Phenomenology 2019 @ University of Pittsburgh

Hao-Ren Jheng, NCU

Phenomenology 2019

- A **theorist/phenomenologist-oriented** conference
- A **PhD student/postdoc-oriented** meeting
  - A special Forum on early career development, aiming at senior PhD students or postdocs
- Conference indico: https://indico.cern.ch/event/777988/overview

The Cathedral of Learning

Phenomenology 2019

- An overview on recent LHC results on HIG, SMP, TOP physics: The Higgs, gauge bosons, and top quark at LHC
  - I will not talk about this one…
- An summary of recent results on EXO, SUS, unconventional signatures (long live particles, LLP), dark matter (DM): New physics searches at the LHC
  - I find several analyses interesting, and will show some of them in the following
- Also a good talk on "Multi-messenger cosmology" & an interesting talk on "Deep learning (and deep thinking) in collider physics"
  - I will not talk about these two either… Look at them if you are interested in :)

BSM & Experimental searches

Spin-0

- scalar diquarks
- color-octet scalars
- …

Spin-1

- new spin-1 gauge bosons (W′ and Z′) with SM-like couplings; HVT model
- …

Spin-2

- Randall–Sundrum gravitons
- …

- two-Higgs-doublet-model (2HDM), composite Higgs model, extended gauge sectors as in Grand Unified Theories, string resonances, axigluons, colorons, excited quarks (q*), DM mediators……

Di-jet resonance searches

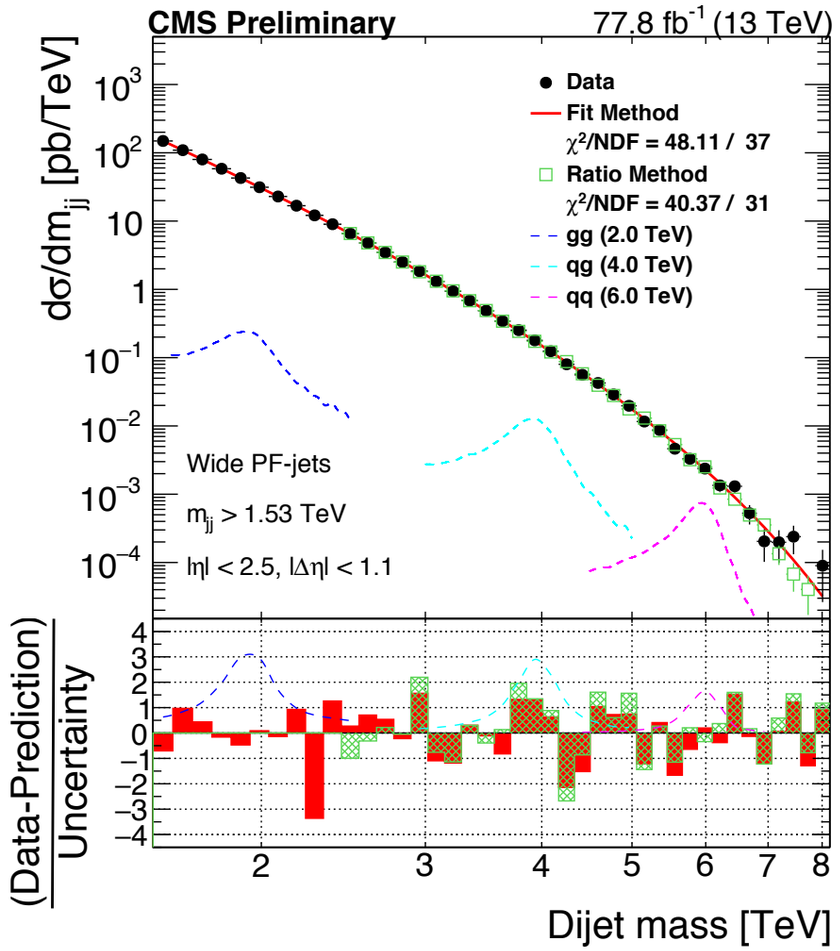
Di-lepton resonance searches

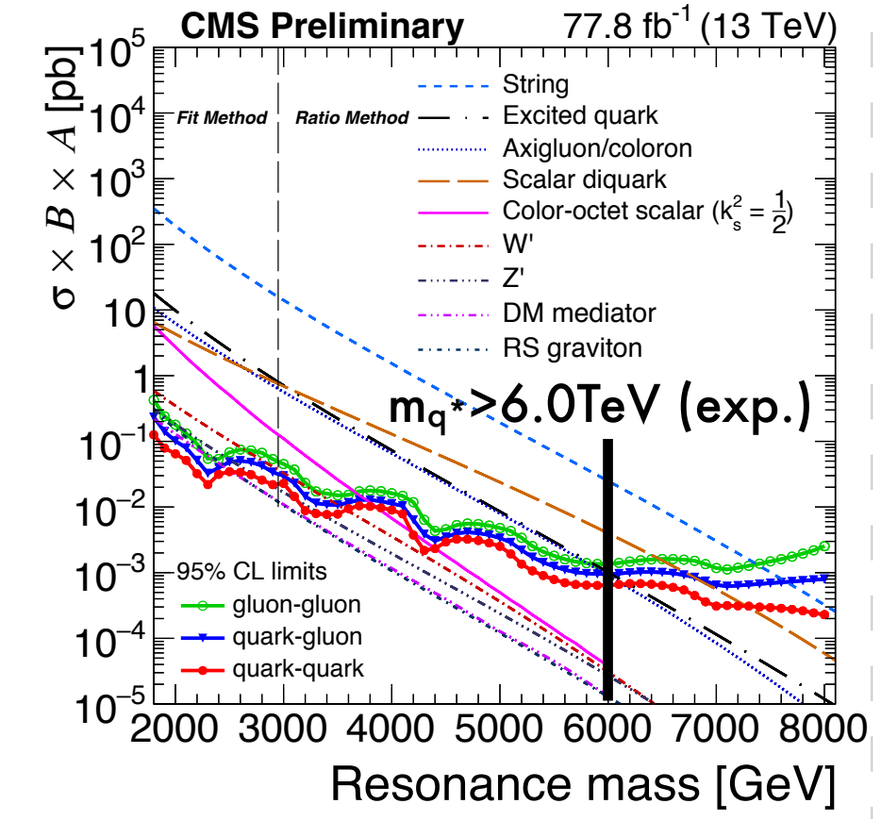
Di-boson resonance searches

Di-jet resonance search

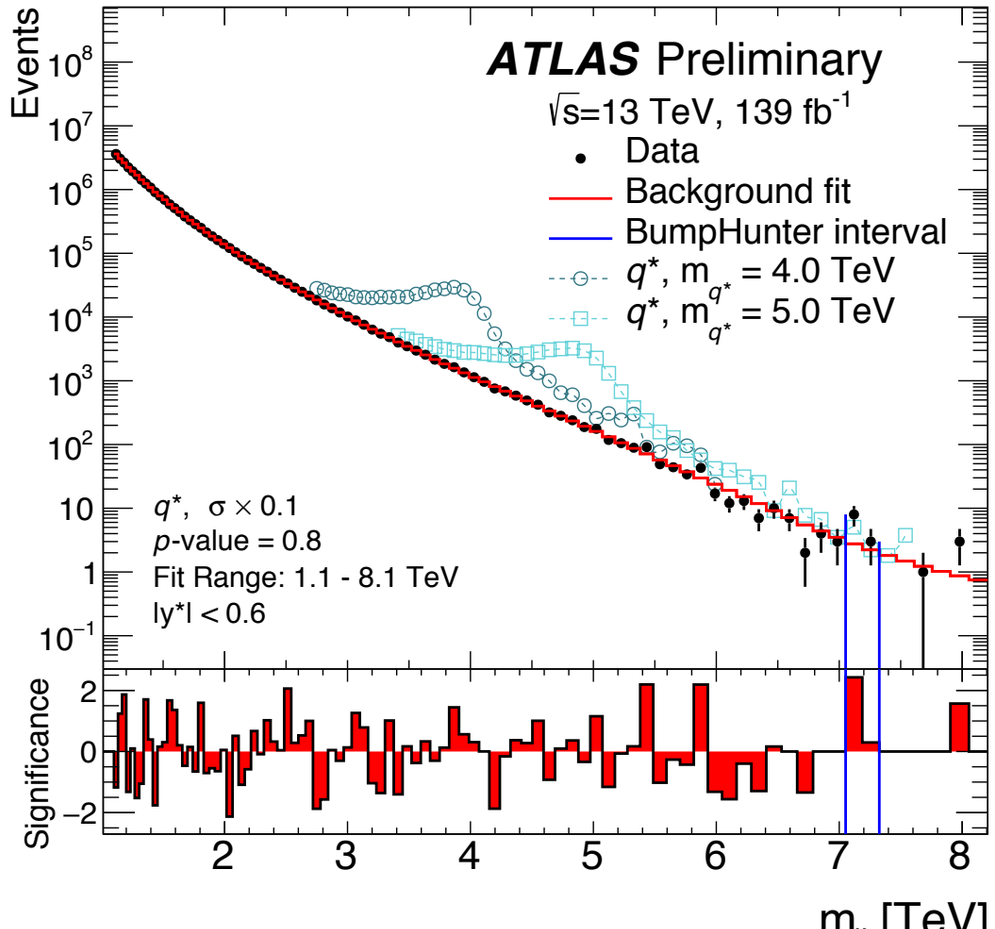
- Both ATLAS and CMS performed relevant searches
  - ATLAS-CONF-2019-007 provides limits on q* model; full Run2 data
  - CMS-PAS-EXO-17-026 provides limits on aforementioned models; 2016+2017 data
- The above two analyses target at high mass signals
  - two resolved jets to form high mass di-jet candidate
- There are also analyses aiming at low mass region (shown later…)

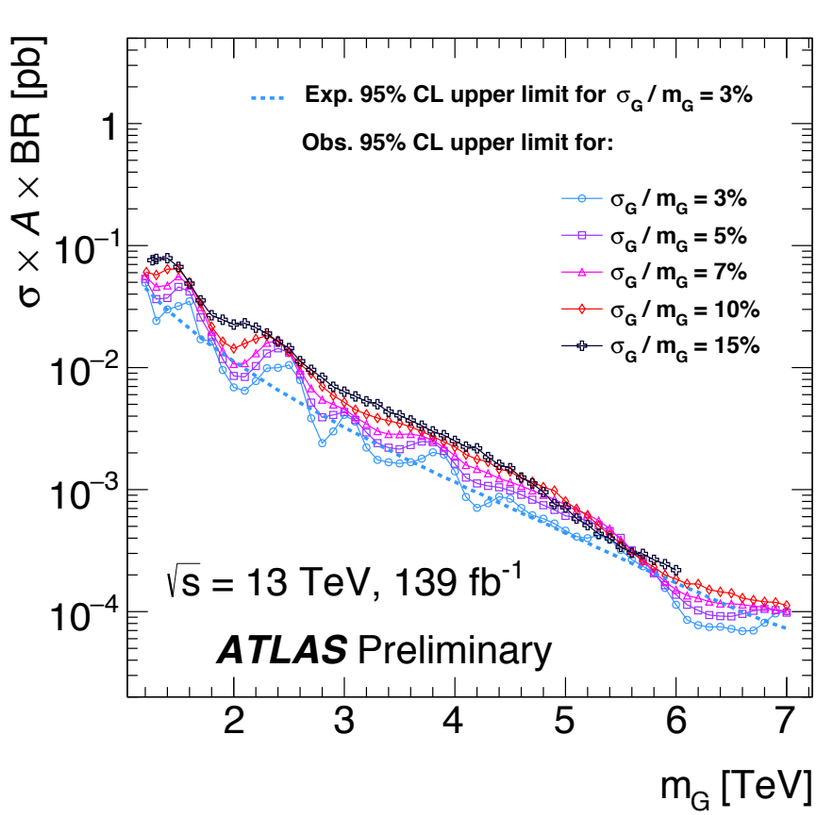
CMS

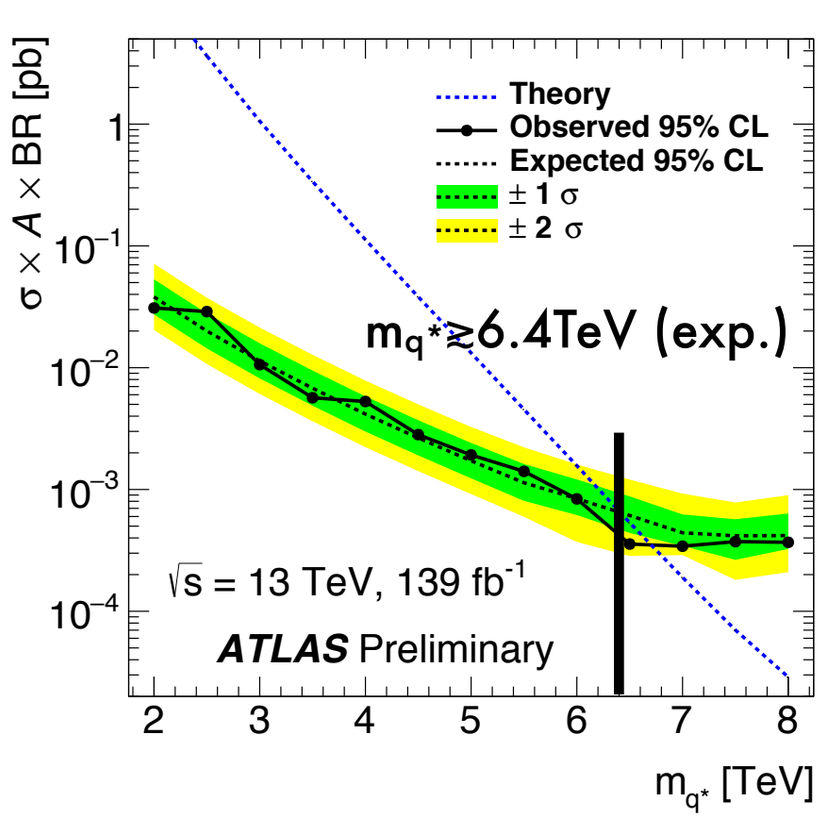

CMS Preliminary
77.8 fb-1 (13 TeV)
Data
Fit Method
χ2/NDF = 48.11 / 37
Ratio Method
χ2/NDF = 40.37 / 31
gg (2.0 TeV)
qg (4.0 TeV)
qq (6.0 TeV)
Wide PF-jets
mjj > 1.53 TeV
|η| < 2.5, |Δη| < 1.1
dσ/dmjj [pb/TeV]
(Data-Prediction)/Uncertainty
Dijet mass [TeV]


CMS Preliminary
77.8 fb-1 (13 TeV)
Fit Method
Ratio Method
String
Excited quark
Axigluon/coloron
Scalar diquark
Color-octet scalar (k2s = 1/2)
W'
Z'
DM mediator
RS graviton
mq*>6.0TeV (exp.)
95% CL limits
gluon-gluon
quark-gluon
quark-quark
σ × B × A [pb]
Resonance mass [GeV]

ATLAS


ATLAS Preliminary
√s=13 TeV, 139 fb-1
Data
Background fit
BumpHunter interval
q*, mq* = 4.0 TeV
q*, mq* = 5.0 TeV
q*, σ × 0.1
p-value = 0.8
Fit Range: 1.1 - 8.1 TeV
|y*| < 0.6
Events
Significance
mjj [TeV]


Exp. 95% CL upper limit for σG / mG = 3%
Obs. 95% CL upper limit for:
σG / mG = 3%
σG / mG = 5%
σG / mG = 7%
σG / mG = 10%
σG / mG = 15%
√s = 13 TeV, 139 fb-1
ATLAS Preliminary
σ × A × BR [pb]
mG [TeV]


Theory
Observed 95% CL
Expected 95% CL
± 1 σ
± 2 σ
mq*≥6.4TeV (exp.)
√s = 13 TeV, 139 fb-1
ATLAS Preliminary
σ × A × BR [pb]
mq* [TeV]

