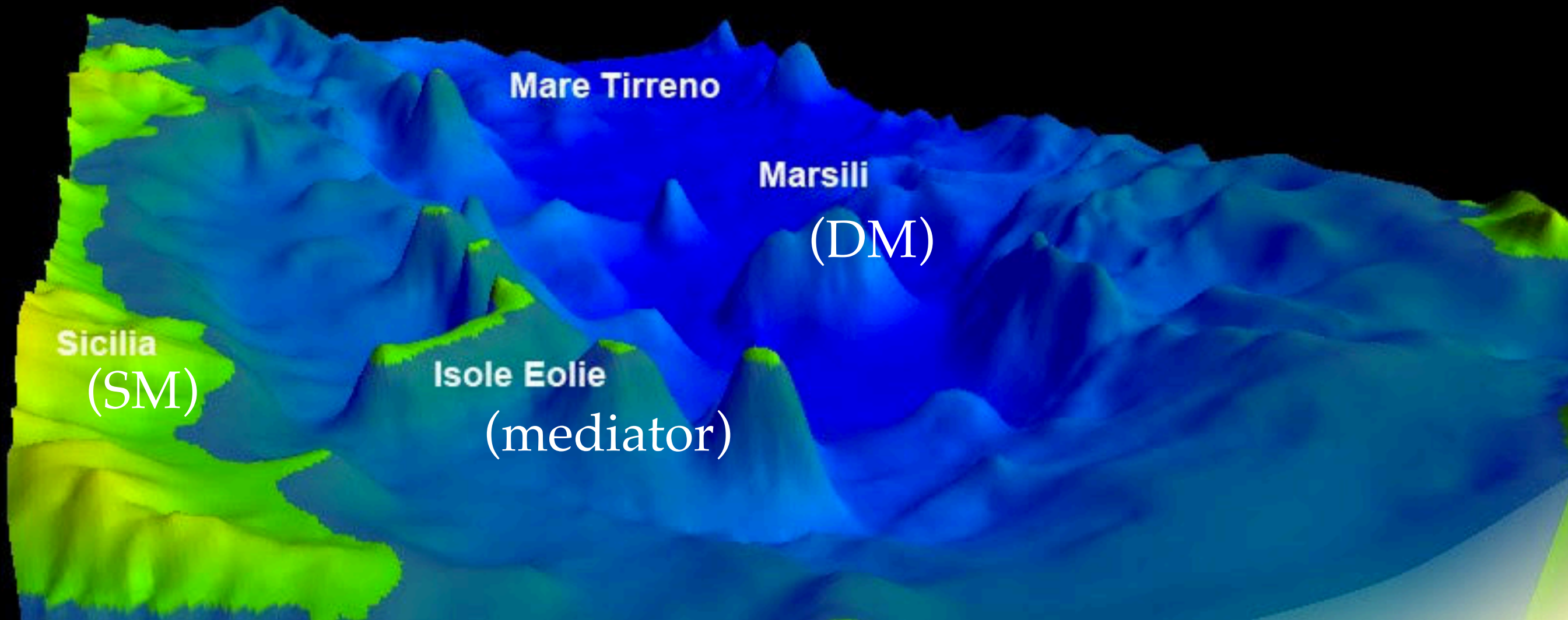
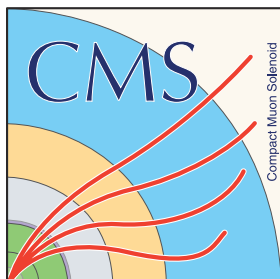




Dark Matter at the LHC

Martino Borsato[†]
[†]Universida de Santiago de Compostela
on behalf of ATLAS, CMS, LHCb



What to look for

◎ Experimental constraints:

- Relic density observed

[Planck, AA 594\(2016\)A13](#)

- (Thermal) DM mass $> \text{keV}$

[e.g. Lovell et al. MNRAS 439\(2014\)300-317](#)

- Effectively EM neutral

[Stable charged particle and direct detection](#)

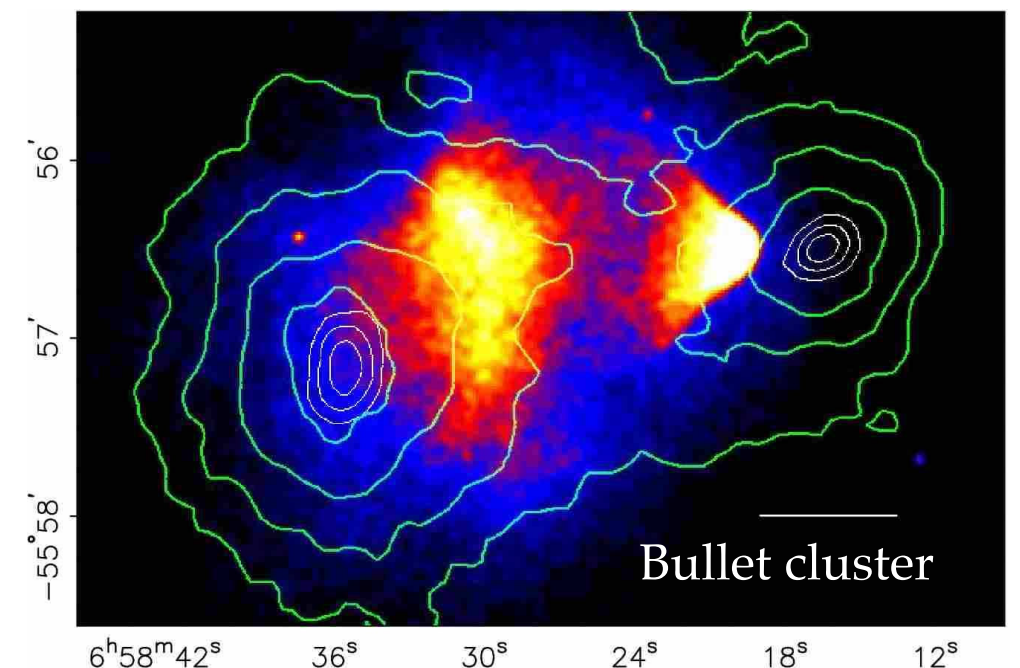
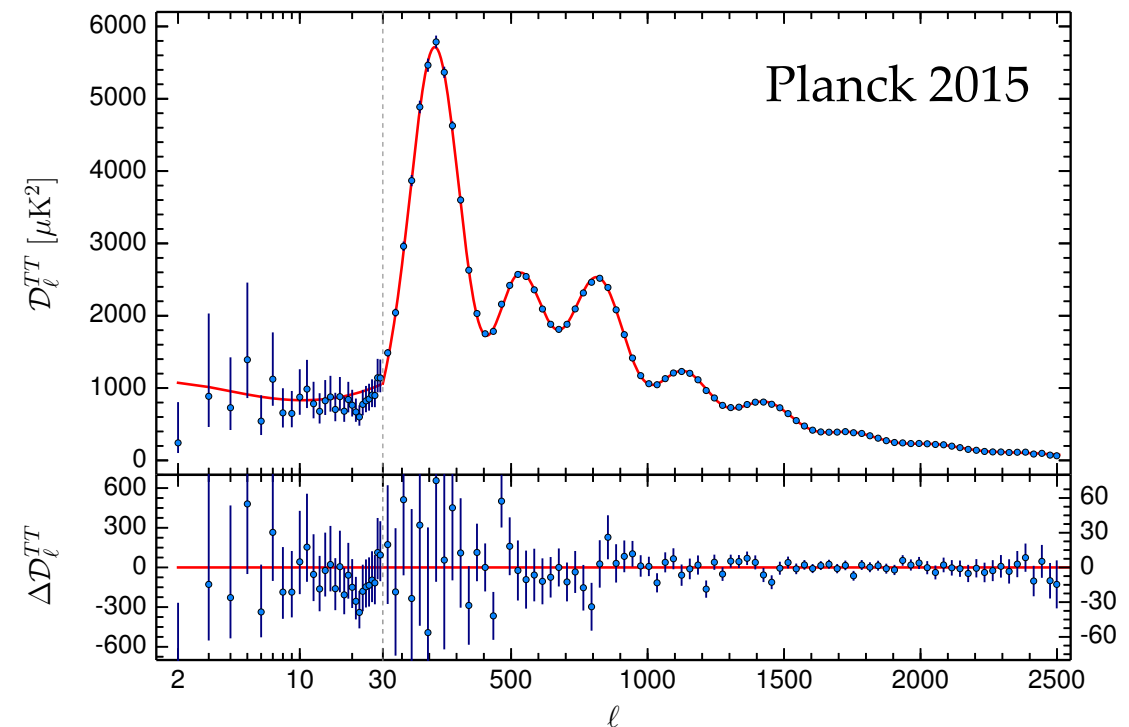
- Cosmologically stable

[or more Slatyer and Wu. PRD95\(2017\)2,023010](#)

- No or small self-interaction

["Bullet cluster" AJ 648\(2006\)L109-L113](#)

→ Compelling WIMP scenario

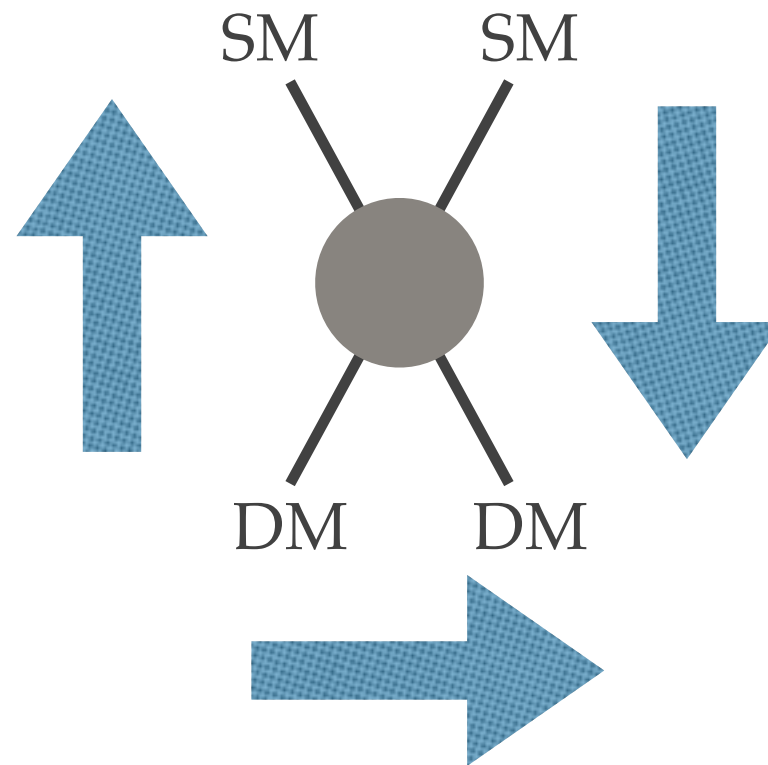


DM signals

Indirect detection

Signals from DM annihilation

FERMI, PAMELA, AMS, HESS, IceCube, CTA, ...



Collider search

- **Mediator** $\rightarrow$ **DM** (holistic search)
- **Mediator** $\rightarrow$ **SM** (peak search)

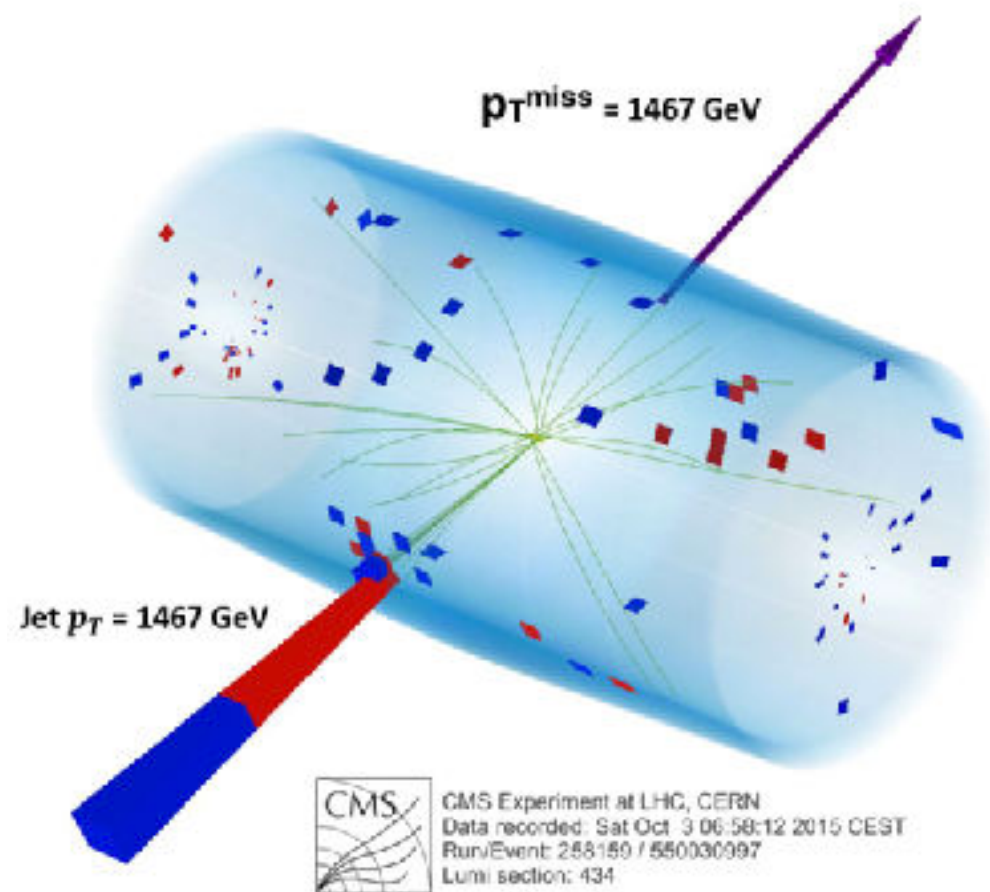
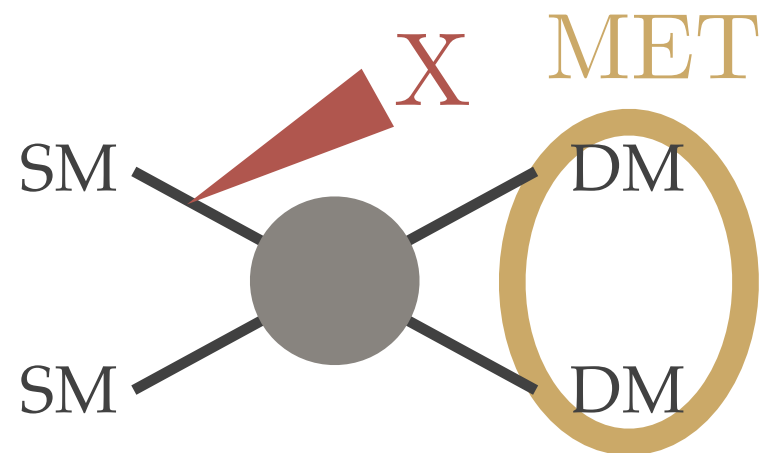
Direct detection

Detect interactions of the DM wind

XENON, Panda, Lux, DarkSide, ...

