Note to Reviewers

- Here is a first draft of the talk on "Collider constraints on dark matter, dark energy and cosmology" that I will be giving at Kruger2018 next thursday, December 6th. The talk is 40 minutes long, plus 5 minutes questions.

- As you can see the slides are still not entirely complete, in particular:
  - I'm still working on the wording of the bullets of some slides;
  - I still have to rehearse it, and if I see that I have some extra time, I'll probably add the search for emerging jets (https://arxiv.org/pdf/1810.10069.pdf);
  - I'm not sure what the title meant by "cosmology" but I can't think of anything **specifically** cosmological we are doing at colliders, except for what I put.

Collider constraints on Dark Matter, Dark Energy and Cosmology

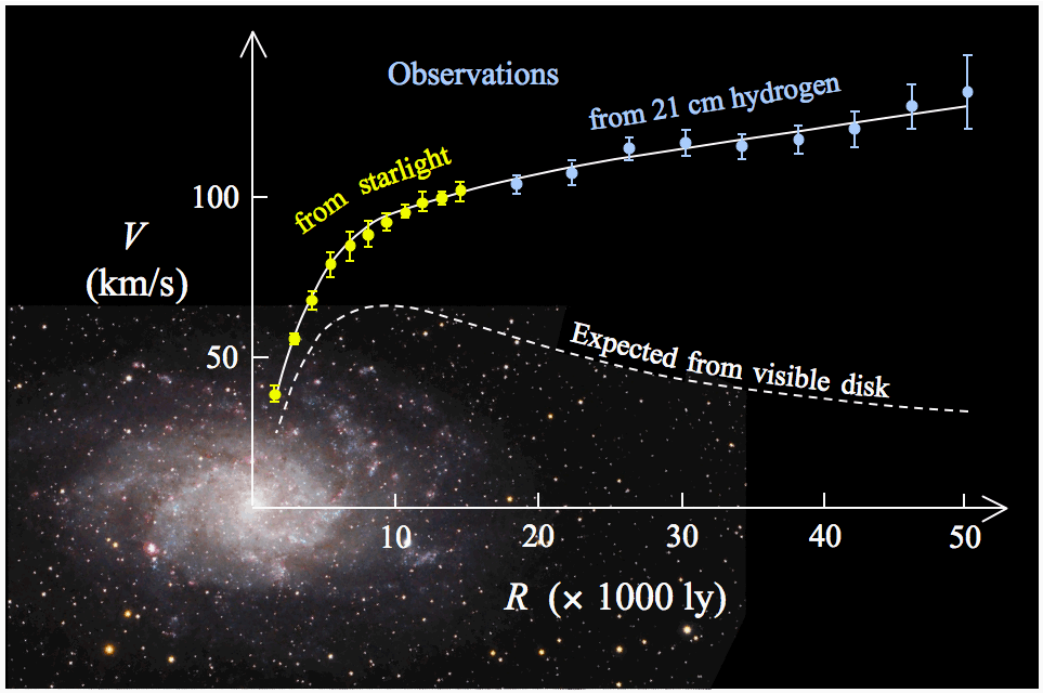
Francesco Pandolfi

INFN Rome

On behalf of the CMS and ATLAS Collaborations

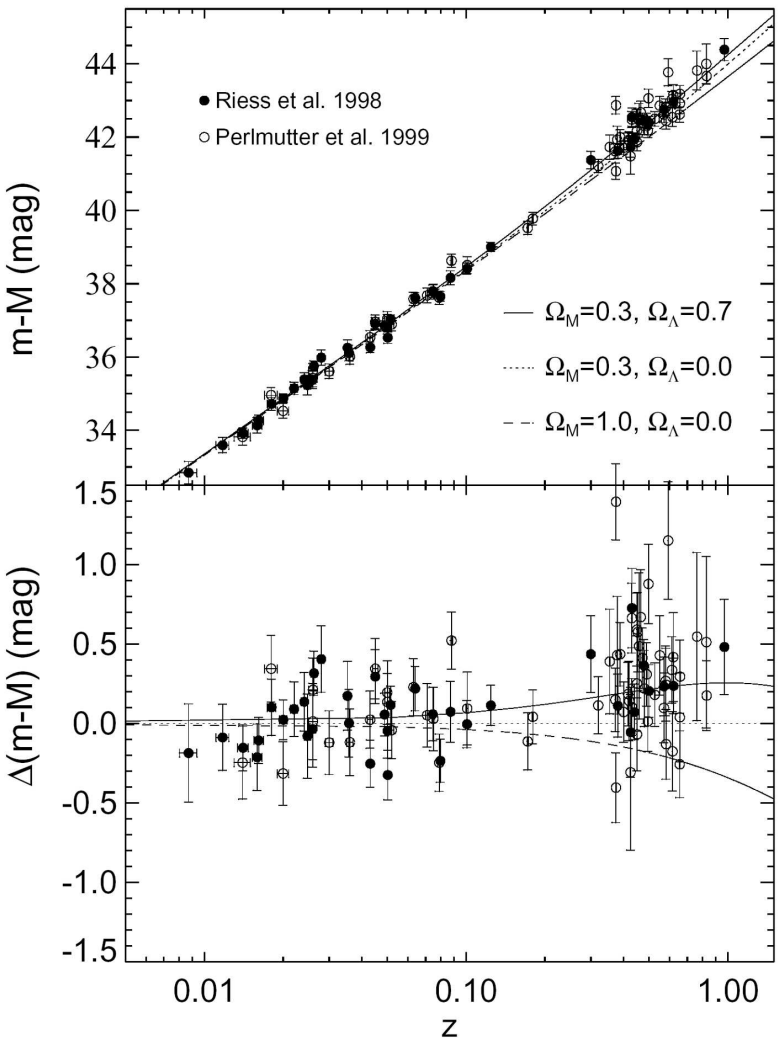
Kruger2018: Discovery Physics at the LHC
Kruger National Park, 06.12.18

Most Cosmological Matter Unaccounted For

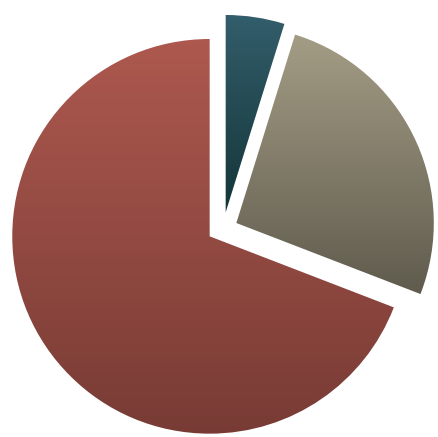


- **Anomalies** in observed universe: galaxy rotation, galaxy clusters, supernovae
  - **Simplest** explanation: existence of an unknown, **dark** state of matter

Most of the Universe is Not Even Matter



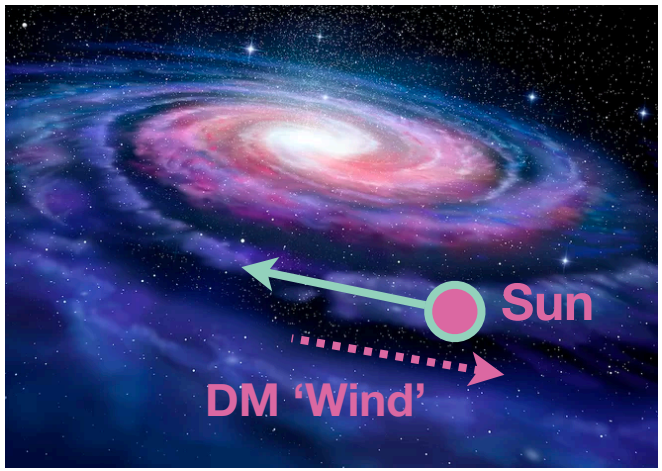
- CMB tells us universe is flat: $\Omega_{tot} \sim 1$
- Supernovae Ia: universe is accelerating
  - **Incompatible** with matter-only universe

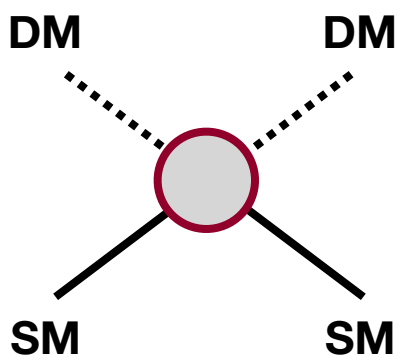


	Ω	$\Omega \cdot h^2$
Atoms	0.048	0.022
Dark Matter	0.26	0.12
Dark Energy	0.69	—

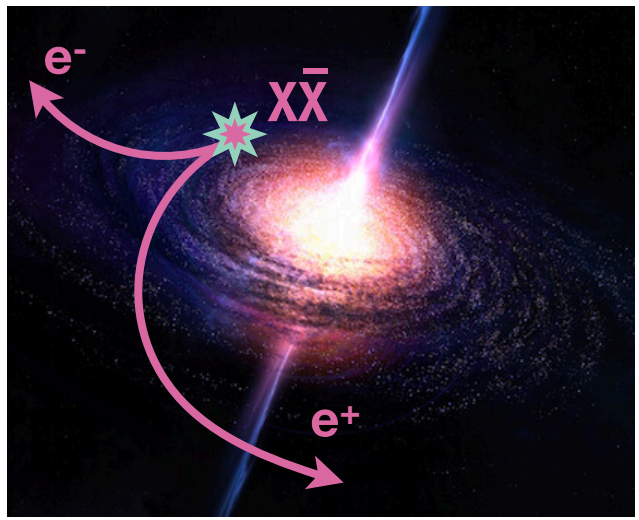
Three Types of Searches for Dark Matter

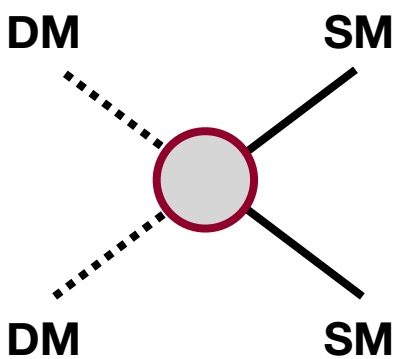
Direct



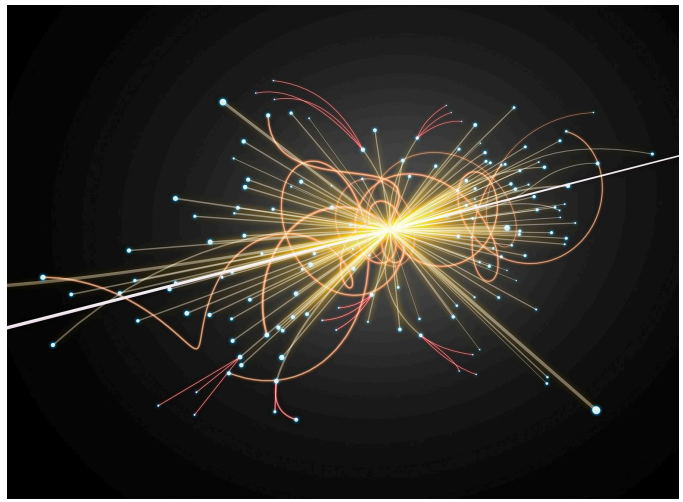


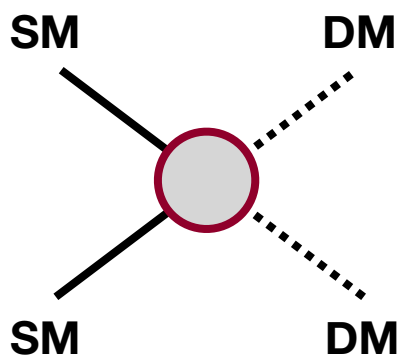
Indirect



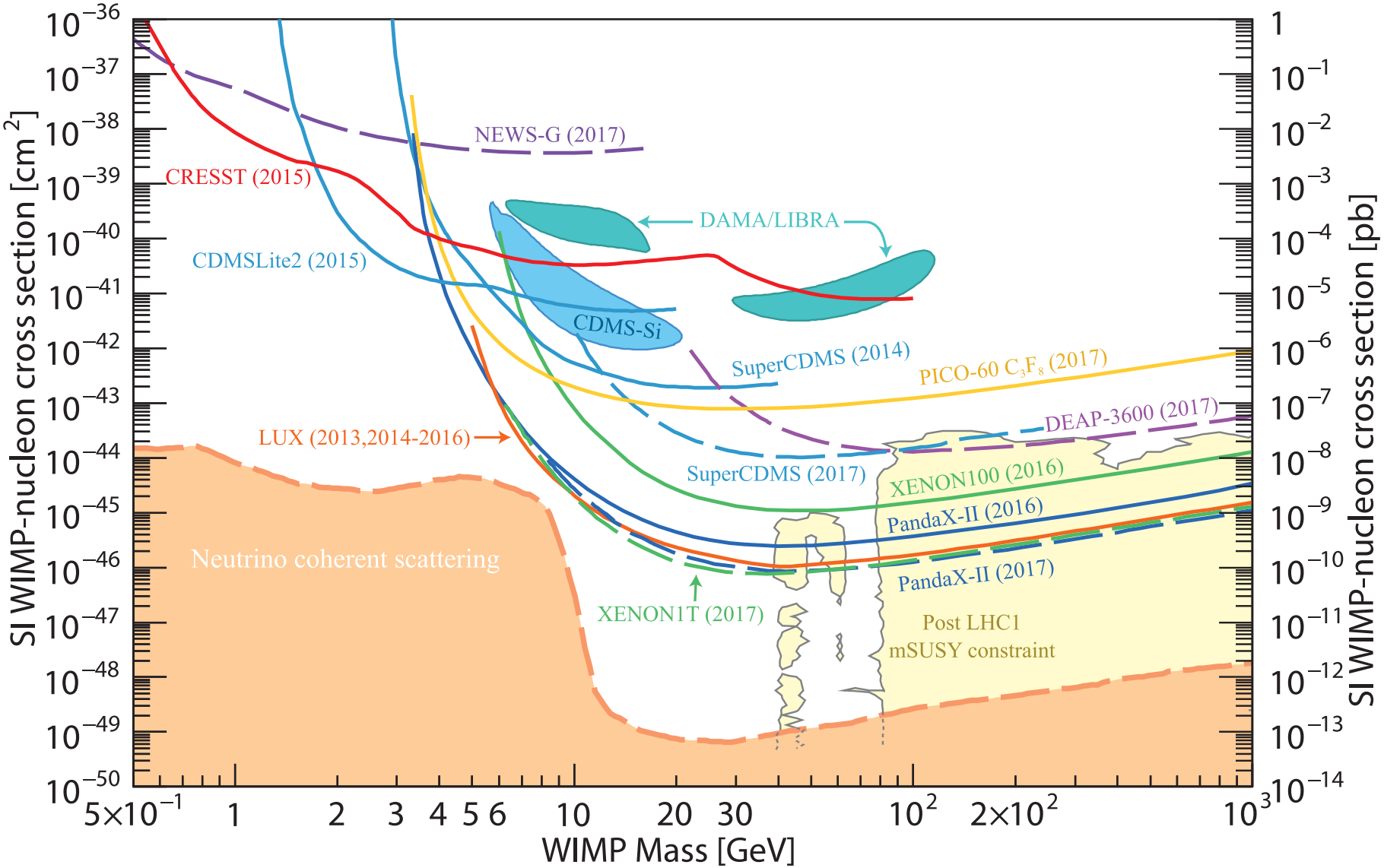


Colliders



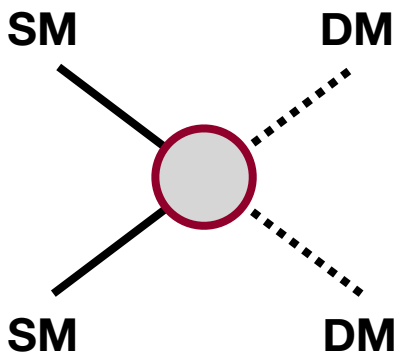


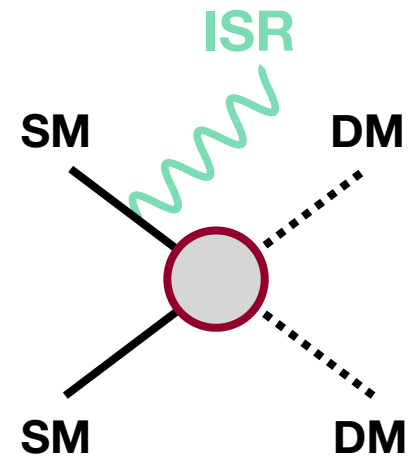
Latest Results from Direct Searches



Searches at Colliders: Need DM to Recoil vs ISR

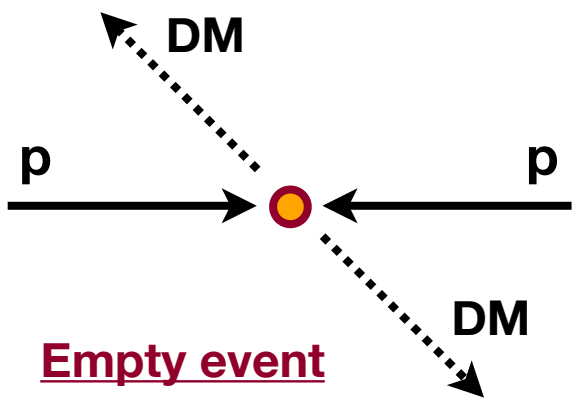
- **Need** ISR to see the event
- ISR can be: g, γ, Z, W, H…
  - ‘MonoX’ searches
- **Two** free parameters (EFT)
  - Scale Λ
  - DM mass
- EFT has been **surpassed**…



