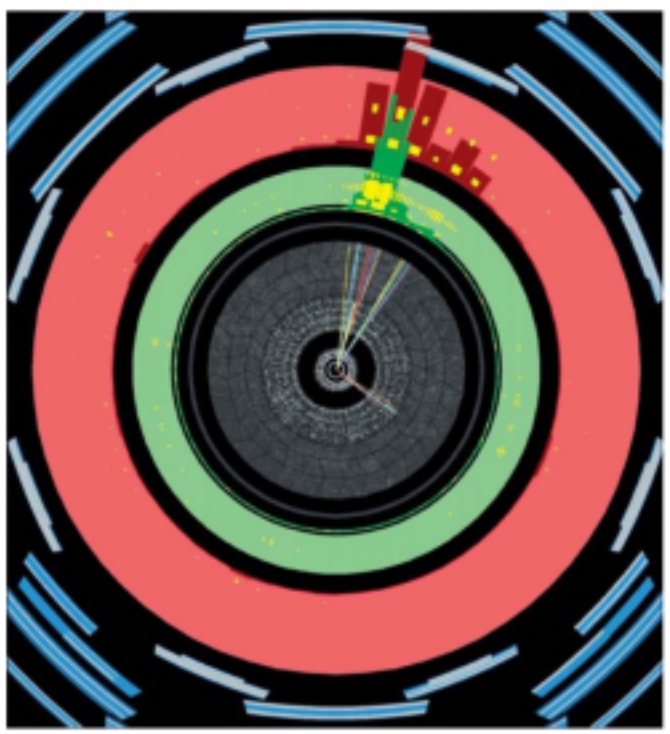
Dark Photon Searches @ LHCb

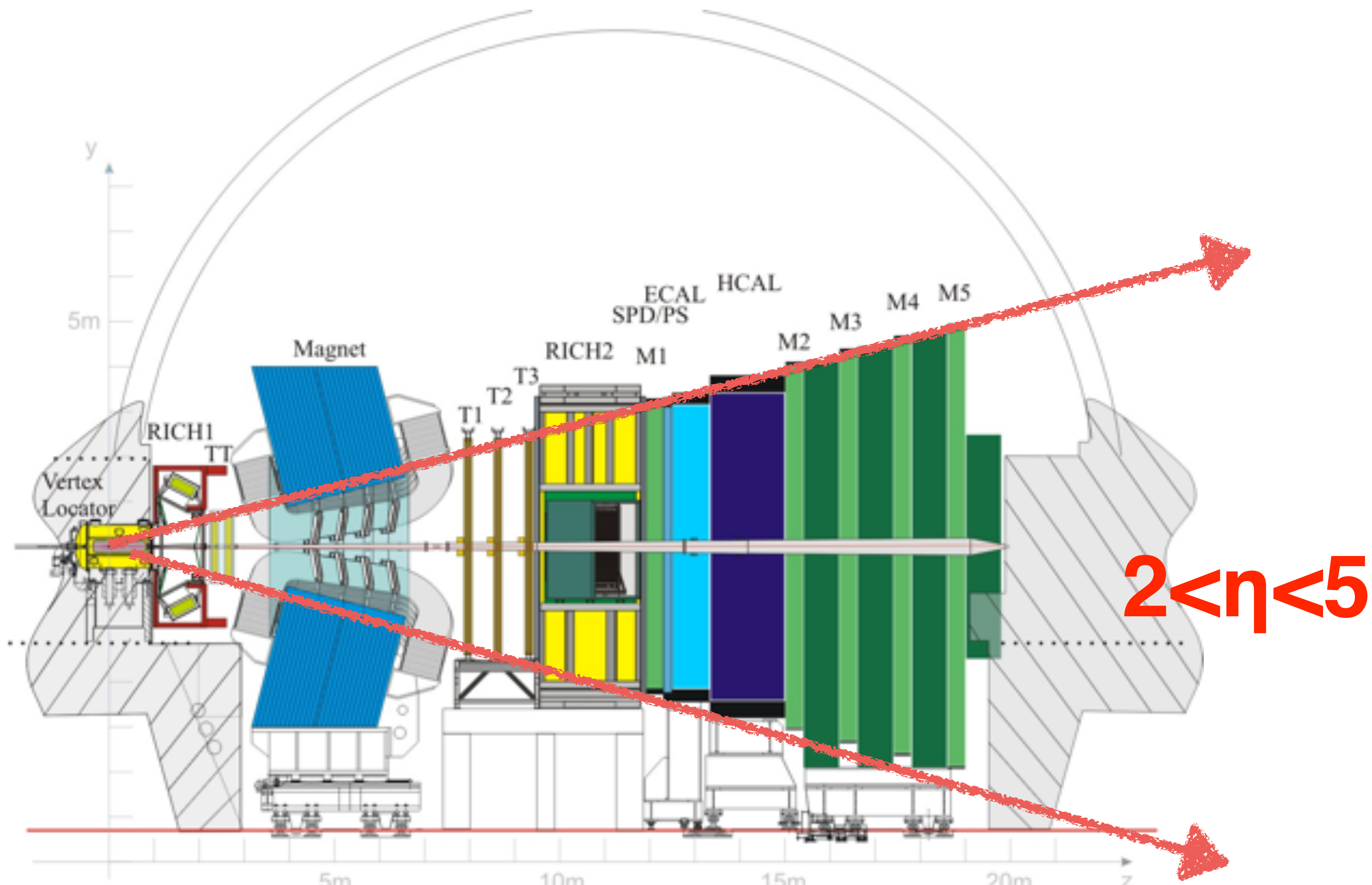
Wei Xue

Sep 13, 2016
TeVPA

Dark Matter Search
Why not LHCb?


Mono-jet event from ATLAS (credit: CERN courier)

ATLAS/
CMS



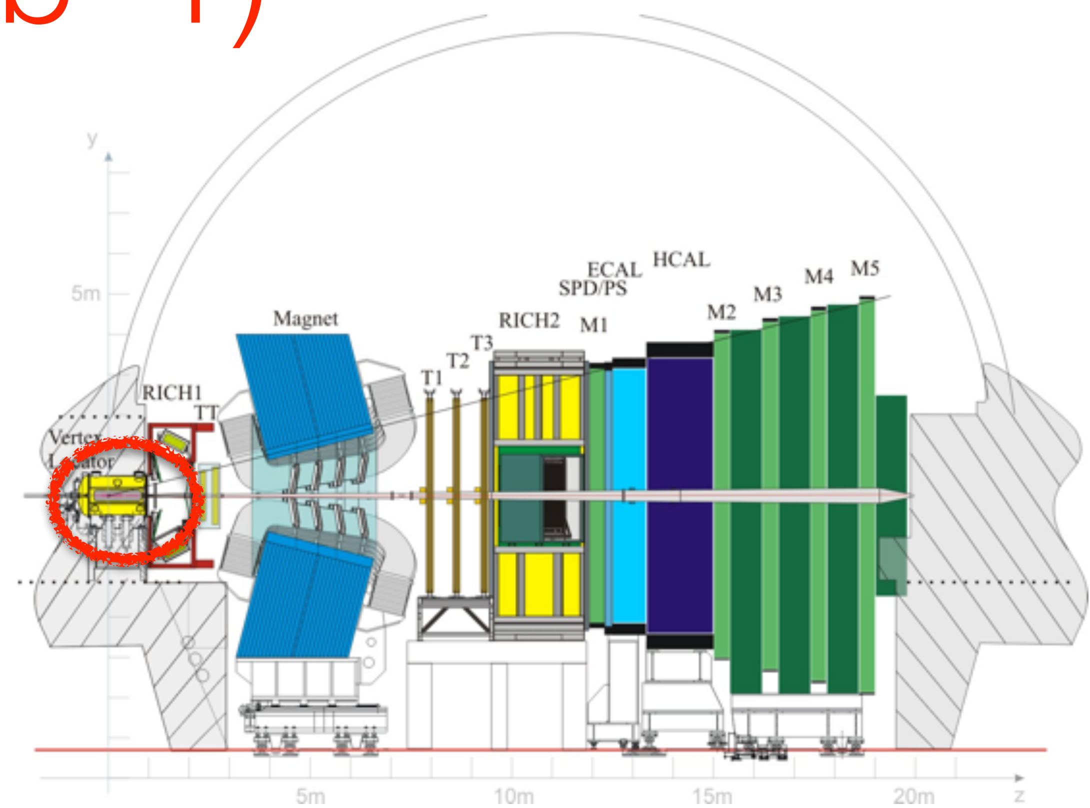
LHCb

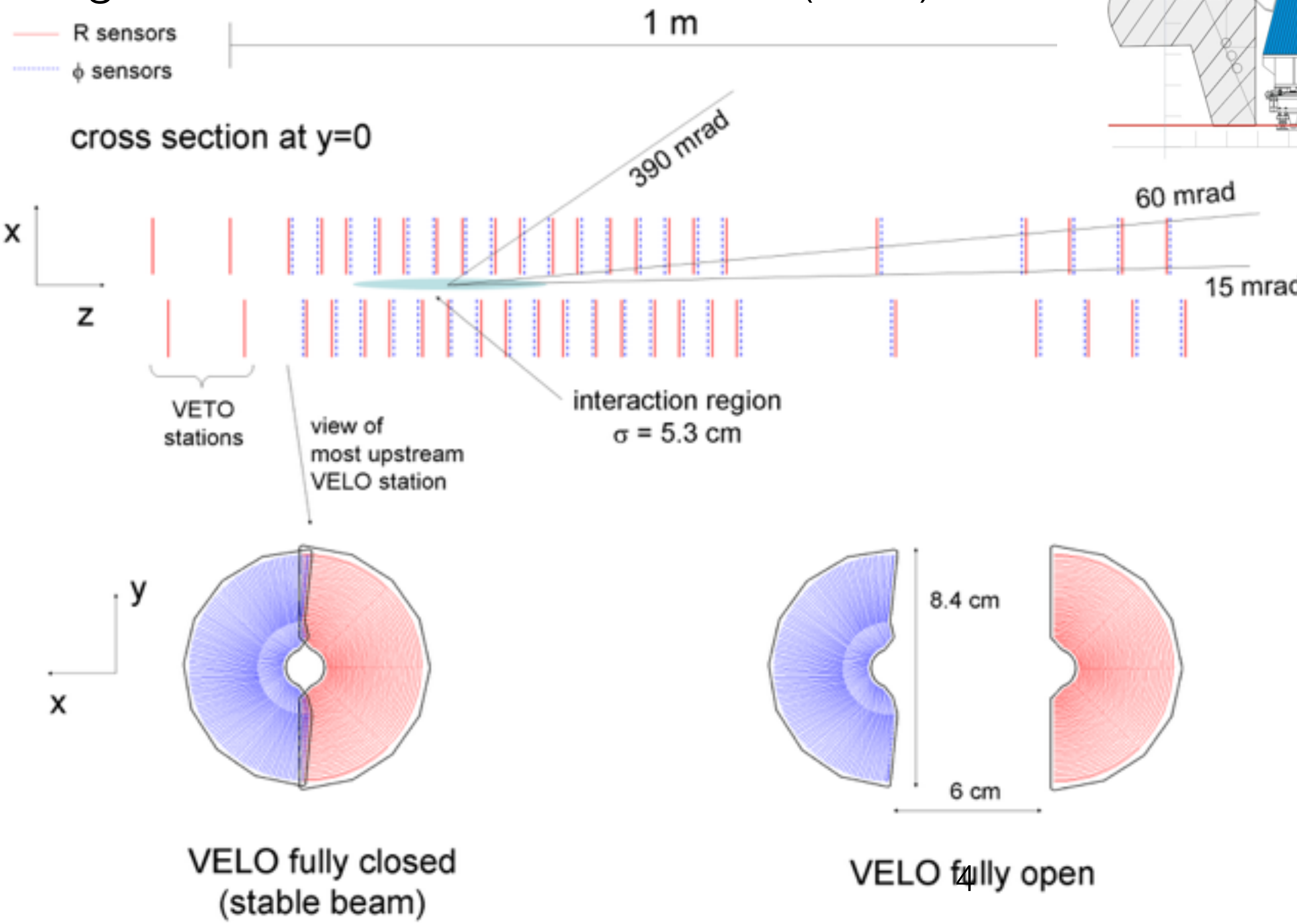
Outline

- why LHCb
- introduction to dark photon
- dark photon search from meson decay
  (1509.0676, PRD 2015, P. Ilten, J. Thaler, M. Williams, **WX**)
- dark photon search from inclusive di-muon
  (1603.08926, Accepted by PRL, P. Ilten, Y. Soreq, J. Thaler,
  M. Williams, **WX**)
- conclusion

Why LHCb 1)

- no pile-up
- good vertexing :VELO detector (10 μm)
- good invariant mass resolution (MeV)



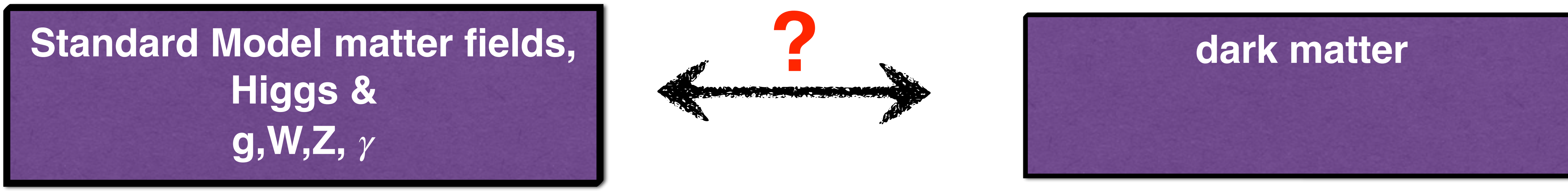


Why LHCb 2)

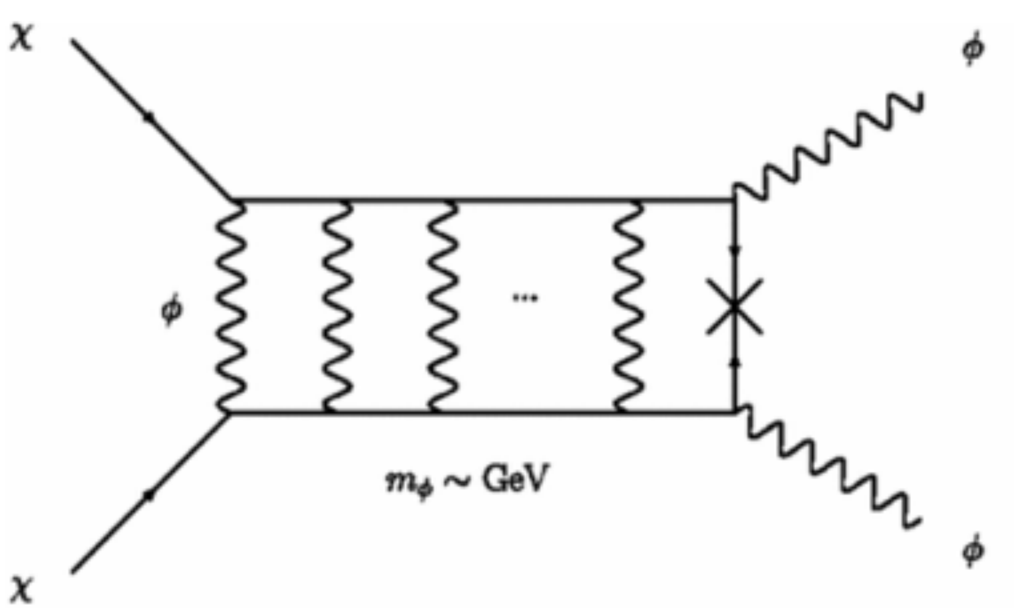
- Run 3 triggerless readout:
  - removing the first-level hardware trigger
  - realtime calibration
  - no hardware limited
    only disk space limitation
  - triggerless readout opens new possibilities for particle physics search in Run3
  - we should test it right now!

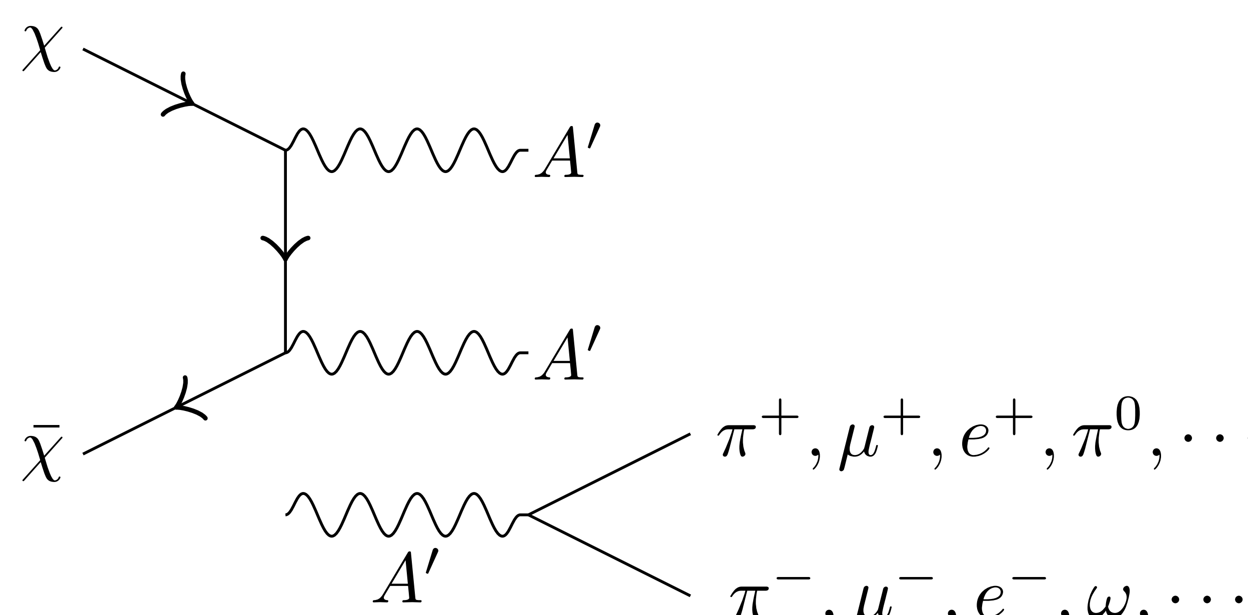
Dark Sector

- dark matter implies a hidden sector, neutral under the standard model forces



- e.g. indirect detection





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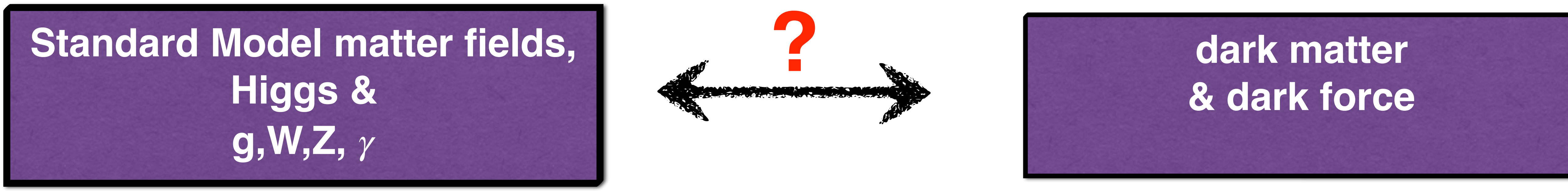

