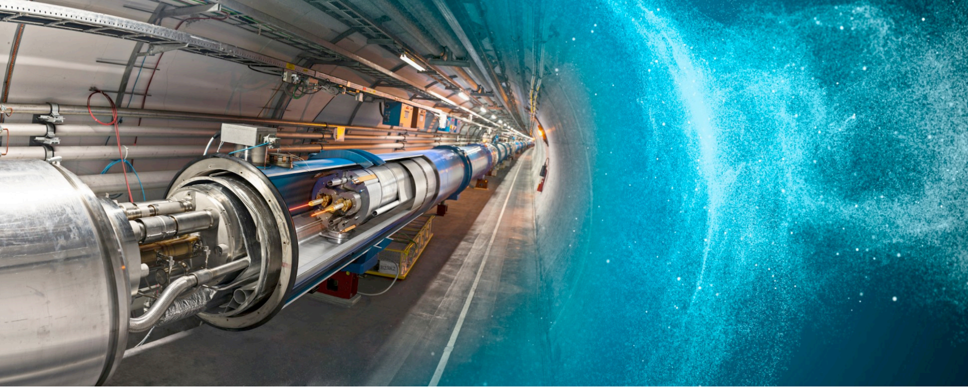


Exotic NP searches at high-p_{T} experiments

Lesya Shchutska

ETH Zürich

CMS Collaboration

ZPW2018 - Flavours: light, heavy and dark

January 15, 2018

LHC pace up to now

Beam energy rise:

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

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

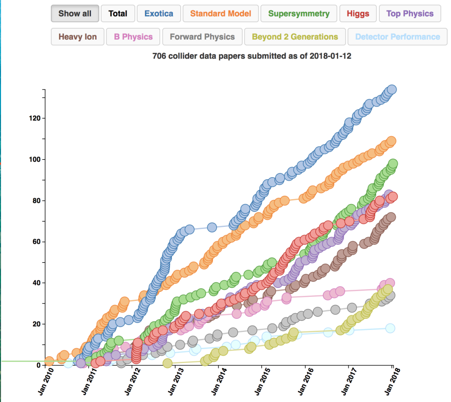
3 fb^{-1} @ 13 TeV (2015)

Huge luminosity jump:

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

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

Next: intellectual rise?

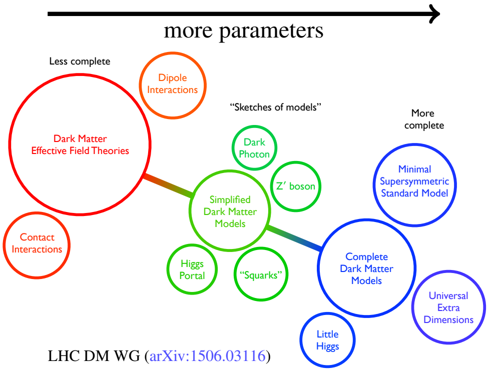


A general purpose detector

Higgs boson discovery (2012)

Wide physics programme

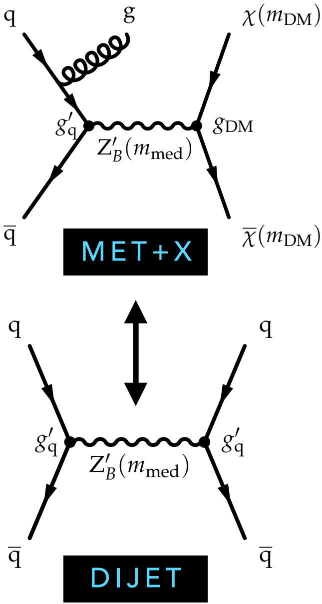
Dark matter searches at the LHC



LHC DM WG (arXiv:1506.03116)

- in Run 2 of the LHC moved from the EFT to the simplified dark matter models description
  - to overcome issues with large momentum transfer at 13 TeV
- major part of possible DM manifestations at the LHC is captured
- and a comparison with the other experiments is done in a consistent way

