BSM experimental overview

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LFC24 - Fundamental Interactions at Future Colliders

Where is new physics?

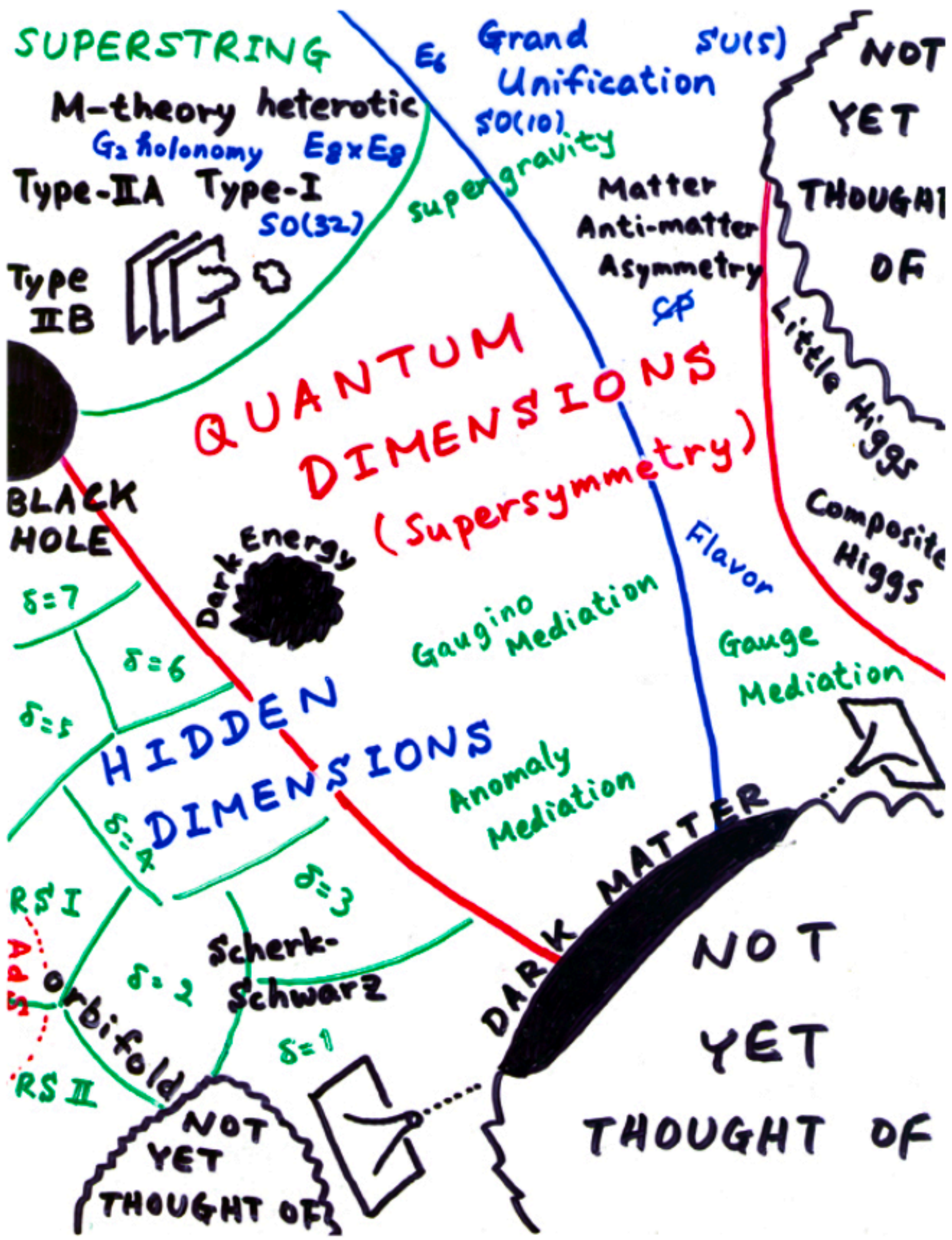
Exploring the unknown

Many mysteries still unsolved:

- Nature of Dark Matter
- Hierarchy Problem
- Matter-Antimatter Asymmetry
- Neutrino Masses
- …

signature-based generic searches

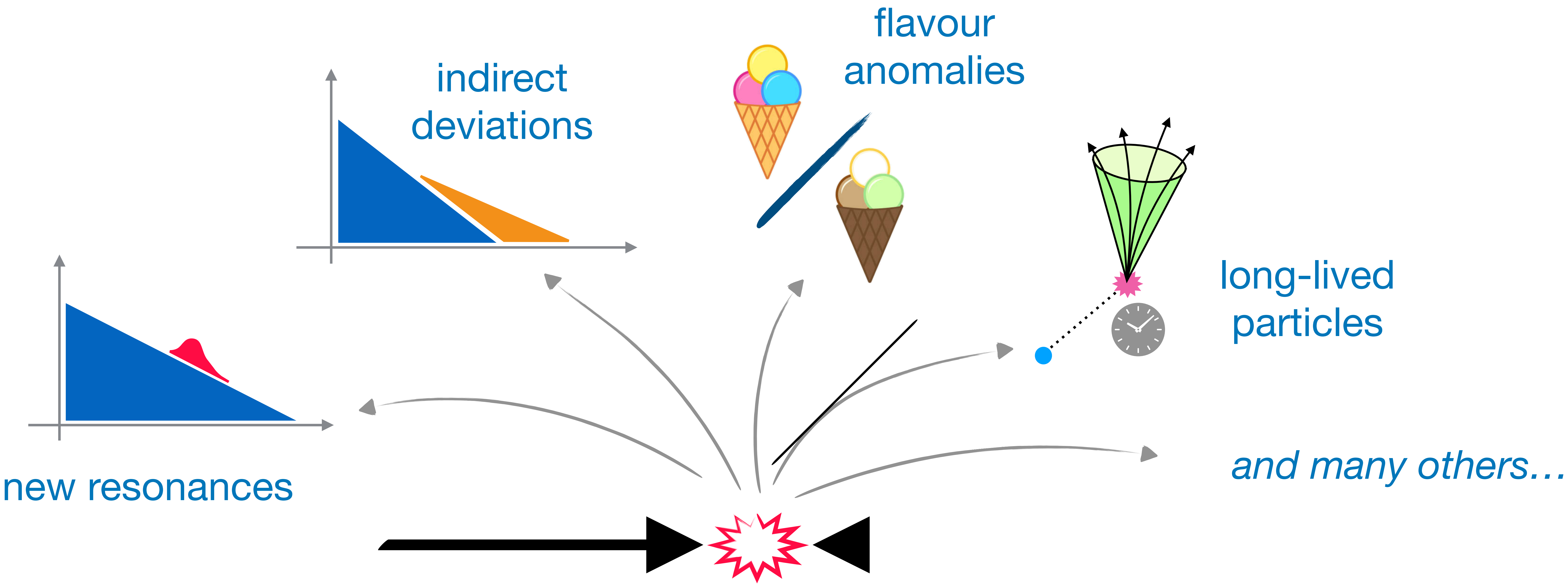
(new) model-driven targeted searches



Vast *research program combining*

- variety — *exploring a wide range of signatures*
- effectiveness — *interplay between different kinds of searches*

How searching for new physics?



The Run-3 opportunities

new centre-of-mass energy

- gain limited to few signatures: QBH, Z’/W’

Increased stats

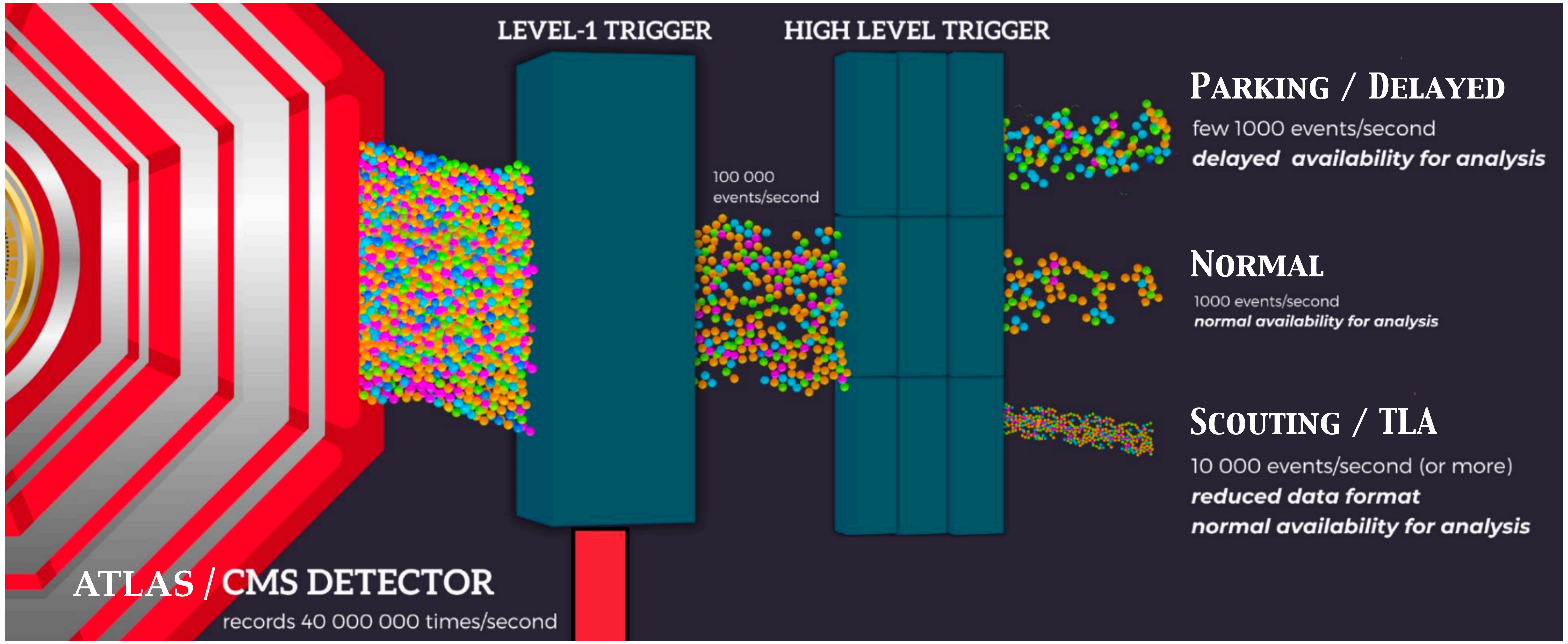
- open new channels

New ideas

- triggers, tools, strategies

Triggers @ Run-3

Larger rates → GPUs acceleration [CMS, LHCb, ALICE]
→ Multi-Threading [ATLAS]



Triggers @ Run-3

CMS-EXO-23-007

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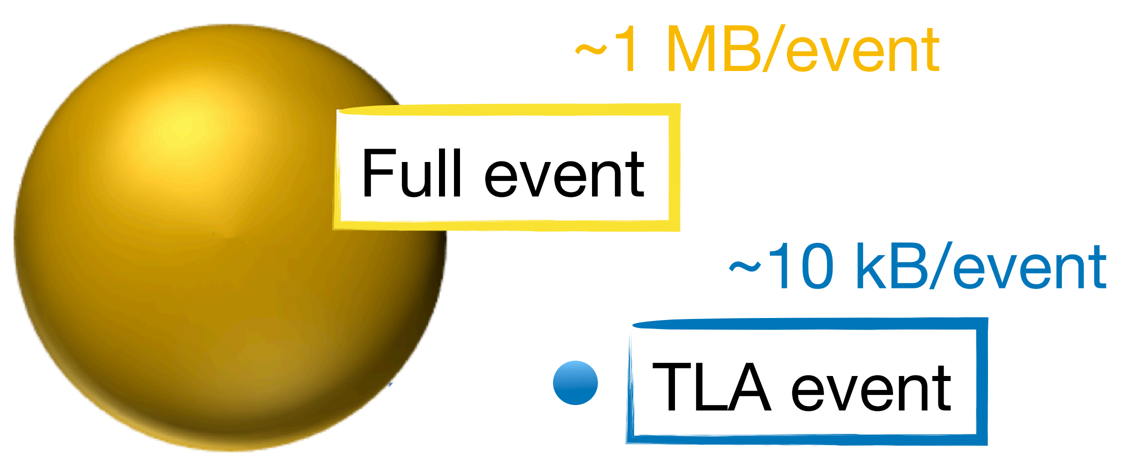

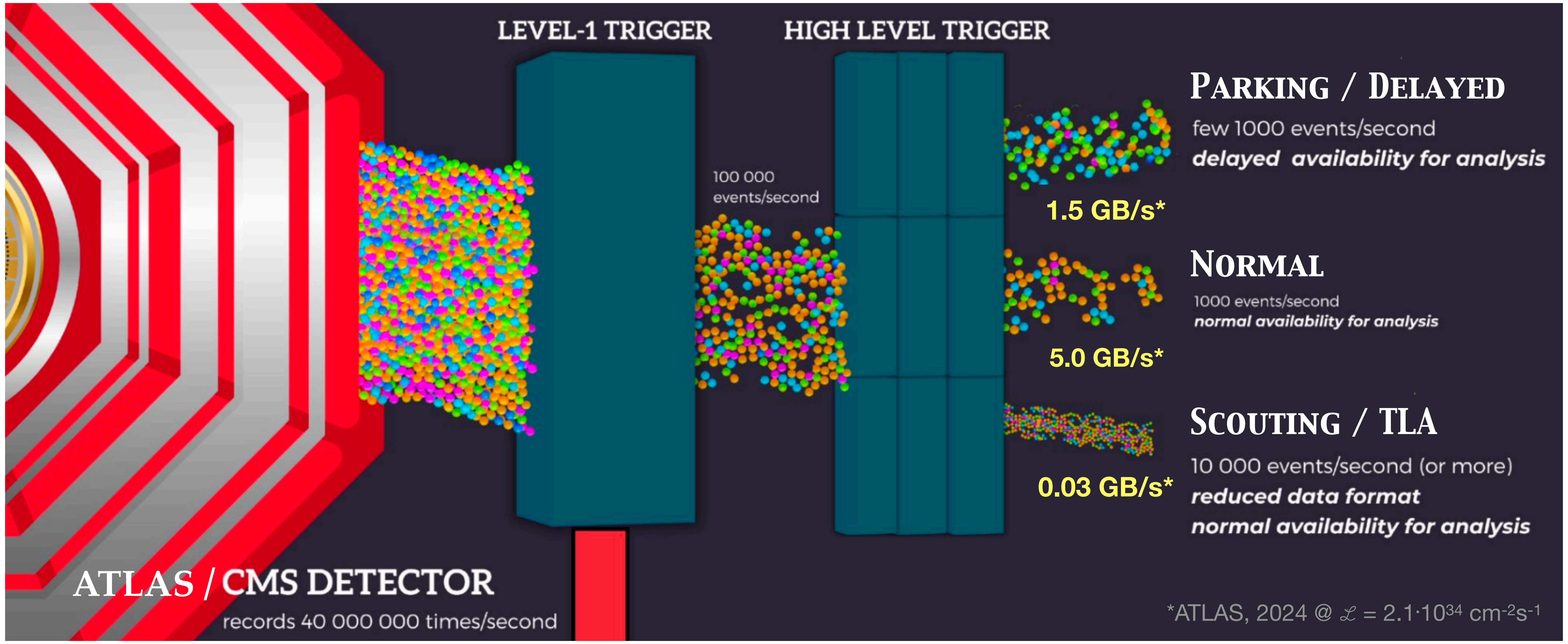

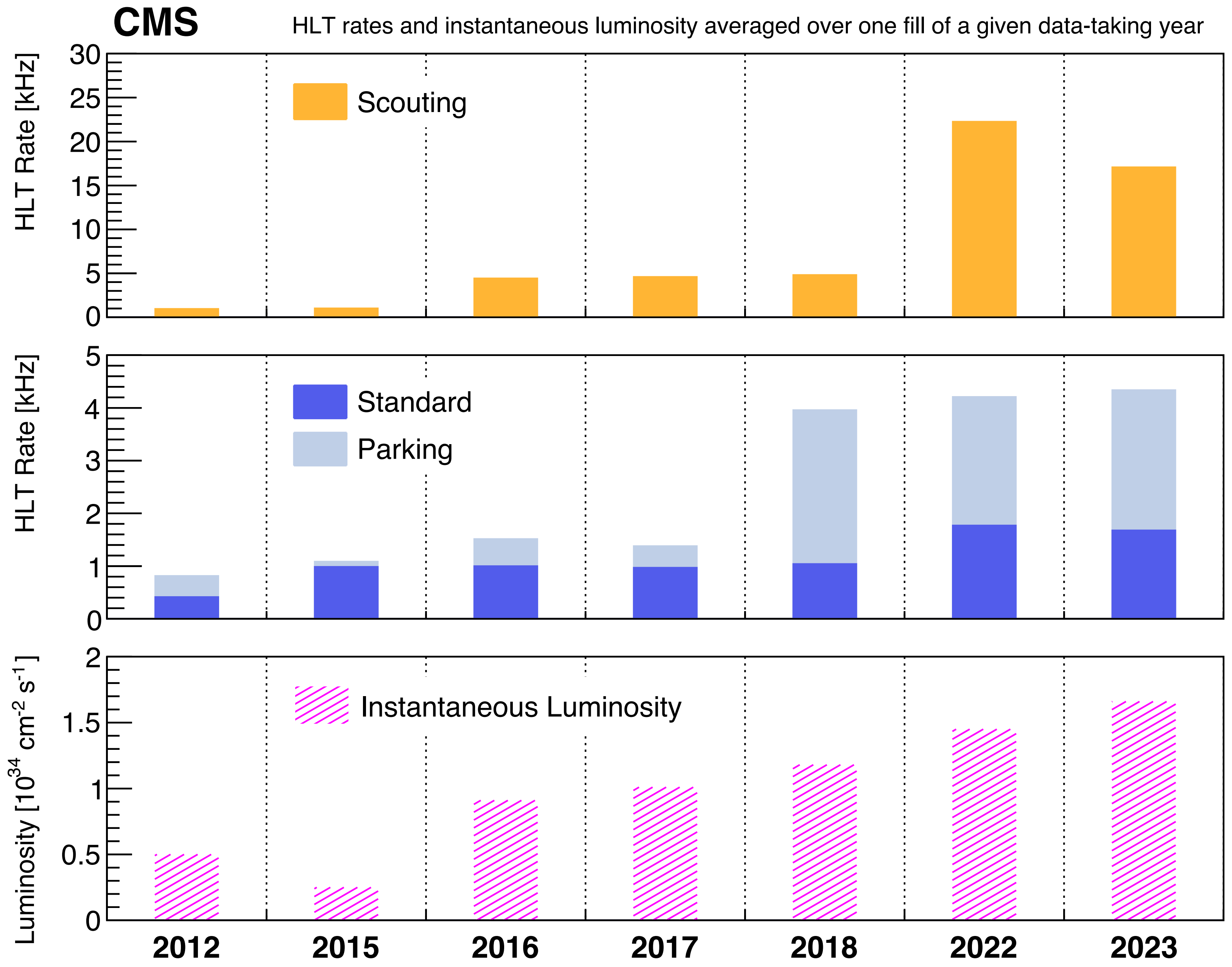

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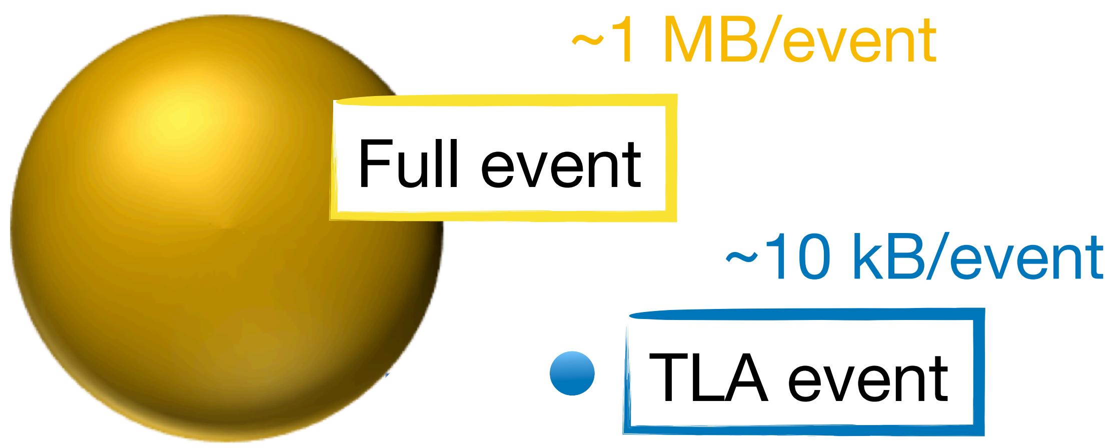
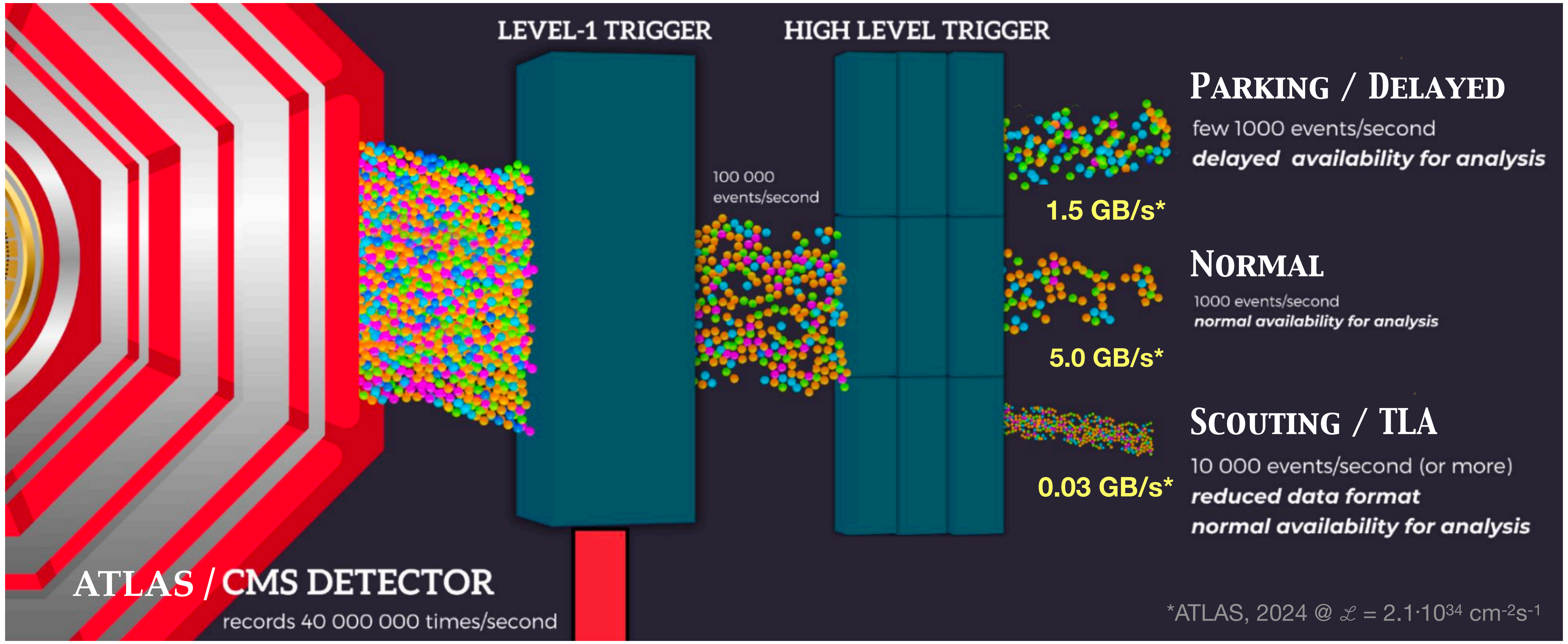
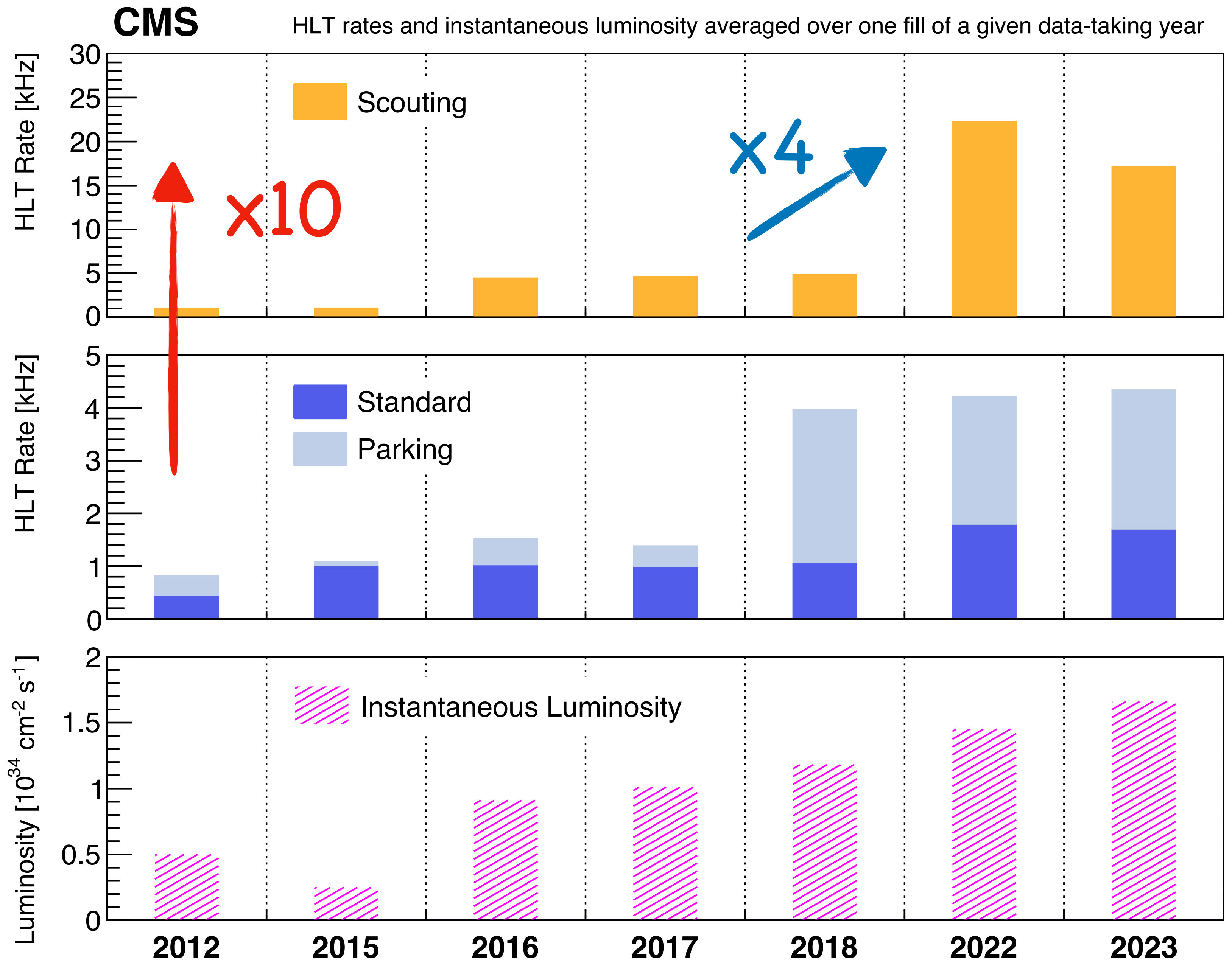






Expanded Parking and Scouting strategies in **ATLAS** and **CMS** → many different final states covered!

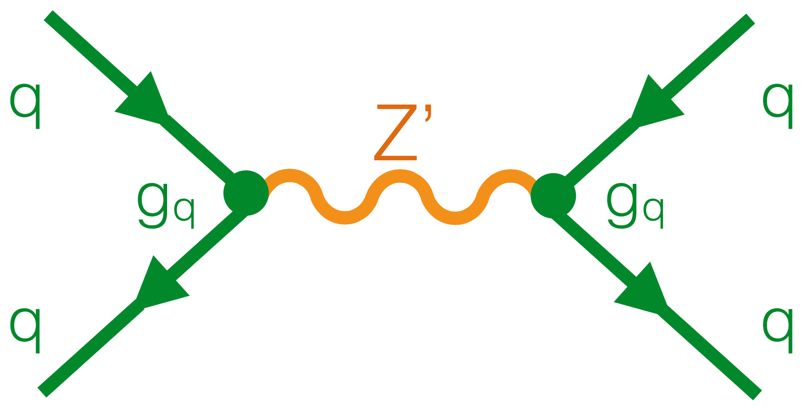
LHCb full SW-based boosting efficiencies of HF decays

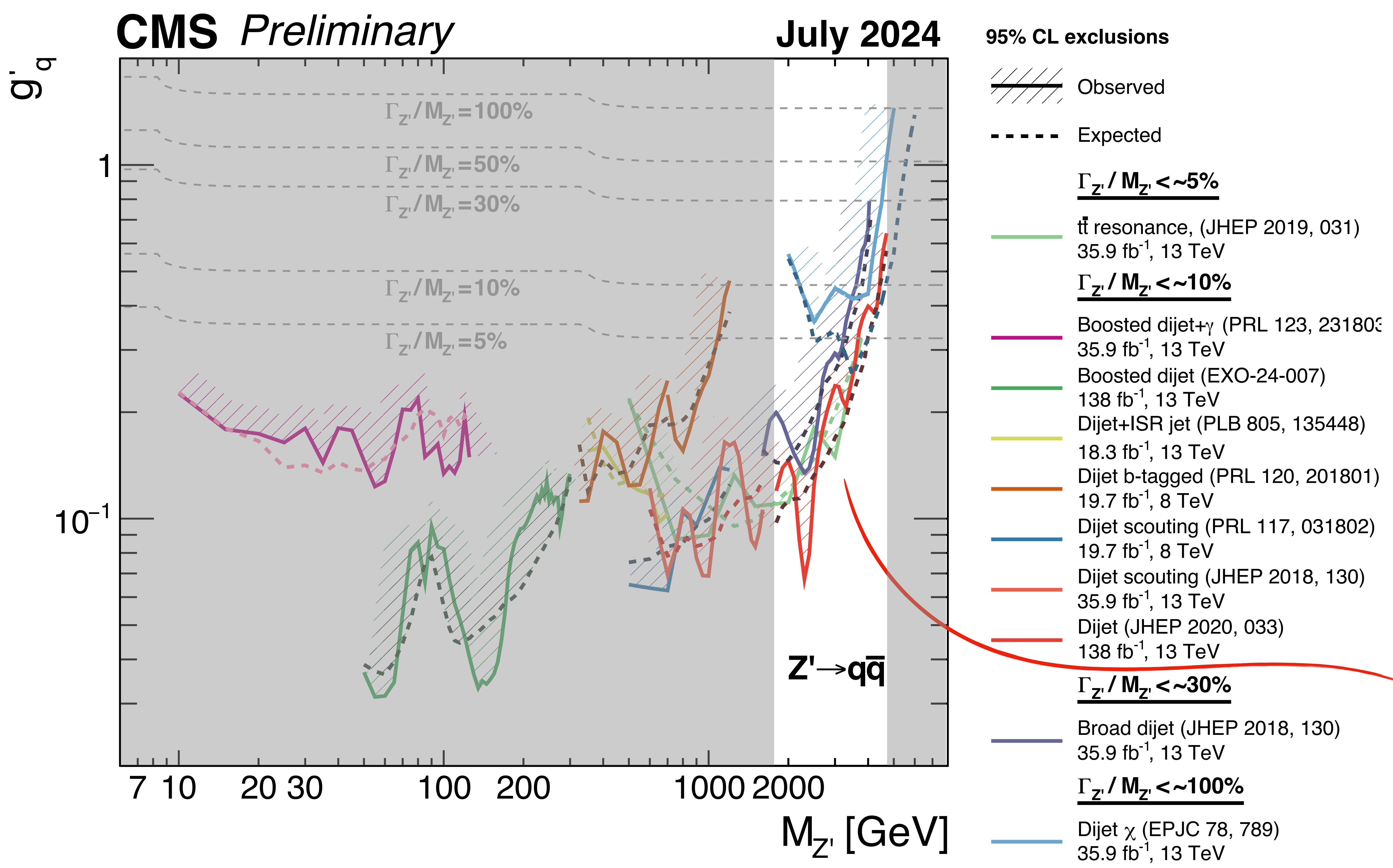
ALICE trigger-less acquisition: 50 kHz (x50 Run-2)

Bump-hunting

Beyond the standard di-jet/lepton resonant search!

