

# Dark Photon Searches @ LHCb

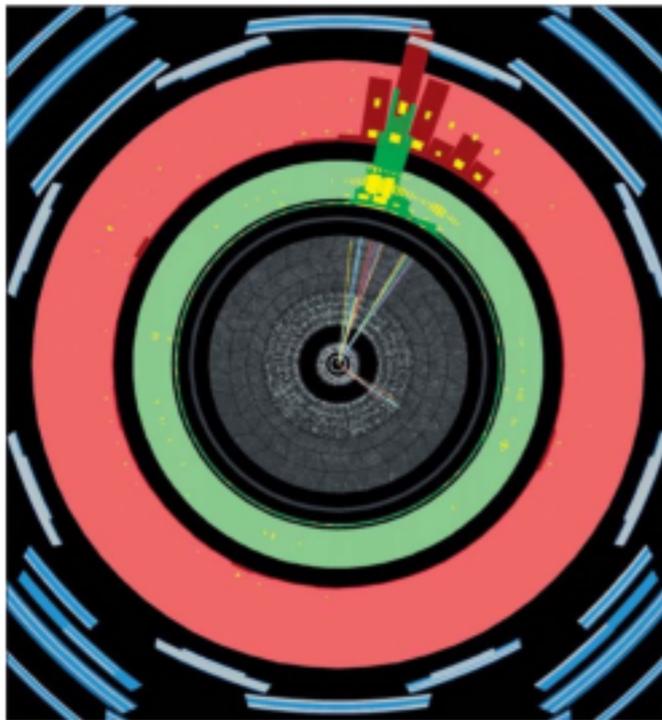
**Wei Xue**



May 9  
Pheno 2016

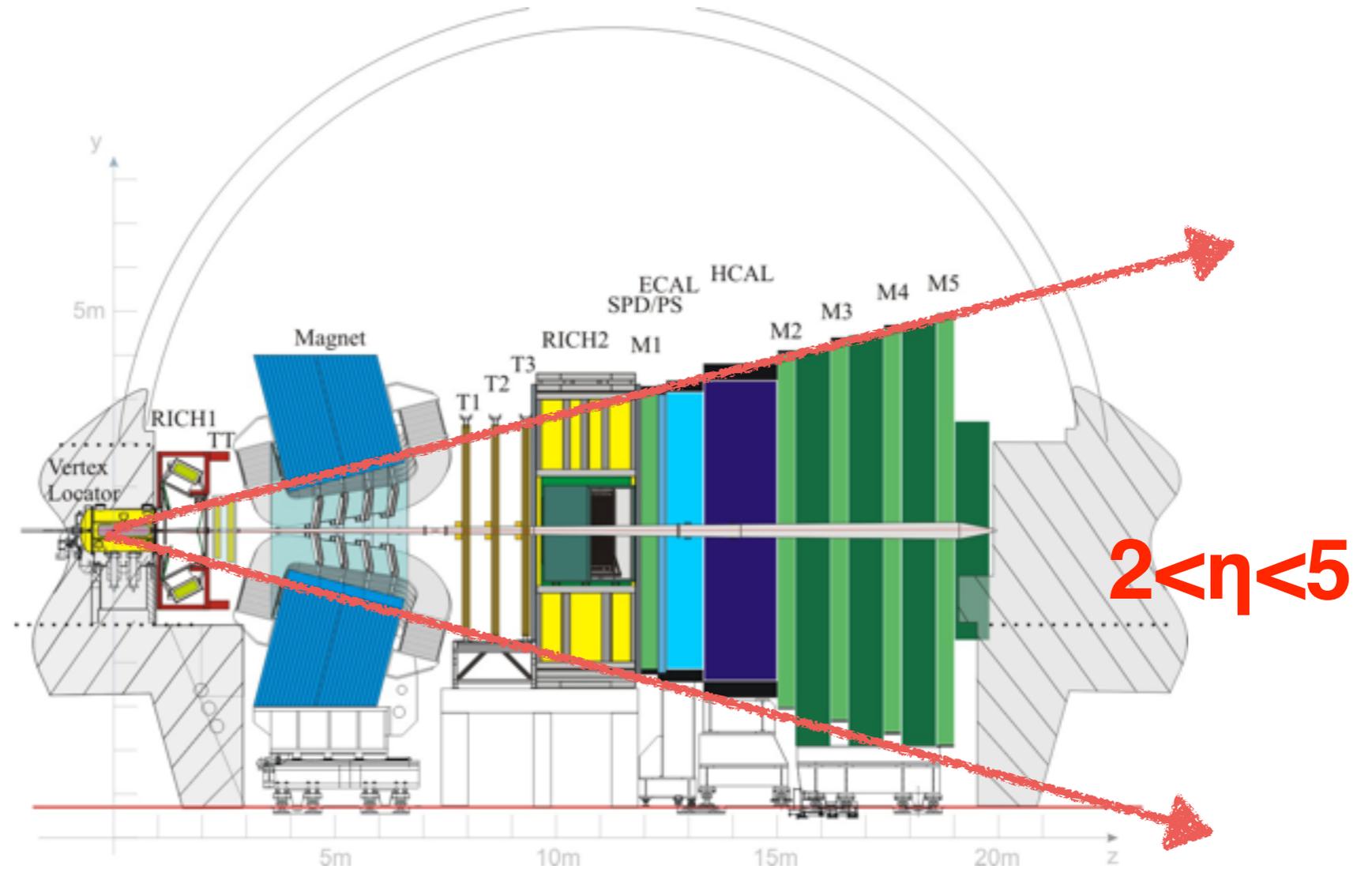
# Dark Matter Search

## Why not LHCb?



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

ATLAS/  
CMS



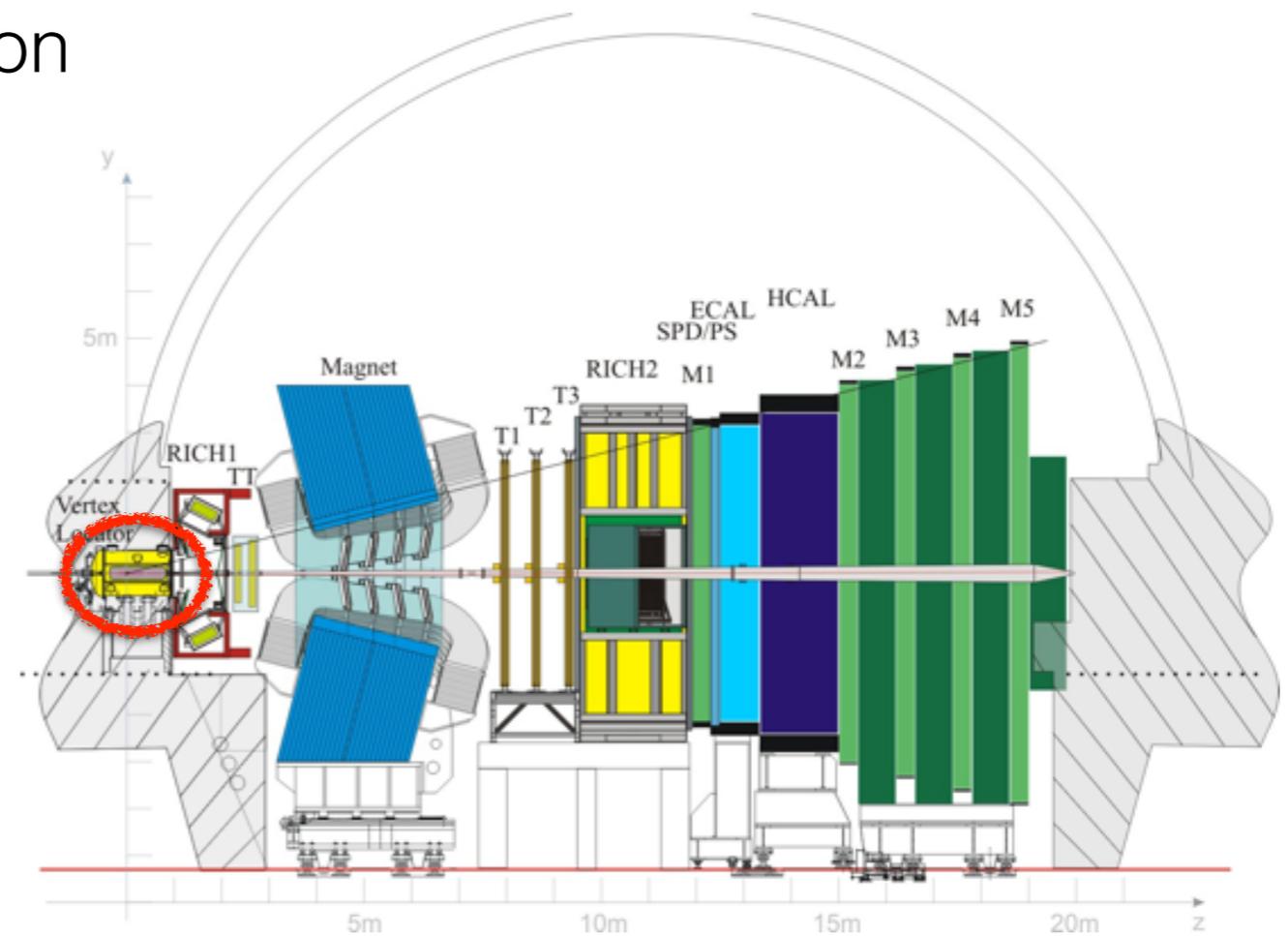
LHCb

# Outline

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

# Why LHCb 1)

- no pile-up
- good vertexing :VELO detector (10  $\mu\text{m}$ )
- good invariant mass resolution

