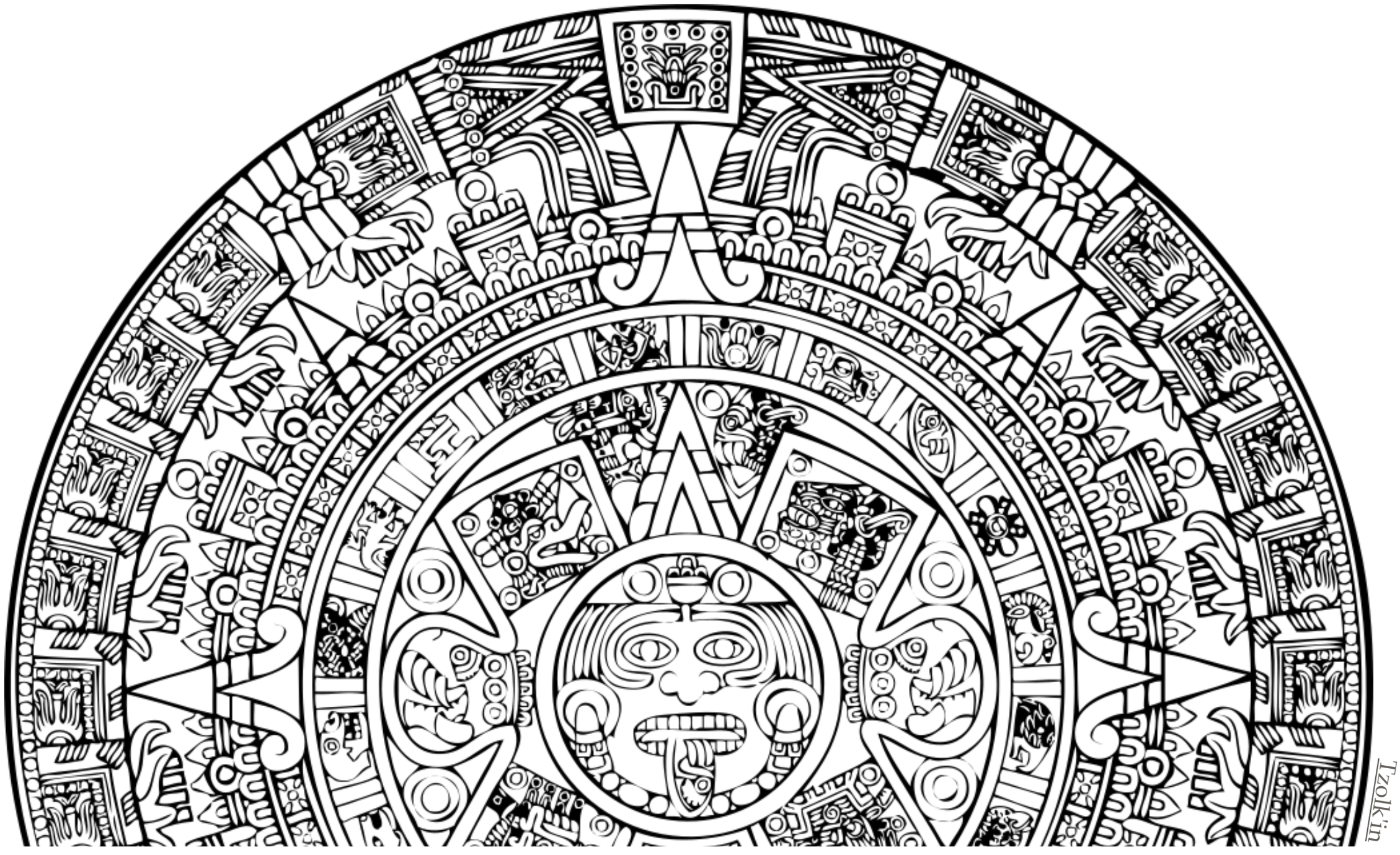


Searches for long-lived particles and other unconventional signatures

LHCP 2019 -Puebla

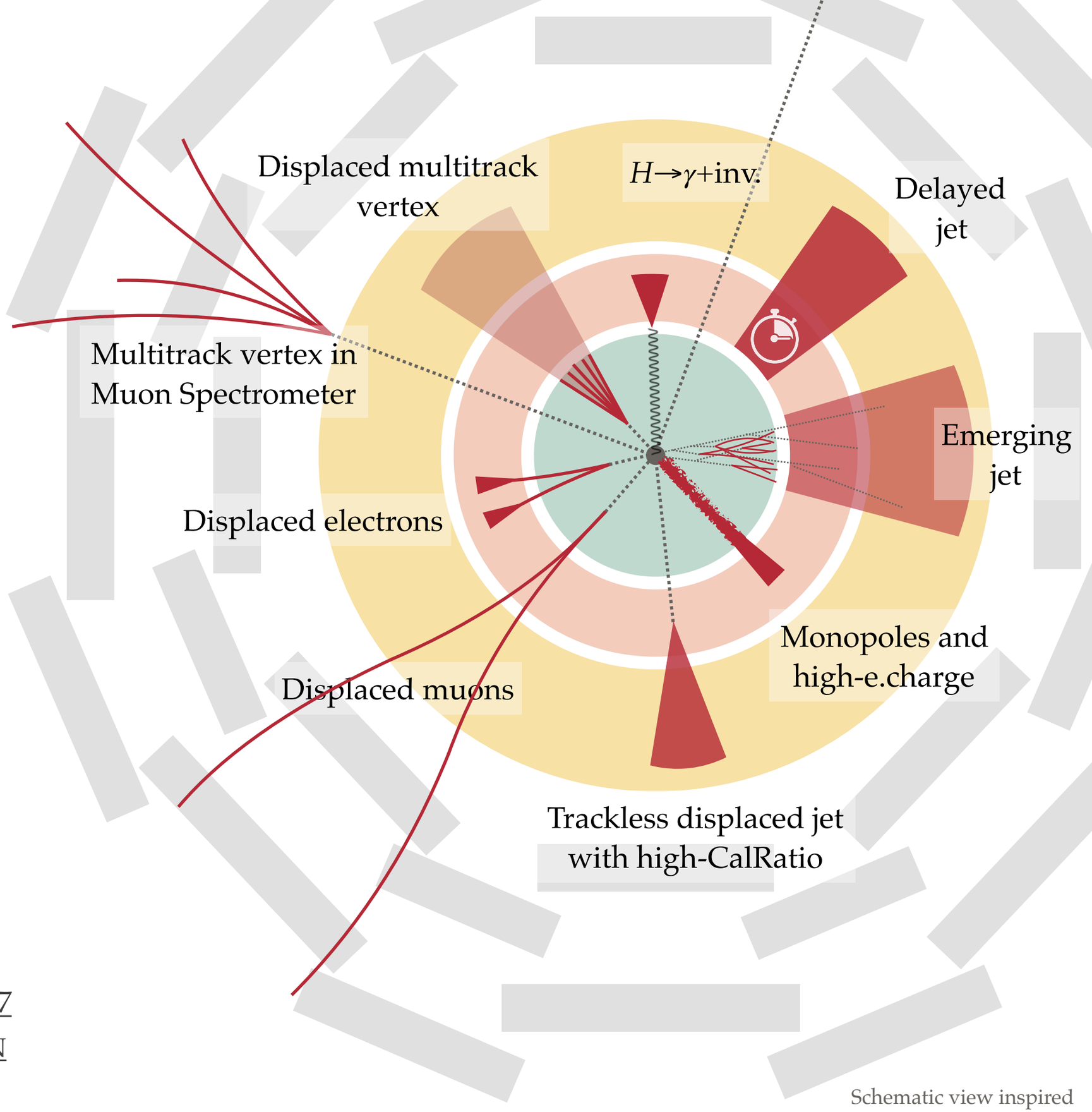
Martino Borsato

University of Heidelberg

On behalf of the ATLAS, CMS and LHCb Collaborations

- We need physics Beyond the SM
- No shortage of models
- No precise guidance

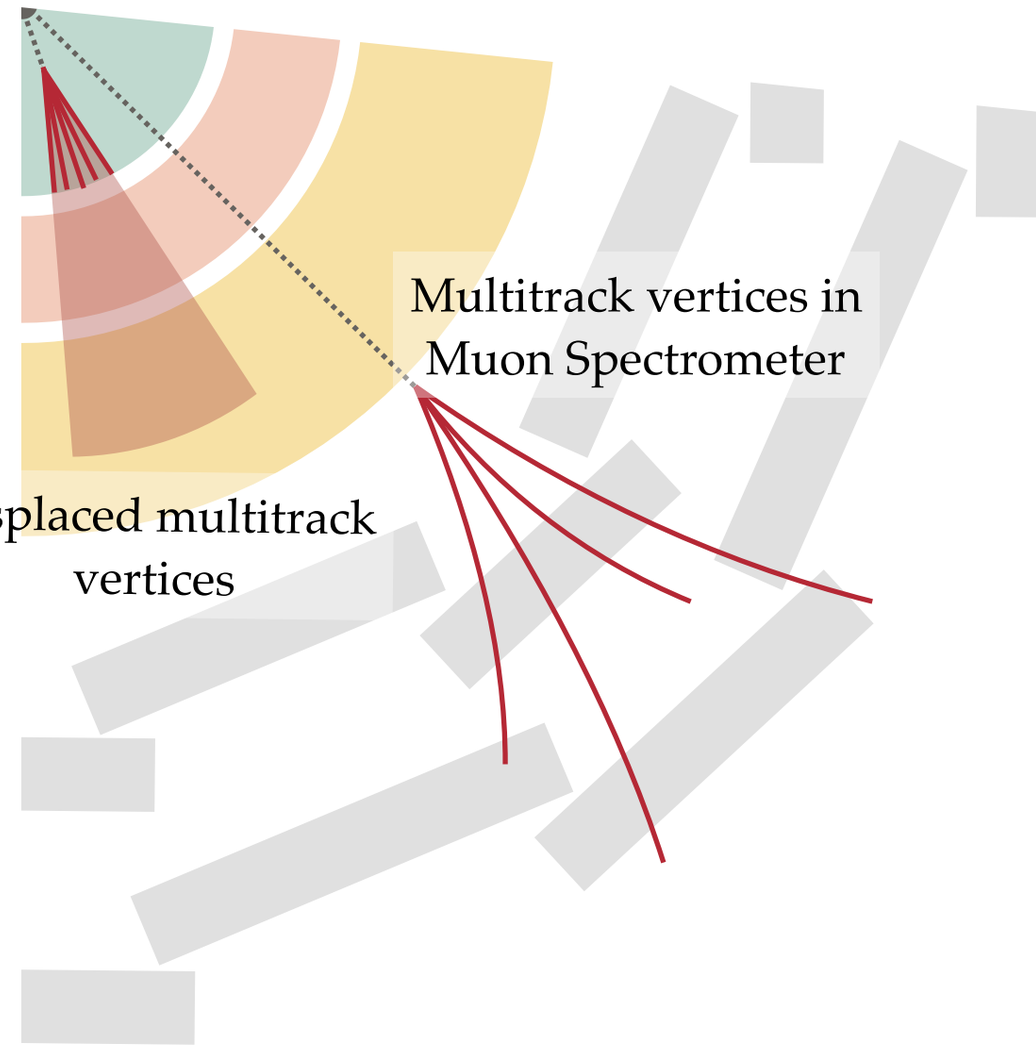
- Shift to **signature-first model-second** mindset
- Make sure we do not miss NP at the LHC
- Map signature space
  → Long-lived particles
  → Other unconventional
- LLP@LHC community
  → White paper arXiv:1903.04497
  → 5th workshop 27-29 May @CERN



Schematic view inspired from H.Russell's talk

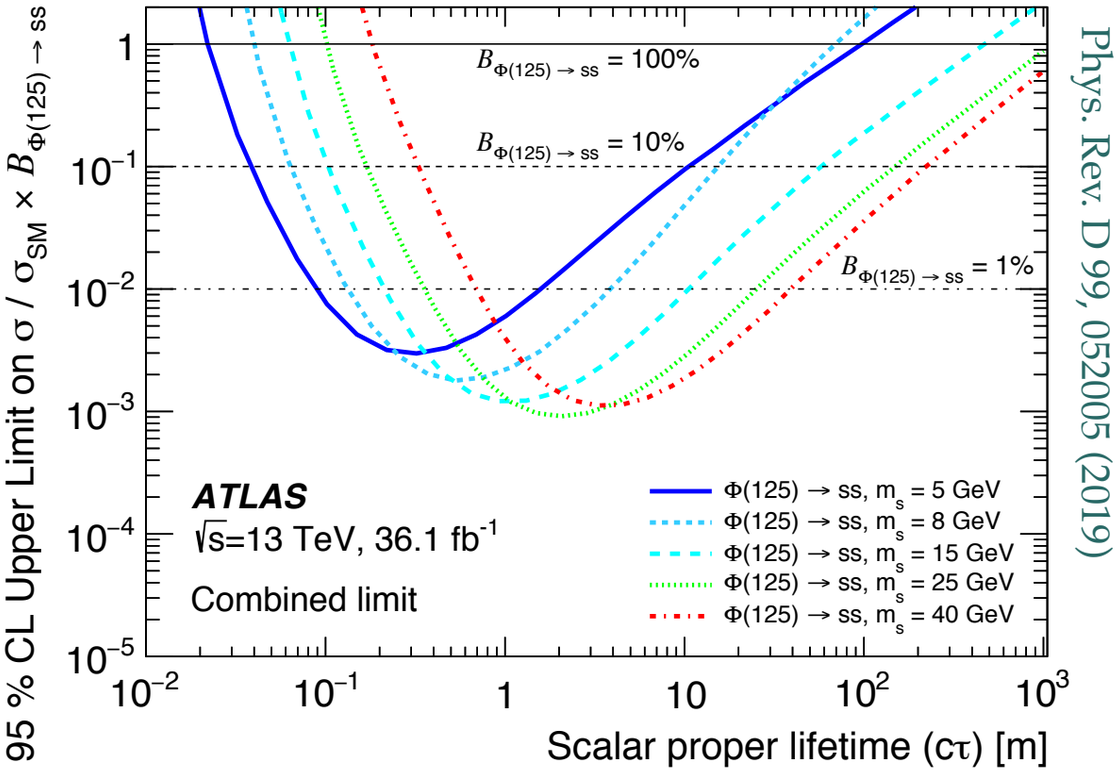
Displaced jets with tracks

- **CMS** search in tracker:
  - Phys. Rev. D 99, 032011 (2019)
  - 35.9 fb^{-1} of 13 TeV 2016 data
  - One displaced dijet (or two displaced jets)
  - $L_{xy} < 55$ cm
- **ATLAS** search in Muon Spectrometer
  - Phys. Rev. D 99, 052005 (2019)
  - 36.1 fb^{-1} of 13 TeV 2016 data
  - 2 displ. vertices or one + additional activity
  - Barrel: $4 < L_{xy} < 7$ m, Endcap: $6 < L_z < 13$ m
- **LHCb** search in VErtex LOcator
  - Eur. Phys. J. C77 (2017) 812
  - 2.0 fb^{-1} of 7-8 TeV data
  - One displaced dijet in Vertex Locator
  - $L_z < 20$ cm (forward boosted)



