Lepton Jets Searches at the LHC

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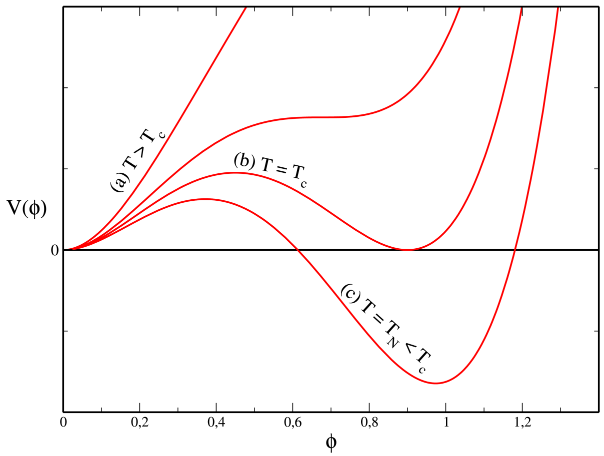
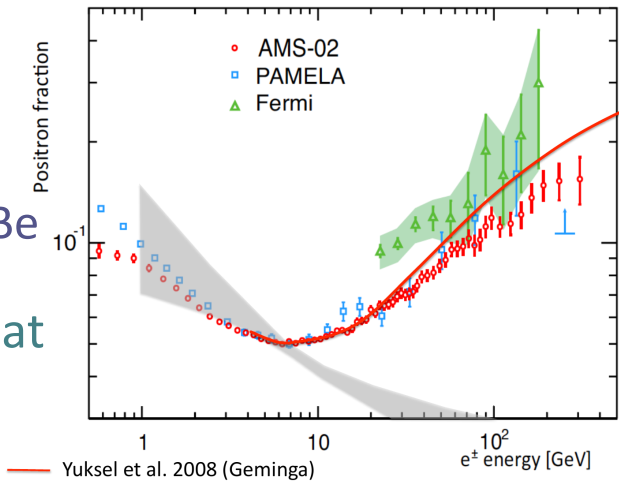
Broad Landscape of New Sectors

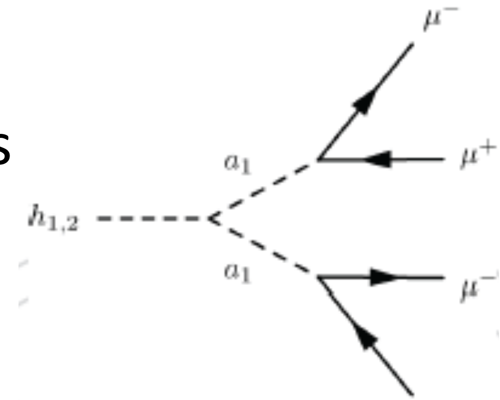
- More focus on and new models with new sectors in the past decade or so
  - Some explicit, e.g. hidden valleys and dark sectors
  - Some implicit, e.g. NMSSM with weak mixing (singlet/doublet) in Higgs is effectively a hidden sector model
- Motivation varies broadly
  - Solving our usual problems
    - Dark matter, naturalness and fine tuning, baryon asymmetry via electroweak baryogenesis etc.
  - Inspired by unexpected experimental results
    - Bumps in LEP dilepton spectra, Fermi-LAT/Pamela/AMS positrons (thermal DM exlanation likely incompatible with PLANCK), anomaly in ^{8}Be nuclear transitions
  - More evolved models replacing simpler ones that get ruled out by experimental data and opportunistic considerations (Higgs portal)

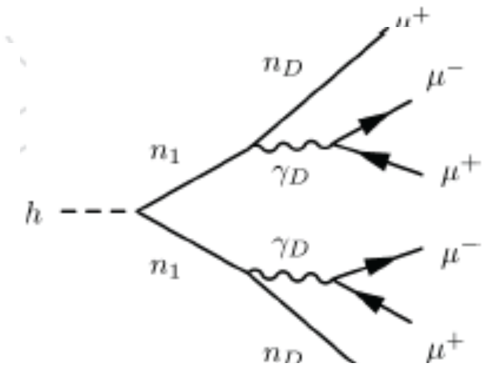


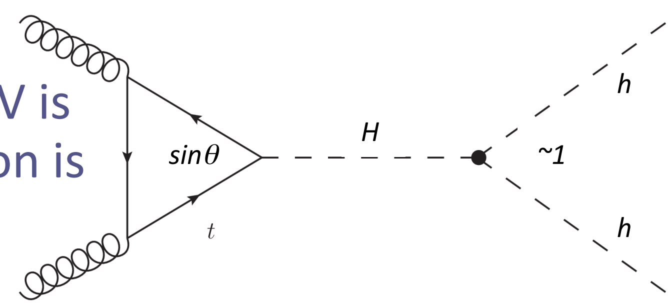


But Often Small or Complicated Signals

- Different models have different motivation and can have a hugely different mass scales
  - But common to interact with SM sector via mixing
- Can be very hard to find experimentally
  - NMSSM: a is a singlet
    - Coupling of *a* to SM suppressed, h_1 ($=h^{SM}$) can have a tiny small singlet fraction so BF(h_1->aa) is small, h_2 can have tiny cross-section
  - Dark photons: mix with SM photons
    - Weak mixing – long lived dark photons
  - xSM: mixing naturally small
    - H has suppressed coupling to SM so H->VV is small, need to look for H->hh (but x-section is also suppressed)

