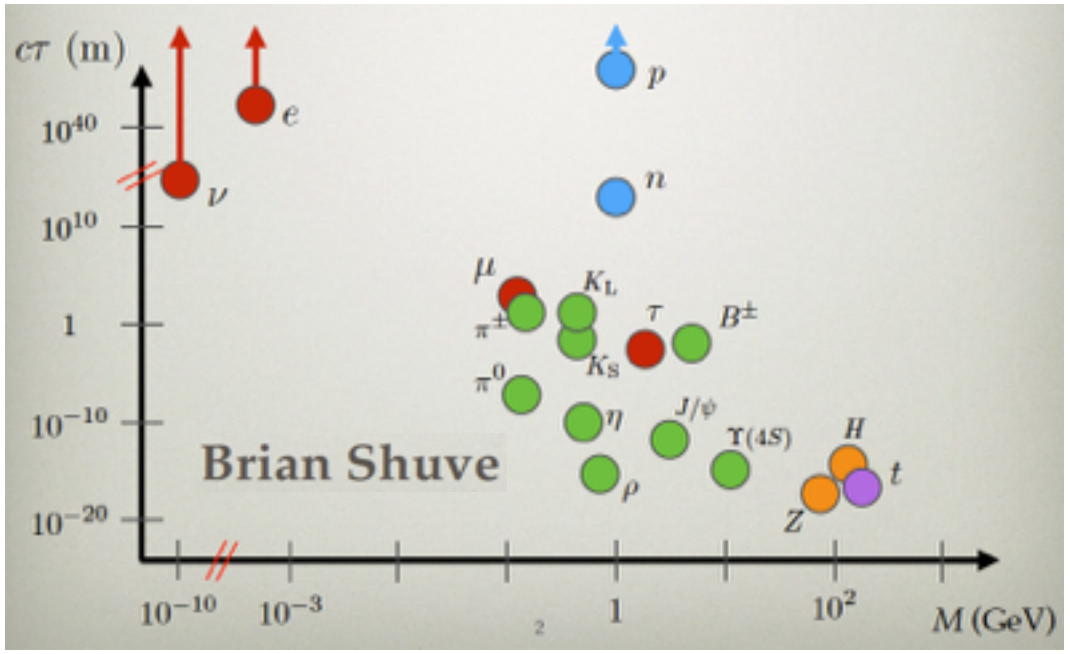
Long lived particle decay searches @ LHC

Simone Gennai
on behalf of the
ATLAS, CMS and LHCb Collaborations

Why searching for LLP?

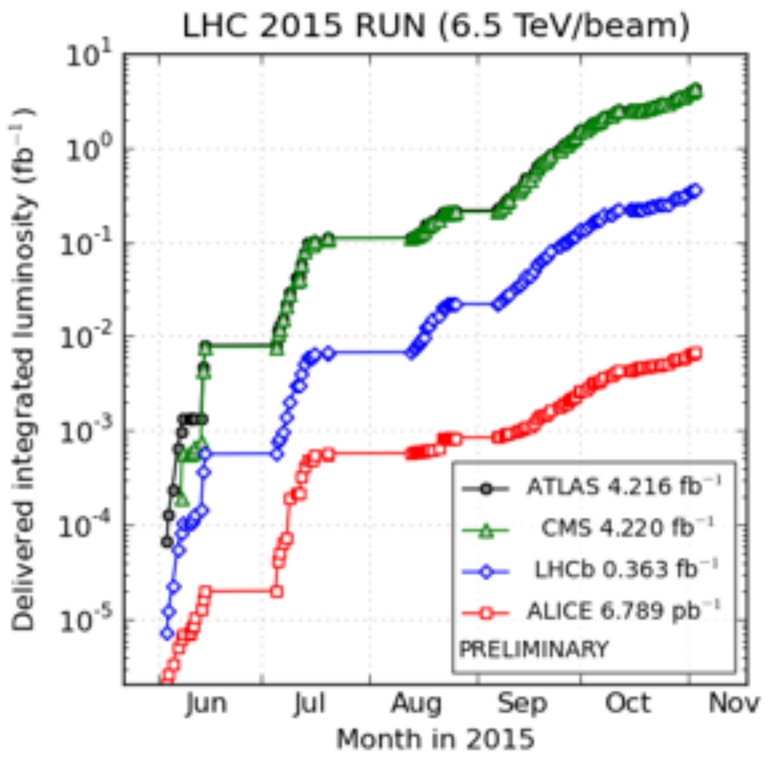


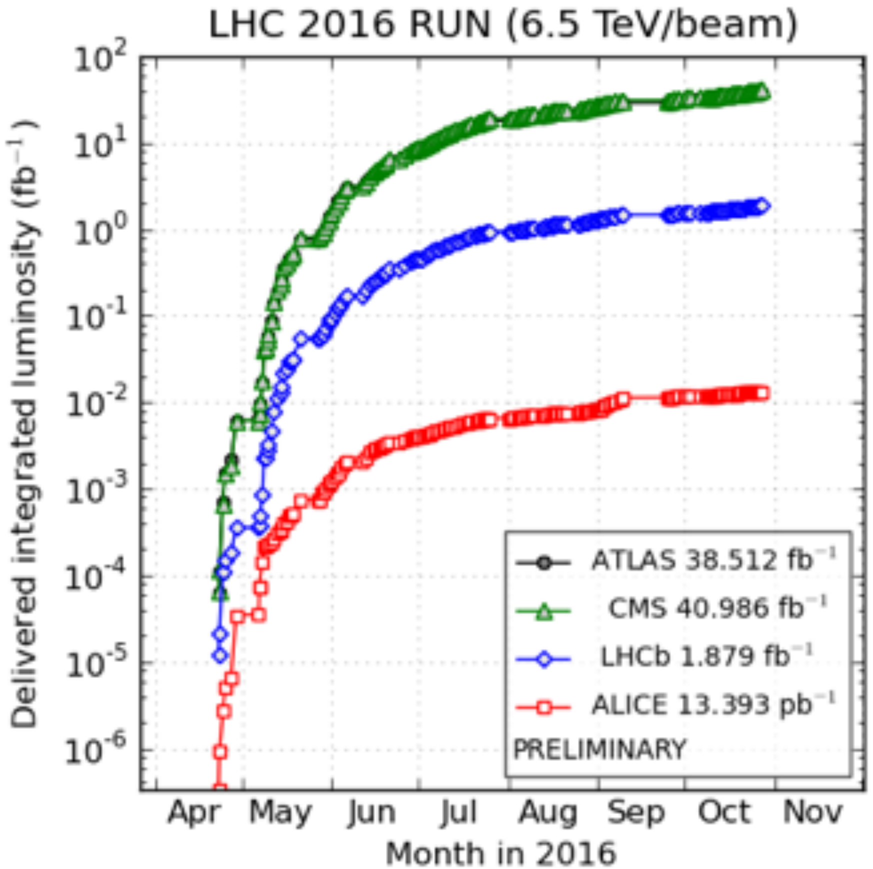
- Standard Model includes quite few LLP
  - it is natural to assume they can populate BSM theories as well
  - we cannot exclude we have not seen susy because we were concentrating on prompt particle decays!
- There are several models that can predict LLP
  - Split susy
  - Stealth susy
  - RPV susy
  - Hidden valley (HV), dark bosons, etc. etc.
- From the experimental point of view they give raise to different signatures
  - depending on the number of particles in the final state, and their spectrum in pT
- A non zero lifetime adds a further dimension in the sea of possible topologies to consider
  - this poses yet another challenge for those final states that requires ad hoc reconstruction techniques
- Excellent review in October 2017:
  - https://indico.cern.ch/event/649760/timetable/

Simone.Gennai@cern.ch

Data analyzed

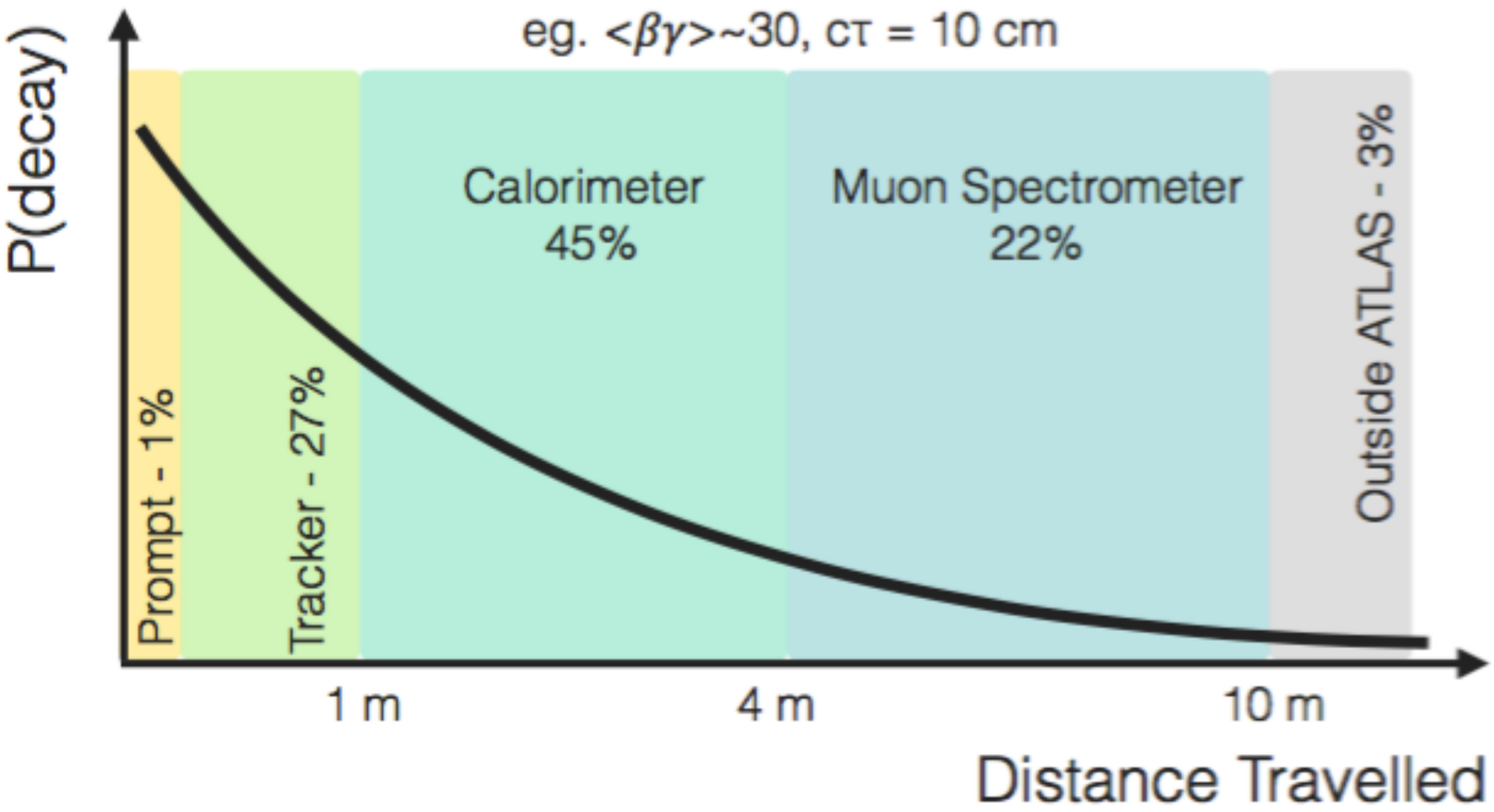
- LHC performed very well in Run2!
  - more than 40/fb collected in 2015 and 2016
- I will concentrate mostly on analysis using this data sample
- I will deal with decaying particles
  - i.e. no HSCP will be discussed
    - anyway you can find them in the back up …

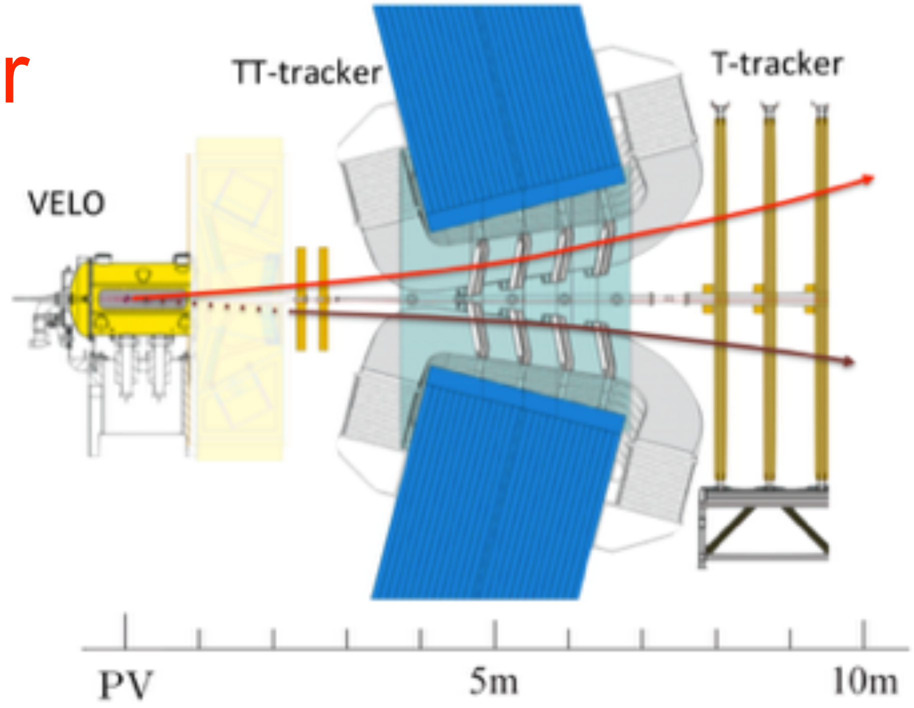




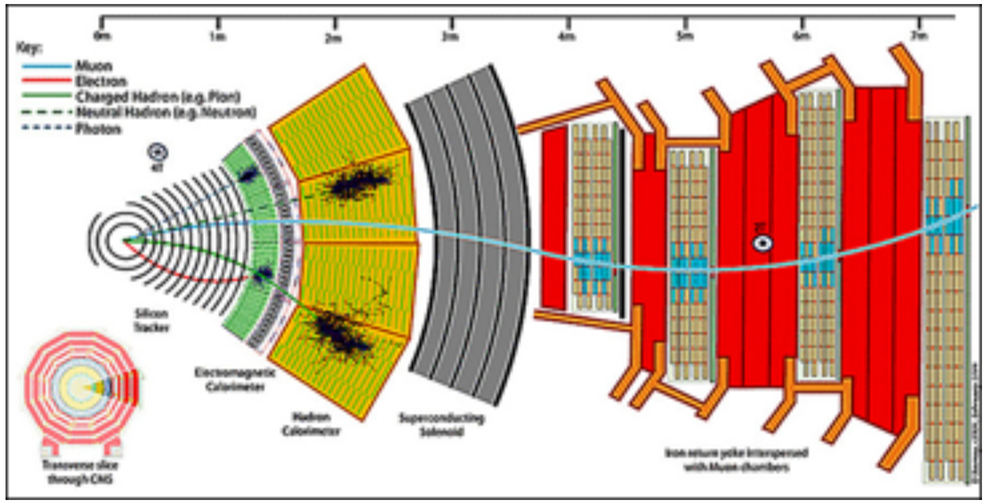
Disclaimer

- Particles with a similar lifetime may leave different signals in different experiments
  - on the other hand different phenomenological models can give similar signature
- I will try to group similar signatures together
  - even if different experiments may have considered different models and the results may not always be directly comparable

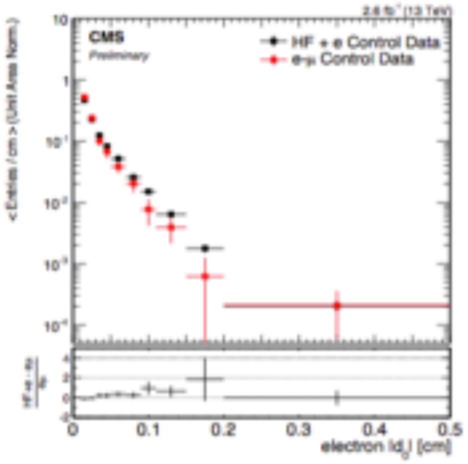


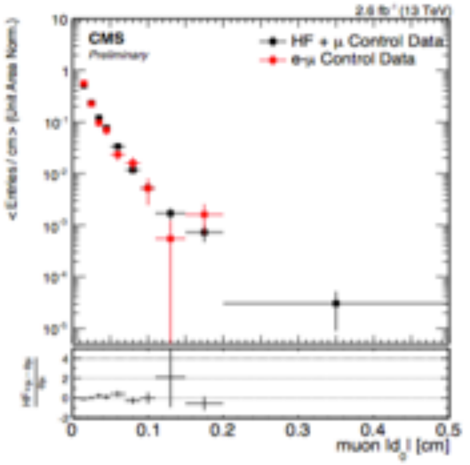


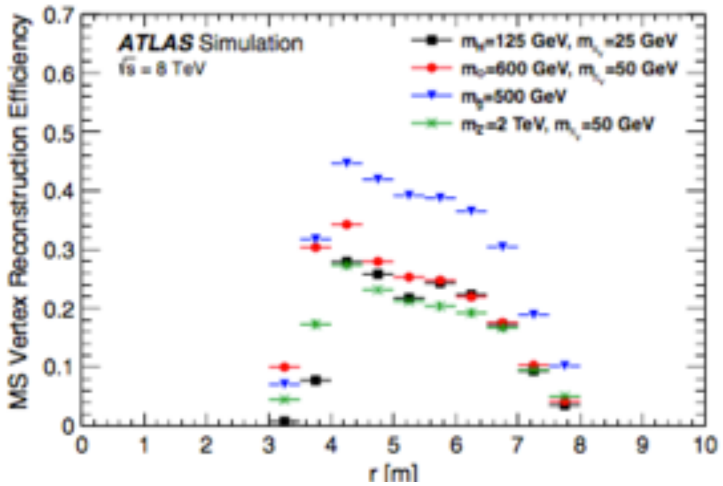
1m 2m 3m 4m

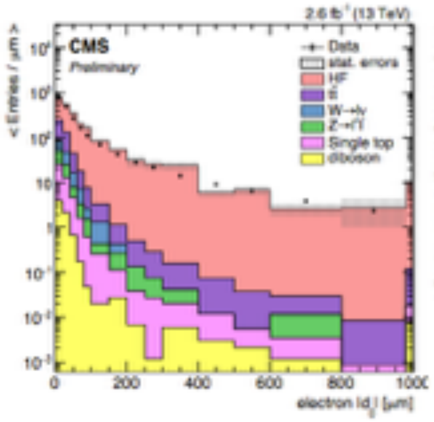


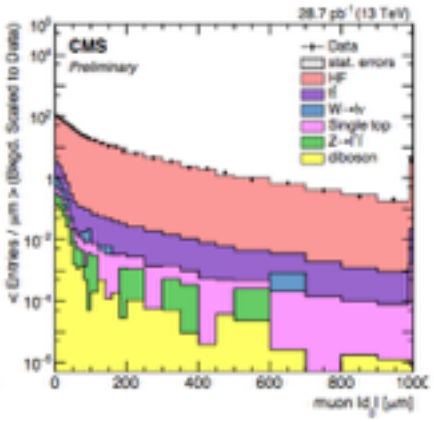
Reconstructing displaced particles

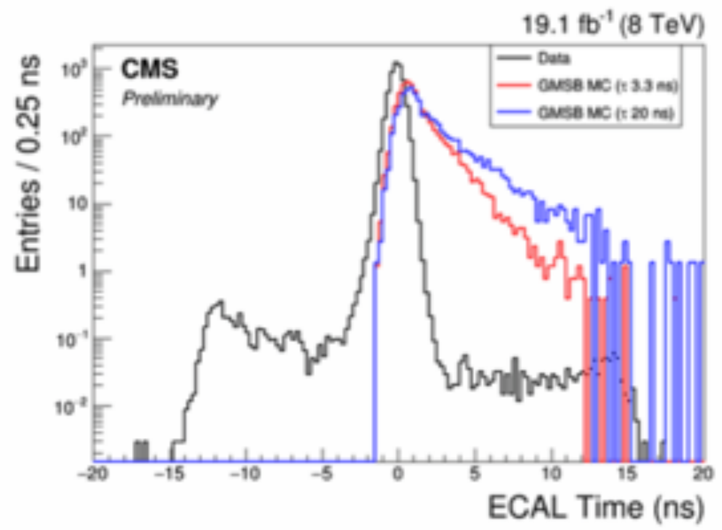


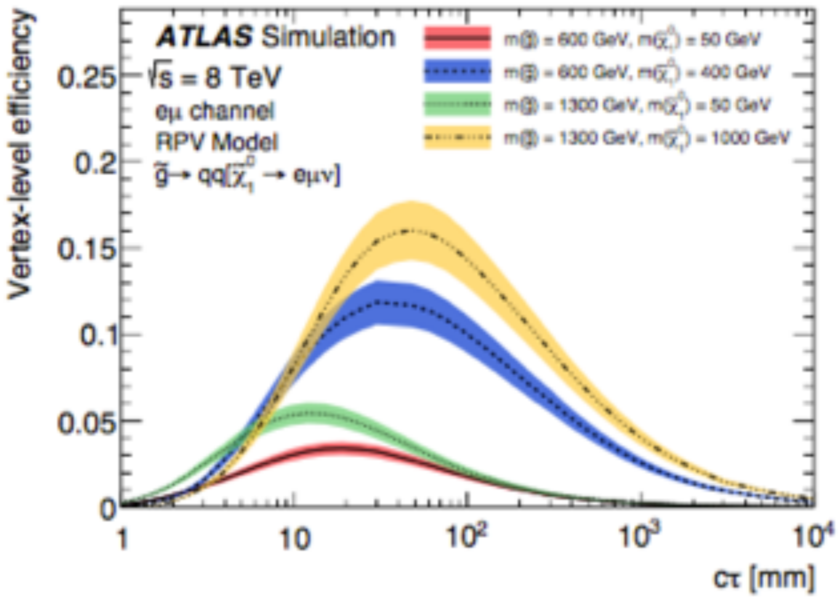


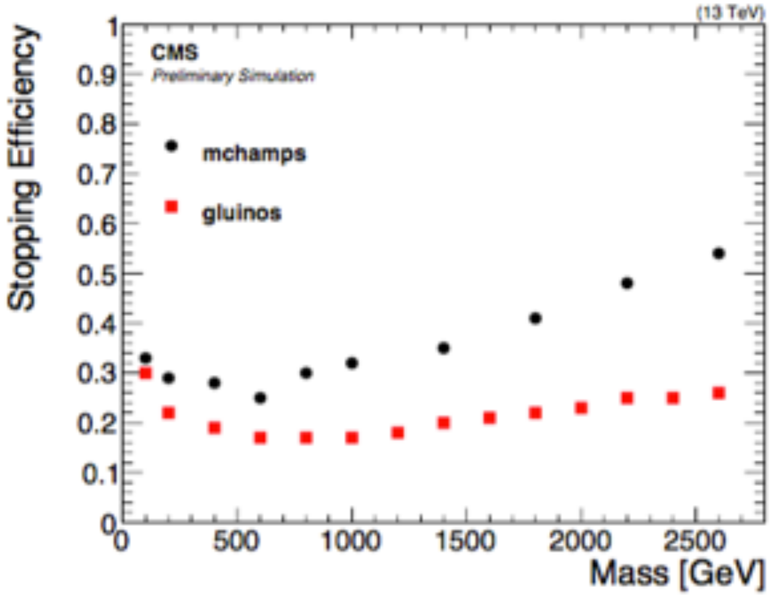


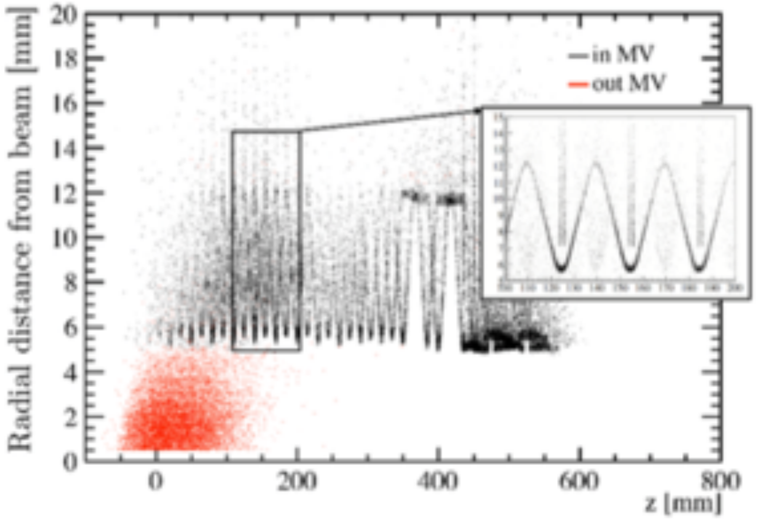


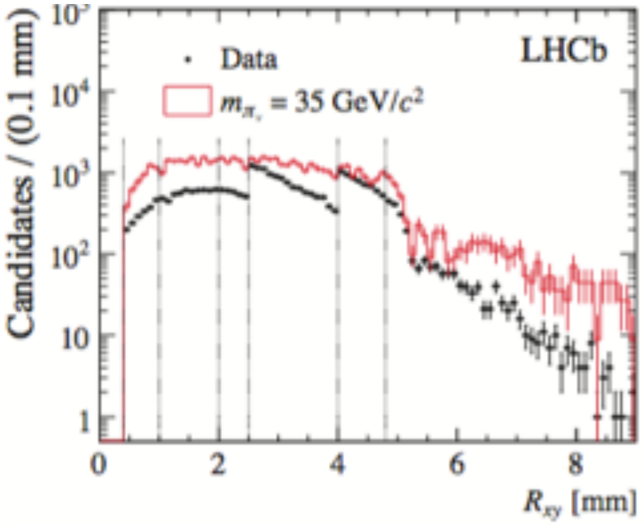


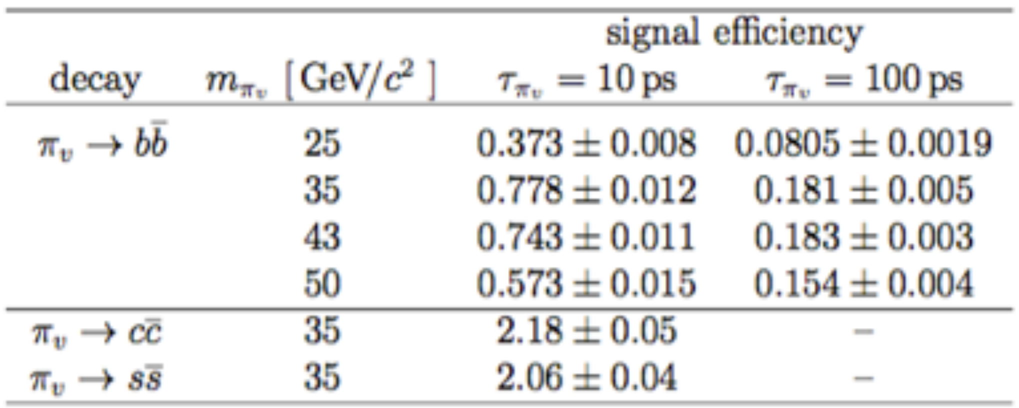






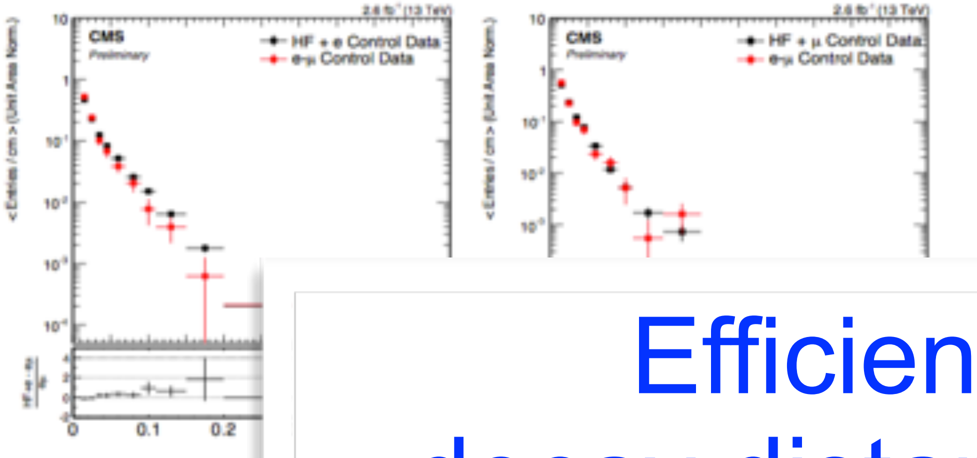


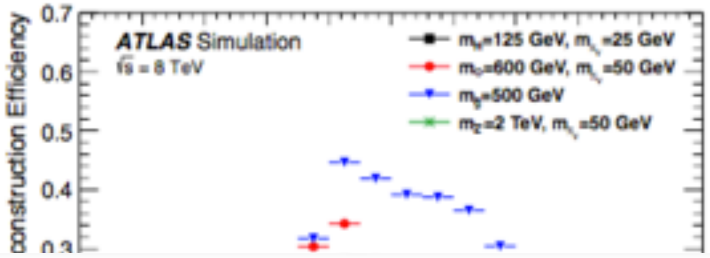


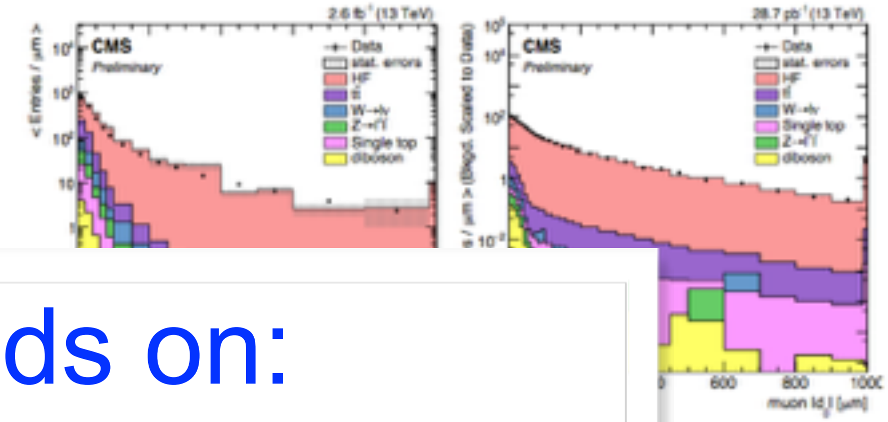


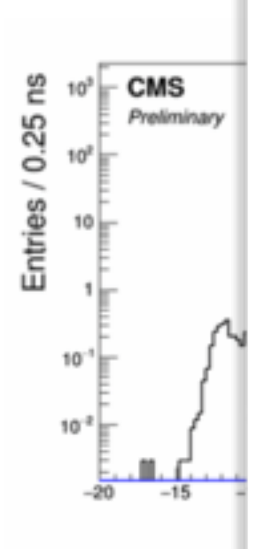
decay	m_{π_v} [GeV/c^2]	signal efficiency $\tau_{\pi_v} = 10$ ps	signal efficiency $\tau_{\pi_v} = 100$ ps
$\pi_v \to b\bar{b}$	25	0.373 ± 0.008	0.0805 ± 0.0019
	35	0.778 ± 0.012	0.181 ± 0.005
	43	0.743 ± 0.011	0.183 ± 0.003
	50	0.573 ± 0.015	0.154 ± 0.004
$\pi_v \to c\bar{c}$	35	2.18 ± 0.05	–
$\pi_v \to s\bar{s}$	35	2.06 ± 0.04	–

