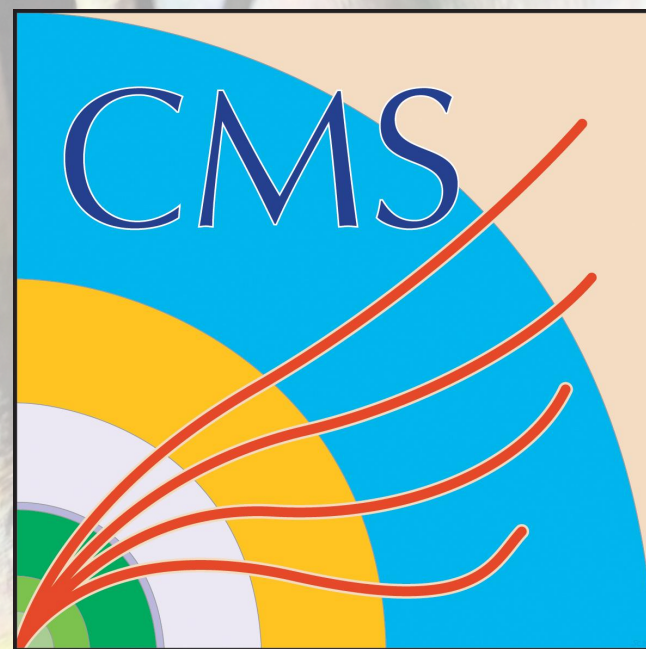
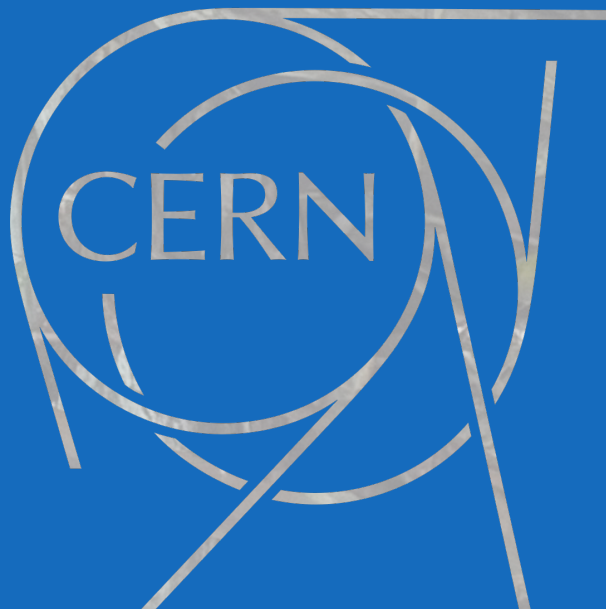




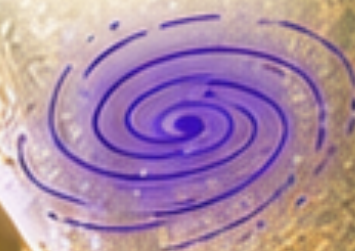
RETHINKING DATA-TAKING AT THE LHC: CMS SCOUTING, FROM SPECIALISED STREAMS TO NEW PHYSICS

CEA Paris Saclay - October 12th, 2026

Elisa Fontanesi (CERN)

on behalf of the CMS Collaboration

Quantum Gravity



Origin of Matter

- Baryogenesis
- $C\bar{P}$

Neutrino Mass



Dark Energy



Dark Matter

THE STANDARD MODEL

Hidden Sectors

- Supersymmetry
- Composite Higgs
- Little Higgs
- Extra Dimensions

Strong CP Problem

Flavour Anomalies

Axions / ALPs

Long-Lived Particles

Black Hole

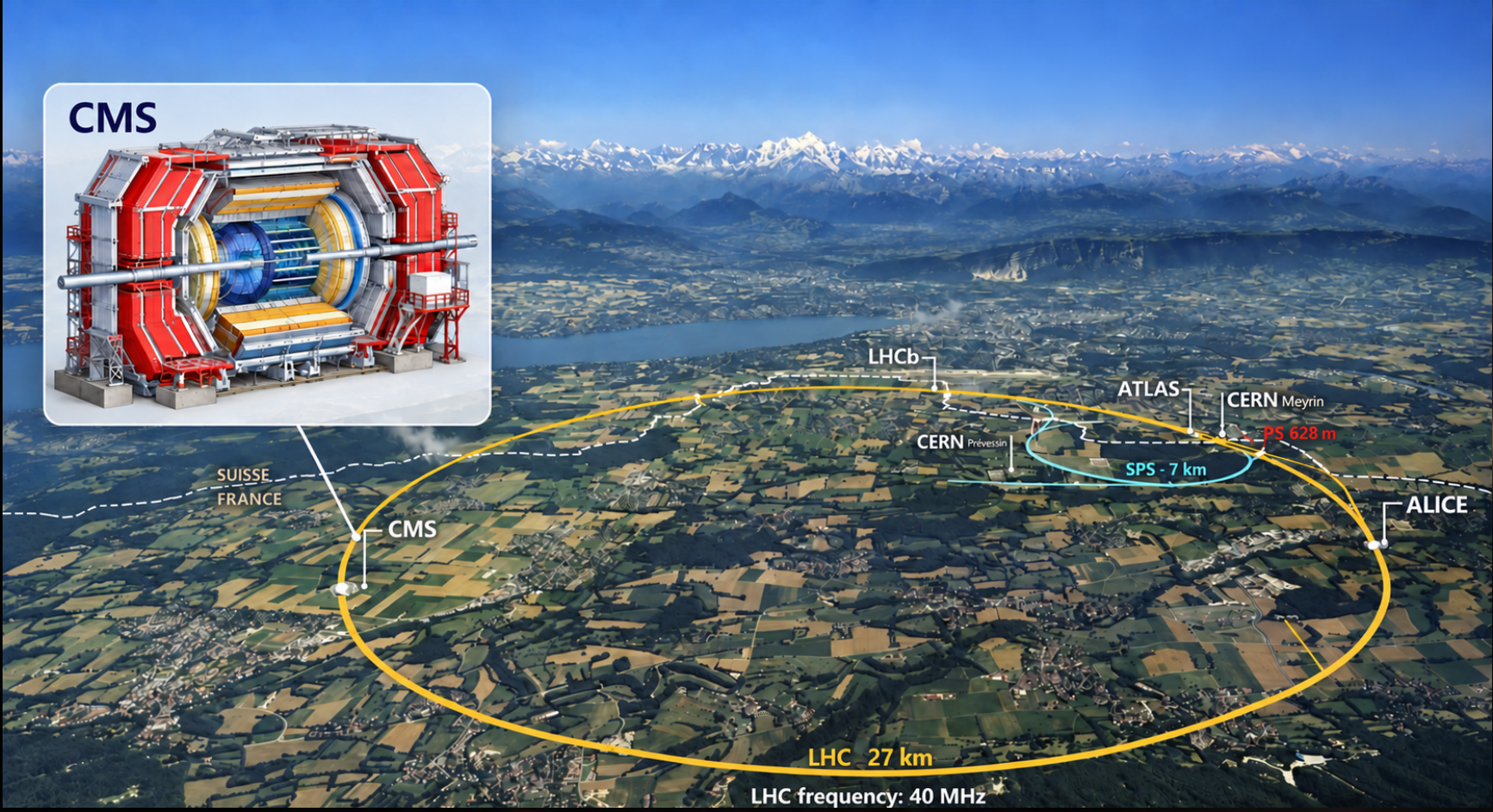


Grand Unification

Anomaly Mediation

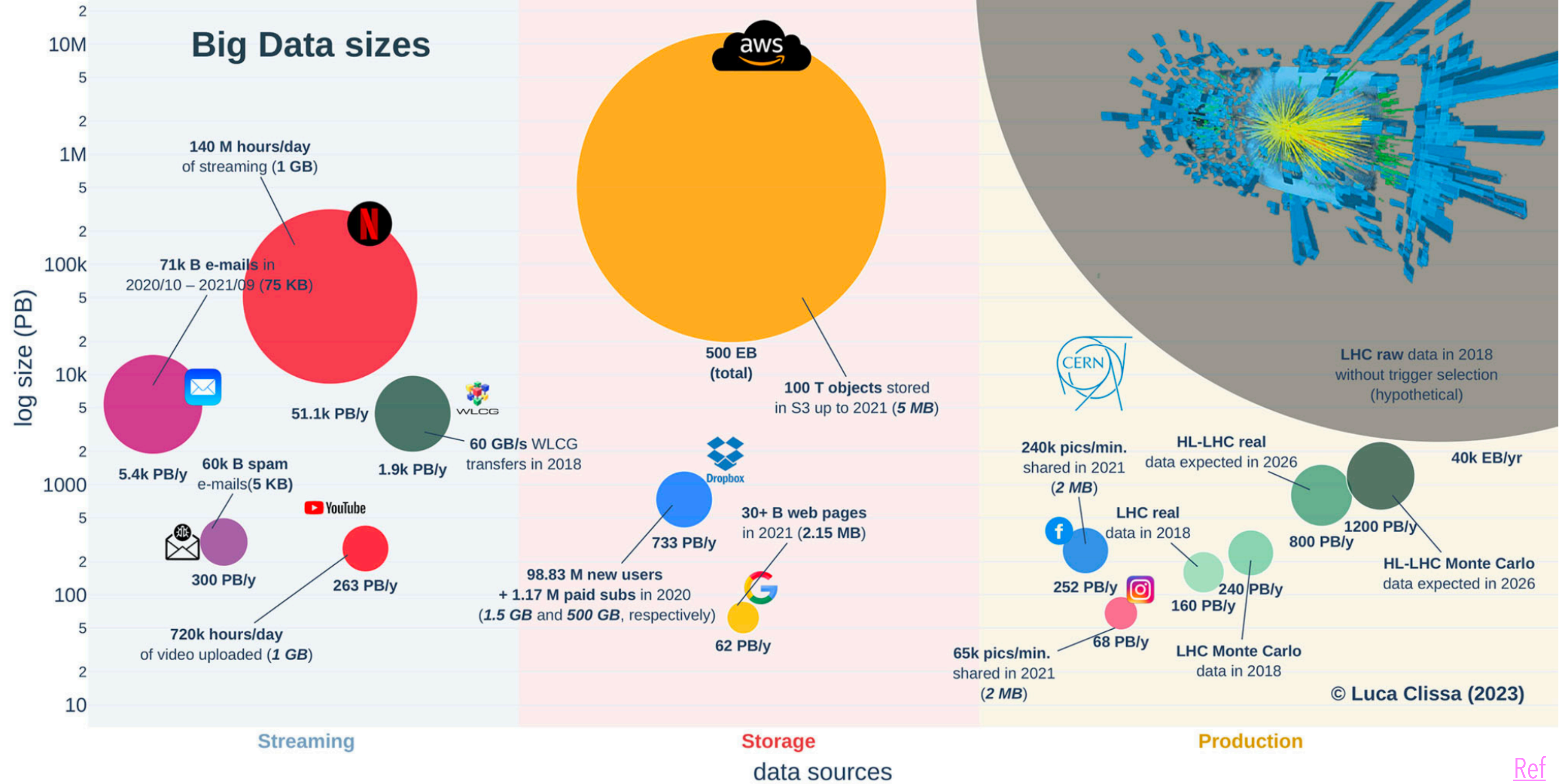
NOT YET THOUGHT





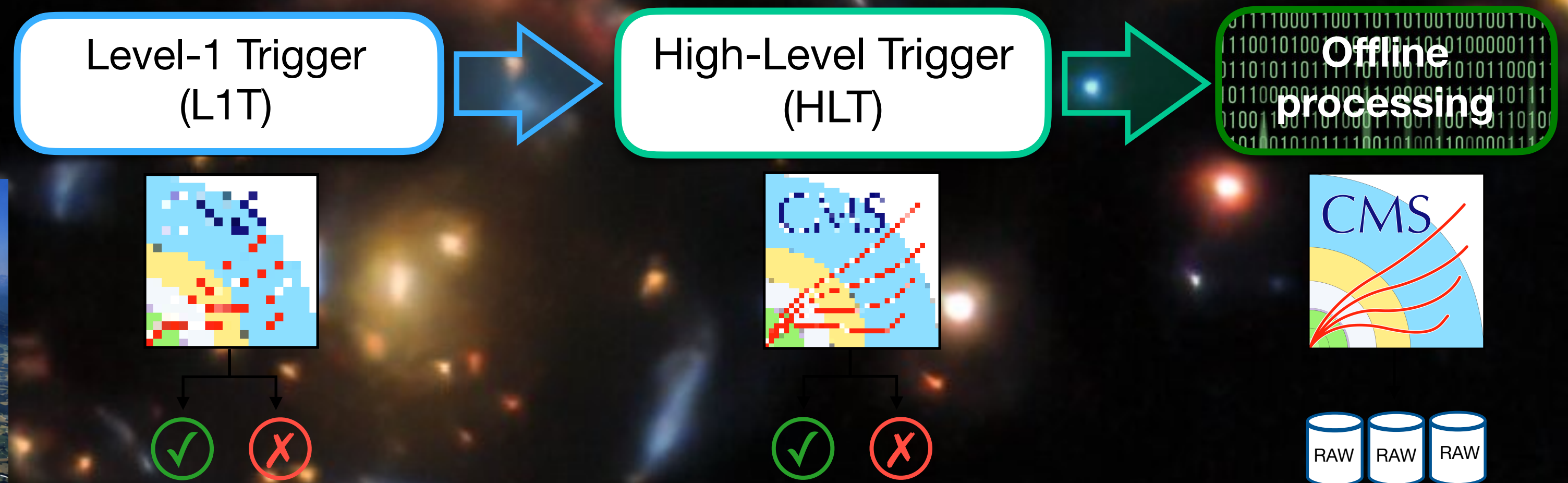
The challenge!

Big Data sizes



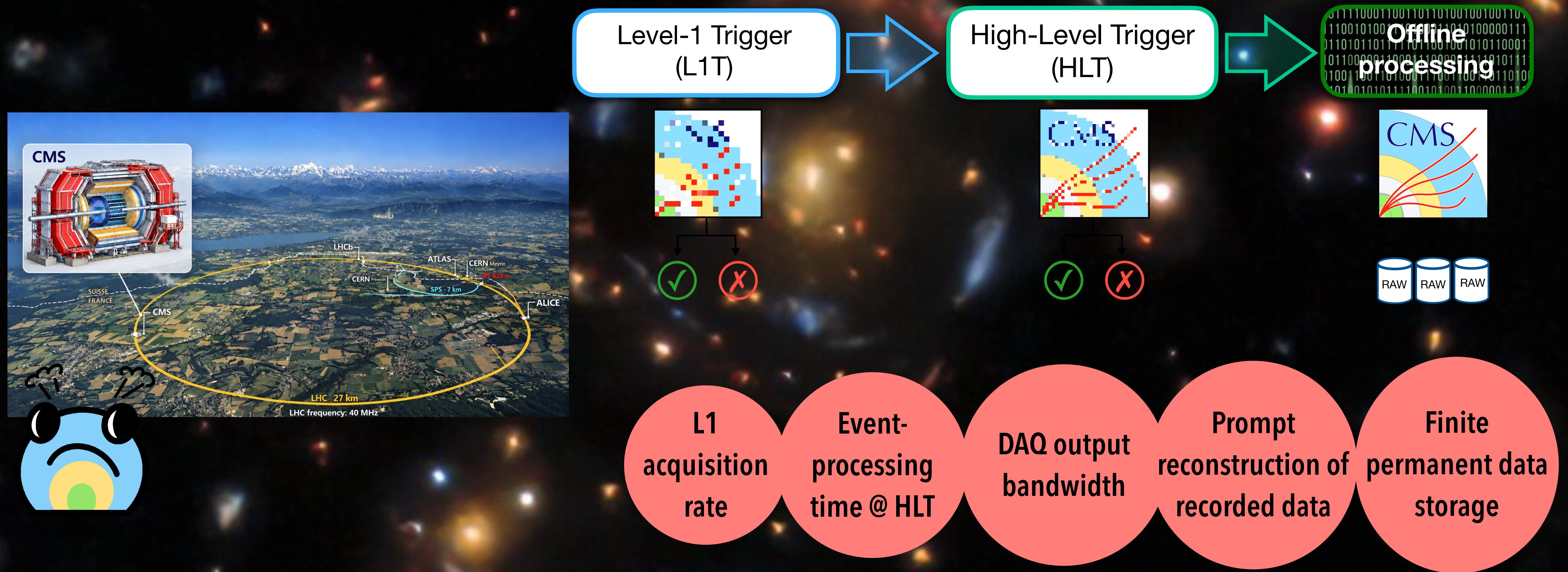
Ref

The investigation of the hottest topics and questions about our universe requires new data:
not only a matter of how much data, but of which data we wanna collect, and how we do that!

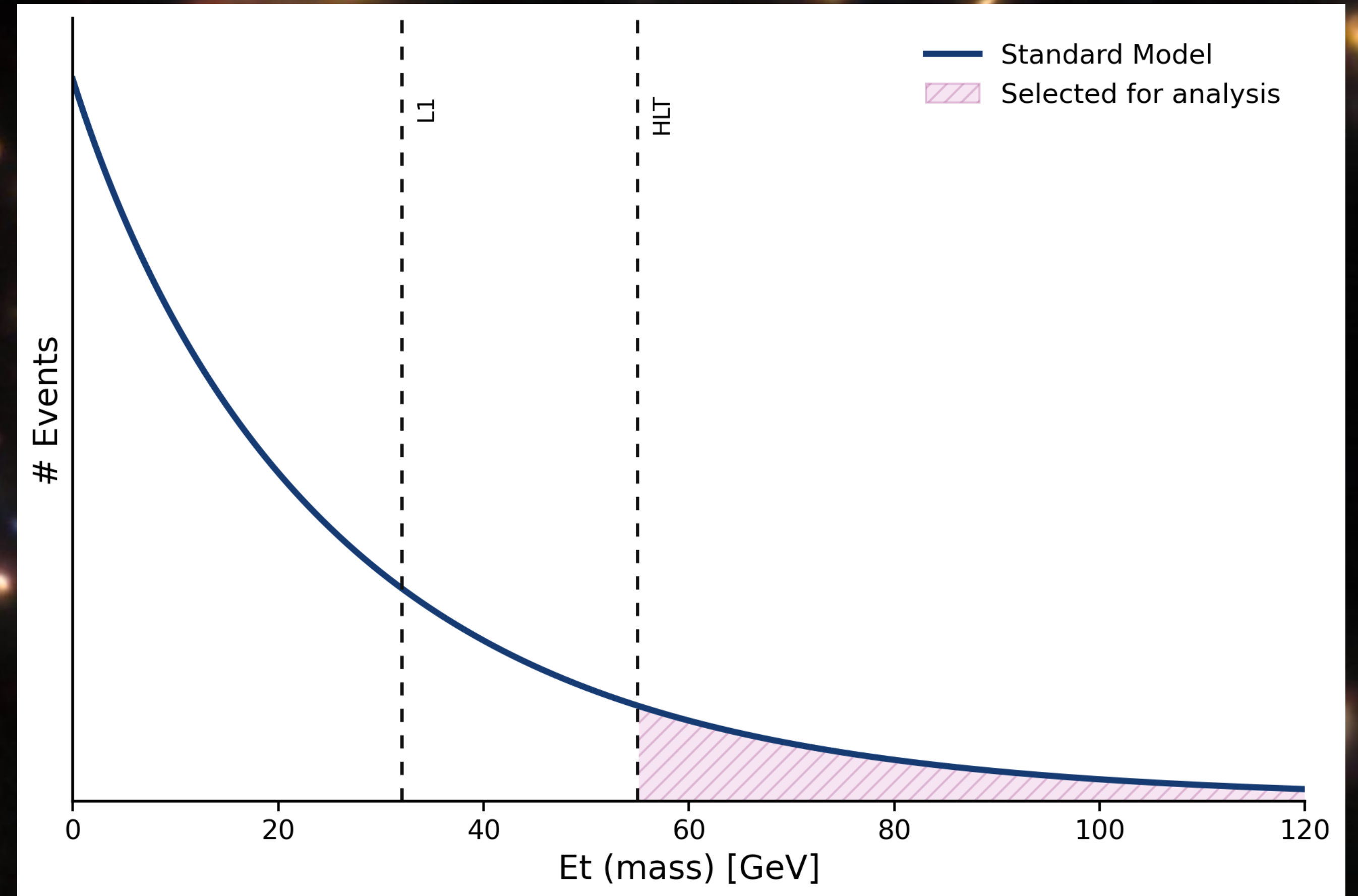


The "solution"...

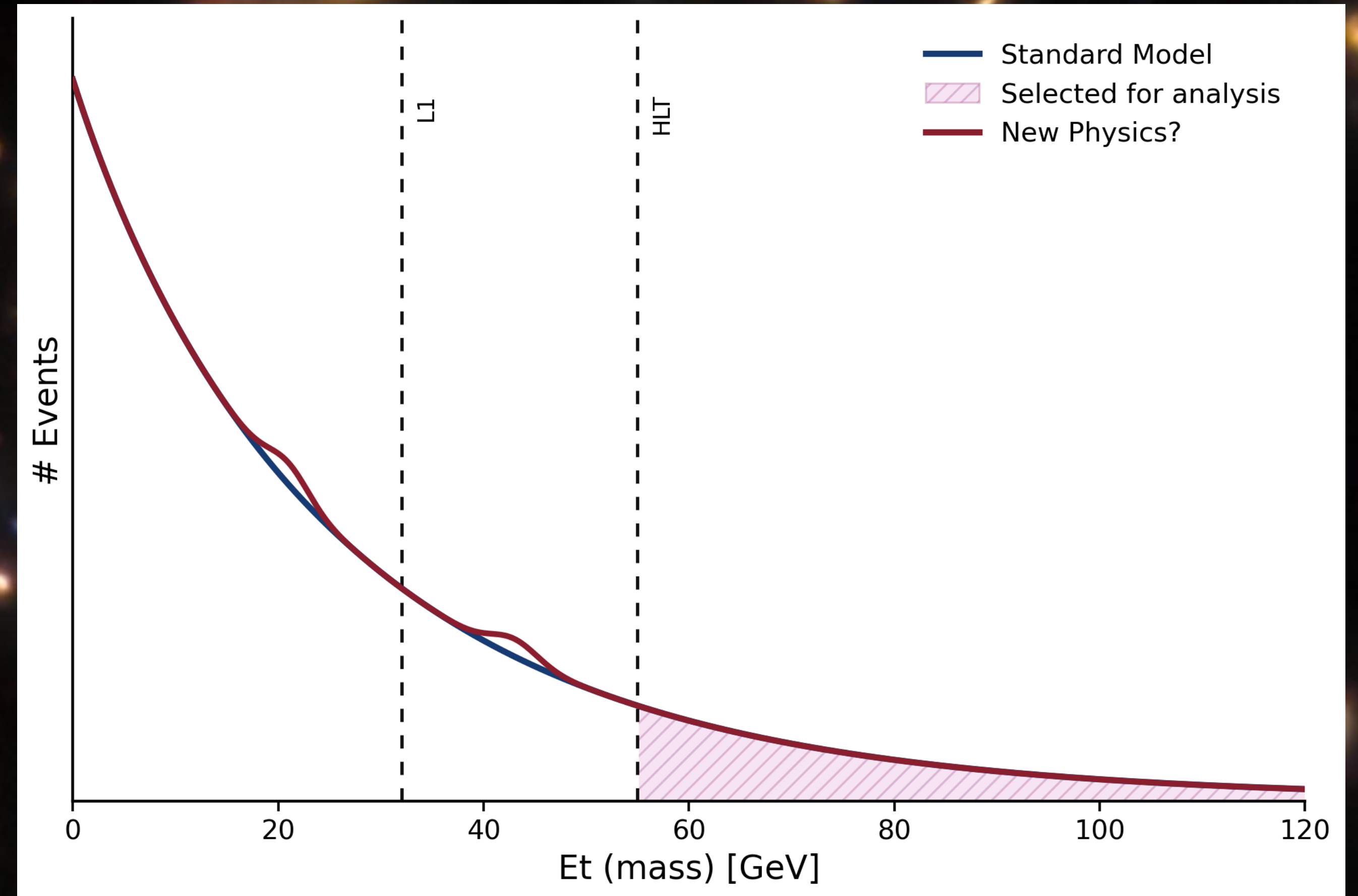
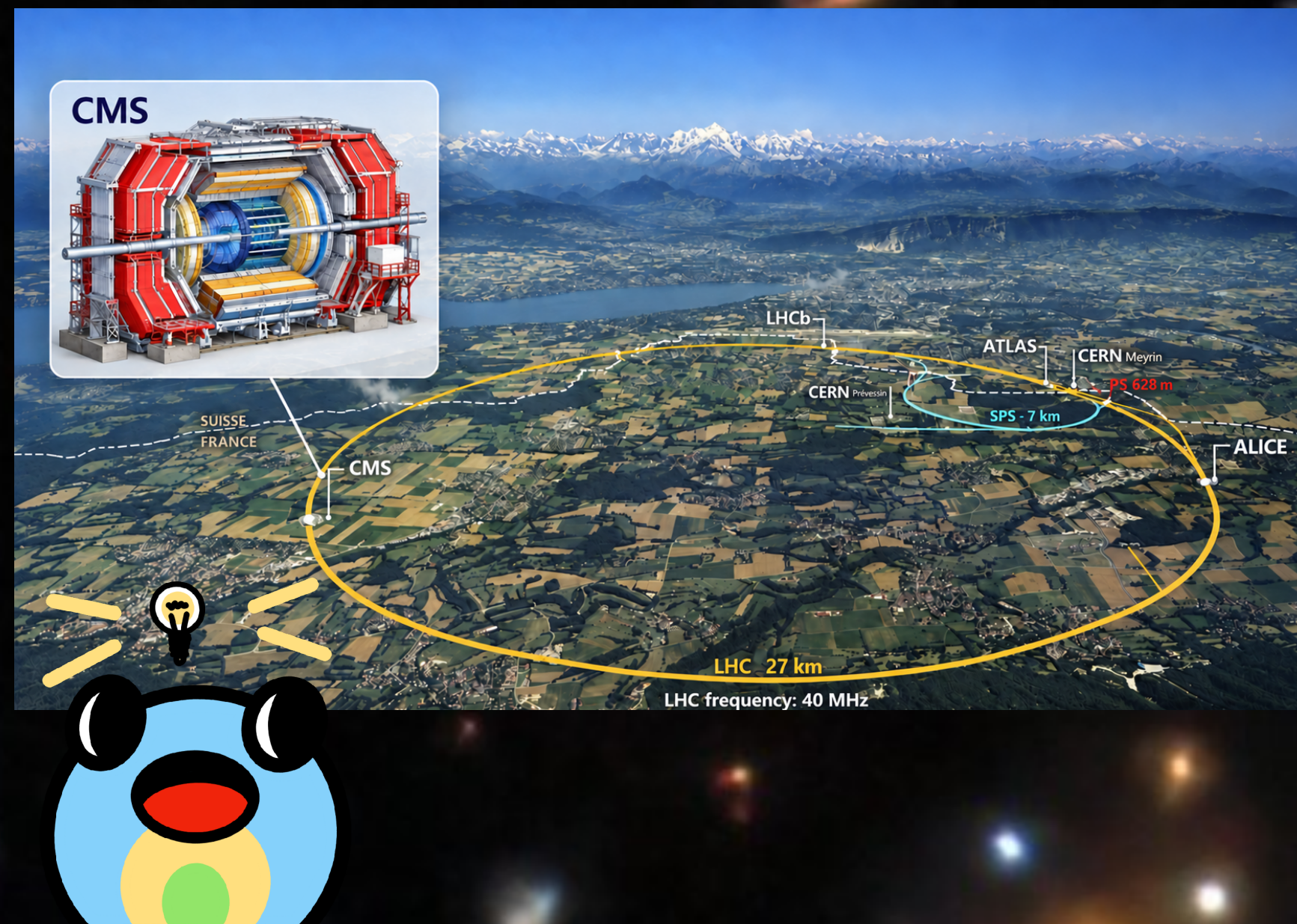
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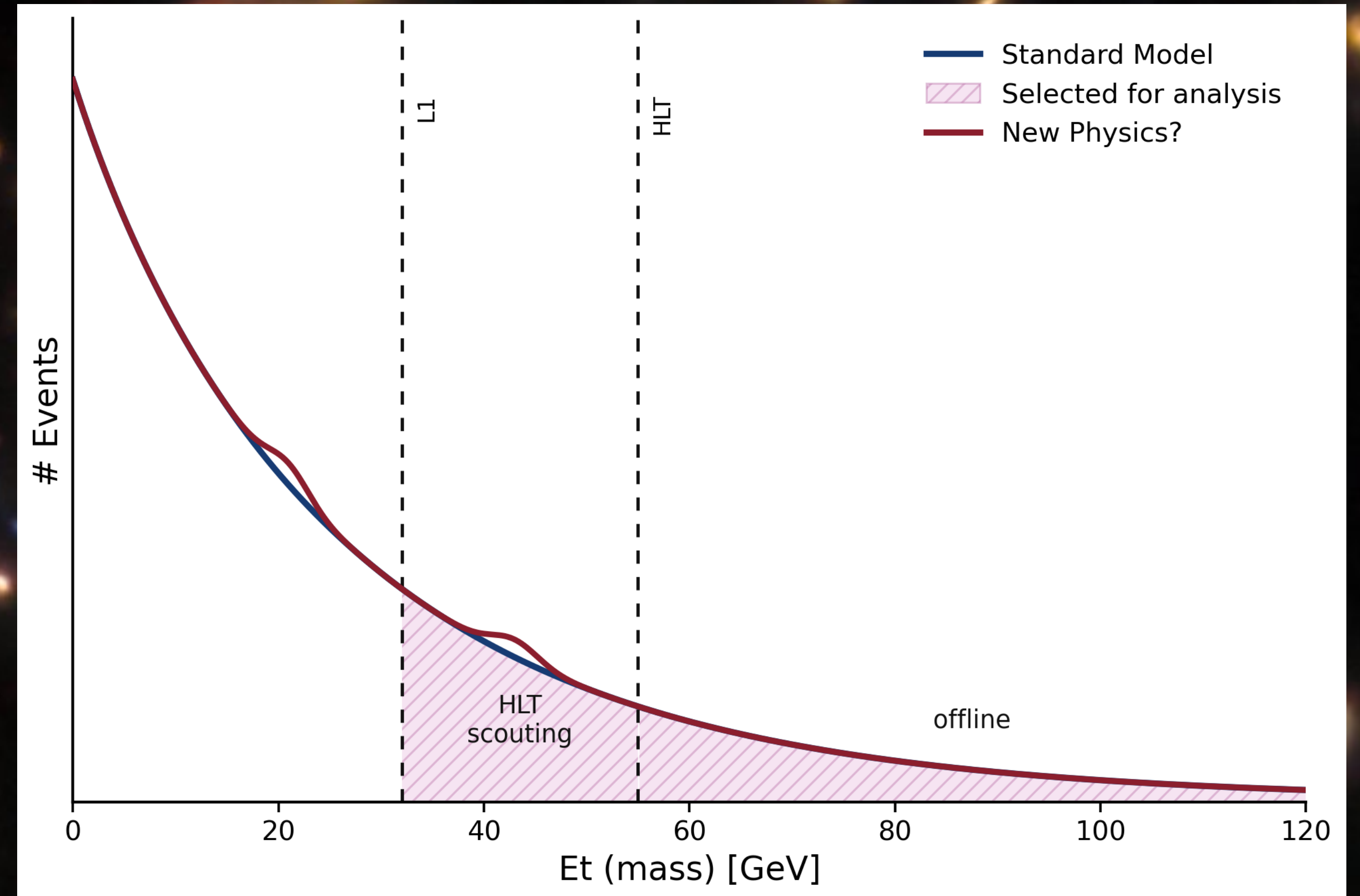
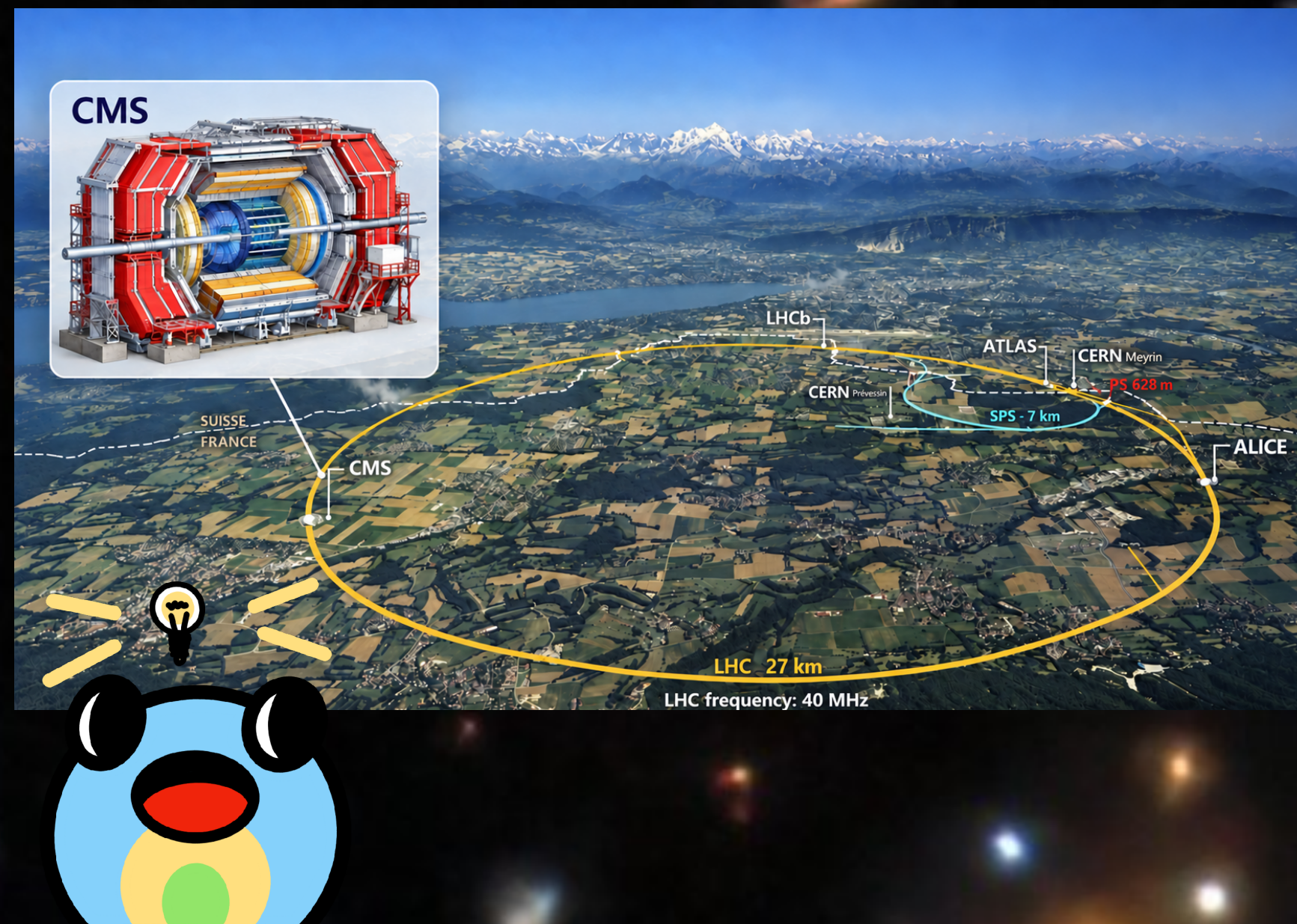
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WHAT DOES “HLT SCOUTING @ CMS” MEAN?

No offline reconstruction!

Online reconstruction
and calibrations

= Offline reconstruction or data
reprocessing is not permitted

Reduced object
information stored

Lower thresholds
on trigger objects

Higher rates

Reduced event size w.r.t.
standard data (= no need for RAW)

15 kB/ev vs ~1 MB/ev

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- ❖ *How much the scouting triggers allow to gain w.r.t. the standard data?*
- ❖ *How do the scouting objects compare to the standard objects? Are they good enough?*
- ❖ *Can we perform physics analyses with the reduced information that we store?*

OUTLINE OF TODAY'S PRESENTATION



Data Scouting Foundations: From Run 1 to Run 2



Motivation and challenges



Data scouting at the origins



Development and consolidation



Physics highlights: a proof of concept

Data Scouting Today: Performance, Physics, and Prospects



New HLT farm (CPU + GPU)



HLT reconstruction improvements



Current performance and capabilities



Physics highlights and opportunities

...and Beyond



Future opportunities



Scouting evolution

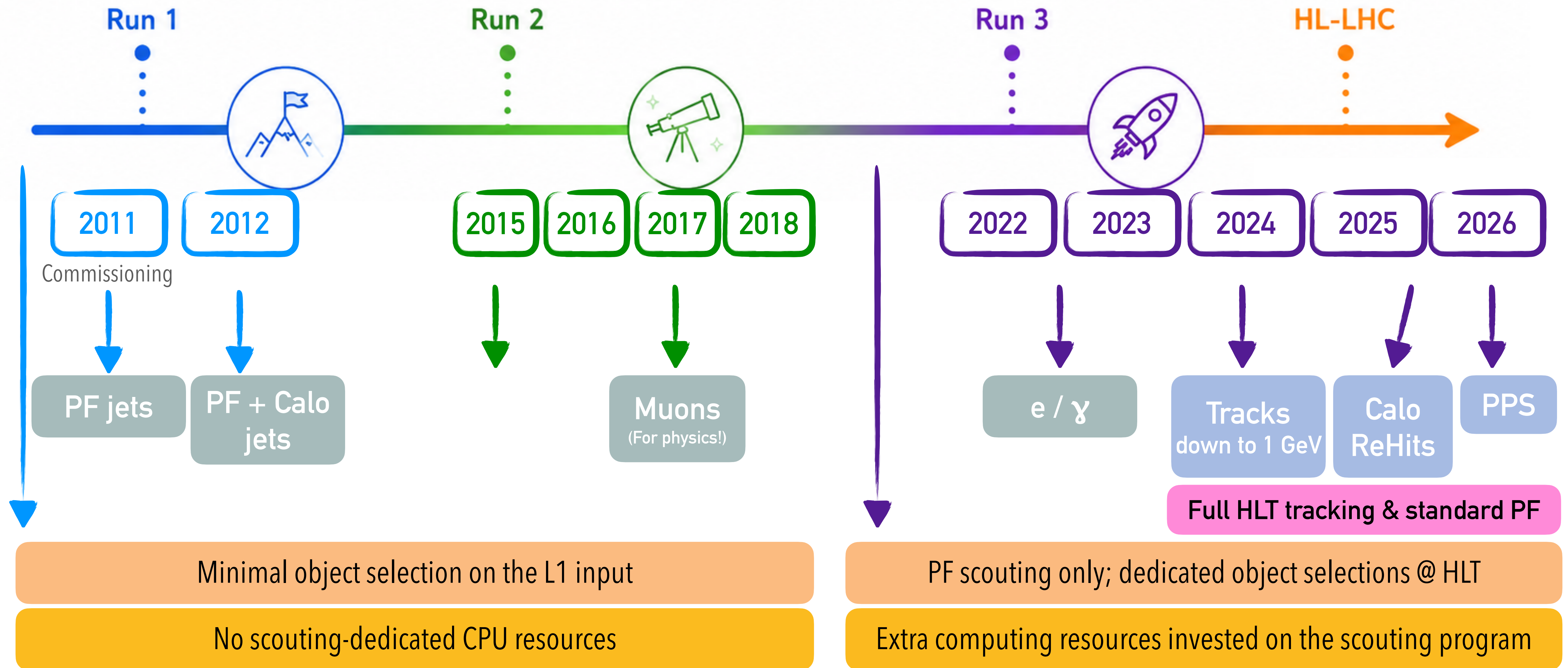


Real-time analysis and AI

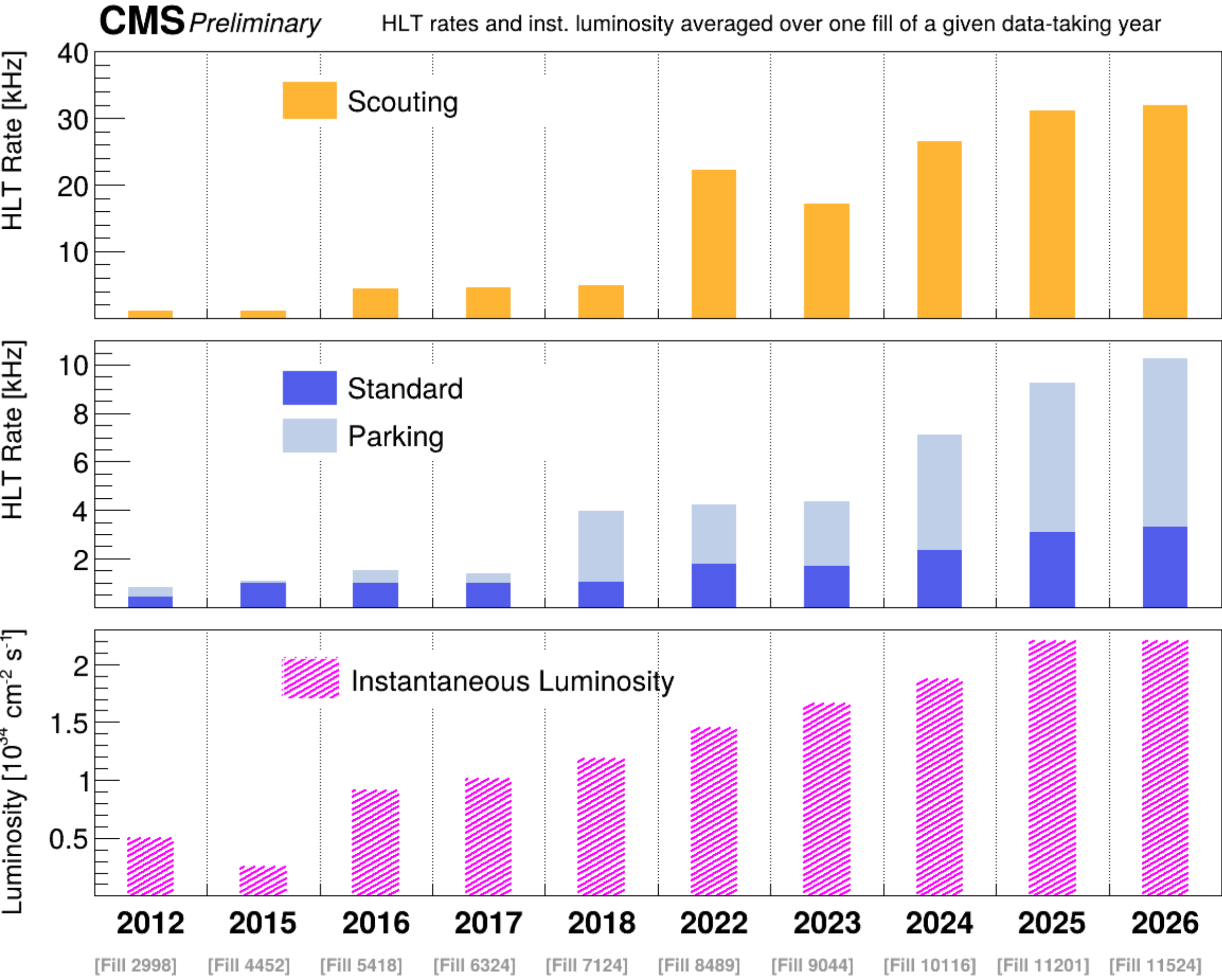


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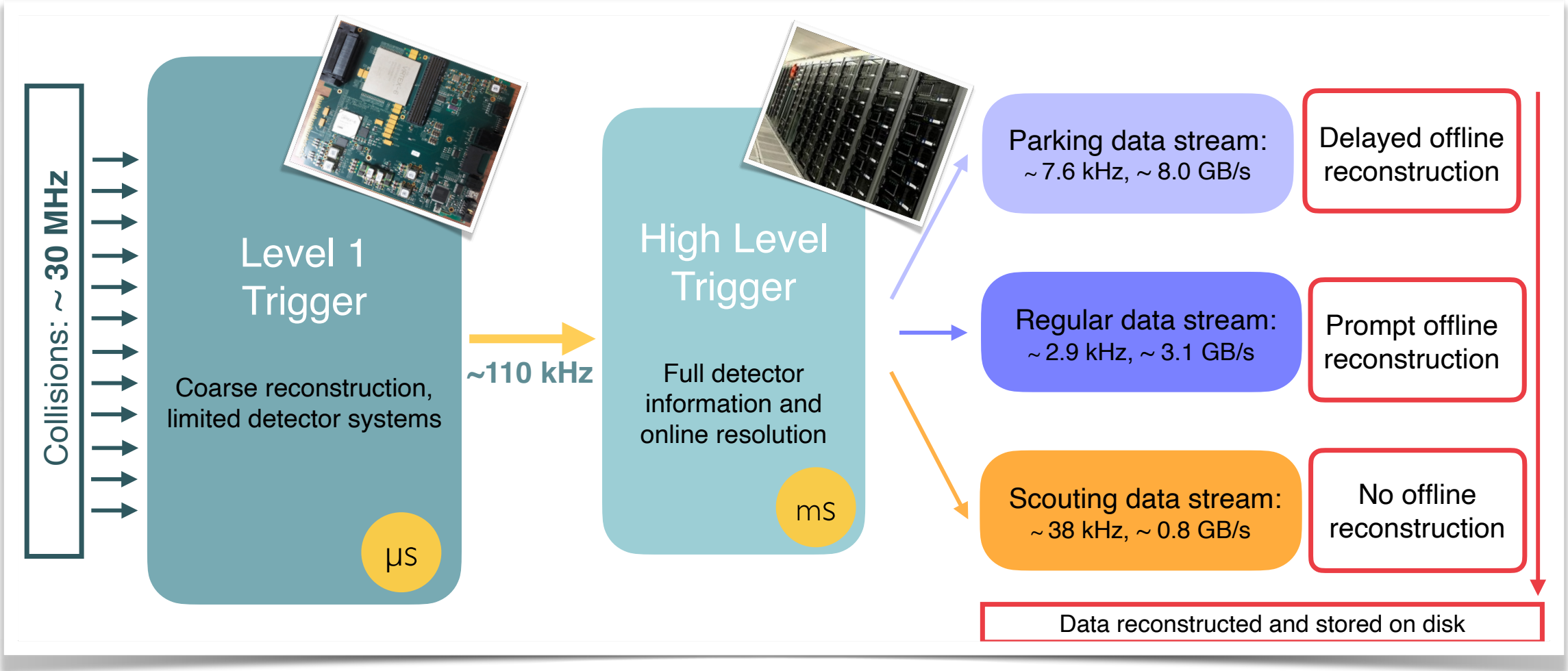
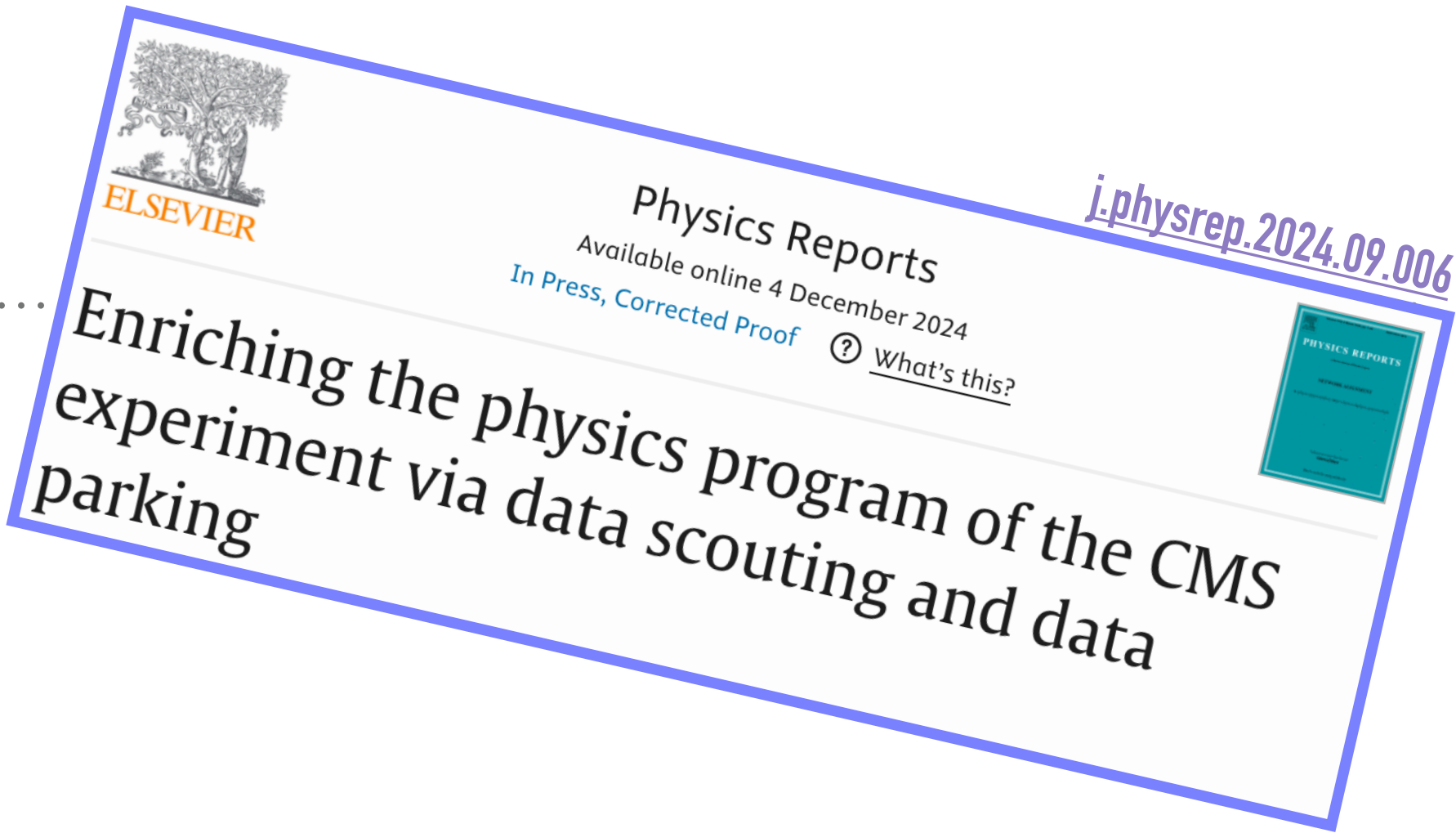
A TIMELINE OF SCOUTING



A TIMELINE OF SCOUTING: RUN 3 EXPANSION

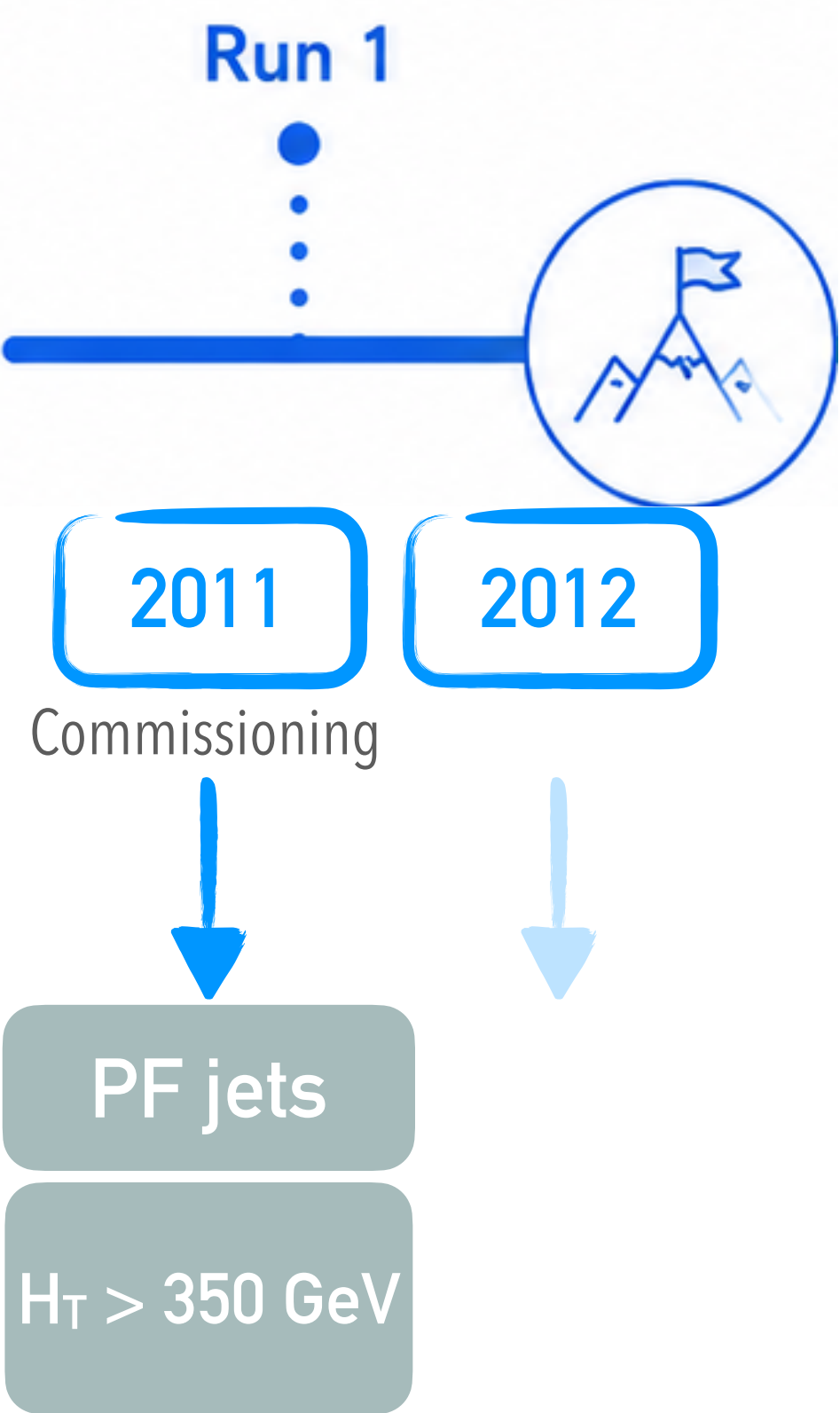


CMS-DP-2026-023



Extra computing resources invested on the scouting program

RUN 1: COMMISSIONING



CMS Physics Analysis Summary

[CMS-PAS-EXO-11-094](#)

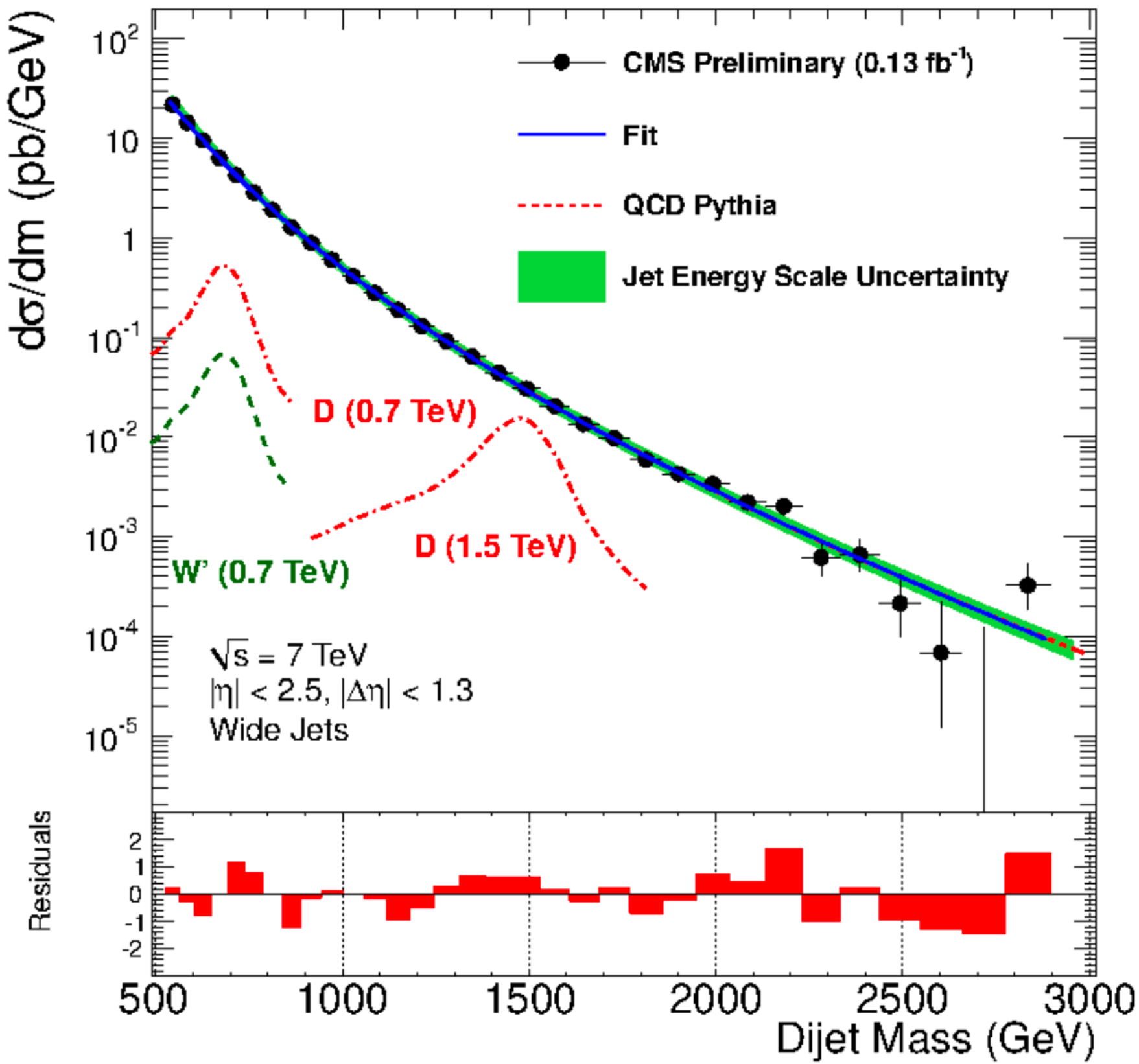
Contact: cms-pag-conveners-exotica@cern.ch 2012/07/11

Search for Narrow Resonances using the Dijet Mass Spectrum in pp Collisions at $\sqrt{s} = 7 \text{ TeV}$