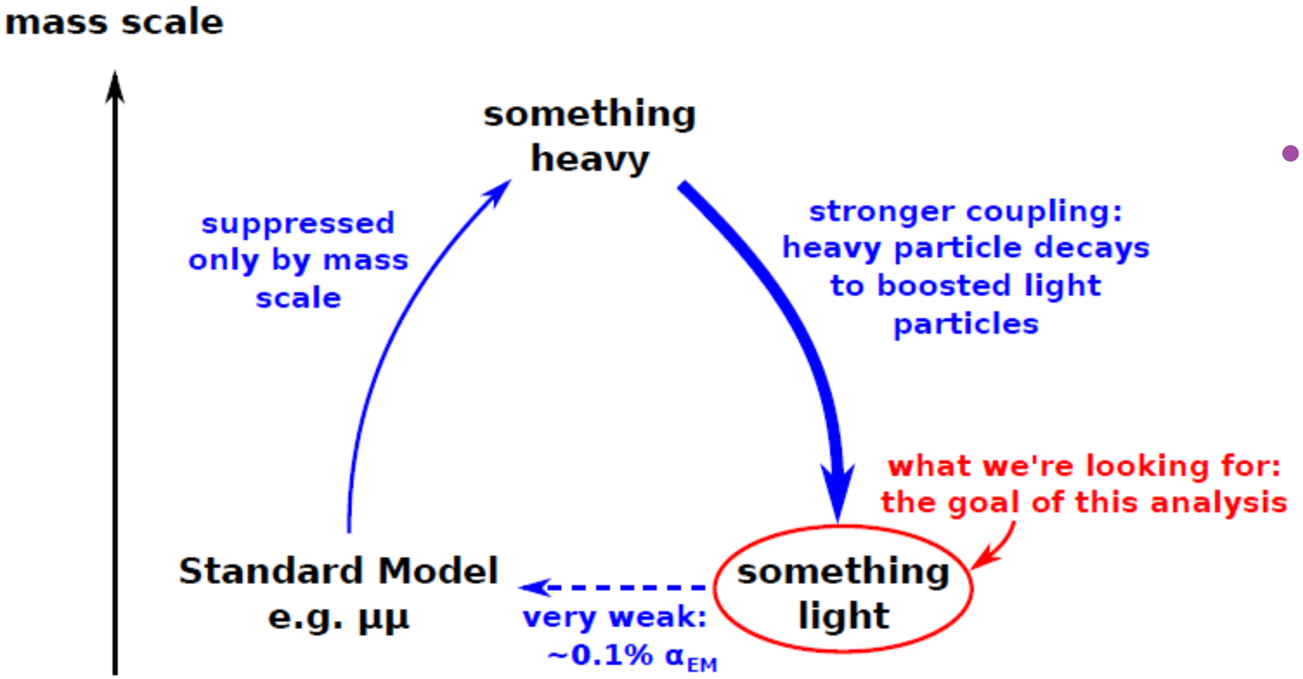






Searching for Hidden Things

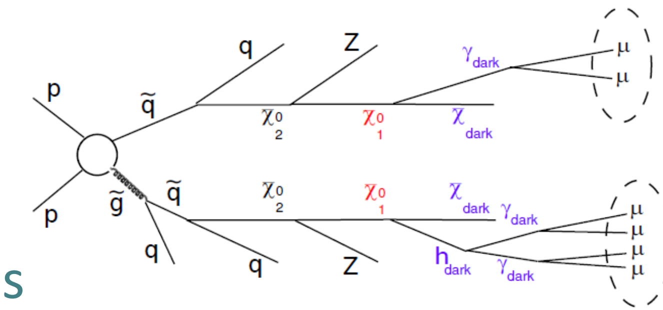
- Generalize for many classes of new physics searches:
  - High energy colliders can have enough energy to make the heavy stuff that couples to new hidden particles
  - They will eventually decay to SM particles
    - All you have to do is sit back and patiently watch

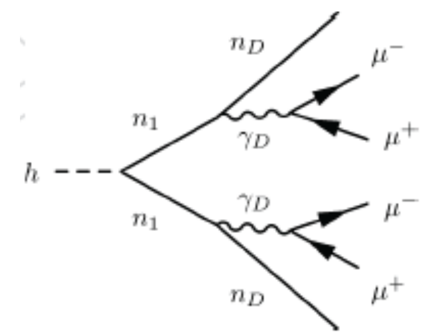


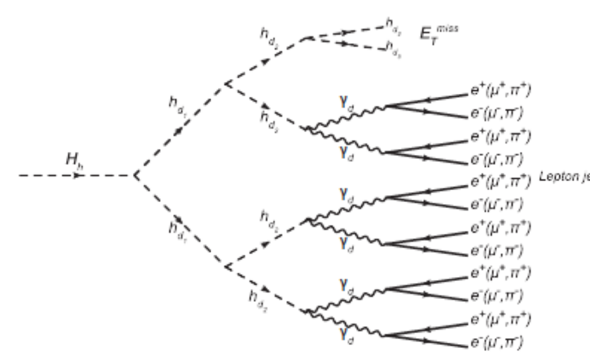
- Same strategy if "something heavy" is what's "hidden"
  - E.g. heavy Higgs in xSM decaying to SM-like Higgses

Experimental Challenges

- Hard to design a handful of analyses sensitive to all signatures
- True even for seemingly simple lepton jets searches (i.e. dark photons)
  - Branching fractions change fast with mass
  - Variations in production modes
    - Use of isolation may kill sensitivity if dark photons are produced with jets
  - Complexity of the hidden sector and coupling strengths
    - Cascade decays with many dark photons decaying via a variety of channels or a couple of isolated dark photons
  - Mixing strength: dark photons can decay promptly or be long-lived
    - Triggering may be very non-trivial

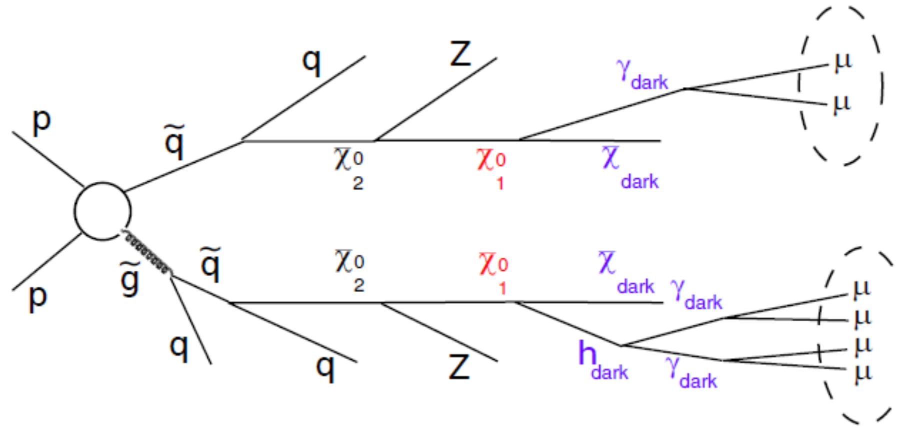




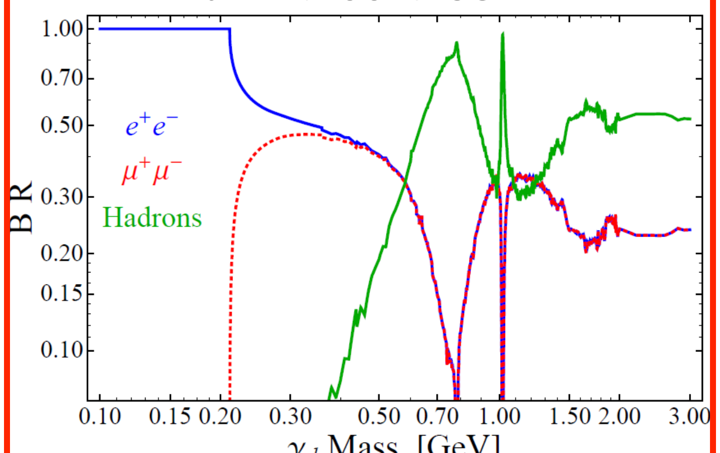


Lepton Jet Production Portals at LHC

- SUSY with squarks/gluinos if accessible by LHC:
  - MSSM LSP (neutralino) no longer stable decaying to dark neutralino and light γ^{dark}/h^{dark}
  - MSSM LSP is a squark decaying to q and light dark fermion and γ^{dark}/h^{dark}
- Higgs decaying via hidden sector cascades
- Dark photons mixes with the SM γ
  - Appreciable branching fractions to leptons except gaps near resonances



Branching fraction of γ↓D
arxiv:1002.2952



CMS Muon Jets Analysis

- Very old analysis, has not been updated
  - The first LHC analysis of this type
  - 35 pb^{-1} of 2010 LHC data
  - Inclusive muon trigger p_T>15 GeV
- Offline:
  - Require at least 1 muon with p_T>15 GeV, $|\eta|$<0.9
  - Identify all other muons with p_T>5 GeV, $|\eta|$<2.4
  - Reconstruct muon jets and categorize
  - No isolations, cluster using pairwise mass of muons
- Assume new bosons produced on-shell (may not be true, though)

