Exploring the lifetime frontier with ATLAS

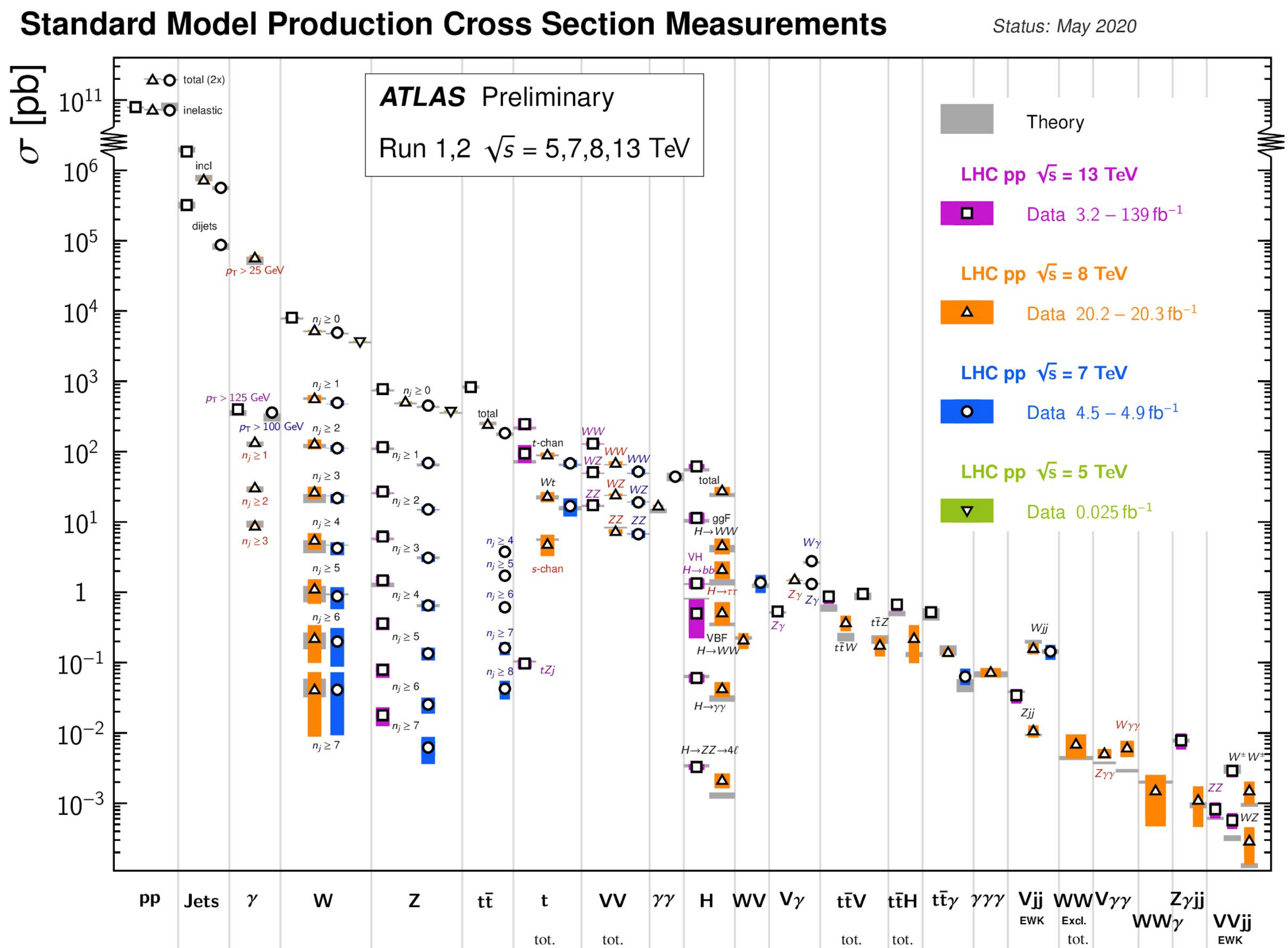
A journey beyond the beam-pipe

Federico Meloni (DESY)

HEP seminar, virtual Liverpool
09/12/2020

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

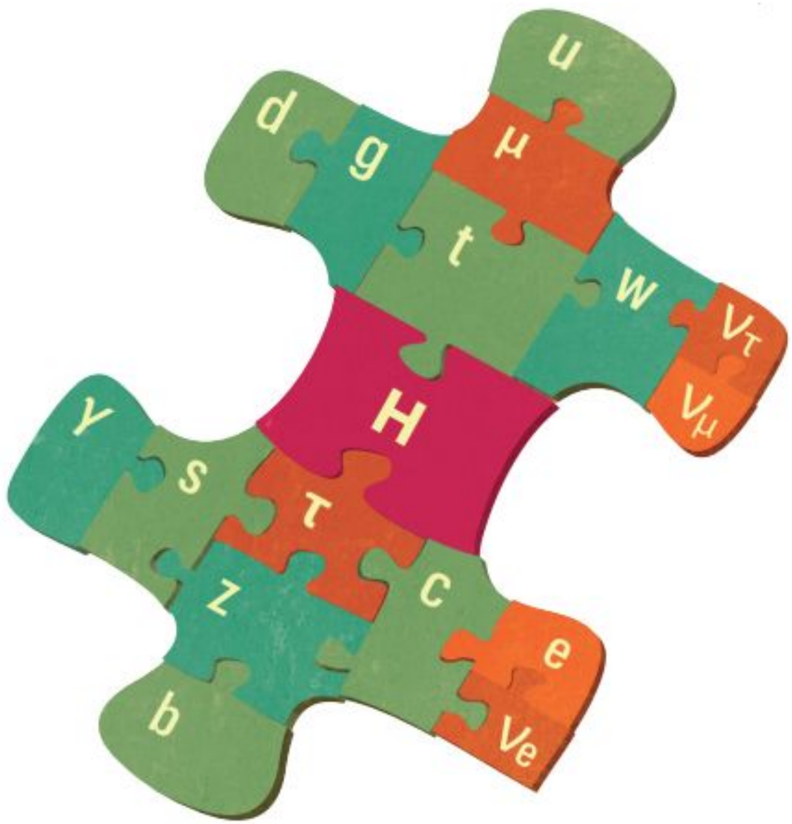
The glory of the Standard Model



DESY

Standard Model summary plots

Why do we need long-lived particles?



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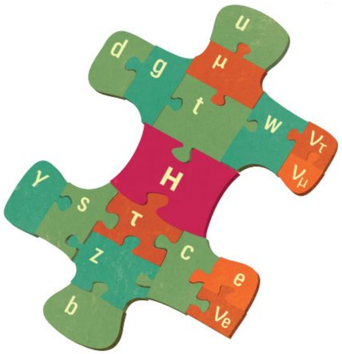

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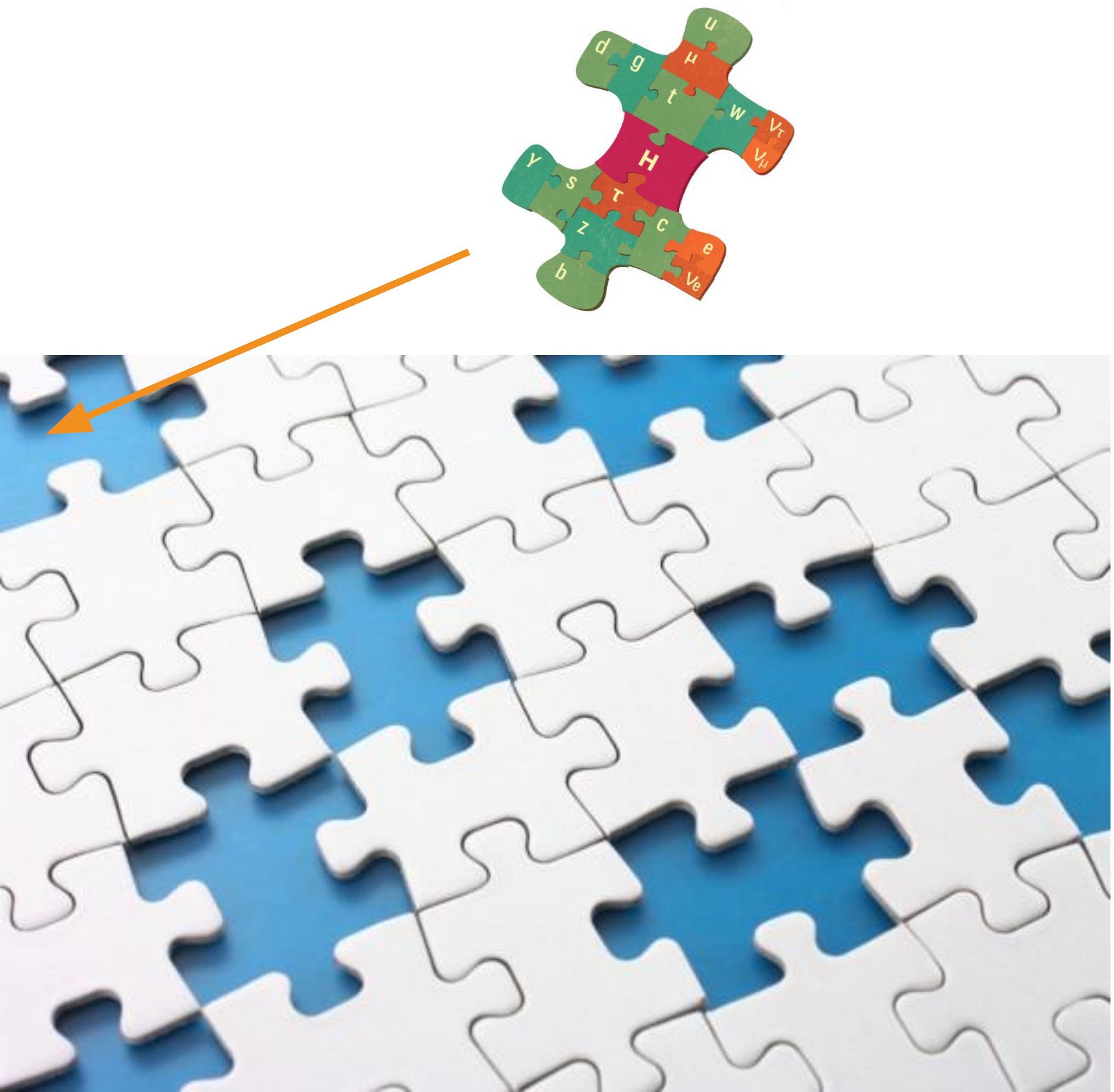

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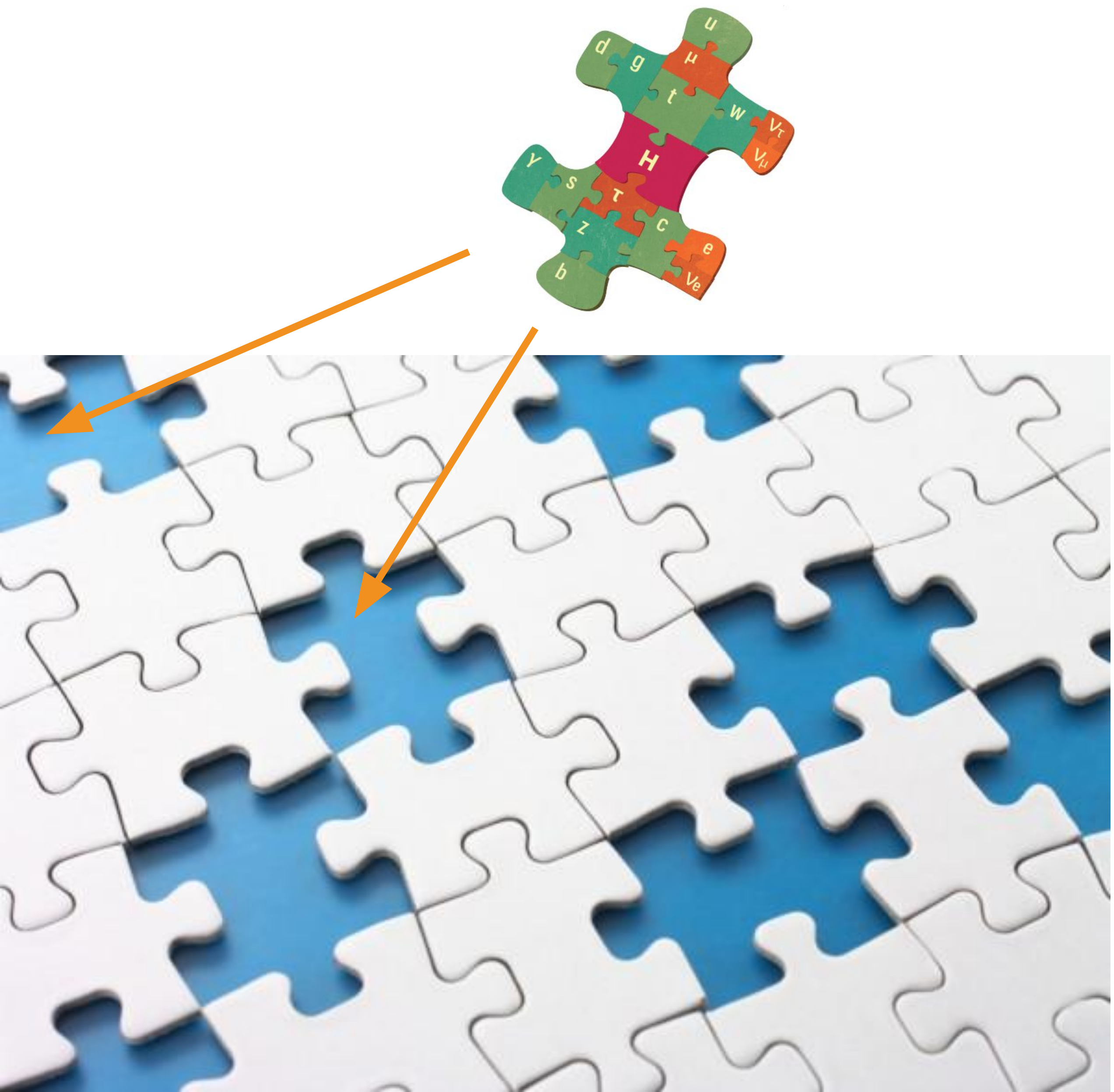

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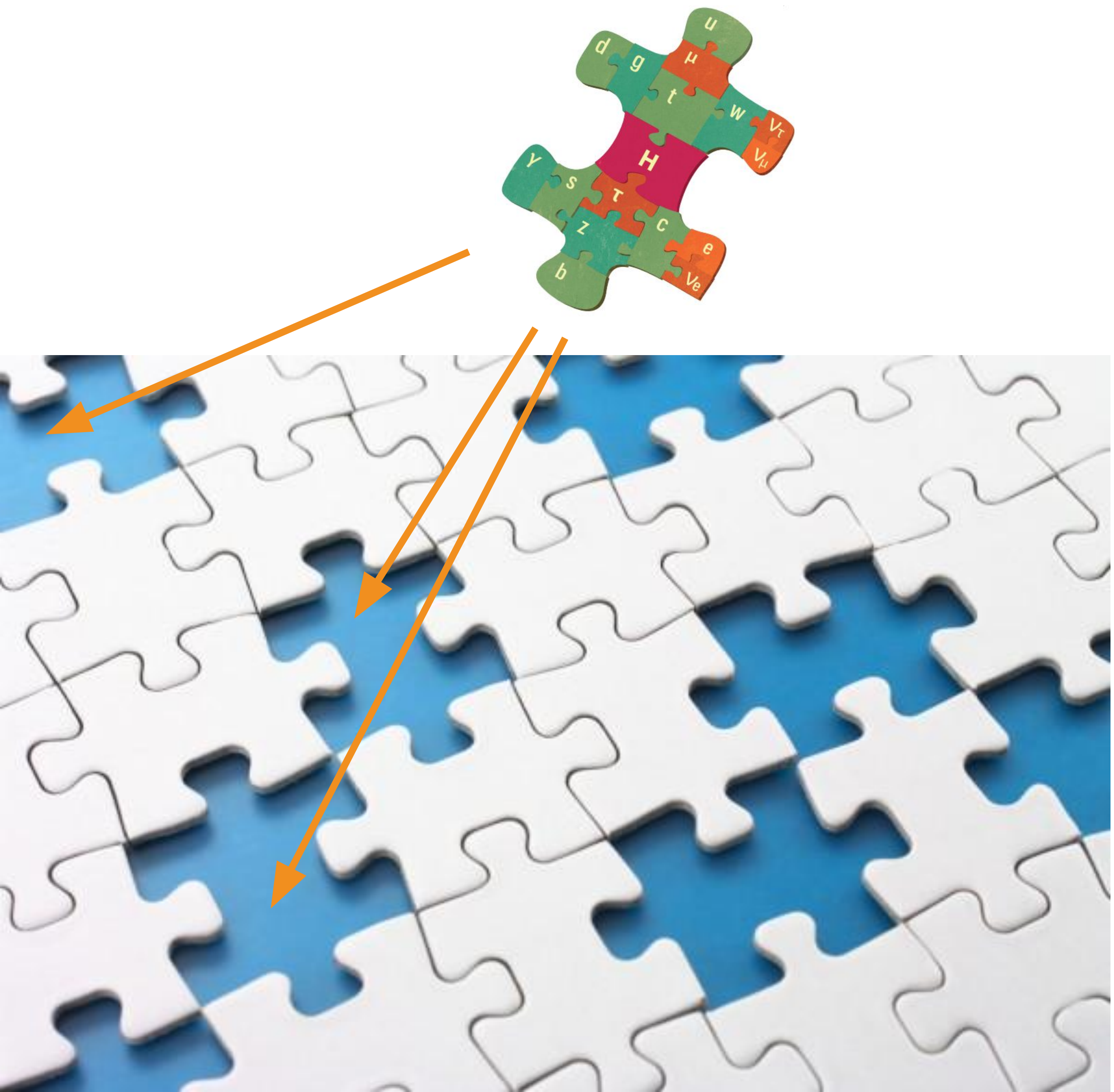

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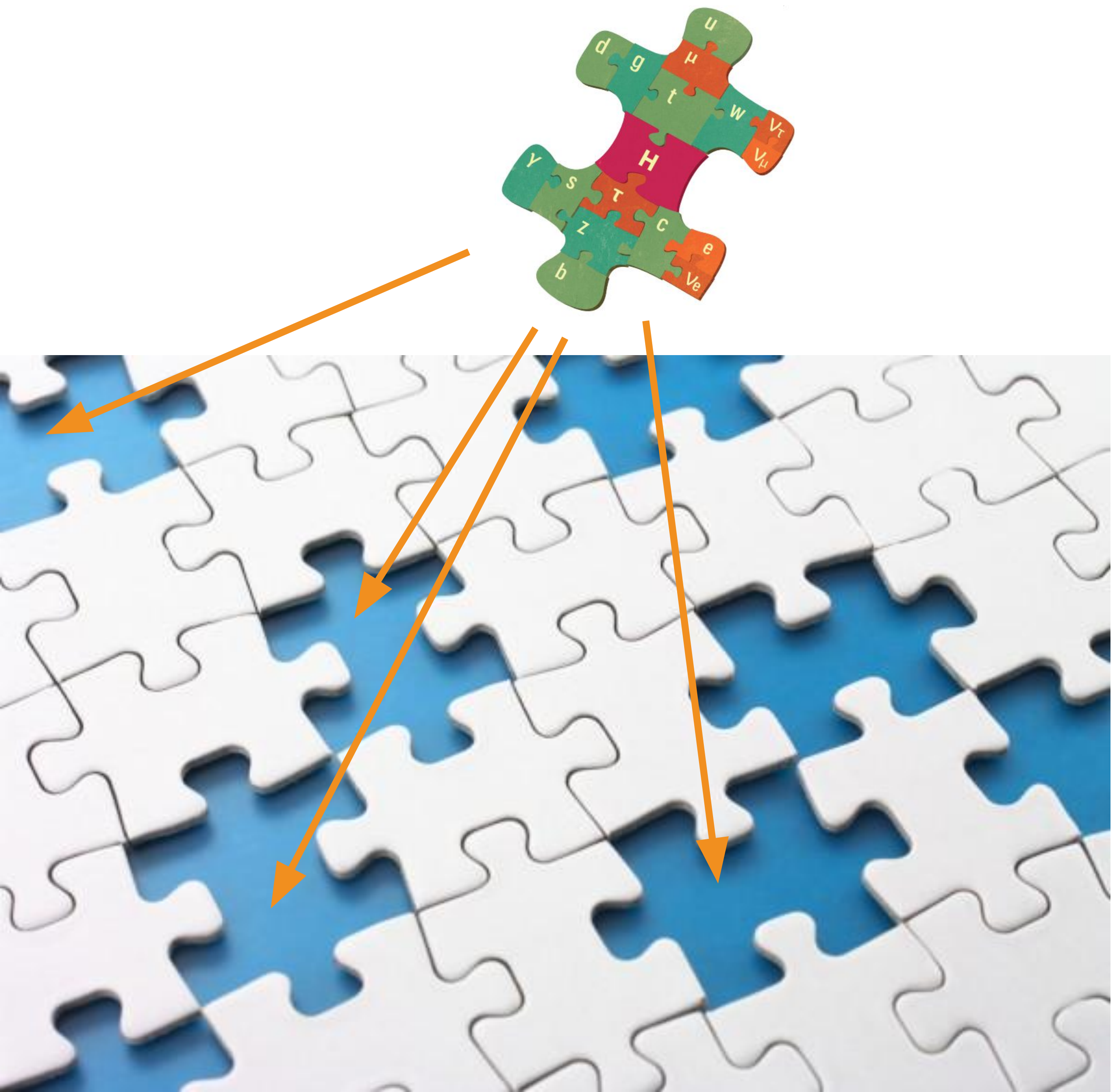

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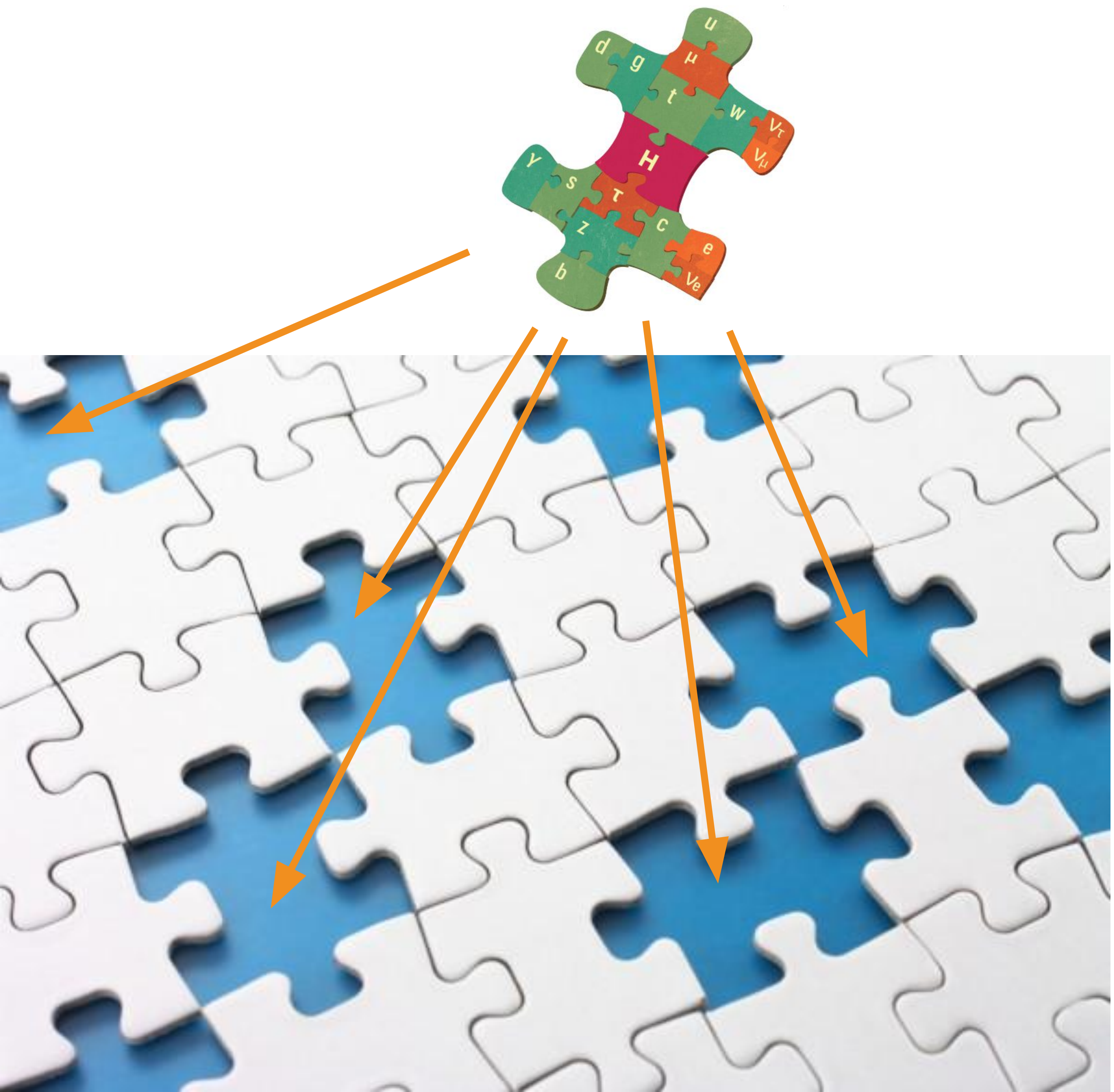