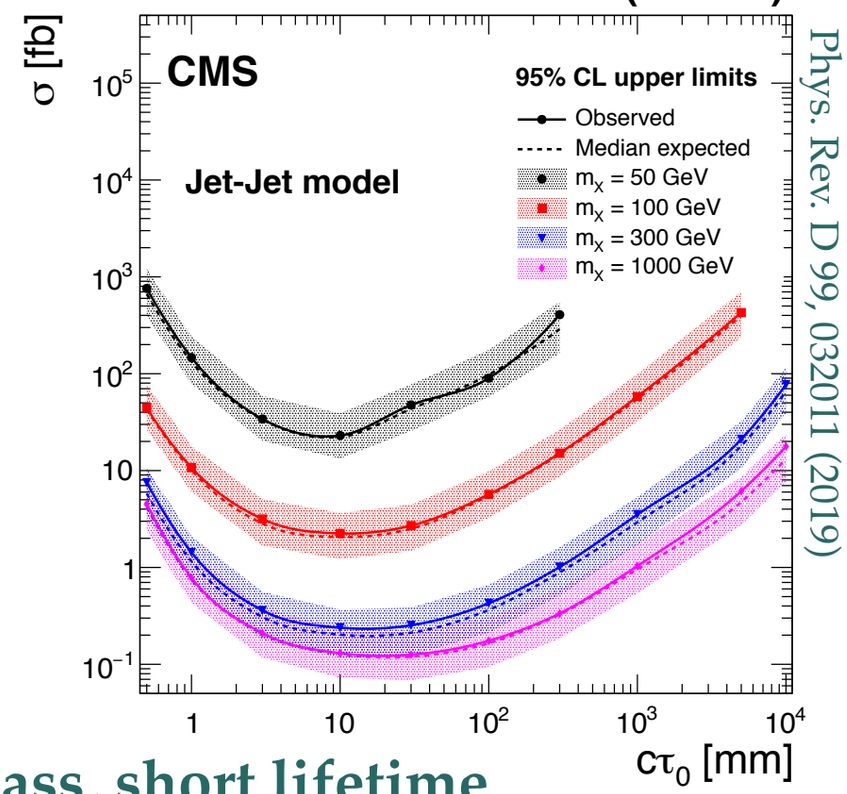
Displaced jets with tracks

Low mass, long lifetime



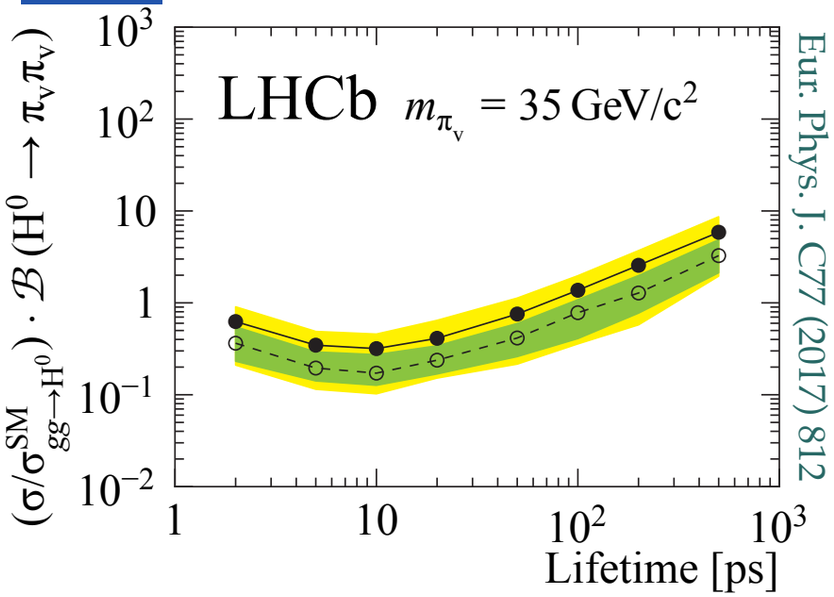
Phys. Rev. D 99, 052005 (2019)

Large mass, short lifetime



Phys. Rev. D 99, 032011 (2019)

Low mass, short lifetime

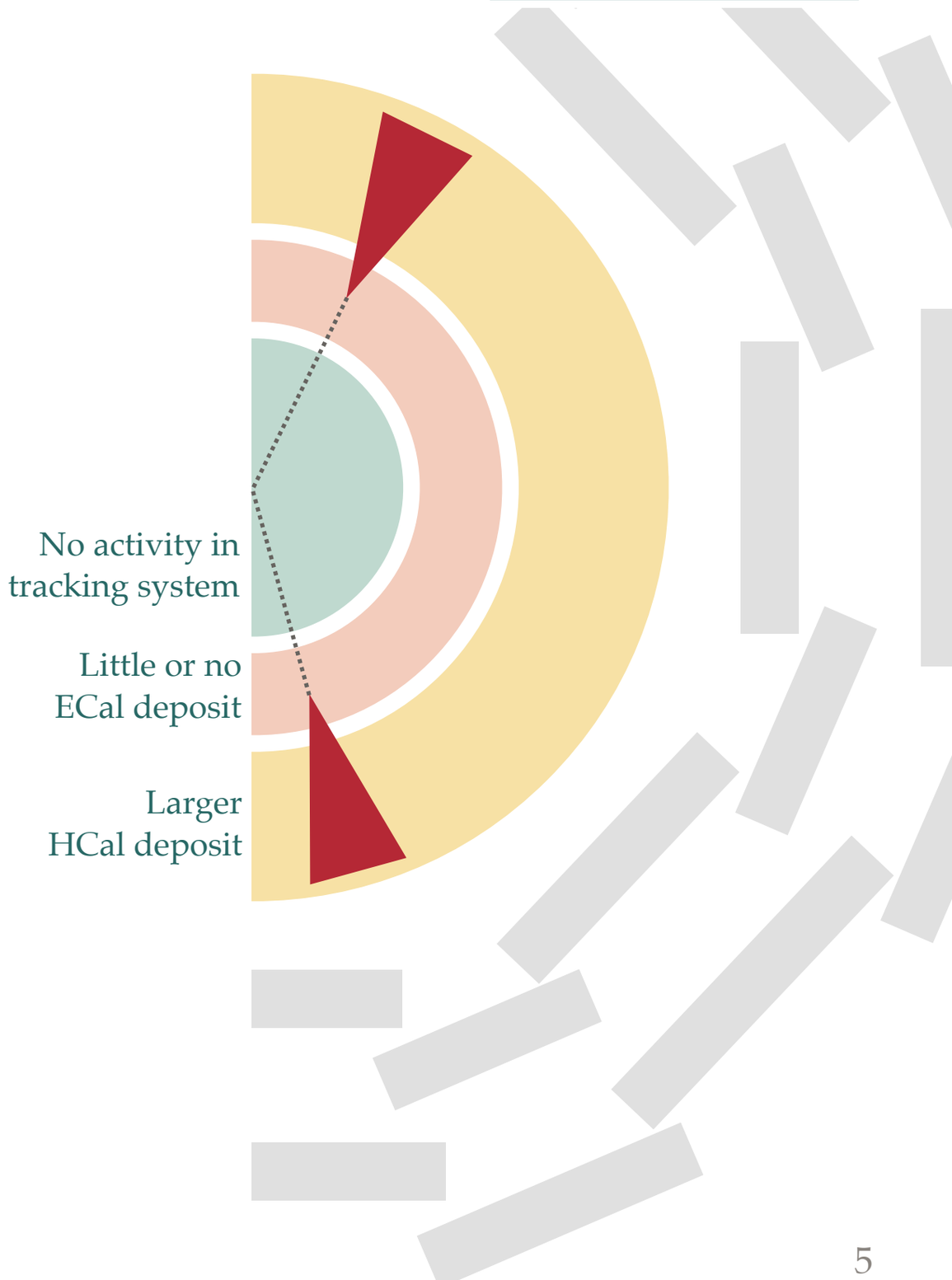


Eur. Phys. J. C77 (2017) 812

Trackless displaced jets

arXiv:1902.03094

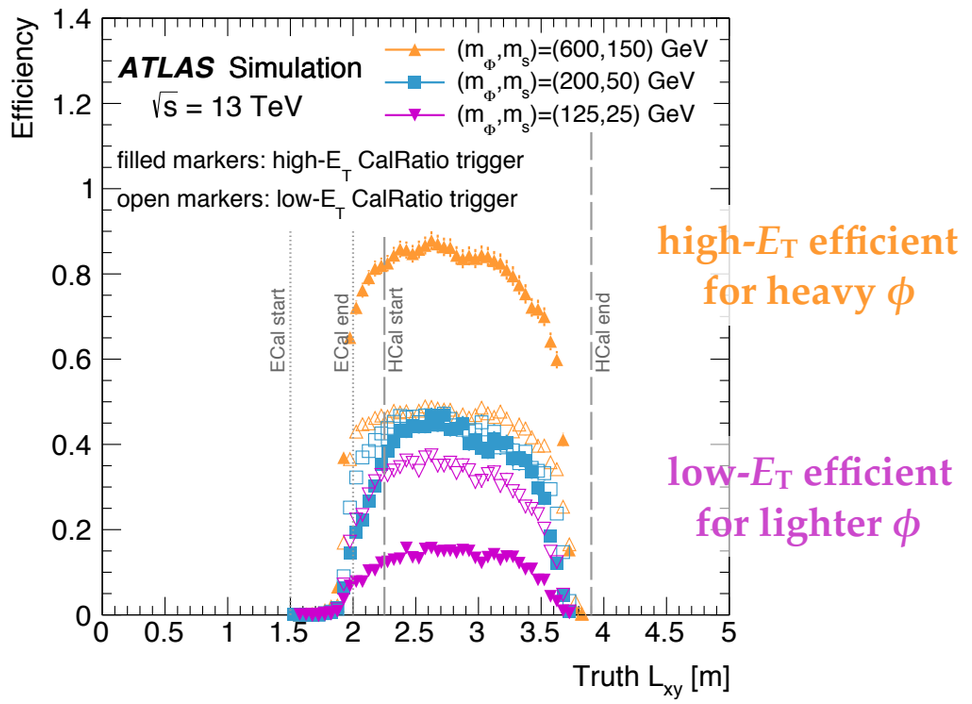
- Signature:
  - **Pair** of displaced jets decaying in calorimeters
  - No associated tracks
  - Narrow jet with high CalRatio = E_T(Hcal)/E_T(ECal)
- Dataset:
  - 33.0 fb^{-1} of 13TeV 2016 data of which 10.8 fb^{-1} with low-ET trigger
- Update of 8 TeV result PLB 743 (2015) 15 with many improvements



Trackless displaced jets

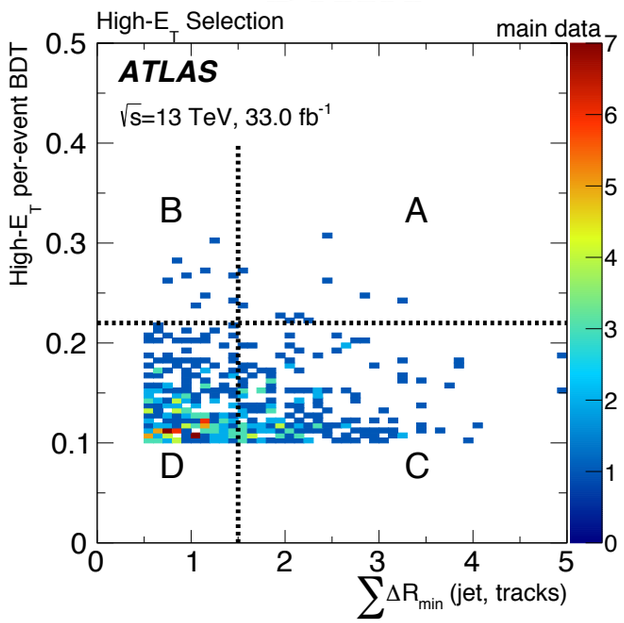
arXiv:1902.03094

- Hardware triggers:
  - **High-E_T jet** with E_T(HCal+ECal) > 60 GeV
  - **Low-E_T jet** with E_T(HCal) > 30 GeV and corresponding E_T(ECal) < 3 GeV
    → Possible in upgraded L1 trigger (Sep 16)

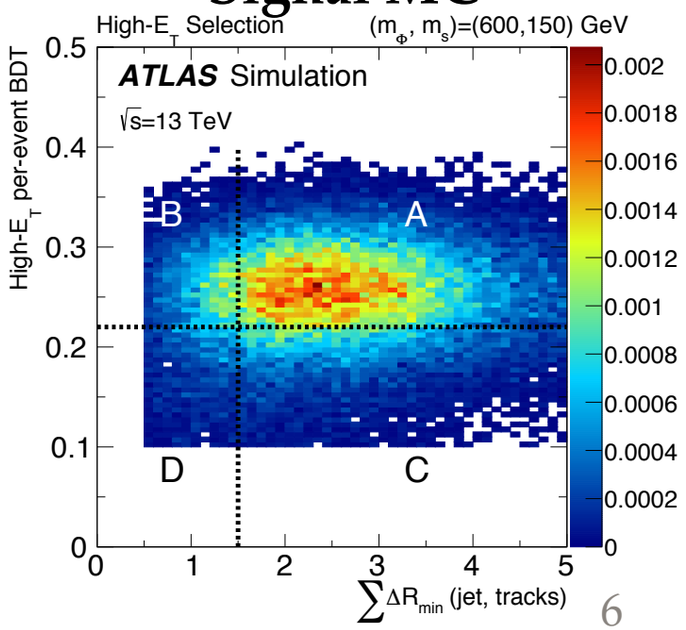


- Background:
  - Prompt multijet dominant
  - Estimated with **ABCD method**
    - **BDT for signal-vs-multijet**
    - **Proxy of trackless-ness**