The CMS Collaboration

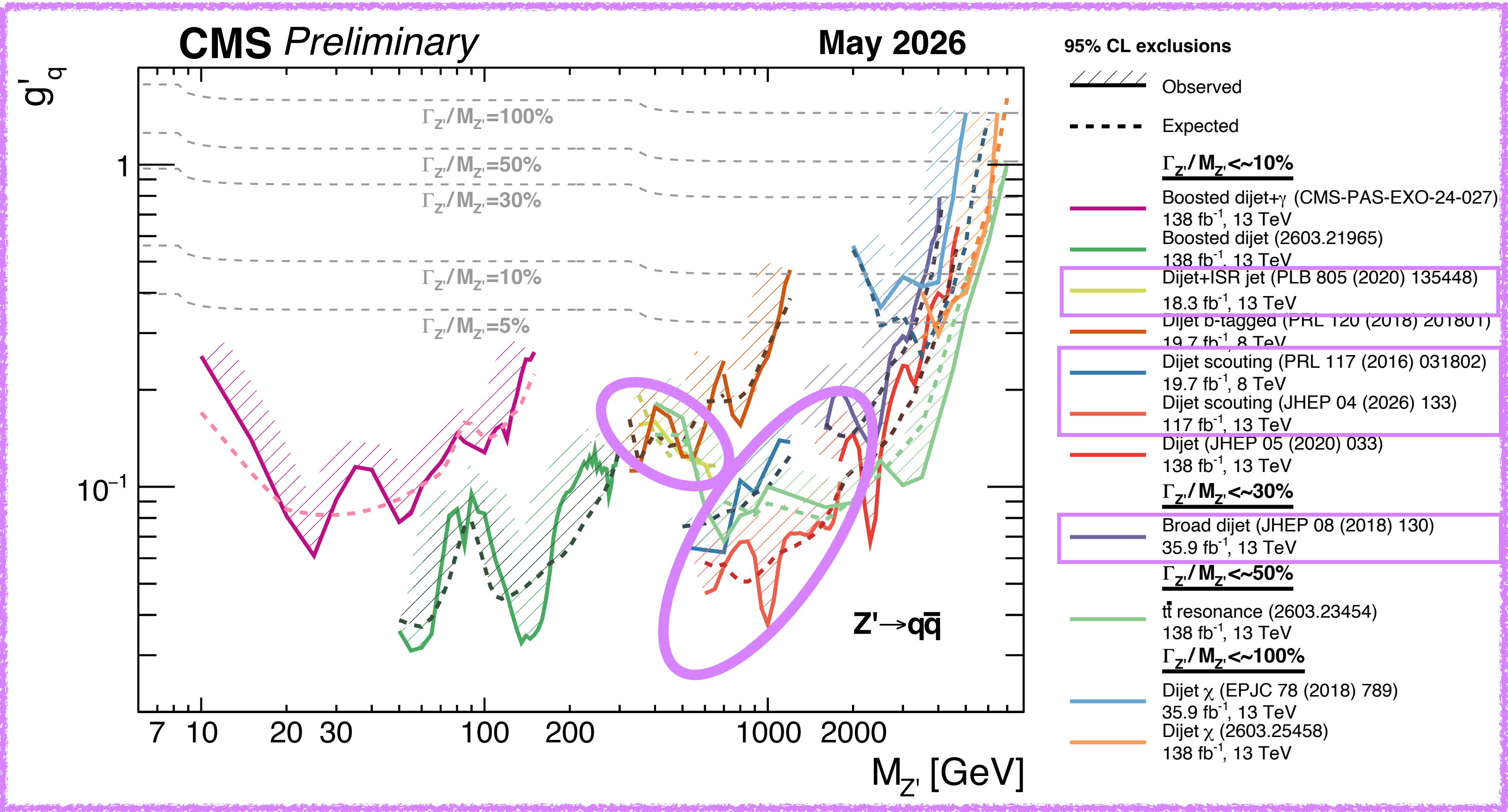
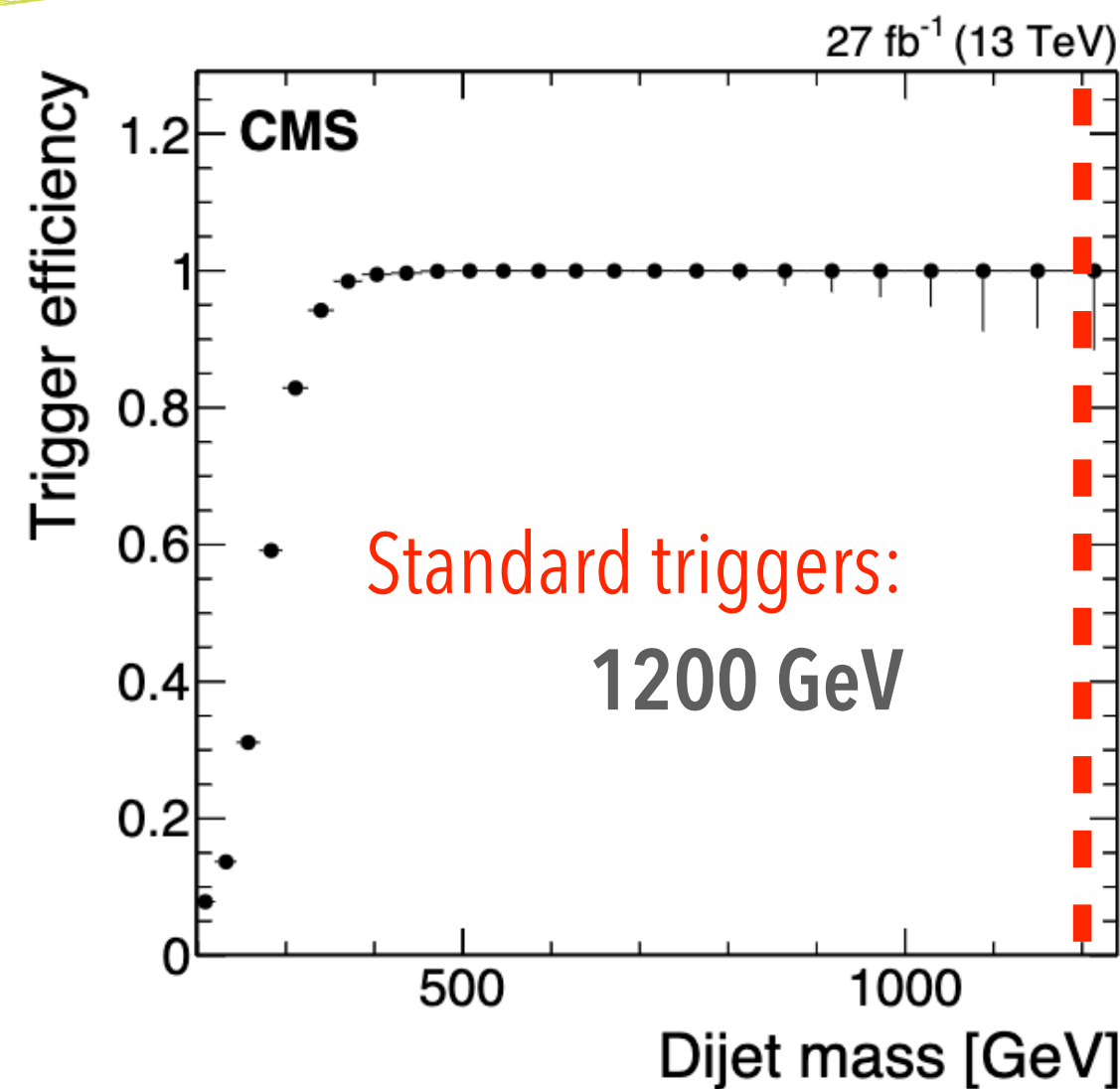
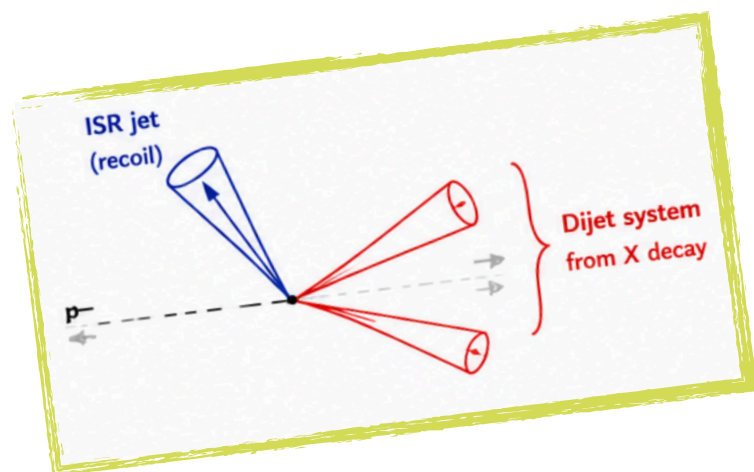
Abstract

We present a search for new particles decaying to a pair of jets in pp collisions at $\sqrt{s} = 7 \text{ TeV}$. The data sample for events with dijet invariant mass above 0.9 TeV corresponds to an integrated luminosity of 5 fb^{-1} collected by the CMS detector at the LHC. In order to extend the sensitivity in the 0.6–0.9 TeV range, a complementary low-mass analysis is performed employing a special dataset with reduced event content, corresponding to an integrated luminosity of 0.13 fb^{-1} and collected in the last days of the 2011 data taking period. We set specific lower limits on the mass of string resonances, excited quarks, axigluons, colorons, s8 resonances, E_6 diquarks, W' and Z' bosons, and RS gravitons in the 0.6–4.3 TeV range, most of which extend previous exclusions from the dijet mass search technique.



RUN 2: PROBING DATA SCOUTING POTENTIAL IN HADRONIC FINAL STATES

Calo jets: $H_T > 250$ GeV



- 95% CL exclusions
- Observed (solid line)
 - Expected (dashed line)
- $\Gamma_{Z'}/M_{Z'} < \sim 10\%$
- Boosted dijet+ γ (CMS-PAS-EXO-24-027) 138 fb⁻¹, 13 TeV
 - Boosted dijet (2603.21965) 138 fb⁻¹, 13 TeV
 - Dijet+ISR jet (PLB 805 (2020) 135448) 18.3 fb⁻¹, 13 TeV
 - Dijet b-tagged (PRL 120 (2018) 201801) 19.7 fb⁻¹, 8 TeV
- $\Gamma_{Z'}/M_{Z'} < \sim 30\%$
- Dijet scouting (PRL 117 (2016) 031802) 19.7 fb⁻¹, 8 TeV
 - Dijet scouting (JHEP 04 (2026) 133) 117 fb⁻¹, 13 TeV
 - Dijet (JHEP 05 (2020) 033) 138 fb⁻¹, 13 TeV
- $\Gamma_{Z'}/M_{Z'} < \sim 50\%$
- Broad dijet (JHEP 08 (2018) 130) 35.9 fb⁻¹, 13 TeV
- $\Gamma_{Z'}/M_{Z'} < \sim 100\%$
- $t\bar{t}$ resonance (2603.23454) 138 fb⁻¹, 13 TeV
 - Dijet χ (EPJC 78 (2018) 789) 35.9 fb⁻¹, 13 TeV
 - Dijet χ (2603.25458) 138 fb⁻¹, 13 TeV

Link SummaryPlots2026

- ❖ Dijet resonances:
 - Run 1: CMS-PAS-EXO-11-094 (7 TeV), EXO-14-005 (PhysRevLett.117.031802)
 - Run 2: EXO-16-032 (j.physletb.2017.02.012), EXO-16-056 (JHEP08(2018)130); EXO-23-004 (JHEP04(2026)133); EXO-19-004 (j.physletb.2020.135448)

RUN 2: PROBING DATA SCOUTING POTENTIAL IN HADRONIC FINAL STATES

PF jets: $H_T > 410$ GeV

MET

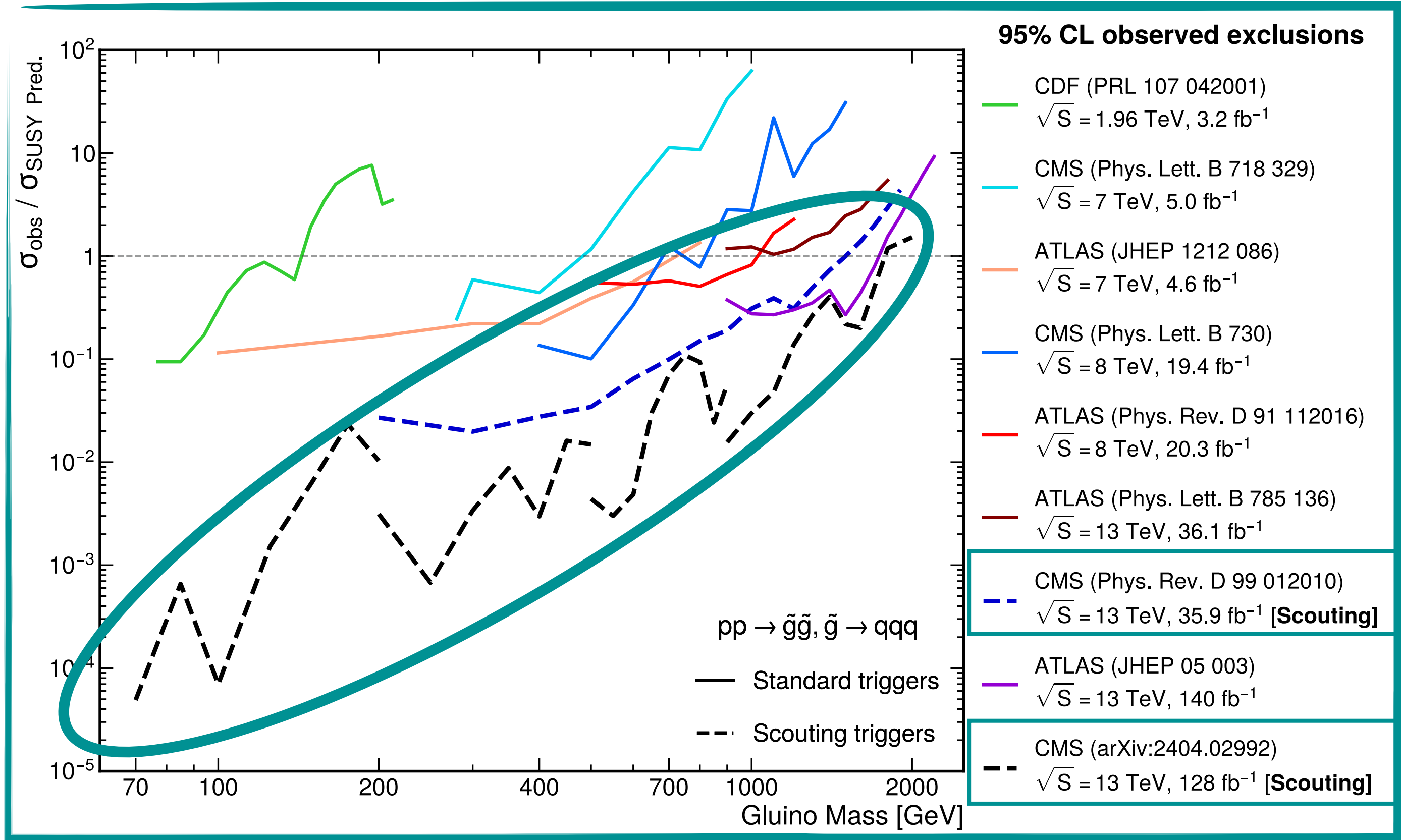
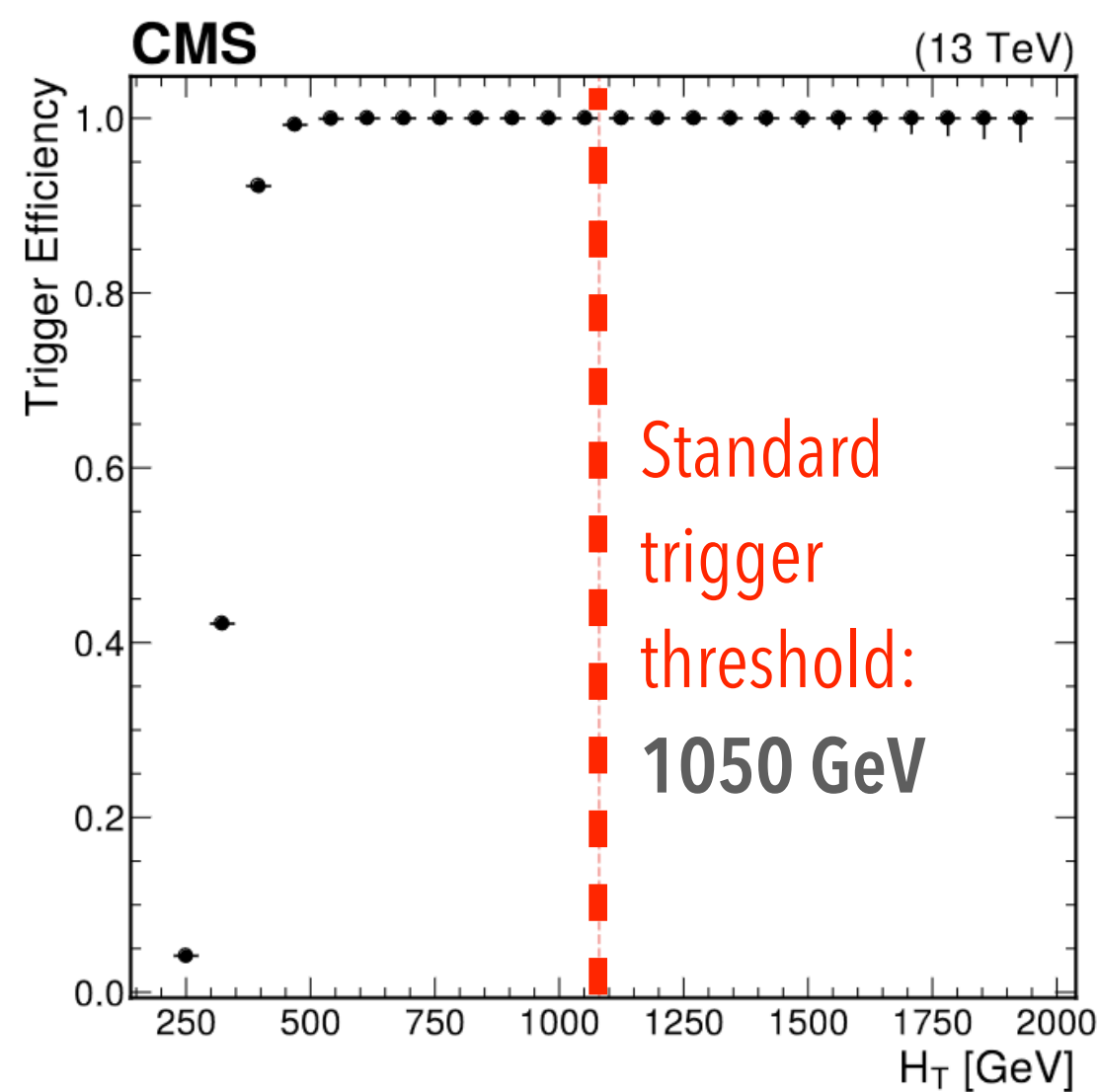
ρ

AK4 jets

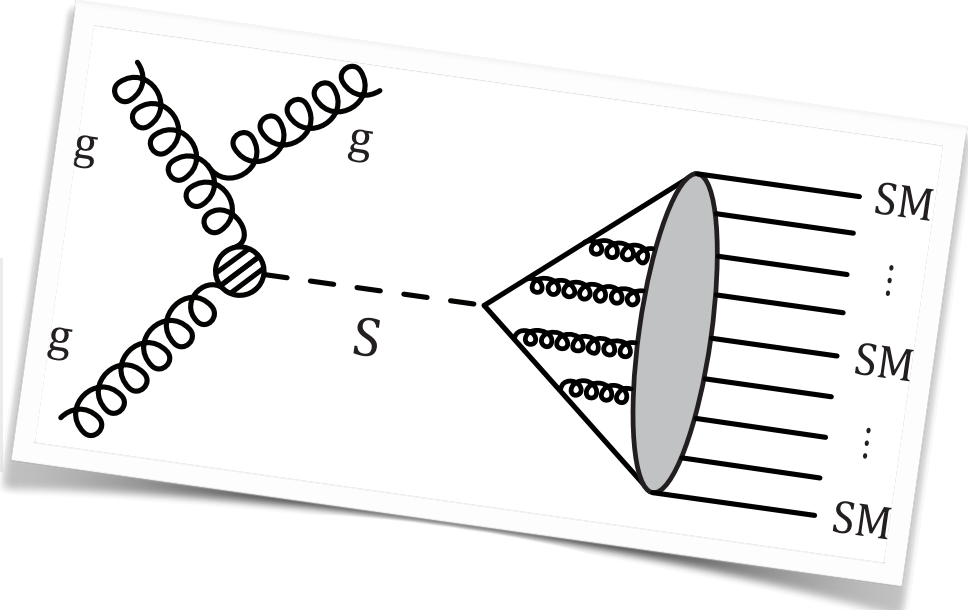
μ

Vertices

PF candidates



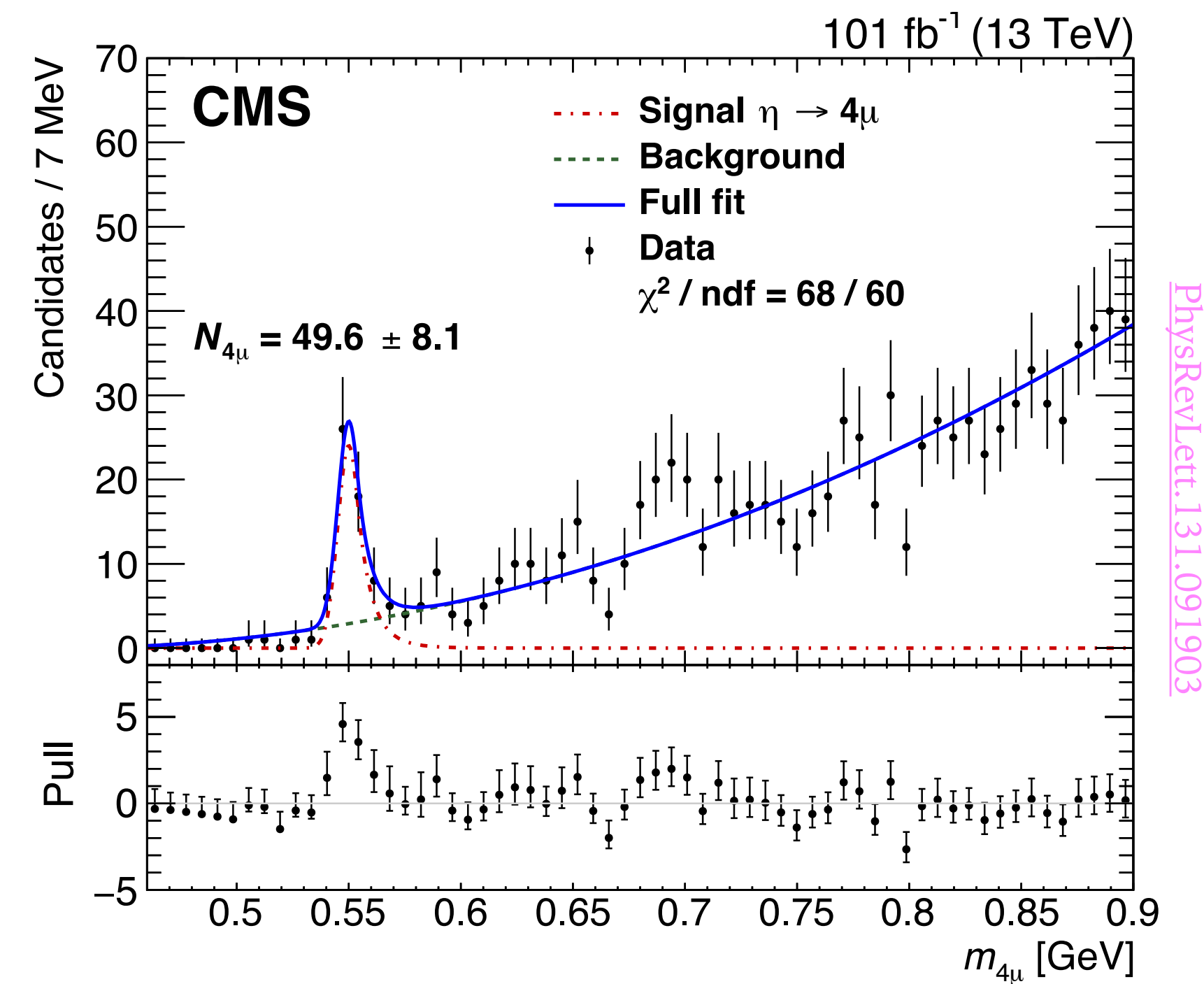
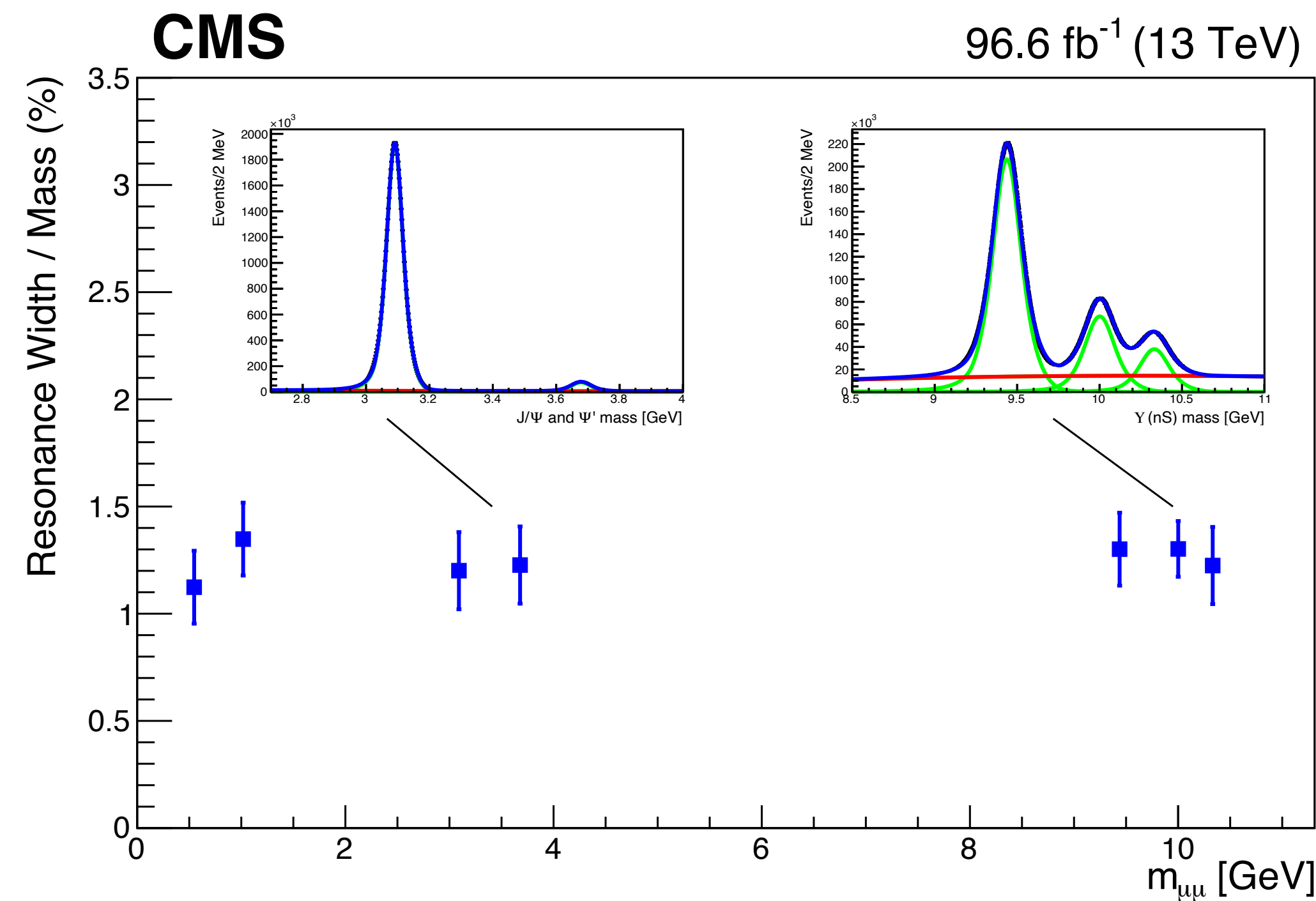
- ❖ Pair produced dijet and trijet resonances: EXO-17-030 (PhysRevD.99.012010), EXO-21-004 ([PhysRevLett.133.201803](#))
- ❖ Soft unclustered energy patterns: EXO-23-001



i.physrep.2024.09.006

RUN 2: PROBING DATA SCOUTING POTENTIAL IN DIMUON FINAL STATES

Dedicated muon triggers with low p_T thresholds (3 GeV) and no constraints on the primary vertex efficiently target dimuon resonances at the GeV scale

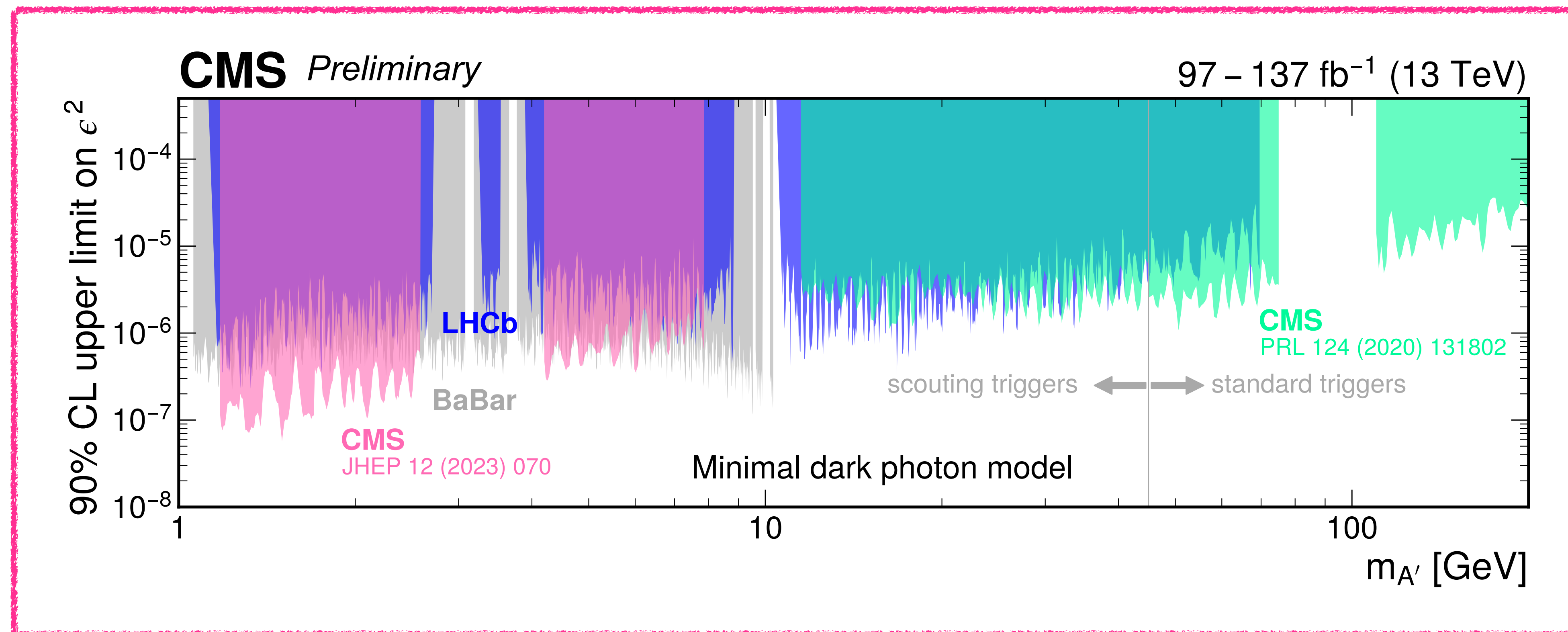


PhysRevLett.131.091903

Muons from online reconstruction @ HLT are high quality objects, directly usable for physics analysis!

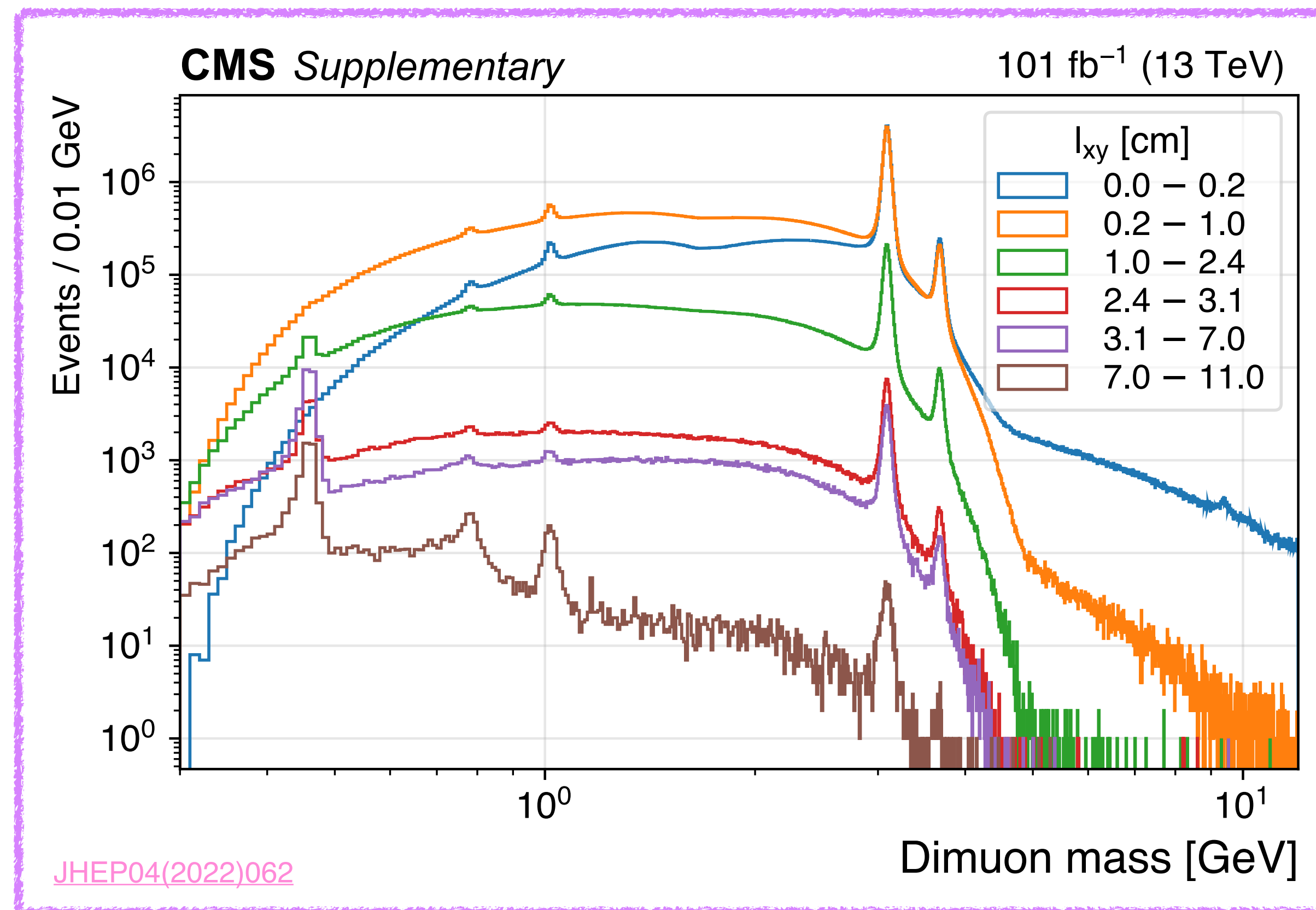
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accessing otherwise inaccessible phase spaces both for **prompt** and **displaced** resonance production searches



RUN 2: PROBING DATA SCOUTING POTENTIAL IN DIMUON FINAL STATES

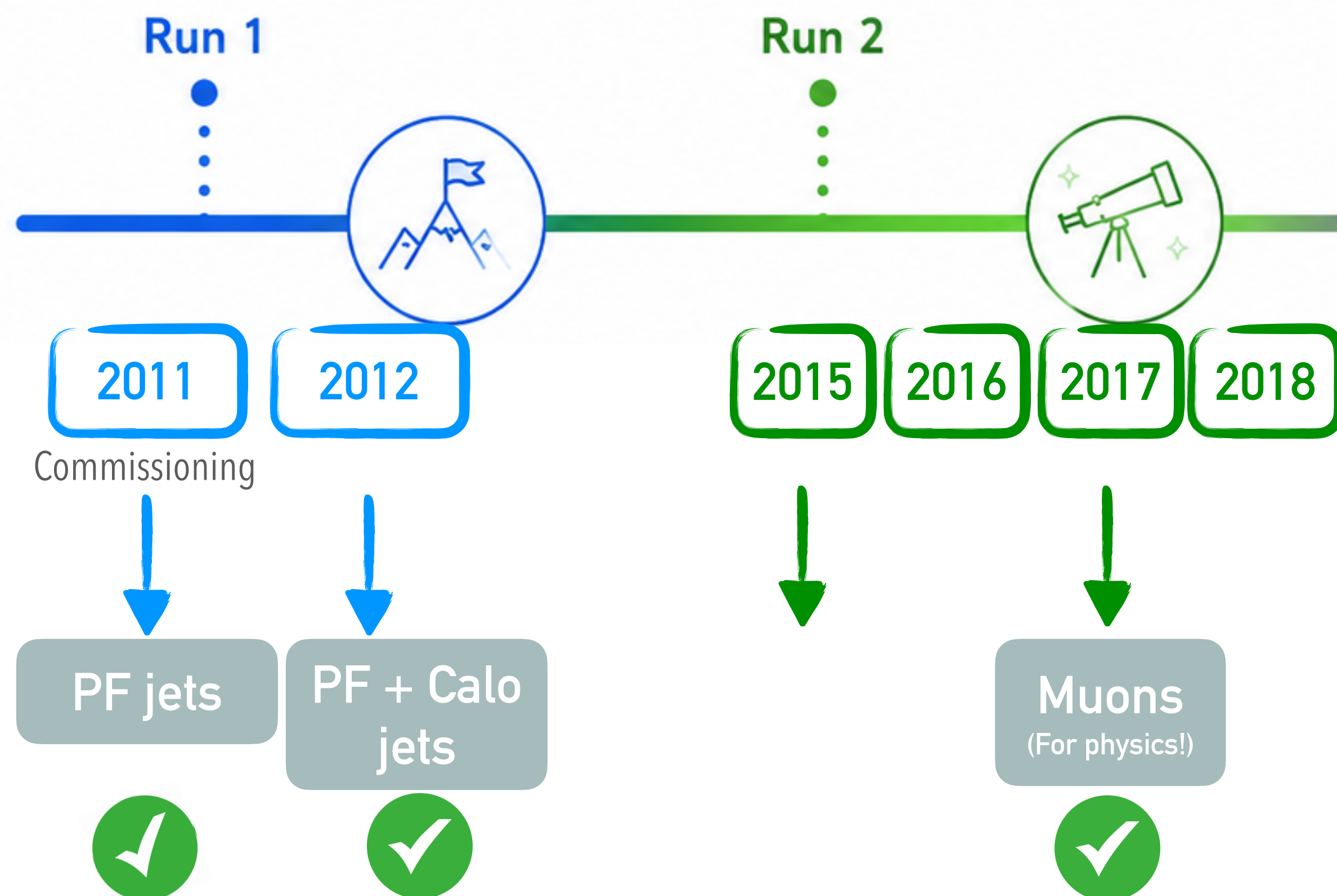
Dedicated muon triggers with low p_T thresholds (3 GeV) and no constraints on the primary vertex
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accessing otherwise inaccessible phase spaces both for **prompt** and **displaced** resonance production searches



- ❖ Dedicated vertex reconstruction with minimal constraints to the primary vertex (NoVtx)
- ❖ Sensitivity on displaced dimuon resonances at GeV scale
 - ❖ In Run 2, limited to displacements of 11 cm due to a requirement of at least two pixel hits in the tracker

THE RUN 2 LESSON

“It is not down in any map; true places never are.”
(Herman Melville, Moby-Dick)



Lower thresholds on trigger objects
→ Gaining new phase spaces

Online reco @ HLT:

- ❖ Muons are solid objects (1-2% differences w.r.t. offline)
- ❖ Jets and PF candidates are usable (within 10% resolution effects)

Unconventional data format

Customized analysis workflows and calibrations

No info in simulation by default

Harder processing of large data sets

Facing challenges, but achieving high quality physics results which opened up new phase spaces and possibilities!



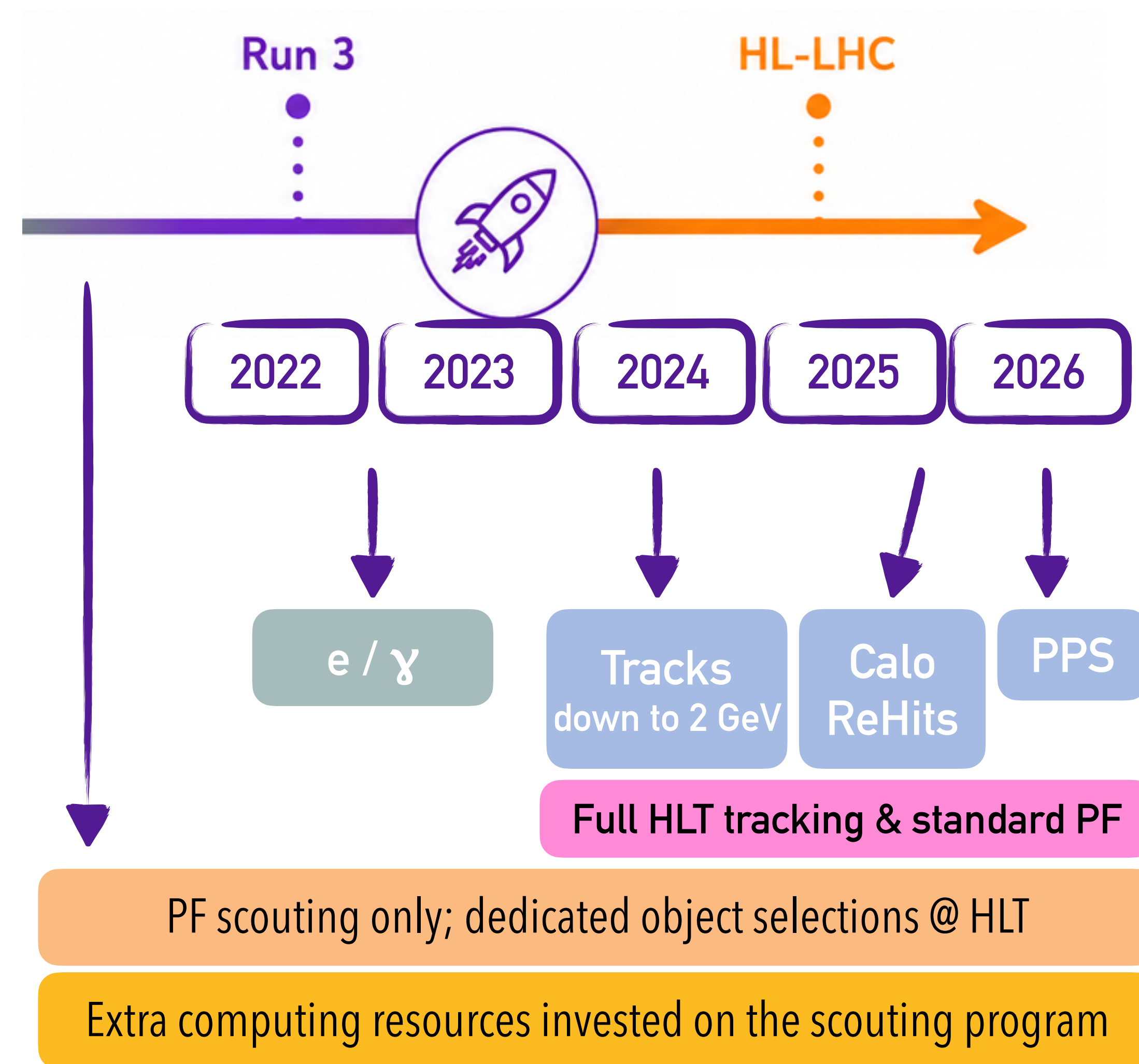
*How can we make scouting
more useful
and
more accessible?*

*Developments and prospects for the
Run 3 scouting program*

SETTING THE STAGE FOR THE RUN 3 SCOUTING PROGRAM: A NEW ERA

Software-based trigger running on new CPU + GPU computer farm

- ◆ CMS HLT computer farm completely renewed at the beginning of Run 3, for the 2022 data taking: 200 nodes
 - ➔ Further extended by 20% with the addition of 18 nodes in 2024
- ◆ **Increasing usage of GPUs at Run 3**, very powerful in parallel computing
 - 30% of the HLT reconstruction offloaded to GPU
 - acceleration with GPU of
 - pixel tracking and vertexing
 - calorimeter reconstruction
 - strip unpacker
 - part of the PF clustering

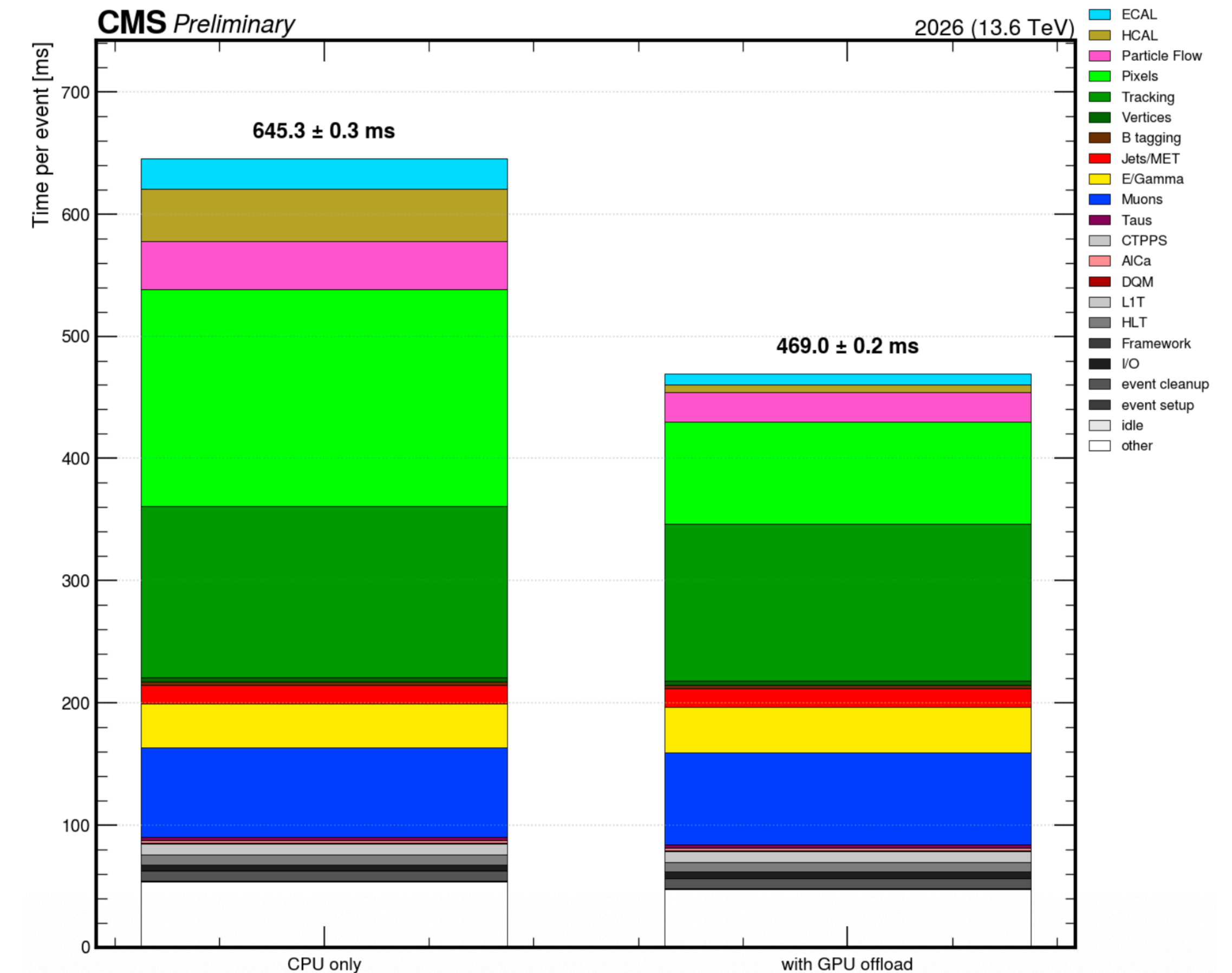


SETTING THE STAGE FOR THE RUN 3 SCOUTING PROGRAM: A NEW ERA

CMS-DP 2026-024

Software-based trigger running on new CPU + GPU computer farm

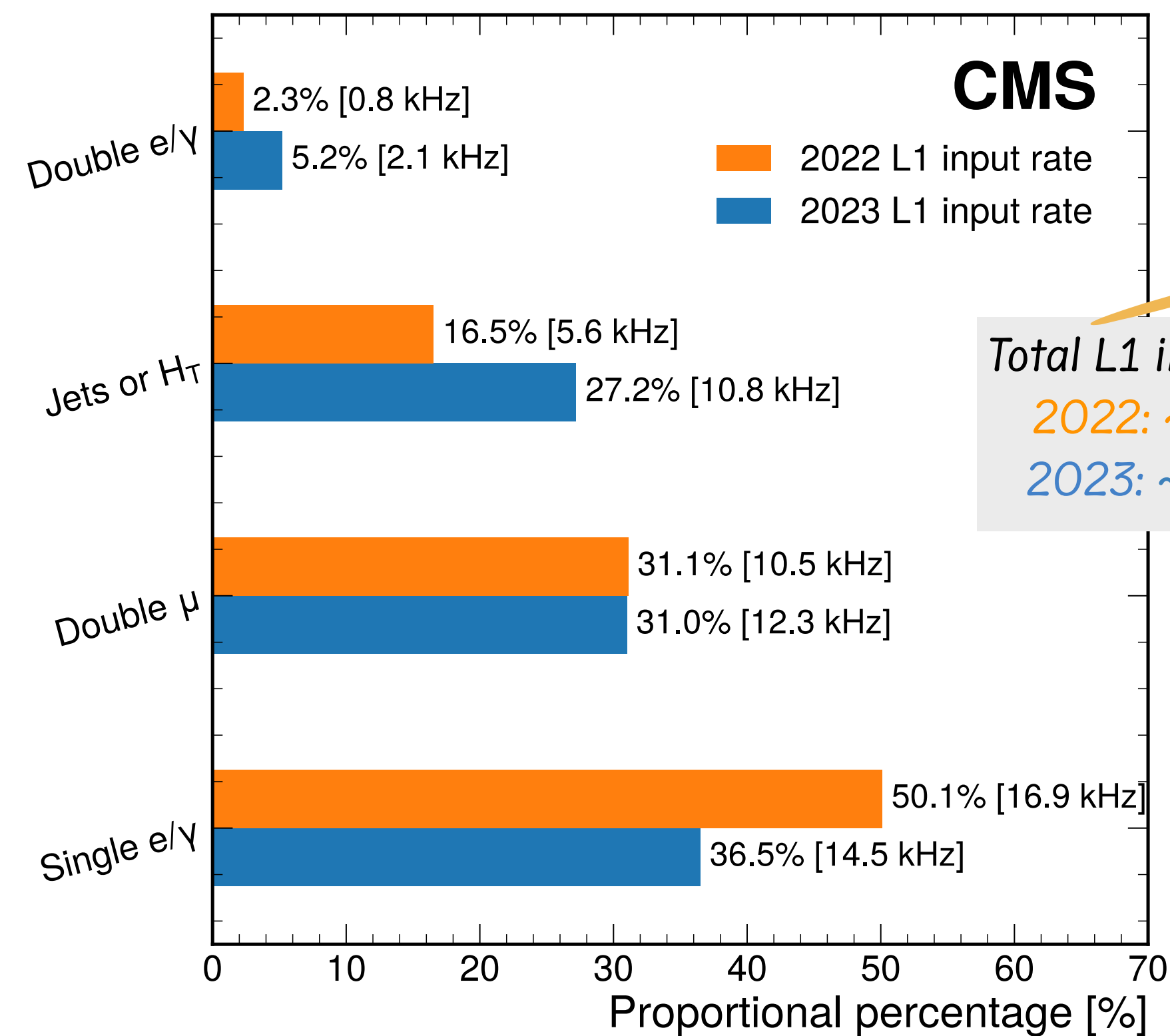
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Speed up of **37.6% ± 0.1%**

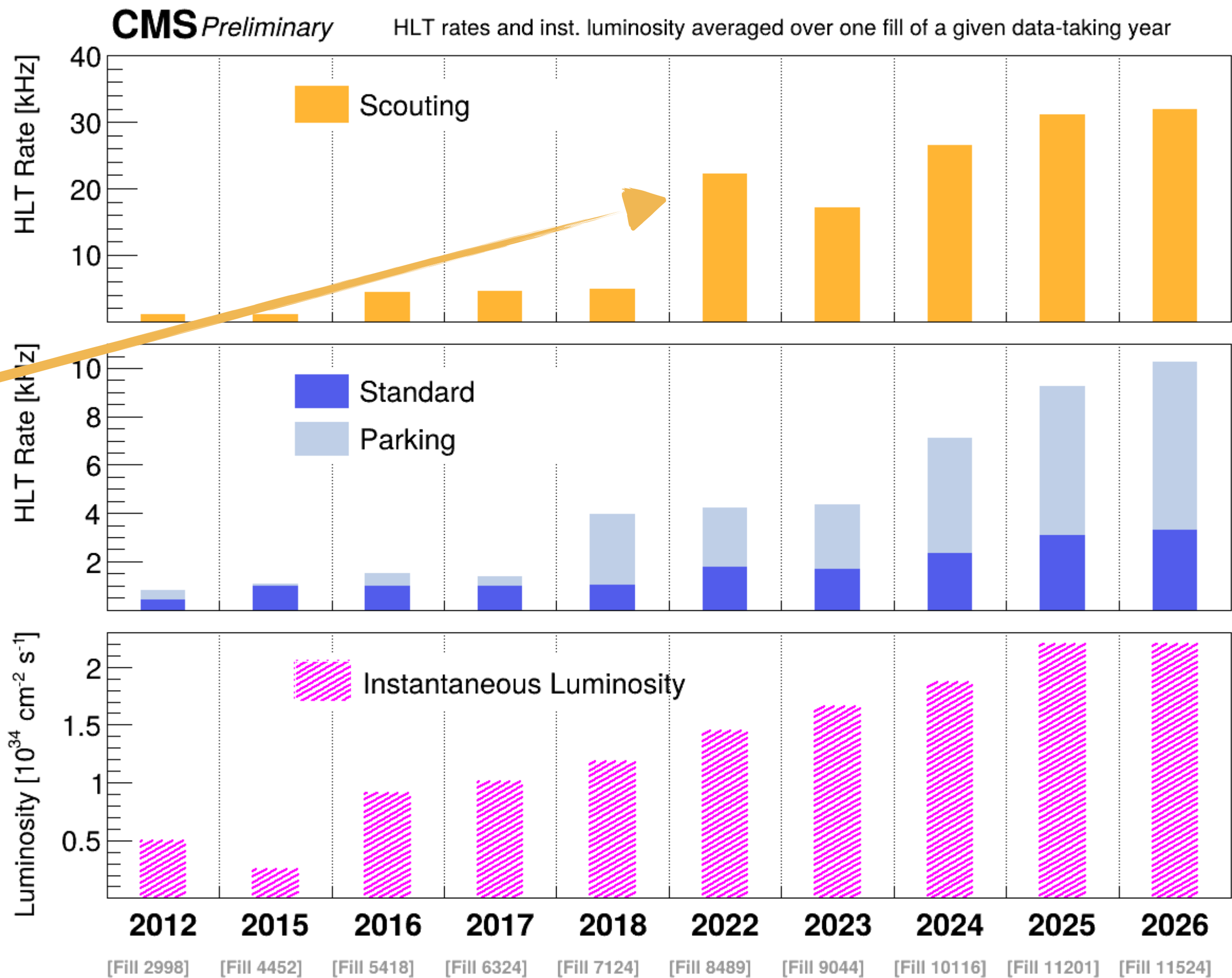
RUN 3 EXPANSION OF DATA SCOUTING: RATE

Approximately 30% of the L1 trigger rate is provided as input to the scouting stream!