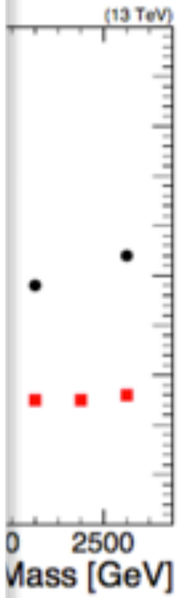
Reconstructing displaced particles







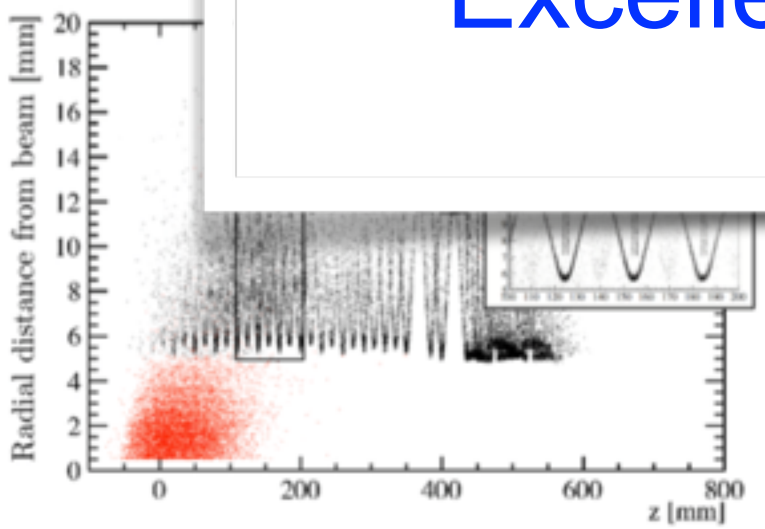


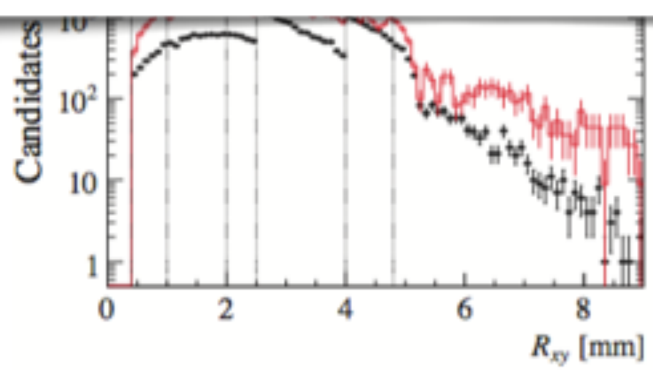


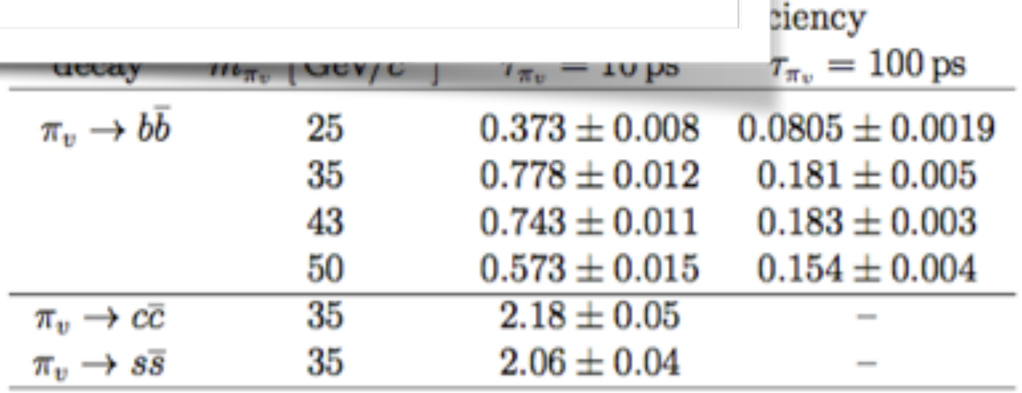
Efficiency usually depends on:
decay distance, time distribution, speed

Acceptance may change as a function of the mother particle mass due to the boost

Excellent knowledge of the detector material is required







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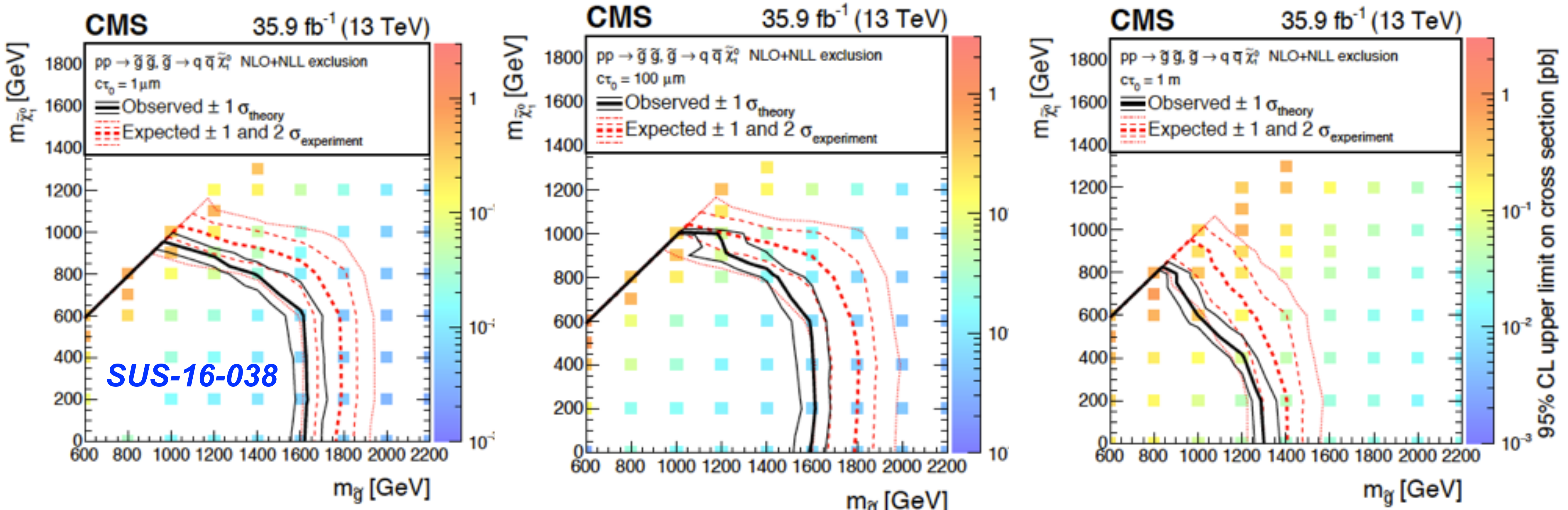
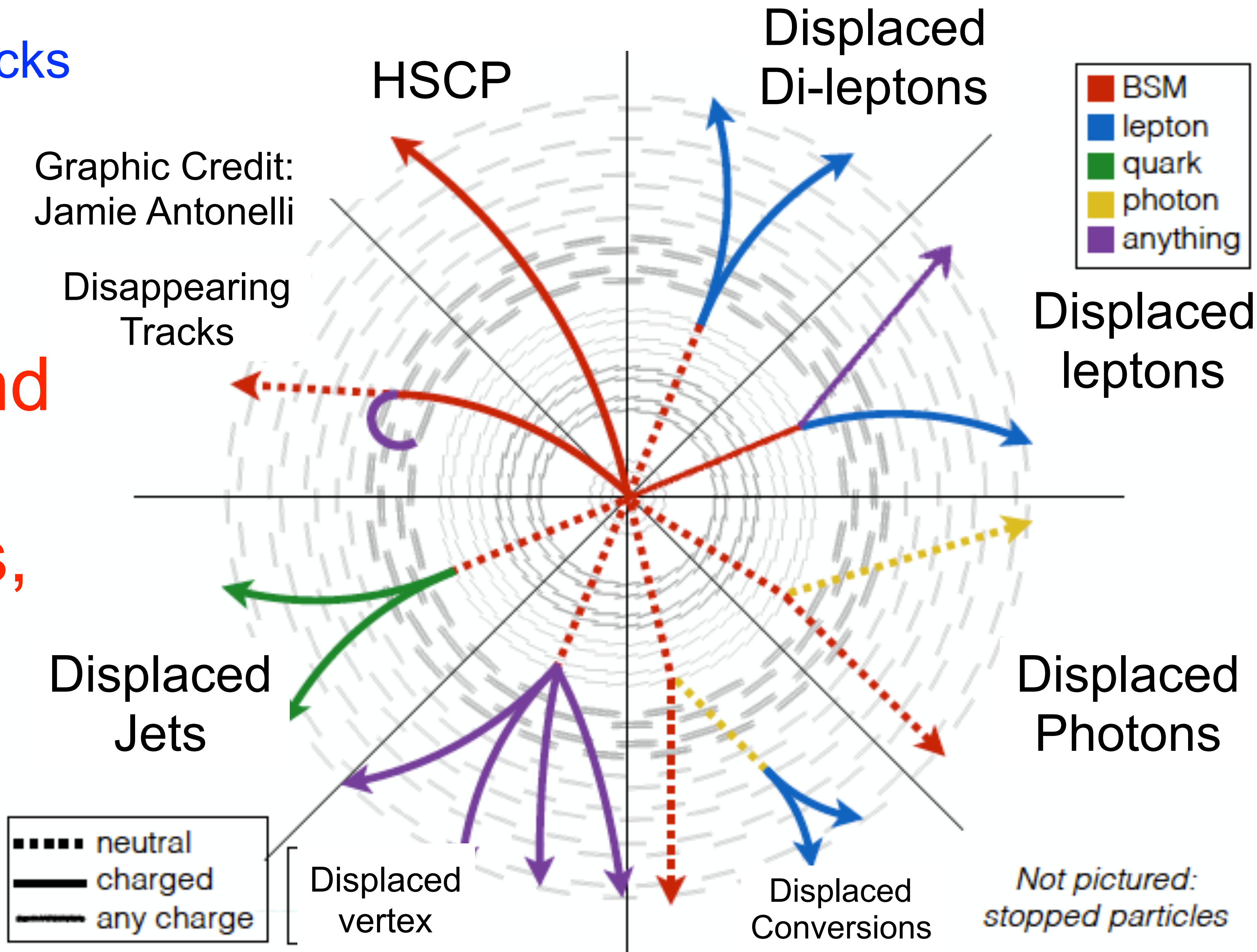
Re-interpretation of prompt searches

- "Poor man" approach
  - do not need any special reconstruction
  - consider loss in acceptance due to non zero lifetime
    - or category migration due to the presence of more b-like tagged particles
- Impact measured in terms of exclusion limits
  - an example from CMS: search for split supersymmetry



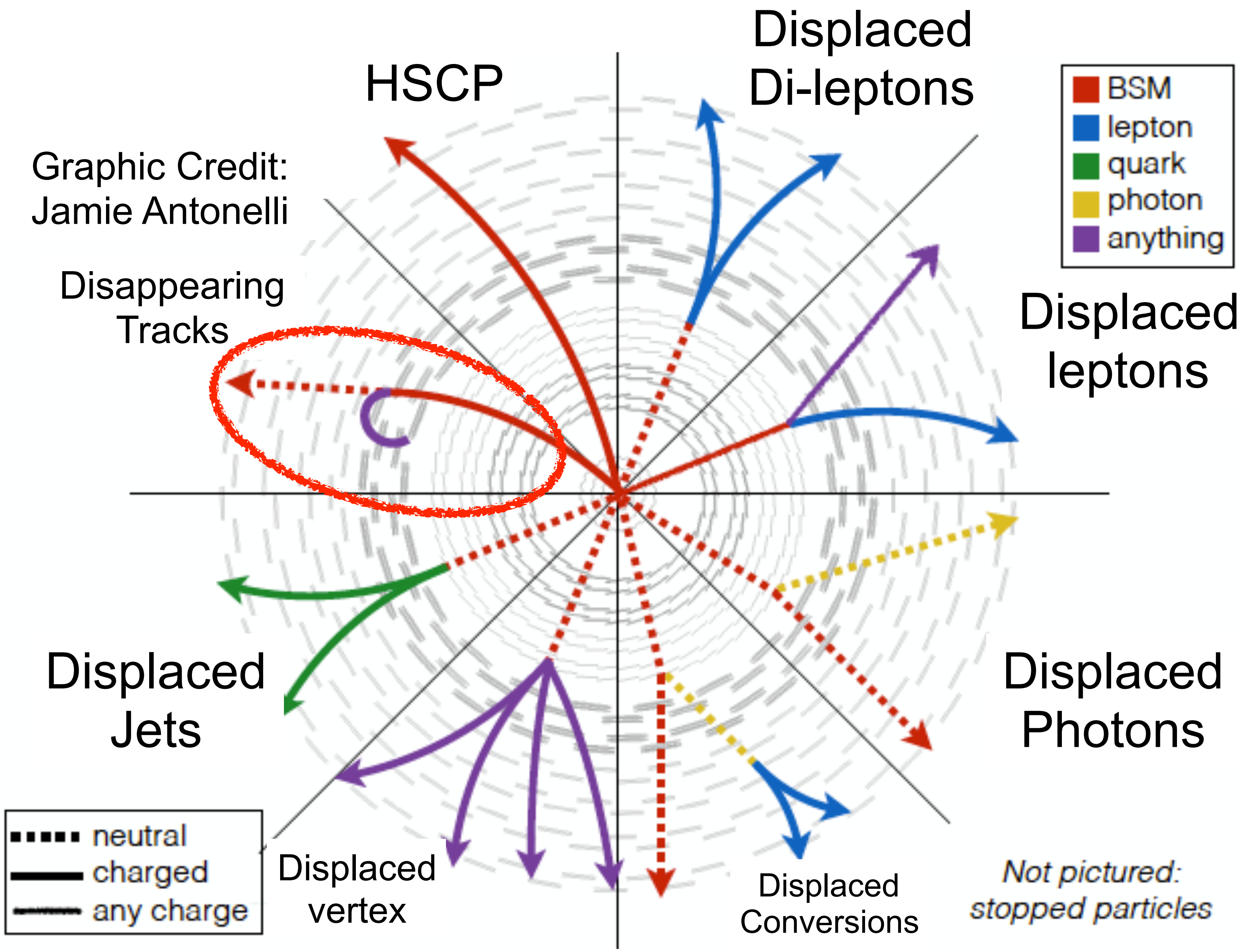
Displaced signal topologies

- Different signatures may requires special triggers and offline reconstruction
  - narrow jets, displaced and delayed calorimeter/muon reconstruction
  - Large impact parameter tracks
- In many cases non “standard" background from cosmic rays, beam induced events, detector material interactions



Graphic Credit: Jamie Antonelli

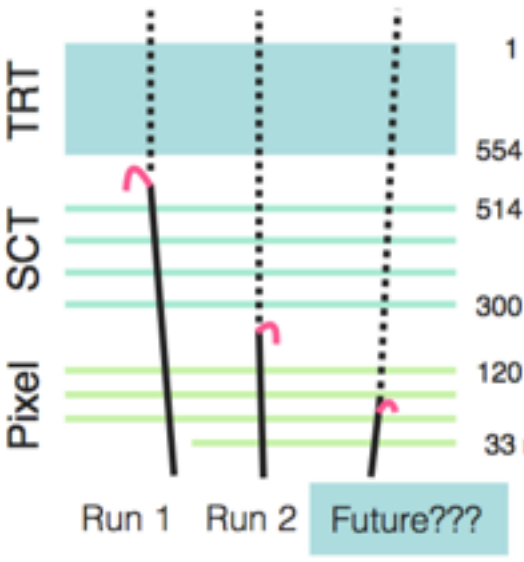
Disappearing tracks

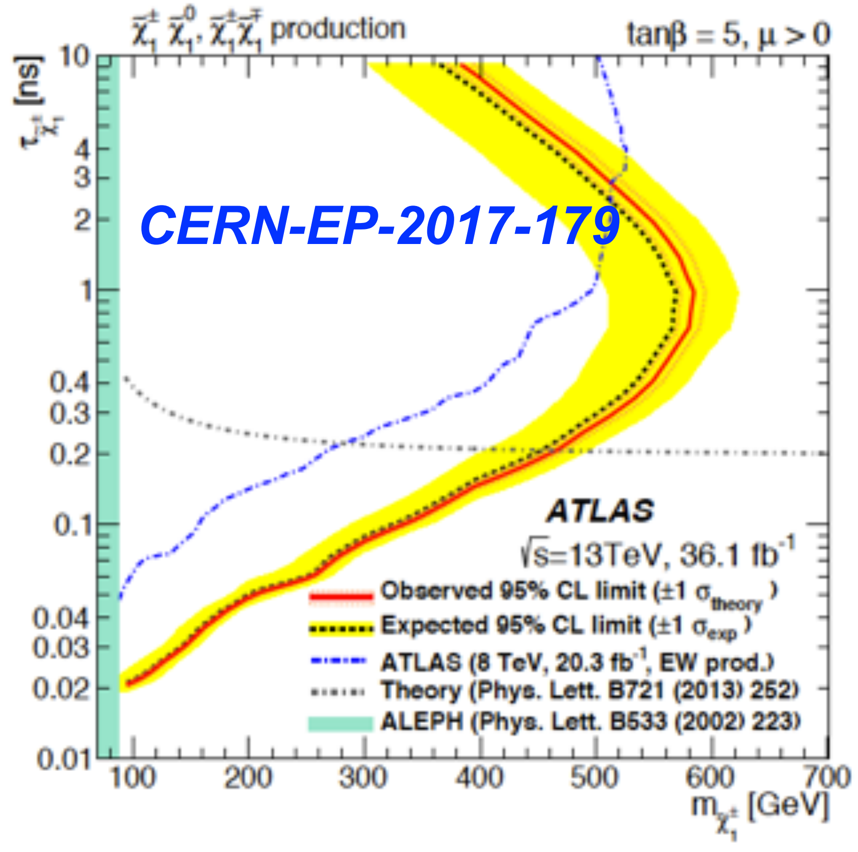


Graphic Credit: Jamie Antonelli

N.B. 1 ns corresponds to 30 cm

ATLAS and CMS Disappearing tracks





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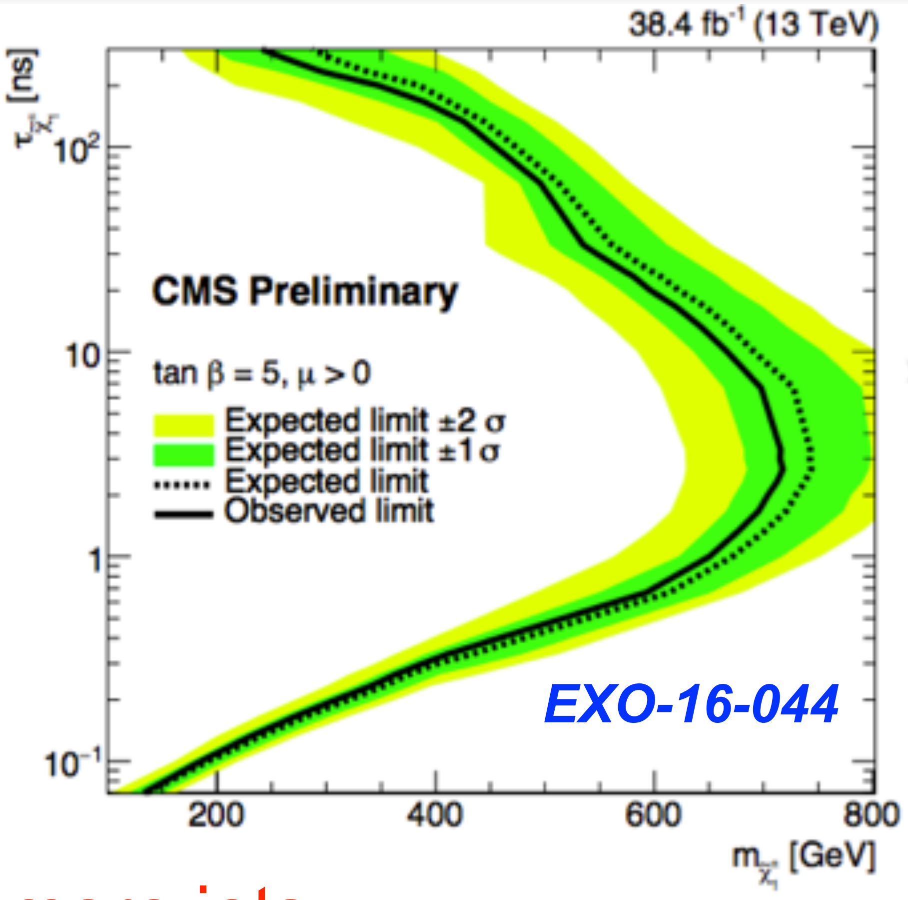
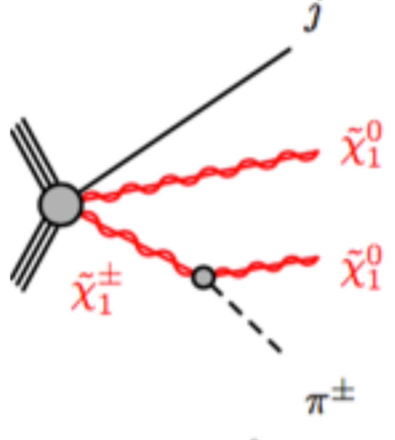
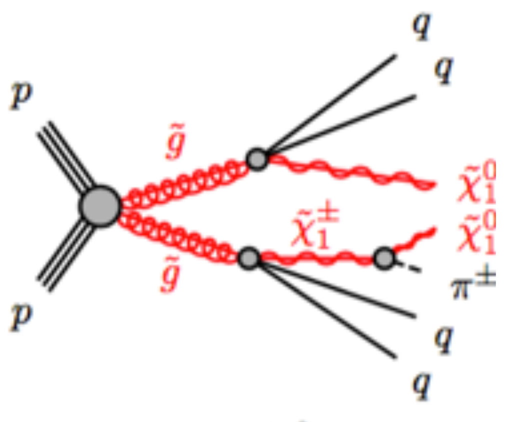


EXO-16-044

- ☐ Chargino and neutralino production plus one or more jets
  - ☐ triggering on the rest of the events
- ☐ Very few events expected, almost background free…



(a) $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0 j$



(b) $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0 qqqq$

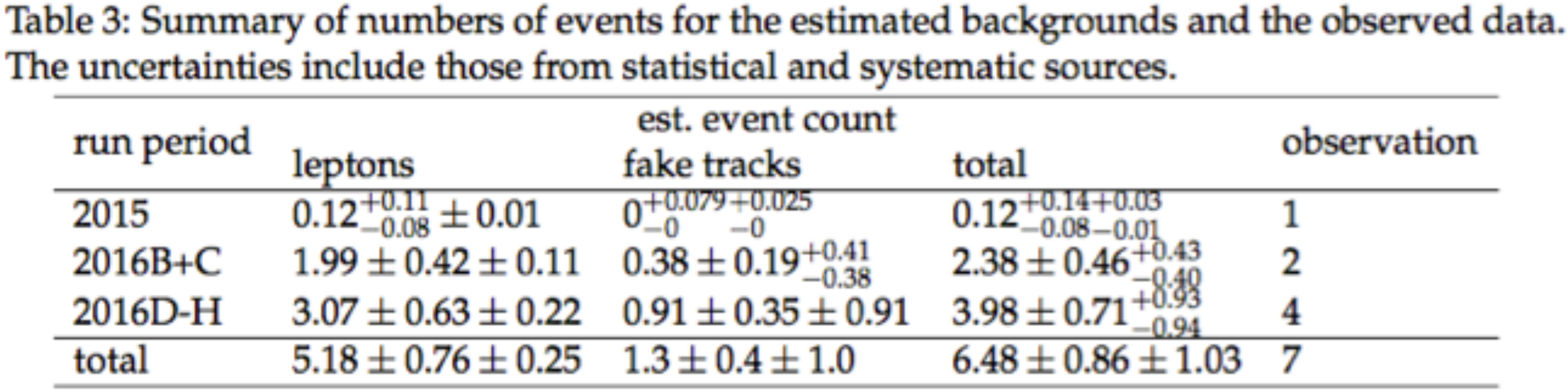
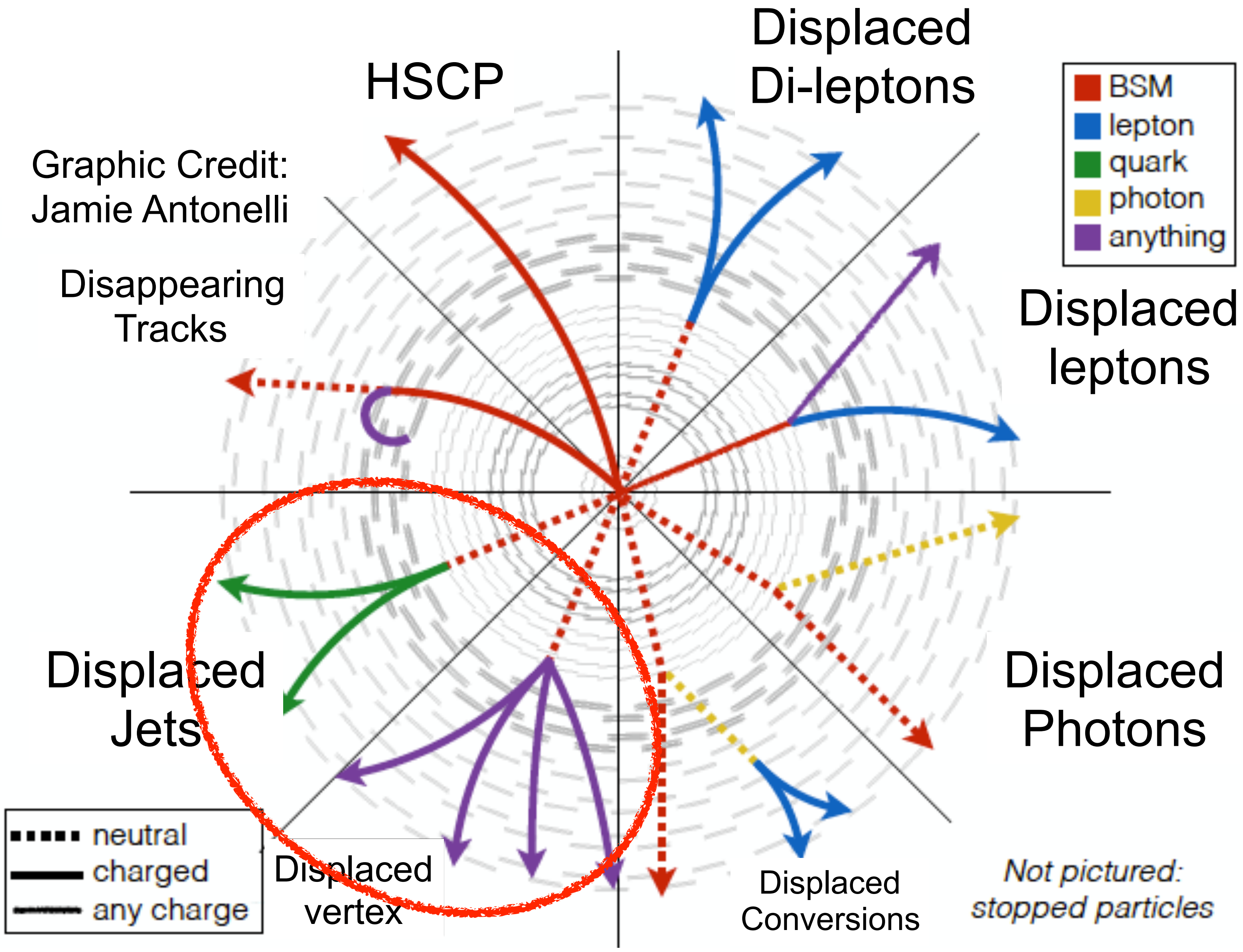


Table 3: Summary of numbers of events for the estimated backgrounds and the observed data. The uncertainties include those from statistical and systematic sources.

