Dark Sector searches at LHC and prospects for HL-LHC

Unveiling the invisible: connecting dark matter with the Standard Model

9.1.25 - LNGS

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Ministero dell'Università e della Ricerca

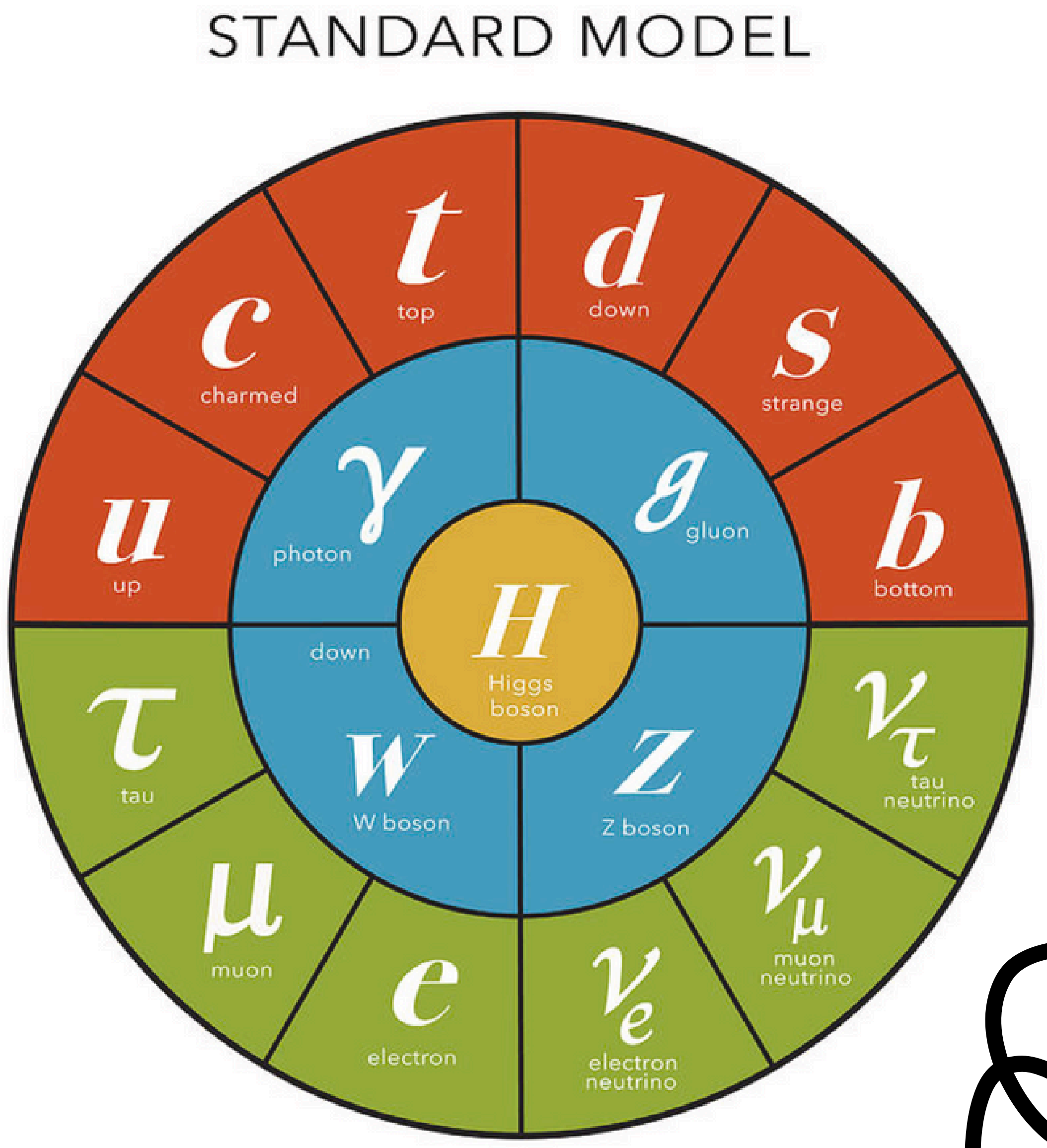
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

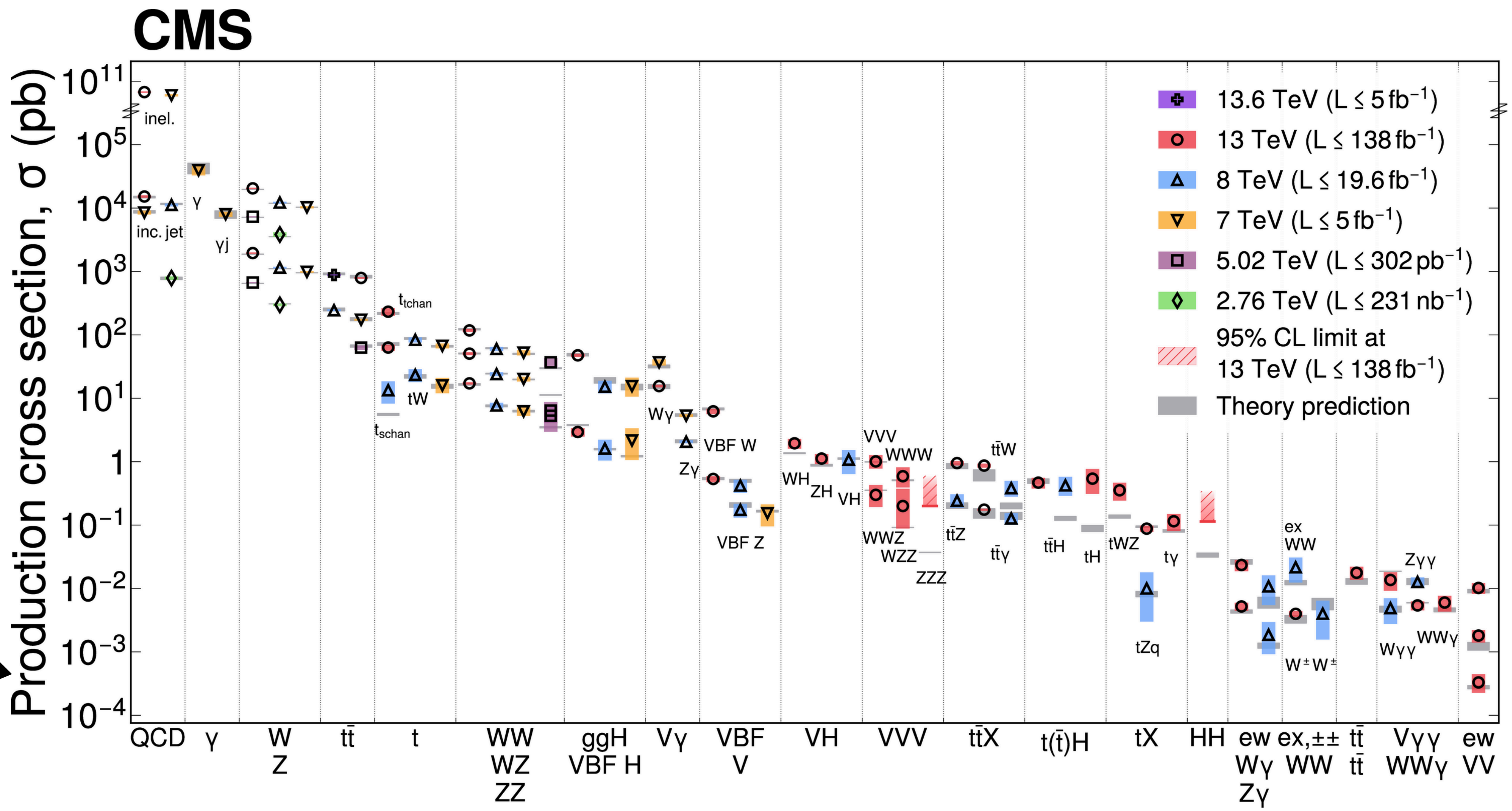
Livia Soffi

Outline

- Dark sector searches at LHC
- Common experimental challenges
- Signature based physics program
- Towards HL-LHC

New Physics Searches at LHC





- **Standard Model (SM) consistent and precise theory** but no clear indication about what the missing pieces are

- **Unexplained phenomena** as gravity, dark matter, dark energy and **experimental tensions** as $g-2\ \mu$, mW, $R(D*)$ or $X17$ and fine-tuning problems: hierarchy problem, neutrino masses

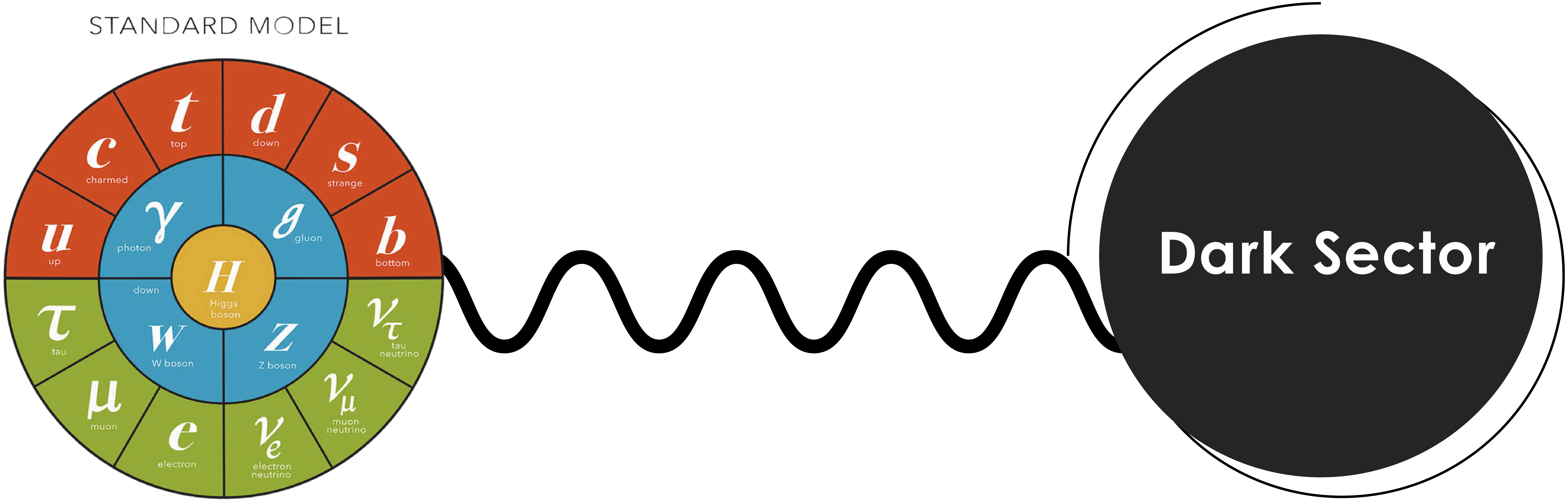
New Physics Searches at LHC
Dark Sector

STANDARD MODEL

- New interactions with the standard model (SM) can **provide dark matter (DM) candidates**
- **New symmetries** can solve other theoretical and fine-tuning problems
- **New particles** can explain experimental tensions
- Can have **rich structure** b/c dark sectors have their own dark charges, so are stable under their conservation laws
- Masses, couplings, gauge structures, portals, are **very unconstrainted**
- **Zoo of theories**: ALPs, WIMPs, SUSY, Hidden Valleys, Extra Dimensions, Axions, Dark Photons, …

New Physics Searches at LHC

Dark Sector

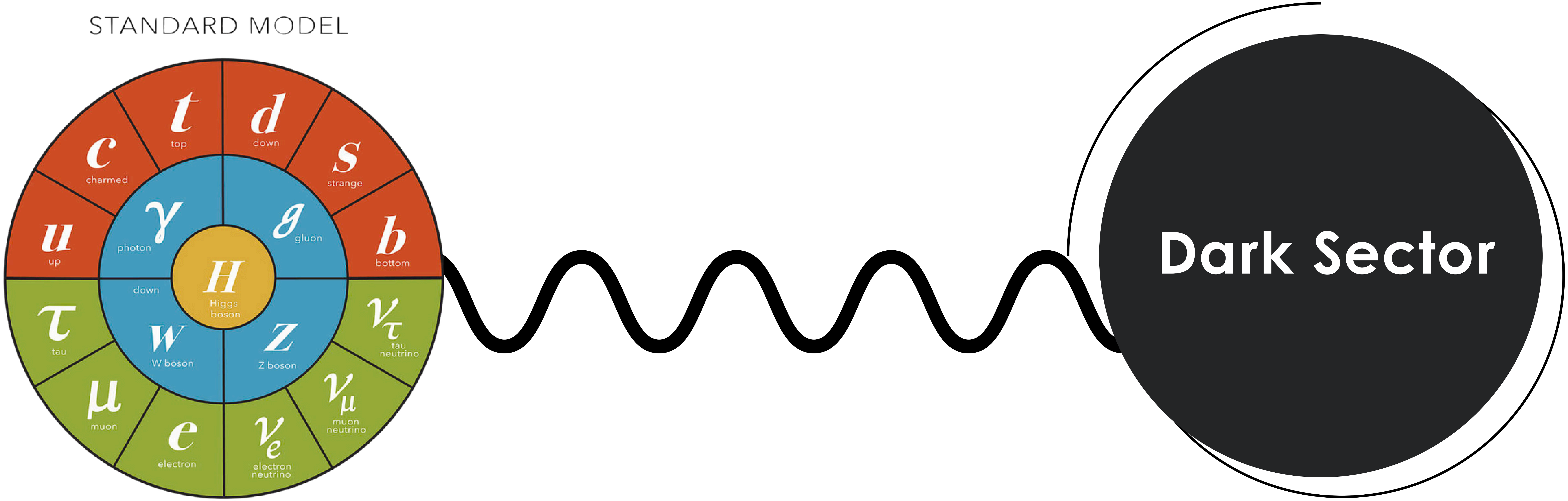


To avoid breaking SM symmetries, four commonly studied ways to communicate with DS:

- **Spin-1 Portal**: new $U(1)$ interaction mixes with SM hypercharge
- **Spin-0 Portal**: scalar (Higgs-like) or pseudoscalar (e.g. ALPs) that couple to DS
- **Fermion Portal**: Yukawa couplings between DS and SM fermions
- **Neutrino Portal**: HNLs mix with neutrinos

Many portals **within LHC reach**

New Physics Searches at LHC
Dark Sector



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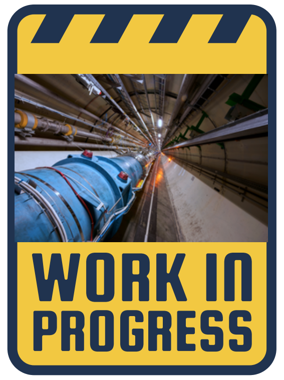
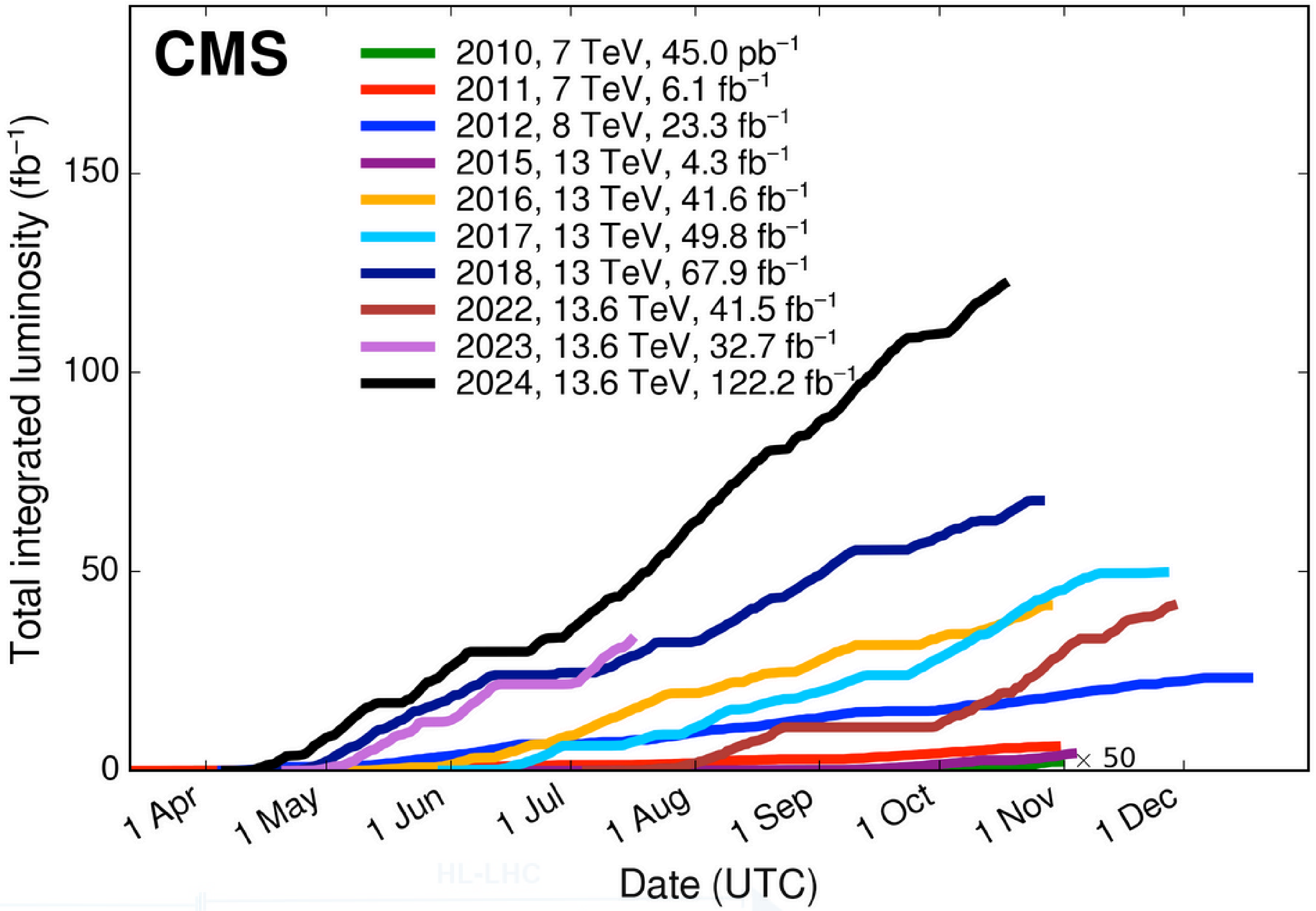
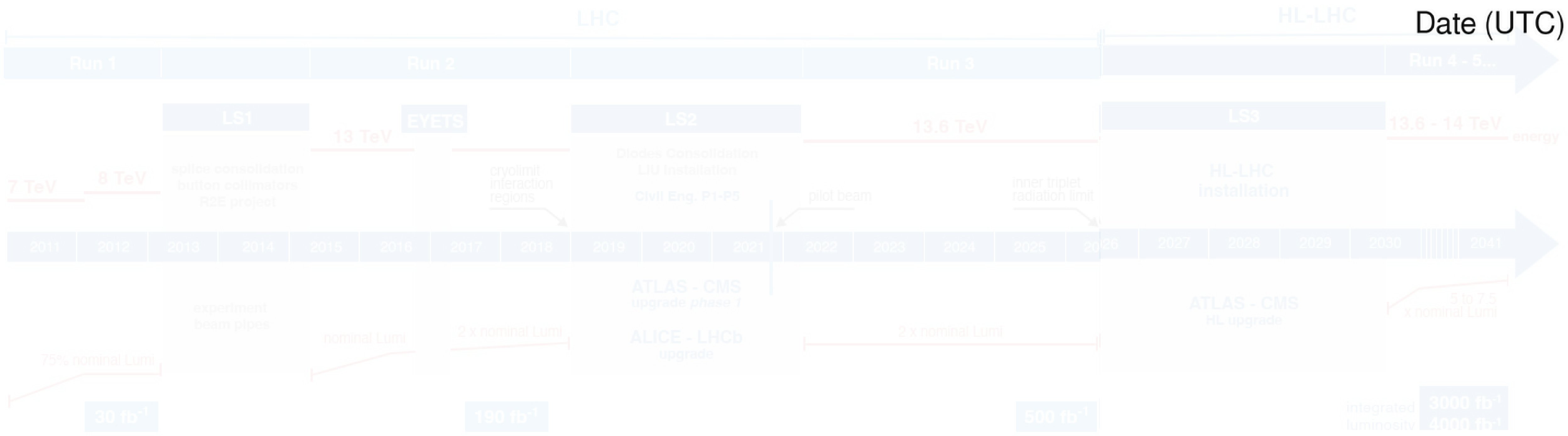


LHC unique high-energy collision environment

<u>Current Operational Highlights:</u>

- Run 3 underway with **√s = 13.6 TeV proton proton** collisions
- Peak luminosities in key experiments (CMS **3.7e4 Hz/μb**)
- Roughly **360/fb of data** collected for ongoing physics analysis
- **Dedicated heavy-ion runs** to study quark-gluon plasma and collective phenomena





- Insights from Run 3 will directly inform the High-Luminosity LHC (HL-LHC), set to begin in early 2030s.

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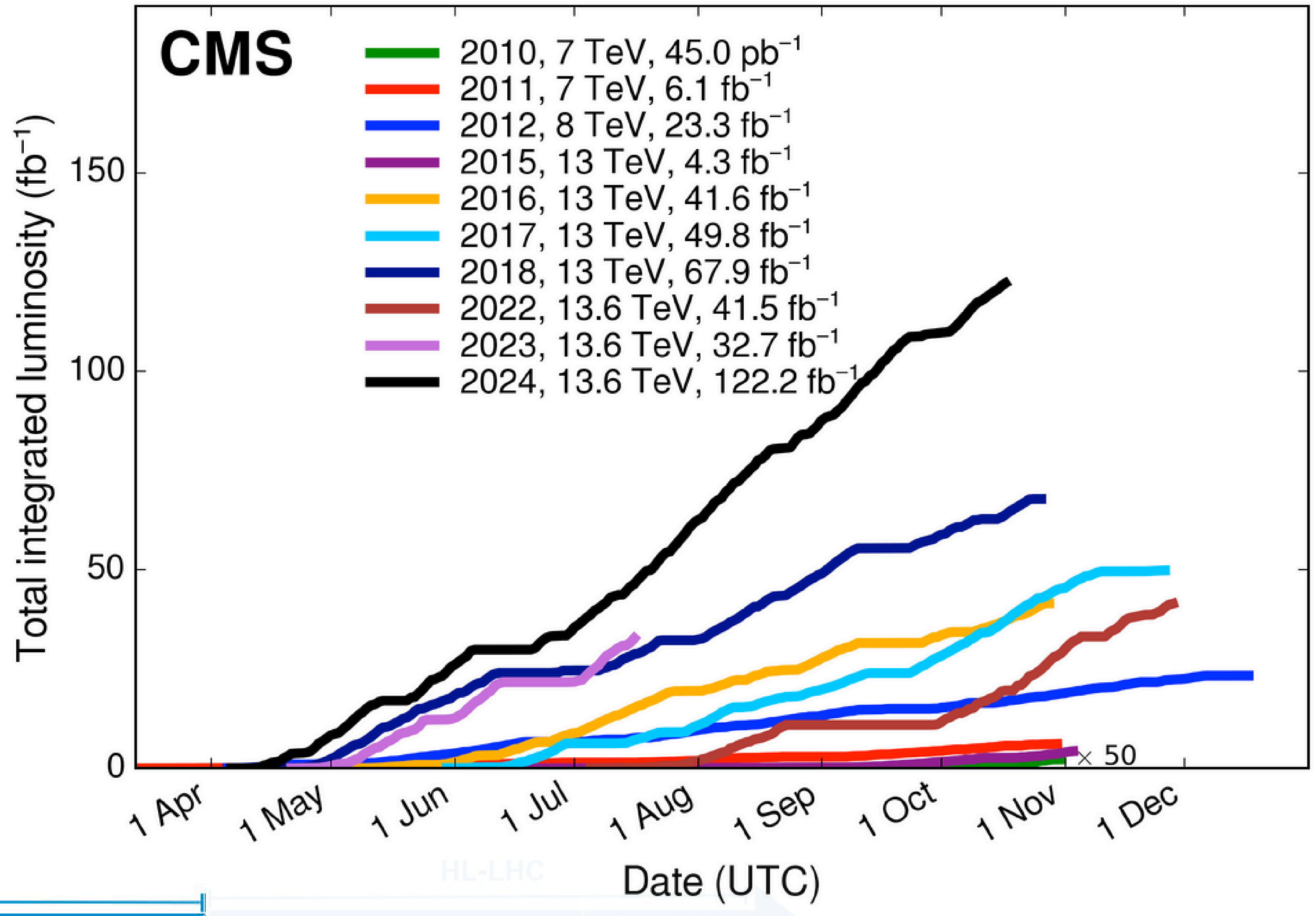

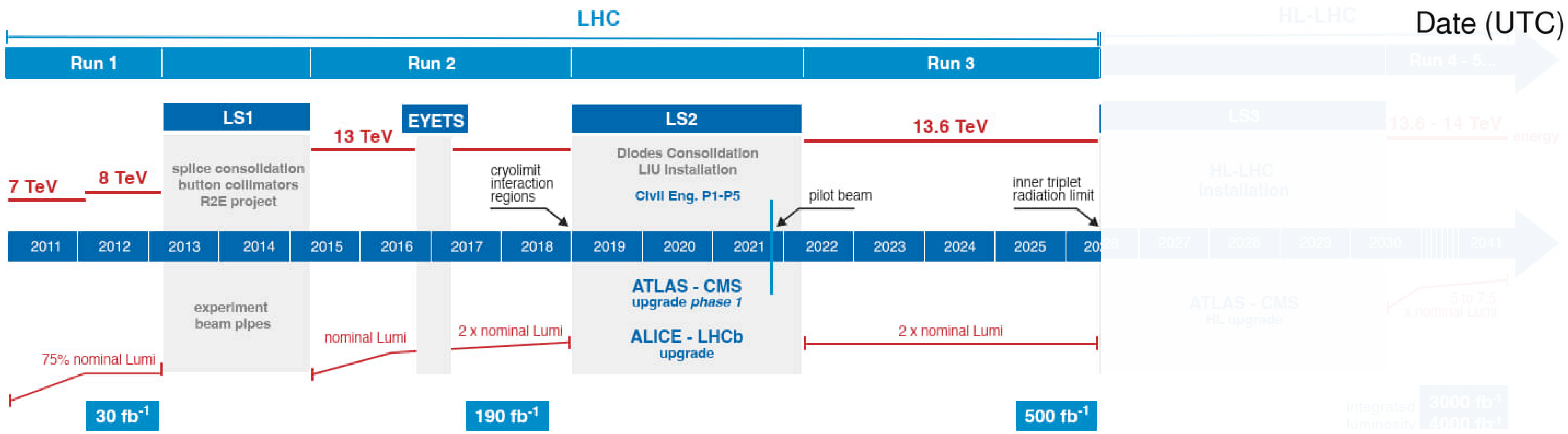

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A random LHC experiment: CMS

Silicon Tracker

Pixel (100 x 150 μm) - 66M channels

MicroStrips (80 x 180 μm) - 9.6M channels

- ✓ P_T resolution ~ 1.5% @100 GeV
- ✓ dE/dx measurement

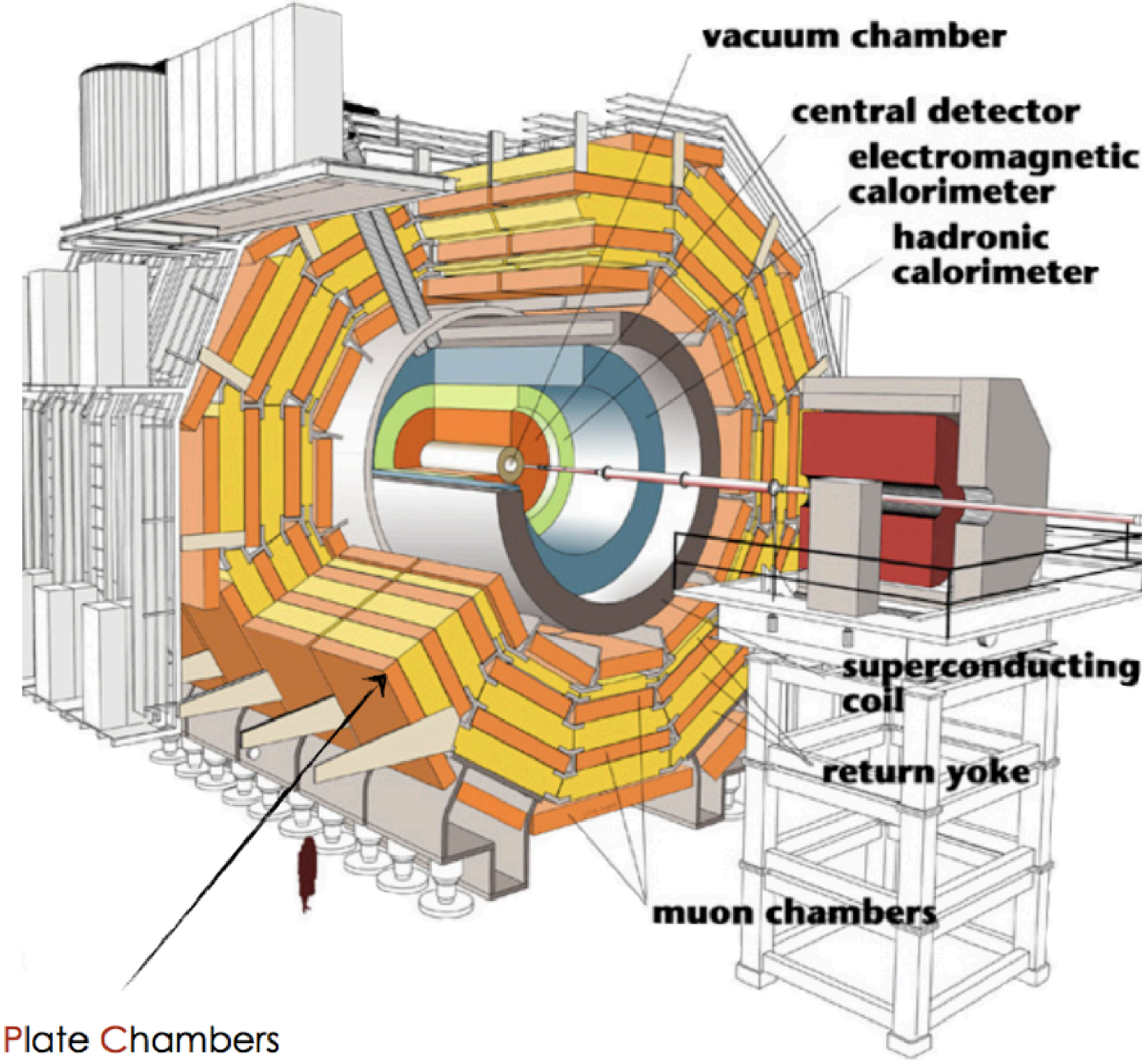
Electromagnetic CALorimeter

76K PbWO4 crystals

- ✓ Designed energy resolution ~0.5% for E(γ) > 100 GeV
- ✓ Fast scintillation scale: > 80% of the light emitted in ~ 25 ns

Brass/Scintillator Hadron Calorimeter

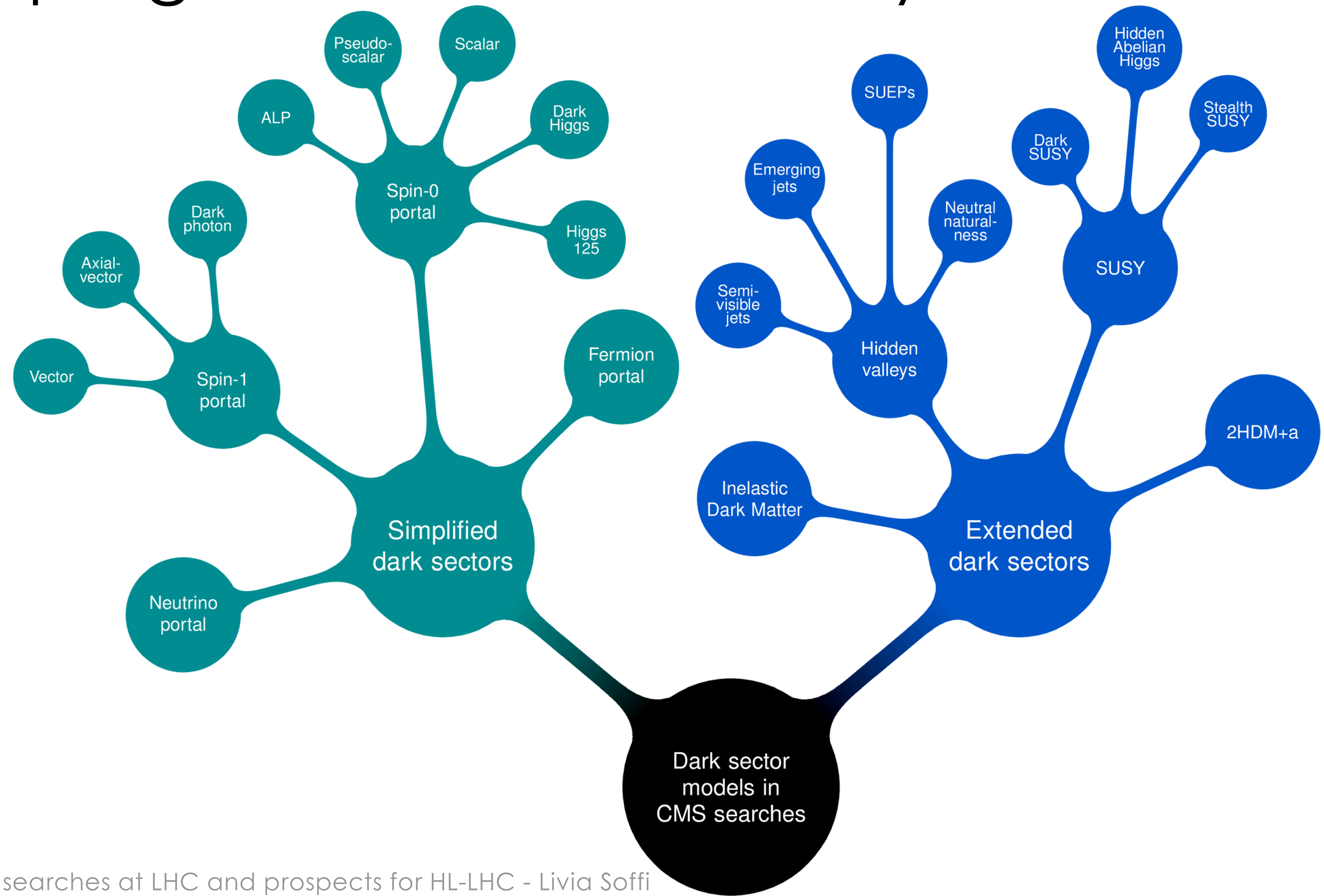
Muon Chambers



Drift Tube - Cathode Strips Chambers - Resistive Plate Chambers

- ✓ Single-point resolution ~ 200 μm
- ✓ σ_{DT} ~ 3ns
- ✓ σ_{CSC} ~ 7ns

Mapping Uncharted Territory



arXiv:2405.13778

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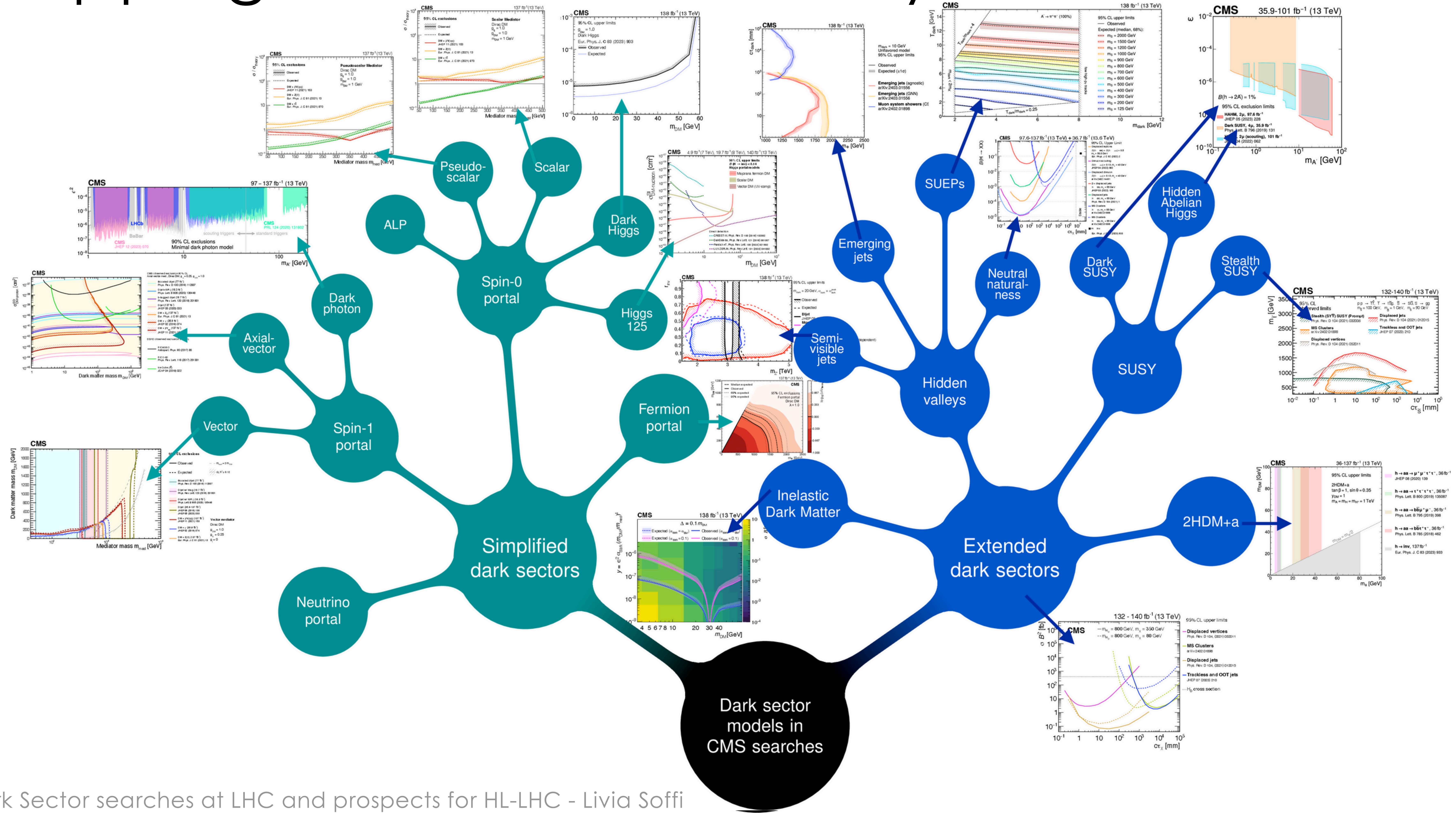
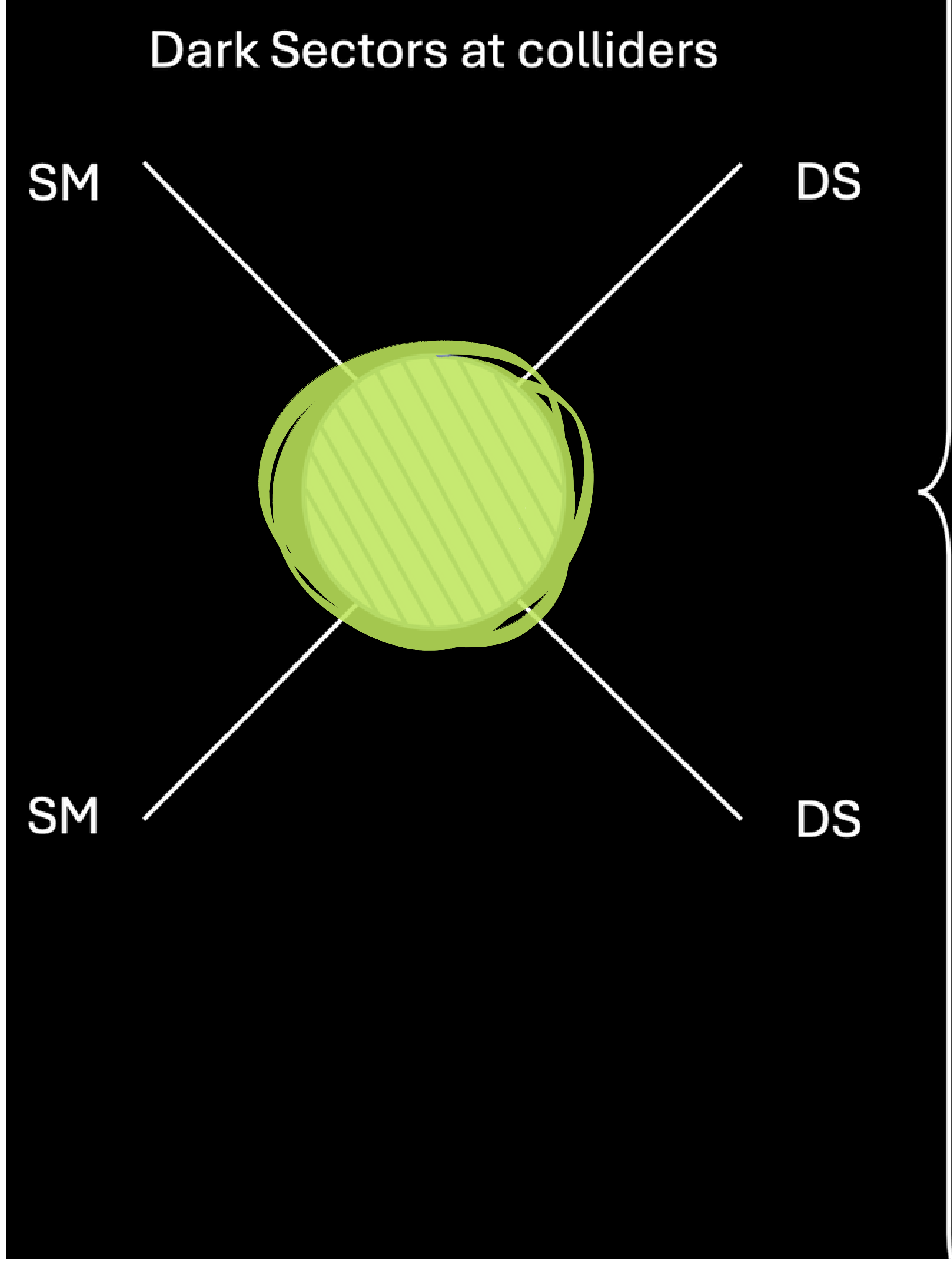
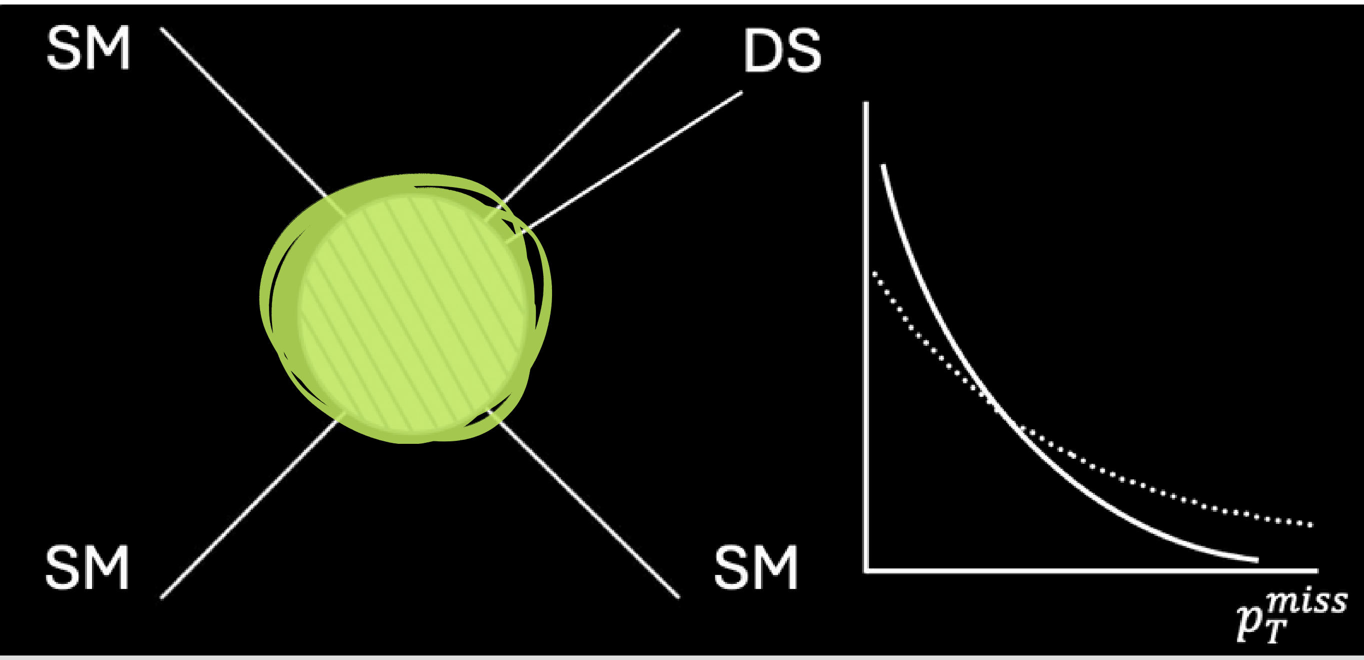


Overview of experimental signatures at LHC





MET+X searches

- DS produced recoiling against SM system
- Missing transverse energy since DS invisible

Portal resonances

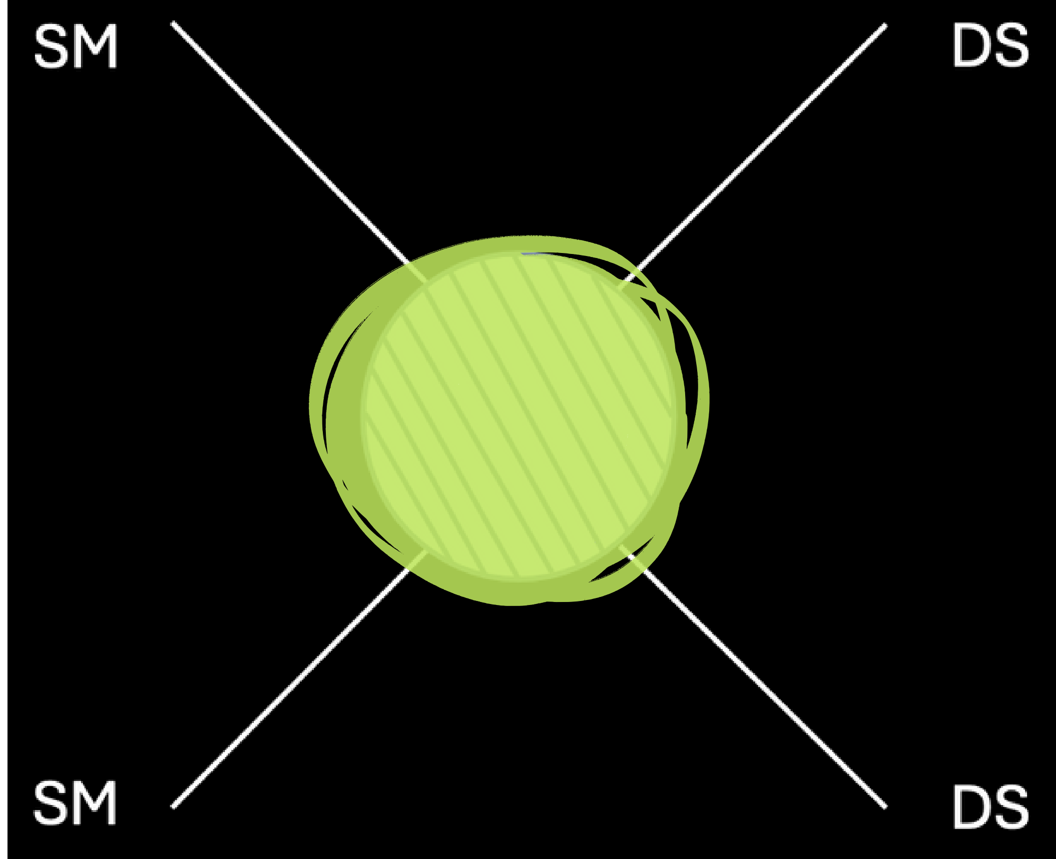
- Known SM processes cross sections are affected by DS
- Search for bumps in mass distributions

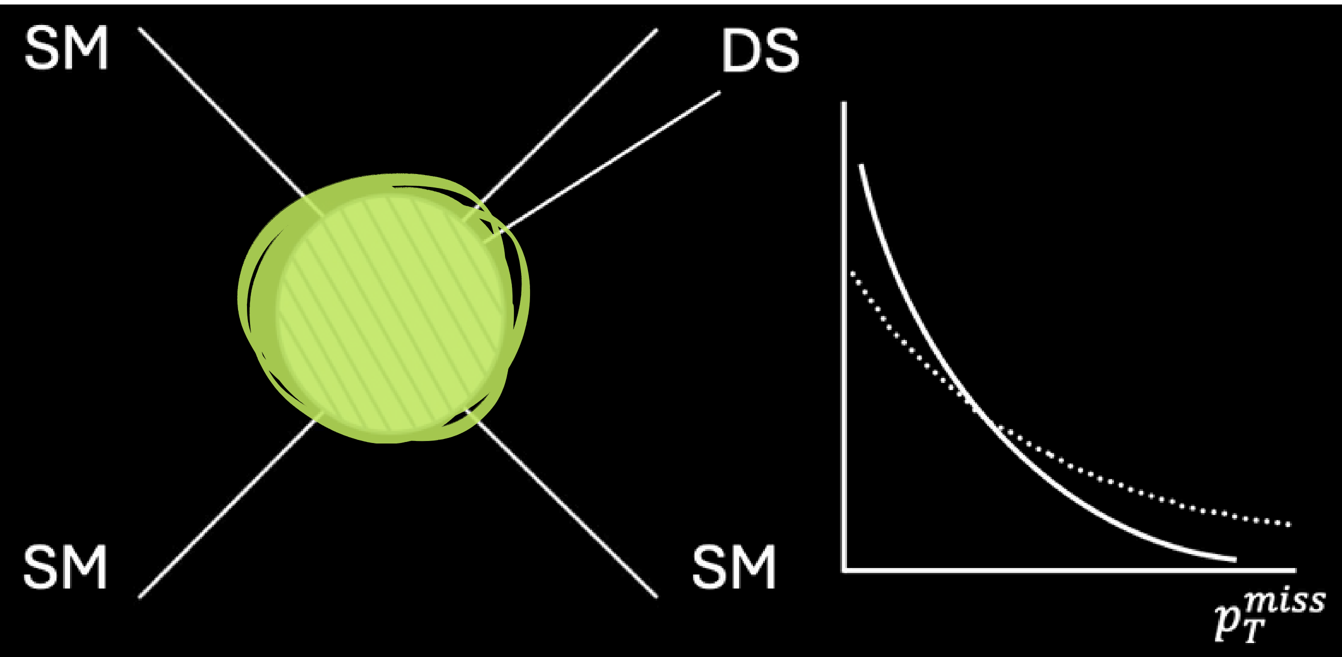
Unconventional signatures

- More complicated DSs can produce signatures completely different from SM (disappearing tracks, emerging jets, displaced leptons, etc.)
- New reconstructed objects often necessary

Overview of experimental signatures at LHC

Dark Sectors at colliders





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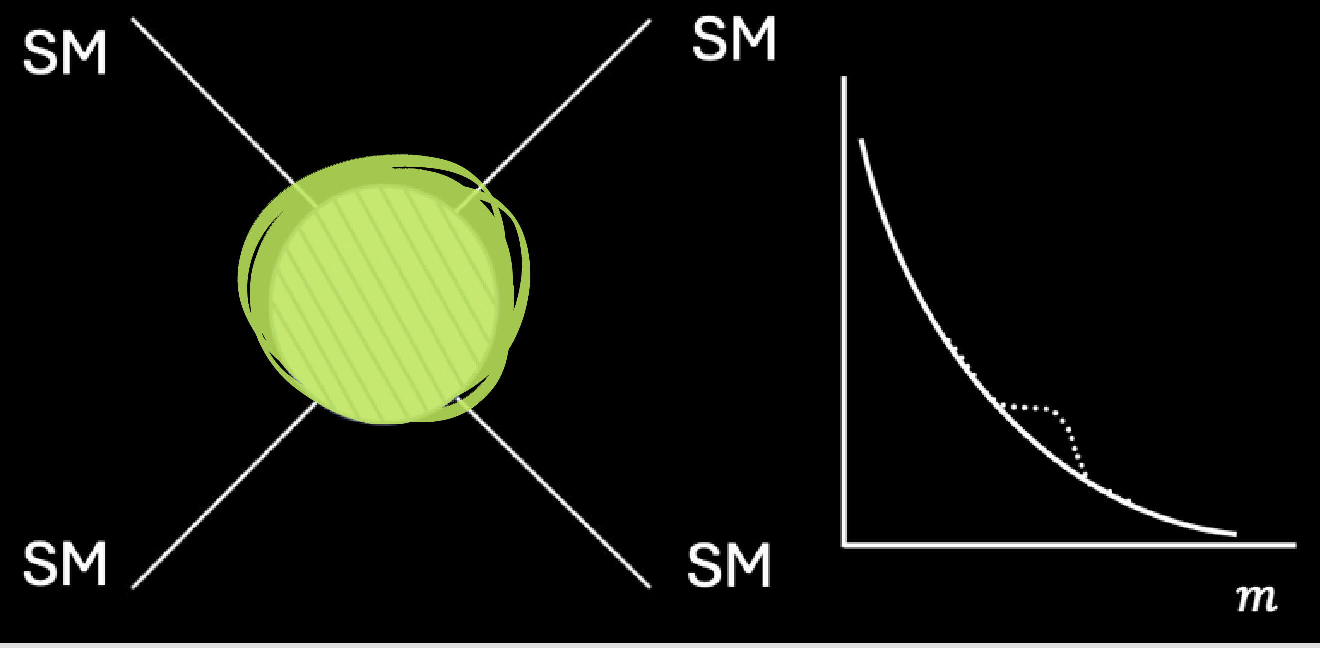

