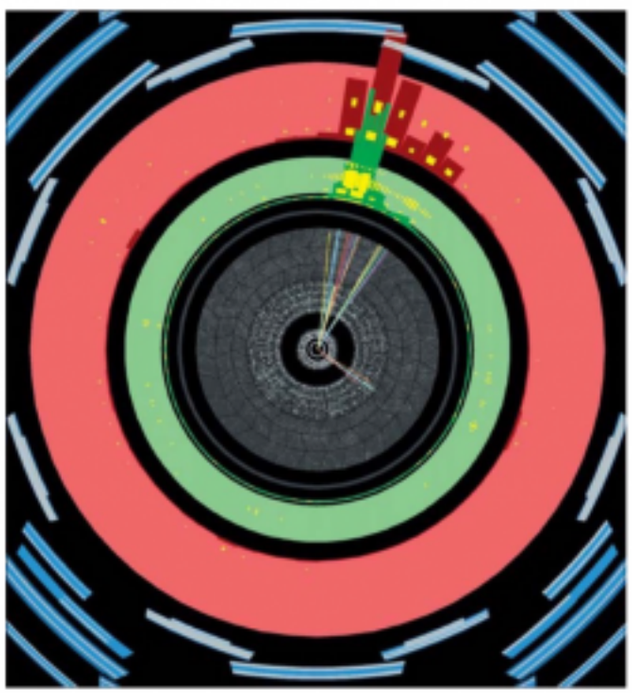
Dark Photon Searches @ LHCb

Wei Xue

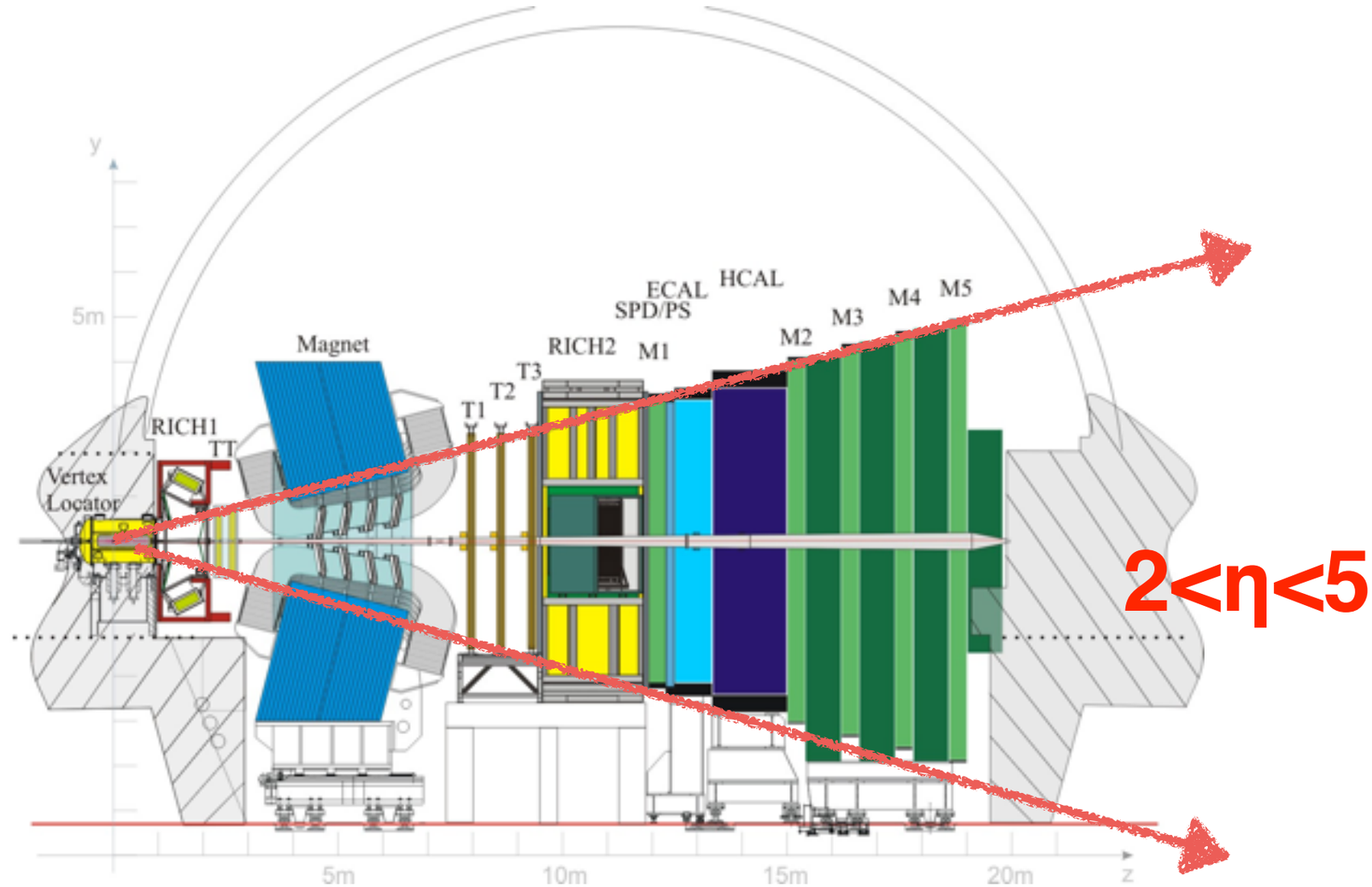
Oct 6, 2016
Dark Interactions

Dark Matter Search
Why not LHCb?



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

ATLAS/
CMS



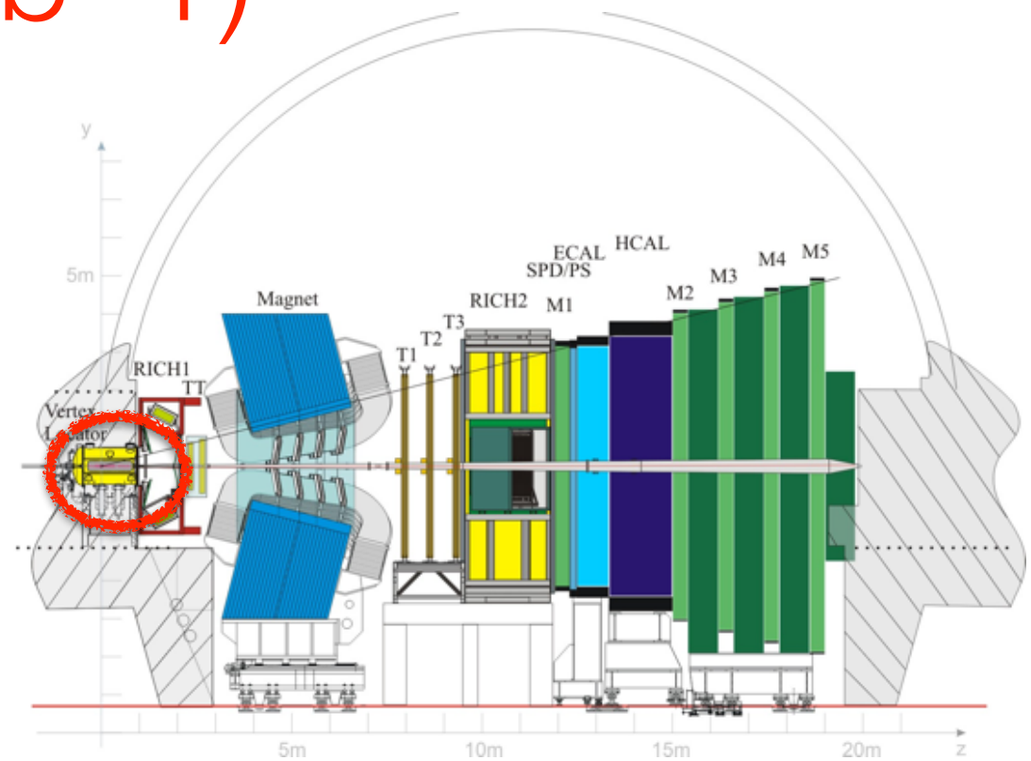
LHCb

Outline

- why LHCb
- 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, PRL 2016, 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)

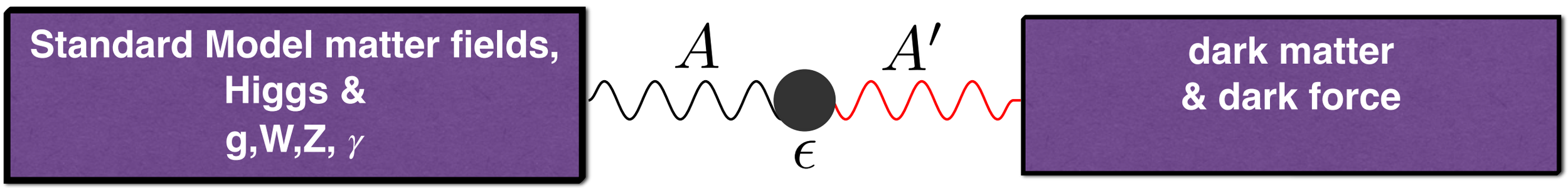


Why LHCb 2)

- 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 Photons

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



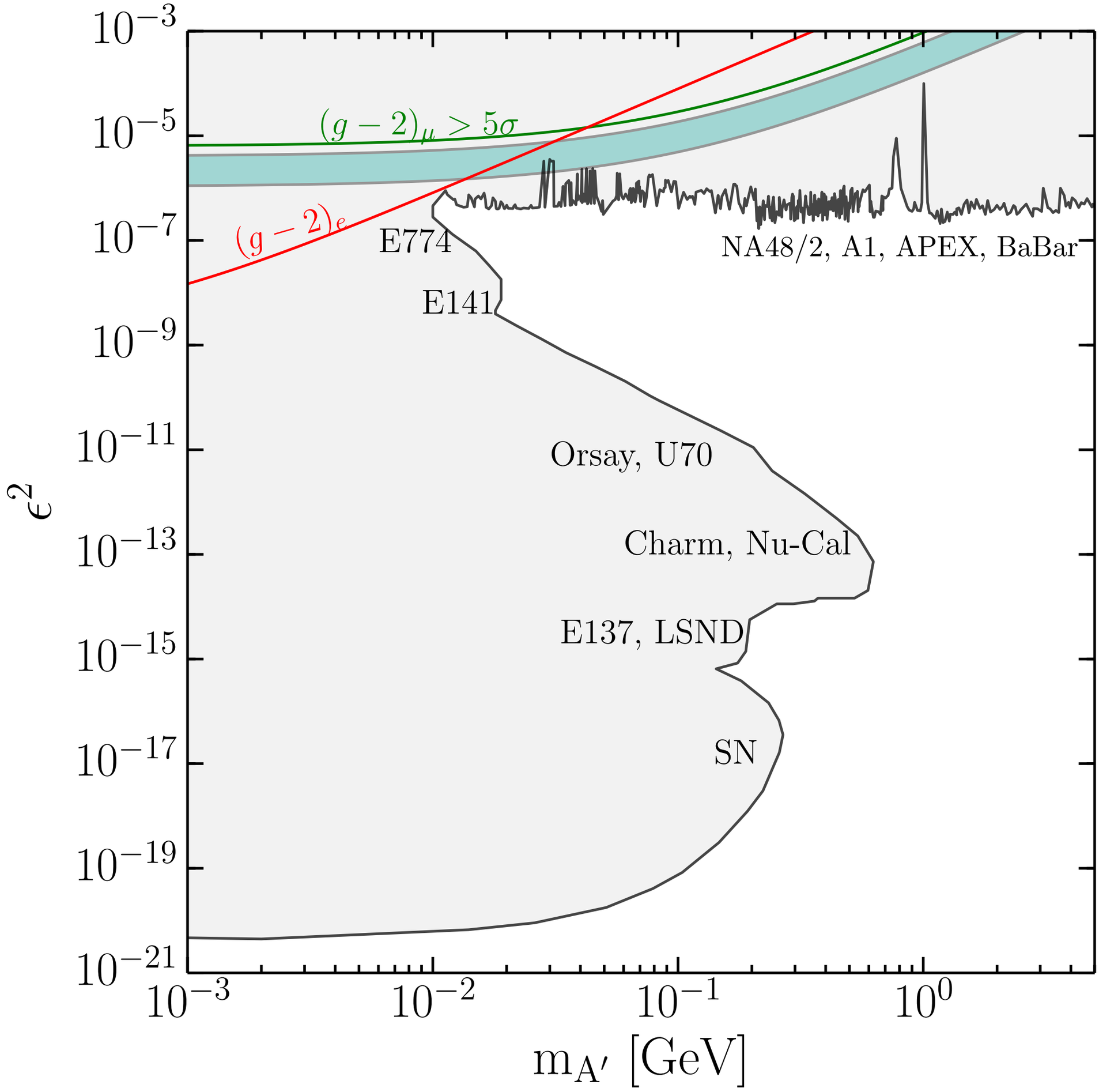
$$\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