Dijet resonant searches cover a mass range from multi-GeV to multi-TeV!





di-jet

Bump-hunting

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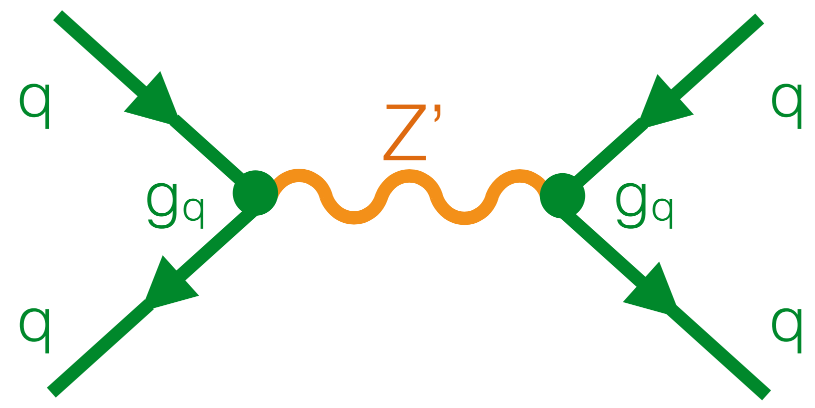
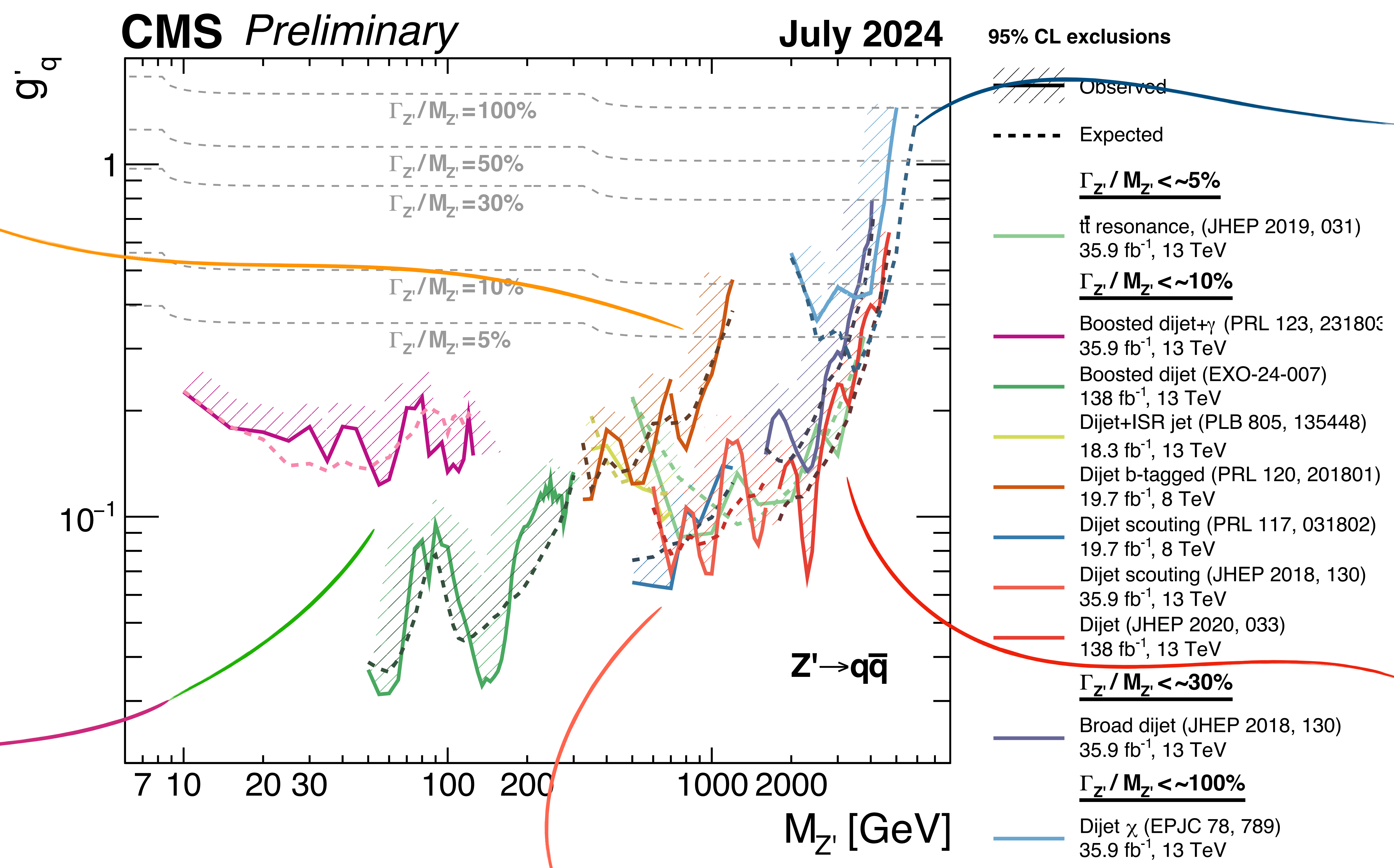


flavour tagging



Di-jet angular

correlation allows probing high mass and large-width

boosted topology and

initial state radiation

di-jet

data-scouting

Jet flavours

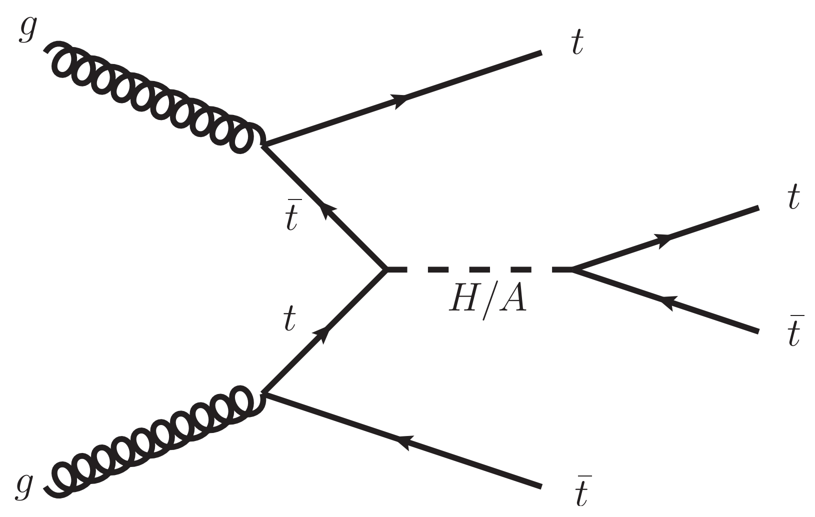
4 top EXOT-2022-13
multi-b: SUS-24-001
Z'+bb: EXO-22-006

To probe flavoured structures and categories reducing bkgs

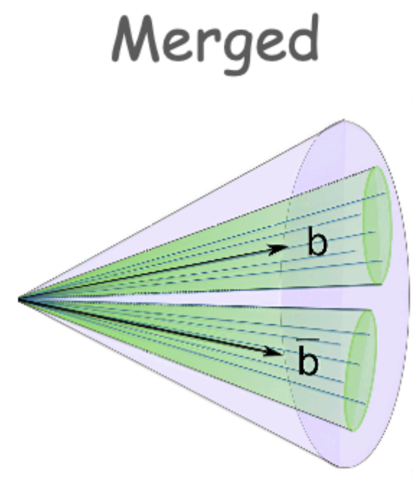
tt/bb+X

to probe exclusive channels

* recent **4 top process observation**

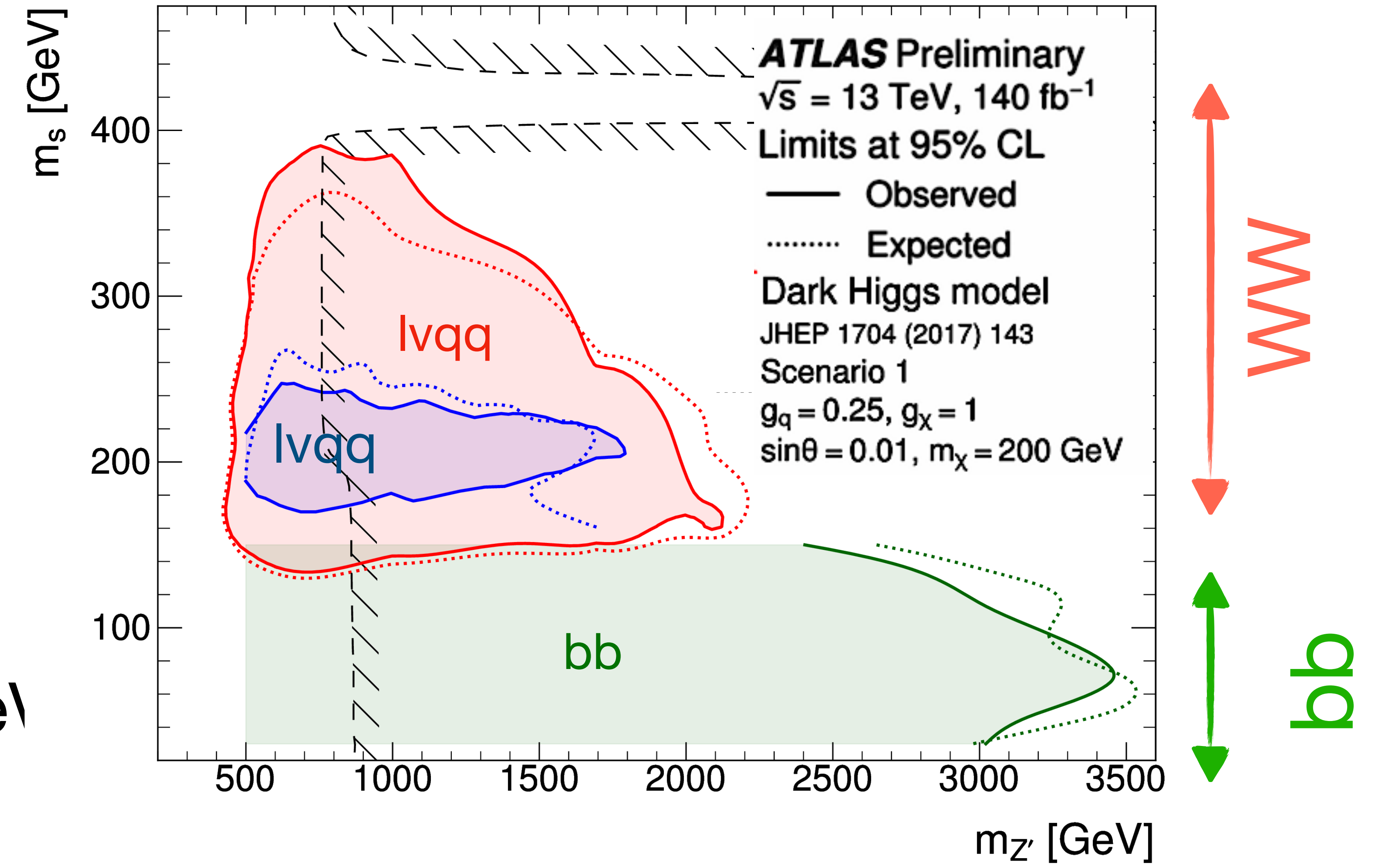


s→bb



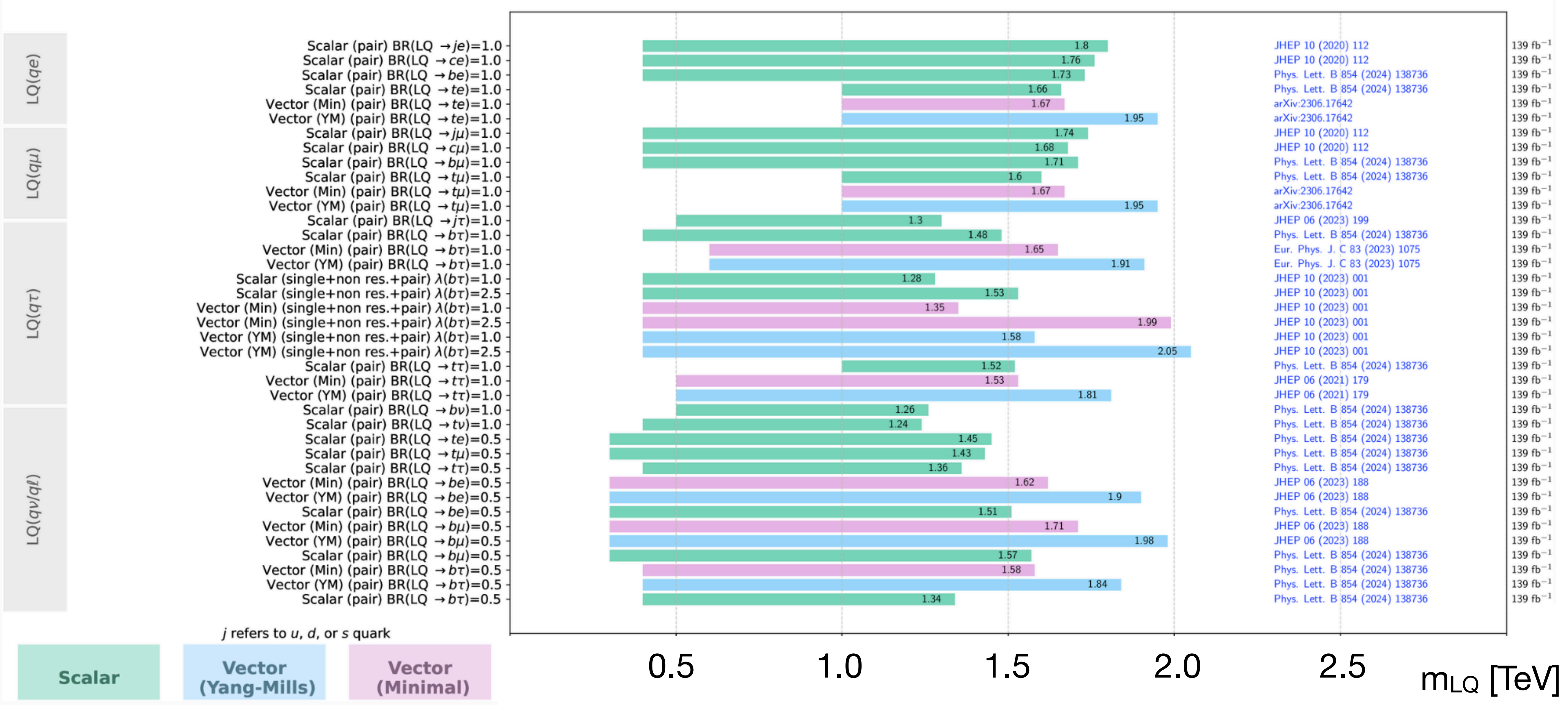
Large-R jets + **Xbb tagger** to explore m_s down to 30 GeV

ATL-PHYS-PUB-2024-010



Rich search program of **LQ**!

…same for **VLQ** and **excited quarks**!

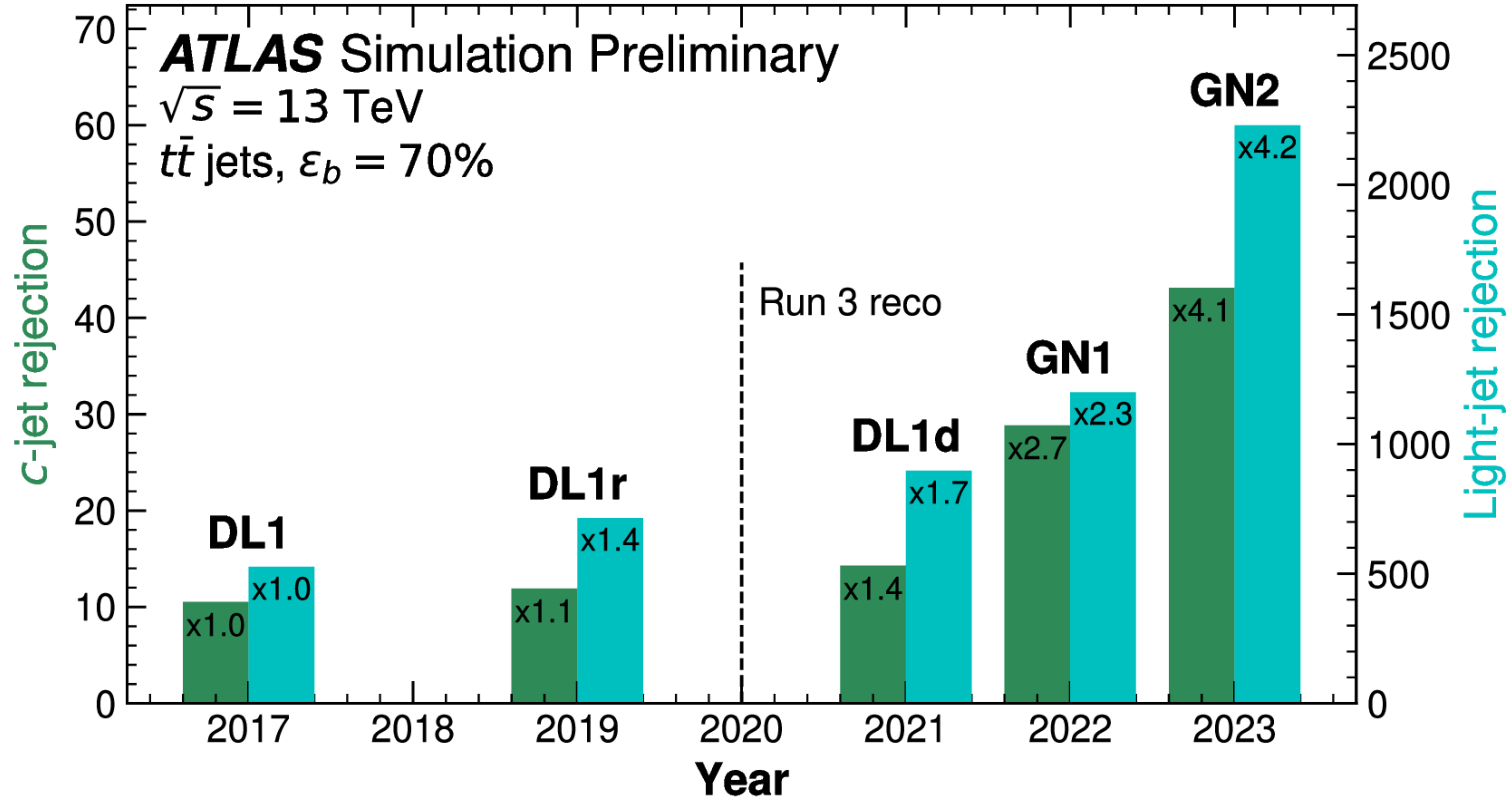


ATL-PHYS-PUB-2024-012

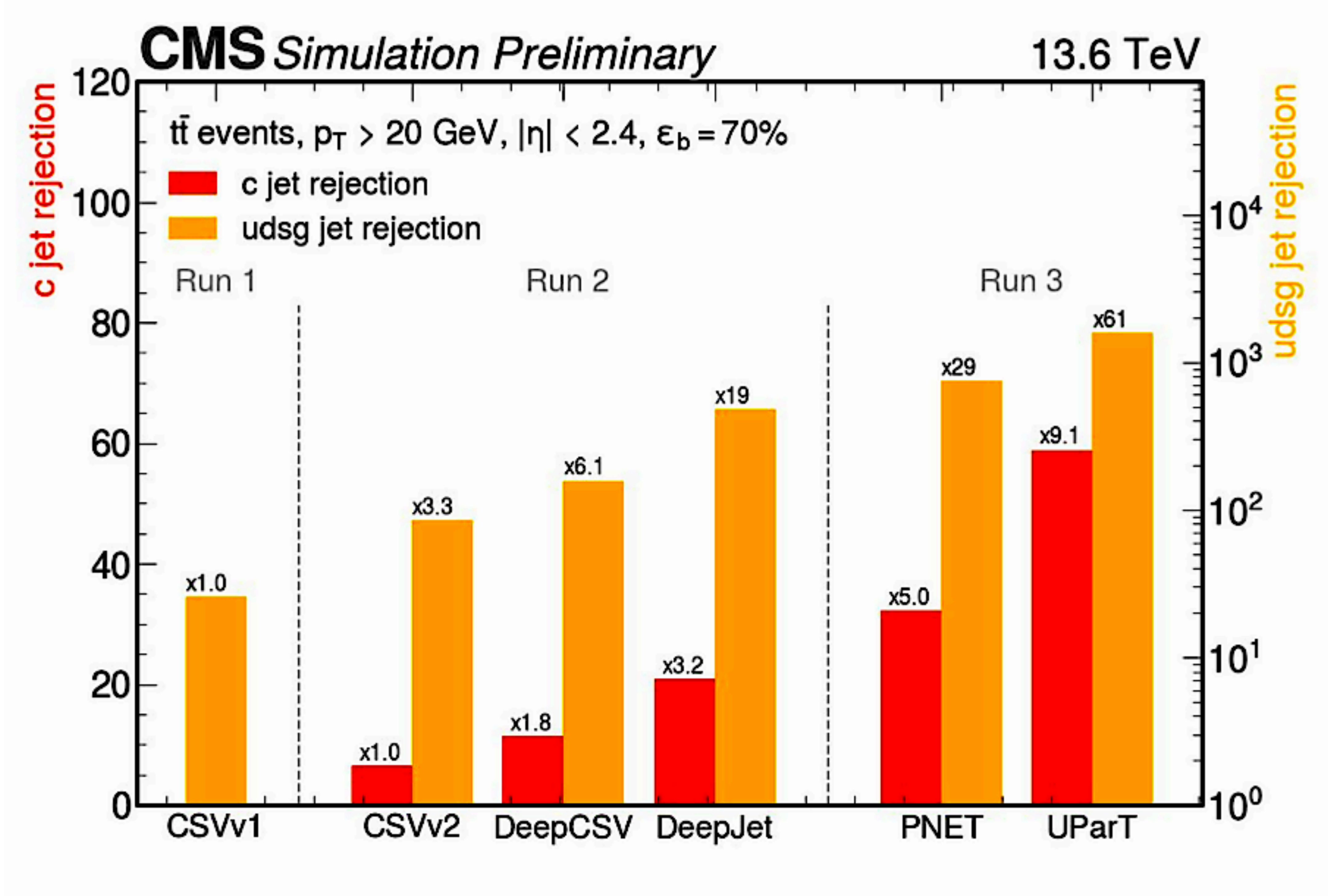
Jet flavours

Keep improving!

new **GNN/transformers-based tagger**
in ATLAS and CMS greatly improve performances…
…still to be widely exploited!



FTAG-2023-01

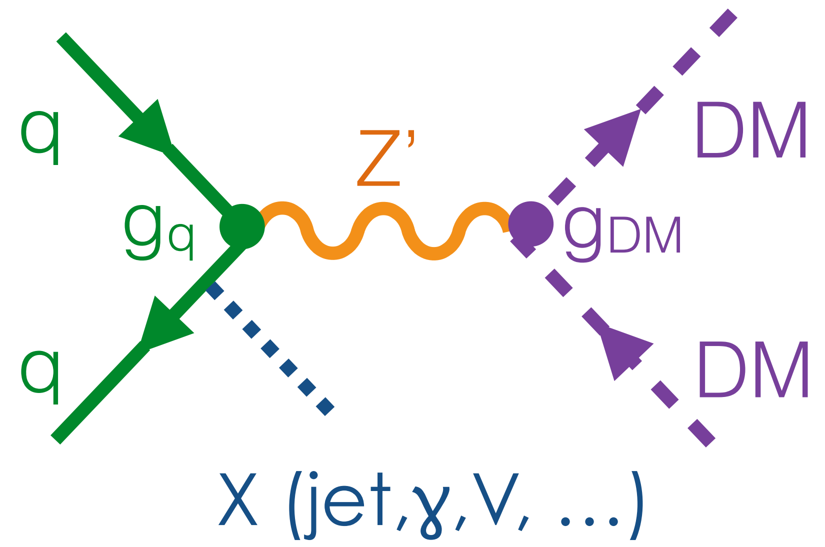


CMS-DP-2024-066

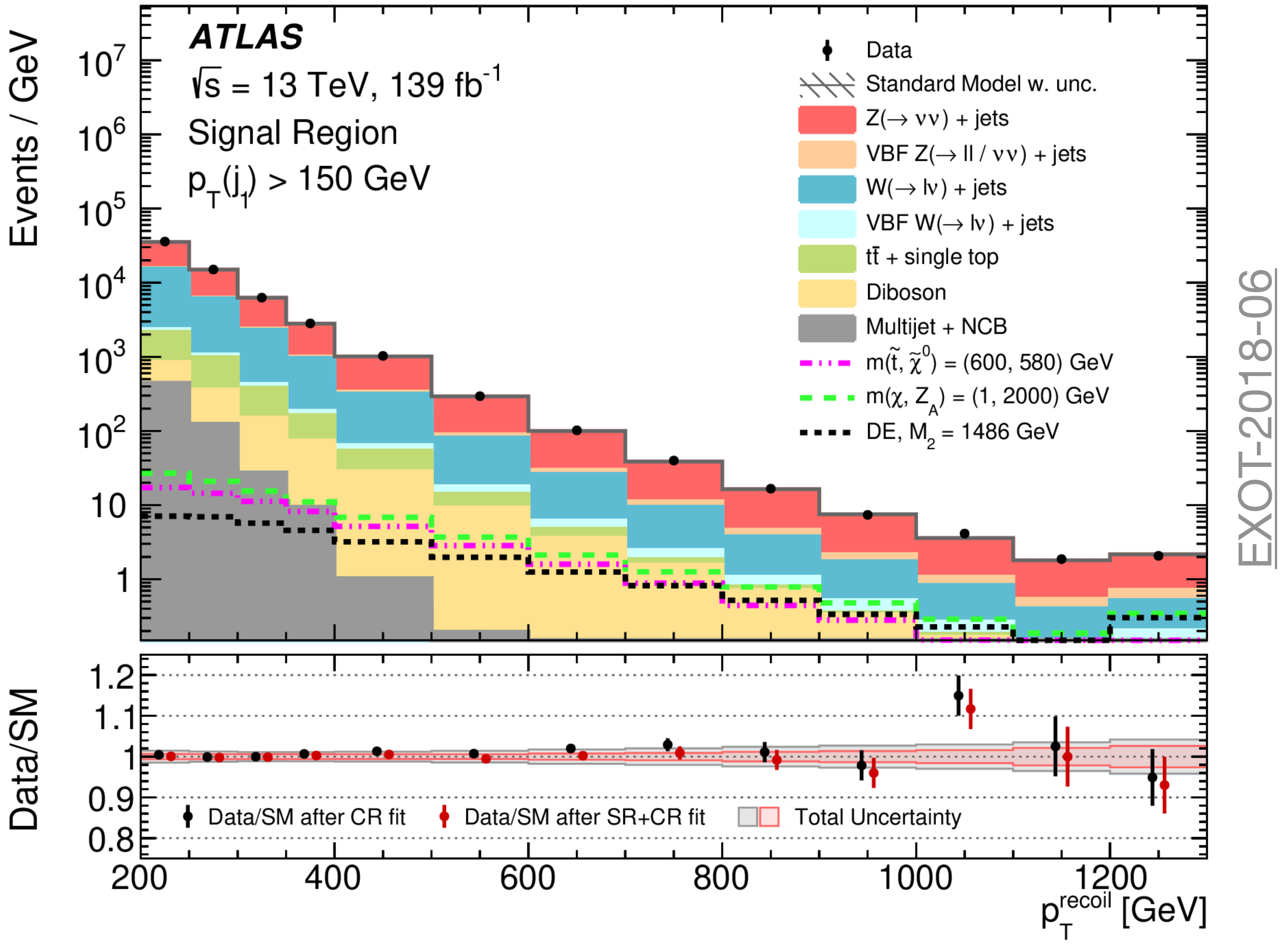
MET+X

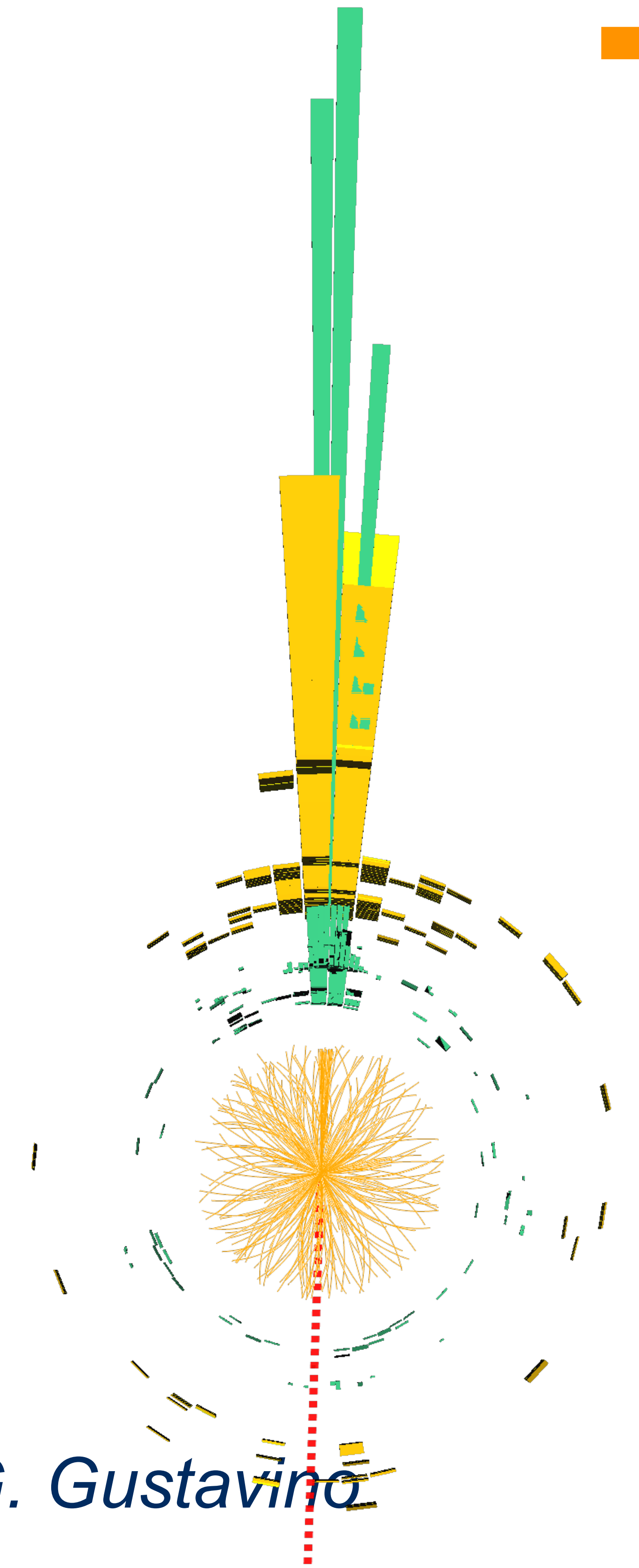
General Analysis Strategy:

- Require MET (➡ recoil system p_T)
- Select for X (jet, photon…)
- Veto other objects
- Control regions to estimate bkg (mainly Z(vv)+X)



➡ Looking for an excess in the MET tail

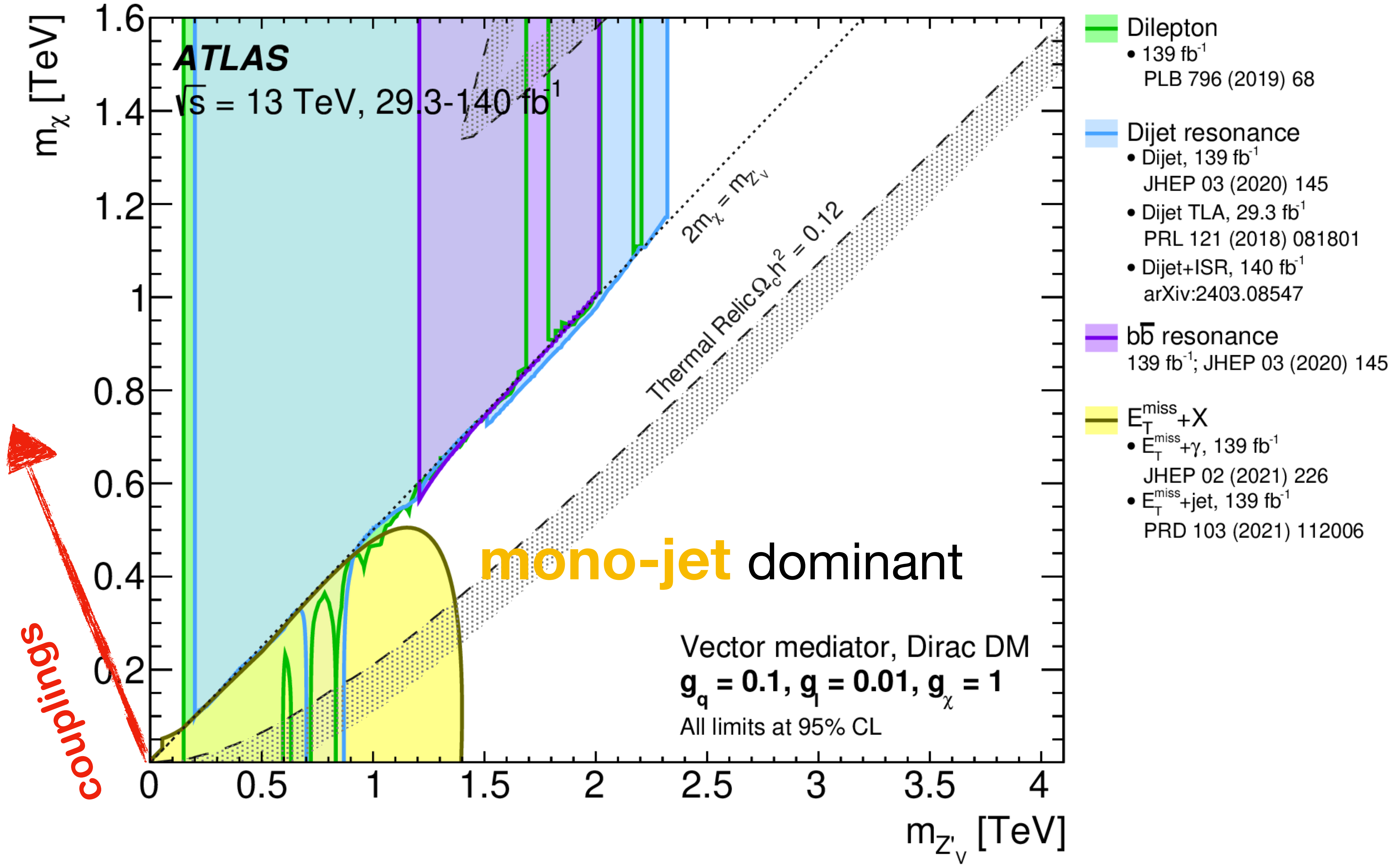




Mono-X and di-jet/lepton provide complementary results

Additional objects in the final states, e.g. HF objects, allow to

- suppress the bkg
- reduce the high trigger thresholds

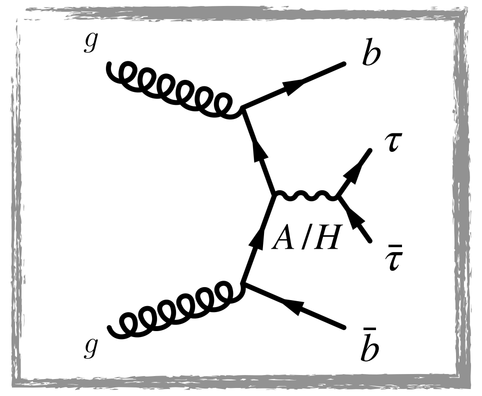
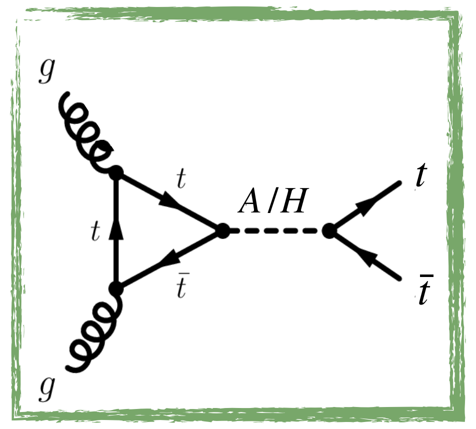
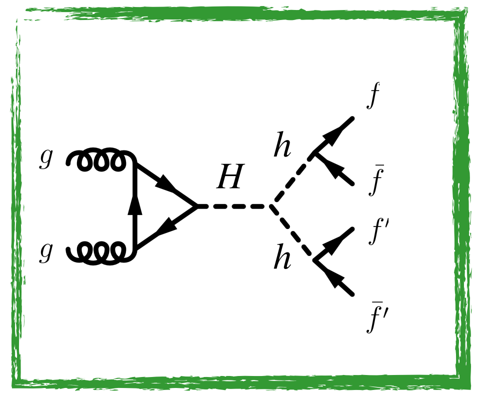
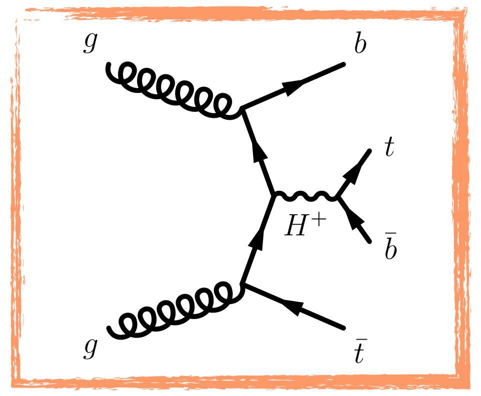