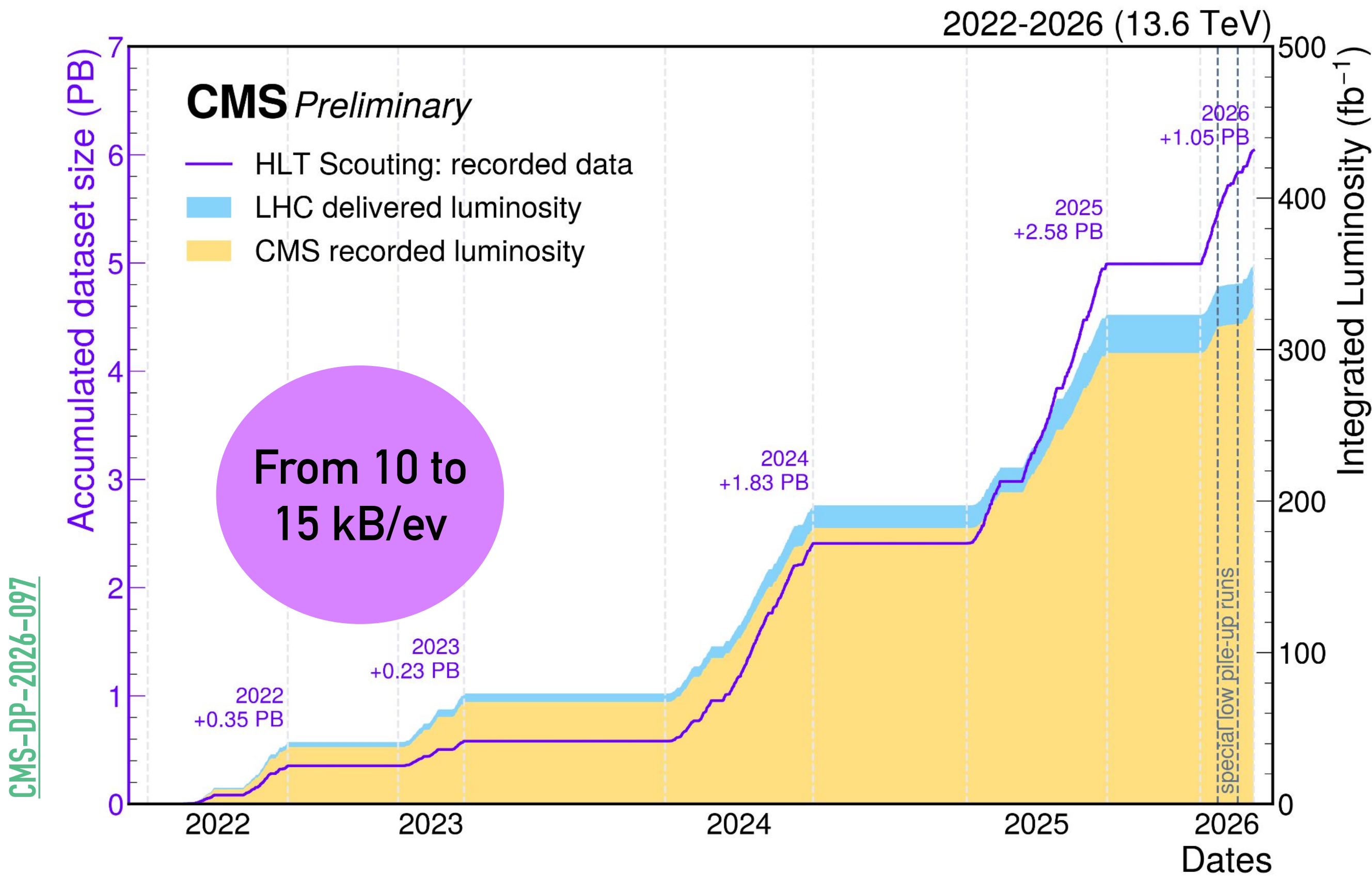
Total L1 input rate:
2022: ~34 kHz
2023: ~37 kHz

[i:physrep.2024.09.006](#)



CMS-DP-2026-023

RUN 3 EXPANSION OF DATA SCOUTING: EVENT CONTENT



Scouting obj	Selections
Muons	$p_T > 0$ (3) GeV
PF jets	$p_T > 20$ GeV; $ \eta < 5$ (3)
PF candidates	$p_T > 0.6$ GeV; $ \eta < 3$
Vertices	quality threshold
Tracks	$p_T > 1$ (3) GeV
e/γ	$p_T > 1$ GeV, $ \eta < 2.65$, $H/E < 0.2$; if no pixel match = γ
Calorimeter hits	ECAL: - / HBHE: energy > 1 GeV

e/γ

Tracks
down to 1 GeV

Calo
RecHits

PPS

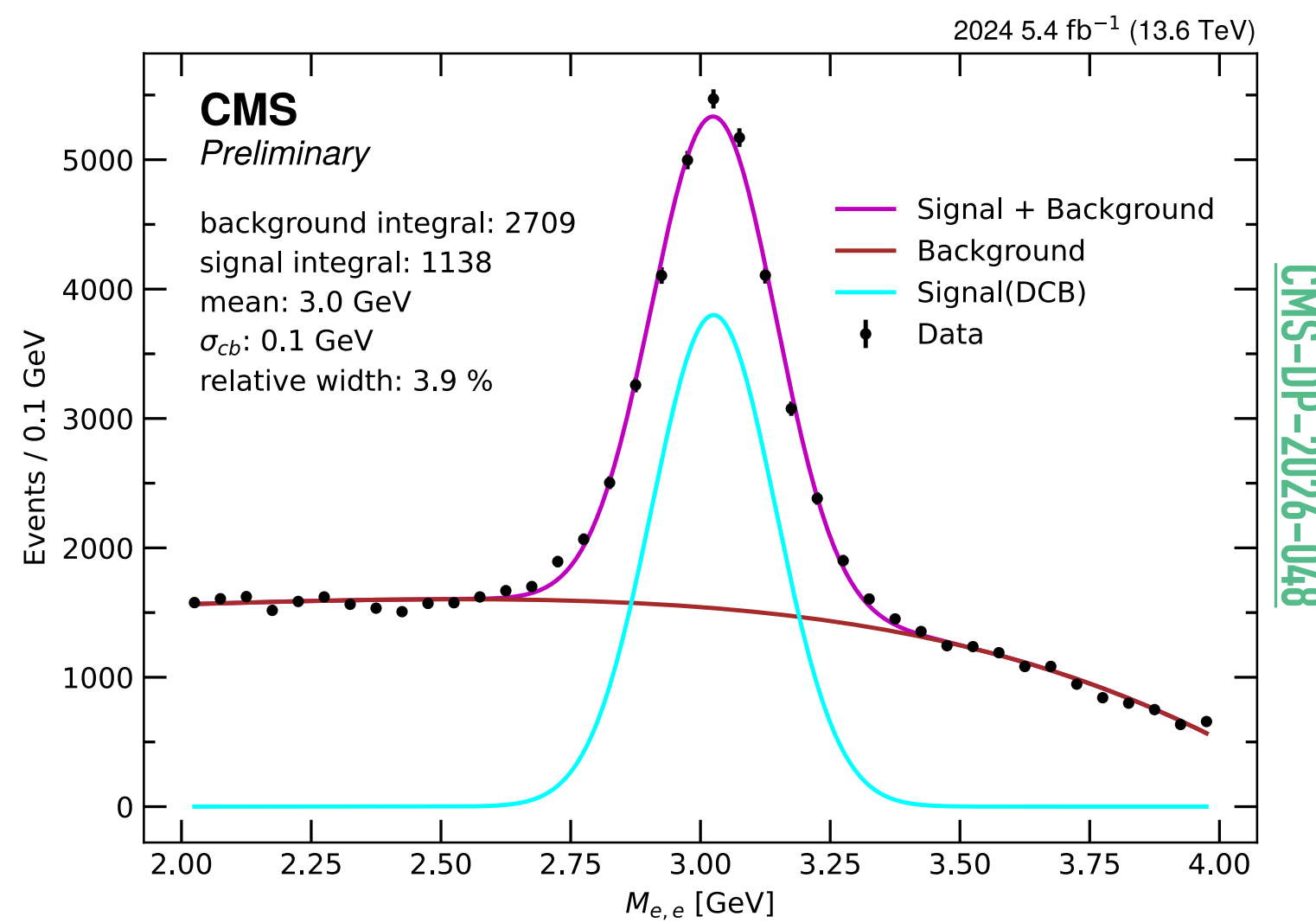
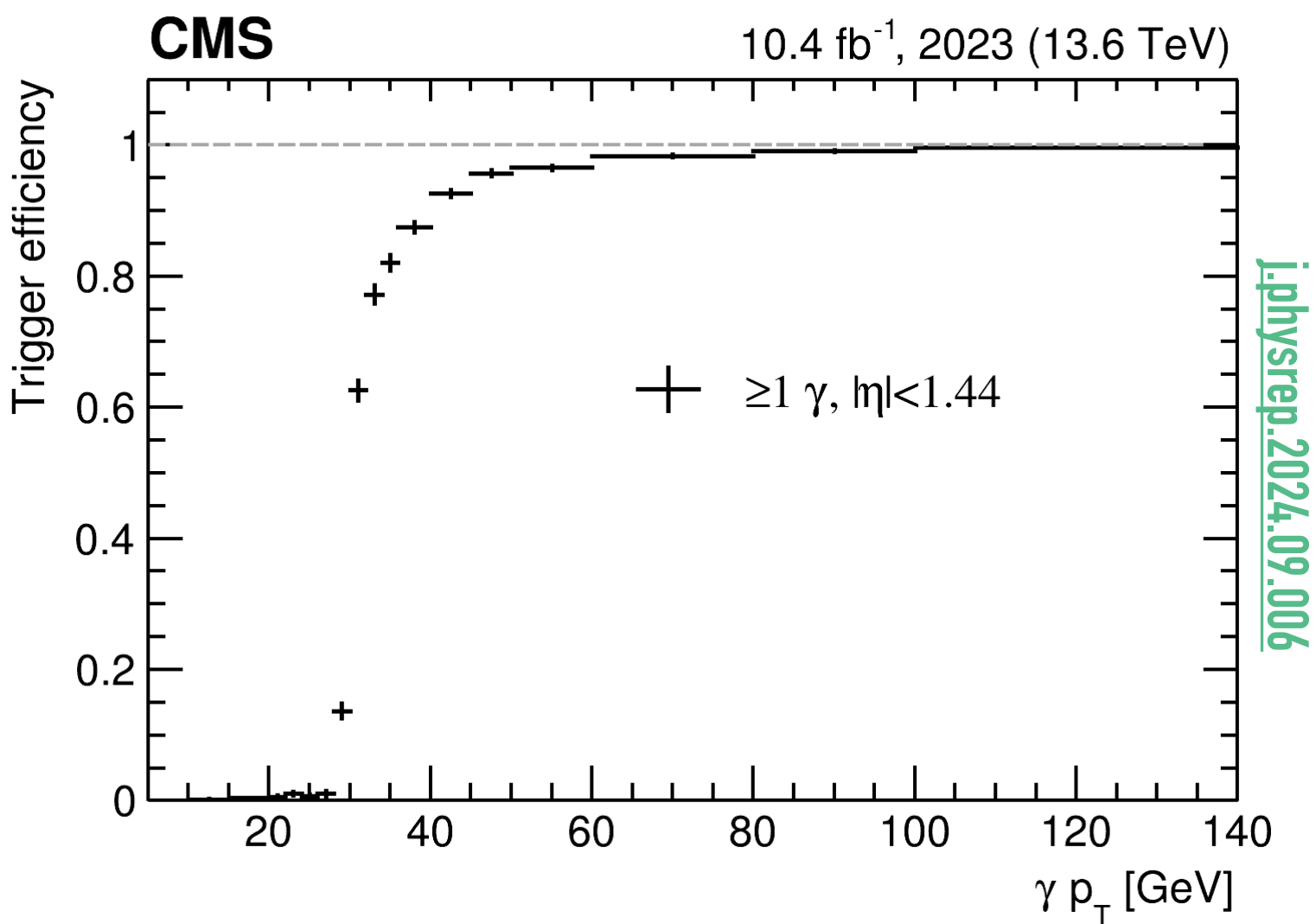
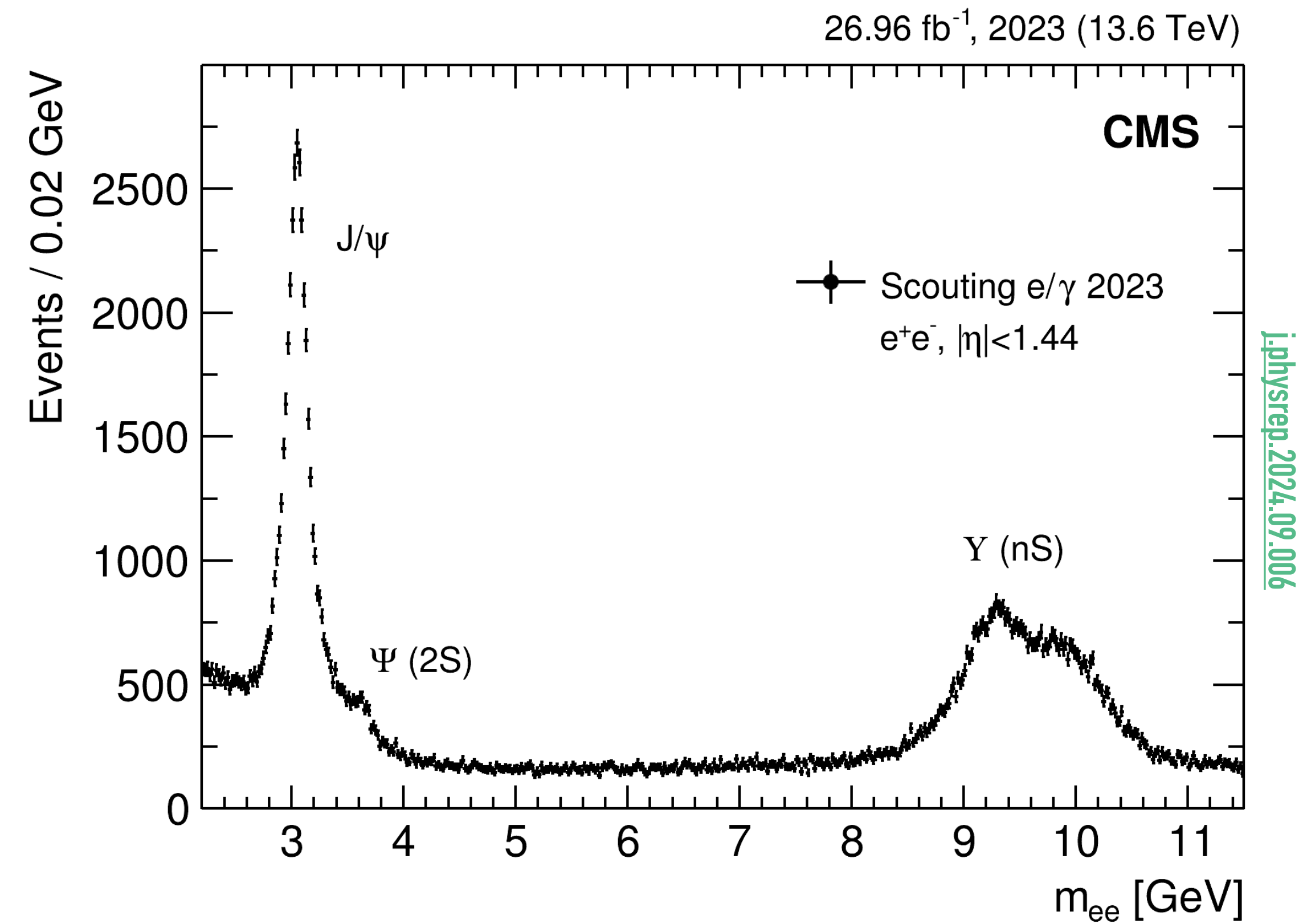
Tagging protons in the Precise Proton Spectrometer

Jets up to $|\eta| = 5$

Enabling the tagging of VBF topologies

RUN 3 HLT SCOUTING: ELECTRONS AND PHOTONS

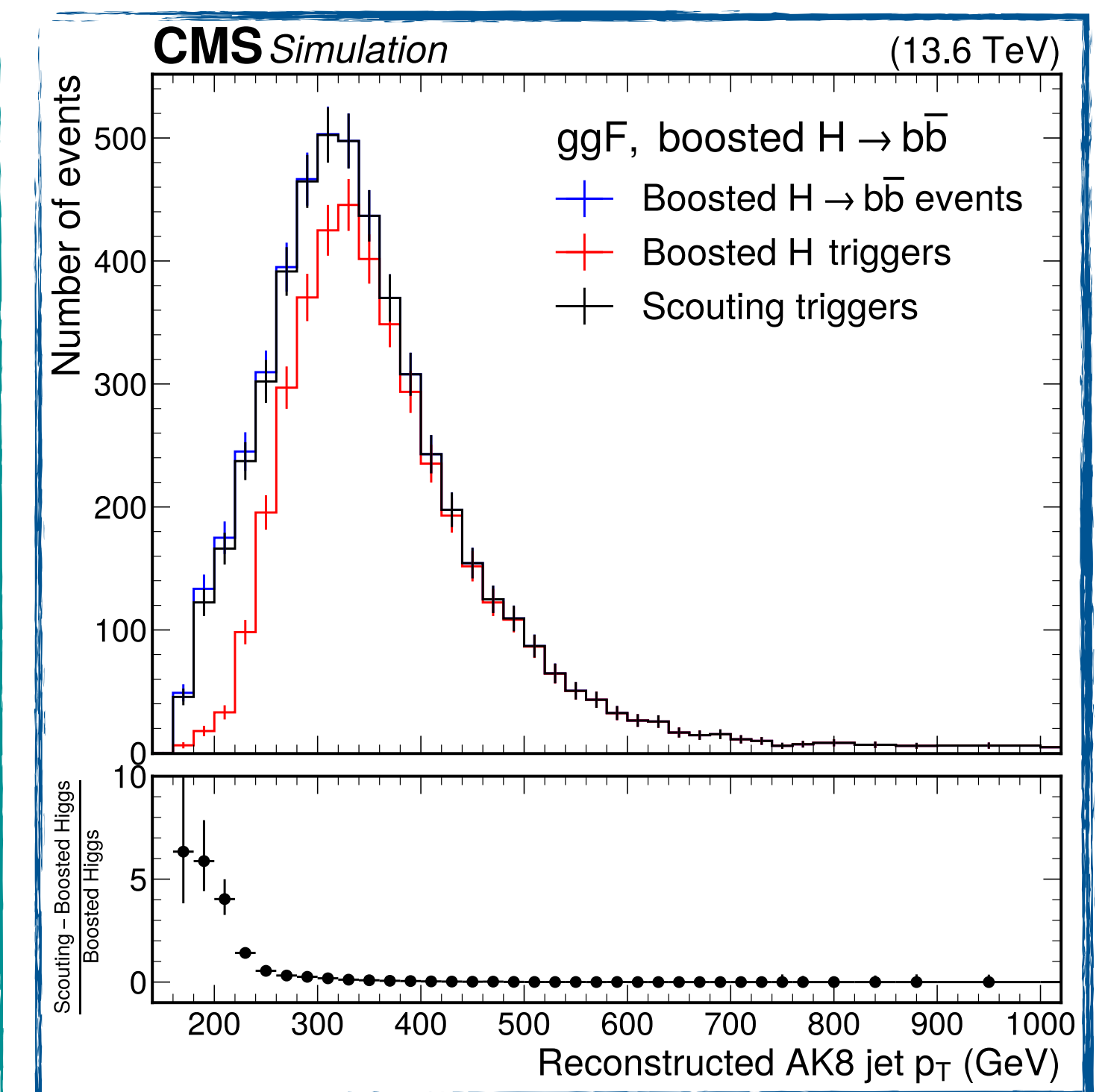
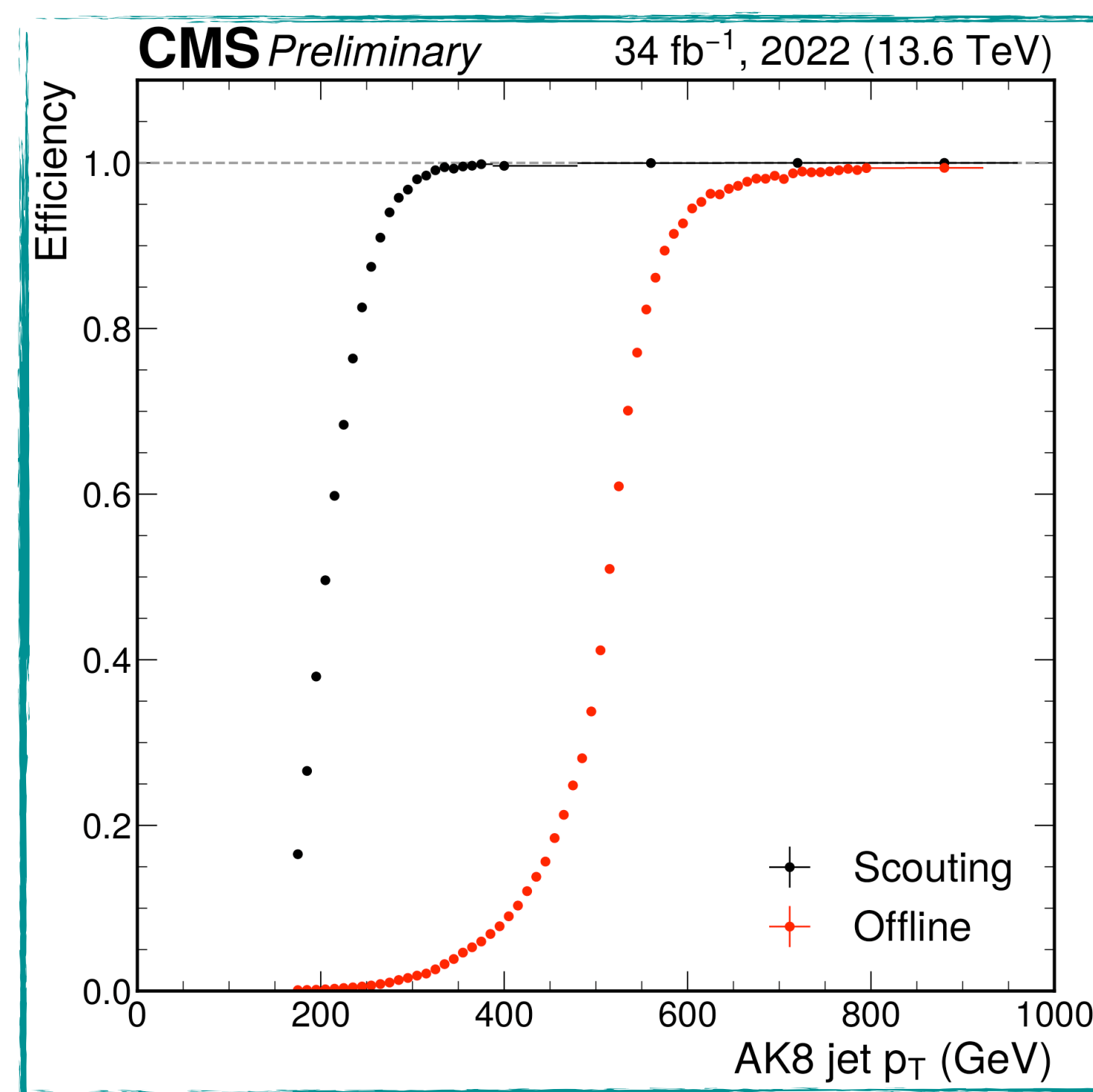
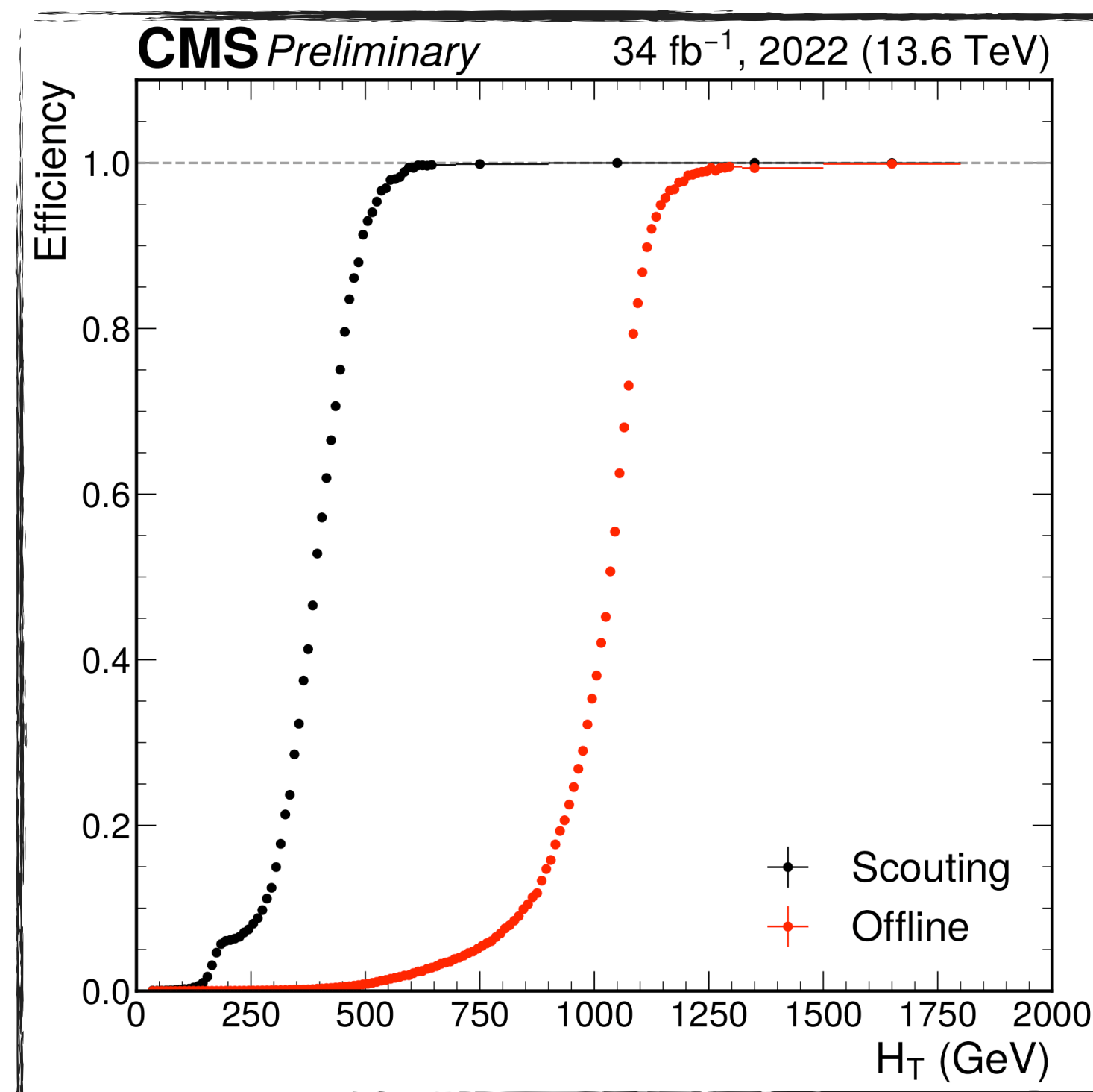
- ◆ Single photon triggers in scouting lowered the thresholds down to 30 GeV
 - ◆ NOTE: standard trigger thresholds on single photon are historically 200 GeV, later in Run 3 lowered to 40 GeV
- ◆ Dielectron pairs are collected at the GeV scale



RUN 3 HLT SCOUTING: JETS AND PF CANDIDATES

j.physrep.2024.09.006

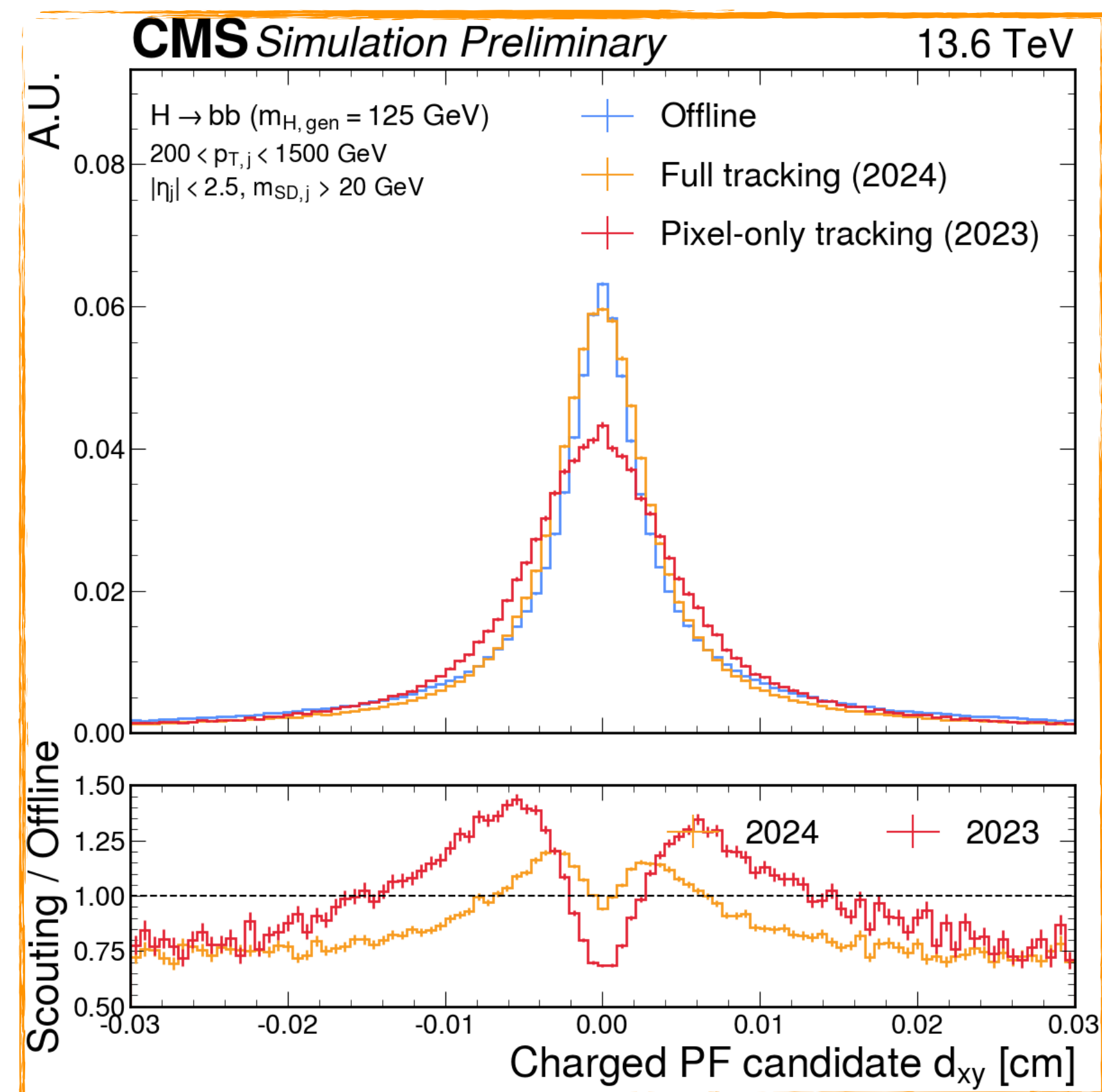
- ◆ Hadronic triggers in scouting notably **enlarge the accessible phase** space w.r.t. **standard triggers with offline thresholds**:
 - good jet scale and resolution with respect to offline reconstruction;
 - **boosted topologies** can be explored with scouting objects building large-radius jets from PF candidates!
 - Significant **increase (20%) in event selection efficiency** for boosted Higgs decaying to two b quarks, especially at low p_T



RUN 3 HLT SCOUTING: JETS AND PF CANDIDATES

CMS-DP-2026-105

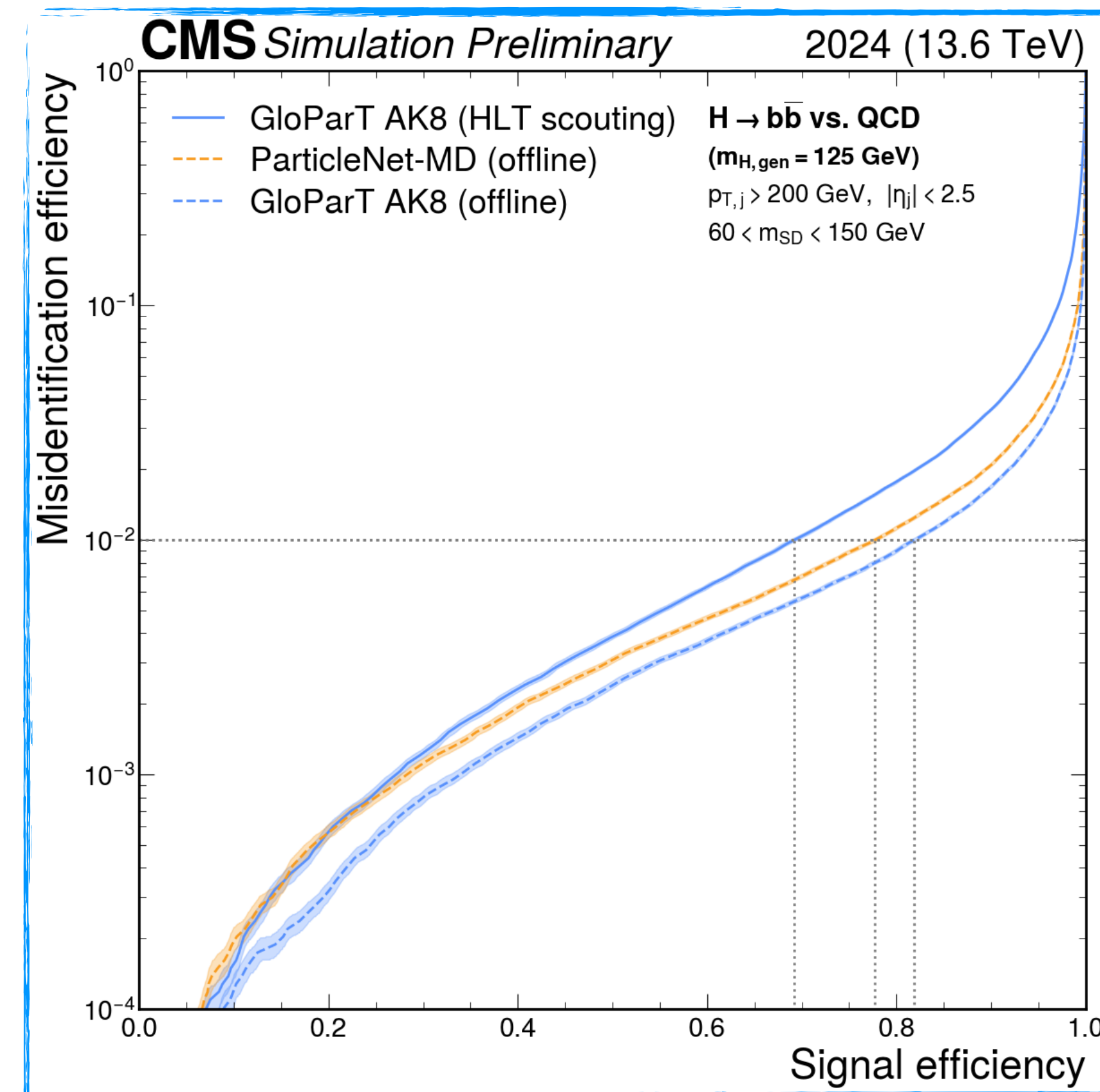
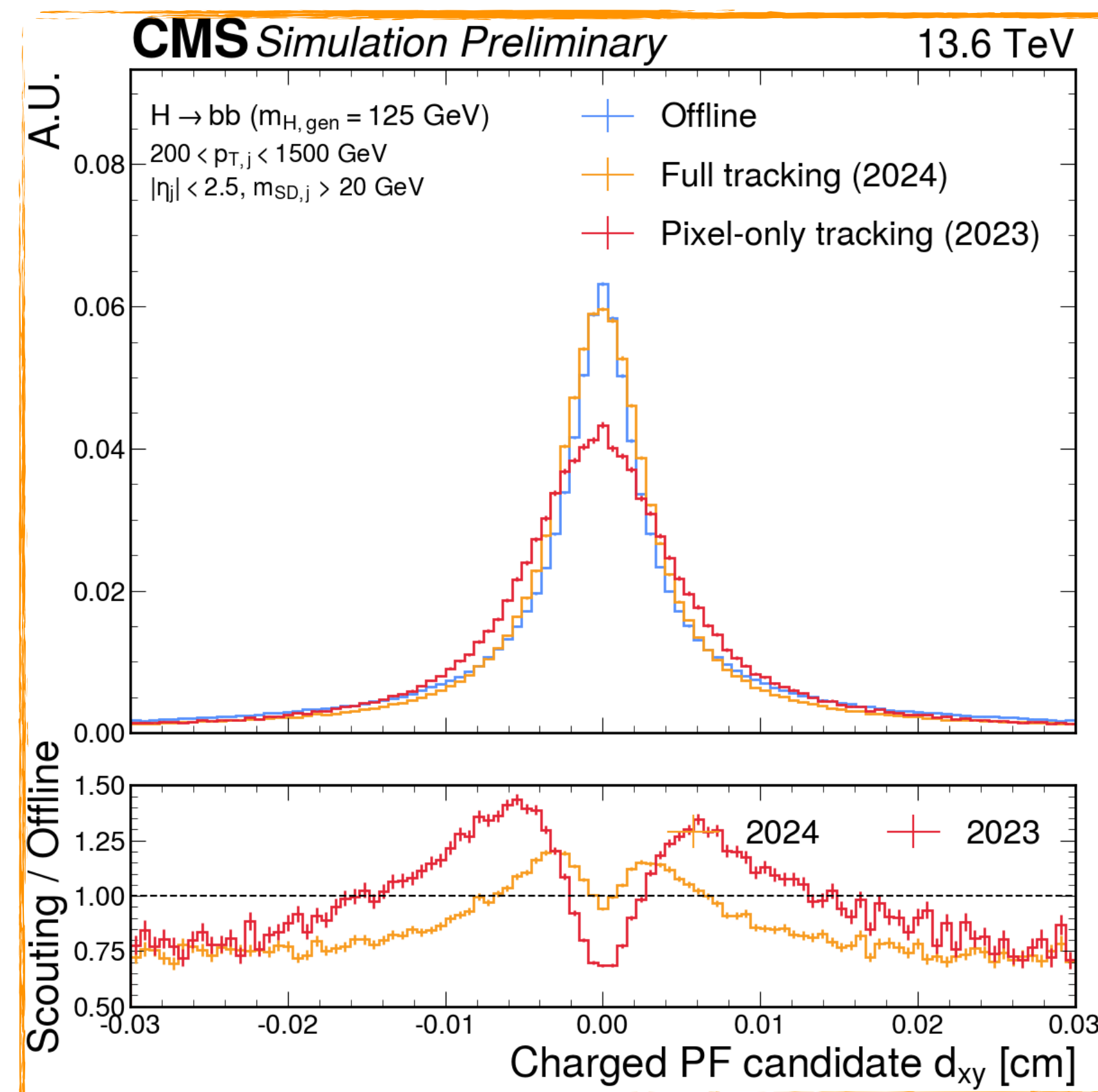
- ◆ Full HLT tracking (instead of pixel-only tracking) and standard PF reconstruction improve PF-object and jet resolutions



RUN 3 HLT SCOUTING: JETS AND PF CANDIDATES

CMS-DP-2026-105

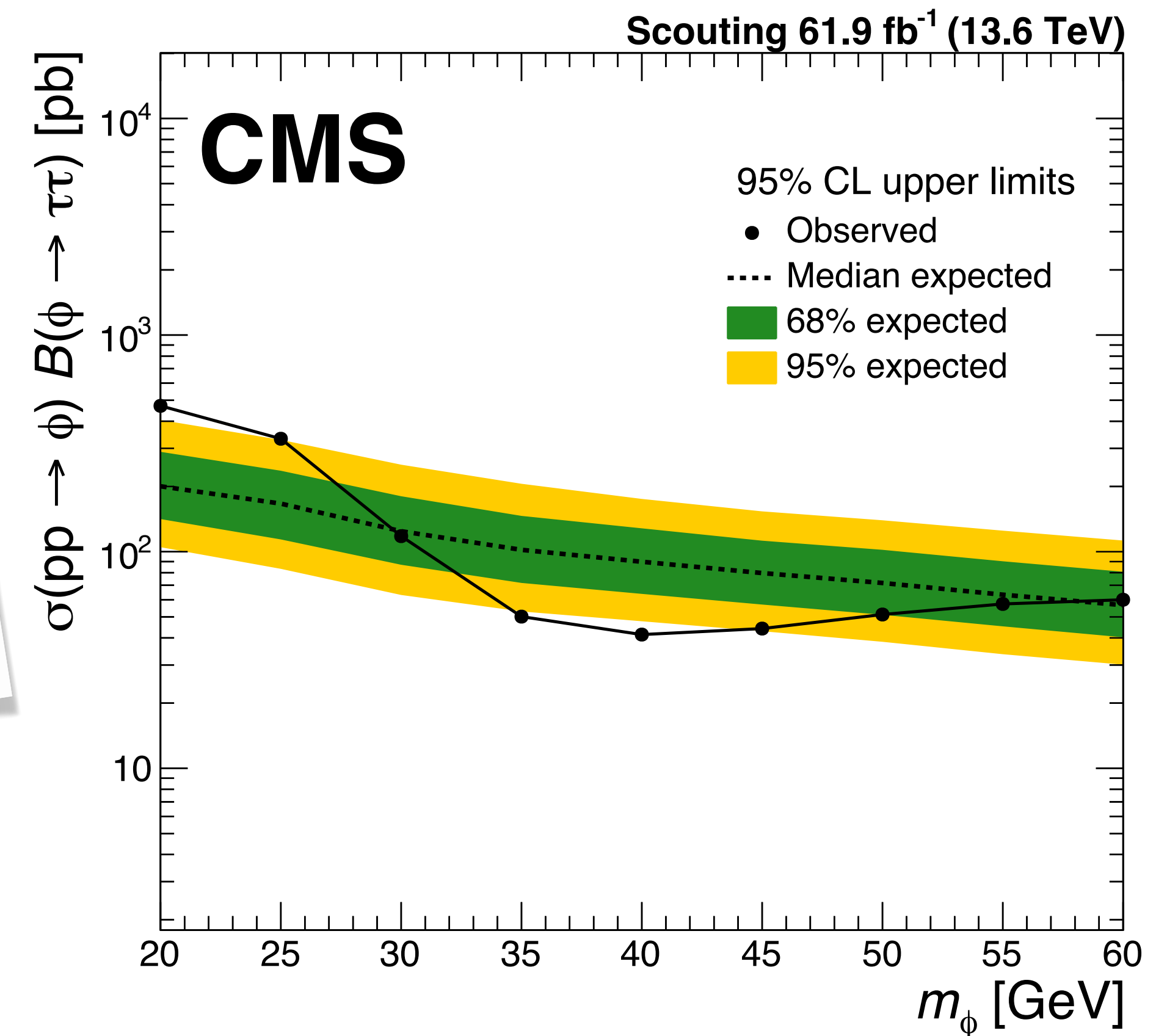
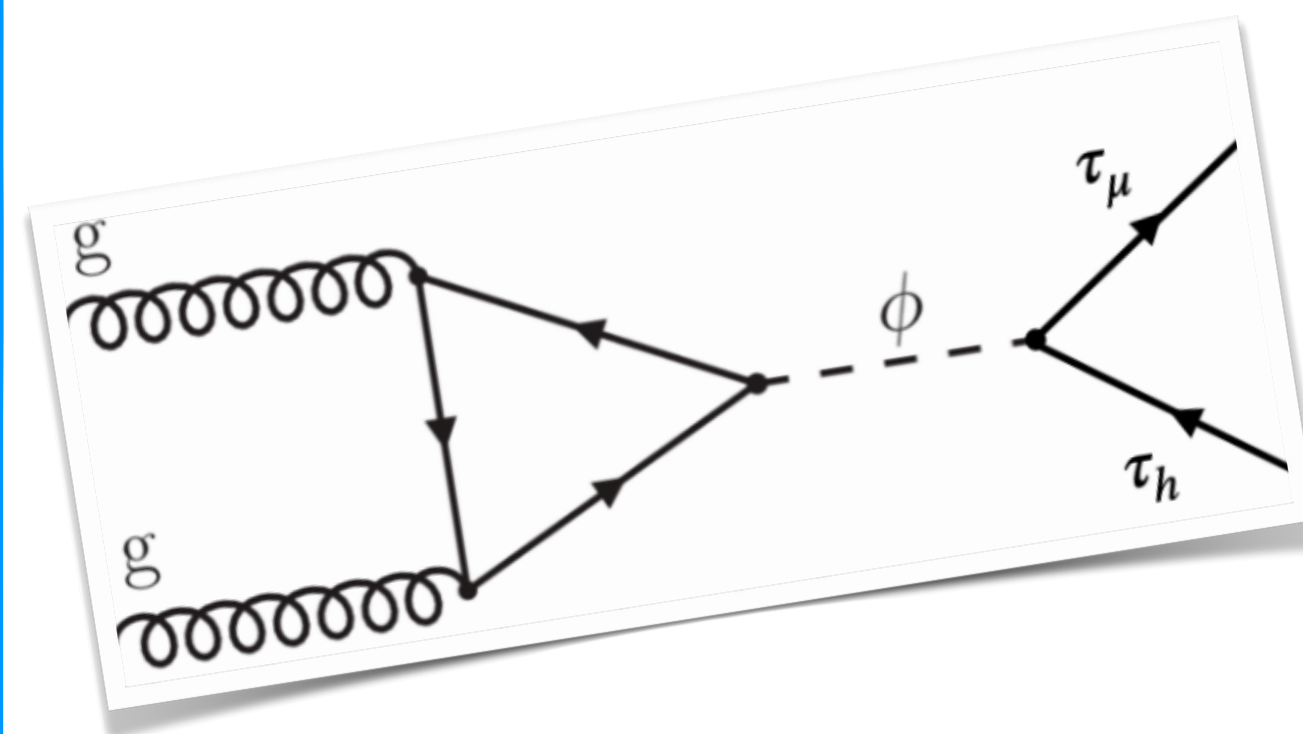
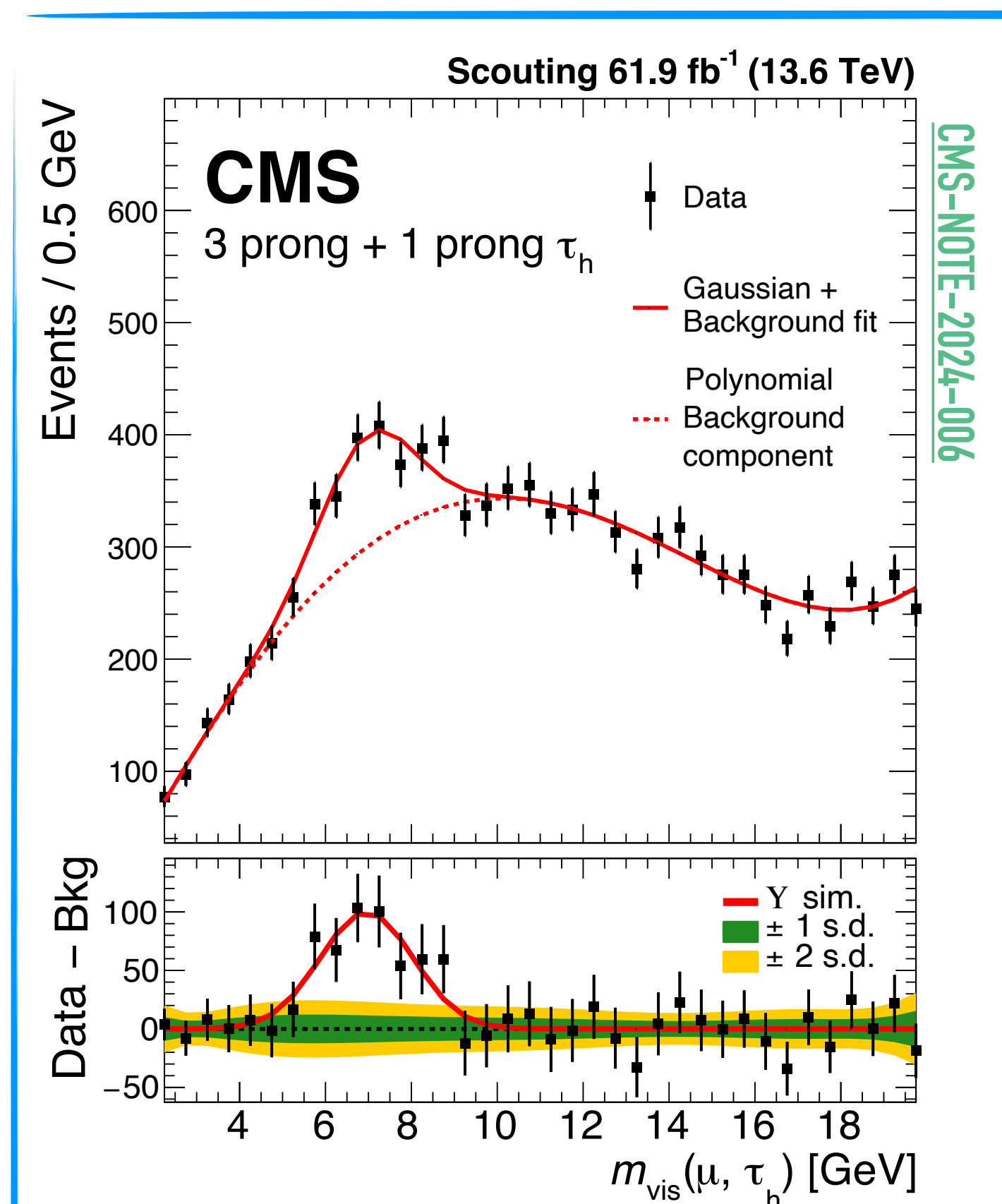
- ◆ Full HLT tracking (instead of pixel-only tracking) and standard PF reconstruction improve PF-object and jet resolutions
- ◆ A new chapter opening for dedicated scouting taggers based on PF candidates information!



DITAU RESONANCE SEARCHES AT LOW MASS

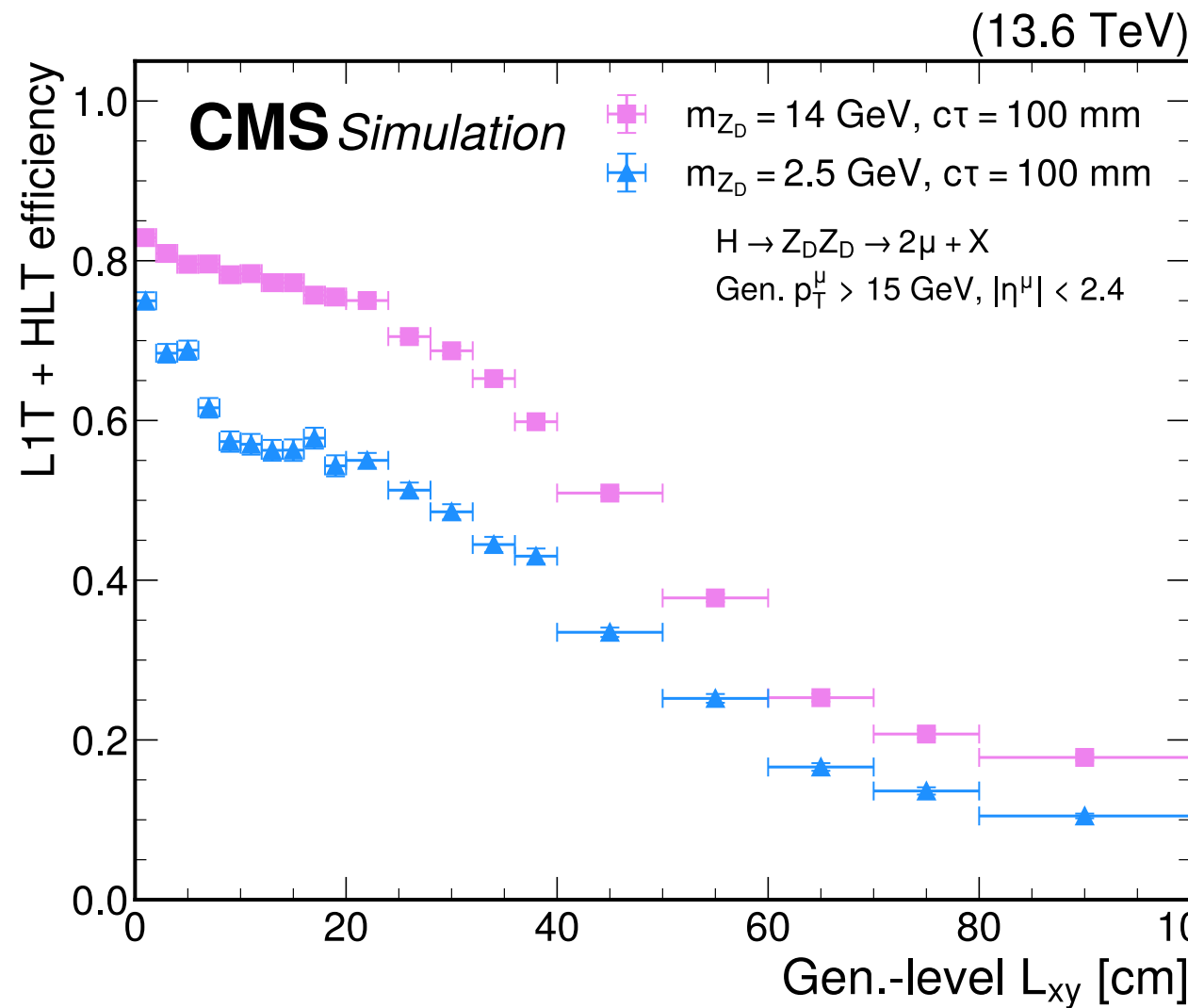
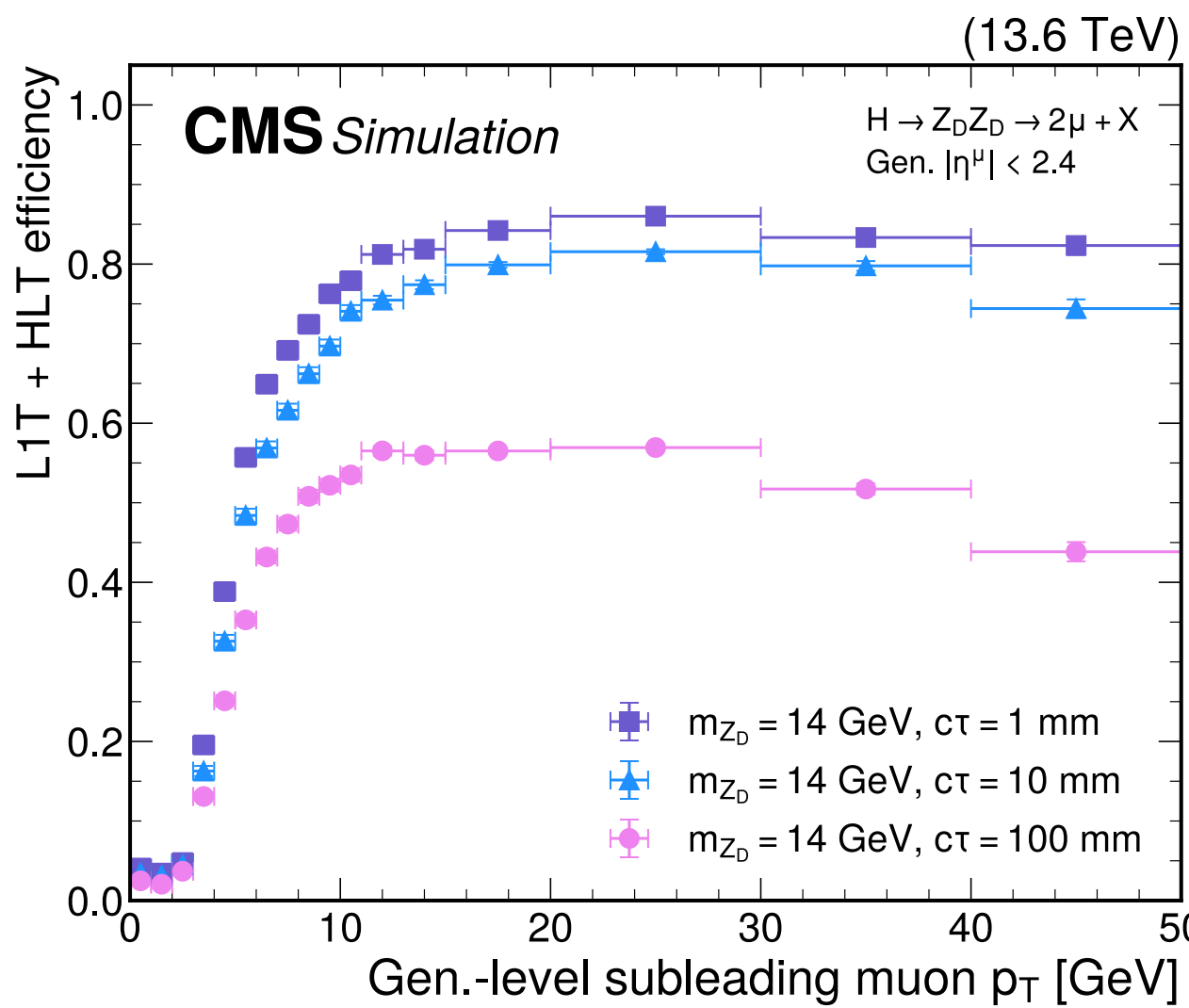
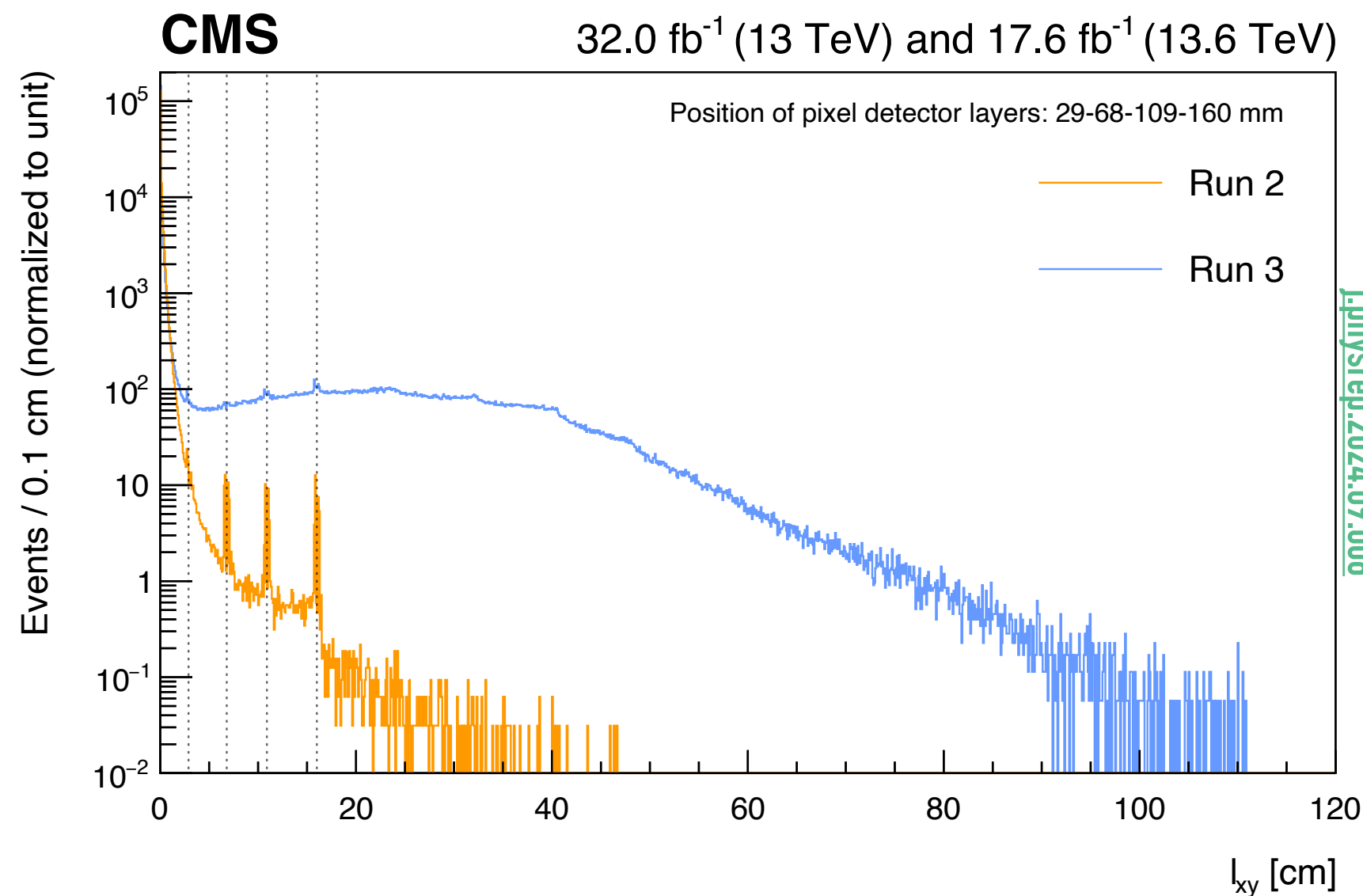
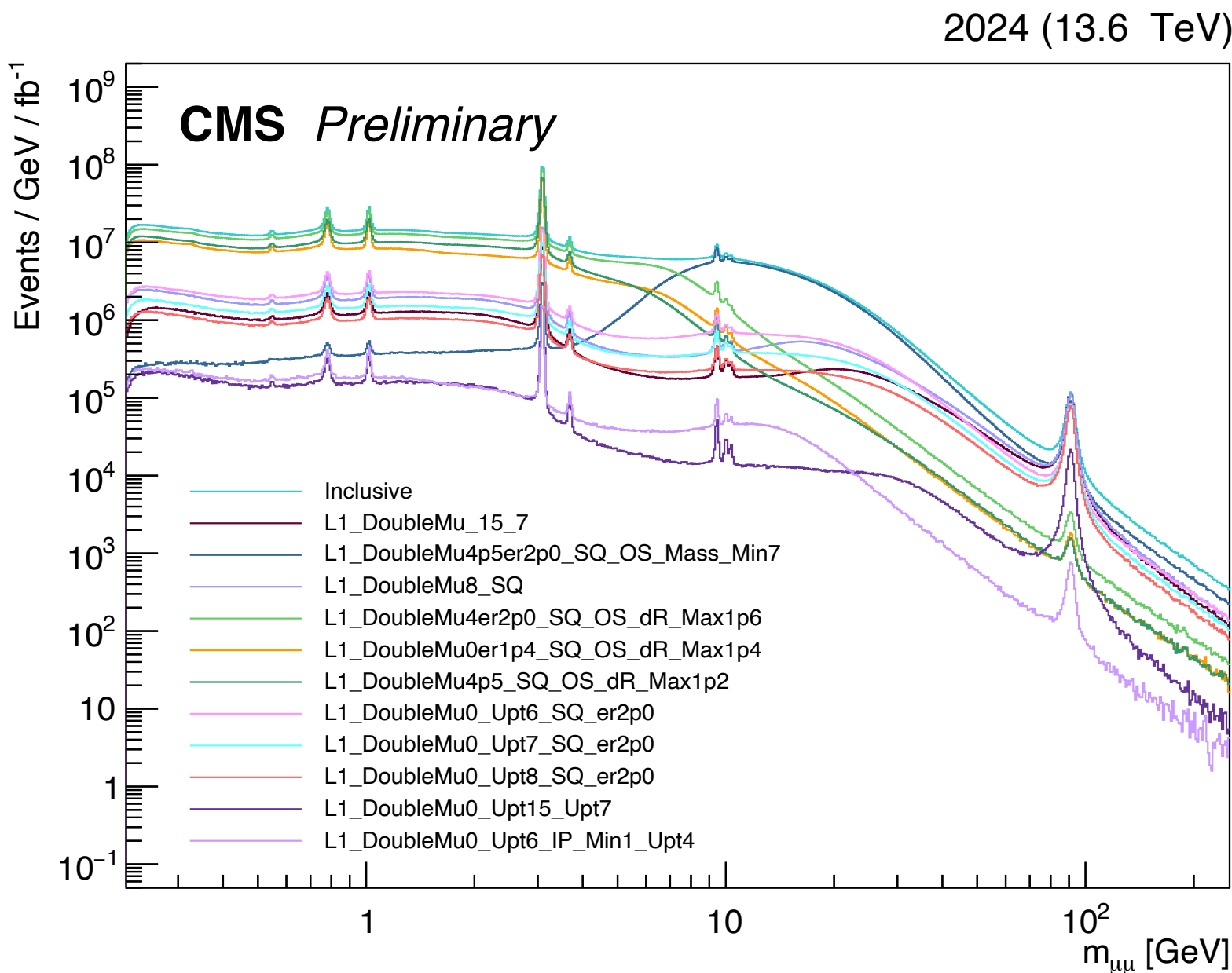
Submitted to Physical Review Letters