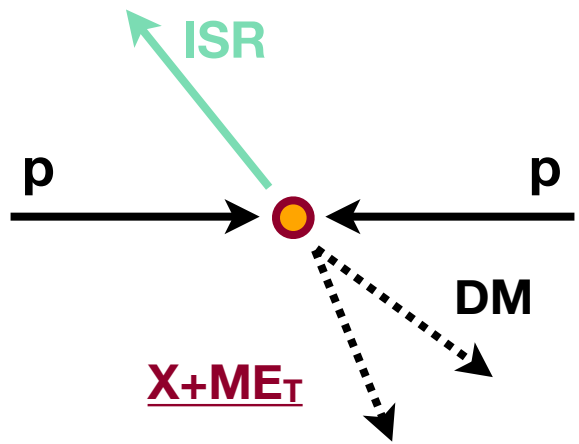


Undetectable

Detectable

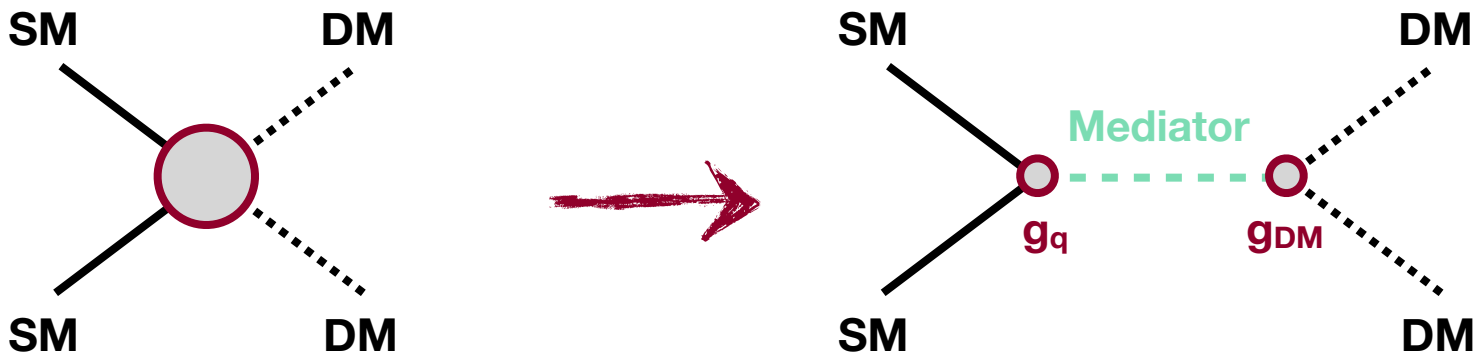


Empty event



X+ME$_T$

Beyond EFT: Simplified Models



- Since LHC Run-2: **dropped** EFT framework, moved to **simplified models**
  - Not yet full-blown theory, but **more structure** (eg. gauge invariance)

- Also more **parameters**:

Λ, M_{DM}

M_{DM}, M_{Med}, g_q, g_{DM} (g_l)

RECOMMENDED MODELS

Model	g_{DM}	g_q	g_l
vector	1	0.25	0
vector	1	0.1	0.01
axial-vector	1	0.25	0
axial-vector	1	0.1	0.01
scalar	1	1	0
pseudoscalar	1	1	0

'simple' spin-0 models not gauge-invariant being dropped

More Structure to Spin-0 Models: 2HDM

- **Simple** extension of SM: **two** Higgs doublets Φ_1 and Φ_2 **$\tan\beta = v_1 / v_2$**
  - Renormalizable and UV-complete
  - **Five** Higgs particles:

$H^{\pm}$	charged scalars
h	'SM Higgs'
H^0	other neutral scalar
A	pseudoscalar

eg SUSY

- Will focus on 'type-II' models: Φ_1 (Φ_2) couples to up-(down-) quarks
- Recently **popular**: 2HDM+Z' and 2HDM+a
  - Additional vector (Z') or axial-vector (a) **mediator** to dark sector
  - Couples **only** to Higgs and dark matter: **eludes** experimental constraints

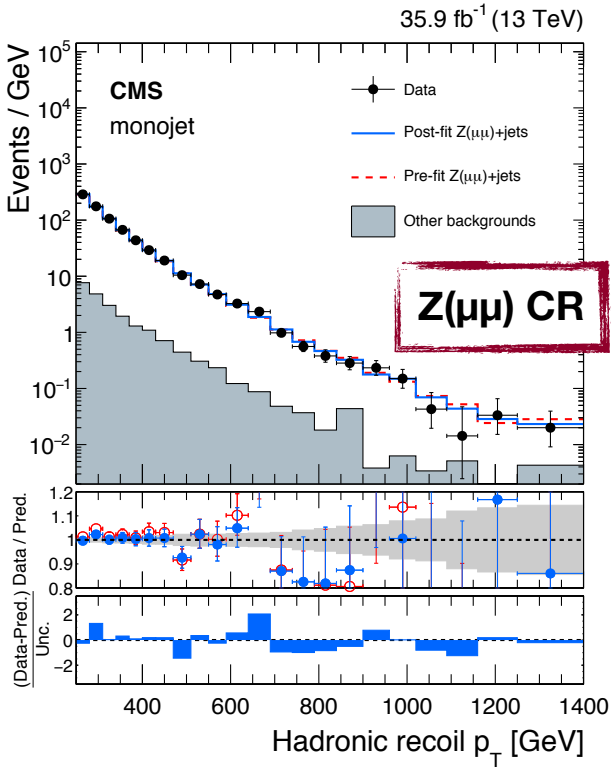
This is By No Means a Comprehensive Review

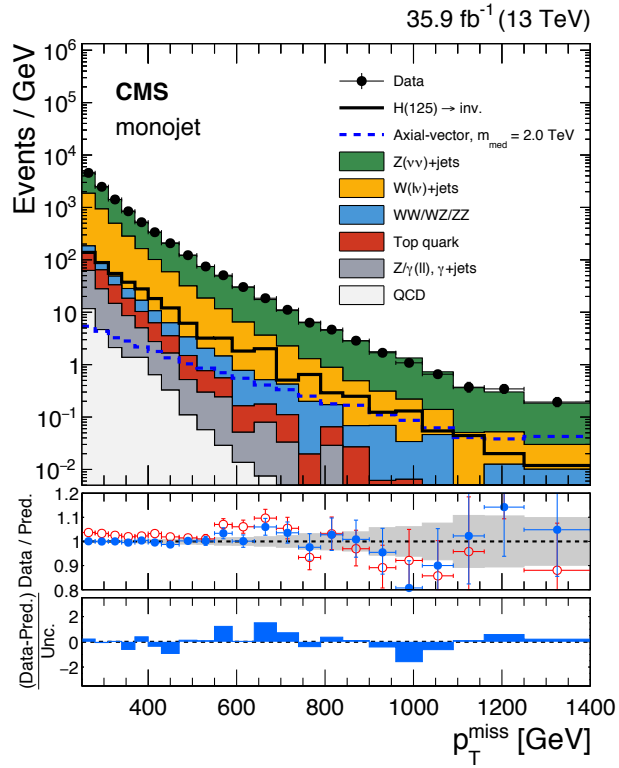
- Performance of dark matter searches often **very similar** in ATLAS and CMS
  - **Won't** show both ATLAS and CMS results for each channel
  - Will make a **personal** selection (to avoid repetition)

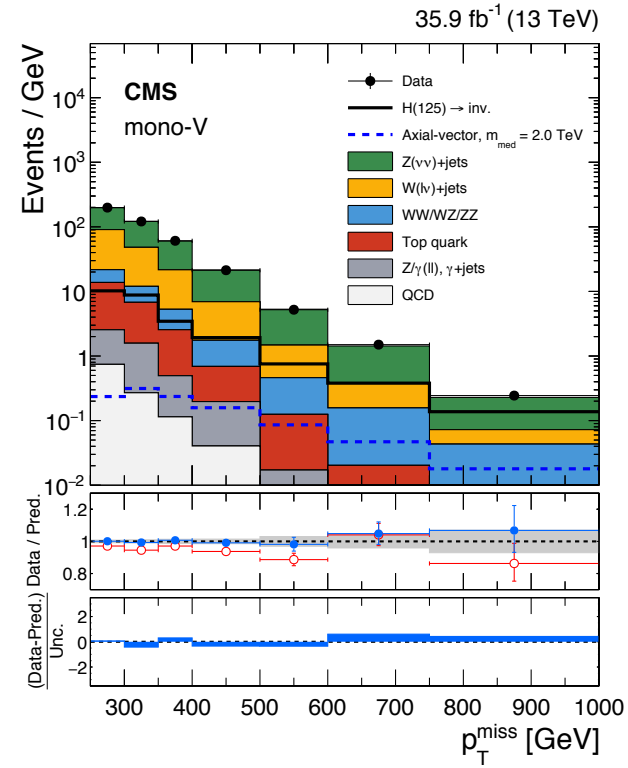
Channel	In this talk	Not in this talk
MonoJet	CMS 36 fb^{-1}	ATLAS 36 fb^{-1}
H(bb)+ME_T	ATLAS 80 fb^{-1}	CMS 36 fb^{-1}
tt+ME_T	CMS 36 fb^{-1}	ATLAS 36 fb^{-1}
DiJet	CMS 78 + 36 fb^{-1}	ATLAS 36 fb^{-1}
DiJet+ISR	ATLAS 15 + 36 fb^{-1}	CMS 36 fb^{-1}
DiLepton	ATLAS 36 fb^{-1}	CMS 36 fb^{-1}
Dark Energy	ATLAS 36 fb^{-1}	—

MonoJet: A Classical Collider DM Search

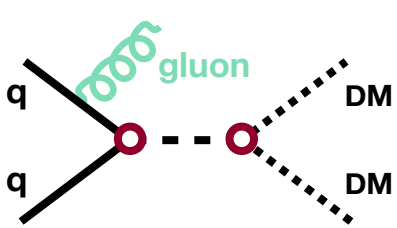
Phys. Rev. D 97 (2018) 092005

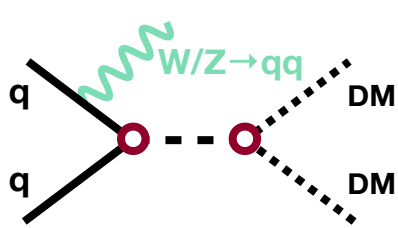






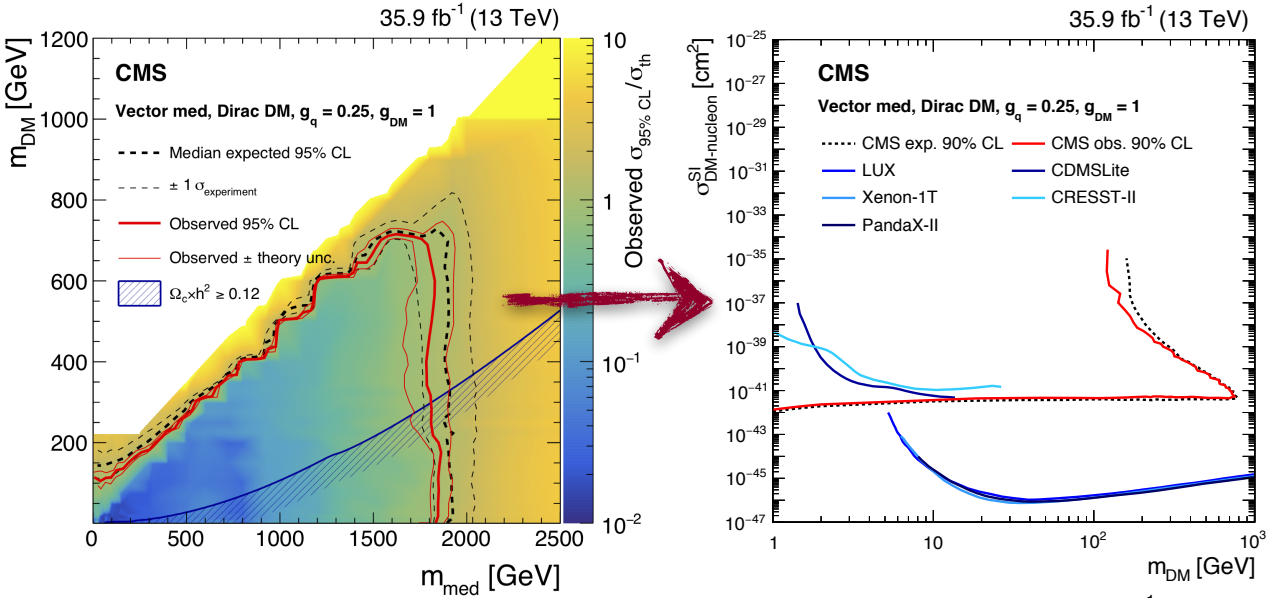
- Extended to include **hadronic W/Z**
  - Pruned AK(0.8) + substructure (τ_{21})
- ME_T tail: need **careful** BG estimation
  - Cannot trust simulation
- **Simultaneous fit** to data control regions ($\gamma/Z_{\mu\mu}/Z_{ee}/W_{e\nu}/W_{\mu\nu}$) and signal region

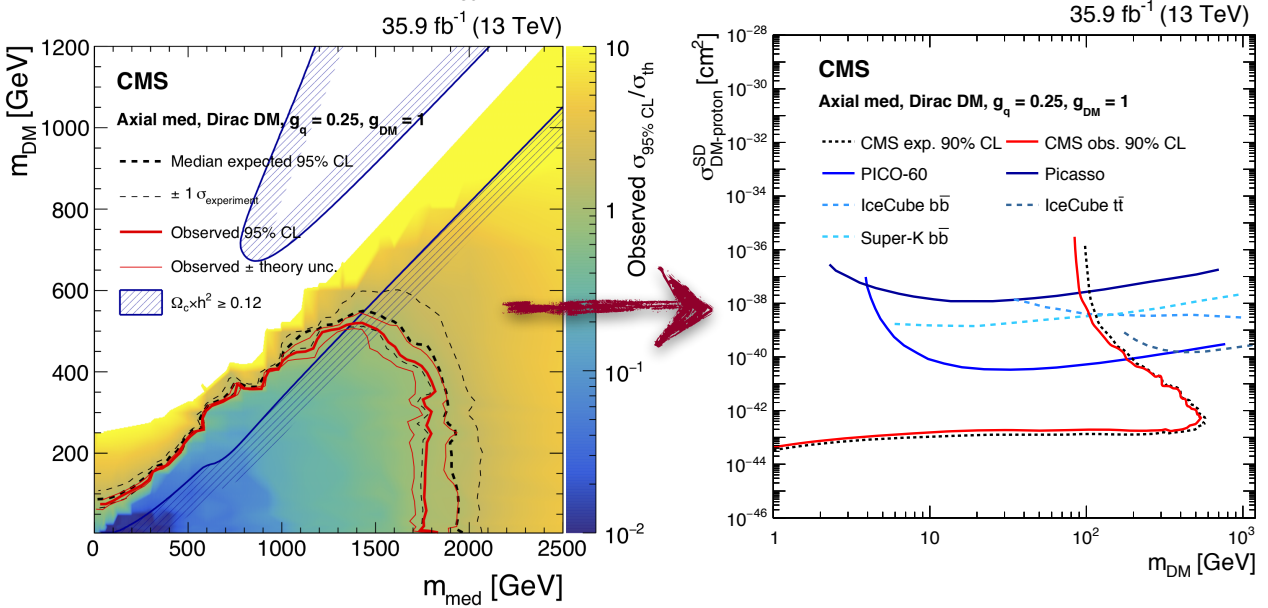




MonoJet Results Complement Direct Searches

Phys. Rev. D 97 (2018) 092005

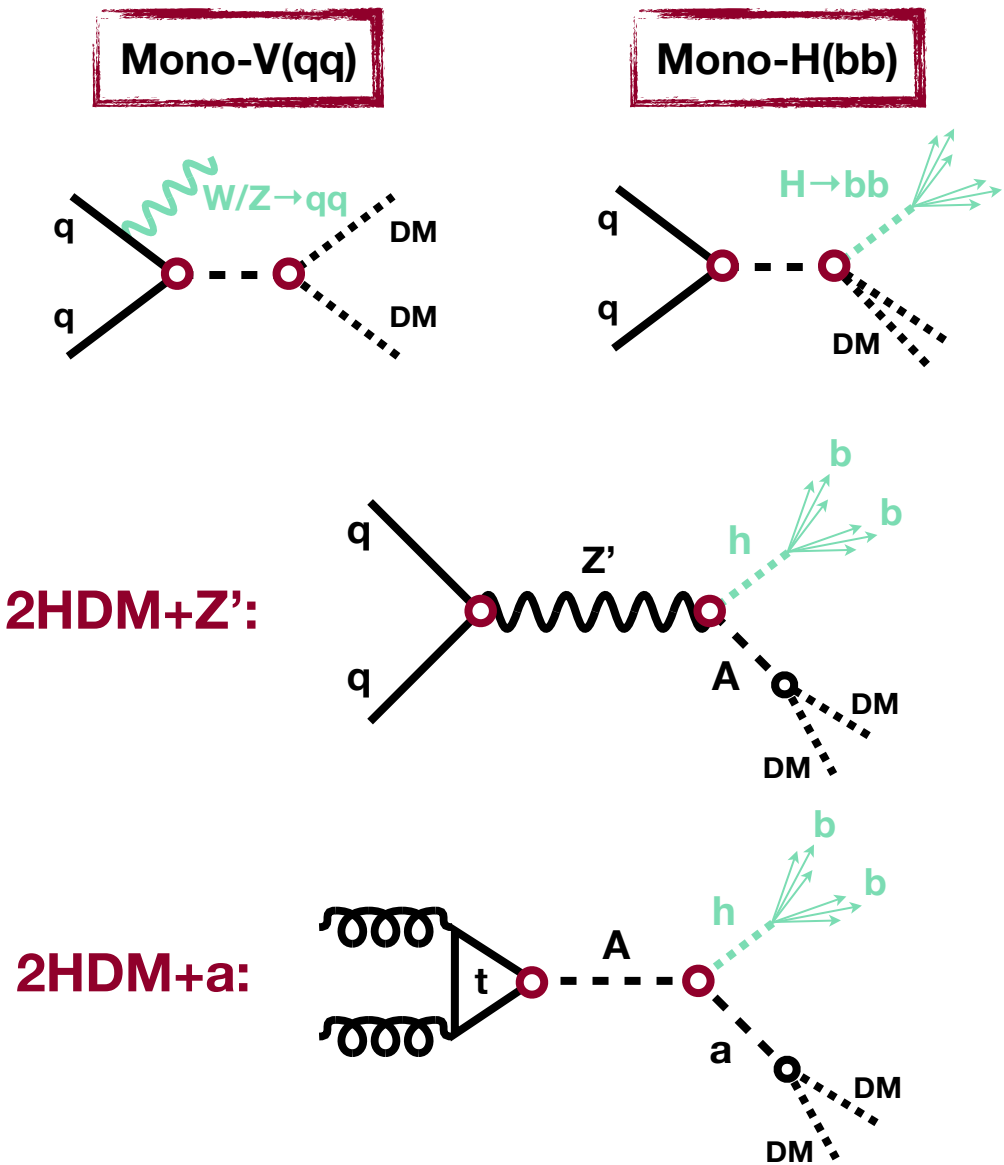




- Limits in M_{med}/M_{DM} plane
  - Cast to σ(DM-nucleon)
- Colliders **complementary** to direct searches
  - Extend to **low** M_{DM}
- But a lot of caveats!
  - Very model-dependent