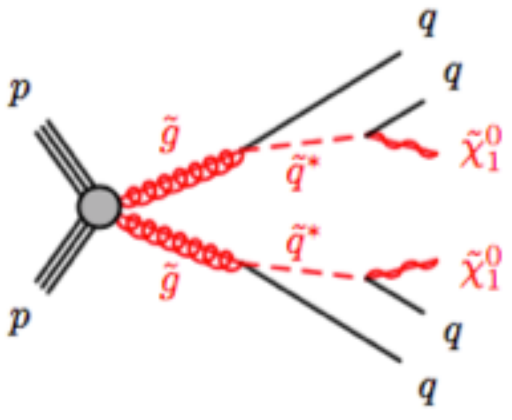
run period	est. event count			observation
	leptons	fake tracks	total	
2015	$0.12^{+0.11}_{-0.08} \pm 0.01$	$0^{+0.079}_{-0}{}^{+0.025}_{-0}$	$0.12^{+0.14}_{-0.08}{}^{+0.03}_{-0.01}$	1
2016B+C	$1.99 \pm 0.42 \pm 0.11$	$0.38 \pm 0.19^{+0.41}_{-0.38}$	$2.38 \pm 0.46^{+0.43}_{-0.40}$	2
2016D-H	$3.07 \pm 0.63 \pm 0.22$	$0.91 \pm 0.35 \pm 0.91$	$3.98 \pm 0.71^{+0.93}_{-0.94}$	4
total	$5.18 \pm 0.76 \pm 0.25$	$1.3 \pm 0.4 \pm 1.0$	$6.48 \pm 0.86 \pm 1.03$	7

Displaced vertices

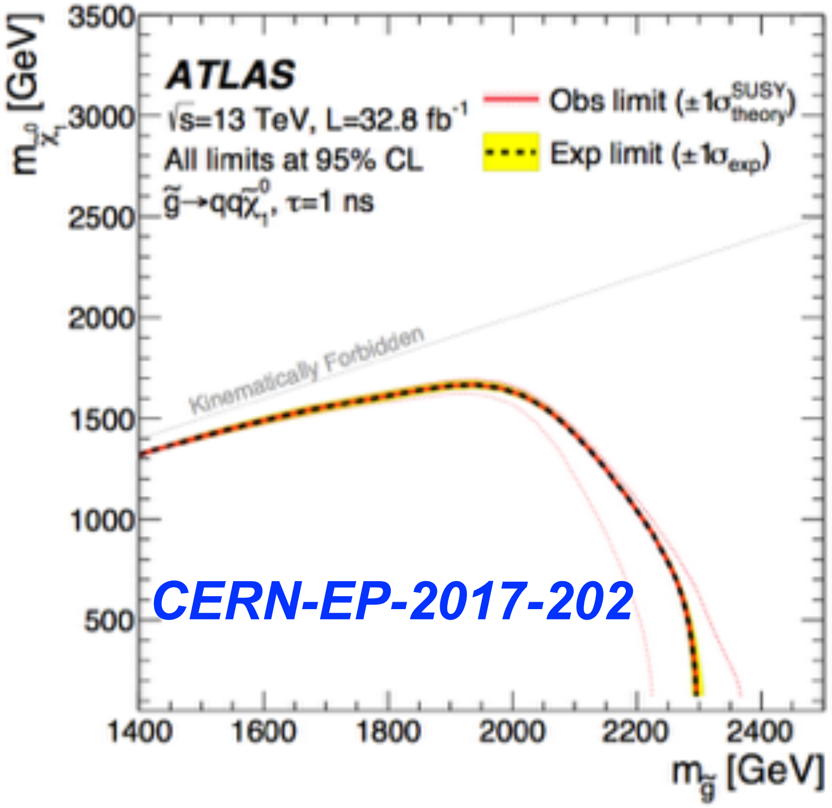


ATLAS and CMS Displaced vertices and appearing jets

- Broad class of signatures
  - Massive particles decaying with displaced vertices associated to large number of track based invariant mass
    - ATALS looks for long lived gluinos in split susy
    - CMS aims to a model independent search and interprets the results in a couple of benchmark scenarios one being stop production in RPV decays to b-quarks+leptons
      - makes use of an ad hoc trigger to select jets associated to displaced tracks



- One of the main background coming from interactions with the detector material.
  - detailed maps with the material descriptions are used to compute the interaction probability



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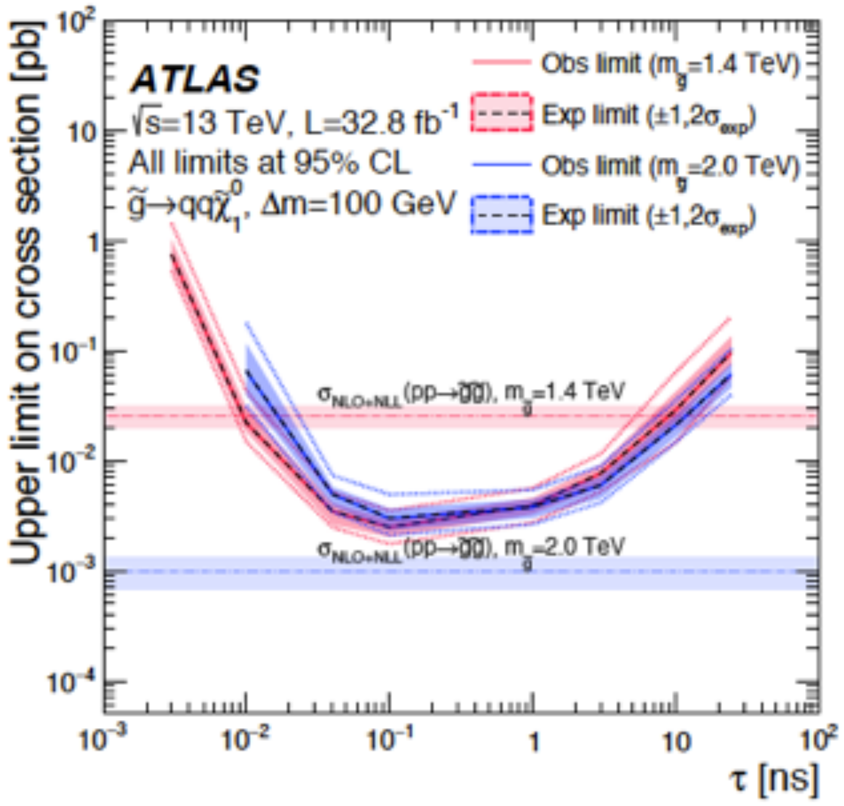
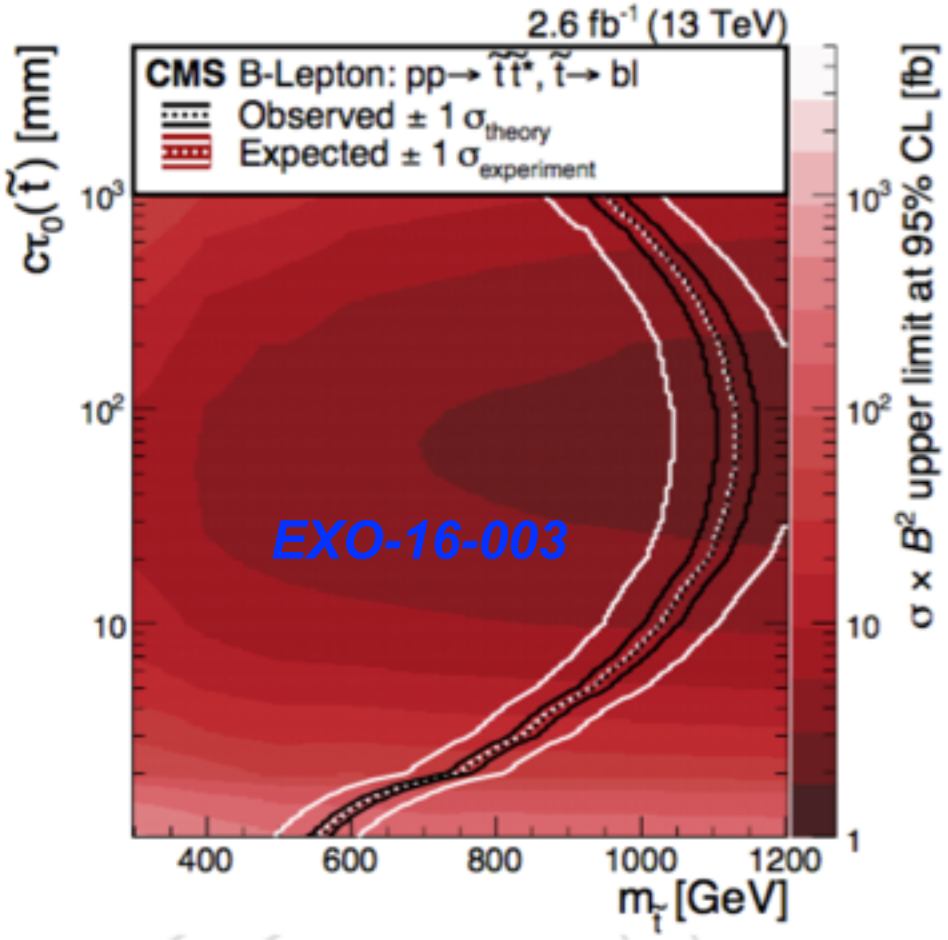
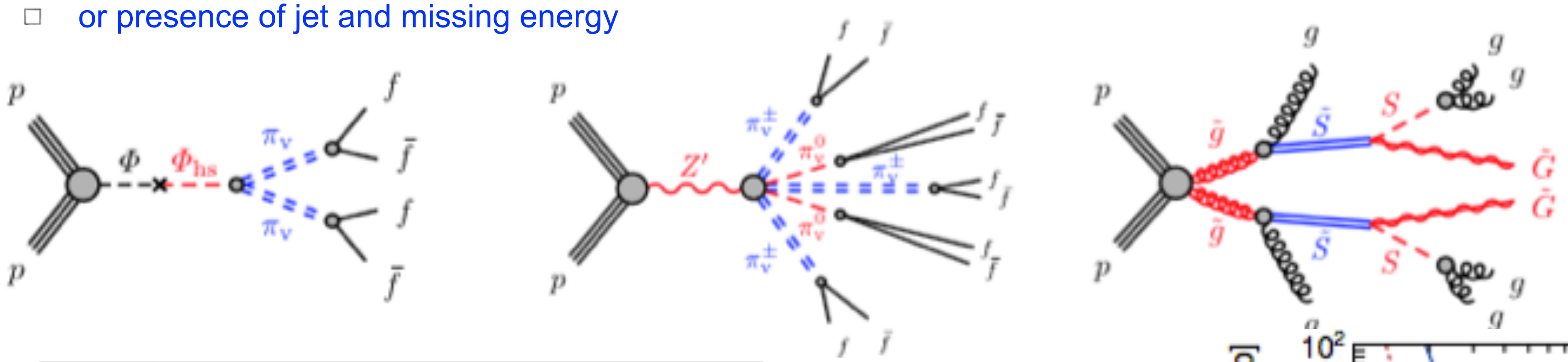




EXO-16-003

ATLAS Displaced Jets (from Run I)

- Different models considered with a variable number of jets in the final state (looking for longer lifetime wrt the previous slide)
  - Hidden valley scalar and large mass mediator
  - Stealth susy
- Differently from Run 2 analysis, this also exploits the presence of secondary vertices reconstructed in the muon system (larger lifetimes considered)
- Trigger based on:
  - clustered tracks in the muon spectrometer
  - or presence of jet and missing energy



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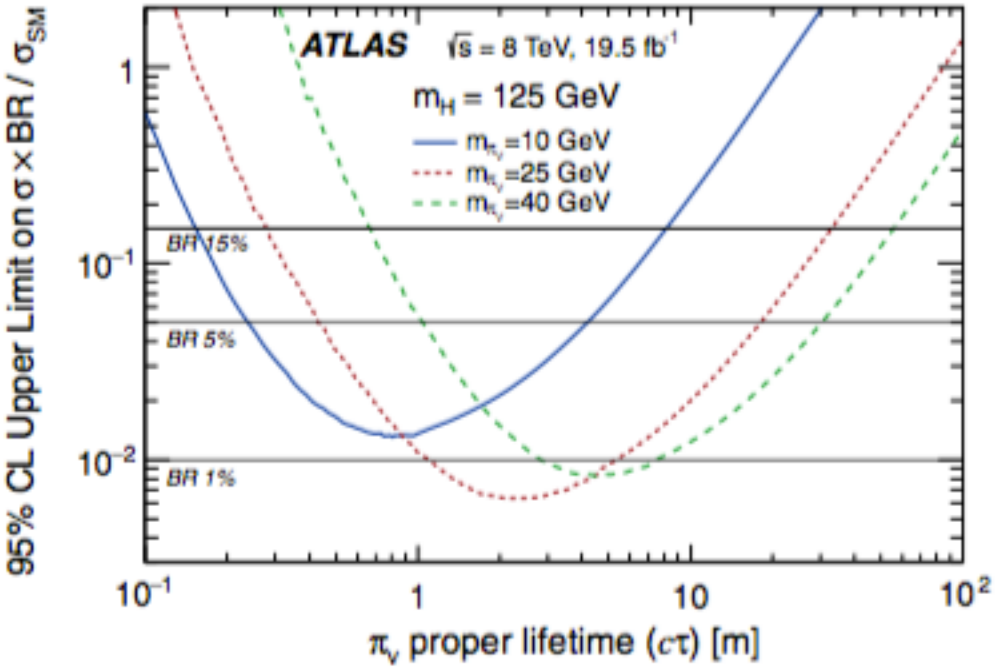
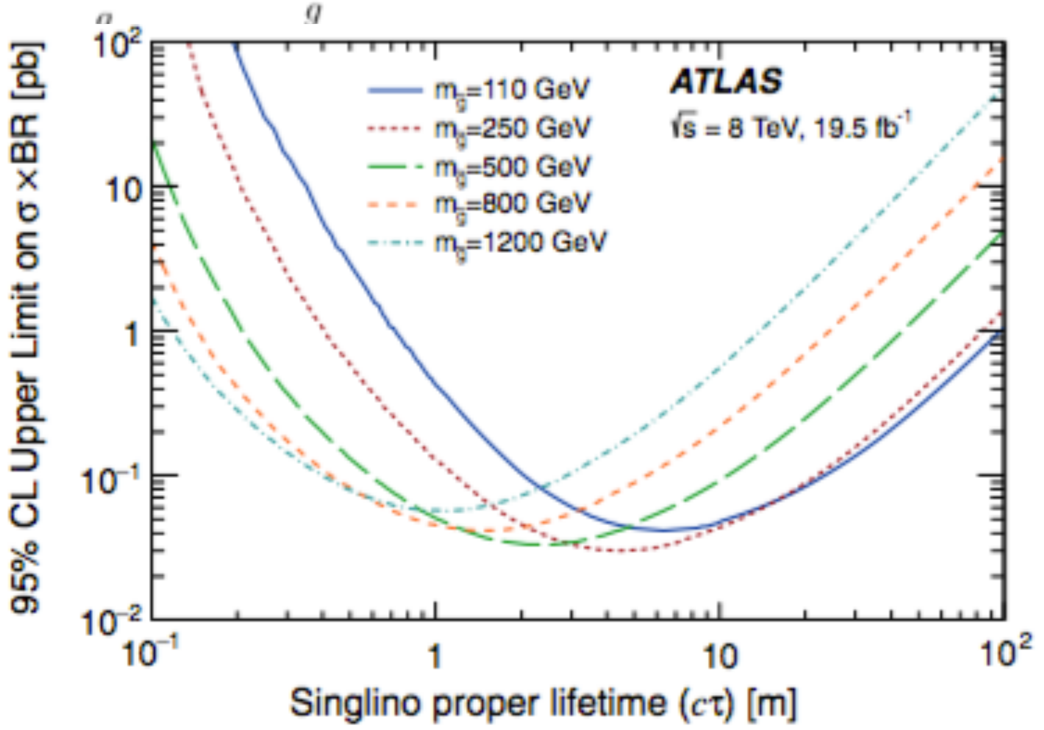
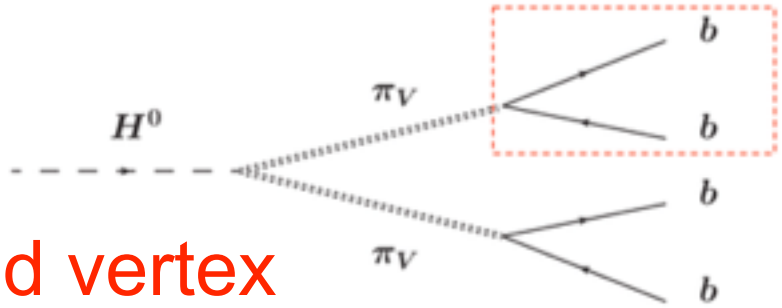


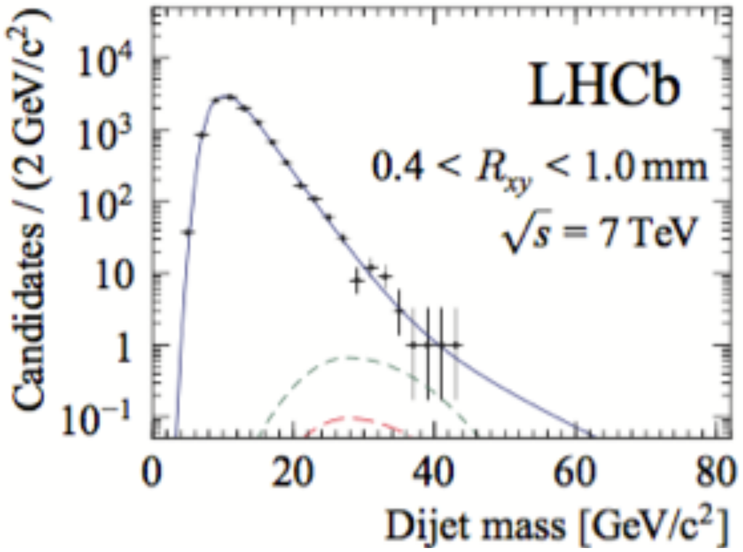


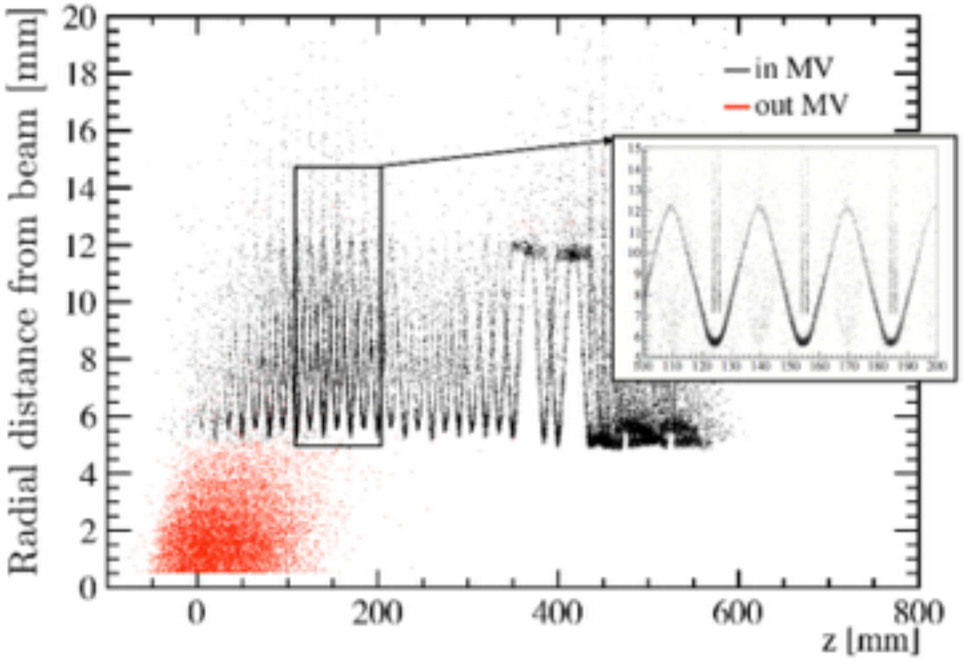
LHCb Displaced vertices and appearing jets

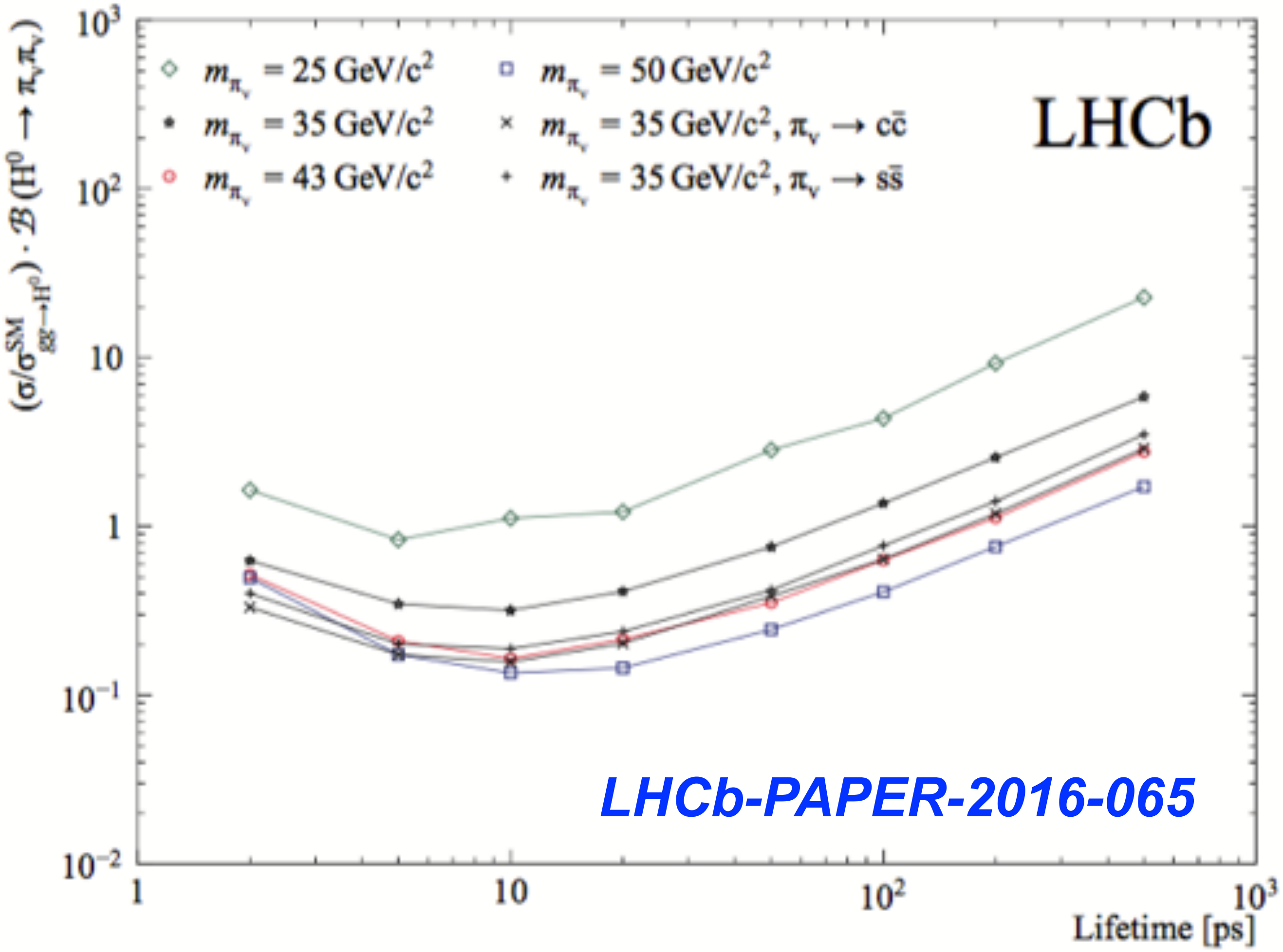
- Hidden valley signatures
  - LHCb looks for a b-jet pair from a hidden valley pion



- Sensitivity depends on the position of the displaced vertex
  - fit performed on the diet invariant mass in bins of the distance from the origin of the displaced vertex



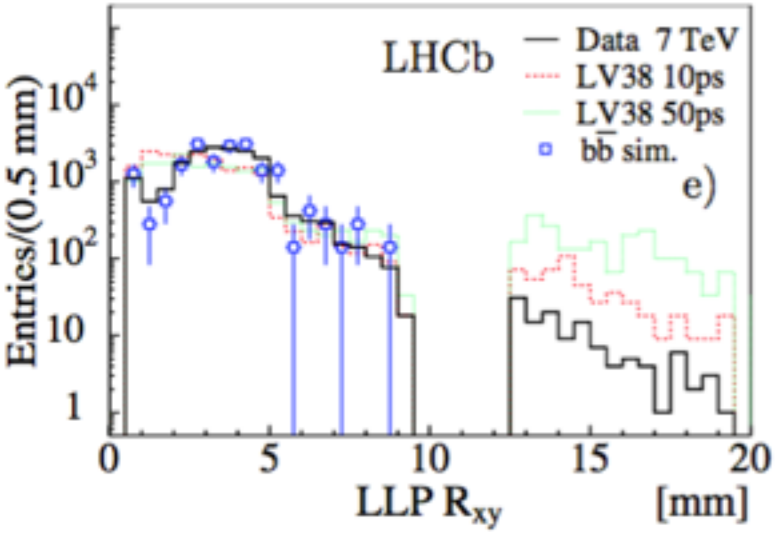


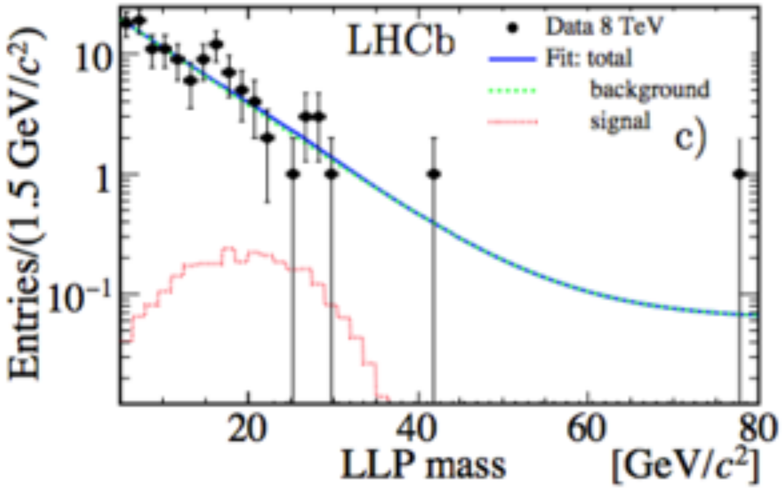


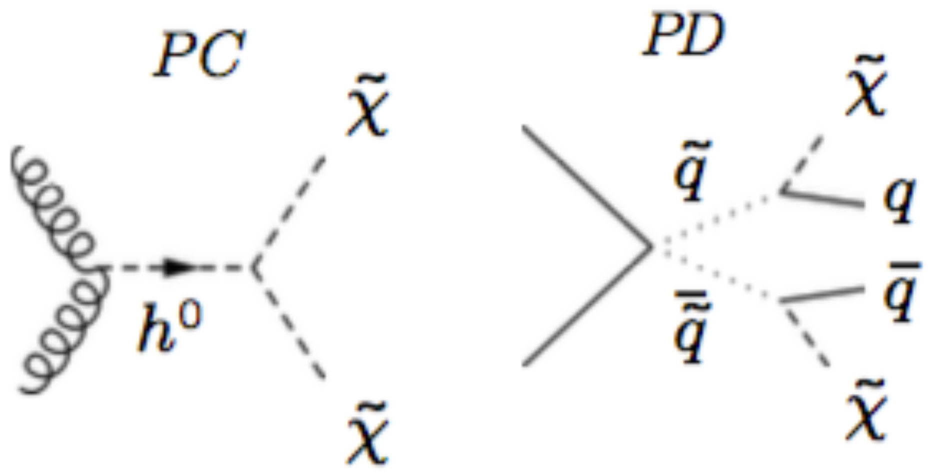
LHCb-PAPER-2016-065

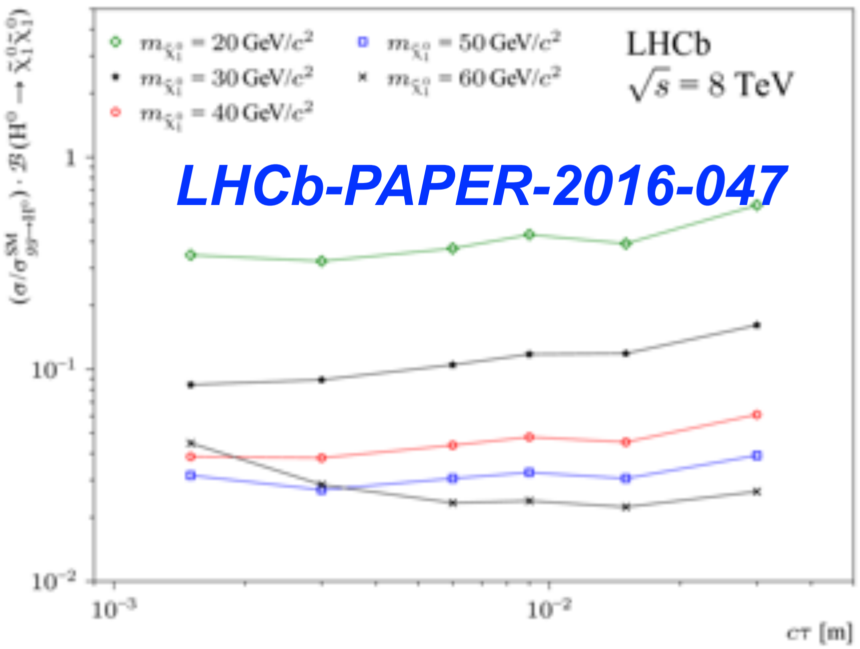
LHCb Displaced vertices and leptons

- ☐ LHCb explores few different scenarios
  - ☐ RPV neutralino decays and production of intermediate particles from Higgs boson decay
    - ☐ looking for a displaced vertex with a reconstructed muon plus jet

