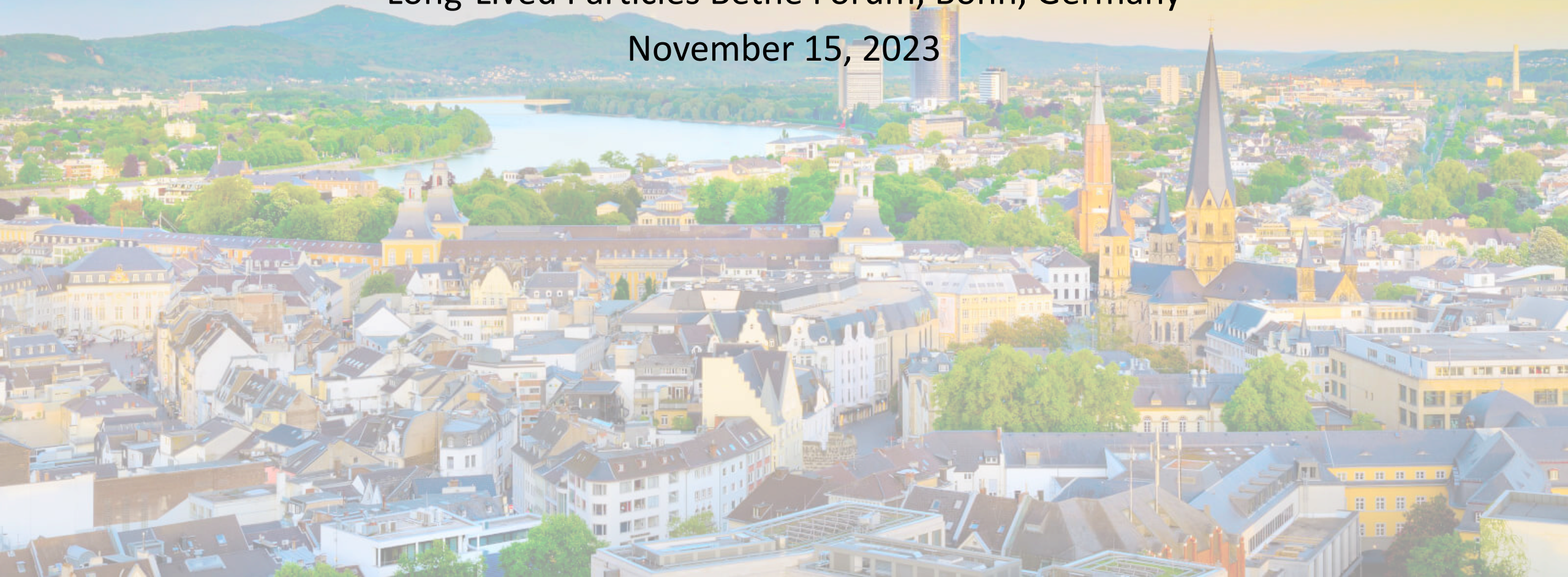
LLP Experimental Coverage:
Complementarity, Overlaps, and Gaps

Juliette Alimena (DESY)

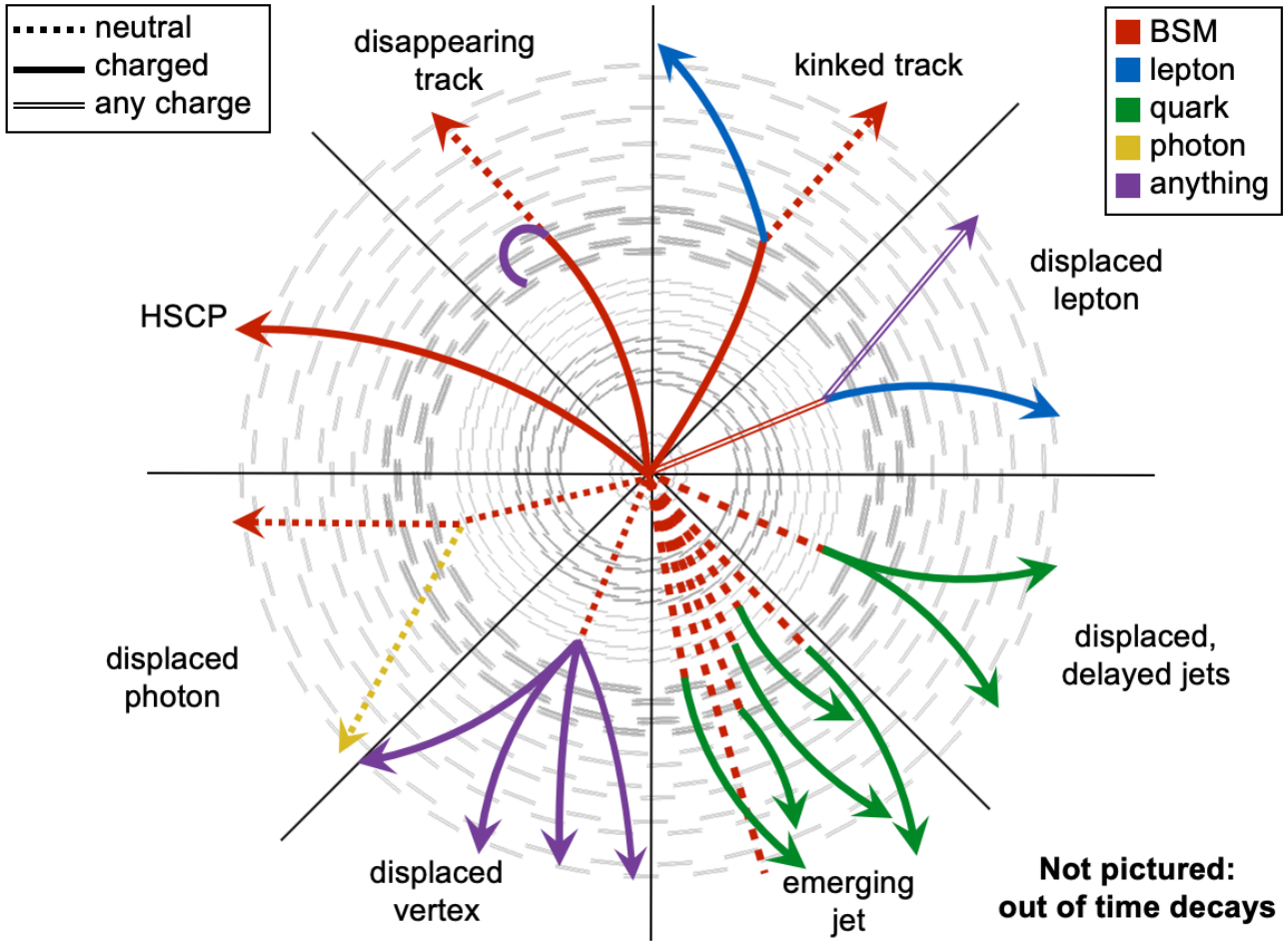
Long-Lived Particles Bethe Forum, Bonn, Germany

November 15, 2023



LLP Coverage & Gaps

- The **ever-expanding** LLP search program is **super impressive** and full of **creative ideas!**
  - We've come a long way
  - LLPs used to be *fringe* but they are now a *major focus* of the LHC search program



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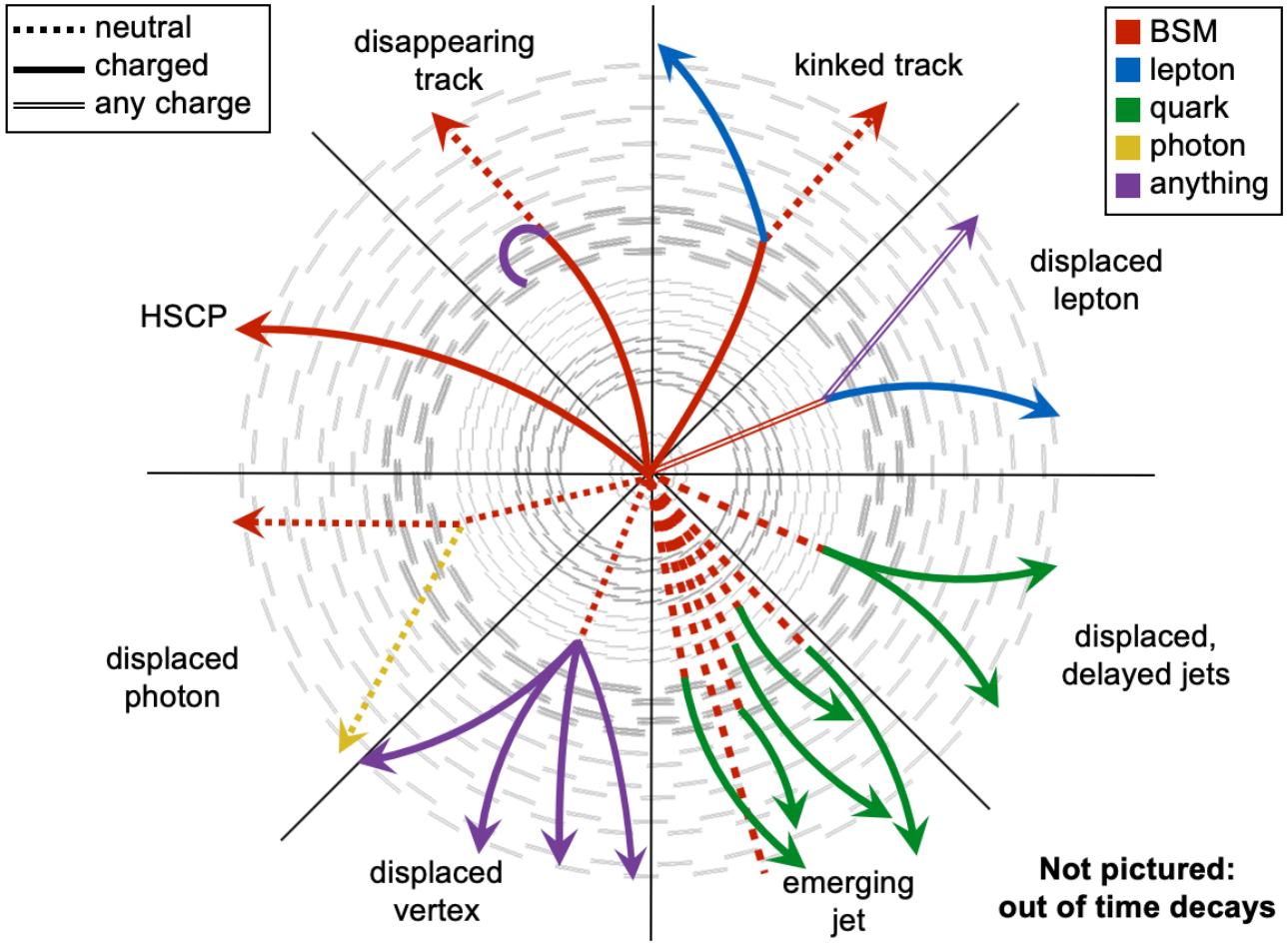
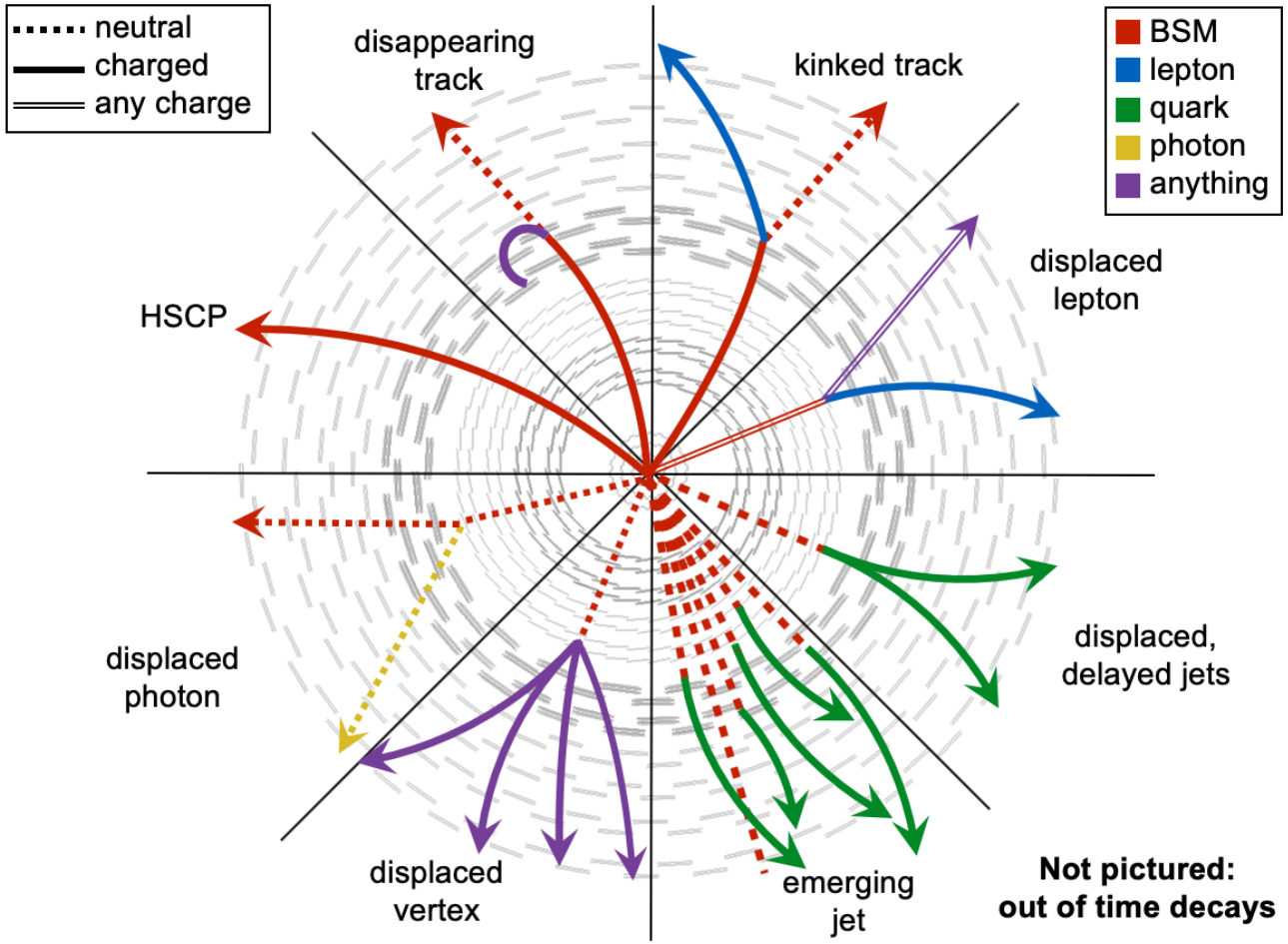
  - We've come a long way
  - LLPs used to be *fringe* but they are now a *major focus* of the LHC search program
- However, **gaps** in coverage remain
  - Where can we improve?

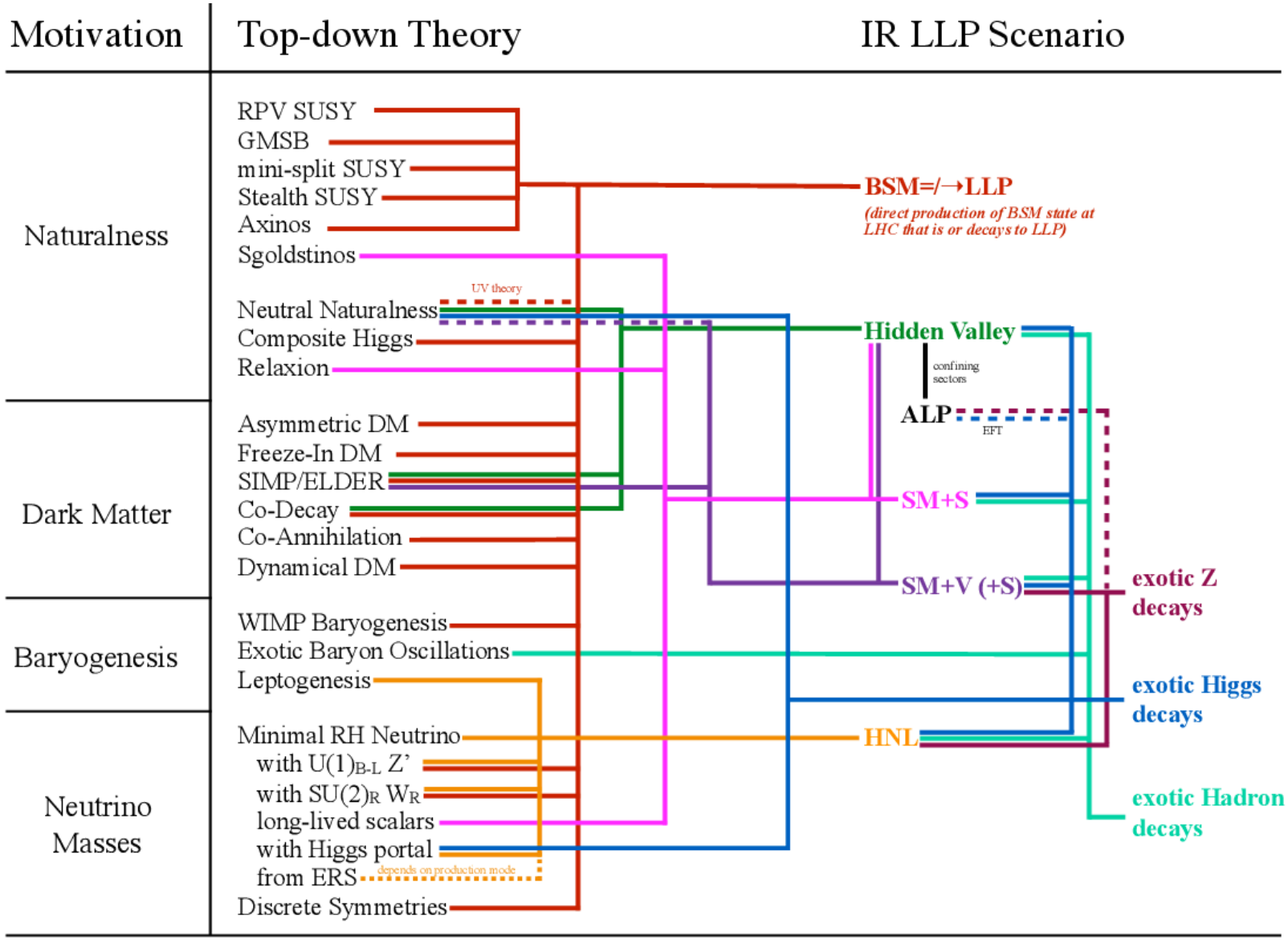


LLP Coverage & Gaps

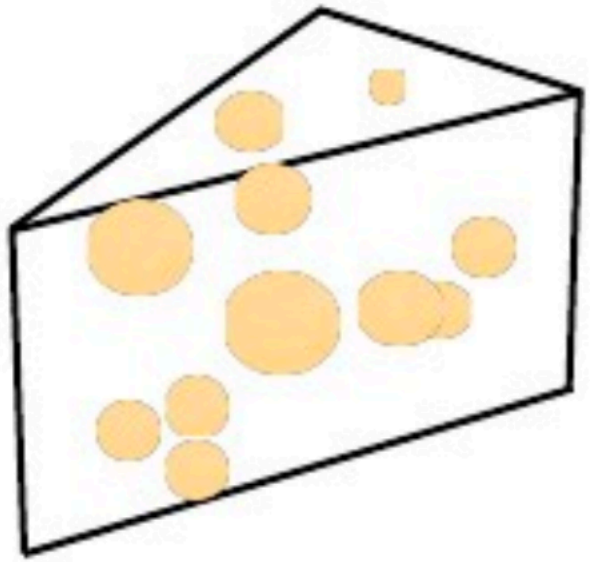
- The **ever-expanding** LLP search program is **super impressive** and full of **creative ideas!**
  - We've come a long way
  - LLPs used to be *fringe* but they are now a *major focus* of the LHC search program
- However, **gaps** in coverage remain
  - Where can we improve?
- NB: My personal view! Biased from my CMS (CODEX-b, FCC) perspective
  - Meant to generate discussion. Tell me what I missed!



How are we doing, for a variety of models?



Status?



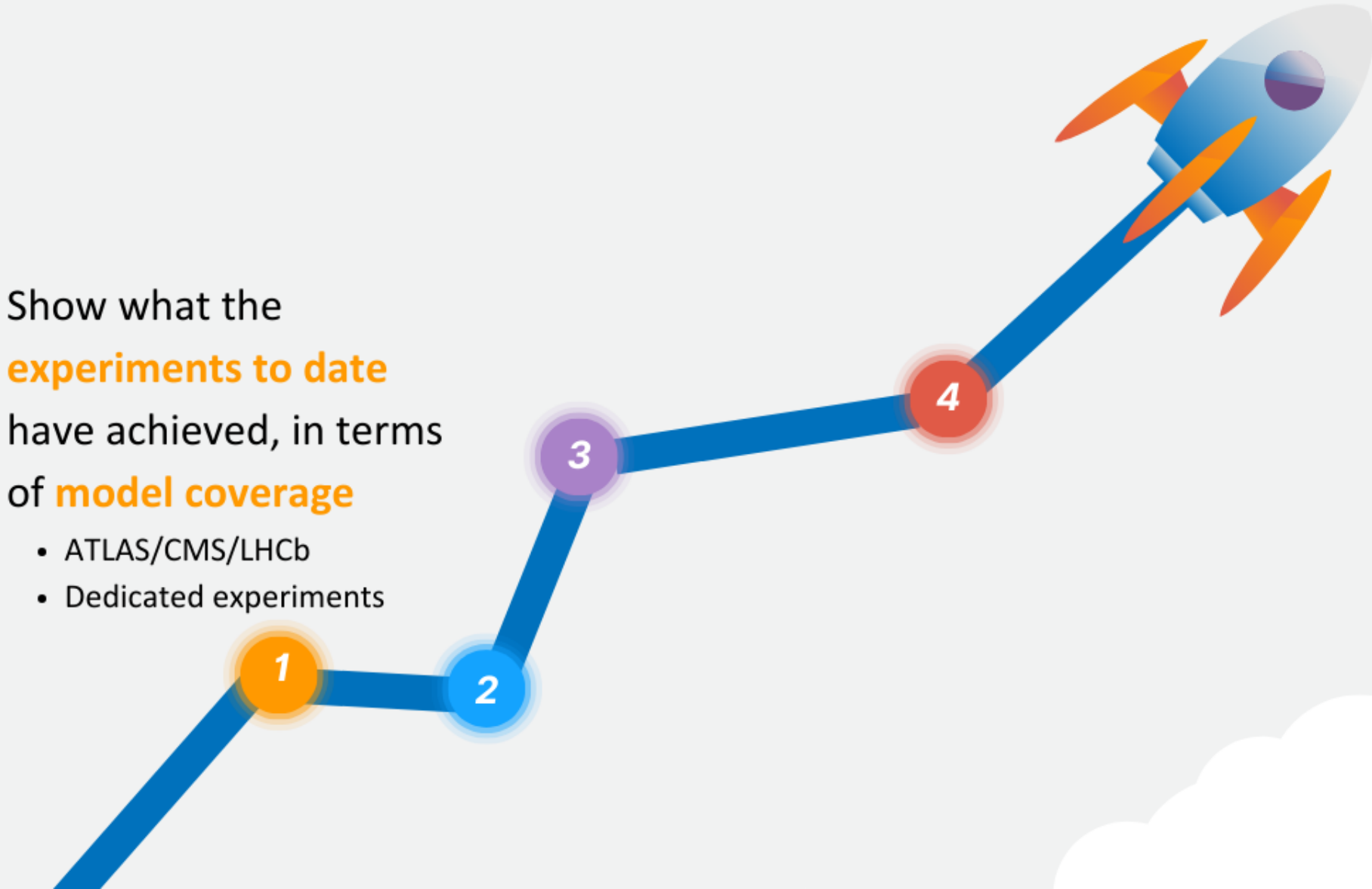
OR

?

My Goals for this Talk

Show what the **experiments to date** have achieved, in terms of **model coverage**

- ATLAS/CMS/LHCb
- Dedicated experiments

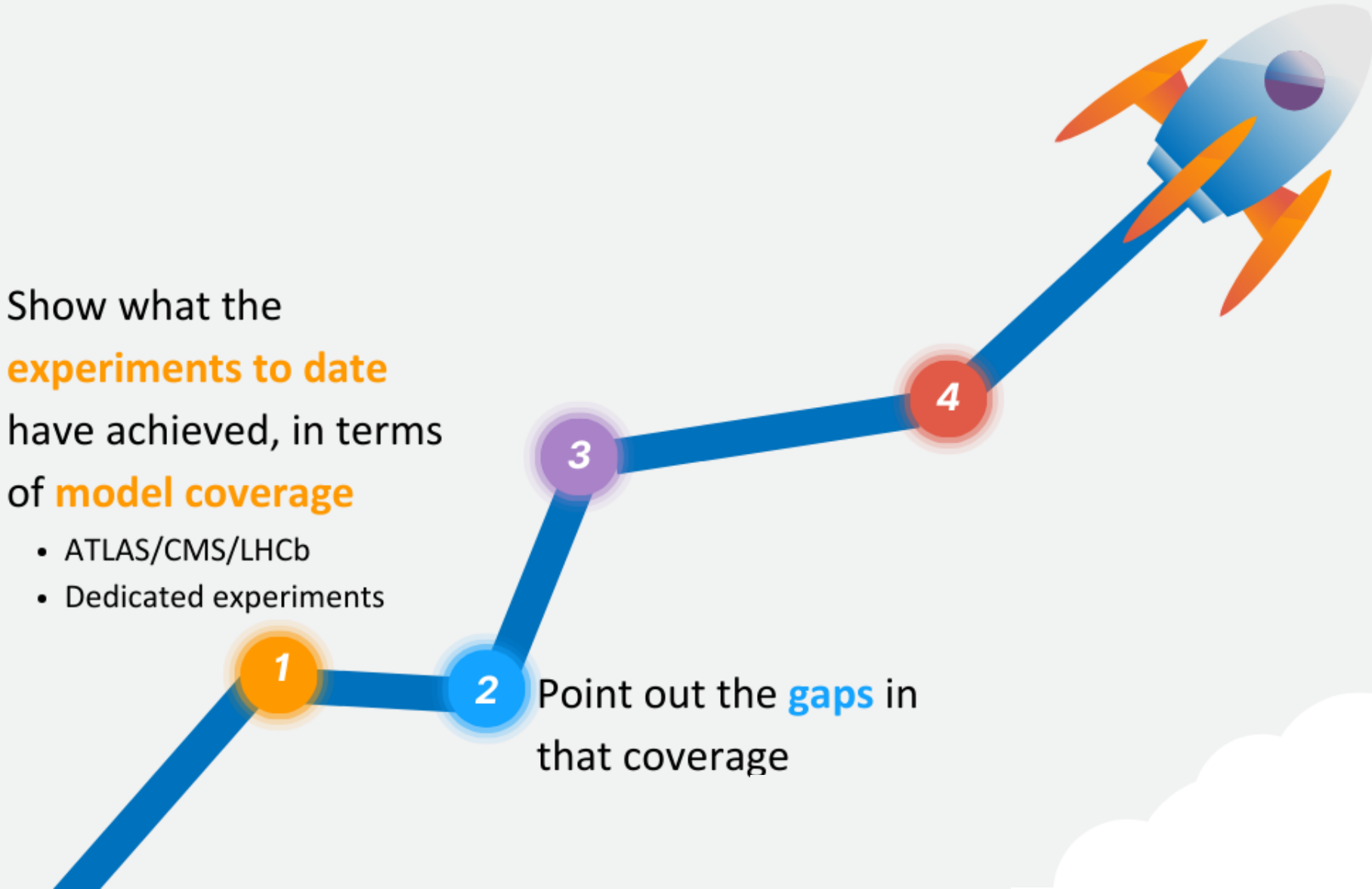


My Goals for this Talk

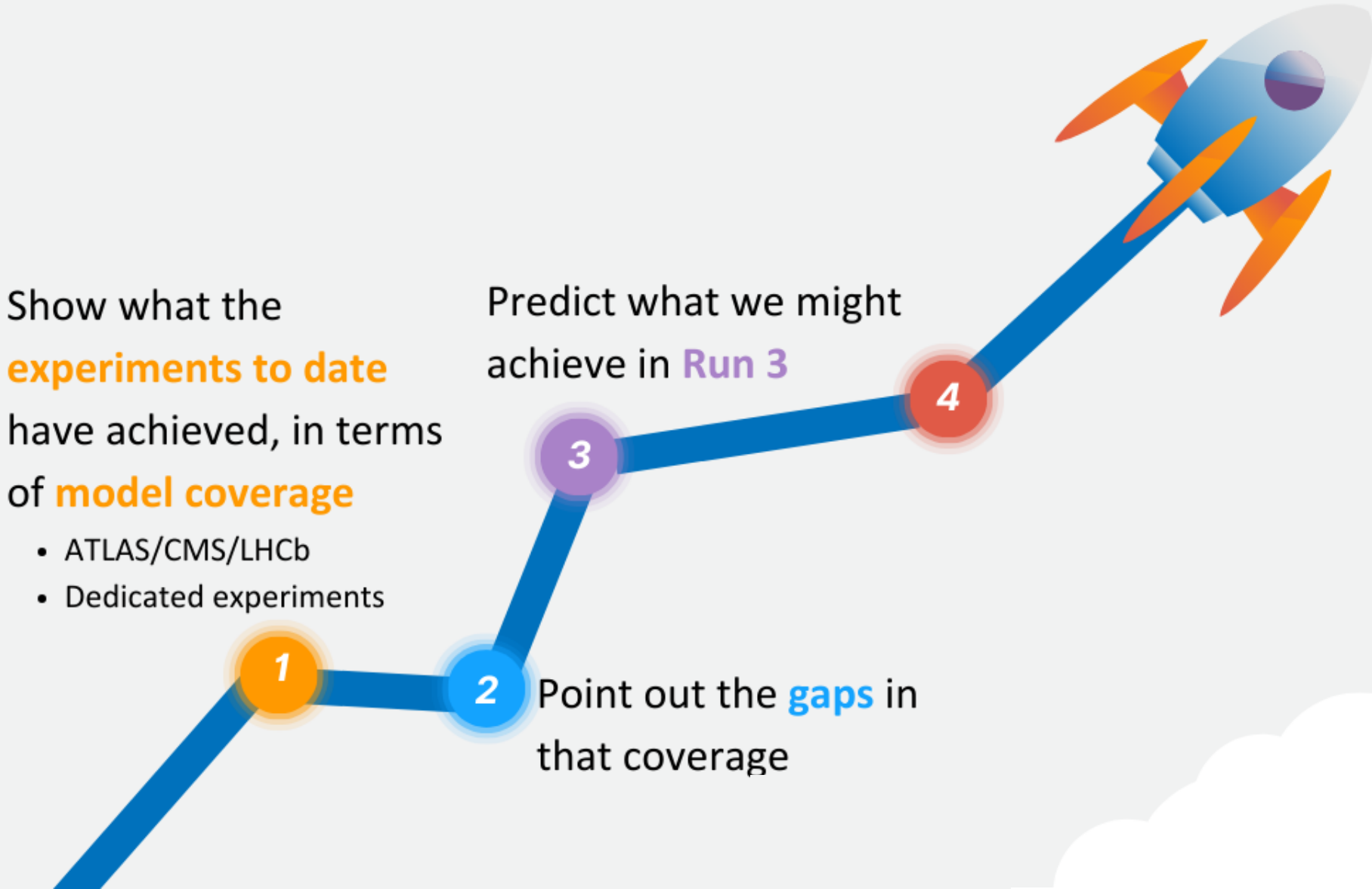
Show what the **experiments to date** have achieved, in terms of **model coverage**