Simplified DM models guidance



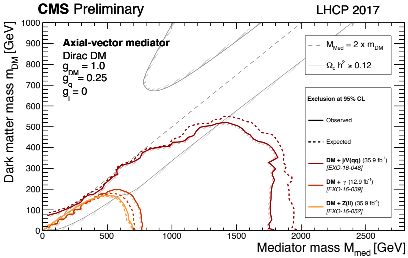
Typical signatures at the LHC:

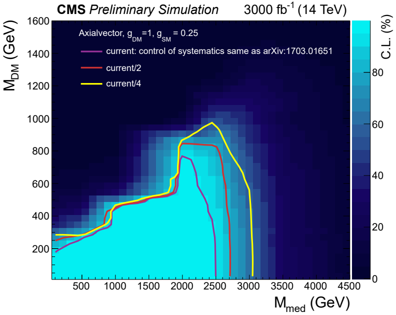
- mono-X (X = jet, photon, W, Z, H, t)
  - jet: generally the most powerful
  - photon: first used for the DM searches
  - W: distinguish DM coupling to u/d-quarks
  - Z: clean signature
  - H: Higgs portal
  - t: coupling to tops
- di-X resonance (X = jet, photon, W, Z, H, t)
  - X = jet is naturally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

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

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

Current snapshot and projections





- current monojet search probes mediator mass up to 1.7 TeV and dark matter mass up to 500 GeV
- after collecting 3000/fb the reach can expand up to
  - $m_{med} \sim$ 2.5-3.0 TeV
  - $m_{\rm DM} \sim$ 0.8-1.0 TeV

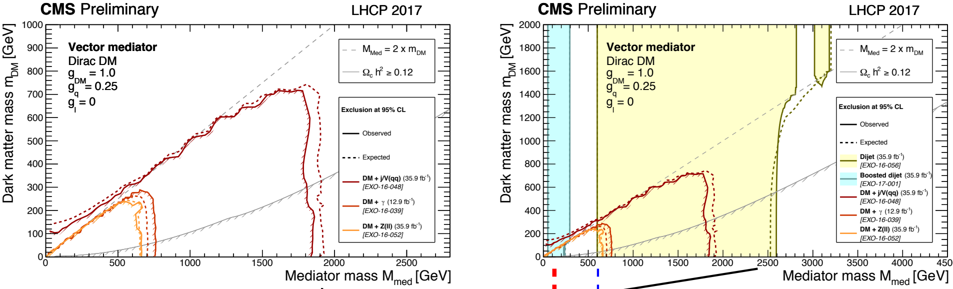
  depending on the systematics treatment

Meanwhile, explore other possibilities!

CMS-PAS-FTR-16-005

Results complementarity

mono-X + E_T^{miss} searches: **+ dijet resonance searches**



limited by $\sqrt{s}$

limited by trigger

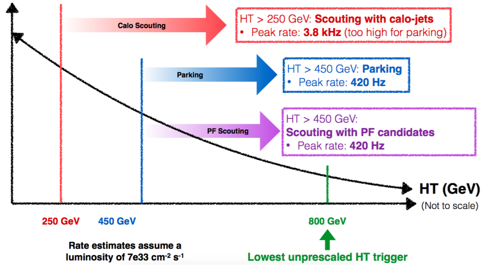
new ideas and techniques to cover the gaps

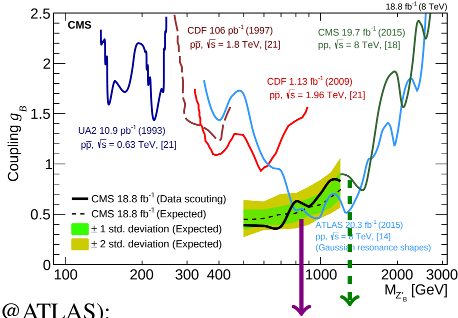
CMS-PAS-EXO-16-056

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

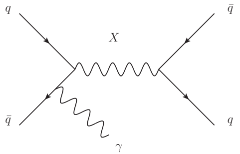
- 10 kB/event: PF scouting, $H_T > 450$ GeV (CPU-limited)
- in Run 2: 1.5 kB/event: Calo scouting, $H_T > 250$ GeV