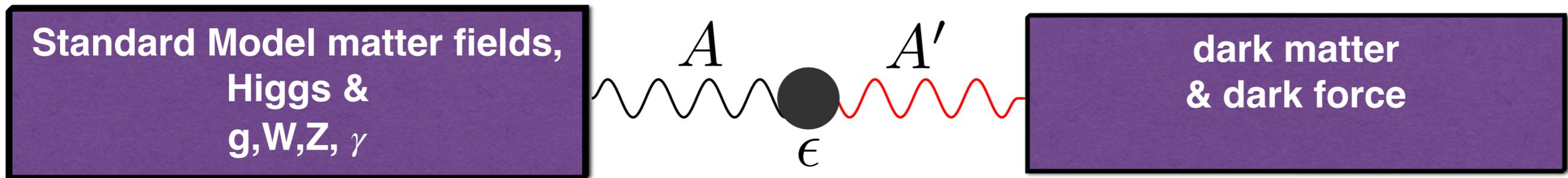


# Why LHCb 2)

- 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

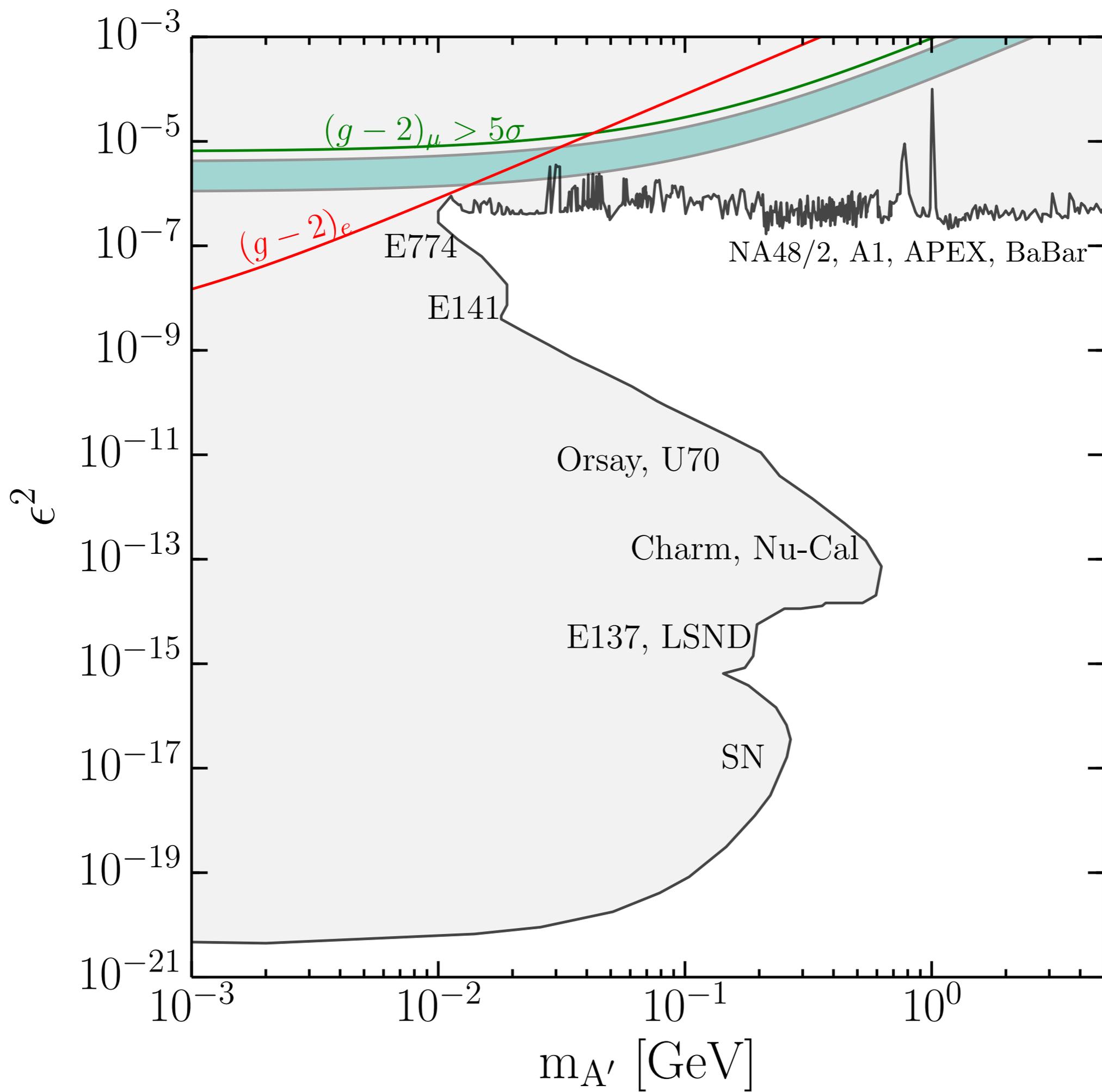


$$\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

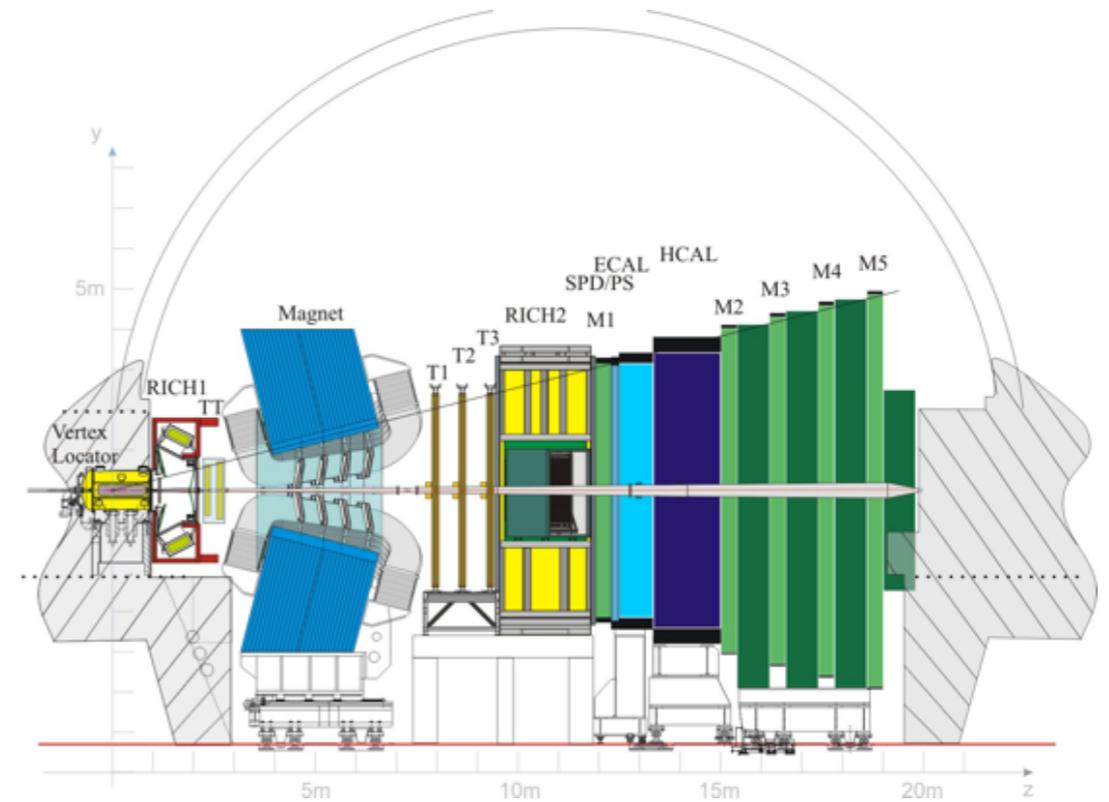
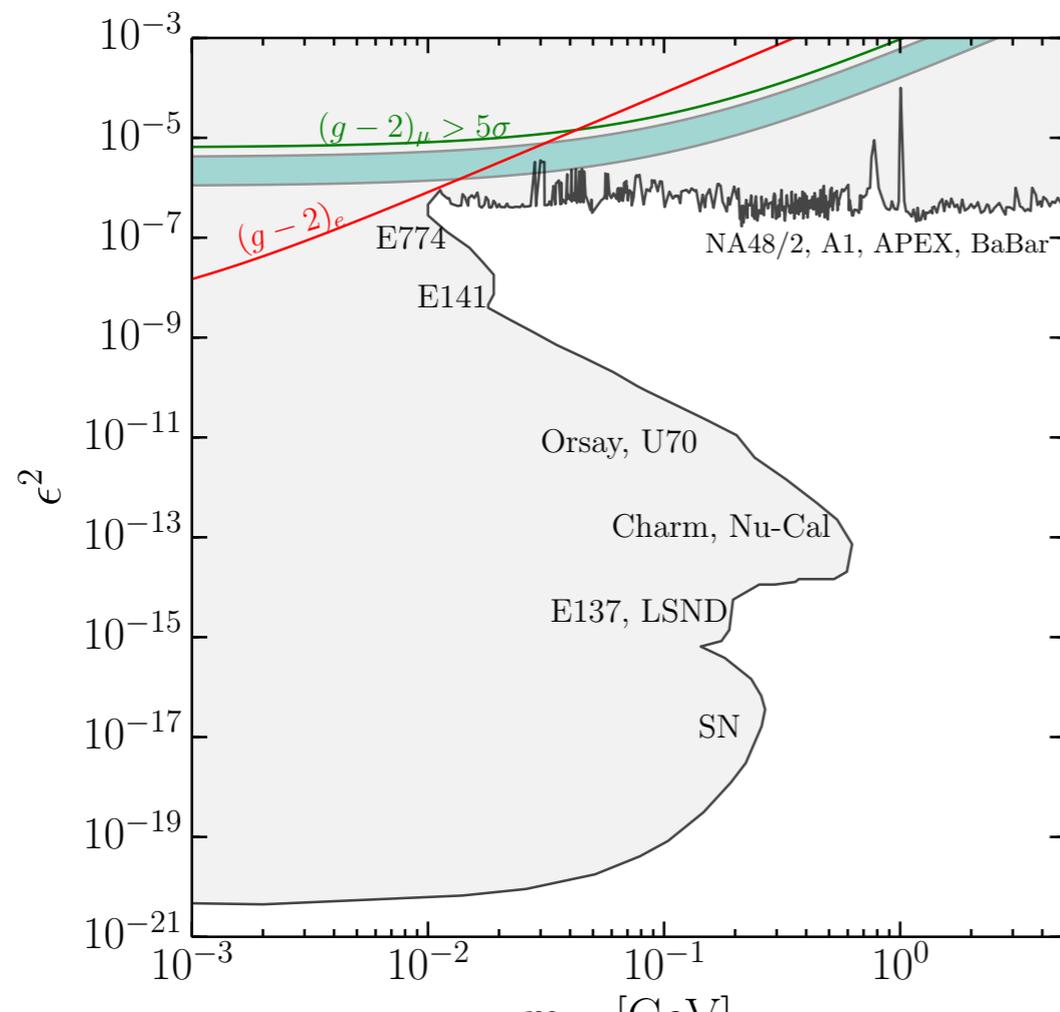
- effective Lagrangian

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

- focusing : mass range of  $m_{A'}$  (  $\epsilon$  MeV - 10 GeV )  
 $\epsilon \sim 10^{-3}, 10^{-6}$

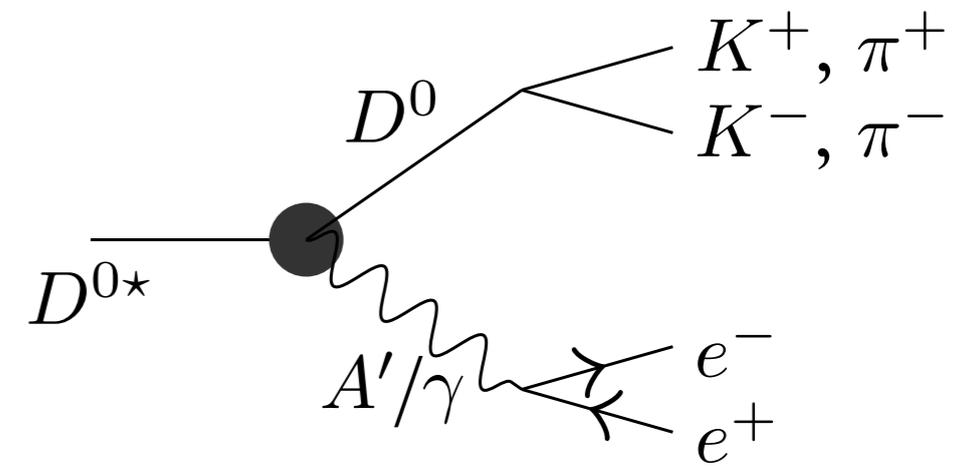


# LHCb searches



# Very Promising Channel: Charm Meson

- decay to photon ( dark photon )
  - Large Branching ratio  
(phase space suppression of  $D^{*0} \rightarrow D^0 \pi^0$ )
  - 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.

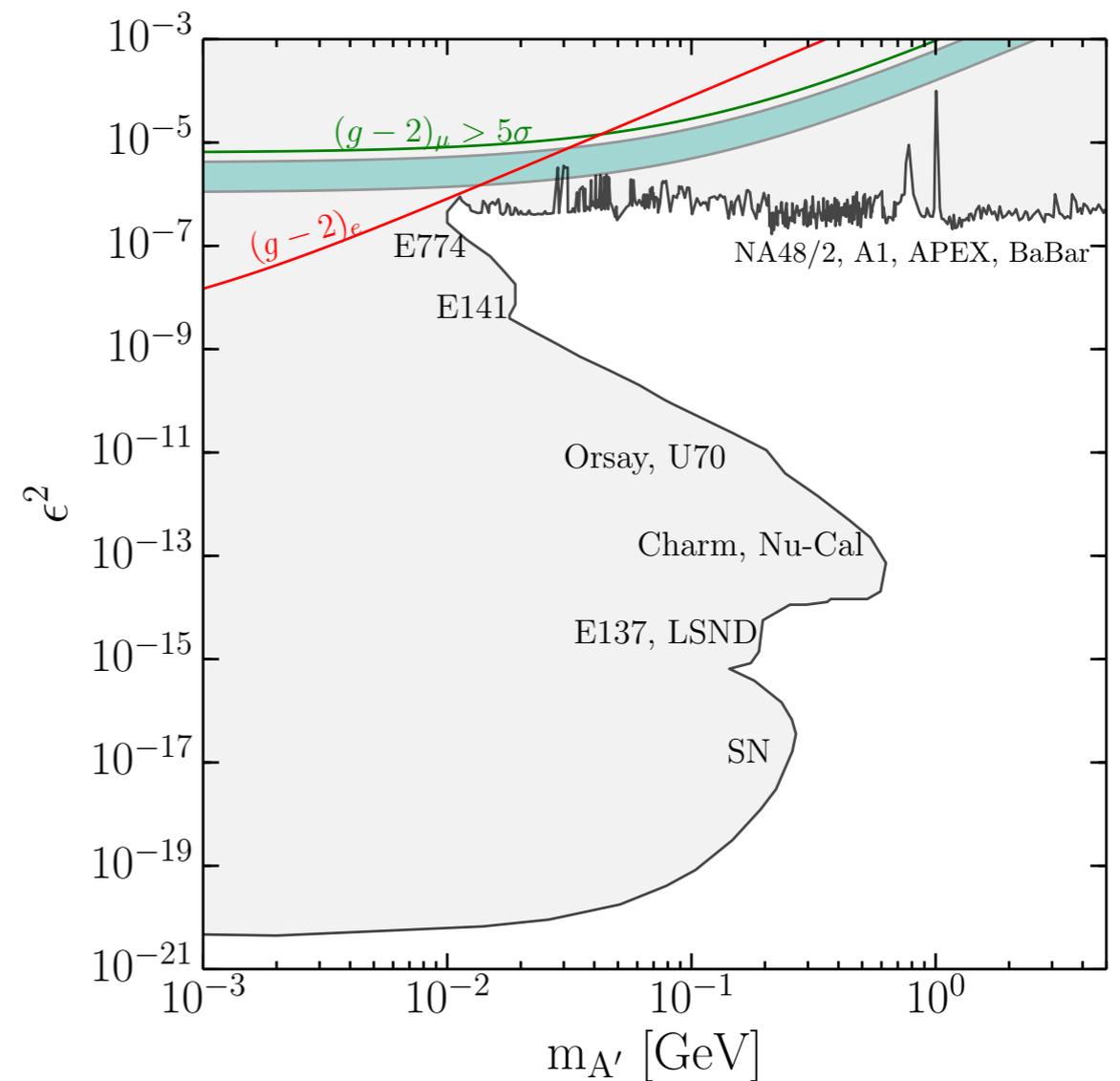
Mass  $m = 2006.96 \pm 0.10$  MeV  
 $m_{D^{*0}} - m_{D^0} = 142.12 \pm 0.07$  MeV  
 Full width  $\Gamma < 2.1$  MeV, CL = 90%

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

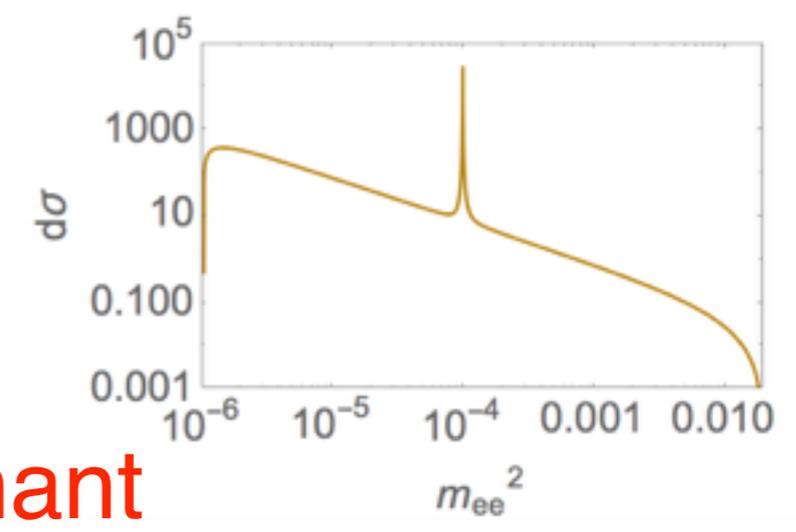
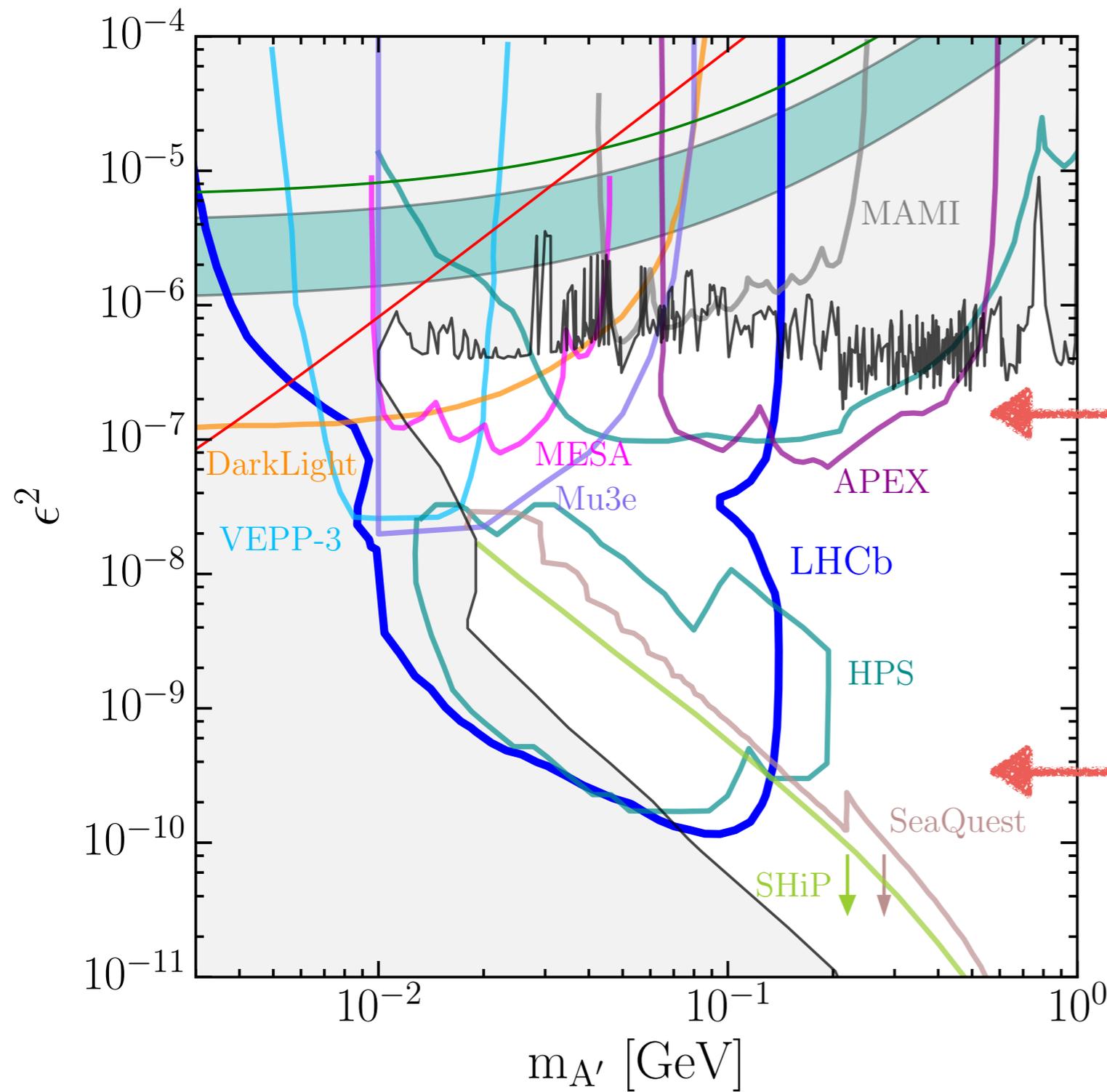
| <b><math>D^*(2007)^0</math> DECAY MODES</b> | Fraction ( $\Gamma_i/\Gamma$ ) | $p$ (MeV/c) |
|---|--------------------------------|-------------|
| $D^0 \pi^0$                                 | $(61.9 \pm 2.9) \%$            | 43          |
| $D^0 \gamma$                                | $(38.1 \pm 2.9) \%$            | 137         |

# D\*0 Production

- How many  $D^{0*}$  in LHCb Run3 (15 fb<sup>-1</sup>)?  
 $\sim 5 \times 10^{12}$  (pythia simulation)
- How many  $\pi^0$  in NA48/2 ?  $\sim 10^{10}$