- ATLAS/CMS/LHCb
- Dedicated experiments

Point out the **gaps** in that coverage

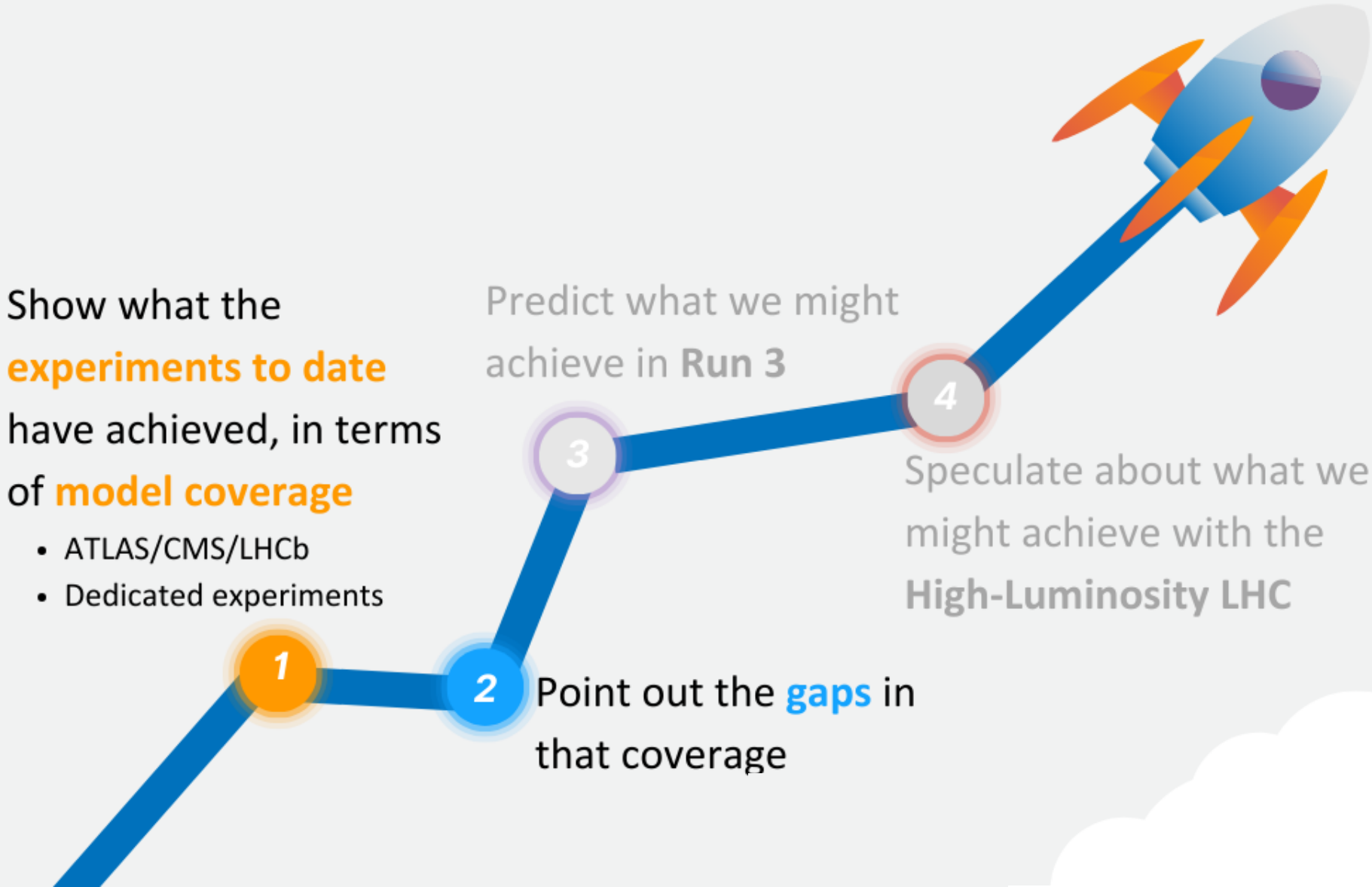


My Goals for this Talk



My Goals for this Talk

Current Model Coverage & Gaps

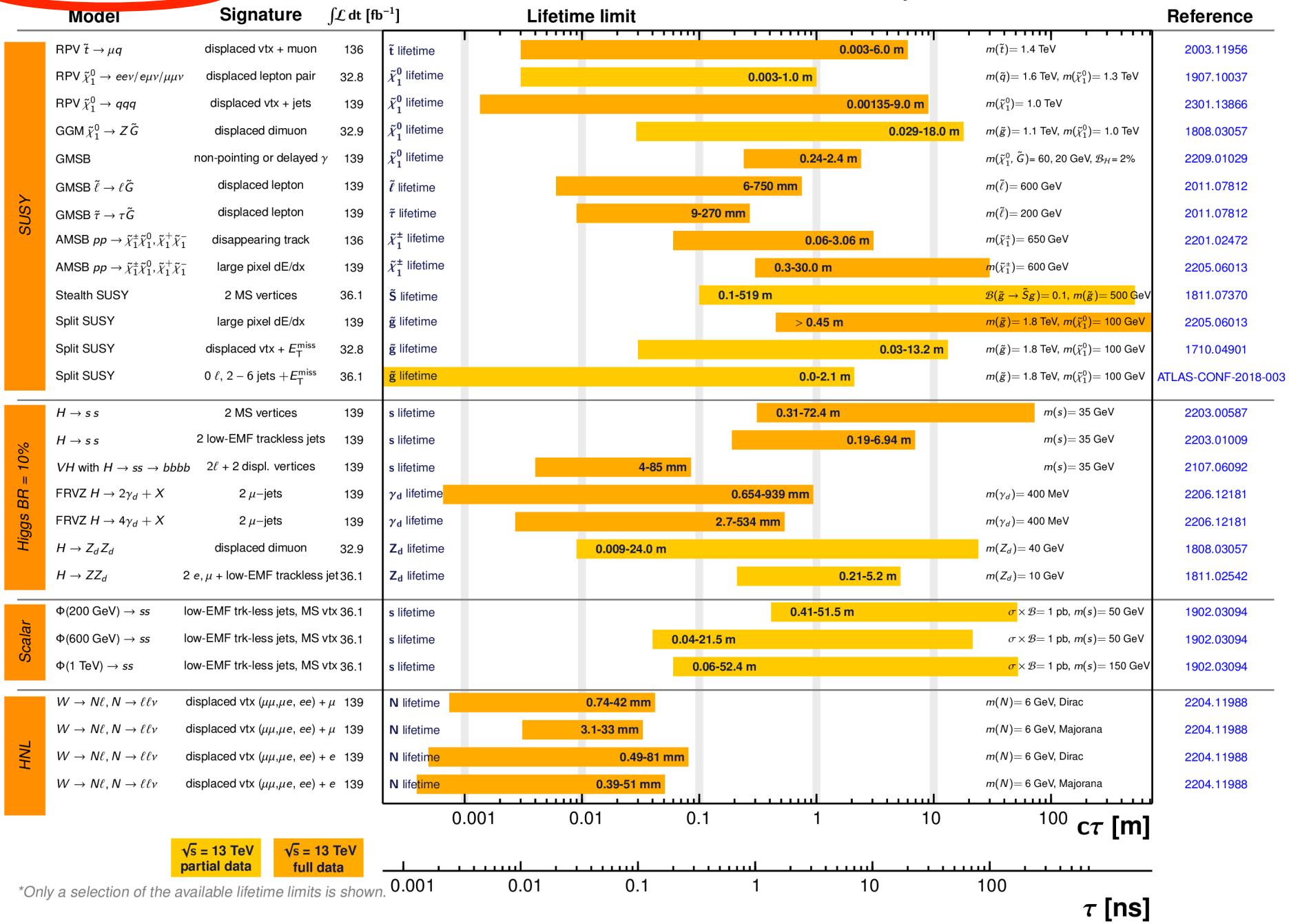


ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: March 2023

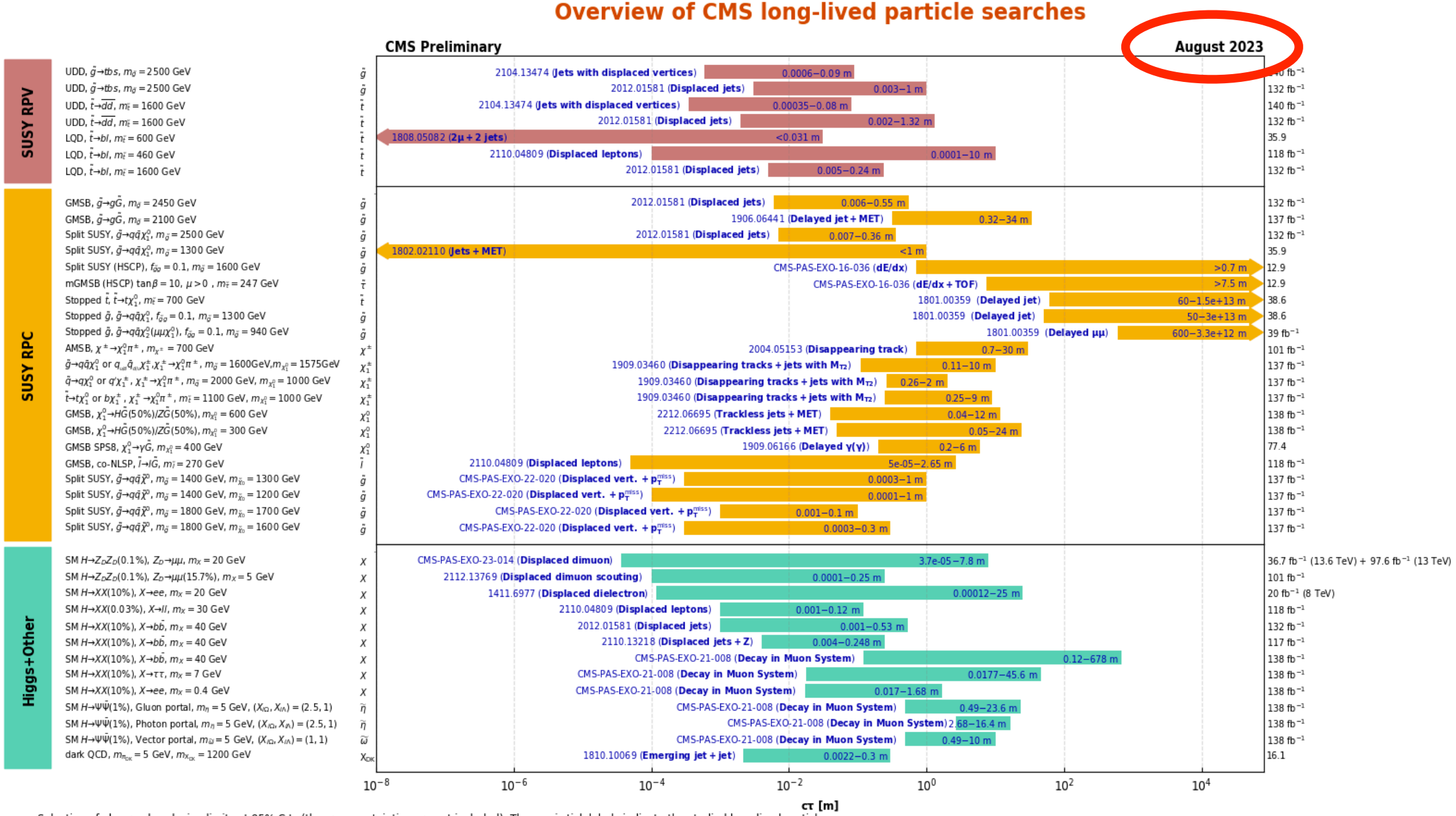
ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (32.8 – 139) fb^{-1} $\sqrt{s}$ = 13 TeV



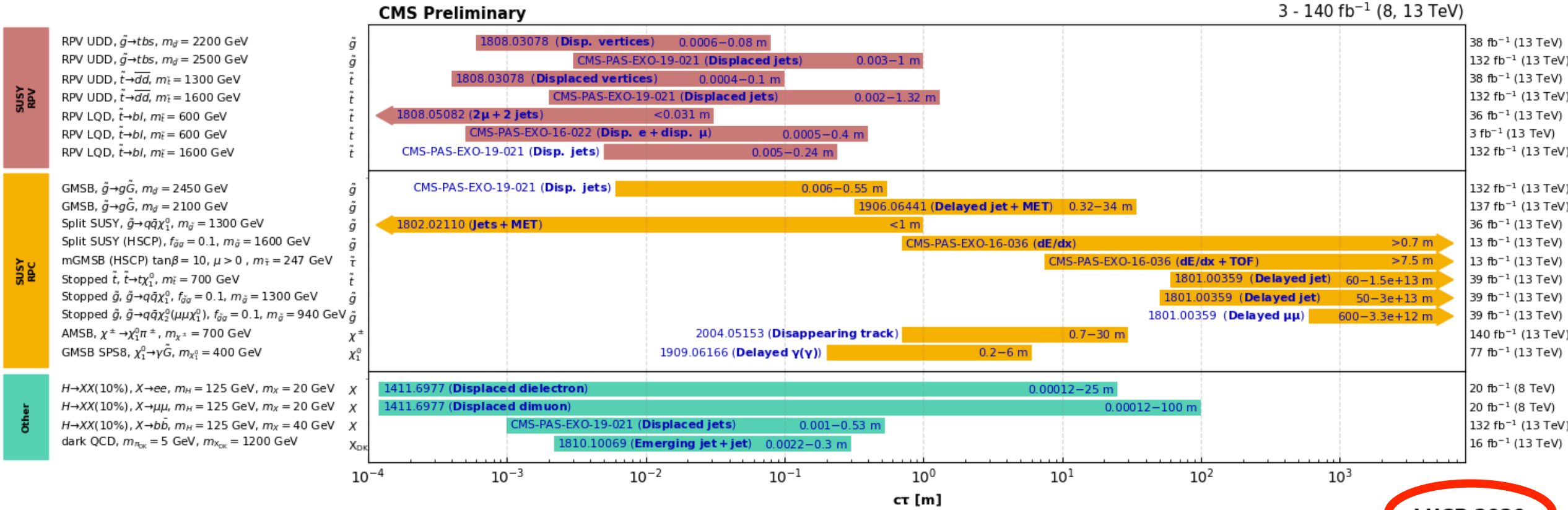
*Only a selection of the available lifetime limits is shown.

Wide range of signatures, models, and lifetimes explored at the LHC



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Overview of CMS long-lived particle searches

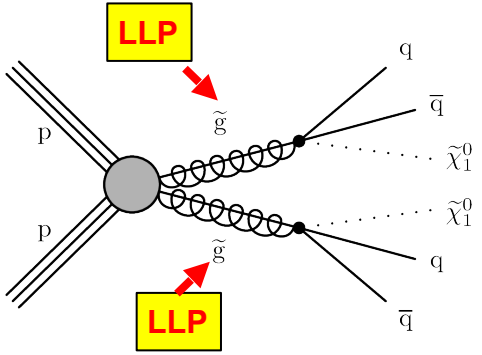


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

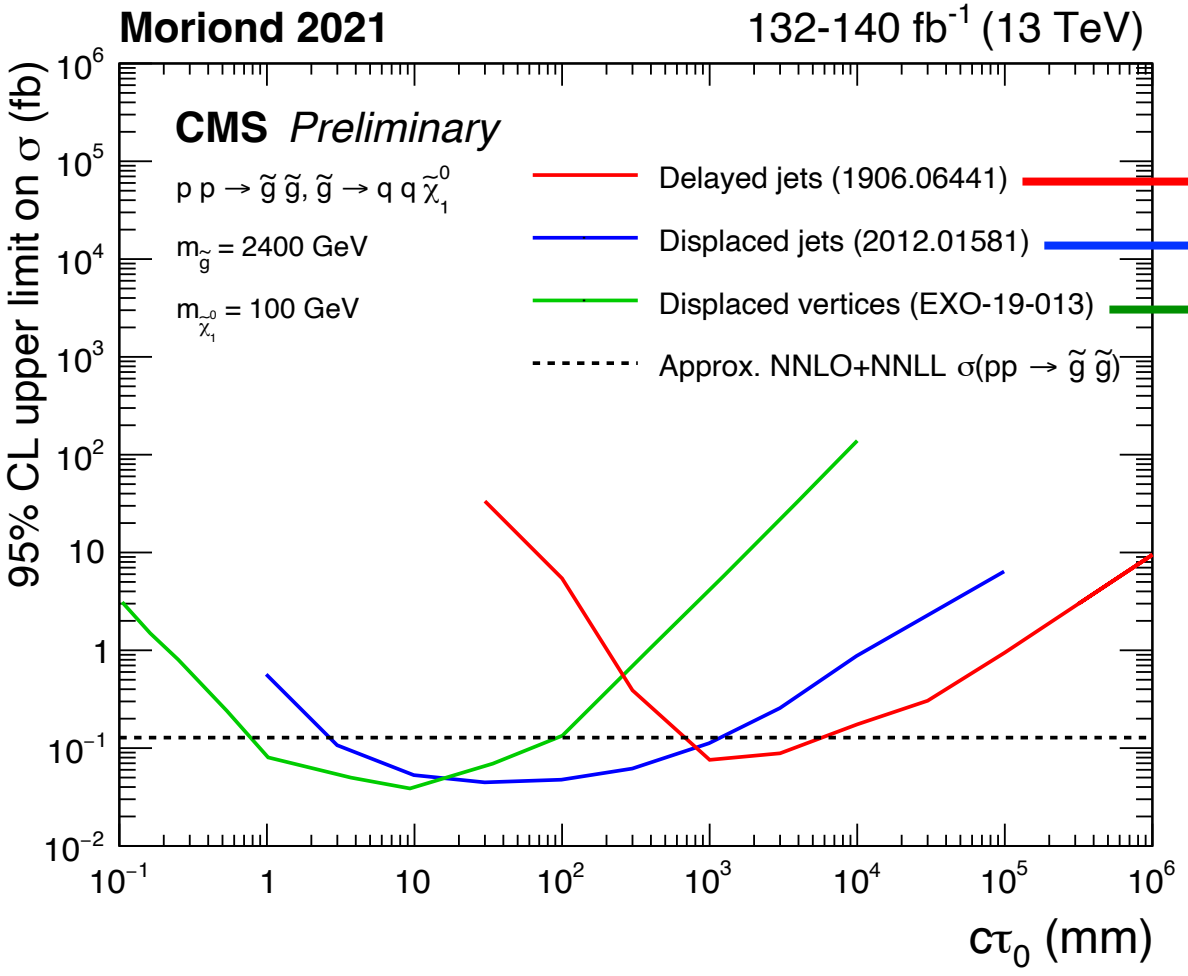
LHCP 2020

Clearly we've made some progress…

SUSY



Split SUSY: $\tilde{g} \rightarrow qq\tilde{\chi}^0$



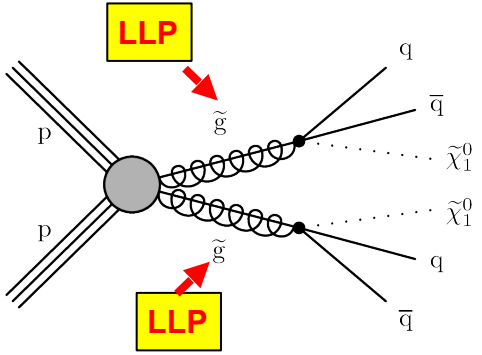
Target decays in:

Delayed jets (1906.06441) → Calorimeters

Displaced jets (2012.01581) → Tracker

Displaced vertices (EXO-19-013) → Beam pipe

- Analyses with complementary lifetime coverage
- Target fairly high mass here



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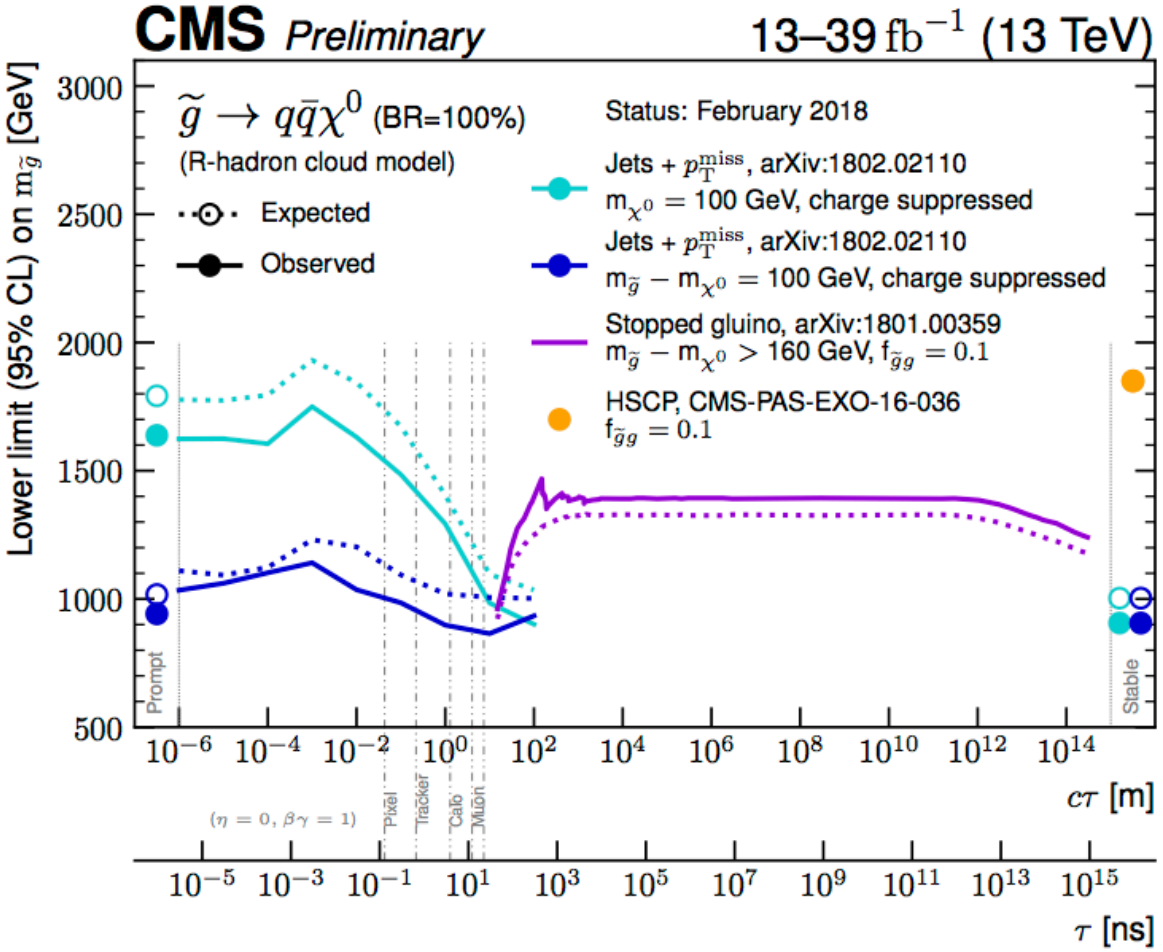
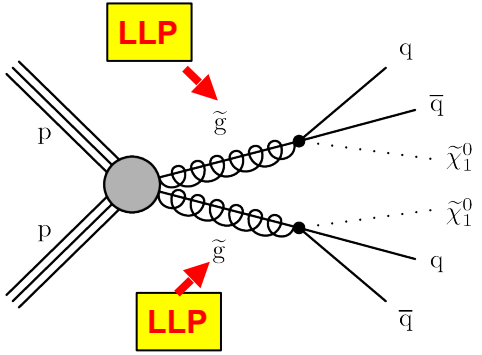


- For the same model, can also go to:
  - Smaller lifetimes when you reinterpret a prompt search
  - Longer lifetimes with searches for stopped particles (EXO-16-004) and HSCPs (EXO-16-036)



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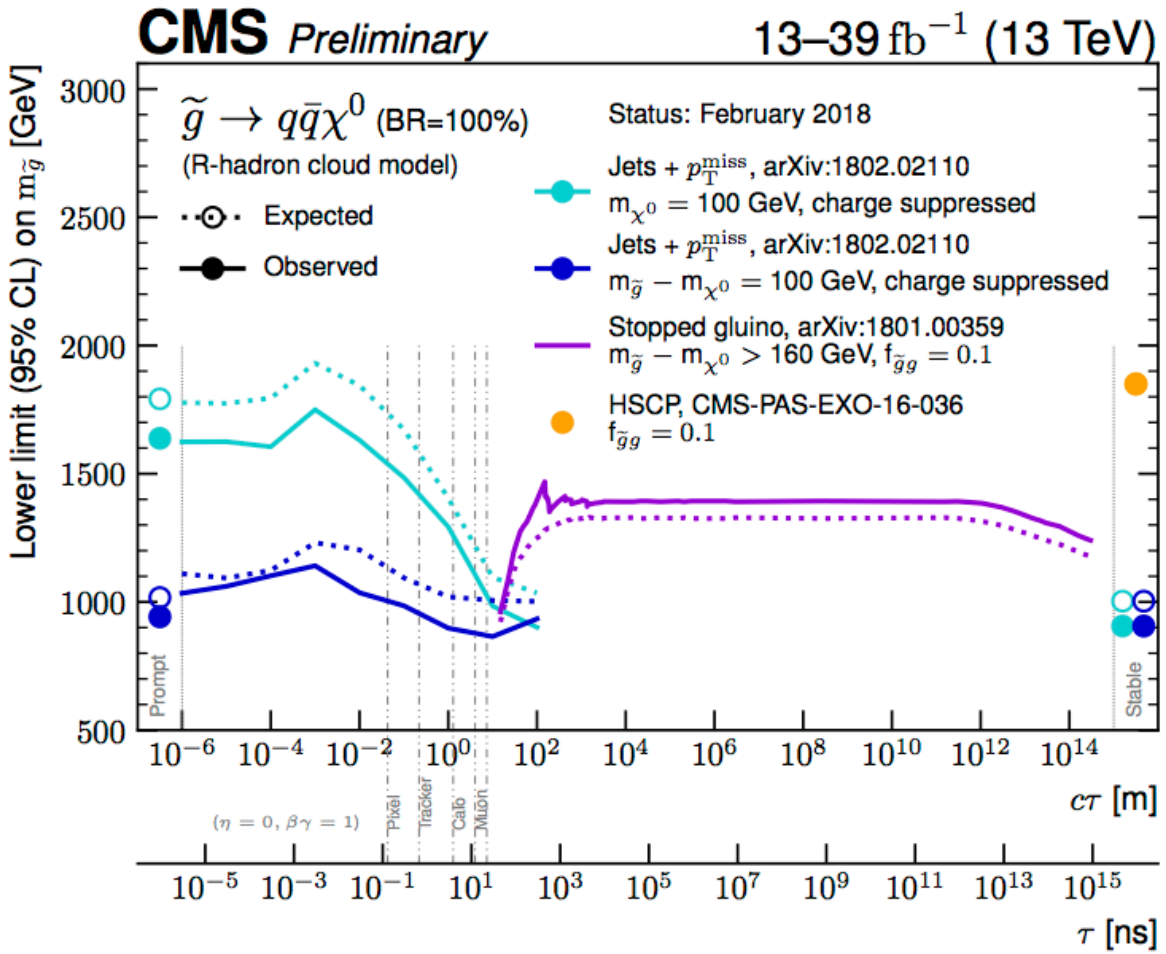
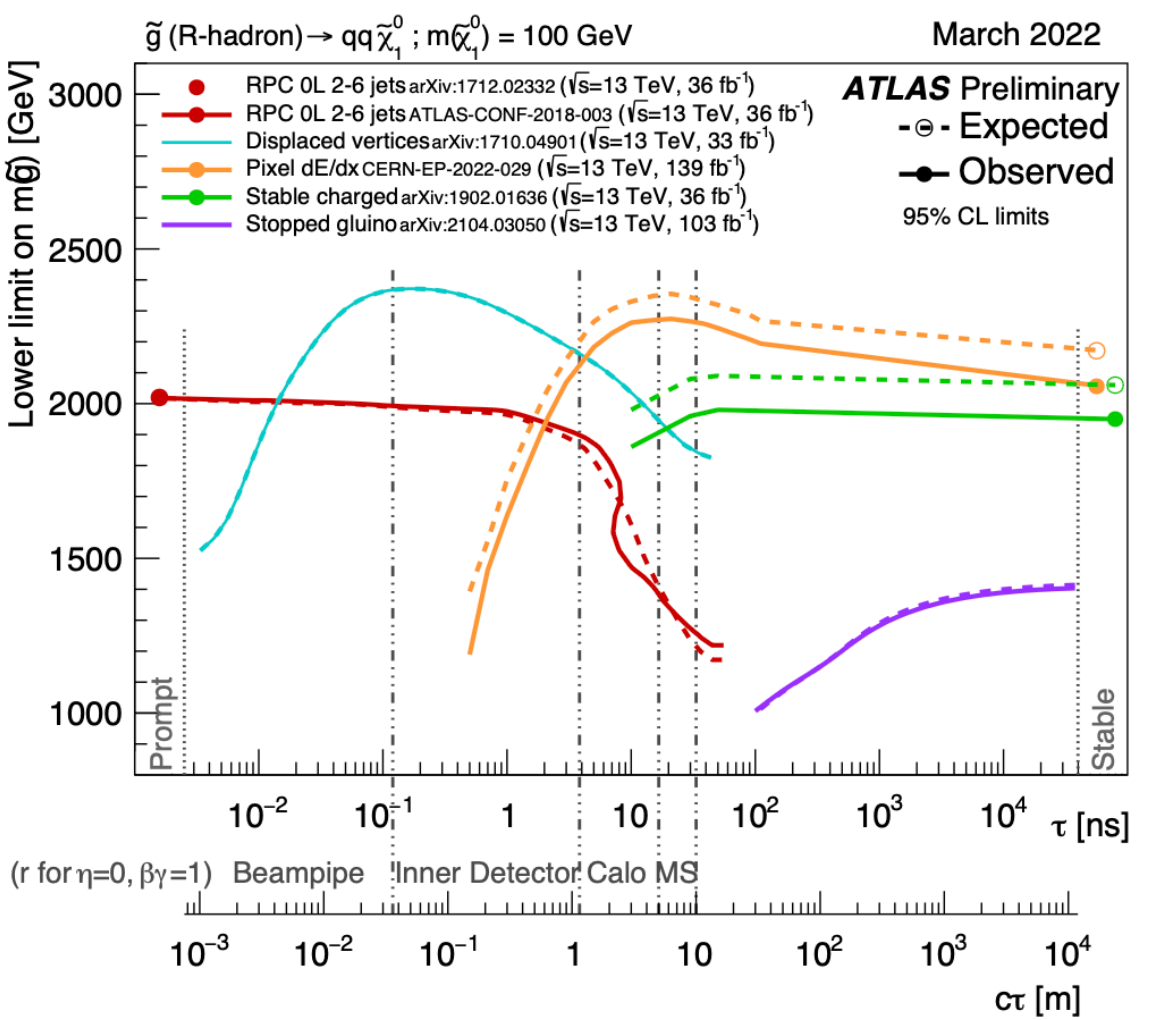
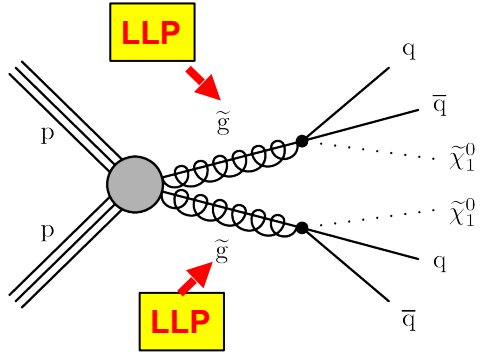


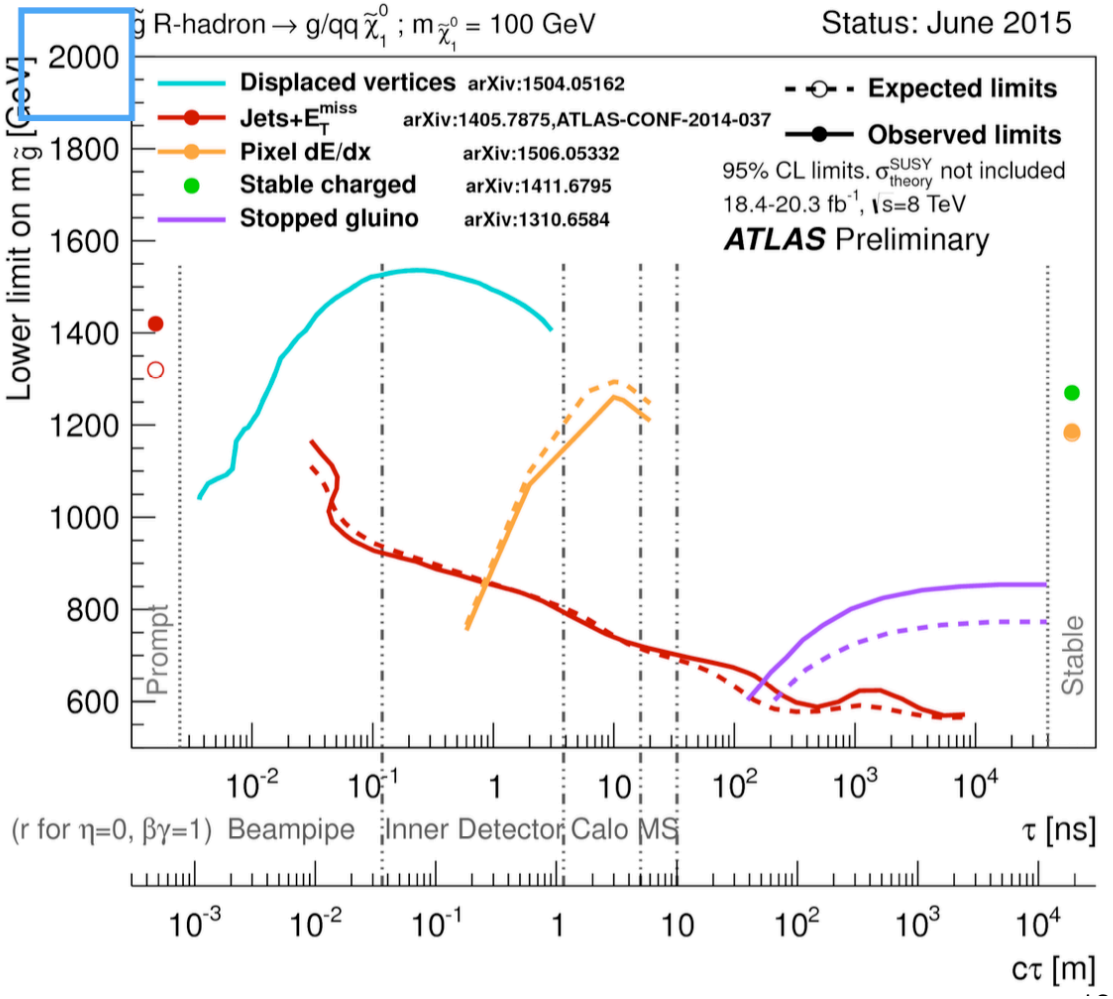




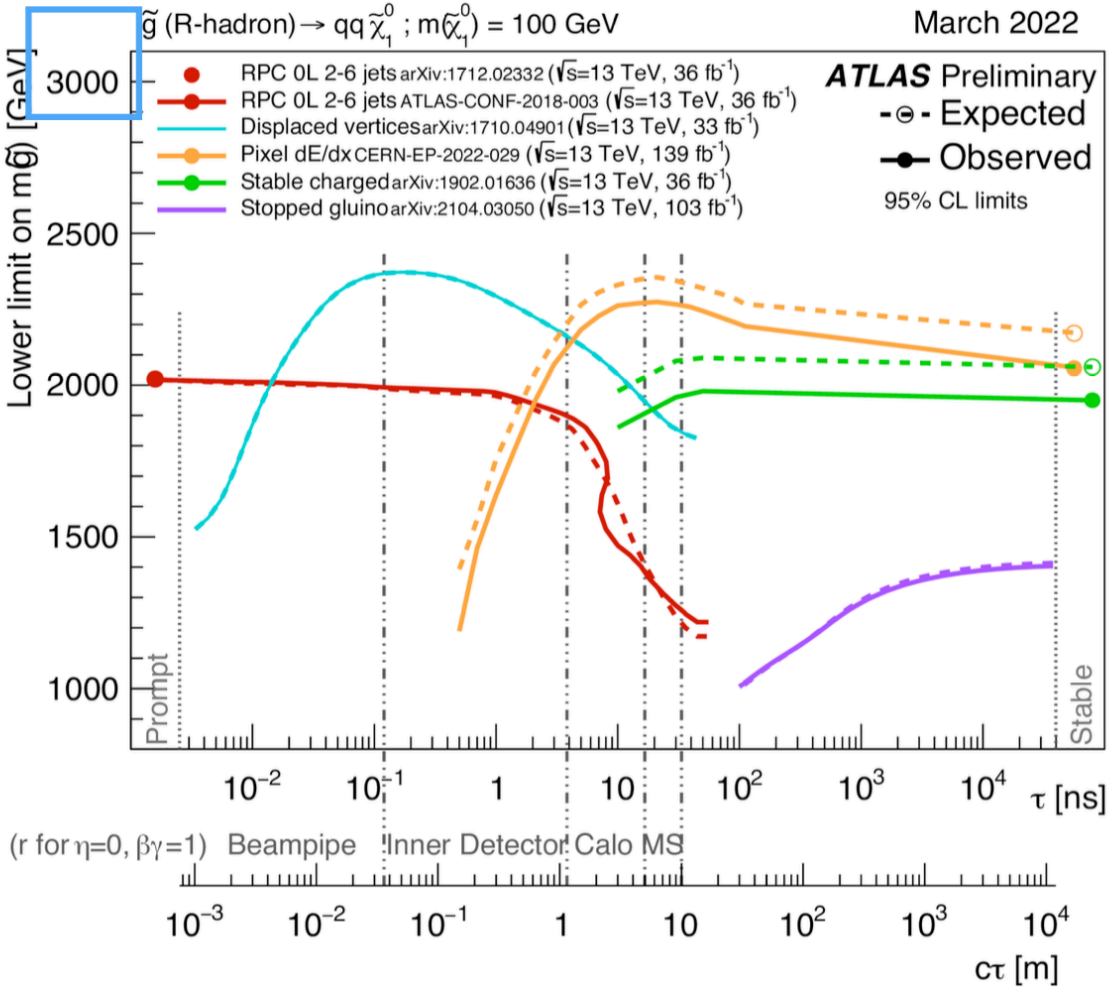
Split SUSY: $\tilde{g} \rightarrow qq\tilde{\chi}^0$

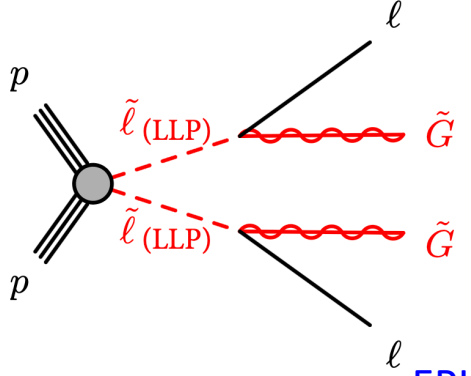
Look how far we've come!