- effective Lagrangian

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

- focusing : mass range of $m_{A'}$ ($\in$ MeV - 10 GeV)

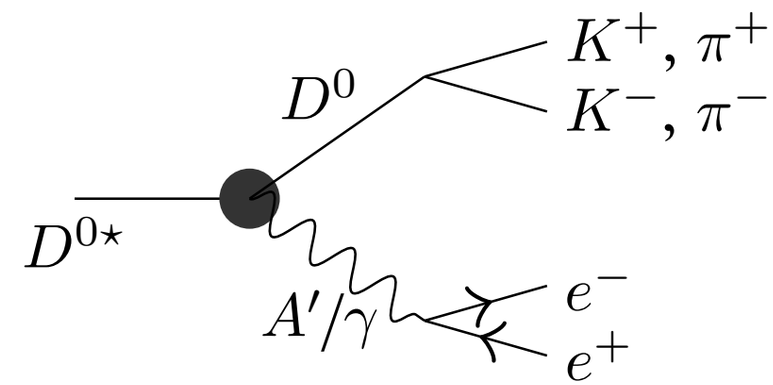
  $\varepsilon^2 \sim 10^{-6}, 10^{-12}$

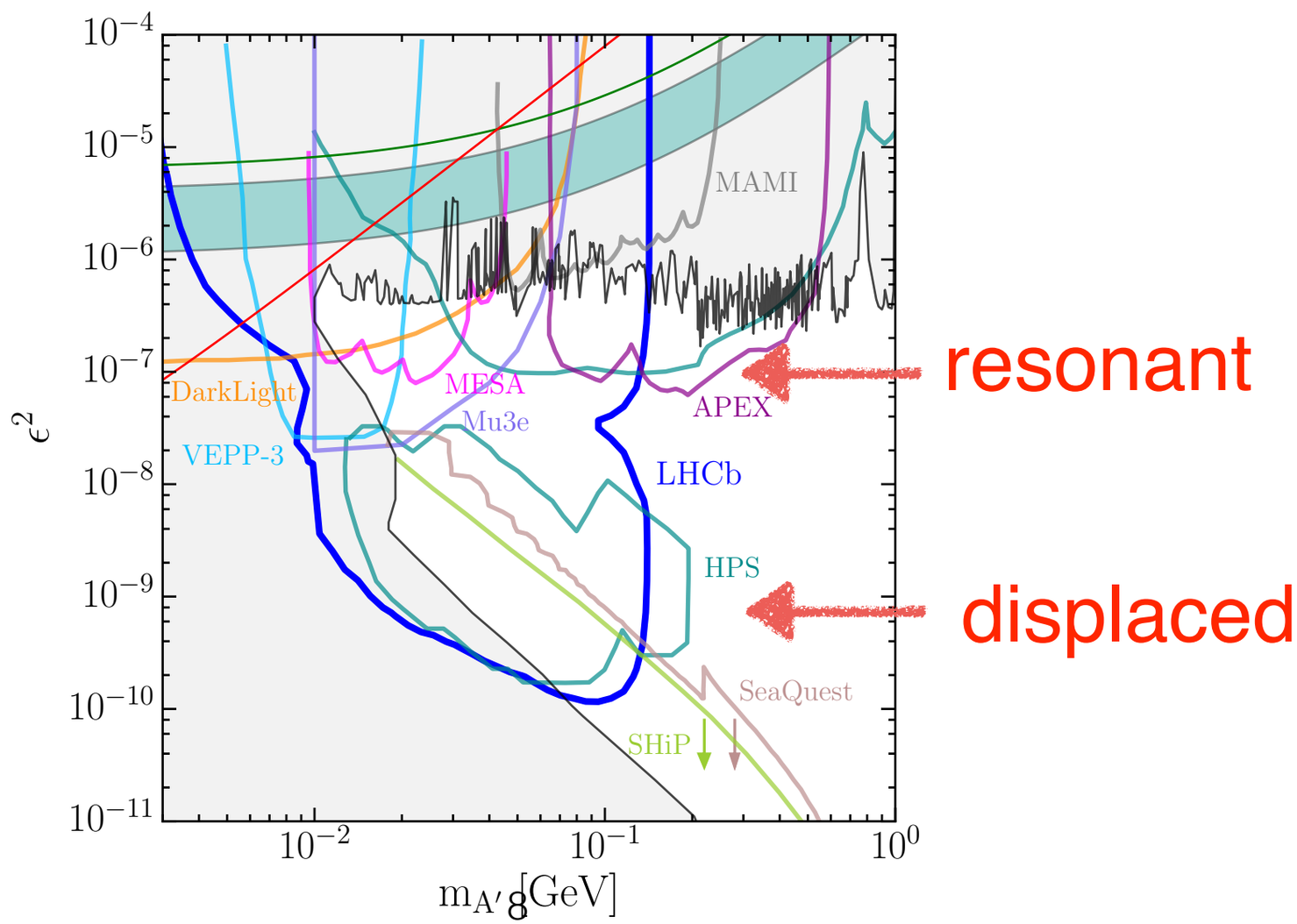

$(g-2)_\mu > 5\sigma$
$(g-2)_e$
E774
E141
NA48/2, A1, APEX, BaBar
Orsay, U70
Charm, Nu-Cal
E137, LSND
SN
ϵ^2
$m_{A'}$ [GeV]
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-3}
10^{-2}
10^{-1}
10^{0}