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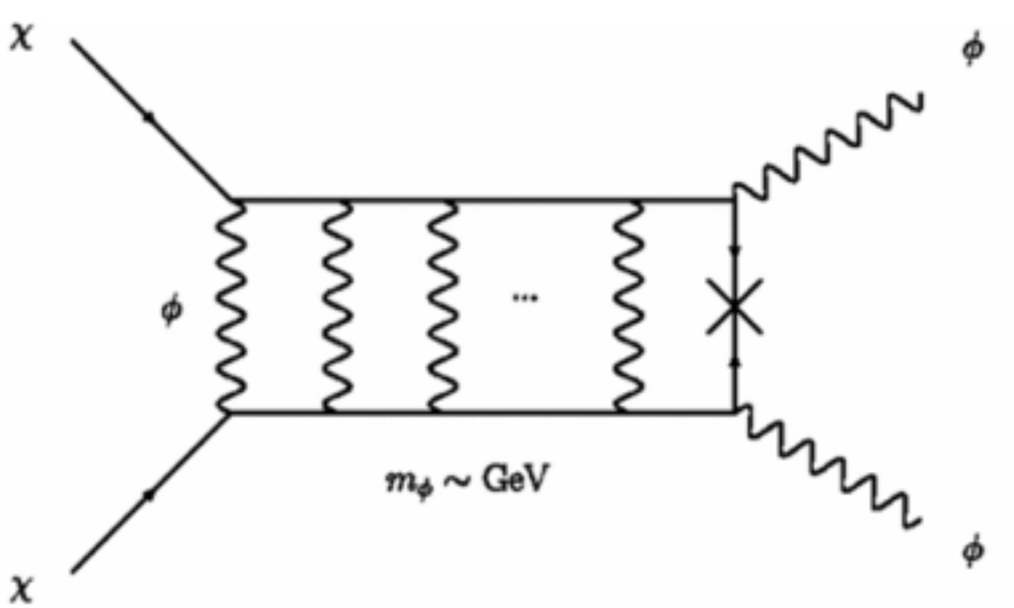
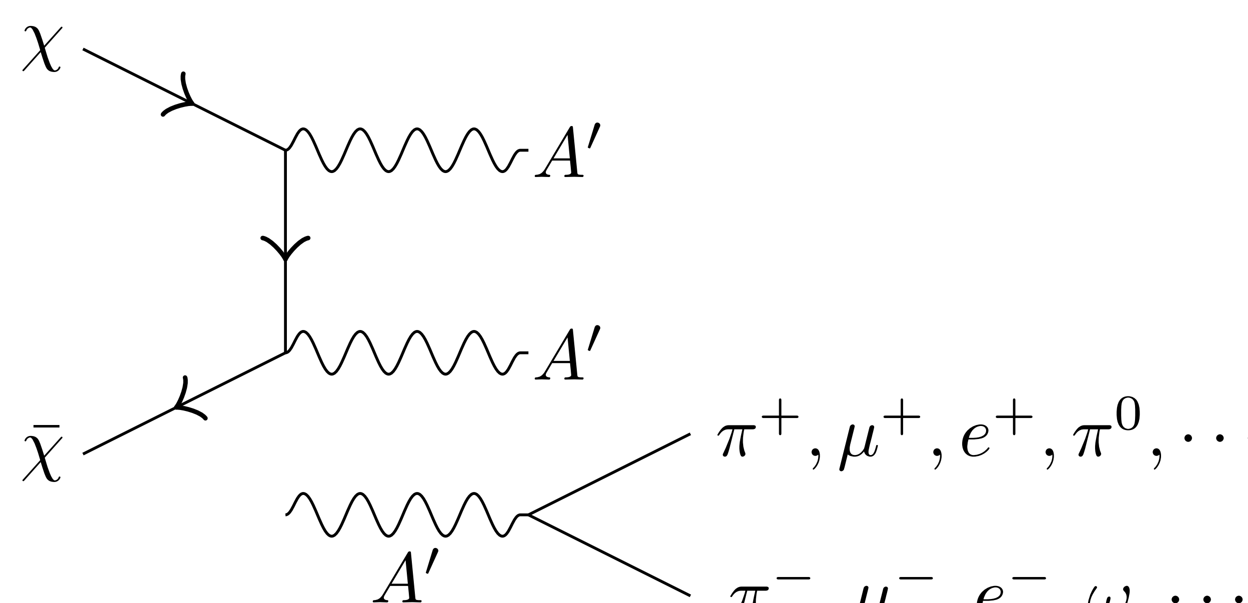
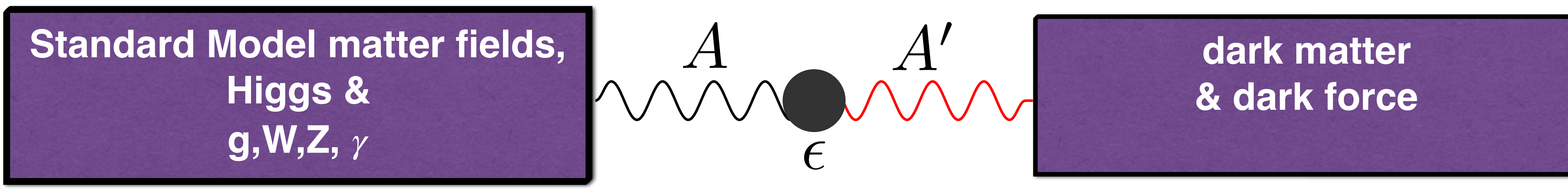




Dark Photons

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



$$\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

- effective Lagrangian

$$\mathcal{L} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m^2_{A'} A'_\mu A'^\mu + \epsilon e A'_\mu J^\mu_{\text{EM}}$$

- focusing : mass range of $m_{A'}$ ($\in$ MeV - 10 GeV)
  $\varepsilon^2 \sim 10^{-6}, 10^{-12}$

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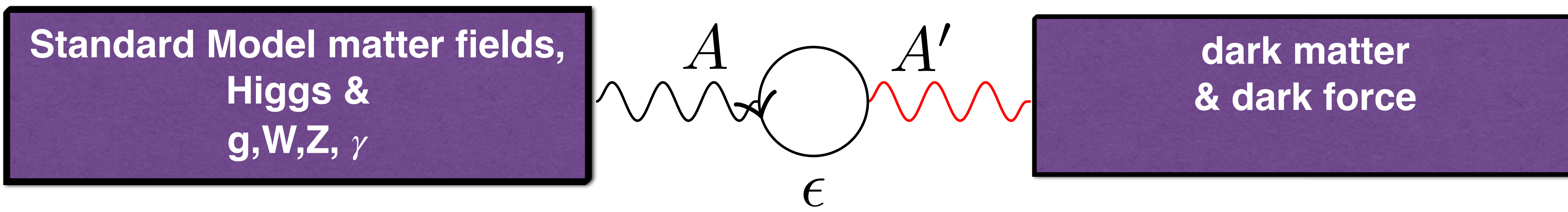

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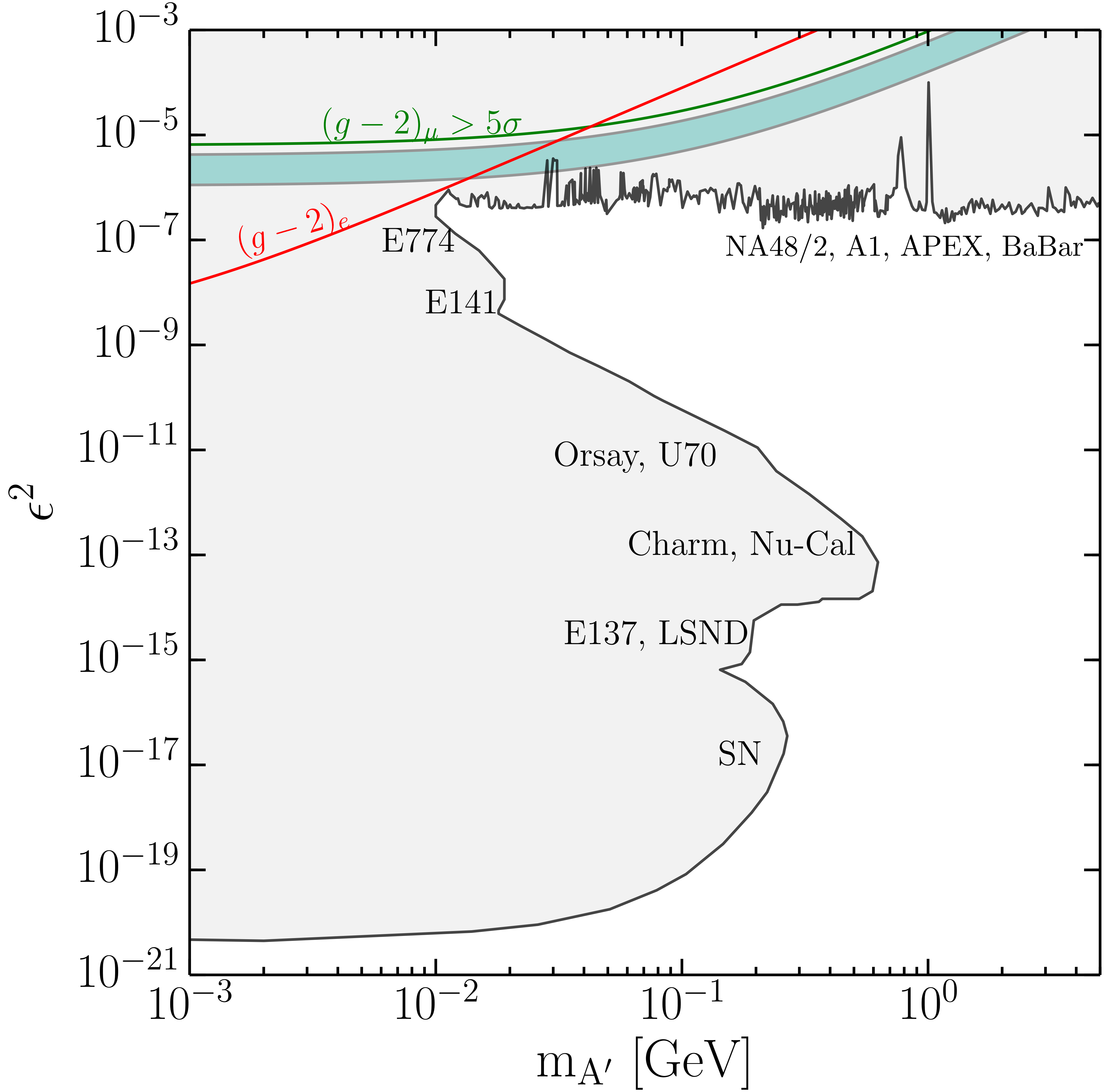
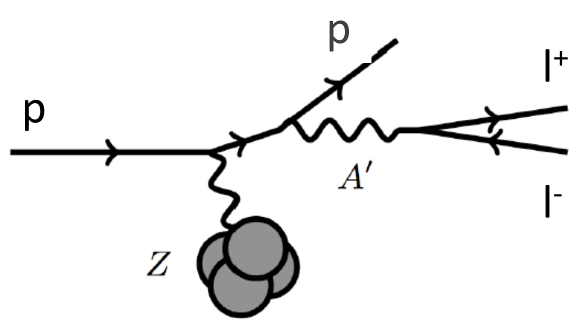


$(g-2)_\mu > 5\sigma$
$(g-2)_e$
E774
E141
NA48/2, A1, APEX, BaBar
Orsay, U70
Charm, Nu-Cal
E137, LSND
SN
ϵ^2
$m_{A'}$ [GeV]
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-3}
10^{-2}
10^{-1}
10^{0}

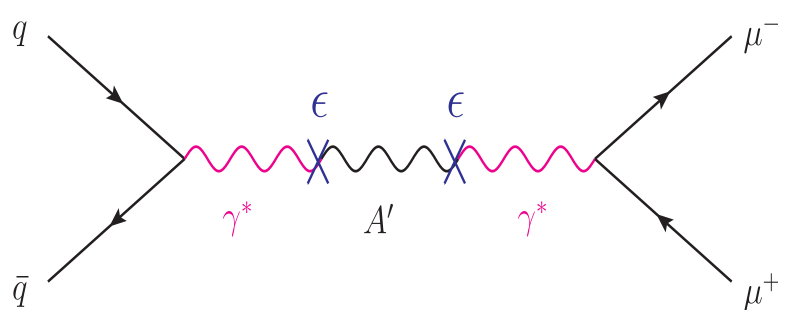
Dark Photon Production in collider

Whenever a photon is produced, a dark photon can also be produced, but with different coupling and mass

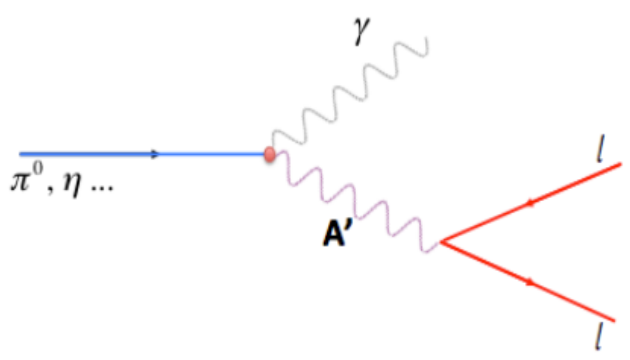
A. Bremsstrahlung



B. Drell-Yan like



C. Meson decay
($\pi^0 \rightarrow \gamma\ e^+\ e^-$)



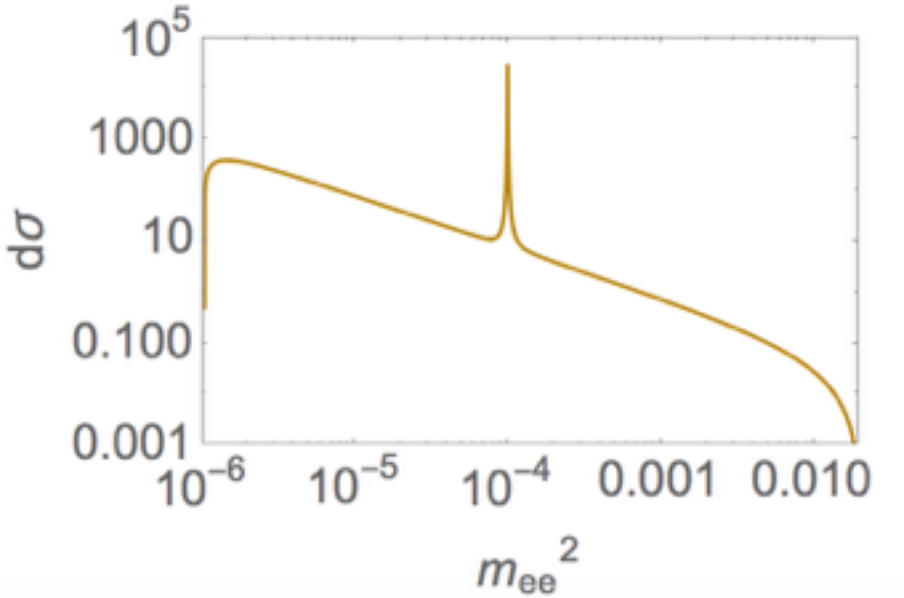
Resonant Search

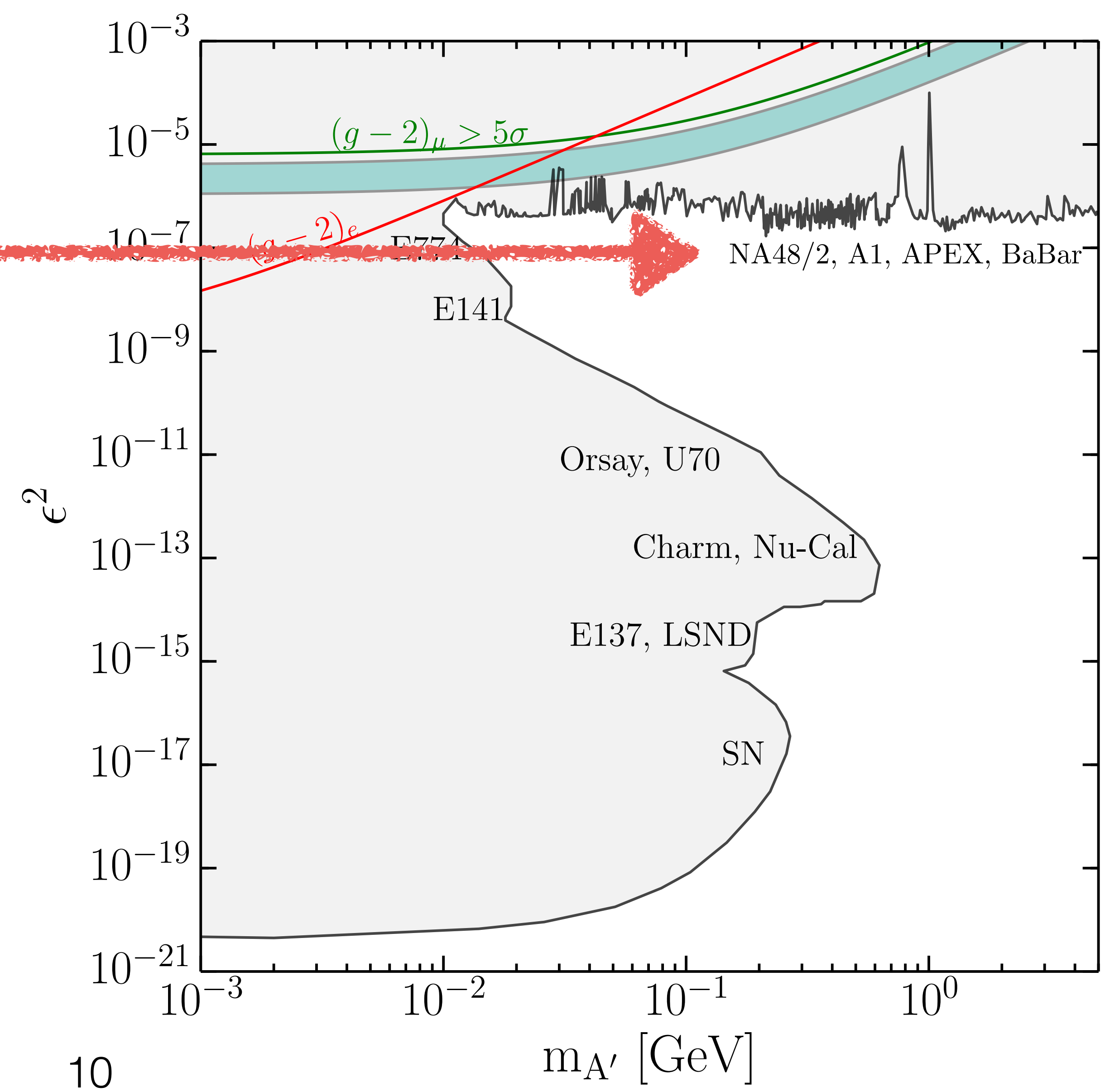
- A’ → $e^+ e^-$, A’ → $\mu^+ \mu^-$

- background from off-shell photon
  S/√B ~ ε^2 √N

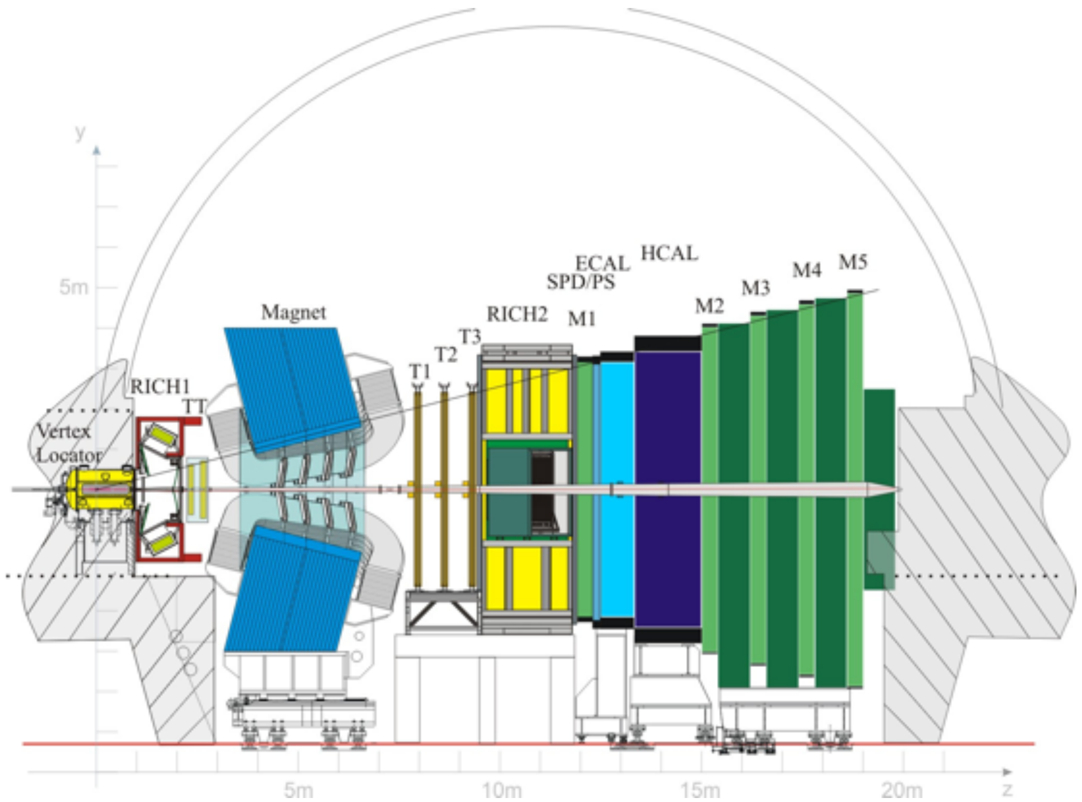
- NA48/2
  meson decay
  $10^{10}\,\pi^0$

$$K^\pm \to \pi^\pm \pi^0, \quad \pi^0 \to \gamma A', \quad A' \to e^+ e^-$$



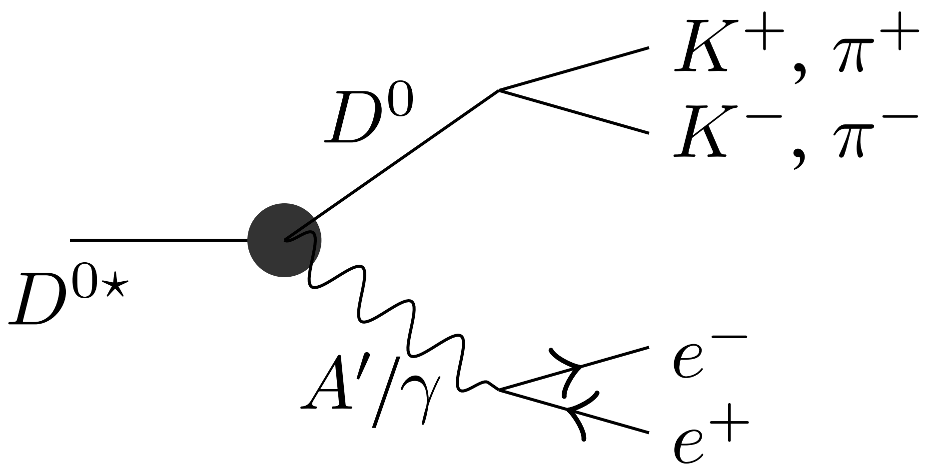


LHCb searches



Very Promising Channel: Charm Meson

- decay to photon (dark photon)
  - Large Branching ratio
    (phase space suppression of $D^{*0} \to D^0 \pi^0$)
  - clean decay modes
- MeV decay width
  well reconstructed , to reduce backgrounds



$D^*(2007)^0$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2006.96 \pm 0.10$ MeV
$m_{D^{*0}} - m_{D^0} = 142.12 \pm 0.07$ MeV
Full width $\Gamma < 2.1$ MeV, CL = 90%