- ◆ Run 3 hadronic scouting stream successfully used for searches of low-mass ditau resonances using newly developed τ objects **post processing the scouting PF candidates**: dedicated τ reconstruction to improve efficiency at low p_T
 - First exploration of low mass (< 60 GeV) $\Phi \rightarrow \tau\tau$ with $\tau_\mu\tau_h$ final state



RUN 3 HLT SCOUTING: MUONS

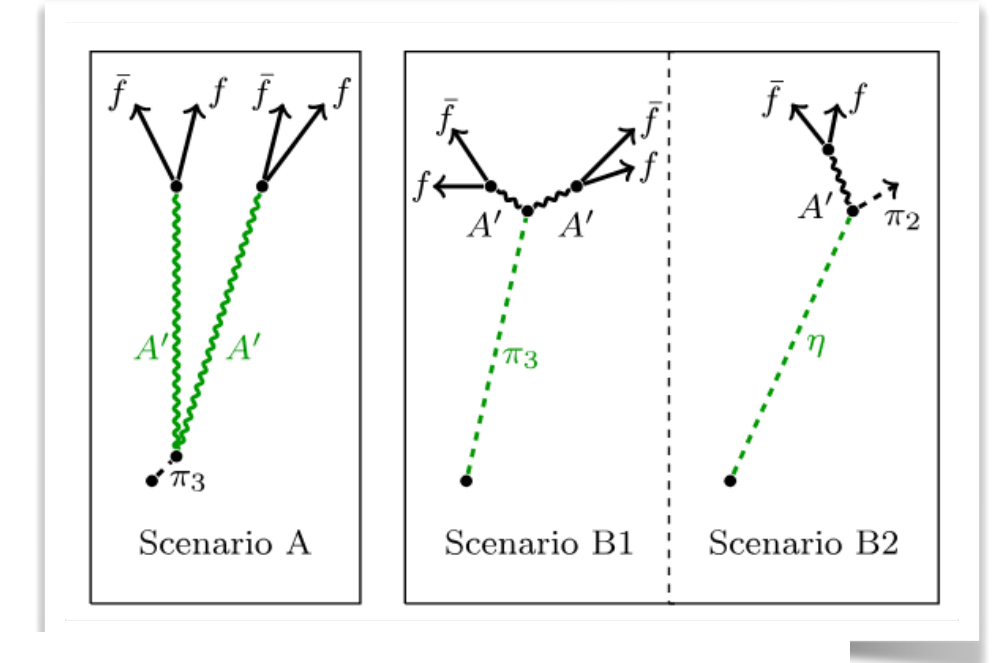
- ◆ Enlarged **scouting dimuon program** optimising it for displaced muon signatures
 - Dedicated algorithms @ L1T based on unconstrained p_T requirements **[early Run 3]**
 - Updated NoVtx reconstruction to enhance sensitivity above displacements of 11 cm **[early Run 3]**



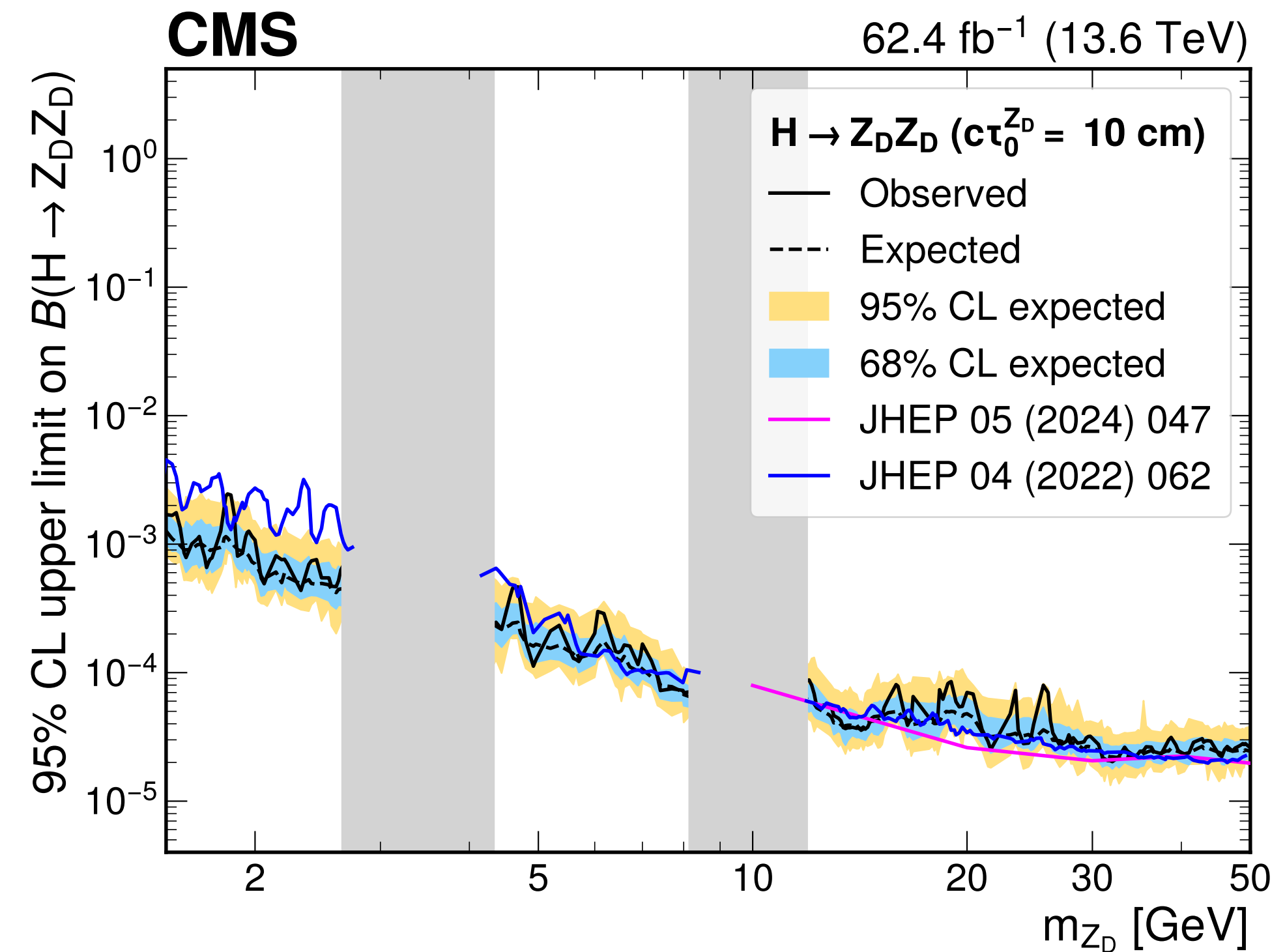
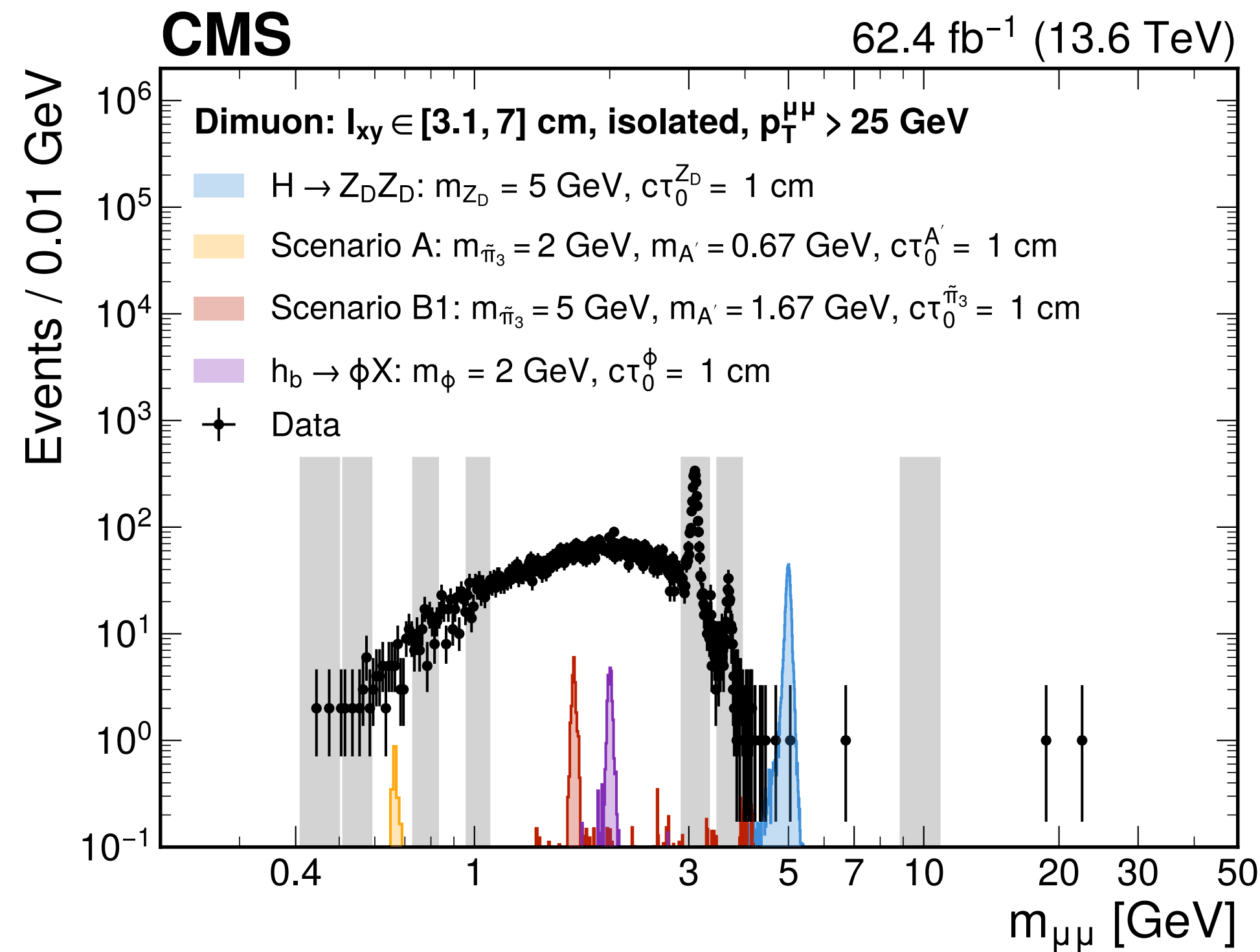
DISPLACED DIMUON RESONANCE SEARCHES AT LOW MASS

Accepted for publication in the
Journal of High Energy Physics

- Enhanced searches for displaced dimuon resonances at low mass ($m_{Z_D} < 10$ GeV) with Run 3 scouting:
 - Looking for LLP decaying into μ pairs ($m_{LLP} > 2m_\mu$) with single or multiple secondary vertices
 - Target minimal dark photon and dark shower models with long-lived dark photons

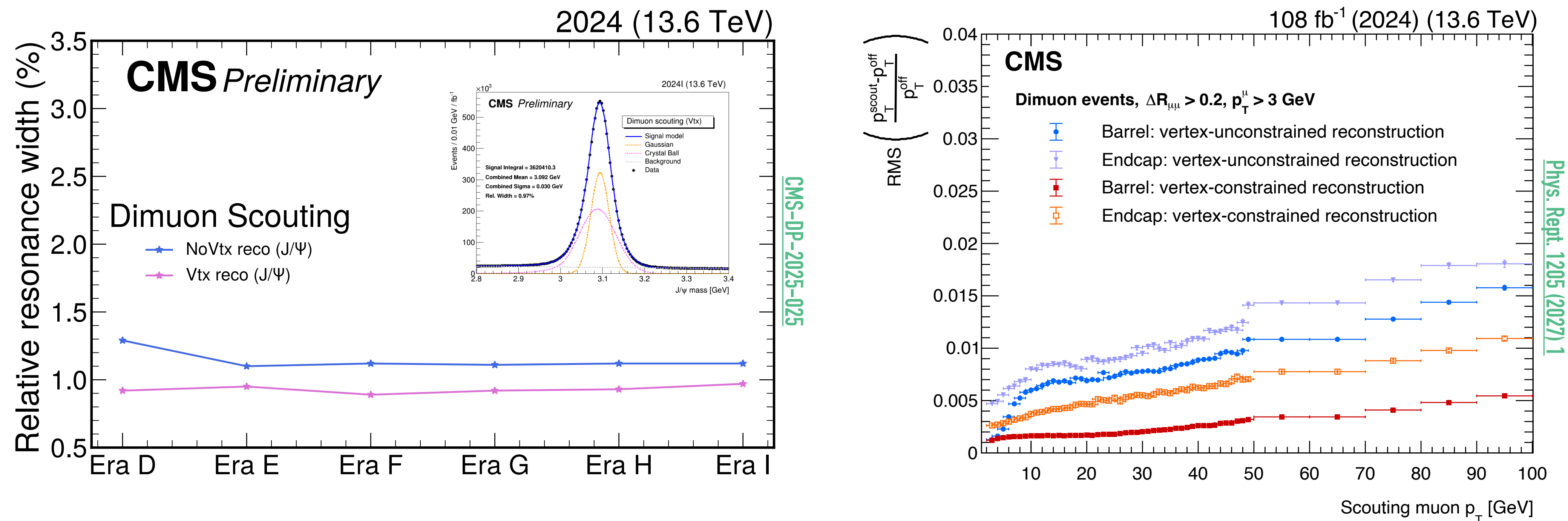


PhysRevD.108.035034



RUN 3 HLT SCOUTING: MUONS

- ◆ **Single-muon**: complementary strategy in scouting and parking to collect high purity muons at L1T → novelty of 2024
 - About 10 kHz of heavy flavour decays with muon $p_T > 11$ GeV (barrel-only) at the lumi-levelling, down to 5 GeV during the lumi-decay
 - Added the standard Vtx reconstruction (= offline-like vertex-constrained reconstruction) in scouting to complement the NoVtx reconstruction

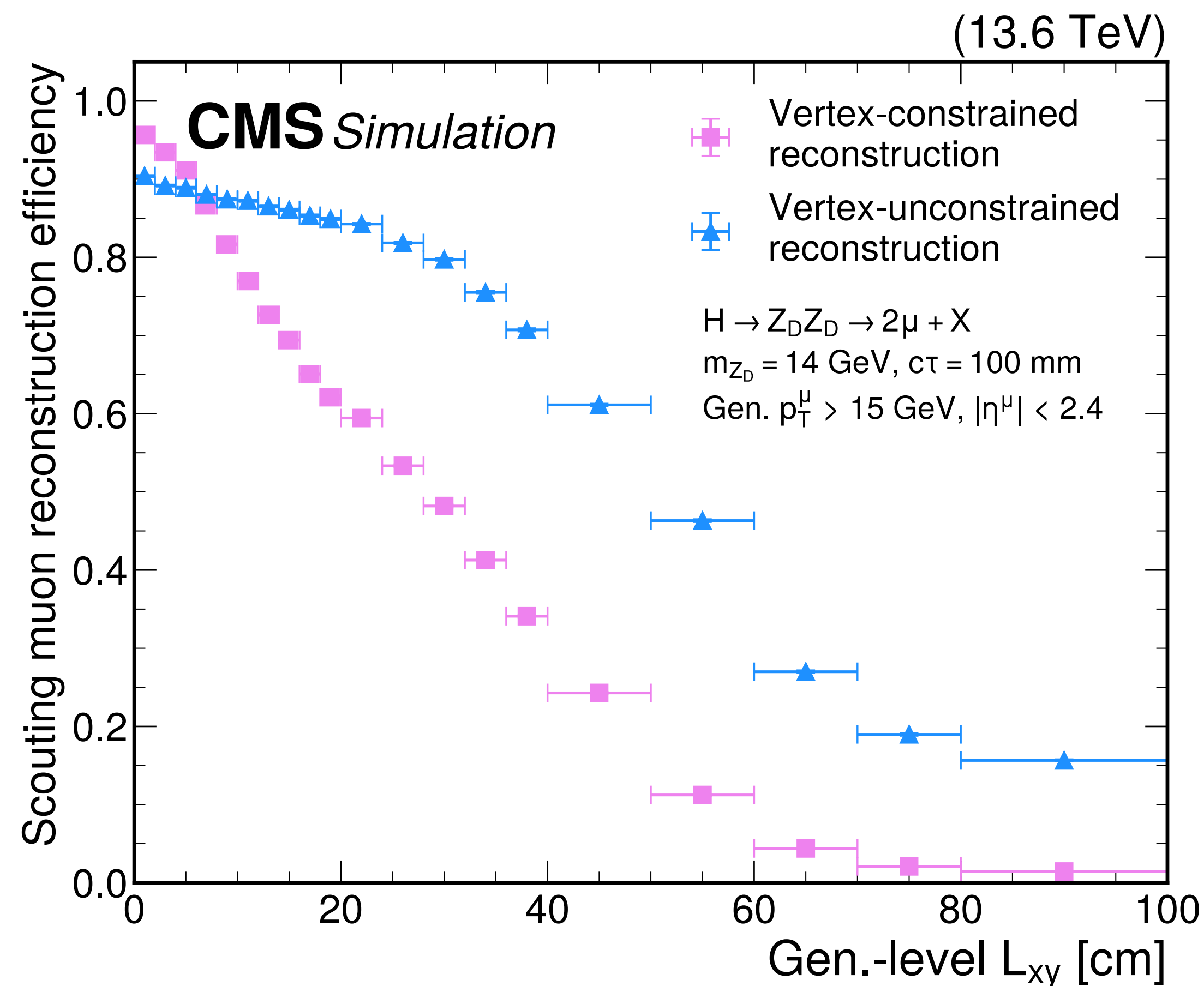
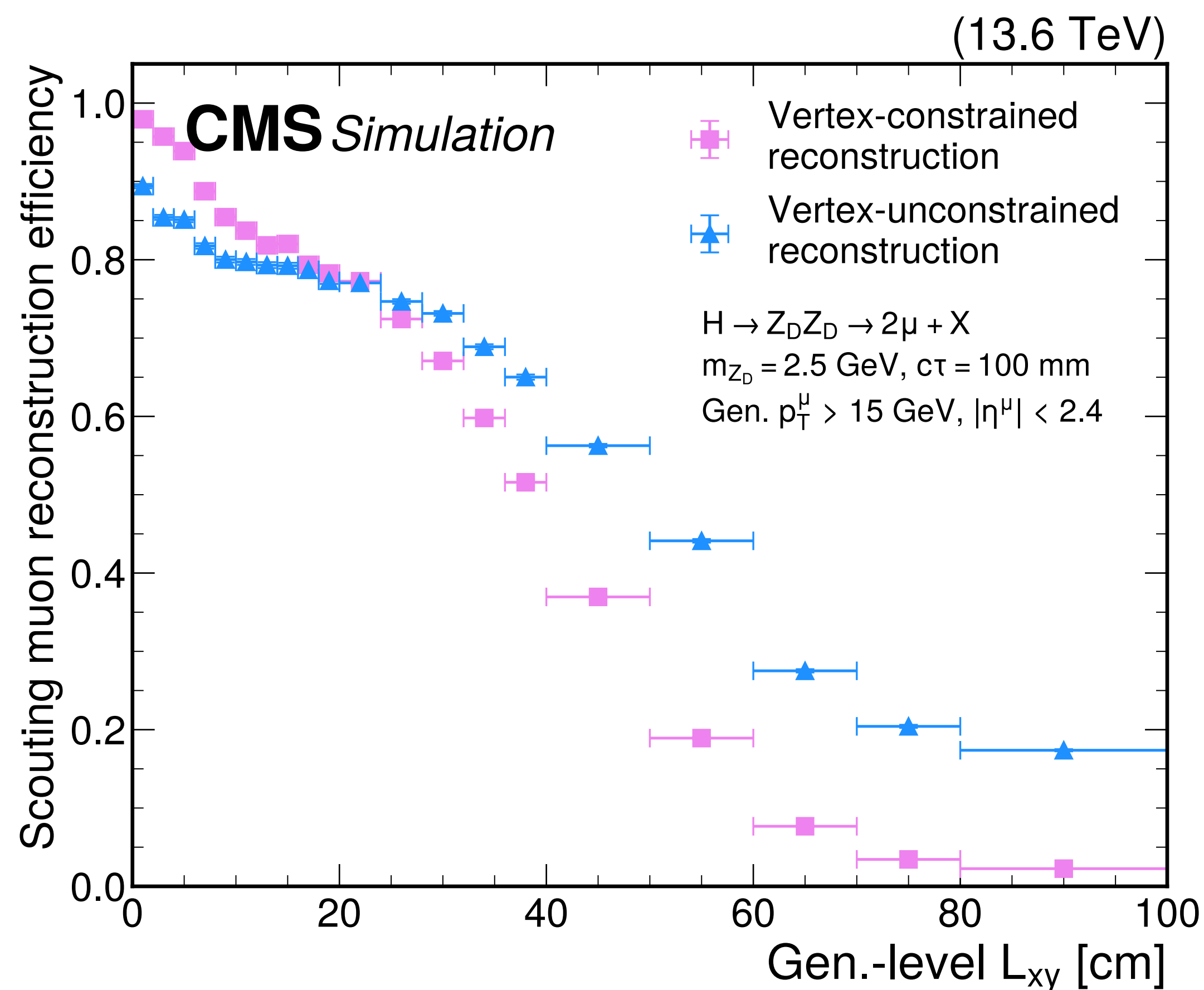


Resolution effects due to the online reconstruction are found to be between 1-2% for both the mass spectrum and the transverse momentum in all eta regions

RUN 3 HLT SCOUTING: MUONS

Phys. Rept. 1205 (2027) 1

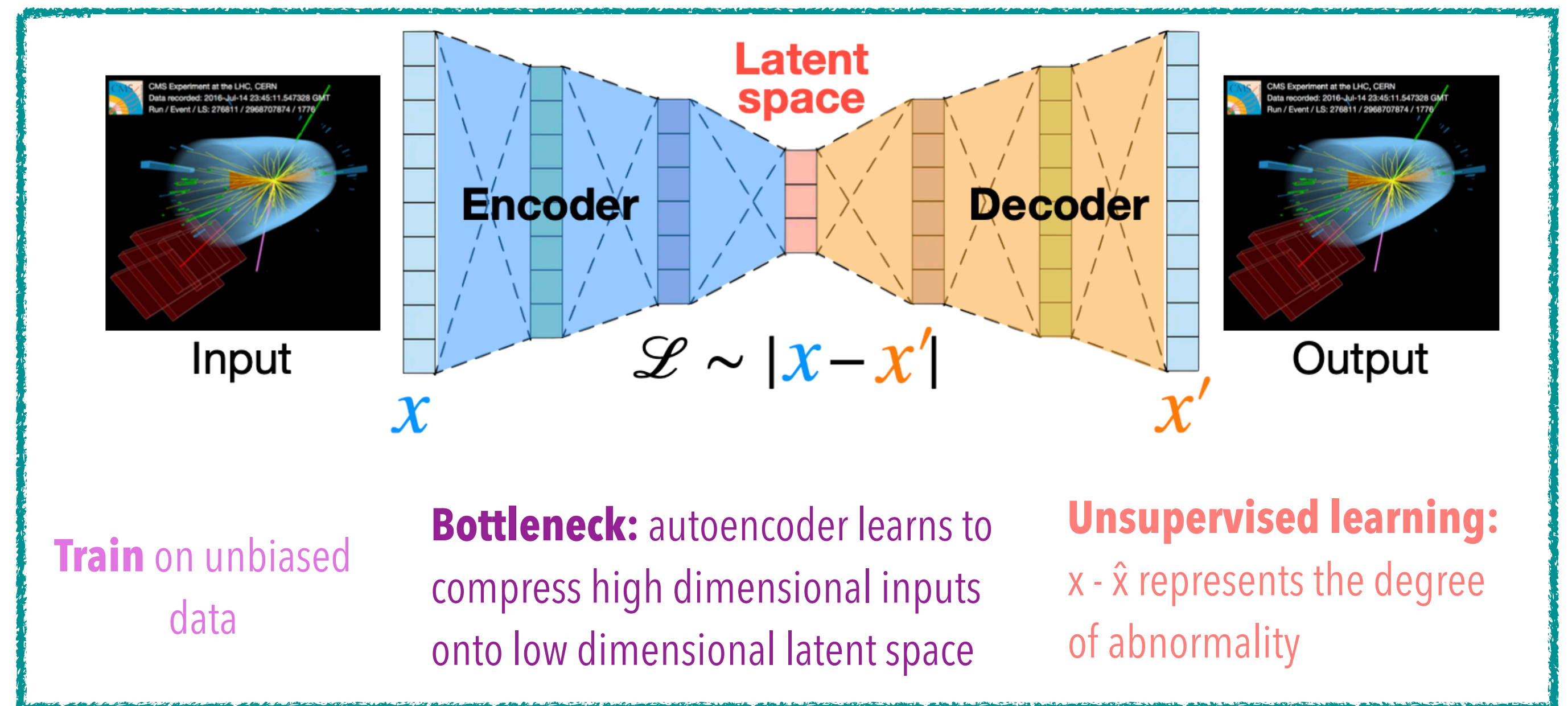
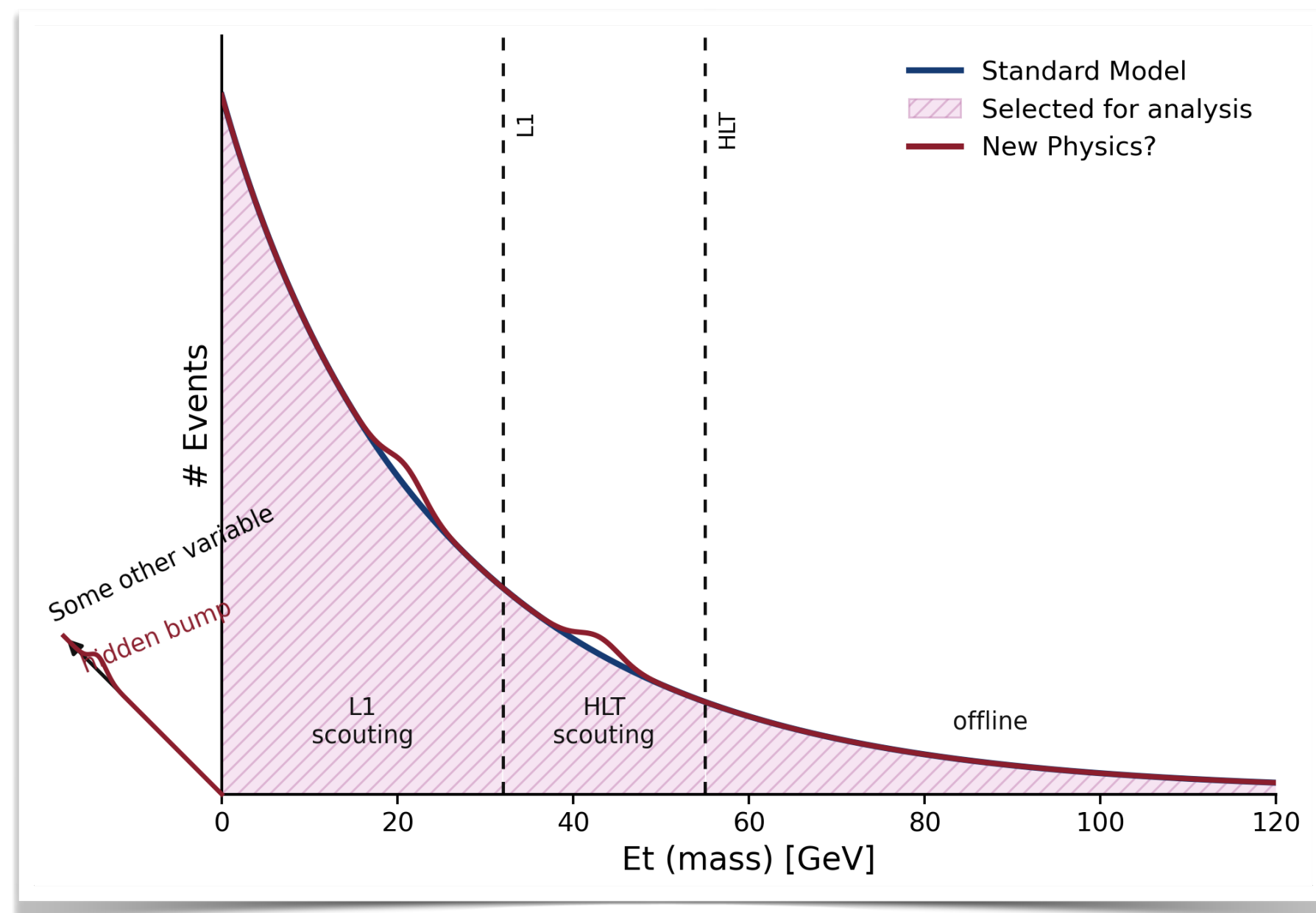
- ◆ Exploiting complementarity of Vtx and NoVtx reconstruction for maximal sensitivity at all displacements [end of Run 3]



RUN 3 HLT SCOUTING: ANOMALY DETECTION WITH AUTOENCODERS @ L1

What if new physics doesn't look as expected, and it's instead buried under the bulk of the background events we are throwing away due to the trigger selections?

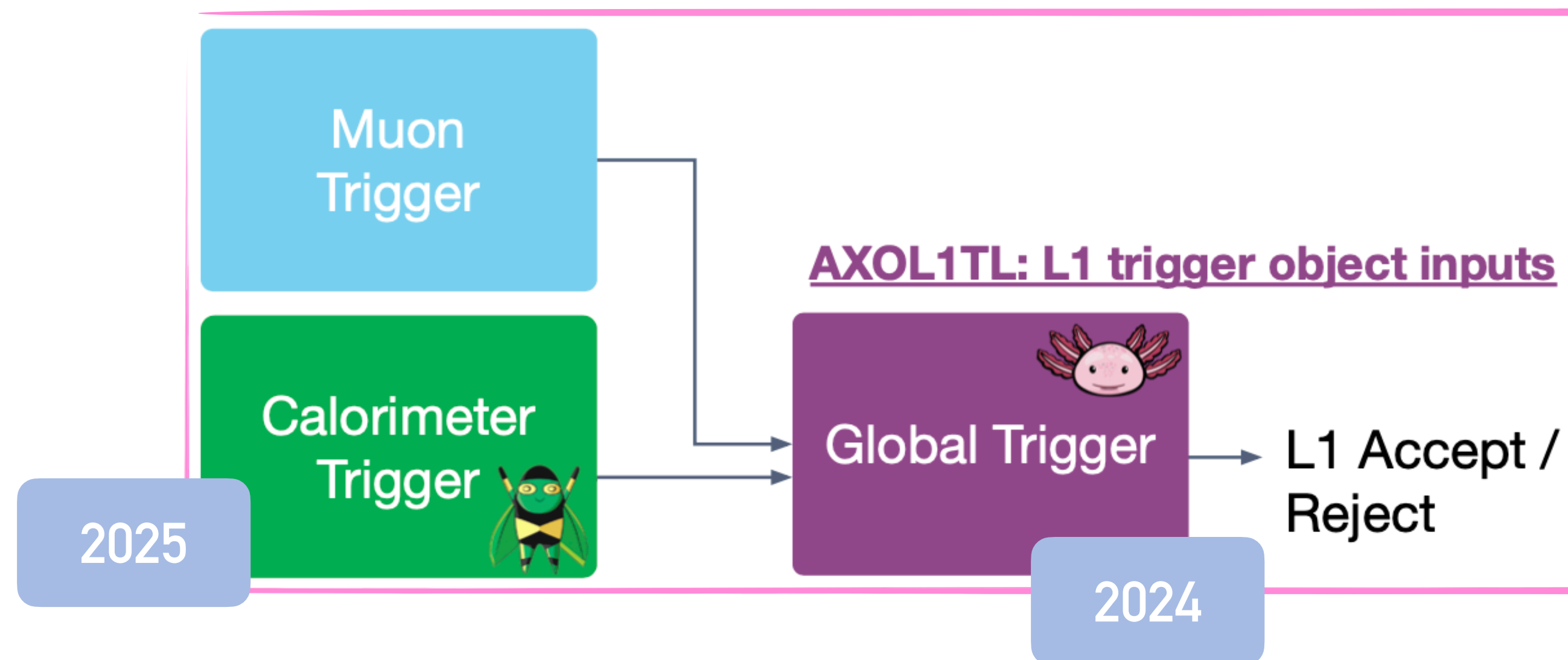
→ Another way: trigger on "anomalous" events using **ML unsupervised models** (sub- μ s autoencoders!):



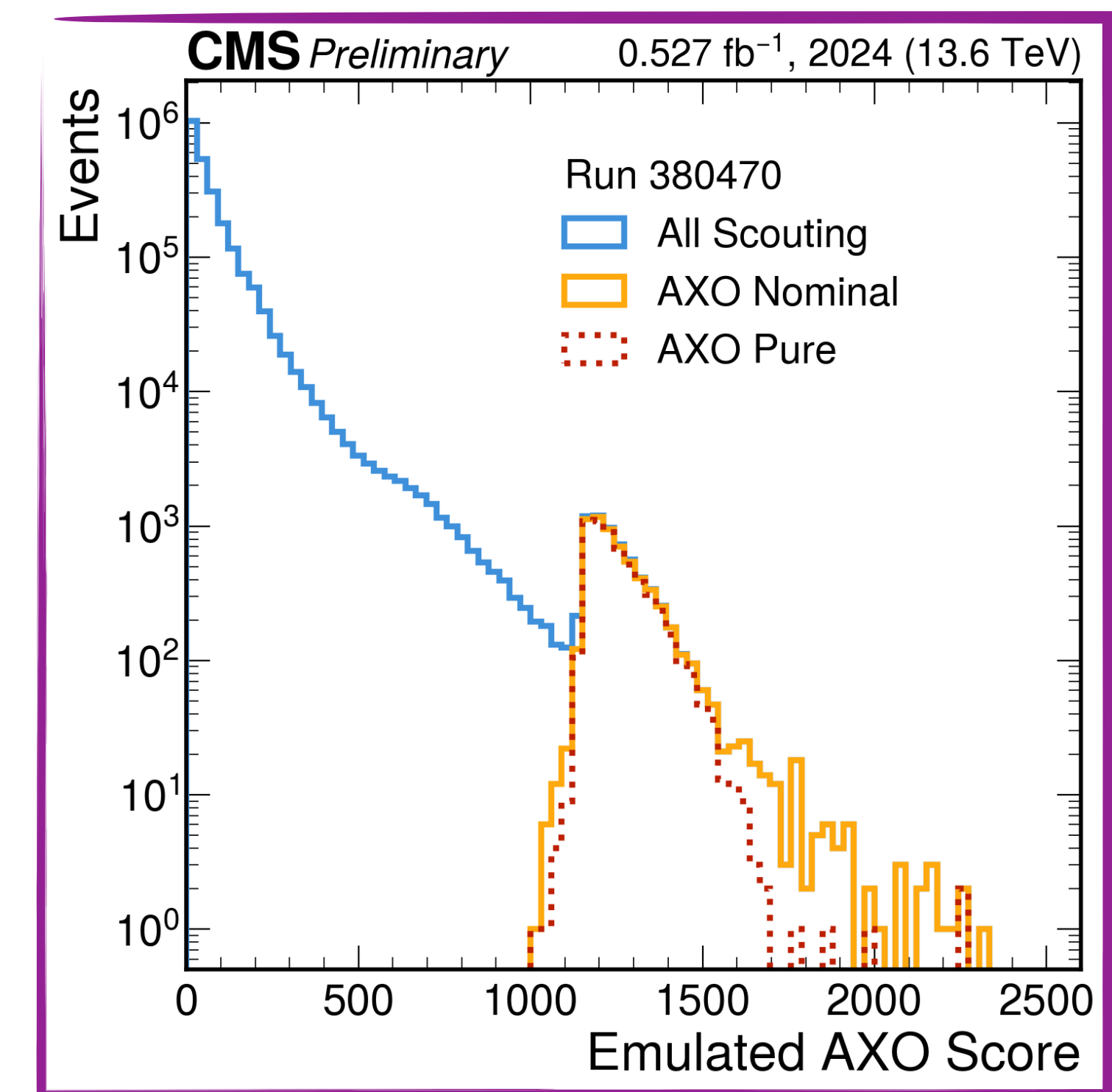
RUN 3 HLT SCOUTING: ANOMALY DETECTION WITH AUTOENCODERS @ L1

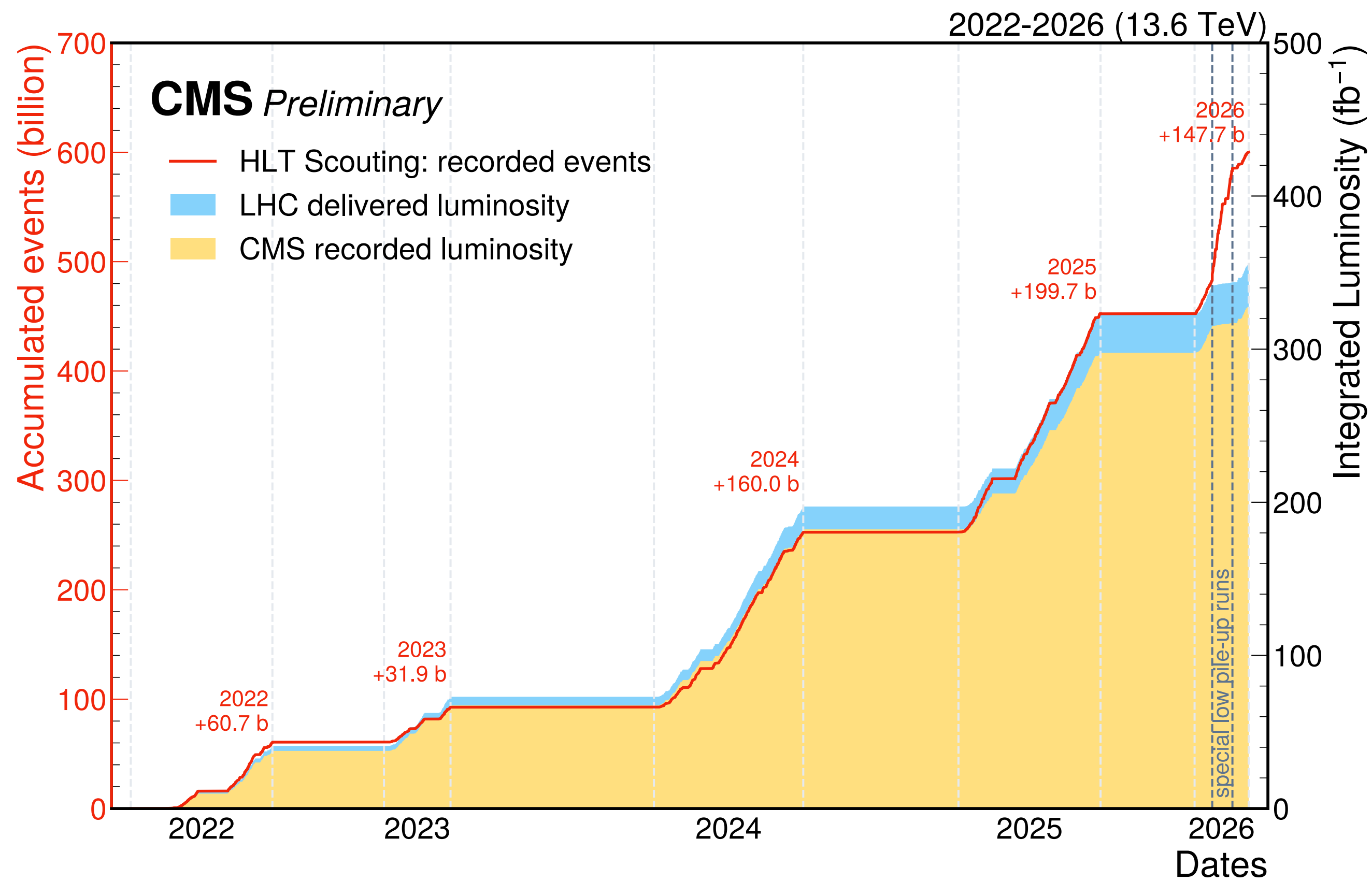
What if new physics doesn't look as expected, and it's instead buried under the bulk of the background events we are throwing away due to the trigger selections?

→ Another way: trigger on "anomalous" events using [ML unsupervised models](#) (sub- μ s autoencoders!):
implemented in FPGAs in the L1 trigger system and commissioned online throughout the last years of data-taking!



Complementary anomaly detection algorithms:
low-level (calo images) + high-level (L1T reco objects) inputs



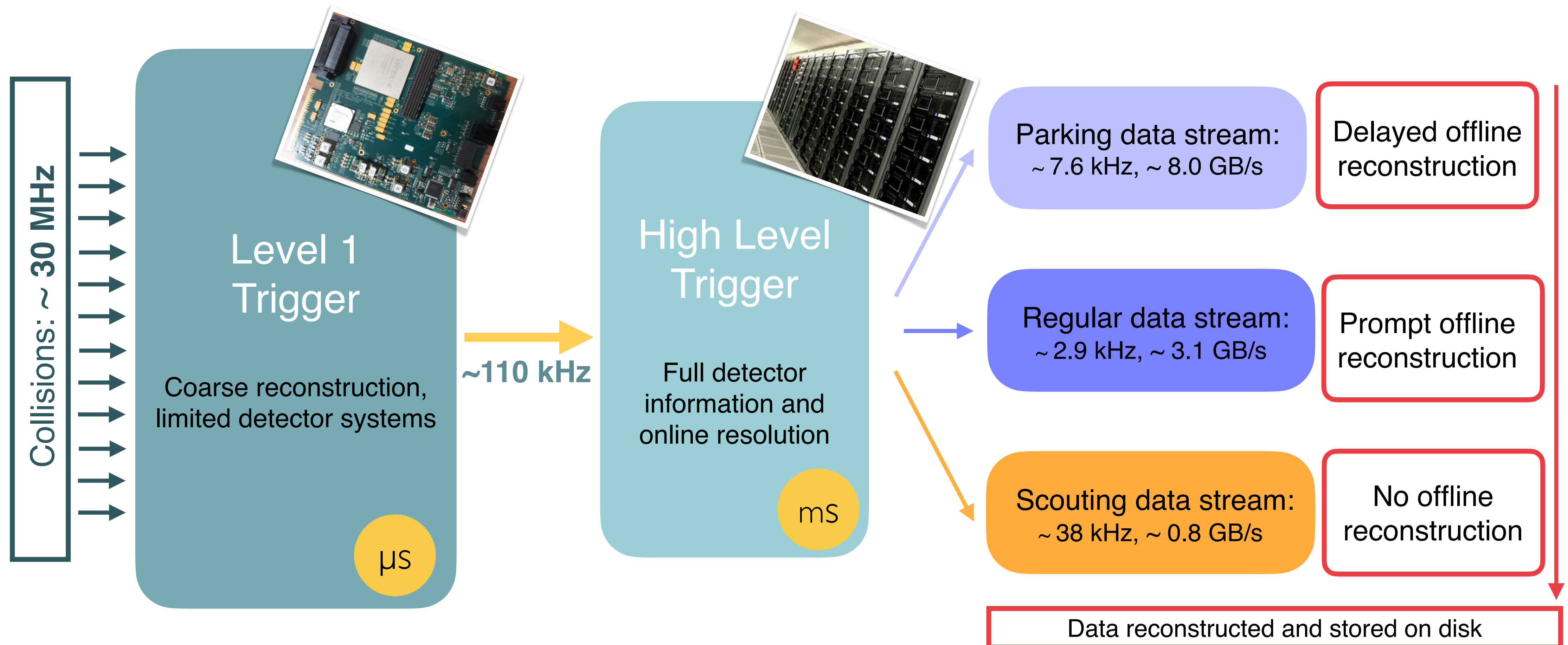


The Run 3 scouting program today



FINAL REMARKS AS OF TODAY...

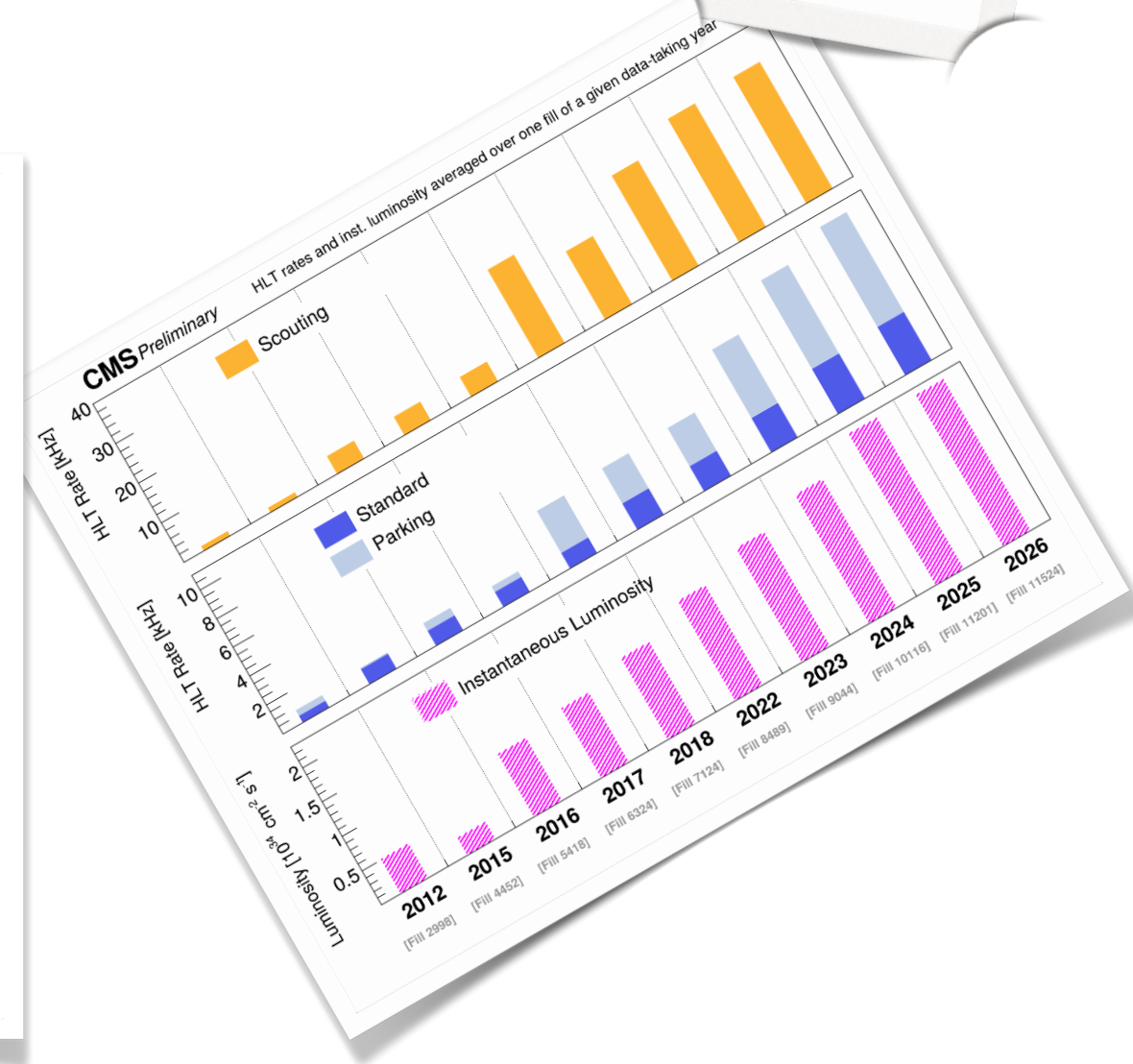
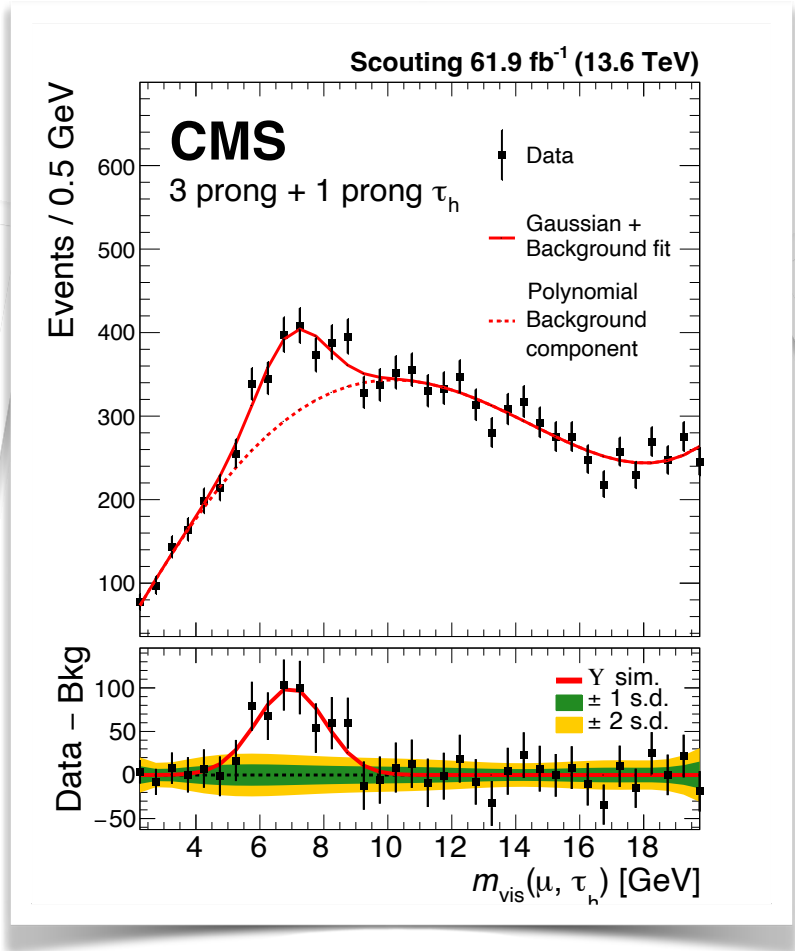
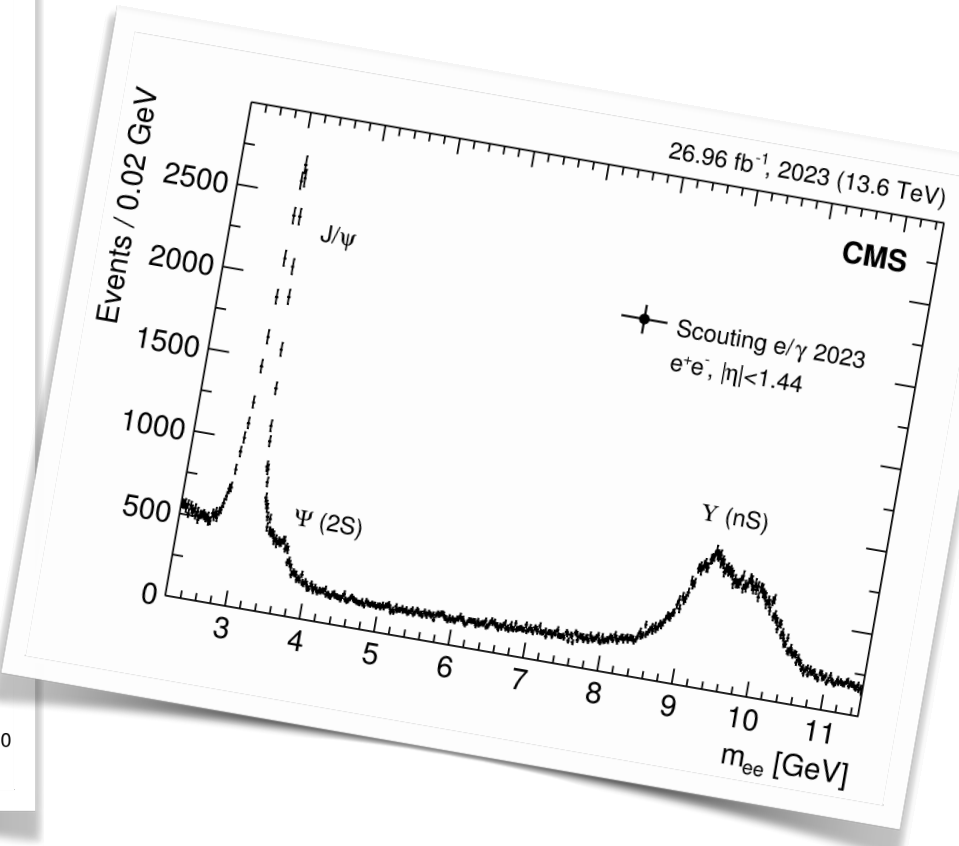
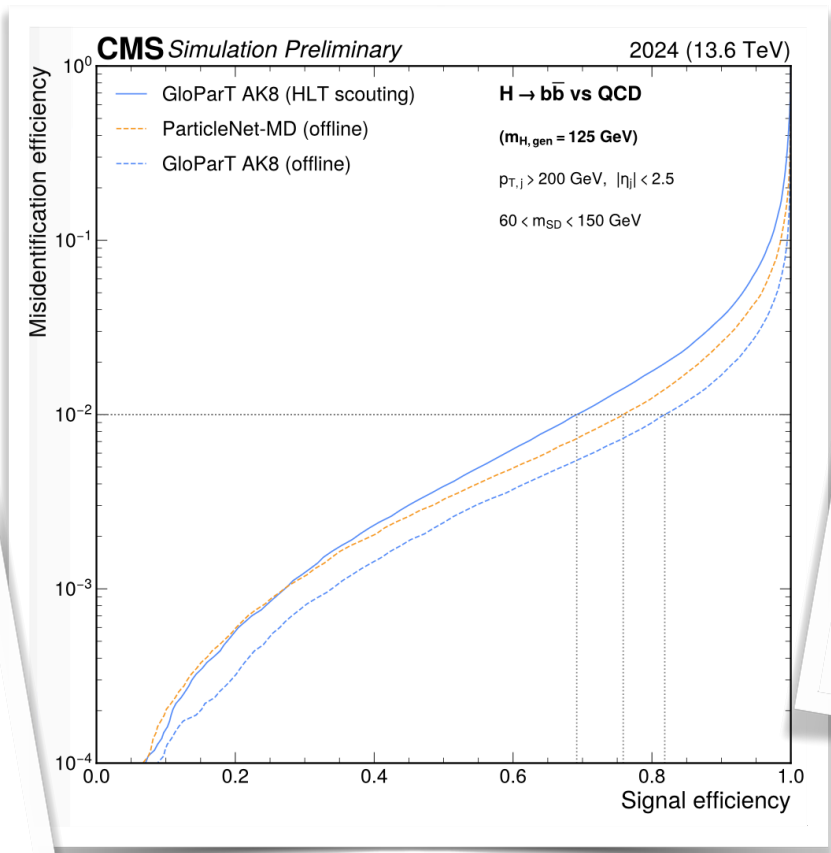
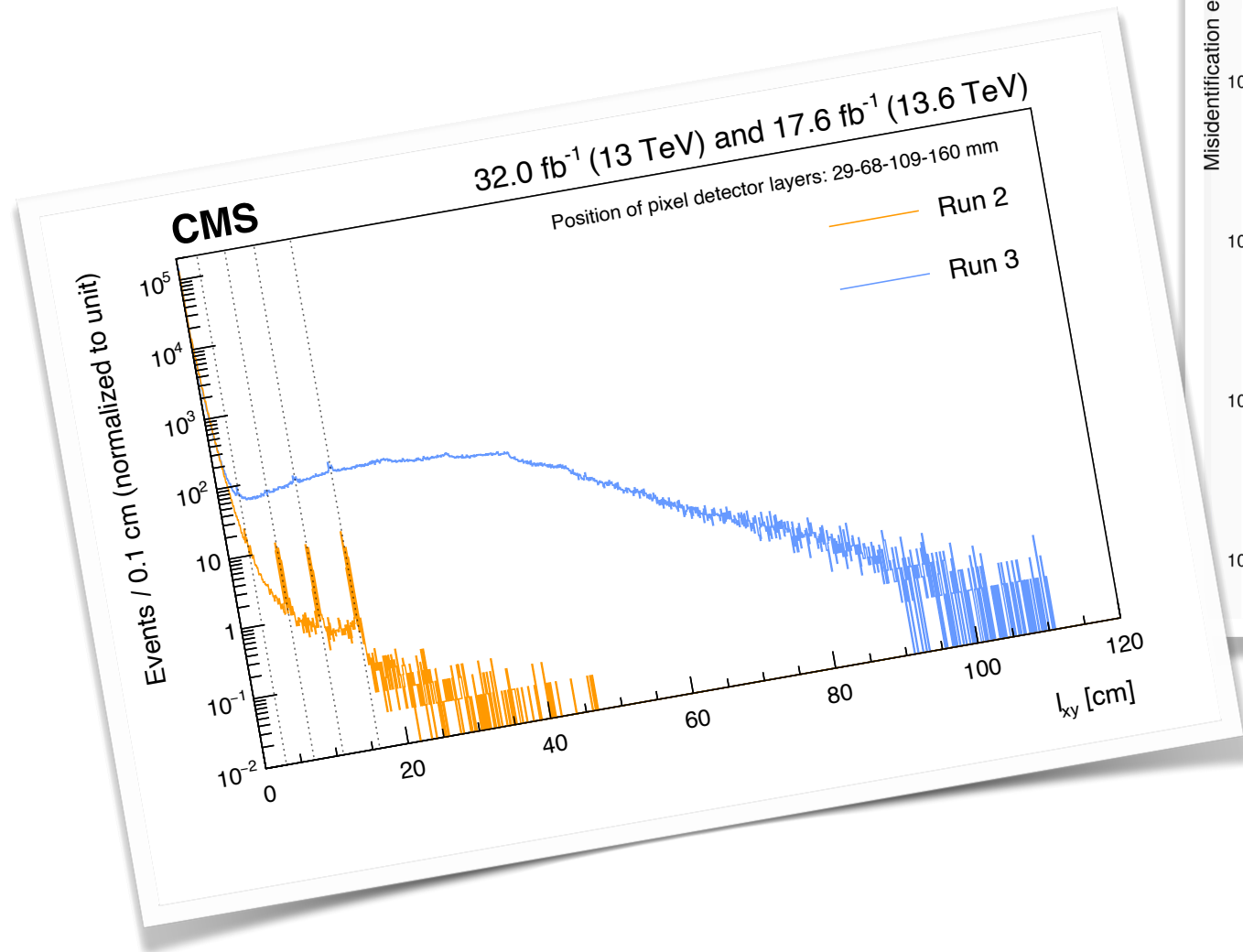
Over the years, data scouting has evolved from a specialized data stream into a core component of the CMS trigger and operation strategy.



