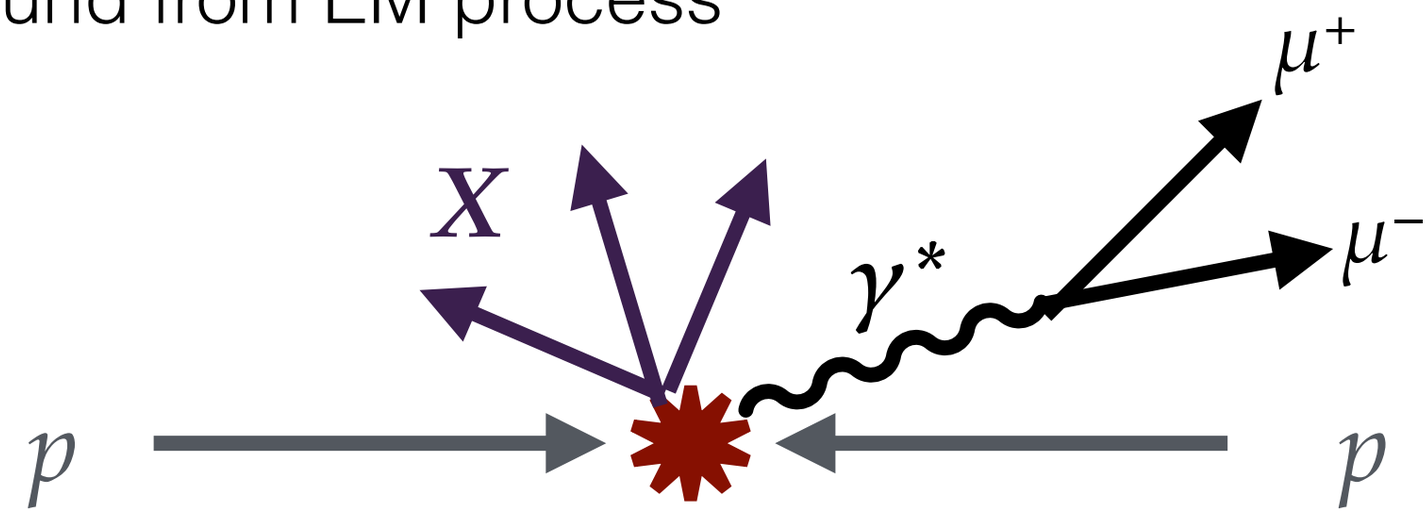


Inclusive Dimuon

- dark photons as signal



- Background from EM process



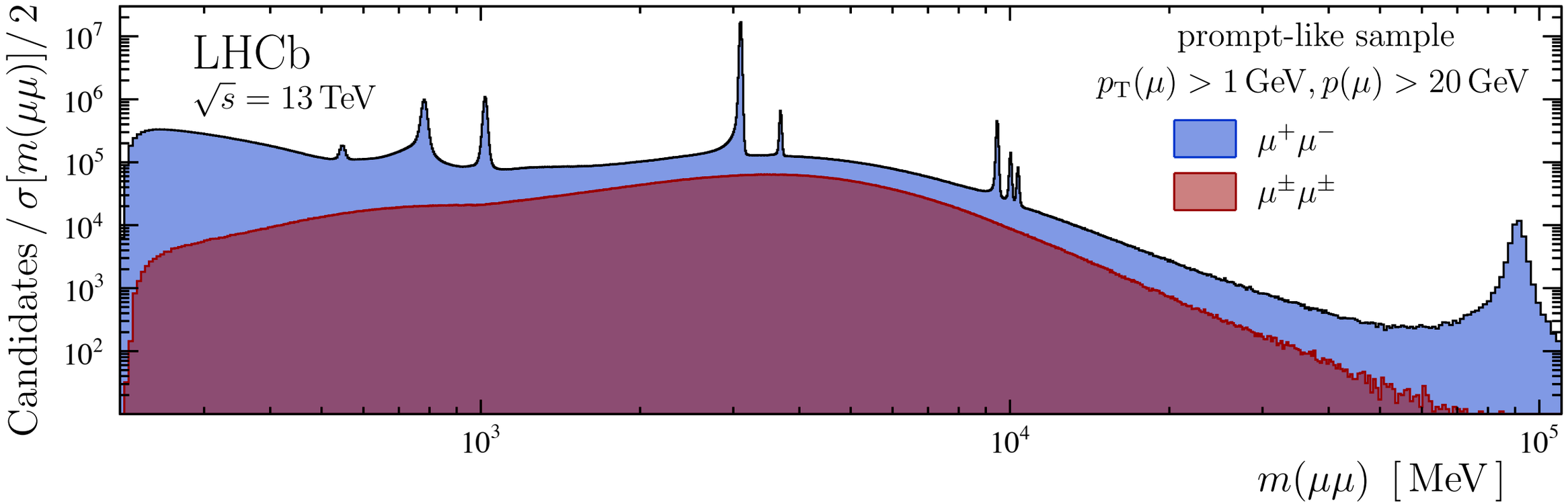
Data Driven Method

- ratio (complicated factors are cancelled)

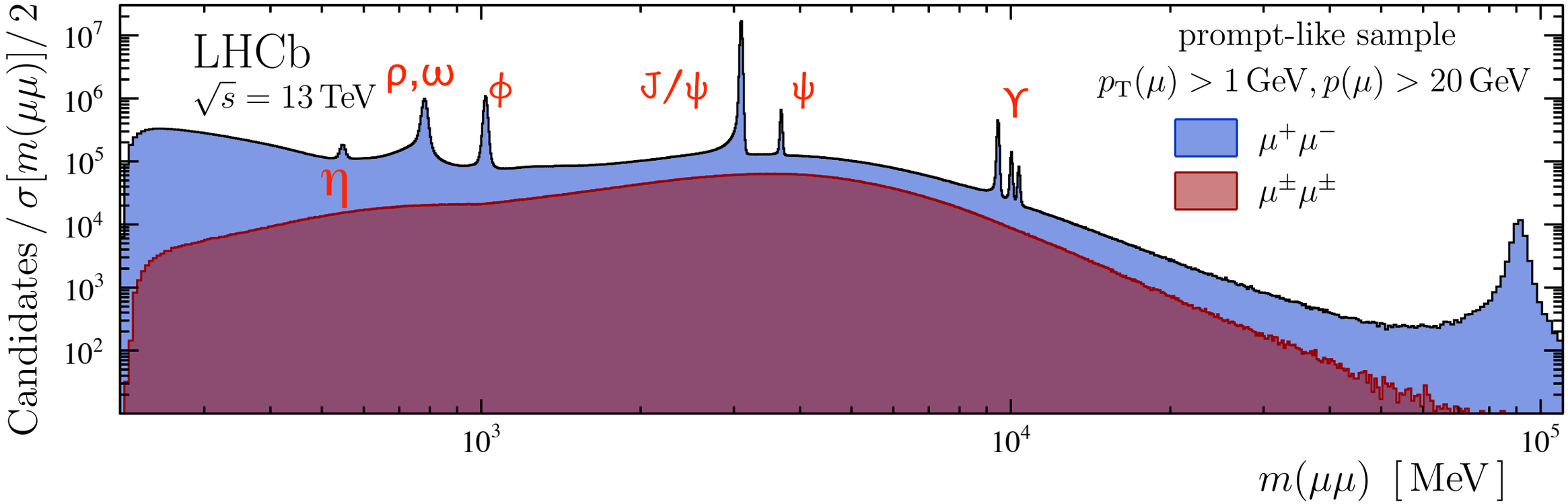
$$\frac{\text{Signal}}{\text{Background}_{EM}} \sim \frac{\epsilon^4 m_{A'}^2}{\Gamma_{A'} \times \text{binwidth}}$$

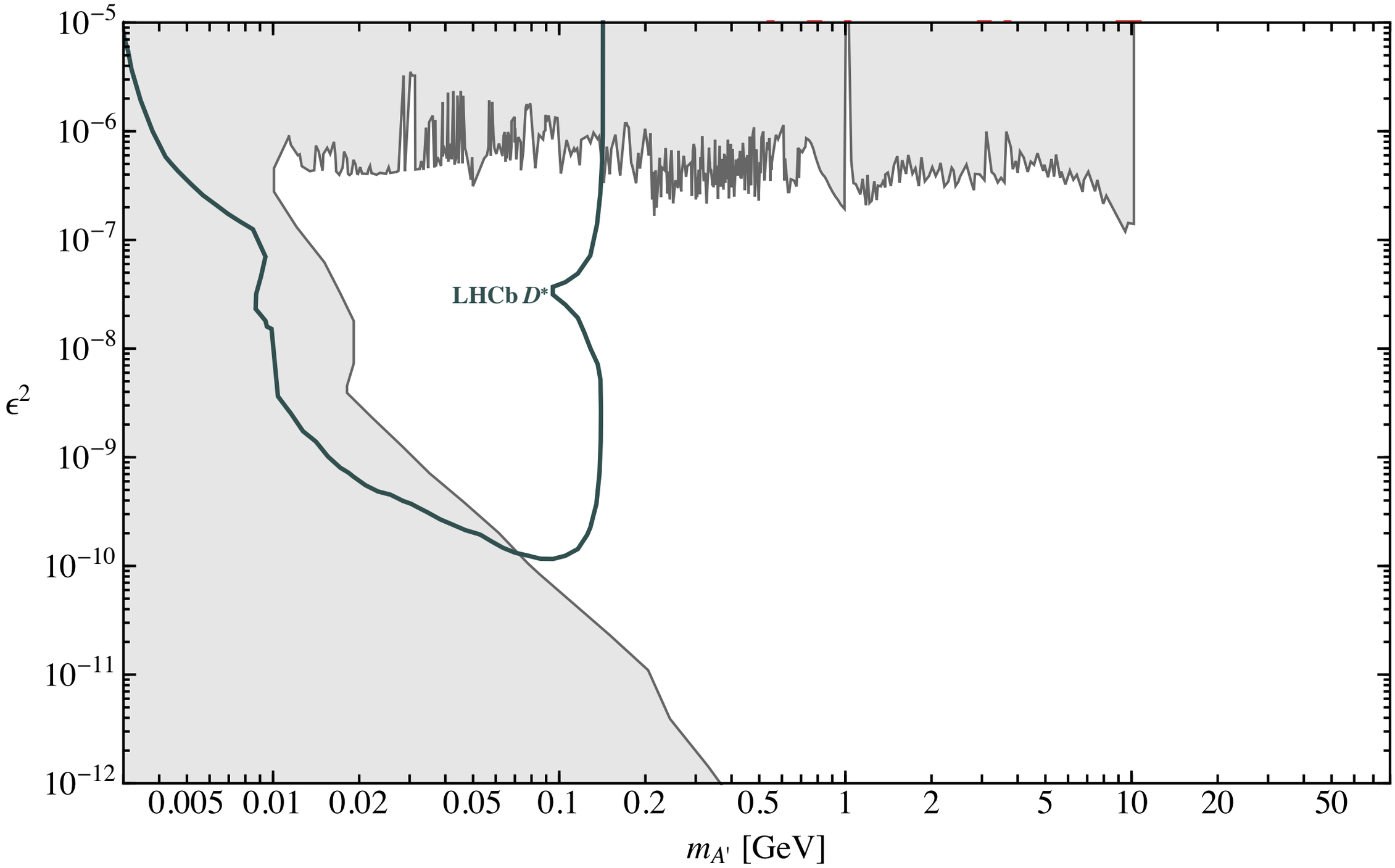
- the measured dimuon spectrum is Background_{EM}