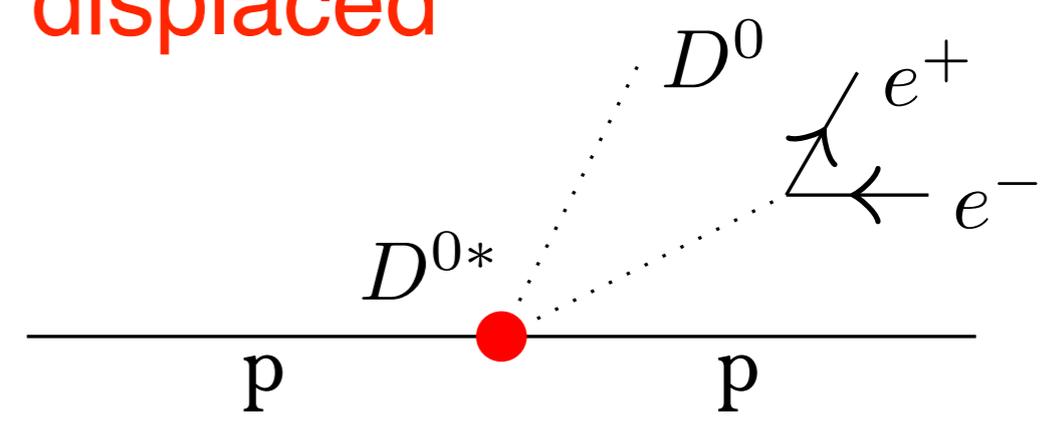
# Comparison to Other Experiments

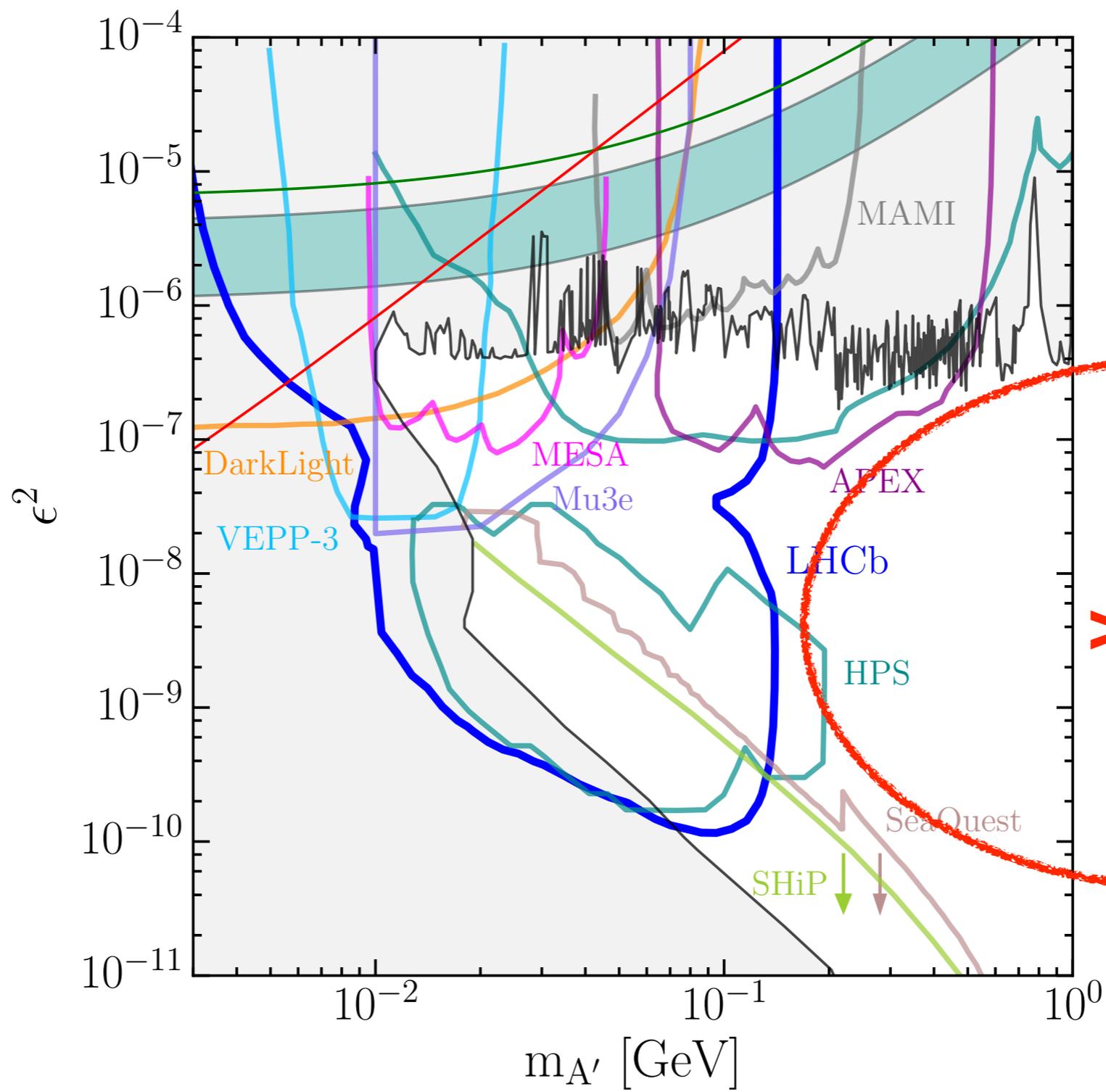


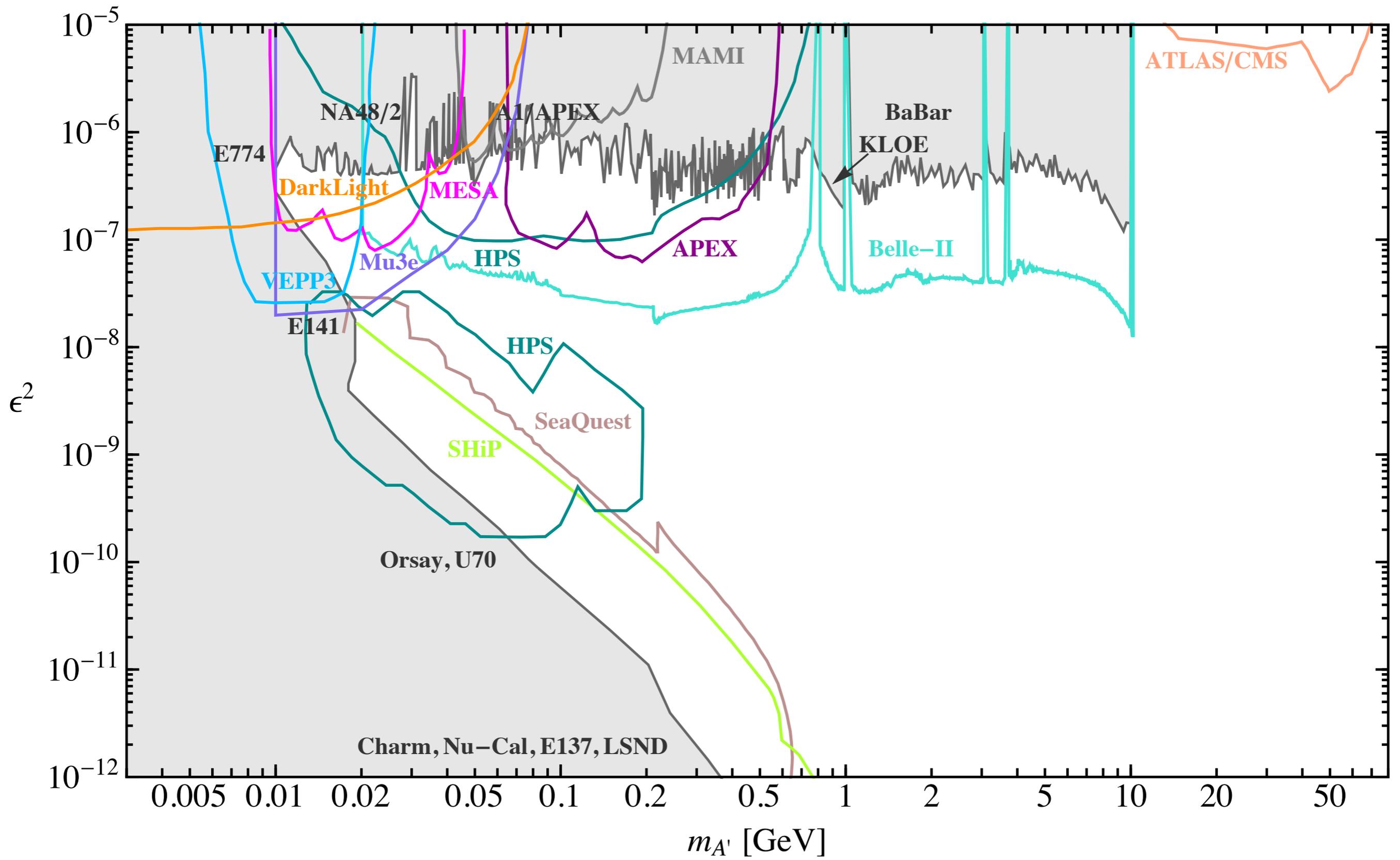
← resonant

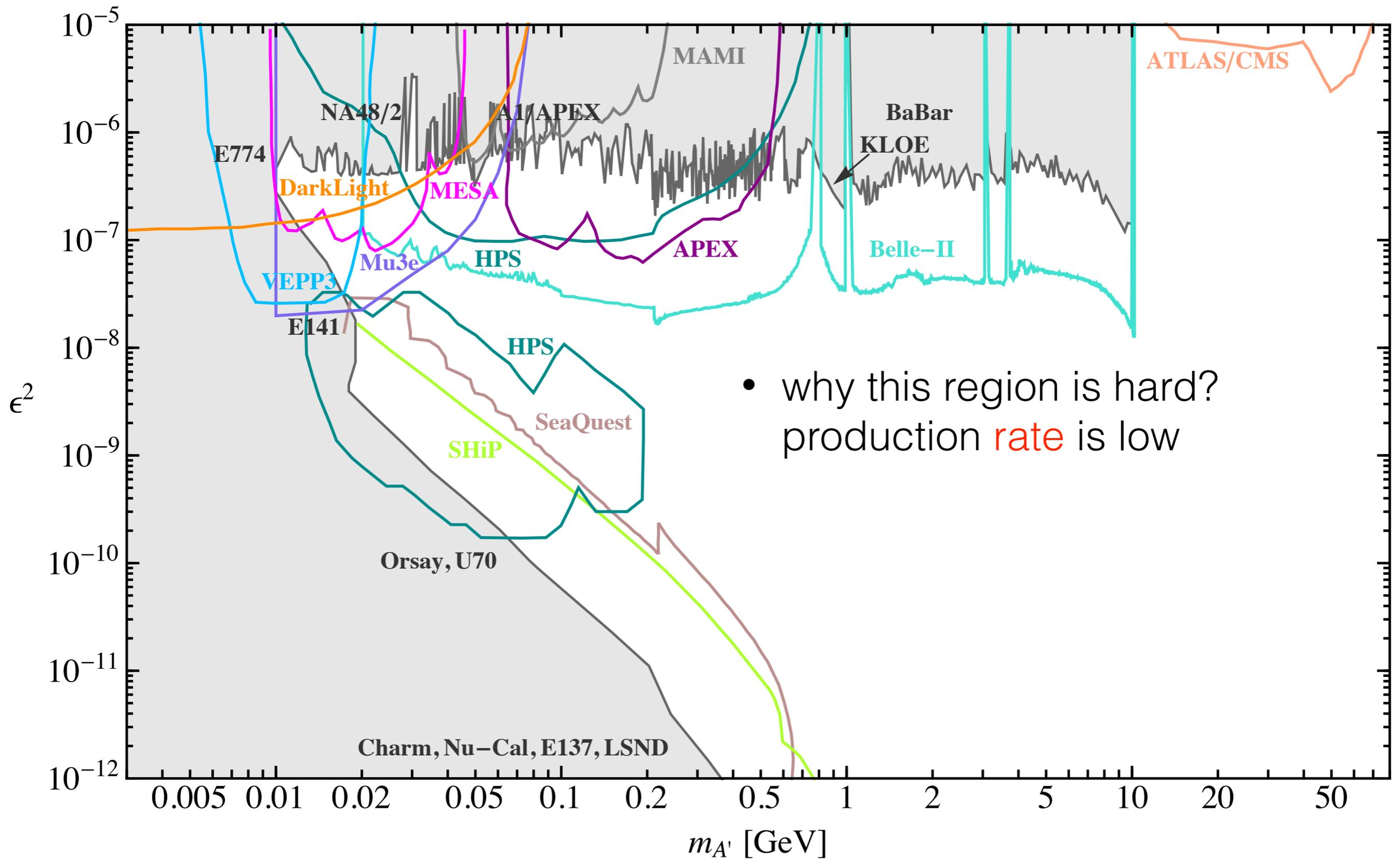
$$5\sigma_{\ell T} < \ell_T < 22 \text{ mm}$$

← displaced



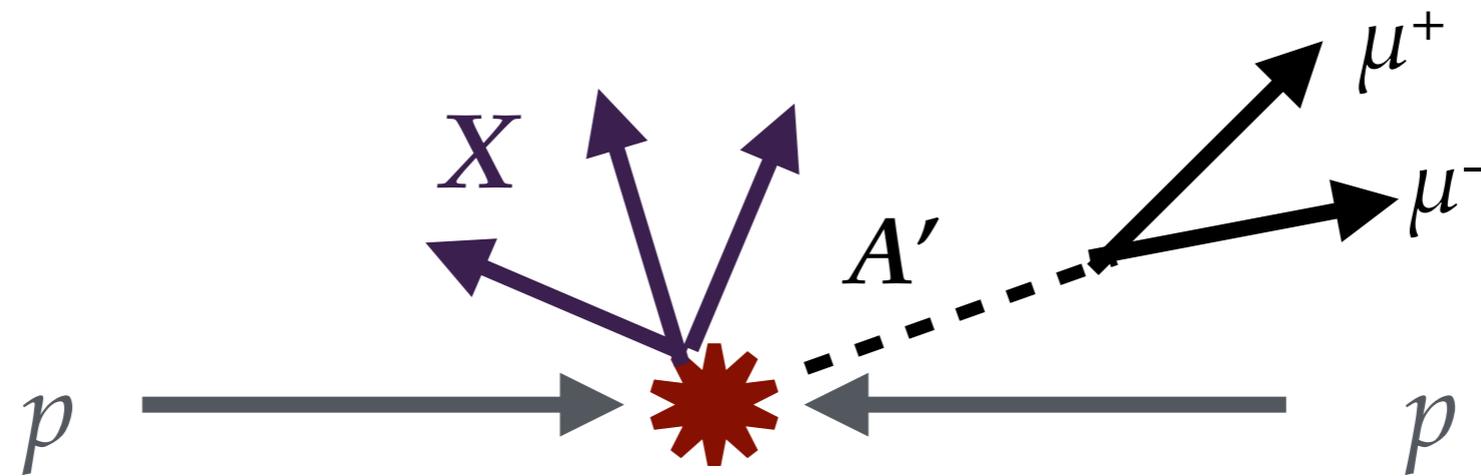




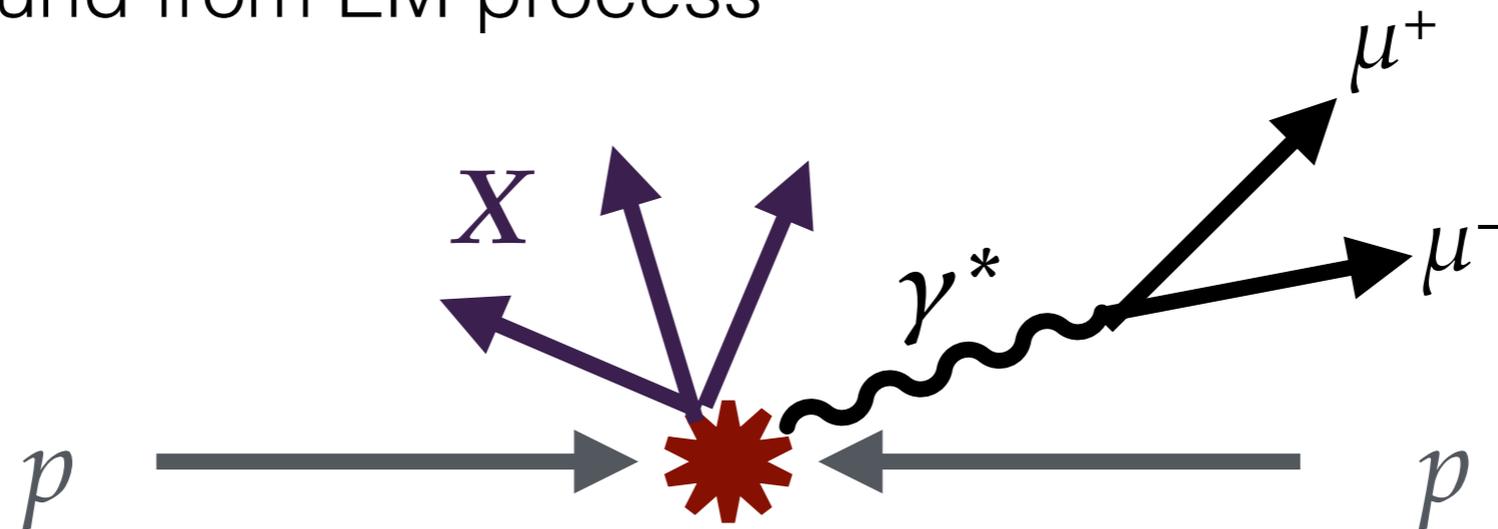


# inclusive dimuon search

- dark photon mix with photon and also vector mesons



- Background from EM process



# Background and Signal Rate

- amplitude generating dark photon

$$i\mathcal{M}_{X \rightarrow Y A'} = i\epsilon e \langle Y | J_{\text{EM}}^\mu | X \rangle \epsilon(k)_\mu$$