FINAL REMARKS AS OF TODAY...

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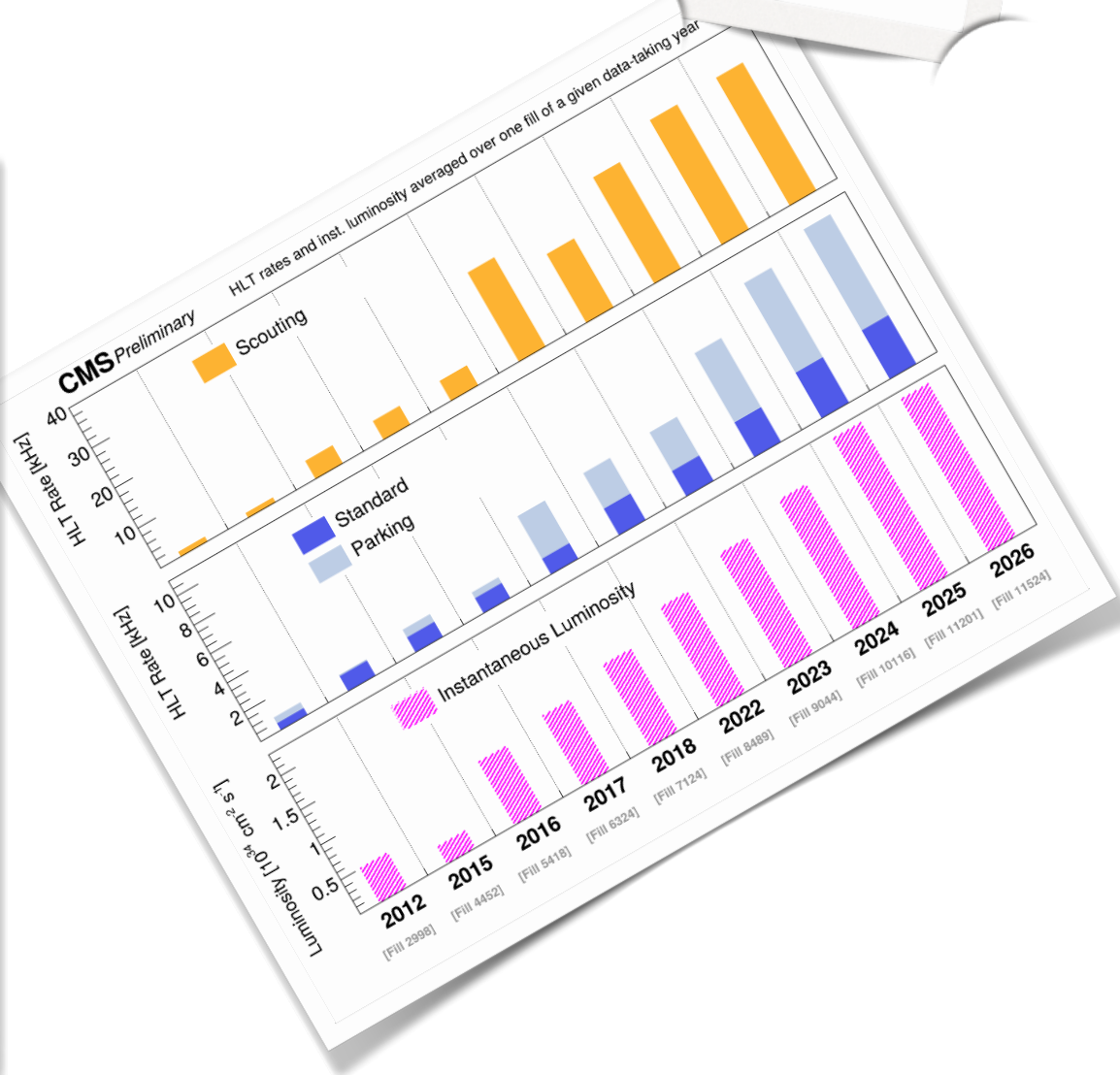
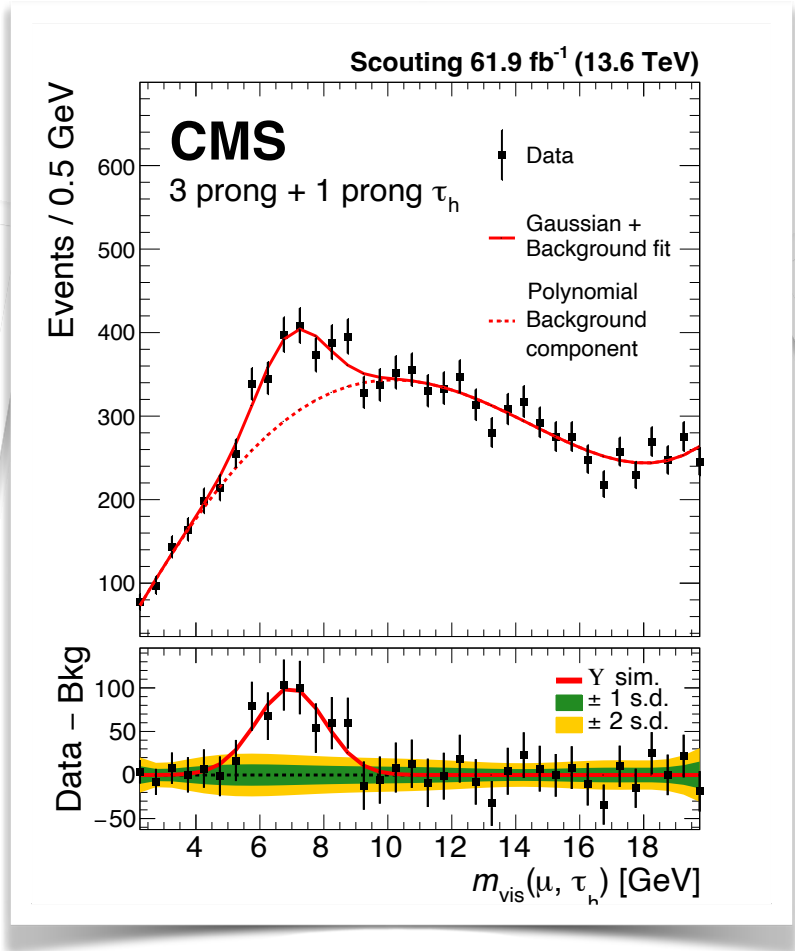
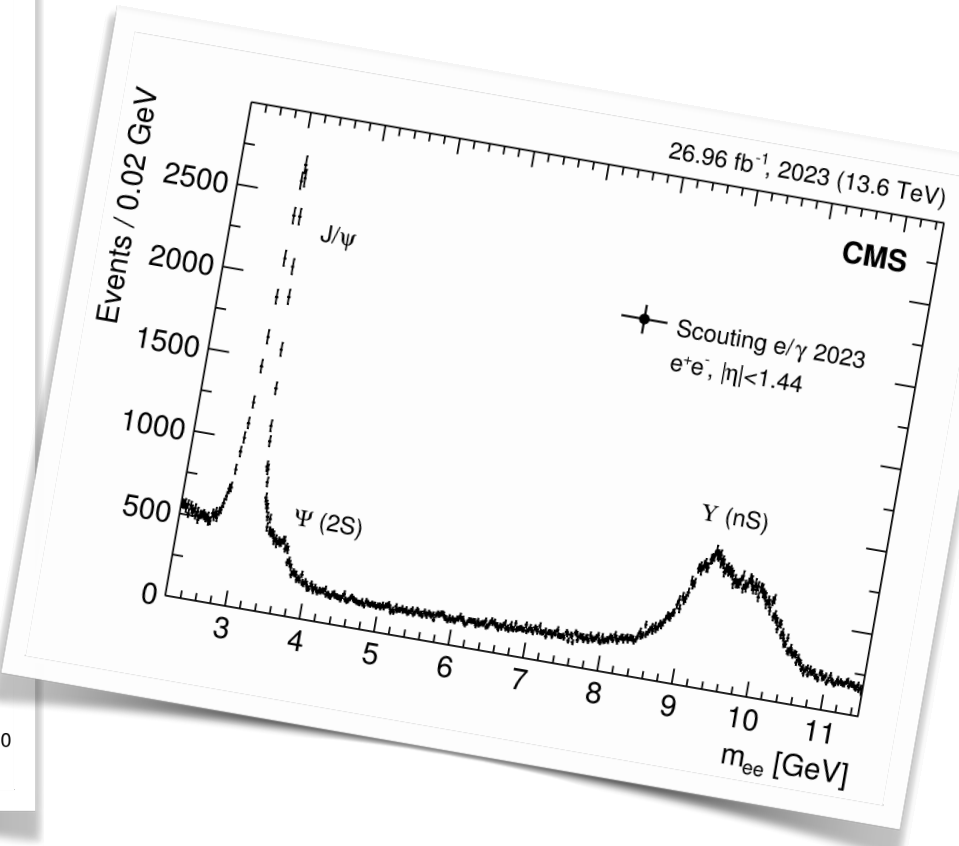
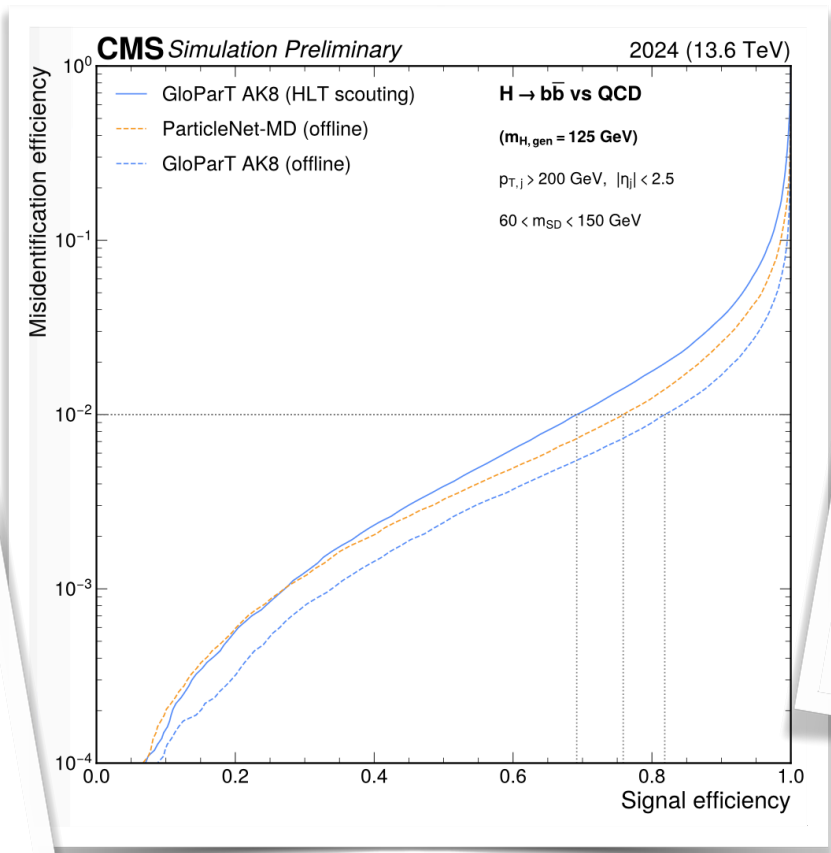
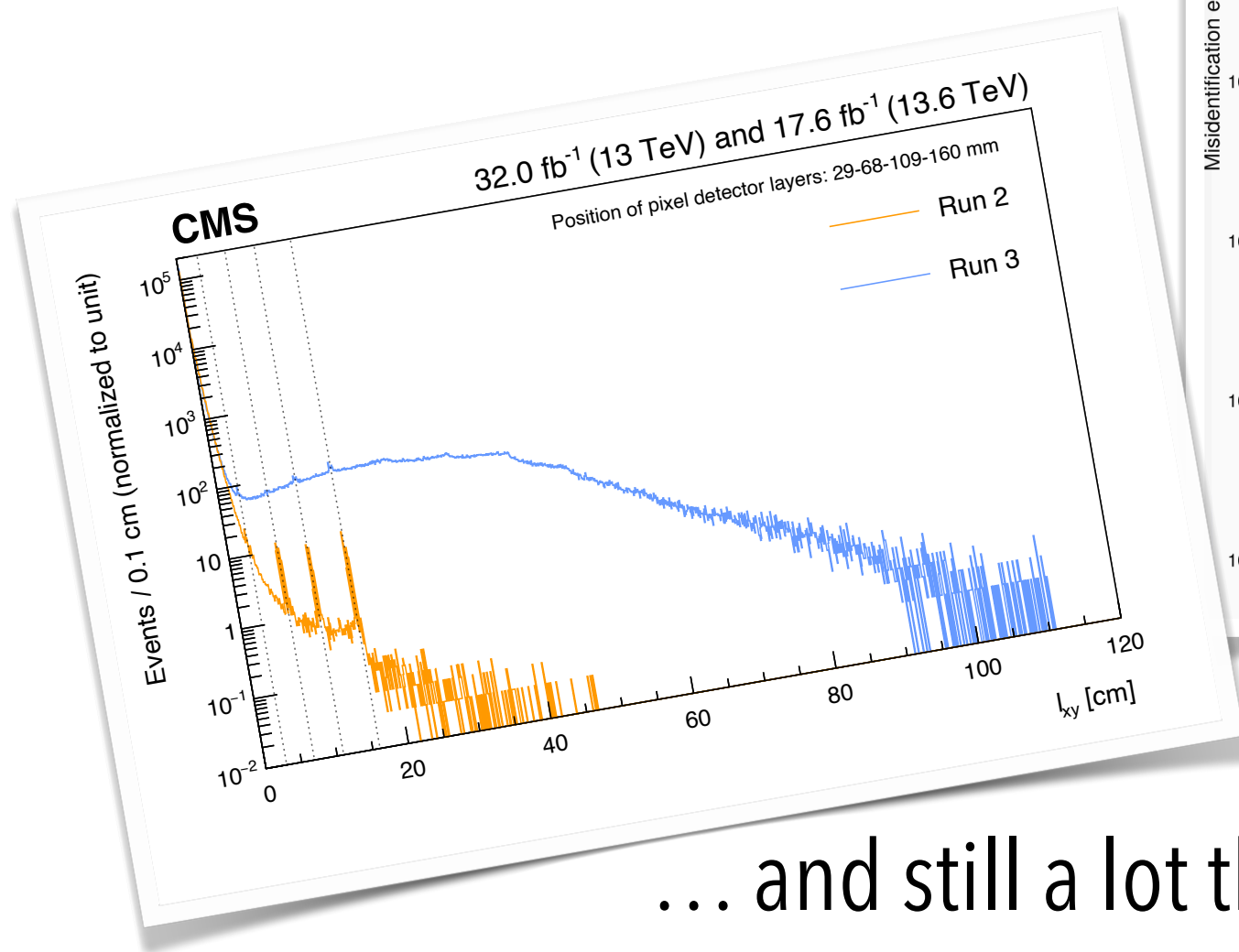
Run 3 has been a fertile ground for creativity, innovation, and experimentation in trigger development, laying the groundwork for the Phase-2 HL-LHC era!



FINAL REMARKS AS OF TODAY...

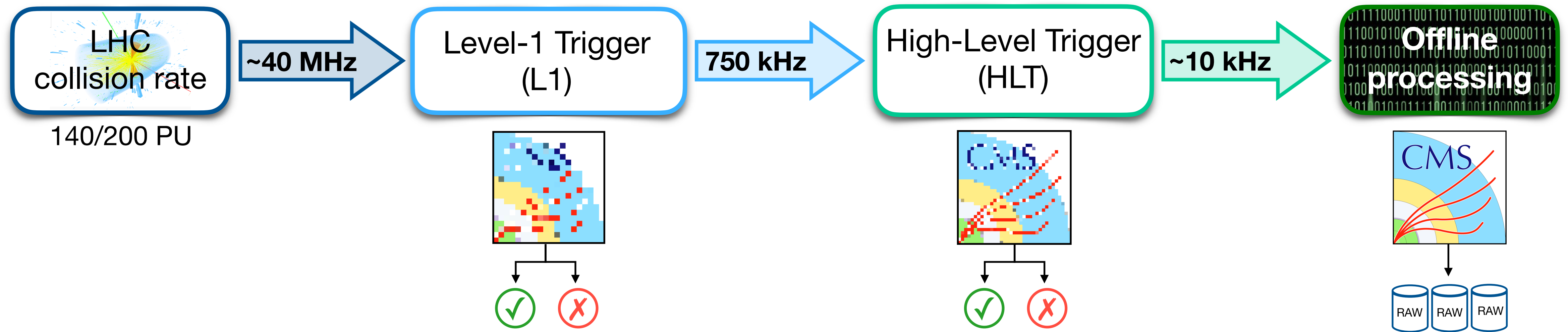
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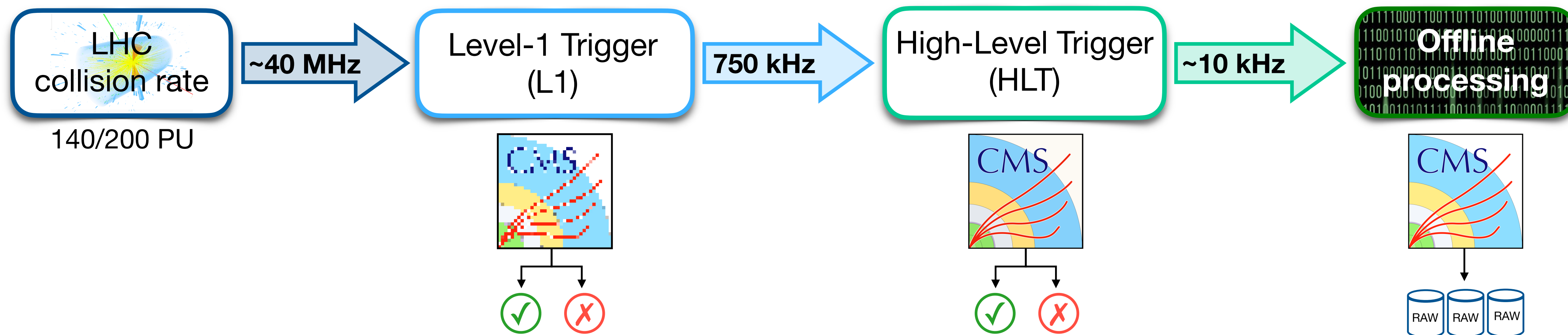
... and still a lot that we can keep learning with the huge and precious Run 3 data set collected.

MORE FINAL REMARKS... WHAT'S THE FUTURE OF SCOUTING @ HL-LHC?



Main goal: keep the current acceptance of the CMS physics program @ 200 pile-up!

MORE FINAL REMARKS... WHAT'S THE FUTURE OF SCOUTING @ HL-LHC?



❖ For the first time @ L1:

- tracking at 40MHz ($p_T > 2$ GeV)
- higher granularity from Calo/Muon
- PF and PUPPI
- ❖ Much more powerful FPGAs: 7.5x more resources
- ❖ More time to make the decision (12.5 μ s)
- ❖ Increased output rate: 750 kHz to HLT

❖ More processing power

❖ More heterogenous computing

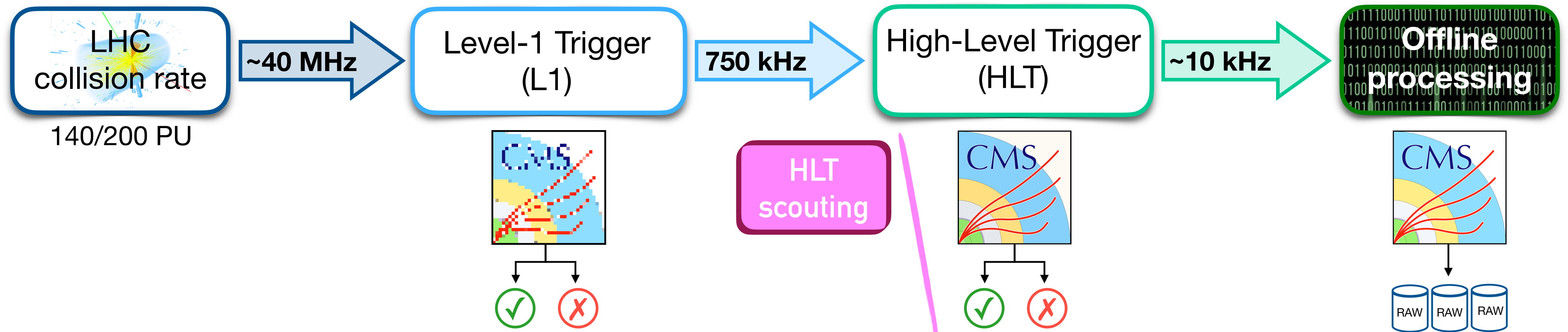
- up to 50 (80) % of code execution offloaded to GPUs in Run 4 (Run 5)

❖ Faster and smarter reconstruction algorithms

- Patatrack Pixel tracking; Line Segment Tracking (LST); The Iterative CLustering (TICL)

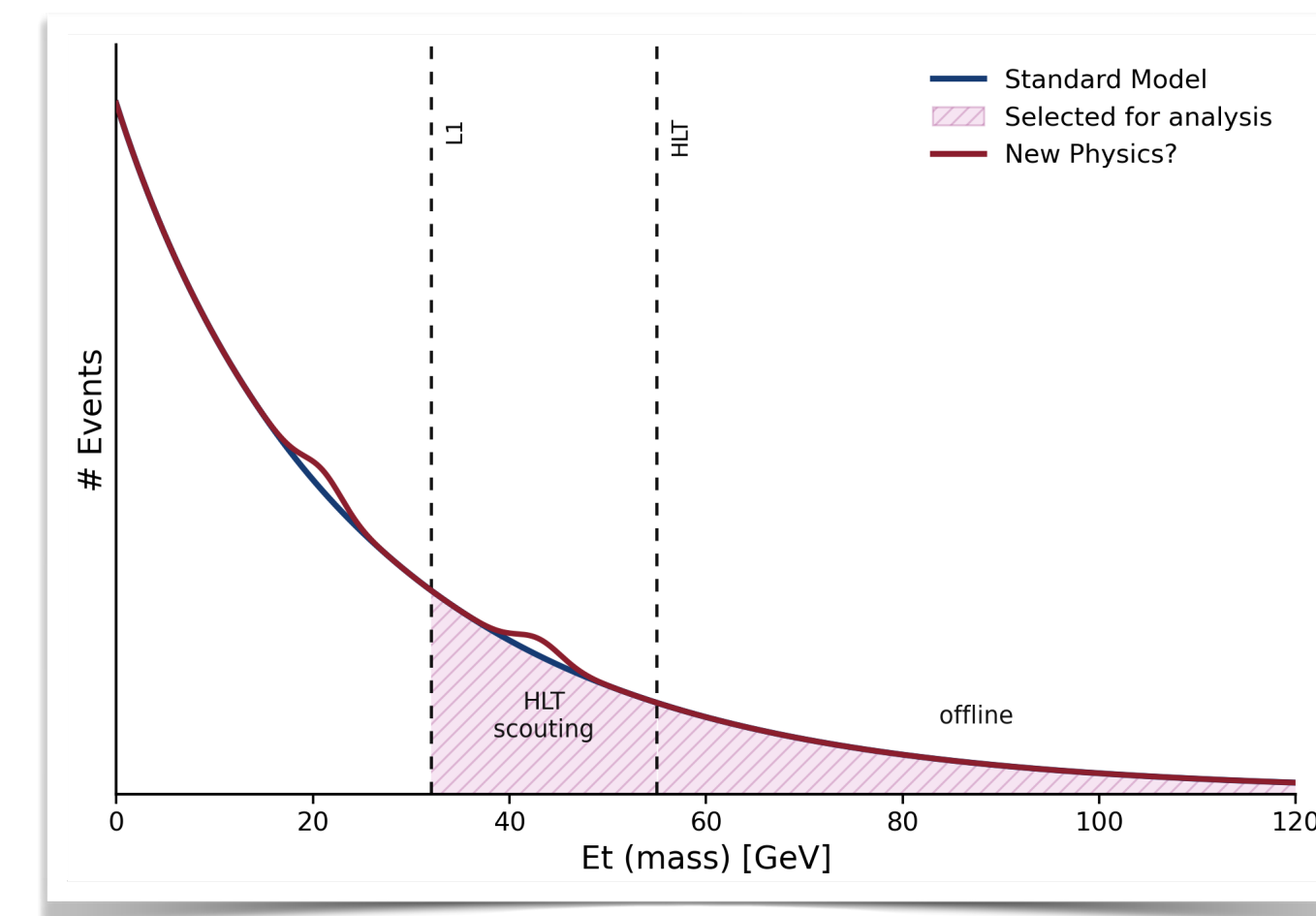
❖ Provide **calibrated, offline-like** quality objects

SCOUTING @ HL-LHC: AN ENHANCED HLT SCOUTING PROGRAM



HLT SCOUTING @ HL-LHC:

- ✿ Reconstruct at HLT at least 30% of the L1T input
 - ✿ Next-Generation-Triggers Target: Event output rate **at 750 kHz**
- ✿ Analysis-driven output with **reduced event size**
 - ✿ Optimised **compression** strategies
- ✿ Exploit **offline-like** quality objects



SCOUTING @ HL-LHC: TRACKING @ HLT SCOUTING

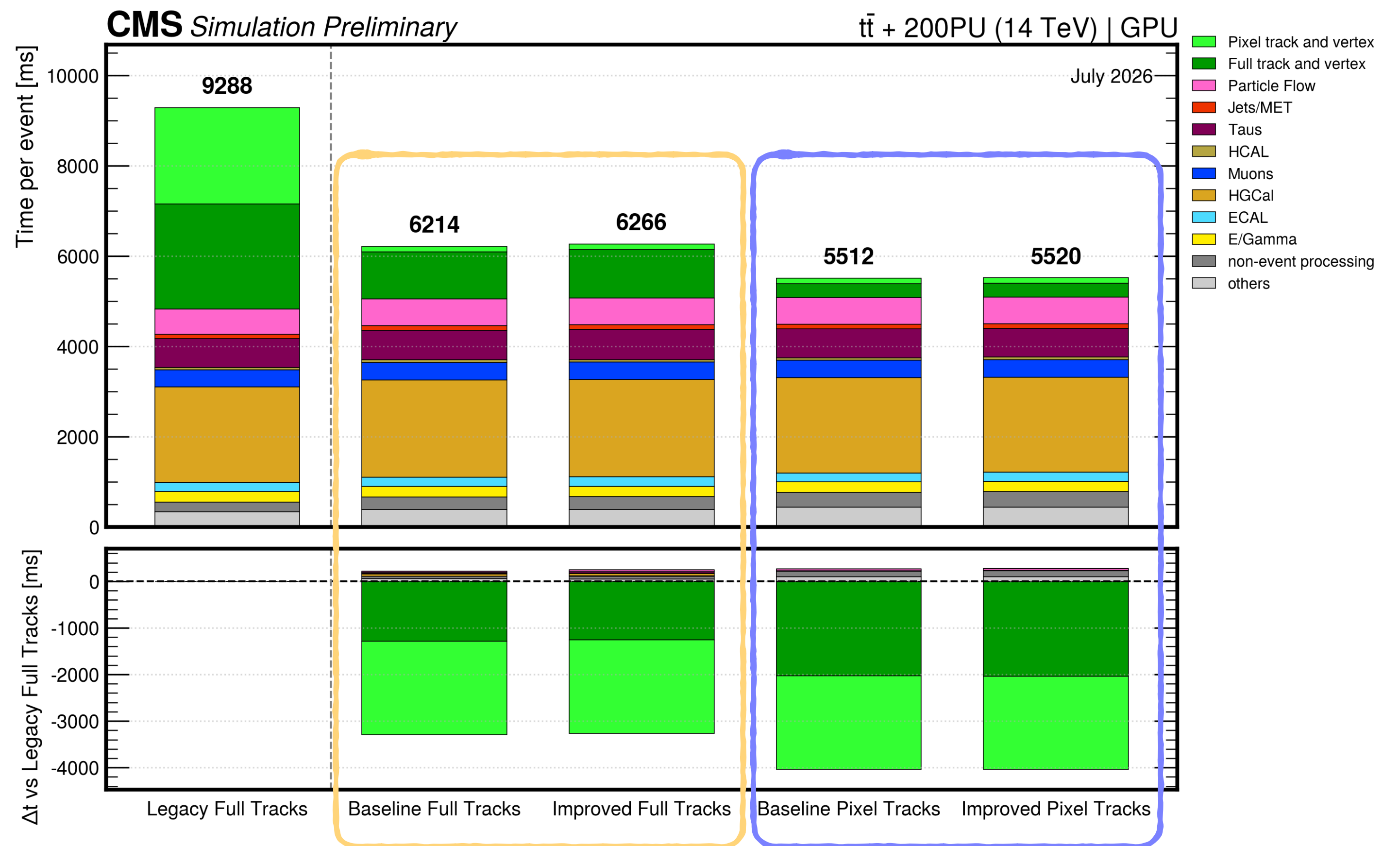
CMS-DP-2026-114

HLT reconstruction highlights: tracking

- ❖ To resolve the high hit **combinatorics**, tracks are reconstructed sequentially via:
 - ❖ Track seeded (Cellular-Automaton)
 - ❖ Track building (Combinatorial Kalman Filter)

CPU + GPU implementation provide
~**30% speed-ups** for all
configurations algorithm

Patatrack is used to accelerate the
track seeding step (12% gain)

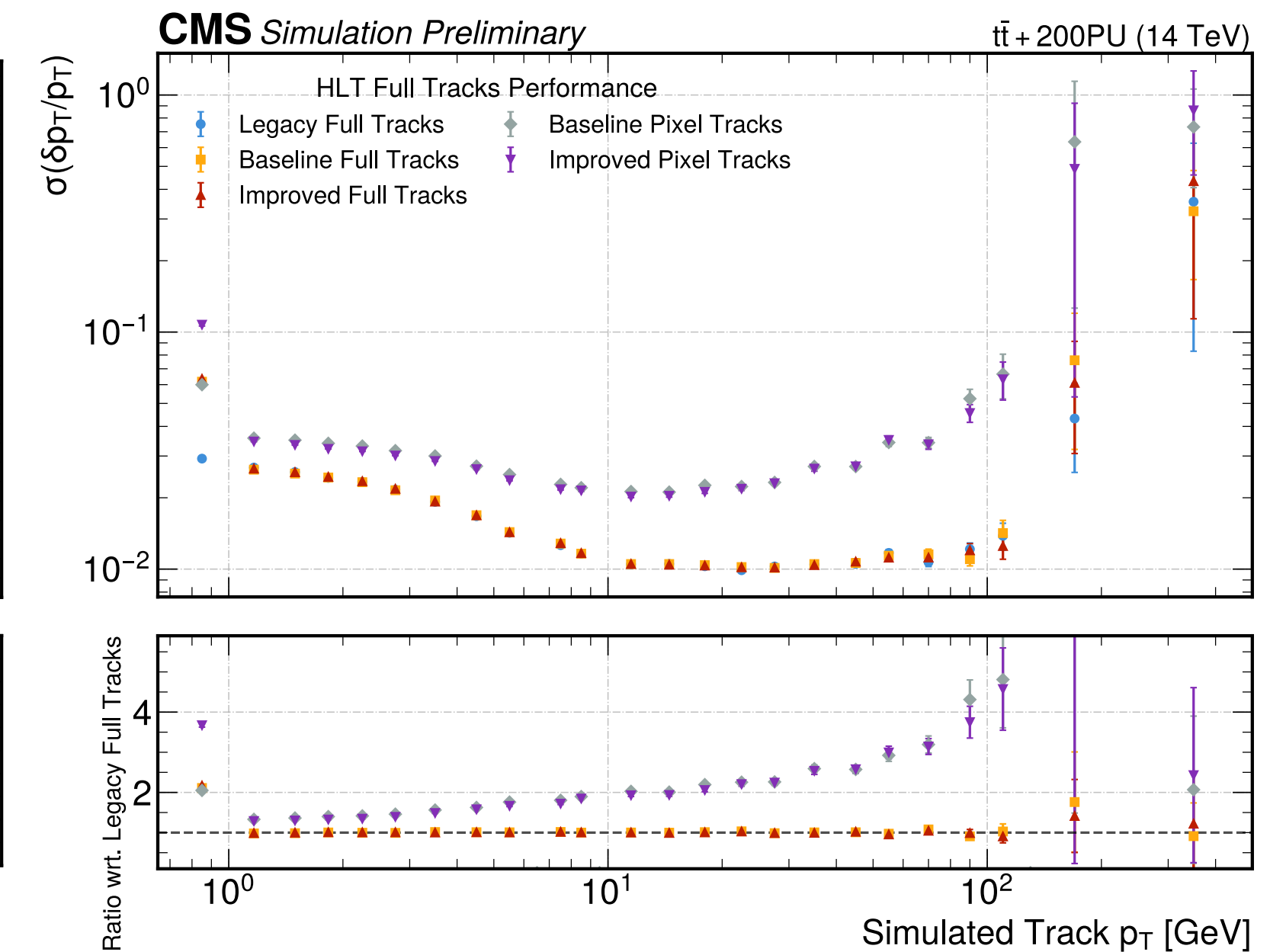
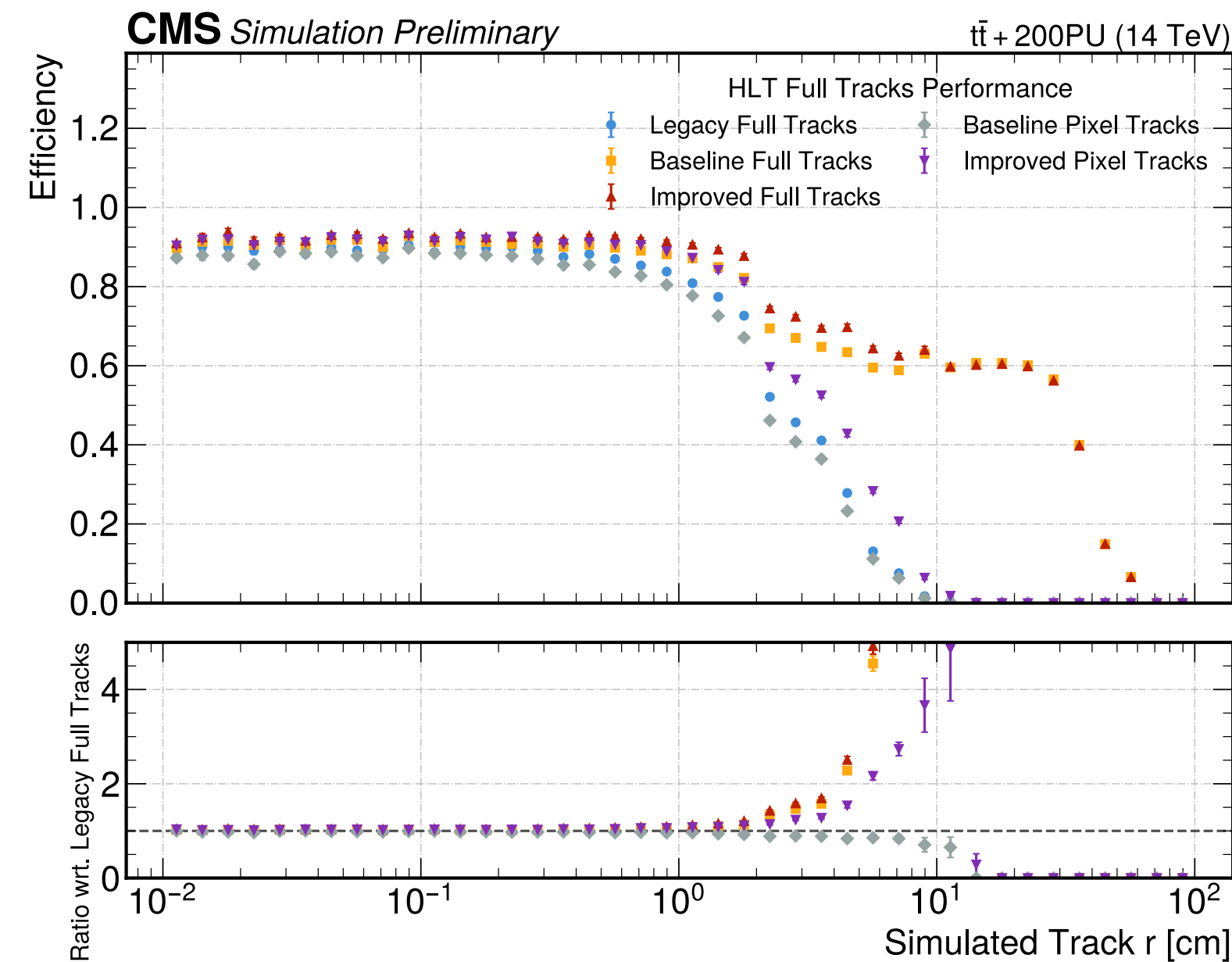
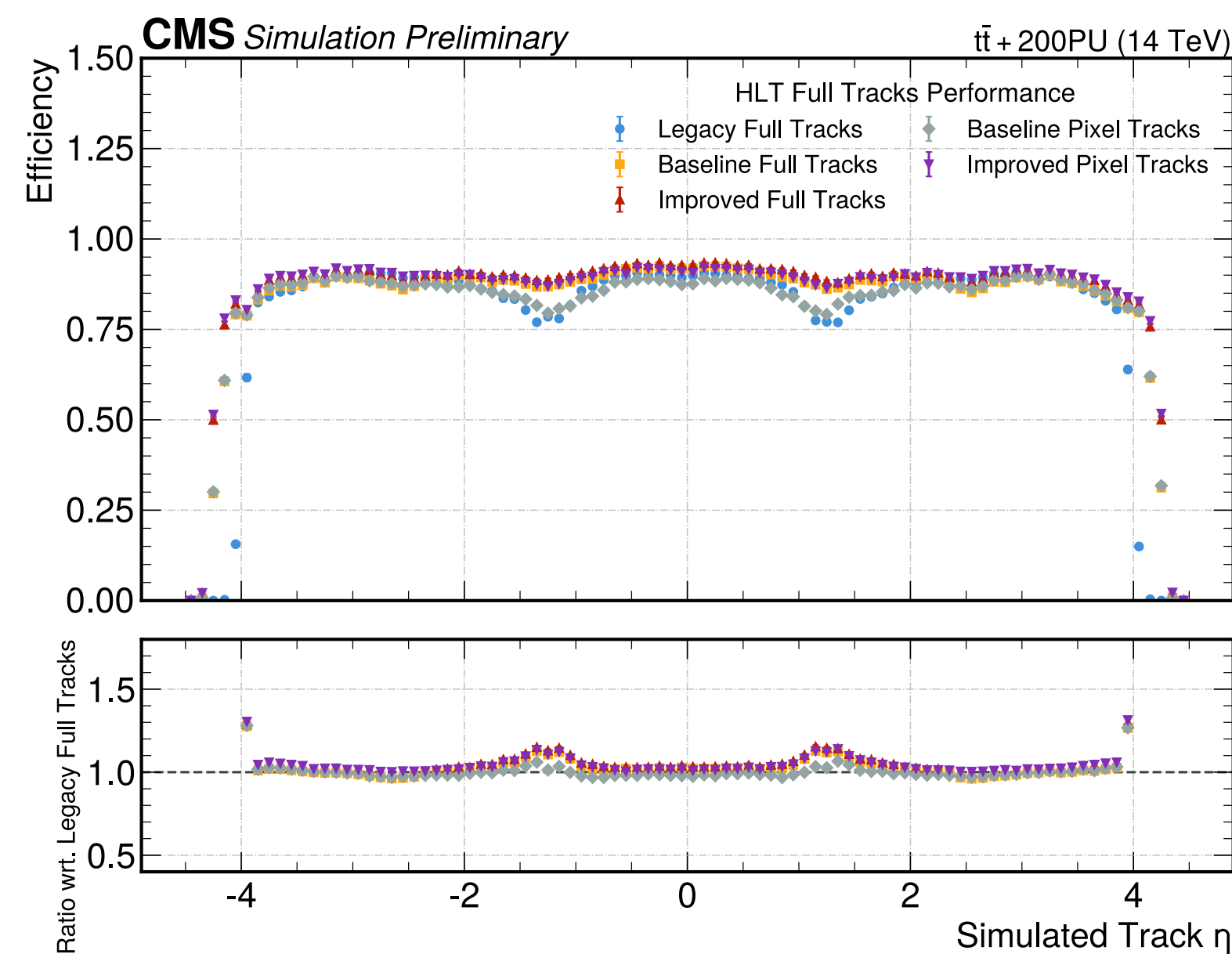


SCOUTING @ HL-LHC: TRACKING @ HLT SCOUTING

CMS-DP-2026-114

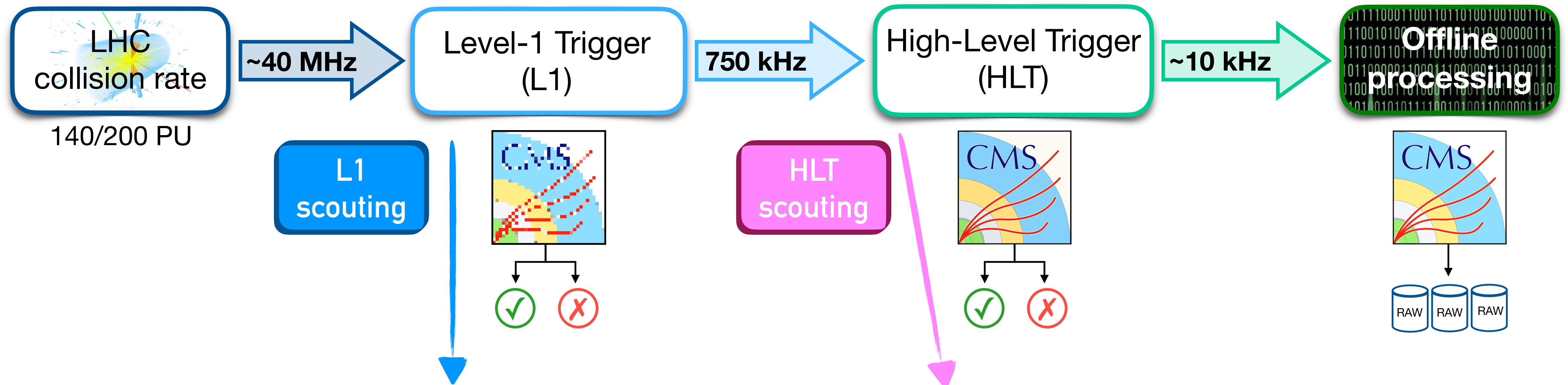
HLT reconstruction highlights: tracking

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Higher efficiency as a function of pseudo-rapidity and displacement, at the cost of slightly degraded track resolution

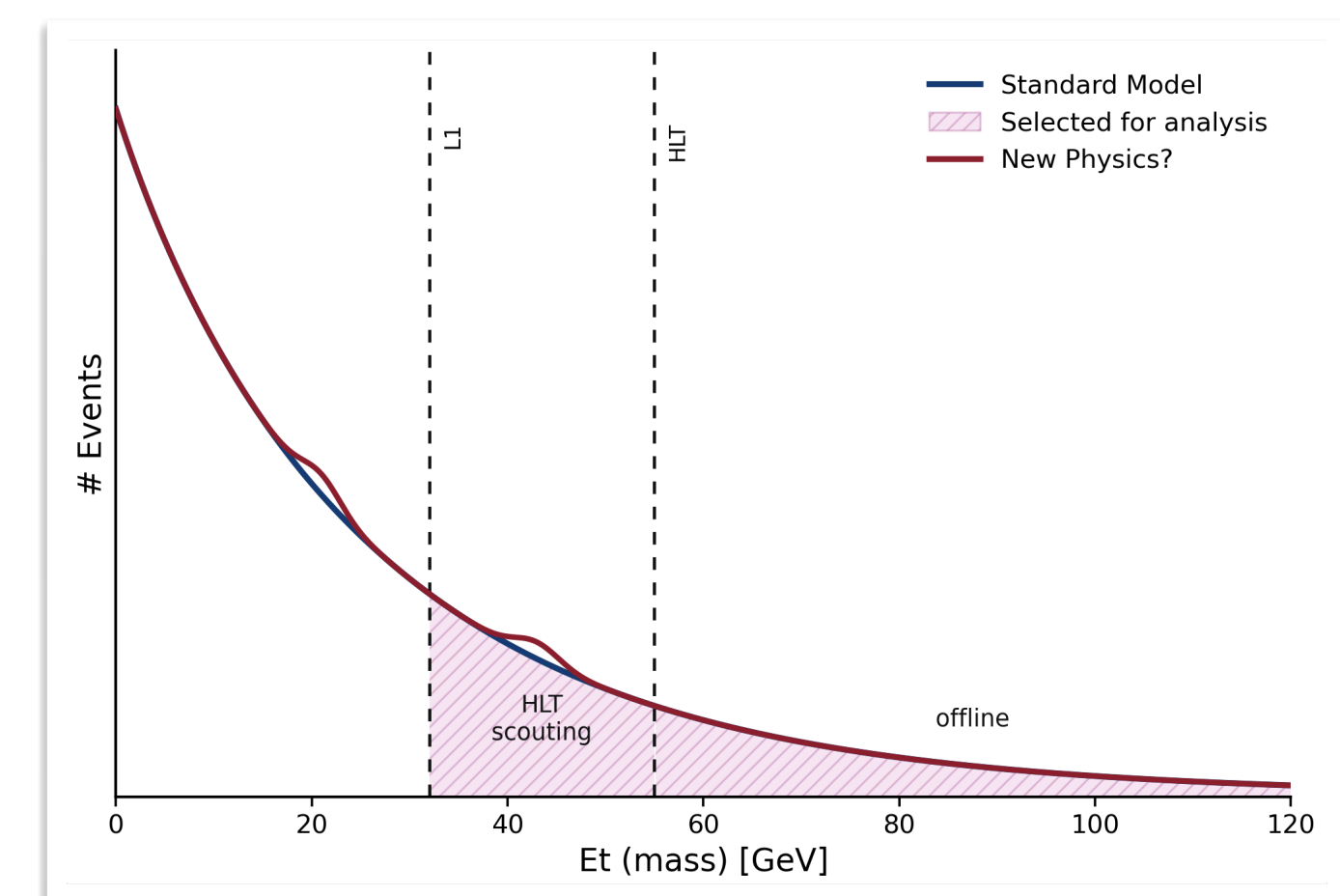
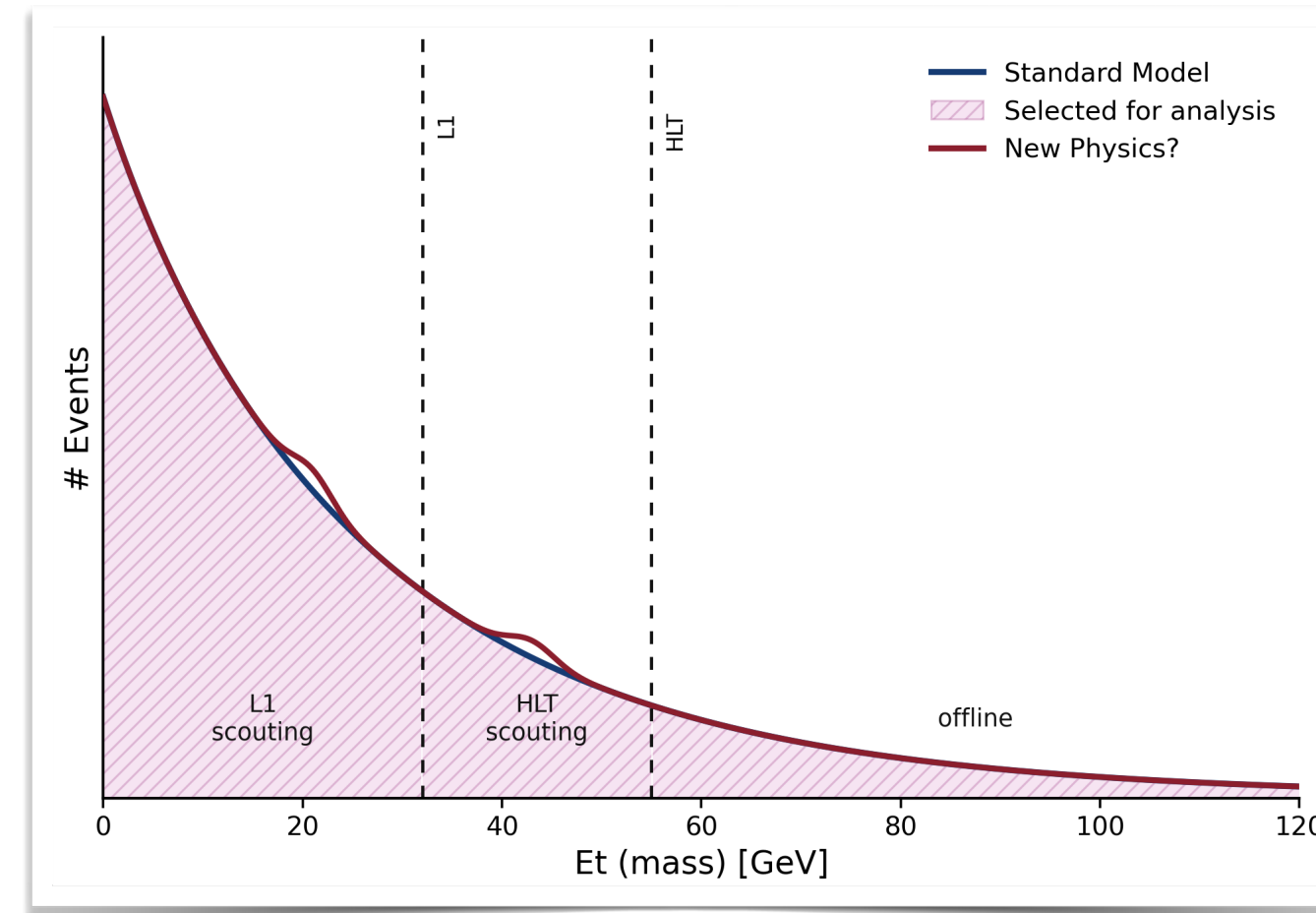
SCOUTING @ HL-LHC: A NOVEL L1 SCOUTING PROGRAM



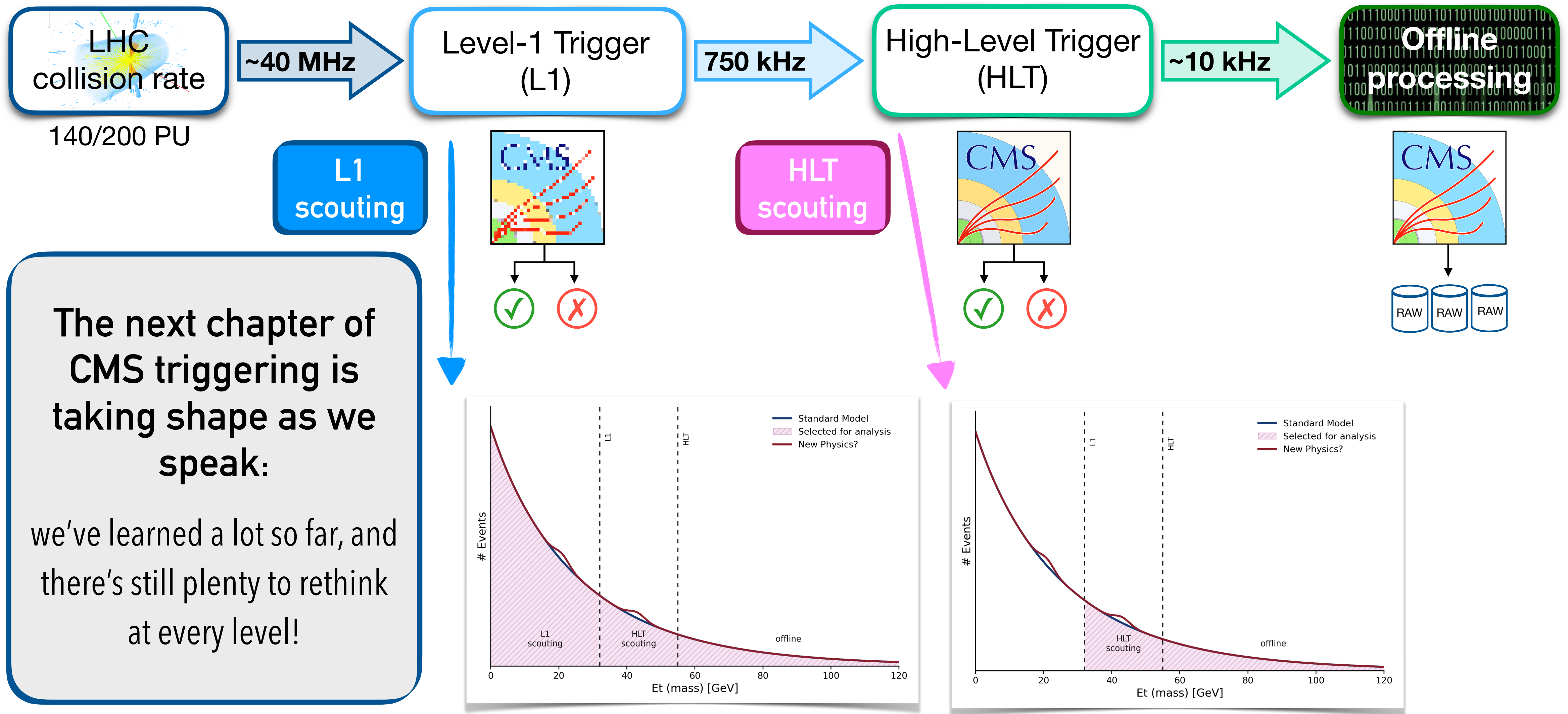
40 MHz SCOUTING @ L1T

- ❖ Successful Run 3 demonstrator
- ❖ [CMS-PAS-EXO-25-010](#): Search for heavy long-lived charged particles with Level-1 Scouting data from proton-proton collisions at $\sqrt{s}=13.6$ TeV

First CMS physics result!



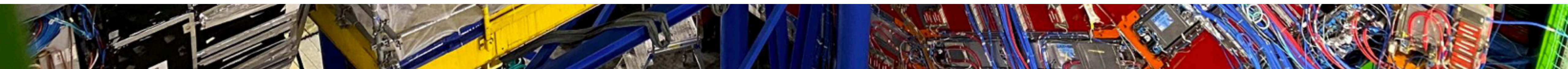
CONCLUSION: WORKING ON THE FUTURE OF SCOUTING @ HL-LHC!