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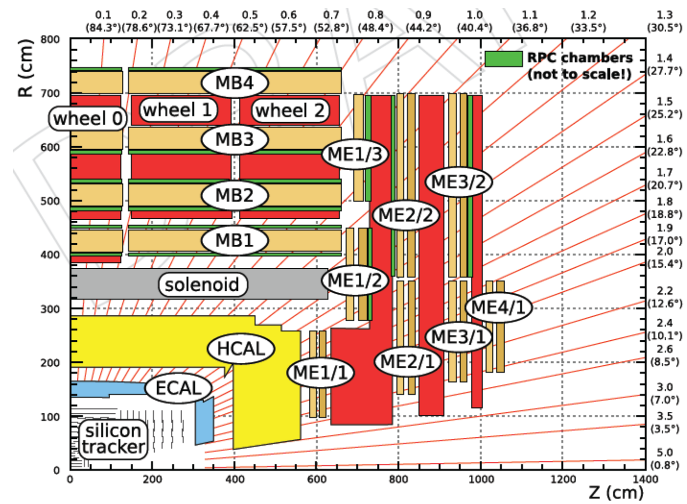

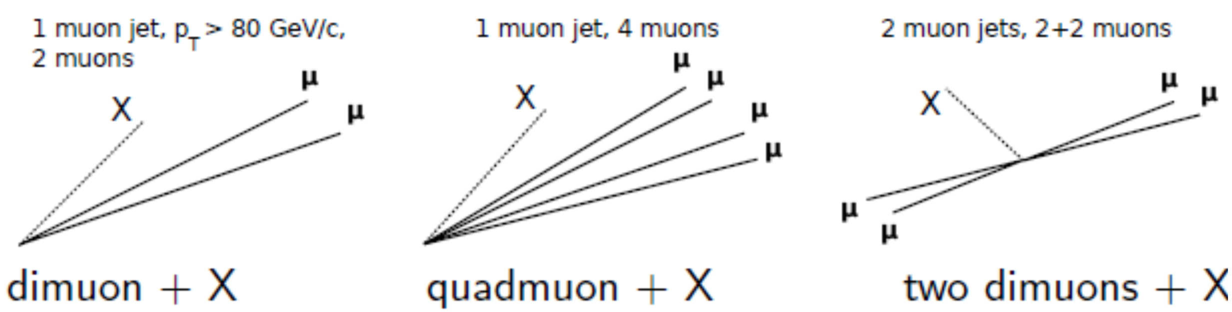

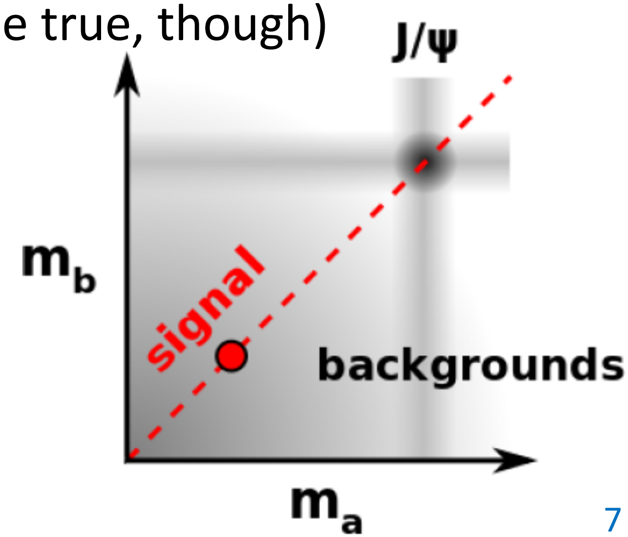

Topologies: Data and Backgrounds

name	description	Lead μ-Jet p_T	Backgrounds
R^1_2	Single dimuon+X	>80 GeV/c	2μ's from a b-jet, Drell Yan
R^1_4	Single quadmuon+X	no explicit cut	2μ's from a b-jet + 2 fakes
R^2_{22}	Two dimuons+X	no explicit cut	bb-bar+X, 2μ's from each b
R^N_{5+}	All other categories	no explicit cut	Rare, from bb-bar+X/fakes

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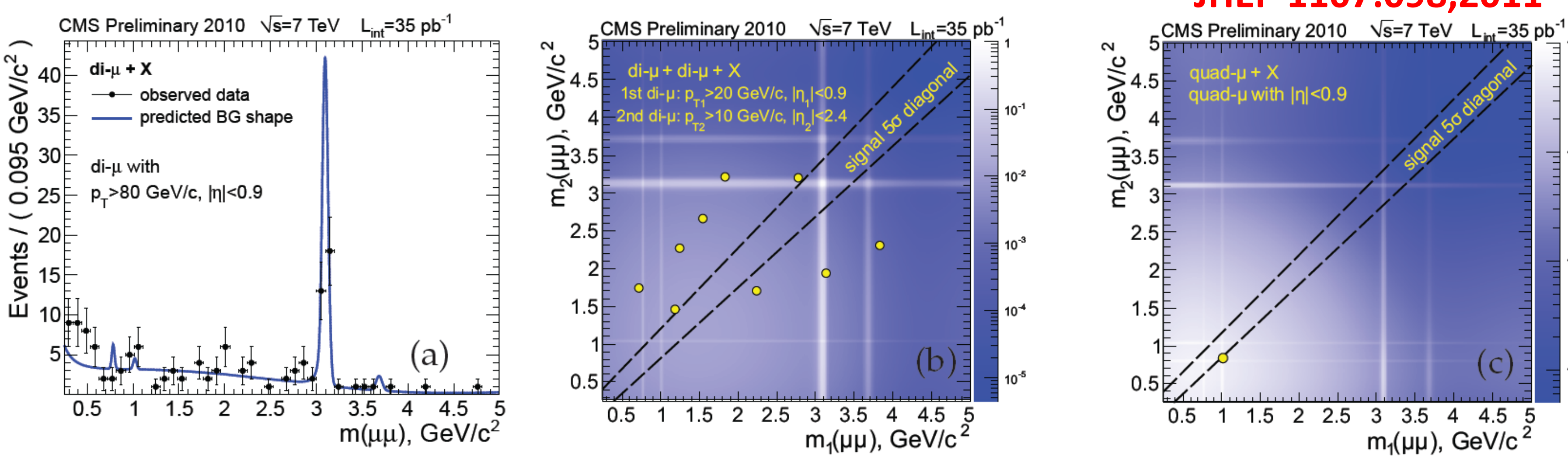
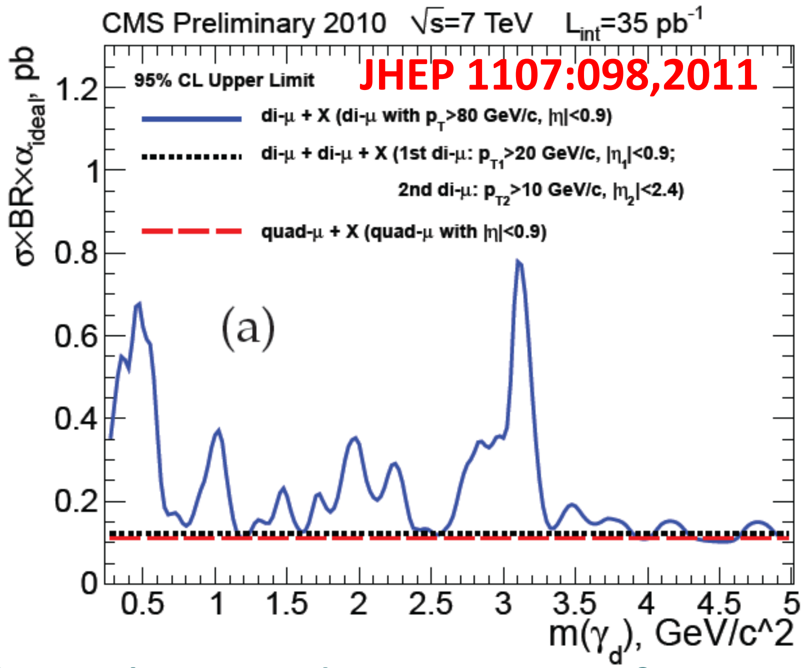