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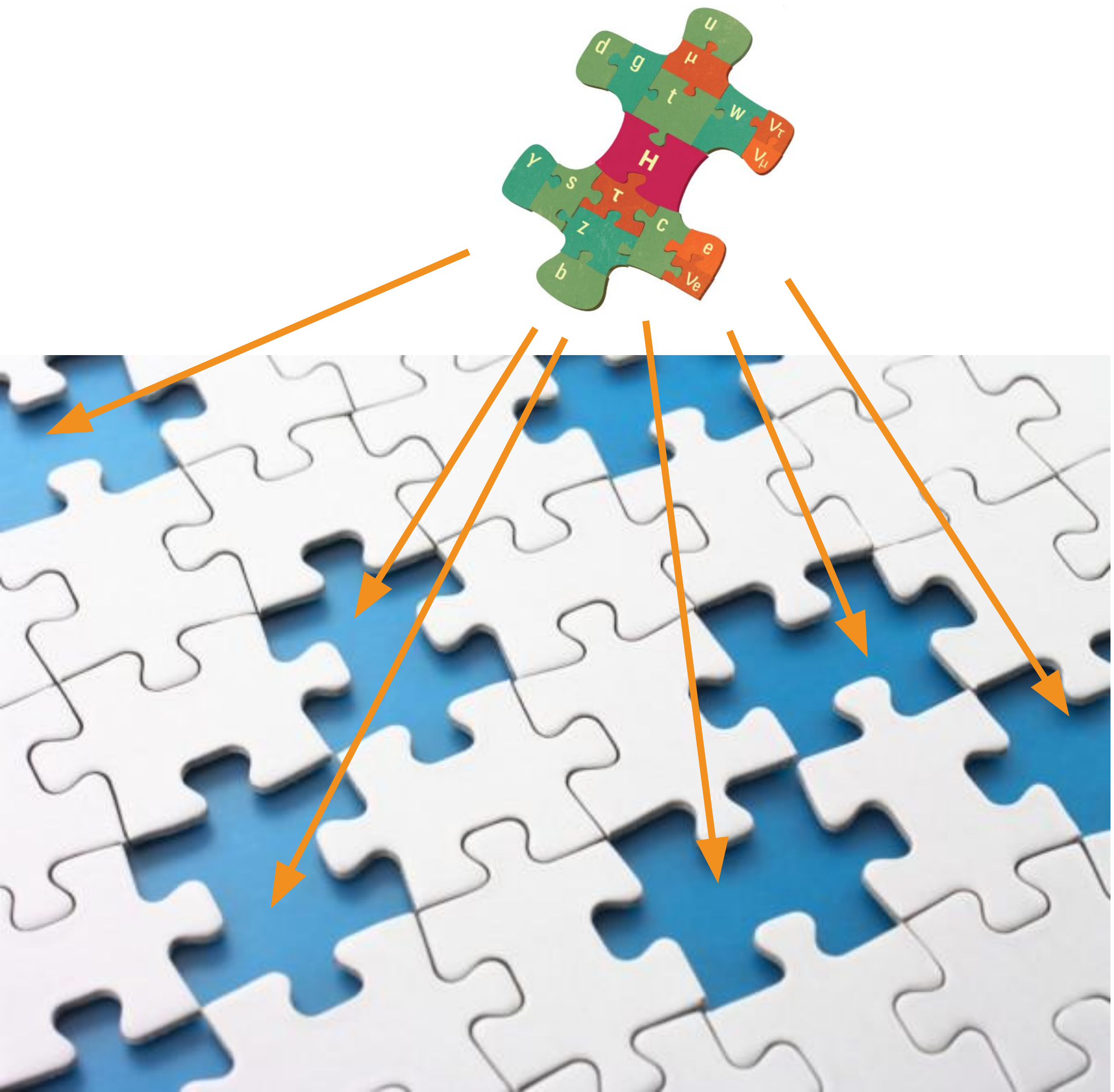

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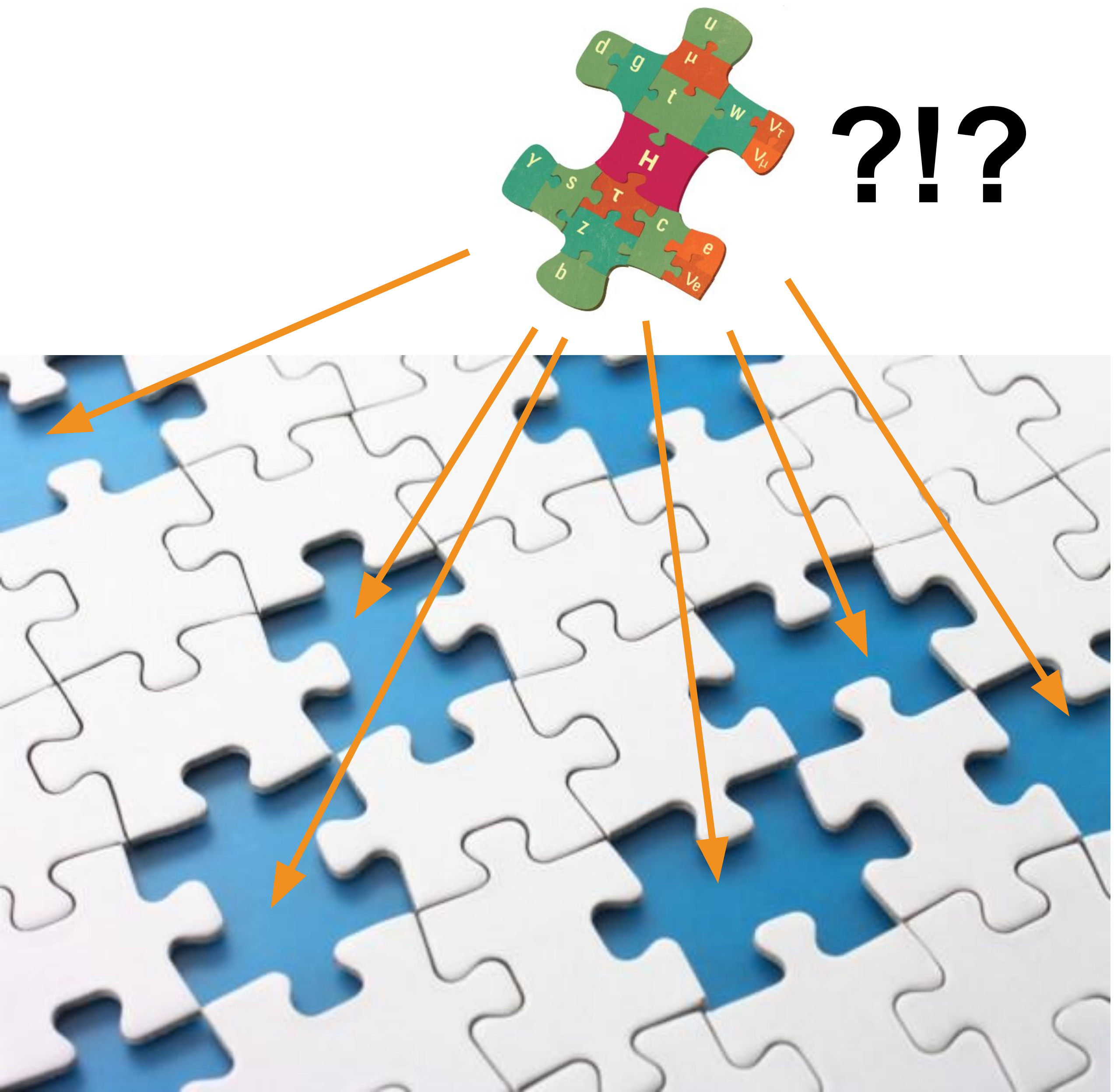

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Long-lived Standard Model extensions

These problems can be solved by adding BSM physics.

Several theoretical models predict additional long-lived particles (LLPs)

- Heavy neutral leptons, supersymmetry, hidden valleys, dark QCD, neutral naturalness, Higgs portal, Z' portal, ...

$$\Gamma \sim \varepsilon^2 (m/\Lambda)^{2n}\, \Phi$$

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Mass hierarchies
(suppressed loops)

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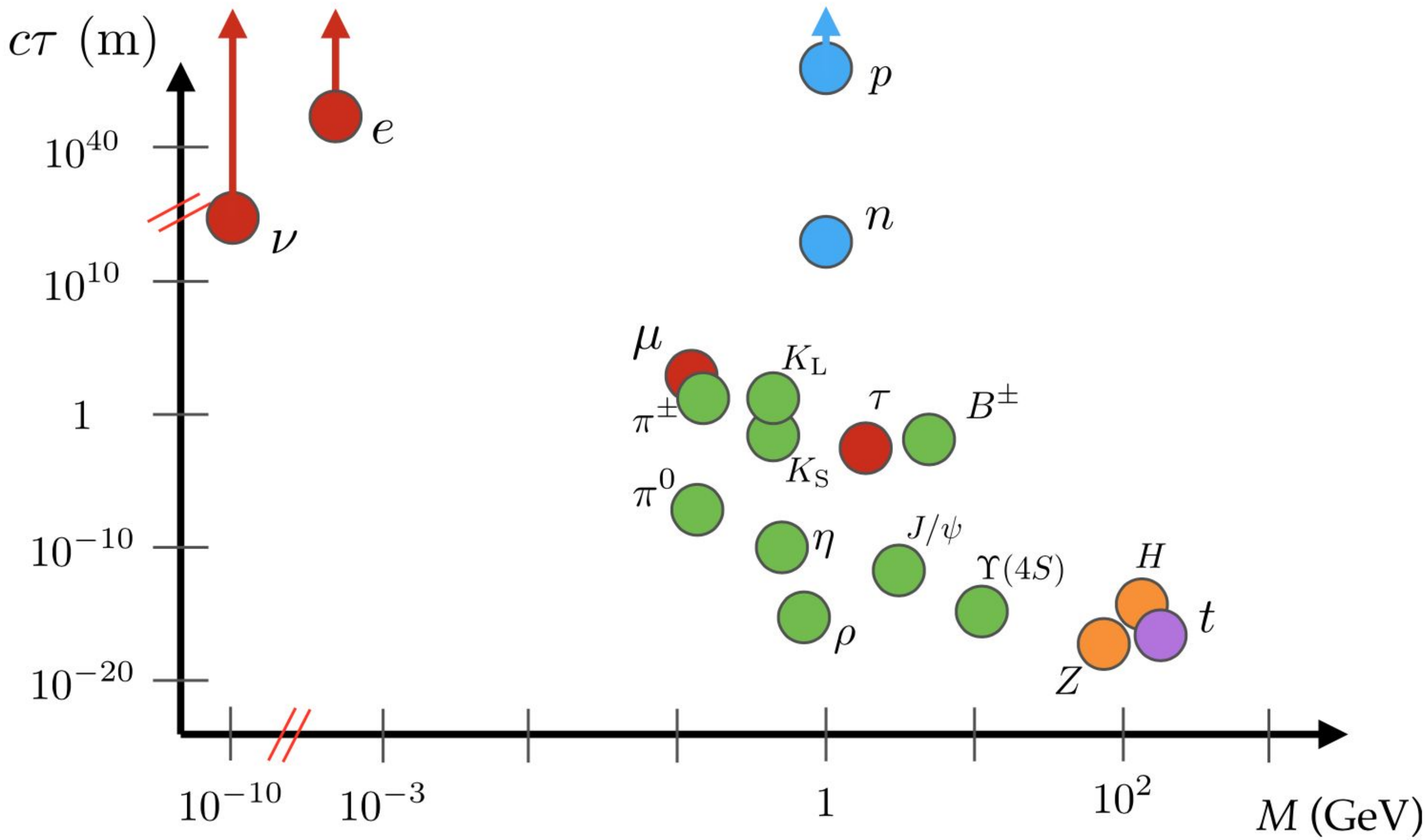
Small couplings

Phase space

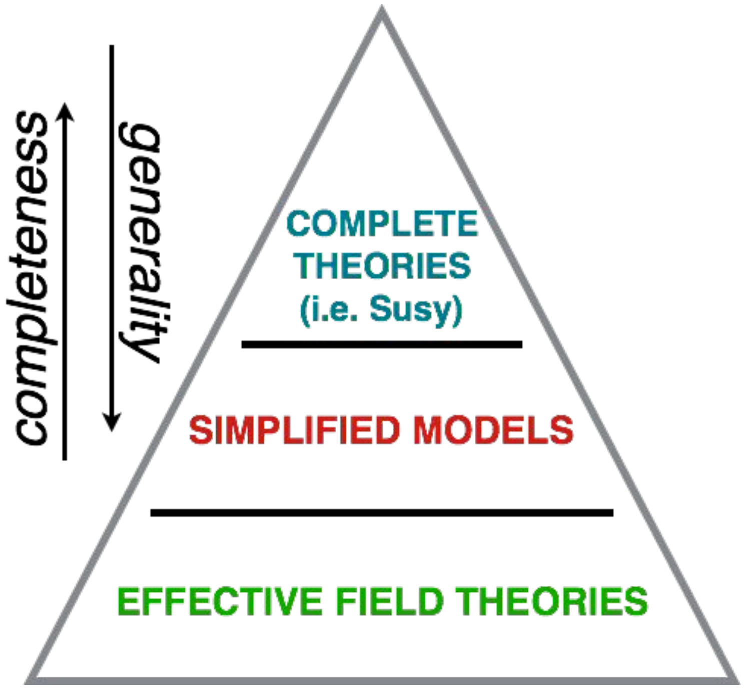
Mass hierarchies (suppressed loops)

Long-lived particles are already here!



J. Phys. G 47 090501 (2020)

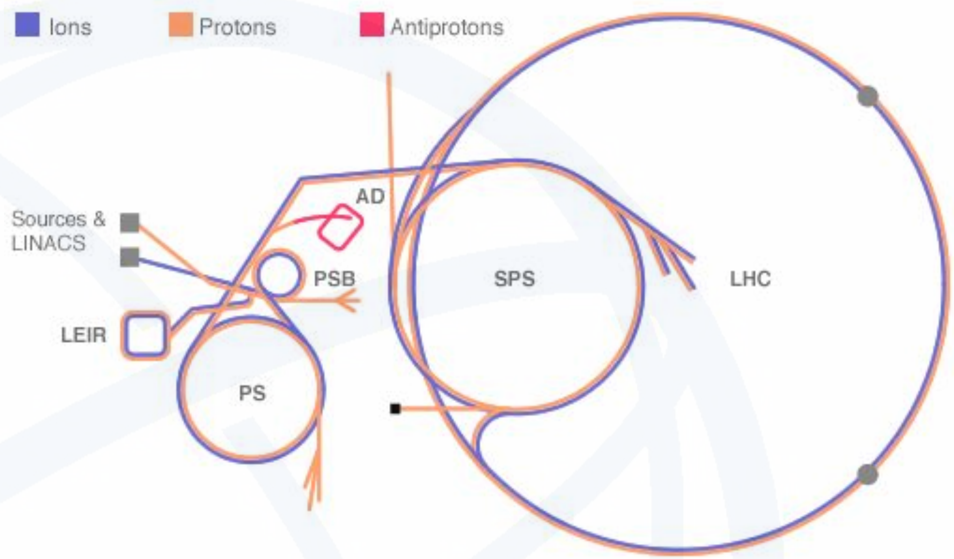
Modelling guidance



Need to balance between generality and completeness.

- Simplified Models are used as guidance
- Few free parameters:
  - Masses
  - Couplings / lifetimes
  - Nature of BSM particles
- Visualisation of results is easier

The Large Hadron Collider



LHC at CERN is the largest particle collider in the world

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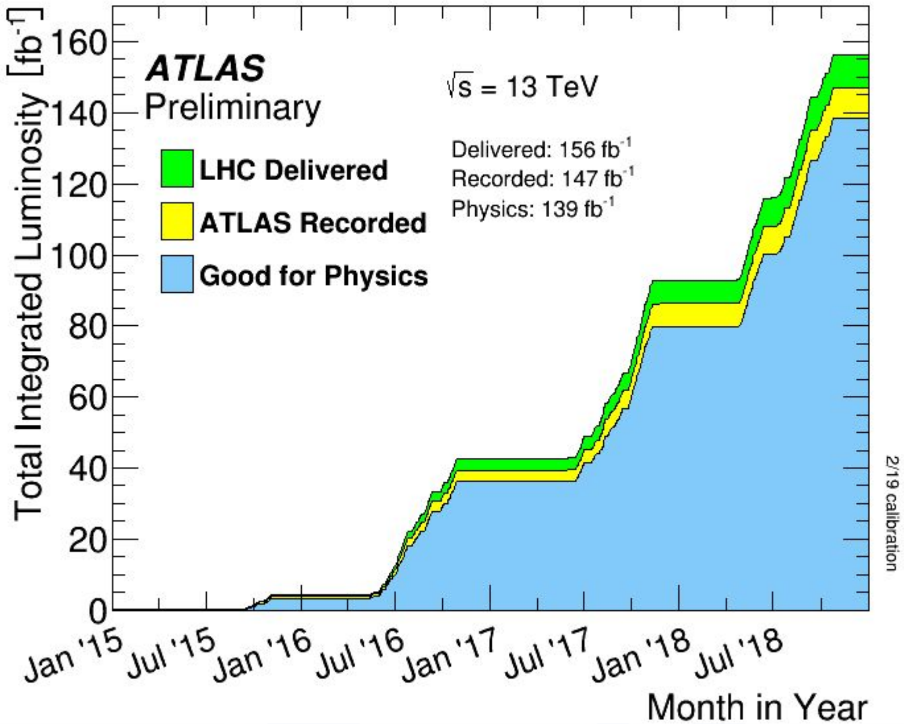


LHC at CERN is the largest particle collider in the world

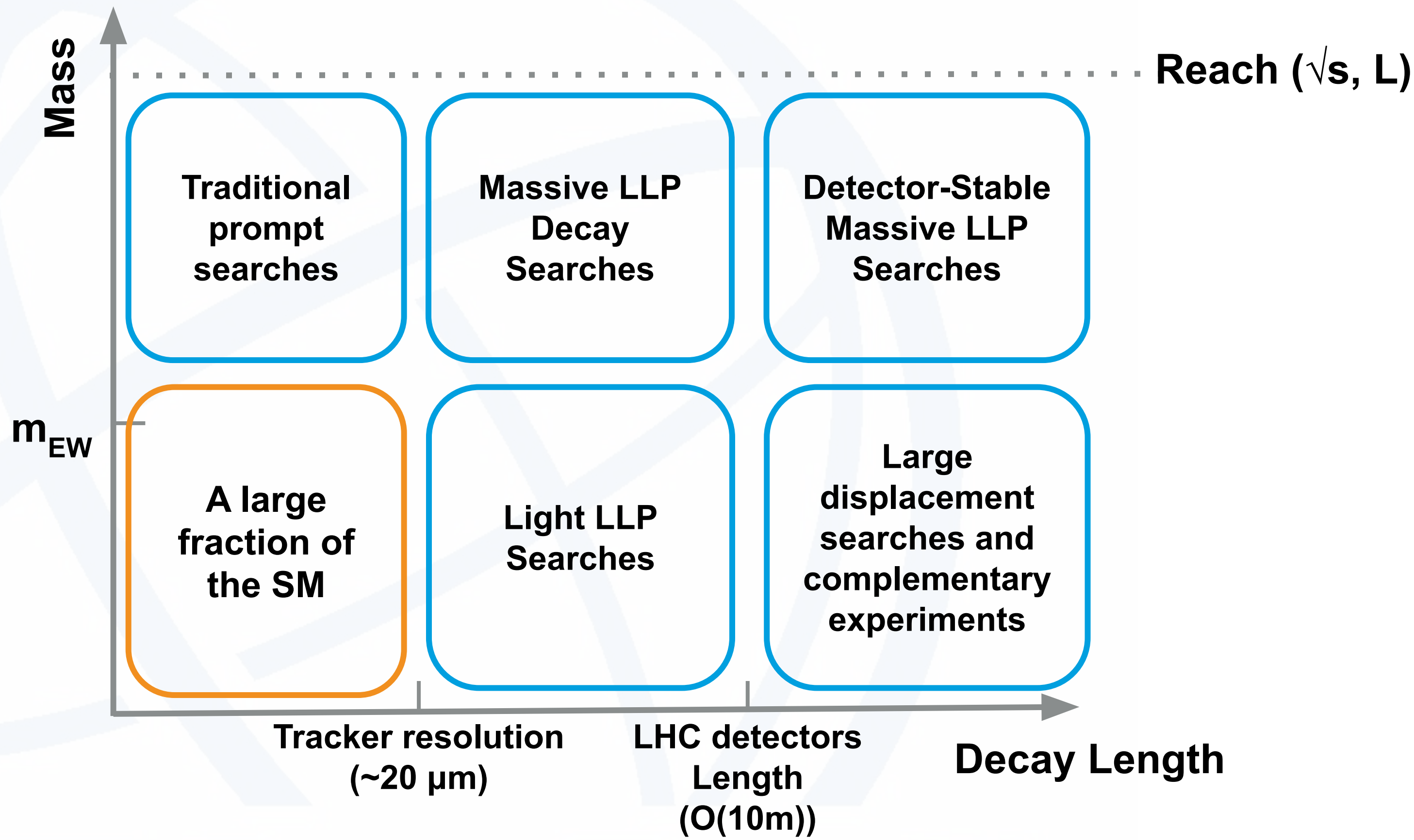
- pp collisions at $\sqrt{s}$ = 7 TeV (2010-2011)
- pp collisions at $\sqrt{s}$ = 8 TeV (2012)
- pp collisions at $\sqrt{s}$ = 13 TeV (2015-2018)

Today: full ATLAS Run 2 data ($\sqrt{s}$ = 13 TeV, 139 fb^{-1})