Measured Dimuon Spectrum by LHCb

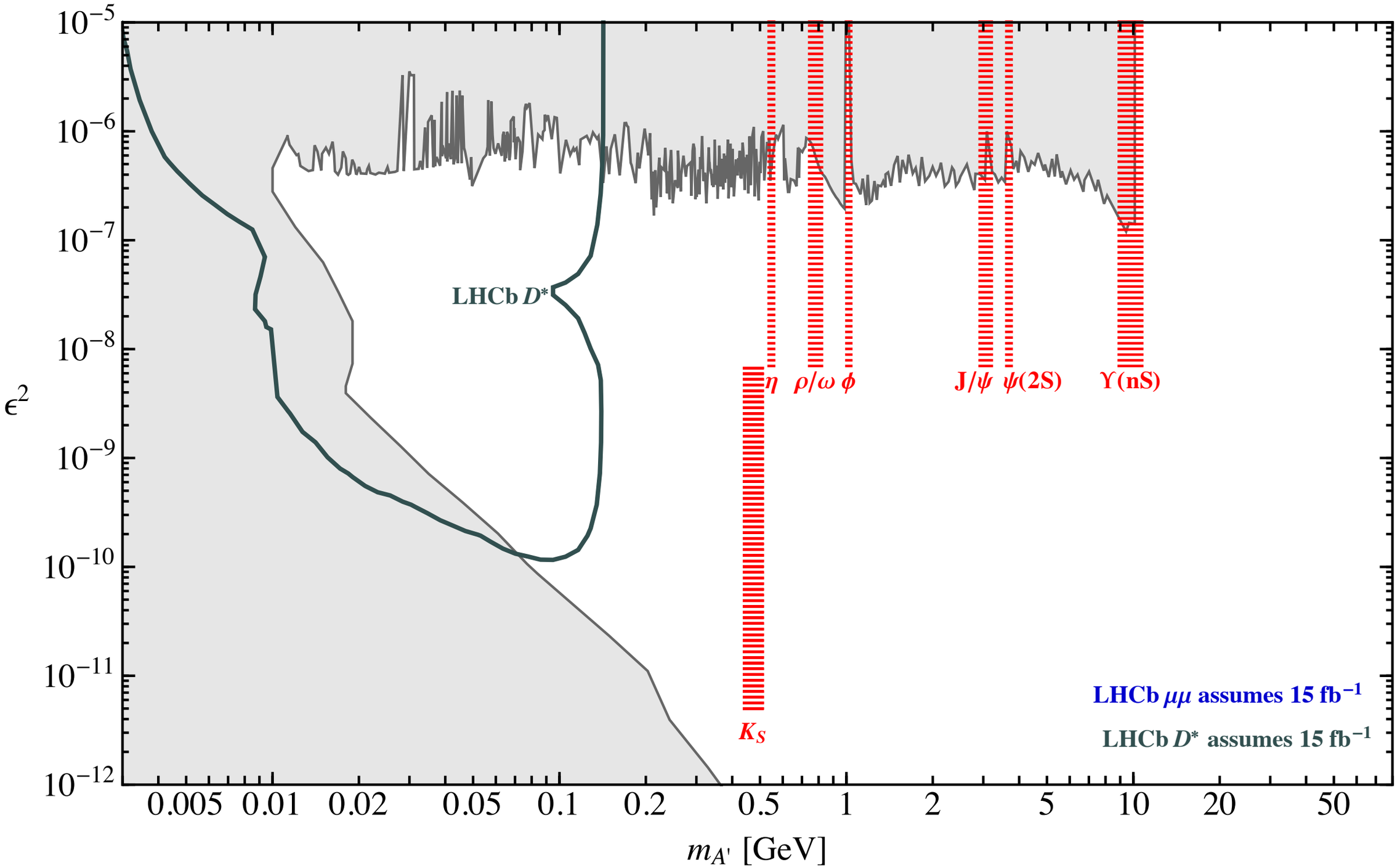


Measured Dimuon Spectrum by LHCb

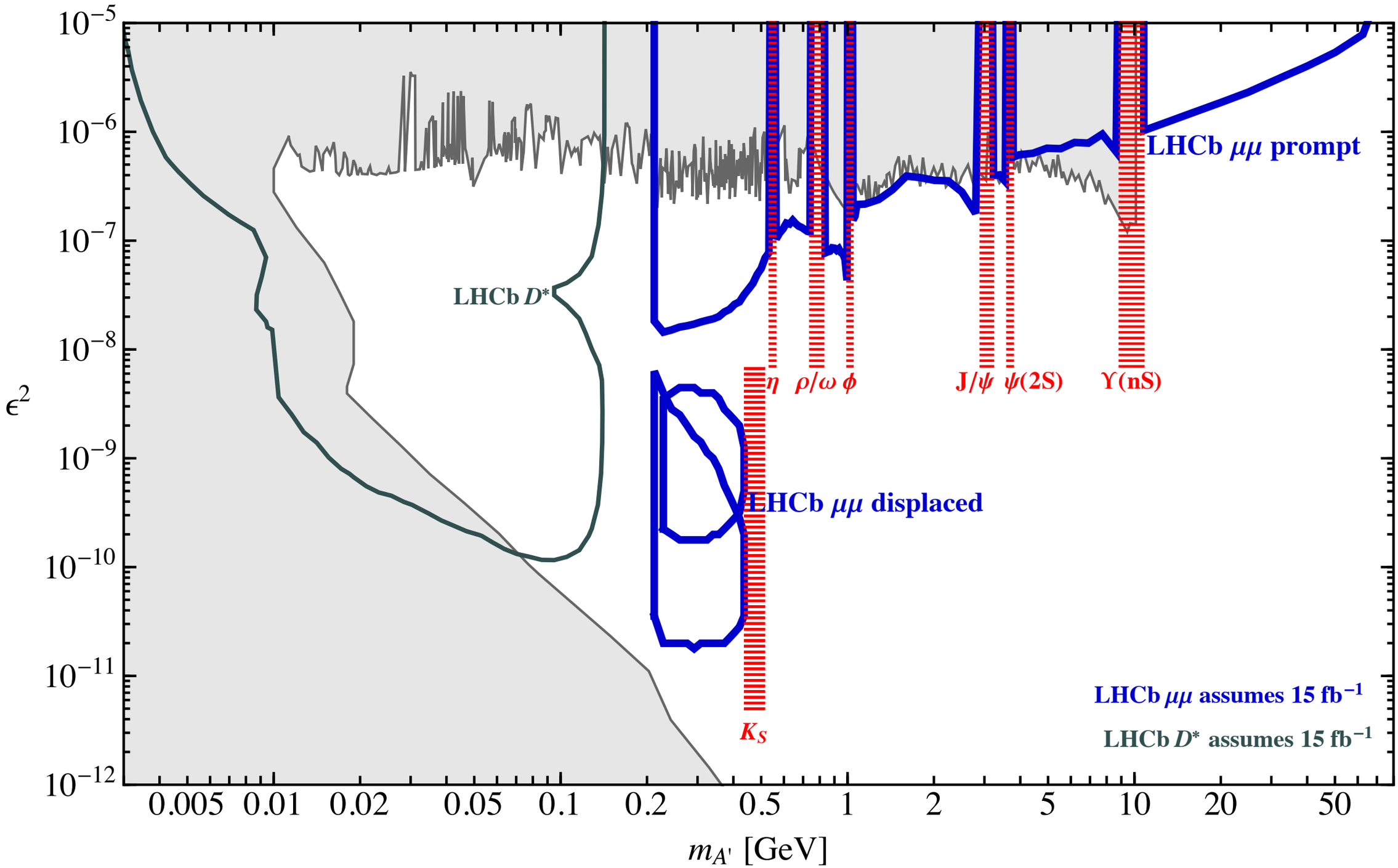




*[P. Ilten, Y. Soreq, J. Thaler, M. Williams, **WX** (2016)]*



*[P. Ilten, Y. Soreq, J. Thaler, M. Williams, **WX** (2016)]*



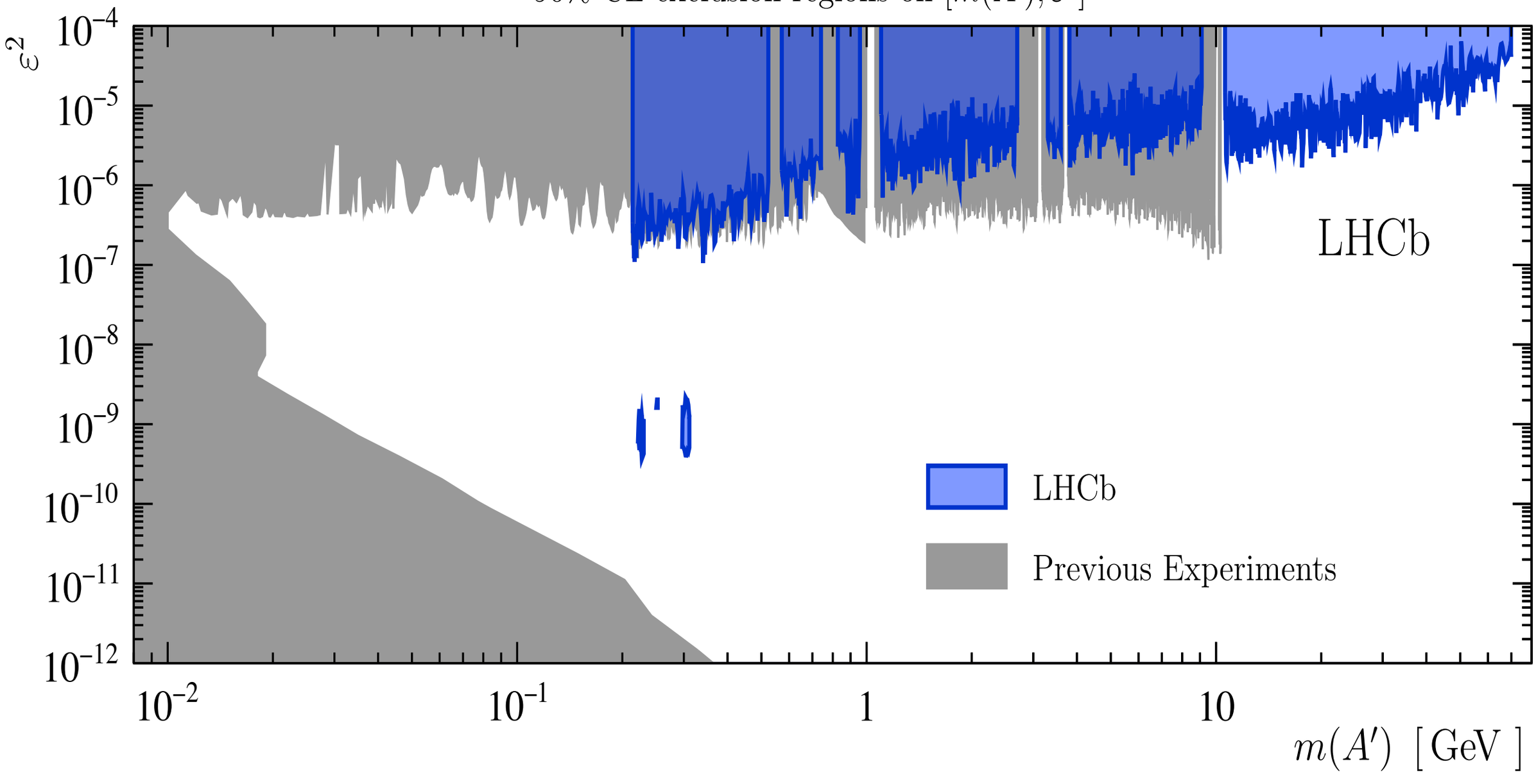
*[P. Ilten, Y. Soreq, J. Thaler, M. Williams, **WX** (2016)]*

Results from LHCb

real data

2019 LHCb New Results in backup slides

2016 data, 1.6 fb^{-1}



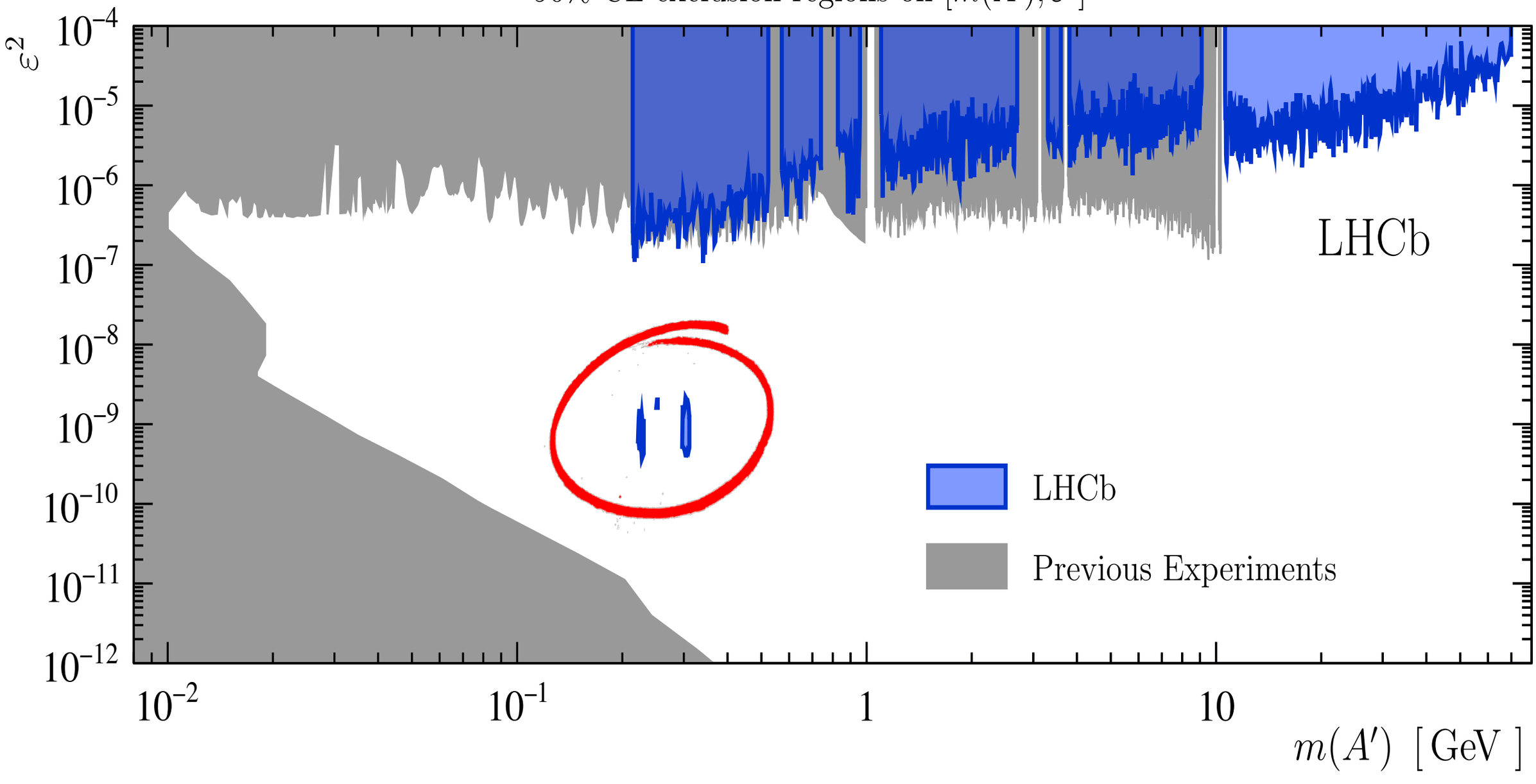
LHCb collaboration (2017), arXiv:1710.02867