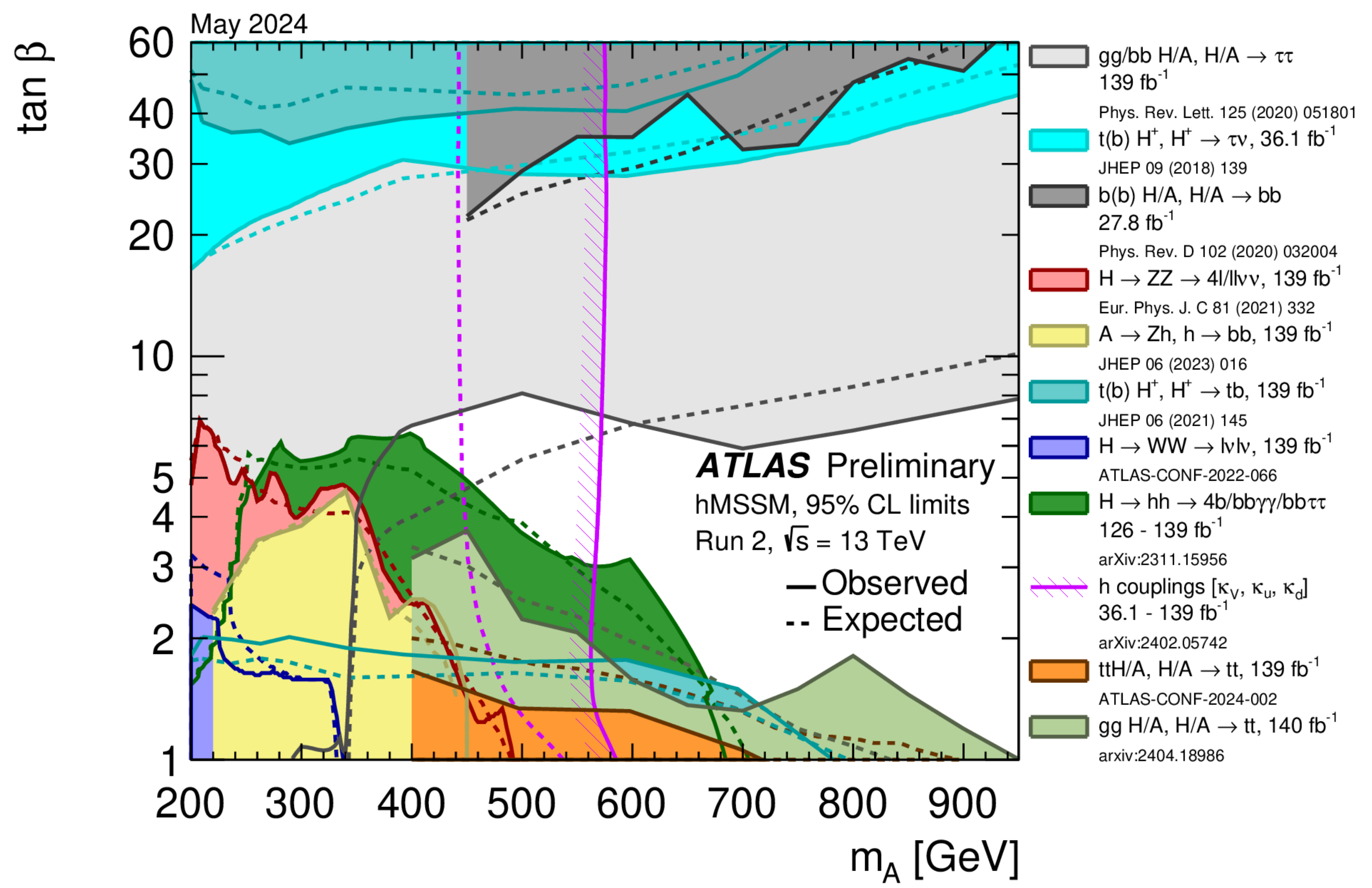
G. Gustavino

Model-driven searches

hMSSM

simplified description of the Higgs sector in the MSSM

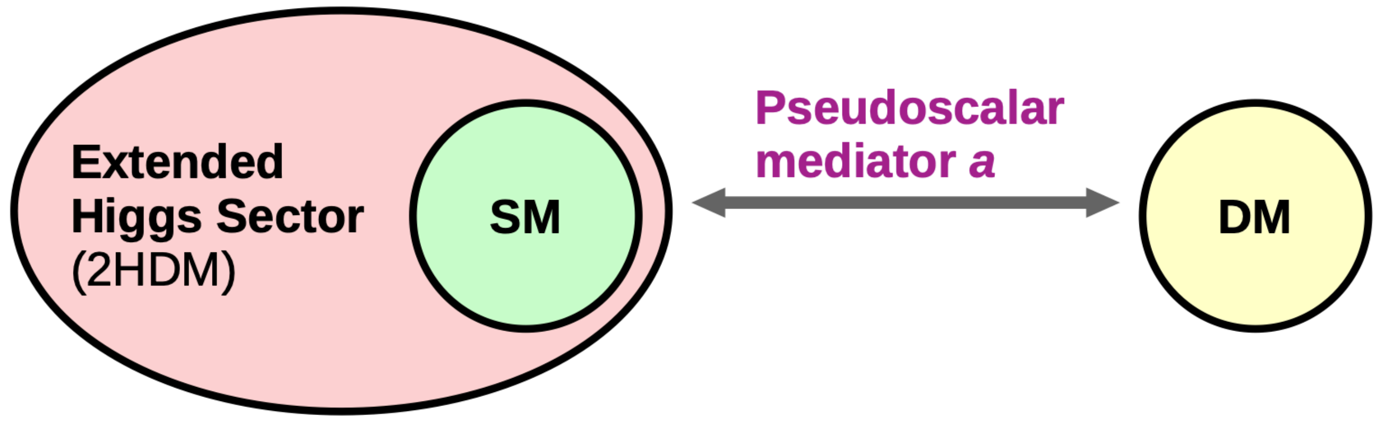


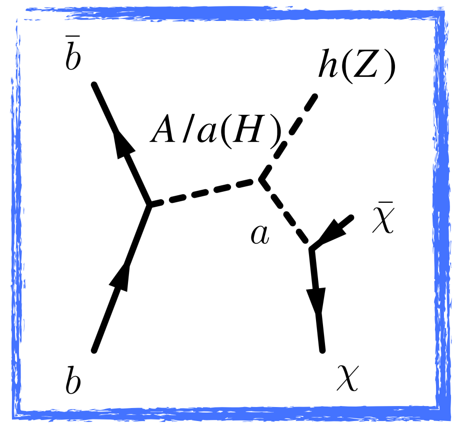
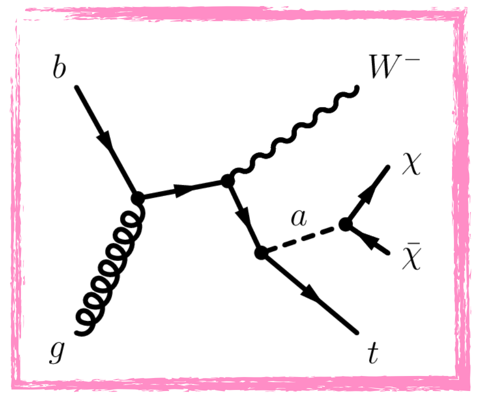
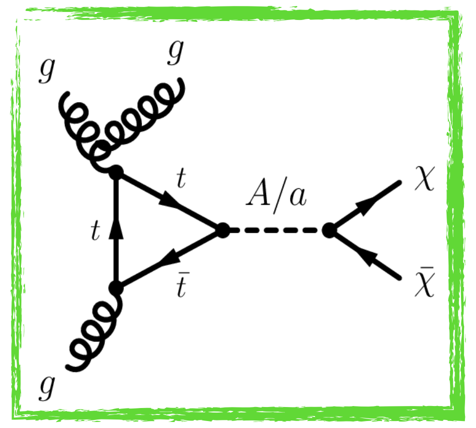
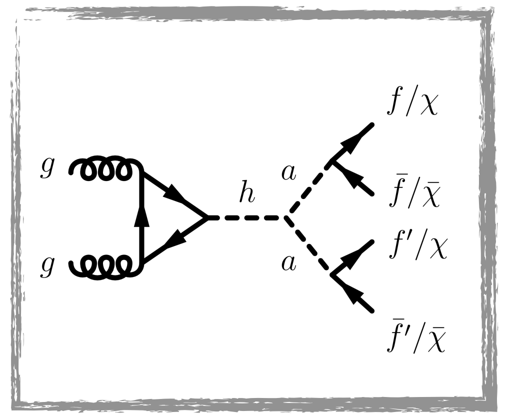
2HDM+a

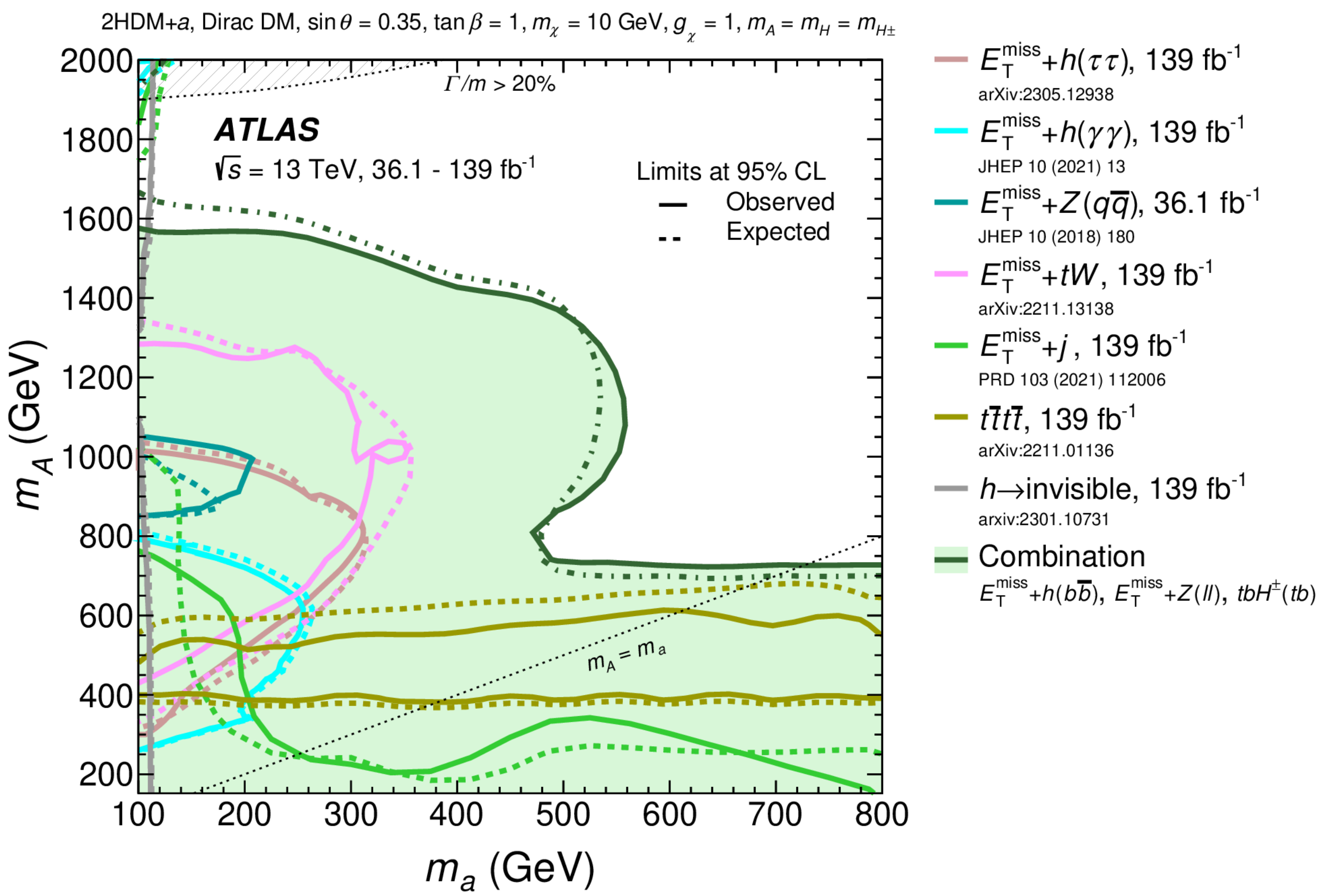
2HDM **resonant** scenarios

+ invisible final state component

from pseudoscalar mediator





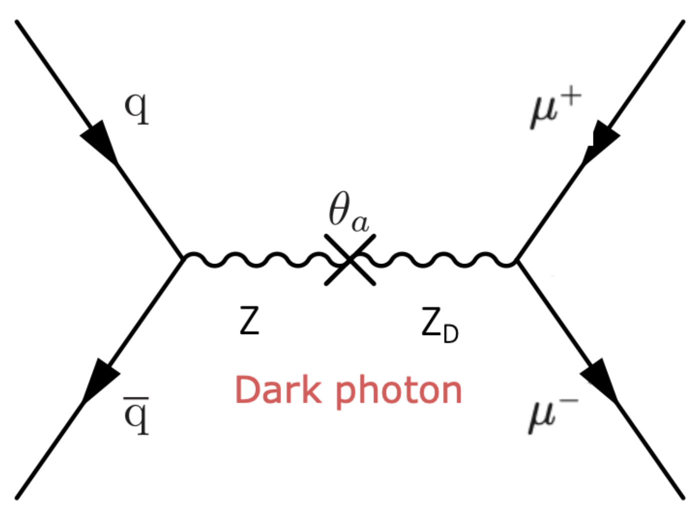
➡ Rich phenomenology and great signature interplay.

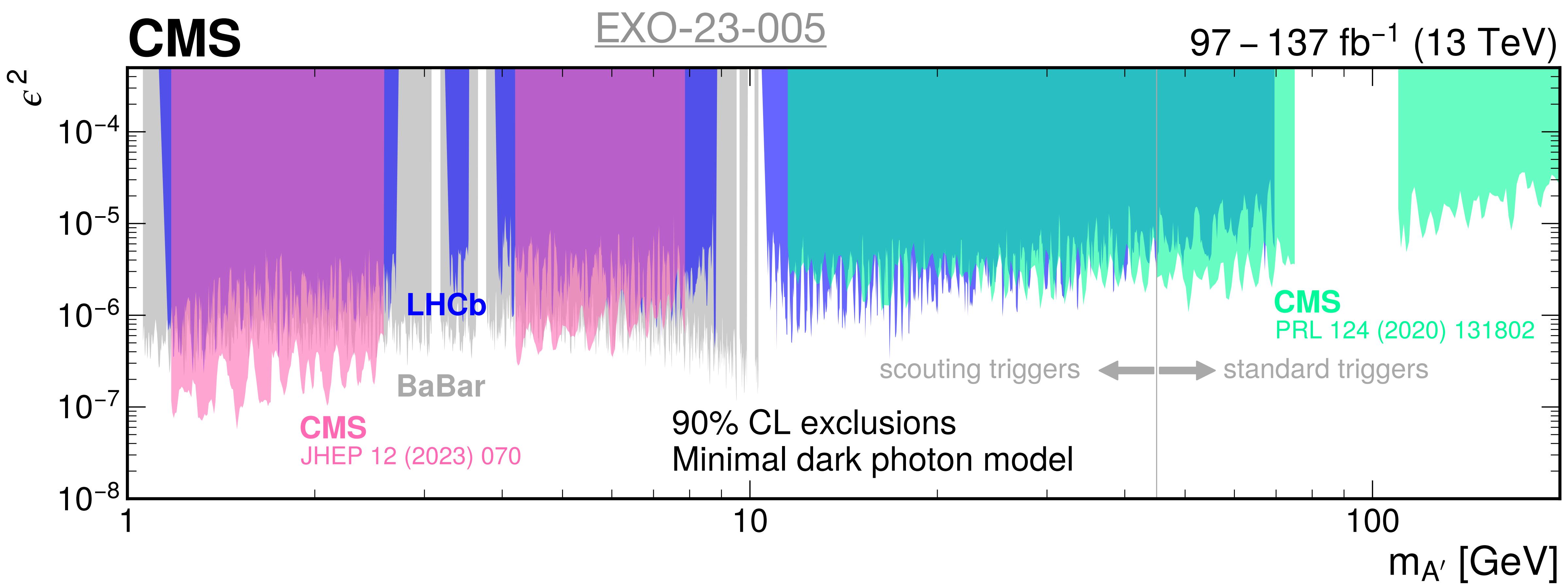
Searches with Leptons

Low mass

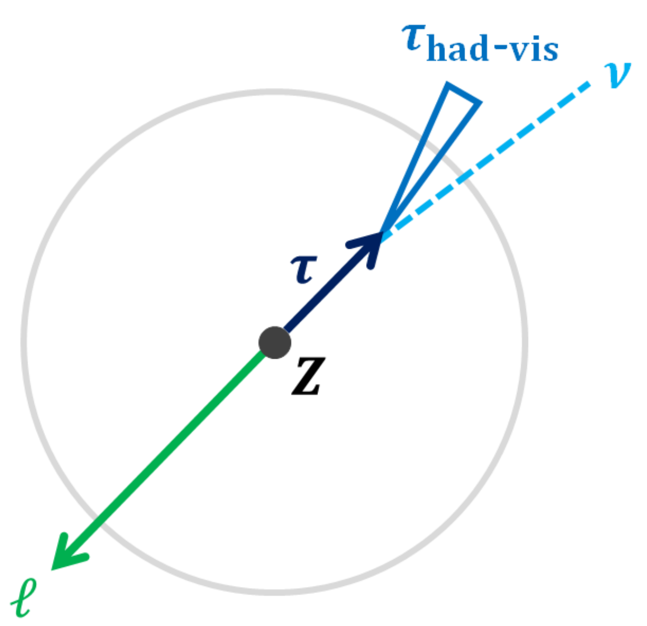
Resonant mediator search bounds are driven by di-lepton

Data scouting ➡ $m_{\gamma D} \sim 1$ GeV





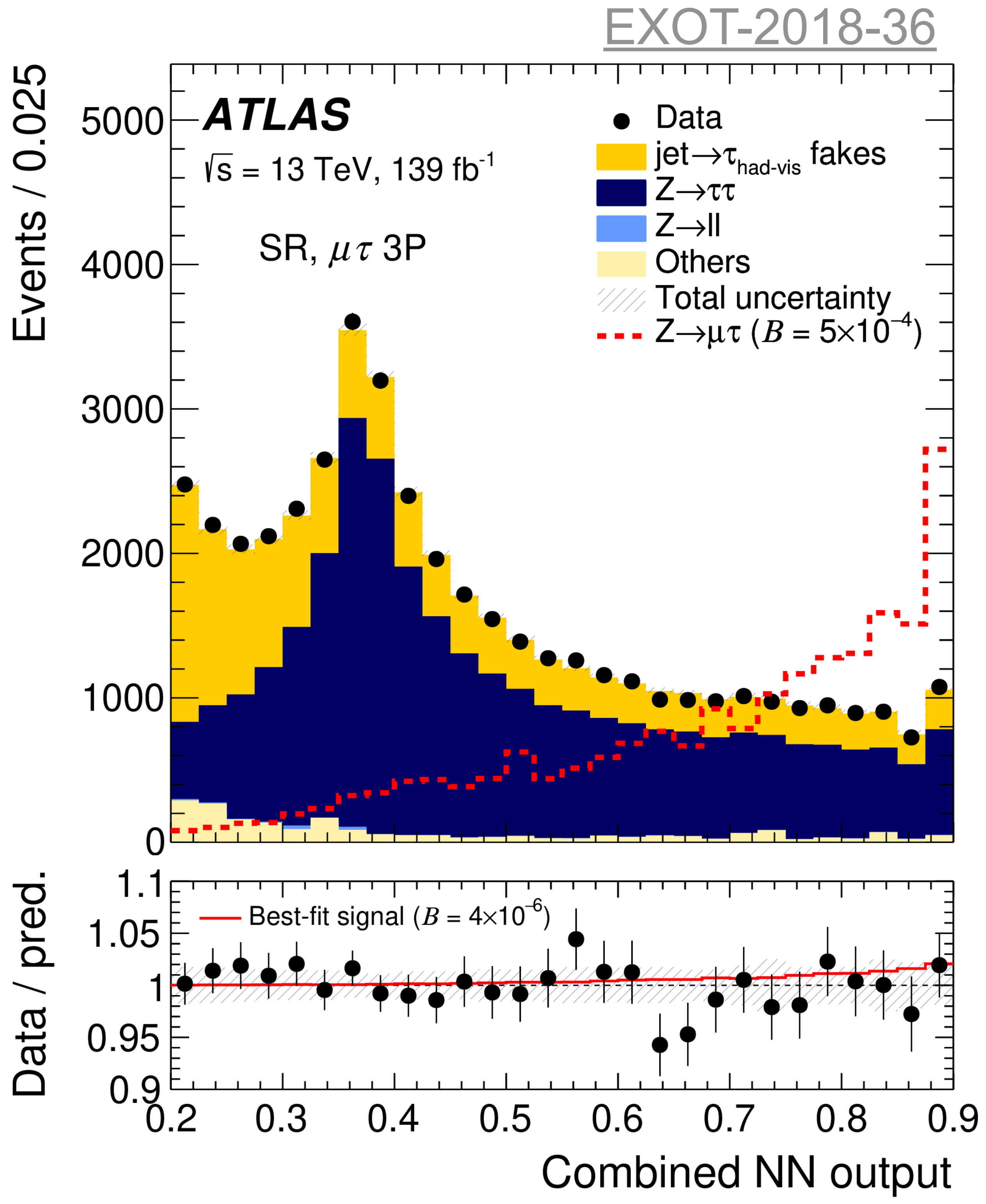
LFV



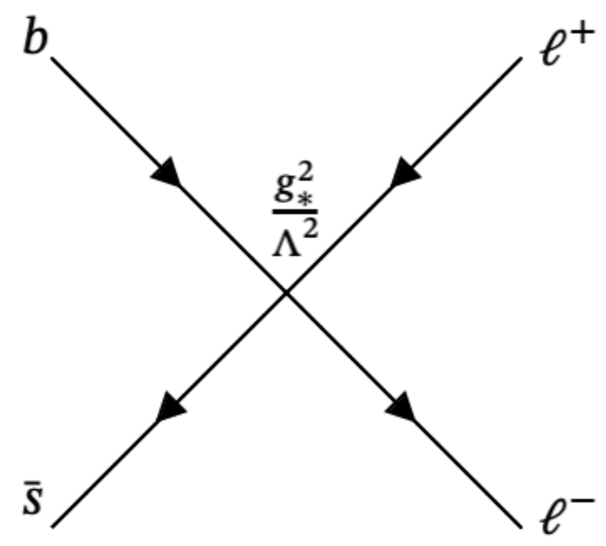
$BR(e\tau) < 8.1\times10^{-6}$ @95%

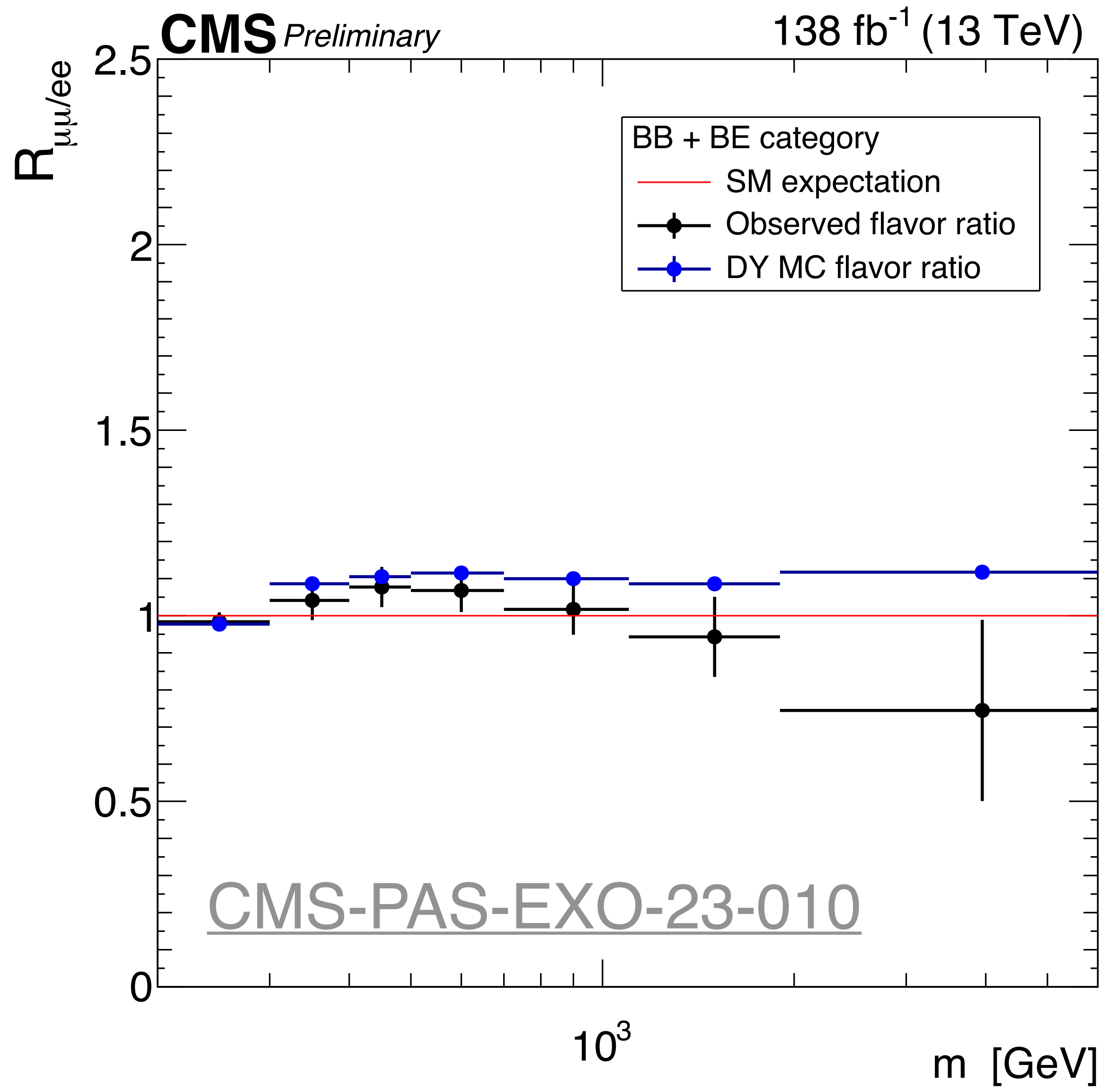
$BR(\mu\tau) < 9.5\times10^{-6}$ @95%

better than LEP!



Non-resonant decays



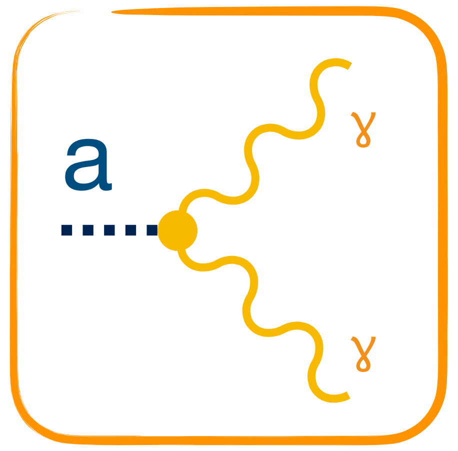


lepton flavour universality and lower limits to new physics scale up to 9 TeV

Searches w/ Photons

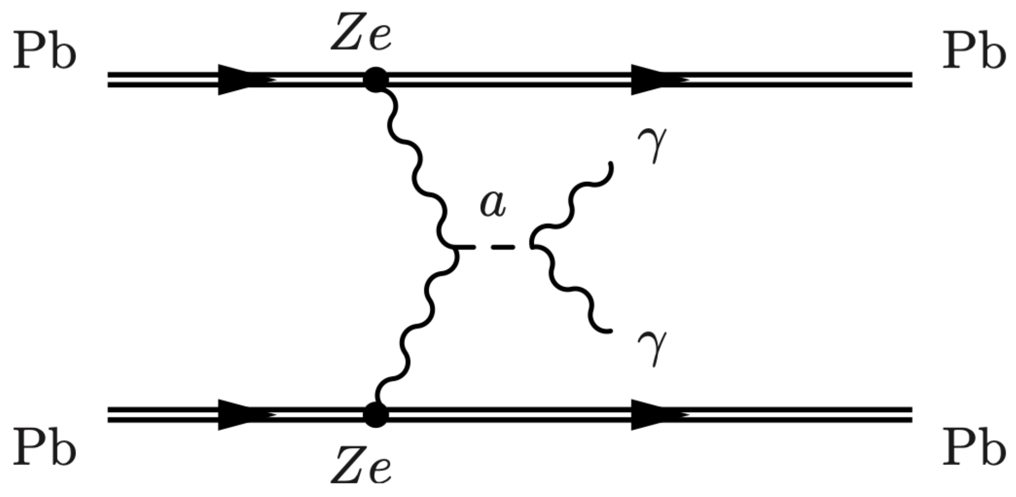
Light-by-Light scattering: ATLAS-HION-2019-08, CMS-FSQ-16-012
Proton tagging: ATLAS-EXOT-2019-28, CMS-EXO-18-014
Higgs decays to ALPS: ATLAS-HDBS-2019-09 CMS-HIG-21-003
ATLAS-HDBS-2019-19 CMS-HIG-21-016

Axion-Like Particles among the main motivations to search for di-photon final states



Light-by-light scattering

* PbPb boosts ALPs production (flux∝Z^4)
* extremely clean event signatures



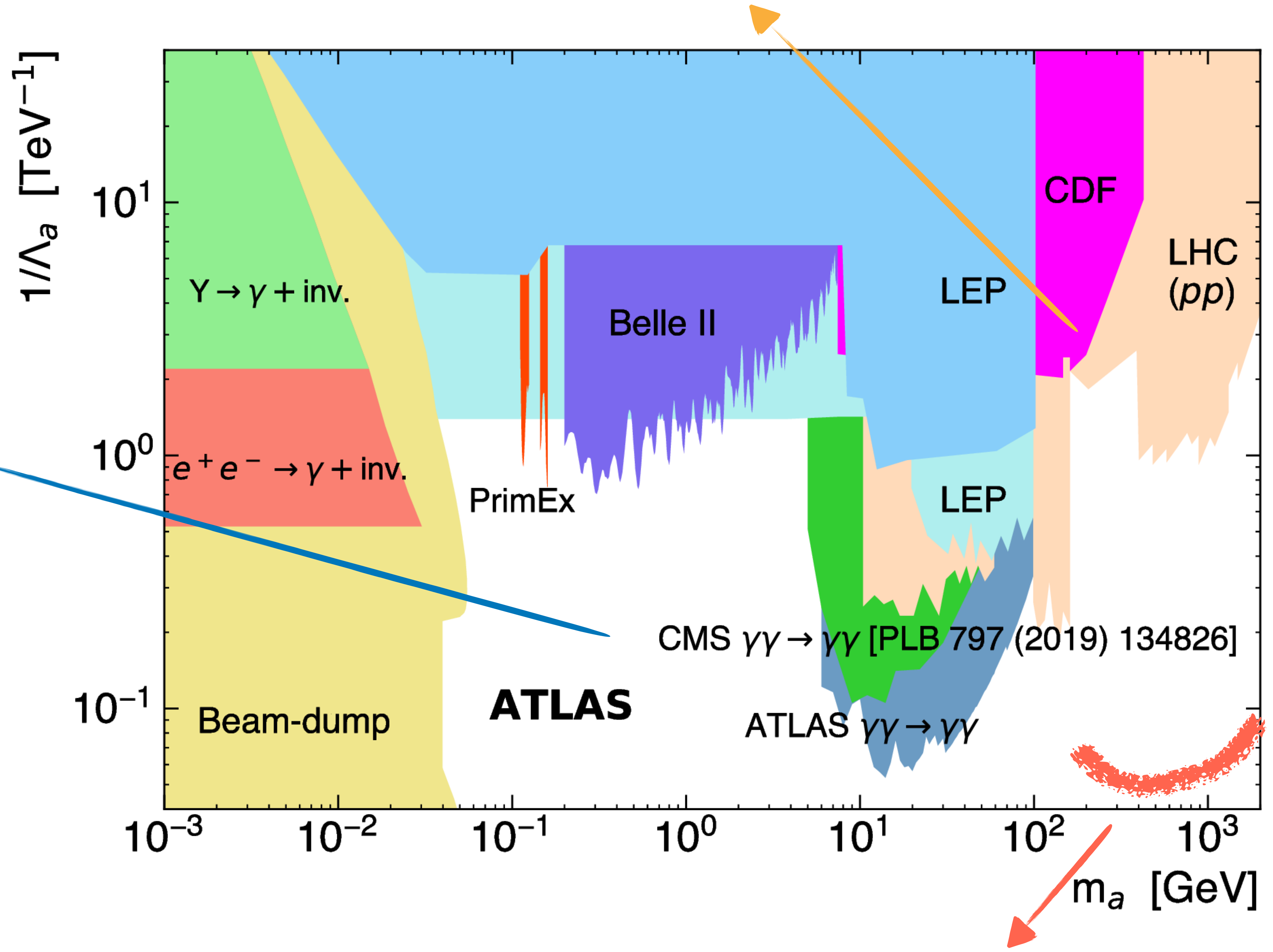
Proton tagging

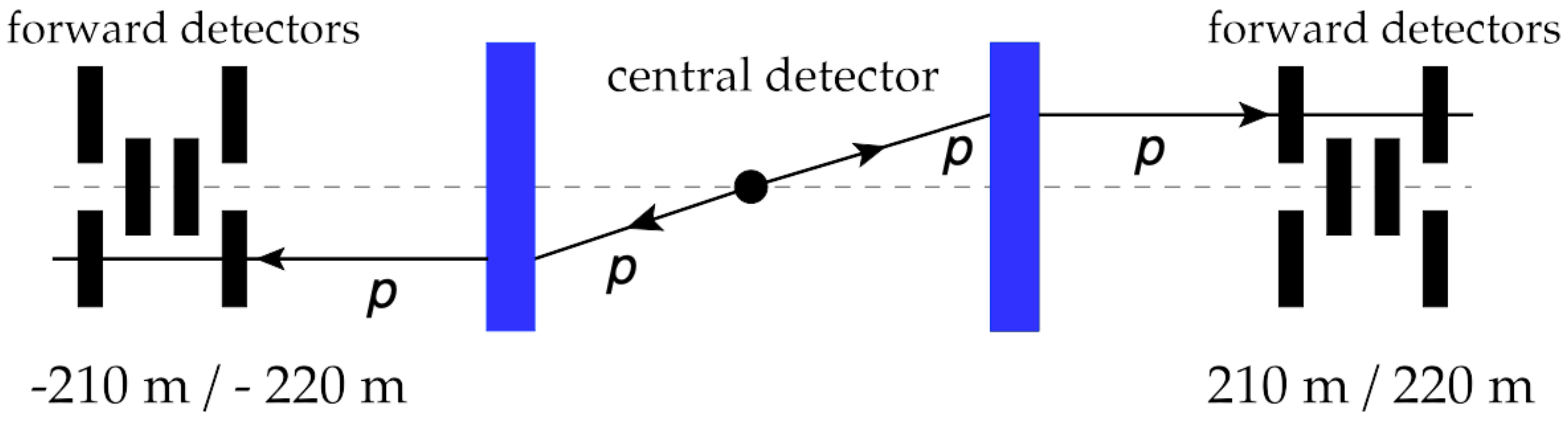
* 2 back-to-back photons + proton in AFP
  * exploiting fwd detectors (AFP/TOTEM) at ~200 m
  * proton energy loss ~ production energy