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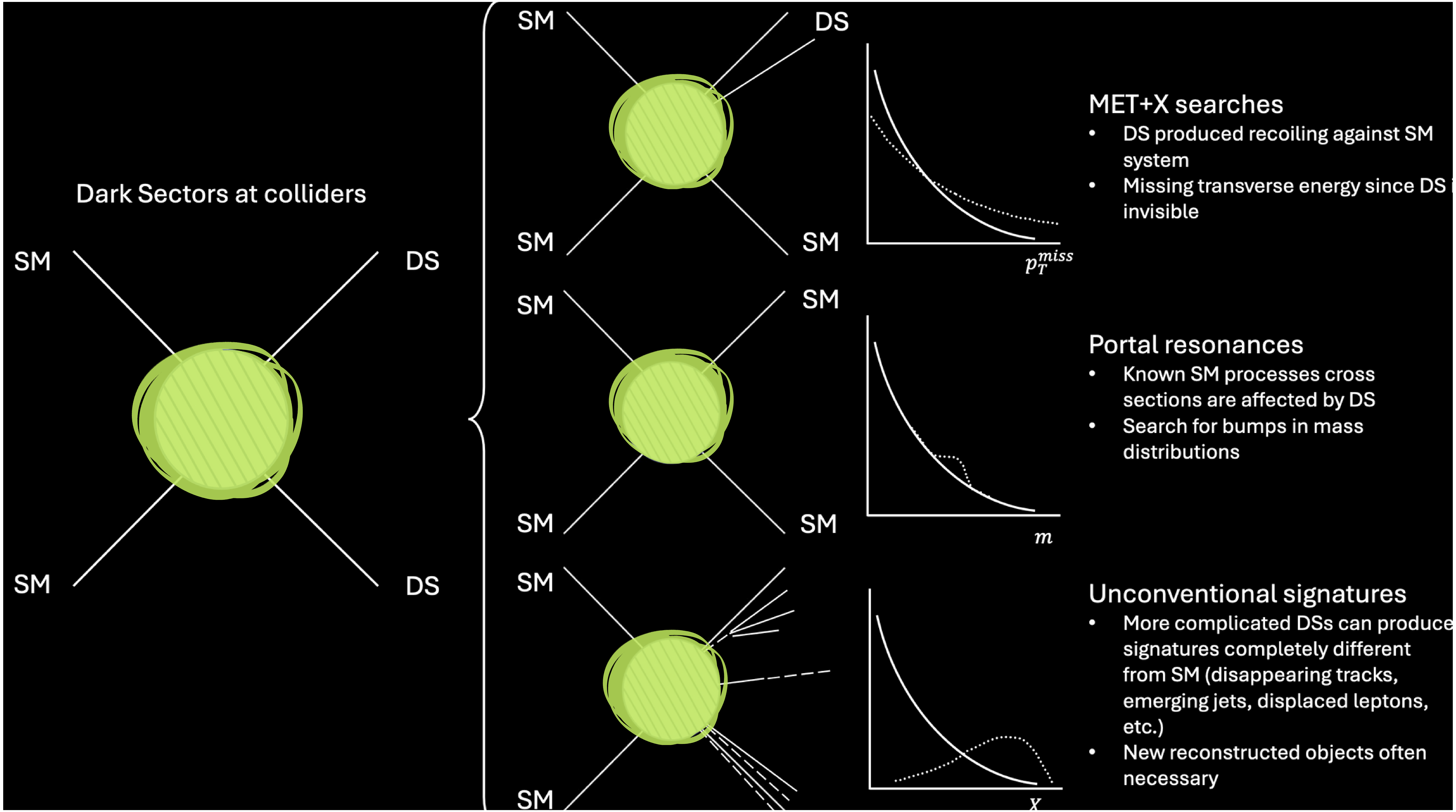

Common experimental challenges

- Dedicated triggers and data streams
- Pileup mitigation and background removal
- Ad hoc objects reconstruction

Dedicated triggers and data streams

- Many triggers developed to target a **wide variety of final states** predicted by DS physics: stringent **kinematic thresholds** applied to keep low rates
- Challenges arise in obtaining **sensitivity to theories w/ exotic topologies**, e.g. new low-mass states

- Intense **scouting/pakring Run 3 program with complex objects** building upon Run 2 experience
- Dedicated triggers featuring **special reconstruction for displaced or delayed objects** deployed

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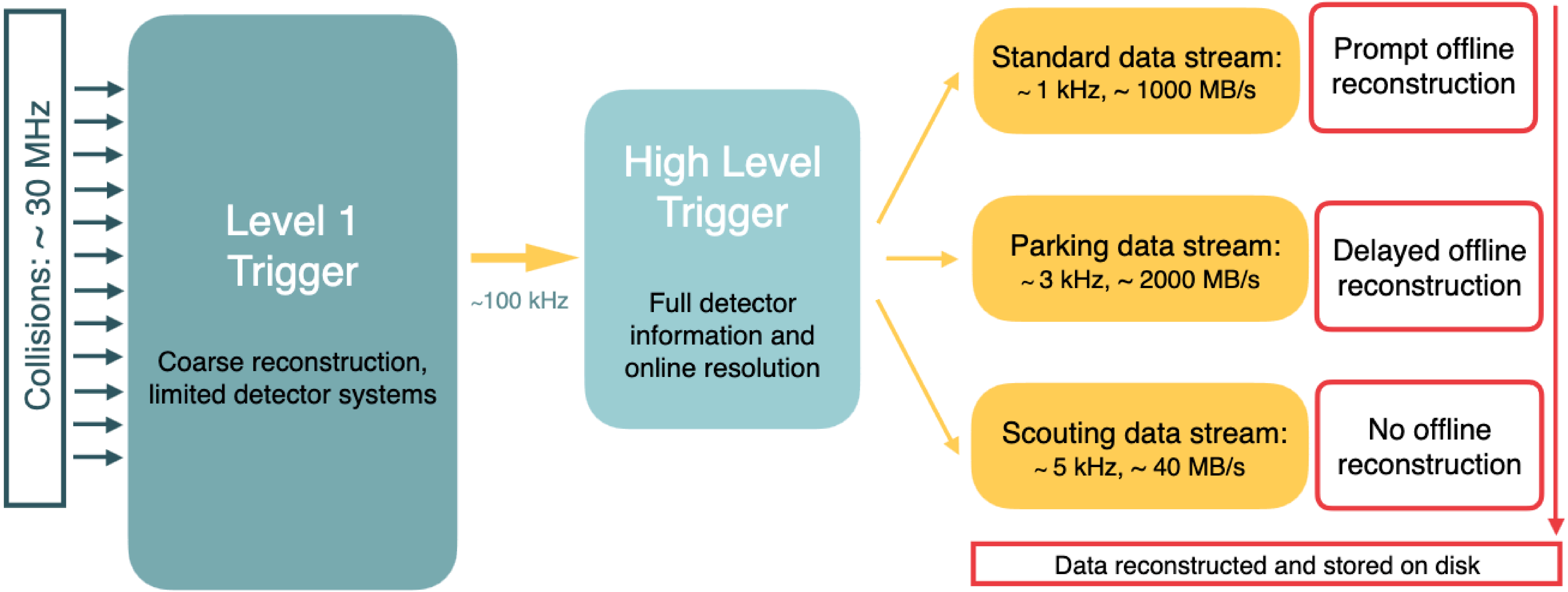

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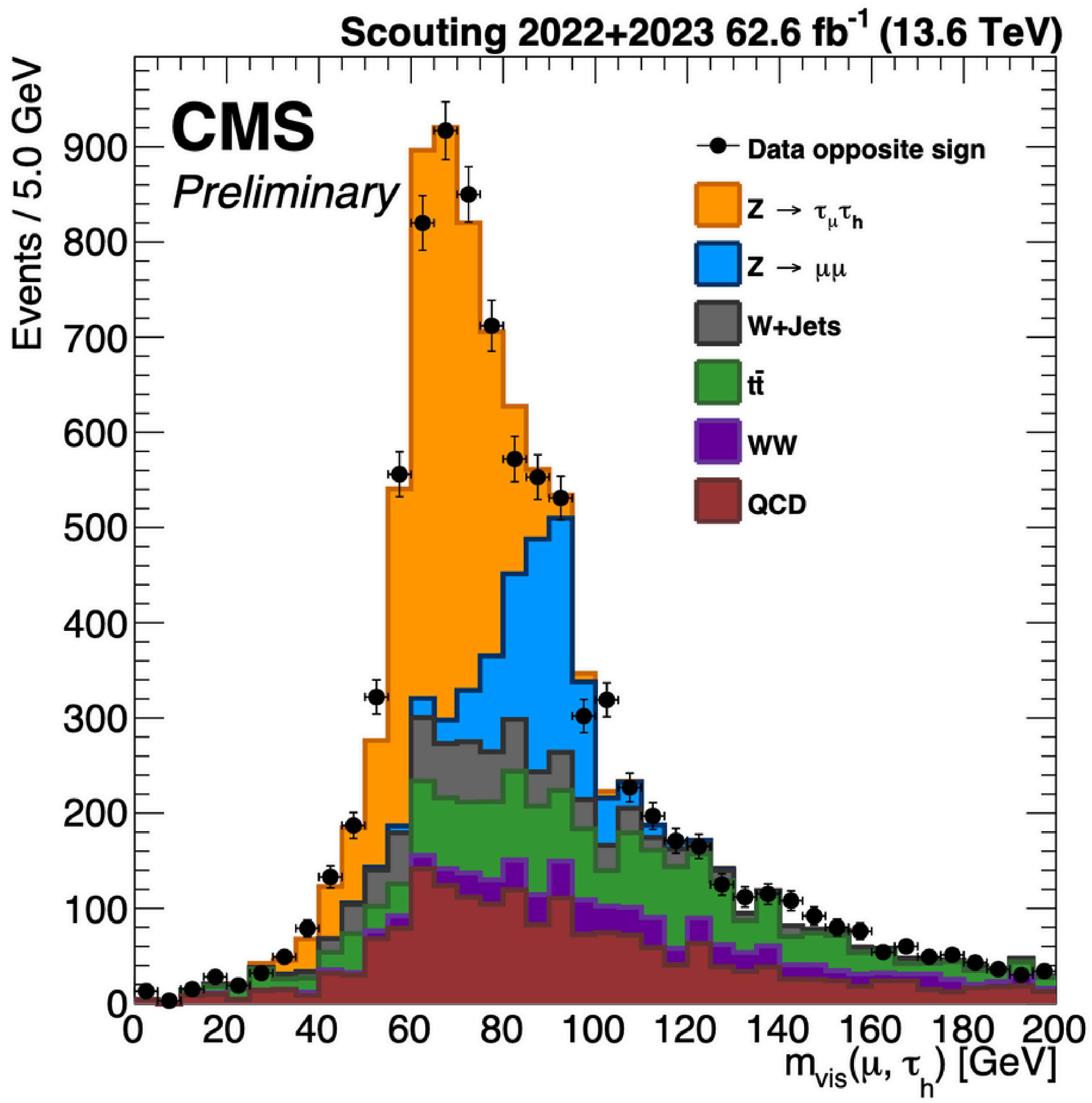
first time in Scouting data



CMS NOTE-2024/006

arXiv:2403.16134

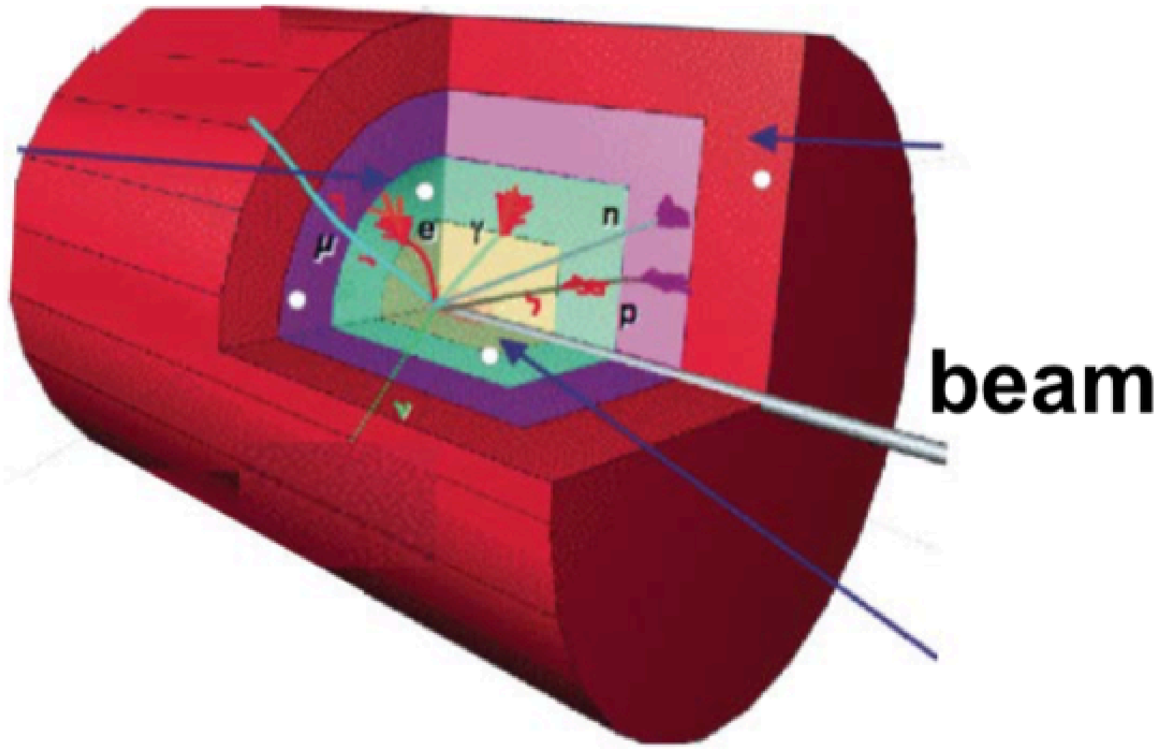
- Intense **scouting/pakring** … on Run 2 experience
- Dedicated triggers featuring **special reconstruction for displaced or delayed objects** deployed

A key ingredient for Dark Matter searches at LHC

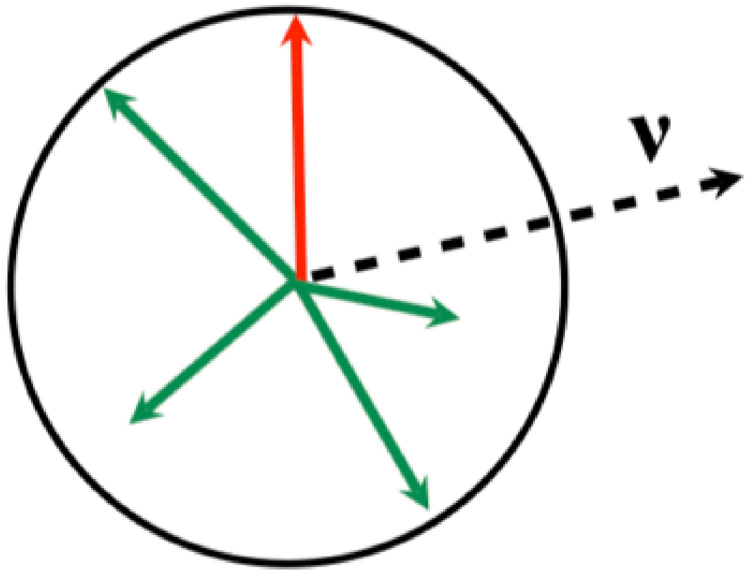
MET vector : negative of vector sum of momenta of all particles **transverse to the beam direction**

MET : magnitude of MET vector

$$\vec{P}_T^{P_1} + \vec{P}_T^{P_2} = 0 = \sum_i \vec{P}_T^{i}(measured)$$



$$\vec{P}_T^{miss} = -\sum_i \vec{P}_T^{i}(measured) \neq 0 \Rightarrow$$



Some particles are not detected (e.g. ν, neutralino)

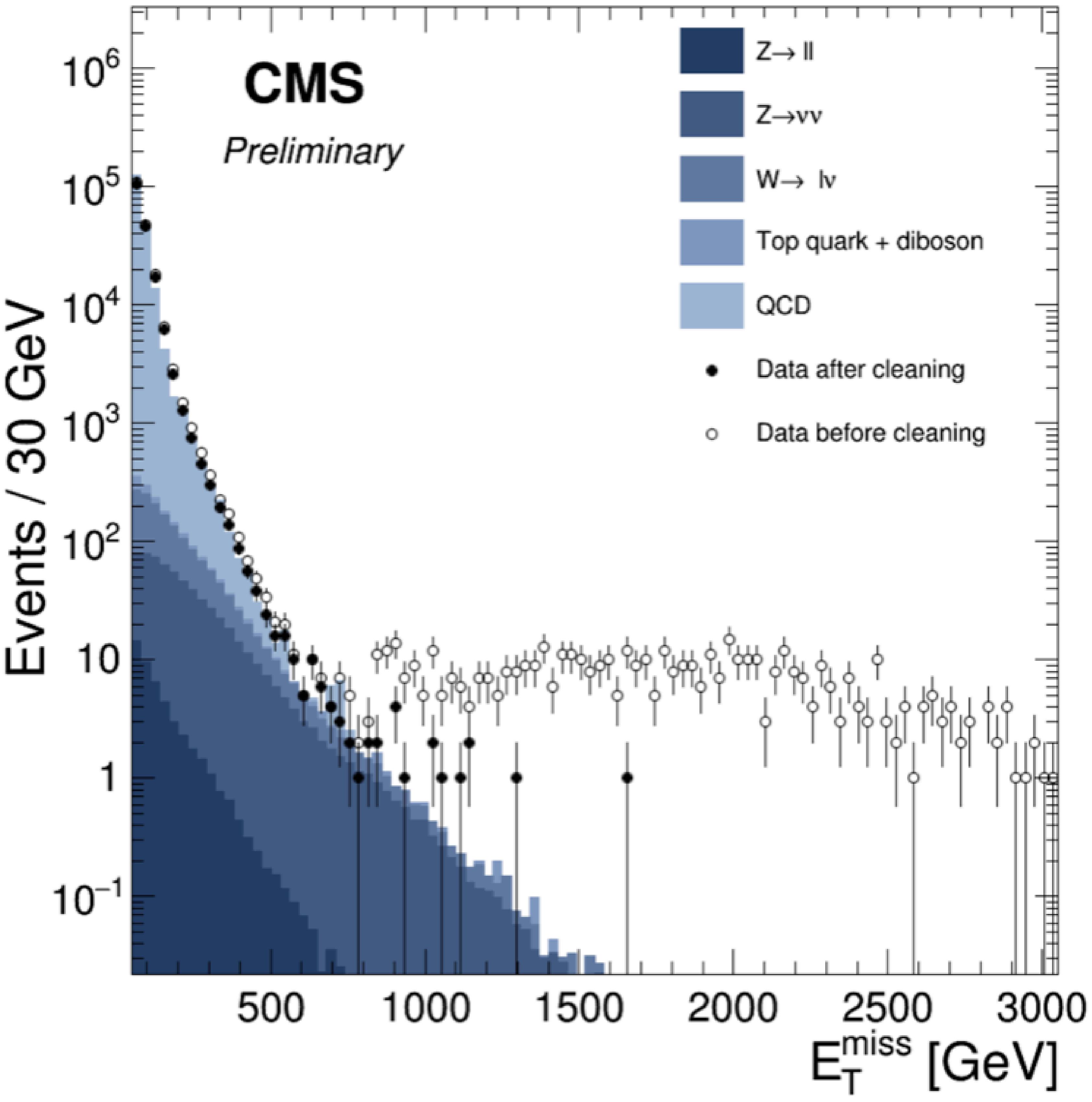
A key ingredient for Dark Matter searches at LHC

$$\vec{E}_T^{miss} = -\sum_i \vec{E}_T^i$$

$$\not{E}_T = \left|\vec{E}_T^{miss}\right|$$

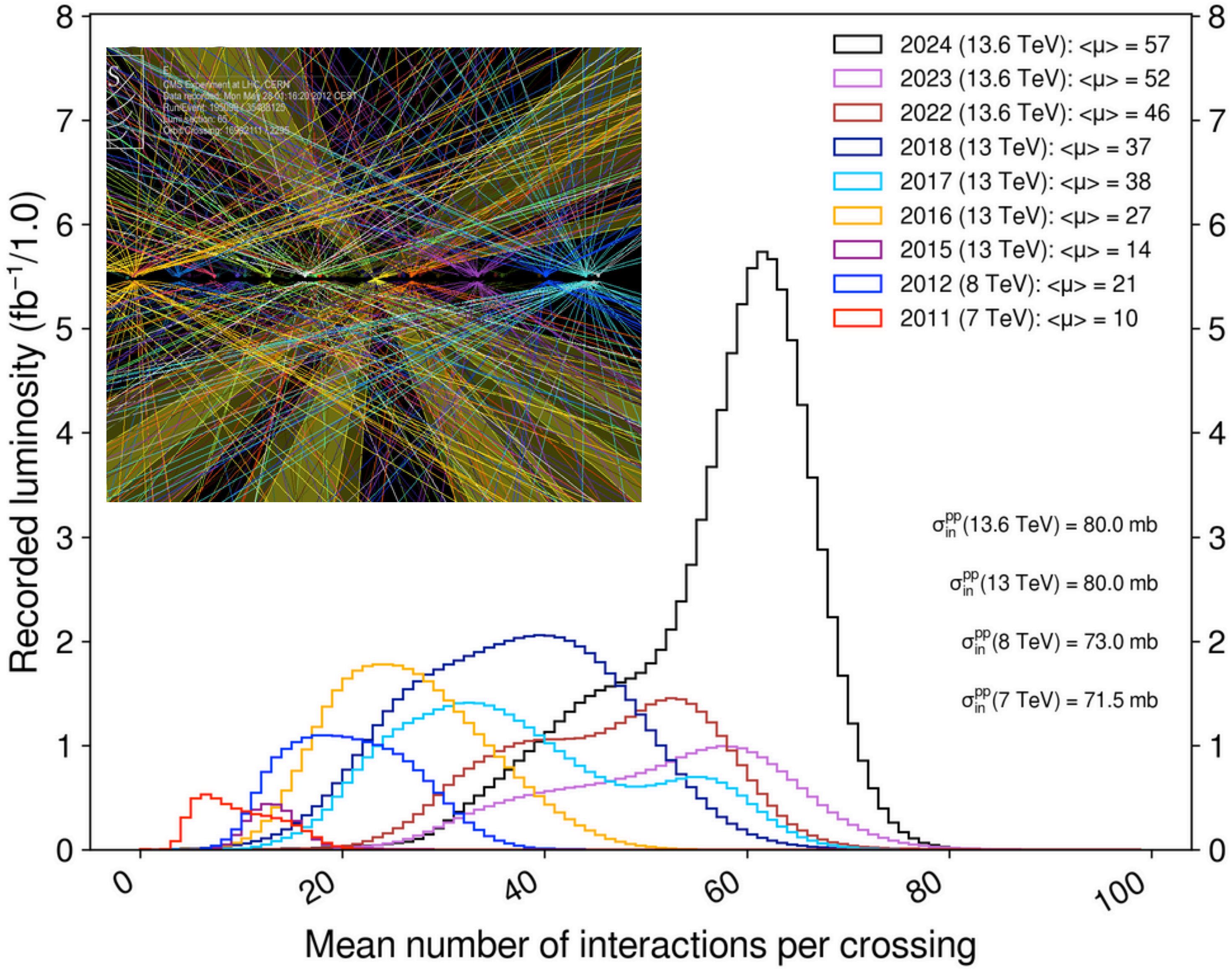
First step to measure MET: understand what is going on in your detector !

- Beam background, cosmics, various kind of noise some of which not really expected.
- Special filters developed to eliminate noise, which could otherwise affect MET performance



Pileup mitigation

- **Multiple pp interactions** per LHC bunch crossing.
- Challenge: **Distinguishing primary collision** signals from overlapping events
- Increased particle multiplicity affects energy and momentum and **objects quality.**



CMS-LUMI-TWIKI

Mitigation Techniques

- **Pileup Per Particle Identification (PUPPI):** assigns weights to particles based on their likelihood of originating from primary interaction.
- **Improve jet and Missing Energy (MET) resolution** by suppressing pileup contributions.

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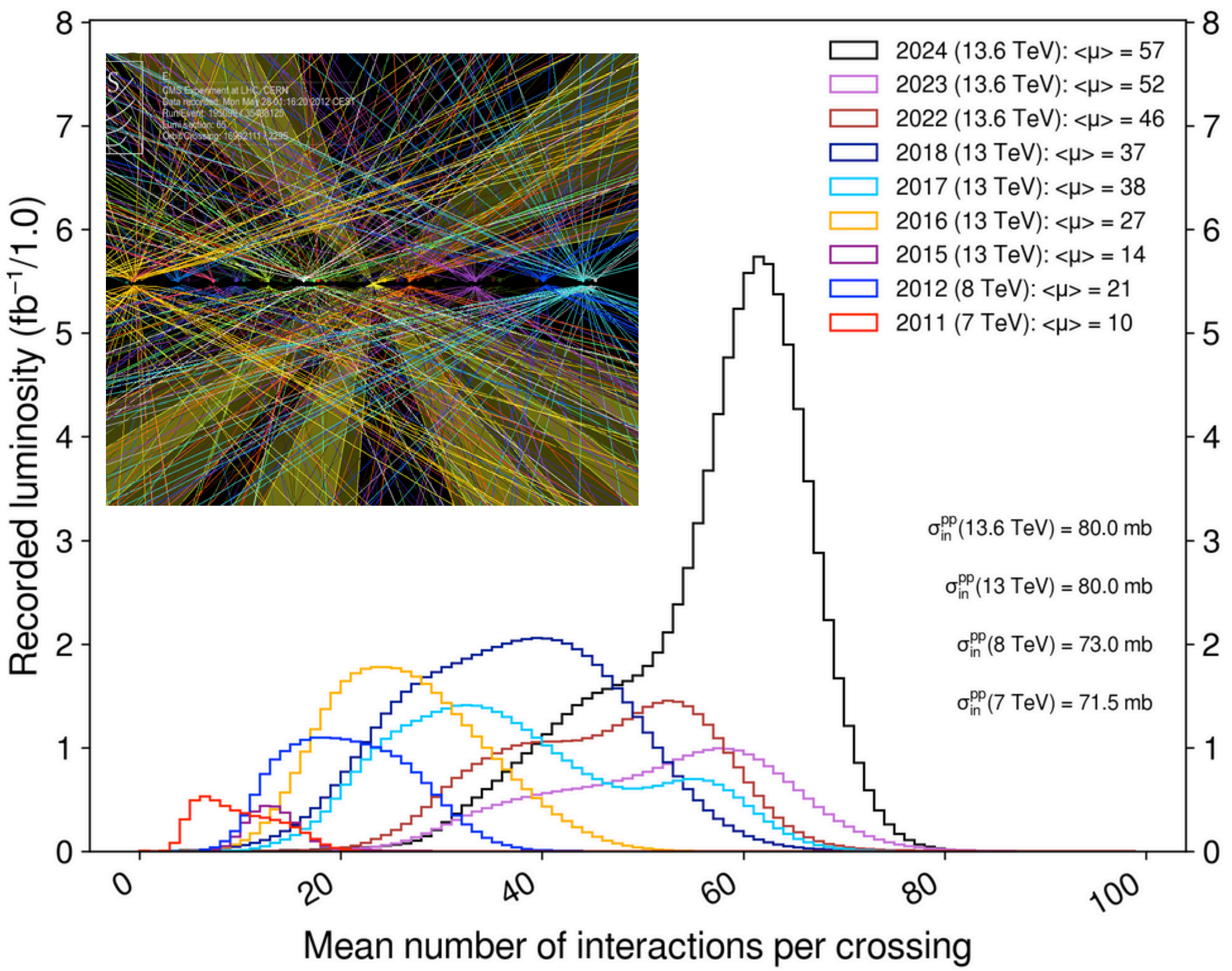

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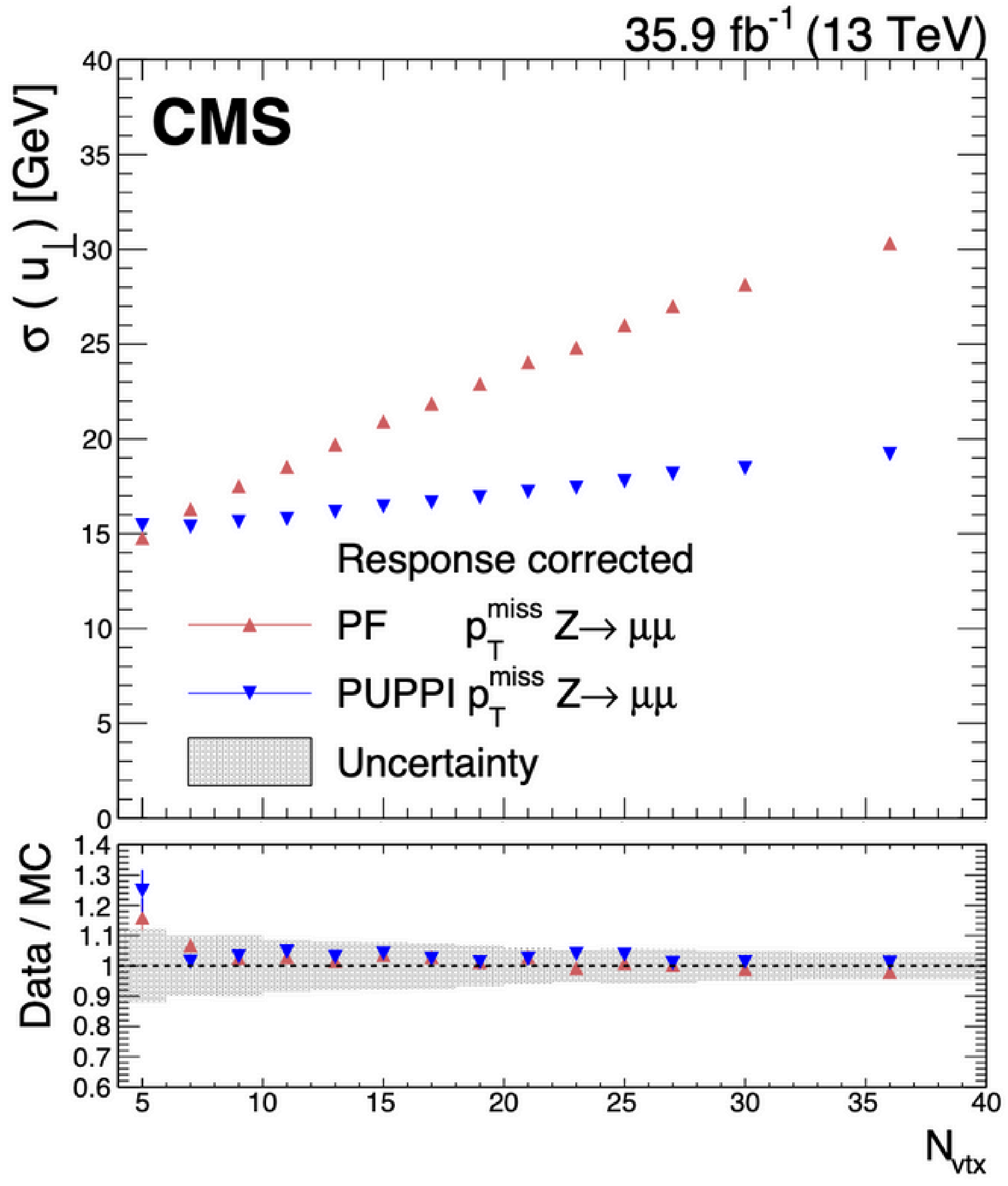

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Ad hoc objects reconstruction

- Specific examples of **LLP signatures** include displaced and delayed leptons, photons, and jets; disappearing tracks; and nonstandard tracks
- **Standard triggers, object reconstruction usually inadequate** b/c designed for promptly decaying particles

E.g.1: Identify energy deposits from slow-moving particles w/ **delayed calorimetry (300ps-1ns resolution)**

E.g.2: Use **muon detector as a sampling calorimeter** to identify displaced showers produced by LLPs.

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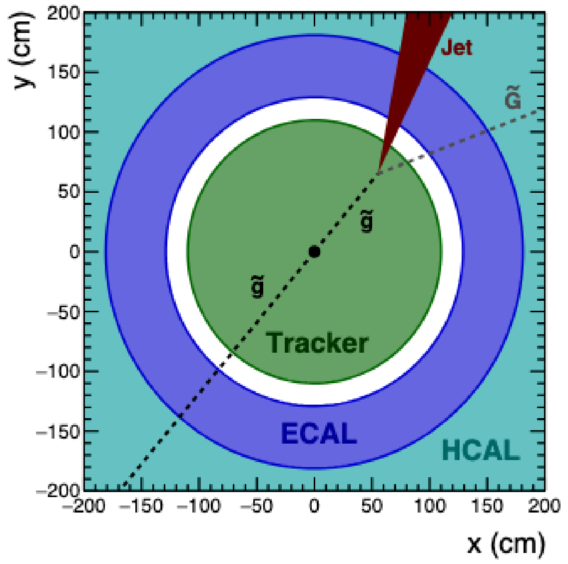

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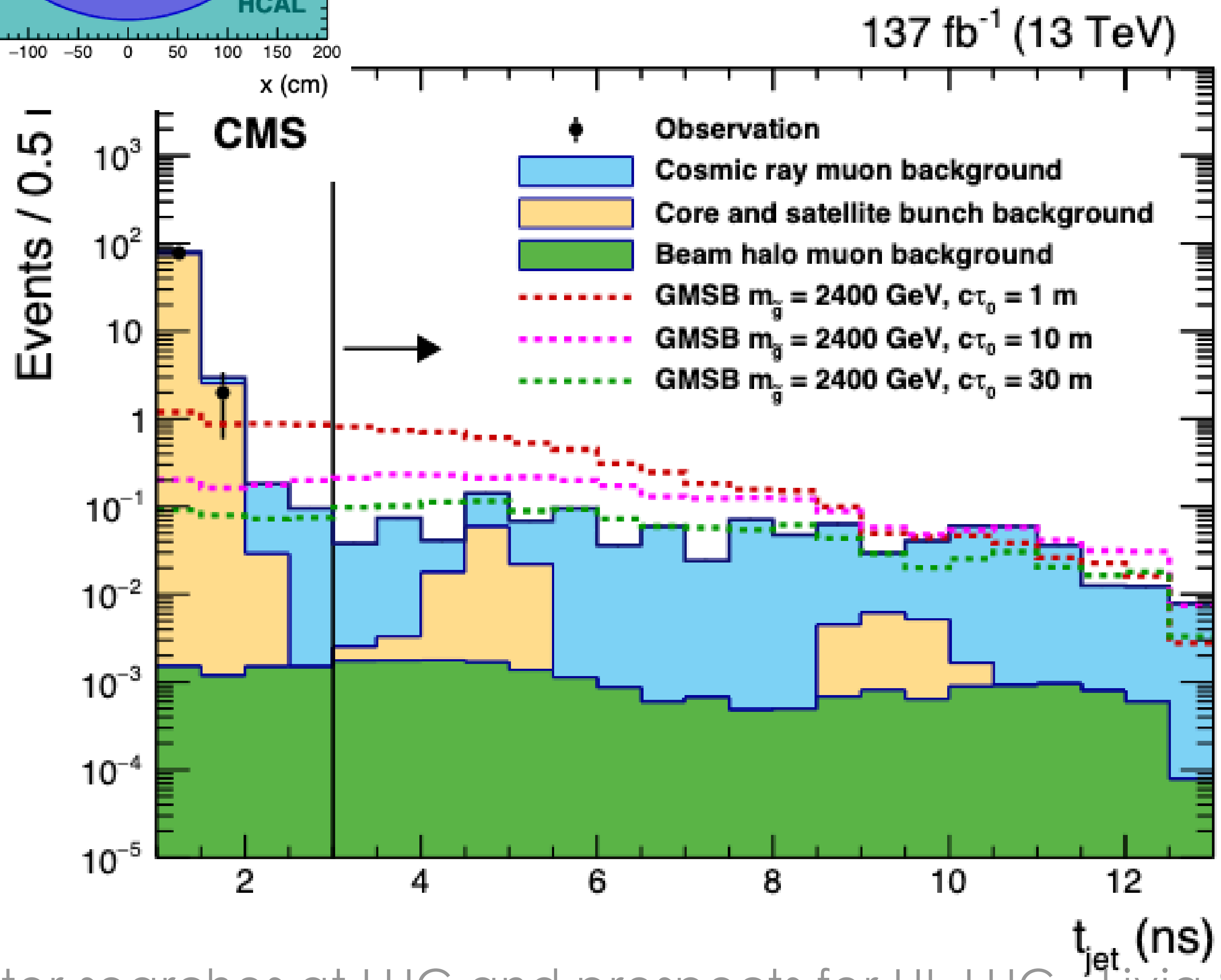
arXiv:1906.06441



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CMS-PAS-EXO-23-015

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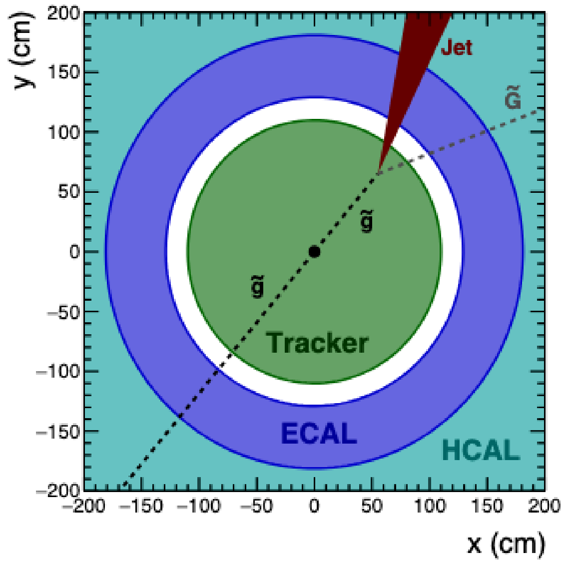

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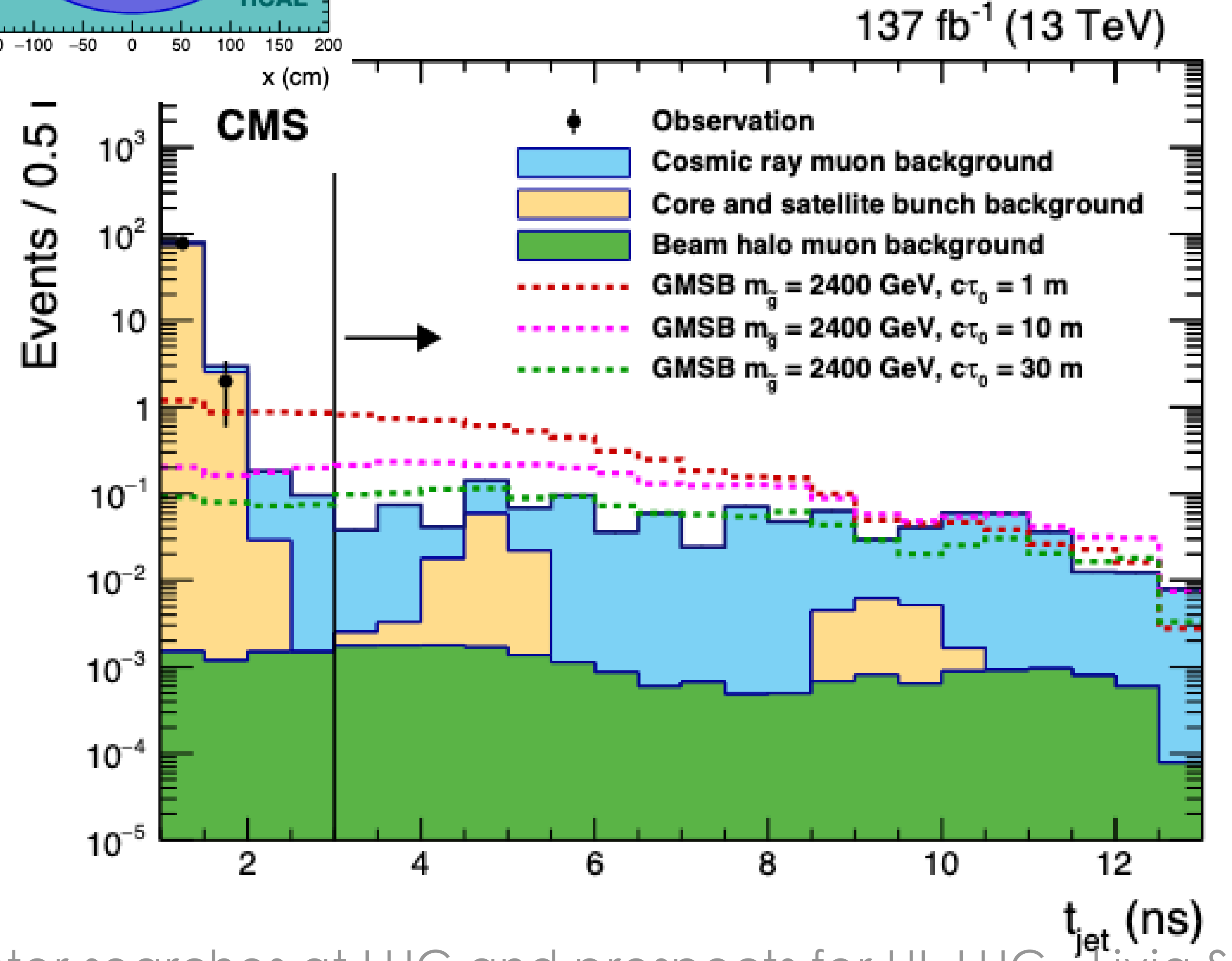

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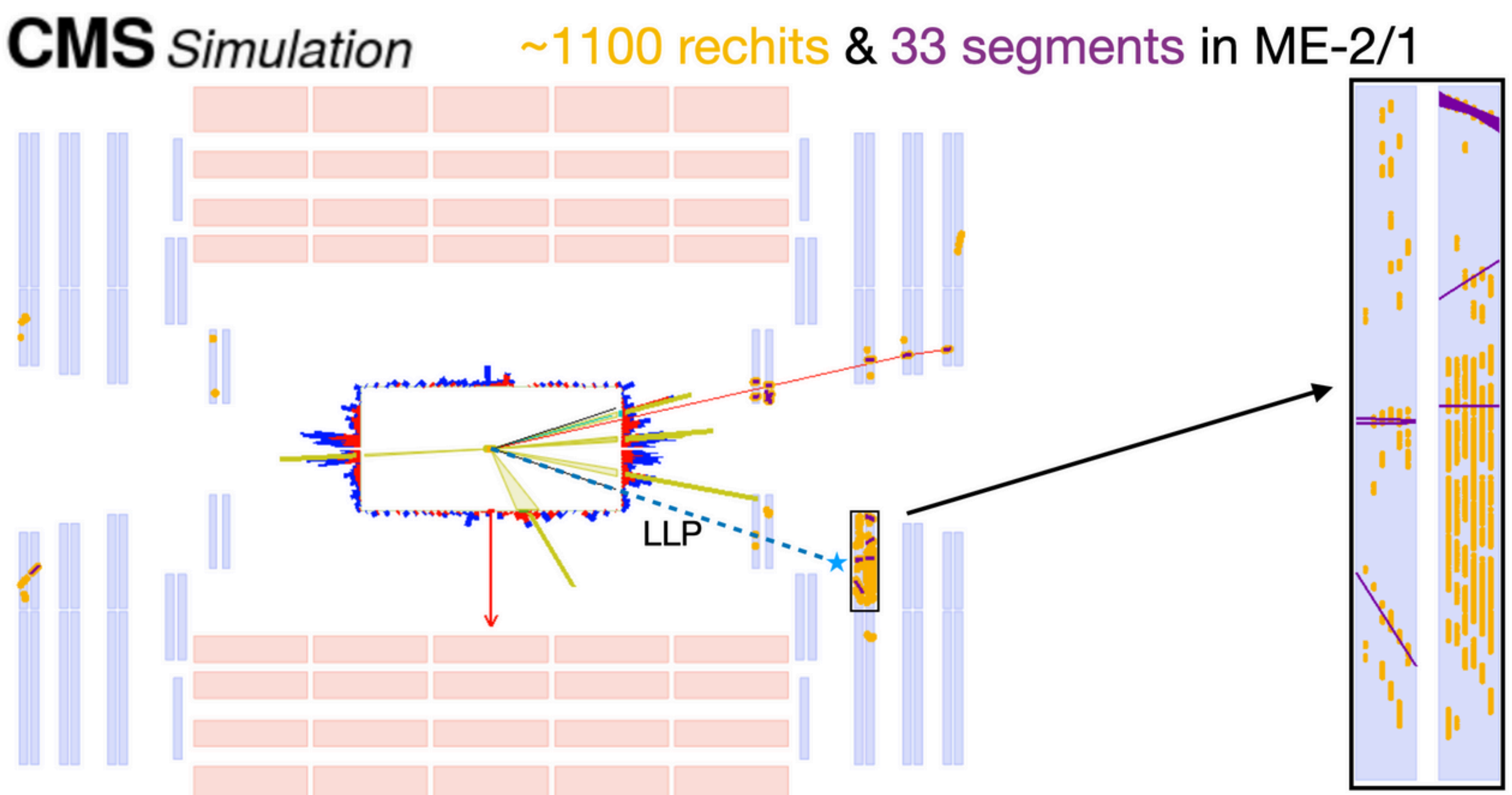

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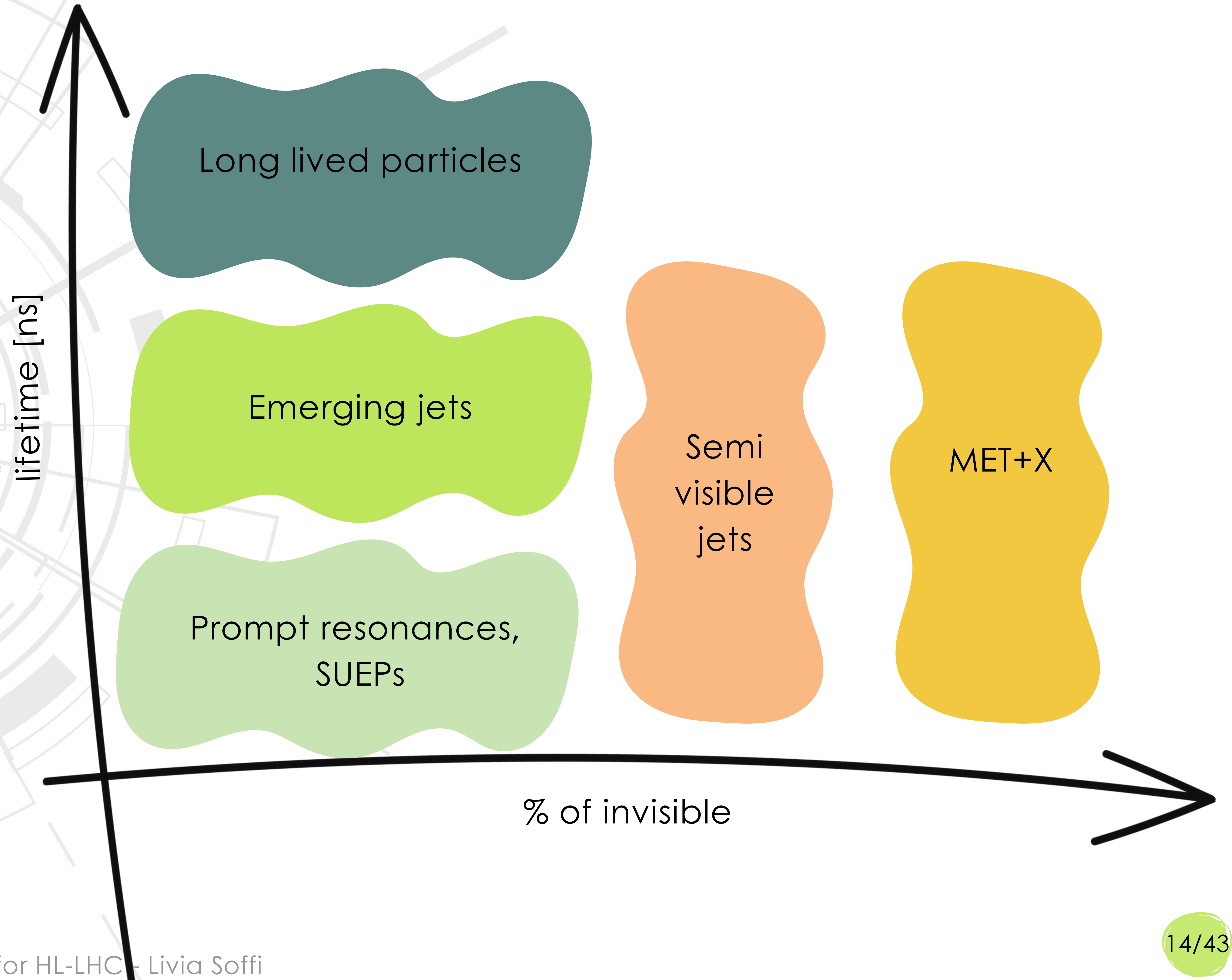
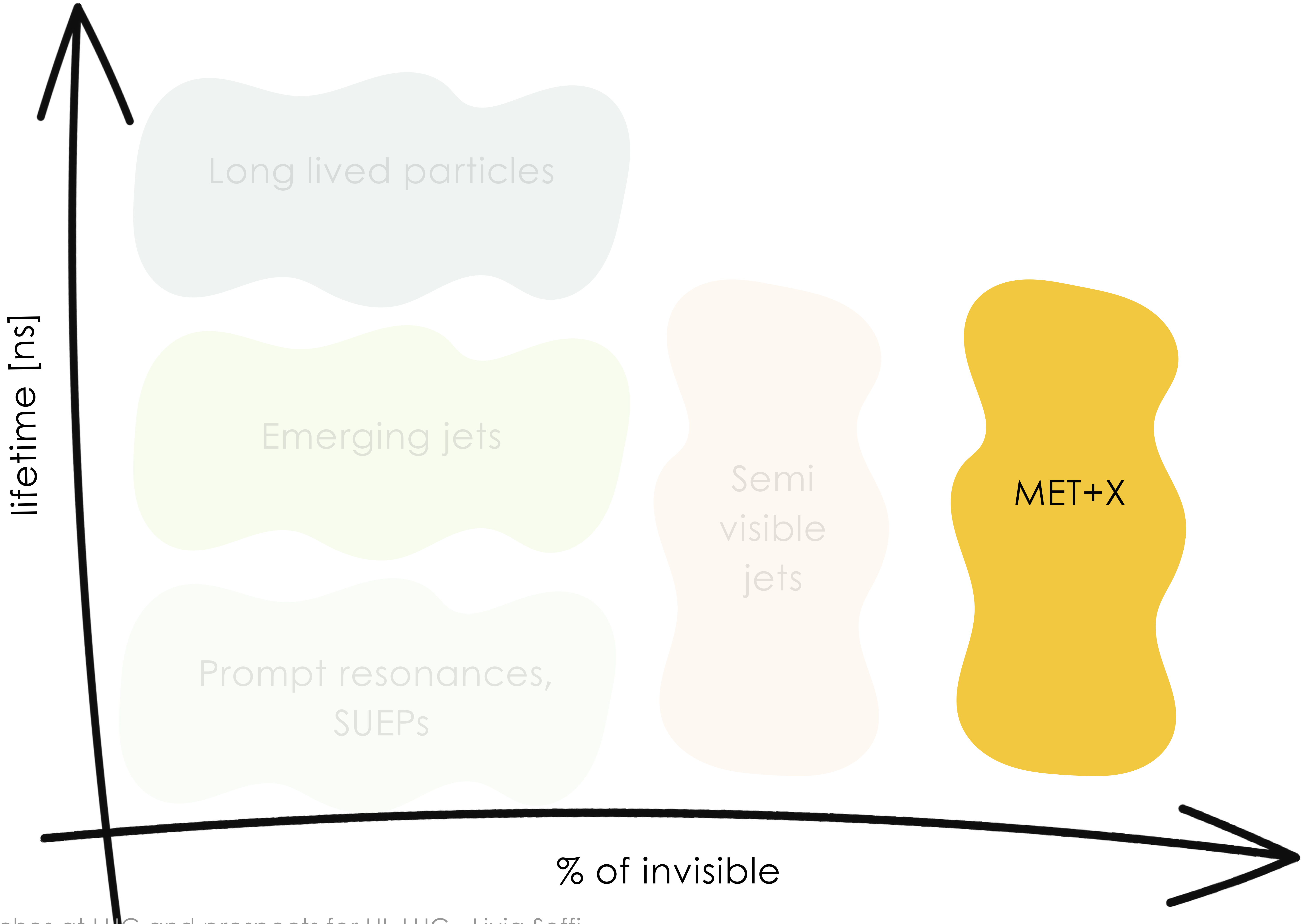
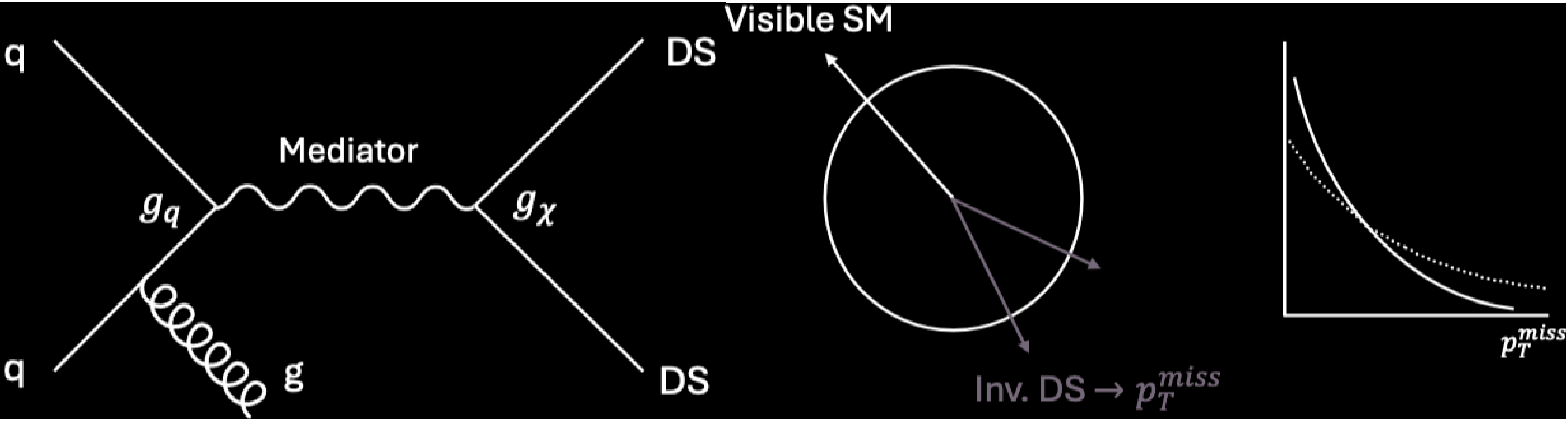
Signature based physics program





lifetime [ns]
Long lived particles
Emerging jets
Prompt resonances,
SUEPs
Semi
visible
jets
MET+X
% of invisible

MET based searches for invisible

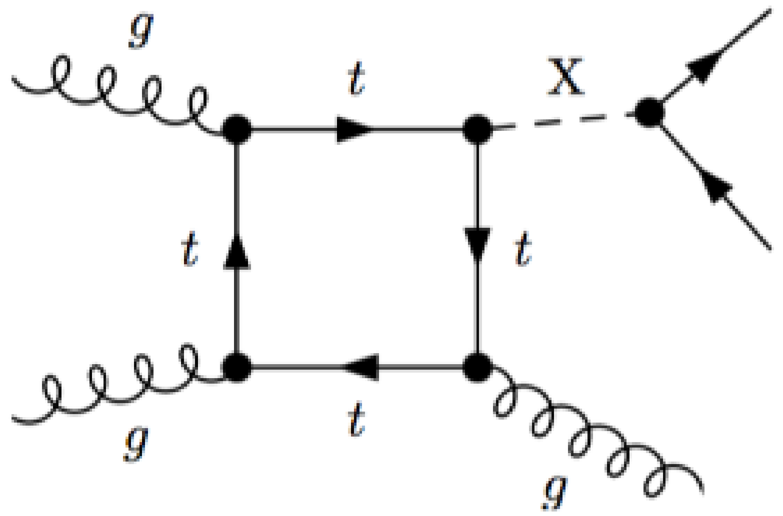


- Strategy:
  - Invisible DS particles produced via **mediator that couples to SM and DS**
  - DS particles recoil against SM (jet, photon, V, Higgs, t/b, tt/bb, etc.)