Results from LHCb

real data

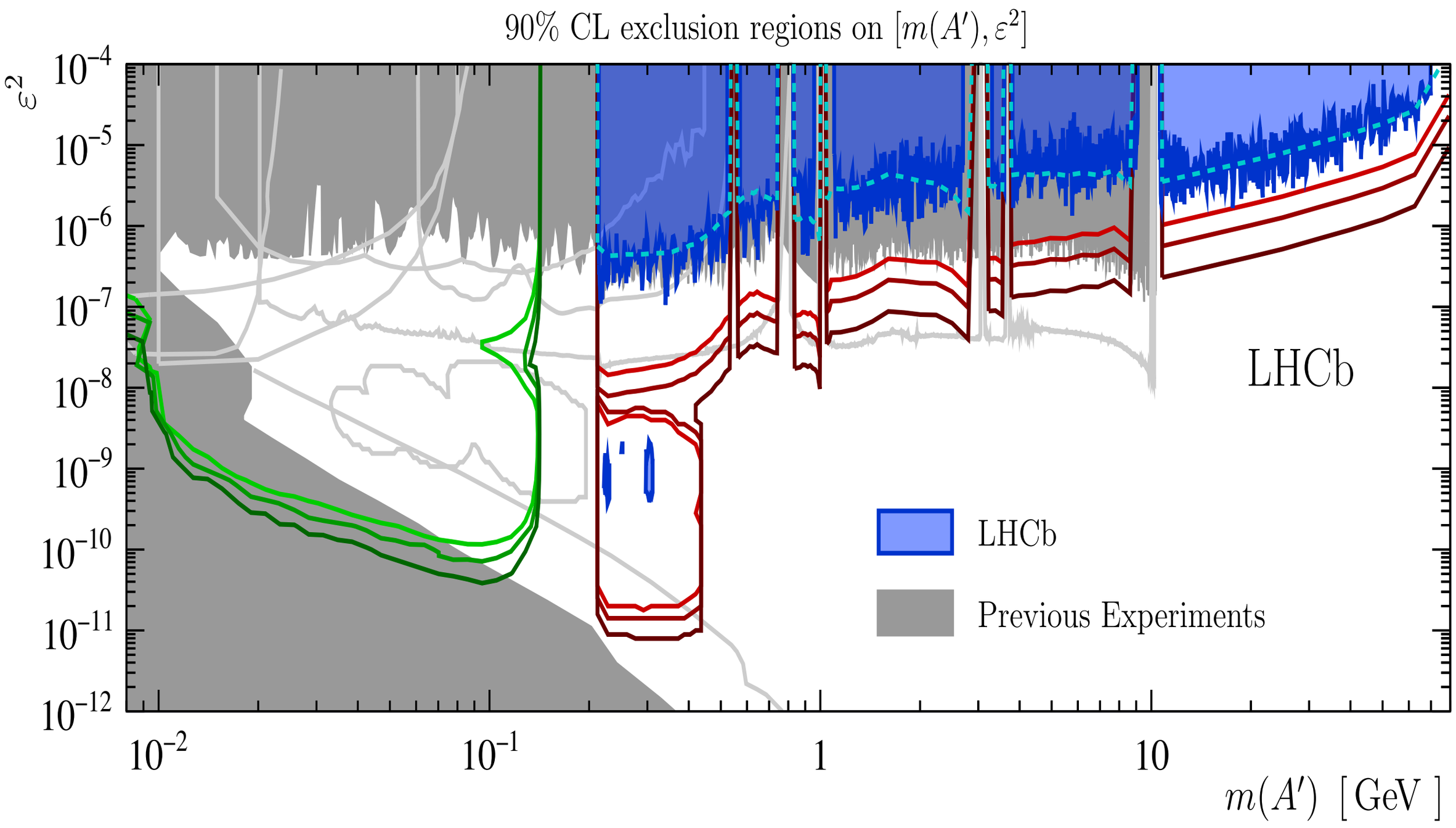
2019 LHCb New Results in backup slides

2016 data, 1.6 fb^{-1}



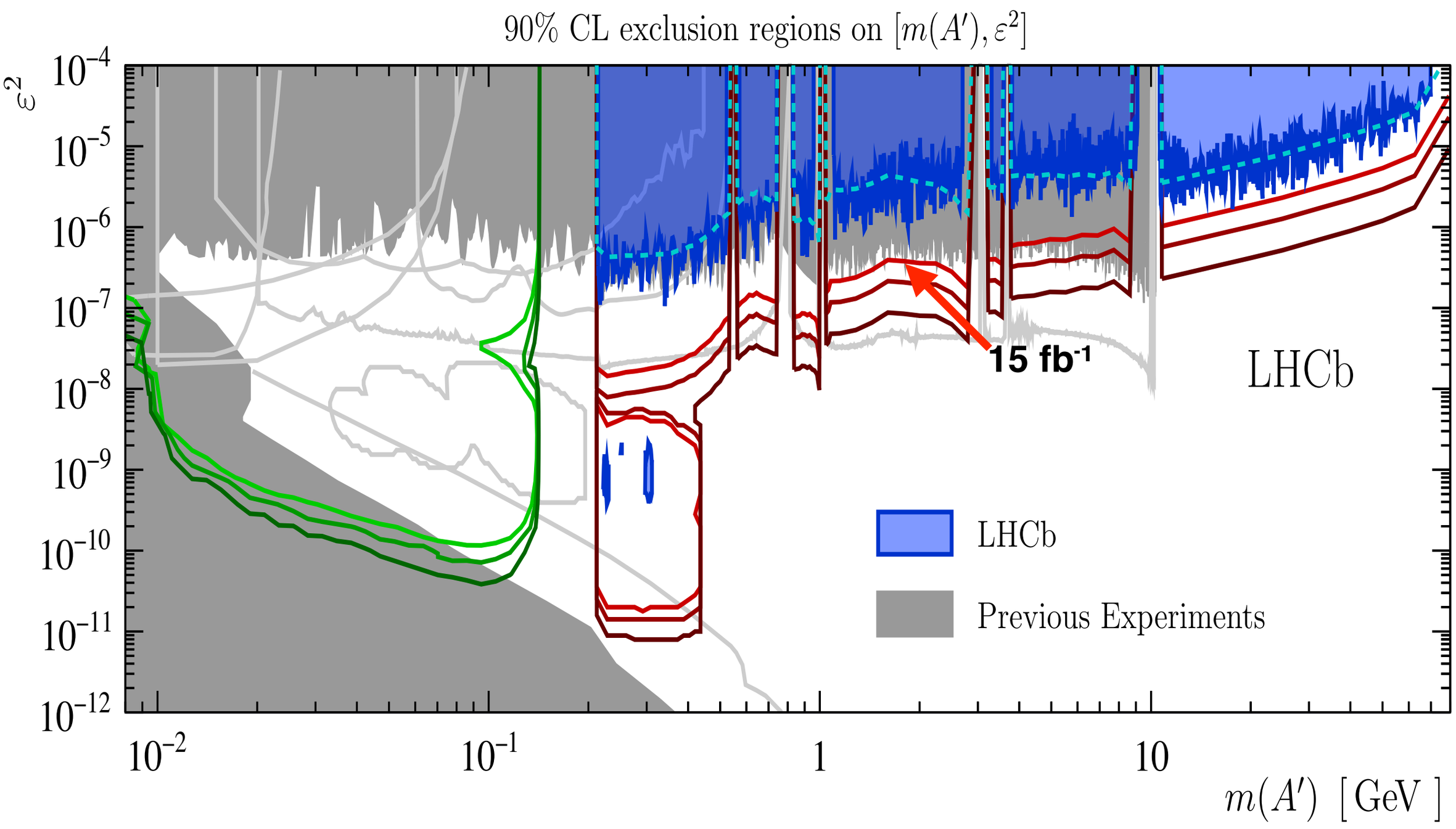
LHCb collaboration (2017), arXiv:1710.02867

Possible Improvement



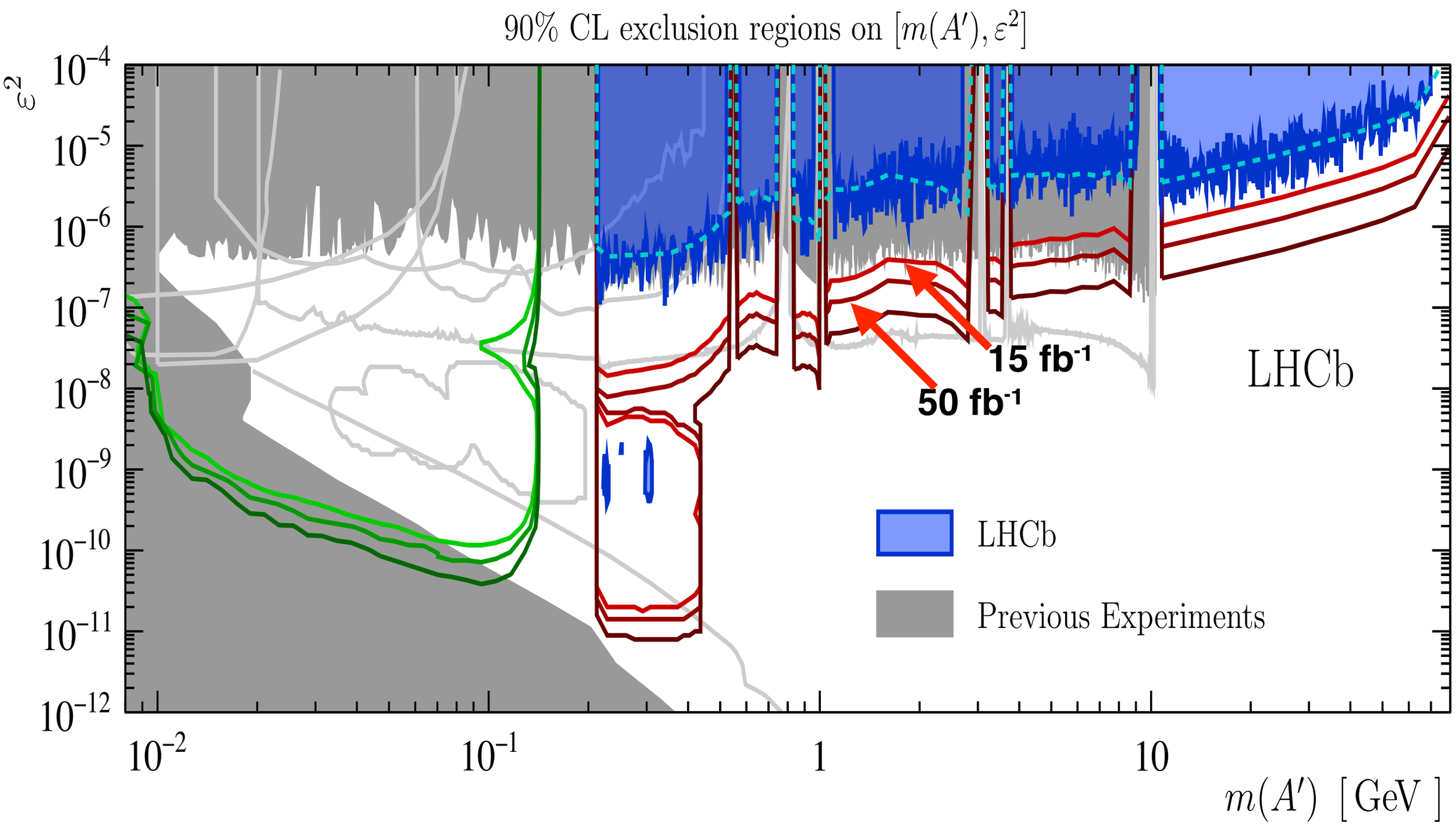
*[P. Ilten, Y. Soreq, J. Thaler, M. Williams, **WX** PRL(2016)]*

Possible Improvement



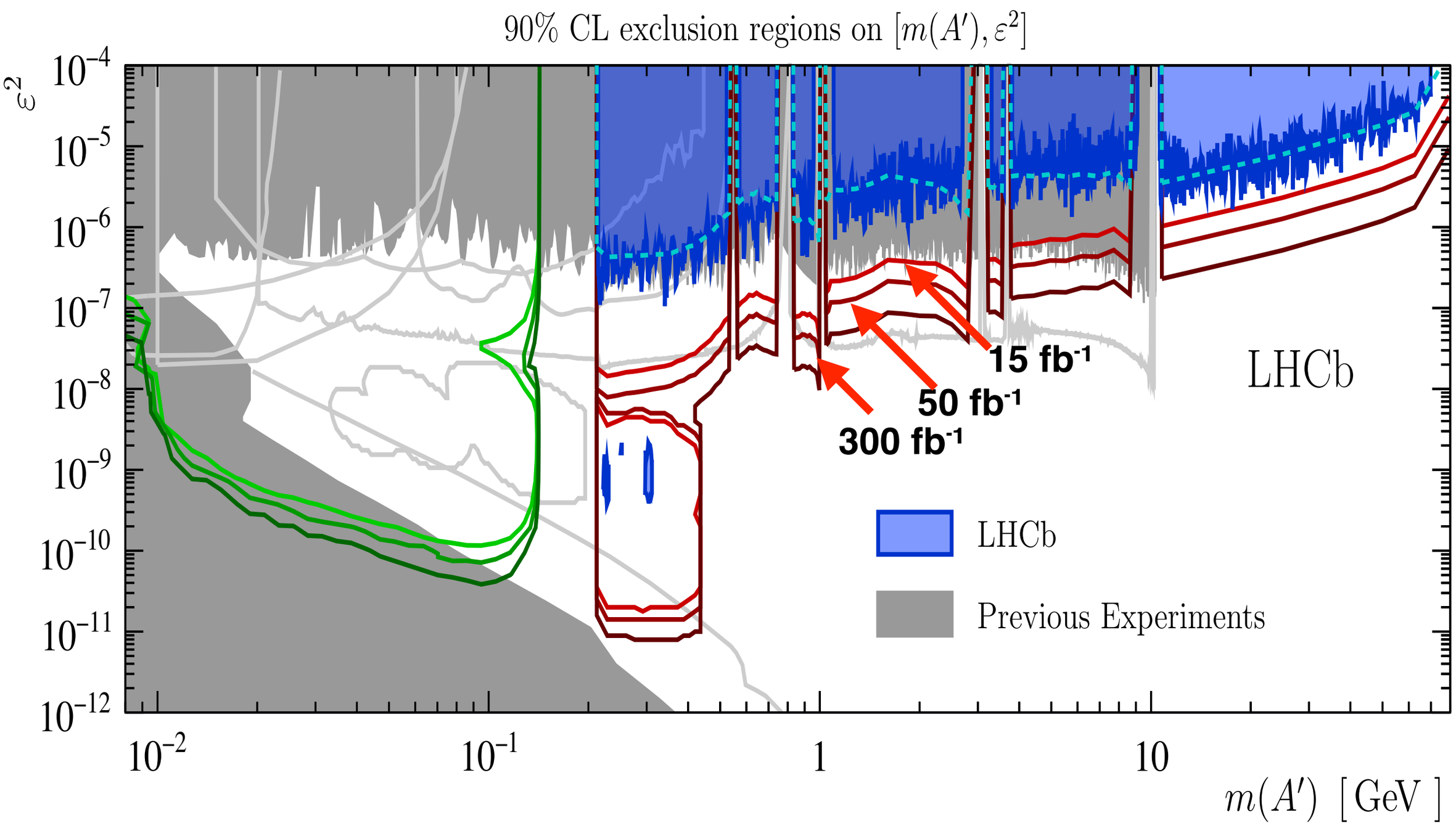
*[P. Ilten, Y. Soreq, J. Thaler, M. Williams, **WX** PRL(2016)]*