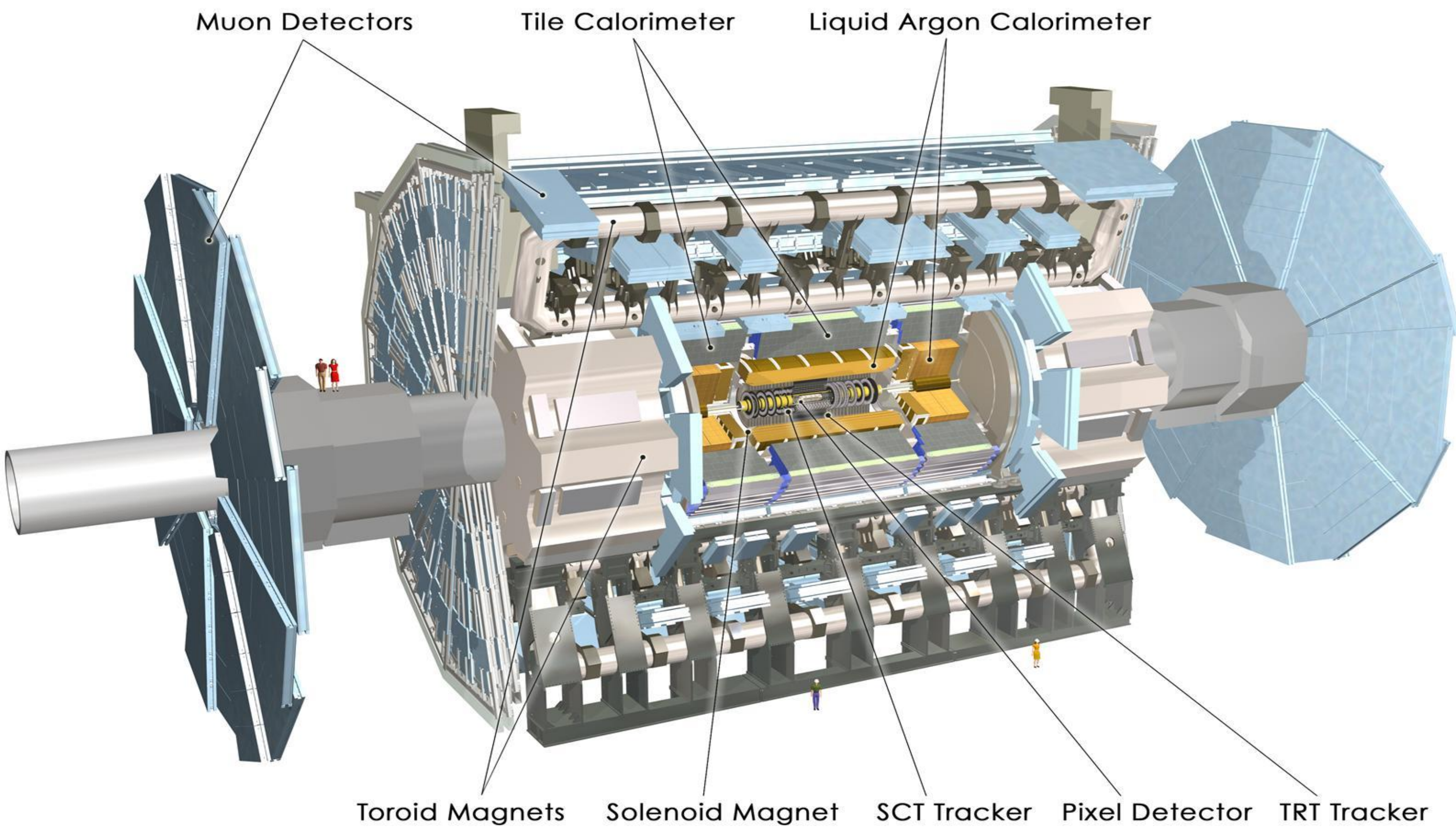
ATLAS Luminosity plots

What can be done at the LHC

A mass vs decay length map



The ATLAS experiment

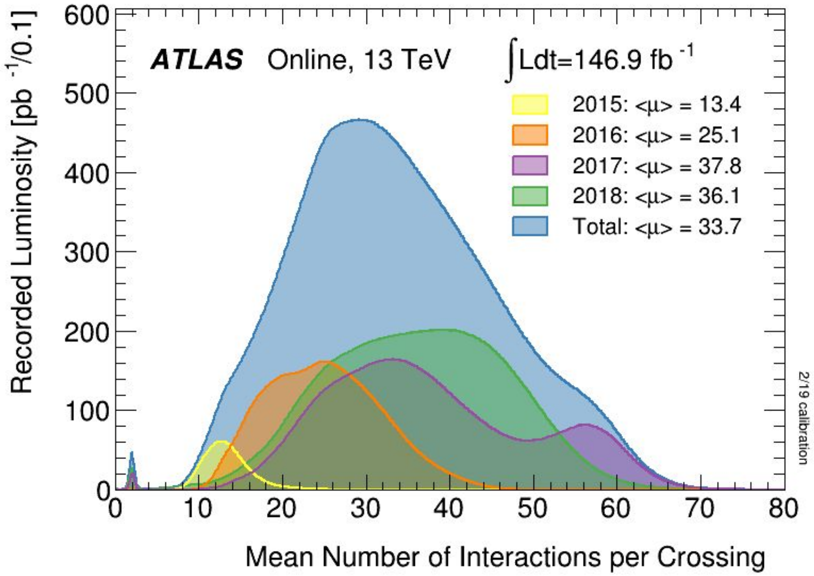


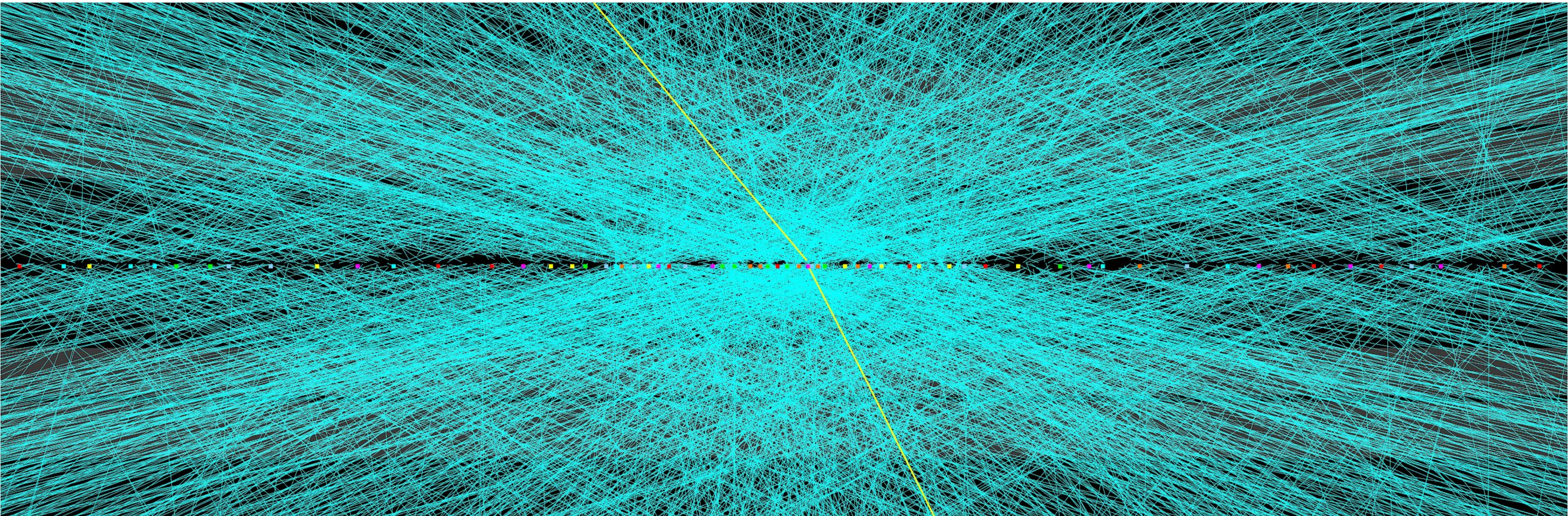
Detection environment

The pile-up challenge

In order to collect a large amount of interesting data, we need to increase the collision intensity

- Several *pp* interactions happen for each bunch crossing
- Need robust reconstruction techniques

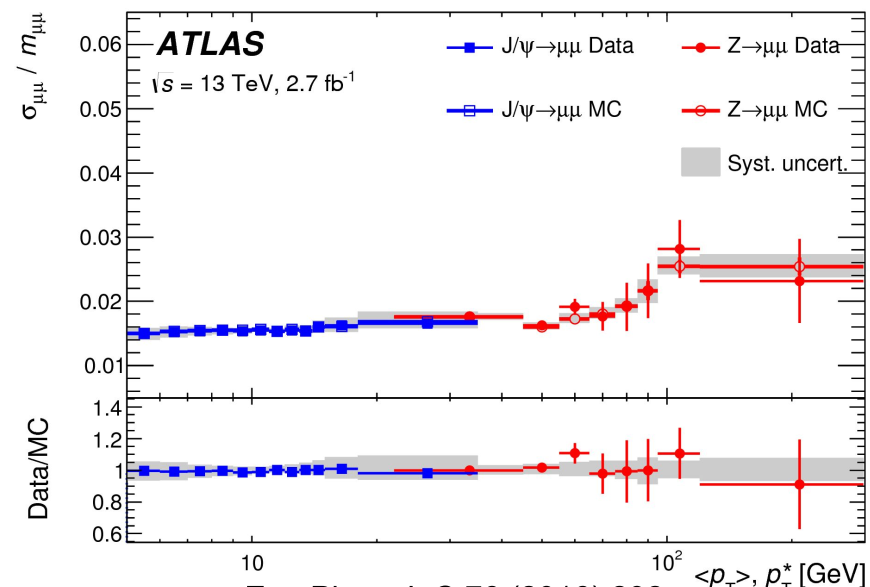




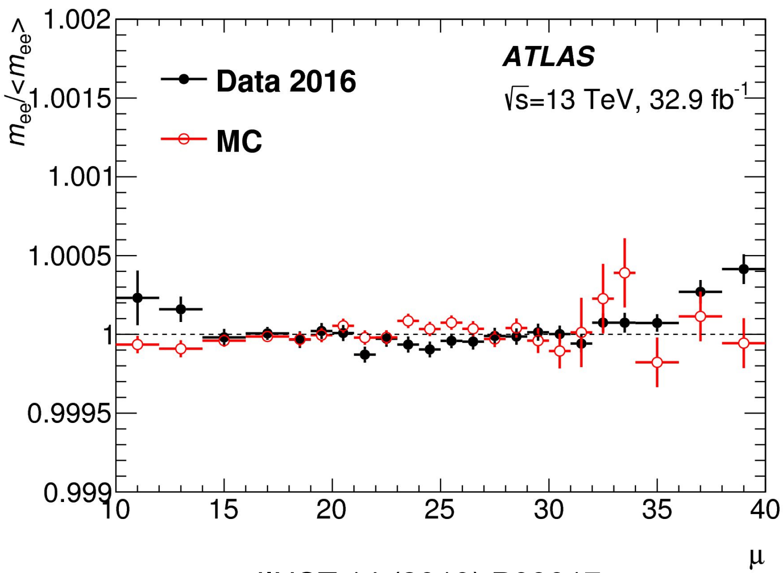
Detector performance

Impressive performance

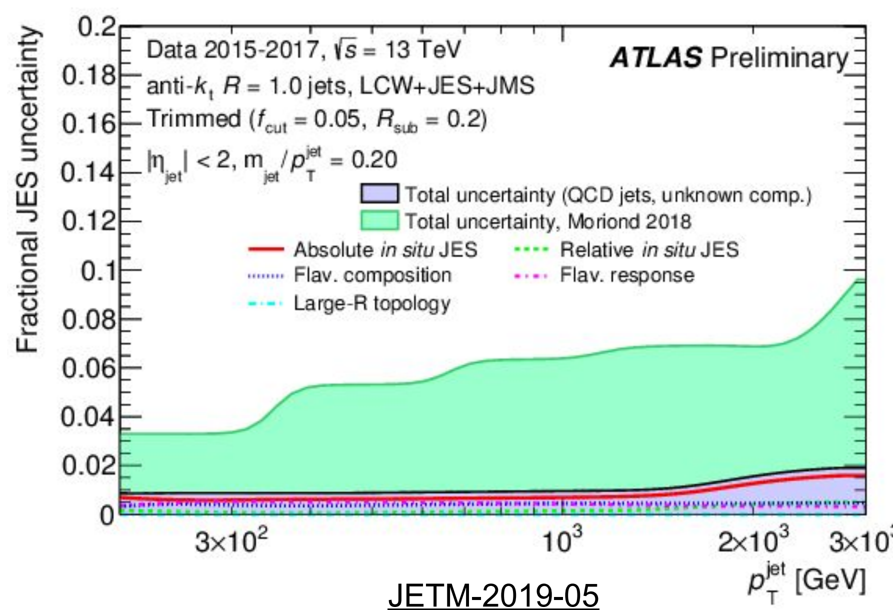
- Precision attained in LHC Run 1 surpassed, even in a harsher environment



Eur. Phys. J. C 76 (2016) 292



JINST 14 (2019) P03017



JETM-2019-05

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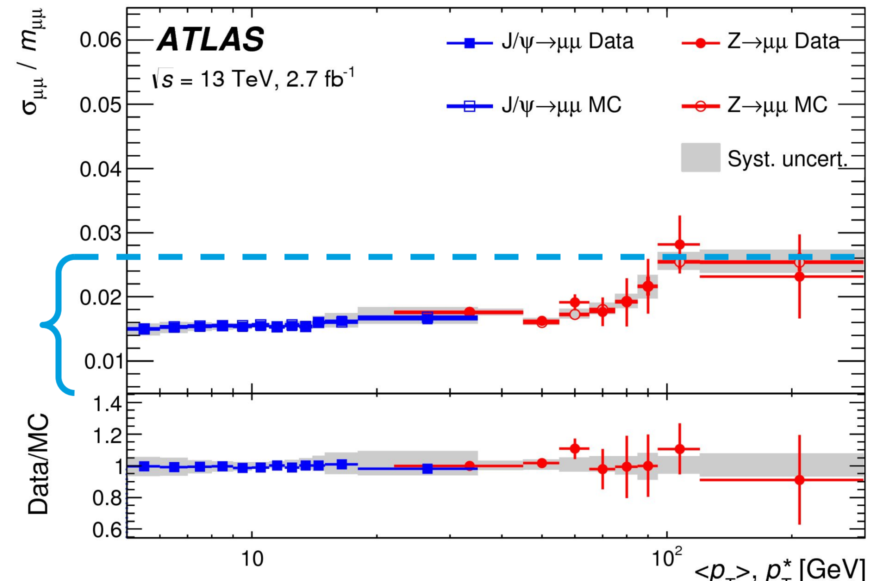

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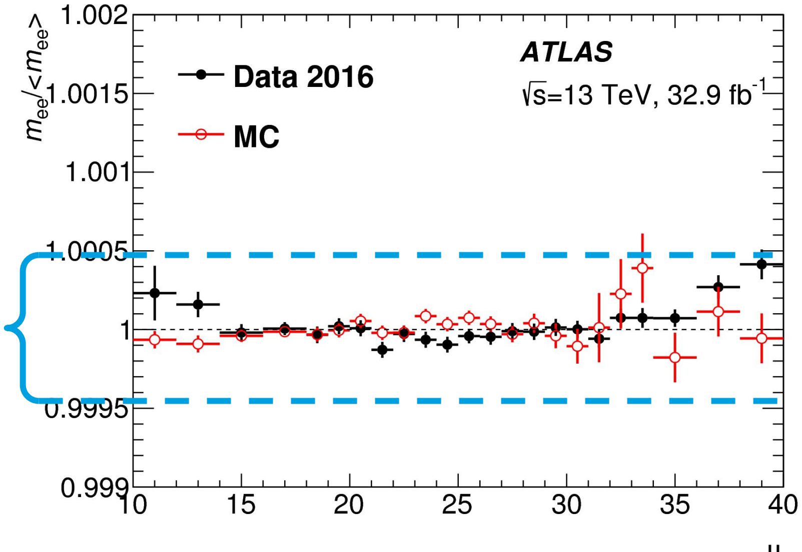

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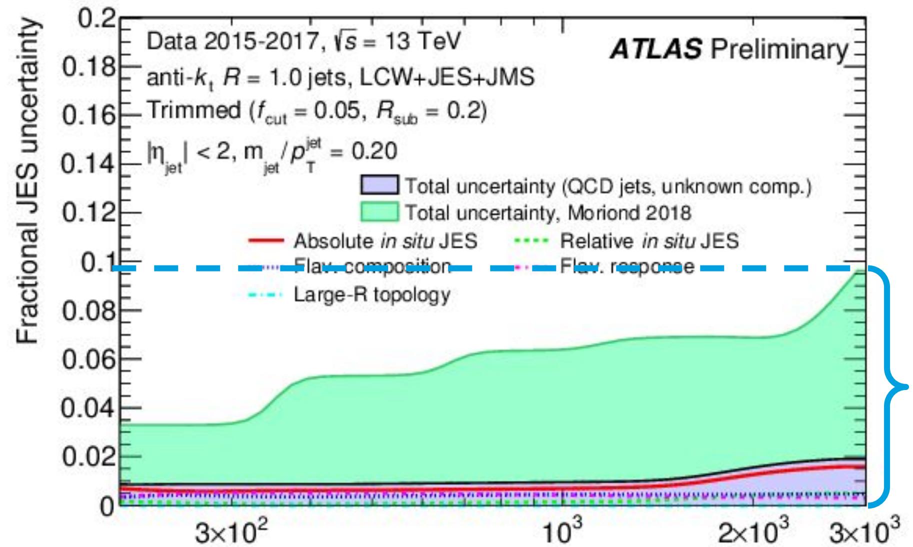
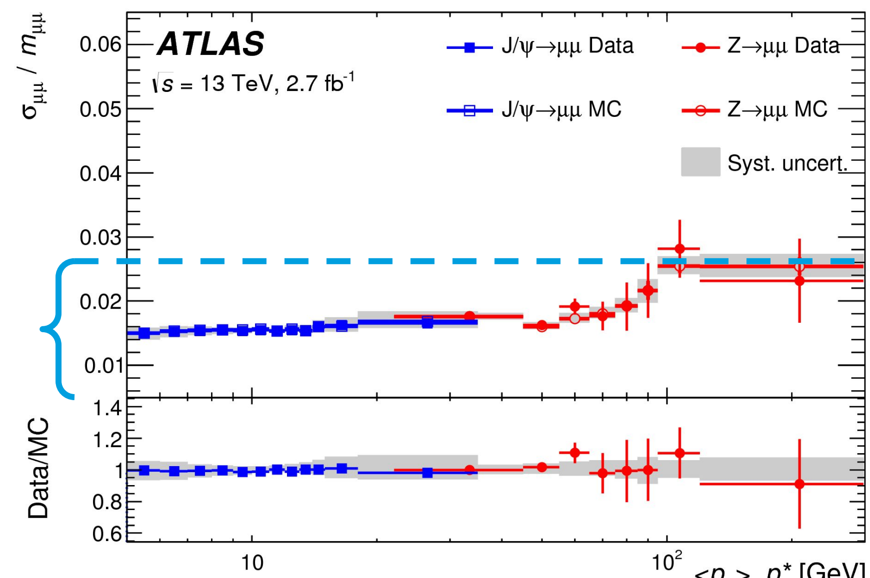


JETM-2019-05

Detector performance

Impressive performance

- Precision attained in LHC Run 1 surpassed, even in a harsher environment
- **LLPs need specialised tools!**



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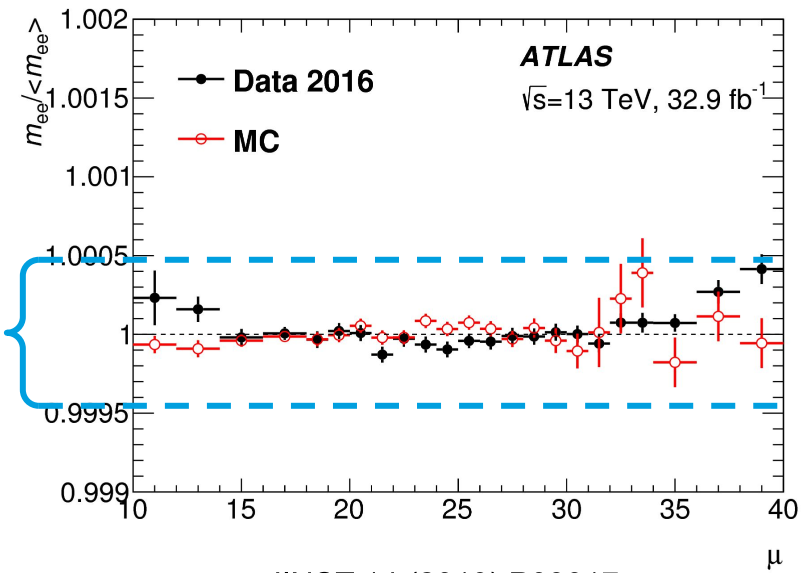

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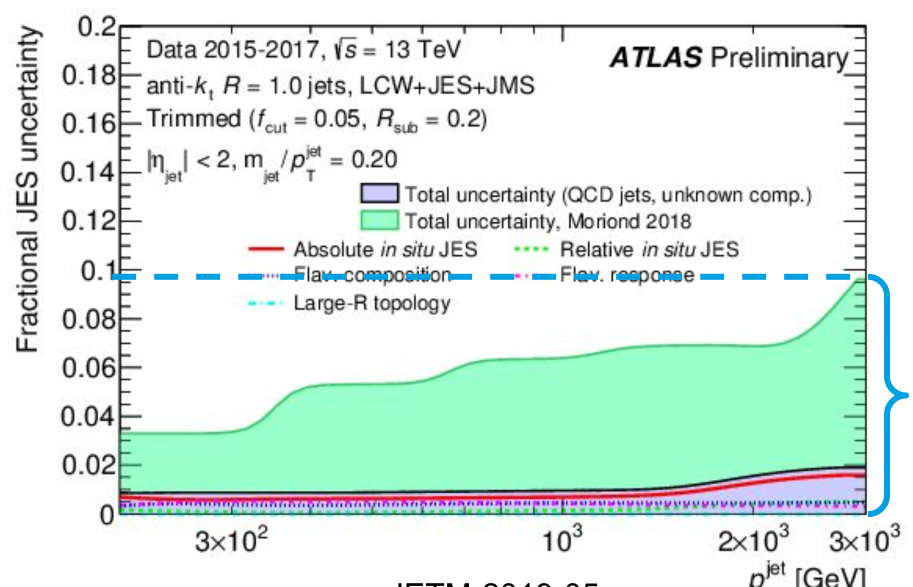

JETM-2019-05

Reconstructing tracks with large displacement

The ATLAS "large radius" tracking

Standard tracking is optimised for tracks originating from interaction point

	Standard	Large radius
Maximum d_0 (mm)	10	300
Maximum z_0 (mm)	250	1500
Maximum $\|\eta\|$	2.7	5
Maximum shared silicon modules	1	2
Minimum unshared silicon hits	6	5
Minimum silicon hits	7	7
Seed extension	Combinatorial	Sequential

ATL-PHYS-PUB-2017-014

Reconstructing tracks with large displacement

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Standard tracking is optimised for tracks originating from interaction point

Large radius tracking (LRT) is an additional pass of tracking with loosened impact parameter and hit requirements

- Perform inside-out tracking **using unused hits** with loose cuts
- Output track collection merged with standard track collection

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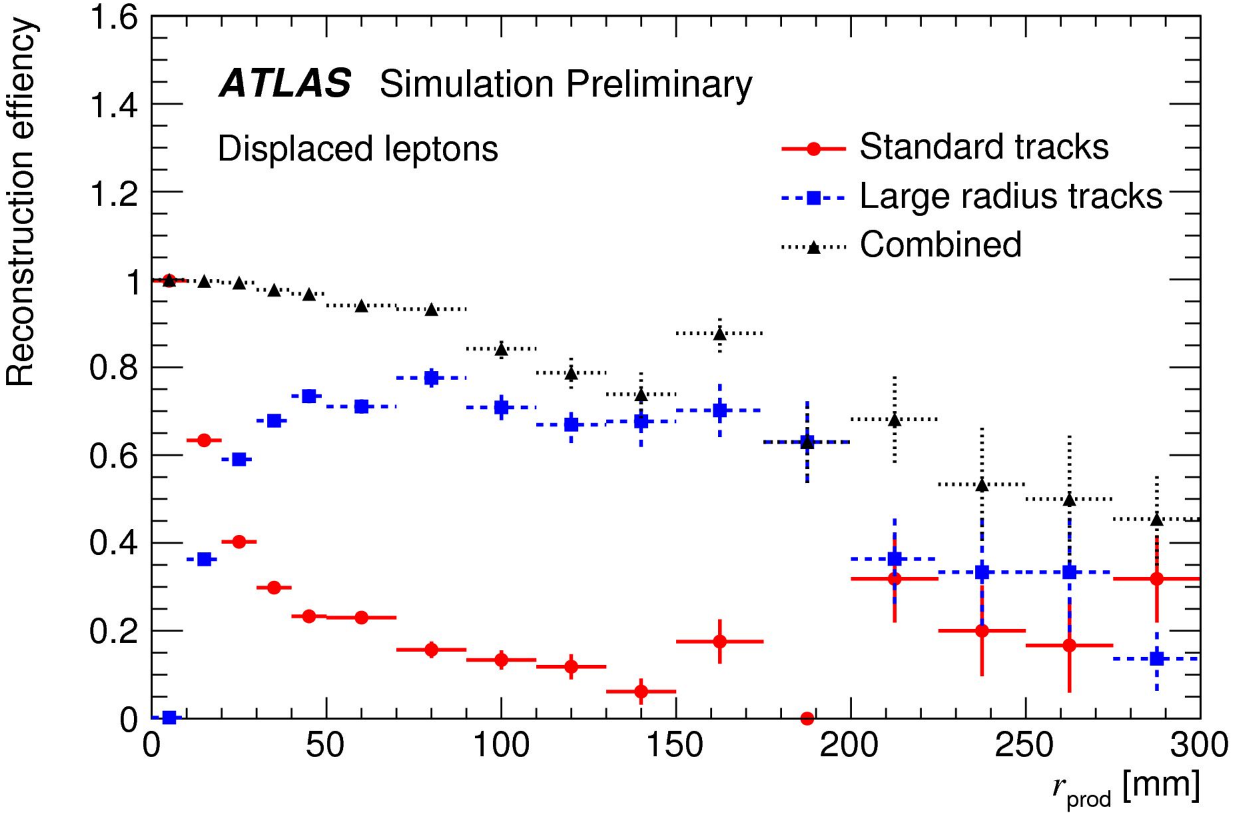
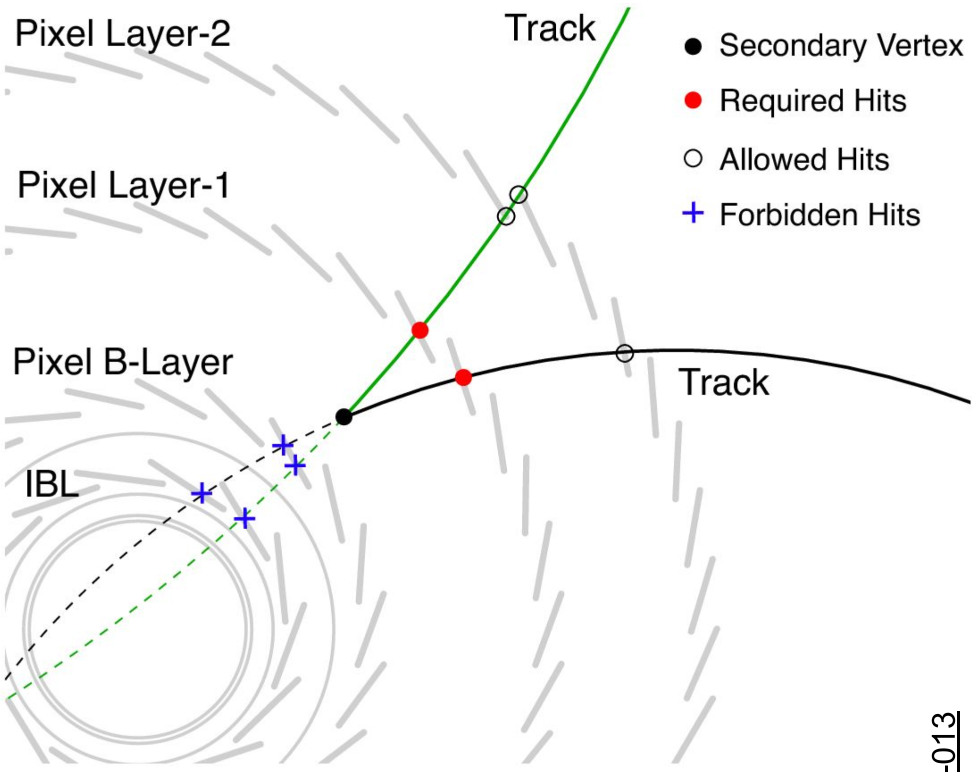