Similar results by ATLAS

Mono-H(bb): Tagging on Final State Radiation

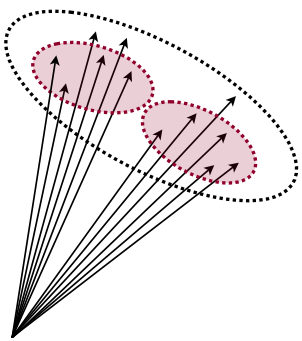


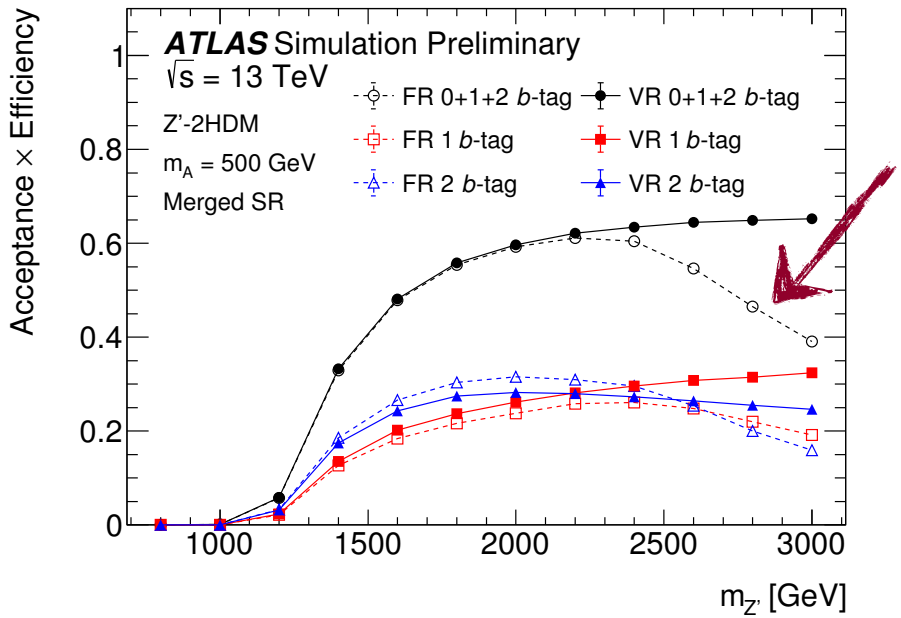
- **Similar** signature to mono-V(qq)
  - Both **'(X→qq)+ME$_T$'**
- Yet **very different** probe: FSR, not ISR
  - Higgs ISR Yukawa-**suppressed**
  - Probing mediator-H coupling
  - **Both** for 2HDM+Z' and 2HDM+a

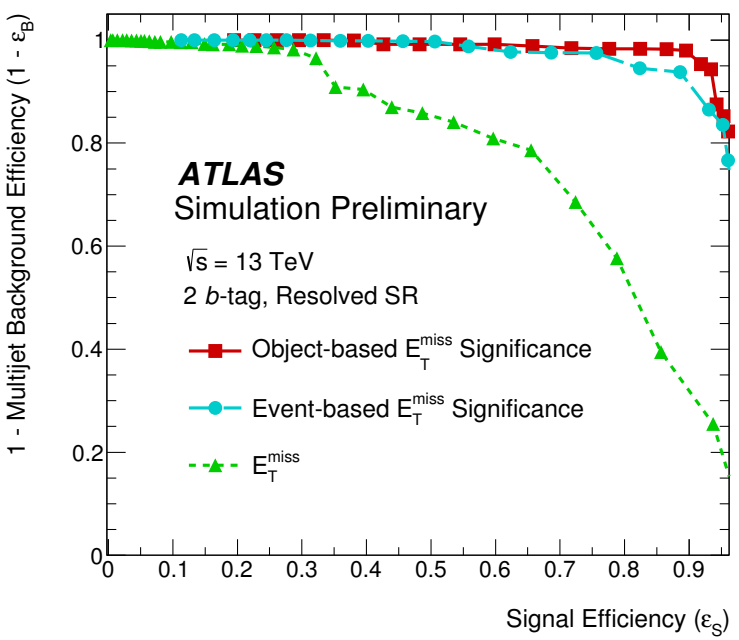
Not Just a Top-Up: Big Performance Boost

PRL 119 (2017) 181804

- **Variable-radius** track jets for H(bb)-tagging
  - $R \rightarrow R_{eff} \sim \rho/p_T$
  - **Large** efficiency gain at high mass



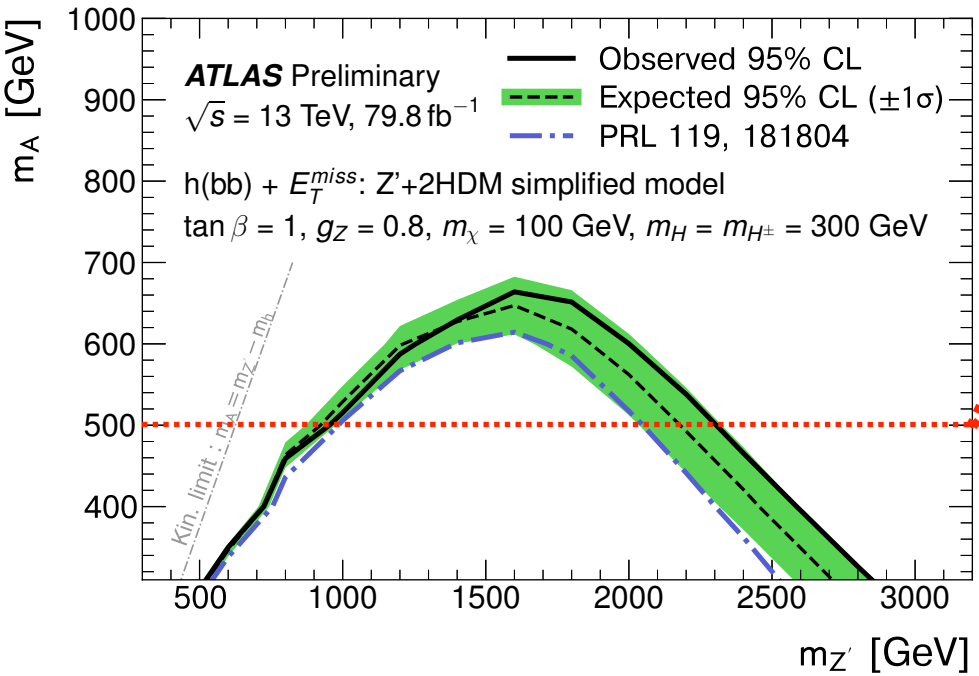


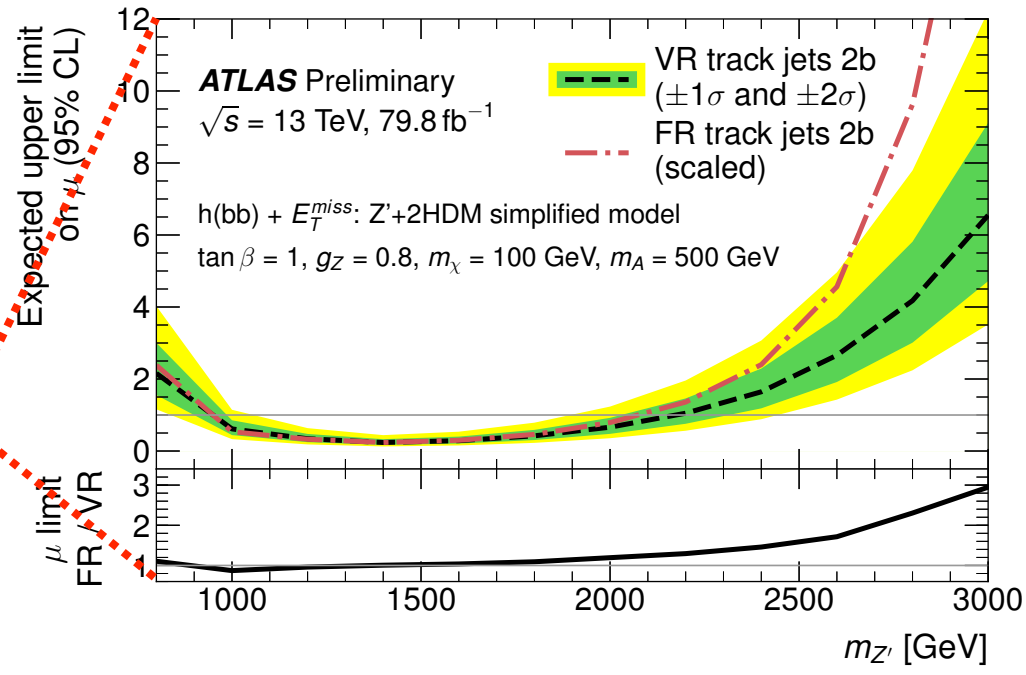


- Object-based ME_T **significance**
  - Better performance for low-ME_T signals
  - 'Simple' ME_T affected by **mismeasurements**
  - Event-based significance **worse** for high-ε_S

Mono-H(bb) Results in 2HDM+Z' Framework

PRL 119 (2017) 181804



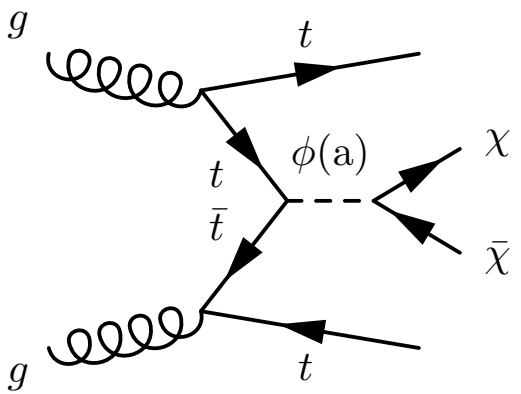


- Setting limits in 2HDM+Z' framework
  - Excluding m(A) up to 660 GeV and m(Z') up to 2.8 TeV
  - High mass UL up to **3× better** than fixed-radius jets

with given choice of parameters

Similar results by CMS

Maximal Yukawa with Mono-ttbar



- Spin-0 mediator with Higgs Yukawa couplings
  - **Maximal** to top quarks
- A tt+ME_T search in **seven** categories

ALL-HADRONIC

ME_T > 200 GeV
N(j) ≥ 4
N(b) ≥ 1
Two tagged tops

ME_T > 200 GeV
N(j) ≥ 4
N(b) ≥ 1
0,1 tagged tops

DI-LEPTON

e^+e^- or $\mu^+\mu^-$
Z-mass veto
N(j) ≥ 2, N(b) ≥ 1
m_{T2}(ll) < 110 GeV

e^+e^- or $\mu^+\mu^-$
Z-mass veto
N(j) ≥ 2, N(b) ≥ 1
m_{T2}(ll) > 110 GeV

$e^+\mu^-$ or μ^+e^-
Z-mass veto
N(j) ≥ 2, N(b) ≥ 1
m_{T2}(ll) < 110 GeV

$e^+\mu^-$ or μ^+e^-
Z-mass veto
N(j) ≥ 2, N(b) ≥ 1
m_{T2}(ll) > 110 GeV

SINGLE LEPTON

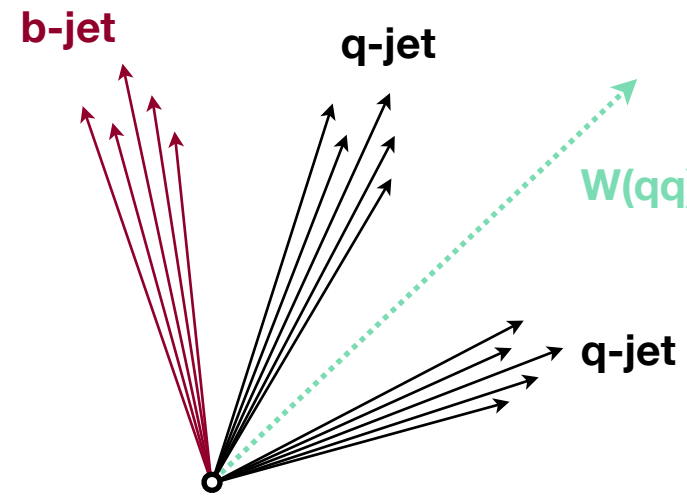
One e or μ
ME_T > 160 GeV
N(j) ≥ 3
N(b) ≥ 1

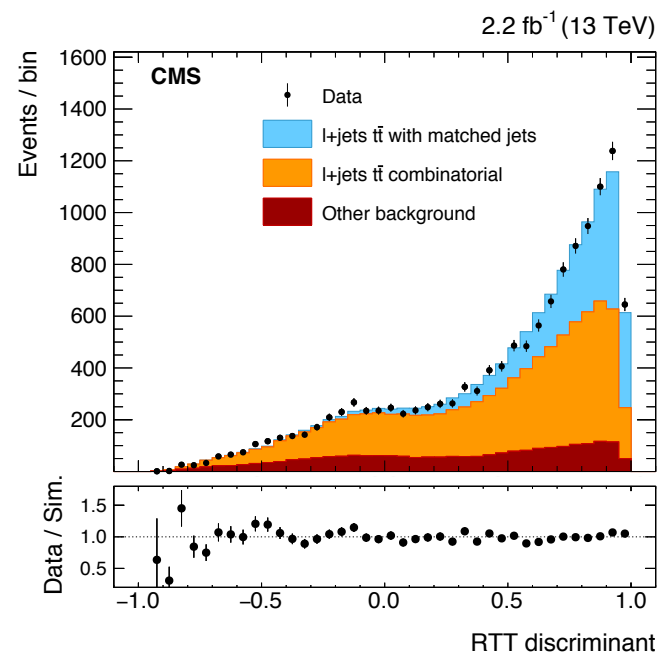
m_{T2} 'stranverse mass'

RTT: Top-Tagging with Kinematics and Substructure

EPJC 77 (2017) 845

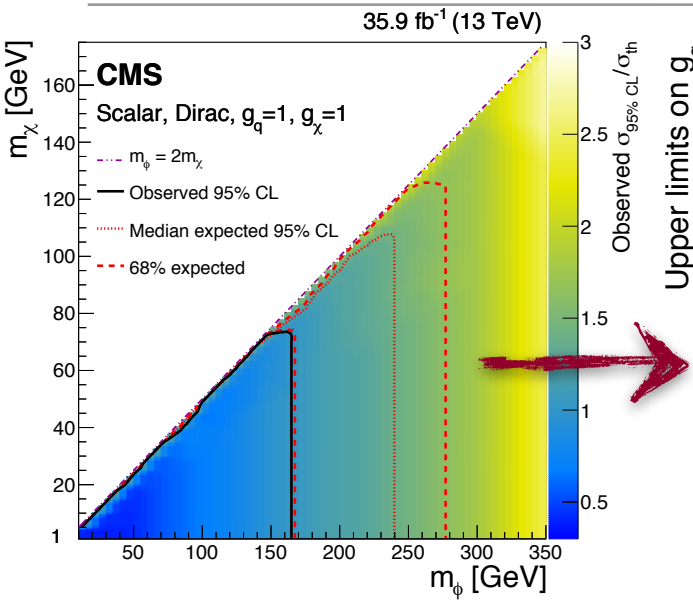
- Resolved Top Tagger (RTT) for **jet triplets**
  - Multivariate discriminant that combines **kinematics** and **substructure**
- Kinematics:
  - Highest b-tag → b-jet
  - Kinematic fit to M_W for qq
  - Kinematic fit to M_{top} for bqq
- Then BDT discriminant with input variables:
  - **Quark/gluon** likelihood
  - **b-tag** discriminant
  - **Angle** between W(qq) and b-jet