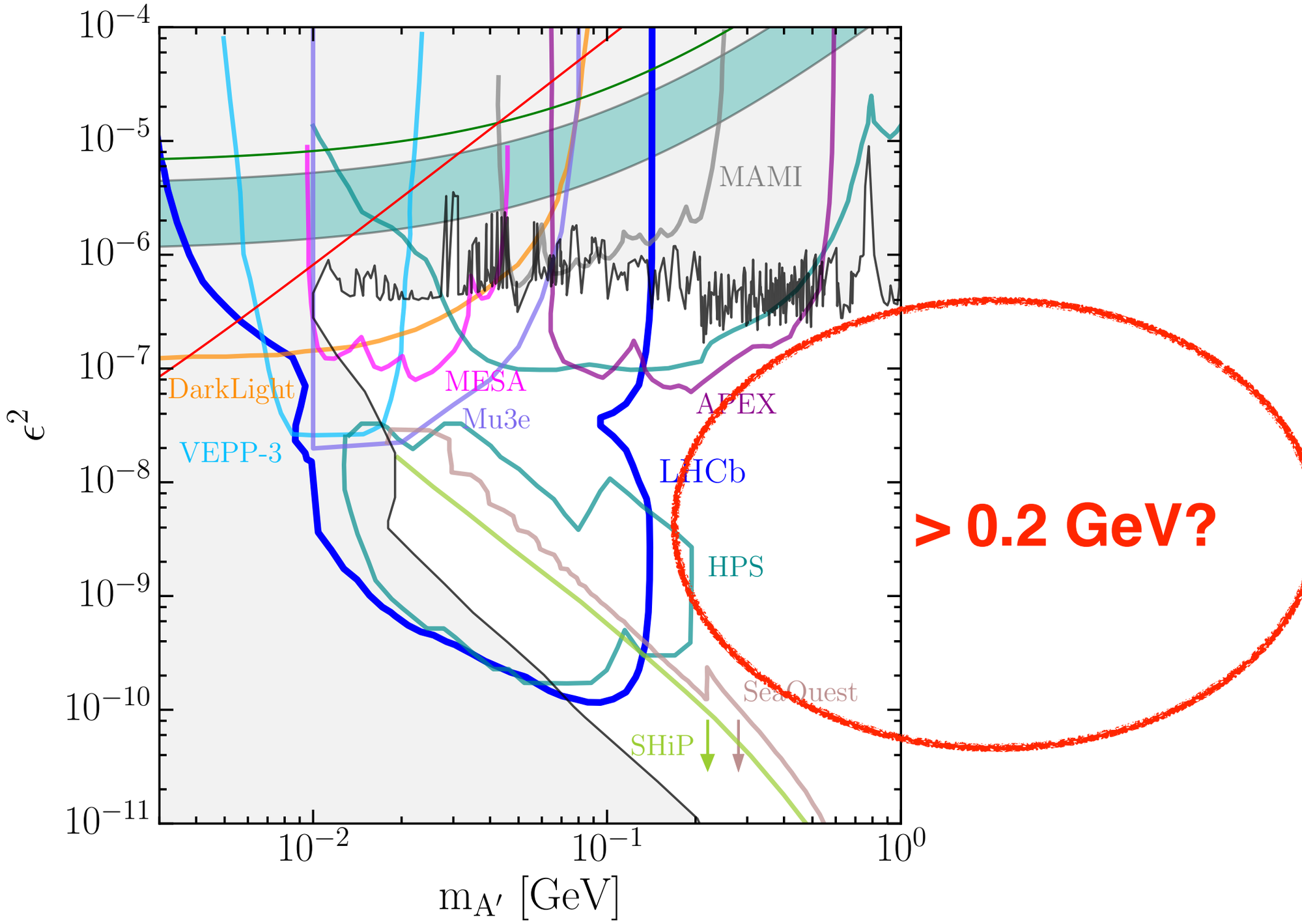
Very Promising Channel: Charm Meson

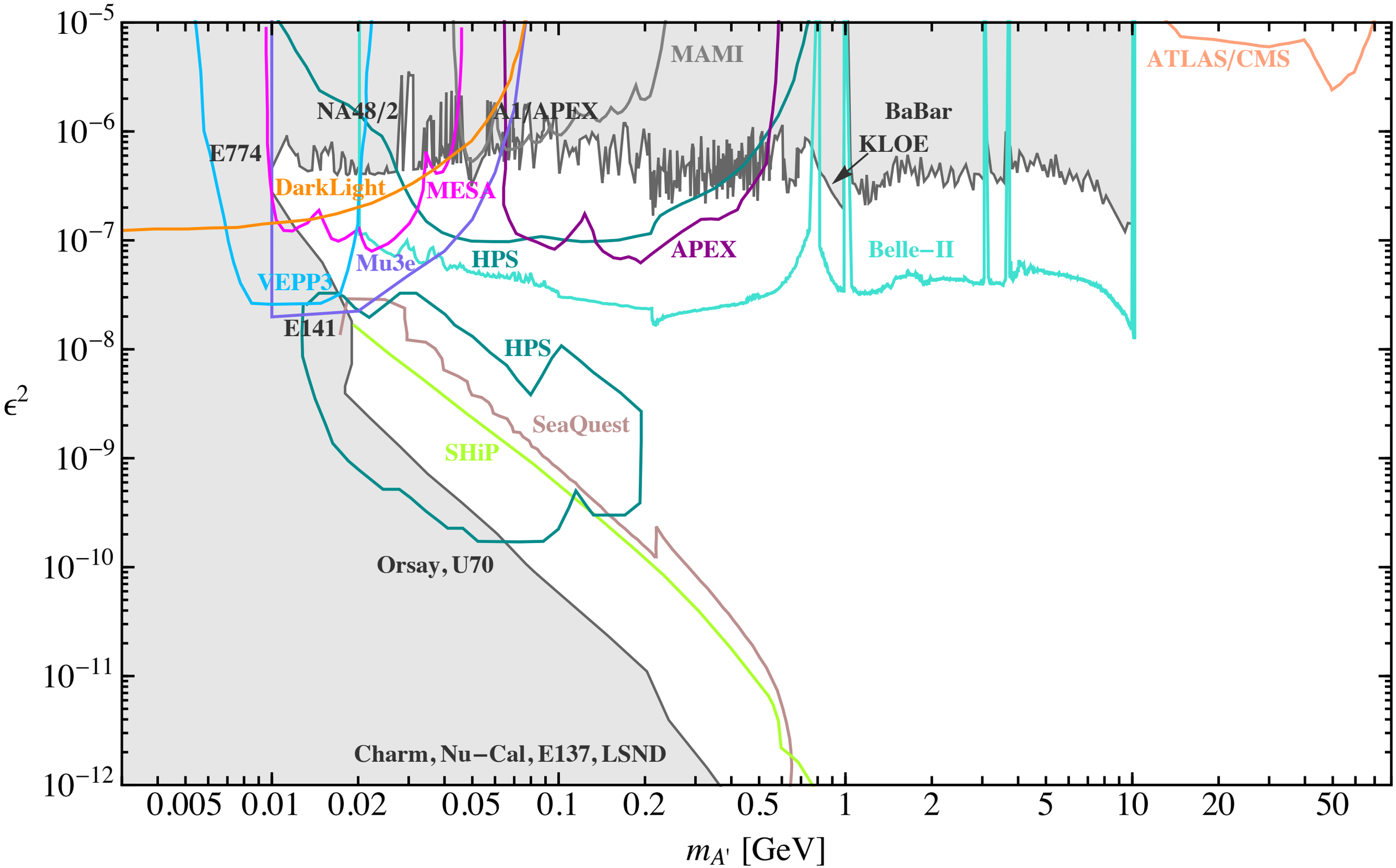
- 5×10^{12} $D^{*0} \rightarrow D^0 + \gamma$

- good vertex resolution ~ 10 μm






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


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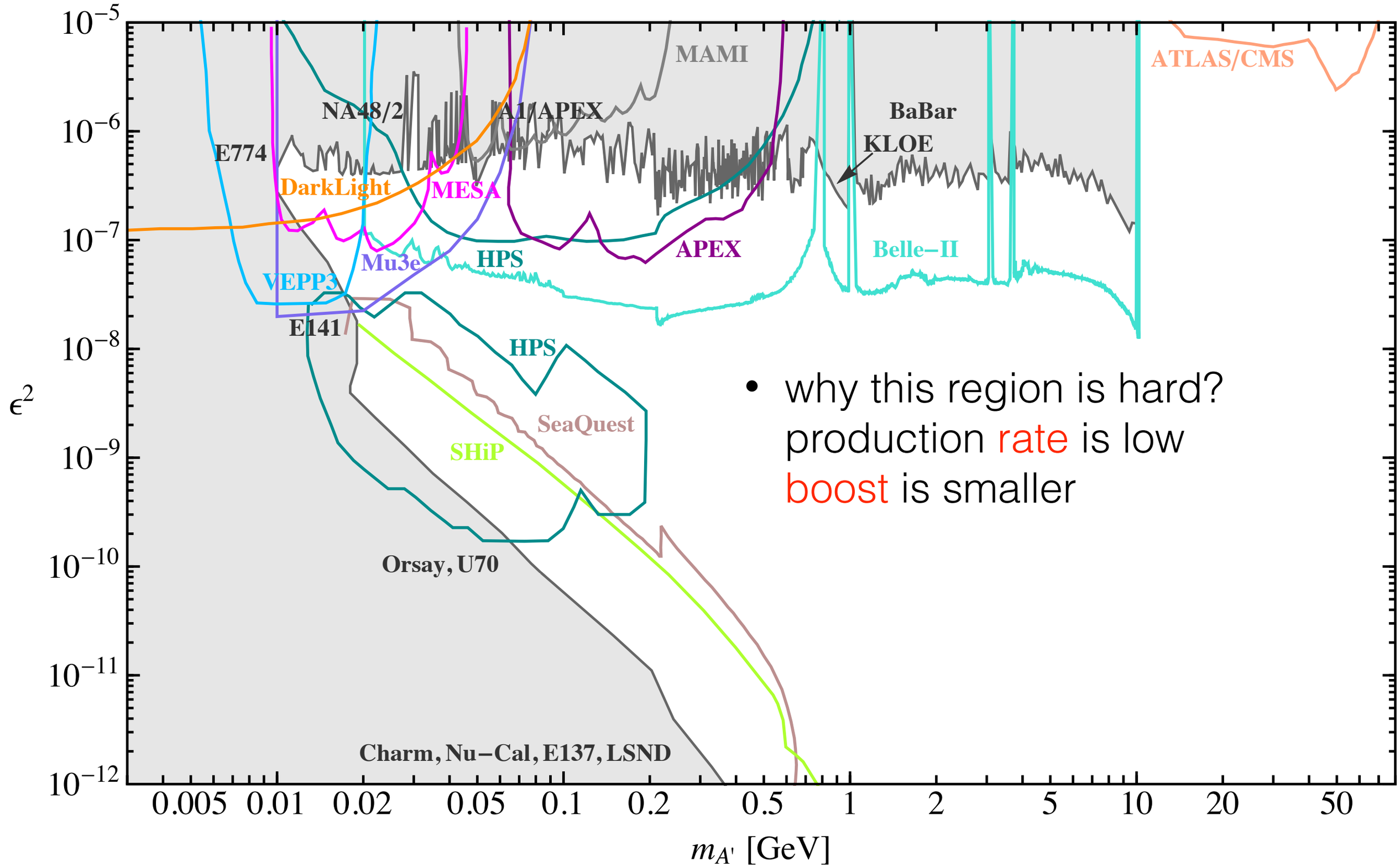
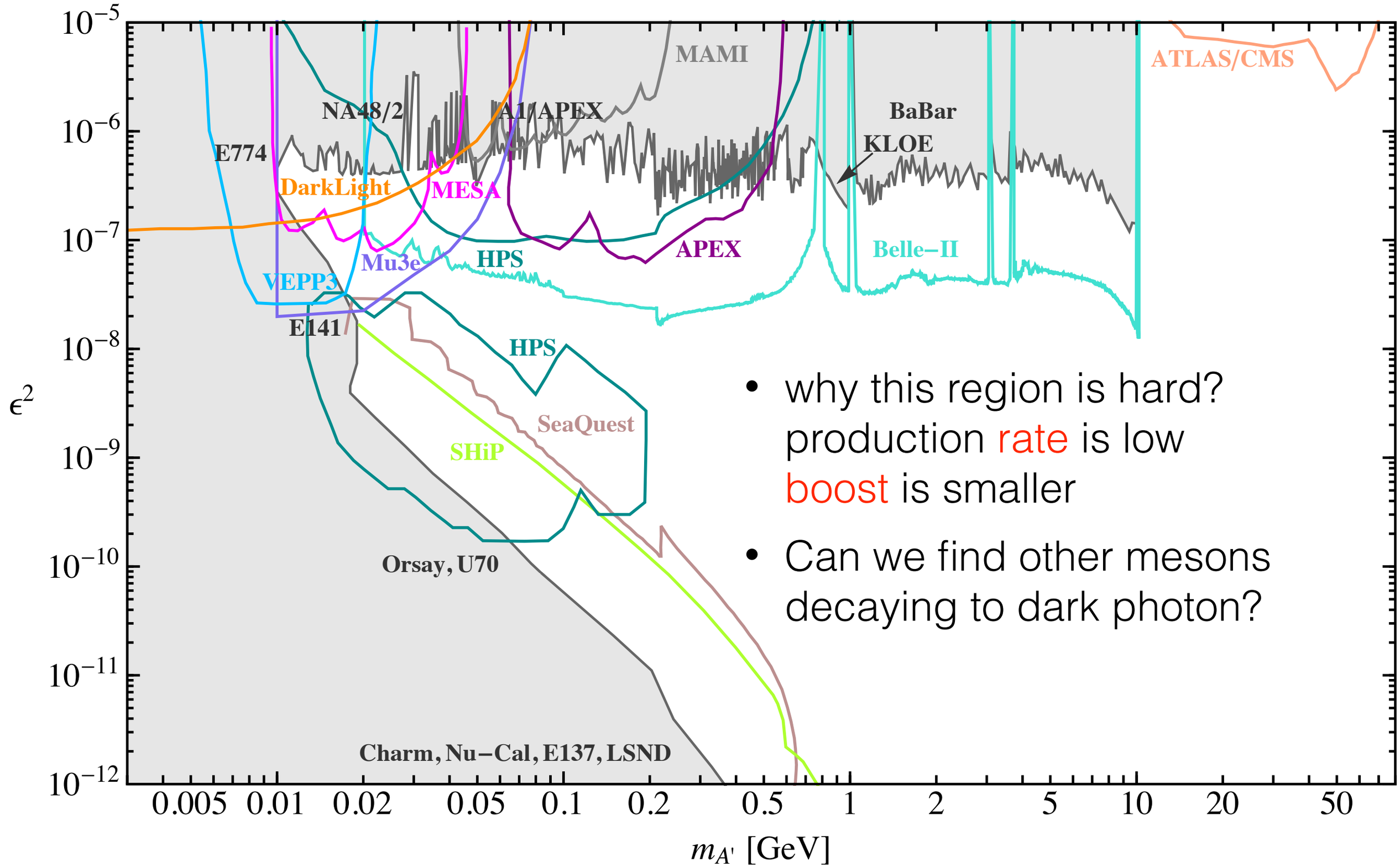
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
ϵ^2
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1
2
5
10
20
50
$m_{A'}$ [GeV]



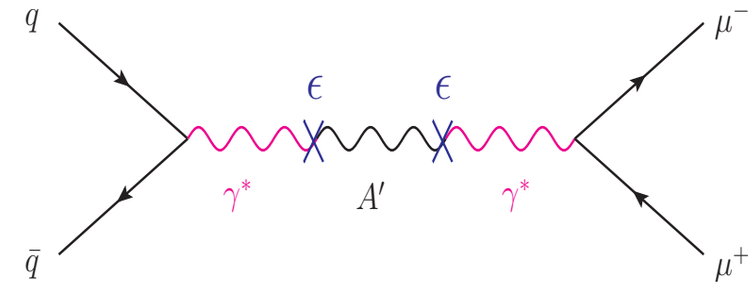
- why this region is hard?
  production rate is low
  boost is smaller



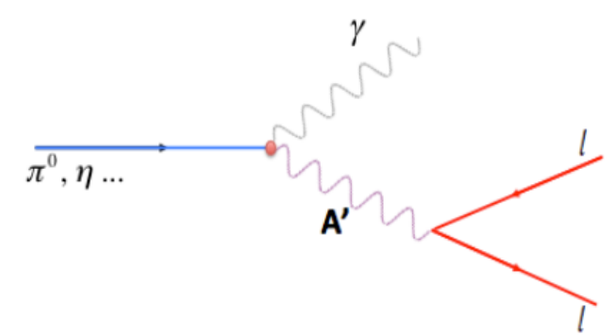
- why this region is hard?
  production rate is low
  boost is smaller
- Can we find other mesons decaying to dark photon?

Can we combine all the channels?