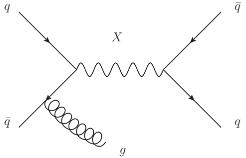
arXiv:1604.08907

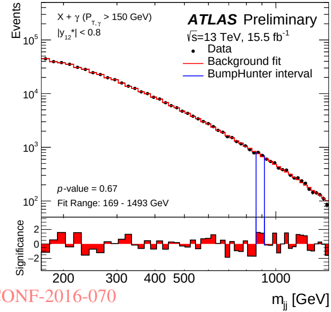
New ideas: employing ISR to go lower...

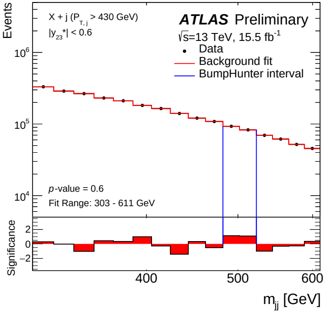
Sacrifice in coupling sensitivity to go lower in mass:
trigger on initial-state radiation (jet or photon) and search for recoiling dijets

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



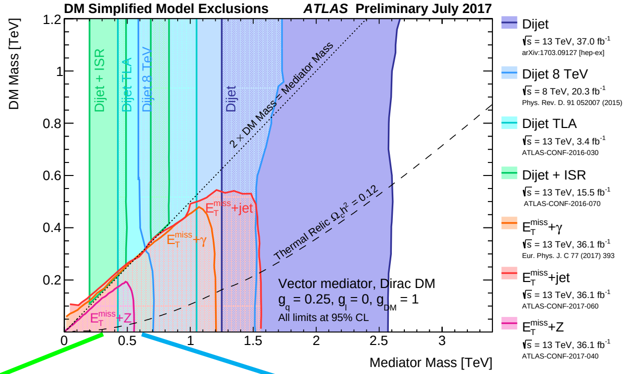






ATLAS-CONF-2016-070

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**):