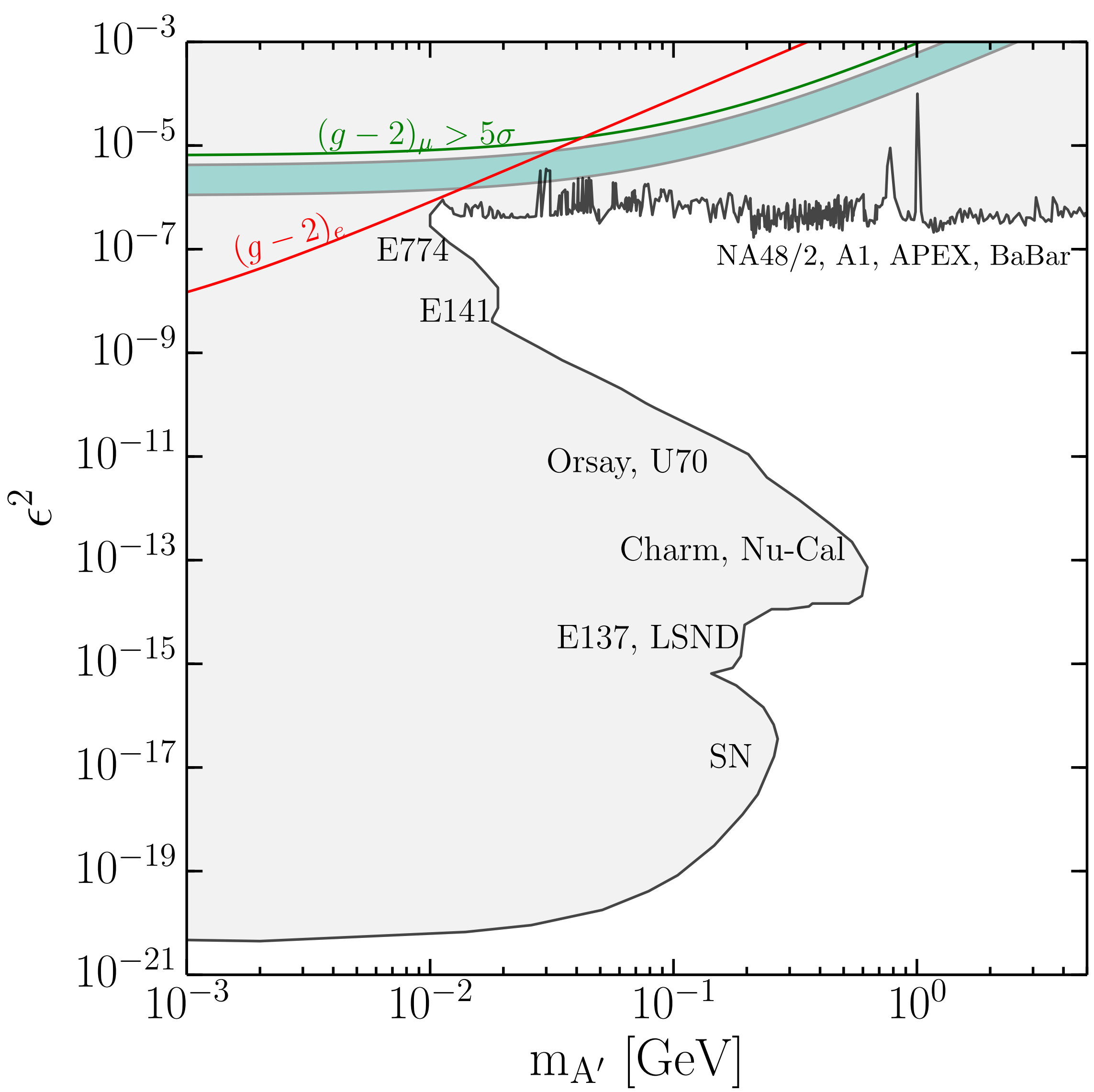
$\overline{D}^*(2007)^0$ modes are charge conjugates of modes below.

$D^*(2007)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^0$	(61.9±2.9) %	43
$D^0\gamma$	(38.1±2.9) %	137

D^{*0} Production

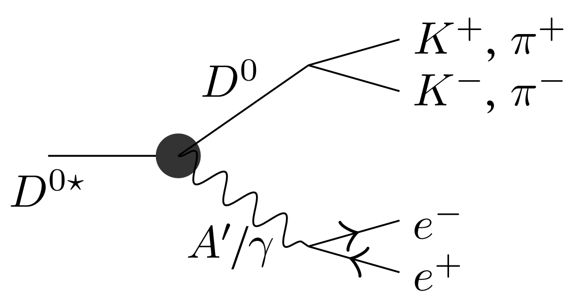
- How many D^{*0} in LHCb Run3 (15 fb^{-1})?
  ~5 ×10^{12} $D^{*0} \rightarrow D^0 + \gamma$ (PYTHIA simulation)

- How many π^0 in NA48/2 ? ~10^{10}



Resonant Search

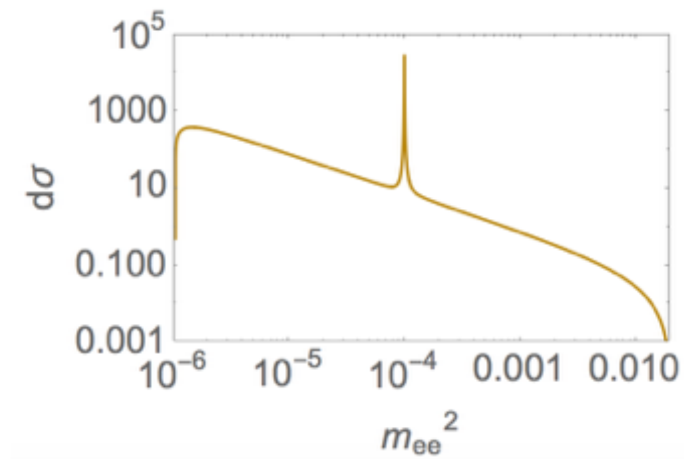
- Displaced D^0 and Prompt A'

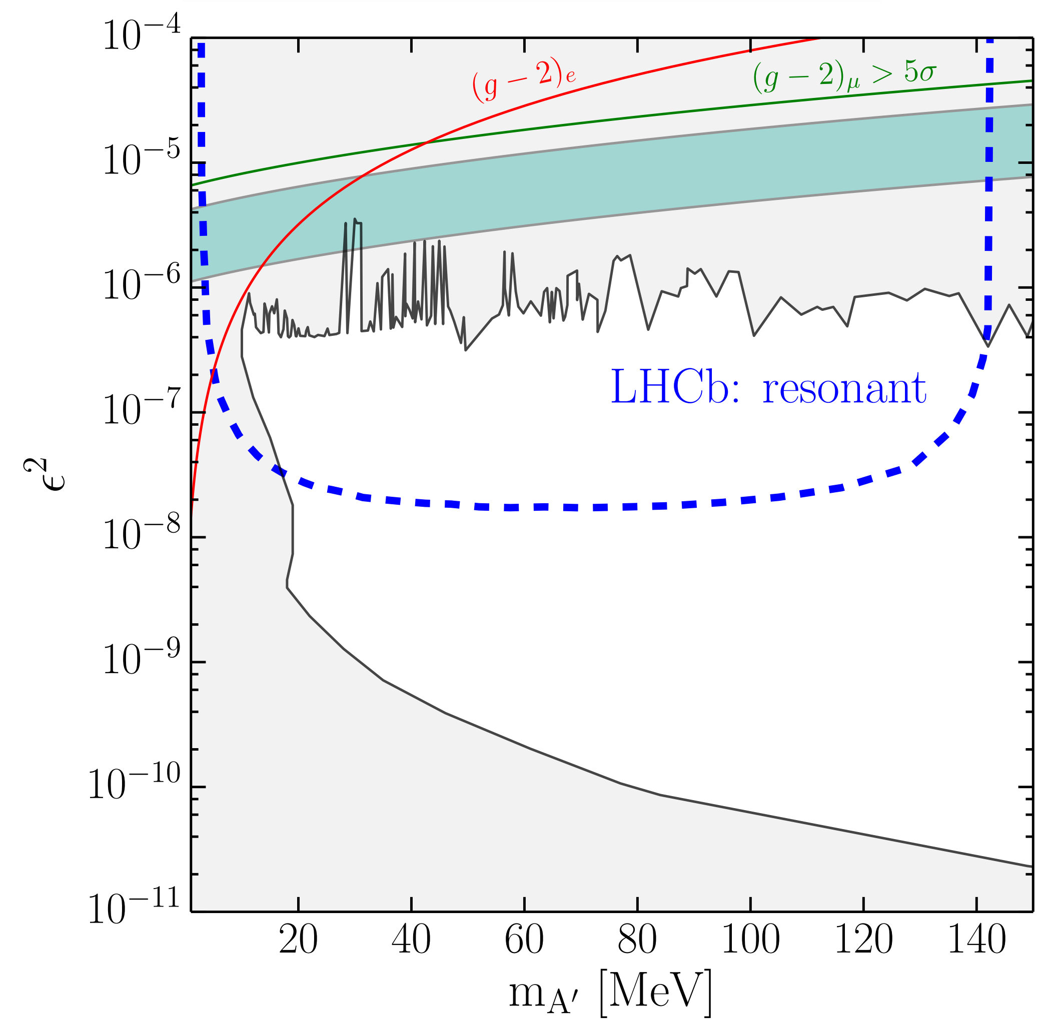


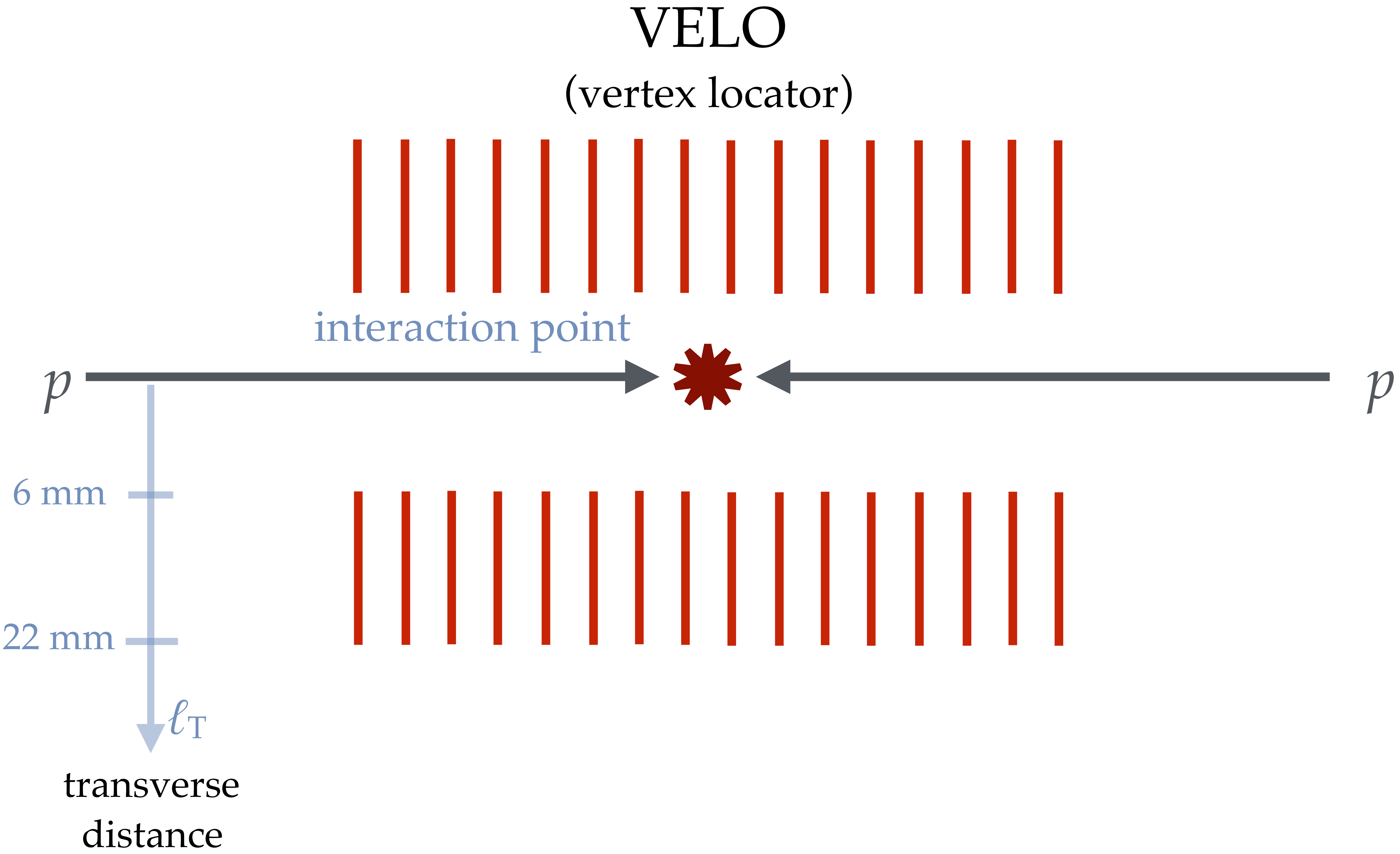
- How do we know e^+e^- from D0* decay?
  reconstruct e^+ e^- D^0 to D^{0*}

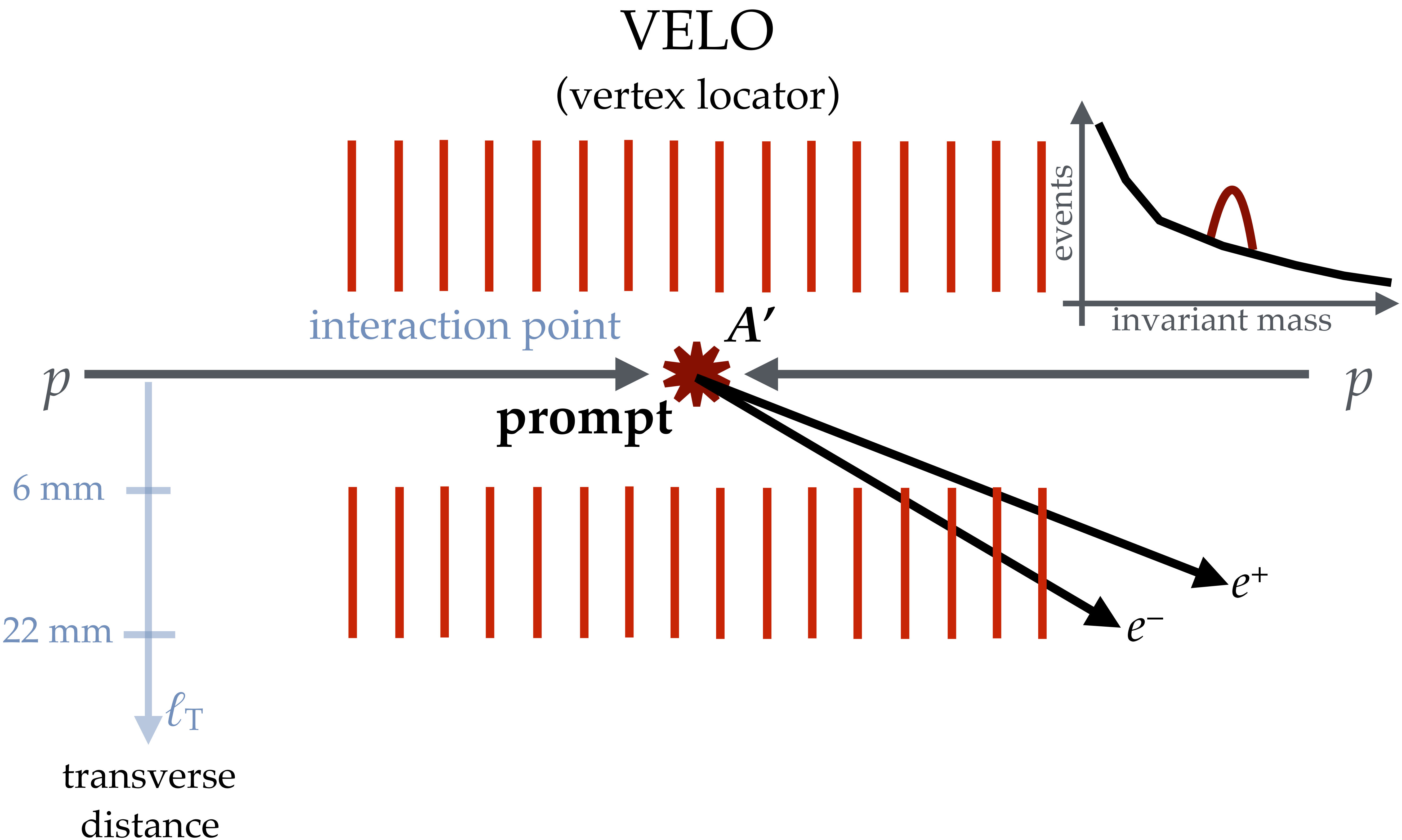
$$-50\,\mathrm{MeV} < \Delta m_D^{\mathrm{reco}} - \Delta m_D < 20\,\mathrm{MeV}$$

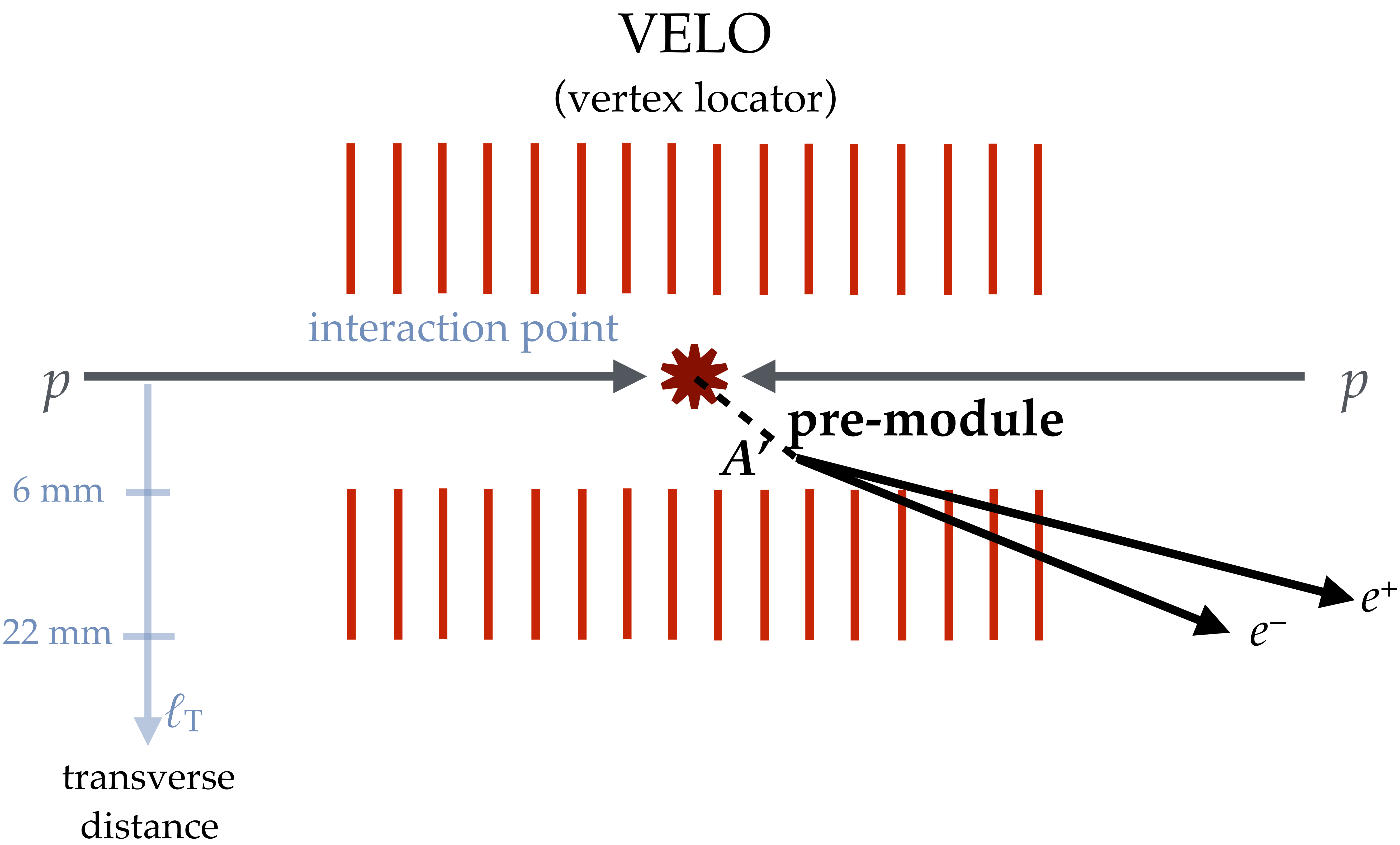
- invariant mass constraint
  D^0 e^+ e^- inv mass = m(D^{0*})
  the decay width of D0* ~ MeV matters here

