Dark Matter at the LHC

December 4, 2019

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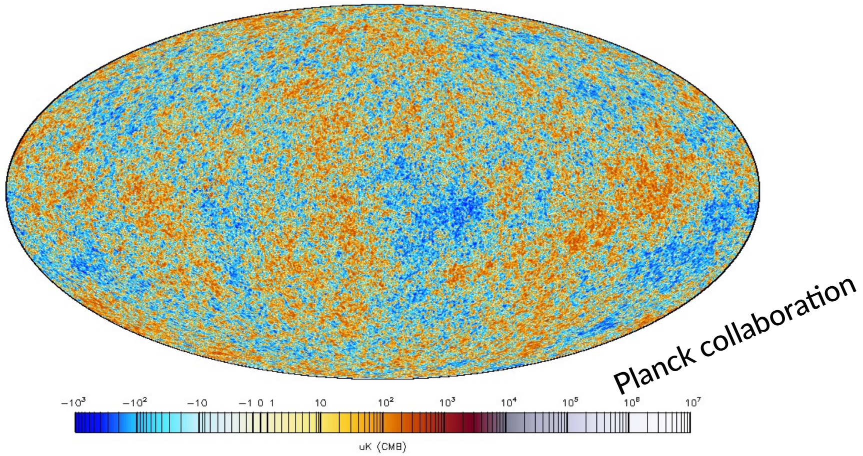
on behalf of ATLAS and CMS

COMHEP

BOSTON UNIVERSITY

Dark matter?

Ample evidence from the cosmos



Cosmic microwave background

"Picture of electromagnetic matter,

30k years after big bang"

→ ≈ 27% of energy in universe is DM

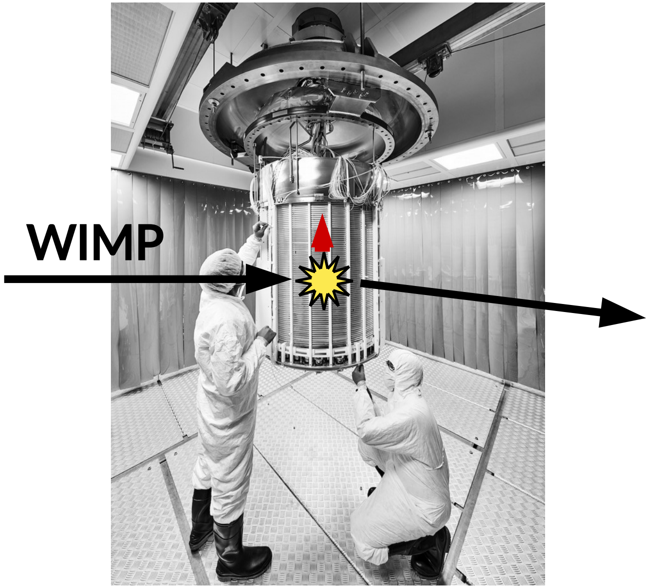
One Candidate:

"Weakly interacting massive particle" (WIMP)

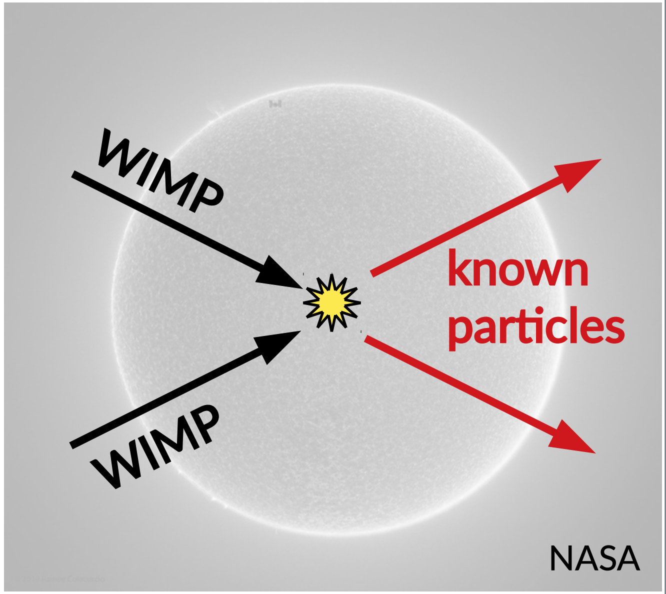
- Weak coupling to known particles
- Can account for observed DM phenomena

How to find WIMPs?

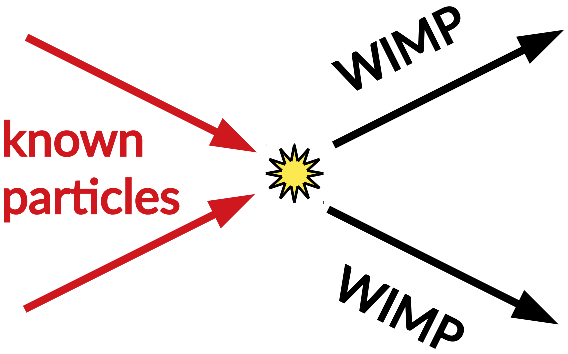
Direct detection
"WIMP from universe bumps into our detector"



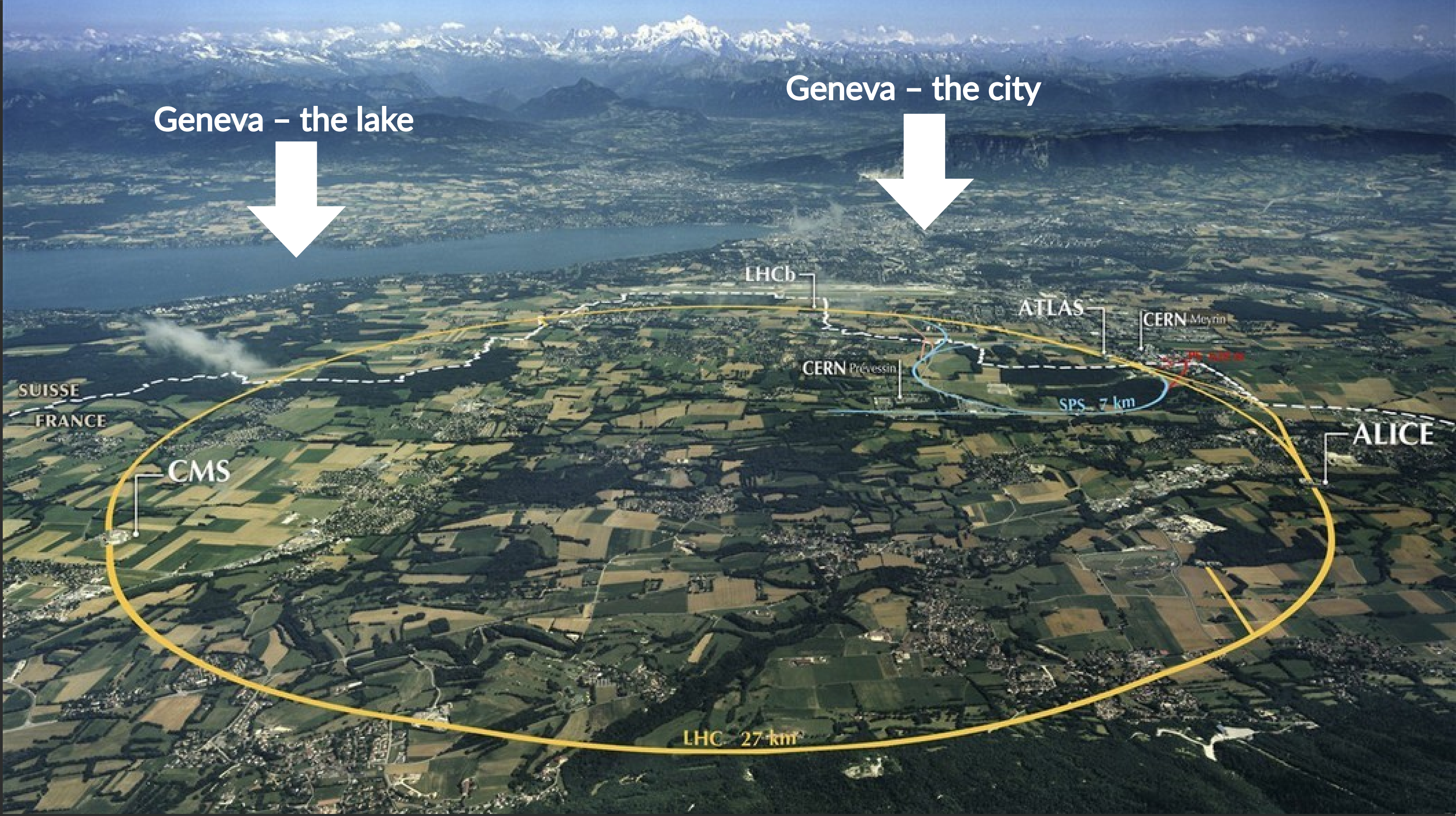
Indirect detection
Observe DM annihilation in the universe



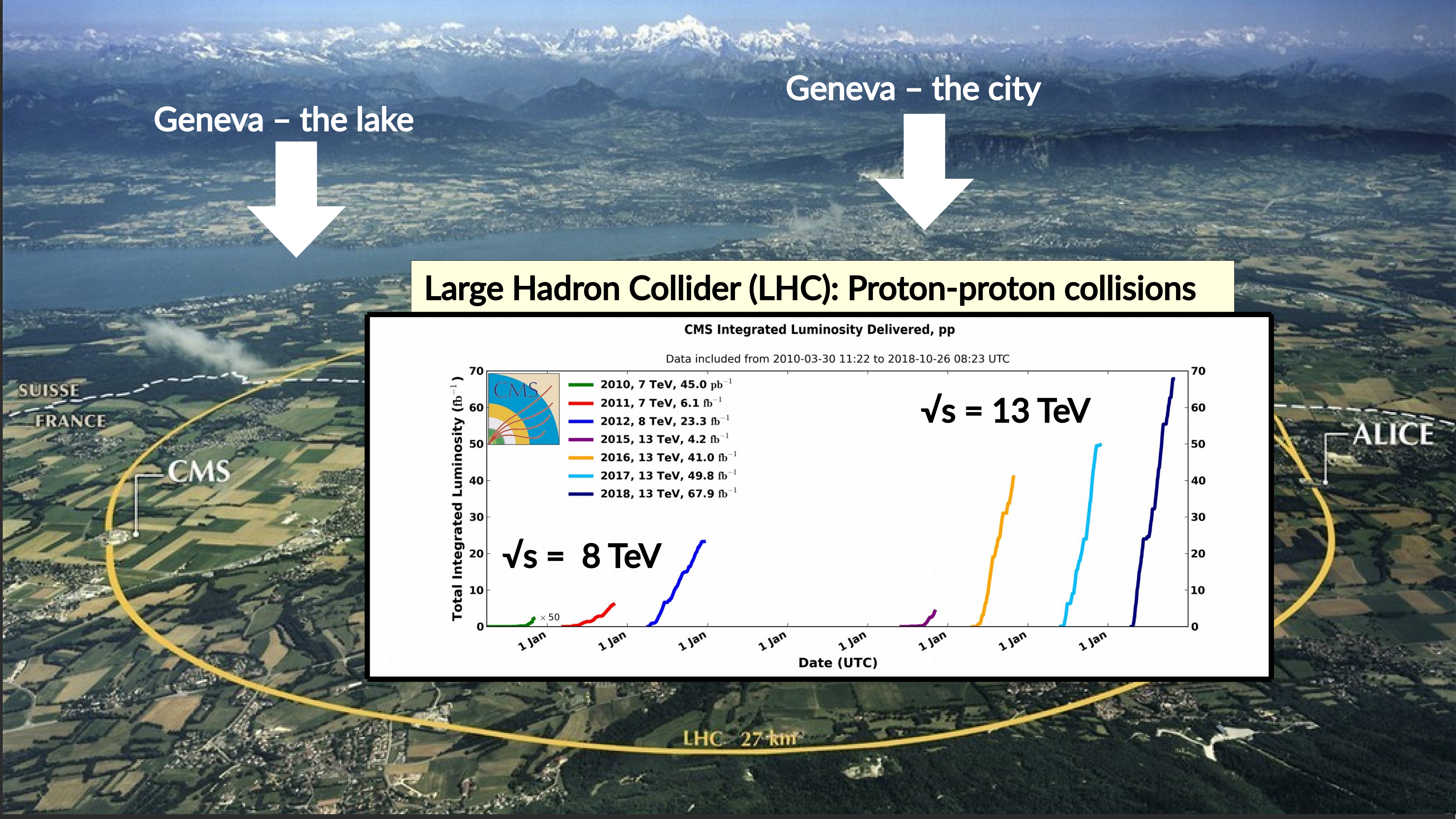
Collider
Produce DM from collisions of known particles

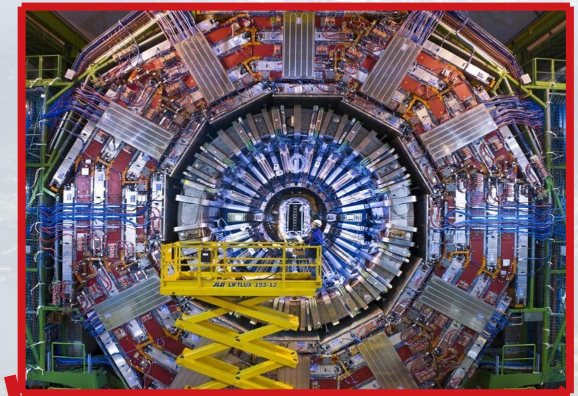


Certainty only if results from all three are consistent!

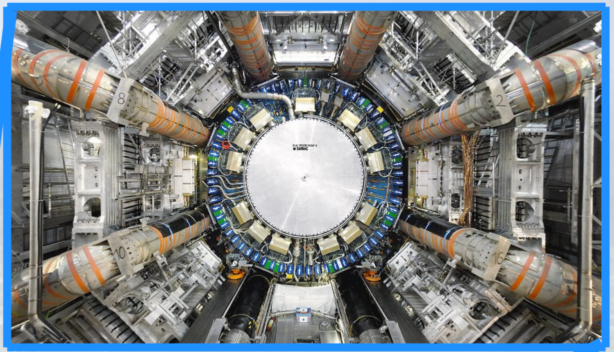

Geneva – the lake
Geneva – the city
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

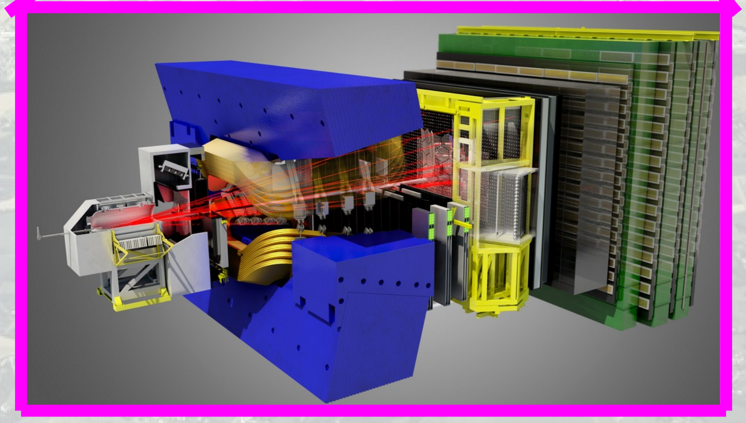
Large Hadron Collider (LHC): Proton-proton collisions





ATLAS + CMS:
Multi-purpose, can observe large range of SM and BSM, work best at low η

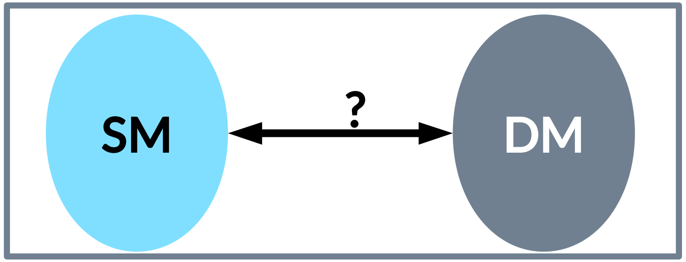




LHCb:
Focus on B physics, large η only

How do searches work? Depends!

How do SM and DM particles interact?



How do SM and DM particles interact?

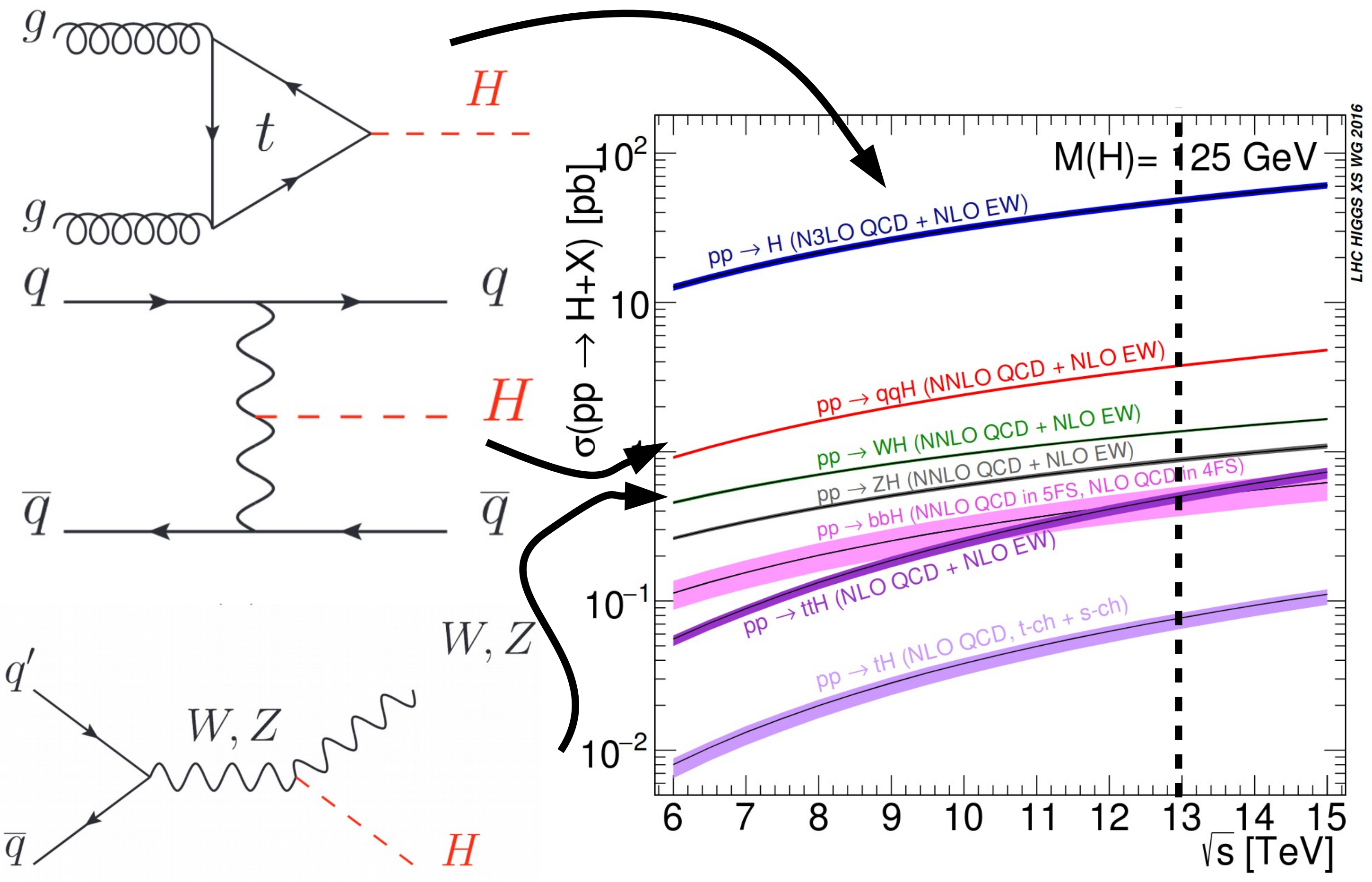
The Higgs portal

H(125) → invisible

Attractive because simple: No new interaction needed!