Higgs production

* constraints down to m_a~0.1 GeV in h→aa/Za w/ LLP scenarios

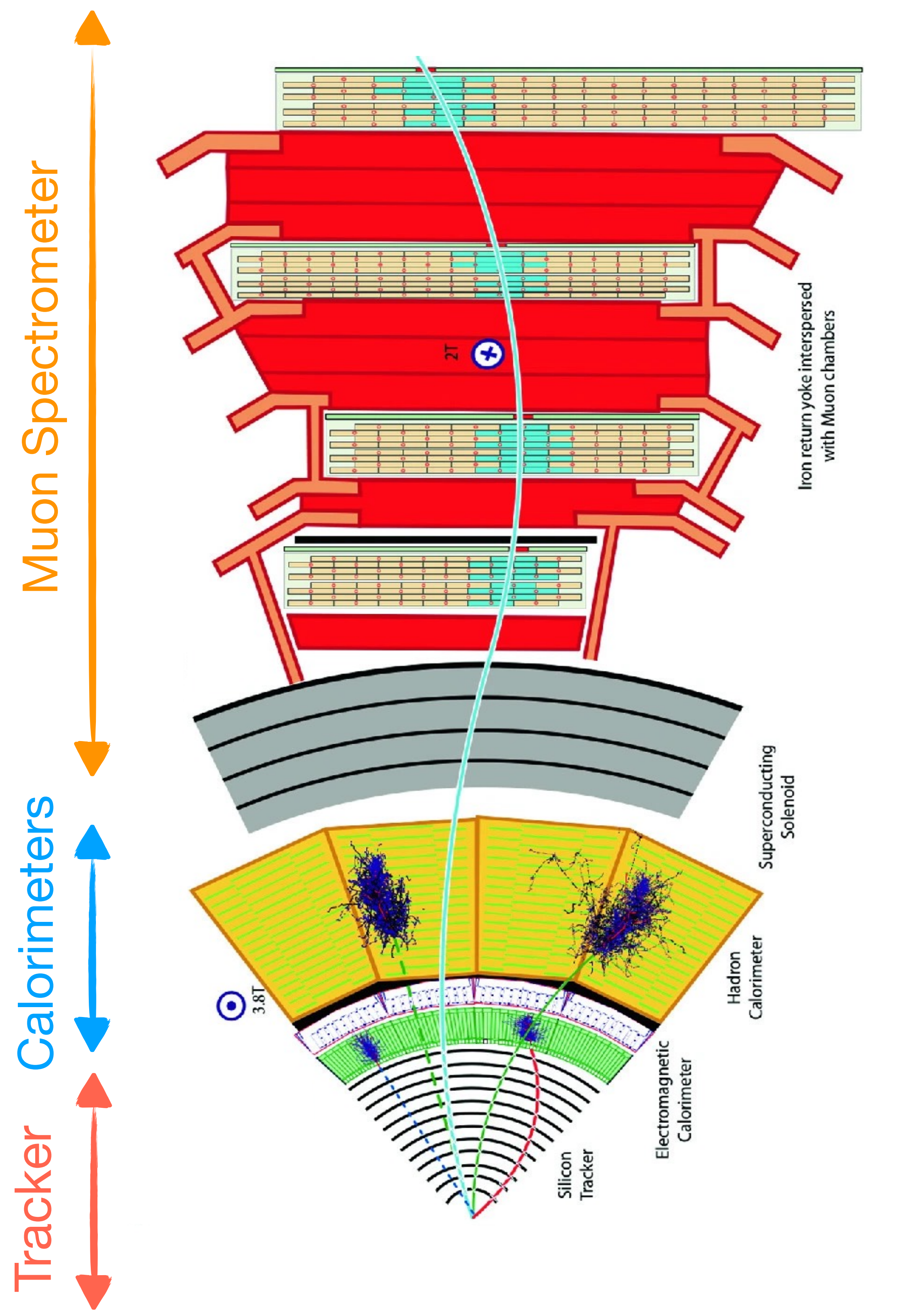
γγ resonant searches



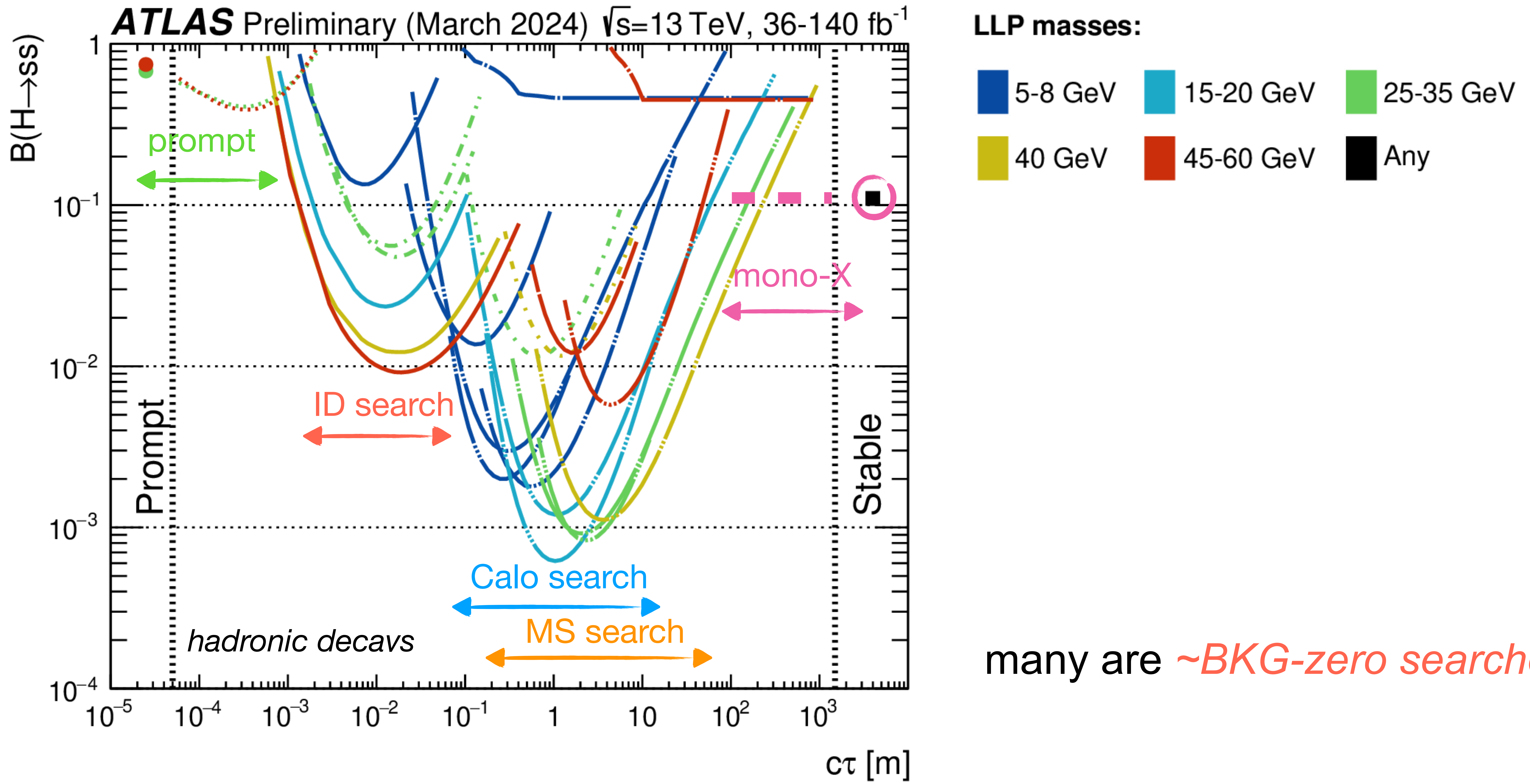


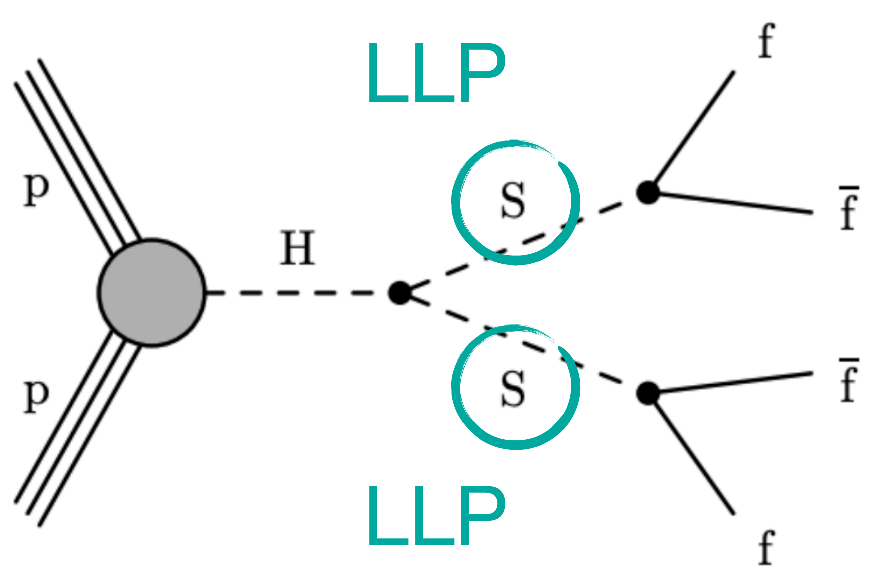
Long-Lived particles

Exploiting all subdetectors at their full potential



ATLAS LLP summary plot





many are *~BKG-zero searches*

LLPs in ID

DV in the ID: CMS-PAS-EXO-23-013, ATL-EXOT-2021-32
displaced leptons: ATLAS-CONF-2024-011, CMS-EXO-23-014
CMS B-parking: CMS-EXO-22-019

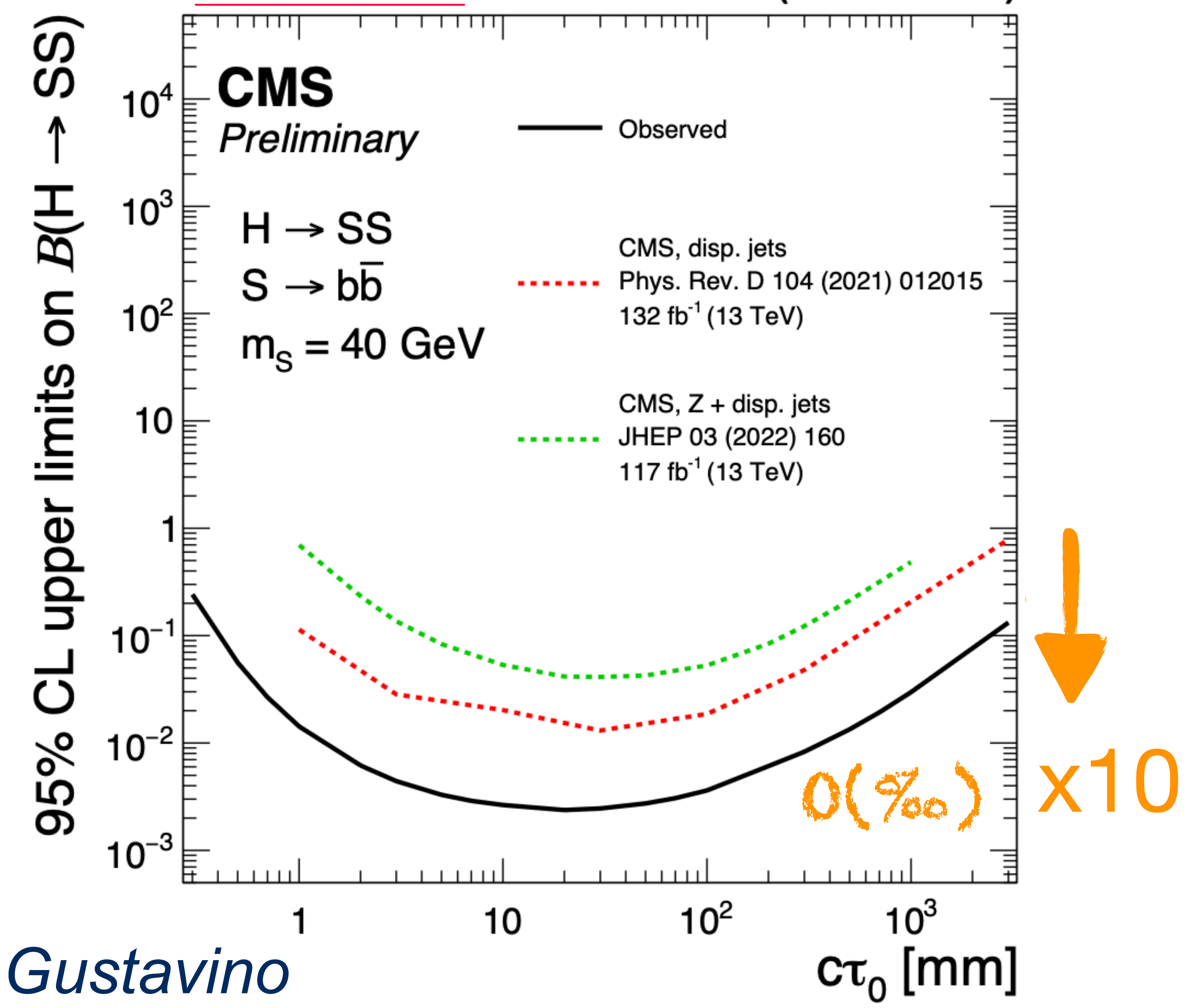
HUGE progresses on tracking algorithms both online and offline @ Run-3

DV in the ID NEW

- reconstruction algorithms
- dedicated triggers
  - even w/ b-enriched decays

➡ *recent x10 improvements w/ 1/4 of the Run-2 stats*

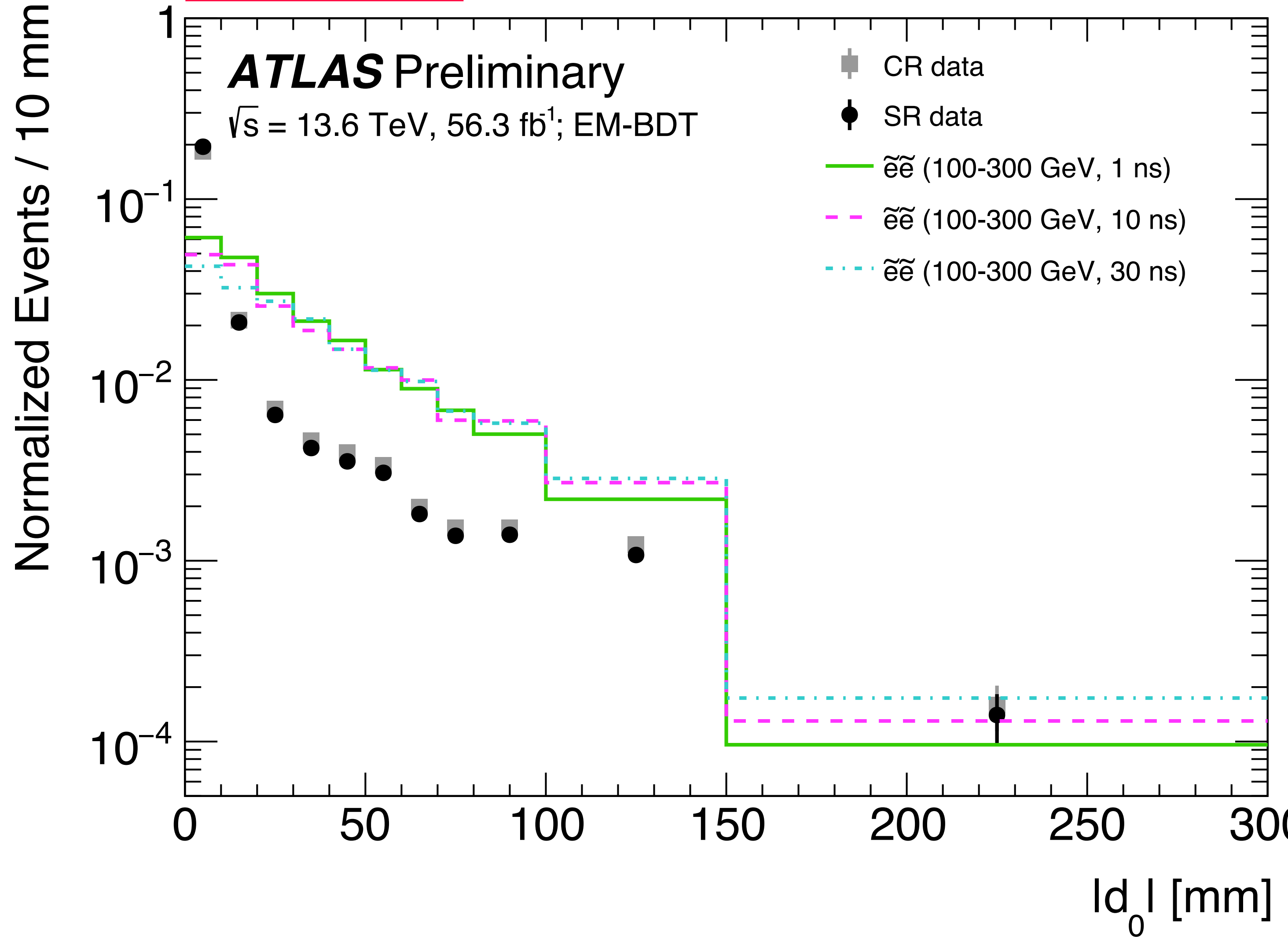
RUN-3



Displaced leptons NEW

- new large-radius objects based on displaced tracks *@ the trigger level*!
- new low muon p_T triggers w/ relaxed parameter impacts

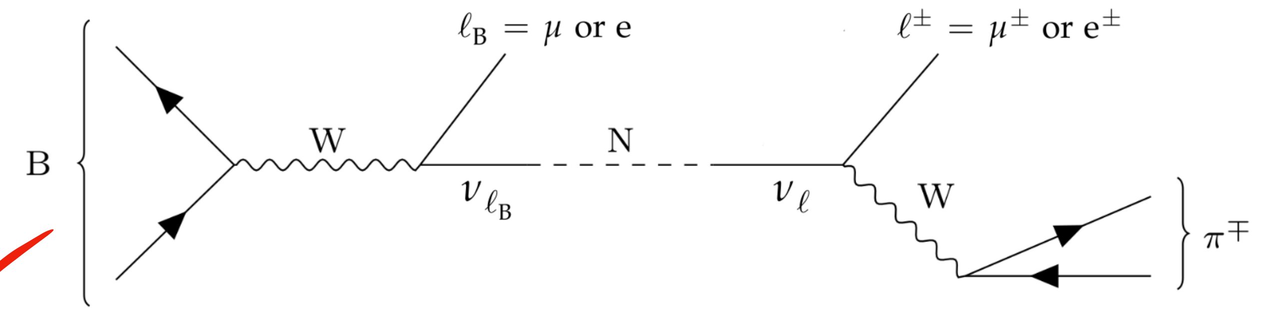
RUN-3

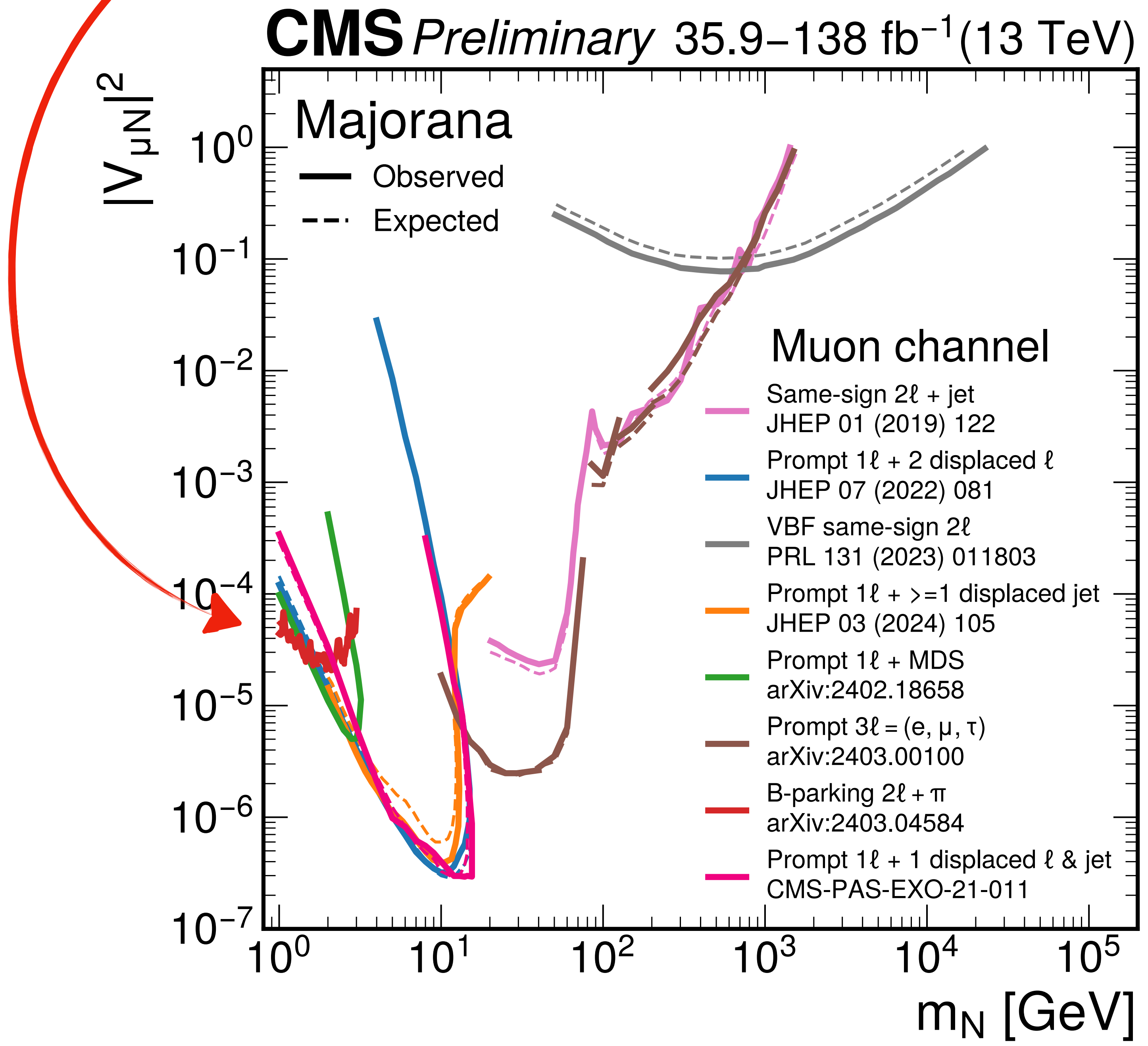


B-parking NEW

O(10B) events

➡ DV with lepton + track





LLP in calorimeters

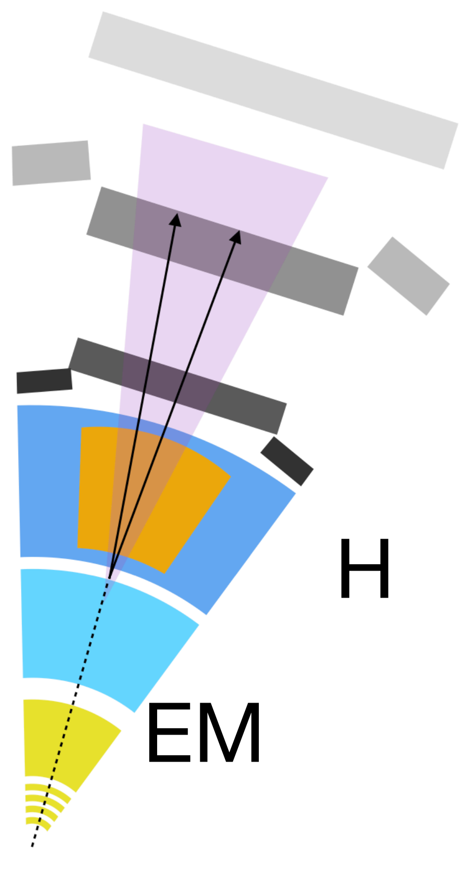
ATLAS displaced jets: EXOT-2022-04 JHEP 06 (2022) 005

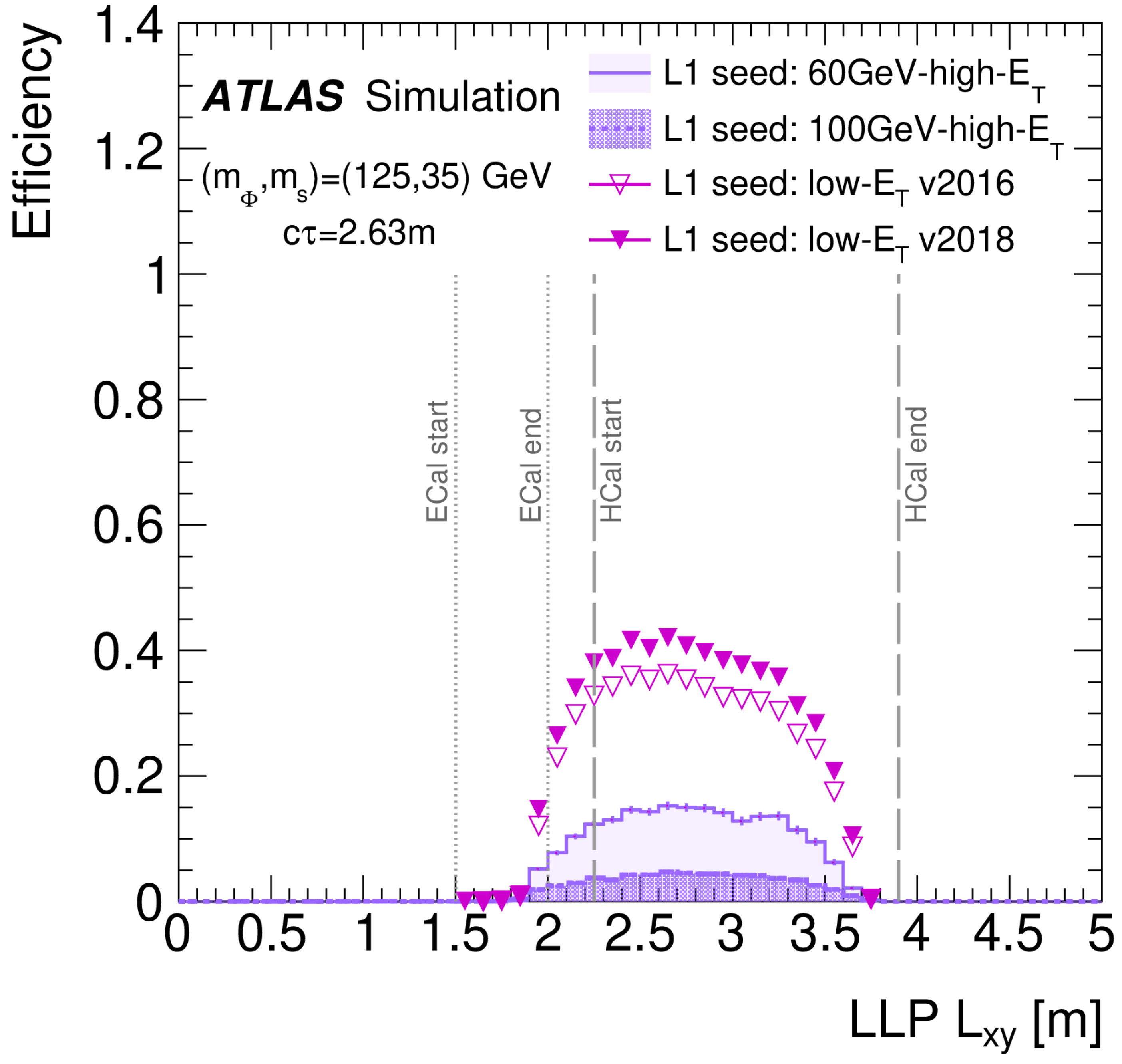
CMS displaced jets: PLB 797 (2019) 134876

Non-pointing photons: CMS-EXO-19-005, ATLAS-SUSY-2020-28

Trackless jets

exploiting E_H/E_{EM}





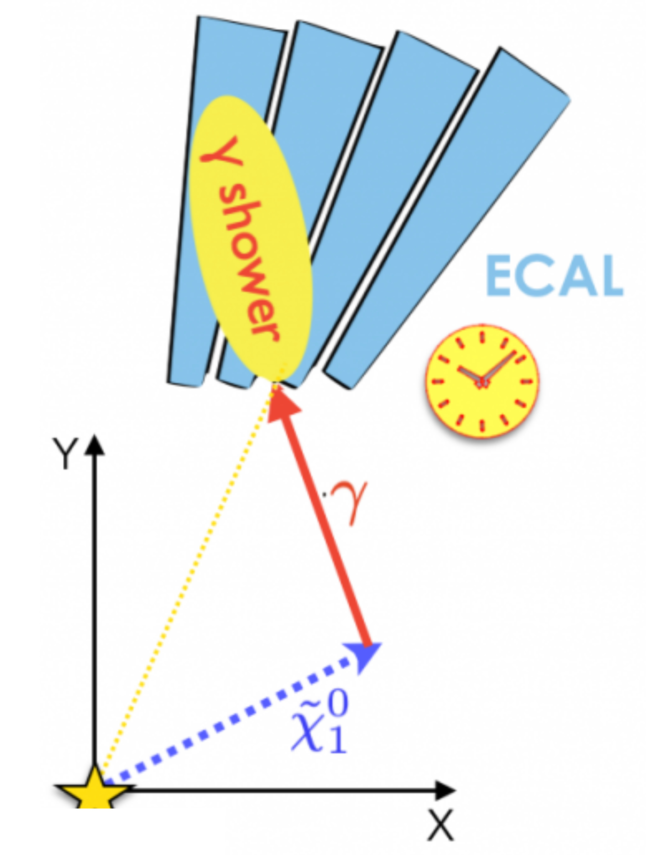
Associated production for triggering and access low-mass/boost regions

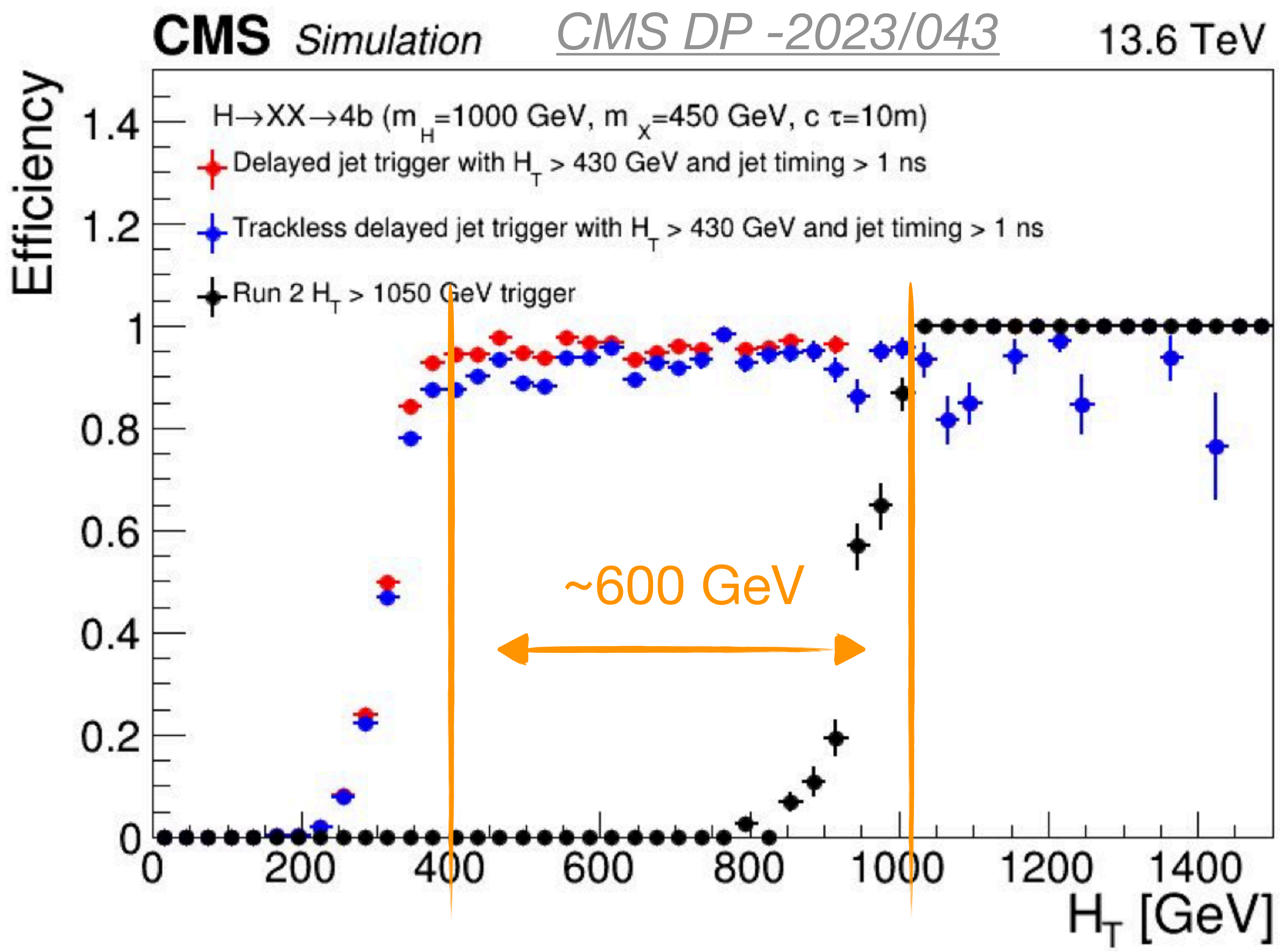
- x3 improvements

Timing

- **Non-pointing photons**
  EM calorimeter segmentation & time resolutions

- new triggers exploiting **jet timing**





LLP in MS

Large fiducial volume with air gaps

* **reconstructing displaced tracks & vertices**

* Dedicated **Trigger**
  - multiple ROIs
* Dedicated **Vertex algorithm**
  - multiple tracklets in MDTs