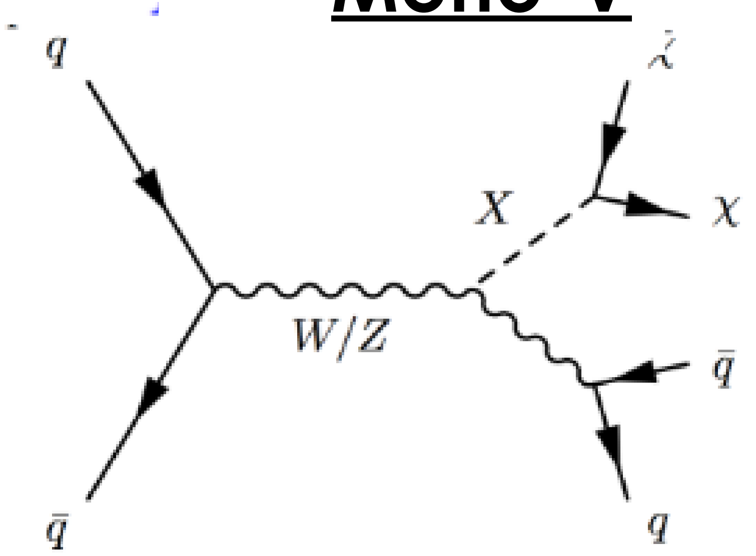
- Target:
  - Simplified DM models (e.g. WIMPs) with **parameters:** *mmed*, *mDM*, *gq*, *gχ*
  - Higgs portals
  - Any model with invisible decays! Very model independent search

The Mono-Jet search

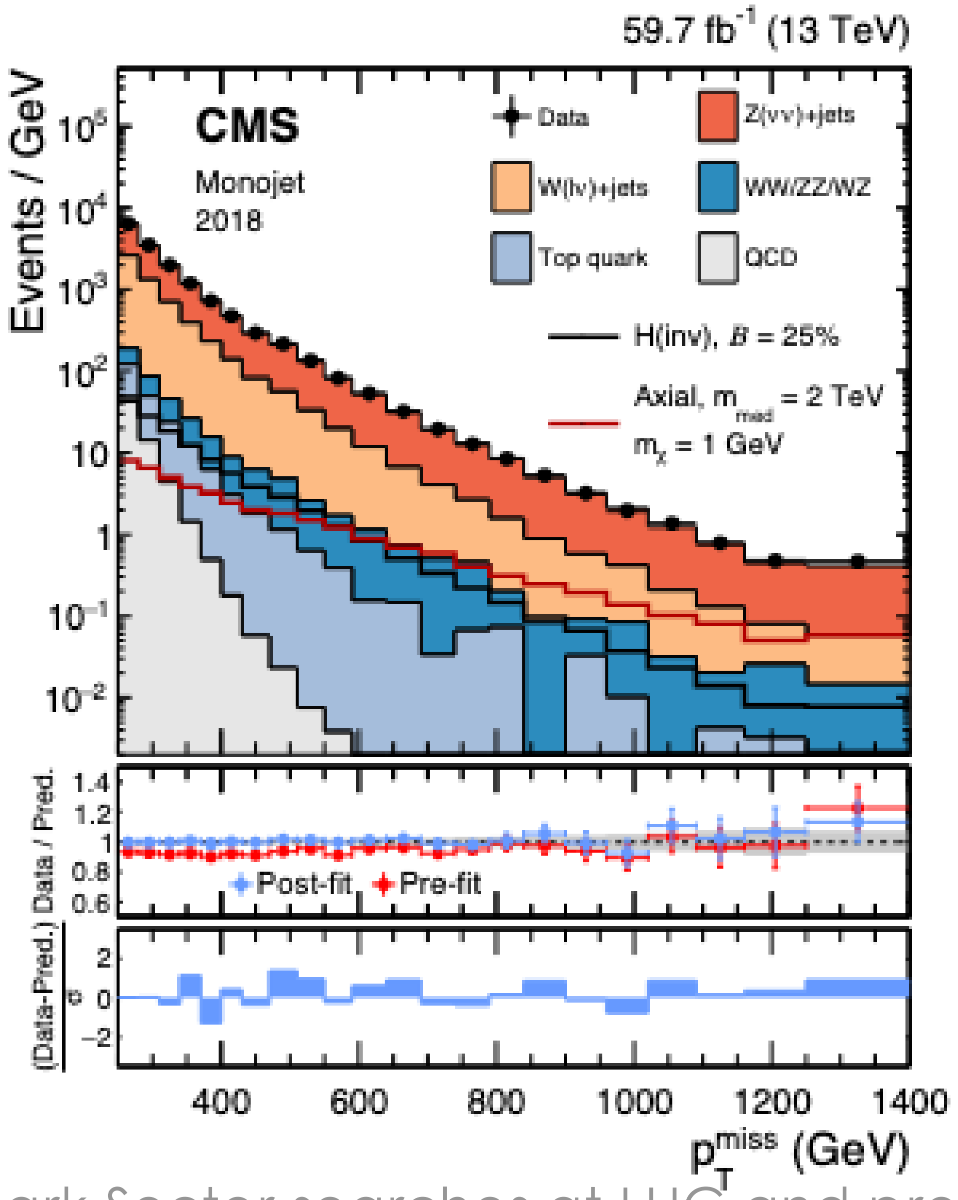
Mono-Jet

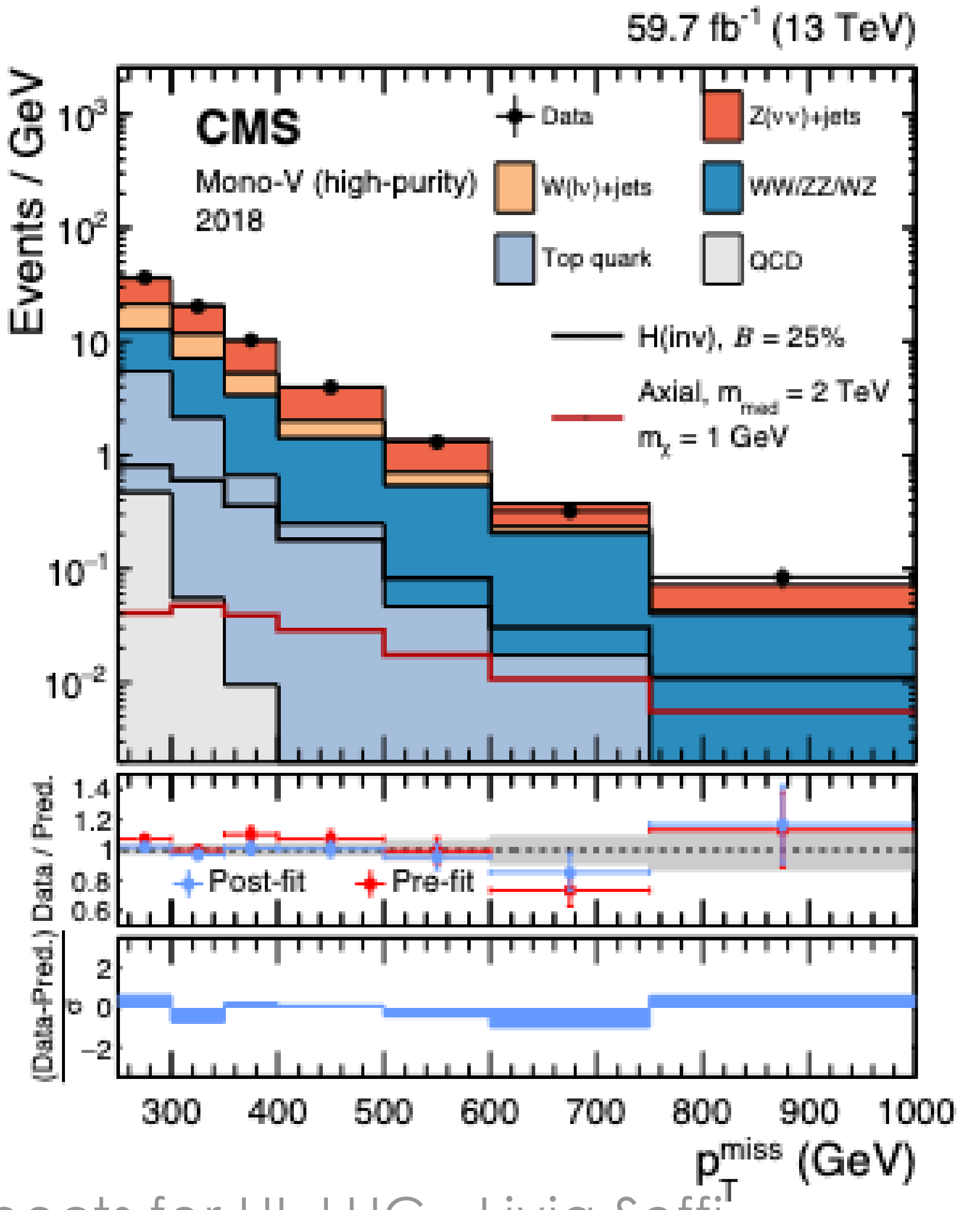


Mono-V



- Main Backgrounds
  - Z→νν is the main background and is irreducible
  - W→lν when one lepton out of acceptance/not identified
- Minor Backgrounds
  - Top: mainly from semi-leptonic tt̄
  - Di-boson: WW and WZ production mainly
  - γ+jets
  - QCD multi-jet





Main Back. estimated **from data considering 5 Control Regions**

Z→νν

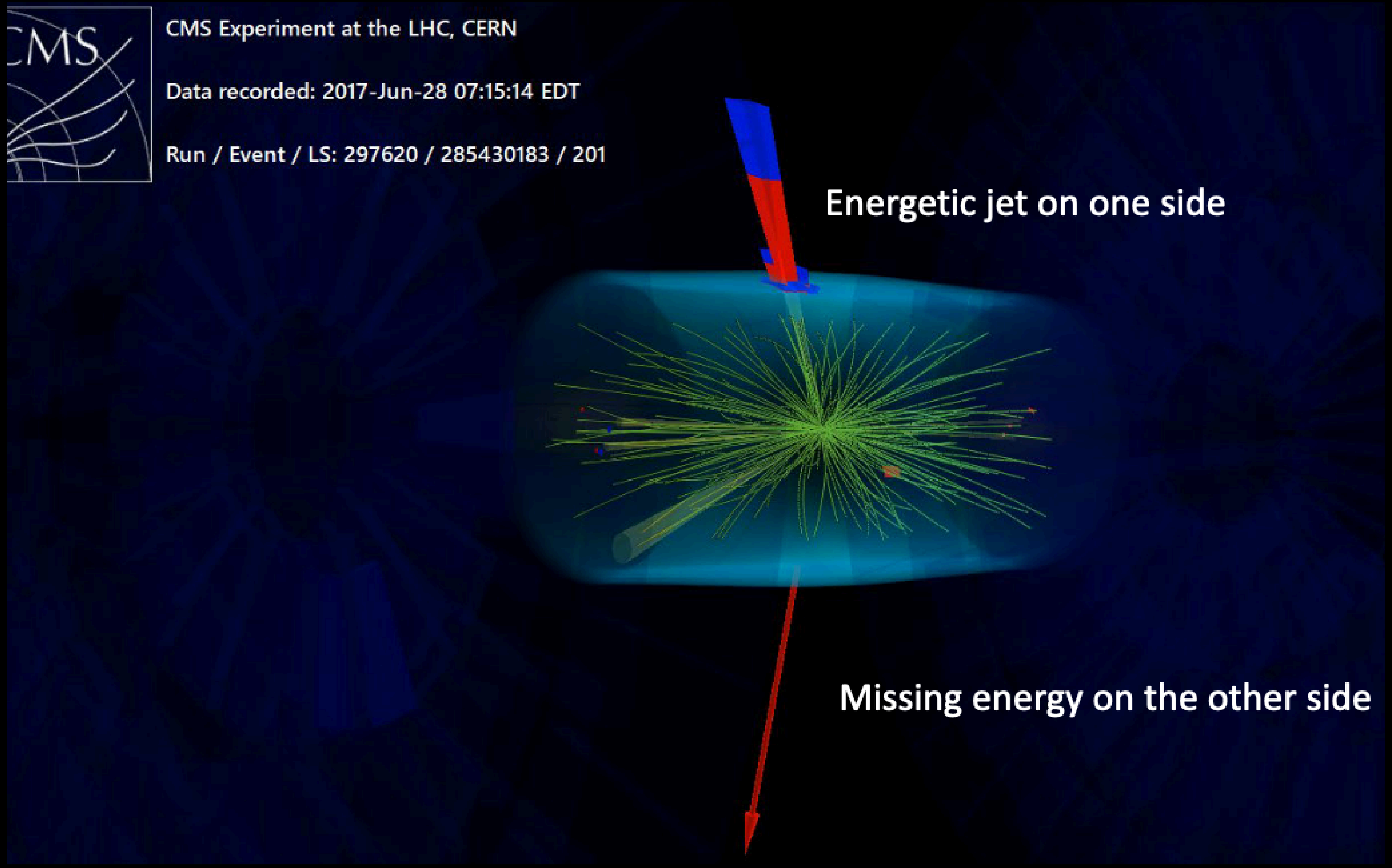
Di-muon events (Z→μμ enriched)
Di-electron events (Z→ee enriched)
Photon+jets events

W+jets

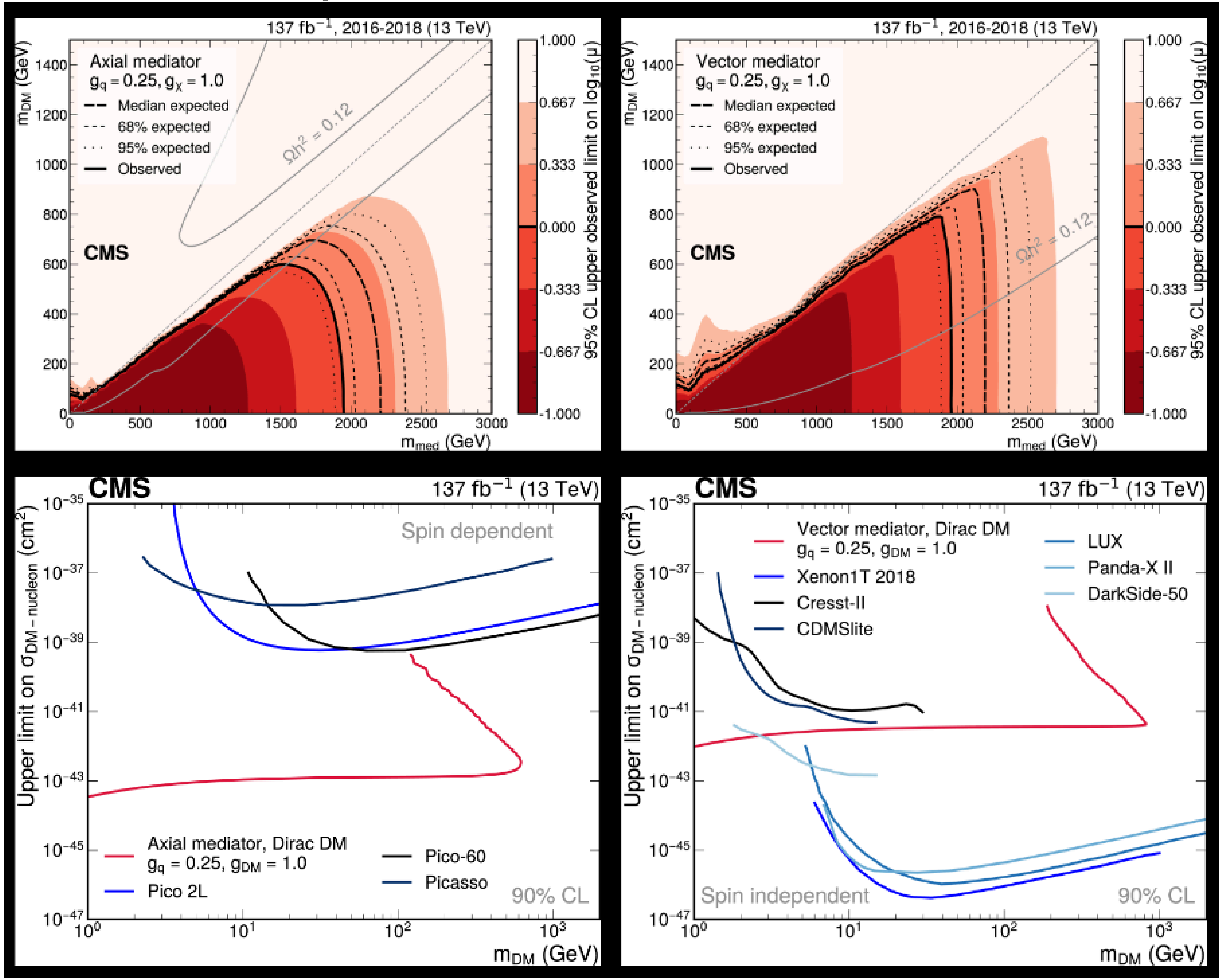
Single muon (W→μν enriched)
Single electron (W→eν enriched)

arXiv:2107.13021

A mono-Jet search



Sensitivity from Mono-Jet

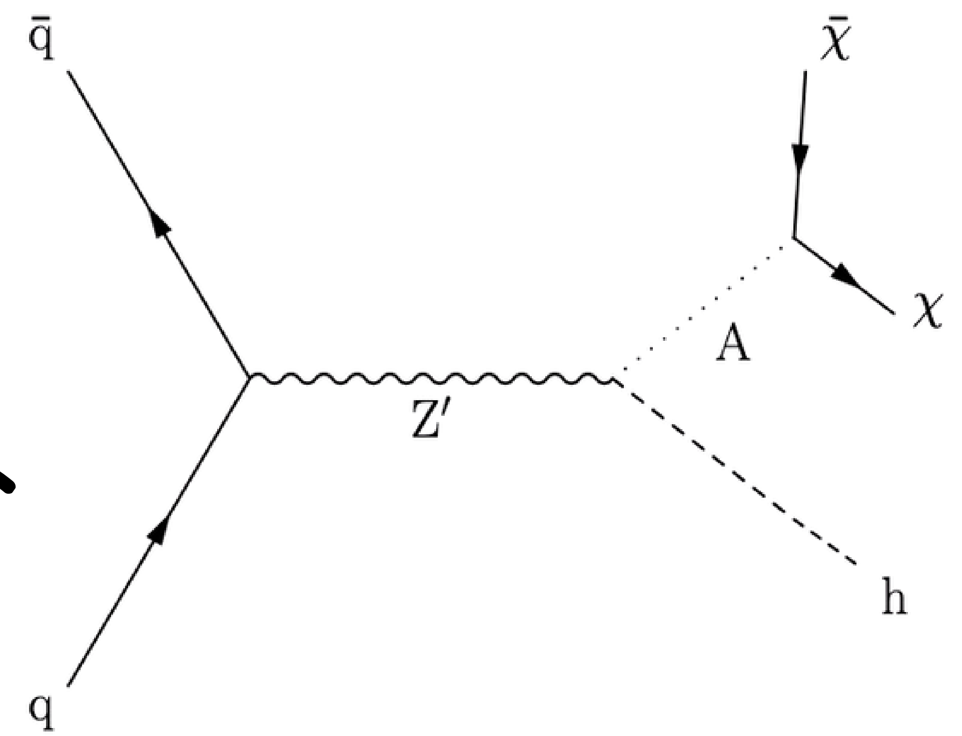


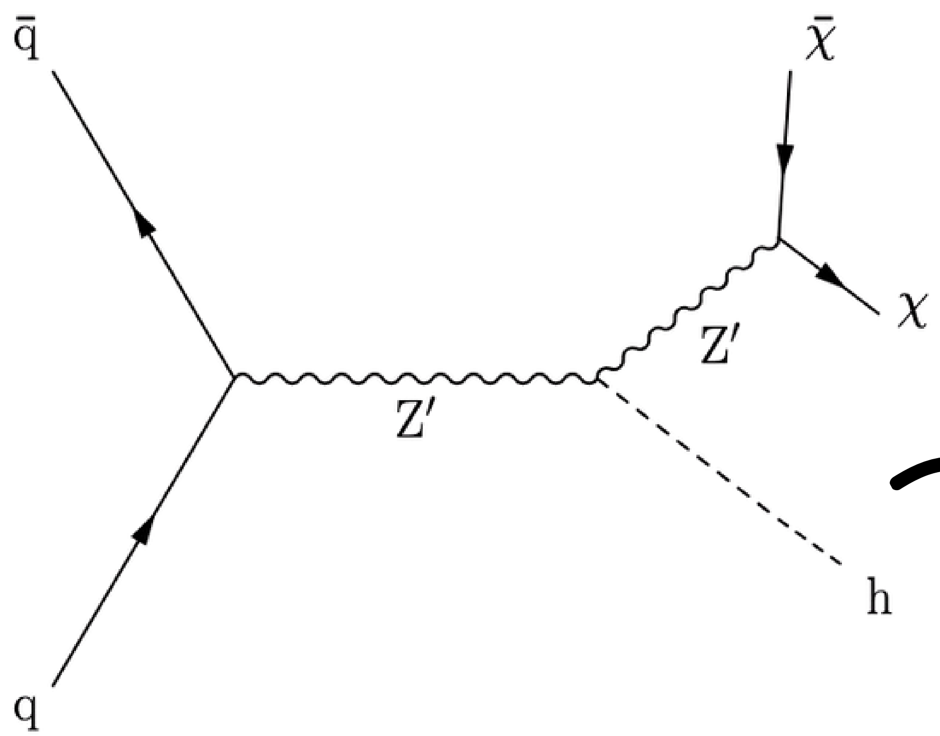
- As an example, the same mono-jet search can be re-interpreted for many DS/DM models
  - **Simplified DM models**: WIMPs with vector, axial, pseudoscalars, fermion portals
  - $\mathcal{B}(H \rightarrow inv)$
  - **Leptoquarks** & other more complex models

- For WIMPs, can constrain directly mDM and $mmed$
  - Can **interpret these as limits on** $\sigma DM\text{−}nucleon$
  - **Compare with direct-detection experiments**

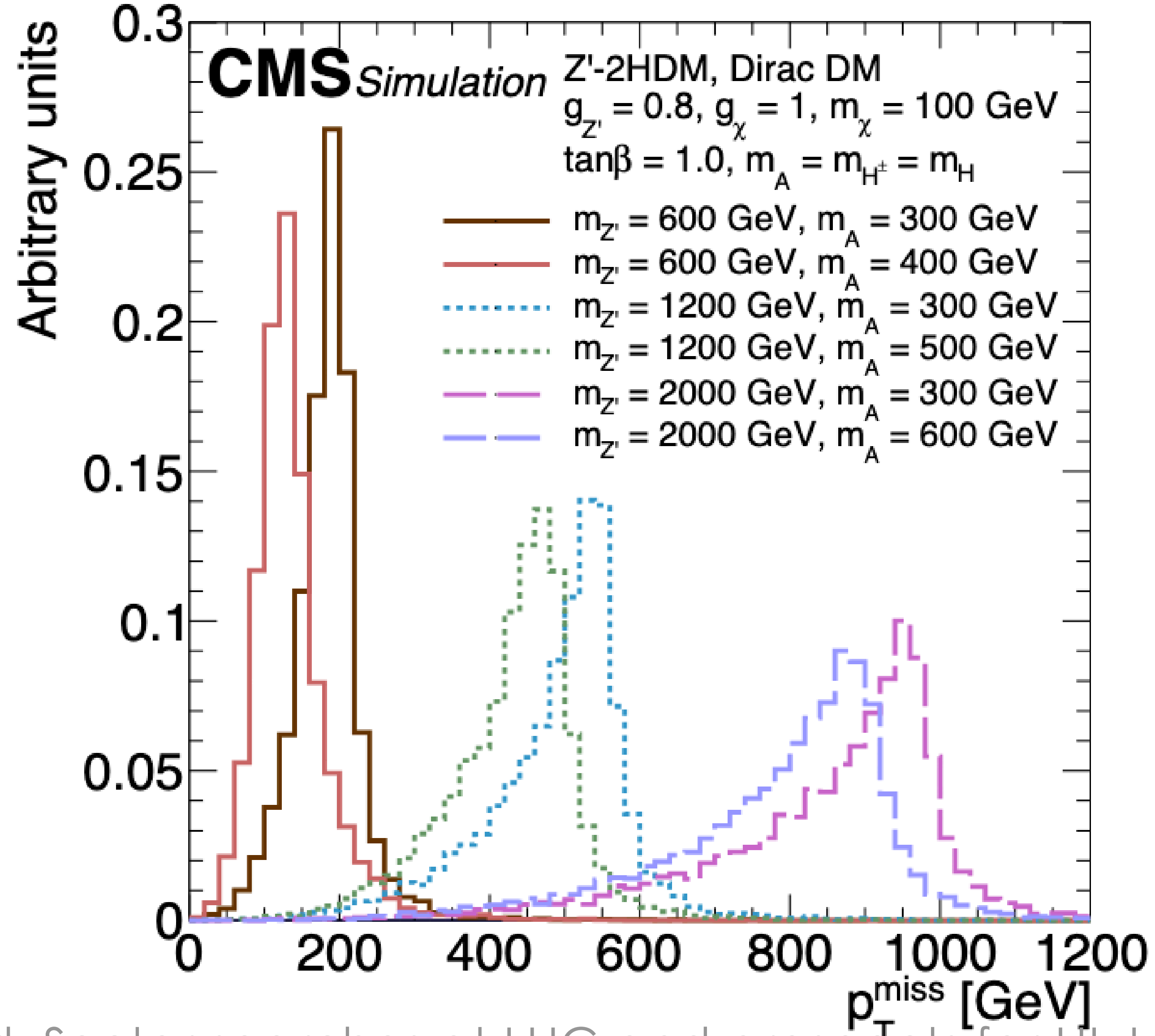
arXiv:2107.13021

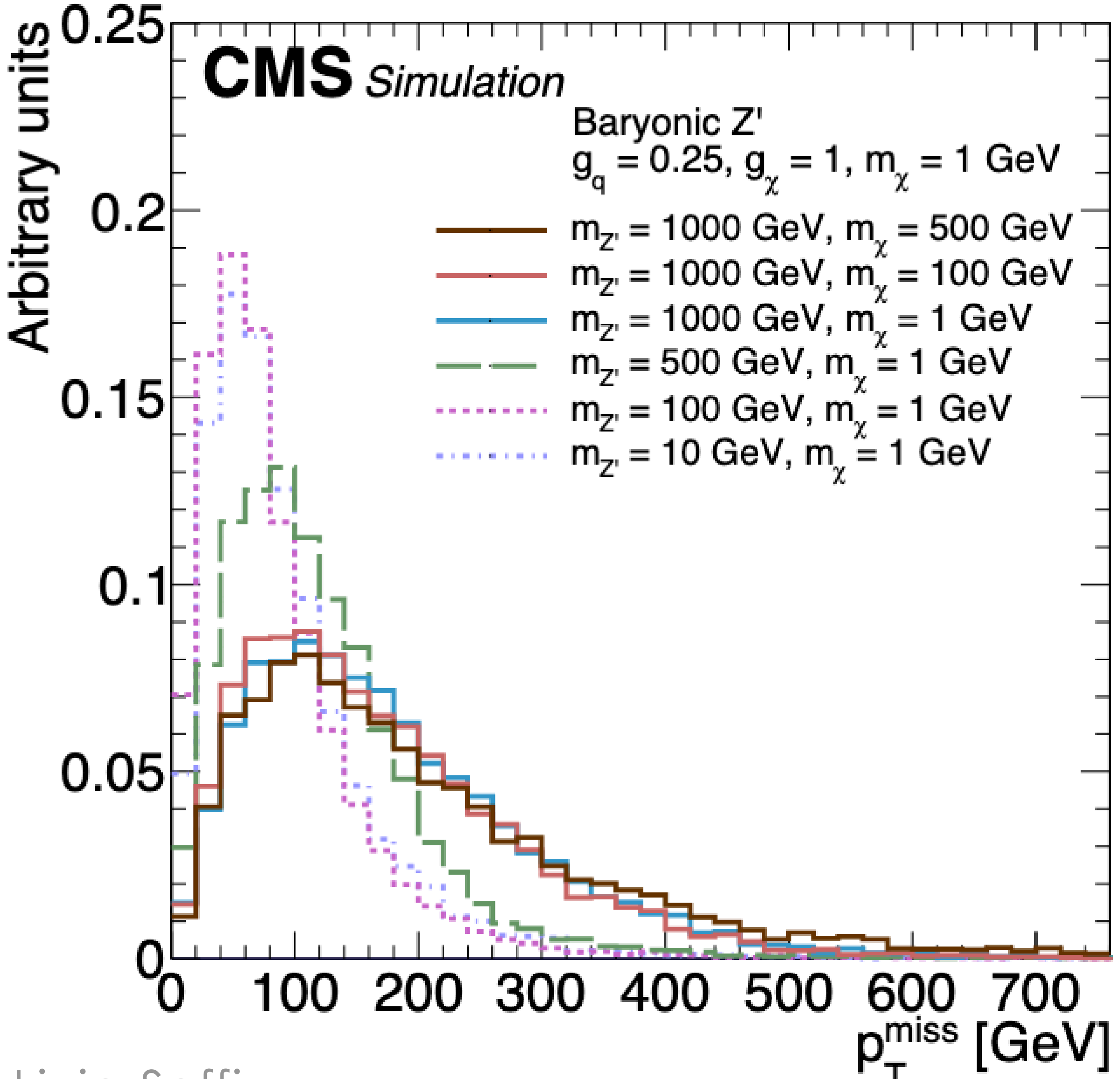
The Mono-Higgs search

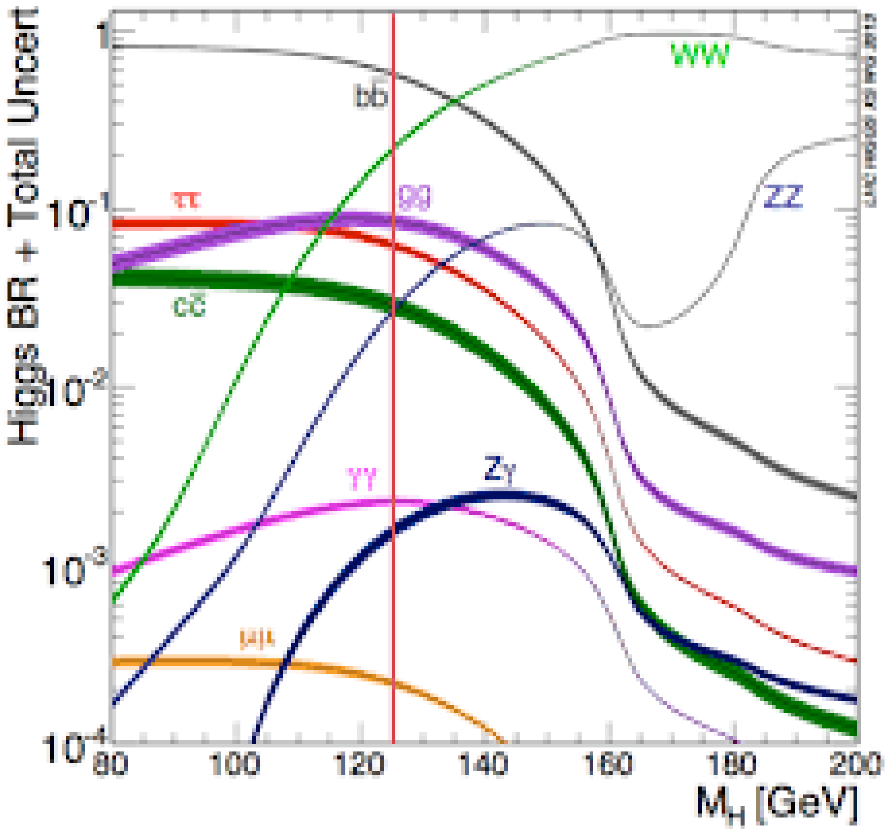




Decay channel	Final state or category
$h \to bb$	AK8 jet (Z′-2HDM) CA15 jet (Baryonic Z′)
$h \to \gamma\gamma$	$p_T^{miss} \in$ 50–130 GeV $p_T^{miss} >$ 130 GeV
$h \to \tau\tau$	$\tau_h\tau_h$ $\mu\tau_h$ $e\tau_h$
$h \to WW$	$e\nu\mu\nu$
$h \to ZZ$	4e 4μ $2e2\mu$







arXiv:1908.01713

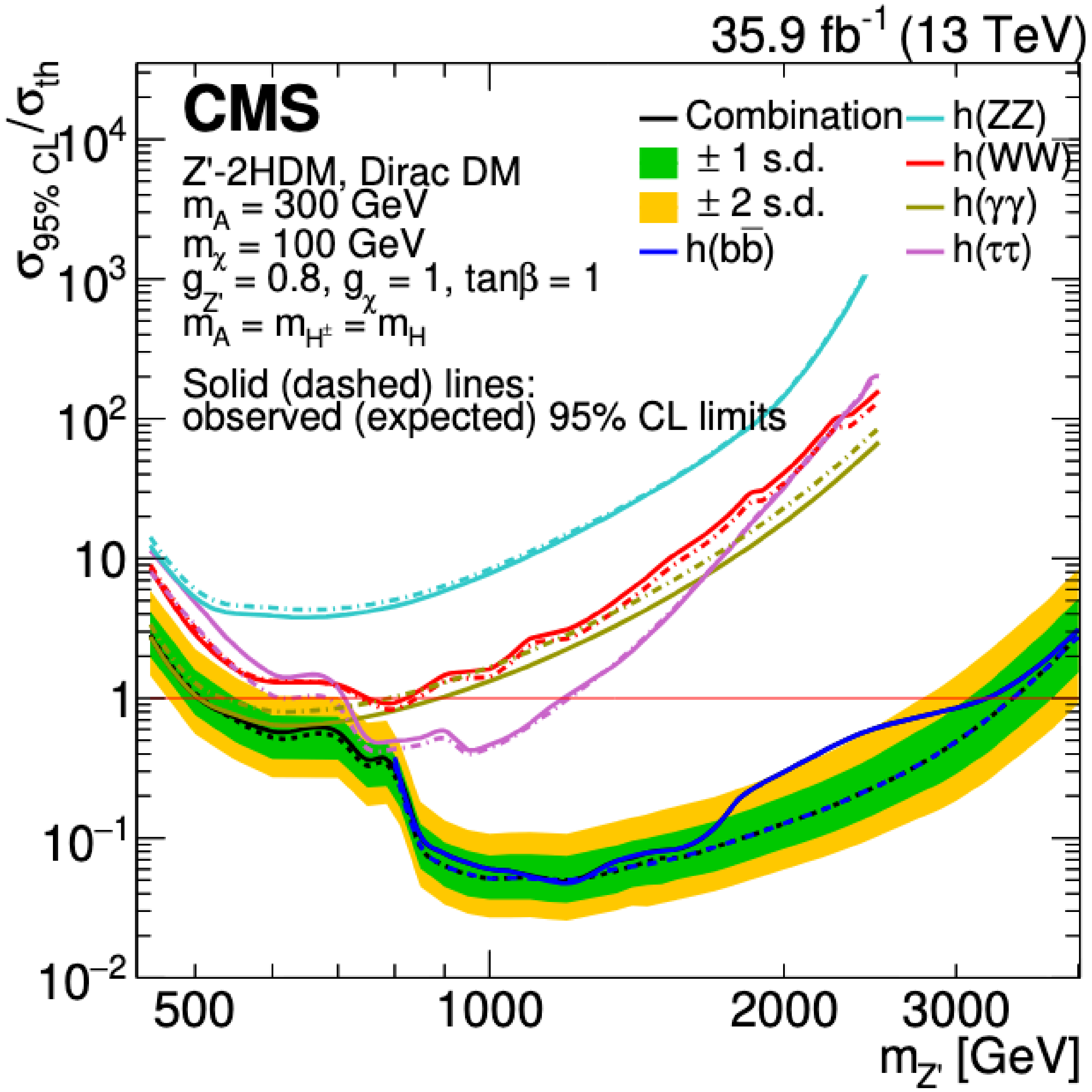
Mono-Higgs combination at CMS

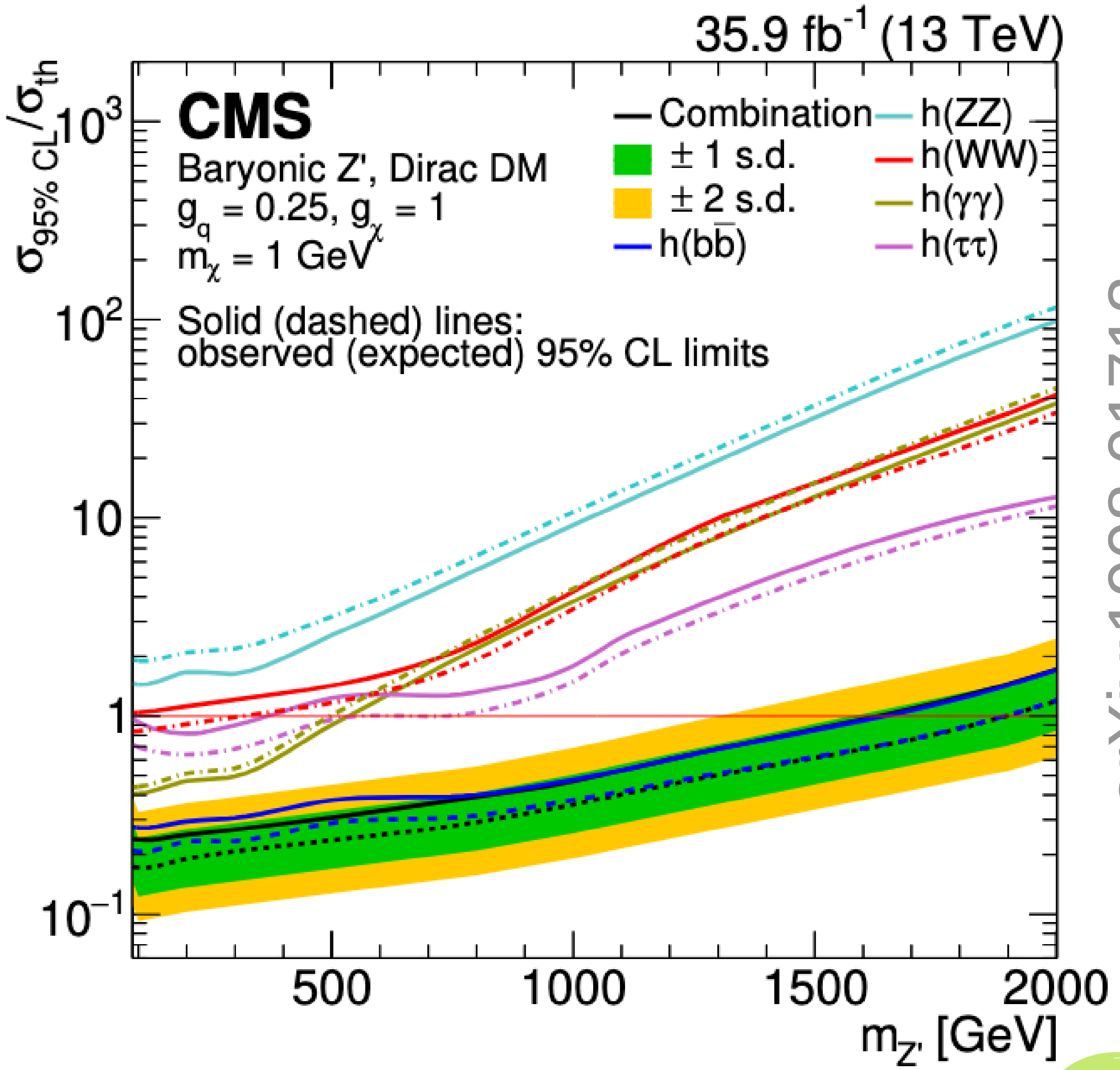
Orthogonality & complementarity

- Channel selection needed for the **big combination of ll 5 channels**

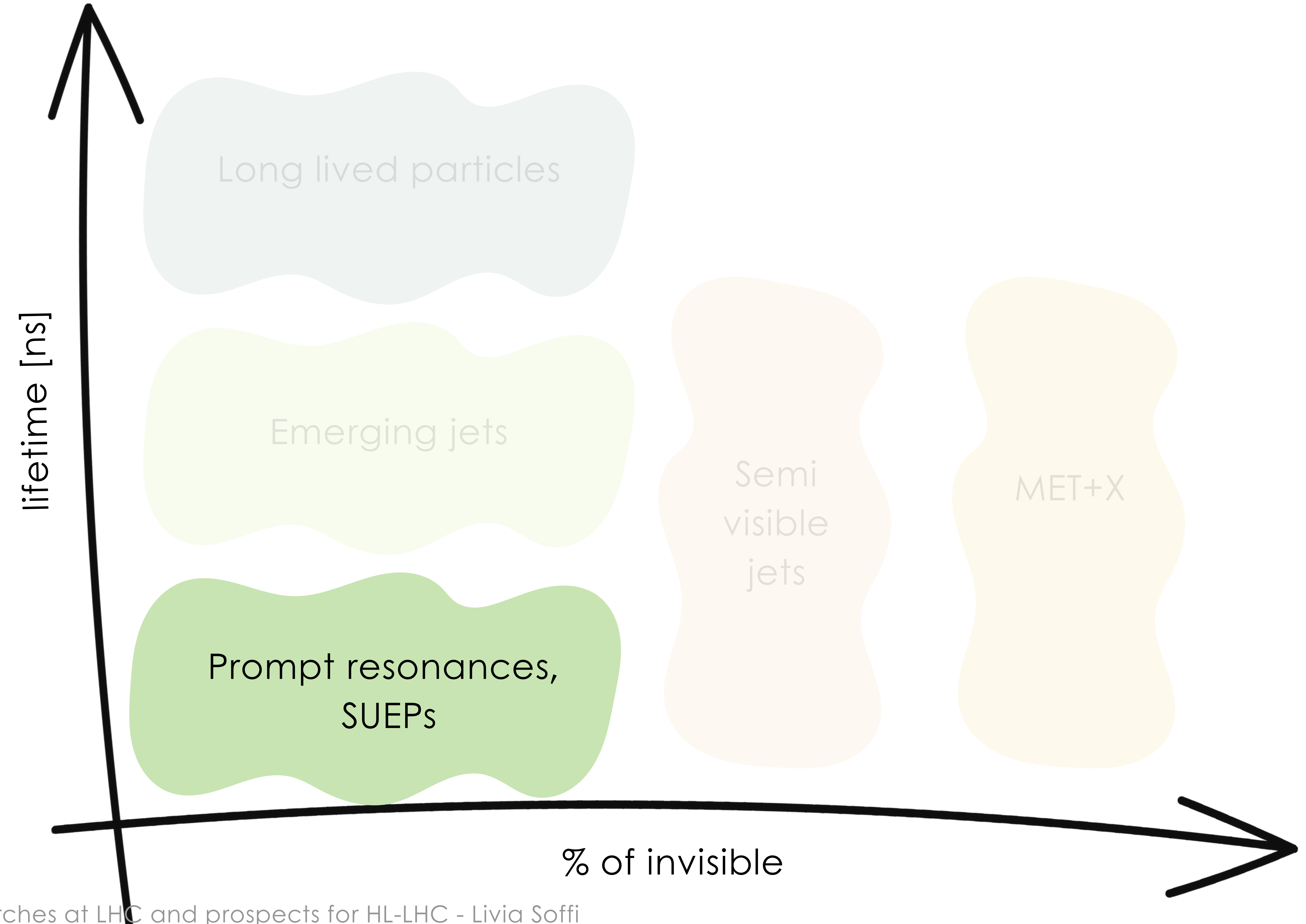
Object	$h \to bb$	$h \to \gamma\gamma$	$h \to \tau\tau$	$h \to WW$	$h \to ZZ$
Electron	=0	—	=0	=0	=0
Muon	=0	—	=0	=0	=0
τ lepton	=0	—	—	=0	—
Photon	=0	—	—	—	—
AK4 Jet	≤1	≤2	—	—	—
b tagged AK4 jet	=0	—	=0	=0	≤1

- The **h → γγ and h → ZZ channels exhibit better resolution** in the reconstructed Higgs boson invariant mass, while the **h → ττ, h → WW, and h → ZZ channels benefit from lower SM backgrounds**, which results in a higher sensitivity for signals with a soft MET

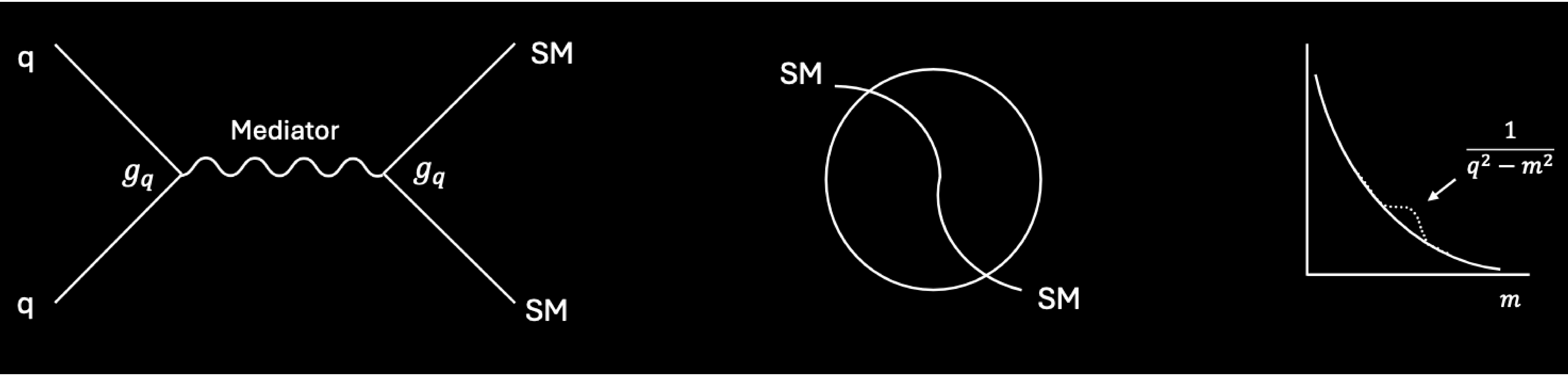




arXiv:1908.01713


lifetime [ns]
Long lived particles
Emerging jets
Prompt resonances,
SUEPs
Semi
visible
jets
MET+X
% of invisible

Resonances searches

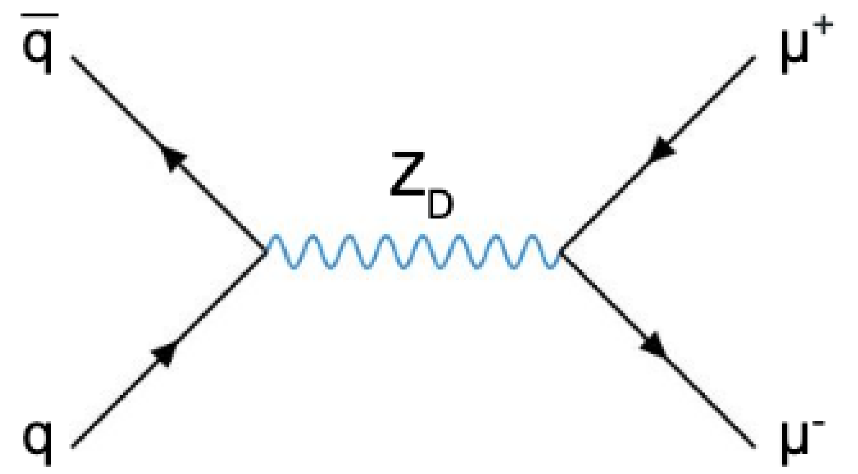


- Strategy:
  - New DS-SM mediator produced in pp collisions
  - **Mediator decays back to SM** (instead of decaying to DS like in MET+X scenario)
  - Look for Breit-Wigner resonances – **"bumps" – in mass distributions**

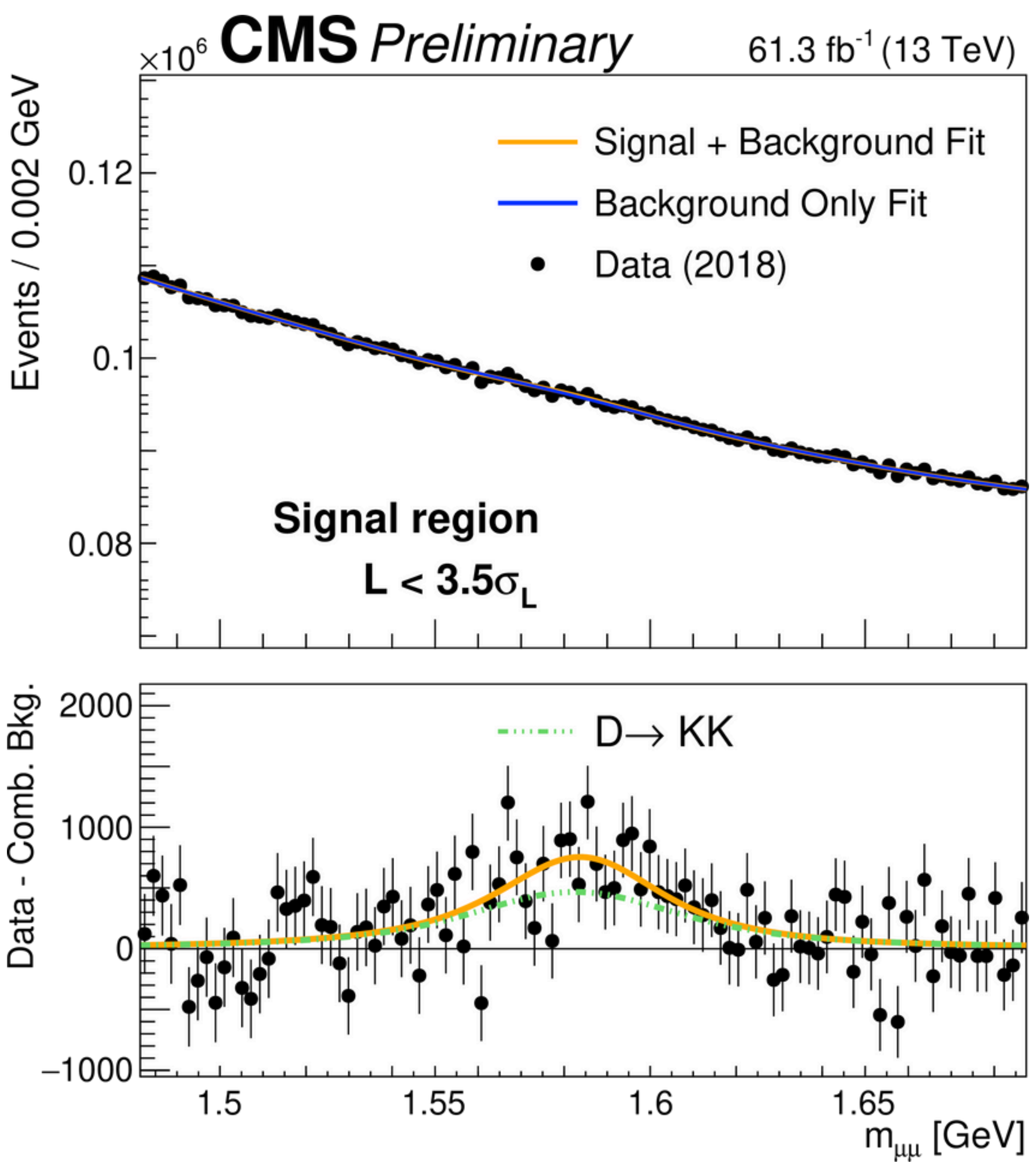
- Target:
  - **Model-independent limits** on $\sigma\ pp \rightarrow X\ B\ X \rightarrow SM\ SM\ A$ as function of $mmed$
  - Target high masses (~TeV) via traditional triggers and low masses (~GeV) via production of another particle to trigger on or via high-rate ("scouting") triggers