DATA

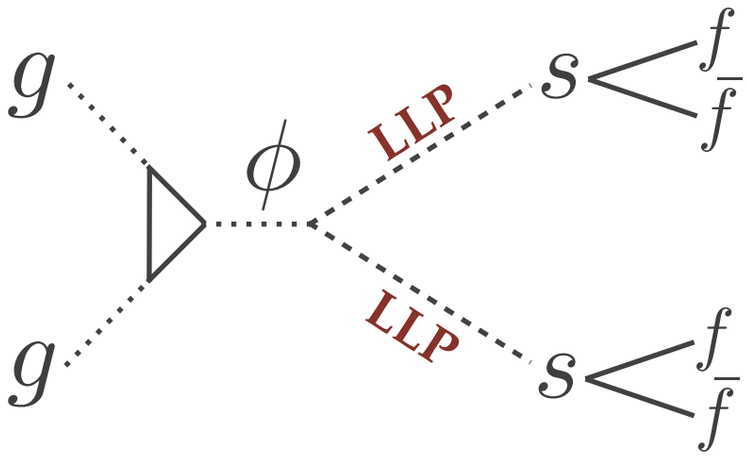


Signal MC

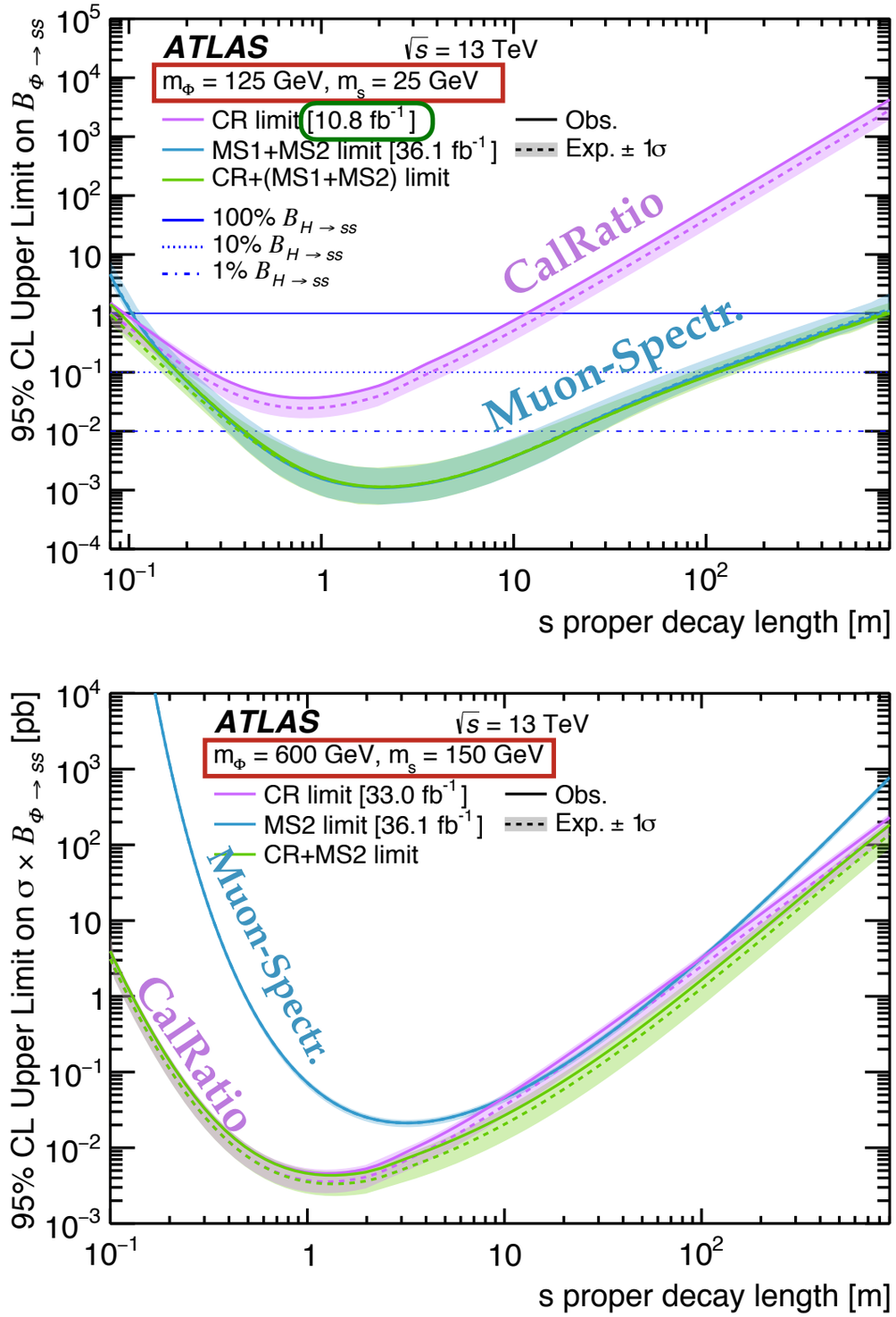


Trackless displaced jets

arXiv:1902.03094



- Upper limits on $\phi \rightarrow ss$ models (Hidden Valley, Higgs portal)
  - m_ϕ ~125 - 1000 GeV, m_s ~5 - 400 GeV
  - Improving MS search for lower cτ
  - Good prospects for low-E_T trigger

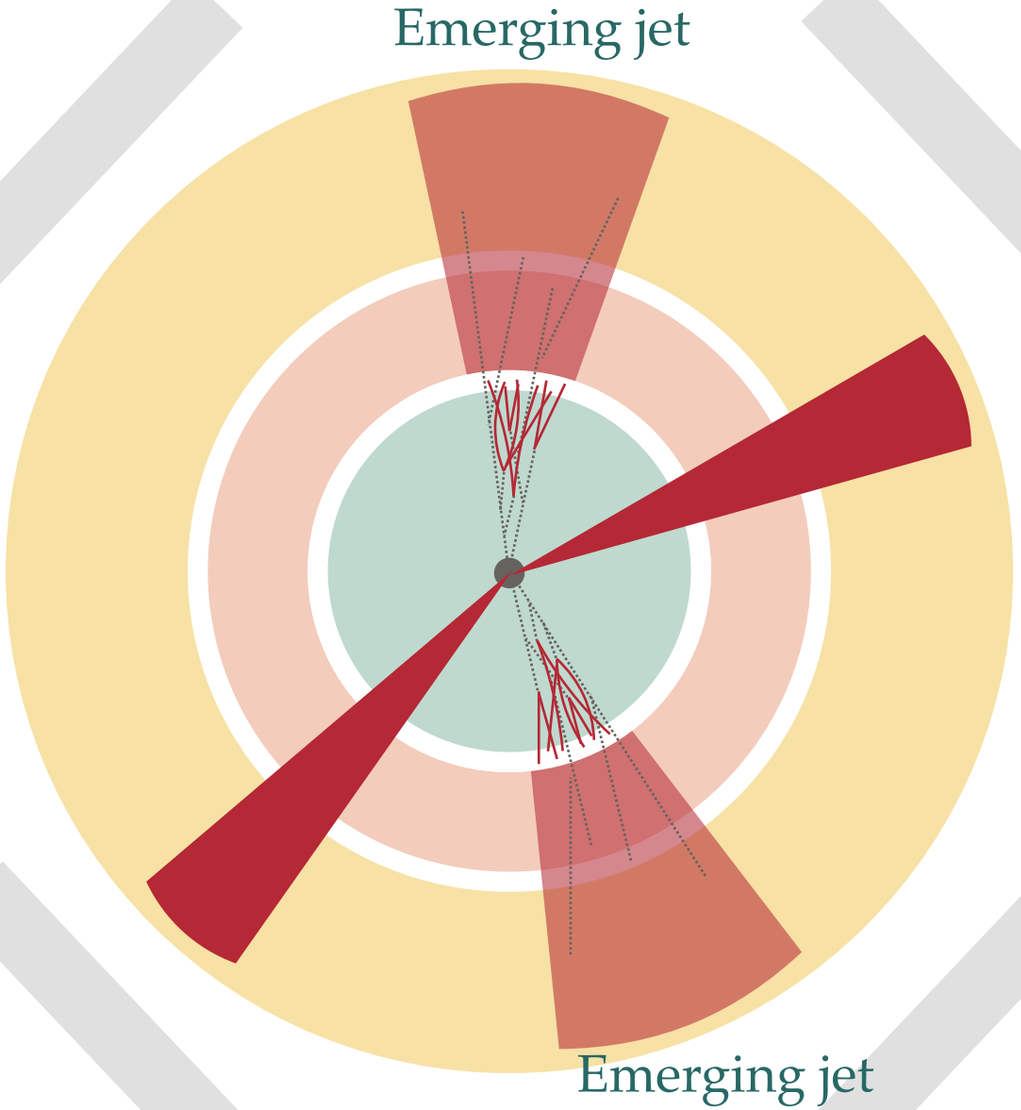


Jet + emerging jet

JHEP 02 (2019) 179

more details in J.Duarte's talk

- Signature:
  - **2 regular jets + 2 emerging jets (or 1 emerging jet + missing p_T)**
  - Emerging jet = containing many displaced vertices
- Dataset:
  - 16.1 fb^{-1} of 13TeV 2016 data
- First search of this kind

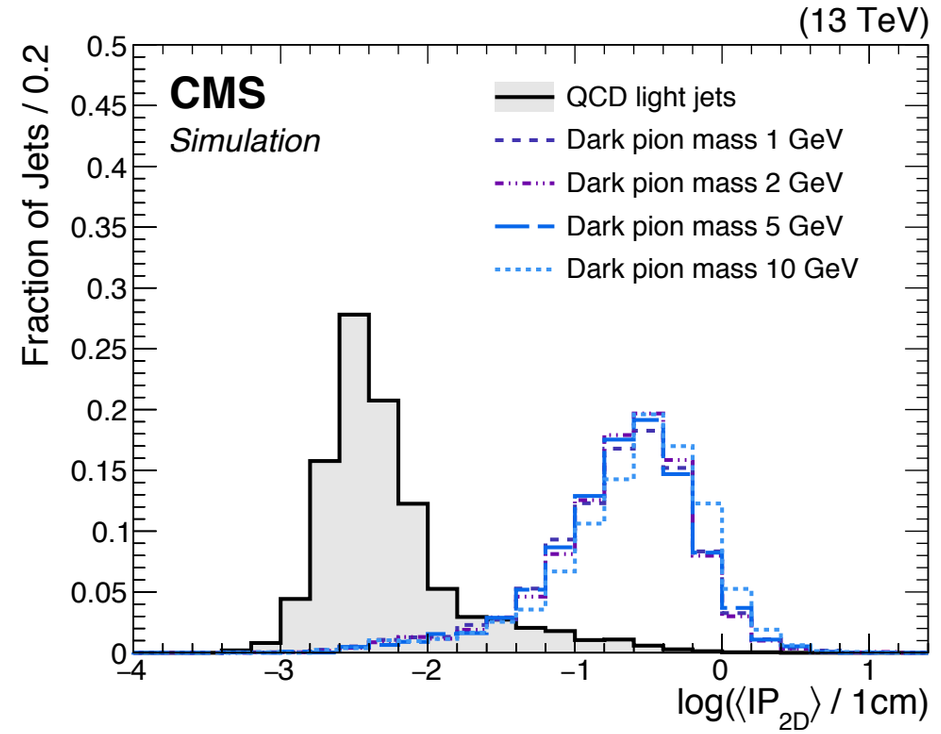


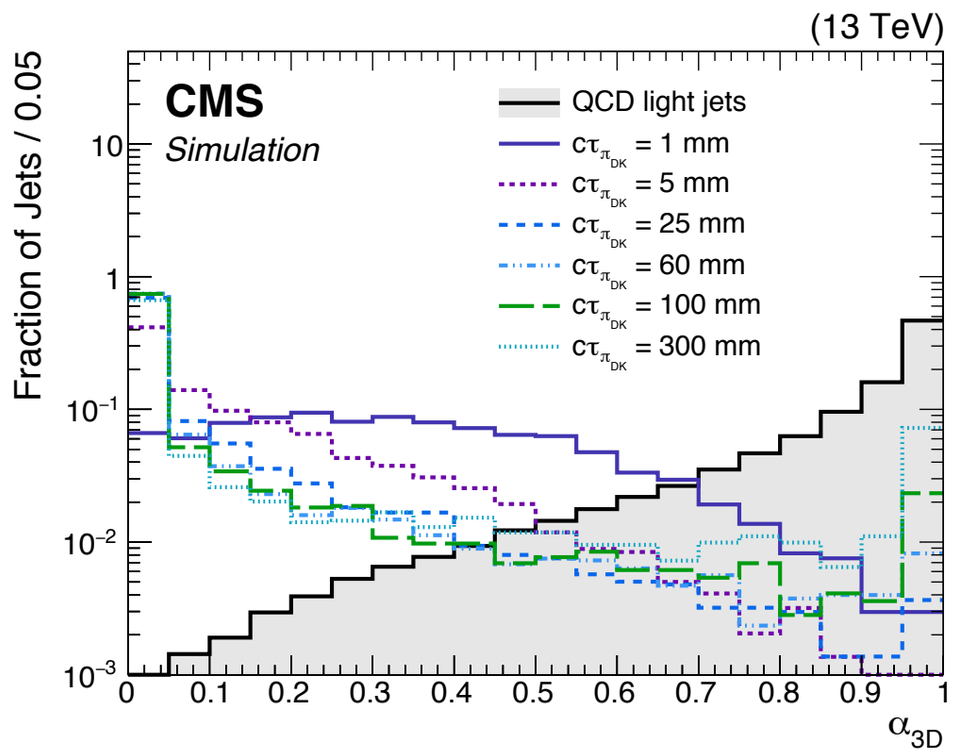
Jet + emerging jet

JHEP 02 (2019) 179

more details in J.Duarte's talk

- Trigger:
  - $\sum p_T(\text{hadronic}) > 900\,\text{GeV}$
- Selection:
  - Displaced jets identification:
    - displaced tracks (large **median 2D IP**)
    - Small fraction of jet p_T associated with prompt tracks (α_{3D})
- Background:
  - Data driven with 4-jets events
  - MisID probability of light jet as emerging jet modelled depending on parton flavour and jet multiplicity