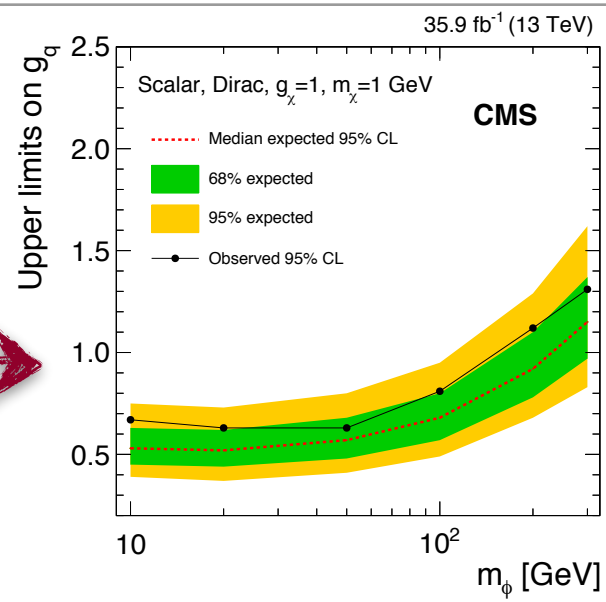


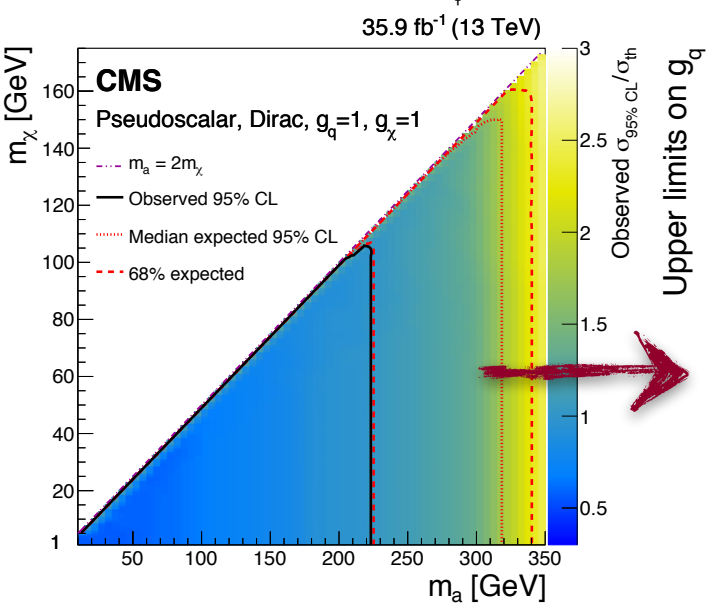


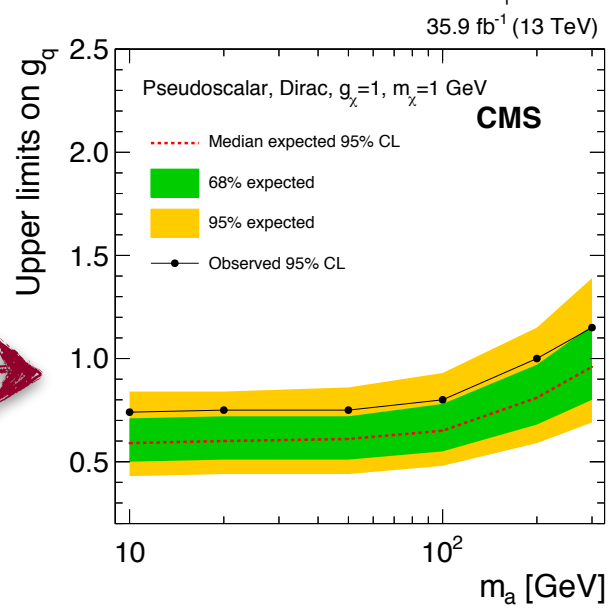
Mono(tt) Interpreted in Simplified Models

CMS-EXO-16-049 (subm. to PRL)







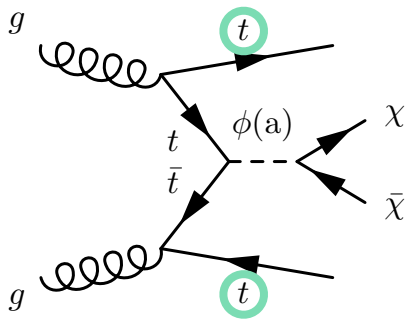


- Limits on scalar (ϕ) and pseudoscalar (a) models
- With $g_q = 1$ excluding:
  - $m(\phi) < 160$ GeV
  - $m(a) < 220$ GeV
- With $m_{DM} = 1$ GeV excluding $g_q \gtrsim 0.6\text{-}0.7$ for low m_{med}

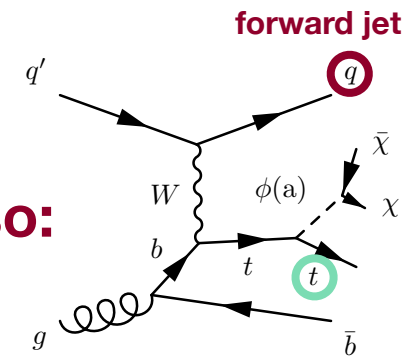
Similar results by ATLAS

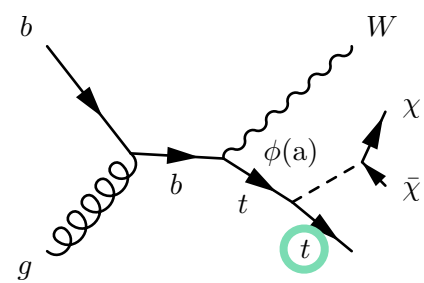
Single-Top Search: Integrating Mono-ttbar

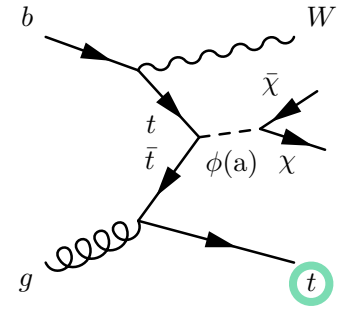
if:



then also:







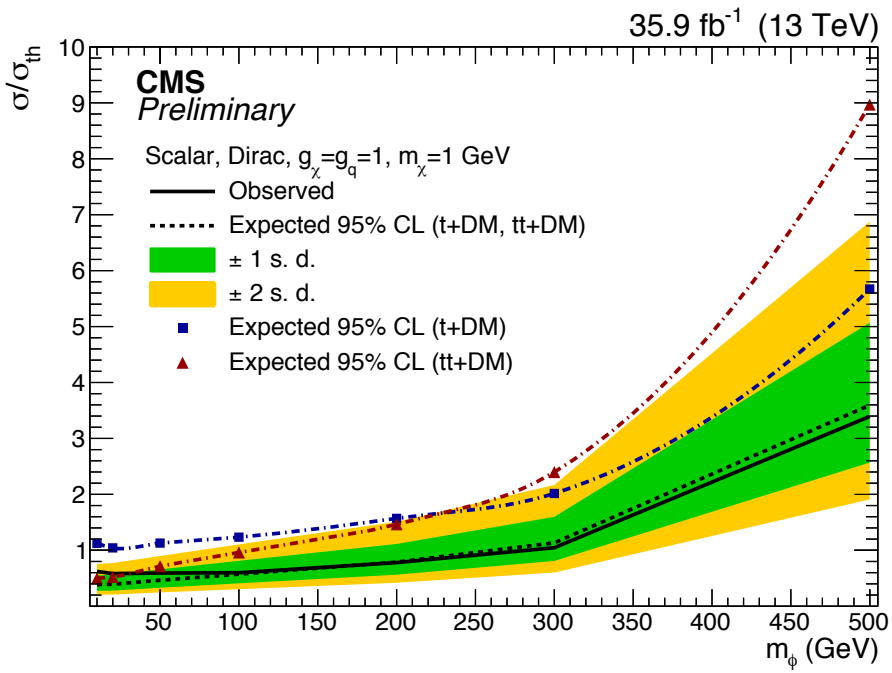
- Within same model **other** diagrams with **only one top** in final state

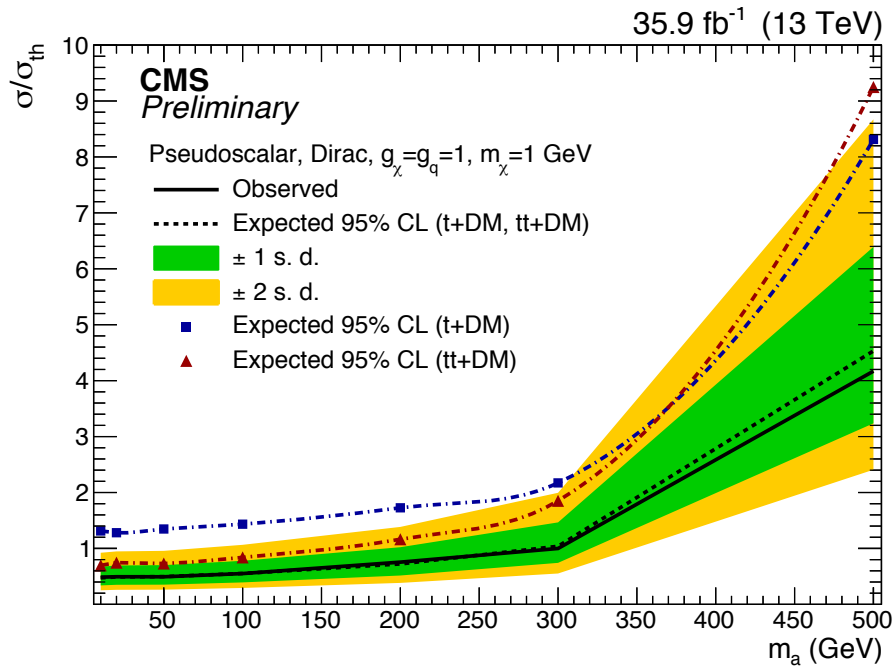
- **Nine** single-top categories **added** to Mono-ttbar search
  - **Six** single-lepton (3 for e, 3 for μ)
  - **Three** all-hadronic

Single electron **N(b) = 1** **No forward jet**	**Single electron** **N(b) = 1** **≥ 1 forward jet**	**Single electron** **N(b) ≥ 2**
Single muon **N(b) = 1** **No forward jet**	**Single muon** **N(b) = 1** **≥ 1 forward jet**	**Single muon** **N(b) ≥ 2**
No leptons **N(b) = 1** **No forward jet**	**No leptons** **N(b) = 1** **≥ 1 forward jet**	**No leptons** **N(b) ≥ 2**

Adding Single-Top Brings Large Improvements

CMS-EXO-18-010 (accepted by JHEP)





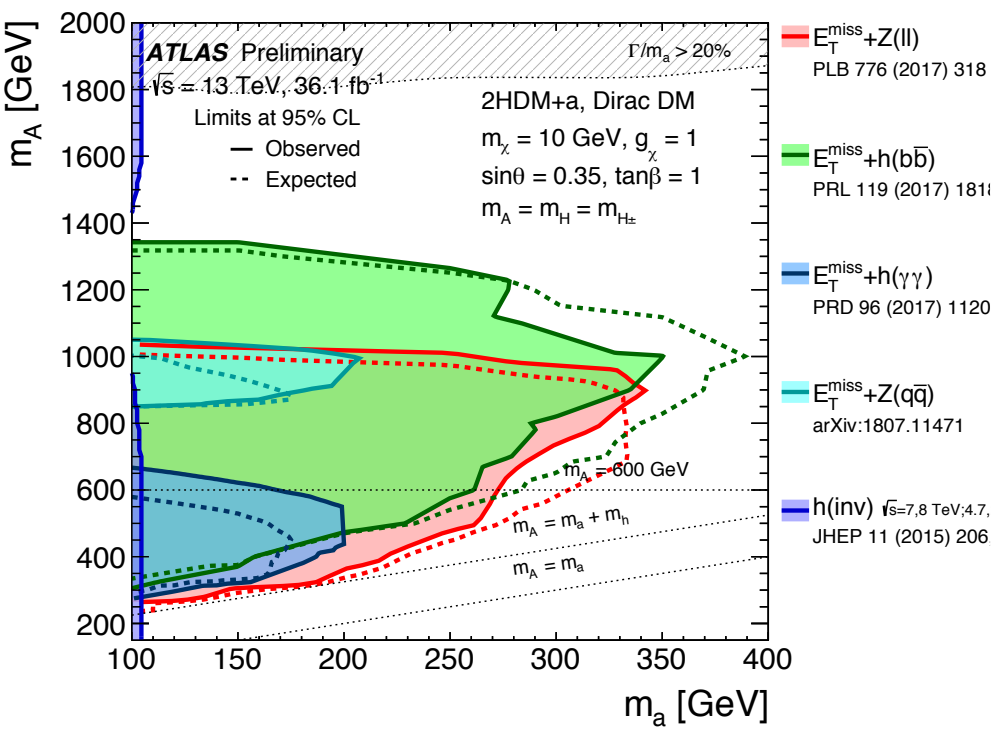
- Adding single-top categories brings up to **2.5× better limits** for high M_{med}
  - At low M_{med} σ(tt+DM) > σ(t+DM), but σ(t+DM) drops **less rapidly** with M_{med}
  - For given M_{med}, single-top has slightly **harder** ME_T

Single-top dominant at high M_{med}

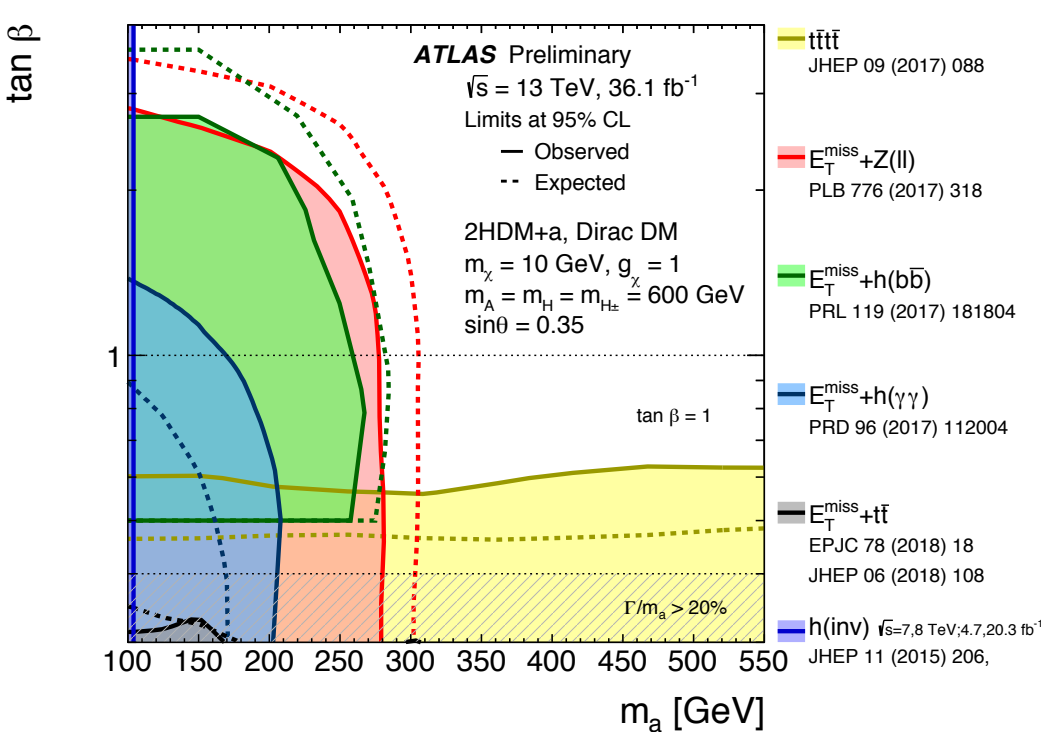
Summary of ME_T+X Limits in 2HDM+a Models

ATLAS-CONF-2018-051

m_A vs m_a, tanβ = 1

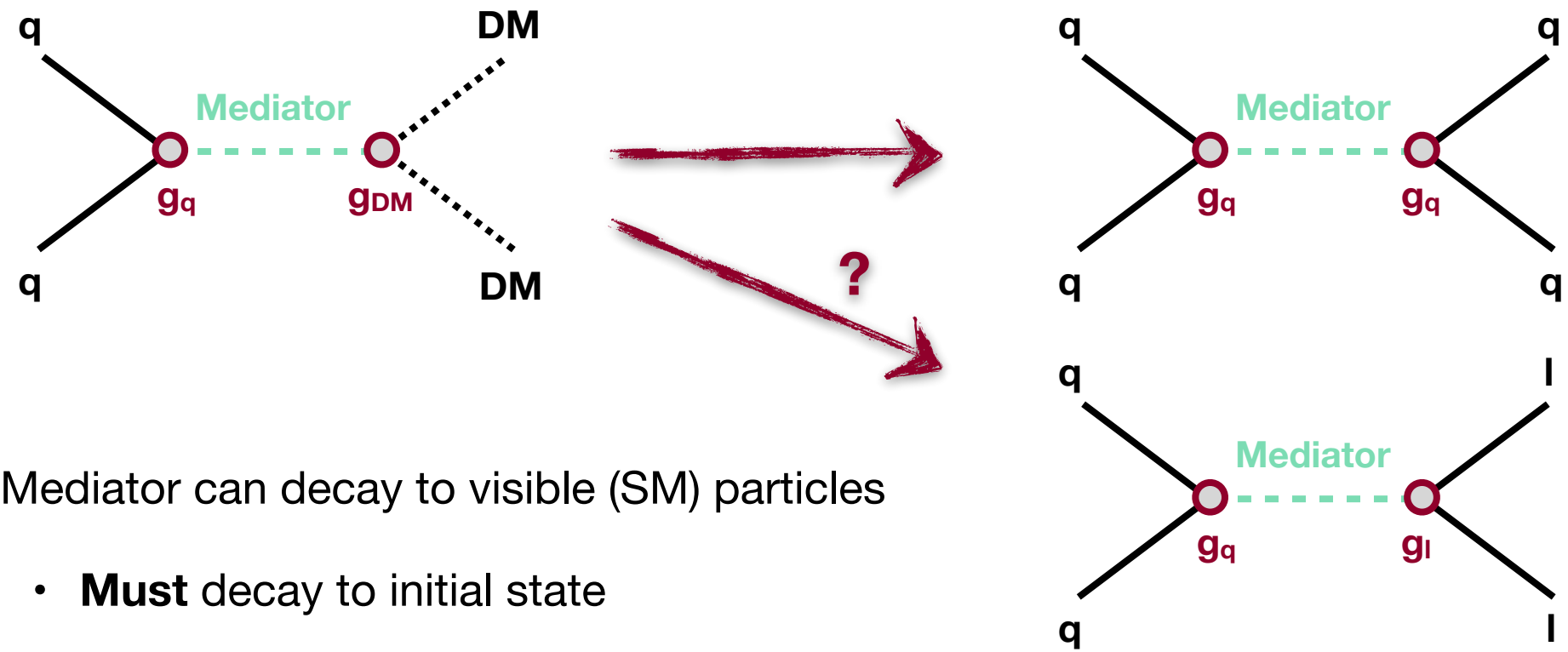


tanβ vs m_a, m_A = 600 GeV



- Same limits plotted in **two** different planes

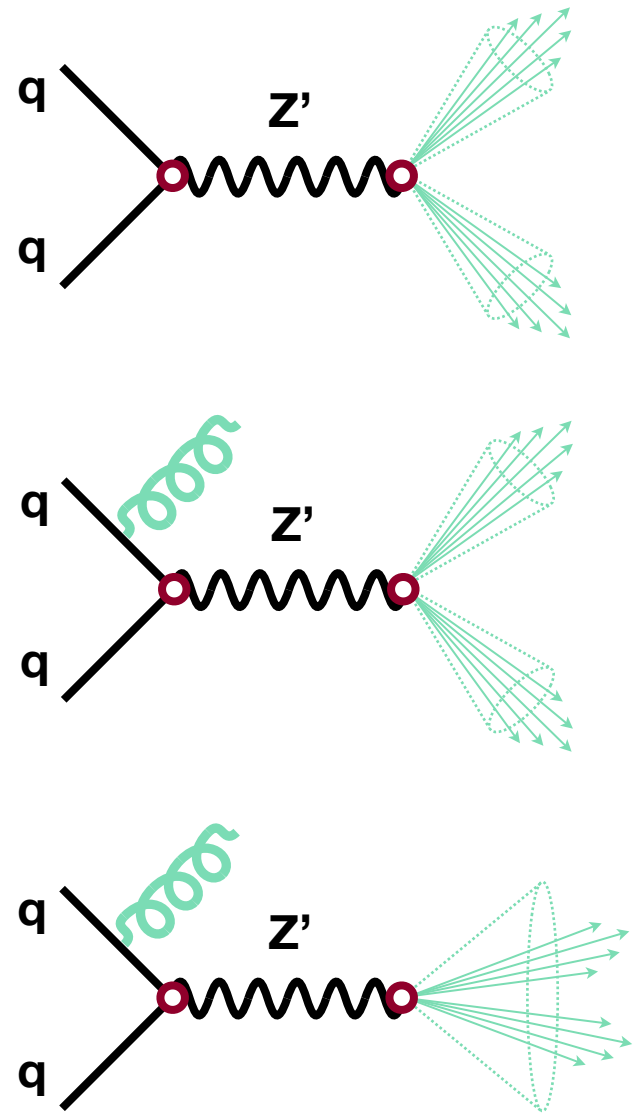
An Important Consequence of Simplified Models