- amplitude generating off-shell photon

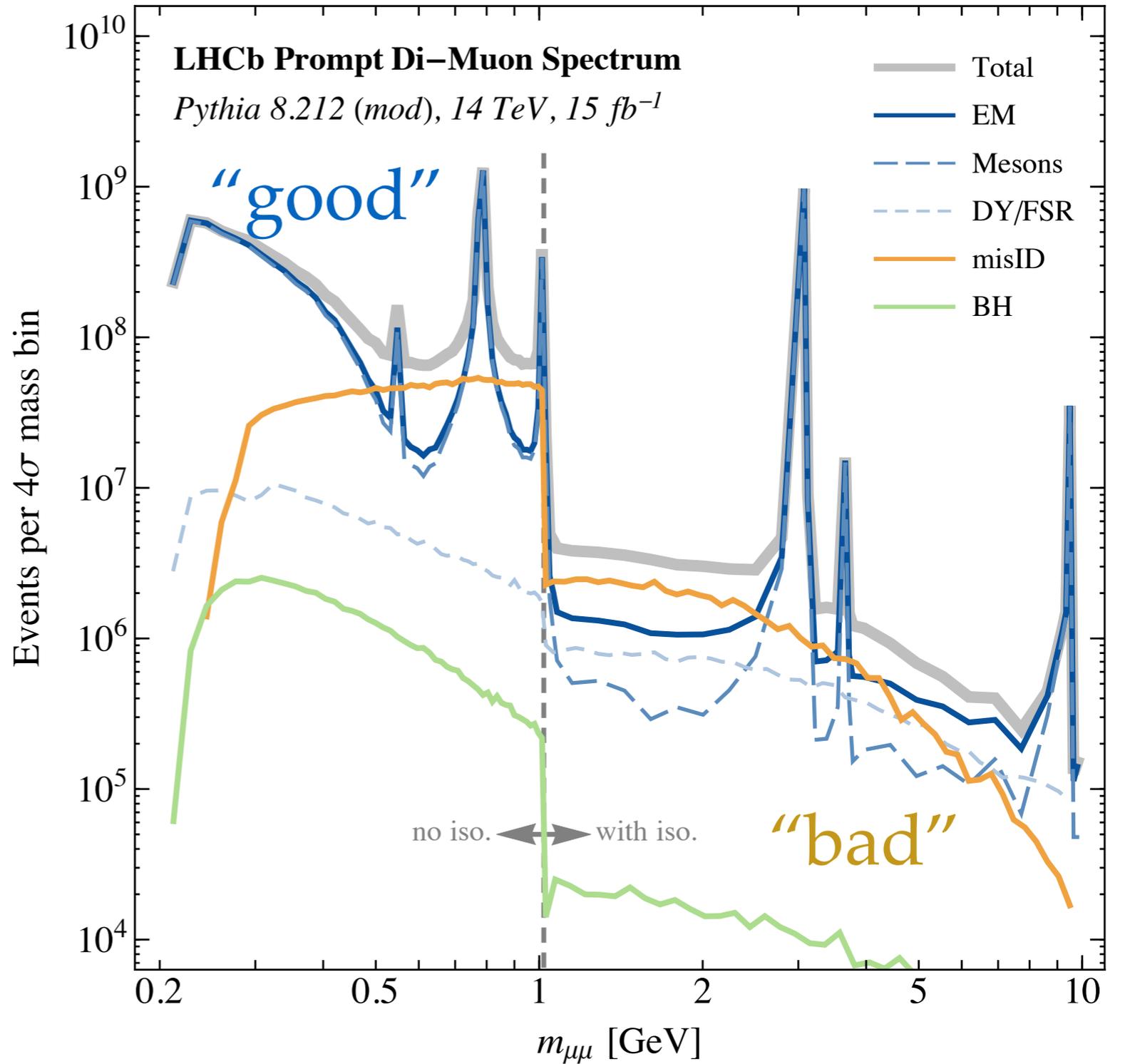
$$i\mathcal{M}_{X \rightarrow Y \ell^+ \ell^-} = i e^2 \langle Y | J_{\text{EM}}^\mu | X \rangle \frac{-i g_{\mu\nu}}{(k_1 + k_2)^2} \bar{u}(k_1) \gamma^\nu v(k_2)$$

- ratio ( form factor are cancelled )

$$\frac{d\sigma_{pp \rightarrow X A' \rightarrow X \mu^+ \mu^-}}{d\sigma_{pp \rightarrow X \gamma^* \rightarrow X \mu^+ \mu^-}} = \epsilon^4 \frac{m_{\mu\mu}^4}{(m_{\mu\mu}^2 - m_{A'}^2)^2 + \Gamma_{A'}^2 m_{A'}^2}$$

selections:

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



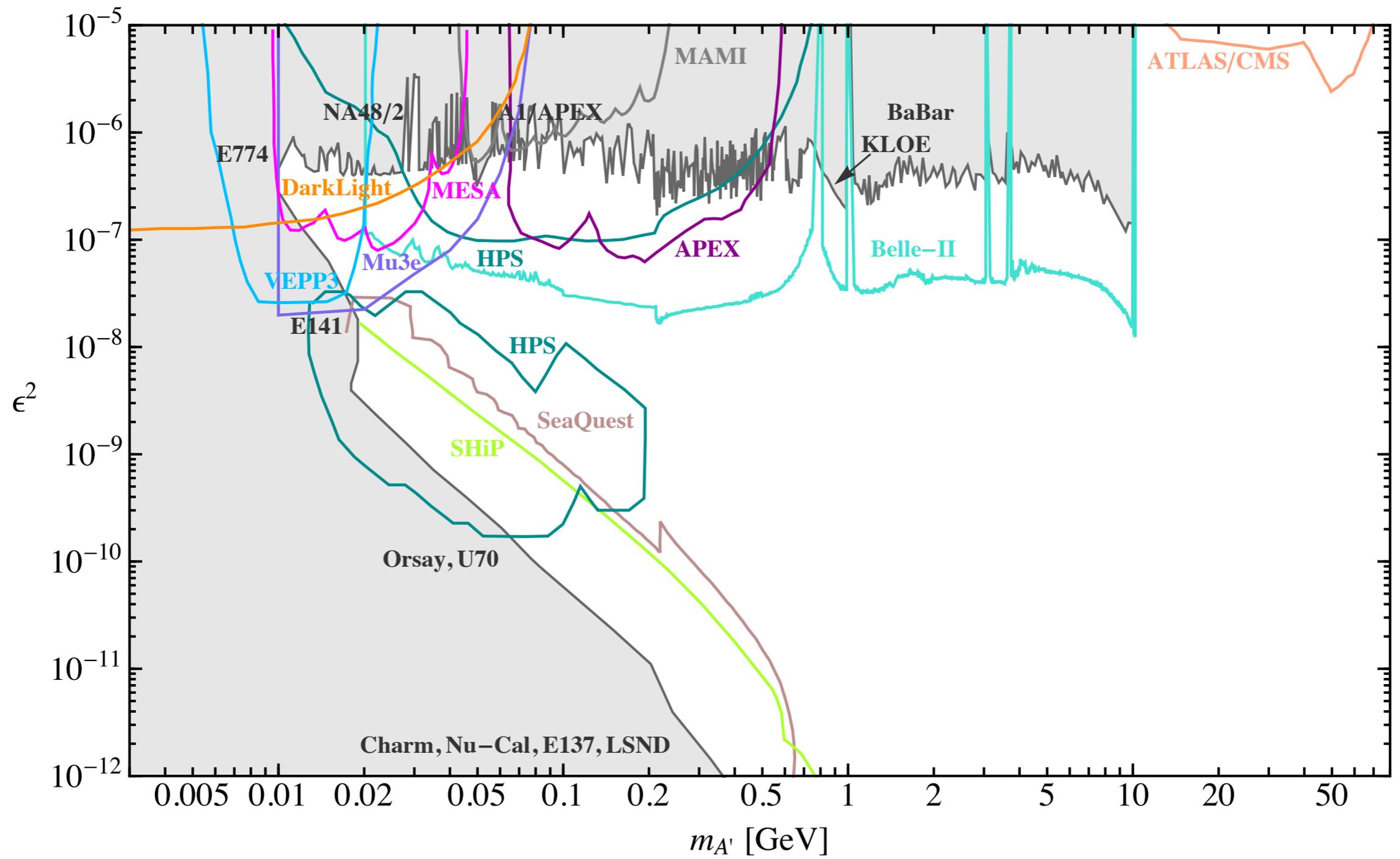
$$B_{\text{prompt}} = \underbrace{B_M + B_{\text{FSR}} + B_{\text{DY}}}_{B_{\text{EM}}} + \underbrace{B_{\text{misID}}^{\pi\pi} + B_{\text{misID}}^{\pi\mu}}_{B_{\text{misID}}}$$

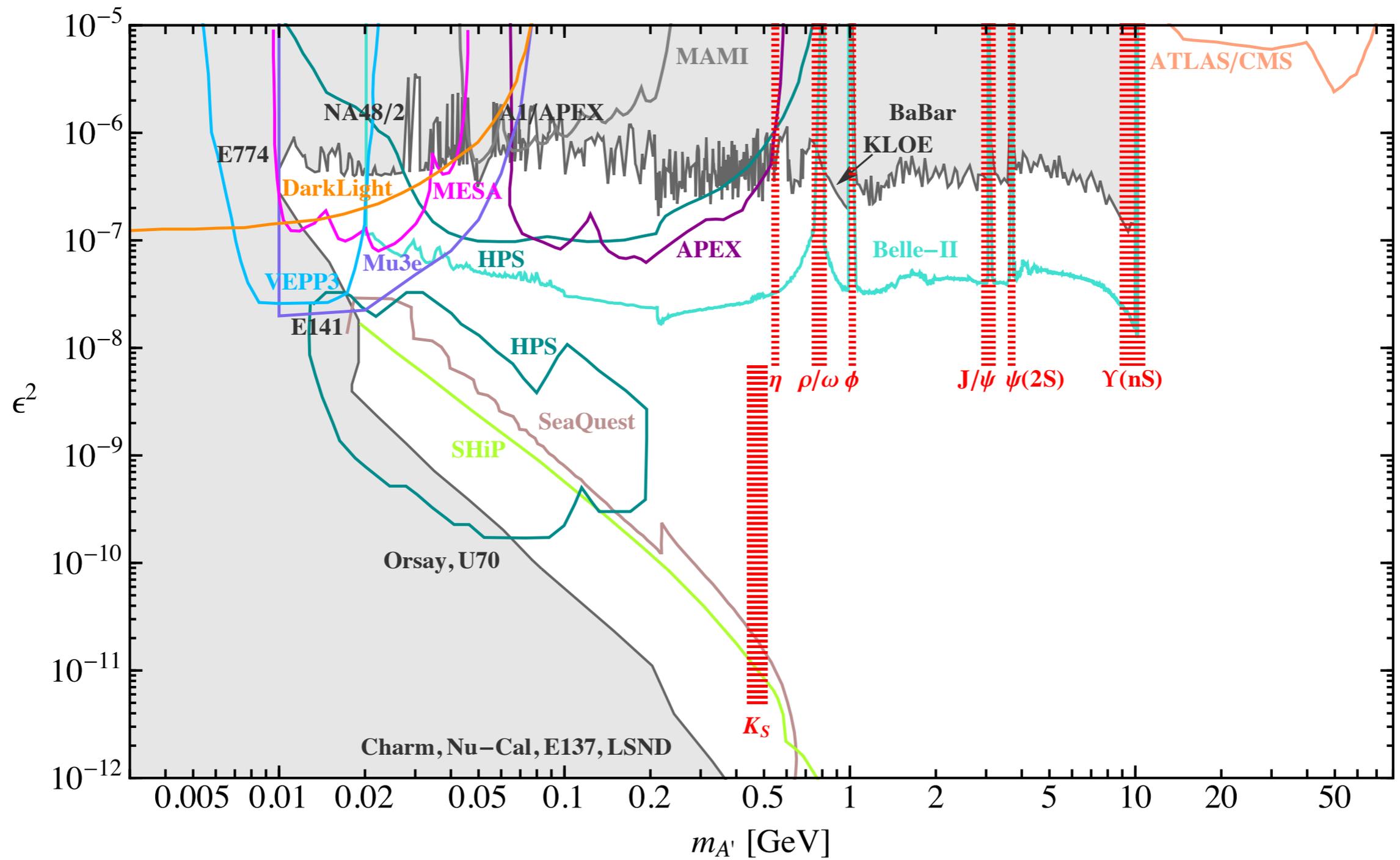
“good”

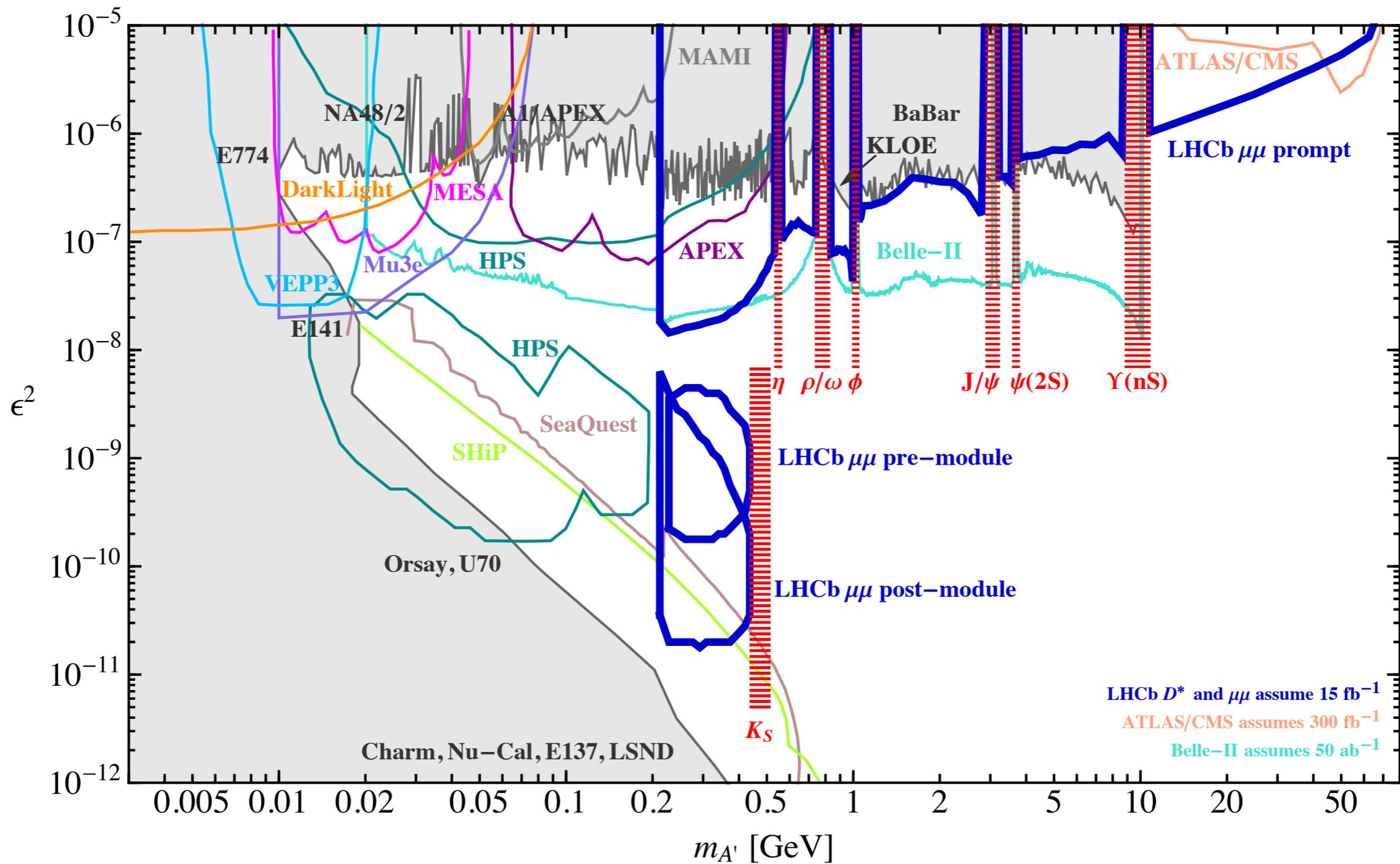
scales as signal

“bad”