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



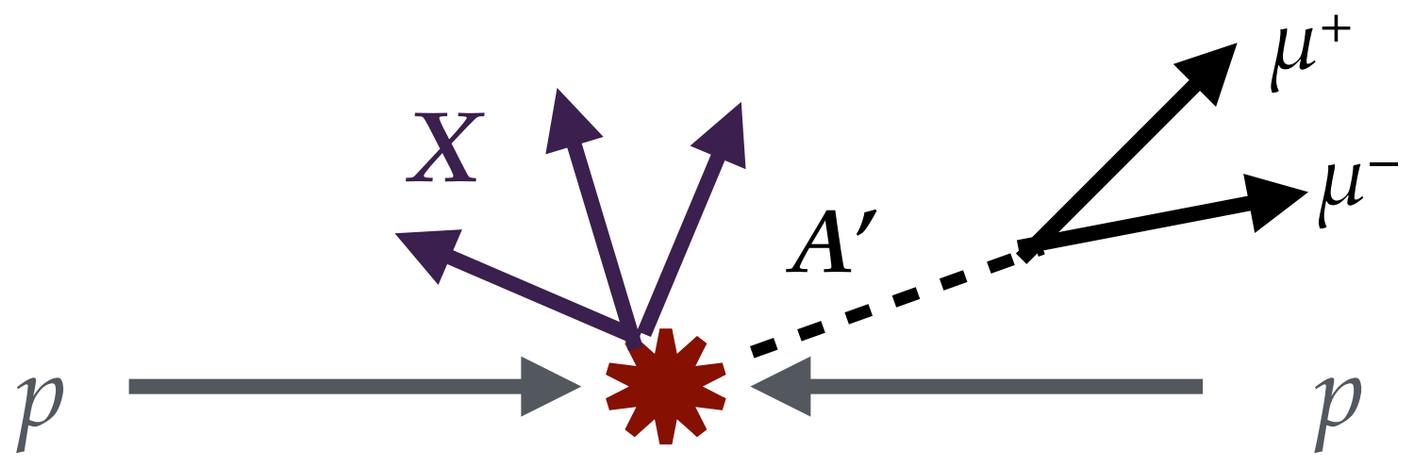
  - meson decays



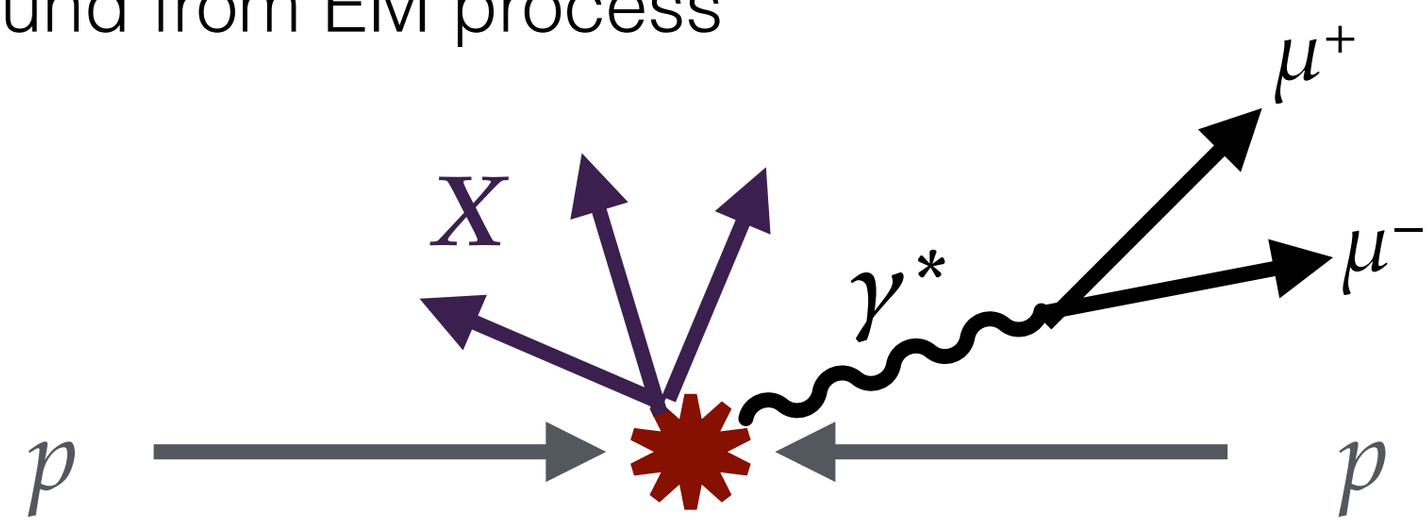
- Challenge 1:
  what is the signal rate?
  many potential sources of dark photons
  with uncertain production rates

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.

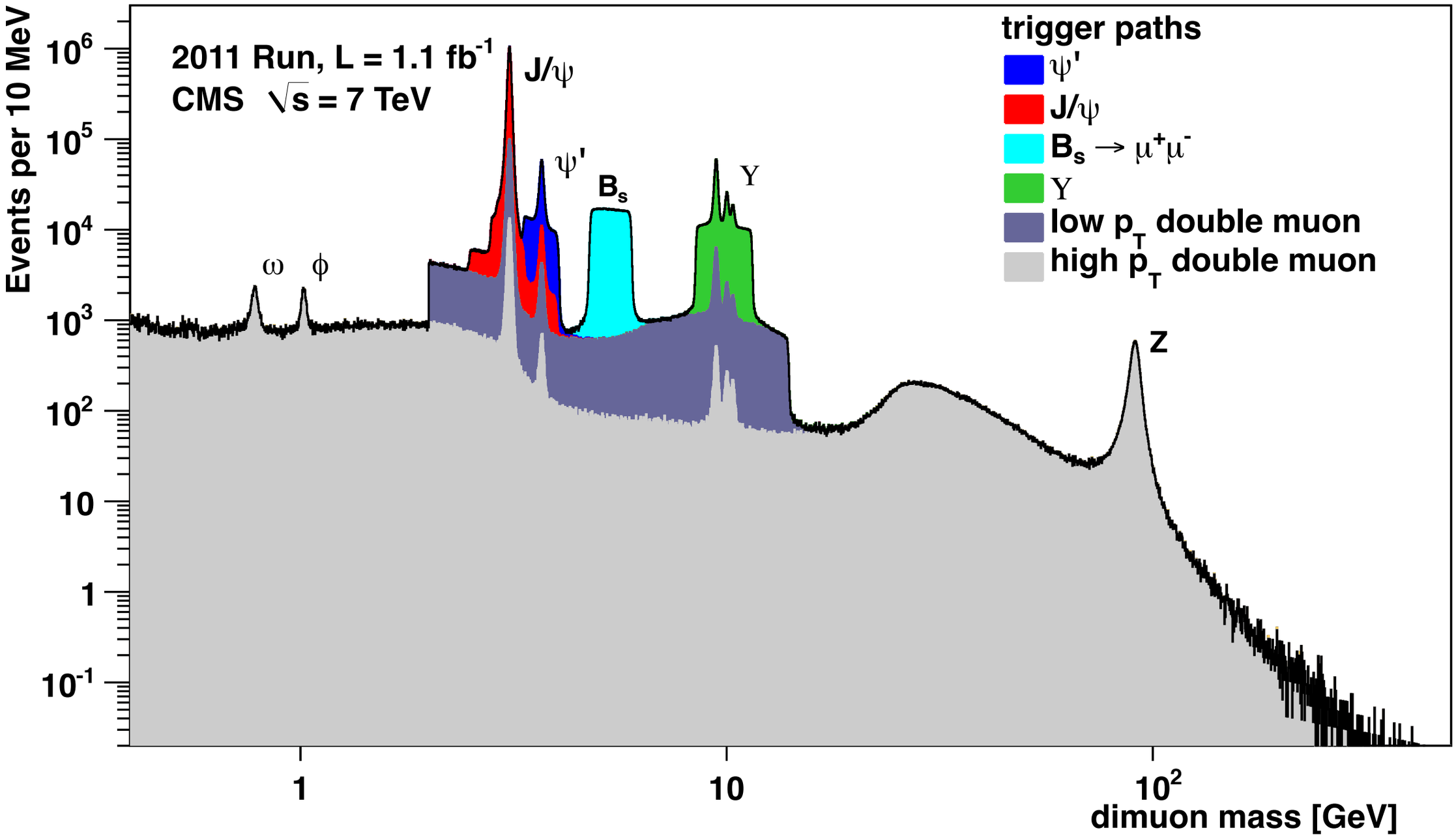
- per mass bin

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

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

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

Measured Di-muon Spectrum

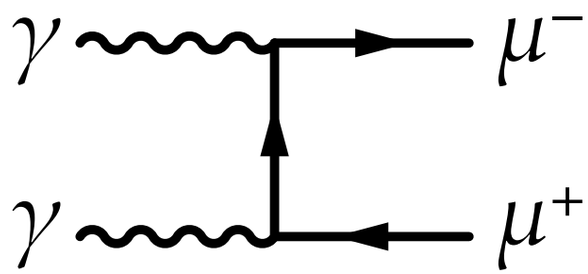


Prompt Search

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

- “bad” Background

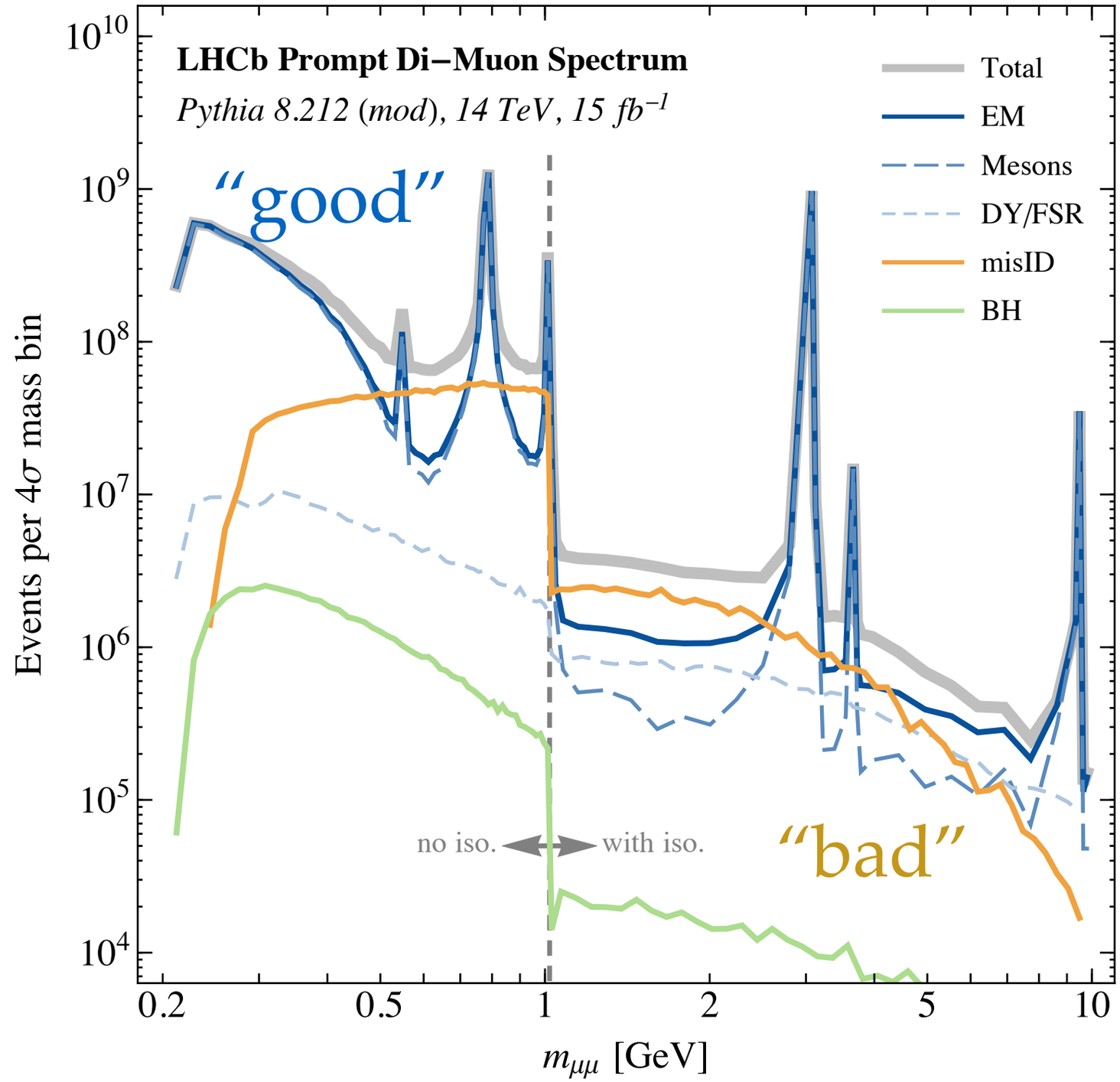
  - Beith-Heitler, subdominant, small photon PDF