- No events with consistent masses of dimuons in higher order categories

CMS LJs: Model-Independent Interpretation

- Use three simplest topologies to set "conservative" model independent limits:
  - Dimuon+X
  - Two-dimuon+X
  - Quadmuon+X
- Limits of applicability:
  - Mean p_T(μ-jet)≤250GeV
  - Assume on-shell dark photons
  - No sensitivity below 2μ mass
    - Need electrons
- Easy to apply to other models:
  - Follow analysis steps to calculate branching and acceptance for a specific final state assuming an ideal detector
  - Compare with the limit plot
    - Complex topologies can be reduced to one of these three



ATLAS "Prompt" Lepton Jet Analysis

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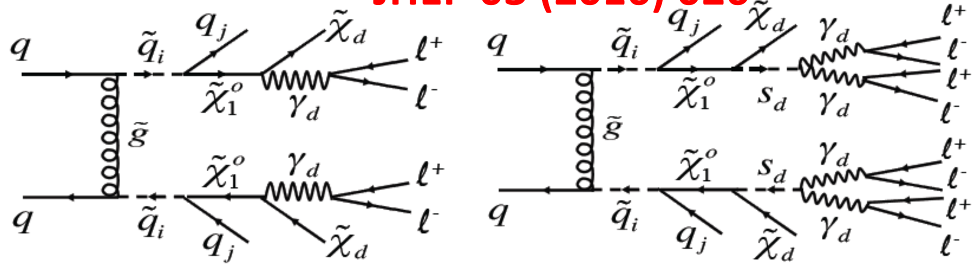

- 8 TeV, ~20 ifb of data
- "SUSY Portal" production
- Allow for all decays of γ_d, including hadrons
- Iterative jet cone algorithm running on tracks to form lepton jets:
  - Add all tracks w/ p_T>5 GeV and within DR=0.5 of current jet direction
- Categorization of lepton jets:
  - Electron-jet if at least one electron candidate with E_T>10 GeV, 2 or more tracks w/ p_T>10 GeV, no muons
  - Muon-jet if at least 2 muons with pT>10 GeV and no electrons
  - Mixed-jet if at least one electron w/ E_T>10 GeV and at least one muon with p_T>10 GeV
- Triggers:
  - Single e w/ E_T>60 or double e w/ E_T>35/25 GeV
  - Single μ w/ p_T>36 or double μ w/ p_T>13/13 GeV

ATLAS Lepton Jet Analysis

- Identification to suppress backgrounds **JHEP 03 (2016) 026**
  - Various selections emphasizing electron and/or muon dominance
- Isolation: ratio of the isolation sum over p_T(LJ)
  - Sum: all tracks w/ p_T>1 GeV in ΔR=0.5 around LJ, excluding:
    - E-jets: LJ tracks (p_T>5 GeV) matching the EM cluster or among two tracks closest to the cluster
    - Mu-jets: LJ tracks matching muon candidates
    - Mixed-jets: LJ tracks matching electron or muon candidates
- Optimize for S/B to define LJ ID selections
  - Works well for single dark photons, got to be difficult to find one size fit all for cases with multiple dark photons close-by (especially if decaying to hadrons)

ATLAS Lepton Jets: Acceptance

- Acceptance for SUSY Portal models

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State	eLJ–eLJ	muLJ–muLJ	eLJ–muLJ	eLJ–emuLJ	muLJ–emuLJ	emuLJ–emuLJ
SUSY-portal						
$2\,\gamma_d + X$	4.4 ± 0.2 %	6.4 ± 0.3%	3.4 ± 0.2 %	-	-	-
$2\,(s_d \to \gamma_d \gamma_d) + X$	6.3 ± 0.4 %	25.1 ± 0.7%	7.2 ± 0.3 %	4.0 ± 0.2 %	8.1 ± 0.3 %	7.1 ± 0.3 %

- Background expectation and data

Channel	Background (ABCD-likelihood method)	Background (total)	Observed events in data
eLJ–eLJ	2.9 ± 0.9	4.4 ± 1.3	6
muLJ–muLJ	2.9 ± 0.6	4.4 ± 1.1	4
eLJ–muLJ	6.7 ± 1.4	7.1 ± 1.4	2
eLJ–emuLJ	7.8 ± 2.0	7.8 ± 2.0	5
muLJ–emuLJ	20.2 ± 4.5	20.3 ± 4.5	14
emuLJ–emuLJ	1.3 ± 0.8	1.9 ± 0.9	0

- Limits: consider each combination a counting experiment, set limit on the number of signal events
  - One limit for all dark photon mass values

ATLAS Lepton Jet Analysis Limits

- Results: limits for each of 6 combinations and a final limit
  - Relatively straightforward for the model with only two dark photons away from each other
  - For the model with close-by pairs of dark photons, LJ reconstruction and ID efficiency is dependent on the mass of the “dark higgs”