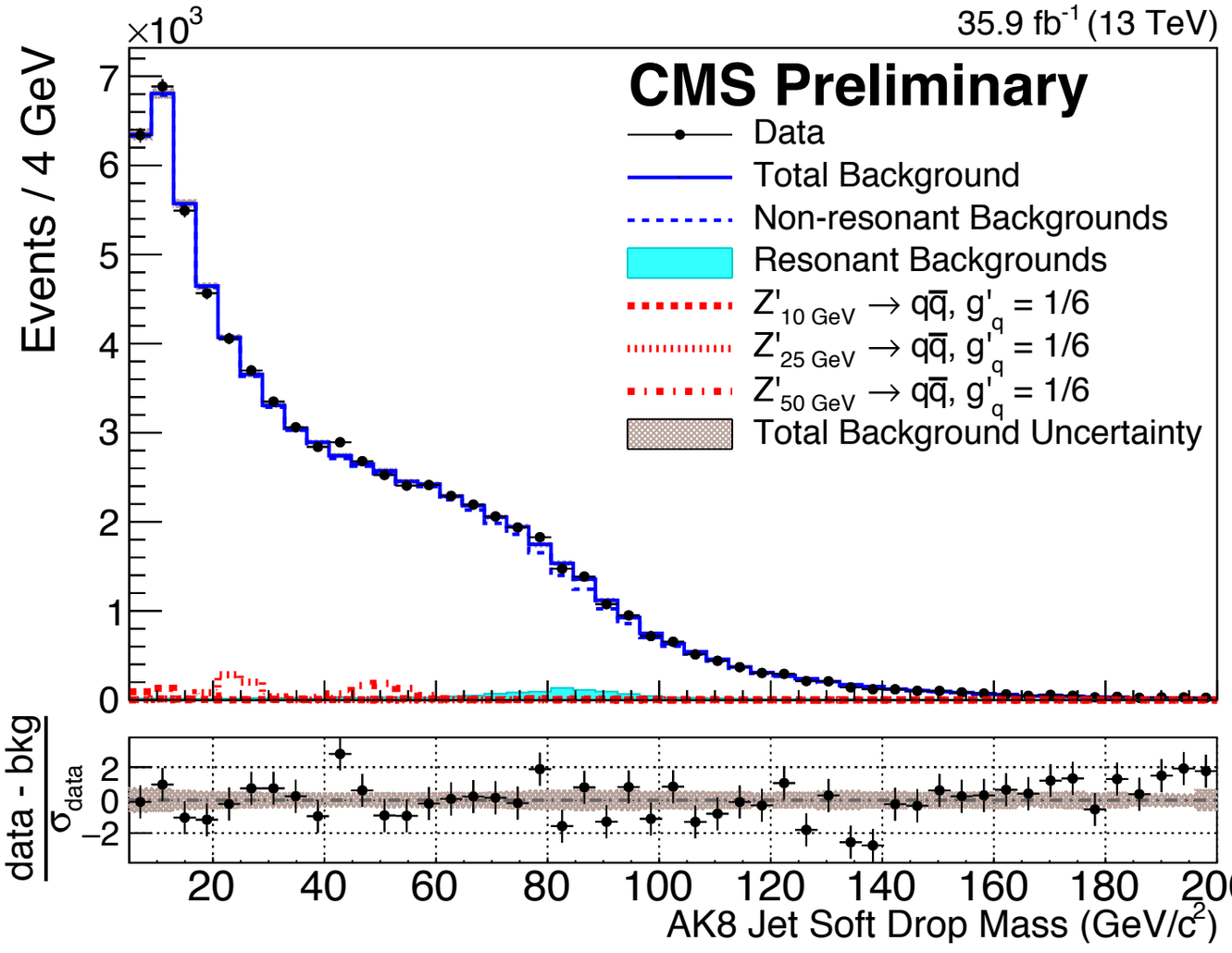
Di-jet resonance search

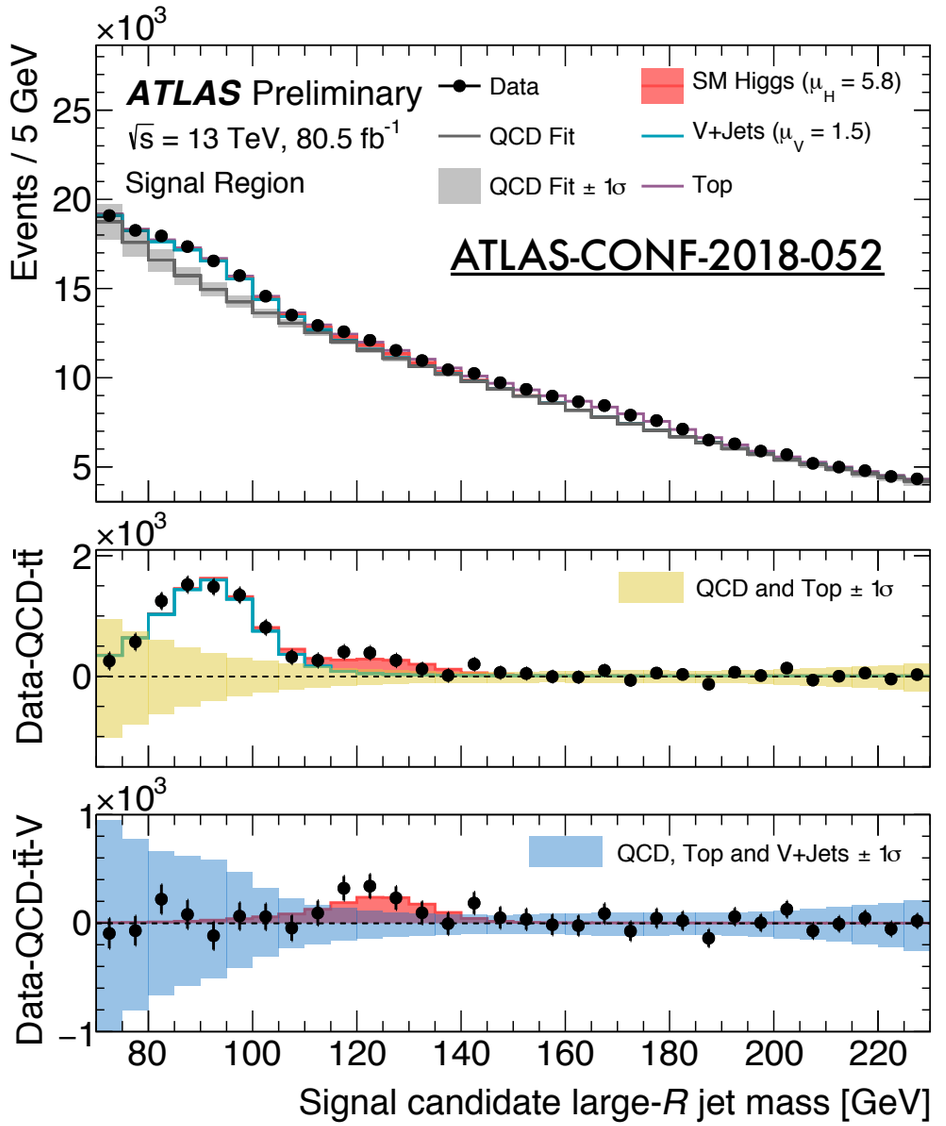
- Sensitivity to lower mass resonances is poor:
  - (1) The increasing cross section of background multi-jet events (2) Tightening online requirements in order to handle increasingly large event rates (3) large numbers of simultaneous collisions per bunch crossing

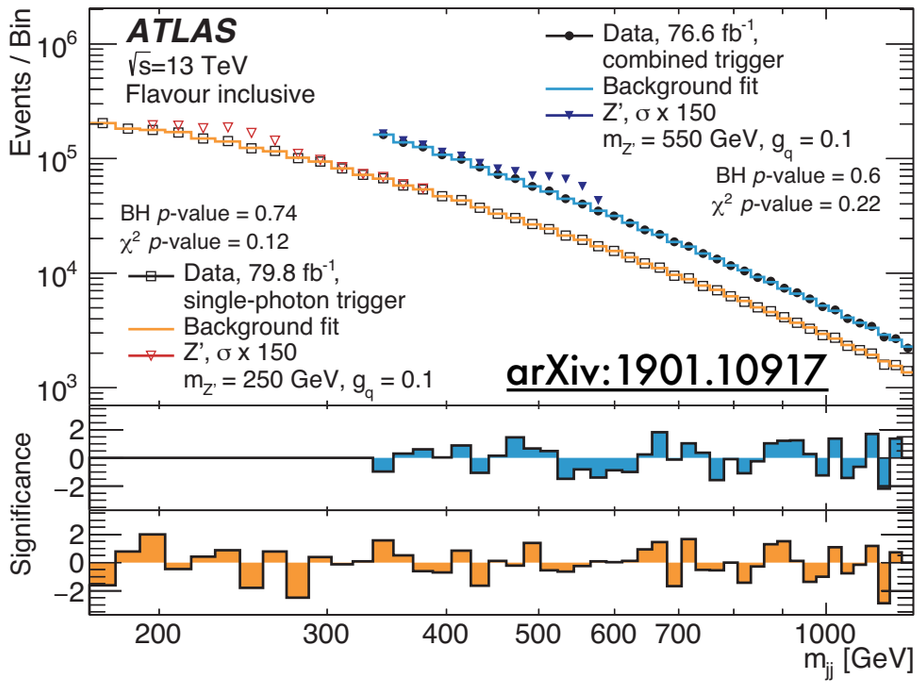
- Special event signature is exploited: the resonance is produced in association with high p_T photon or jet
  - arXiv:1901.10917: ATLAS's search on resolved di-jet resonance + photon (E_T^γ >95/150GeV for combined*/single-γ HLT)
    *: combined HLT requires additional jets to allow a lower pT requirement on the photon
  - ATLAS-CONF-2018-052 looks for merged jet with b-quark pair substructure + an additional jet (leading/trailing jet p_T>480/250GeV)
  - CMS-PAS-EXO-17-027 looks for merged jets with 2-prone substructure + photon E_T^γ>200GeV (events collected by single-γ HLT)