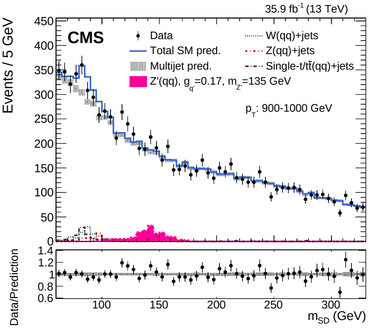
- masses between 450 and 1100 GeV

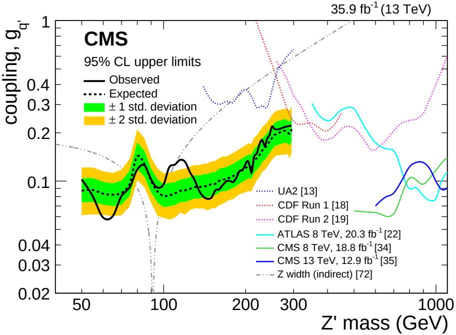
ATLAS-CONF-2016-070 ATLAS-CONF-2016-030

Going below 200 GeV: CMS ISR+merged jet search

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

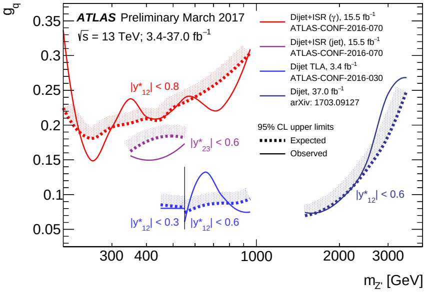


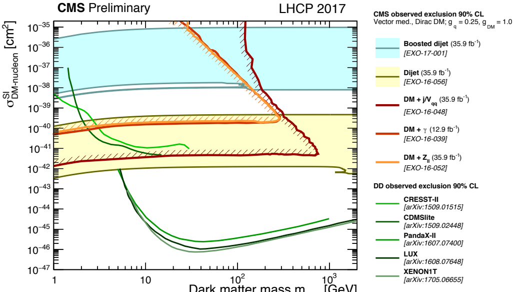


Local (global) significance 2.9σ (2.2σ) at 115 GeV

arXiv:1710.00159

Remembering about other dimensions: g_q

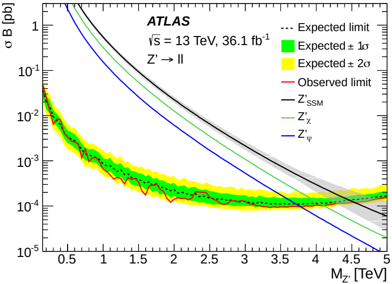


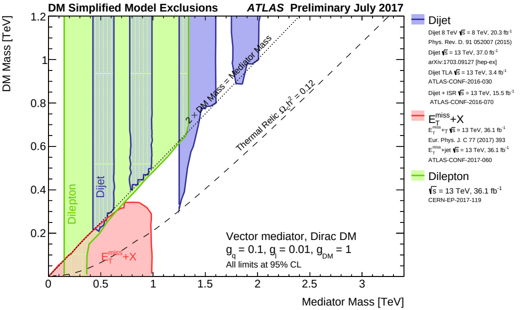


- **TLA**/**data scouting** probes lower mass and similar coupling as traditional searches
- topologies with **ISR** suffer from reduced acceptance:
  - probed couplings/equivalent cross sections are lower

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

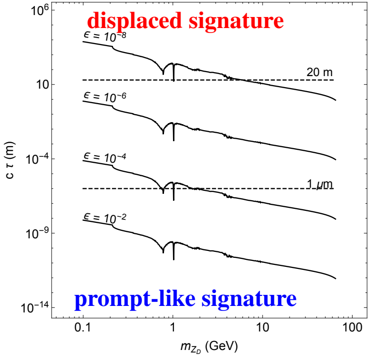
Is there a sensitivity to lower masses at the LHC?

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}

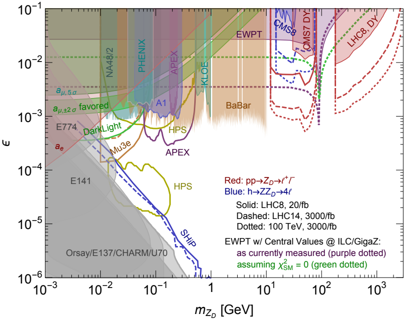


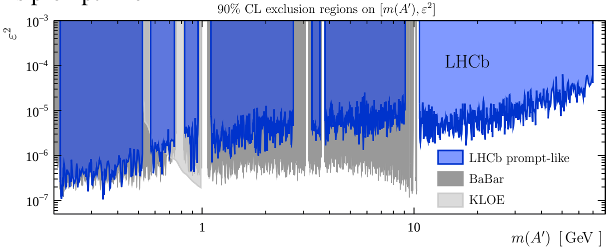
To cover all parameter-space becomes essential to add a new parameter: look for displaced vertices / decay products

arXiv:1412.0018

Existing constraints on dark photons

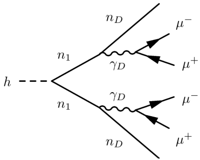
- for $m < 10$ GeV strongest limits come from BaBar
- for $m > 10$ GeV sensitivity comes from Drell-Yan diff. cross-section measurements and EW fit (Z mass and fermion couplings)
- a recent new result from LHCb for $10 < m < 70$ GeV for $\varepsilon \sim 10^{-3}$
- no other direct searches at the LHC
- at the coupling $\varepsilon \sim 10^{-3}$ the dark photon is prompt-like