- Mediator can decay to visible (SM) particles
  - **Must** decay to initial state
  - Could **also** couple to other particles (eg leptons)
- **Visible** searches (bump hunts) for mediator

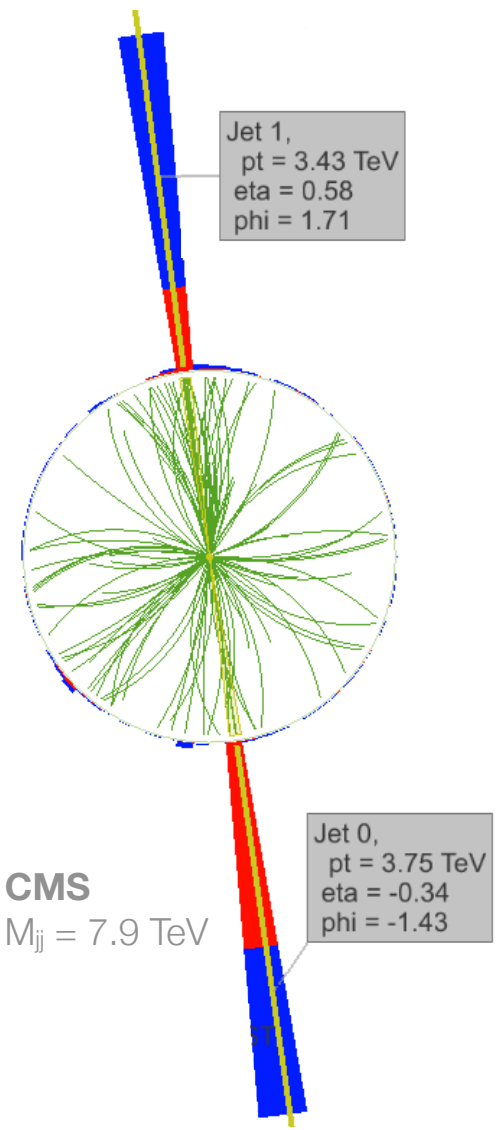
DiJet: Different Strategies for Different Masses

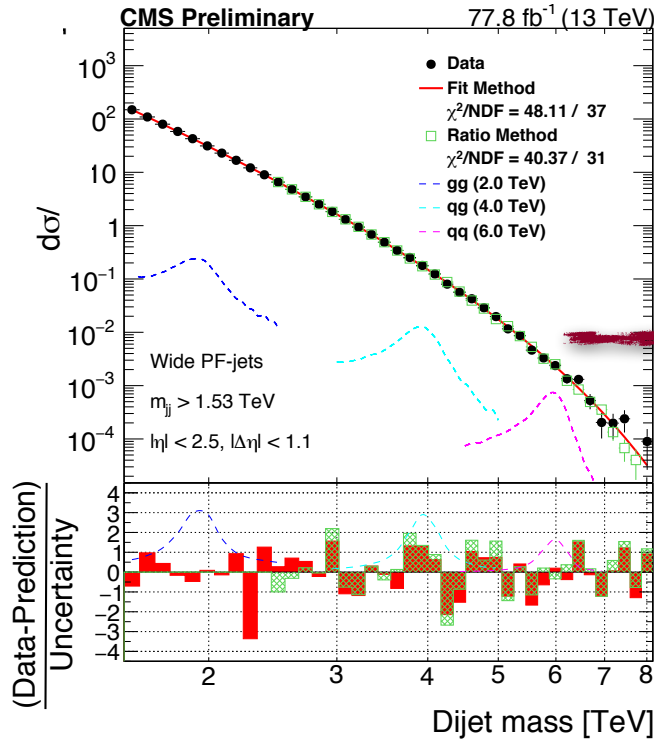
- **High mass** (M > 1.5 TeV)
  - Resonance at rest, high energy jets
  - No problems with trigger
- **Intermediate mass** (0.5 < M < 1.5 TeV)
  - High rate: cannot write full event
  - Analysis on reduced data format
- **Low mass** (0.2 < M < 0.5 TeV)
  - Trigger on high-p_T photon or gluon ISR
- **Very low mass** (M < 0.3 TeV)
  - ISR + boosted dijet (large jet + substructure)

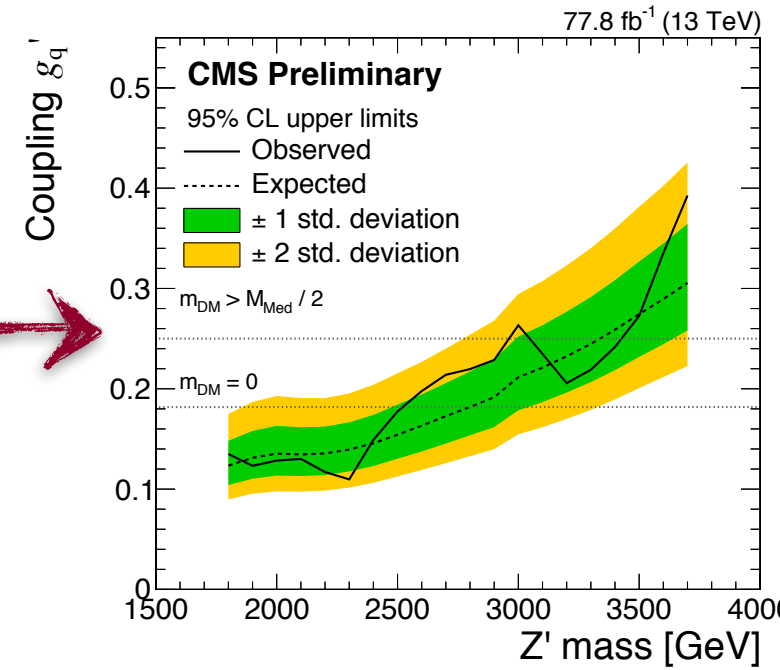


High-Mass Dijet Search: Setting Limits on g_q

CMS PAS EXO-17-026







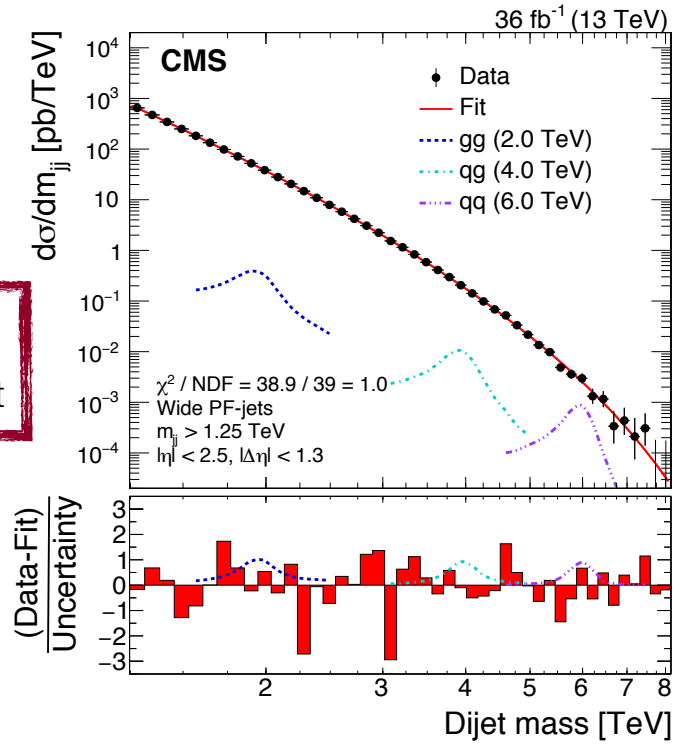
- Cross section $\sigma \sim g^4/\Gamma_{tot}$ **and** $\Gamma_{DM} = \Gamma_{DM}(m_{DM}/M_{med})$
  - Can set limits on g_q:

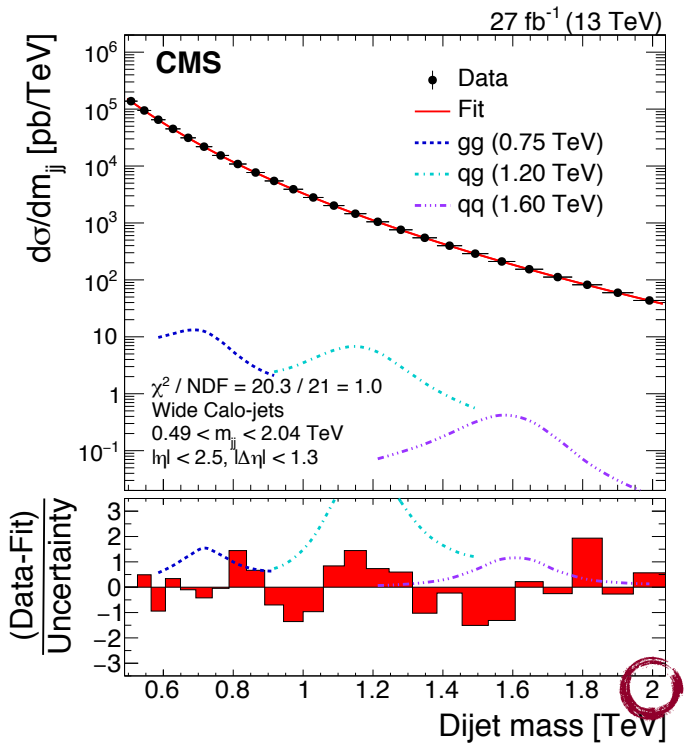
$$g_{UL} = \frac{g_q}{1 + \frac{g_{DM}^2}{18\, g_q}\left(1 - 4\left(\frac{m_{DM}}{M_{med}}\right)^2\right)^{\frac{3}{2}}}$$

Going to Lower Mass with Trigger-Level Objects

JHEP 08 (2018) 130

High mass
Full event readout





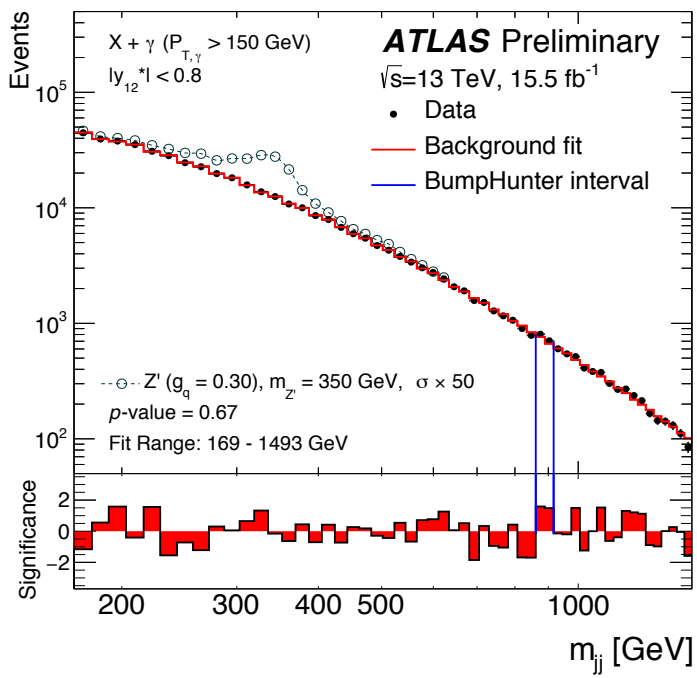
Lower mass
Reduced data format

- Lower mass: **higher** QCD BG
  - Rate **too high** for trigger
  - Need **reduced** data format
- **Solution:** save HLT jet 4-momenta
  - CMS: ‘Data scouting’
  - ATLAS: ‘Trigger-Level Analysis’

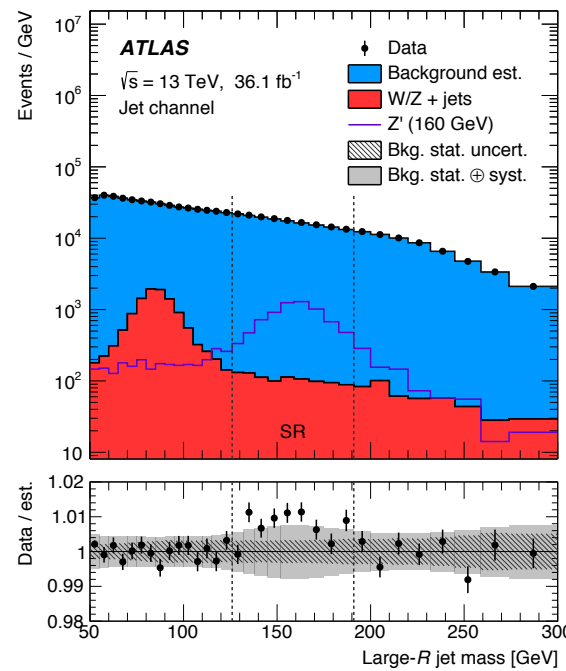
Even Lower Mass: Triggering on ISR

ATLAS-CONF-2016-070 and CERN-EP-2017-280 (accepted by PLB)