$$\textit{Mediator} \rightarrow \textit{DM}$$

Mono-X searches at the LHC

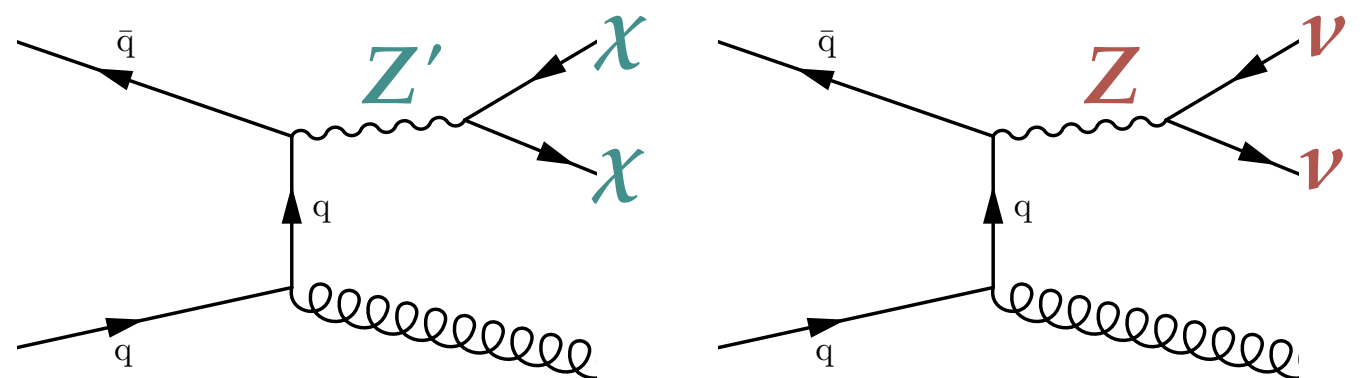


- Exploit initial state radiation

- Missing energy + large- p_T
 - $X = \text{jet, photon, W, Z}$

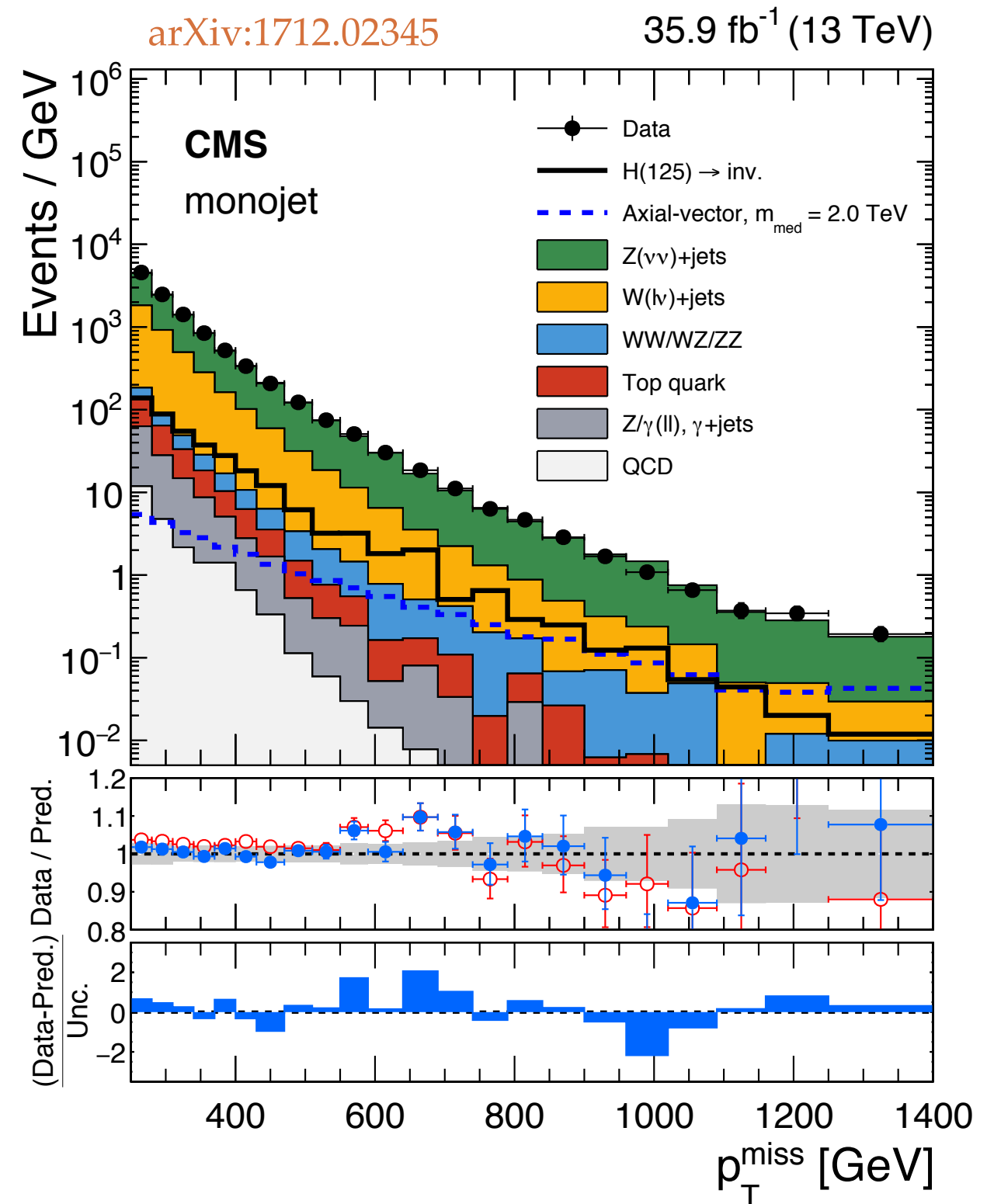
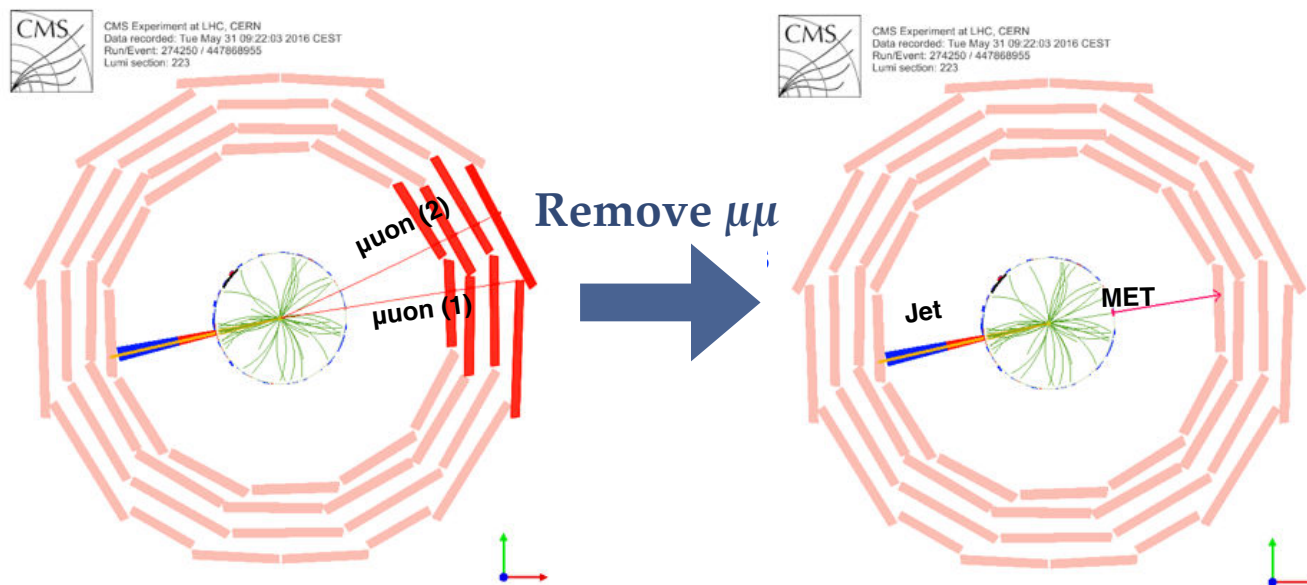
- Main challenge: measure precisely SM backgrounds

- e.g. $Z(\nu\nu)+X$ is irreducible



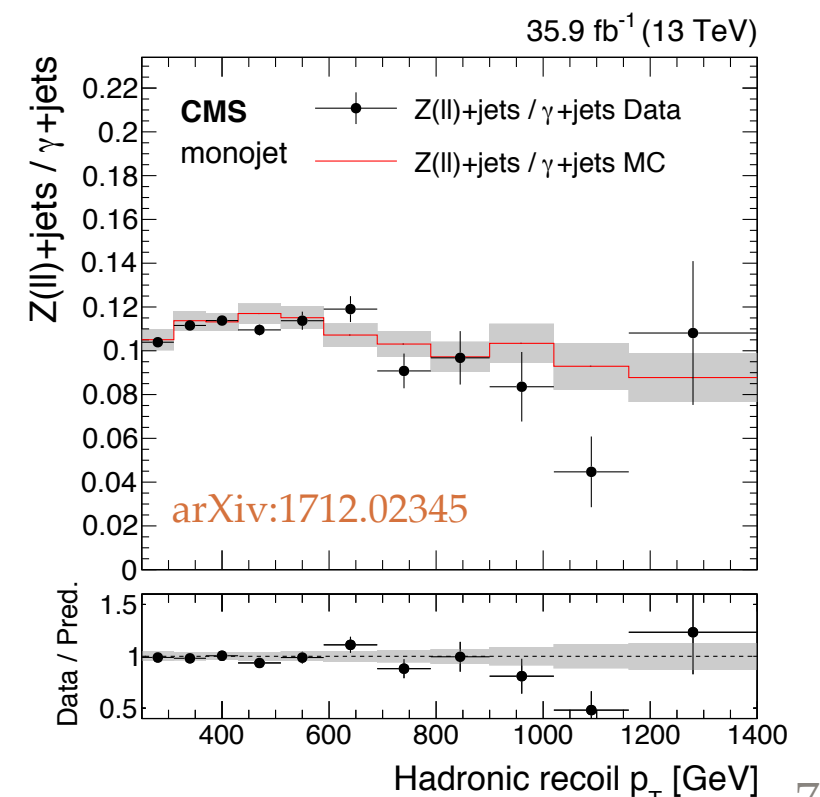
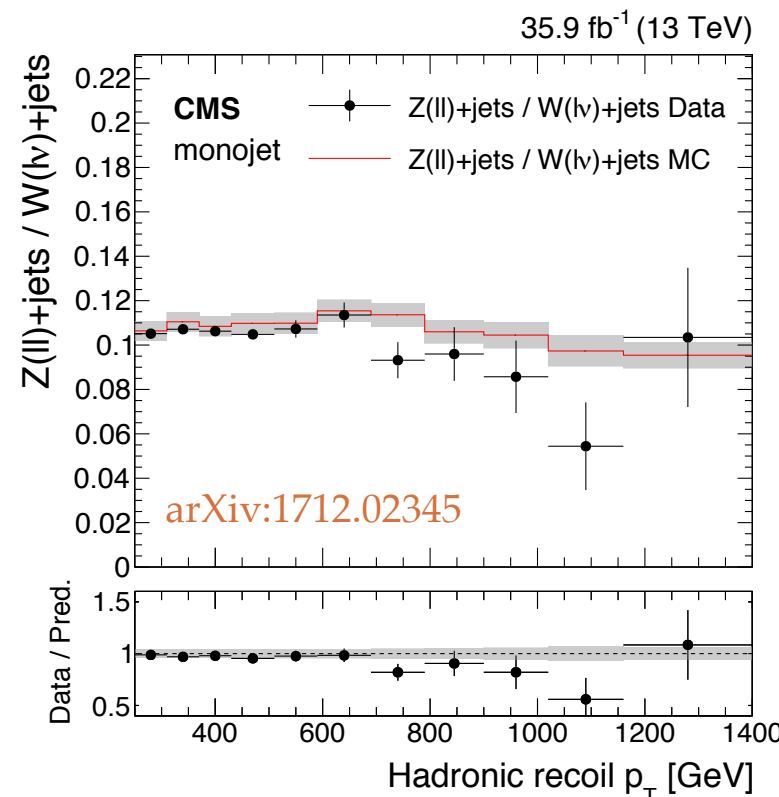
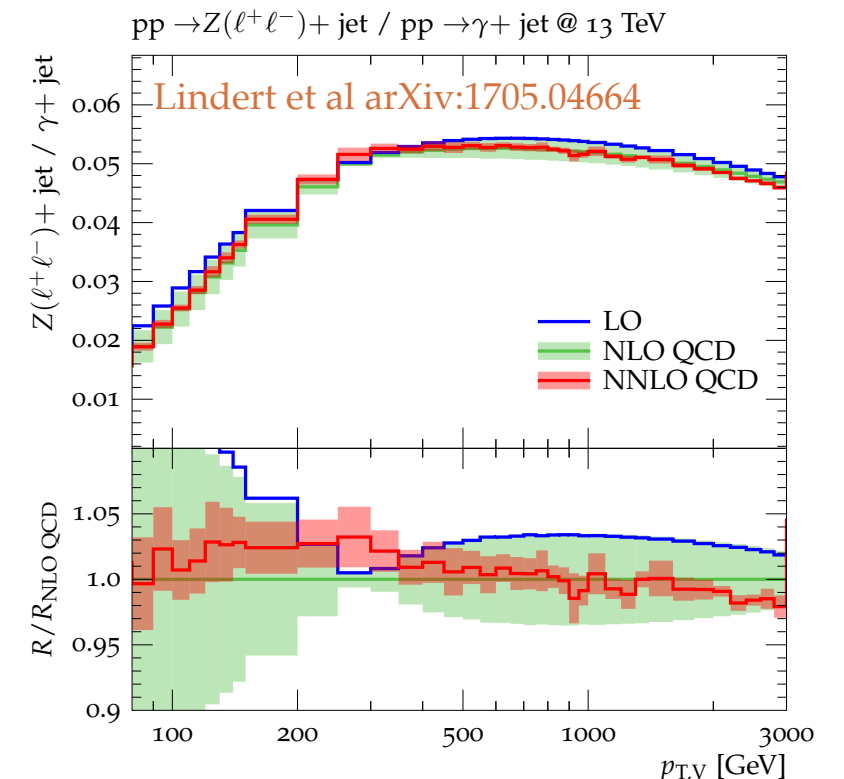
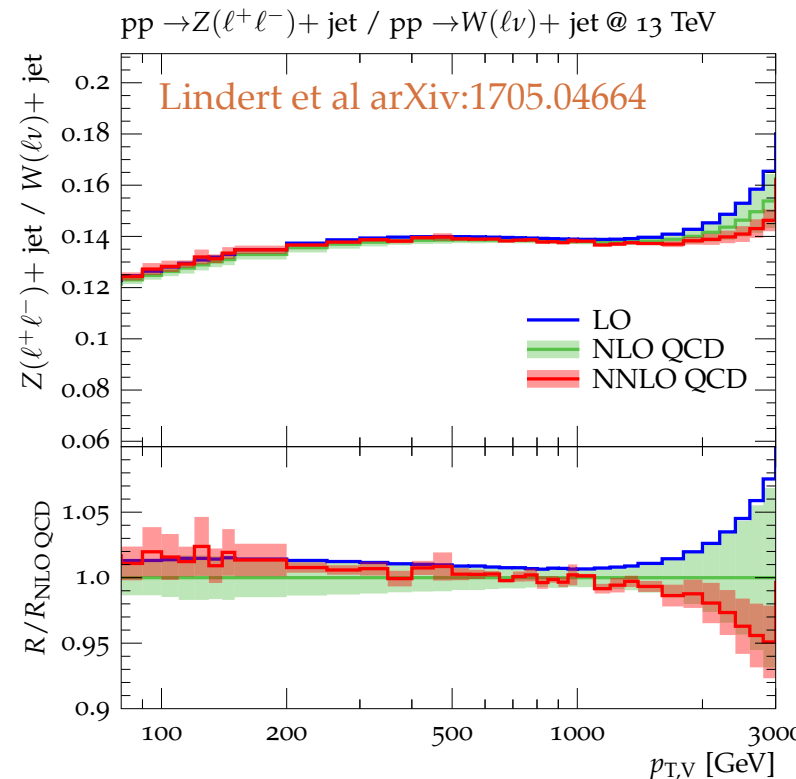
Mono-jet backgrounds

- **Vector+jet backgrounds**
 - 50-80% is $Z(\nu\nu)+\text{jet}$ (irreducible)
- Estimate using control regions:
 - $Z(\ell\ell)+\text{jet}$, removing $\ell\ell$ from event
 - $W(\ell\nu)+\text{jet}$, removing ℓ from event
 - $\gamma+\text{jet}$, removing γ from event



Mono-jet backgrounds

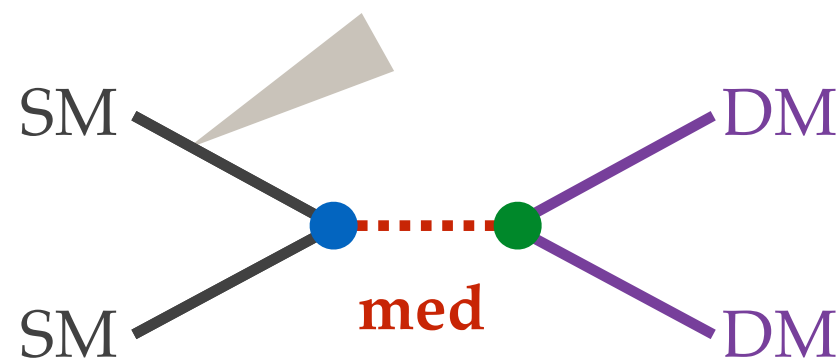
- Ratio $d\sigma(Z+\text{jet})/d\sigma(W+\text{jet})$ and $d\sigma(Z+\text{jet})/d\sigma(\gamma+\text{jet})$ to simplify modelling
 - Control-region to signal-region *transfer factors* from theory
- Progress in theory
 - p_T dependent NLO QCD+EW corrections of LO MC
 - Including p_T dependent correlations for corrections
 - Ratios stable at few %
- Validation test on data
 - Jet uncertainties cancel out
- Simultaneous fits of control and signal regions



