Dark Sectors, Higgs-Charm, Etc.

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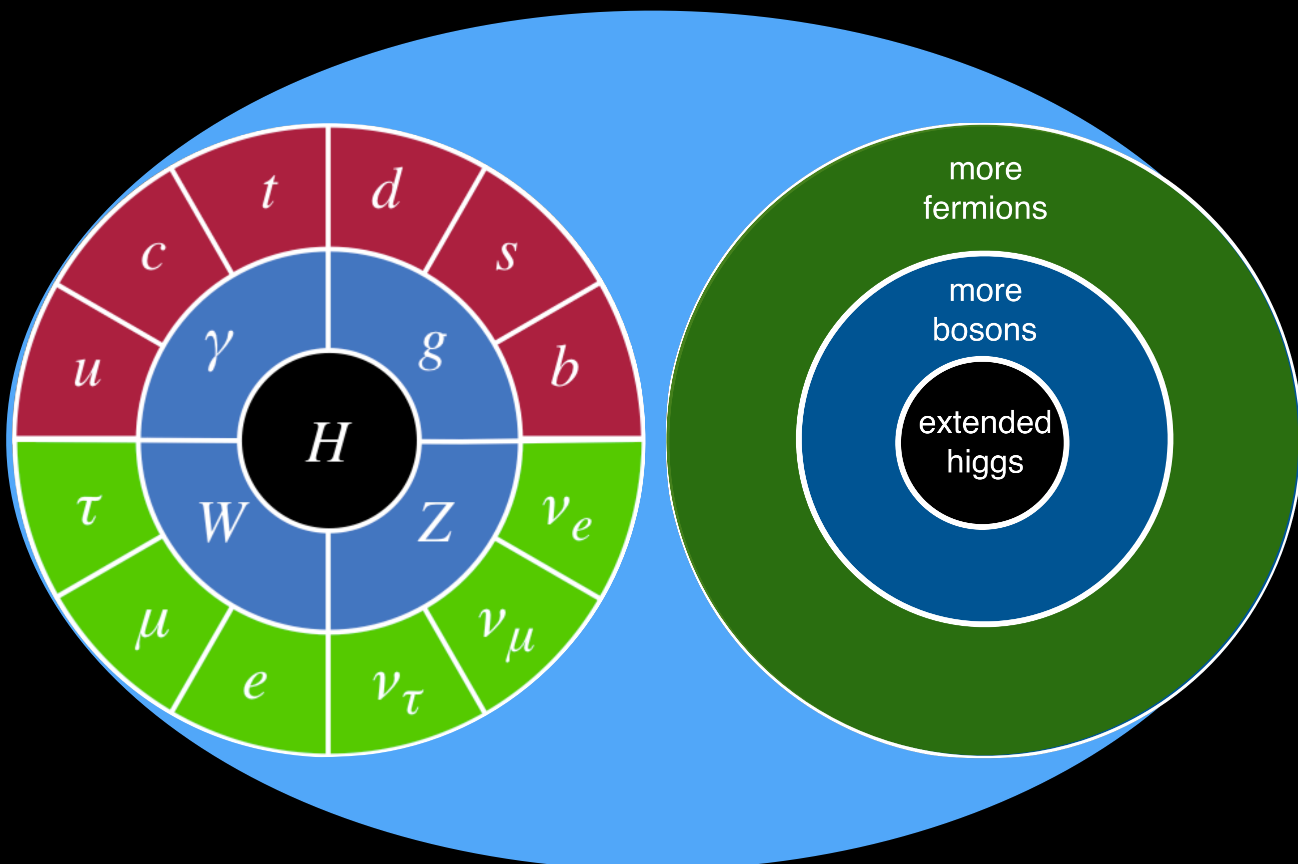
Dark Matter Paradigms

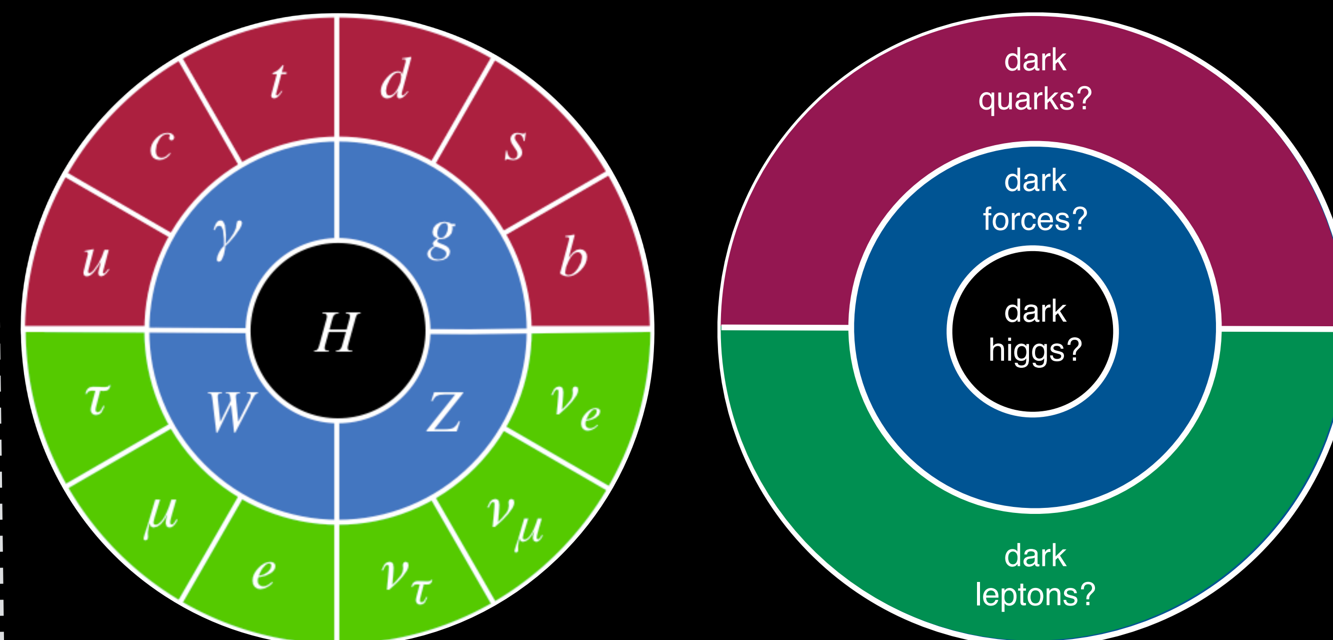
WIMP



SM and DM particles are part of a larger unified theory at the TeV scale.

LHCb searches for indirect evidence of this via quantum effects (flavor physics, aka core physics program).

Hidden Sector(s)



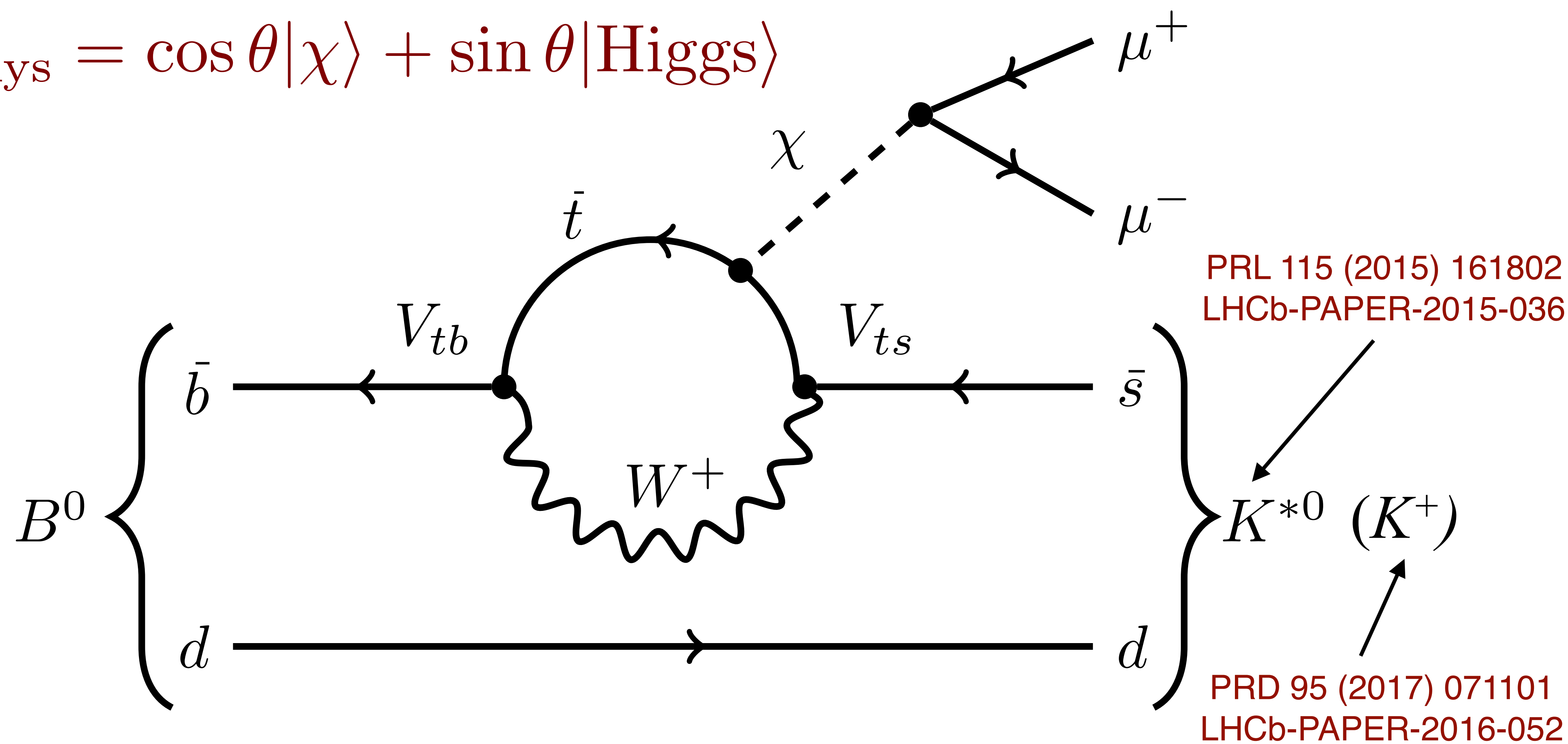
No direct SM-DM connection. LHCb searches for this directly, and has (or will have) world-leading sensitivity in certain regimes.

