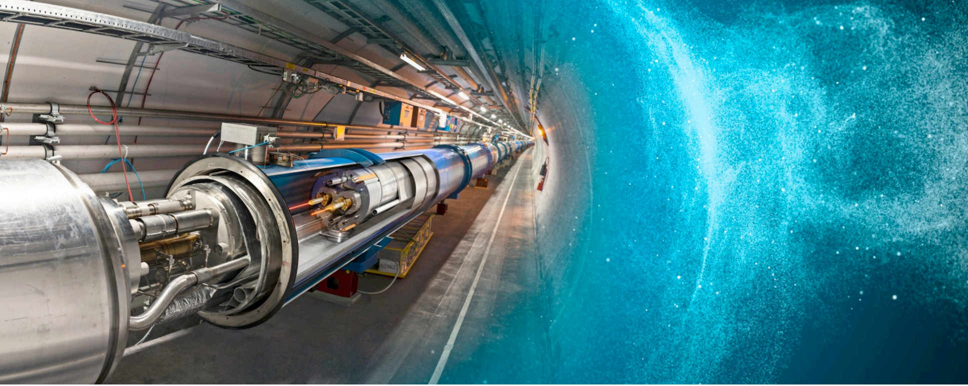


Searches for new physics in exotic signatures at the LHC

Lesya Shchutska
ETH Zürich
CMS Collaboration

LTP/PSI Thursday Colloquium
October 11, 2018

European Research Council
Established by the European Commission

LHC pace up to now

Beam energy rise:

5 fb^{-1} @ 7 TeV (2011)

25 fb^{-1} @ 8 TeV (2012)

3 fb^{-1} @ 13 TeV (2015)

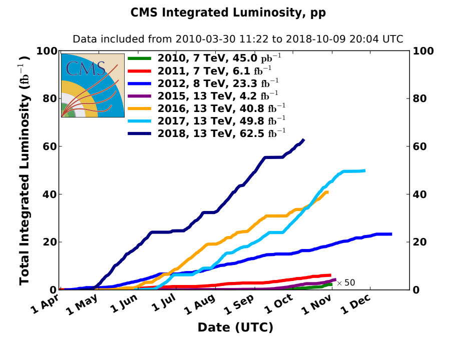
Huge luminosity jump:

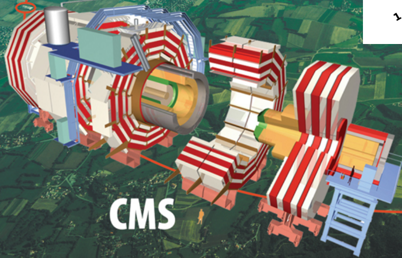
40 fb^{-1} @ 13 TeV (2016)

50 fb^{-1} @ 13 TeV (2017)

60 fb^{-1} @ 13 TeV (2018)

Next: intellectual rise?





A general purpose detector

Higgs boson discovery (2012)

Wide physics programme

8 years and 1 week ago:

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2010-035
2010/10/04

CMS-EXO-10-010

October 4, 2010

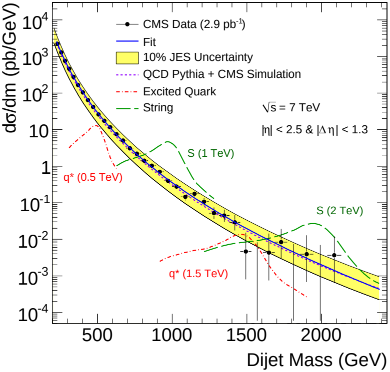
First CMS Exotica paper

2.9 pb^{-1} of 7 TeV pp collisions

dijet mass spectrum up to 2 TeV

Search for Dijet Resonances in 7 TeV *pp* Collisions at CMS

The CMS Collaboration*



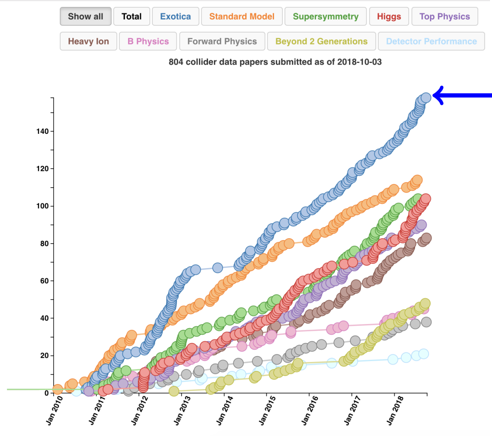
Abstract

A search for narrow resonances in the dijet mass spectrum is performed using data corresponding to an integrated luminosity of 2.9 pb^{-1} collected by the CMS experiment at the Large Hadron Collider. Upper limits at the 95% confidence level are presented on the product of the resonance cross section, branching fraction into dijets, and acceptance, separately for decays into quark-quark, quark-gluon, or gluon-gluon pairs. The data exclude new particles predicted in the following models at the 95% confidence level: string resonances, with mass less than 2.50 TeV, excited quarks, with mass less than 1.58 TeV, and axigluons, colorons, and E_6 diquarks, in specific mass intervals. This extends previously published limits on these models.

Submitted to Physical Review Letters

arXiv:1010.0203

Productive period

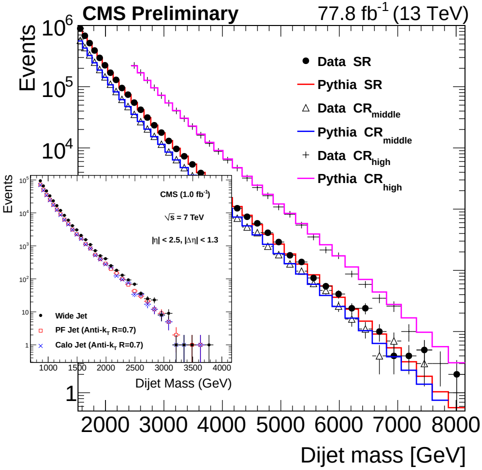


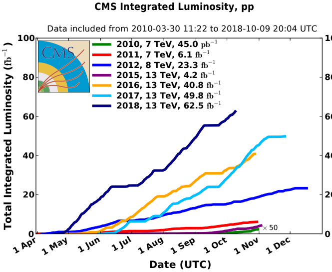
158 Exotica papers (CMS)

Impossible to cover everything! Concentrate on recent milestones and new strategies instead

http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

7→8→13 TeV: excitement period!





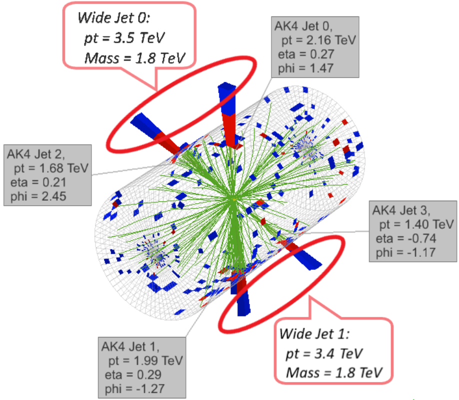
7 TeV → 13 TeV

$1.0\ \text{fb}^{-1} \rightarrow \sim 100\ \text{fb}^{-1}$

in m(X): 3.5 TeV → 8 TeV!