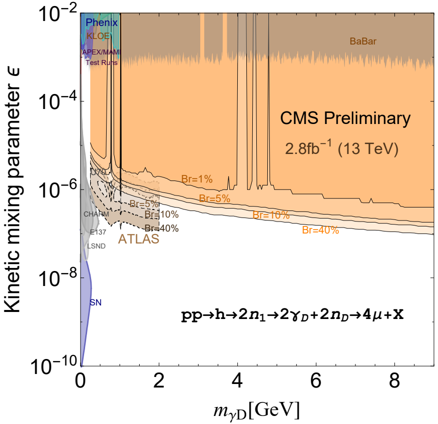




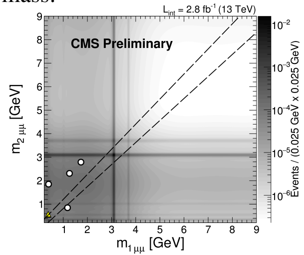
arXiv:1412.0018 arXiv:1710.02867

Higgs portal: Z_{D} pair production





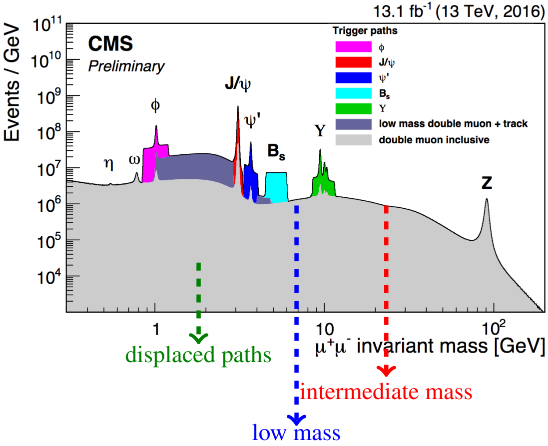
- search for a pair of displaced dimuons $0.2 < m_{Z_D} < 8.5$ GeV
- employ a dedicated trimuon trigger w/o a vertex constraint
- special offline muon reconstruction: does not require a pointing to a primary vertex
- allowed displacements are:
  - $L_{xy} < 9.8$ cm (3rd pixel barrel layer)
  - $L_z < 48.5$ cm (2nd 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

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



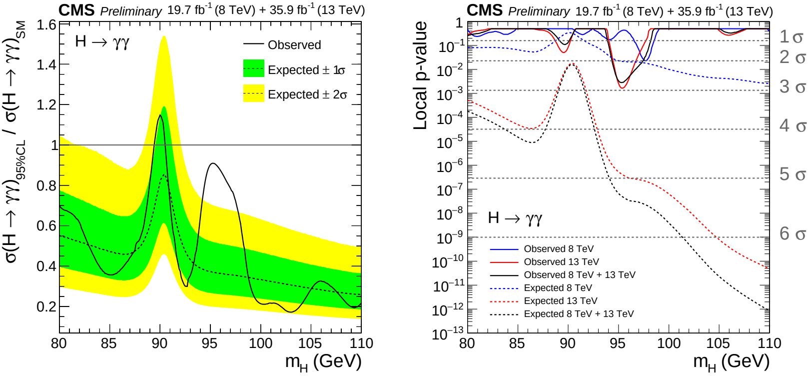
- existing triggers for dimuon ($p_T > 17/8$ GeV) and B-physics
- can provide coverage down to 200 MeV
- additional scouting paths with lower muon p_T thresholds are also employed
- will test feasibility towards higher volumes of data

$X \to \gamma\gamma$: 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



(no ATLAS result for Run 1 and Run 2 yet in this mass range)

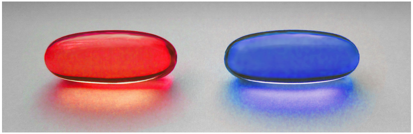
CMS-PAS-HIG-17-013

Are we looking everywhere?

- most new physics searches are designed to be sensitive to deviation from the SM expectation in a broad phase-space
- in specific cases of extremely low cross sections the optimization is more targeted

To be open to any possibility - cannot stay too specific in new physics searches

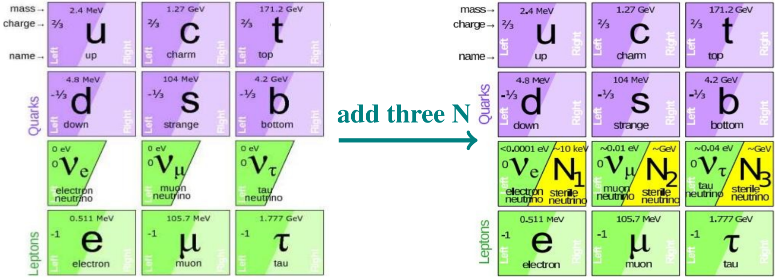
Choose which price to pay: sensitivity vs. generality