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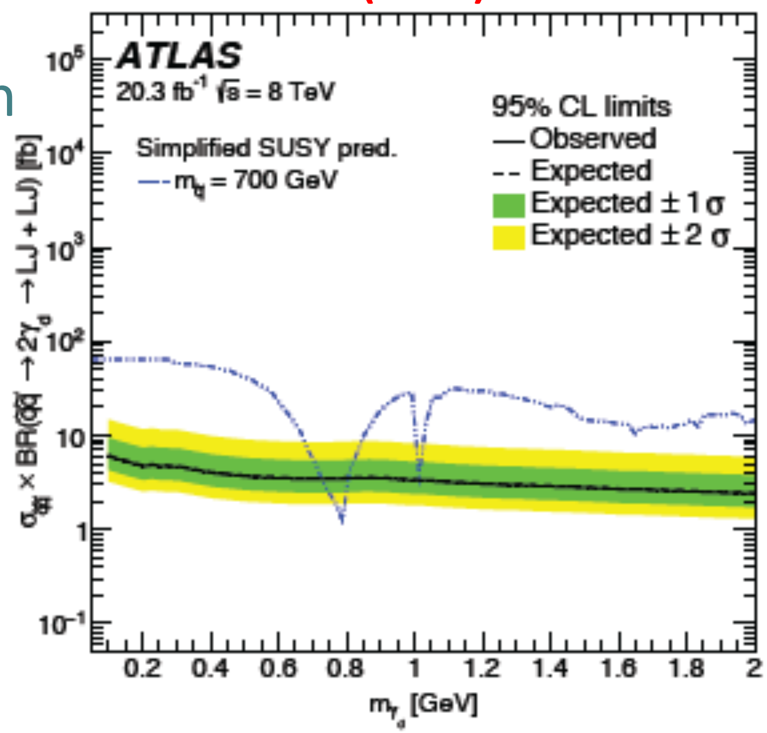
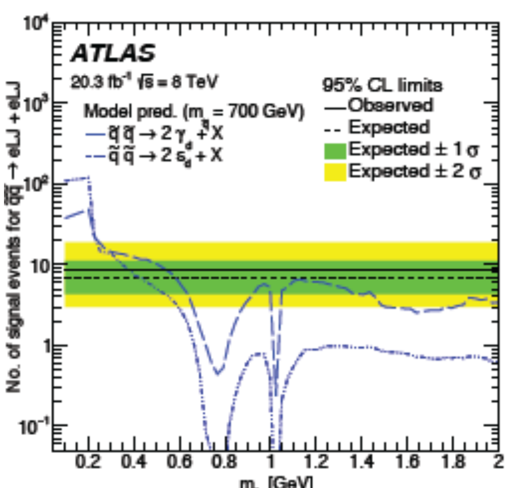
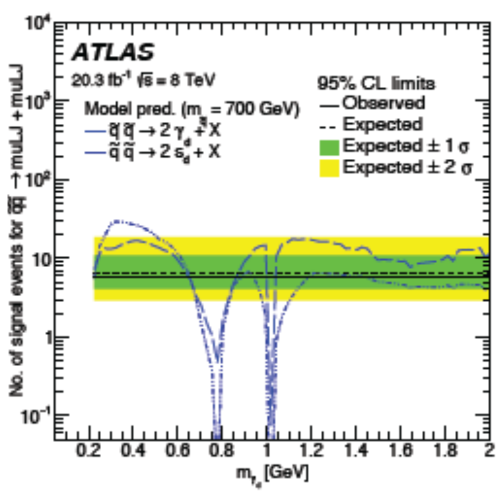
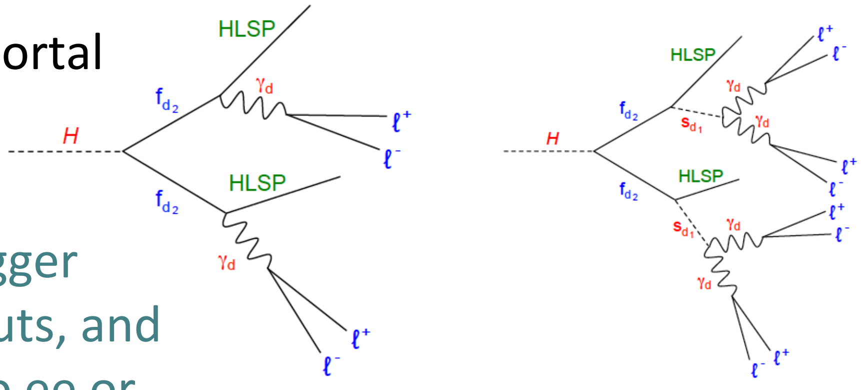






ATLAS Lepton Jets: Higgs Portal

- Same analysis, but now focus on Higgs Portal production
- Acceptance x Efficiency table:
  - Corresponds to $c\tau=0$ and Includes trigger selections, LJ reconstruction and ID cuts, and do not include the BRs for decays into ee or $\mu\mu$ pairs in each channel



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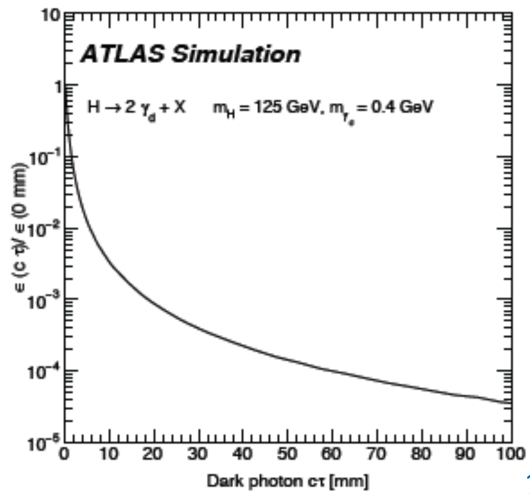
State Higgs-portal	eLJ–eLJ	muLJ–muLJ	eLJ–muLJ	eLJ–emuLJ	muLJ–emuLJ	emuLJ–emuLJ
$2\,\gamma_d + X$	0.23 ± 0.02 %	1.31 ± 0.04 %	0.20 ± 0.01 %	-	-	-
$2\,(s_d \to \gamma_d\gamma_d) + X$	0.03 ± 0.02 %	0.50 ± 0.07 %	0.08 ± 0.01 %	0.05 ± 0.01 %	0.22 ± 0.03 %	0.08 ± 0.02 %

  - To compare to results from non-LHC experiments, include dependence on mixing between dark photon and SM photon
    - Very small mixing implies non-negligible lifetime
  - Quantify dependence of the analysis on non-zero lifetime $c\tau$ of the dark photon



ATLAS Lepton Jets: Higgs Portal

- Set limits on the cross-section x branching H->2LJs as a function of cτ
- Reinterpret in terms of mixing parameter ε and mass