Higgs Portal

$b \to s$ penguin decays are an excellent place to search for low-mass hidden-sector particles (e.g., anything that mixes with the Higgs sector).

$$|\text{Higgs}\rangle_{\text{phys}} = -\sin\theta|\chi\rangle + \cos\theta|\text{Higgs}\rangle$$

$$|\chi\rangle_{\text{phys}} = \cos\theta|\chi\rangle + \sin\theta|\text{Higgs}\rangle$$



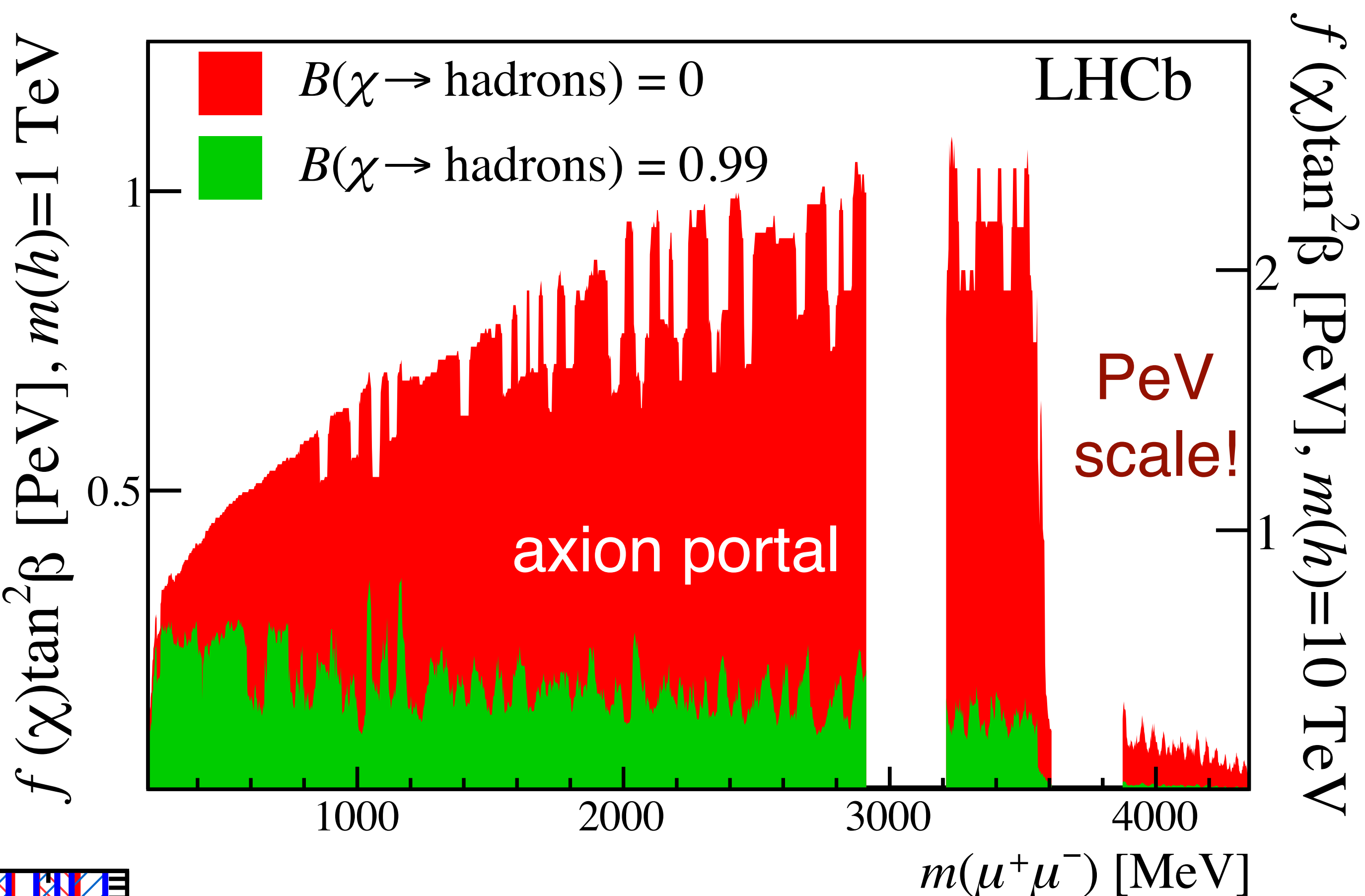
No evidence for a hidden-sector boson, so stringent model-independent limits are set on B($B \to K^{(*)}X$)xB($X \to \mu\mu$) vs m(X) and τ(X).

PRD 95 (2017) 071101
LHCb-PAPER-2016-052

Benchmark Models

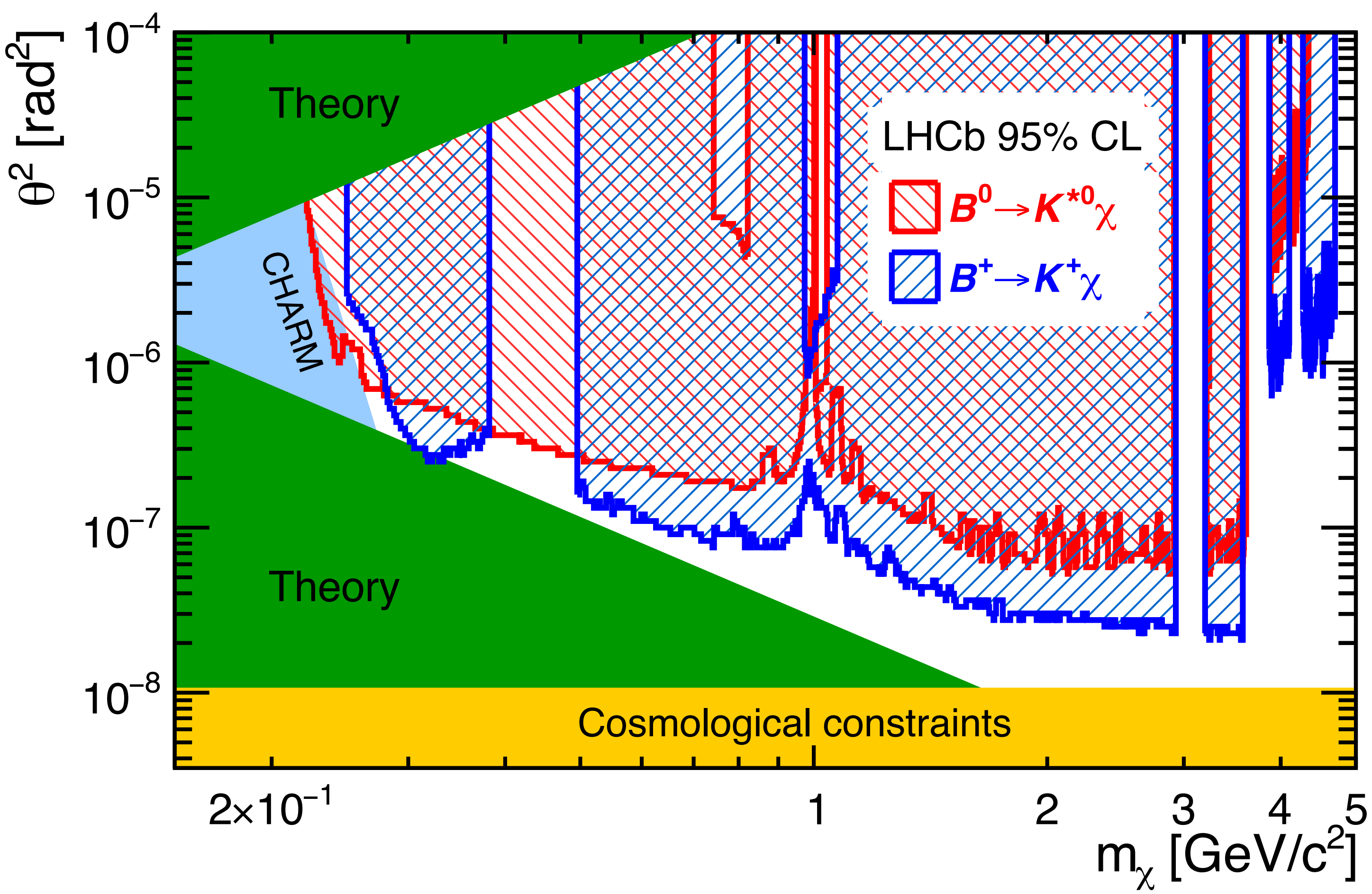
PRL 115 (2015) 161802
LHCb-PAPER-2015-036

Constraints in the axion portal reach the PeV scale on the axion decay constant in 2HDMs.[Freytsis,Ligeti,Thaler, 0911.5355]



Strongest constraints on a scalar with $2m(\mu)<m<2m(\tau)$ mixing with the Higgs. Nearly rules out the Inflaton parameter space below $2m(\tau)$ in these models.

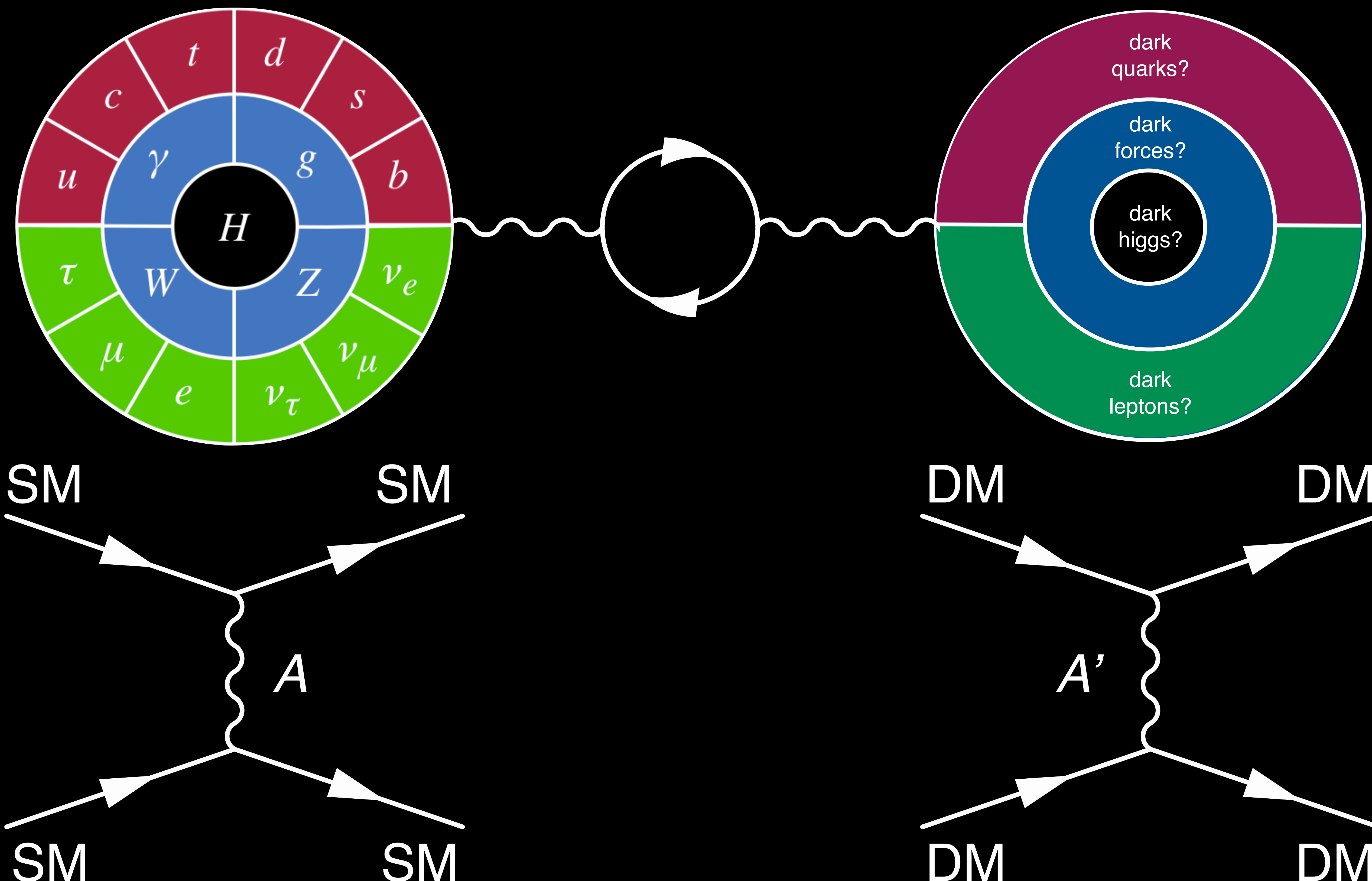
Batell, Pospelov, Ritz [0911.4939];
Bezrukov, Gorbunov [0912.0390,1303.4395]



How can we do better? Inclusive searches, also use hadrons, downstream tracks, more LUMI, etc.