Possible Improvement



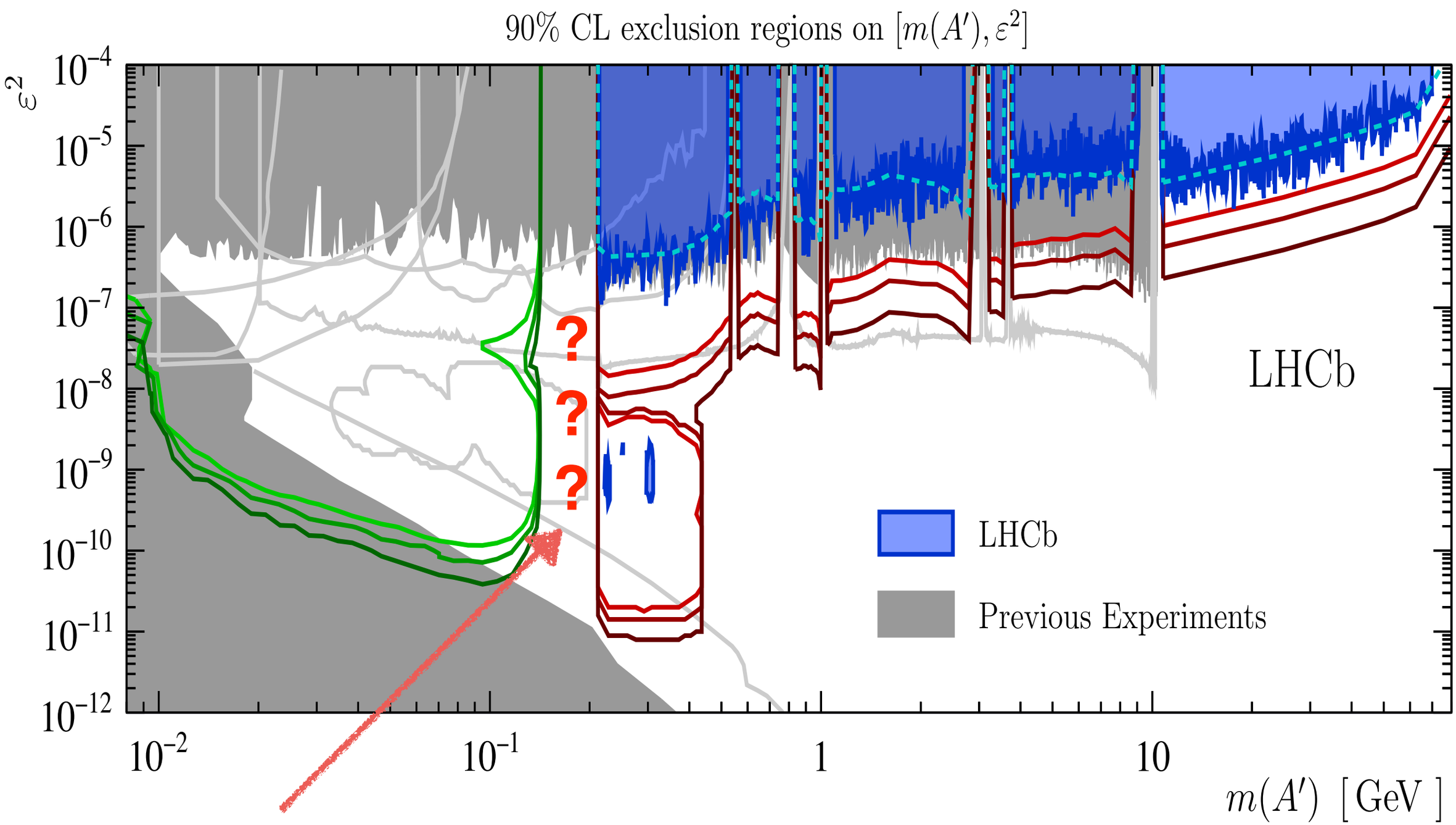
*[P. Ilten, Y. Soreq, J. Thaler, M. Williams, **WX** PRL(2016)]*

Possible Improvement



*[P. Ilten, Y. Soreq, J. Thaler, M. Williams, **WX** PRL(2016)]*

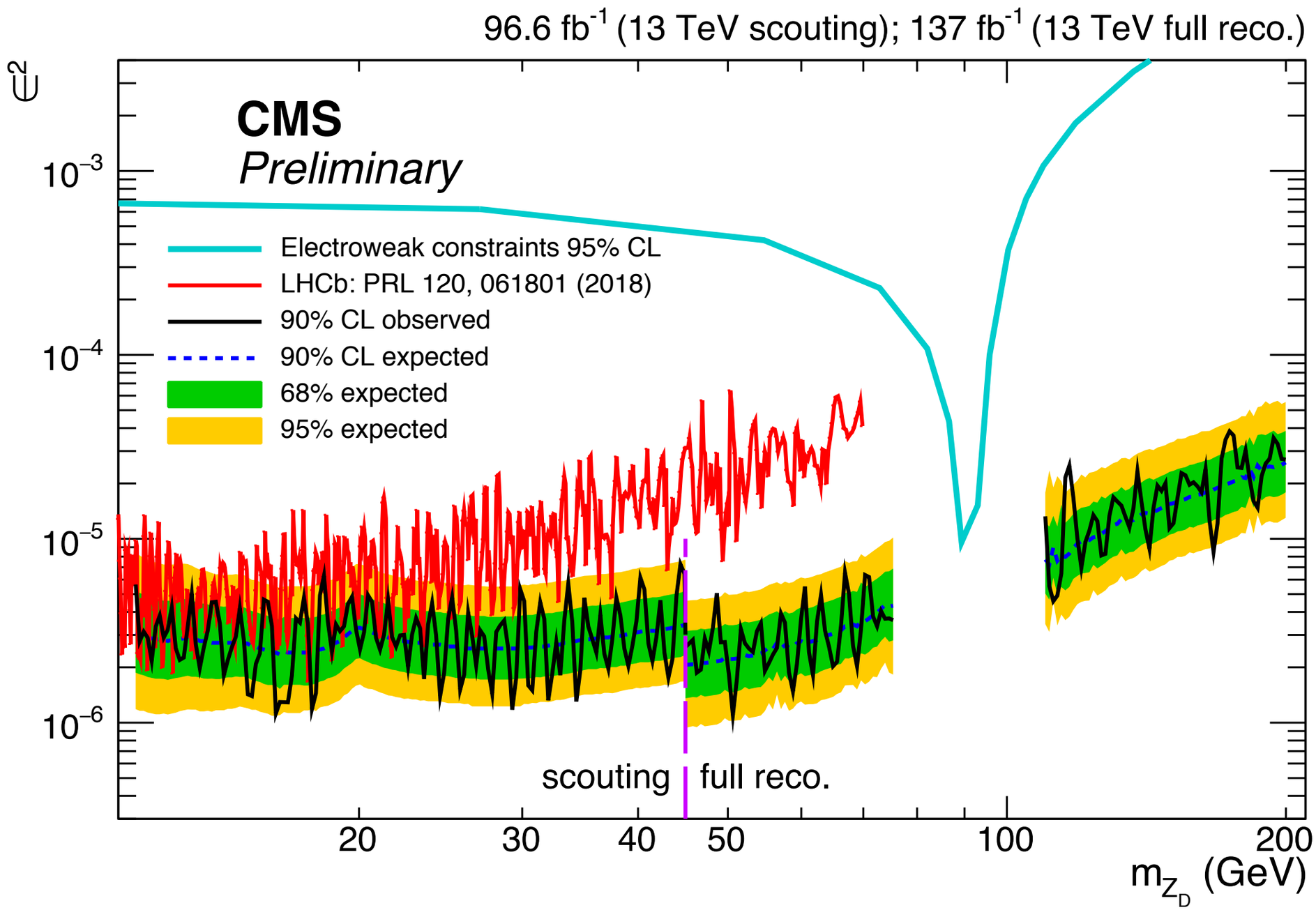
Possible Improvement



?η → A’ + … ?

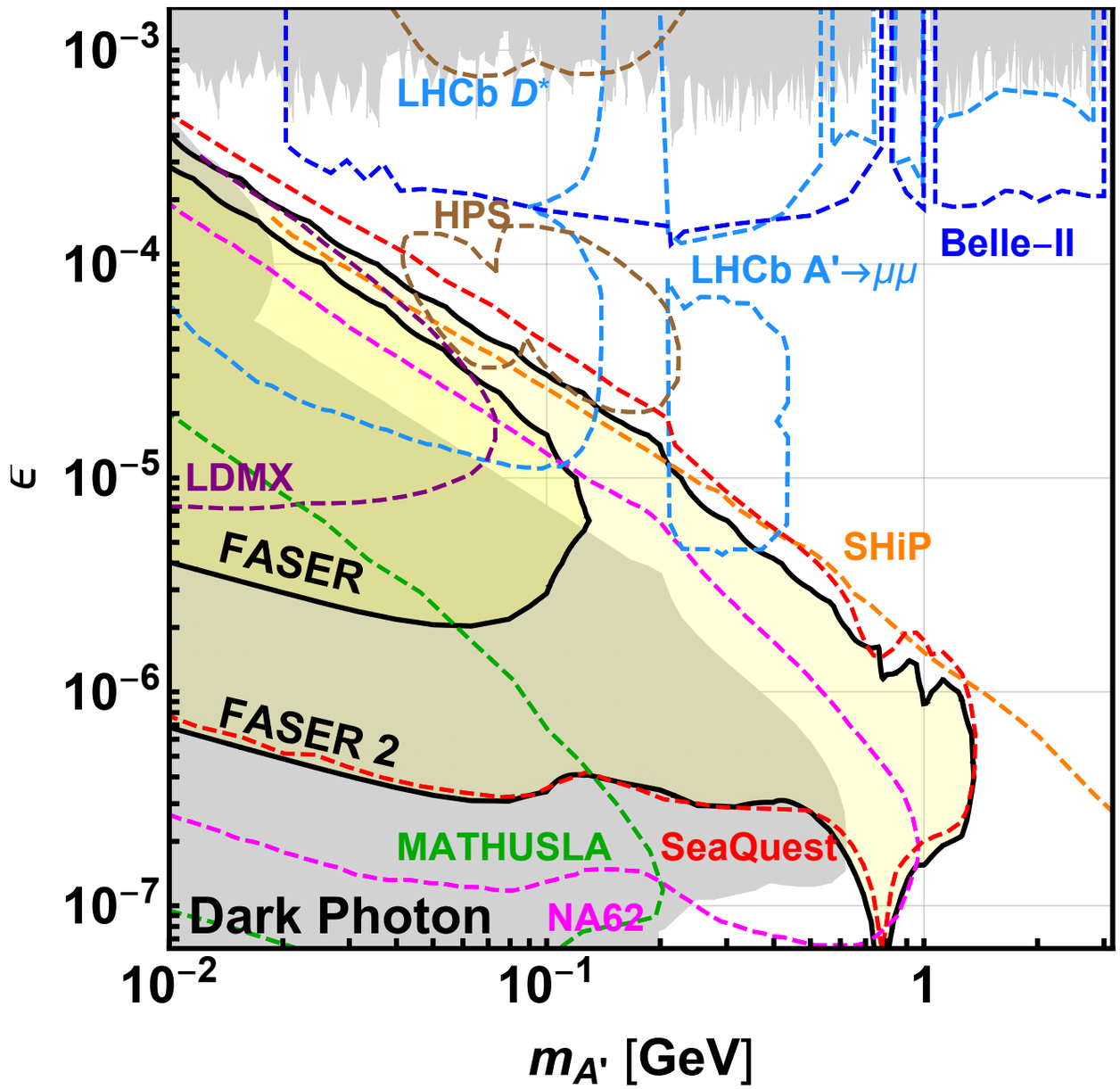
*[P. Ilten, Y. Soreq, J. Thaler, M. Williams, **WX** PRL(2016)]*

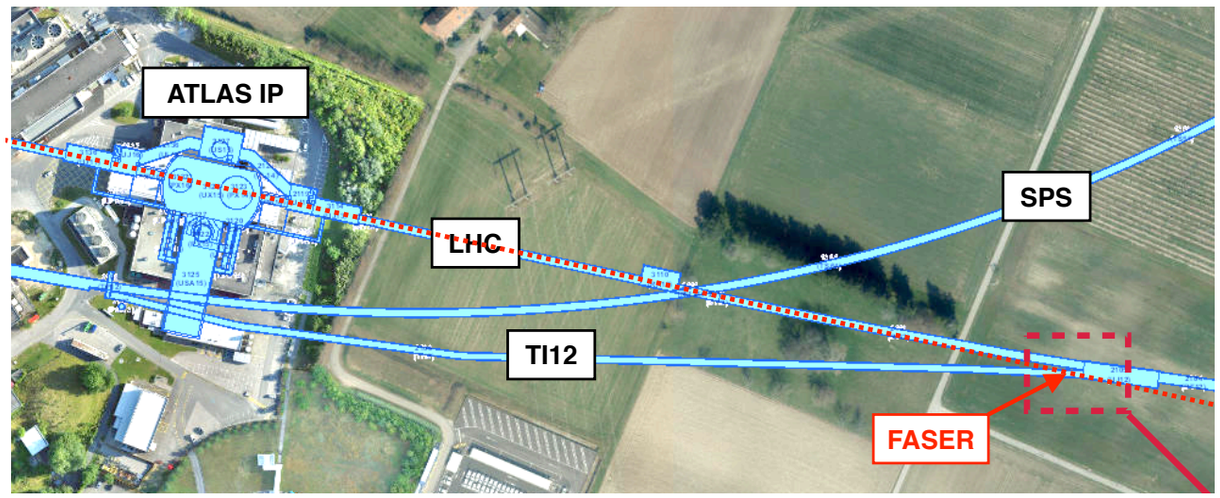
CMS goes scouting for dark photons



[CMS-PAS-EXO-19-018]

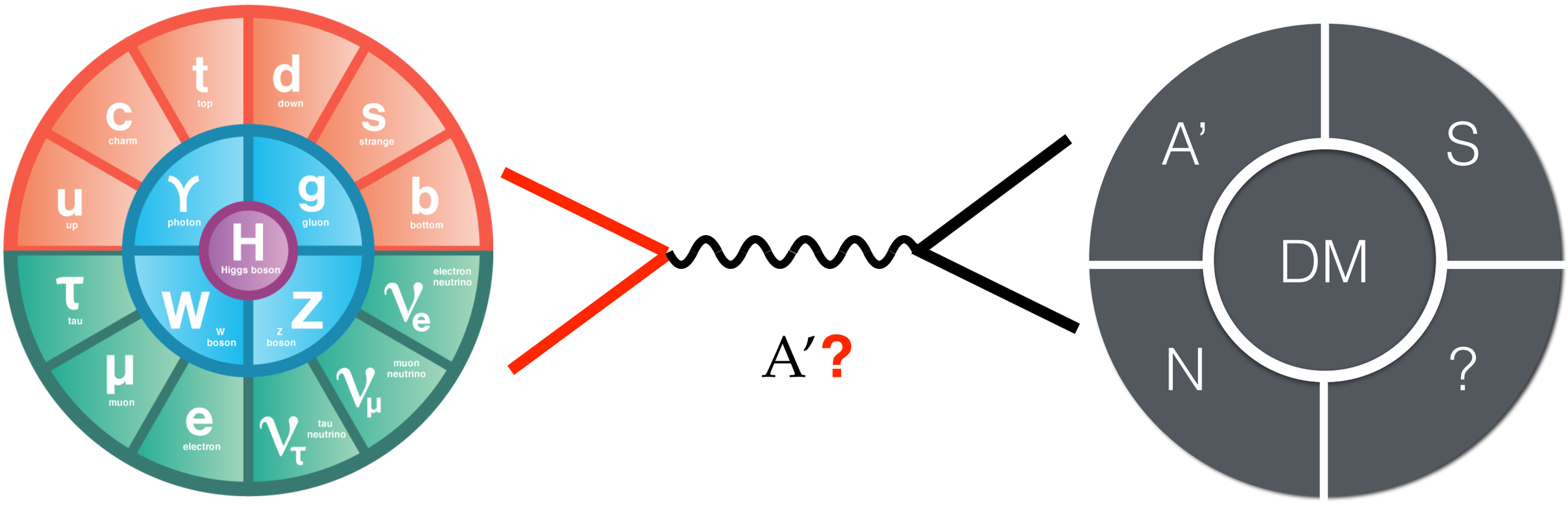
FASER


LHCb D^*
HPS
Belle–II
LHCb A'→μμ
LDMX
FASER
SHiP
FASER 2
MATHUSLA
SeaQuest
Dark Photon
NA62
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
ϵ
10^{-2}
10^{-1}
1
$m_{A'}$ [GeV]