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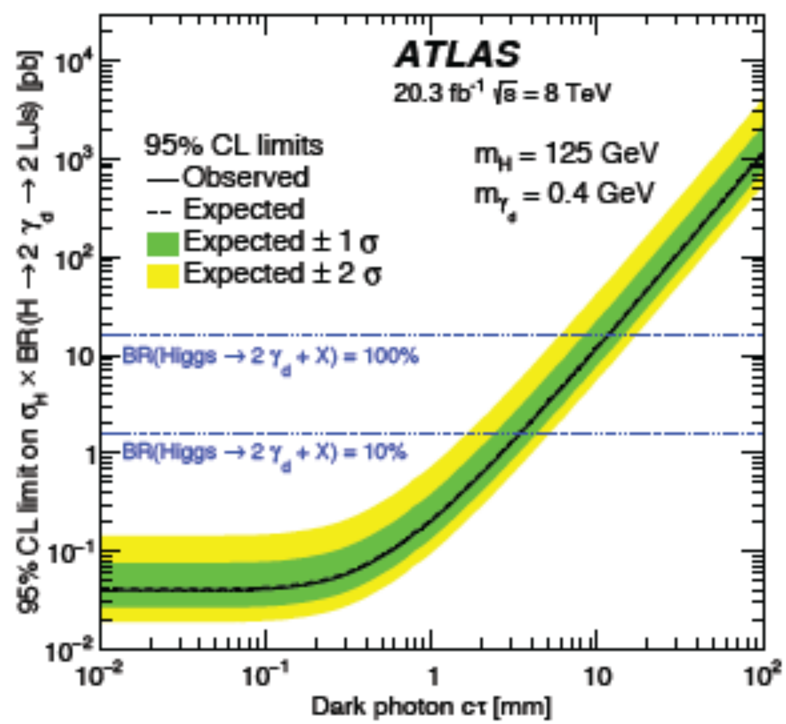
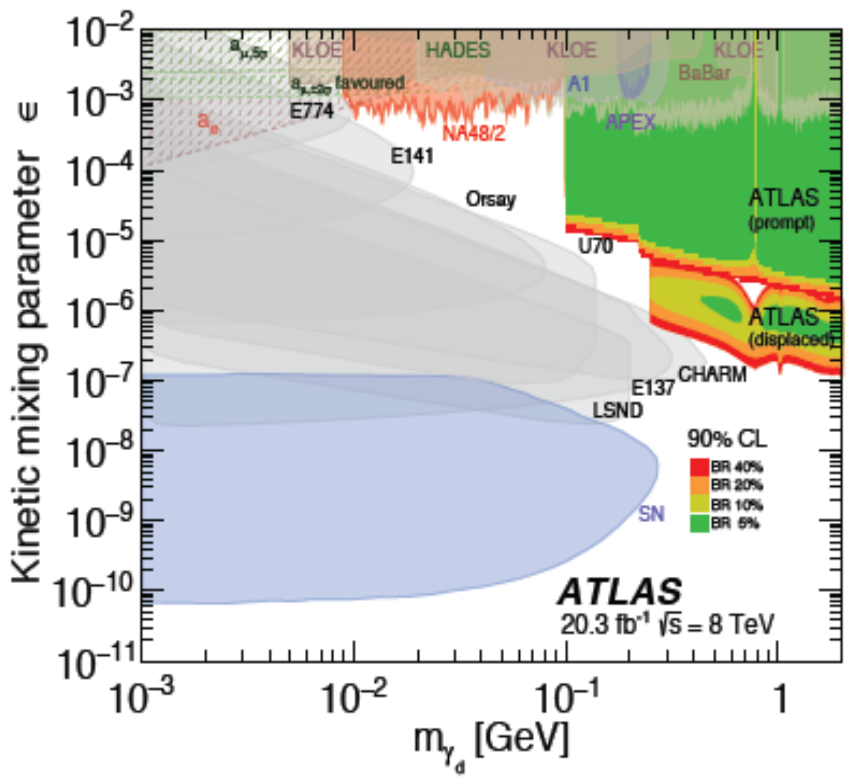
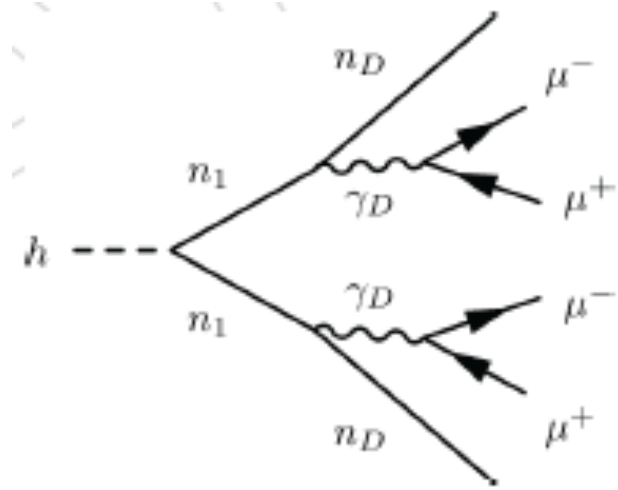




CMS Lepton Jets: Higgs Portal

- Update of the NMSSM 4μ search with 20 ifb of 8 TeV data
- Selections:
  - P_{T1}>17 GeV in η<0.9, $P_{T2/3/4}$>8 GeV anywhere in η<2.4
  - 2 pairs of close-by muons
    - Clustering based on the invariant mass
  - No requirement on 4μ mass
  - Isolations applied on dimuons
    - Else high backgrounds
- Search for the excess on the diagonal of m_1 vs m_2
- Heavy focus on preserving model-independent version of the results so they can be recast



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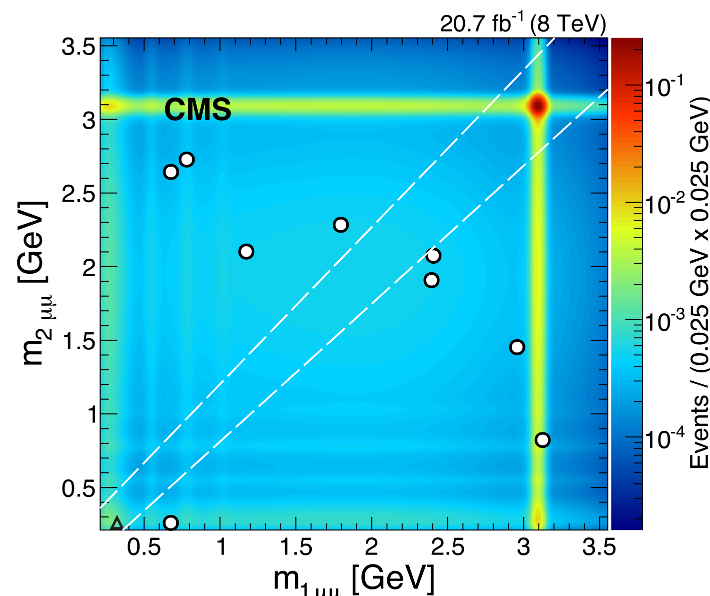
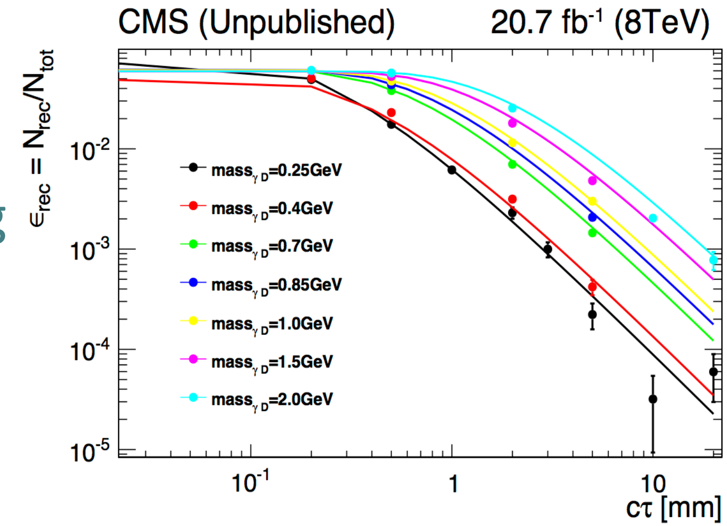