- can check performance of a general new physics search on a new model as an example

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

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

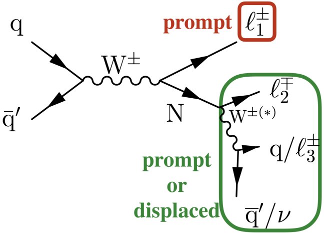


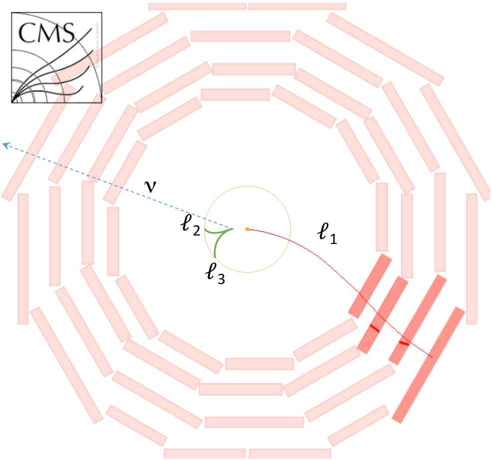
1. **neutrino masses**
   - via seesaw mechanism
2. **matter-antimatter asymmetry**
   - degenerate N_2 and N_3 (mass from ~ 1 to $\sim 10^2$ GeV) could lead to dramatic increase of CP violation
3. lightest N_1 (a few keV) is a perfect **dark matter candidate**
   - observable decay mode $N_1 \to \nu\gamma$
   - 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

Heavy neutrinos at the LHC

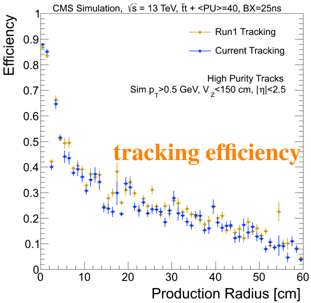


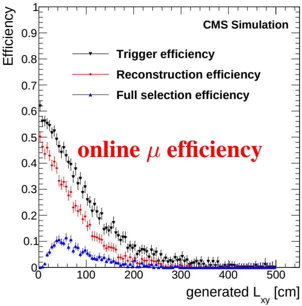


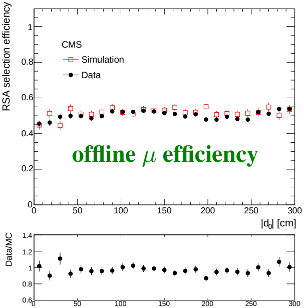
- **N production**: in decays of W bosons
- **N decays**: $N \to W\ell$ or $N \to Z\nu$ or $N \to H\nu$
- **N lifetime**: from very small (**prompt** decays) to macroscopic distances from production vertex (**displaced** decays) as $\tau \propto |V_{\ell N}|^{-2} m^{-5}$

Advantage of some model-dependence

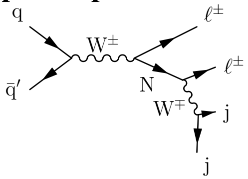
- **tracking efficiency** drops drastically at displacement of ∼60 cm: to 10%
- using μ reconstructed with **muon chambers only** allows to extend search up to **3m**
- **online (trigger) efficiency** for such muons is poor after ∼2m
- if trigger on the prompt lepton in the event - profit from the stable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