Compact spectrometer with lots of steel

* **used as a sampling calorimeter**
  searching for shower decays

* High cluster reconstruction
  - > 50 hits with ε up to 80-90%

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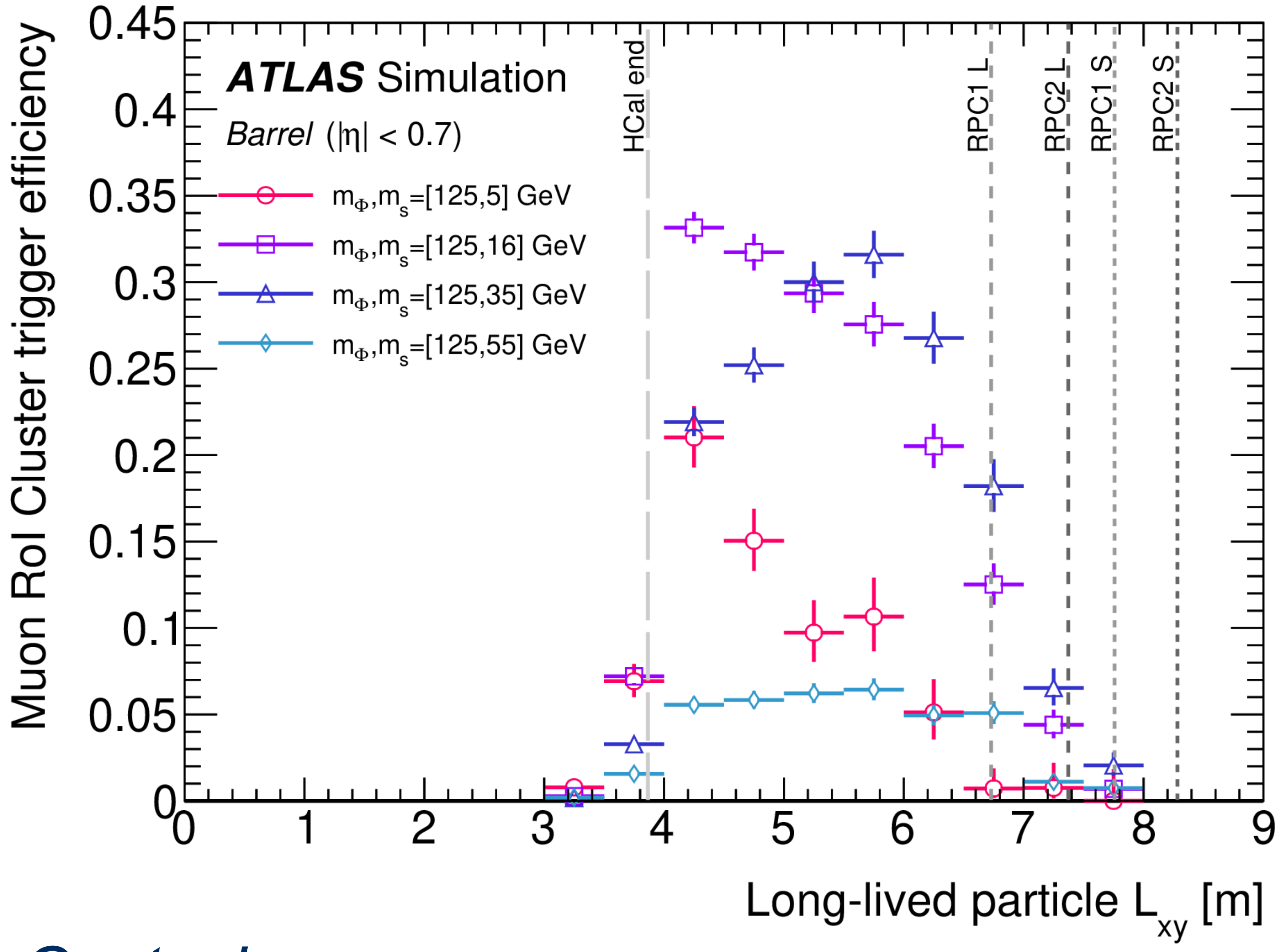
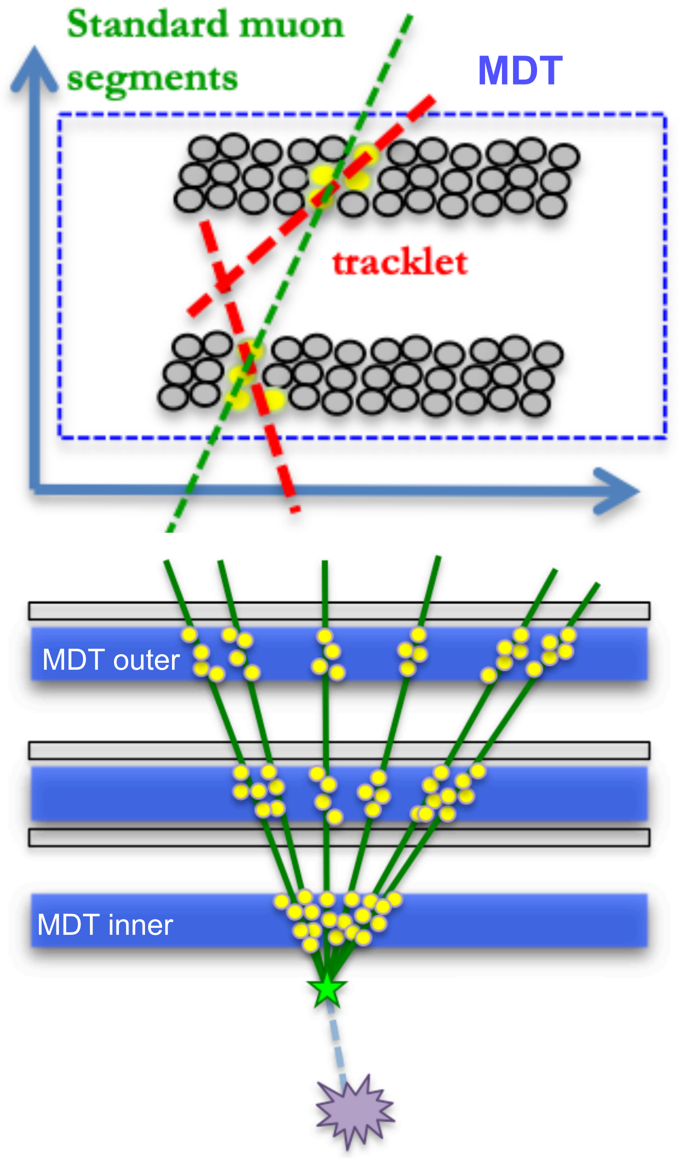
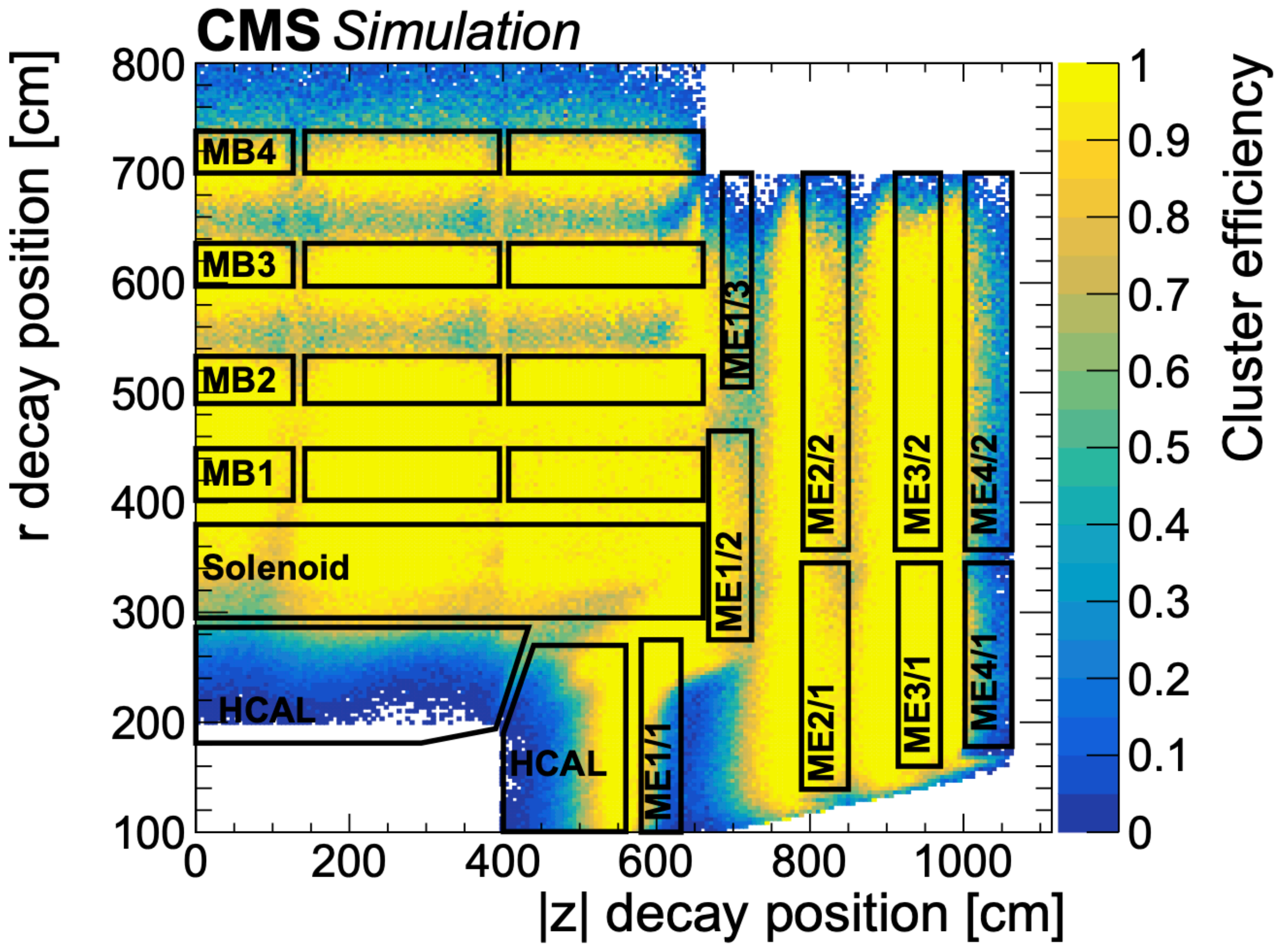
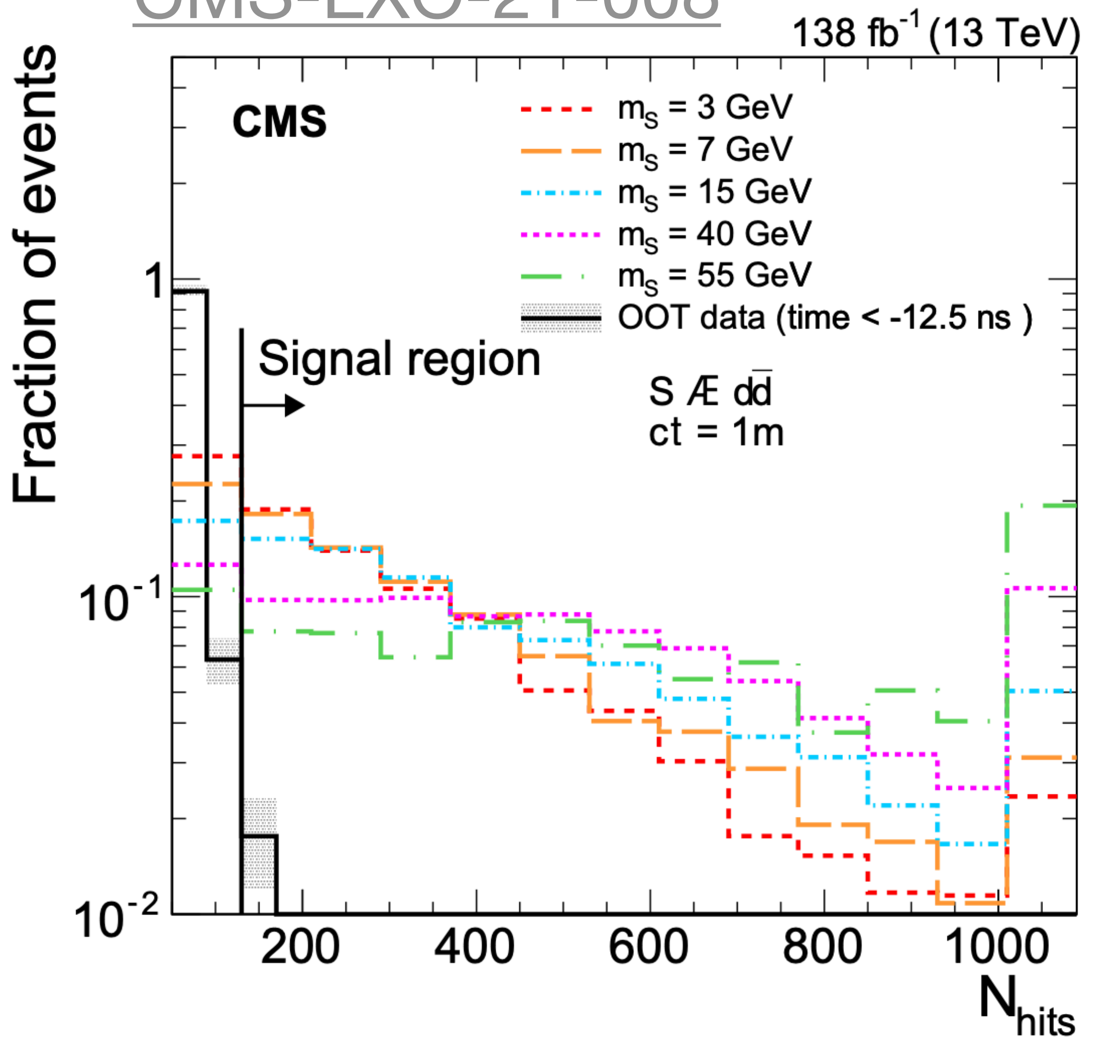






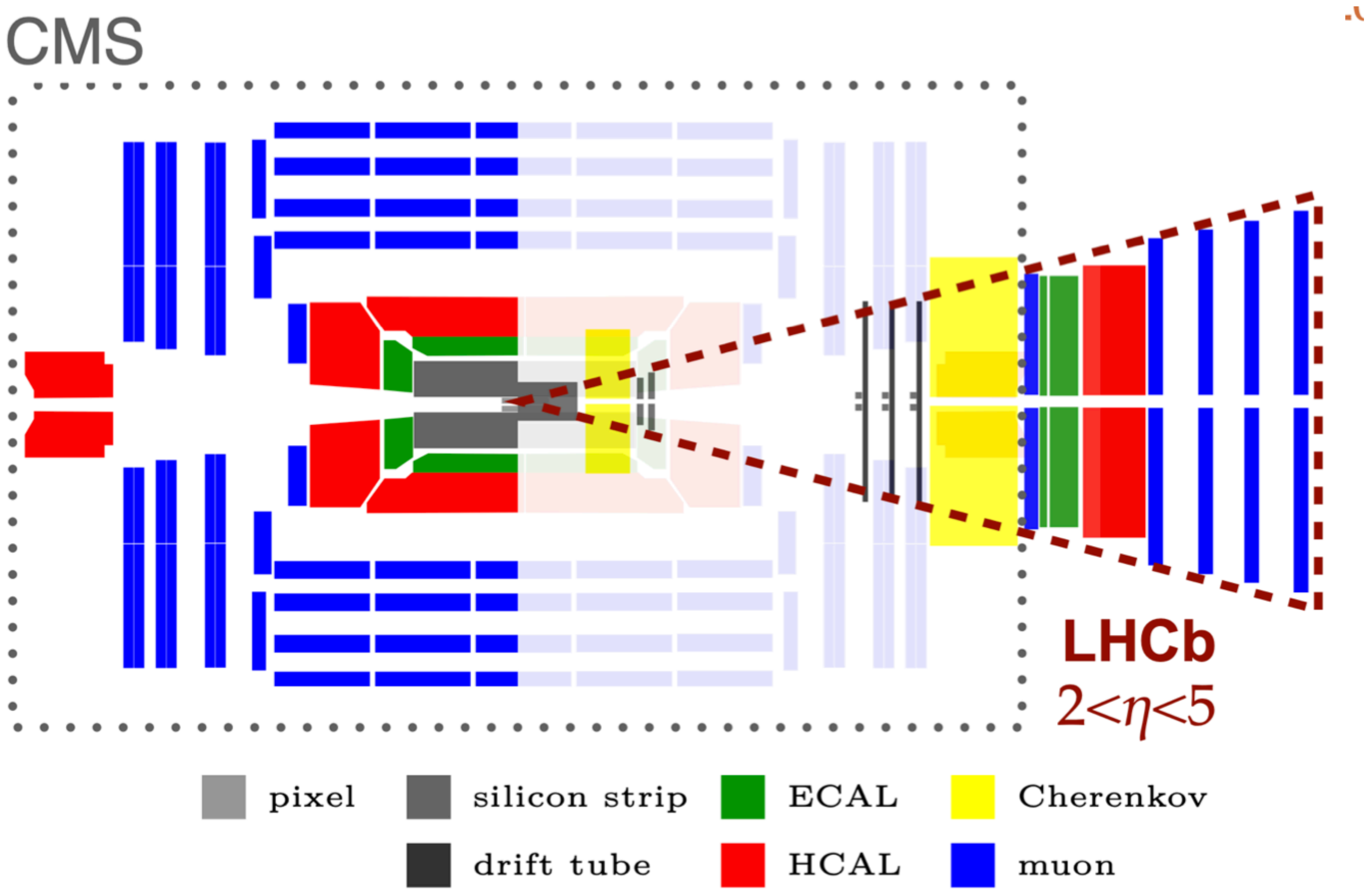
CMS-EXO-21-008



LLP in Forward Region

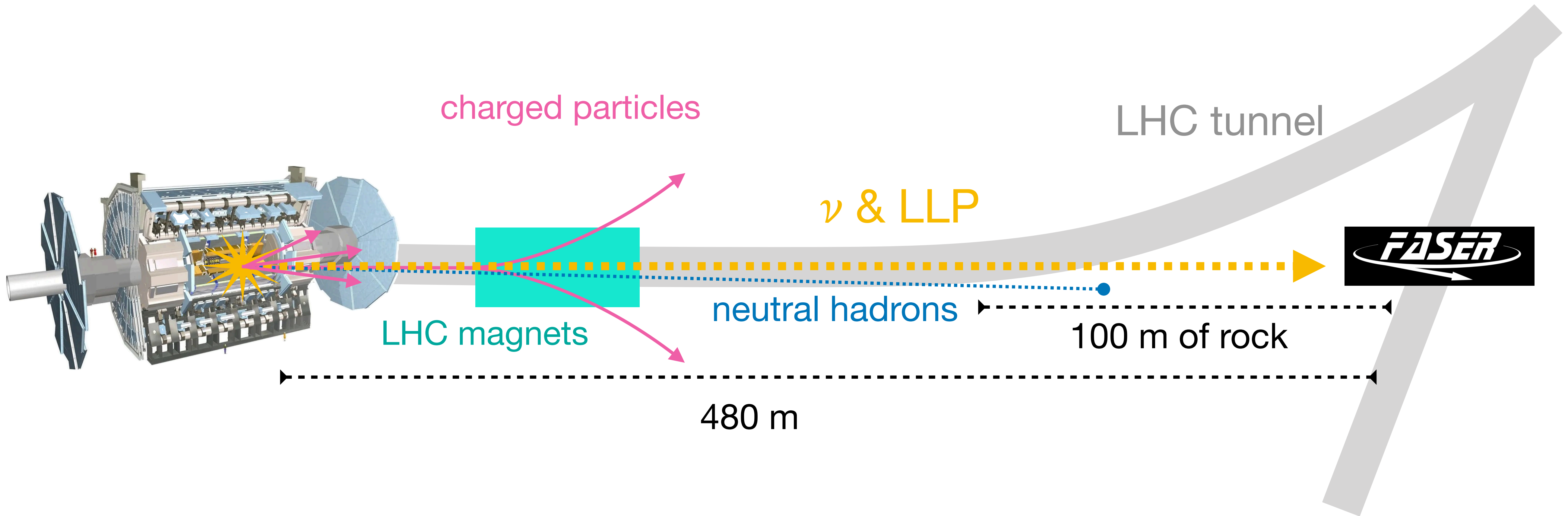
Forward region: high/low-x partons involved

competitive at low cτ & low masses



Forward LHC experiment designed to detect
light and weakly interacting particles

- Situated 480m downstream of the ATLAS IP



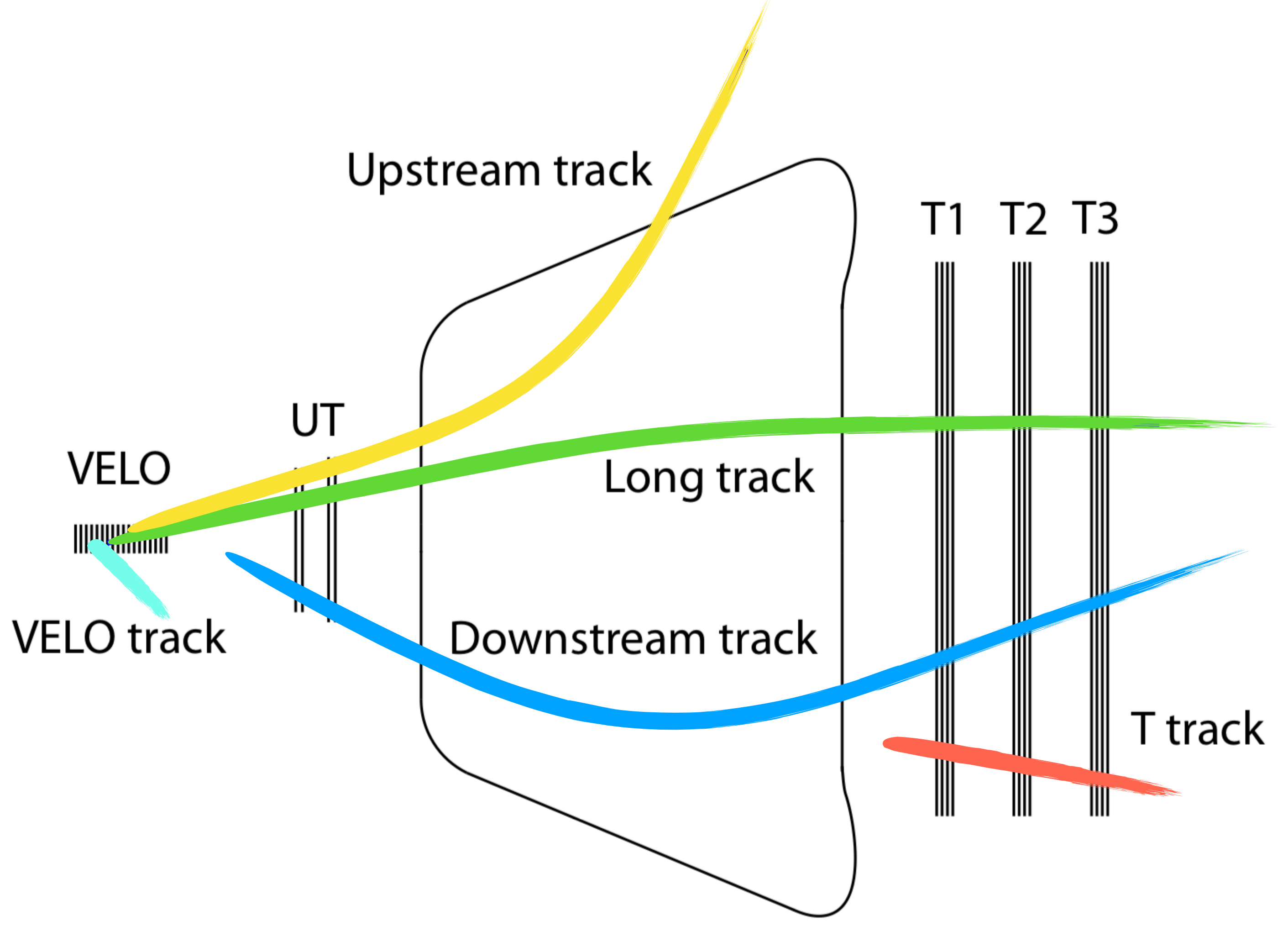
G. Gustavino

LLP in Forward Region

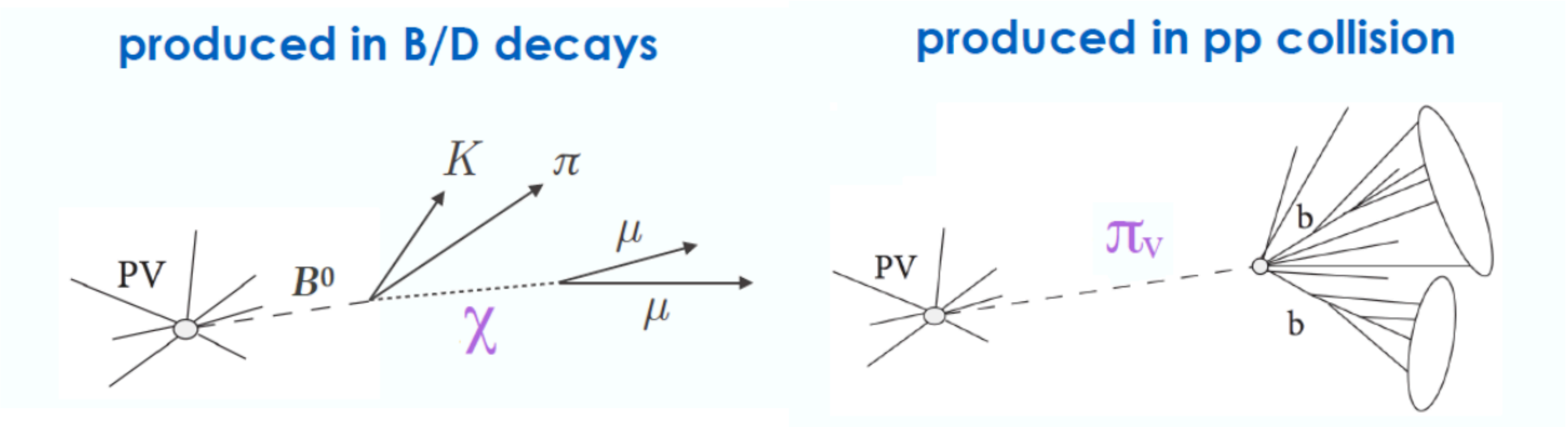
Forward region: high/low-x partons involved

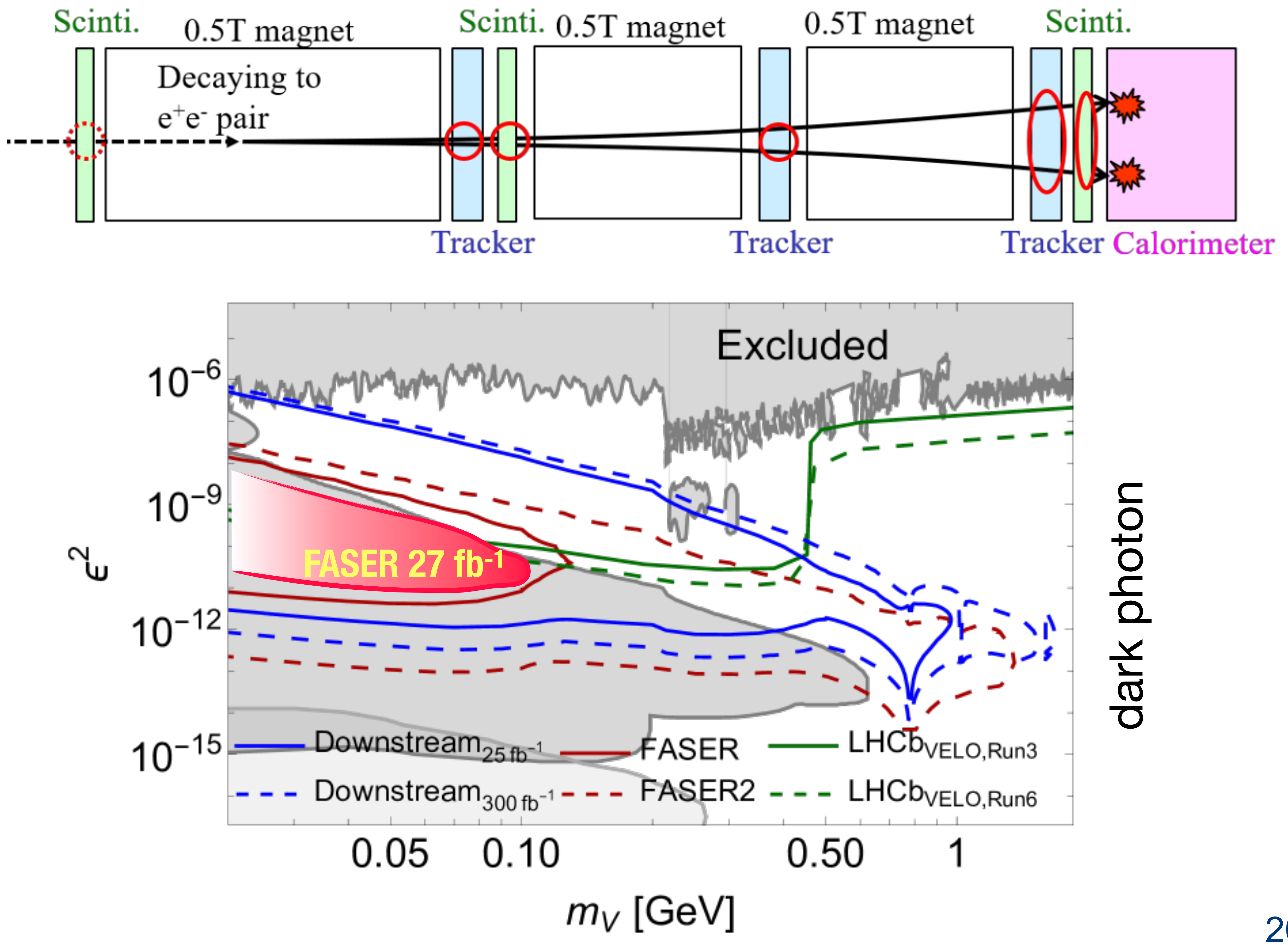
MAX displacement:

Long ~ 1m
Downstream ~2m
T tracks ~8m



- can trigger on downstream tracks [1]
- effort to extend searches with T tracks [2]



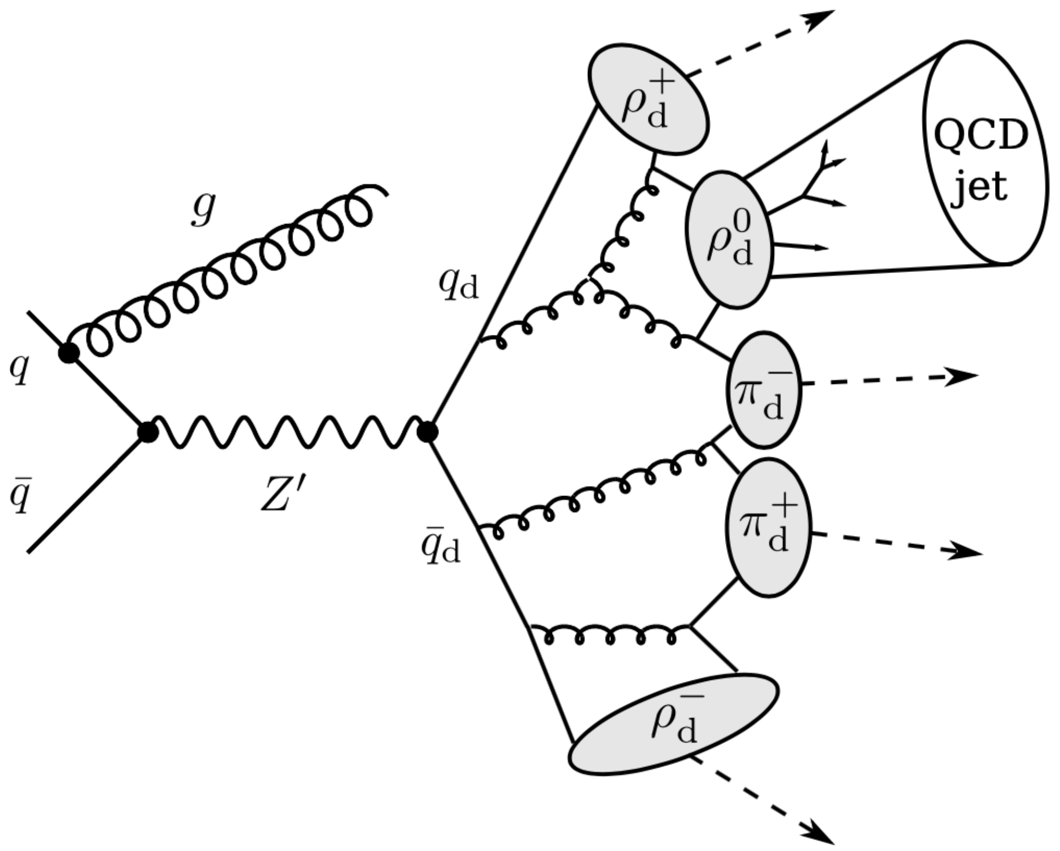


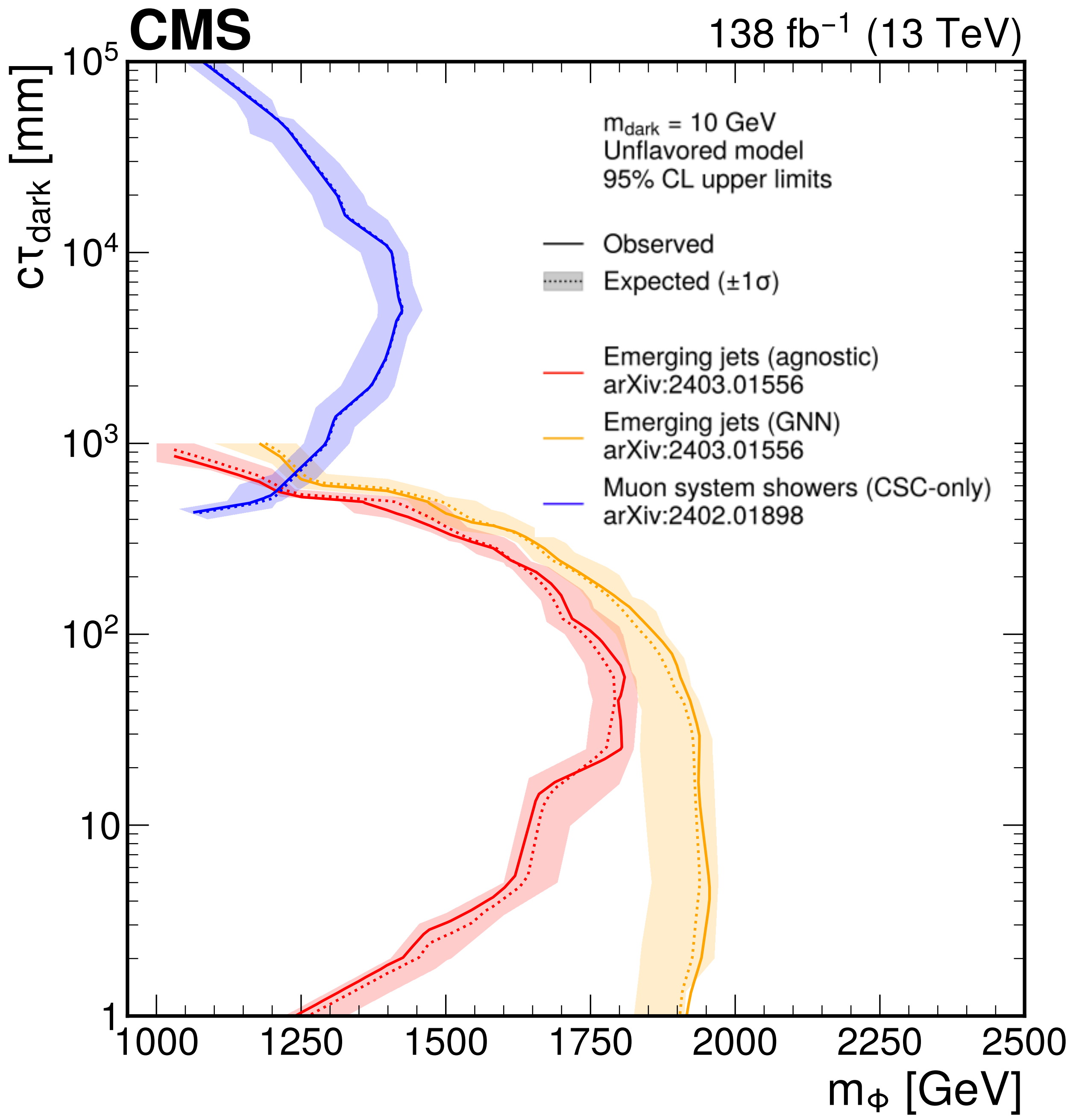
Dark showers

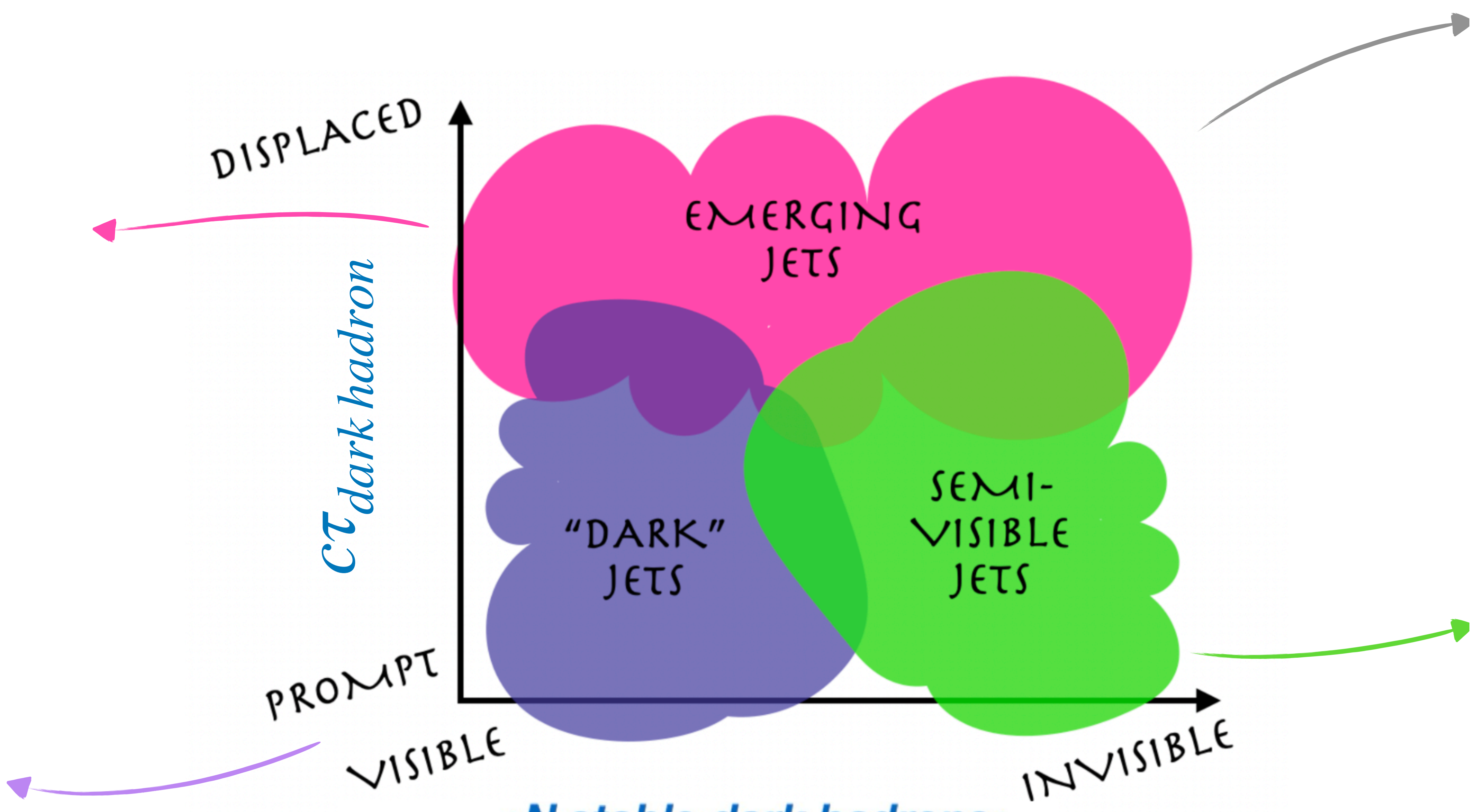
ATLAS dark jet: HDBS-2018-45
ATLAS SV jets: EXOT-2022-3
CMS SV jets: EXO-19-020
CMS emerging jet: EXO-22-015
CMS SUEP: EXO-23-002
ATLAS dark mesons: EXOT-2023-09