ADDITIONAL SLIDES

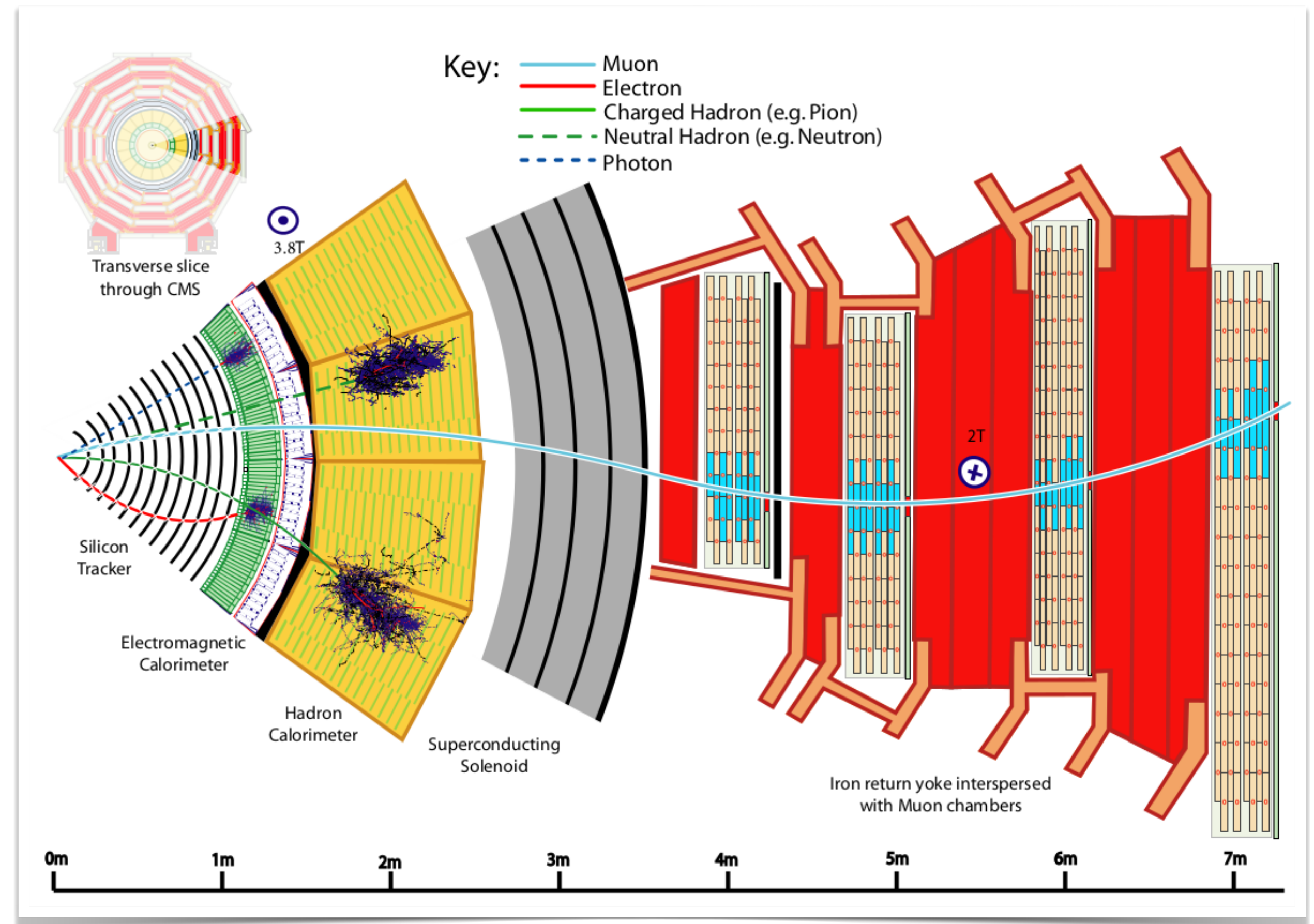
Thank you for listening!



COMPACT MUON SOLENOID AT LHC

CMS was designed as a general purpose detector able to run at the highest luminosity at the LHC and it was optimized for the SM H boson search over a mass range from 90 GeV to 1 TeV

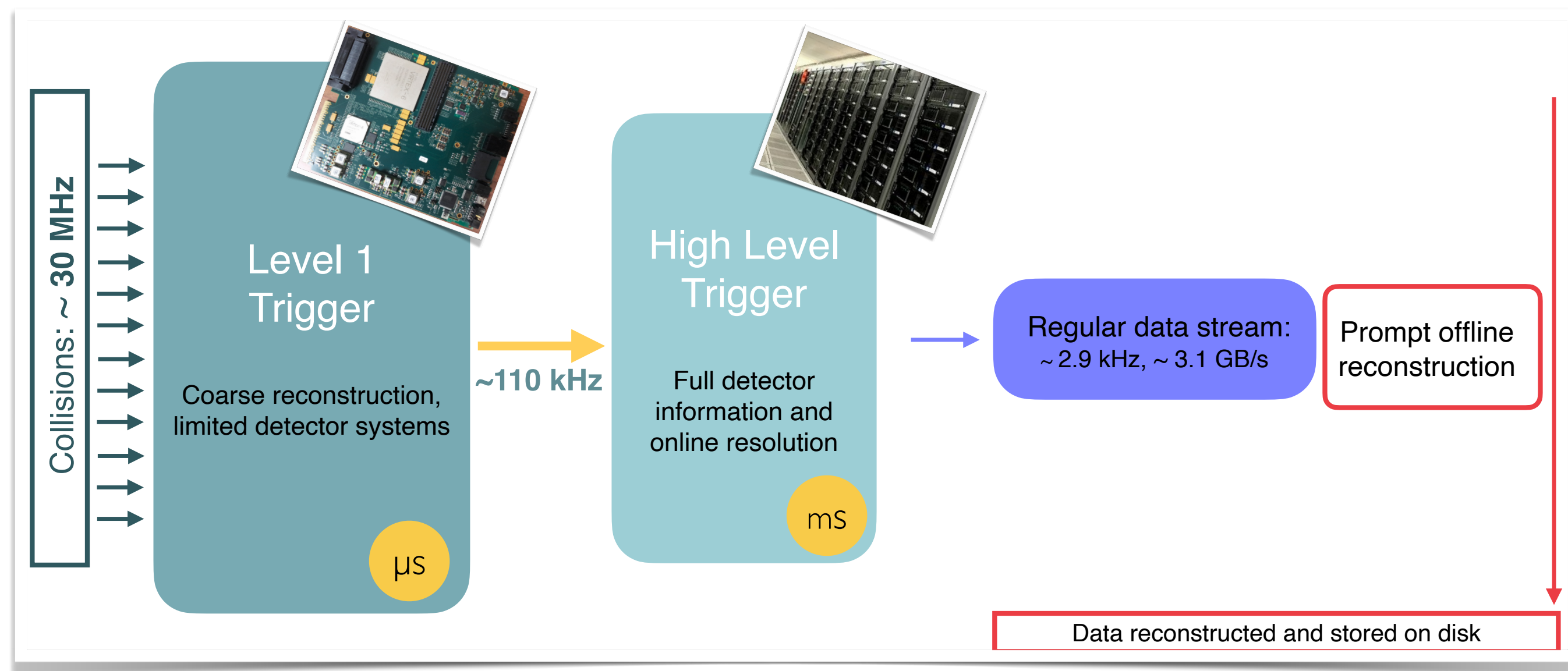
- ❖ 3.8T superconducting solenoidal magnet with 6m diameter
- ❖ **Tracker System:** silicon strip+pixel system which reconstructs the trajectories of charged particles
- ❖ **Electromagnetic calorimeter (ECAL):** scintillator made from lead tungstate crystals sensitive to energy deposits from electrons and photons
- ❖ **Hadronic calorimeter (HCAL):** brass scintillator sensitive to energy deposits from hadrons, mainly pions and kaons
- ❖ **Gas ionization chambers for muon detection**



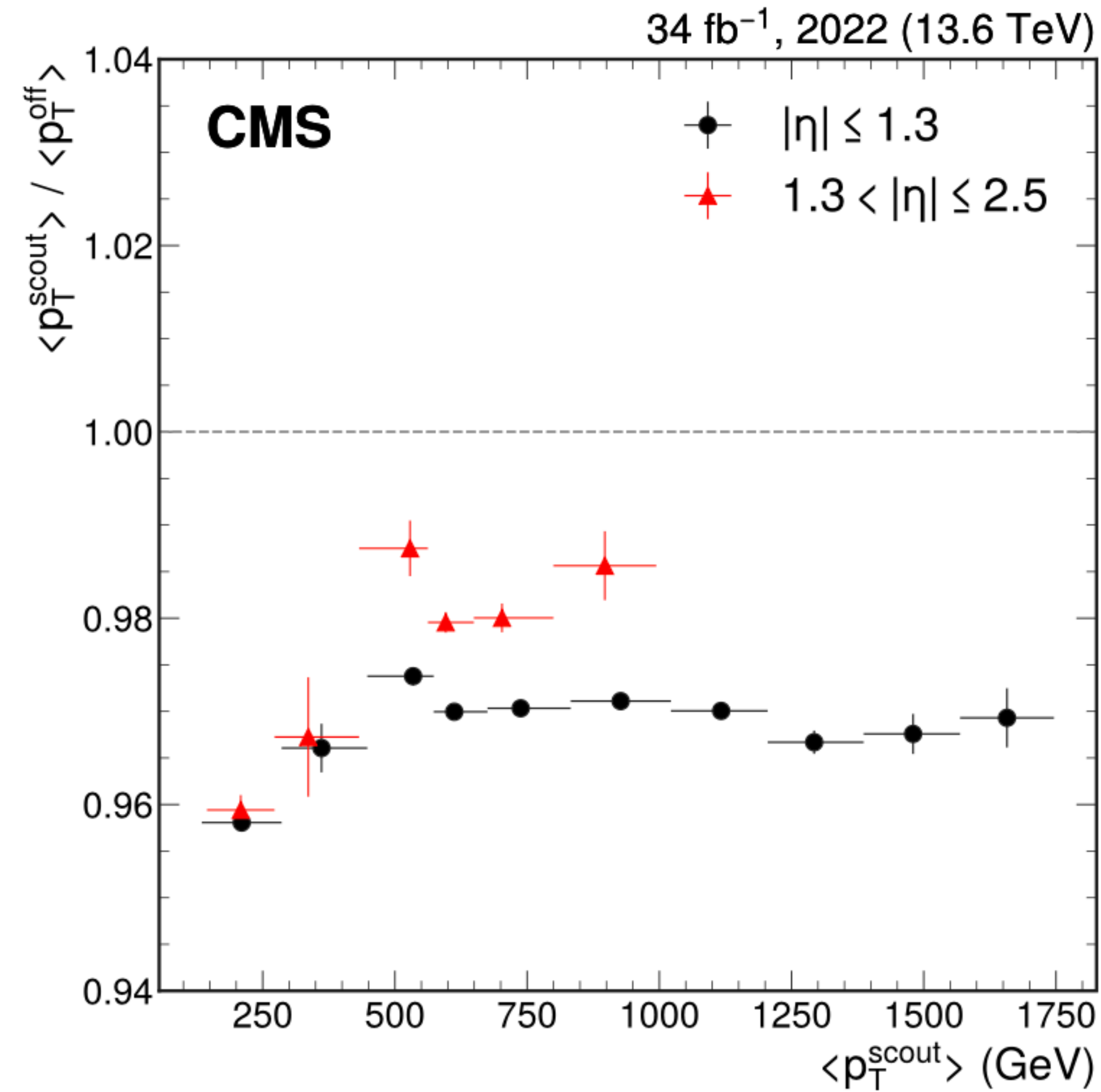
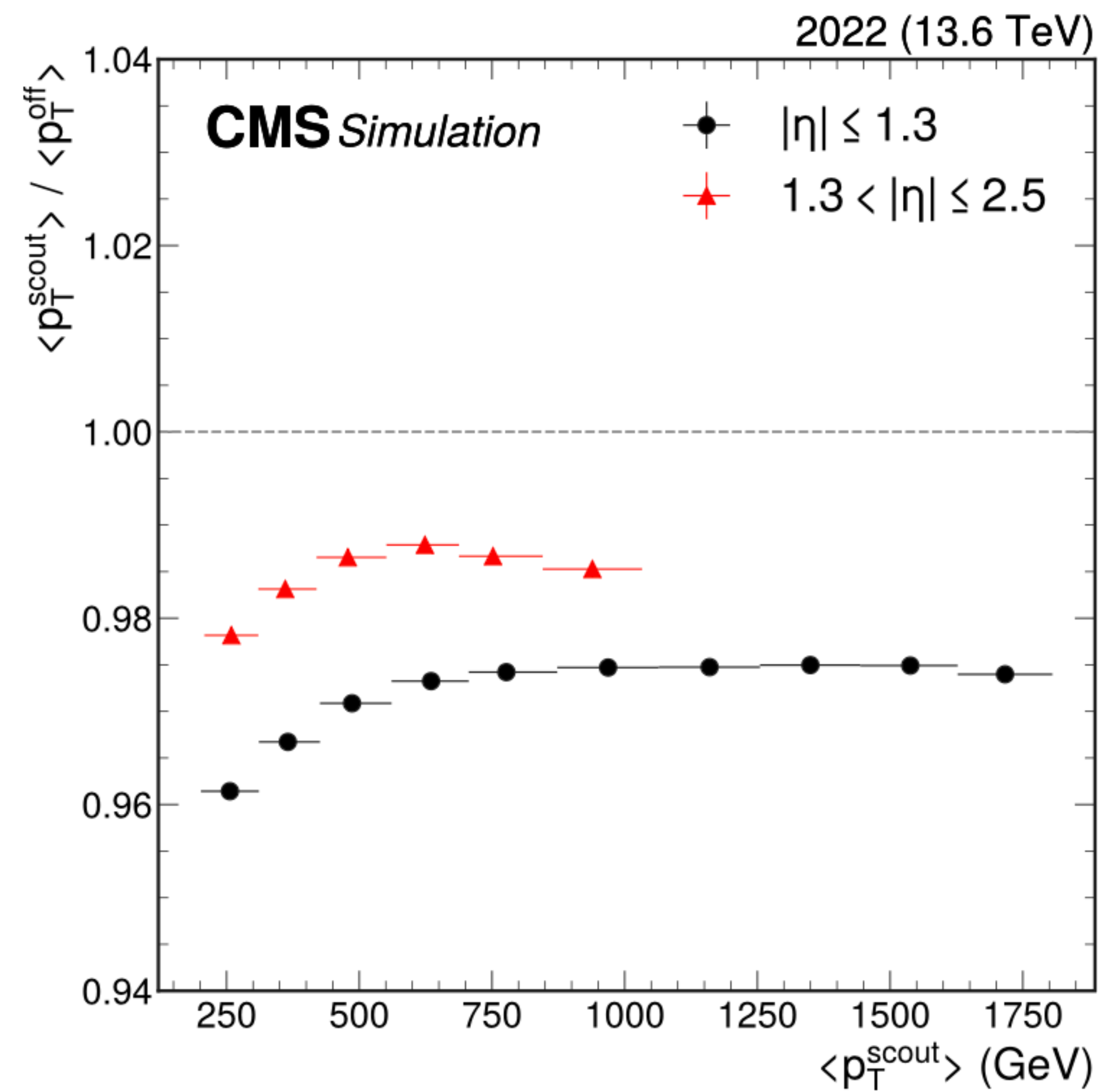
THE CMS TRIGGER SYSTEM

The CMS experiment was designed as a general purpose detector able to run at the highest luminosity at the LHC:

- optimized for the SM H boson search;
- perfect compromise between technological limitations and theory motivating new physics with electroweak-like cross sections.
- Very flexible system! Going beyond the baseline physics program...

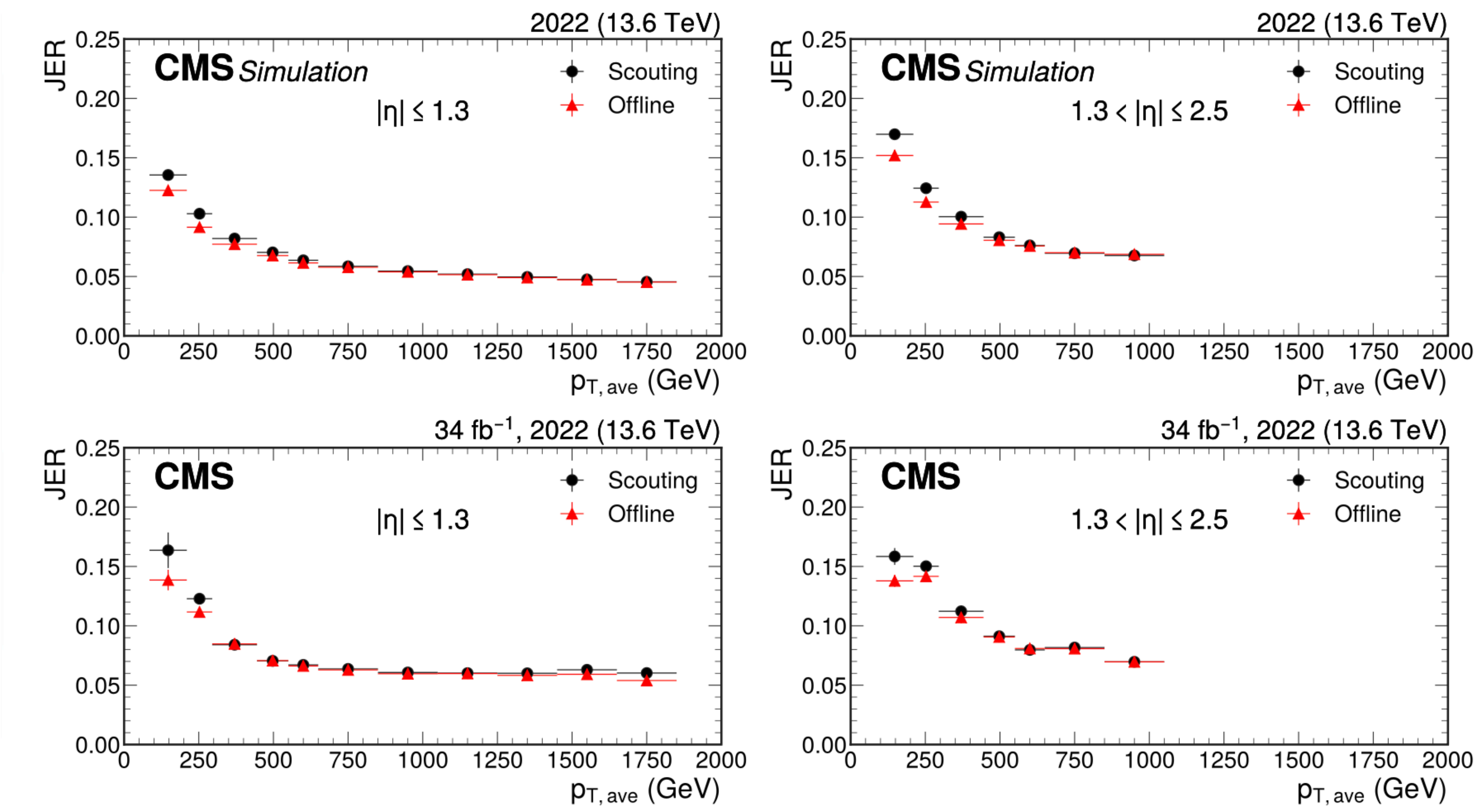


SCOUTING JETS: JET ENERGY SCALE



j.physrep.2024.09.006

SCOUTING JETS: JET ENERGY RESOLUTION



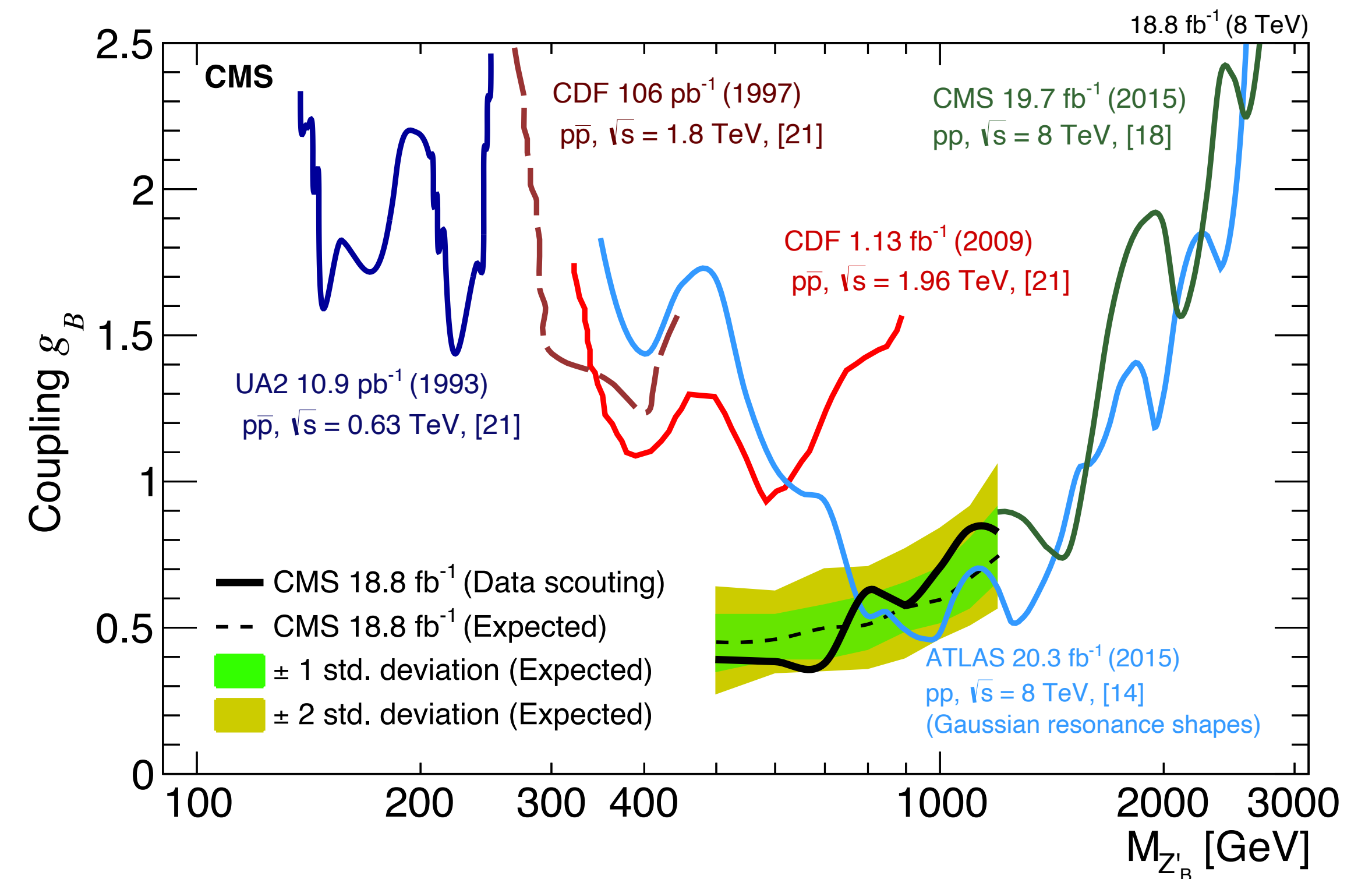
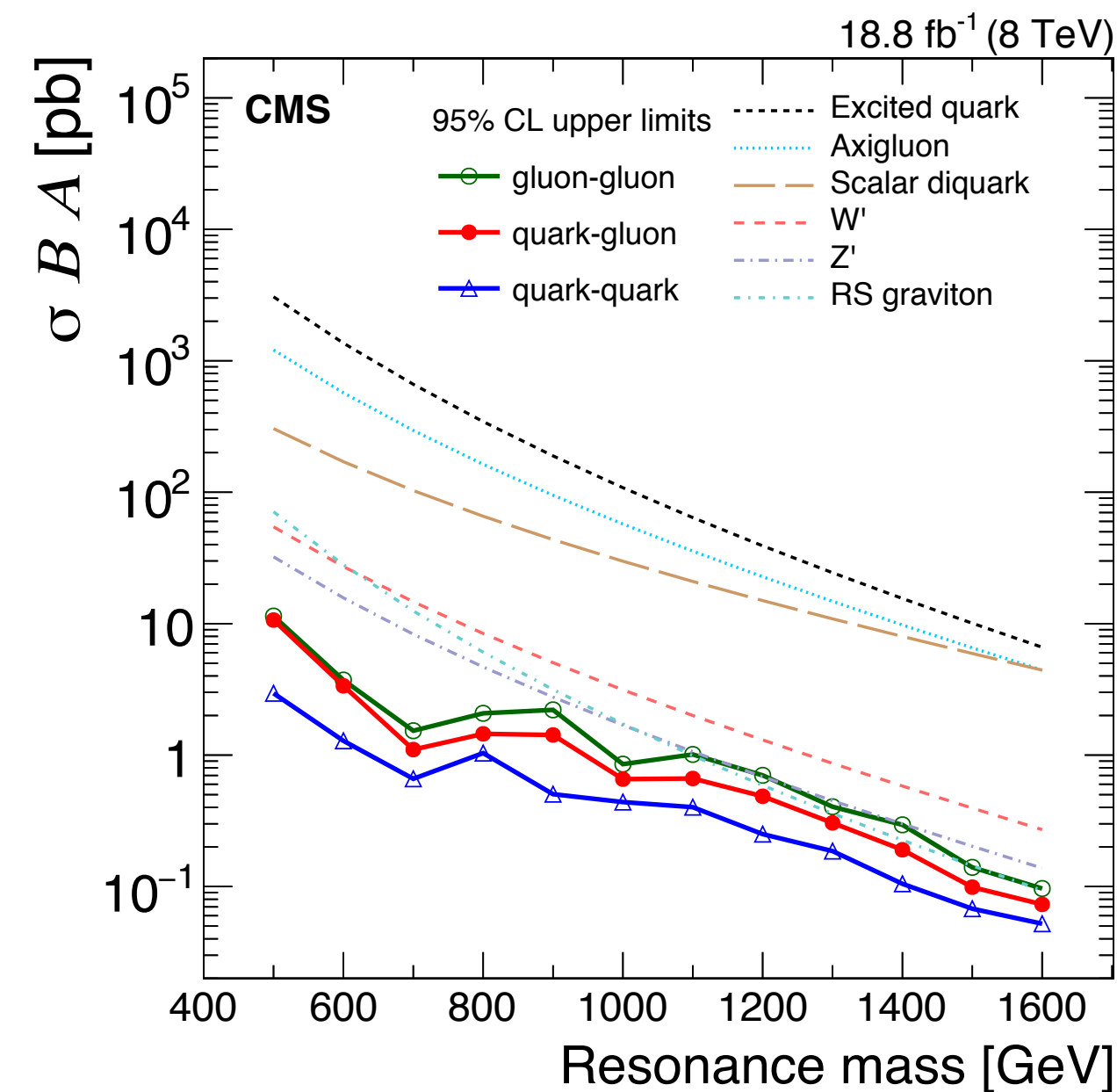
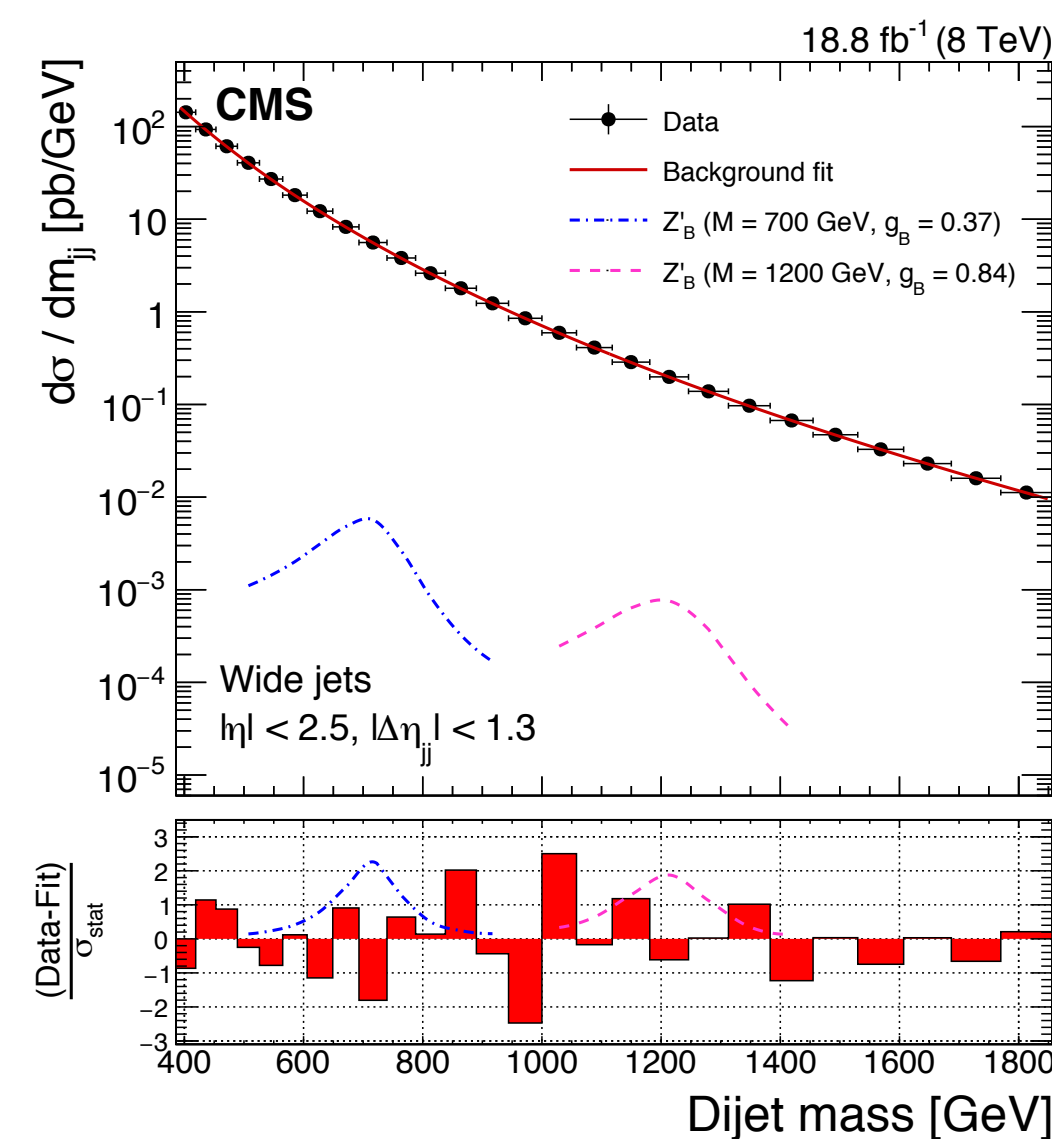
j.physrep.2024.09.006

PHYSICS RESULTS WITH RUN 2 SCOUTING DATA: HADRONIC FINAL STATES

Low H_T requirement hugely boosts signal sensitivity at low masses and low couplings:

❖ Dijet resonances:

- Run 1: CMS-PAS-EXO-11-094 (7 TeV), EXO-14-005 (PhysRevLett.117.031802)

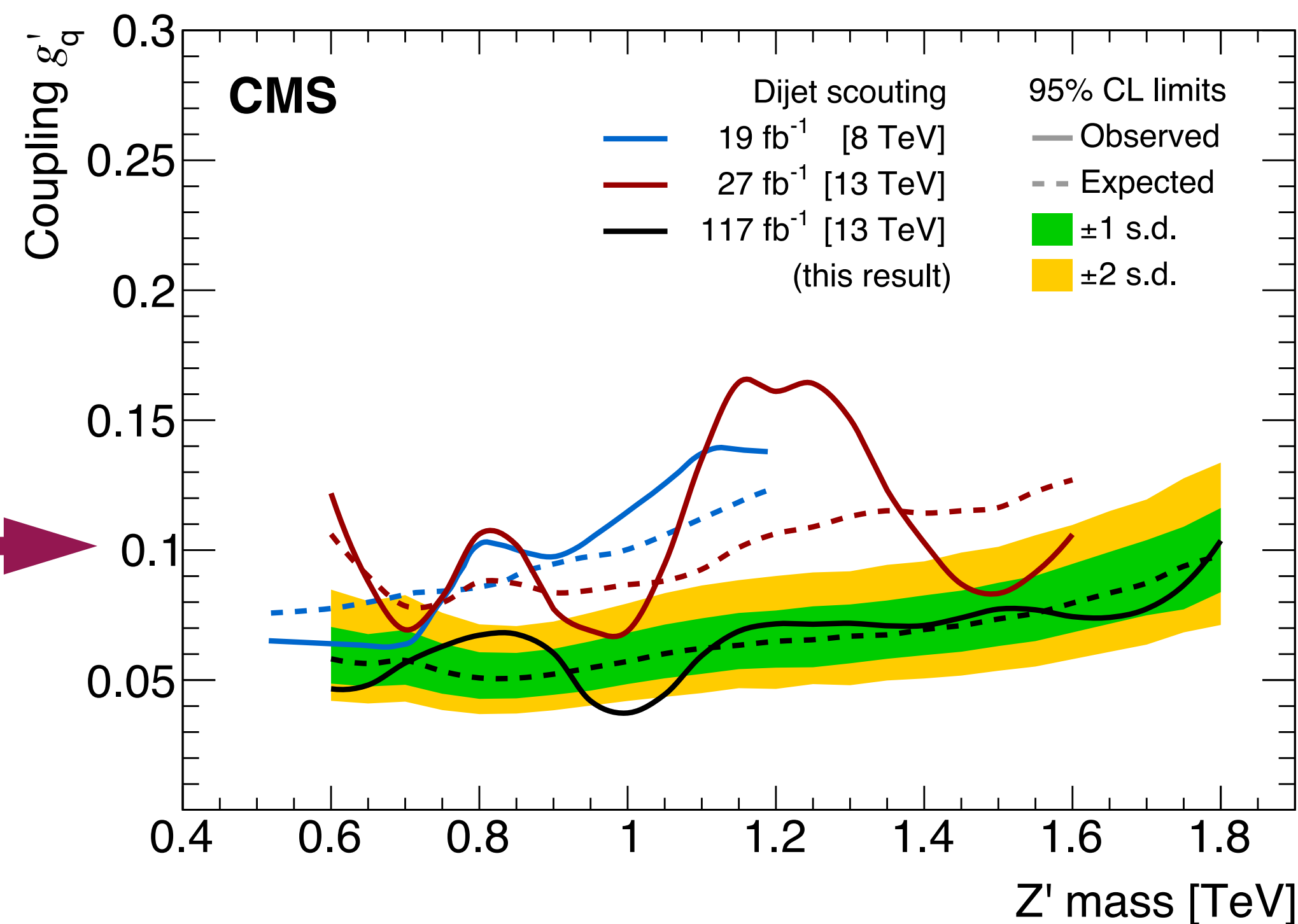
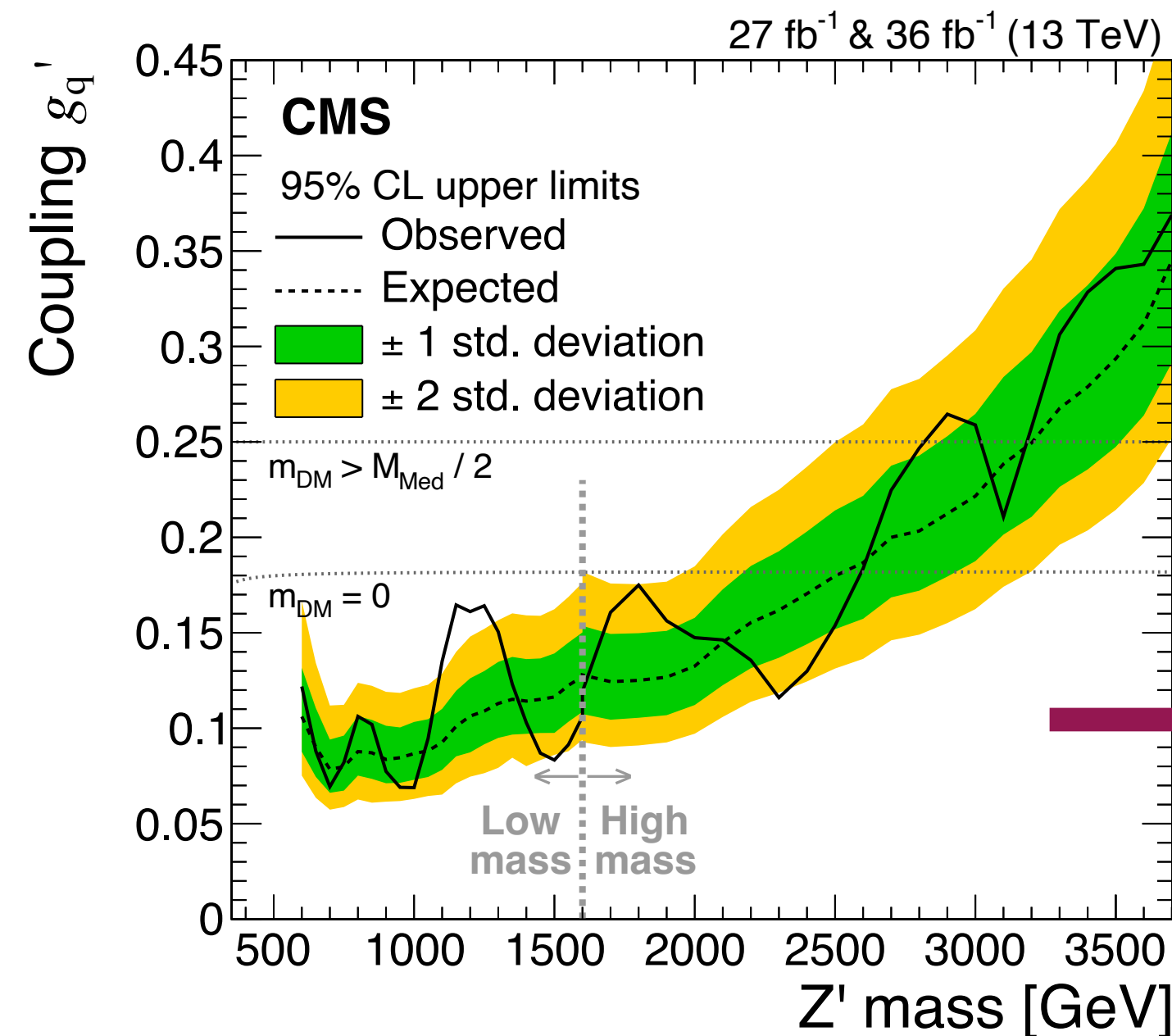
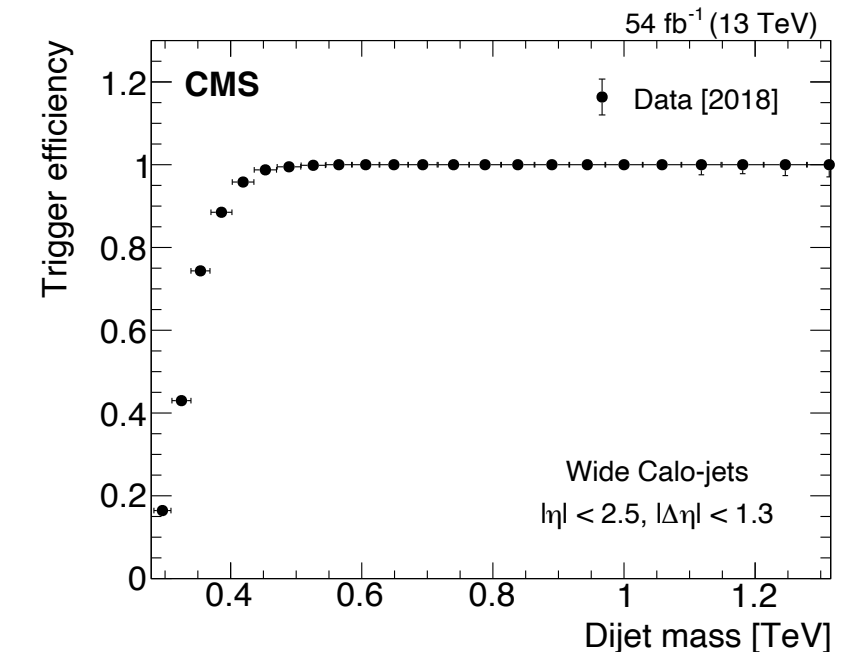


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- Run 2: EXO-16-032 (j.physletb.2017.02.012), EXO-16-056 (JHEP08(2018)130); EXO-23-004 (JHEP04(2026)133)



Dijet resonance search (full Run 2 data set)

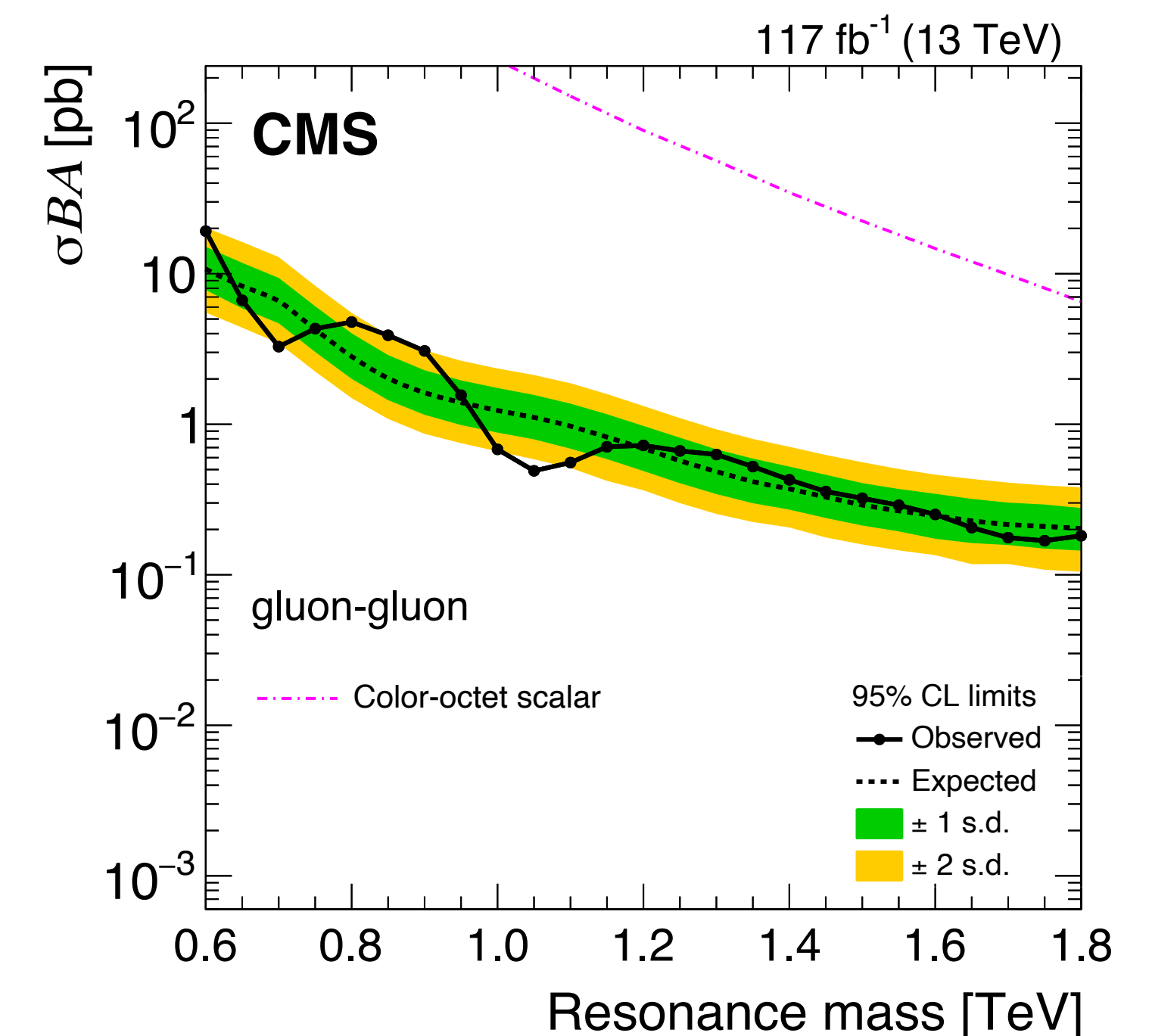
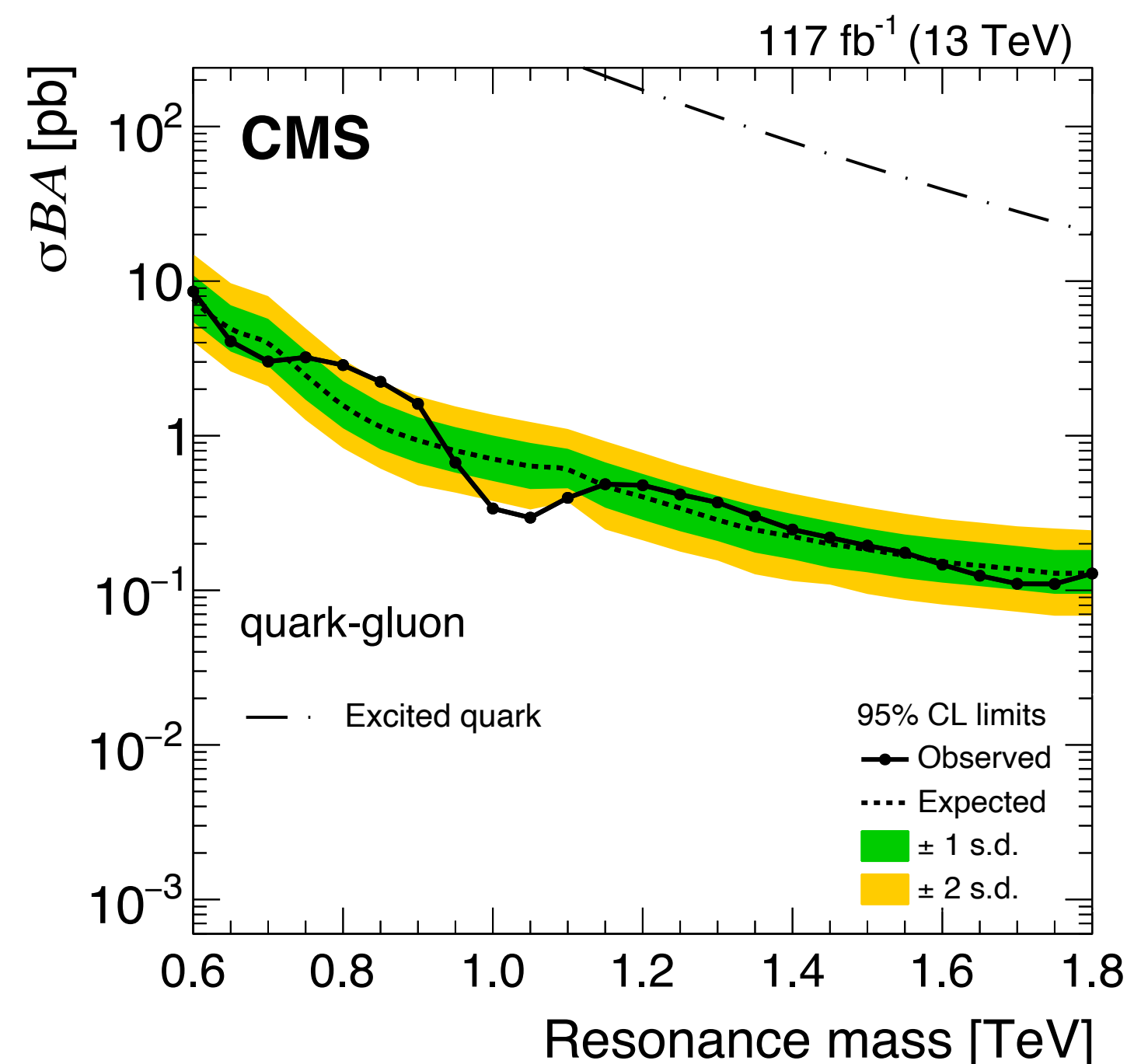
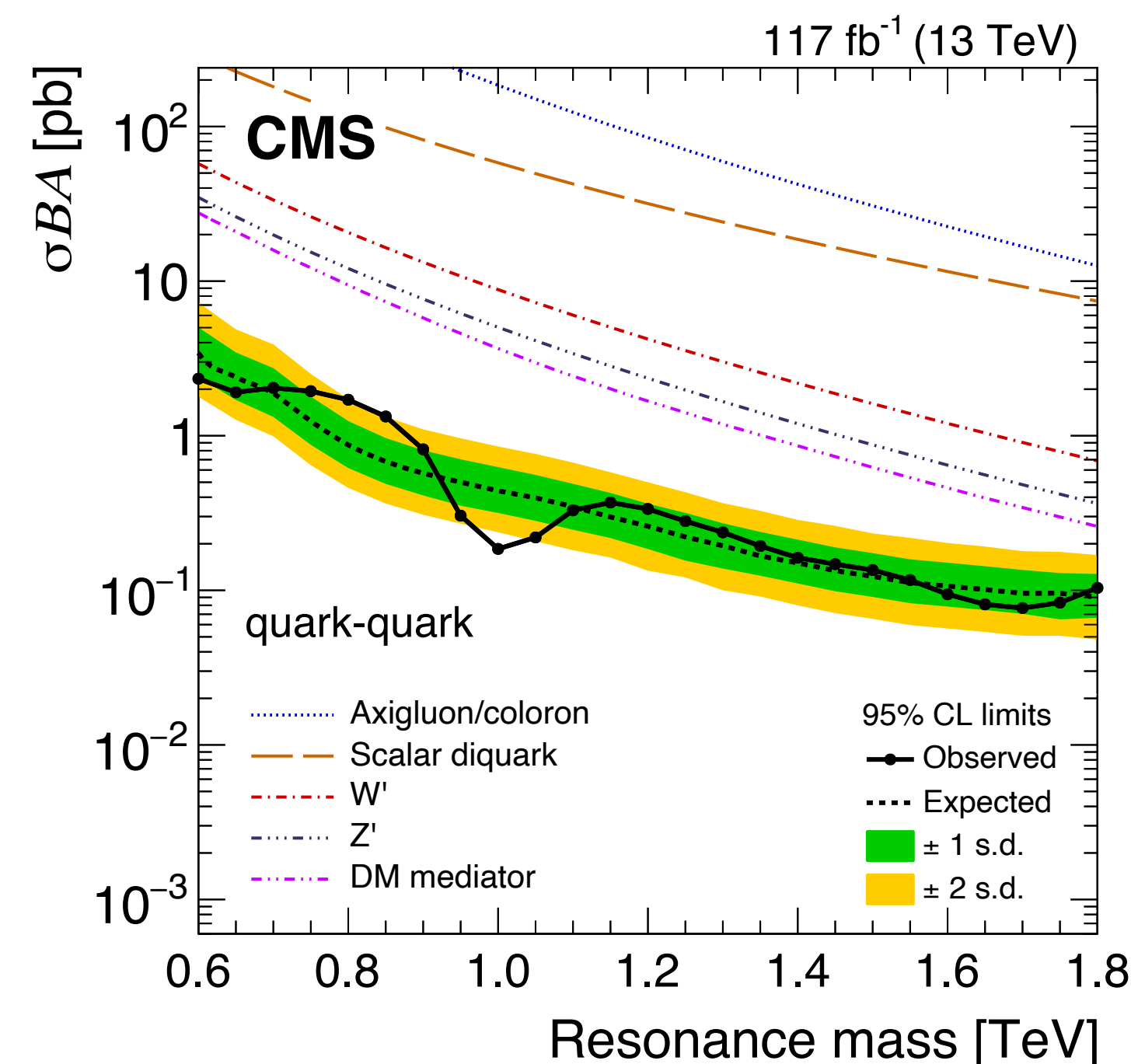
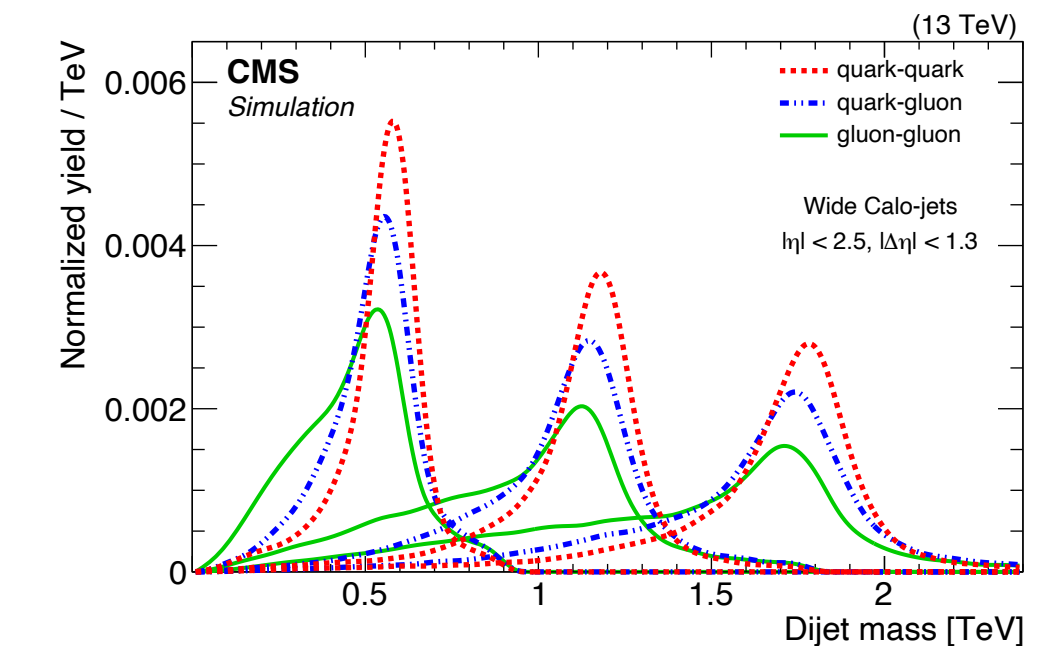
- ❖ Calo Scouting : $H_T > 250$ GeV
- ❖ Calo jets reclustered into wide jets
- ❖ Separate signal hypotheses for qq , qg , and gg resonances
- ❖ Broad set of BSM models considered (excited quarks, RS gravitons, diquarks, leptophobic resonances, ...)