2015



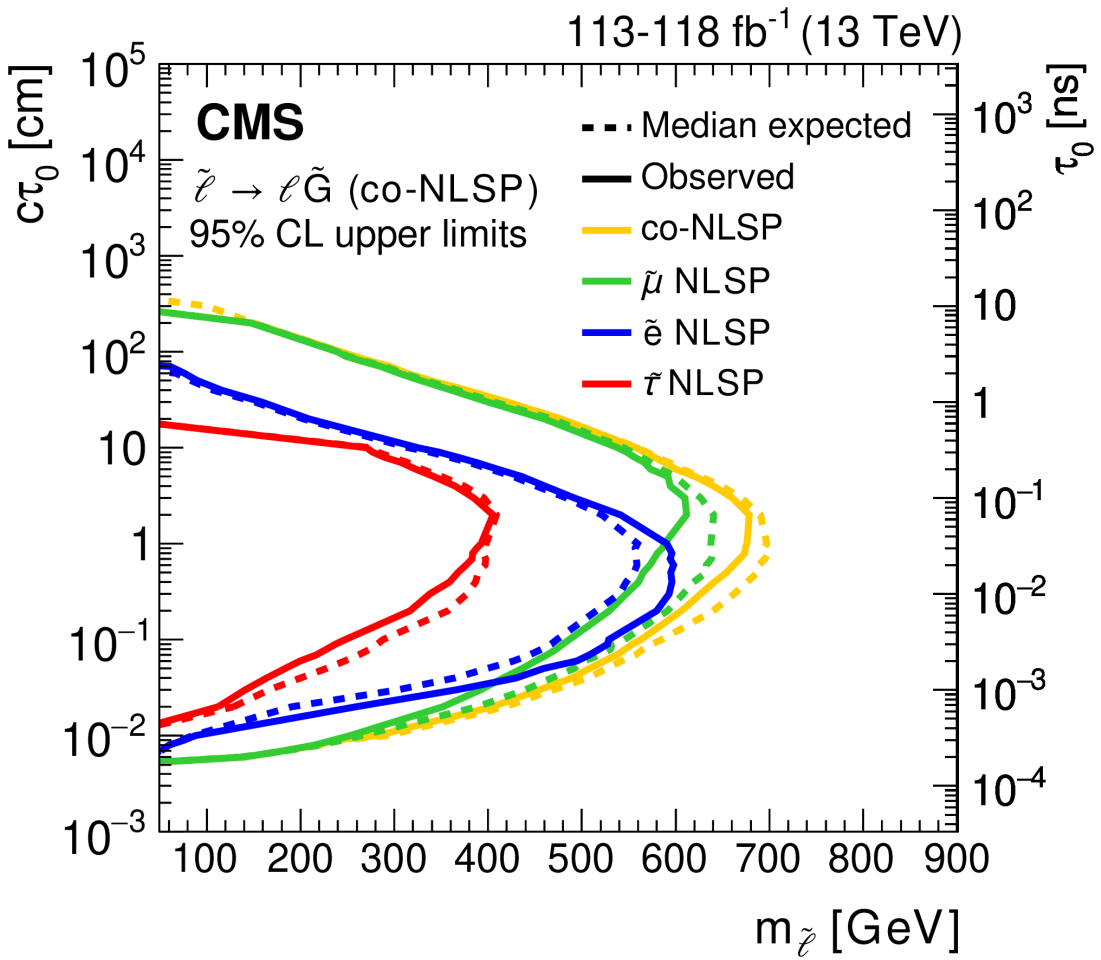
2022



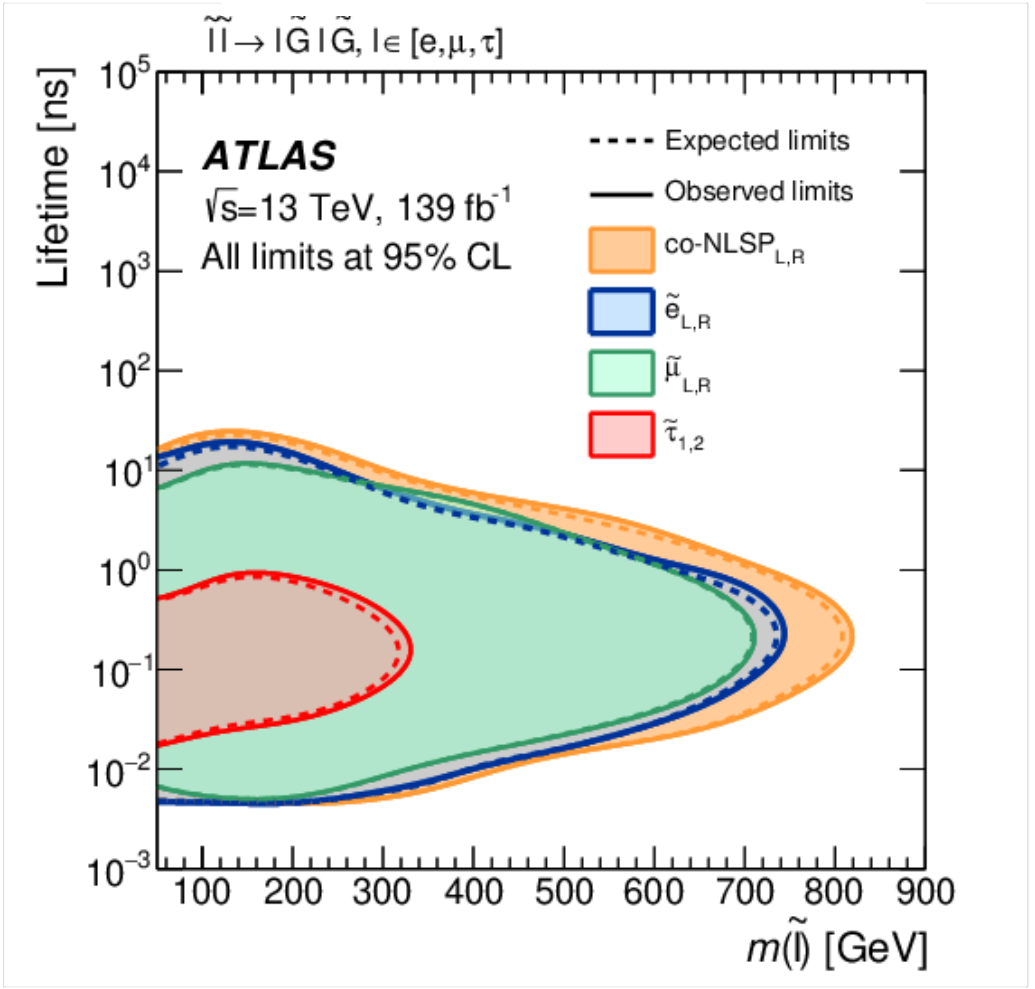


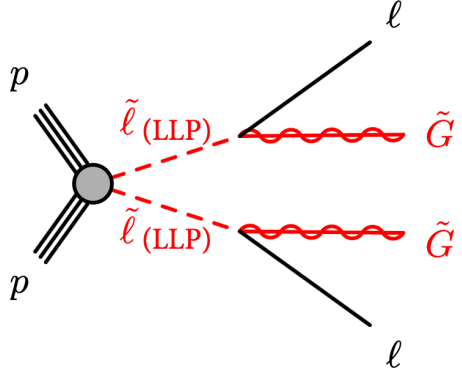
GMSB: Displaced leptons

EPJC 82 (2022) 153 (EXO-18-003, CMS)



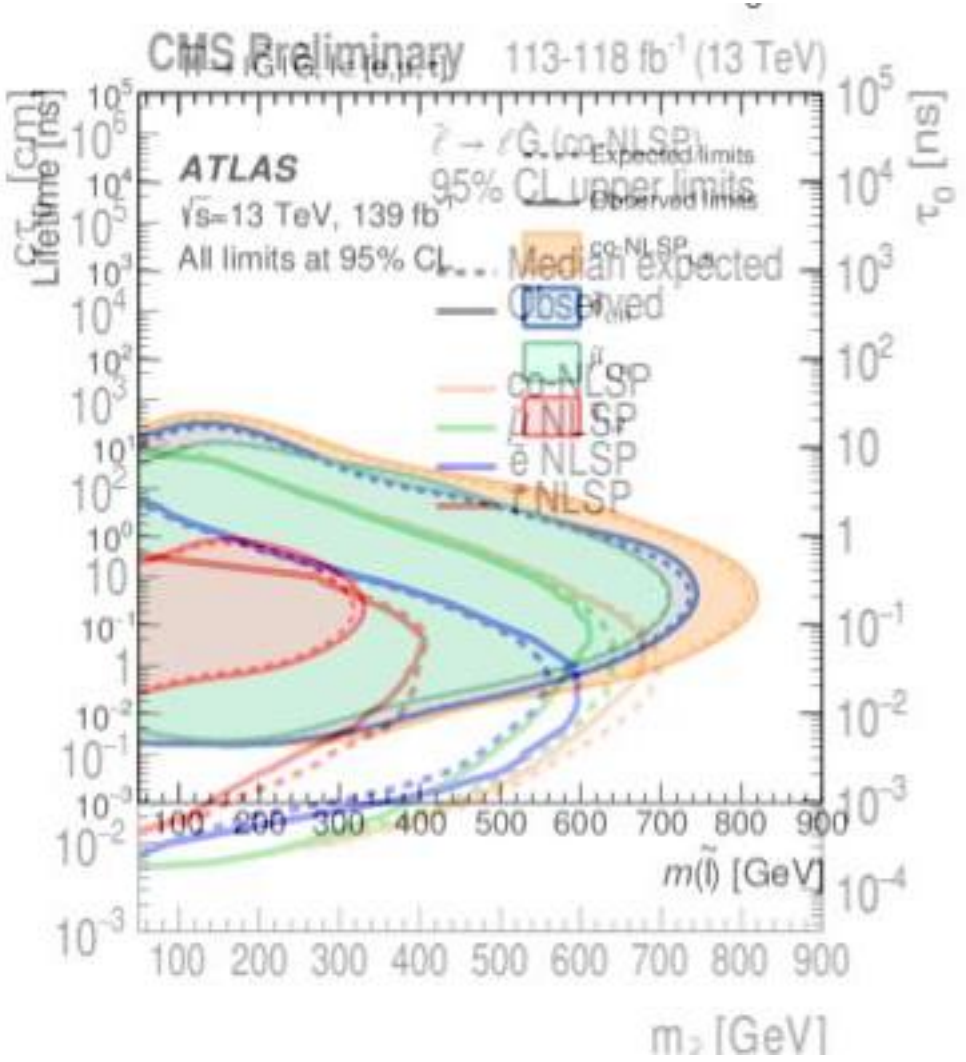
Phys. Rev. Lett. 127, 051802 (2021) (ATLAS)



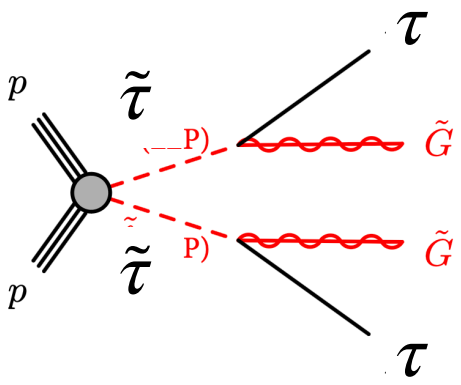


GMSB: Displaced leptons

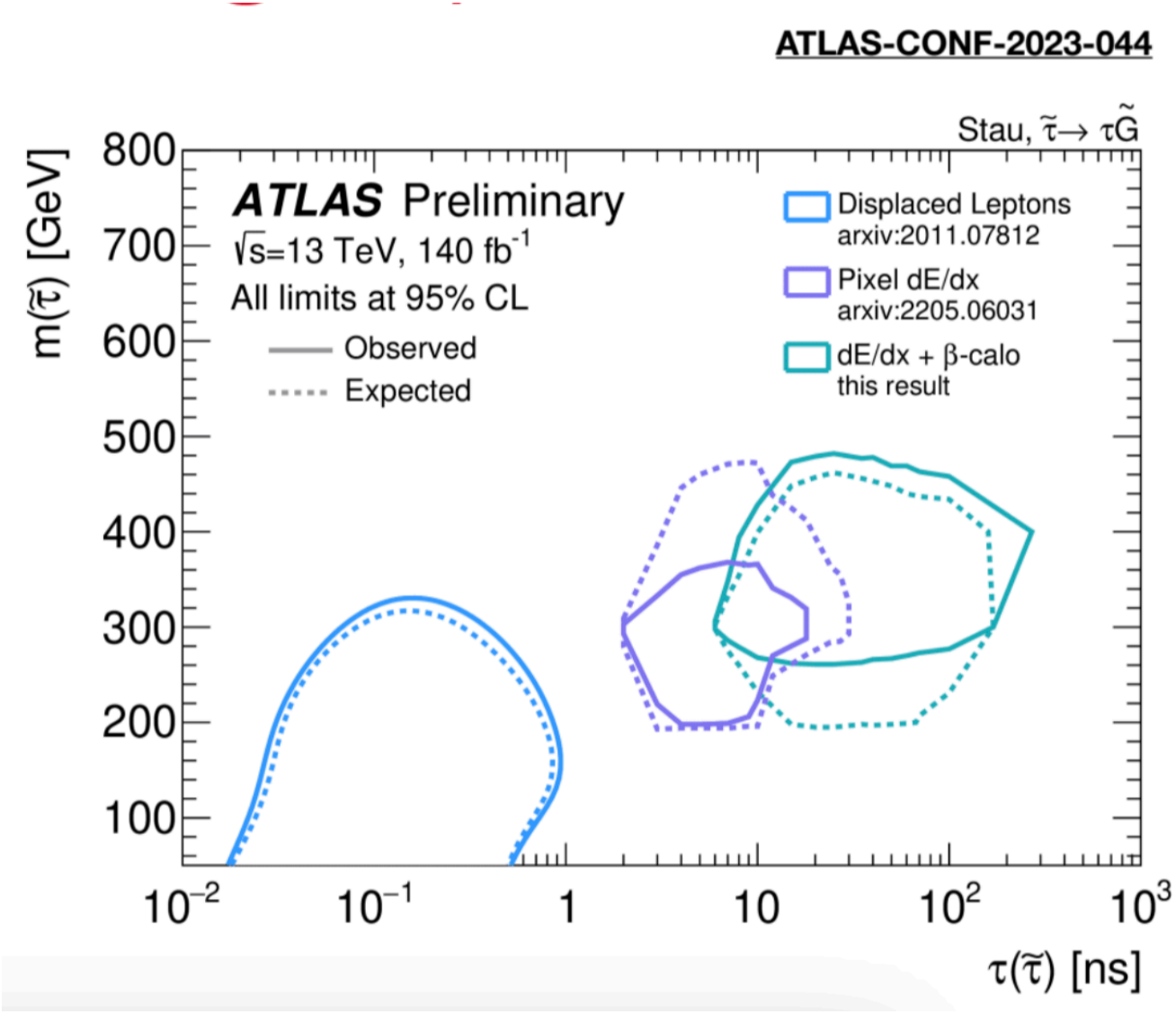
- **CMS search better at shorter lifetimes, ATLAS better at longer lifetimes**
  - ATLAS has a bigger detector! Naively this difference in results makes sense
- **Room for improvement for CMS search:**
  - Can take advantage of more displaced muon reconstruction
  - Better displaced electron reconstruction would be great!
- **For both CMS and ATLAS:**
  - Can try with non-isolated leptons (harder! more bkg)
  - Could try for lower masses if have improved triggers
  - Displaced hadronically decaying taus! Stay tuned :)



GMSB Staus



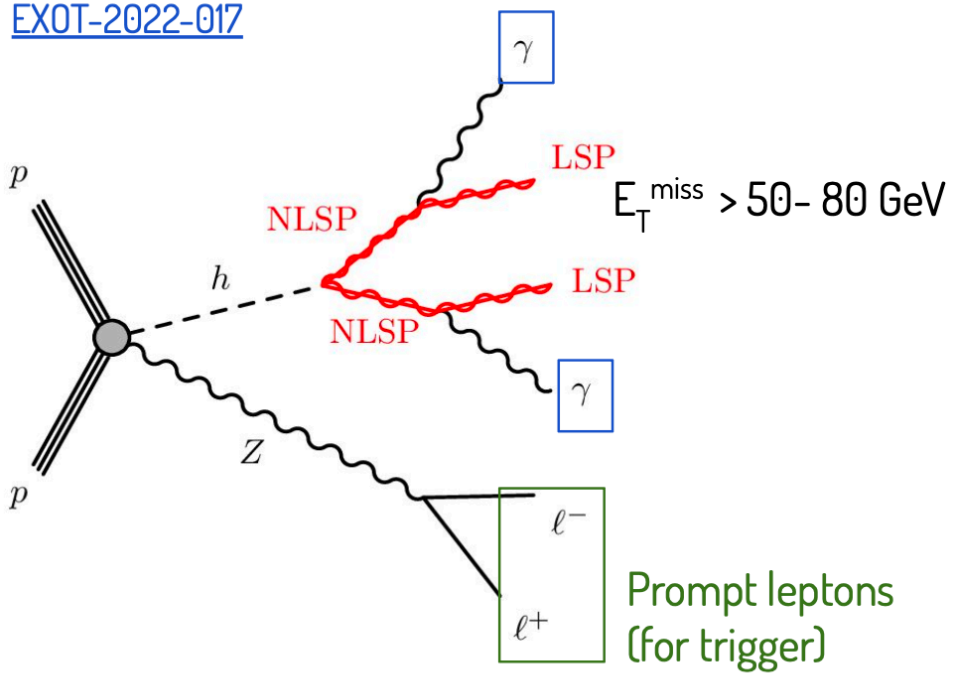
- ATLAS has this nice plot to show both displaced lepton searches and searches for highly-ionizing particles at once
  - I think CMS should do this once our full Run 2 HSCP analysis finally comes out :)
- Also missing: displaced taus!

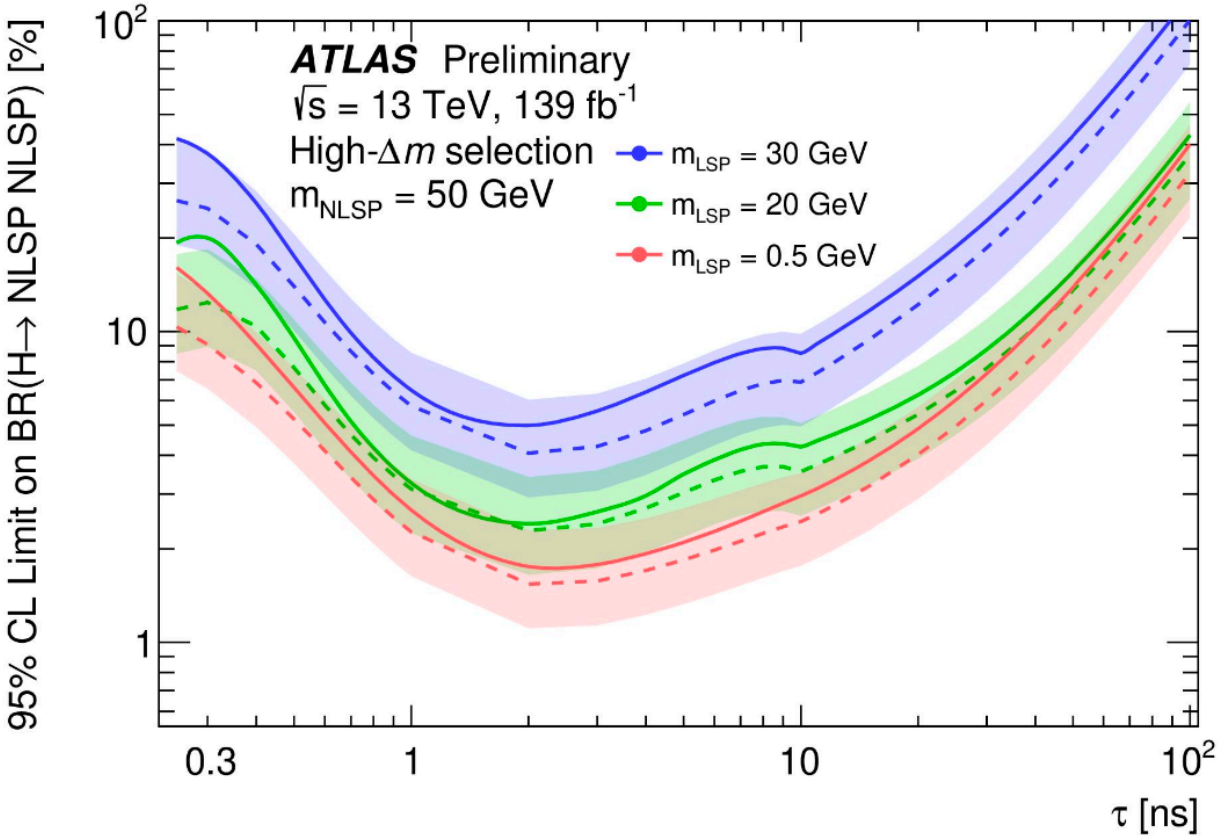


GMSB: Delayed/Non-pointing Photons

ATLAS targets GMSB SUSY via H →NLSP NLSP…

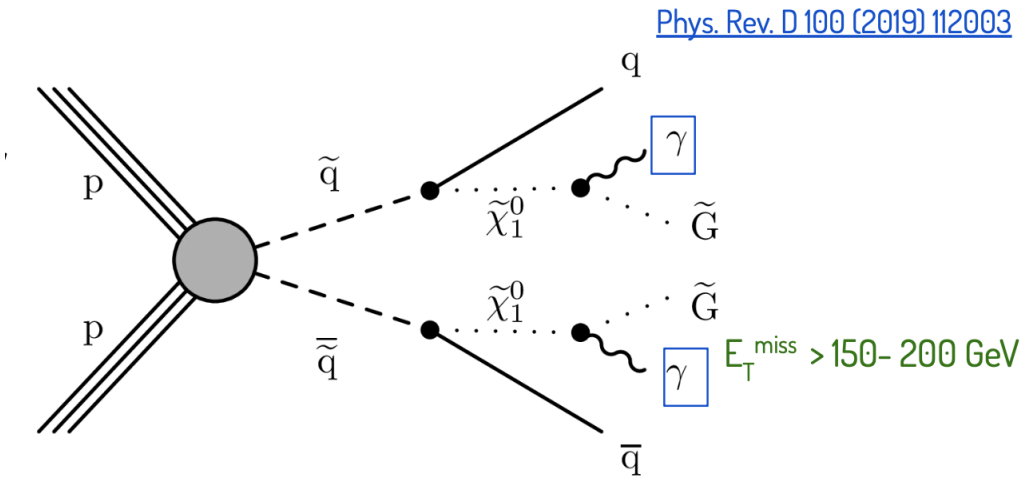
EXOT-2022-017

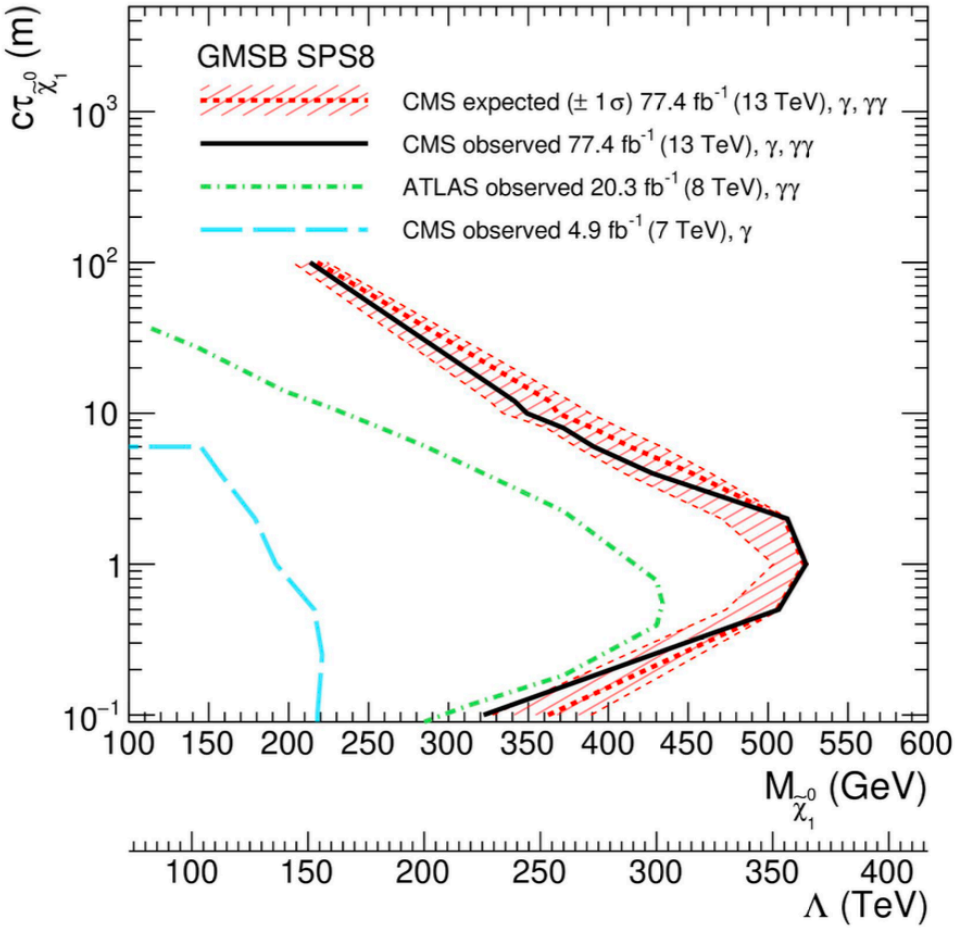




GMSB: Delayed/Non-pointing Photons

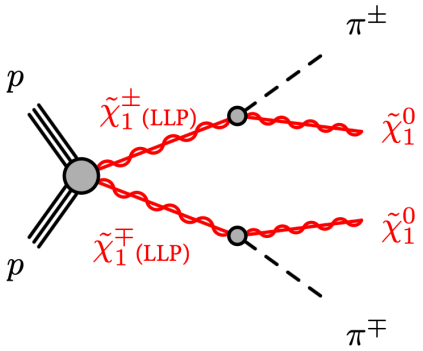
… while CMS targets GMSB SUSY via SPS8

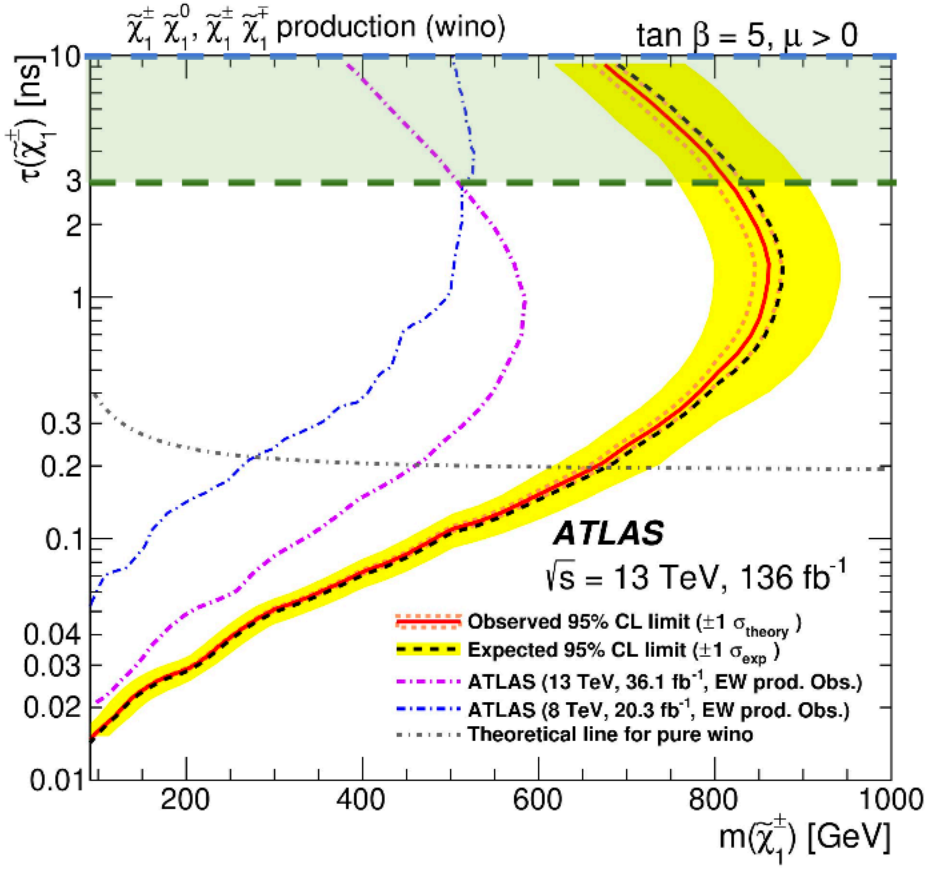




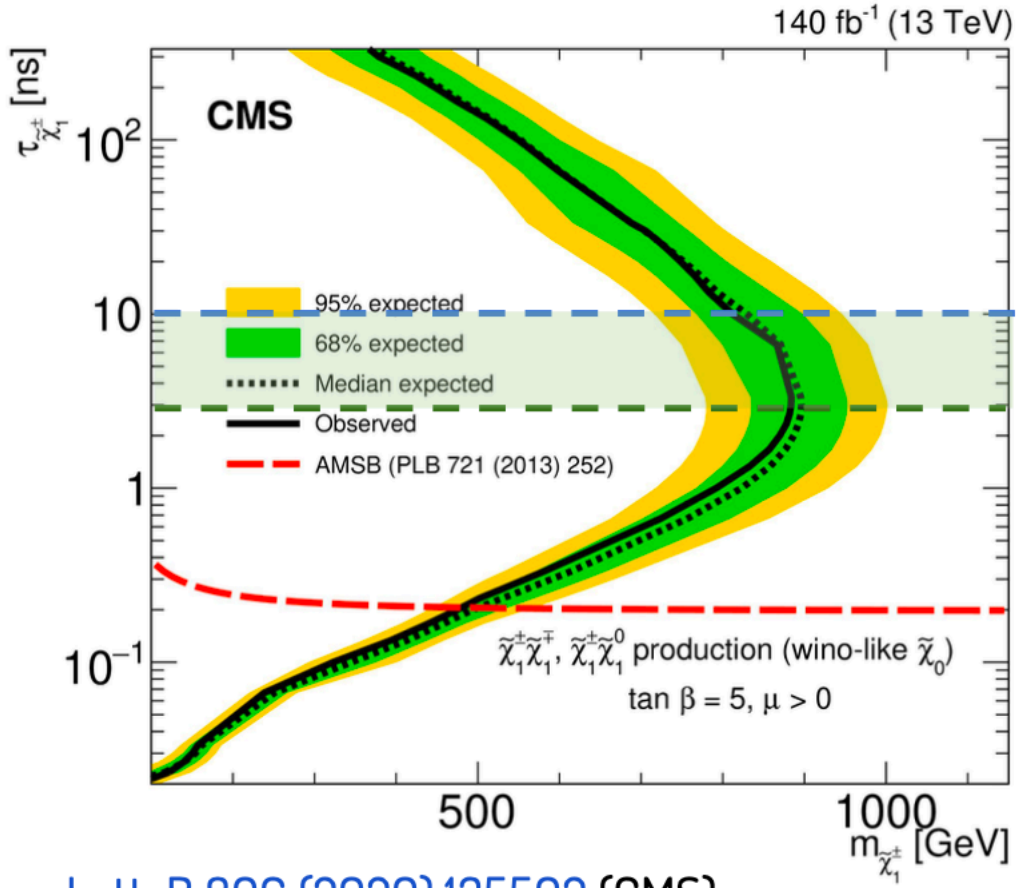
not easy to compare ATLAS and CMS for delayed photons, since production mechanism is different