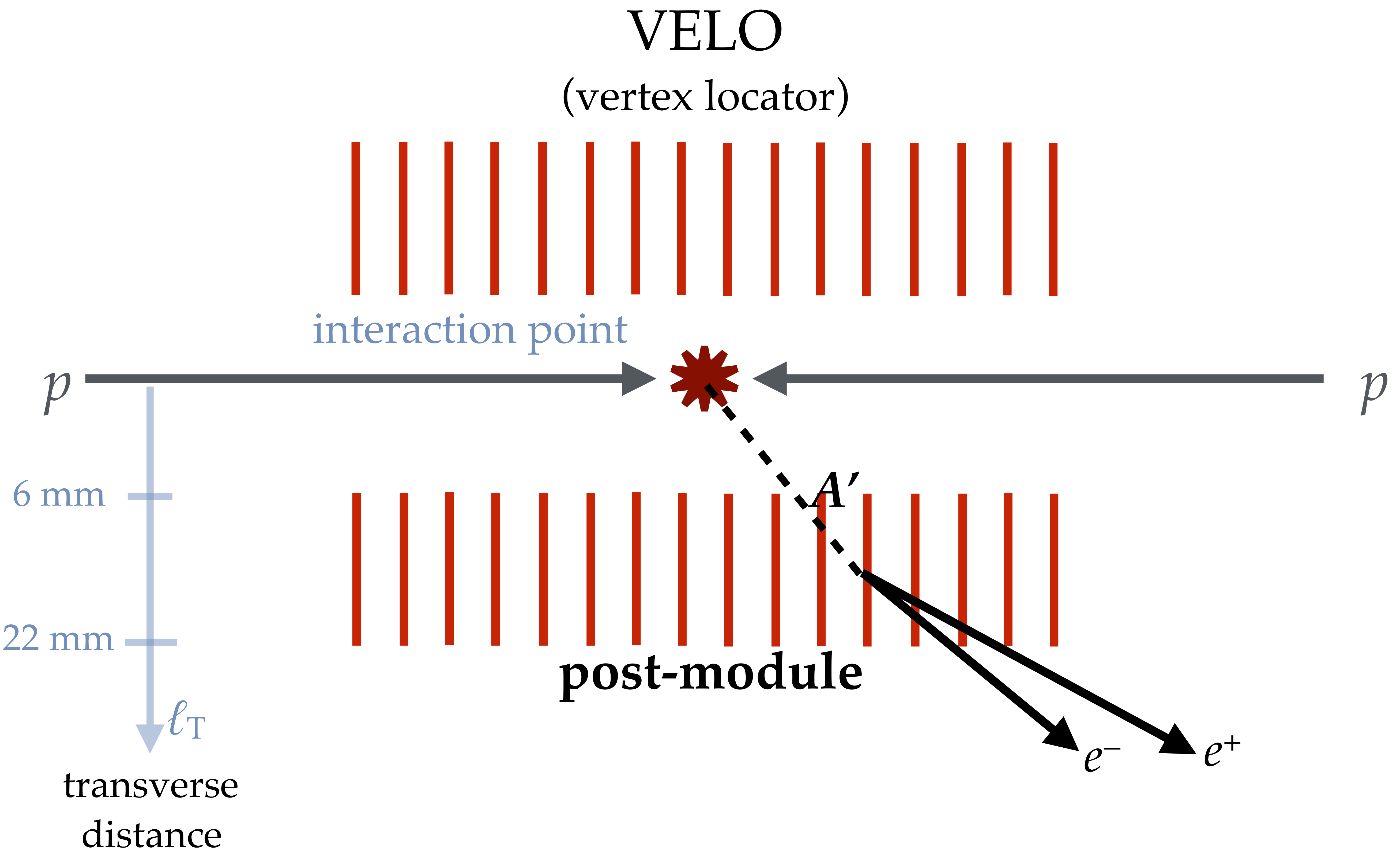





VELO
(vertex locator)
interaction point
p
p
6 mm
22 mm
ℓ_T
transverse distance


VELO
(vertex locator)
events
invariant mass
interaction point
A′
p
p
prompt
6 mm
22 mm
e+
e−
ℓT
transverse
distance


VELO
(vertex locator)
interaction point
p
p
pre-module
A'
6 mm
22 mm
e+
e−
ℓT
transverse
distance

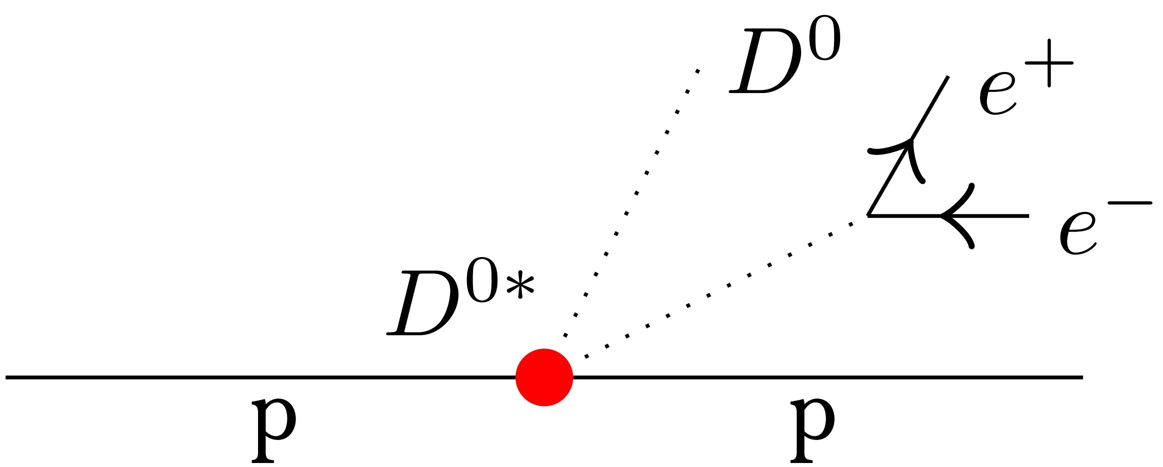

VELO
(vertex locator)
interaction point
p
p
A′
6 mm
22 mm
ℓT
transverse
distance
post-module
e−
e+

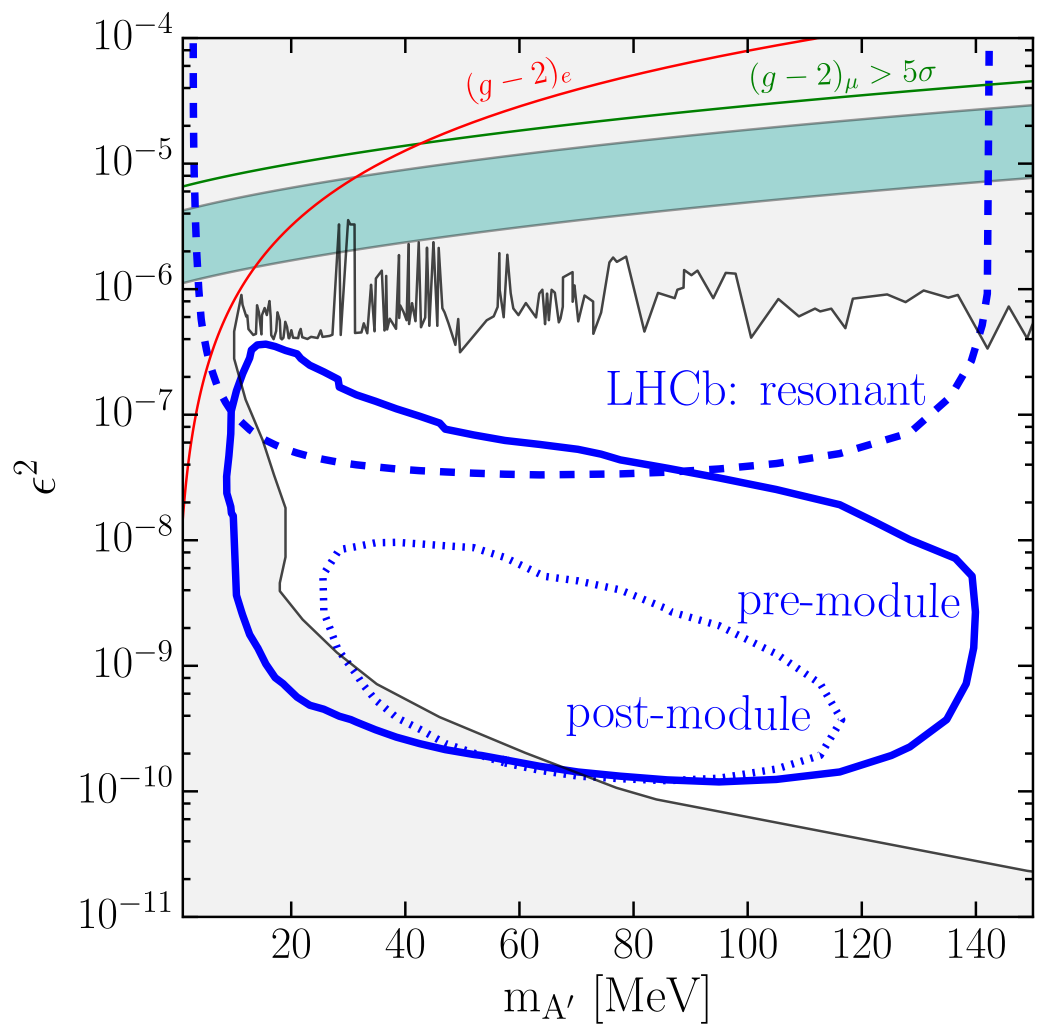
Displaced Search

- In addition to D^0 giving a displaced decay, A' can give displaced decay
- good vertex resolution ~ 10 μm
- small e+e- opening angle ~ 3 mrad
- Large boost factor

$$\ell_{A'} \simeq 1.6\text{ cm}\left(\frac{\gamma}{10^2}\right)\left(\frac{10^{-8}}{\epsilon^2}\right)\left(\frac{50\text{ MeV}}{m_{A'}}\right)$$

- nearly background free





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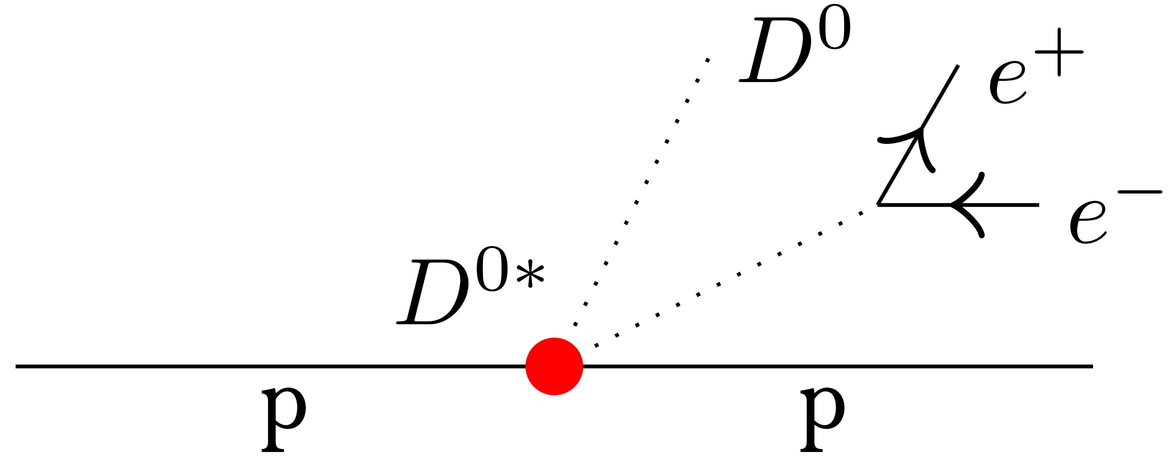
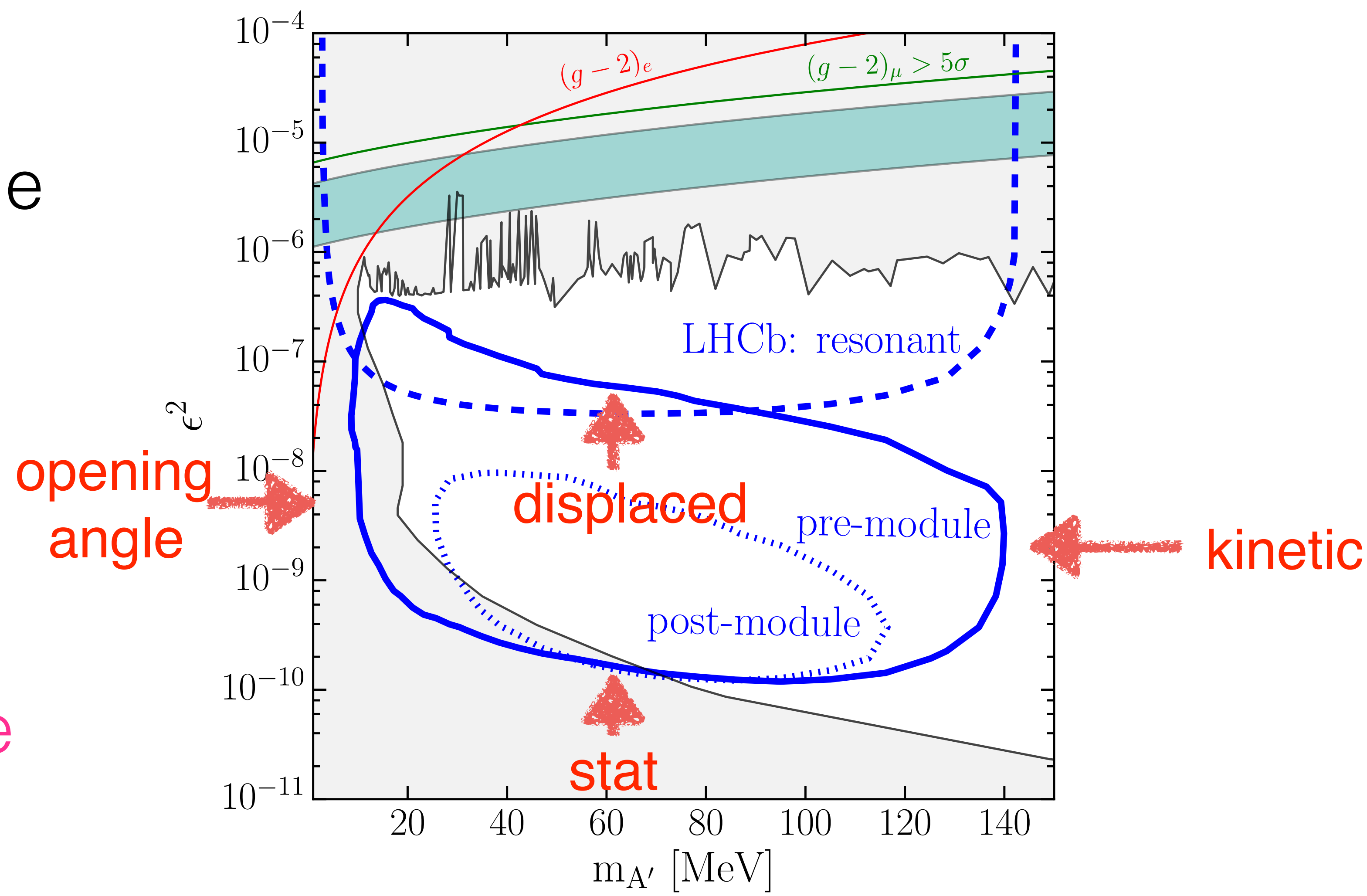
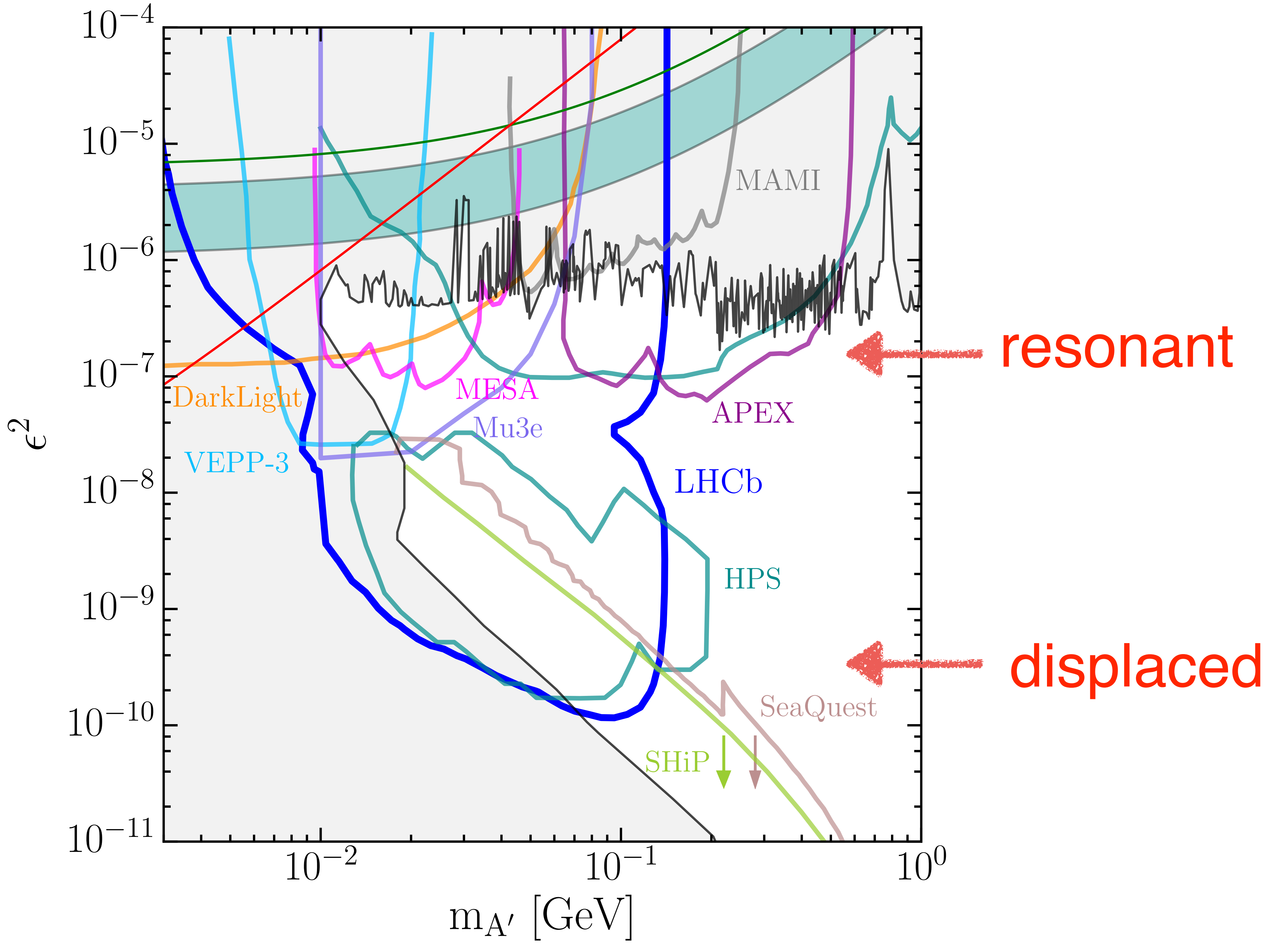
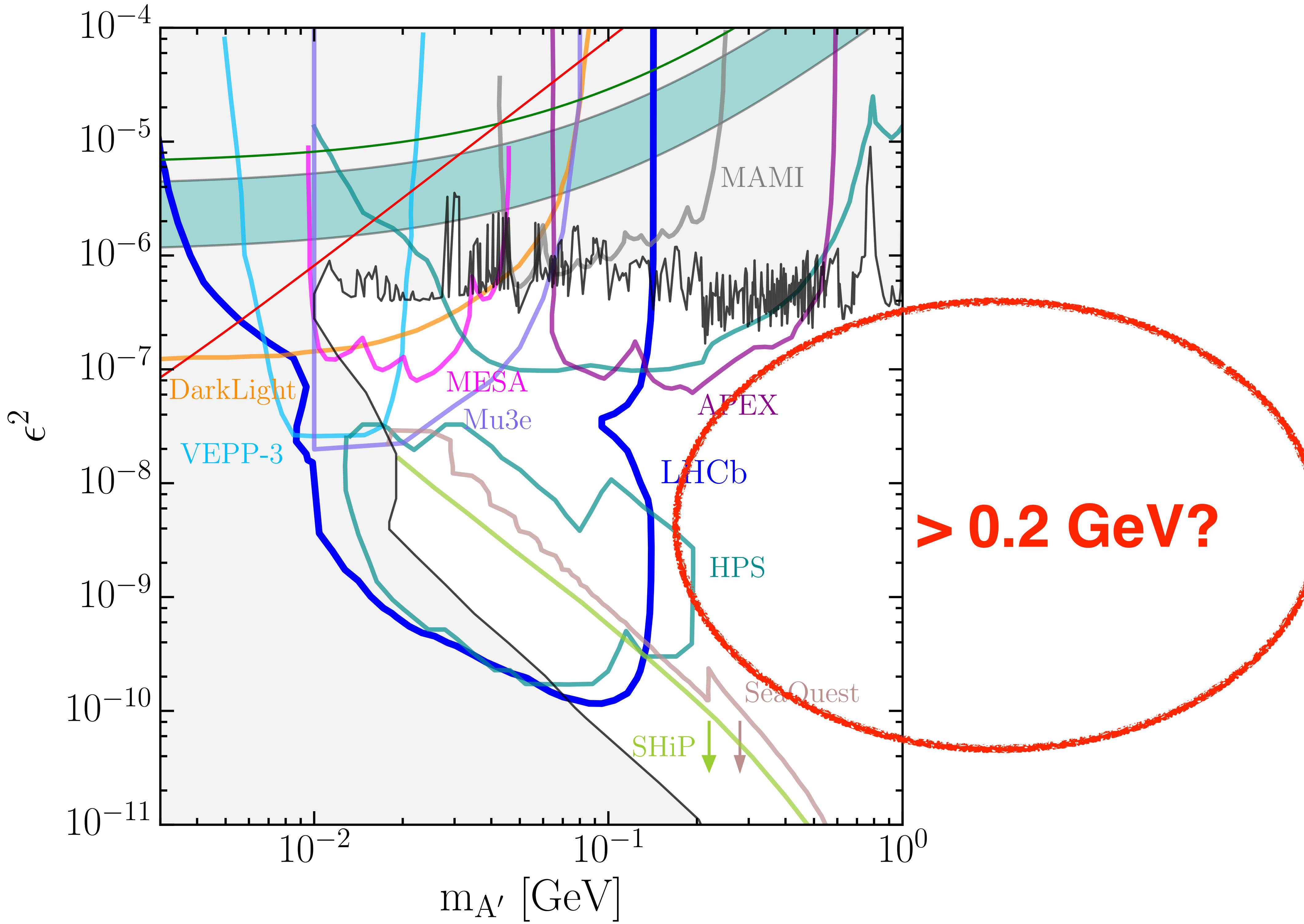
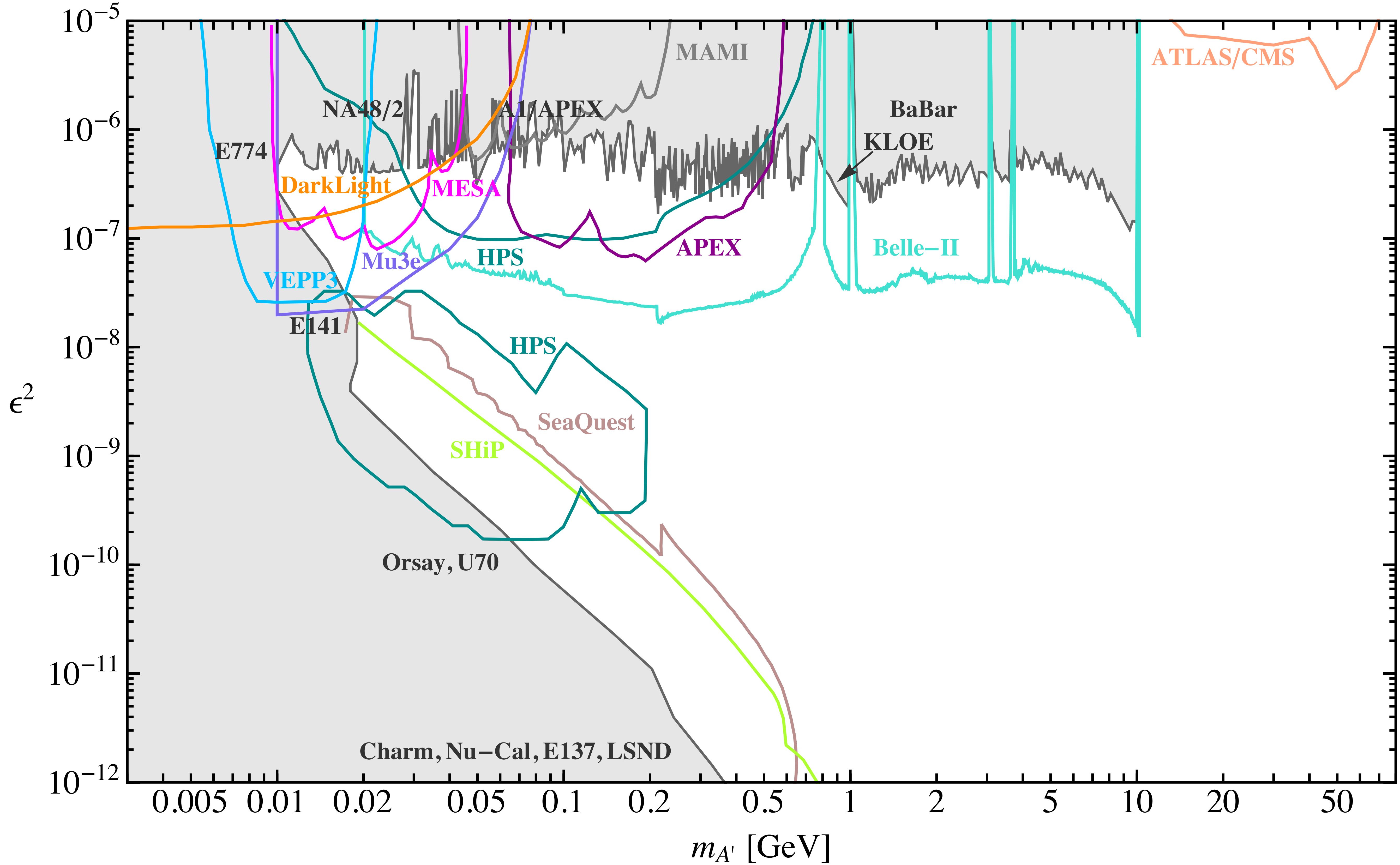