Mono-jet results

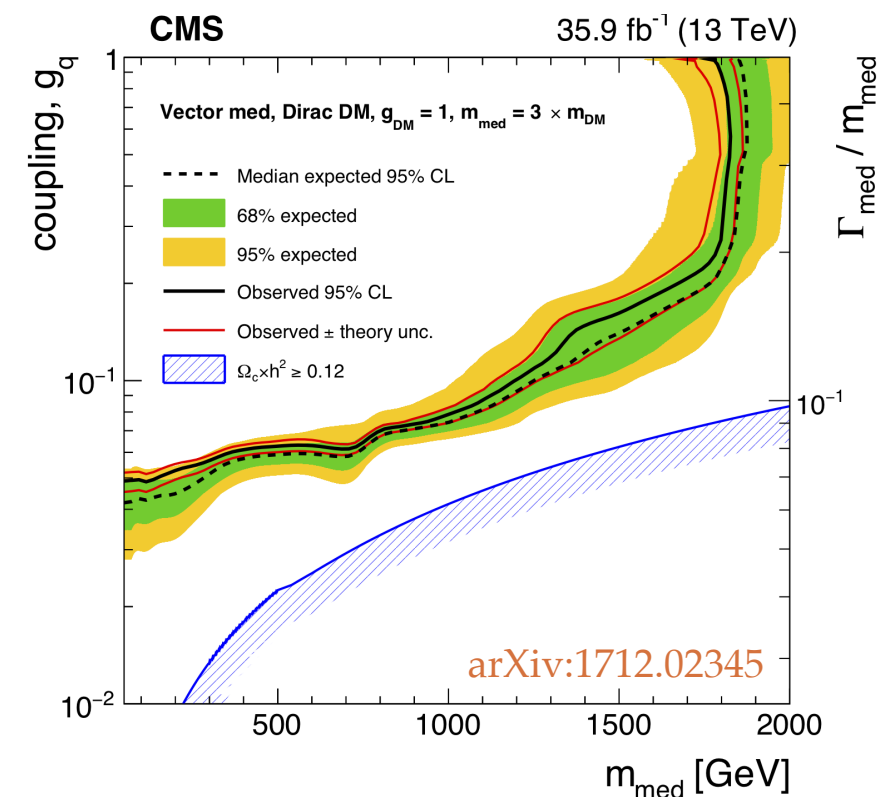
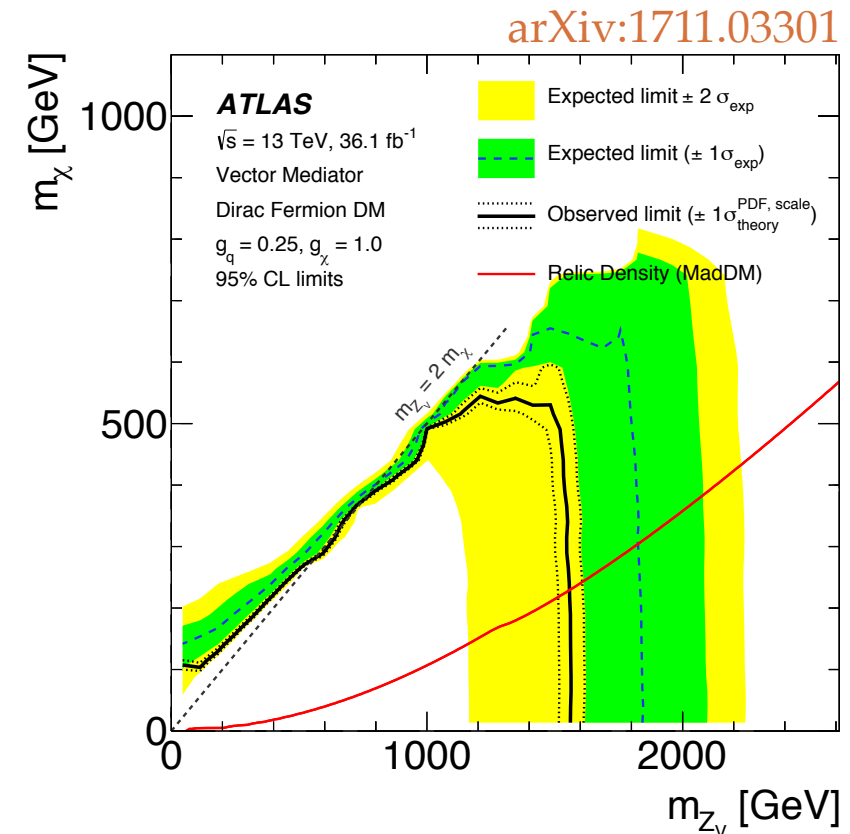
Results on simplified DM models

- Vector, axial-vector, scalar, pseudo-scalar mediator (s-channel)
- 4 parameters: m_{DM} , m_{med} , g_{SM} , g_{DM}



Reach for $g_{\text{DM}}=1$, $m_{\text{med}} = 3 m_{\text{DM}}$:

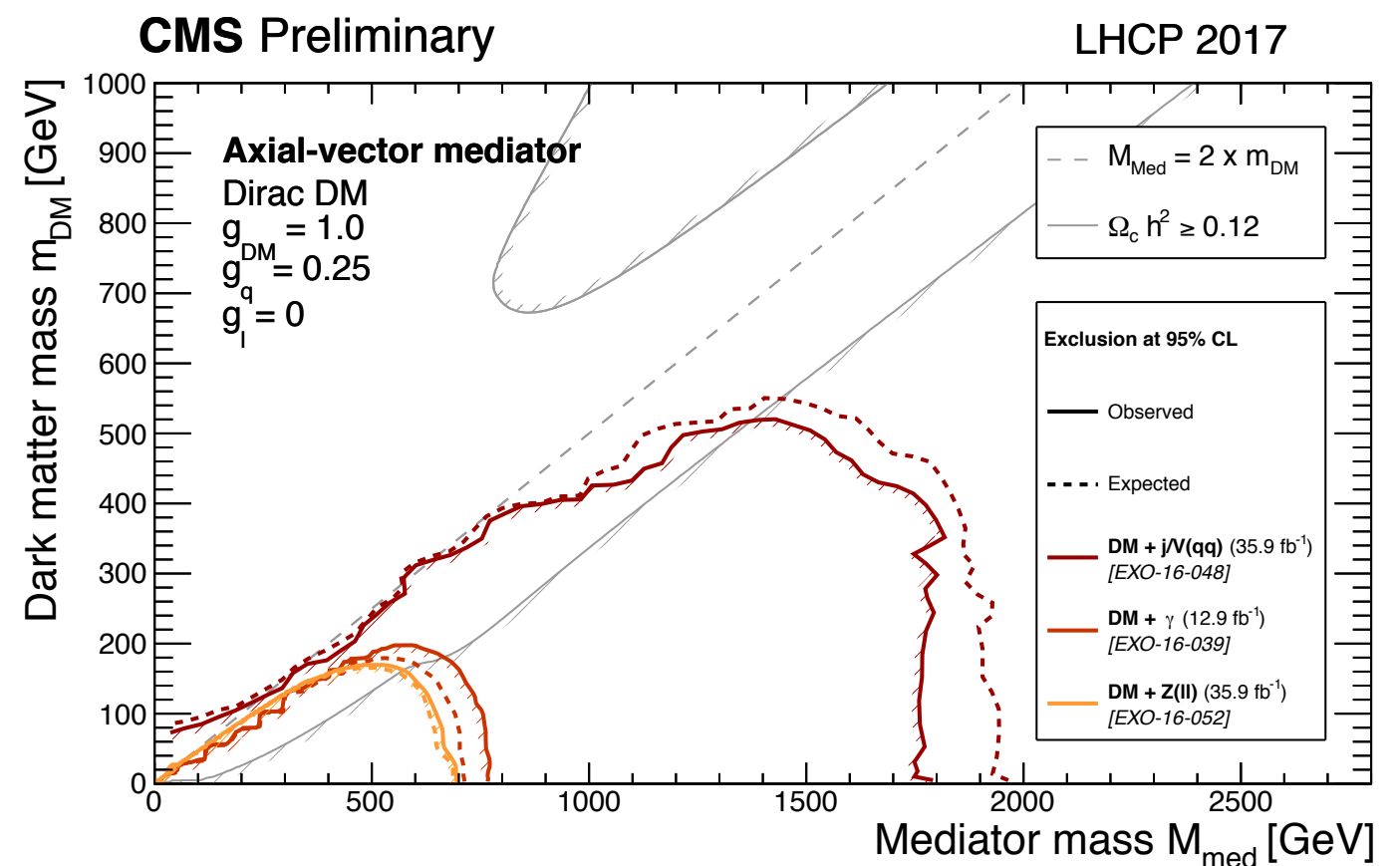
- Up to ~ 1.6 - 1.8 TeV for m_{med} (vector)
- Below $g_{\text{SM}} \sim 0.1$ for low $m_{\text{med}} < 1\text{TeV}$



Mono-X results

- Searched in mono-jet, but also mono- γ and mono-V
- **No excess in ATLAS+CMS**
(36/fb from 2015+2016)
 - Best sensitivity to date
 - In the era of precision searches
- 40/fb on tape from 2017 and 2018 run happening now
- Challenging analysis in future high-luminosity upgrade

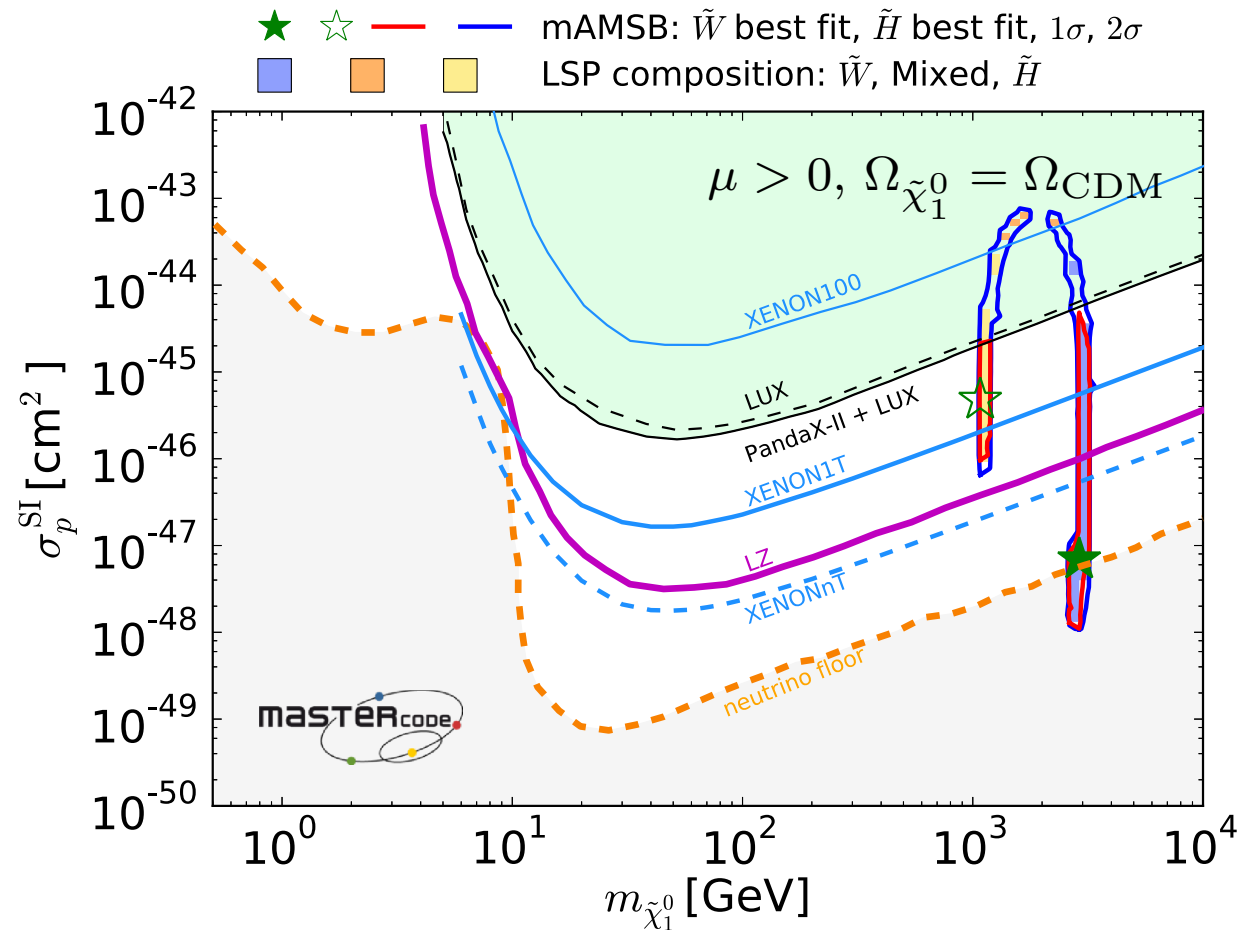
Signature	ATLAS	CMS
Mono-jet	36/fb 1711.03301	36/fb 1712.02345
Mono- γ	36/fb 1704.03848	13/fb 1706.03794
Mono-V(had)	3.2/fb 1608.02372	36/fb 1712.02345
Mono-Z(lep)	36/fb 1708.09624	36/fb 1711.00431
Mono-H($\gamma\gamma, \tau\tau b, b$)	36.1/fb 1706.03948, 1707.01302	36/fb EXO-16-055