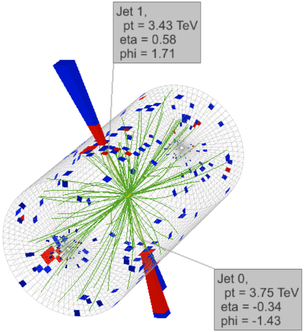
pp collisions we have: events with m = 8 TeV

dijet mass = 8.0 TeV



CMS Experiment at LHC, CERN
Data recorded: Sat Oct 28 12:41:12 2017 EEST
Run/Event: 305814 / 971086788
Lumi section: 610
Dijet Mass: 8 TeV

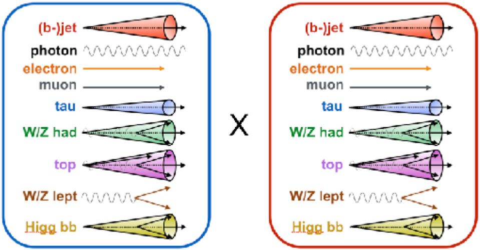
dijet mass = 7.9 TeV



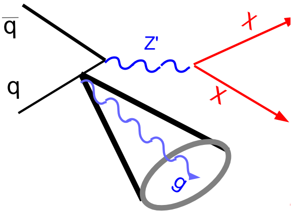
CMS Experiment at LHC, CERN
Data recorded: Mon Aug 7 06:49:37 2017 EEST
Run/Event: 300575 / 65453124
Lumi section: 39
Dijet Mass: 7.9 TeV

158 papers on:

Resonances: all possible combinations of particles

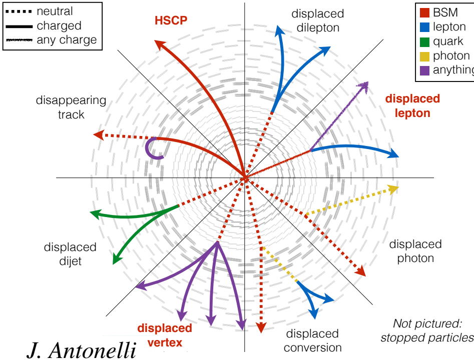


Dark matter: X + missing transverse energy



Various signatures, often common goal:
e.g. dark matter signals in the collider

Long-lived and unconventional signatures:
heavy, long-lived, charged particles;
neutral particles decaying in the detector



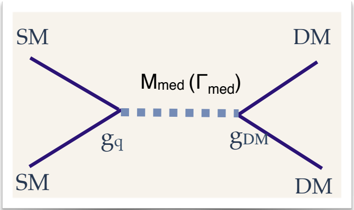
J. Antonelli

Dijets and dark matter relation at the LHC

Move from effective field theory to simplified dark matter models descriptions:

- add a mediator in DM production
- constraints on mediator translate to stringent constraints on the DM phase space!

See e.g.
arXiv:1407.8257
arXiv:1507.00966
arXiv:1603.04156



s-channel

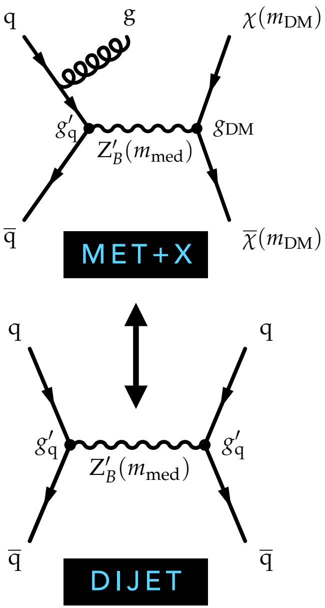
Define simplified model with (minimum) 4 parameters	
Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

DM	
Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar

arXiv:1407.8257 arXiv:1507.00966 arXiv:1603.04156

Dark matter interpretations



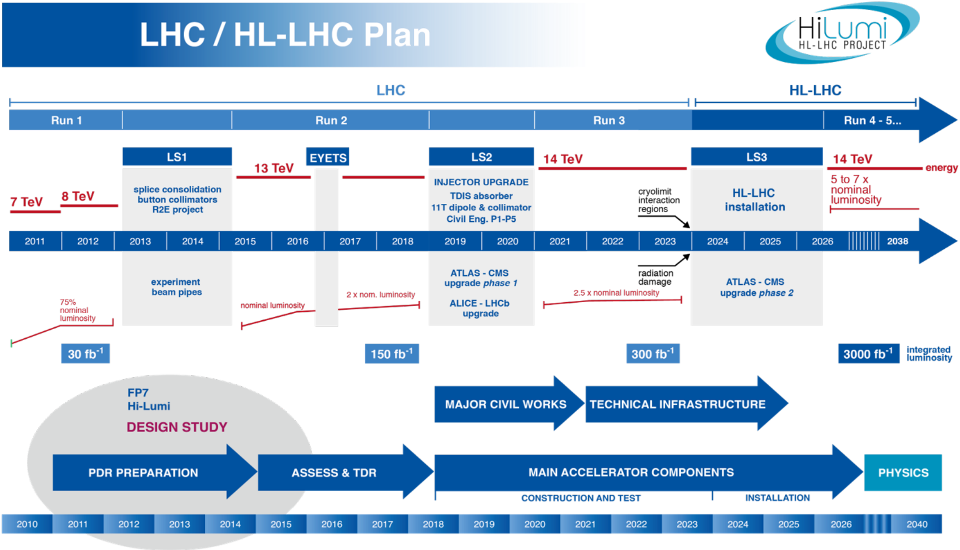
Typical signatures at the LHC:

- mono-X+$E_{\rm T}^{\rm miss}$ (X = jet, photon, W, Z, H, t)
  - jet: generally the most powerful
  - photon: first used for the DM searches
  - W: distinguish DM coupling to u/d-quarks
  - Z: clean signature
  - H: Higgs portal
  - t: coupling to tops
- di-X resonance (X = jet, photon, W, Z, H, t)
  - X = jet is naturally connected with the DM@LHC
  - others are more model-dependent

4D parameter space: $g_{\rm DM}$, $g_{\rm q}$, $m_{\rm DM}$, m_{med}:

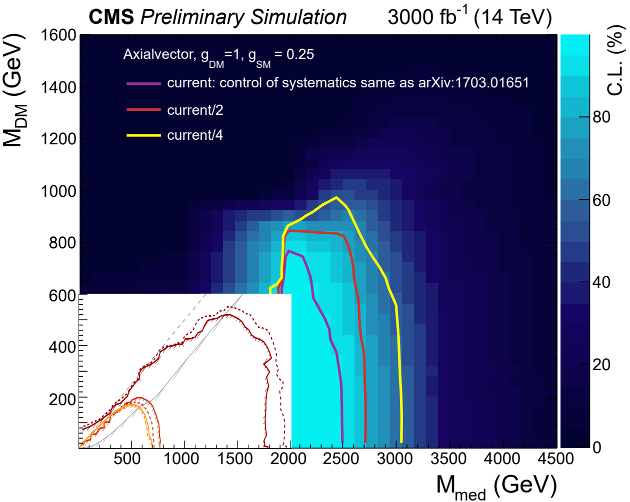
- masses $m_{\rm DM}$, m_{med} pushed by energy rise
- couplings $g_{\rm DM}$, $g_{\rm q}$ require luminosity

Waiting period?