GeV scale Dimuon Resonances with scouting

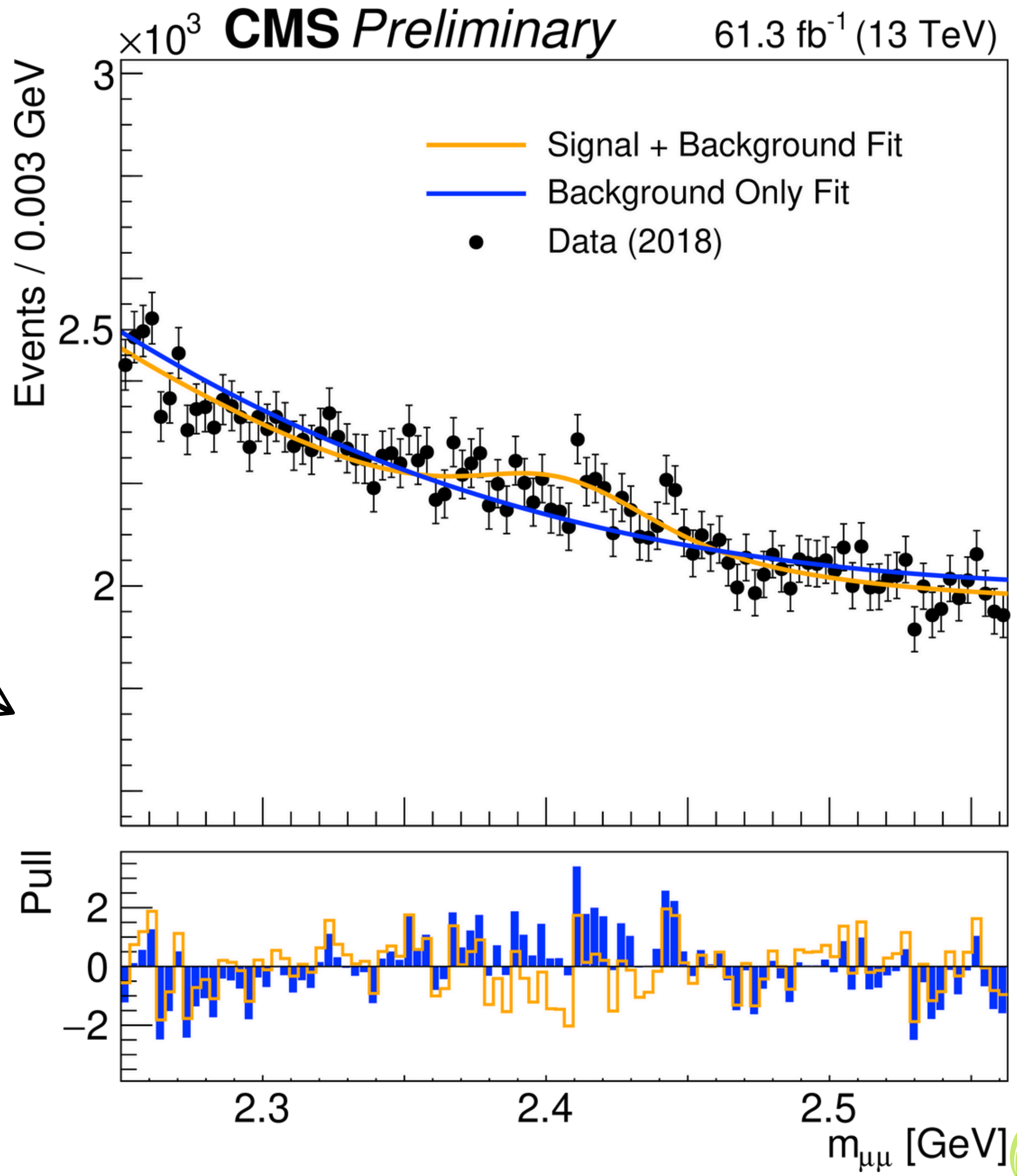
- Searching for **light (1-8 GeV) BSM mediator** decaying into a pair of opposite sign muons using **Run II scouting data** collected by CMS



- **Excellent resolution** allowed to “detect” unexpected peaking background from D0 → KK/Kπ



- Most significant **excess at 2.41 GeV** in a boosted category
- Local significance: **3.24σ, global significance 1.27σ**



arXiv:2309.16003

GeV scale Dimuon Resonances with scouting

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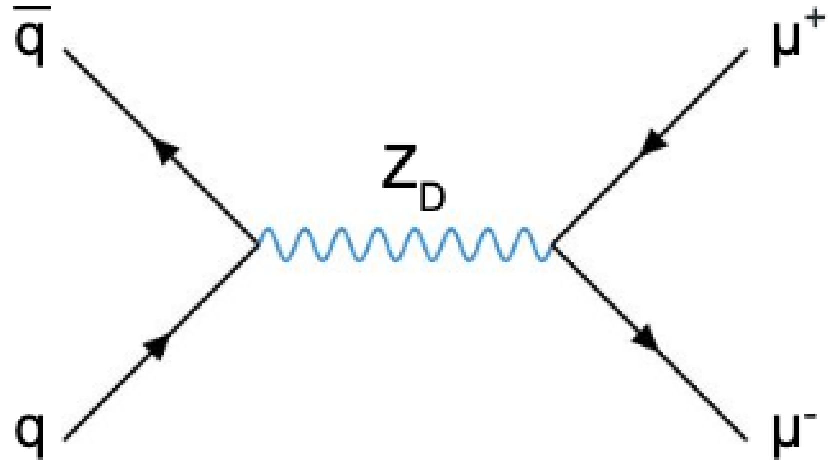
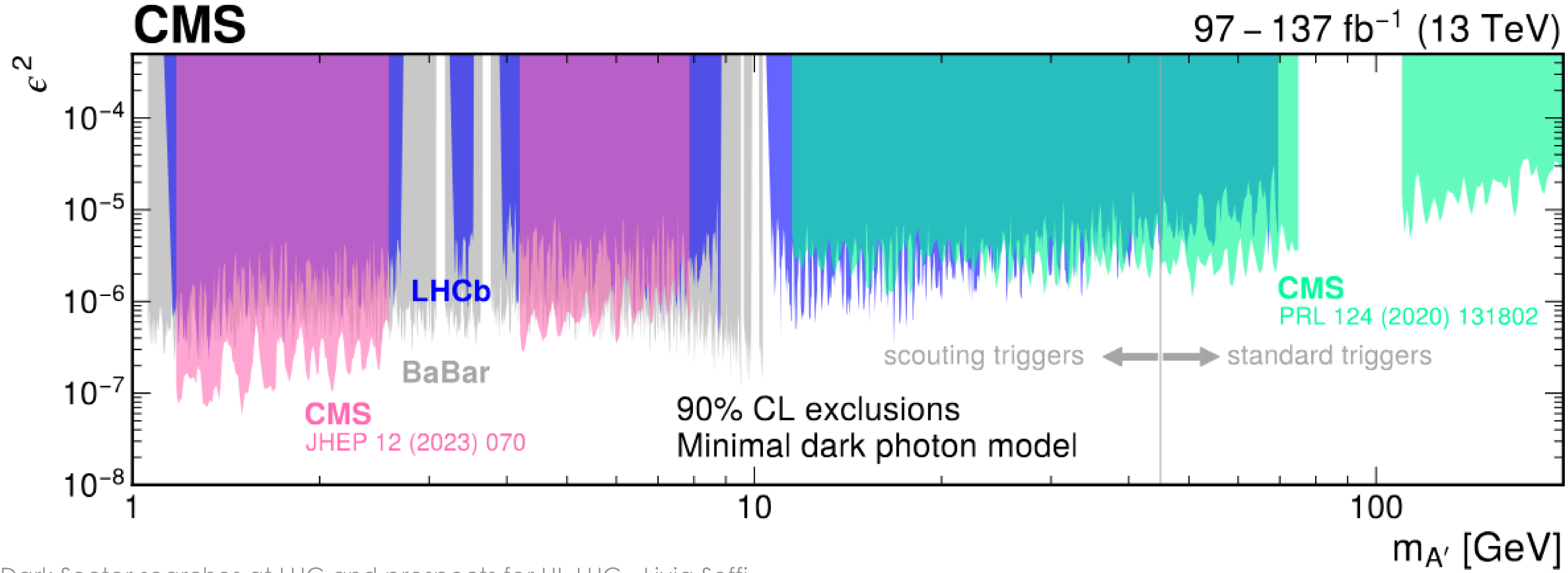
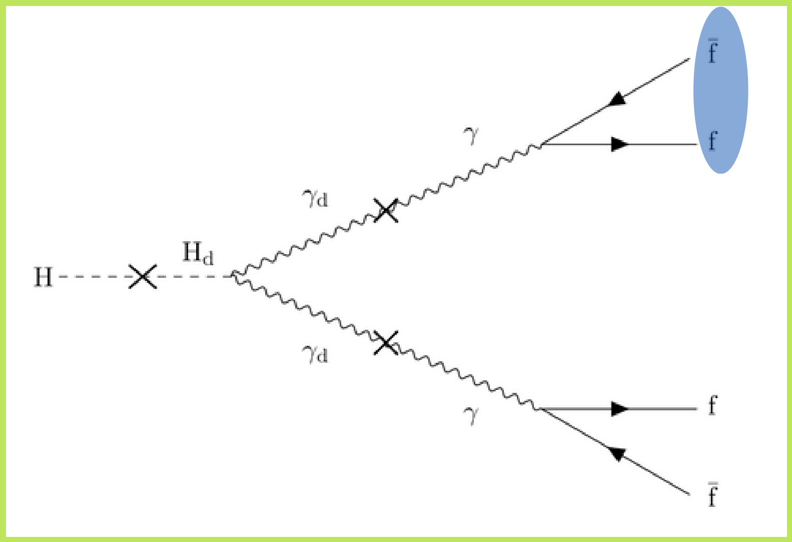


- Upper limit on **dark photon coupling (ε^2)** at 90% CL
  - Compared with results from LHCb (blue) and BaBar (grey)



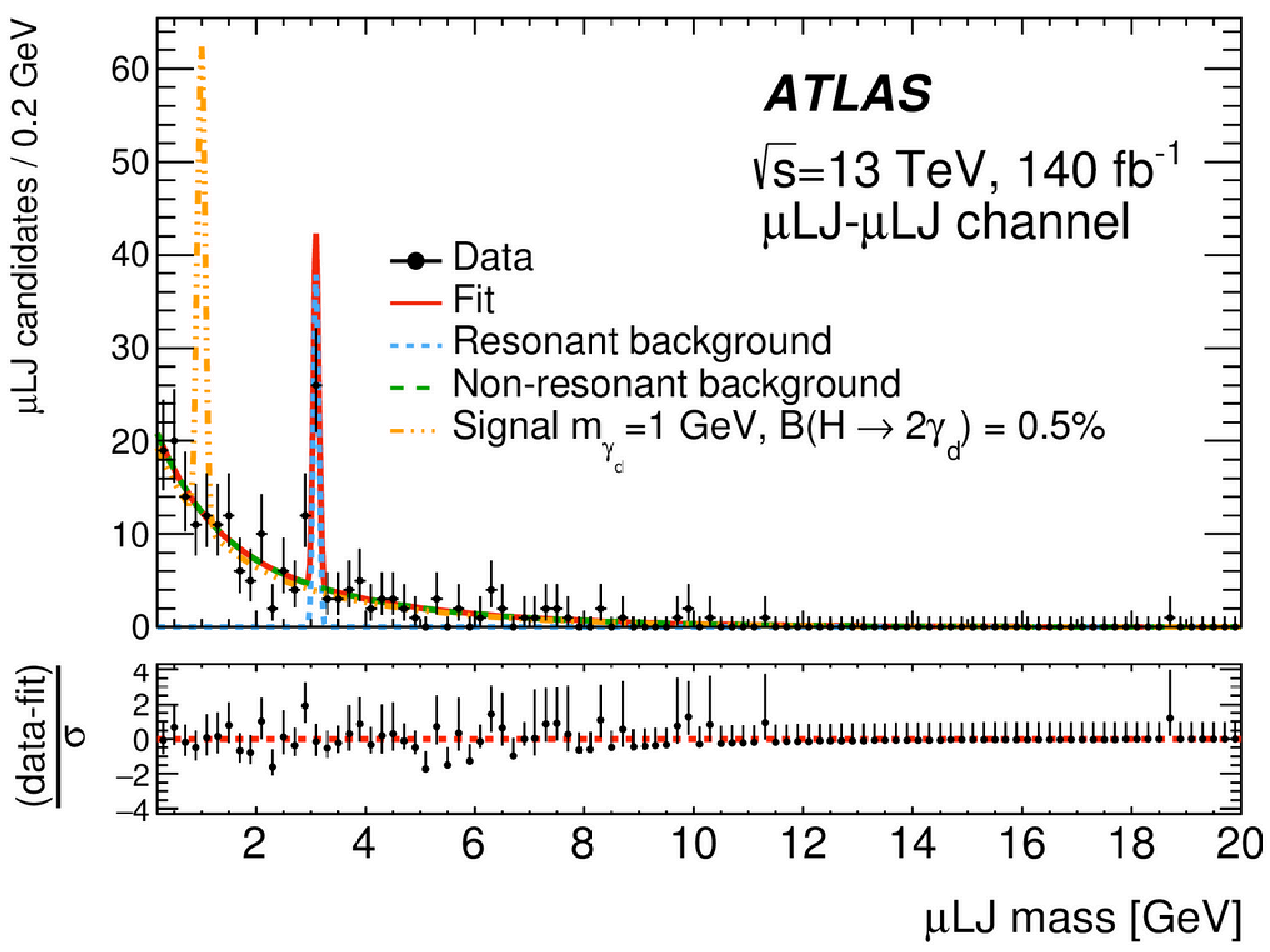
arXiv:2309.16003

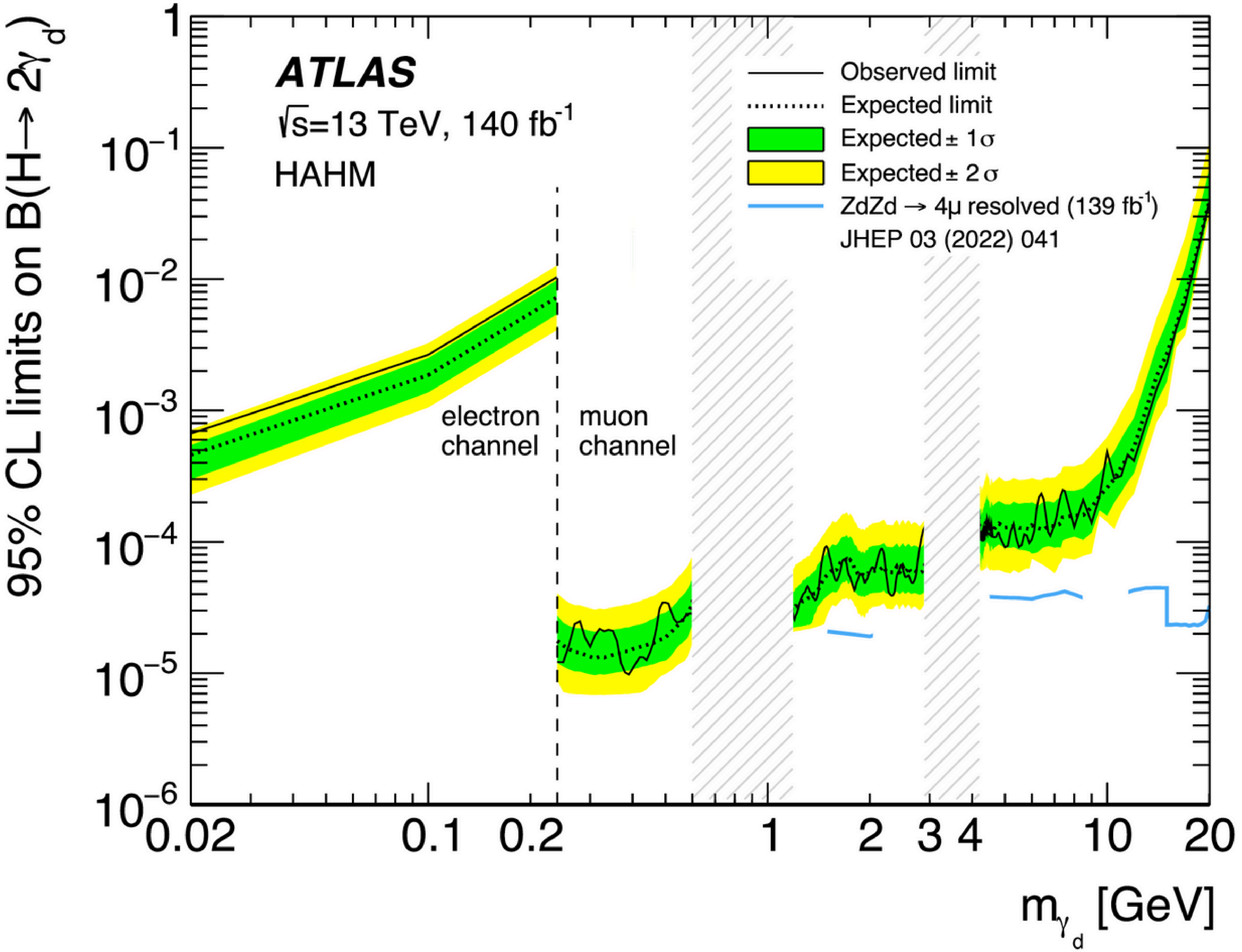
Low mass collimated pairs of leptons



LeptonJets (LJs): highly collimated pairs of electrons or muons from light neutral particles decay

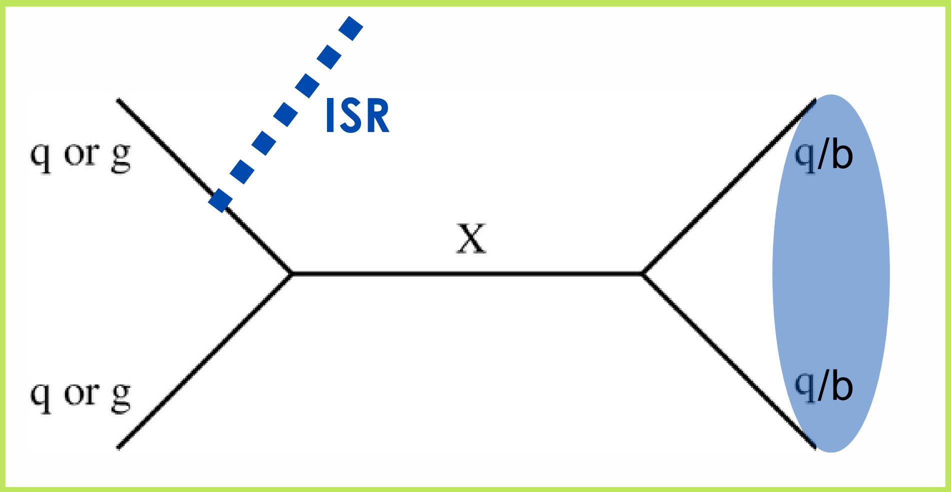
Dedicated reconstruction and ID of merged dilepton pairs





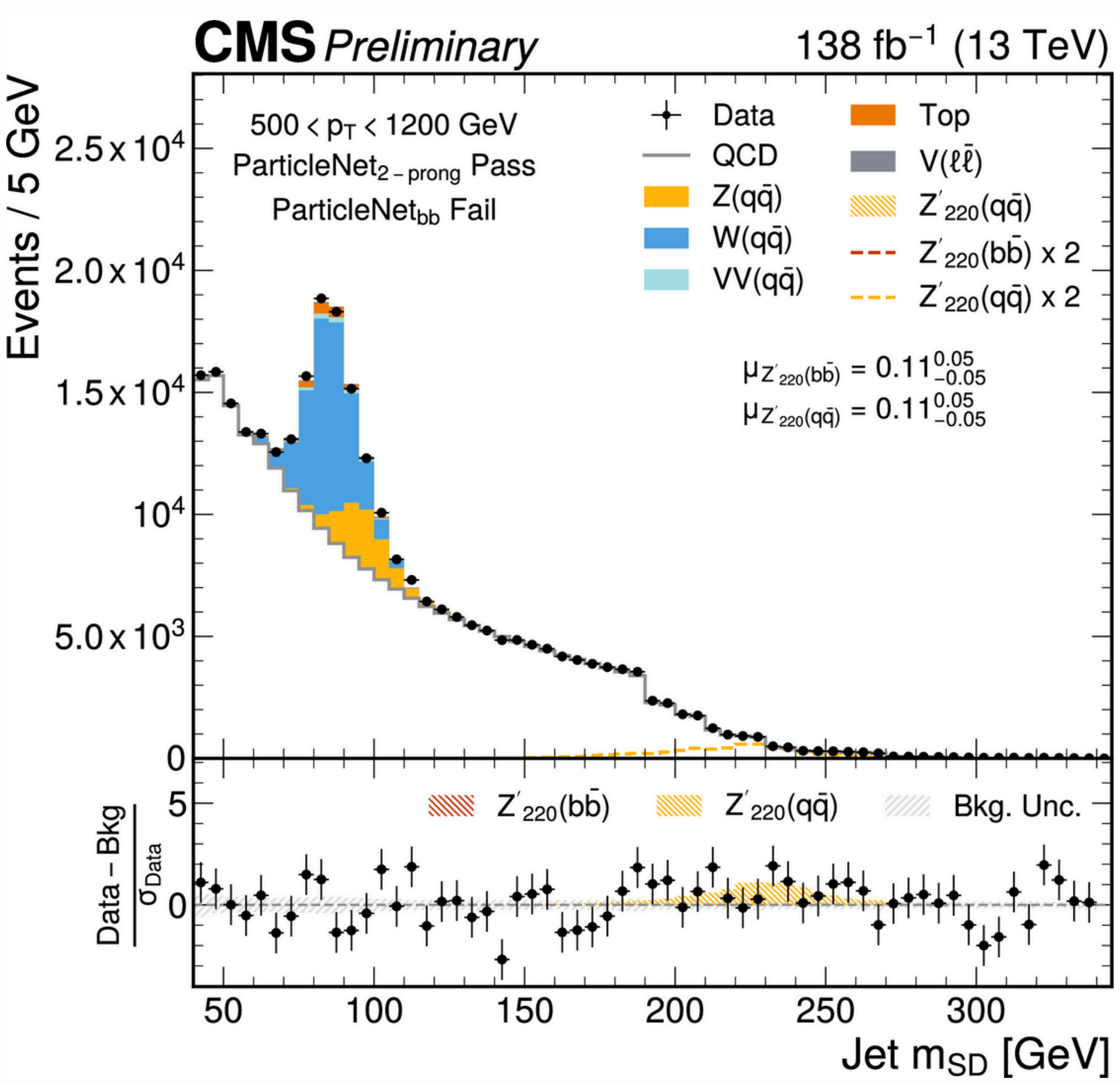
arXiv:2407.09168

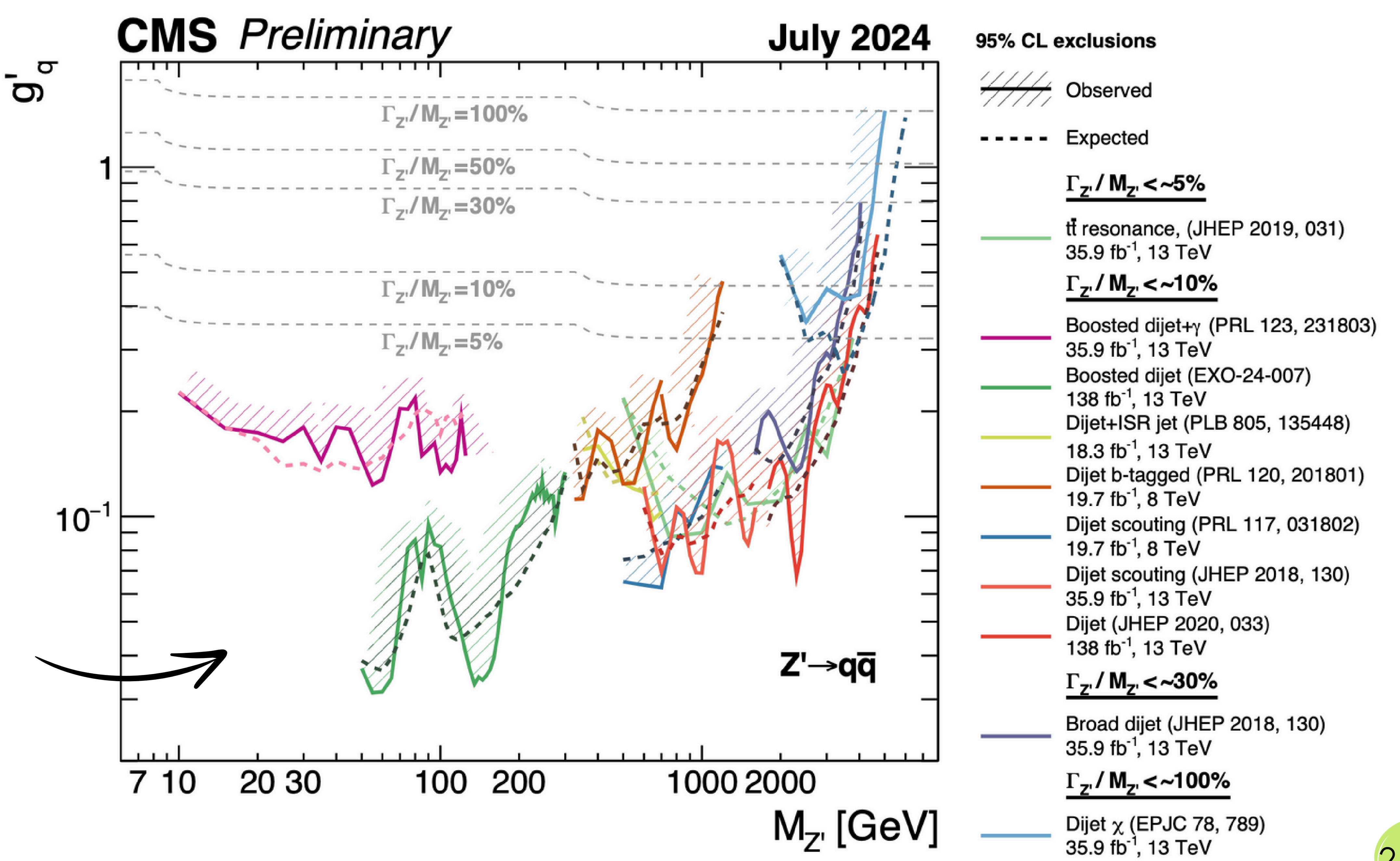
Low-mass dijet search with Machine Learning



ParticleNet algorithm reconstructs **Large Radius Jet w/ 2 pronged substructure**

CMS-PAS-EXO-24-007

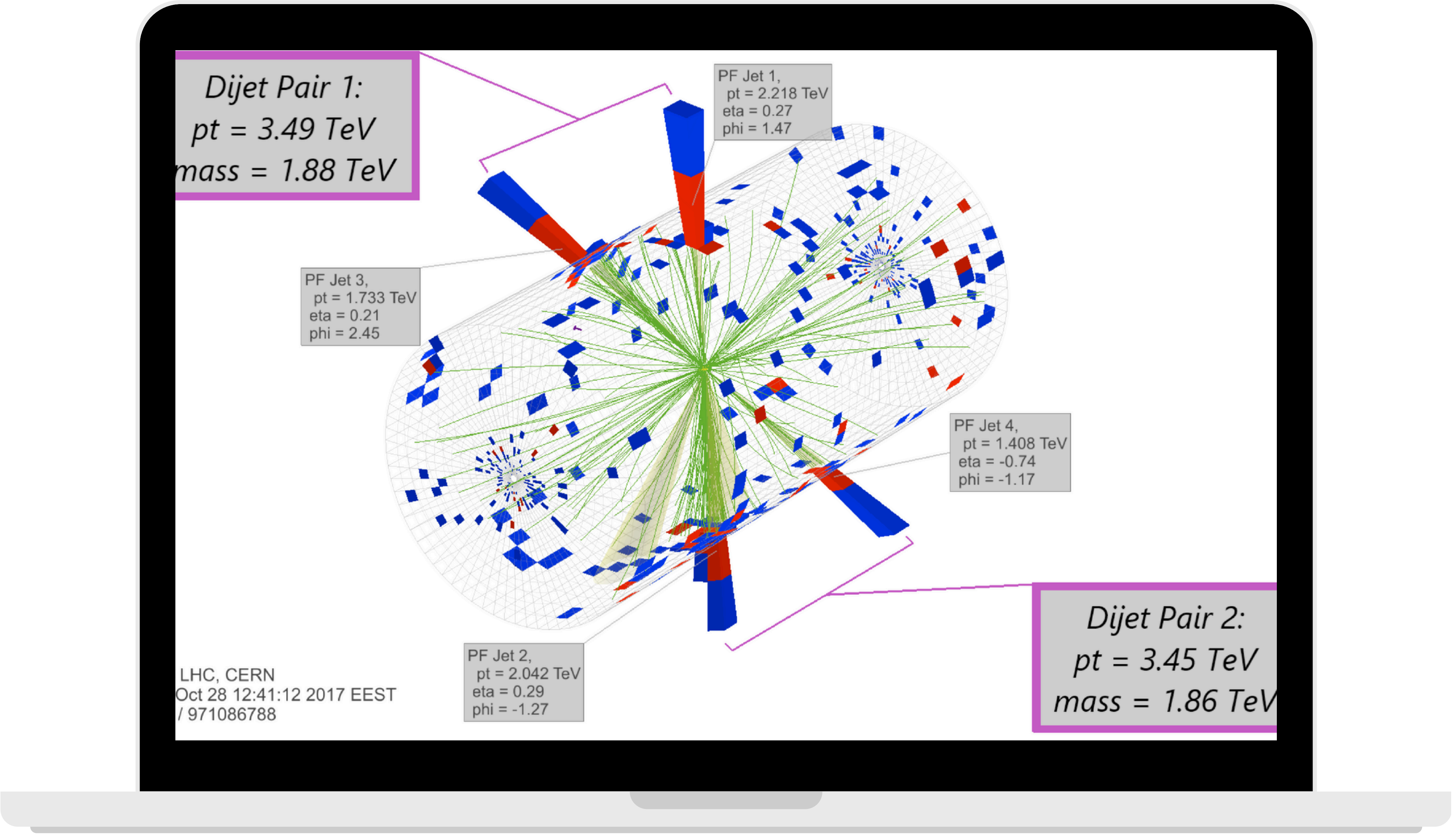


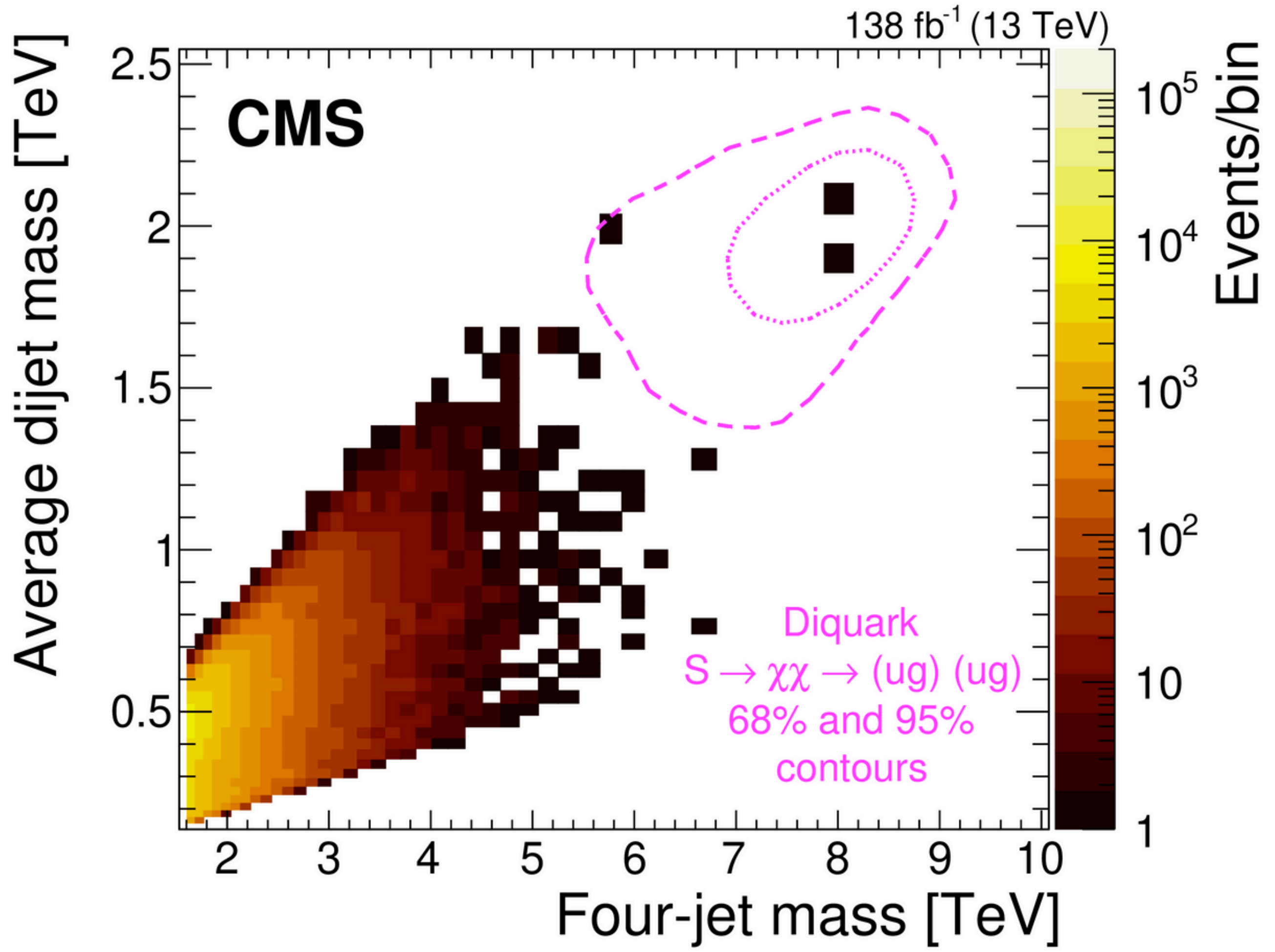


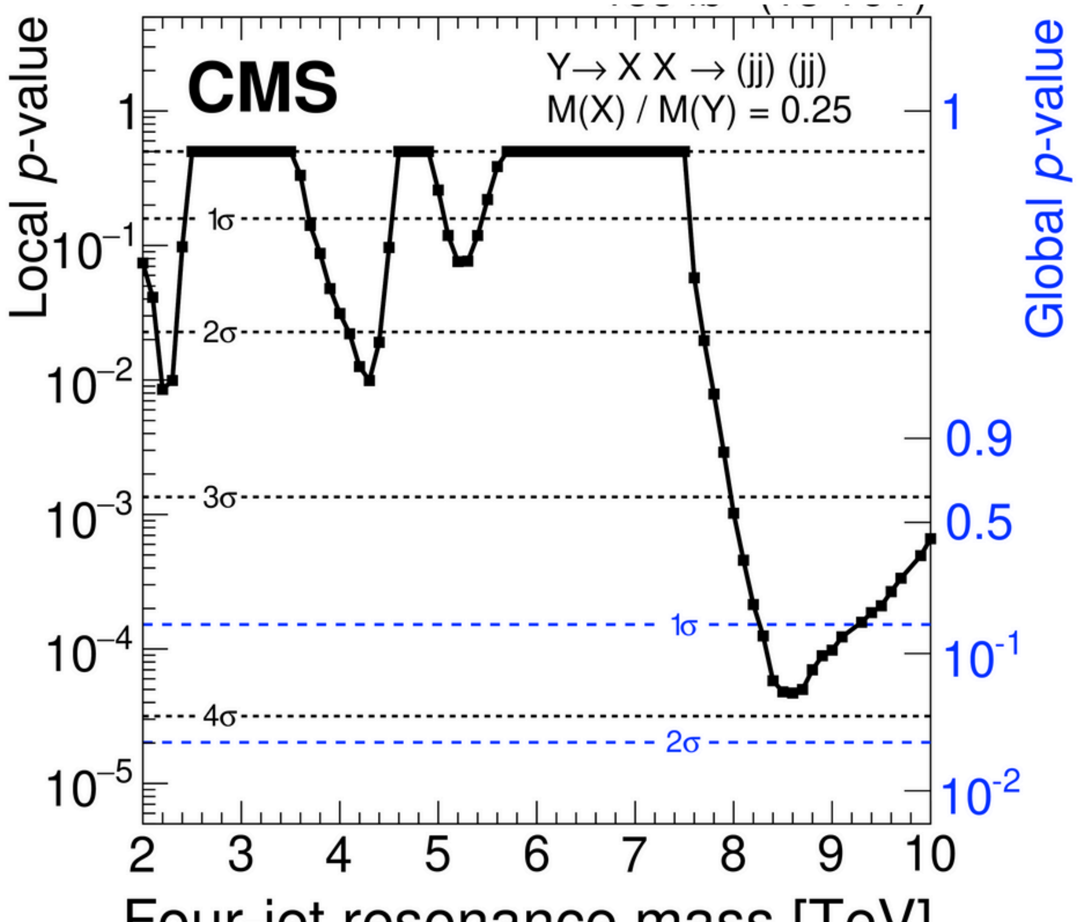
Backup CMS-EXO-Summary-Plots

The high mass range and its excess

- **Massive scalar diquark** decaying to a pair of vector-like quarks, each decaying to a ug pair.



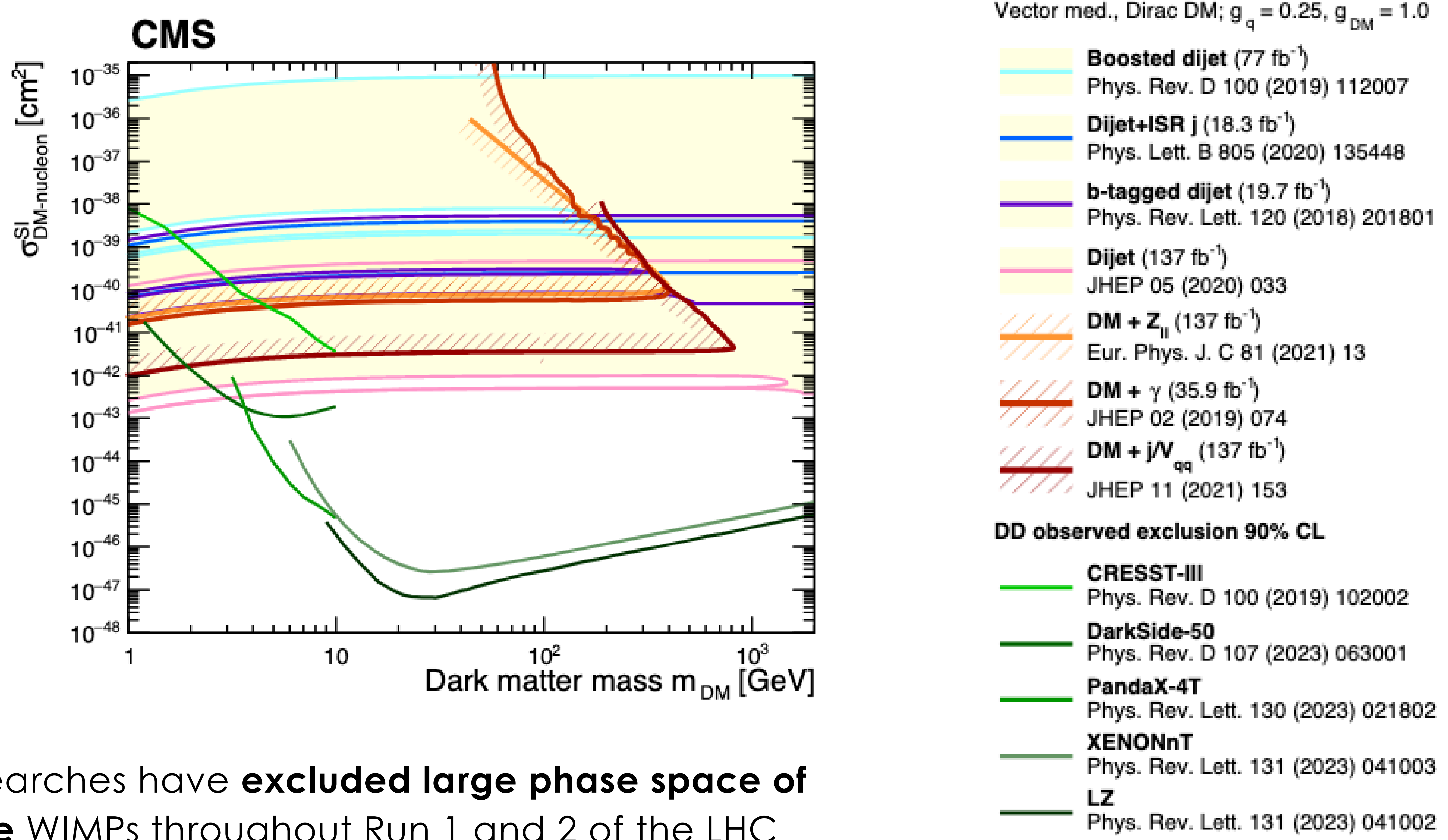




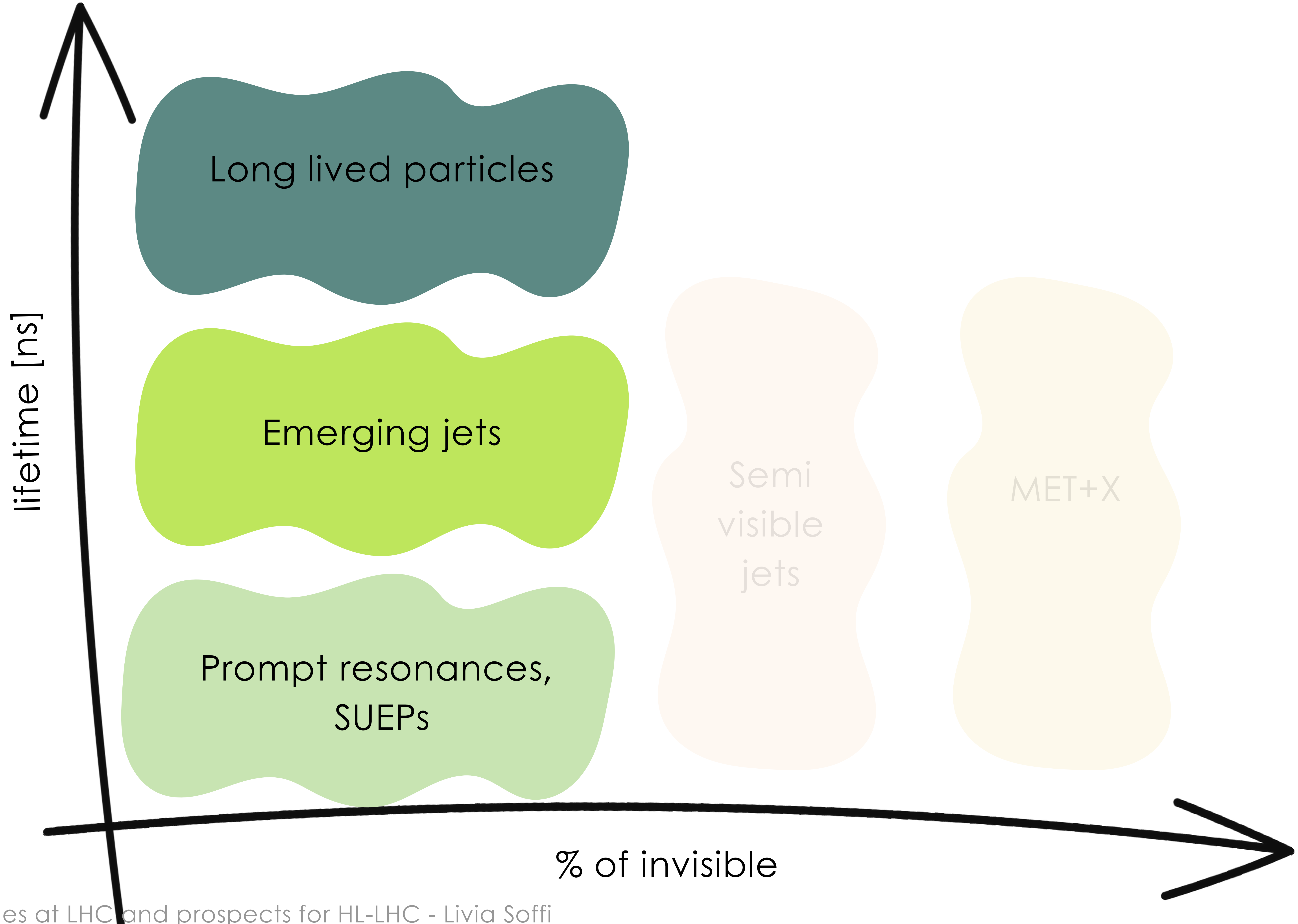
arXiv:2206.09997

- **Largest excess** corresponds to the two isolated events at ~ $\mathbf{8\ TeV: 3.9\sigma\ (1.6\sigma)}$ local (global) significance.

