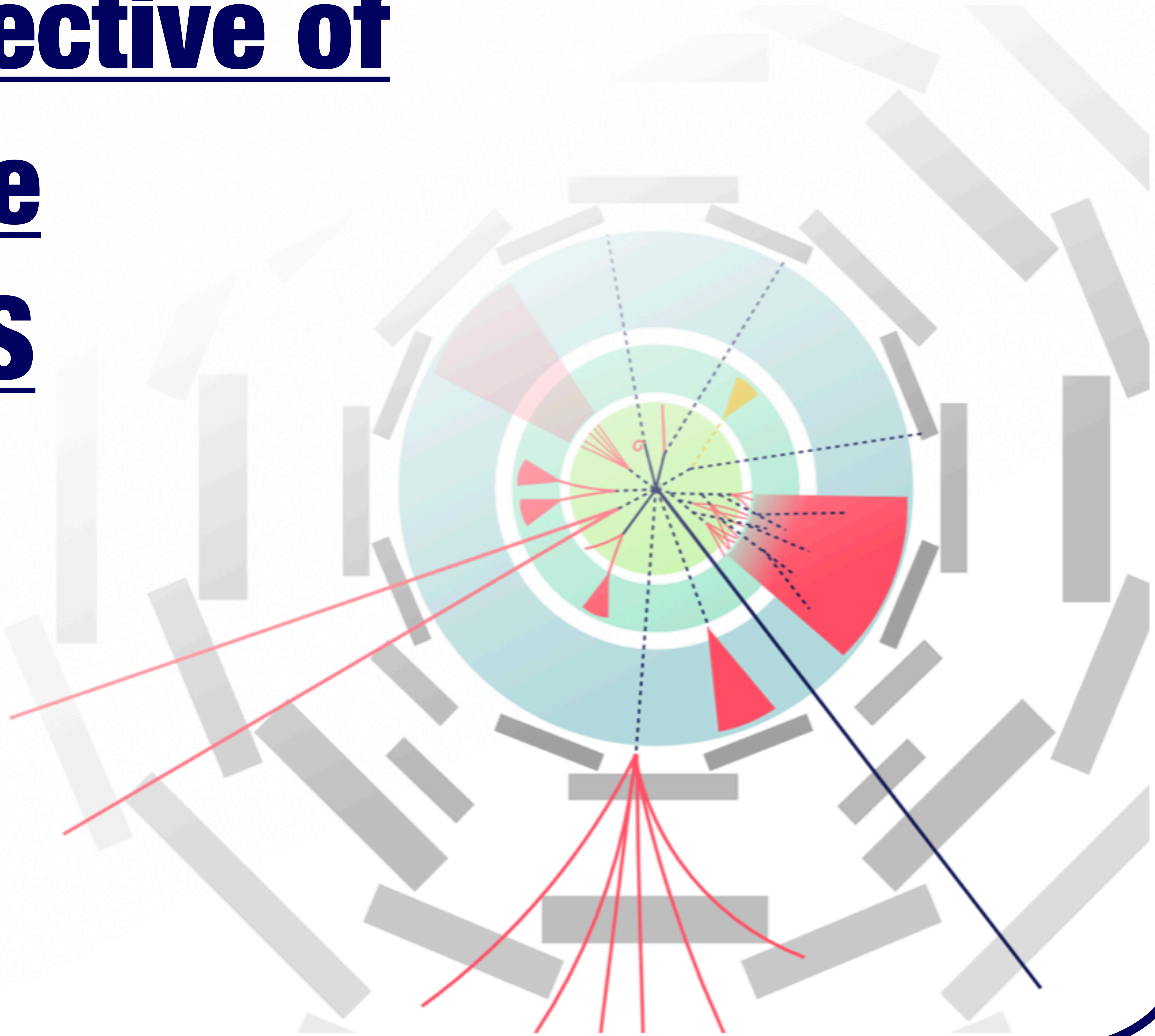
Status and perspective of long-lived particle searches in ATLAS

Giuliano Gustavino

27 November 2023



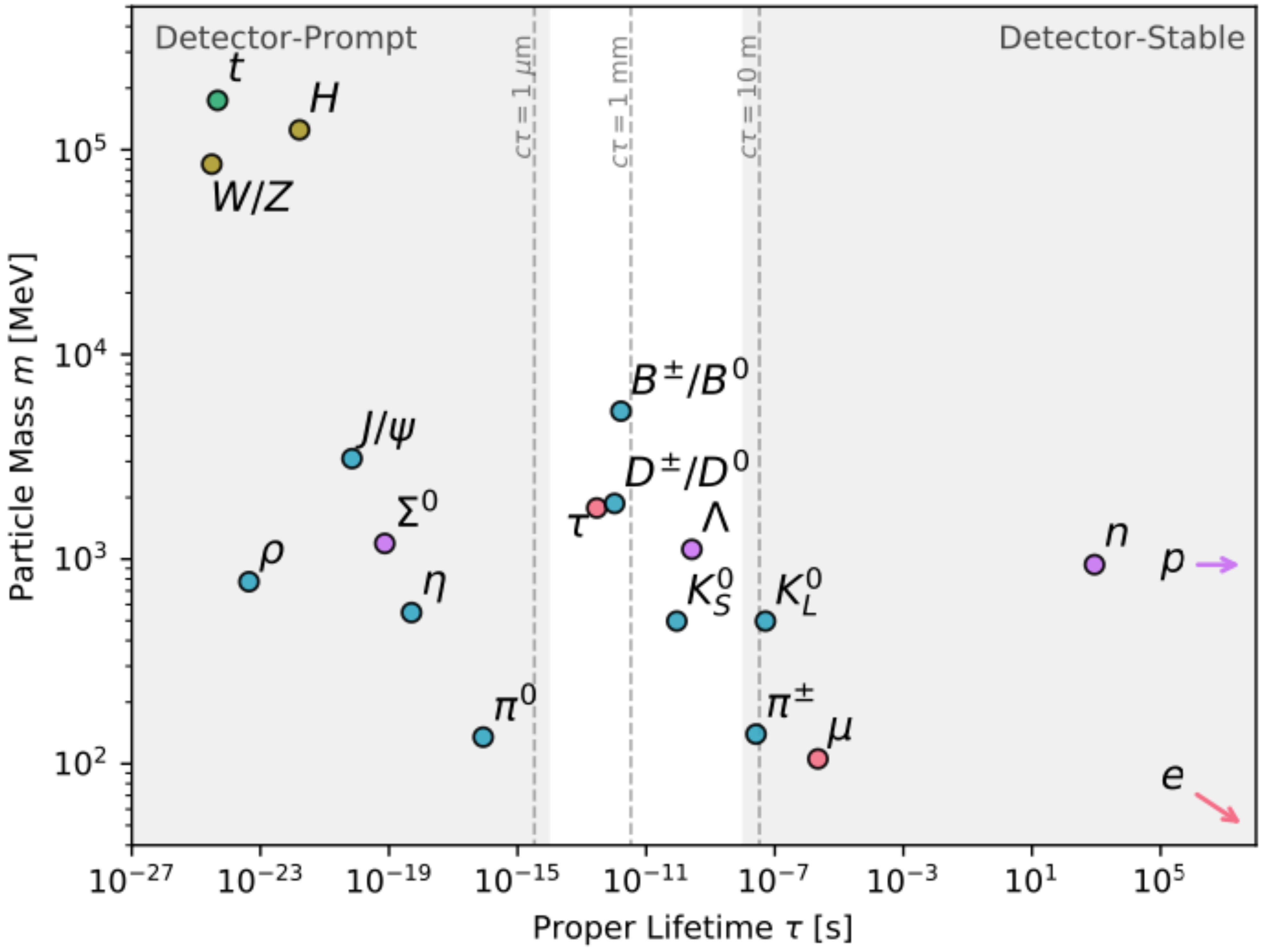
The time dimension

ATLAS was not initially conceived to search for long-lived particles…

…but they are all around us!

Detector - prompt

Detector - stable



Long-lived particles

The search for beyond the Standard Model LLPs is **well motivated** from a theoretical perspective and **exciting from an experimental point of view**

Why long-lived particles?

decay rate ~ coupling^2 · mass dimension · phase space

Standard Model

Feeble Coupling

e.g. $b \to cl\nu$, off-diagonal CKM, τ ~ ps

Mass Scale suppression

e.g. $\mu \to e\nu_\mu\nu_e$, via W-boson, τ~1.6 μs

Phase space suppression

e.g. $n \to pe^-\nu$, $m_n - m_p$ ~ 1 MeV, τ = 15 min

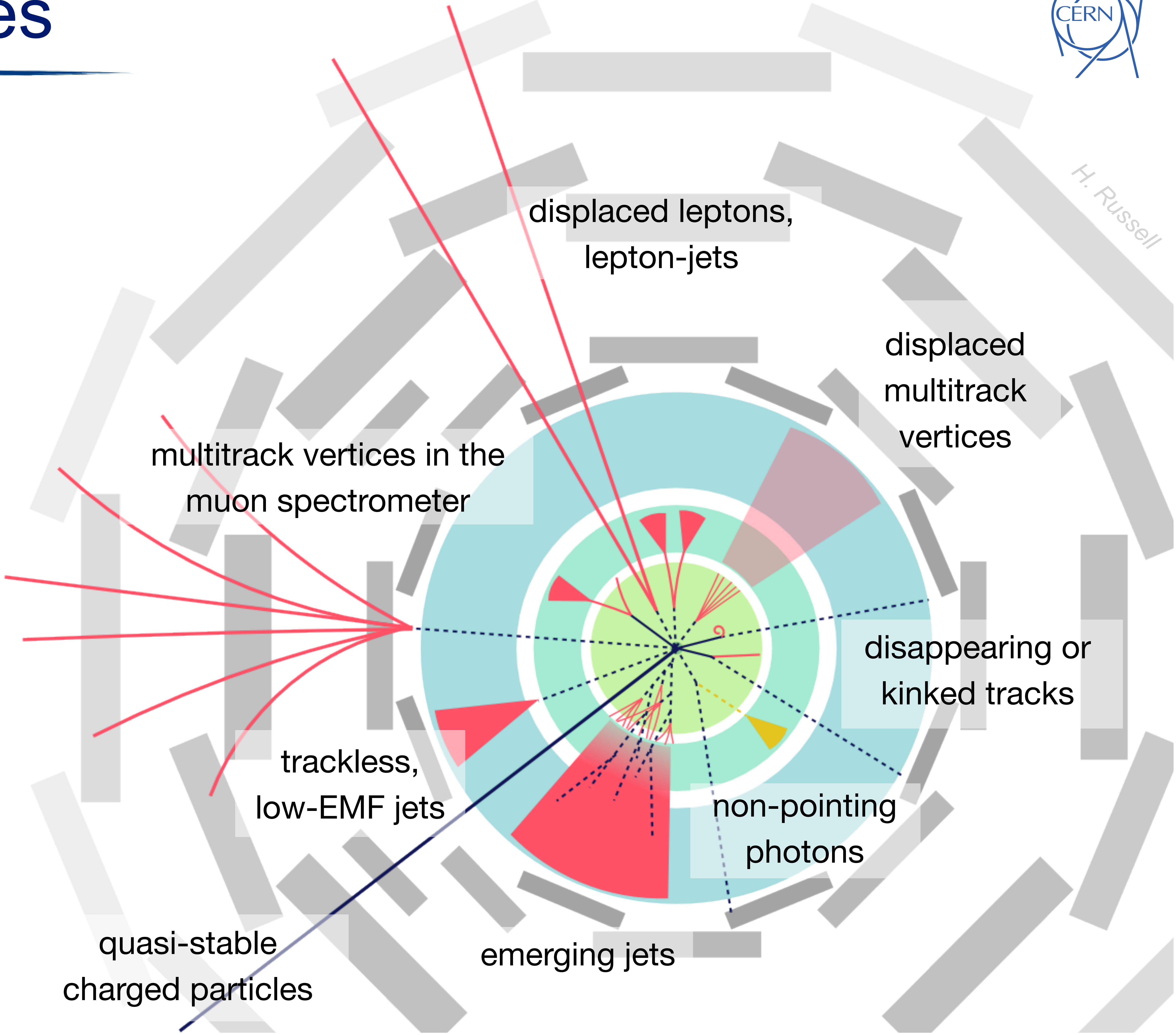
Beyond the Standard Model

		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

A plethora of signatures

ATLAS has led an extensive search program for LLPs

- signature-inspired rather than model-inspired searches whenever possible



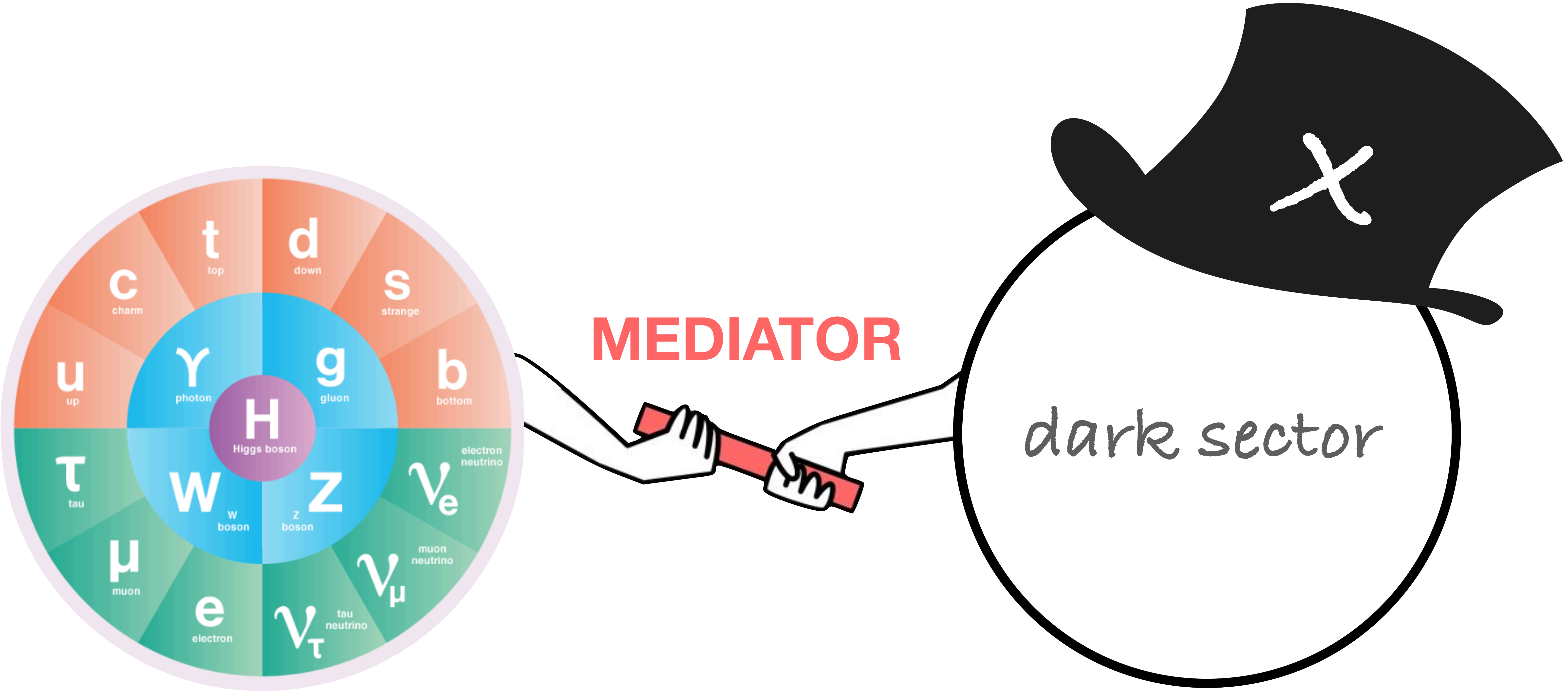
Disclaimer:

I don't wish to cover everything about the LLP search program in ATLAS.

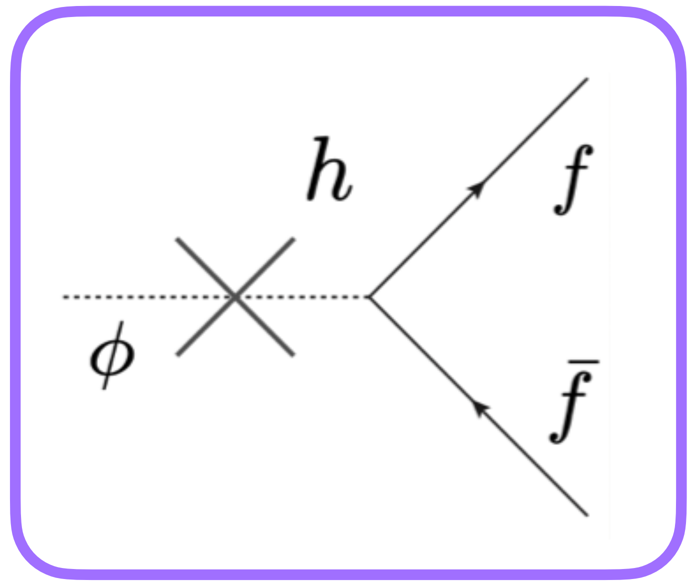
I am just diving into some bits often using Rome1 and Rome1 expats' studies as examples.

Dark Sectors

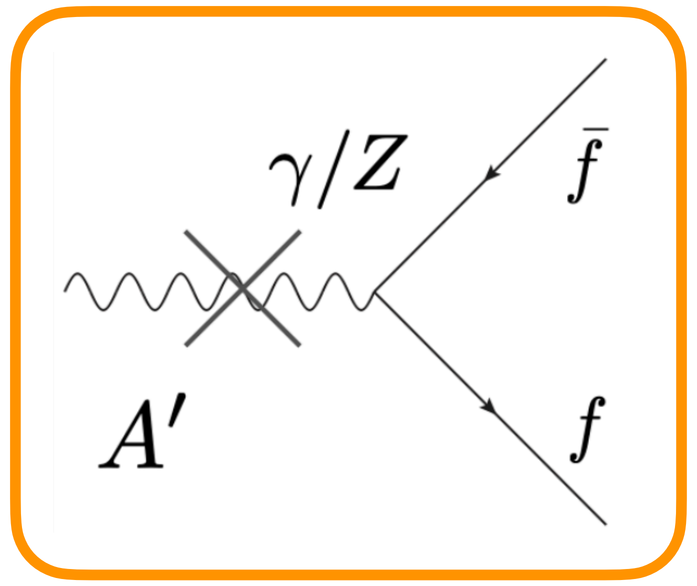
Simplified benchmarks are often used to allow a **reinterpretation** in more complete, complex and novel theories



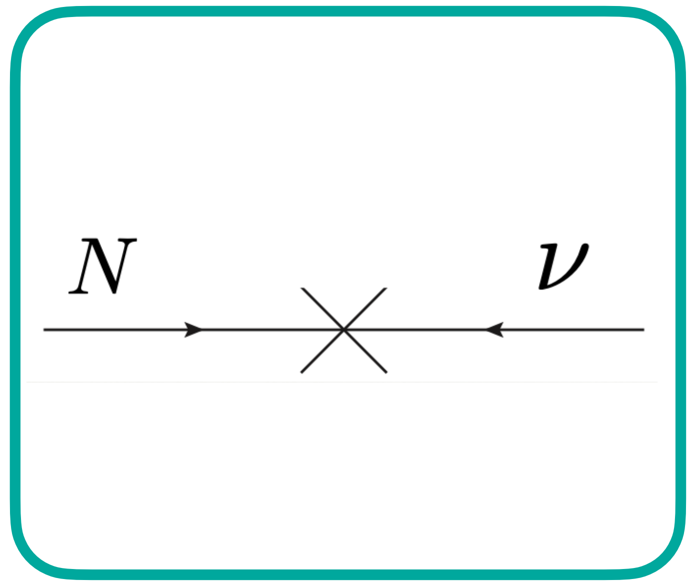
scalar portal



vector portal



neutrino portal

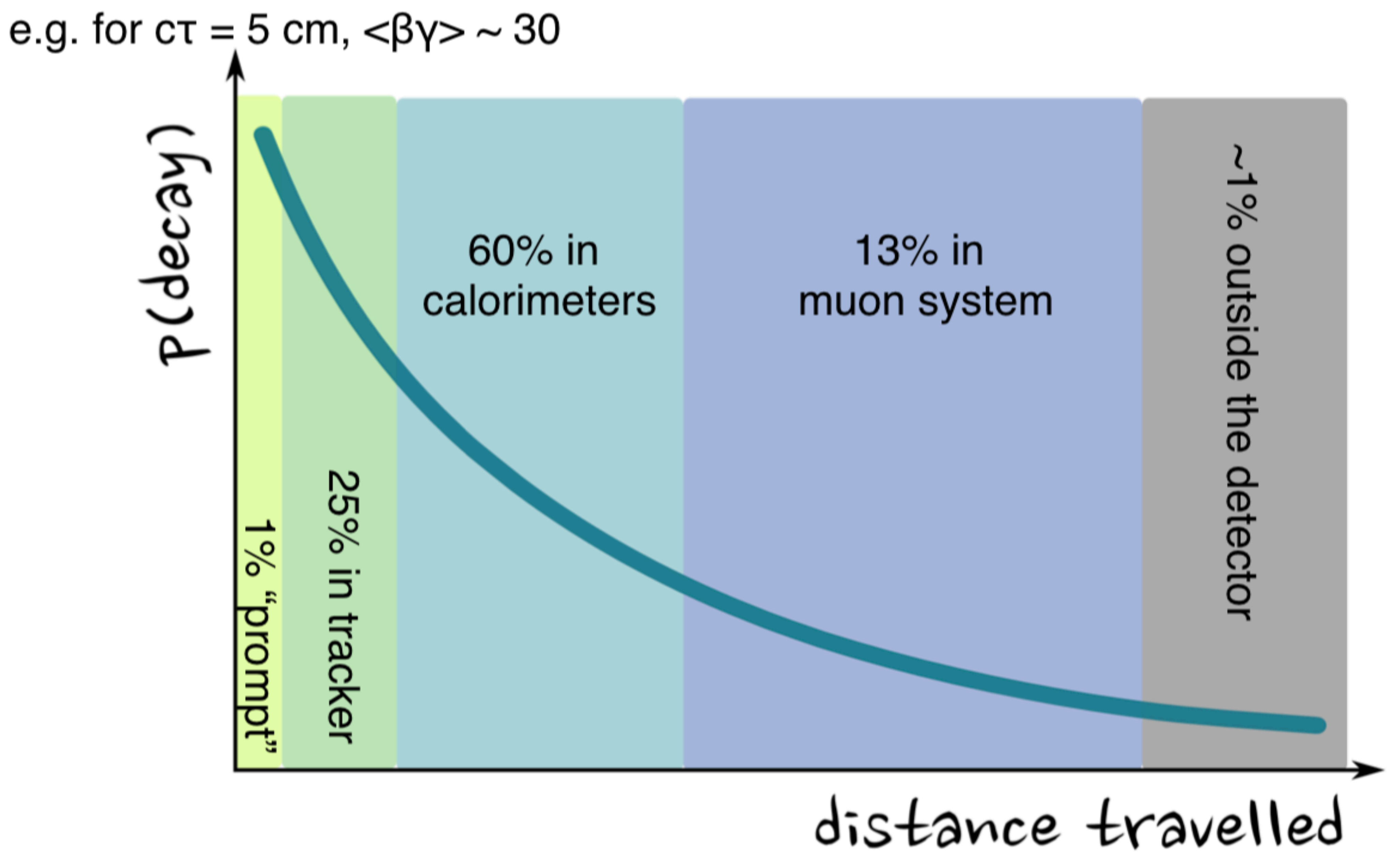


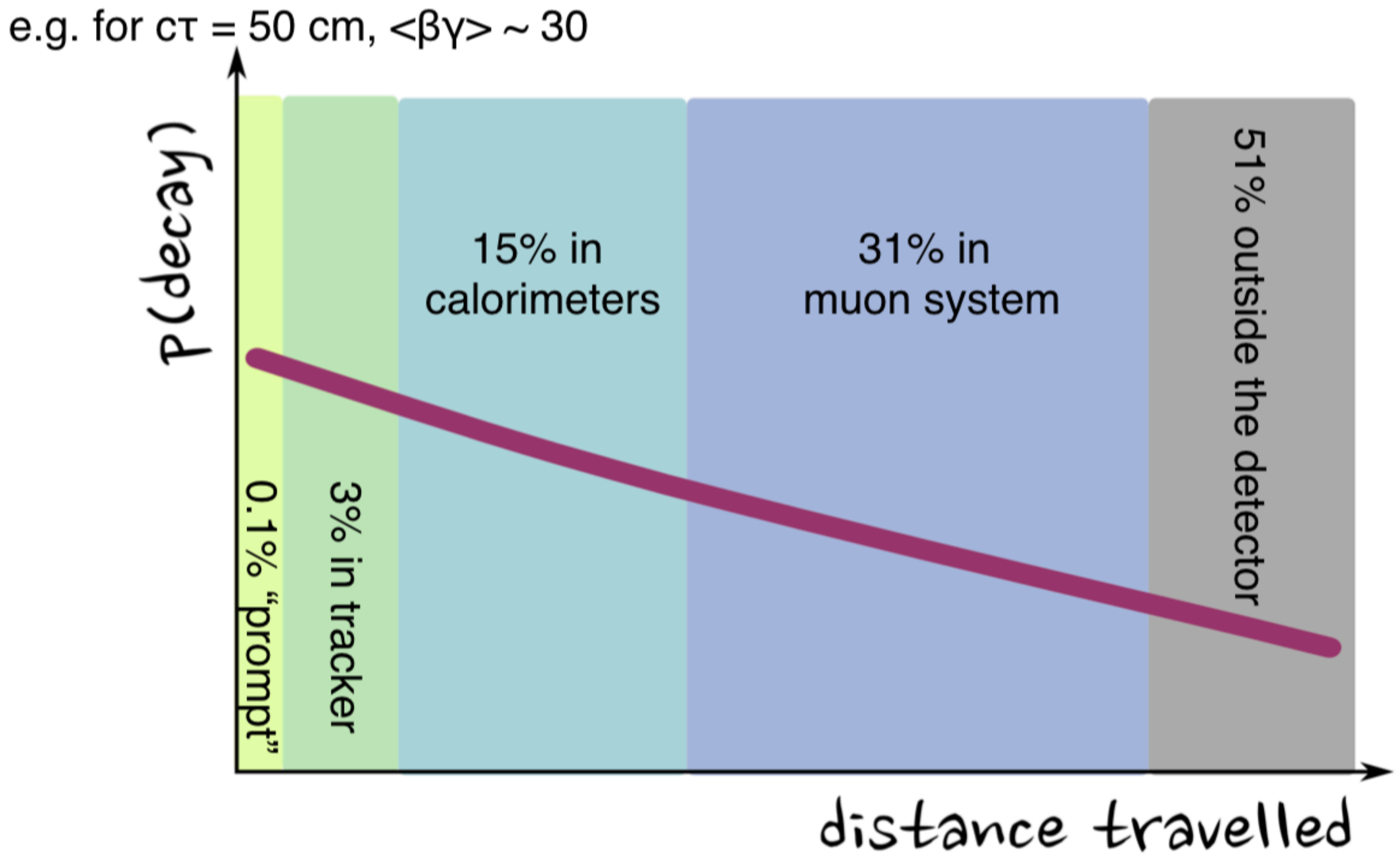
Decay length

Any given particle's lifetime follows an exponential distribution:

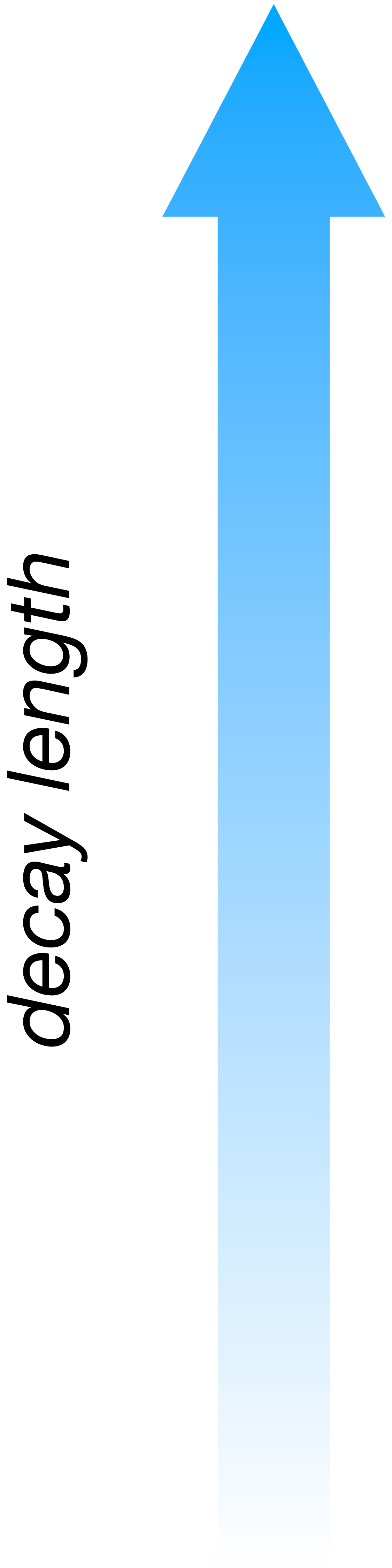
particles with a short proper lifetime can decay with a large lab-frame distance

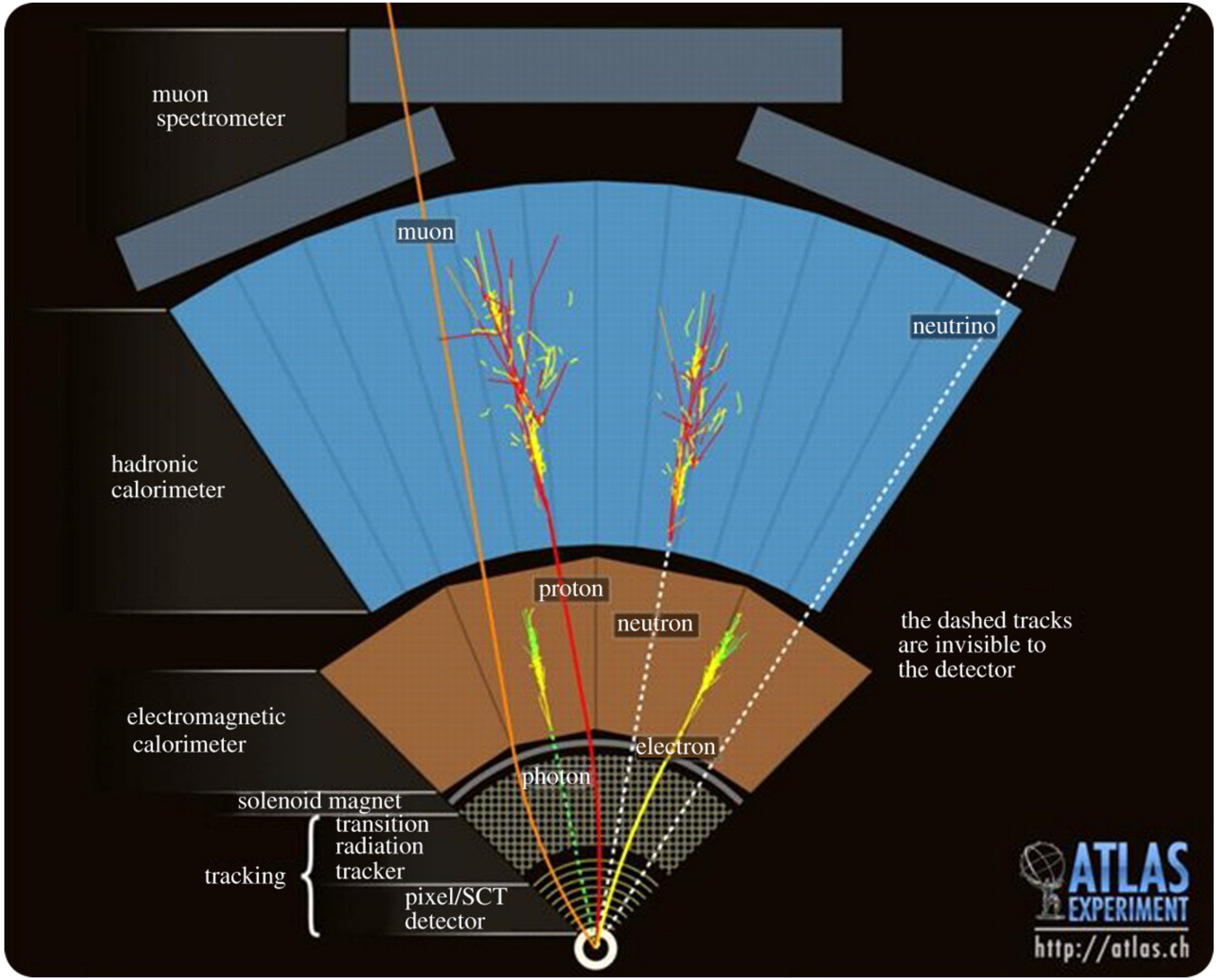
- all subdetectors must be used for optimal results
- **prompt** and **invisible** final states searches can play a fundamental role!