SUSY searches

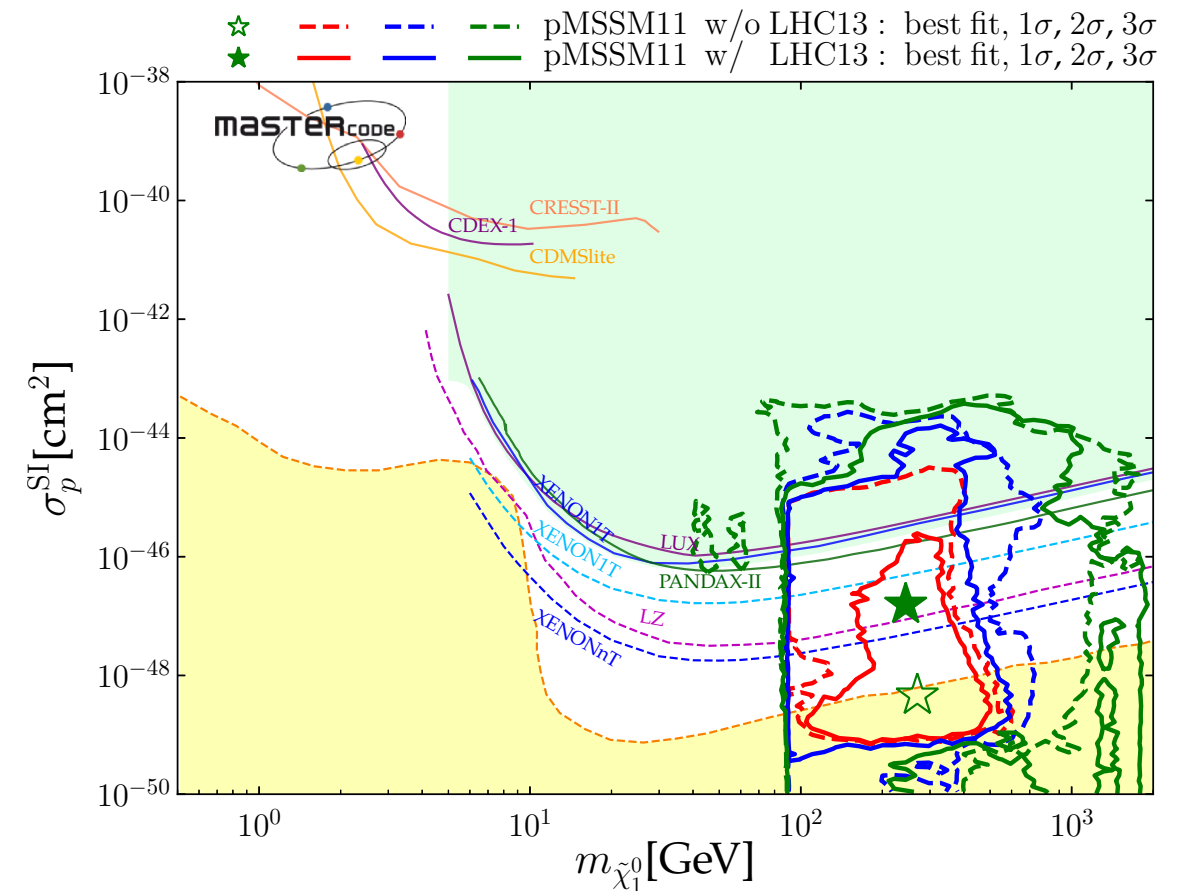
mAMSB EPJC77(2017)4-268

E.Bagnaschi, MB, K.Sakurai, et al



pMSSM11 EPJC78(2018)3-256

E.Bagnaschi, K.Sakurai, MB, et al

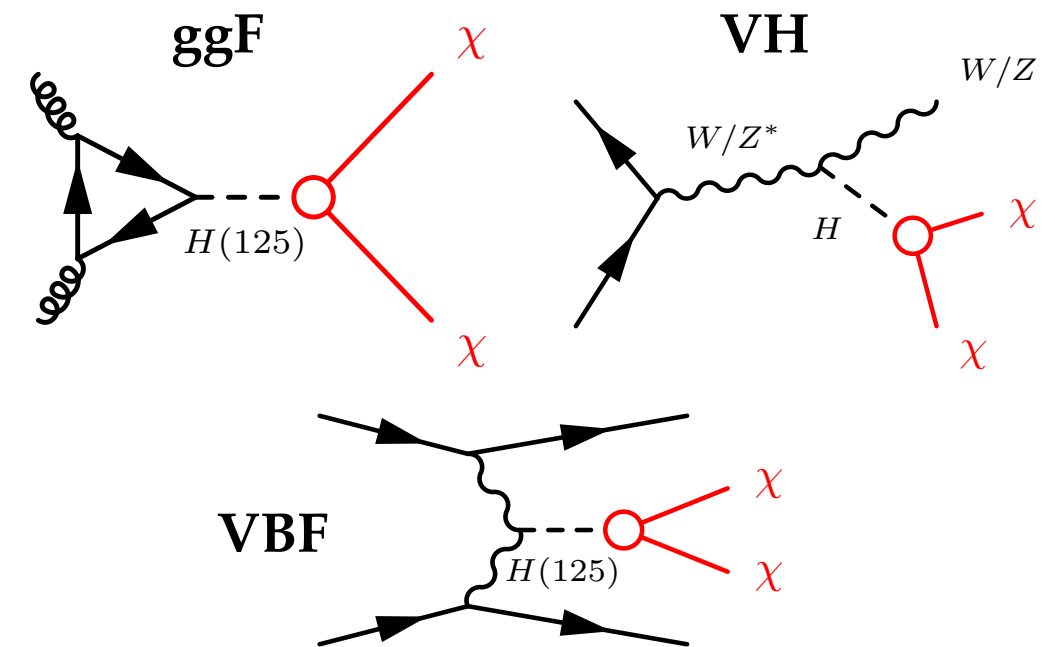


⊙ SUSY provides a candidate for DM

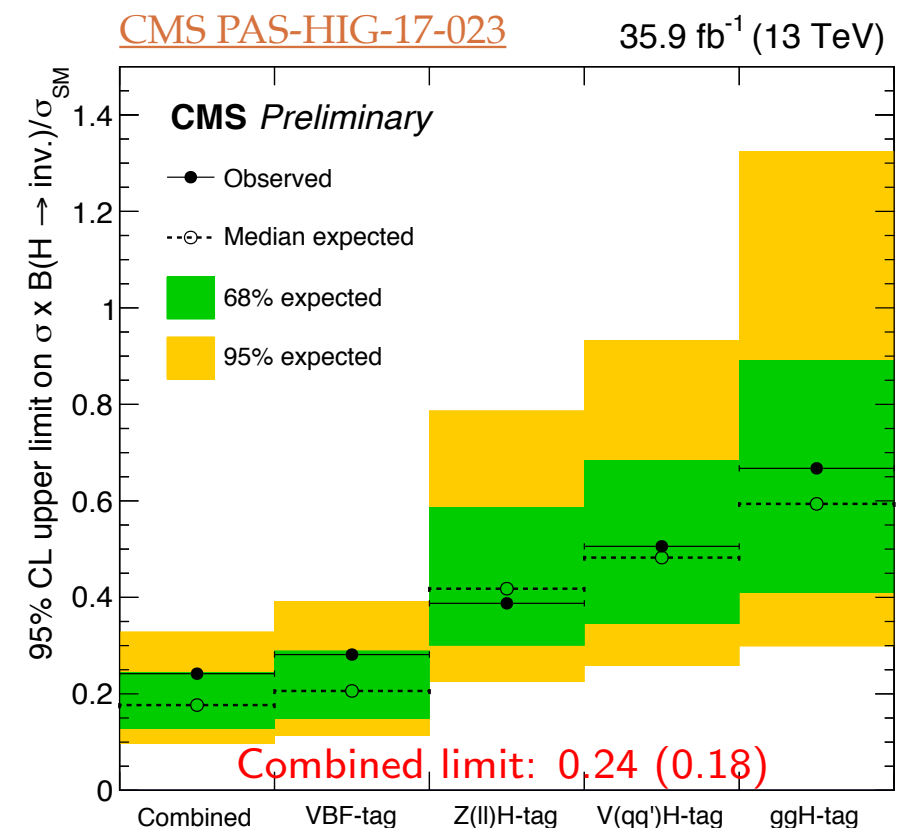
- χ^0 down to 100 GeV still allowed
- Many different searches constraining DM candidate
- Interplay with direct searches investigated with global fits

DM from Higgs decays

- Powerful search channel if $m_{\text{DM}} < m_H/2$
 - H(125) only scalar we know, a **portal to DM**?
- Gluon fusion and VH**
 - Tag with ISR jet or a boson $V(hh)$ or $Z(\ell\ell)$
 - Same final state as monoX searches
- Vector-boson fusion (VBF)**
 - Tag using forward jets (large $\Delta\eta$)
 - Low backgrounds (S/B ~ 0.5)
 - Most sensitive signature**
 - 13TeV result from CMS BR $< 28\%$ (21% exp)
 - $Z(\nu\nu)$, $W(\ell\nu)$ bkg from control regions
 - Shape fit to maximise sensitivity
 - 8TeV result from ATLAS BR $< 28\%$ (31% exp)
 - Still competitive, update soon!



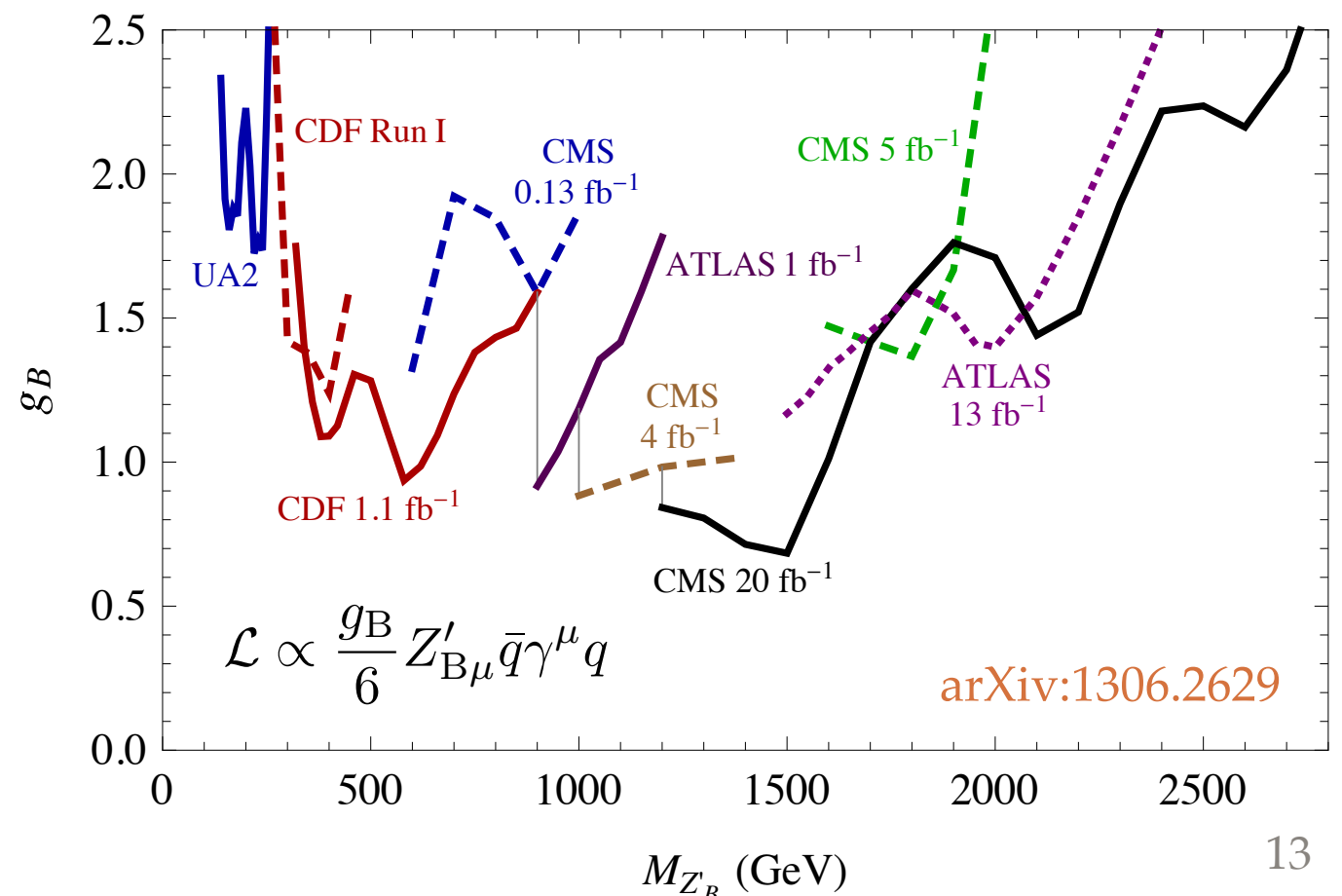
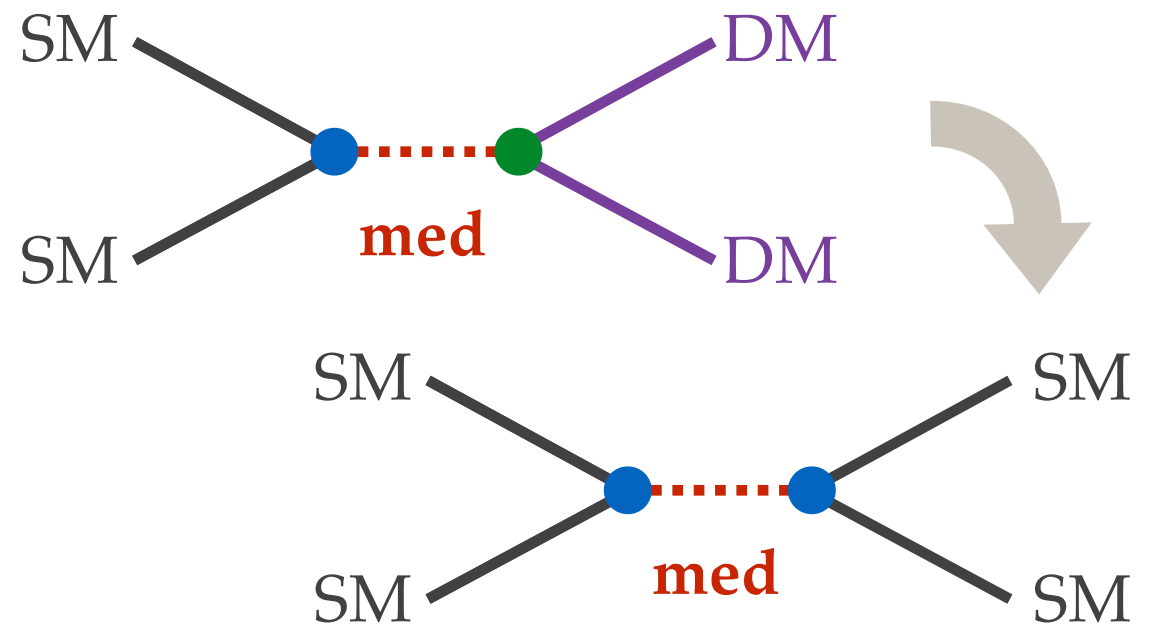
[CMS PAS-HIG-17-023](#)
[ATLAS 1508.07869](#)



Mediator $\rightarrow$ *SM*

Mediator searches

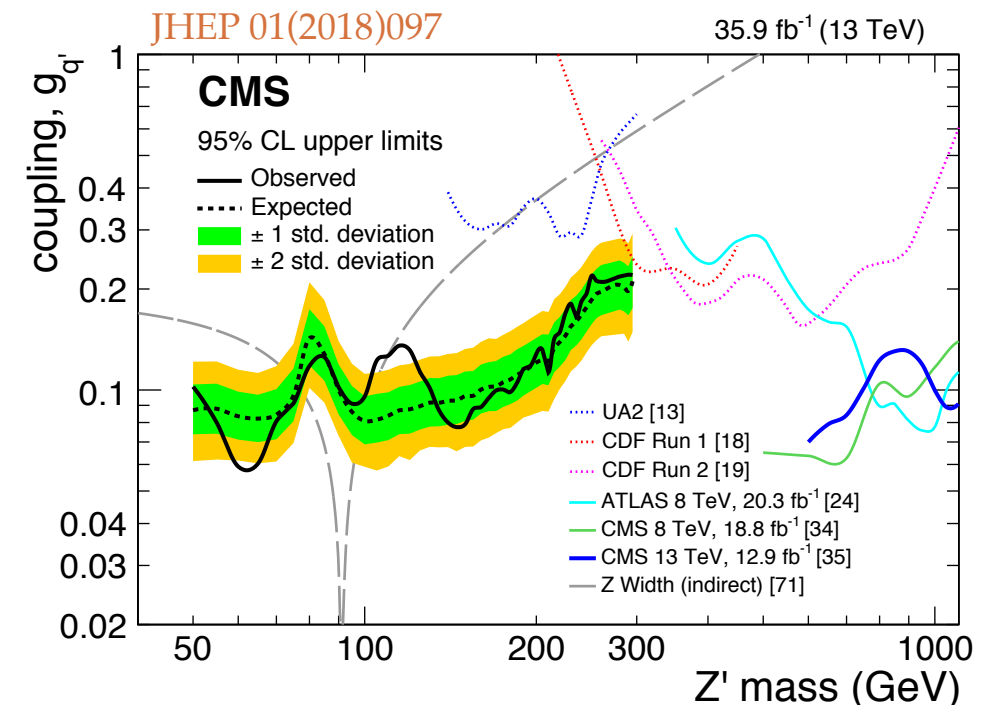
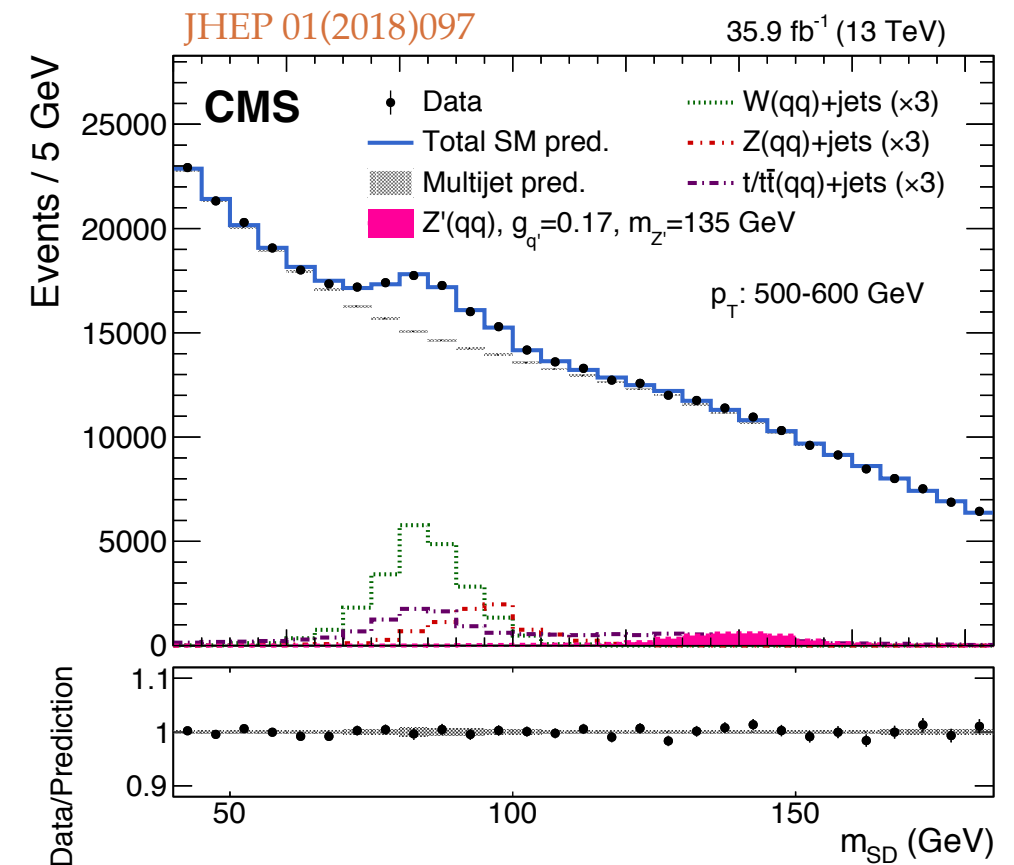
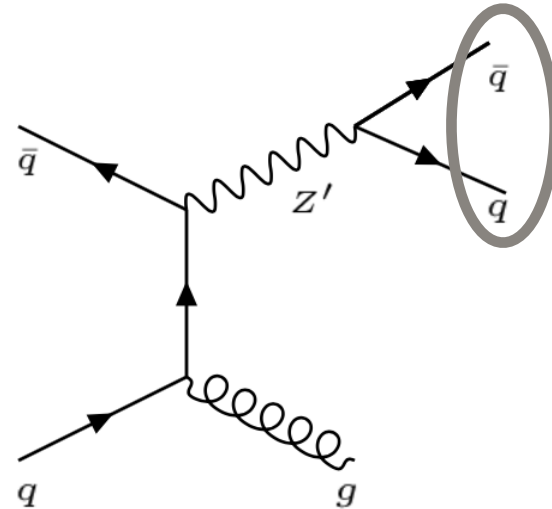
- New mediator can decay back to SM
- If m_{med} accessible at LHC could be key to establish characteristics of DM interaction
- **Low sensitivity for light m_{med}** due to trigger p_T thresholds
- ▶ Recently progress on this front:
 1. **Boosted dijets** (ISR jet tag)
 2. **Data scouting** (trigger-level jets)