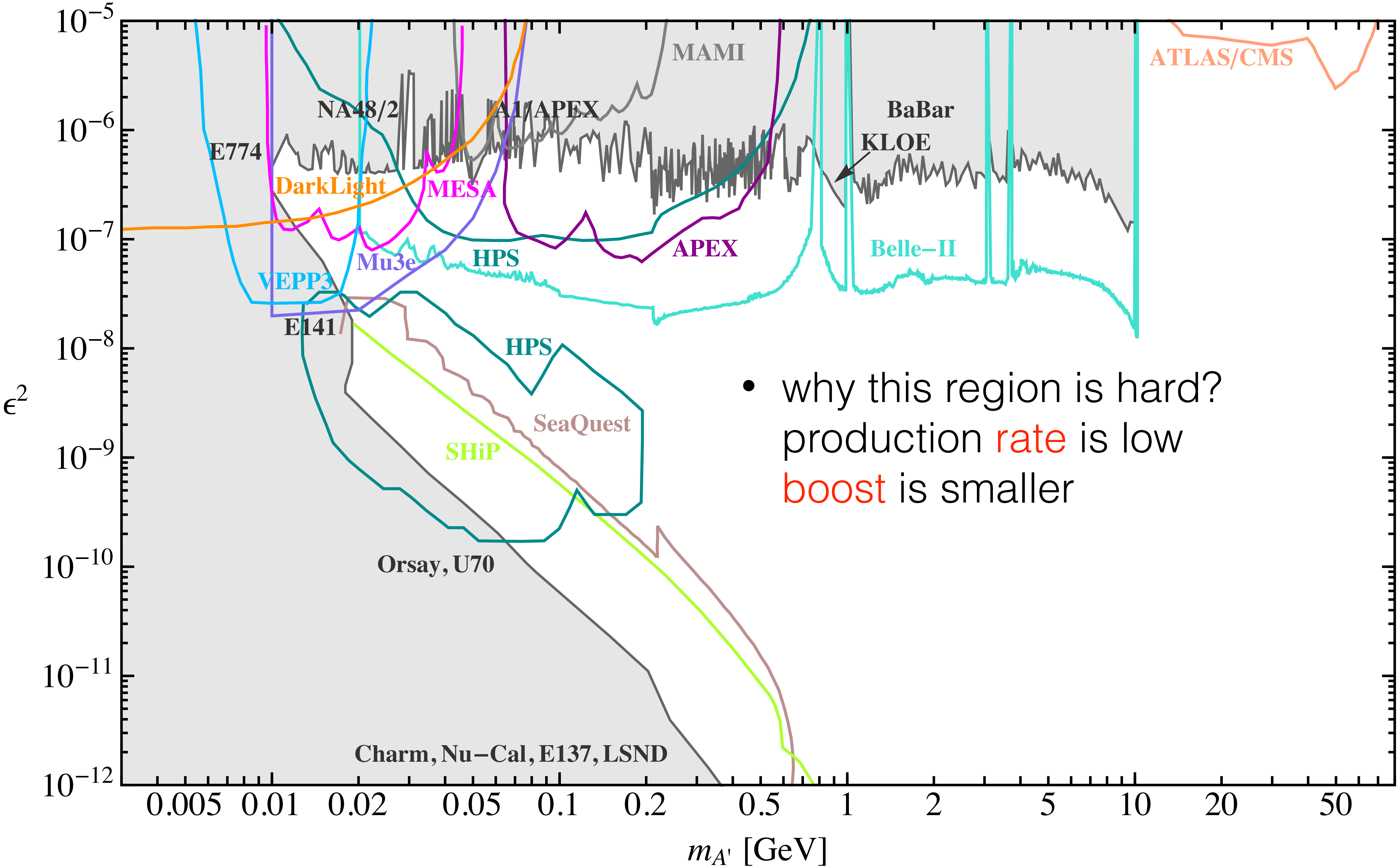
Comparison to Other Experiments



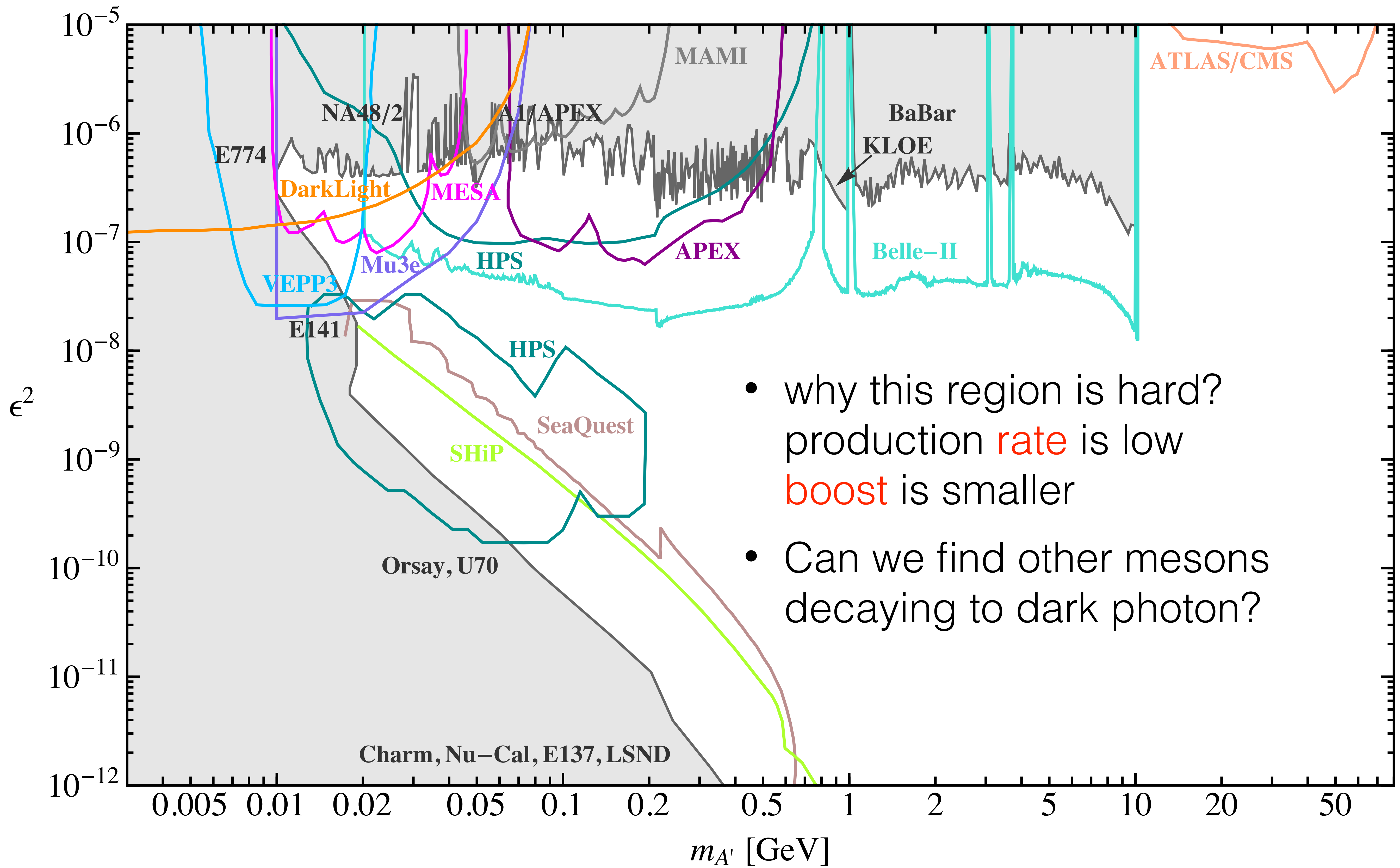

10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
ϵ^2
MAMI
DarkLight
MESA
Mu3e
APEX
VEPP-3
LHCb
HPS
SeaQuest
SHiP
10^{-2}
10^{-1}
10^{0}
$m_{A'}$ [GeV]
> 0.2 GeV?



MAMI
ATLAS/CMS
NA48/2
A1/APEX
BaBar
KLOE
E774
DarkLight
MESA
APEX
Belle−II
HPS
Mu3e
VEPP3
E141
HPS
SeaQuest
SHiP
Orsay, U70
Charm, Nu−Cal, E137, LSND
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
ϵ^2
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1
2
5
10
20
50
$m_{A'}$ [GeV]



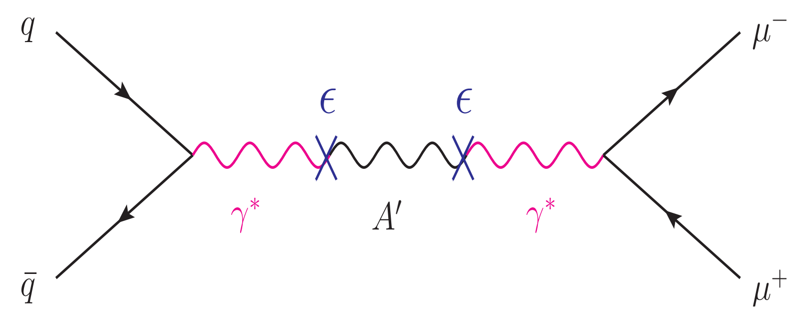
- why this region is hard? production rate is low boost is smaller

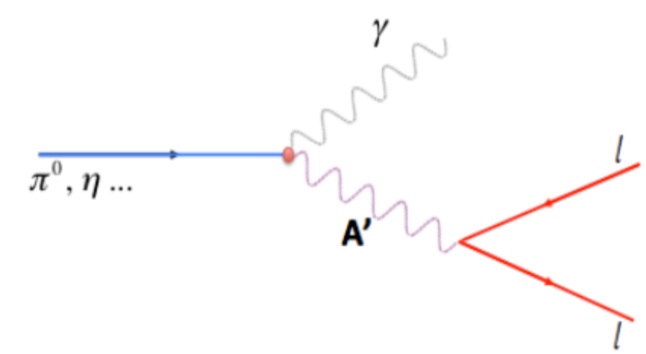


- why this region is hard?
  production rate is low
  boost is smaller
- Can we find other mesons decaying to dark photon?

Can we combine all the channels?

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

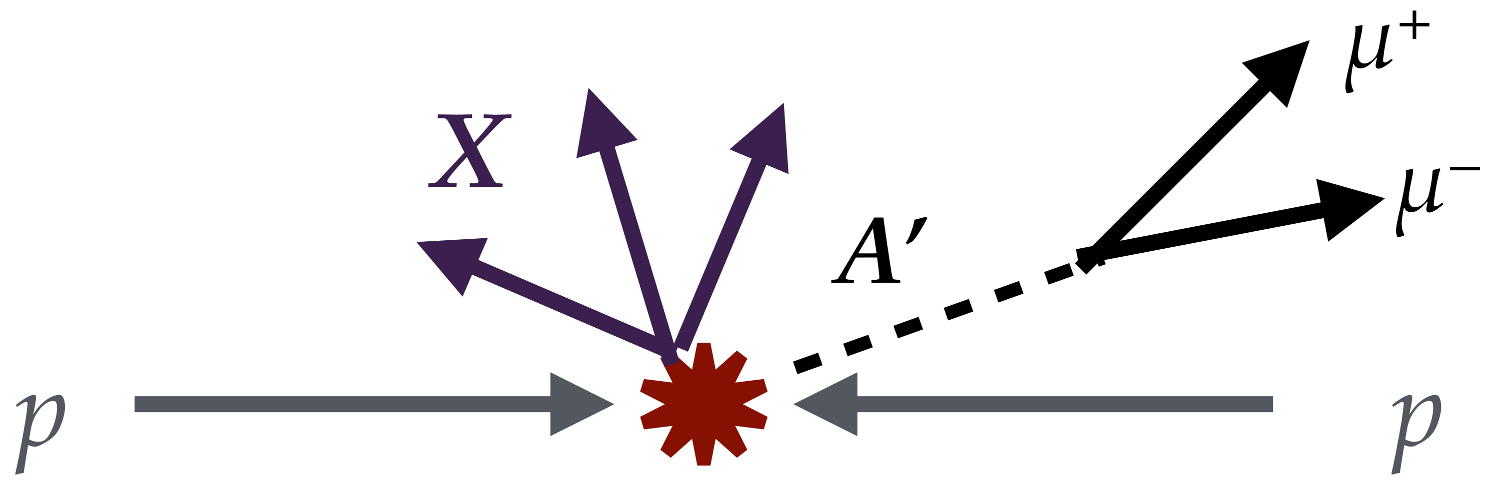




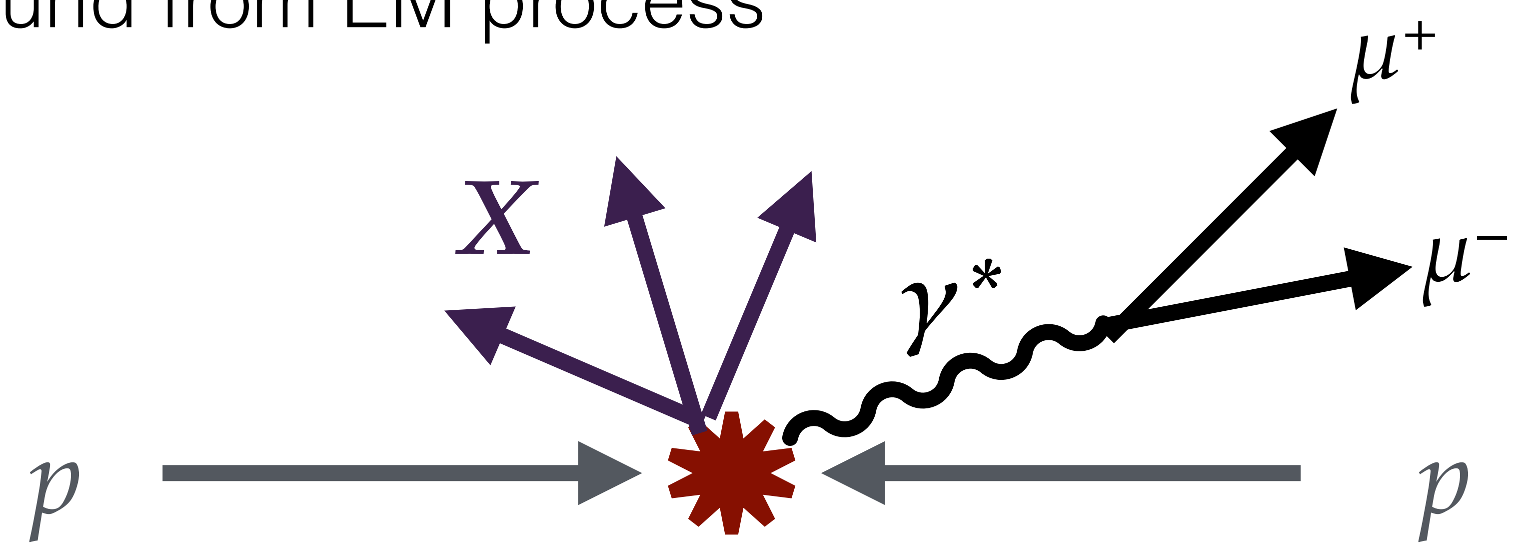
- Challenge 1:
  what is the signal rate?
  many potential sources of dark photons
  with uncertain production rates

inclusive dimuon search

- dark photon mix with photon and also vector mesons



- Background from EM process



Background and Signal Rate

- amplitude generating dark photon

$$i\mathcal{M}_{X\to YA'} = i\epsilon e\langle Y|J^\mu_{\rm EM}|X\rangle\epsilon(k)_\mu$$

- amplitude generating off-shell photon

$$i\mathcal{M}_{X\to Y\ell^+\ell^-} = ie^2\langle Y|J^\mu_{\rm EM}|X\rangle\frac{-ig_{\mu\nu}}{(k_1+k_2)^2}\bar{u}(k_1)\gamma^\nu v(k_2)$$

- ratio (form factor are cancelled)

$$\frac{{\rm d}\sigma_{pp\to XA'\to X\mu^+\mu^-}}{{\rm d}\sigma_{pp\to X\gamma^*\to X\mu^+\mu^-}} = \epsilon^4\frac{m^4_{\mu\mu}}{(m^2_{\mu\mu}-m^2_{A'})^2+\Gamma^2_{A'}m^2_{A'}}$$

Data driven method

- the continuous dimuon spectrum that LHC have is the background.