AMSB

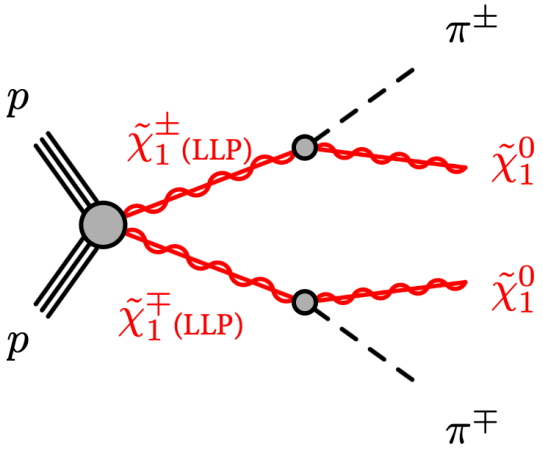




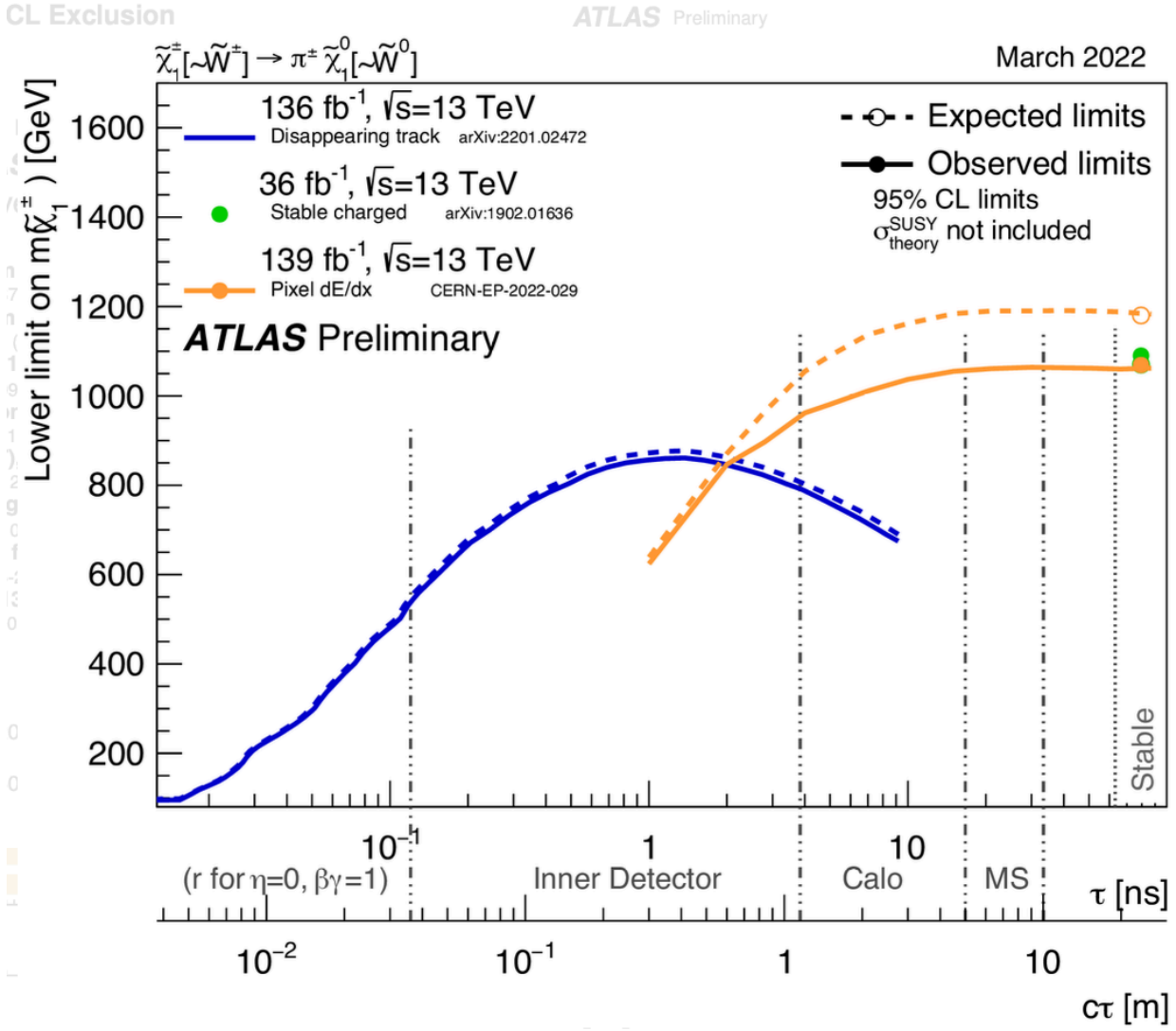
2201.02472 (ATLAS)



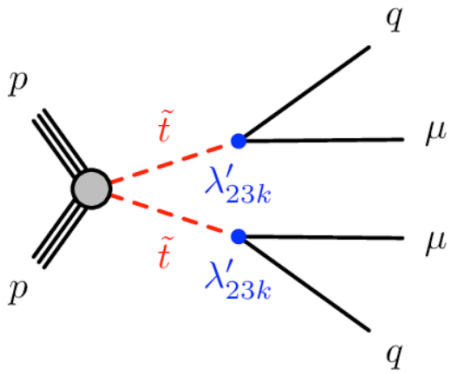
Phys. Lett. B 806 (2020) 135502 (CMS)

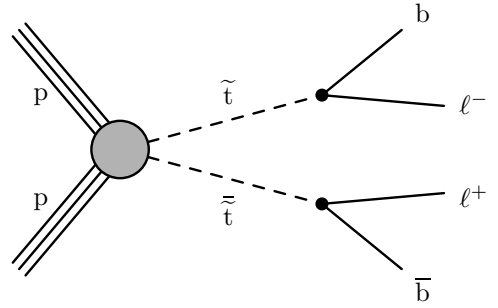

$\pi^{\pm}$
p
$\tilde{\chi}_1^{\pm}$ (LLP)
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^{\mp}$ (LLP)
p
$\pi^{\mp}$

AMSB


CL Exclusion
ATLAS Preliminary
$\tilde{\chi}_1^{\pm}[\sim\tilde{W}^{\pm}] \rightarrow \pi^{\pm}\tilde{\chi}_1^0[\sim\tilde{W}^0]$
March 2022
136 fb^{-1}, $\sqrt{s}$=13 TeV
Disappearing track arXiv:2201.02472
36 fb^{-1}, $\sqrt{s}$=13 TeV
Stable charged arXiv:1902.01636
139 fb^{-1}, $\sqrt{s}$=13 TeV
Pixel dE/dx CERN-EP-2022-029
ATLAS Preliminary
Expected limits
Observed limits
95% CL limits
σ^{SUSY}_{theory} not included
Lower limit on $m(\tilde{\chi}_1^{\pm})$ [GeV]
1600
1400
1200
1000
800
600
400
200
Stable
(r for η=0, $\beta\gamma$=1)
Inner Detector
Calo
MS
τ [ns]
10^{-2}
10^{-1}
1
10
$c\tau$ [m]

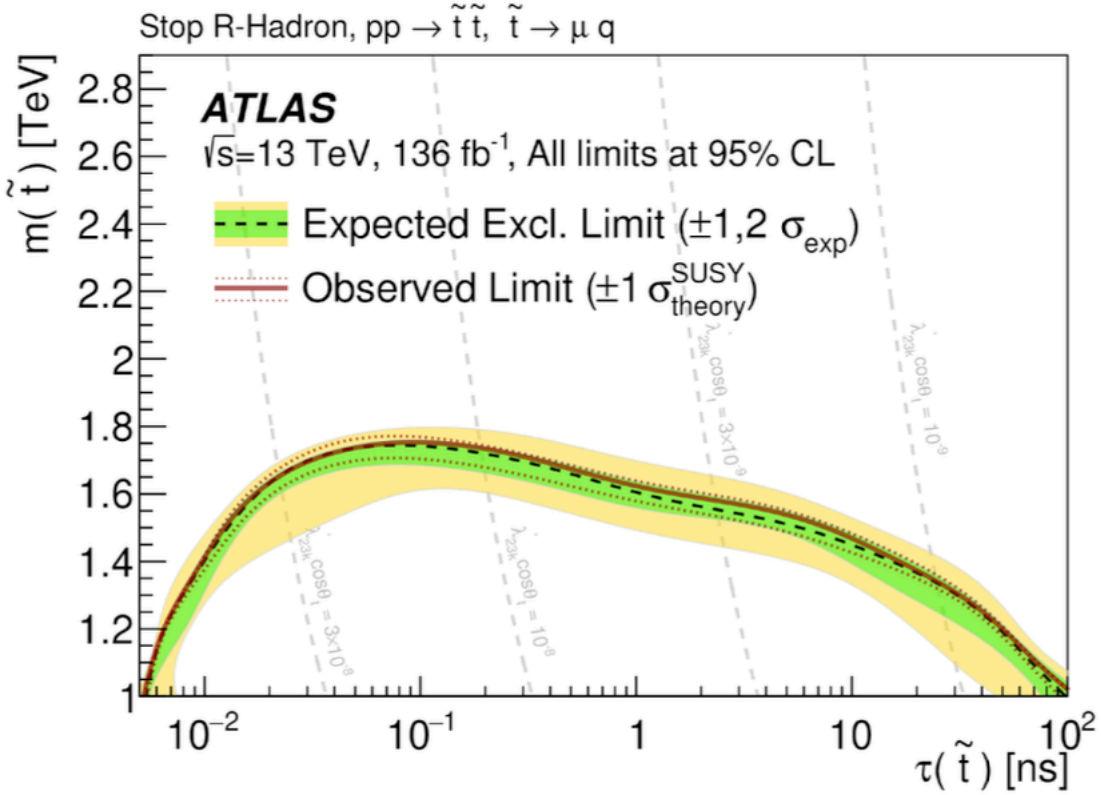
RPV SUSY





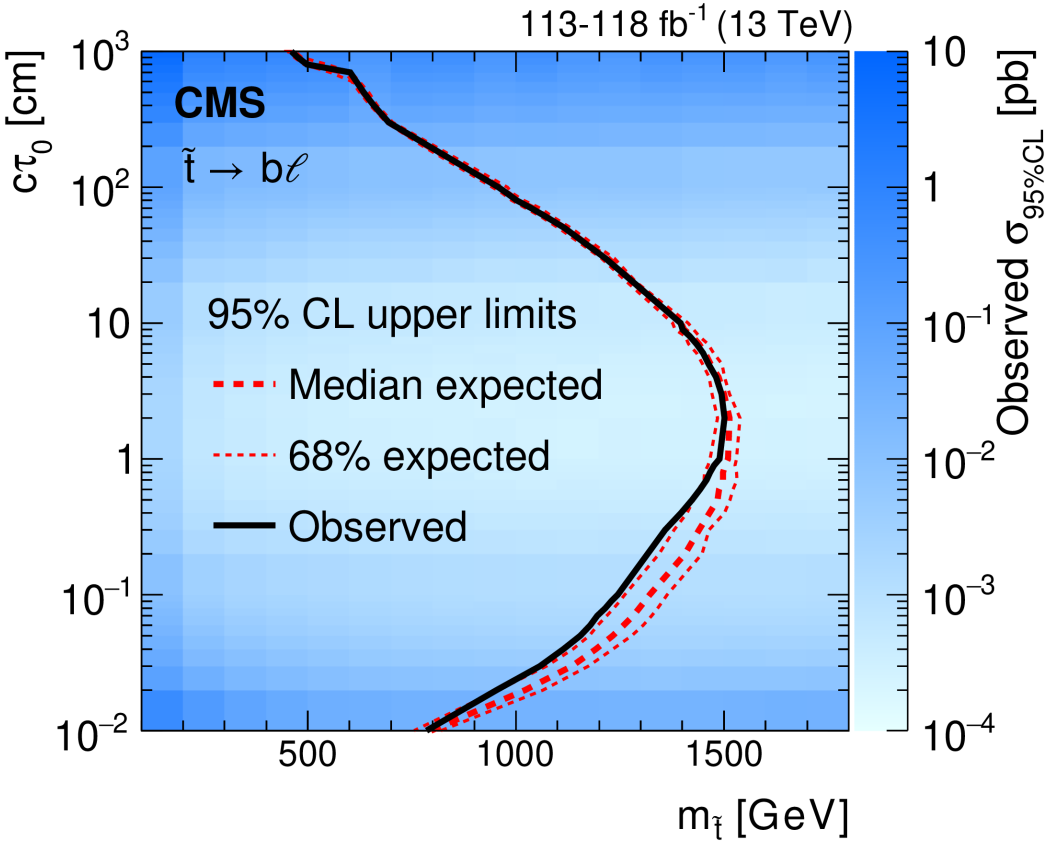
DV + muon

SUSY-2018-33

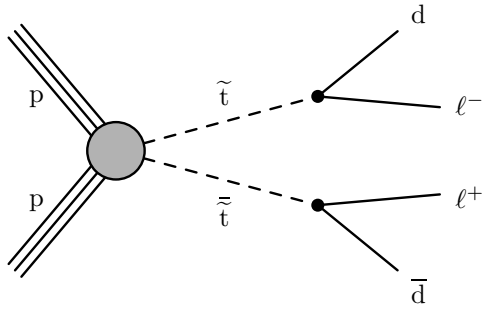


Displaced leptons (no vertex required)

EXO-18-003

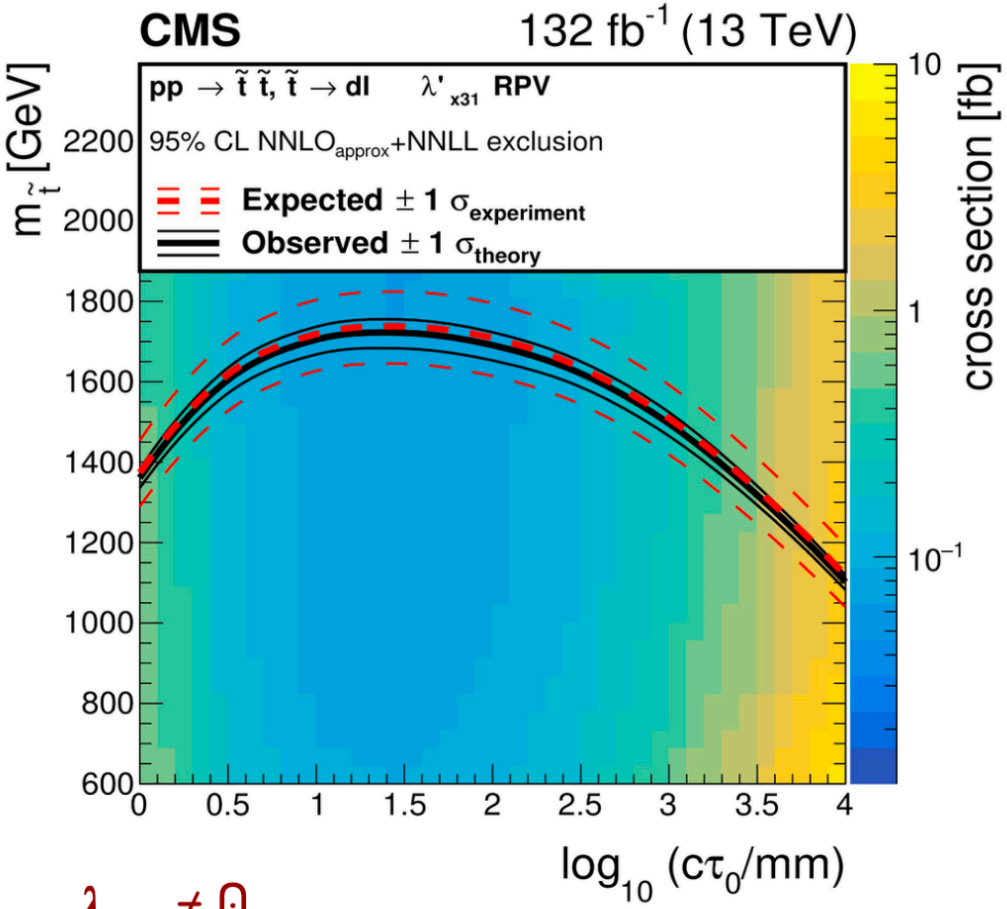


RPV SUSY



Displaced jets

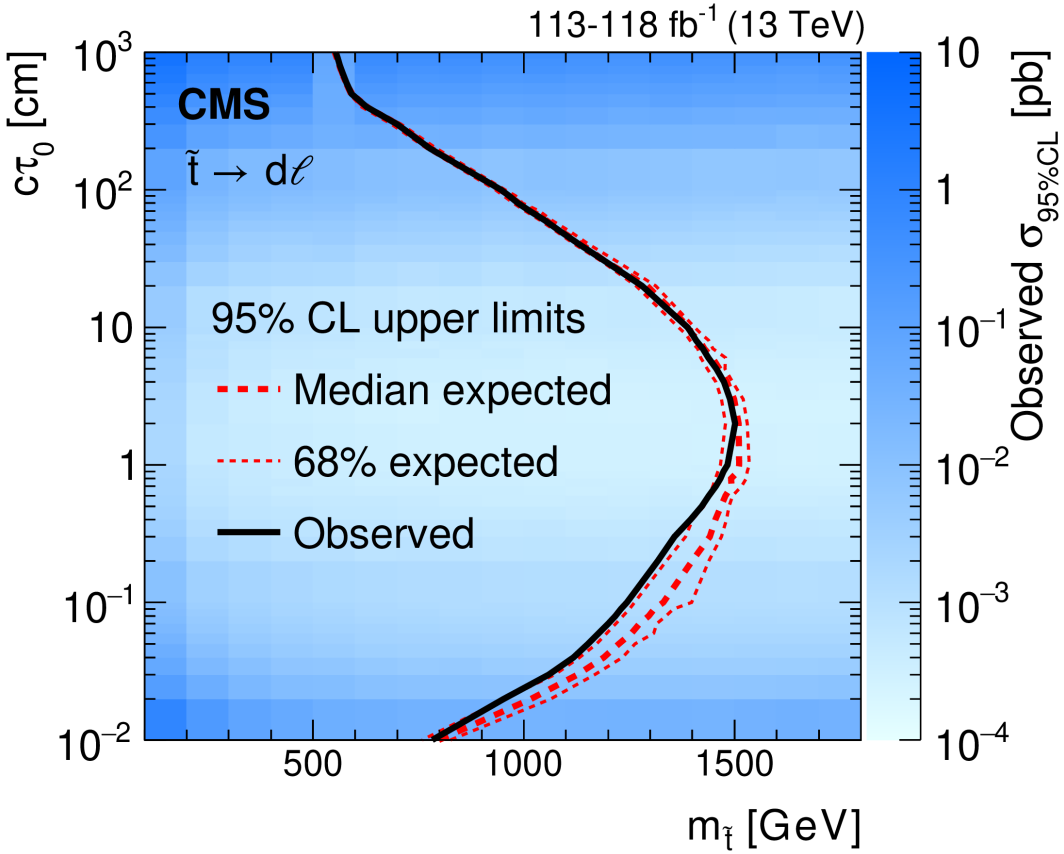
EXO-19-021



$\lambda_{X3X} \neq 0$

Displaced leptons (no vertex required)

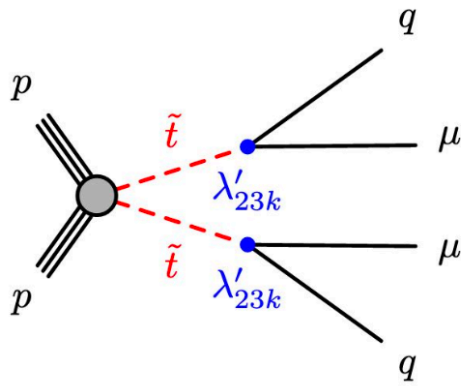
EXO-18-003



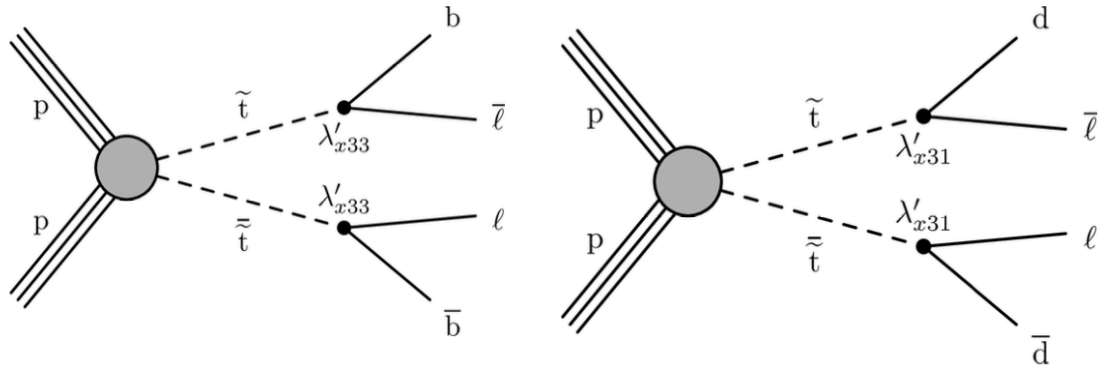
RPV SUSY

- In general, different benchmark RPV SUSY interpretations in LLP searches
- Need a more systematic approach to facilitate comparisons across the experiments

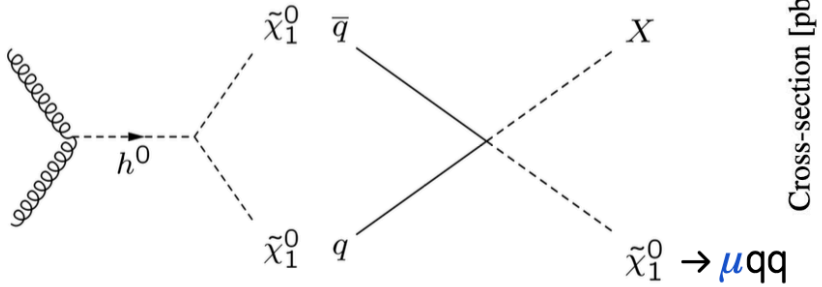
Phys. Rev. D 102, 032006 (2020) (ATLAS)

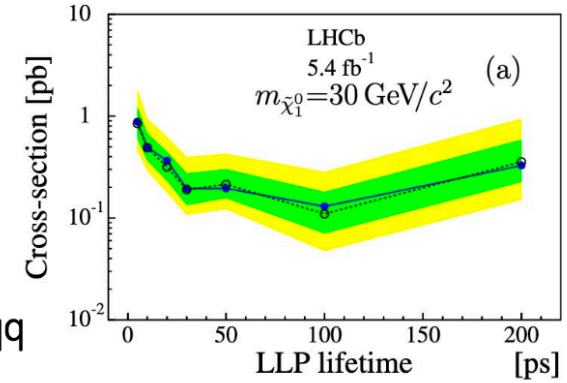


Phys. Rev. D 104, 012015 (2021) and Eur. Phys. J. C 82 (2022) 153 (CMS)

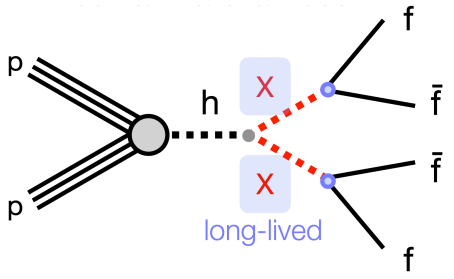


and 2110.07293 (LHCb)



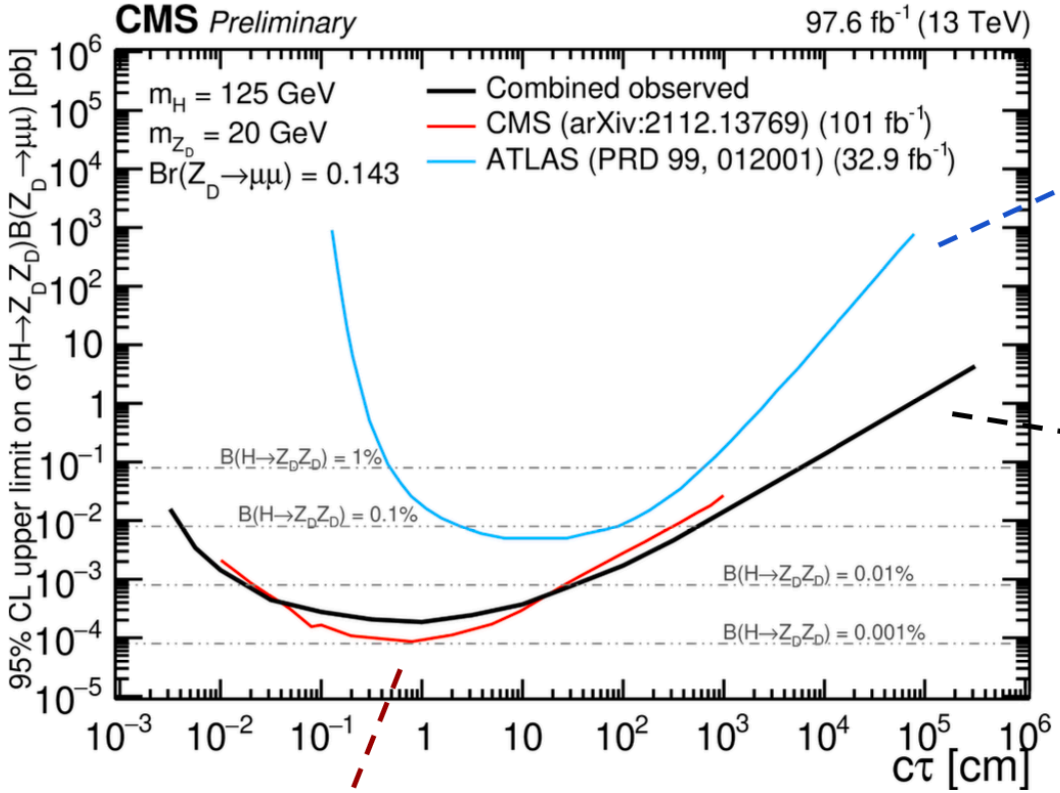


(Exotic) Higgs and Dark Photons



H→XX: Non-Hadronic

Displaced Dimuons Vertex



$\mu\mu$ in Tracker (101 fb^{-1}, CMS Scouting data) JHEP 04 (2022) 062 (CMS)

Strong constraints for $c\tau$ ~ tracker

- Limited to dimuon vertices within pixel tracker

$\mu\mu$ in Muon System (32.9 fb^{-1})

Search sensitive to $c\tau \gtrsim 0.1$ cm

- Limited to small $\Delta R_{\mu\mu}$ (due to trigger)

Phys. Rev. D 99, 012001 (2019) (ATLAS)

$\mu\mu$ Tracker+Muon System (97 fb^{-1})

Wide range of $c\tau$ from μm to km

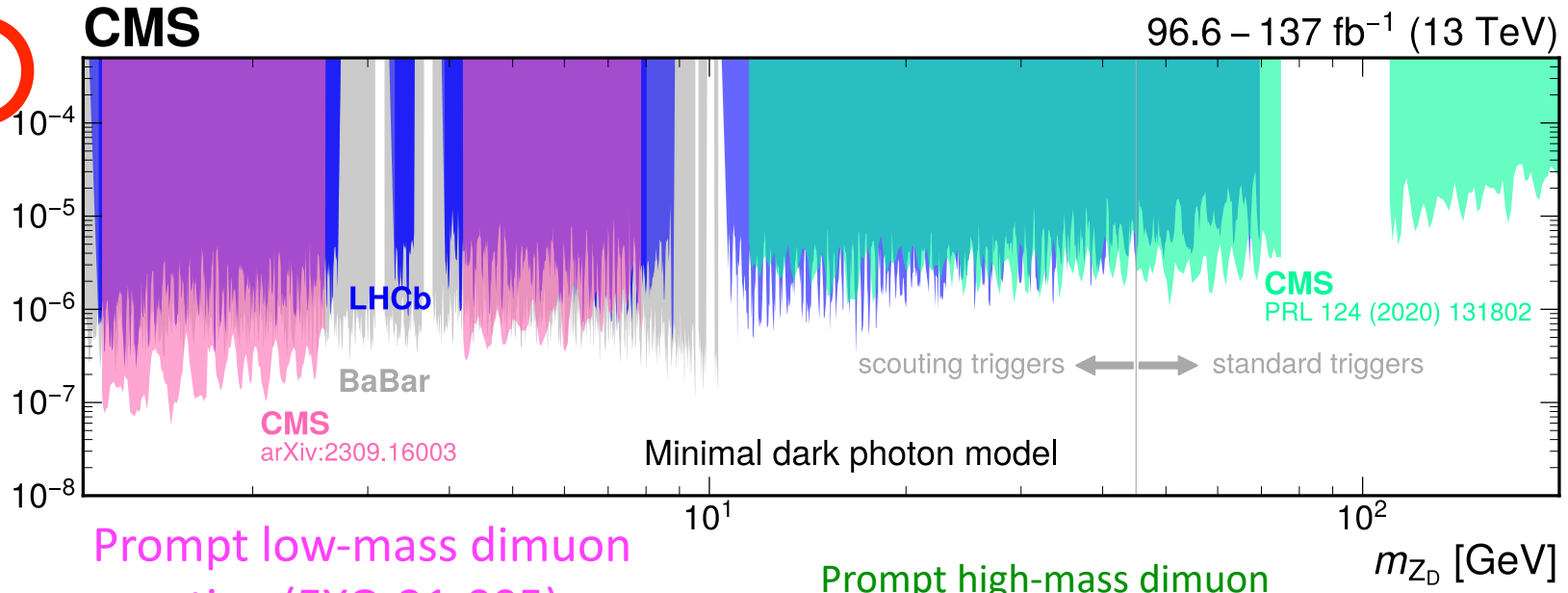
- Limited by trigger efficiency

2205.08582 (CMS)

No analogous result (common vertex) for X → ll (l=e or τ_{had}) at 13 TeV

In all cases, room for improvement with improved lepton triggers

Dark Photons to Dimuons: CMS

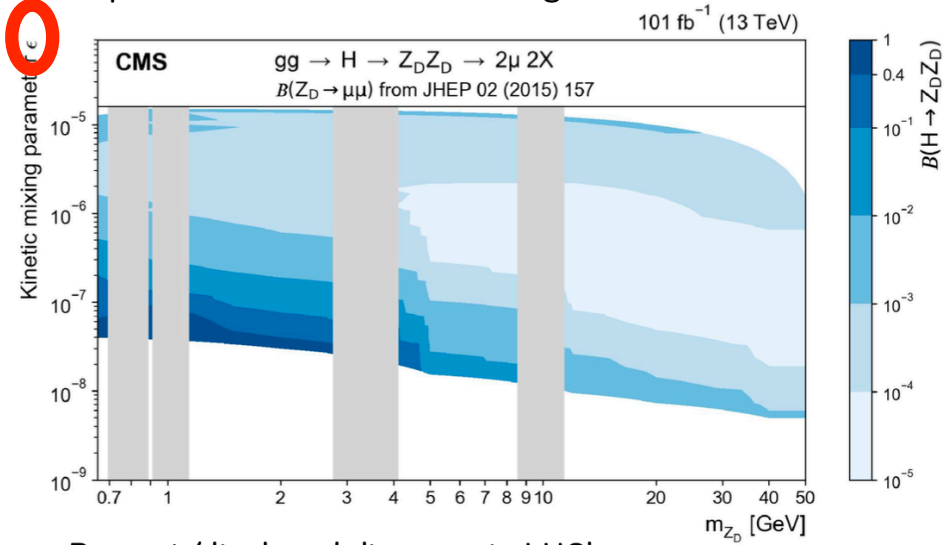


Prompt low-mass dimuon scouting (EXO-21-005)

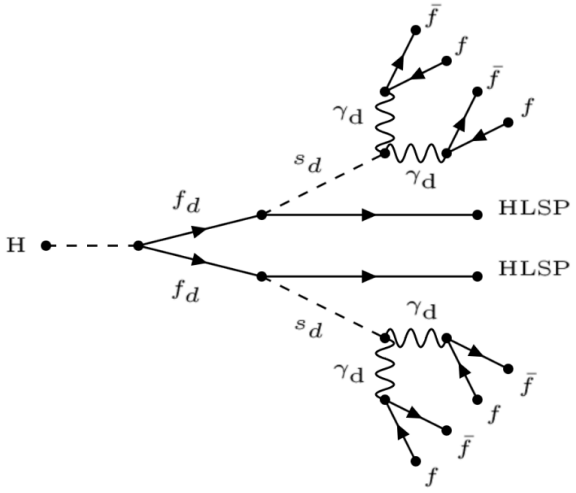
Prompt high-mass dimuon standard + scouting (EXO-19-018)