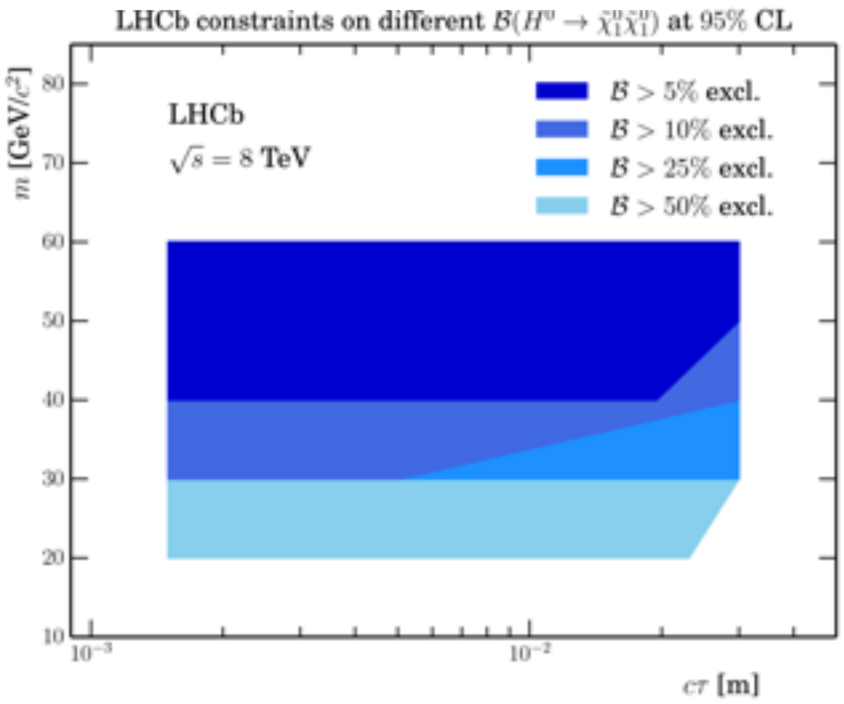


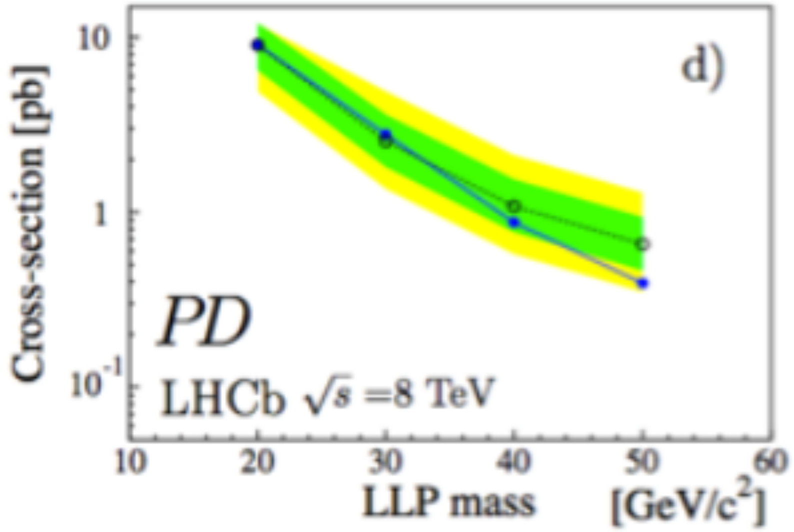




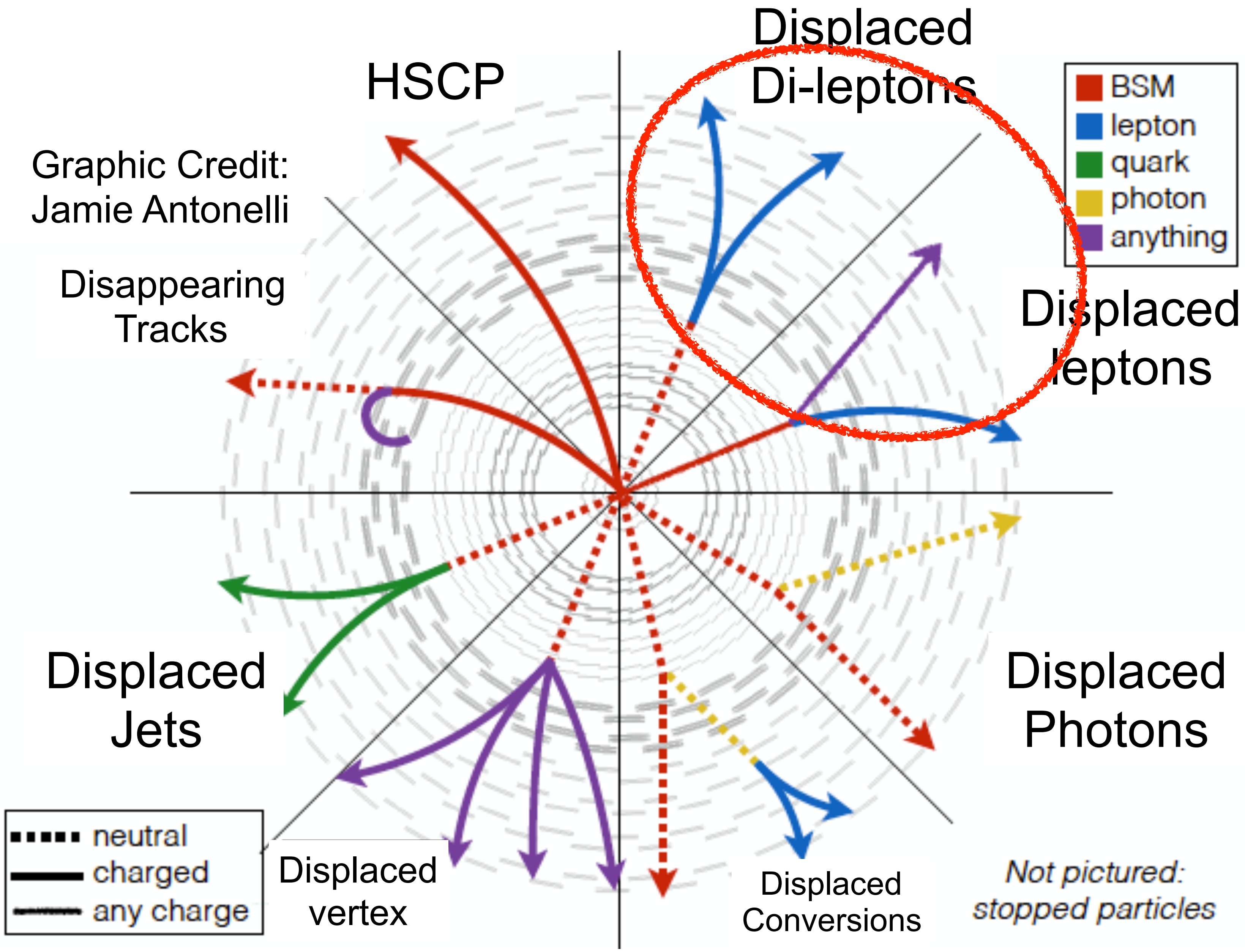


LHCb-PAPER-2016-047





Displaced Leptons



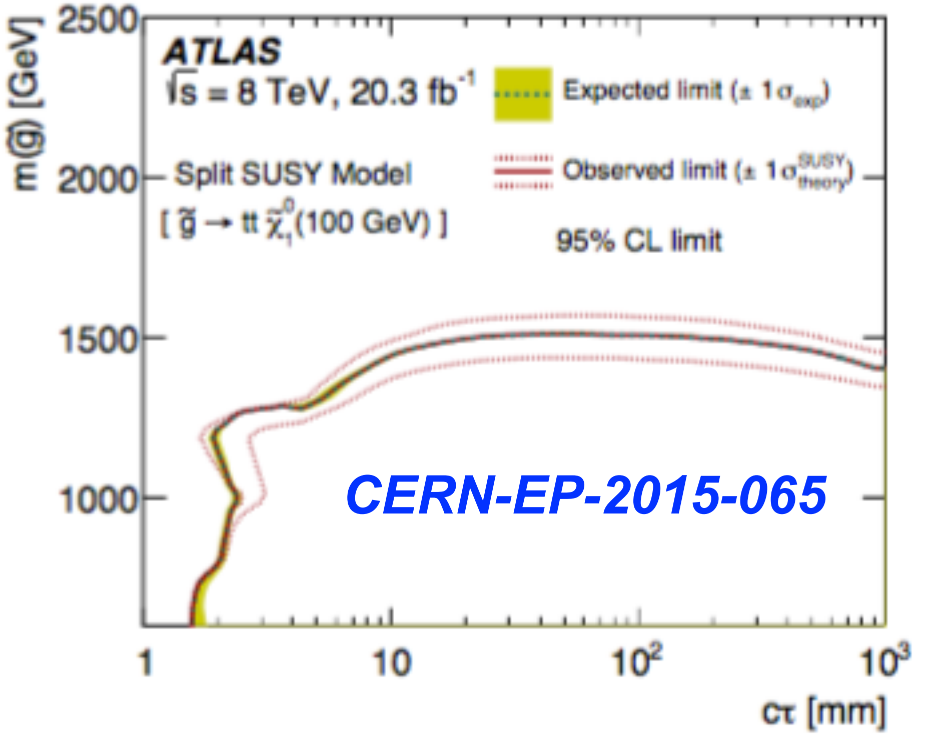
Graphic Credit: Jamie Antonelli

Not pictured: stopped particles

Simone.Gennai@cern.ch

Displaced leptons ATLAS and CMS

- ATLAS looking for the presence of leptons associated to a displaced multitrack secondary vertex
  - associated to split susy models
- CMS in the most recent analysis looks for electron-muon final state from stop decays
  - associated to RPV susy models
  - lower limit on the m_stop with respect to slide 12



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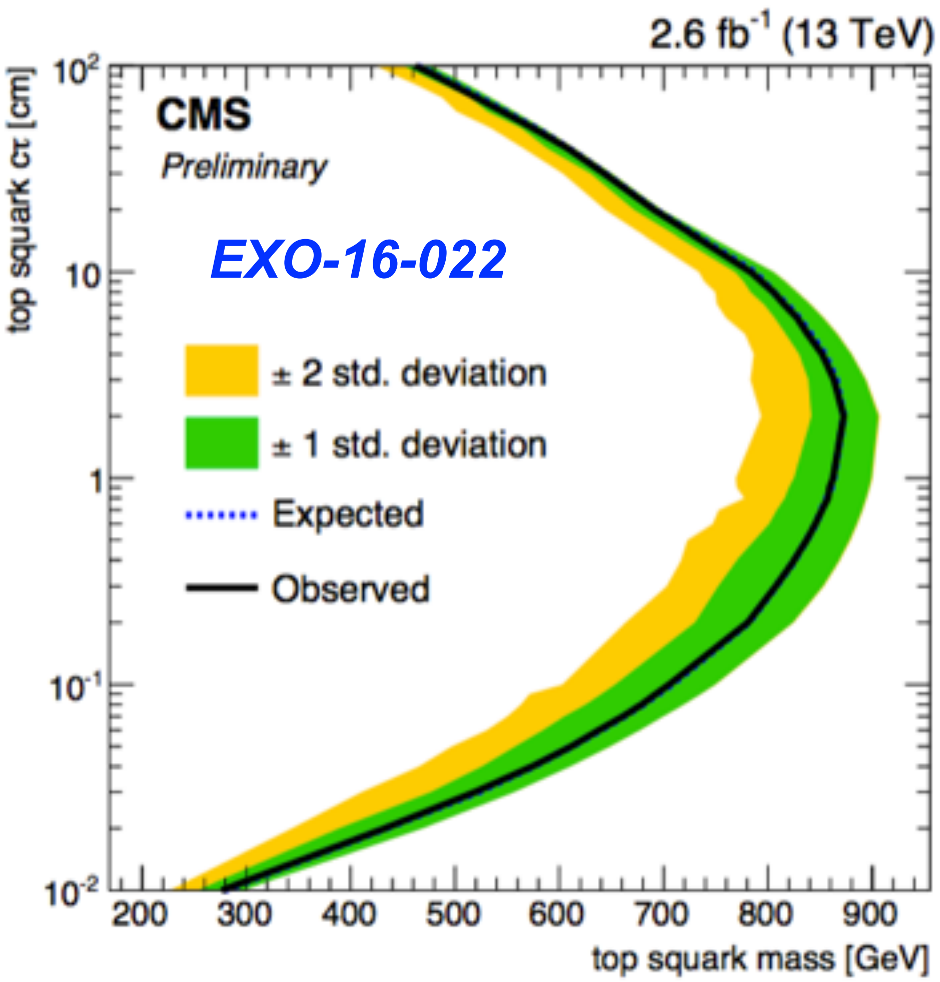
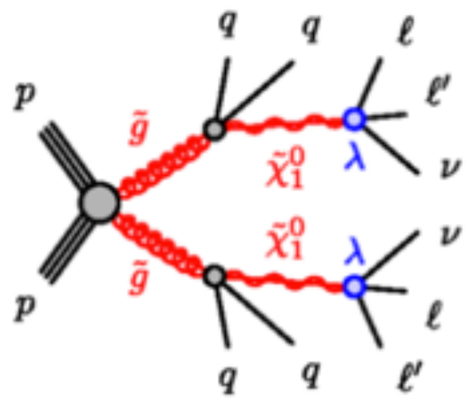
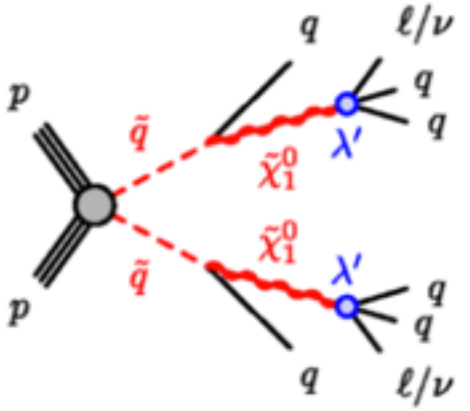
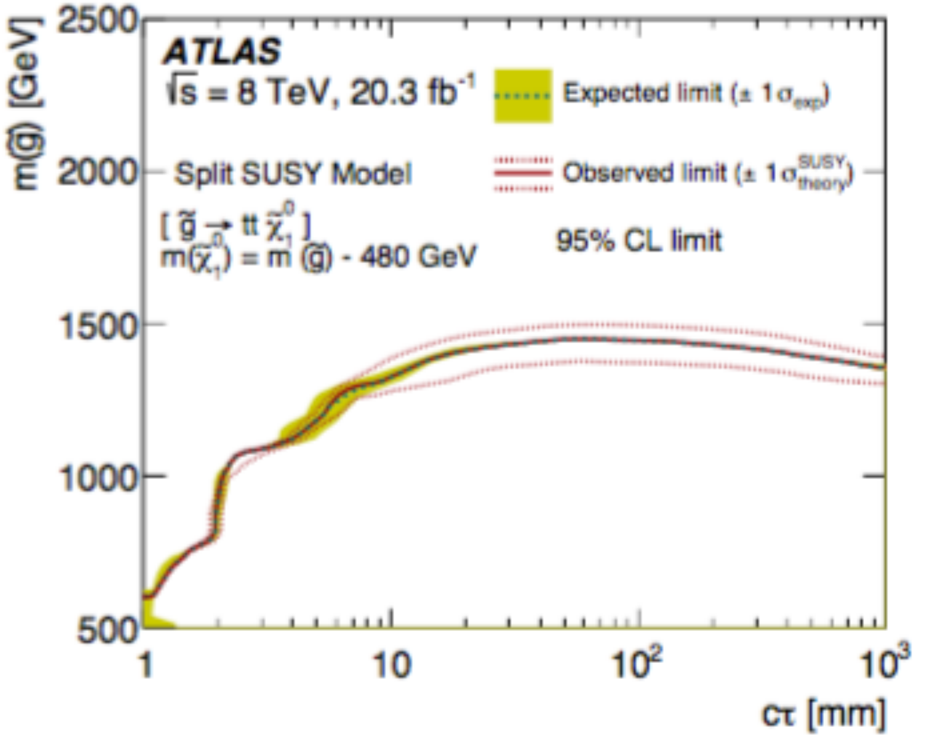
(a)



EXO-16-022

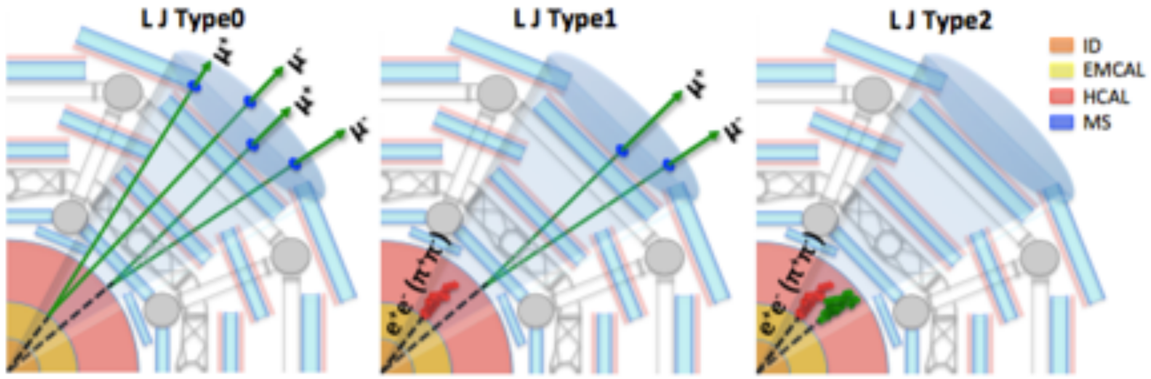




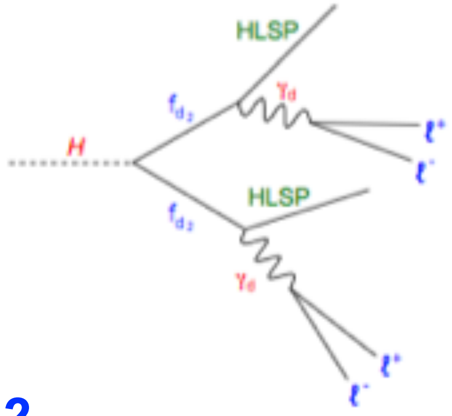


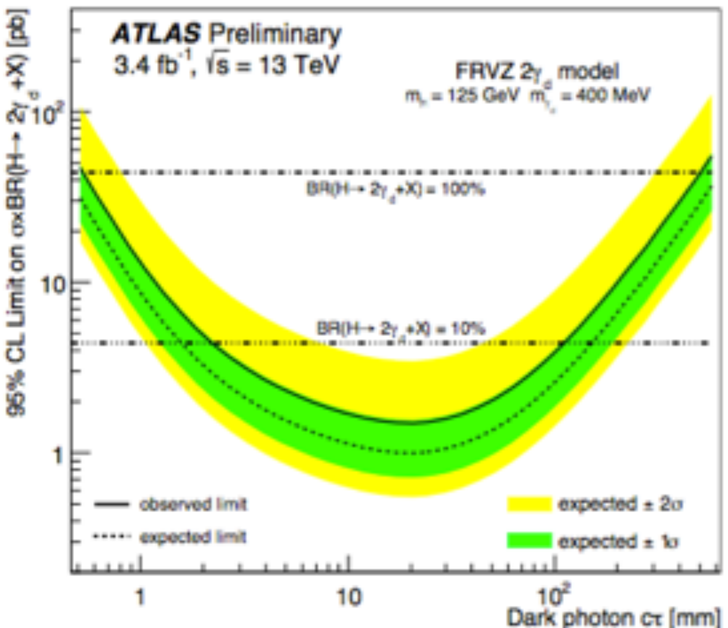
ATLAS displaced di-leptons

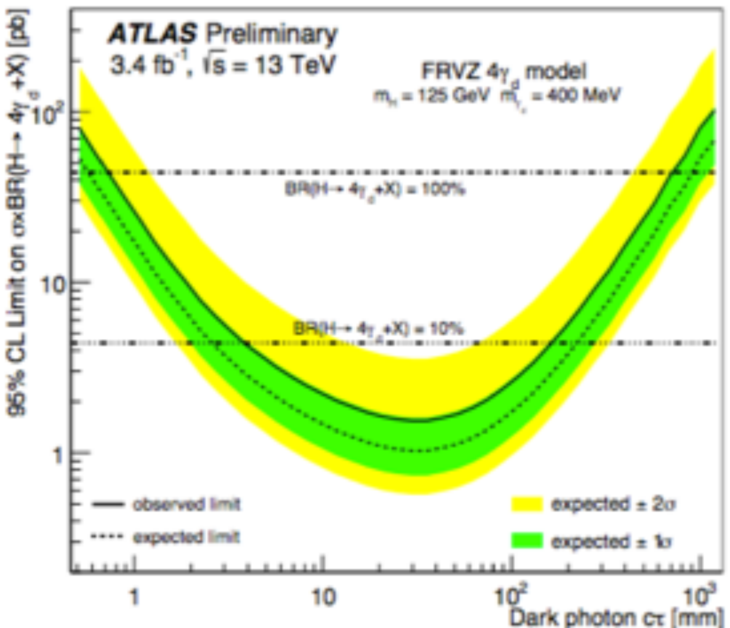
- Main production mechanism is through Higgs decay to hidden fermions which decays to dark photons
  - two different signal benchmarks considered with 2 or 4 dark photons
- Events categorized depending on the number of reconstructed muon pairs



  - N.B. due to large boost, events with 4 dark photons are still reconstructed as two lepton-jet objects





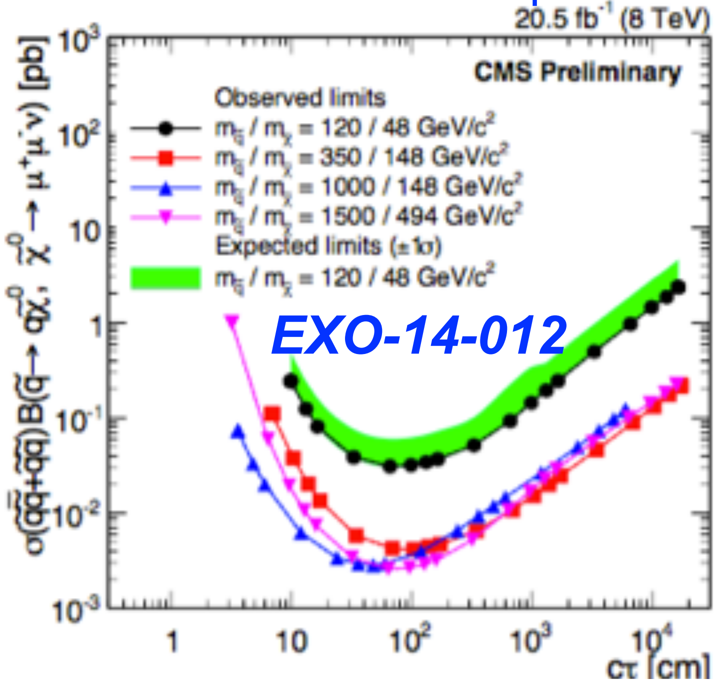


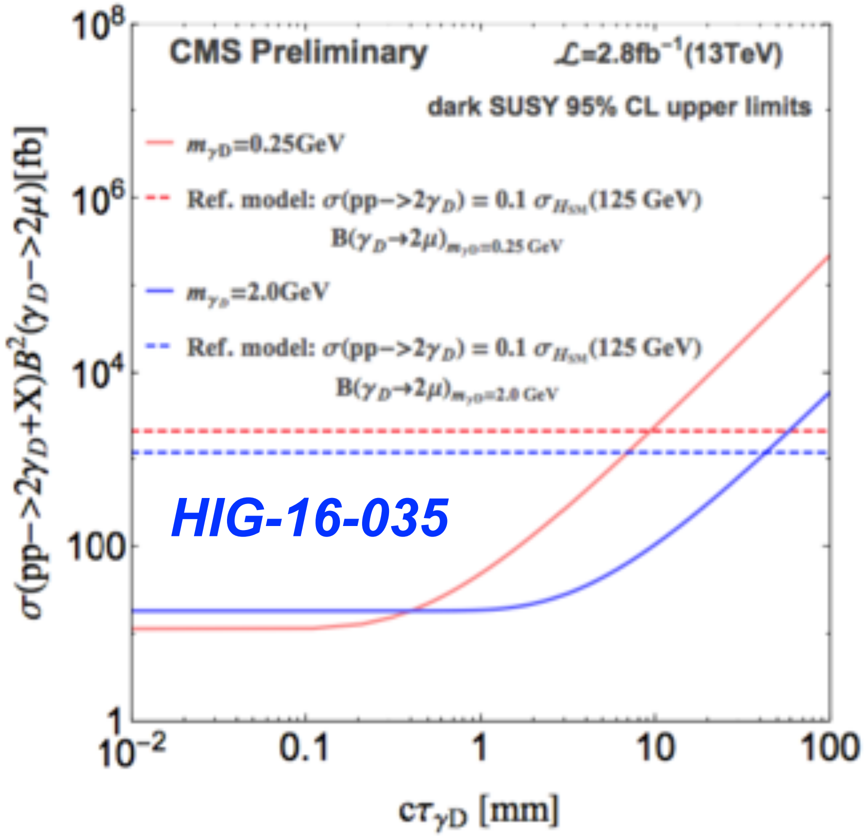
ATLAS-CONF-2016-042

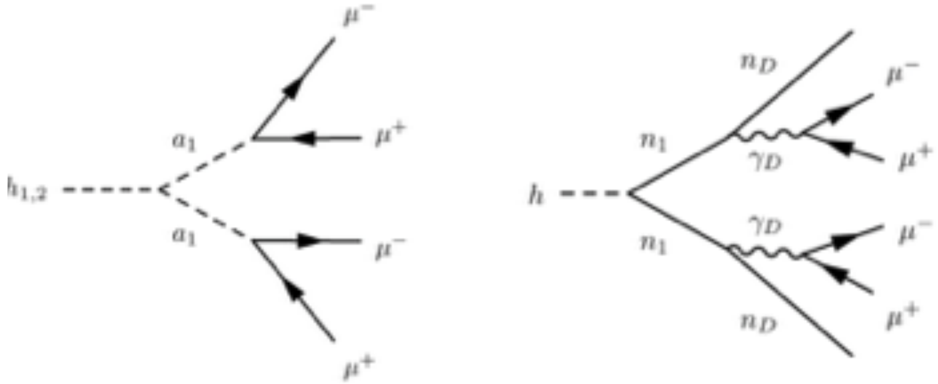
FRVZ model	m_H (GeV)	Excluded $c\tau$ [mm]
Higgs → $2\gamma_d + X$	125	$2.2 \leq c\tau \leq 111.3$
Higgs → $4\gamma_d + X$	800	$3.8 \leq c\tau \leq 163.0$
Higgs → $2\gamma_d + X$	125	$0.6 \leq c\tau \leq 63$
Higgs → $4\gamma_d + X$	800	$0.8 \leq c\tau \leq 186$