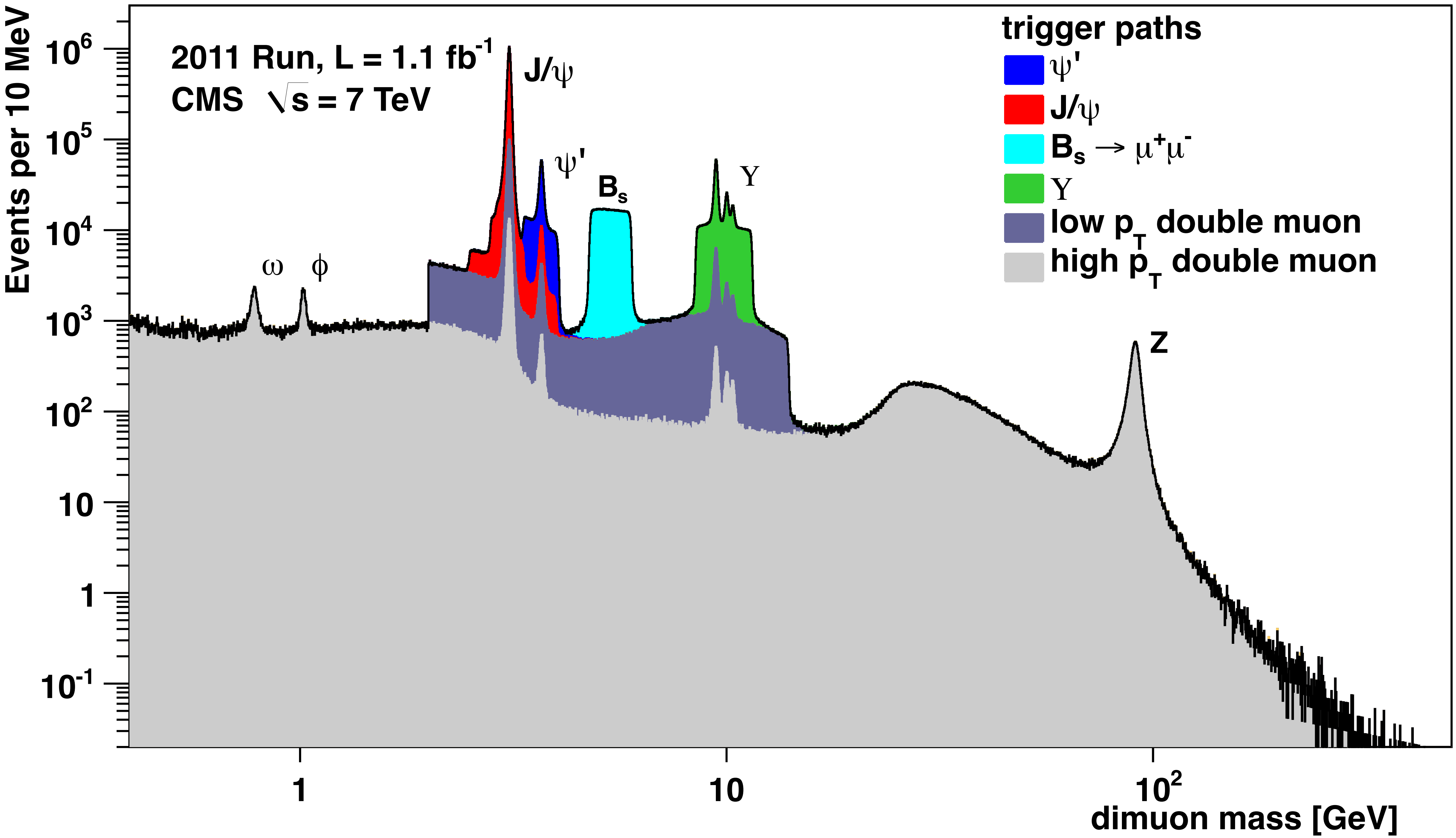
- per mass bin

$$\frac{S}{B_{\rm EM}} \approx \epsilon^4 \frac{\pi}{8} \frac{m_{A'}^2}{\Gamma_{A'}\sigma_{m_{\mu\mu}}} \approx \frac{3\pi}{8} \frac{m_{A'}}{\sigma_{m_{\mu\mu}}} \frac{\epsilon^2}{\alpha_{\rm EM}(N_\ell + \mathcal{R}_\mu)}$$

number of leptons with mass below $m_{A'}$

$$\frac{\sigma_{e^+e^-\to \rm hadrons}}{\sigma_{e^+e^-\to\mu^+\mu^-}}$$

Measured Di-muon Spectrum

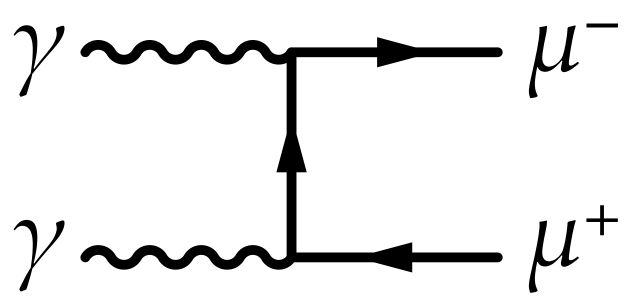


Prompt Search

- "good" Background
  proportional to EM currents
  Mesons, FSR/DY

- "bad" Background

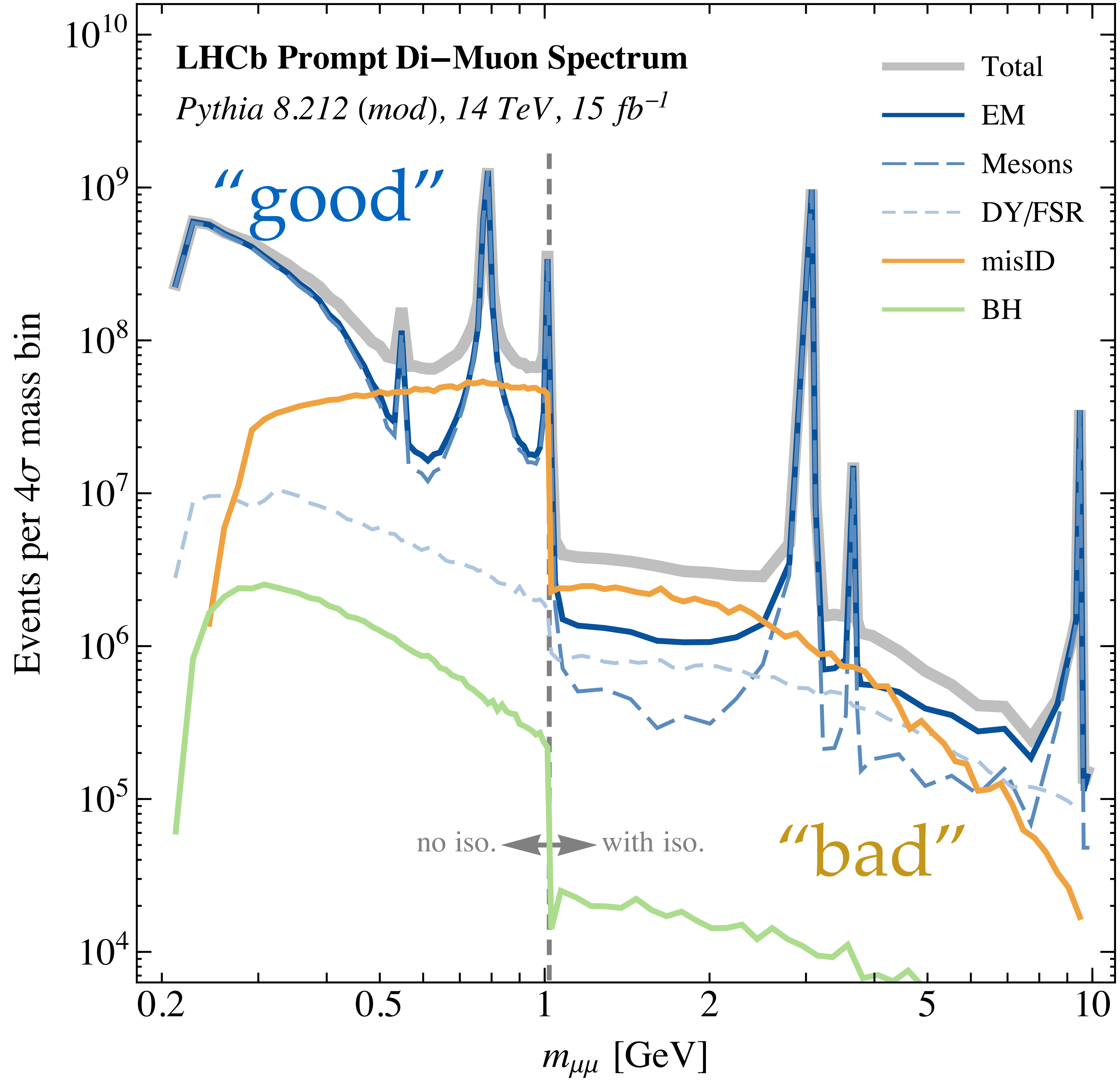
  - Beith-Heitler, subdominant, small photon PDF



  - mis-identified pions (fake rate ~ 10^{-3}):
    $B^{\pi\pi}$ - two pions are misidentified
    $B^{\pi\mu}$ - one pion is misidentified and one real muon
    subtract them in a data-driven way (same-sign dimuon)

selections:

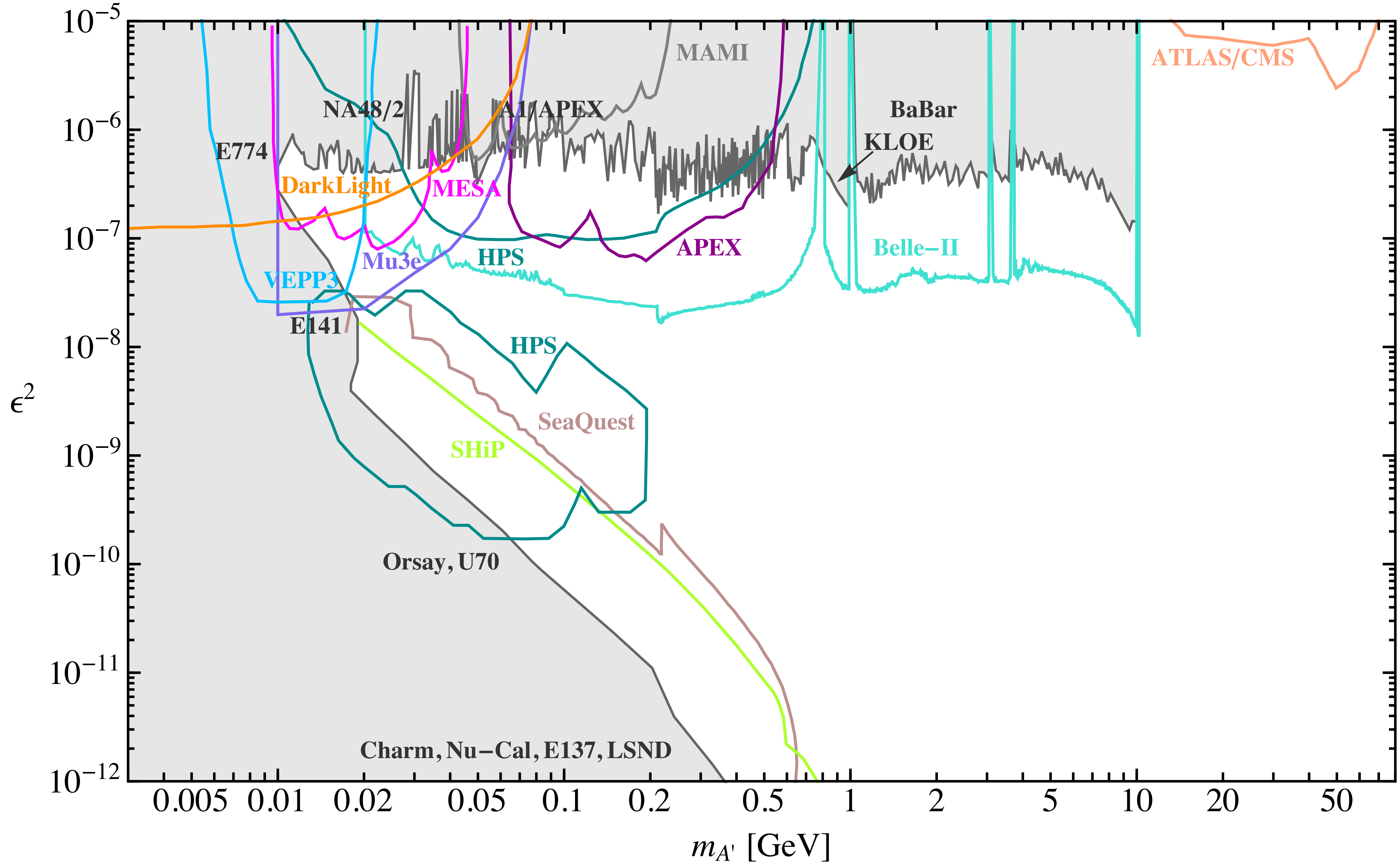
- $2<\eta(\mu^{\pm})<5$
- $p(\mu^{\pm})>10$GeV
- $p_T(\mu^{\pm})>0.5$GeV
- $p_T(A')>1.0$GeV
- μ isolation: $m_{A'}>m_{\phi}\sim 1$ GeV



$$B_{\text{prompt}} = \underbrace{B_M + B_{\text{FSR}} + B_{\text{DY}}}_{B_{\text{EM}}} + \underbrace{B_{\text{misID}}^{\pi\pi} + B_{\text{misID}}^{\pi\mu}}_{B_{\text{misID}}}$$

"good" scales as signal

"bad" does not scale as signal



MAMI
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VEPP3
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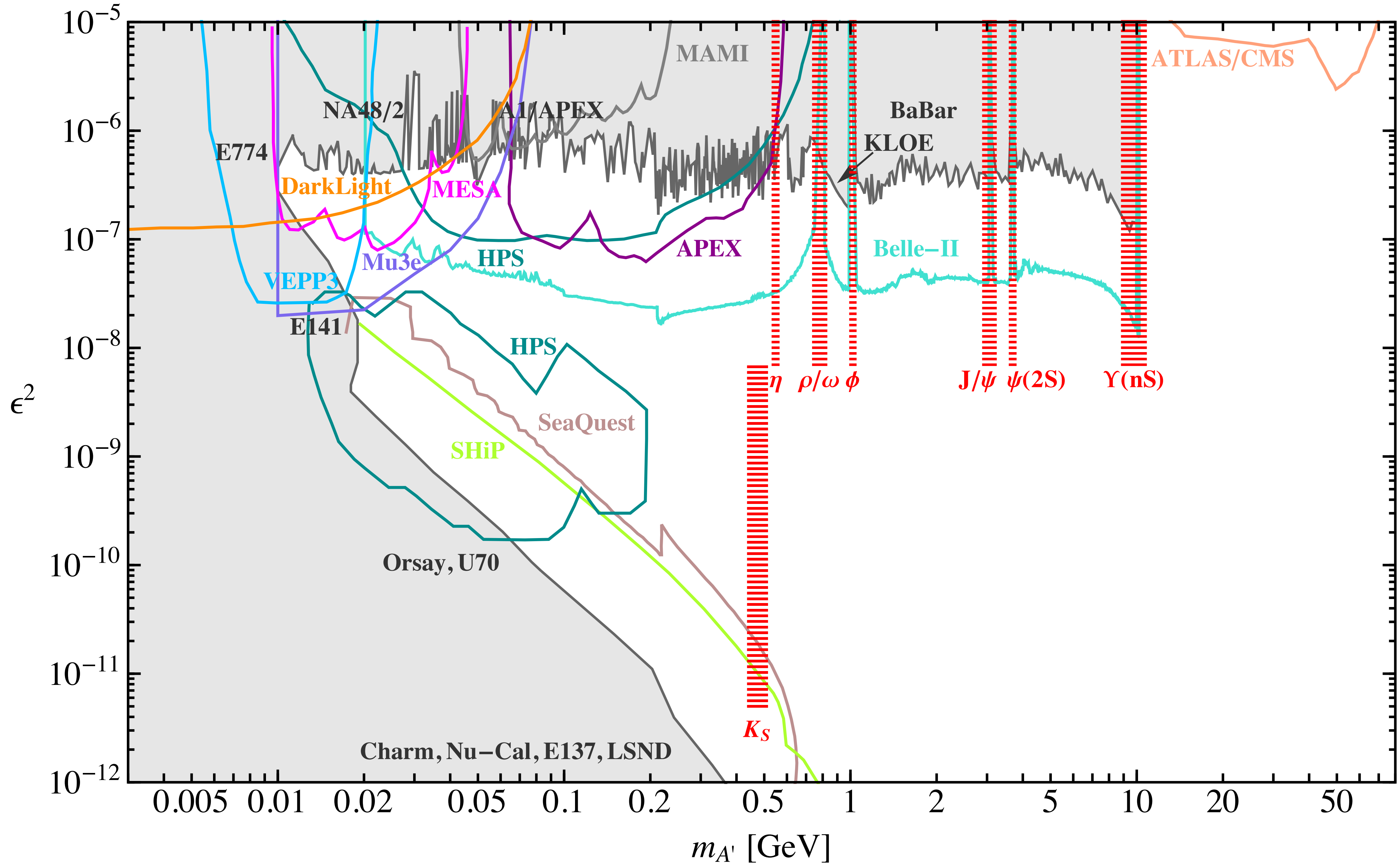
HPS
SeaQuest
SHiP
Orsay, U70
Charm, Nu−Cal, E137, LSND
ϵ^2
$m_{A'}$ [GeV]



MAMI
ATLAS/CMS
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DarkLight
MESA
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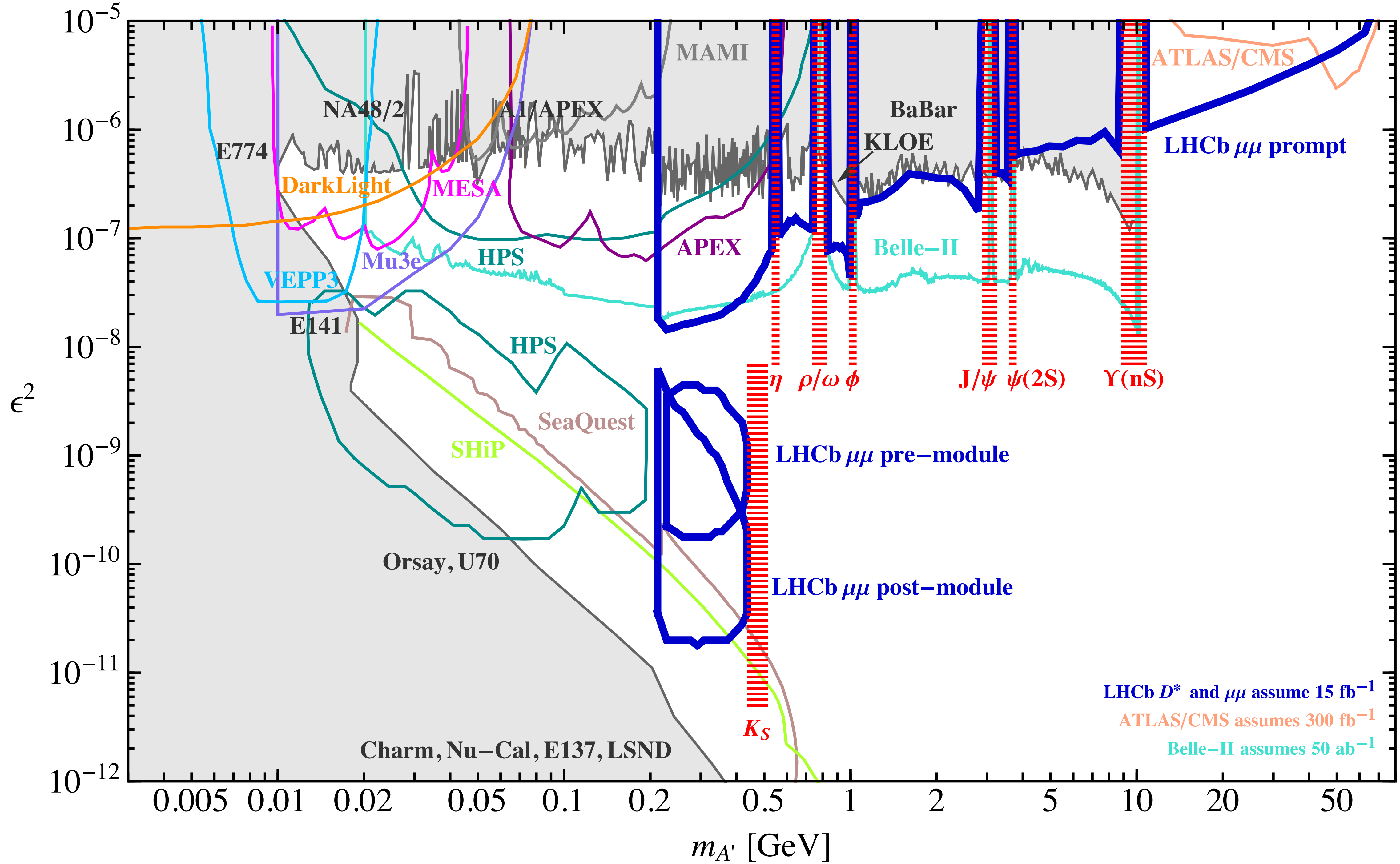
Belle−II
HPS
Mu3e
VEPP3
E141
HPS
SeaQuest
SHiP
Orsay, U70
Charm, Nu−Cal, E137, LSND
K_S
η
ρ/ω
ϕ
J/ψ
ψ(2S)
Υ(nS)
ϵ^2
$m_{A'}$ [GeV]