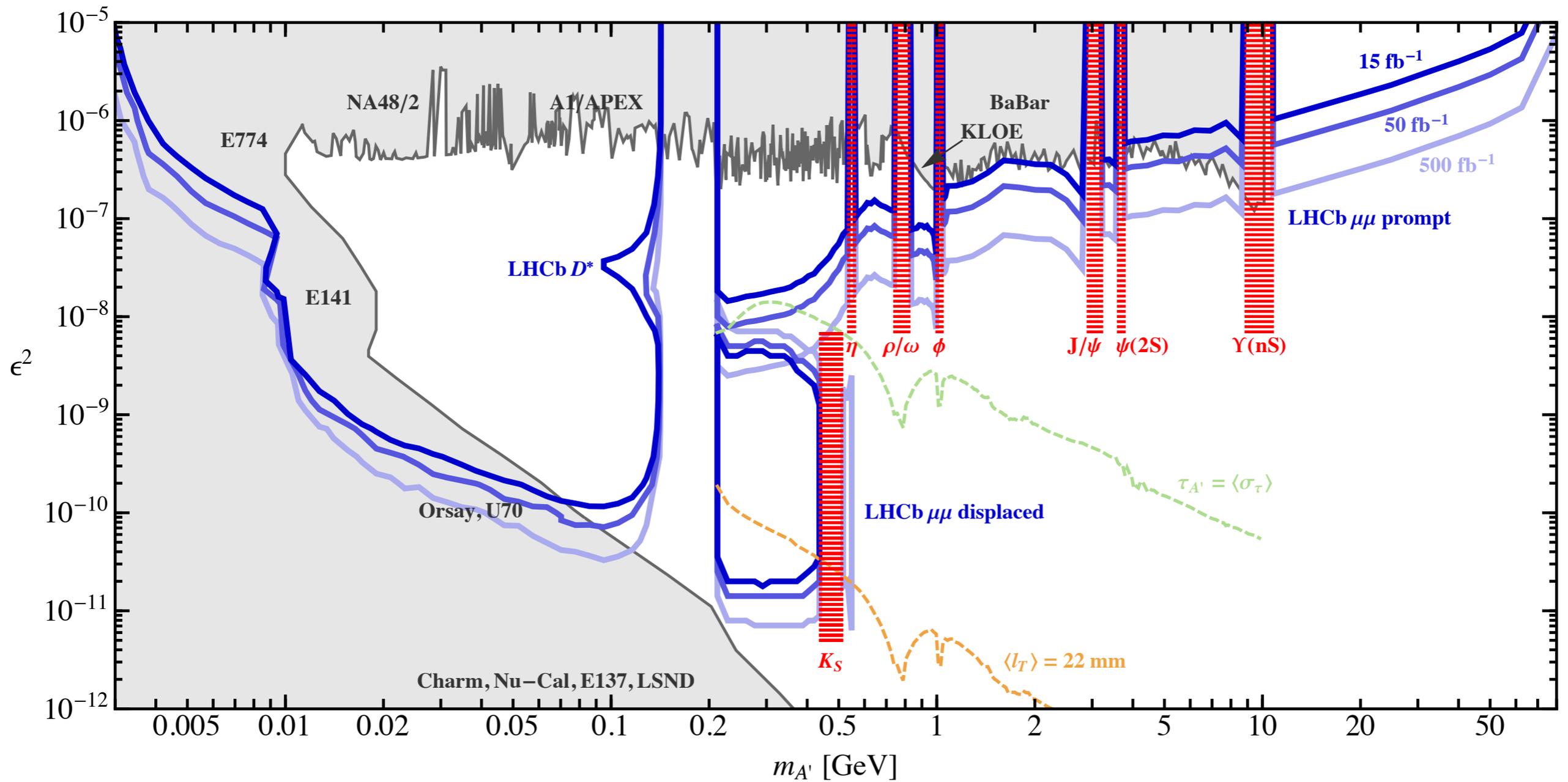
does not scale as signal

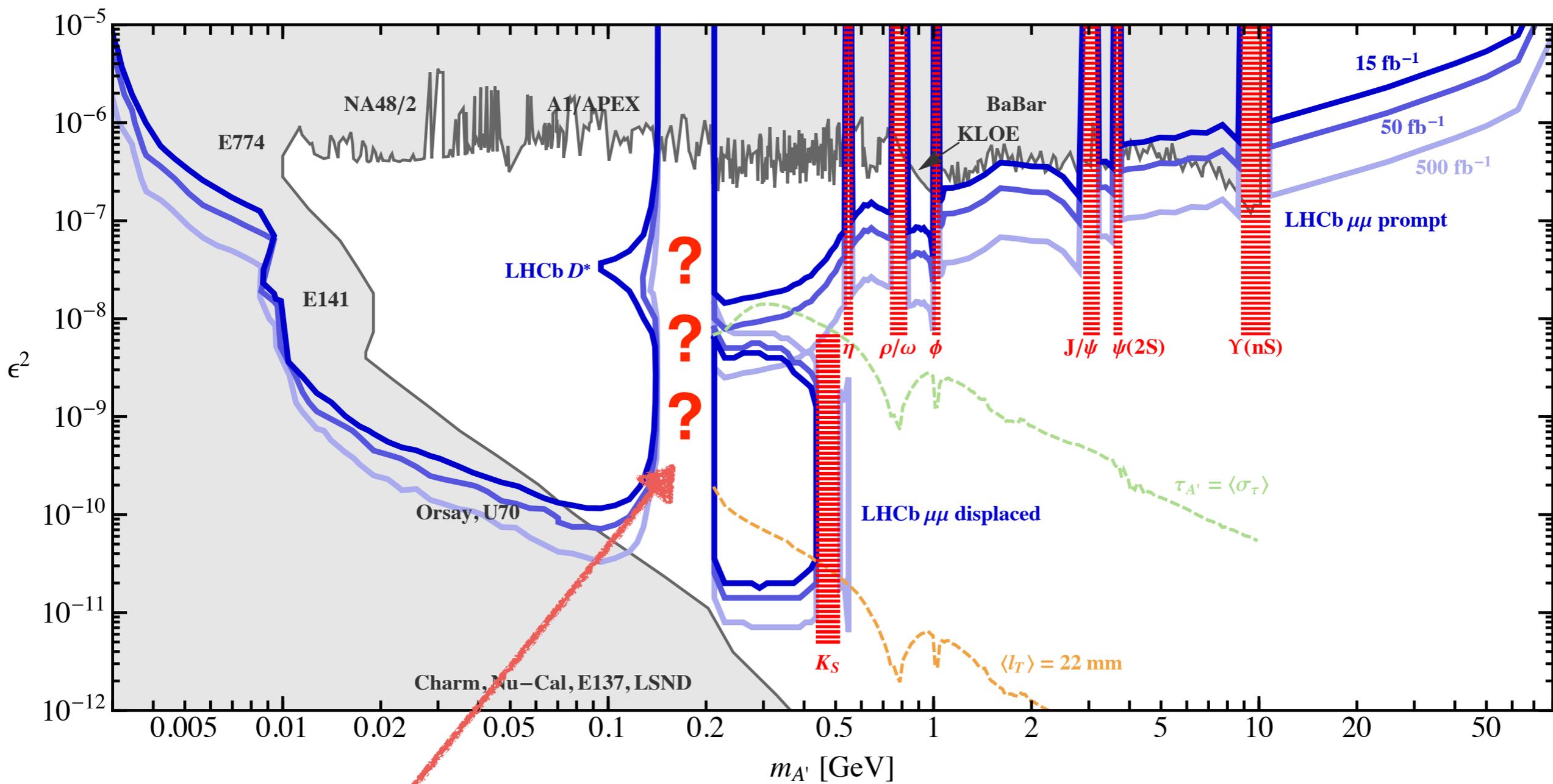




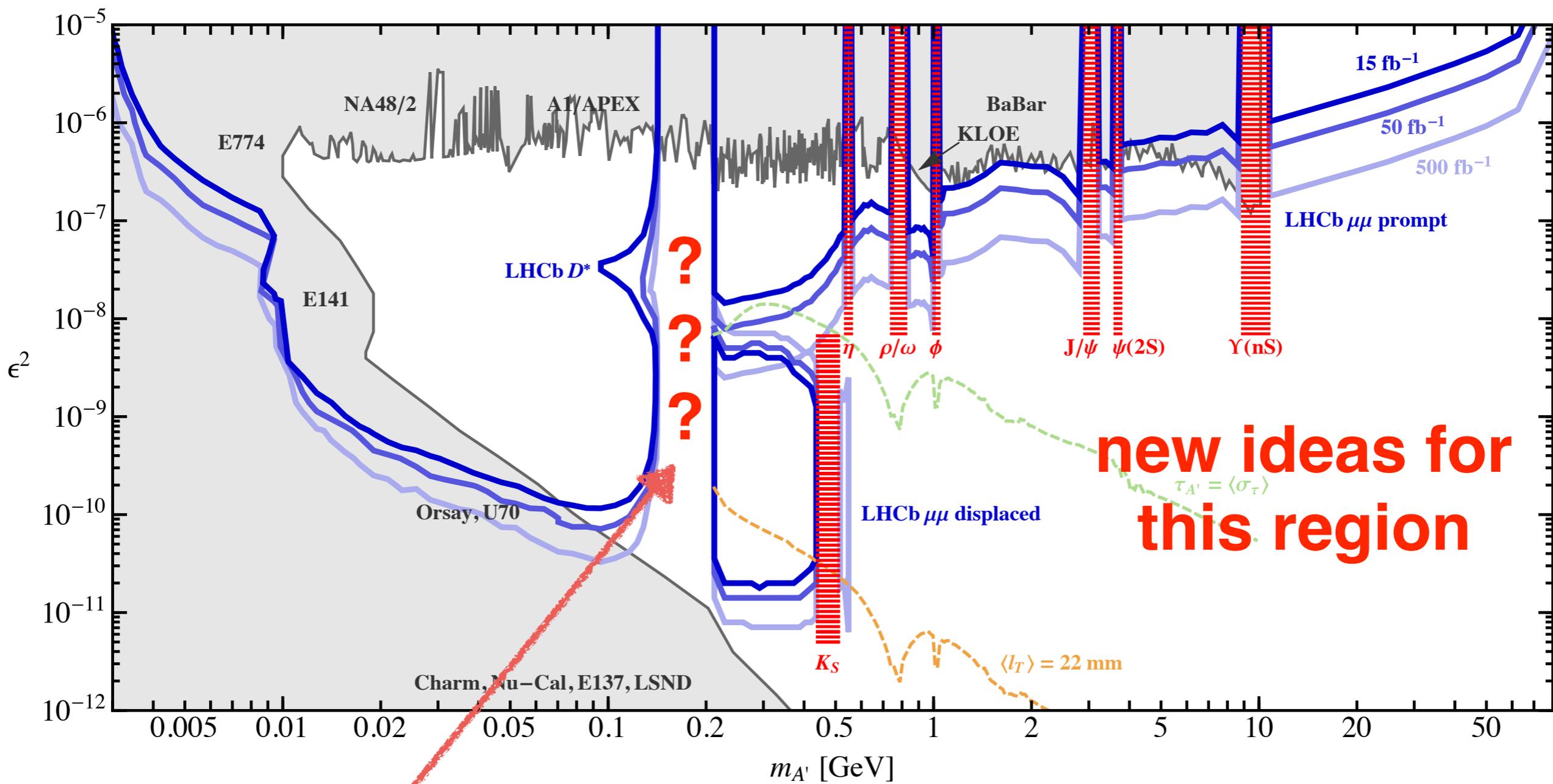


# Possible improvement





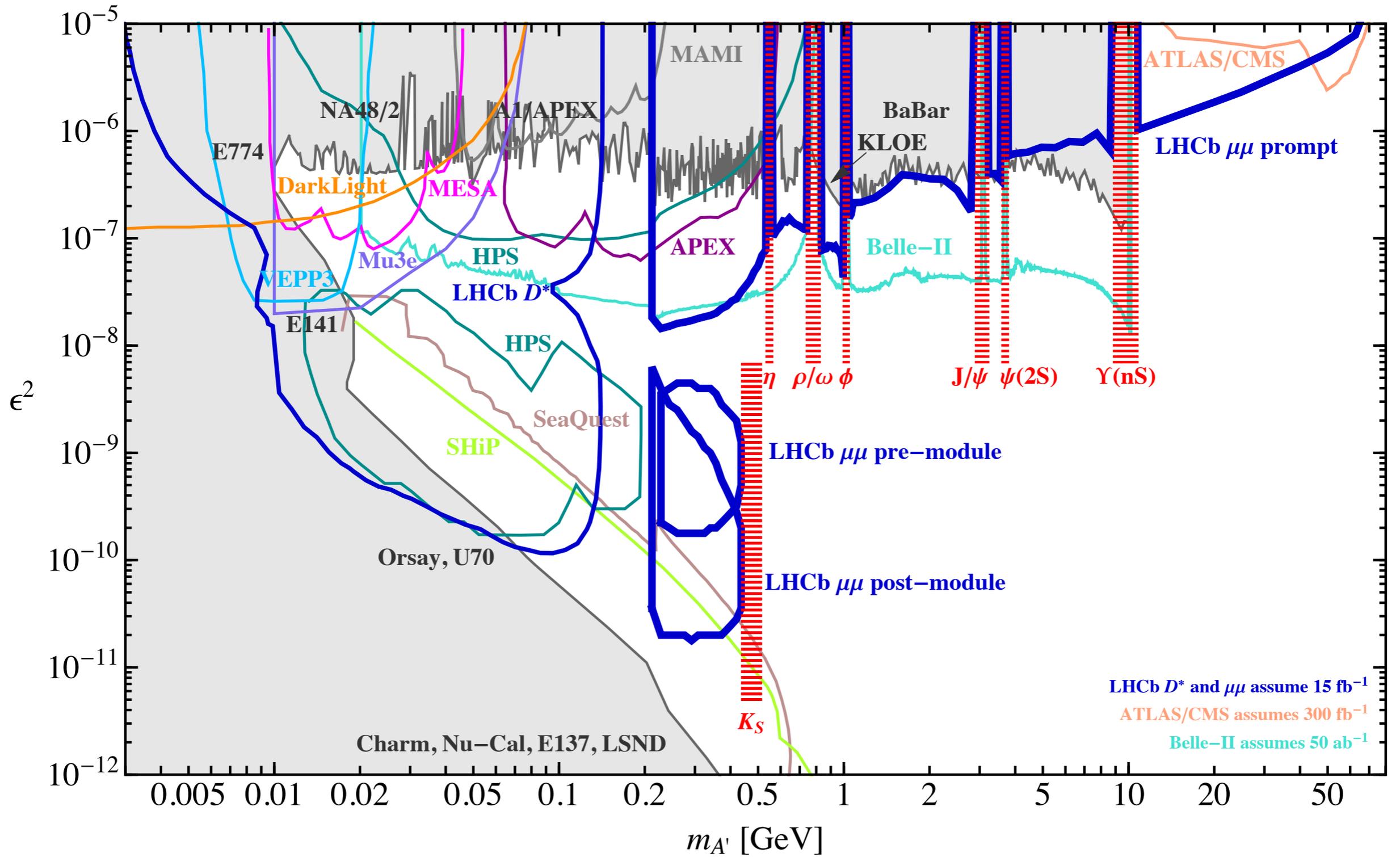
$\eta$  decay ?



$\eta$  decay ?

# Conclusion

- VELO
- Triggerless readout
- dark photon search at LHCb
  - $D^{0*} \rightarrow D^0 + \gamma$  and inclusive search
  - prompt search and displaced search
  - the (di-muon) data-drive method can be apply to other experiments
- LHCb search for new physics