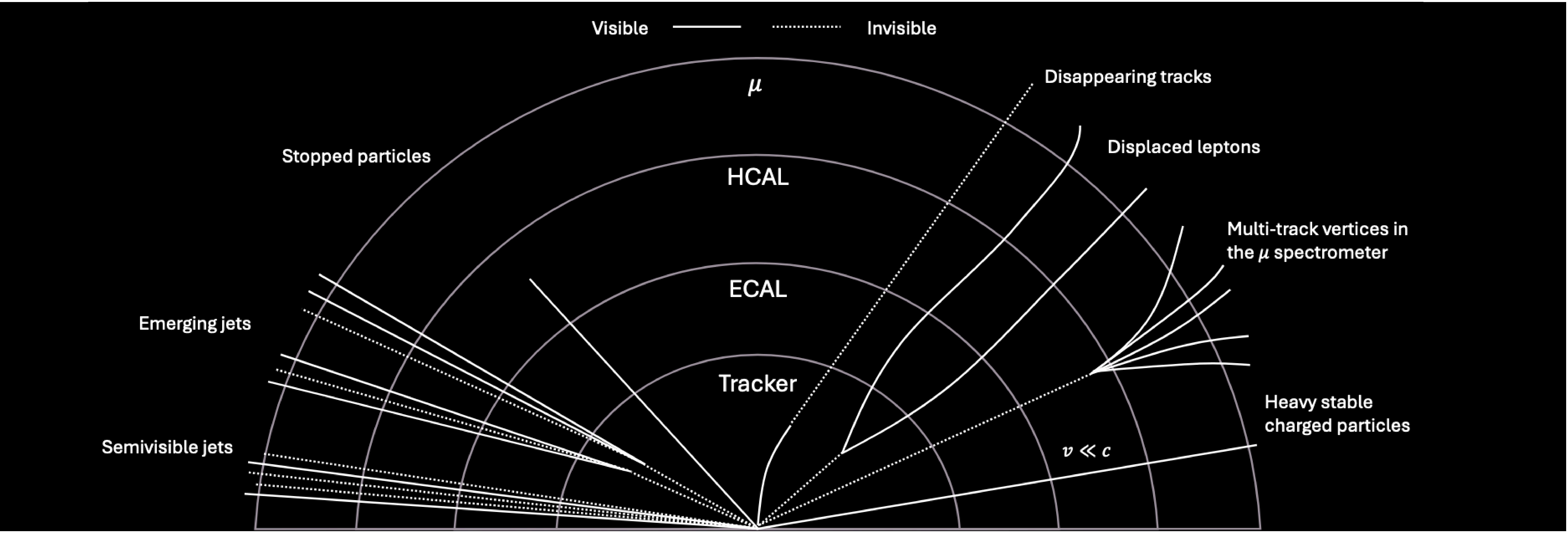
Ground covered



- MET+X and resonance searches have **excluded large phase space of simplified DM models like** WIMPs throughout Run 1 and 2 of the LHC
- Important **complementarity between colliders and direct detection experiments** for simplified DM models
  - Spin dependence
  - Nature of mediator and dark matter particle(s)


Long lived particles
Emerging jets
Prompt resonances, SUEPs
Semi visible jets
MET+X
lifetime [ns]
% of invisible

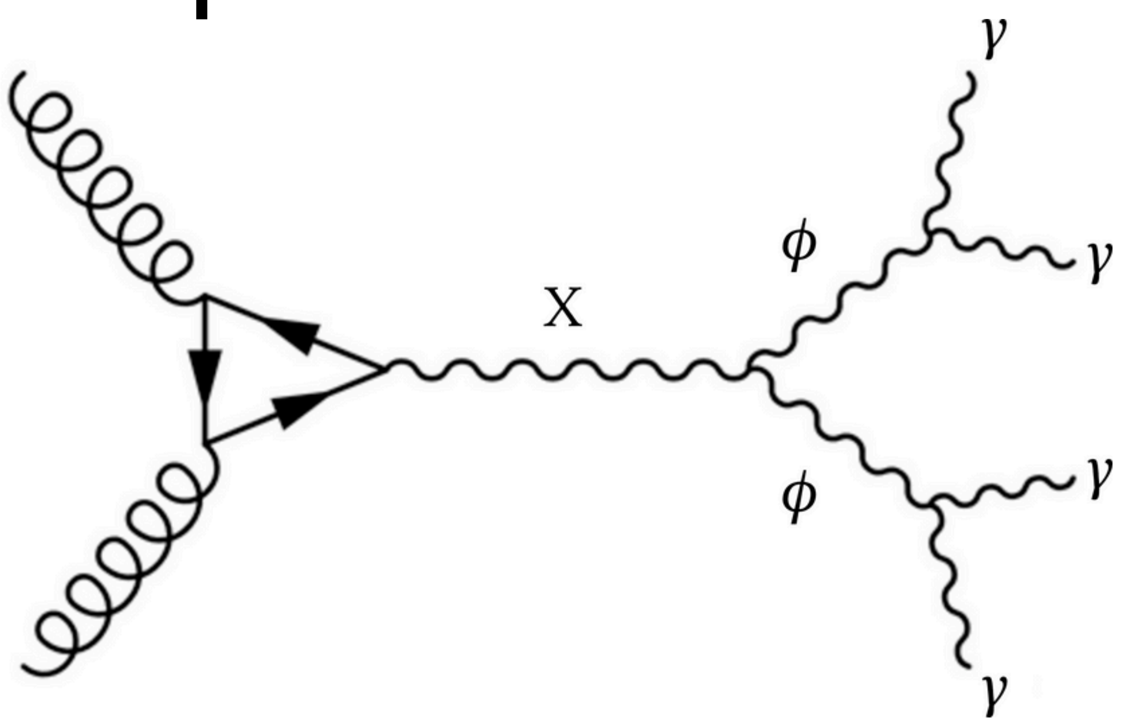
Unconventional signatures



- First-generation of searches at colliders found no convincing evidence for BSM
- **New ideas (scouting, ML, etc.)** are able to improve sensitivity (analyses re-iterated with Run 3 data (ongoing!))
- More complex DS models and/or alternative DM mechanisms (non WIMP) being investigated
  - Freeze-in, inelastic DM, FIMPs, etc.
- Give rise to **new types of signatures that we don't typically reconstruct at colliders**

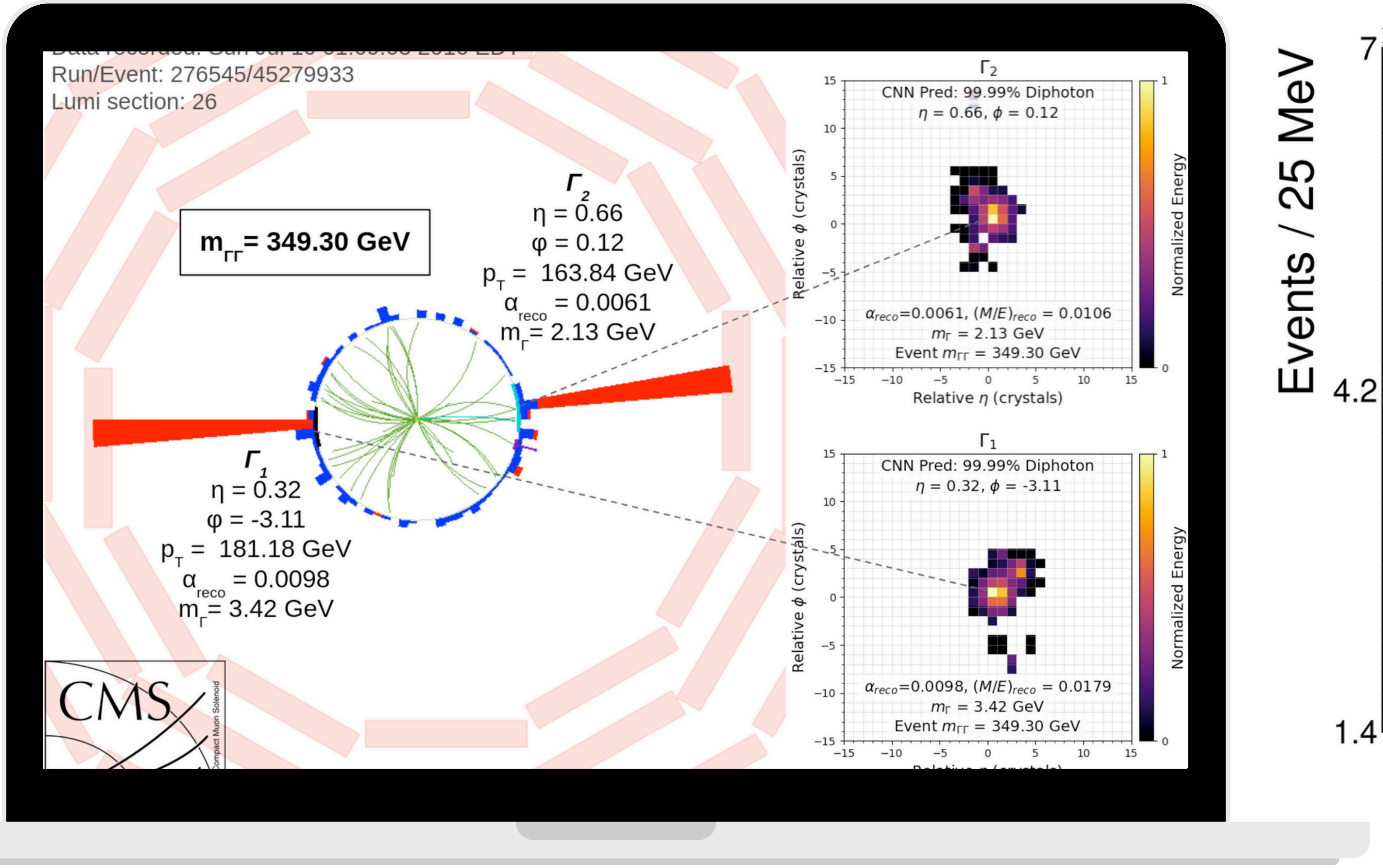
Low mass particles in merged diphotons

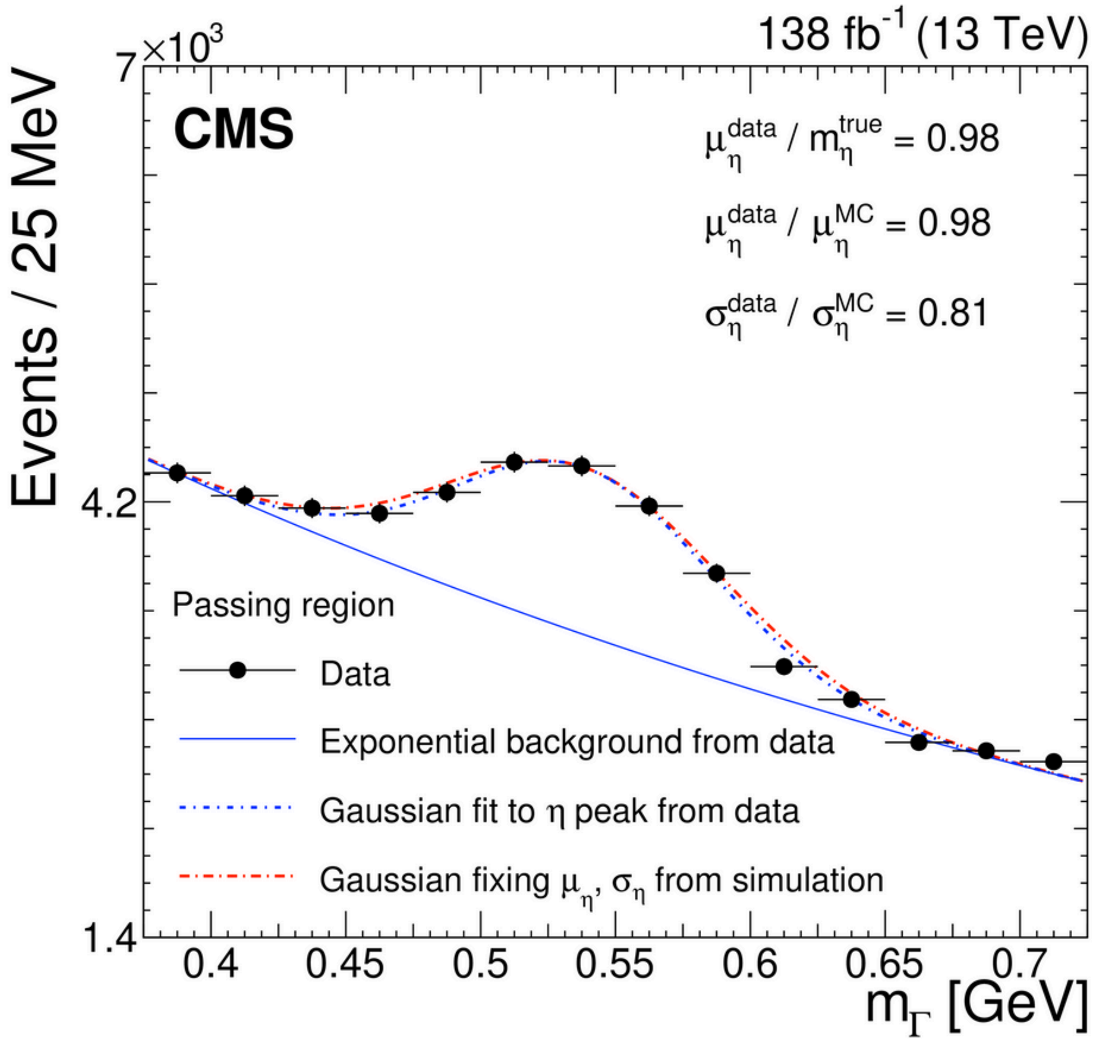
- Extended Higgs sector with two new spin-0 particles (X and φ)
- Looking at **topologies with highly merged photons**
- No standard photon reconstruction: requires **new analysis tools (ML)**

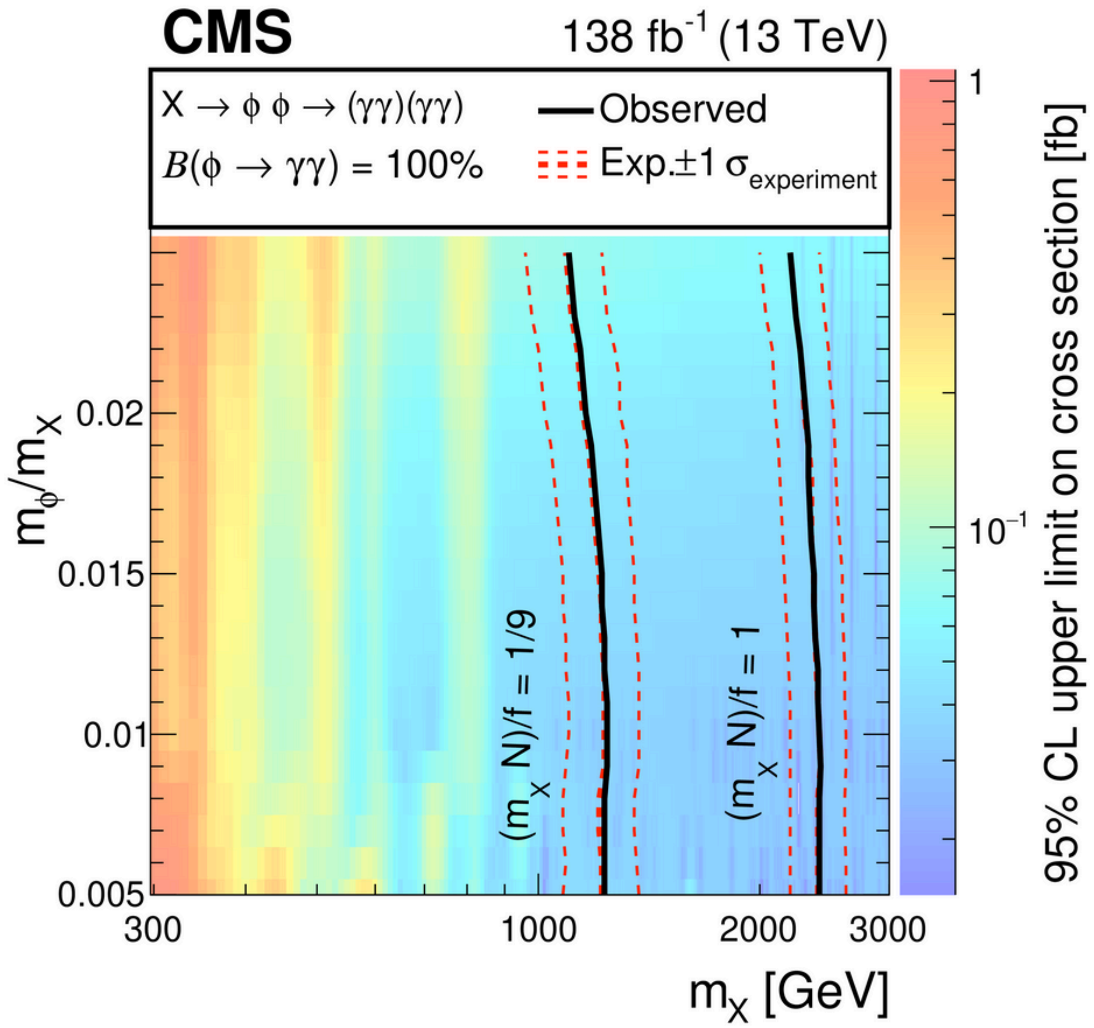


arXiv:2405.00834

- **Dedicated CNN developed to analyze ECAL deposits**
  - Distinguish single γ, two γ's, or hadronic activity



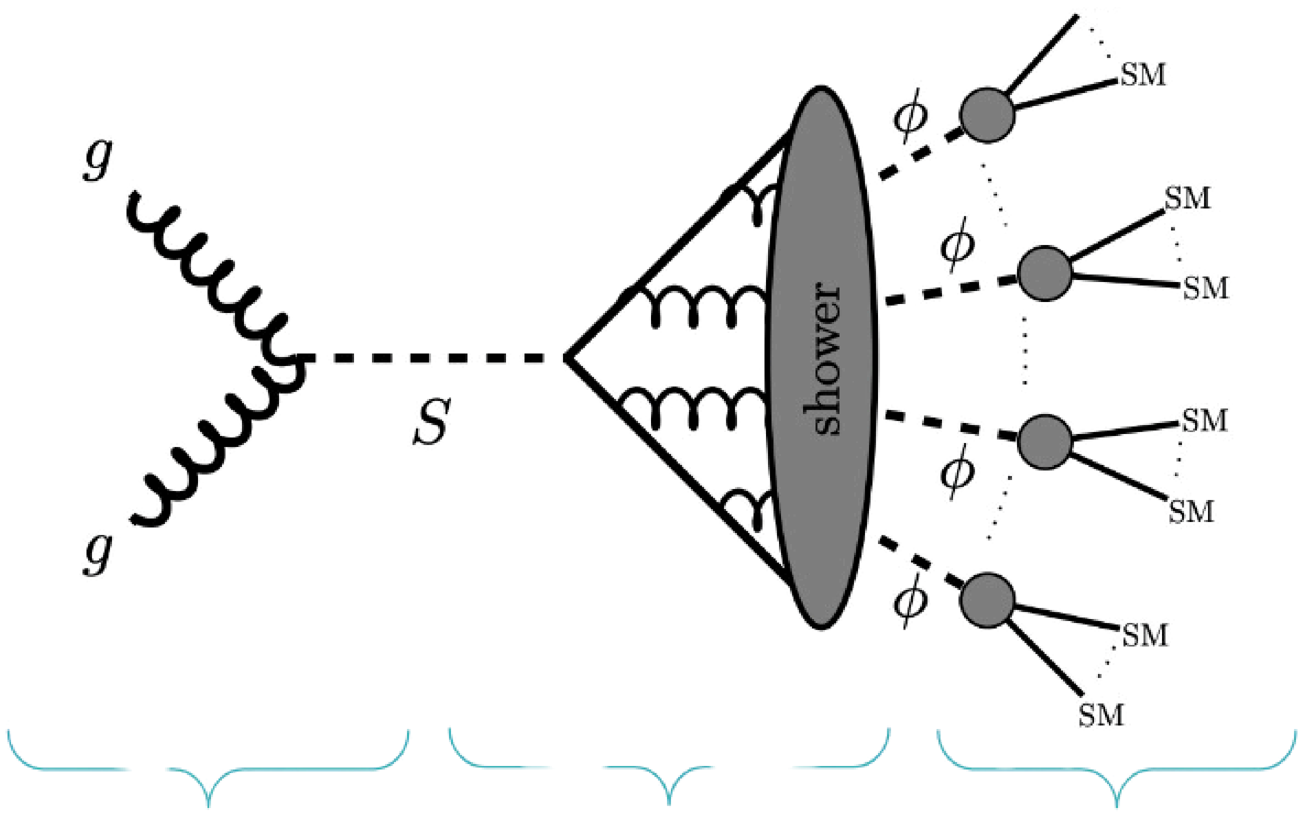




Soft Unclustered Energy Patterns (SUEPs)

- Dark quark matter masses below ΛD → **dark quarks hadronize in "dark shower"**
- Large 't Hooft coupling → **dark particles emitted isotropically**
- Mass gap b/w dark hadrons < mass of portal state → **high multiplicity** of soft dark particles

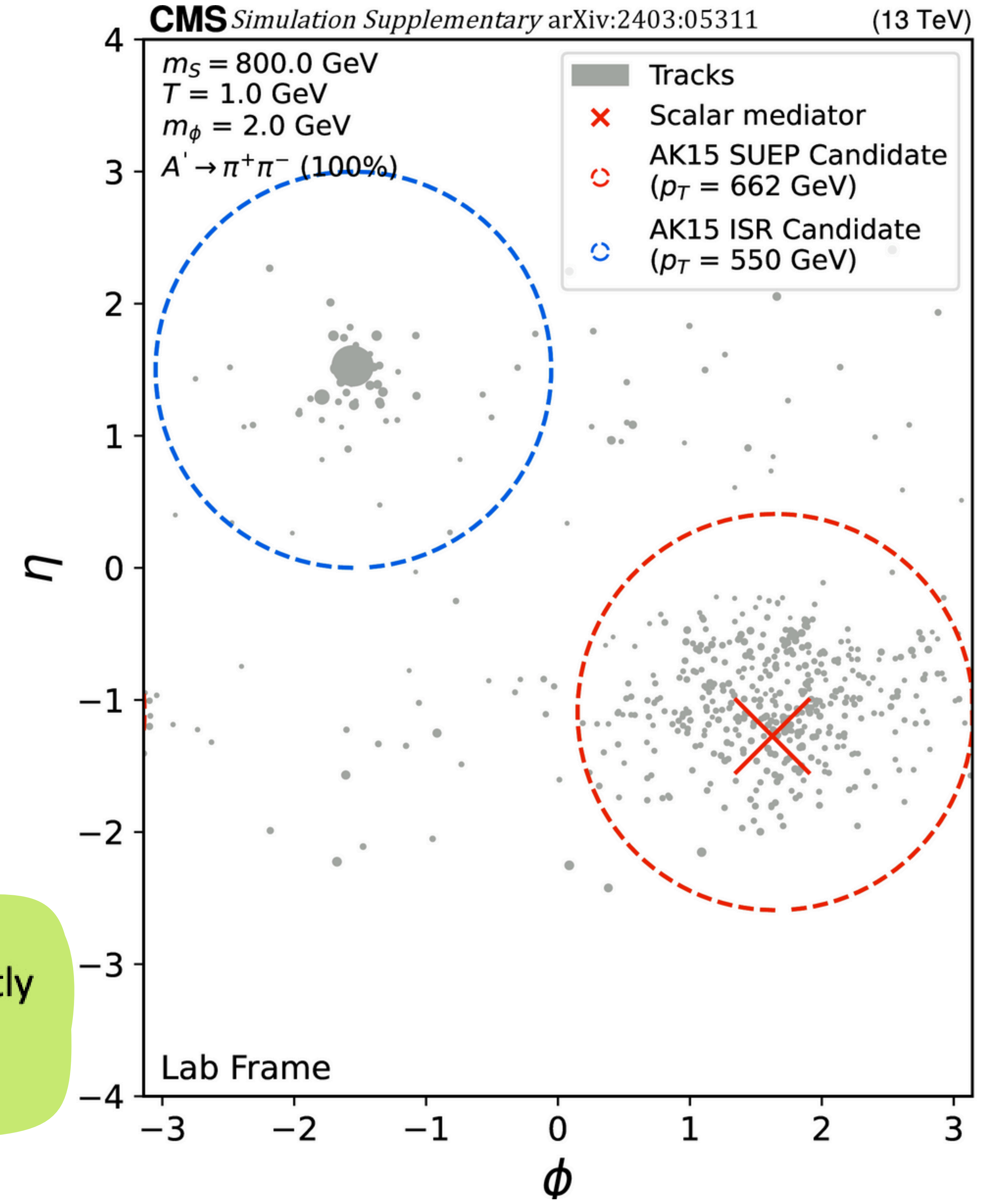
- Particularly interesting portal case: **portal mass = 125 GeV**



Production
Scalar narrow resonance (mediator S) produced through gluon-gluon fusion

Showering
Mediator S decays into dark mesons (ϕ) due to dark QCD

Decay
Dark mesons (ϕ) decay promptly to SM particles through dark photons (A')



arXiv:2403.05311

Soft Unclustered Energy Patterns (SUEPs)

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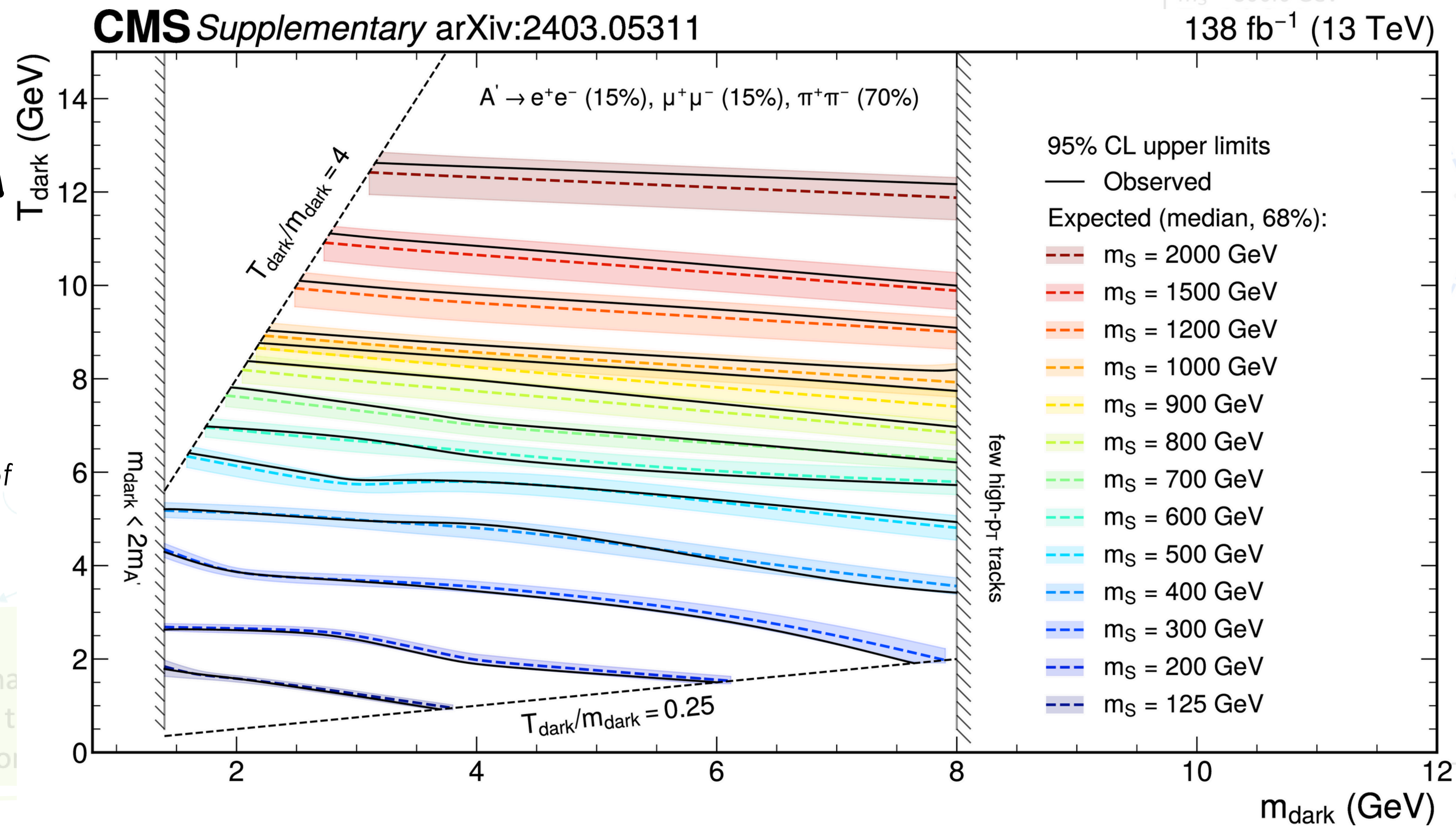
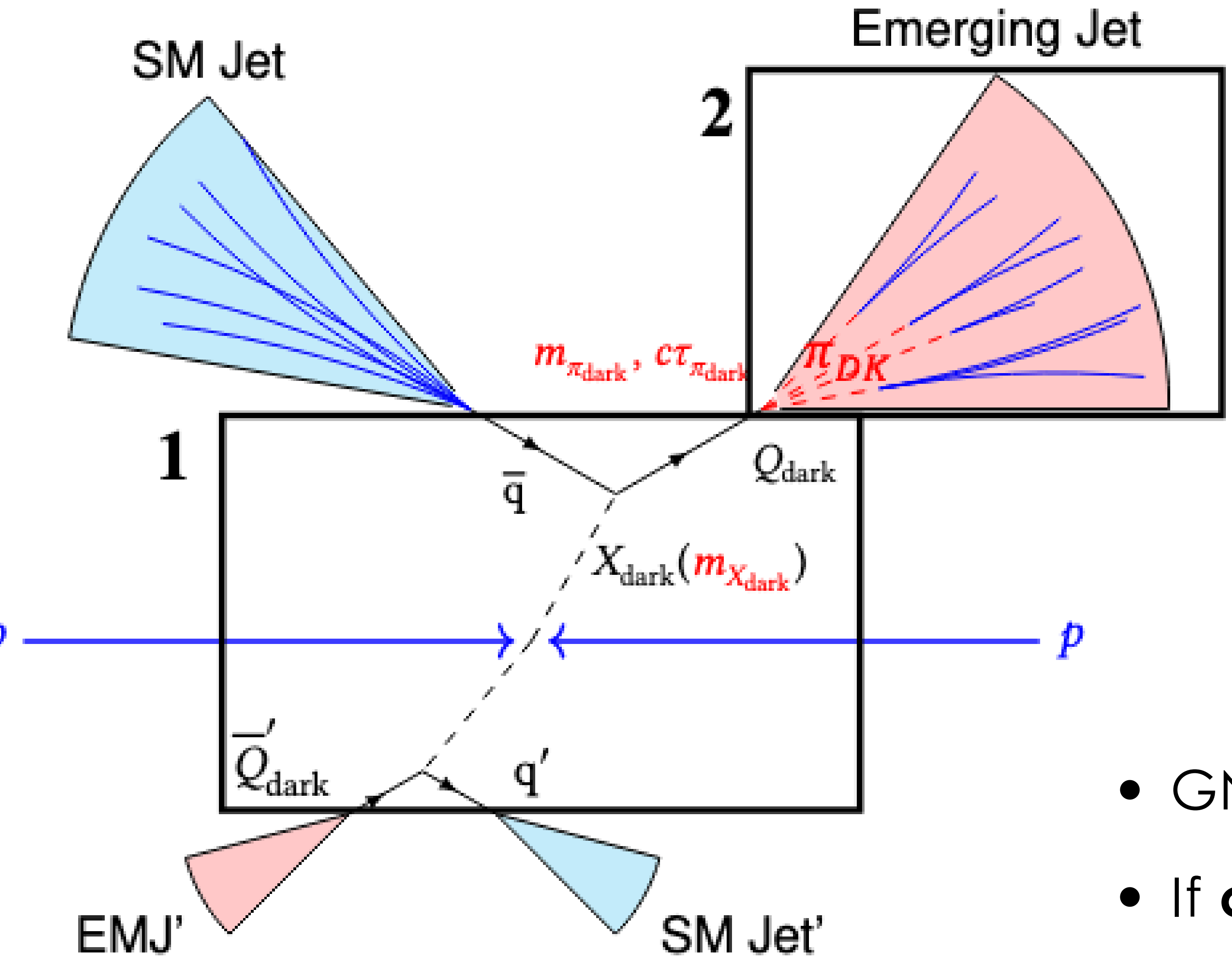
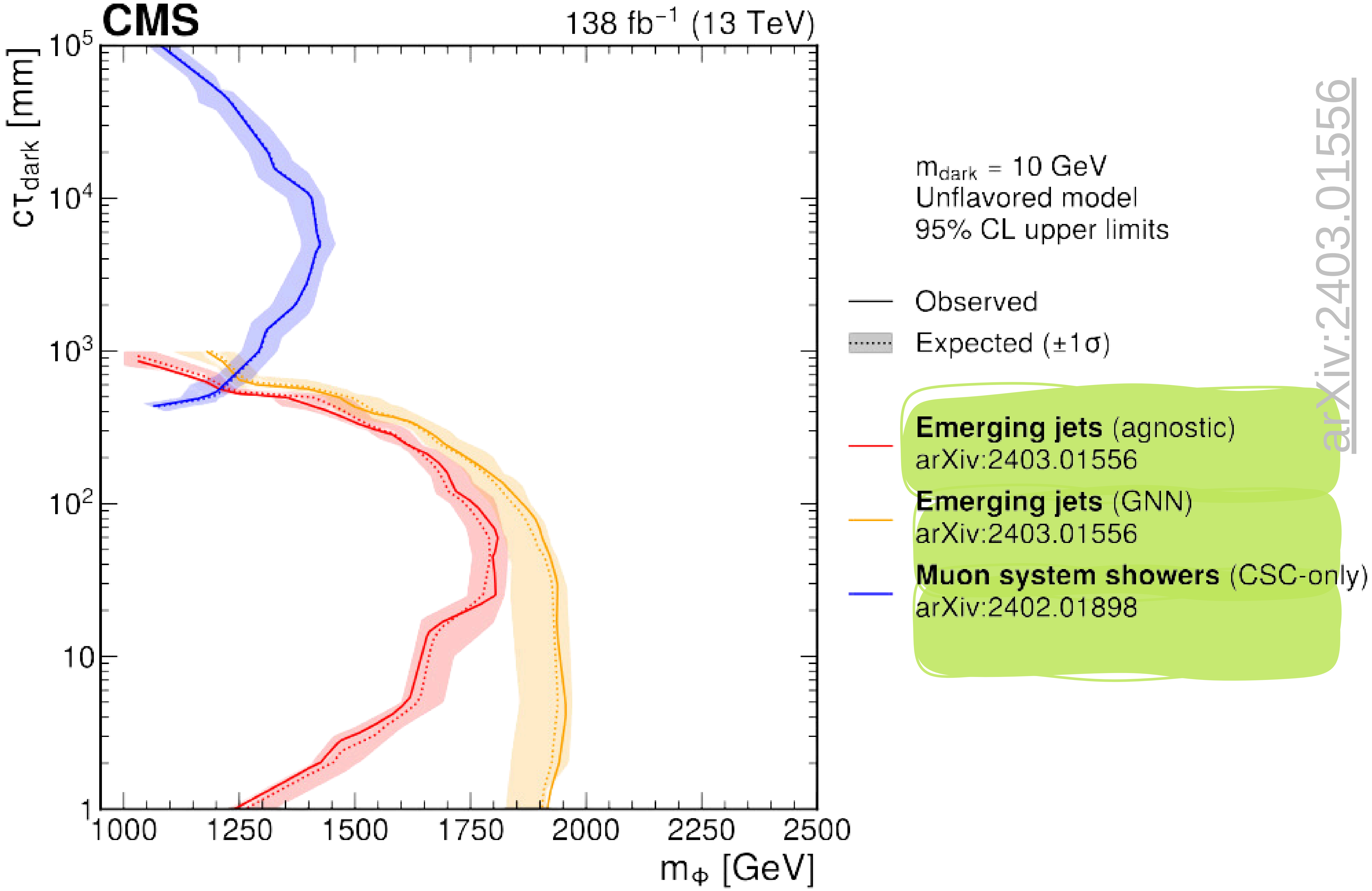
associated with the kinetic energy distribution of these particles and characterizes the softness and isotropy of the energy patterns.



Search for emerging jets

- **Unstable dark pions decay to SM**
- Free parameters scanned
  - mX: [1, 2.5] TeV
  - m(πdark) : [6, 20] GeV
  - $c\tau$(πdark) : [1,1000] mm



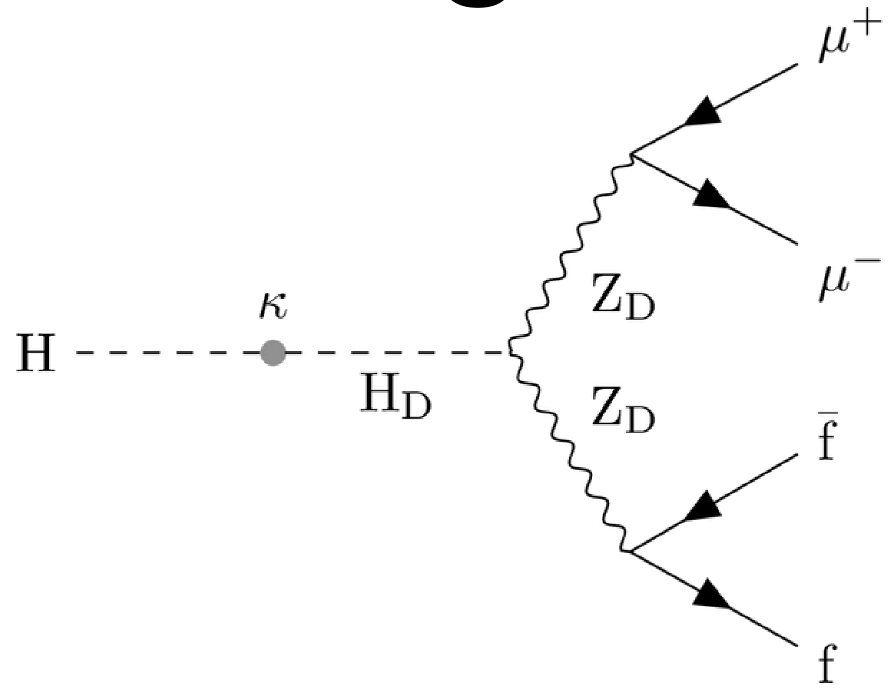


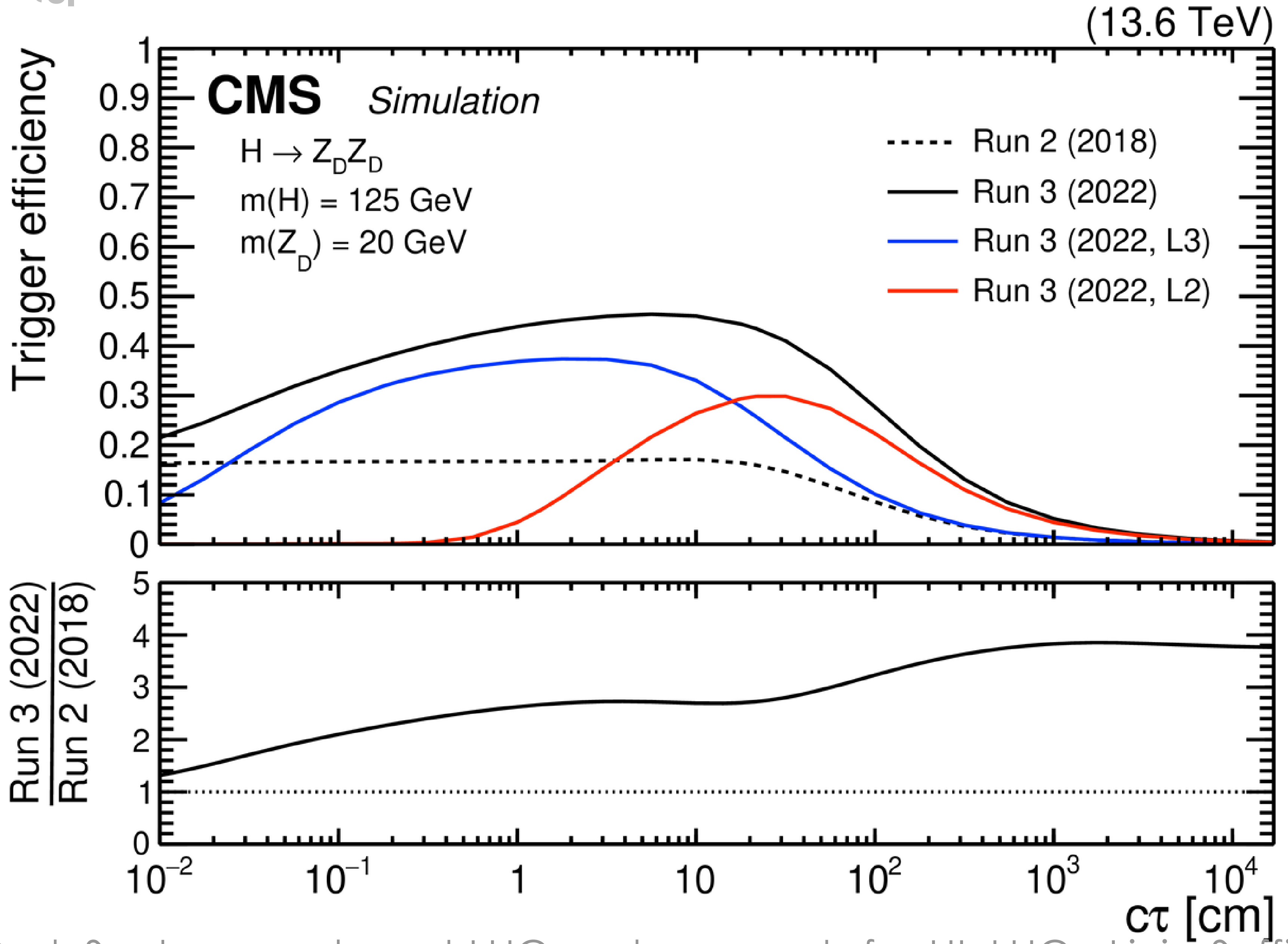
arXiv:2403.01556

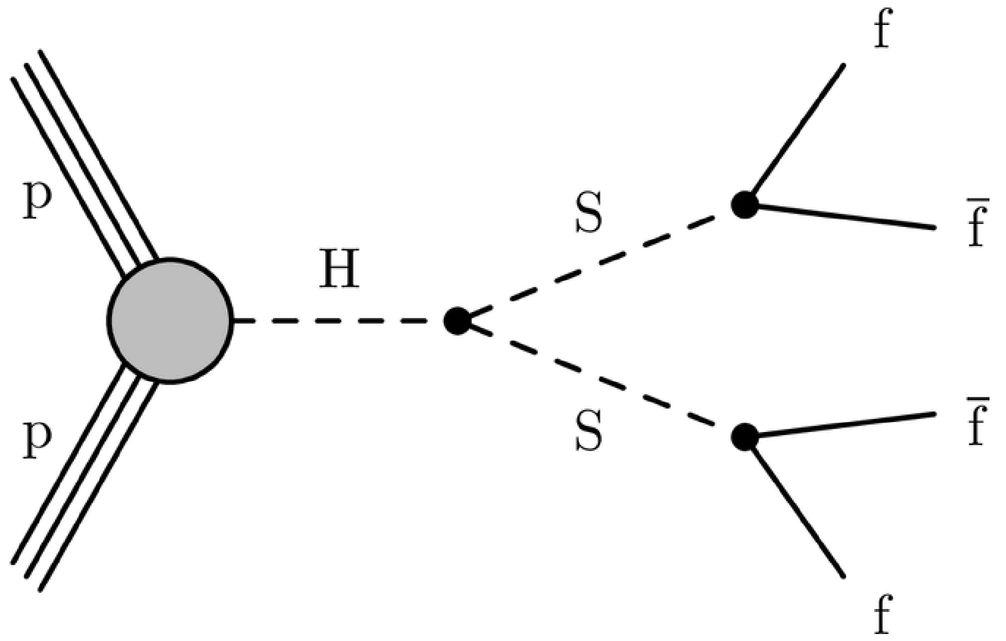
- GNN significantly improves the sensitivity for $c\tau$(π dark) ≲ 100 mm
- If **$c\tau$(πdark) ≳ 1m, the signature becomes a muon detector shower**

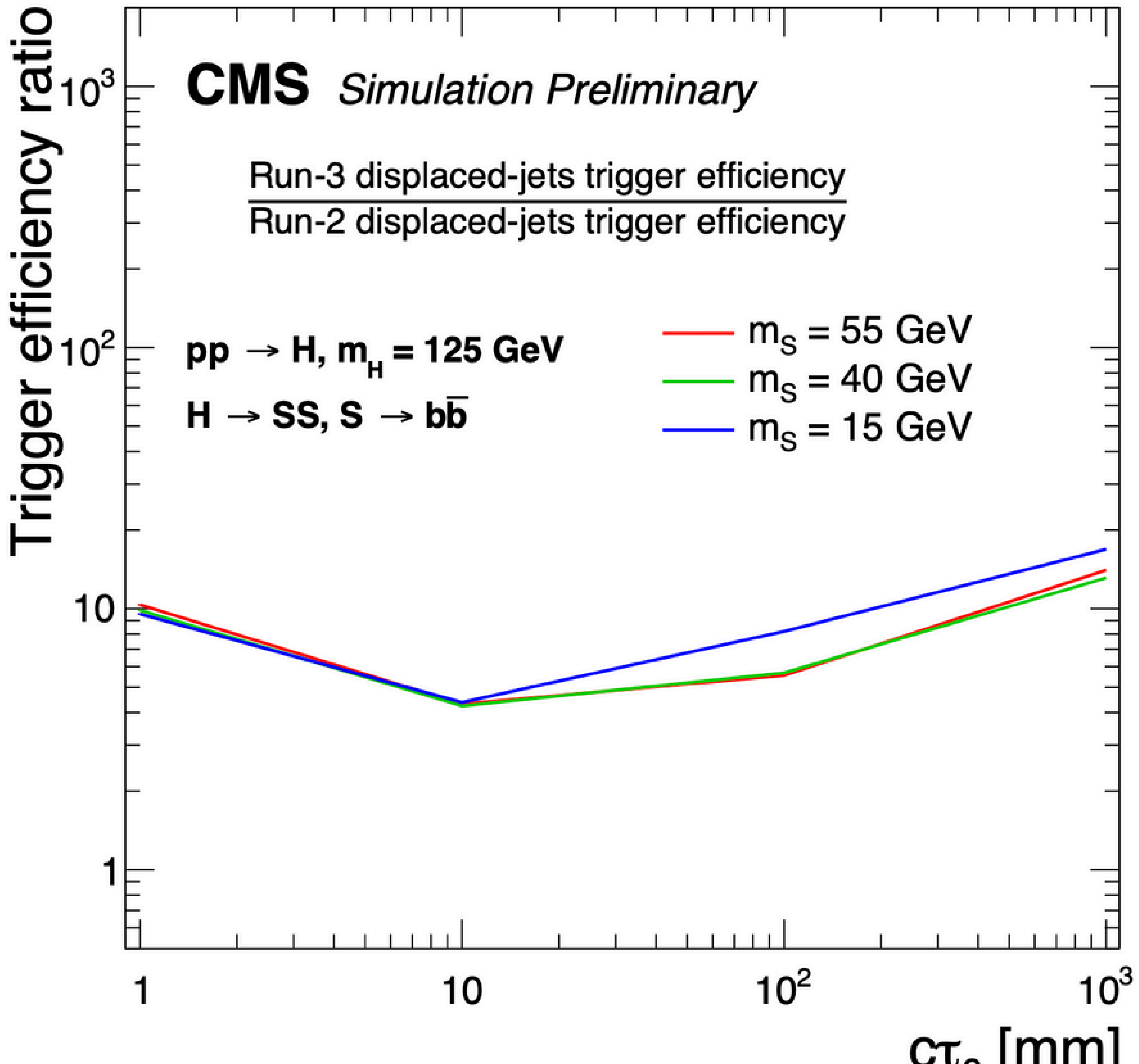
Displaced signatures: building upon new Run 3 triggers

arXiv:2402.14491





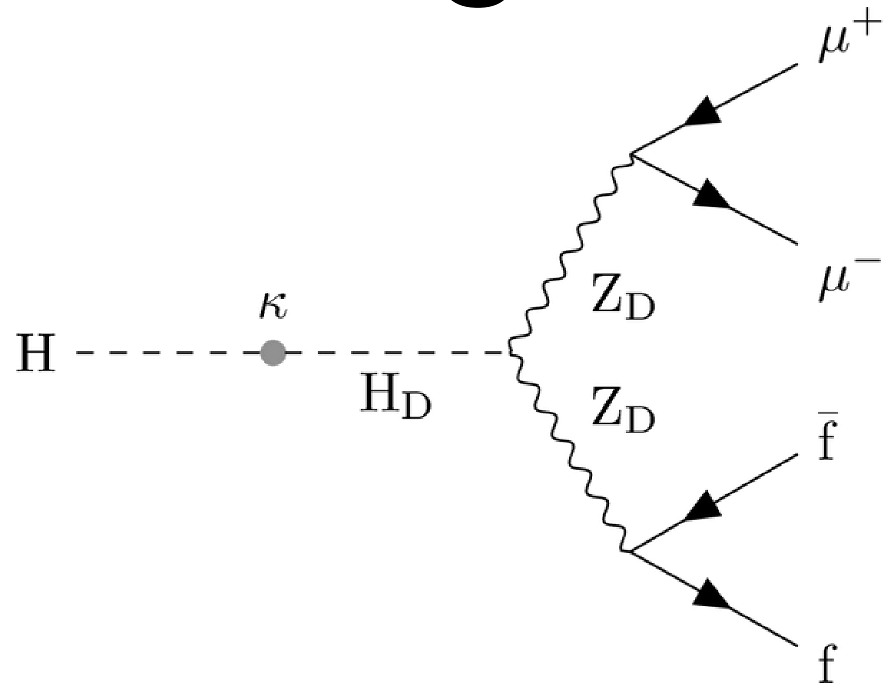


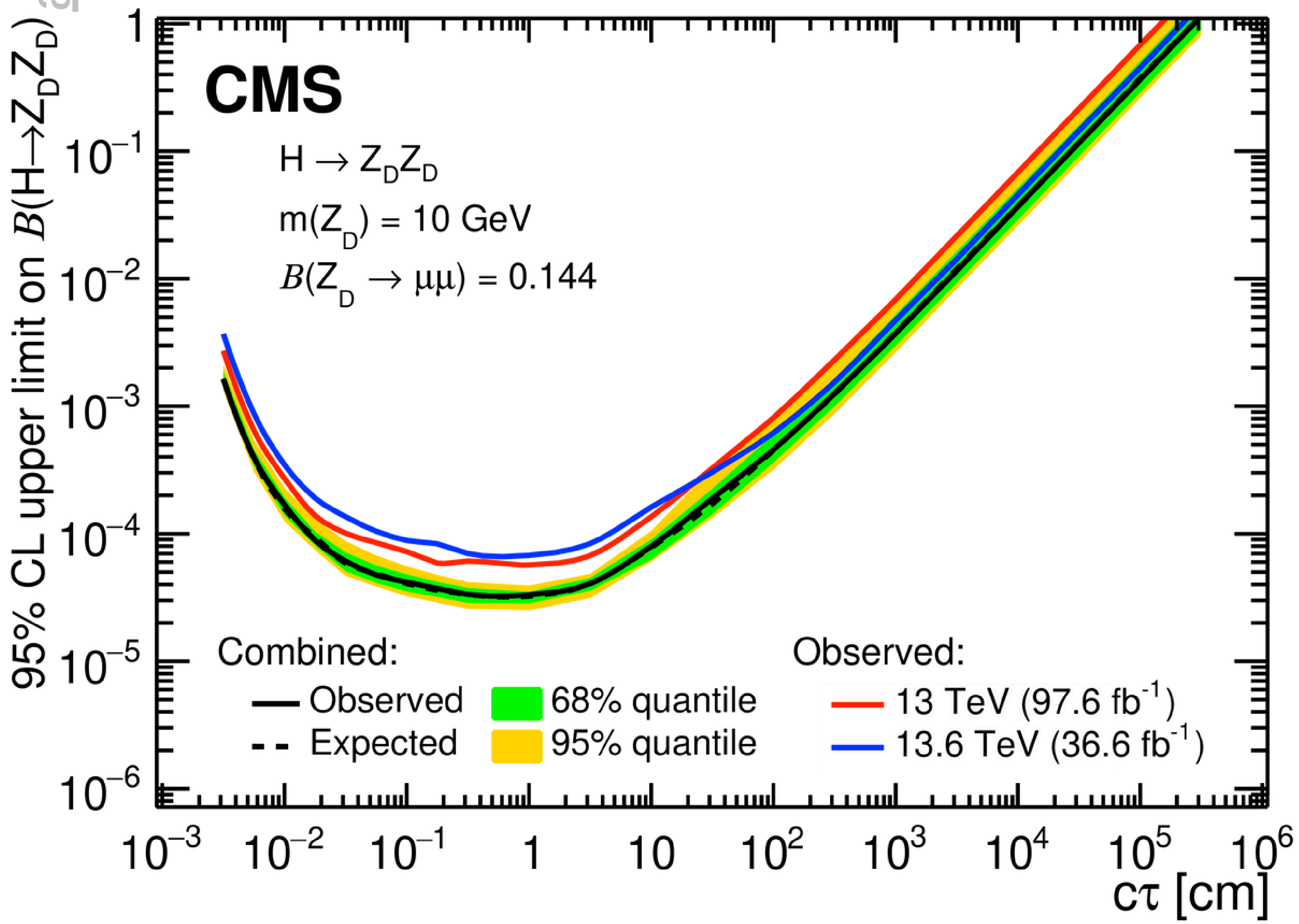


CMS-DPS-2023-043

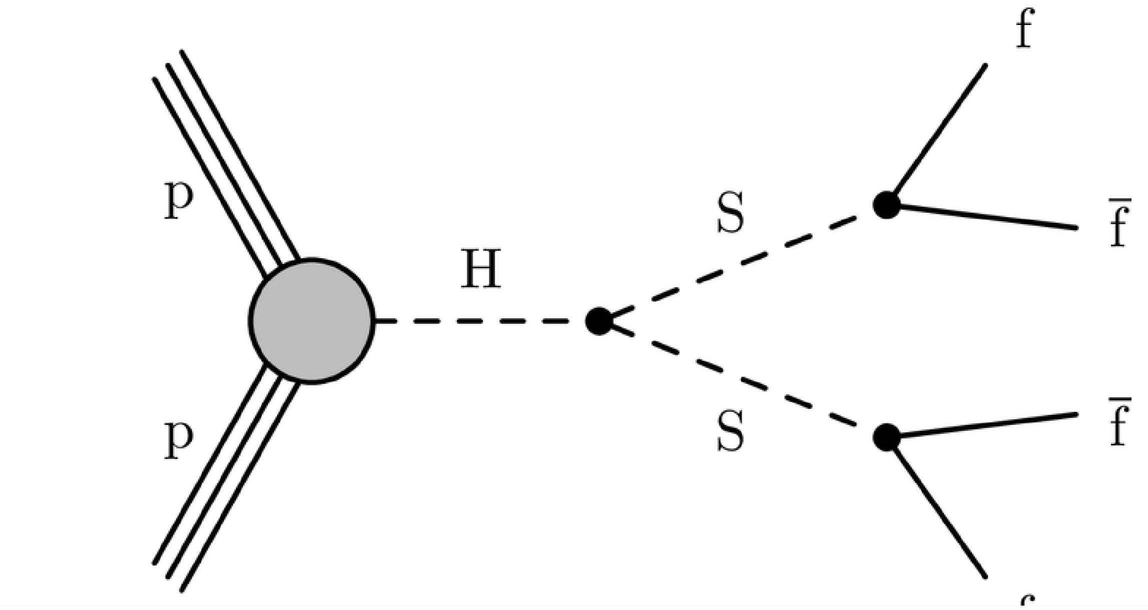
Displaced signatures: building upon new Run 3 triggers