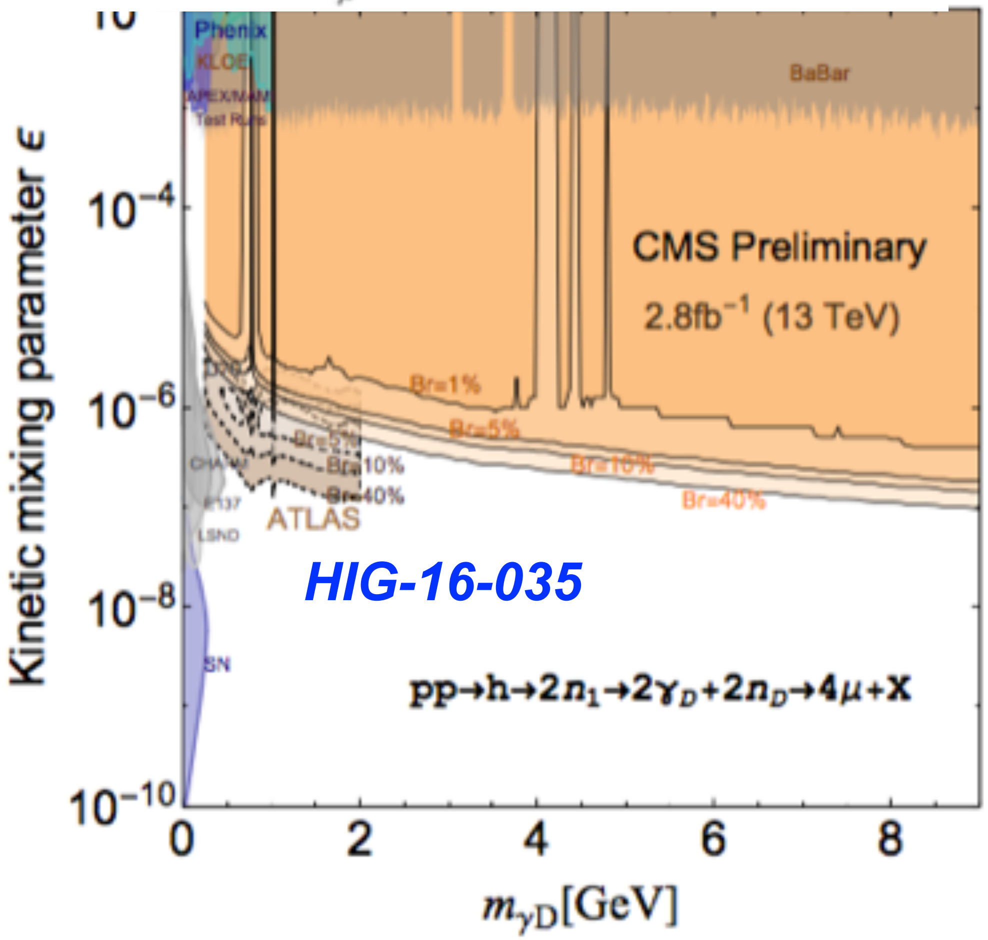
CMS displaced di-leptons

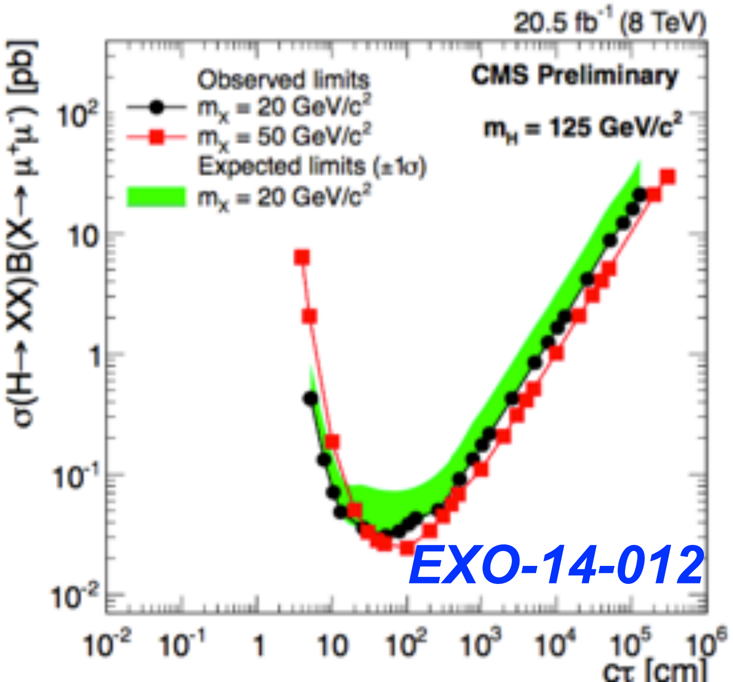
- Two different analysis one with RunI data and one with 2015 data
  - EXO-14-012 is looking for a dark-photon like signature as well as displaced muons from long lived neutralinos in RPV models
  - HIG-16-035 specifically deals with dark-photons models, even if with limited lifetime reach





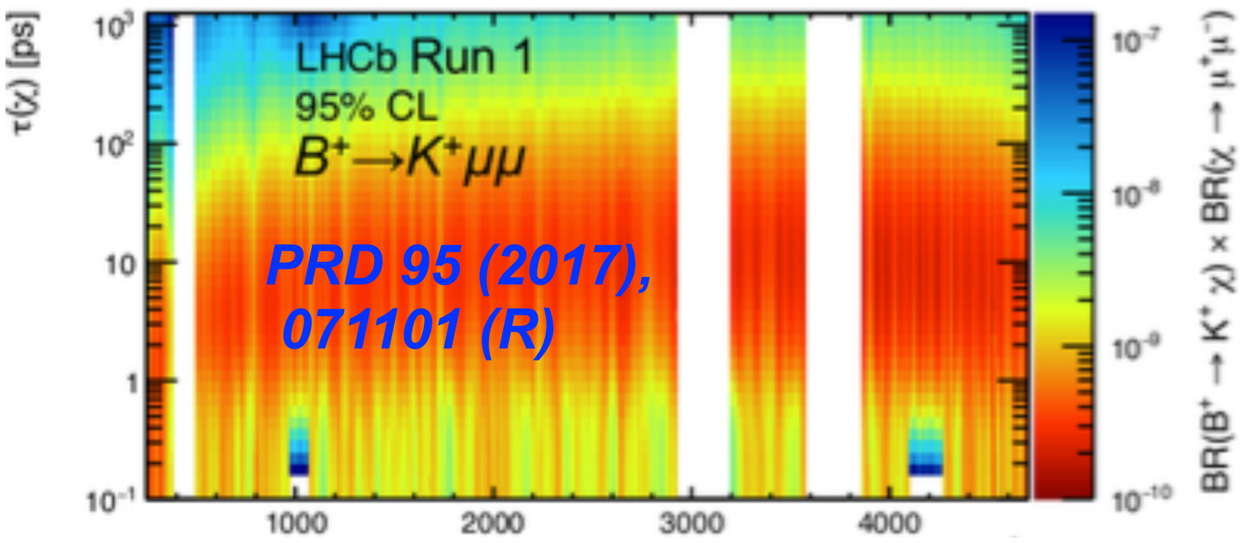




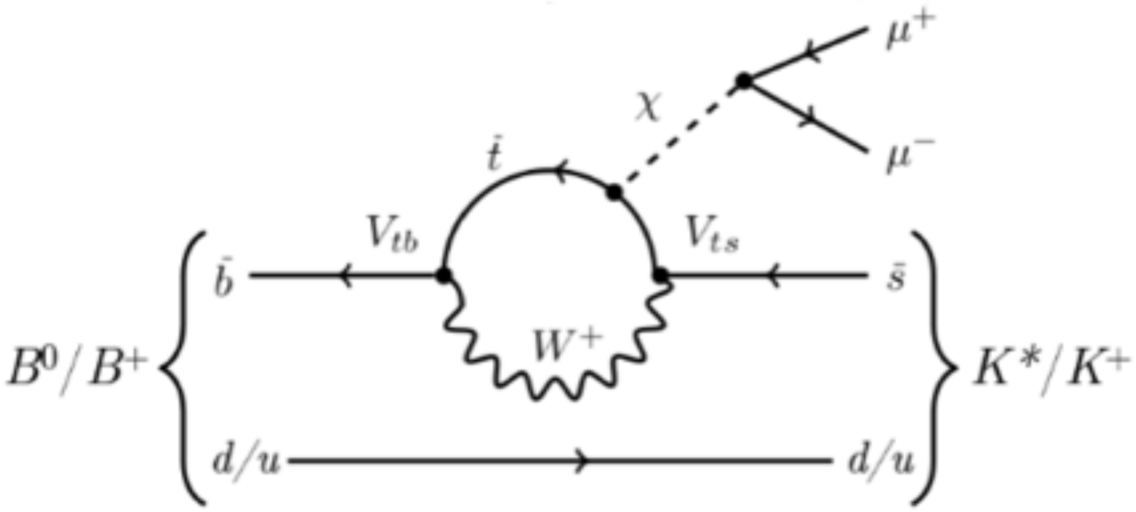


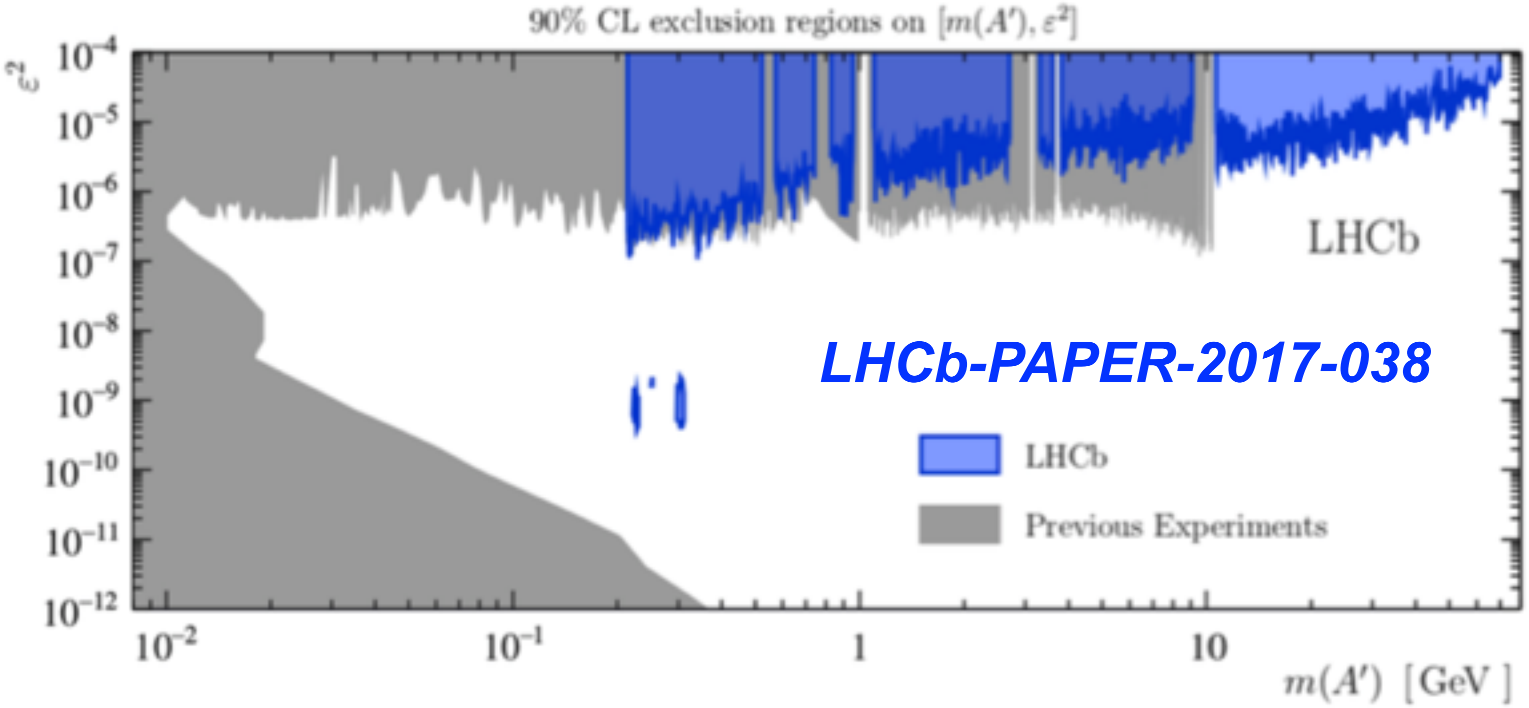
LHCb displaced di-leptons

- ☐ LHCb can probe much lower mass regions than ATLAS and CMS
  - ☐ several benchmark models considered
    - ☐ Axions, inflaton and dark photons

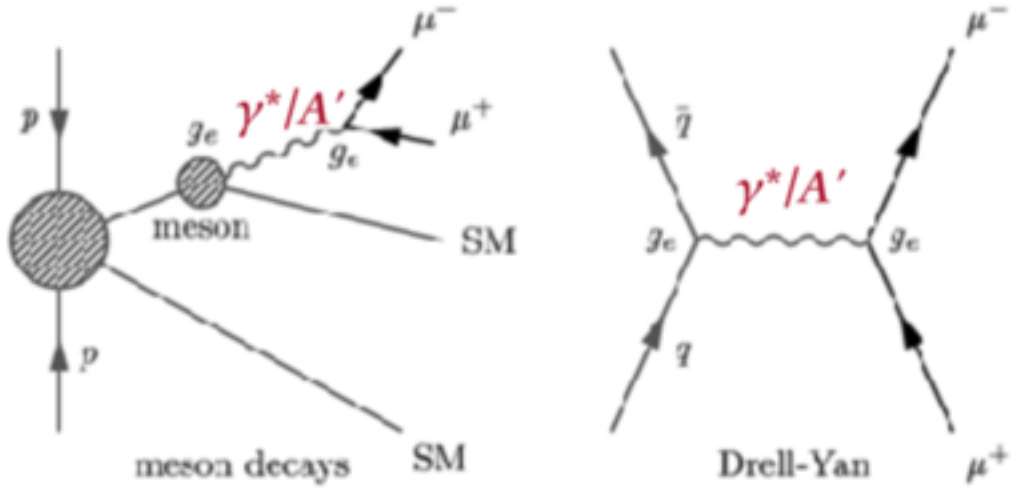


PRD 95 (2017), 071101 (R)



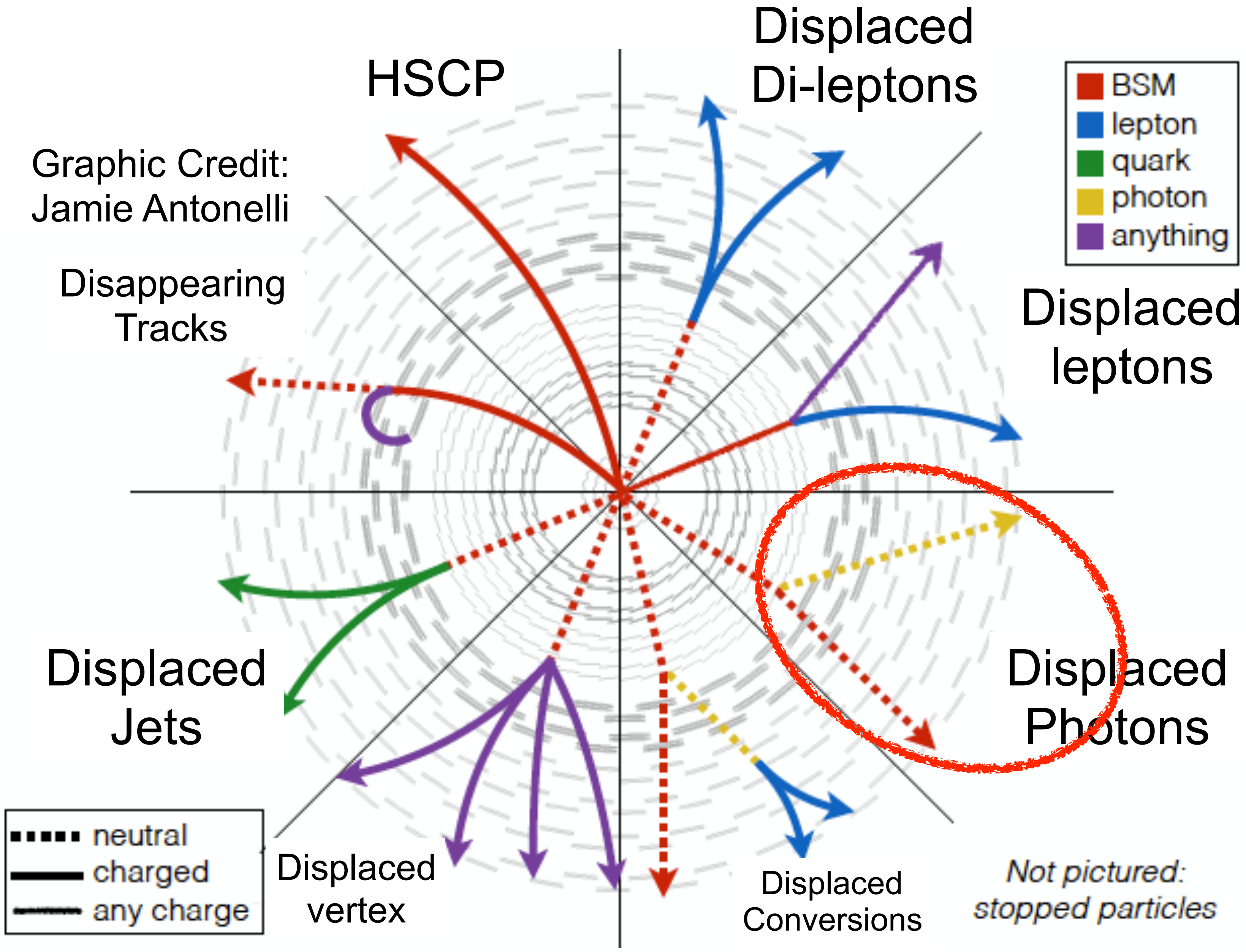


LHCb-PAPER-2017-038



Simone.Gennai@cern.ch

Displaced photons and jets



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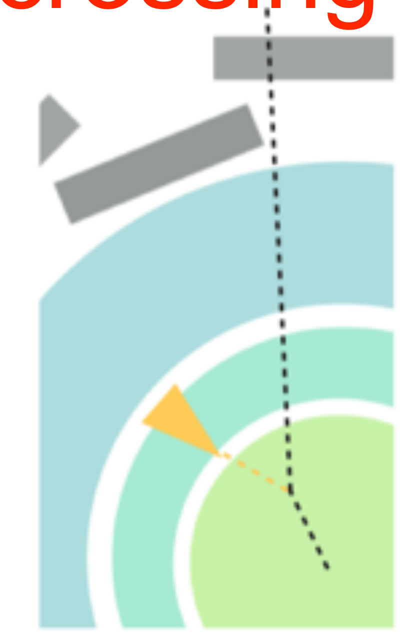
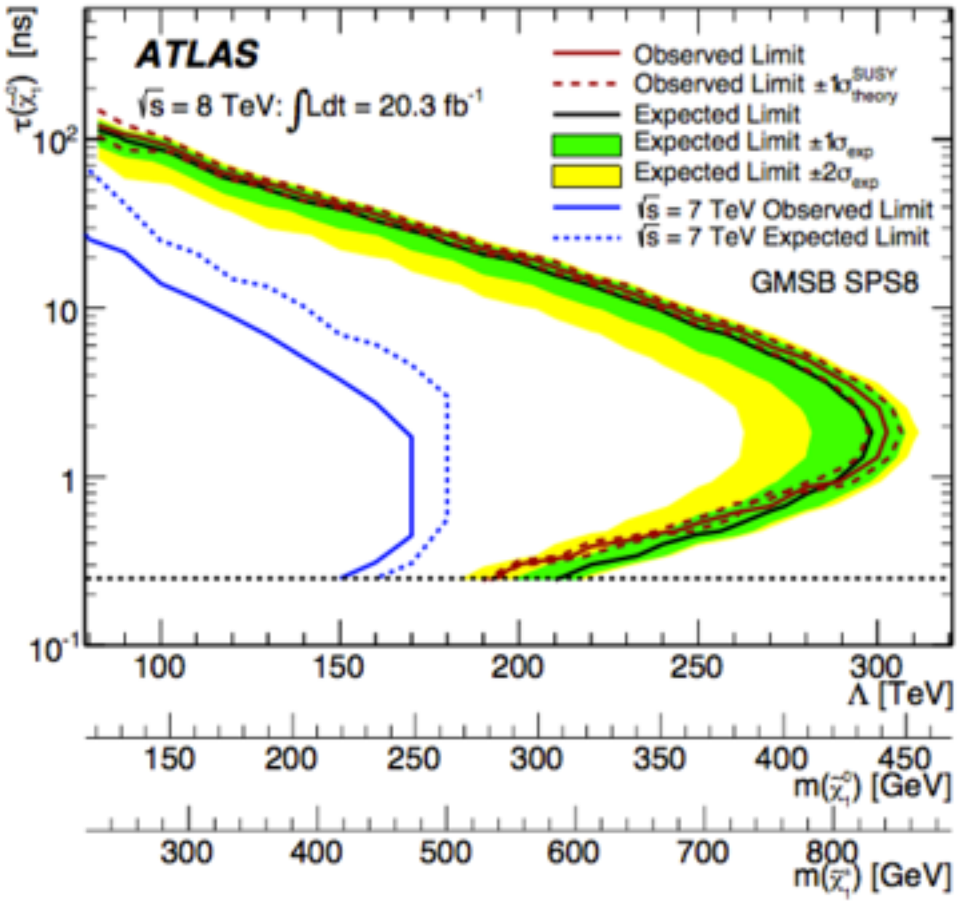
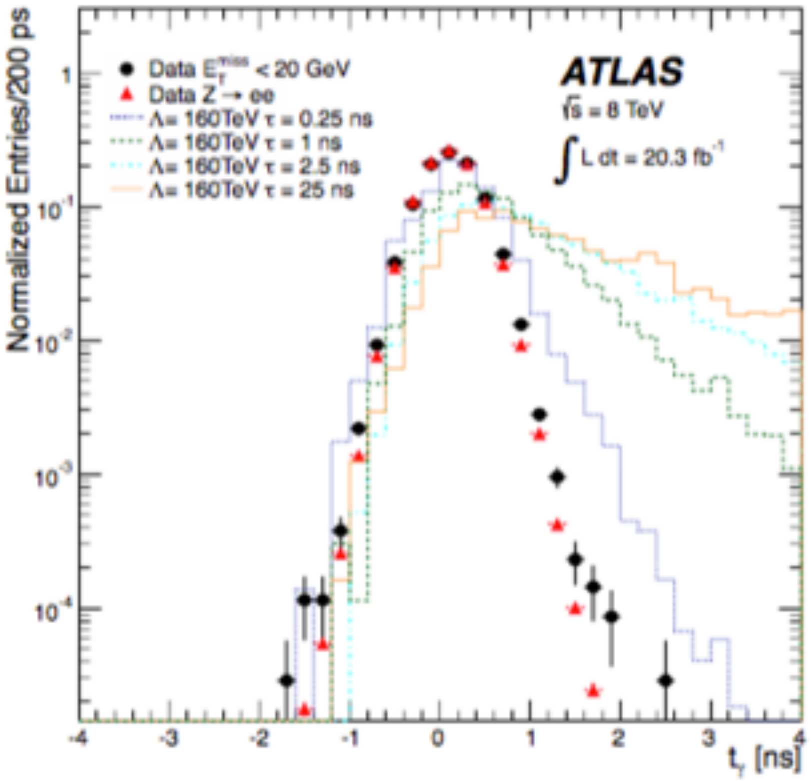
ATLAS Non-pointing/Delayed photons

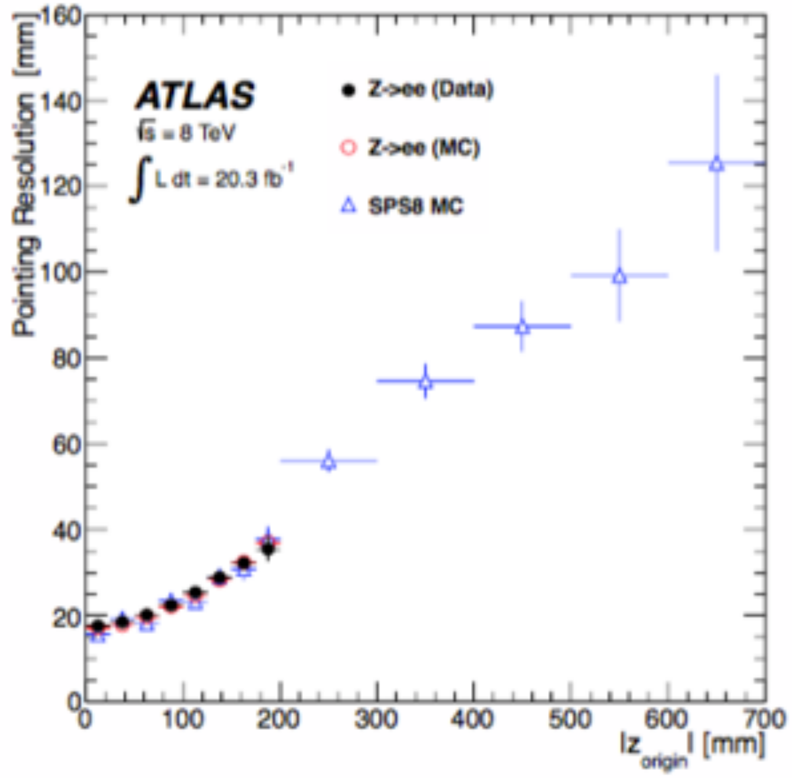
- Neutral LLP decaying to photons that do not point to the primary vertex or delayed wrt the bunch crossing
  - Assuming GMSB susy scenario
    - presence of photons and MET