$3000\ fb^{-1}$ are there in 2038

Example of gain with the HL-LHC: Monojet

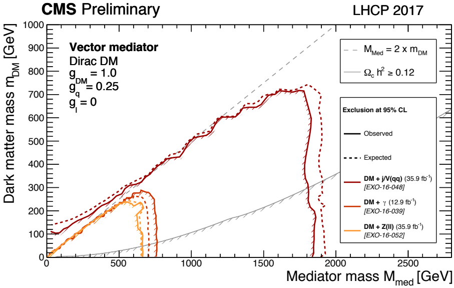


- now: mediator mass up to 1.7 TeV and dark matter mass up to 0.5 TeV
- in 20 years (with 3000/fb): $m_{med} \sim$ 2.5-3.0 TeV, $m_{\rm DM} \sim$ 0.8-1.0 TeV depending on the systematics treatment $\Longrightarrow$ Meanwhile, explore other possibilities!

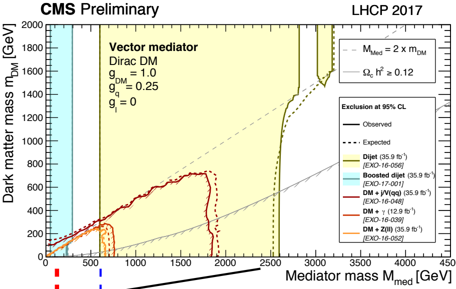
CMS-PAS-FTR-16-005

$X + E_T^{miss}$ and resonances searches complementarity

mono-X + E_T^{miss} searches:



+ dijet resonance searches



limited by $\sqrt{s}$

limited by trigger

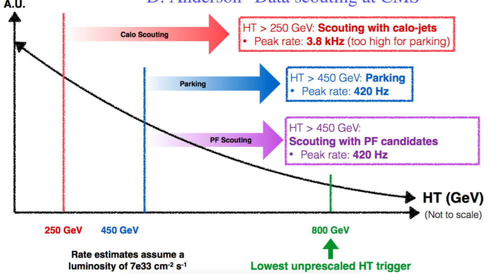
new ideas and techniques to cover the gaps

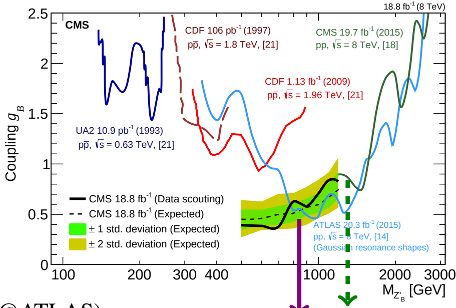
CMS-PAS-EXO-16-056

Overcoming high trigger rates

An approach already tested in Run 1: store only objects reconstructed with trigger

D. Anderson "Data scouting at CMS"





usual HT trigger

PF scouting result

Data scouting concept (*Trigger-level analysis*@ATLAS):

- physics objects are reconstructed online
- the HLT objects are saved in a minimal format
- no additional offline reconstruction

Reduce event size from 500 kB/event to

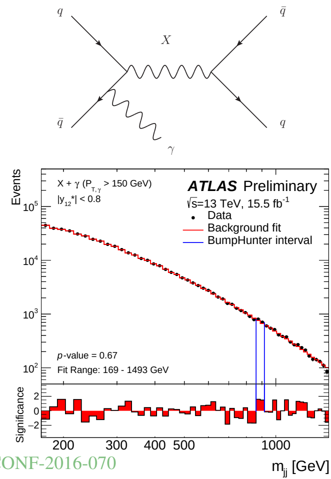
- 10 kB/event: PF scouting, $H_T > 450$ GeV (CPU-limited)
- in Run 2: 1.5 kB/event: Calo scouting, $H_T > 250$ GeV

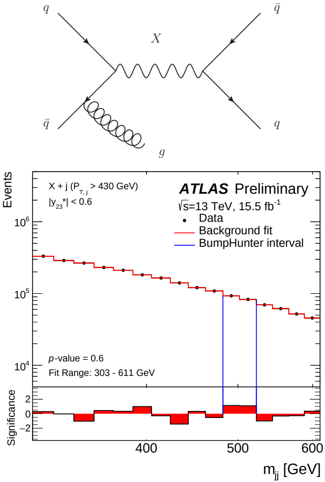
arXiv:1604.08907

New ideas: employing ISR to go lower...

Sacrifice in coupling sensitivity to go lower in mass:
trigger on initial-state radiation (jet or photon) and search for recoiling dijets

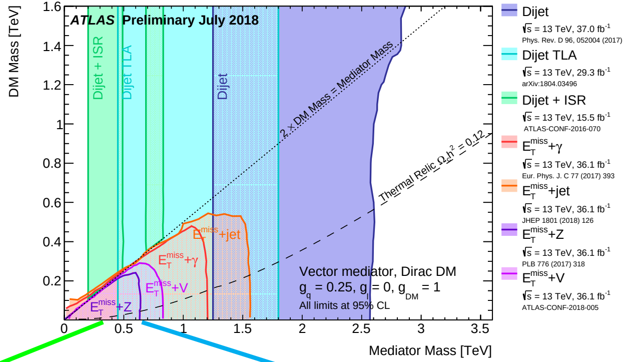
- ISR γ threshold: $E_\mathrm{T} > 150$ GeV
- ISR jet threshold: $E_\mathrm{T} > 430$ GeV





ATLAS-CONF-2016-070

Closing the gaps: ATLAS searches



Dijet + ISR:

- γ ISR: masses between 200 and 1000 GeV
- jet ISR: masses between 450 and 1000 GeV

Trigger-level analysis (**Dijet TLA**):

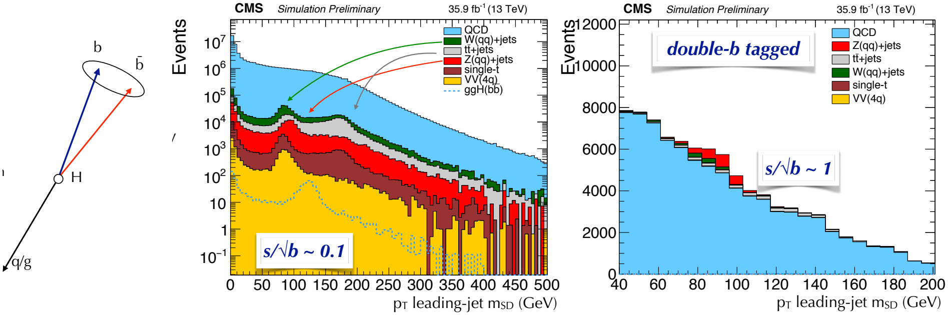
- masses between 450 and 1800 GeV

ATLAS-CONF-2016-070 *Phys. Rev. Lett. 121 (2018) 081801*

Proof of concept: ISR as a discovery tool

H$\to$ b$\bar{\text{b}}$ in gluon fusion: the QCD background is immense ($\times 10^7$ H rate)!
ISR tagging removes jet pairing issue, and allows to look for a mass peak:

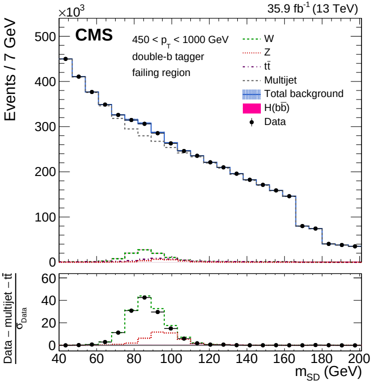
- ISR jet threshold: $p_{\text{T}} > 450$ GeV
- asking for double b-tagged peak reduces QCD by orders of magnitude



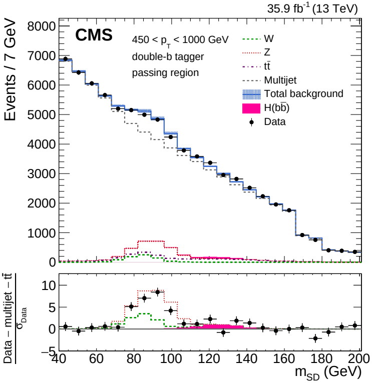
Phys. Rev. Lett. 120 (2018) 071802

Proof of concept: ISR as a discovery tool

anti-double-b tagged: $W \rightarrow q\bar{q}'$



double-b tagged: $Z \rightarrow b\bar{b}$ and H!