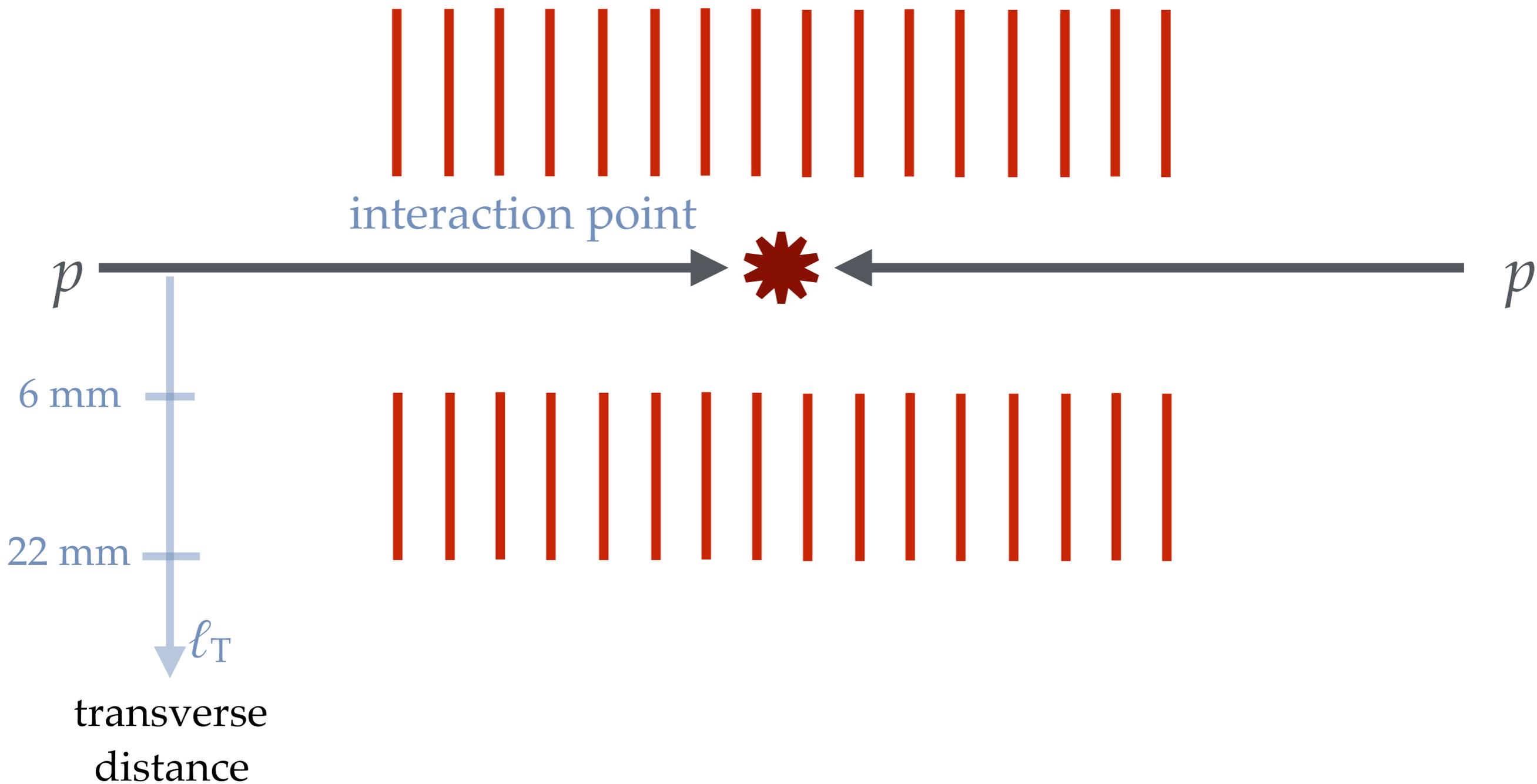


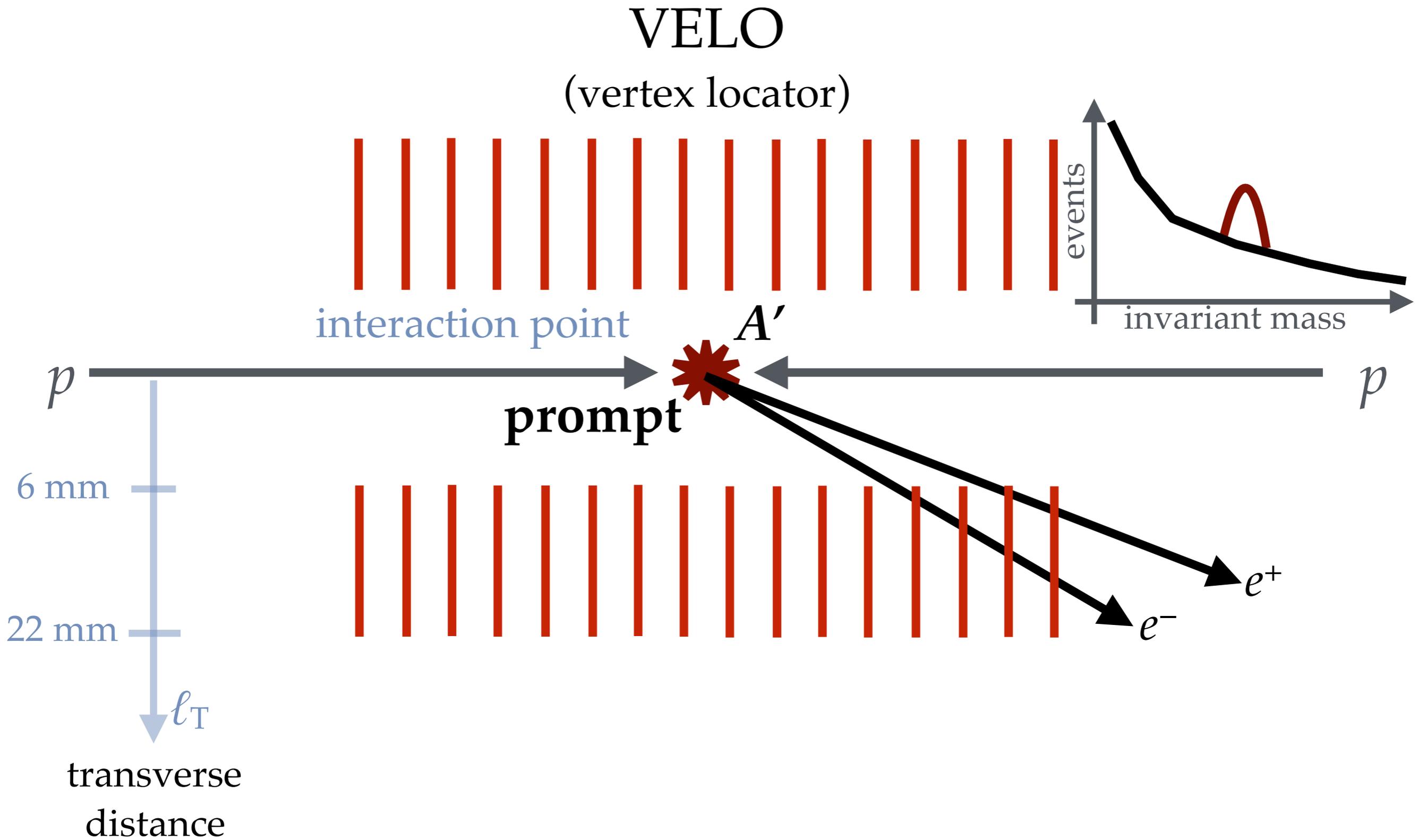
Backup slides



# VELO

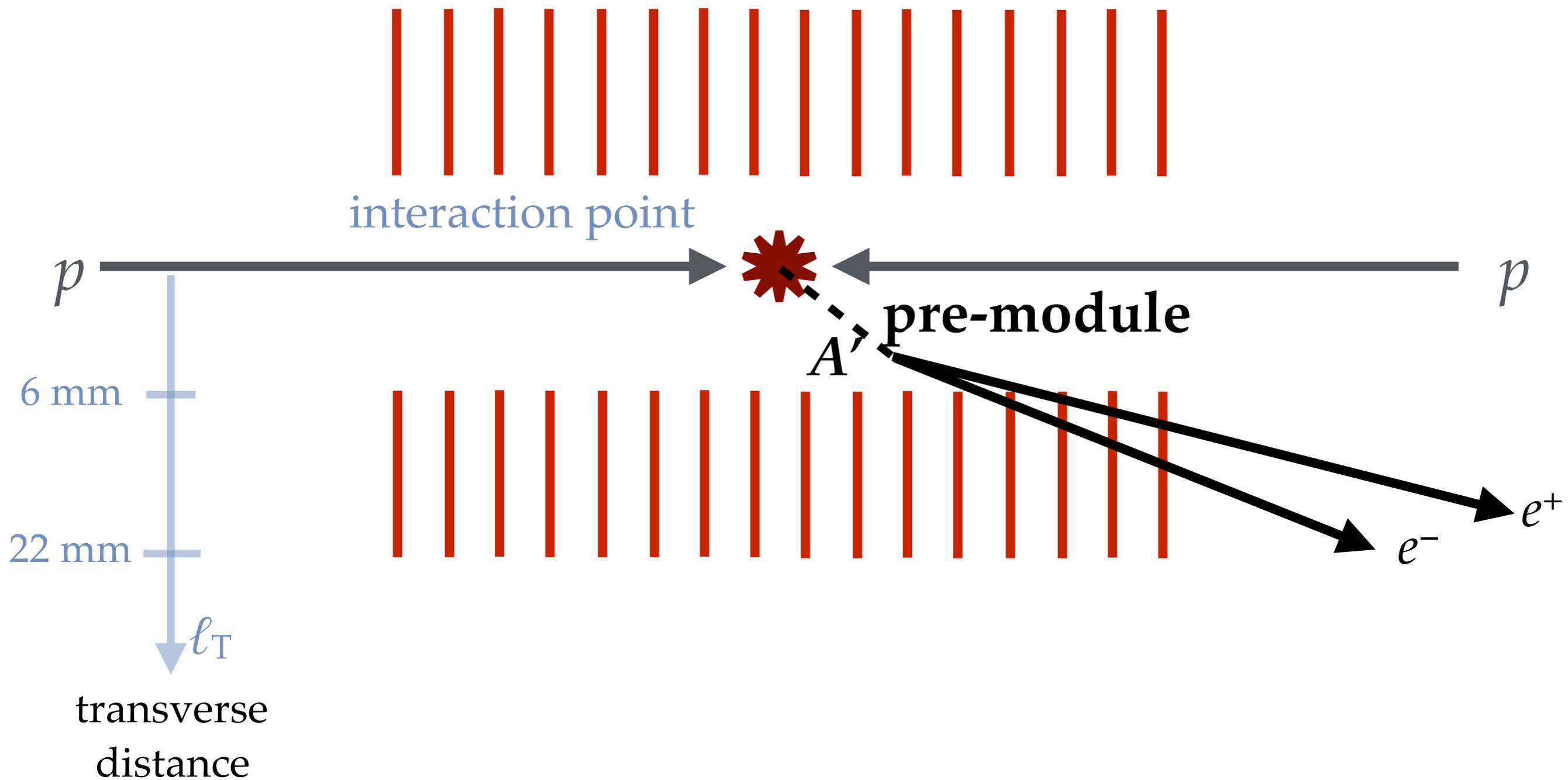
(vertex locator)

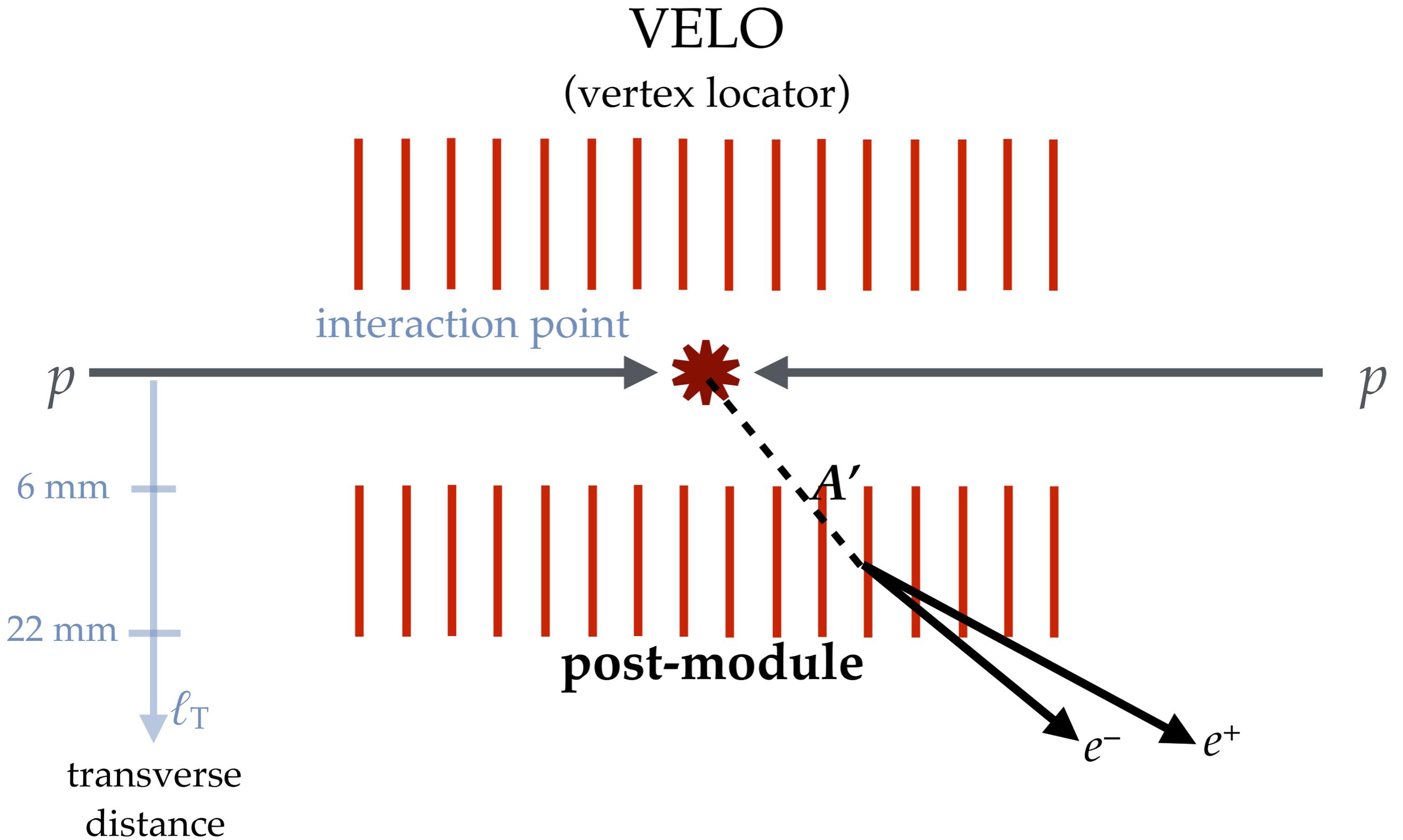




# VELO

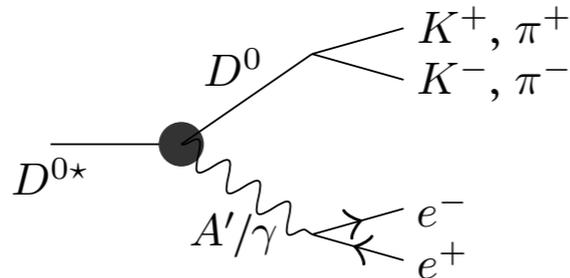
(vertex locator)





# Resonant Search

- Displaced  $D^0$  and Prompt  $A'$

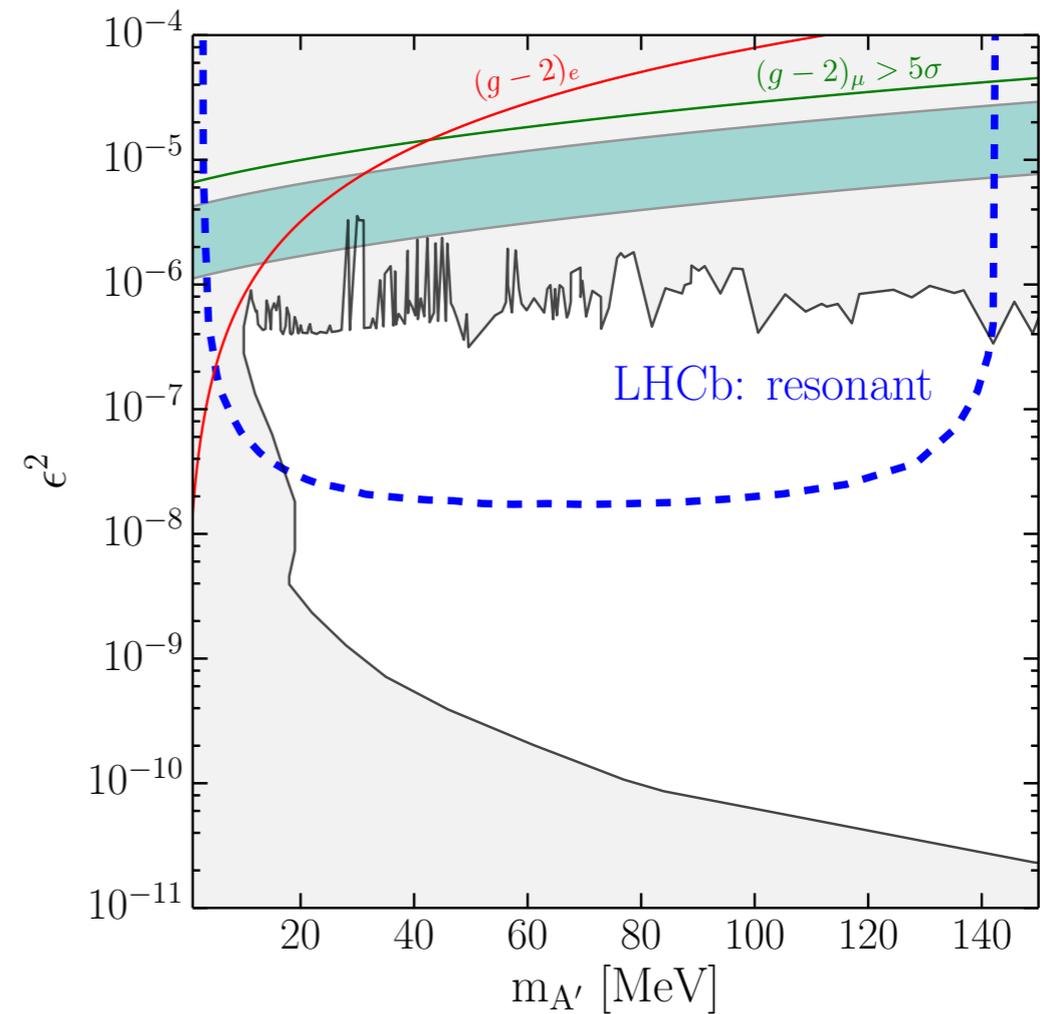
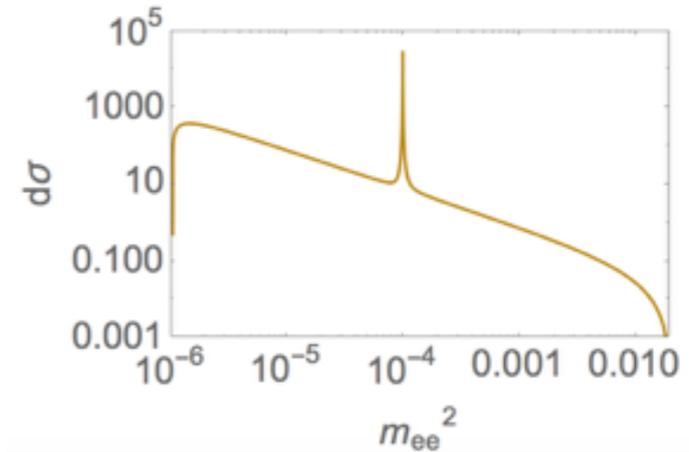


- How do we know  $e^+e^-$  from  $D^0$  decay?

reconstruct  $e^+ e^- D^0$  to  $D^{0*}$

$$-50 \text{ MeV} < \Delta m_D^{\text{reco}} - \Delta m_D < 20 \text{ MeV}.$$

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



# Displaced Search

- In addition to  $D^0$  giving a displaced decay,  $A'$  can give displaced decay