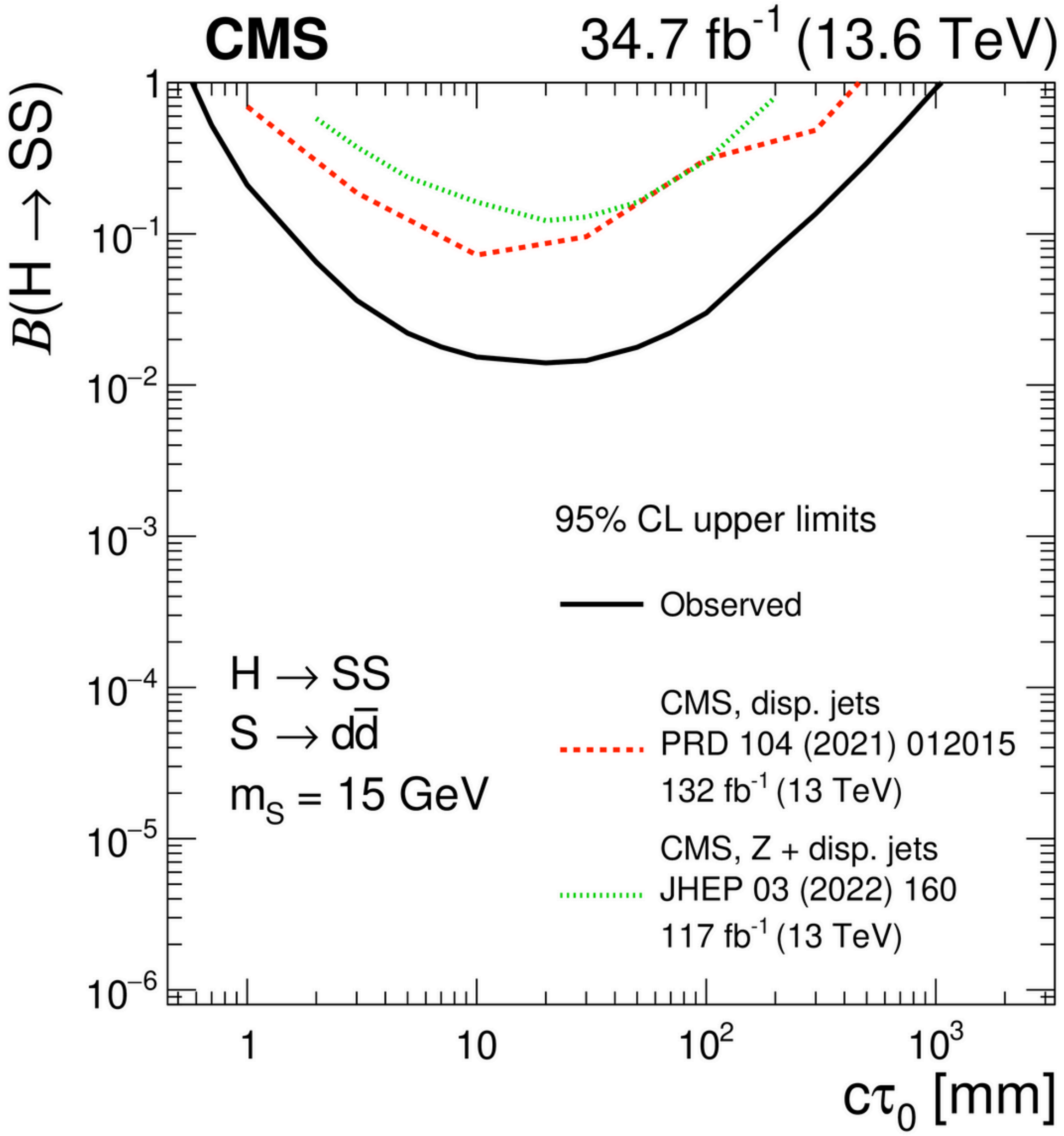
arXiv:2402.14491



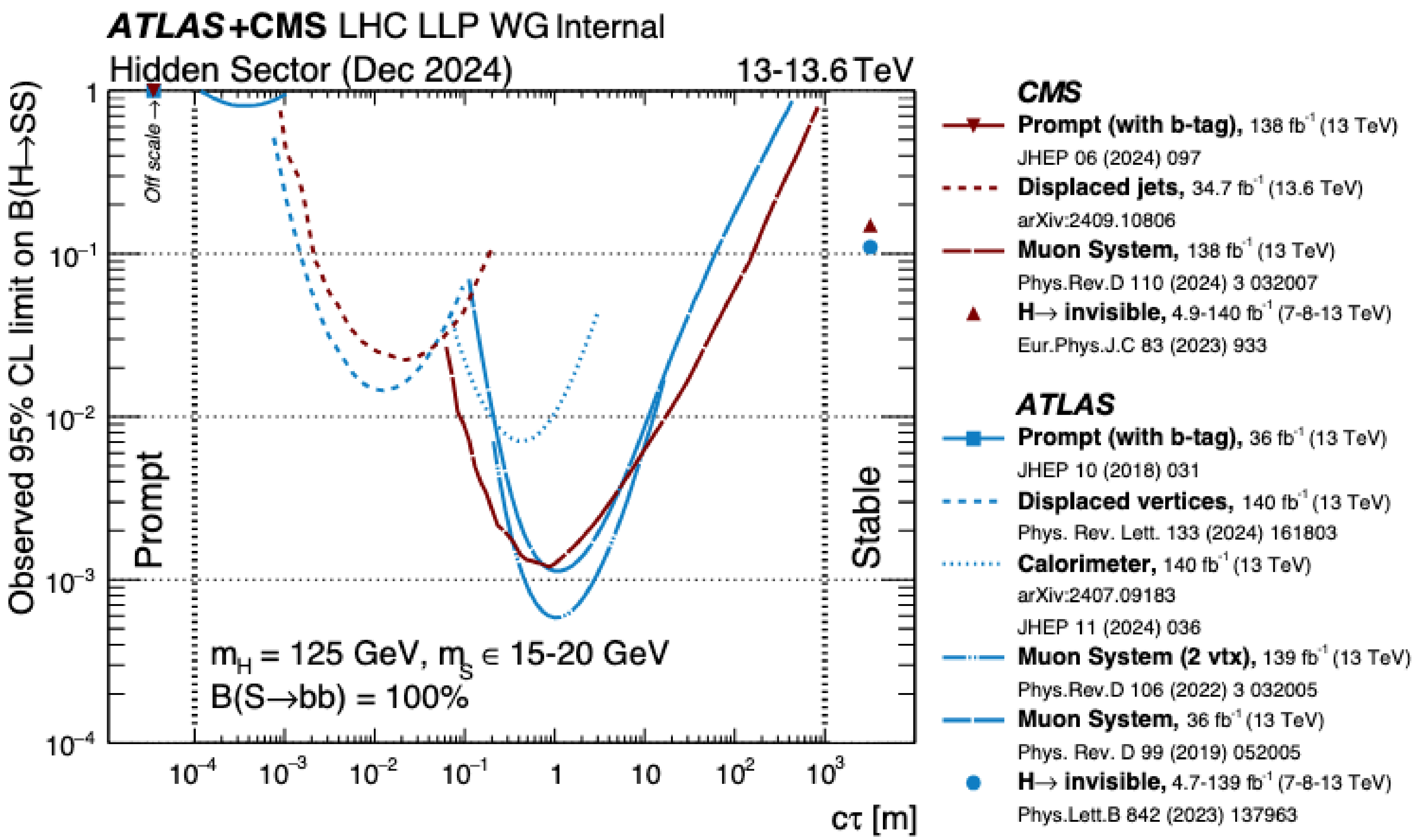


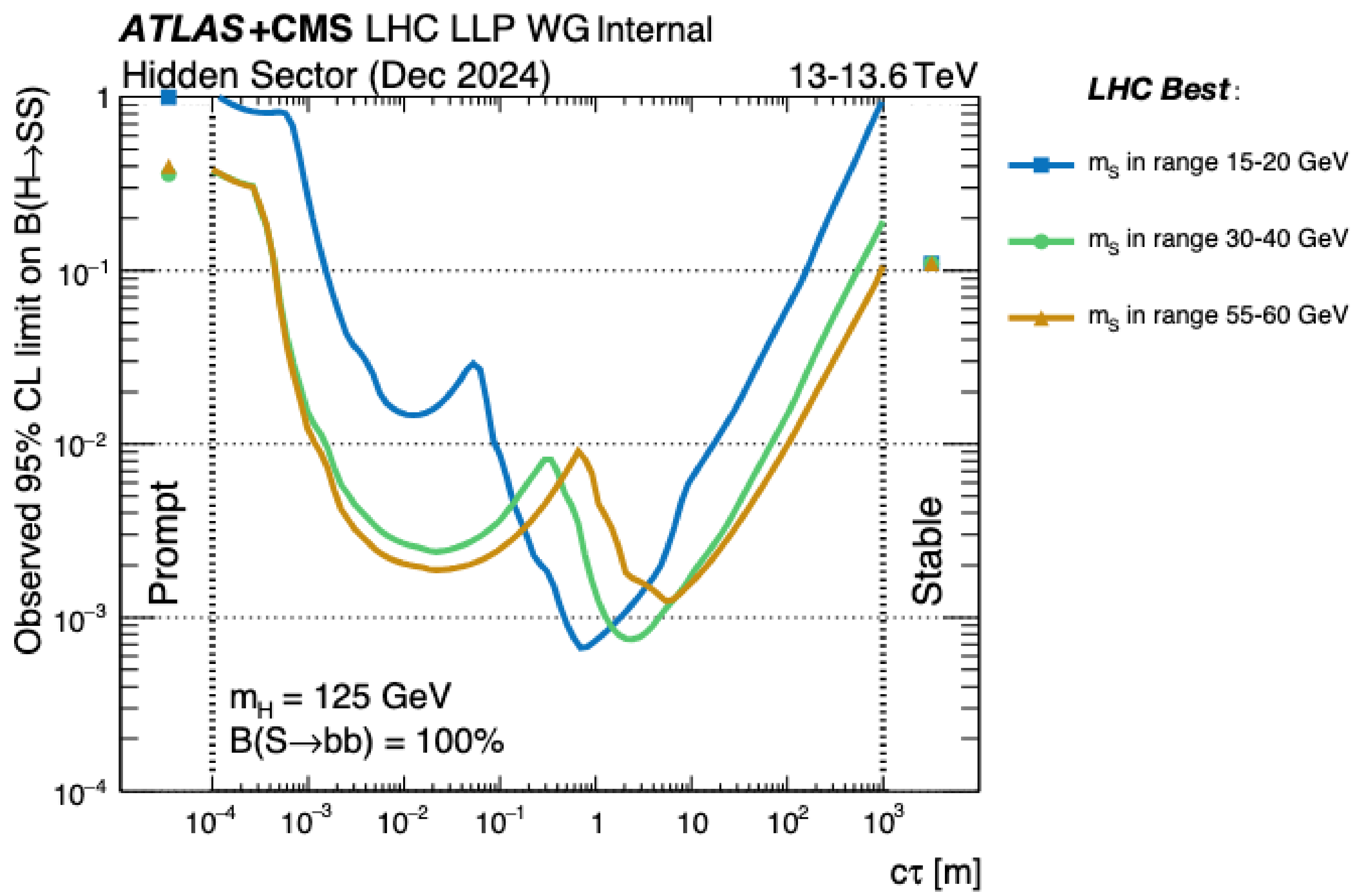
arXiv:2409.10806

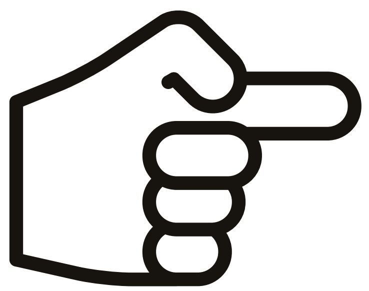




Hidden sector searches complementarity







<u>2024: the newly formed **BSM LHC WG**</u>

https://lpcc.web.cern.ch/content/lhc-bsm-wg

- Consolidated and broad overview of **BSM LHC physics program** and of **current state of the art and plans** from LHC experiments

Towards HL-LHC

Novel opportunities for Run 3

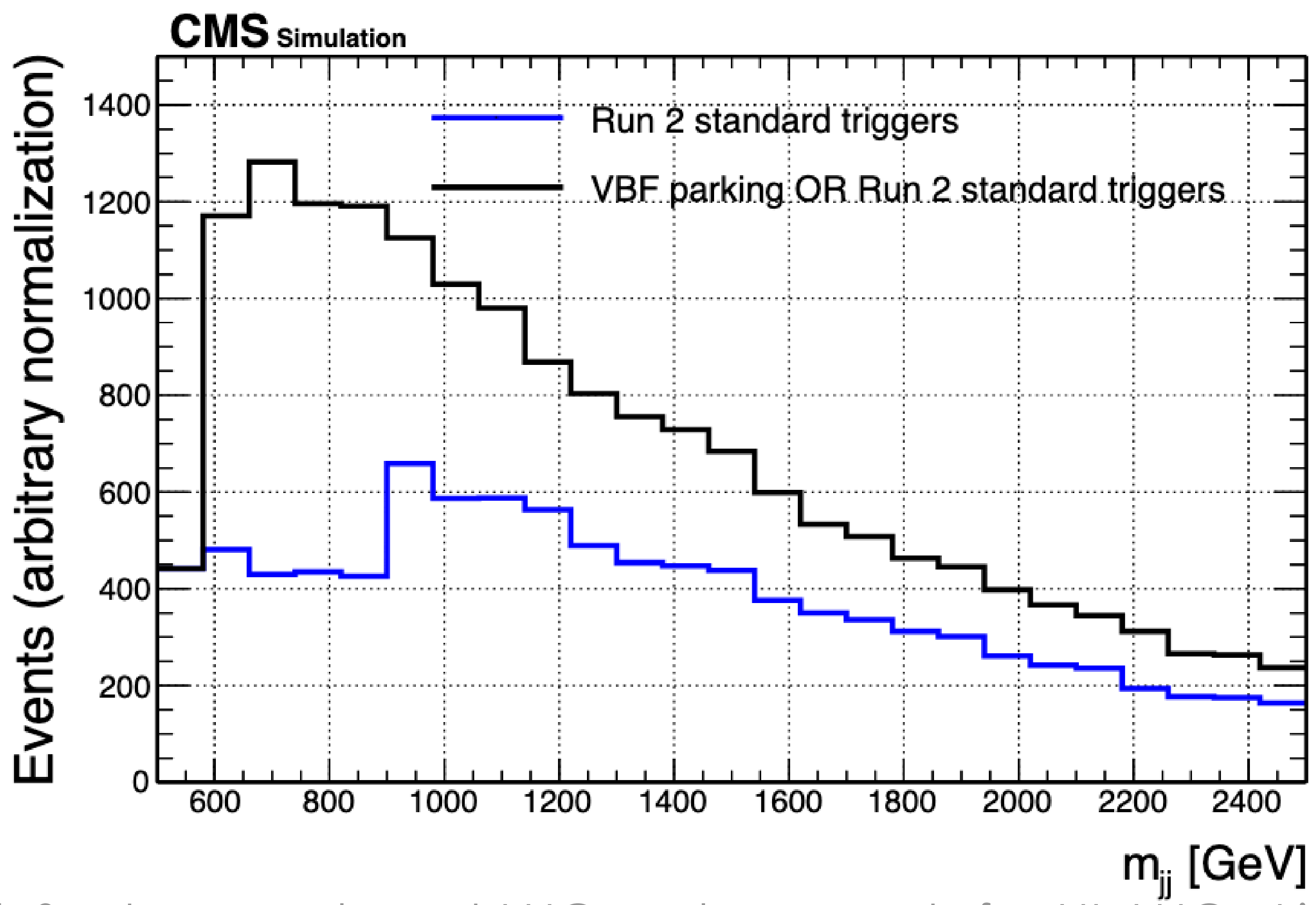
Prospects for HL-LHC

Accessing new phase space w/ timing detectors

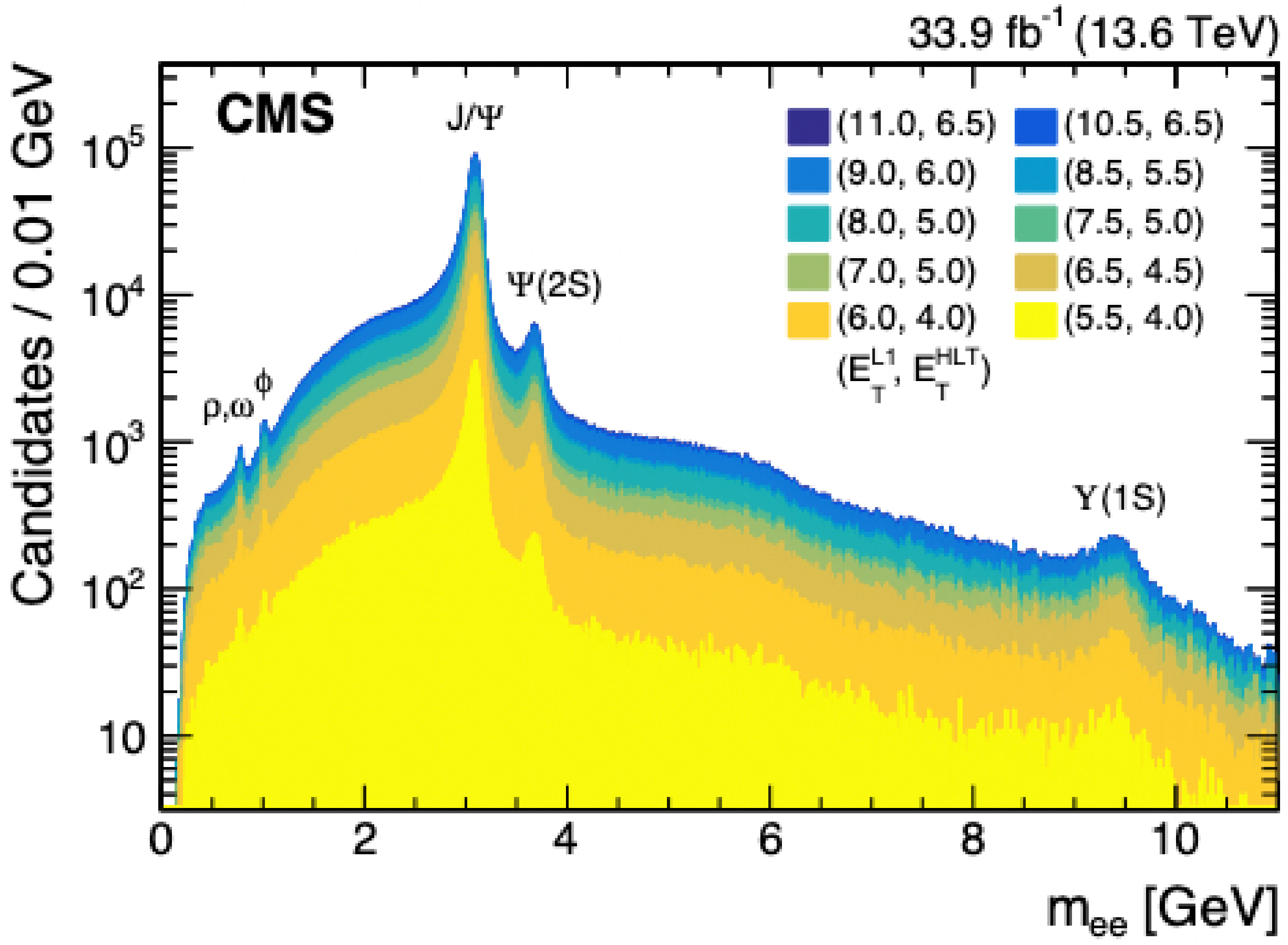
Novel opportunities for Run 3

- Successful execution of the **B parking program during Run 2** garnered significant interest, propelling the **evolution of the parking technique** into a comprehensive and diverse program.
- Since 2022, the definition of data parking has shifted somewhat to include prompt reconstruction (i.e., **processing typically starting within 48 hours**), upon the availability of computing resources.
- **New parking strategies** enable efficient probing currently unexplored experimental signatures that may become of interest in the future.

VBF parking

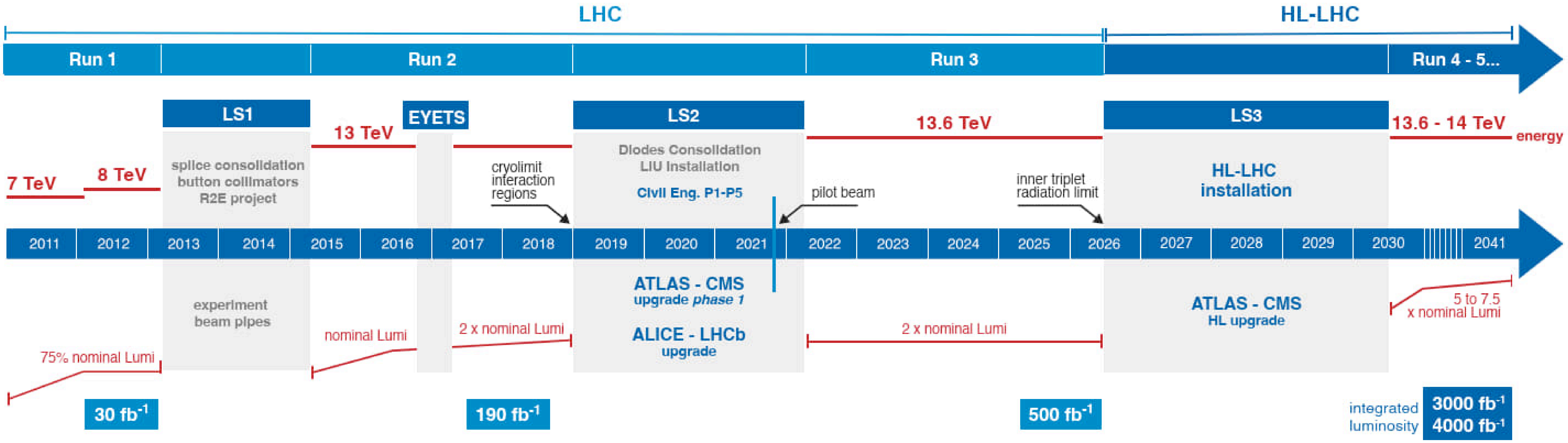


Dielectrons parking



Prospects at HL-LHC

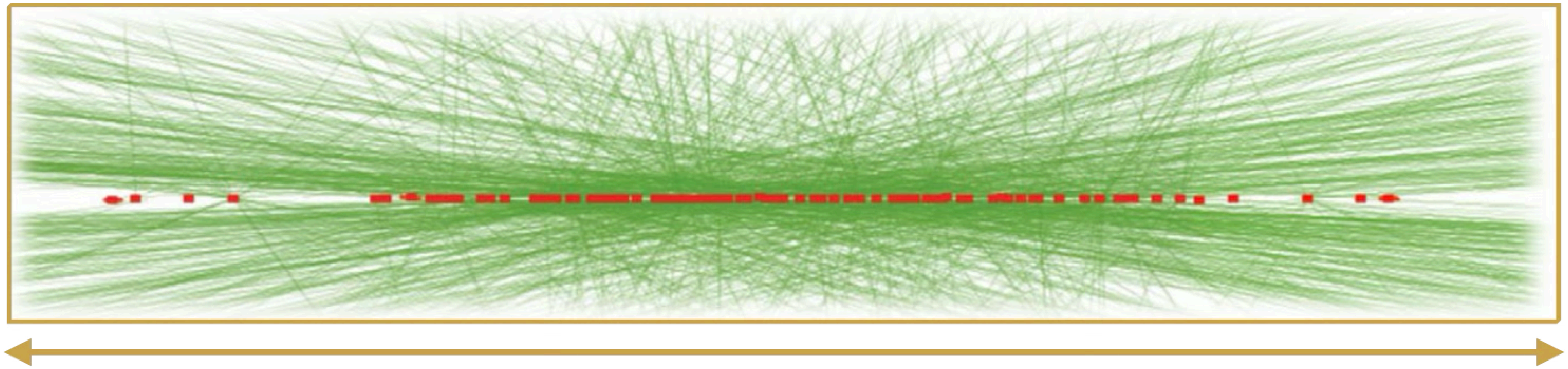
- HL-LHC represents the ultimate evolution of LHC machine performance: operation at up to L=7.5·1034 Hz/cm²



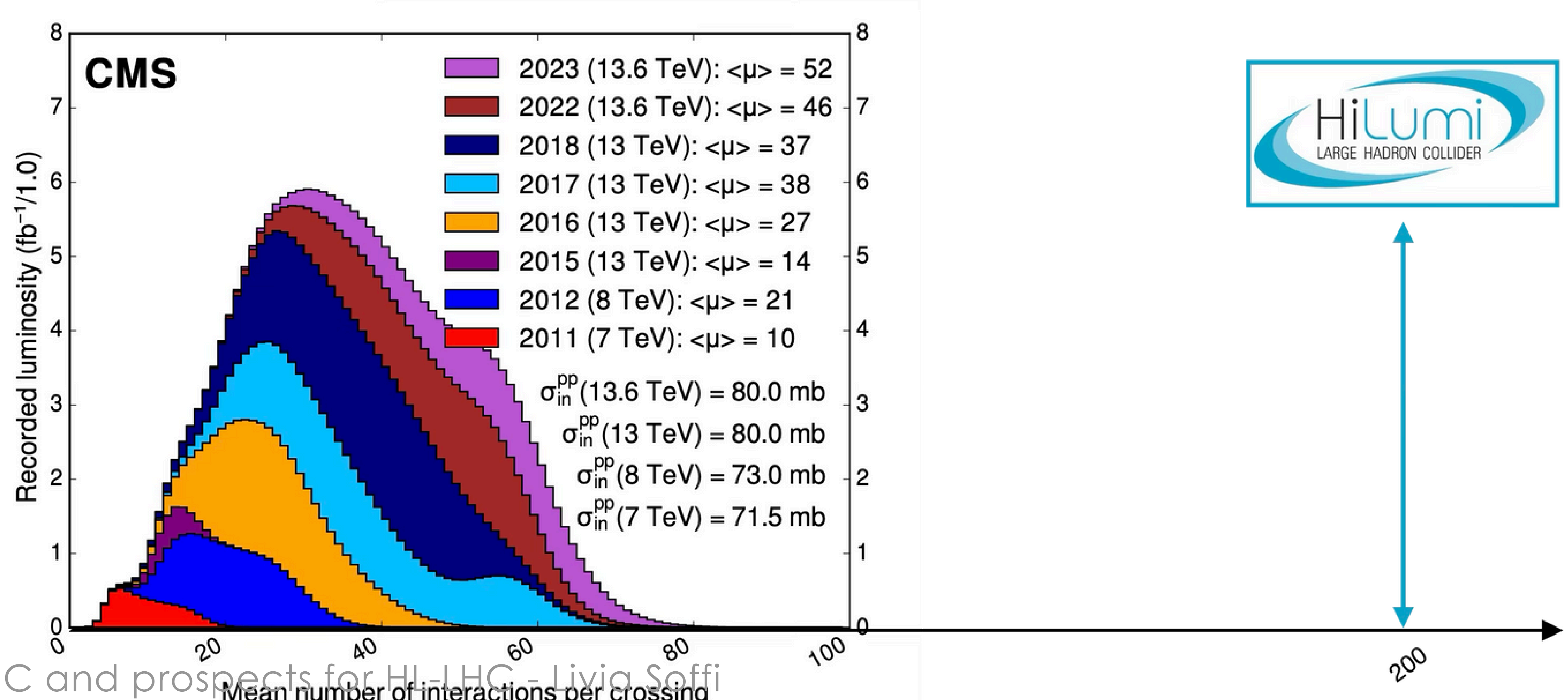
- Major boost in statistics expected at HL-LHC from 2029:
- 3000 fb−1 for ATLAS&CMS, 50 fb−1for LHCb 5 fb−1 for ALICE
- Pb–Pb (13 nb−1)and p–Pb (50 nb−1)

Raising the challenge at HL-LHC

- Pileup (PU) particularly challenging for data-taking: detector irradiation, higher occupancy and trigger rates
- Much higher collision rates will far exceed the capabilities of the existing detectors



140-200 vertices in beam-spot space [5 cm]



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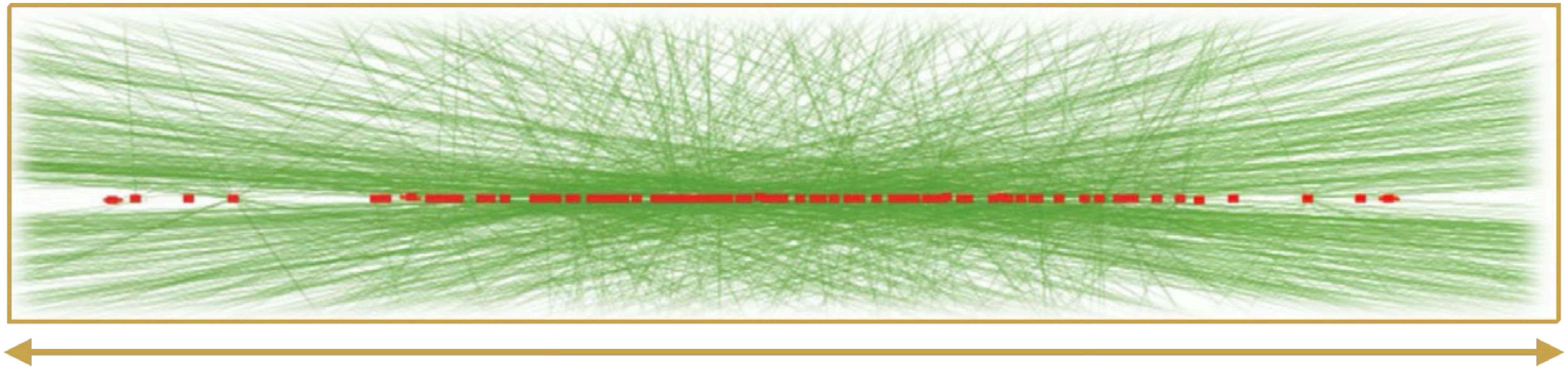
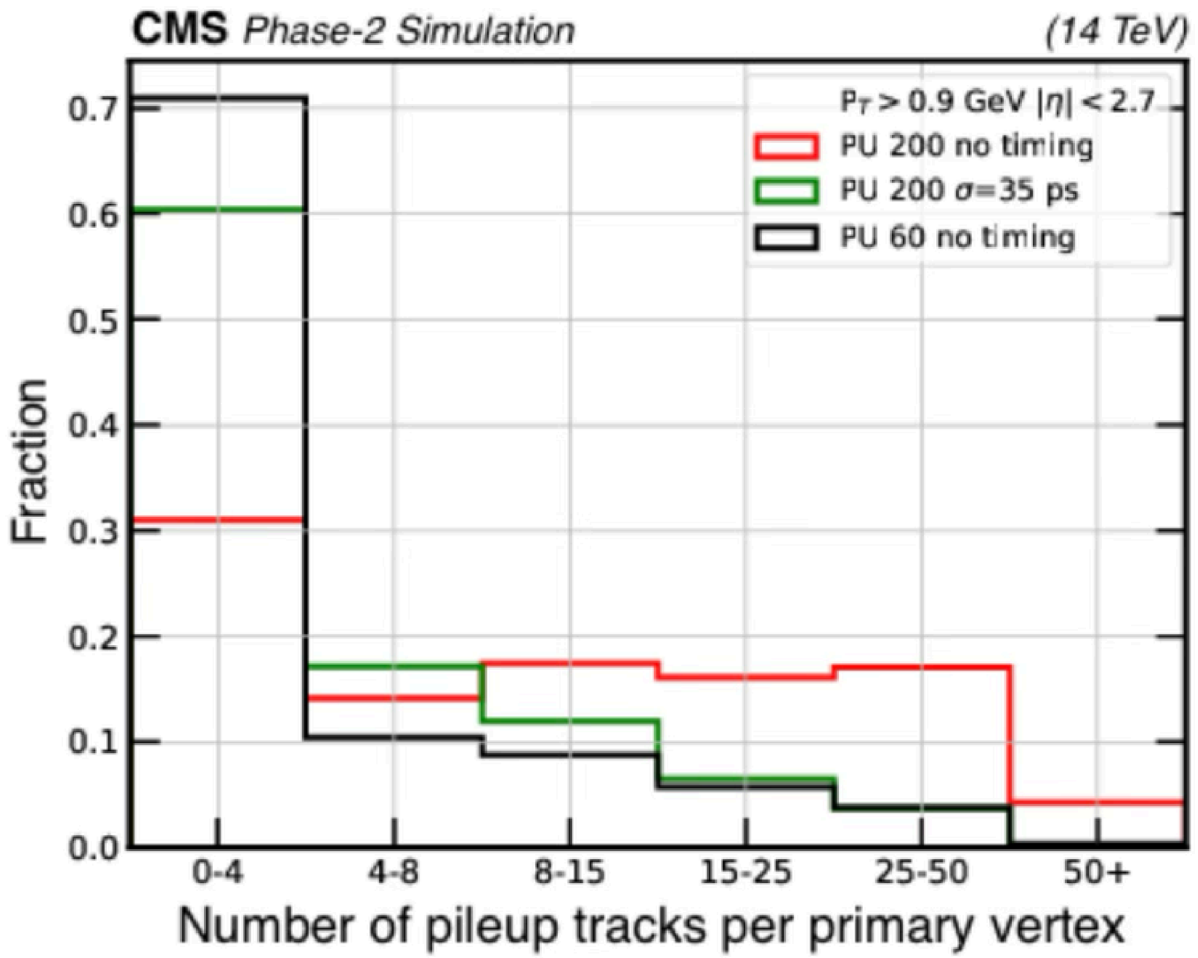
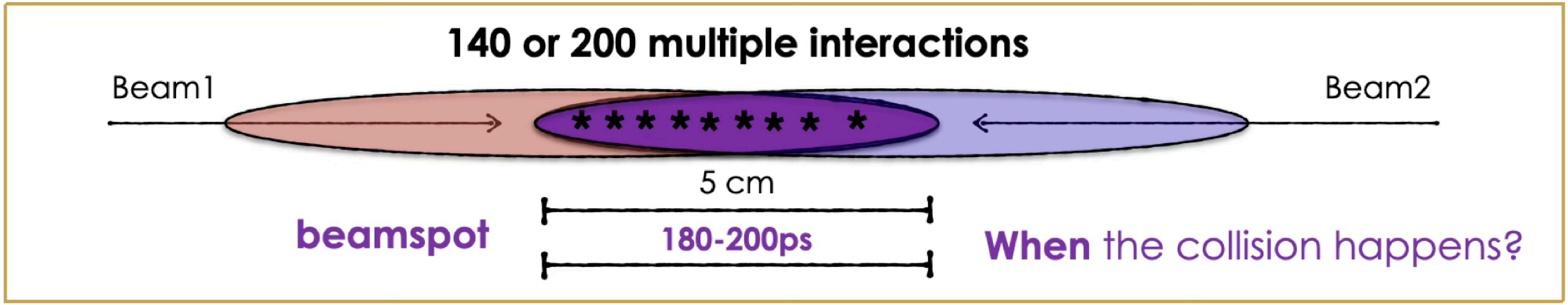


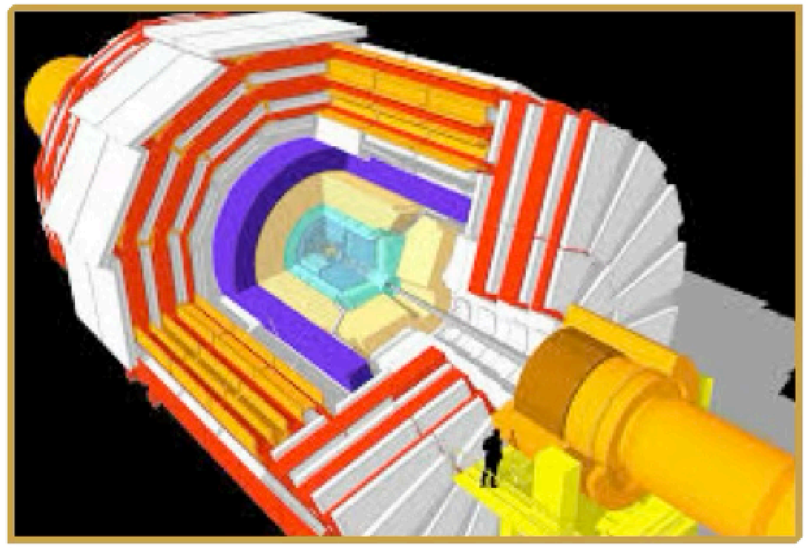
140-200 vertices in beam-spot space [5 cm]

- Primary goal at HL-LHC is to **maintain the current excellent** detectors performance in terms of efficiency, resolution, and background rejection for all final state particles and physics observables used in data analyses.

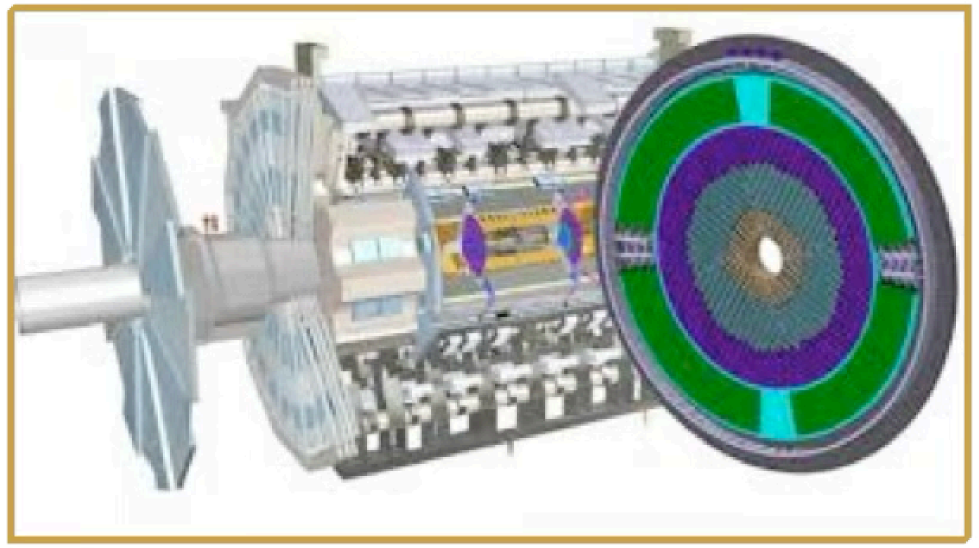


New timing detectors at LHC

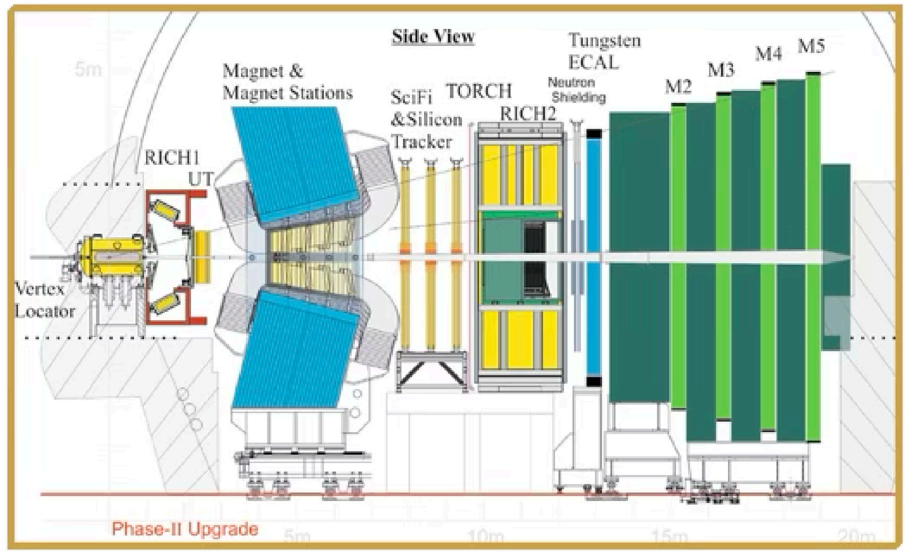




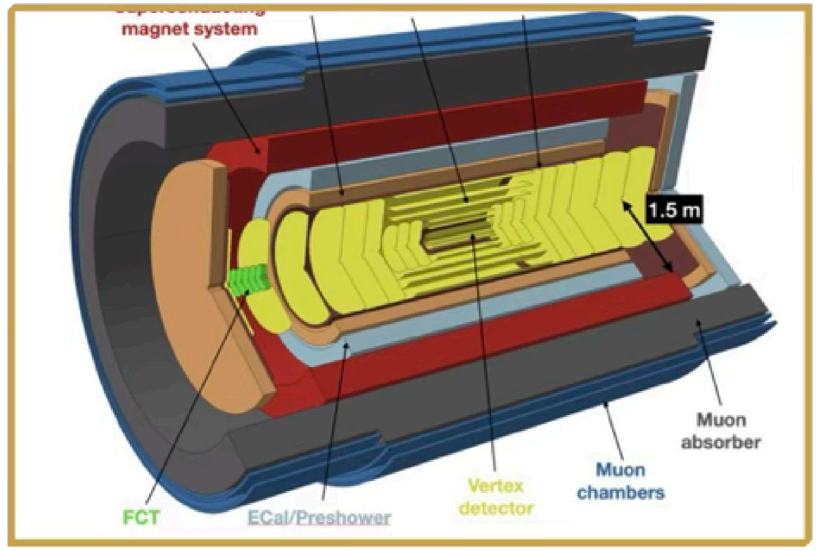
Mip Timing Detector @CMS



High-Granularity Timing Detector @ ATLAS



TORCH @ LHCb

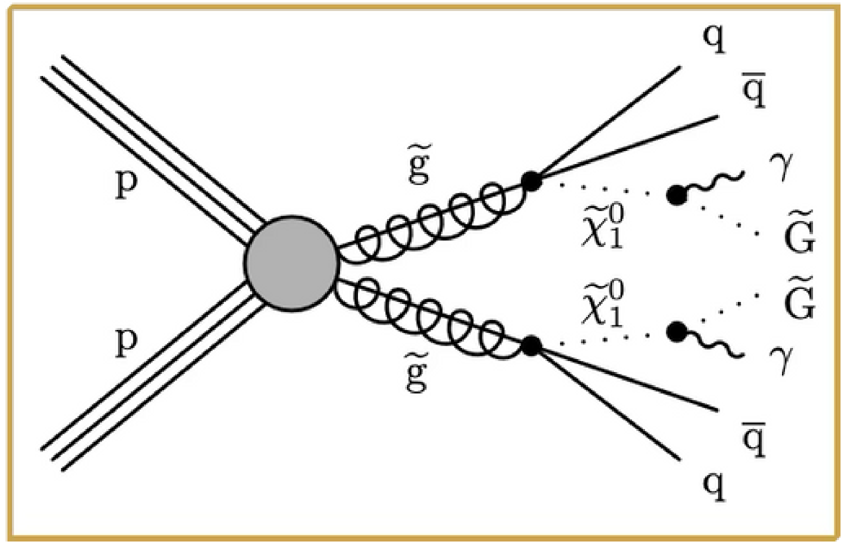


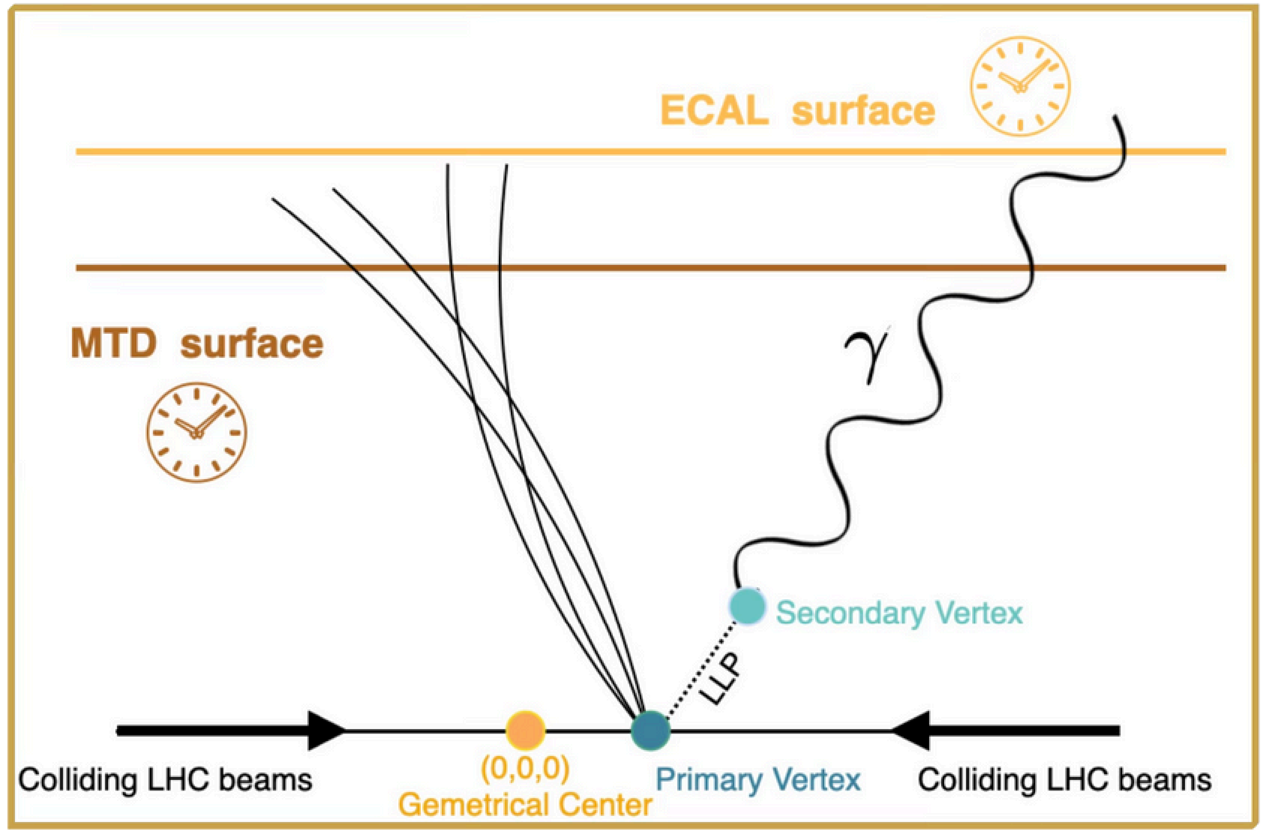
ALICE3

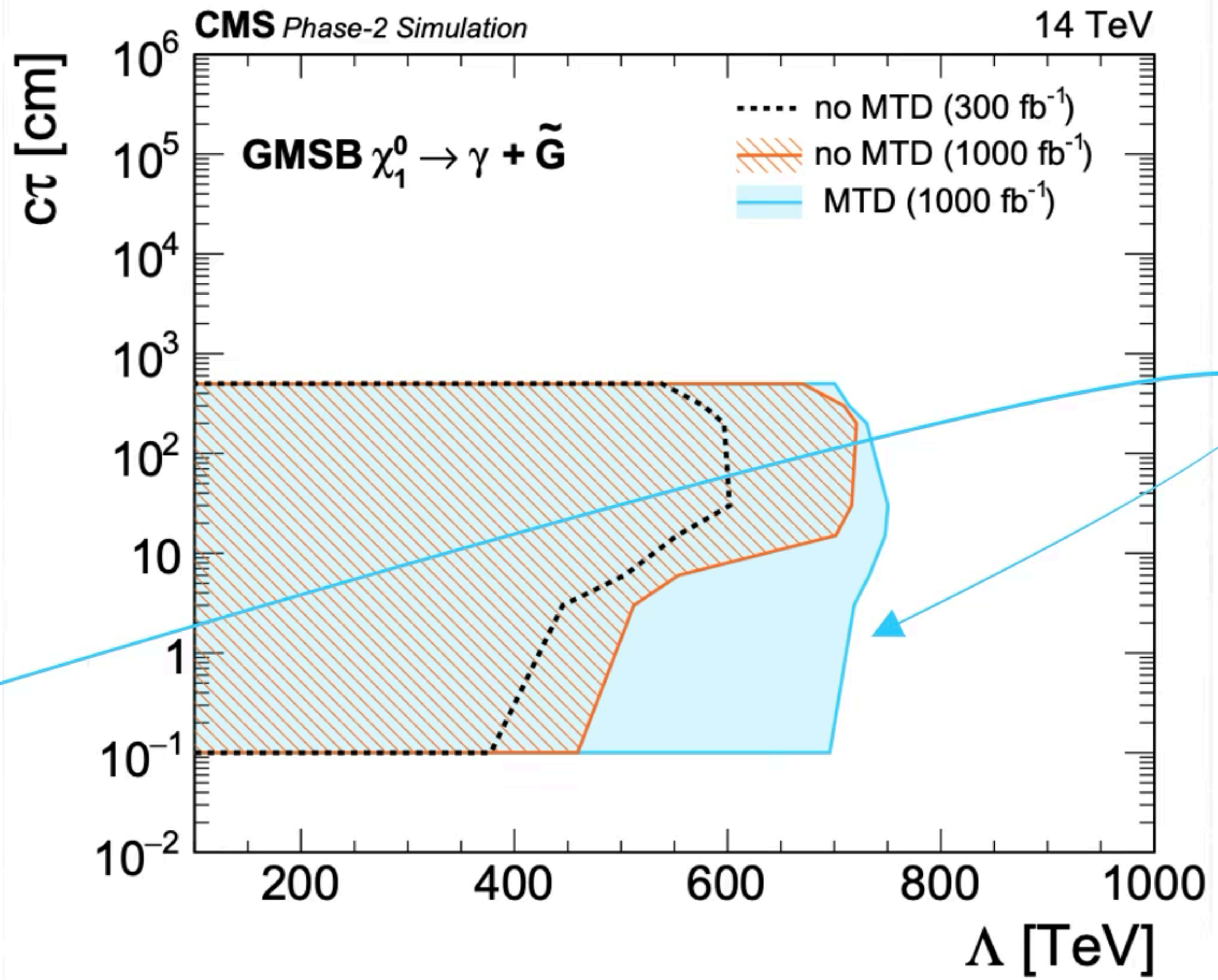
- Significant reduction of beamspot uncertainty w/ tens ps target resolution
- Remove pileup tracks and rejects spurious secondary vertices
- Extend the physics reach in precision measurements
- Provides a new capability for LLP searches and Particle ID

Detection of late photons with CMS MTD

- New **30 ps Mip Timing Detector (MTD)** essential to properly determine the primary vertex time and particles' time of flight
- Signatures with delayed photons: (**ECAL time resolution: 30 ps)**
- Weighted vertex time resolution: estimating number of tracks in barrel/endcap





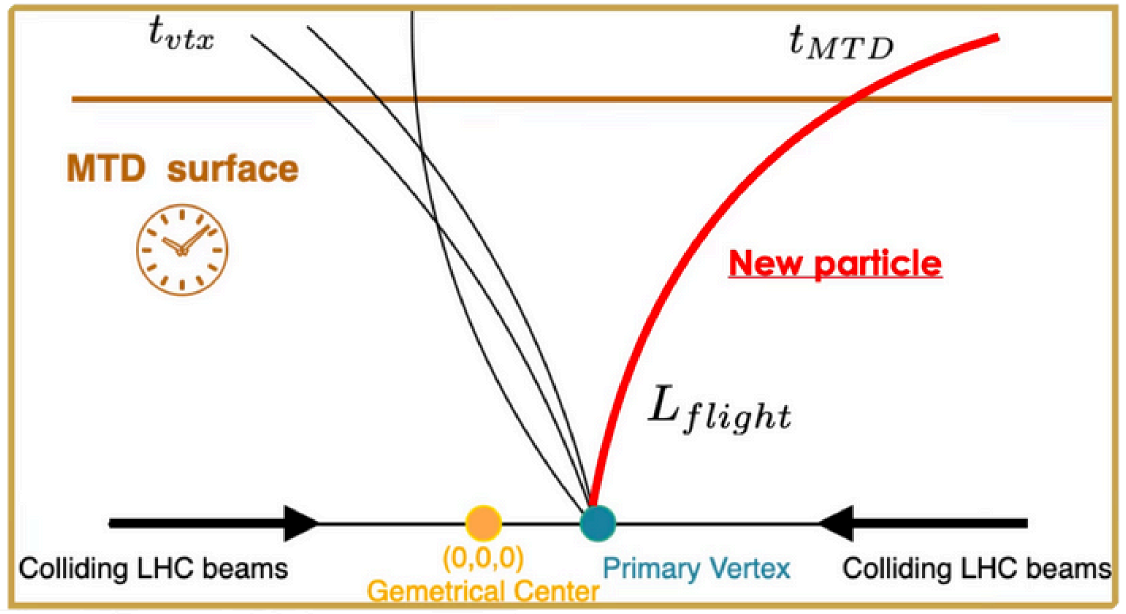


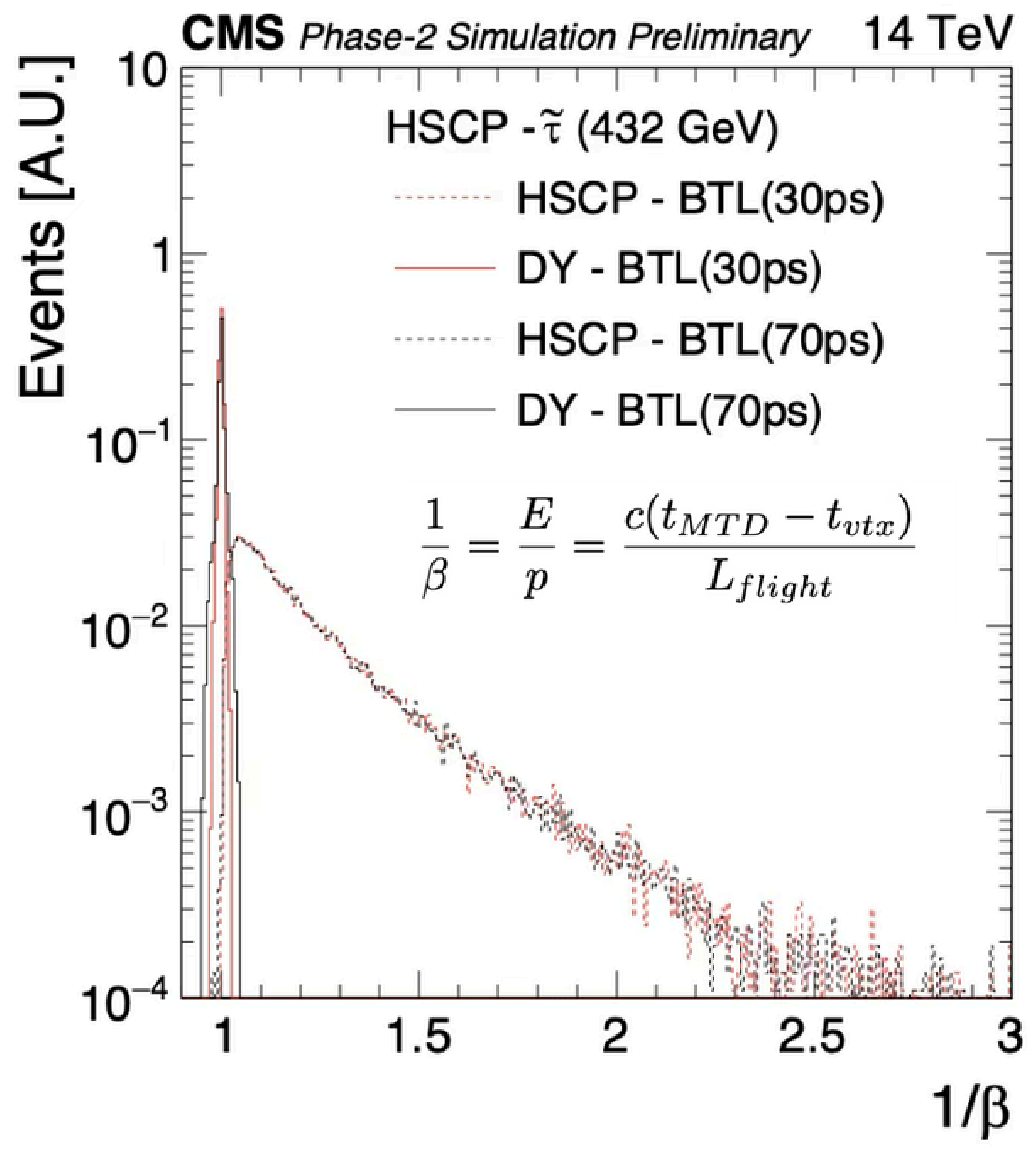
large gain in sensitivity w.r.t. ECAL only scenario