CERN-EP-2014-215

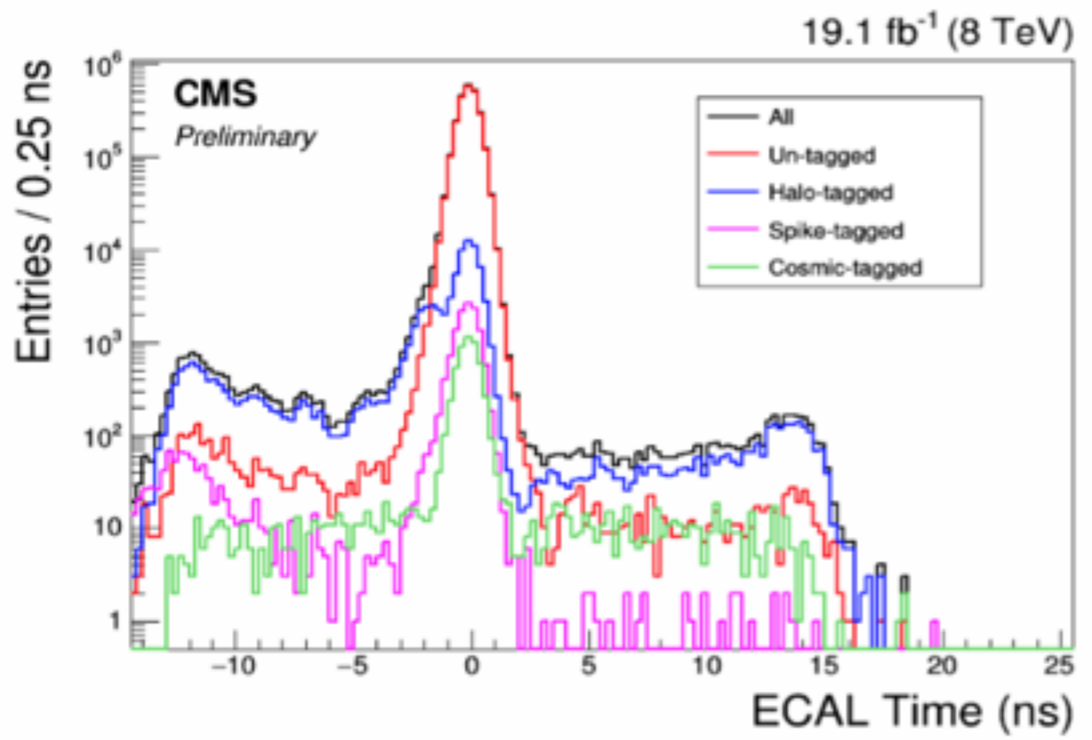


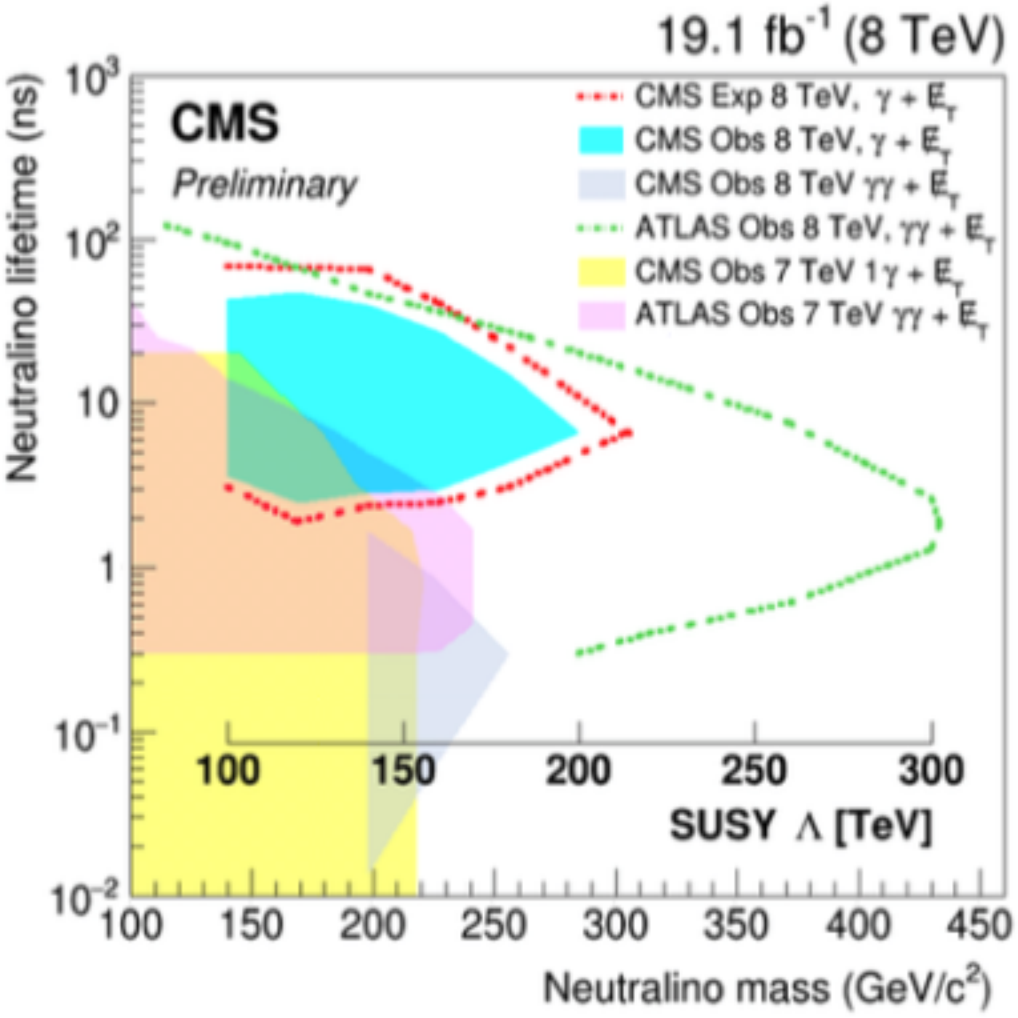


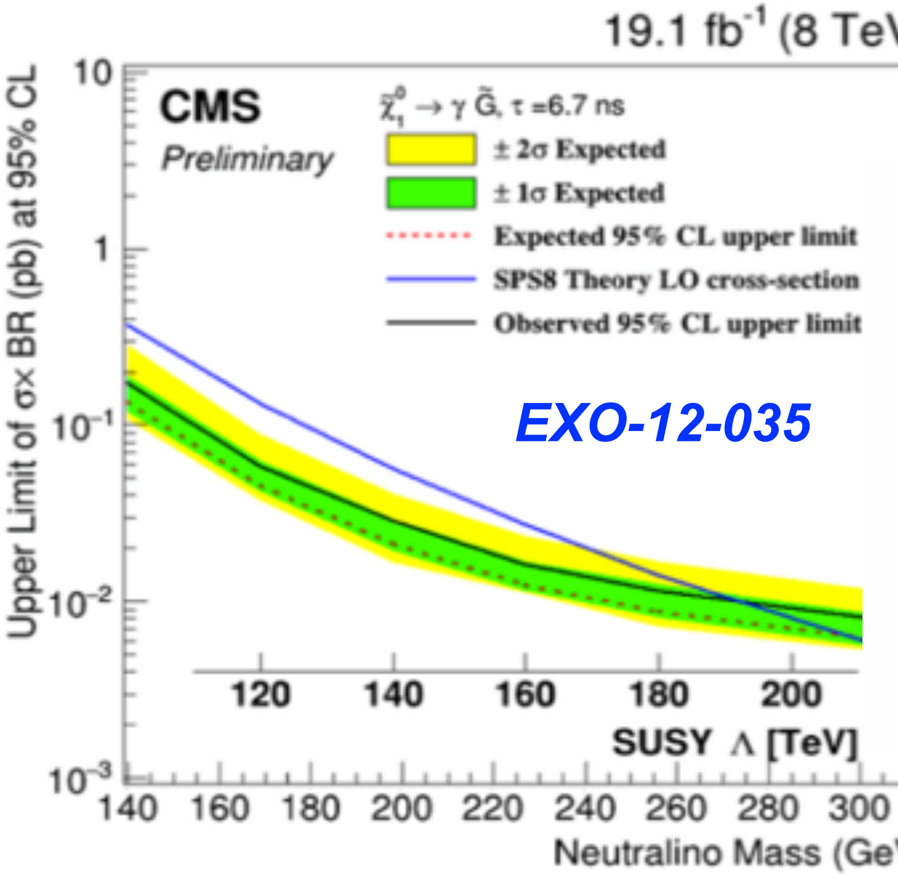


CMS Non-pointing/Delayed photons

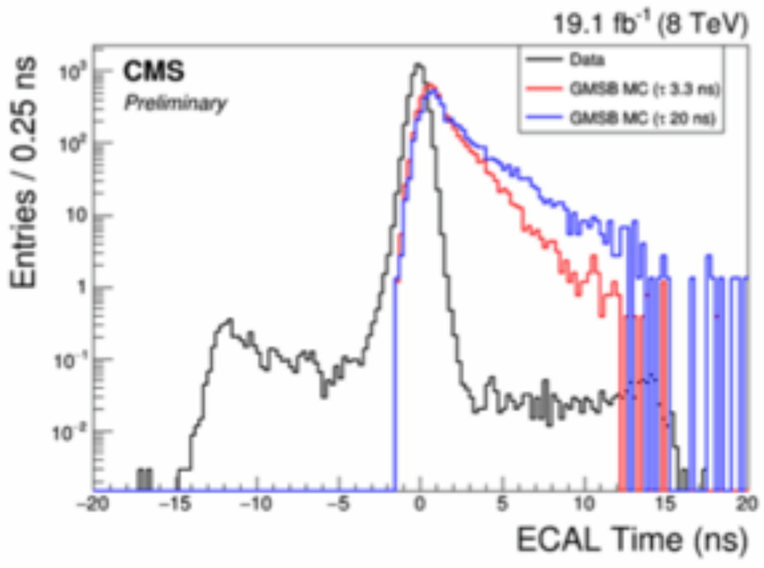
- Similar GMSB model as in ATLAS
  - This allows an apple-to-apple comparison
  - Analysis mostly relying on the ecal time measurement







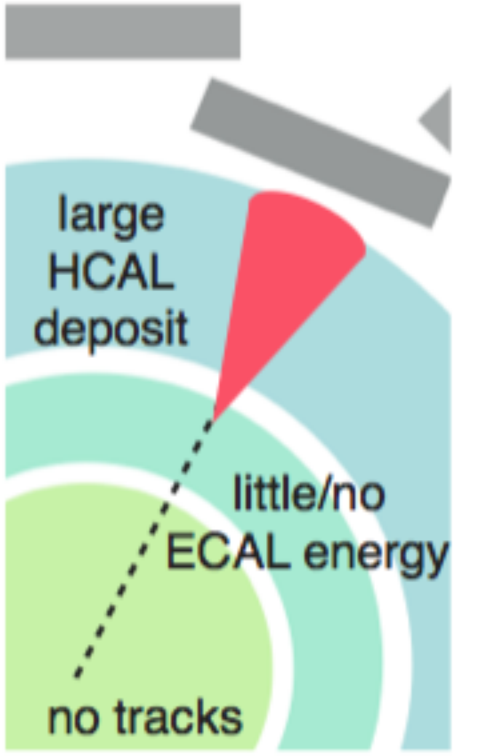
EXO-12-035

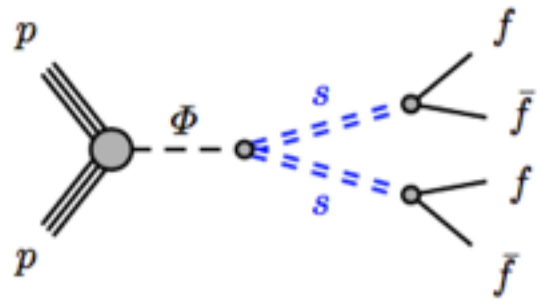


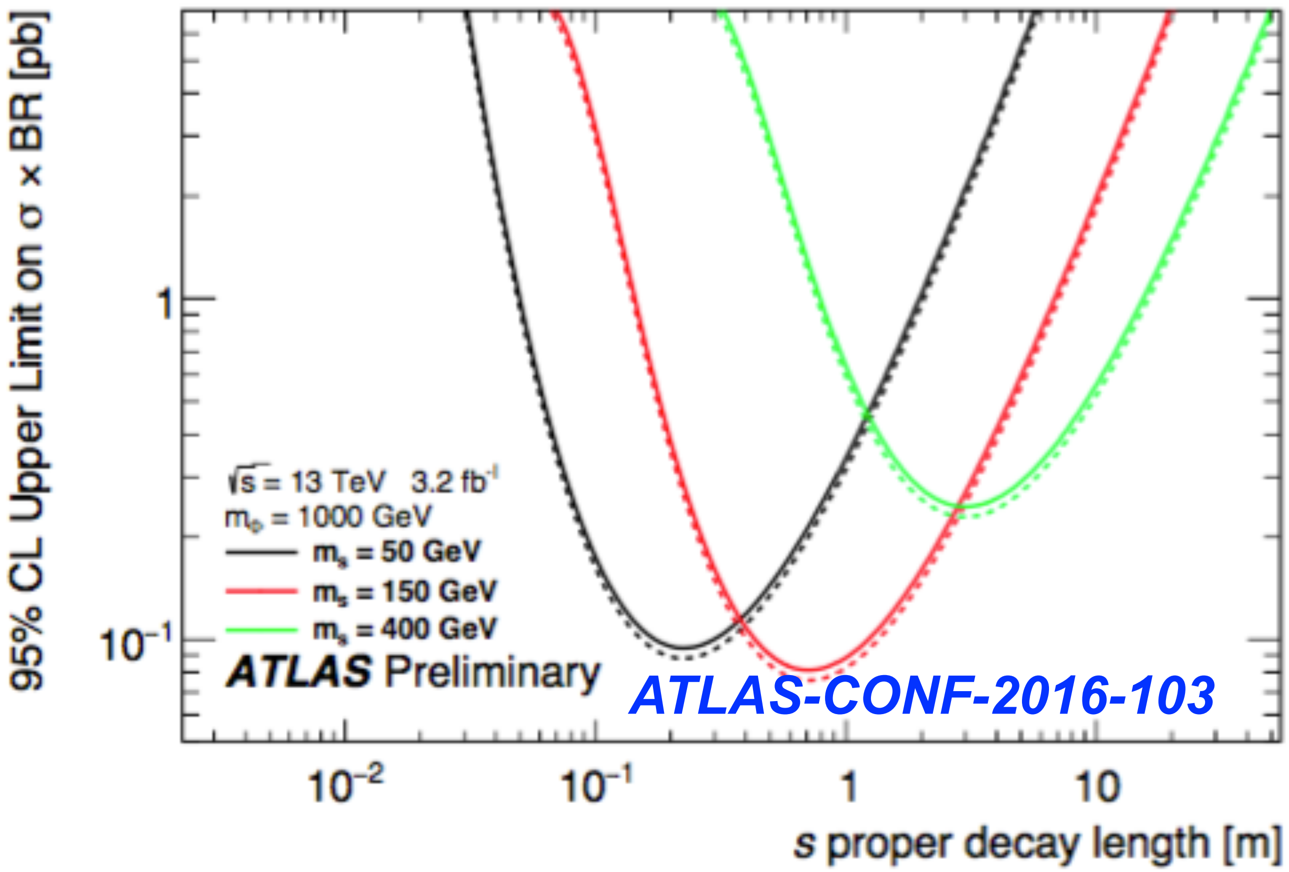
Simone.Gennai@cern.ch

ATLAS "appearing" Jets in the calorimeters

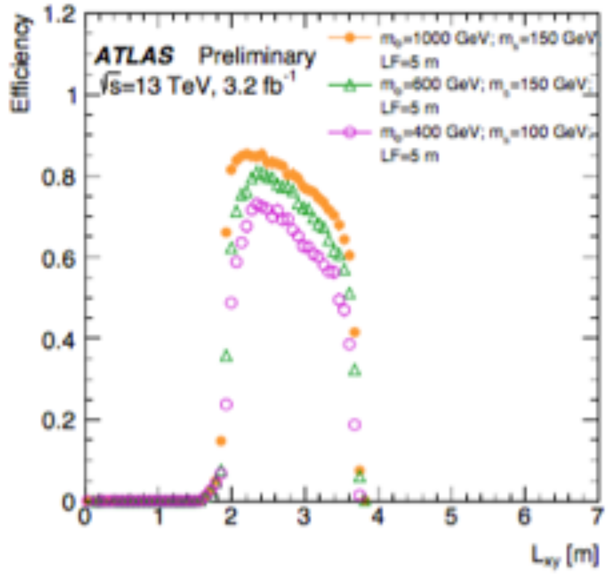
- Looking for showers initiated in the hadronic calorimeter
  - special jet reconstructions, to cope with the shower initiated later than usual
    - basically looking for narrower than usual jets, low electromagnetic fraction energy and no tracks associated
- Similar model as one already discussed in slide 13

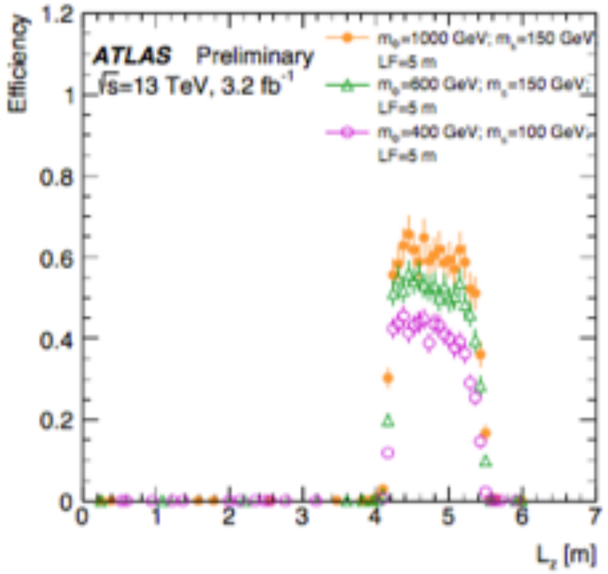




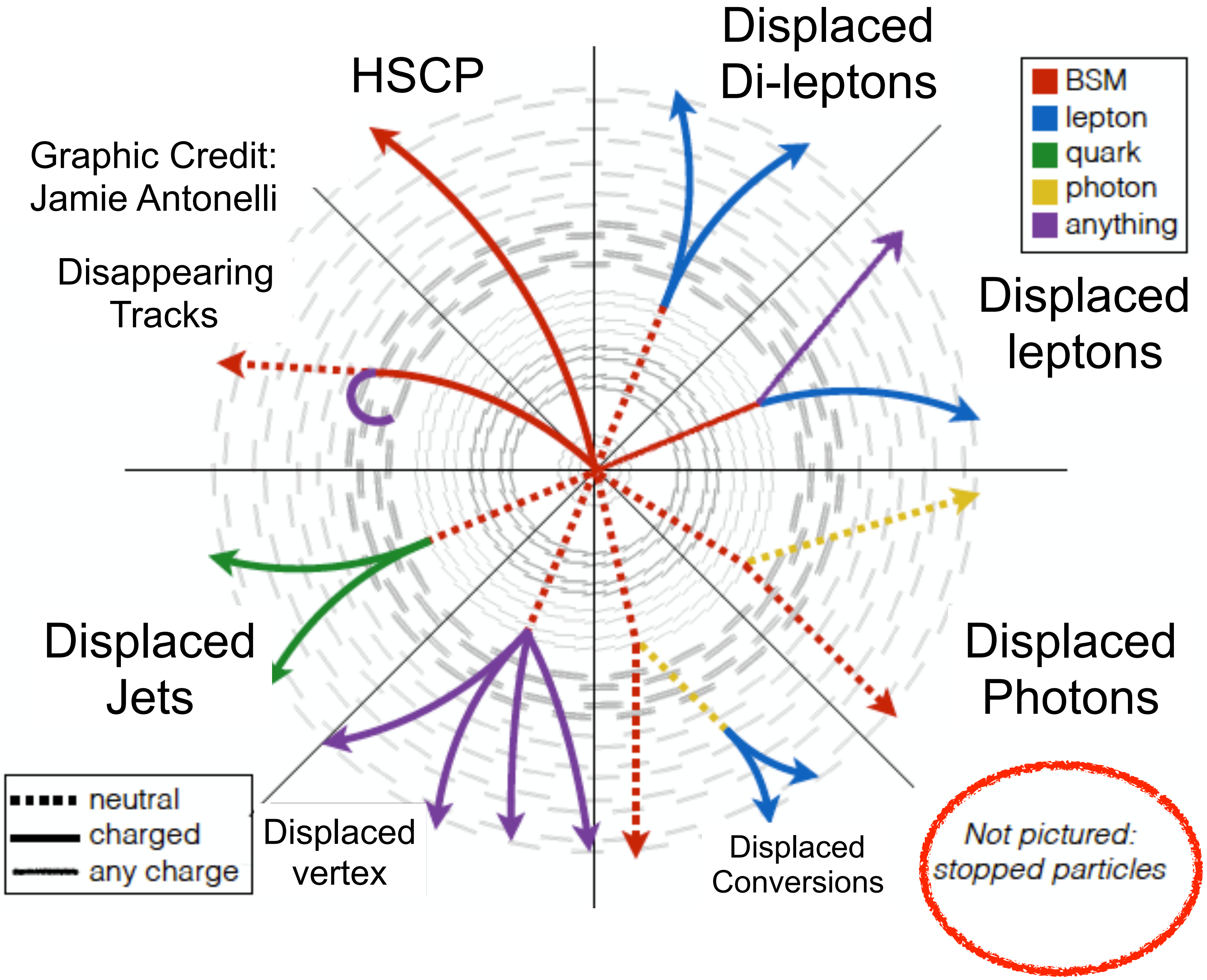


ATLAS-CONF-2016-103





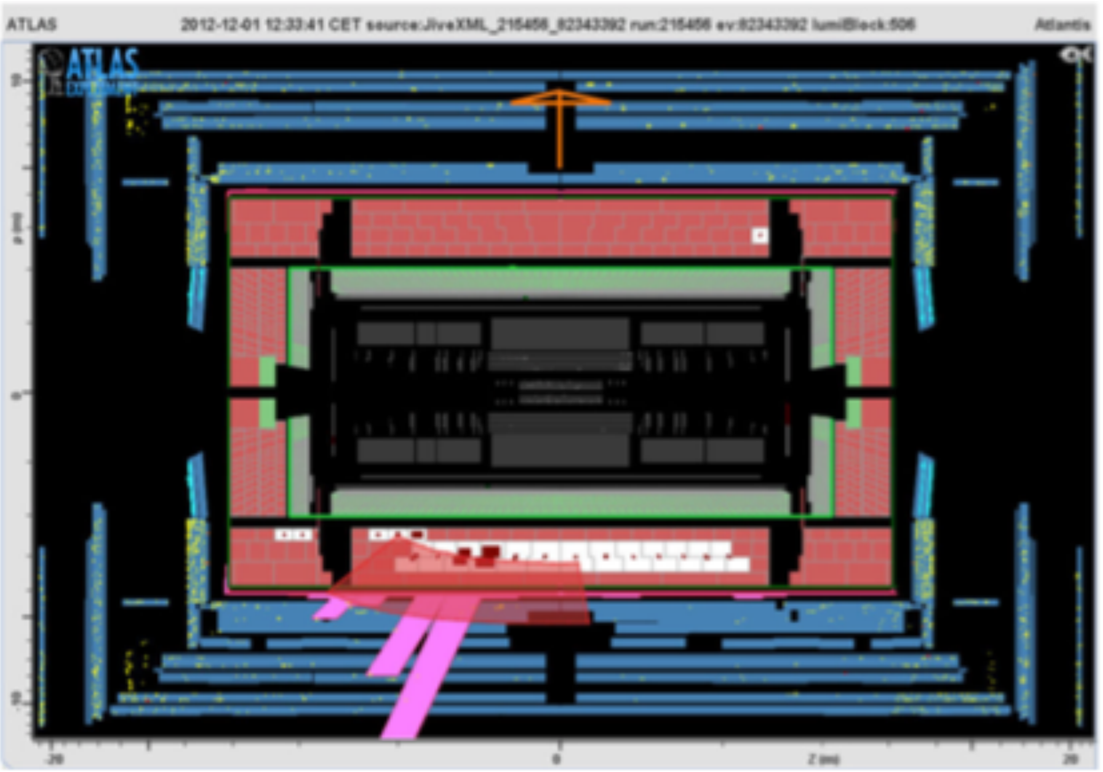
Stopped Particles

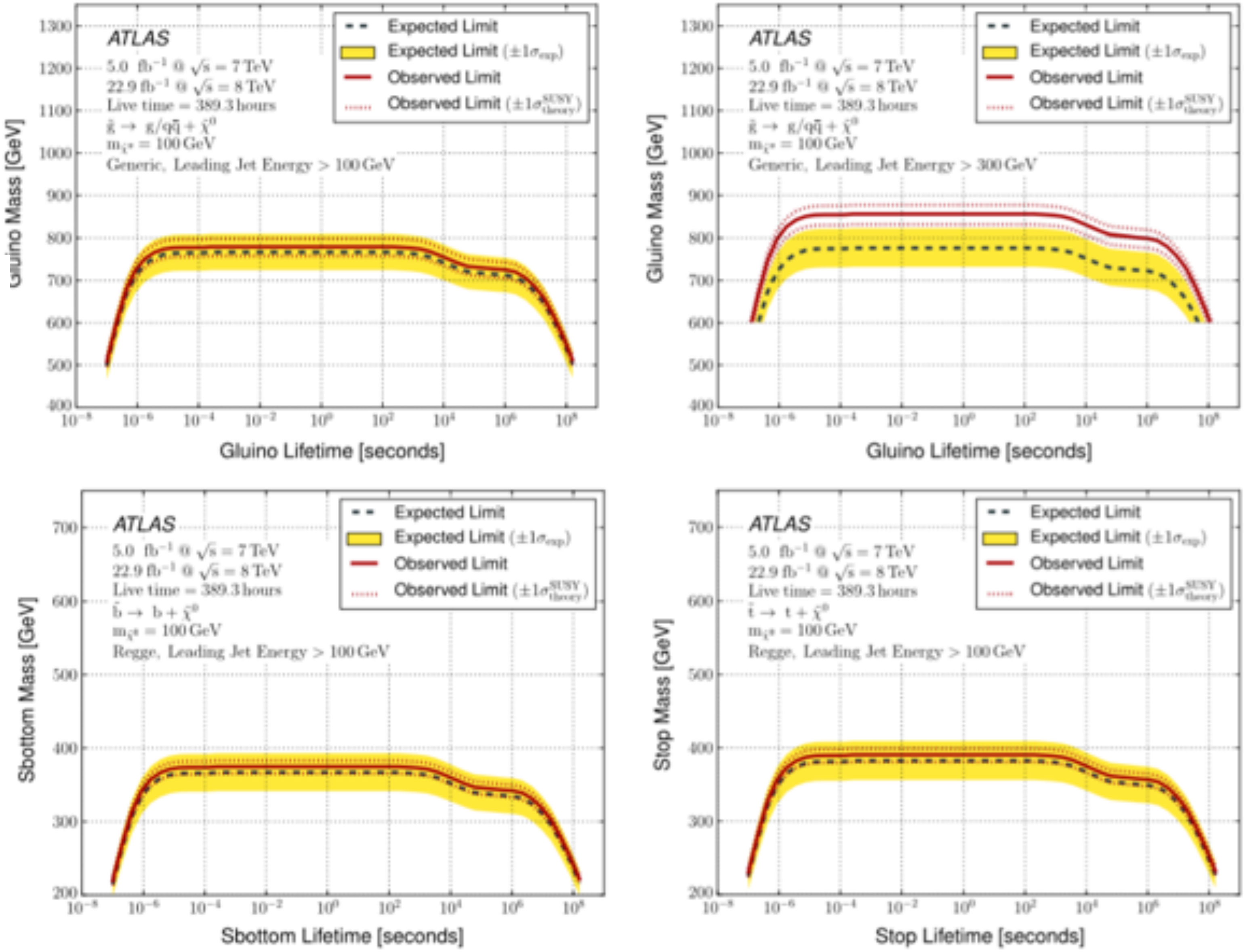


ATLAS Stopped Particles

- Looking for R-hadrons stopped in the calorimeter
  - triggering on empty bunch crossings, low pT jet and ET-missing
  - several models considered in the results interpretation

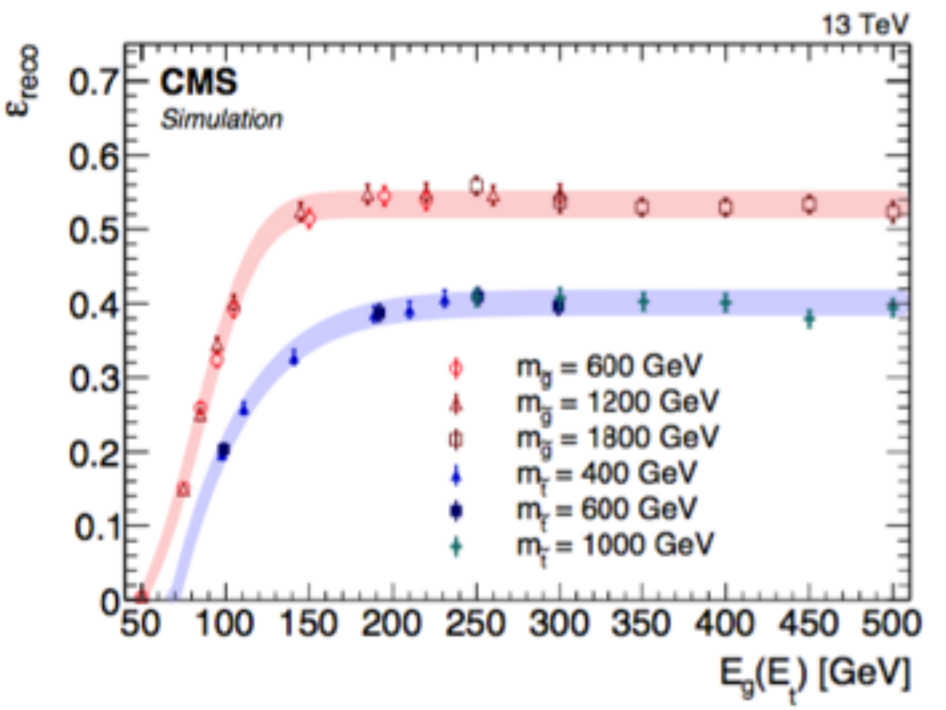
PRD 88 (2013) 112003

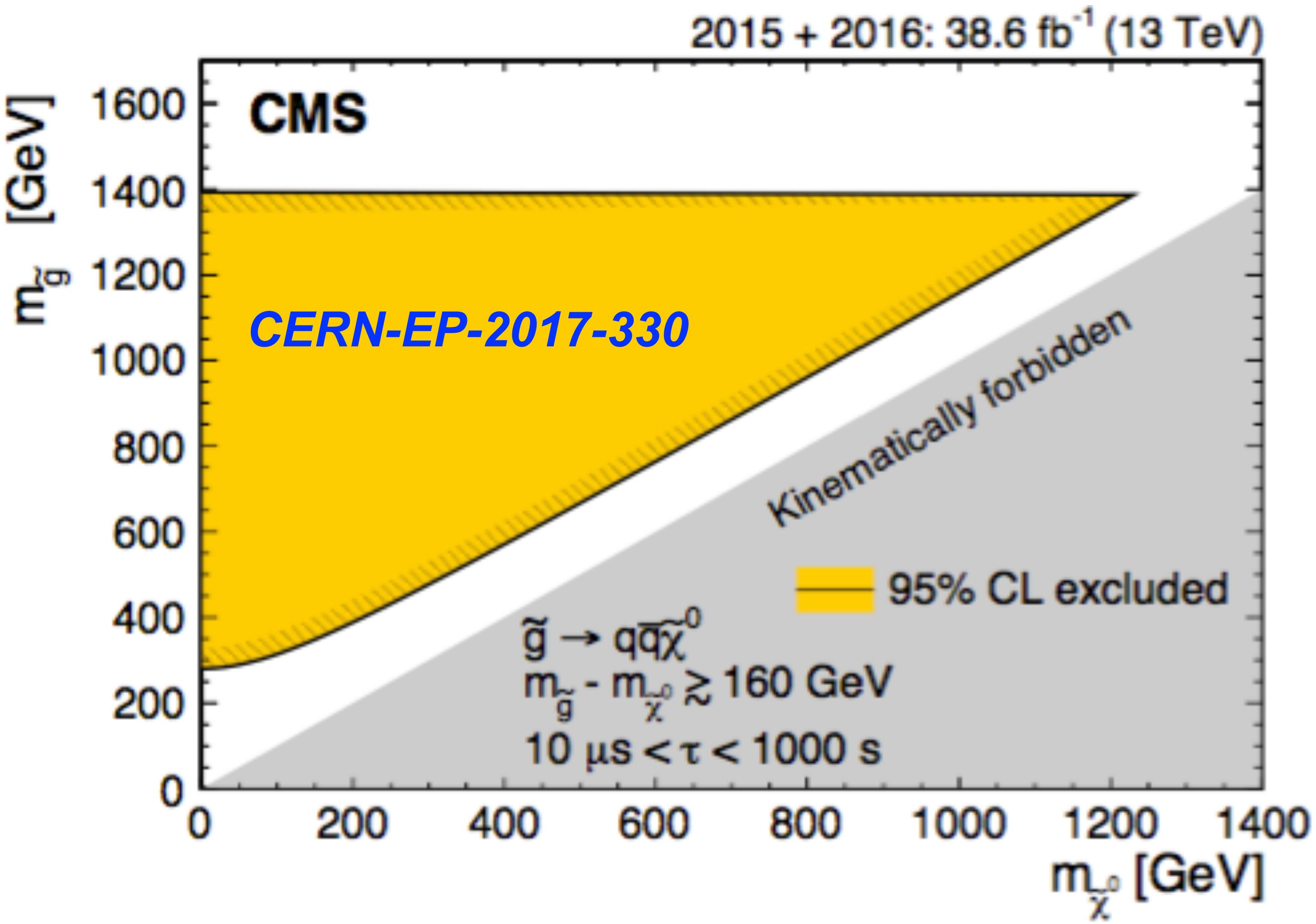




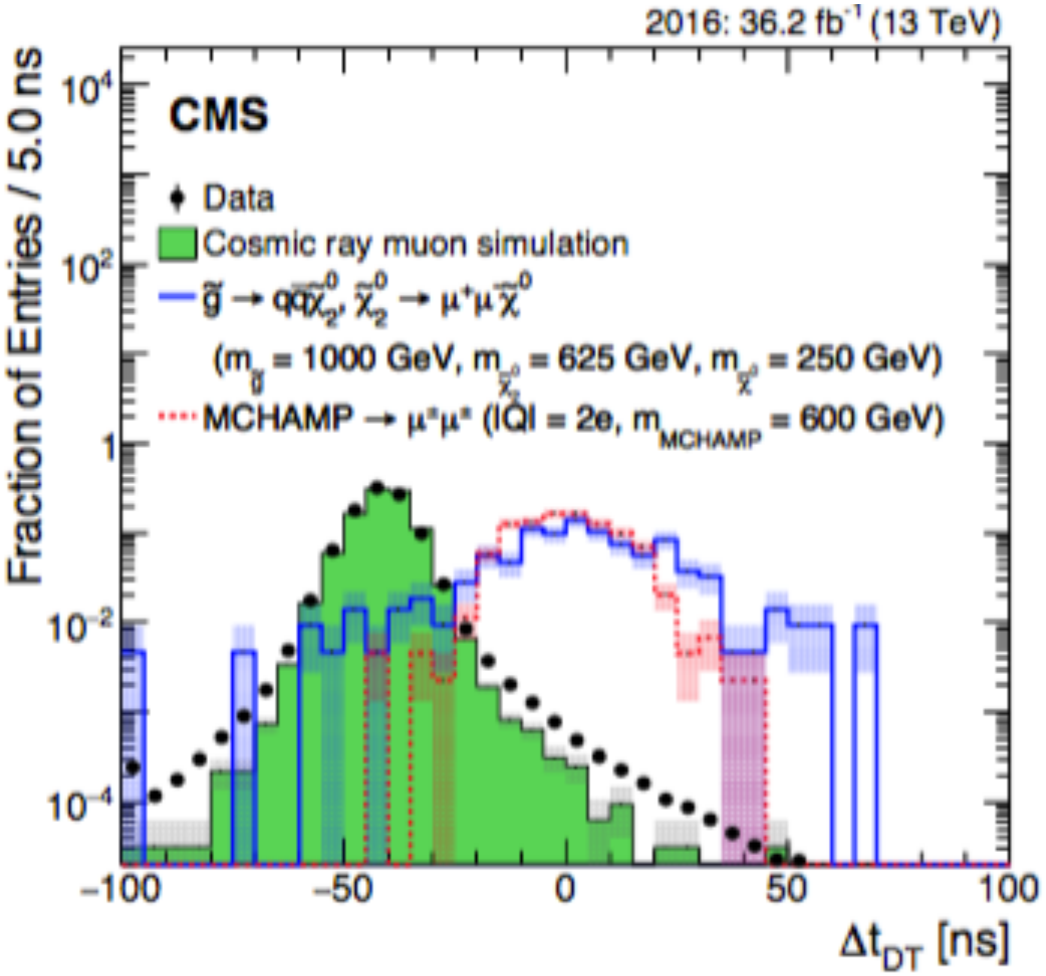
CMS Stopped particles

- R-hadrons which travel up to the calorimeter and then decay
  - analysis consider both hadronic decays in the calorimeters and decays into muons in the muon chambers
  - events recorded with special triggers focusing on out of bunch crossings activity