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Low H_T requirement hugely boosts signal sensitivity at low masses and low couplings:

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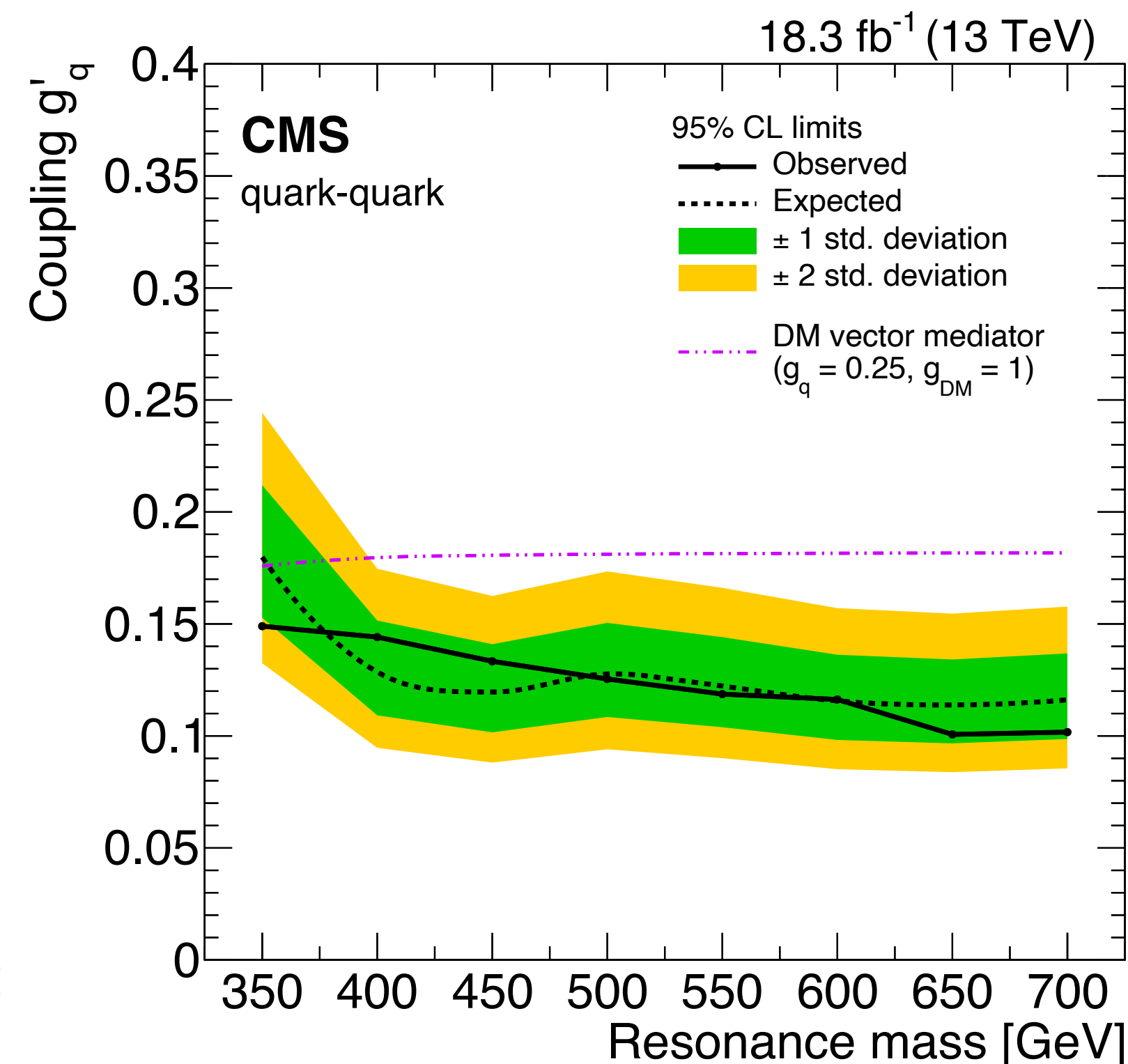
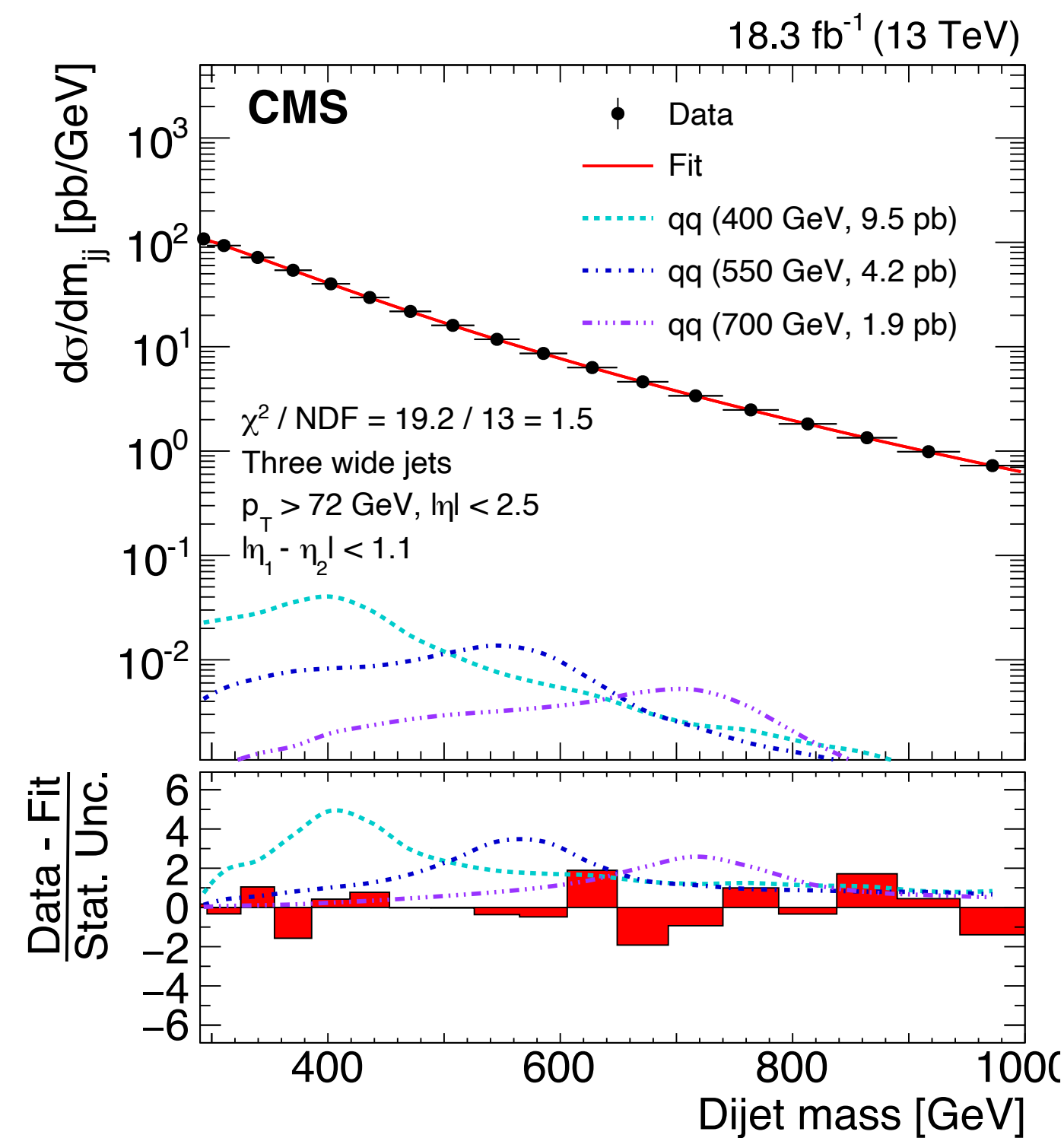
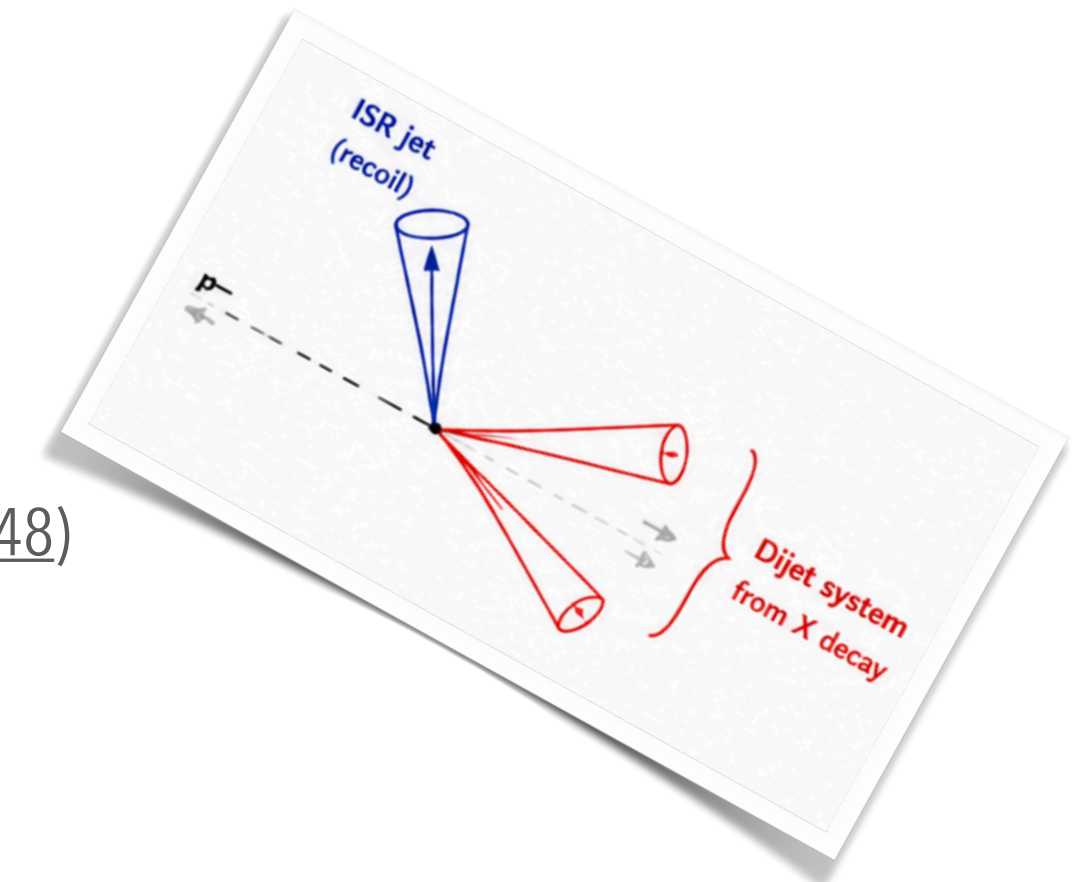


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First ISR scouting search at CMS (2016 data set)

- ❖ Trigger threshold bypass via recoil jet
- ❖ Three-jet selection
- ❖ Data-driven background
- ❖ Reach extended to 350–700 GeV

PHYSICS RESULTS WITH RUN 2 SCOUTING DATA: HADRONIC FINAL STATES

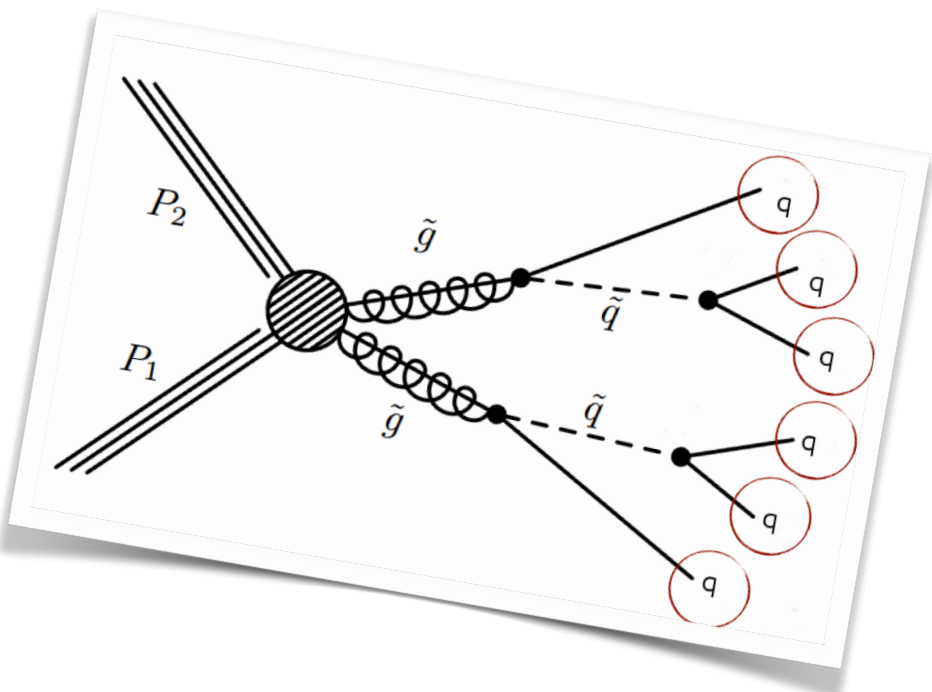
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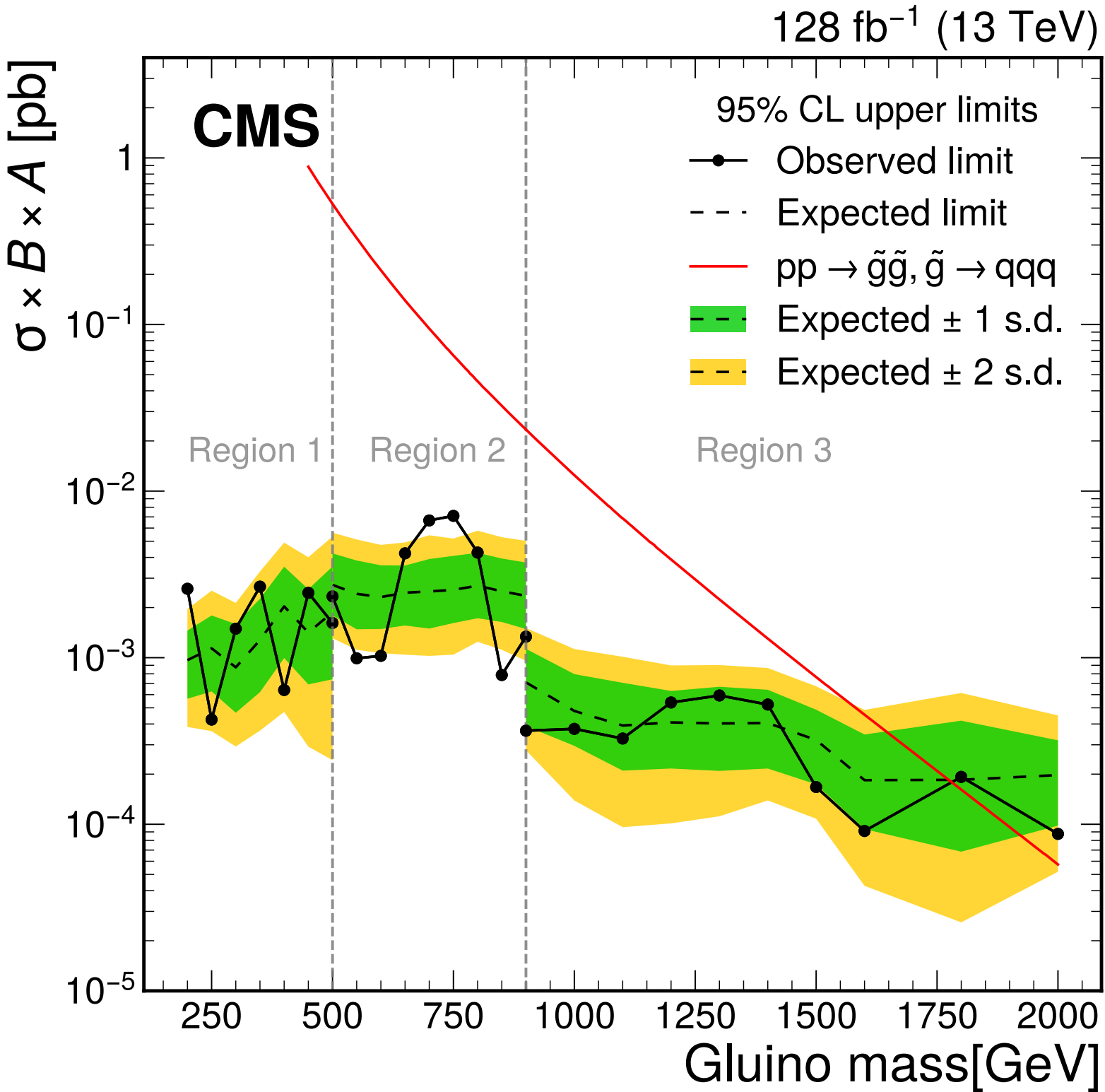
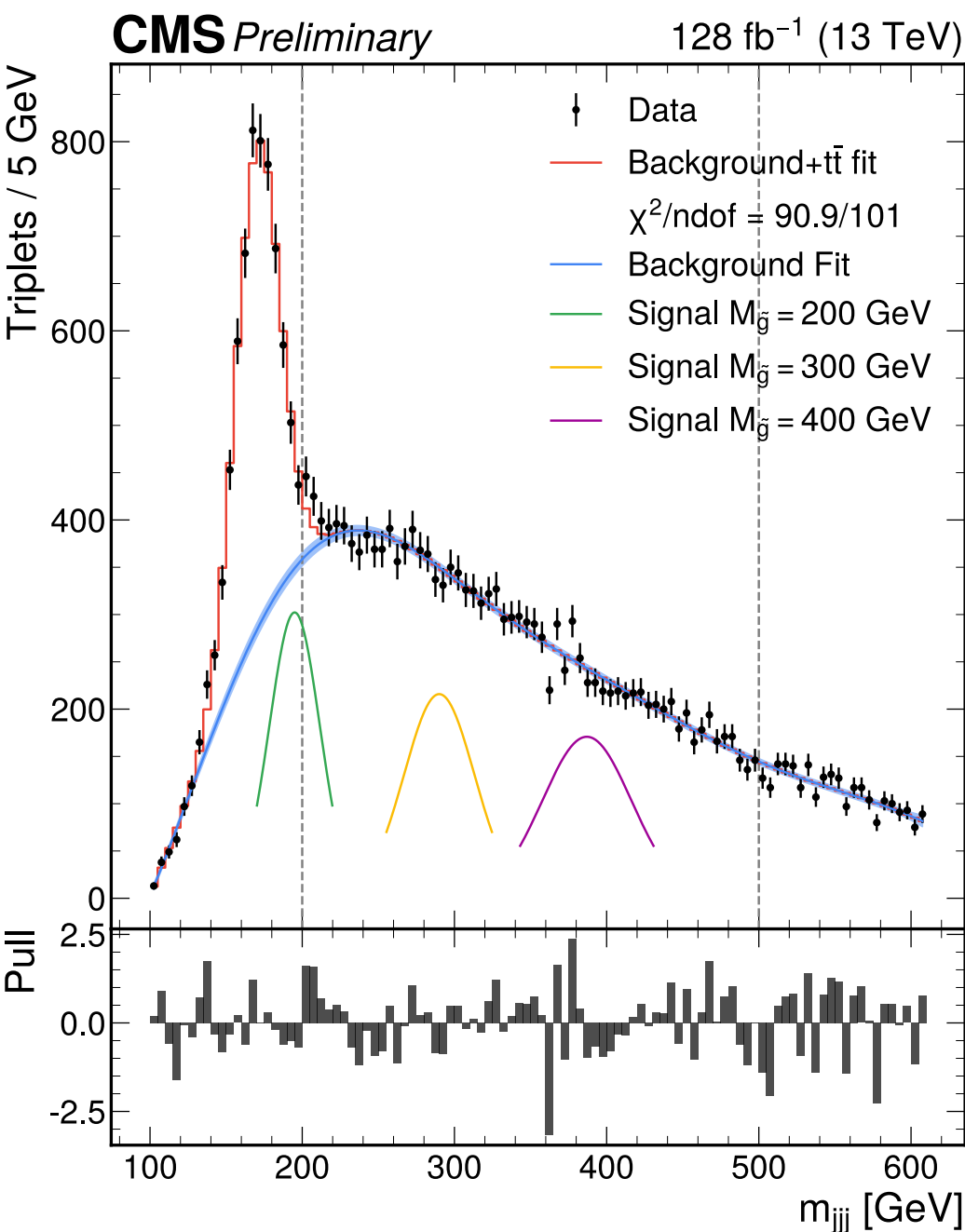
❖ **Pair produced dijet and trijet resonances:**

- EXO-17-030 (PhysRevD.99.012010), EXO-21-004 (PhysRevLett.133.201803)

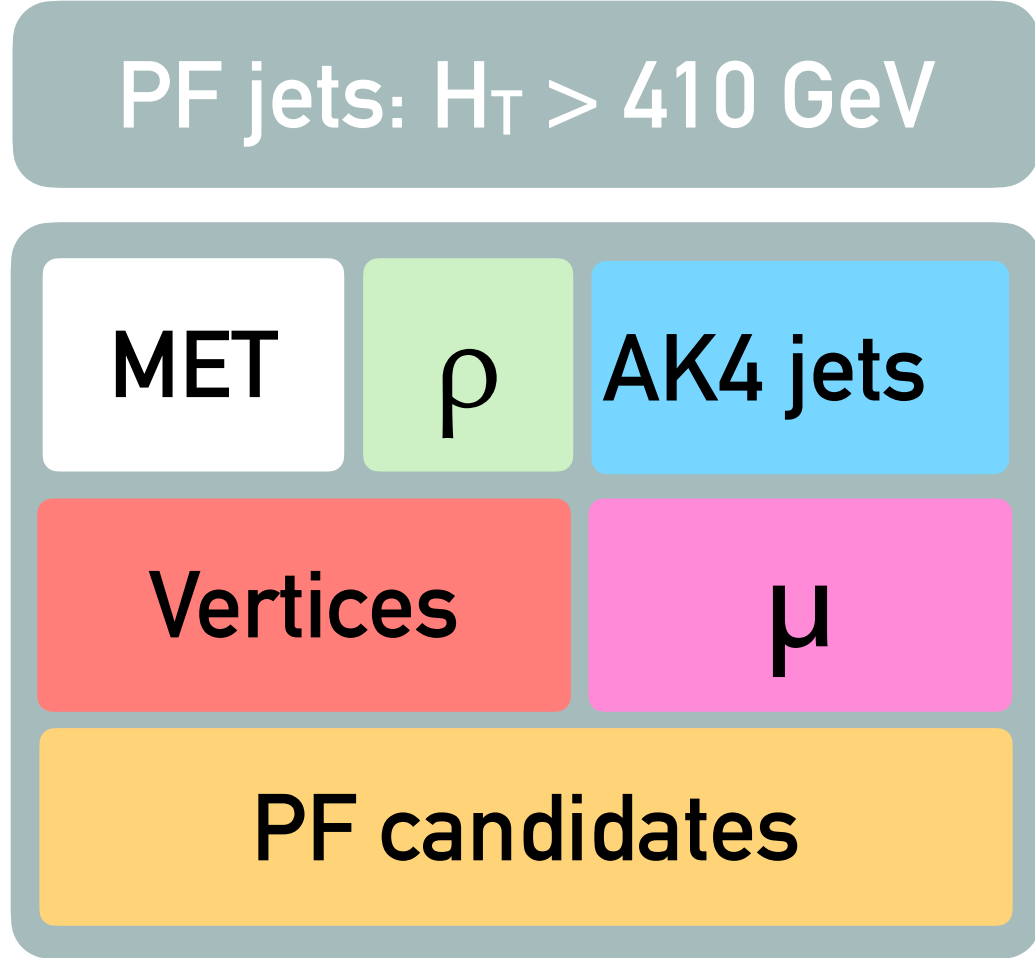


**Pair-produced multijet resonance search
(full Run 2 data set)**

- ❖ PF scouting: $H_T > 410$ GeV
- ❖ Resolved and merged jet topologies:
 - ❖ quark-gluon discrimination methods for the resolved topology
 - ❖ jet substructure techniques for the merged topologies
- ❖ RPV gluinos, top squarks, and higgsinos
- ❖ First fully hadronic search for EW RPV higgsinos



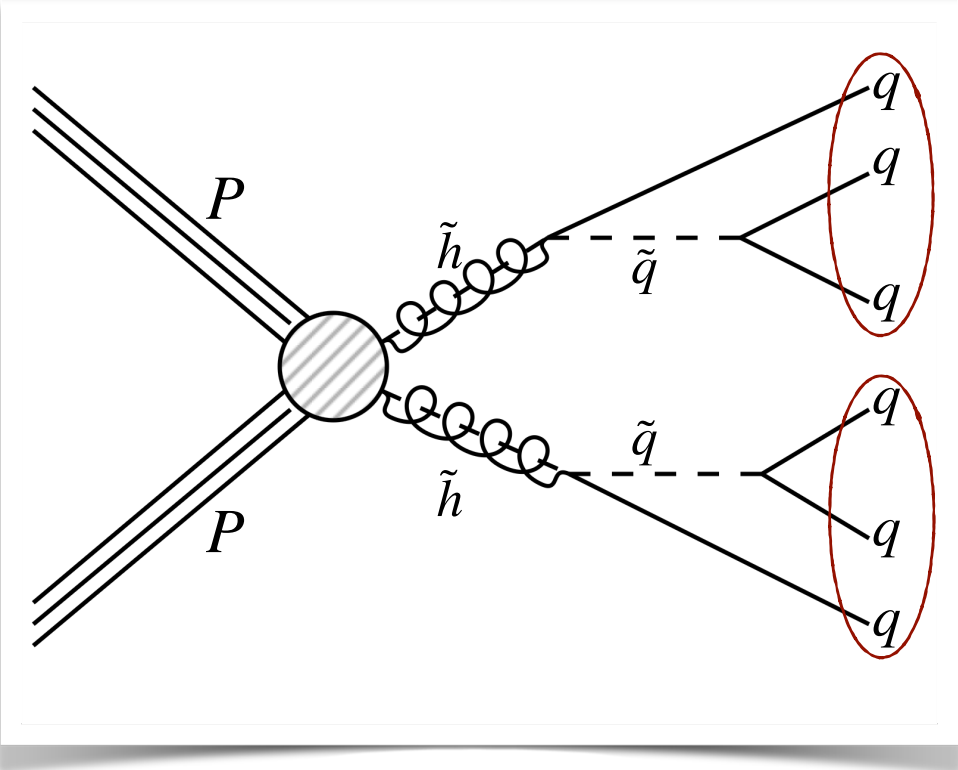
RUN 2: PROBING DATA SCOUTING POTENTIAL IN HADRONIC FINAL STATES



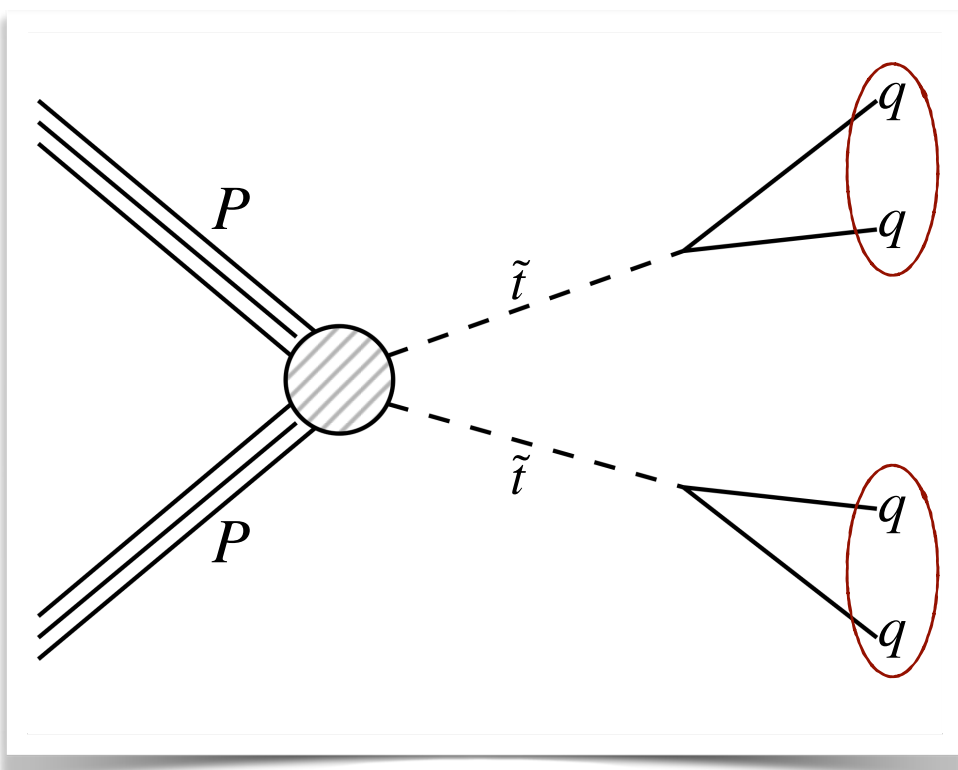
Pair-produced multijet resonances

(full Run 2 data set: [PhysRevLett.133.201803](#))

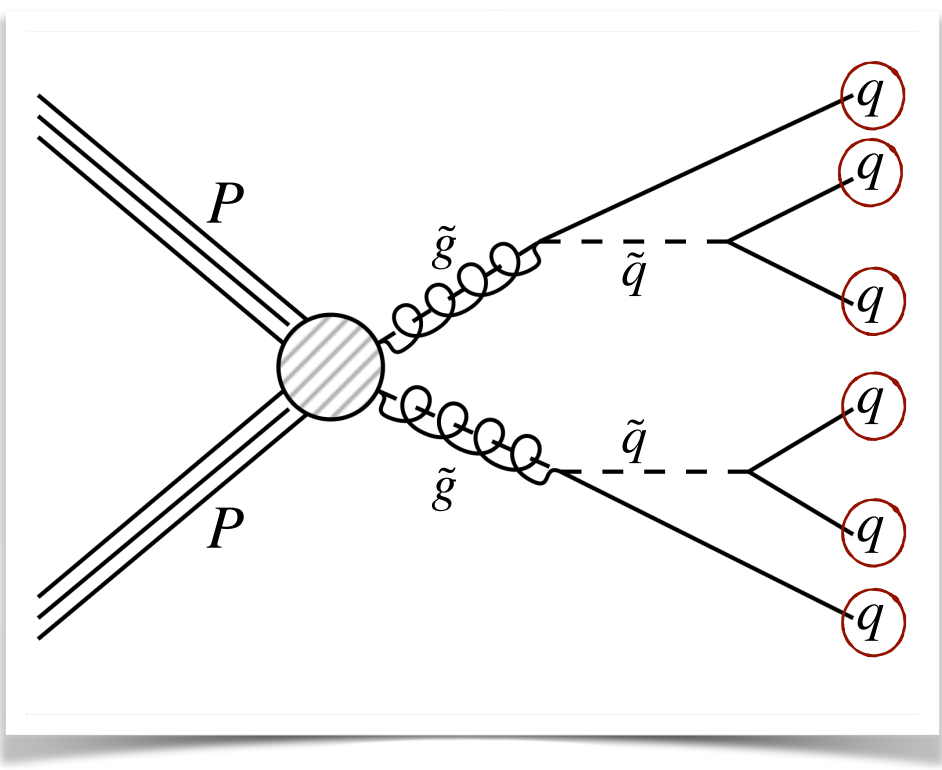
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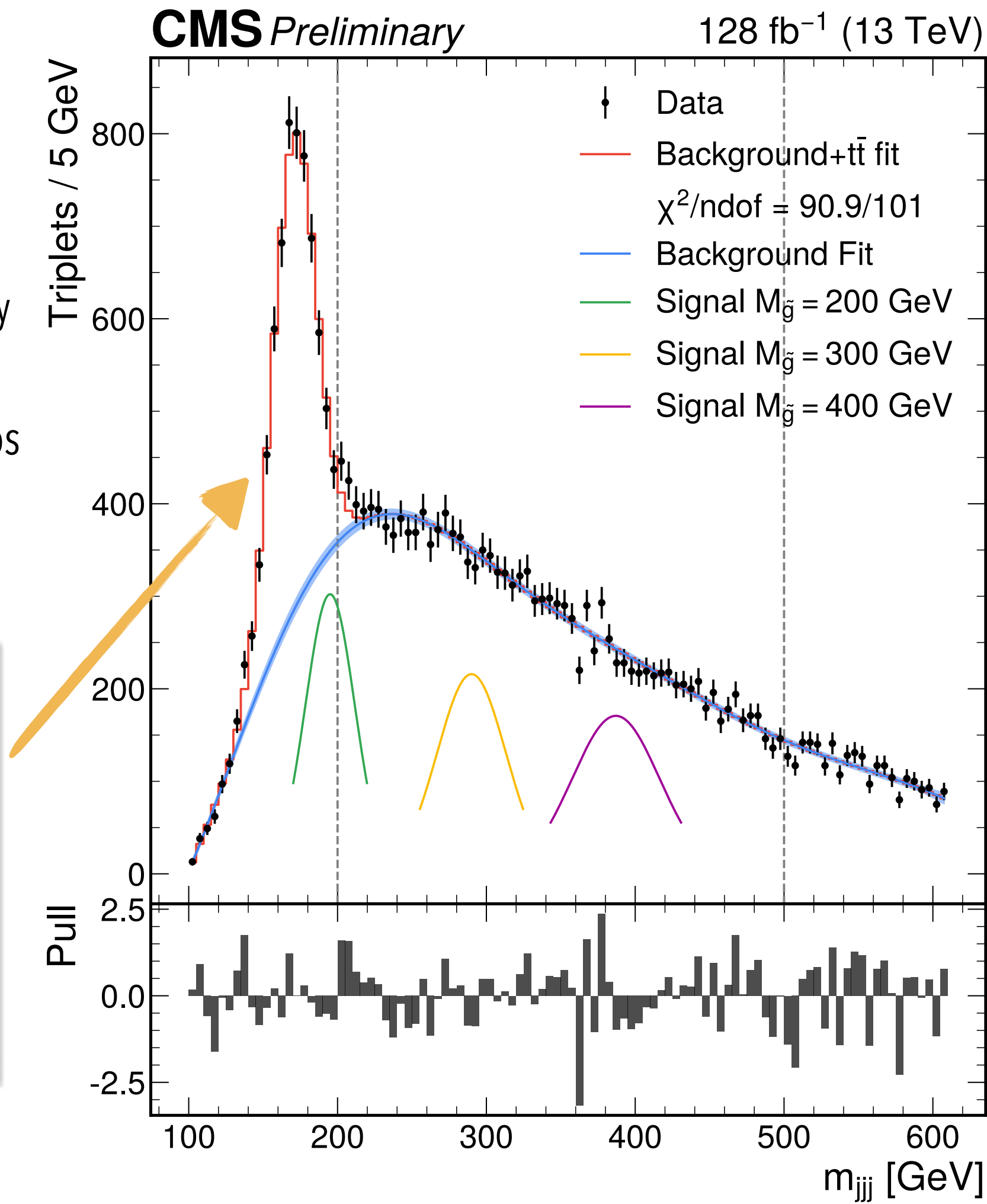
Merged trijet



Merged dijet



Resolved trijet



PHYSICS RESULTS WITH RUN 2 SCOUTING DATA: HADRONIC FINAL STATES

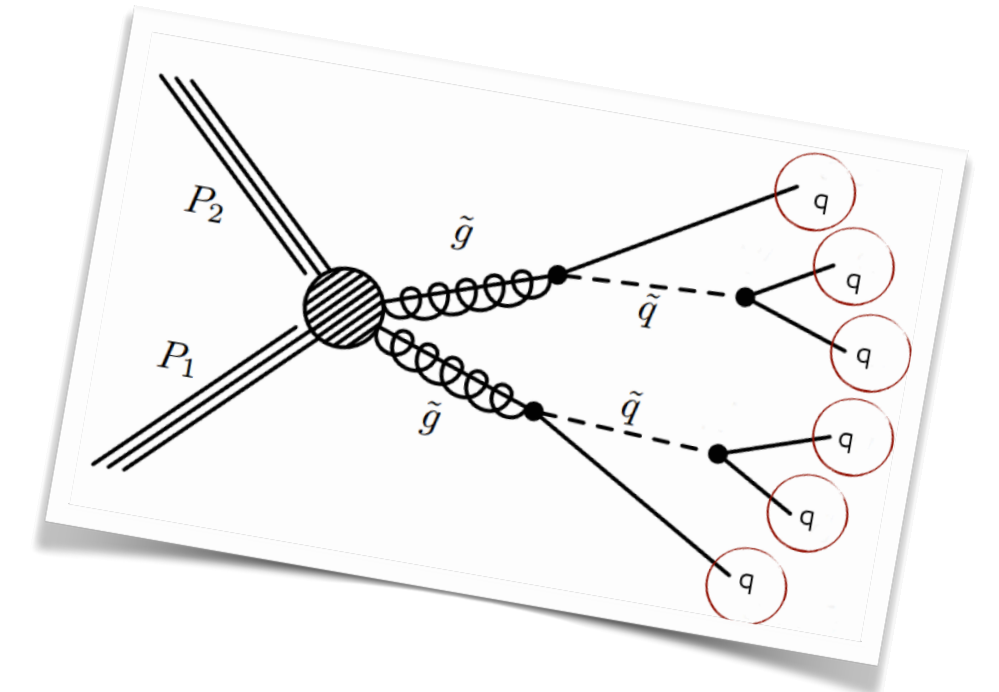
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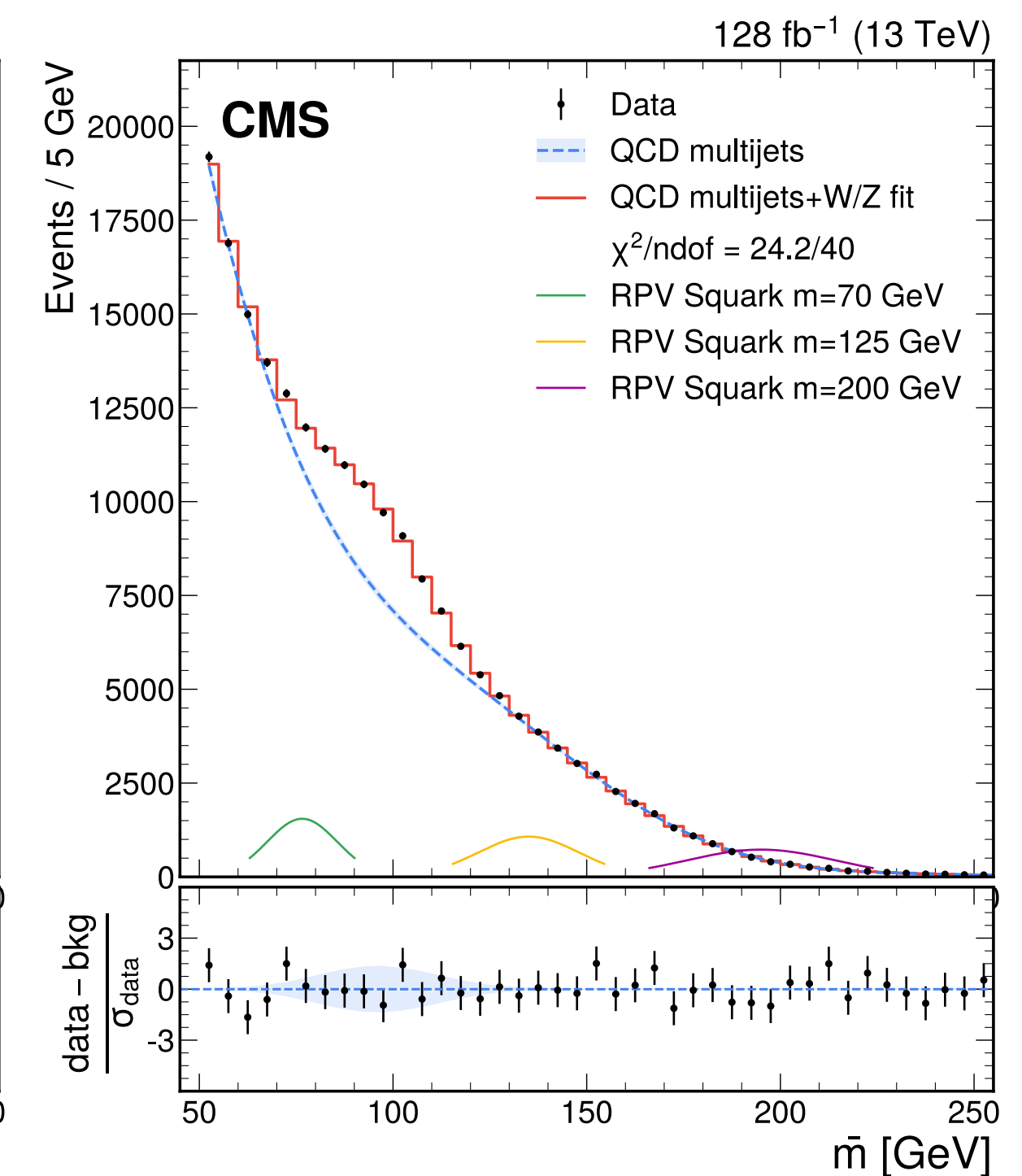
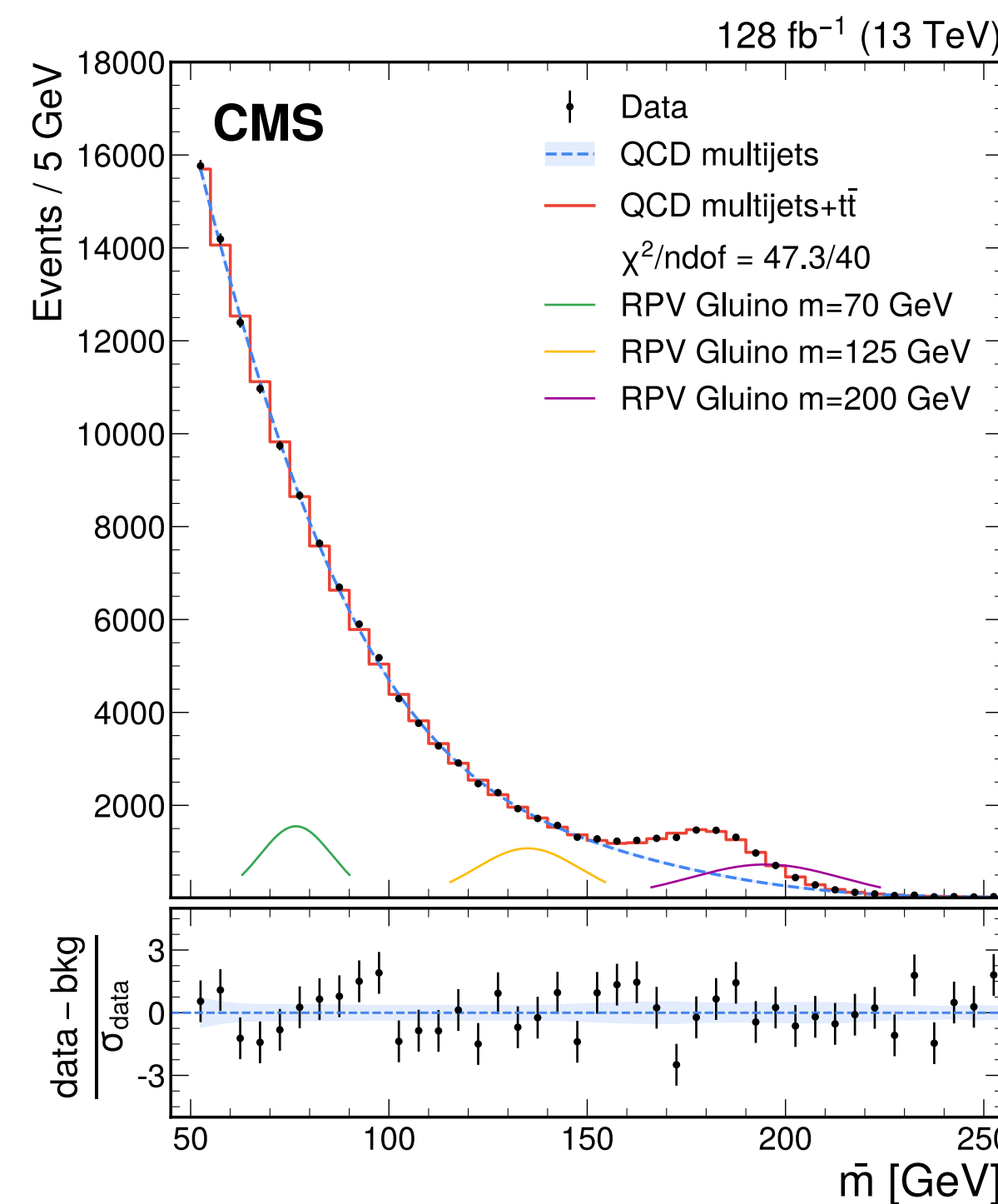
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- ❖ RPV gluinos, top squarks, and higgsinos
- ❖ First fully hadronic search for EW RPV higgsinos

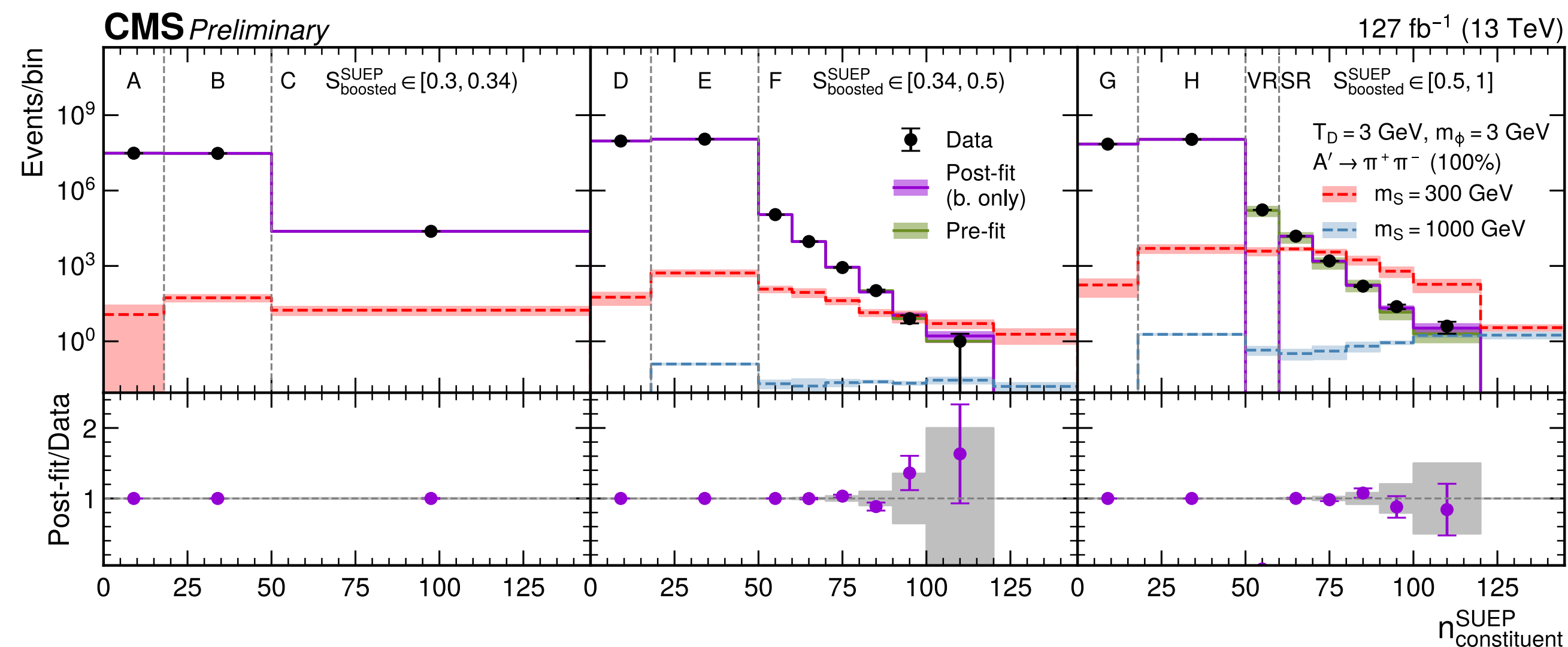
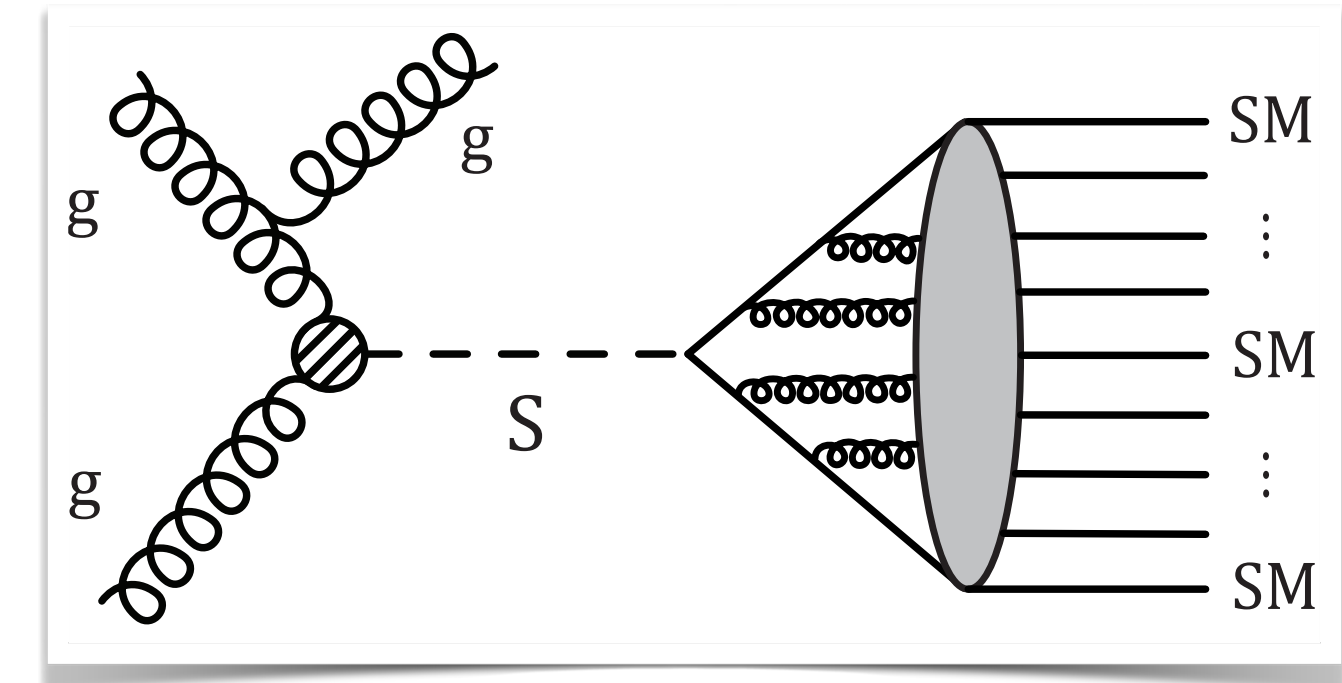


PHYSICS RESULTS WITH RUN 2 SCOUTING DATA: SUEP_s

Search for soft unclustered energy patterns in p-p collisions (full Run 2 data set)

◆ Model:

- High multiplicities of diffusely distributed, low-momentum charged particles
- Predicted by hidden valley models with a large 't Hooft coupling



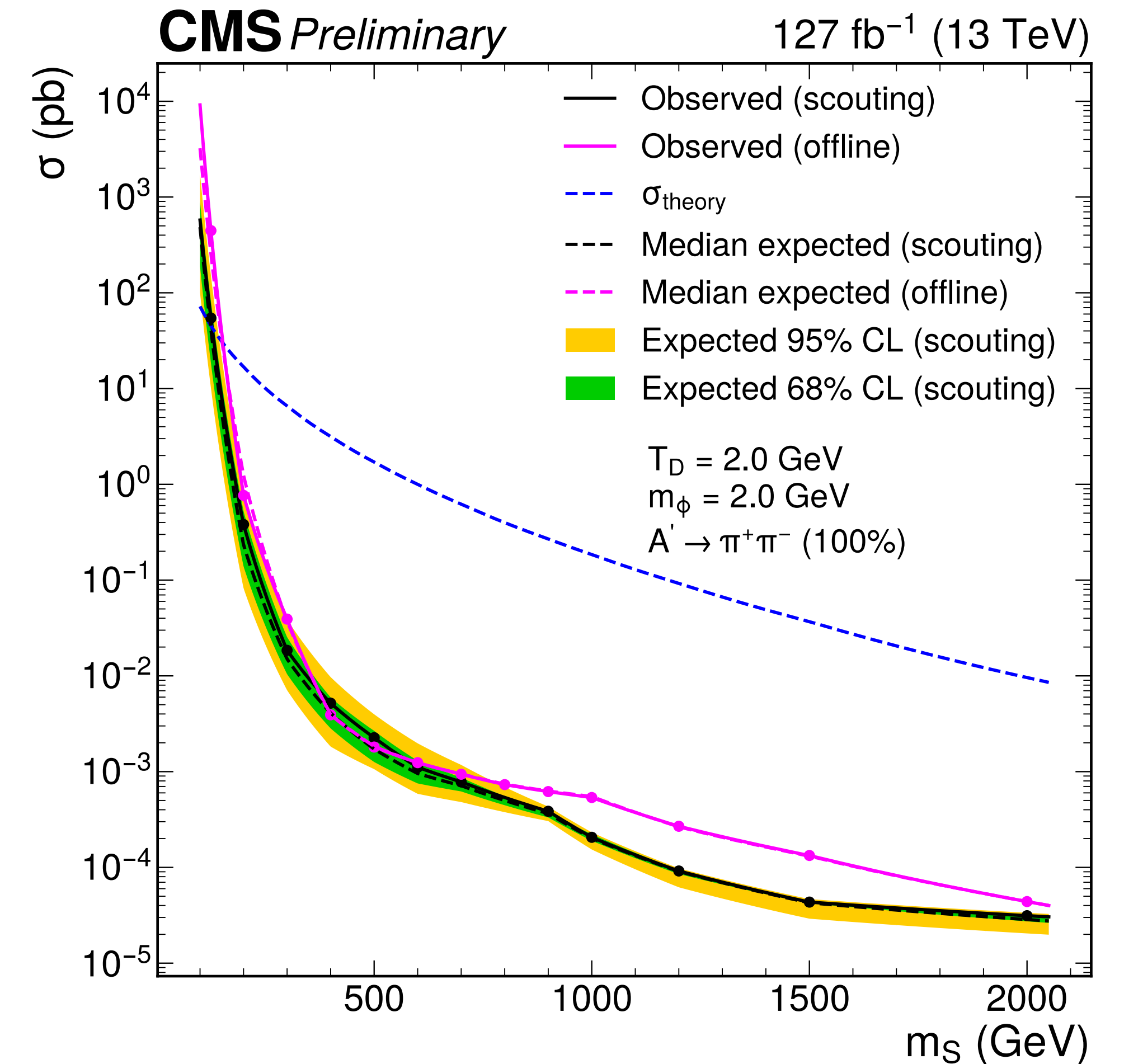
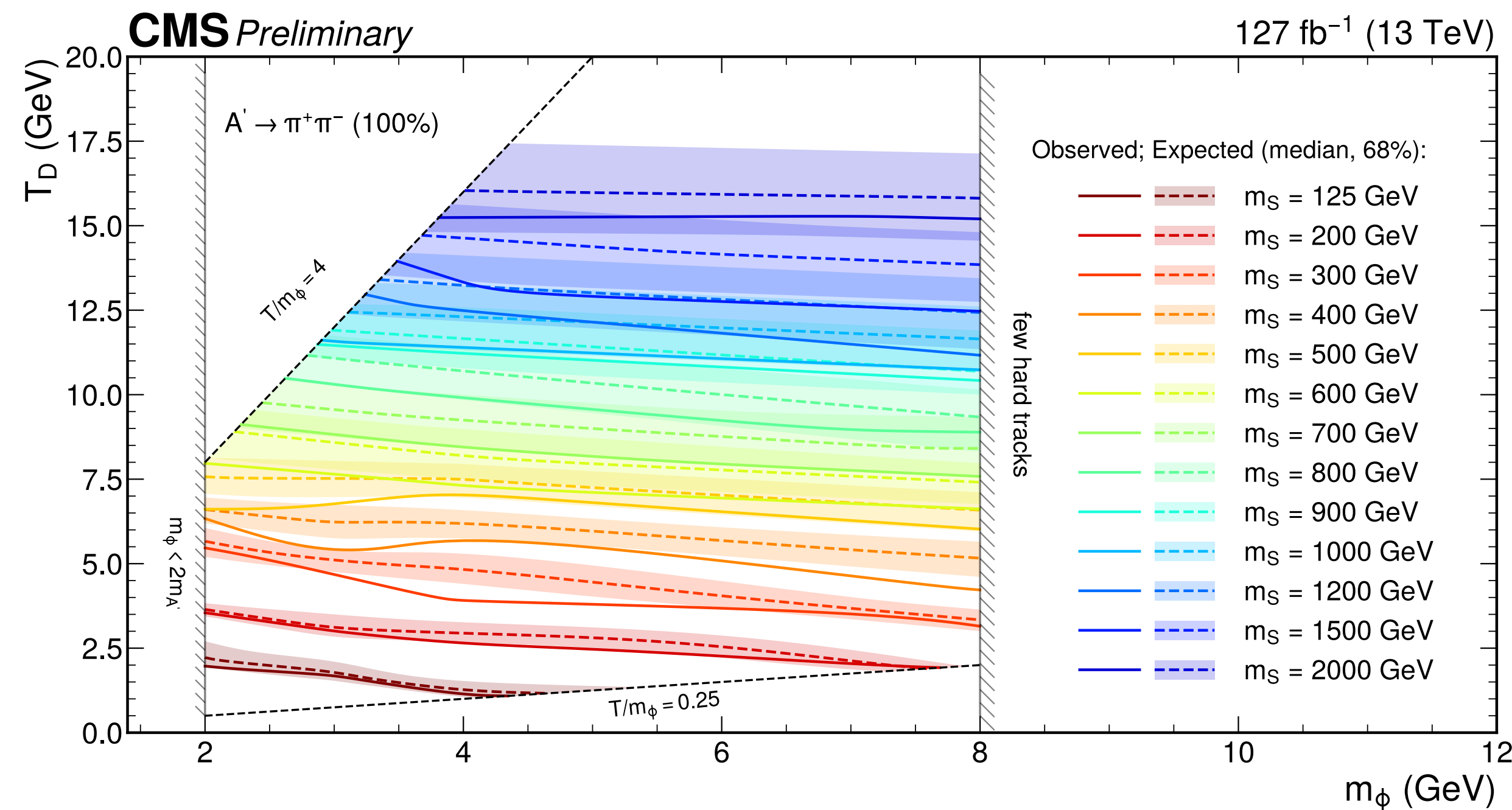
◆ Analysis strategy:

- PF Scouting stream
- Lower threshold on the hadronic activity at HLT (from 1050 to 410 GeV) increase acceptance for SUEP signatures, especially for lower mediator mass models
- Large radius objects (AK15) reconstructed from PF candidates
 - able to mimic the offline capabilities even with online objects reliably

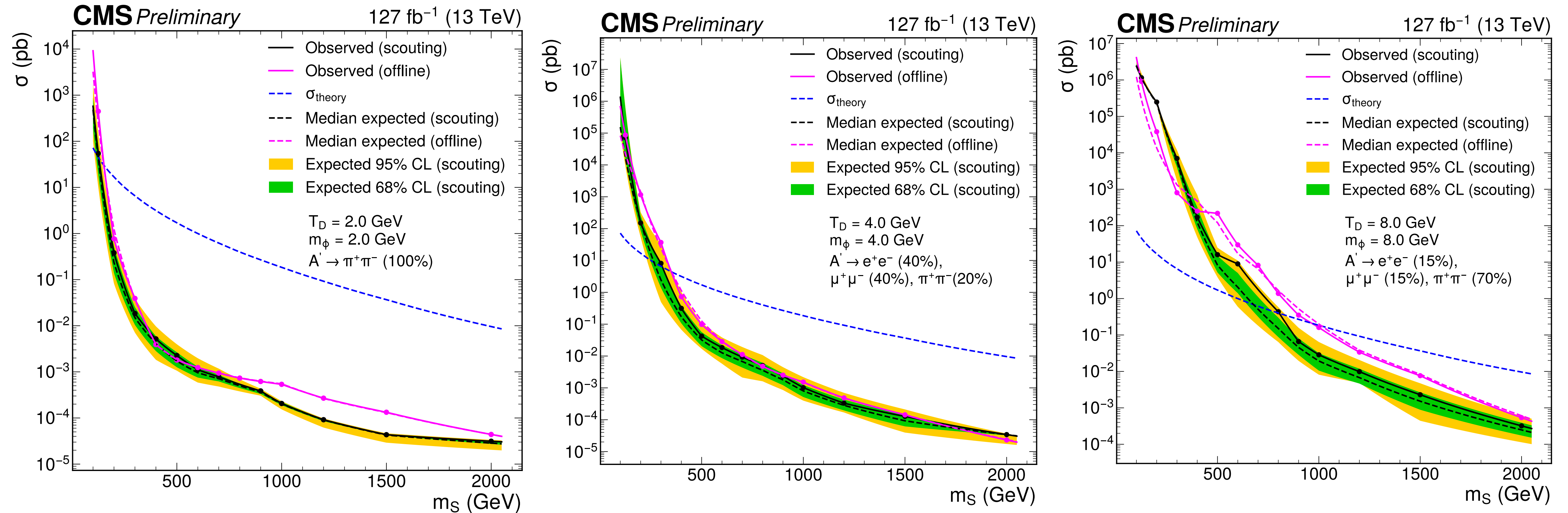
PHYSICS RESULTS WITH RUN 2 SCOUTING DATA: SUEP_s

Search for soft unclustered energy patterns in p-p collisions (full Run 2 data set)

- Most stringent limits to date are set on the gluon fusion production of heavy scalar mediators

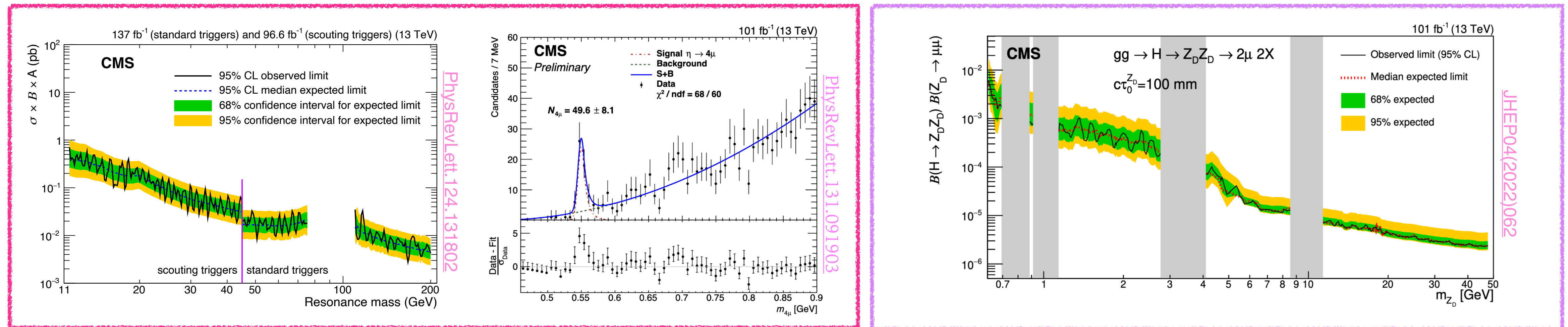


PHYSICS RESULTS WITH RUN 2 SCOUTING DATA: SUEP_s



PHYSICS RESULTS WITH RUN 2 SCOUTING DATA: PROMPT & DISPLACED MUONS

Dedicated muon algorithms with low p_T thresholds (3 GeV) and no constraints on the primary vertex allowed to access otherwise inaccessible phase spaces both for **prompt** and **displaced** resonance production searches



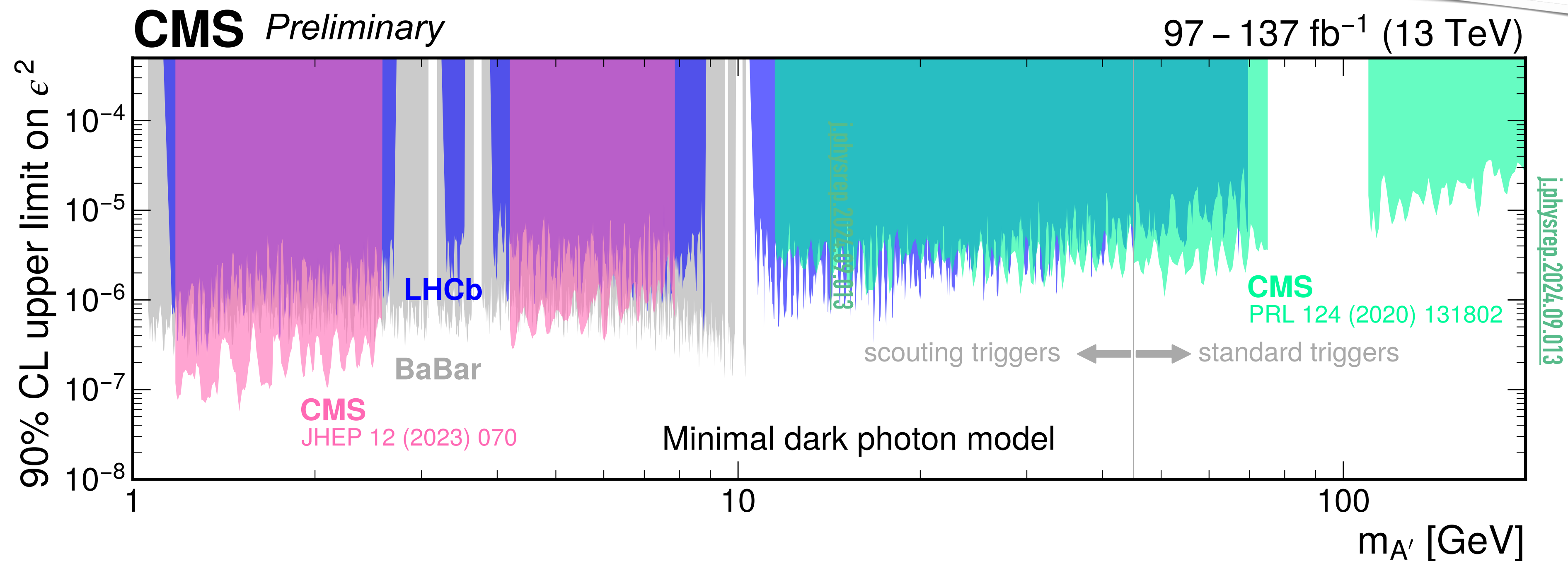
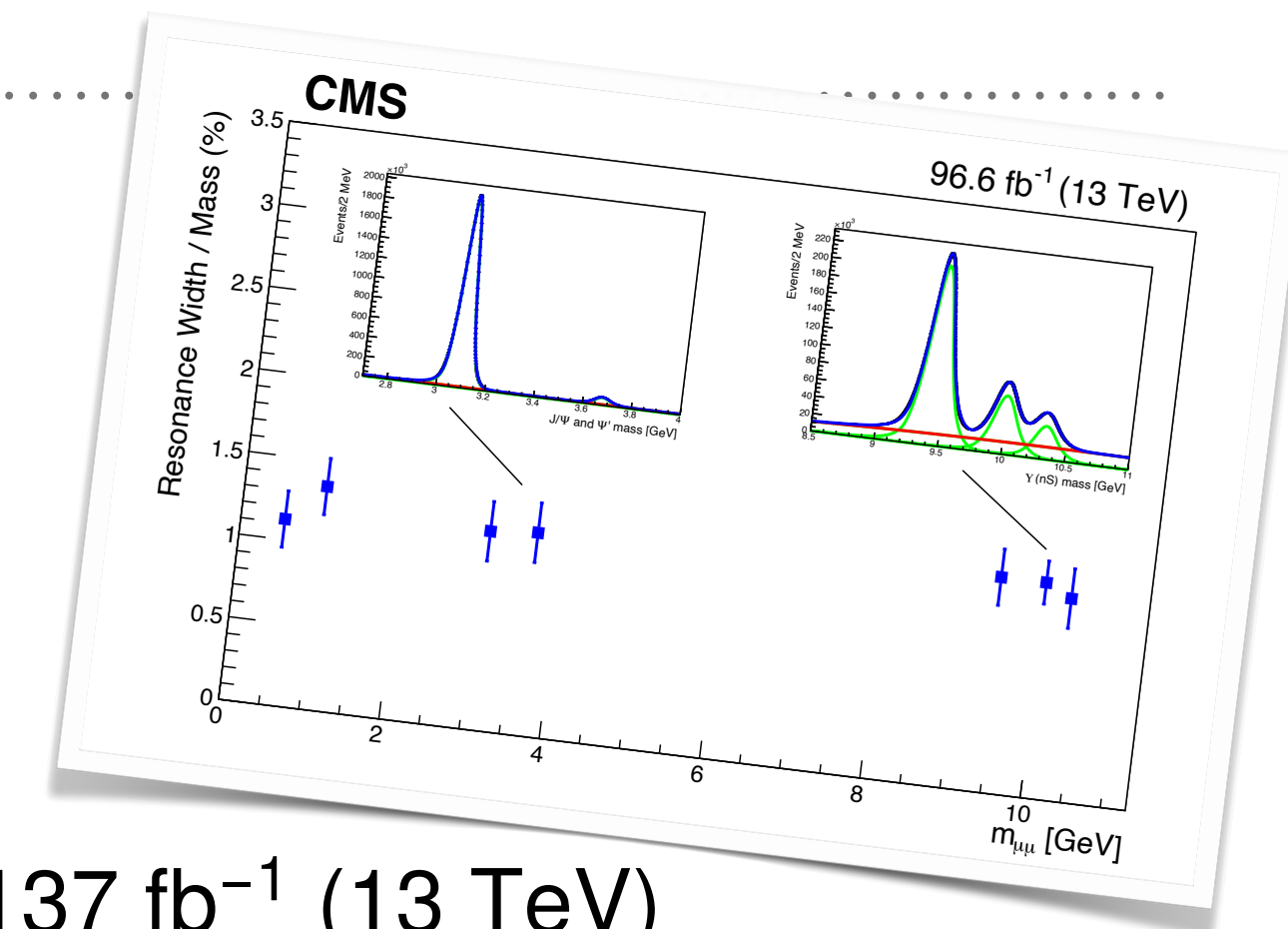
Why muons are special objects for physics analyses (both measurements and searches)
also in scouting?