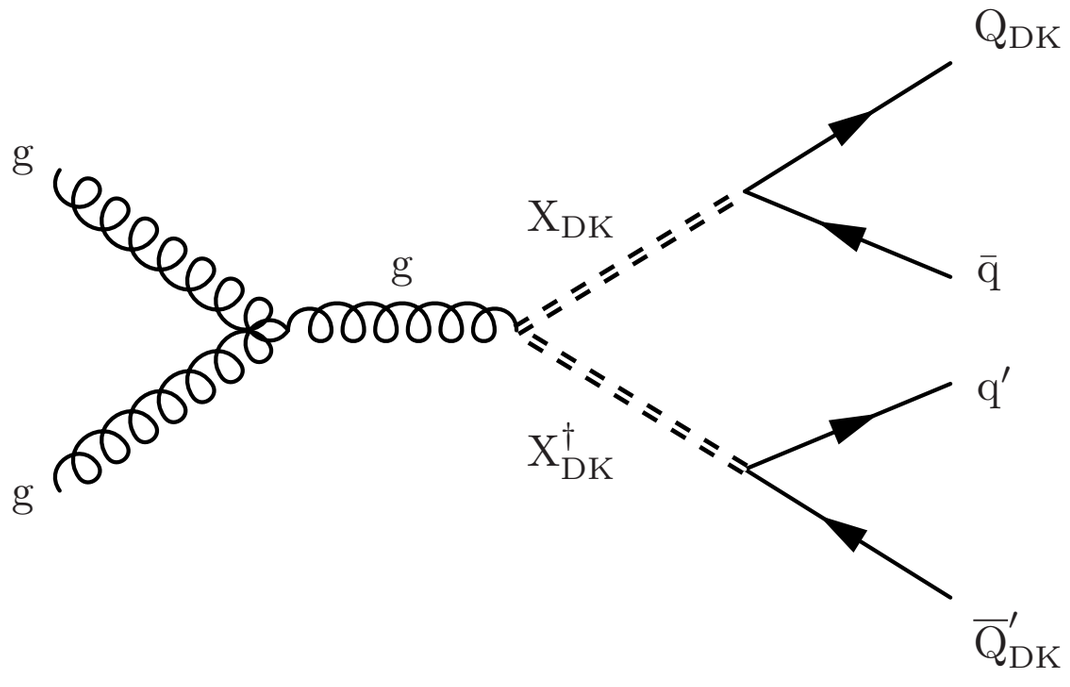


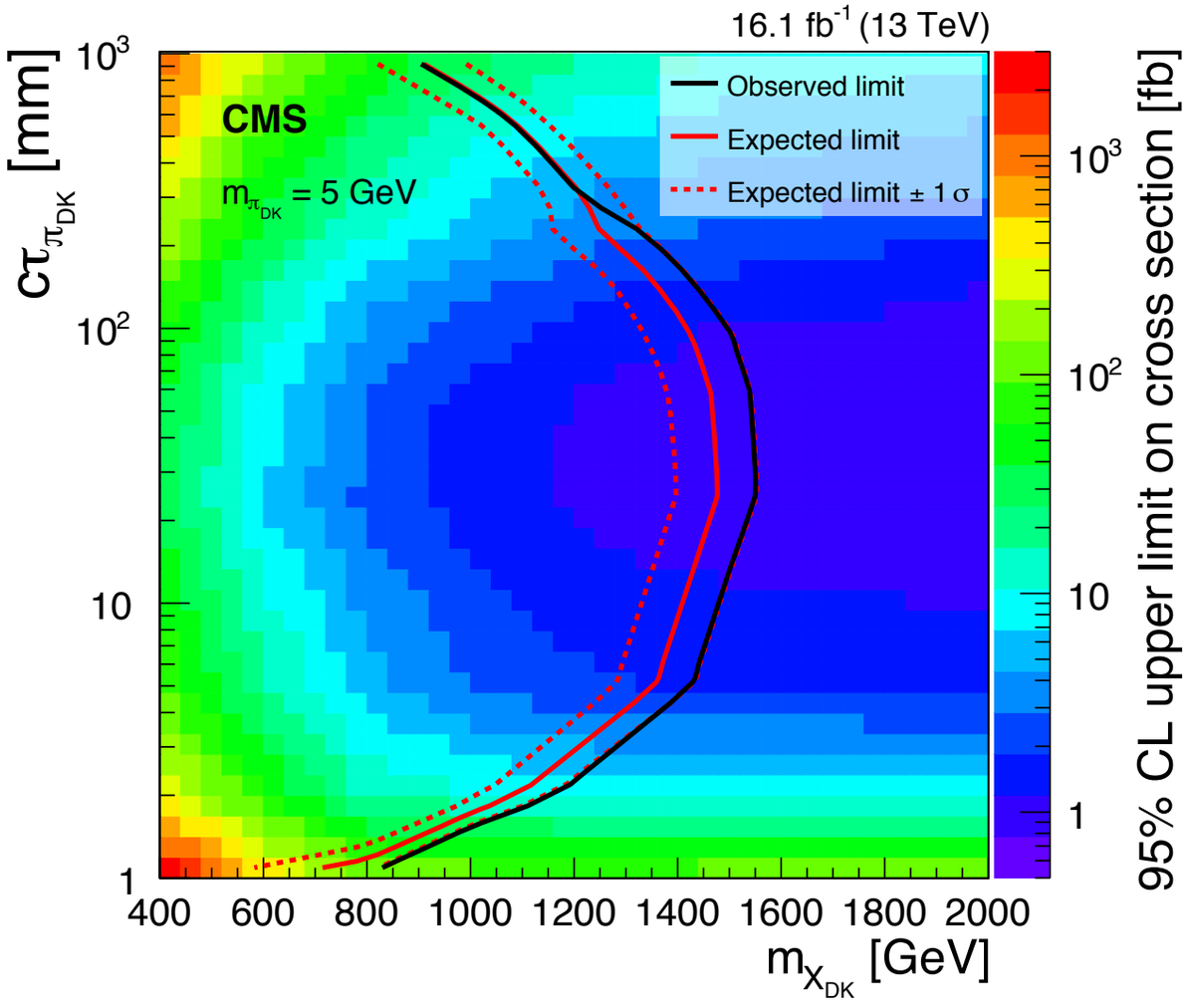
Jet + emerging jet

JHEP 02 (2019) 179

more details in J.Duarte's talk

- Dark QCD model
- Signal simulation discussed in P.Schwaller et al JHEP05(2015)059
- Pair produced heavy mediator $\mathbf{X_{DK}}$ (complex scalar)
- Dark quarks $\mathbf{Q_{DK}}$ shower in dark pions (emerging jet)

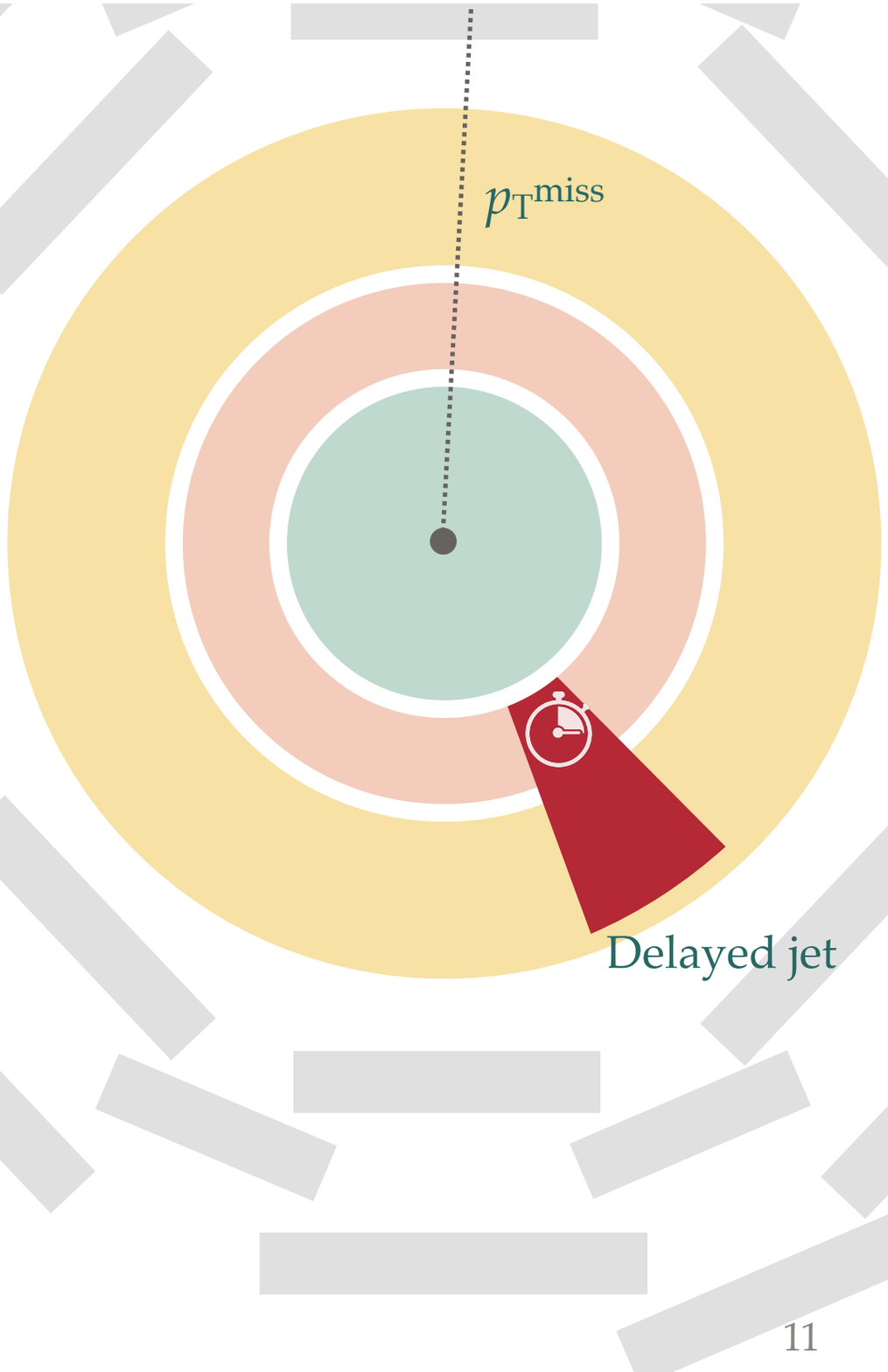




Delayed jet + MET

CMS-PAS-EXO-19-001

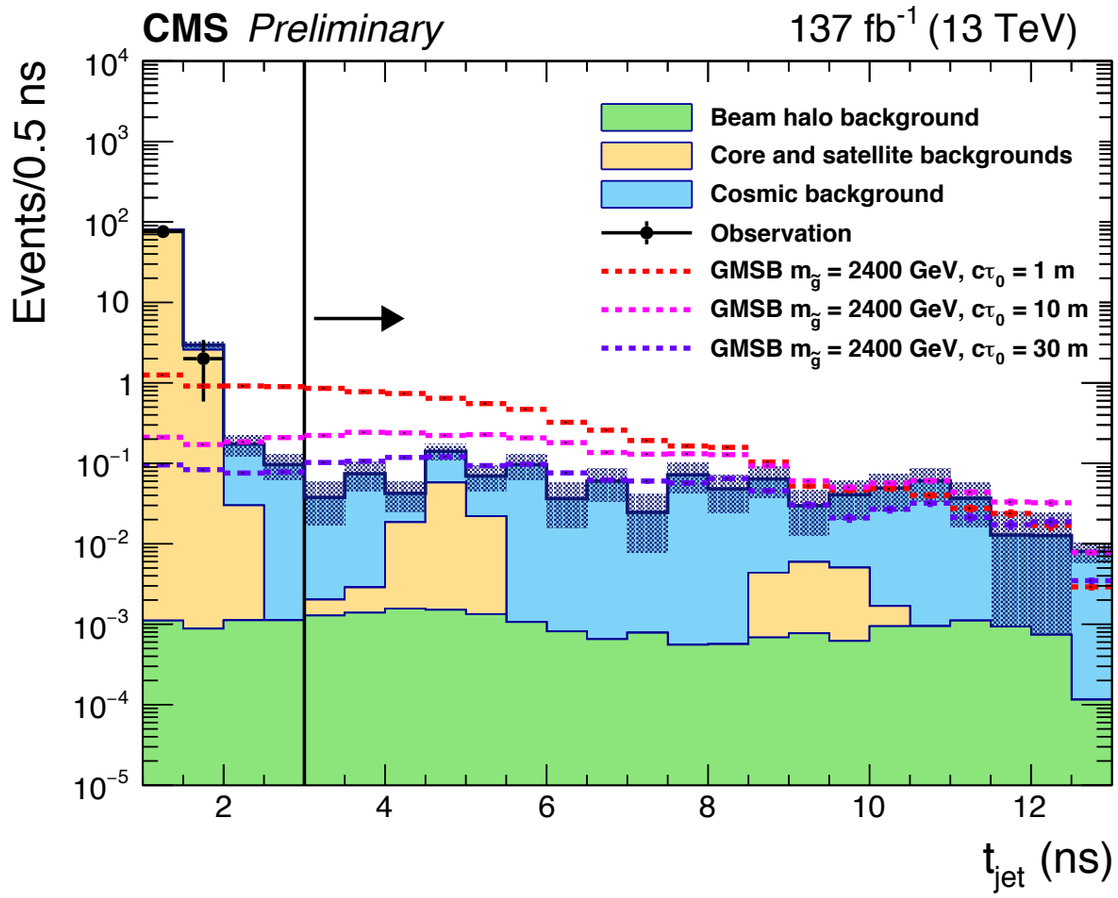
- Signature:
  - Missing p_T
  - **One delayed jet** ($t_{ECal} > 3$ ns)
- Dataset:
  - **Full Run-2**: 137 fb^{-1} at 13TeV
- Motivation:
  - Gauge-mediated SUSY breaking
  - Split SUSY, stealth SUSY, Hidden Valley, …



Delayed jet + MET

CMS-PAS-EXO-19-001

- Trigger:
  - $p_{\mathrm{T}}^{\mathrm{miss}} > 120\,\mathrm{GeV}$
- Selection:
  - Jet in barrel ECal
    → better t resolution = 0.2 ns
  - Small jet time RMS
  - 3 ns $< t_{\mathrm{jet}} <$ 20 ns
- Background:
  - Estimated with data using various control regions