The ATLAS Detector





Main experimental challenges

*Missing transverse energy:
momentum imbalance on the transverse plane

Triggering

- trigger systems (especially Level-1) usually do not have sufficient information to tag LLP particle/decay
- often used standard ‘prompt’ physics trigger (e.g. ISR jet, MET*, prompt leptons)
  - reducing sensitivity and increasing model dependence of results

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- Non-standard reconstruction needed

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- Unusual background sources
- **Data-driven approach** is adopted
  usually cannot rely on simulation

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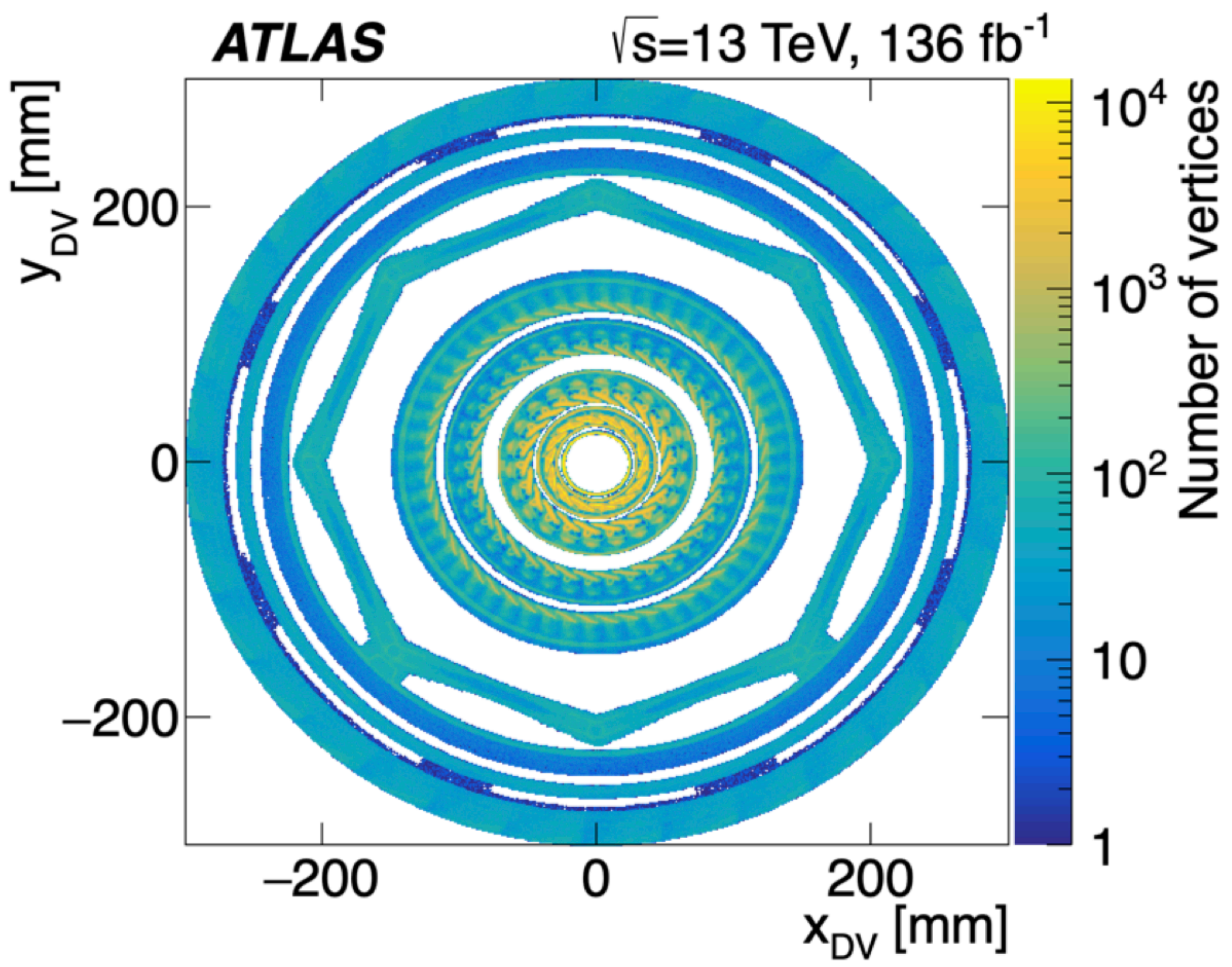

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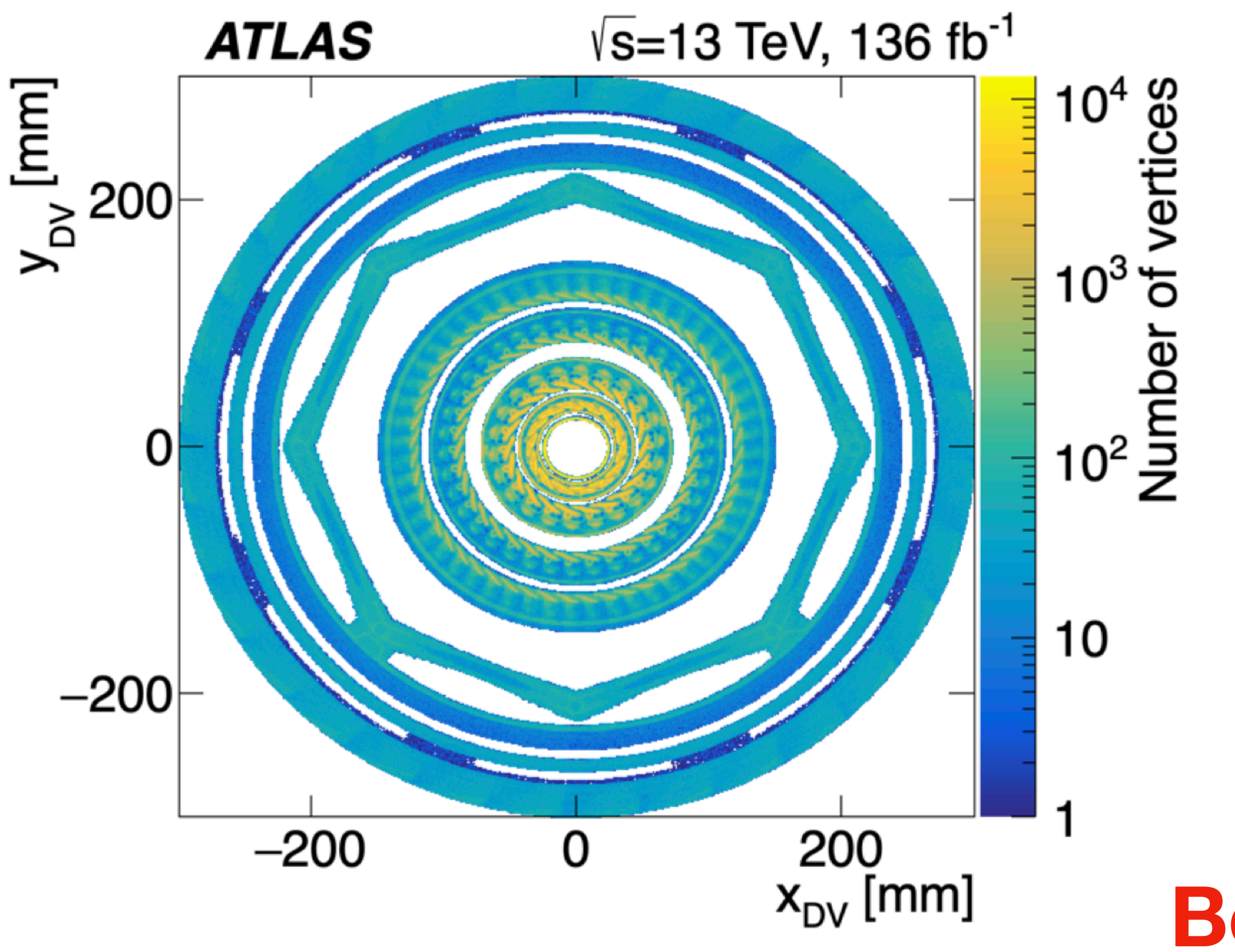

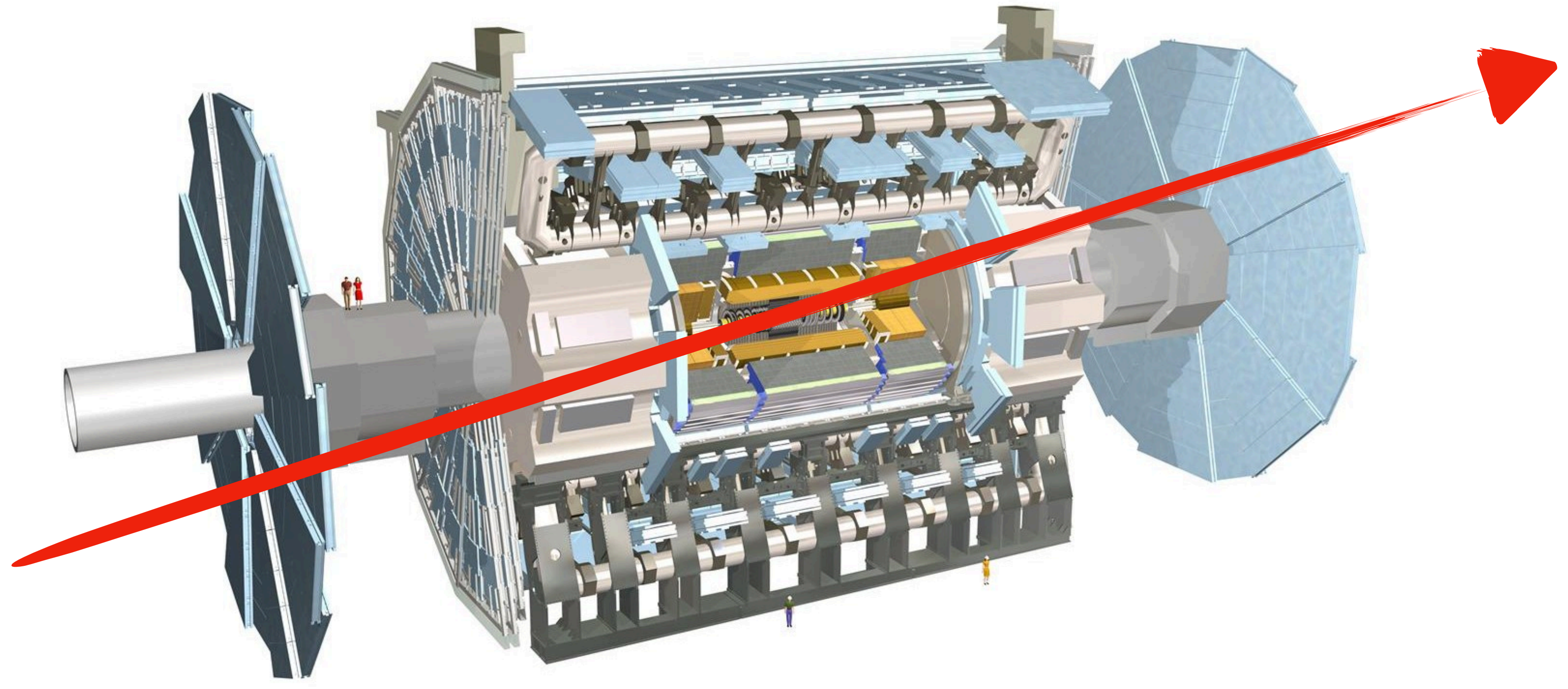

Beam induced background

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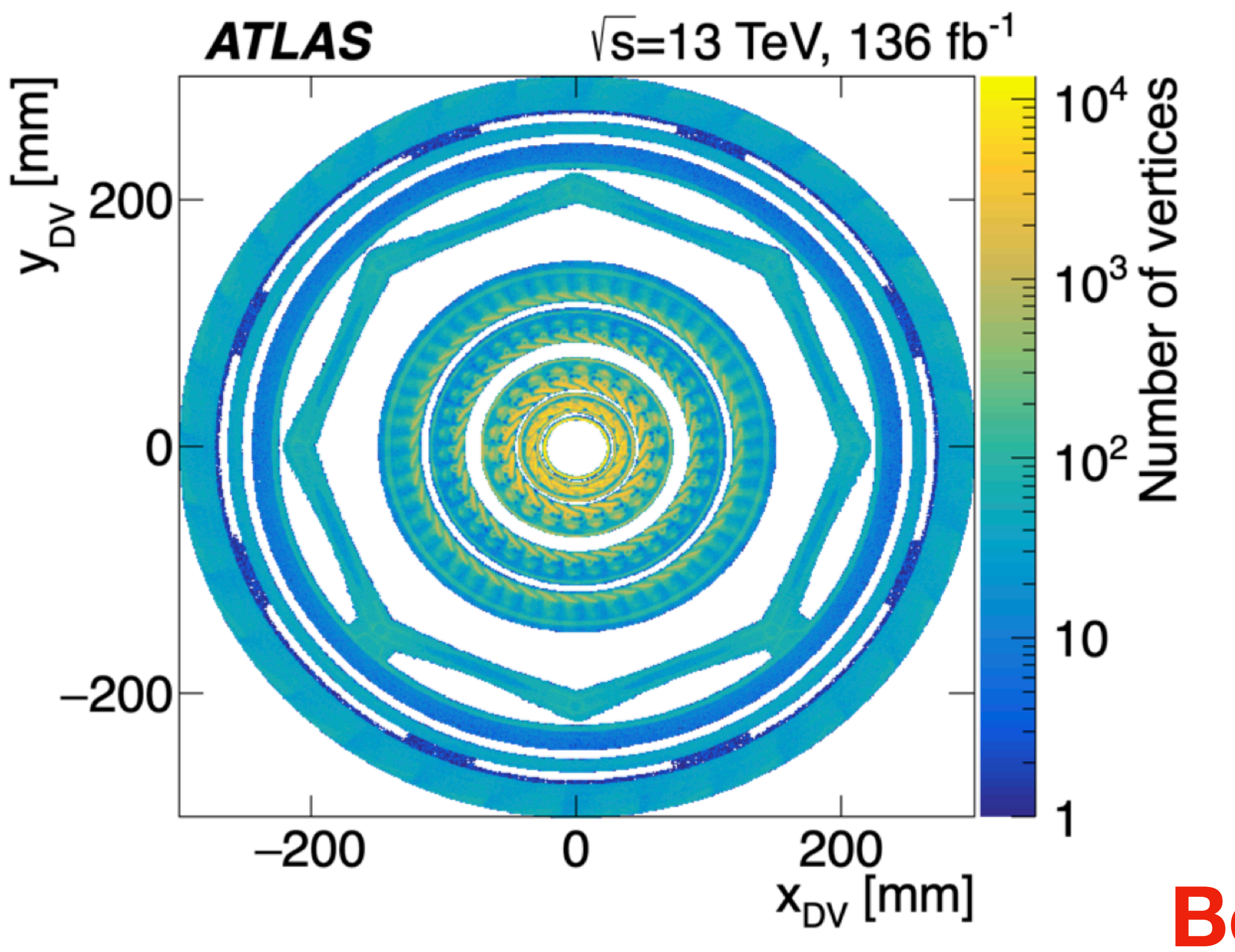
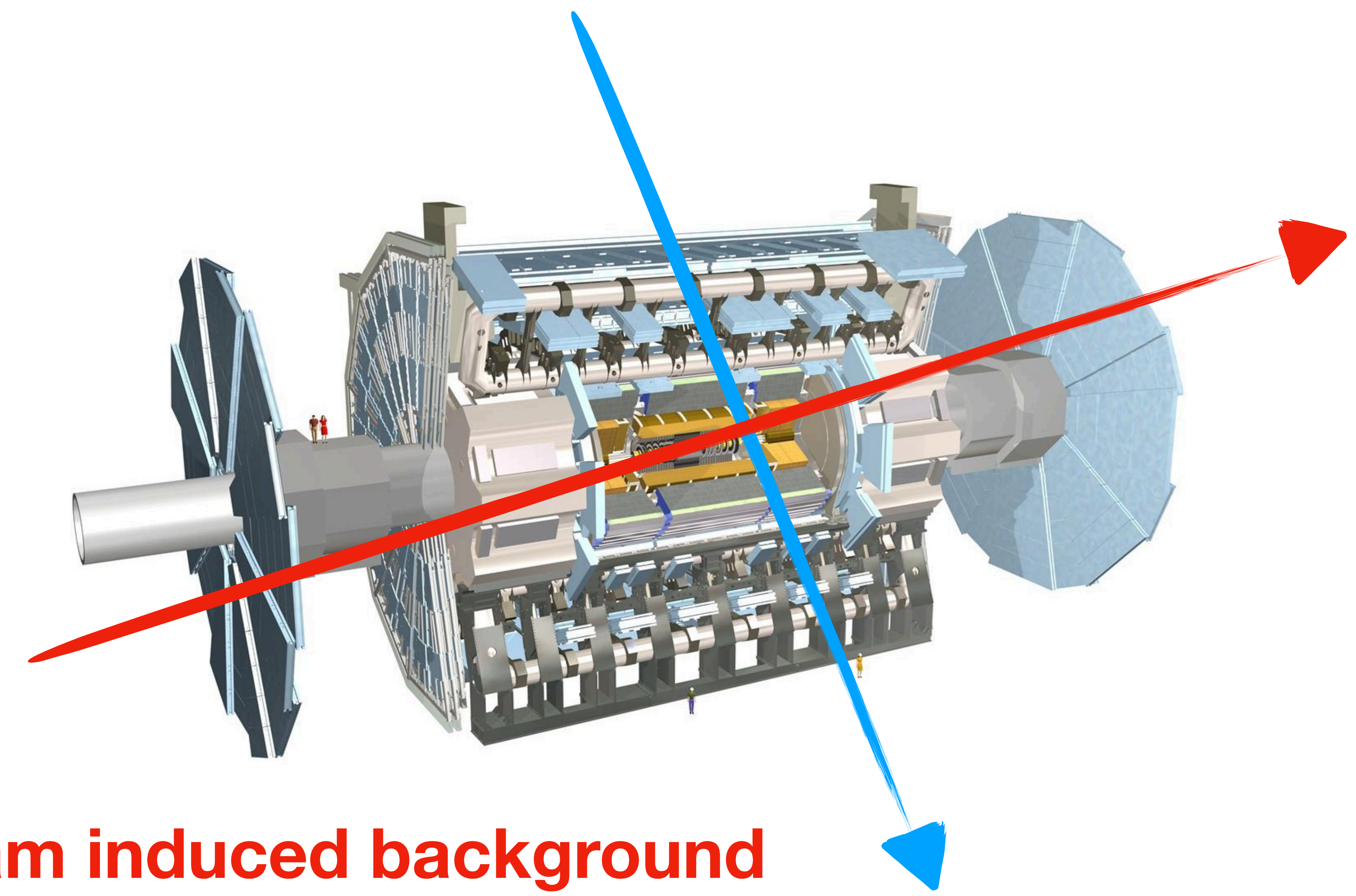


cosmic muons



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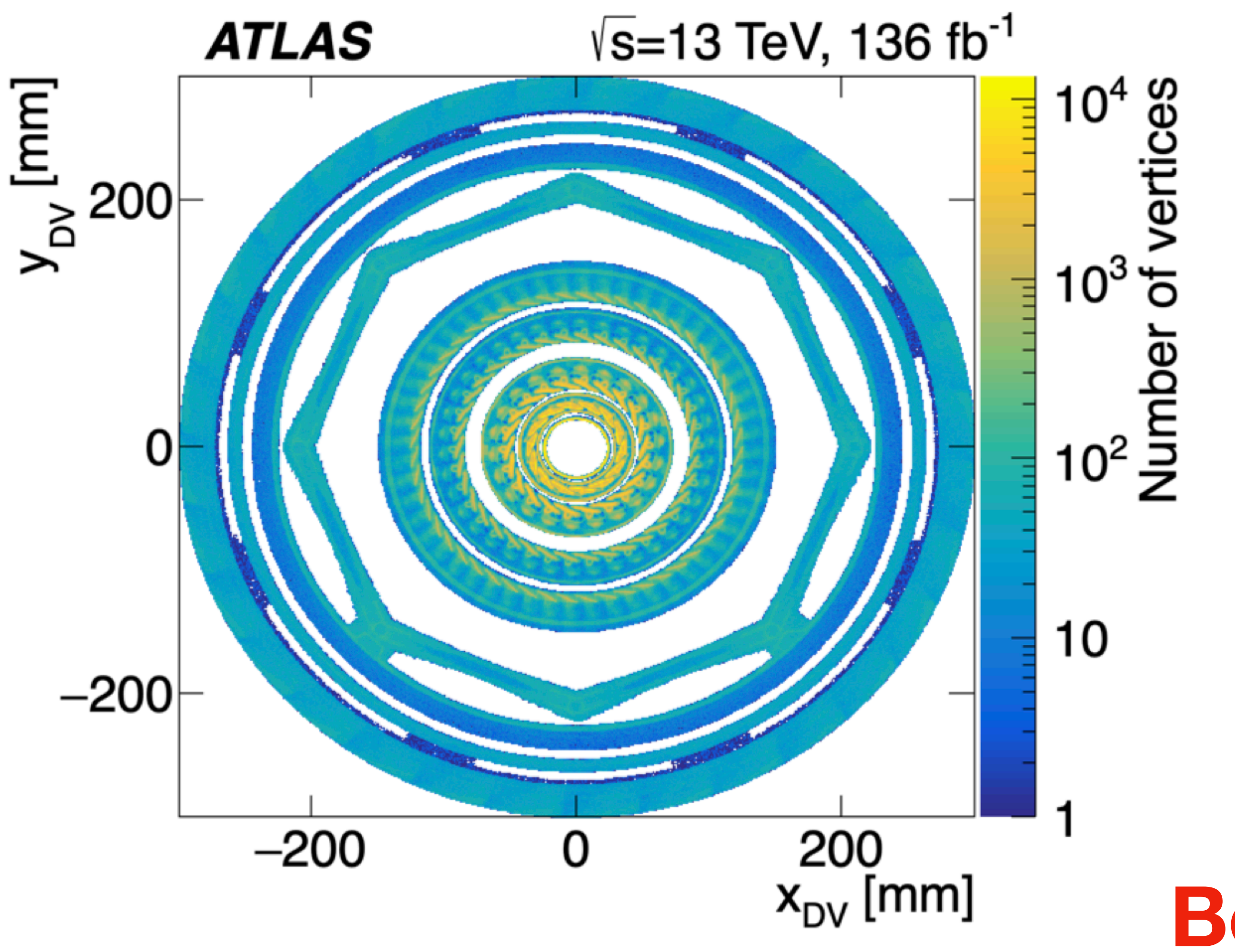

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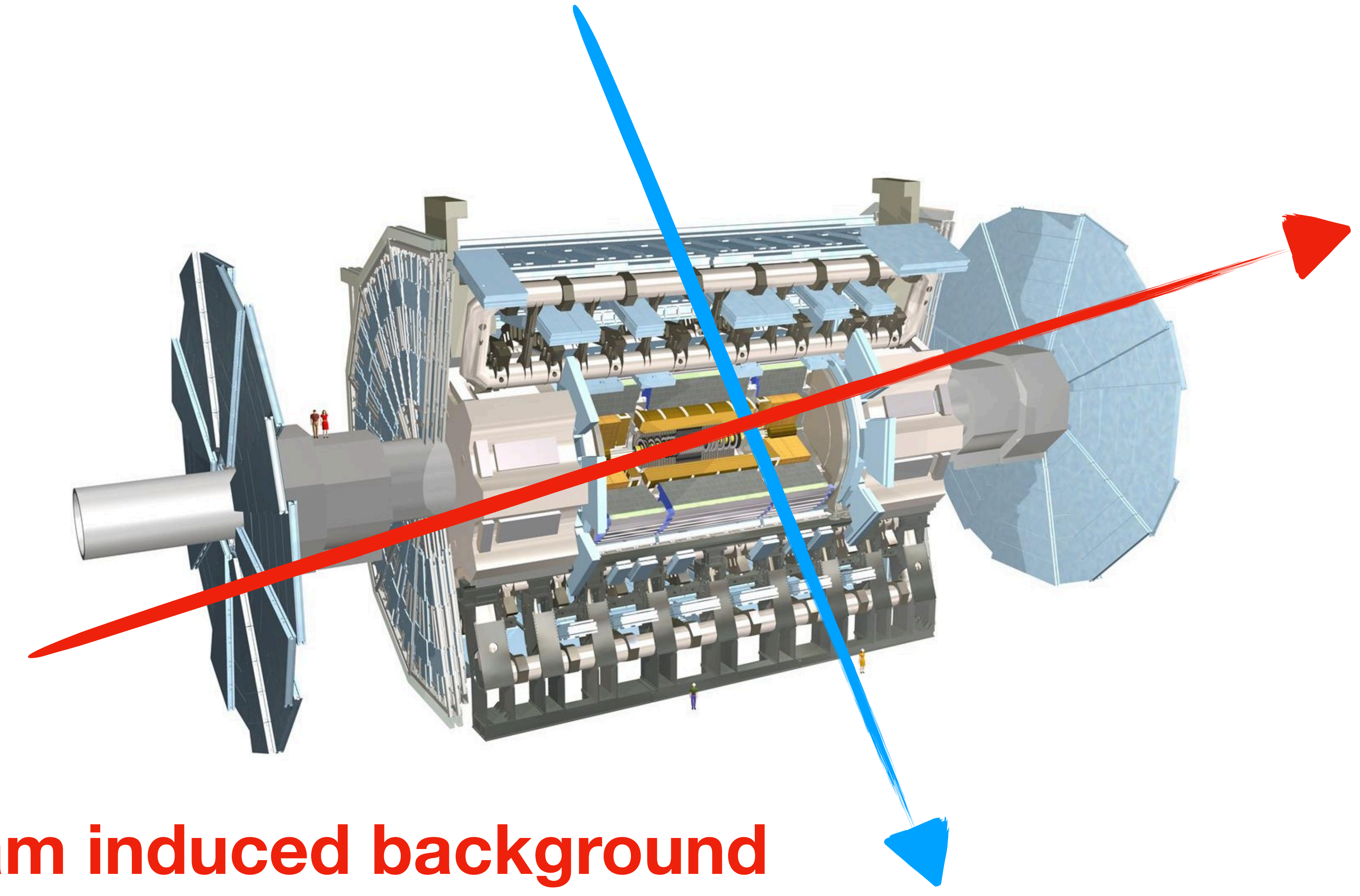


Beam induced background

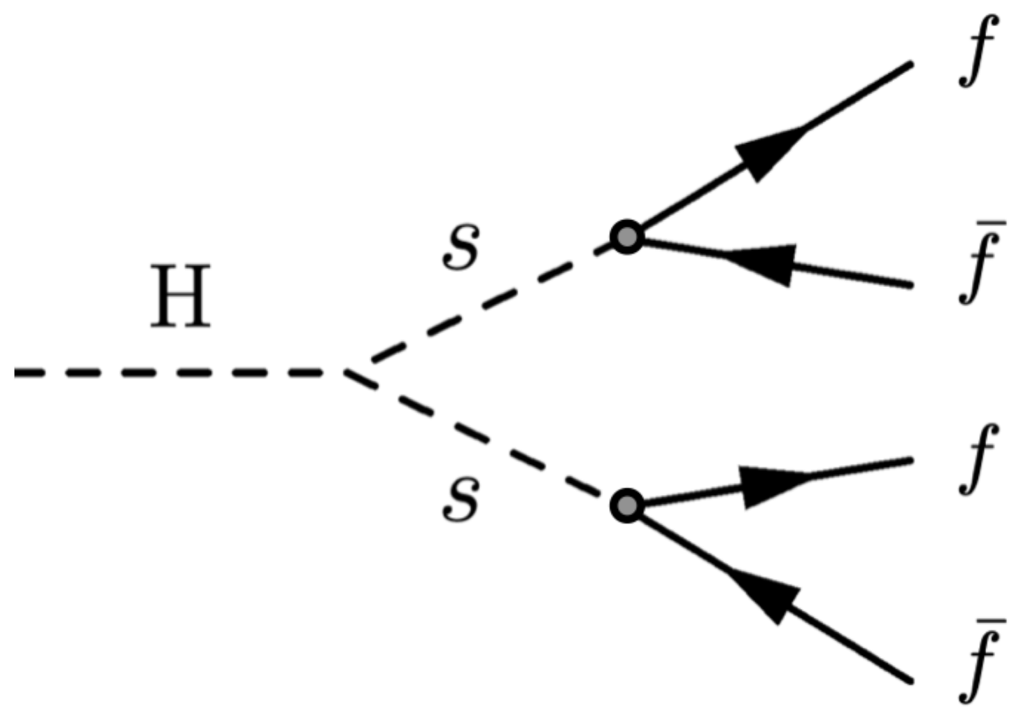
Estimation of signal efficiency

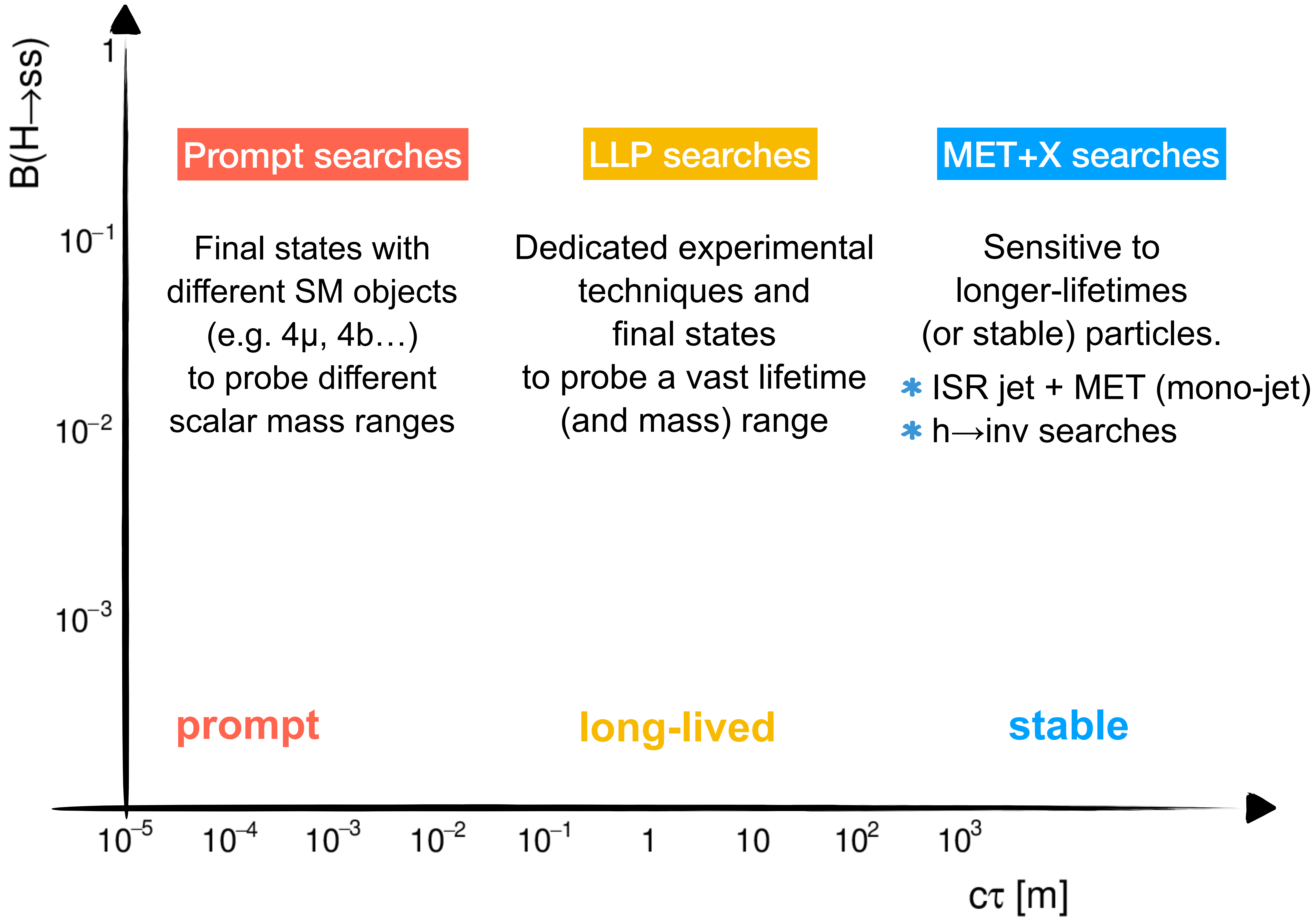
- Often not possible, as no SM standard candle giving sufficiently LLP signatures / decay signatures

Higgs / scalar portal

Scalar portal

Benchmark model showing a nice interplay by different signatures which exploit the potential of the subdetectors and different reconstruction strategies.