For reference: invisible BR of Z is known to ≈ 3 per-mille

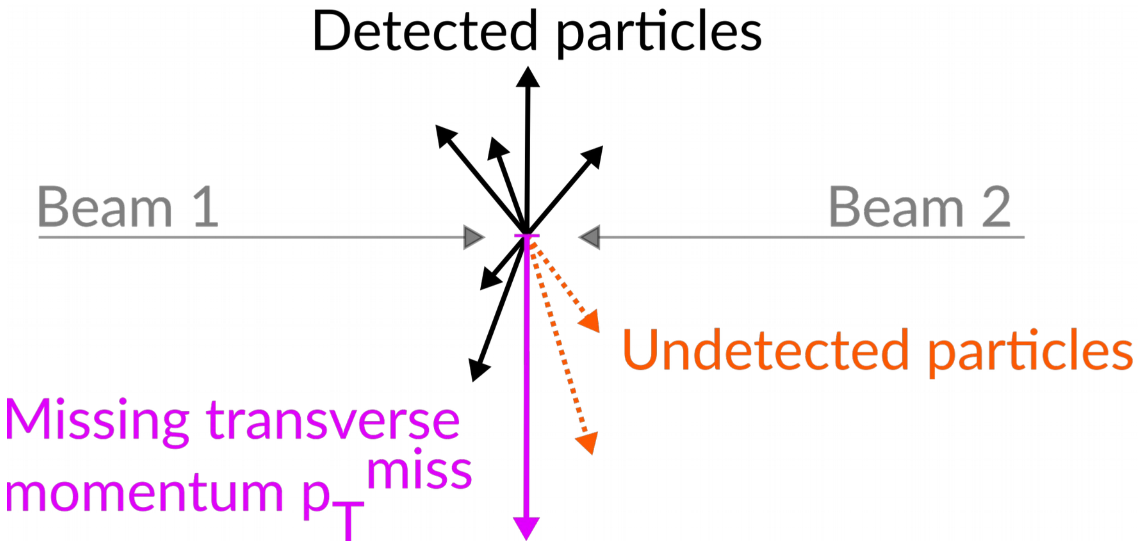
Measurement strategies driven by Higgs production modes



PDG Higgs review

Principle of detection: p_T^{miss}

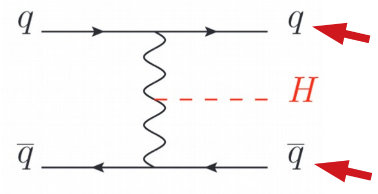
Detect "invisible" particles from momentum balance of reconstructed particles



$$\vec{p}_{\mathrm{T}}^{\,miss} = - \sum_{\mathrm{PF\ candidates}} \vec{p}_T$$

Experiment requires presence of detectable "tag" particles: Jets, photons, ...

VBF H(inv)



10.1016/j.physletb.2019.04.025

Distinctive dijet signature drives sensitivity

$\eta_{j1} \times \eta_{j2} < 0$

small $\Delta\varphi_{jj} < 1.5$

large $\Delta\eta_{jj} > 1.0$

large $m_{jj} > 200$ GeV

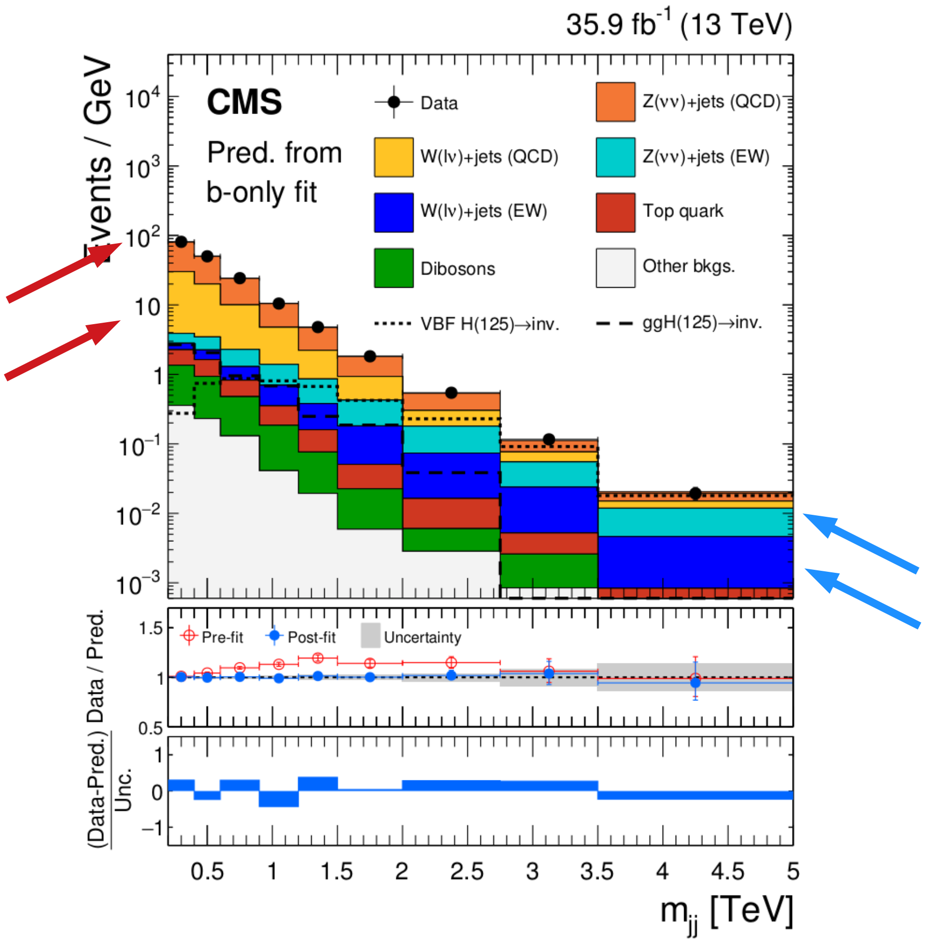
+

large $p_T^{miss} > 250$ GeV

Backgrounds dominated by Z(νν), W(lν)

Low-m_{jj}: jets from ISR ("QCD")

high-mjj: W, Z from VBF ("EW")



Background estimation + signal extraction

Basic likelihood

Poisson fluctuation of **data counts n_i** around expectation from **signal s_i** and **background b_i**

$$\mathcal{L}(\text{data} \mid \mu, \theta) = \prod_{i \in \text{bins}} \frac{(\mu \times s_i(\theta) + b_i(\theta))^{n_i}}{n_i!} \exp(-\mu \times s_i(\theta) - b_i(\theta)) \times \prod_{j \in \text{nuisances}} p_j\left(\tilde{\theta}_j | \theta_j\right)$$

← Gaussian constraint term for θ

- s_i, b_i from Monte Carlo simulation + corrections
- Uncertainties modeled with nuisance parameters θ
- θ dependence from alternative templates (i.e. re-running analysis)

→ Determine best-fit θ, signal strength μ by maximizing likelihood

10.1016/j.physletb.2019.04.025

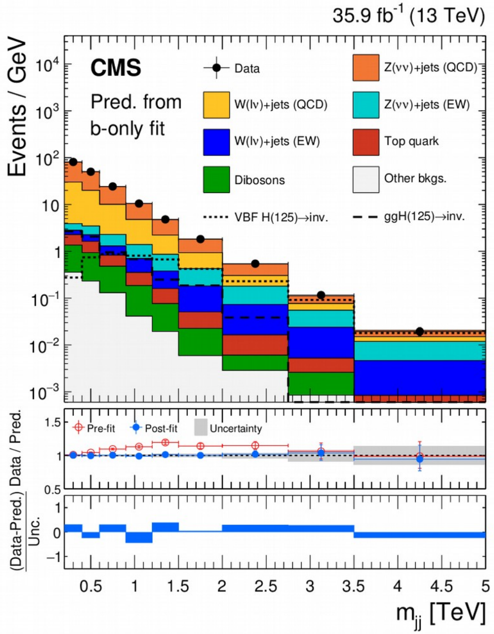
Using control regions

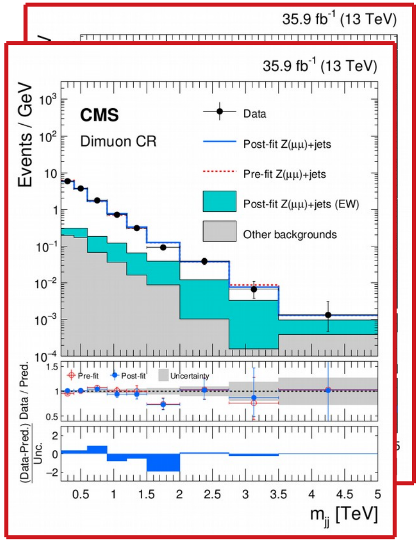
Goal: Estimate mjj shape for W, Z

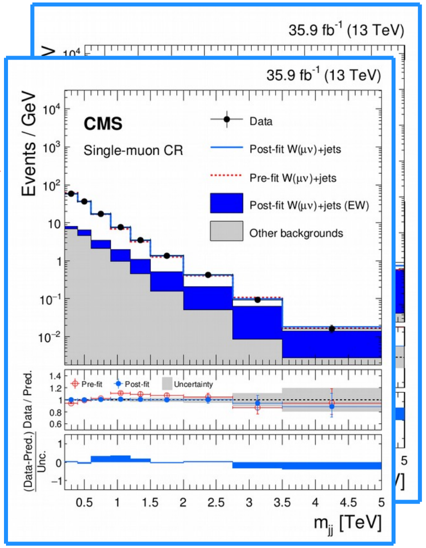
Control regions with leptonic decays:
Z(ee), Z(μμ), W(eν), W(μν)

Combined maximum-likelihood fit
transfer factors + uncertainties based on simulation

→ Only process *ratios* from sim, shape + norm form data



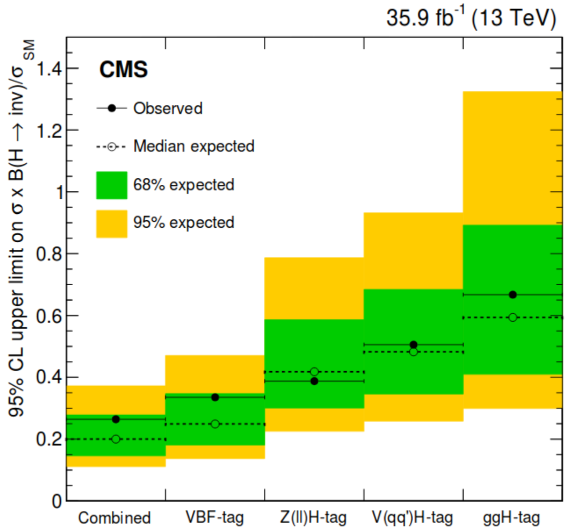


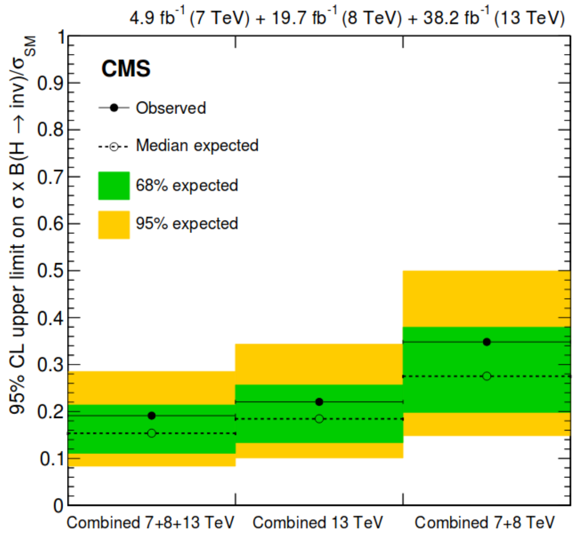


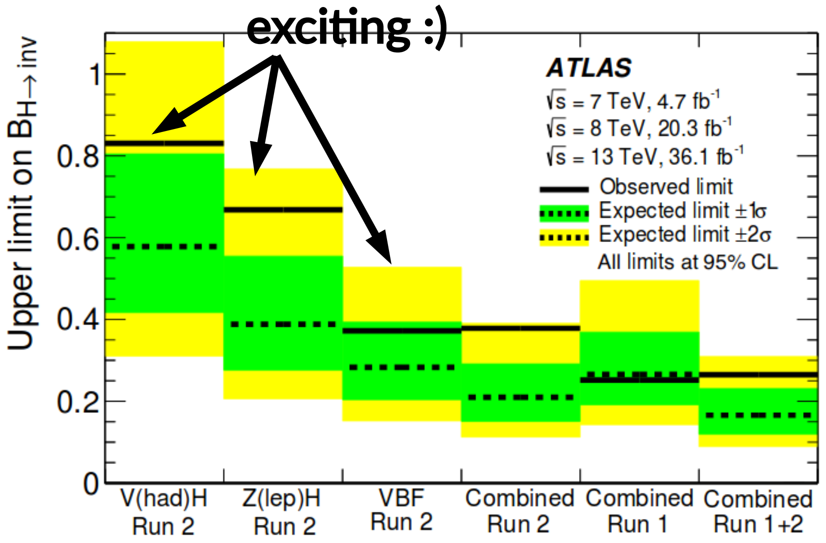
Uncertainties partially factorize!

One observable, may channels: combine, combine, combine

VBF dominates combined results, but others still contribute







Full Run-2 results in the making!

Limitations to attack: p_T^{miss} trigger threshold, theory uncertainties

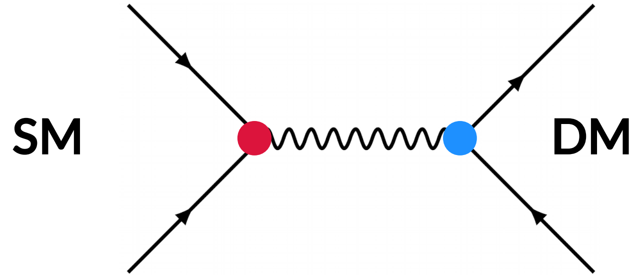
10.1016/j.physletb.2019.04.025

Phys. Rev. Lett. 122 (2019) 231801

Simplified models

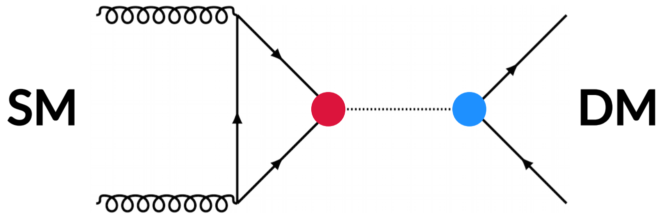
Interpretation: Simplified models

Spin-1 mediator



$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_{\mu} \bar{\chi} \gamma^{\mu} \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_{\mu} \bar{q} \gamma^{\mu} q$$

Spin-0 mediator



$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}} \phi \bar{\chi} \chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q$$

Simplified models with few free parameters:

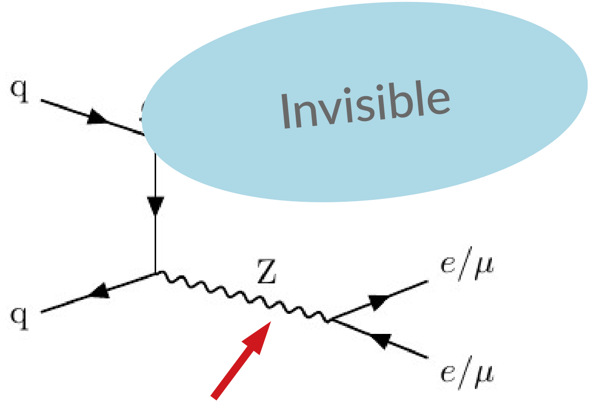
m_{med}, m_{DM}, mediator-quark coupling, mediator-DM coupling

minimal flavour violation

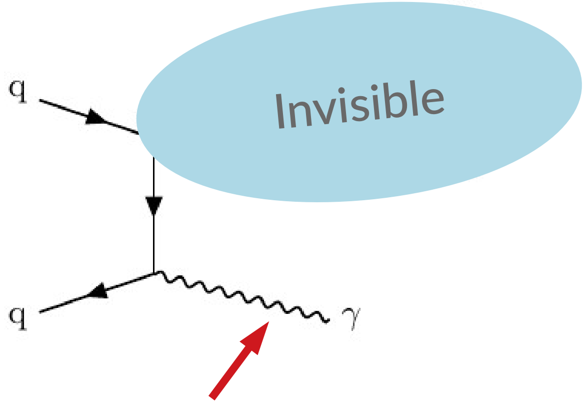
Benchmarks defined by LHC Dark Matter working group