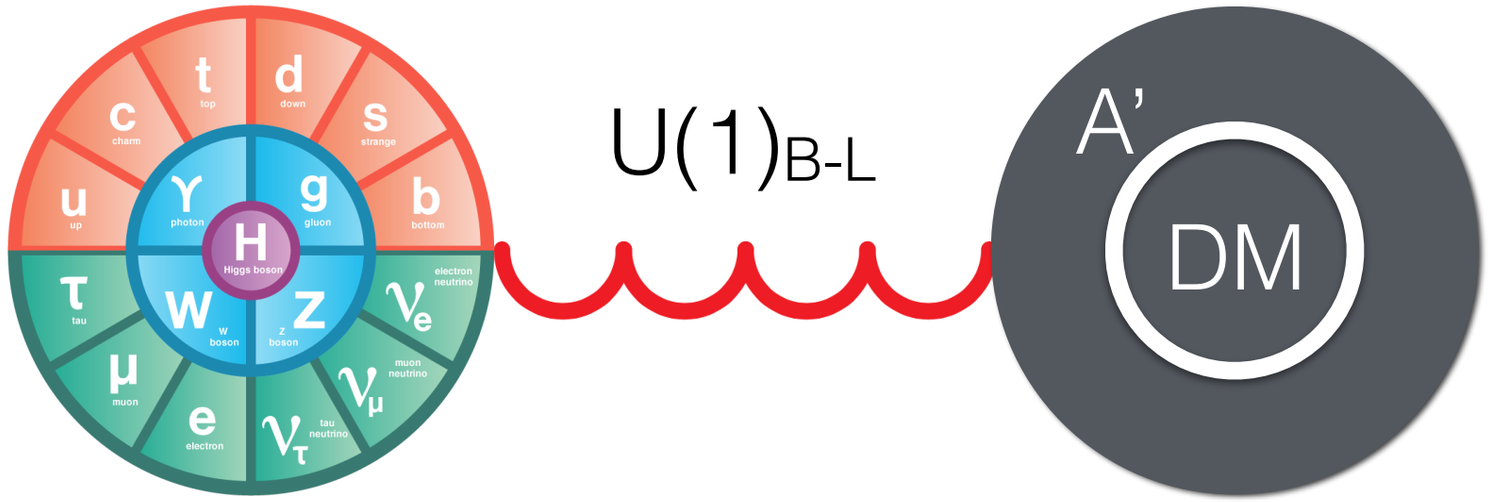

ATLAS IP
LHC
SPS
TI12
FASER

Beyond Dark Photons

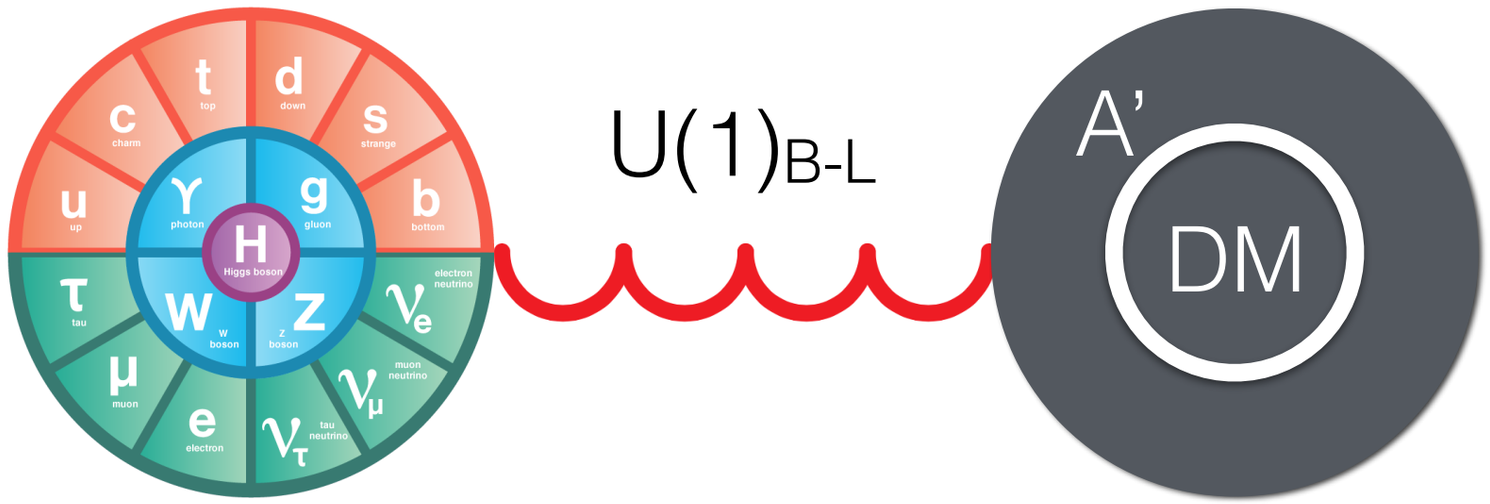
$$\mathcal{L} \subset g_X \sum_f x_f \bar{f} \gamma^\mu f X_\mu + \sum_\chi \mathcal{L}_{X\chi\bar{\chi}}$$