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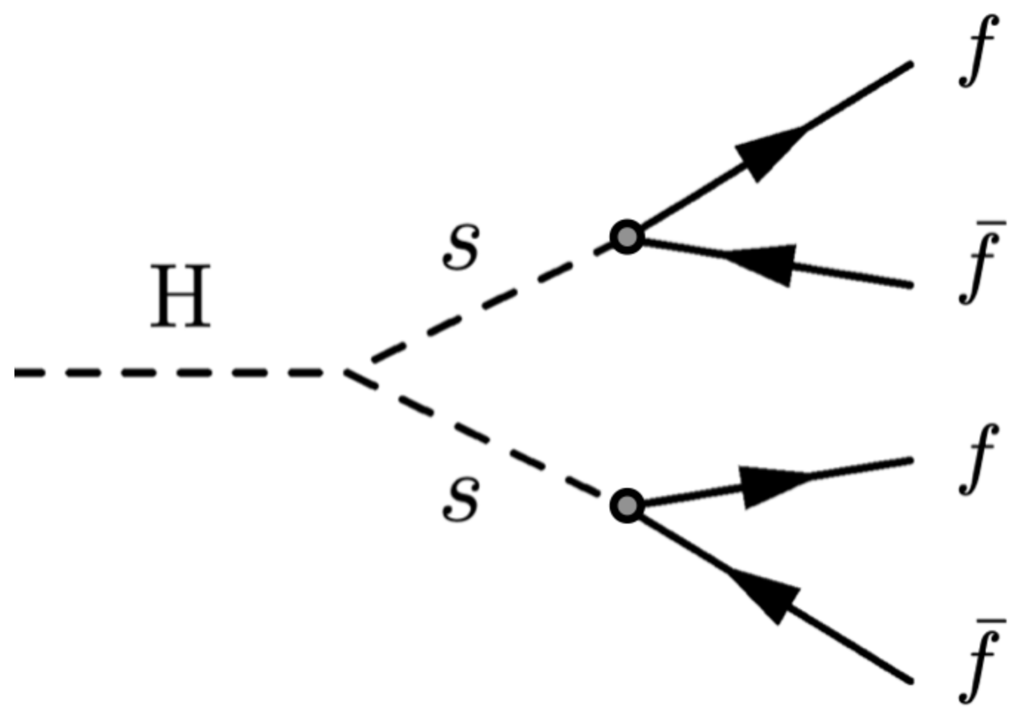
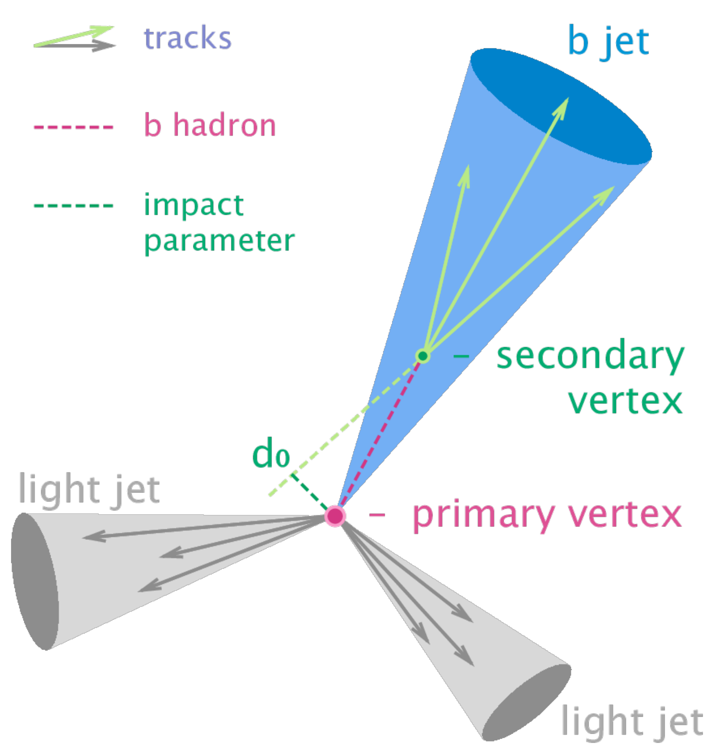
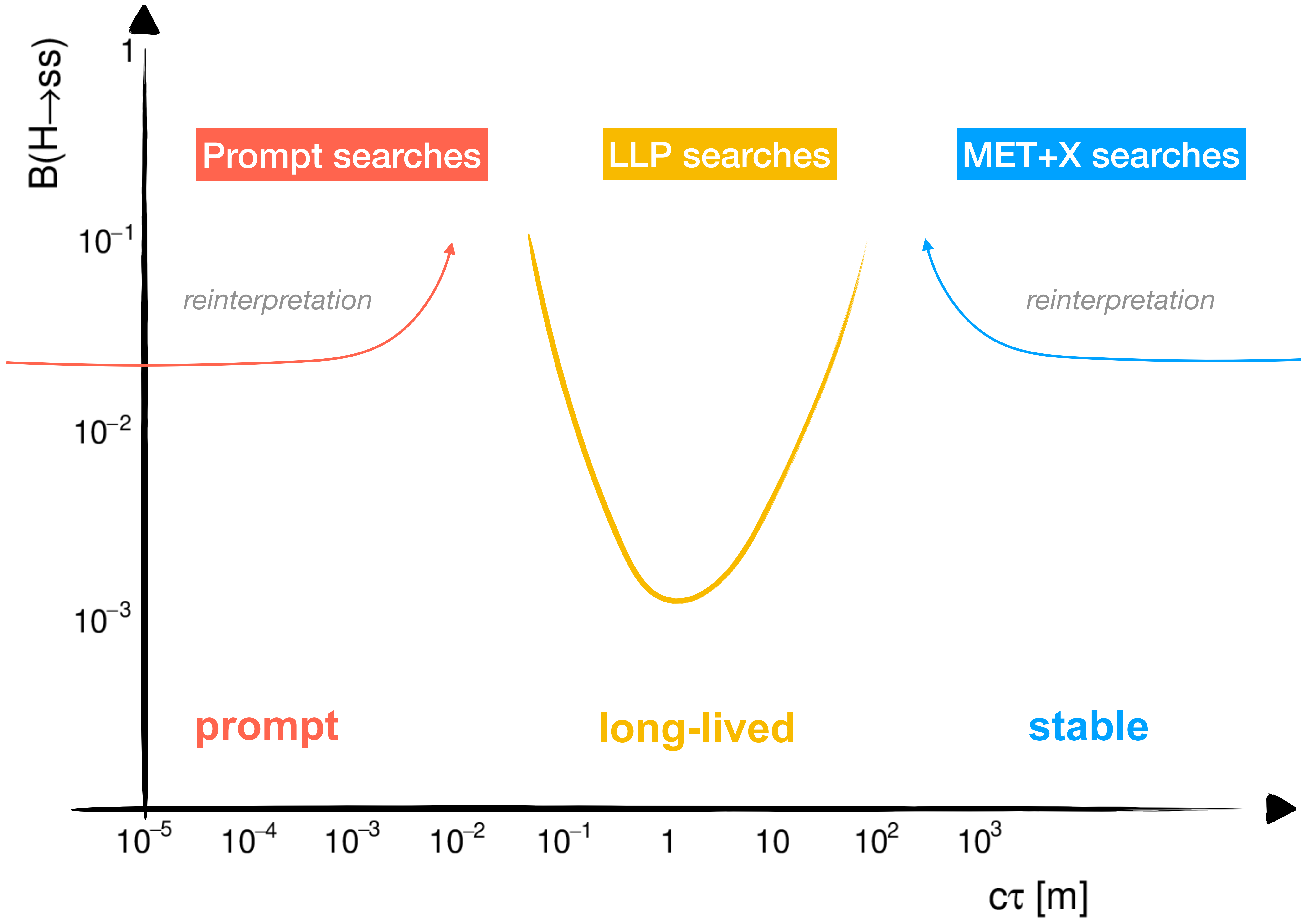
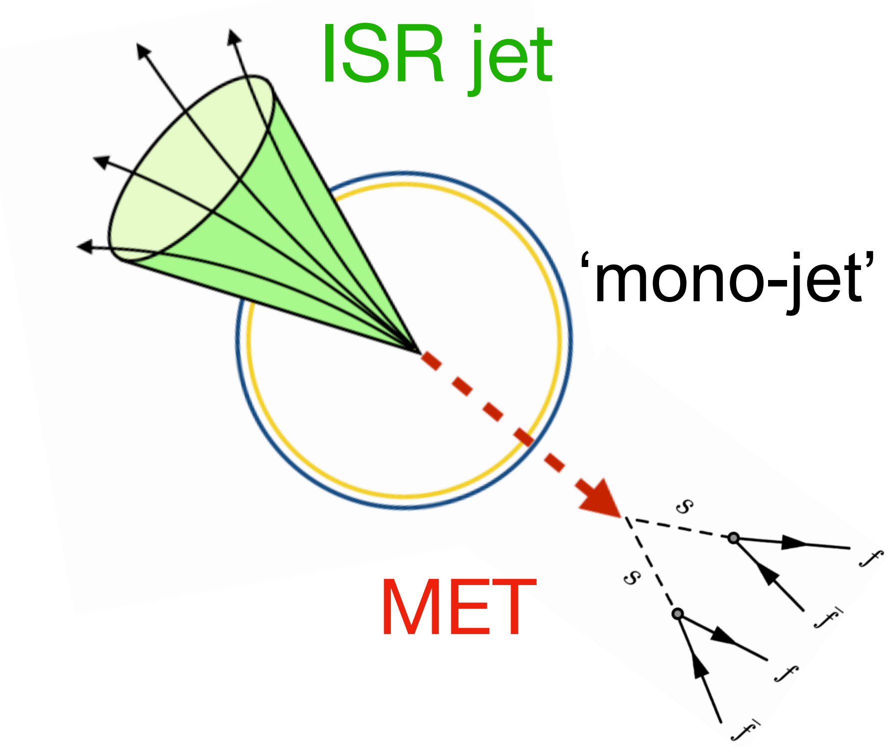




exploiting the object identification algorithms (e.g. b-jet tagging) to probe shorter lifetimes





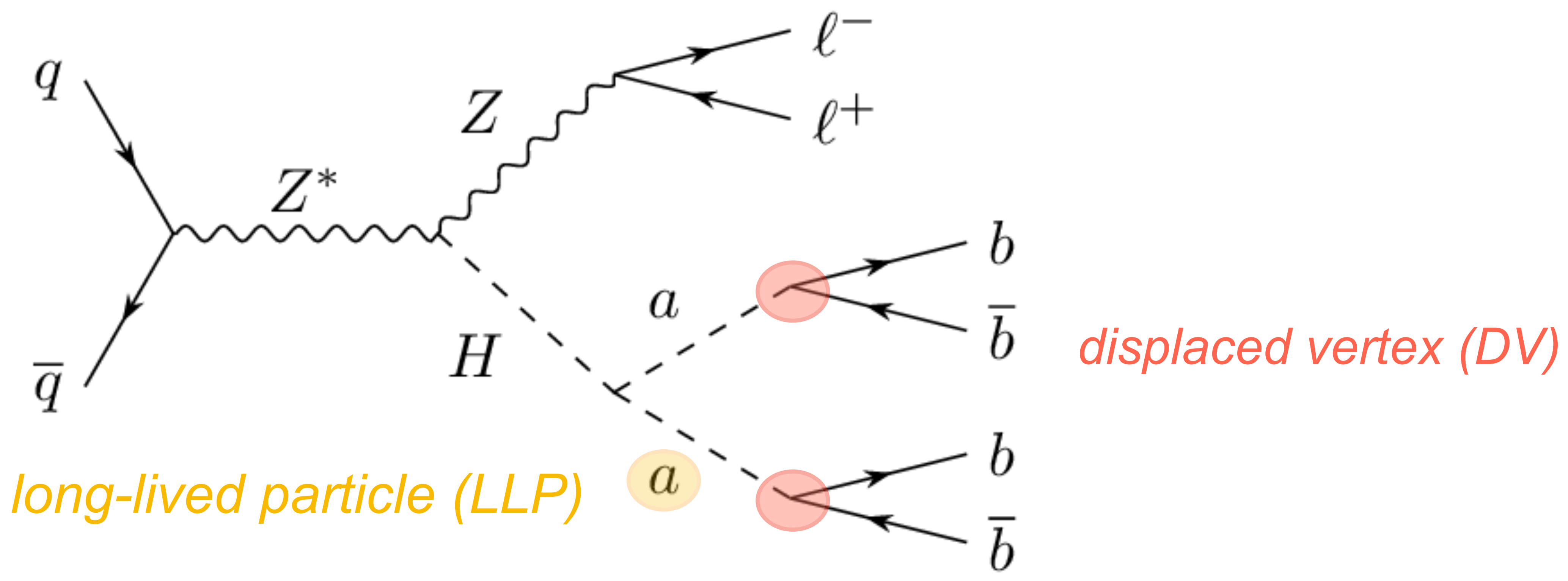
the initial state radiation boosts the Higgs system which decays outside the detector acceptance

Search for LLP in ID

VH4b LLP: JHEP 11 (2021) 229

Search of displaced vertices in the ID

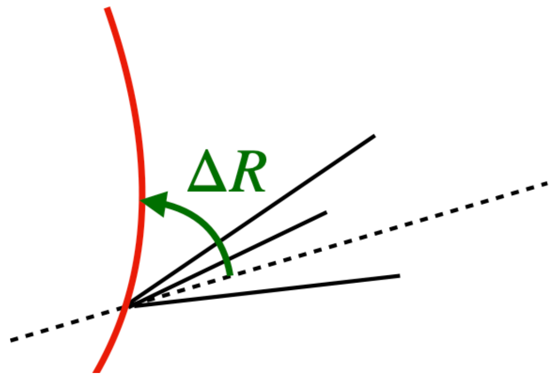
* ZH production
  - to exploit the **lepton triggers**

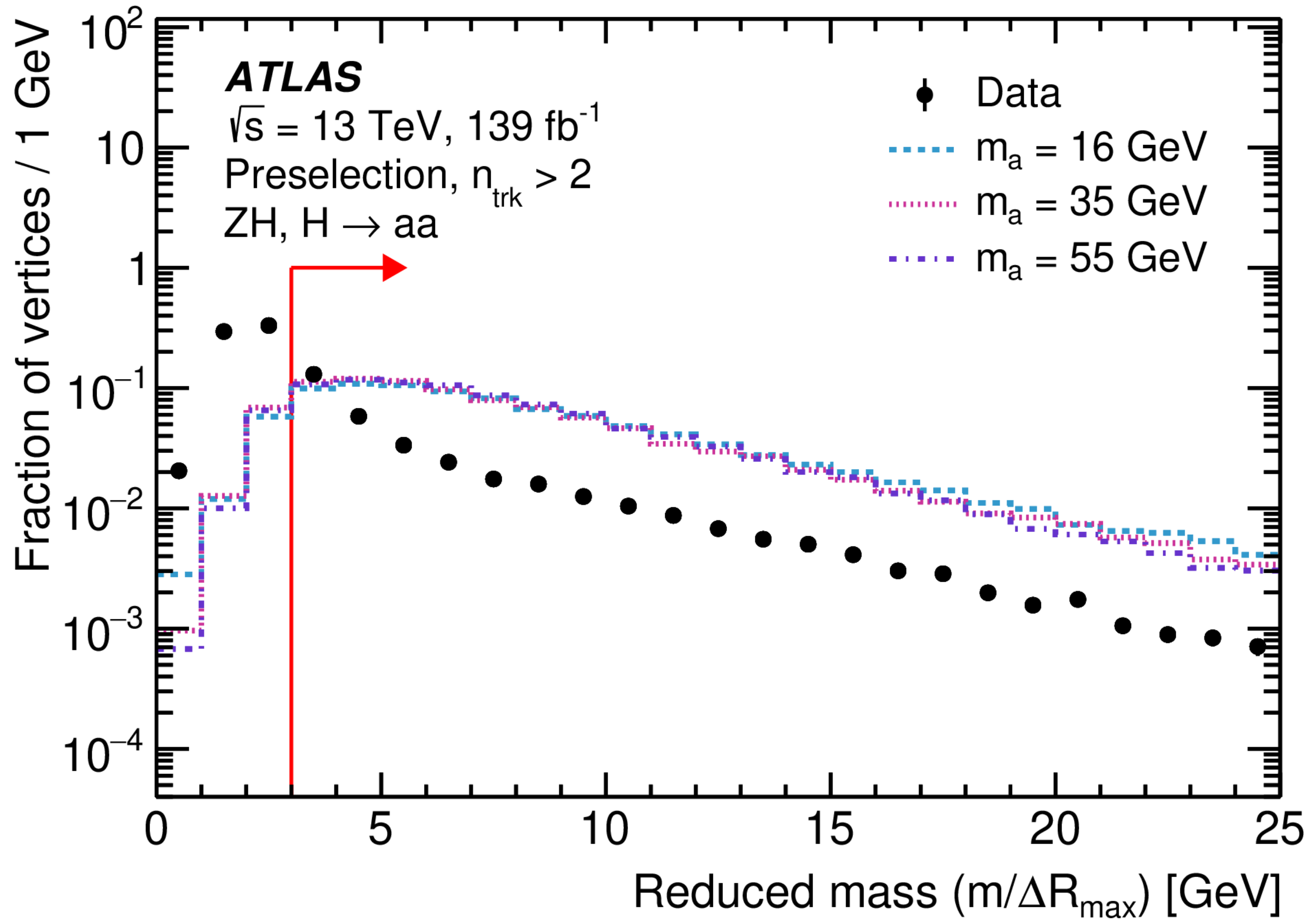


1. select events with **displaced jet** candidates
   * based on tracks information
2. select **large-radius tracks** exploiting a dedicated reconstruction algorithm
3. reconstruct 2 displaced vertices in the ID
   * matched to jets

Key selection variables:

* n_{trk} per vertex
* $m/\Delta R_{max}$ reduced mass
  - ratio of reco vertex invariant mass and ΔR_{max}(track, DV)





Data-driven bkg estimate

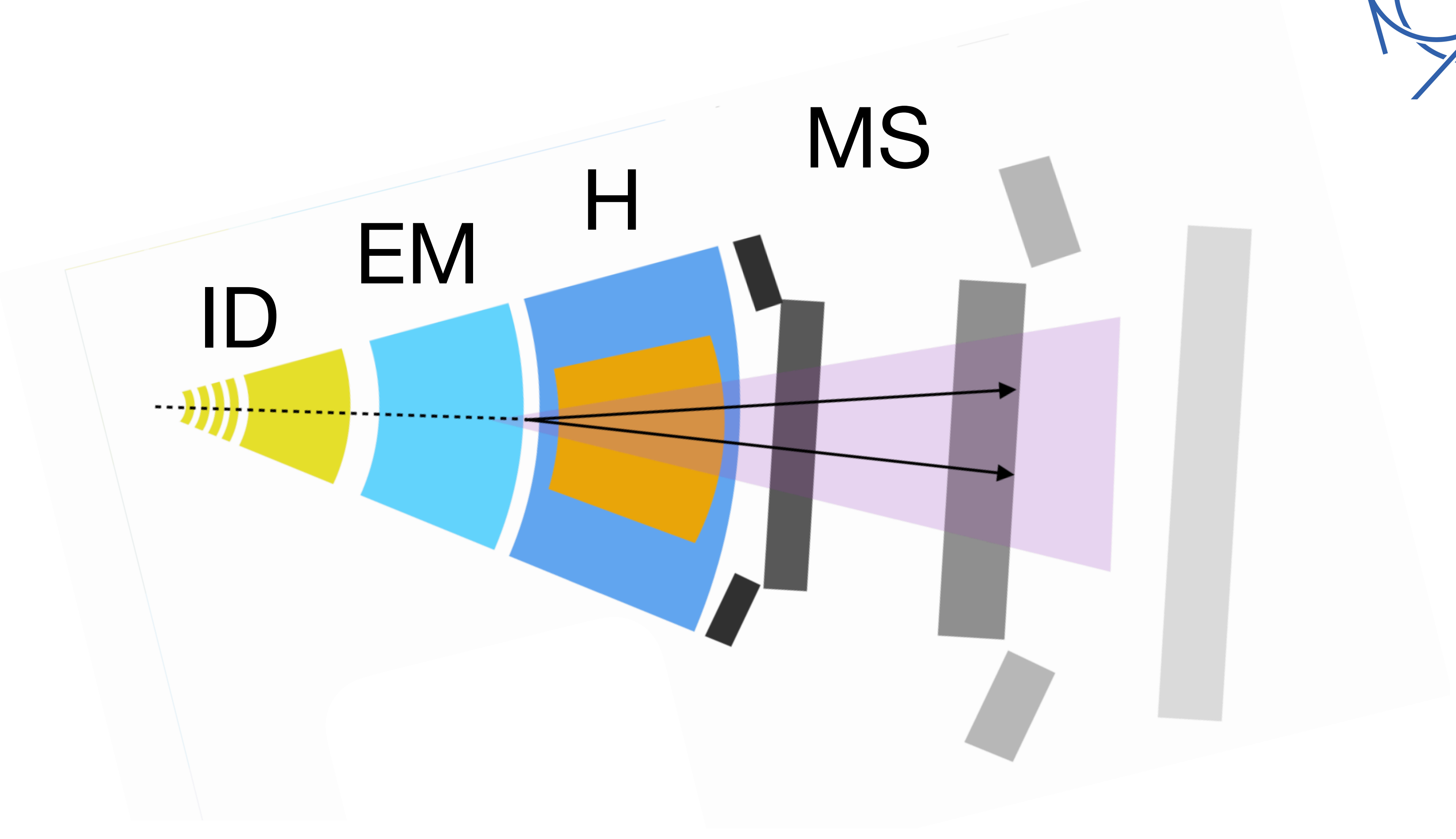
- bkg from Z+jets
* per-jet probability of DVs in CR
* B = 1.30 ± 0.08 ± 0.27

No events observed in the signal region

H→aa - LLP in Calorimeter

JHEP 06 (2022) 005

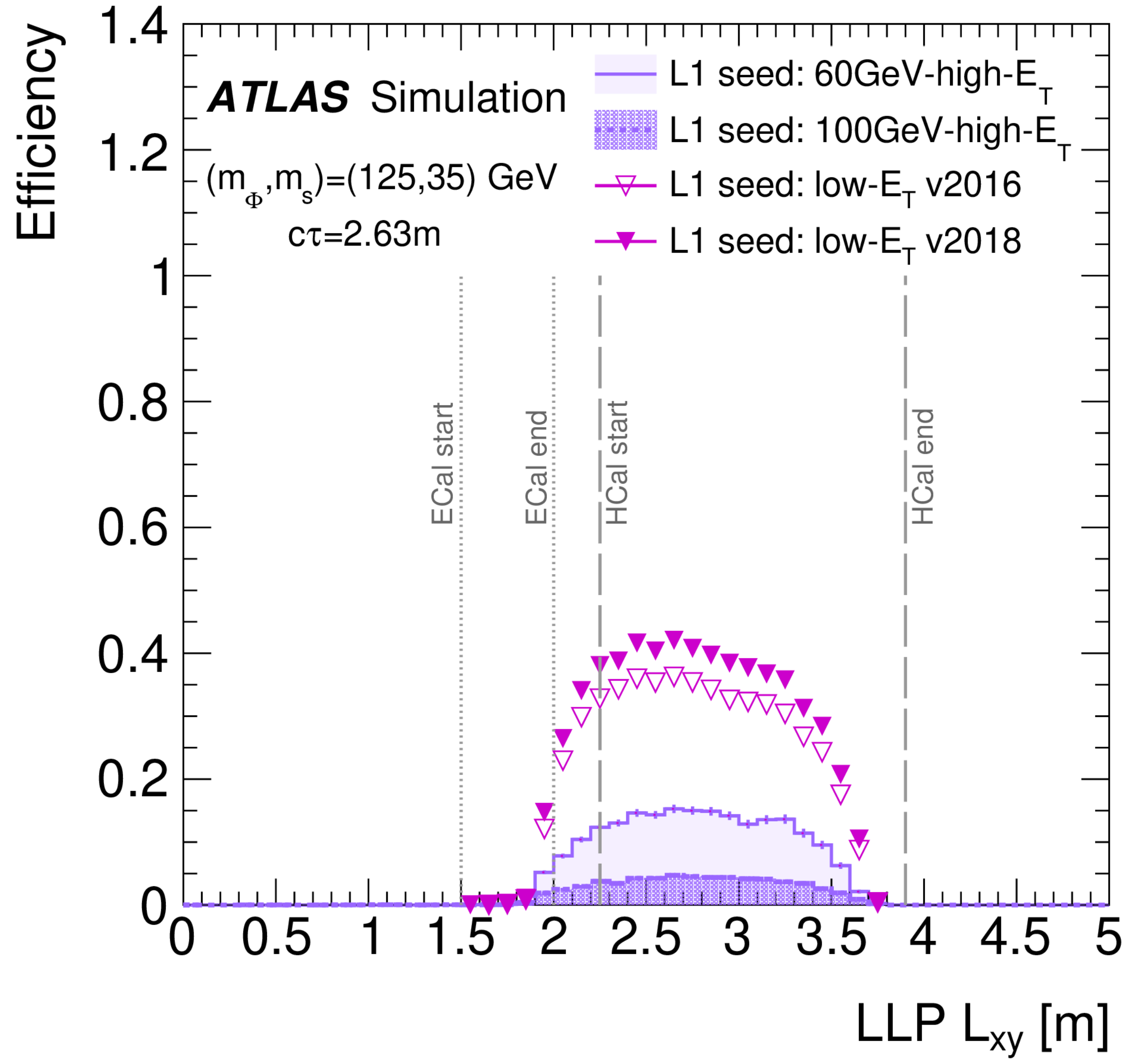
Searching for displaced jets in the calorimeter system

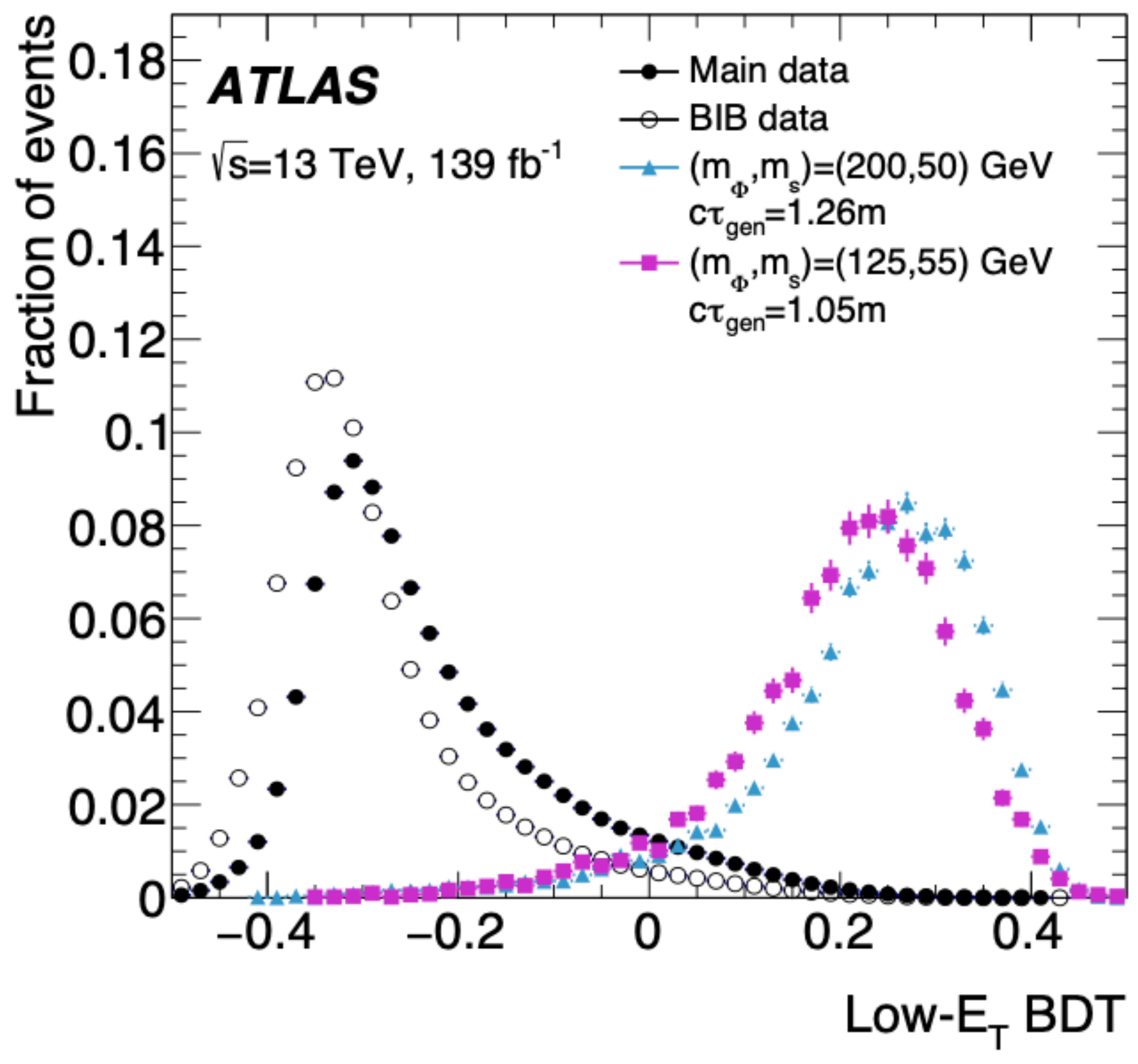


Dedicated triggers exploiting E_H / E_{EM}

+ BIB-enriched sample for the bkg estimation

- displaced jet tagger based on NN
  - based on tracks, topoclusters, muon segments
  - adversary NN to mitigate MC mismodeling
- per-event BDT discriminant
  - BIB, multijet vs signal





Data-driven ABCD method to estimate the bkg

H→aa - DV in MS

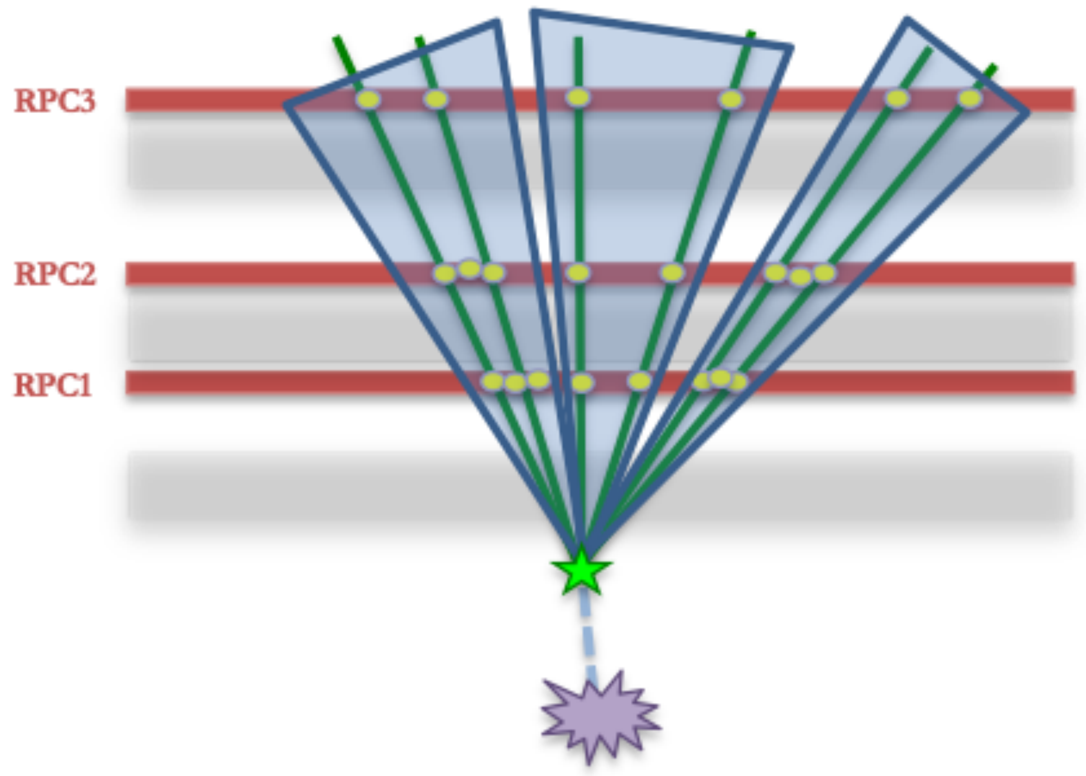
Phys. Rev. D 106, (2022) 032005

Searching for narrow, high multiplicity hadron showers in MS

➡ no matched tracks in the ID

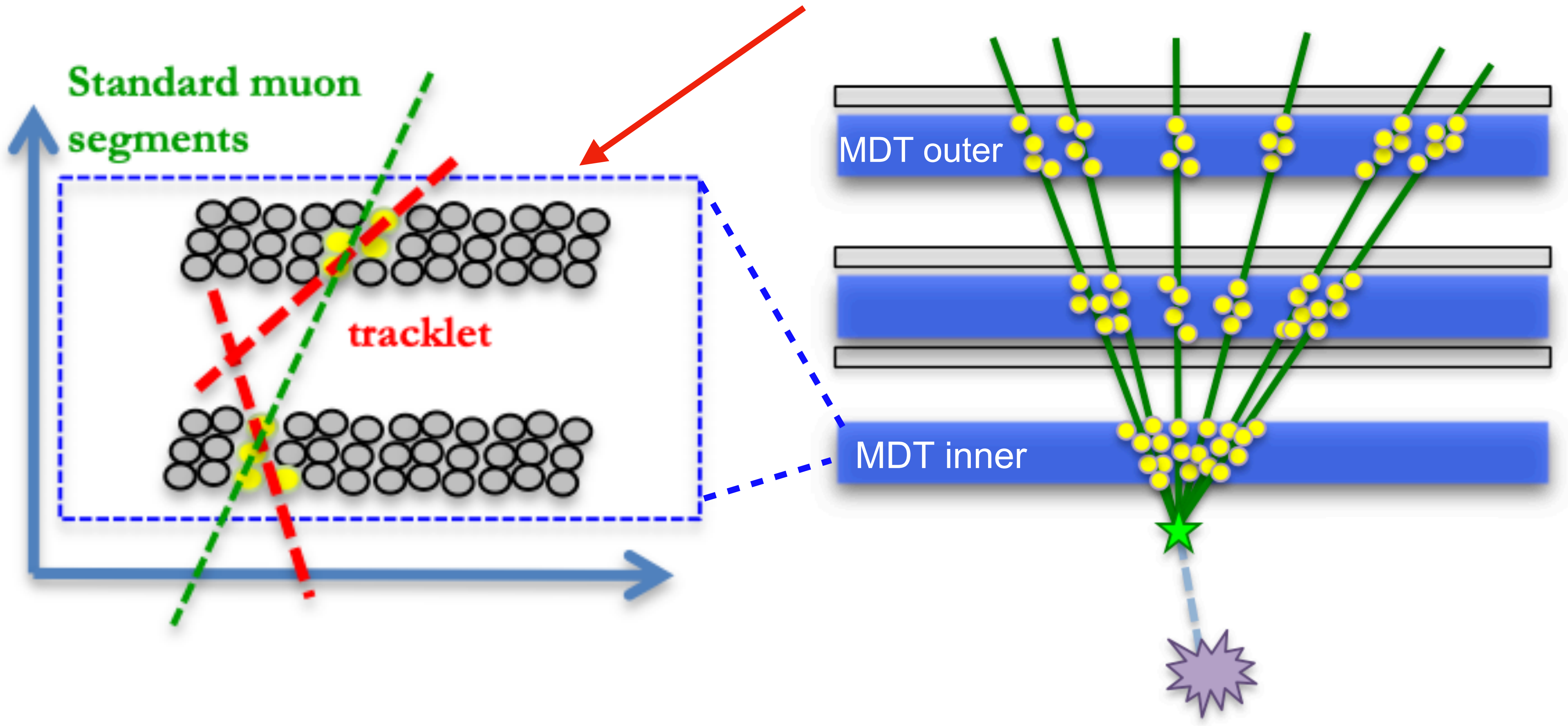
Dedicated **Trigger**

* events w/ a cluster of ≥ 3 (4) ROIs in the barrel (EC)