Mediator searches

Boosted dijets

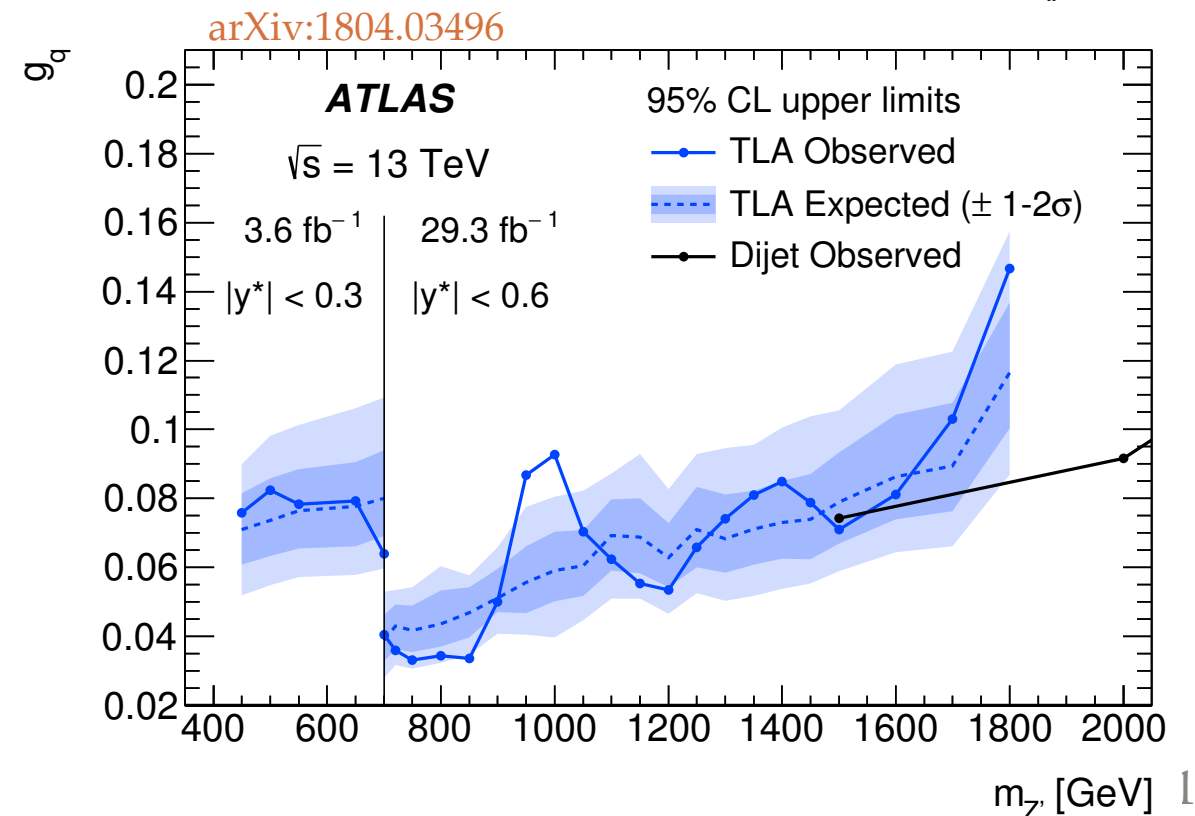
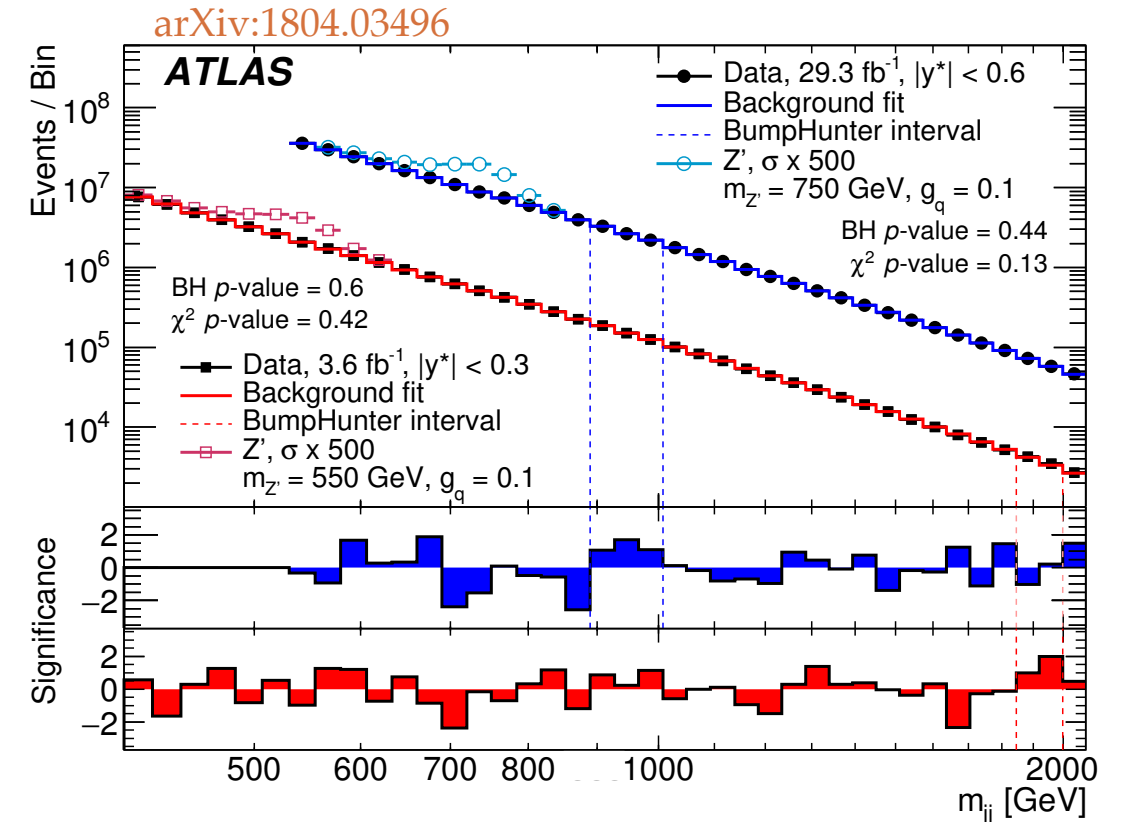
- Require an ISR jet or γ to satisfy trigger threshold
- Boosted collimated dijet reconstructed as large-R jet
 - Use jet substructure to separate from single-jet background
- Example: CMS JHEP 01(2018)097**
 - Narrow ISR jet $p_T > 500$ GeV
 - Probing $m(Z')$ down to 50 GeV
 - Background from single-jet control regions (substructure variable uncorrelated from mass)
- Example: ATLAS arXiv:1801.08769**
 - Extending down to $m(Z') = 100$ GeV



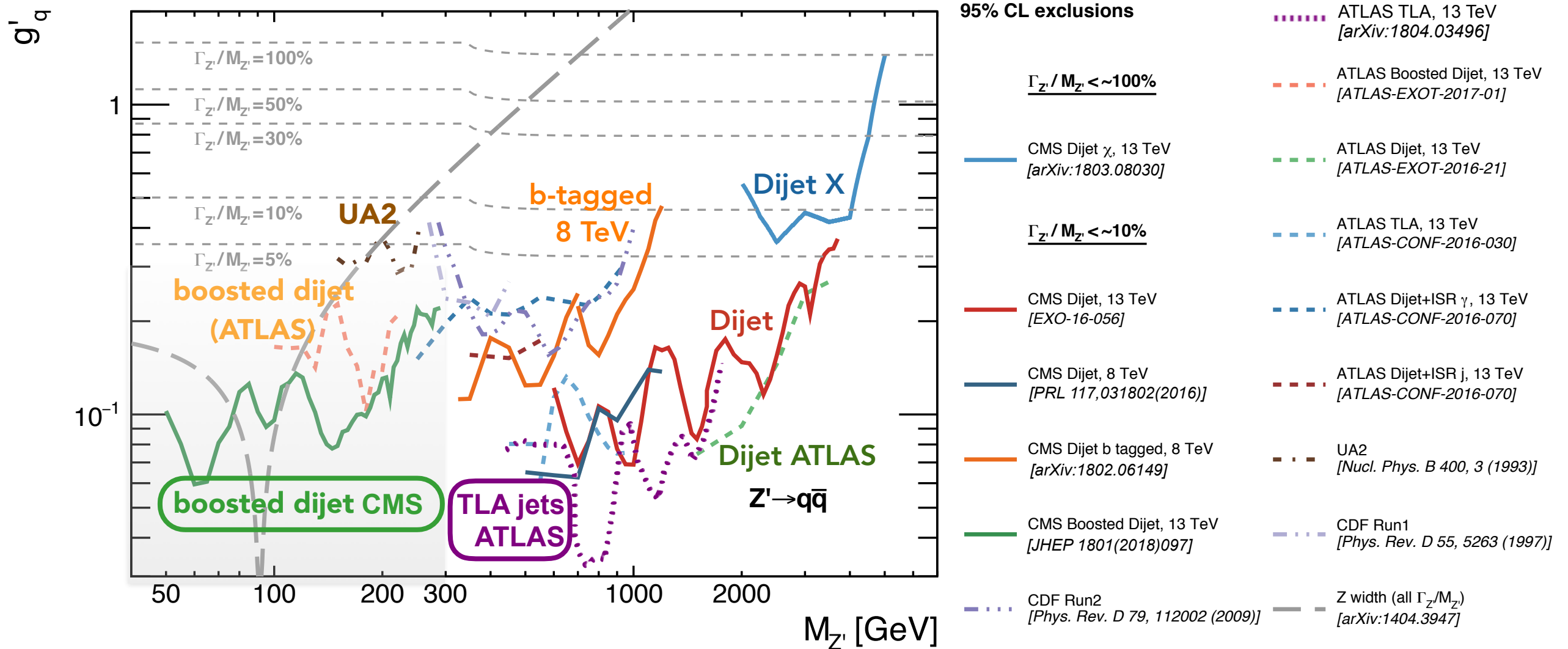
Mediator searches

Data scouting

- Reduce trigger rates at “low” mass
 - Online jet reconstruction
 - Compact event format
- **Example: ATLAS** arXiv:1804.03496
 - Construct jets in HLT from *Calorimeter*
 - Only jets p_i and quality to disk (0.5%)
 - $E_T > 100$ GeV (29/fb), $E_T > 75$ GeV (3.6/fb)
 - Searching down to $m(Z') = 450$ GeV
- **Example: CMS** PAS-EXO-16-056
 - Calorimeter scouting $m > 0.5$ TeV:
 - Particle-Flow scouting $m > 1.25$ TeV:



Summary of dijet searches

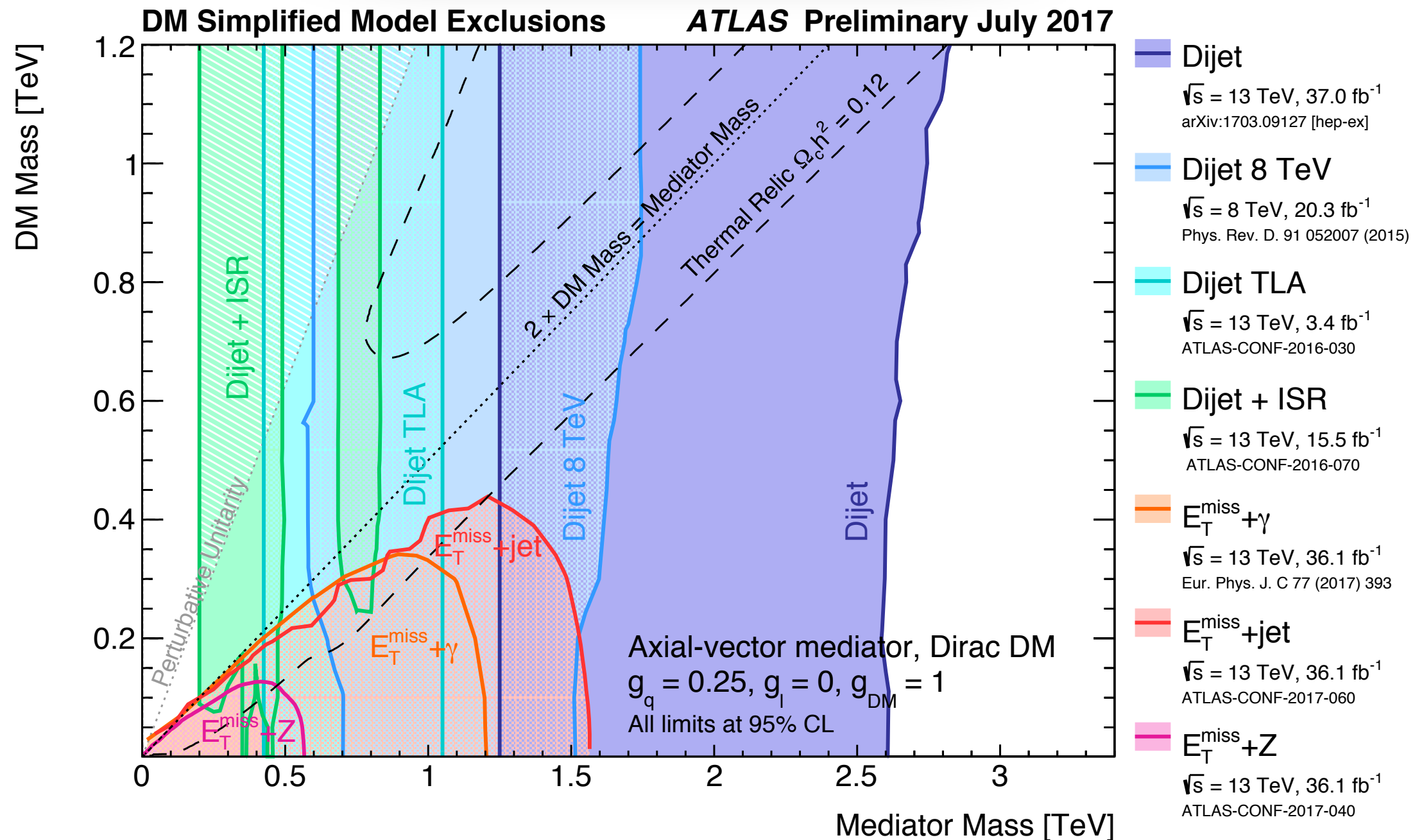


- Searched also $Z' \rightarrow \ell\ell$
 - CMS PAS-EXO-16-031
 - ATLAS arXiv:1707.02424