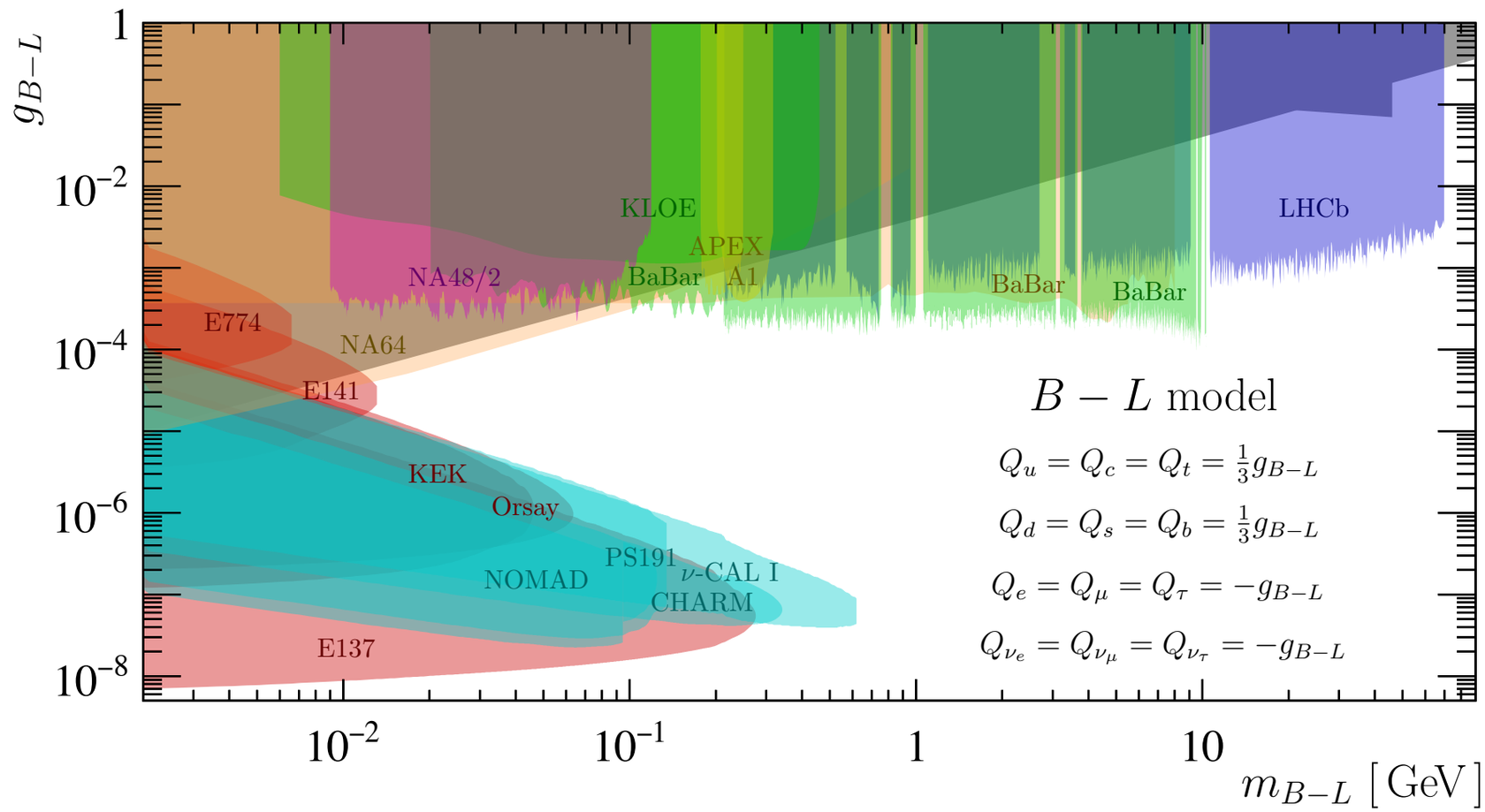


Beyond Dark Photon



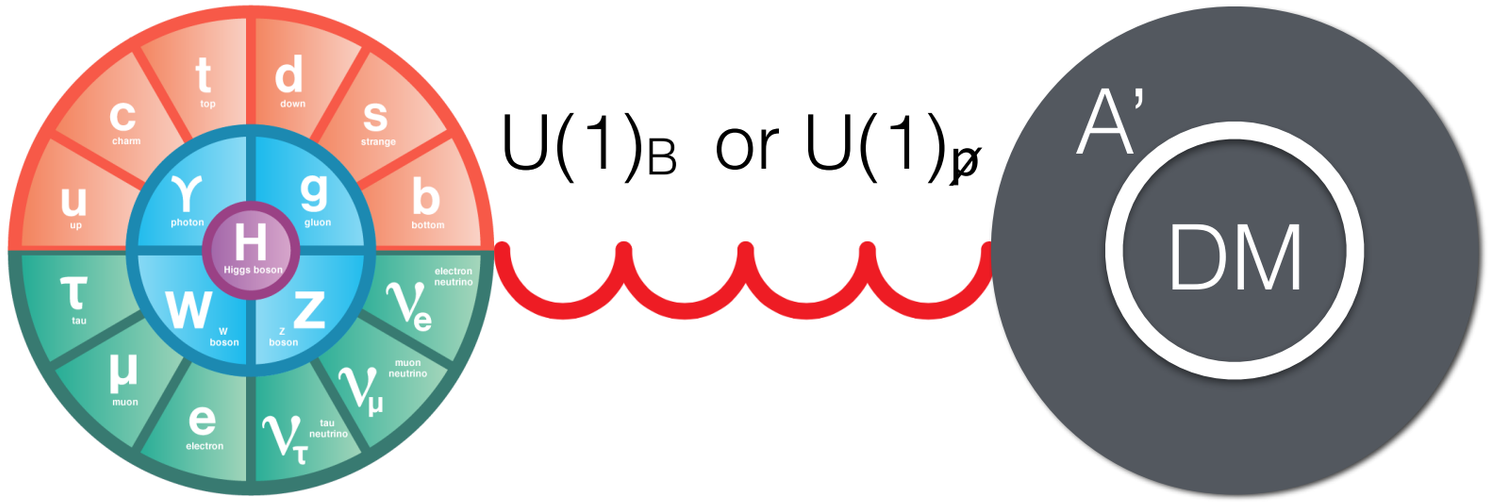
Beyond Dark Photon

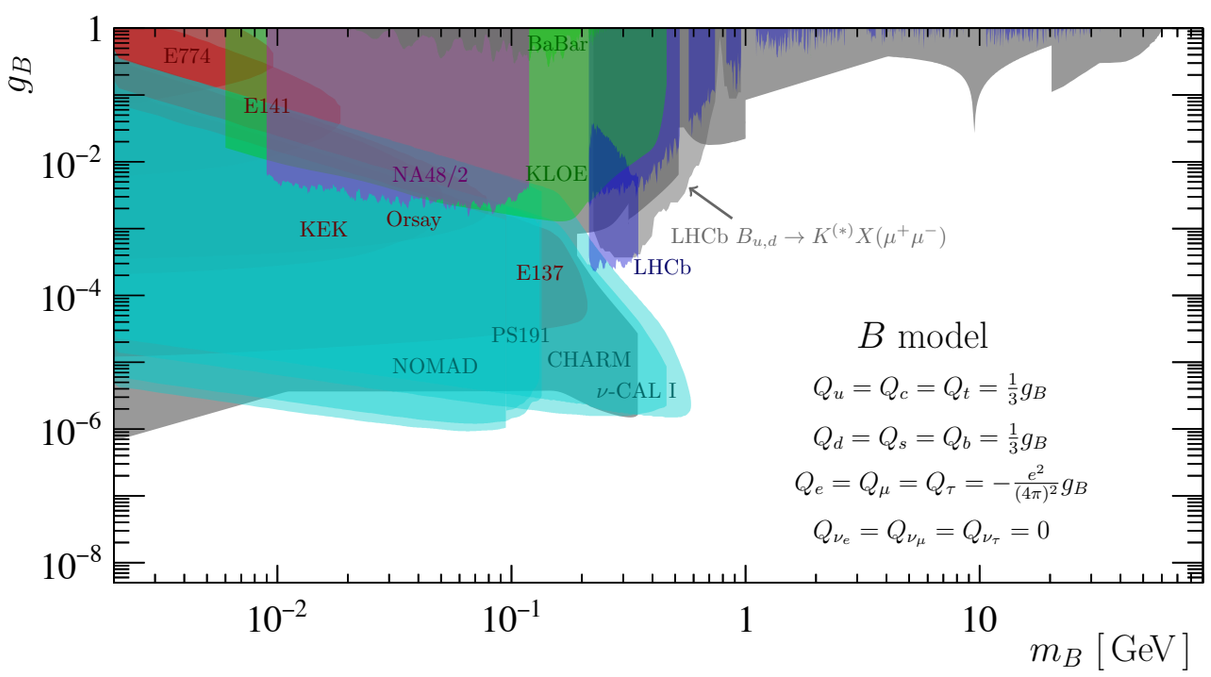


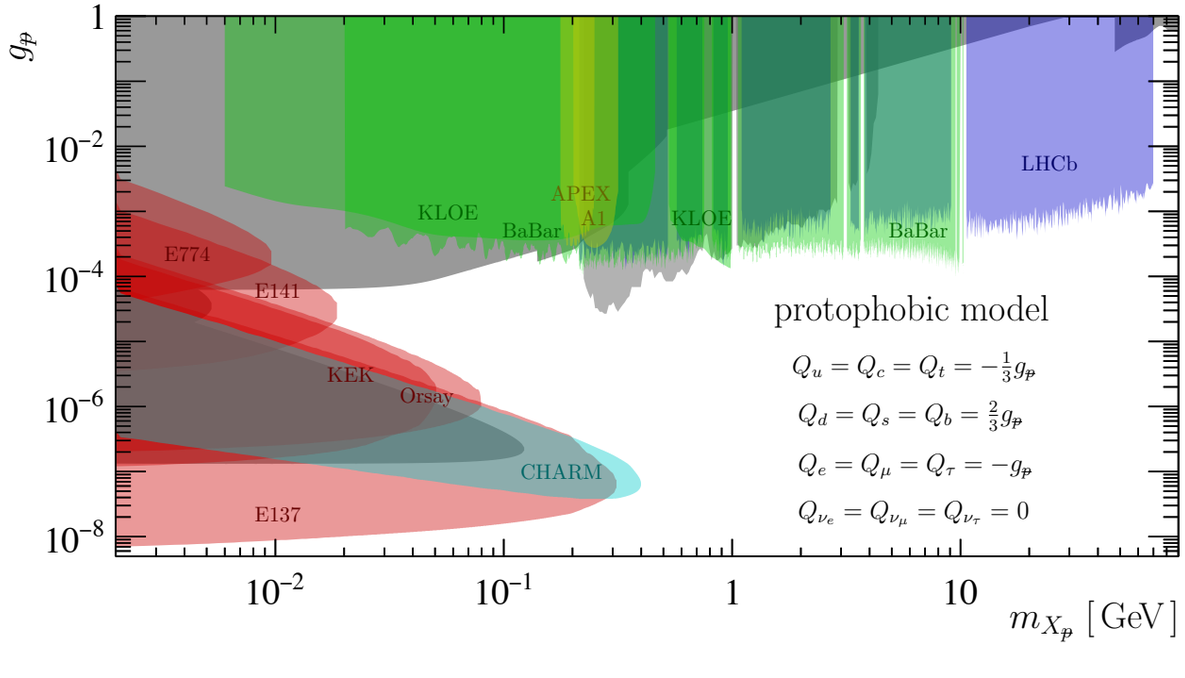


*[P. Ilten, Y. Soreq, M. Williams, **WX** (2018)]*

Beyond Dark Photon







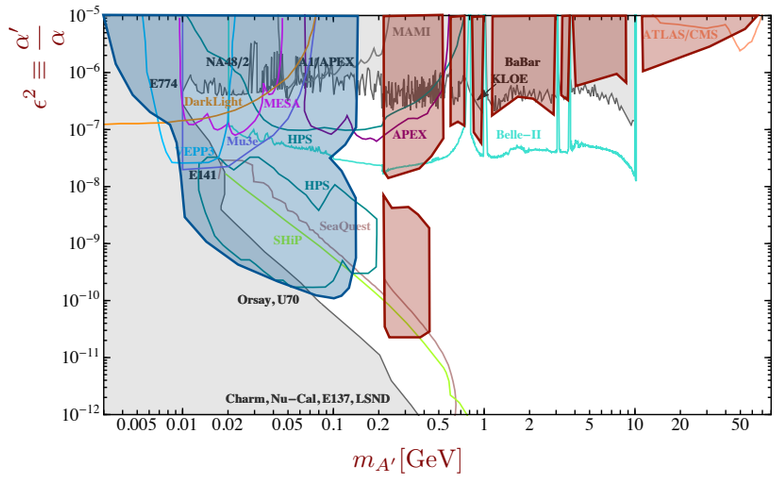
*[P. Ilten, Y. Soreq, M. Williams, **WX** (2018)]*

Summary

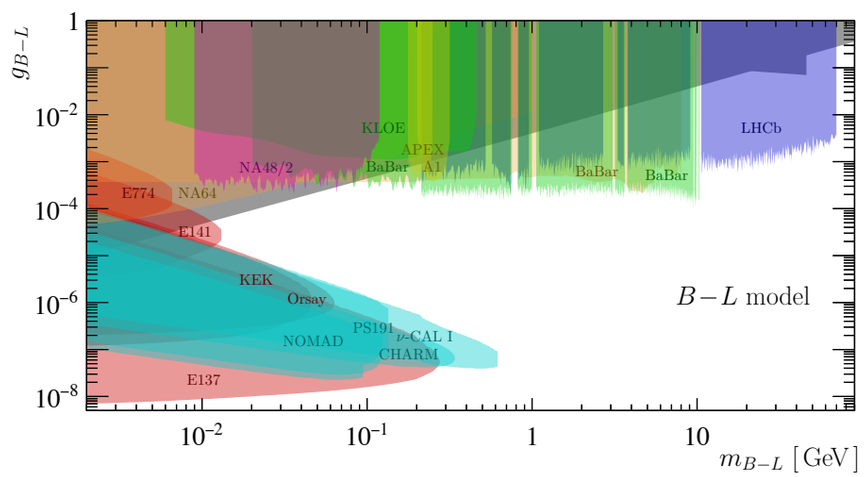
- dark photon searches @ LHCb

  $D^{0*} \rightarrow D^0 + \gamma$

  inclusive search

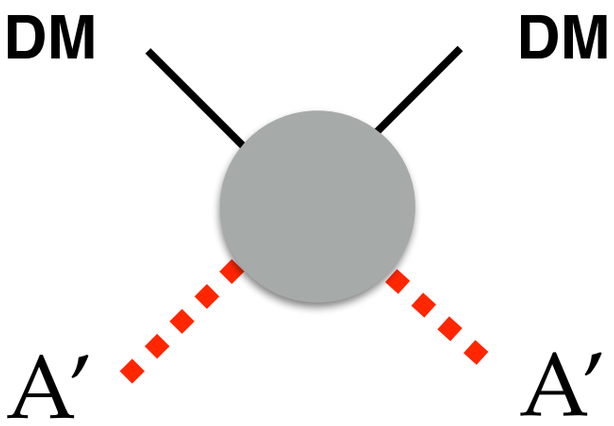


- beyond dark photon



Colliders

dark photon searches with



Cosmology, Galaxies and Stars

dark photon dark matter

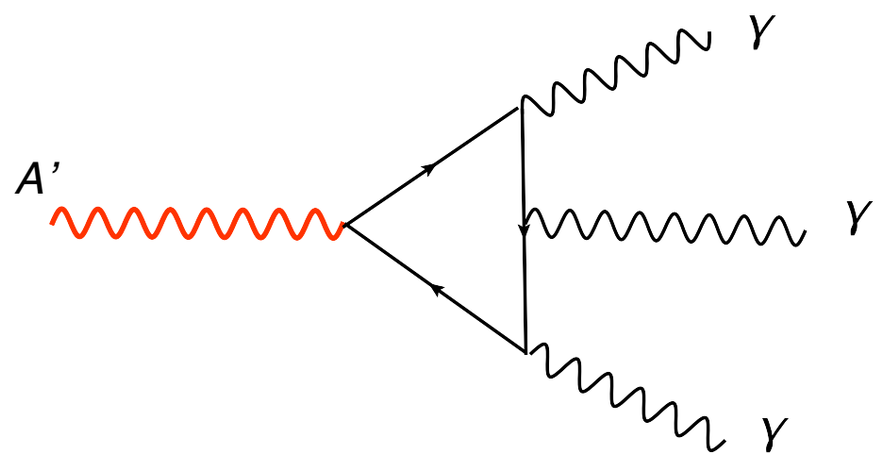
production , small scale issues

detections

Dark Photon Dark Matter

- light dark photon mass
  10^{-22} eV < m_γ ≪ eV

- stable in the cosmological time scale



- de Broglie wavelength
  galactic scale for dark matter of mass 10^{-22} eV

  $\ell \sim$ kpc ($m_{A'}$ / 10^{-22} eV)$^{-1}$ (v_0 / 10^{-3})$^{-1}$

- large occupancy number

$$\langle \mathcal{N}^{A'} \rangle \sim \frac{\rho_{A'}/m_{A'}}{m_{A'}^3 v_0^3} \sim 3 \times 10^{76} \times \left(\frac{\rho_{A'}}{0.1 \mathrm{M}_\odot/\mathrm{pc}^3}\right) \left(\frac{m_{A'}}{10^{-18}\mathrm{eV}}\right)^{-4} \left(\frac{v_0}{10^{-3}}\right)^{-3}$$

Dark Photon Dark Matter Production

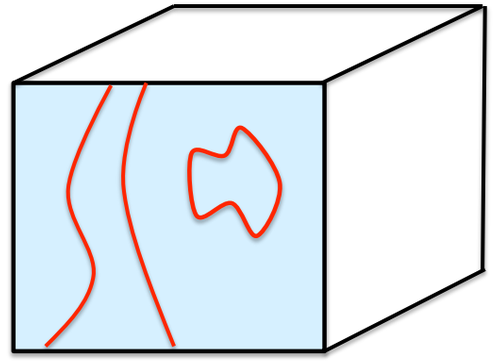
- normal thermal freeze-out or freeze-int does NOT work

- by inflationary quantum fluctuations

  [P. Graham, J. Mardon, S. Rajendran (2015)]

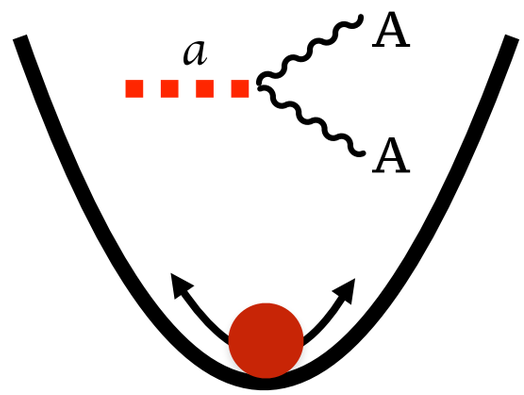
- cosmic string decays

  [A. Long, L. Wang (2019)]



- $a \rightarrow \gamma' \gamma'$

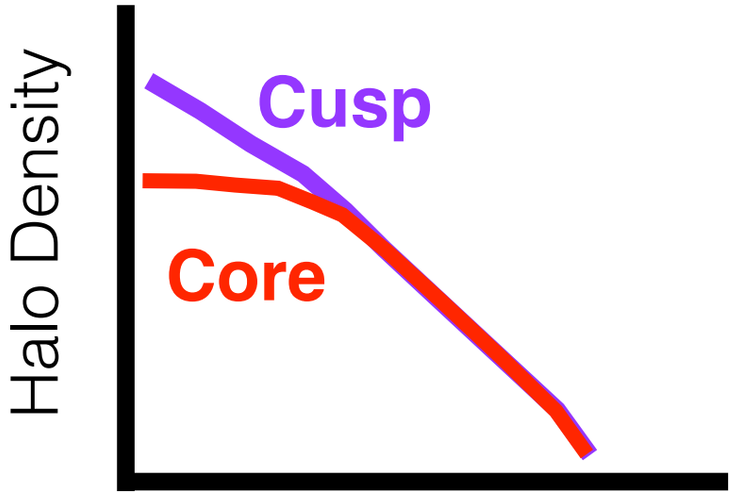
  [Co, Pierce, Zhang, Zhao. Long (2018)]
  [Argrawal, Kitajima, Reece, Sekiguchi, Takahashi(2018)]
  [Dror, Harigaya, Narayan (2018)]
  [Bastero-Gil, Santiago, Ubaldi, Vega-Morales (2018)]



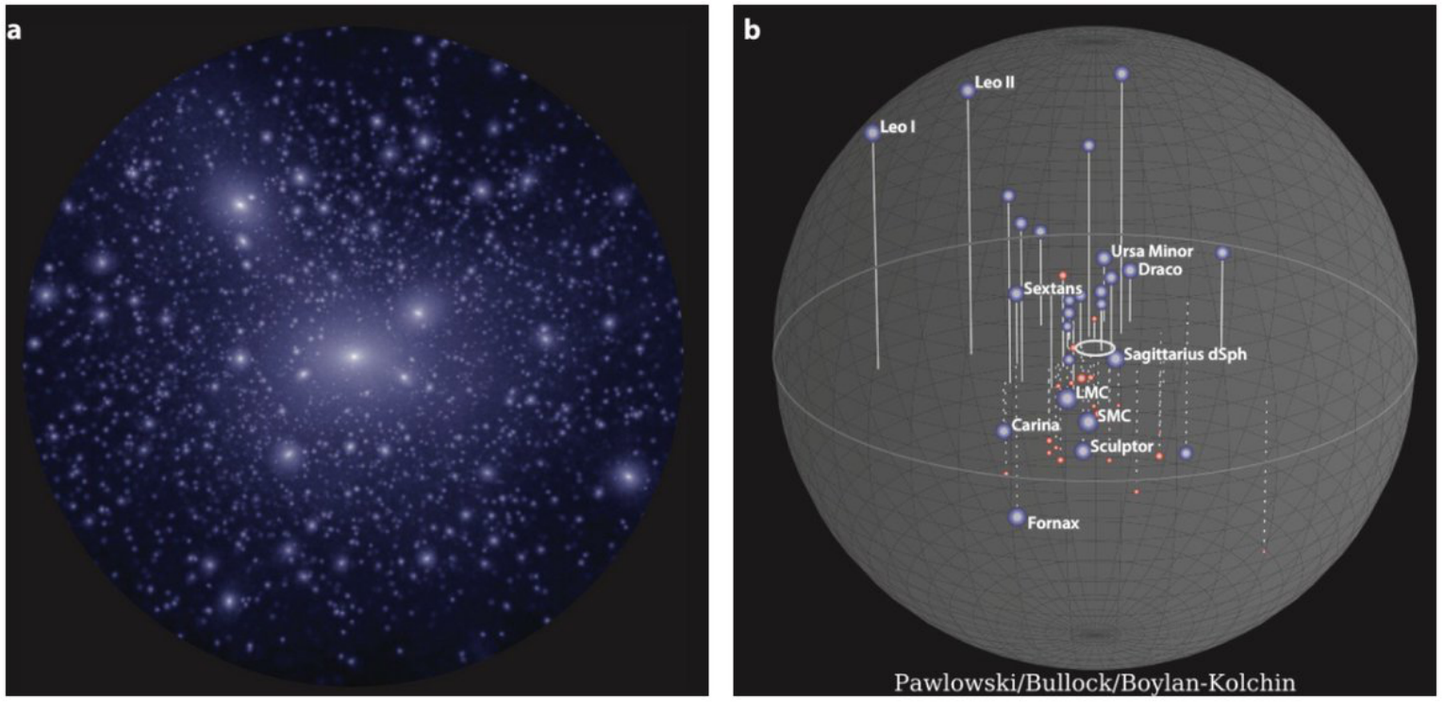
*See also [P. Agrawal, G. Marques-Tavares, **WX** (217)]*