Displaced vertex reconstruction

Building on large radius tracks

Dedicated secondary displaced vertex (DV) reconstruction algorithm

- Two-track seed vertices from high-quality tracks
- Merge nearby vertices
- Lower-quality tracks not initially preselected for vertex seeding are attached to compatible vertices



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Displaced vertex reconstruction

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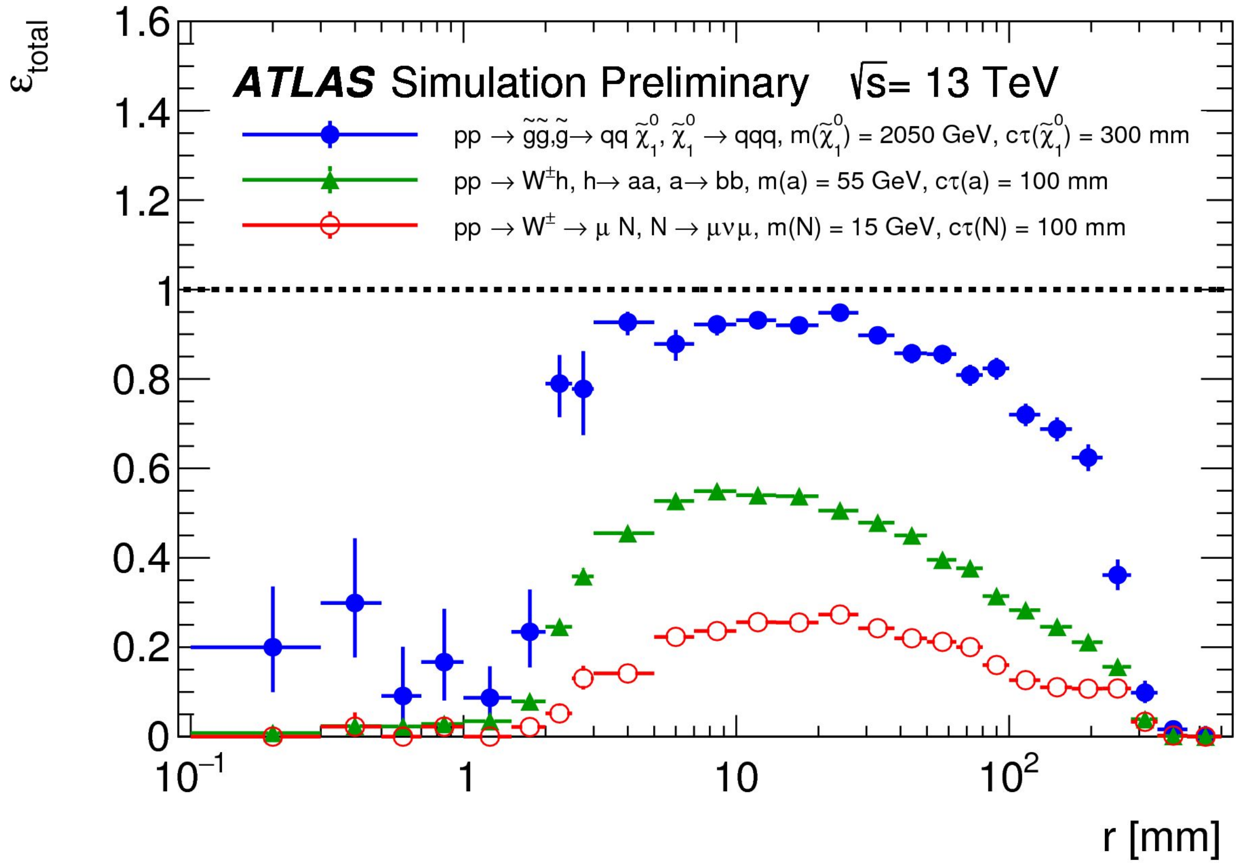

The ATLAS LLP search programme

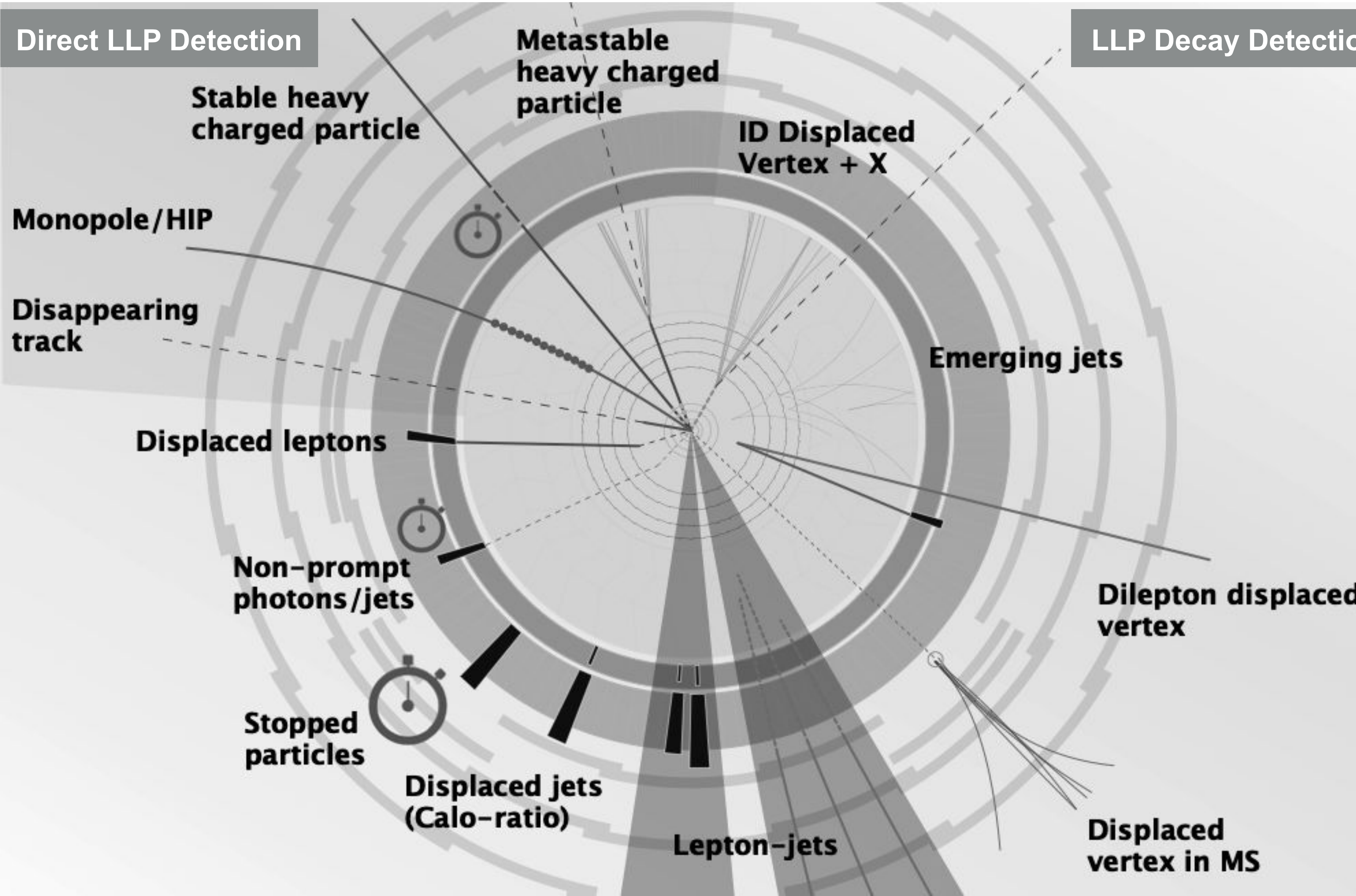

Image credit : H.Oide

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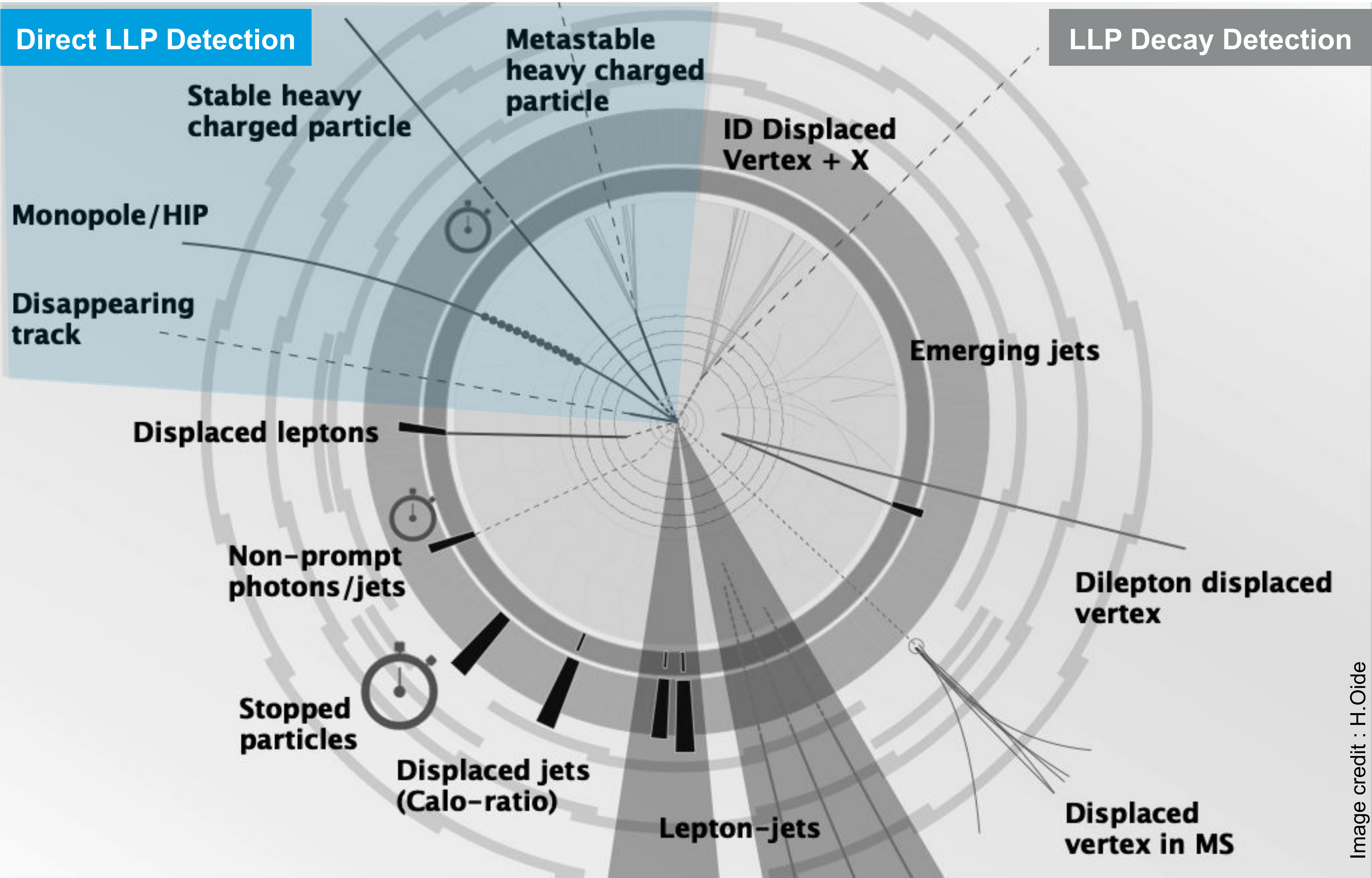

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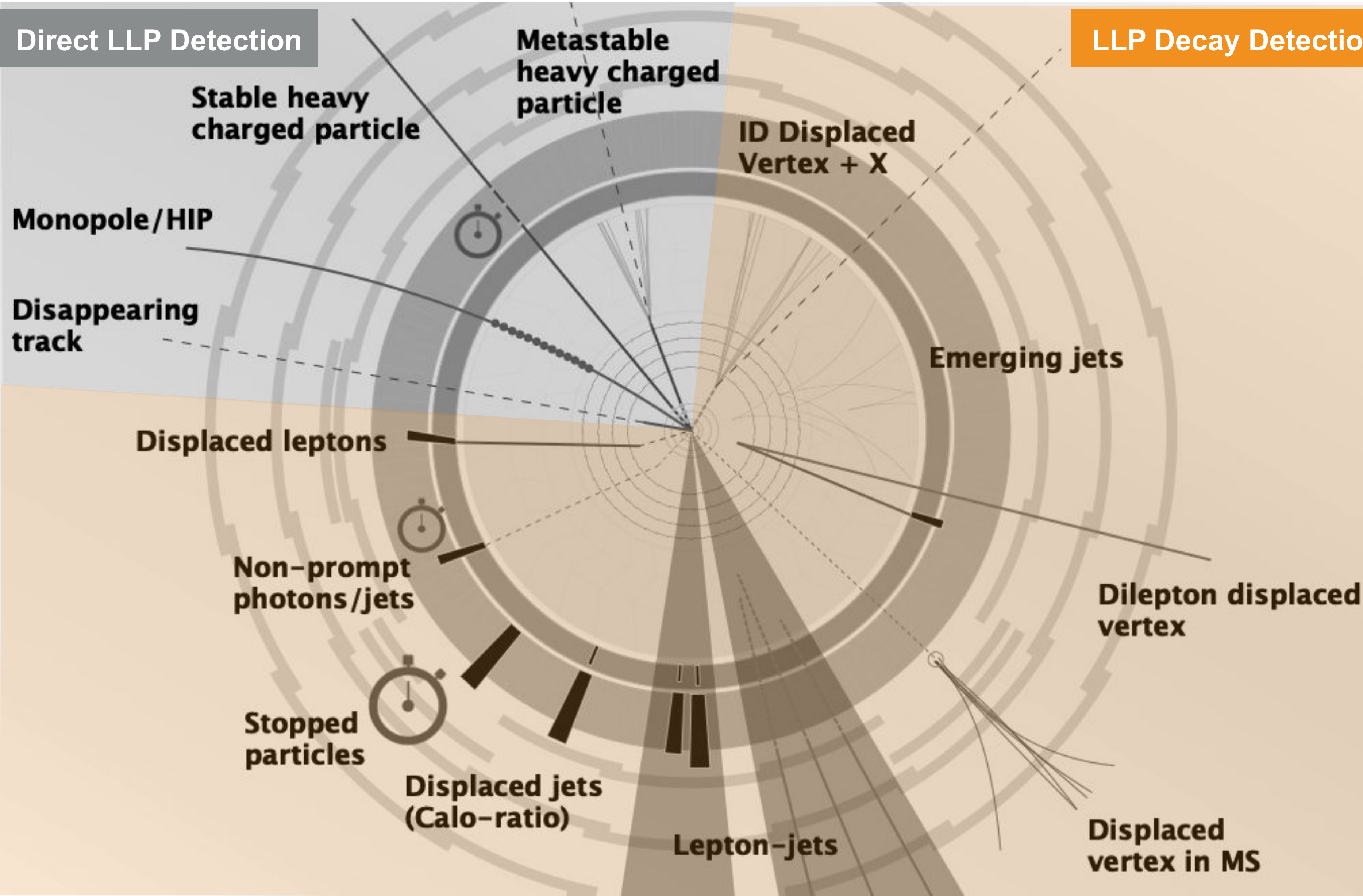


Image credit : H.Oide

Common analysis strategies

The path to discovery

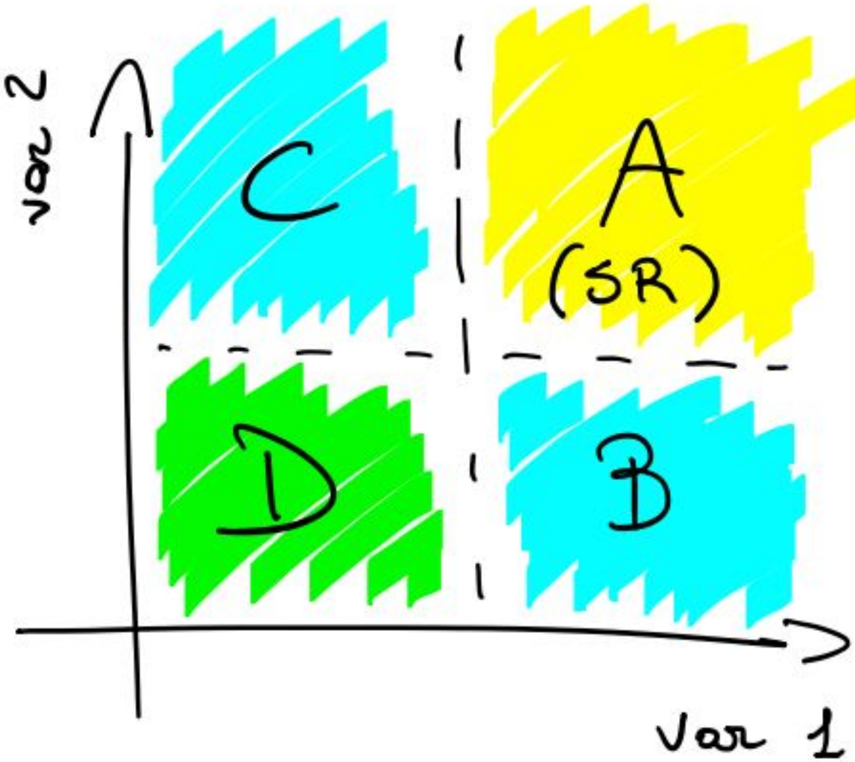
1. Define a signal region (SR) based on signal kinematic features
   - **Often nearly background free!**

2. Build a background model:

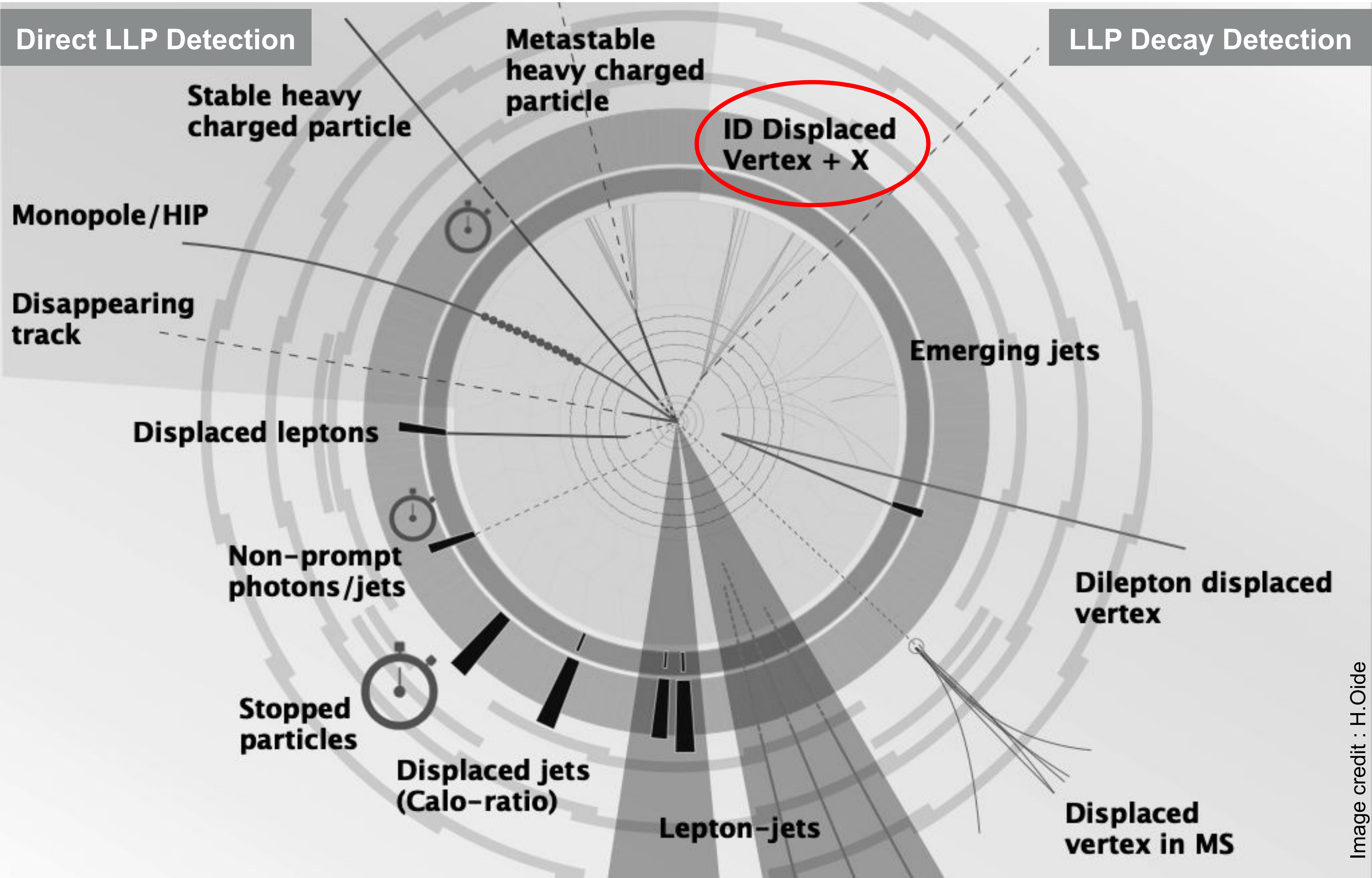
   - LLP backgrounds are non-standard
   - Prefer data-driven to Monte Carlo based
   - Keep it simple! “ABCD”