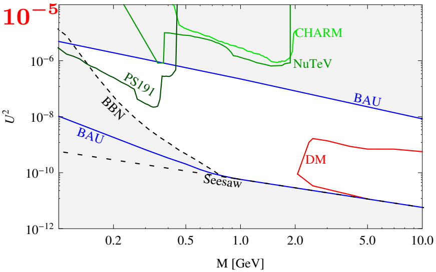


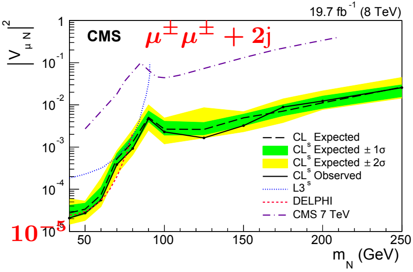


Interesting phase space



- so far dedicated searches were done in prompt same-sign dileptons for high mass
- probed phase-space is far beyond the range of the preferred phase-space derived from BAU





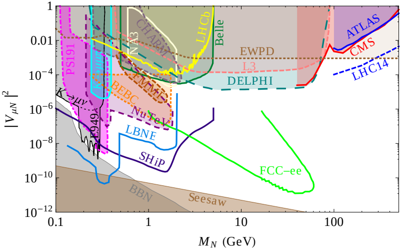
- from cosmology to create needed BAU:
  - $M_N < M_W$ [hep-ph/0505013]
  - or $M_N \sim$ TeV [hep-ph/0506107]

arXiv:1204.3902 EXO-12-057

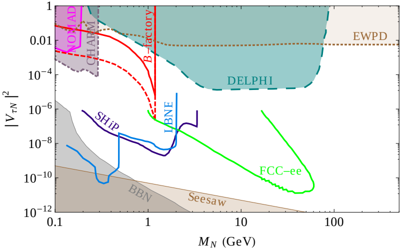
Expanding interesting phase space

- these dedicated searches just start to probe regions not excluded by the electroweak precision data (EWPD)
  - plot: filled areas - excluded; contours - projected experiments

coupling to muons



coupling to taus

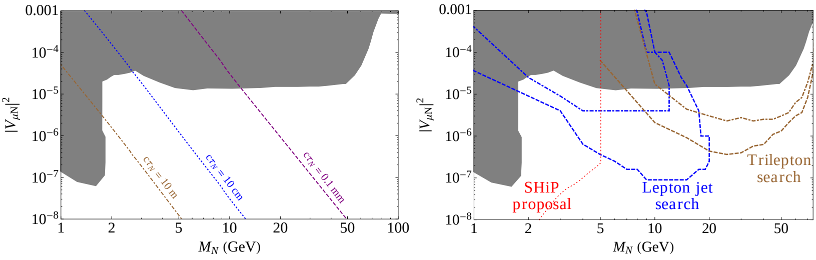


- not in these plots: existing new physics searches at the LHC which are already sensitive to a region of m_{N} 5-100 GeV with very low couplings

arXiv:1502.06541

Phenomenological estimates

Reinterpretation of existing multilepton SUSY searches + guesstimates:
arXiv:1504.02470:



1. **trileptons**: recasted CMS SUSY multilepton analysis
2. **lepton-jet**: 2 displaced leptons sensitivity (background estimated from another topology)

Reach reported for the 20 fb^{-1} @ 8 TeV and for 300 fb^{-1} @ 13 TeV

With the dedicated search and larger dataset could probe interesting phase-space already now!