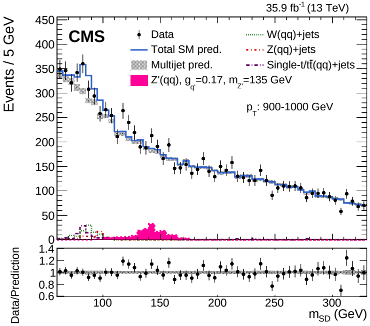
- $Z \rightarrow b\bar{b}$ observation with 5.1σ
- Inclusive $H \rightarrow b\bar{b}$ is seen with 1.5σ

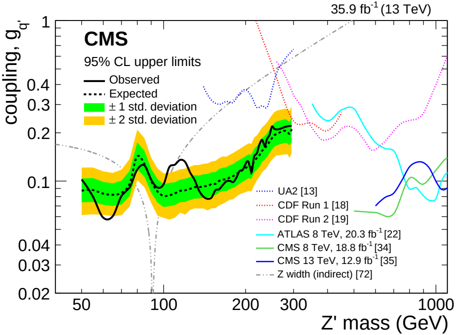
Phys. Rev. Lett. 120 (2018) 071802

ISR trick in searches: ISR+merged jet

Going even lower in mass: dijets start to merge into one jet with substructure

- exploring masses between 50 and 300 GeV
- a challenge: simple bump-hunt does not work anymore (SM Z boson is in the range)
- use “fail” substructure variable sideband to estimate SM bkg shape and yield

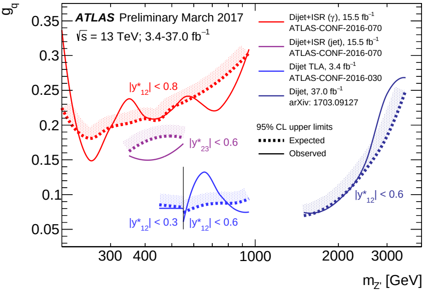


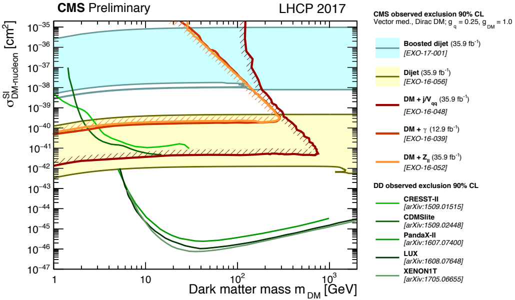


Local (global) significance 2.9σ (2.2σ) at 115 GeV

arXiv:1710.00159

Remembering about other dimensions: coupling g_q

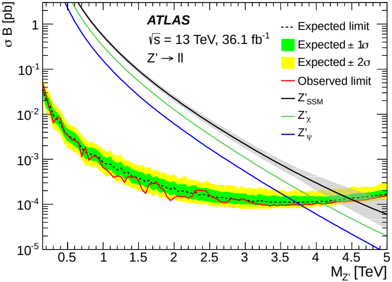


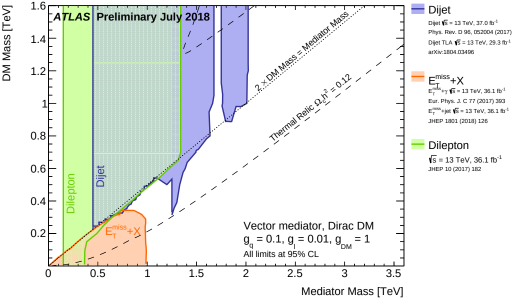


- **TLA**/**data scouting** probes lower mass and similar coupling as traditional searches
- topologies with **ISR** pay a penalty on acceptance:
  - probed couplings/equivalent cross sections are lower

Adding leptons: Z′, dark photon

Assuming in addition mediator coupling to leptons $g_\ell = 0.01$:





Mediator masses are probed from $m_{med} > 150$ GeV

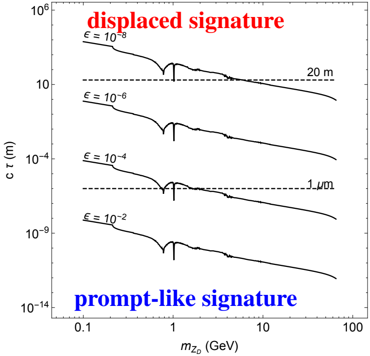
Is there a sensitivity to lower masses at the LHC?

arXiv:1707.02424 CMS-PAS-EXO-16-031

Dark photon framework

Additional broken $U(1)_D$ gauge force in dark (hidden) sector:

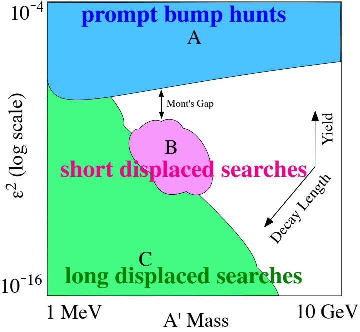
- creates a connection between the SM and possible dark sector
- kinetic mixing term ε induces mixing between dark photon Z_D and the SM photon and Z
- ε impacts Z and SM fermions coupling at $\mathcal{O}(\varepsilon^2)$
- if the dark sector is heavy, dark photons decay to SM particles
- their width and lifetime depend on ε and m_{Z_D}

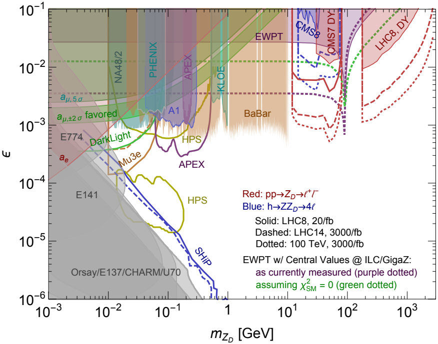


To cover all parameter-space becomes essential to add a new parameter: look for displaced vertices and displaced decay products

arXiv:1412.0018

Existing constraints on dark photons





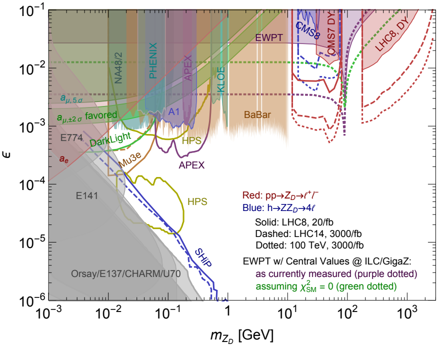
The gap between regions A and B, which has come to be called "Mont's Gap" after JLAB Director Hugh Montgomery's observation that HPS coverage in coupling strength was incomplete, highlights the challenge to fill in the transition region between bump hunts and displaced vertex searches by either increased luminosity (for bump hunts) or improved vertex resolution for short decay lengths, or both.

arXiv:1412.0018 arXiv:1608.08632

Existing constraints on dark photons

- for $m < 10$ GeV strongest limits come from BaBar
- for $m > 10$ GeV sensitivity comes from Drell-Yan differential cross-section measurements and EW fit (Z mass and fermion couplings)