3. Validate background model in dedicated regions

4. Look at the data!

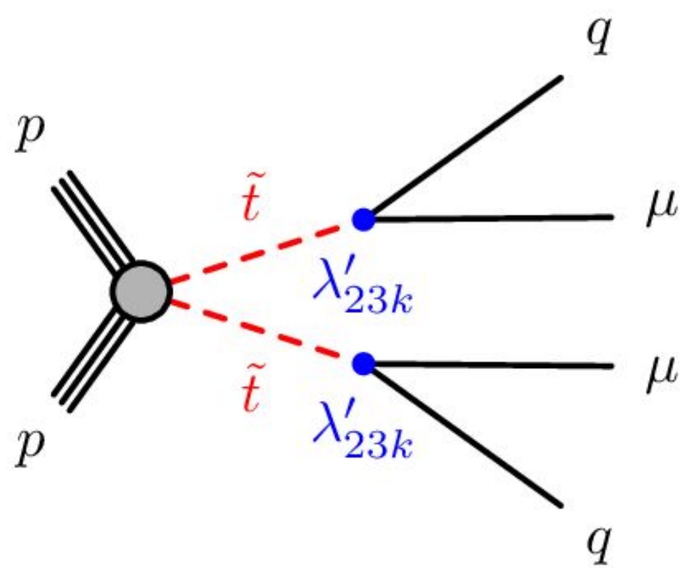


First example: displaced ID vertex + muon



Displaced ID vertex + muon

R-parity violating Supersymmetry



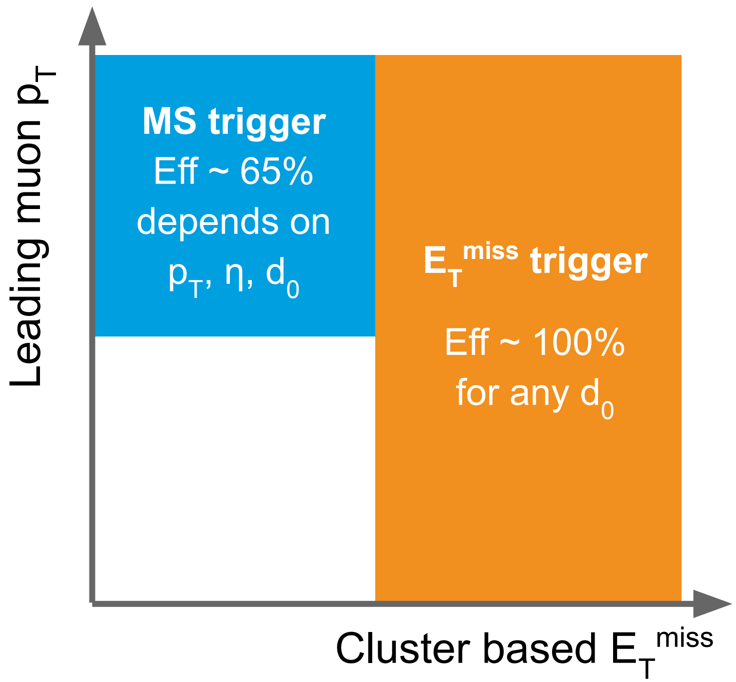
Small λ' couplings result in a long-lived top squark

Use model as a benchmark but retain sensitivity to other signals

- The muon is not required to originate from the displaced vertex

Phys. Rev. D 102 (2020) 032006

Online selection strategy (trigger)

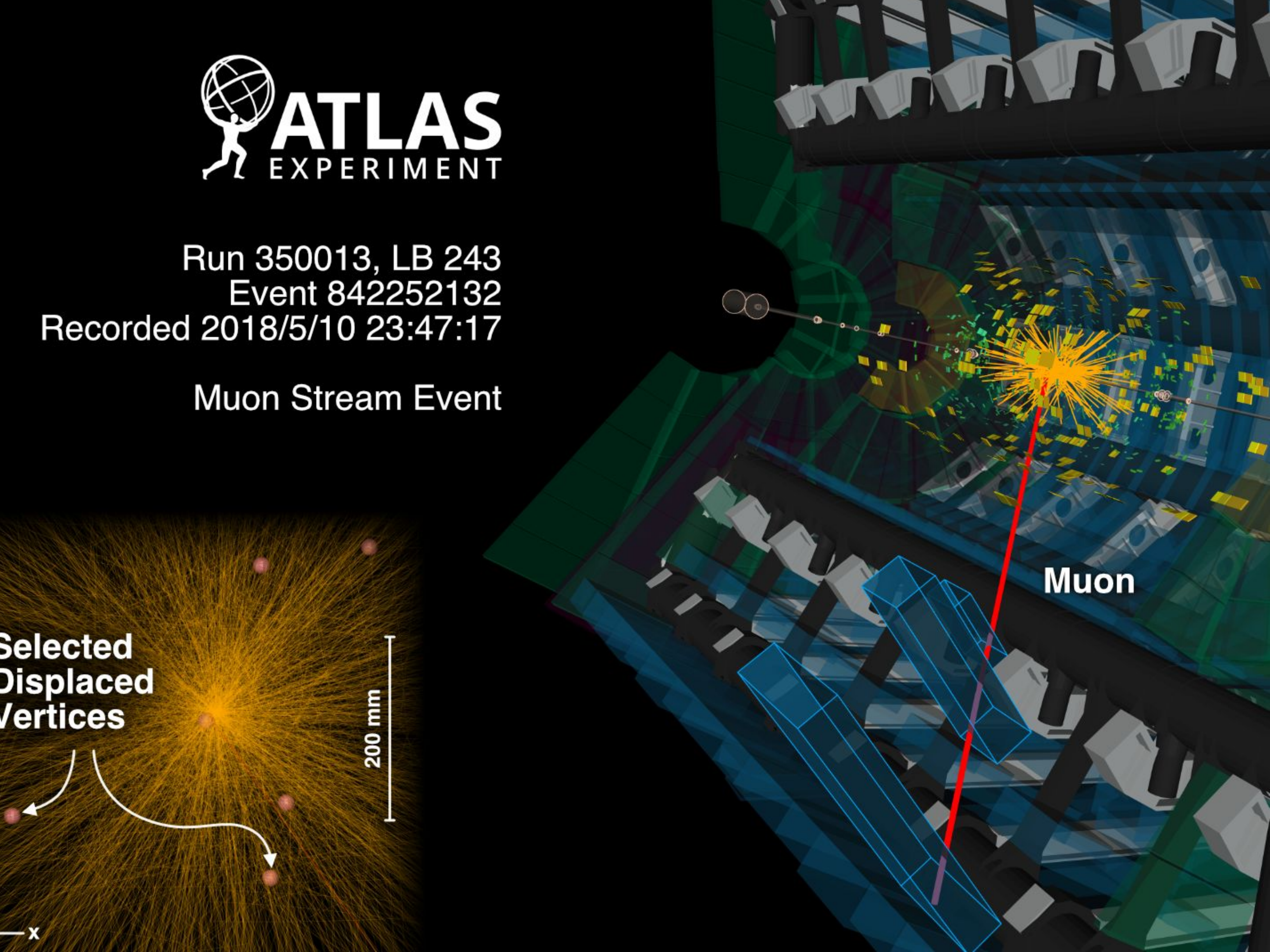


Two complementary triggers for displaced muons:

- Muon Spectrometer-only trigger ($p_T(\mu) > 62$ GeV, $|\eta| < 1.05$)
- **New since Run 1: E_T^{miss} trigger** ($p_T(\mu) > 25$ GeV, $|\eta| < 2.5$)

Keep selections fully orthogonal:

- Different backgrounds (cosmic-ray vs fake muons)


ATLAS
EXPERIMENT
Run 350013, LB 243
Event 842252132
Recorded 2018/5/10 23:47:17
Muon Stream Event
Muon
Selected
Displaced
Vertices
200 mm
x

Displaced vertex selections

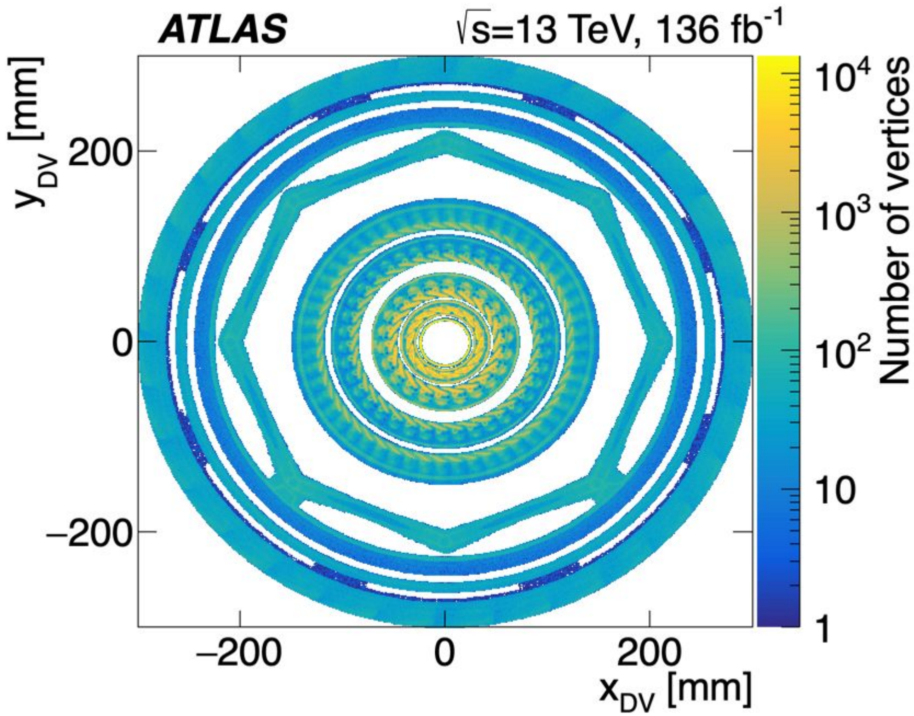
Loose preselection:

- R_{xy} < 300 mm and |z| < 300 mm
- Displacement: R_{xy} > 4 mm

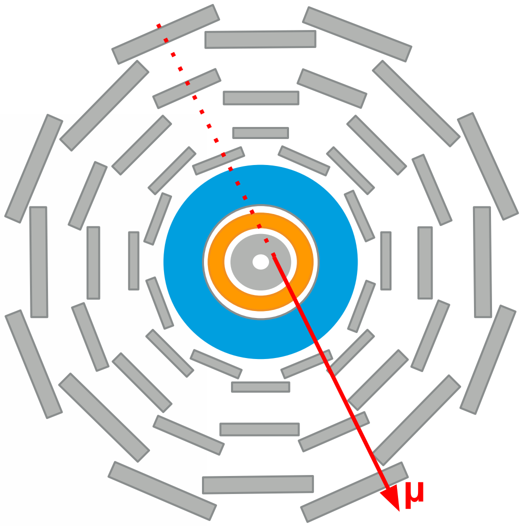
- **Hadronic interactions veto** via data-driven material map built from low-mass vertices

Signal displaced vertices:

- ≥3 tracks
- m_{vis} > 20 GeV



Muon selections



Dedicated vetoes to reject muons from backgrounds:

- *Cosmic-ray muon veto*
  - Events that have activity in the MS on the side opposite to the muon are rejected
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Muon selections

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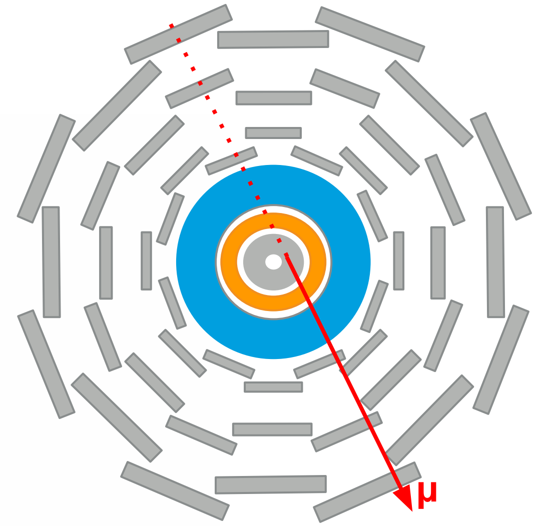
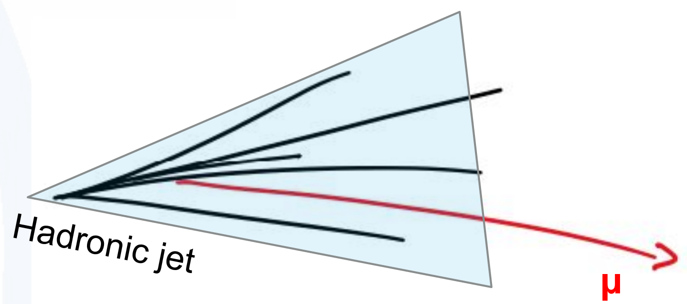
  - Muons are isolated from nearby ID tracks and calorimeter energy deposits





Muon selections

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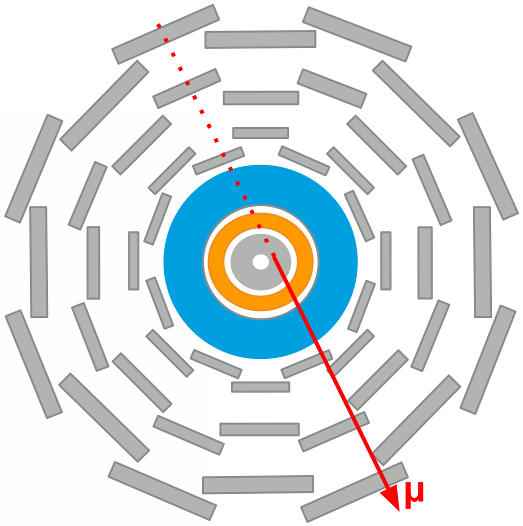
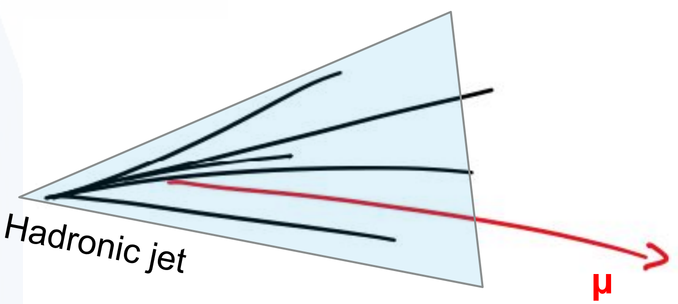
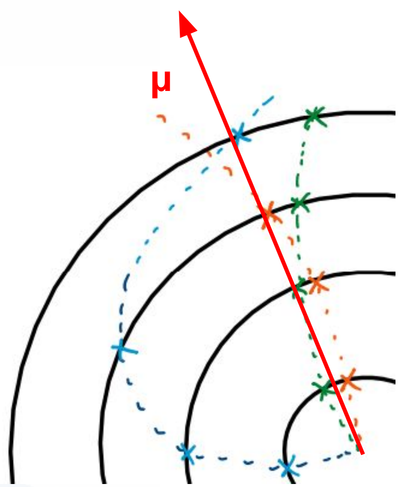
- *Heavy-flavour veto*
  - Muons are isolated from nearby ID tracks and calorimeter energy deposits
- *Fake-muon veto*
  - Muons are reconstructed from at least three MS stations
  - Quality of fit $\chi^2/N_{\mathrm{DoF}} < 8$



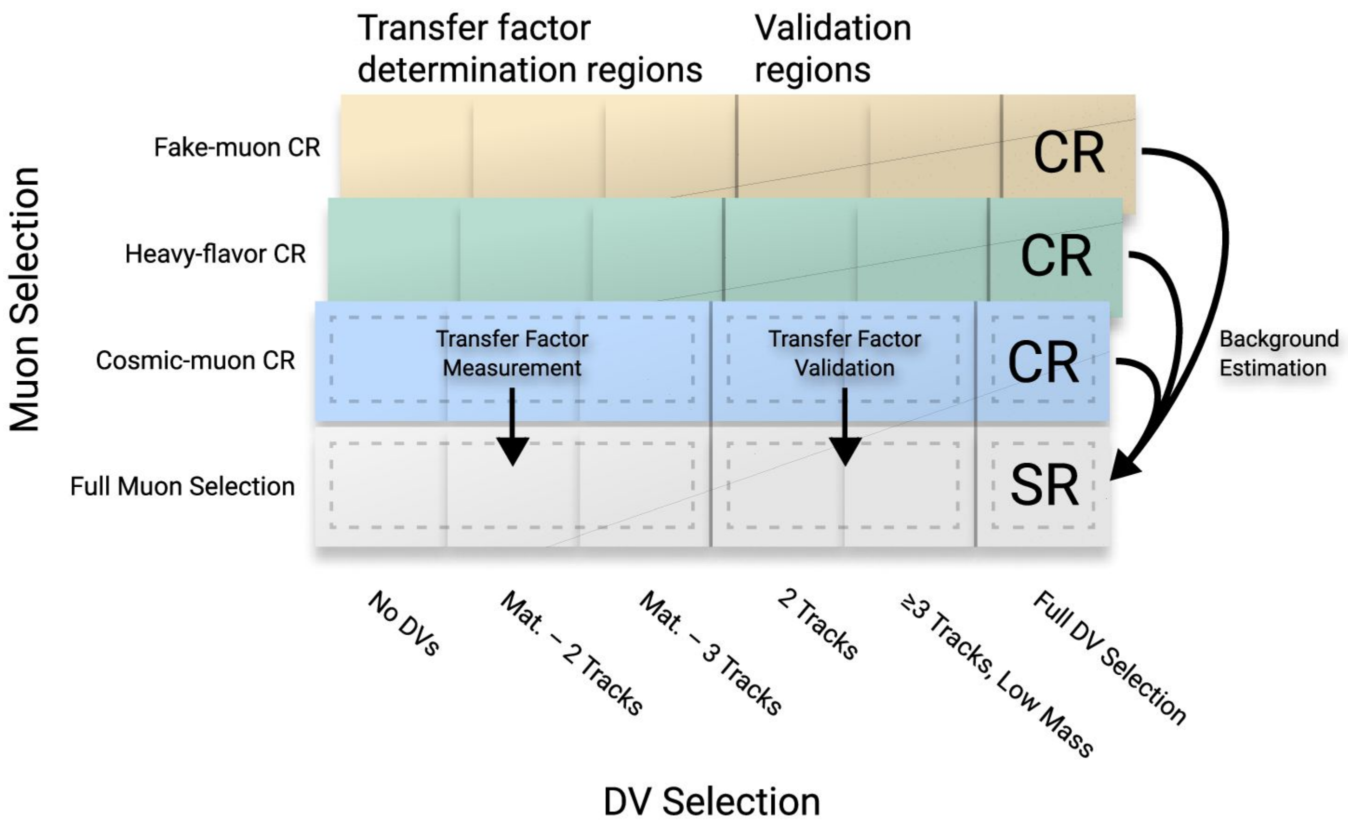




Data-driven background estimation

$$\boxed{N_{SR} = TF \times N_{CR}}$$

Data-driven background estimation

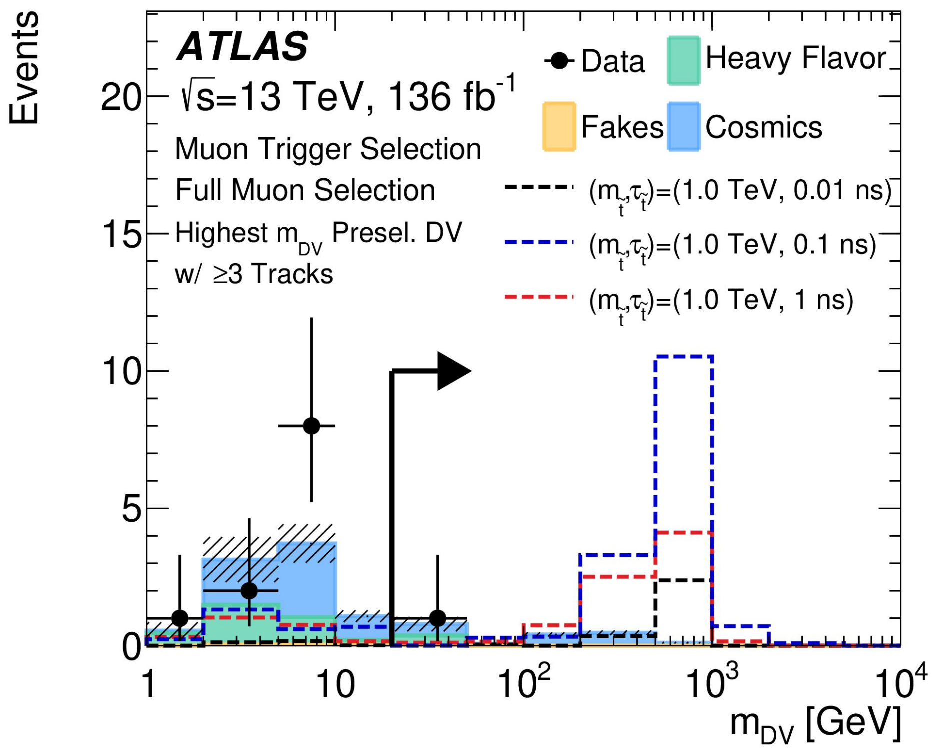


DV uncertainties evaluated using sub-regions with different track multiplicity

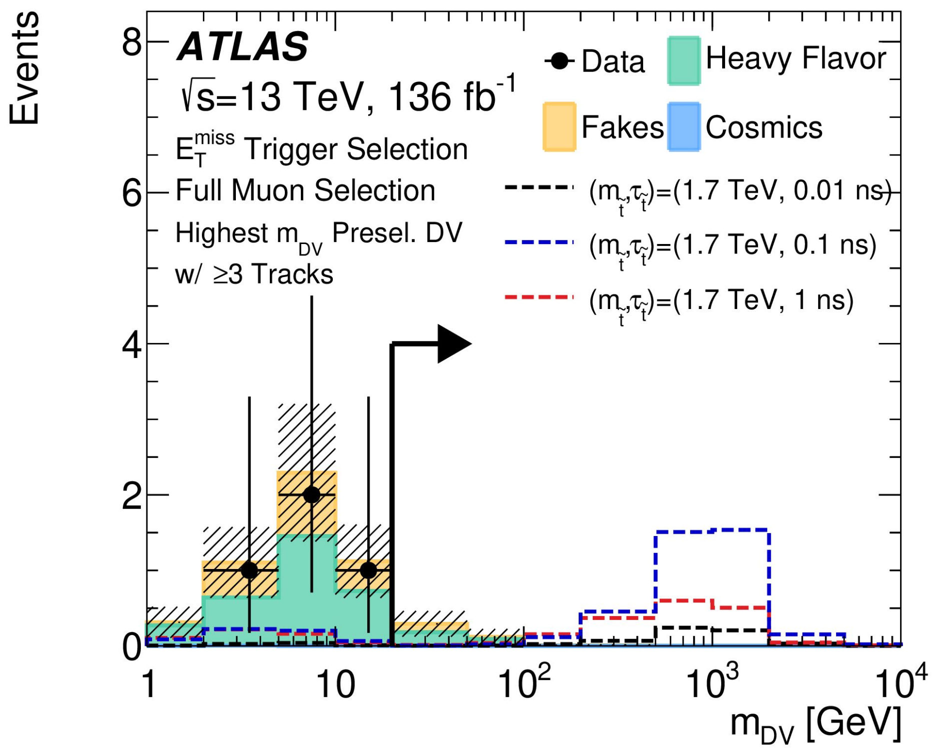
Muon uncertainties evaluated varying d_0 requirements