Always present: Initital state radiation

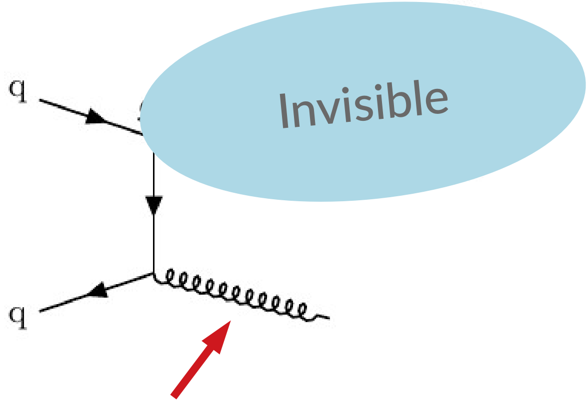
Mono-Z



Monophoton



Monojet



larger signal, larger background

Experimentally clean → **Experimentally harder**

ATLAS monojet 2015+16

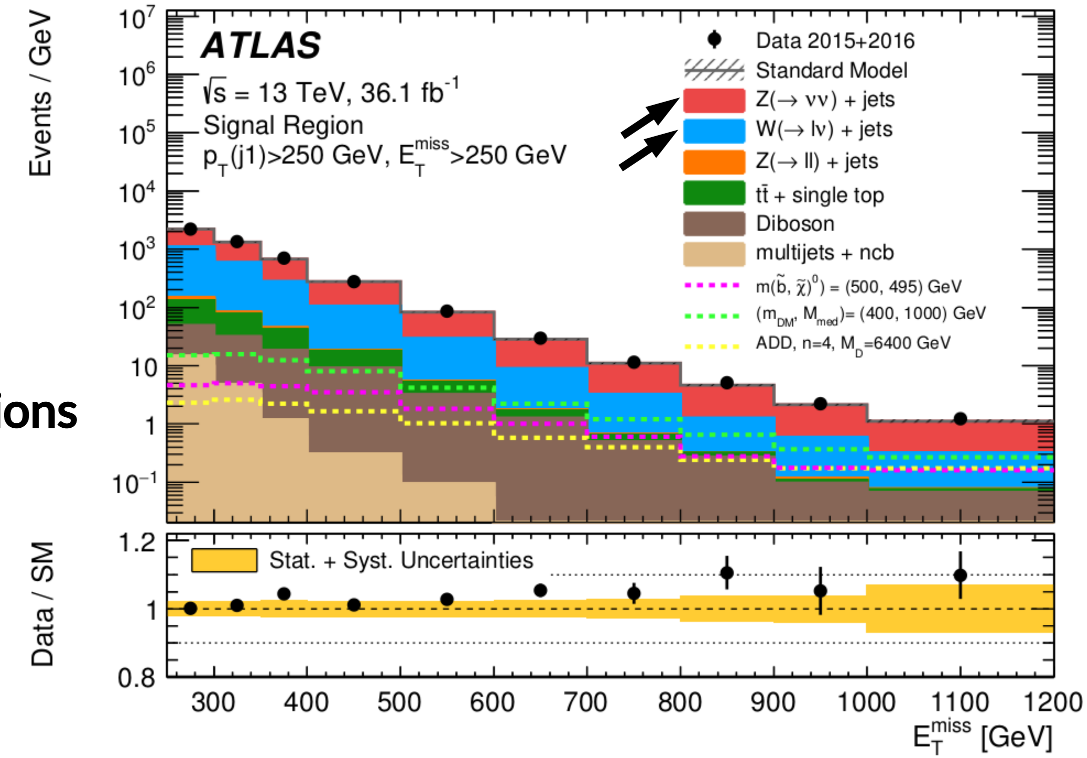
Similar strategy to VBF H(inv): More inclusive, no VBF topology

jet pt > 250 GeV
p_T^{miss} > 250 GeV
no leptons

→ W and Z are leading BG

Combined fit with W(lv) and Z(ll) control regions
this time only get normalization + nuisances from data

Strategy varies a bit in CMS, but similar in principle



10.1140/epjc/s10052-017-5389-1

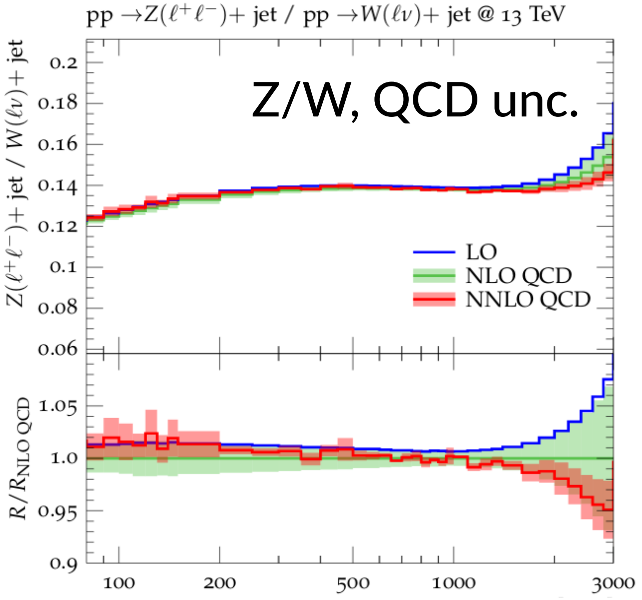
Sensitivity driver: theory uncertainties on process ratios

Precise predictions for V+jets dark matter backgrounds

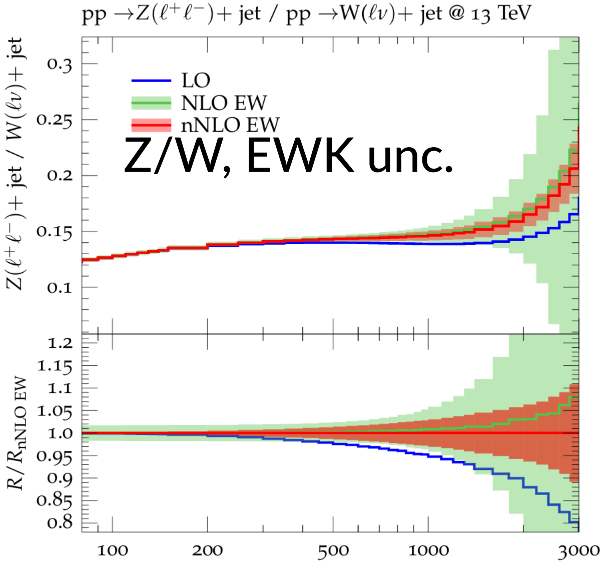
J. M. Lindert[1], S. Pozzorini[2], R. Boughezal[3], J. M. Campbell[4], A. Denner[5], S. Dittmaier[6], A. Gehrmann-De Ridder[2,7], T. Gehrmann[2], N. Glover[1], A. Huss[7], S. Kallweit[8], P. Maierhöfer[6], M. L. Mangano[8], T.A. Morgan[1], A. Mück[9], F. Petriello[3,10], G. P. Salam[a,8], M. Schönherr[2], C. Williams[11]

SM theory community project: specifically tailored uncertainty prescription for this type of search

→ uncertainties on *ratios*



Boson pt (GeV)

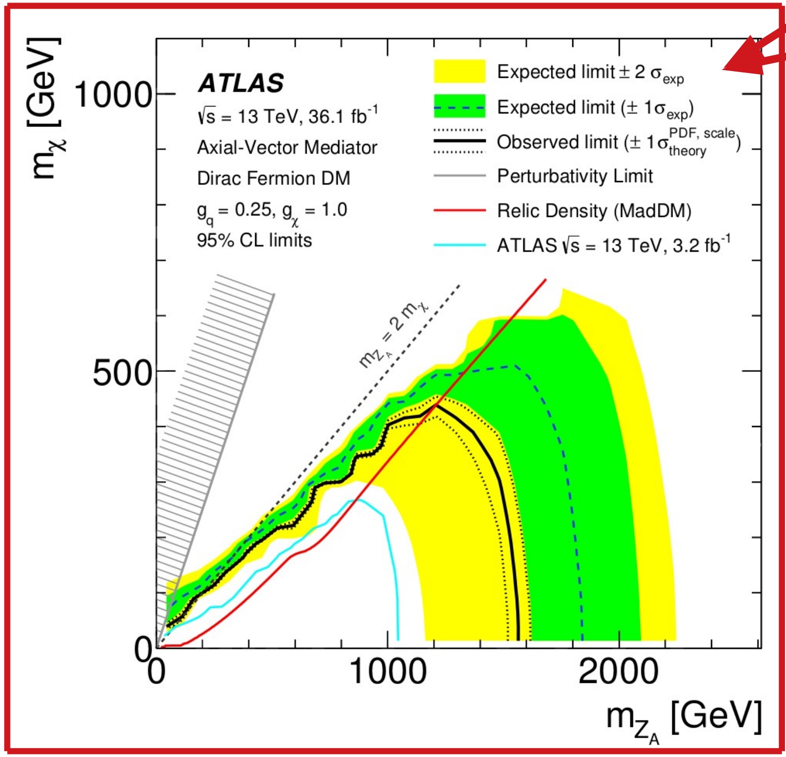


Boson pt (GeV)

JHEP 01 (2018) 126

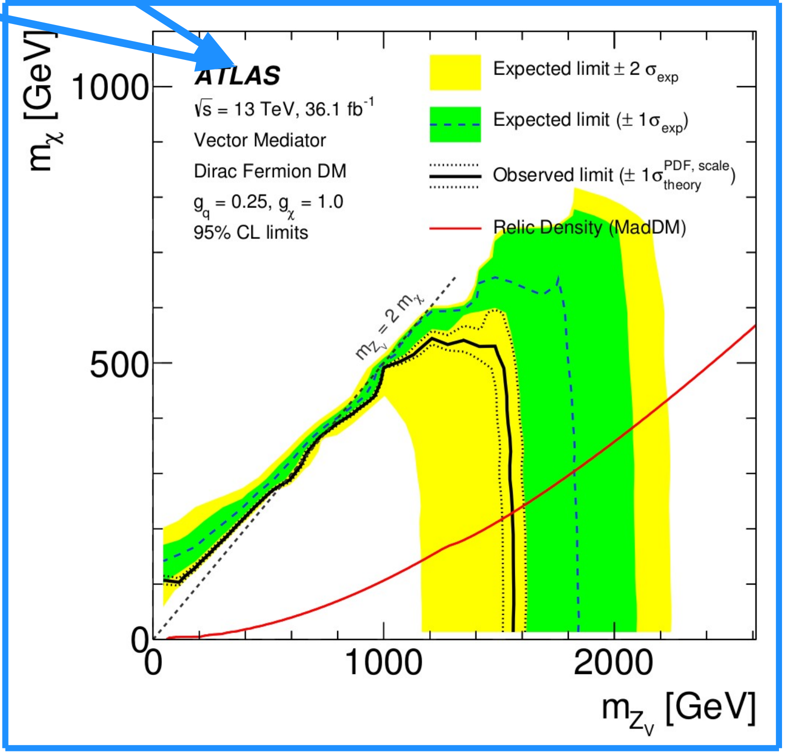
Monojet: Spin-1 exclusion

$$\mathcal{L} \subset \sum_q Z'_\mu \bar{q}\gamma^\mu (g_q^V - g_q^A \gamma_5) q - Z'_\mu \bar{\chi}\gamma^\mu (g_{DM}^V - g_{DM}^A \gamma_5)\chi$$



m_{DM} only relevant in terms of $m_{DM} < m_{Z'} / 2$

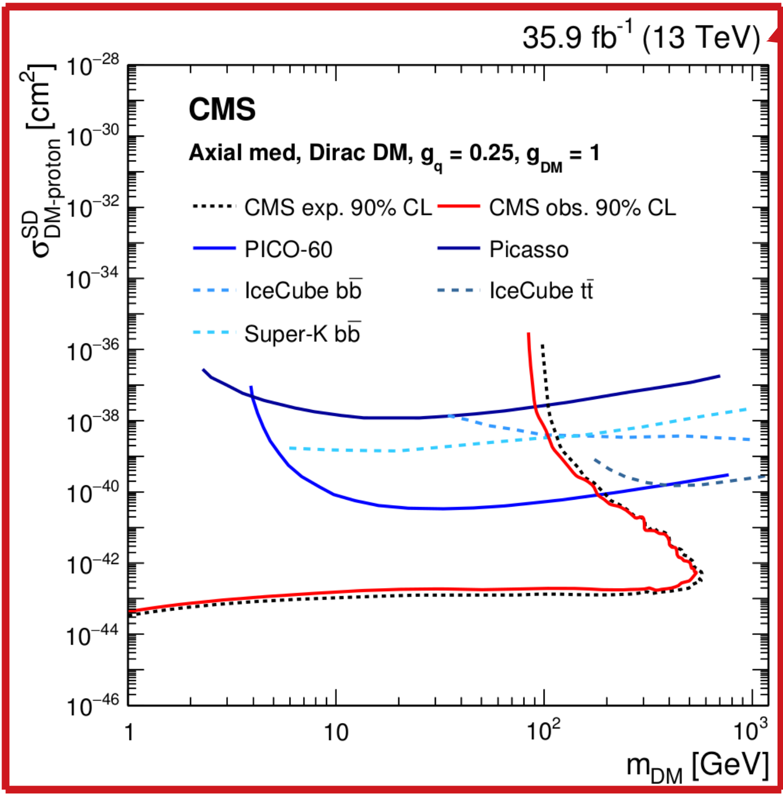
Coupling type has small effect @ LHC



10.1103/PhysRevD.97.092005

Monojet: Spin-1 exclusion

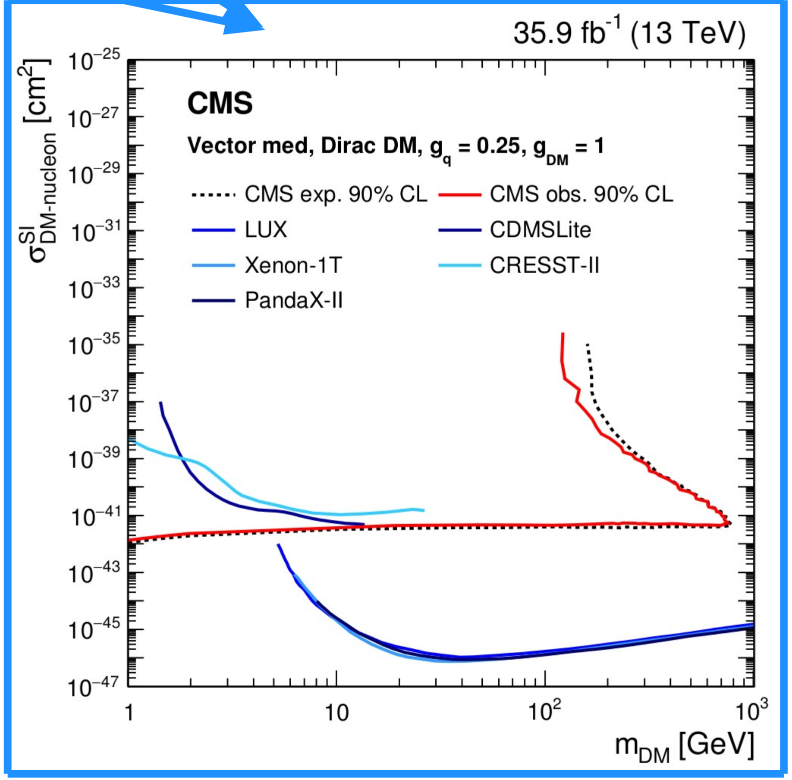
$$\mathcal{L} \subset \sum_{q} Z'_{\mu}\bar{q}\gamma^{\mu}(g_q^V - g_q^A\gamma_5)q - Z'_{\mu}\bar{\chi}\gamma^{\mu}(g_{DM}^V - g_{DM}^A\gamma_5)\chi$$



Can compare to direct detection

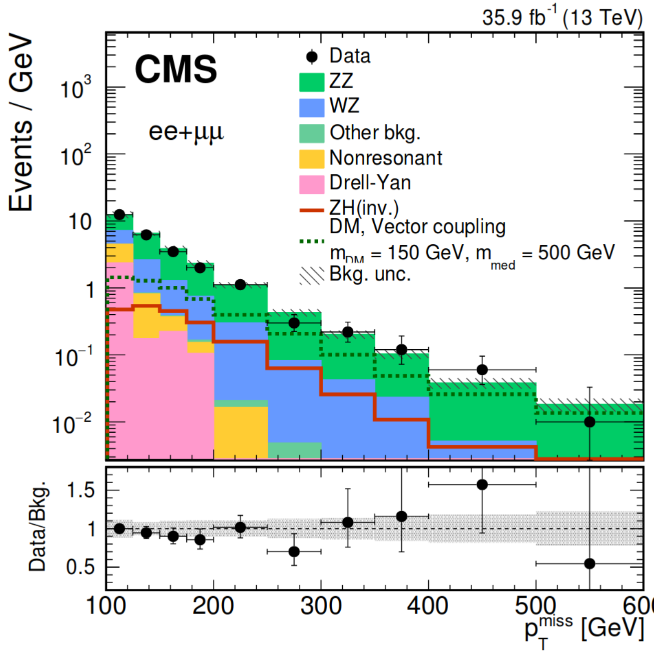
LHC useful at low m_{DM}, for axial couplings

Model dependence!