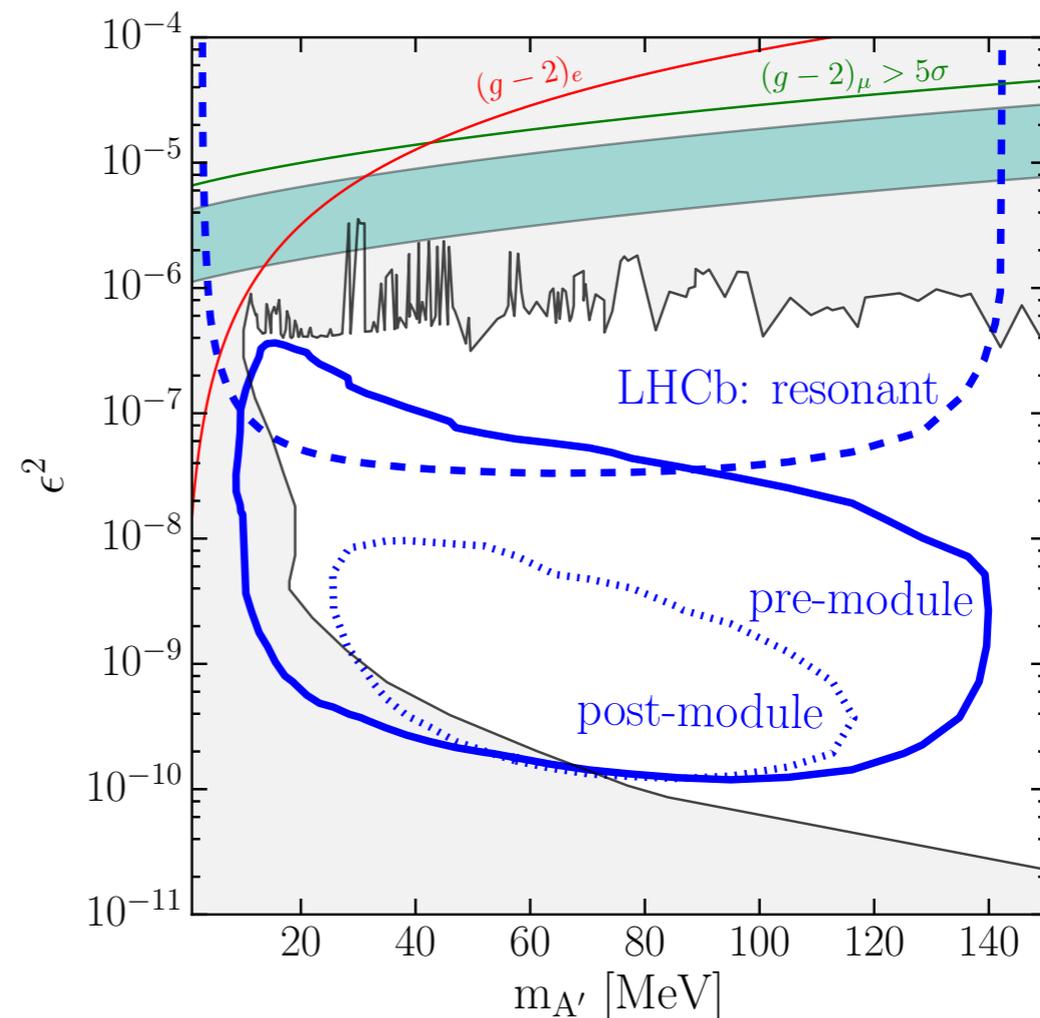
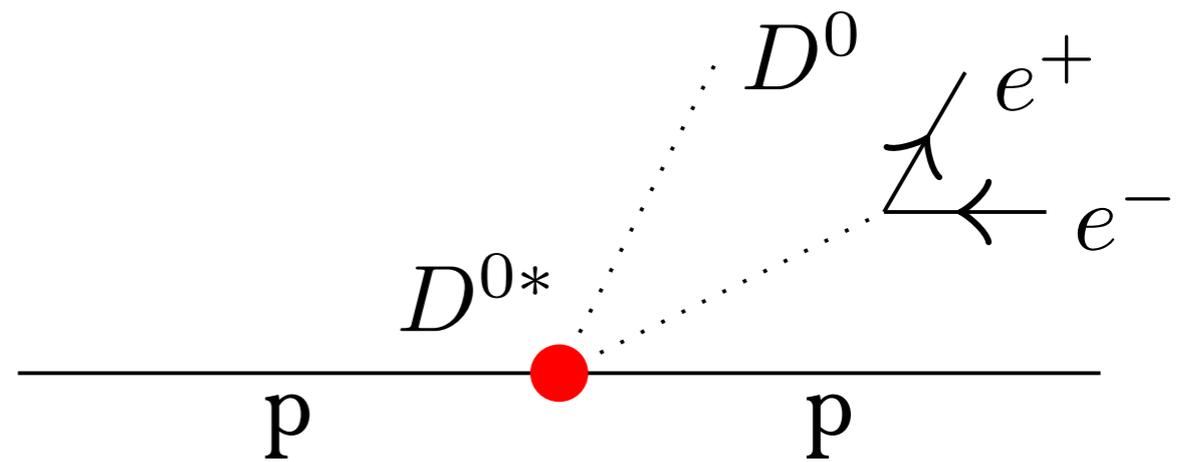
- good vertex resolution  
 $\sim 10 \mu\text{m}$

- small  $e^+e^-$  opening angle  
 $\sim 3 \text{ mrad}$

- 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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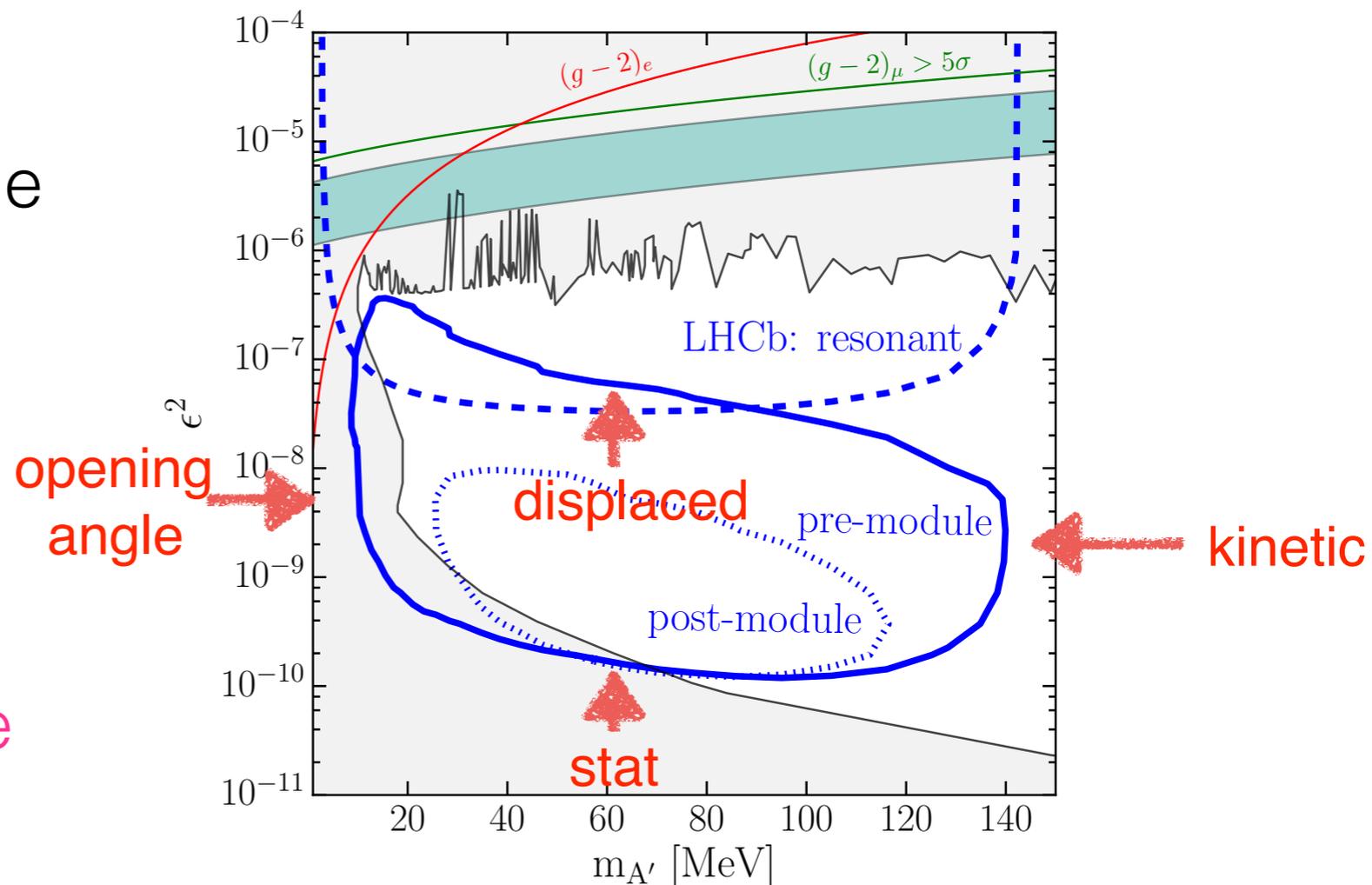
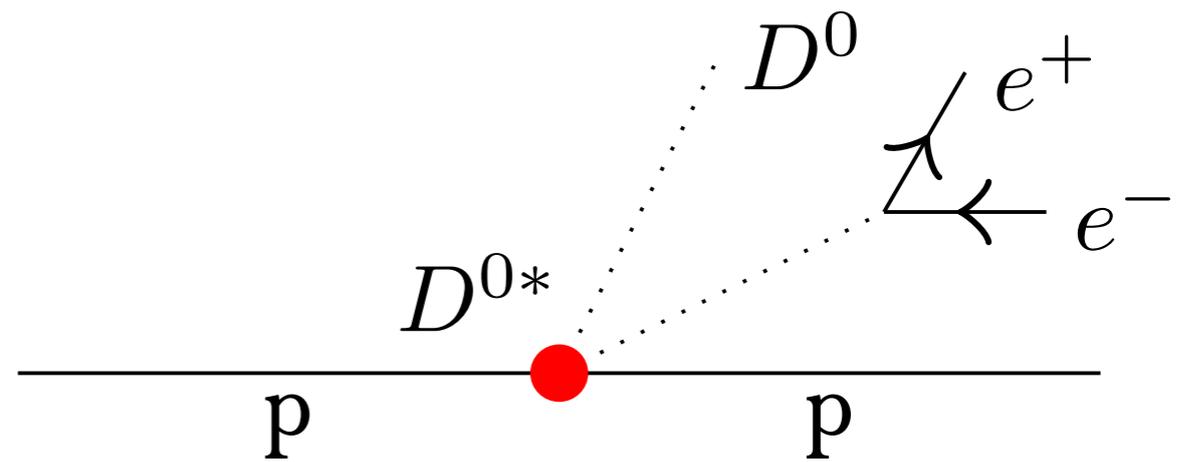
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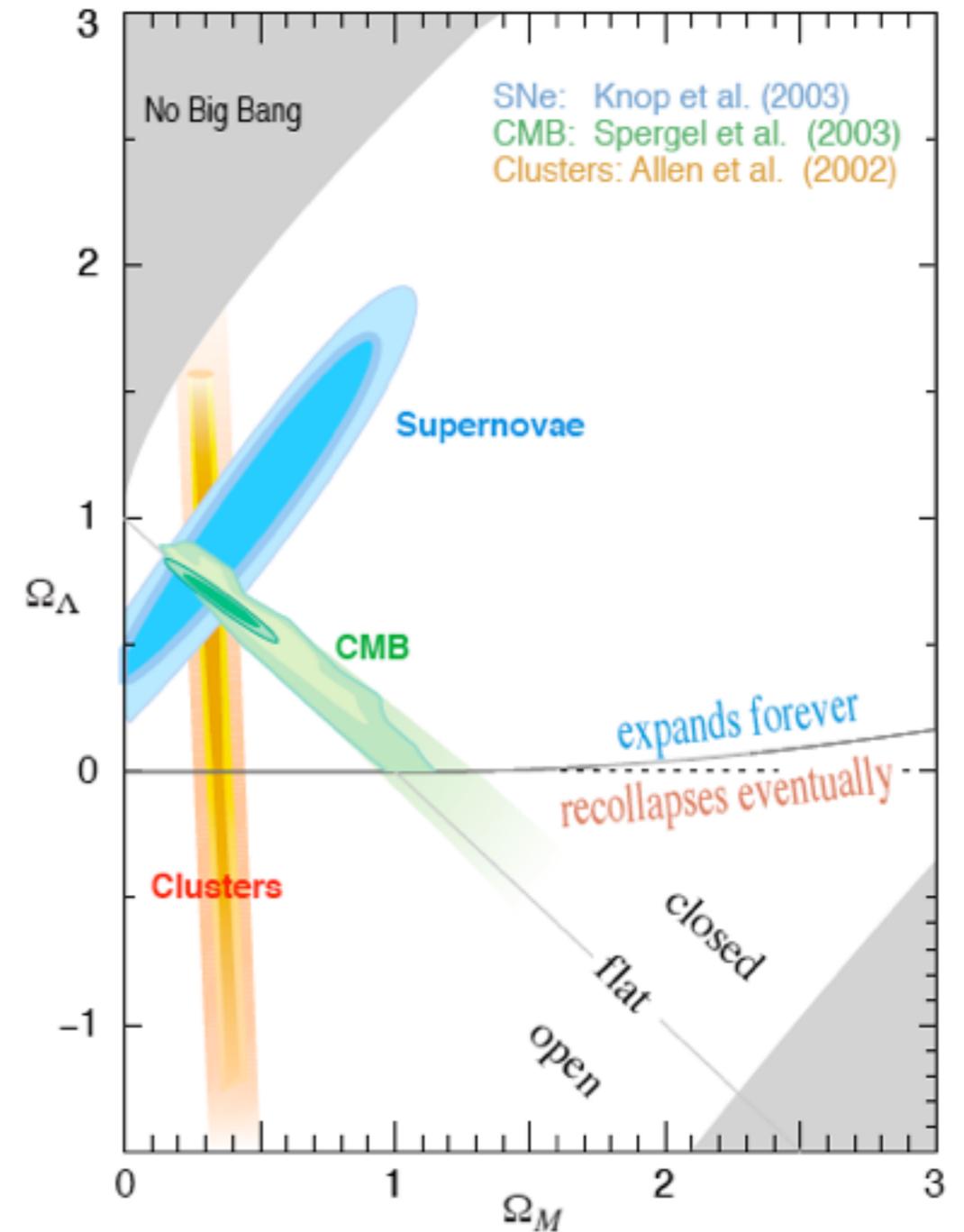
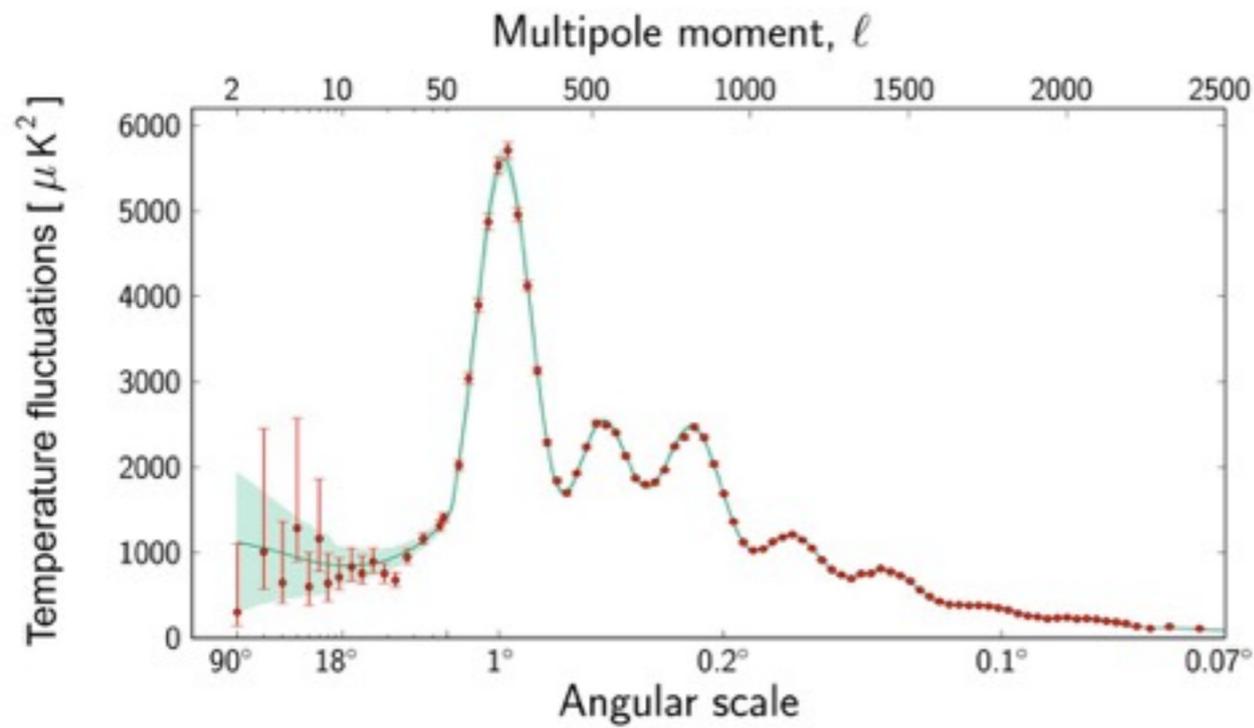
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# Dark Matter