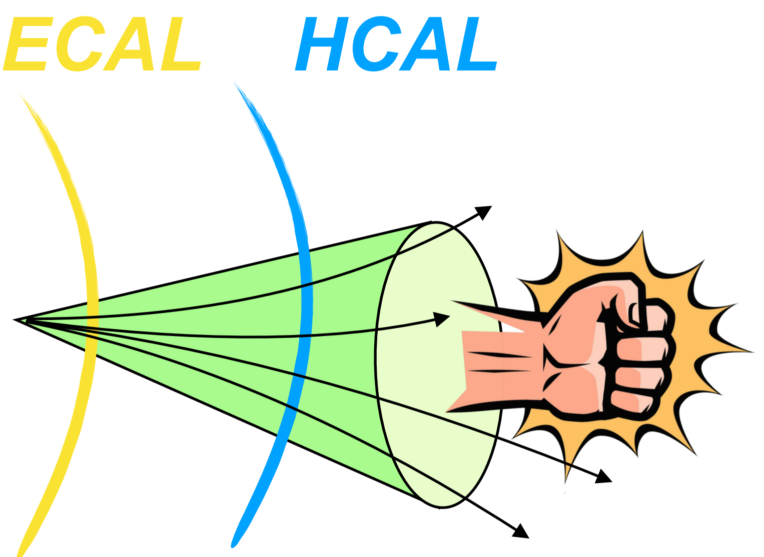
Dedicated **Vertex algorithm**

* reco vertices with ≥ 3 (4) **tracklets** in the barrel (EC)



Main **BKGs**

* punch-through jets
* BIB



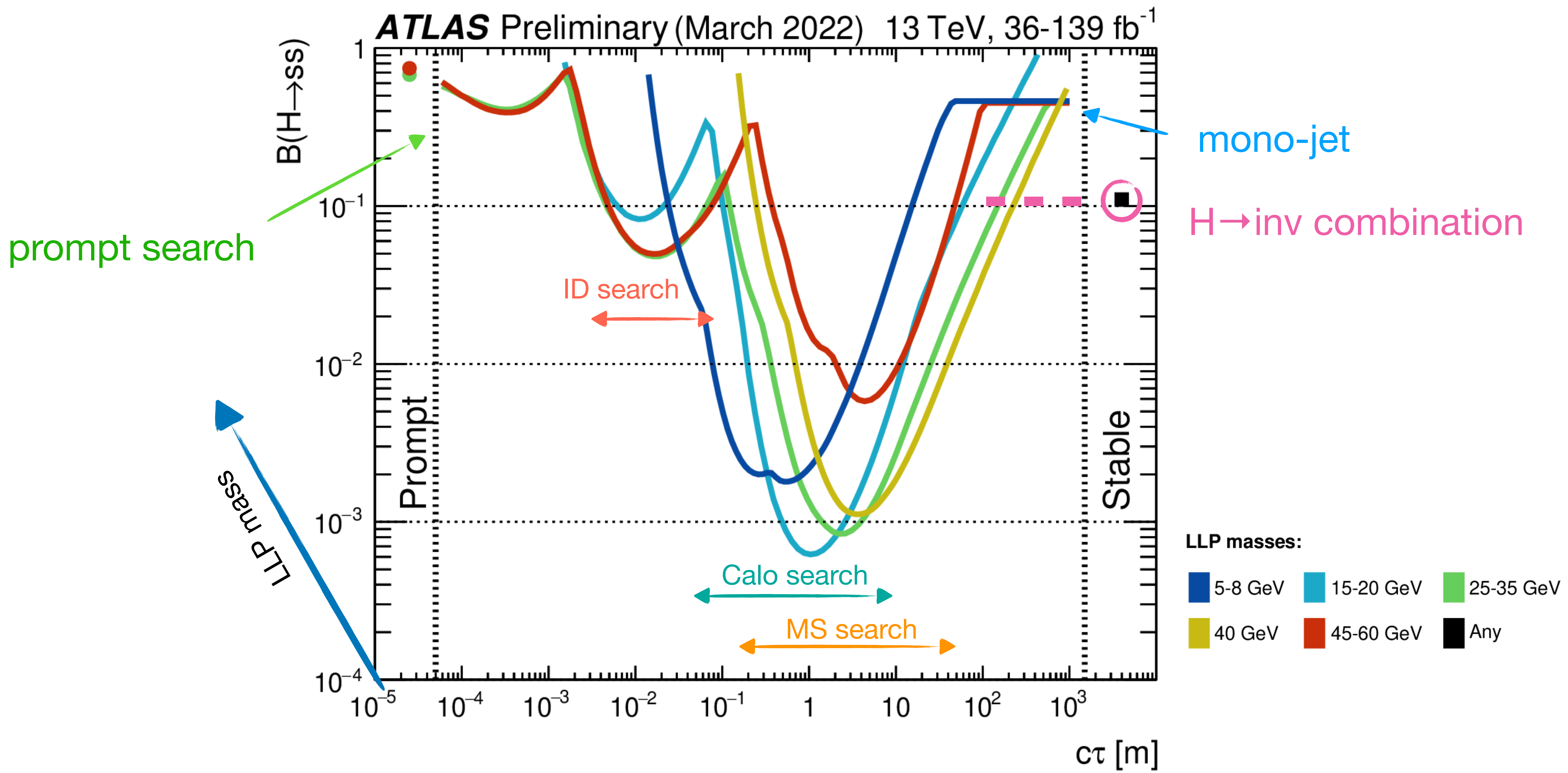
Estimated from main & zero-bias stream

$$N_{2Vx} = 0.32 \pm 0.05$$

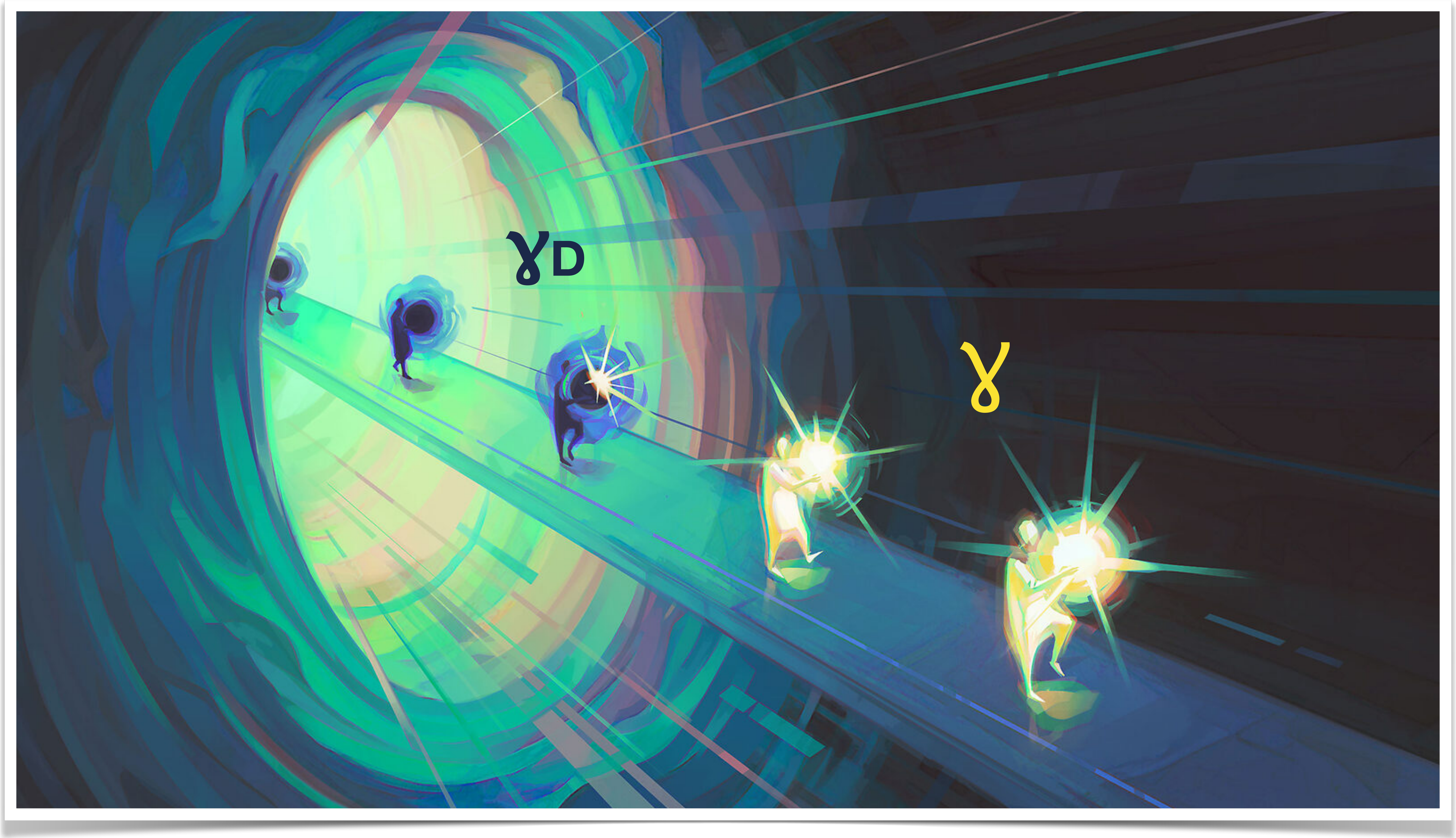
No observed events

Exotics H→ss decays: now

LLP summary plots: ATL-PHYS-PUB-2022-007

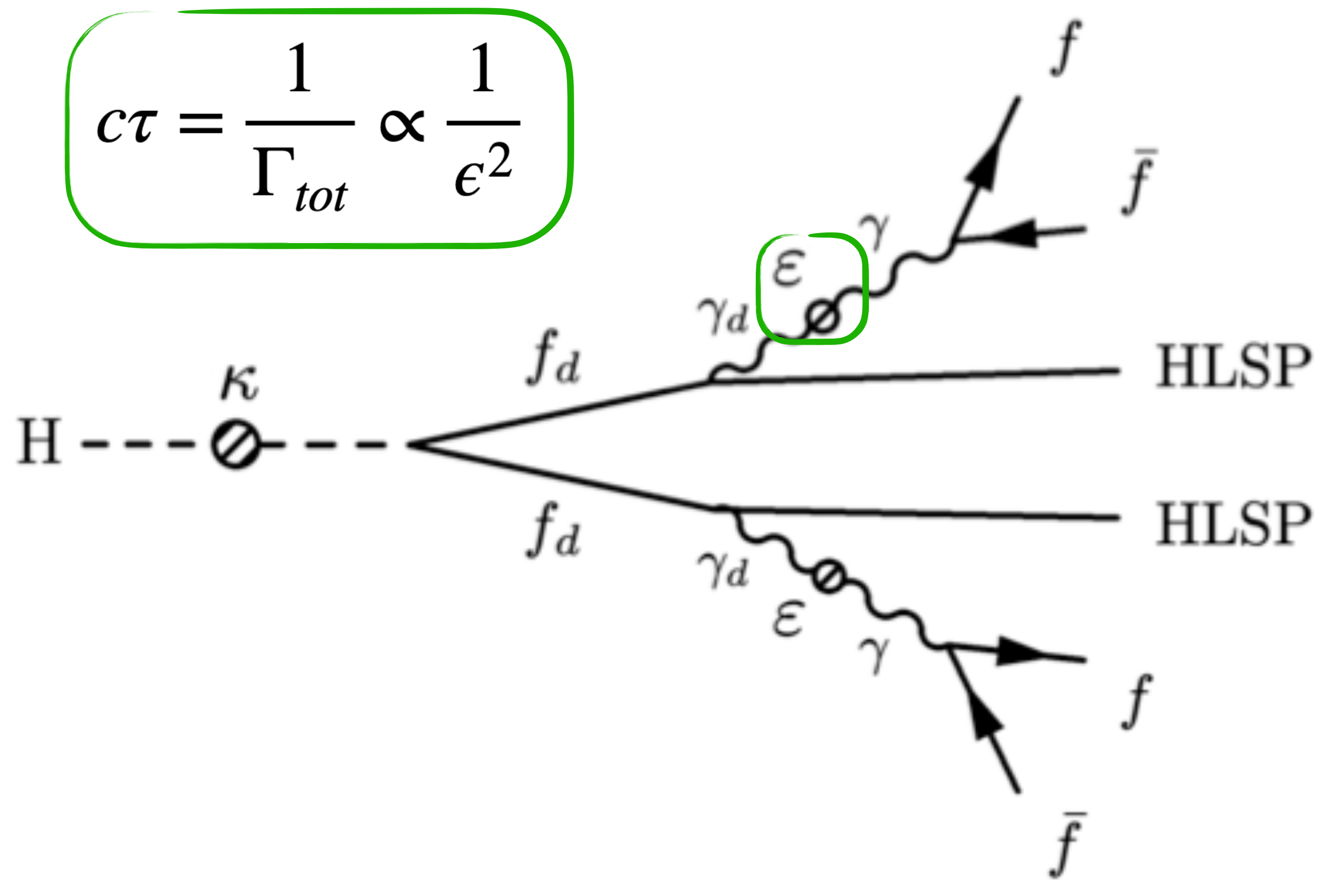


Vector portal



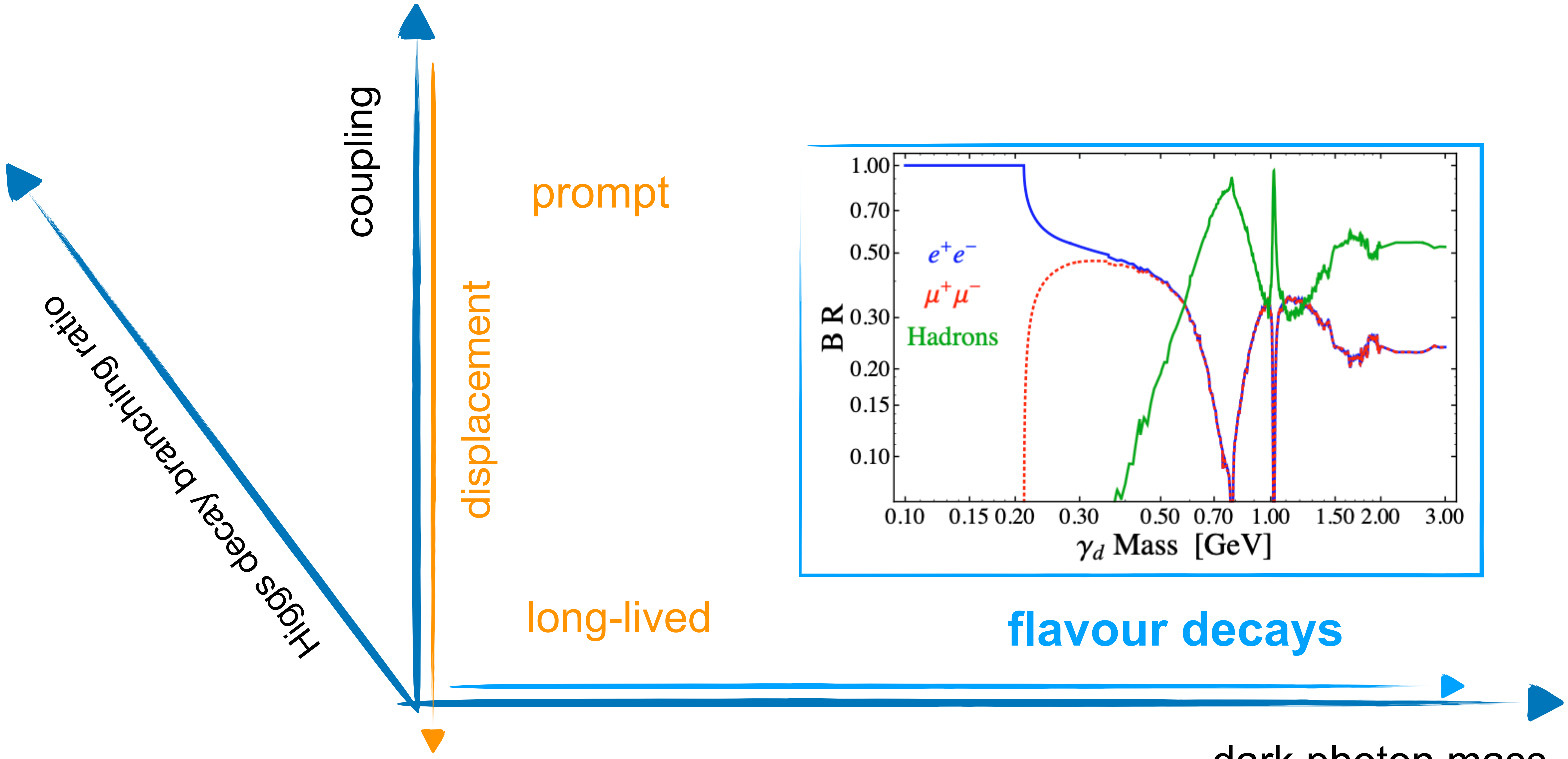
Dark Photons

$$c\tau = \frac{1}{\Gamma_{tot}} \propto \frac{1}{\epsilon^2}$$



Dark sector containing a dark abelian gauge group U(1)$_D$

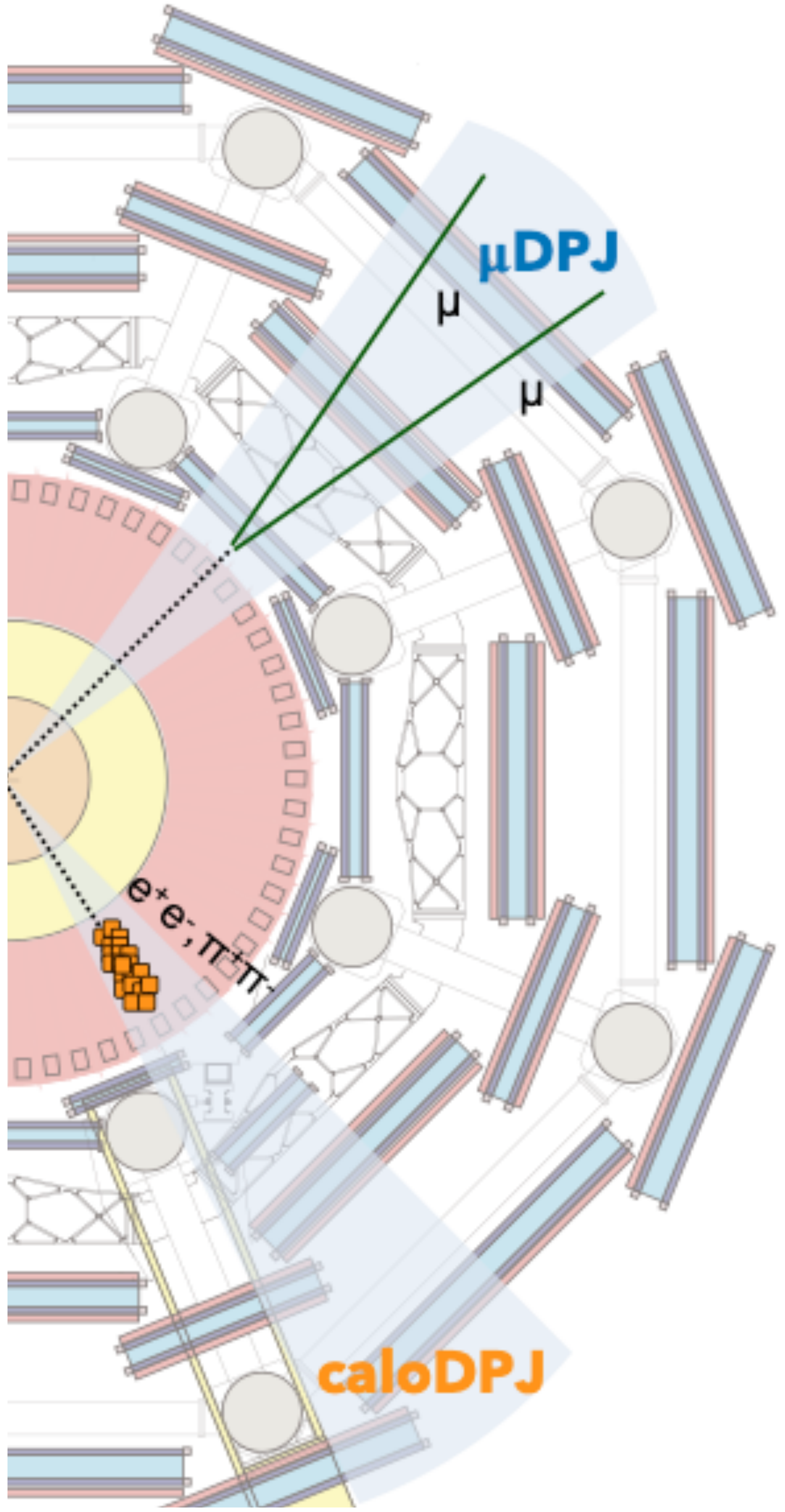
Dark photon mixes with the SM photon



Displaced lepton jets

JHEP 06 (2023) 153
ATLAS-CONF-2023-051

Search for light LLPs decaying into collimated jet structures of leptons or light hadrons



- ggF & WH & VBF productions

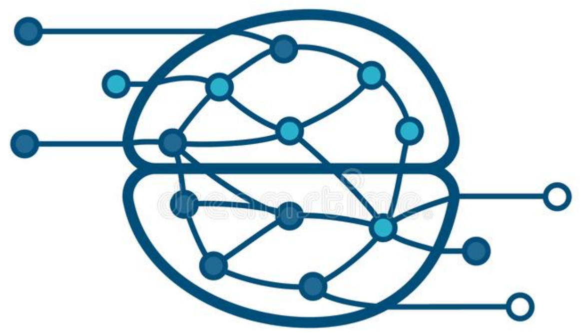
Collimated bunch of muons w/o tracks in the ID

- Low-p_T muons hard to trigger
- Cosmic-ray muons bkg

Displaced jet with most of energy deposit in the HCAL

- High bkg from QCD events

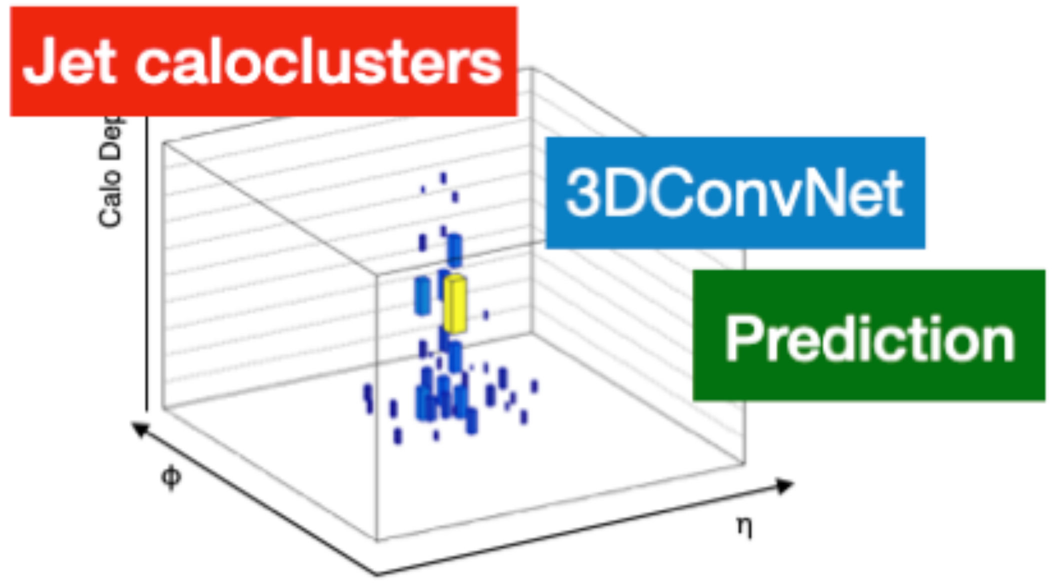
NN taggers

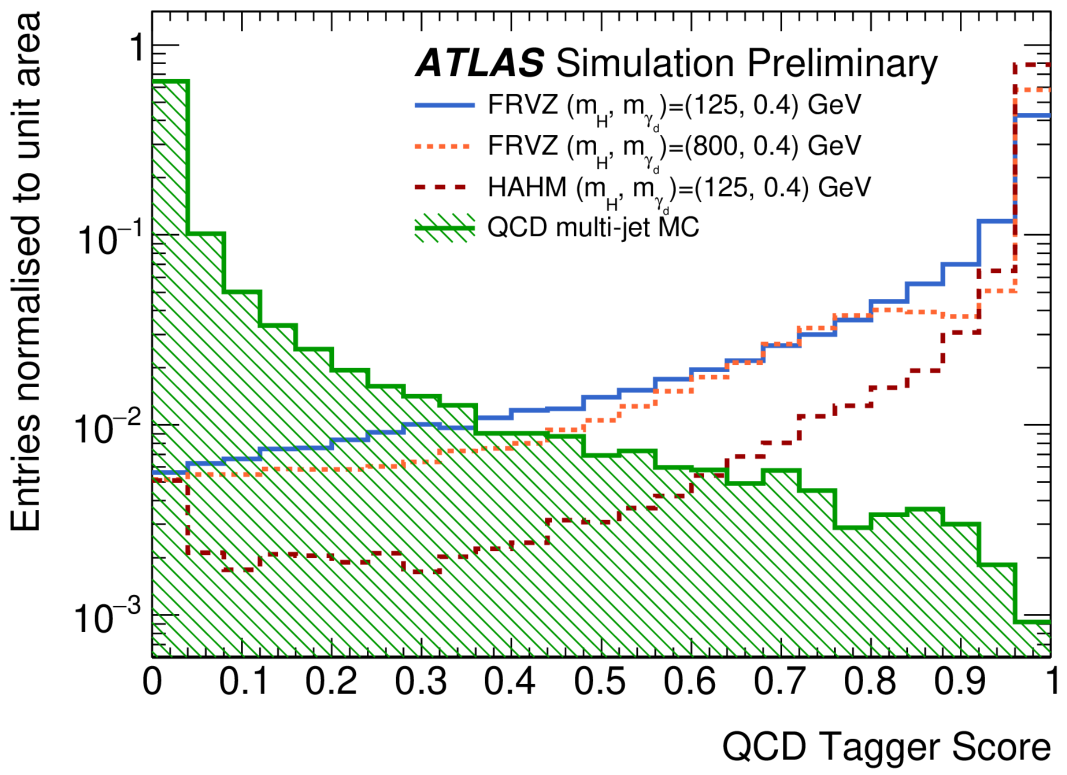


Dense NN-based (per track) tagger in **μ-channels** to reject cosmics

Convolutional NN-based taggers in **calo-channels** to reject QCD and BIB

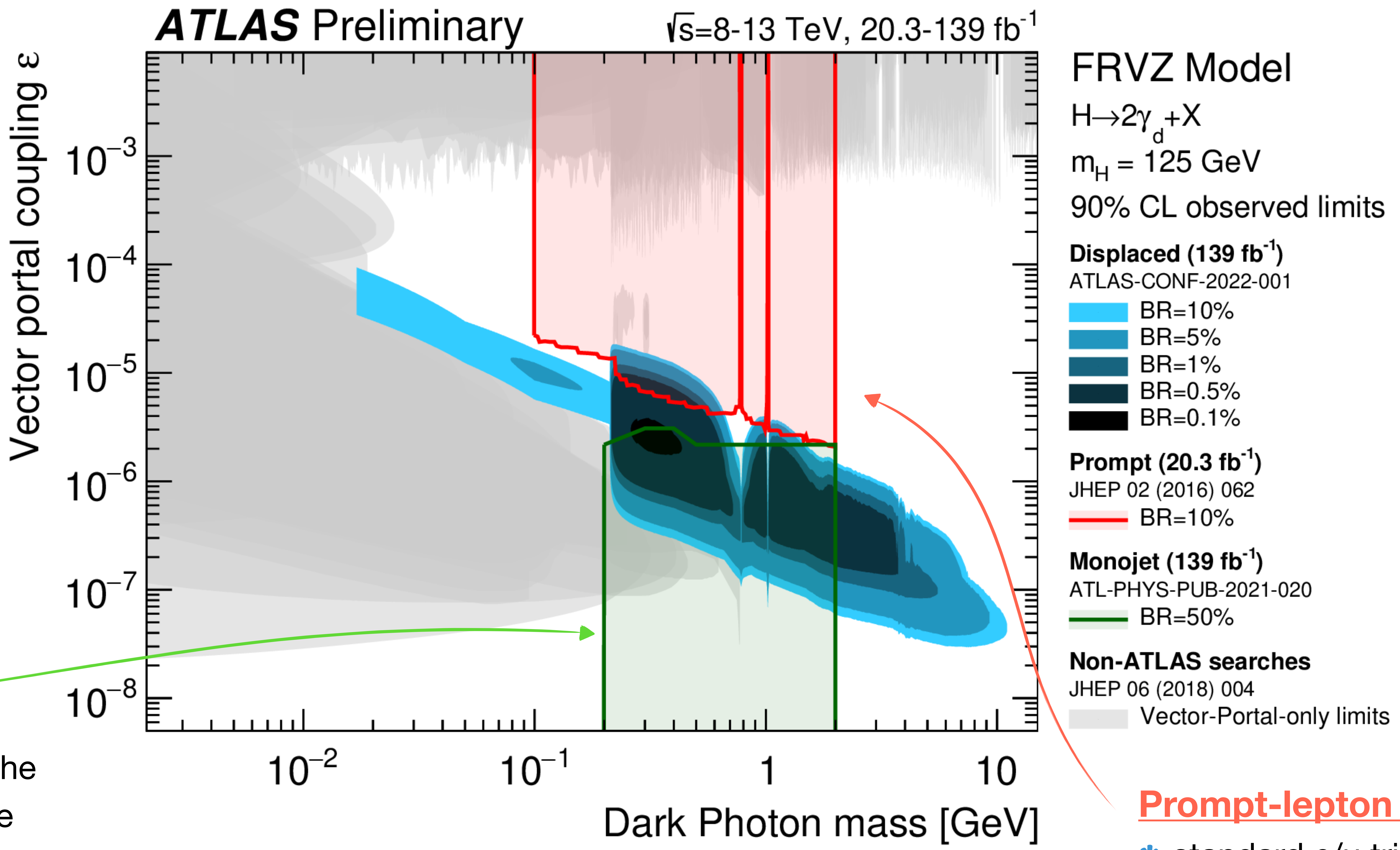
trained on low-level inputs (3D jet images from calorimetric clusters)





Dark Photons summary

ATL-PHYS-PUB-2022-007
JHEP 06 (2023) 153



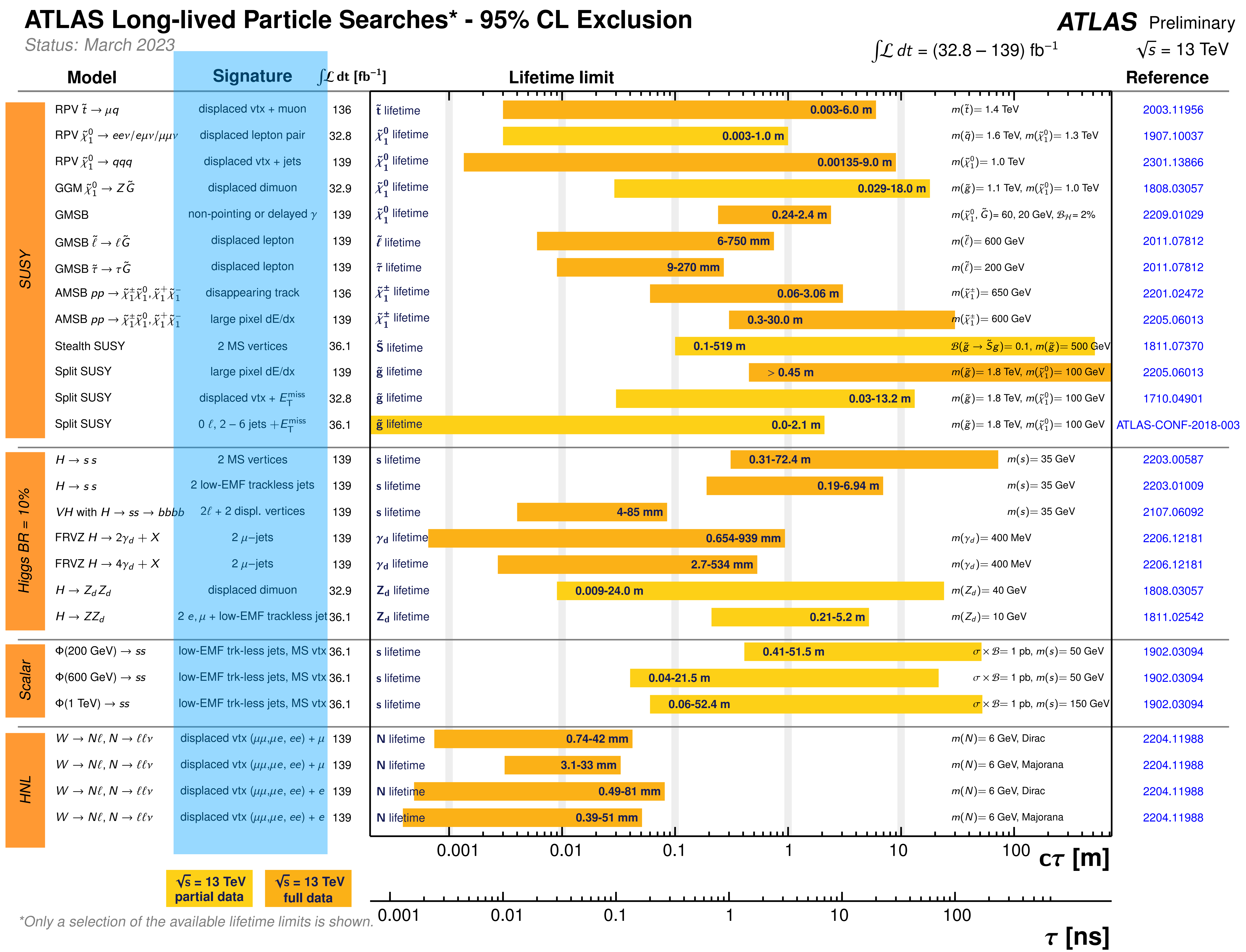
Mono-jet

- reinterpreted to cover the smaller coupling regime
  - similarly can be done with
    - Hinv combination