Rinse and repeat

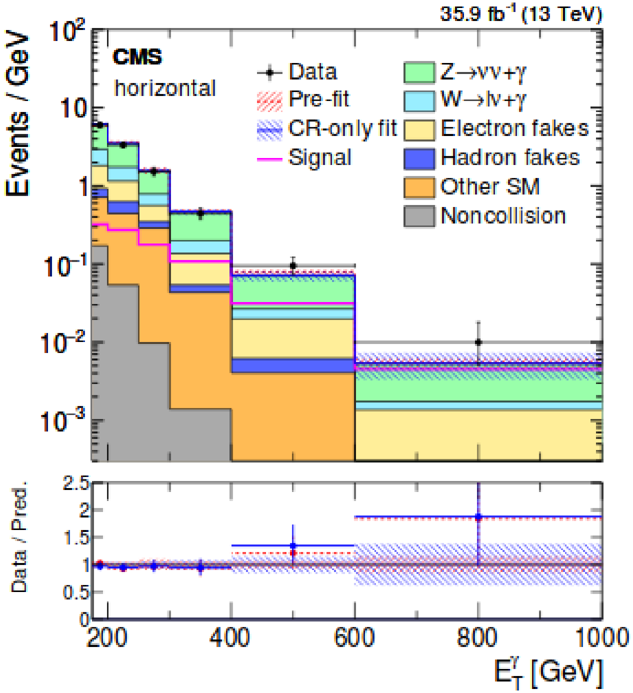
Mono-Z



Backgrounds: Z+Z, W+Z

10.1140/epjc/s10052-018-5740-1

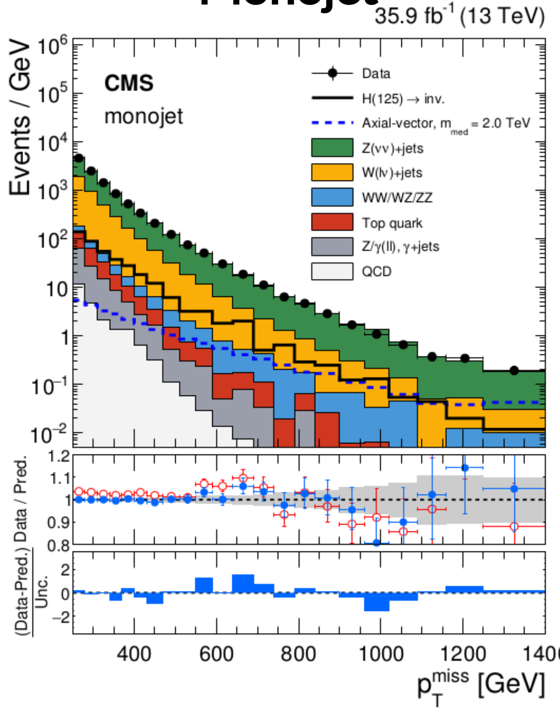
Monophoton



Backgrounds: Z+γ, W+γ

10.1007/JHEP02(2019)074

Monojet

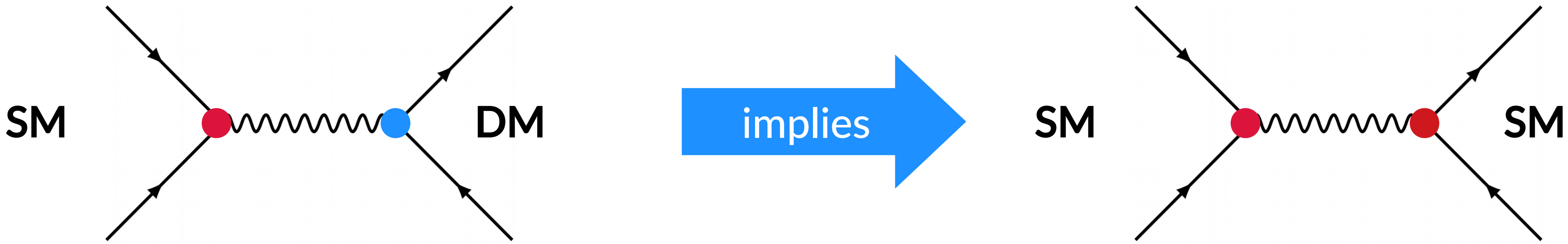


Backgrounds: Z+jet, W+jet

10.1103/PhysRevD.97.092005

Statistical uncertainties + reconstruction different, strategy similar

Searching for the mediator



Resonance searches

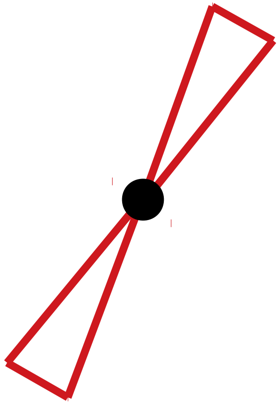
arXiv:1910.08447

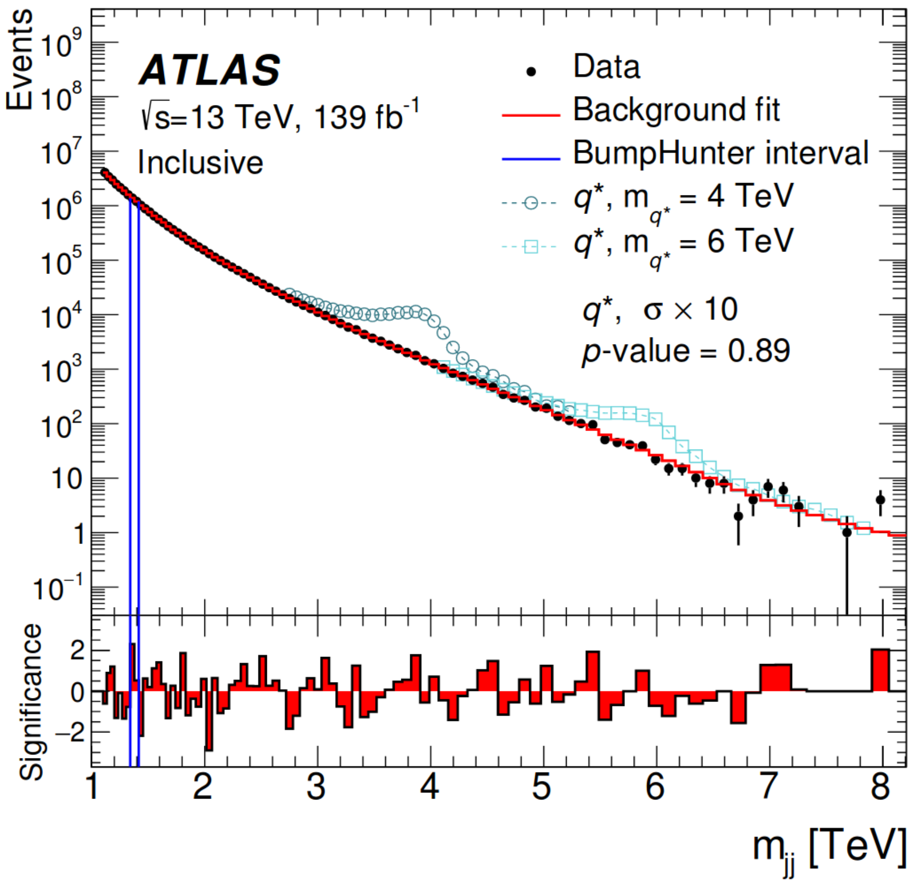
"Bump hunt"
Look for resonance on top of smoothly falling background

BG can be fully data-driven, few uncertainties

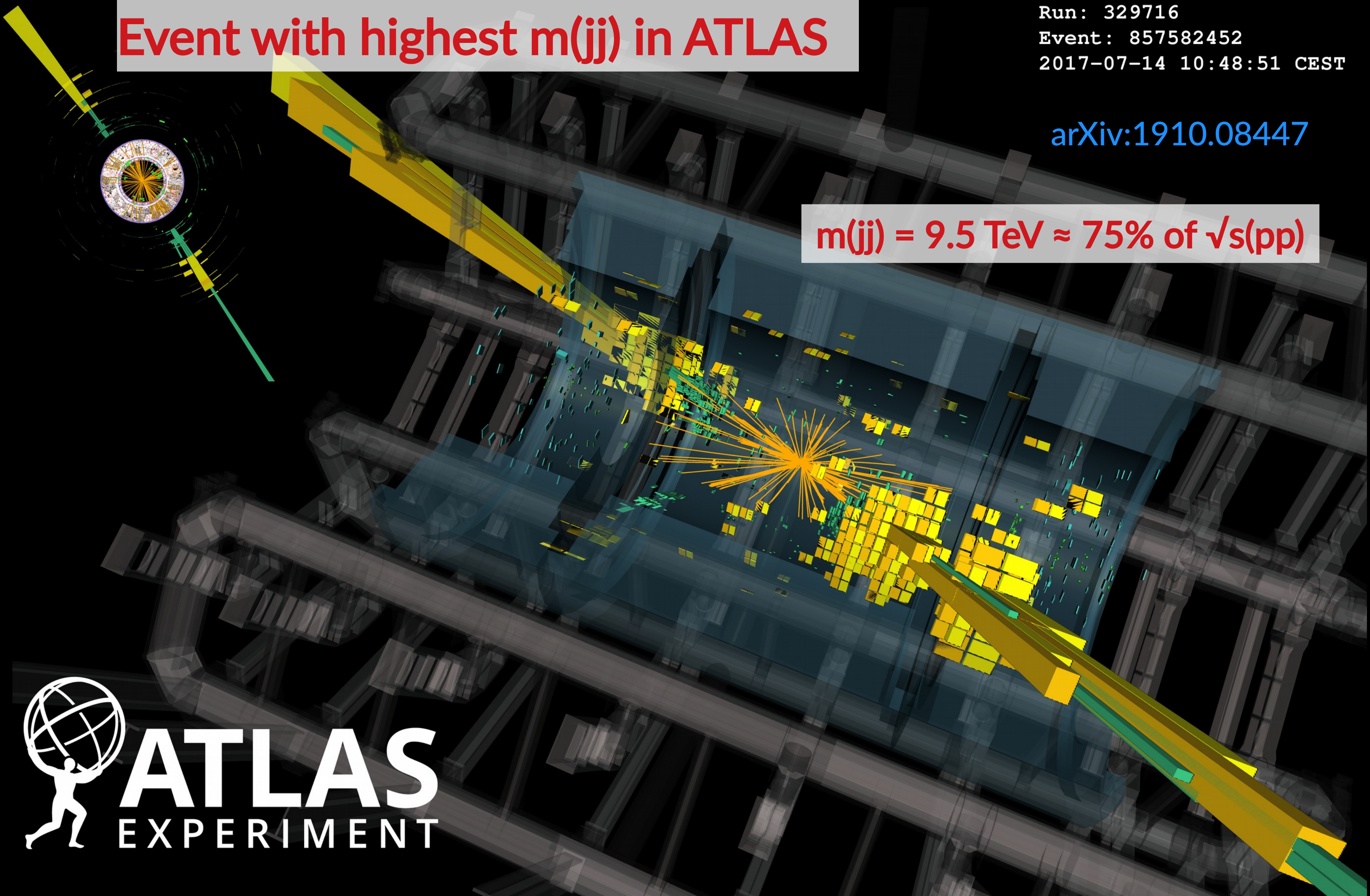
Important:
- Signal shape (resolution, proton PDF)
- triggering

E.g.: "Classical dijet"
Triggering based on high-p_T jets
→ powerful at high mass
→ Cannot extend to low masses
(trigger rates too high)



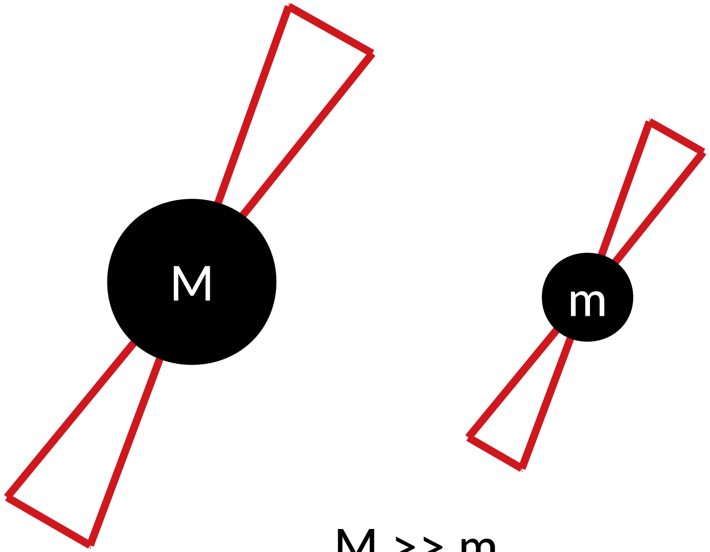


Event with highest m(jj) in ATLAS



Main challenge: How to cover the full mass range?

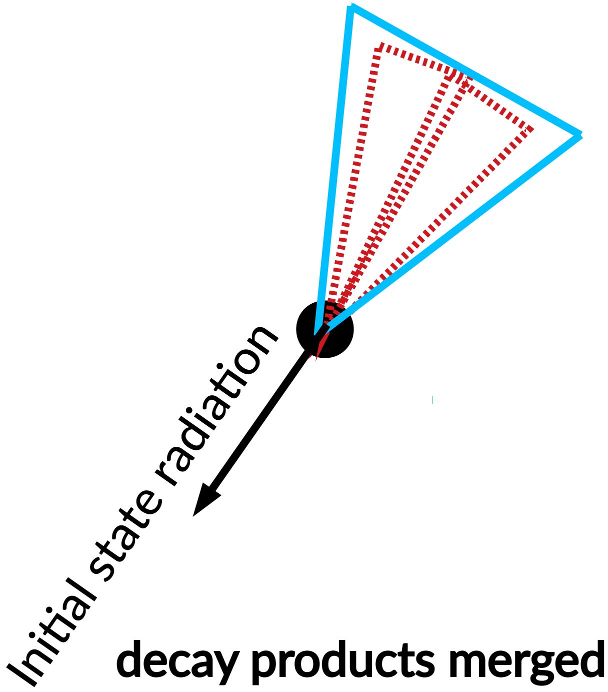
Resonance produced at ≈ rest



M >> m

Trigger on decay product pt
alone works only at high mass

Instead: low-mass resonance with high pt



decay products merged into
single large-radius jet
Use ISR for triggering (γ, jet)

10.1007/JHEP01(2018)097

Key: Substructure techniques

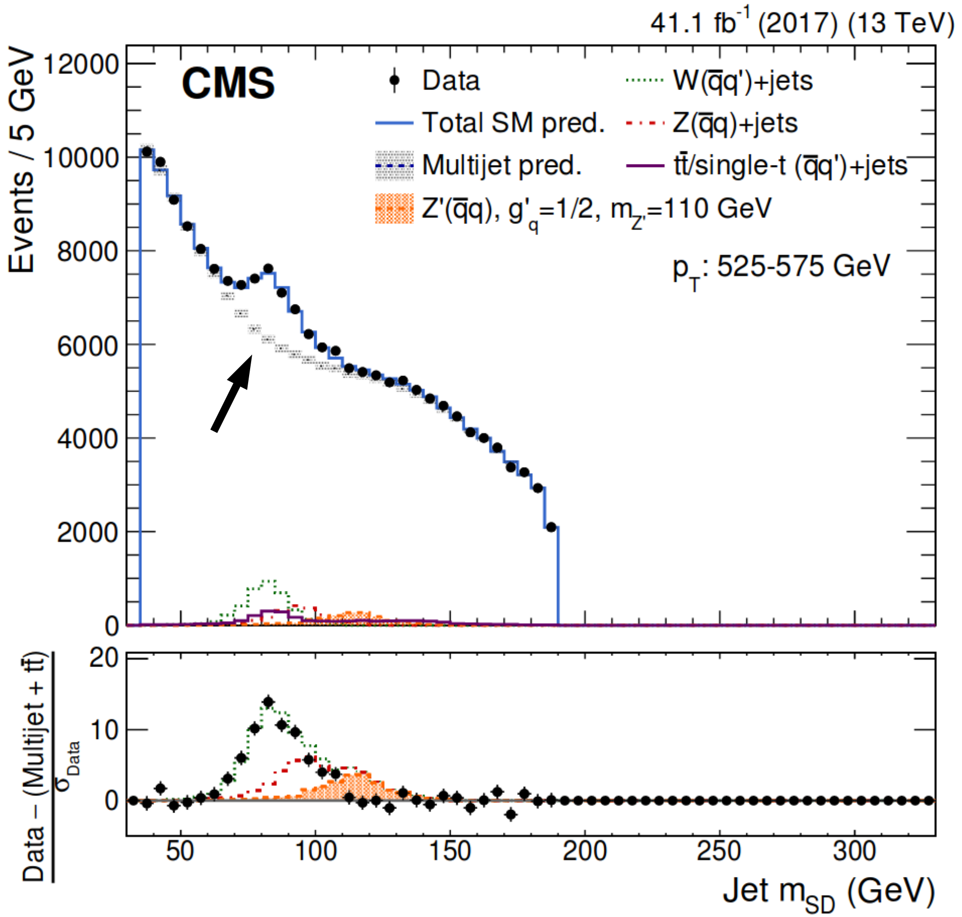
Select Z' → qq, reject QCD multijet

Jet mass "grooming"
soft-drop (SD) algorithm corrects for parton shower, pileup contributions

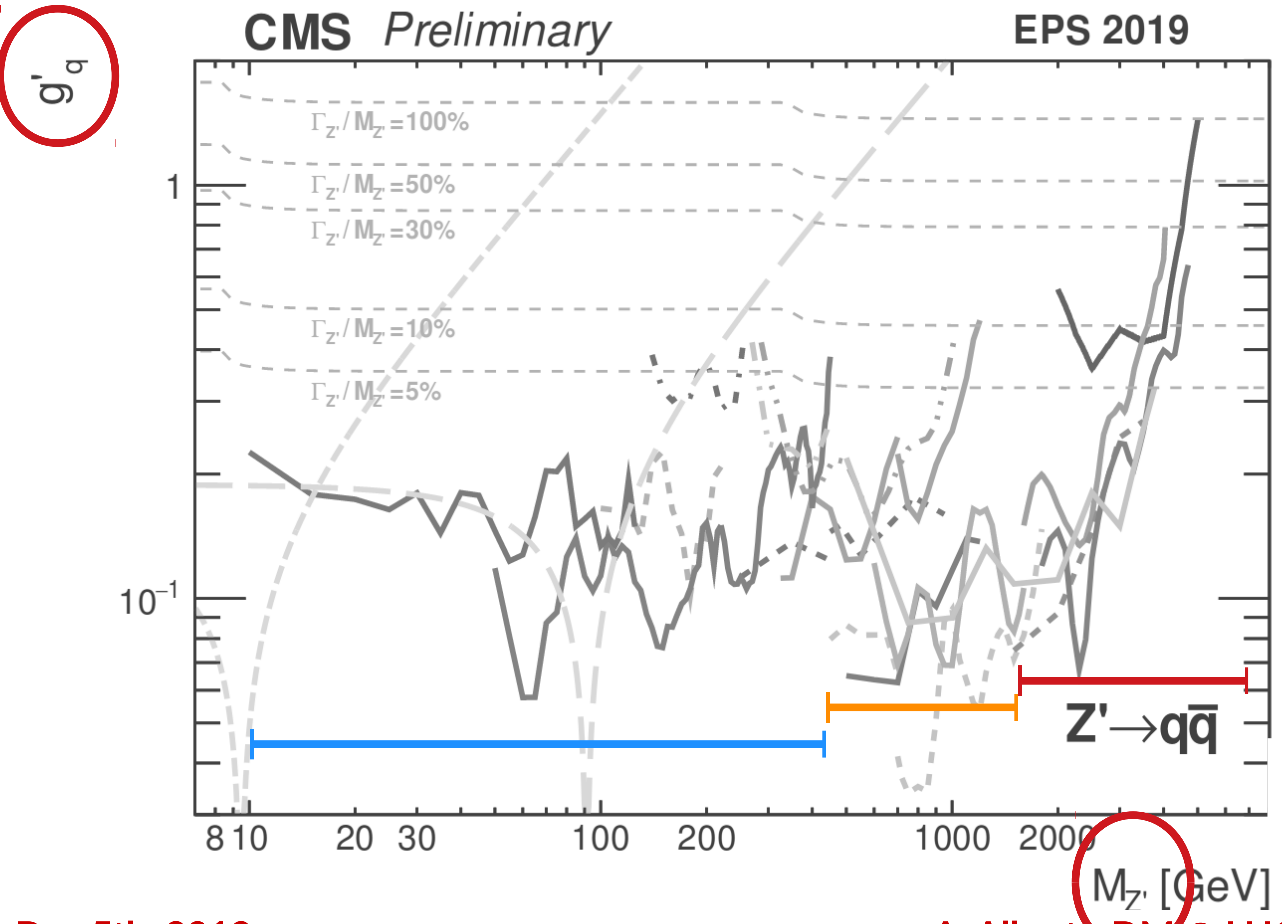
Two-prong tagging with mass-decorrelated high-level variable based on analytical energy correlation functions

→ Not a neural network!