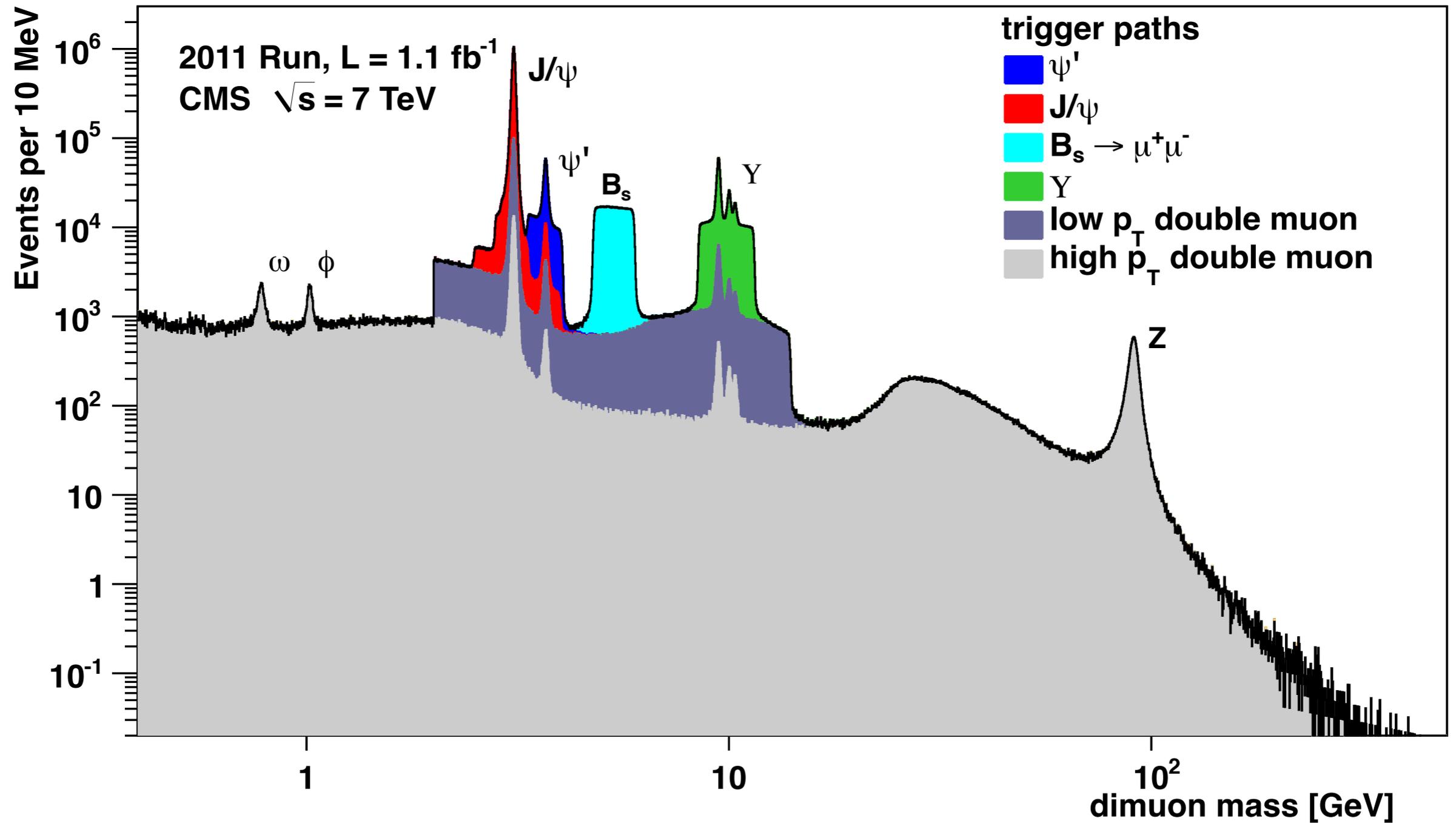
- dark matter energy density  $\sim 25\%$



# Intensity Frontier vs Energy Frontier

- LHC good at energy frontier  
it is searching for new particles with  $m \sim \text{TeV}$ ,  
coupling about SM size
- hard for  $\alpha < 10^{-6}$ ,  $m \sim \text{GeV}$
- After Run 3, LHC will reach the intensity frontier
- dark photon is a promising example

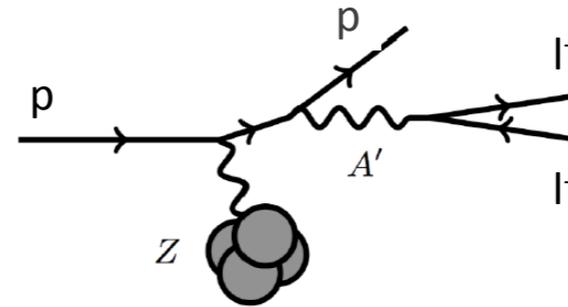
# Measured Di-muon Spectrum



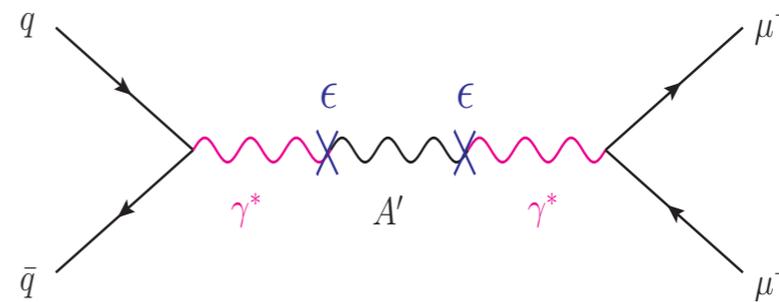
# Dark Photon Production in collider

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

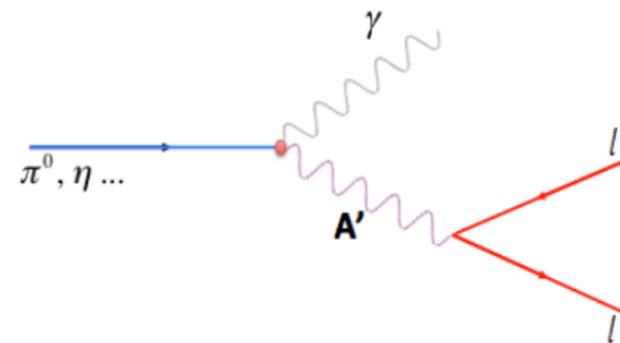
A. Bremsstrahlung



B. Drell-Yan like



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



# Data driven method

- the continuous dimuon spectrum that LHC have is the background.
- per mass bin

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

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

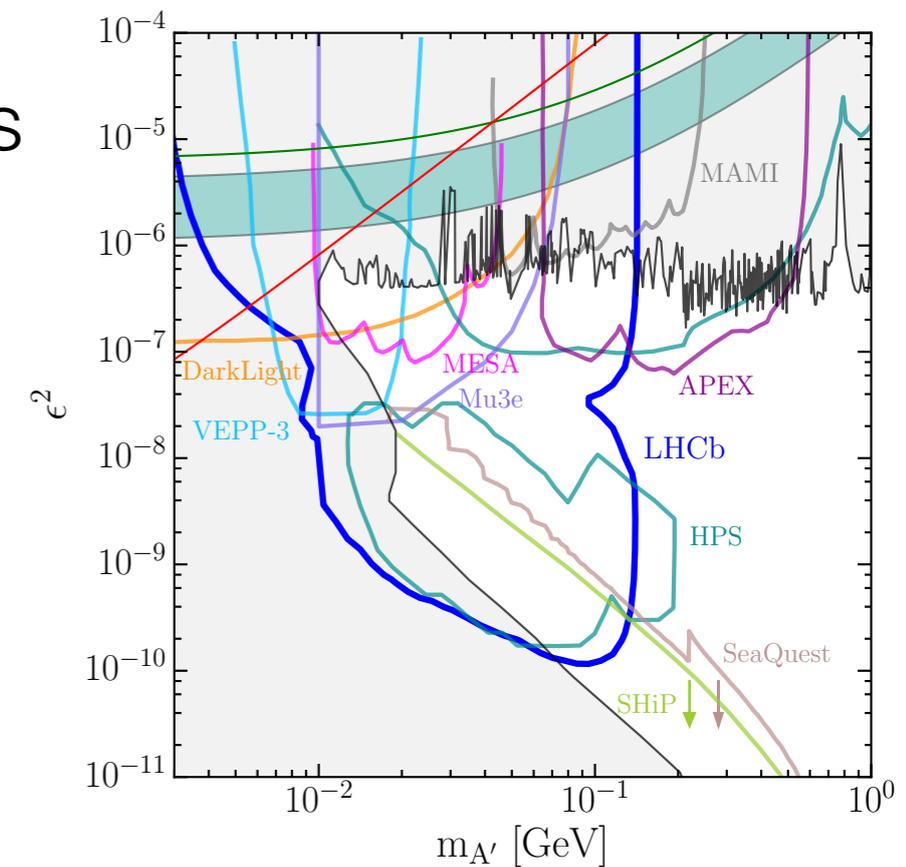
$$\frac{\sigma_{e^+e^- \rightarrow \text{hadrons}}}{\sigma_{e^+e^- \rightarrow \mu^+\mu^-}}$$

# Displaced search Background

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

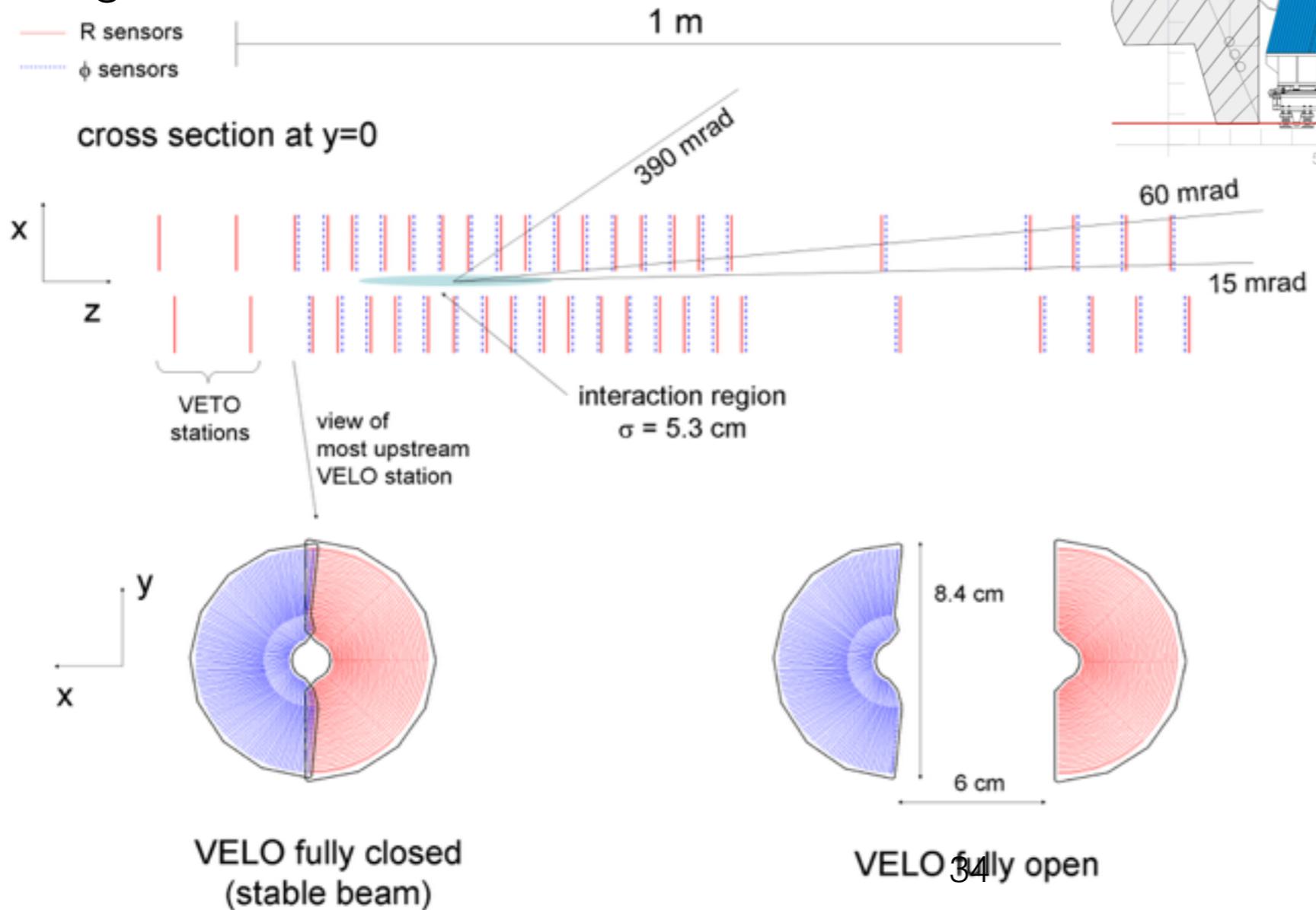
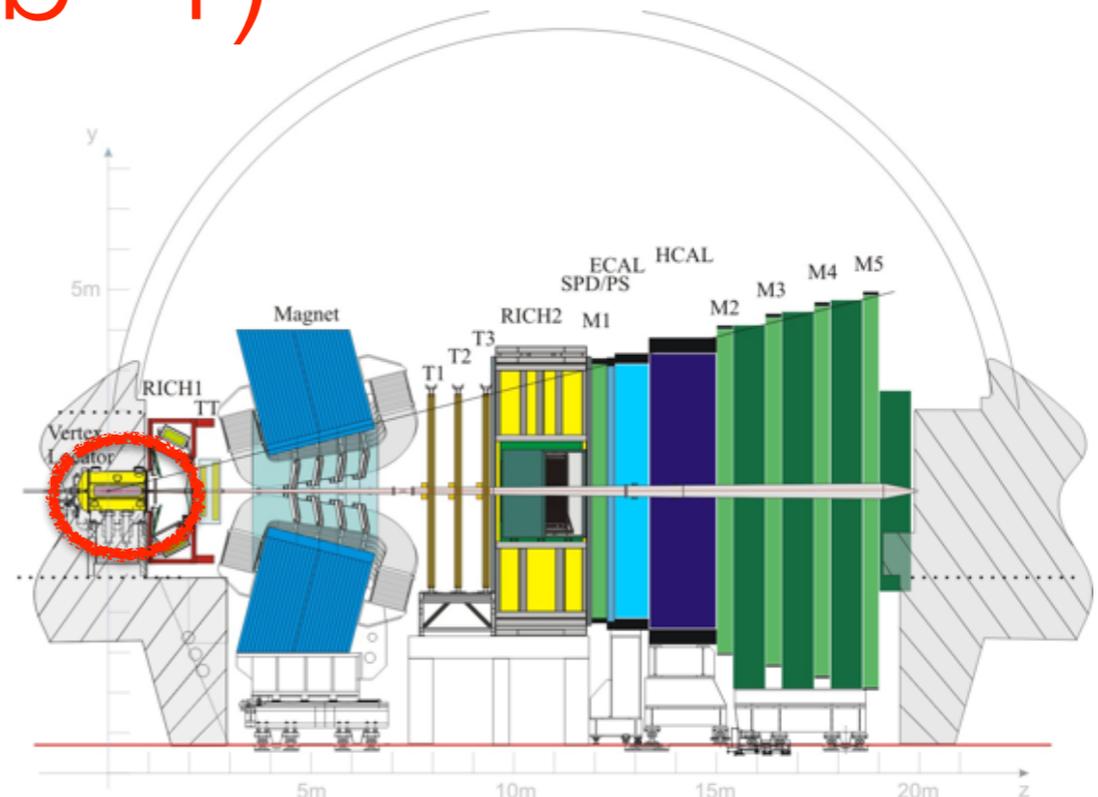
# Comparison to Other Experiments

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



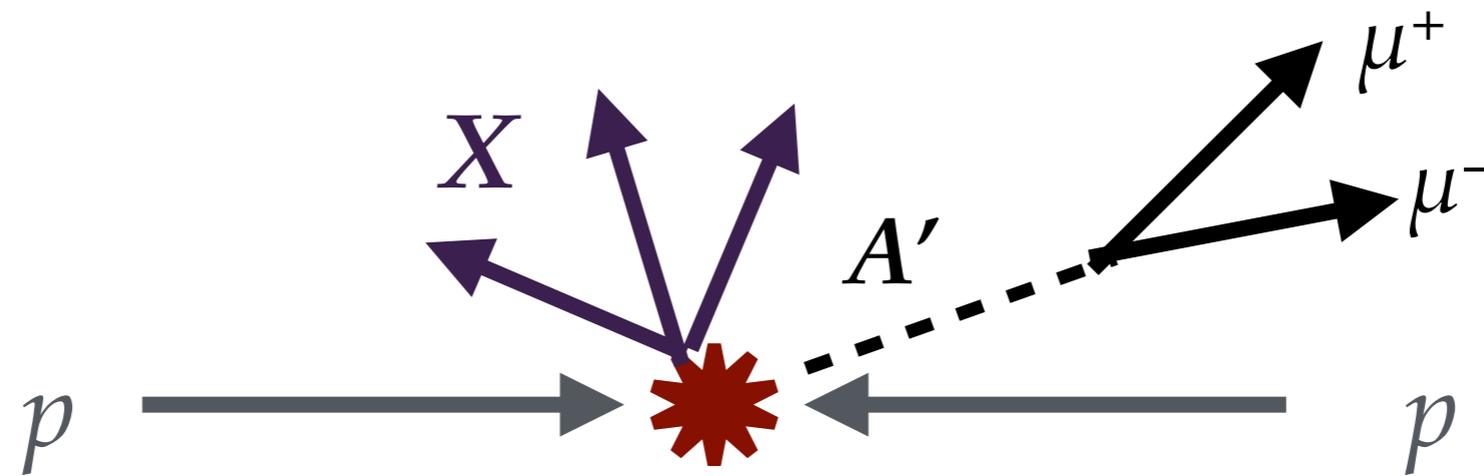
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