ATLAS

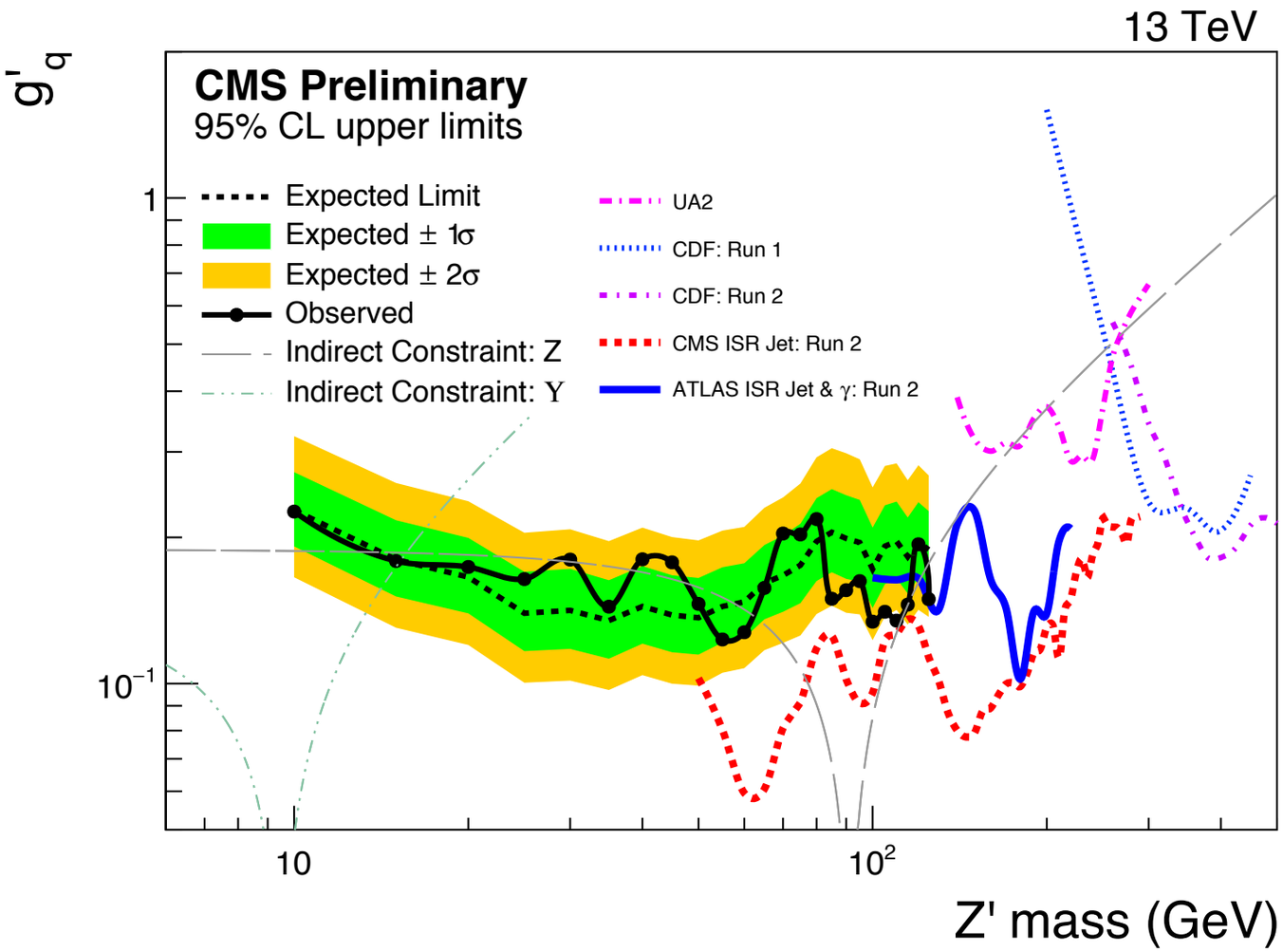
CMS-PAS-EXO-17-027



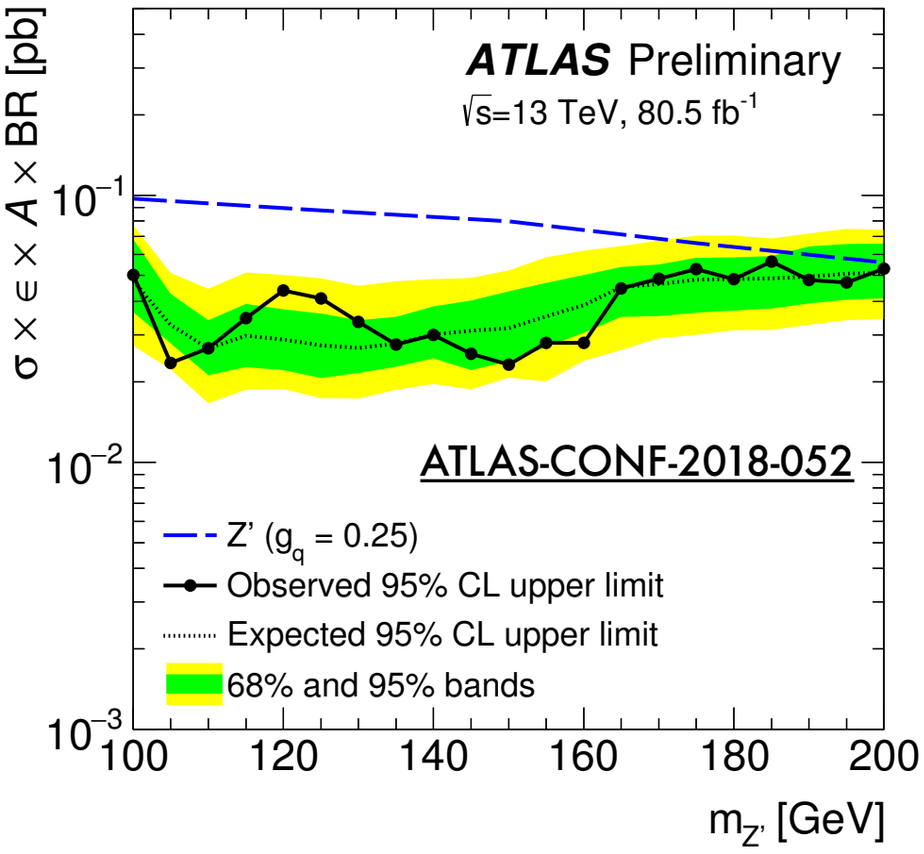


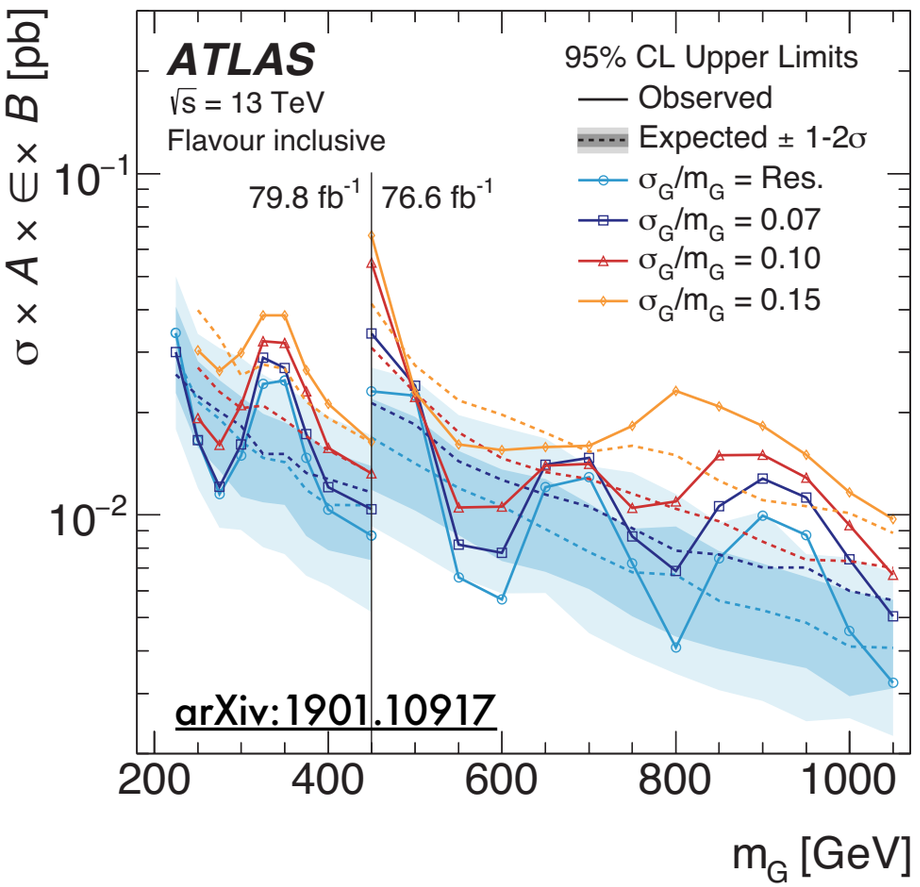


CMS-PAS-EXO-17-027



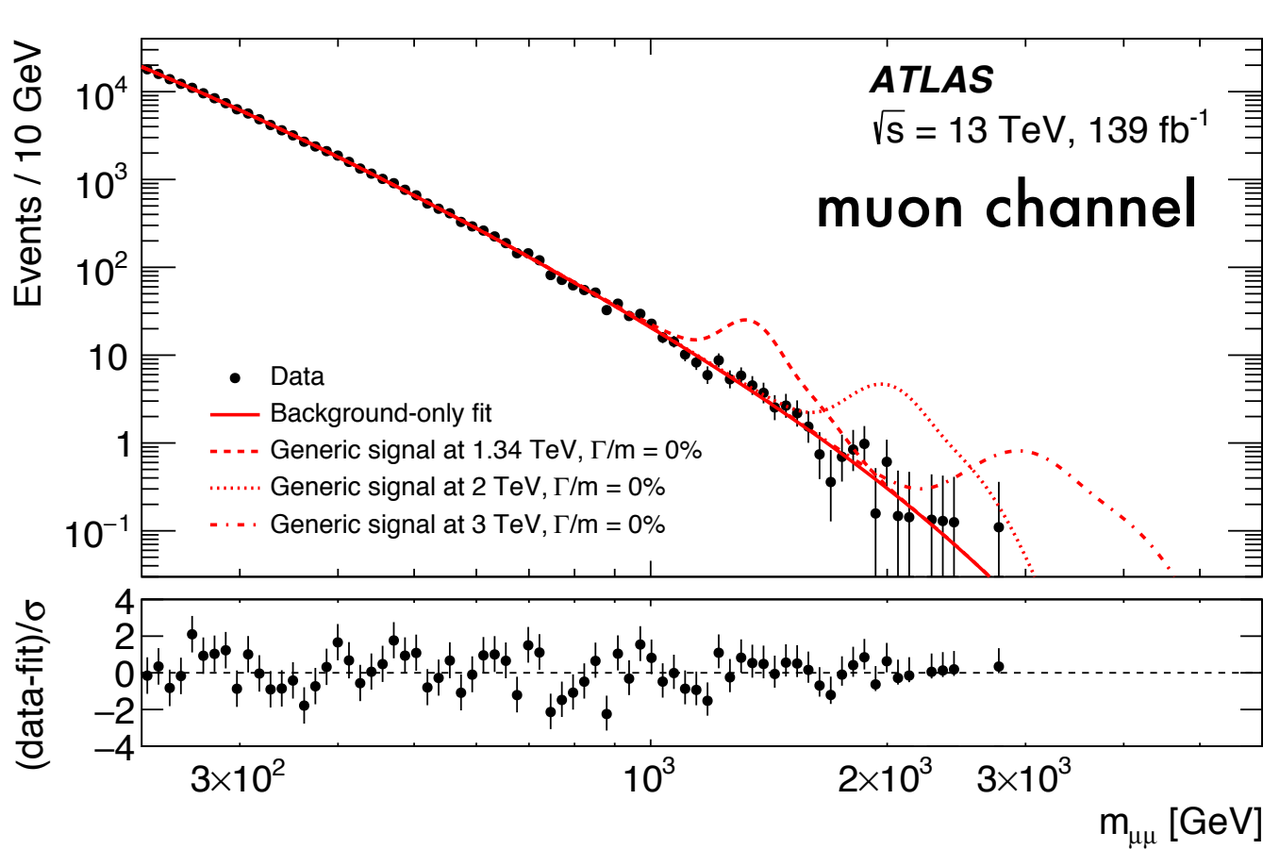
ATLAS

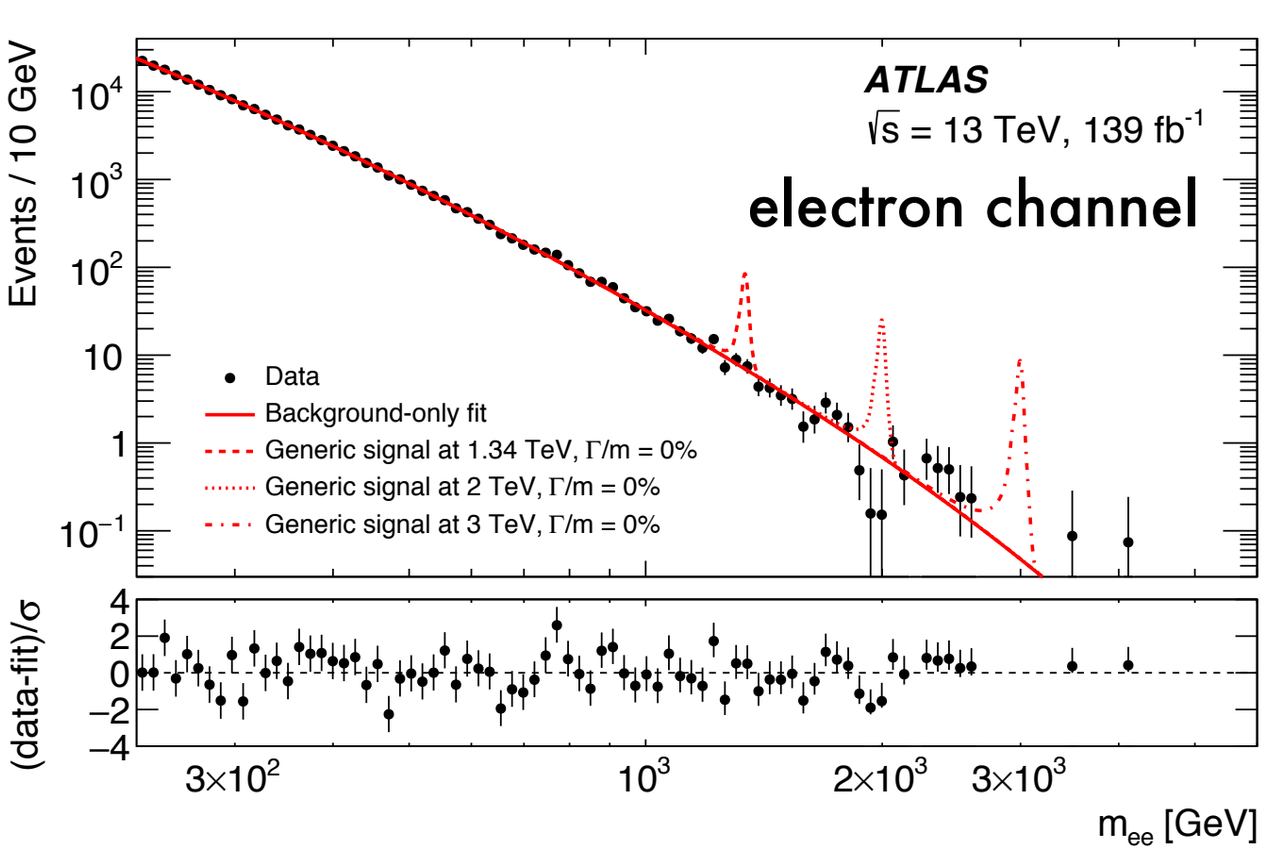




Di-lepton resonance search

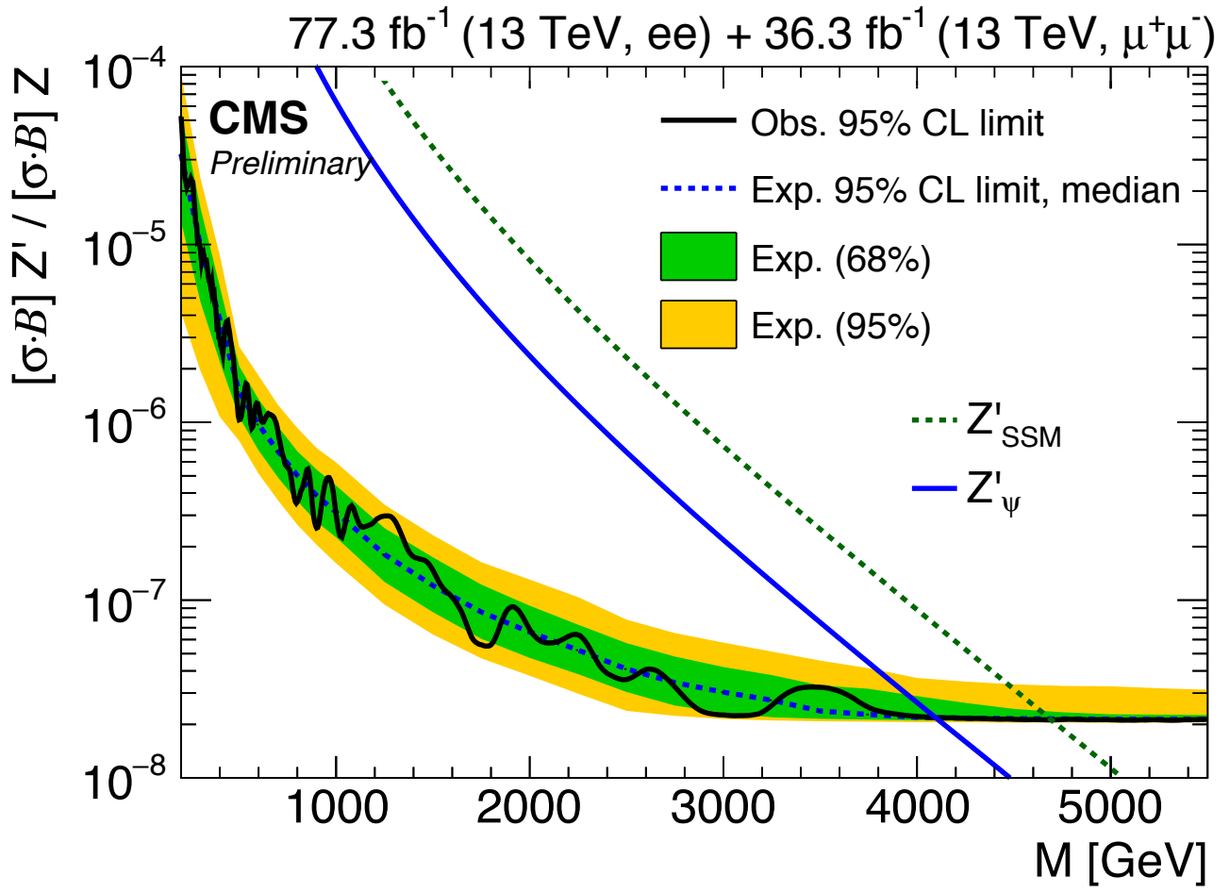
- arXiv:1903.06248: ATLAS's search on high mass di-lepton resonance with full Run2 data; provides limits on spin-0/1/2 signal hypotheses
- CMS-PAS-EXO-18-006: CMS's search on di-electron resonance with 2016+2017 data; focuses on Z' model
- CMS-PAS-EXO-16-031: CMS's search on di-lepton resonance with 2016 ICHEP dataset; focuses on Z' model



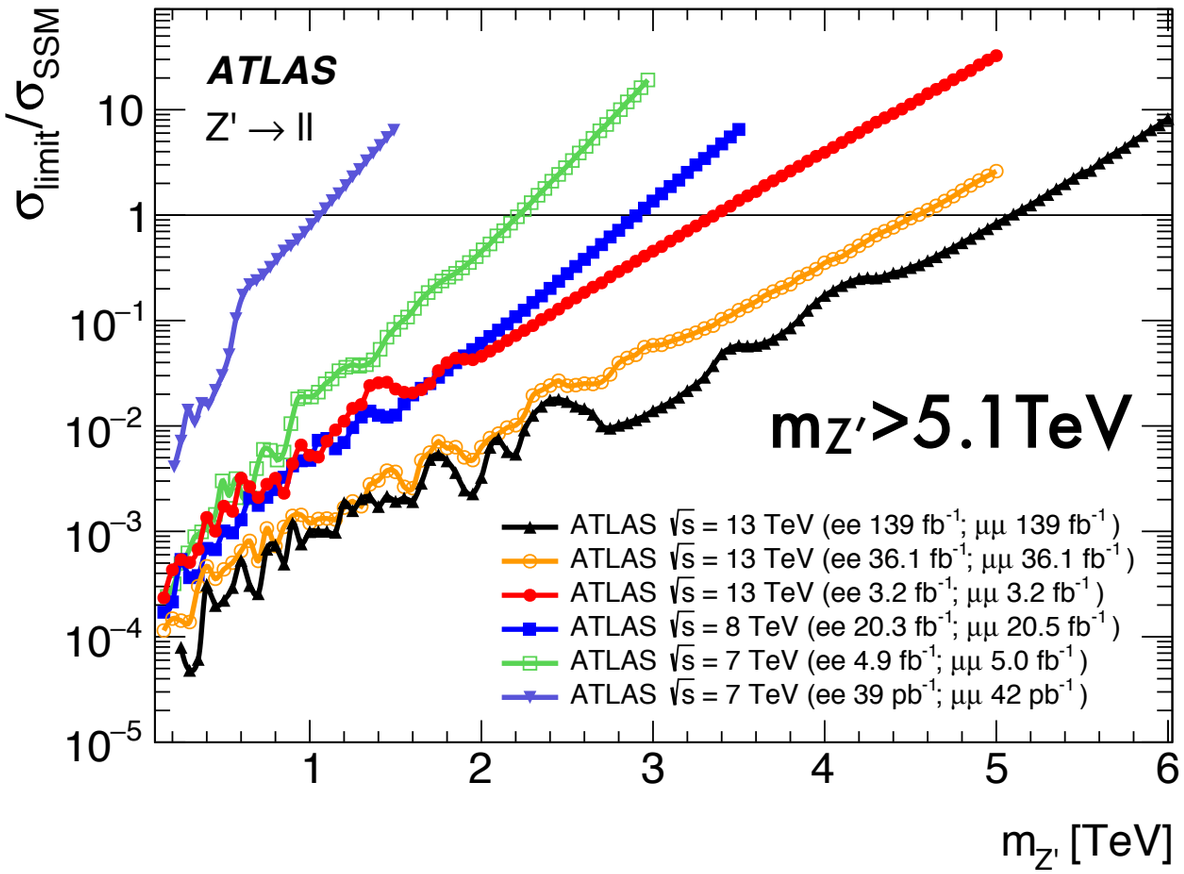


Di-lepton resonance search

CMS



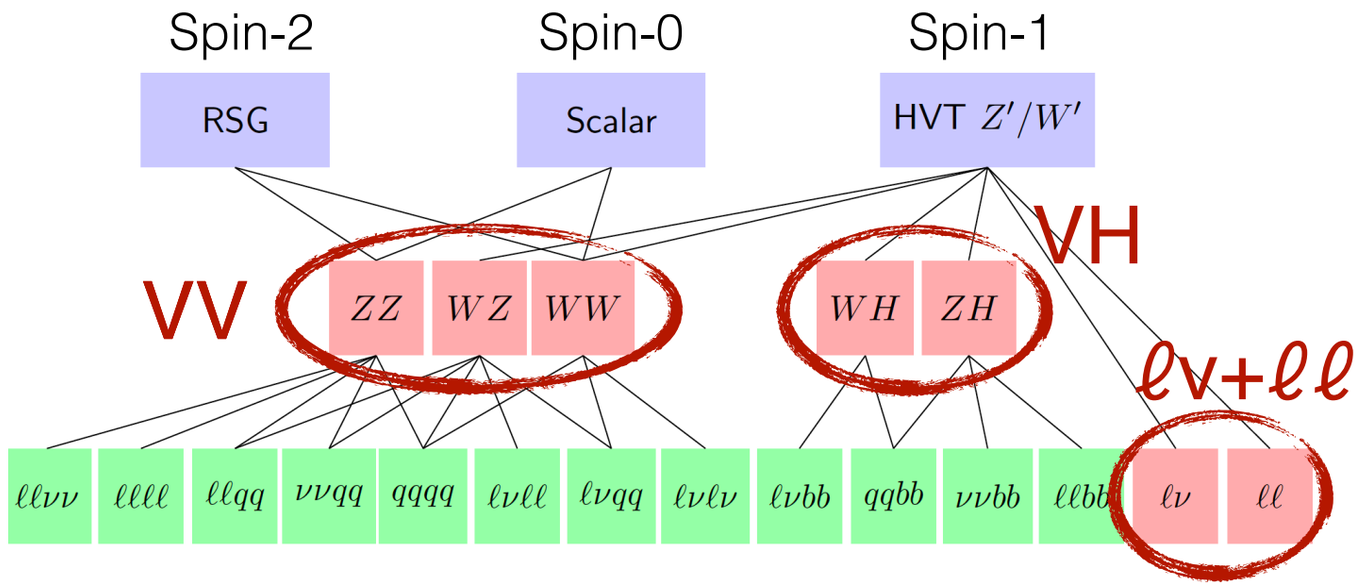
ATLAS



The evolution of limits over years...