Observing Z/W→ qq in this way was not seen as possible 10 years ago!



Z' coupling to quarks, assume BR(Z'→qq) = 100%



95% CL exclusions

Boosted + ISR

"Scouting" / "Trigger-level analysis"
circumvent trigger rate limitation by only recording relevant event info

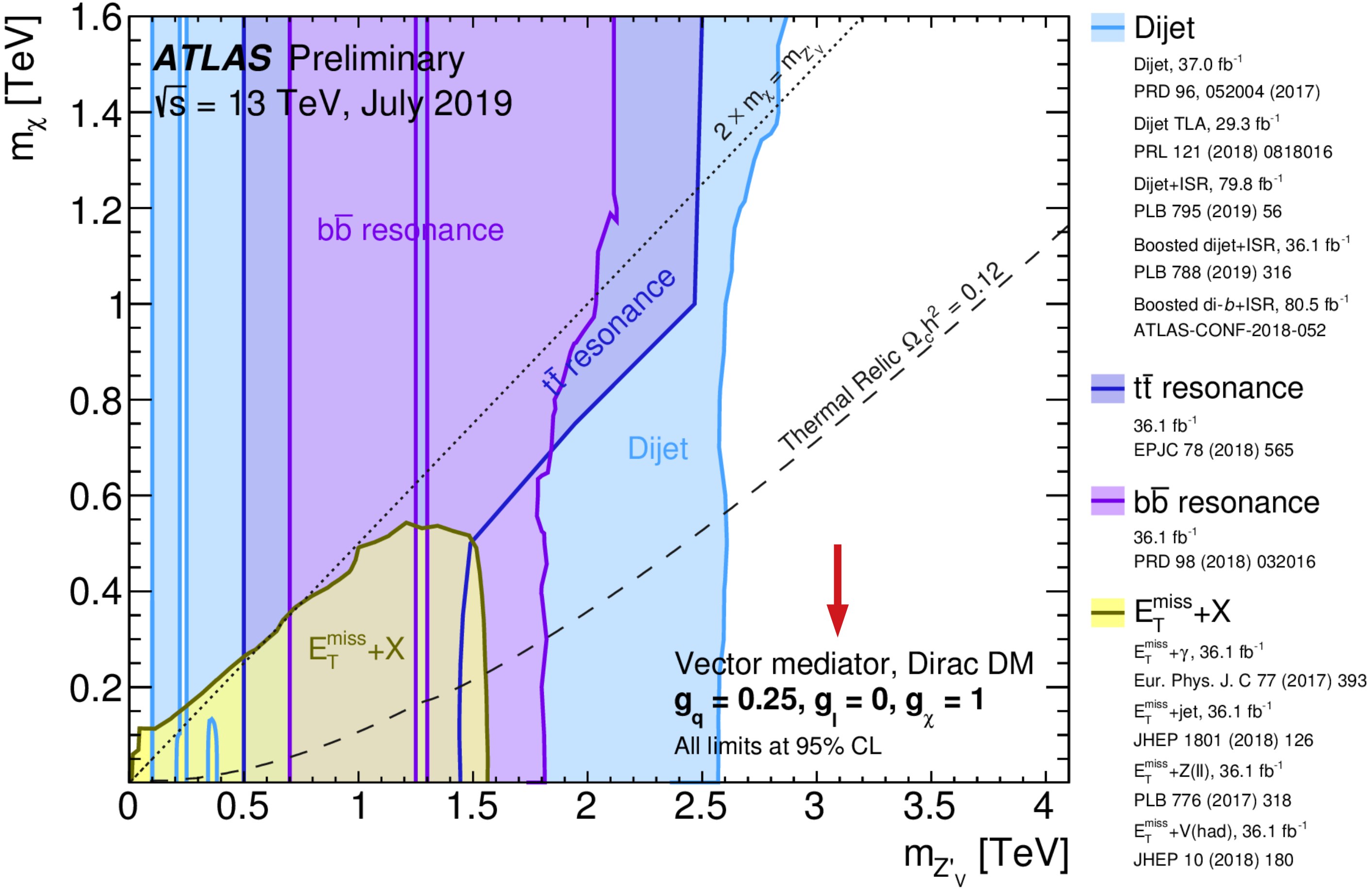
"Classic"

Can typically target couplings down to ≈ 0.1

have to correct for BR(Z'->inv)!

Putting the pieces together

Simplified model spin-1 summary: gq = 0.25

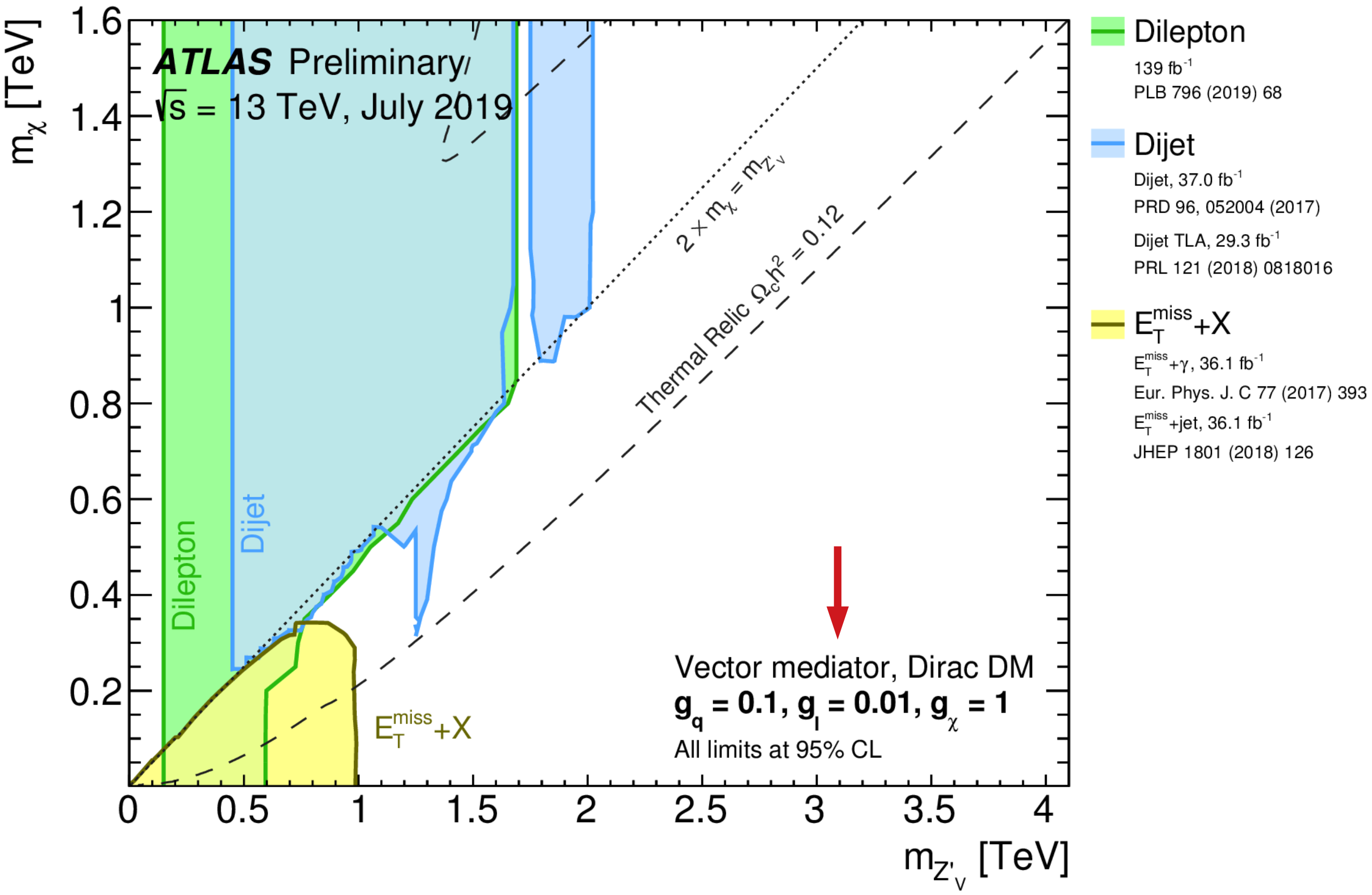


Large quark coupling

ptmiss searches:
probe mDM < mmed / 2

Mediator searches:
highest mass reach for

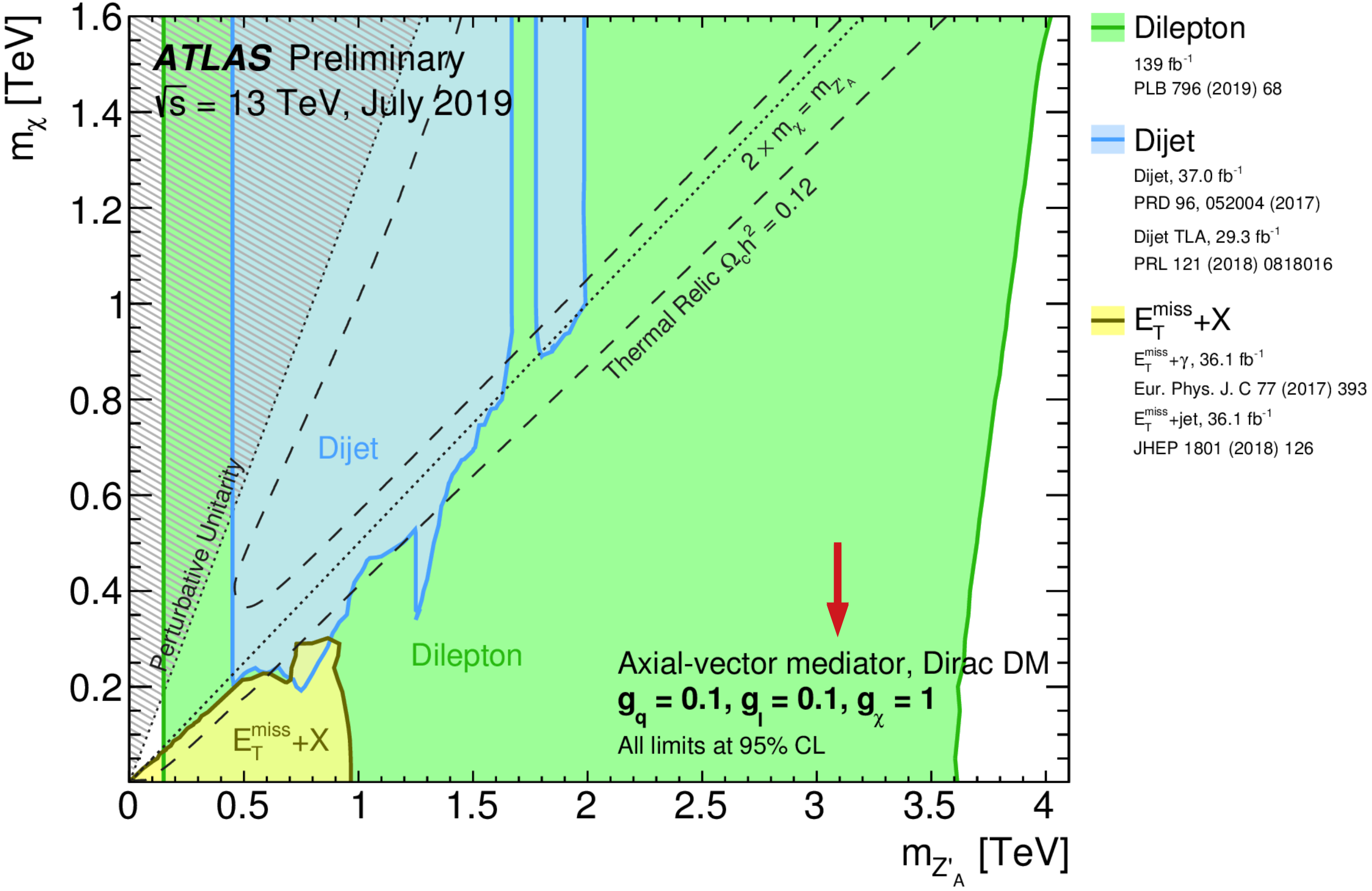
Simplified model spin-1 summary: gq = 0.1



Lower quark couplings:
Dijet scales as $\approx g_q^4$, ptmiss as $\approx g_q^2$ (naively)

For $g_q = 0.1$, mediator width is low enough that resonant dilepton search can contribute

Simplified model spin-1 summary: $g_q = 0.1, g_l = 0.1$



Increased lepton coupling: almost no effect on ptmiss and dijet, but dramatic dilepton sensitivity

Multidimensional problem, no single "best search"

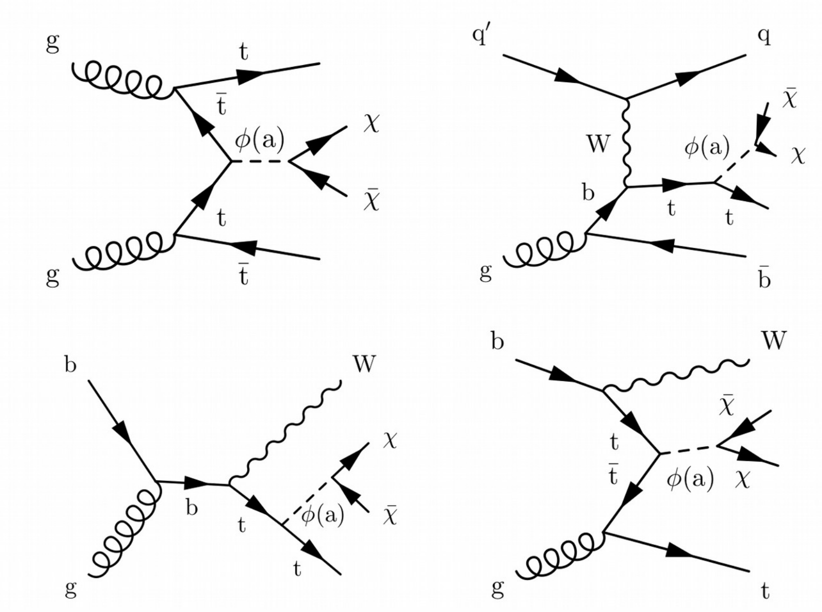
Spin-0 mediators

10.1007/JHEP03(2019)141

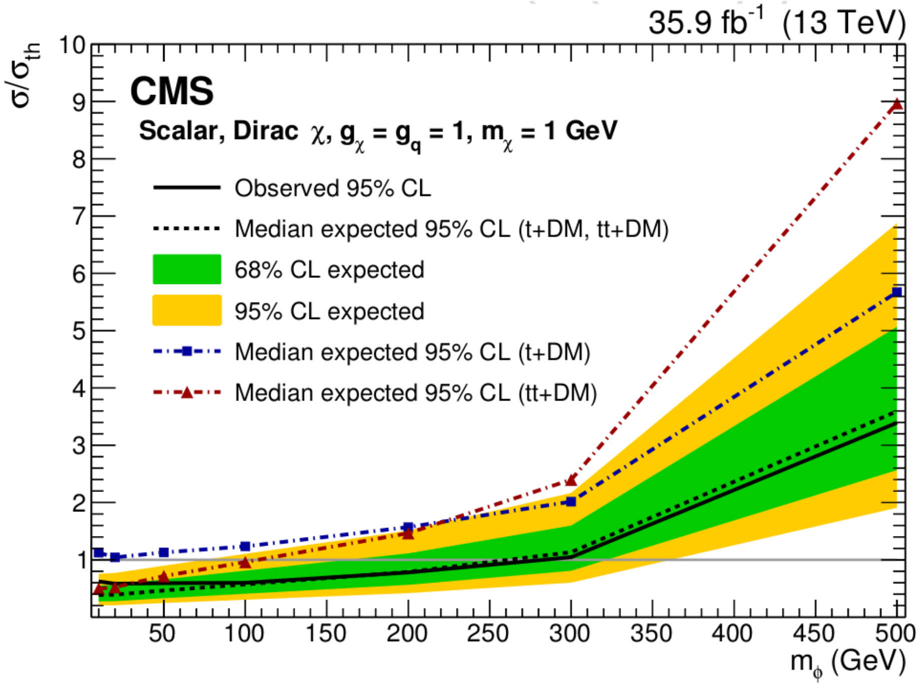
Top + DM

Minimal model: mediator is only new boson

Mass-dependent coupling → tops!



Same fit strategy as before, but categorize based on object multipl.



Previously underappreciated:
single top + MET adds significant sensitivity

Probe up to ≈ 300 GeV
(same for pseudoscalar)

Top + DM: Post-discovery potential?