  - 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:

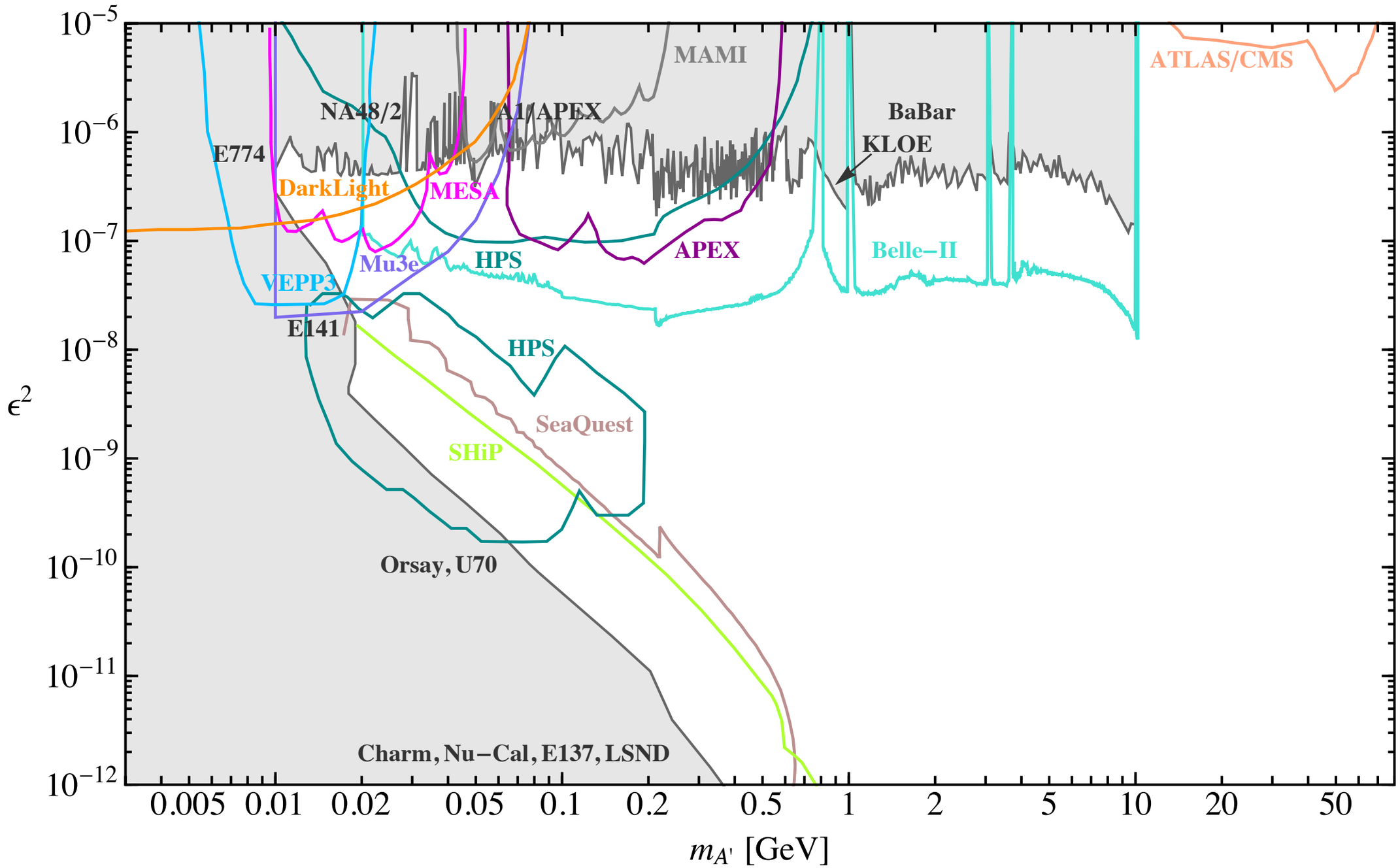
- $2<\eta(\mu^{\pm})<5$
- $p(\mu^{\pm})>10$GeV
- $p_T(\mu^{\pm})>0.5$GeV
- $p_T(A')>1.0$GeV
- μ isolation: $m_{A'}>m_{\phi}\sim 1$ GeV

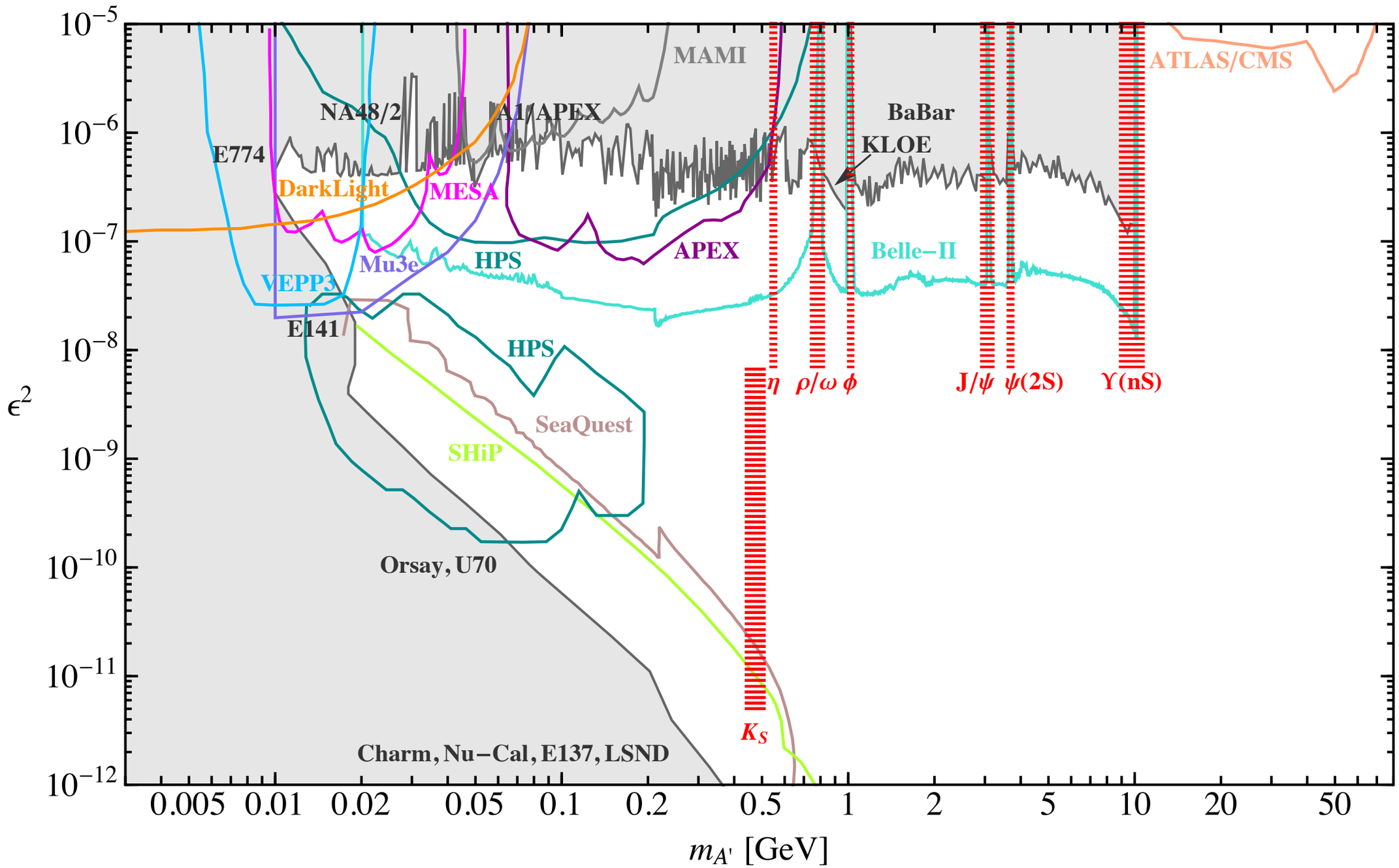


$$B_{\text{prompt}} = \underbrace{B_M + B_{\text{FSR}} + B_{\text{DY}}}_{B_{\text{EM}}} + \underbrace{B^{\pi\pi}_{\text{misID}} + B^{\pi\mu}_{\text{misID}}}_{B_{\text{misID}}}$$

"good" — scales as signal

"bad" — does not scale as signal


MAMI
ATLAS/CMS
NA48/2
A1/APEX
BaBar
KLOE
E774
DarkLight
MESA
APEX
Belle−II
Mu3e
HPS
VEPP3
E141
HPS
SeaQuest
SHiP
Orsay, U70
Charm, Nu−Cal, E137, LSND
ϵ^2
$m_{A'}$ [GeV]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HPS
η
ρ/ω
φ
J/ψ
ψ(2S)
ϒ(nS)
SeaQuest
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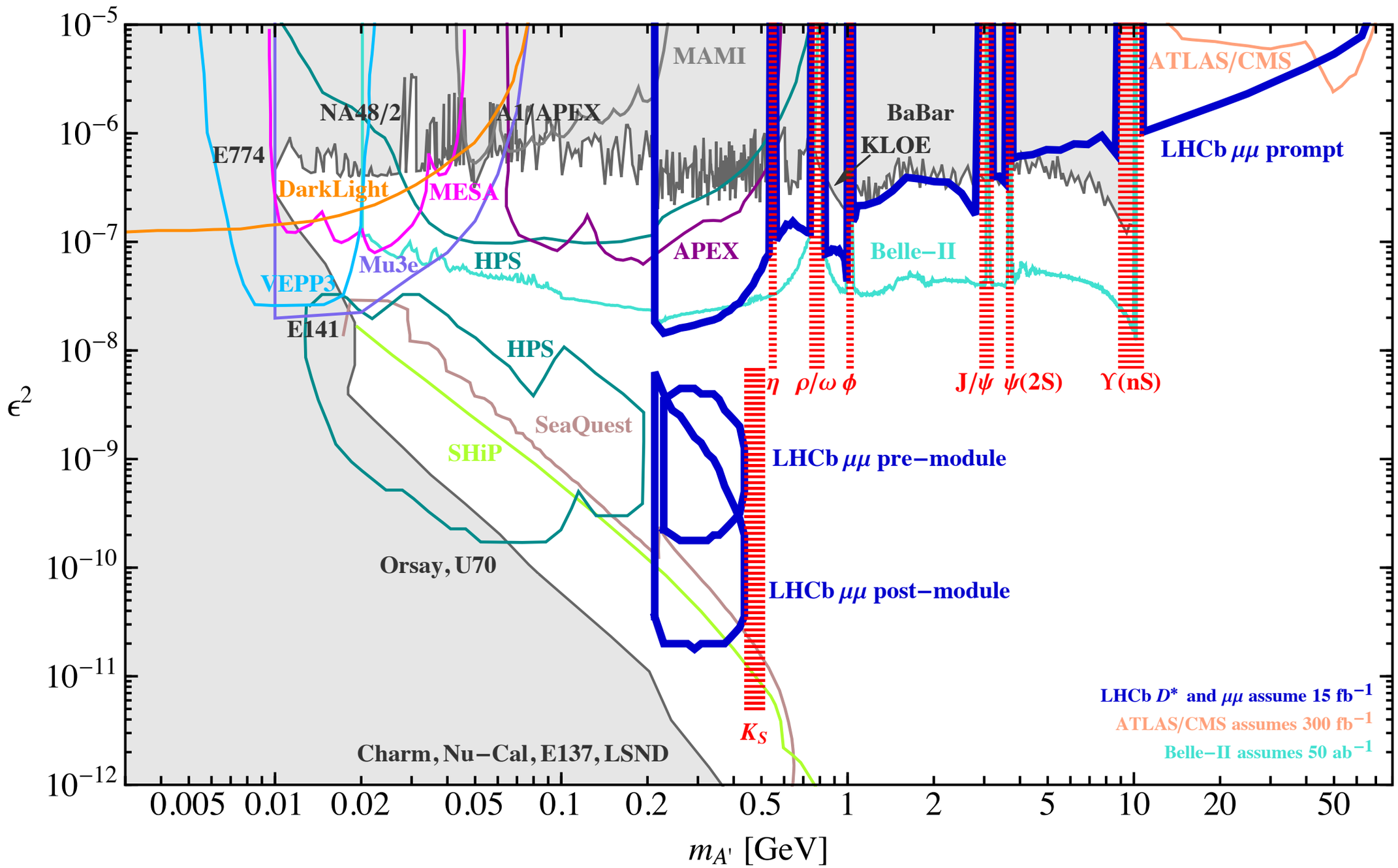
Orsay, U70
K_S
Charm, Nu−Cal, E137, LSND
ϵ^2
m_A' [GeV]