Strongly interacting dark sector → **dark-QCD**

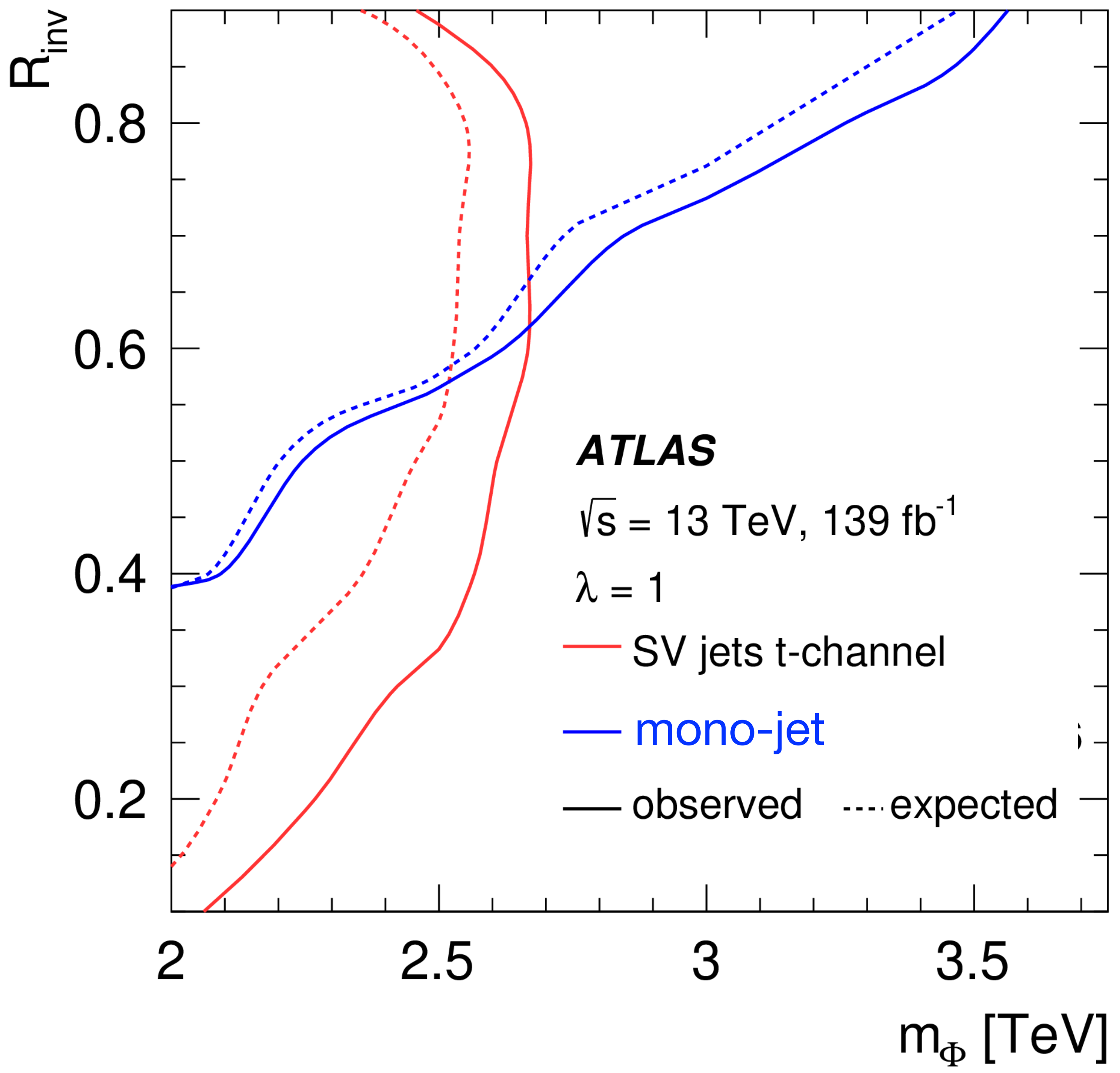
- dark quarks lead to dark hadron showers
  - dark hadrons (DH) can couple to SM







$$r_{inv} = \left\langle \frac{\text{N stable dark hadrons}}{\text{N dark hadrons}} \right\rangle$$



NEW Dedicated EJ triggers

NEW SUEP (N_{cD}>>1)
- high multiplicity of isotropic tracks

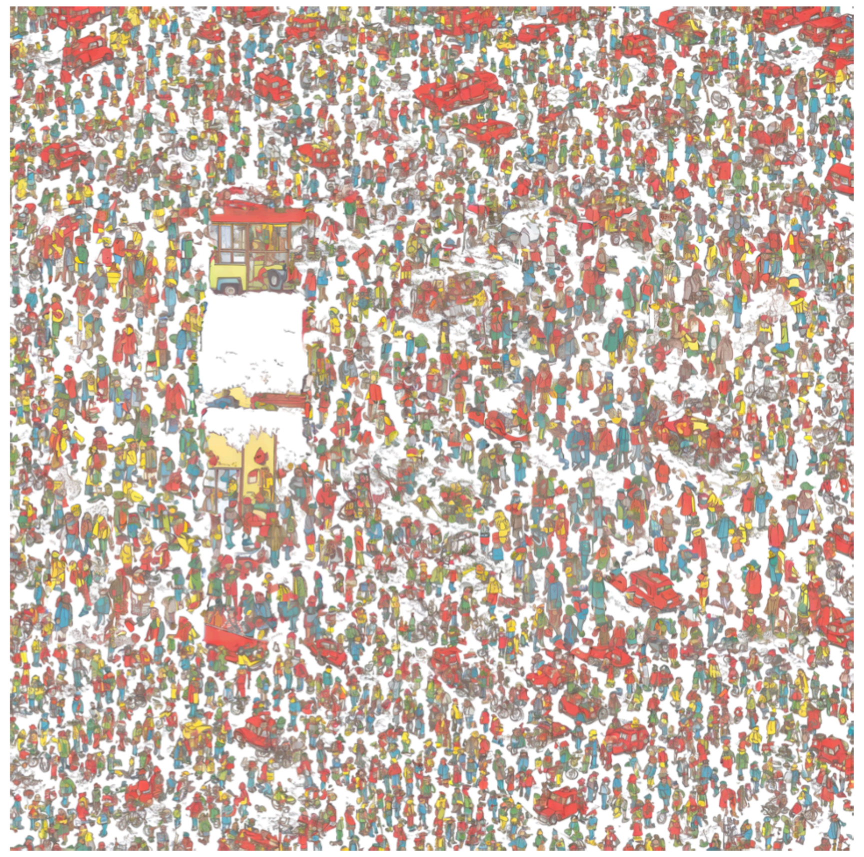
NEW Dark meson w/ flavoured decays
- large-R jet w/ flavoured constituents

Anomaly detection

CMS-PAS-EXO-22-026

Building a **model-agnostic approach**!

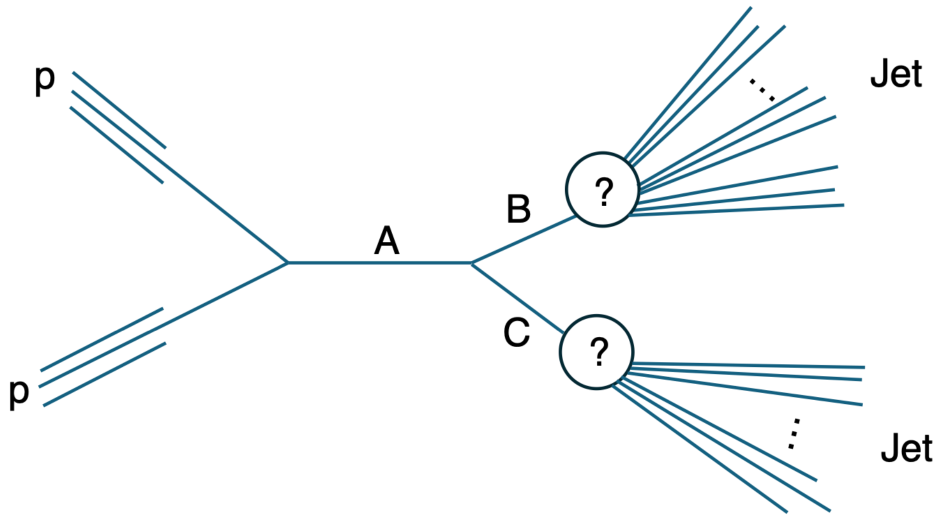
- unsupervised or semi-supervised learning
  - → **auto-encoders**



it's a "Where's Waldo" w/o knowing how Waldo looks like

Offline

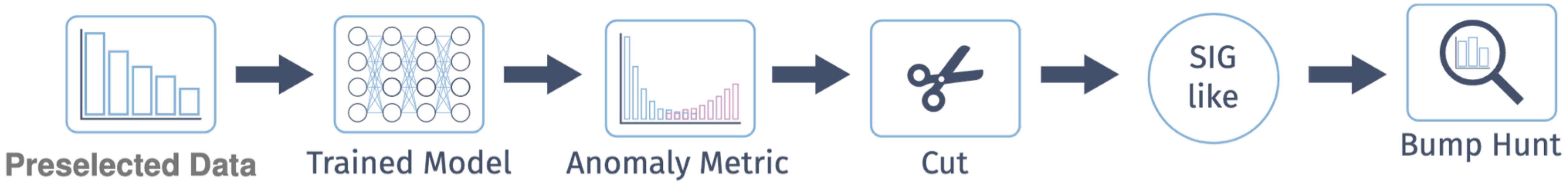
dijet resonances w/ anomalous jet substructure



different methods explored

learn standard jets and look for outliers (VAE)	train and classify signal vs bkg on data (w/o labels)	encode a prior of BSM physics look for similar

model dependence →



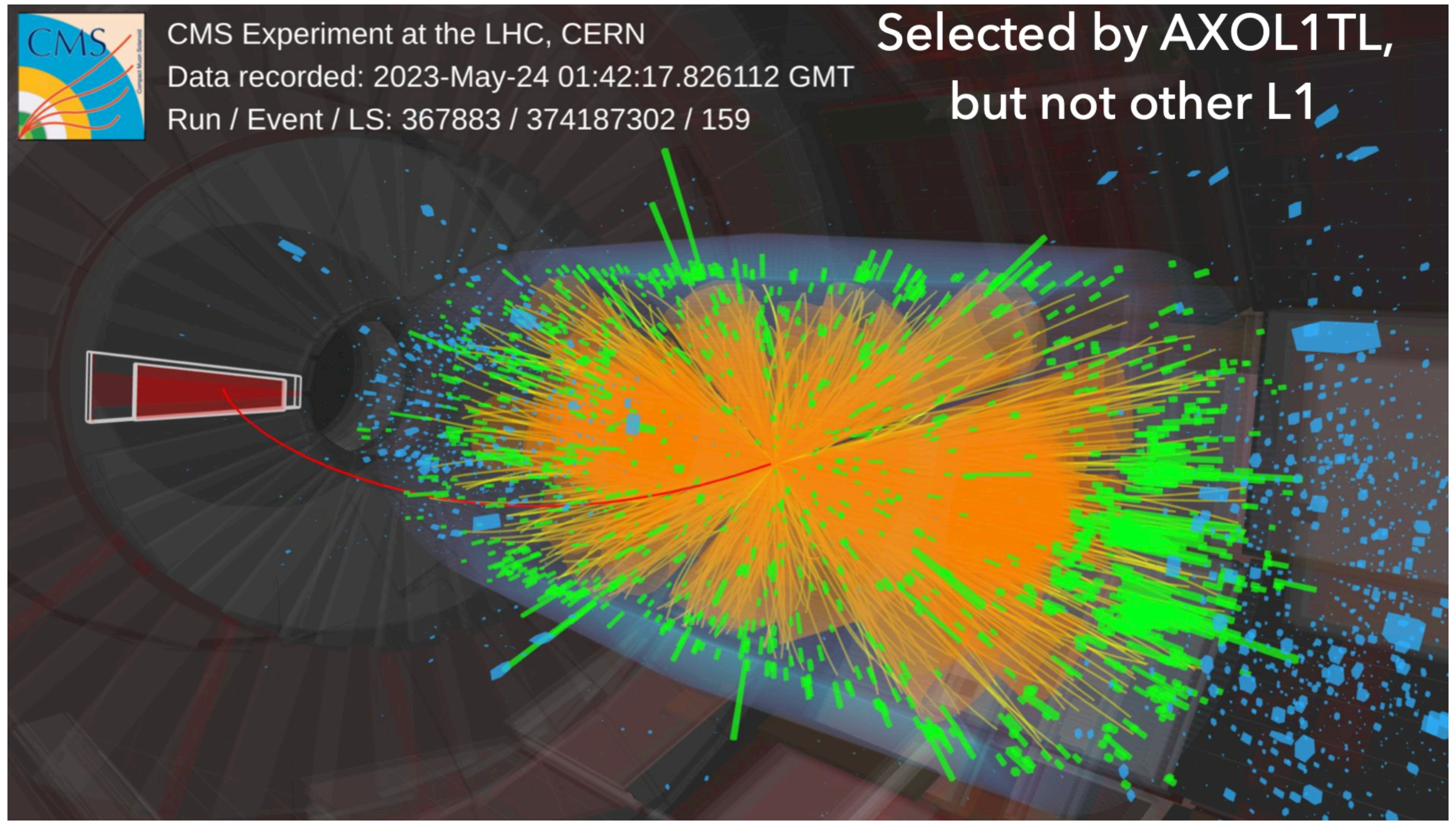
AD improves by 3 (7) wrt cut-based (inclusive) searches

Online

AE implementation @ **L1 trigger**

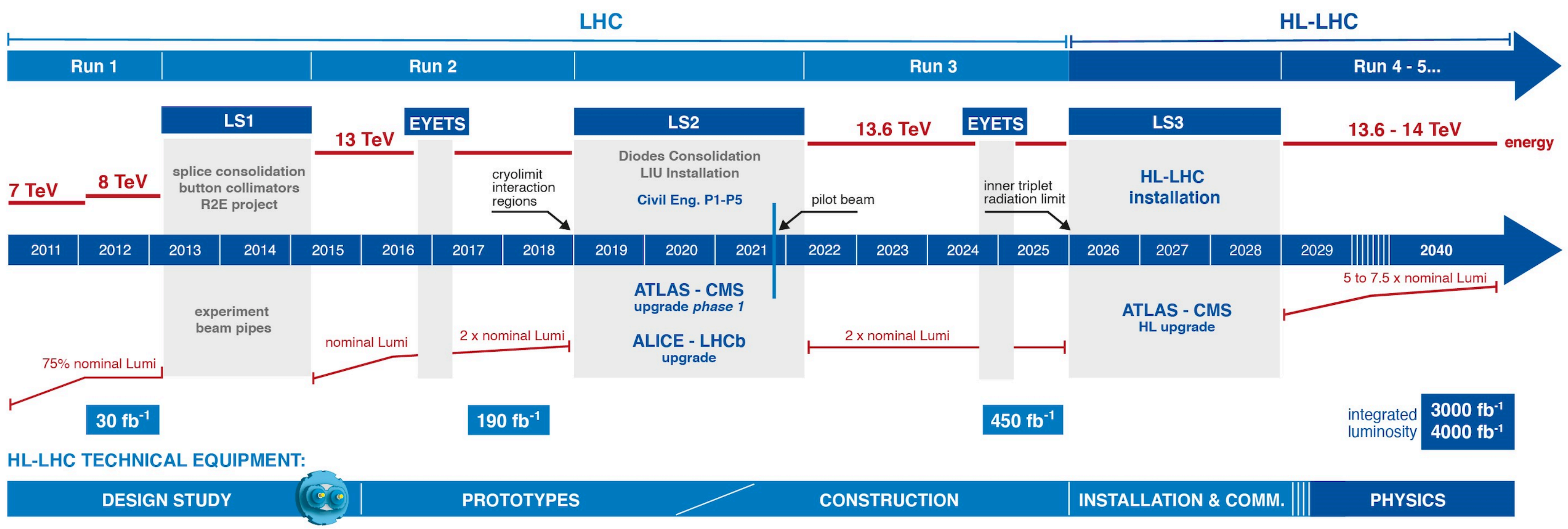
AXOL1TL [1] — event-level AE

CICADA [2] — CNN AE on CaloTowers



HL-LHC

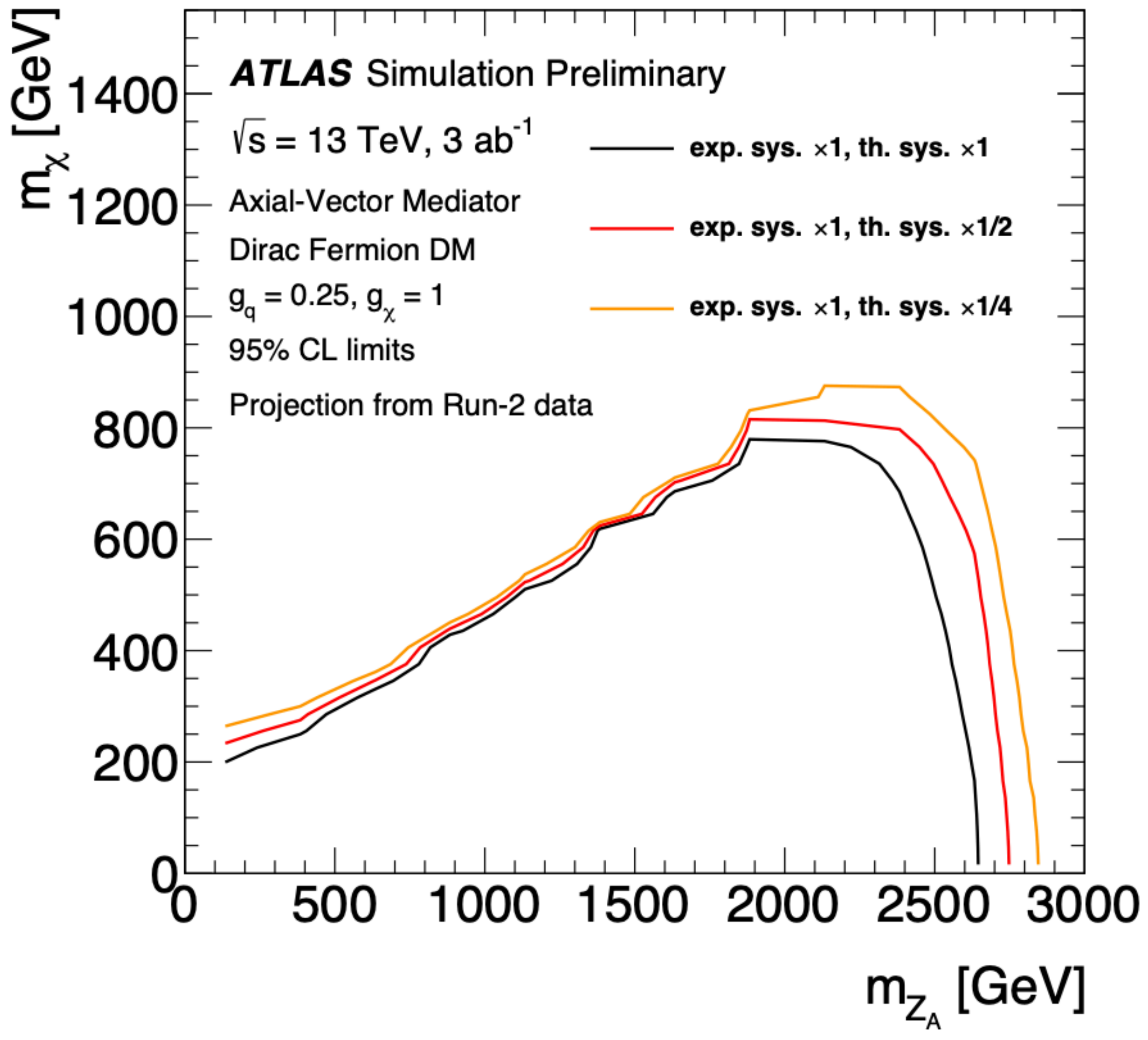
- 3000 fb^{-1} of data to both ATLAS & CMS
- $\sqrt{s}$ = 14 TeV
- L = 7.5 x 10^{34} $cm^{-2}s^{-1}$
- up to 200 interactions/bunch-crossing



- O(10) more statistics
  - beneficial to stats limited searches
  - often lower experimental uncertainties
- new detectors
  - timing information
  - extended tracking
  - new trigger strategies

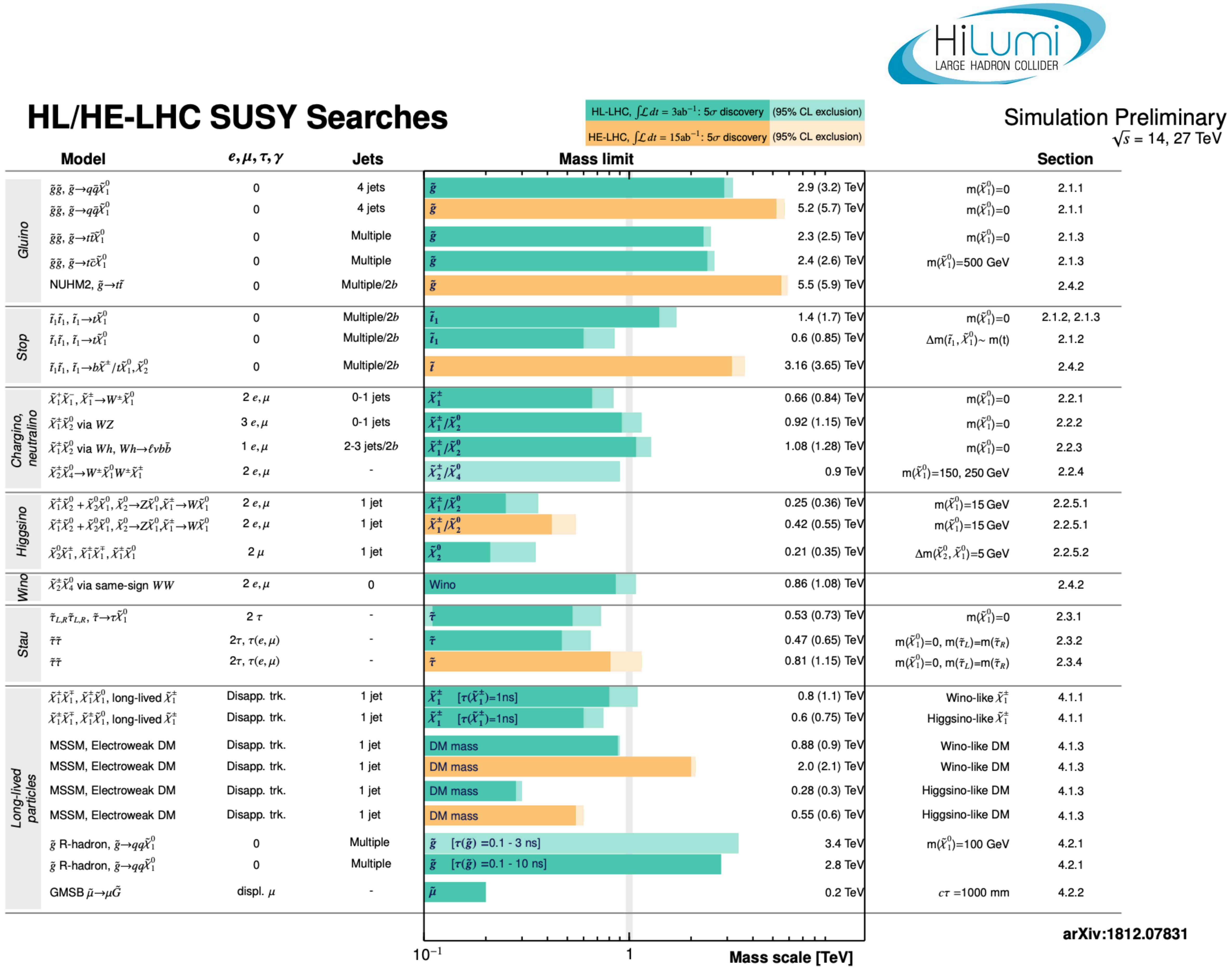
control of model and theoretical uncertainties is critical

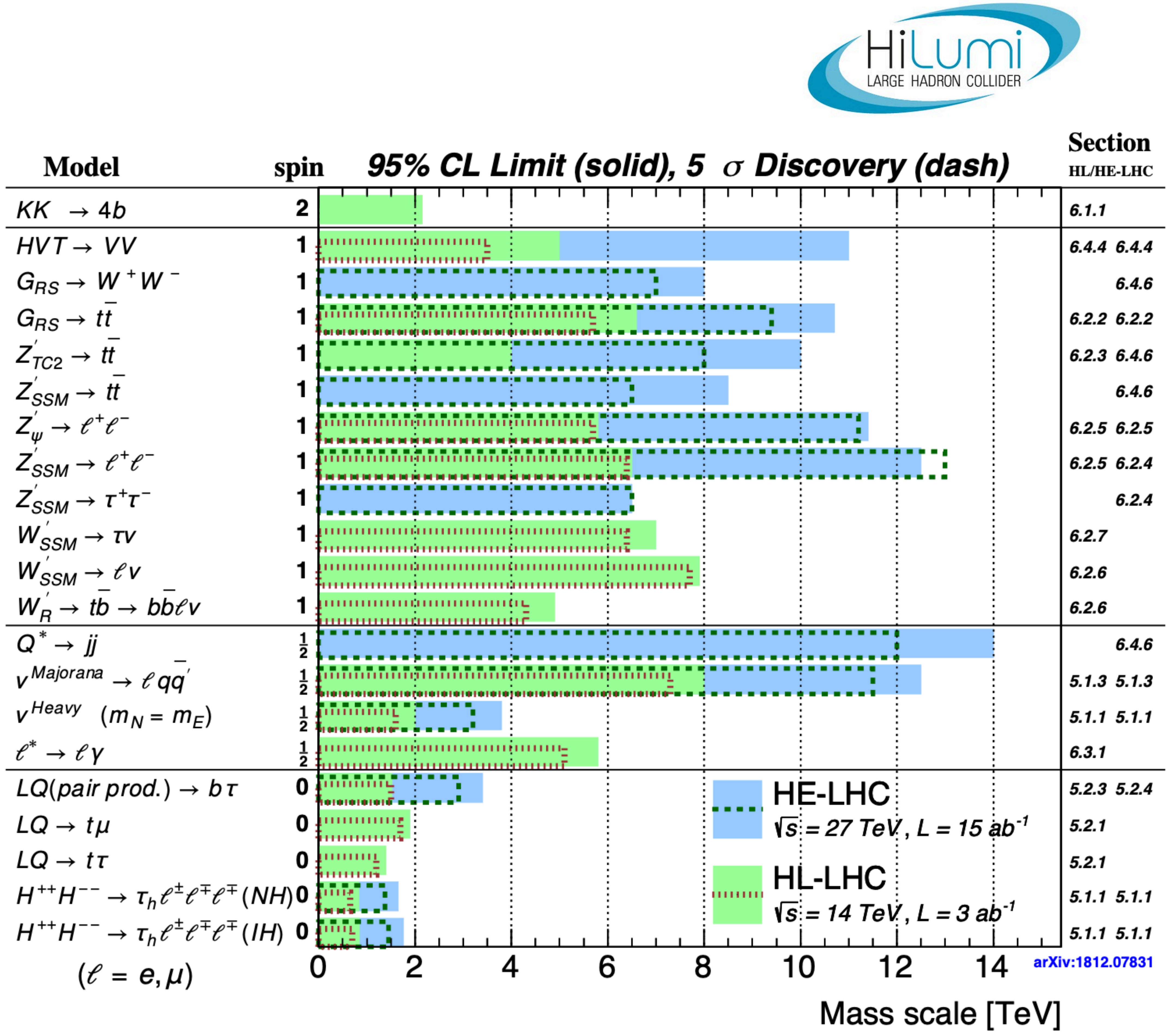
ATL-PHYS-PUB-2018-043



Reaches @ HL-LHC

[CERN Yellow Rep.Monogr. 7 (2019) 585-865]





Discovery potential increased by x1.5 to x2 times

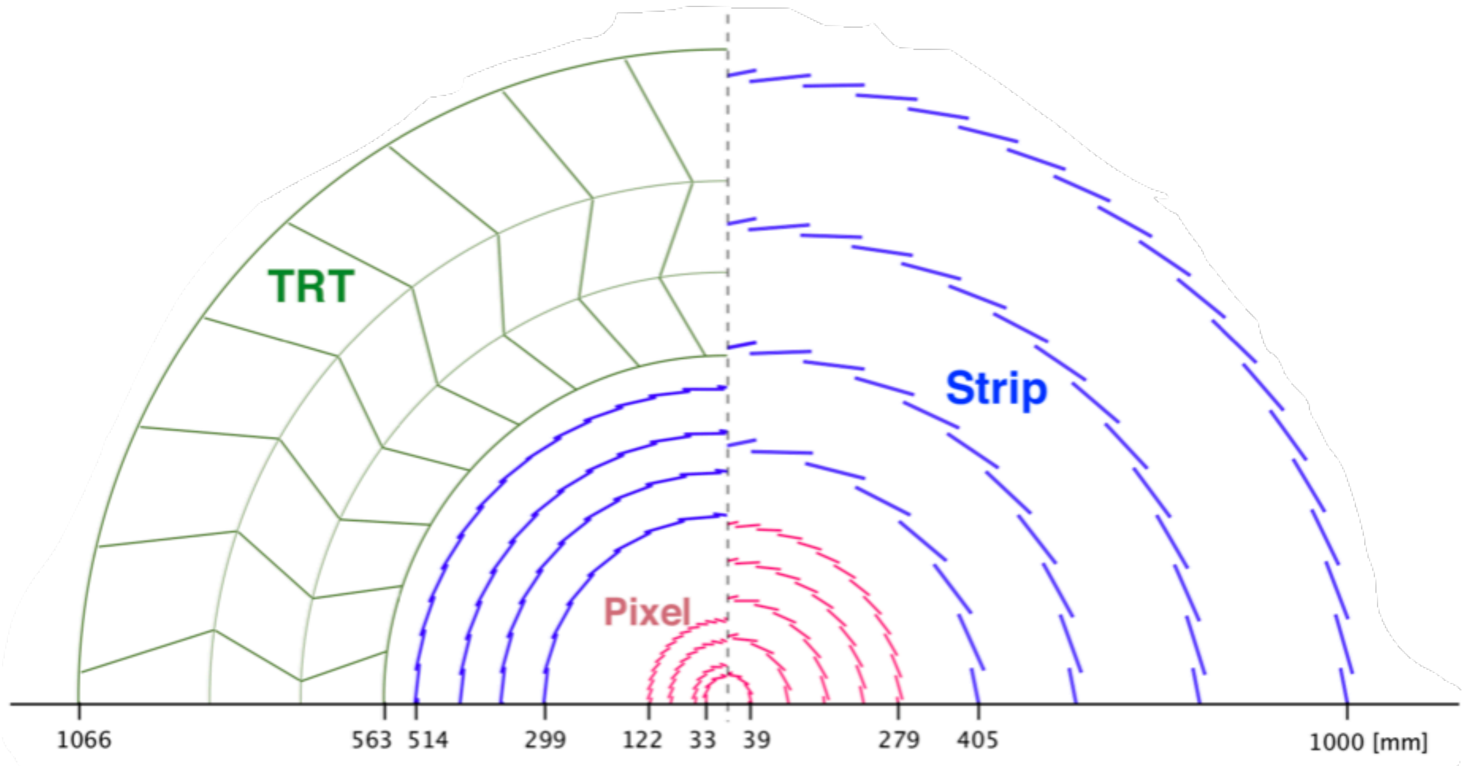
to be taken with a grain of salt!

we (likely) have already largely improved the baseline results used to produce the HL-LHC projections