arXiv:1504.02470

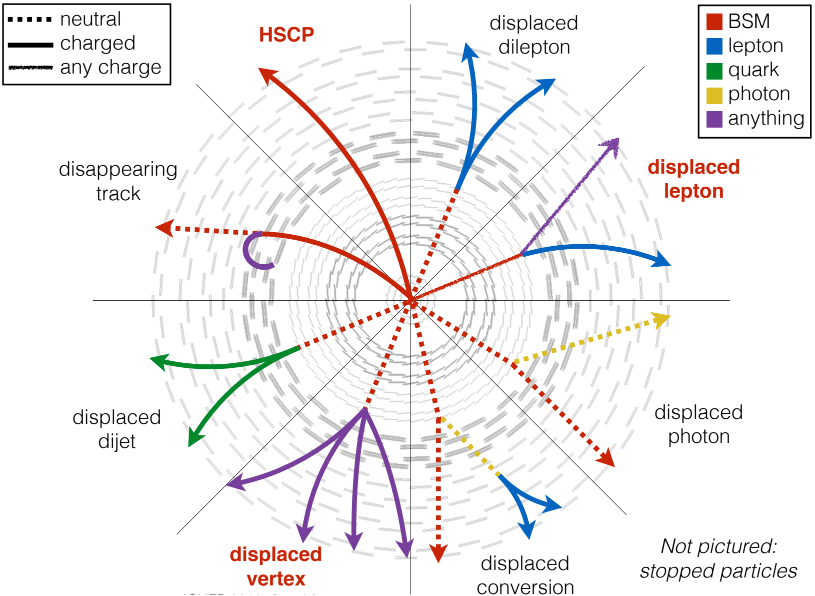
Conclusions

- 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



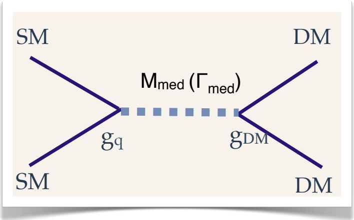
Long-lived particle searches: possible new physics scenarios

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

Dark matter interpretations at the LHC

O. Buchmueller (summary of the LHC DM WG):

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}

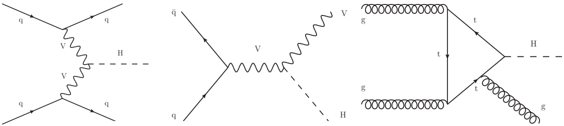
DM	
Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

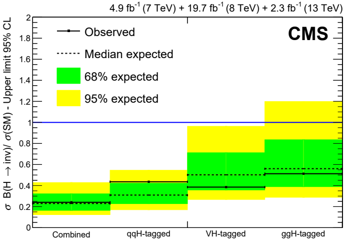
Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar

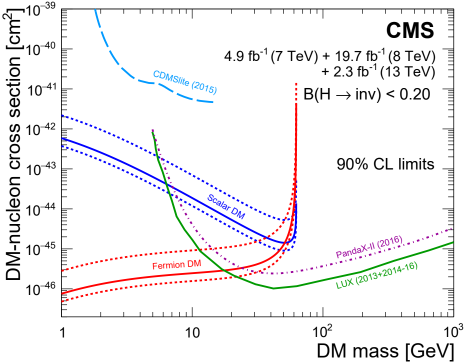
arXiv:1407.8257 arXiv:1507.00966 arXiv:1603.04156

Higgs boson portal to new physics

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







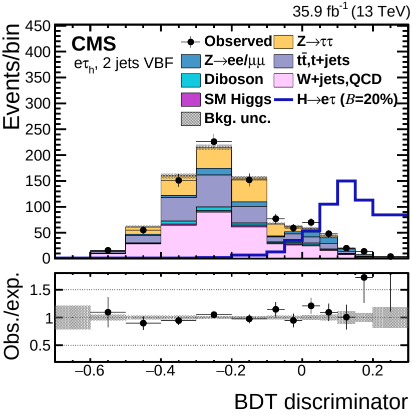
- $\mathcal{B}(\mathrm{H} \to \mathrm{inv}) < 0.24$ @ 95% CL
- SM ($H \to ZZ \to 4\nu$) = 1.06×10^{-3}

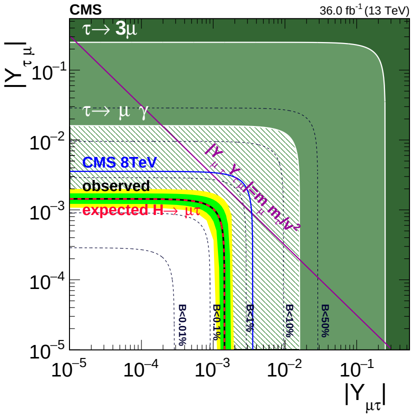
- complementary constraints on low-mass DM

arXiv:1610.09218 arXiv:1708.09624

LFV Higgs boson decays

- look for the off-diagonal Yukawa $\mu\tau$ and $e\tau$ 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 $\mathcal{B}(\mathrm{H} \to e\tau) < 0.61\%$





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