CMS Lepton Jets: Higgs Portal

- Quantified impact of selections on dark photons with non-zero lifetime
  - Depends on the strength of the mixing with the SM sector (SM photon)
- Benchmark using $h(125) \rightarrow n_1 n_1 \rightarrow (\gamma_D n_D)(\gamma_D n_D)$
  - Limits in ε_{mix} versus $m(\gamma_D)$ for a range of values for BR of SM-like Higgs to these states
    - Implies model dependence when comparing to low energy results
  - Nice complementarity with ATLAS analysis searching for decays far from the interaction point
    - Published before ATLAS "prompt" LJ search, now there is an ATLAS-only version of this plot



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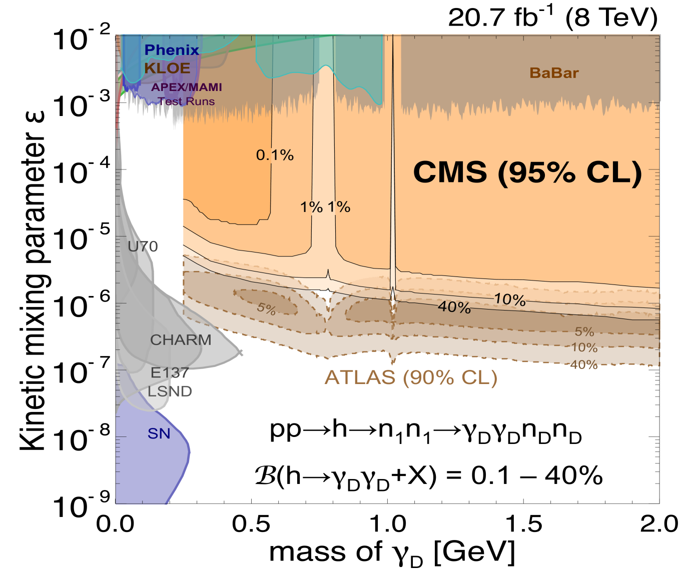

CMS Lepton Jets: Higgs Portal

- 8 TeV analysis: good acceptance for zero-lifetime case (sufficiently low p_T trigger)
  - But drops fast with cτ

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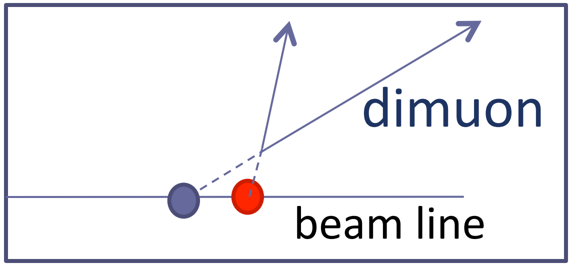
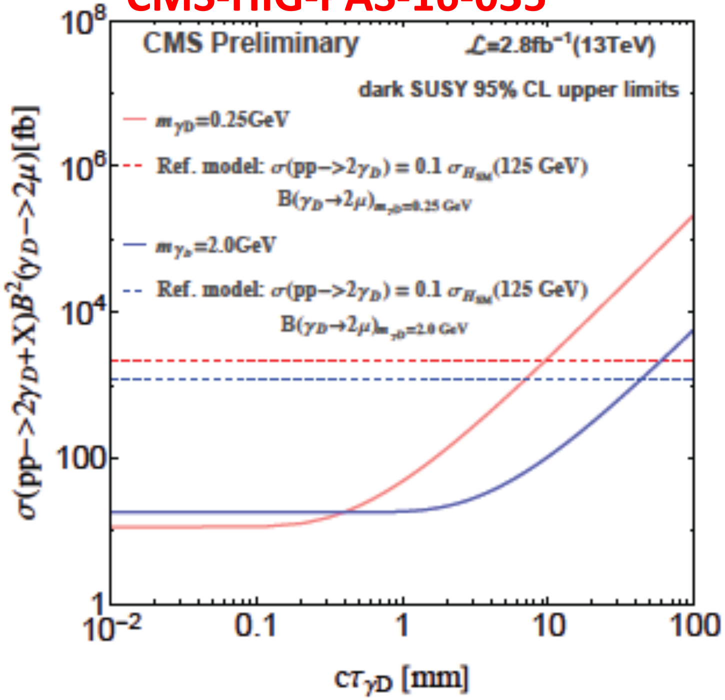
m_{γ_D} [GeV]		0.25			1.0	
$c\tau_{\gamma_D}$ [mm]	0	0.5	2	0	0.5	2
ϵ_{sim} [%]	8.85 ± 0.12	1.76 ± 0.05	0.23 ± 0.03	6.13 ± 0.23	4.73 ± 0.07	1.15 ± 0.04
α_{gen} [%]	14.32 ± 0.14	2.7 ± 0.06	0.31 ± 0.03	8.89 ± 0.28	6.98 ± 0.09	1.68 ± 0.05
$\epsilon_{sim}/\alpha_{gen}$	0.62 ± 0.01	0.65 ± 0.02	0.74 ± 0.13	0.69 ± 0.03	0.68 ± 0.01	0.68 ± 0.03

  - One cause is the trigger Δz cut



- Improvements for 13 TeV data:
  - New 3-muon trigger
    - P_T>15/5/5 GeV, no Δz requirement
  - Analysis selections re-designed and validated to improve higher cτ trend

CMS-HIG-PAS-16-035



CMS Lepton Jets: Higgs Portal

- CMS is also expanding mass range it looks at
  - If it is not just driven by positron/antiproton fractions, the 2 GeV is obsolete

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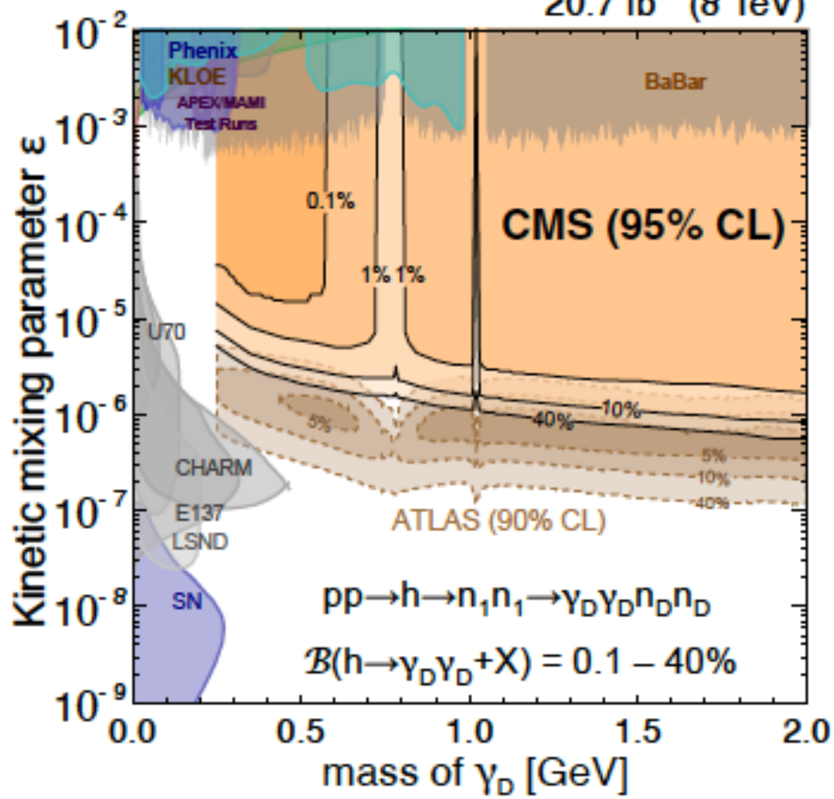