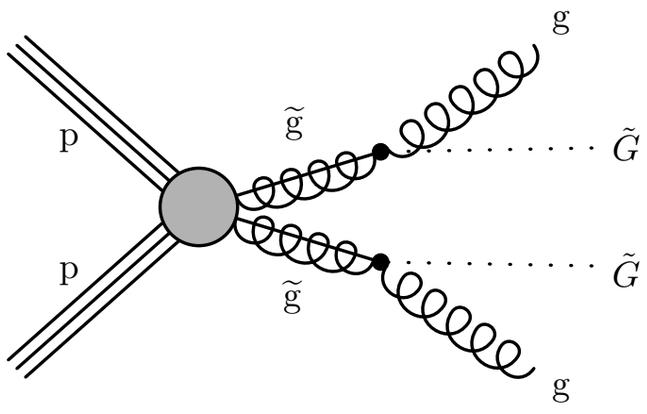


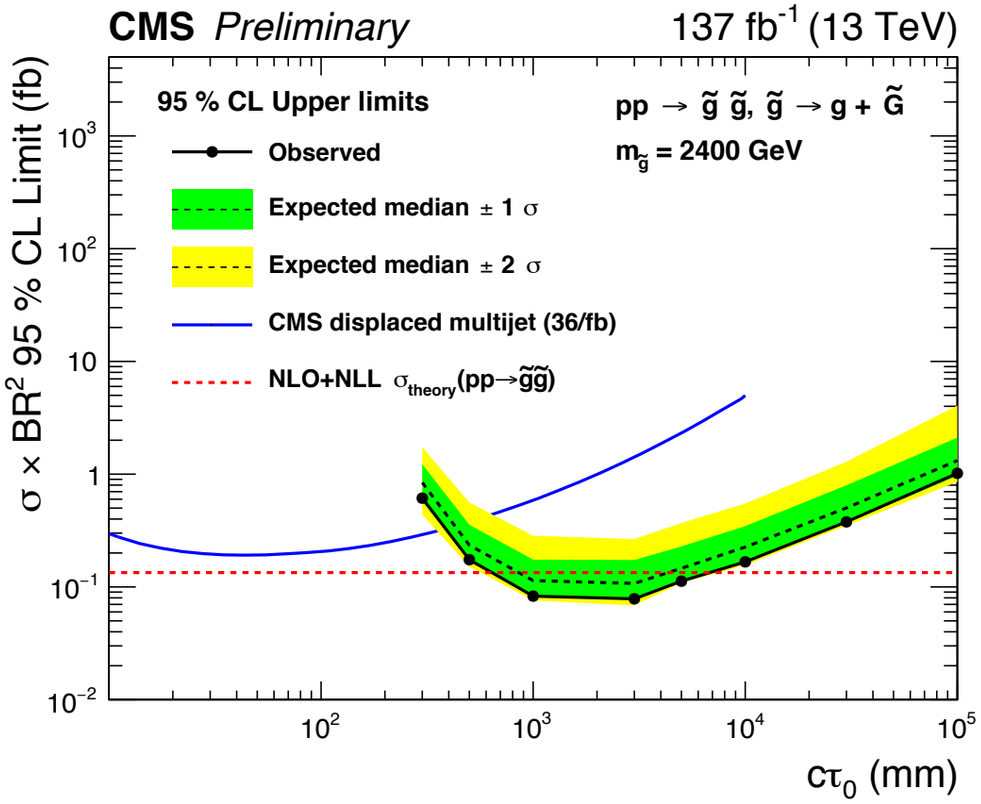
Background	Prediction
Beam halo	$0.02^{+0.06}_{-0.02}\,(\mathrm{stat})\,^{+0.05}_{-0.01}\,(\mathrm{syst})$
Core and satellite bunches	$0.11^{+0.09}_{-0.05}\,(\mathrm{stat})\,^{+0.02}_{-0.02}\,(\mathrm{syst})$
Cosmics	$1.0^{+1.8}_{-1.0}\,(\mathrm{stat})\,^{+1.8}_{-1.0}\,(\mathrm{syst})$

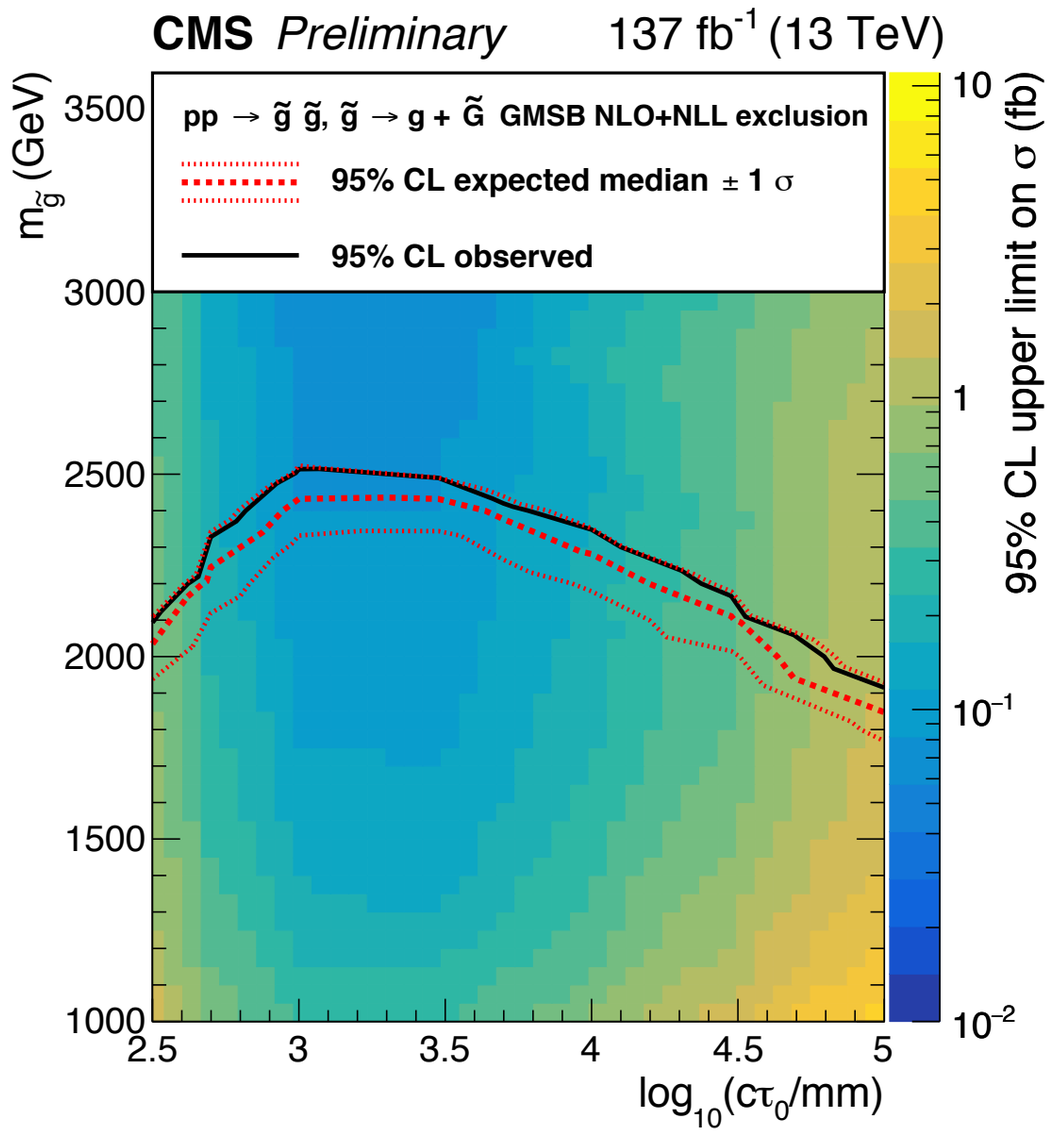
Delayed jet + MET

CMS-PAS-EXO-19-001

Results interpreted in gluino GMSB:







- m(gluino) > 2.1 TeV for $0.3 < c\tau < 30$ m
- Extends displ. vertex search to $c\tau > \sim 1$ m
- First search of this type!

Magnetic Monopoles

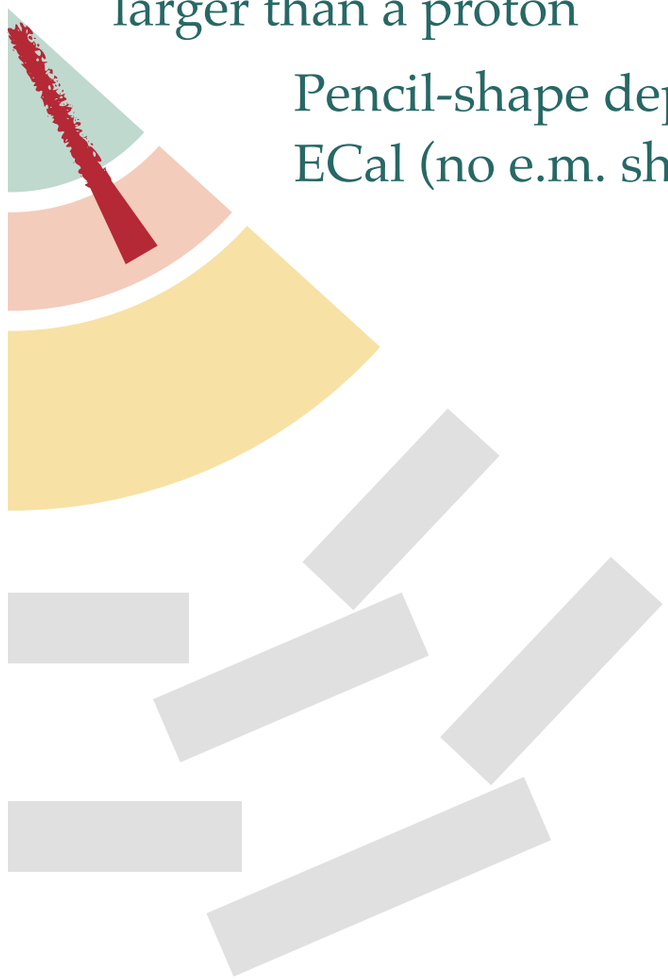
NEW

ATLAS-EXOT-2017-20

- Signature:
  - Single highly ionising particle
    - High ionisation in TRT
    - Pencil-shape deposit in ECal
- Dataset:
  - 34.4 fb^{-1} of 13 TeV 2015-16 data
- Motivation:
  - High-electric-charge objects
  - Dirac magnetic monopoles
    - Can explain charge quantisation
    - Could be accessible at colliders
    - Equivalent to an ion with charge:

$$g = \frac{N}{2\alpha_{\mathrm{em}}} = N \cdot 68.5$$

Ionisation loss $g^2 = N^2\, 4700$
larger than a proton



Pencil-shape deposit in ECal (no e.m. shower)

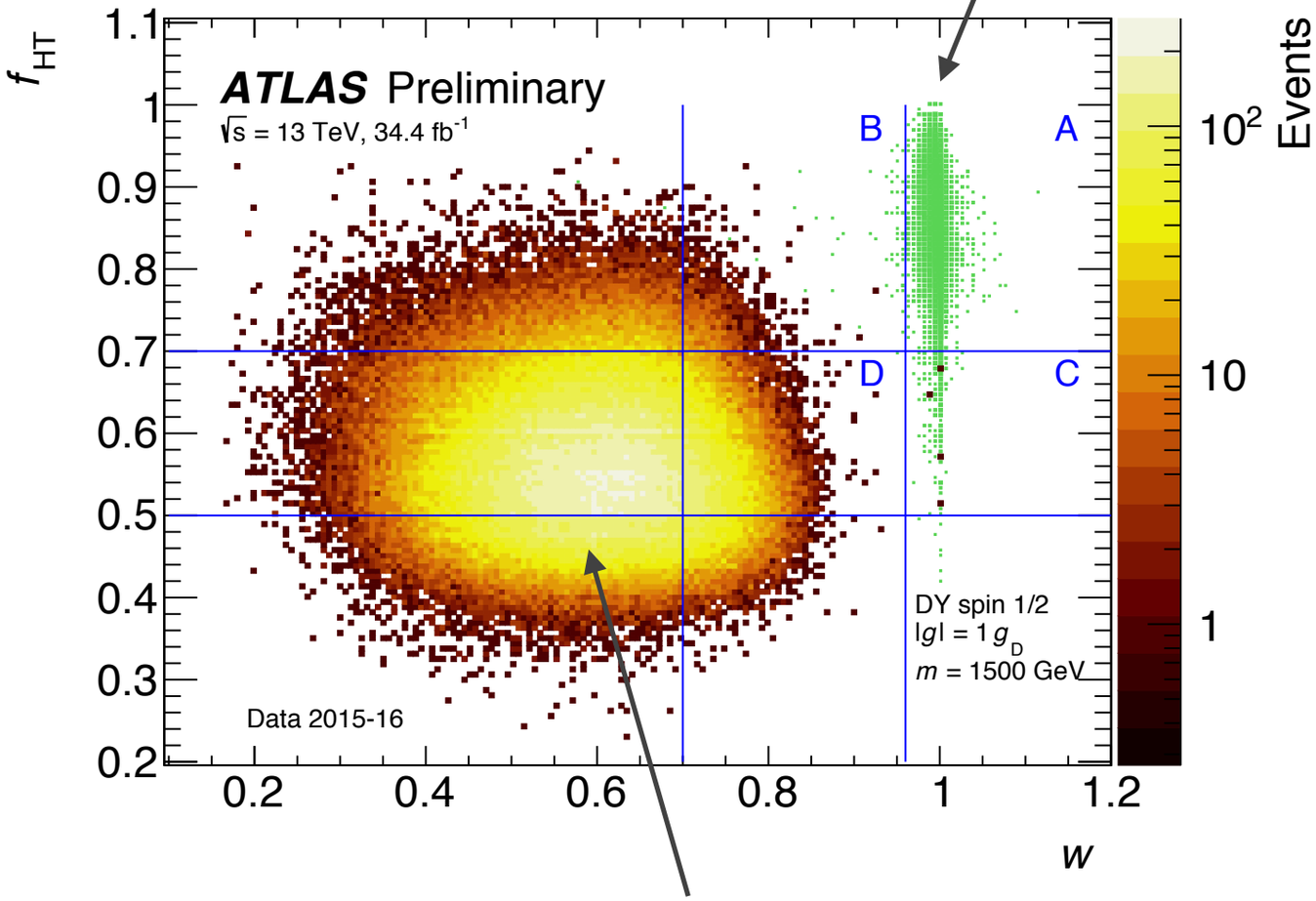
Magnetic Monopoles

NEW

ATLAS-EXOT-2017-20

- Dedicated trigger:
  - Hardware trigger defines RoI in ECal with $E_T > 22$ GeV
  - Software trigger requires high ionisation in corresponding TRT region
  - Veto HCal deposit only if $E_T < 50$ GeV
    - New in Run2, sensitive to lower z
- Efficiency relies on simulation
  - Monopole acceleration in magnetic field
  - Interaction with detector material
- Search in f_{HT} vs w plane
  - f_{HT} is proxy of high-ionisation (fraction of high-energy hits in TRT cluster)
  - w is proxy of pencil shaped ECal deposit (energy dispersion of ECal cluster)
- Background from data with ABCD
  - In region A expect $N_{bkg} = 0.20 \pm 0.11 \pm 0.40$