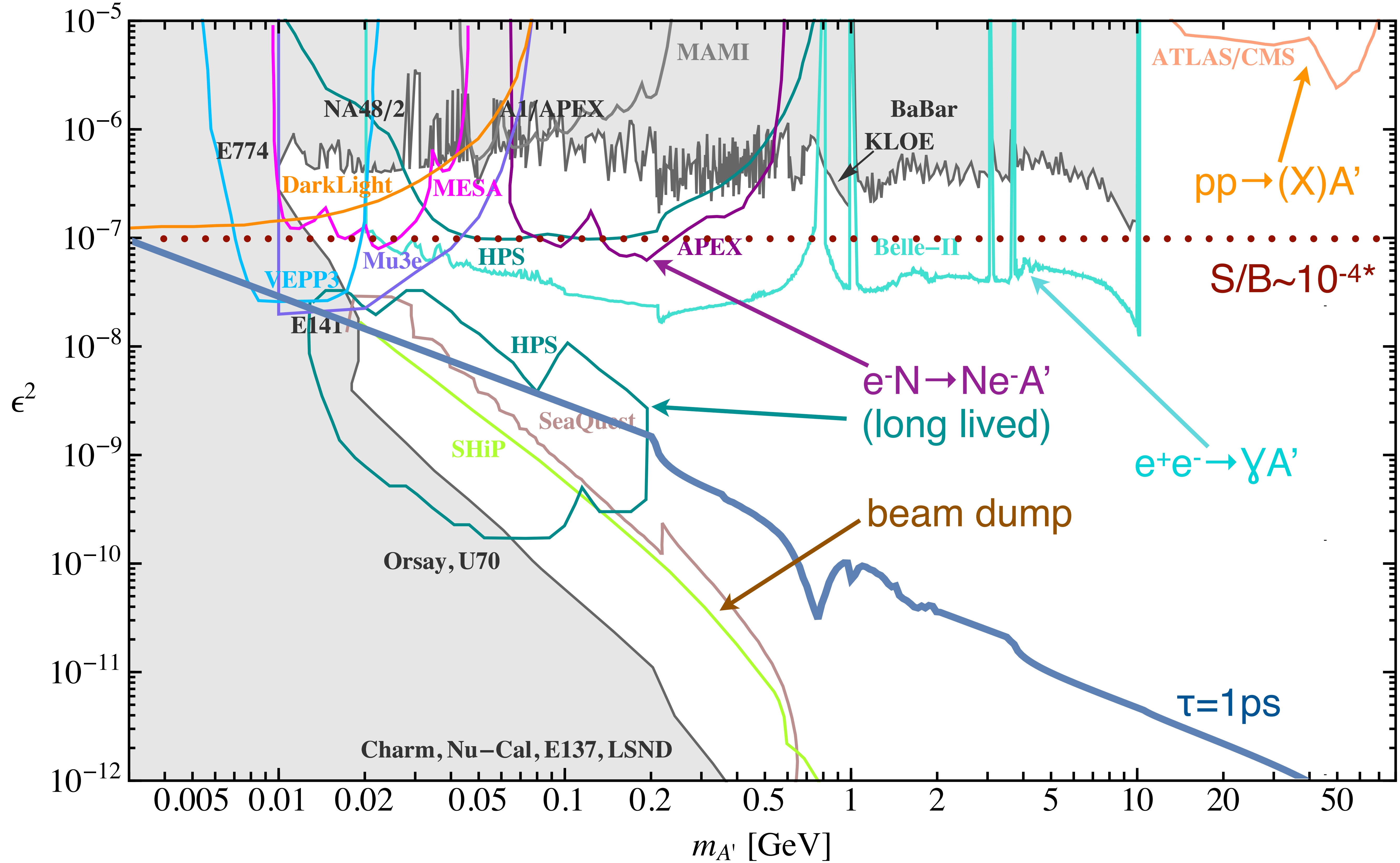
N.b., all such searches eventually run into the curse of longevity, unless open non-SM decay modes exist, or their production and decay couple to the SM in different ways.

Dark Photons



Visible A' Decays

Dedicated worldwide effort to search for dark photon decays.



*see MW [1705.03578] for a guide to proper bump hunting.

Dark Photons

Ilten, Soreq, Thaler, MW, Xue
[1603.08926]

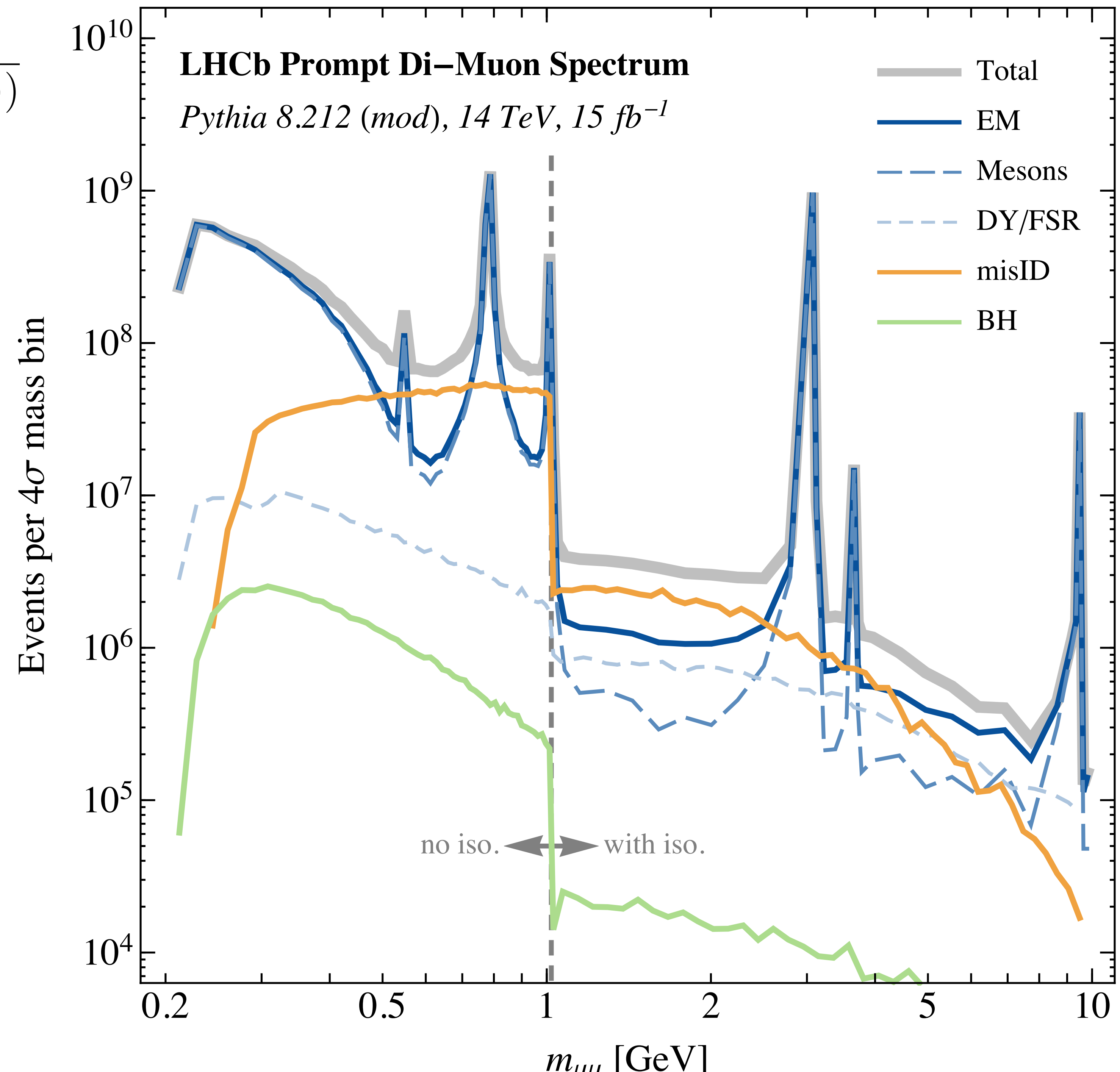
The most experimentally favorable A' decay mode is di-muon. The A' rate can be inferred from the prompt $\gamma^* \to \mu\mu$ rate making this a **fully data-driven search** at the LHC!

$$\frac{N(A' \to \mu^+\mu^-)}{N(\gamma^* \to \mu^+\mu^-)} \approx \frac{3\pi}{8} \frac{m(A')}{\sigma(m(\mu\mu))} \frac{\varepsilon^2}{\alpha_{\rm EM}(n(\ell) + \mathcal{R}(\mu))}$$

We estimated all contributions to the prompt di-muon spectrum for $p_T(\mu) > 0.5$ GeV, $p(\mu) > 10$ GeV, and $2 < \eta(\mu) < 5$, to permit estimating the possible reach using $A' \to \mu\mu$ at LHCb.