- a recent new result from LHCb probes $10 < m < 70$ GeV for $\varepsilon \sim 10^{-3}$
- no other direct searches at the LHC yet
- at the coupling $\varepsilon \sim 10^{-3}$ the dark photon is prompt-like
- in addition, displaced search is carried out for masses [214, 350] MeV

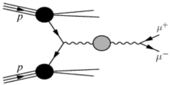


arXiv:1412.0018

Direct dark photon search at the LHC: LHCb result

Spoiler:

Physics SYNOPSIS



LHC Sees No Dark Photons

Published 8 February 2018

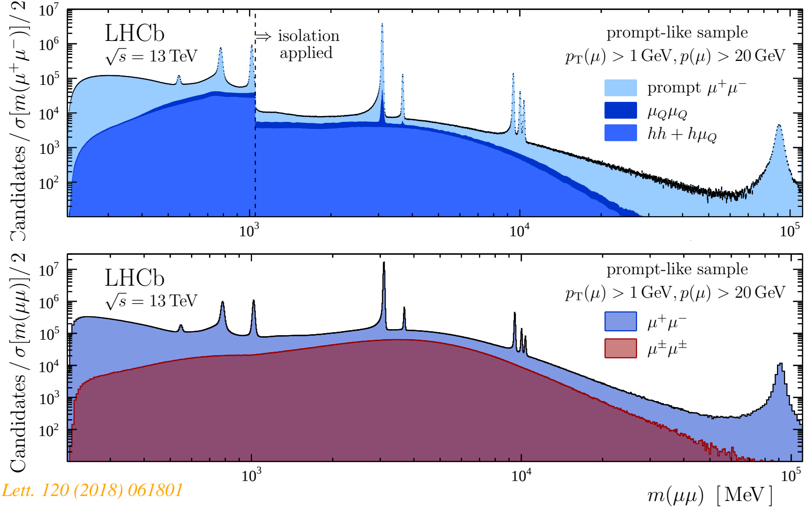
A search for dark photons at the LHC comes up empty but puts new constraints on the strength of the hypothetical particles' coupling to electromagnetic fields.

See more in *Physics*

Phys. Rev. Lett. 120 (2018) 061801

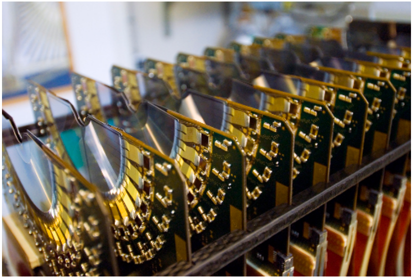
LHCb: prompt-like search

- use same-sign muon events to estimate misidentified μ background
- look for a signal as a bump in a small mass window (regions around known resonances are vetoed)



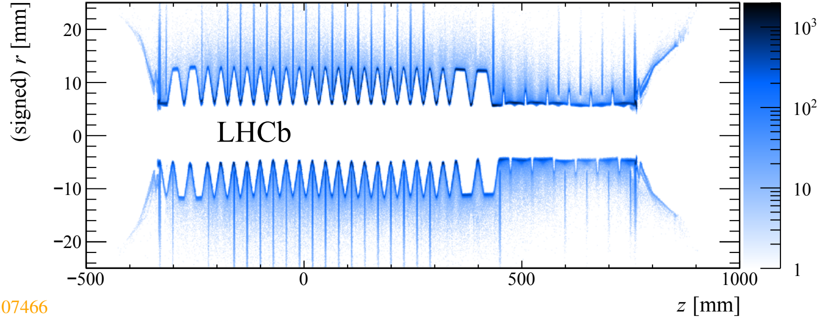
Phys. Rev. Lett. 120 (2018) 061801

LHCb: displaced search



VeLo: vertex locator detector

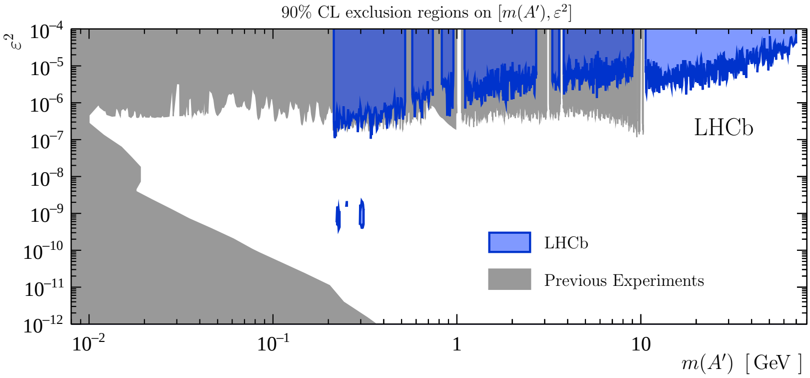
- dedicated effort to map material is the innermost LHCb detector
- results are used to impose a veto on displaced vertices originating in the material



arXiv:1803.07466

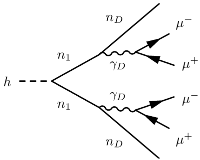
LHCb: results

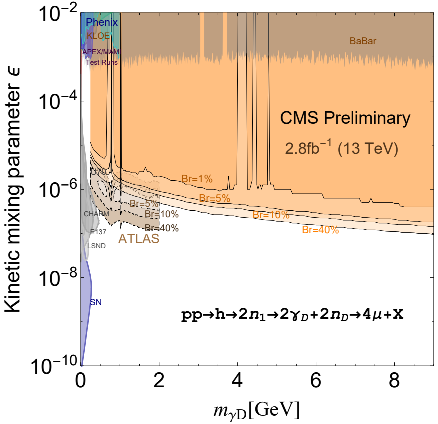
- final limits are competitive to B factories
- this is the only experiment to put direct constraints above 10 GeV
- ATLAS and CMS are catching up



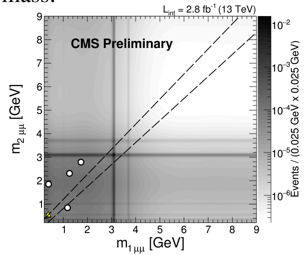
Phys. Rev. Lett. 120 (2018) 061801

Higgs portal: Z_D pair production





- search for a pair of displaced dimuons $0.2 < m_{\mathrm{Z_D}} < 8.5$ GeV
- employ a dedicated trimuon trigger w/o a vertex constraint
- special offline muon reconstruction: does not require a pointing to a primary vertex
- allowed displacements are:
  - $L_{xy} < 9.8$ cm (3^{rd} pixel barrel layer)
  - $L_z < 48.5$ cm (2^{nd} pixel endcap disk)
- signal region is defined for dimuon pairs with close mass:

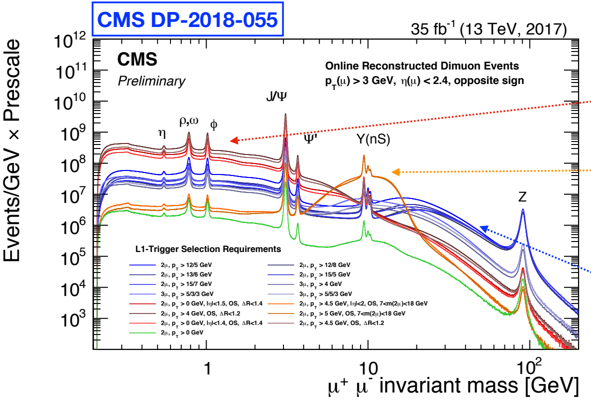


ATLAS-CONF-2016-042 CMS-PAS-HIG-16-035

Towards single dark photon search @ CMS

To overcome high data rate, use scouting techniques for dimuons as done for jets:

- new muon scouting stream was introduced in Run 2
- these triggers has very low p_T thresholds for muons
- record only limited amount of information from such triggers



For masses < 10 GeV

Scouting trigger :
$\Delta R(\mu\mu) < 1.4$ +
$p_T(\mu) > 4$ GeV or $|\eta_\mu| < 1.5$

For masses ~ 10-20 GeV

Scouting trigger :
$7 < m(\mu\mu) < 18$ GeV +
$p_T(\mu) > 4.5$ GeV

For masses above 20 GeV

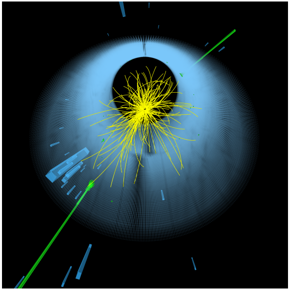
Standard dimuon triggers

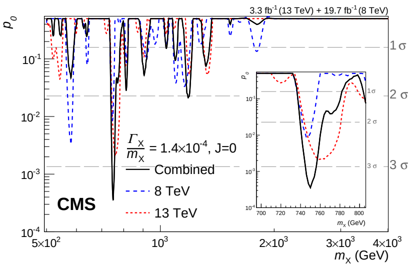
credits: A. Vartak

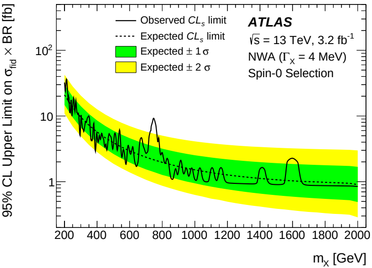
CMS DP-2018/055

Going lower in mass for all resonances: diphotons

Old story: hints of a new particle at 750 GeV (dissolved after $\times 4$ more data)







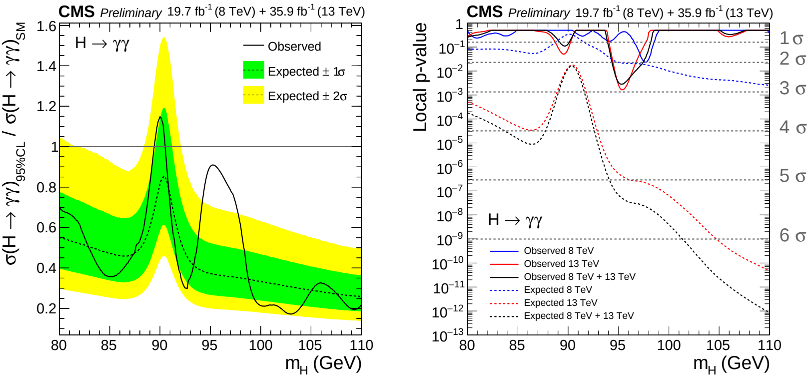
Phys. Rev. Lett. 117 (2016) 051802 *JHEP* 09 (2016) 001

$X \to \gamma\gamma$: always can bring an excitement

X@750 GeV "closed" in August 2016

X@95 GeV released in August 2017:

- 8 TeV data (2σ @ 97.6 GeV) and 13 TeV (2.9σ @ 95.3 GeV)
- combined leads to a 2.8σ excess at 95.3 GeV

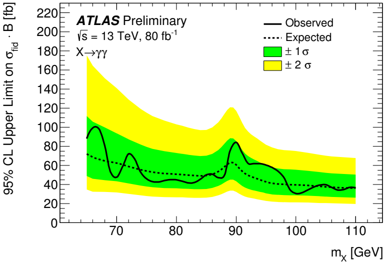


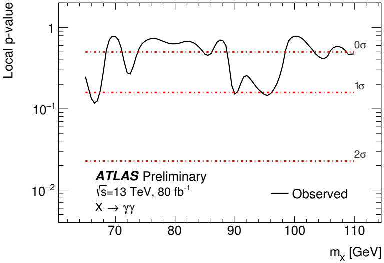
ATLAS has a brand new analysis with Run2 2016 and 2017 data in this mass range!

CMS-PAS-HIG-17-013

$X \to \gamma\gamma$: follow-up

ATLAS has a brand new analysis with Run2 2016 and 2017 data in this mass range:



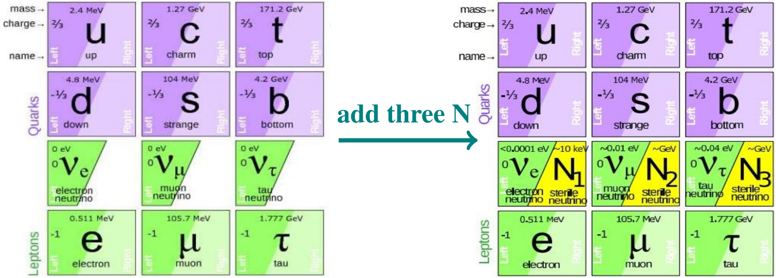


The story is limited to much fewer citations than the previous one.

ATLAS-CONF-2018-025

What's next? High volumes of data: rare processes

νMSM - minimal extension of the SM which solves a range of questions:

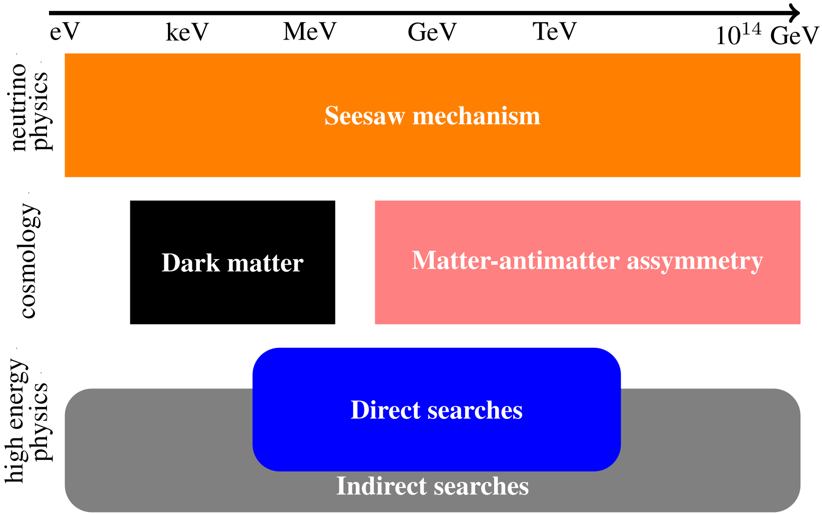


1. **neutrino masses**
   - via seesaw mechanism
2. **matter-antimatter asymmetry**
   - degenerate N_2 and N_3 (mass from ~ 1 to $\sim 10^2$ GeV) could lead to dramatic increase of CP violation
3. lightest N_1 (a few keV) is a perfect **dark matter candidate**
   - observable decay mode $N_1 \to \nu\gamma$
   - search for mono-line in galactic photon spectrum, $E_\gamma = M_N/2$