Typical monopole signal



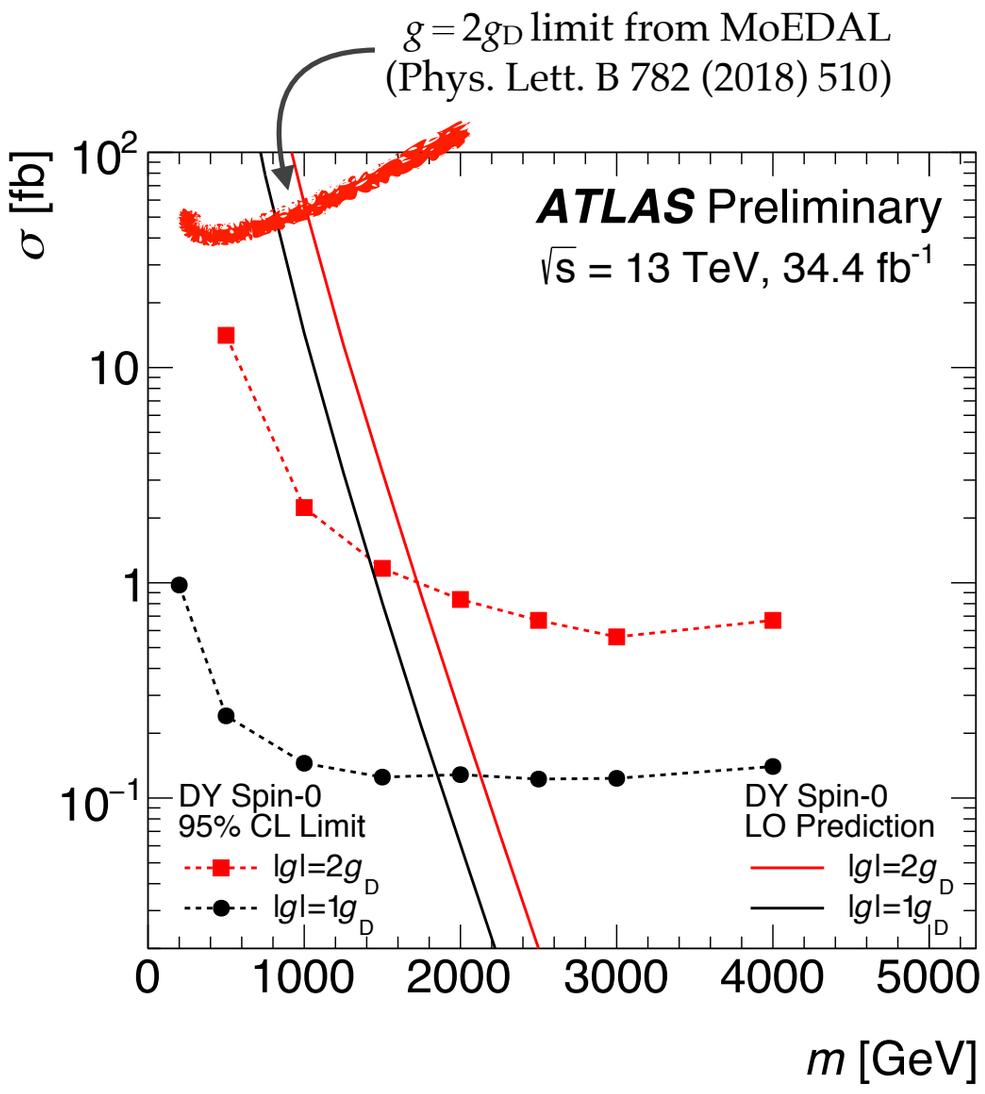
Typically overlapping charged particles and noise in TRT

Magnetic Monopoles

NEW

ATLAS-EXOT-2017-20

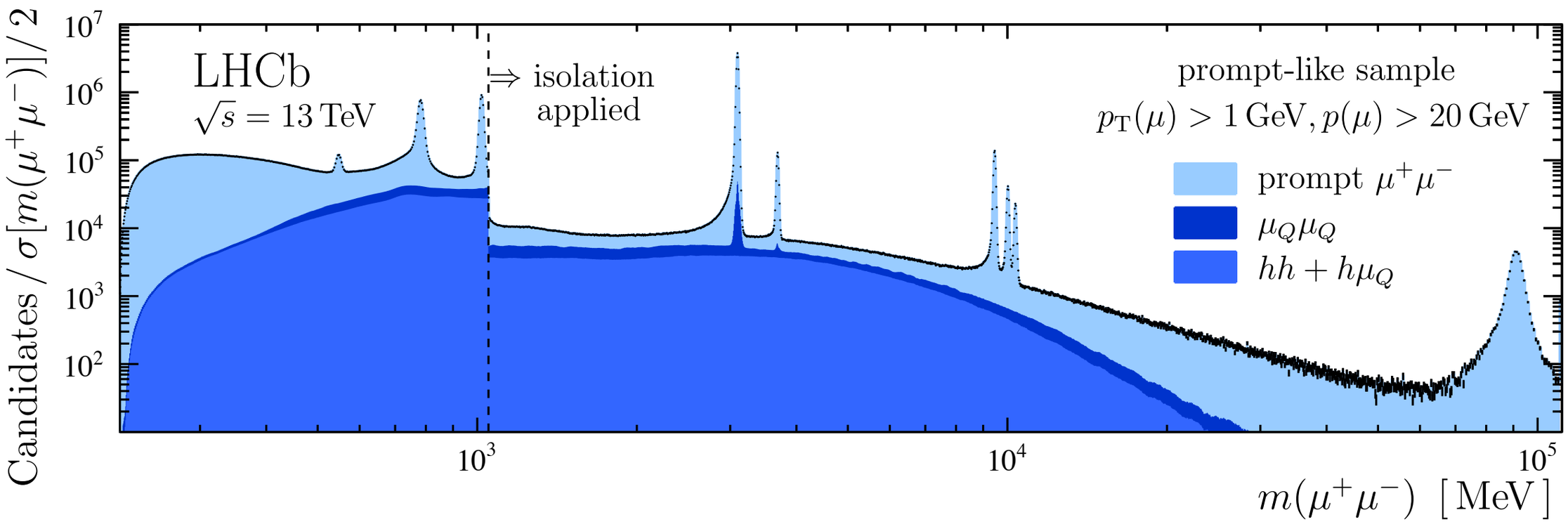
- No events observed
  - Limits for charges $20 < |z| < 100$ (first time above $|z| = 60$)
  - Exclude monopoles with $g = 2g_D$ and m > **1.8 TeV**
    - previous best limit from MoEDAL was at ~**1.0 TeV**
  - Limits on $g = g_D$ surpass by **factor 5** previous ATLAS limits



Visible dark photon in $\ell\ell$

Phys. Rev. Lett. 120, 061801 (2018)

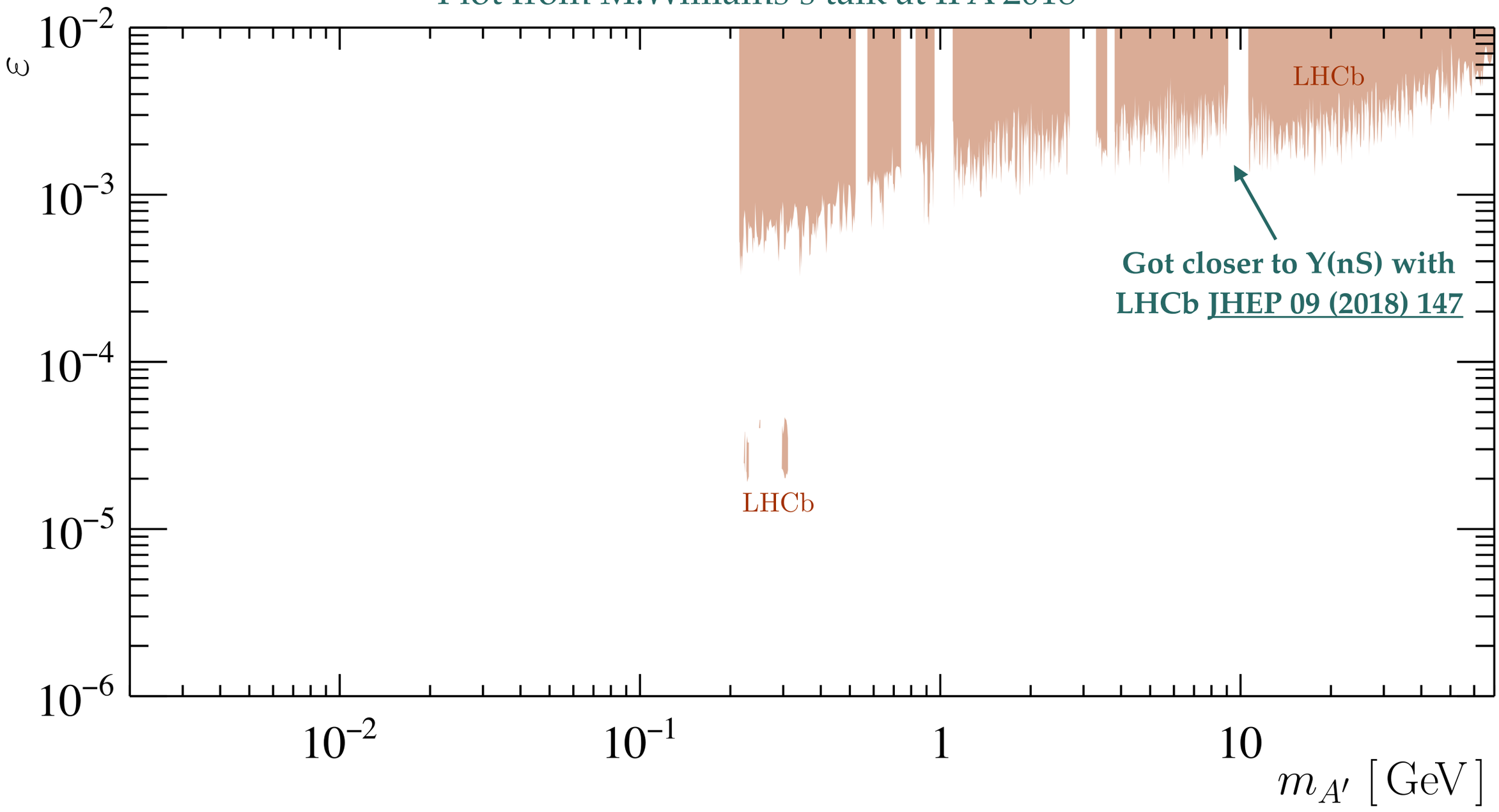
- Signature:
  - Inclusive $\mu\mu$ (prompt or displaced)
  - Sensitive down to $2\,m_\mu$
- Trigger:
  - Hardware $p_T(\mu)$ cut ~1.8 GeV
  - Real-time analysis including μ-ID allows to avoid prescale
- Analysis:
  - Template fit to separate prompt dimuons from heavy-flavour
  - Bump search on top of γ^* background (auto-normalising)
  - Displaced analysis at low mass is almost free of background



Visible dark photon in $\ell\ell$

Phys. Rev. Lett. 120, 061801 (2018)

Plot from M.Williams's talk at IPA 2018



Visible dark photon in $\ell\ell$

Phys. Rev. Lett. 120, 061801 (2018)