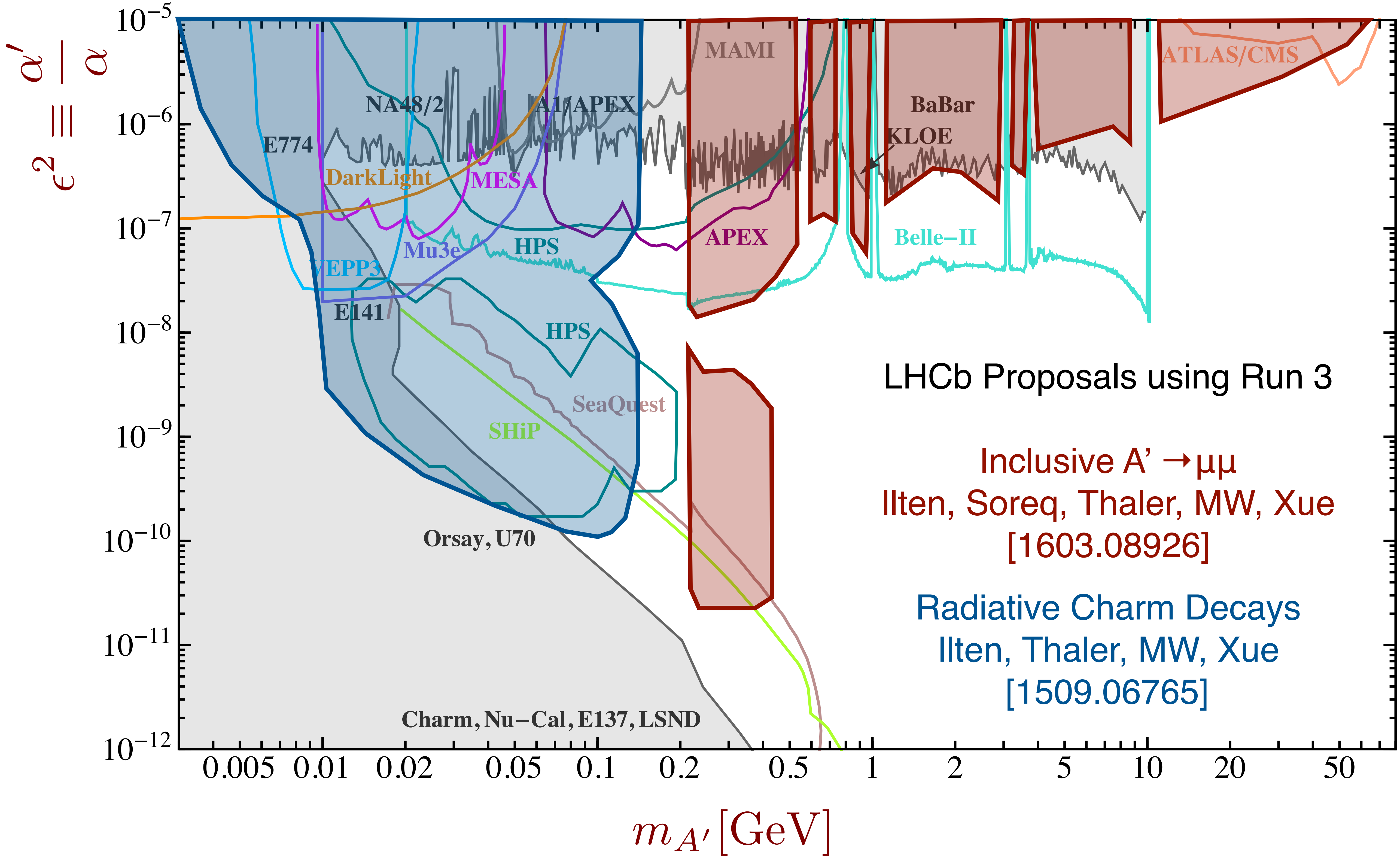
For concreteness, we considered 15/fb expected in Run 3.

"Mesons" and "DY/FSR" can produce A', "BH" and "misID" cannot.



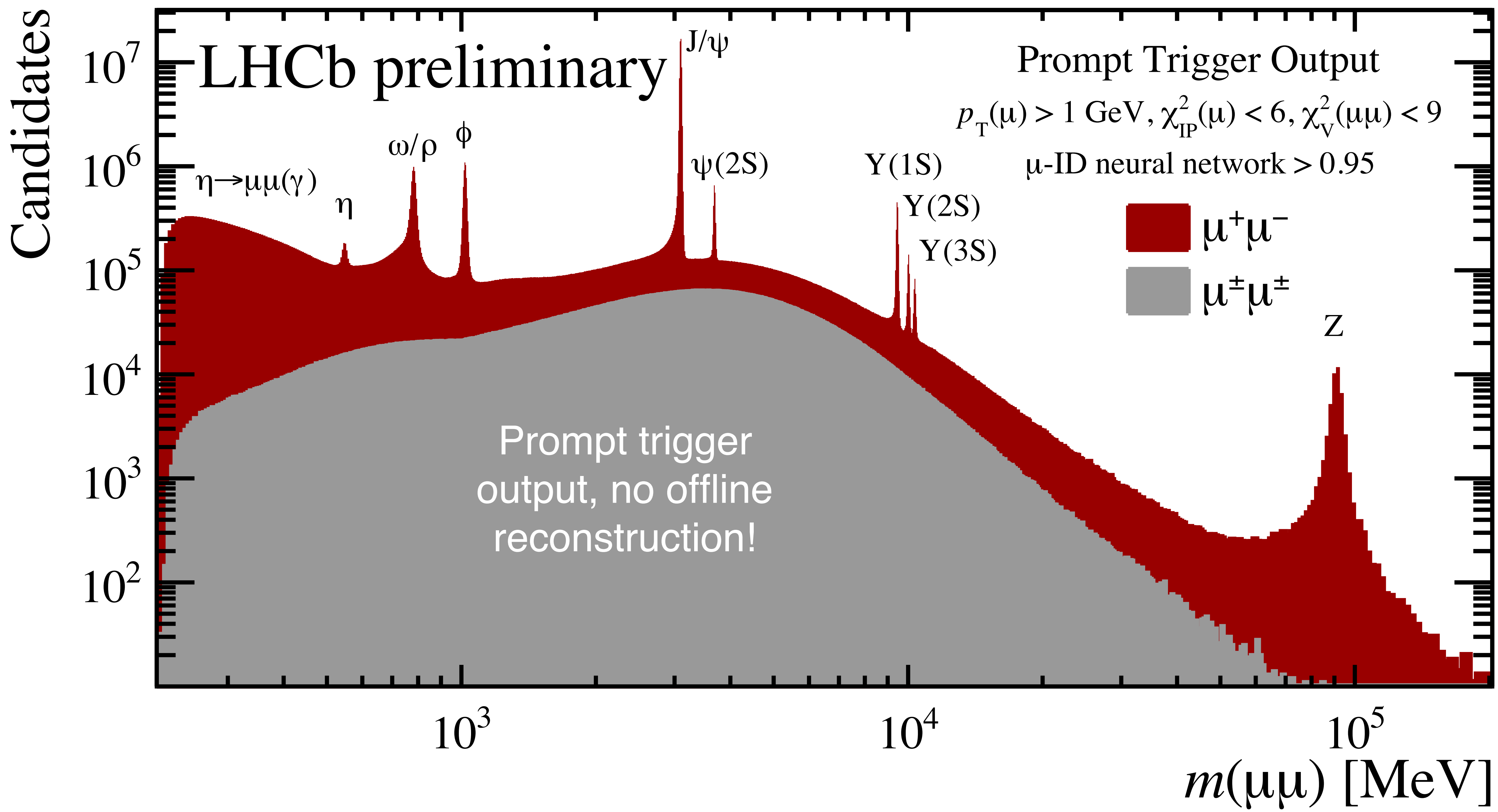
Visible A' Decays

Move to a triggerless detector readout in Run 3 will have a huge impact on low-mass BSM searches, including dark photons.



2016 Data

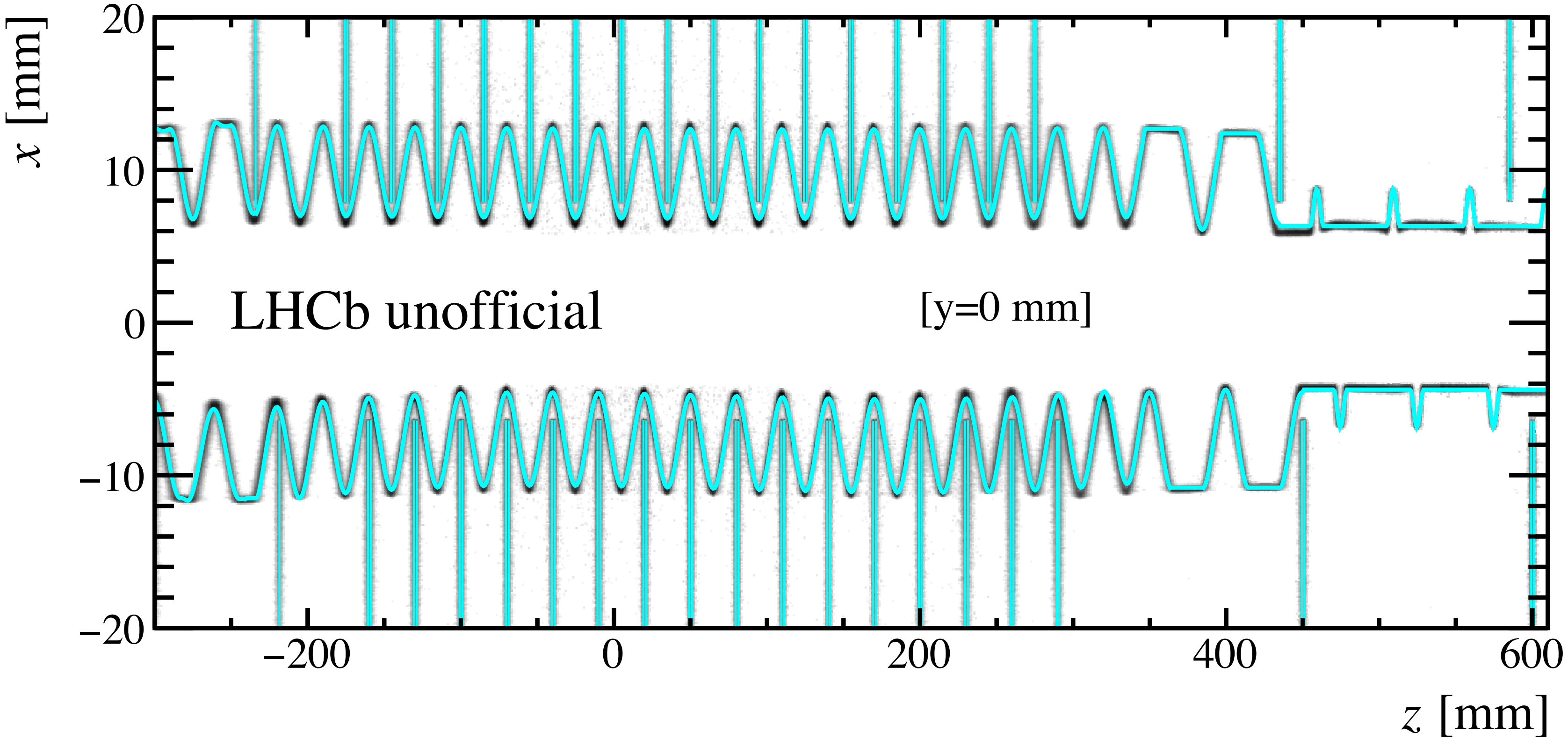
New triggers produced for 2016 to do both the prompt and displaced dimuon searches that rely heavily on advances to the LHCb online system in Run 2 (also new triggers for 4mu, RH neutrinos, split dark matter decays, etc).