MAMI
NA48/2
A1/APEX
E774
DarkLight
MESA
BaBar
KLOE
ATLAS/CMS
LHCb μμ prompt
APEX
Belle−II
HPS
Mu3e
VEPP3
E141
HPS
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η
ρ/ω
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J/ψ
ψ(2S)
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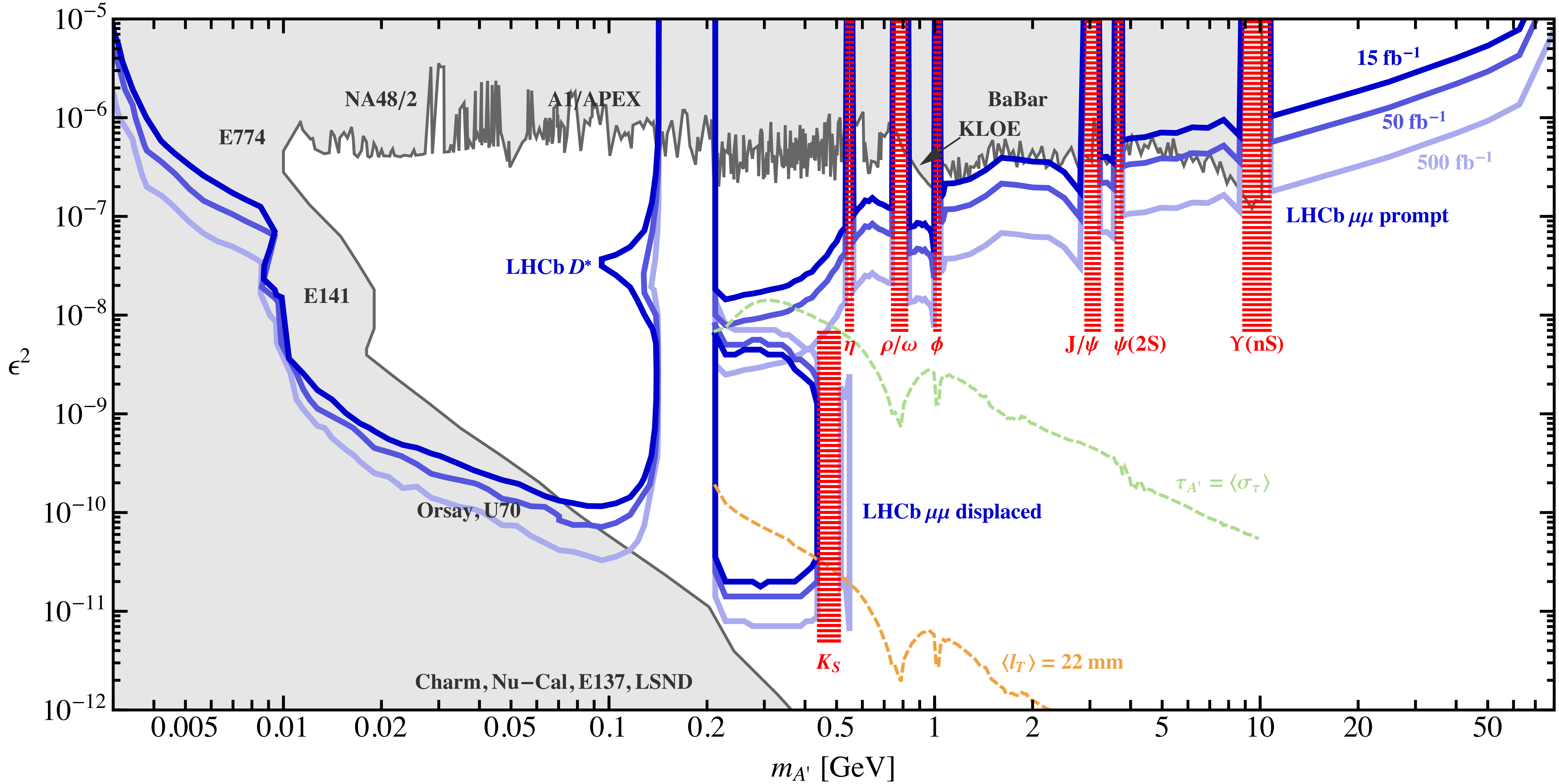
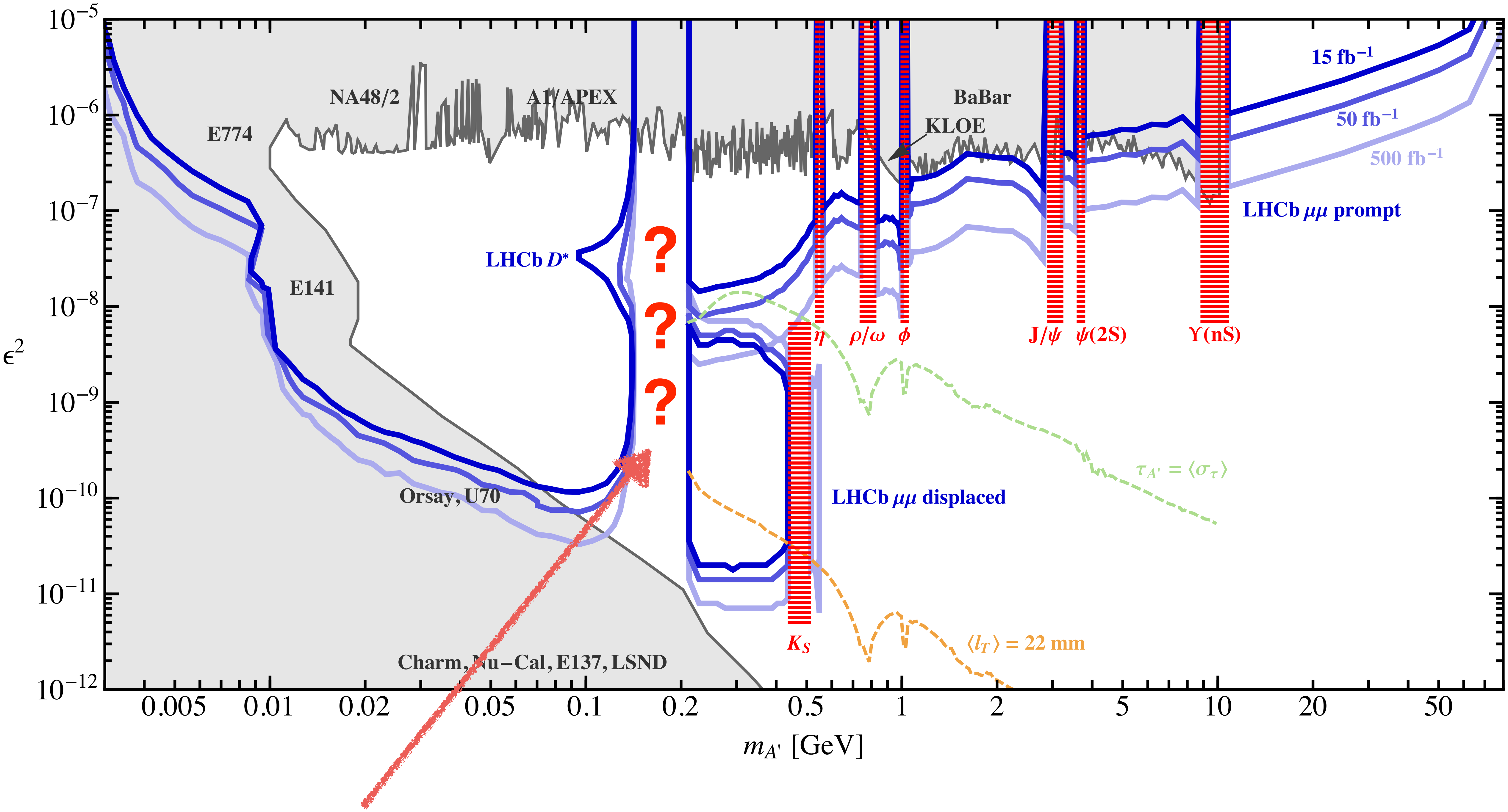
LHCb μμ pre−module
LHCb μμ post−module
Orsay, U70
K_S
Charm, Nu−Cal, E137, LSND
LHCb D^* and μμ assume 15 fb^{-1}
ATLAS/CMS assumes 300 fb^{-1}
Belle−II assumes 50 ab^{-1}
ϵ^2
$m_{A'}$ [GeV]

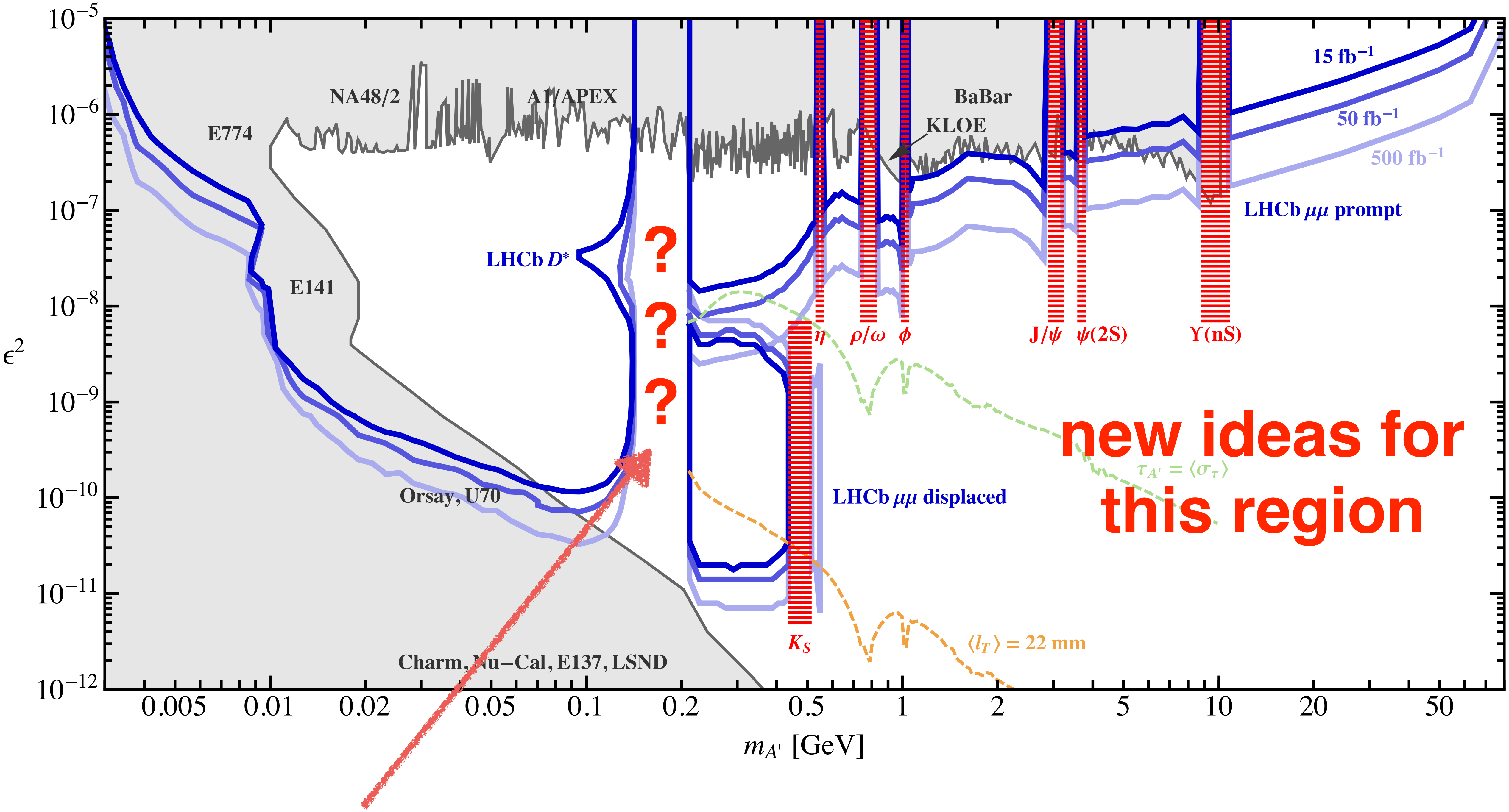
Possible improvement





NA48/2
A1/APEX
E774
BaBar
KLOE
E141
LHCb D*
15 fb⁻¹
50 fb⁻¹
500 fb⁻¹
LHCb μμ prompt
η
ρ/ω
ϕ
J/ψ
ψ(2S)
ϒ(nS)
LHCb μμ displaced
Orsay, U70
K_S
τ_A' = ⟨σ_τ⟩
⟨l_T⟩ = 22 mm
Charm, Nu−Cal, E137, LSND
ε²
m_A' [GeV]

?η → A' + … ?

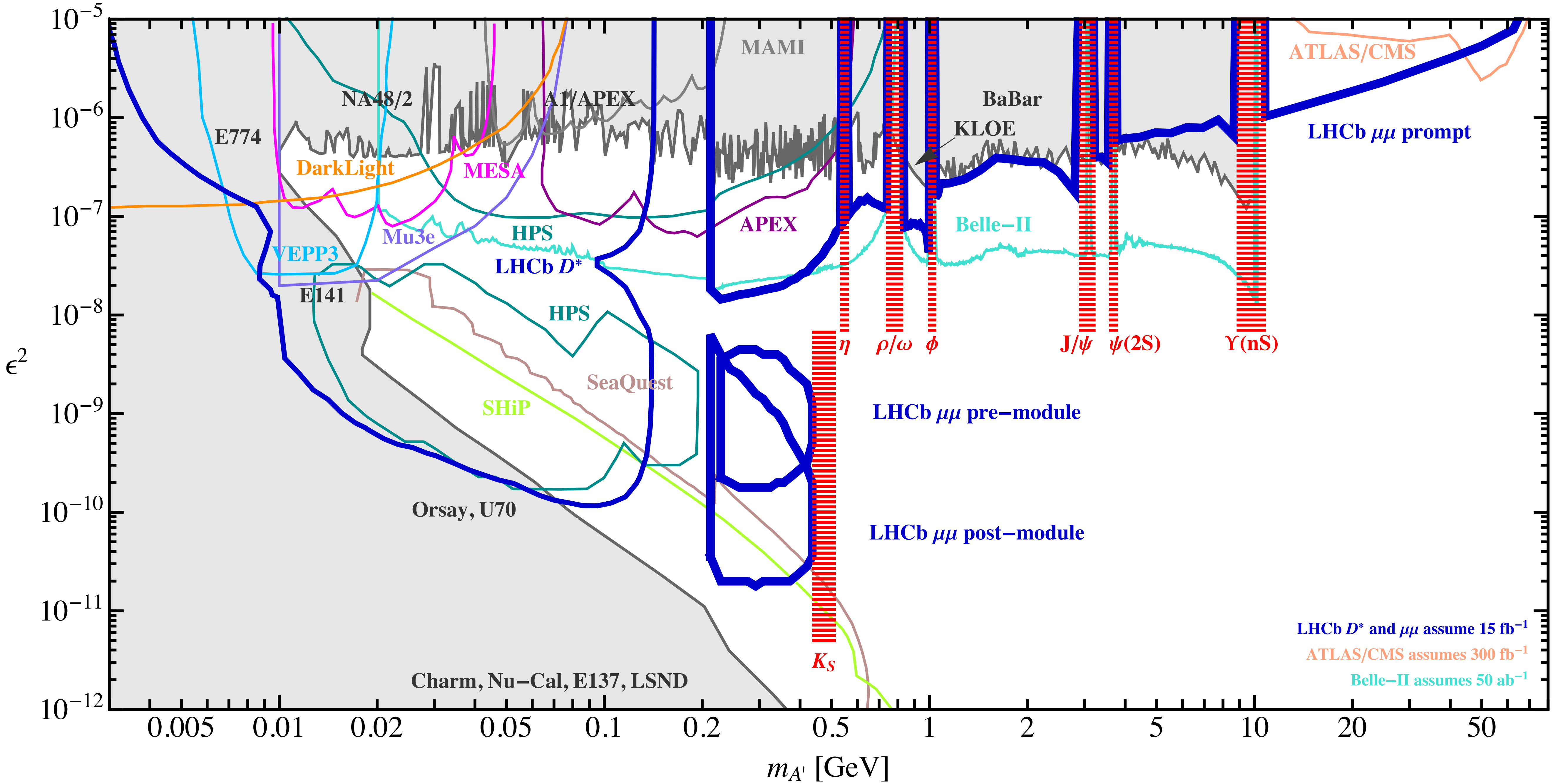


NA48/2
A1/APEX
BaBar
KLOE
E774
E141
LHCb D^*
Orsay, U70
Charm, Nu−Cal, E137, LSND
LHCb $\mu\mu$ displaced
LHCb $\mu\mu$ prompt
15 fb^{-1}
50 fb^{-1}
500 fb^{-1}
η
ρ/ω
ϕ
J/ψ
$\psi(2S)$
$\Upsilon(nS)$
K_S
$\tau_{A'} = \langle\sigma_\tau\rangle$
$\langle l_T \rangle$ = 22 mm
?
?
?
new ideas for this region
ϵ^2
$m_{A'}$ [GeV]

?η → A' + … ?

Conclusion

- VELO
- Triggerless readout
- dark photon search at LHCb
  - resonant search and displaced search
  - $D^{0*} \to D^0 + \gamma$ and inclusive search
  - the (di-muon) data-drive method can be applied to other experiments
  - explore the new territory with current or future collider. the next decade of collider results may give us the first step to understand the hidden sector
- LHCb search for new physics



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$m_{A'}$ [GeV]

Conclusion

- VELO
- Triggerless readout
- dark photon search at LHCb
  - $D^{0*} \rightarrow D^0 + \gamma$ and inclusive search
  - prompt search and displaced search
  - explore the new territory with current or future collider. the next decade of collider results may give us the first step to understand the hidden sector
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Backup Slides

LHCb Trigger

[JINST 8 (2013) P04022]

L0 (15 MHz in → 1 MHz out)

- μ: $p_{\mathrm{T}} > 1.5$ GeV — 340 kHz
- $\mu\mu$: $\sqrt{p_{\mathrm{T}}^1 p_{\mathrm{T}}^2} > 1.3$ GeV — 75 kHz
- h: $E_{\mathrm{T}} > 3.5$ GeV — 405 kHz
- e: $E_{\mathrm{T}} > 2.5$ GeV — 160 kHz
- γ: $E_{\mathrm{T}} > 2.5$ GeV — 80 kHz

1 MHz →

HLT1

- μ: $p_{\mathrm{T}} > 4.8(1)$ GeV — 0.7(5) kHz
- $\mu\mu$: $m > 2.7(1)$GeV — 1.2(1.3) kHz
- track: $p_{\mathrm{T}} > 1.7$ GeV — 33 kHz
- e: $p_{\mathrm{T}} > 10$ GeV
- ...

50 kHz →

HLT2 (→ 5 kHz)

- μ: $p_{\mathrm{T}} > 10(4.8)$ GeV
- $\mu\mu$: $m > 4.8(3)$ GeV
- displaced vertex
- inclusive topological beauty BBDT
- inclusive and exclusive charm
- ...

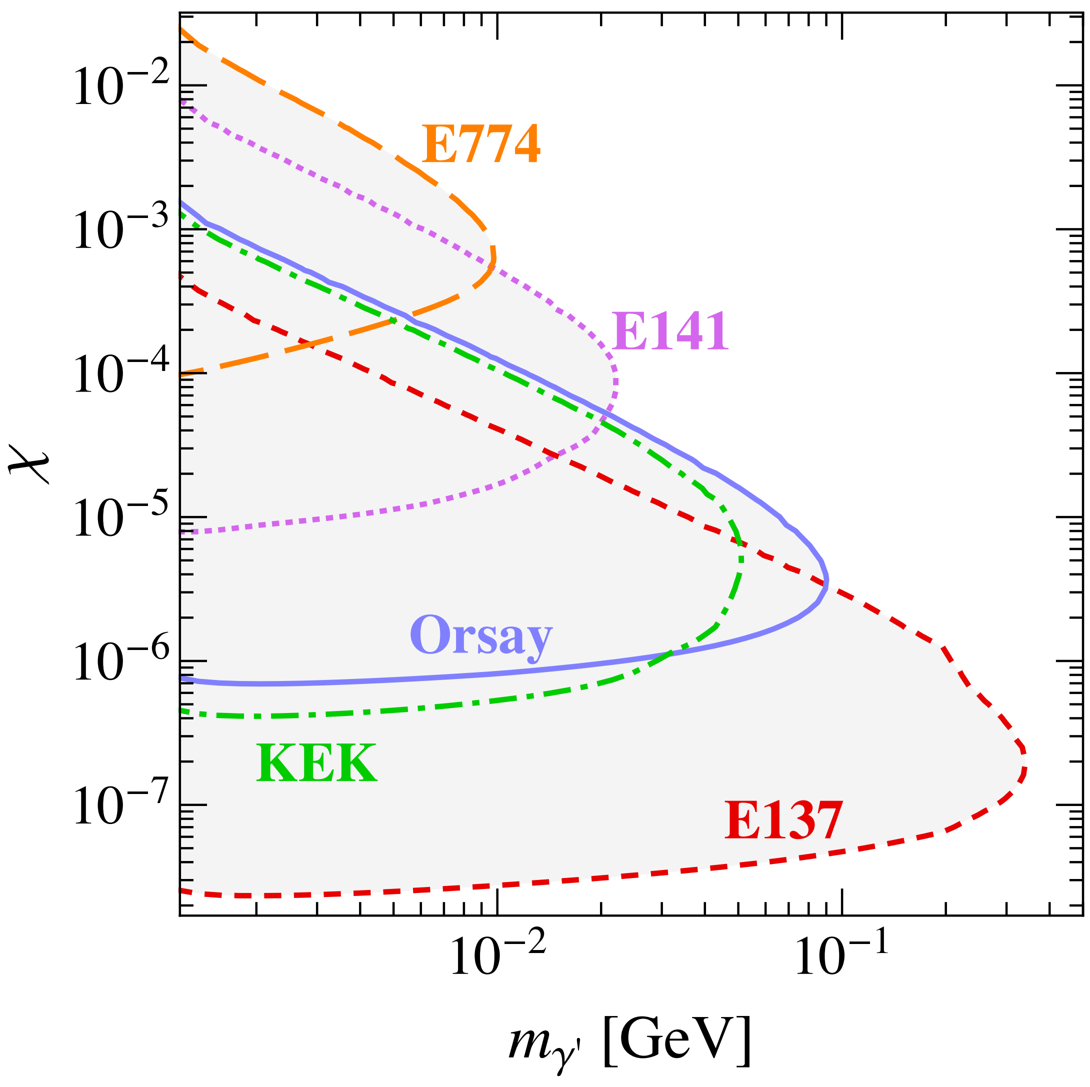
15 MHz

5 kHz

- movable L0 thresholds and software HLT
- low p_{T} leptons/photons and tracks (IP > 0.1 mm)