Di-boson resonance search

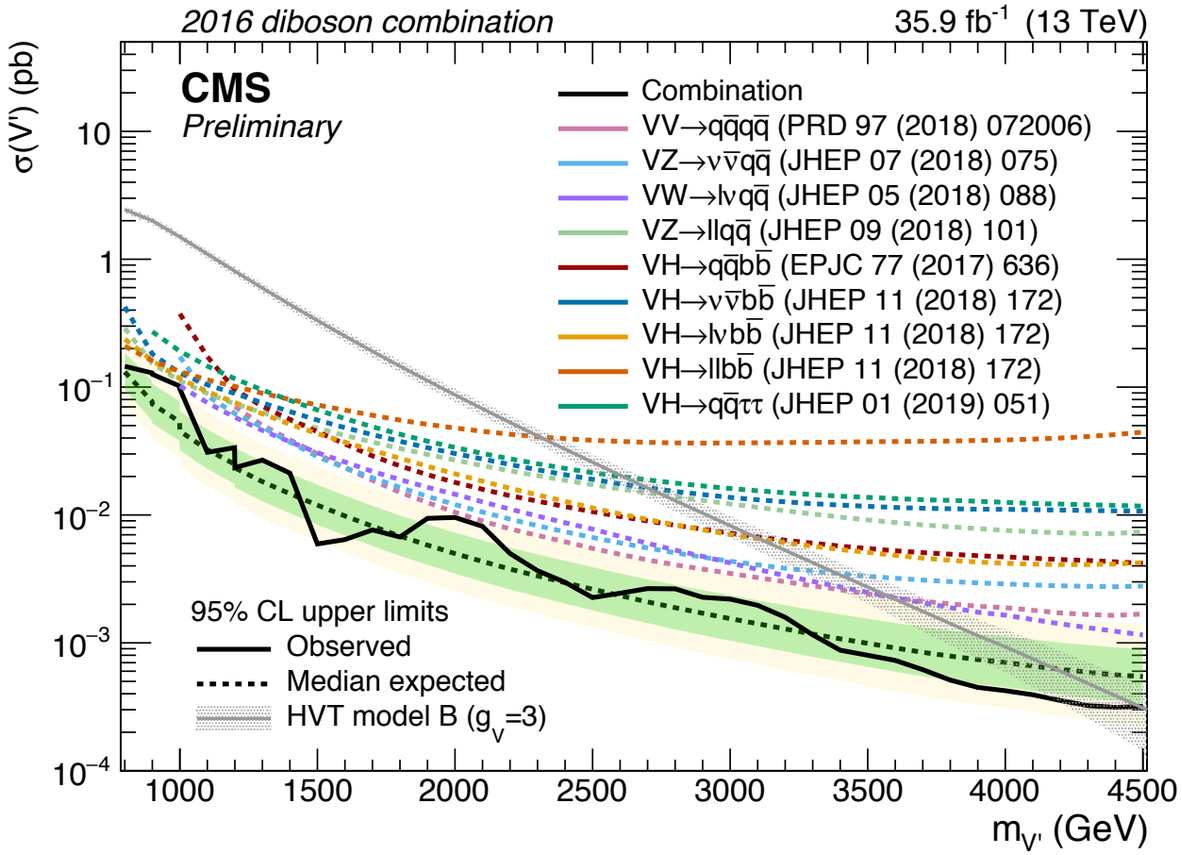
- Mutually independent searches target at different combination of W, Z, H bosons
- Statistical combination for model-dependent interpretations

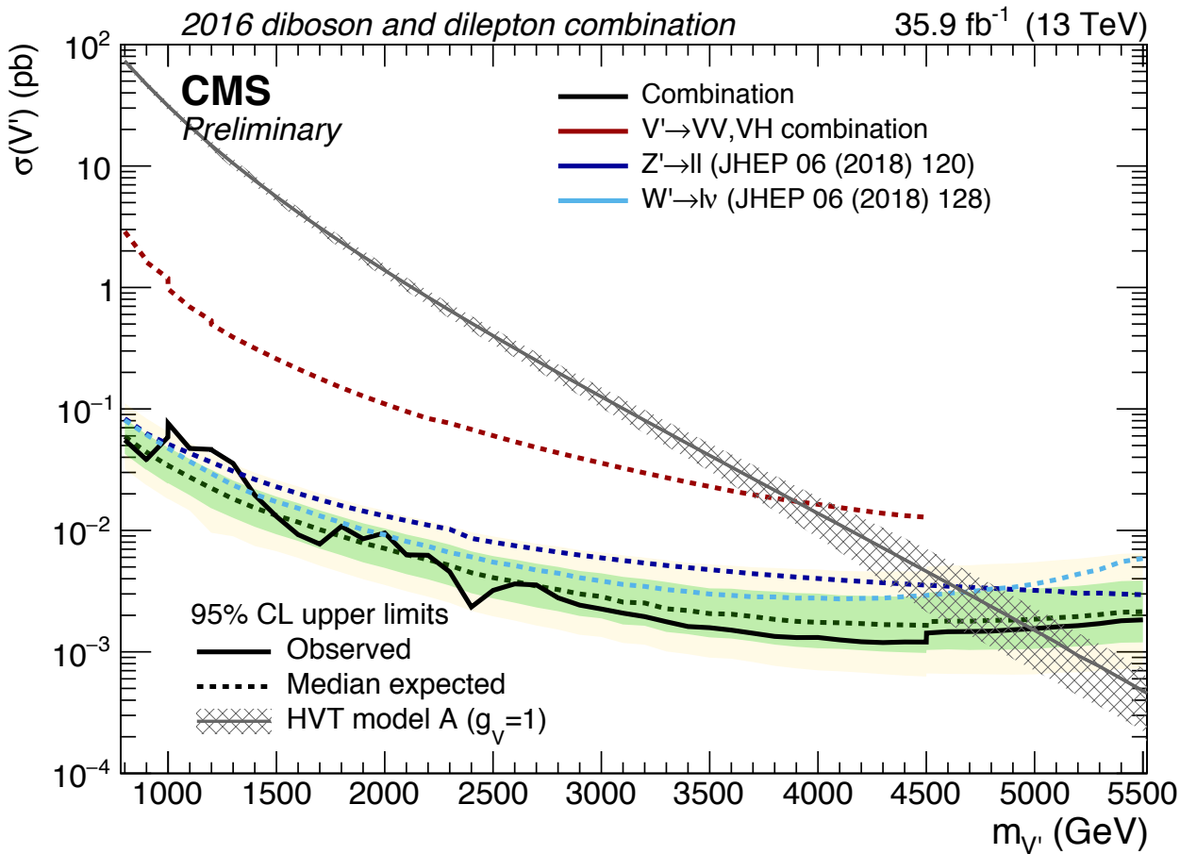


* Diagram taken from New physics searches at the LHC

- PRD 98 (2018) 052008: ATLAS's result on the combination of searches for heavy resonances decaying into bosonic and leptonic final states with 2016 data; provides limits on spin-0/1/2 signal hypotheses
- CMS-PAS-EXO-18-006: CMS's preliminary result on the combination of searches for heavy resonances decaying to a pair of bosons or leptons with 2016 data; provides limits on spin-1/2 signal hypotheses

CMS





ATLAS

Channel	Lower limits on resonance mass [TeV]					
	HVT model A		HVT model B		Bulk RS	
	Obs	Exp	Obs	Exp	Obs	Exp
WW	2.9	3.1	3.6	3.5	1.7	1.9
WZ	3.6	3.6	3.9	3.9	-	-
ZZ	-	-	-	-	1.5	1.7
VV	3.7	3.7	4.0	3.9	2.3	2.2
WH	2.6	2.8	2.8	3.1	-	-
ZH	2.7	2.5	2.8	2.8	-	-
VH	2.8	3.1	3.0	3.4	-	-
$\ell\nu$	4.6	4.6	-	-	-	-
$\ell\ell$	4.5	4.4	-	-	-	-
$\ell\nu/\ell\ell$	5.0	5.0	-	-	-	-
VV/VH	4.3	4.3	4.5	4.4	-	-
$VV/VH/\ell\nu/\ell\ell$	5.5	5.3	-	-	-	-

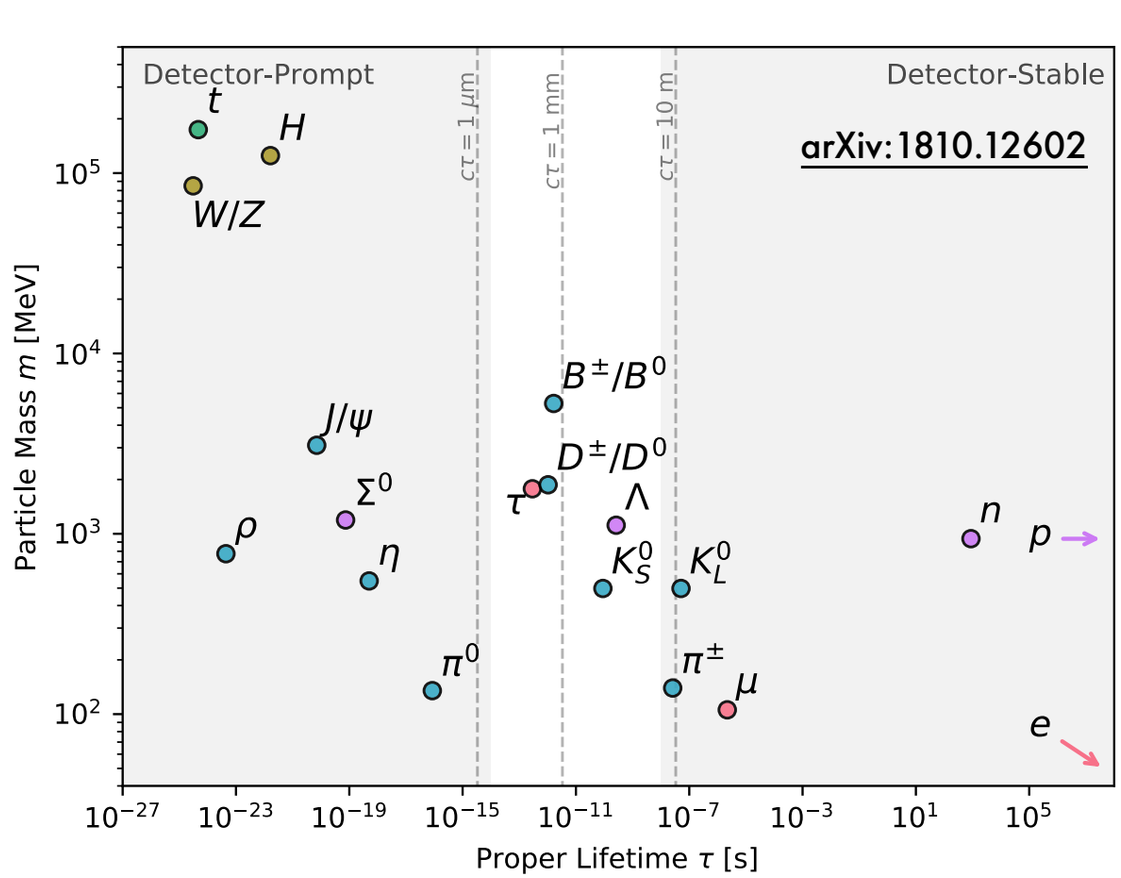
- Too many plots (which can be found in ATLAS twiki)… instead a summary table is shown here
- Explanation on model A/B/C can be also found in ATLAS paper

Di-"X" searches

- (X = jet, lepton, boson)
- Is it reasonable/possible/… to perform a combination for all the di-"X" searches?
  - Overlapped events between different searches?
- What is the limit on the mass constraint $M_{Z'/X/\ldots}$ in LHC?
  - We cannot set a limit on mass greater than the collision energy(?)