Small Scale Observations

- core/cusp



- missing satellites

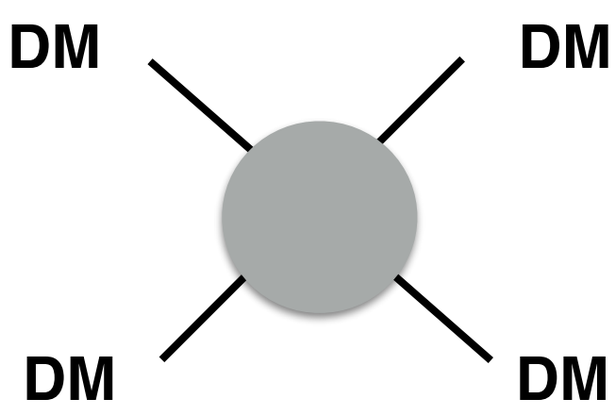


- too big to fail diversity problem

…

Two Dark Matter Solutions

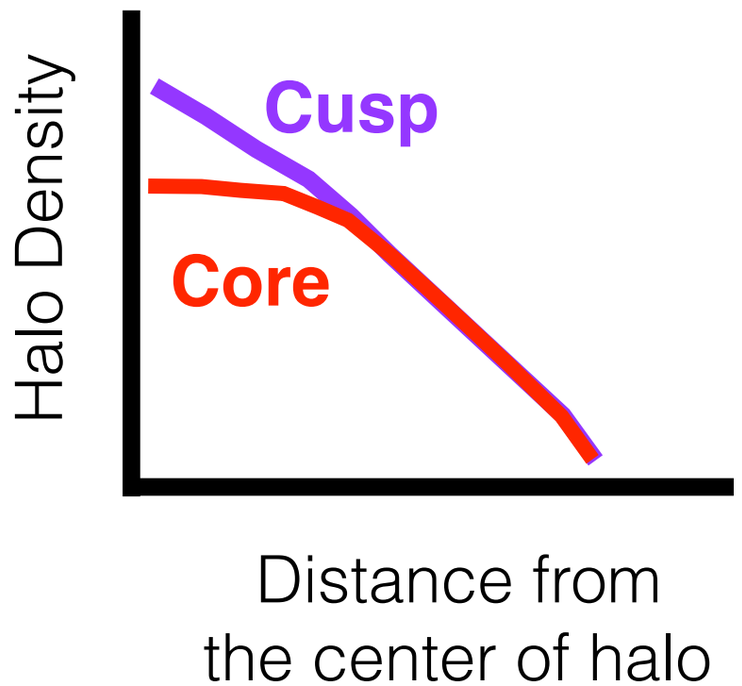
- self-interacting DM
  thermalize in the center
  of galaxies
  m_{DM} ~ 1 GeV



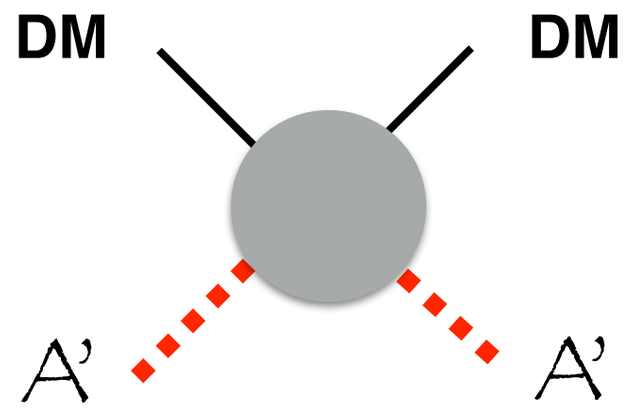
- fuzzy dark matter
  quantum pressure in the center

  m_a ~ 10^{-22} eV
  de Broglie wavelength ~ kpc

  tension with
  Lyman-α measurement



Co-Interacting Dark Matter



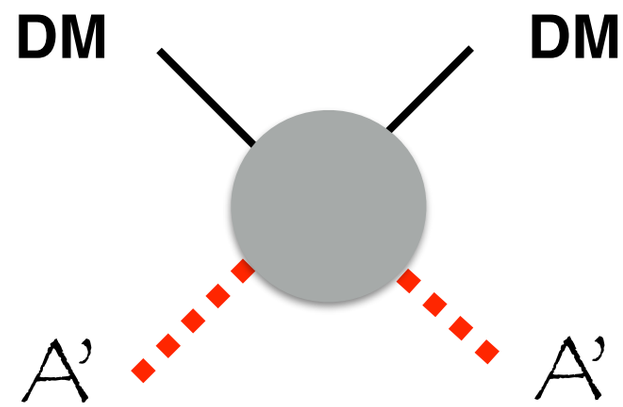
- any interactions can thermalize dark matter

- models
  dark photon + dark electrons

$$\mathcal{L} \supset g' \bar{\psi} \gamma_\mu \psi A'^\mu$$

*[J. Liu, X. Wang, **WX** 2019]*

Thermalization Rate



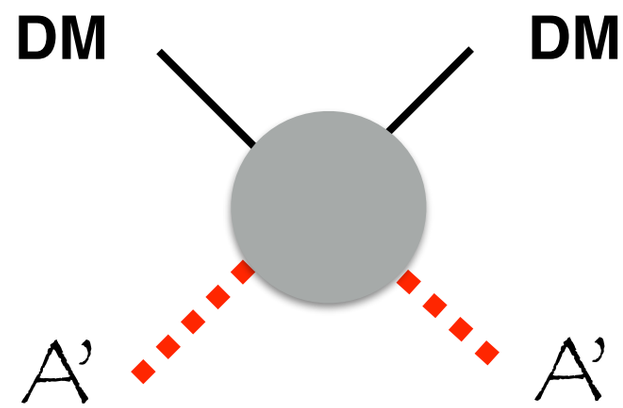
- Boltzmann equations

$$(\partial_t + v_i \partial_{x_i} + \dot{v}_i \partial_{v_i}) \mathcal{N}(\mathbf{x}, \mathbf{p}, \mathbf{t}) = \mathcal{C}(\mathbf{x}, \mathbf{p}, \mathbf{t})$$

- thermalization rate

normal rate $n \langle \sigma v \rangle$

Thermalization Rate



- Boltzmann equations

$$(\partial_t + v_i \partial_{x_i} + \dot{v}_i \partial_{v_i})\,\mathcal{N}(\mathbf{x}, \mathbf{p}, \mathbf{t}) = \mathcal{C}(\mathbf{x}, \mathbf{p}, \mathbf{t})$$

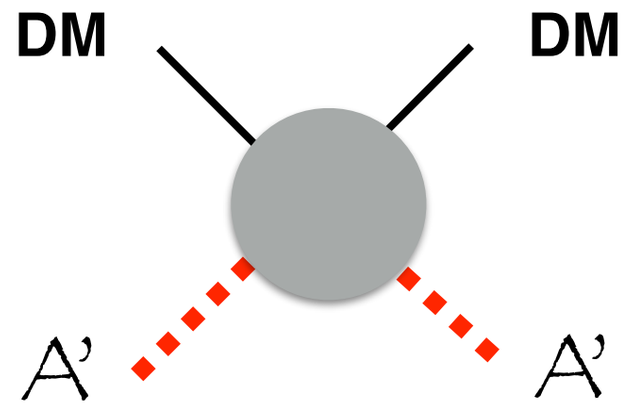
- thermalization rate

  1) large occupancy number enhancement

$$n\langle\sigma v\rangle \mathcal{N}^{A'}$$

$$\langle \mathcal{N}^{A'} \rangle \sim \frac{\rho_{A'}/m_{A'}}{m_{A'}^3 v_0^3} \sim 3 \times 10^{76}$$
$$\times \left(\frac{\rho_{A'}}{0.1\mathrm{M}_\odot/\mathrm{pc}^3}\right) \left(\frac{m_{A'}}{10^{-18}\mathrm{eV}}\right)^{-4} \left(\frac{v_0}{10^{-3}}\right)^{-3}$$

Thermalization Rate



- Boltzmann equations

$$(\partial_t + v_i \partial_{x_i} + \dot{v}_i \partial_{v_i}) \mathcal{N}(\mathbf{x}, \mathbf{p}, \mathbf{t}) = \mathcal{C}(\mathbf{x}, \mathbf{p}, \mathbf{t})$$

- thermalization rate

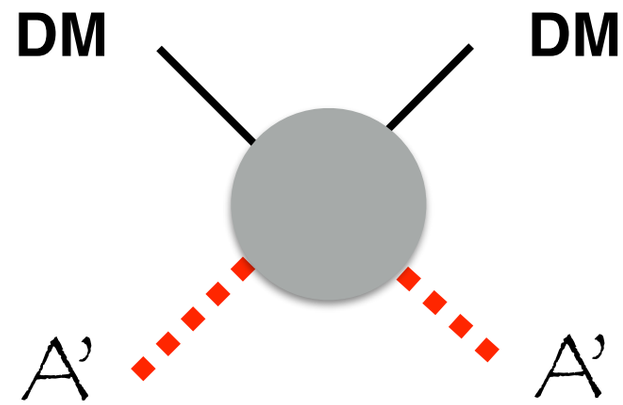
  1) large occupancy number enhancement

$$n\langle\sigma v\rangle \mathcal{N}^{A'}$$

  2) back and forward scattering

$$\Gamma_{A'} \simeq n\langle\sigma v\rangle \langle\mathcal{N}^{A'}\rangle \left(\frac{m_{A'}}{m_\psi}\right)$$

Thermalization Rate



- Boltzmann equations

$$(\partial_t + v_i \partial_{x_i} + \dot{v}_i \partial_{v_i}) \mathcal{N}(\mathbf{x}, \mathbf{p}, \mathbf{t}) = \mathcal{C}(\mathbf{x}, \mathbf{p}, \mathbf{t})$$

- thermalization rate

1) large occupancy number enhancement

$$n\langle\sigma v\rangle \mathcal{N}^{A'}$$

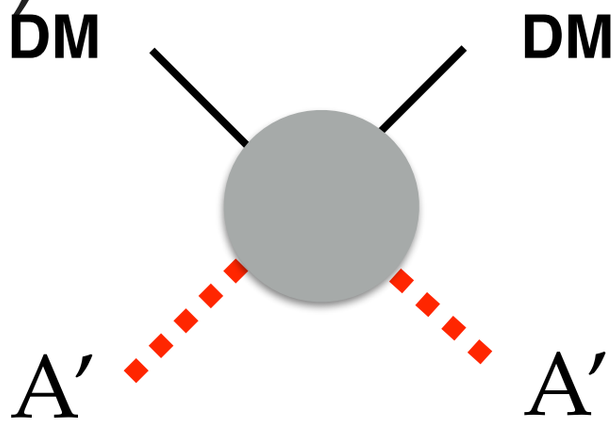
2) back and forward scattering

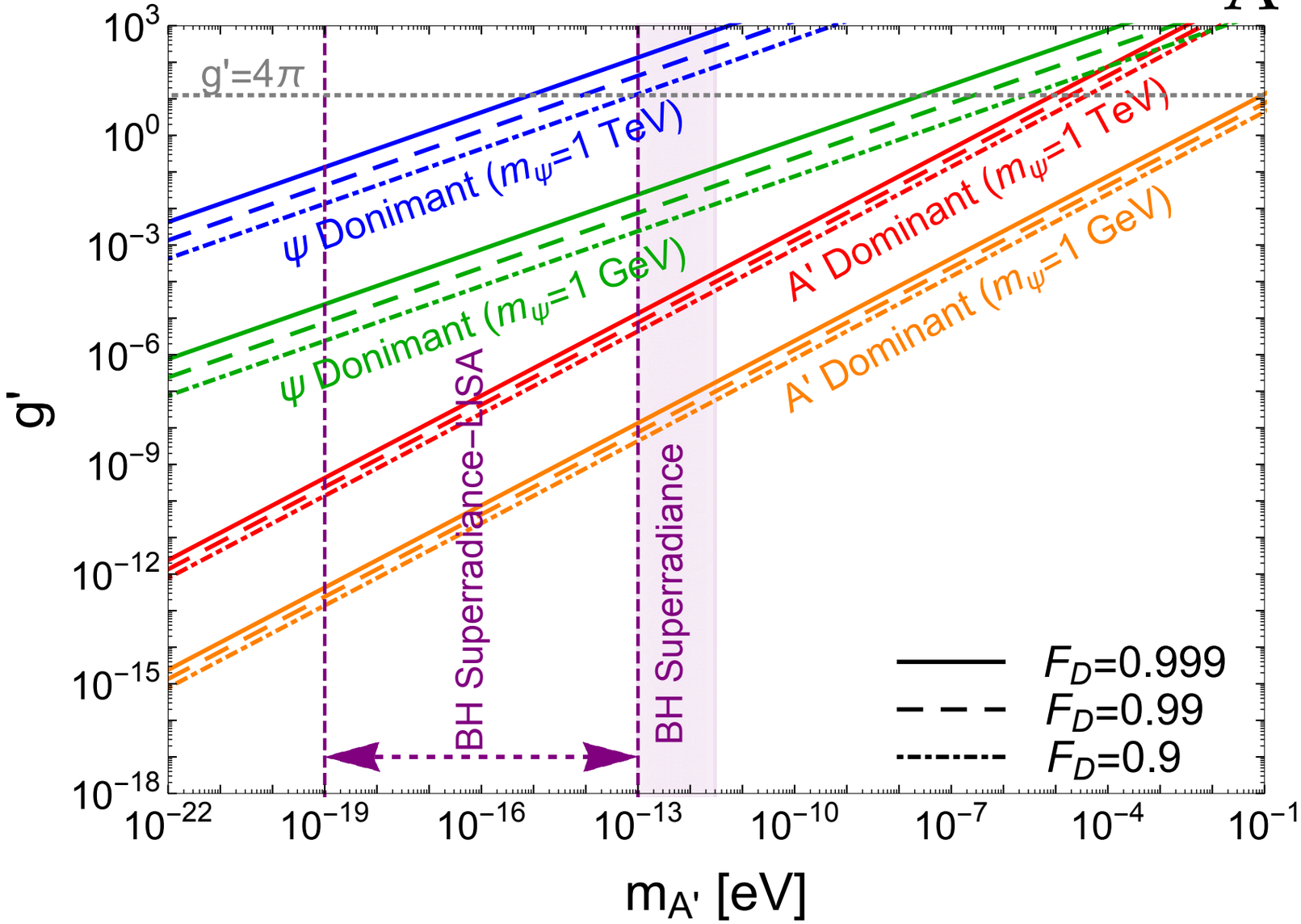
$$\Gamma_{A'} \simeq n\langle\sigma v\rangle \langle\mathcal{N}^{A'}\rangle \left(\frac{m_{A'}}{m_\psi}\right)$$