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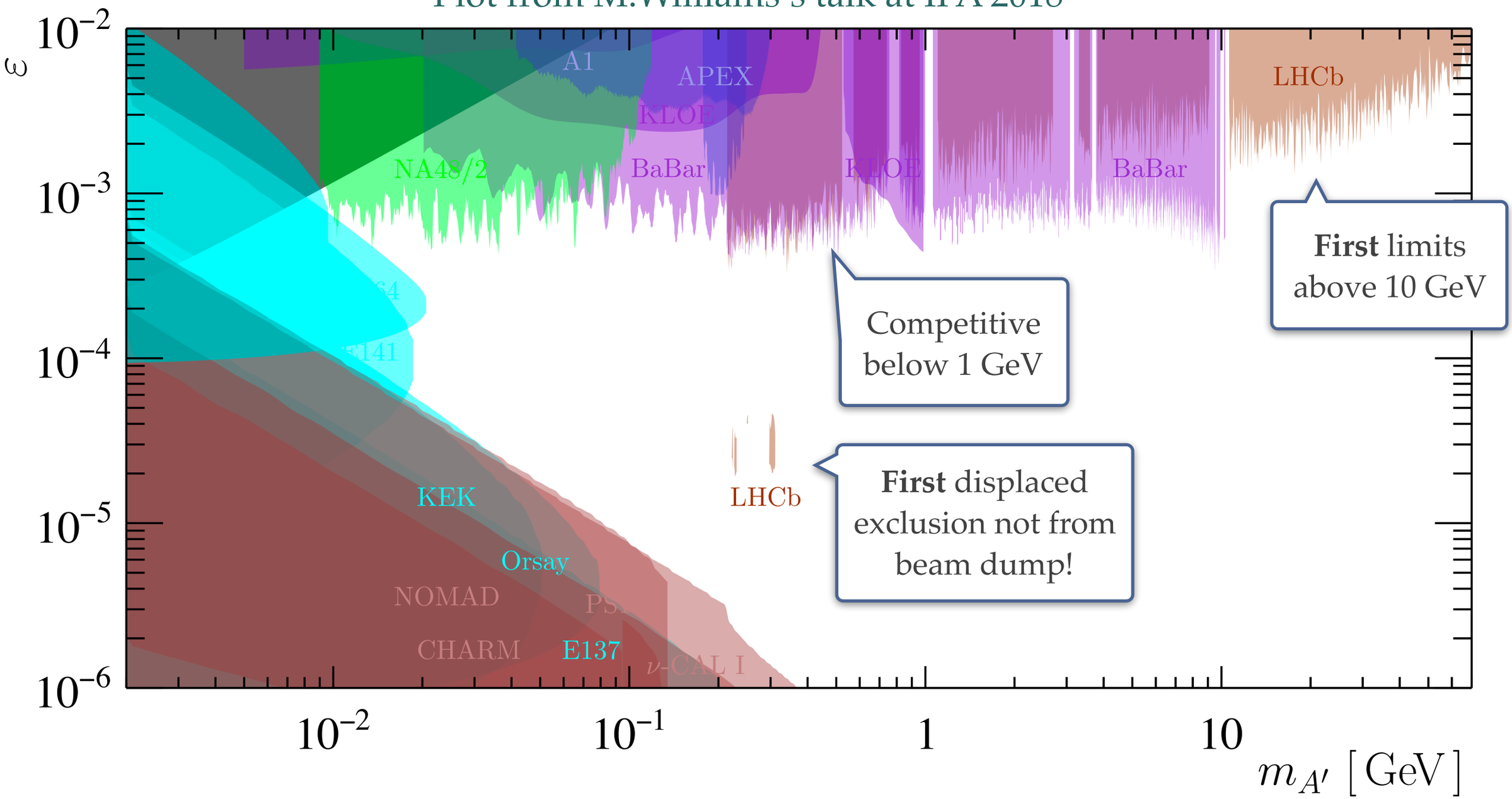
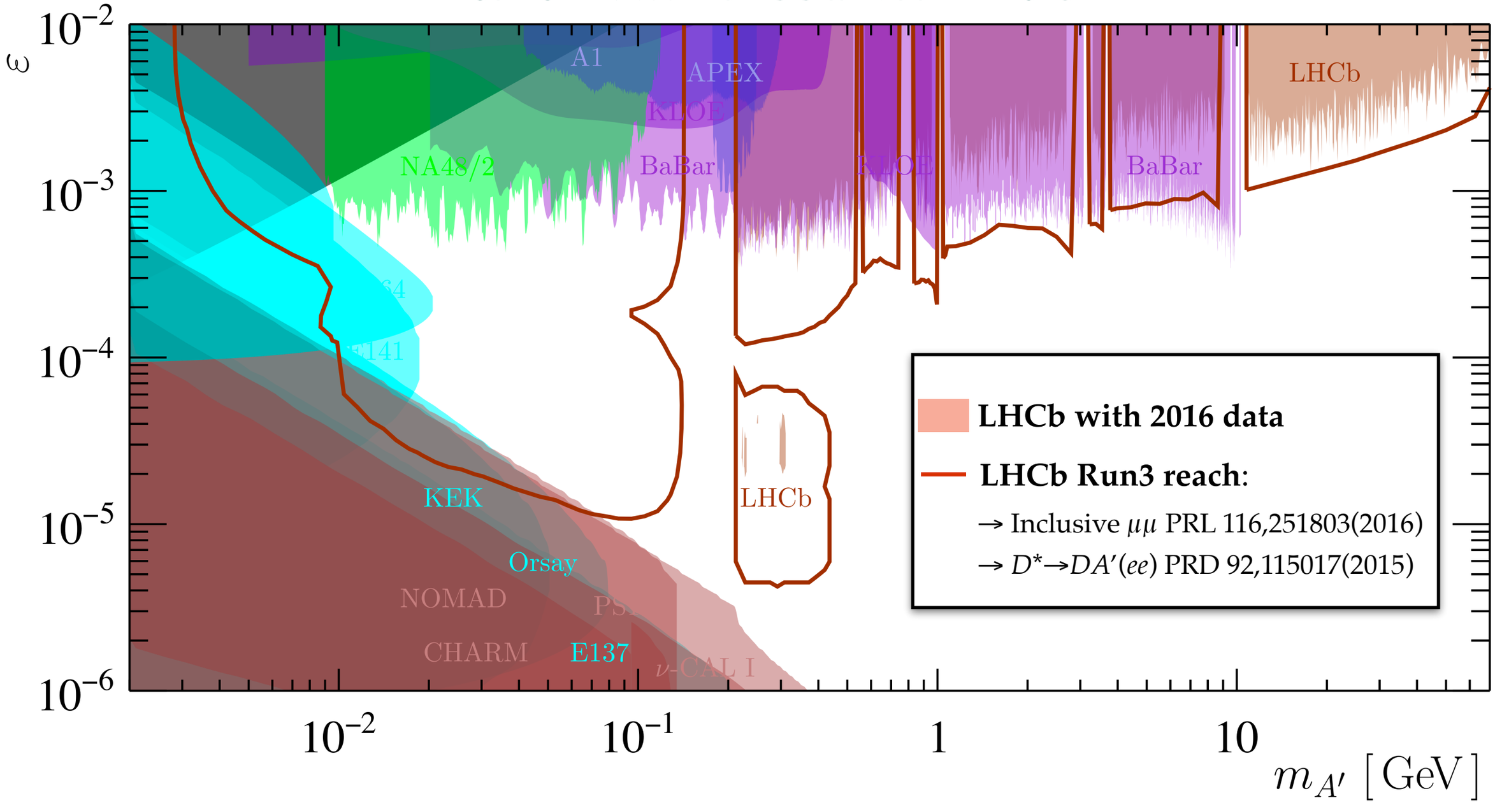


Visible dark photon in $\ell\ell$

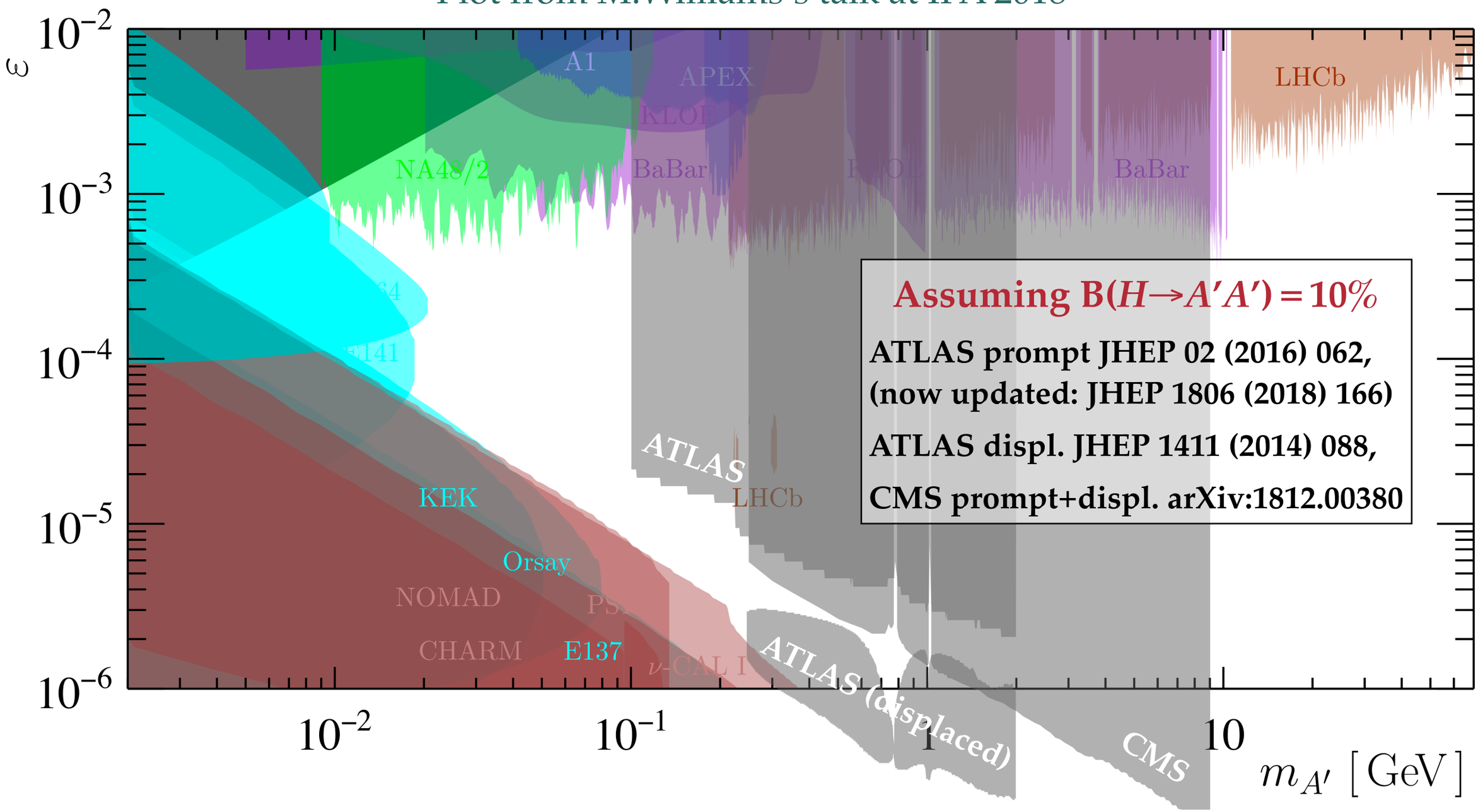
Phys. Rev. Lett. 120, 061801 (2018)

Plot from M.Williams's talk at IPA 2018



$H \to A'(\ell\ell)A'(\ell\ell)$

Plot from M.Williams's talk at IPA 2018



Invisible dark photon from H

NEW

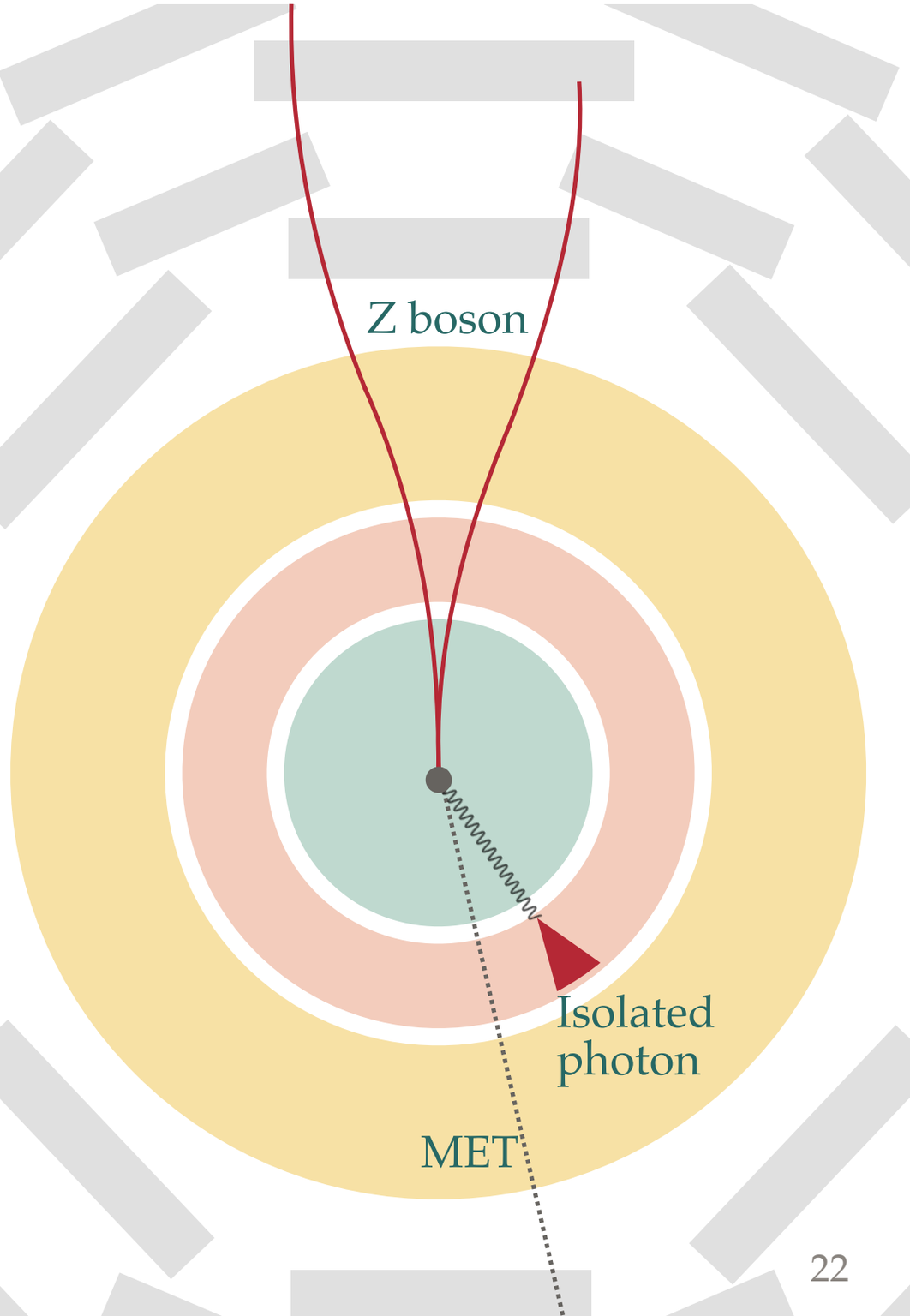
CMS-PAS-EXO-19-007

more details in J.Duarte's talk

- Signature:
  - **(SM) Higgs → photon + invisible**
  - Using ZH associated production
- Motivation:
  - Massless dark photon coupling to H through charged dark sector

    S.Biswas, E.Gabrielli, M.Heikinheimo
    Phys. Rev. D93 (2016), no. 9, 093011
- Dataset:
  - **Full Run-2 data: 137.4 fb^{-1} at 13 TeV**
  - Previously with 19.4 fb^{-1} at 8 TeV