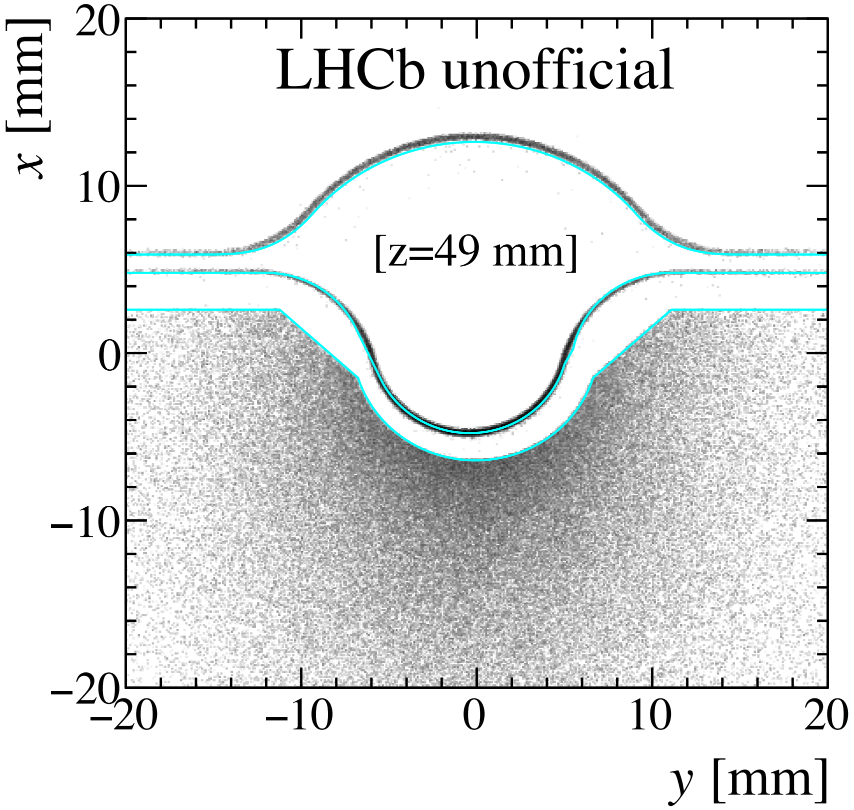


SM rates agree well with our predictions as do backgrounds, which means that the potential A' production rate does too—first search is ongoing.

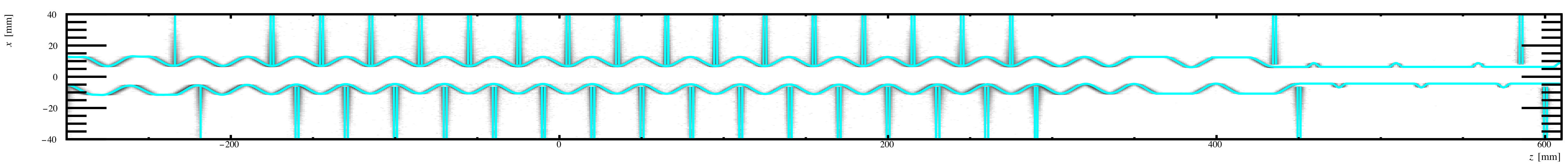
Data-Driven Material Map

High-precision 3-D VELO material map built using beam-gas collision data—and many many hours of fitting. We now know precisely where all the material is, so can proceed with vetoing it.



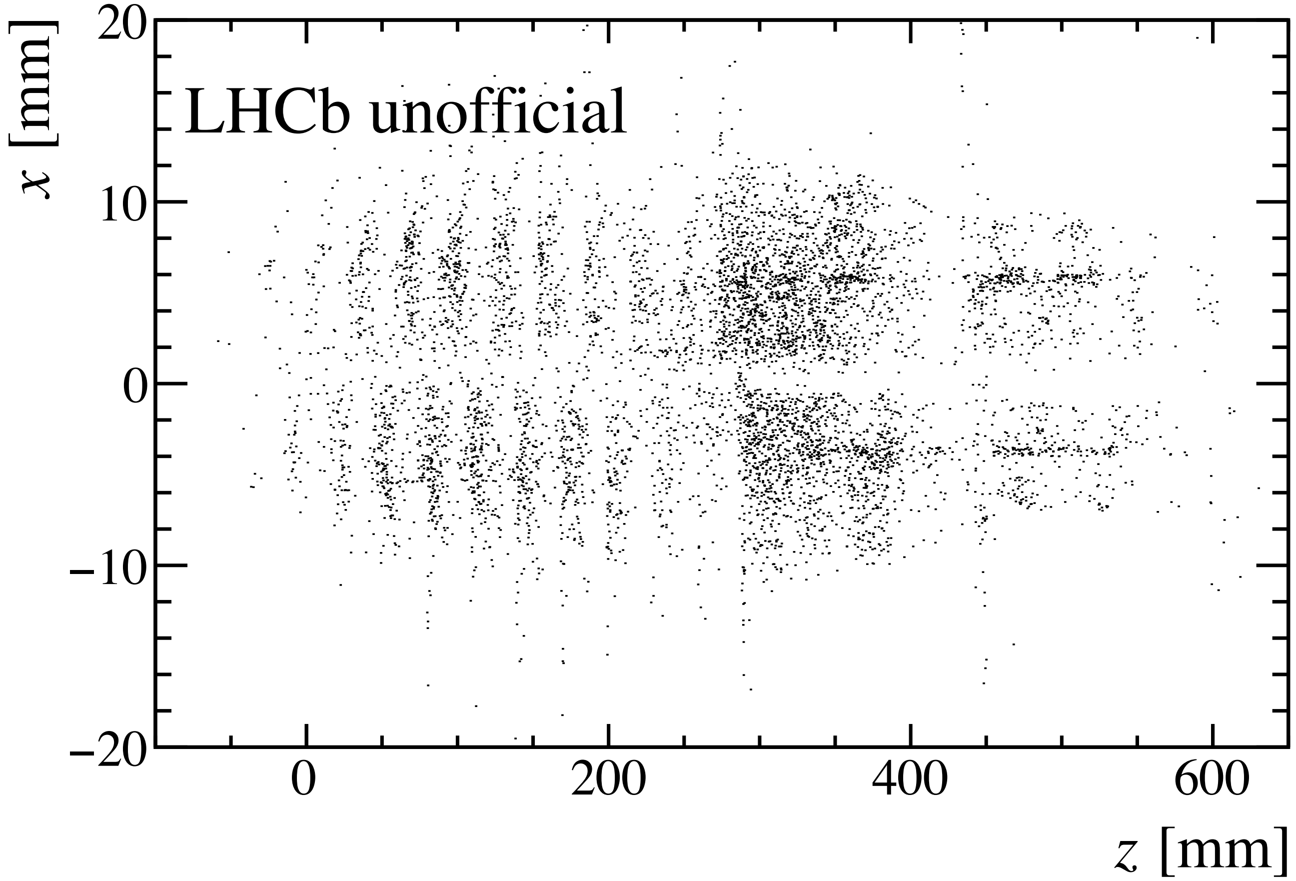


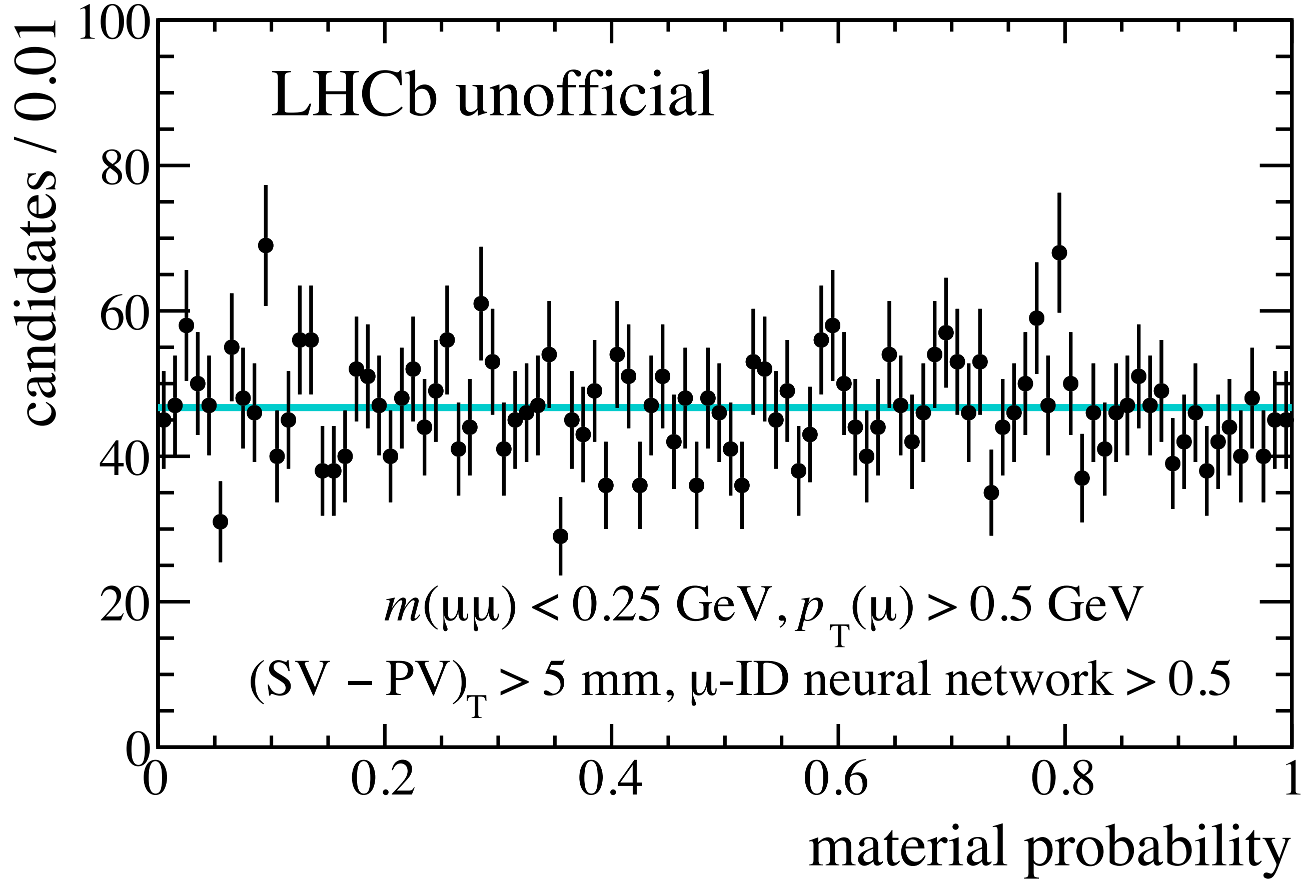
Below is the same map but to scale (i.e. horizontal vs vertical scales).