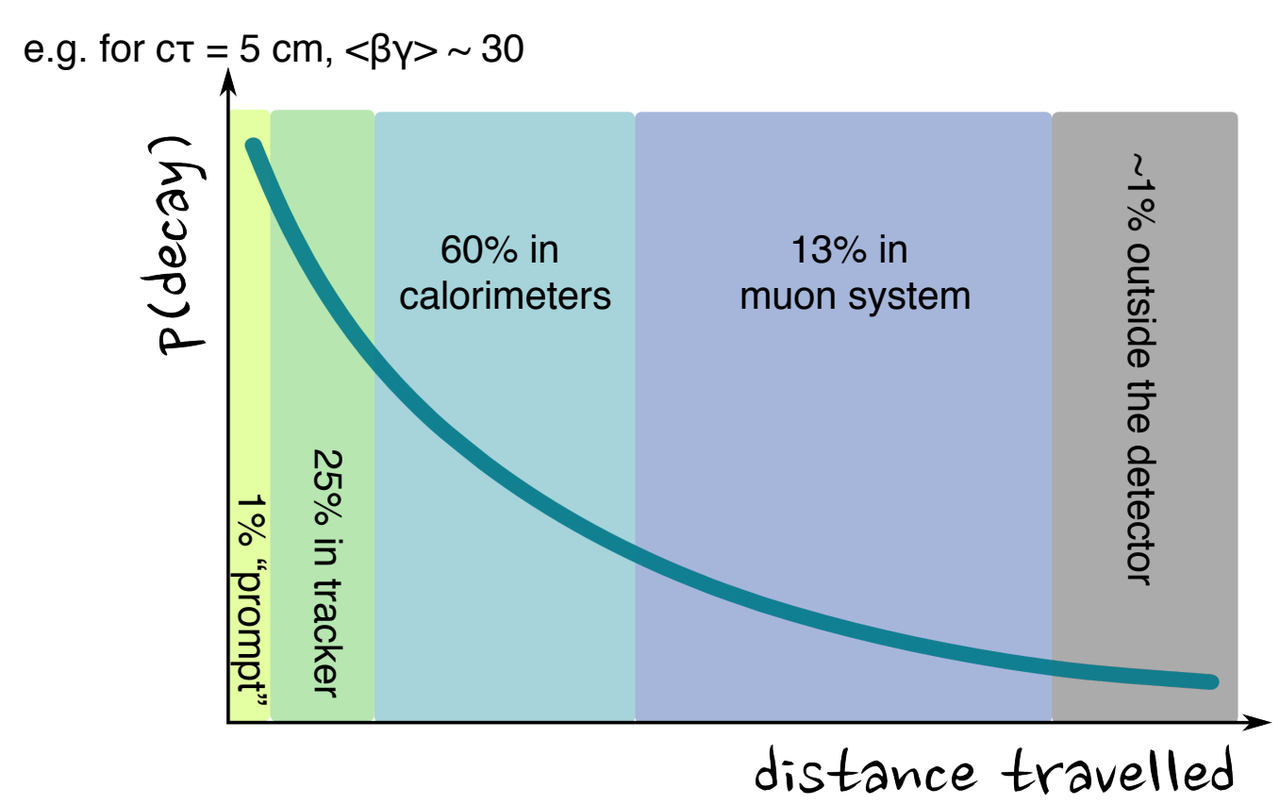
Unconventional signatures

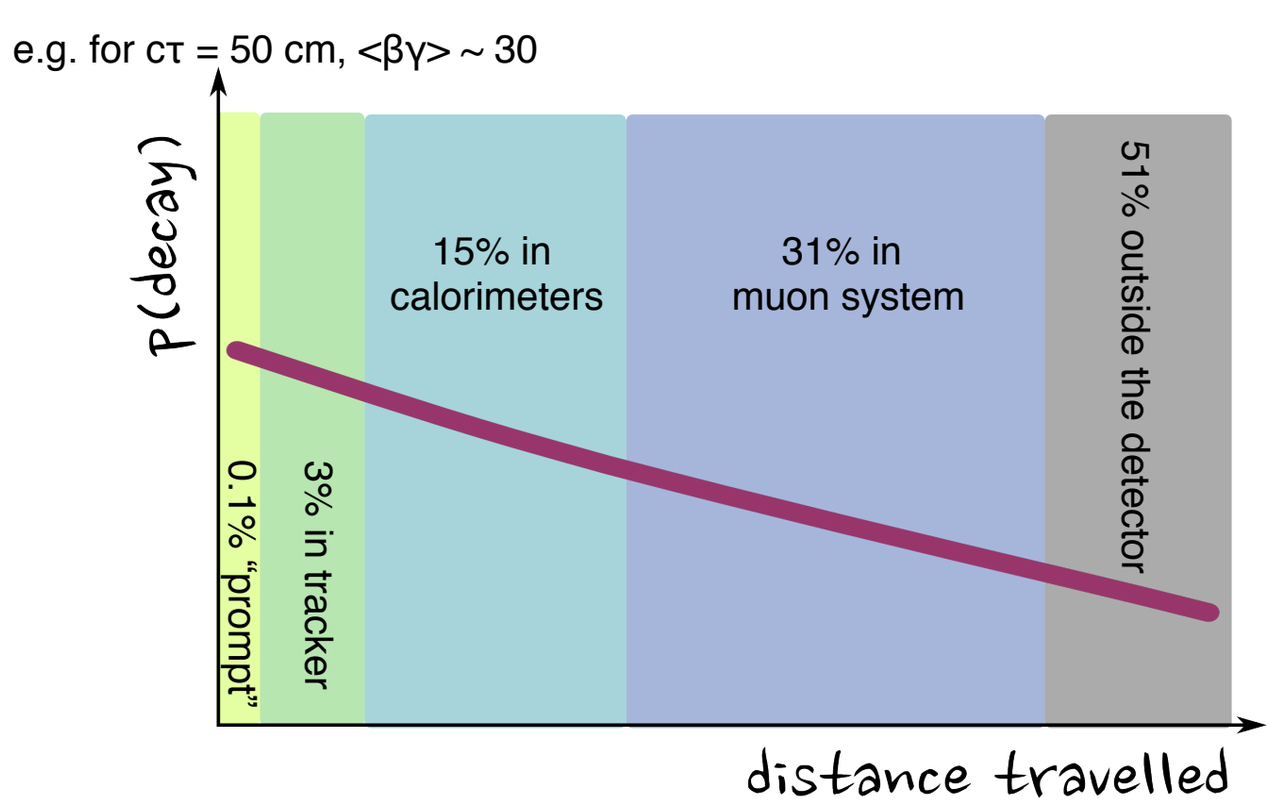
- David Curtin's talk on "Searches for long-lived particles"
- So far, no new physics/BSM has been observed using traditional and conventional event signatures...
  - What if NP/BSM does not result in conventional and simple signature? Then we are all looking in wrong places...
  - In SM, particles can can have long lifetime when the coupling is weak
  - What about BSM? Do they follow the similar trend? (dark matter candidate?)



Unconventional signatures

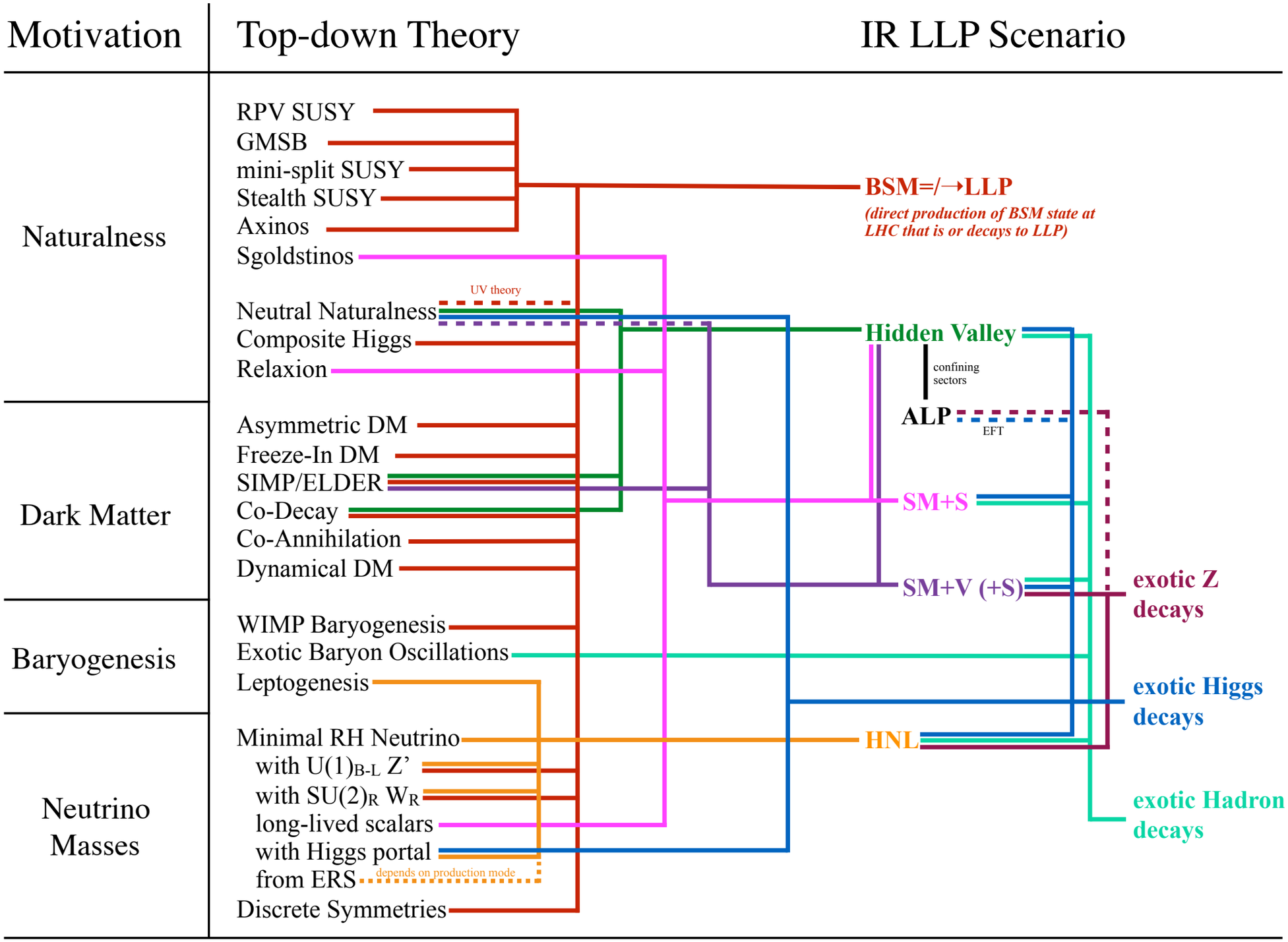
- Particle lifetime follows exponential distribution
- Short-lived v.s long-lived particle
- It doesn't seem feasible to build a detector which can cover both cases (no one-size-fits-all approach)





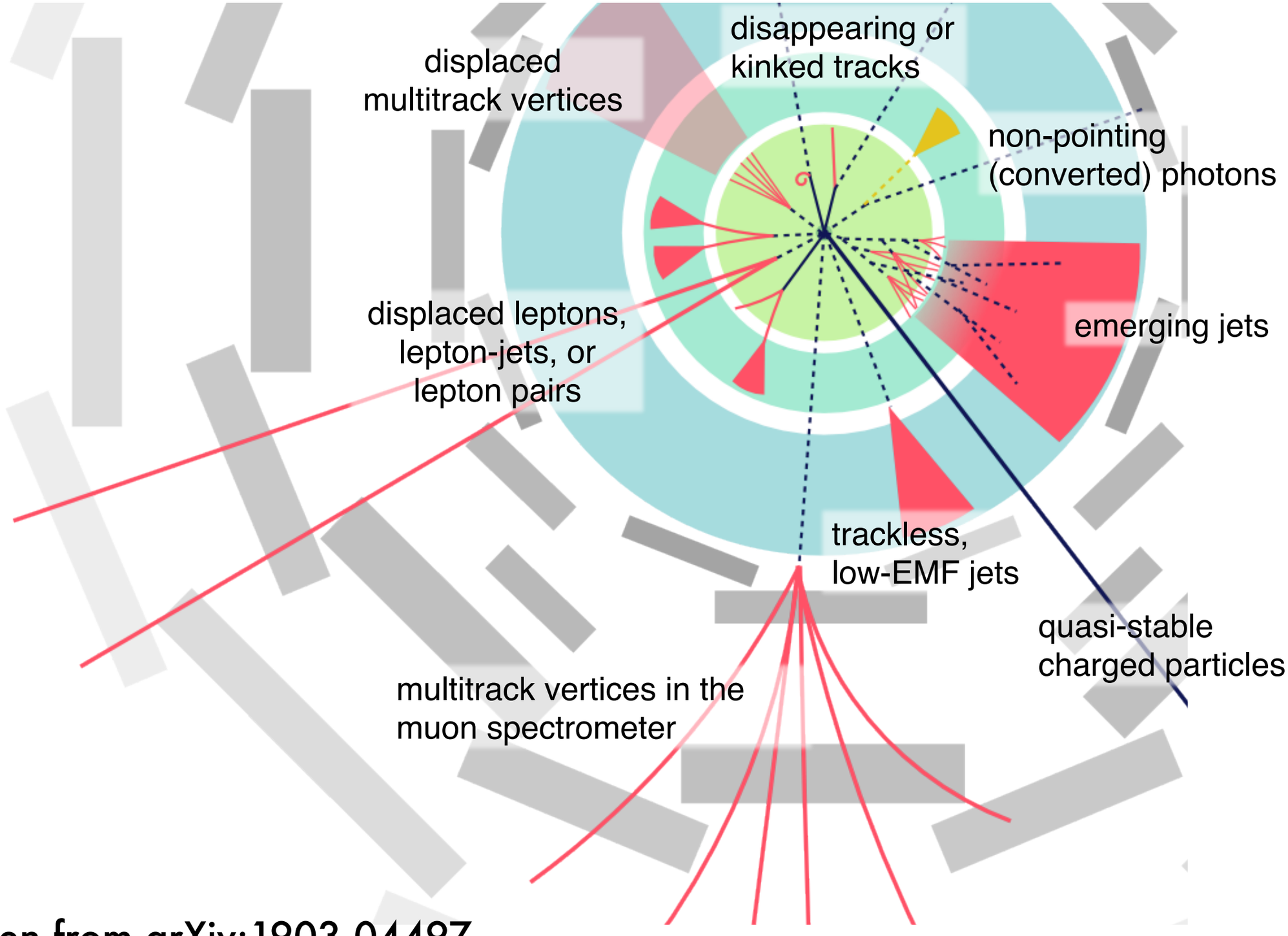
Figures taken from the talk given by Heather Russell