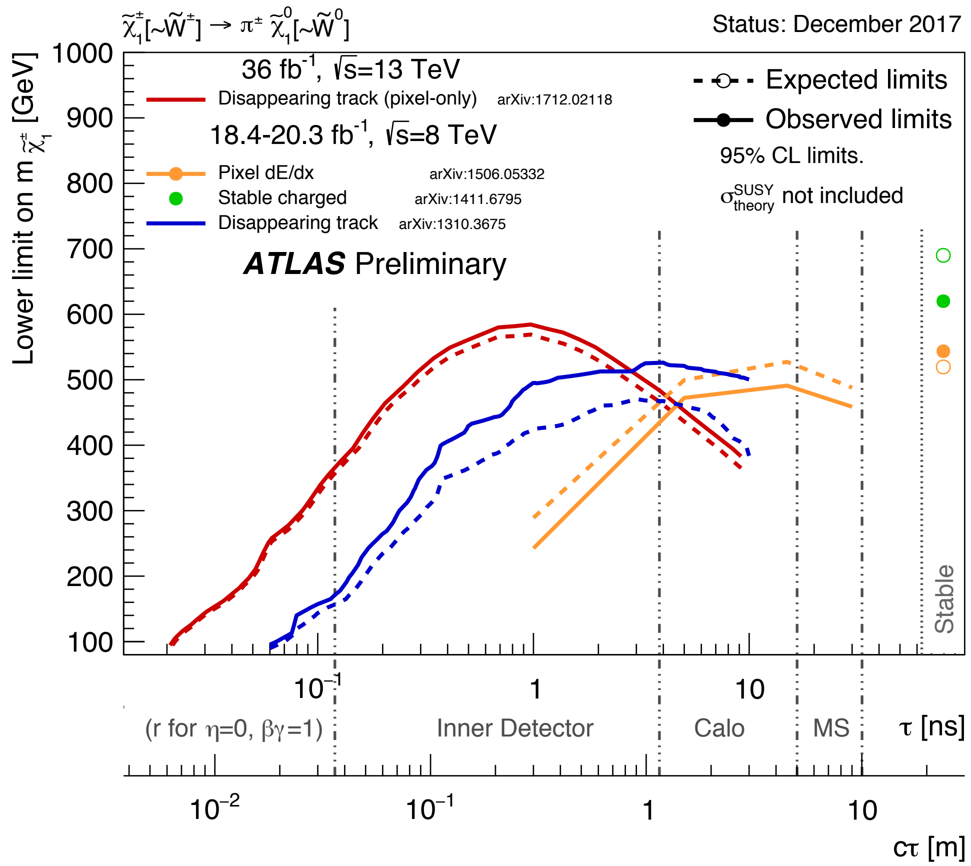


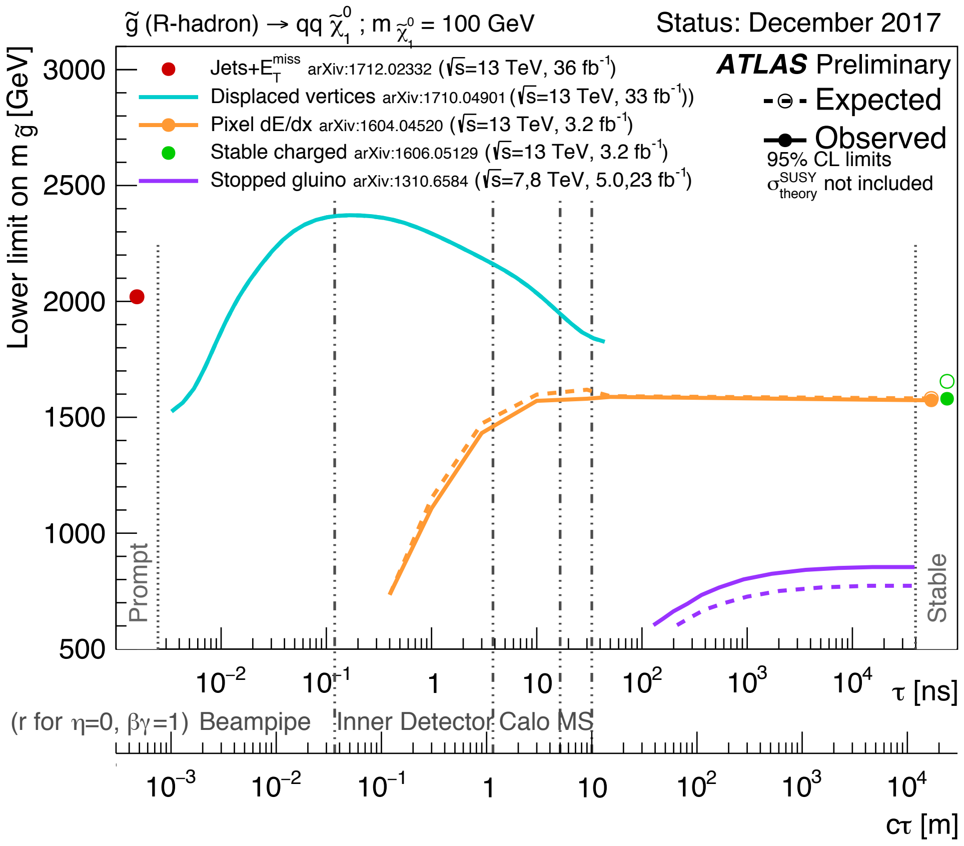


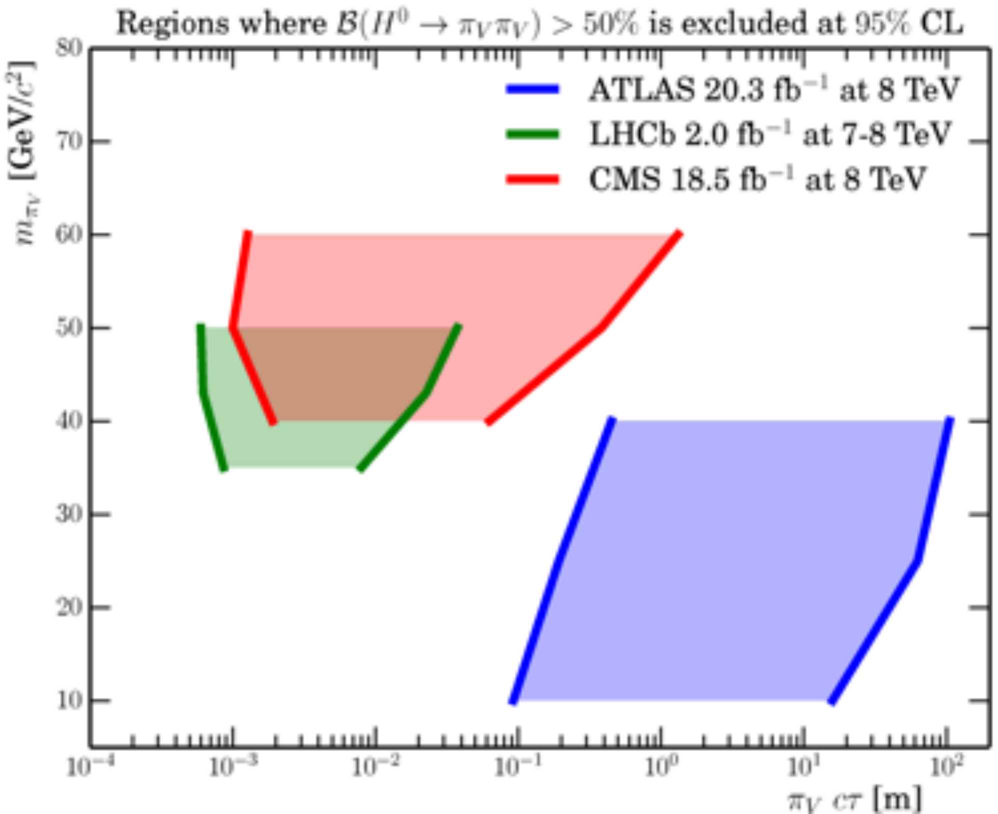
CERN-EP-2017-330

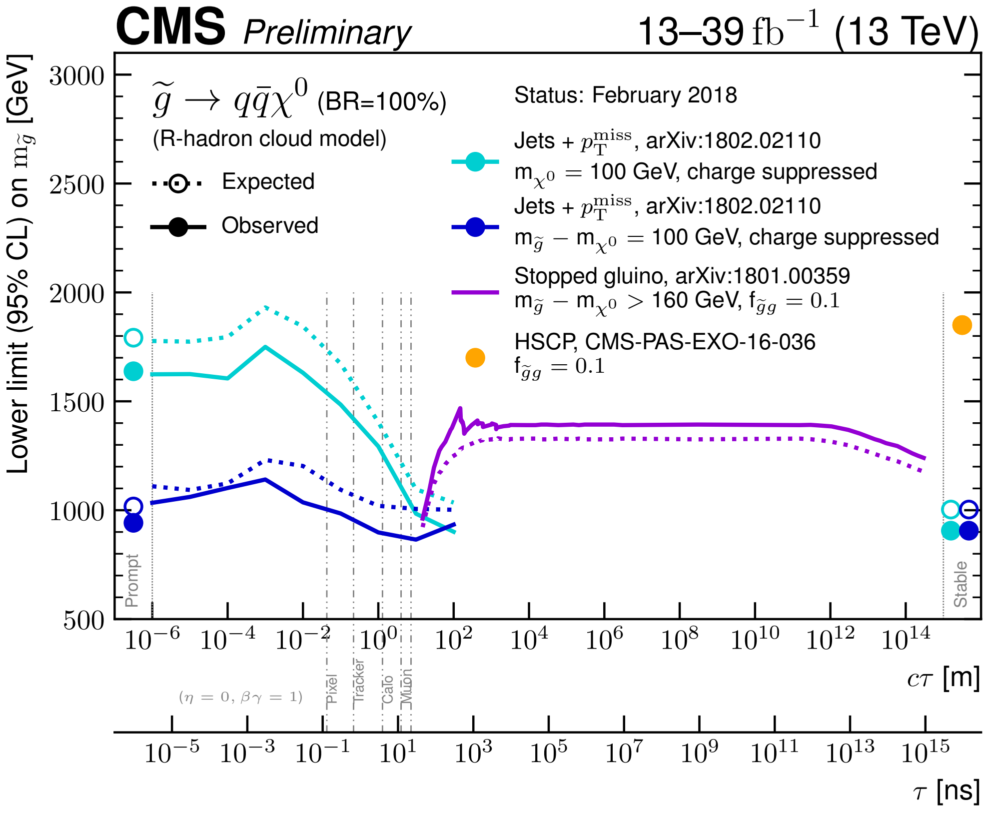


Summary plots







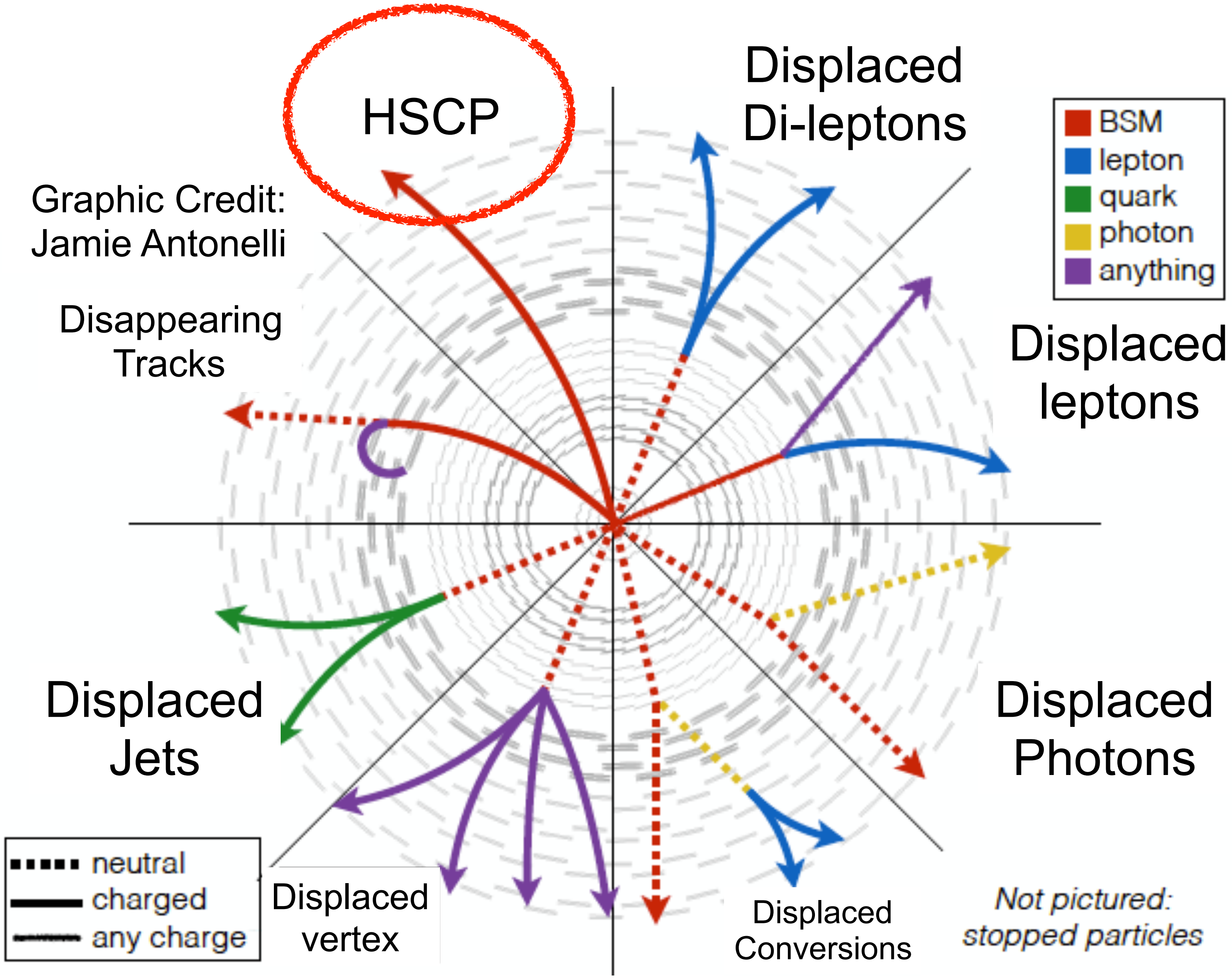


Conclusions

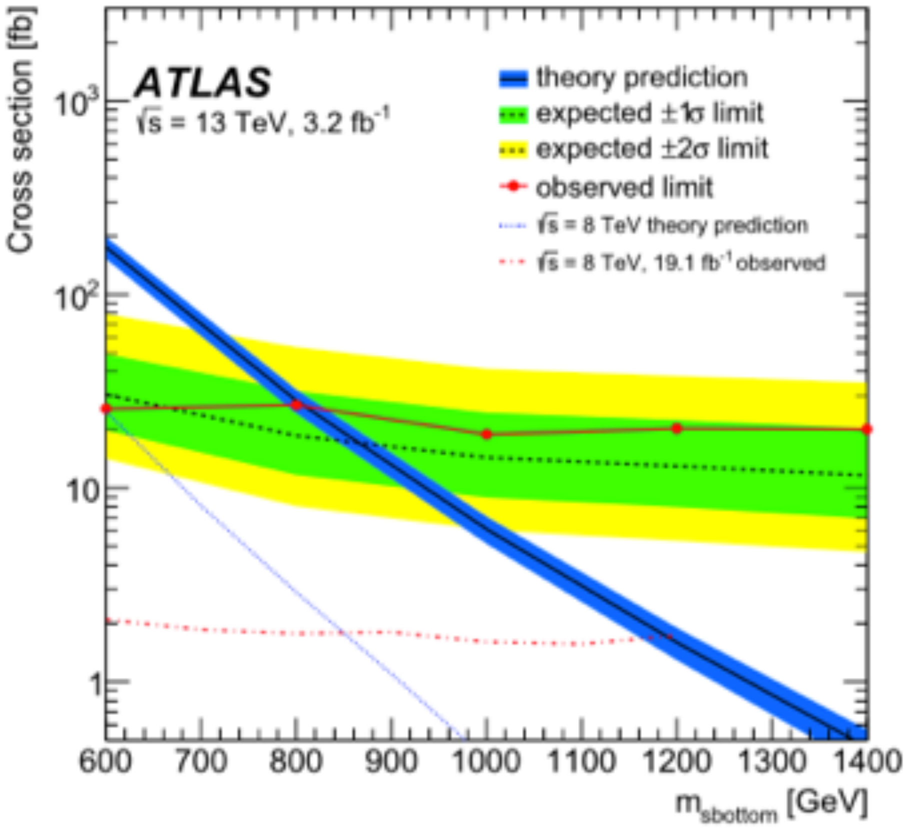
- Long lived particle search is a tough problem since detector is optimized for prompt decays.
  - still, they are becoming more and more popular at LHC
  - different place space probed with different detectors in different experiments
    - very nice redundancy of studies in few cases
    - this also means that it is more difficult to compare results and sensitivity
- We have enthusiastic dedicated (but small) team tackling it in creative ways
- A lot of work on going in defining framework for easier recasting of results in different benchmark scenarios

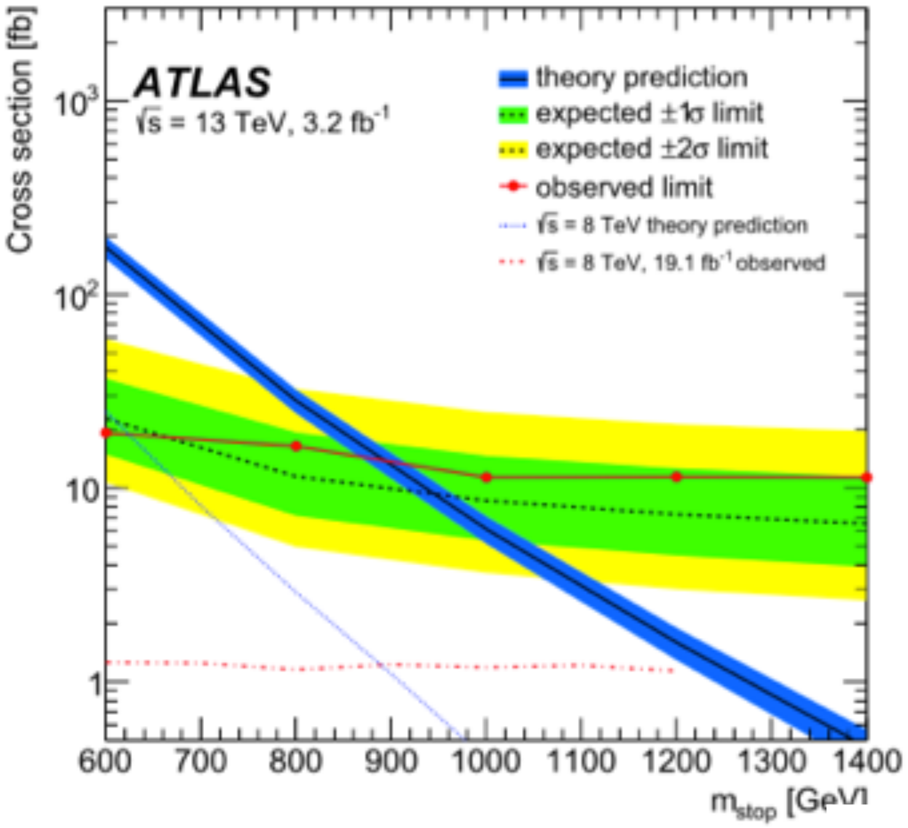
Back up

Stopped Particles



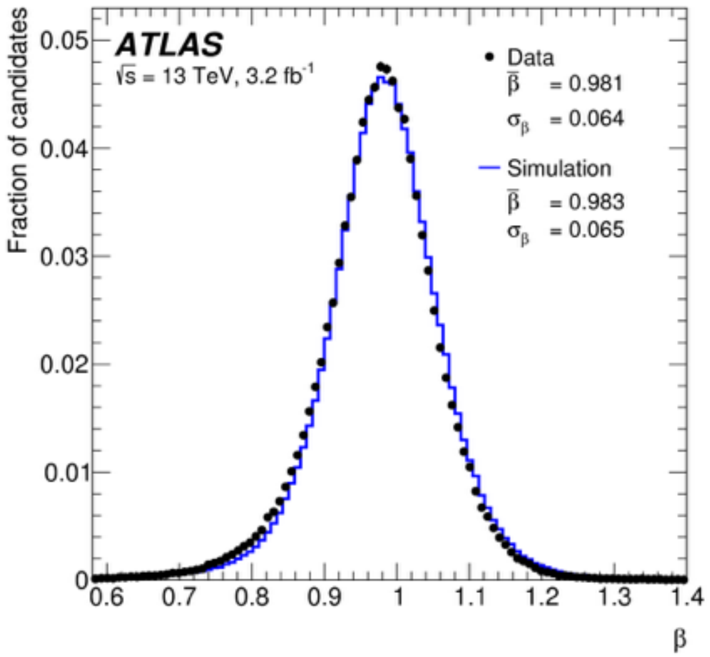
HSCP ATLAS

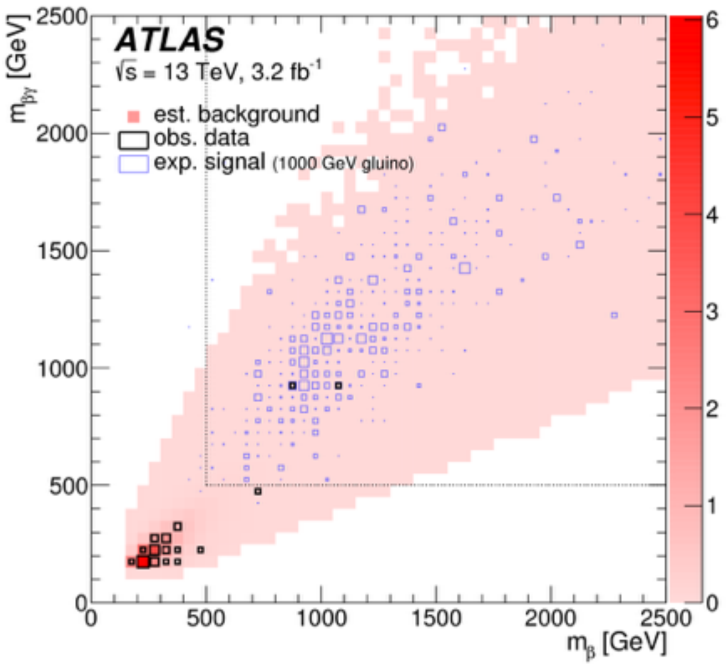


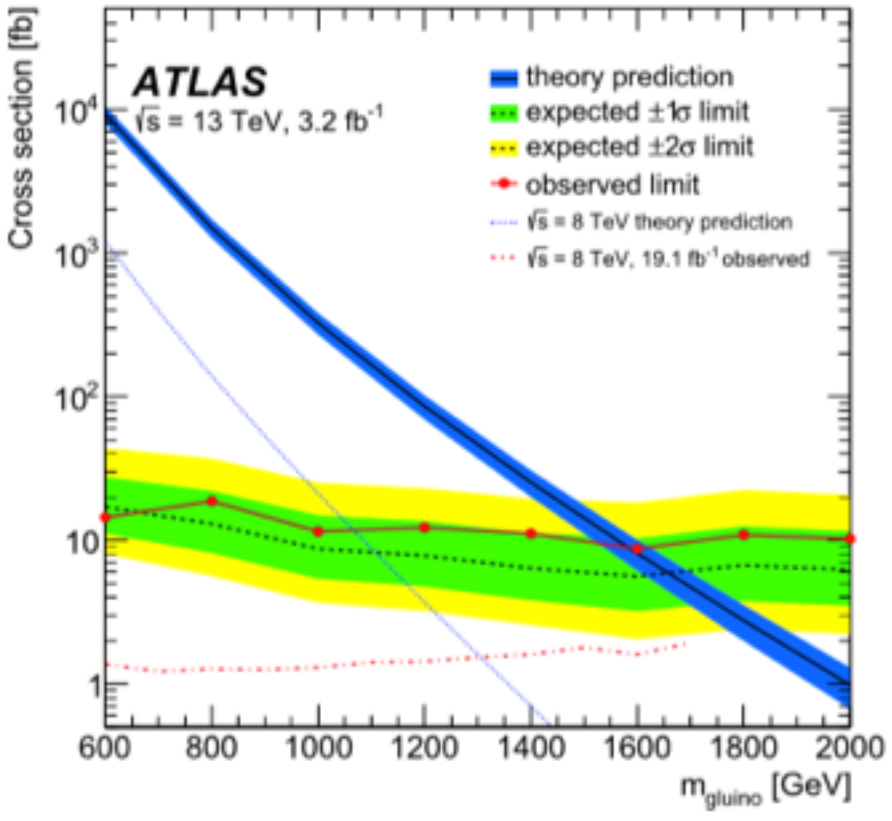


PLB 760 (2016) 647-665
13 TeV 3.2 fb^{-1}

JHEP 01 (2015) 068
8 TeV 19.1 fb^{-1}
ToF from Muon Spectrometer not yet used in Run 2!