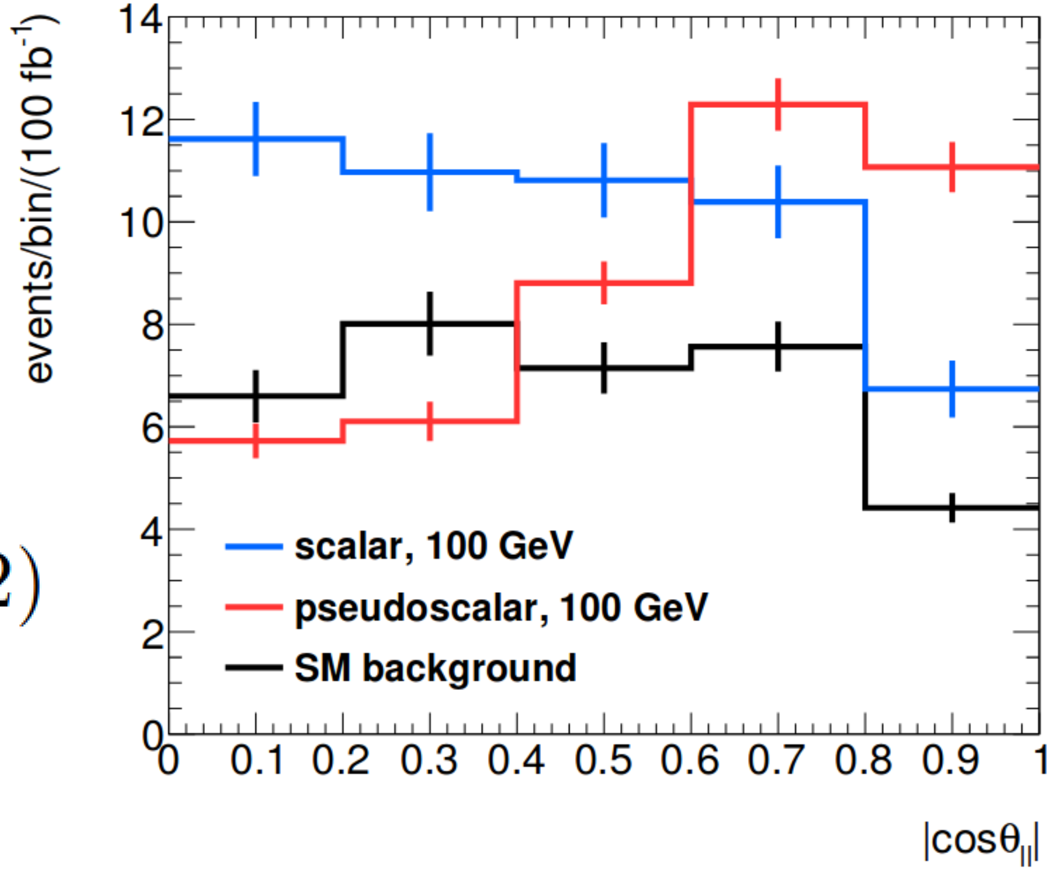
10.1007/JHEP02(2017)131

Fully leptonic channel plays ≈ no role for discovery sensitivity

Dilepton angular distribution could distinguish scalar vs pseudoscalar

$$\cos\theta_{\ell\ell} \equiv \tanh\left(\Delta\eta_{\ell\ell}/2\right)$$

Theory study, 100fb-1 @ 14 TeV

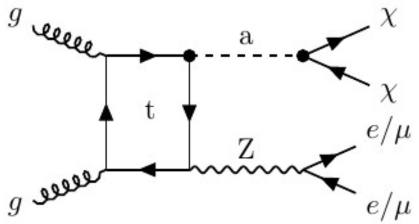


Non-minimal spin-0

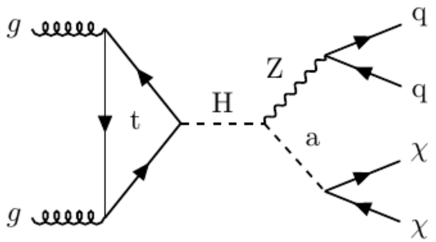
JHEP05(2017)138
JHEP 05 (2019) 142

SM Higgs easiest to observe in interactions with SM bosons. Can we also have that?

Yes! Go from

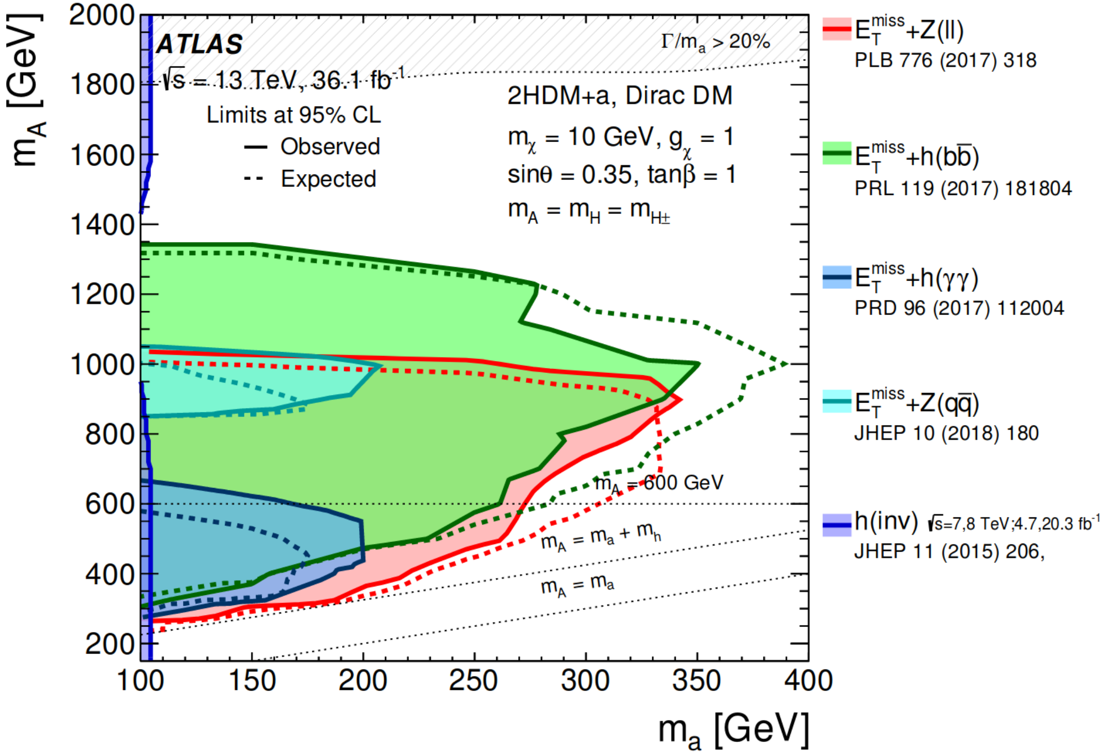


to:



"a+2HDM"

Extra complexity needed for theo. consistency



Suddenly, mono-Z and mono-H are leading, monojet does not compete

More complicated dark sectors

NB: “the dark matter candidate” not always clearly defined here

Dark photons

Image credit: M. Borsato

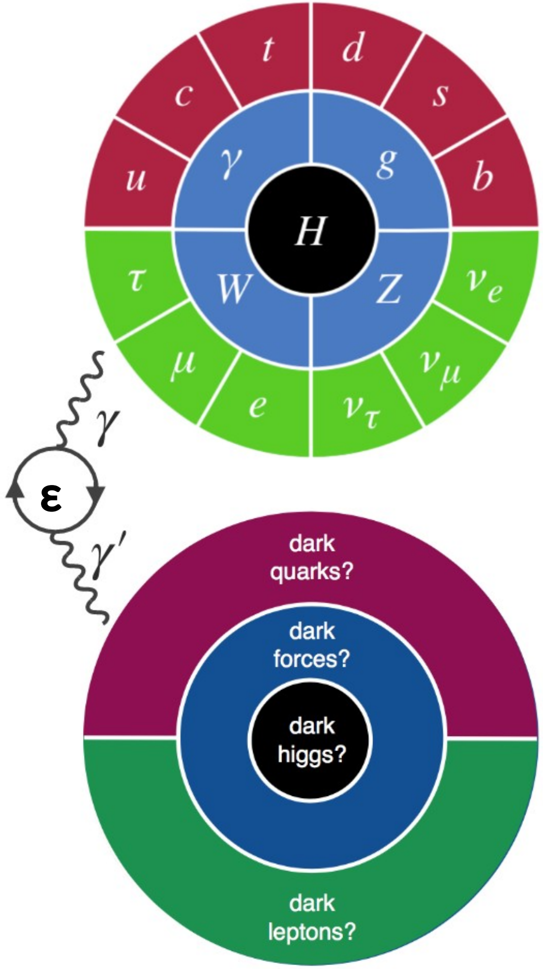
QED-like interaction among dark sector particles

Loop-induced mixing with SM photon, strength ε

Typically assumed that new U(1) is broken to avoid long-range force → massive dark photon

Two scenarios:

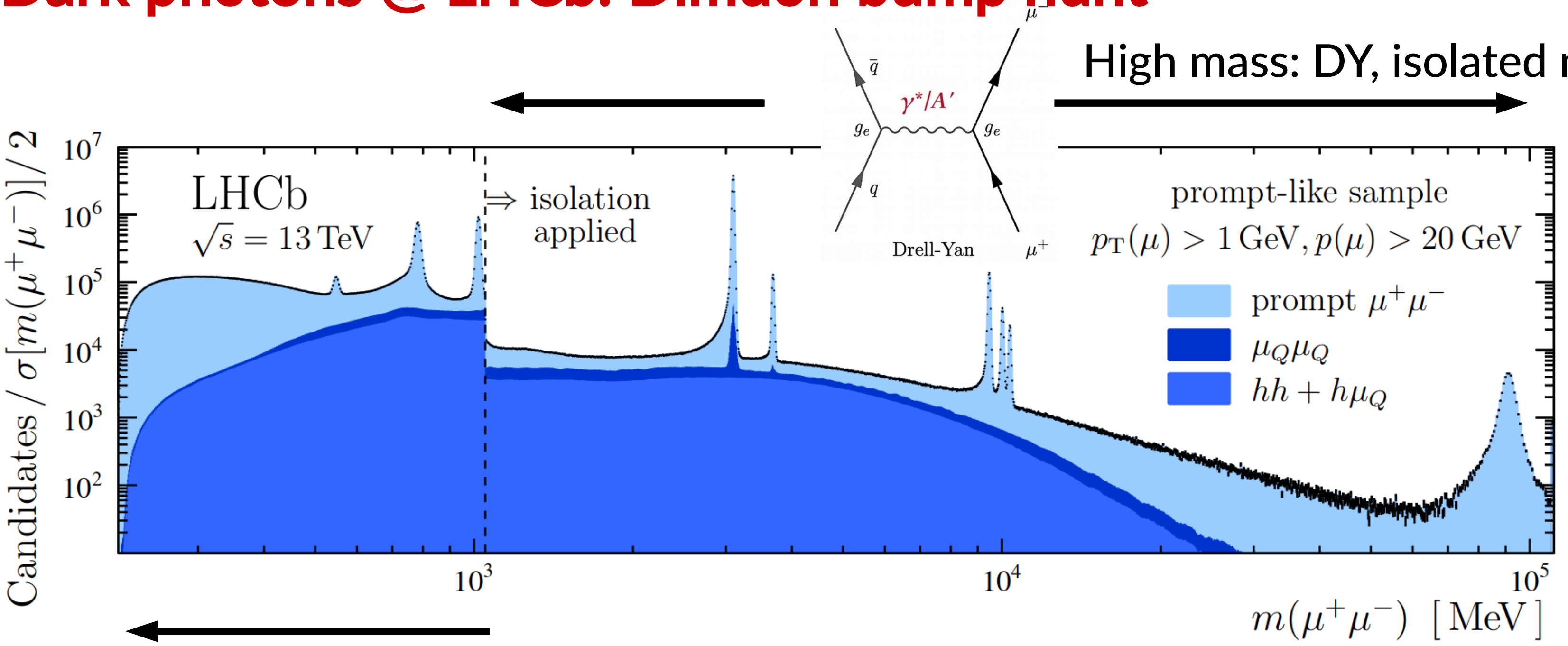
- **Dark sector heavier than γ_D → decays to SM**
- **Dark sector lighter → invisible decays**

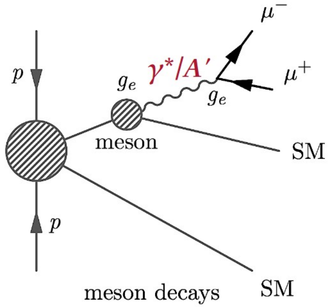


Dark photons @ LHCb: Dimuon bump hunt

10.1103/PhysRevLett.120.061801
arxiv:1910.06926

High mass: DY, isolated muons





Low mass:
meson decays
→ not isolated

$$n_{\text{ex}}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\text{ob}}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\, \epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')]$$

phase space

expected signal yield

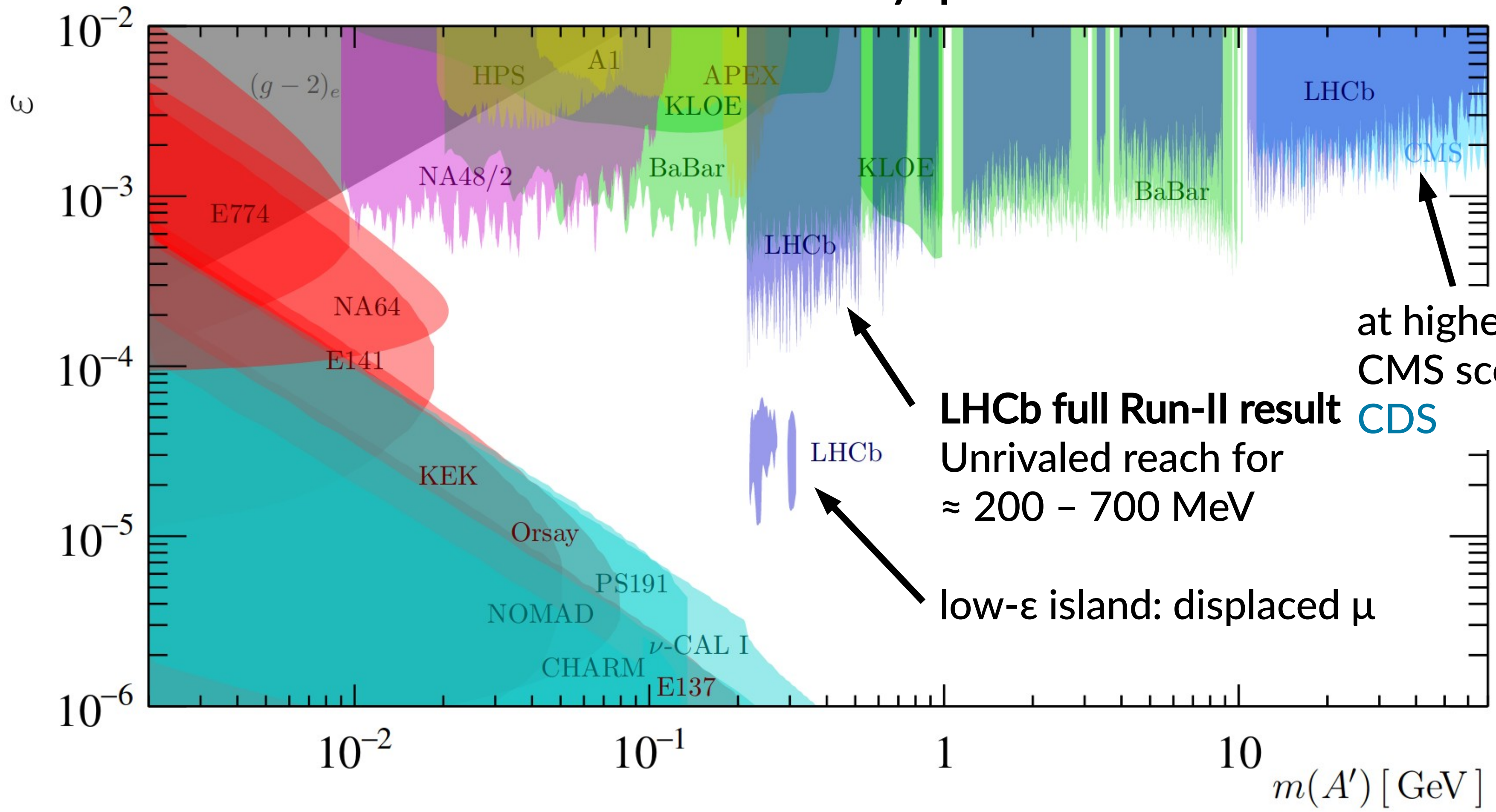
≈observed yield

efficiency corr.
== 1 for prompt

LHCb exclusion reach

10.1103/PhysRevLett.120.061801
arxiv:1910.06926

Production from meson decays proves essential



at higher mass,
CMS scouting enters
CDS

LHCb full Run-II result
Unrivaled reach for
≈ 200 – 700 MeV

low-ε island: displaced μ

Emerging jets

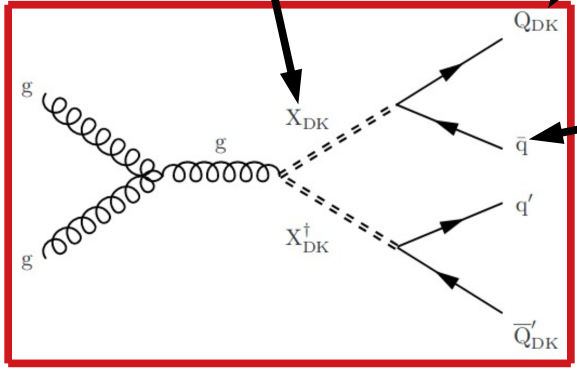
Model: 10.1007/JHEP05(2015)059, search: 10.1007/JHEP02(2019)179

Emerging jets

Posit existence of "dark QCD"
QCD-like interaction between dark sector particles

"dark quark" Q_{DK} (fermion)