LLP theoretical motivation



Taken from David Curtin Searches for long-lived particles

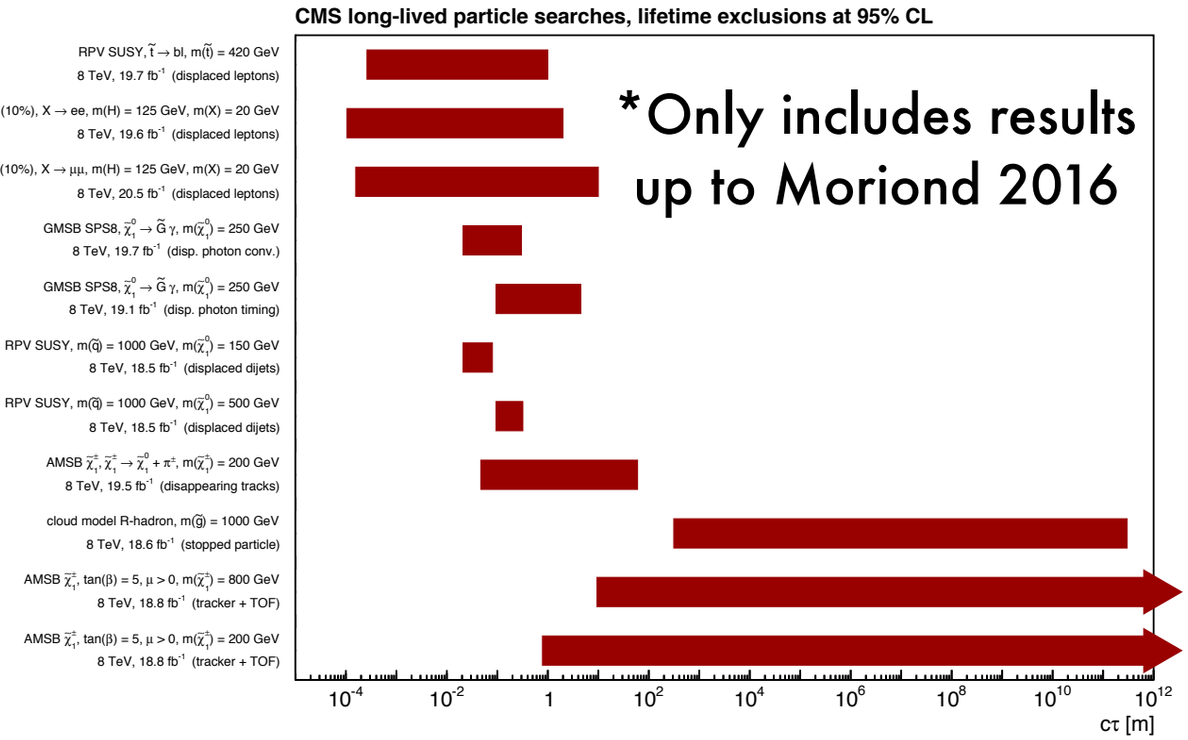
Experimental aspects



Plot taken from arXiv:1903.04497

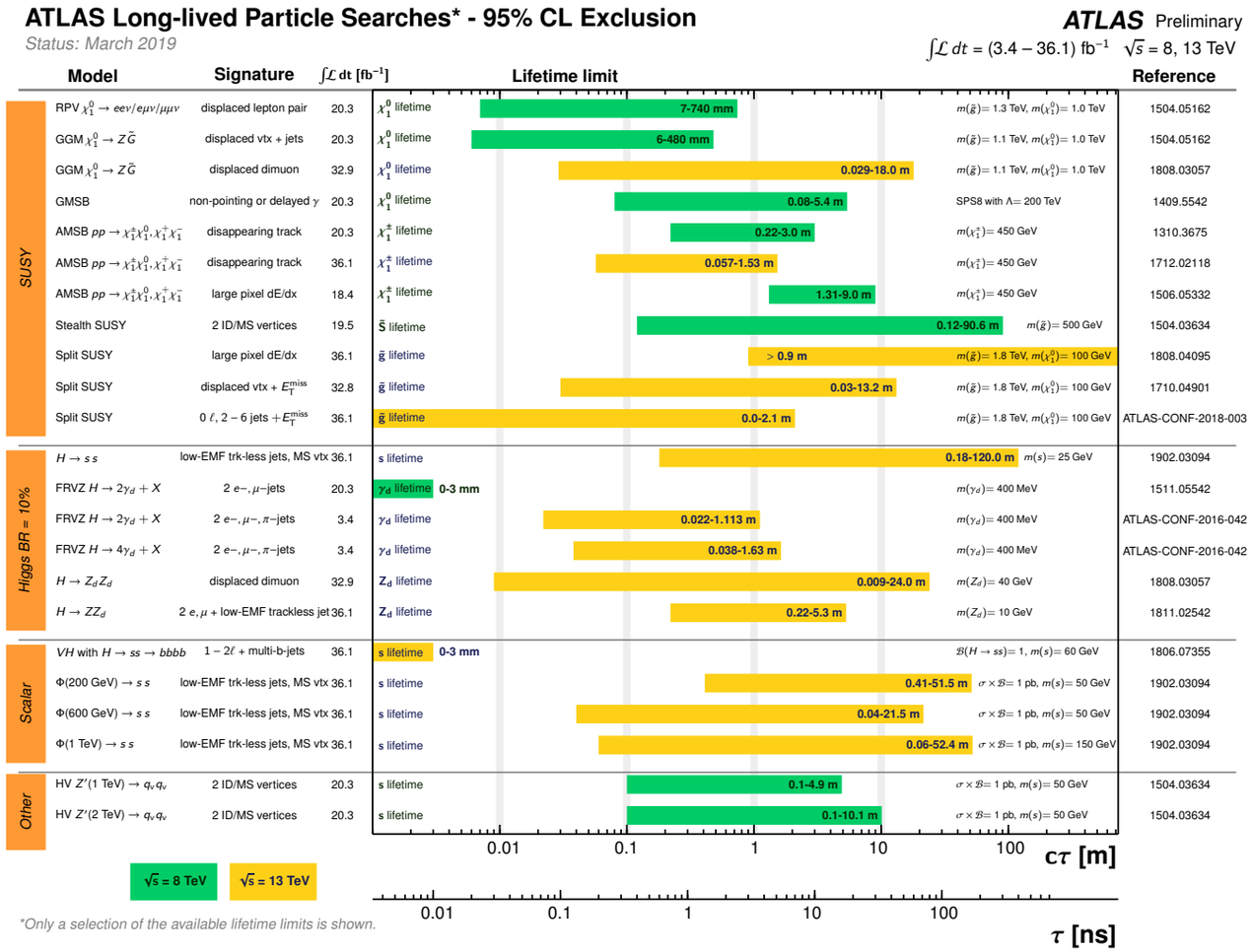
Experimental aspects

CMS summary plot



Signature	Publication @ 13TeV
Displaced jets	PRD 99 (2019) 032011
Displaced vertices	PRD 98 (2018) 092011
Disappearing tracks	JHEP 08 (2018) 016
Decays of stopped exotic long-lived particles	JHEP 05 (2018) 127
New long-lived	PLB 780 (2018) 432
Long-lived charged particles	PRD 94 (2016) 112004

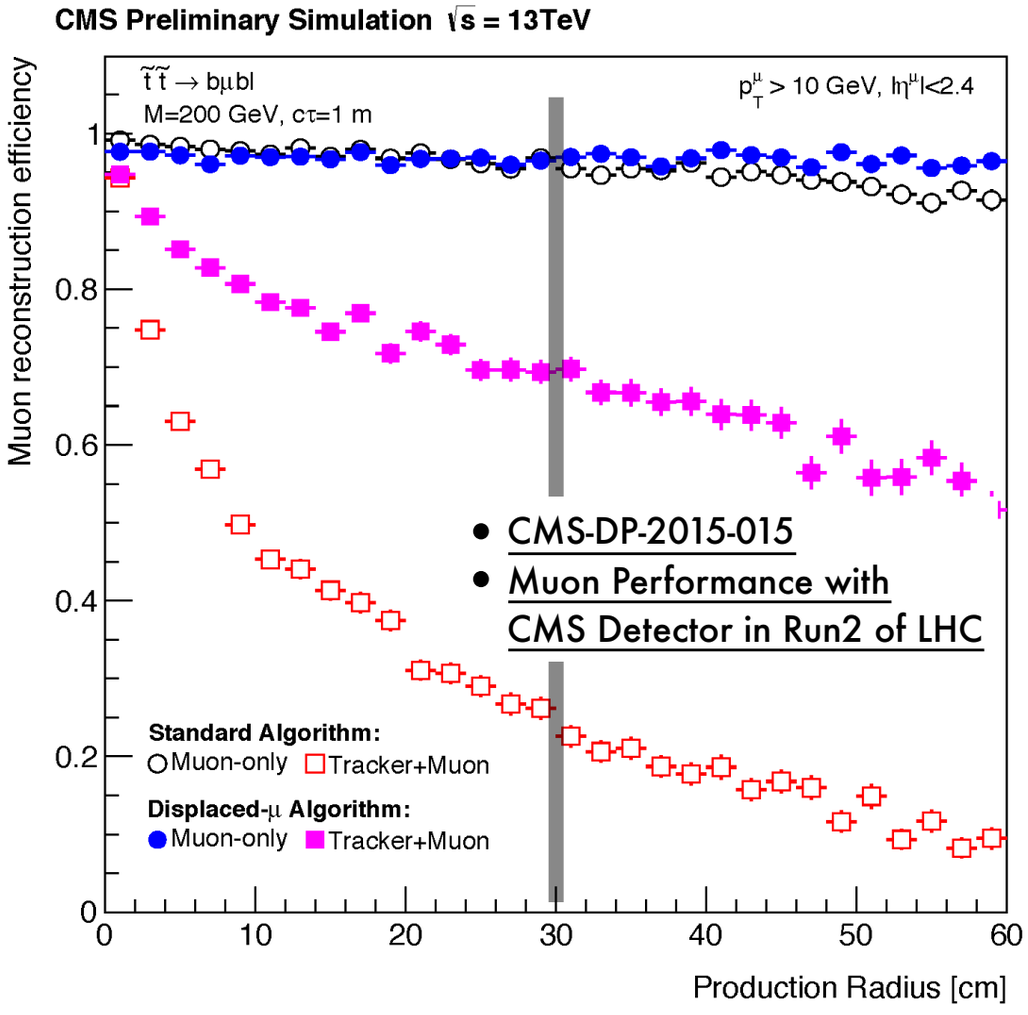
ATLAS summary plot

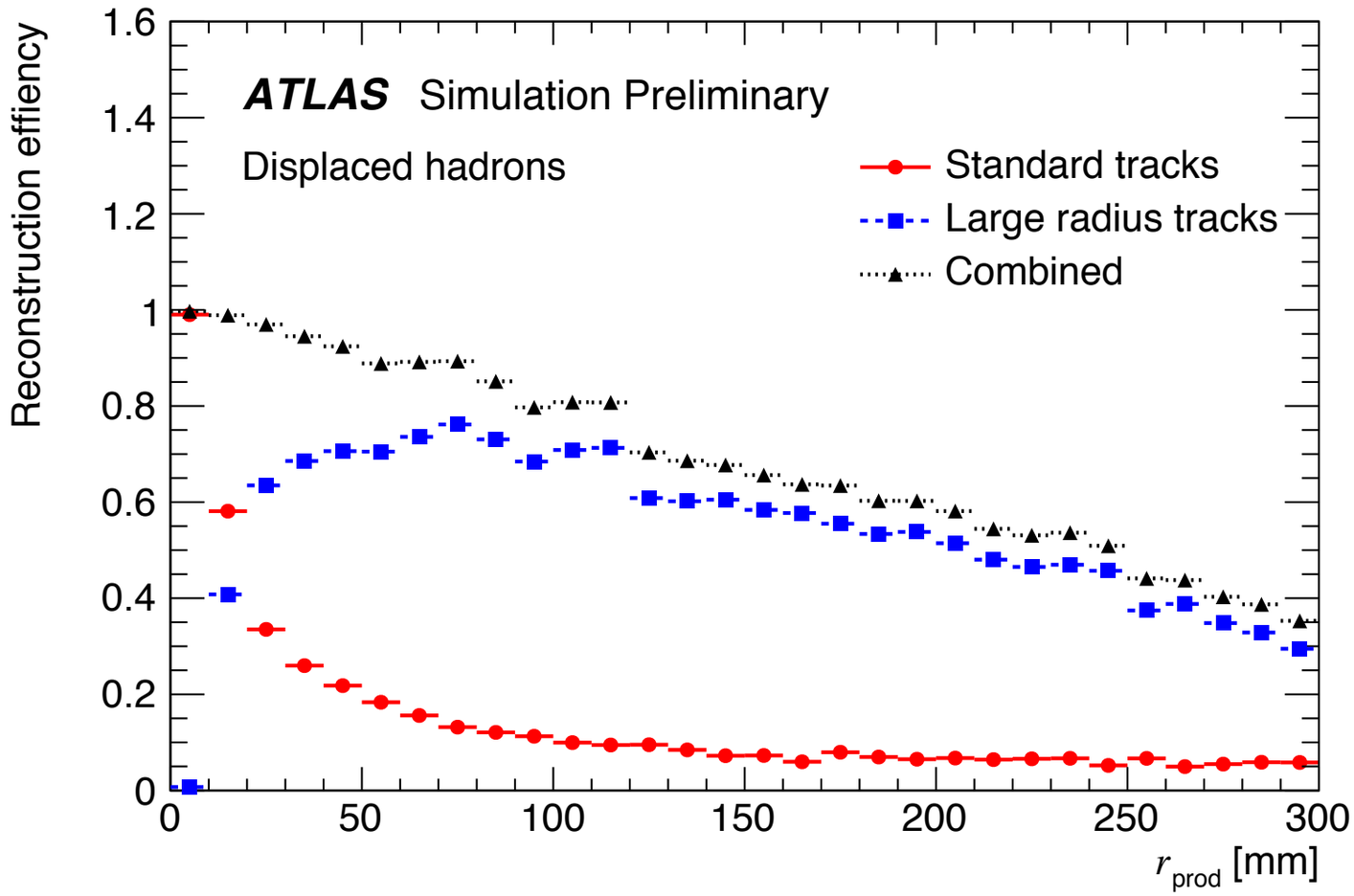


- One can also look at the summary plot (both ATLAS and CMS results are shown) in arXiv:1810.12602

Experimental aspects - tracking

- ATL-PHYS-PUB-2017-014: ATLAS developed a dedicated reconstruction techniques for displaced tracks – Large radius tracking
  - Relaxed selections on track impact parameters and number of hits w.r.t their standard reconstruction





Experimental aspects - tracking

- ATL-PHYS-PUB-2017-014: ATLAS developed a dedicated reconstruction techniques for displaced tracks – Large radius tracking
  - Relaxed selections on track impact parameters and number of hits w.r.t their standard reconstruction
- CMS has better tracking performance for displaced tracks (?), while ATLAS has much larger detector volume (larger acceptance for LLP searches)
  - Who will prevail in the LLP searches at the end, say, HL-LHC?

LLP - future prospects

- LHC LLP Community & "Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider"
  - The latest LLP workshop in Oct. 2018
  - For example, "Triggering on LLP signatures – CMS" summarized the trigger strategies for various signatures, "Data scouting & parking in CMS: its potential to search for LLP" reported the potential of the searches in CMS
  - The status of searches in ATLAS and LHCb & the development in techniques LLP searches can also be found in the workshop indico

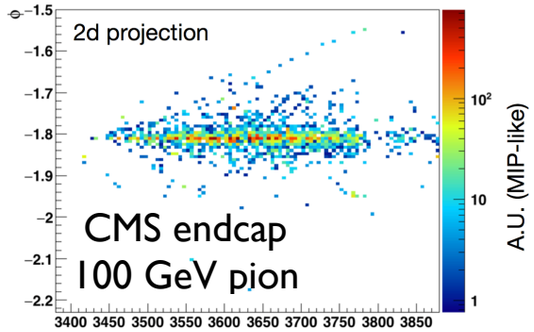
LLP - future prospects

- The upgrade for CMS endcap calorimeter HGCAL
  - "Overdesigned" calorimeter?!
- I don't know if there is any feasibility study regarding how HGCAL can aid LLP searches…

Upgrades: fancy calorimeters

ATLAS and CMS forward calo upgrades have ~30ps timing, great spatial resolution.

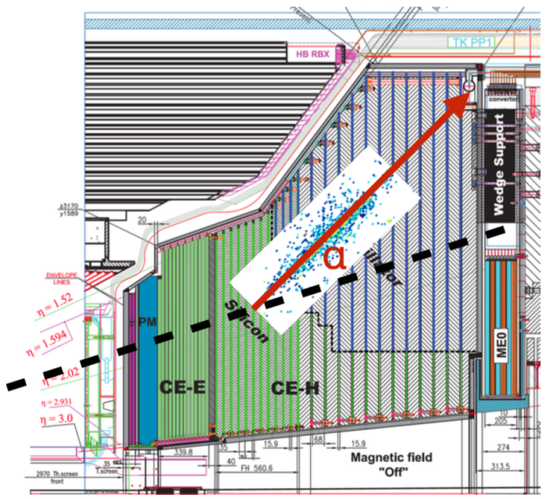
In CMS case, get 4D shower reconstruction.



LLP Opportunities:

1. Search for LLPs decaying to photon via timing information

2. Reconstruct LLP decays in great detail, get a "Calo DV"!
Could L1 trigger on this!
Rival the ATLAS MS for DV searches???



Taken from David Curtin Searches for long-lived particles

LLP - beyond LHC?

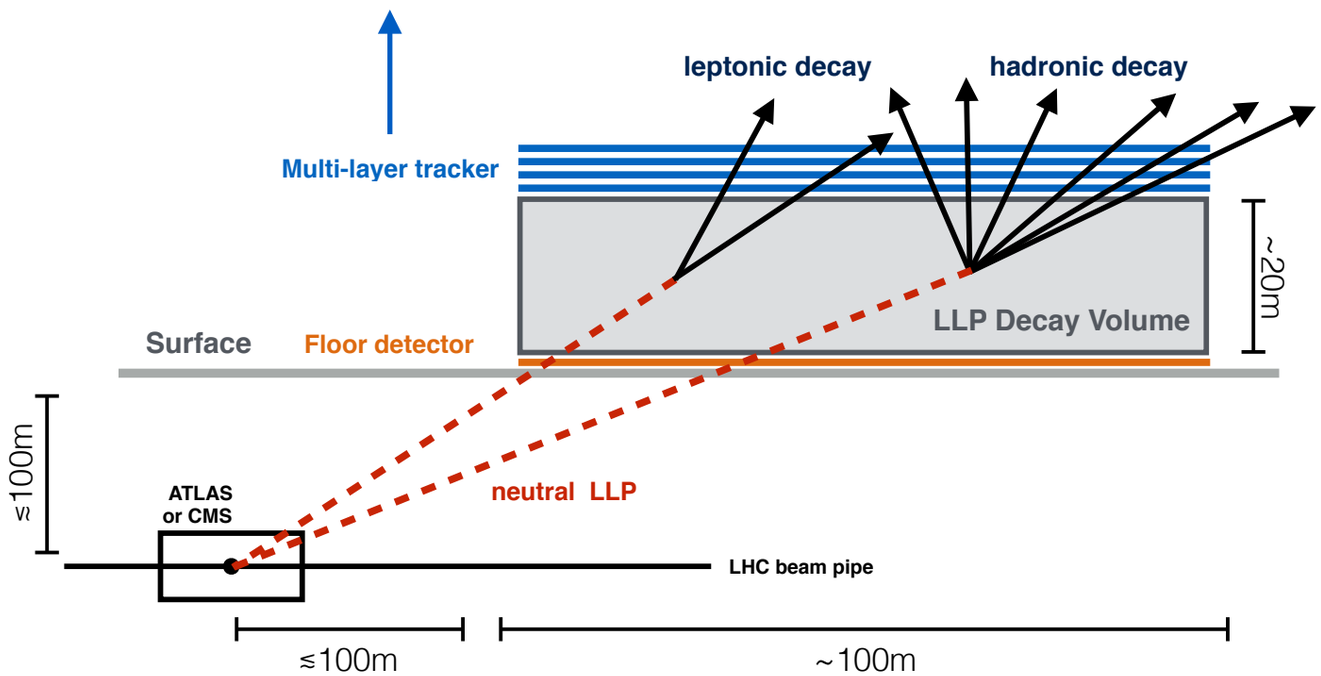
- There are other experiments/proposals that could provide sensitivity in LLP searches