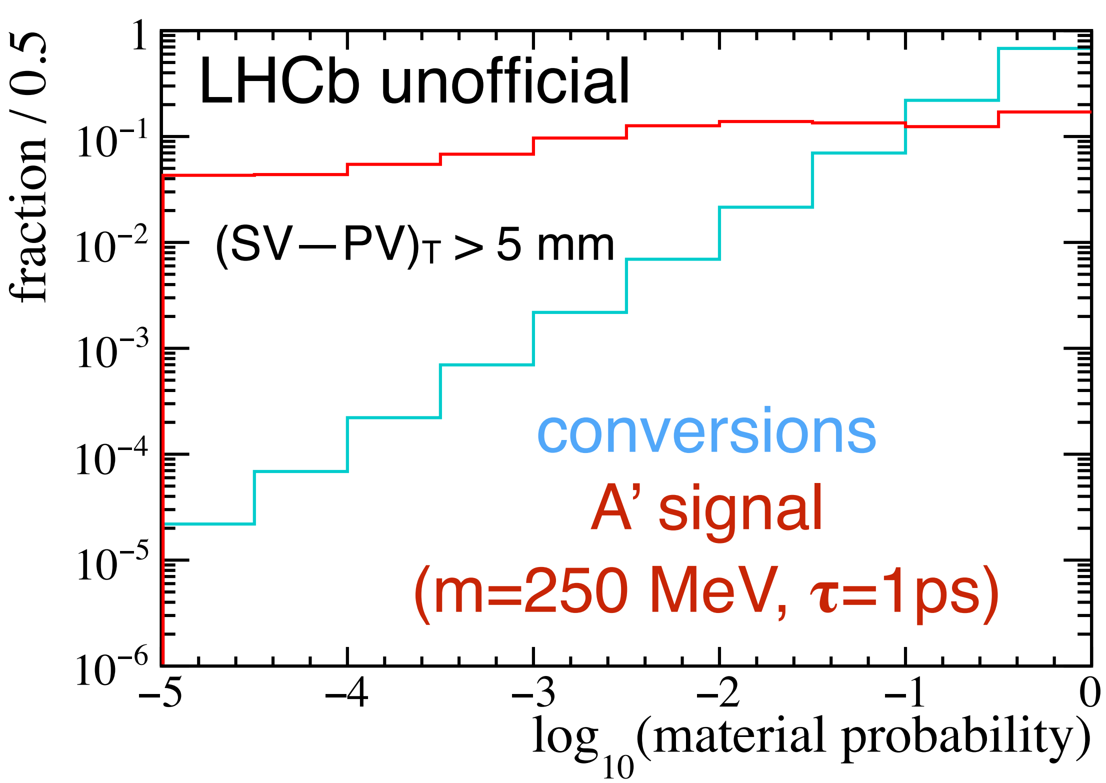


Data-Driven Material Map

By identifying & removing all track/vertex pathologies, we can then calculate the probability an SV originates from material and veto (nearly) all conversions.







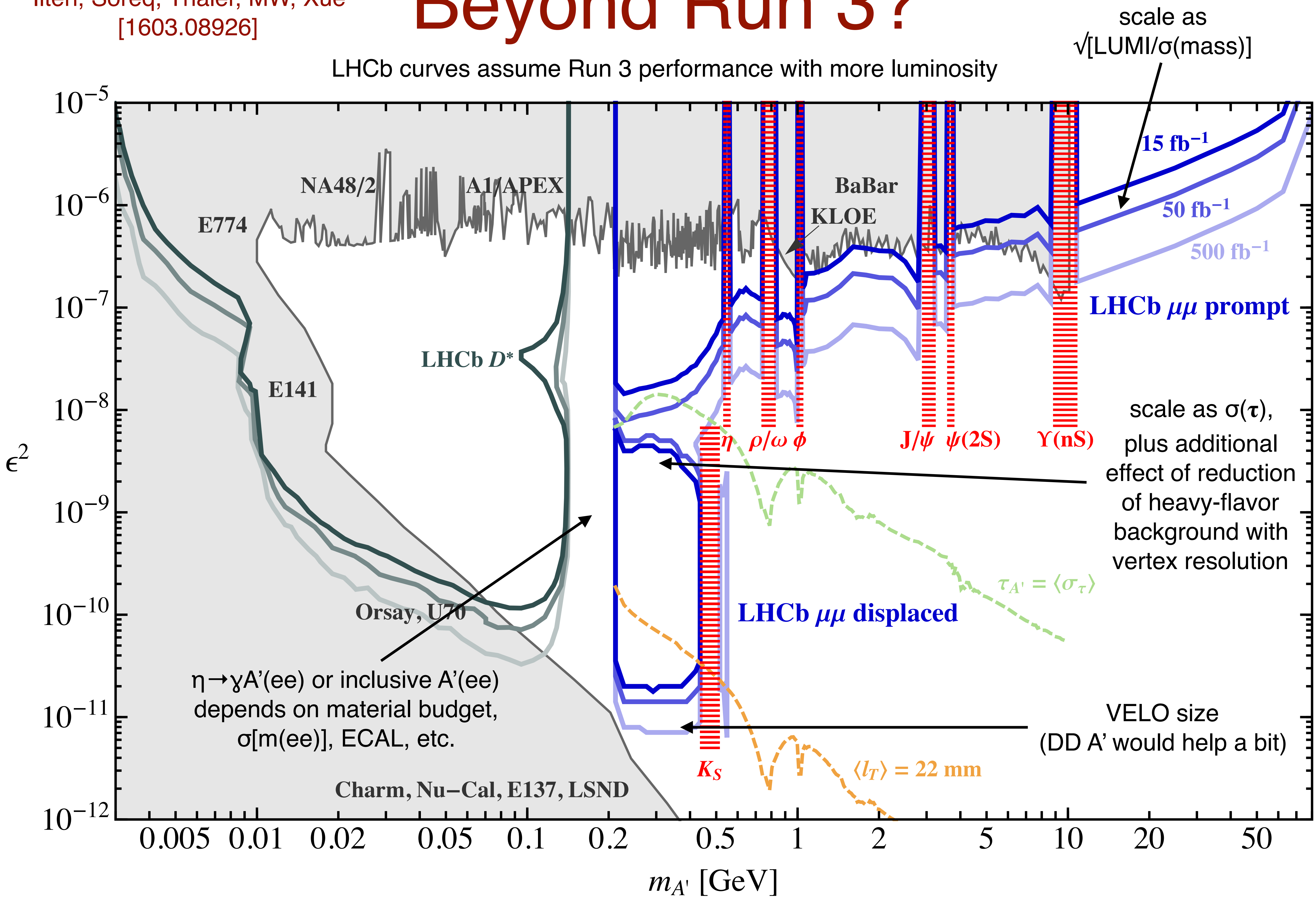
Performance depends on pixel size, material budget (& volume) vertex resolution, etc.

Expect impact of removing the RF foil to be larger for the di-electron decay given that conversions happen at a much larger rate and multiple scattering affects electrons more. Could we just look for $\eta \to \gamma A'(ee)$ or inclusive $A'(ee)$?

Ilten, Soreq, Thaler, MW, Xue
[1603.08926]

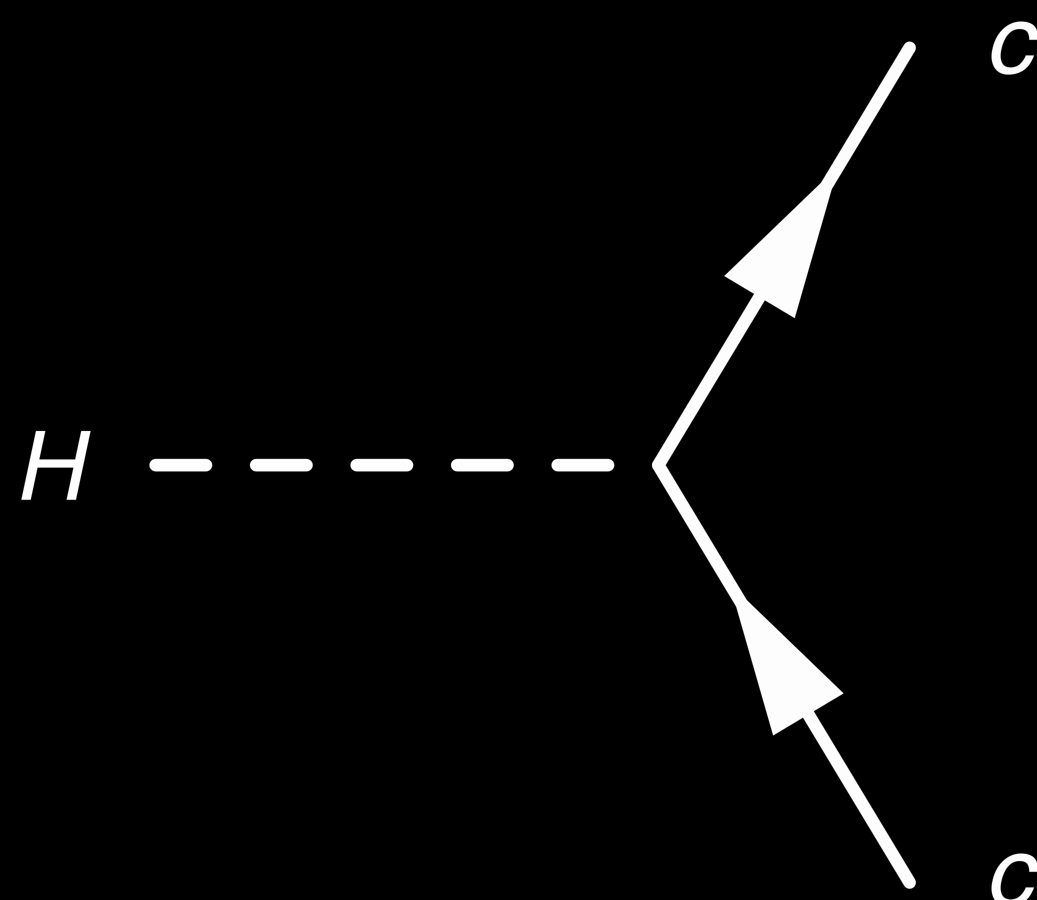
Beyond Run 3?

LHCb curves assume Run 3 performance with more luminosity



Magnet chambers would help with soft A' decays to e+e- (efficiency and/or resolution).