Results

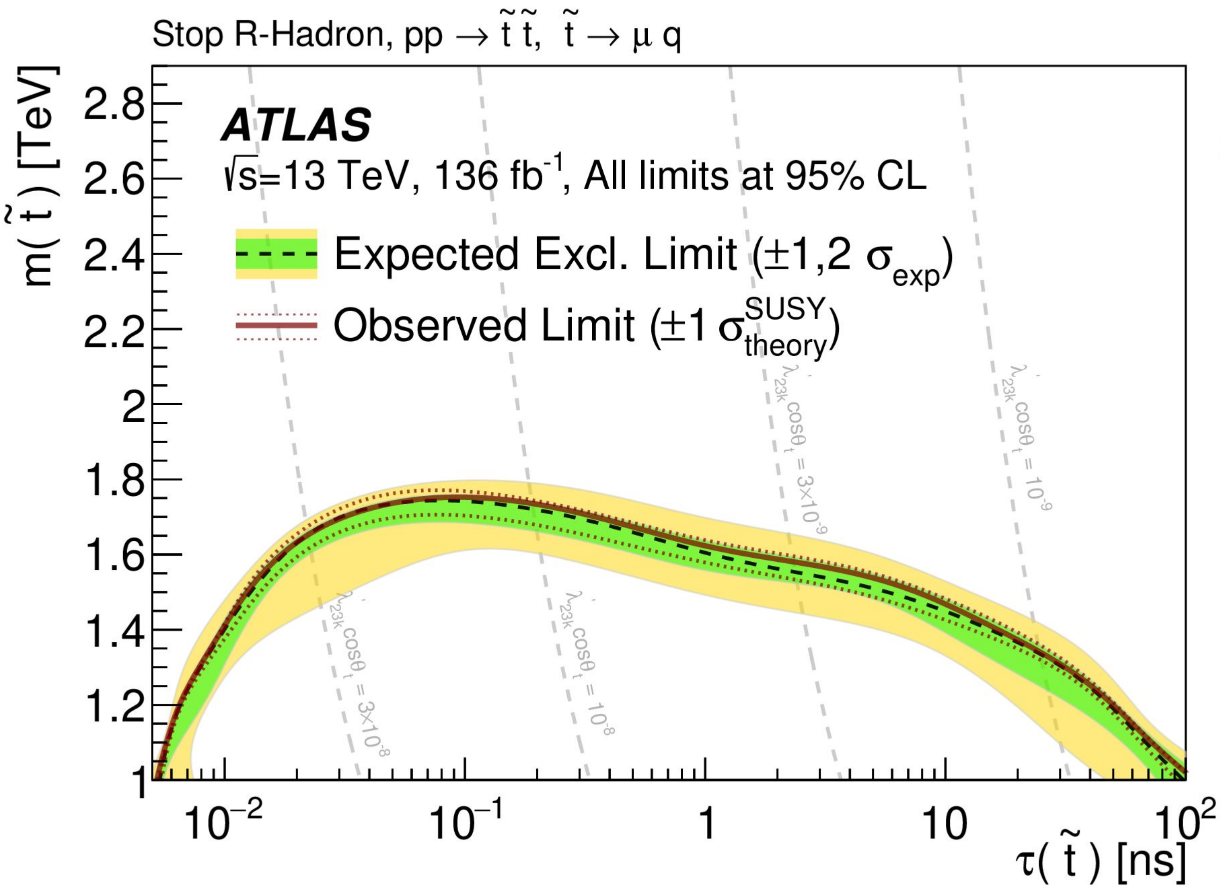
Muon trigger selection

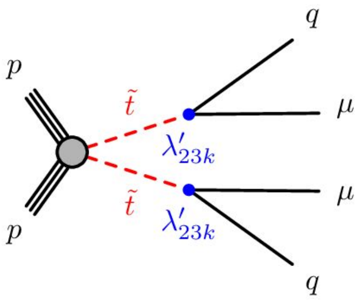


E_T^{miss} trigger selection



Interpretation





Best limits on top squark mass

- Prompt searches reach ~ 1.25 TeV

Second example: displaced leptons

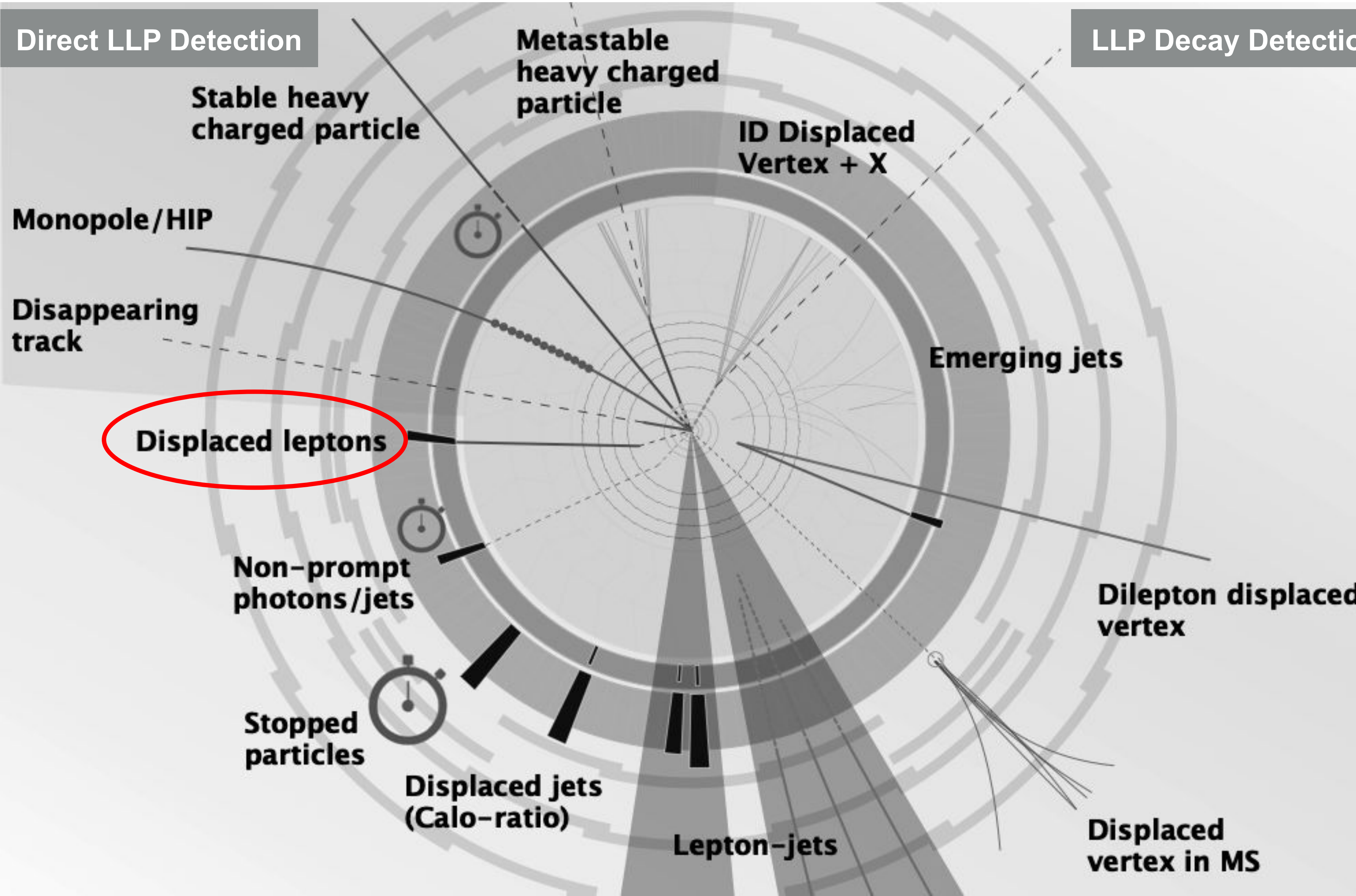
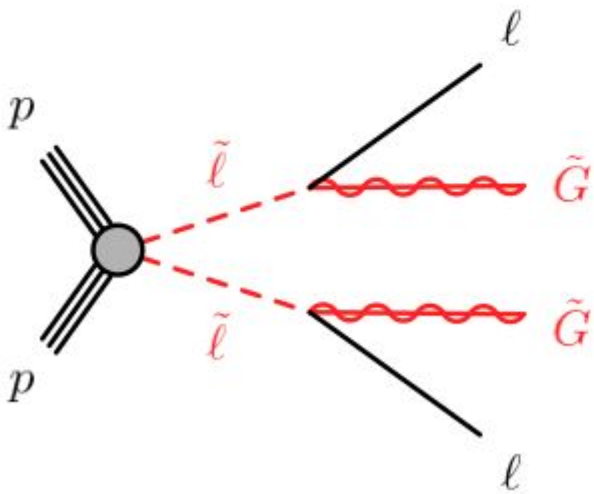
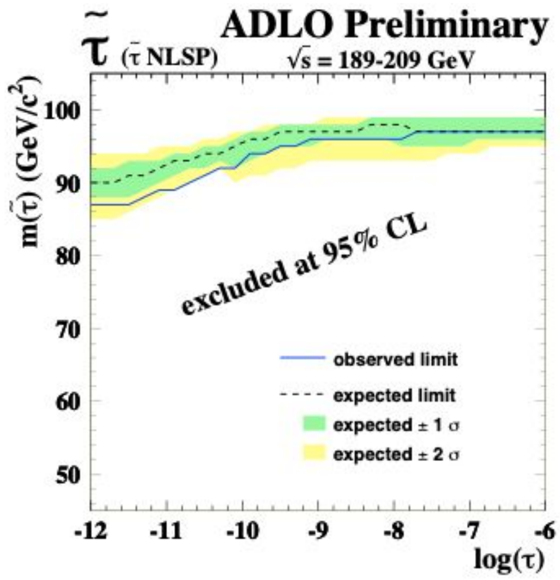


Image credit : H.Oide

Search for displaced leptons

First time in ATLAS



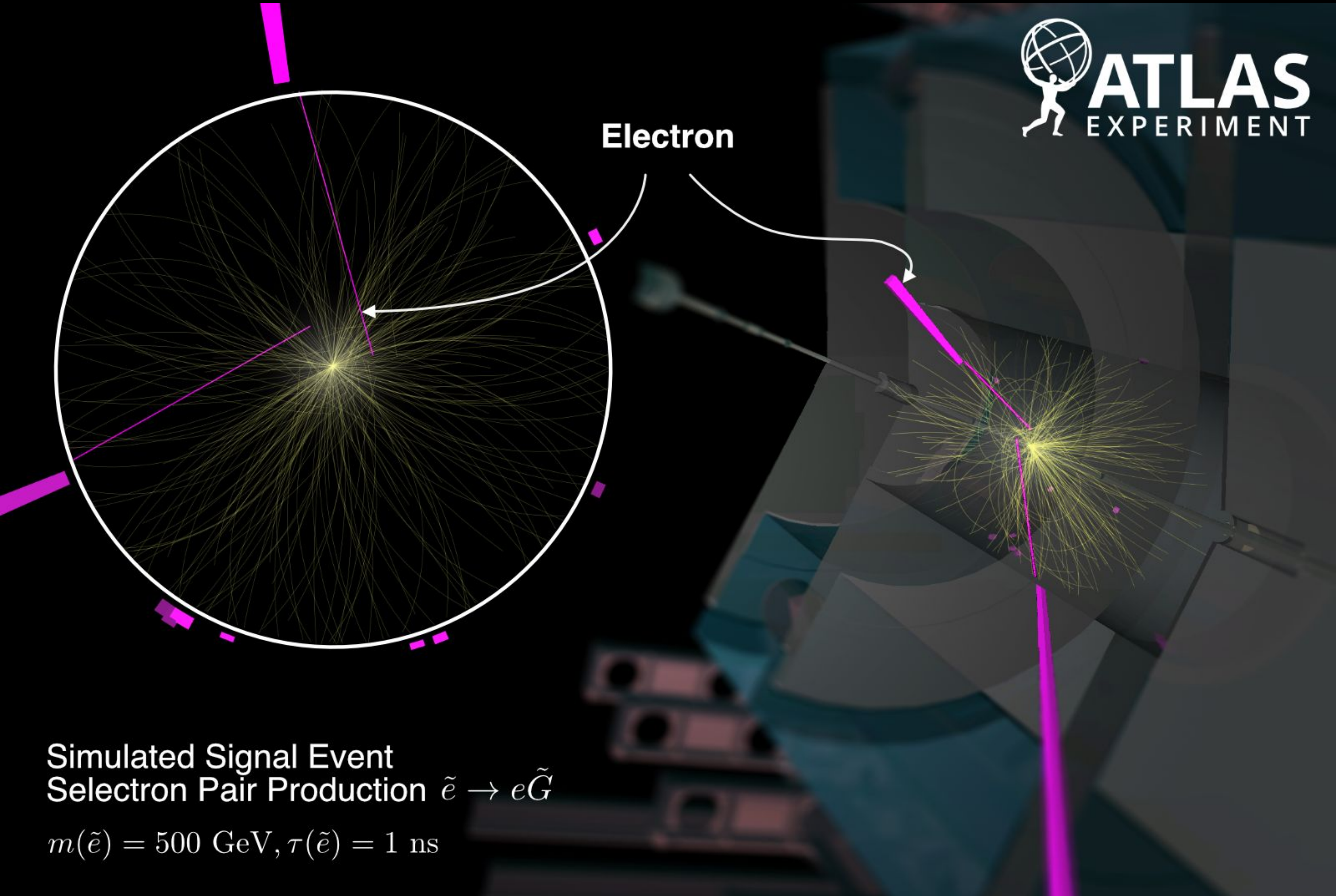


Gauge-mediated SUSY breaking

- Coupling to lightest supersymmetric particle (G) is gravitational and the next-to-lightest SUSY particle (the slepton) becomes long-lived

Previous most stringent limits from LEP: exclude sparticles up to 90 GeV

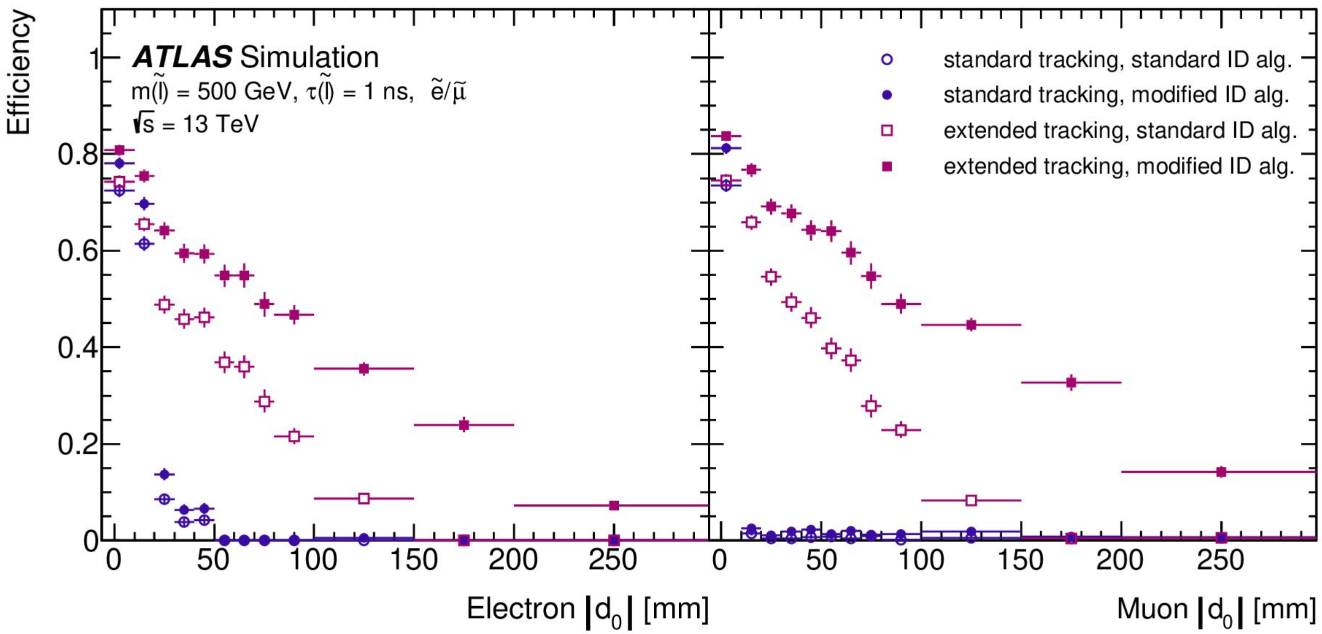
arXiv:2011.07812



Simulated Signal Event
Selectron Pair Production $\tilde{e} \rightarrow e\tilde{G}$

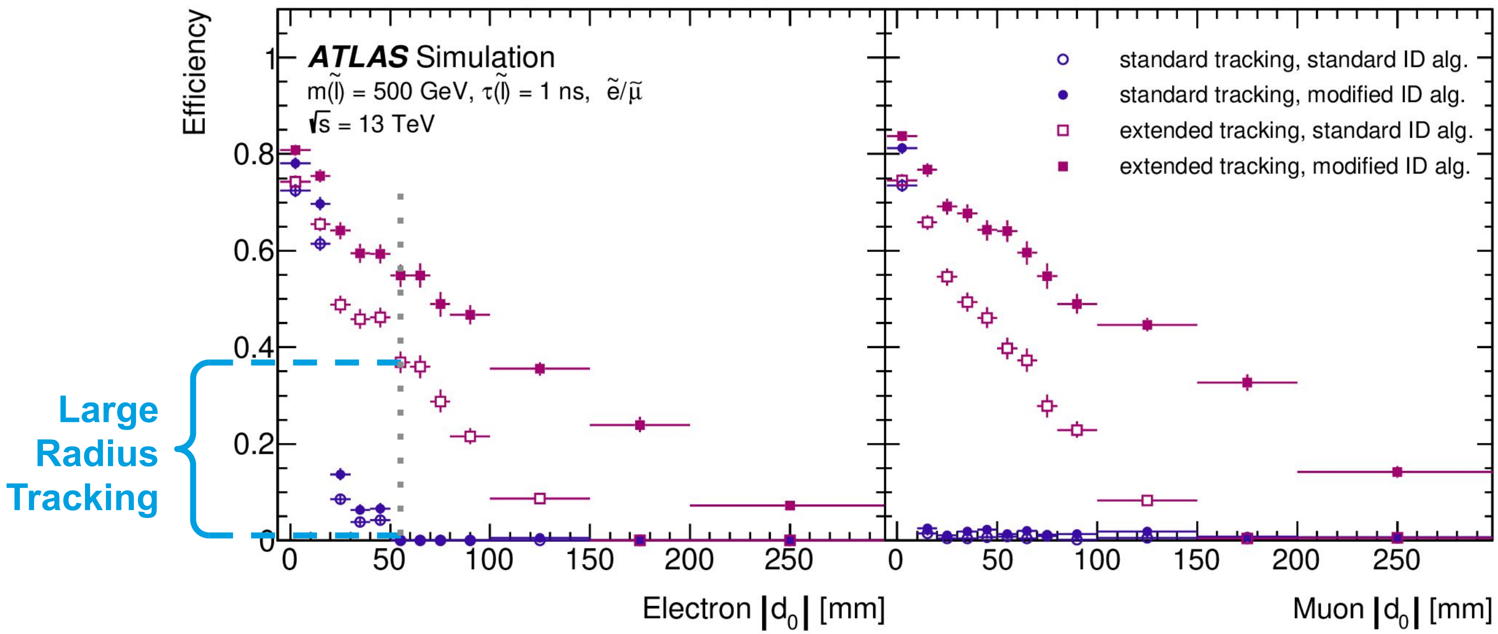
$m(\tilde{e}) = 500\ \mathrm{GeV}, \tau(\tilde{e}) = 1\ \mathrm{ns}$

Dedicated lepton identification



- Exploit tracks from “large radius” reconstruction
- Identification algorithms modified for this search
  - Remove requirements on $|d_0|$ and the number of hits matched to the track

Dedicated lepton identification



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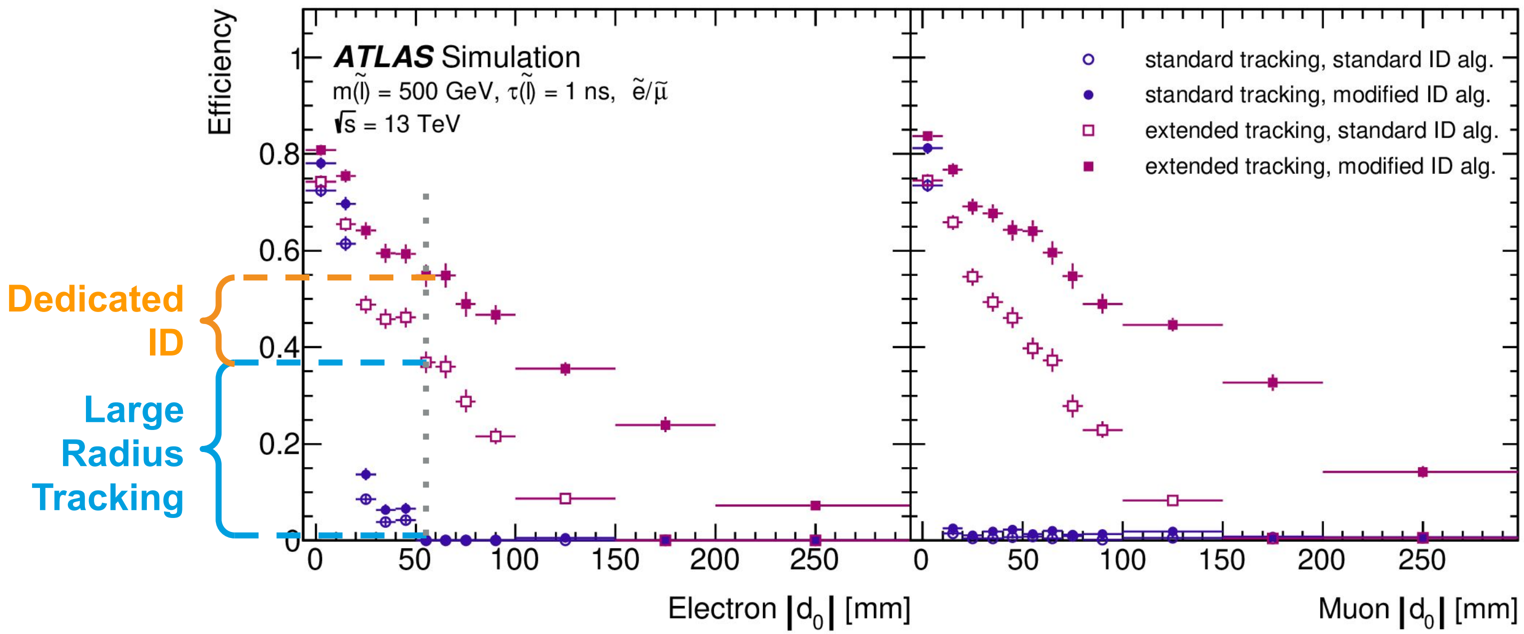

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- **Identification algorithms modified for this search**
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Event selection

Select two leptons (ee, μμ, eμ) with $p_T > 65$ GeV and $|d_0| > 3$ mm

- No requirements on the charge (retain sensitivity to other models)

Trigger requirements (and limitations):

- Single- and di- photon triggers **$p_T > 140$**, 50 GeV
- Muon spectrometer only trigger $p_T > 60$ GeV and **$|\eta| < 1.07$**

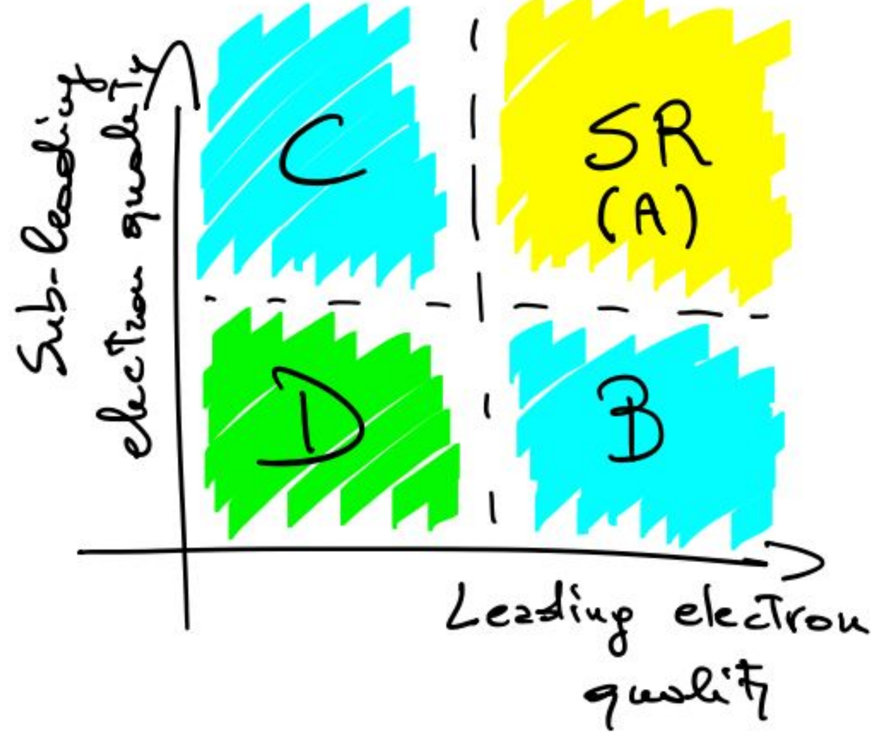
Main backgrounds arise from:

- Cosmic ray muons
- Algorithmic fakes

Algorithmic fakes

Dominant in SR-ee and SR-eμ

- Mostly originates from “large radius” fake tracks.
- More fake electrons than fake muons

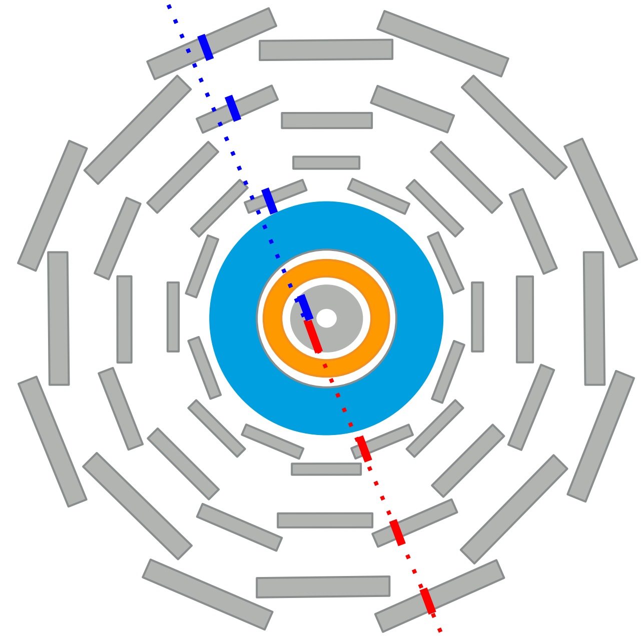


Estimated using ABCD method

Validation:

- Heavy-flavour inverting the isolation requirement
- Fake-lepton contribution inverting and varying the requirements on track quality and lepton consistency