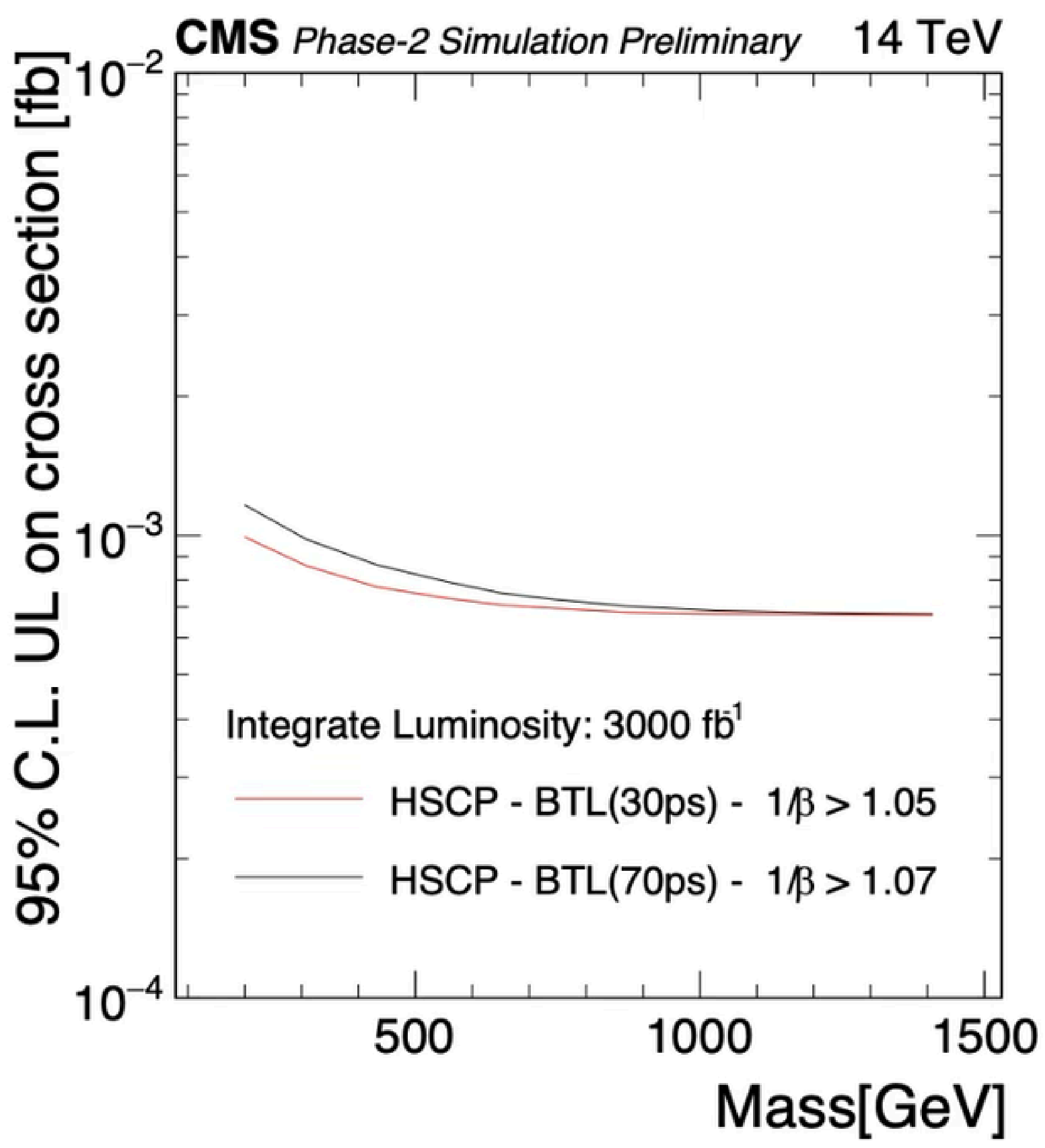
CDS-LINK

CMS MTD as a time-of-flight detector

- Turn the **MTD into a time of flight detector** and look for **anomalous moving particles** (slow velocities, q!=1, large mass)
- Complement Muon Detector based searches at short lifetimes
- Promising performance through the entire HL-LHC data taking period







CDS-LINK

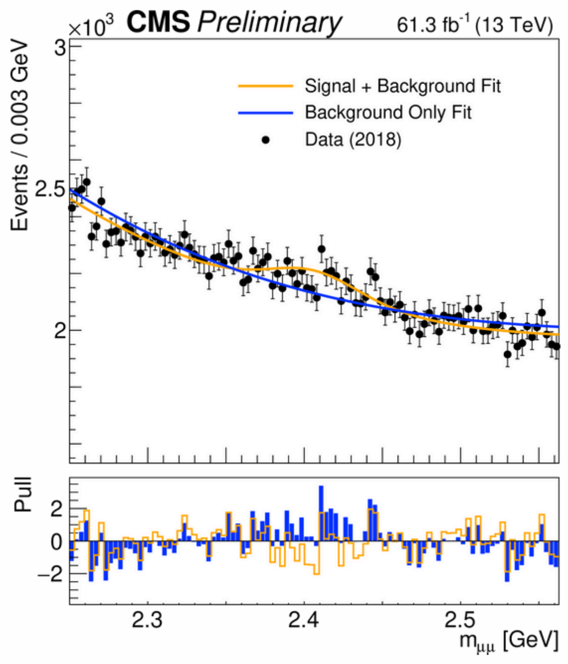
Dark sector searches in our light-cone

Run 3 provides a powerful platform to explore new physics through combination of **higher energy, increased luminosity, and improved experimental techniques**

Some excesses around, w/o Run 3 result yet, to chase..e.g.:

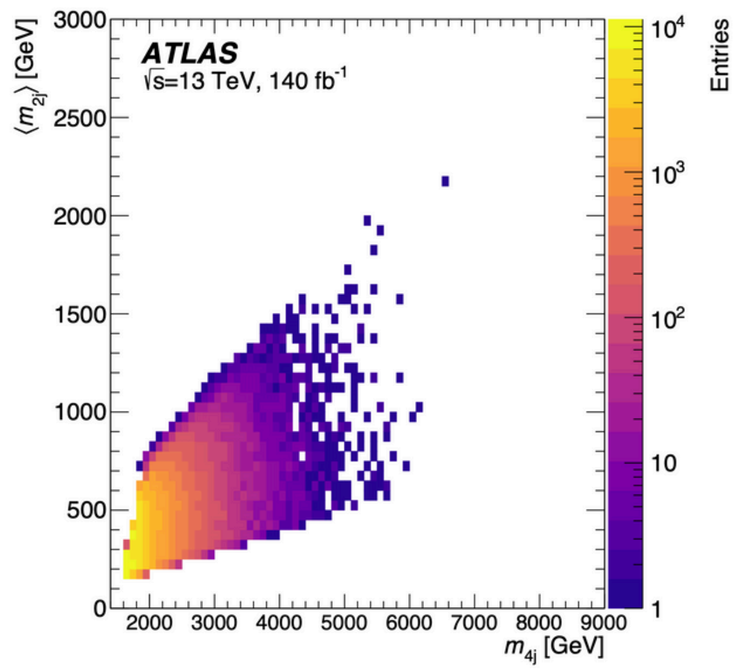
Low-mass dimuon

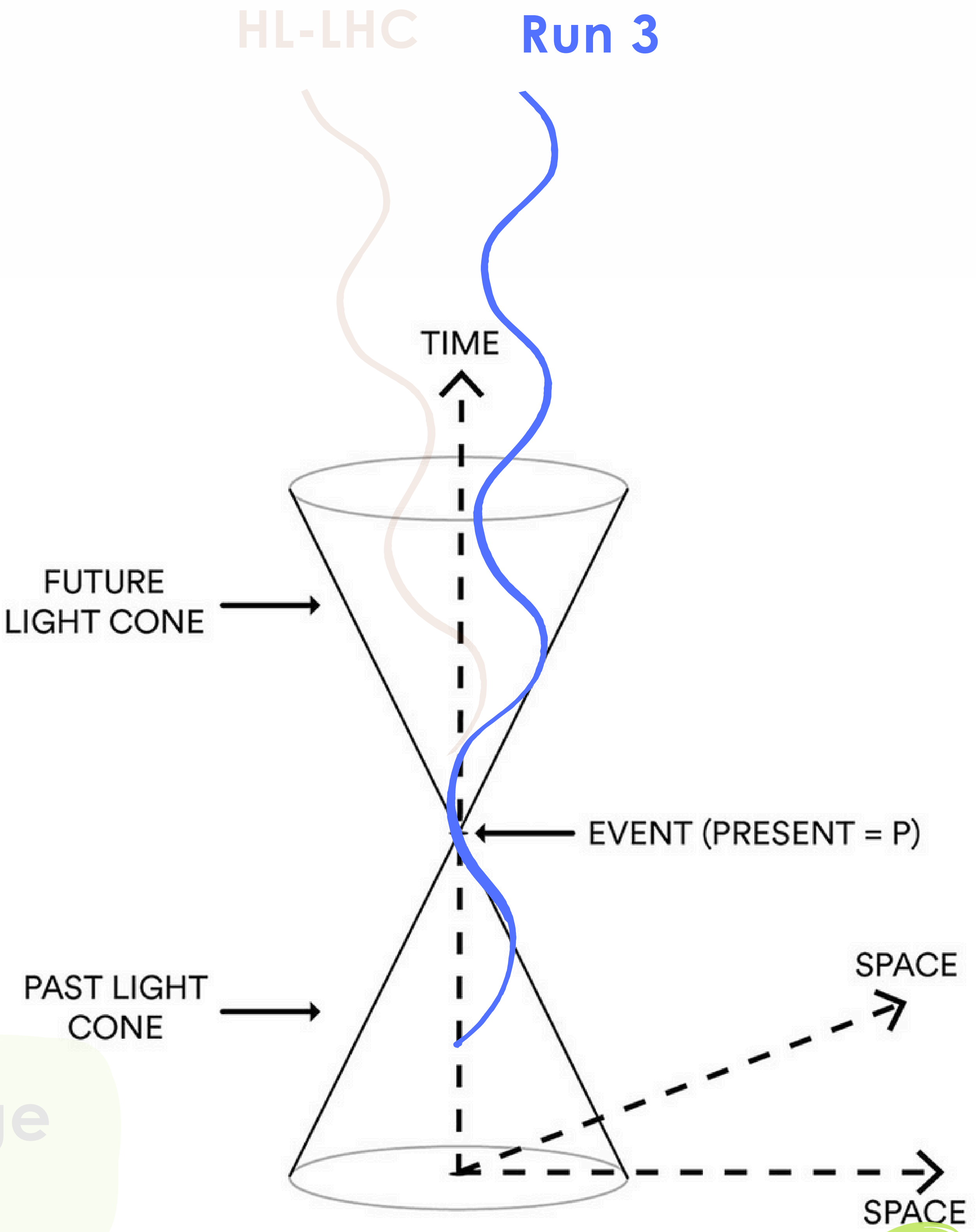
arXiv:2309.16003



High-mass $Y \to XX \to 4j$

arXiv:2307.14944





HL-LHC will significantly increase physics reach: gains from **high lu[m]**
and new detector capabilities

e.g. Long Lived Particles searches and Particle ID with timing detectors

Next years will provide massive amount of new knowledge and we are expecting to exceed expectations!

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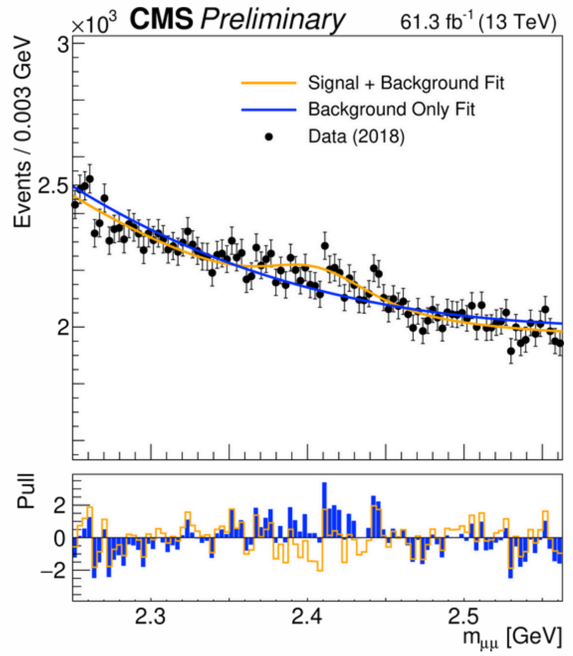

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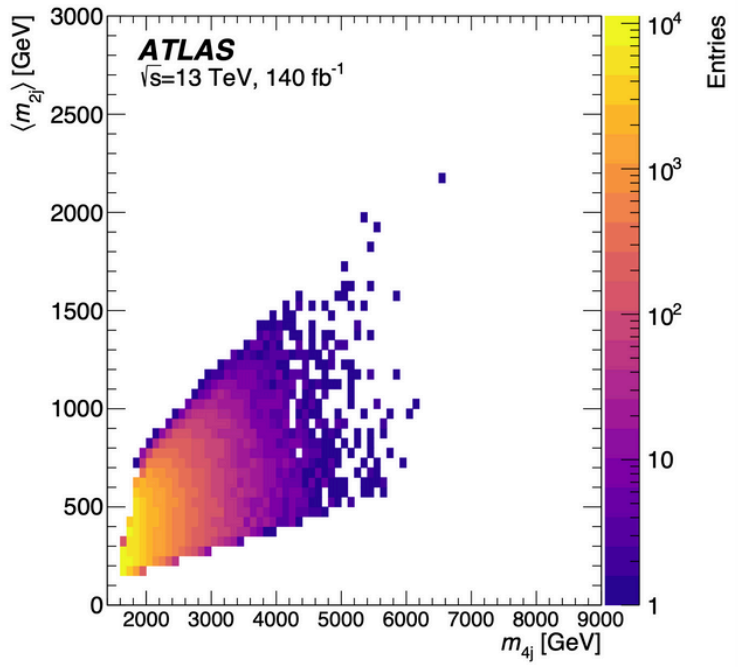

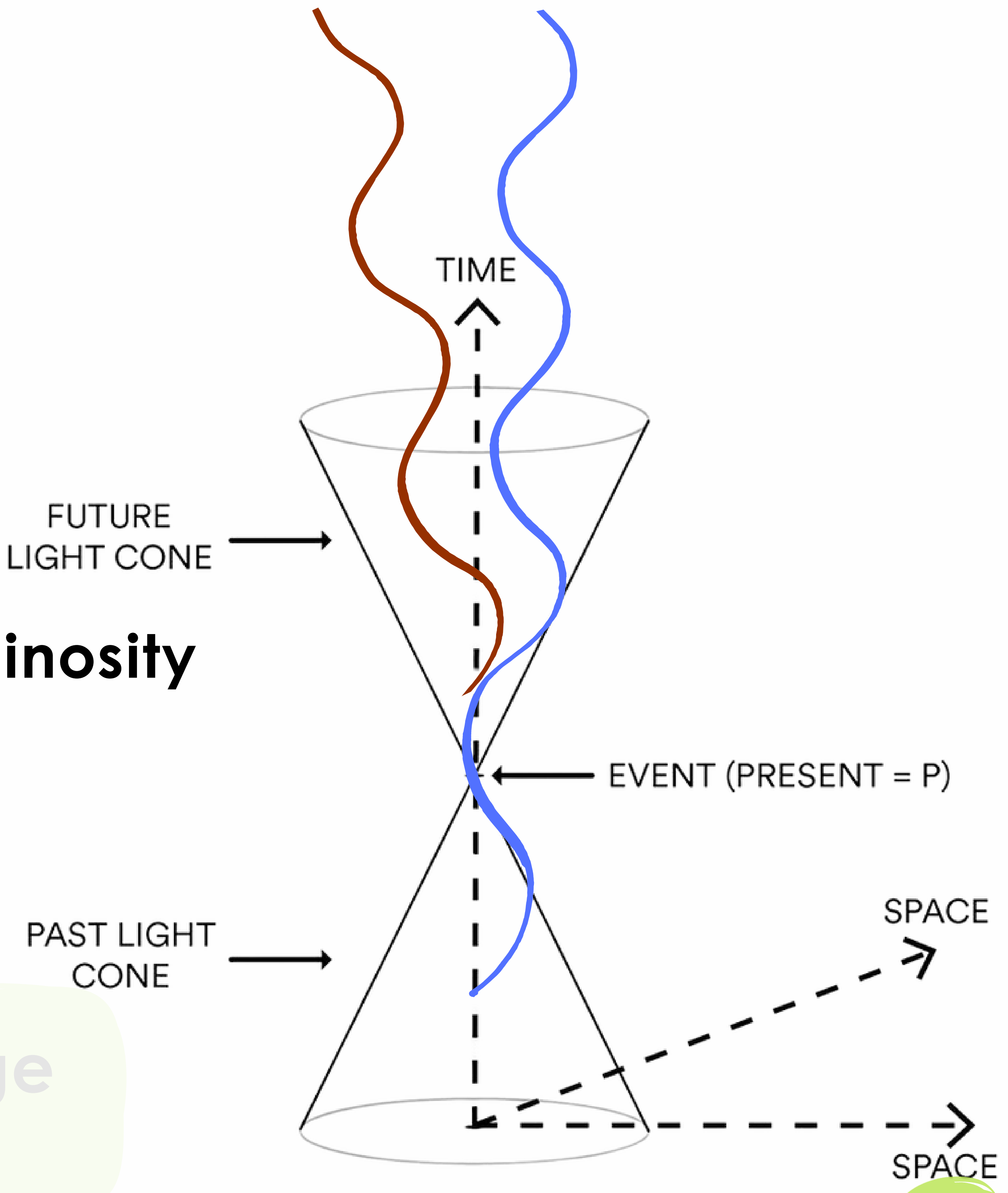

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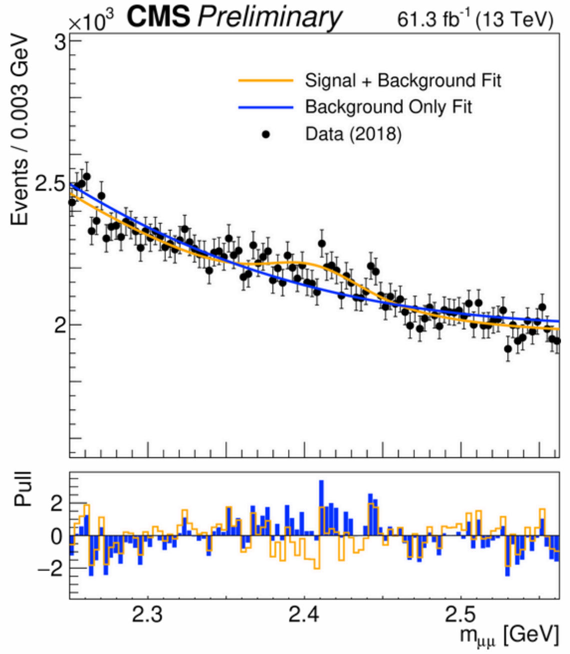

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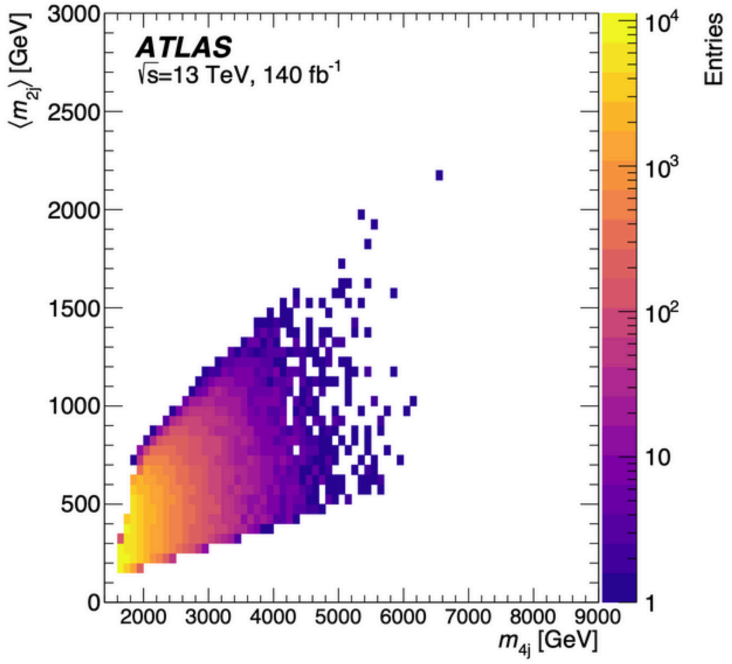

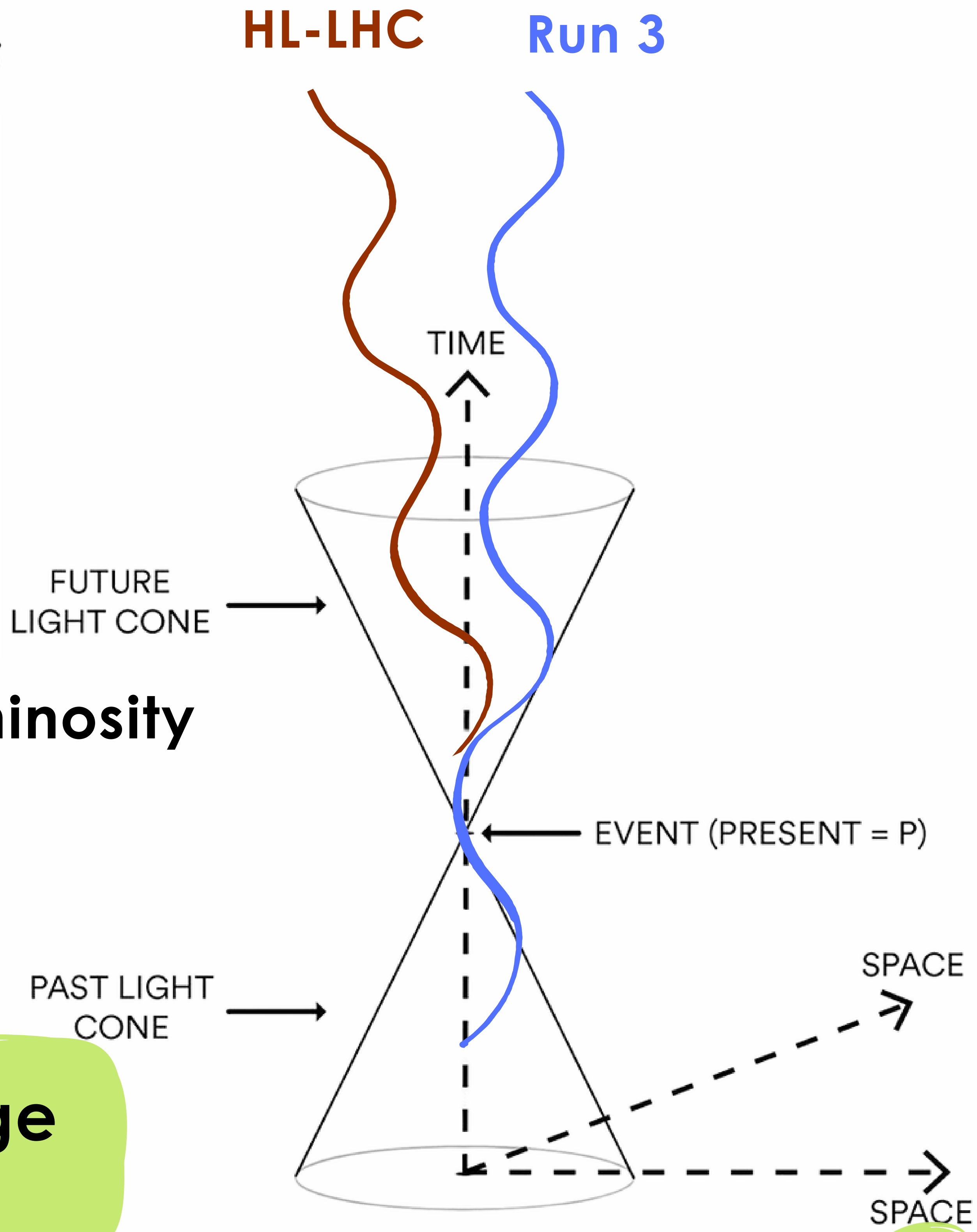

HL-LHC will significantly increase physics reach: gains from **high luminosity and new detector capabilities**

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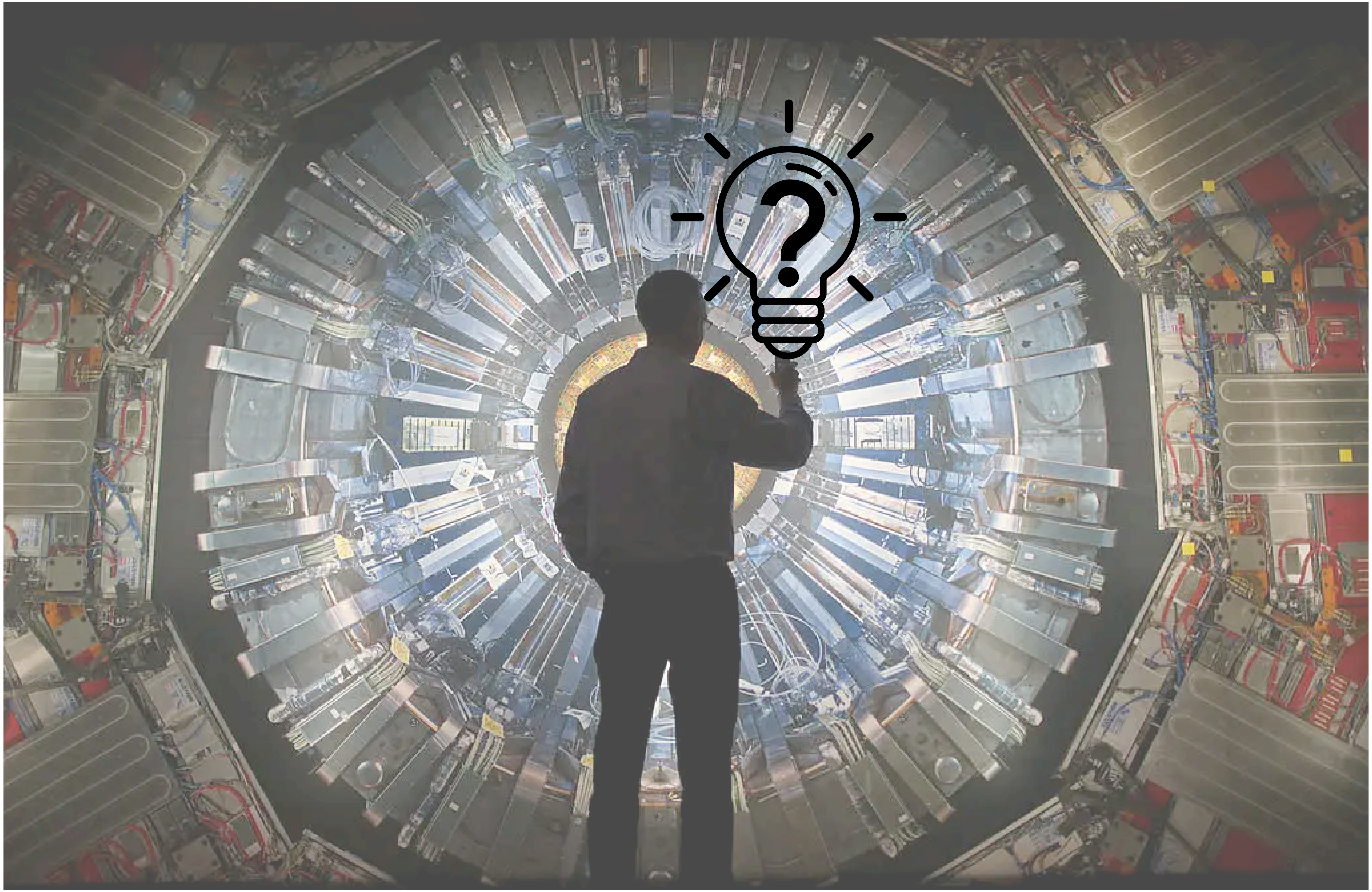
Thank you for listening!



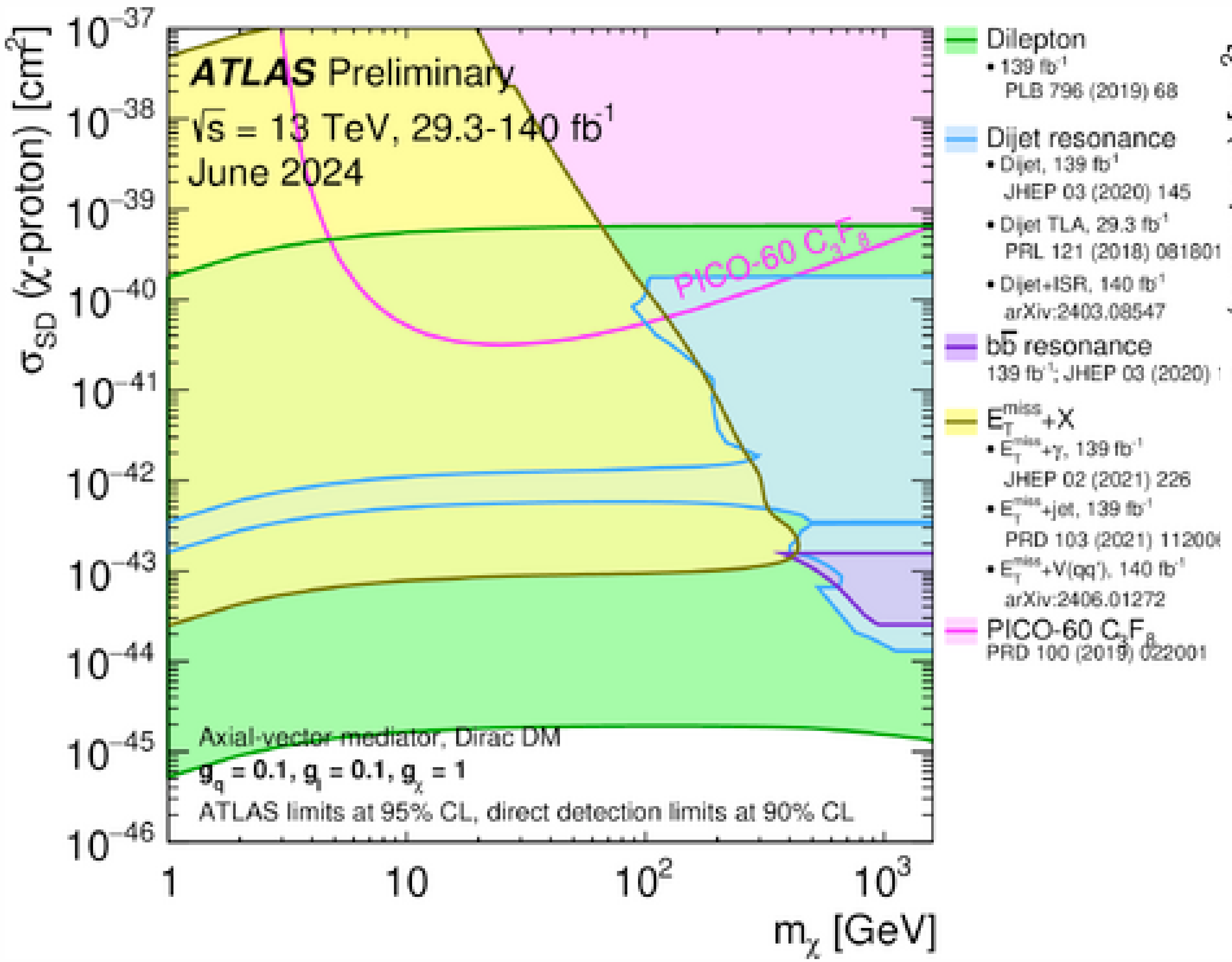
Backup

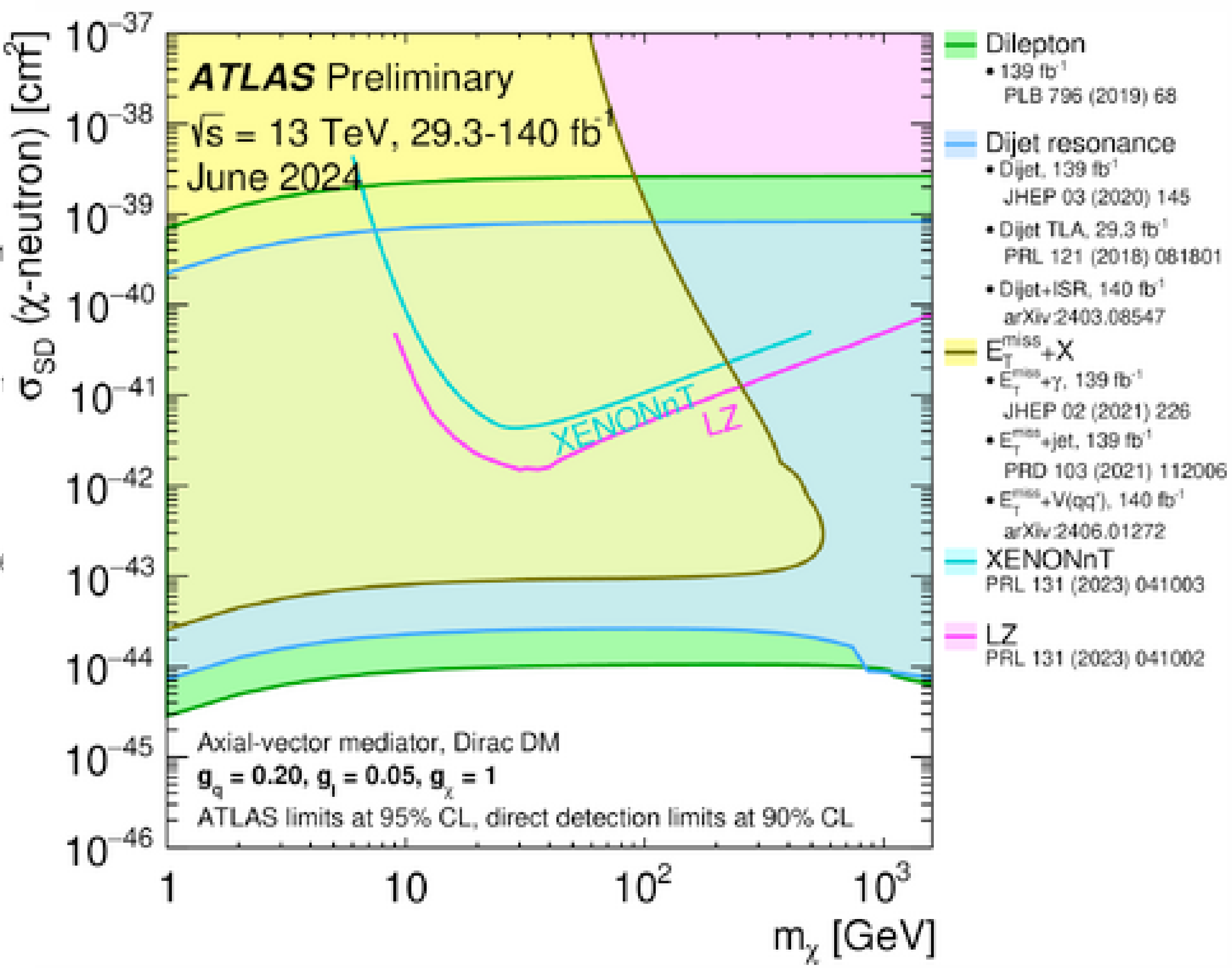
BSM searches since summer 2024

Reference	Topic	Experiment	Model	Explored energy range (0 300 600 900 1200 1500 1800 2100 2400 2700 3000 [GeV])
HDBS-2021-07	$H \to aa \to bb\tau\tau$	ATLAS	Extended Higgs Sector	
HDBS-2020-11 and HDBS-2024-45	$H^{\pm} \to cs$ and $H^{+} \to Wh$	ATLAS		
HDBS-2023-19	Combination of charged Higgs searches	ATLAS		
HDBS-2021-08	$A \to \tau\tau$	ATLAS 🔔		
EXOT-2022-13	$t\bar{t}A \to t\bar{t}t\bar{t}$	ATLAS		
HIG-24-002	$H \to ZZ \to 4l$	CMS		
HIG-22-004	$A \to Zh(\tau\tau)$	CMS		
SUS-24-001	$\phi \to bb$	CMS		
HIG-20-012	$X \to YH \to 4b$	CMS 🔔		
HIG-22-013	$A \to tt$	CMS 🔔		
EXOT-2018-55	Prompt Lepton-Jets	ATLAS	Dark Sector	
EXOT-2022-04	Long Lived Particles in the hadronic calorim.	ATLAS		- displaced
HDBS-2021-09	$H \to Za \to llj$	ATLAS 🔔		
SUS-23-004	mono$-t$	CMS		
SUS-23-012	mono$-h(\tau\tau)$	CMS		
SUS-23-018	$H \to Za \to ll\chi\chi$	CMS		
SUS-24-004	pMSSM	CMS	Supersymmetry	
SUS-23-003	Compressed Supersymmetry	CMS		
ATLAS-CONF-2024-011	Run3 displaced leptons	ATLAS		- displaced
SUS-23-002	Supersymmetry w/ charged leptons and missing	CMS		
ATLAS-CONF-2024-008	Vector Like Leptons (VLL) 4321 model (tau	ATLAS	Heavy Fermions	
EXOT-2021-31	VLL (1st and 2nd gen)	ATLAS 🔔		
EXOT-2021-02	Combination of VLQ	ATLAS		
EXOT-2022-43	VLQ Wb (0L)	ATLAS 🔔		
TOPQ-2019-31	t-HNL	ATLAS 🔔		
EXO-23-015	VLL $\to \tau a(\gamma\gamma)$	CMS		- displaced
B2G-22-005	$t^{*} \to tg$	CMS		
EXO-23-010	$ll +$ b $-$ jets, non $-$ resonant	CMS	EFT	
EXOT-2022-33	Low mass dijet + ISR gamma	ATLAS	New Mediators	
EXOT-2020-26	Dark Higgs via Z'	ATLAS		
HDBS-2021-13	S into four leptons	ATLAS 🔔		
EXO-24-007	Low mass dijet+ISR	CMS		
EXO-22-006	$Z' \to \mu\mu +$ b $-$ jets, resonant	CMS		
EXO-22-013	t-channel scalar and vector leptoquark	CMS	Leptoquarks	

🔔 == New w.r.t. ICHEP2024 | Shown today

ATLAS Dark Matter summary





ATL-PHYS-PUB-2024-010

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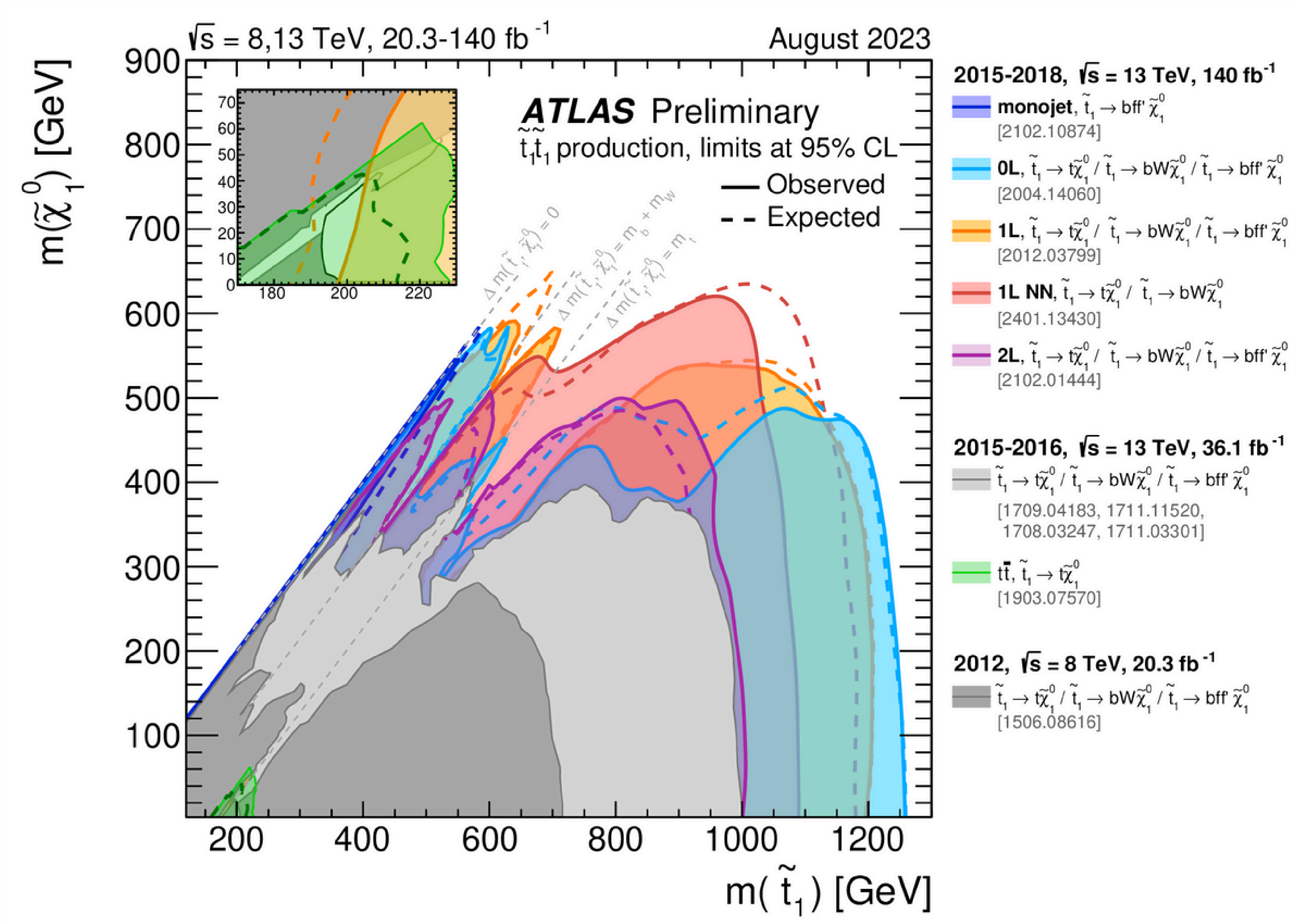
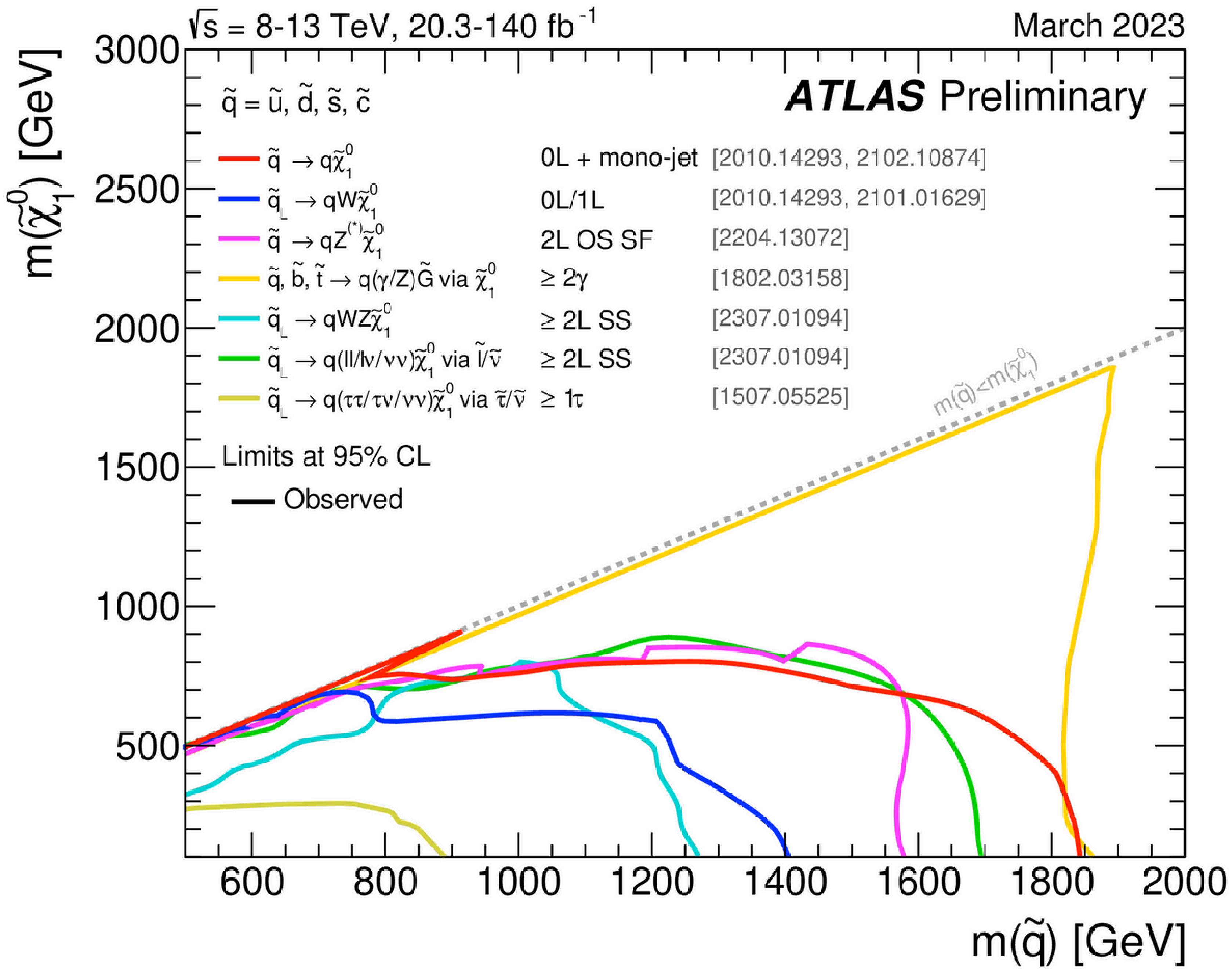
ATLAS SUSY summary





ATL-PHYS-PUB-2024-014

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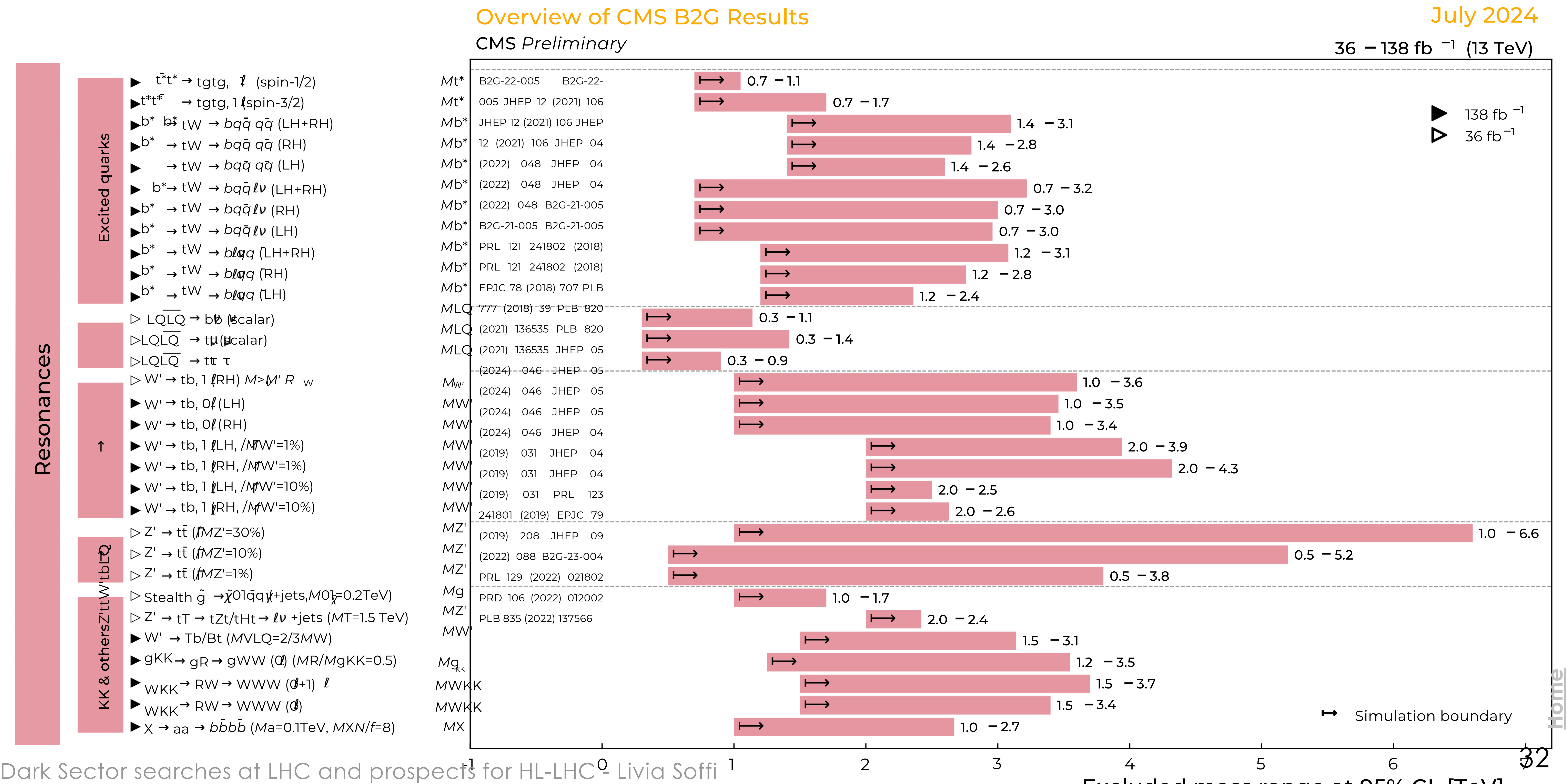
CMS Heavy Resonances summary

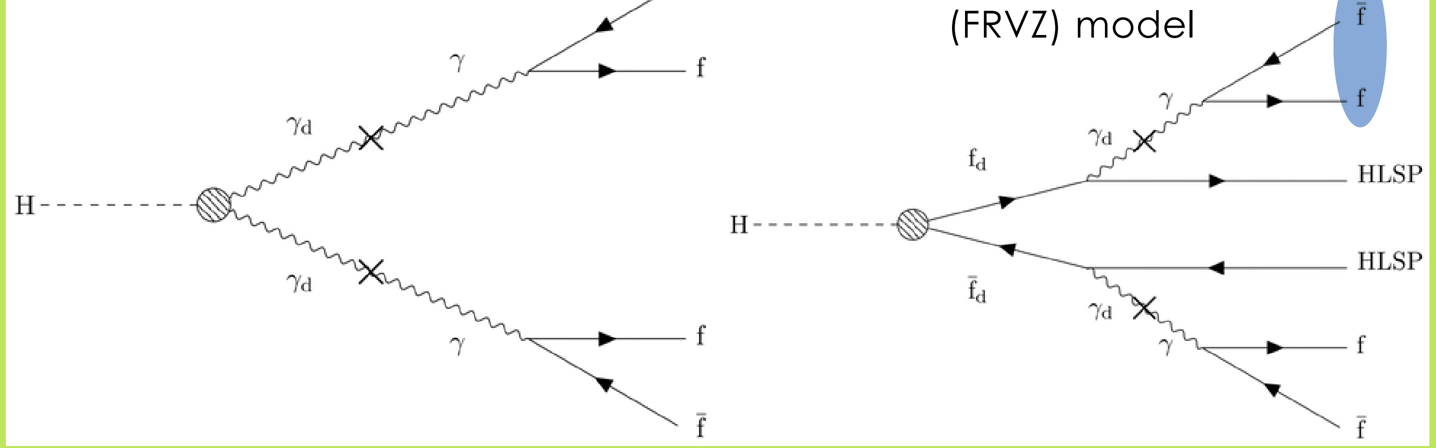


Search for neutral particles decaying promptly to collimated pairs of leptons

$\epsilon \gtrsim$ 10−5 – 10−3: prompt γd decays

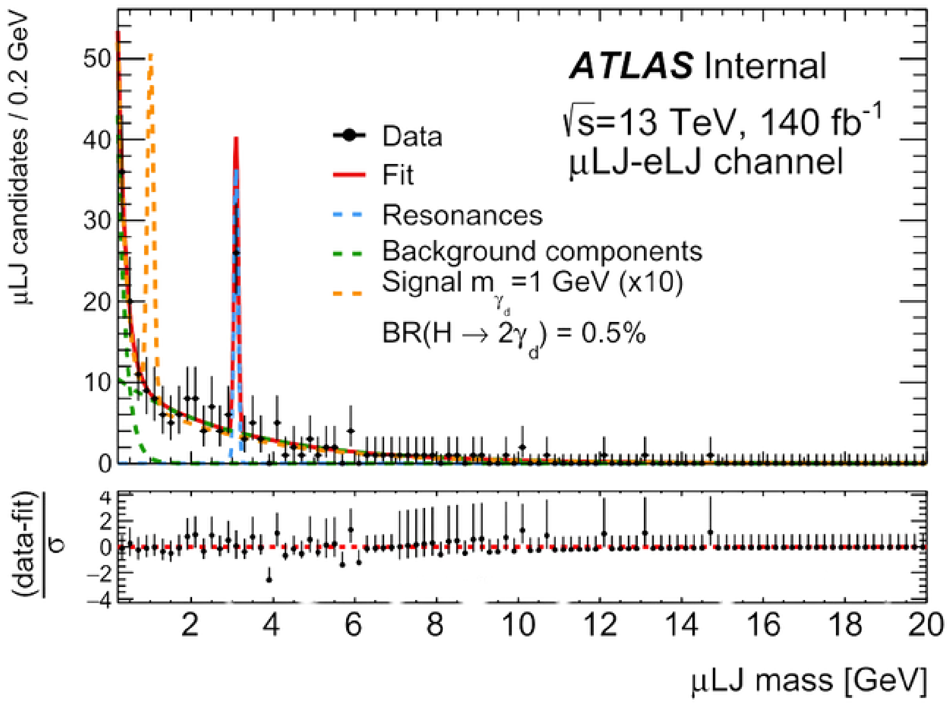
$$O(10\text{MeV}) < M_{\gamma_d} < O(10\text{GeV})$$

Hidden Abelian Higgs Model (HAHM) Falkowski-Ruderman-Volansky-Zupan (FRVZ) model



$\mu LJ - \mu LJ$ $\mu LJ - eLJ$

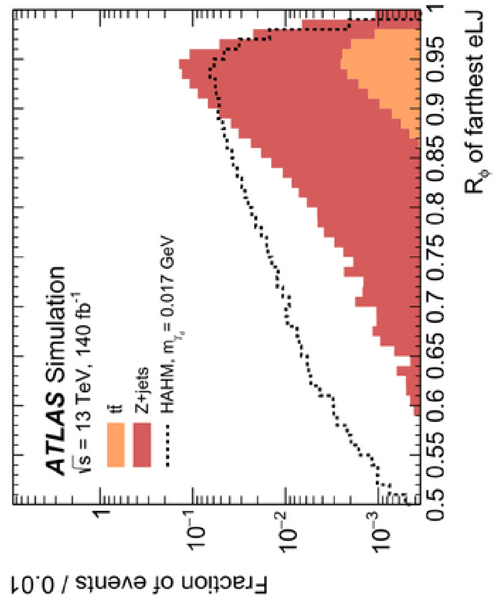
Background estimated data-drive taking the shape from CR based on # of LJ