MAMI
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BaBar
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E774
LHCb μμ prompt
DarkLight
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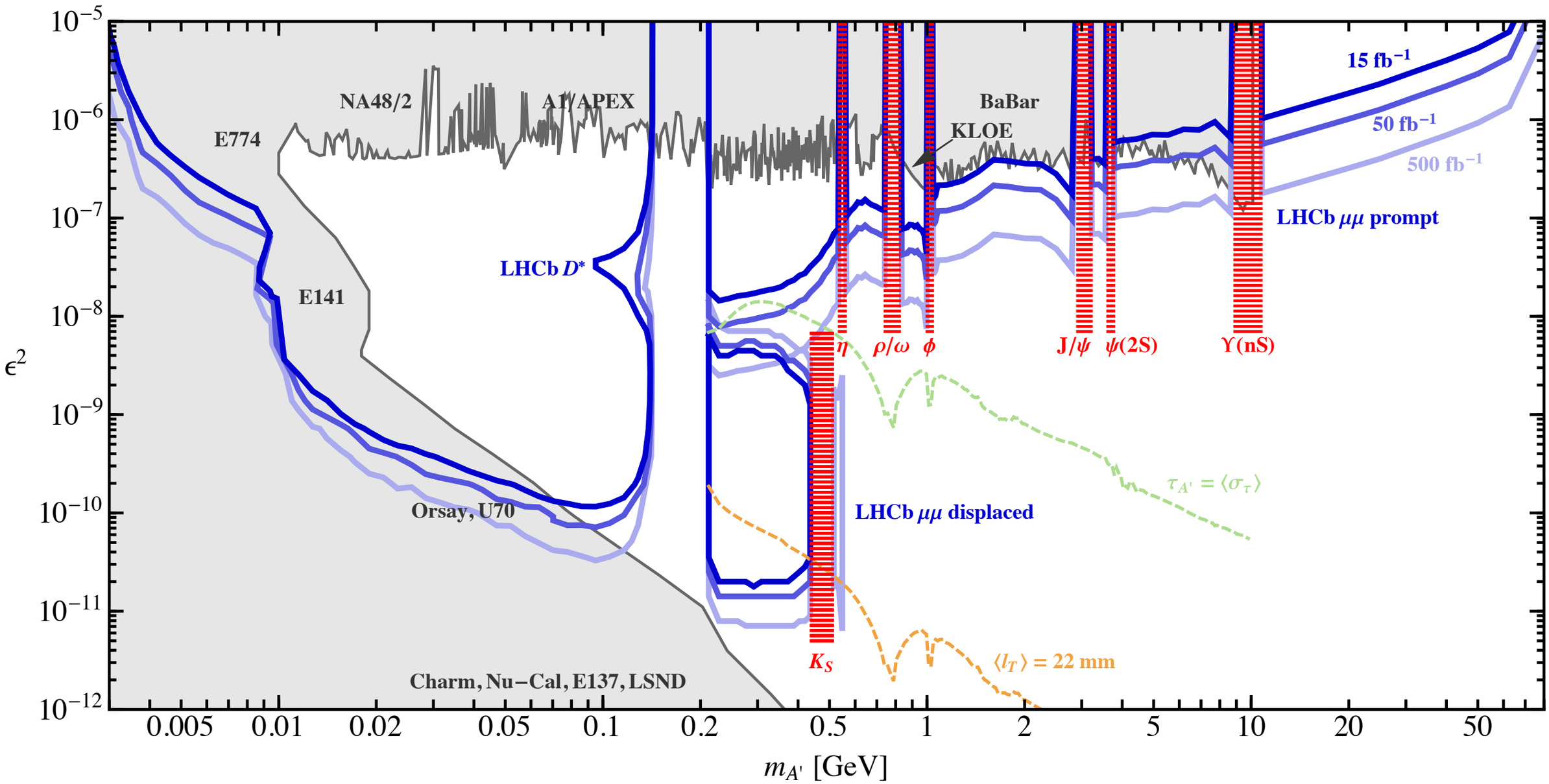
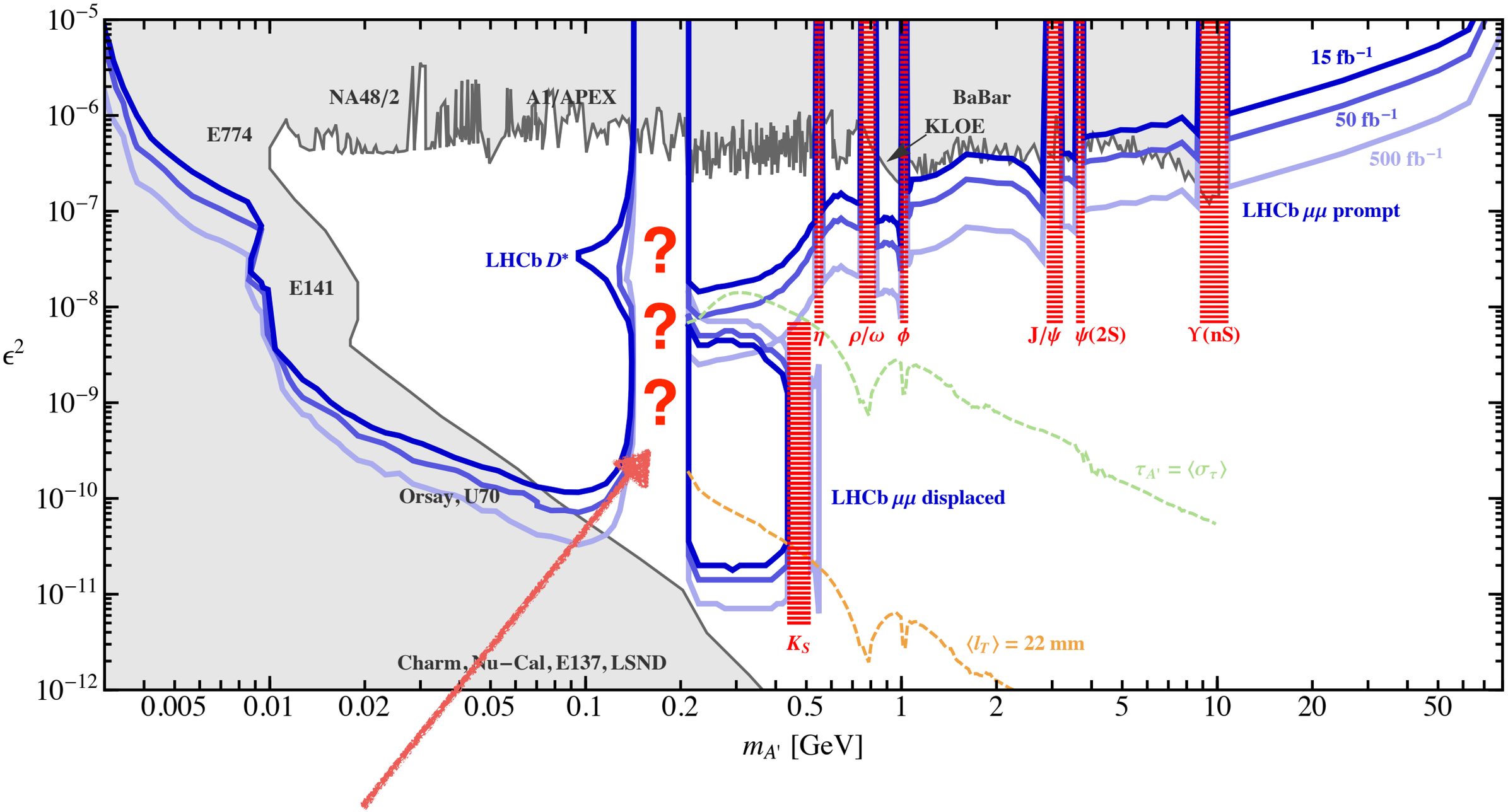
HPS
VEPP3
E141
HPS
η
ρ/ω
φ
J/ψ
ψ(2S)
Υ(nS)
SeaQuest
SHiP
LHCb μμ pre−module
Orsay, U70
LHCb μμ post−module
LHCb D* and μμ assume 15 fb−1
ATLAS/CMS assumes 300 fb−1
Belle−II assumes 50 ab−1
K_S
Charm, Nu−Cal, E137, LSND
ε²
m_A' [GeV]