Cosmic ray muons

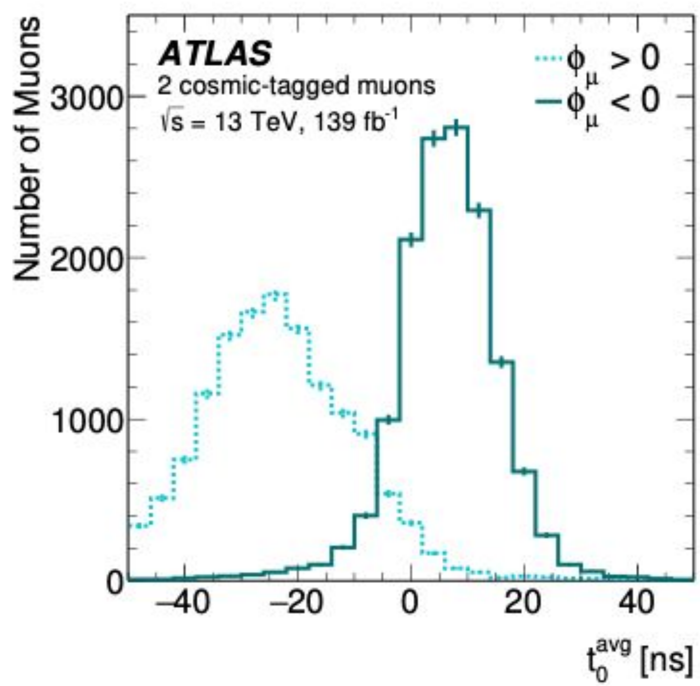


Dominant background for SR-μμ

- One cosmic ray muon can be reconstructed as two correlated high $|d_0|$ muons

Time to traverse detector ~ 1 bunch crossing

- Muons more likely to be more poorly reconstructed
- Add requirement on timing ($t_0^{avg} < 30$ ns)
- Also apply cosmic muons tagging as in previous DV analysis



Background estimated with ABCD (with cosmic tag and muon quality requirements)

Results

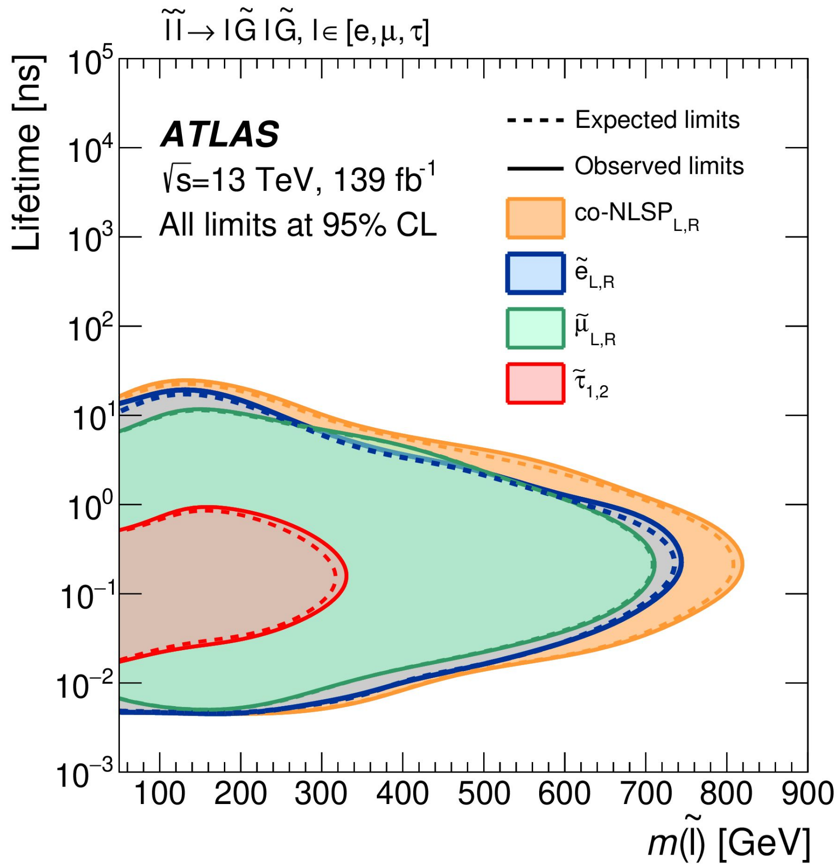
Region	SR-ee	SR-$\mu\mu$	SR-$e\mu$
Fake + heavy-flavor	0.46 ± 0.10	–	$0.007^{+0.019}_{-0.007}$
Cosmic-ray muons	–	$0.11^{+0.20}_{-0.11}$	–
Expected background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$
Observed events	0	0	0

Uncertainties estimated from non-closure of ABCD estimations in validation regions.

- Statistical uncertainties largely dominant

Interpretation

Pushing beyond the LEP coverage for the first time

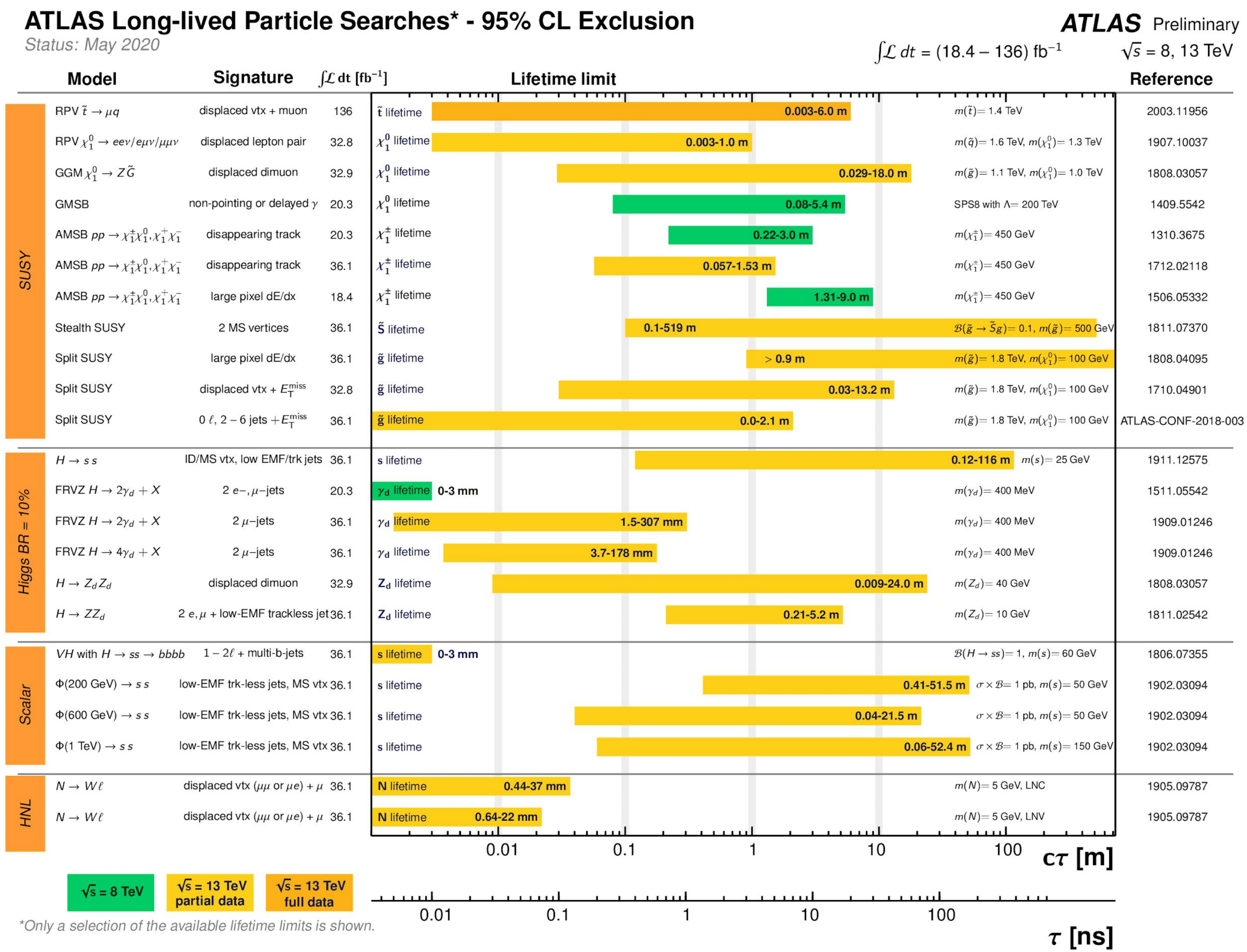


To have some fun, we switched the axes!

Comparing with LEP, for a slepton lifetime of 0.1 ns:

- e_R, μ_R, τ_R excluded up to 580 GeV, 550 GeV and 280 GeV

The many other results I didn't talk about

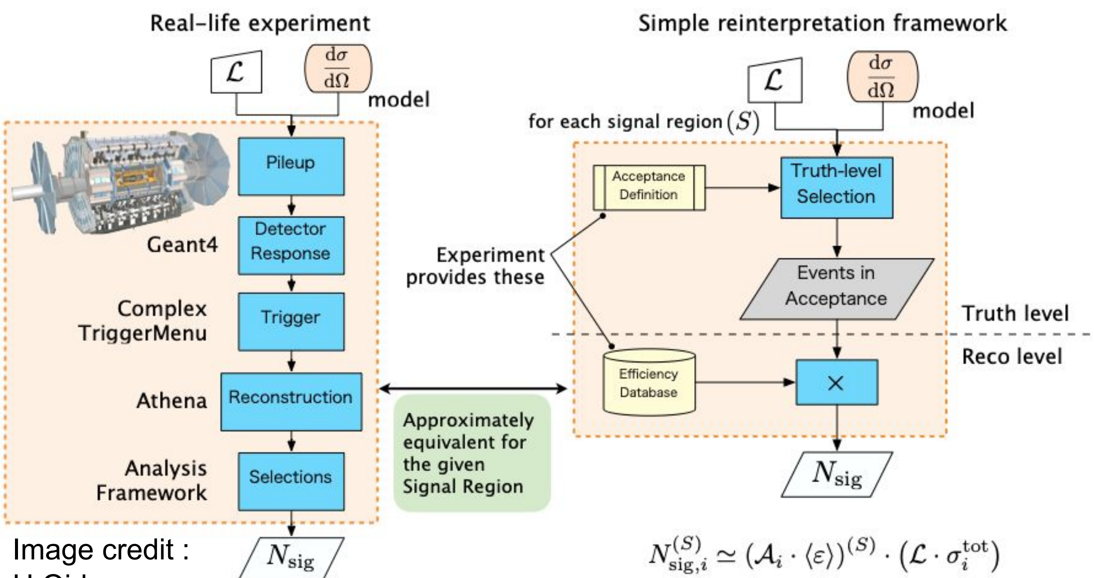


LLP summary plots

DESY.

A word on re-interpretation

Profiting from the lack of signal-specific selections

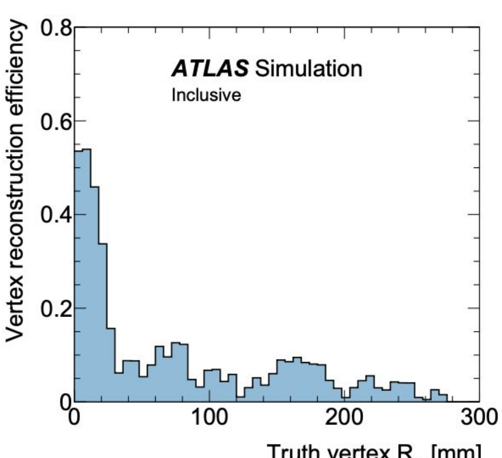


$$N_{\mathrm{sig},i}^{(S)} \simeq (\mathcal{A}_i \cdot \langle\varepsilon\rangle)^{(S)} \cdot (\mathcal{L} \cdot \sigma_i^{\mathrm{tot}})$$

Image credit : H.Oide

Unconventional objects are tricky to emulate

We provide **parameterised efficiencies** such that they can be used for reinterpretation outside the collaboration



Look for this in the public pages

Plots and Tables of HEPDATA information

HepData and document released on paper publication

- Complete statistical likelihoods are released

Summary

LLP searches are a particularly creative field

Special techniques across the experiment are required to be optimal:

- Trigger
- Reconstruction
- Data-driven estimation for unconventional backgrounds

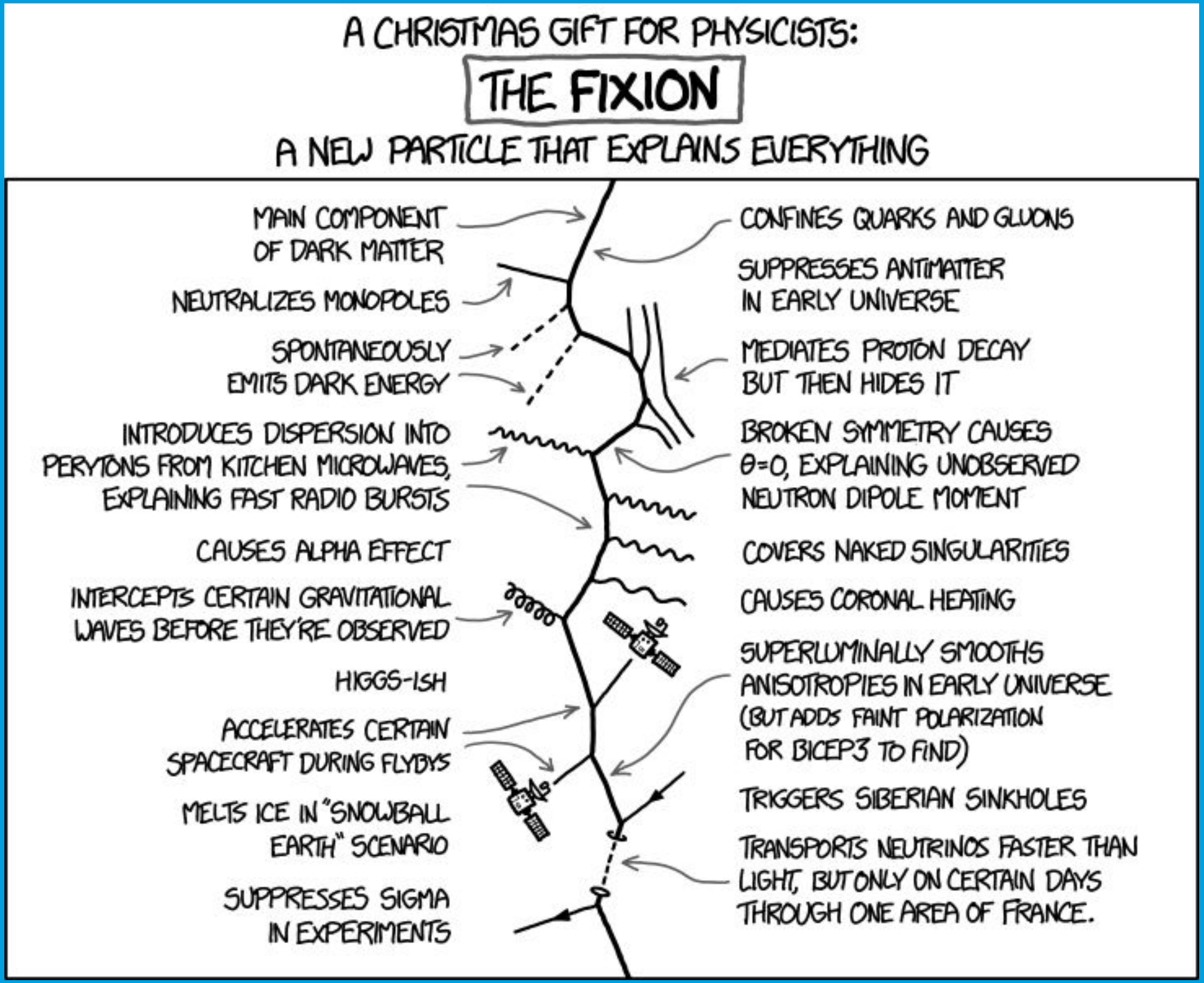
Most of Run-2 results using the full integrated luminosity are yet to be released!

Relatively clean signature:

- Search sensitivity ~ will linearly grow with luminosity and remain interesting for years to come.
  - Discovering something new is an important step
  - Finding out what we have discovered will be even more interesting!

Perhaps not what we think!

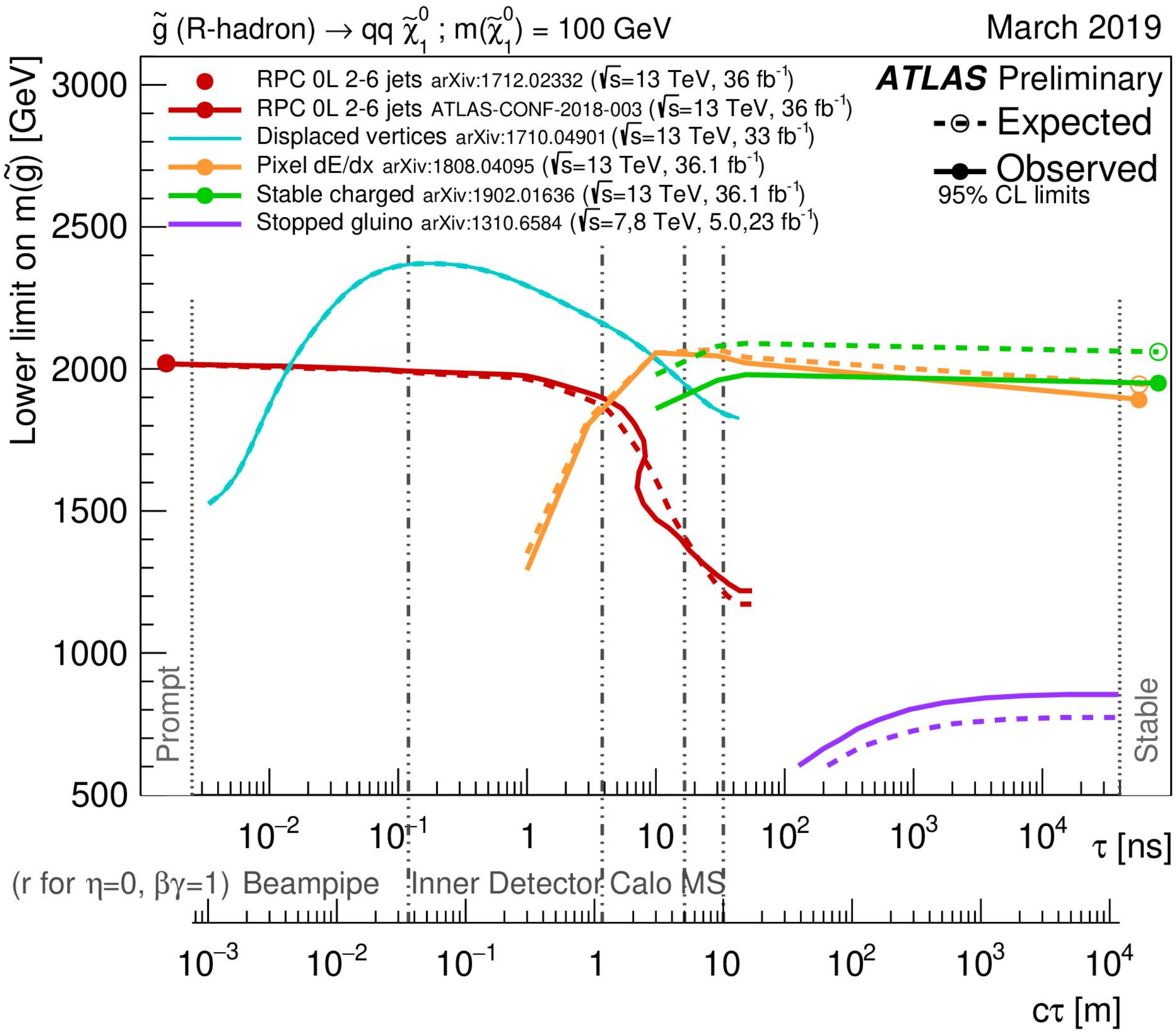
Thank you!



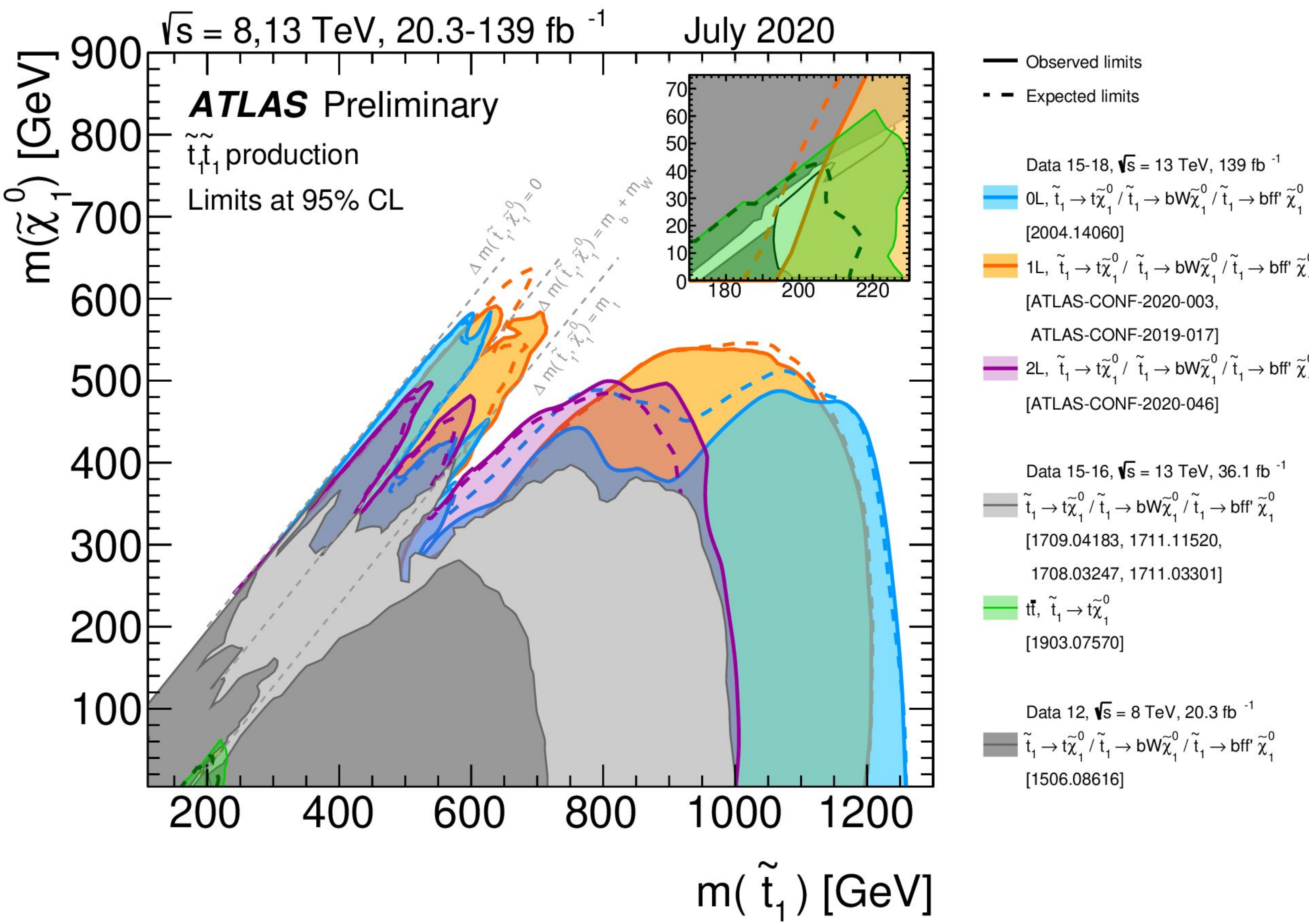
https://xkcd.com/1621/

Lifetime and detection

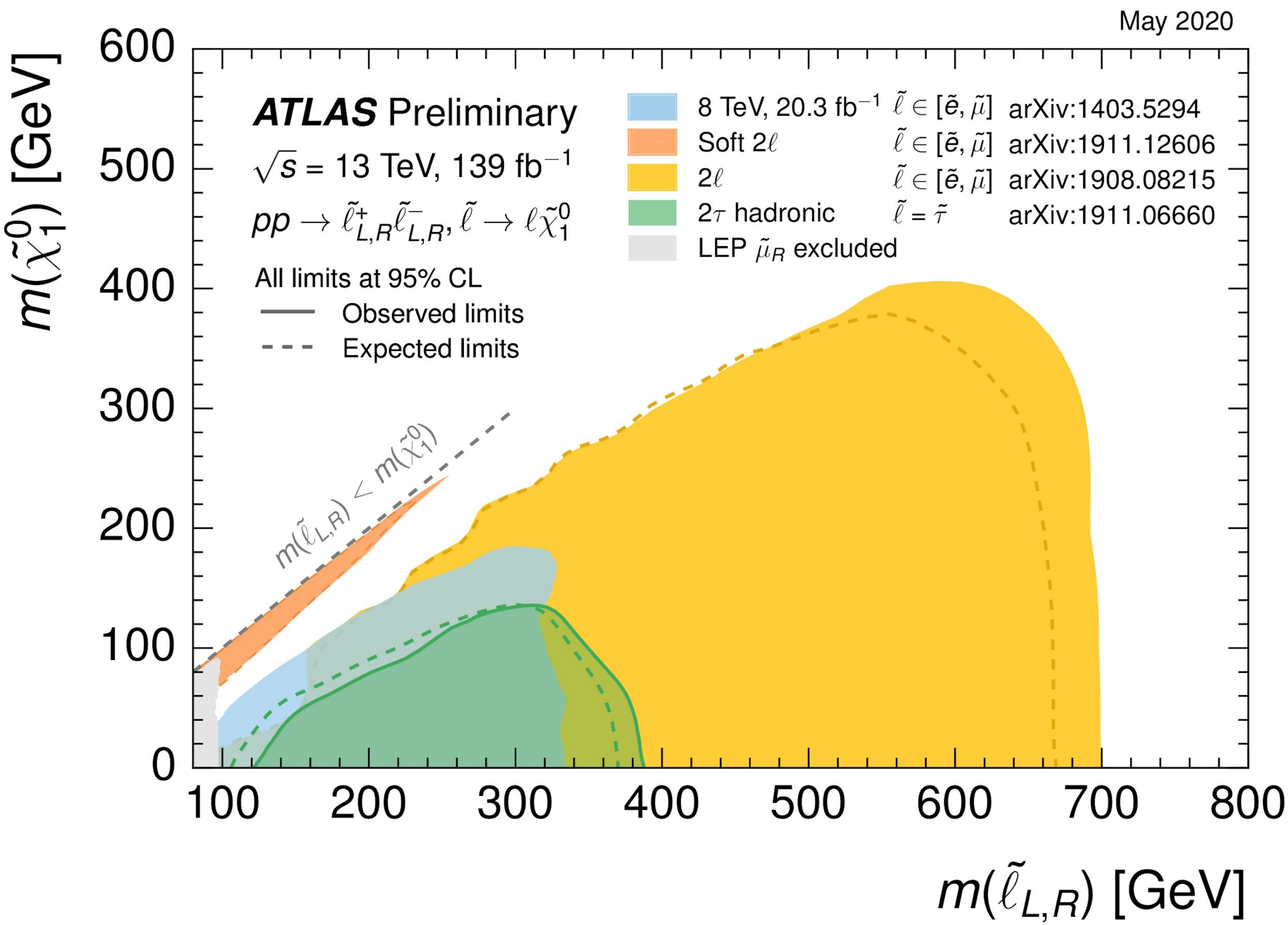
Different tools and strategies for different decay lengths