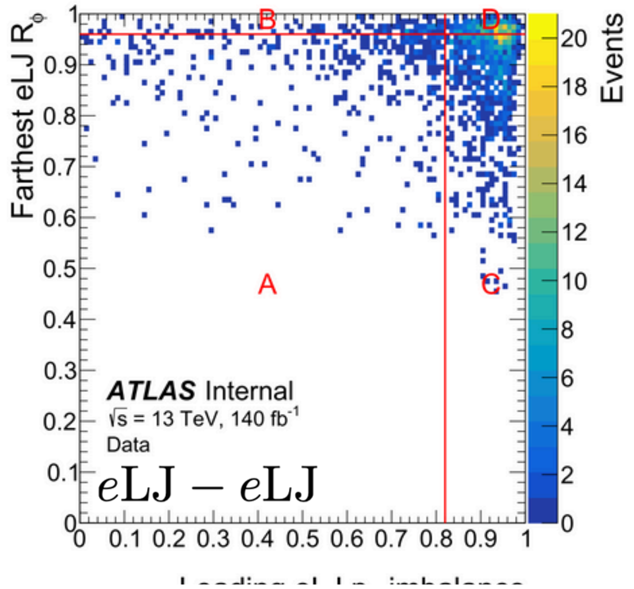


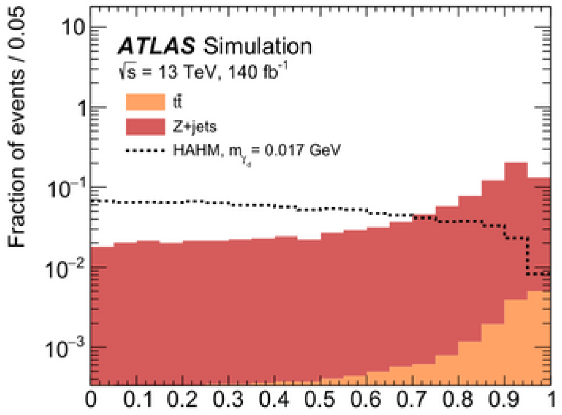
LeptonJets (LJs): relatively small mass of the γd w.r.t. the Higgs boson implies decay products highly collimated

Cambridge–Aachen clustering inclusive in the number of leptons adopted to reconstruct LJs (**Total charge is zero)**

$eLJ - eLJ$







arXiv:2407.09168 Plots Home

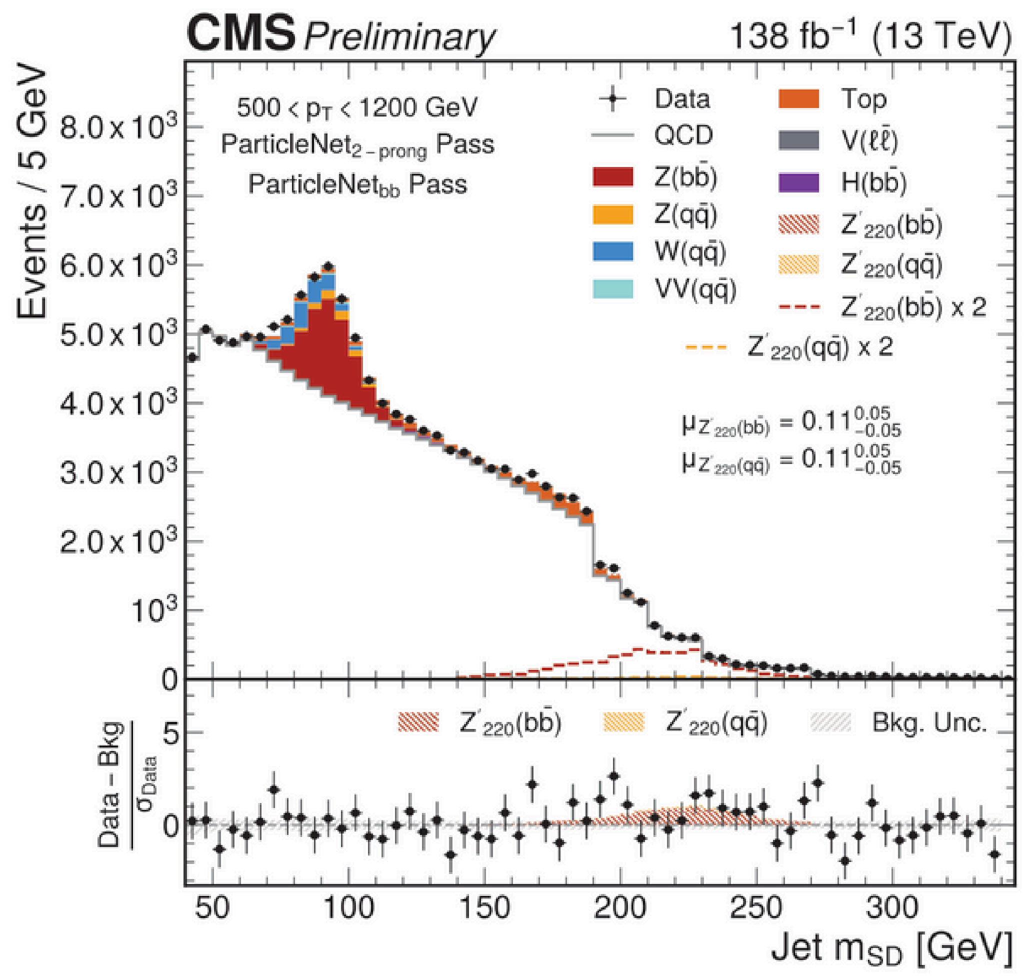
Search for low-mass resonances into hadrons + ISR

62 bins in mSD between 40–350GeV and five pT bins with boundaries of 500, 550, 600, 700, 800, and 1200GeV

ParticleNET algorithm used to define separate signal regions targeting resonances decaying to bb pairs and to light quark pairs: **Convolutional graph NN: 1st discriminant 2 prong vs QCD. 2nd discriminant flavor (bb/cc/other)**

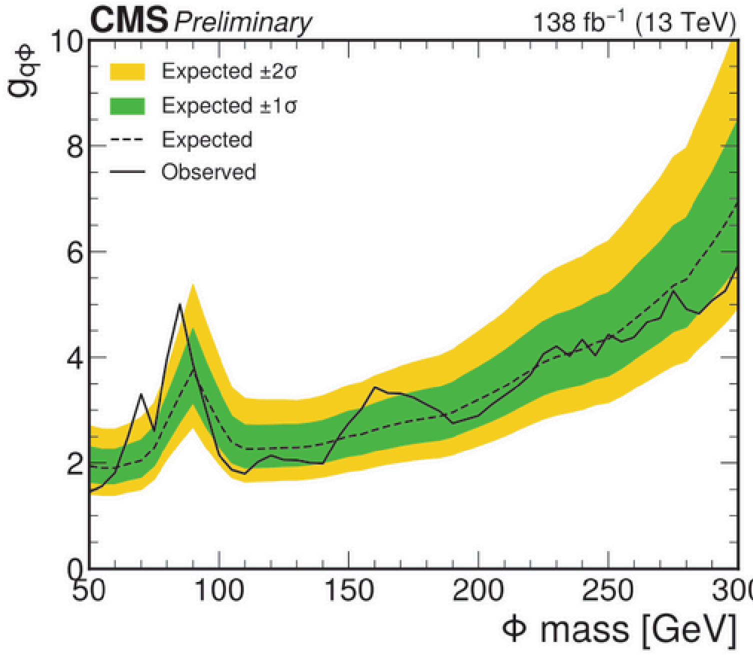
$$50\text{GeV} < M_X < 300\text{GeV}$$

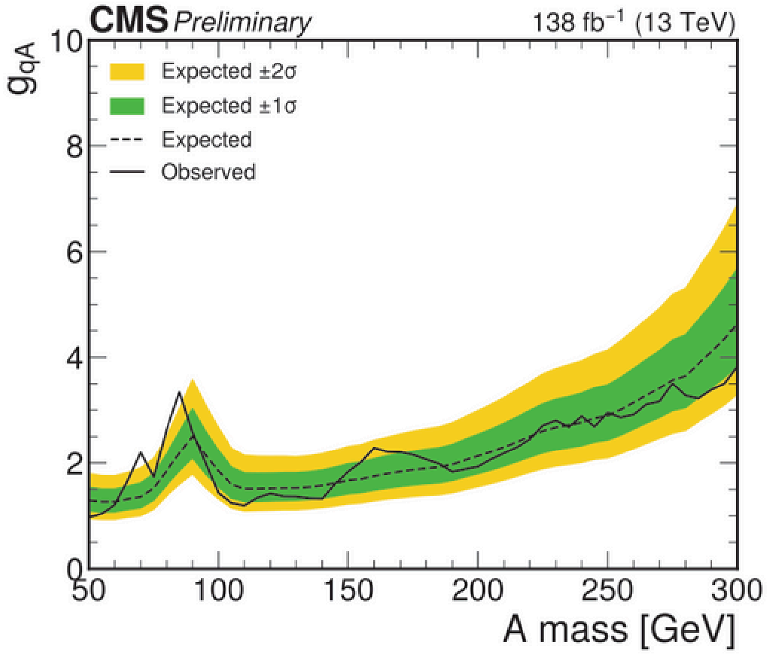
- X produced with large pT, due to significant initial state radiation (ISR)
- **Circumvent huge rate of dijet events from the QCD**



- Simultaneous fit of Jet mass in 5 pT SRs and CRs
  - Maximum fluctuations in the observed(all flav): 2.2 σ (3.0 σ local) at m(Z') = 75GeV 1.9 σ (2.8 σ local) at m(Z') = 225GeV

bb only: 2.6σ (1.6σ) at m(φ) = 75 GeV





CMS-PAS-EXO-24-007

Home

Scouting opportunities at Run 2 & 3

- Events processed in real time with reduced content, permitting recording of larger data samples.

Table 3: Comparisons of the event rate, event size, and total bandwidth between the standard and scouting trigger strategies, for an LHC fill corresponding to data collected in 2018 with $\mathcal{L}_{\text{inst}} \approx 1.8 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ at the start of the fill, one of the highest at the LHC in Run 2, and pileup around 50.

Data stream	Event rate [Hz]	Event size	Total bandwidth [MB/s]
Standard muons	600	0.86 MB	485
Standard jets/H_T	400	0.87 MB	385
Scouting Calo muons and Calo H_T	5970	8.9 KB	45
Scouting PF jets and PF H_T	1766	14.8 KB	25

Year	$\mathcal{L}_{\text{inst}}$ [cm^{-2}s^{-1}]	PU	Standard rate [Hz]	Parking rate [Hz]	Scouting rate [Hz]
2018	1.2×10^{34}	38	1000	3000	5000
2022	1.5×10^{34}	46	1800	2440	22000
2023	1.7×10^{34}	48	1700	2660	17000

arXiv:2403.16134

Home

Main priorities at HL-LHC

Spatial overlap of tracks and energy deposits:

- **degrade the identification and the reconstruction** of the hard interaction
- **increase the rate** of false triggers

→

- good reconstruction efficiency
- **Increase detector granularity**
- **Sophisticated detector**

Higher collision rate:

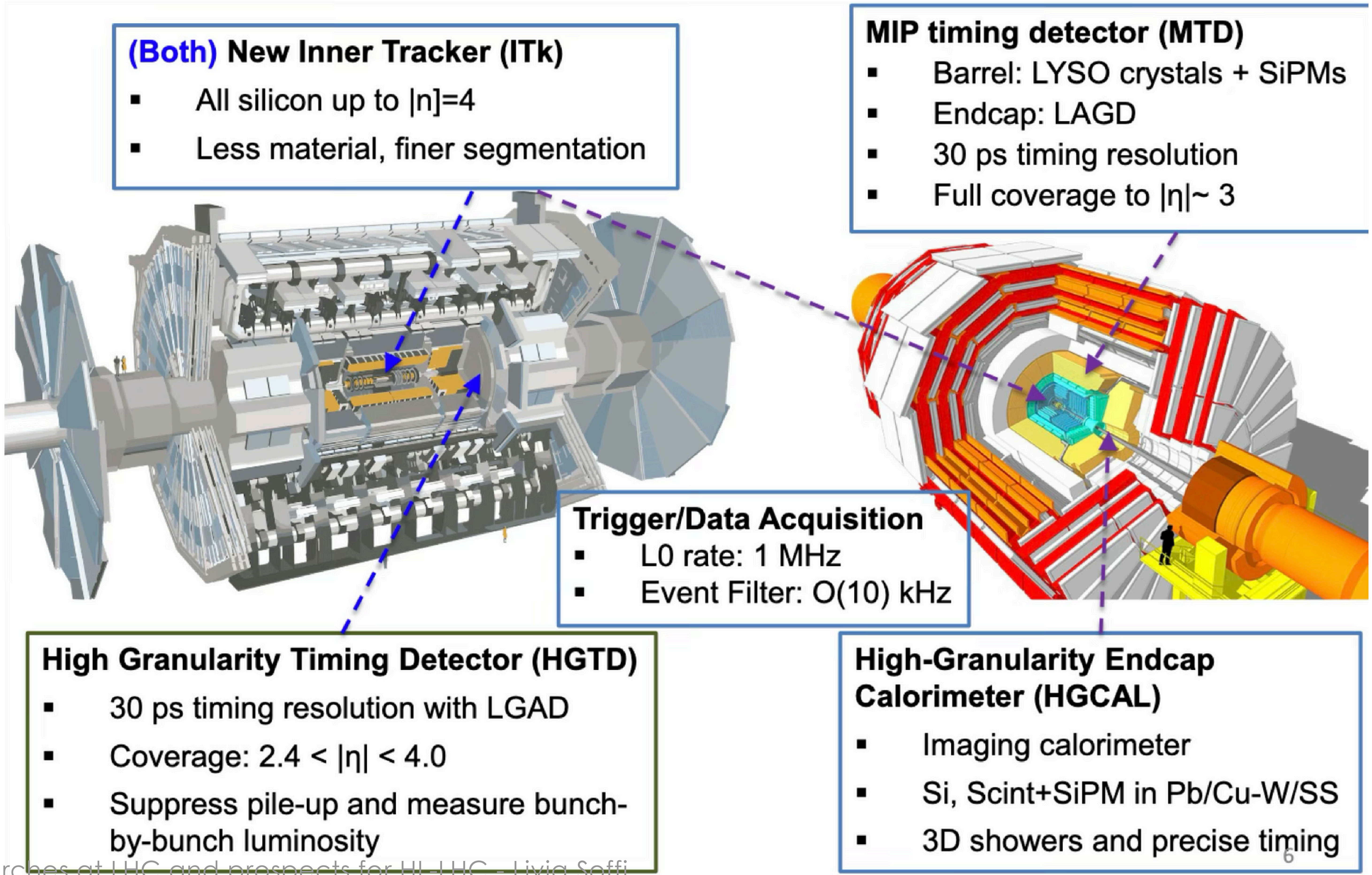
- more **radiation damage**
- **harsher radiation**(~ 10^{16} neq/ cm^2 ; 10 MGy)
- **higher rate** of data

→

- Increase data acquisition **bandwidth**
- Increase **processing power** for online reconstruction

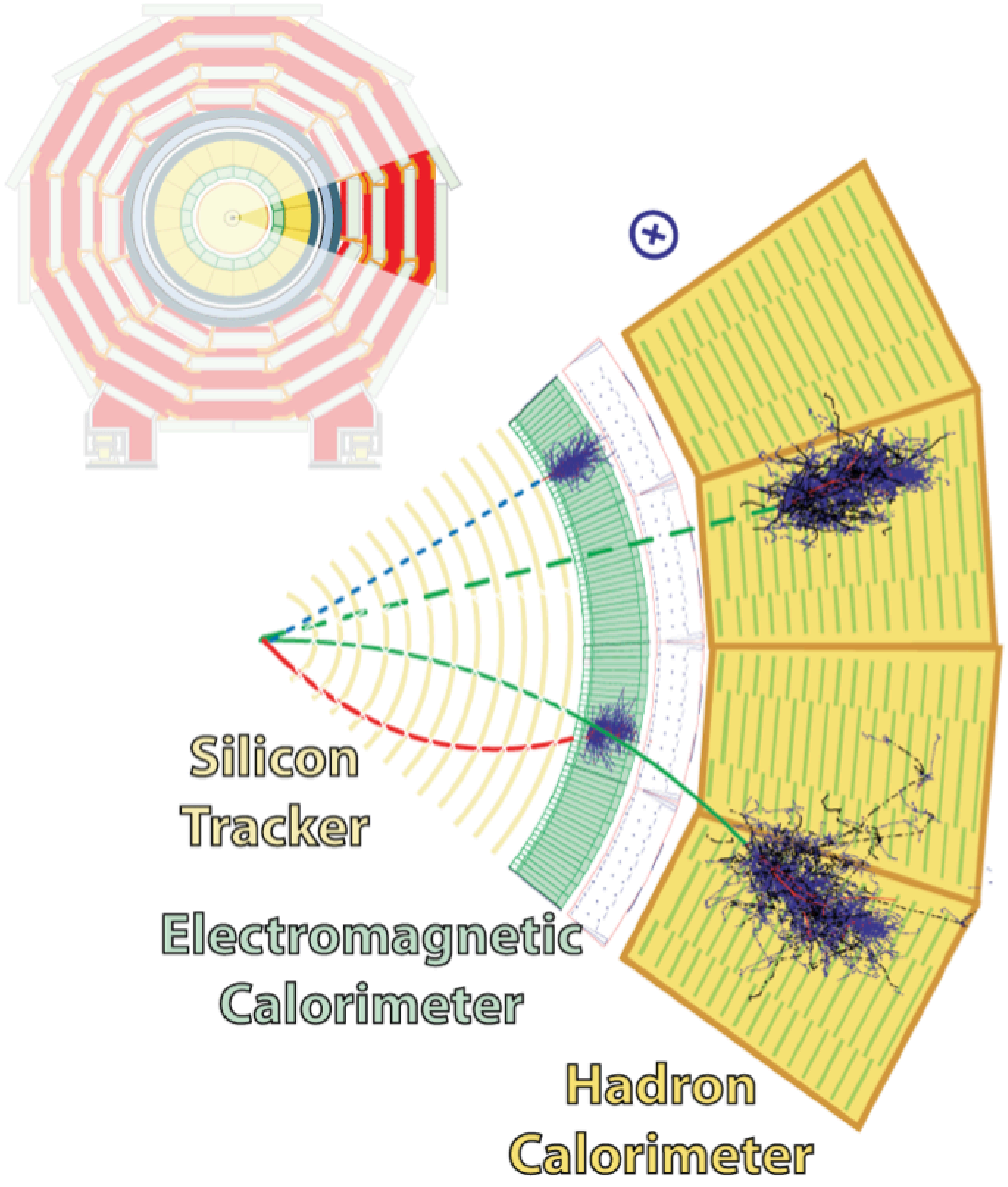
- Phase-2 improvements in detectors, triggers and reconstruction will **extend sensitivity in precision measurements and new physics searches**
- **Higher order theory calculations** and larger MC samples required to fully exploit the HL-LHC

ATLAS and CMS Upgraded Detectors



Particles Interaction in CMS

BACK



Electron

Curves in B field: R=P/0.3B
Signals in Tracker
Energy deposit in ECAL
No energy in HCAL

Photon

No curve in B field
No signals in Tracker
Energy deposit in ECAL
No energy in HCAL

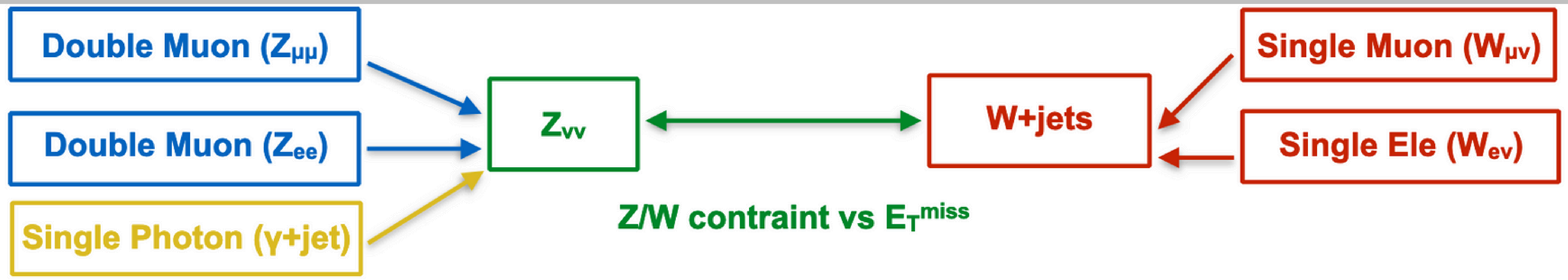
Charged hadron (e.g. pion)

Curves in B field: R=P/0.3B
Signals in Tracker
Possible energy deposit in ECAL
Energy deposit in HCAL

Neutral hadron (e.g. neutron)

No curve in B field
No signals in Tracker
Possible energy deposit in ECAL
Energy deposit in HCAL

Ricerche di Materia Oscura: mono-Jet background estimation



BACK

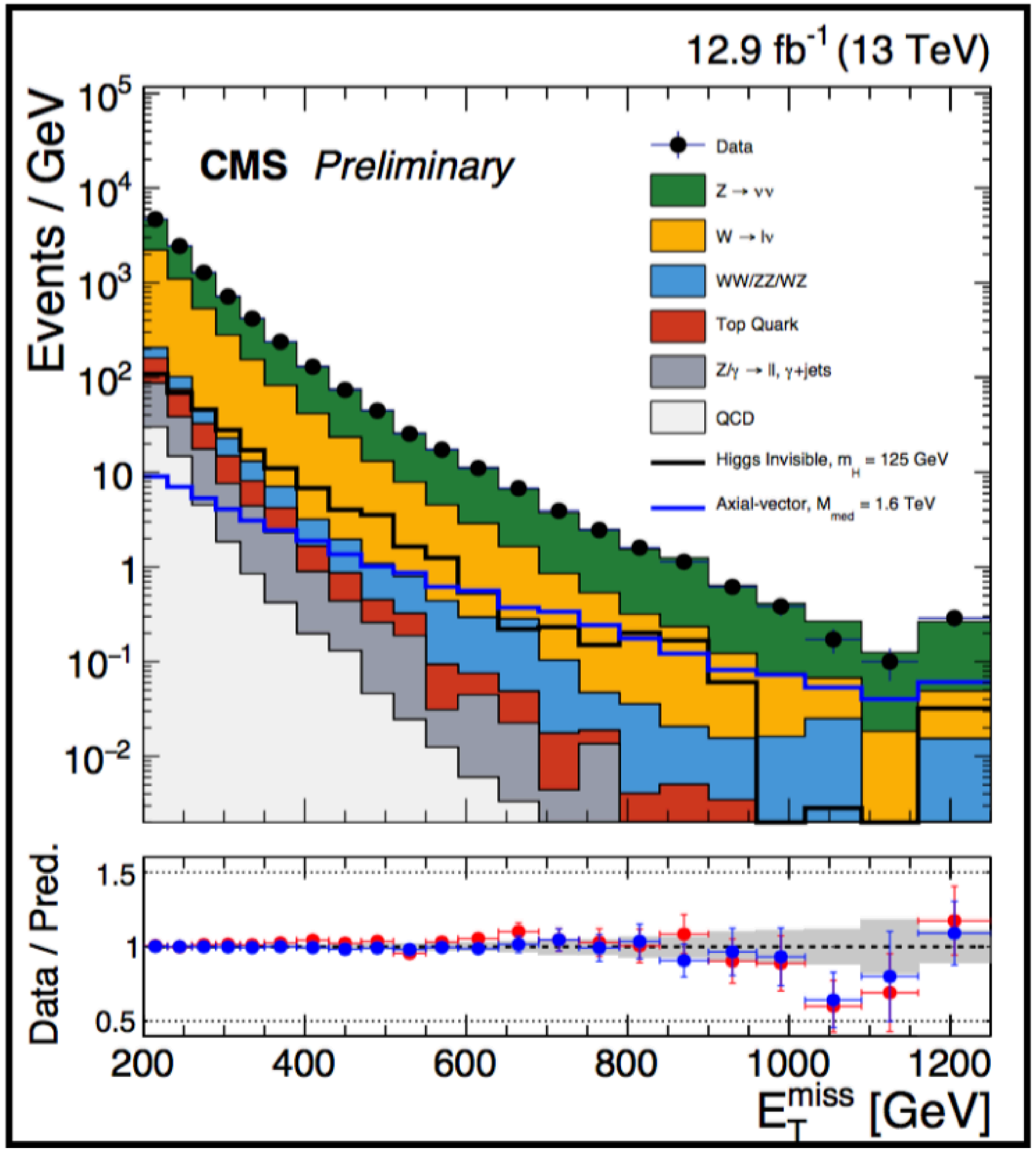
- Derive **binned MC** based **transfer factors (TF)** to translate yields from **CRs** to **SR**
  - **NLO k-factors** used to correct the **TF prediction**
  - **Theoretical** and **experimental uncertainties** on **TF** added as **nuisance parameter** in the final fit

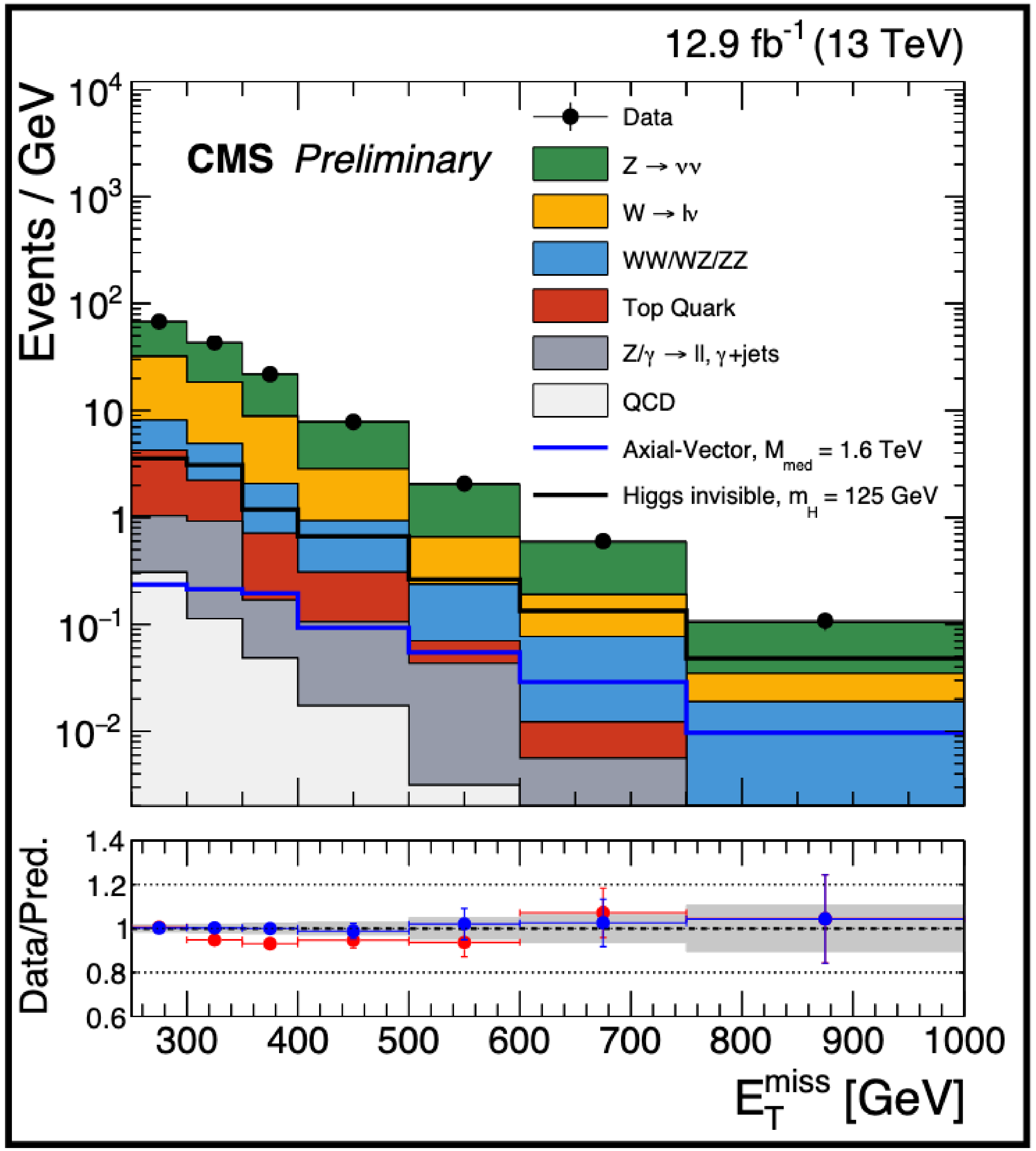
Likelihood model

$$\mathcal{L}_c(\mu^{Z\to\nu\nu}, \mu, \theta) = \prod_i \text{Poisson}\left(d_i^\gamma | B_i^\gamma(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^\gamma(\theta)}\right)$$
$$\times \prod_i \text{Poisson}\left(d_i^Z | B_i^Z(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^Z(\theta)}\right)$$
$$\times \prod_i \text{Poisson}\left(d_i^W | B_i^W(\theta) + \frac{f_i(\theta)\mu_i^{Z\to\nu\nu}}{R_i^W(\theta)}\right)$$
$$\times \prod_i \text{Poisson}\left(d_i | B_i(\theta) + (1 + f_i(\theta))\mu_i^{Z\to\nu\nu} + \mu S_i(\theta)\right)$$

- $\mu_i^{Z\to\nu\nu}$ = Z(inv)+jets rate, free to float
- $R_i^{\gamma/W/Z}$ = binned transfer factors asaf E_T^{miss}
- θ = exp. and theo. nuisance parameters
- $\mu_i^{Z\to\nu\nu}$ x $f_i(\theta)$ = W+jets rate

Ricerche di Materia Oscura: mono-jet post-fit





BACK

Il rivelatore MTD

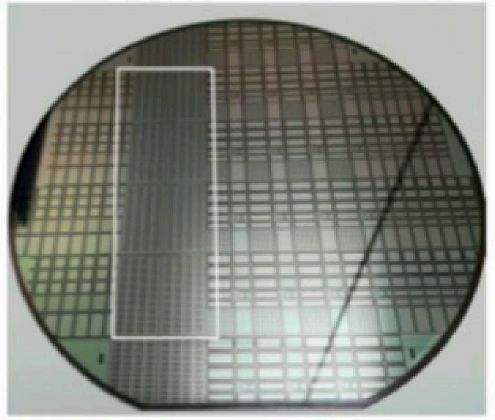
The MTD Detector

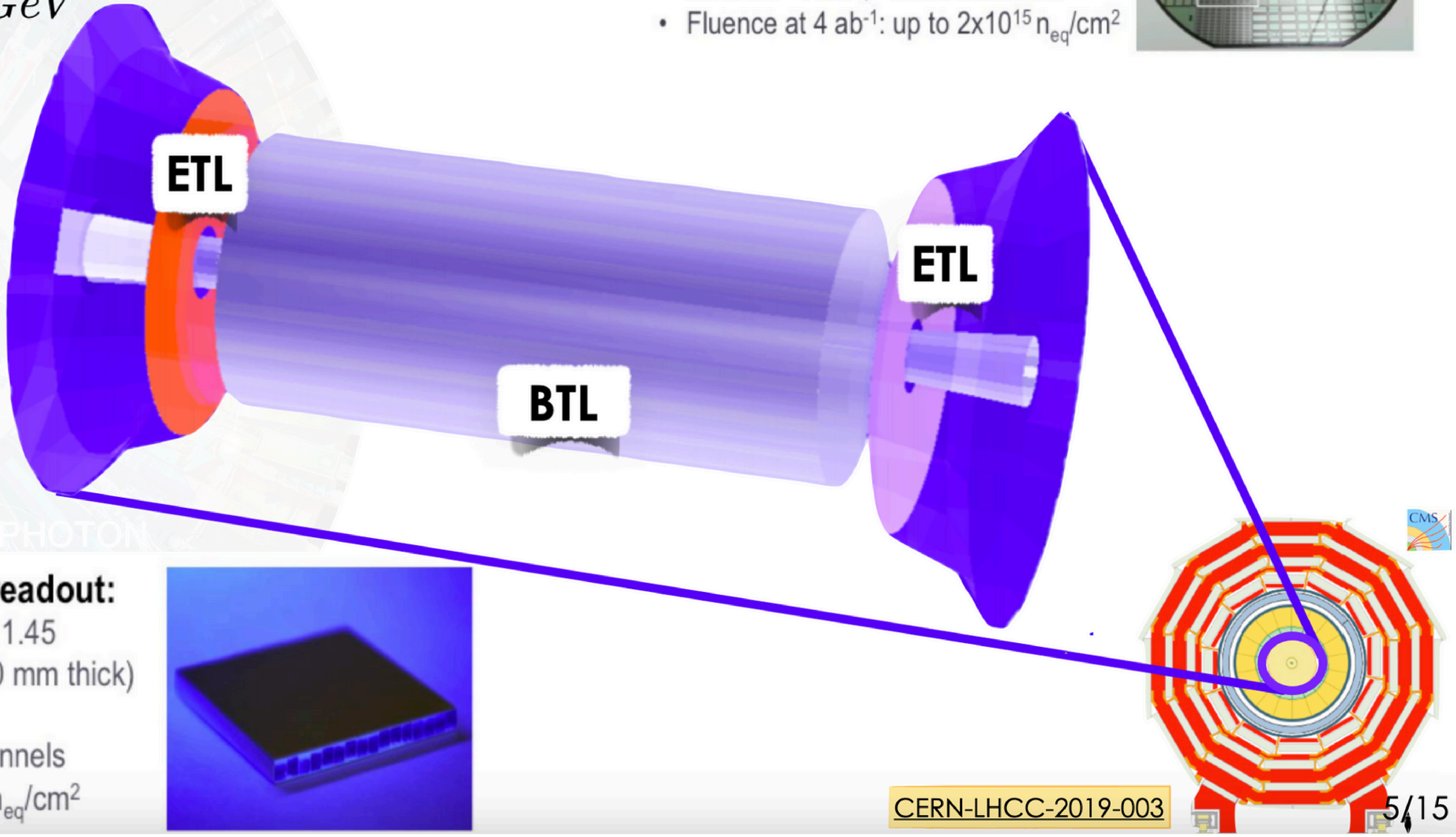
MIP timing detector (MTD) w/ **~30 ps precision**

$|\eta| < 3.0, p_T > 0.7 GeV$

ETL: Si with internal gain (LGAD):

- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2





BTL: LYSO bars + SiPM readout:

- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2

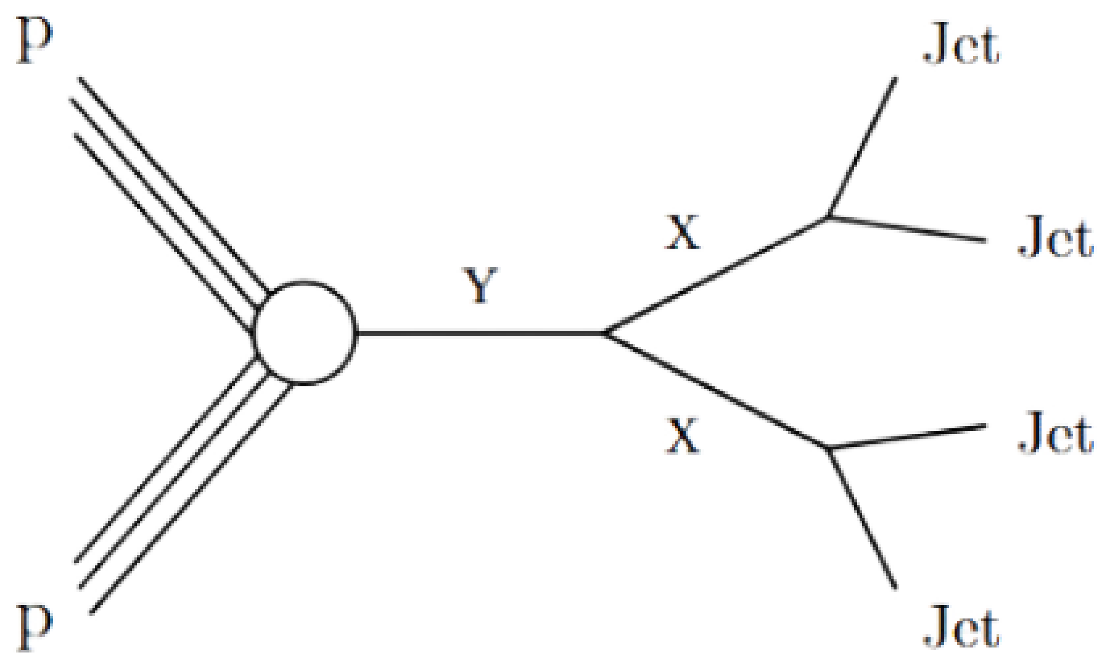
CERN-LHCC-2019-003

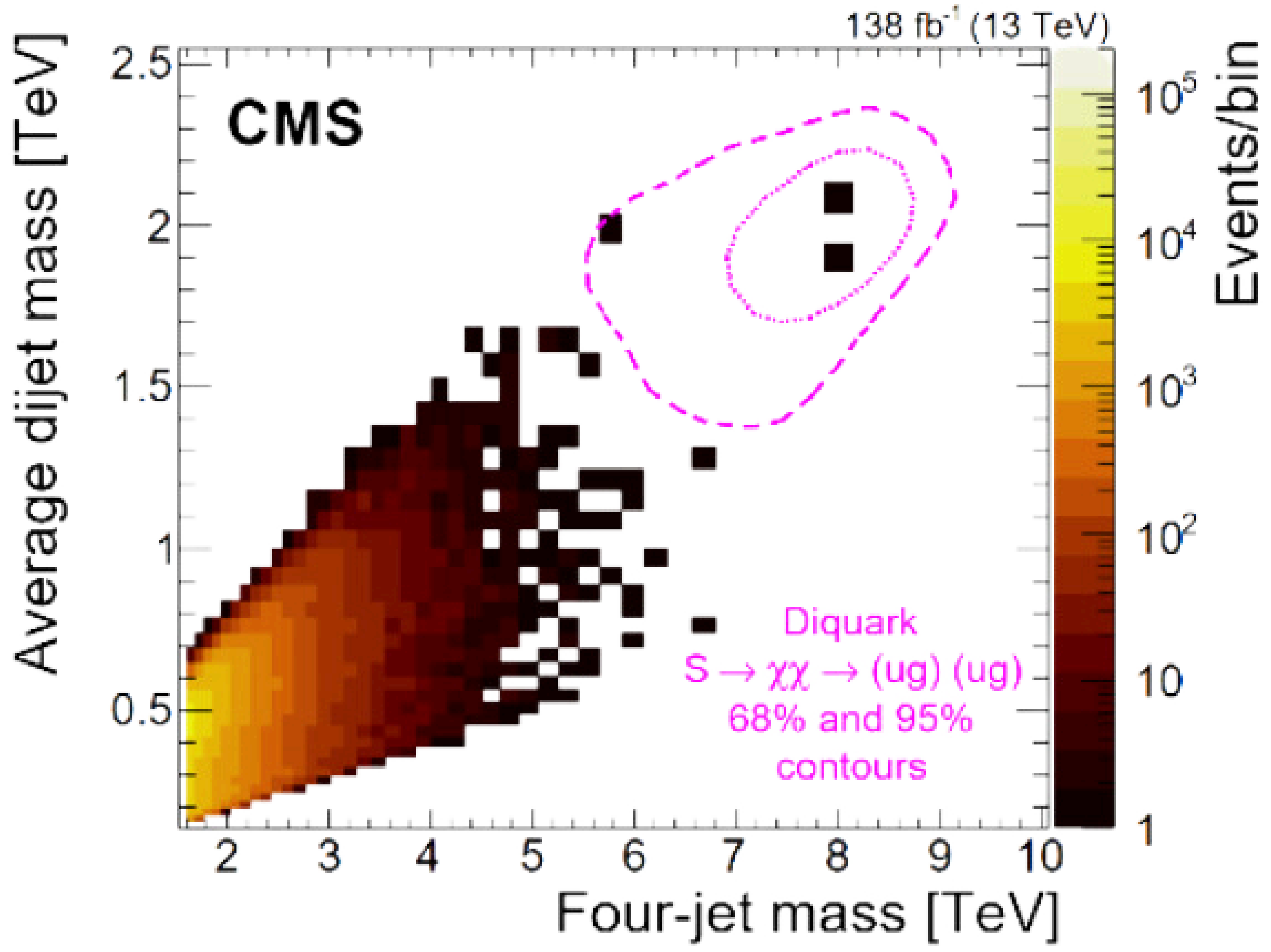
5/15

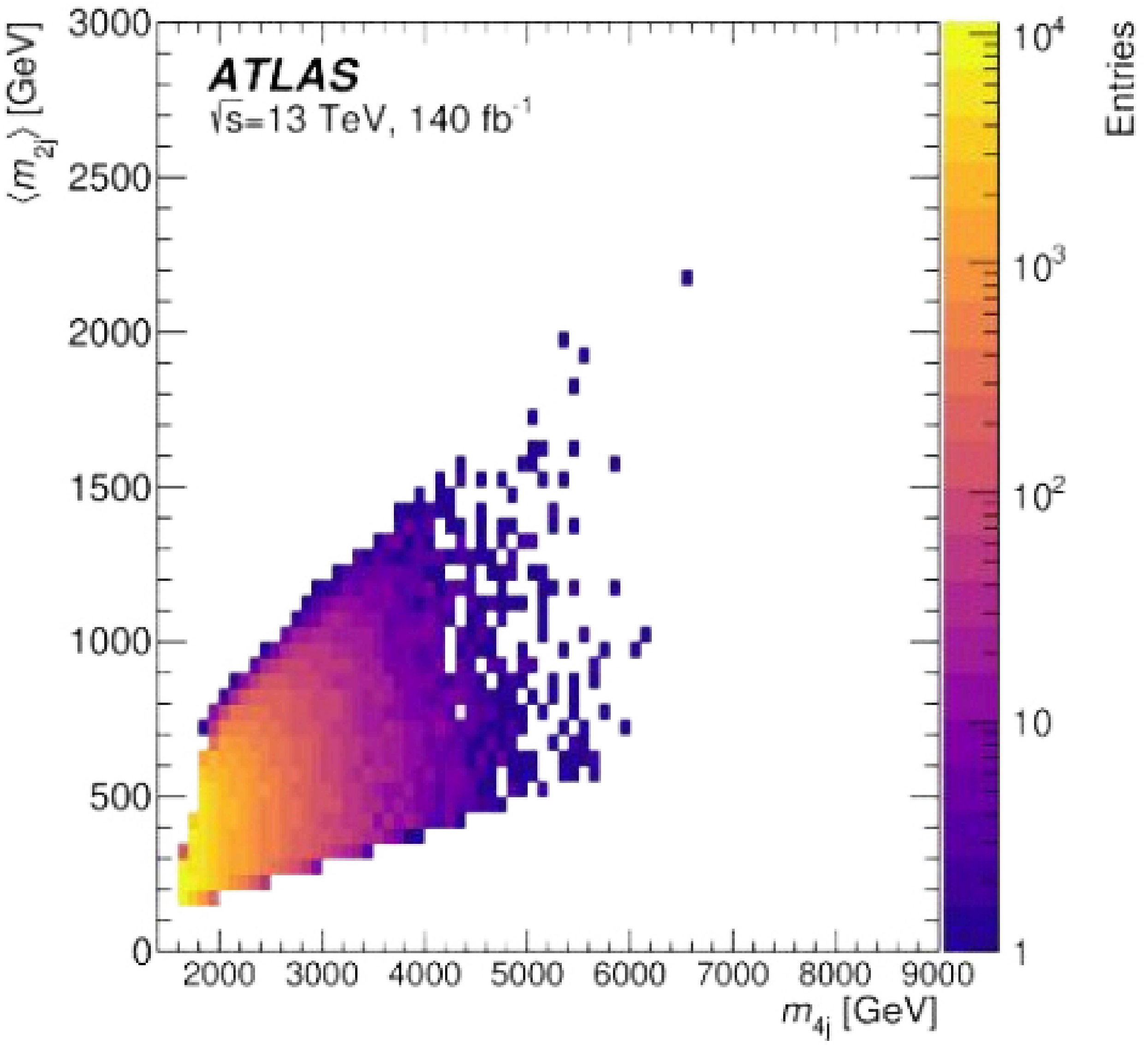
BACK

CMS-EXO-21-010

- Currently, **Run3 data are being analyzed**.
- **Interesting isolated event recorded by the ATLAS experiment** (10.1103/PhysRevD.108.112005).
  - ➢ Motivated by this ATLAS event, and the 3rd isolated CMS event at ~6 TeV, the analysis is being extended by searching for **broader resonances** as well.



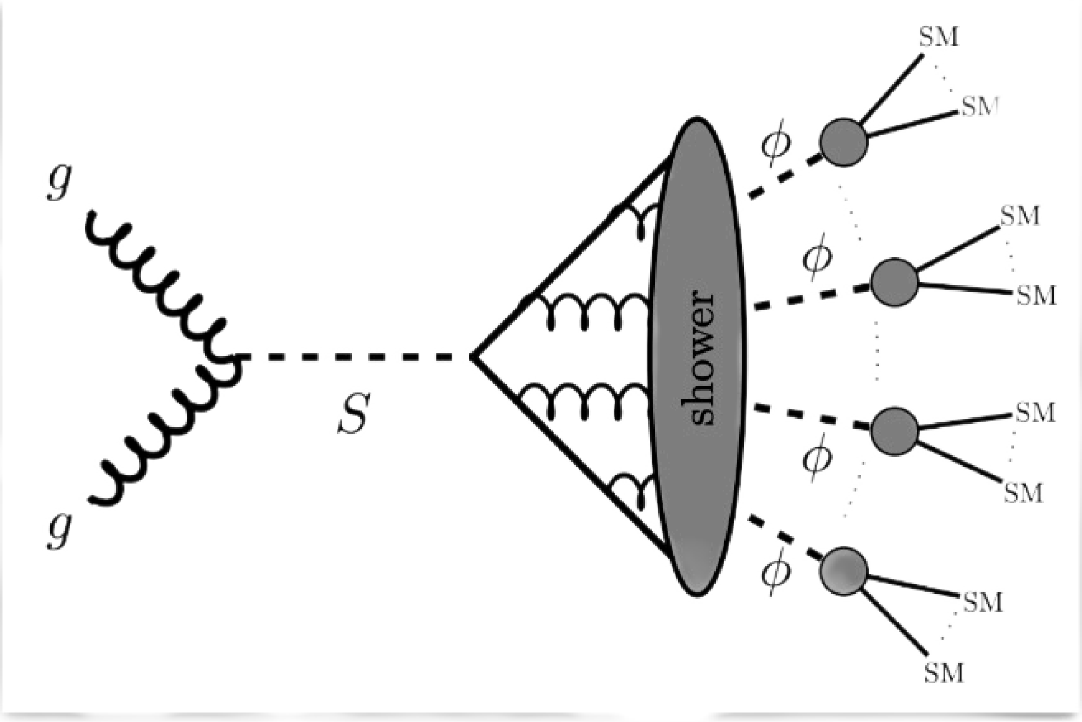




SUEPs

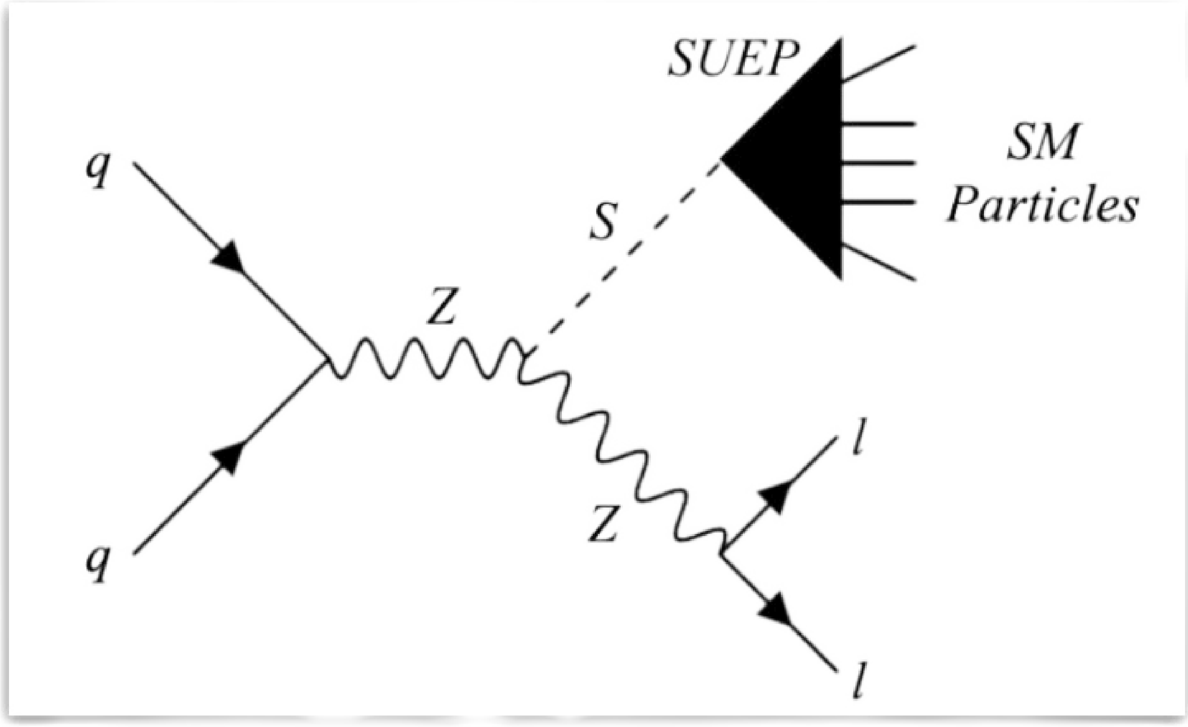
- First dedicated search for SUEPs at the LHC
  - Particularly interesting portal case: portal mass = 125 GeV
  - Search can be generalized to several other models: other strongly coupled dark sectors, instantons, black holes in theories with extra spatial dimensions → also SUEP signatures!
- Two production mechanisms under current investigation:

Gluon Fusion Channel (ggF)



EXO-23-001 (Scouting)
EXO-23-002 (Offline- this talk!)

Associated Production (ZH)

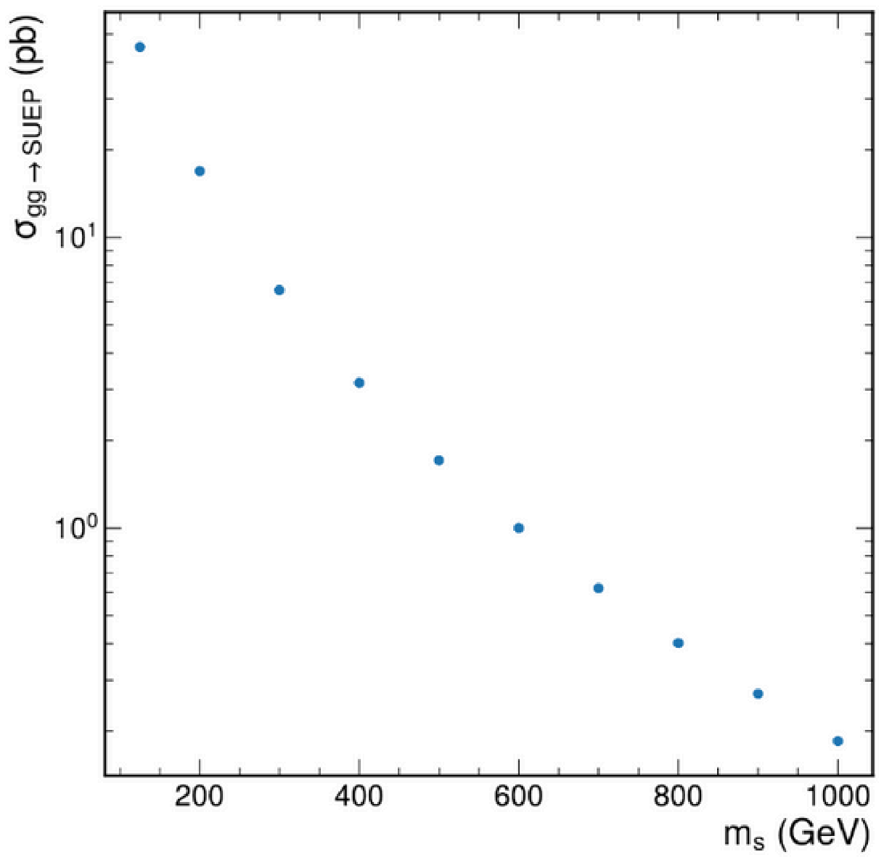


EXO-23-003

SUEPs

- Cross section corresponds to gg fusion of a BSM Higgs (recommended by LHC Higgs WG Yellow report)

$$\mathcal{L}_{eff} \supset -\frac{C}{4v} S G^a_{\mu\nu} G^{\mu\nu}_a$$



Parameters: m_S

- LO Boltzmannian thermal model is employed for the decay

$$\frac{dN_\phi}{dp} \propto e^{-\sqrt{p^2+m^2}/T}$$

- Keep sampling distribution until all energy is used up → multiplicity related by:

$$N \sim \frac{m_S}{m_\phi} \sim \frac{m_S}{T}$$

Parameters: m_ϕ, T