ISR + Two jets

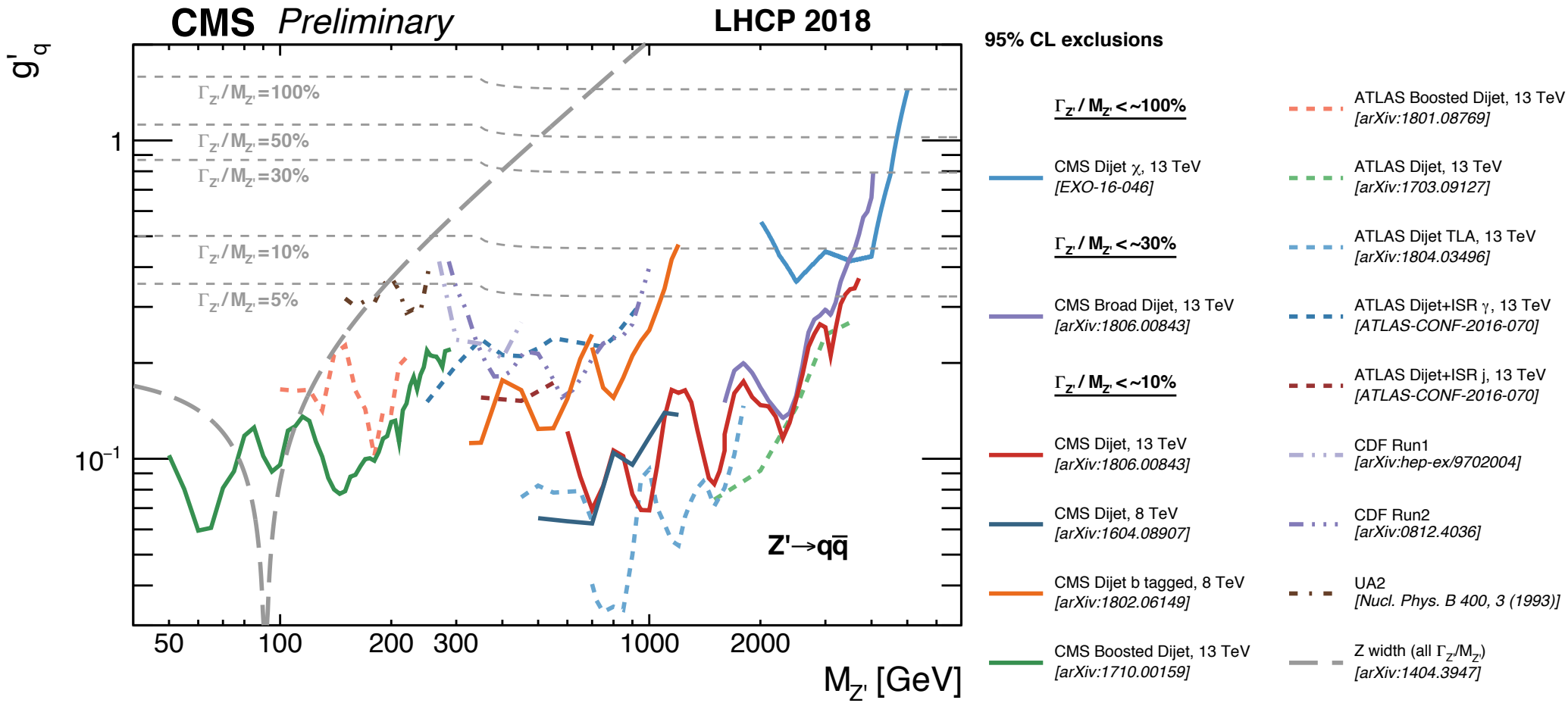


ISR + Boosted jet



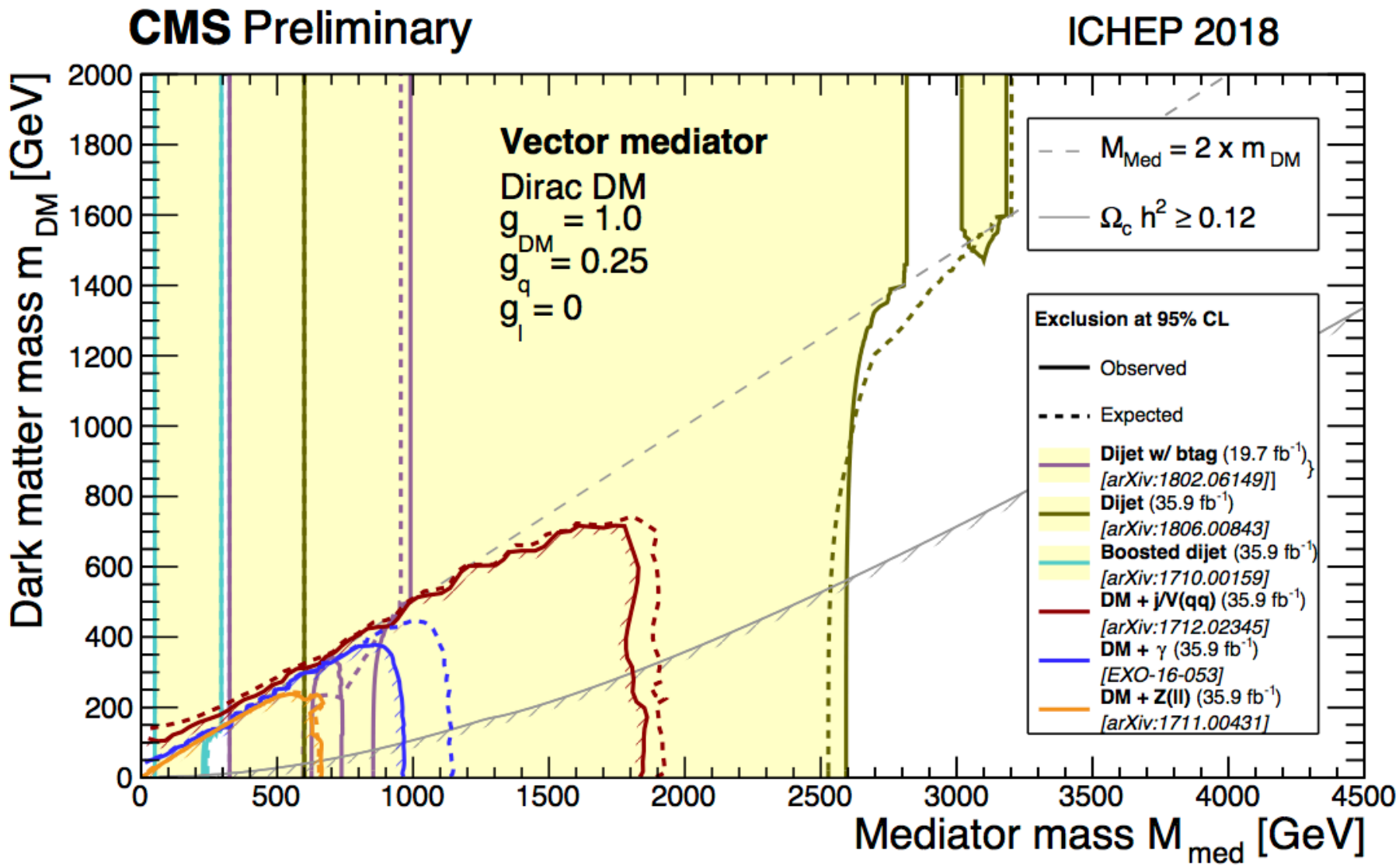
- Use ISR to trigger photon or jet trigger paths: **extend reach** to lower mass
  - ISR+(two jets): down to 200 GeV
  - ISR+(boosted): down to 100 GeV

Interplay of All Dijet Searches



Placing Limits on the M_{DM}-M_{med} Plane

Summary Plots:
ATLAS and CMS



Placing Limits on the M_{DM}-M_{med} Plane

Summary Plots:
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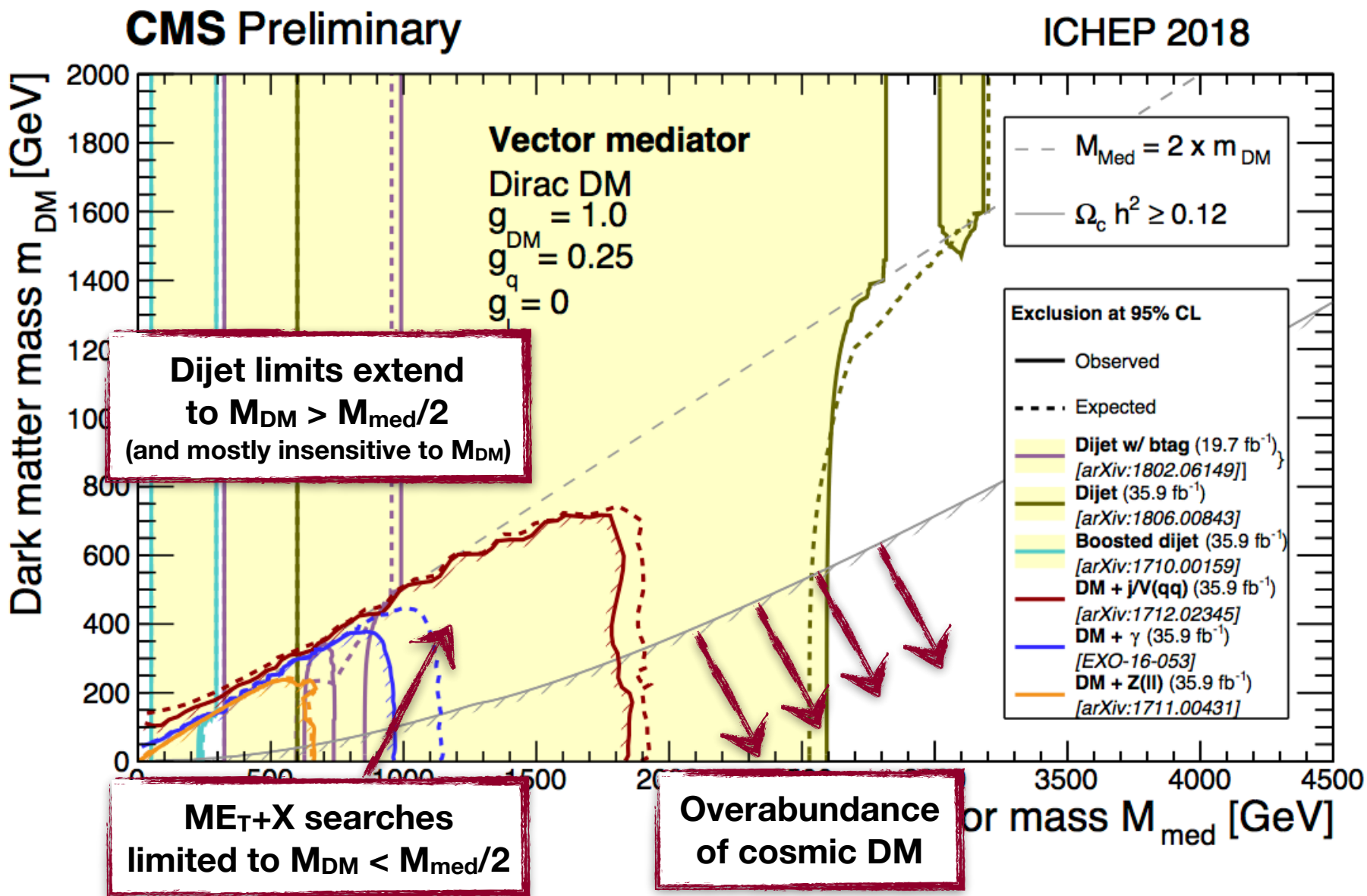
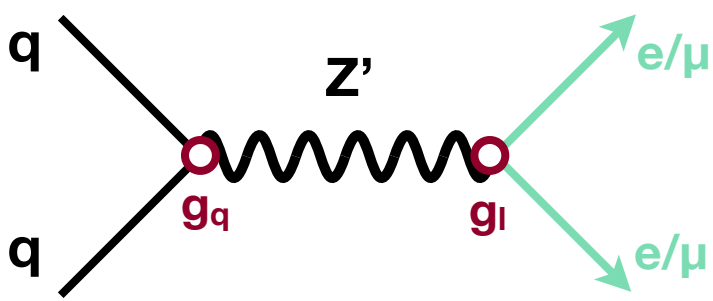
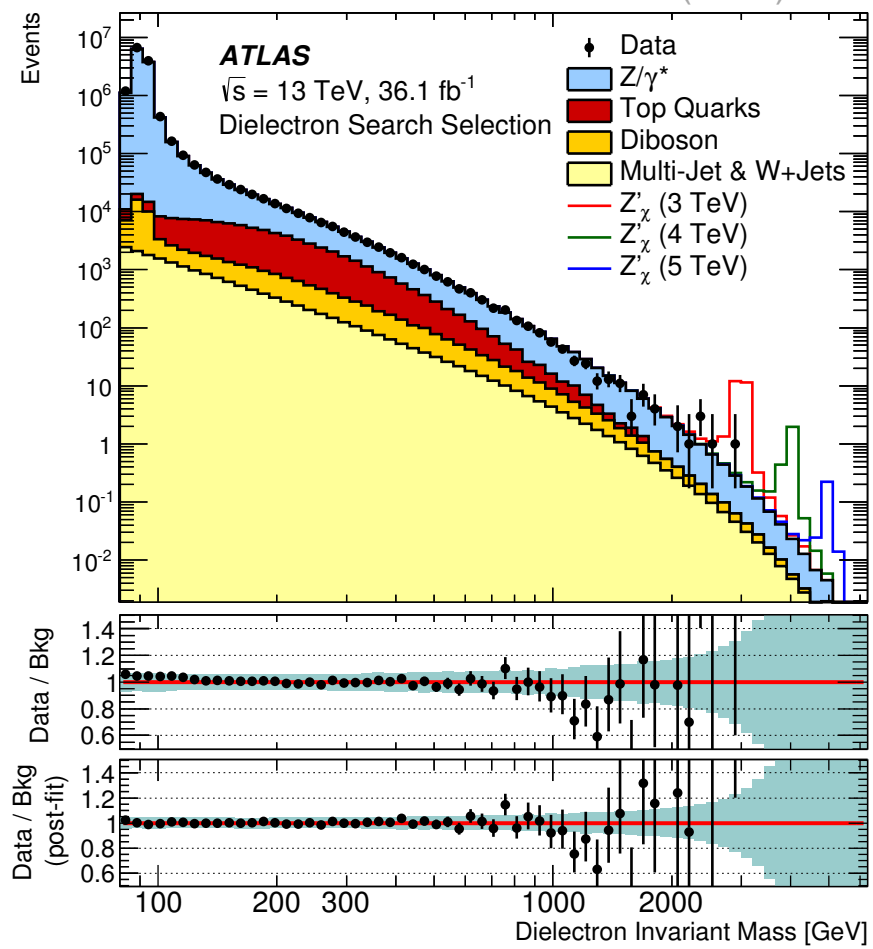


Similar Approach with Dilepton Searches

- Adding **lepton** coupling seems 'natural'
  - But it's an **additional** assumption
- If mediator couples with leptons: can use ee/μμ resonance searches
  - **Similar** to dijet re-interpretation

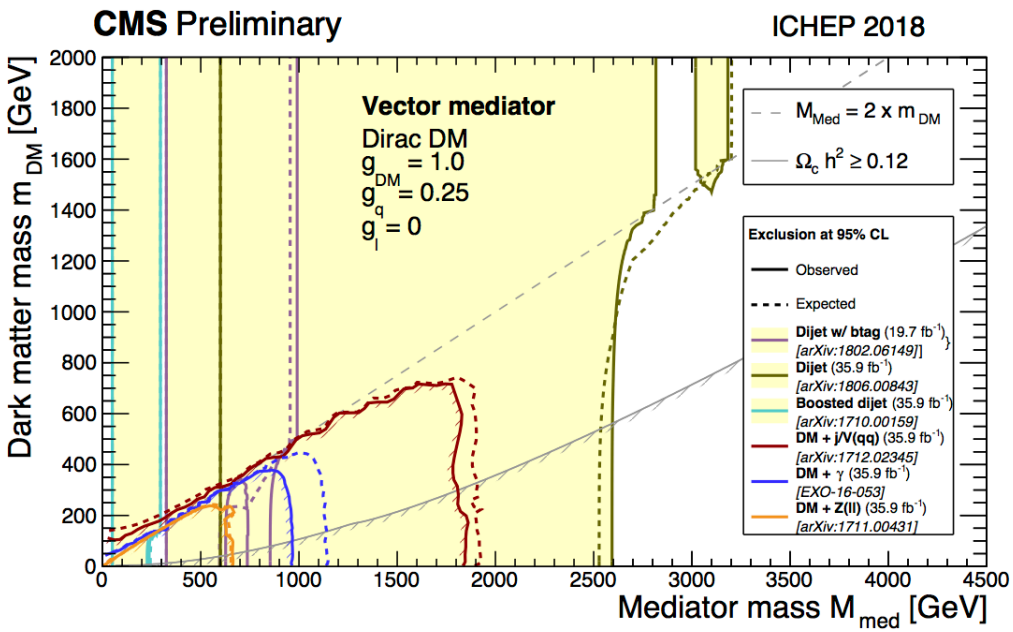


JHEP 10 (2017) 182

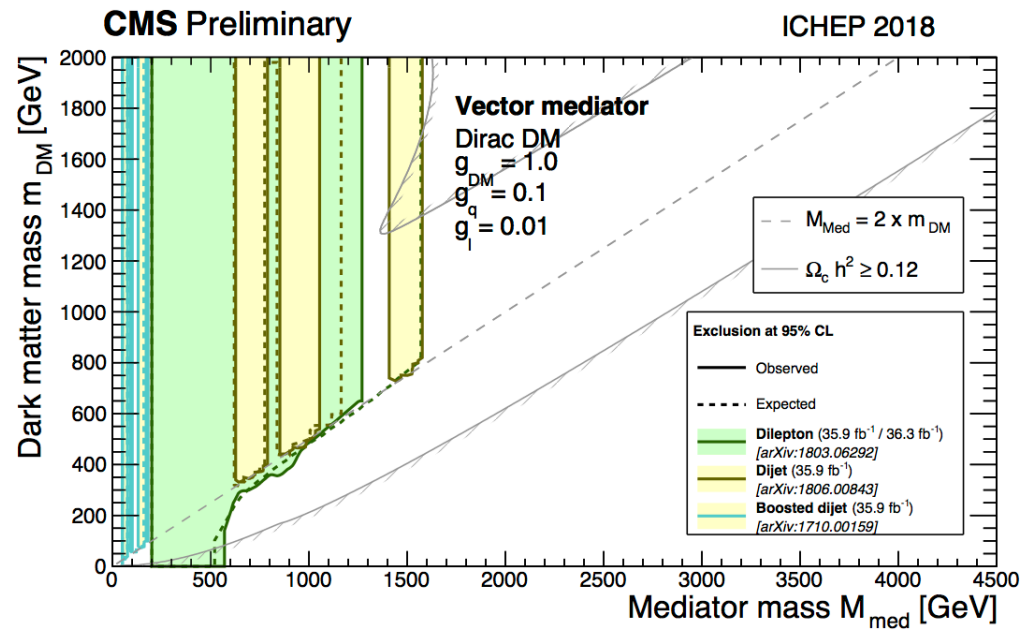


Exclusion Limits Are Very Sensitive to Couplings

$g_q = 0.25$, $g_l = 0$



$g_q = 0.1$, $g_l = 0.01$

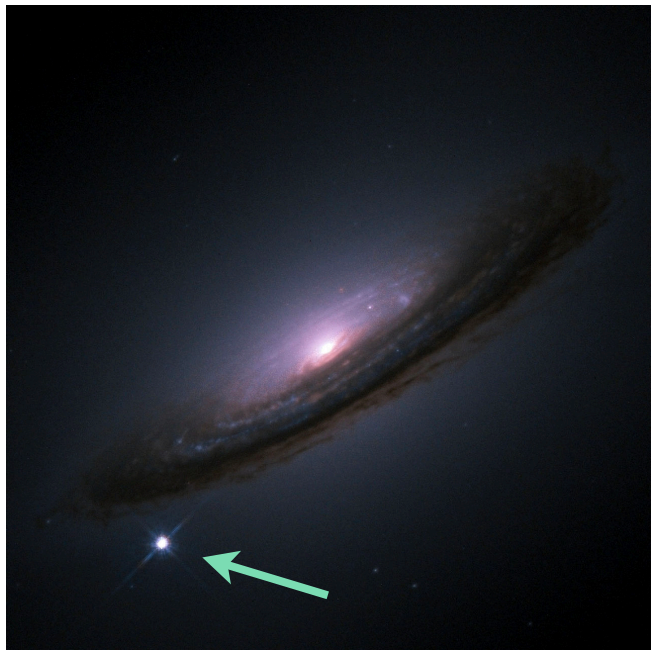


- Already with $g_l = 0.01$ dilepton results **dominant**
- Lowering g_q makes dijet results **less stringent**
  - And **increases** overabundance regions

Higher g_q
↓
more efficient
DM→SM annihilation
↓
lower abundance

What About Dark Energy?