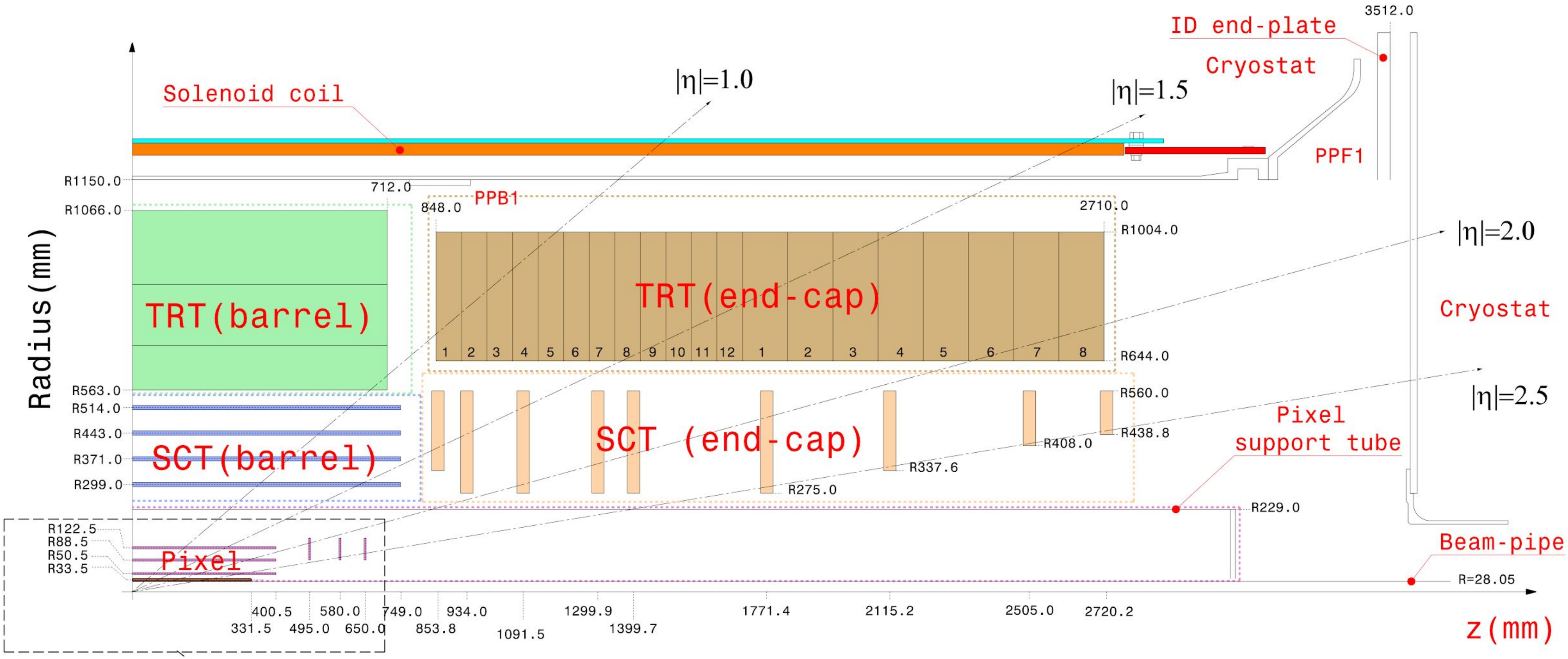
Prompt top squarks



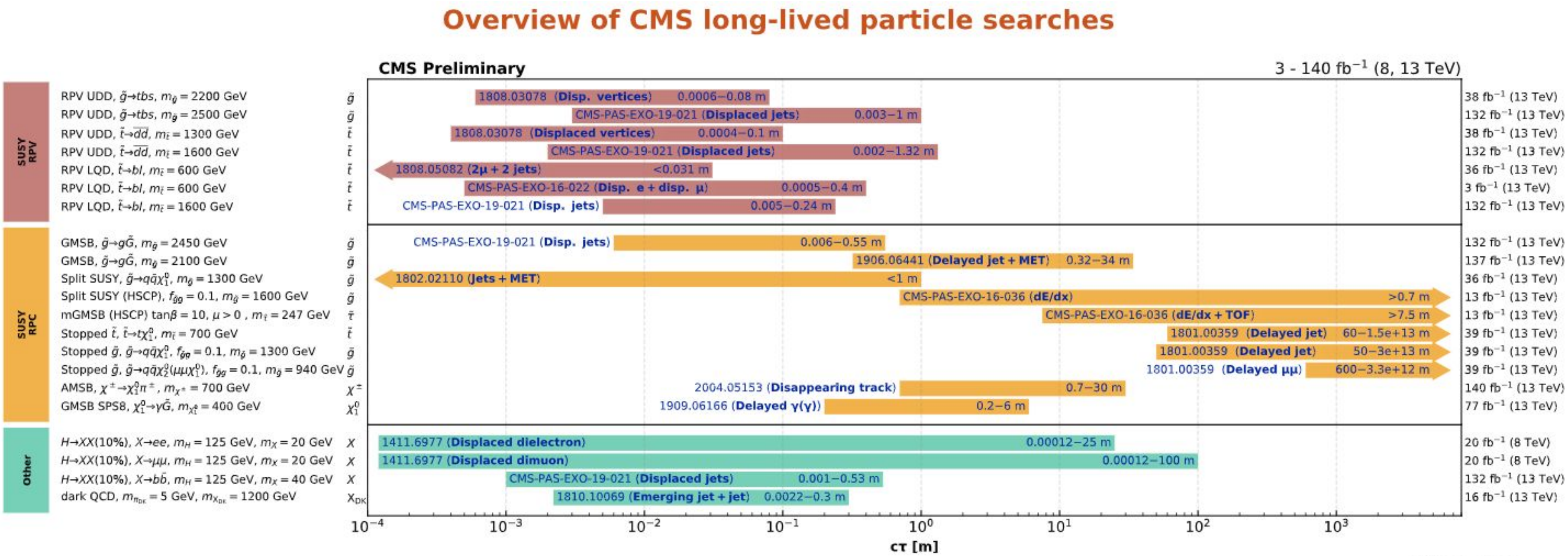
Prompt slepton limits



The ATLAS tracking detector

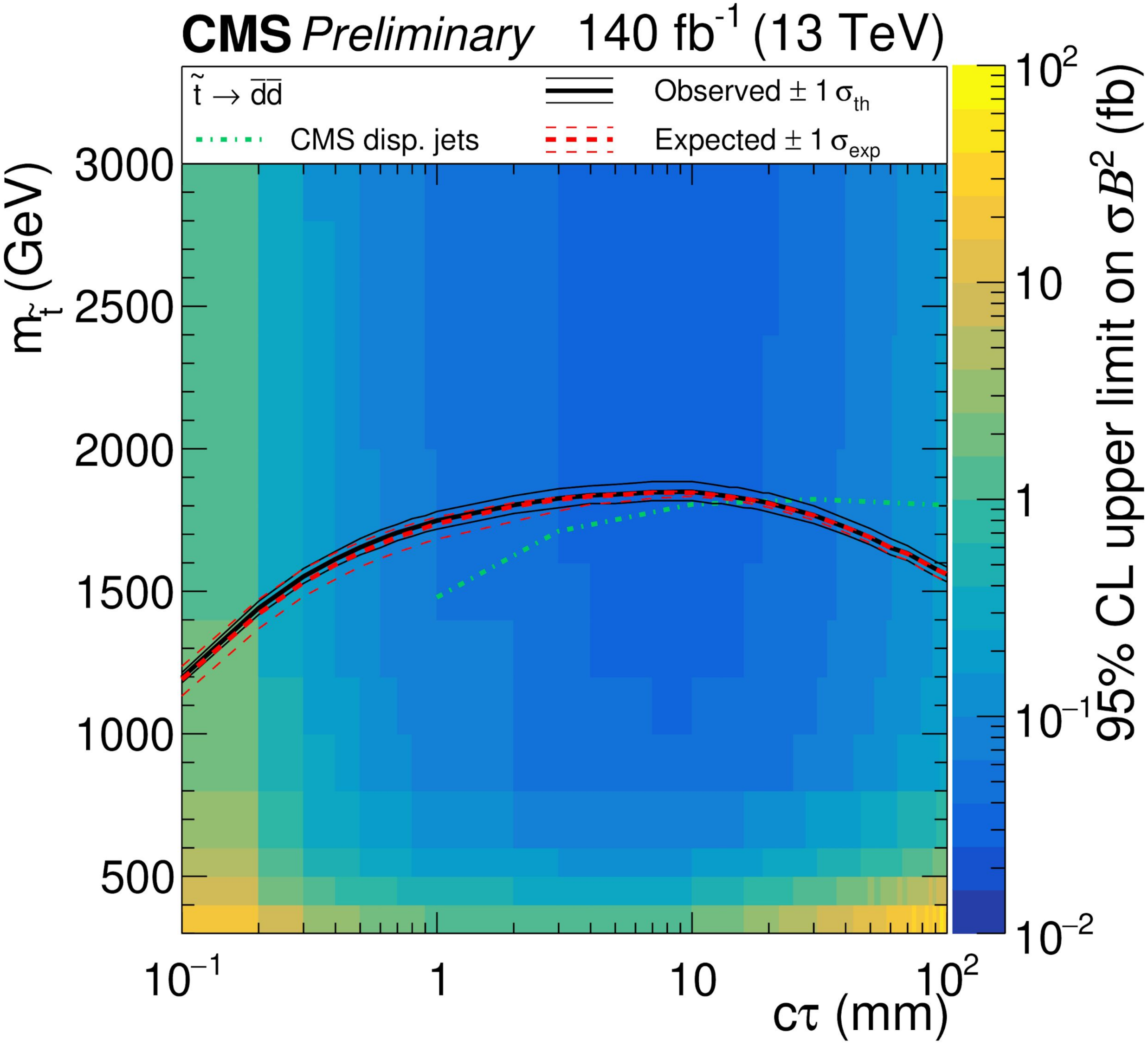


CMS



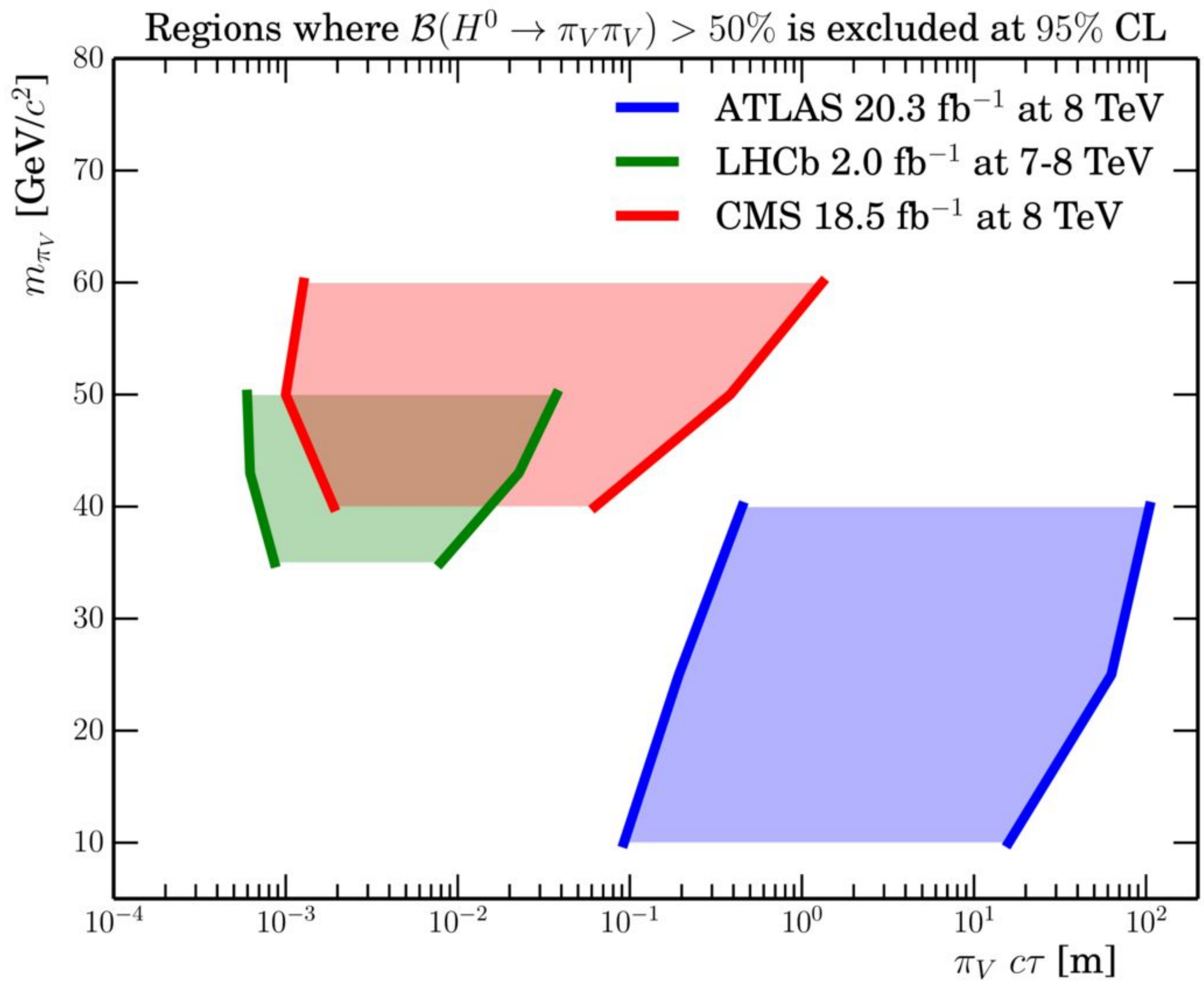
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

CMS



CMS-PAS-EXO-19-013

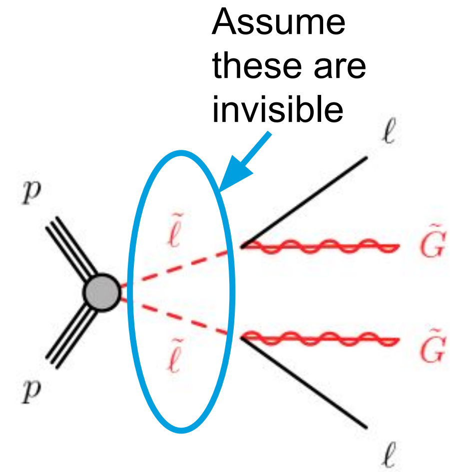
LHCb



Eur. Phys. J. C77 (2017) 812

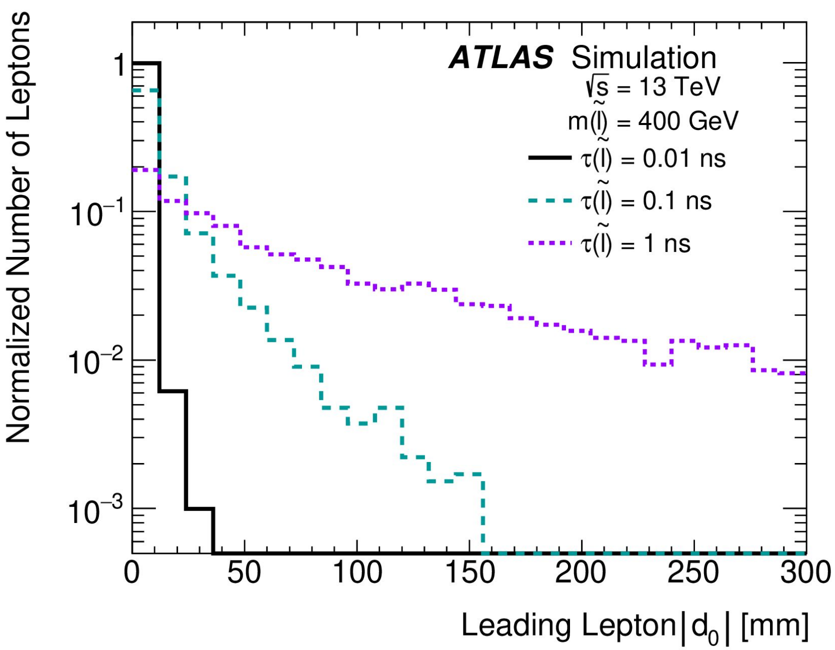
Online selection strategy (trigger)

The typical trigger algorithms cannot be used to select displaced leptons



- Electrons are targeted with photon triggers
- Muons are targeted with MS-only information

- No efficiency dependence vs $|d_0|$
- No requirements on additional jets in Events, which would have been needed to use missing energy triggers



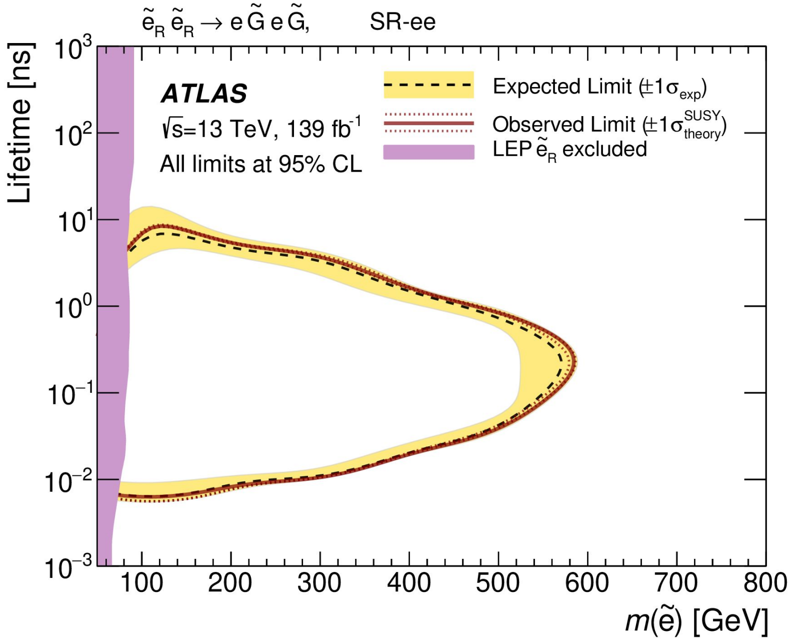
DV+mu signal uncertainties

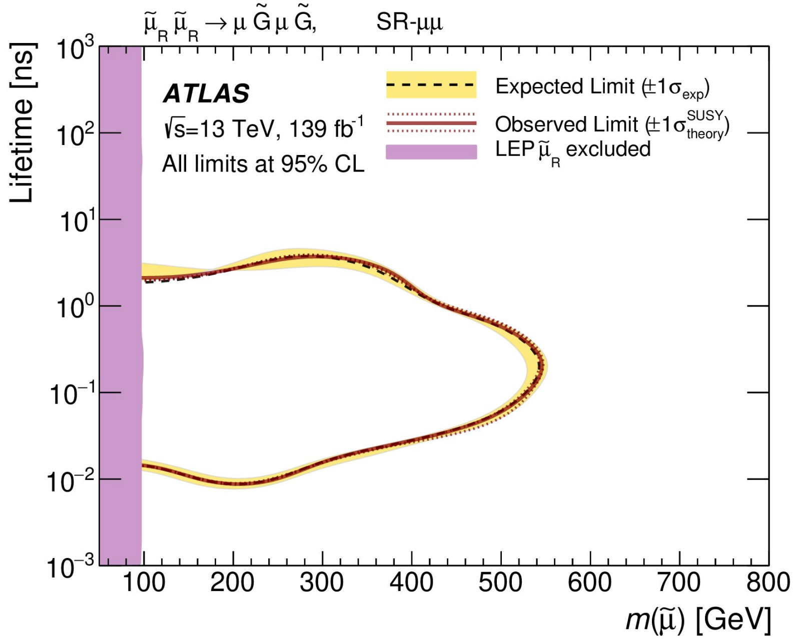
Source of uncertainty	Relative impact on ϵ_{sel} for signal events [%]
Total	18–20
Tracking and vertex reconstruction	15
Displaced muon efficiency	10–12
Prompt muon efficiency	$(0.01–0.7) \oplus (0.9–4.0)$
ISR modeling in MC simulation	3
Pileup modeling	0.37–2.2
Hadronic energy scale and resolution (affecting E_T^{miss})	2.1
Integrated luminosity of dataset	1.7
Trigger efficiency	< 0.2

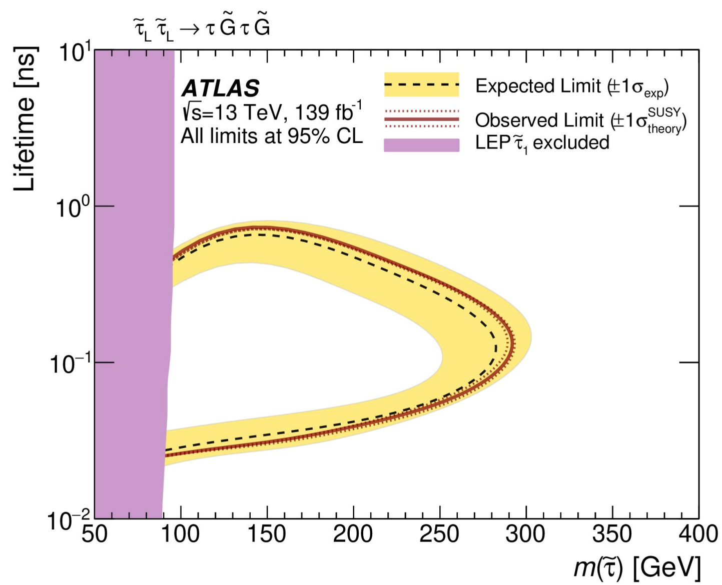
Displaced leptons uncertainties

Background	Uncertainty	Value [%]
ee: fakes and heavy-flavor	statistical	18
	isolation non-closure	11
	fakes non-closure	6
	total	22
$e\mu$: fakes and heavy-flavor	statistical	+257 / −129
	isolation non-closure	92
	fakes non-closure	8
	total	+273 / −159
$\mu\mu$: cosmic muons	statistical	+180 / −95
	R_{good} $\lvert d_0 \rvert$ dependence	38
	estimate variable	16.5
	R_{good} definition muon	13
	total	+185 / −104

Comparison with LEP







My ATLAS detector gslides sketch