Mono-X vs mediator searches

arXiv:1708.09674

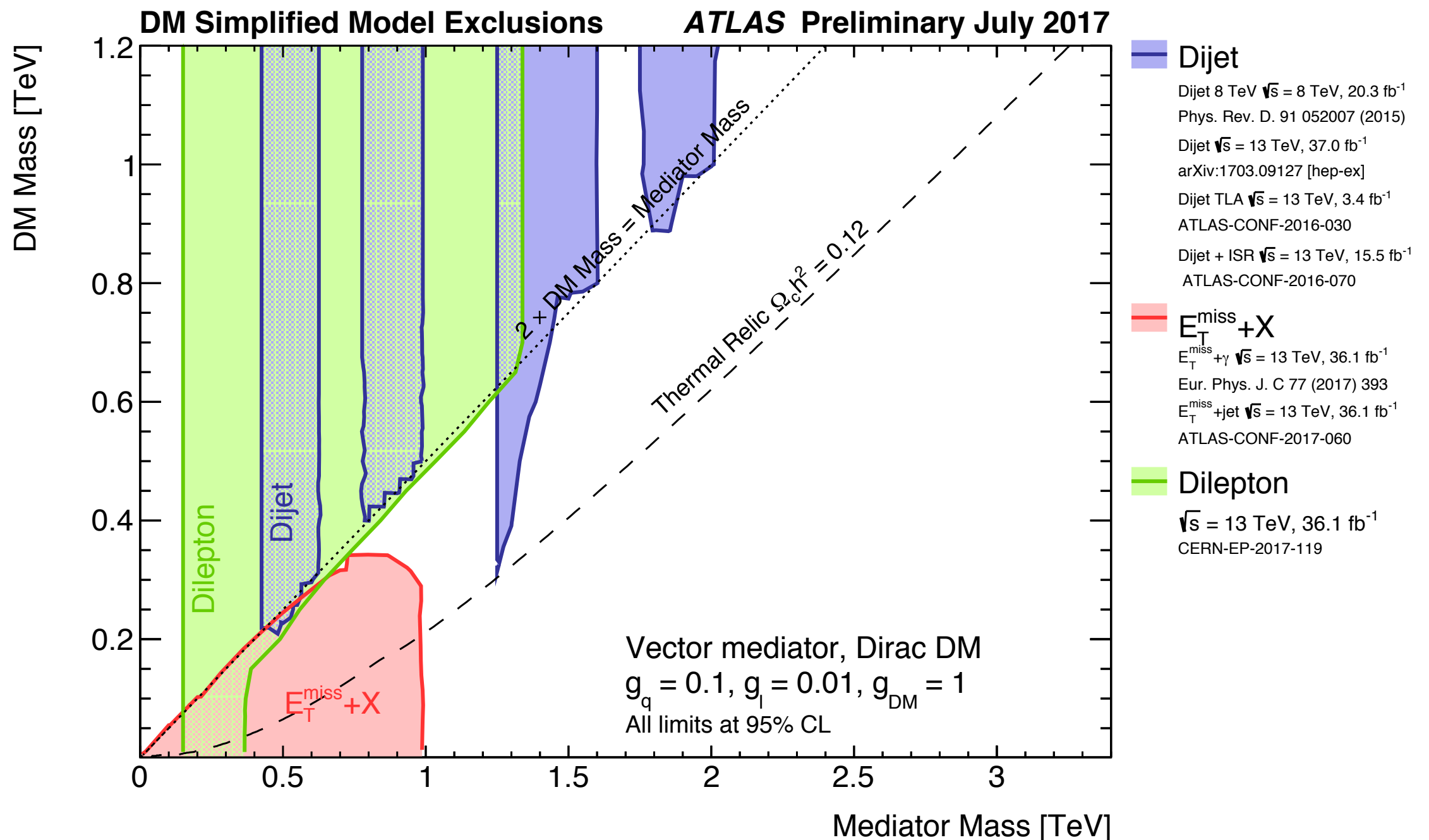
$$g_q = 0.25, g_\ell = 0$$



Mono-X vs mediator searches

arXiv:1708.09674

$$g_q = 0.1, g_\ell = 0.01$$



Lighter mediators $\rightarrow$ SM

Dark Sectors at the LHC

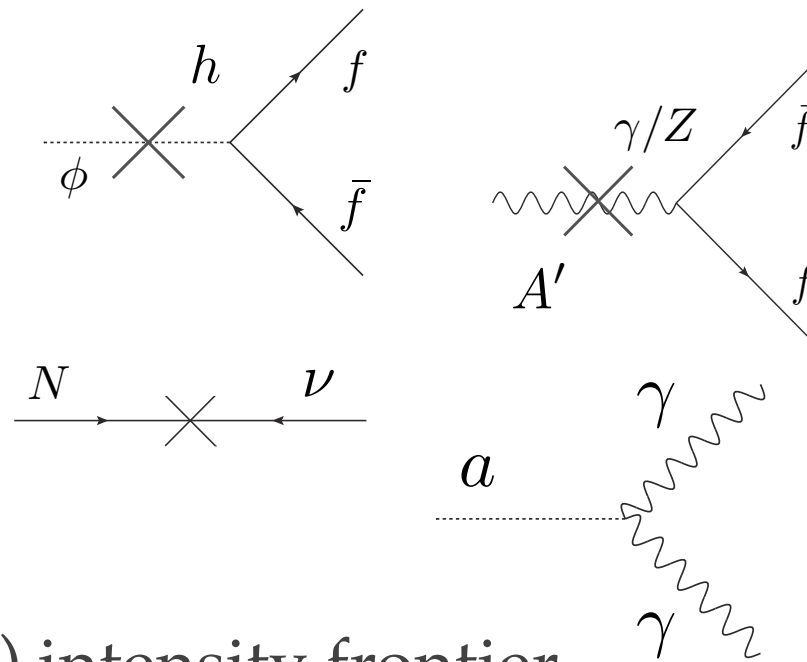
- Address SM problems with light very-weakly interacting states → **Dark Sectors**

► Can get also DM candidate (e.g. freeze-in)

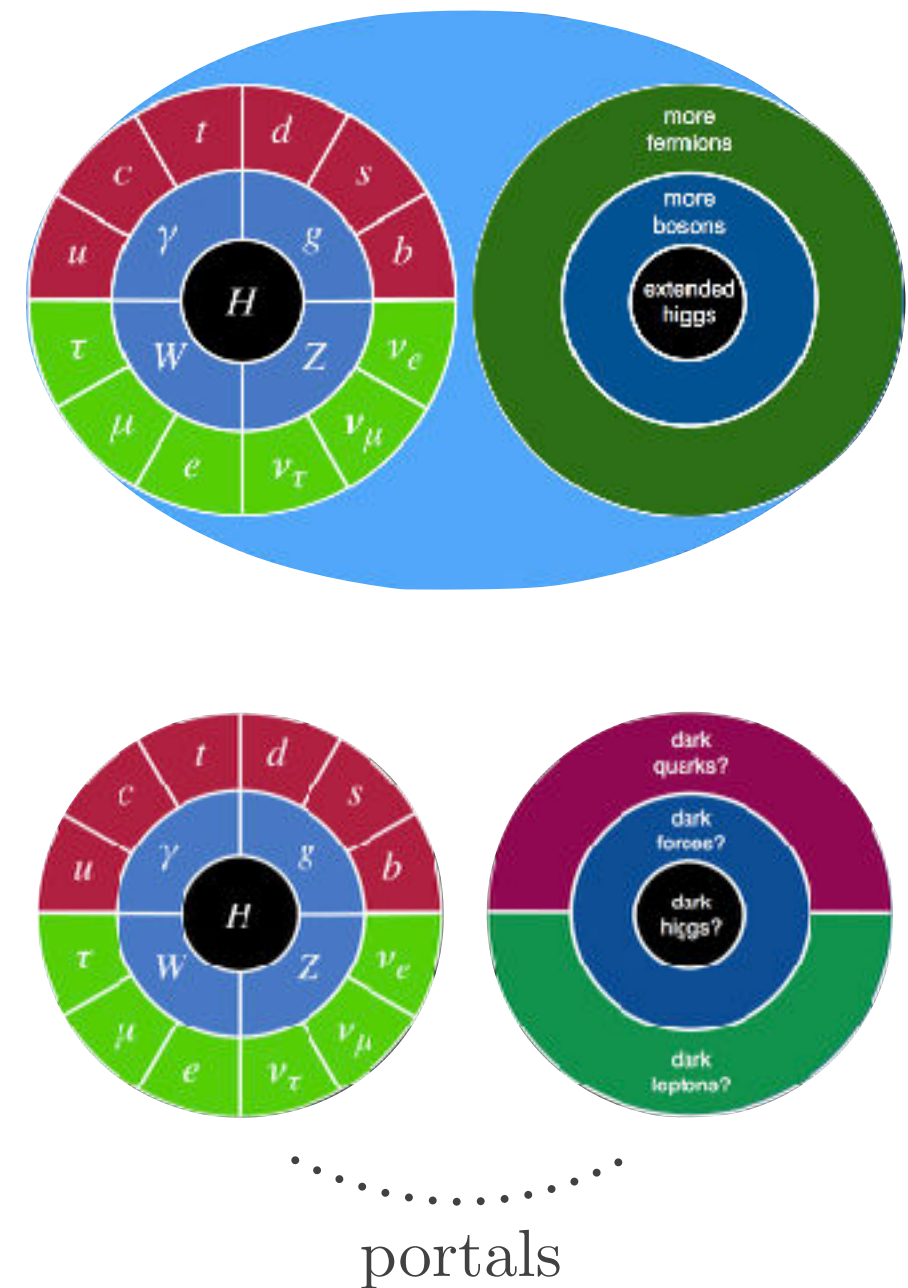
[Recent review: 1608.08632](#)

- Dark sector portals:**

- Scalar portal (ϕ)
- Vector portal (A')
- Neutrino portal (N)
- Axion portal (a)



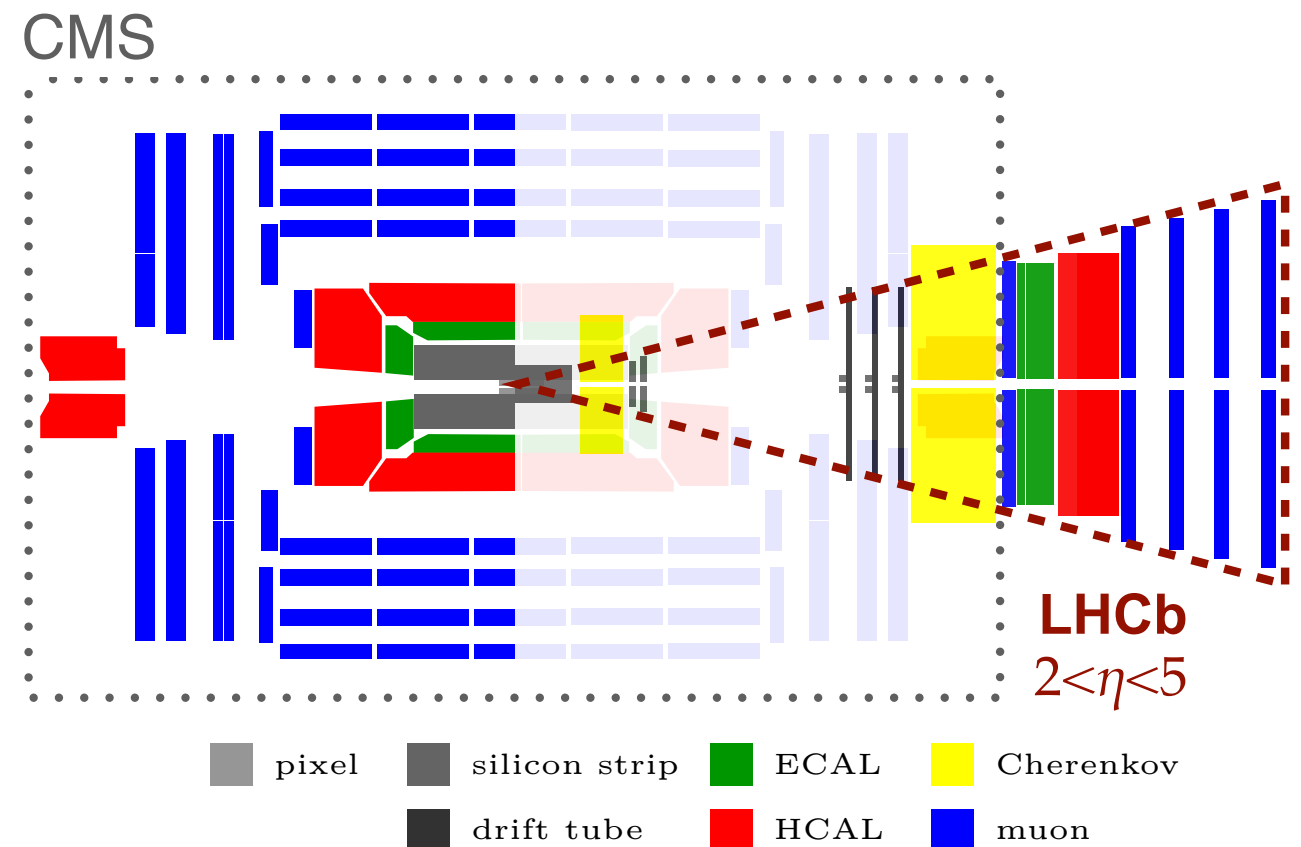
- Search at (low-energy) intensity frontier
 - LHC can exploit huge cross-sections
 - **Main challenge: triggering**



The LHCb potential

Int.J.Mod.Phys. A 30, 1530022 (2015)

- Designed to exploit the LHC **intensity frontier** to do B physics
- Only LHC detector fully instrumented in **forward** region
- $\sim 10\times$ lower luminosity (low pile-up)
- Excellent vertex and mass resolution
- **Capable of very soft triggers:**
 - At hardware level (L0):
 - Muons with $p_T > 1.8 \text{ GeV}$
 - Calo deposits with $E_T > 3 \text{ GeV}$
 - At Software level (HLT):
 - Triggers on detached vertices



- **“Trigger-less” upgrade (2021)**
 - Read-out detector in *real time*
 - Can trigger on detached vertices, precise particle ID and more

TDR: [\[LHCb-TDR-016\]](#)