- Would be easier to interpret if on the same plot and with the same model

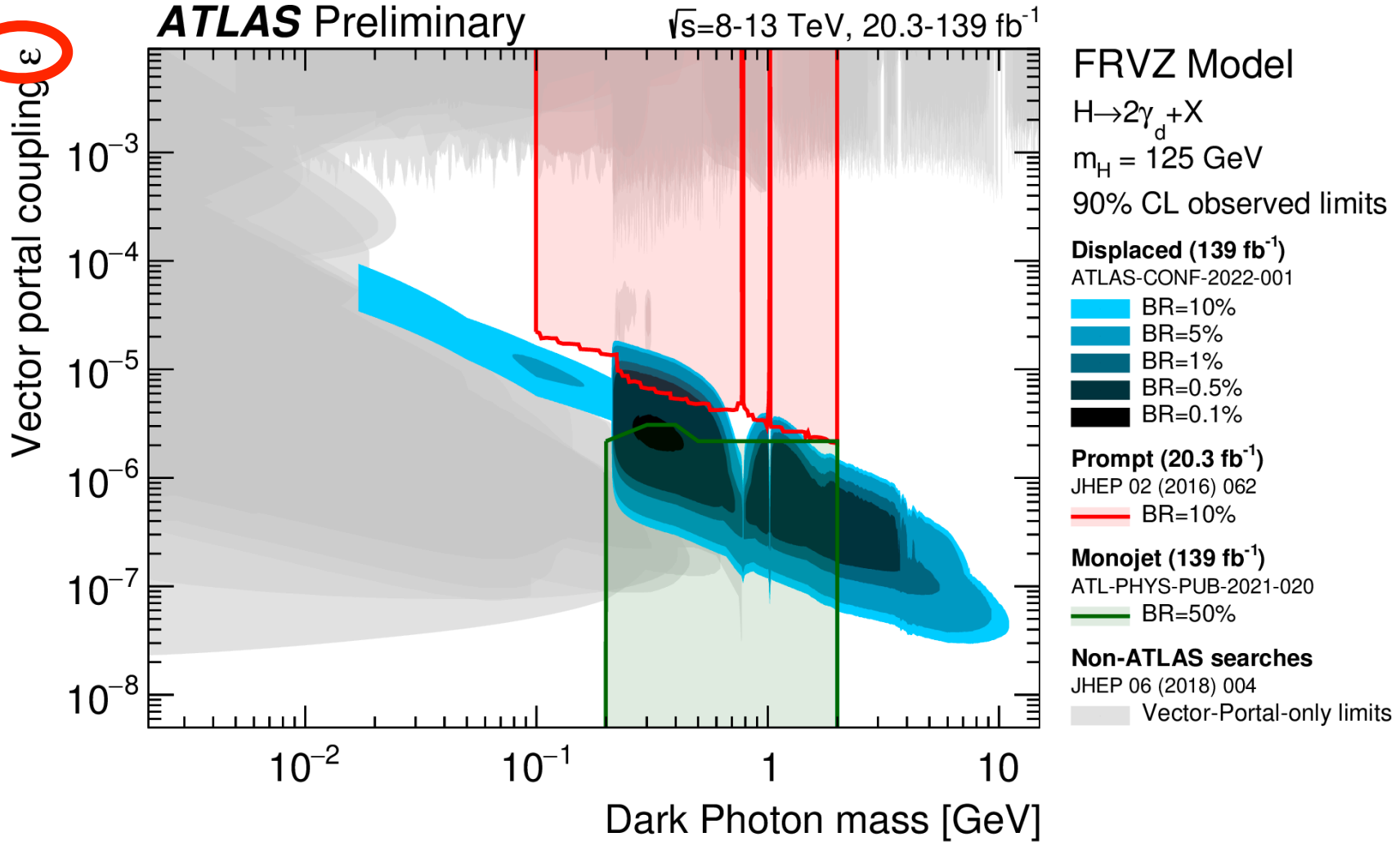
Displaced dimuons with Scouting JHEP 04 (2022) 062 (CMS)



Dark Photons: ATLAS

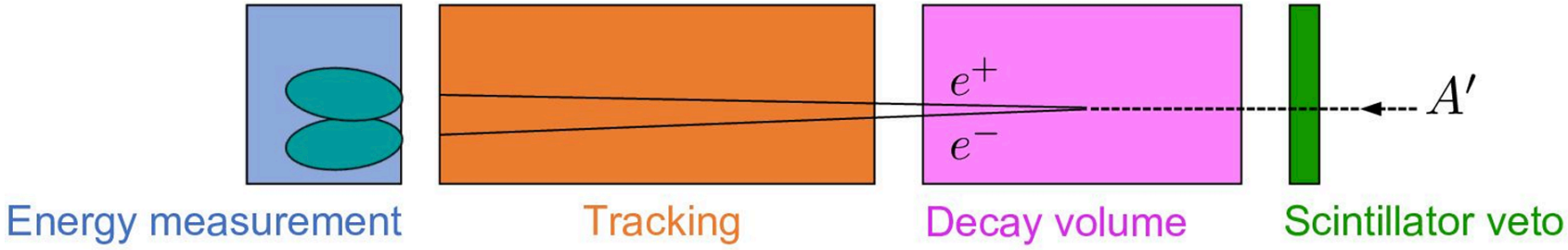


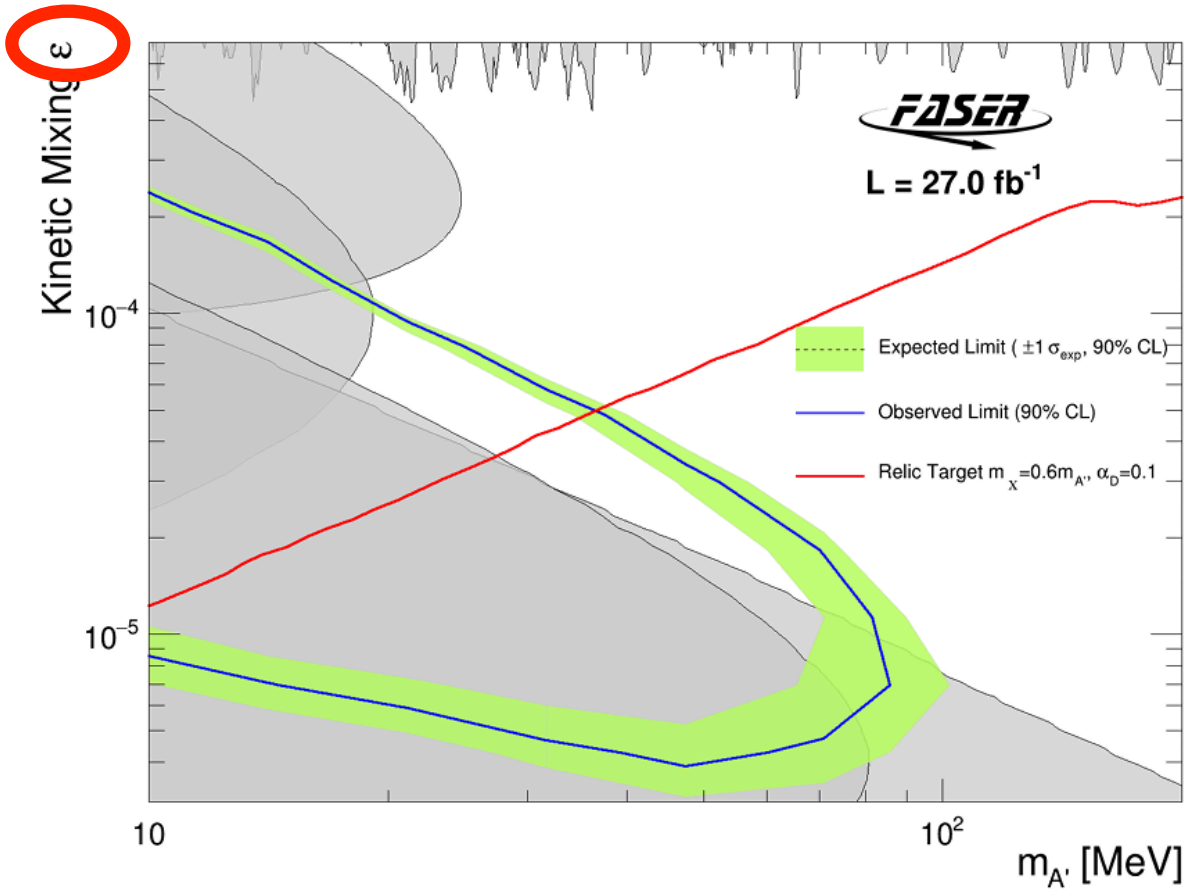
- ATLAS has used lepton jets and other signatures to explore these types of models
- Signature: high multiplicity of collimated displaced leptons
- CMS hasn't probed this signature exactly



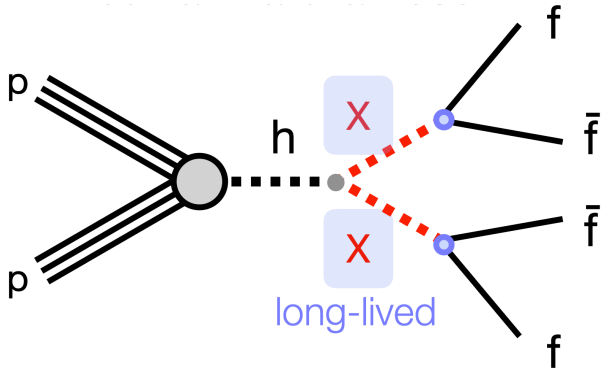
Dark Photons: FASER

arXiv:2308.05587

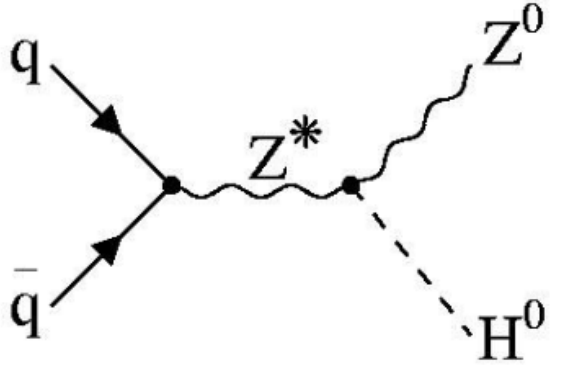


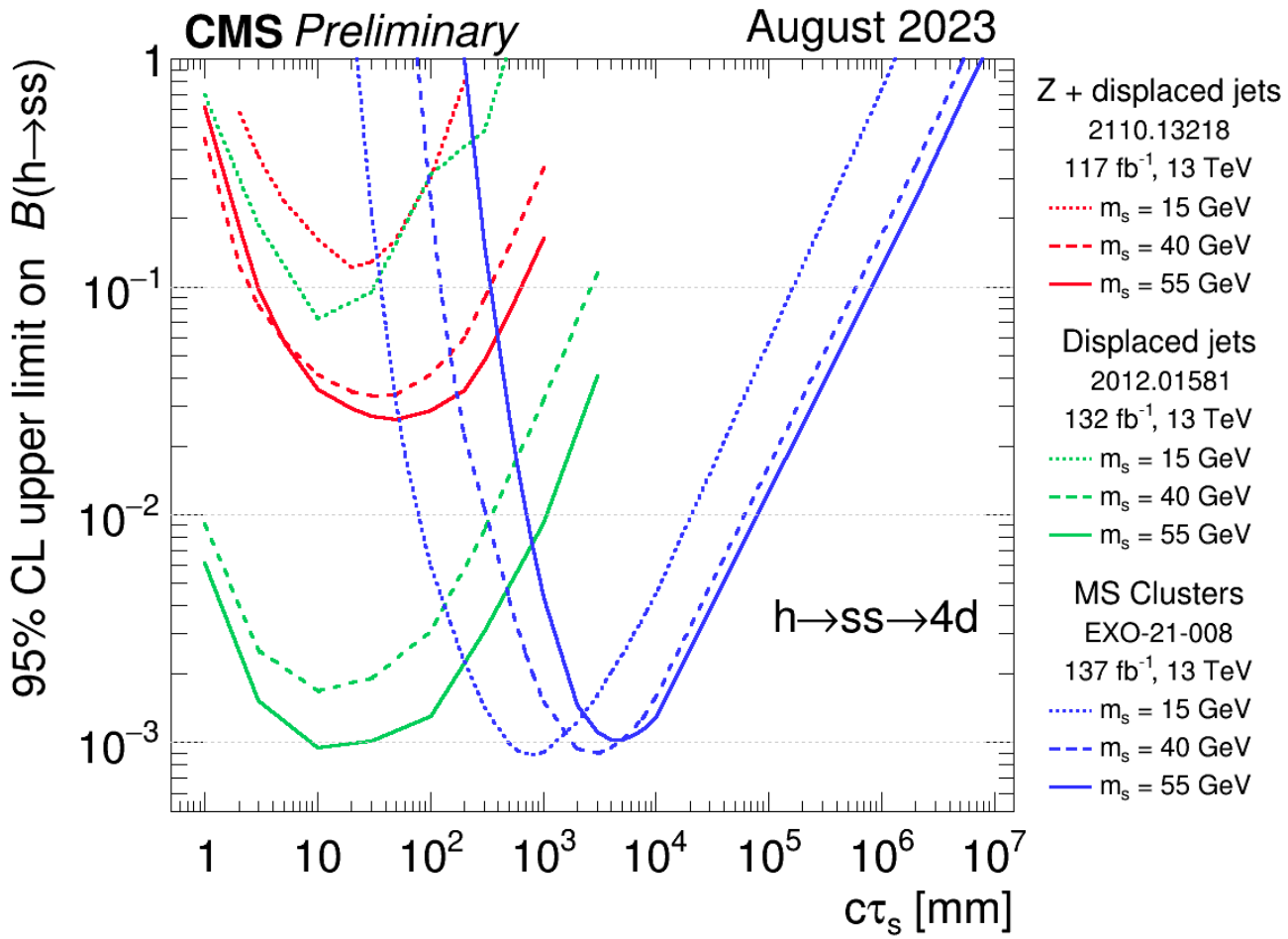


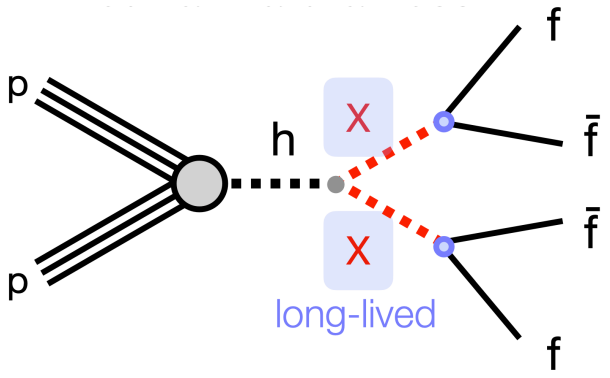
Probing region relevant for thermal relic target & region uncovered by the recent NA62 result



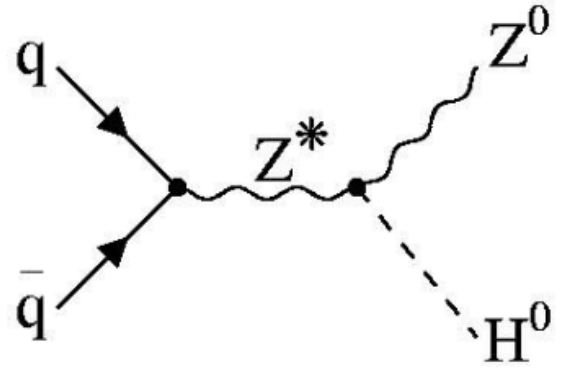
H→XX: Hadronic



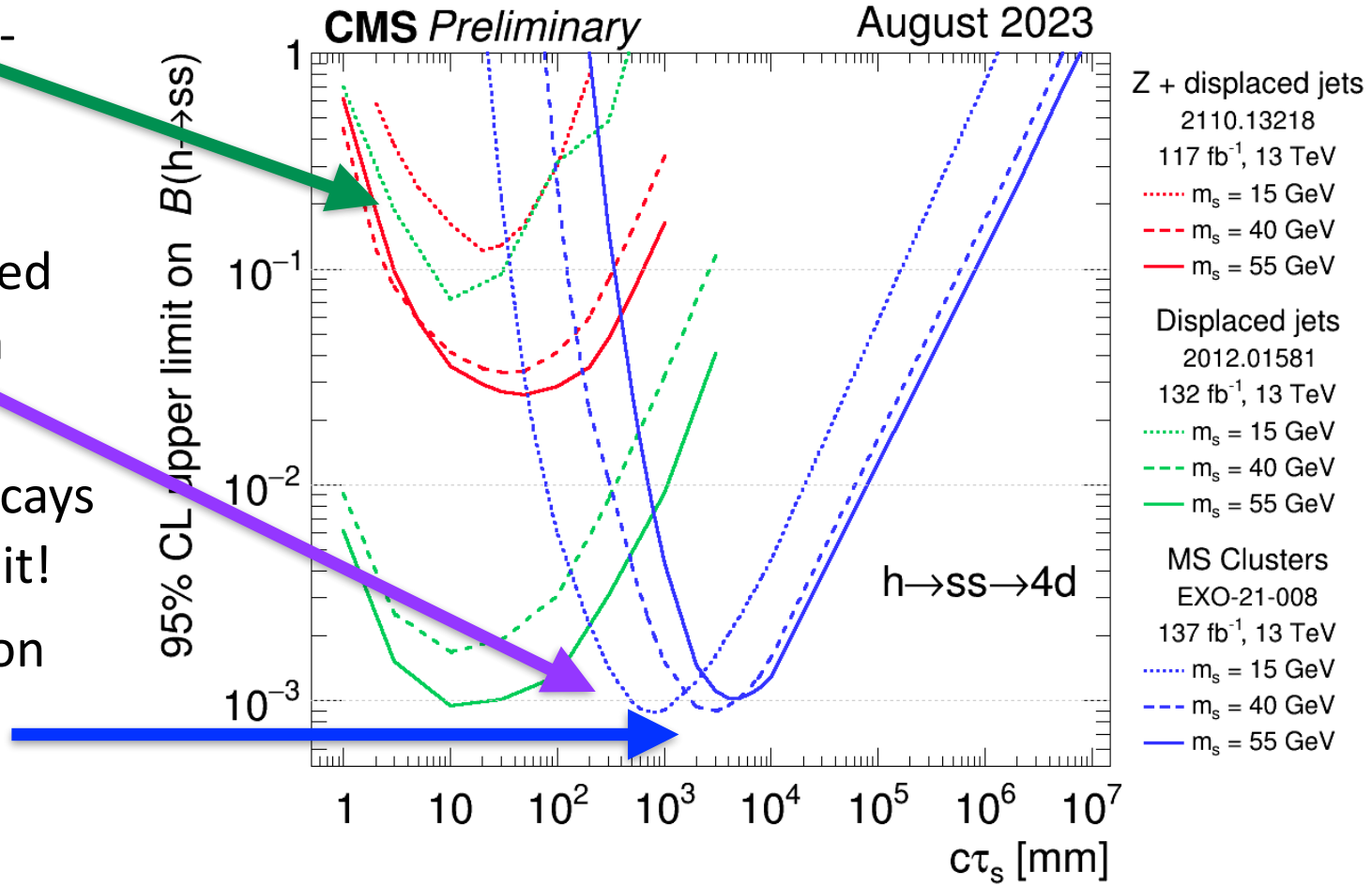


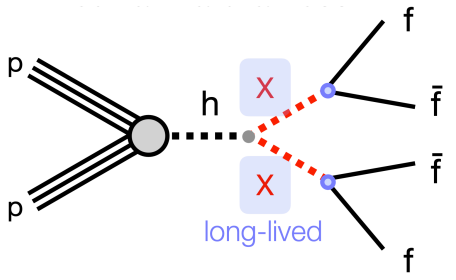


H→XX: Hadronic

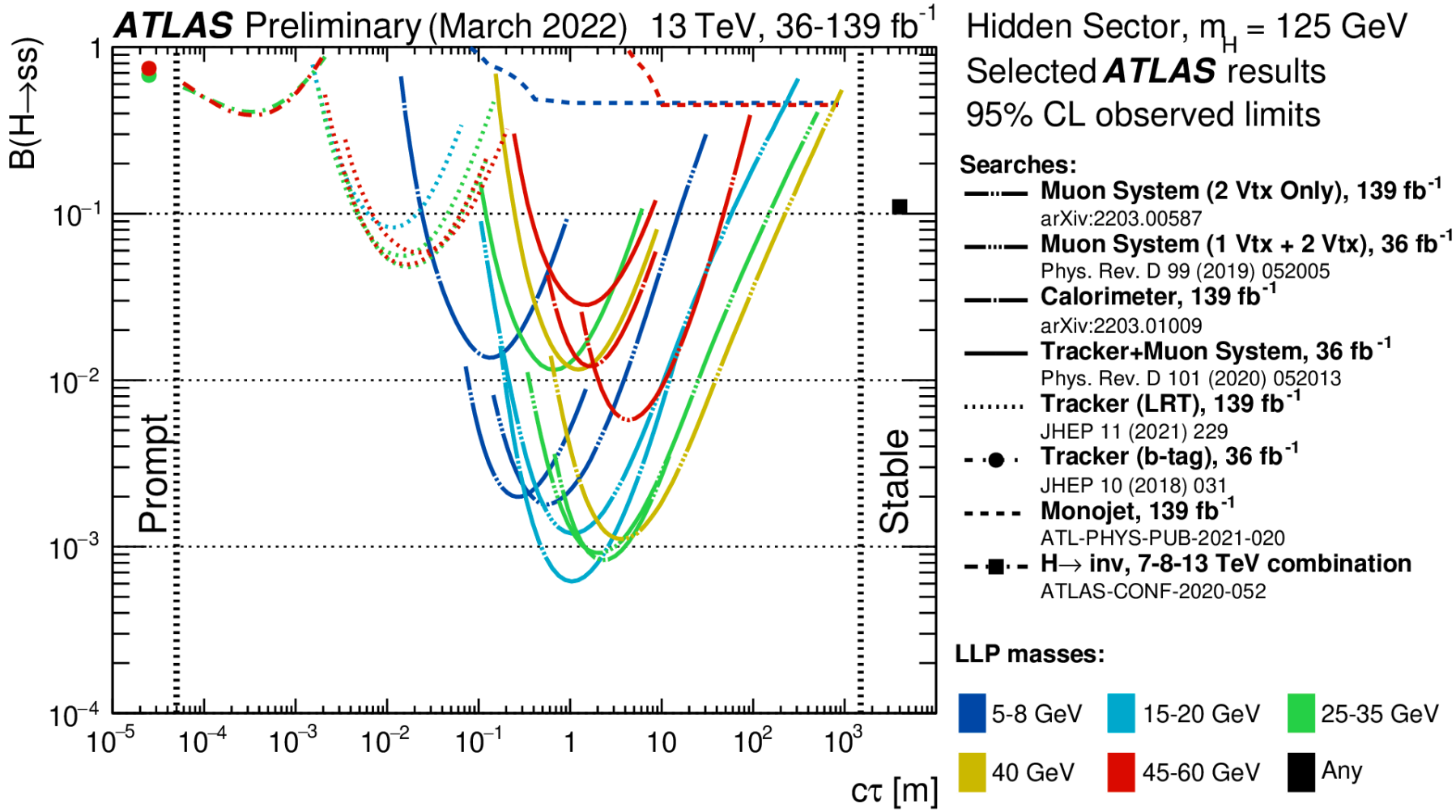


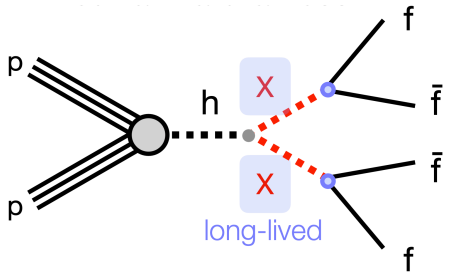
- Room for improvement with tracker-based searches at low mass
  - Wait for it!
- Lifetimes between what tracker-based searches can access and what muon system searches can access:
  - Could be helped by targeting decays in the calorimeters —> Wait for it!
- High multiplicity showers in the muon systems help CMS access longer lifetimes