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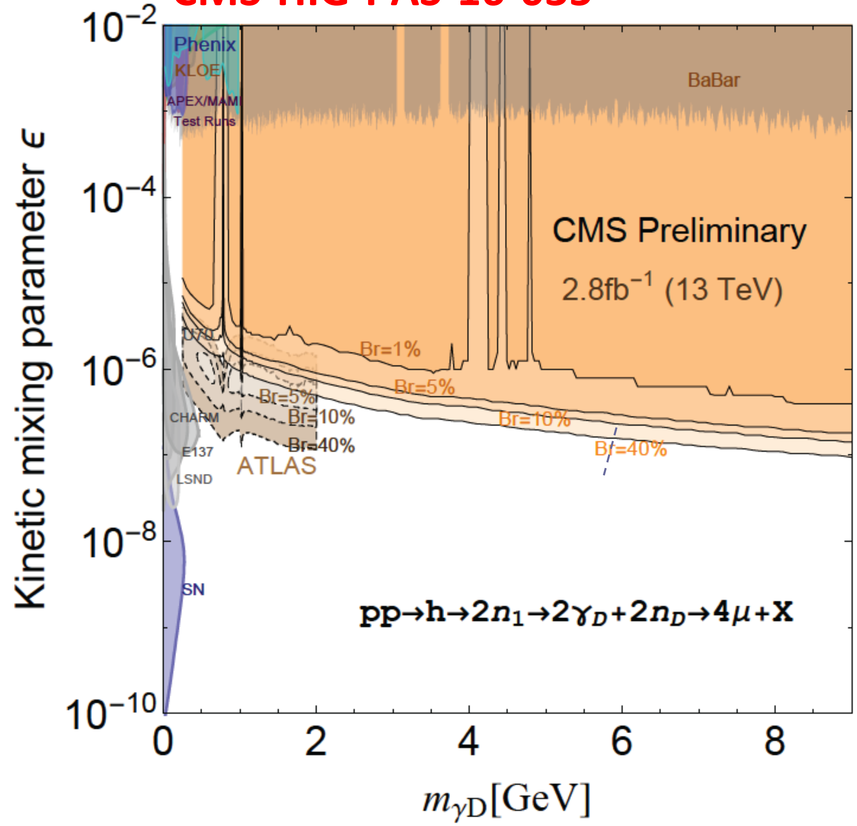


On Lepton Jet Search Strategies

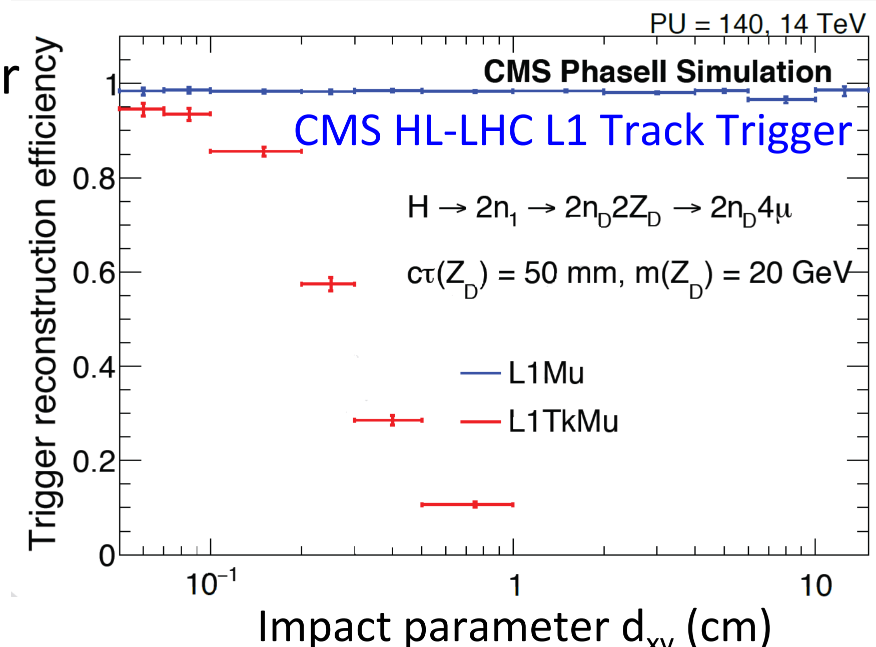
- CMS and ATLAS use different strategies to cope with the same difficulties
  - Signatures can vary widely, e.g. one can have many or few dark photons nearby depending on the complexity and mass spectrum of the dark sector and the coupling constant (lots of showering in the dark sector or little)
    - Lepton jets can be broad or narrow, isolated or highly non-isolated
- The problem is that one size does not fit all, could improve by slicing phase space of models into more specific benchmark “model lines”, e.g.
  - Small “dark coupling“ and simple dark spectrum (no cascades)
    - LJs with low multiplicity of dileptons (single dark photon)
  - Larger coupling or more evolved spectrum
  - Production kinematics types (LJs with high/low p_T)

On Lepton Jet Search Strategies

- Classify LJs by multiplicity in addition to the type (e/mu, used by ATLAS)?
  - Low multiplicity LJ (a pair of leptons), one can apply isolations
  - High multiplicity LJ (more than 2 leptons required)
    - Having extra leptons nearby ought to reduce background, can avoid isolations
- Divide mass range below and above 0.4?
  - If electrons and muons are accounted for, for m(γ_d) below 0.4 GeV, dark photon decays to hadrons never spoil isolation
- Classify LJs into high/low p_T LJs?
  - If looking for LJs arising from decays of ~TeV like objects (SUSY portal), why not explicitly search for LJs w/ p_T>200-300 GeV?
  - Higher thresholds will suppress backgrounds, no need to use isolations
    - A pair of 100 GeV muons close-by is rare, five 40 GeV muons nearby would be pretty striking too
- Mass clustering instead of cone-based algorithm?
  - Would better capture contents of the lepton jets in cascade decays

Outlook for HL-LHC

- HL-LHC luminosity seems like a perfect time to search for rare exotic Higgs decays involving long lived signatures
- Experimentally, this can become exponentially more difficult
  - Much increased rates drive trigger rates up, but Higgs is not going to be any heavier
  - Occupancies will make reconstruction and identification much harder
- Current detectors were not built for this purpose
  - Important to make sure upgraded detectors have necessary capabilities
    - CMS: w/o standalone muon trigger we will lose long lived muons
- Decisions depend on the input from theory community



Summary

- A good number of results on lepton jets over the years from both CMS and ATLAS
- Continuous improvements of the analyses, e.g. long-lived LJs, trigger improvements etc.
- Somewhat different strategies and different strengths
  - ATLAS includes electrons in LJs (sensitivity to lower masses), more inclusive reconstruction
  - CMS reconstructs LJ's content and measures dark photon mass – less backgrounds
- Some unification of benchmarks and reconstruction could be very beneficial
  - Will allow better sensitivity and easier to compare results