Dark Bosons from $b \rightarrow s$

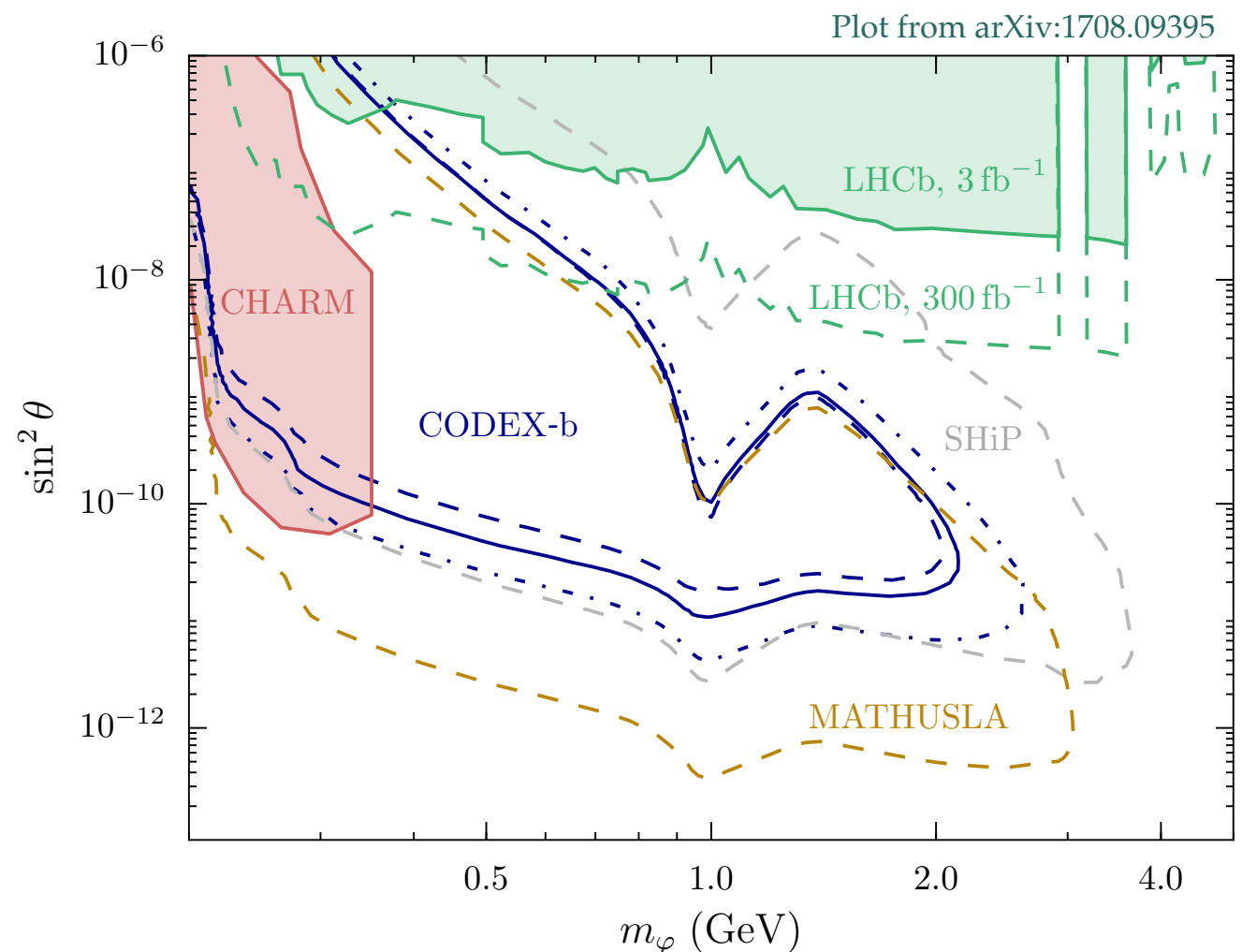
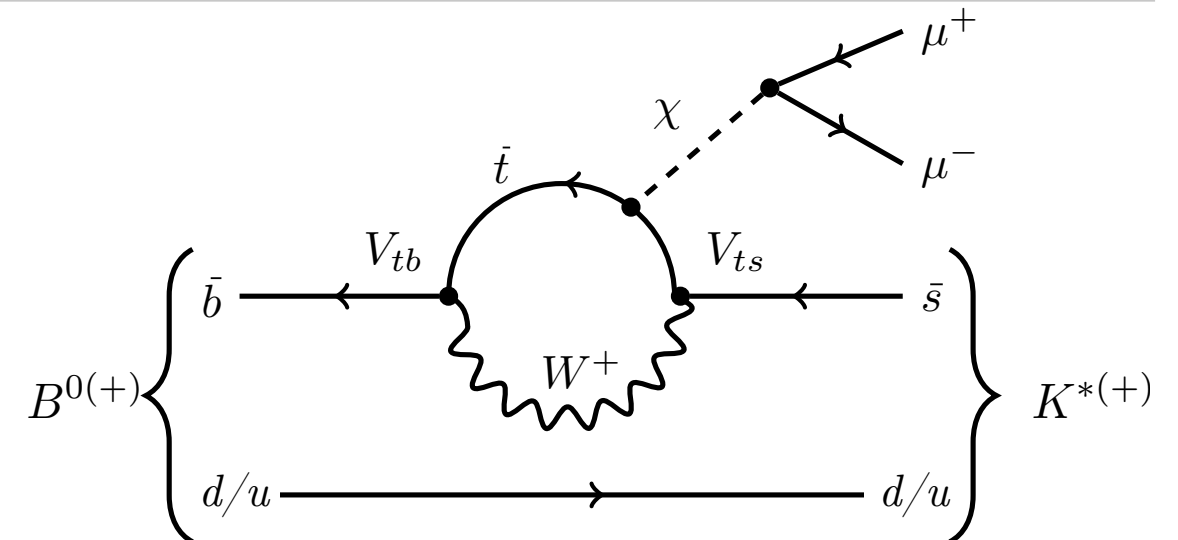
[Phys Rev Lett 115 161802 \(2015\)](#)

[Phys Rev D 95, 071101\(R\) \(2017\)](#)

- Look for new hidden-sector bosons in $b \rightarrow s$ penguin transitions
- World record samples of $B \rightarrow K^{(*)} \mu \mu$
 - search for narrow $\mu \mu$ peak
- Allow detached $\mu \mu$ (within VELO)
 - small SM mixing can give lifetime
- Constrain on light scalars
 - mixing with SM Higgs

$$\tau \propto 1/\theta^2 \quad \mathcal{B}(B^+ \rightarrow K^+ \chi) \propto \theta^2$$
 - world-best limits below $2m_\tau$
 - Complementary to Ship

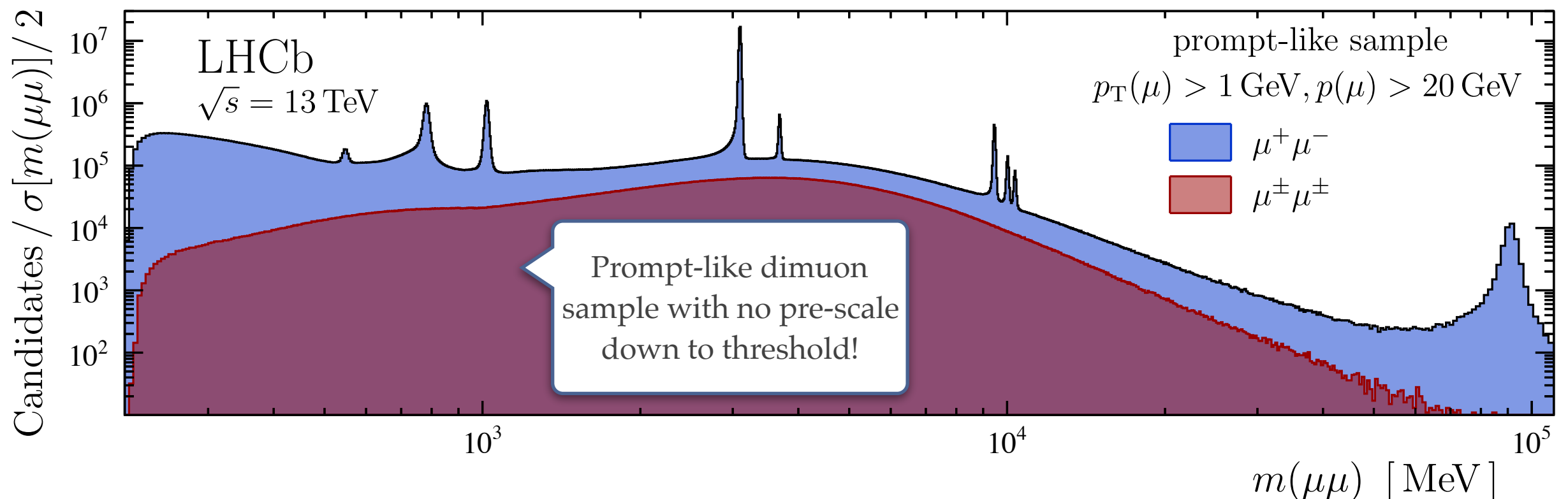
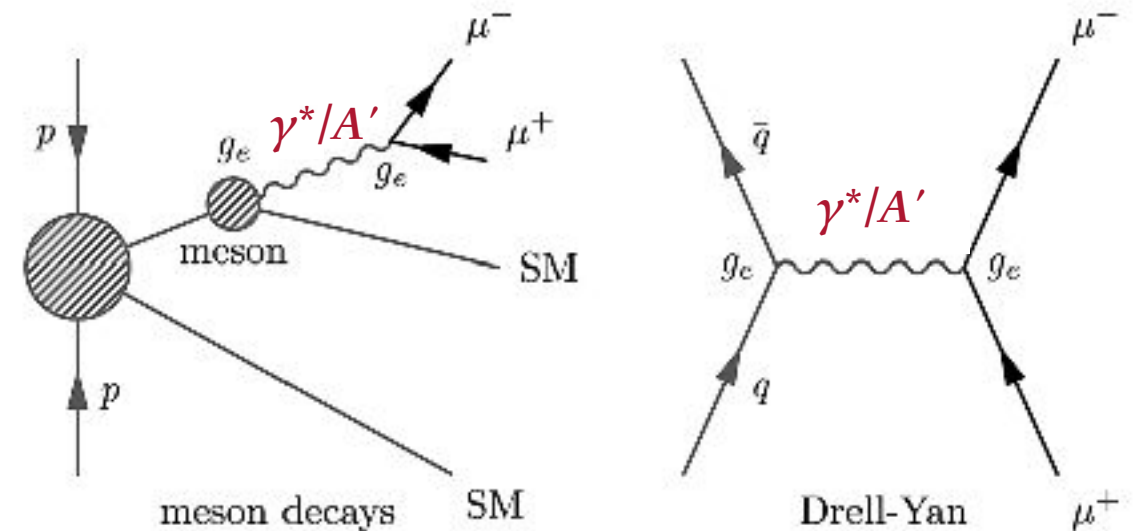
B.Batell, M.Pospelov, A.Ritz, PRD 83, 054005 (2011)
F.Bezrukov, D.Gorbunov, JHEP05(2010)010, JHEP07(2013)140



Dark Photons at LHCb

PRL 120 (2018) no.6, 061801

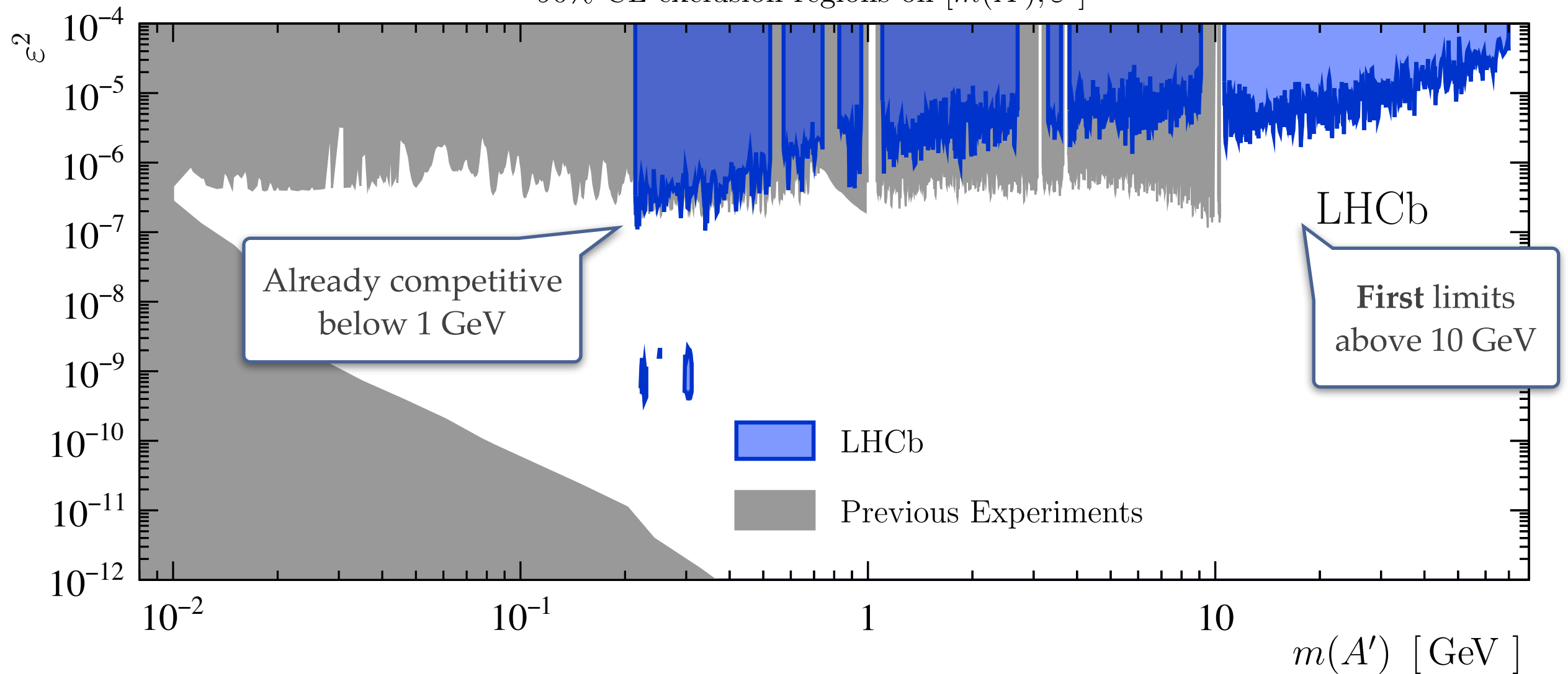
- Can search for **Dark Photons** (A') in $\mu\mu$
 - Can be very light, produced as γ^*
 - Large fraction in forward region, very soft p_T
- Data scouting technique in LHCb Run 2:**
 - Online reconstruction and tight μ -ID
 - Only interesting part of the event to disk
 - **no pre-scale down to threshold $2m_\mu$**



Dark Photons at LHCb

PRL 120 (2018) no.6, 061801

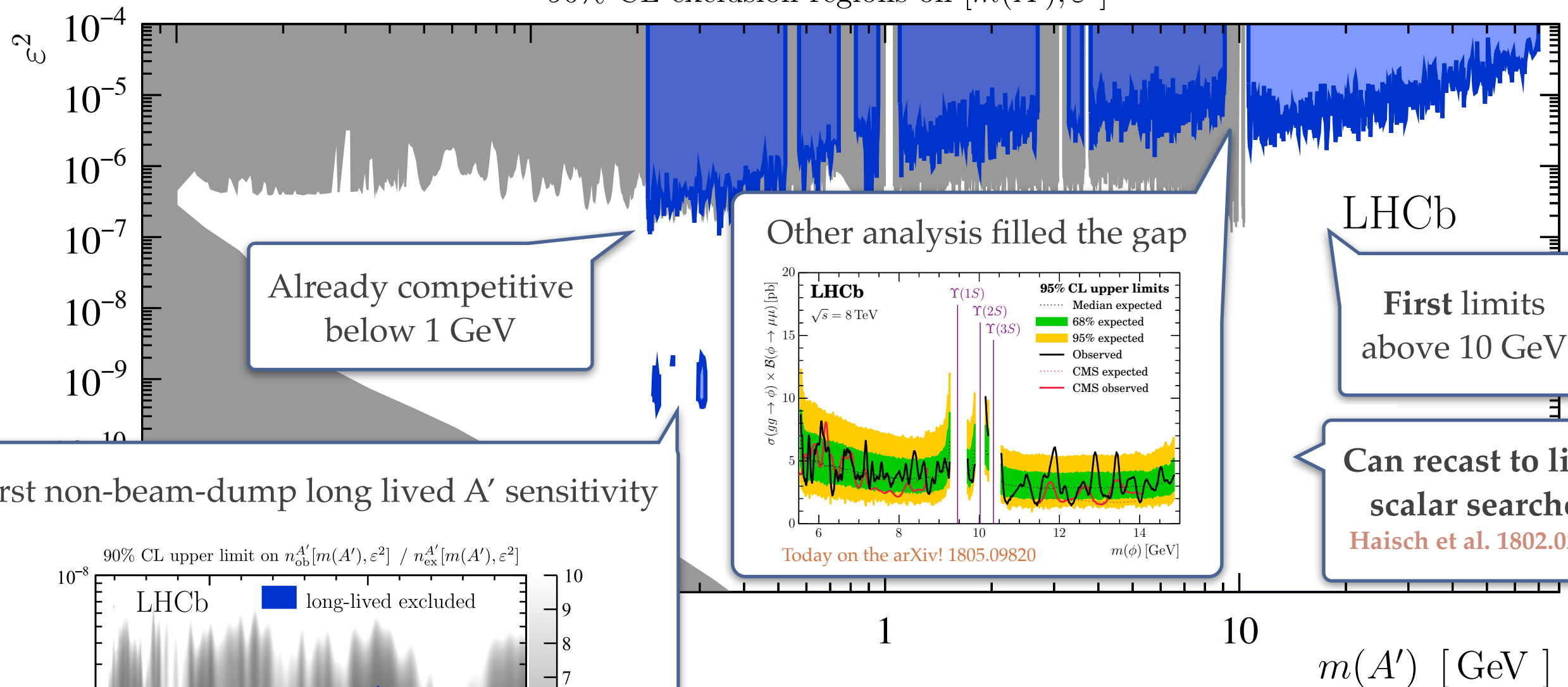
90% CL exclusion regions on $[m(A'), \varepsilon^2]$