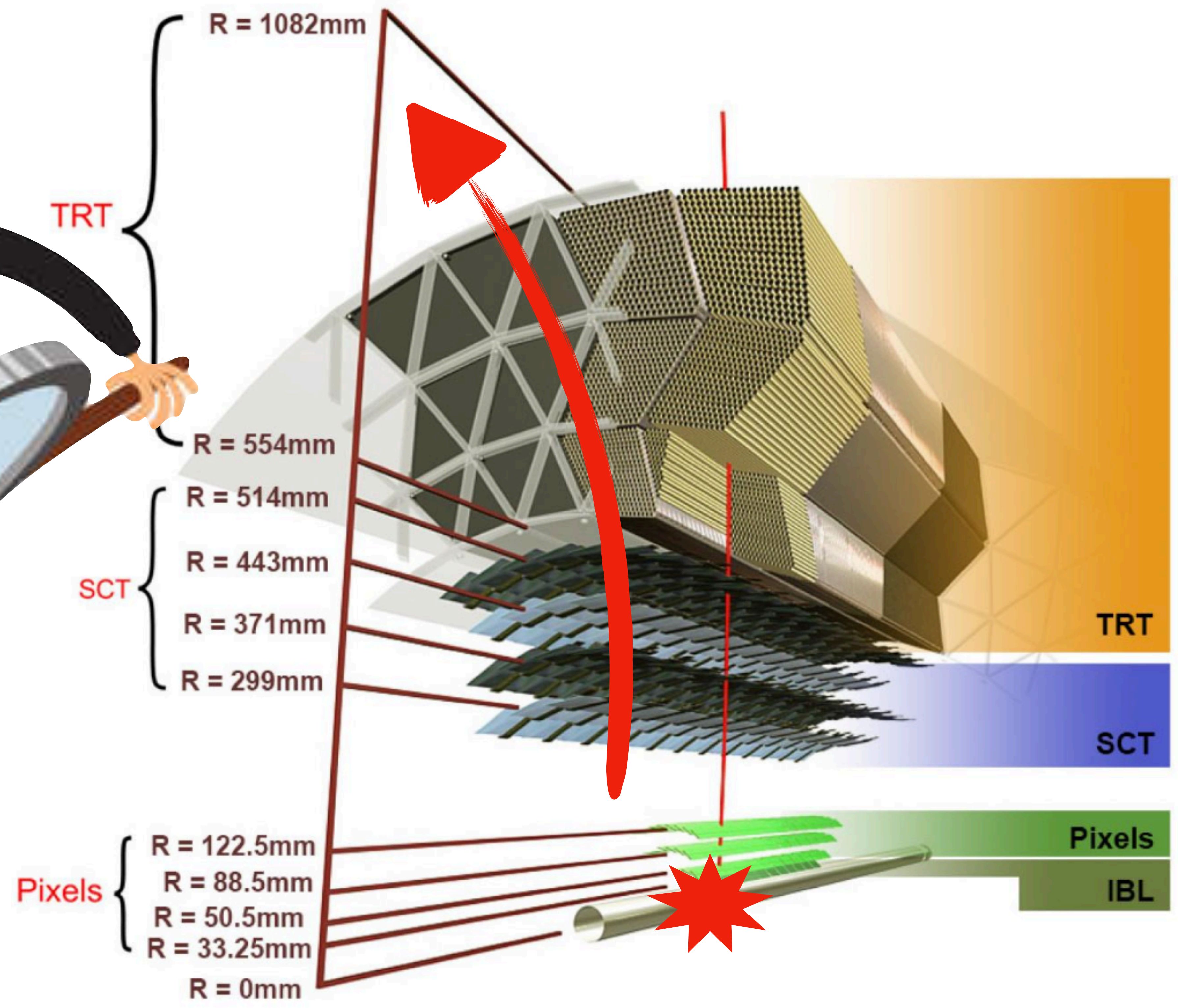
Prompt-lepton jets

- standard e/μ triggers
- e, μ and mixed channels
- *ongoing based on full Run-2 data*

LLP summary plots



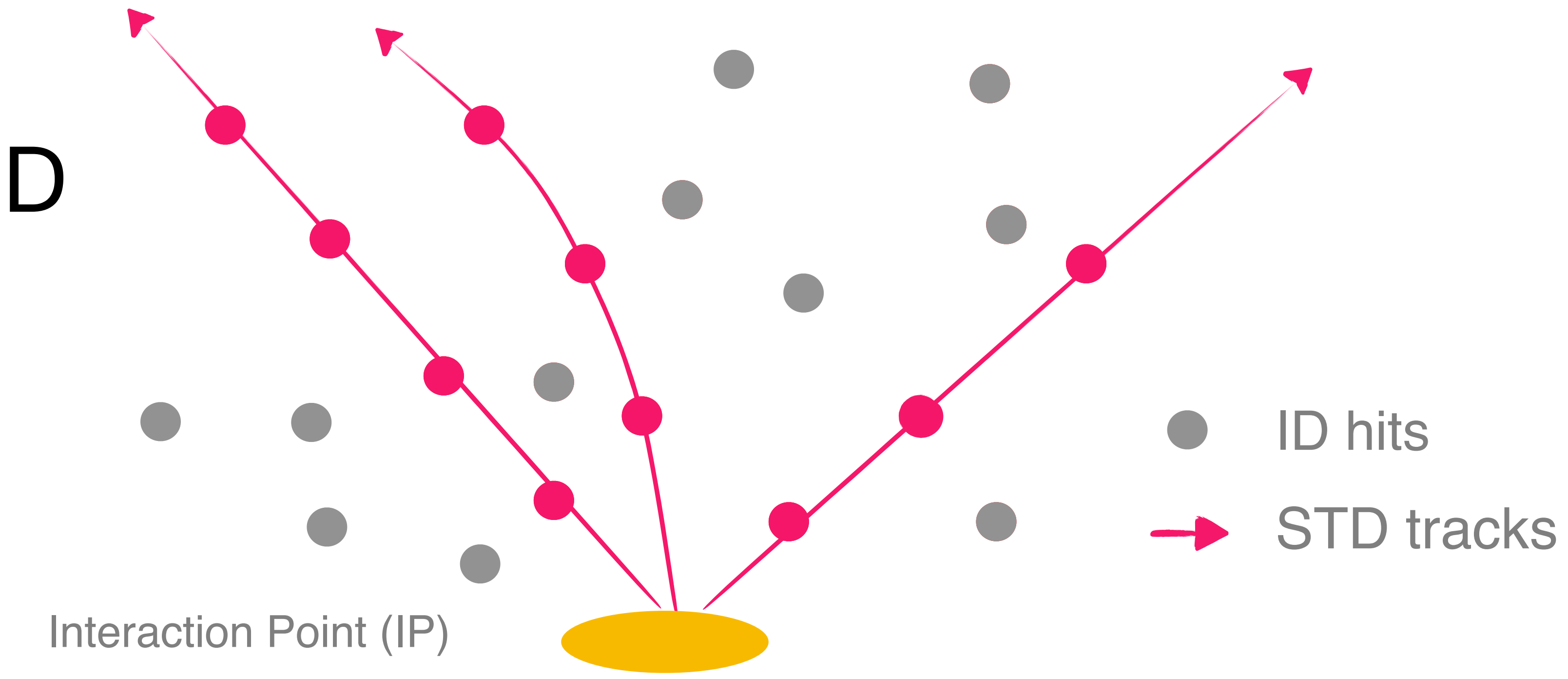
TRACKING Long-Lived particles

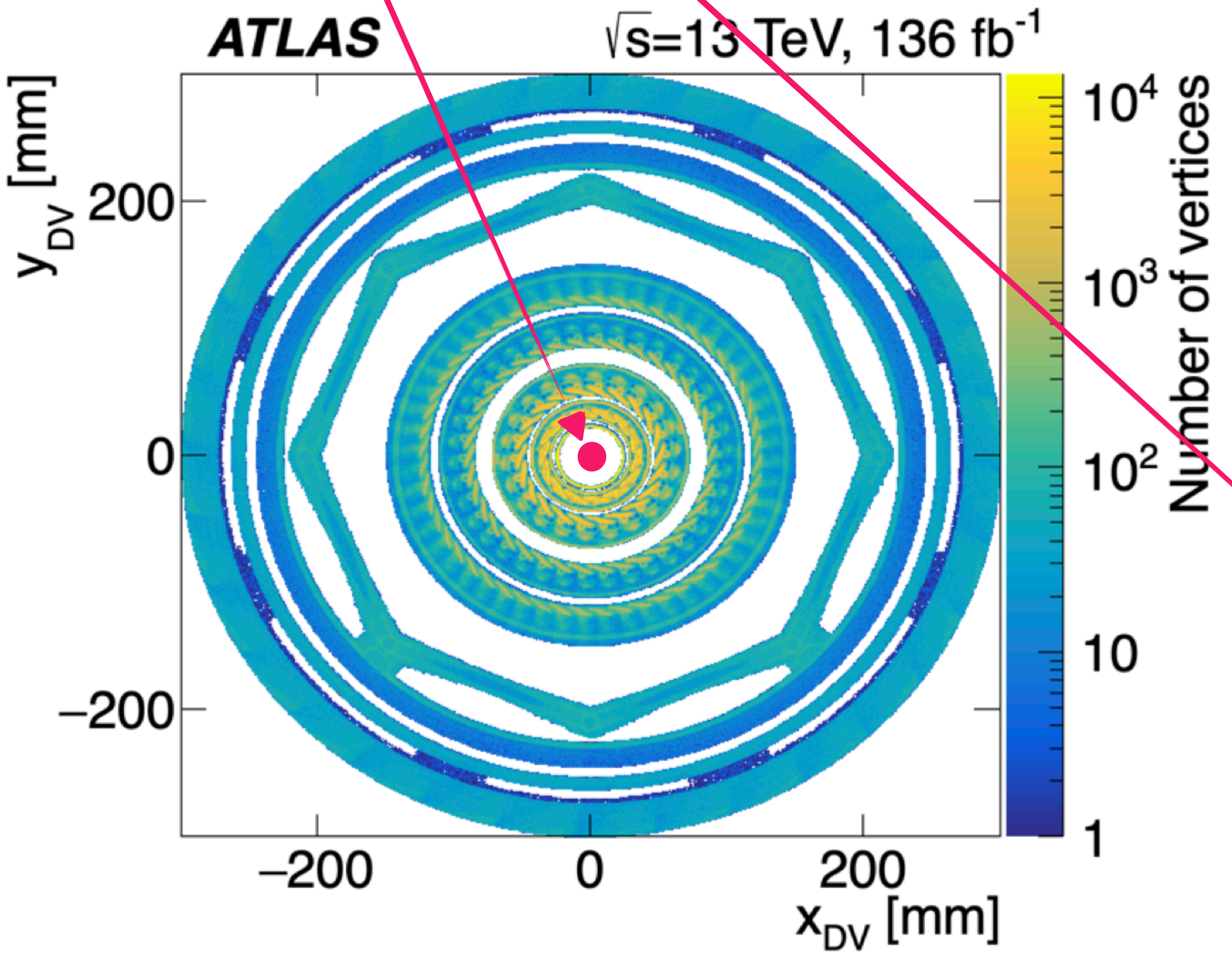


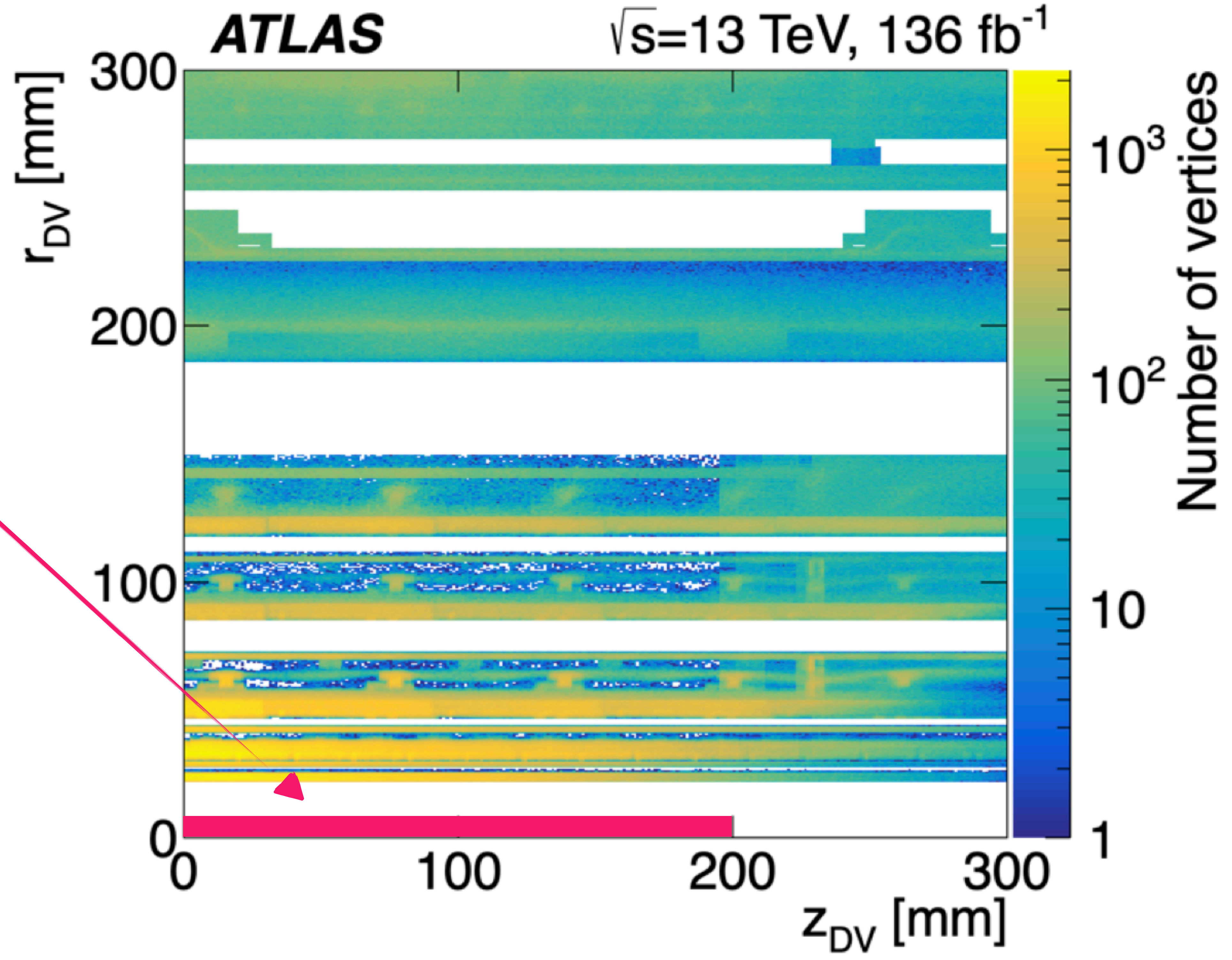
Large-radius tracking in a nutshell

arXiv:2304.12867

Standard Tracking (STD) optimised to reconstruct prompt tracks in the ID







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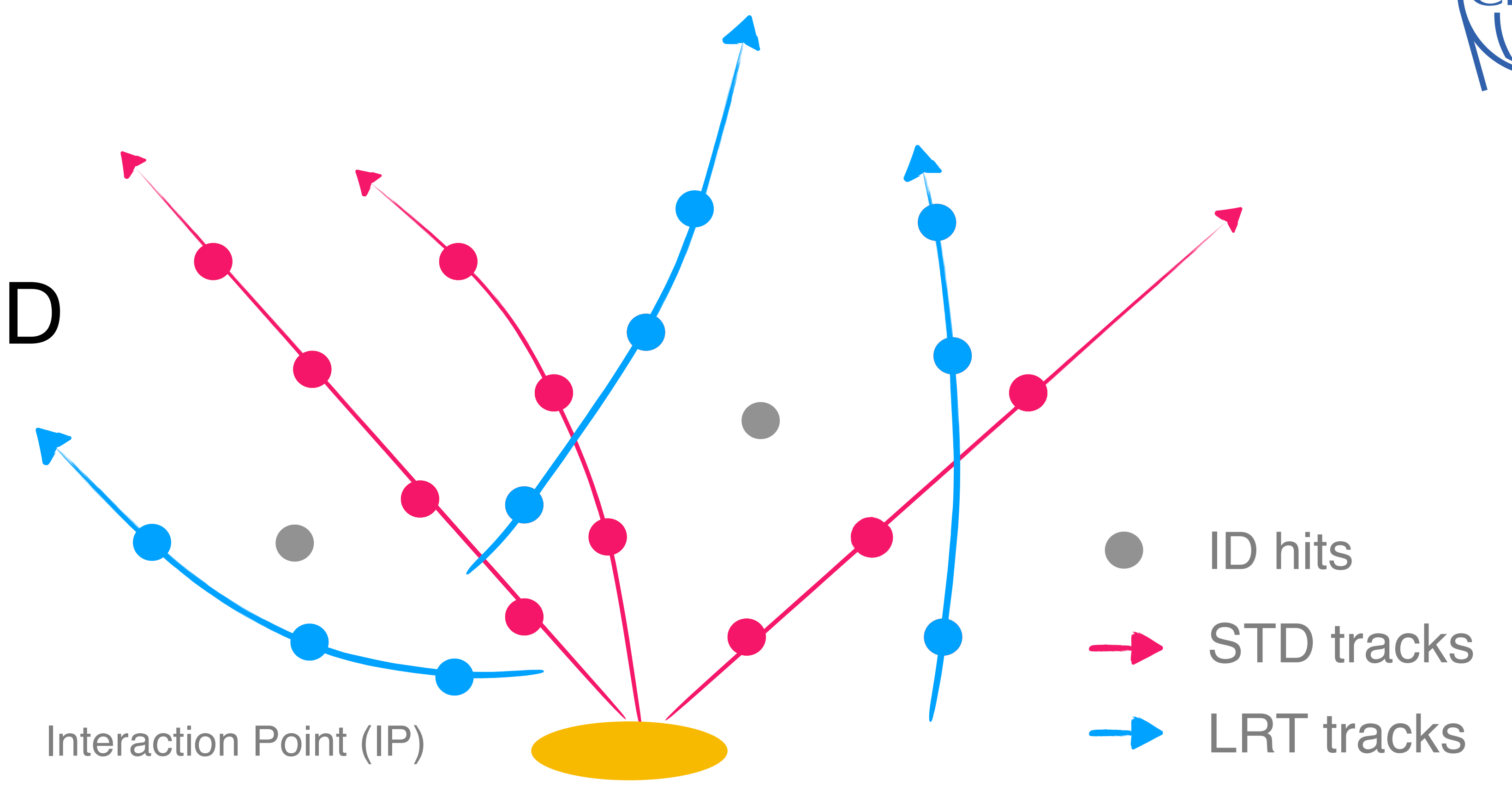
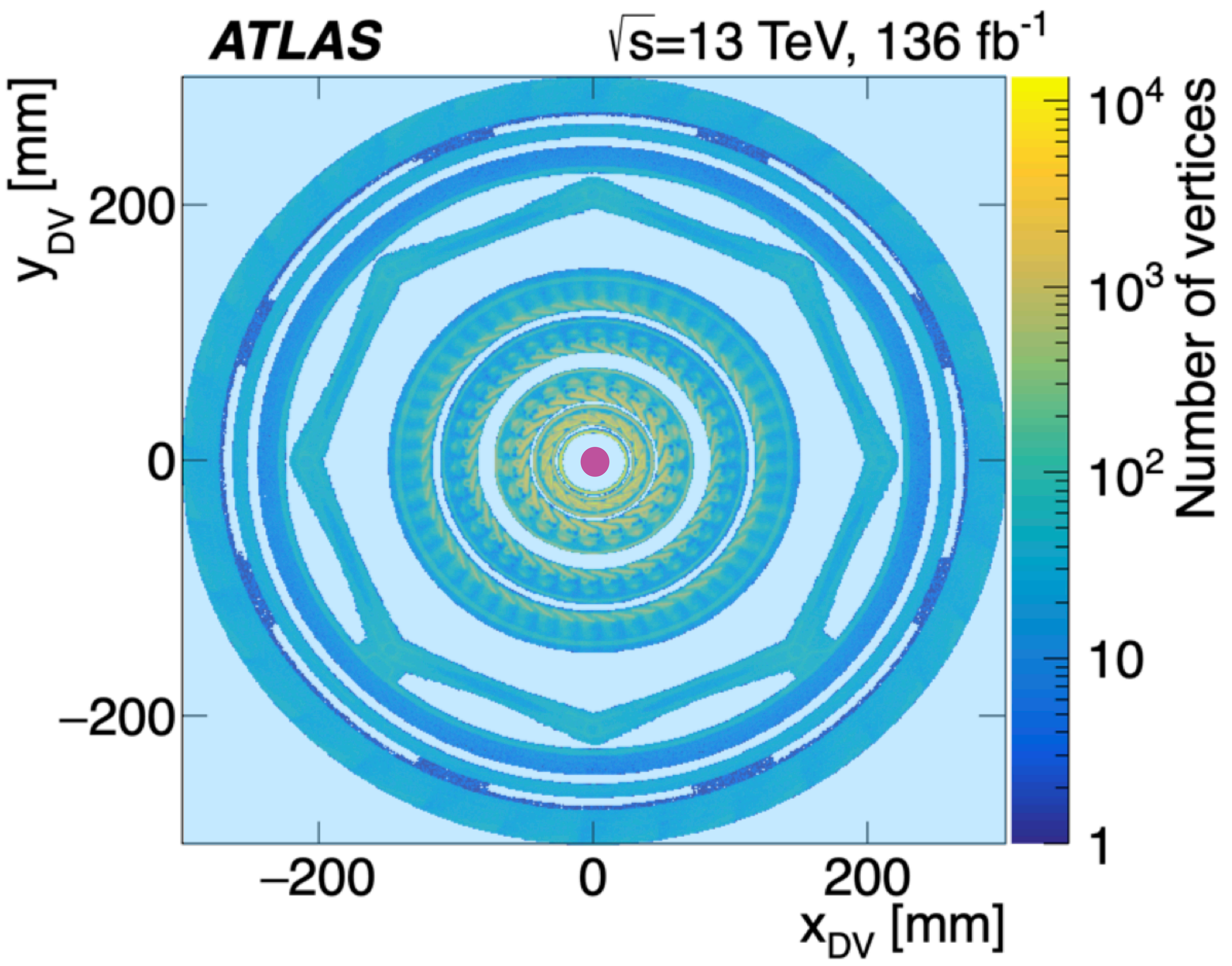
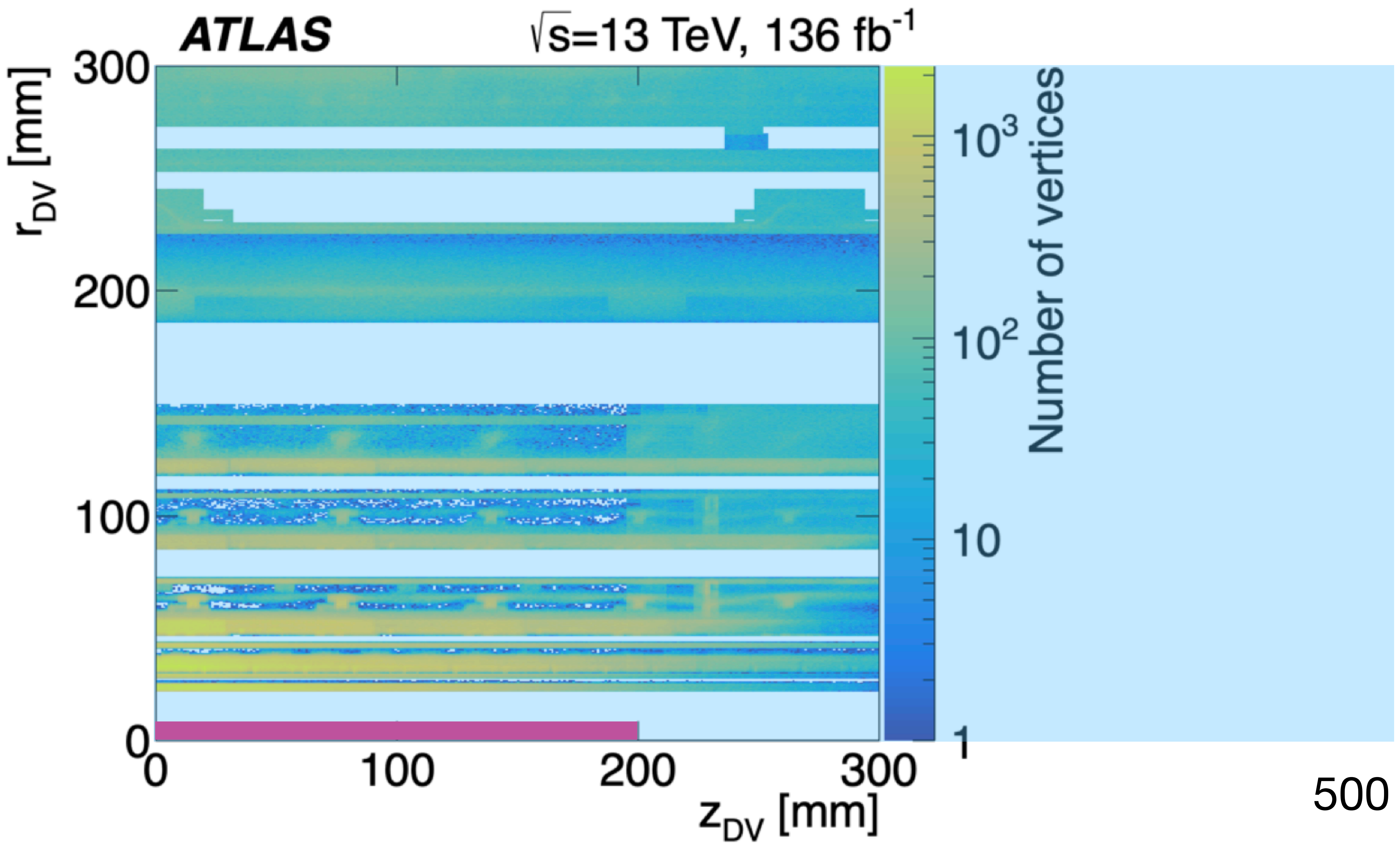
Large-Radius Tracking (LRT) developed to capture the discarded interesting physics (e.g. LLPs)

- uses leftover hits from STD and relaxes the selection criteria







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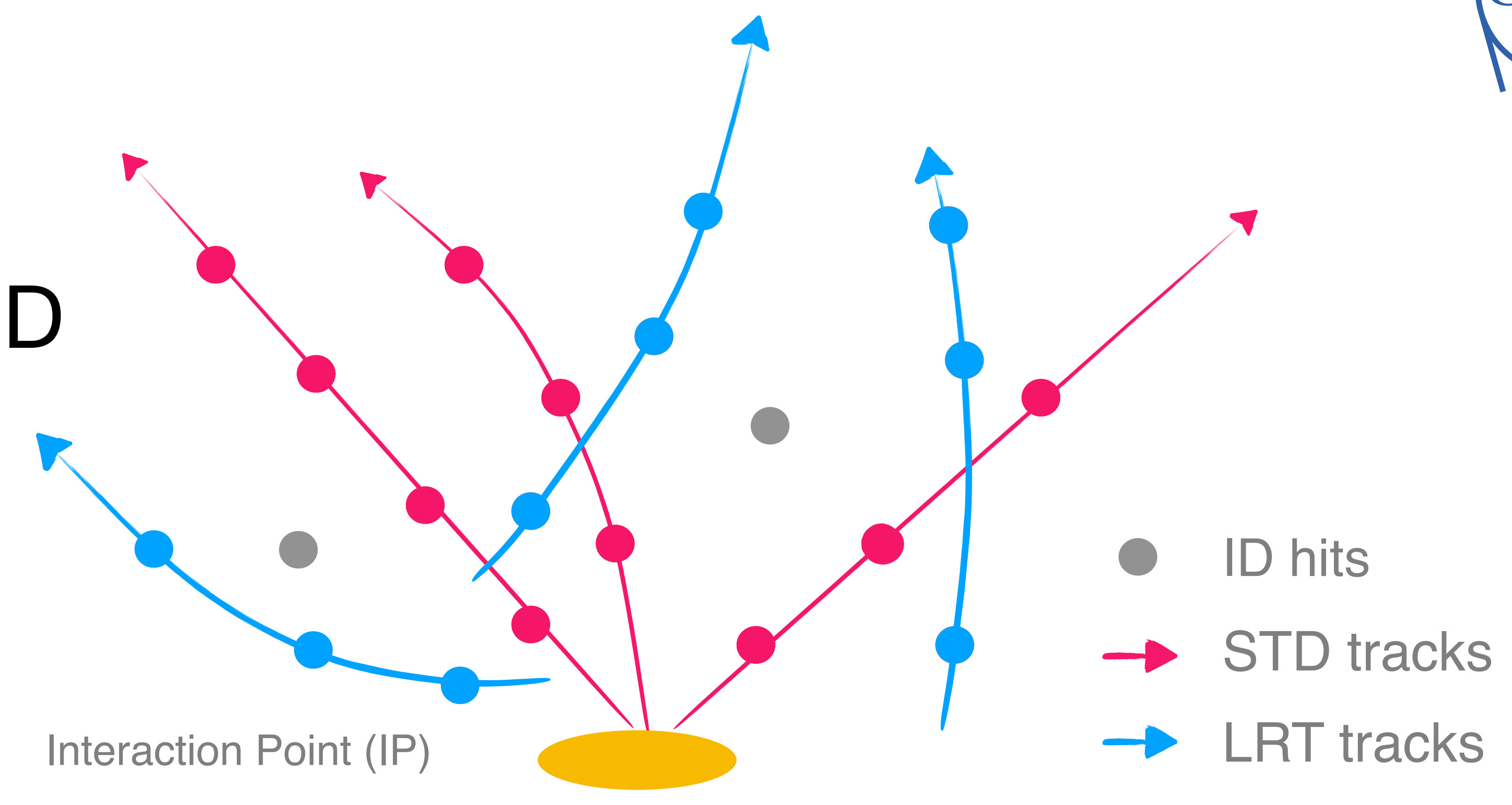