Possible improvement




10^{-5}
10^{-6}
10^{-7}
10^{-8}
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10^{-11}
10^{-12}
ϵ^2
0.005
0.01
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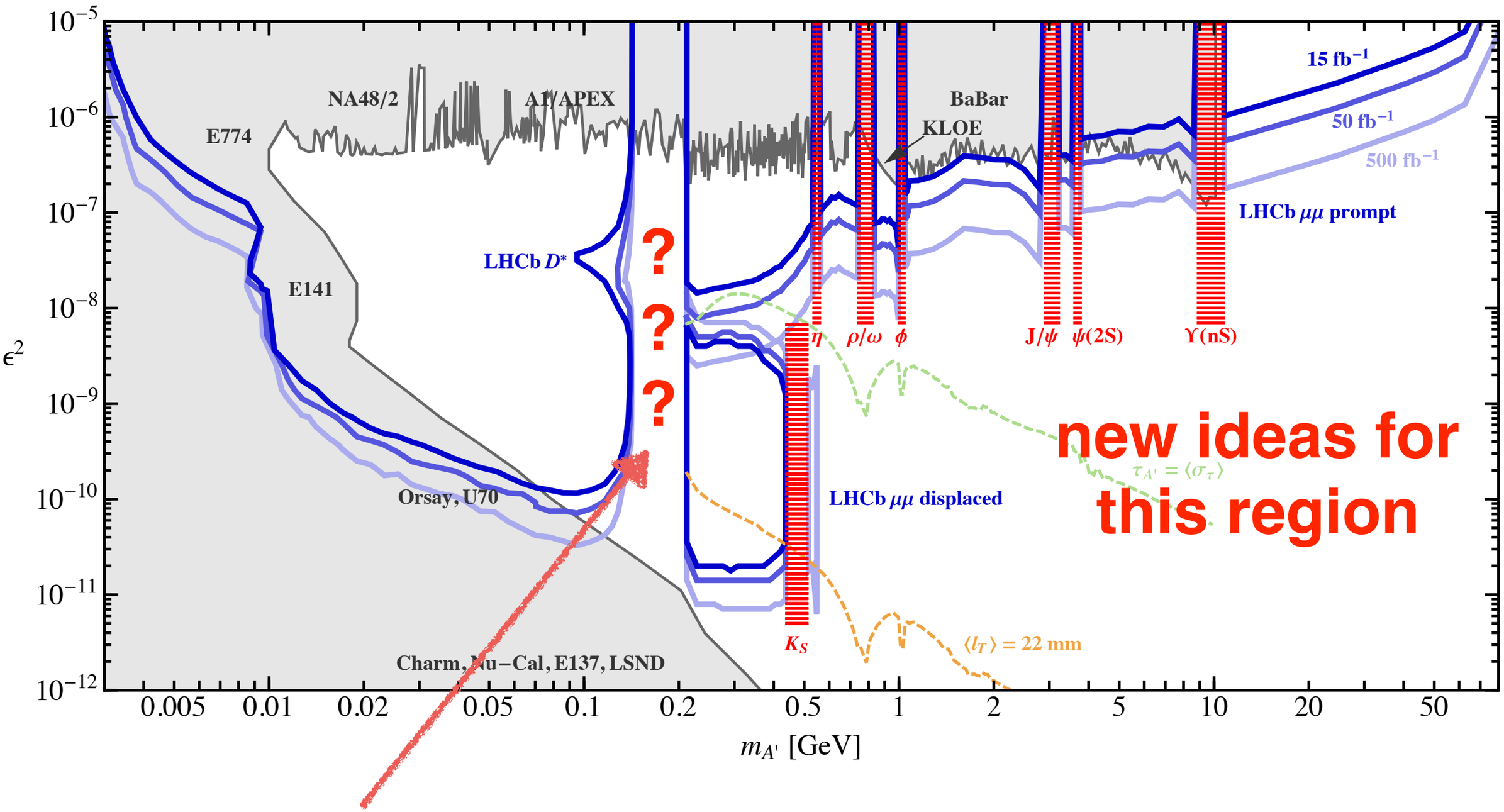
$m_{A'}$ [GeV]
E774
NA48/2
A1/APEX
BaBar
KLOE
E141
LHCb D^*
?
?
?
15 fb^{-1}
50 fb^{-1}
500 fb^{-1}
LHCb $\mu\mu$ prompt
η
ρ/ω
ϕ
J/ψ
ψ(2S)
Υ(nS)
$\tau_{A'} = \langle\sigma_\tau\rangle$
LHCb $\mu\mu$ displaced
K_S
$\langle l_T \rangle$ = 22 mm
Orsay, U70
Charm, Nu−Cal, E137, LSND

?η → A' + … ?


10^{-5}
10^{-6}
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10^{-10}
10^{-11}
10^{-12}
ϵ^2
E774
NA48/2
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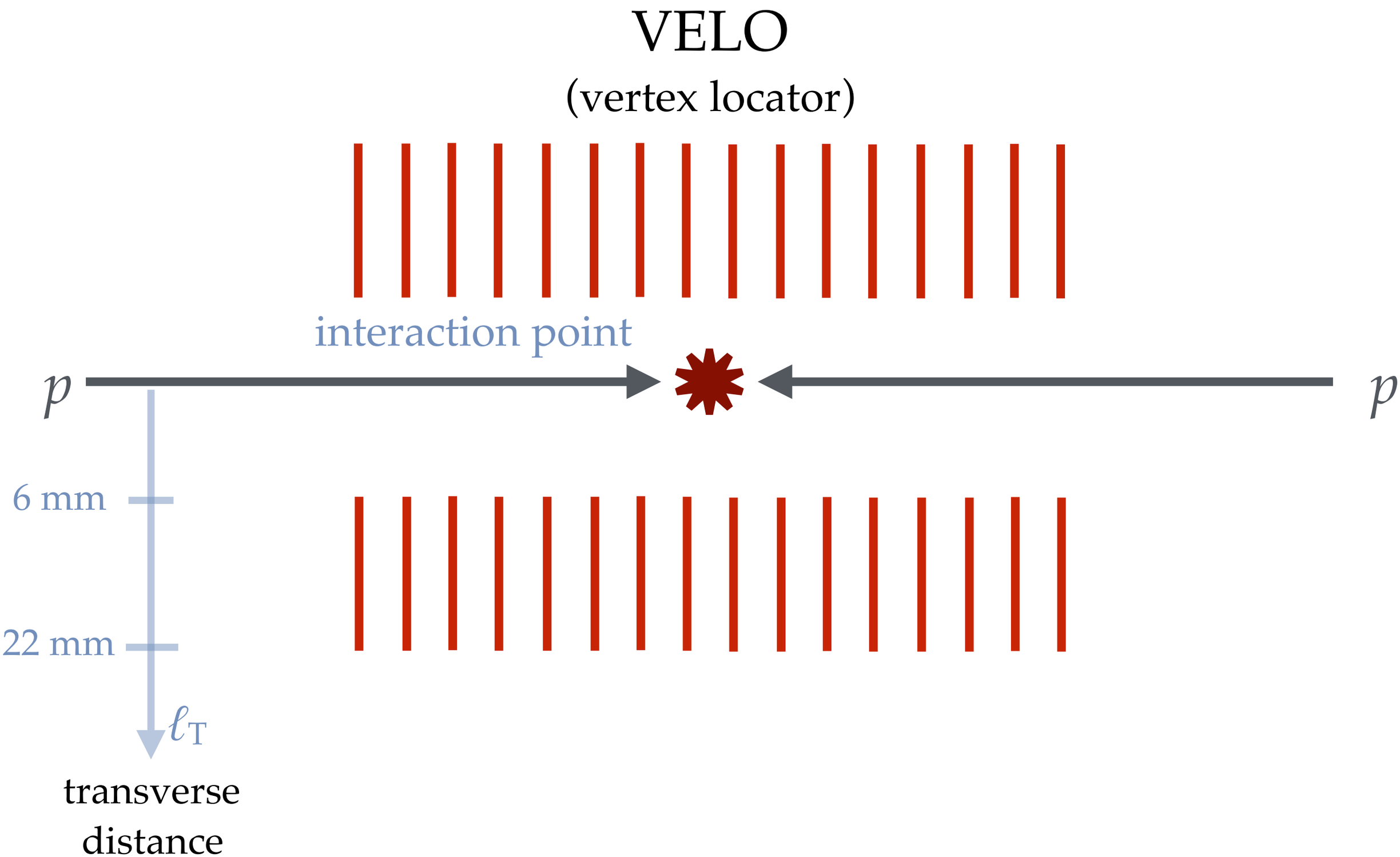
BaBar
KLOE
15 fb^{-1}
50 fb^{-1}
500 fb^{-1}
LHCb $\mu\mu$ prompt
LHCb D^*
E141
?
?
?
η
ρ/ω
ϕ
J/ψ
ψ(2S)
Υ(nS)
new ideas for this region
$\tau_{A'} = \langle\sigma_\tau\rangle$
LHCb $\mu\mu$ displaced
Orsay, U70
K_S
$\langle l_T \rangle$ = 22 mm
Charm, Nu−Cal, E137, LSND
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1
2
5
10
20
50
$m_{A'}$ [GeV]

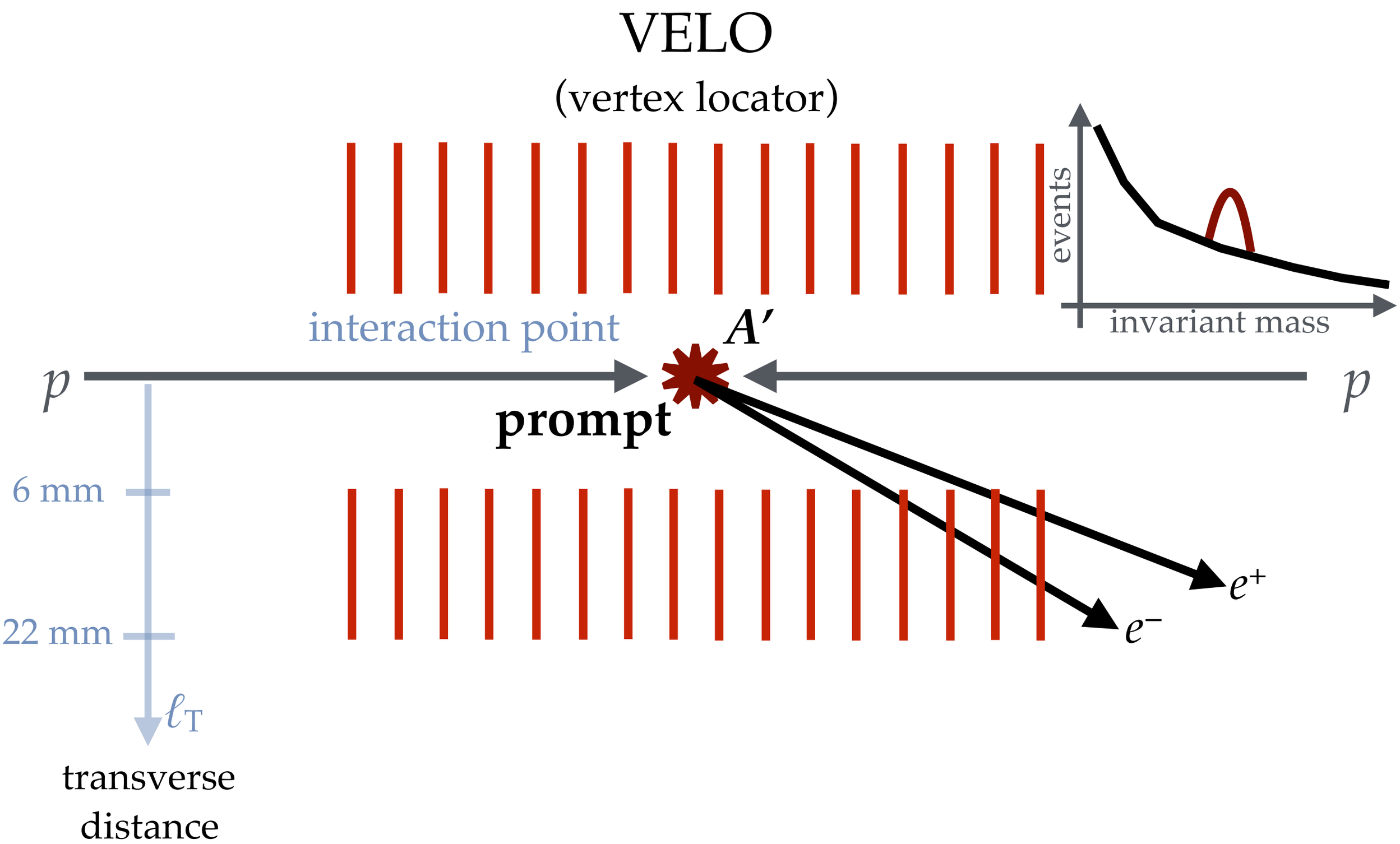
?η → A' + … ?