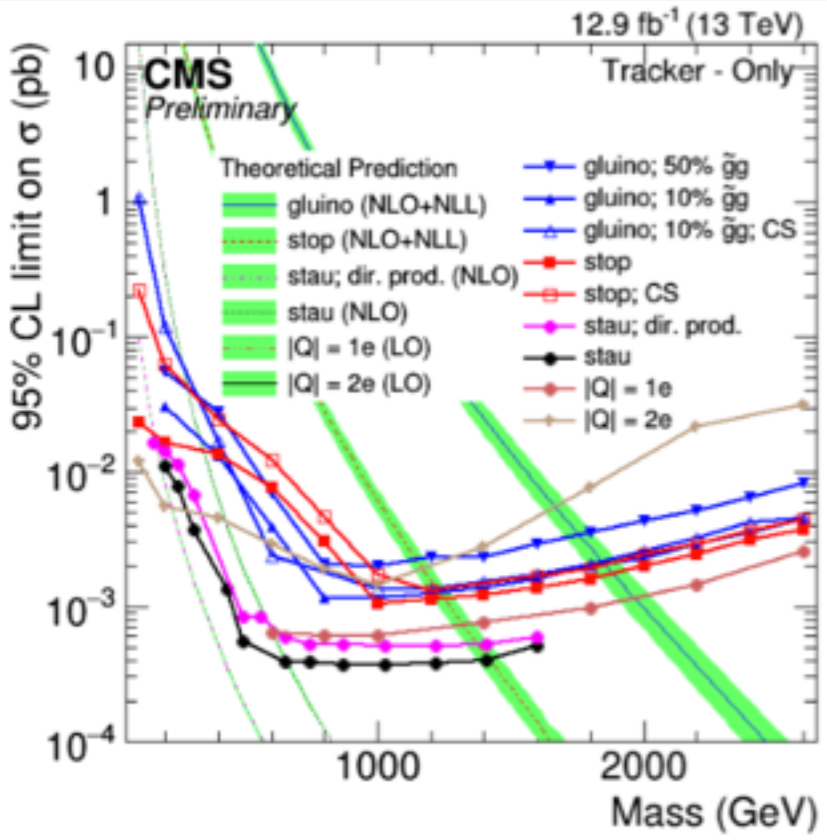


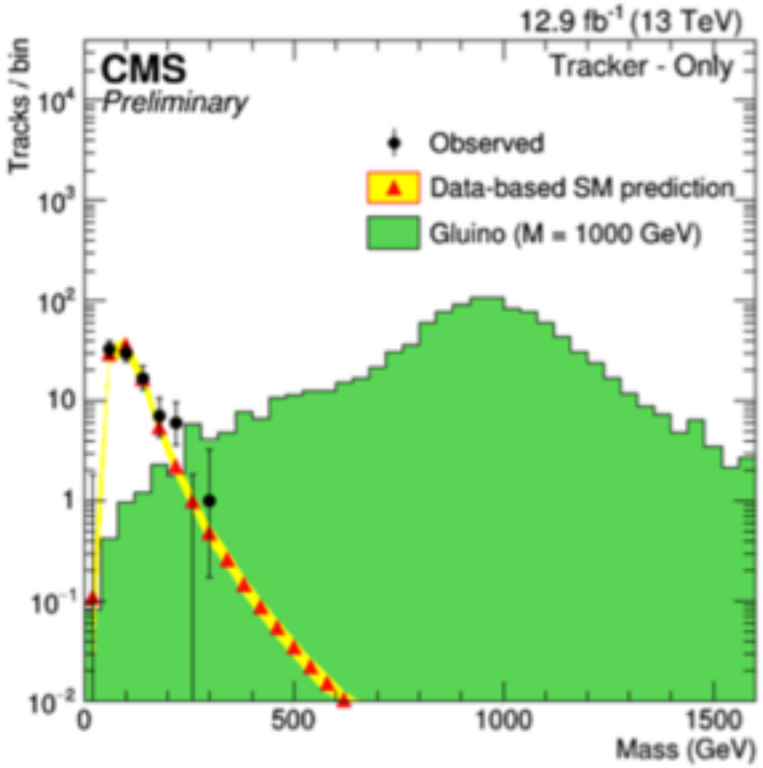


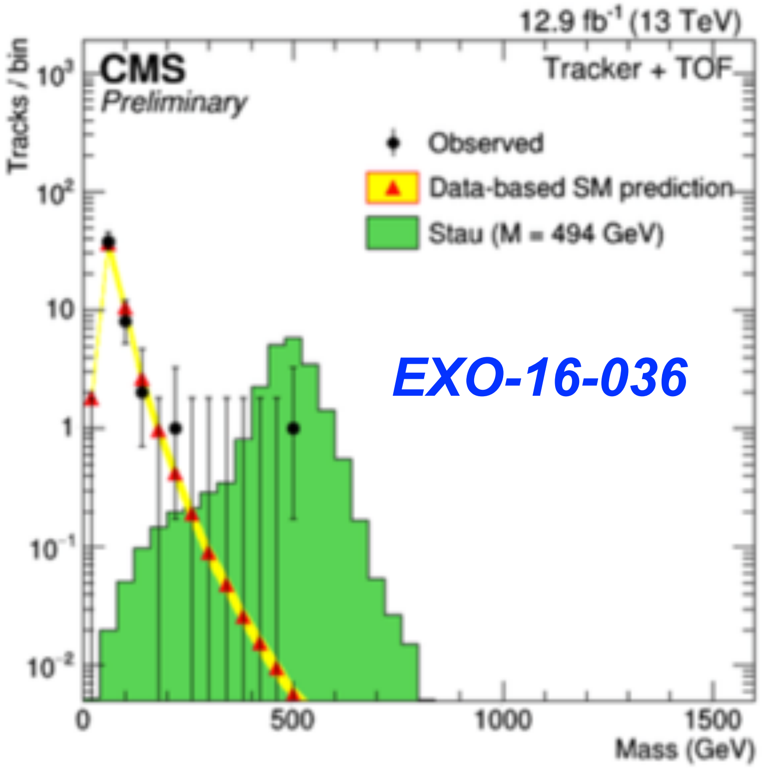


HSCP CMS

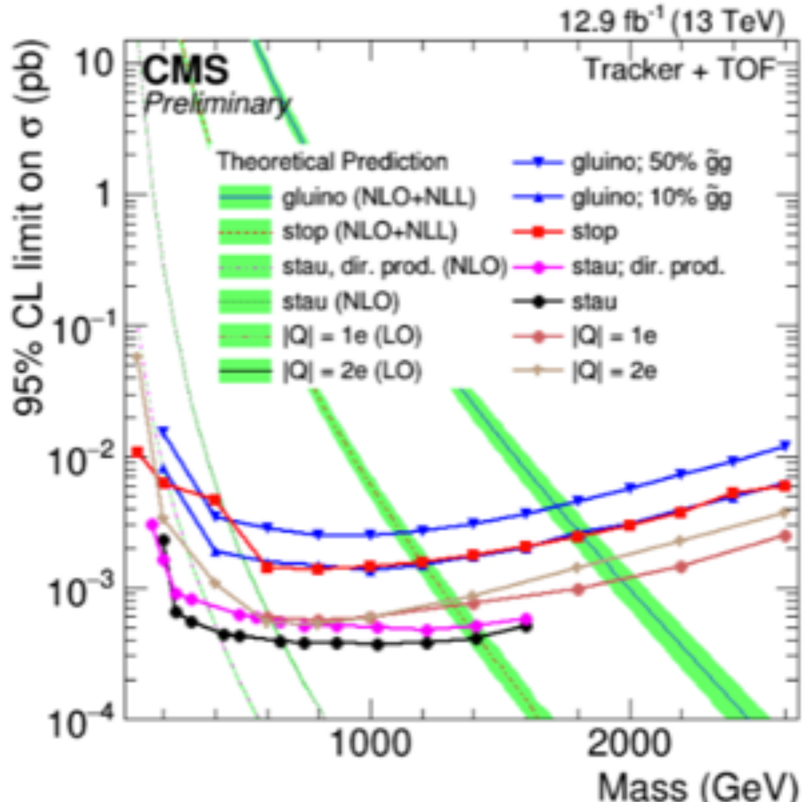
- Analysis with 12.9/fb from Run2
  - looking for R-hadron-like as well as lepton-like models
  - two categories
    - tracker only analysis, using only dE/dX
    - tracker+muon analysis, using dE/dX and TOF
  - trigger used: both muon and ETM based triggers





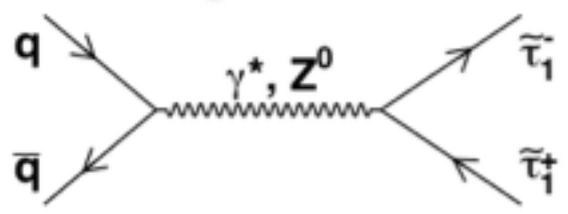


EXO-16-036



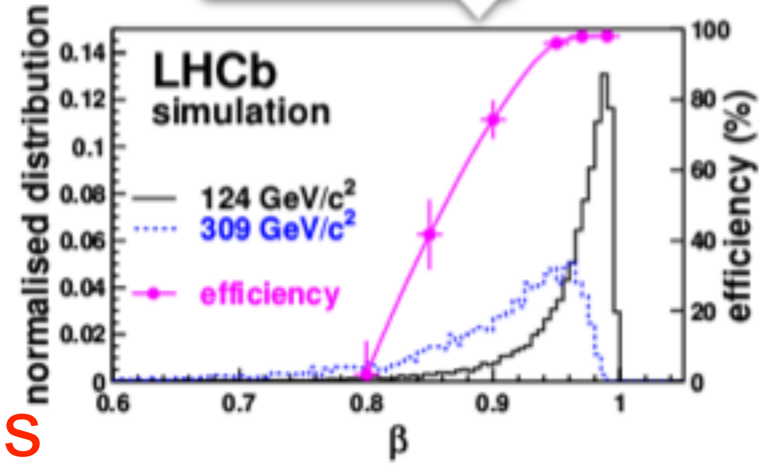
MSCP LHCB

Drell-Yan produced stau pairs



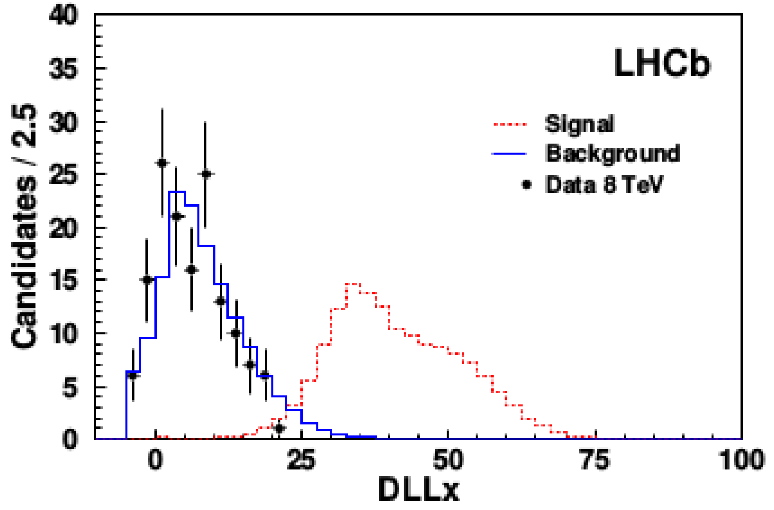
- Stable : can pass through the mu-stations
  - smaller dE/dX
  - Longer life time
  - Absence of Cherenkov signal
- Models:
  - susy stau mGMB
  - long lived with m>100 GeV

β as low as 0.8

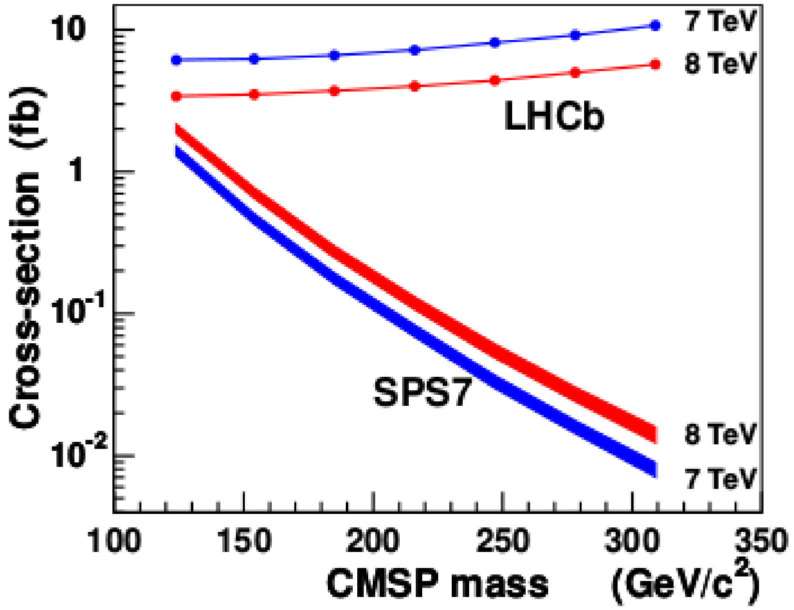


EPJC 75 (2015) 595

RICH information



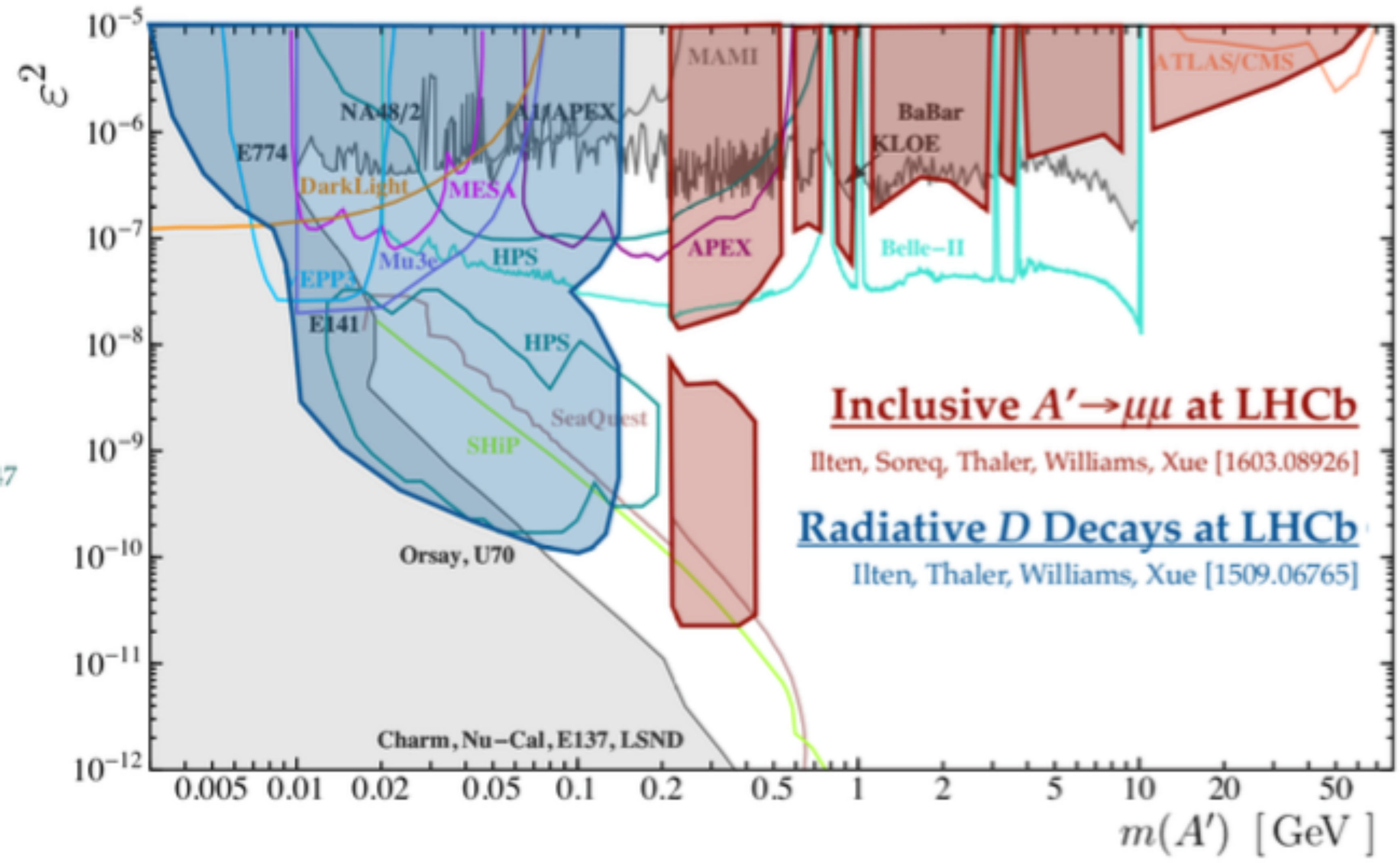
m_{CMSP} (GeV/c^2)	Upper limit (fb)	
	7 TeV	8 TeV
124	6.1	3.4
154	6.2	3.5
185	6.6	3.7
216	7.2	4.0
247	8.1	4.4
278	9.2	5.0
309	10.7	5.7



Simone.Gennai@cern.ch

Dark Photons LHCb future

- Extend searches model-independently
  → i.e. light NMSSM Higgs via ggF [PRD 93 (2016) 055047]
- Search inclusively for four muons,
- Search for $N_{2,3} \to \pi^+\mu^-$, etc.
- Prospected reach for **Run III:**



Inclusive $A' \to \mu\mu$ at LHCb

Ilten, Soreq, Thaler, Williams, Xue [1603.08926]

Radiative *D* Decays at LHCb

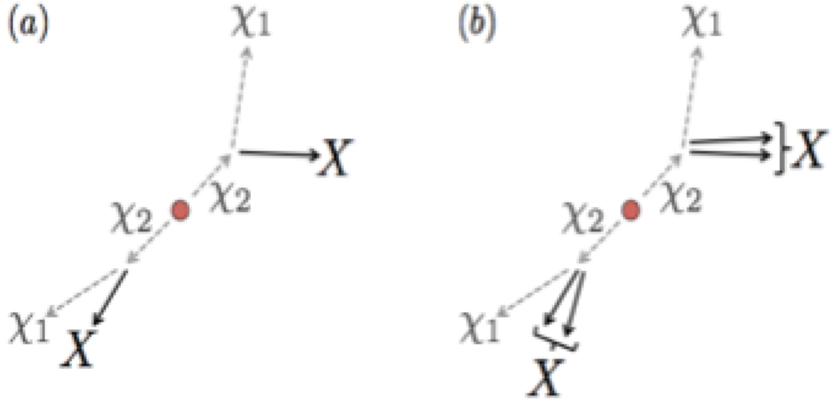
Ilten, Thaler, Williams, Xue [1509.06765]

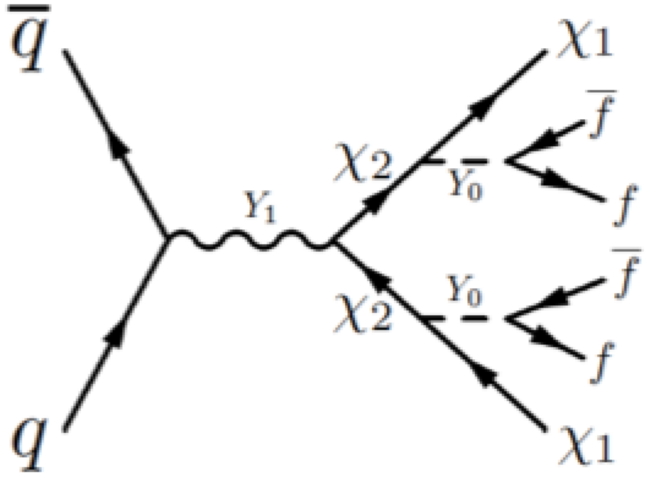
Simone.Gennai@cern.ch

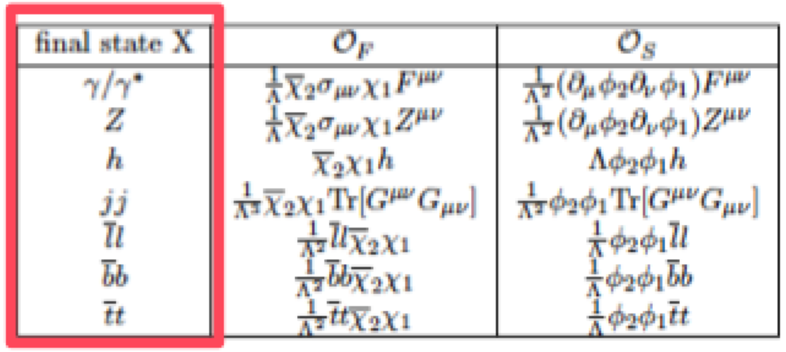
Future CMS

Extension of MET + X and SUSY searches adding long-lived final state: Production of MC based on: arXiv:1704.06515

- Stage 1: Produce a set of long-lived signatures to benchmark where our prompt searches "break"!
  - Revert to a large and well understood portfolio of simplified models that are already in use by the experiments, in SUSY and Dark Matter analyses!
  - Started production with the obvious final states like displaced pairs of jets + MET but eventually will cover more signatures.
  - This might reveal potential holes in our search program, which in turn will inform new dedicated searches.
- Stage 2: Develop dedicated searches with LL objects.
  - Large area of parameter space and new signatures to cover.
  - Various different displaced signatures are possible and are also well motivated.







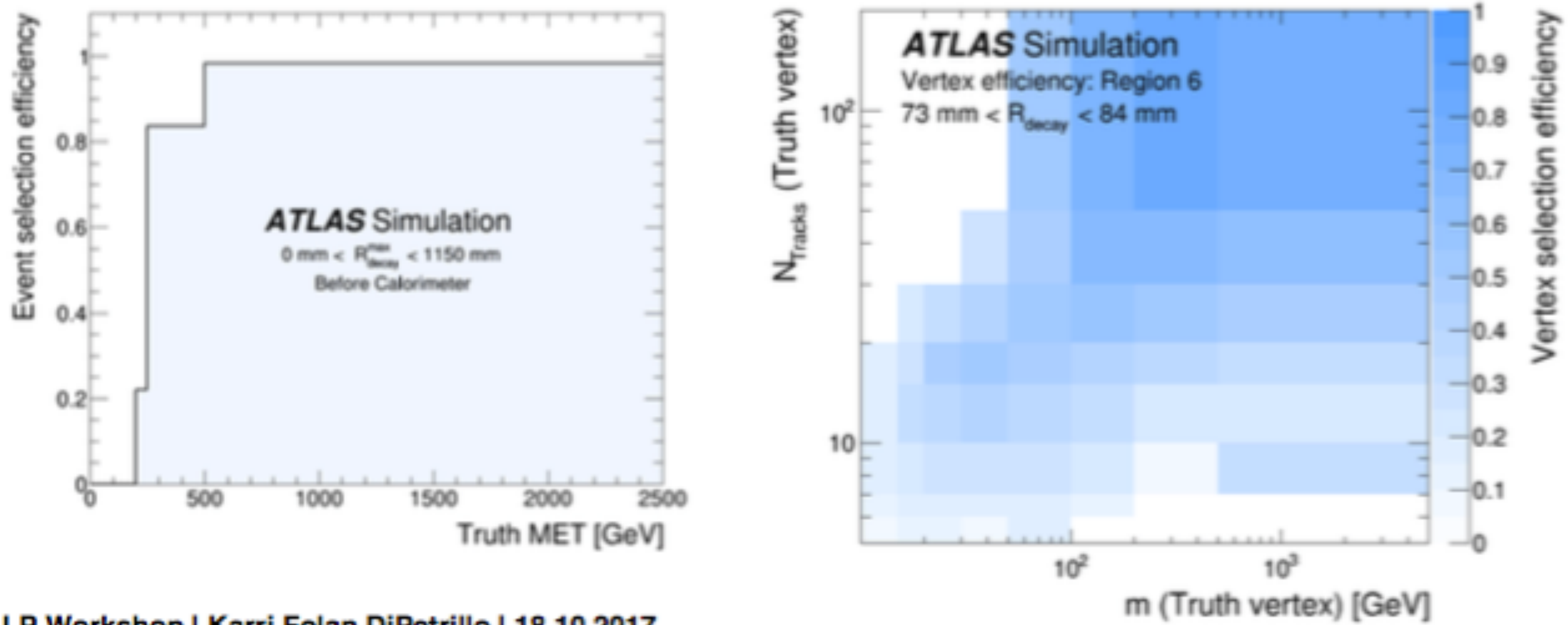
final state X	$\mathcal{O}_F$	$\mathcal{O}_S$
γ/γ^*	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu}$	$\frac{1}{\Lambda^2}(\partial_\mu\phi_2\partial_\nu\phi_1)F^{\mu\nu}$
Z	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 Z^{\mu\nu}$	$\frac{1}{\Lambda^2}(\partial_\mu\phi_2\partial_\nu\phi_1)Z^{\mu\nu}$
h	$\overline{\chi}_2\chi_1 h$	$\Lambda\phi_2\phi_1 h$
jj	$\frac{1}{\Lambda^3}\overline{\chi}_2\chi_1\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$	$\frac{1}{\Lambda^2}\phi_2\phi_1\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$
$\overline{l}l$	$\frac{1}{\Lambda^2}\overline{l}l\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\overline{l}l$
$\overline{b}b$	$\frac{1}{\Lambda^2}\overline{b}b\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\overline{b}b$
$\overline{t}t$	$\frac{1}{\Lambda^2}\overline{t}t\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\overline{t}t$

Reinterpretation

If you're not satisfied w/ our interpretations… we're providing parametrized efficiencies as aux material

with prescriptions for easy use

DV+MET Event & Vertex Level Efficiencies



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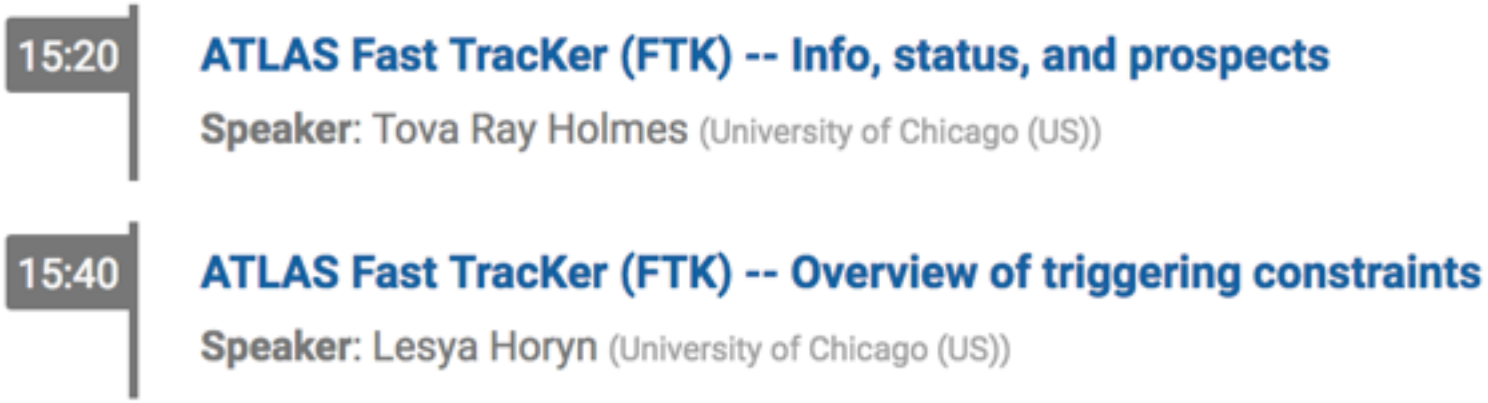
How do we trigger on these objects?

ATLAS trigger basics

- L1: calorimeter & muon information
- HLT: e/μ/γ/τ/jets/MET
- limited tracking info at HLT
- typically d0 requirements on e/μ

Is there room for improvement?

Many HLT ideas limited by L1 constraints



15:20 **ATLAS Fast TracKer (FTK) -- Info, status, and prospects**

Speaker: Tova Ray Holmes (University of Chicago (US))

15:40 **ATLAS Fast TracKer (FTK) -- Overview of triggering constraints**

Speaker: Lesya Horyn (University of Chicago (US))

LLP Strategies

very hard

1. Design your own
displaced lepton jets:
“narrow scan” and
“cal ratio”

2. Be sneaky
displaced e: γ trigger
displaced μ: Muon
Spectrometer only trigger

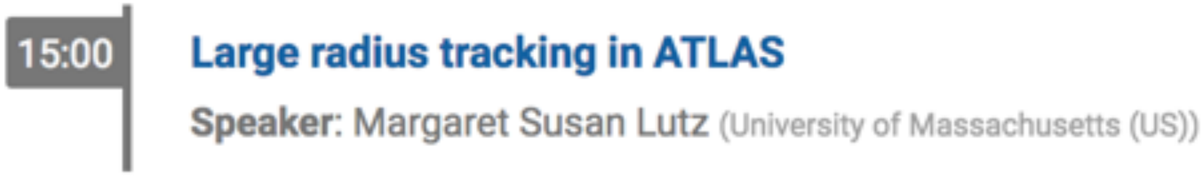
3. Be lucky
Inner Detector displaced
vertices: multi-jet/MET

very easy

How do we reconstruct these signatures?

Lots of work in non-standard reconstruction

- Pixel tracklets
- Large radius tracking
- Slow muons
- Secondary Vertex finding



15:00 **Large radius tracking in ATLAS**

Speaker: Margaret Susan Lutz (University of Massachusetts (US))

These methods are difficult, but essential

- computationally expensive
- require running on raw data
- filter out events using special data streams
- so we can run our non-standard reconstruction a single time