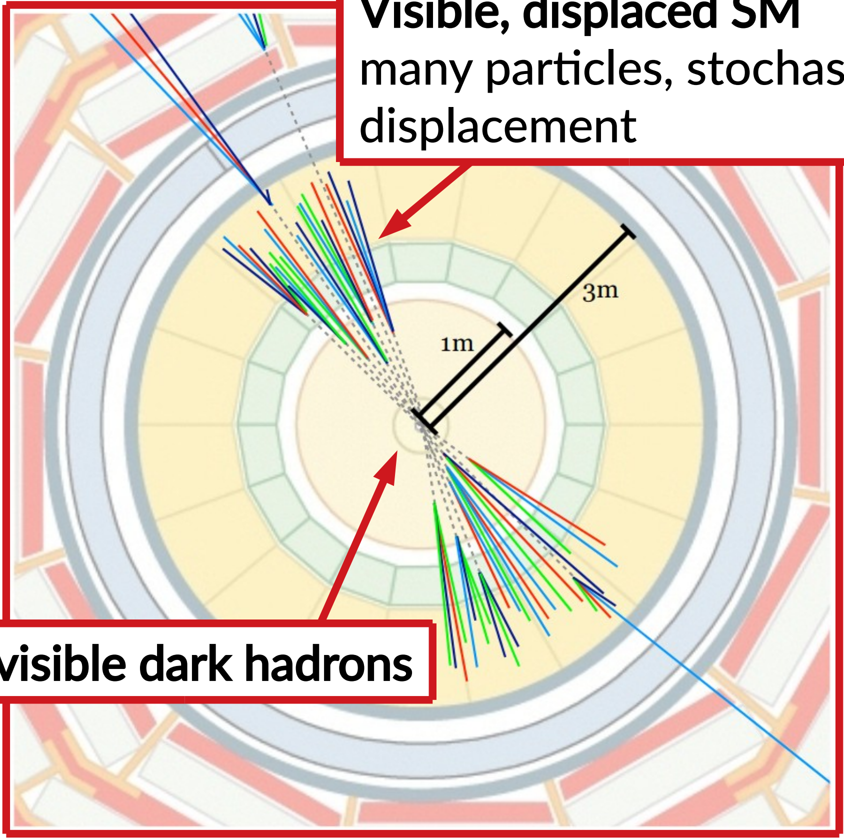
Scalar mediator X_{DK}



SM quark

Parton shower + hadronization in dark sector
At some point, hadrons decay to SM

Visible, displaced SM
many particles, stochastic displacement

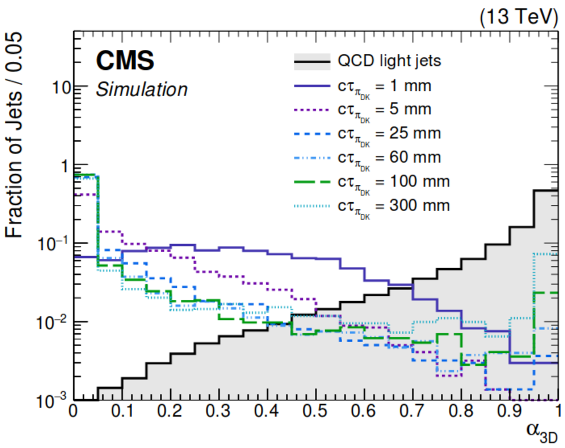


invisible dark hadrons

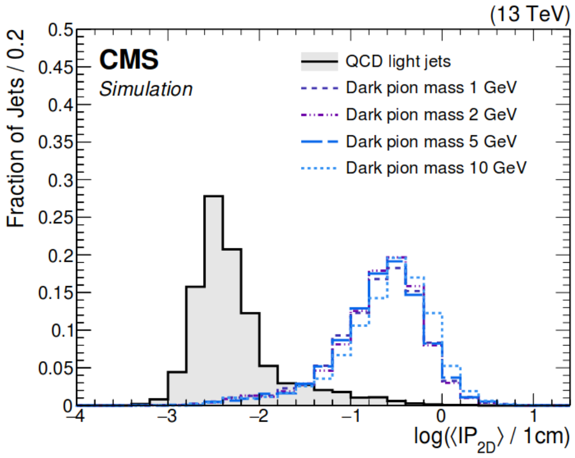
Emerging jets

10.1007/JHEP02(2019)179

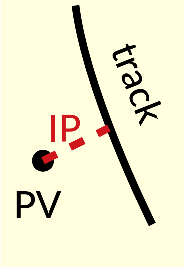
Identify jets based on properties of tracks



jet pt fraction carried by prompt particles



Median 2D impact parameter of tracks in jet



+ z displacement of tracks, IP significance

Categorize based on #tagged jets, HT, jet pts

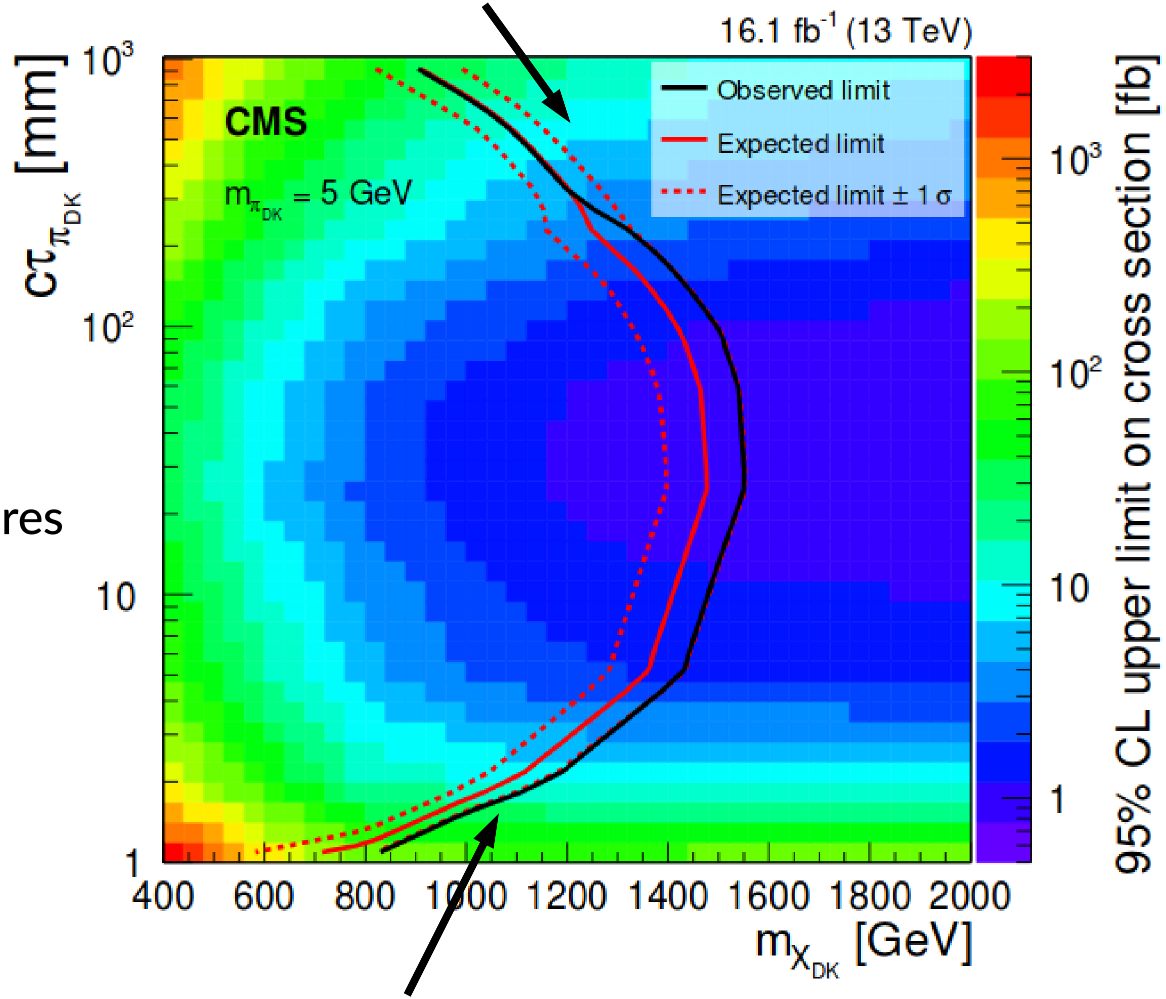
Central challenge: measure rate of SM jet mistags in control region.

Strong flavour dependence!

Emerging jets exclusion

10.1007/JHEP02(2019)179

Decays too displaced



Decays not displaced enough

Can probe wide range of m vs cτ, but that is secondary

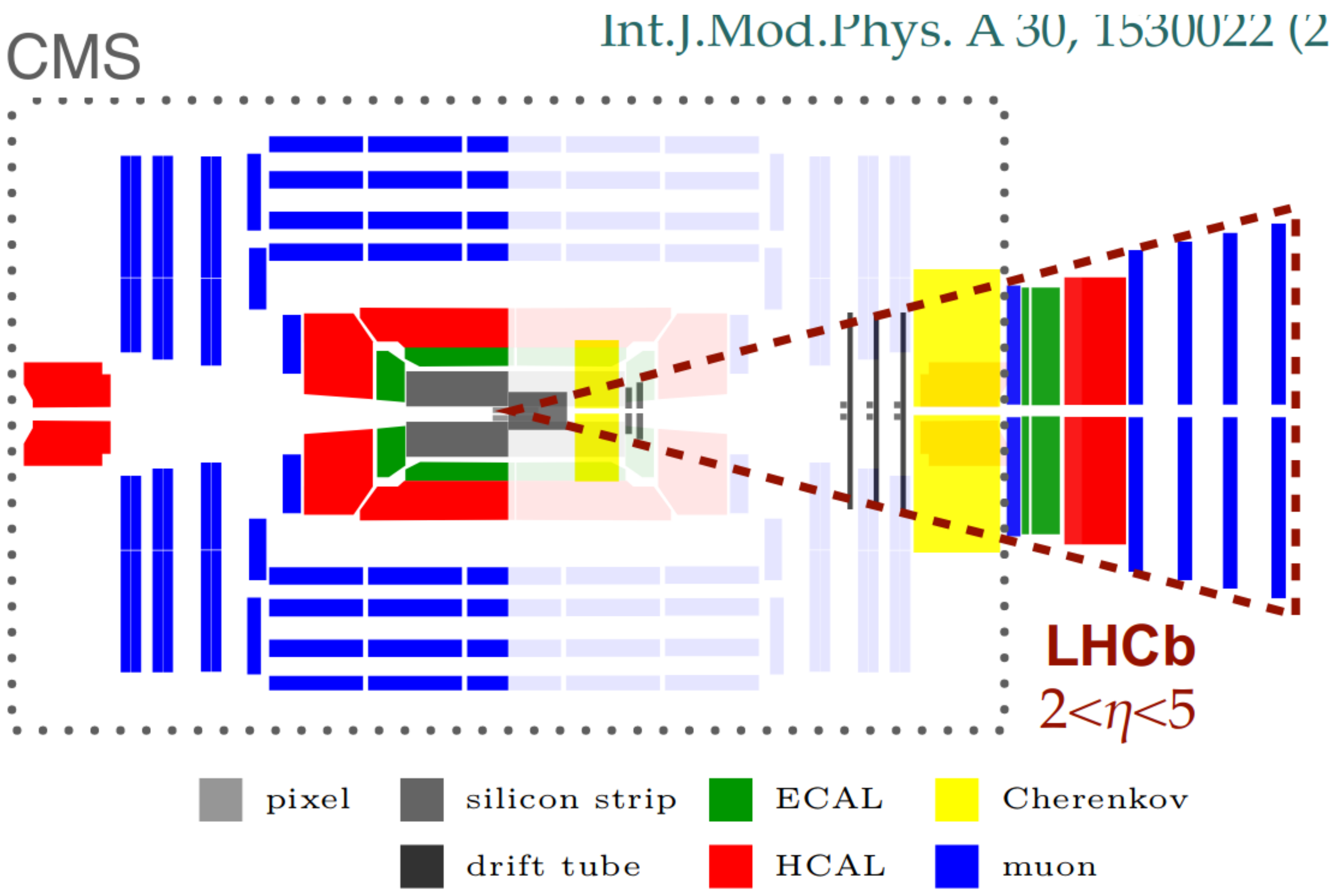
Most important: Dark sector signatures can be **very** exotic. Cover them!

Conclusions

Summary + conclusion

- LHC has mature DM search program
- Many channels, (almost) all of which are necessary
- Standard searches: Full Run-II incoming, after that: no more easy mass gains!
  → Focus on driving down coupling, today's constraints O(0.1) still loose
- Increasing activity in more exotic scenarios. Leave no stone unturned!

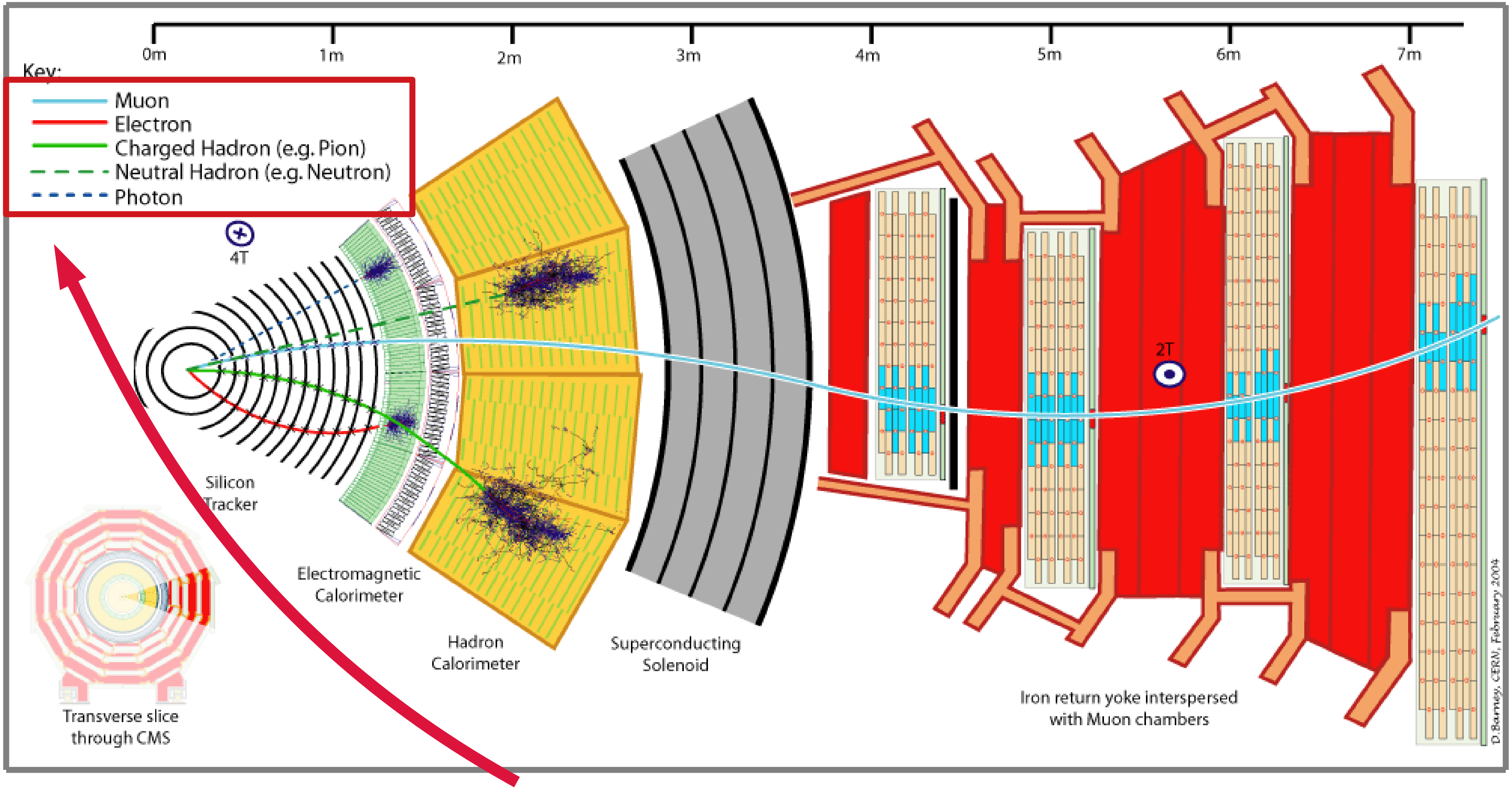
Backup


Int.J.Mod.Phys. A 30, 1530022 (2
CMS
LHCb
2<η<5
pixel
silicon strip
ECAL
Cherenkov
drift tube
HCAL
muon

Emerging jet categorization

Set number	H_T	$p_{T,1}$	$p_{T,2}$	$p_{T,3}$	$p_{T,4}$	p_T^{miss}	$n_{EMJ}(\geq)$	EMJ group	no. models
1	900	225	100	100	100	0	2	1	12
2	900	225	100	100	100	0	2	2	2
3	900	225	100	100	100	200	1	3	96
4	1100	275	250	150	150	0	2	1	49
5	1000	250	150	100	100	0	2	4	41
6	1000	250	150	100	100	0	2	5	33
7	1200	300	250	200	150	0	2	6	103
8	900	225	100	100	100	0	2	7	SM QCD-enhanced
9	900	225	100	100	100	200	1	8	

Table 3. The seven optimized selection sets used for this search, and the two SM QCD-enhanced selections (sets 8 and 9) used in tests of the background estimation methods. The headers of the columns are: the scalar p_T sum of the four leading jets (H_T) [GeV], the requirements on the p_T of the jets ($p_{T,i}$) [GeV], the requirement on p_T^{miss} [GeV], the minimum number of the four leading jets that pass the emerging jet selection (n_{EMJ}), and the EMJ criteria group described in table 2. The last column is the total number of models defined in table 1 for which the associated selection set gives the best expected sensitivity.



"Particle Flow" (PF): Reconstruct **particle candidates** from combined sub-detector information.