    Phys. Lett. B753 (2016) 363–388



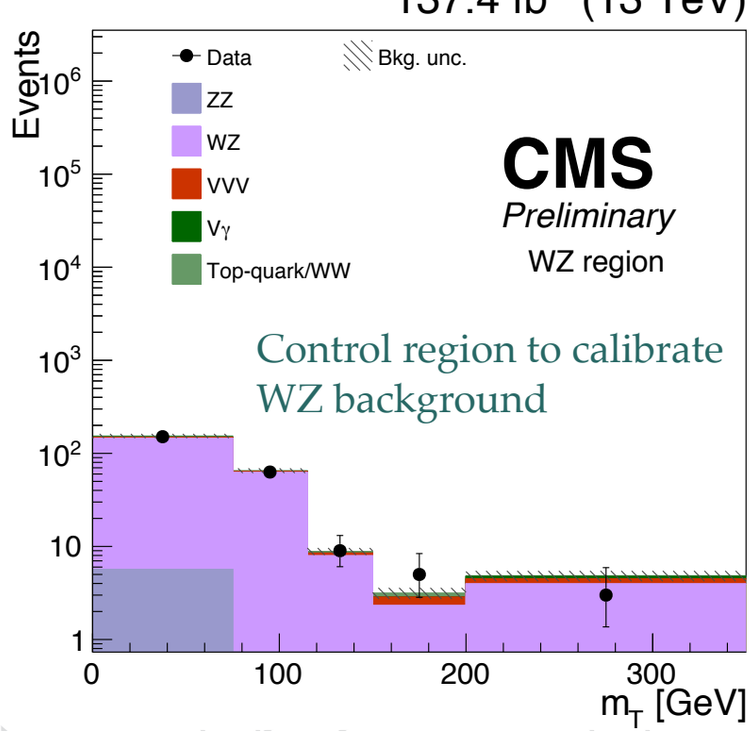
Invisible dark photon from H

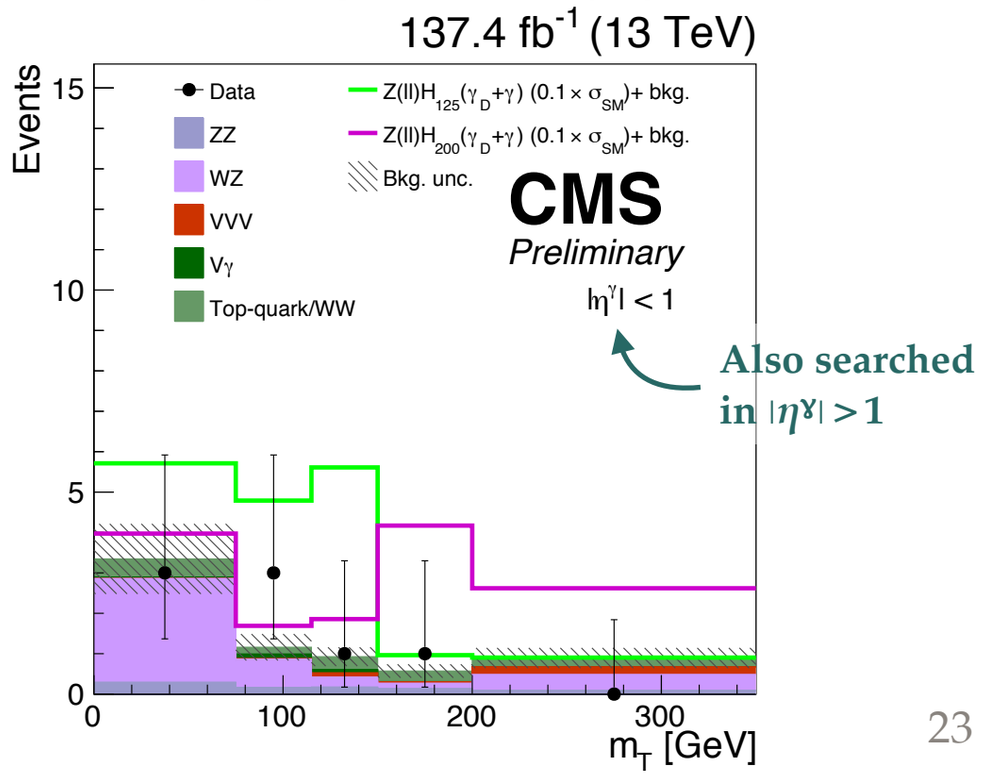
NEW

CMS-PAS-EXO-19-007

more details in J.Duarte's talk

- Trigger using $Z \to \ell\ell$
- Selection:
  - Back-to-back Z and $(\gamma + p_T^{miss})$
  - Reject events with b-tagged jets (background from top)
- Fit $m_T(\gamma + p_T^{miss})$ (**new**)
  - Background normalisation from data control regions
  - Gain 30-50% better sensitivity



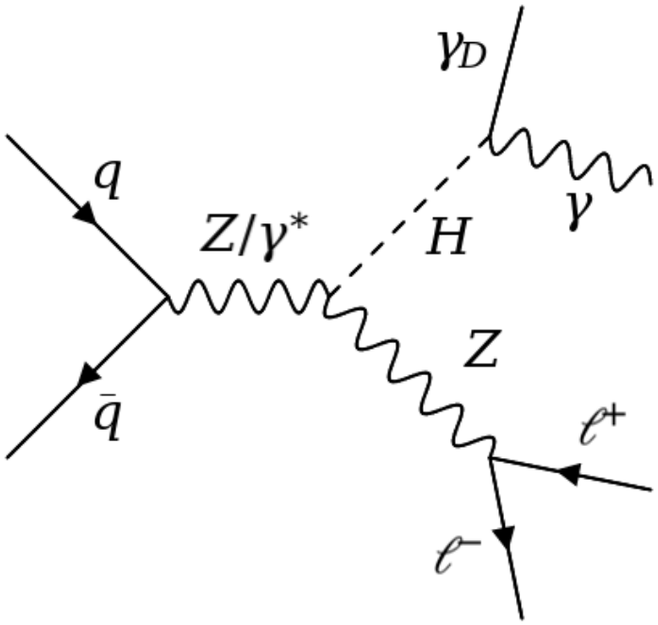


Invisible dark photon from H

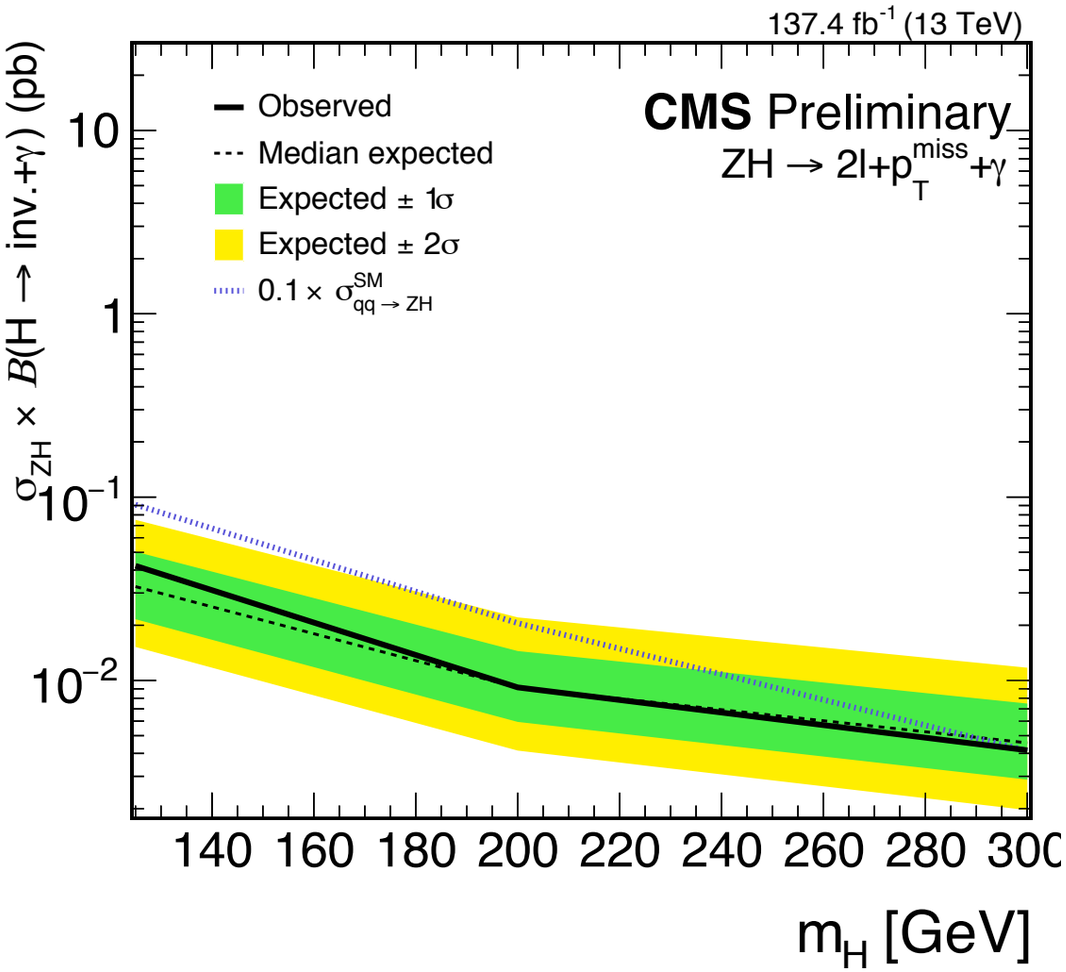
NEW

CMS-PAS-EXO-19-007

more details in J.Duarte's talk



- Interpreted for the first time as massless invisible dark photon
- Upper limit as a function of m_H
- For $m_H = 125\,\text{GeV}$
  - $B(H \to \gamma + \text{inv.}) < 4.6\%$ @95%CL

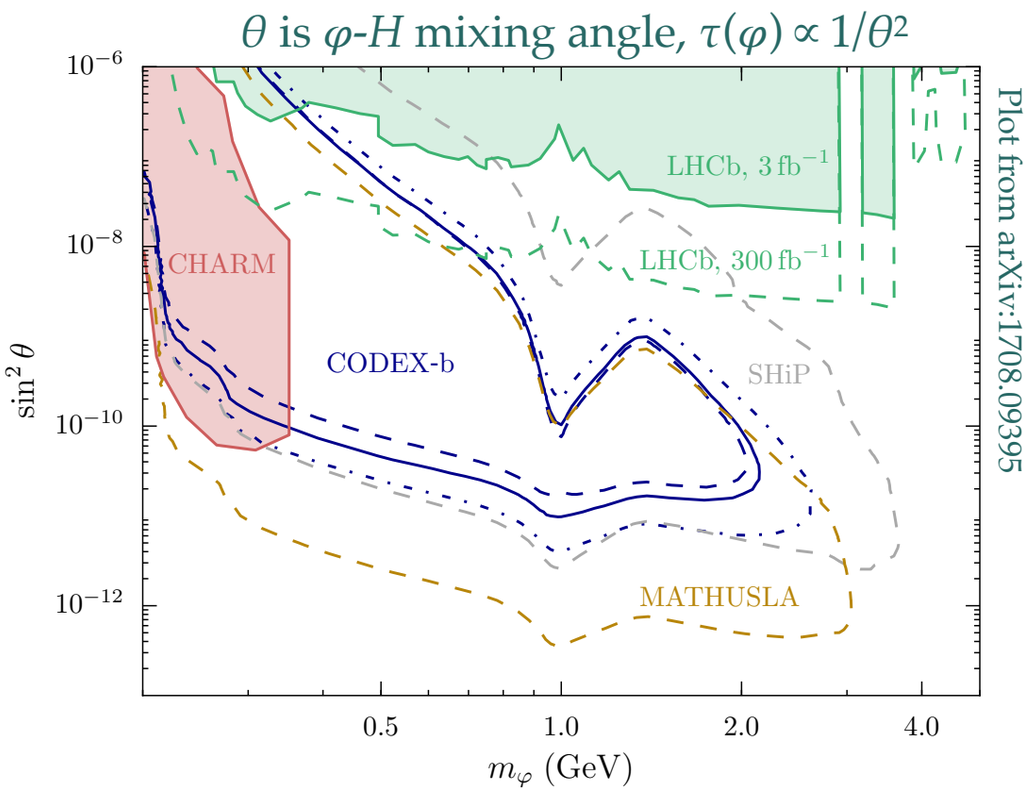


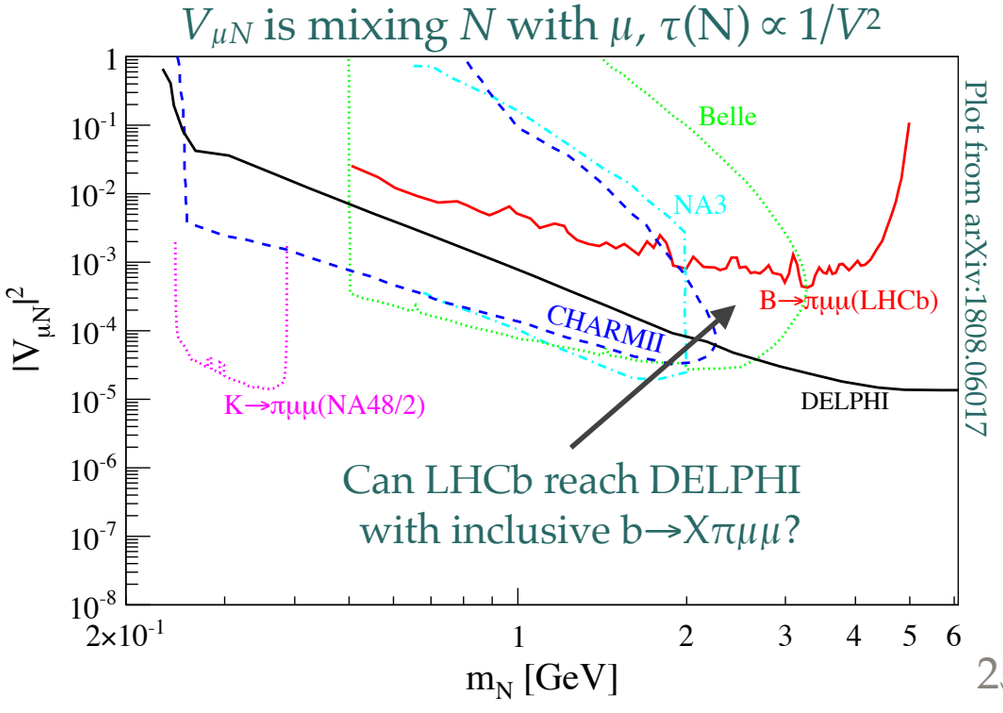
Searches in heavy flavour

- B meson decays to search for light (long-lived) objects
  - Dark Bosons φ
    - In prompt/displaced dimuons
    - Using $b\to s$ channel $B\to\varphi(\mu\mu)K^{+/*}$

      Phys Rev Lett 115 161802 (2015)
      Phys. Rev. D 95, 071101(R) (2017)
  - Heavy Neutral Leptons
    - In displaced $\pi^-\mu^+$ resonances
    - Eventually accompanied by same-sign μ^+ from B
    - So far searched only in $B\to N(\pi^-\mu^+)\mu^+$

      Phys Rev Lett 112 131802 (2014)





Conclusions

- Casting the widest possible net
  - Make sure we don't miss new physics at the LHC
  - Crucial given the importance of triggering
- Very interesting and fun activity
  - Need out-of-the-box thinking to identify signatures
  - Unconventional searches come with unconventional backgrounds (and unconventional systematics)
- Presented a wealth of results for LLPs and others
  - Two new results with the full Run 2 dataset!
  - Many more to come

"If I know what I shall find,
I do not want to find it"
Erwin Chargaff

BACKUP