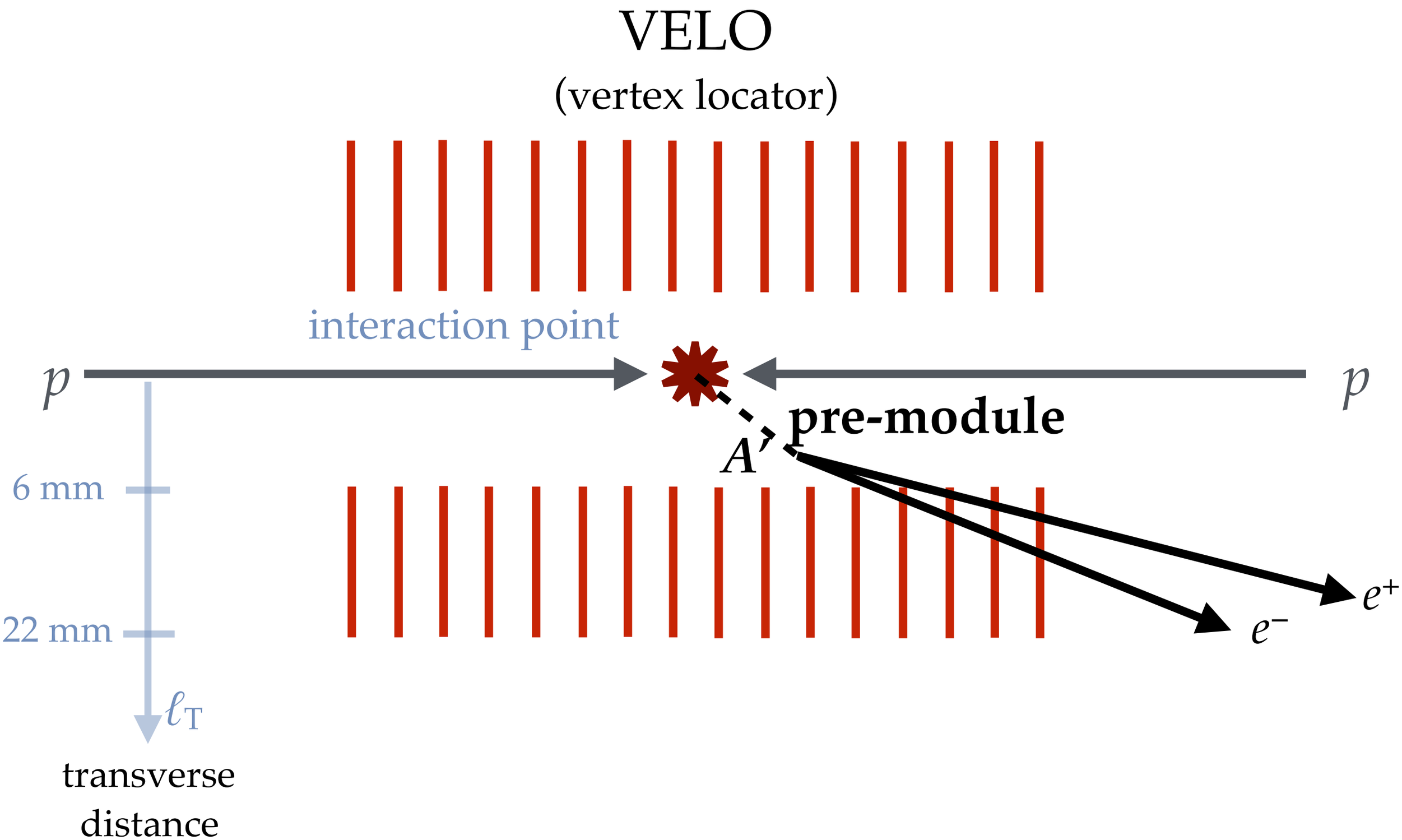
Conclusion

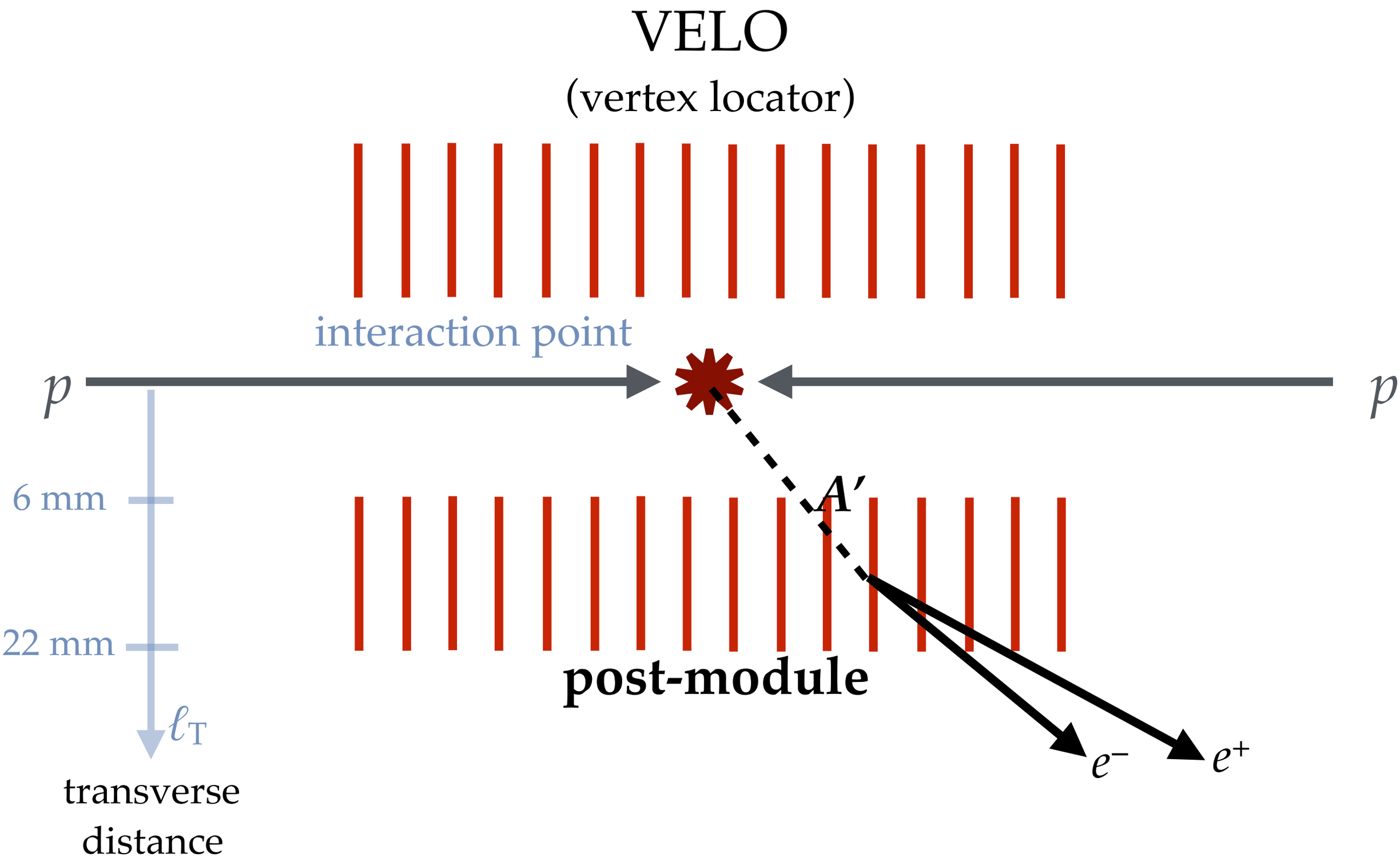
- VELO and triggerless readout
- dark photon search at LHCb
  - resonant search and displaced search
  - $D^{0*} \rightarrow D^0 + \gamma$ and inclusive search
  - the (di-muon) data-drive method can be applied to other experiments
  - explore the new territory with current or future collider. the next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

Backup Slides


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

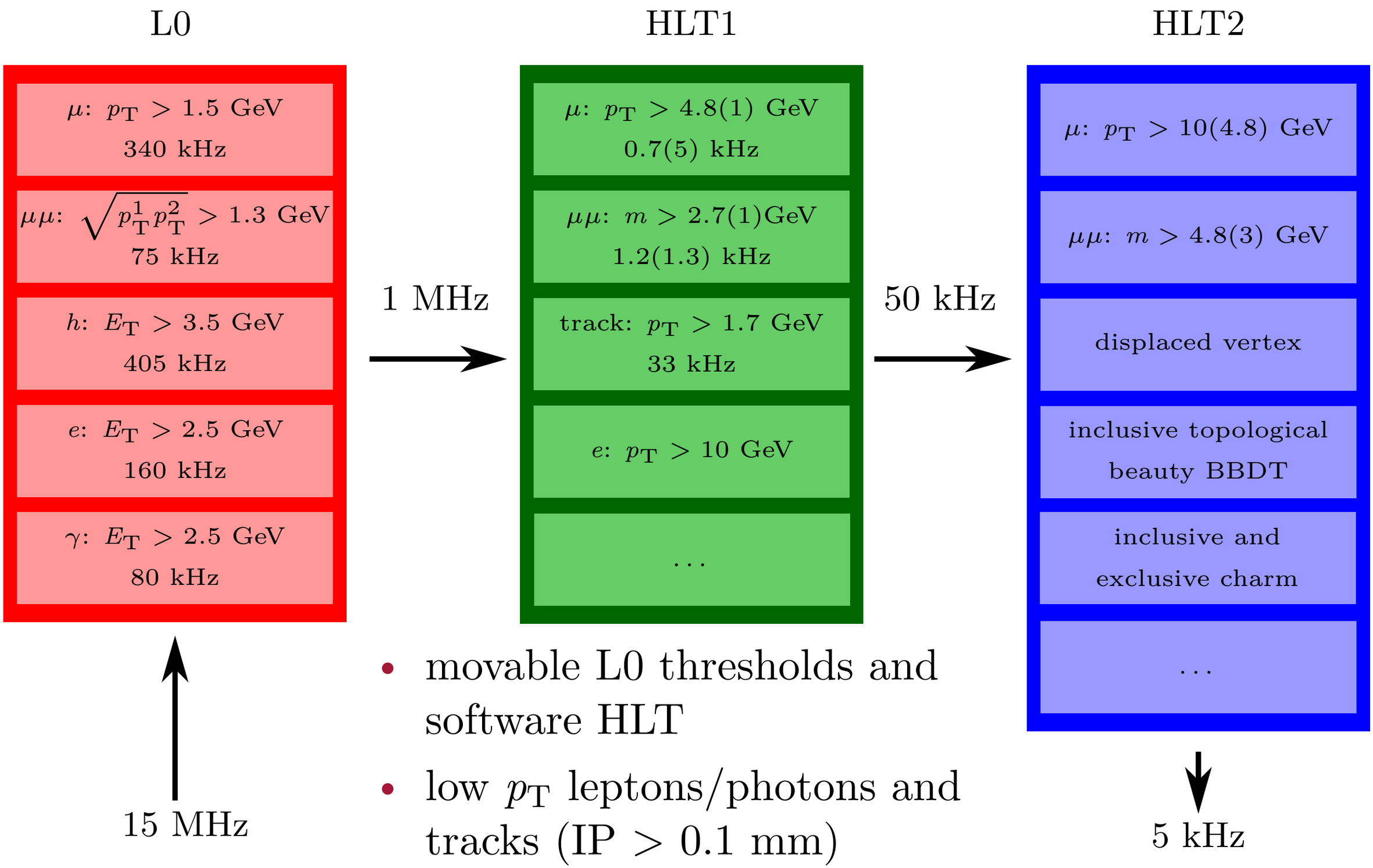

VELO
(vertex locator)
events
invariant mass
interaction point
A′
p
p
prompt
6 mm
22 mm
ℓ_T
transverse
distance
e^+
e^-


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


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

LHCb Trigger

[JINST 8 (2013) P04022]



- movable L0 thresholds and software HLT
- low p_T leptons/photons and tracks (IP > 0.1 mm)

Why LHCb 1)

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