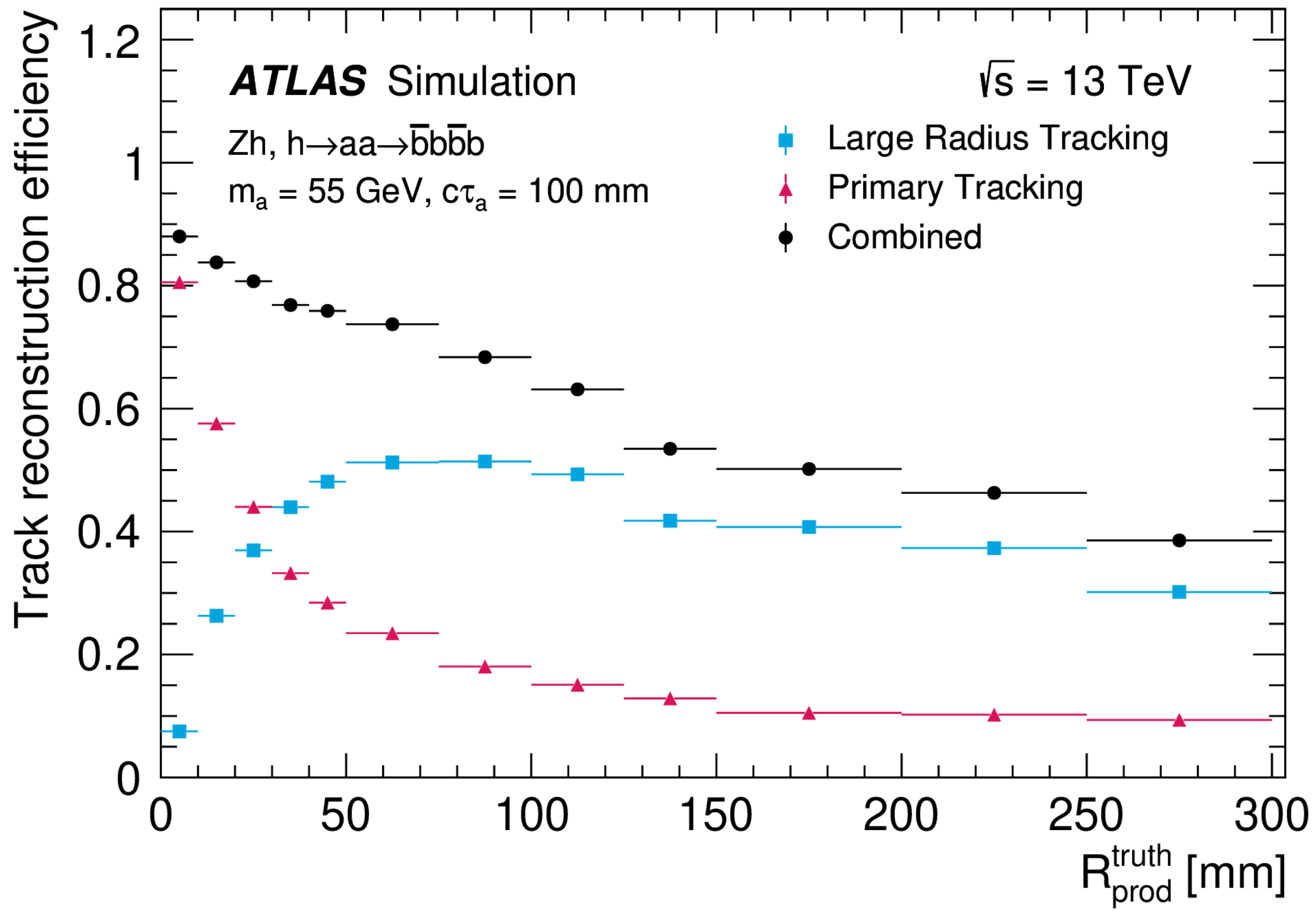

LRT recovers loss of SDT efficiency for particles w/ R > 30 mm

LRT ran only on dedicated data streams ~O(10%) data

- too expensive both in terms of CPU and disk space
  - optimised for high efficiencies
  - **dominated by fake tracks**
    - → combinations of un-related clusters reconstructed as a track
    - → *secondary* tracks (e.g. material interactions)

➡ **LIMITING FACTOR FOR MANY ANALYSES**

LRT overhaul

LRT performance: arXiv:2304.12867

The development of the LRT algorithm focused on reducing the fake rates at the earliest step possible

- narrower phase space (e.g. z_0)
- more stringent requirements (e.g. track quality)
- algorithm logic changes (e.g. strip-only seeds)

✱ *x20 fake rate reduction*

✓ *w/ high ε for LLP signatures*

$\Delta s/\sqrt{b}$ > 400%

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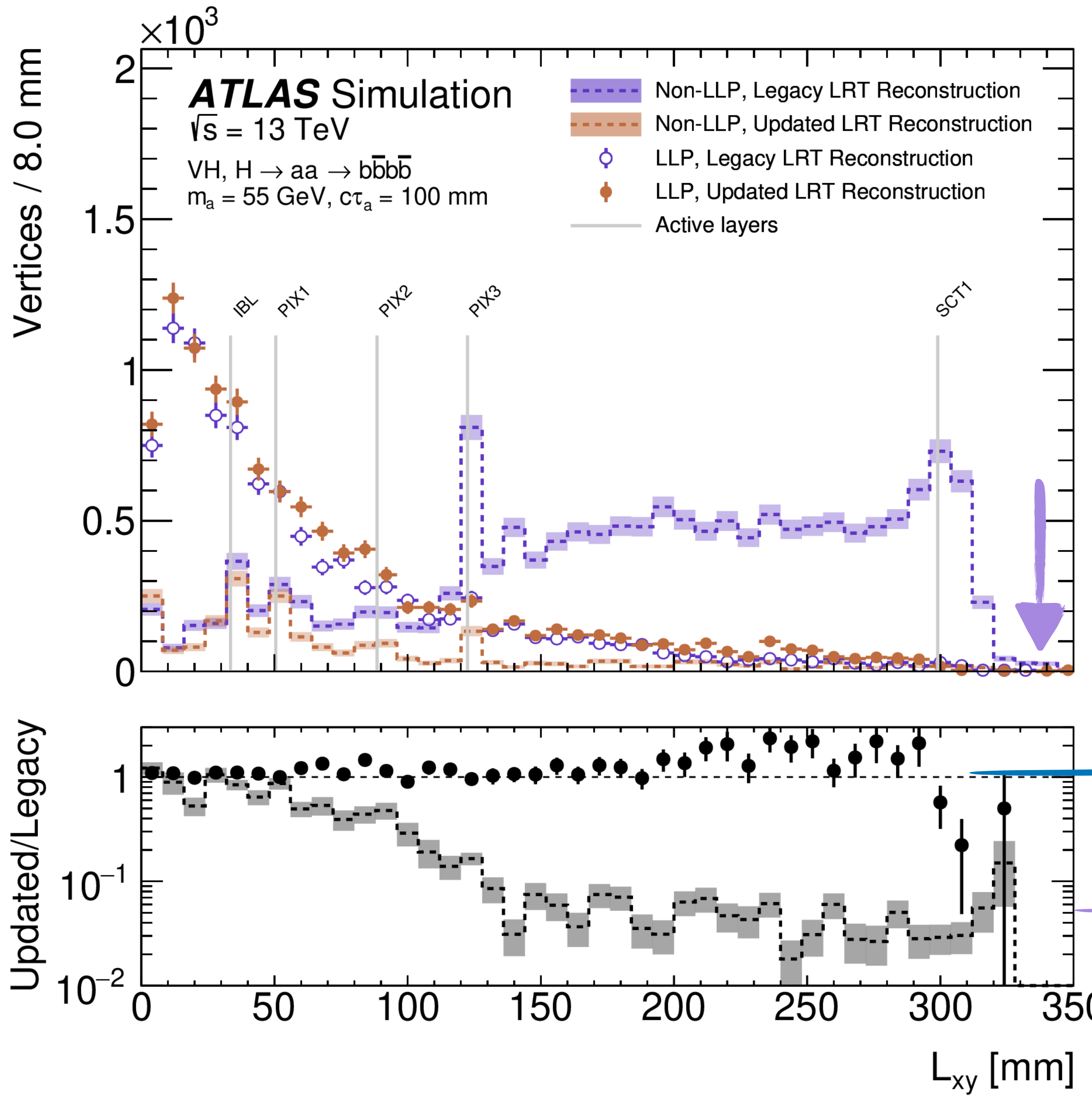

fakes

<1⁄10

LRT performance improvements directly impact the DVs **efficiency** and **fake** reduction!

LRT overhaul

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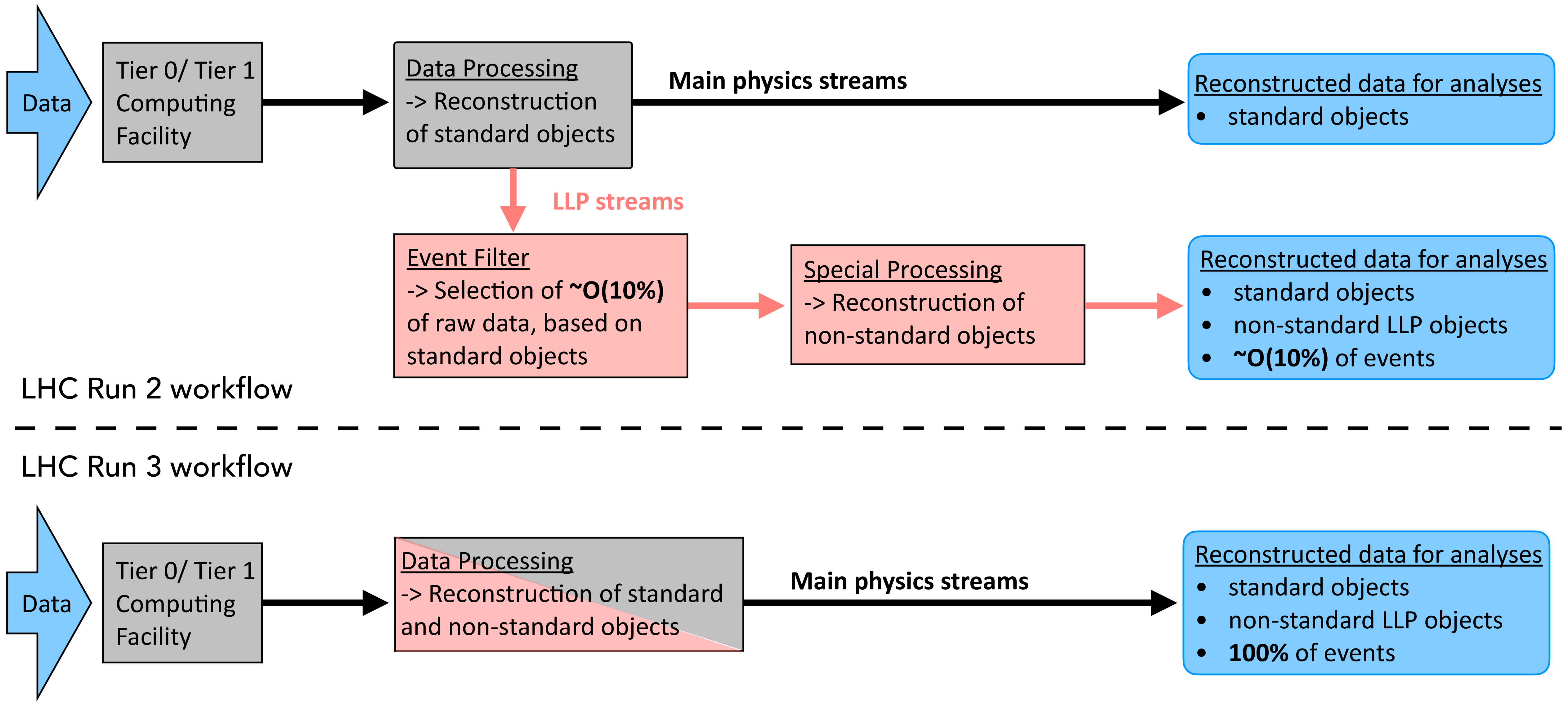
- more stringent requirements (e.g. track quality)
- algorithm logic changes (e.g. strip-only seeds)

✱ *x20 fake rate reduction*

✓ *w/ high ε for LLP signatures*

- *x10 algorithm speed up*
- *x50 less disk consumption*



LRT integrated into the ATLAS reconstruction chain

allows to exploit the FULL dataset

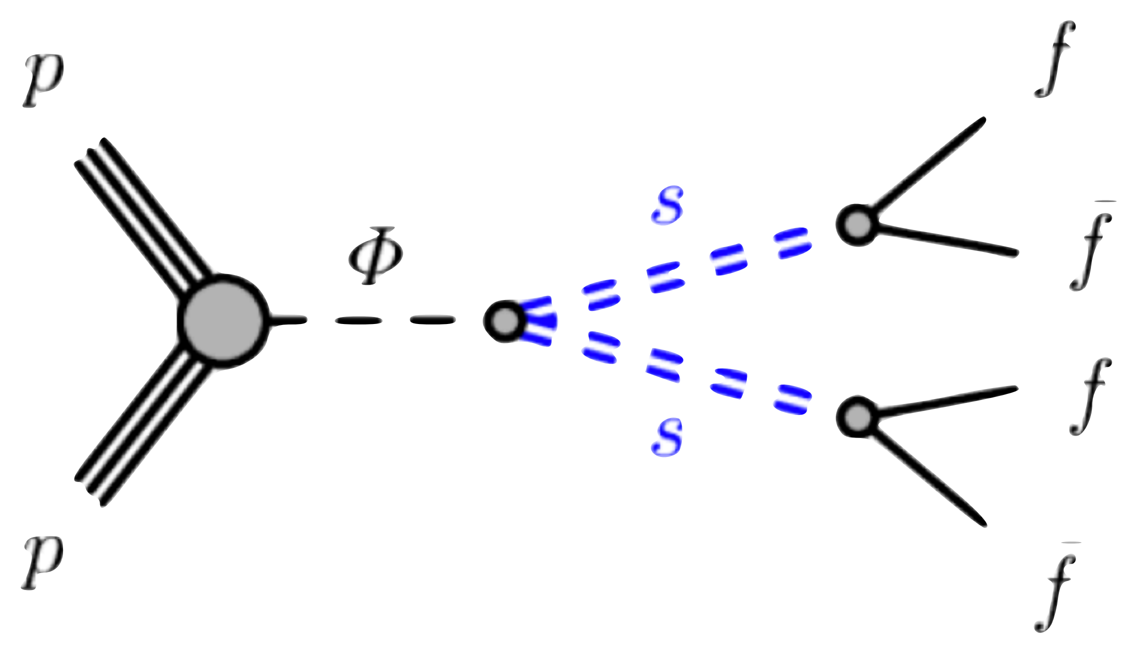
GAME changer for LLP searches

new physics objects (muonLRT, electronLRT, tauLRT)….and new triggers!

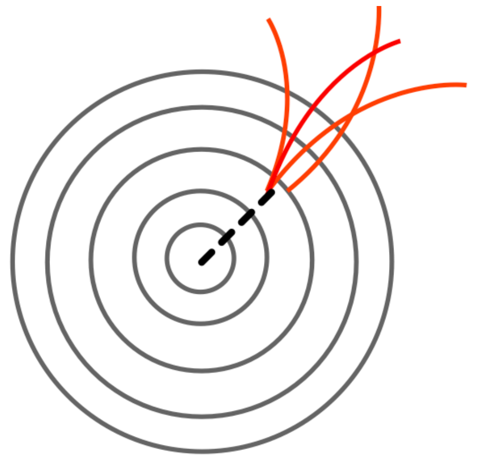
New LLP triggers @ Run-3

Tracking Trigger Public plots

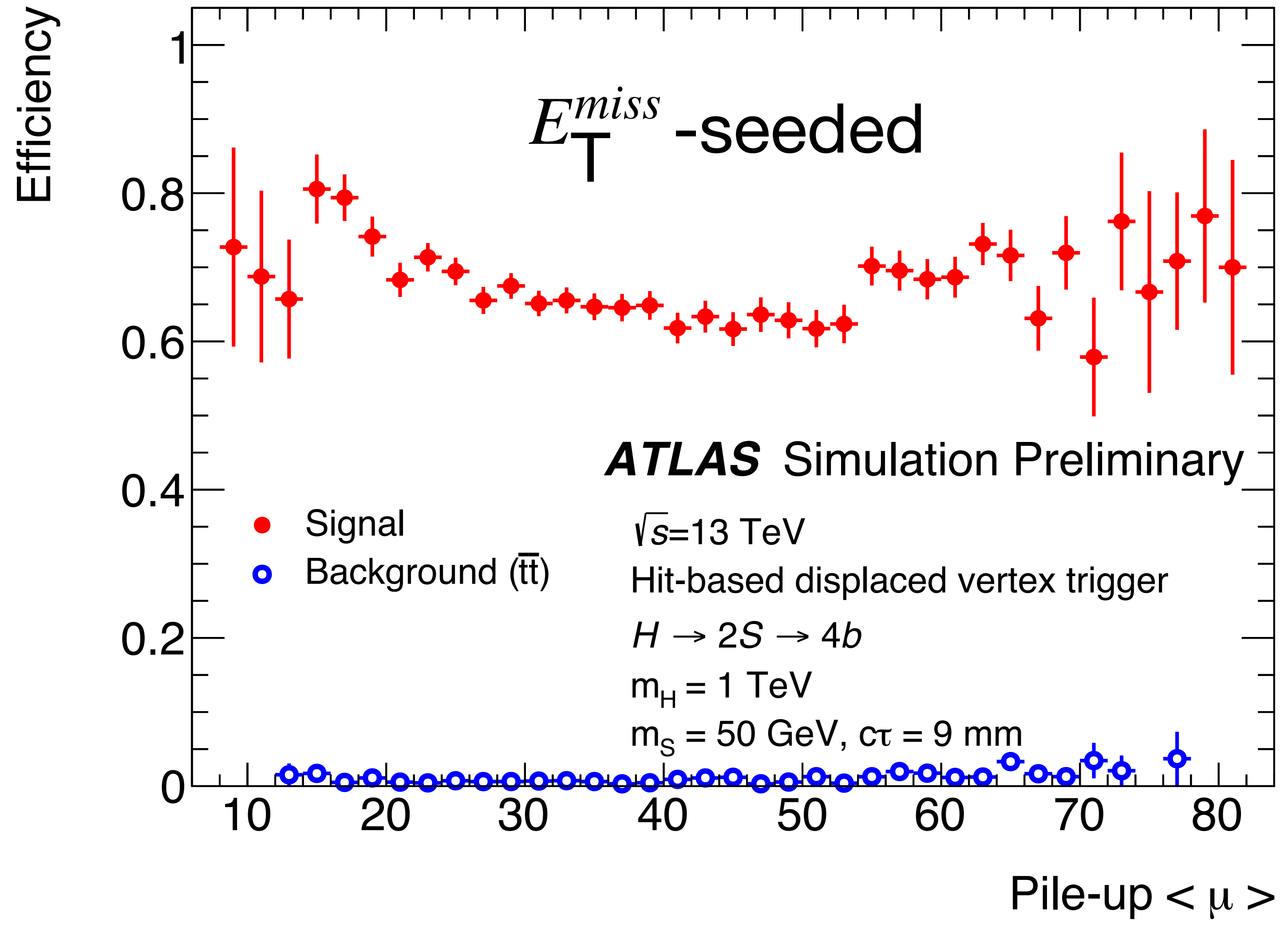
The improvements in terms of CPU execution time of both STD & LRT allowed the integration at trigger level



displaced vertex in ID

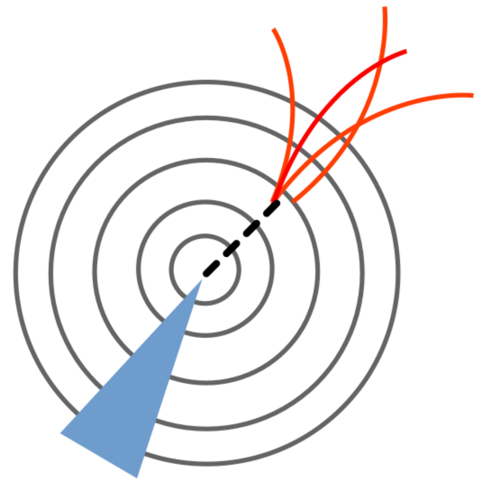


looking for large number of hits on outer layer compared to inner layer
MET or Jet-seeded

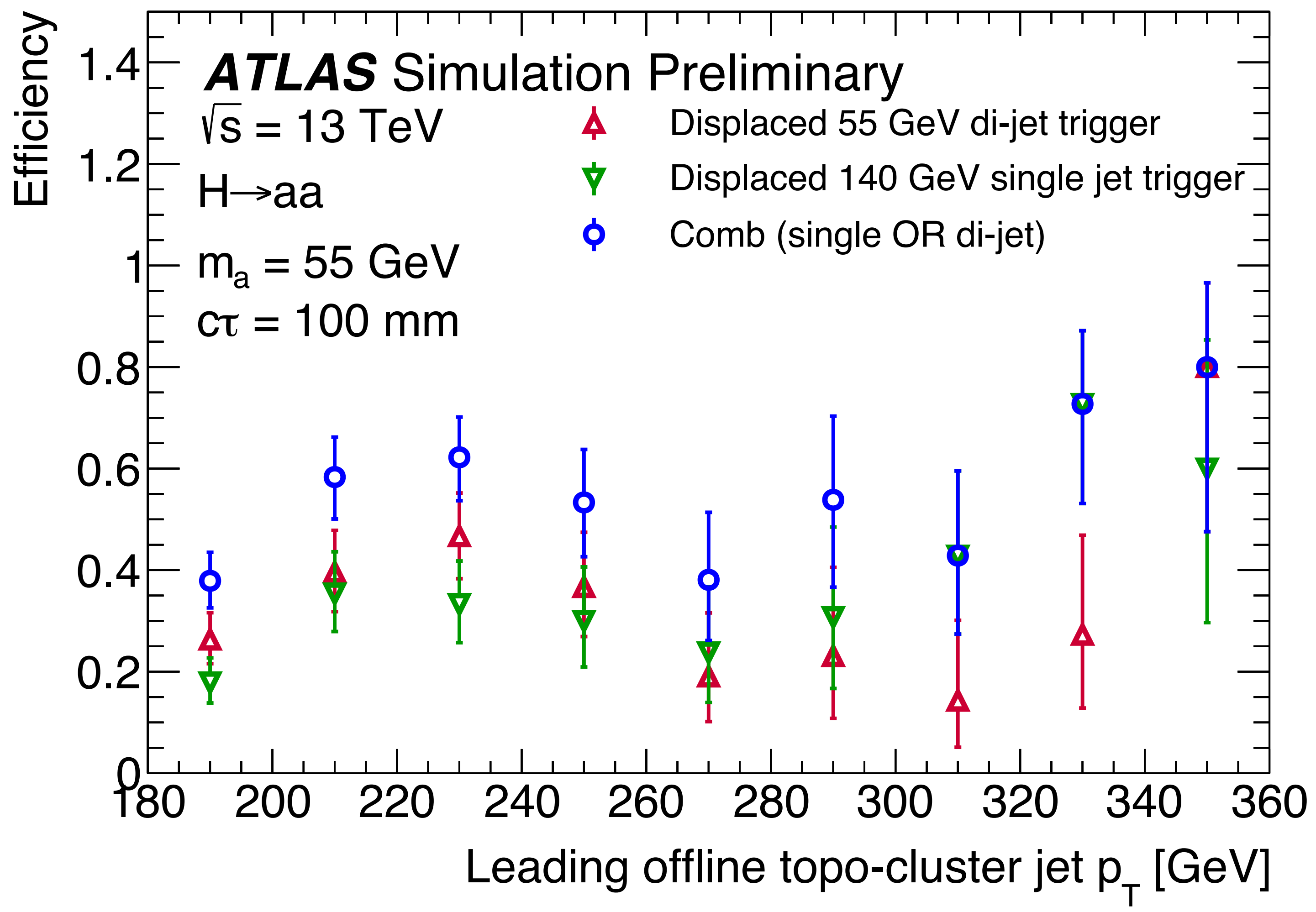


ISR+displaced jet(s)

$p_T > 180$ GeV

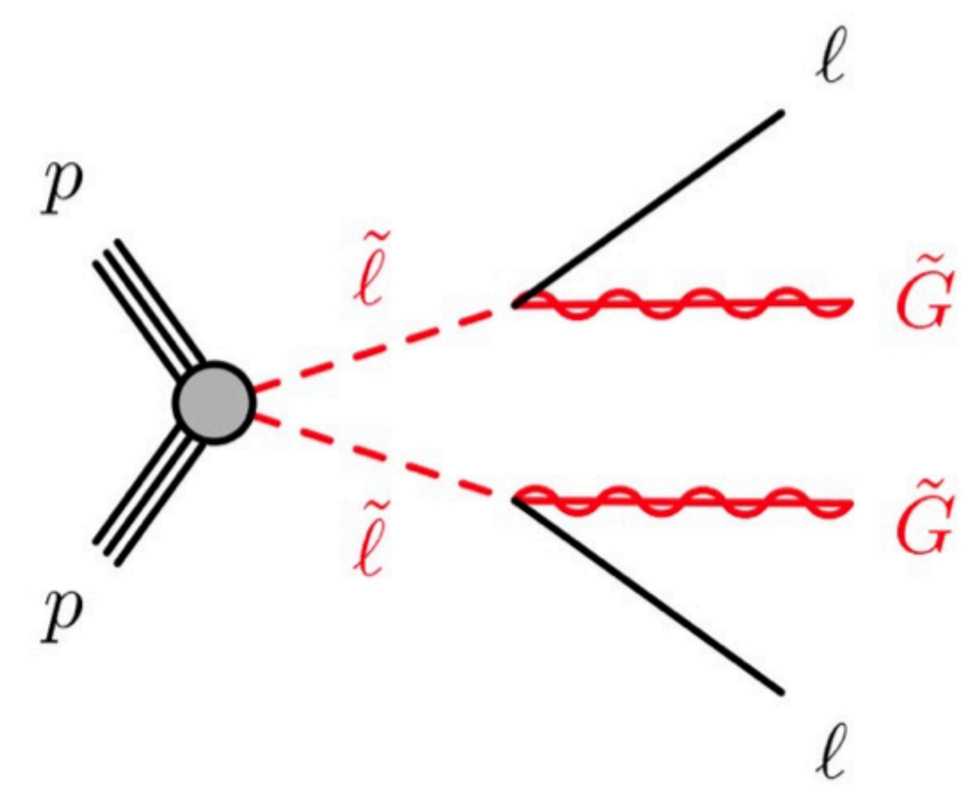


single displaced jet w/ $p_T > 140$ GeV
di-displaced jet w/ $p_T > 55$ GeV
standard single jet trigger w/ **$p_T > 460$ GeV**



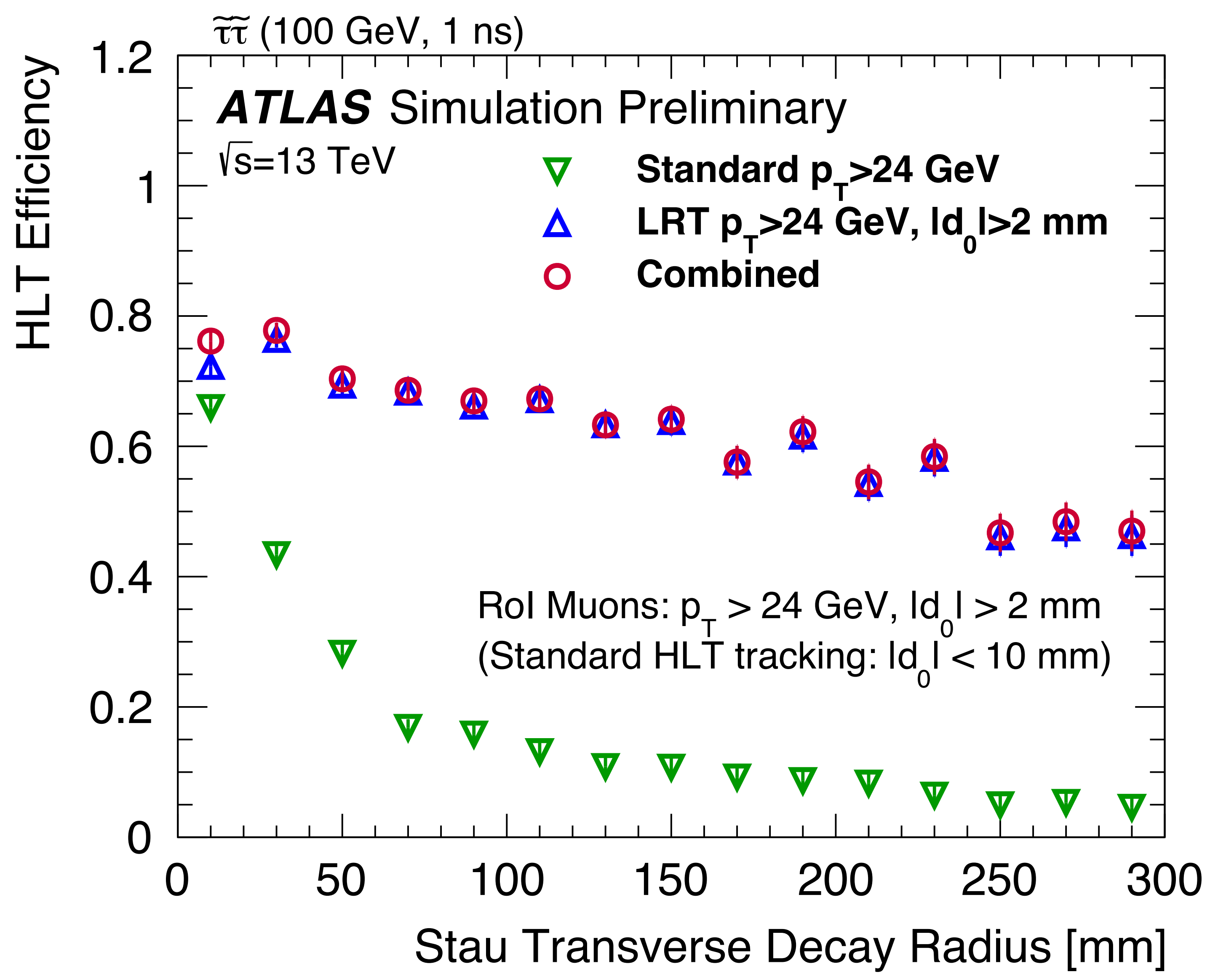
New LLP triggers @ Run-3

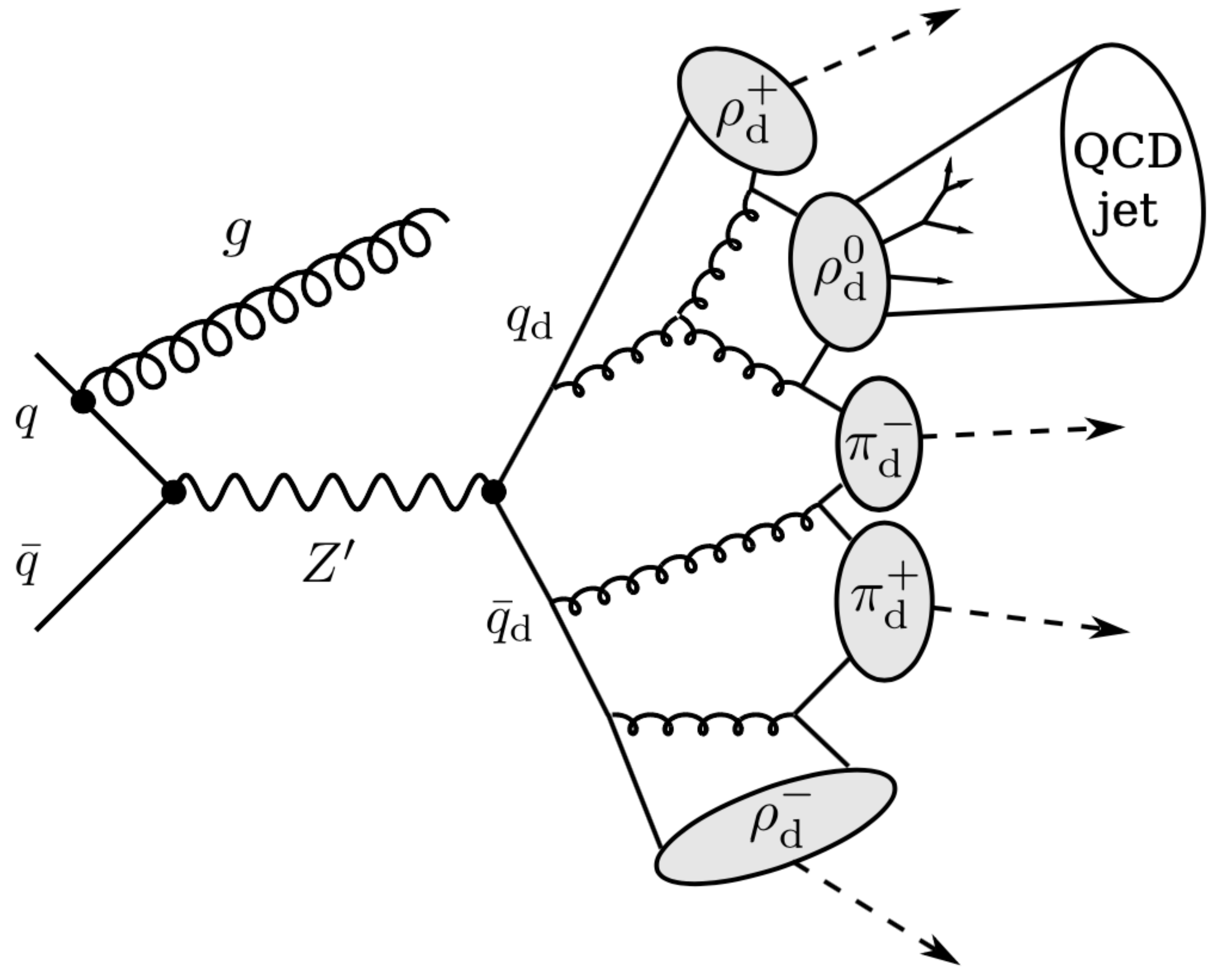
Tracking Trigger Public plots



Displaced electrons and muons

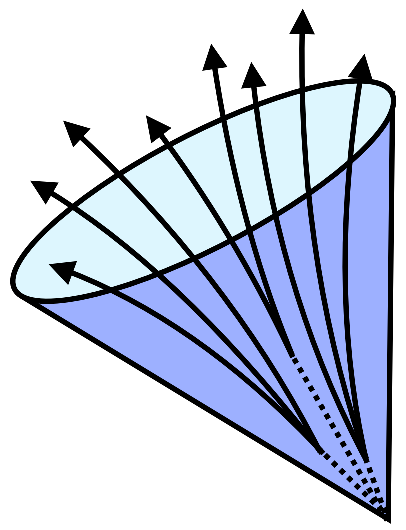
Allows to extend reaches of searches based on photon and μ MS-only triggers