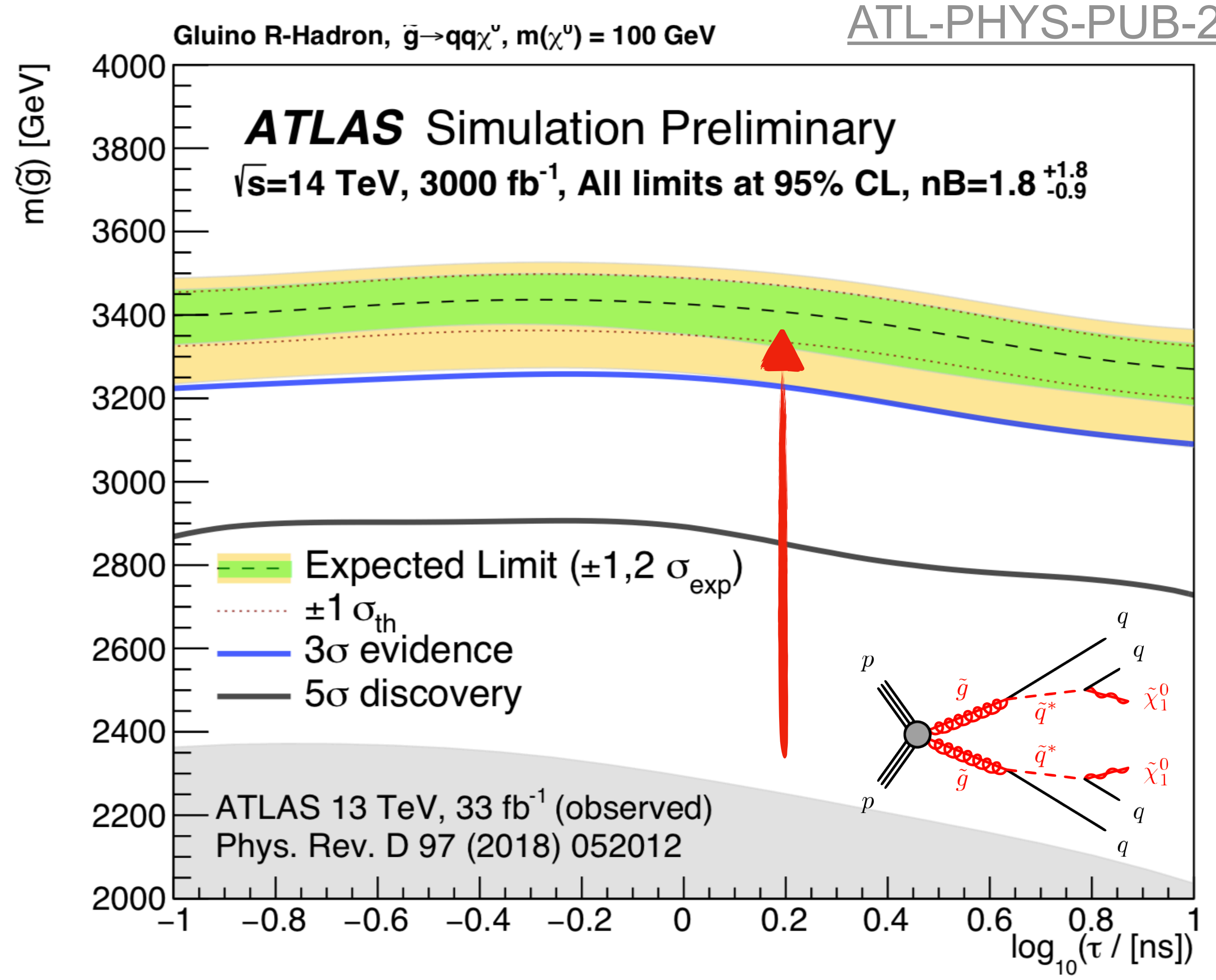
ID upgrade

Higher reco efficiency:

- improved geometry
- larger silicon volume
- lower material budget

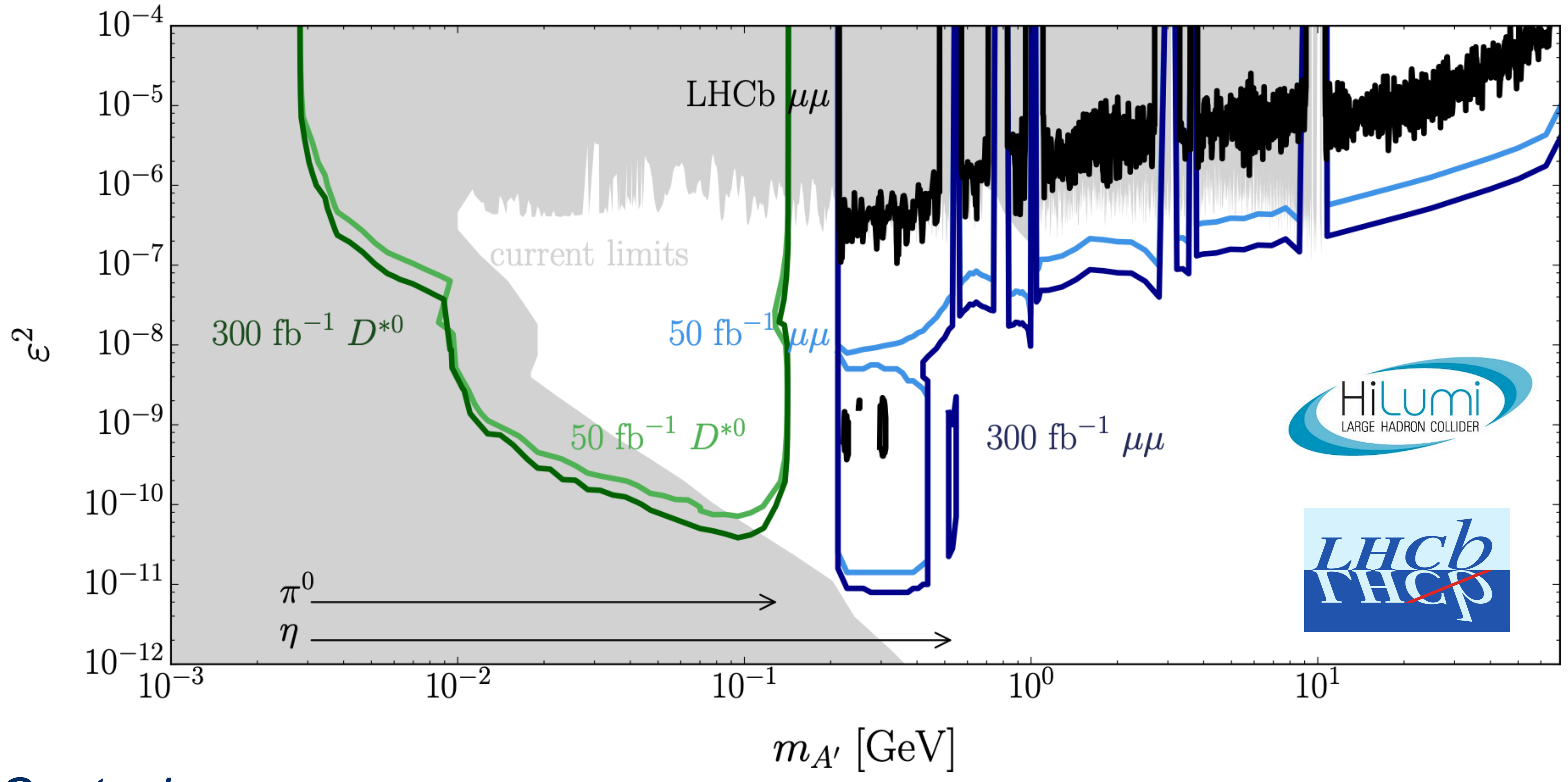


ATL-PHYS-PUB-2018-033



- More hits-on-track with higher resolution;
- **Tracker-based triggers** could further help to increase sensitivity

arXiv:1808.08865



Secondary vertex resolution, PID are keys

\+ real-time data-analysis with software trigger!

Prompt and displaced searches using D_0^* inclusive dimuon production (already in Run-3!)

$D^* \to D^0 A'$ (lower bkg)

$\pi^0/\eta \to A'\gamma$ (higher rate)

The time measurement

New timing detectors in all the big 4 @ HL-LHC

Precision timing helps to reject
- pile-up tracks
- spurious secondary vertices

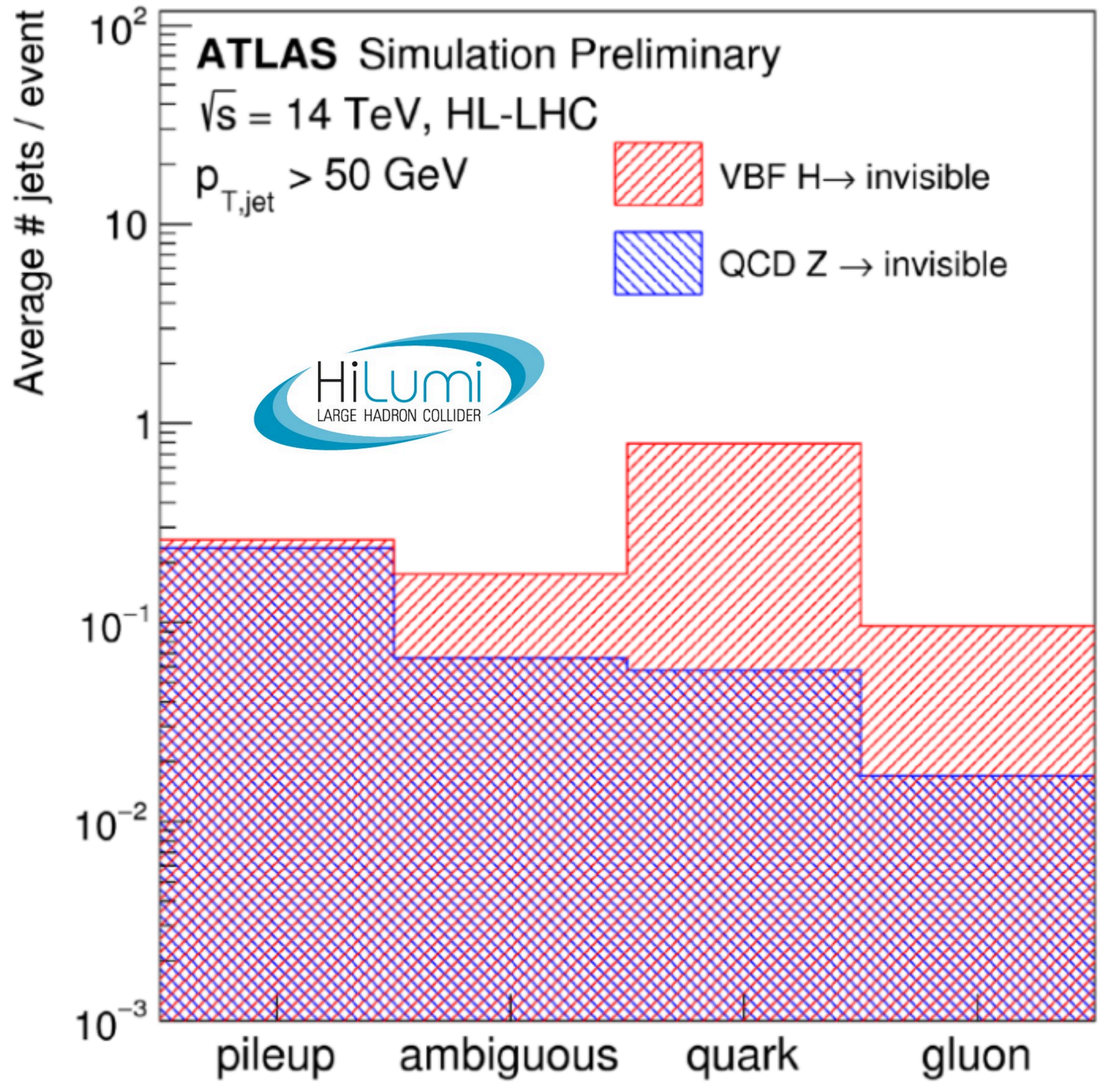
beamspot $\sigma_z = 5$ cm → $\sigma_t \sim 200$ ps

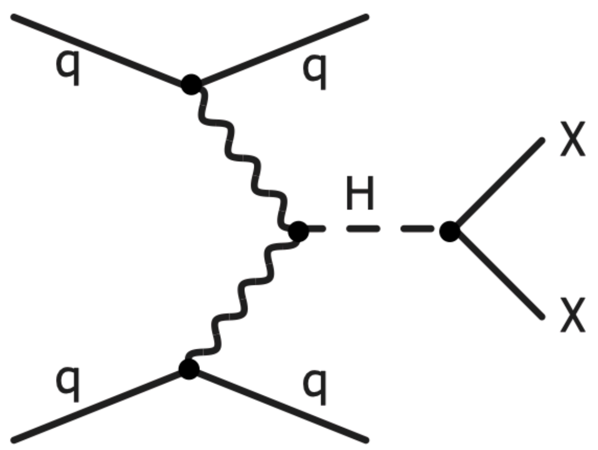
$\sigma_t = 30$ ps

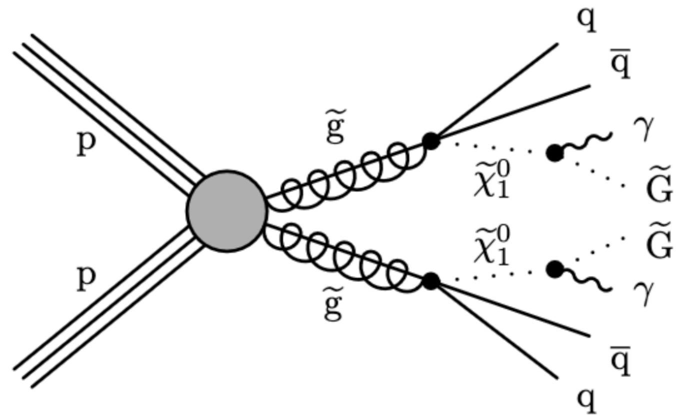
Uncertainty on Higgs to invisible BR (VBF) depends on pile-up rejection method

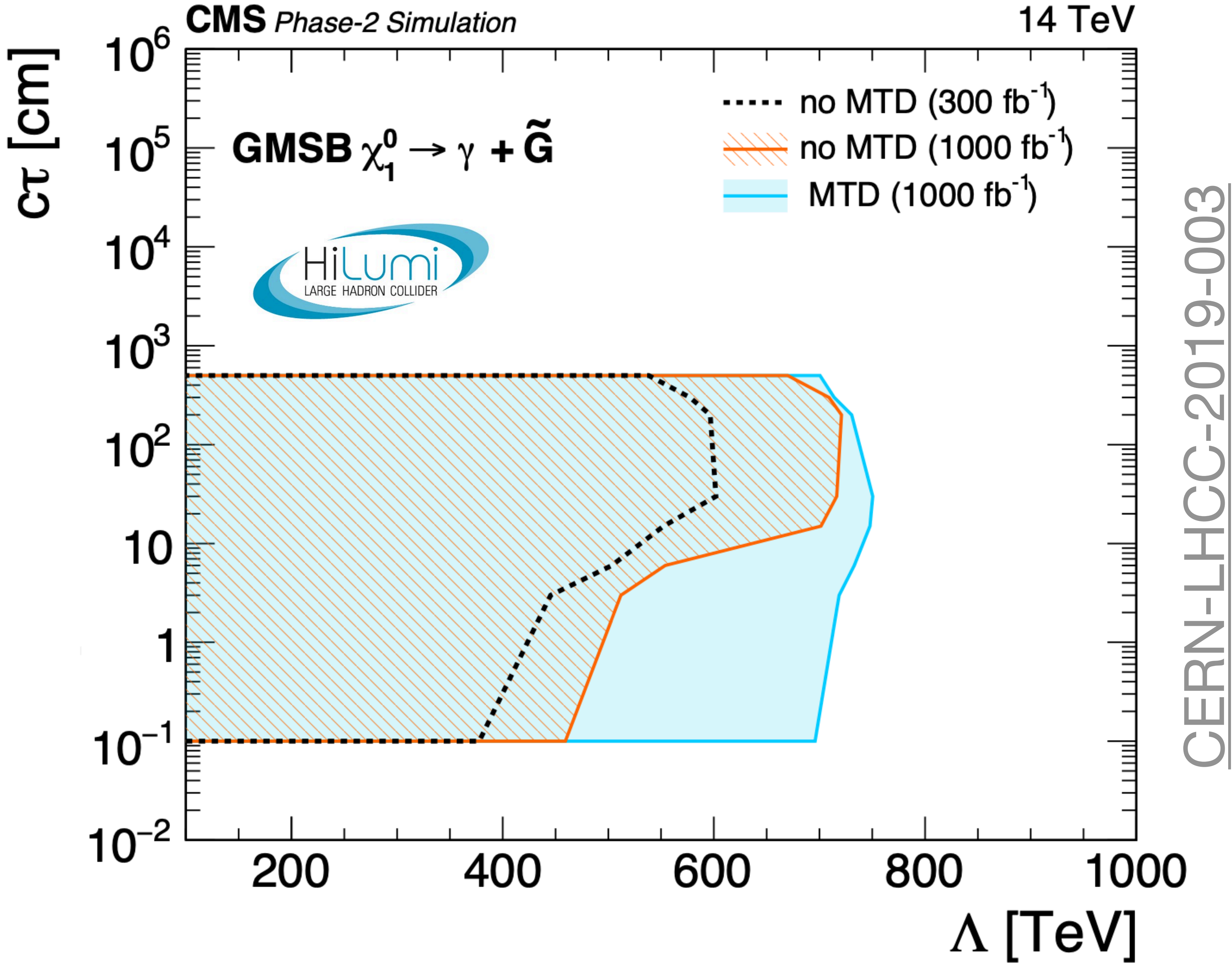
In LLP signatures timing detector essential to identify the PV time and particles' time of flight

ATL-PHYS-PUB-2018-038









CERN-LHCC-2019-003

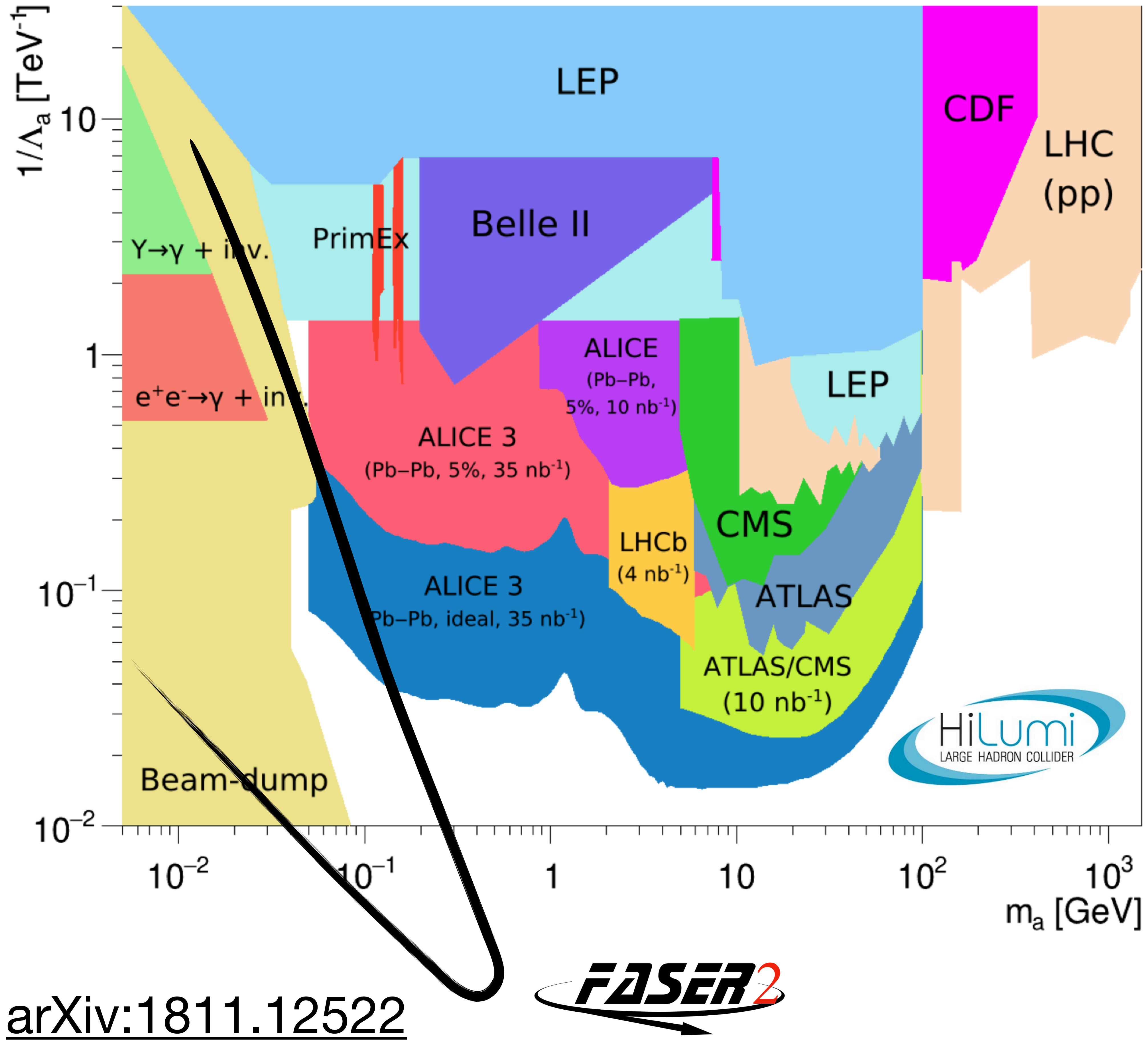
ALPs (→γγ)

arXiv:2211.02491

ALICE 3, **LHCb**, **NA64** :

fill the gap in the ALP 50 MeV < m_a < 5 GeV

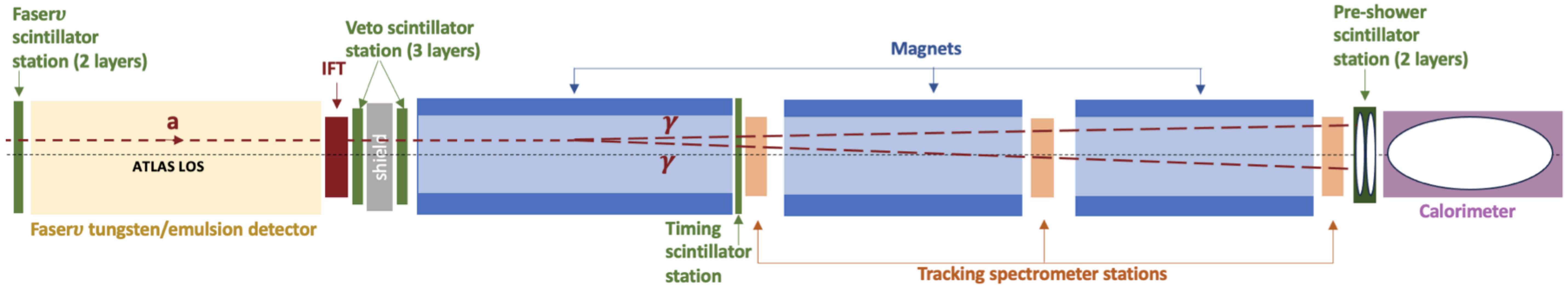
- complementing ATLAS & CMS reaches
  - limited by triggers & selection criteria (E_T < 2 GeV)



arXiv:1811.12522

FASER2, **SHIP** and other dedicated experiments allows to explore LLP scenarios

- smaller couplings



Other LLP detectors

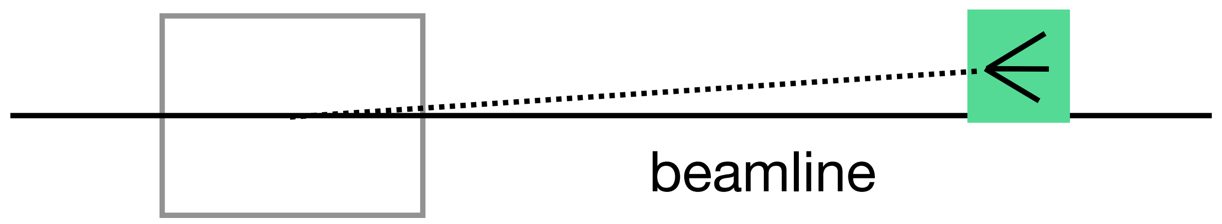
Fixed target experiments and forward detectors to probe low-mass scenarios

FASER

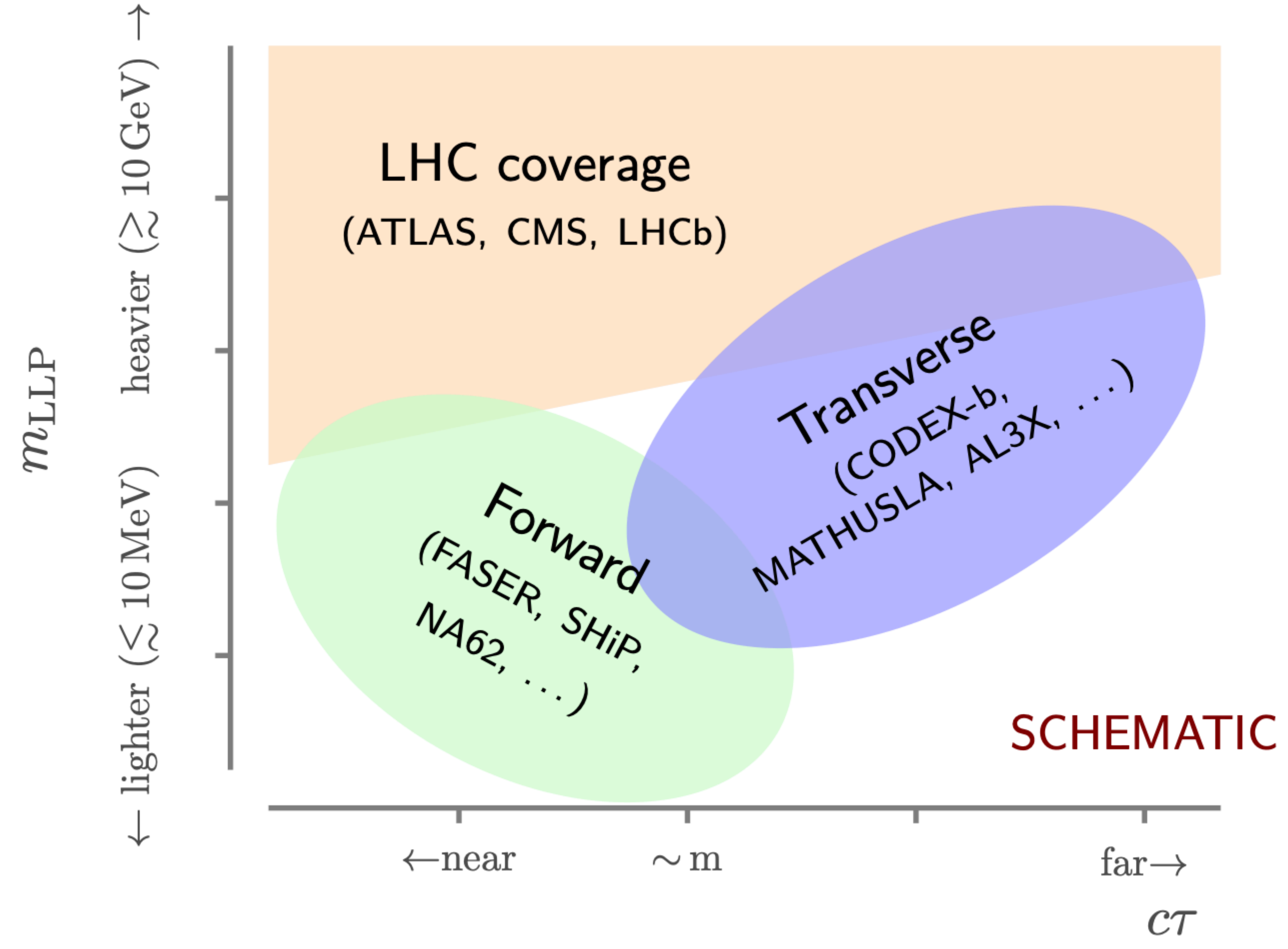
NA64

SHiP
Search for Hidden Particles

new experiment



ATLAS/CMS/LHCb



and many others targeting Run-4 and beyond!

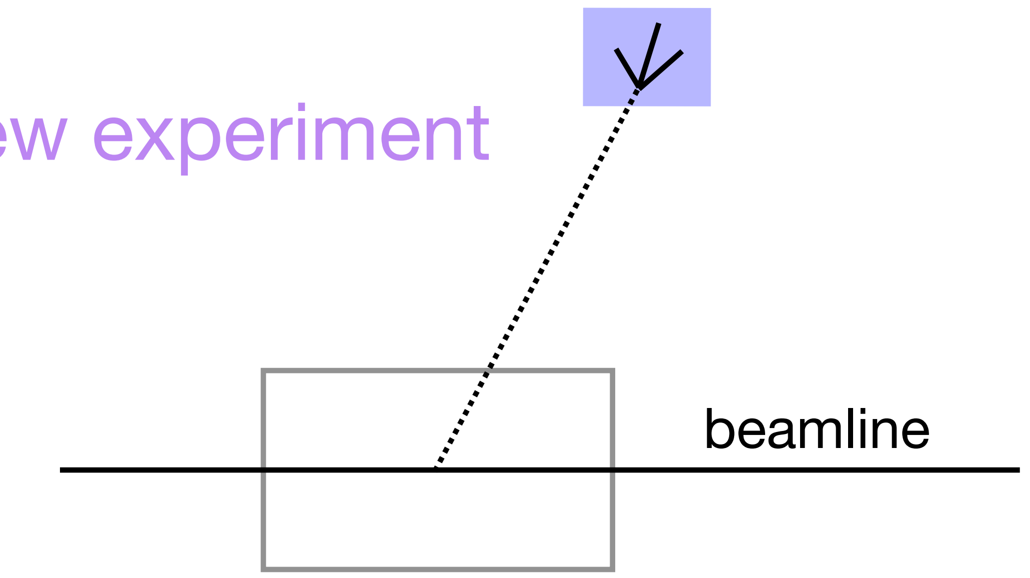
Dedicated detectors searching for LLPs and milli-charged particles at larger angles