- Supernovae Ia: universe expansion is **accelerating**
  - Existence of a ‘fifth’ **repulsive** force
  - New form of matter: dark energy



- **Many** new models, split in **two** categories:
  - Modifications to general relativity
  - Addition of new particles/fields

- Has been shown that two families of models have **same** phenomenology
  - So we can **focus** on particle description

Adding Dark Energy Operators to the SM

- EFT approach
  - Dark energy as **scalar** field ϕ

- **Two** leading operators added to SM Lagrangian:

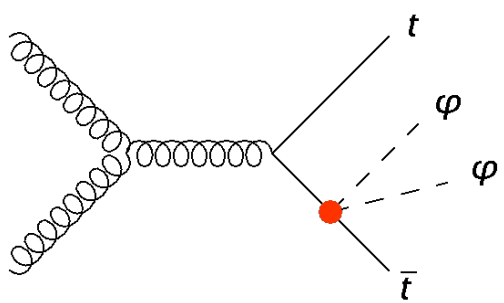
$$\mathcal{L}_{SM} \rightarrow \mathcal{L}_{SM} + \mathcal{L}_1 + \mathcal{L}_2 + \dots$$

$$\mathcal{L}_i \sim (M_i)^{-4}$$

M_i characteristic energy (suppression factor)

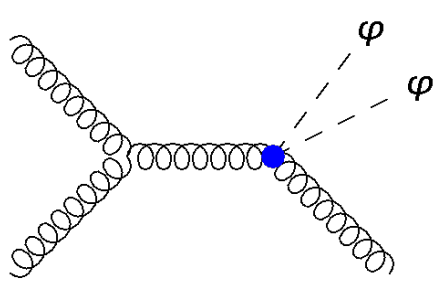
- Corresponding to:

$\mathcal{L}_1$:



ttbar + ME_T

$\mathcal{L}_2$:

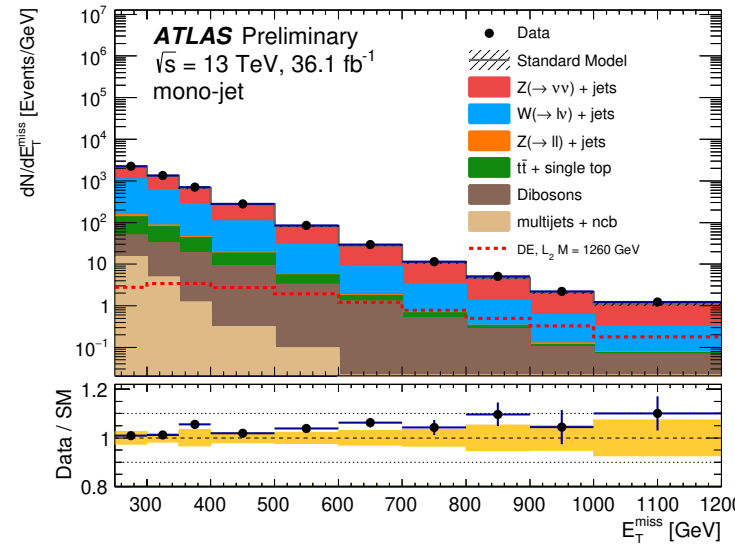


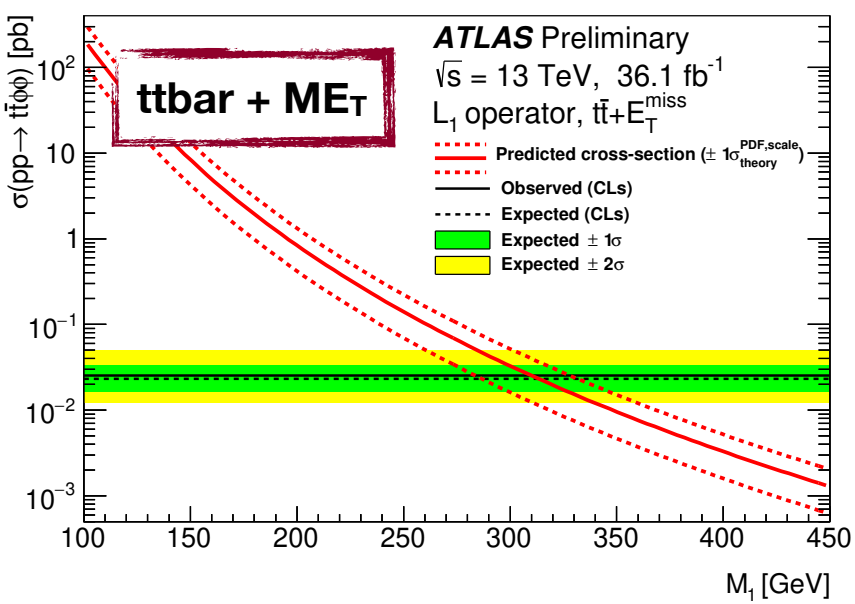
Monojet

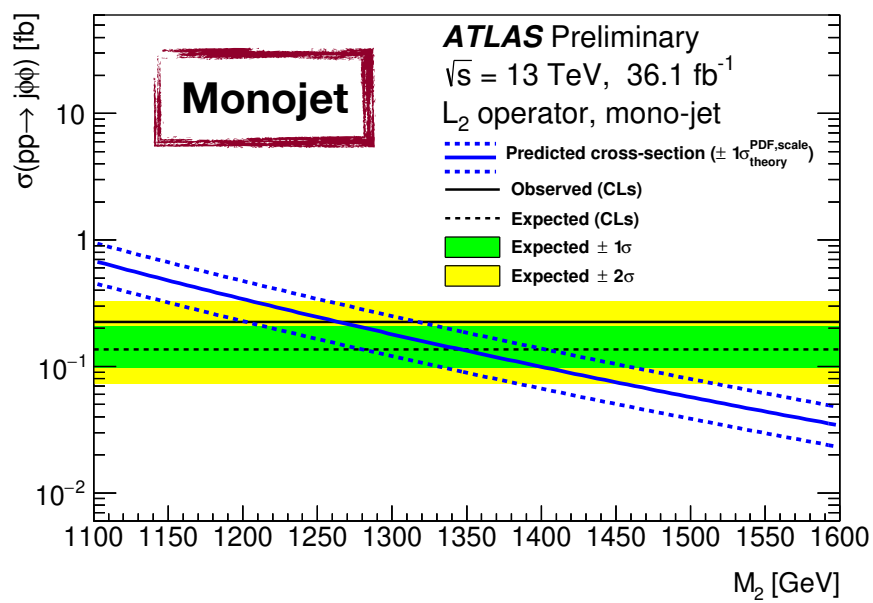
Setting Limits on Dark Energy Operators

ATL-PHYS-PUB-2018-008

- Reinterpretation of tt+ME_T and monojet searches
- Setting limits on operator suppression factors

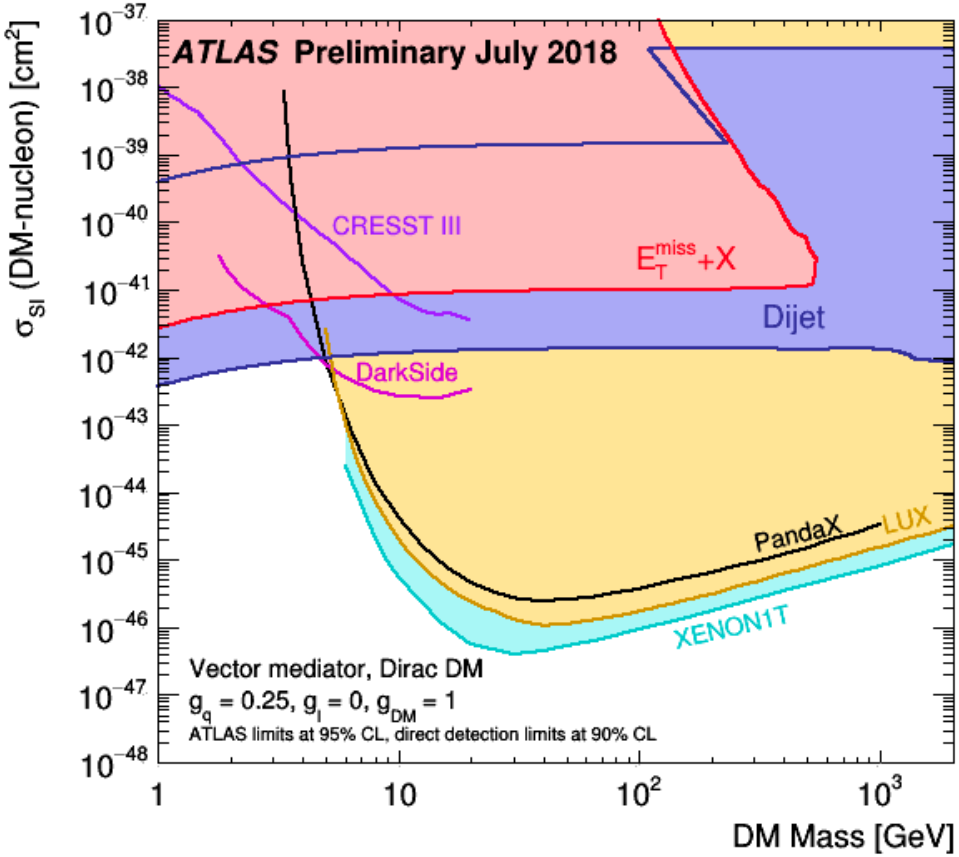




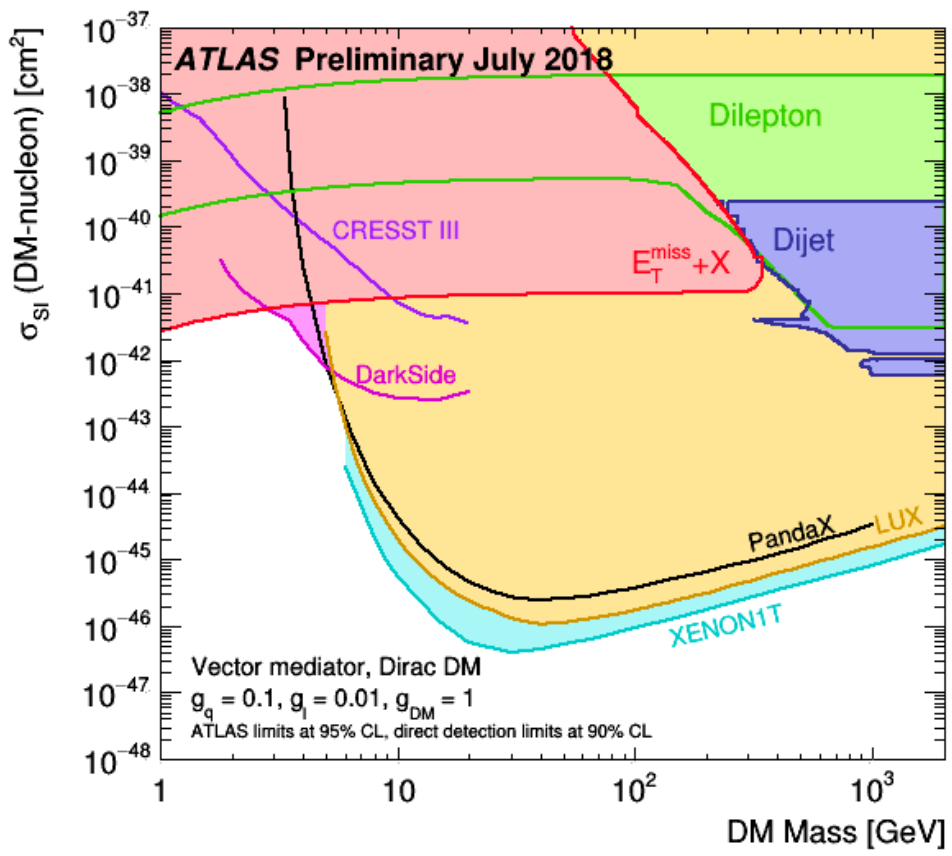


The Big Wrap-Up: Visible and Invisible Searches

$g_q = 0.25, g_l = 0$

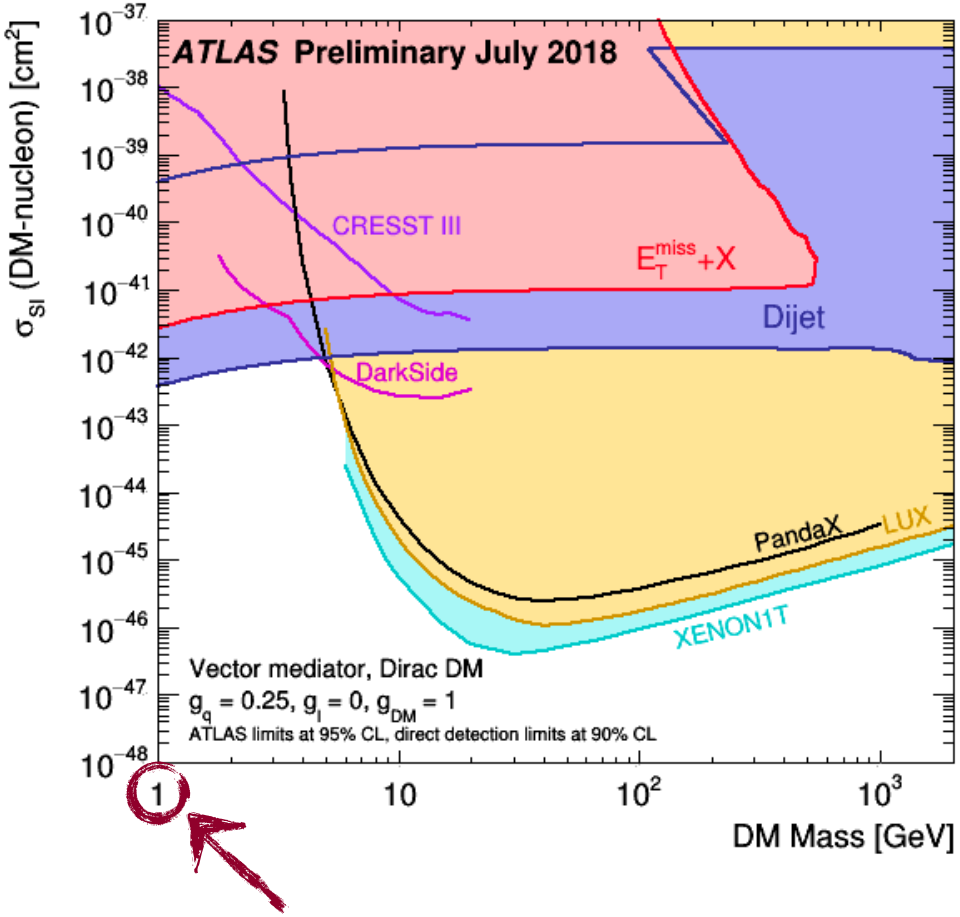


$g_q = 0.1, g_l = 0.01$

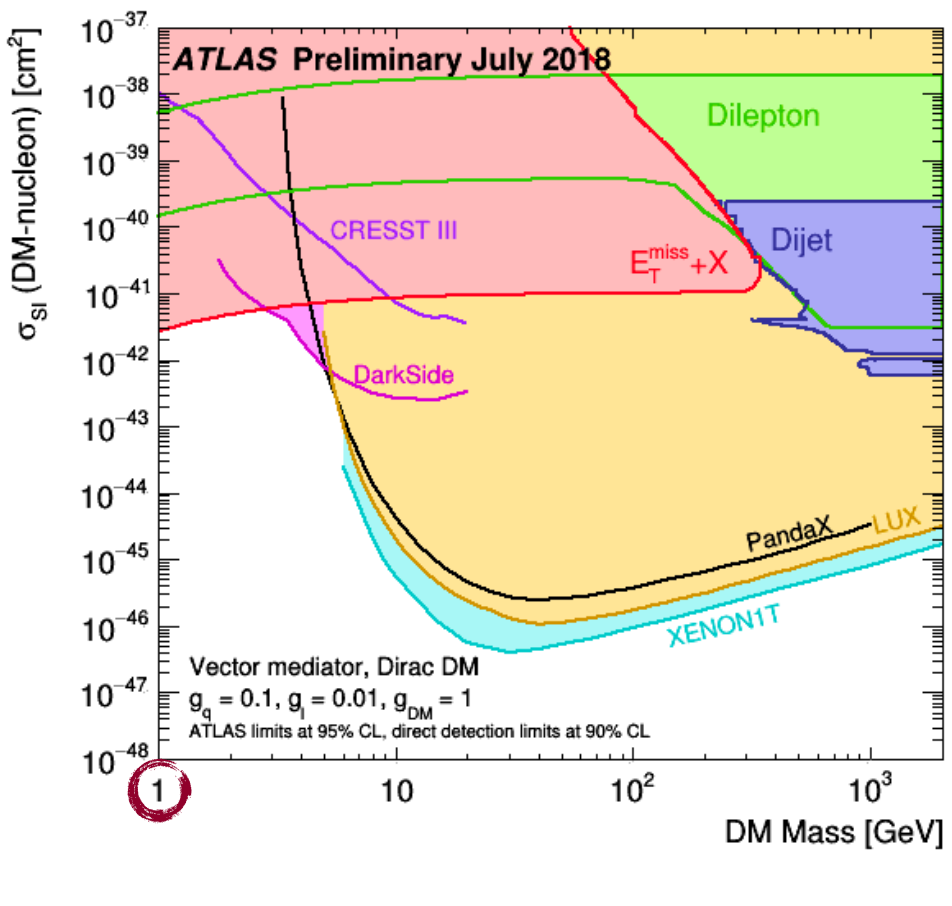


The Big Wrap-Up: Visible and Invisible Searches

$g_q = 0.25, g_l = 0$



$g_q = 0.1, g_l = 0.01$

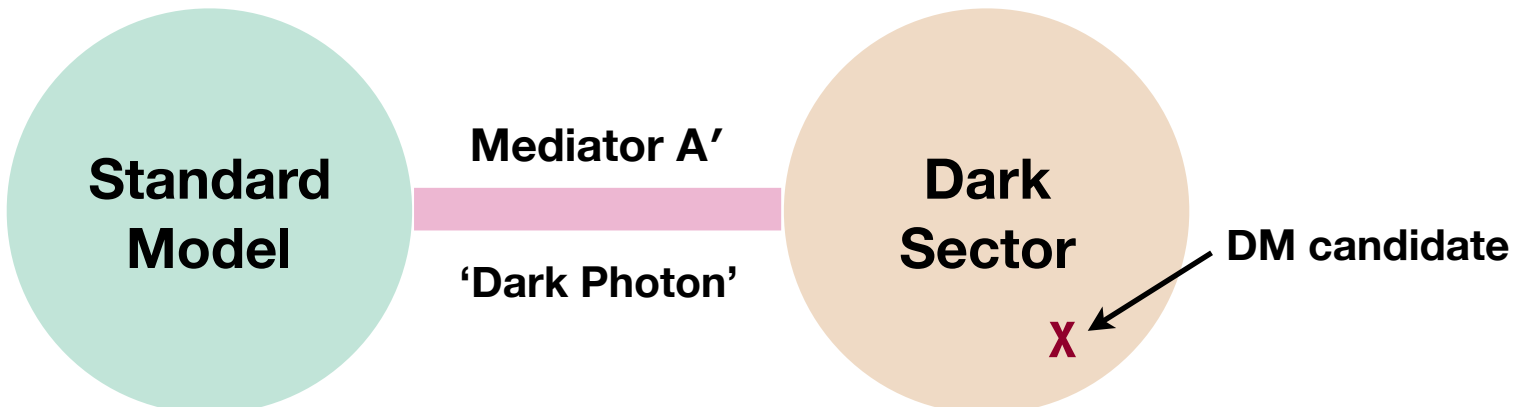


Why stop at 1 GeV? $\sigma \sim m_{DM}\, m_{nucl} / (m_{DM} + m_{nucl})$, breaks down for $m_{DM} \ll m_{nucl}$

What About Sub-GeV Mediators?