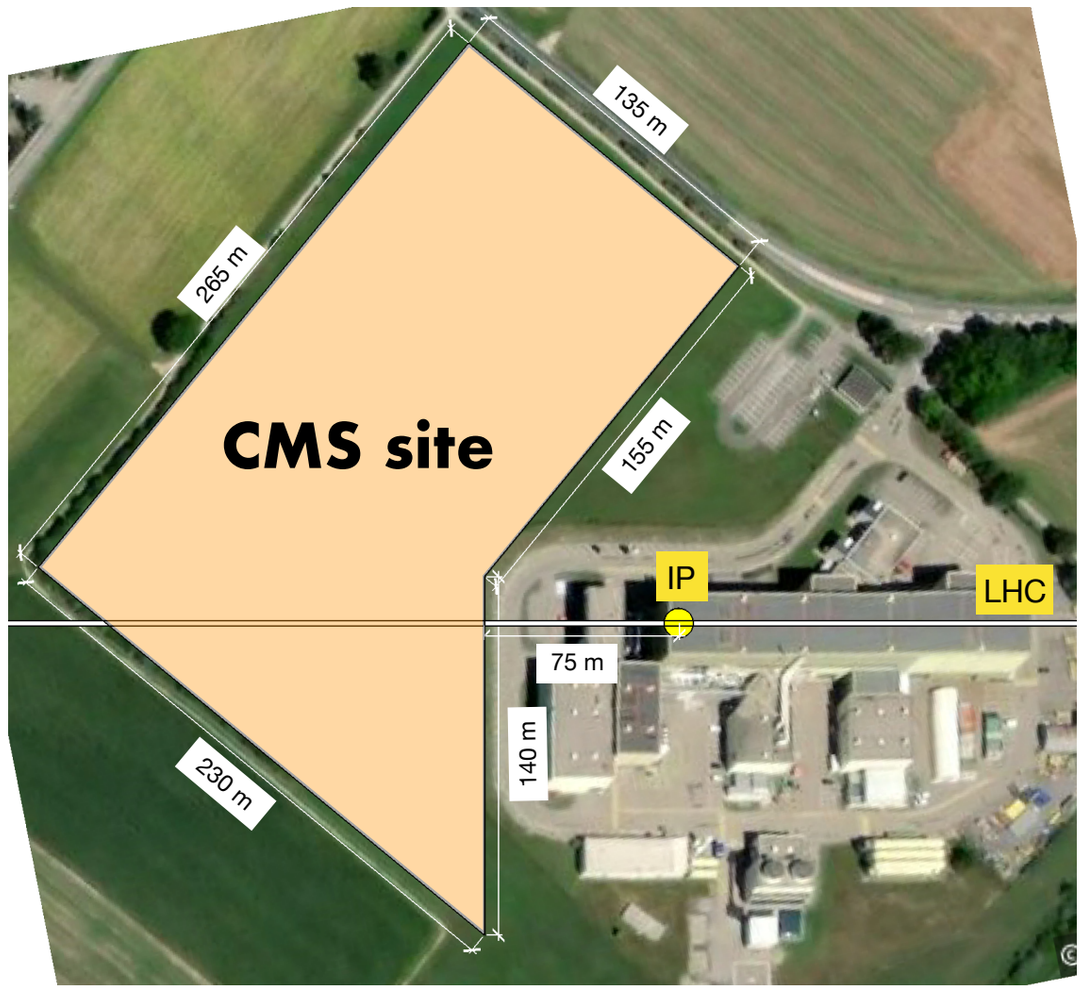
Experiment	Ref: Experimental overview
CODEX-b (A Compact Detector for Exotics at LHCb)	A proposed new detector near LHCb
FASER (ForwArd Search ExpeRiment at the LHC)	A detector in forward direction of an LHC collision point (near ATLAS)
MATHUSLA (MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles)	A detector (on the ground) for ultra-LLPs
milliQan (arXiv:1410.6816)	Search for milli-charged particles
MoEDAL (The Monopole & Exotics Detector at the LHC)	Search for monopole
NA62	Look for vertices of LLPs
SeaQuest	Search for dark-sector
SHIP (A facility to Search for Hidden Particles)	A proposed experiment to look for vertices of LLPs

MATHUSLA

- An above-ground detector (arXiv:1901.04040)
- Plan to operate in HL-LHC period (starting from 2025-26)

- The ceiling tracking system can help reject the dominant source of background - cosmic ray
- Vertical span of the tracker is important





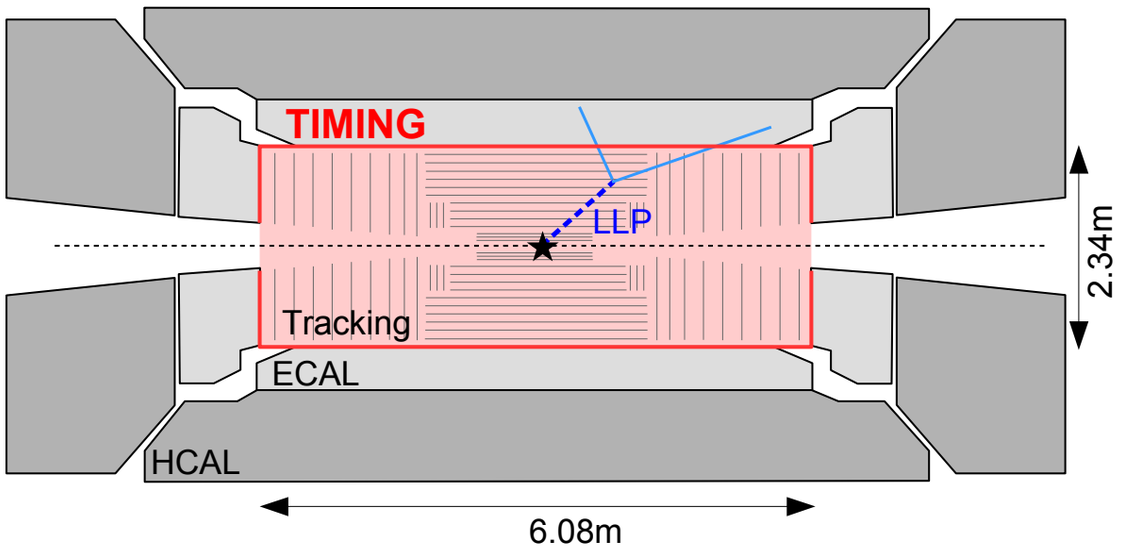
- Resistive Plate Chambers (RPCs) and plastic scintillators providing timing info. can further reduce background

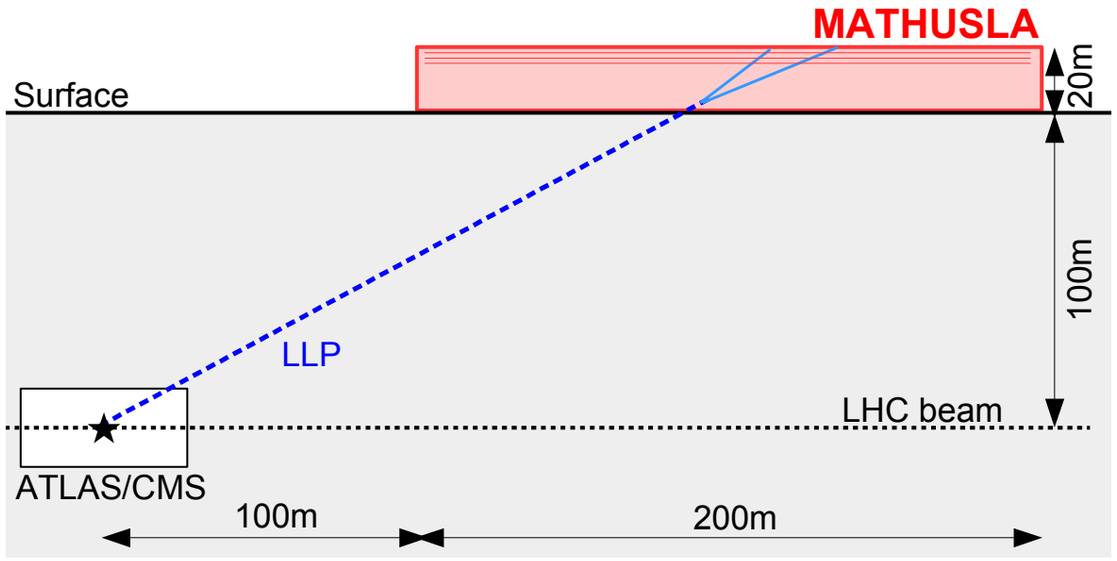
MATHUSLA

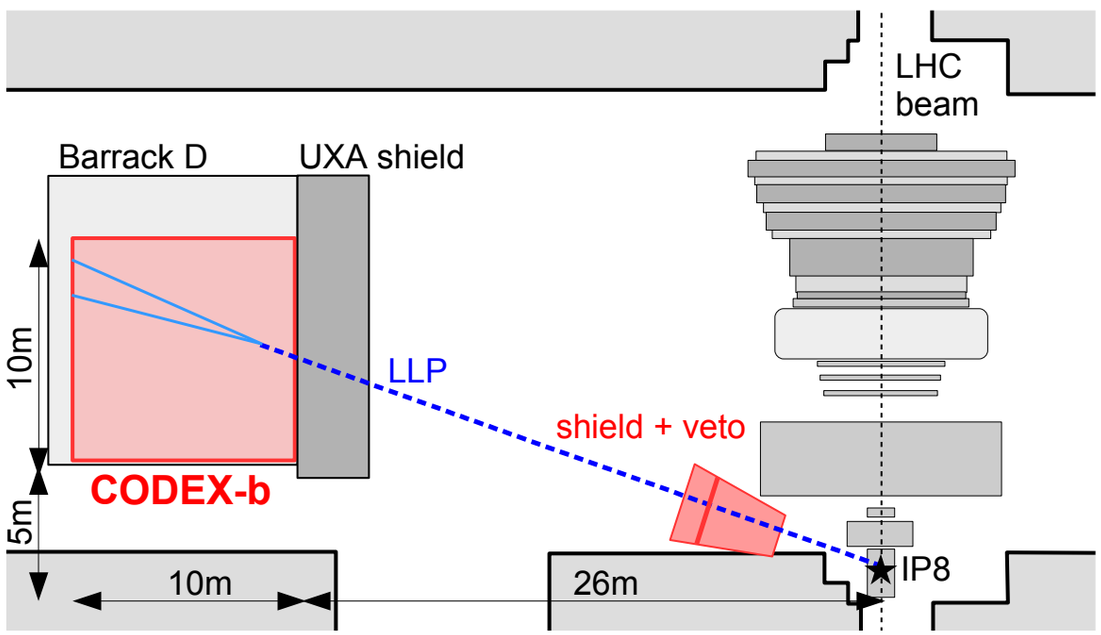
- An above-ground detector (arXiv:1901.04040)
- Plan to operate in HL-LHC period
- Zero-background or near-zero-background?
- In the talk "Dynamical Dark Matter at the Lifetime Frontier", the presenter claimed that "A mere ~4 LLP events at the HL-LHC would be sufficient for discovery"
  - Is this reasonable?
  - My question: assuming a background-free and systematic-uncertainty-free analysis, what is the least number of observed signal events for experimentalists to claim an observation?
    - 25?

Complementarity between experiments

- Simplified layouts of CMS, MATHUSLA, CODEX-b and FASER







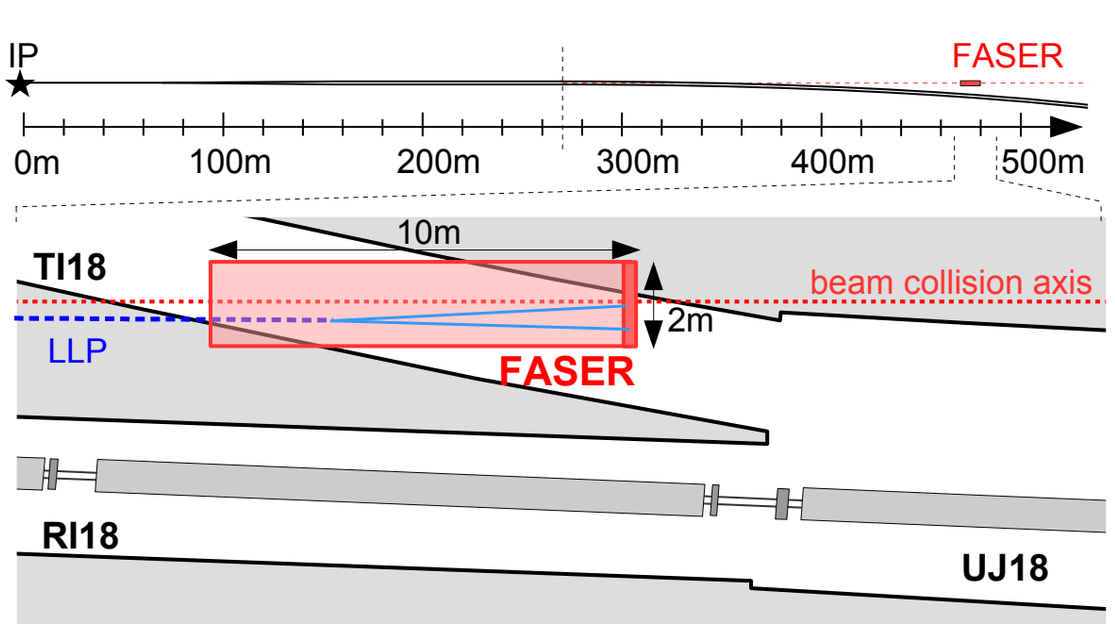
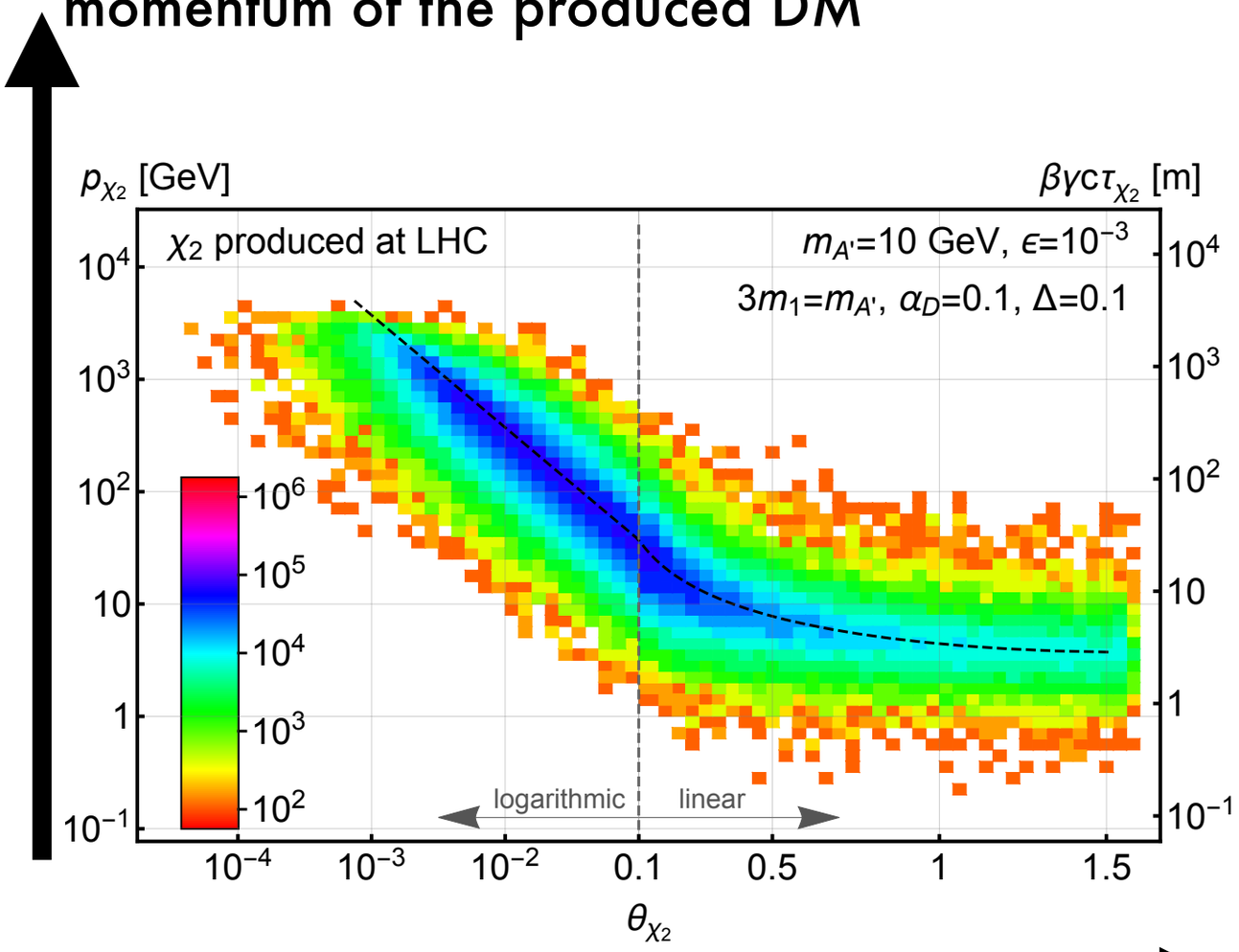