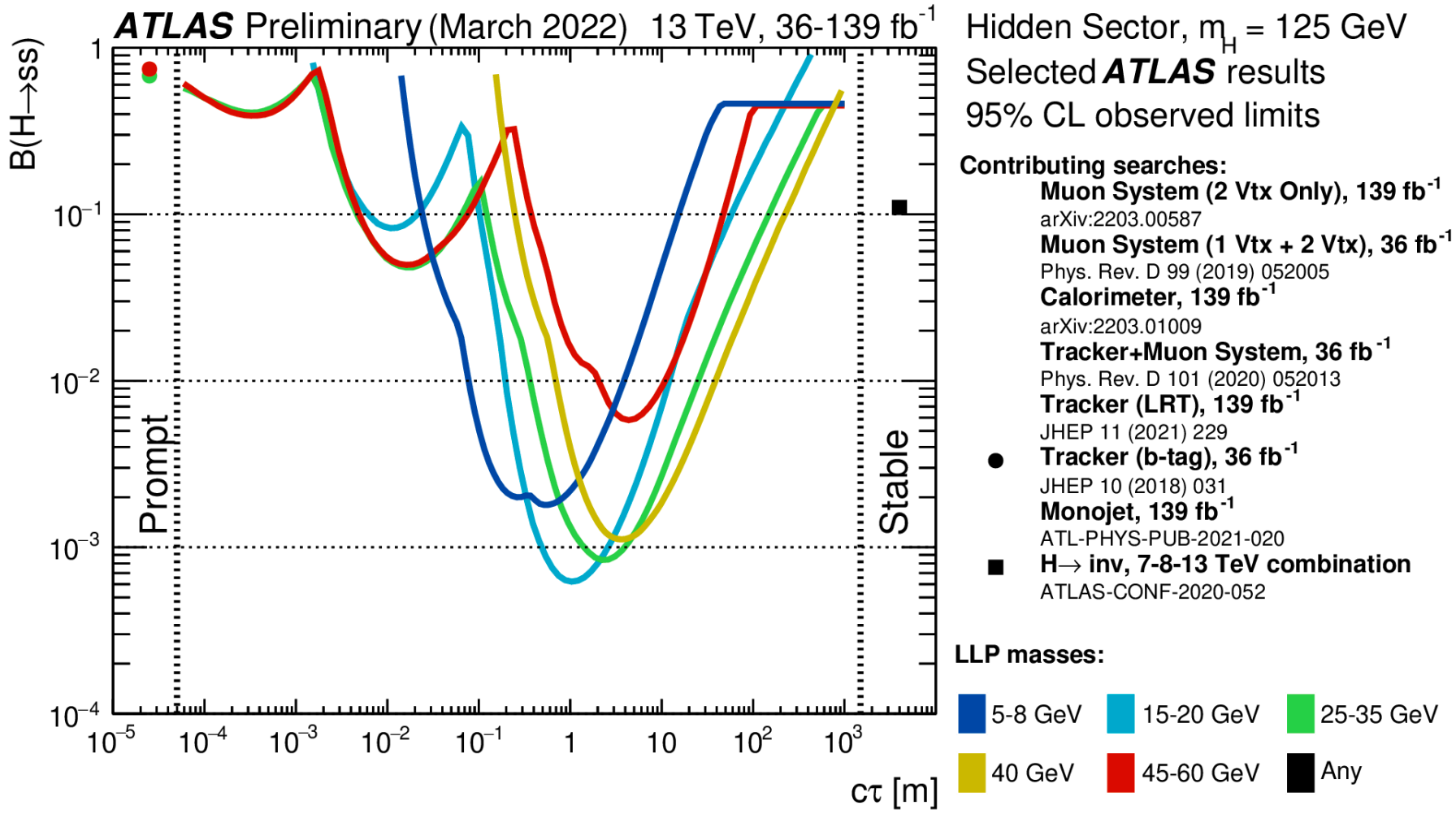


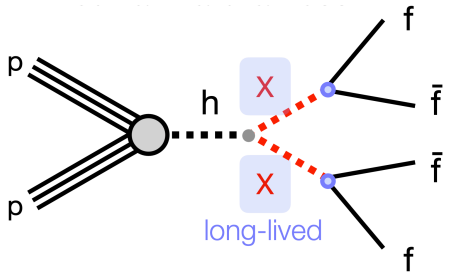
H→XX: Putting it All Together





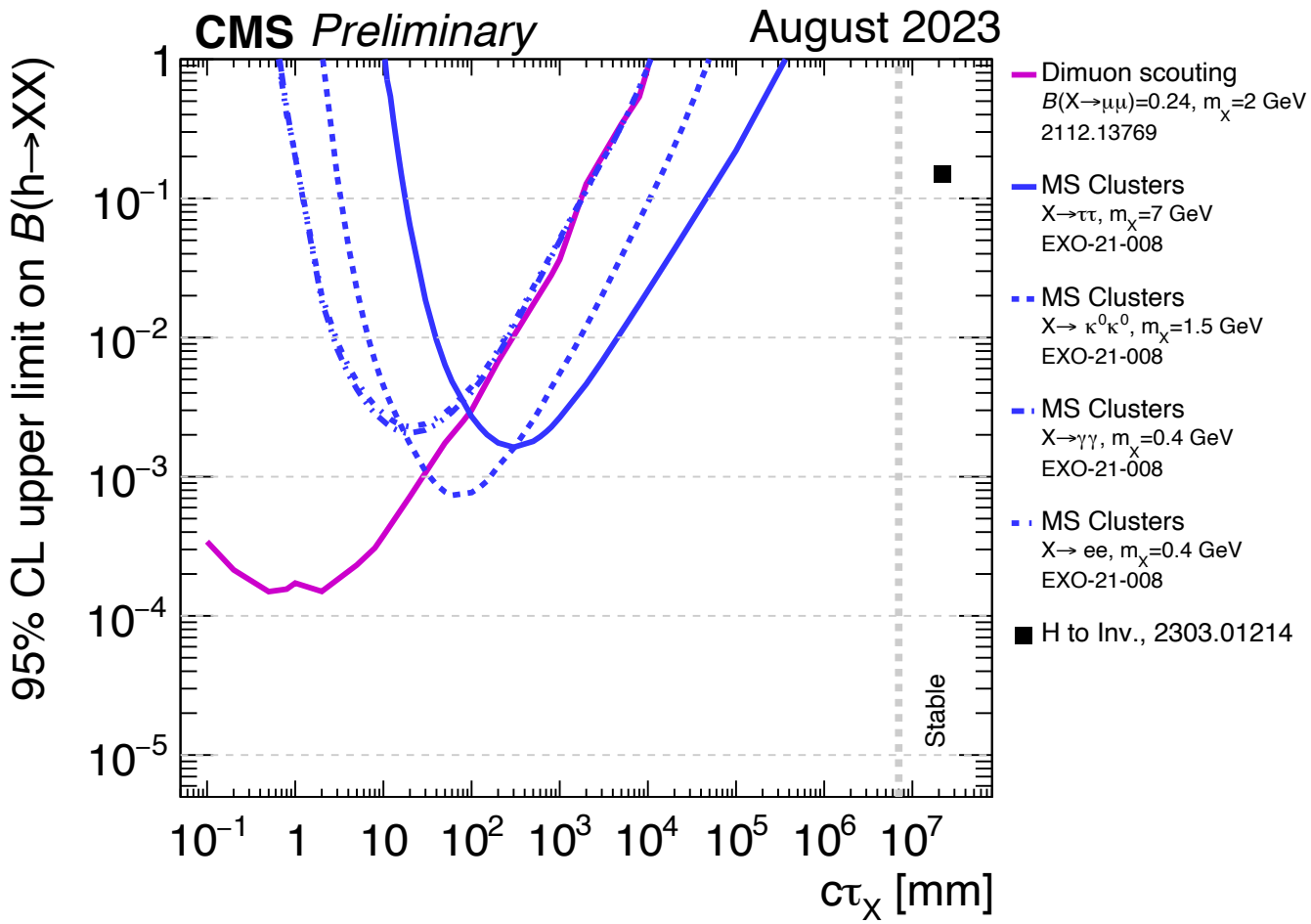
H→XX: Putting it All Together





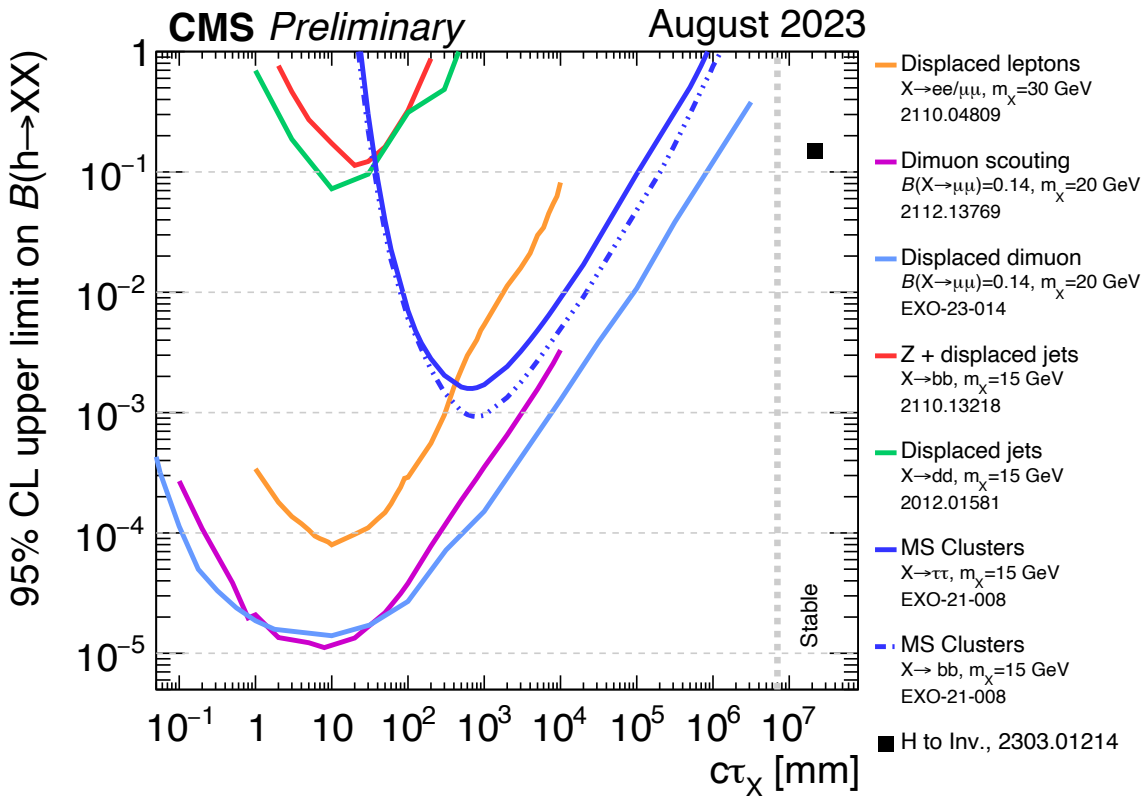
H→XX: Putting it All Together

$0.4 < m_X < 2$ GeV

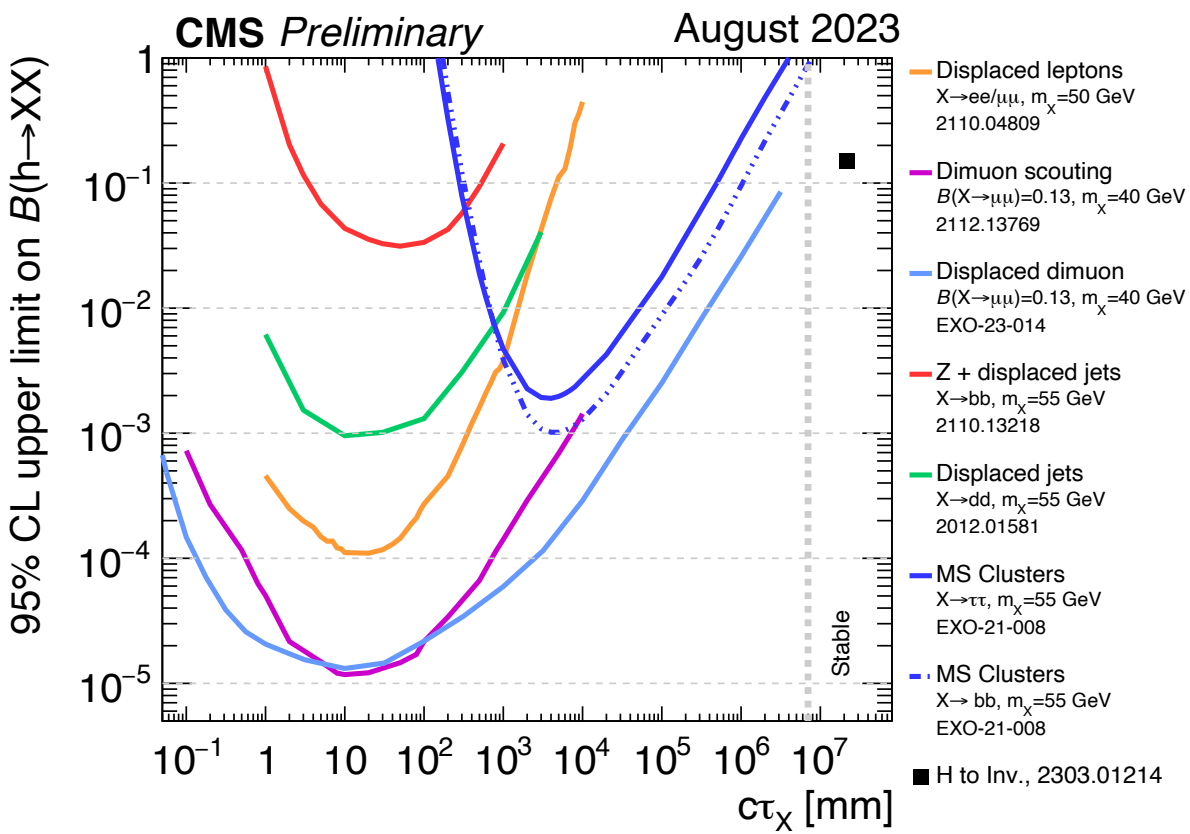


H→XX

5 < m_X < 30 GeV

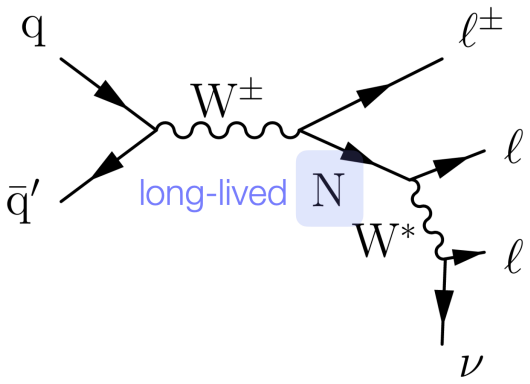


40 < m_X < 55 GeV

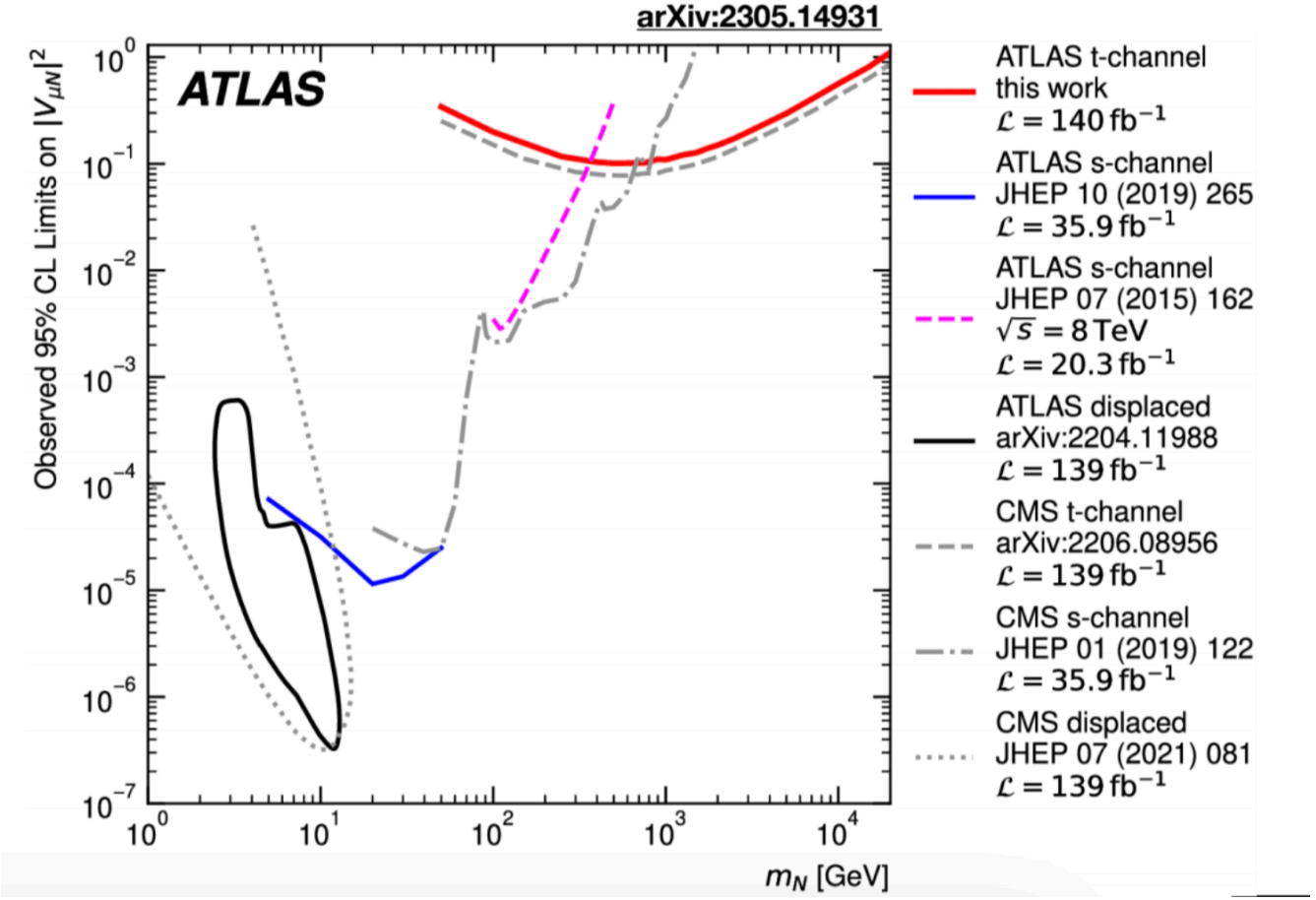


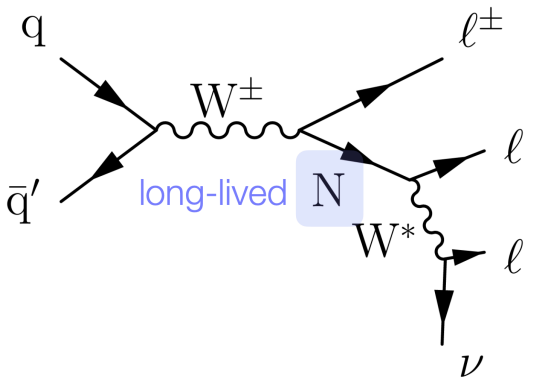
- If B(X → qq) ~ B(X → ll), non-hadronic searches set stronger constraints than hadronic searches (depending on B(X))
- But B(X → qq) >> B(X → ll) often in BSM models → **complementarity and coverage is the key**

Heavy Neutral Leptons

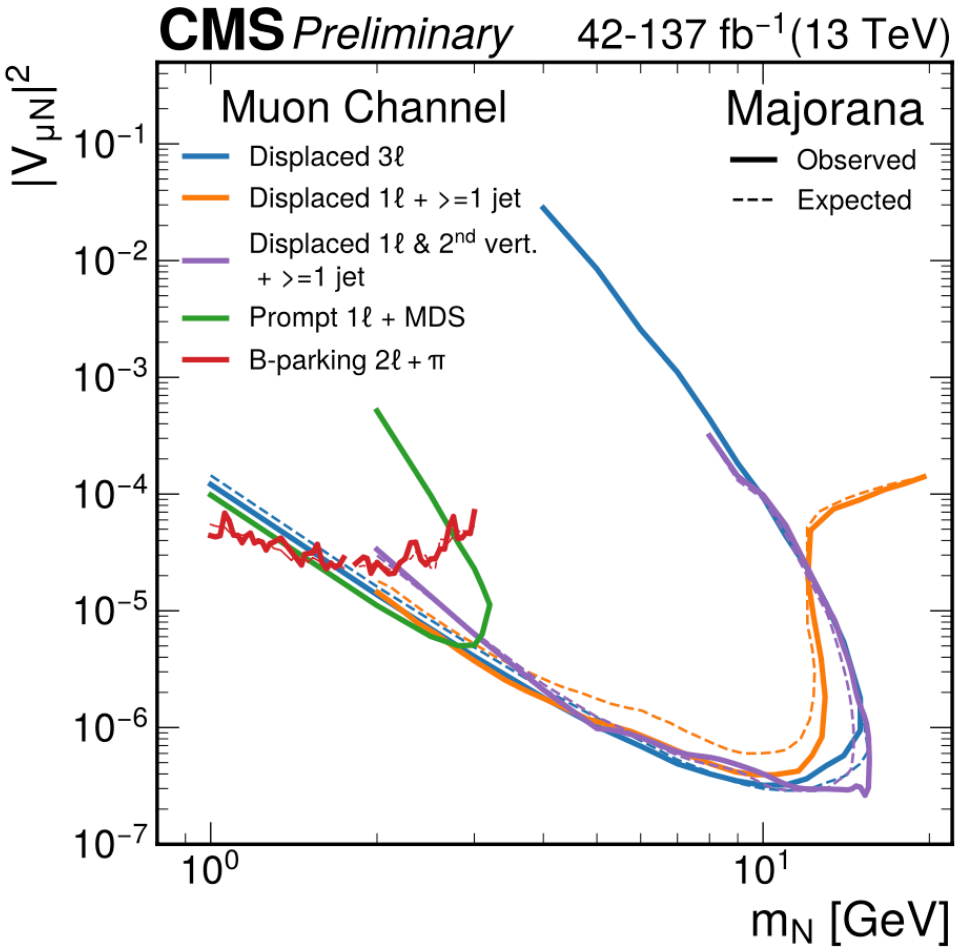


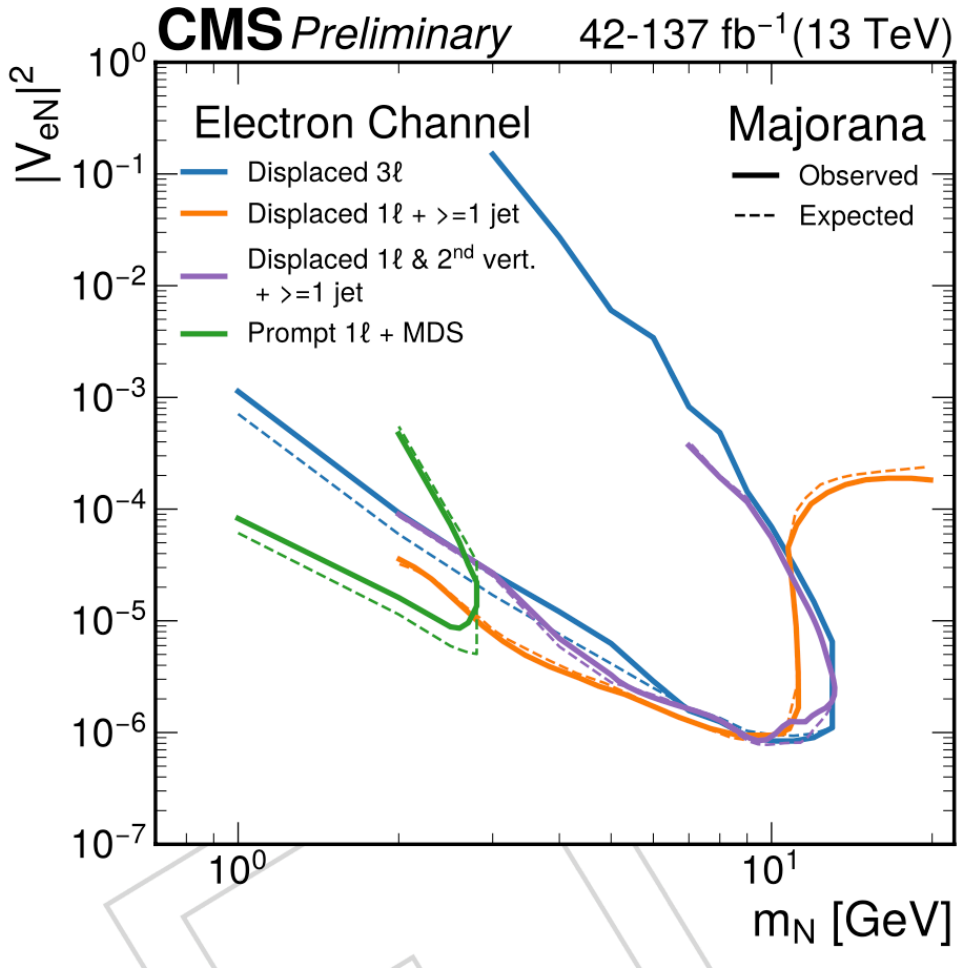
Heavy Neutral Leptons



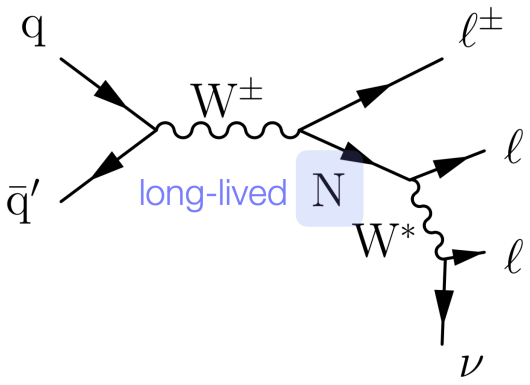


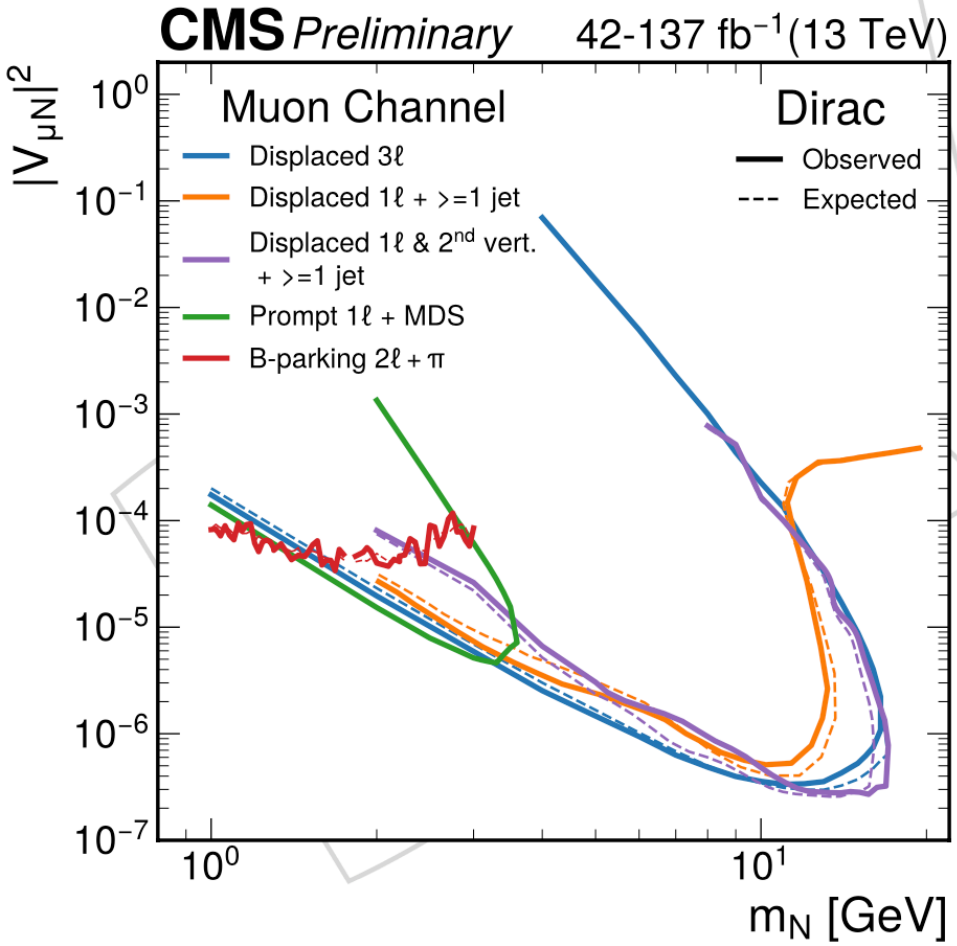
Heavy Neutral Leptons

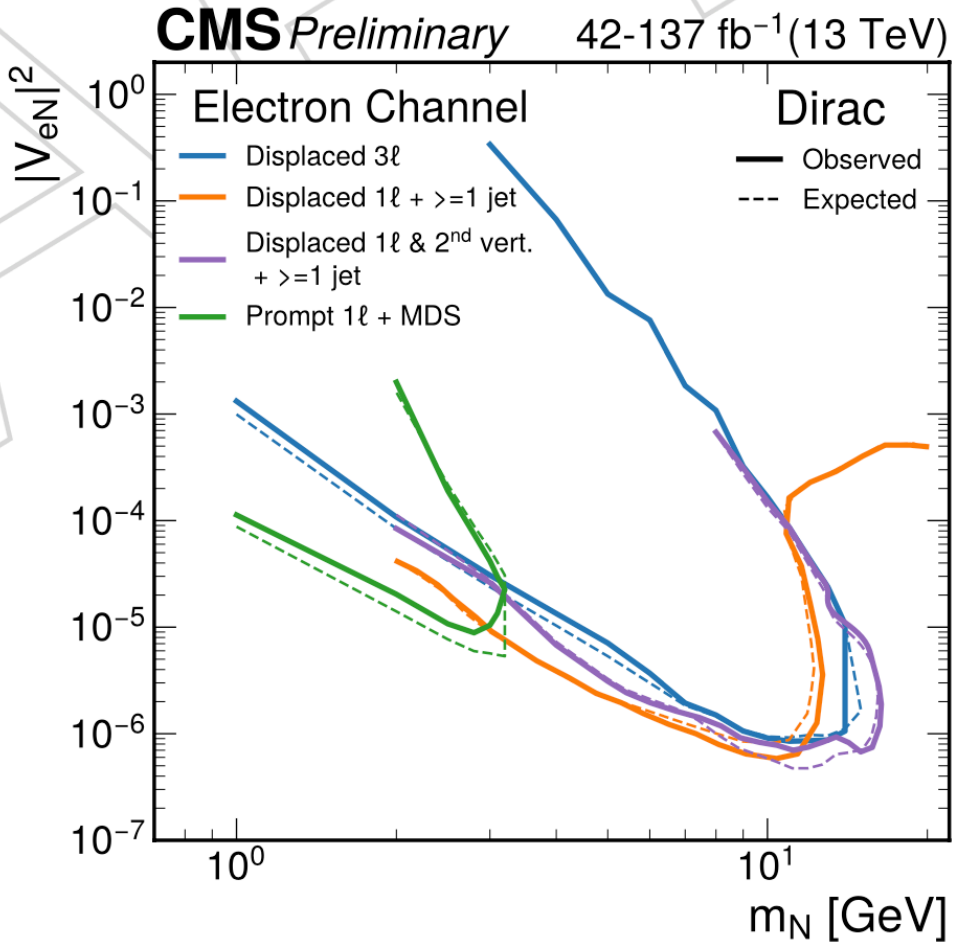




Heavy Neutral Leptons

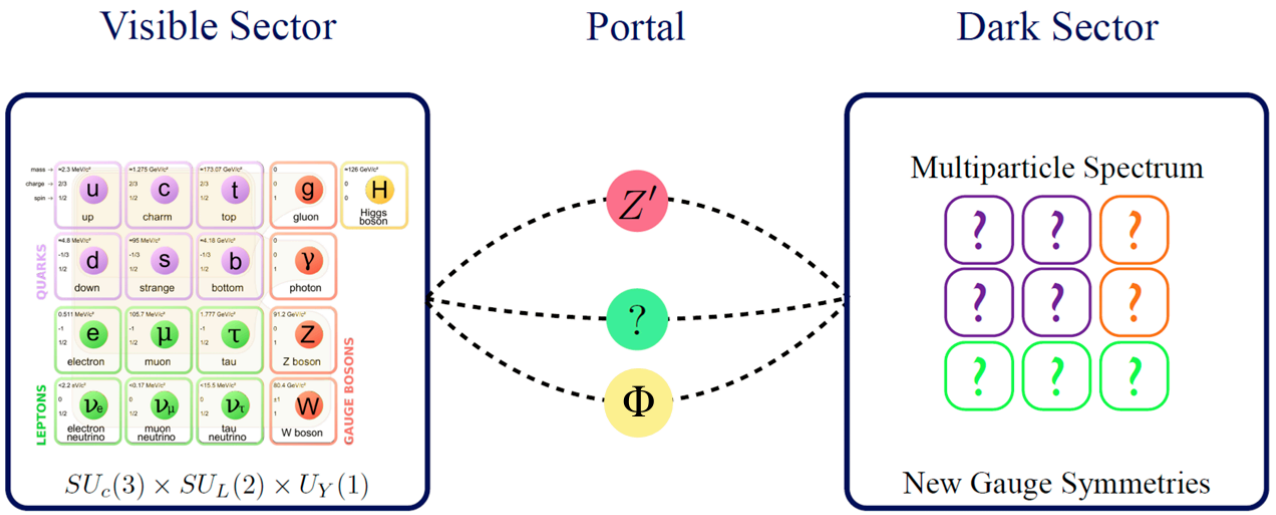






Hidden Valleys, Dark QCD, Dark Showers

Hidden Valleys

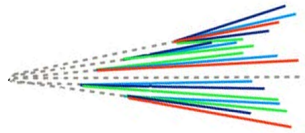


M. Lisanti

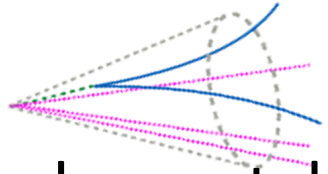
- Complex dark sector w/ new force from non-Abelian gauge group
- No prior expectation for N_c^{dark} (group dimension) or N_f^{dark} (matter fields)
- Behavior can be QCD-like ($m_\chi \lesssim \Lambda_{dark}$), but other phenomena also possible

Dark QCD, Dark Showers

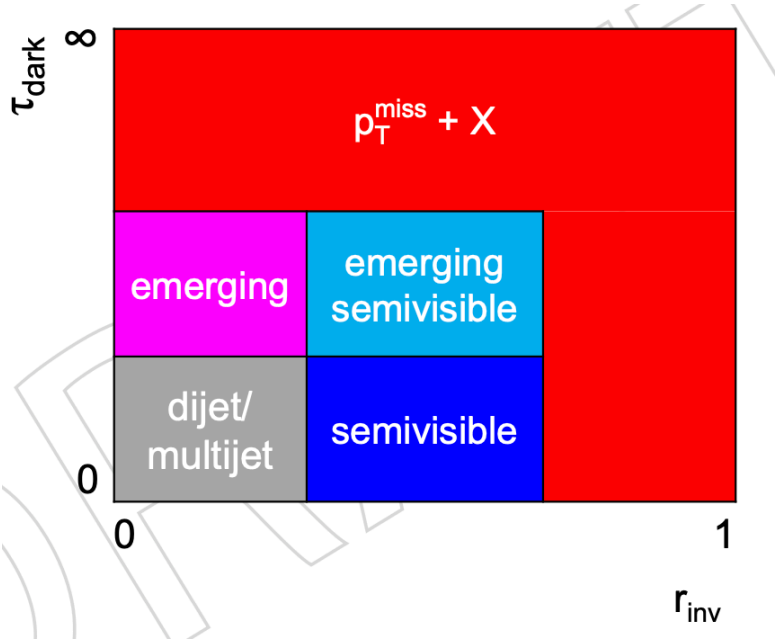
- **Dark shower:**
  - Confinement and hadronization in the dark sector result in a spray of composite hidden sector states, dark hadrons
- **Many pheno scenarios possible, including:**
  - **Emerging jets**



    - Dark hadrons have decay length $c\tau_{dark}$
    - Multiple displaced vertices within a single jet
  - **Semivisible jets**

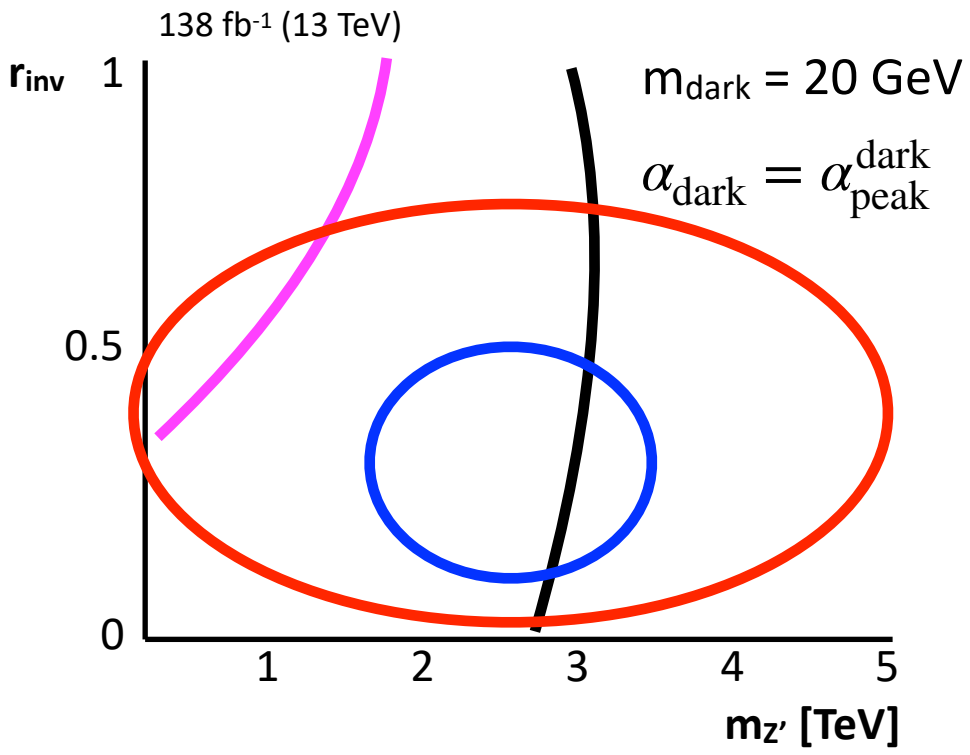


    - Some dark hadrons stable, others unstable and decay promptly
    - $r_{inv} = N_{stable} / (N_{stable} + N_{unstable})$

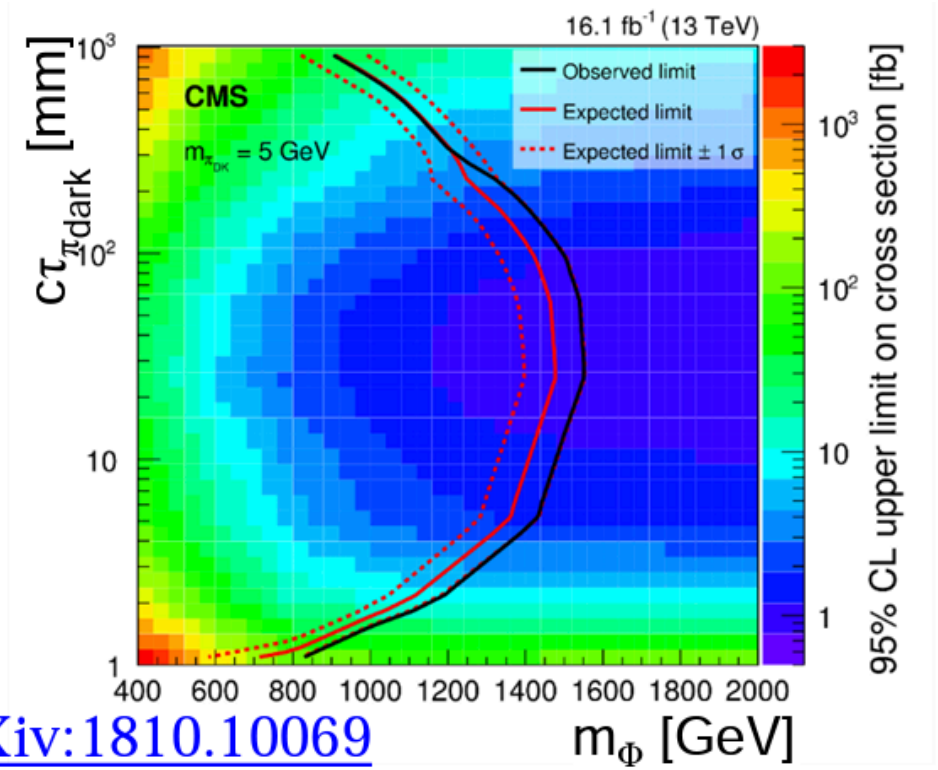


Dark QCD

Sketch of plot that will be coming from **CMS** soon:



CMS emerging jets



arXiv:1810.10069

High mass dijet resonances (EXO-19-012)

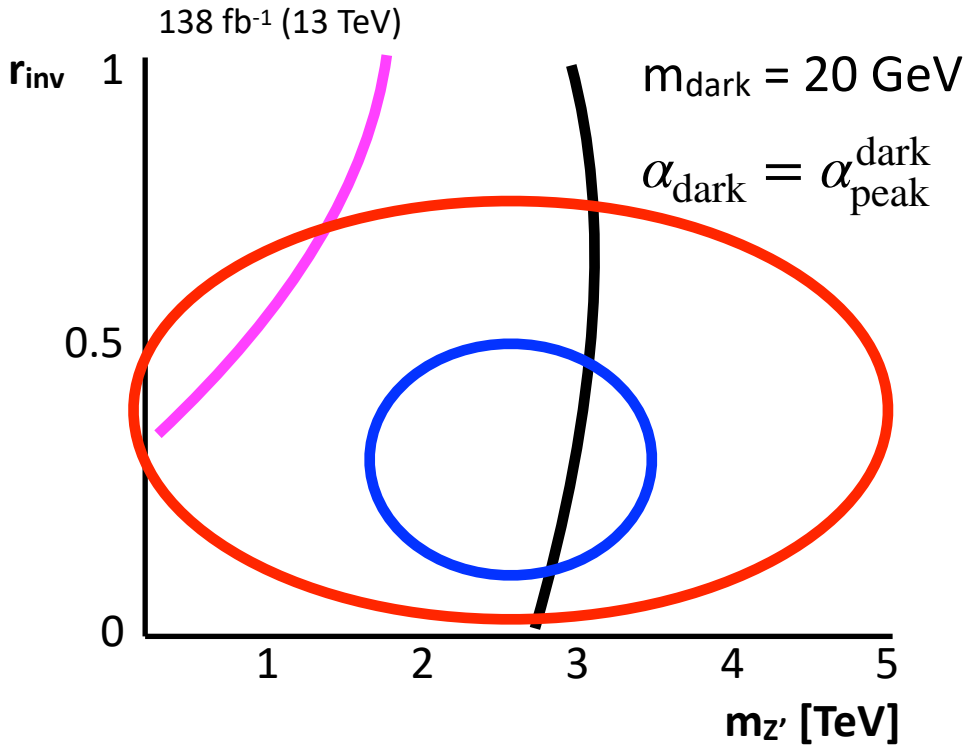
Monojet and mono-V(had) (EXO-20-004)

Semivisible jets (cut-based, EXO-19-020)

Semivisible jets (BDT-based, model-dependent, EXO-19-020)

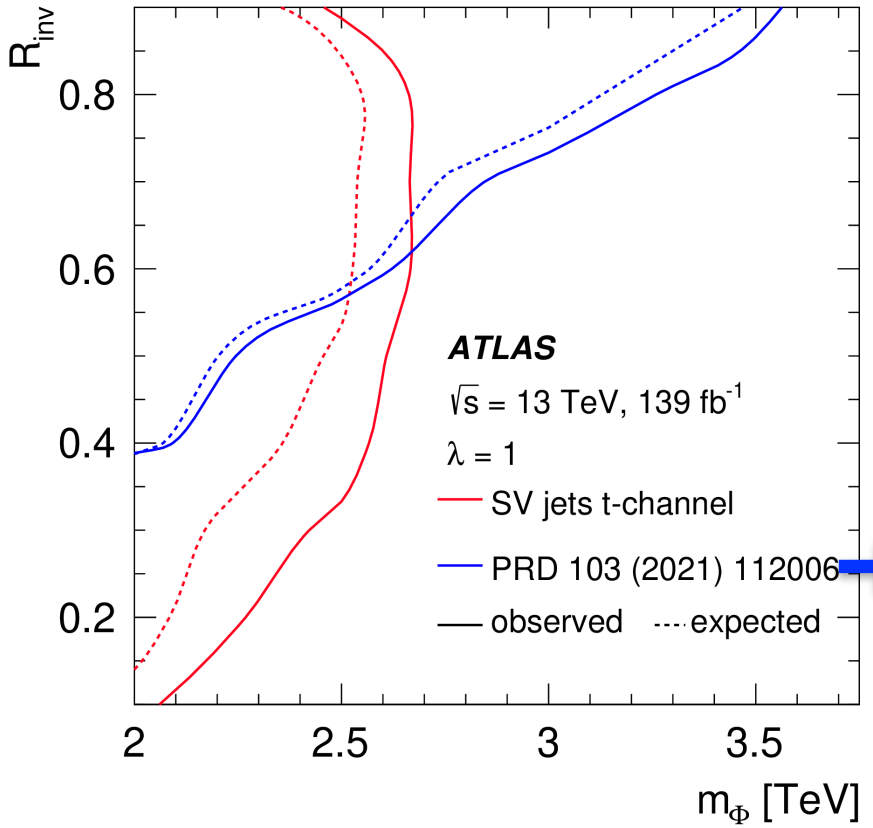
Dark QCD

Sketch of plot that will be coming from **CMS** soon:



ATLAS

EXOT-2022-37



→ Monojets

High mass dijet resonances (EXO-19-012)

Monojet and mono-V(had) (EXO-20-004)

Semivisible jets (cut-based, EXO-19-020)

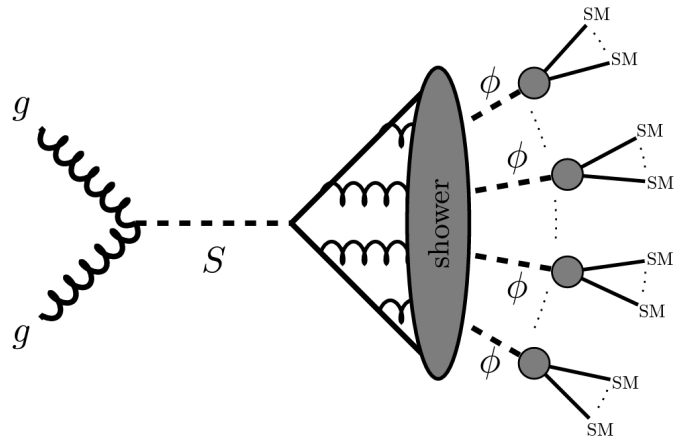
Semivisible jets (BDT-based, model-dependent, EXO-19-020)

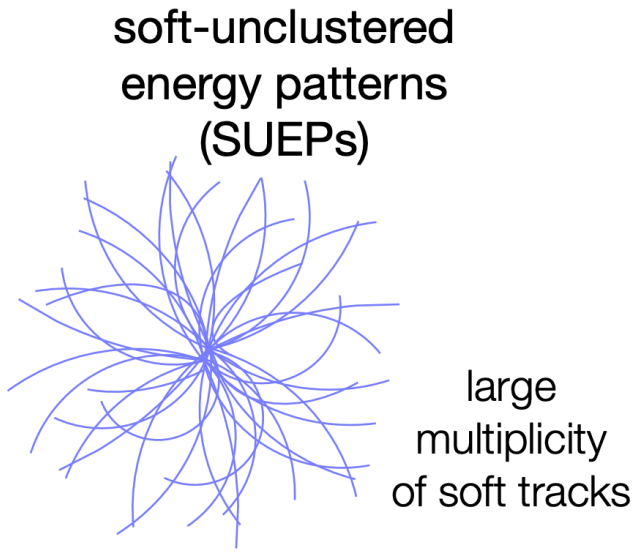
Dark QCD

- Some gaps:
  - Room for more dedicated searches with range of possible final states depending on mediator!
  - Only a small fraction of dark QCD scenarios probed at the LHC so far: more parameters to change —> different phenomenology

Beyond QCD-Like

- **Soft Unclustered Energy Patterns (SUEPs)**
  - Large $\lambda \equiv \alpha_{dark} N_c^{\ dark}$('t Hooft coupling): unsuppressed large angle radiation → wide, spherical showers
  - Search strategies: trigger on HT, use particle/ track multiplicity and event shape variables to reject background
  - *Results coming soon from CMS and ATLAS!*
- **Glueballs**
  - Hard to simulate…

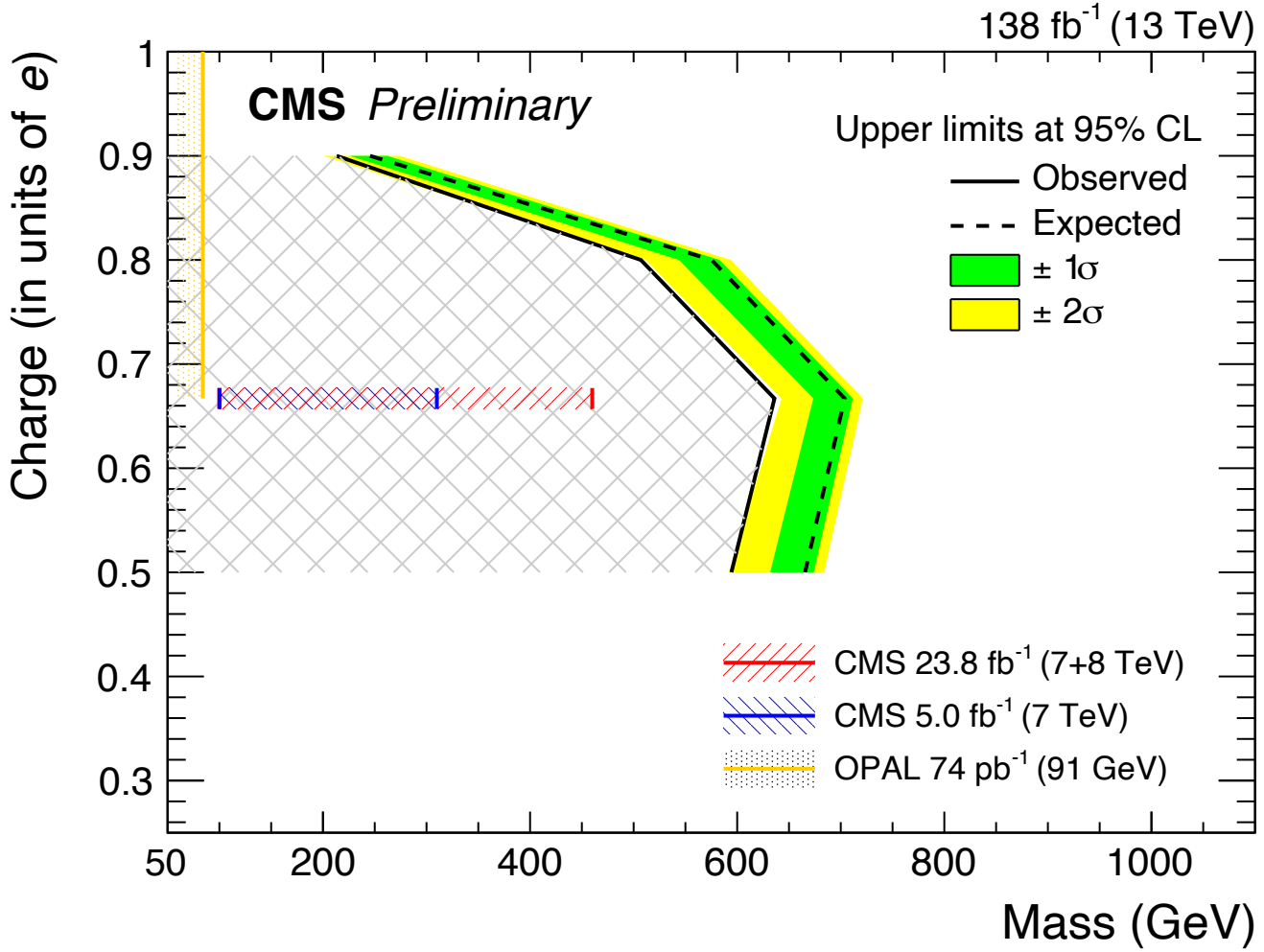




Fractional and Milli Charged Particles

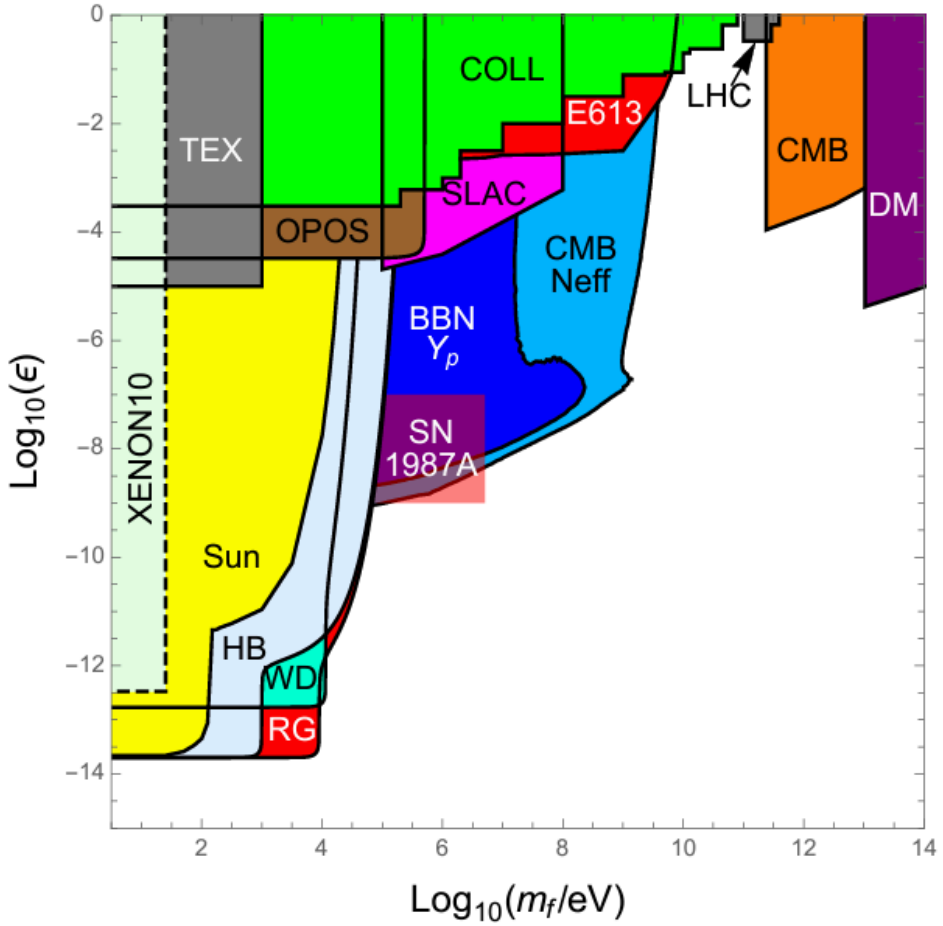
Fractional Charge

EXO-19-006

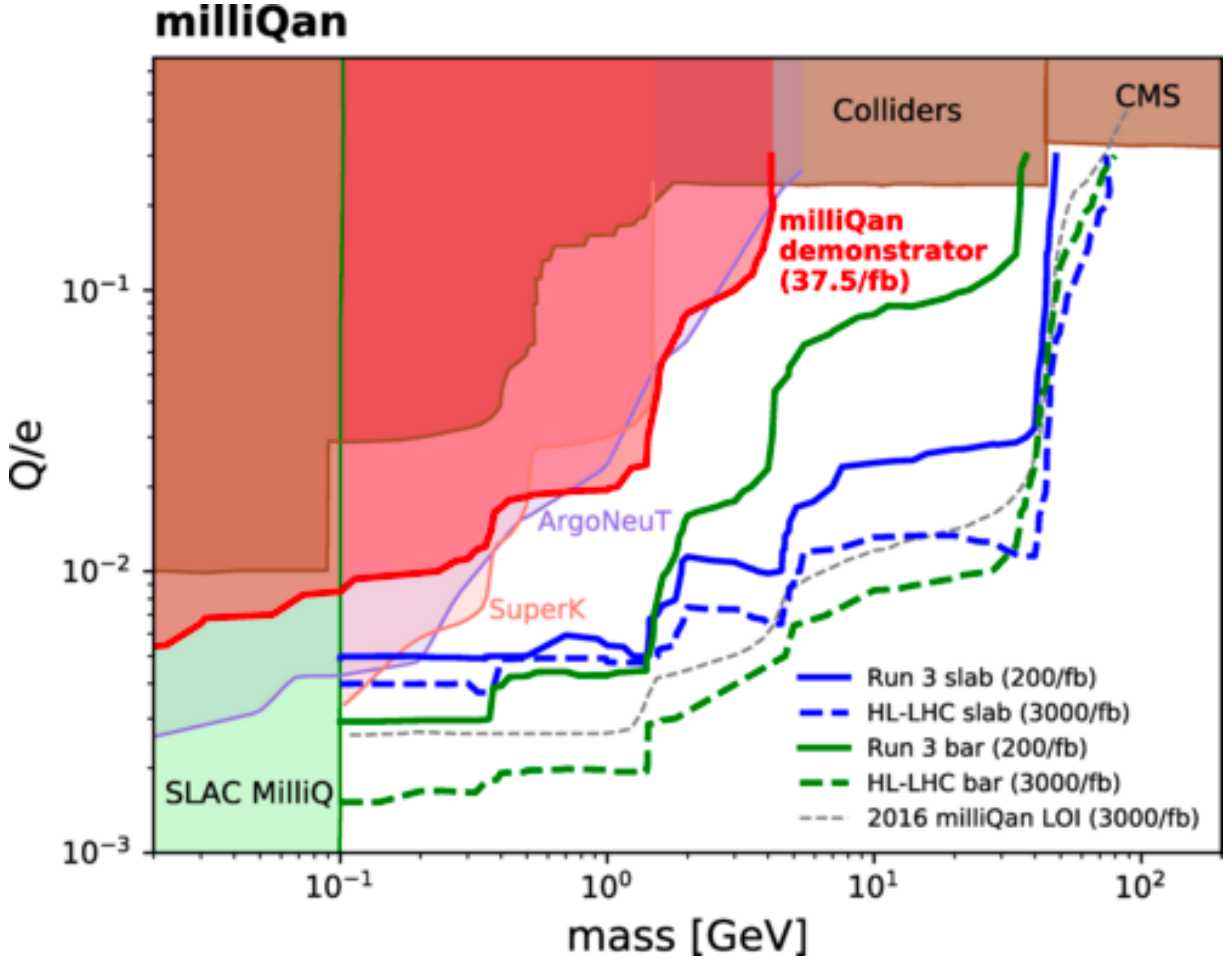


Milli Charge

arXiv:1511.01122v2

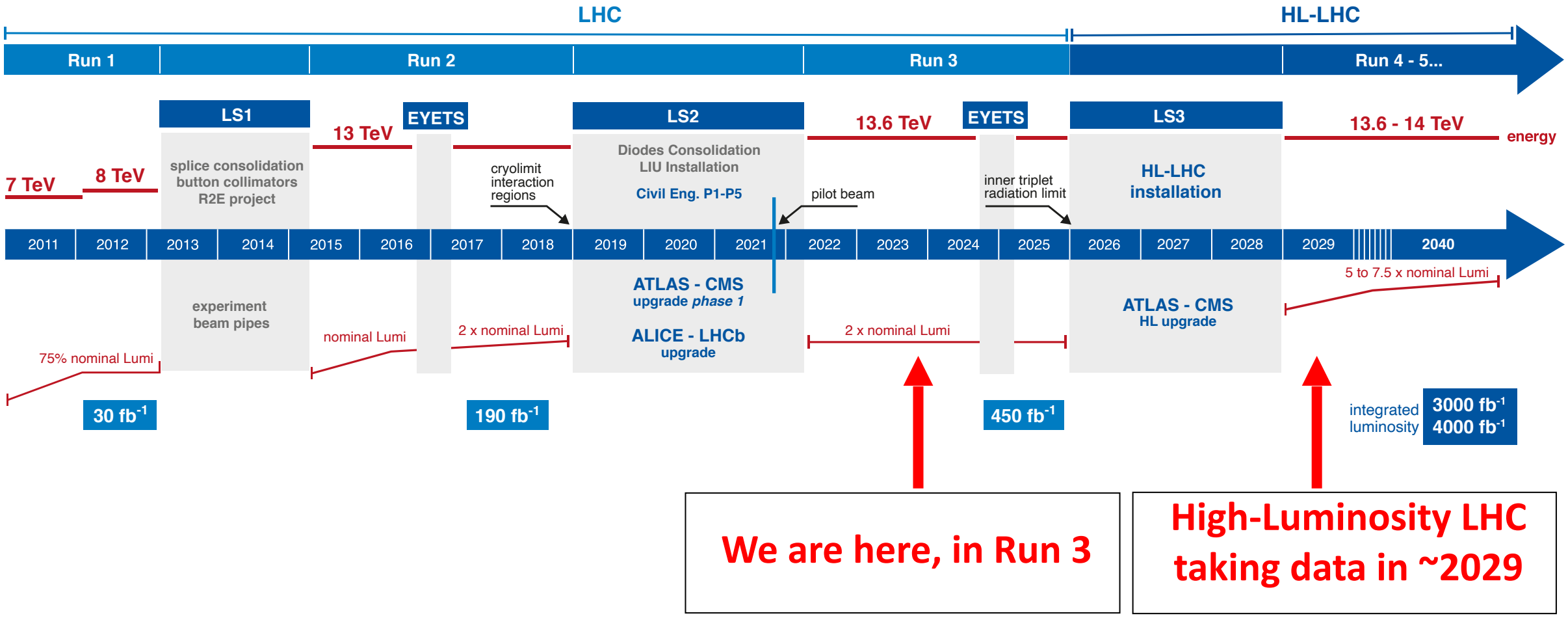


Phys. Rev. D **104**, 032002

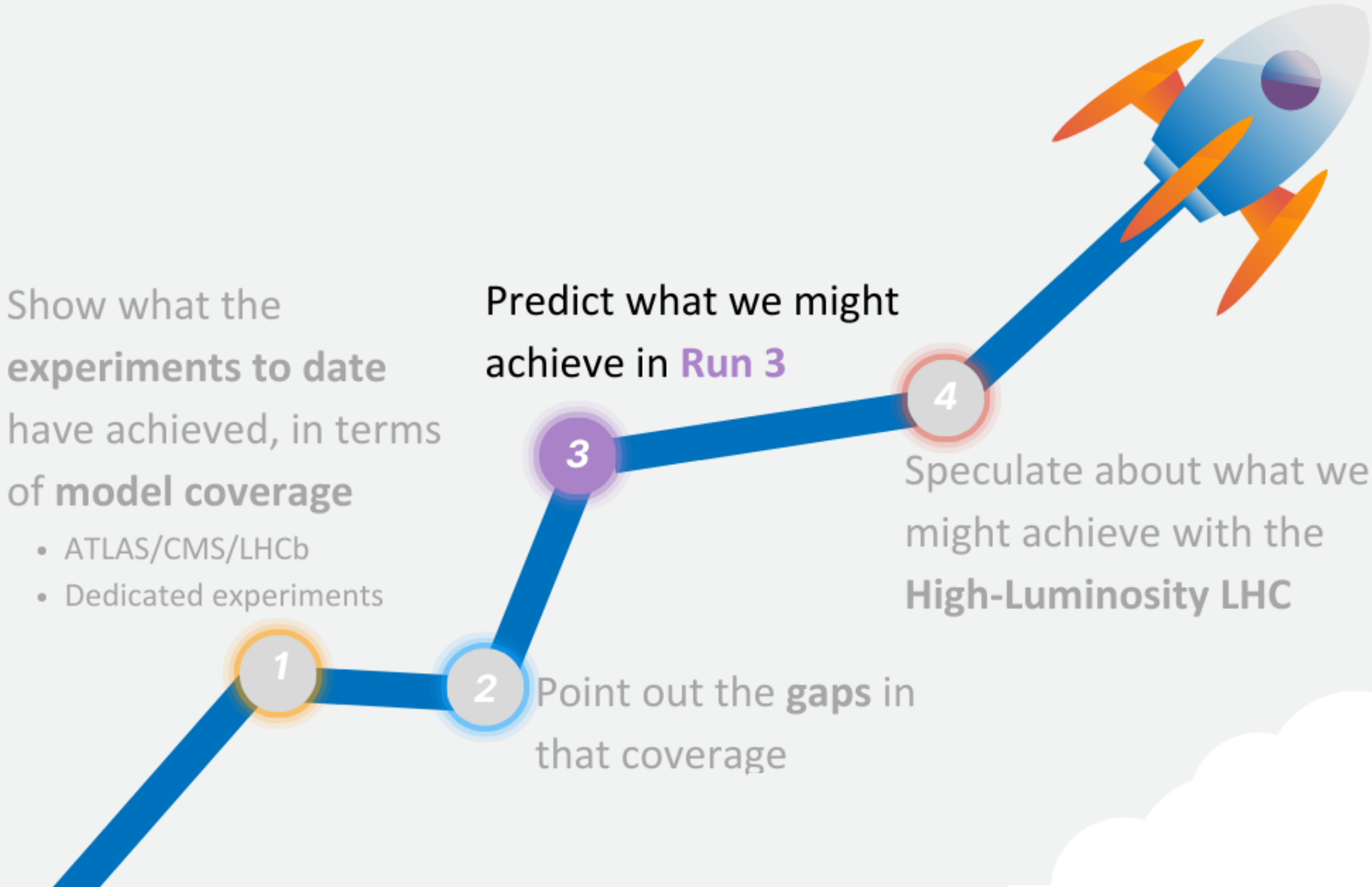


What's Next?

LHC / HL-LHC Plan

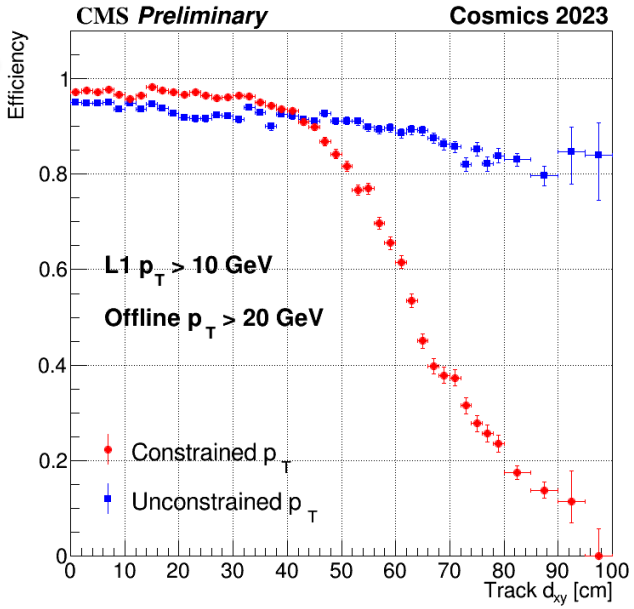


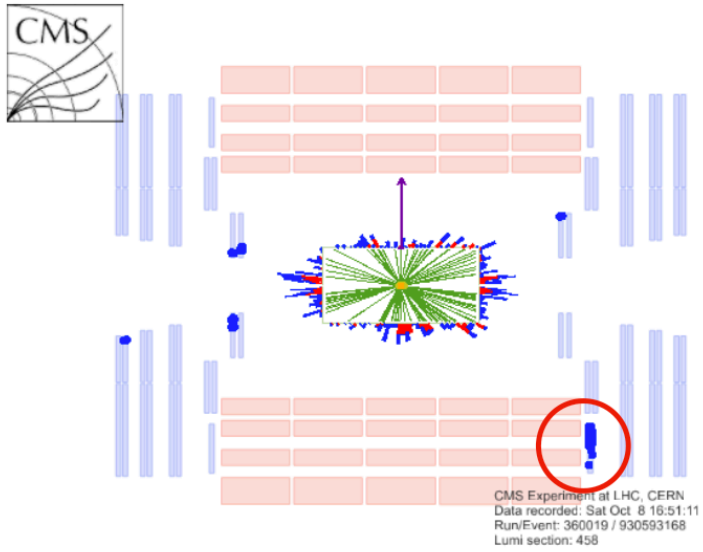
Run 3

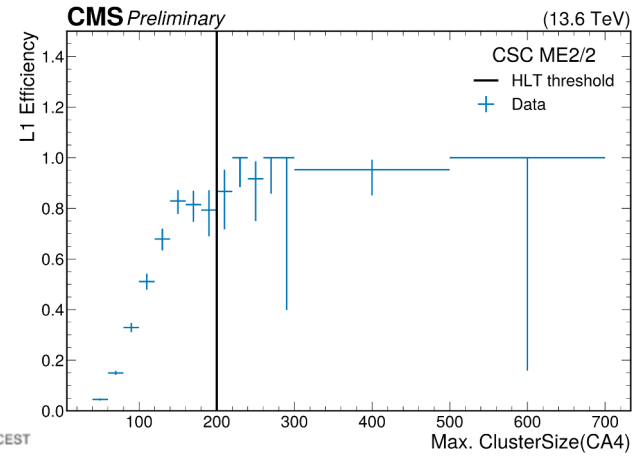

Show what the **experiments to date** have achieved, in terms of **model coverage**
• ATLAS/CMS/LHCb
• Dedicated experiments
1
2
Point out the **gaps** in that coverage
Predict what we might achieve in **Run 3**
3
4
Speculate about what we might achieve with the **High-Luminosity LHC**

New Triggers in CMS for Run 3

- New L1 & HLT algorithms for **displaced muons**
- New L1 & HLT triggers for **showers in the muon system**

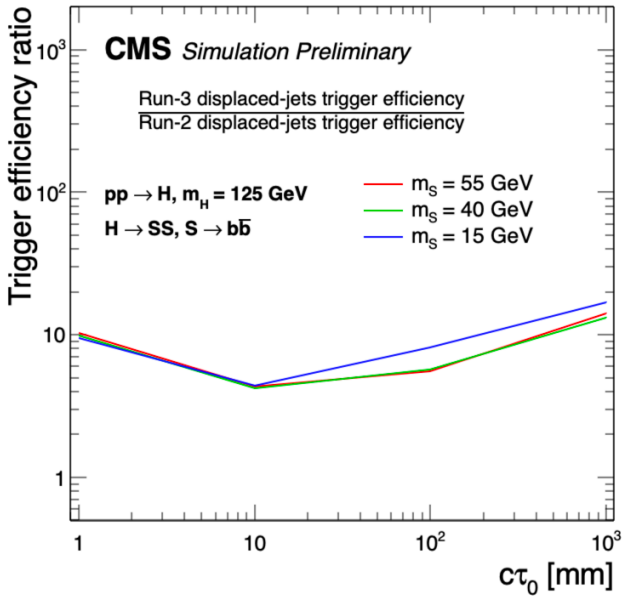


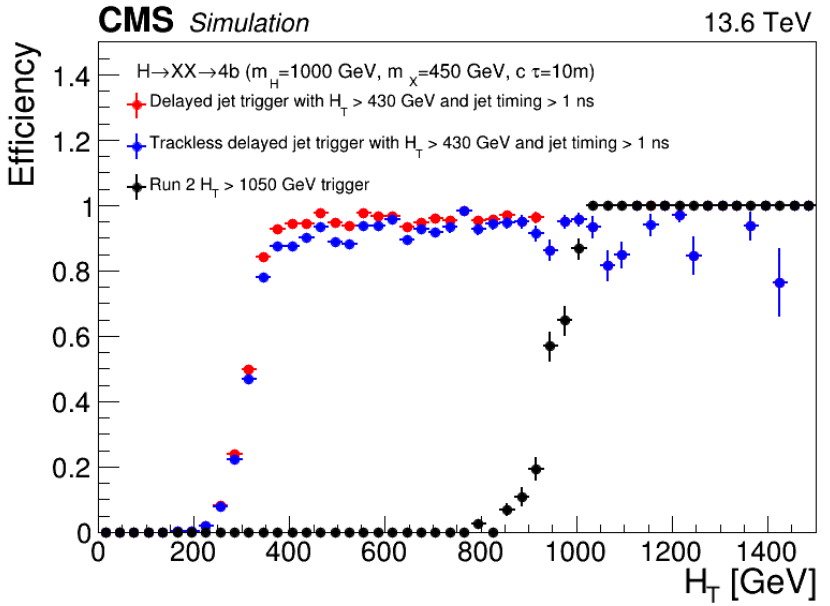




New Triggers in CMS for Run 3

- New L1 & HLT algorithms for **displaced muons**
- New L1 & HLT triggers for **showers in the muon system**
- New triggers for **delayed jets:**
  - Using HCAL depth and timing (thanks to HCAL upgrade): L1 & HLT
  - Using ECAL timing: HLT
- New HLT triggers for **displaced taus**
- **More rate: parking displaced and delayed jet triggers**



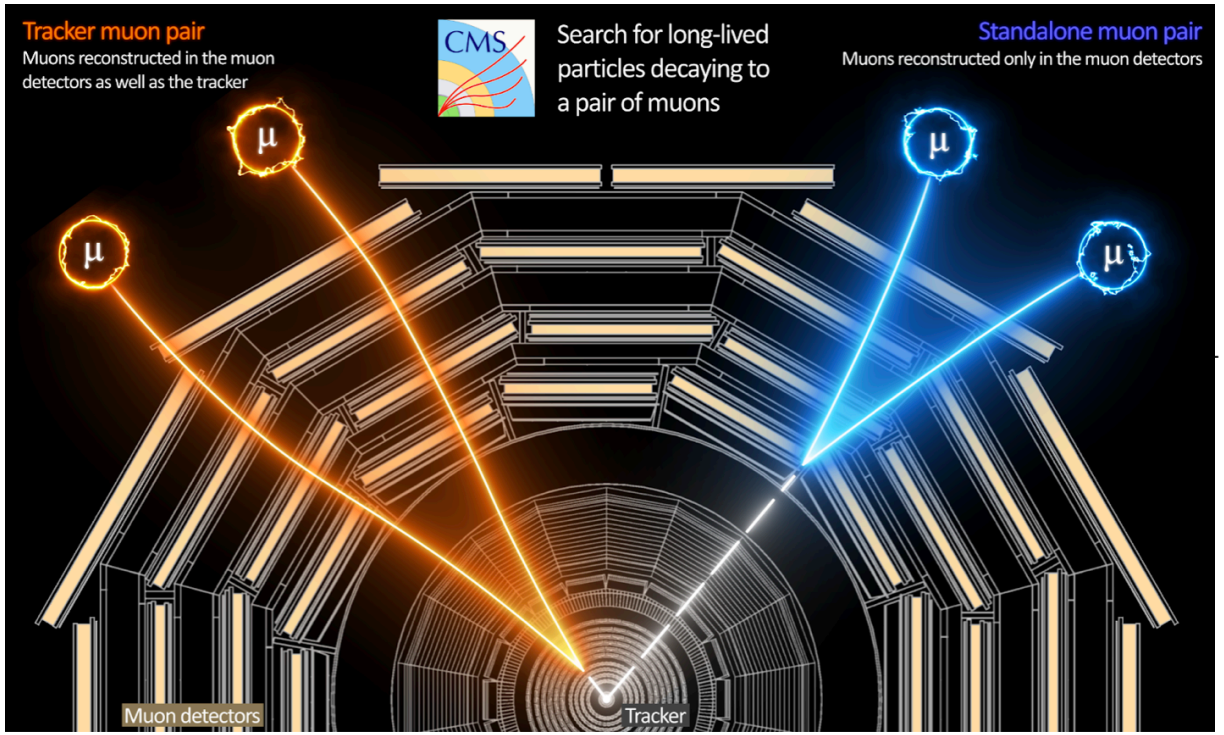


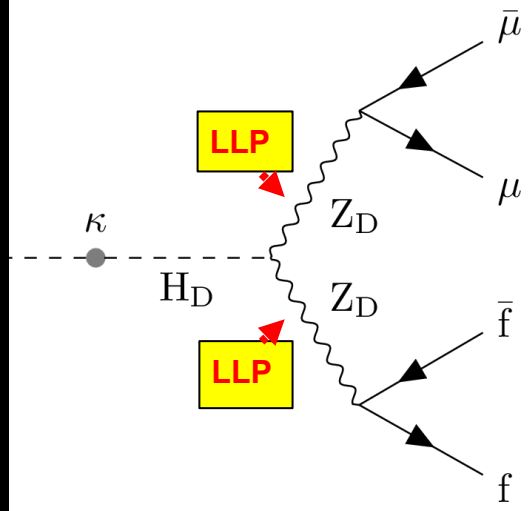
EXO-23-014

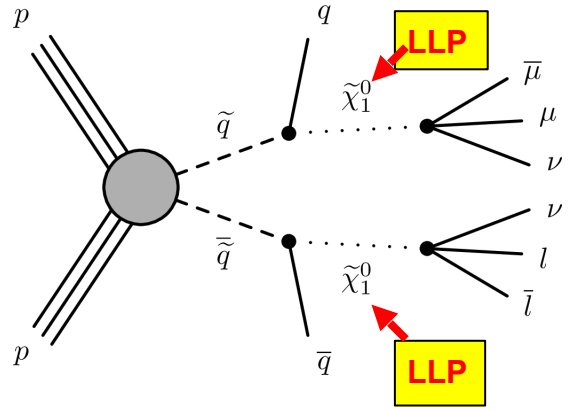
New Triggers → Increased Coverage

First CMS Run 3 search: Displaced dimuons (common vertex)

- **Generic, inclusive search** for long-lived particles decaying into pairs of oppositely-charged muons (displaced dimuons) within the tracker and beyond
- Uses 36.7 fb^{-1} of 13.6 TeV data taken in 2022







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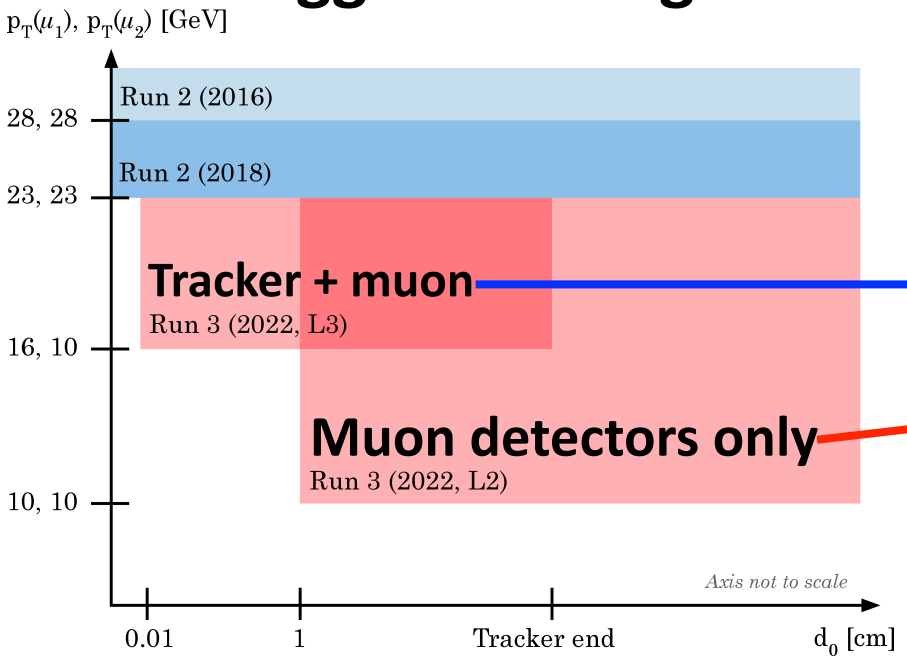
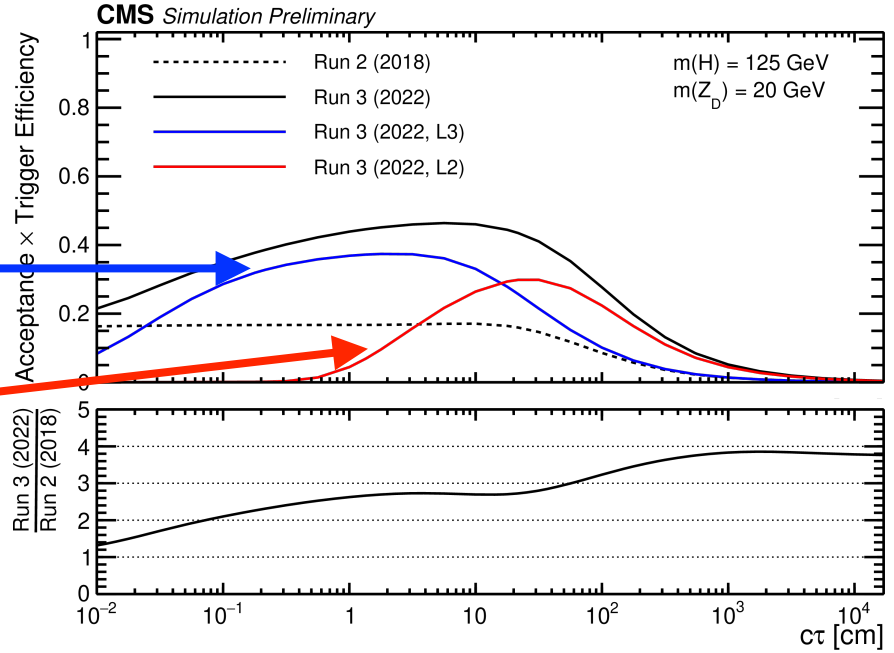
Trigger Coverage