Energy correlation functions

https://arxiv.org/pdf/1710.00159.pdf

pairwise angles among n-jet constituents [63]. In particular, the 2-point (${}_1e_2$) and 3-point (${}_2e_3$) correlation functions are defined as:

$$ {}_1e_2 = \sum_{1 \le i < j \le n} z_i z_j \Delta R_{ij} \,, \tag{1} $$

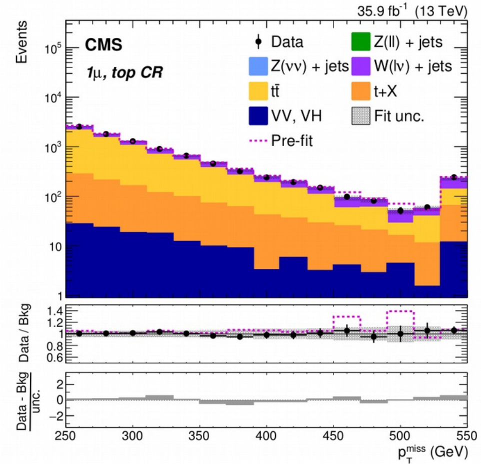
$$ {}_2e_3 = \sum_{1 \le i < j < k \le n} z_i z_j z_k \min\{\Delta R_{ij}\Delta R_{ik}, \Delta R_{ij}\Delta R_{jk}, \Delta R_{ik}\Delta R_{jk}\} \,, \tag{2} $$

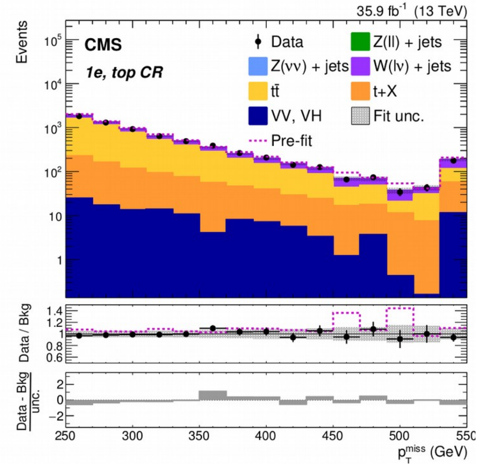
where z_i represents the energy fraction of the constituent i in the jet and ΔR_{ij} is the angular separation between constituents i and j. For a two-prong structure, signal jets have a stronger 2-point correlation than a 3-point correlation. The discriminant variable N_2^1 is then constructed via the ratio:

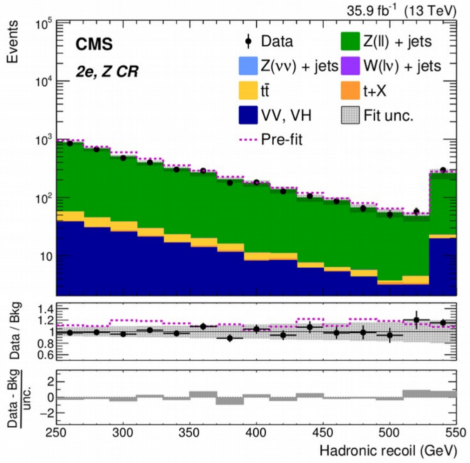
$$ N_2^1 = \frac{{}_2e_3}{({}_1e_2)^2} \,. \tag{3} $$

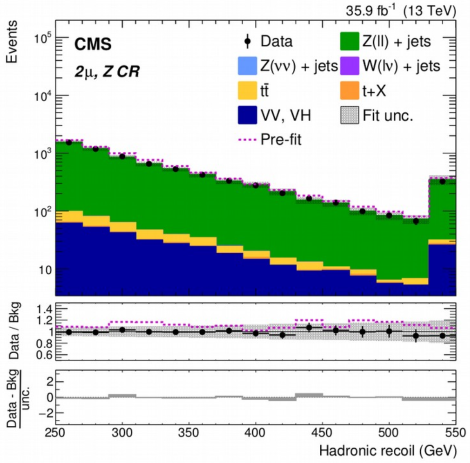
Top + DM: Control regions for hadronic selection

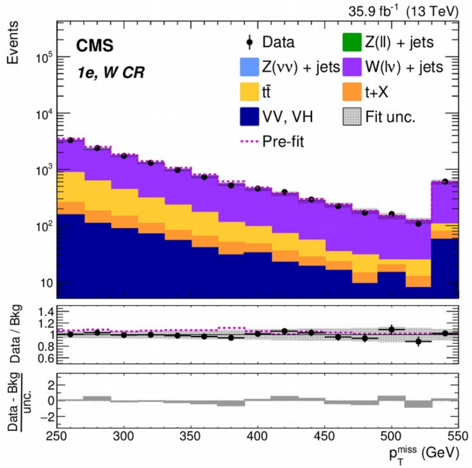
	Single-lepton CRs		All-hadronic CRs		
	CR $t\bar{t}(2\ell)$	CR $W(\ell\nu)$	CR $t\bar{t}(1\ell)$	CR $W(\ell\nu)$	CR $Z(\ell\ell)$
n_b	≥ 1	$=0$	≥ 1	$=0$	$=0$
n_{lep}	$=2$	$=1$	$=1$	$=1$	$=2$
n_{jet}	≥ 2	≥ 2	≥ 3	≥ 3	≥ 3
p_T^{miss}	>160 GeV	>160 GeV	>250 GeV	>250 GeV	>250 GeV
m_T	—	>160 GeV	<160 GeV	<160 GeV	—
$\min\Delta\phi(j_{1,2}, \vec{p}_T^{miss})$	—	—	>1.0 rad.	—	—
$m_{\ell\ell}$	—	—	—	—	$[60, 120]$ GeV

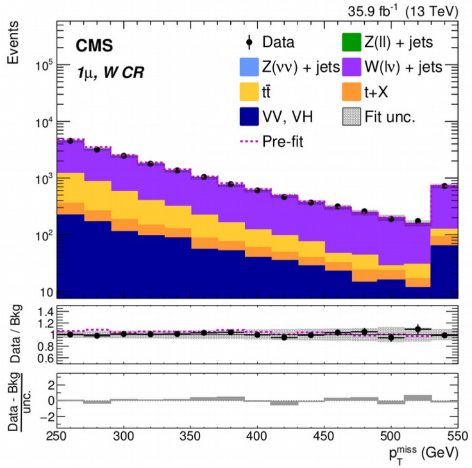






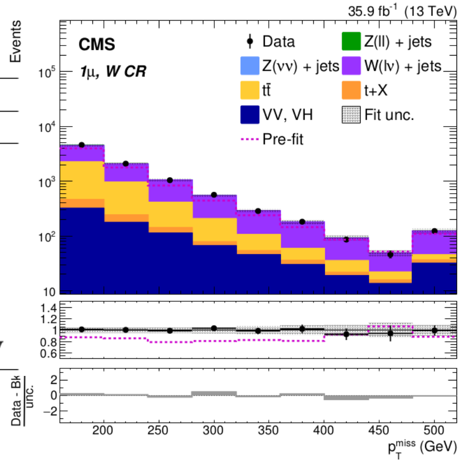


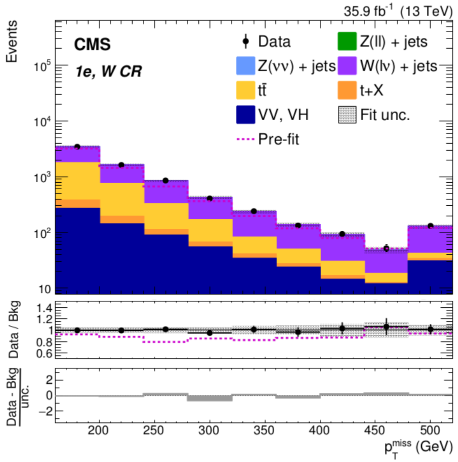


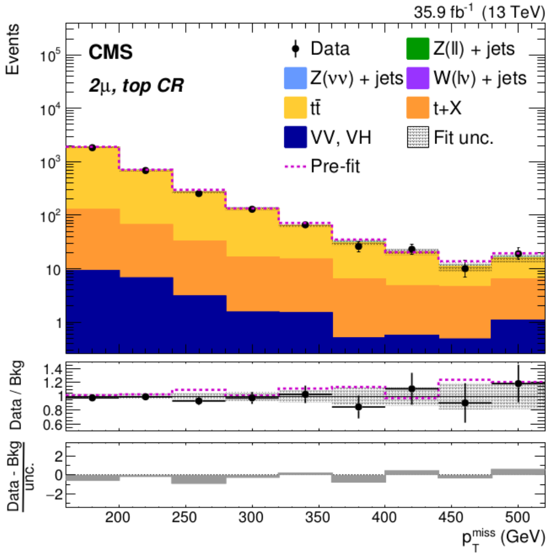


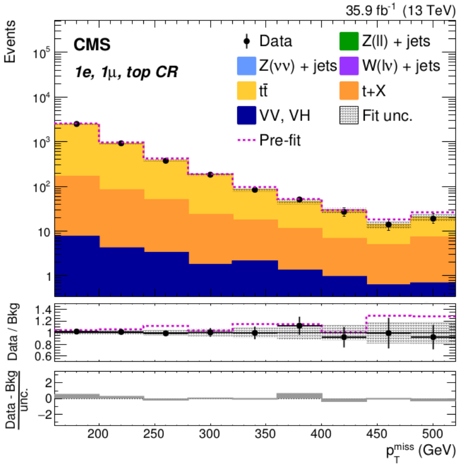
Top + DM: Control regions for leptonic selection

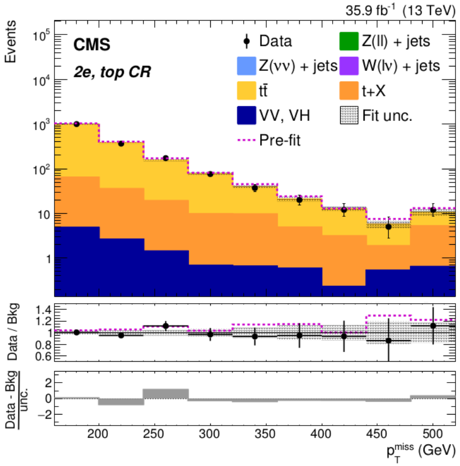
	Single-lepton CRs		All-hadronic CRs		
	CR $t\bar{t}(2\ell)$	CR $W(\ell\nu)$	CR $t\bar{t}(1\ell)$	CR $W(\ell\nu)$	CR $Z(\ell\ell)$
n_b	$\geq$1	=0	$\geq$1	=0	=0
n_{lep}	=2	=1	=1	=1	=2
n_{jet}	$\geq$2	$\geq$2	$\geq$3	$\geq$3	$\geq$3
p_T^{miss}	>160 GeV	>160 GeV	>250 GeV	>250 GeV	>250 GeV
m_T	—	>160 GeV	<160 GeV	<160 GeV	—
$\min\Delta\phi(j_{1,2}, \vec{p}_T^{miss})$	—	—	>1.0 rad.	—	—
$m_{\ell\ell}$	—	—	—	—	[60, 120] GeV





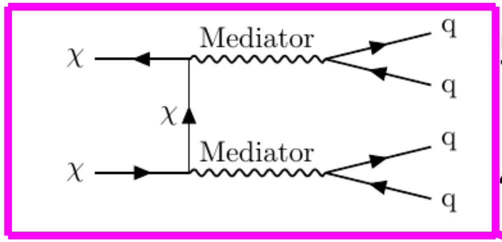






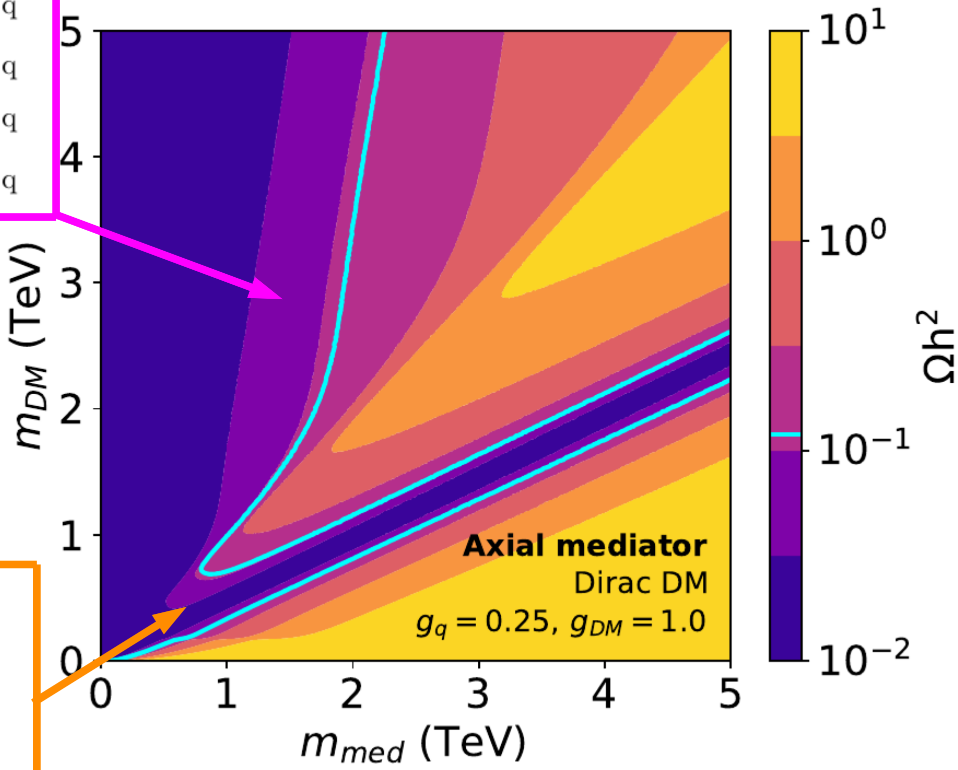
Relic density for spin-1 mediator

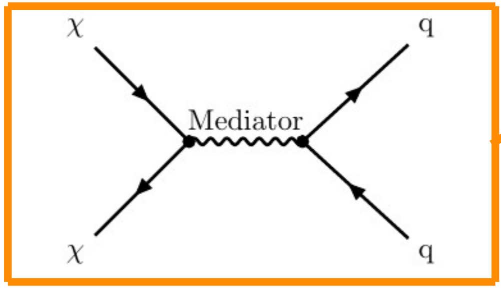
Check relic density as a function of mediator and dark matter particle mass



Density low where annihilation efficient, high otherwise
→ features correspond to kinematic thresholds

≈ correct parameter combinations exist!

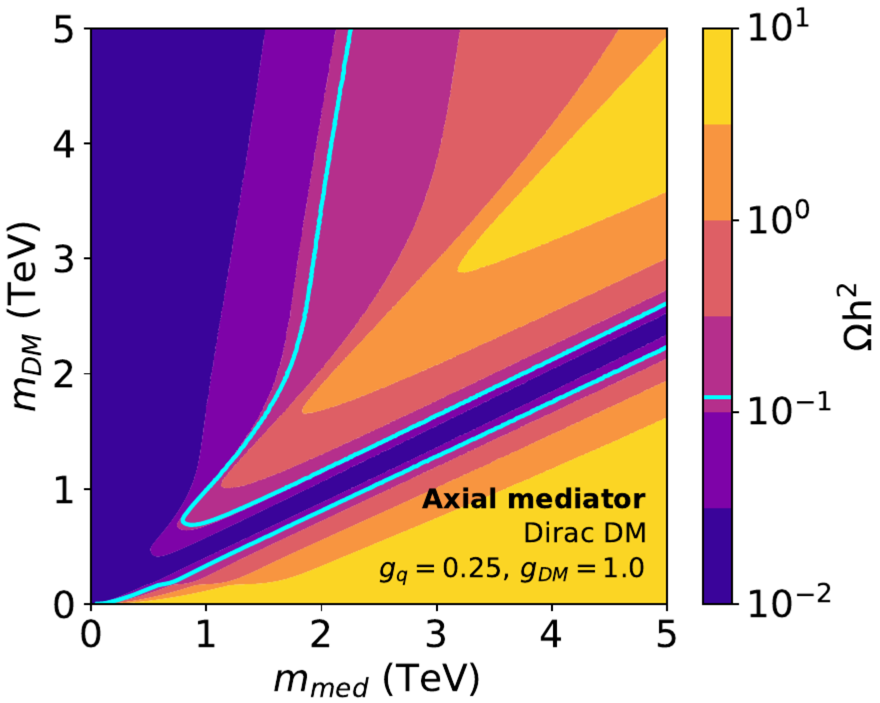


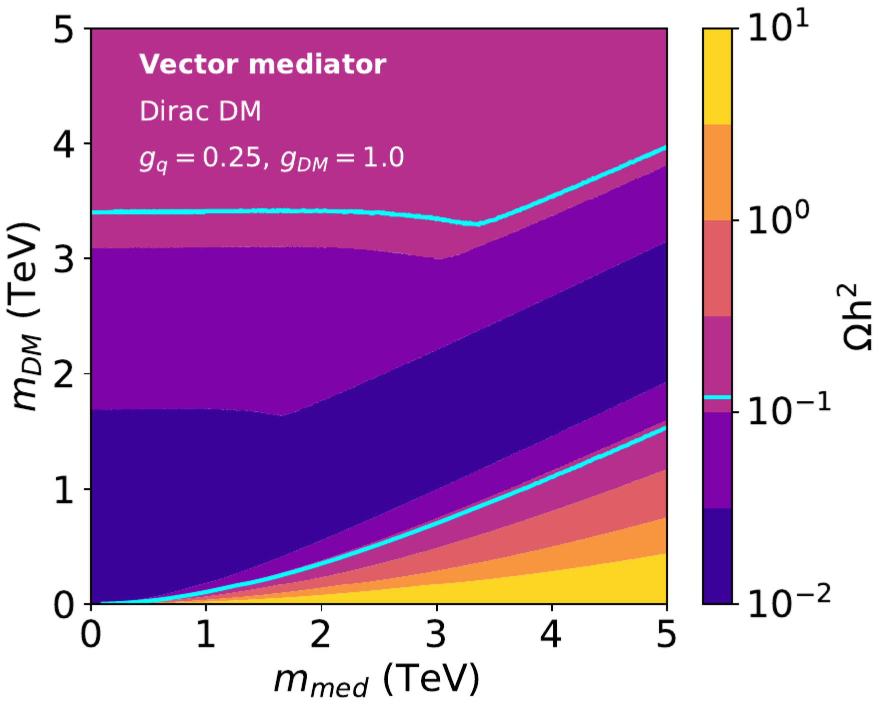


Beware of model dependence!

$$\mathcal{L} \subset \sum_q Z'_\mu \bar{q}\gamma^\mu (g_q^V - g_q^A \gamma_5) q - Z'_\mu \bar{\chi}\gamma^\mu (g_{DM}^V - g_{DM}^A \gamma_5)\chi$$

Same coupling values, but different coupling structure





Both cases look identical at the LHC!