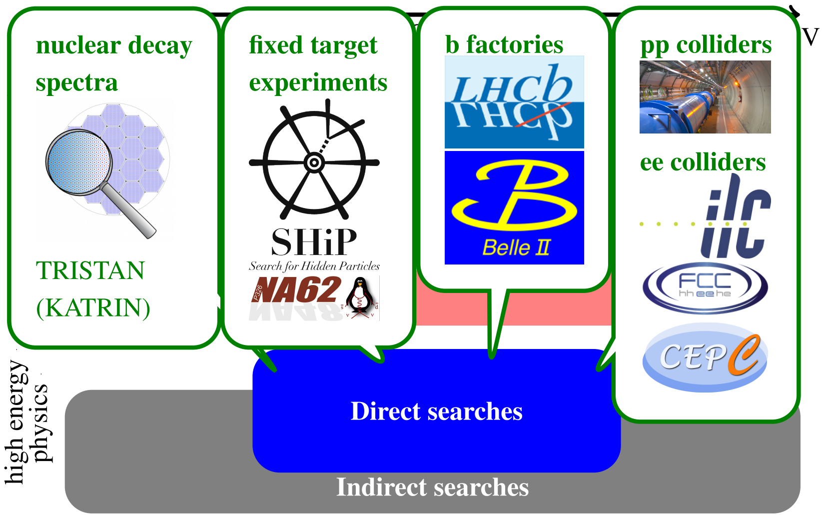
Heavier N_2 and N_3 can be searched for at the LHC

Shaposhnikov and Asaka

Possible masses of N

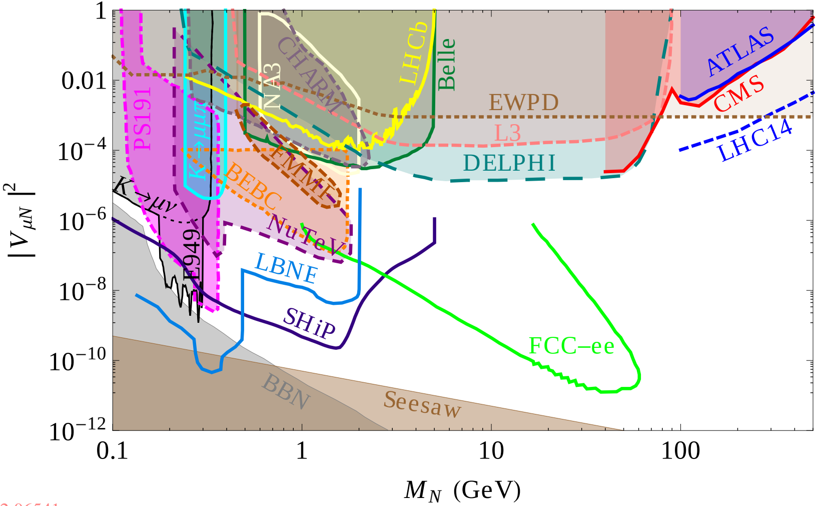


Possible masses of N: tools to find them



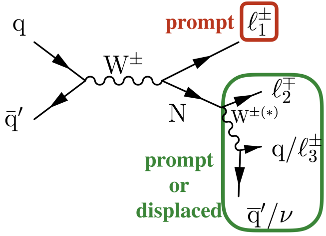
Existing constraints and some projections

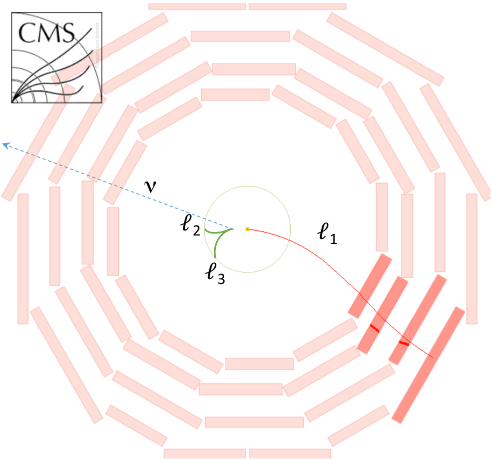
- LHC just starts to probe region not excluded by the electroweak precision data (EWPD) (*filled areas - excluded; contours - projected experiments*)



arXiv:1502.06541

Heavy neutrinos at the LHC

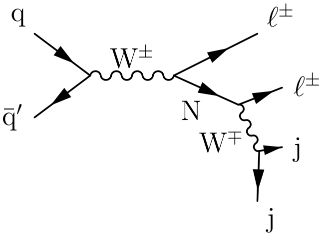




- **N production**: in decays of W bosons
- **N decays**: $N \to W\ell$ or $N \to Z\nu$ or $N \to H\nu$
- **N lifetime**: from very small (**prompt** decays) to macroscopic distances from production vertex (**displaced** decays) as $\tau \propto |V_{\ell N}|^{-2} m^{-5}$

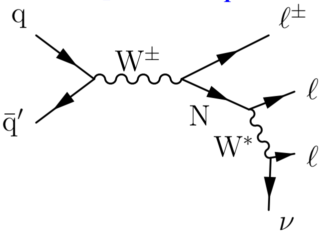
Signatures with prompt N decays

Same-sign dileptons + 2 jets:



- allows to fully reconstruct N mass peak
- N has to be heavy (jet $p_T > 30$ GeV)
- sensitive only to **lepton-number-violating (LNV)** N decays

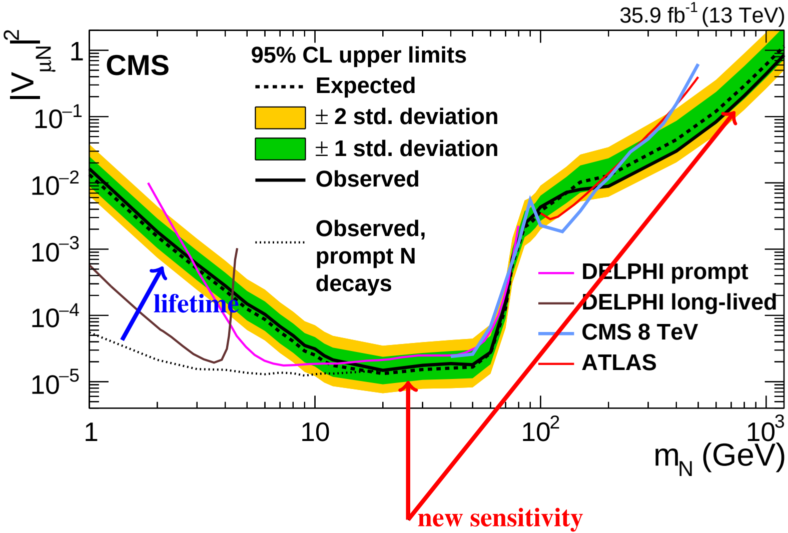
Trileptons (+ E_T^{miss}):



- no clear N mass peak due to escaping ν
- can detect decay products of very light N (lepton $p_T > 5$ GeV)
- sensitive to both LNV and **LN-conserving (LNC)** N decays

Explore a new territory with looking at the prompt trilepton (e, μ) final state!

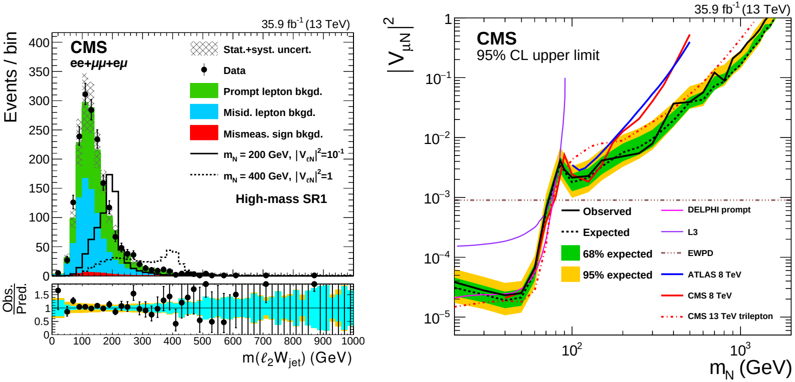
Prompt trilepton search: coupling to muons



High mass: VBF production channel drives production cross section.