Trigger Efficiency



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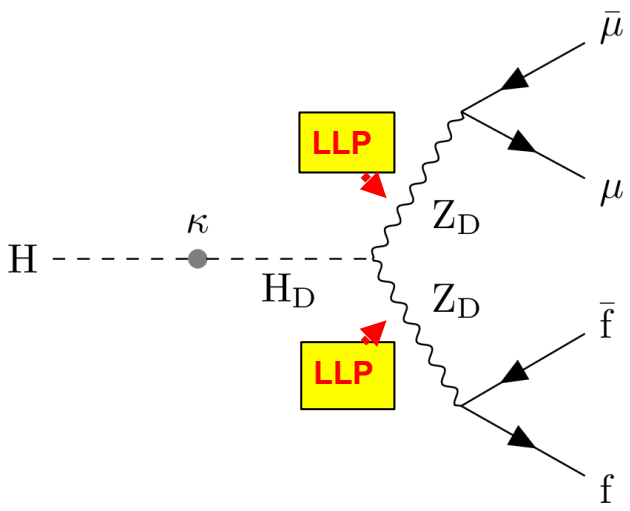
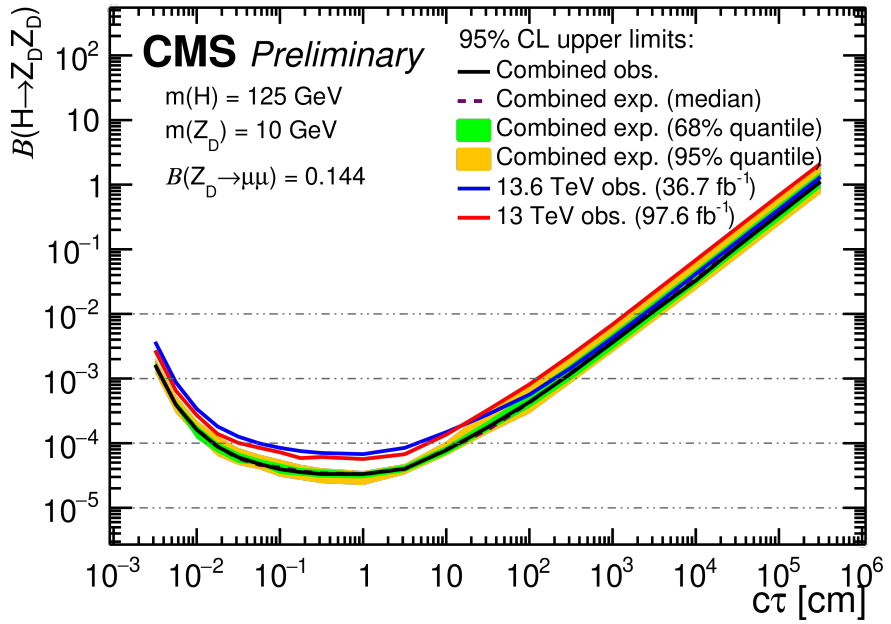
- Improve signal efficiency at low mass and large displacements up to a factor of 4
- **Comparable or better sensitivity than Run 2 with only 38% of the data**

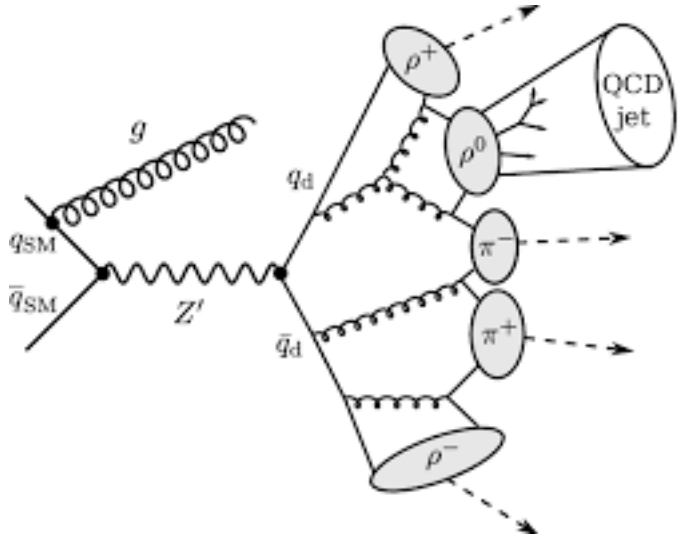




How are we trying to improve? (I)

Trends in late Run 2, early Run 3:

- More emphasis on **more complicated models/ signatures**:
  - E.g. Dark QCD/semivisible/emerging jets/ SUEPs
- Emphasis on **low mass** signatures
  - SM Higgs → LLPs, Heavy neutral leptons, Dark photons, Compressed SUSY, SUEPs
- **Small cτ:** pushing into prompt backgrounds
  - E.g. with prompt object (often used to trigger) produced in association with LLP(s)
- **Large cτ:** extending acceptance beyond tracker

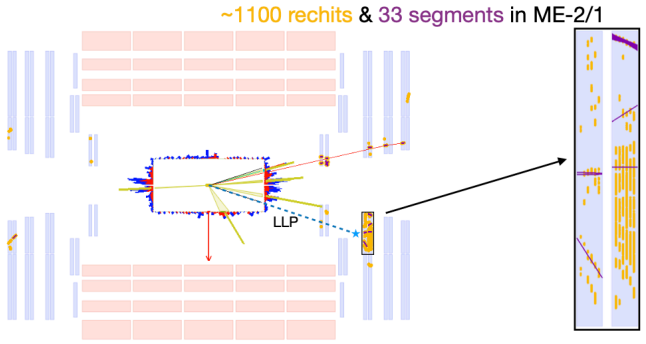


How are we trying to improve? (II)

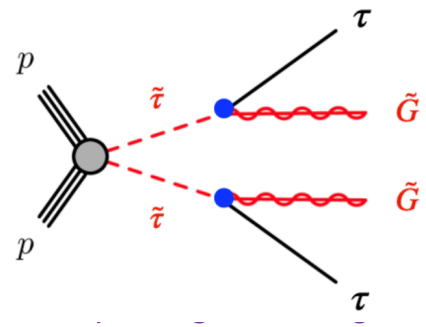
Trends in late Run 2, early Run 3:

- CMS is developing an **extensive muon showers program**
  - Suite of analyses/papers looking for muon shower + other object
  - Dedicated L1 and HLT triggers in Run 3!
- **New & improved trigger strategies:**
  - More dedicated triggers: Displaced muons, displaced jets (ECAL and HCAL), displaced taus, disappearing tracks, showers in muon system, …
  - Scouting/ Trigger Level Analysis/ Turbo Stream
  - Parking
- Increased use of **machine learning** (deep networks & other advanced techniques)
  - E.g. for challenging backgrounds

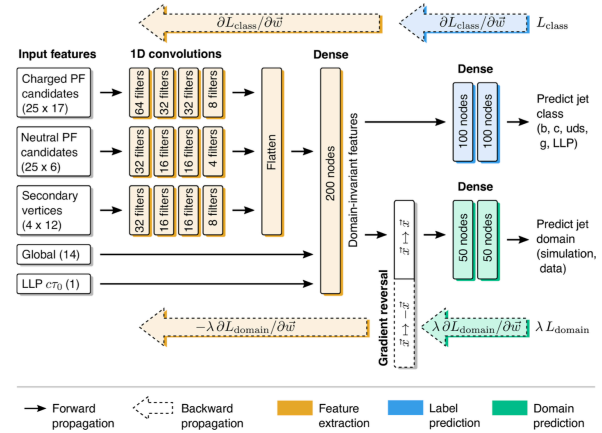
Muon showers



Displaced taus



Machine learning



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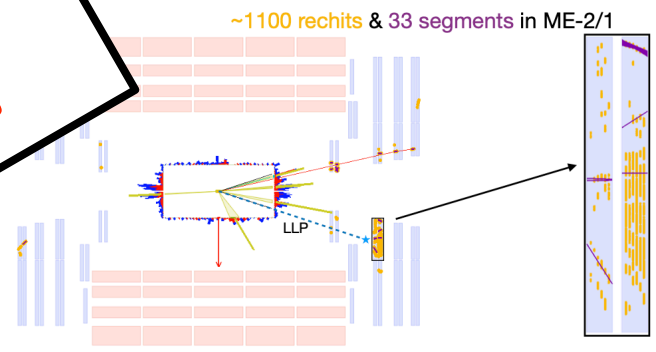
Harder and cooler stuff!

Muon



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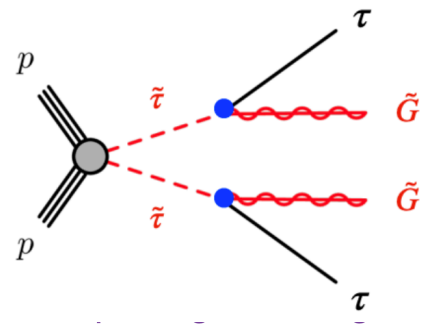

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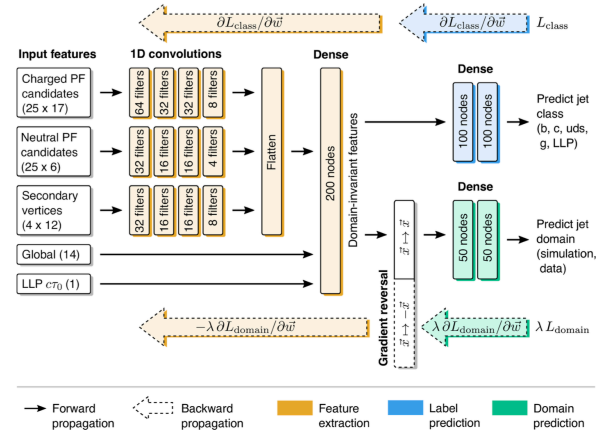
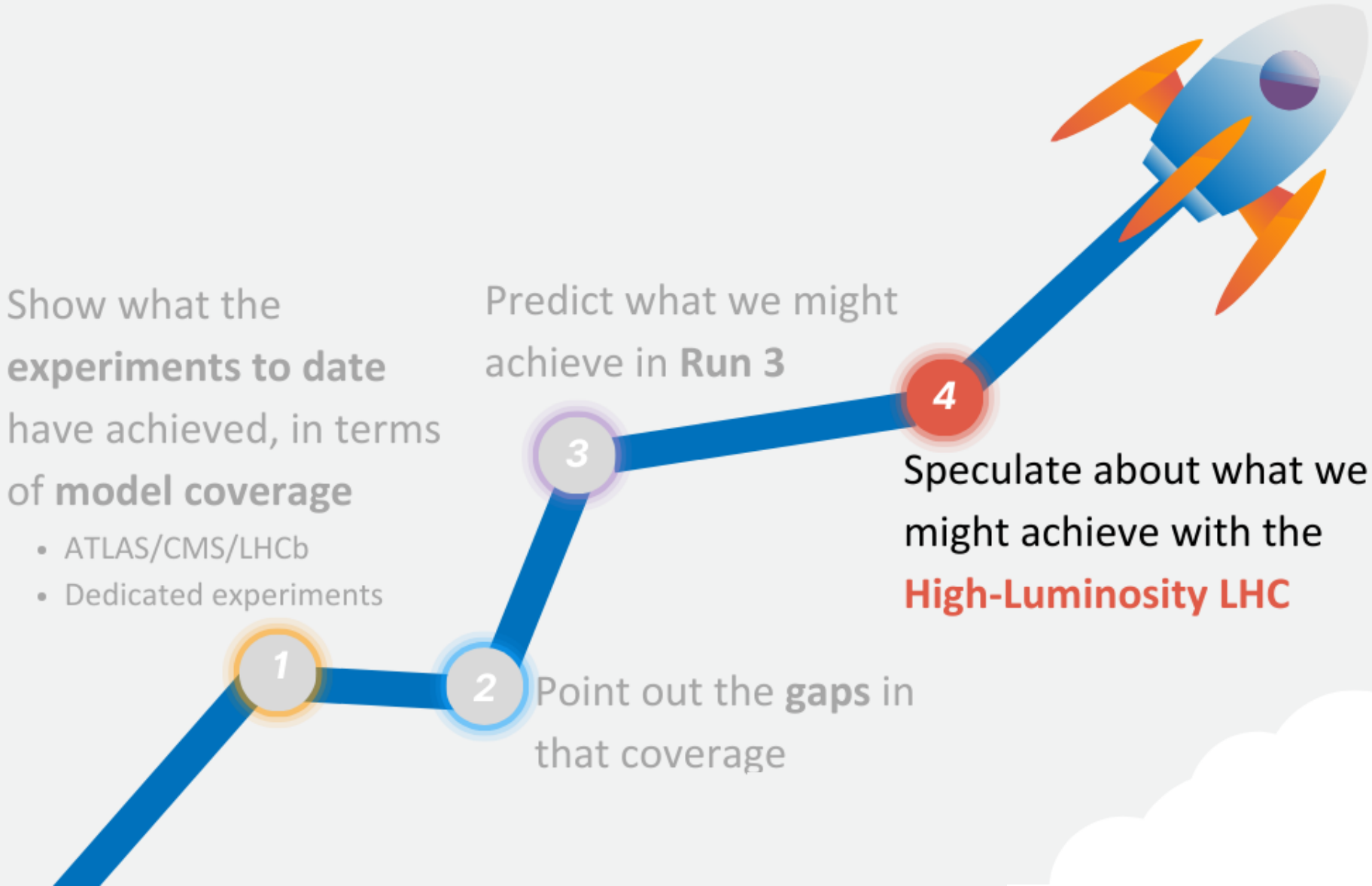


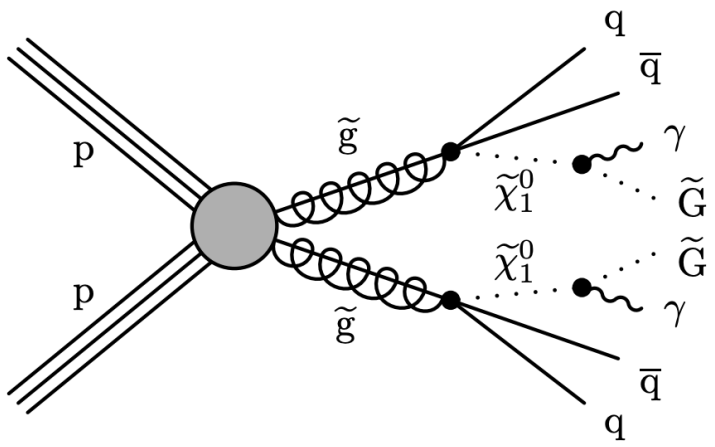
HL-LHC

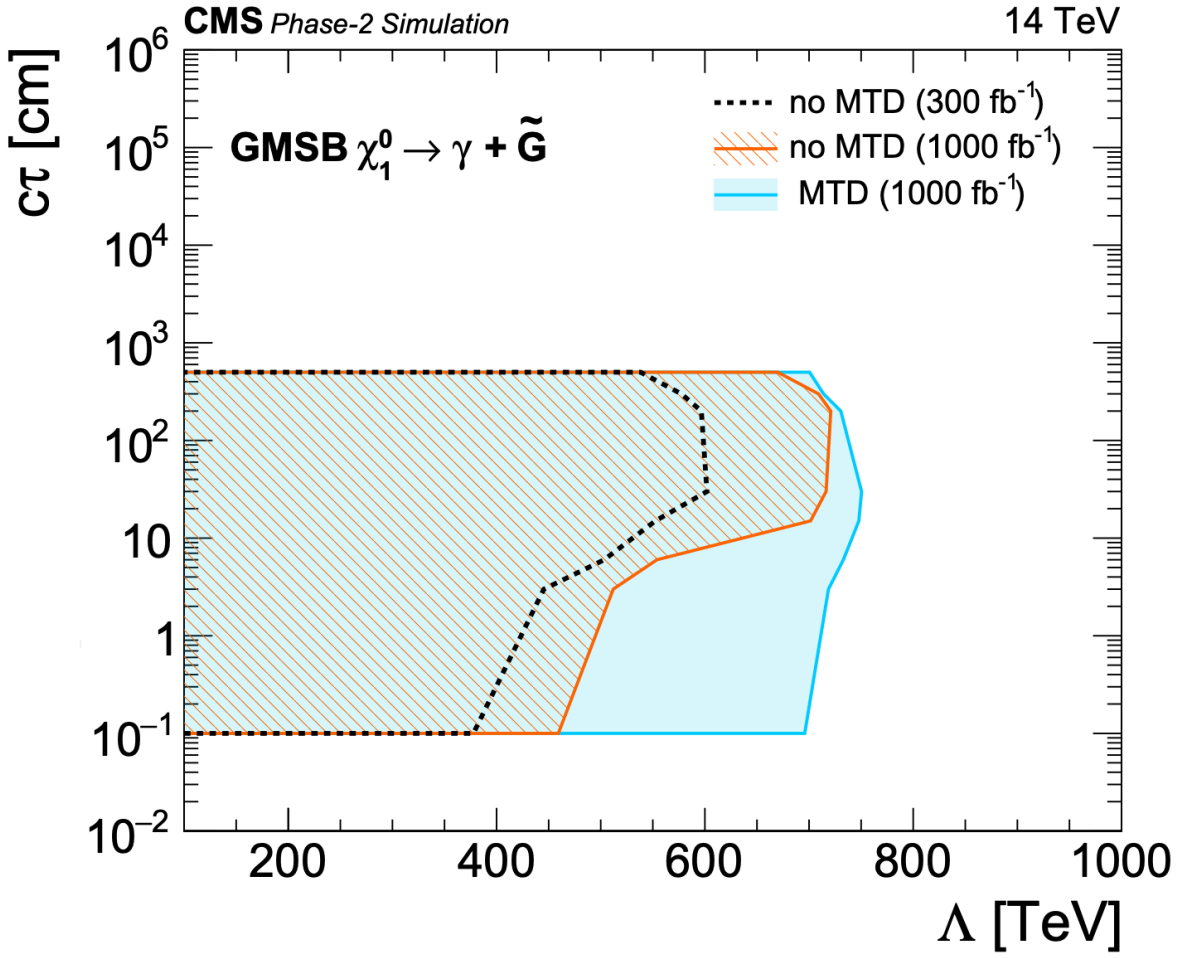

Show what the **experiments to date** have achieved, in terms of **model coverage**
• ATLAS/CMS/LHCb
• Dedicated experiments
1
2
Point out the **gaps** in that coverage
3
Predict what we might achieve in **Run 3**
4
Speculate about what we might achieve with the **High-Luminosity LHC**

LLPs at the HL-LHC

- See Flavia's talk on Monday for a nice comparison of the ATLAS and CMS detectors at the HL-LHC, and how that could impact LLP searches
- Lots of potential! Will show just a quick (biased) sampling of some options

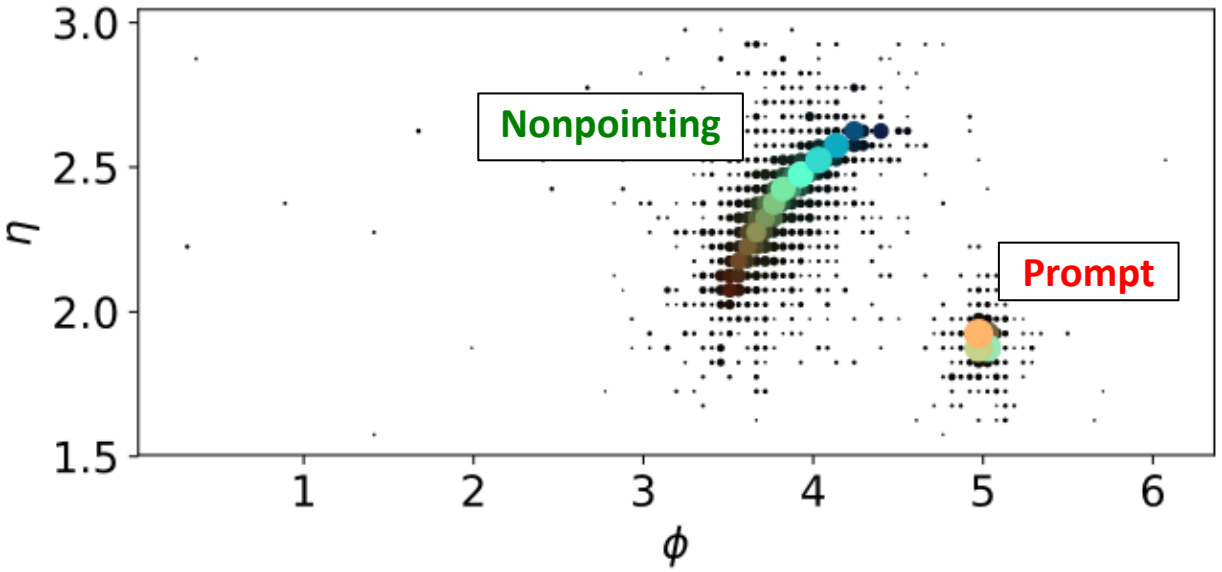
Delayed Photons in Timing Detectors

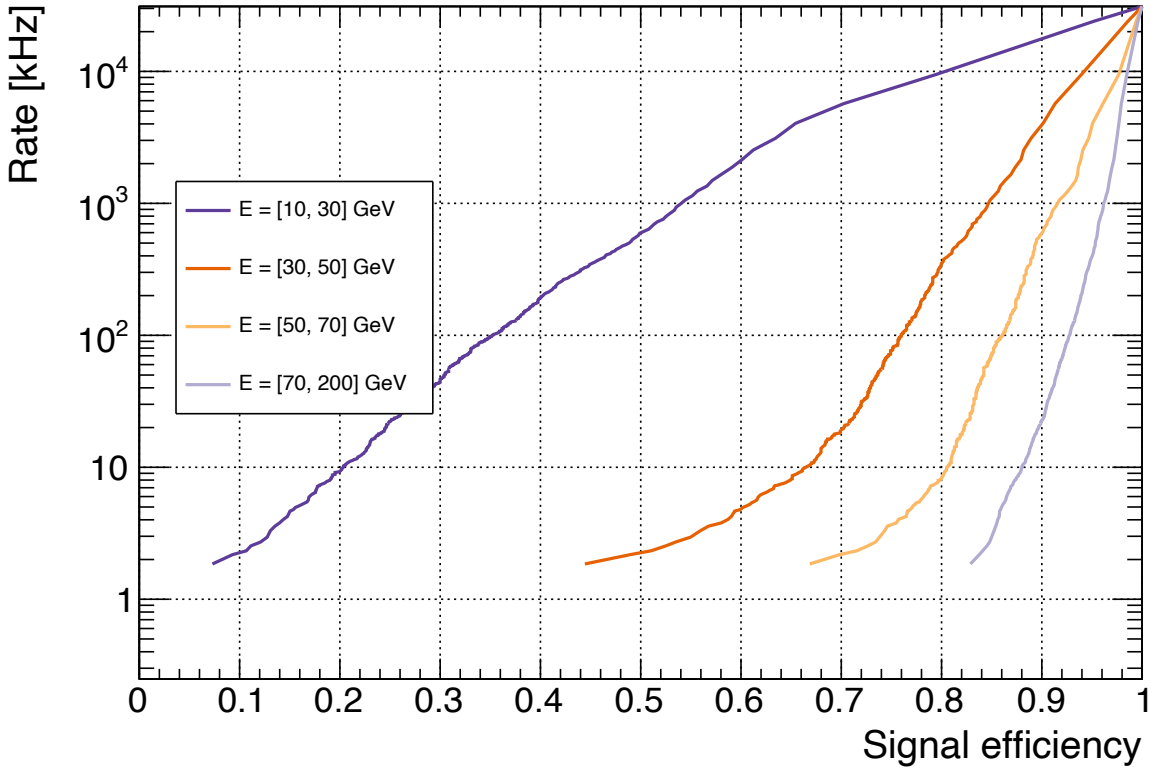




PRD 105 (2022) L051701

ML Trigger for Nonpointing Particles in HGCAL





Needs:

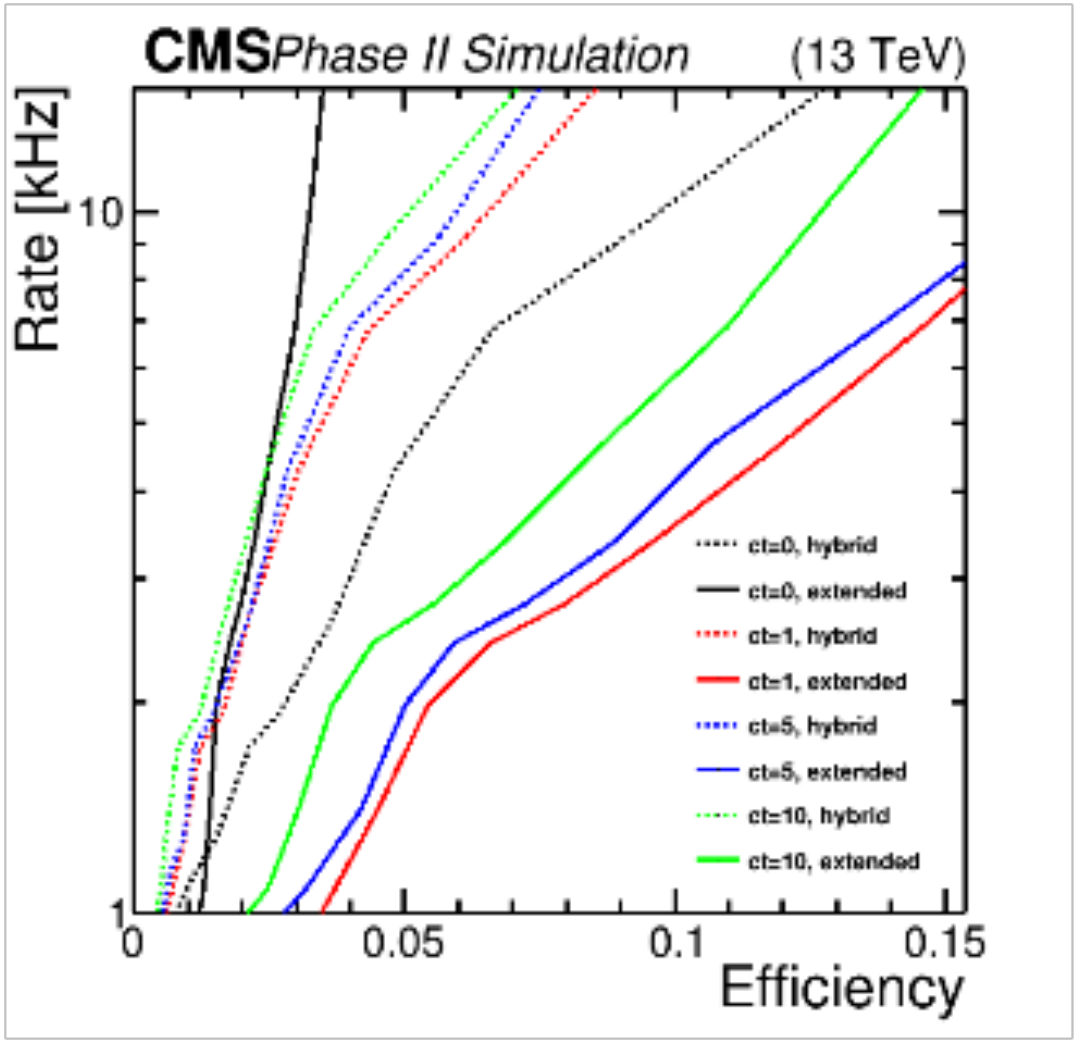
- HLS4ML (showed it works)
- Realistic CMS implementation (to do)

Wants:

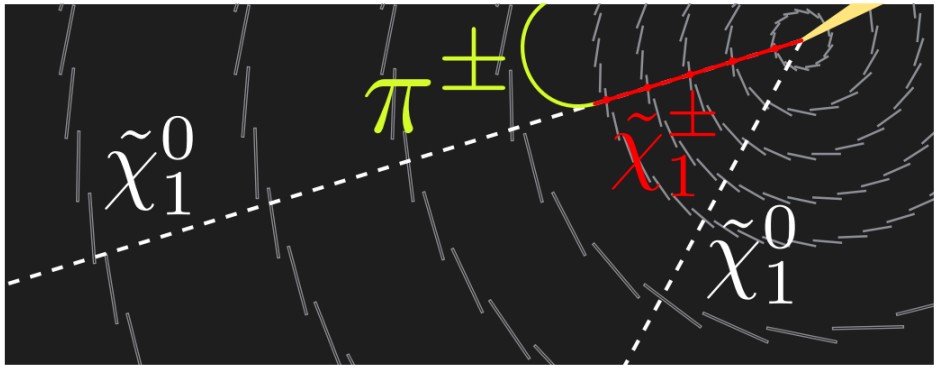
- Collaboration with ATLAS? Possibility for your High Granularity Timing Detector?

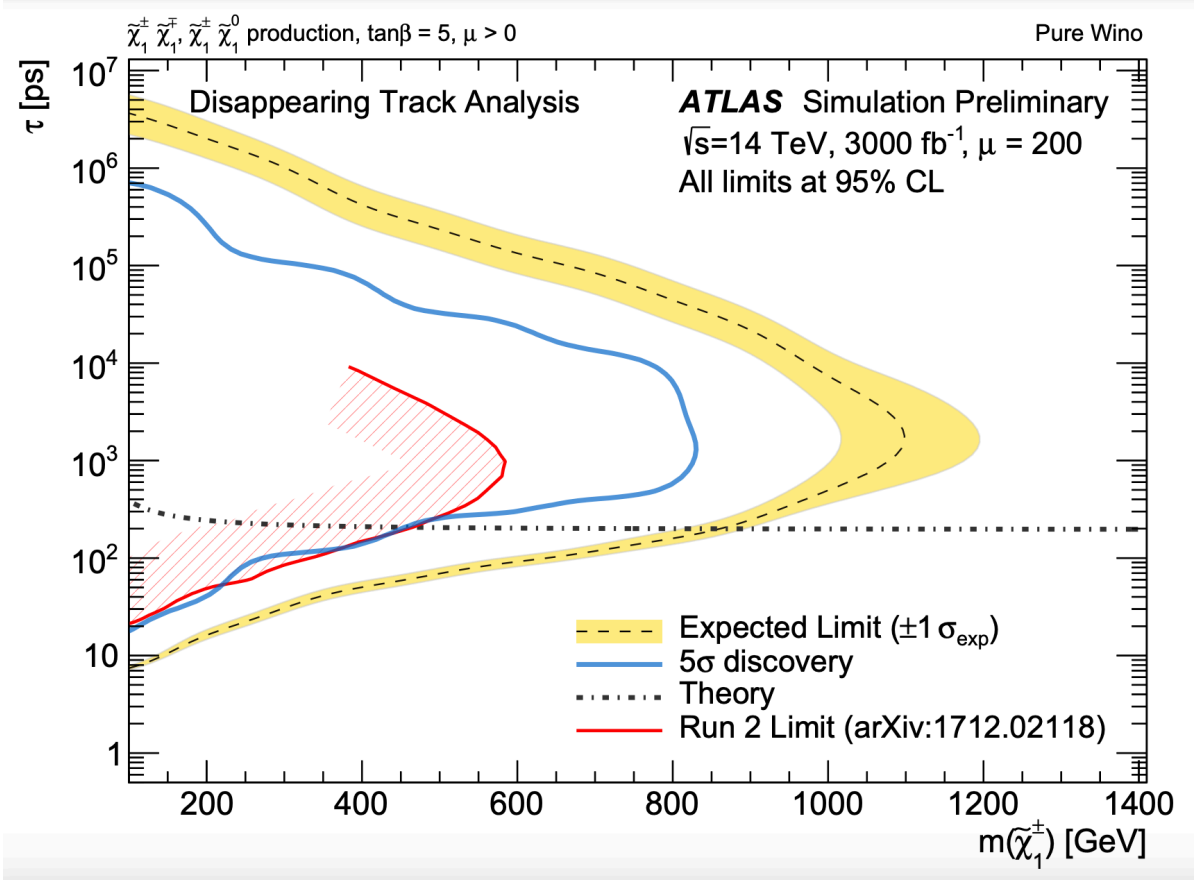
L1 Track Triggers for Displaced Jets

m(H)=125 GeV, m(Φ)=30 GeV



Disappearing Tracks





Summary

- I've summarized **how well we are covering different models/scenarios** with experimental searches for LLPs
  - Probably I've missed models/analyses/summary plots: please tell me!
  - [Or we see which summary plots we should make ;)]
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  - Run 1 → Run 2 → Run 3 → HL-LHC
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Only up from here!

The future looks bright :)

Backup