MATHUSLA

ANUBIS

CODEX-b

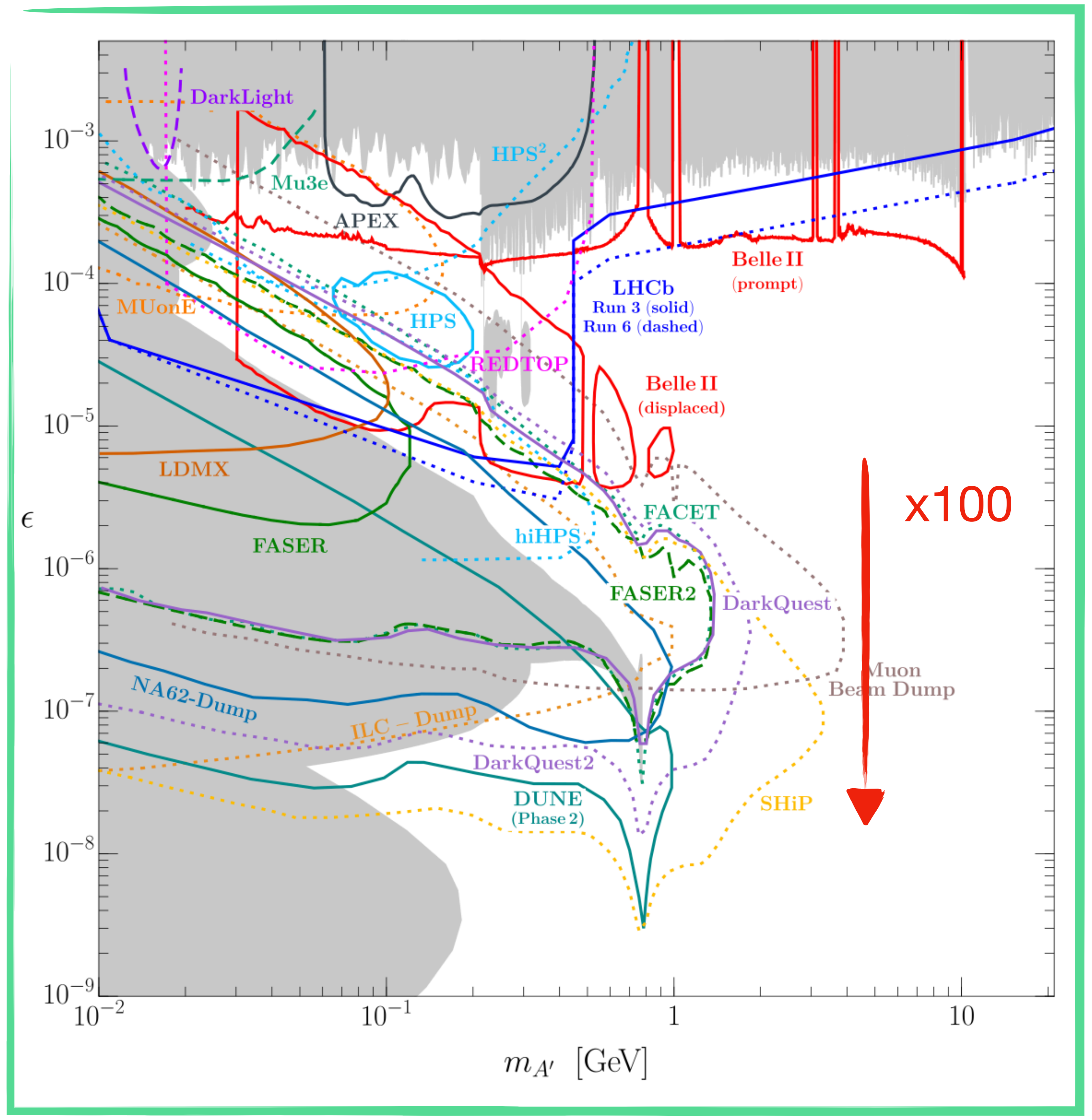
new experiment

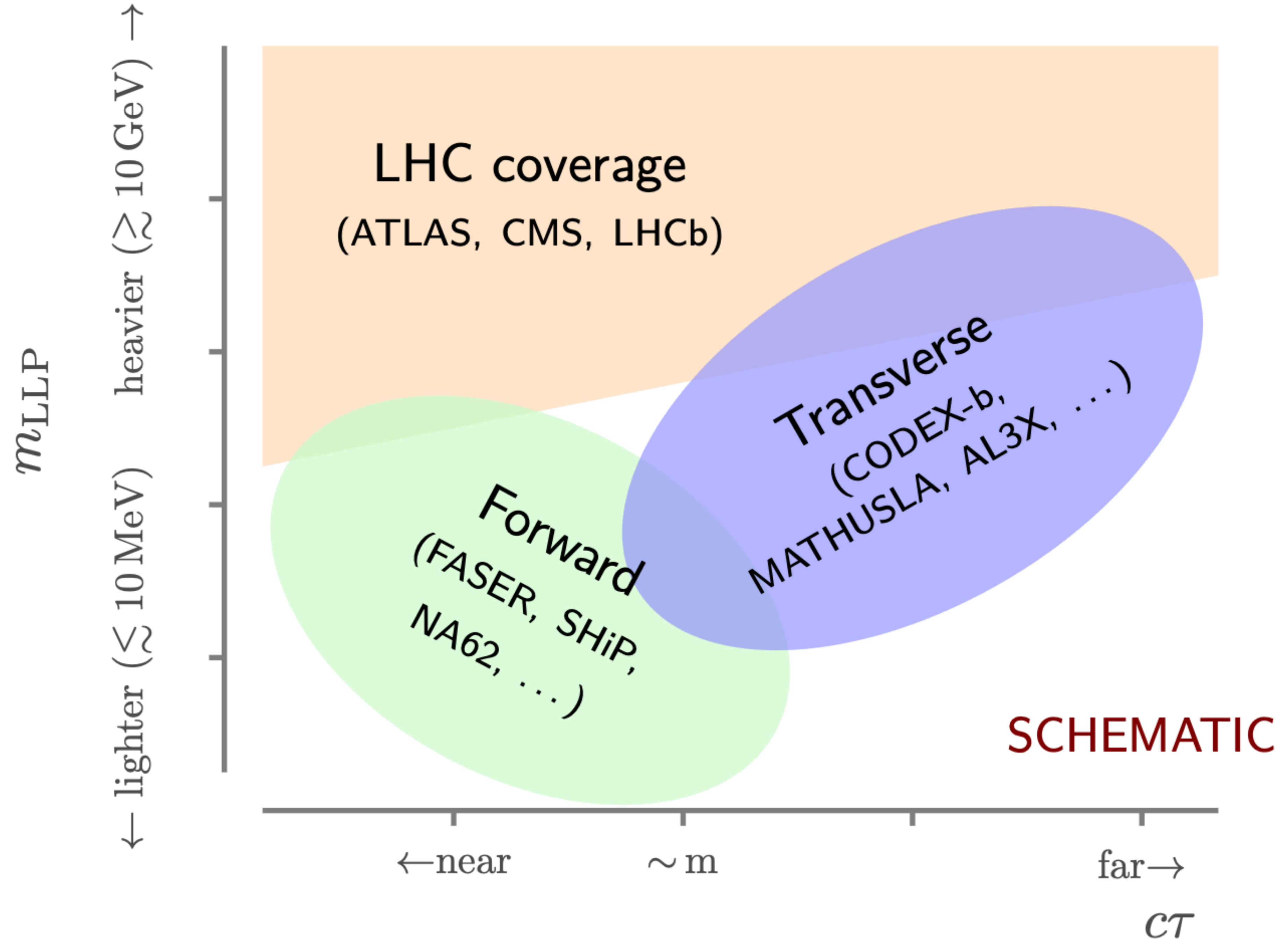


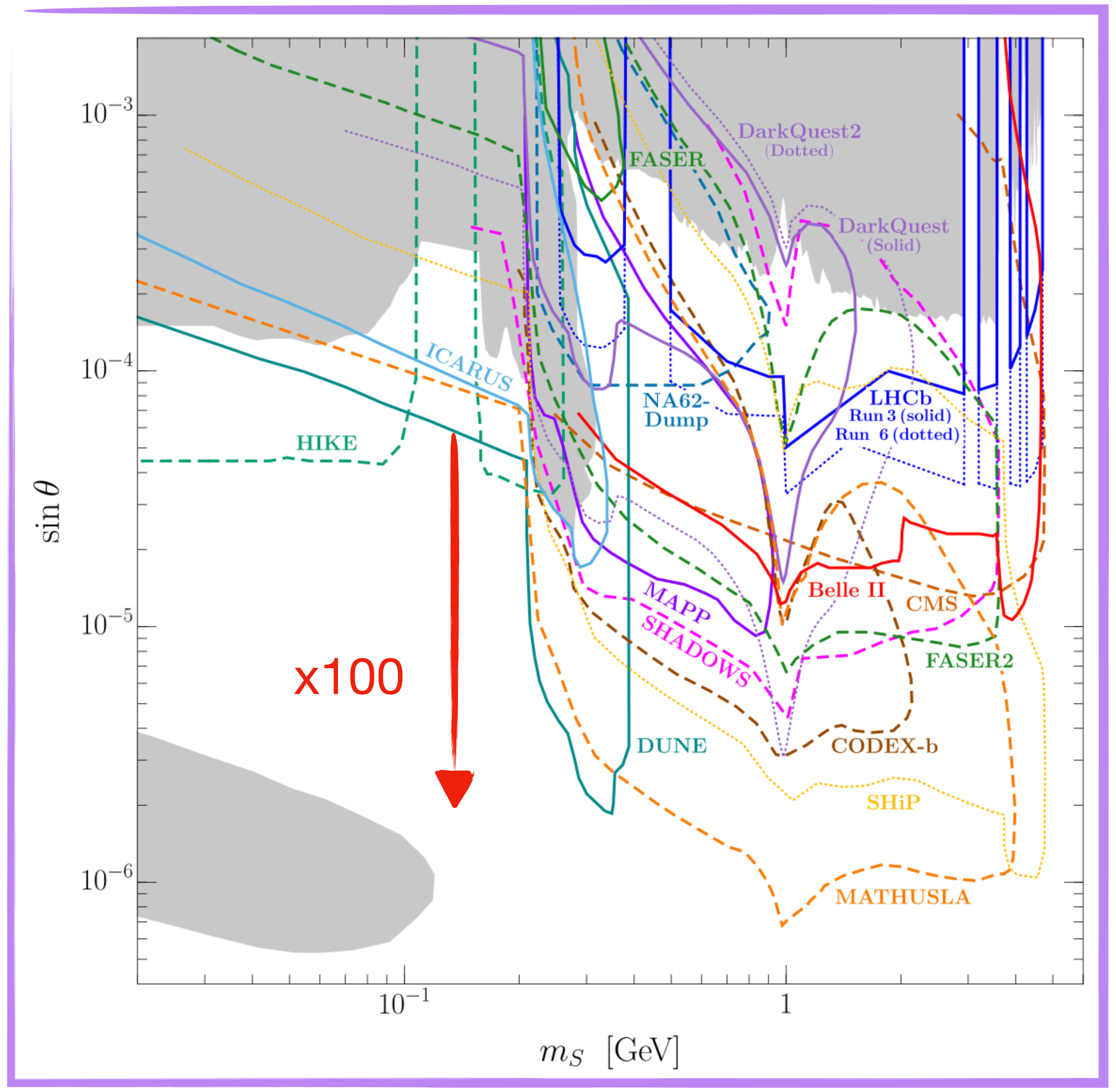
ATLAS/CMS/LHCb

Other LLP detectors

arXiv:2207.06905







< O(GeV)

O(GeV)

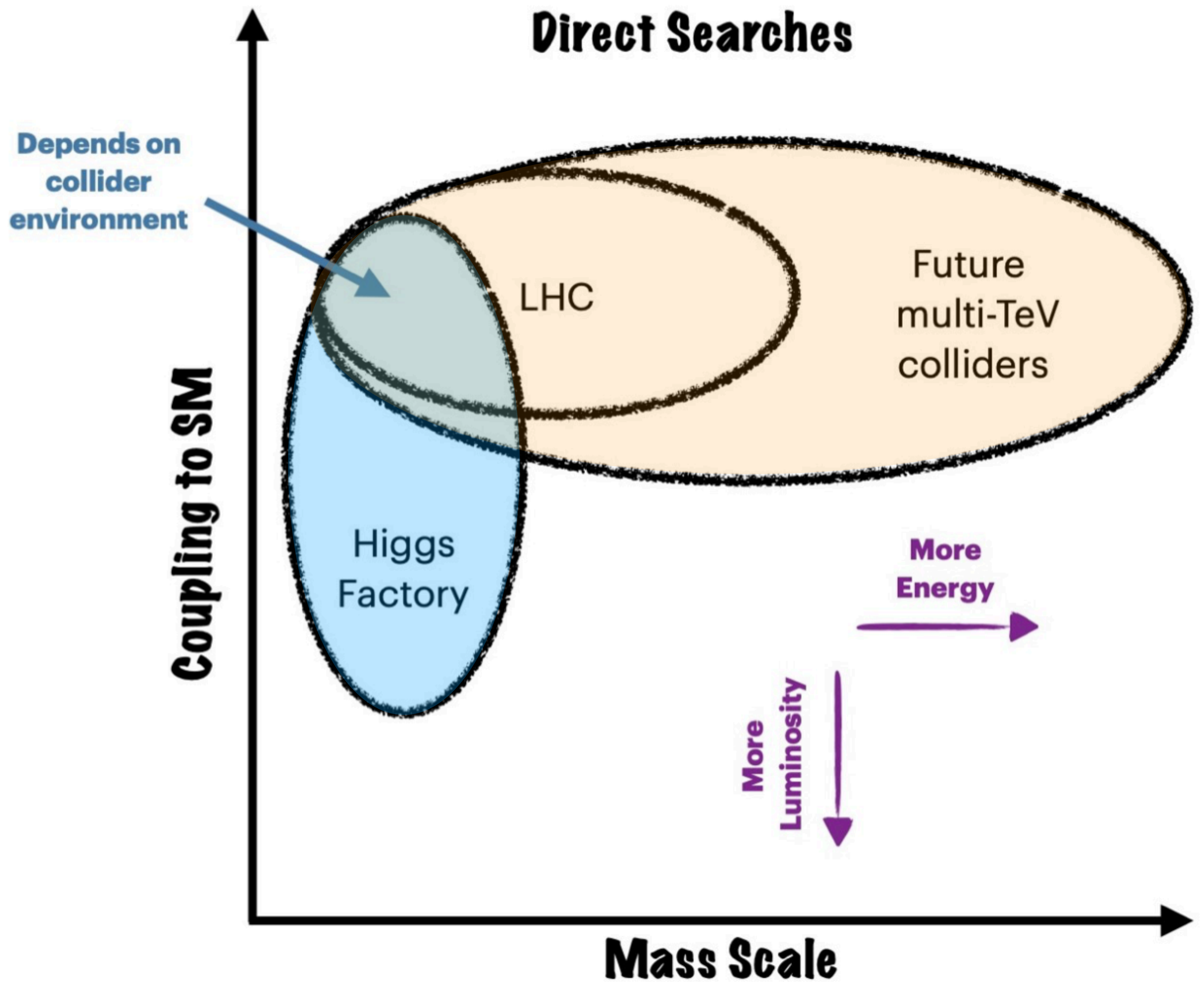
and many others targeting Run-4 and beyond!

NP beyond LHC

arXiv:2211.11084

ROMA

Four main paths to advance in HEP



dark sectors

new heavy states

higgs sector

indirect effects

Projects beyond LHC

arXiv:2211.11084

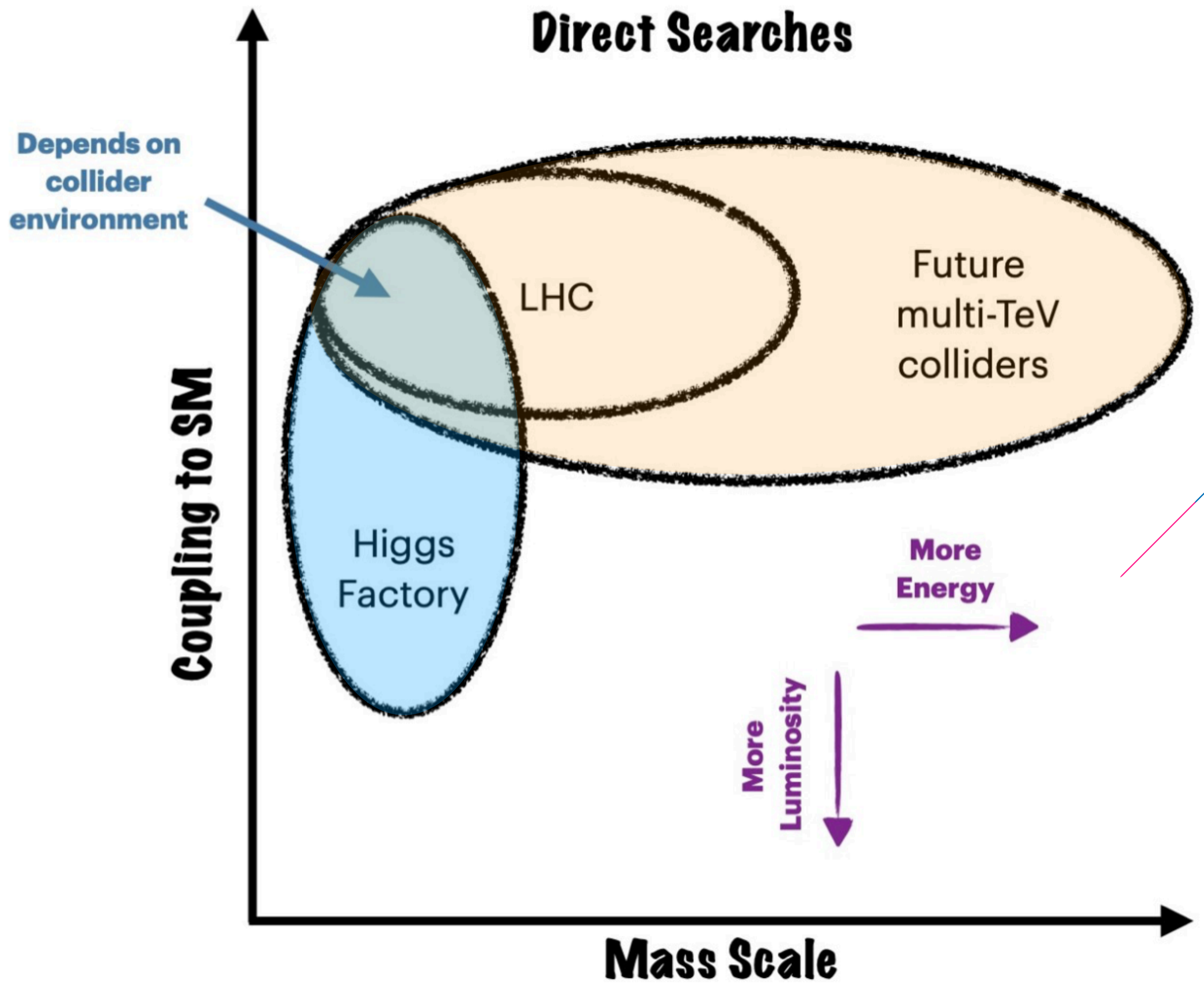
$\sqrt{s} = m_h$ — higgs couplings

$\sqrt{s} \simeq m_h + m_Z$ — light NP w/ feeble couplings

$\sqrt{s} \gg m_h$ — heavy NP

higgs factories

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500 GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
CEPC	ee	M_Z		50
		$2M_W$		3
		240 GeV		10
		360 GeV		0.5
FCC-ee	ee	M_Z		75
		$2M_W$		5
		240 GeV		2.5
		$2\ M_{top}$		0.8
μ-collider	$\mu\mu$	125 GeV		0.02

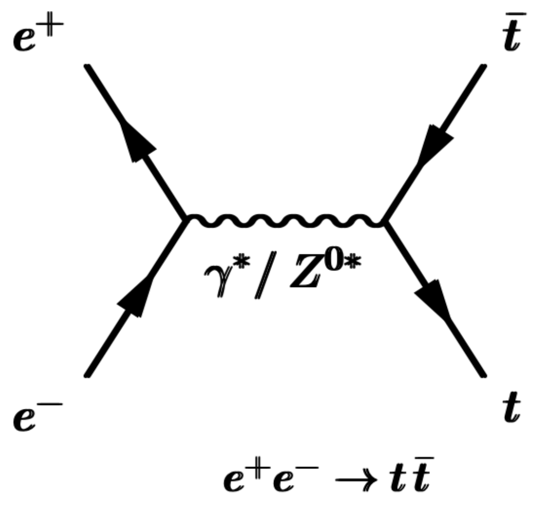


multi-TeV colliders

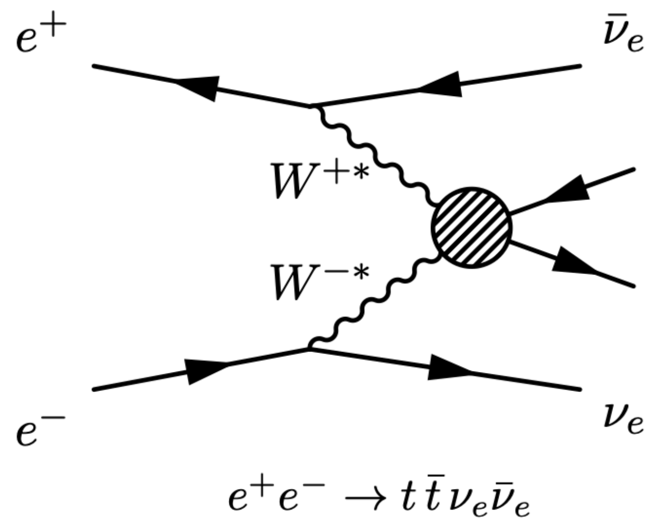
Collider	Type	$\sqrt{s}$ (TeV)	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP
HE-LHC	pp	27		15
FCC-hh	pp	100		30
SPPC	pp	75-125		10-20
LHeC	ep	1.3		1
FCC-eh		3.5		2
CLIC	ee	1.5	$\pm80/0$	2.5
		3.0	$\pm80/0$	5
μ-collider	$\mu\mu$	3		1
		10		10

μ-colliders

combine the great potential
of/ high energy & high luminosity



$\sigma_{\mu\mu\to X}$ ~$1/s$

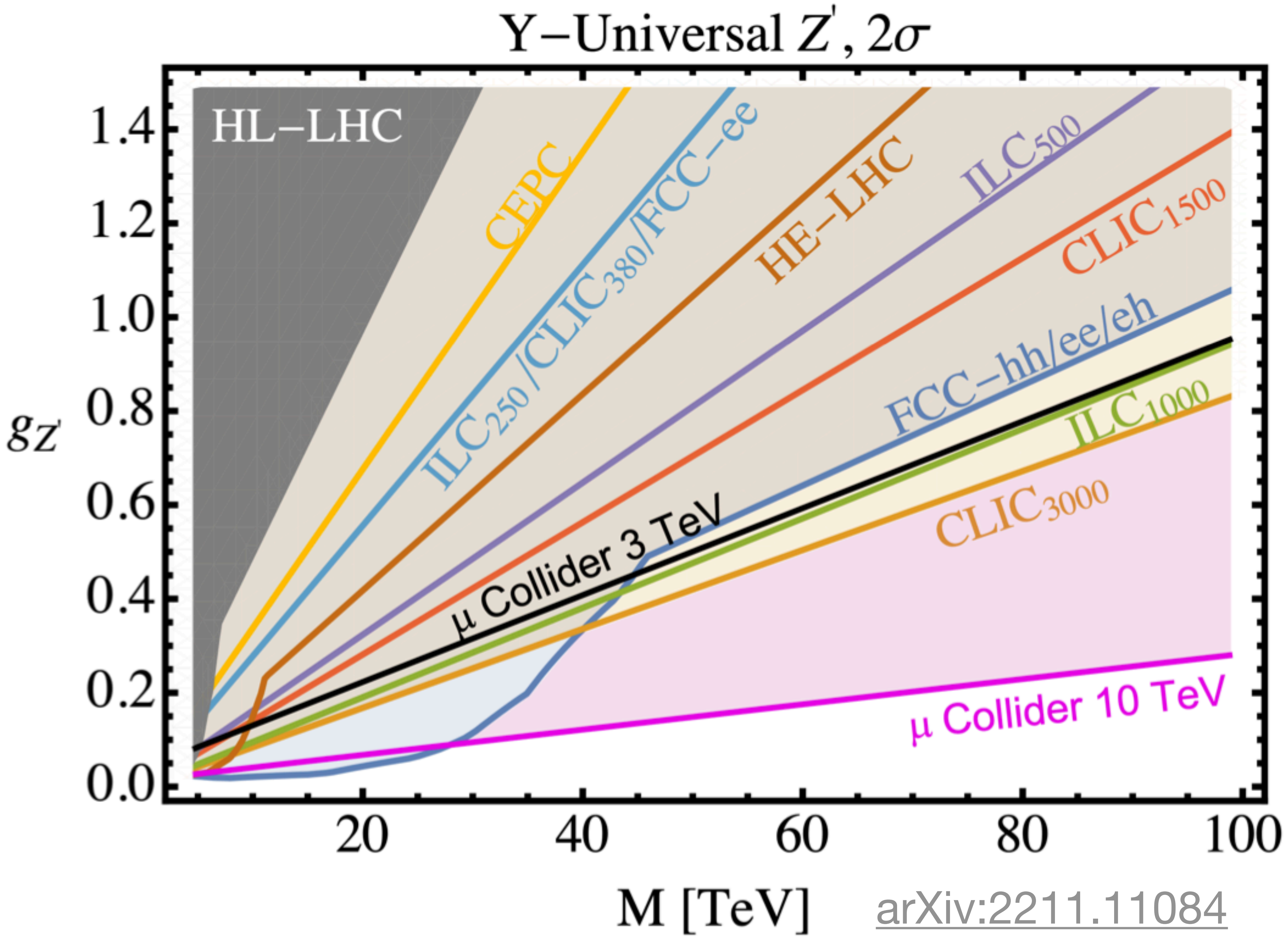


$\sigma_{WW\to X}$ ~ $\log^n s$

Future Collider reaches

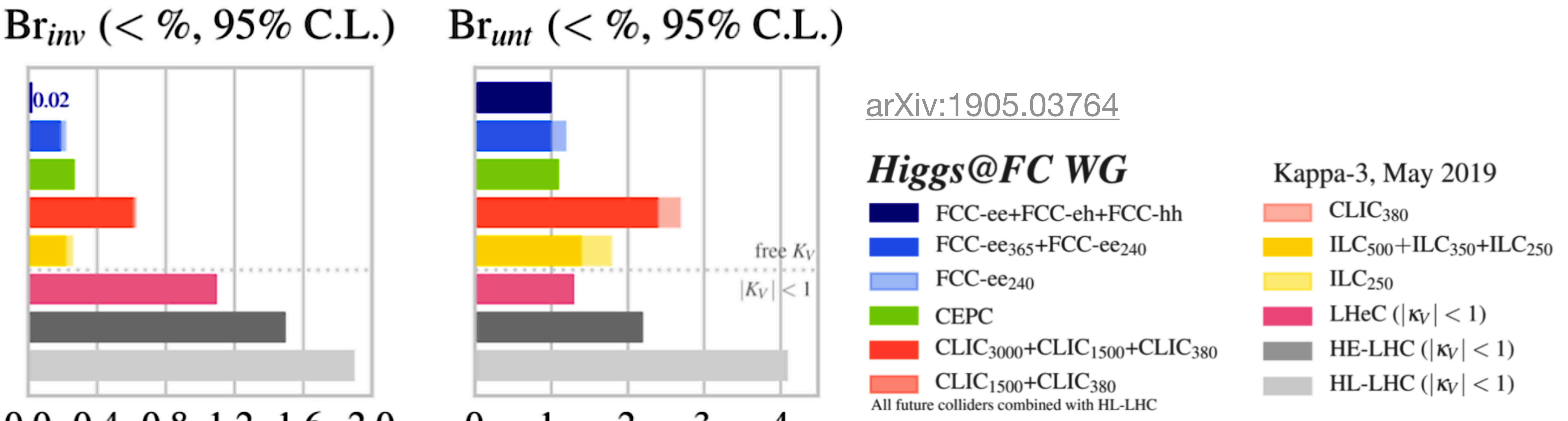
Heavy particles

- Indirect searches
  - very stringent constraints from lepton colliders
- Direct searches
  - relevant at small corner at low masses & couplings
  - high mass accessible only with multi-TeV machines



arXiv:2211.11084

H→inv, unt



arXiv:1905.03764

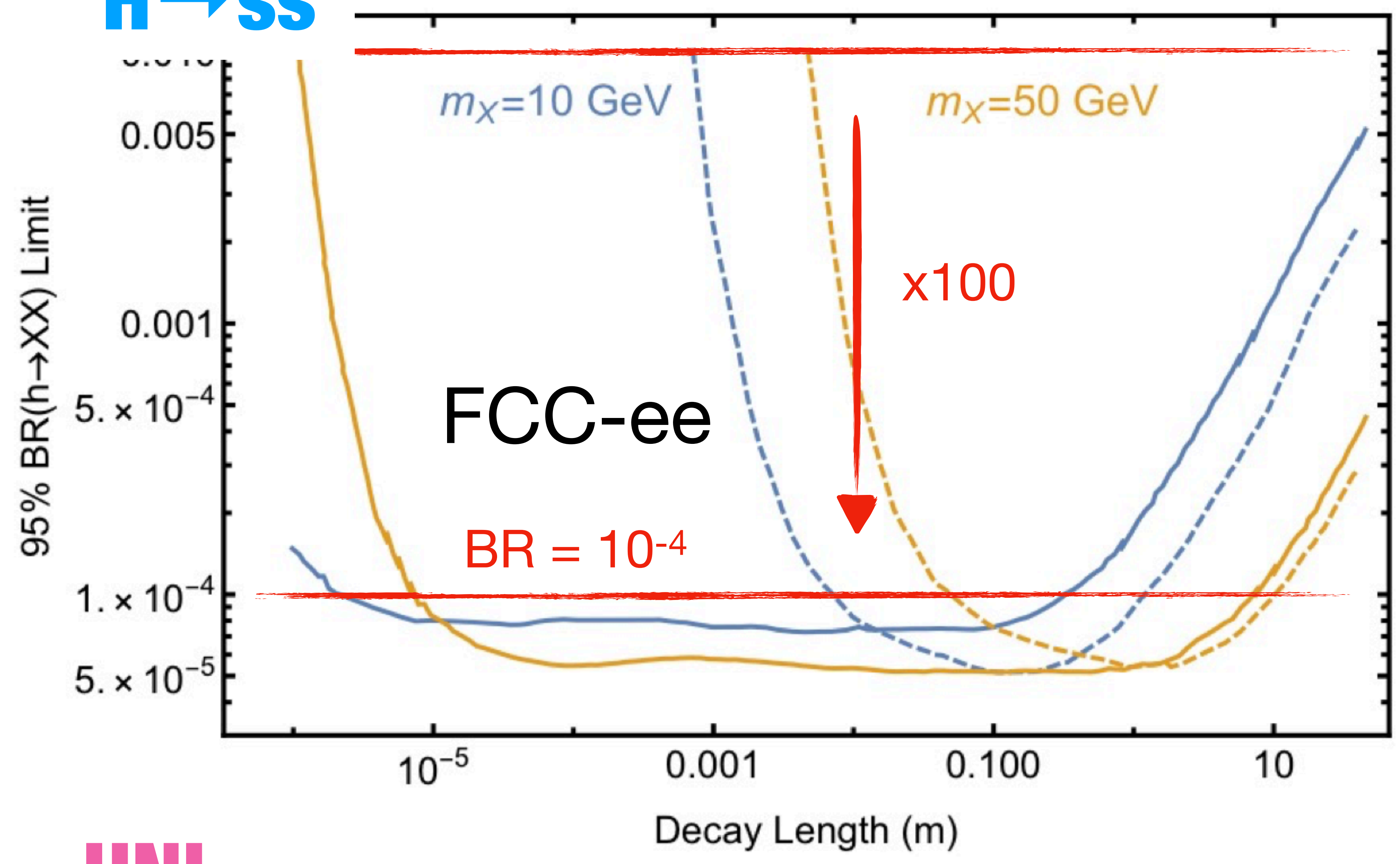
- Access to sub-percent BR
  - close to SM BR(H->inv) = 0.11%
  - similar constraints from direct searches

LLP beyond LHC

Higgs mediated processes dominated by FCC-ee

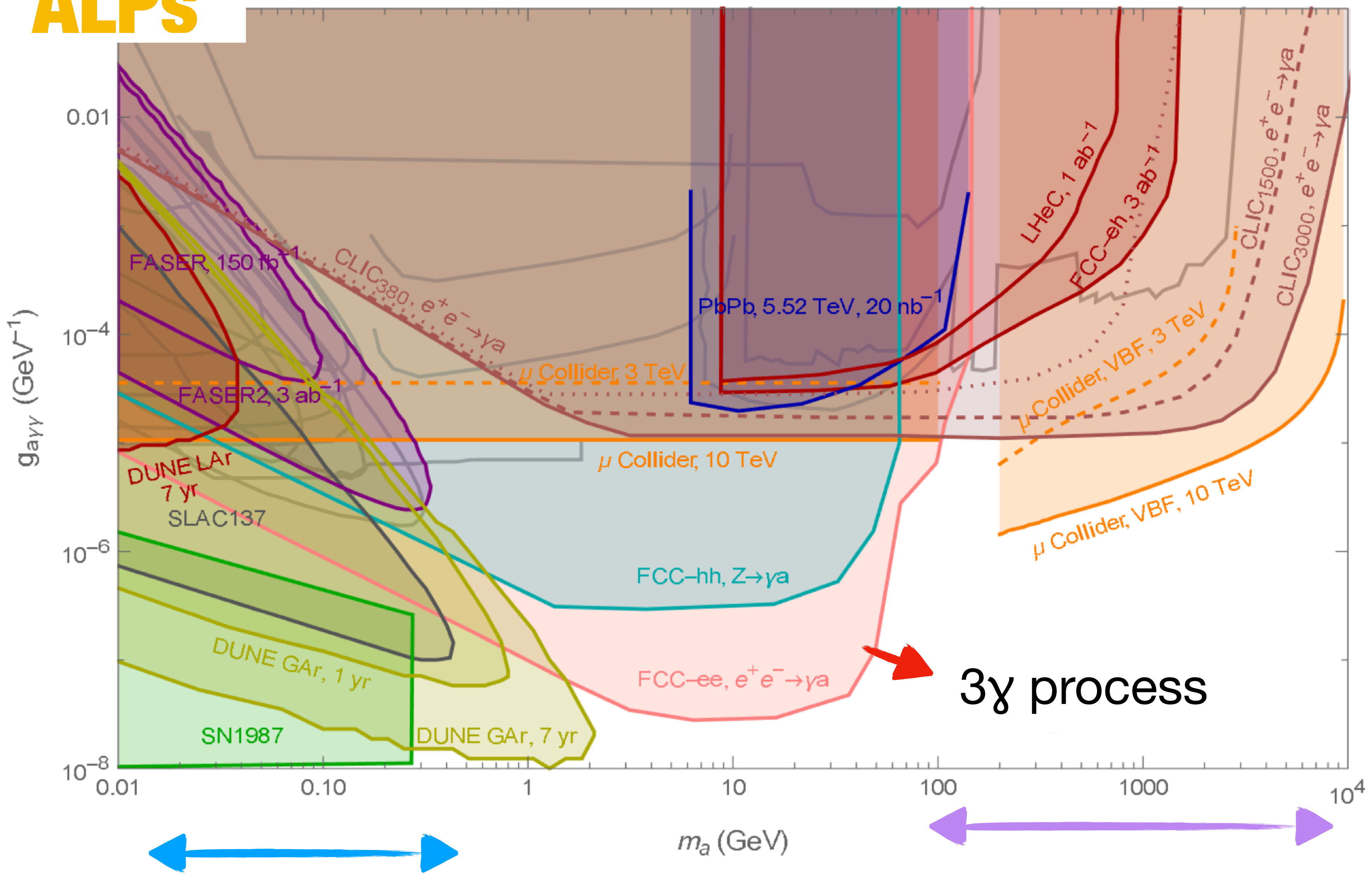
Several mass ranges better covered by different beyond LHC projects or LLP dedicated experiments

H→ss



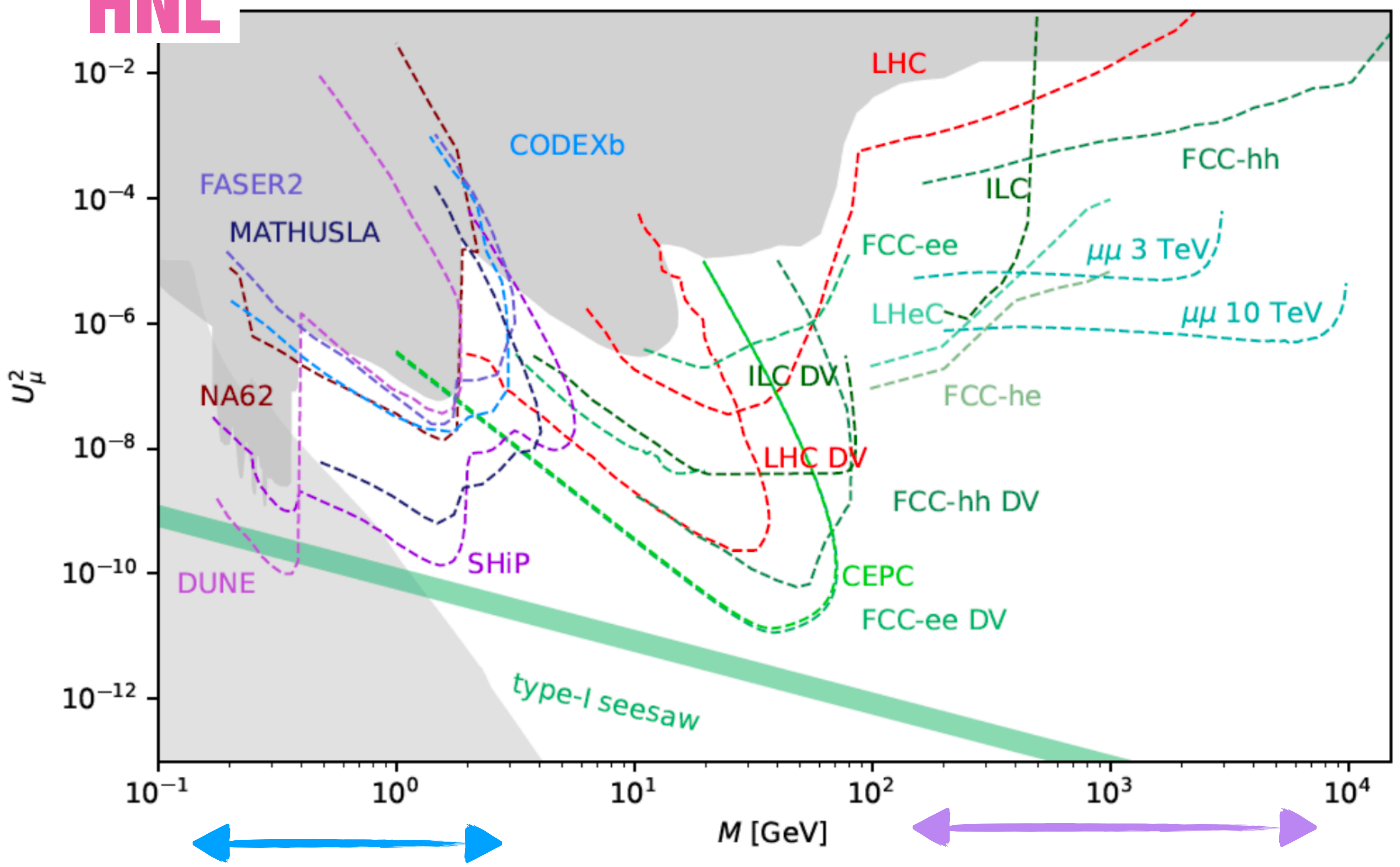
arXiv:2203.05502

ALPs



dedicated exp — ee-collider — μ-collider

HNL



arXiv:2211.11084 arXiv:2203.05502

dedicated exp — ee-collider — μ-collider

Conclusions

INFN ROMA

Rich dark sector *EXPLORATION* program @ collider experiments

- **Interplay** between different kinds of searches
- Exploit the full potential of the **detector technologies**

- **The increased statistics**
  → open up a **variety of final states**
  → hugely benefit **stats limited & bkg-zero searches** (e.g. LLP)

BUT new ideas and tools will open up new scenarios…

New triggers

Machine learning is more and more widely used!

New (dedicated) detectors and technologies

Future colliders
→ feeble **couplings**
→ **heavy new physics**