Displaced Search
Beam Dump Experiments

	target	E_0 [GeV]	N_{el} $\#_{electrons}$	Coulomb	L_{sh} [m]	L_{dec} [m]	N_{obs}	$N_{95\%up}$
KEK	${}^{183.84}_{74}\mathrm{W}$	2.5	1.69×10^{17}	27 mC	2.4	2.2	0	3
E141	${}^{183.84}_{74}\mathrm{W}$	9	2×10^{15}	0.32 mC	0.12	35	1126^{+1312}_{-1126}	3419
E137	${}^{26.98}_{13}\mathrm{Al}$	20	1.87×10^{20}	30 C	179	204	0	3
Orsay	${}^{183.84}_{74}\mathrm{W}$	1.6	2×10^{16}	3.2 mC	1	2	0	3
E774	${}^{183.84}_{74}\mathrm{W}$	275	5.2×10^{9}	0.83 nC	0.3	2	0^{+9}_{-0}	18

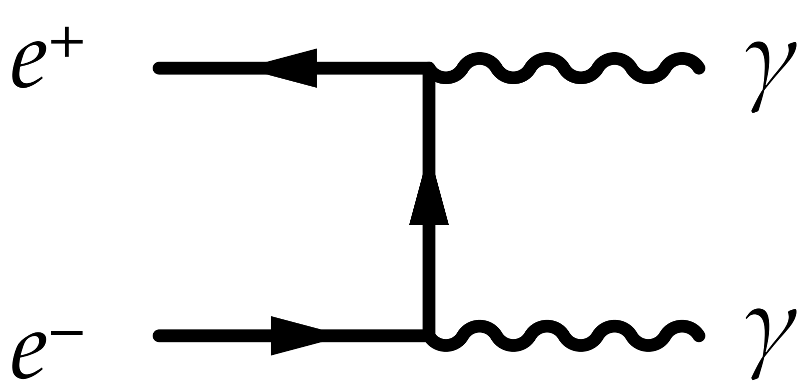


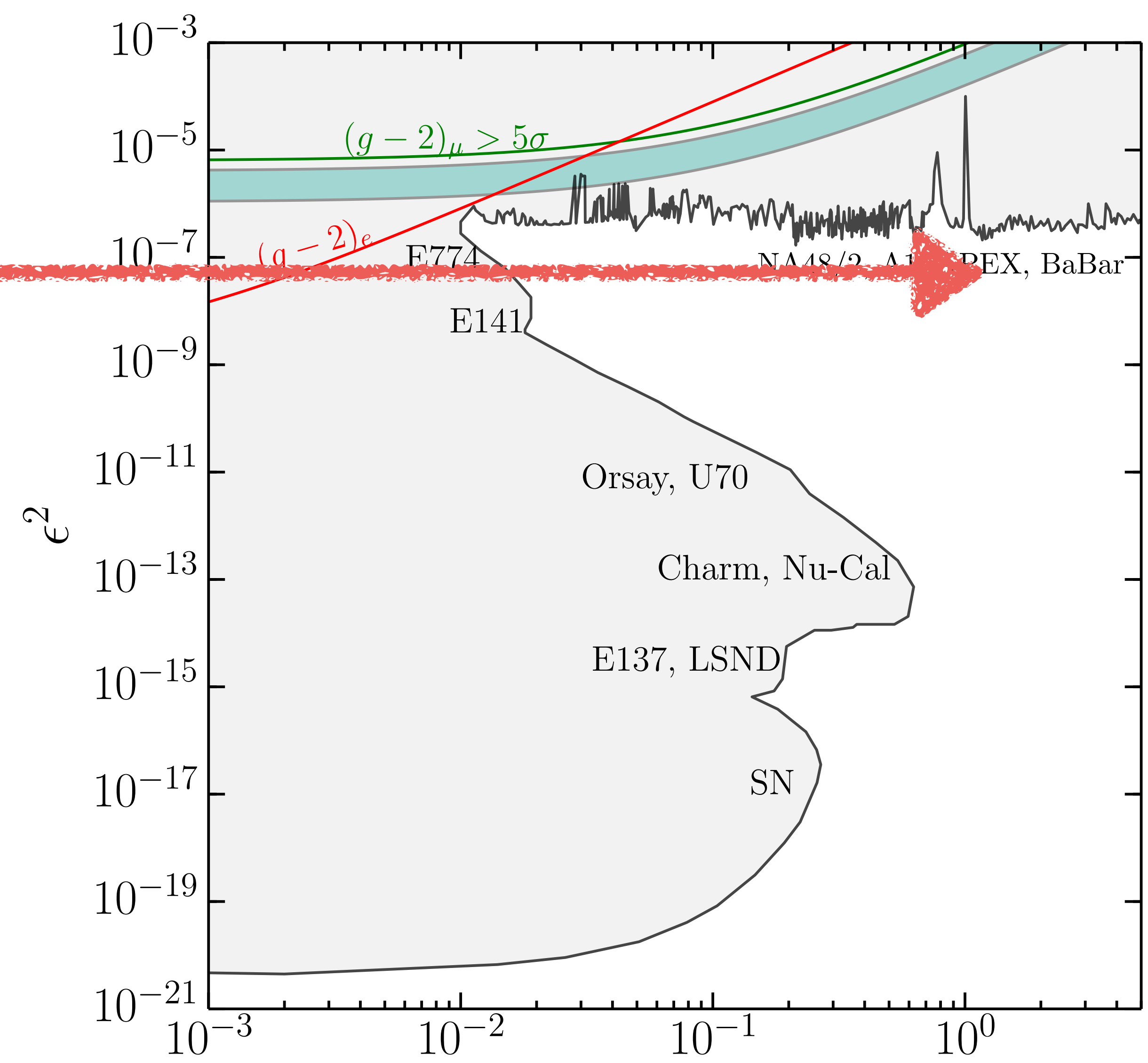
Photon-Dark Photon Mixing

- photon mixes with dark photon
- vector mesons also mix with dark photon
- the off shell photon current includes all the possible mixings

Resonant Search

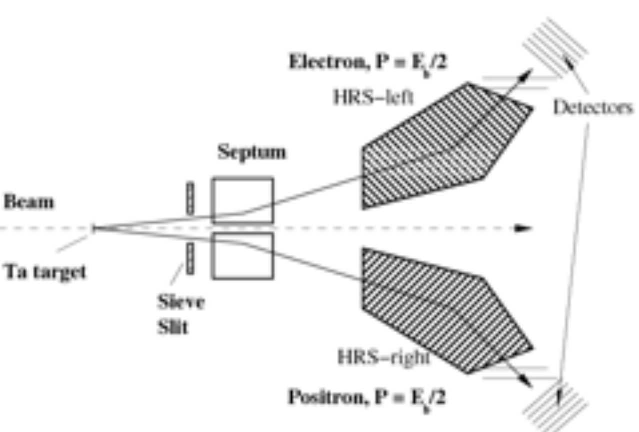
- $A' \to e^+ e^-$, $A' \to \mu^+ \mu^-$
- background from off-shell photon
  $S/\sqrt{B} \sim \varepsilon^2 \sqrt{N}$
- BaBar
  collider

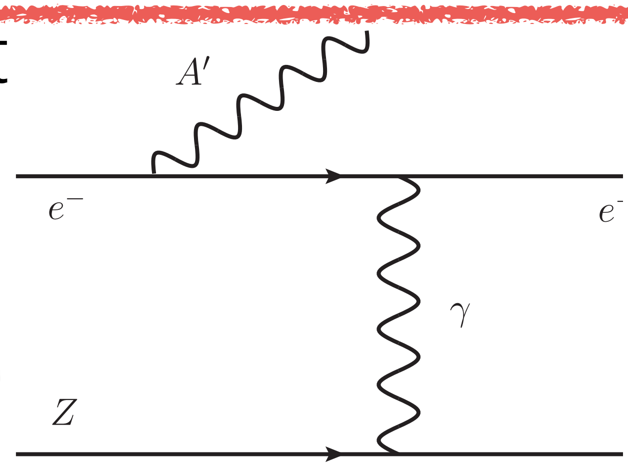


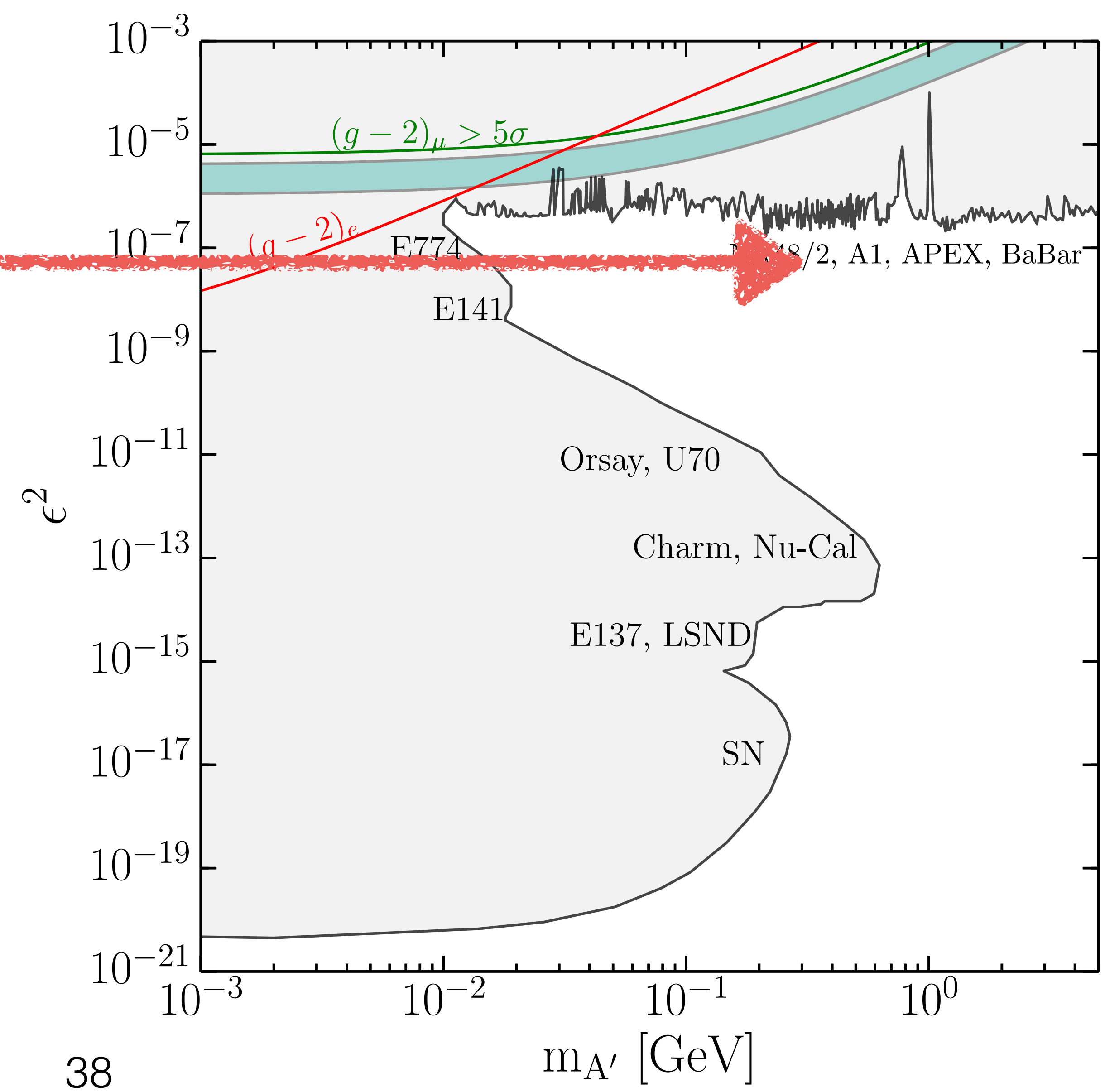


Resonant Search

- A’ → e⁺ e⁻ , A’ → μ⁺ μ⁻
- background from off-shell photon
  S/√B ~ ε^2 √N
- A1, APEX
  fixed target







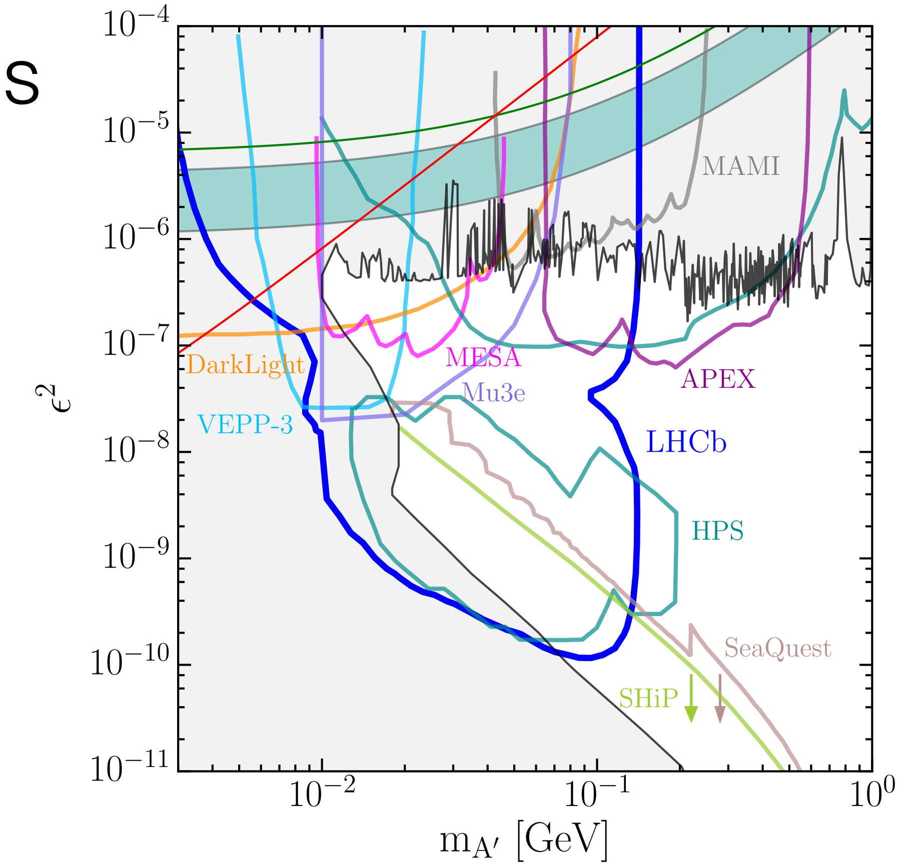
Displaced search Background

- pre-module :
  $D^{0*} \to D^0 e^+ e^-$, $D^{0*} \to D^0 \pi^0 (\gamma e^+ e^-)$
  due to a hard electron scatter in material.
  method to remove: A' vertex occurring in the proper decay plane

- post-module:
  $D^{0*} \to D^0 \gamma$, gamma covert to e^+e^- by interacting with the detector material.
  method to remove: vertex of e+e- will not consistent with any detector material

Comparison to Other Experiments

- HPS (Heavy Photon Search) @ Jefferson Lab
  HPS has a state-of-the-art tracking and vertax detector
  but
  - LHCb Larger Lorentz boosts (3 times)
  - fixed target: pushing A' flight direction into detection
  - LHCb access to smaller opening angles



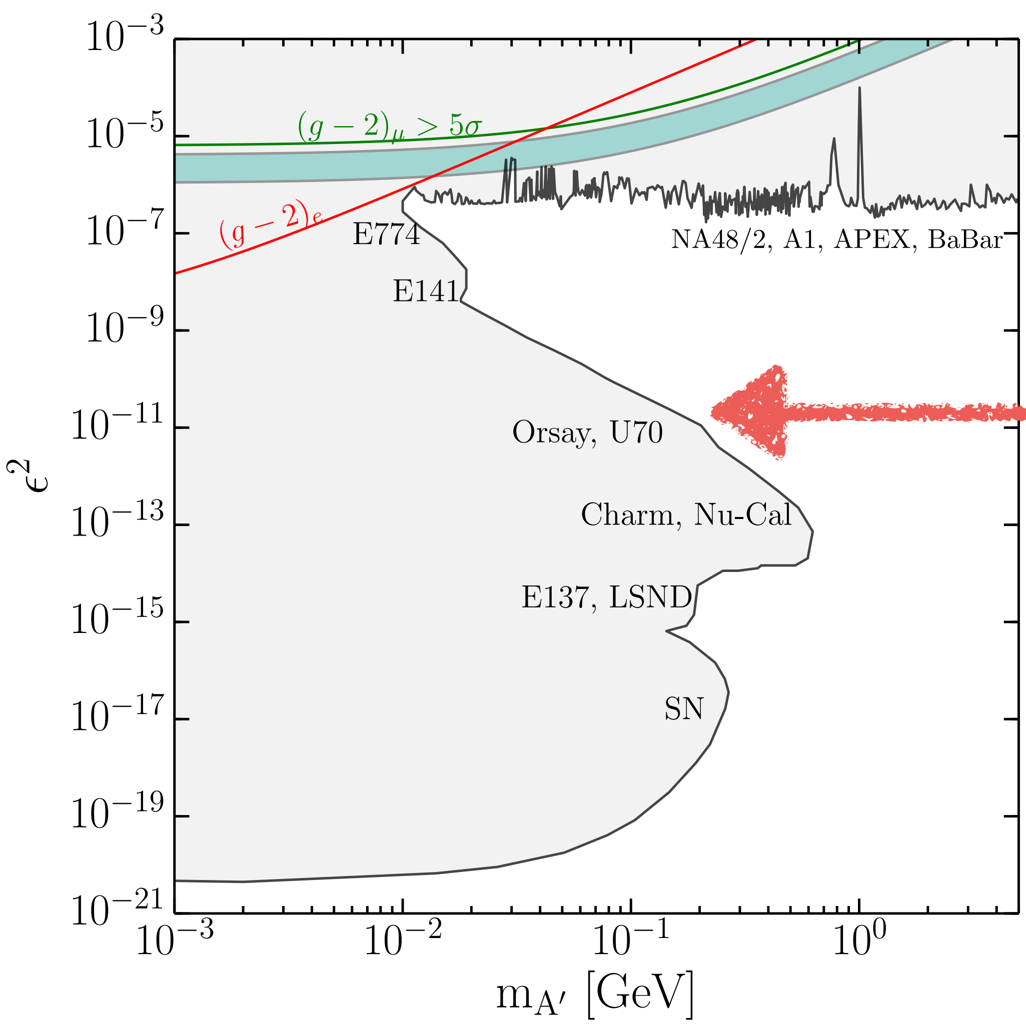
Displaced Search Background

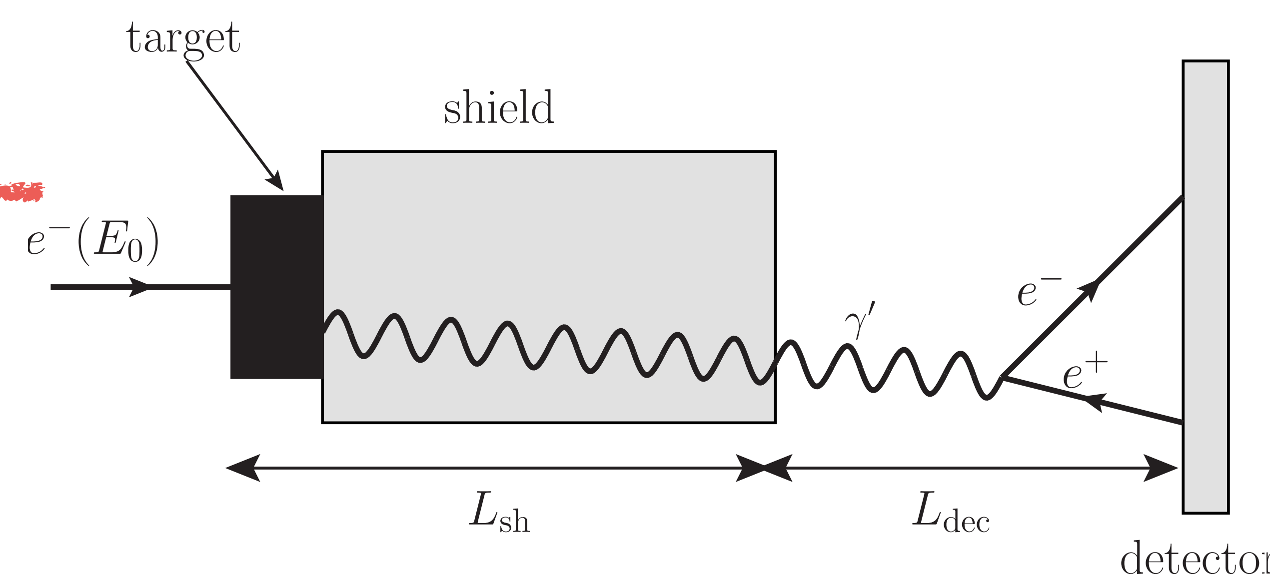
- pre-module : semi-leptonic heavy meson decays
  $b \to c\,\mu^{\pm}\,X$, $c \to \mu^{\pm}\,Y$
  10^4 events per $\pm\,2\,\sigma$ inv mass bin

- post-module : $\tau_A \gg \tau_{D,B}$
  mostly material interactions.
  25 events per mass bin
  (rescaled from $K_s \to \mu^+\,\mu^-$ search)

Displaced Search
e.g. beam dump experiments

- A' decay rate $\Gamma \propto \boldsymbol{\varepsilon}^2 \times m_{A'}$
- Background free
- shield length: cm - m





Resonant Search

- A’ → $e^+ e^-$, A’ → $\mu^+ \mu^-$

- background from off-shell photon
  $S/\sqrt{B} \sim \epsilon^2 \sqrt{N}$