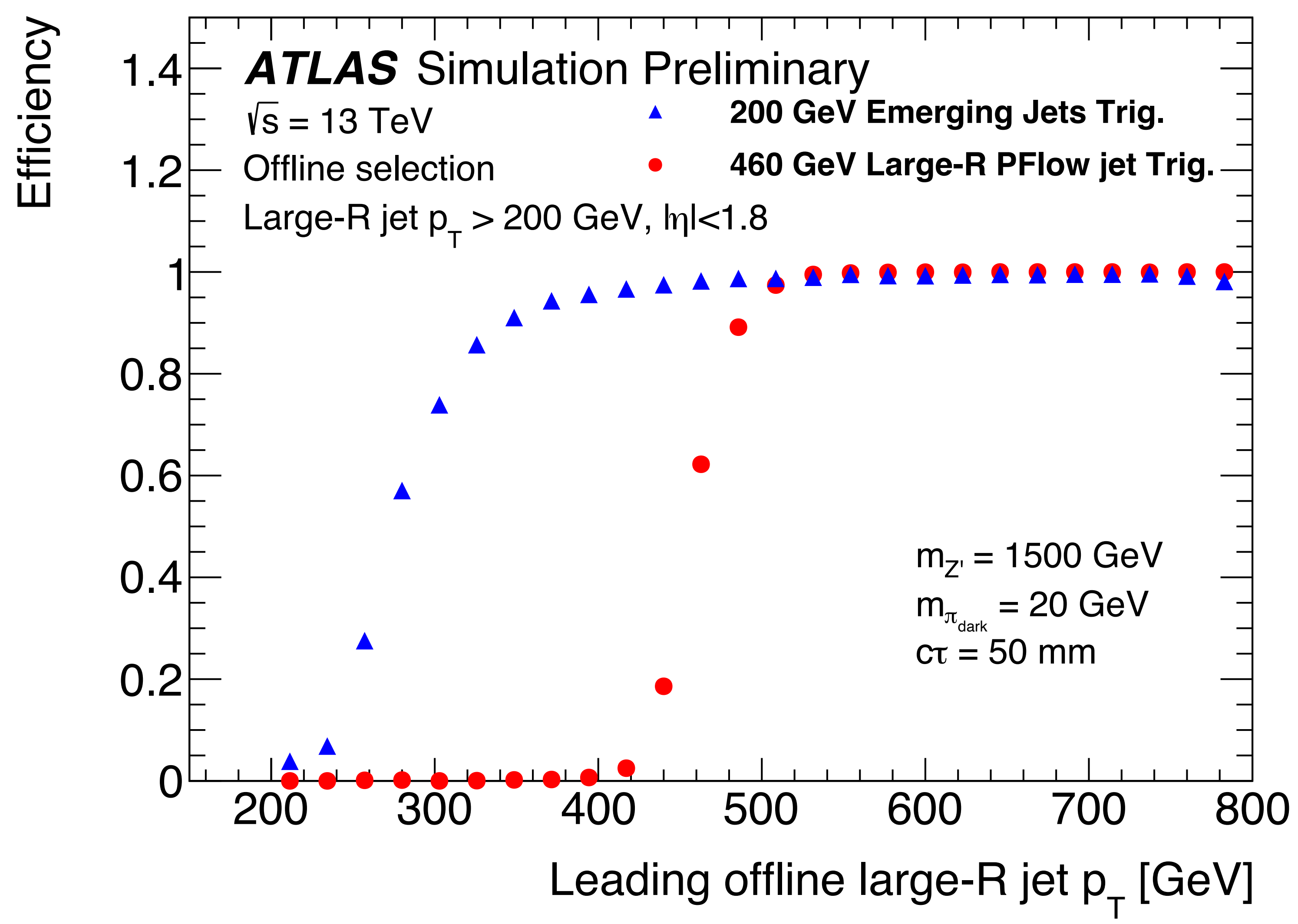
QCD-like dark sector producing dark showers

- Dark hadrons can decay in a QCD-like fashion
- Dark pions can have a non-null lifetime



Emerging jets

- high multiplicity of DVs and displaced tracks



- selecting jets with small prompt track fraction

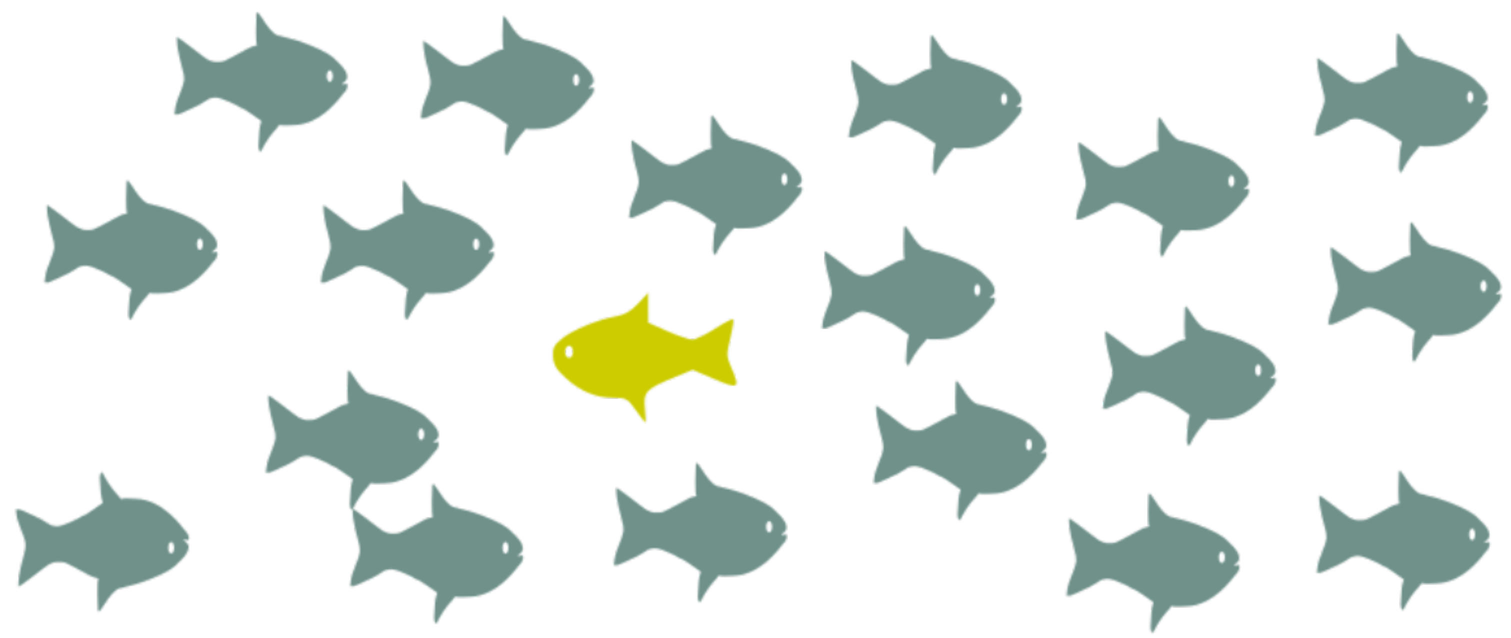
Conclusions

Rich search LLP program in ATLAS

Interplay between

- dedicated analyses
- reinterpretations

→ allows to extensively probe different lifetime regimes

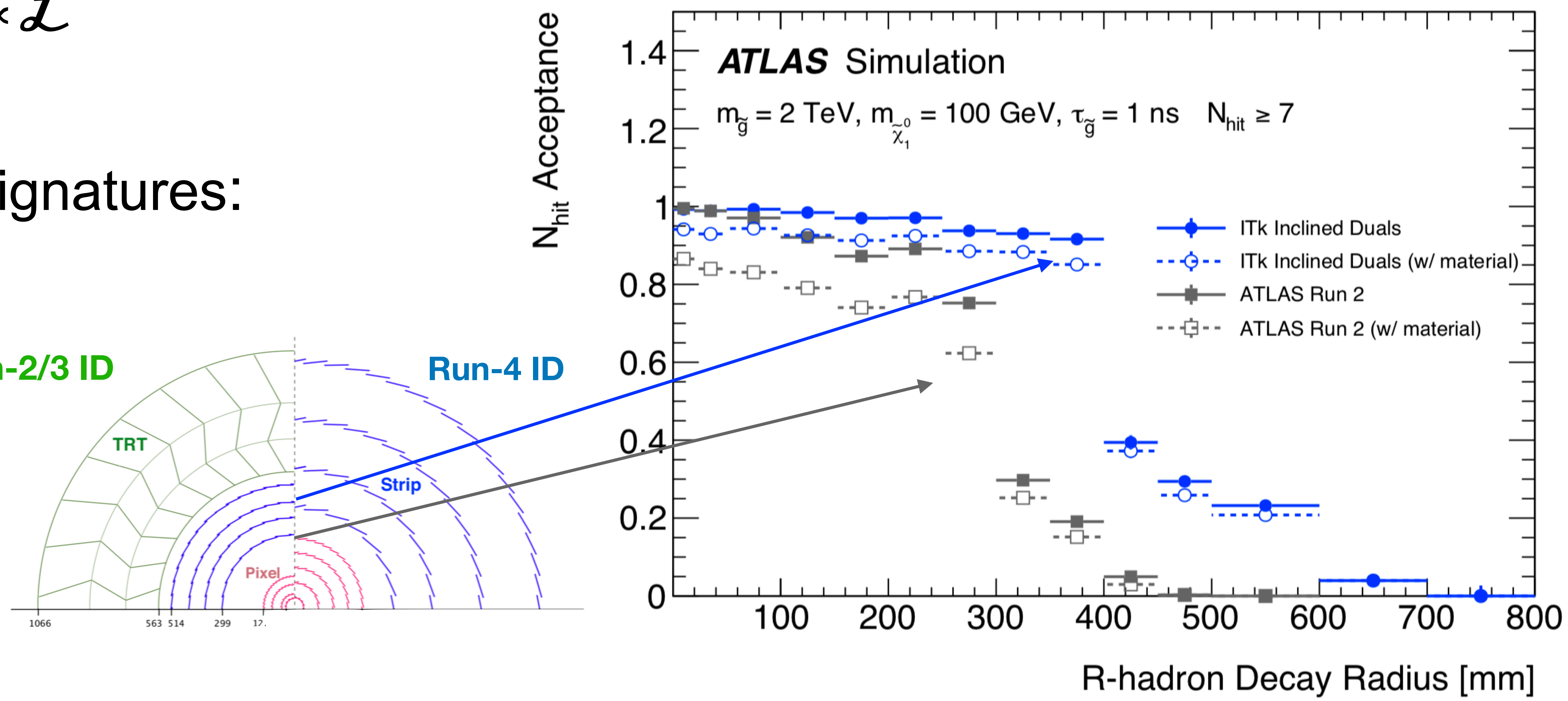


LLP searches are often **statistically limited**!

- Background-zero searches sensitivity $\propto \mathcal{L}$

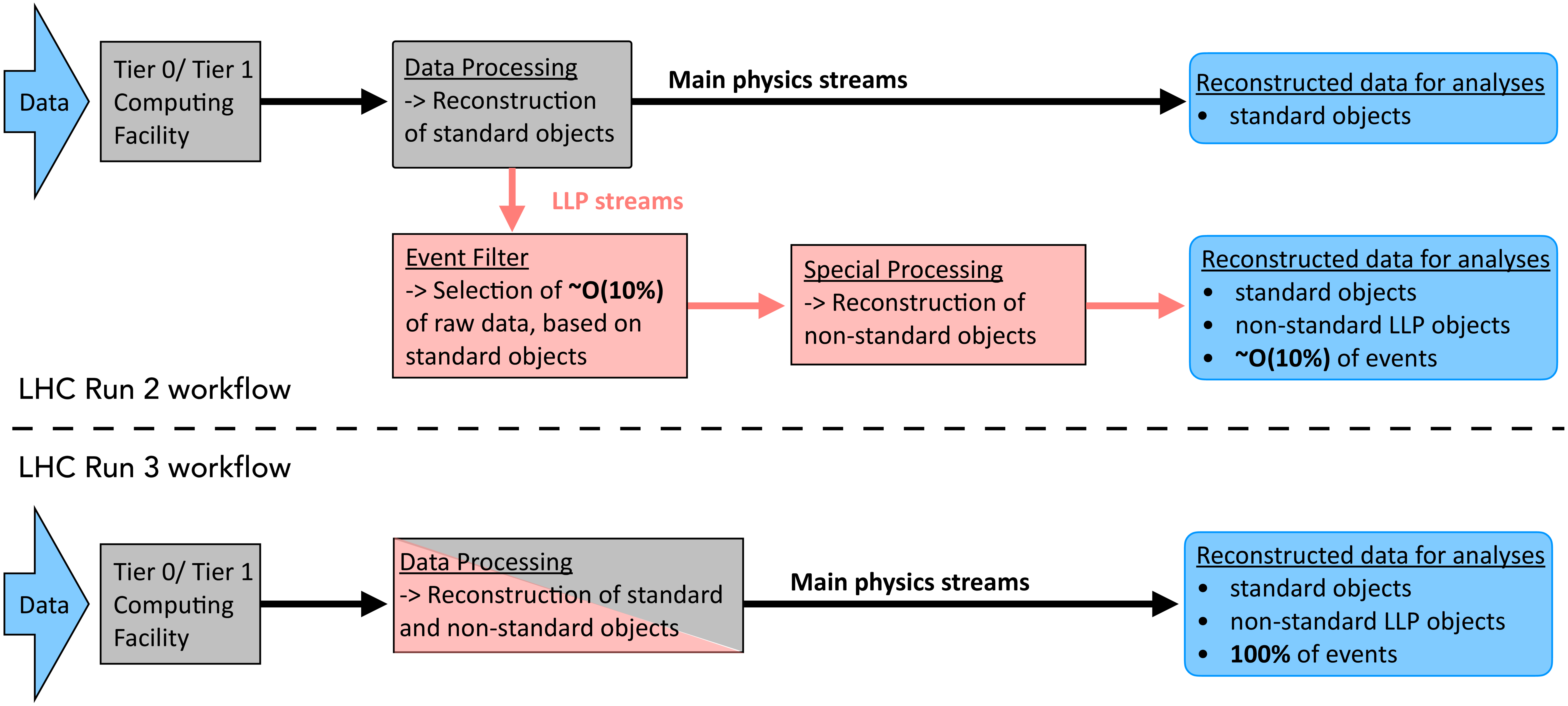
NEW IDEAS to probe such an '*anomalous*' signatures:

- new algorithms (e.g. **LRT**)
- new trigger strategies
- deep learning ↔ model-independence
- new detectors technologies @ Run-4



BACKUP

Large-radius tracking



Changes in Run-3 LRT highlights

The earlier the cuts can be applied, the less CPU time is wasted processing fake tracks in later steps

- **CPU dominated by *track finding* and *ambiguity resolution* steps**

Tightening of cuts which are applied at several stages of track reconstruction
(d0, z0 etc. to reduce lookelsewhere range to search)

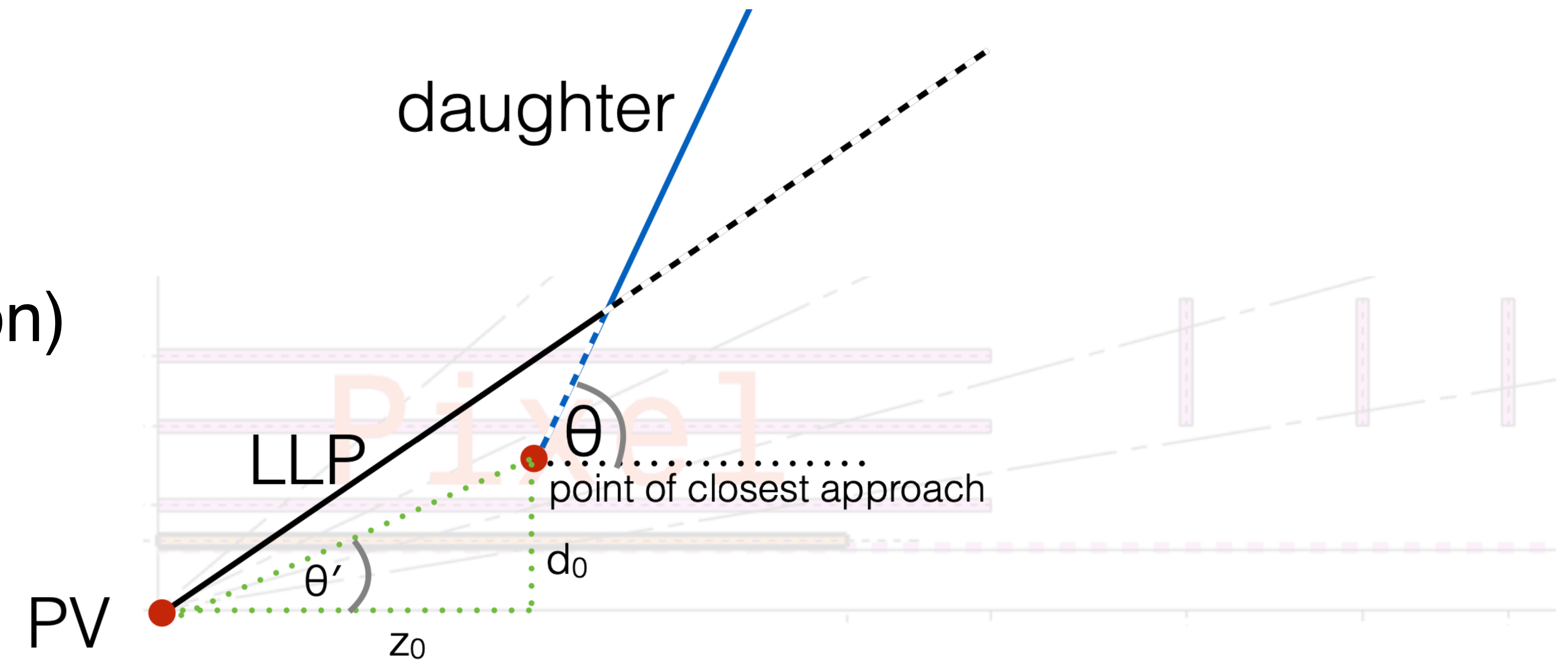
ATLAS Large-Radius Tracking

Space Point Formation → **Seed Finding** → **Track Finding** → **Ambiguity Resolution** → **TRT Extension**

Only SCT is used for seeding as opposed to SCT or Pixel seeds

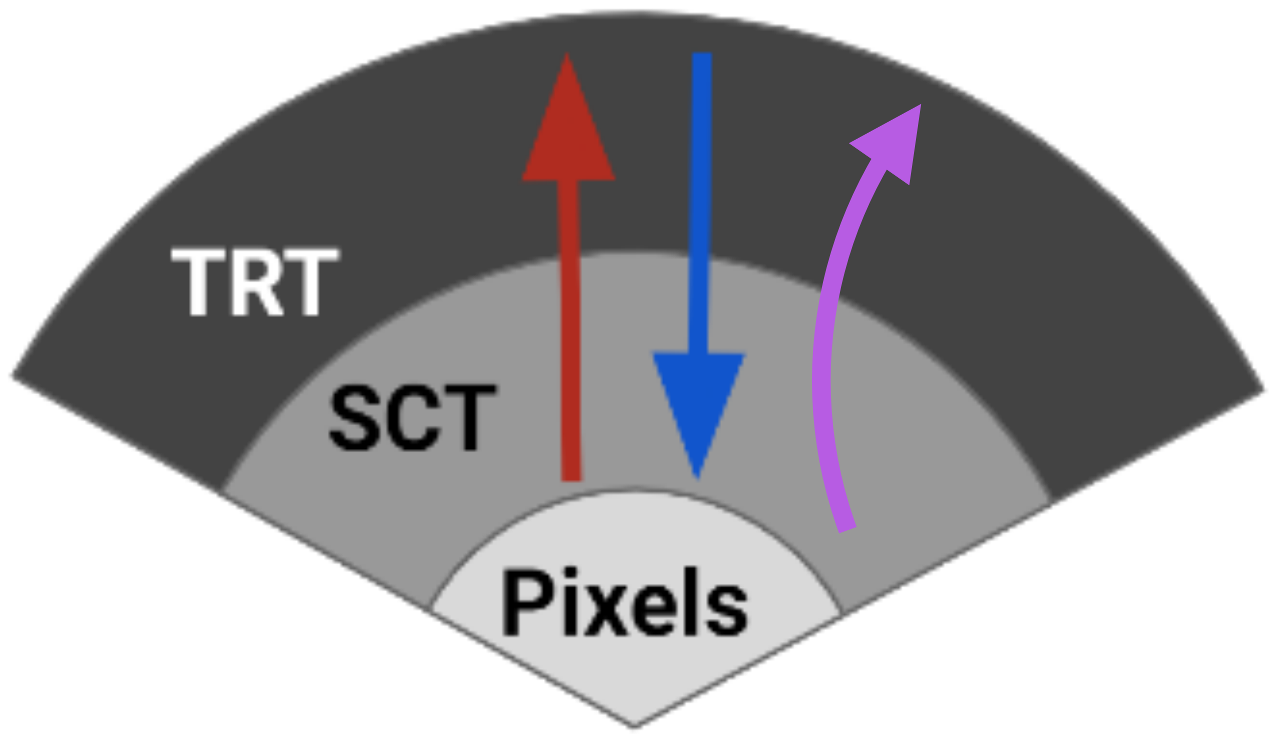
3-space-point seeds must be confirmed by a 4th
➥ as in standard tracking

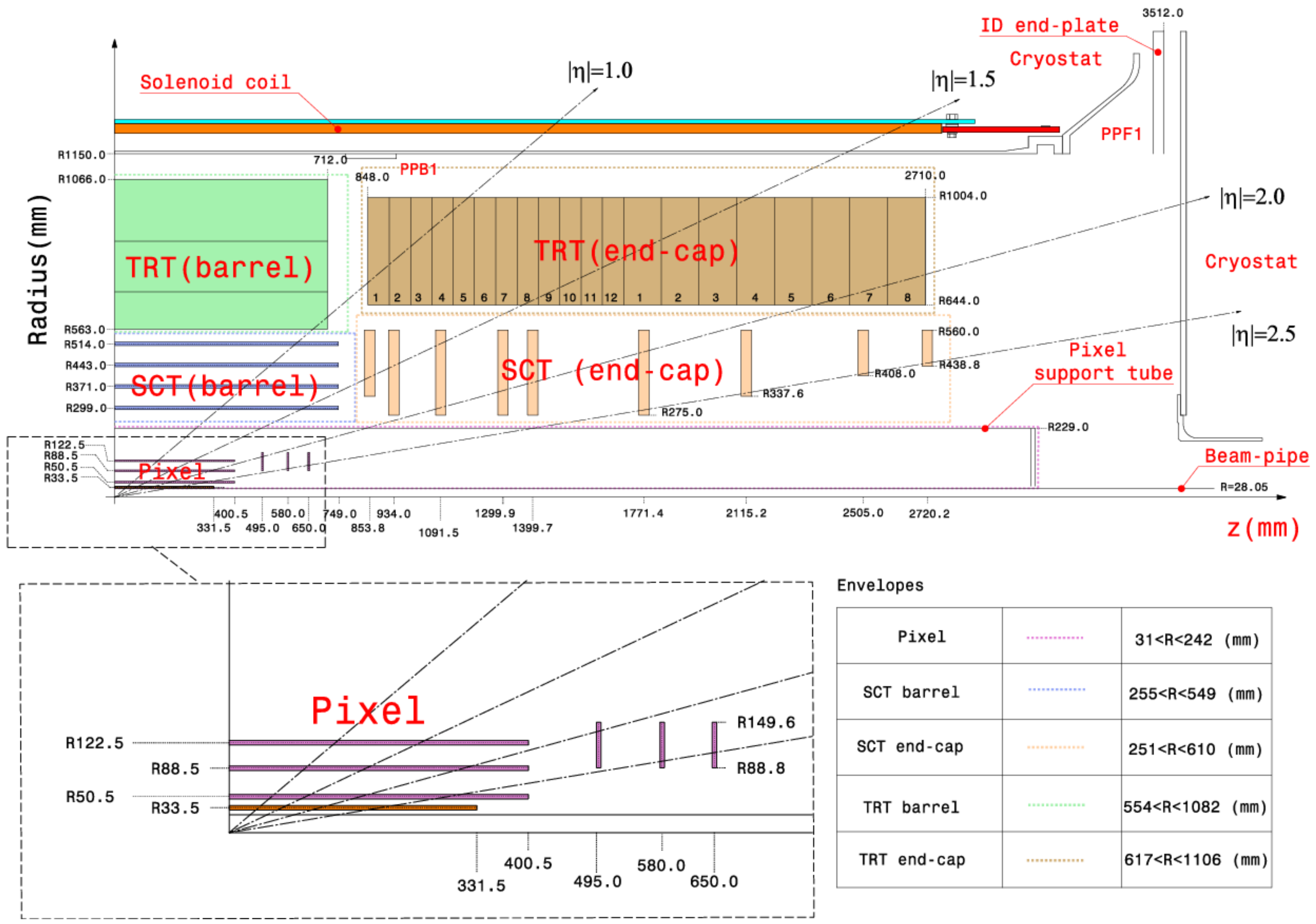
Changes in the seed ranking decides the order in which tracks are processed (combining d0 with LLP and children direction)



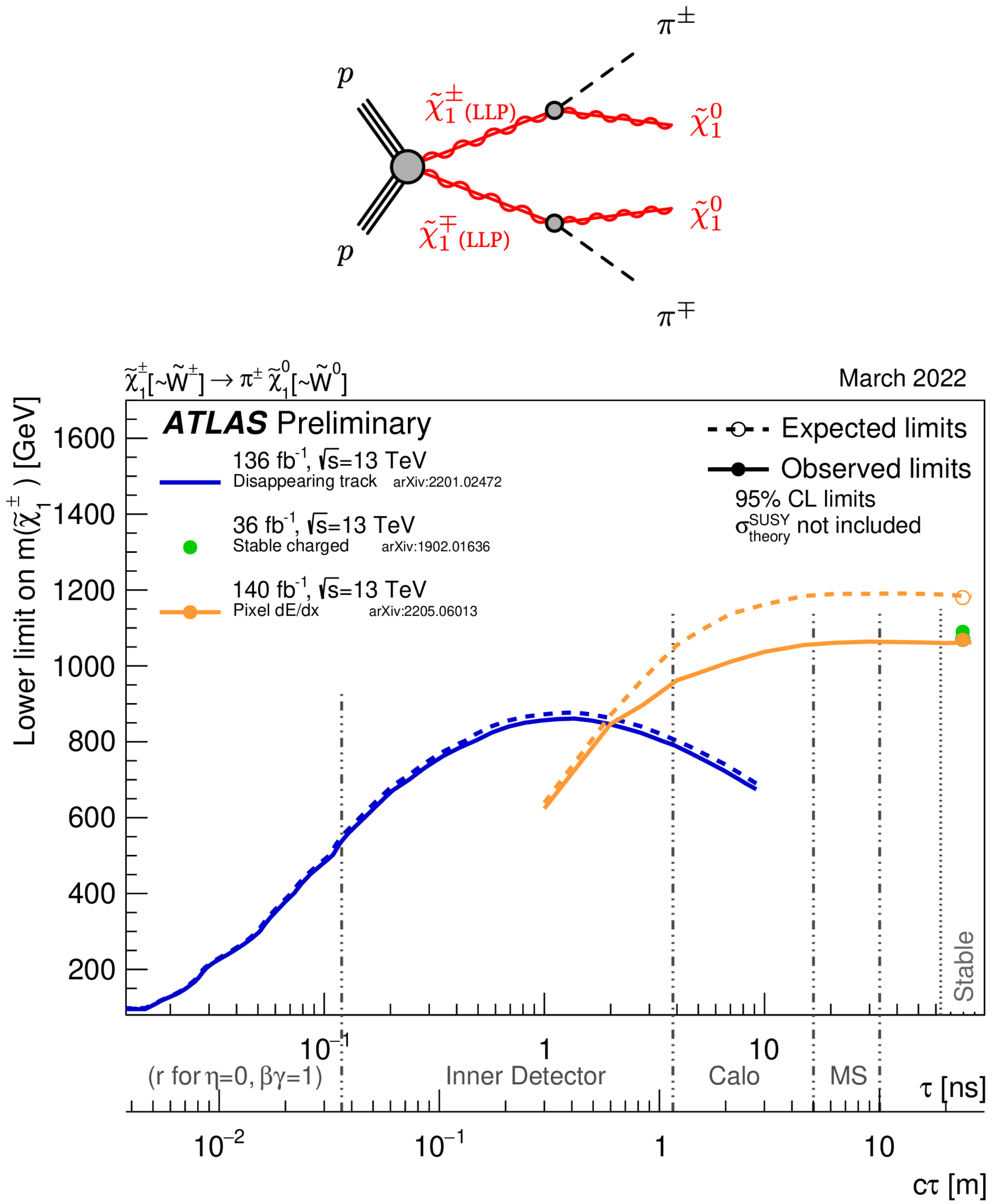
STD vs LRT

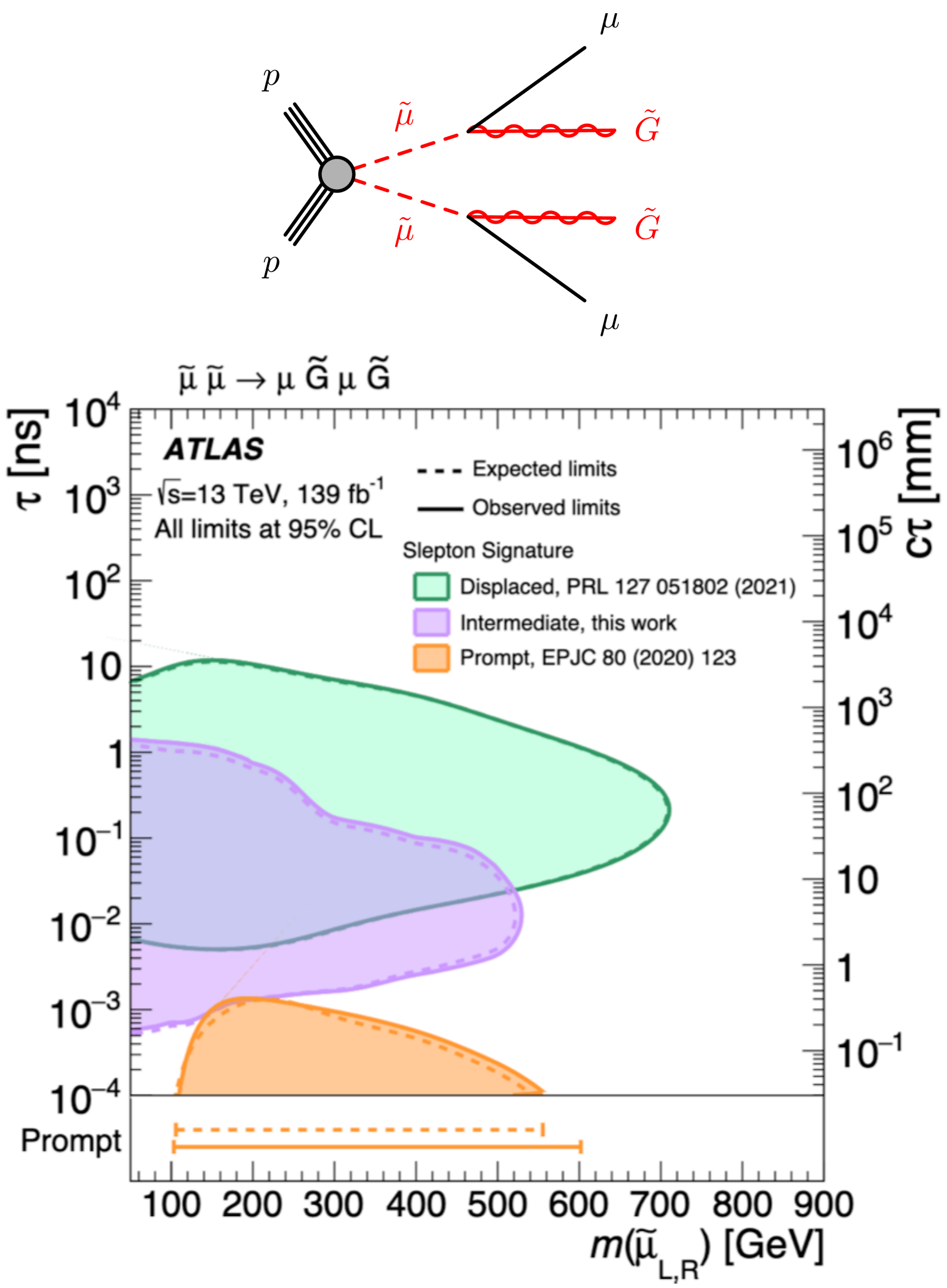
Selection criteria	Primary	LRT
max. $\lvert d_0 \rvert$ [mm]	5	300
max. $\lvert z_0 \rvert$ [mm]	200	500
min. p_T [GeV]	0.5	1
max. $\lvert \eta \rvert$	2.7	3.0
max. silicon holes	2	1
max. double holes	1	0
max. holes gap	2	1
road width [mm]	12	5
seeding	Pixels and SCT	SCT only
max. seeds per middle Pixel SP	1	–
max. seeds per middle SCT SP	5	1
Common selection criteria		
min. silicon hits	8	
min. unshared silicon hits	6	
max. track χ^2/n_{DoF}	9	
keep all confirmed seeds	true	