3) random walk suppression (momentum exchange~ $m_{A'}v$)

$$\Gamma_\psi \simeq n\langle\sigma v\rangle \langle\mathcal{N}^{A'}\rangle \left(\frac{m_{A'}}{m_\psi}\right) \left(\frac{m_{A'}}{m_\psi}\right)^2$$

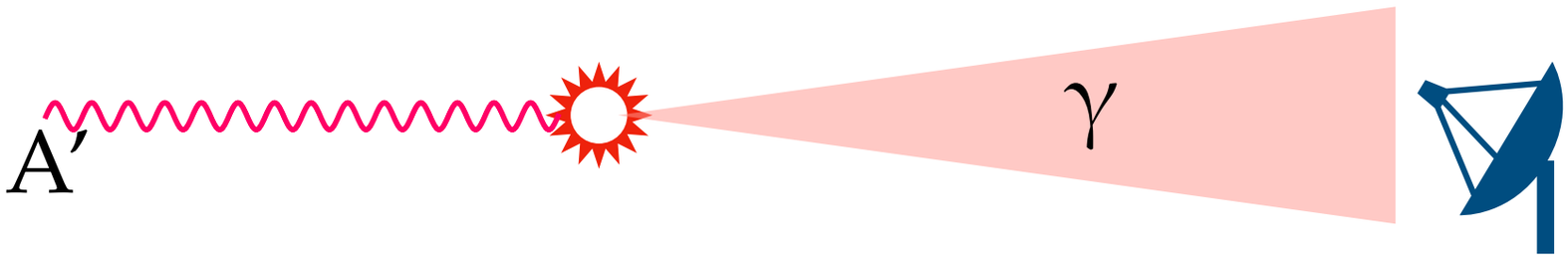
Co-Interacting Dark Matter (Co-IDM)

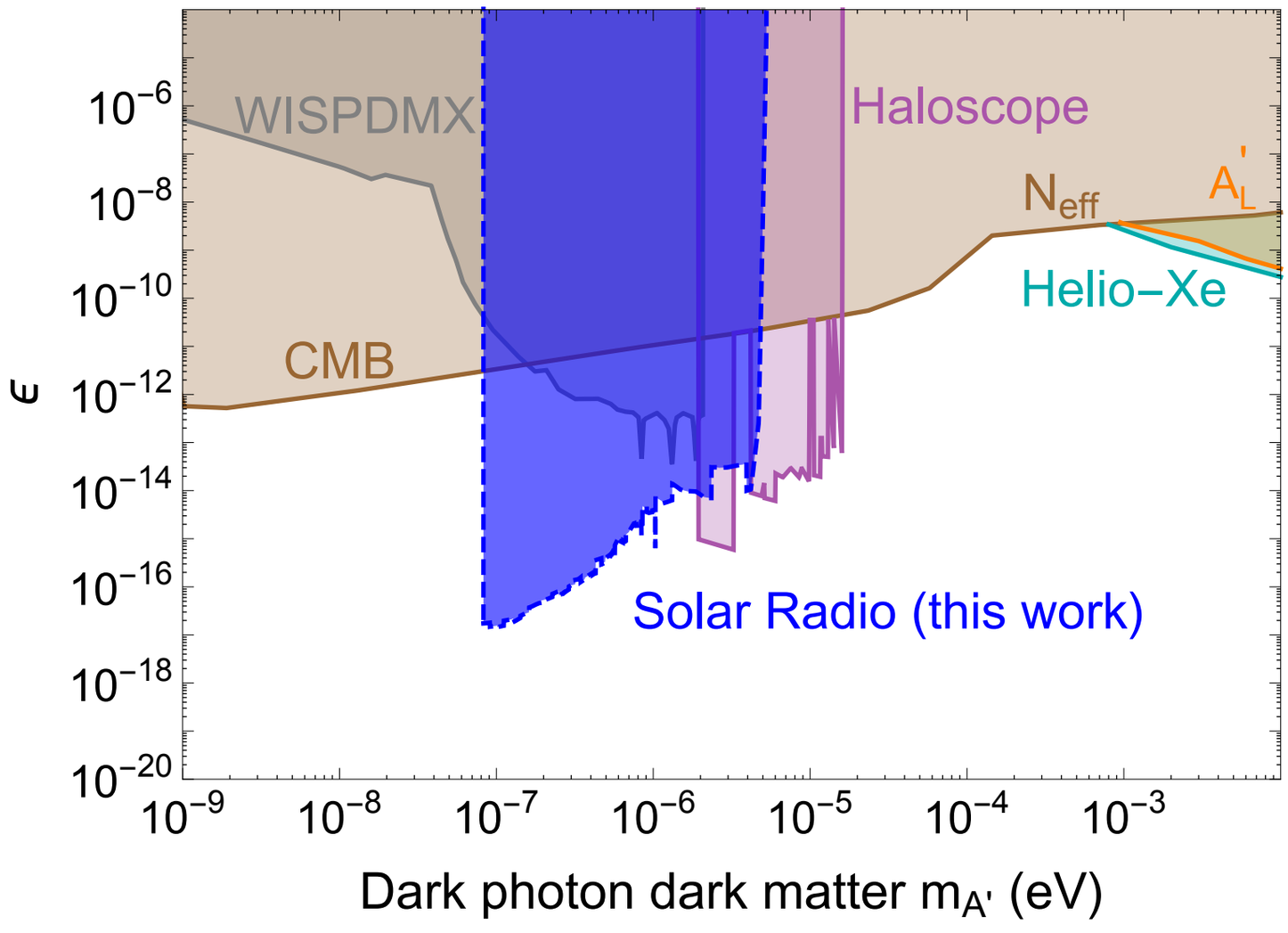




*[J. Liu, X. Wang, **WX** 2019]*

Dark Photon Detection (preliminary)





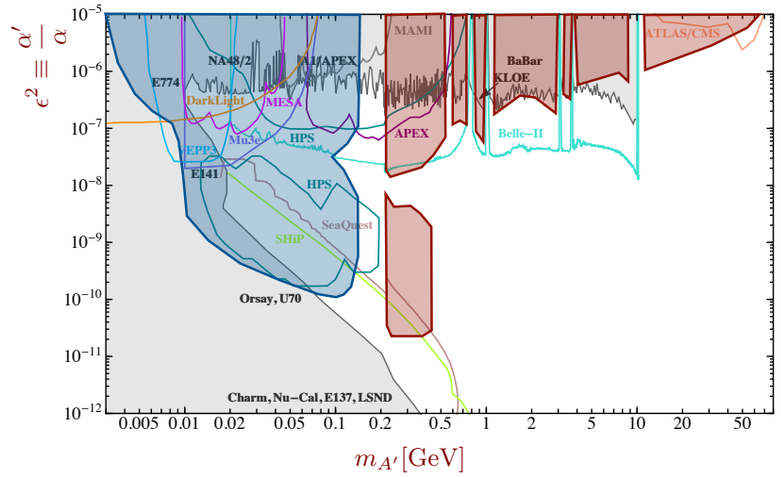
*[H. An, F. Huang, J. Liu, **WX** in progress]*

Conclusion

- dark photon searches @ LHCb

  $D^{0*} \rightarrow D^0 + \gamma$

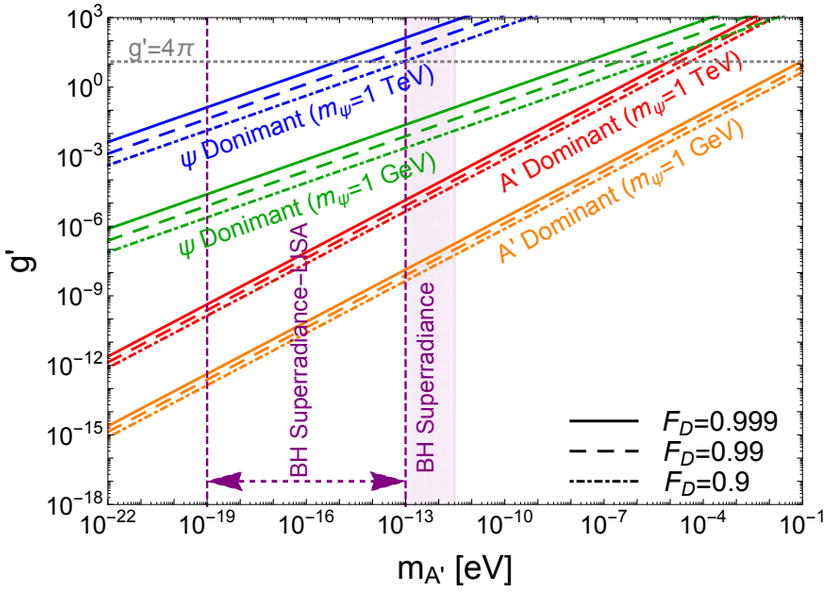
  inclusive search



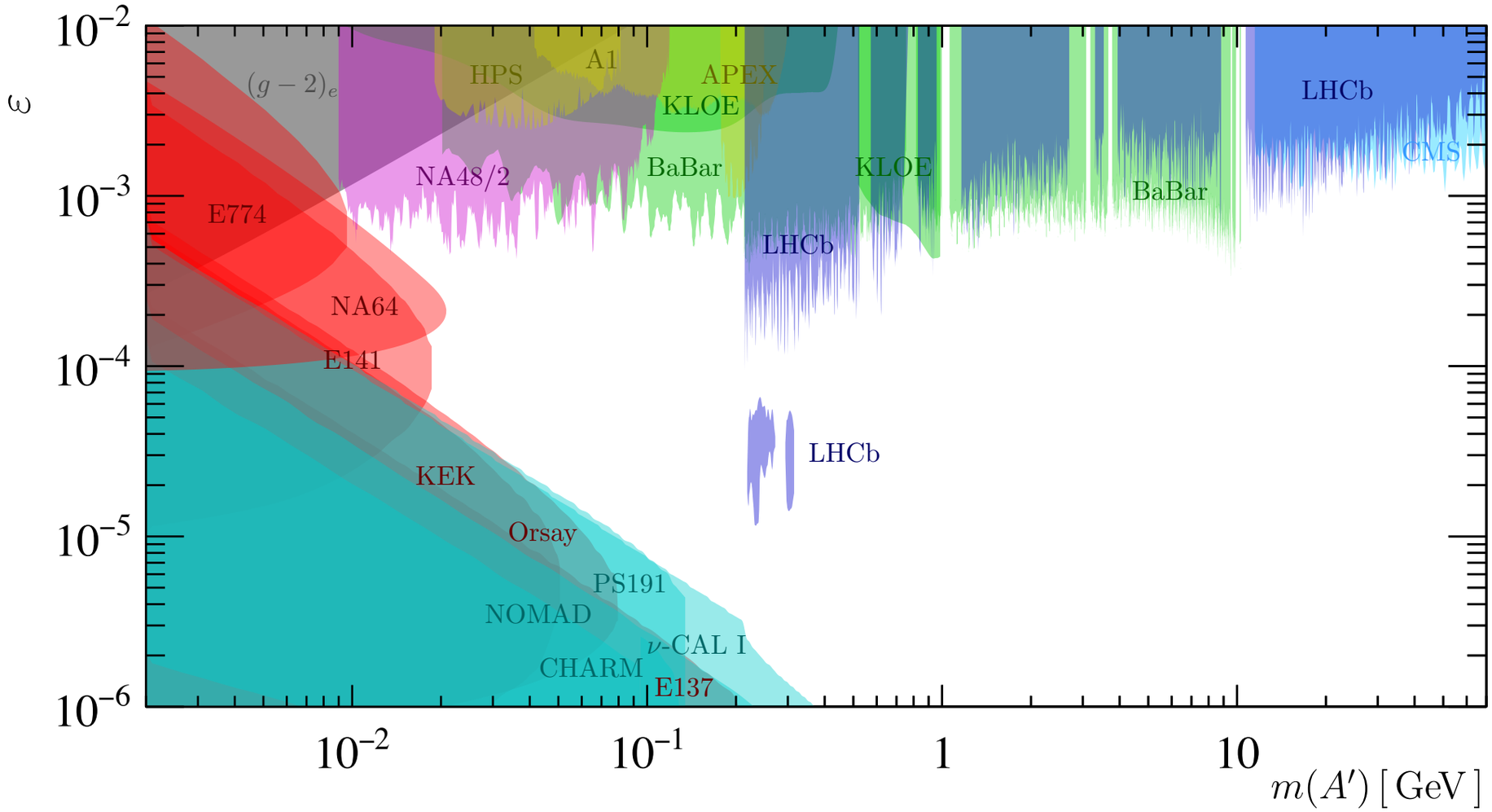
- dark photon dark matter

  solve small structure issues

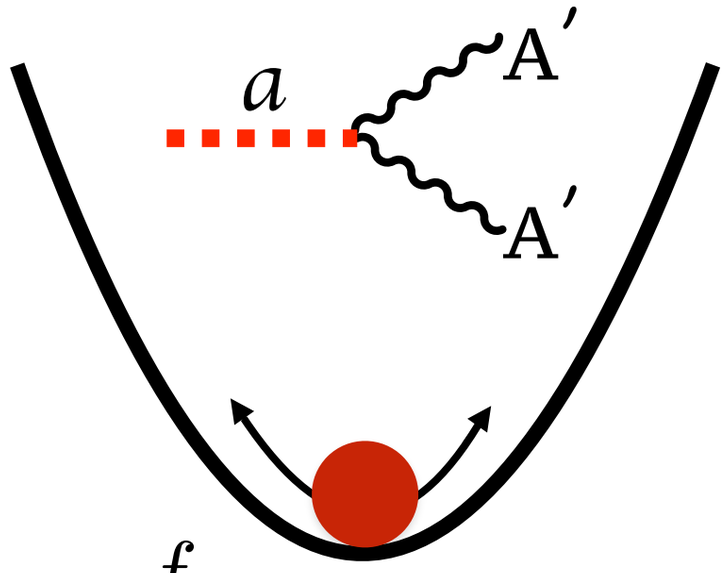
  detect dark photons from the Sun



new LHCb result



axion $\rightarrow \gamma' \gamma'$



- axion couples to massless dark photons

$$\mathcal{L} = \frac{1}{4f_d}\phi F_D^{\mu\nu}(\tilde{F}_D)_{\mu\nu} = \frac{r}{4f_a}\phi F_D^{\mu\nu}(\tilde{F}_D)_{\mu\nu} \qquad r \equiv \frac{f_a}{f_d}$$

- particle production

$$A''_{\pm} + (k^2 \mp \frac{k\phi'}{f_d})A_{\pm} = 0$$