Phys. Rev. Lett. 120 (2018) 221801

Prompt same-sign dilepton search: coupling to muons

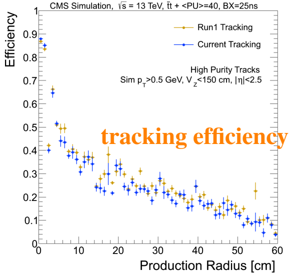


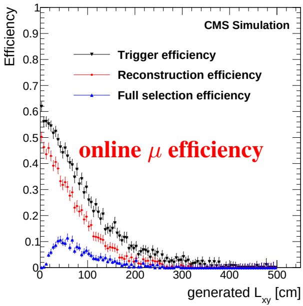
High mass: same-sign dilepton channel is more powerful due to larger signal acceptance
Low mass: trilepton channel is more powerful due to lower SM background

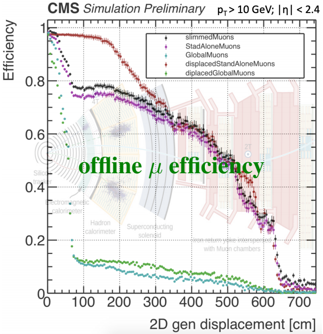
arXiv:1806.10905

Displaced search prospects

- **tracking efficiency** drops drastically at displacement of ∼60 cm: to 10%
- using μ reconstructed with **muon chambers only** allows to extend search up to **3m**
- **online (trigger) efficiency** for such muons is poor after ∼2m
- if trigger on the prompt lepton in the event - profit from the stable high offline efficiency in all range!







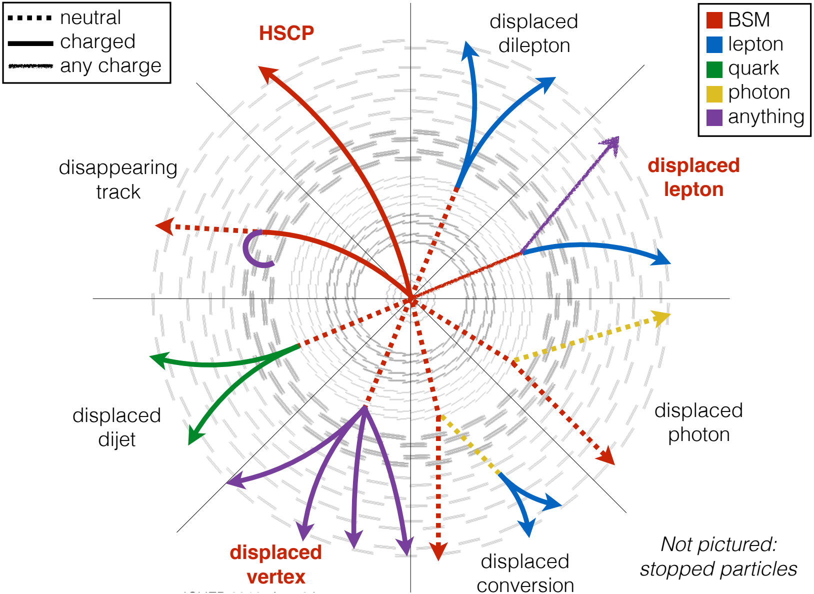
Conclusions

- with the available dataset sensitive to processes with very low rates
- using new data recording and analysis techniques open a window to new phase-space with low masses and low couplings
- existing searches are sensitive to other new physics scenarios:
  - including those which would **appear only in one signature**
  - and those which always **profit from larger dataset**
  - e.g. **dark matter particles with low couplings**, **hidden sector**, **sterile neutrinos with low mixing parameter**...

The LHC still gives an opportunity for a discovery!

Long-lived particle signatures in a detector

J. Antonelli

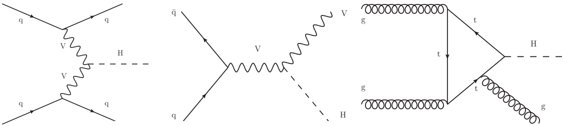


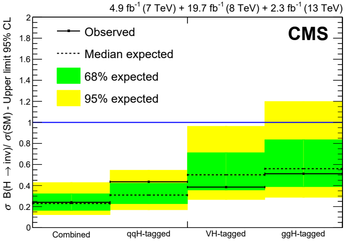
Long-lived particle searches: possible new physics scenarios

- small mass-splittings: close in mass NLSP SUSY particle
- small couplings: RPV SUSY, heavy neutrinos
- hidden valley sector

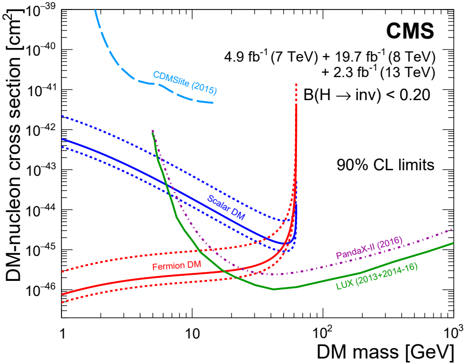
Higgs boson portal to new physics

- DM search in the invisible H decays H $\rightarrow \chi\chi$
- combine all H production modes





- $\mathcal{B}(\mathrm{H} \rightarrow \mathrm{inv}) < 0.24$ @ 95% CL
- SM (H→ZZ→ 4ν) = 1.06×10^{-3}

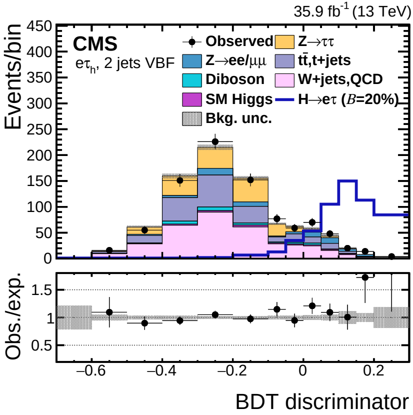


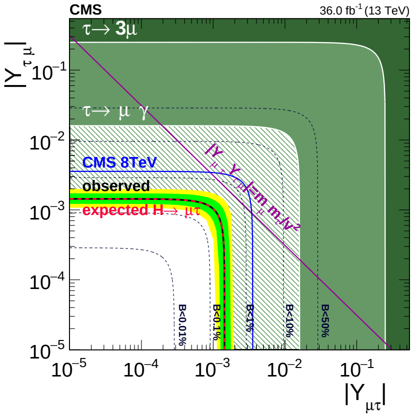
- complementary constraints on low-mass DM

arXiv:1610.09218 arXiv:1708.09624

LFV Higgs boson decays

- look for the off-diagonal Yukawa $\mu\tau$ and eτ couplings
- analysis is complementary to $\tau \to 3\mu$ and other LFV processes searches
- upper limits are set at $\mathcal{B}(\mathrm{H} \to \mu\tau) < 0.25\%$ and $\mathcal{B}(\mathrm{H} \to \mathrm{e}\tau) < 0.61\%$





arXiv:1712.07173