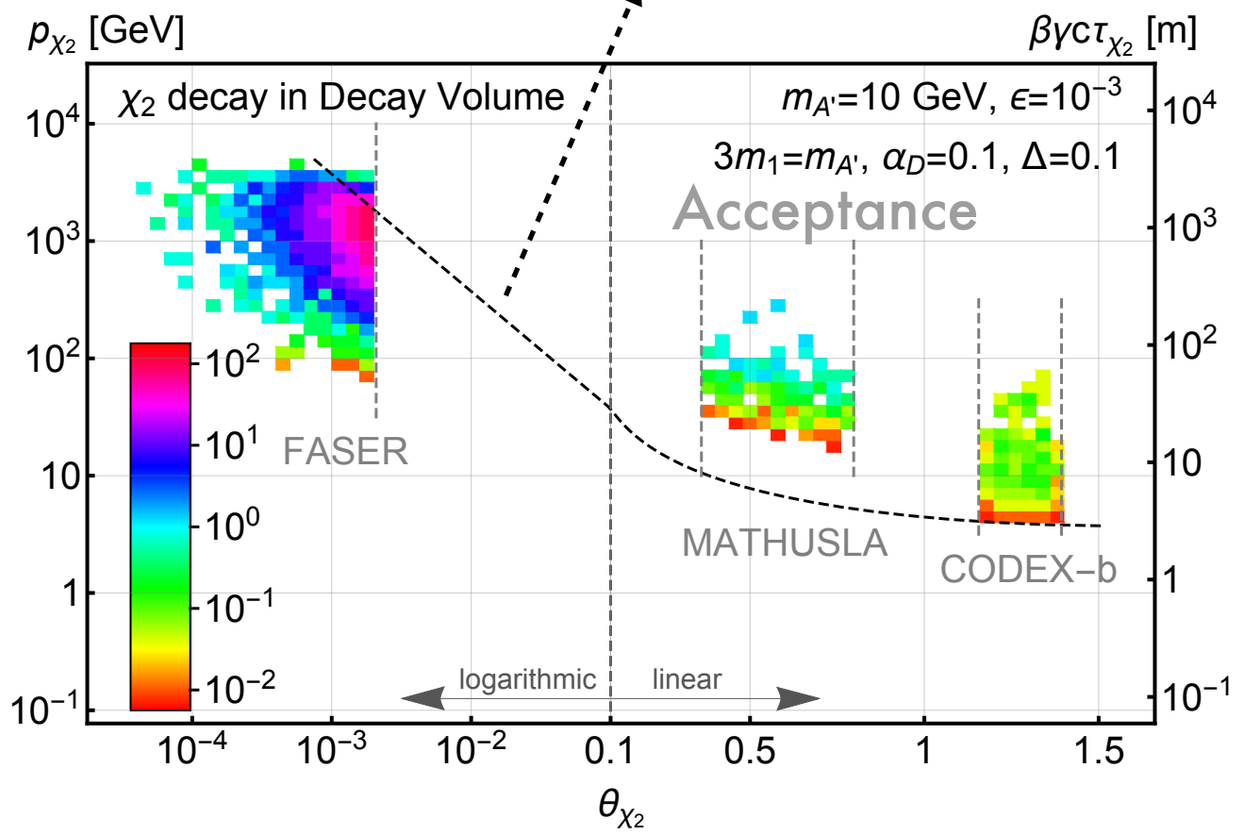
Figure taken from arXiv:1810.01879

Acceptance

momentum of the produced DM



The expected momentum calculated from 2-body decay



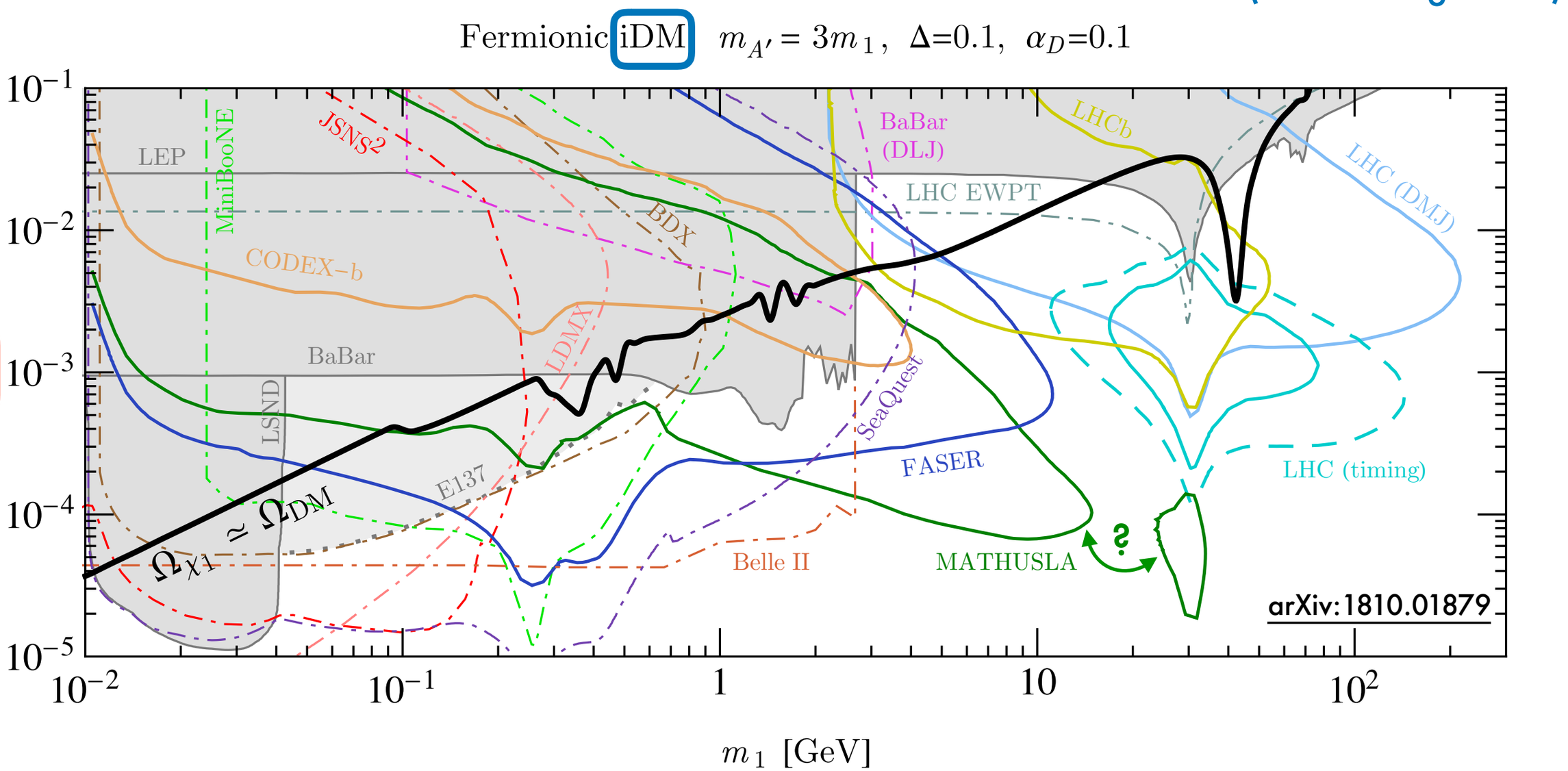
produced angle w.r.t beam direction

arXiv:1810.01879

Complementarity between experiments

- Countless summary plots for phase-space constraints, reaches for sensitivity, e.t.c

inelastic dark matter: a theoretical framework (valid for light DM)



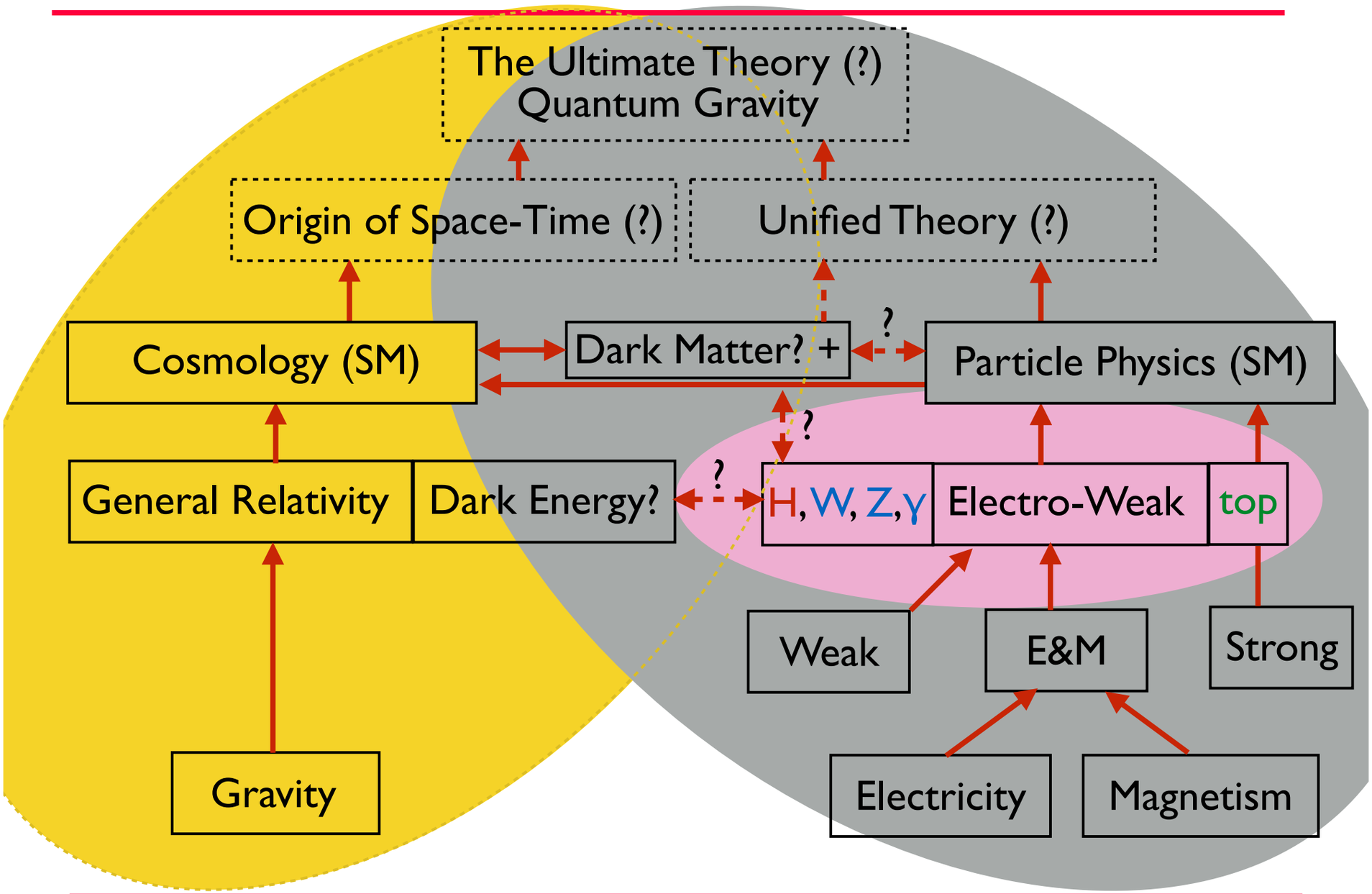
The mixing between dark-sector and SM-sector

Summary

- The majority of the talks were theory-related (I had difficulty understanding any of them…) 😐
- Plenty of interesting and exciting experiments/analyses/proposals 🙂
  - See, for example, those listed in S24, or the white paper from the workshop U.S. Cosmic Visions: New Ideas in Dark Matter
- Great opportunity to learn something about EXO/SUSY world
- "Do you want to spend your whole career or life on setting upper limits?"
  - What do you guys think?

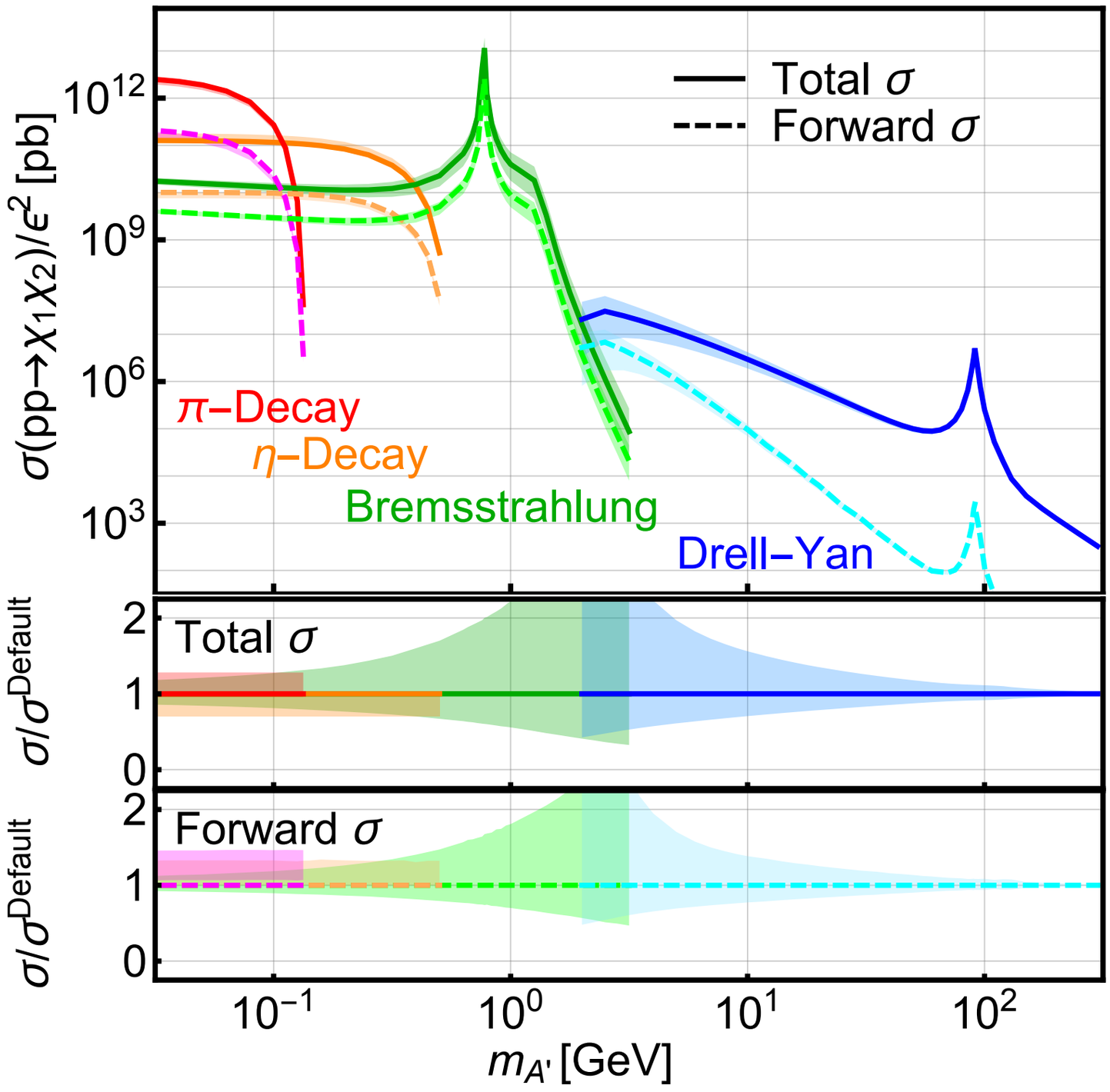
Backup

Picture



Slide in https://indico.cern.ch/event/777988/contributions/3409113/

Why forward region?



arXiv:1810.01879