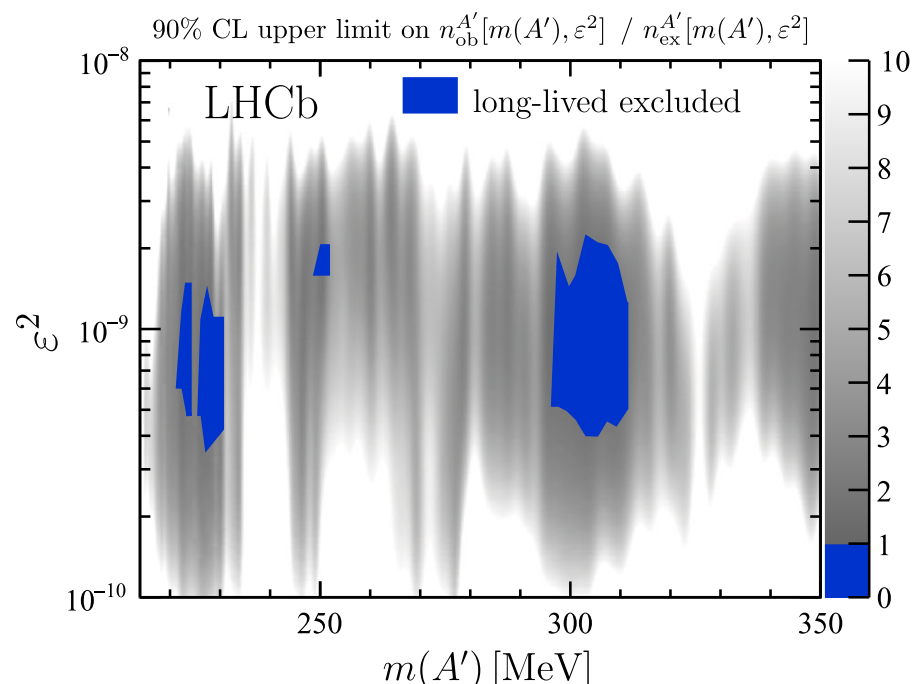
Dark Photons at LHCb

PRL 120 (2018) no.6, 061801

90% CL exclusion regions on $[m(A'), \varepsilon^2]$

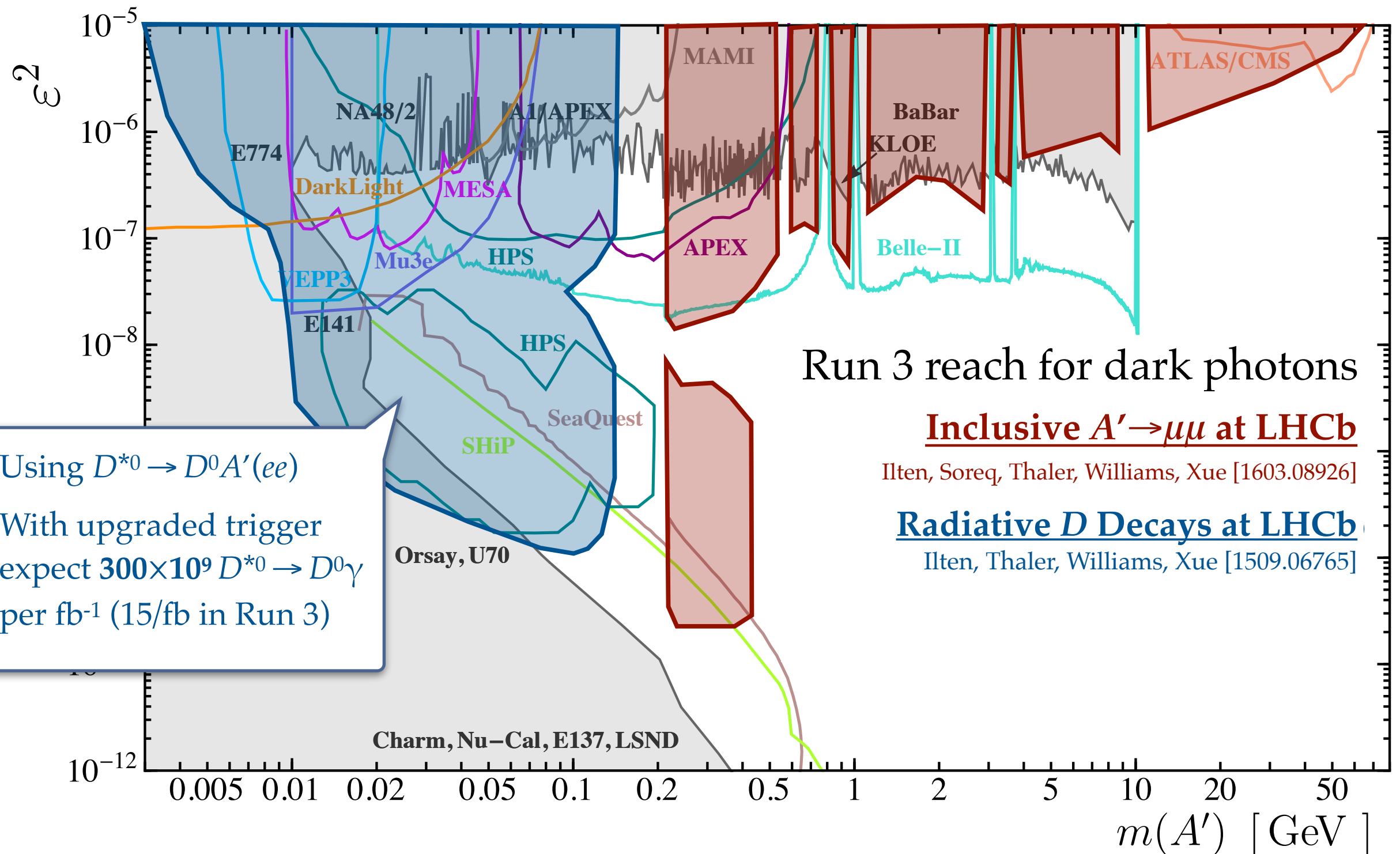


First non-beam-dump long lived A' sensitivity



- Proof of concept for soft μ searches at LHCb
 - Multiple dimuons from dark cascade
[A.Pierce et al. arXiv:1708.05389](#)
 - Heavy neutral leptons in displaced $\pi\mu$

LHCb Upgrade Dark Photon Reach



- Using $D^{*0} \rightarrow D^0 A'(ee)$
- With upgraded trigger expect $300 \times 10^9 D^{*0} \rightarrow D^0 \gamma$ per fb^{-1} (15/fb in Run 3)

Conclusions

- ◎ Investigating the origin of Dark Matter is one of the main goals of the LHC program
- ◎ Different and often complementary searches:
 - **Mediator** → **DM** (holistic)
 - Mono-X searches
 - Higgs to invisible searches
 - **Mediator** → **SM** (peak search)
 - Searching structure in dijet (dilepton) spectrum
 - Data scouting and boosted jets to reach lower masses
 - **Lighter mediators** → **SM** (dark sectors)
 - LHCb recently demonstrated to be very sensitive

BACKUP

Theory uncertainties for mono-X

CMS mono-X arXiv:1712.02345

Uncertainty source	Process (magnitude)	Correlation
Fact. & renorm. scales (QCD)	$Z \rightarrow \nu\nu/W \rightarrow \ell\nu$ (0.1 – 0.5%) $Z \rightarrow \nu\nu/\gamma+\text{jets}$ (0.2 – 0.5%)	Correlated between processes; and in p_T
p_T shape dependence (QCD)	$Z \rightarrow \nu\nu/W \rightarrow \ell\nu$ (0.4 – 0.1%) $Z \rightarrow \nu\nu/\gamma+\text{jets}$ (0.1 – 0.2%)	Correlated between processes; and in p_T
Process dependence (QCD)	$Z \rightarrow \nu\nu/W \rightarrow \ell\nu$ (0.4 – 1.5%) $Z \rightarrow \nu\nu/\gamma+\text{jets}$ (1.5 – 3.0%)	Correlated between processes; and in p_T
Effects of unknown Sudakov logs (EW)	$Z \rightarrow \nu\nu/W \rightarrow \ell\nu$ (0 – 0.5%) $Z \rightarrow \nu\nu/\gamma+\text{jets}$ (0.1 – 1.5%)	Correlated between processes; and in p_T
Missing NNLO effects (EW)	$Z \rightarrow \nu\nu$ (0.2 – 3.0%) $W \rightarrow \ell\nu$ (0.4 – 4.5%) $\gamma+\text{jets}$ (0.1 – 1.0%)	Uncorrelated between processes; correlated in p_T
Effects of NLL Sudakov approx. (EW)	$Z \rightarrow \nu\nu$ (0.2 – 4.0%) $W \rightarrow \ell\nu$ (0 – 1.0%) $\gamma+\text{jets}$ (0.1 – 3.0%)	Uncorrelated between processes; correlated in p_T
Unfactorized mixed QCD-EW corrections	$Z \rightarrow \nu\nu/W \rightarrow \ell\nu$ (0.15 – 0.3%) $Z \rightarrow \nu\nu/\gamma+\text{jets}$ (<0.1%)	Correlated between processes; and in p_T
PDF	$Z \rightarrow \nu\nu/W \rightarrow \ell\nu$ (0 – 0.3%) $Z \rightarrow \nu\nu/\gamma+\text{jets}$ (0 – 0.6%)	Correlated between processes; and in p_T

HNL in $B \rightarrow \pi^+ \mu^- \mu^-$

[Phys Rev Lett 112 131802 \(2014\)](#)

- Lepton number violating $B^- \rightarrow \pi^+ \mu^- \mu^-$ can proceed via on-shell Majorana neutrinos
- Look for B mass peak, then extract limit as a function of m_N
- Limit set on $N(\pi\mu)$ lifetimes up to 1000 ps
- Constraints on mixing angle $V_{\mu 4}$
 - Recently revisited

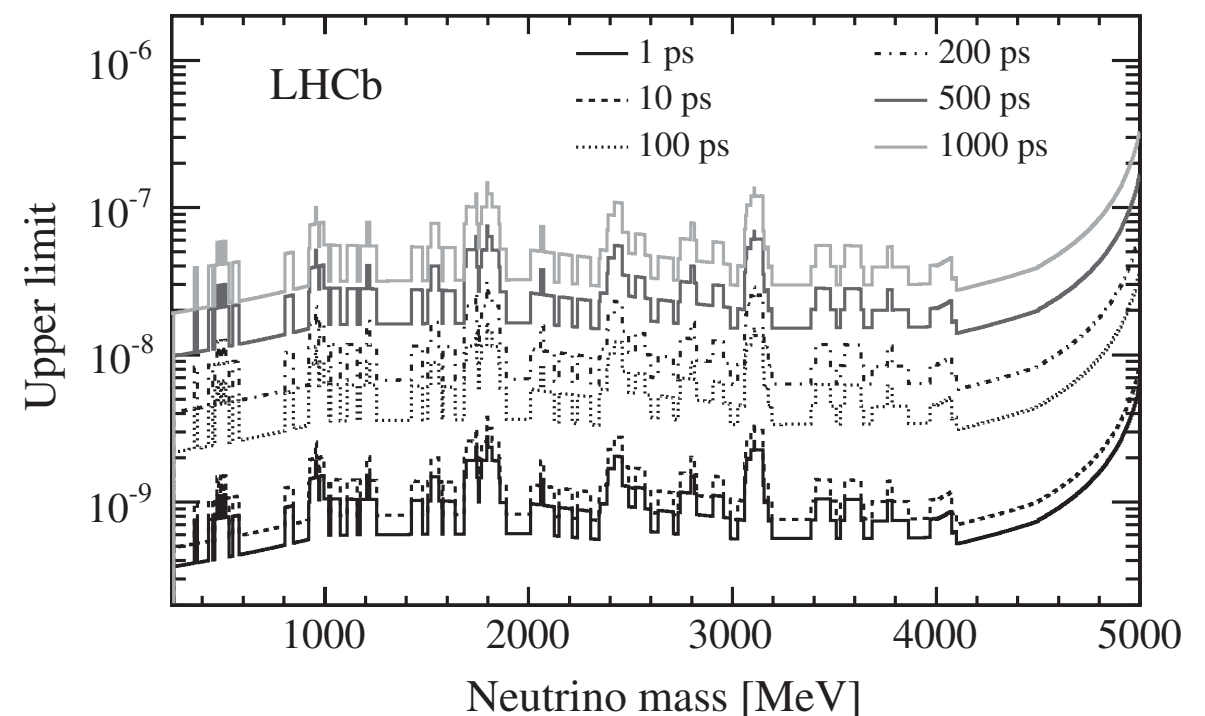
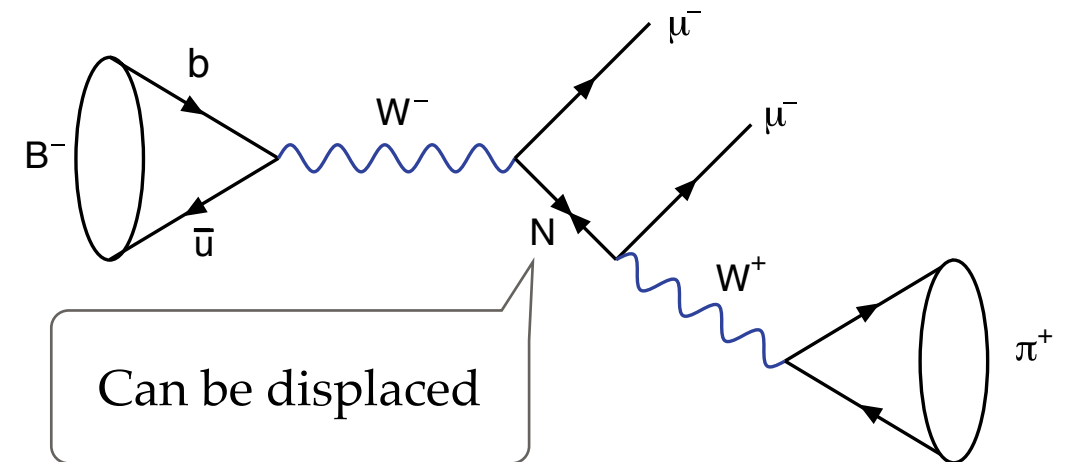
[B Shuve, ME Peskin, PRD94 \(2016\) no.11, 113007](#)

- Also searched in charm $D^+ \rightarrow \pi^- \mu^+ \mu^+$

[PLB 724 \(2013\) 203-212](#)

$$\mathcal{B}(D^+ \rightarrow \pi^- \mu^+ \mu^+) < 2.2 (2.5) \times 10^{-8},$$

$$\mathcal{B}(D_s^+ \rightarrow \pi^- \mu^+ \mu^+) < 1.2 (1.4) \times 10^{-7}.$$



Future HNL at LHCb

- ⊙ Inclusive search $b \rightarrow X \mu^+ \mu^+ \pi^-$

$$\frac{\mathcal{B}(b \rightarrow X \mu^+ \nu)}{\mathcal{B}(B^+ \rightarrow \mu^+ \nu)} > 10^5$$

- ⊙ Can also search higher masses using on-shell $W^- \rightarrow \text{jet } \mu^- \mu^-$