And now for something completely different…



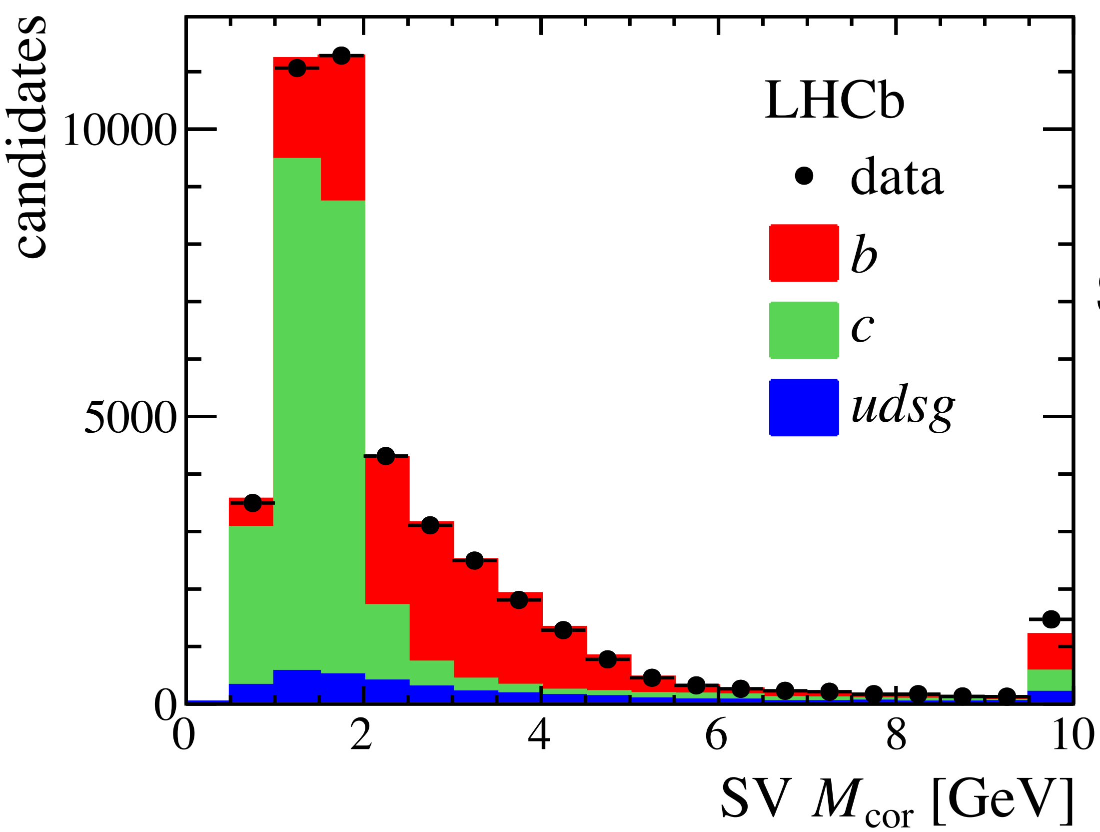
…the Higgs-Charm Yukawa coupling.

Jet Tagging (Now)

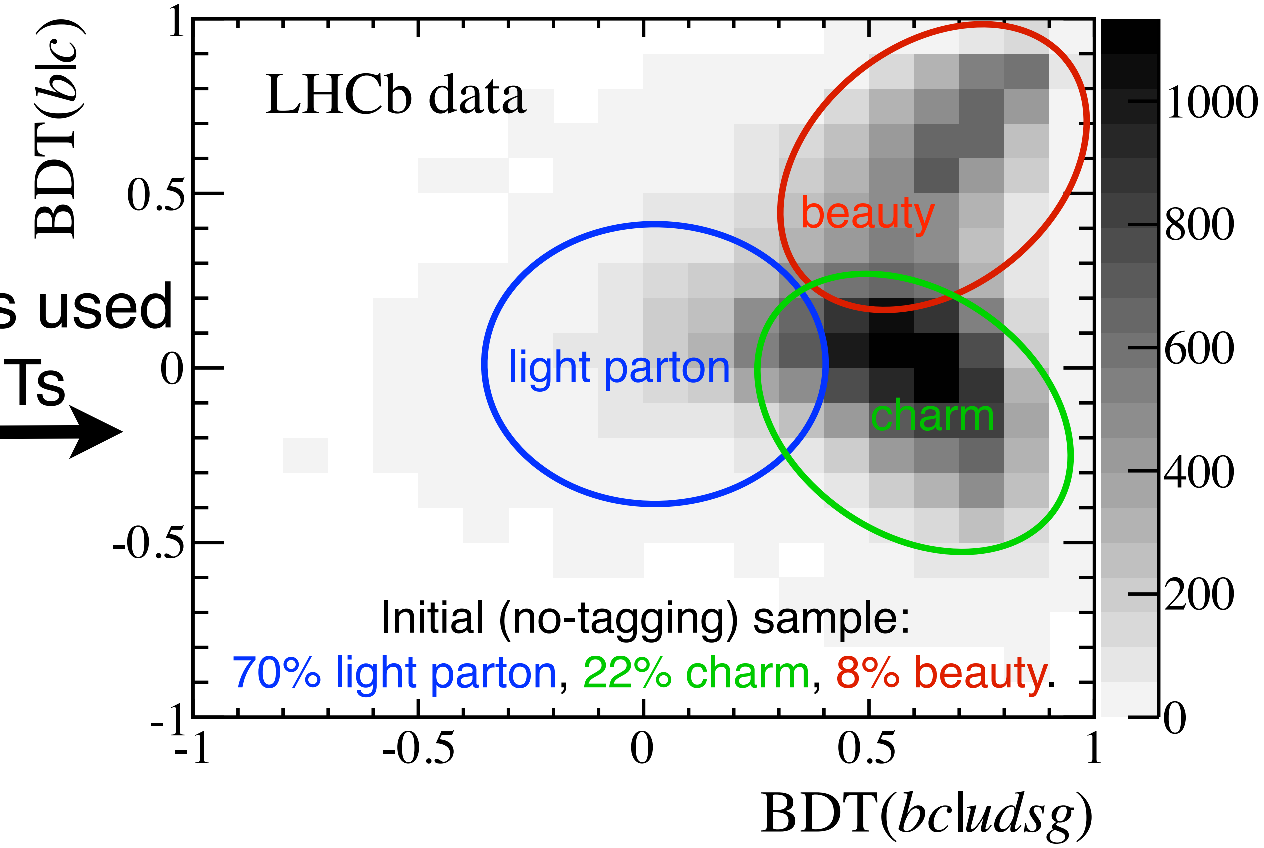
JINST 10 (2015) P06013
LHCb-PAPER-2015-016

Use a SV-based algorithm to identify b and c jets (leveraging LHCb VELO), achieving 65% b-tag and 25% c-tag efficiencies (with some p_T dependence).

example SV feature: “corrected mass”



SV features used in 2 BDTs



Used in Run 1 to observe top (PRL 115 (2015) 112001), study Wc, Wb (PRD 92 (2015) 052001), Wbb, Wcc (PLB 767 (2017) 110), & set limits on VH[bb,cc] (LHCb-CONF-2016-006).

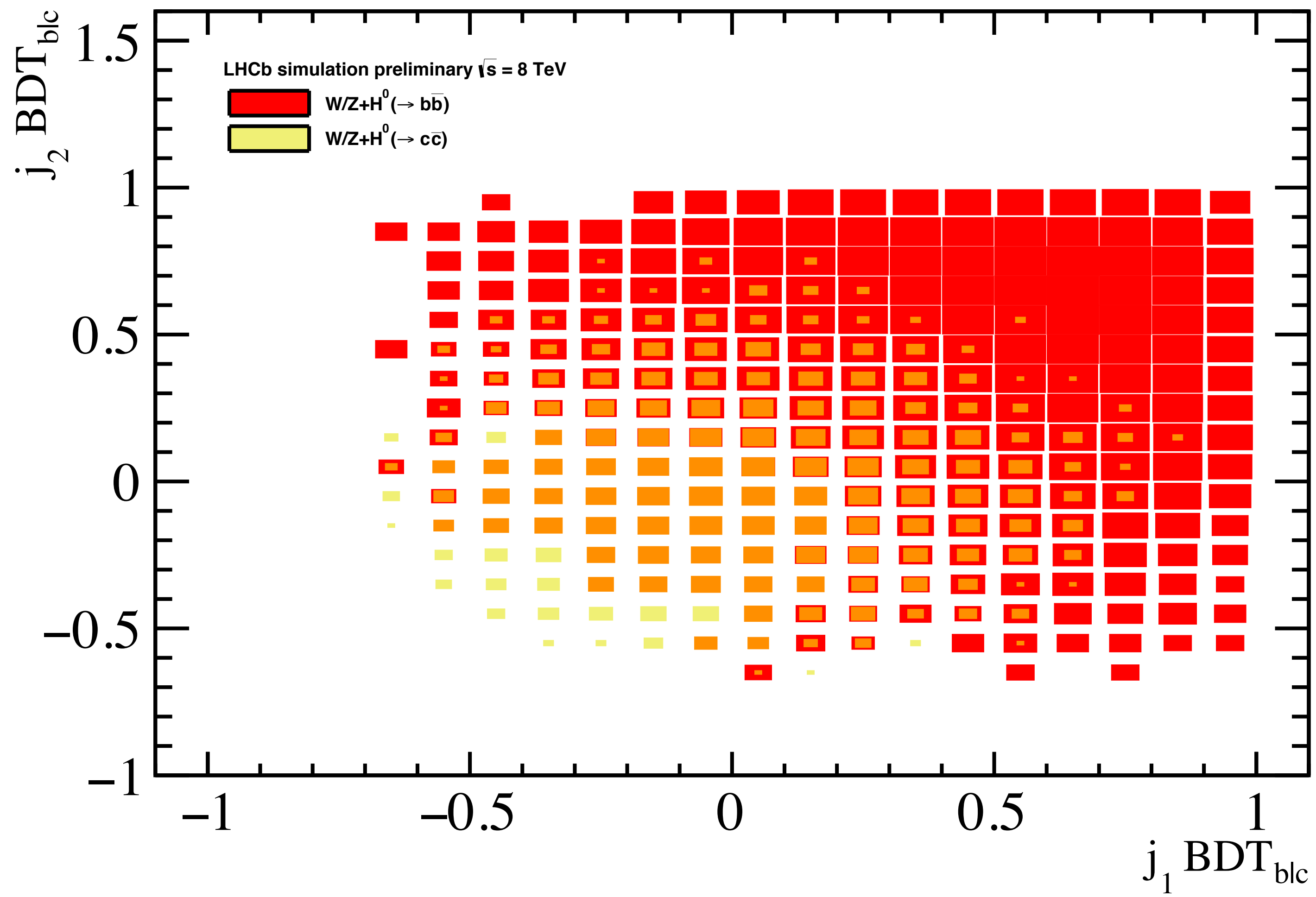
Can also be used to measure the massive QCD splitting kernels and to study gluon splitting to heavy flavor (Ilten, Rodd, Thaler, MW [1702.02947]), to probe charm PDFs (Boettcher, Ilten, MW [1512.06666]), etc.

LHCb-CONF-2016-006

VH[cc] in Run 1

LHCb set 95% CL ULs of 50xSM on σ(pp→VH)xB(H→bb) and 6400xSM on σ(pp→VH)xB(H→cc) (observed 0 events) using 2/fb of 8 TeV Run 1 data (the di-c-tag efficiency for the criteria used in VH[cc] was about 2%).