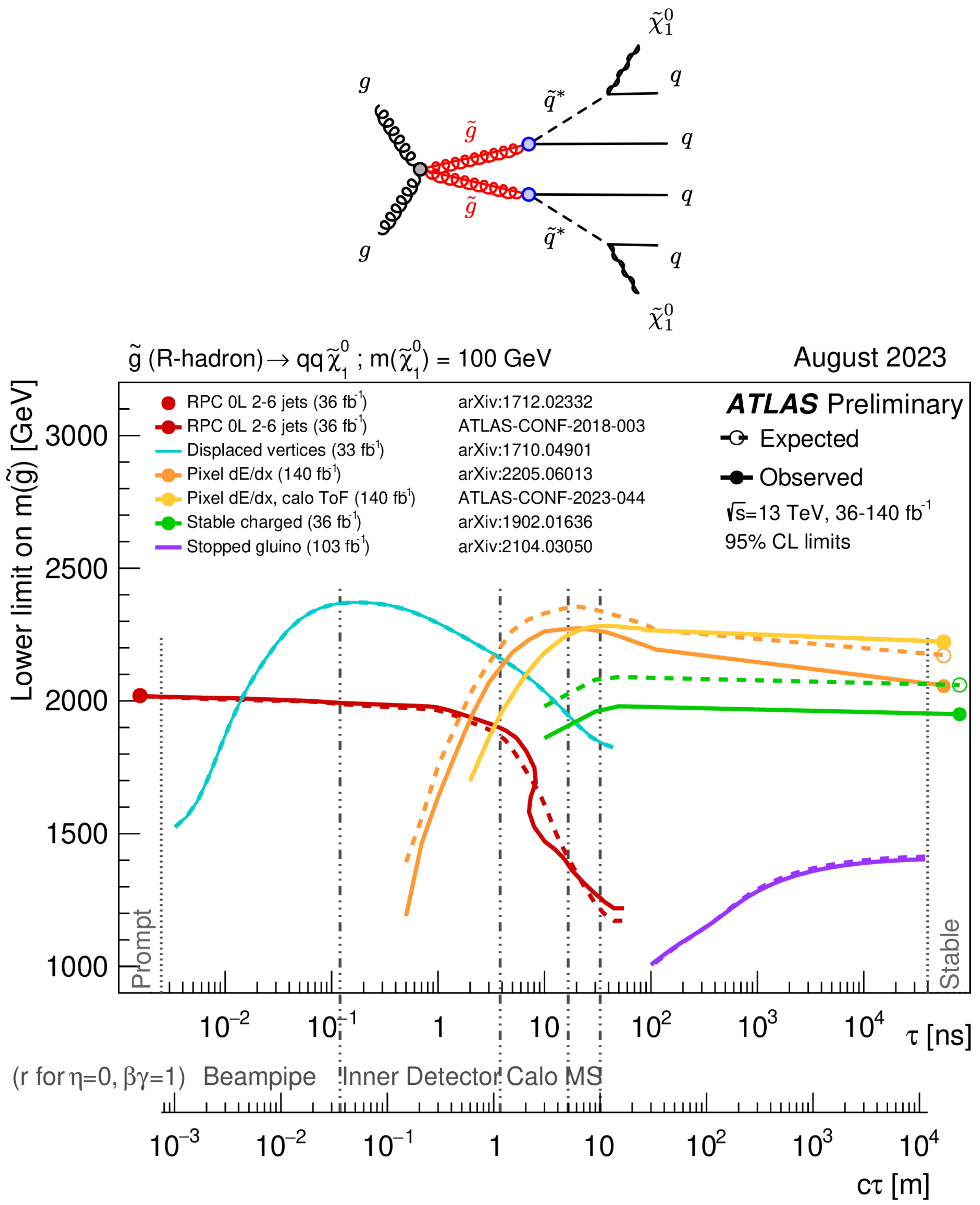




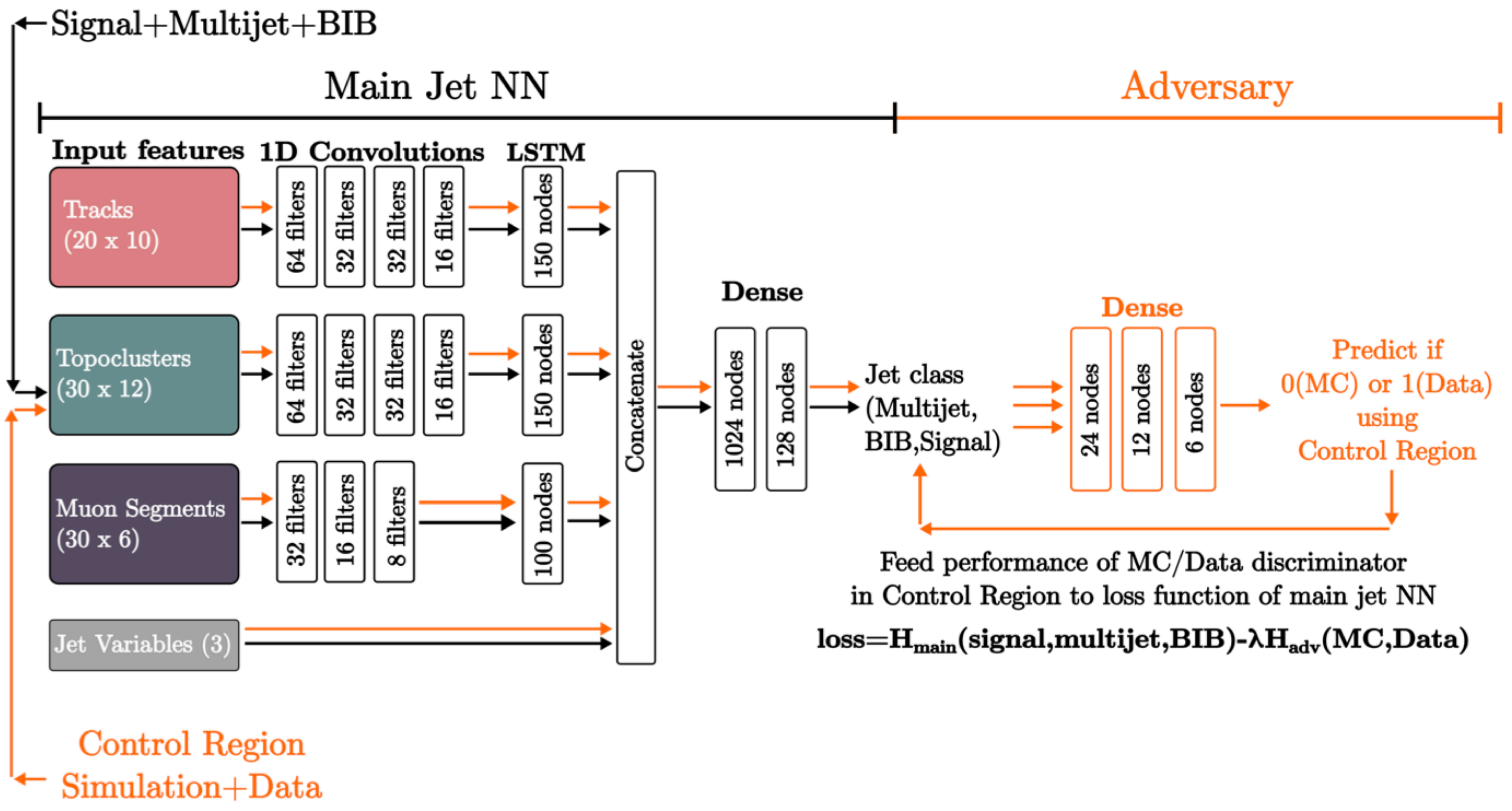
SUSY LLP summary plots







CalRatio NN



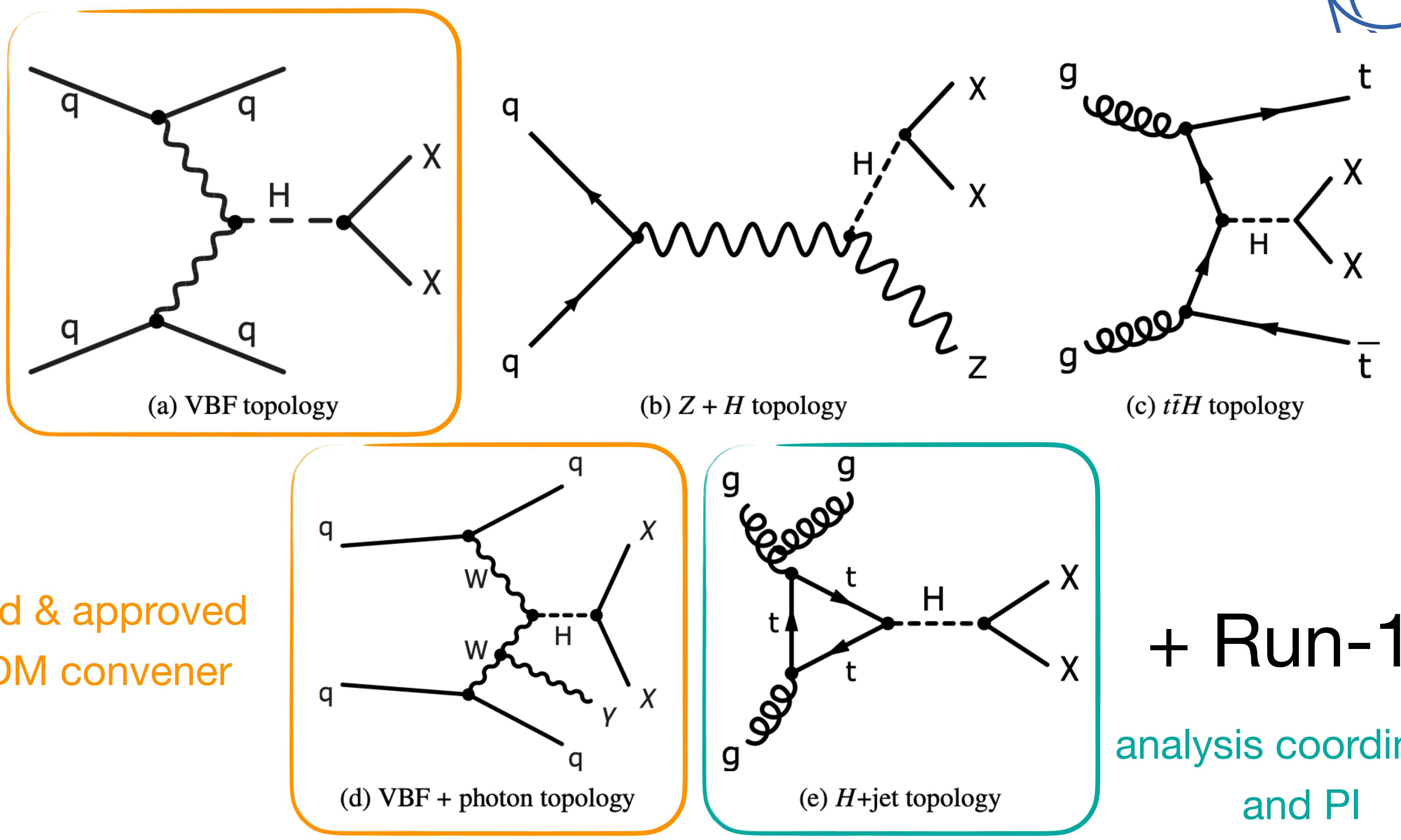
Signal+Multijet+BIB
Main Jet NN
Adversary
Input features
1D Convolutions
LSTM
Tracks (20 x 10)
Topoclusters (30 x 12)
Muon Segments (30 x 6)
Jet Variables (3)
64 filters
32 filters
32 filters
16 filters
150 nodes
64 filters
32 filters
32 filters
16 filters
150 nodes
32 filters
16 filters
8 filters
100 nodes
Concatenate
Dense
1024 nodes
128 nodes
Jet class (Multijet, BIB,Signal)
Dense
24 nodes
12 nodes
6 nodes
Predict if 0(MC) or 1(Data) using Control Region
Feed performance of MC/Data discriminator in Control Region to loss function of main jet NN
loss=H_{main}(signal,multijet,BIB)-λH_{adv}(MC,Data)
Control Region Simulation+Data

Higgs to invisible

Hinv Legacy combination: Phys. Lett. B 842 (2023) 137963

In SM invisible Higgs decay has BR(H→ZZ*→4ν) ~ 0.1%

- a deviation can be sensitive to BSM contribution



reviewed & approved as a JDM convener

+ Run-1

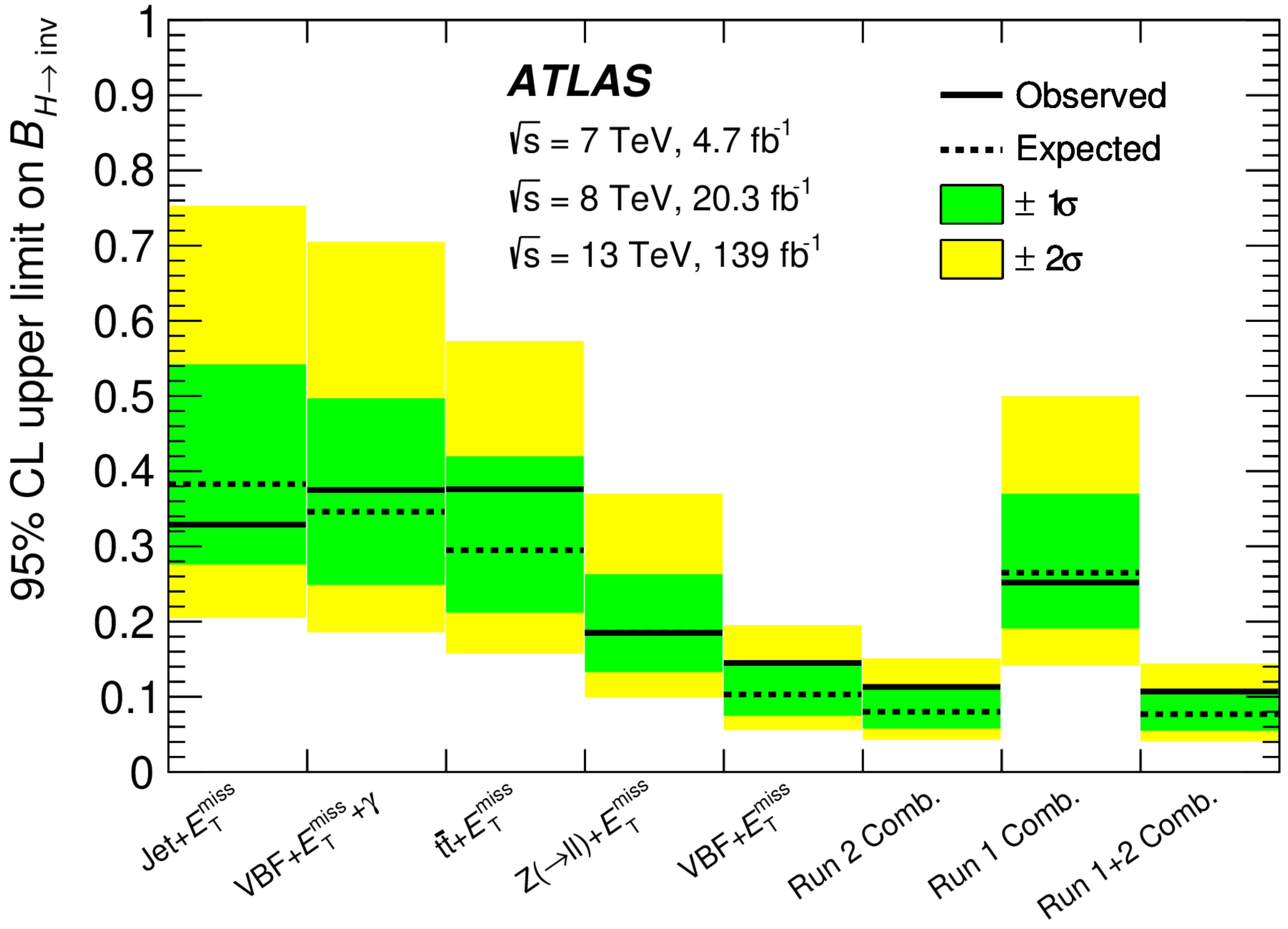
analysis coordinator and PI

Analysis combination of searches for H→inv

- exploiting **ALL** the Higgs production processes
  - VBF+MET is the leading channel

B(H→inv) < 10.7 (7.7) % @ 95% CL obs (exp)

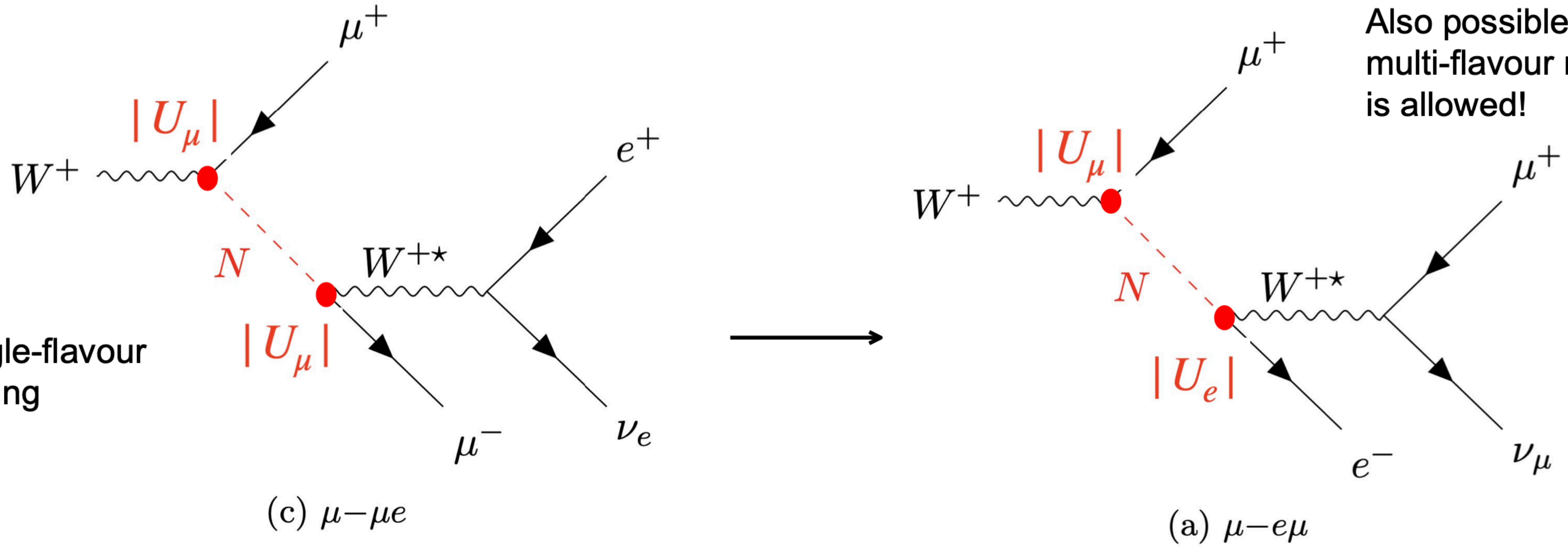
- **most stringent limits on the B(H→inv) to date!**
  - main limitations of VBF+MET:
    - data stats, V+jets modelling, lepton systs



HNL LFC & LFN

single-flavour mixing

Also possible if multi-flavour mixing is allowed!



$|U_\mu|^2 \neq 0 \quad |U_e|^2 = 0$

$|U_\mu|^2 \neq 0 \quad |U_e|^2 \neq 0$

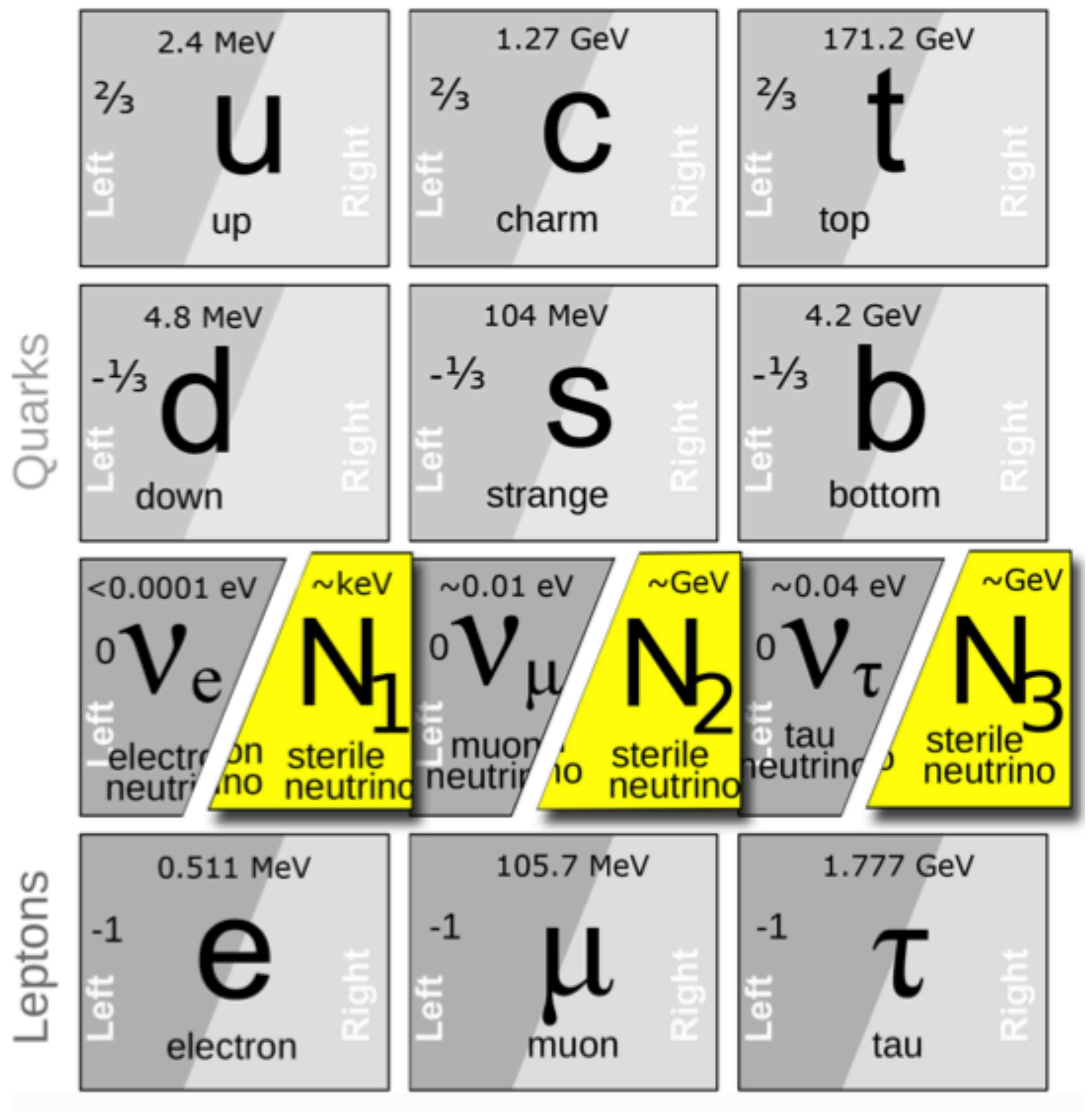
Neutrino Portal

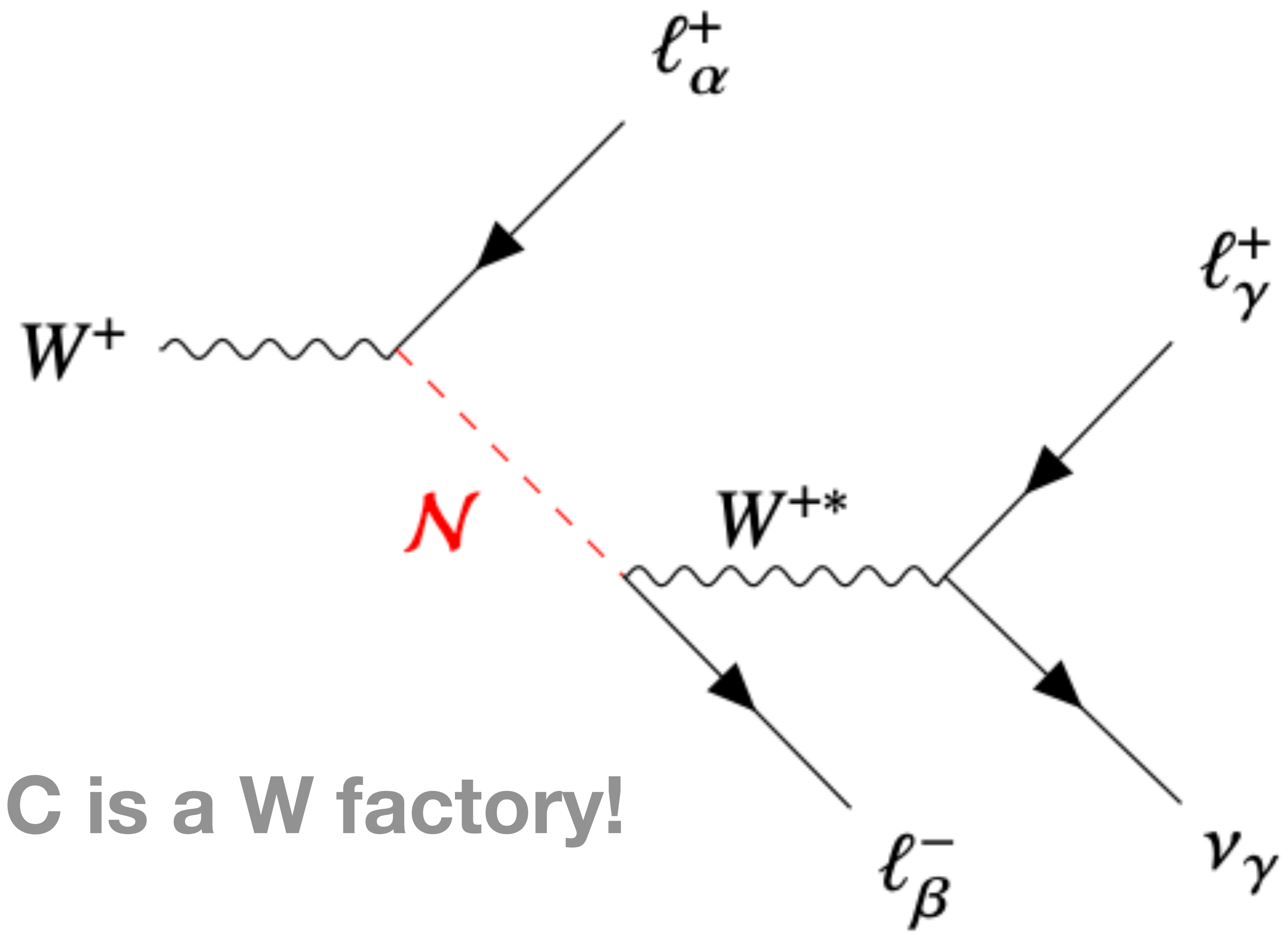
Heavy right-handed neutrino mixes with SM neutrino

- long lifetime due to **off-shell decay**

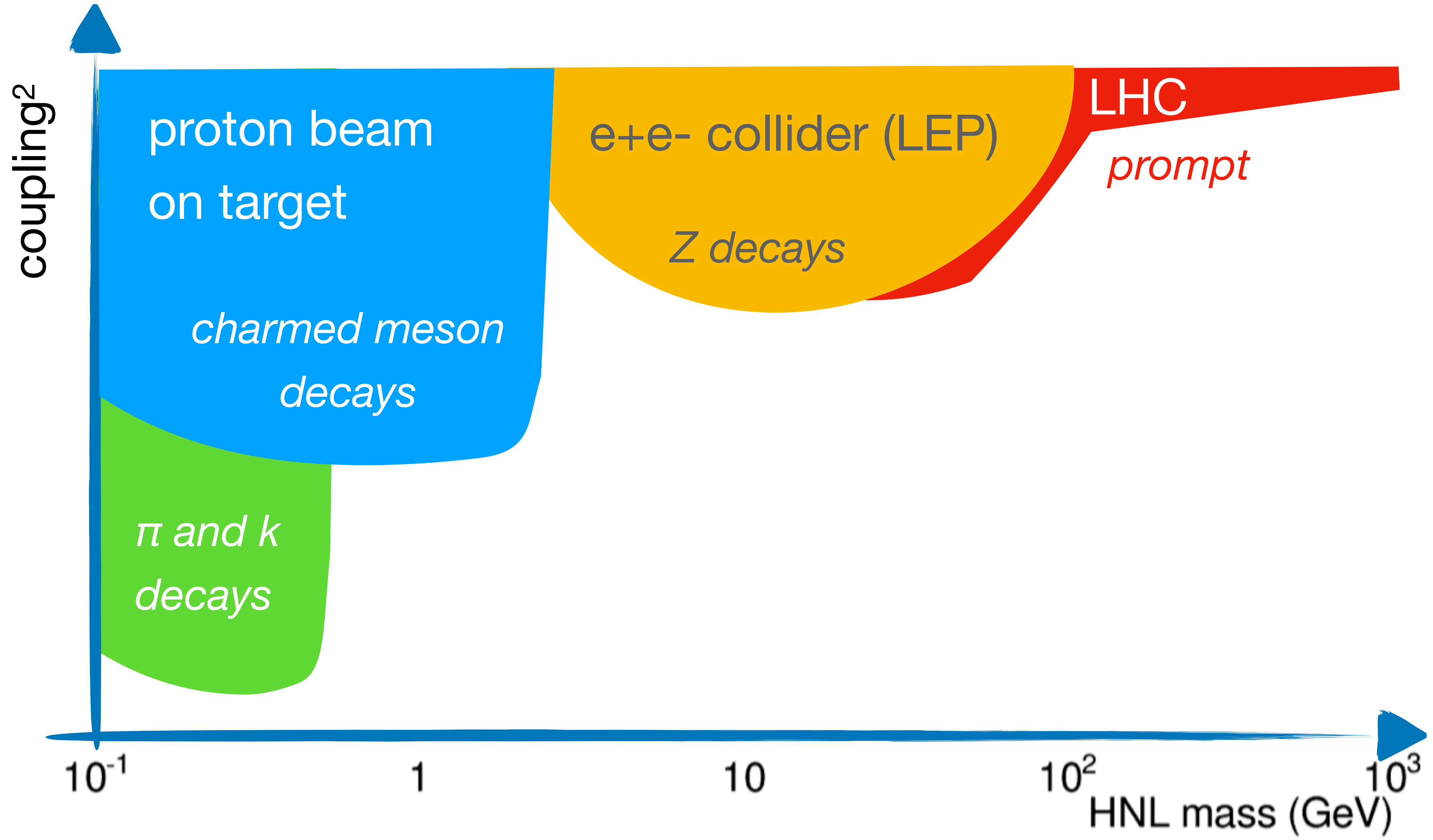
It can explain

- neutrino masses
- baryon asymmetry in the universe
- dark-matter abundance





LHC is a W factory!



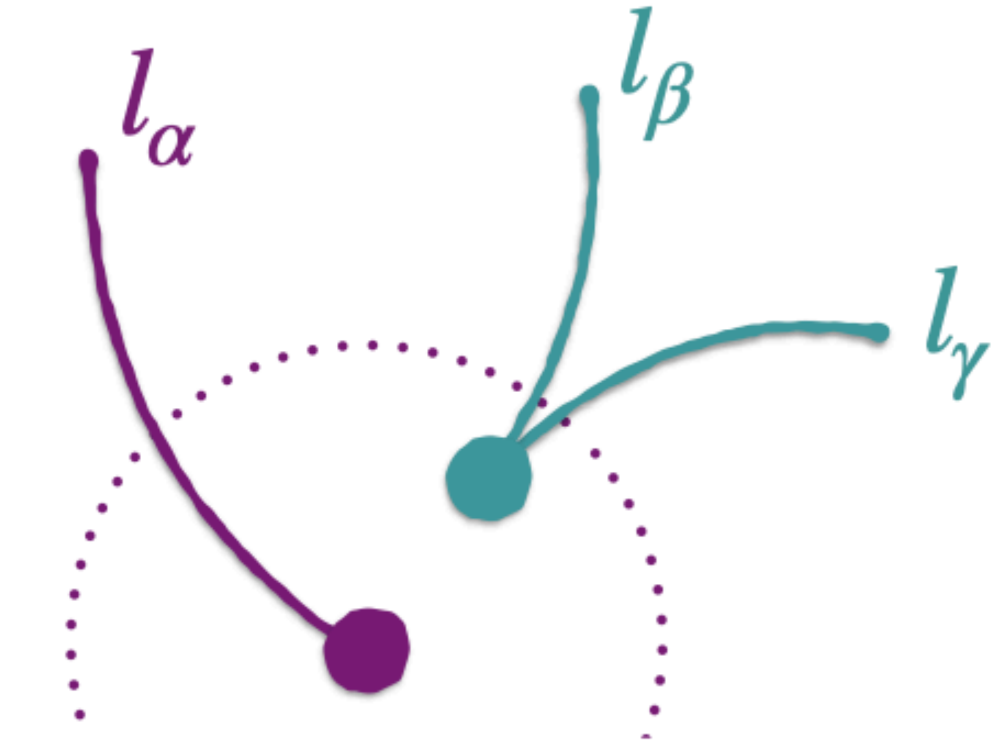
HNL: Run-2 analysis

Phys. Rev. Lett. 131 (2023) 061803

Prompt lepton + 2 OS displaced leptons → secondary vertex

6 different channels → sensitive to different coupling scenarios

Channel 1 $\mu\mu\mu$	Channel 2 $\mu\mu e$
Channel 3 $\mu e e$	Channel 4 eee
Channel 5 $ee\mu$	Channel 6 $e\mu\mu$



irreducible **BKG** from random track-crossing

- *estimated from CR*

shuffling prompt SS DV and OS DV regions