- Historically, sub-GeV mediators jurisdiction of ‘dark photon’ searches

‘Dark Sector’ Models



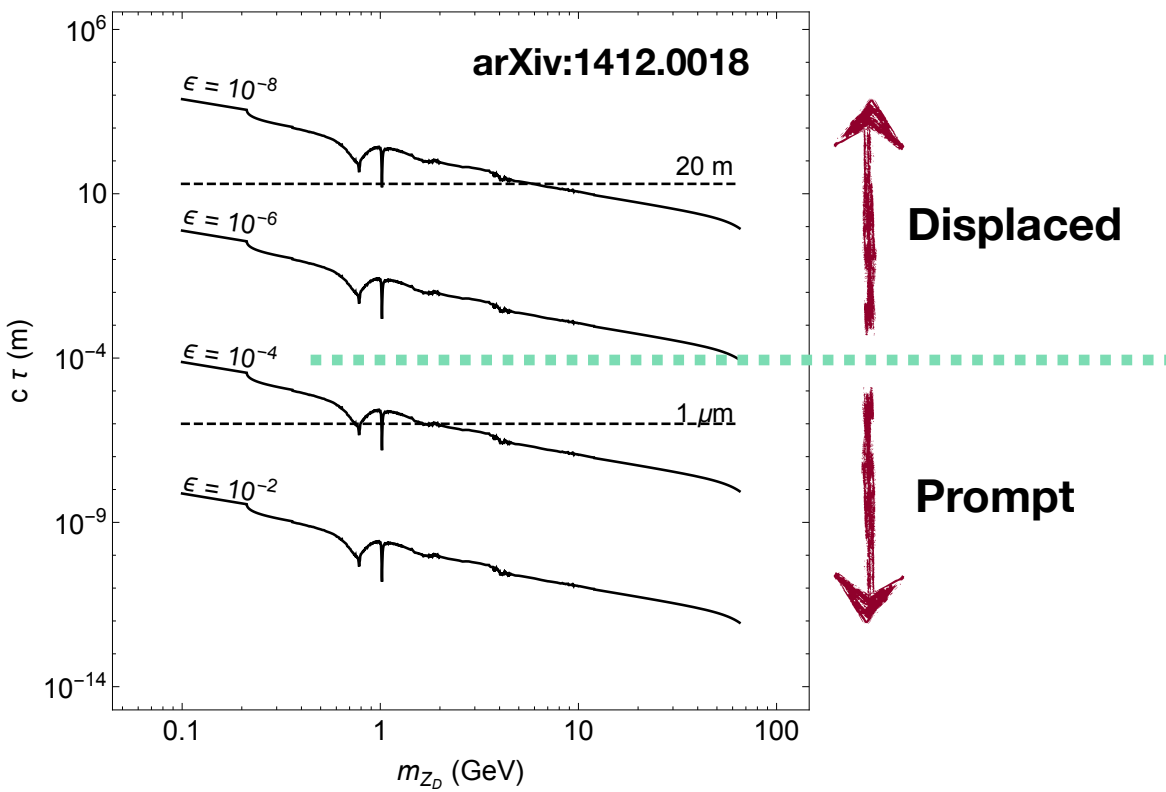
Dark photon: an additional U(1), connected to SM U(1) through kinetic mixing

$$\mathscr{L} \subset \frac{1}{2}\frac{\epsilon}{\cos\theta}(\partial^\mu A_D^\nu - \partial^\nu A_D^\mu)(\partial^\mu B^\nu - \partial^\nu B^\mu)$$

ε: kinetic mixing parameter

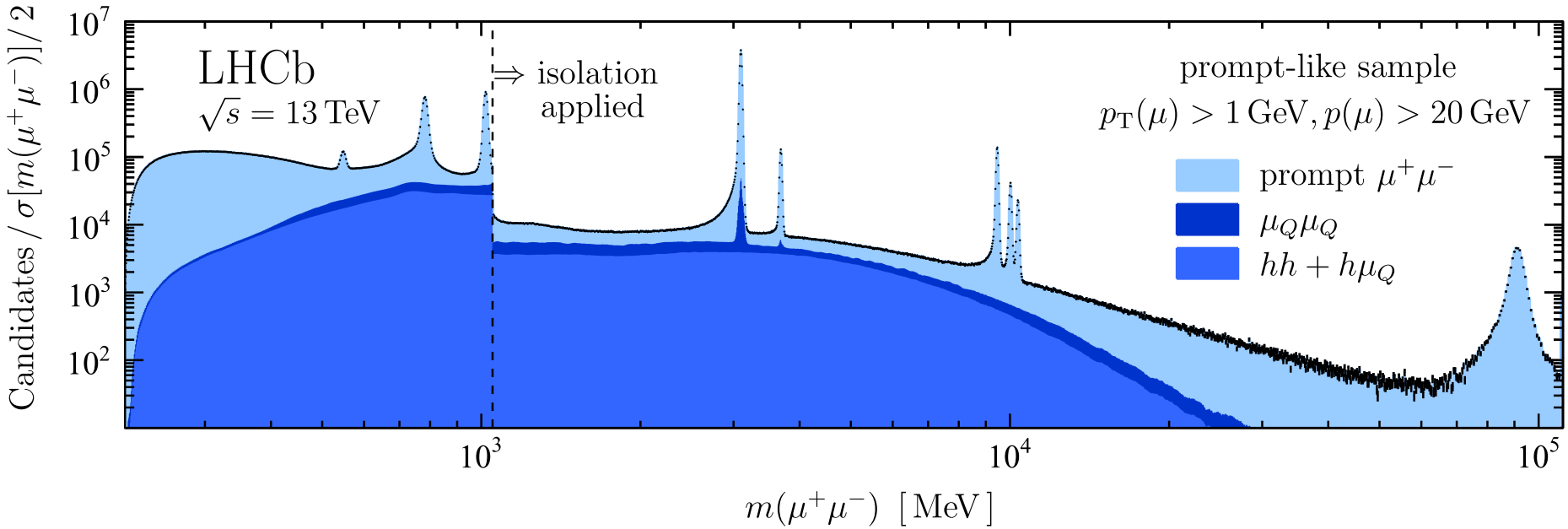
The Mixing Parameter ε

- Mixing parameter ε fixes **strength** of dark photon coupling
  - m(A′) ≪ m(Z): A′ interactions with SM fermions are **γ-like** with charge εQ
- Dark photon width and **lifetime** depend on ε and $m_{A'}$
  - 'Prompt' for ε > 10^{-4}
  - Can be (very) **displaced**
- Need **both** prompt and displaced searches for full coverage



LHCb Search for A′ Decaying to a Muon Pair

PRL 120 (2018) 061801

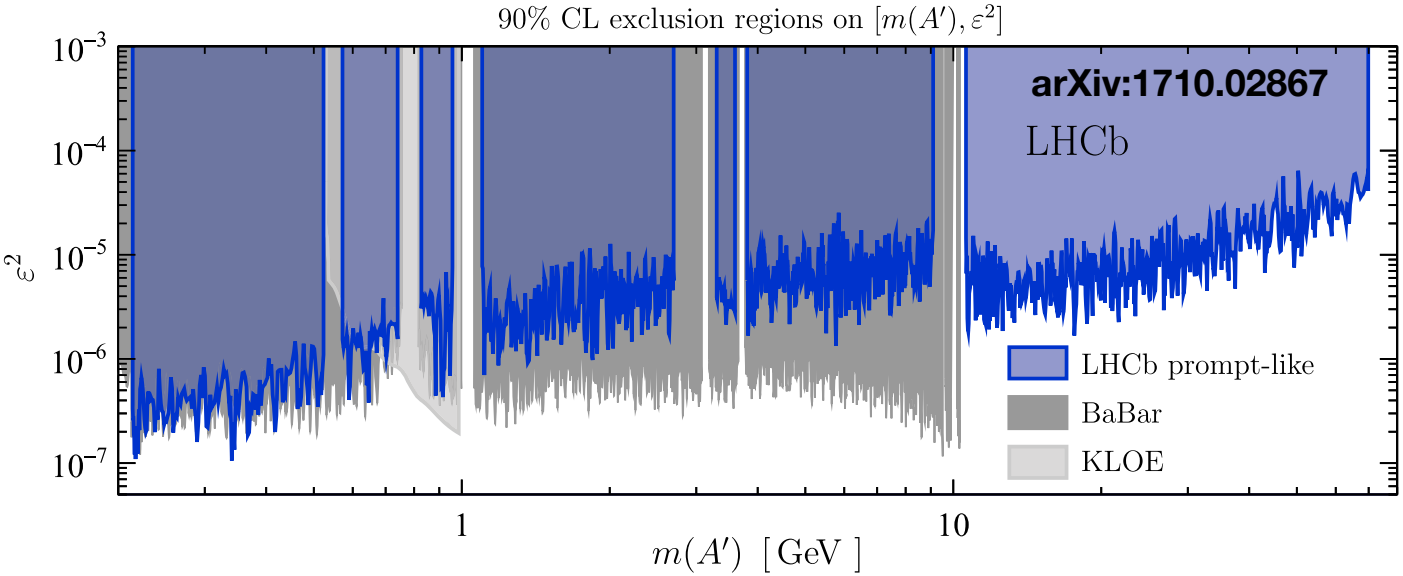


- **Bump hunt** in M(μμ) spectrum
  - Sensitive down to $m_{A'} = 2m_\mu$
  - Both **prompt** and **displaced**
- No trigger! **All** events recorded
  - With **no selection** on M(μμ)

Much lower BG (main BG: γ→μμ conversions)

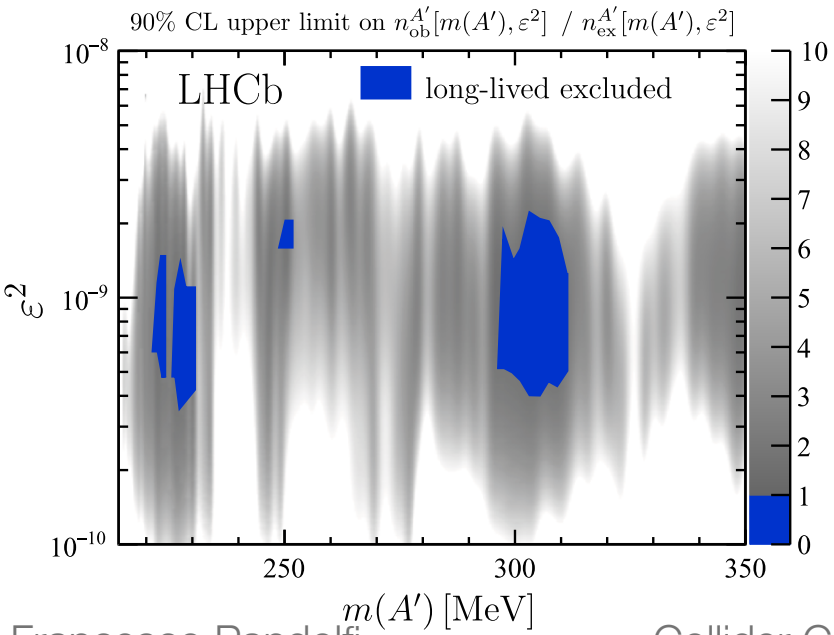
LHCb Limits

PRL 120 (2018) 061801



Prompt A′→μμ

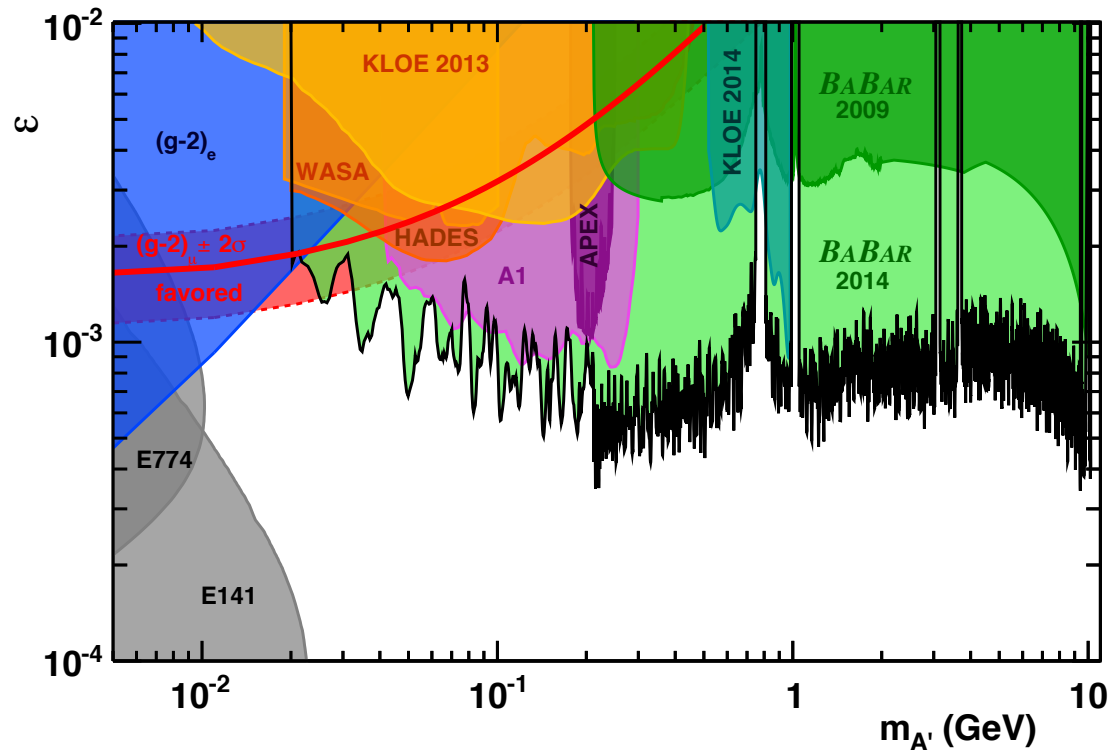
(first limits for M>10 GeV)



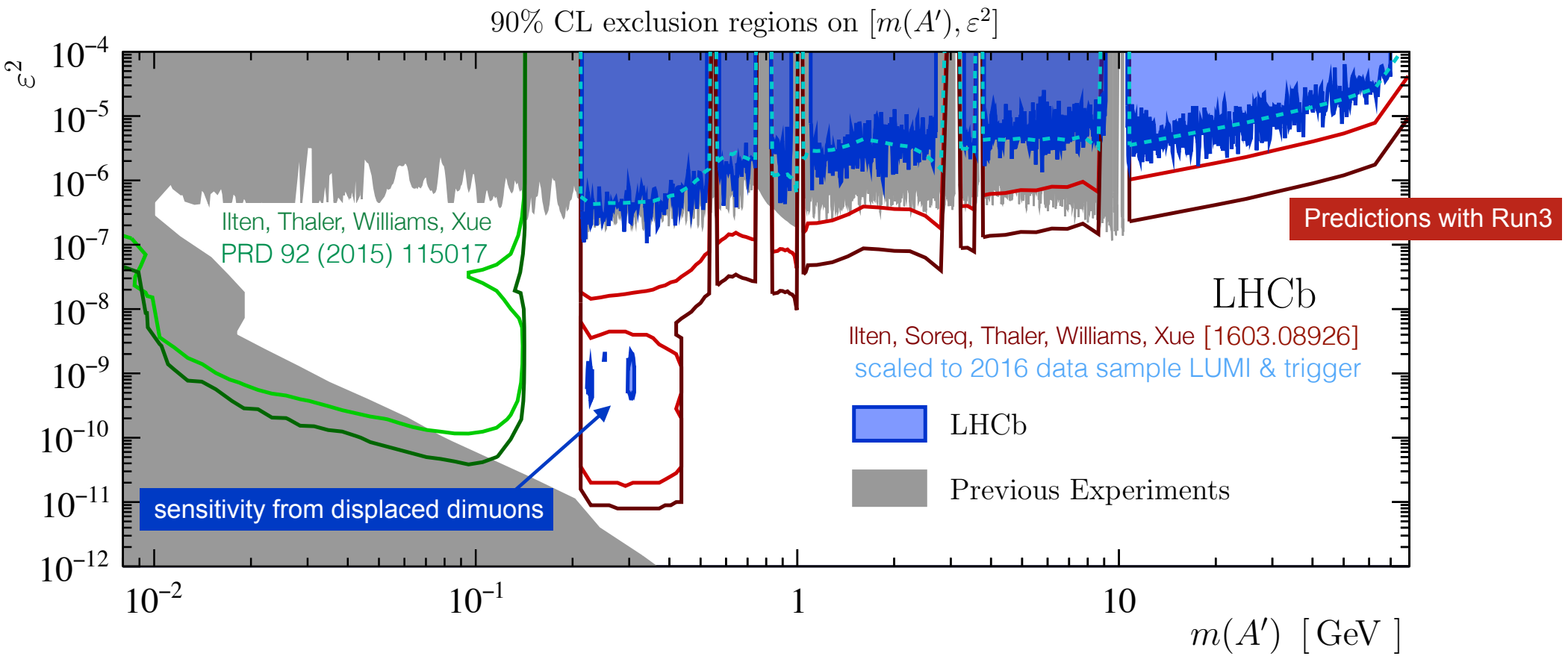
Displaced A′→μμ

BaBar: New Results Six Years After Last Collision

PRL 113 (2014) 201801



Perspectives for Dark Photon Searches



Conclusions