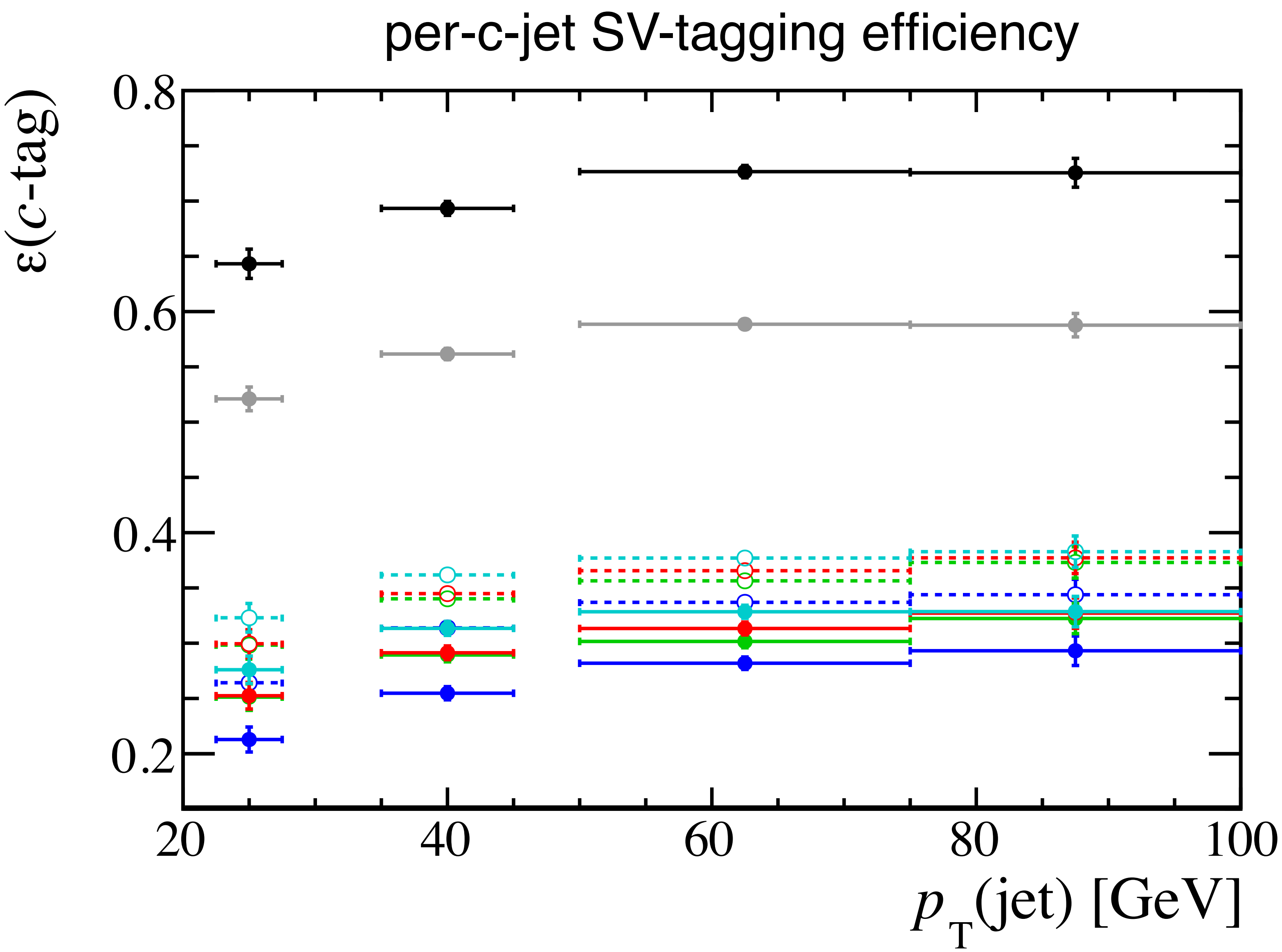
2D jet-tagging BDT distributions for VH[bb] and VH[cc] assuming SM Yukawas.



N.b., the product of the VH[QQ] cross-section x acceptance increases by a factor of ~7 going from 8 to 14 TeV.

Jet Tagging (Then?)

Improvements in the IP resolution directly translate into increased c-tagging efficiency. Similar improvement likely from moving to σ(mcor)-based (rather than IP X^2-based) selection as in LHCb-PAPER-2015-013 and Ilten, Thaler, MW, Xue [1509.06765].



Perfect detector, i.e. has true SV in kinematic fiducial region.

Perfect IP resolution, but including RECO efficiency (assumed to be same as Run 1, which may not be true), etc.

Phase-II Scenario 2

Phase-II Scenario 1

Run 3

Run1

Solid: IP $X^2 > 16$ (as in Run 1)

Dashed: IP $X^2 > 9$

The probability of SV-tagging at least one c-jet in H→cc is 50-55%. Likely best option is to apply a looser tag to the other jet, giving ~30% di-c-tag efficiency.

VH[cc] @ 300/fb

Projecting the 8 TeV VH[cc] limit to 300/fb @ 14 TeV gives ~50xSM, ignoring any improvements in the analysis or detector.

Assuming a 30% di-c-tag efficiency reduces this to 13xSM, while also improving electron reconstruction gives 9xSM. Assuming a dedicated c-tagging algorithm can suppress the non-Wcc background to be negligible results in 6xSM. Better analysis (DL?) gives ???

Independently of LHCb-CONF-2016-006, we estimated the sensitivity using NLO Powhegbox VH[cc] and Vcc events (Vcc assumed to be only relevant background). Applying a pre-selection similar to the LHCb top observation paper, then an ML-based selection similar to that of the CMS VH[bb] analysis, predicts a limit of 5xSM assuming 15% jet pt resolution.* The reach scales as √(lumi x efficiency / m(cc) resolution). *See talk by Will Barter for discussion on jet energy resolution.

Therefore, a SM-like observation of VH[cc] is likely out of reach (due to lack of signal events), but a limit below 5-10xSM (2-3xSM on the Yukawa coupling) seems plausible with 300/fb.

N.b., VBF appears to be useless in LHCb acceptance (too QCD-like).

Etc

- LHCb-PAPER-2016-065: World's best sensitivity to *low-mass* long-lived particles, e.g. hidden-valley pions, produced in Higgs decays for lifetimes below 300ps. By adopting a fat-jet+substructure approach, we can push down to smaller masses. These results will continue to improve with luminosity for some time (forever?). Other rare Higgs decays? Emerging jets? More ideas than human power ATM.
- Due to curse of longevity, many things we have world-leading sensitivity to now (or in Run 3), may no longer be as interesting in Run 5, but conversely things we have no sensitivity to now will become interesting then.
- 95% exclusion sensitivity is not the same as 5σ discovery potential. We want to make a discovery(!), and then make precision measurements of properties.
- No shortage of viable ideas for dark matter, with little reason to prioritize. Hidden sectors do not need to be heavy (in fact, light mediators are preferred in many scenarios). Need to be lucky, but greatly increase our chances by covering as much space as possible—need to make sure we trigger on everything we can.
- LHCb is a unique detector and moving to a triggerless readout will greatly expand our non-flavor BSM potential, making us the premier low-mass BSM laboratory for many types of DM theories. Even maintaining the Run 3 performance while collecting 300/fb will provide enormous discovery potential.

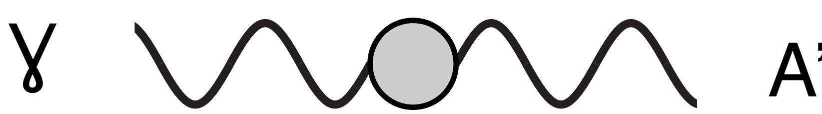
Summary

LHCb is a general-purpose detector in the forward region.

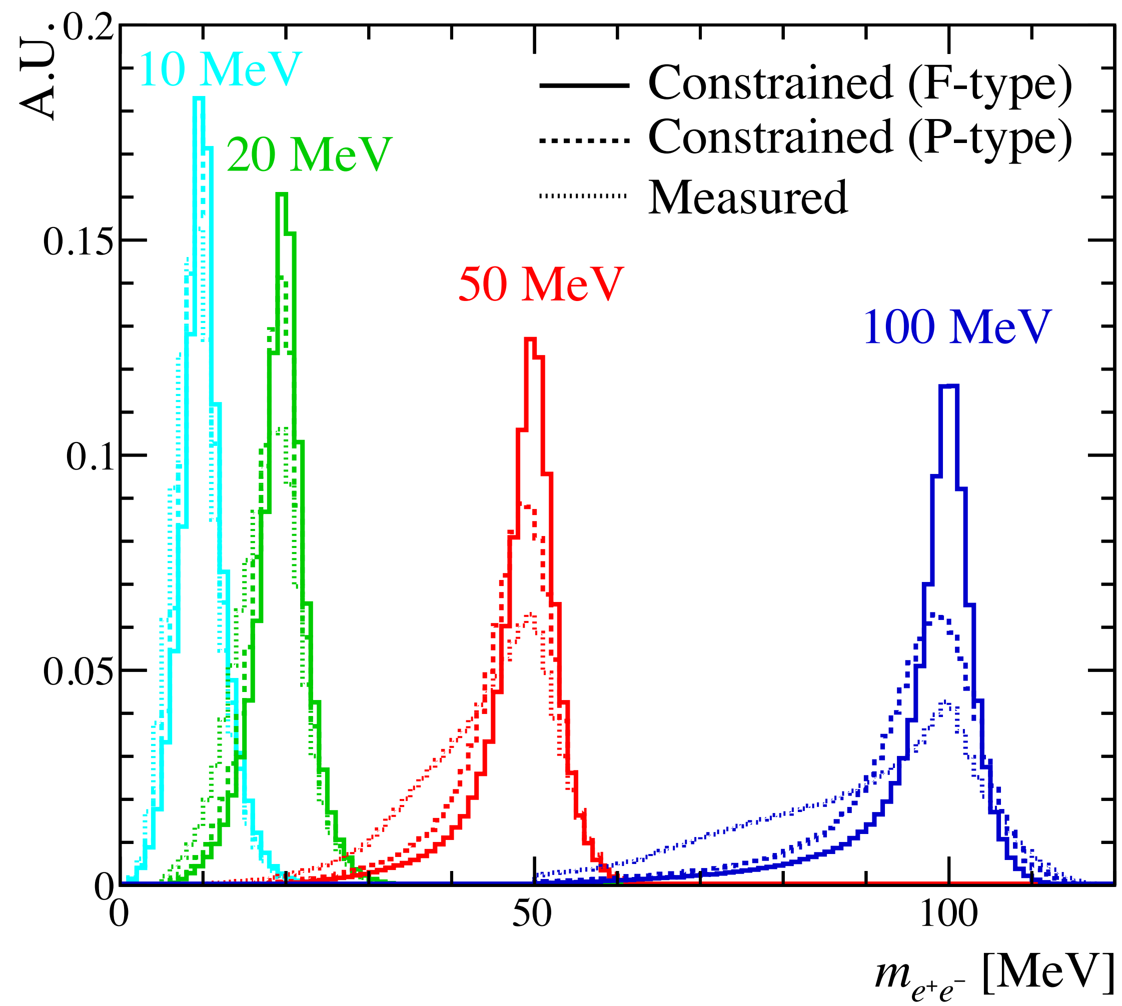
Dark Photons

For the low-mass region, consider the decay $D^{*0} \to D^0 A'(ee)$, which can potentially probe the region 2m(e) to ~142 MeV. The SM decay $D^{*0} \to D^0 \gamma$ will occur within LHCb acceptance at almost 1 MHz in Run 3.

Ilten, Thaler, MW, Xue [1509.06765]



$$\frac{\Gamma(D^{*0} \to D^0 A')}{\Gamma(D^{*0} \to D^0 \gamma)} = \epsilon^2 \left(1 - \frac{m_{A'}^2}{\Delta m_D^2}\right)^{3/2},$$



We required A' decays before reaching material to suppress conversions.

Poor m(ee) resolution due to BREM can be greatly improved by performing a mass-constrained fit using known $m(D^{*0})$ and well-measured D^0. Cutting on $m(D^0ee)$ will suppress combinatorial BKGD.