- [1] Very clean final states which can be completely reconstructed
- [2] Online and offline reconstruction is very similar!

PHYSICS RESULTS WITH RUN 2 SCOUTING DATA: PROMPT MUONS

- ◆ Searches for prompt production of dimuon resonances at GeV scale:

- The dimuon spectrum at the GeV scale was studied by CMS for the first time with scouting data from Run 2
- Calo Scouting stream: muon thresholds down to 3 GeV
- **Expanding the CMS physics reach into territory not originally envisioned for the experiment!**

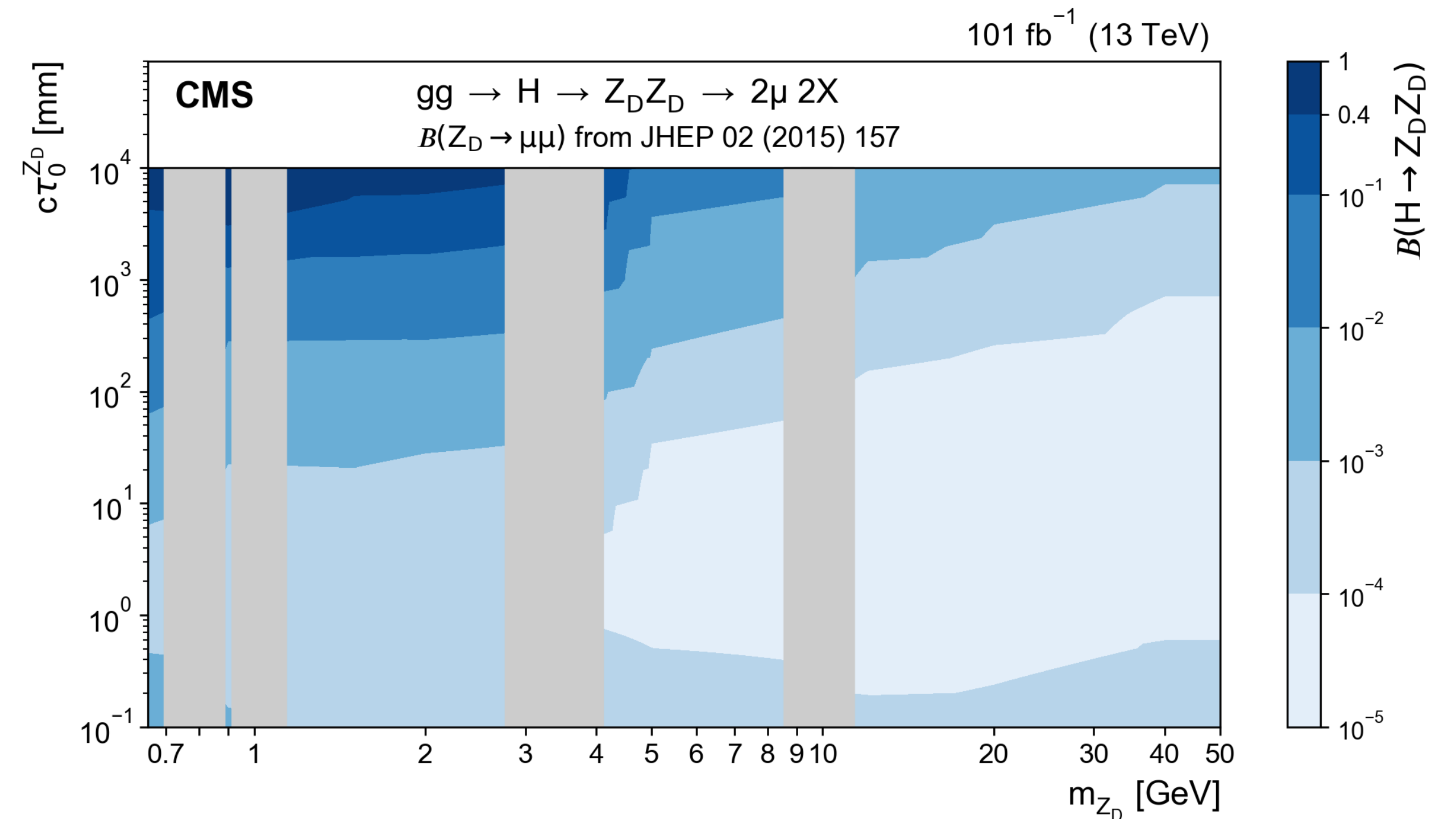
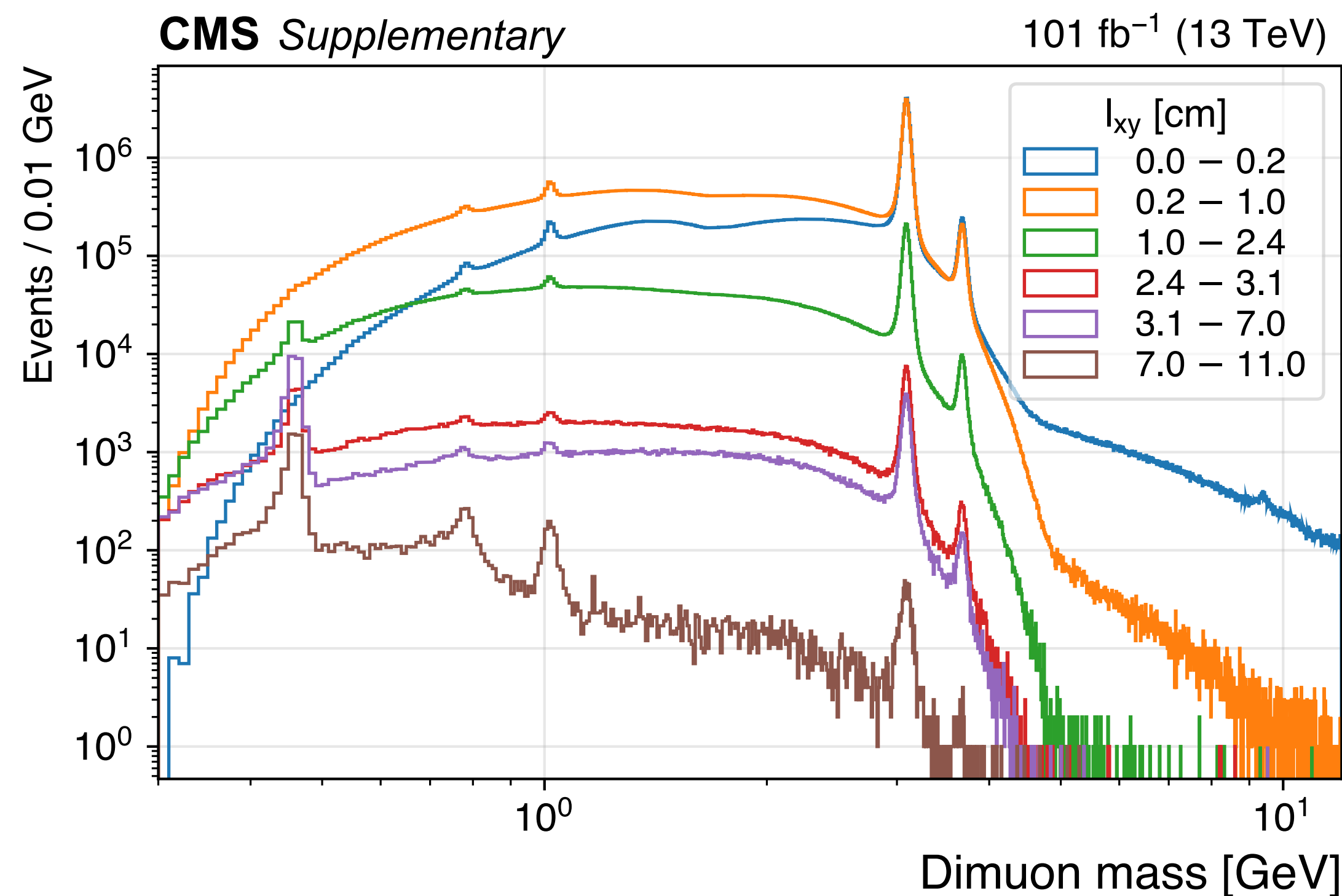
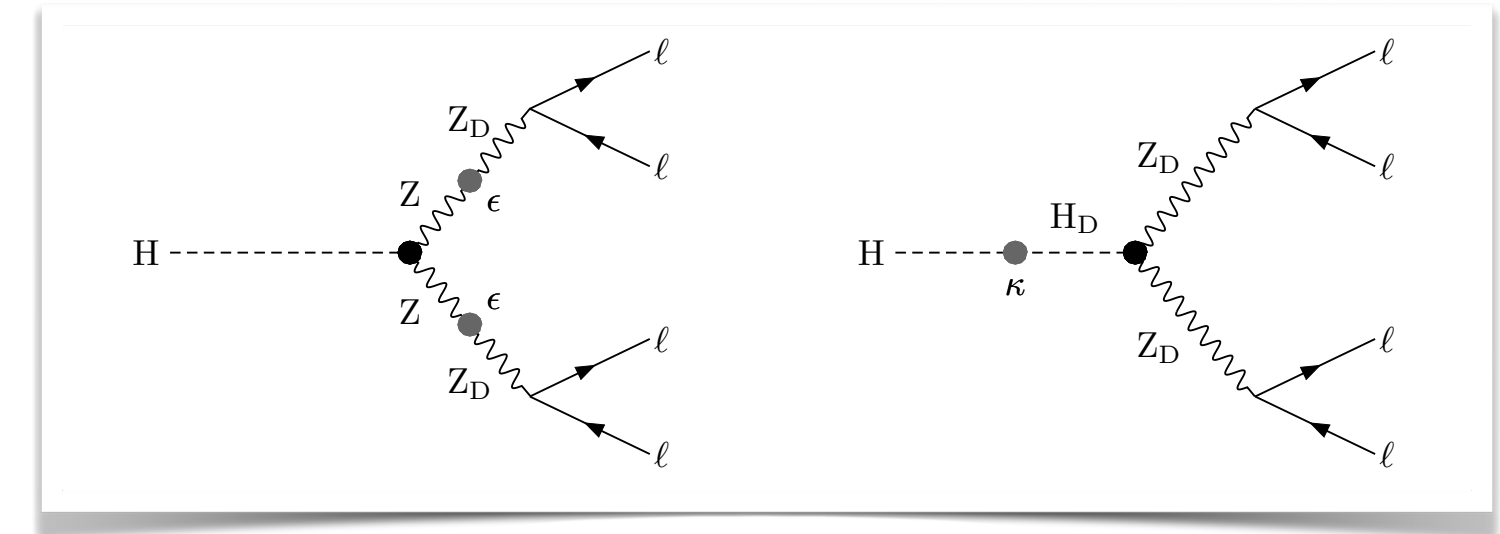


NOTE: Same (and broader) mass range can be now explored with the new Run 3 parking dataset with inclusive dimuon parking triggers!

PHYSICS RESULTS WITH RUN 2 SCOUTING DATA: DISPLACED MUONS

◆ Searches for production of displaced dimuon resonances at GeV scale:

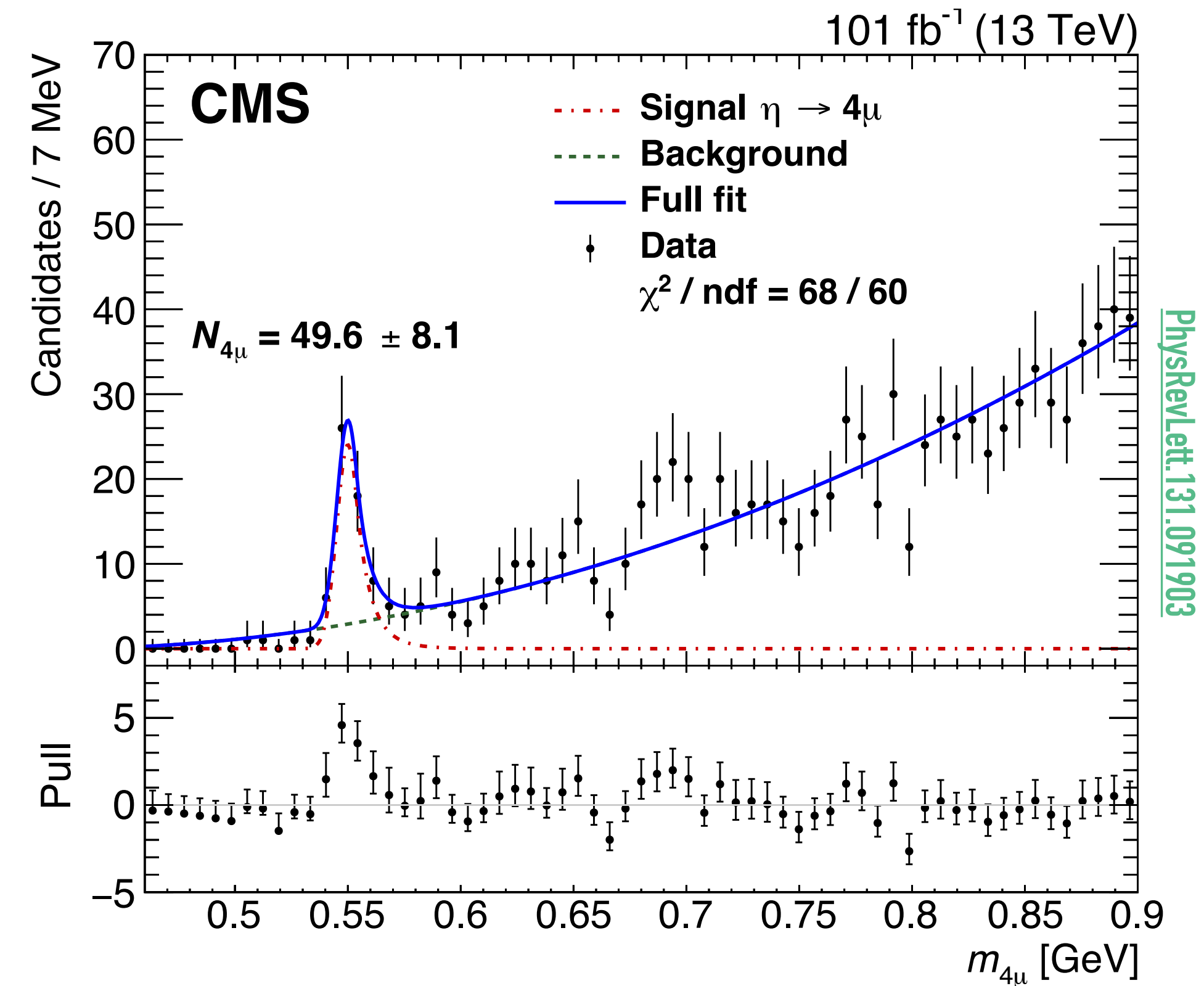
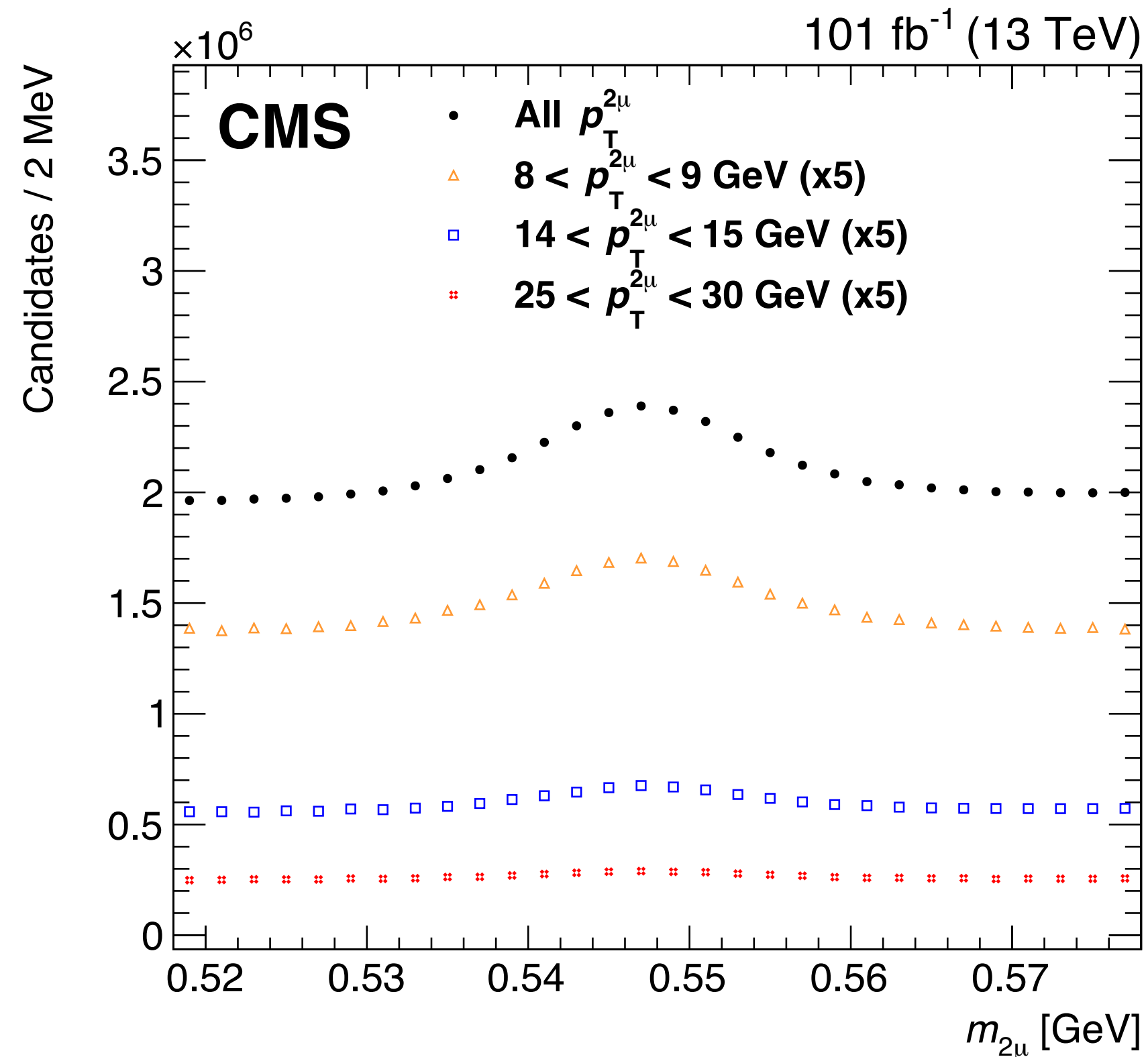
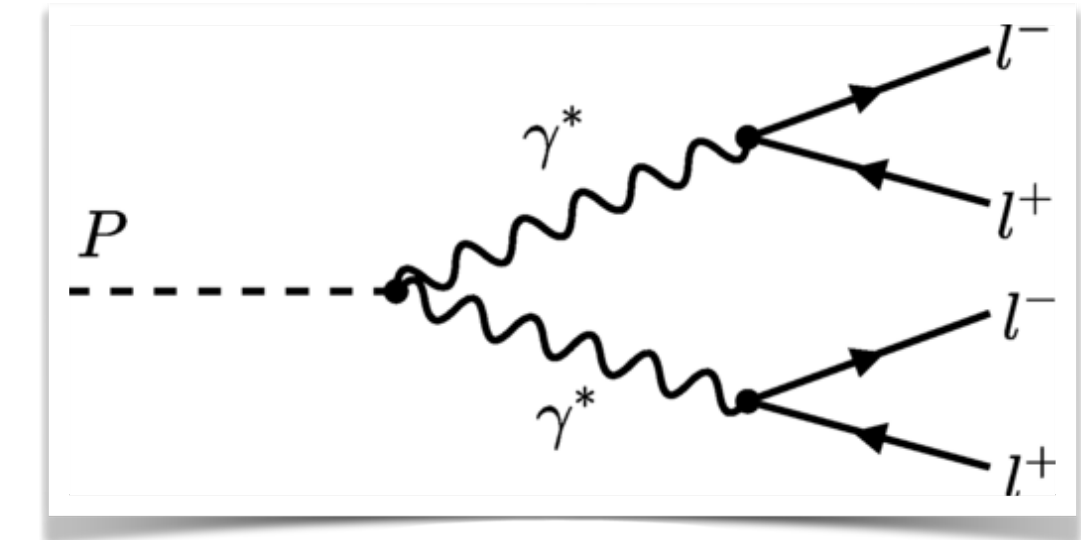
- Calo Scouting stream: muon thresholds down to 3 GeV
- Dedicated vertex reconstruction without constraints to the primary vertex



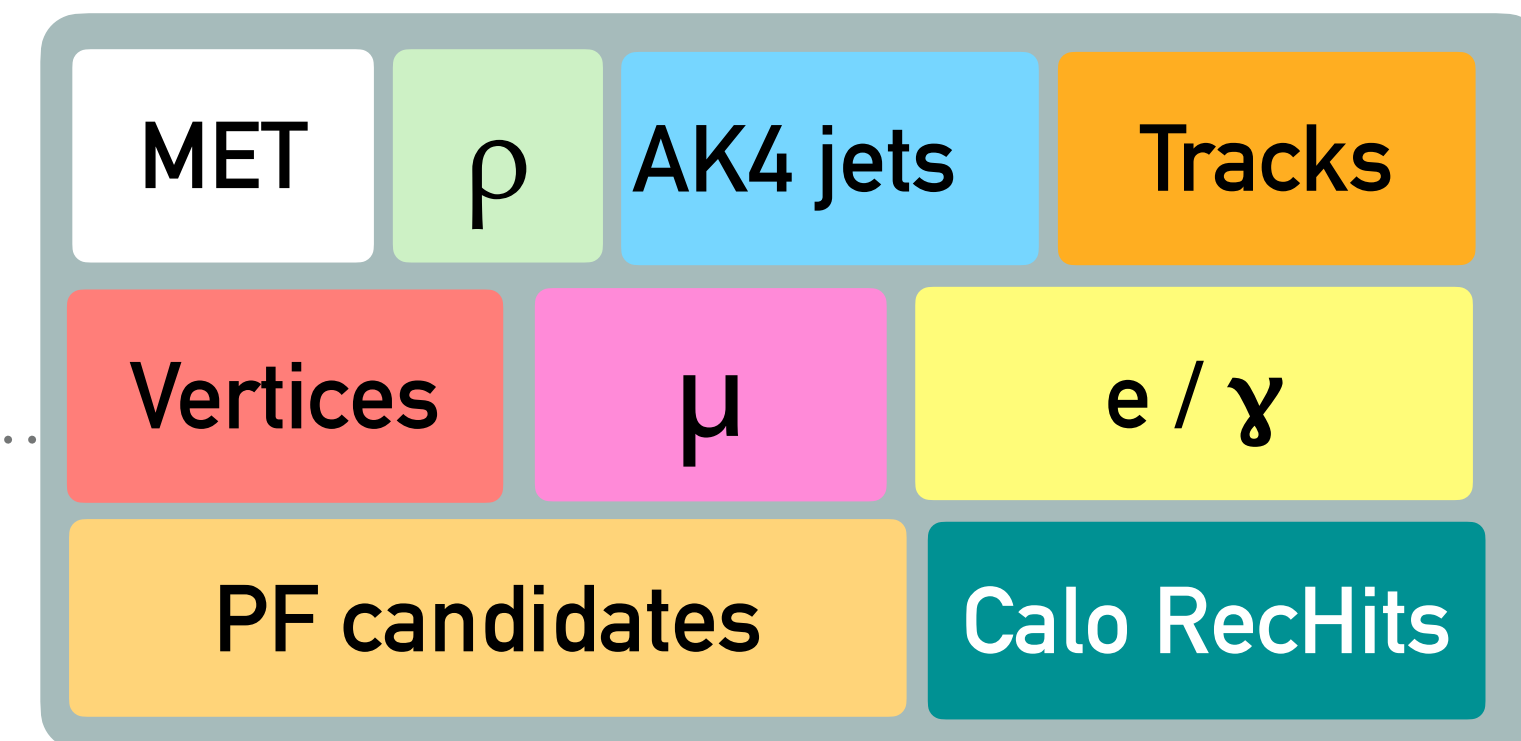
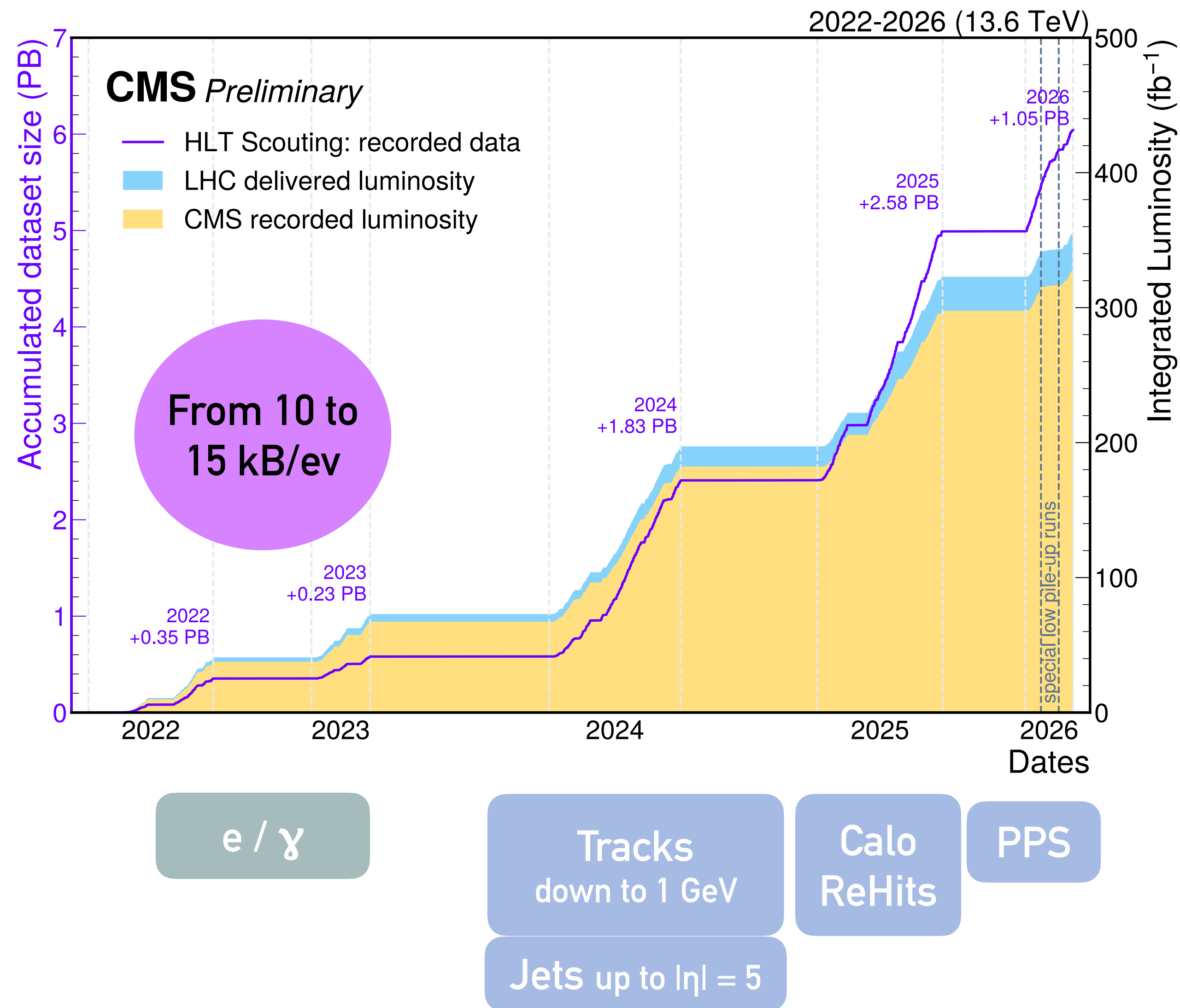
PHYSICS RESULTS WITH RUN 2 SCOUTING DATA: PROMPT MUONS

◆ Measurement of prompt resonance production in muon final states:

- Observation of the muon double Dalitz decay of the η meson ($\eta \rightarrow 4\mu$) with Run 2 scouting data



RUN 3 EXPANSION OF DATA SCOUTING: EVENT CONTENT



Early Run 3 updates:

- Scouting electron reconstruction and updated data format
- Dedicated electron- and photon- triggers
- Updated event content for muons (hit pattern, full track covariance matrix) and dedicated L1 algorithms based on unconstrained p_T requirements

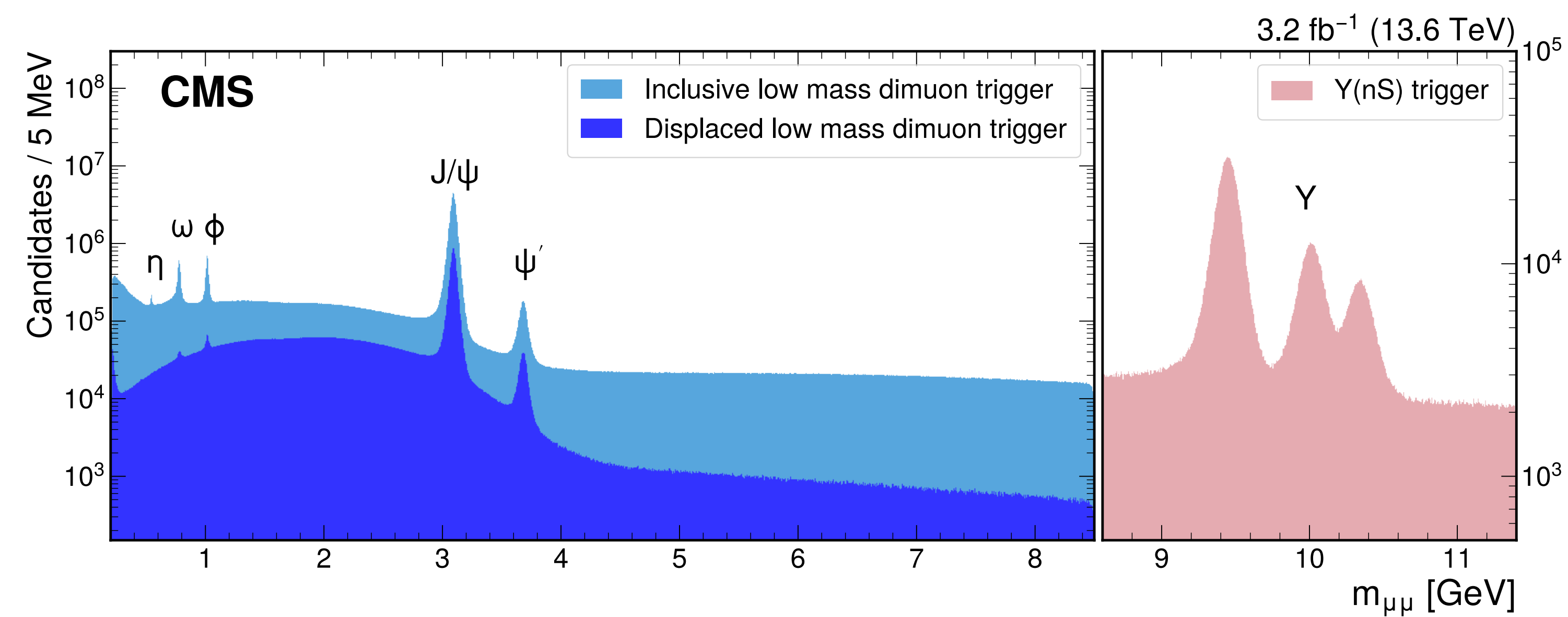
2024 updates:

- Full HLT tracking (instead of pixel-only) and standard PF
- New single-muon scouting trigger relying on high quality L1 muon seeds
 - Tracks saved down to 2 GeV
- Scouting jets saved up to $\eta=5$
- Calorimeter (ECAL/HCAL) RecHits

NEW TRIGGER DEVELOPMENTS: DIMUON PARKING

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Dimuon mass spectra obtained from data recorded in 2022 during the Run 3 data-taking campaign
by two main HLT algorithms: the **inclusive low mass trigger** and the **displaced low mass trigger**



	Run 3	Run 2
Invariant mass range	0.2 – 8.5 GeV	2.9 – 3.3 GeV
Dimuon p_T	>4.9 GeV	>25 GeV
Vertex fit probability	>0.5%	>0.5%
Leading muon p_T	>4 GeV	-
Trailing muon p_T	>3 GeV	-

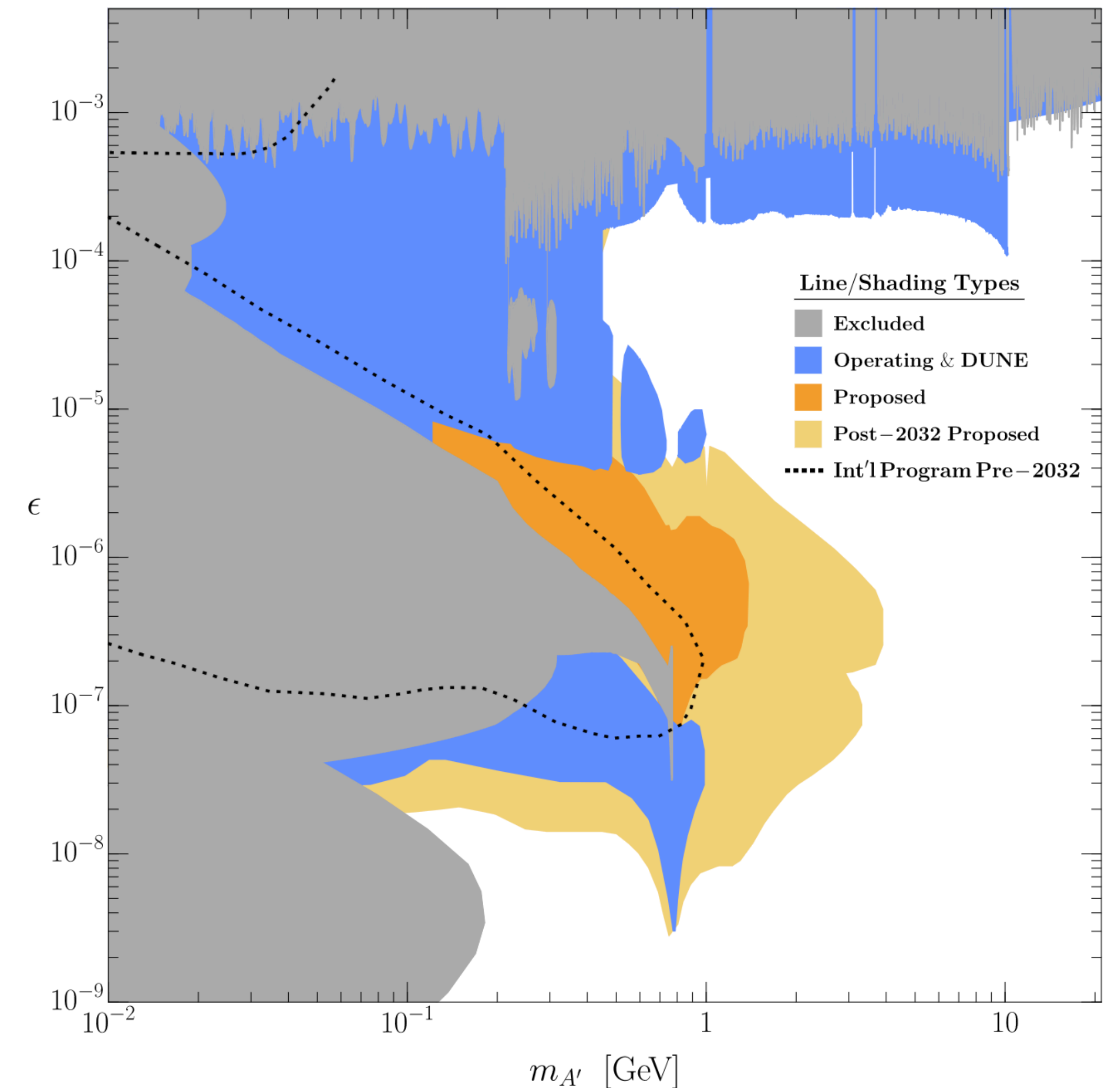
A RICH DATASET FOR INVESTIGATING THE MEV-GEV SCALE

Meson studies provide unique opportunity to discover new vector or scalar mediators in the MeV–GeV mass range

(Precision tests of fundamental physics with η and η' mesons)

- ❖ Dark matter provides one motivation for light mediator particles
- ❖ Light $U(1)'$ vector bosons γ_D can be searched for in meson decays
- ❖ Signatures and rates depend on the gauge coupling g' and mass m_{γ_D} , as well the gauge charges Q' assigned to SM particles

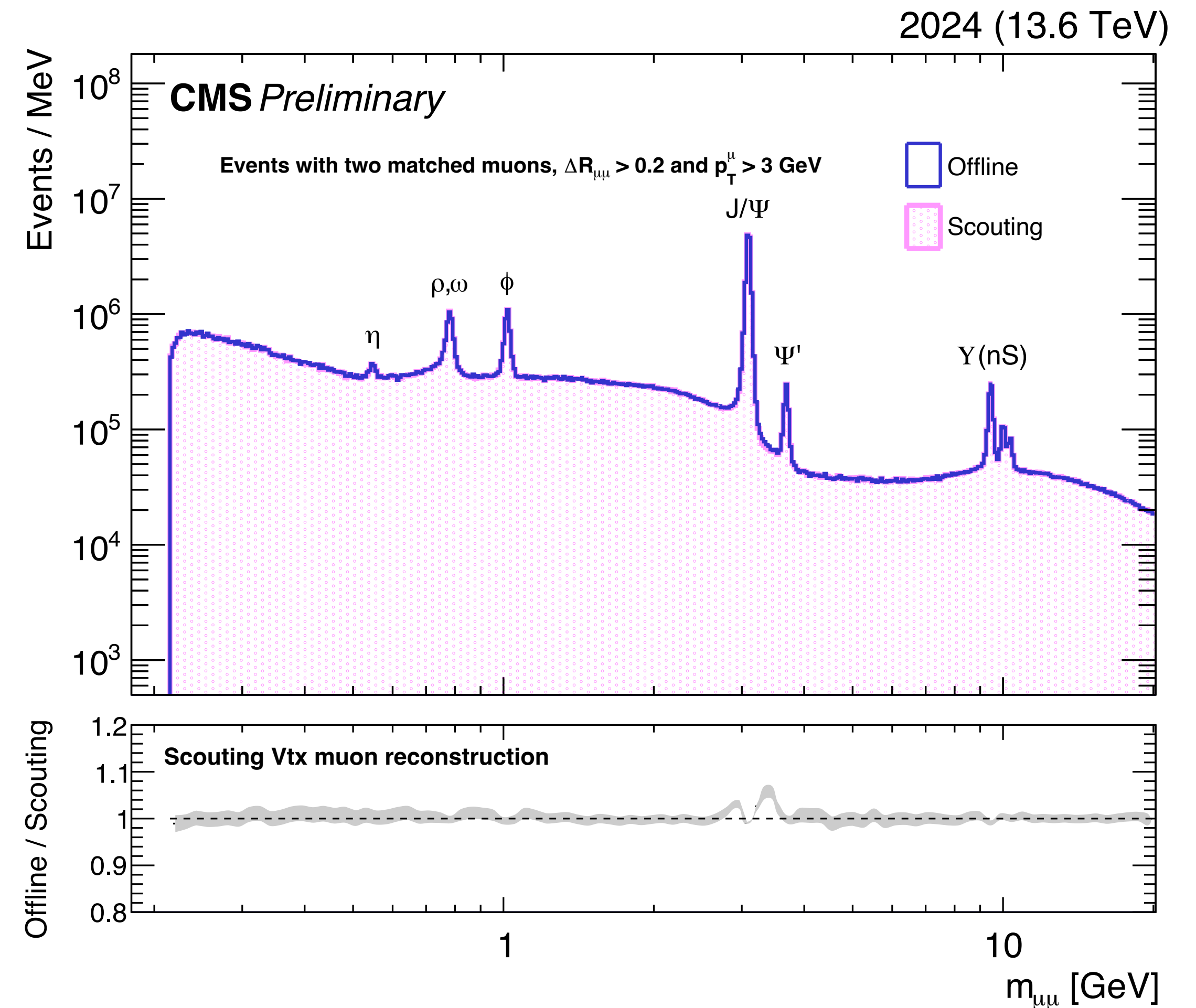
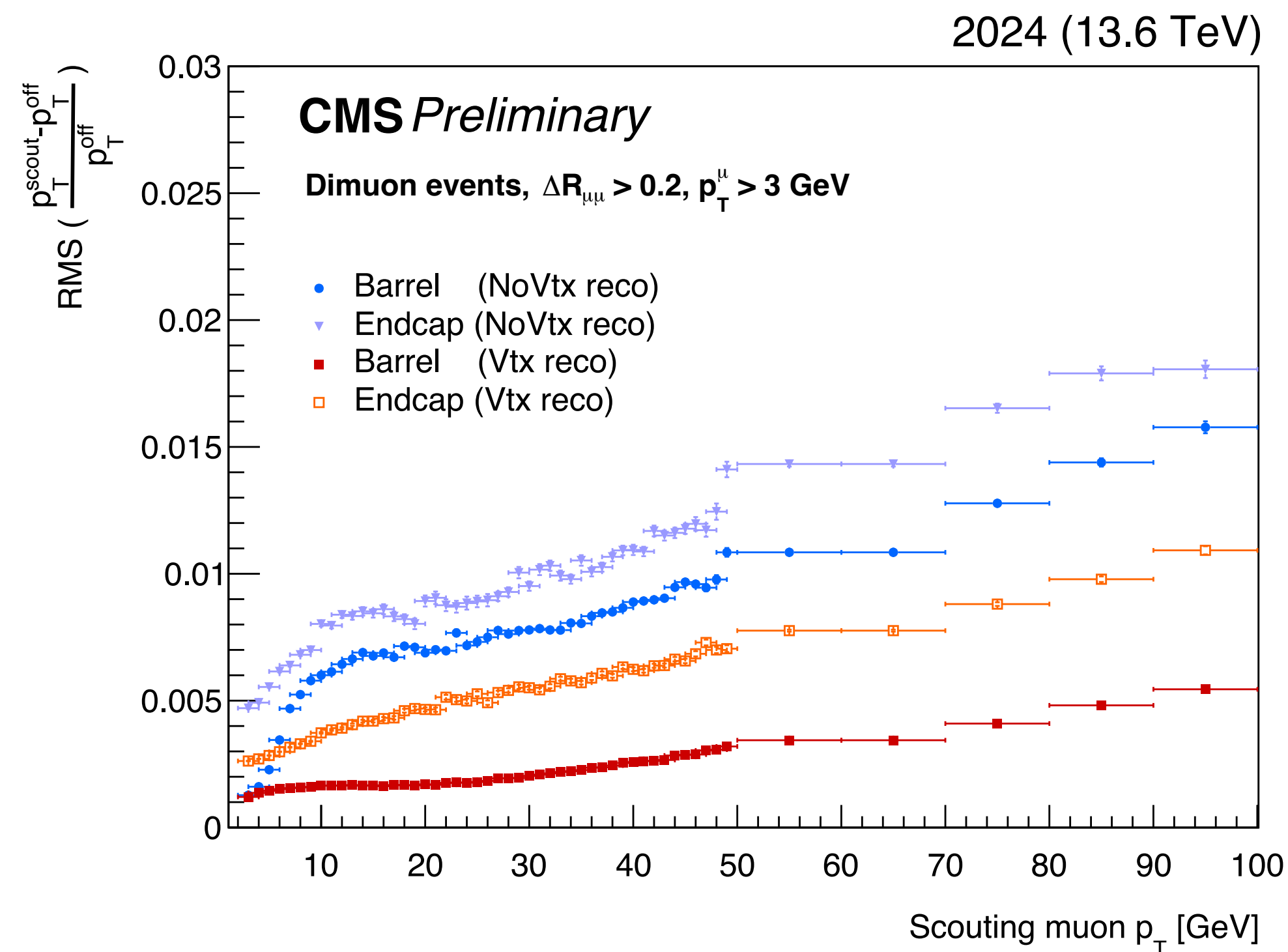
$$\text{Br}(\mathcal{P} \rightarrow \gamma^D \gamma) \simeq 2\varepsilon^2 \left(1 - \frac{m_{\gamma^D}^2}{m_{\mathcal{P}}^2}\right)^3 \text{Br}(\mathcal{P} \rightarrow \gamma \gamma)$$



Snowmass 2021: Dark Sector Physics at High-Intensity Experiments

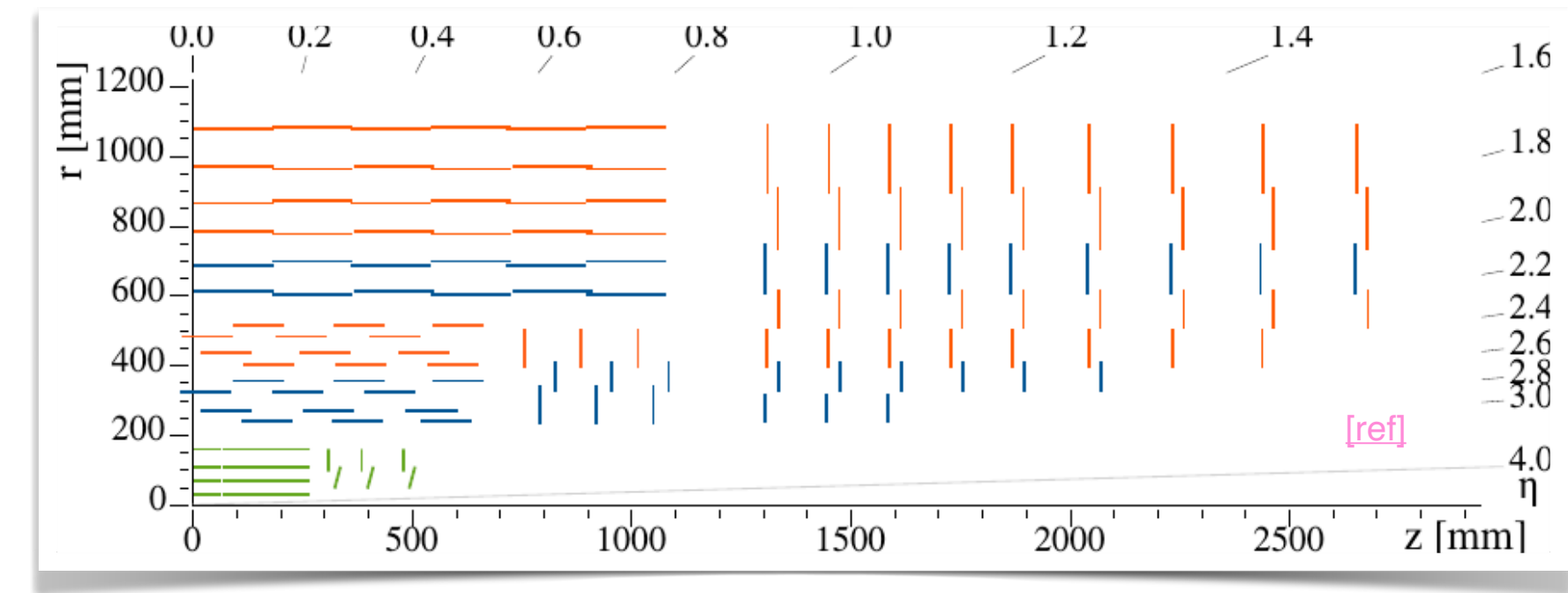
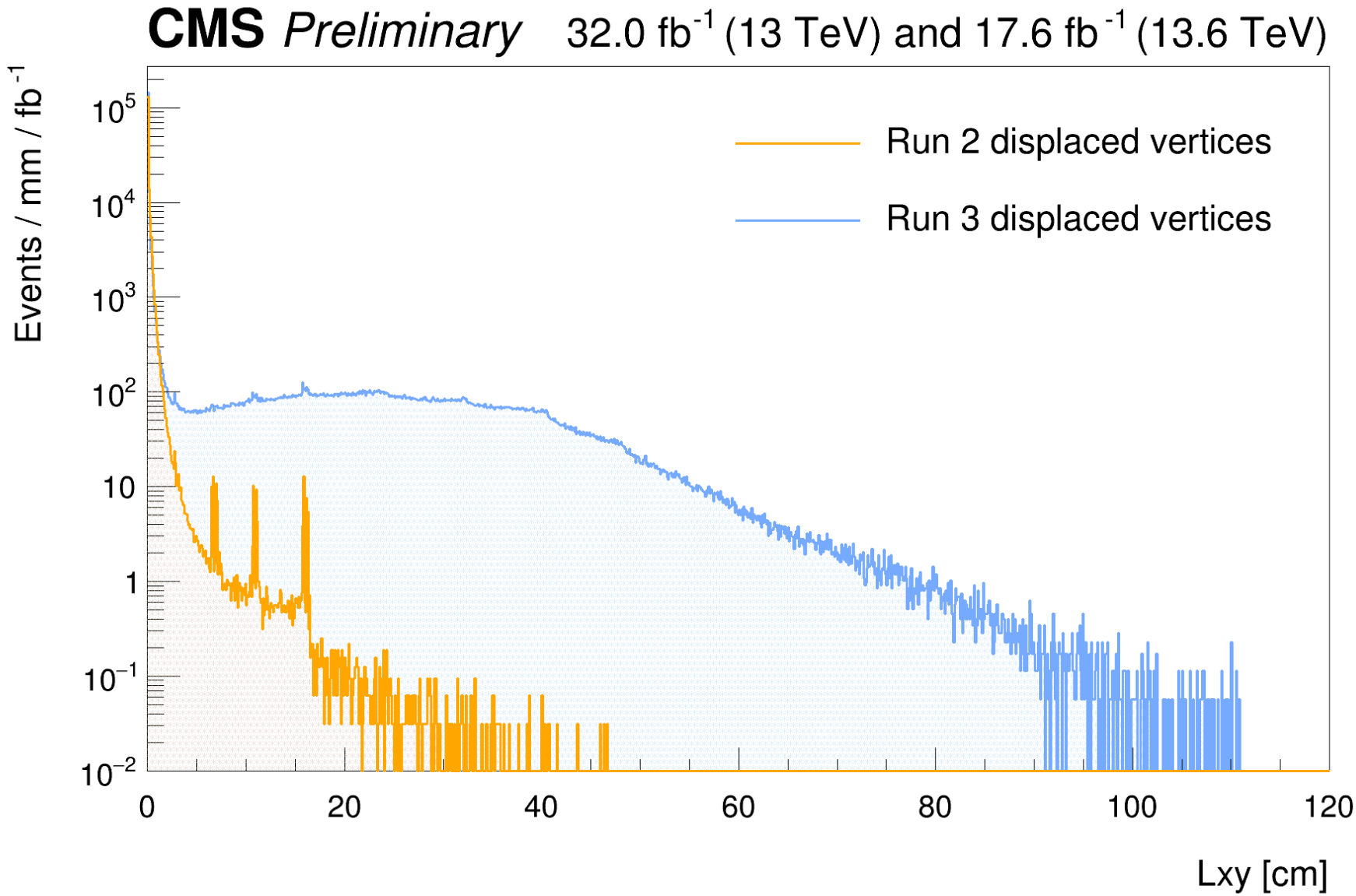
RUN 3 HLT SCOUTING: MUONS

Resolution effects due to the online reconstruction are found to be between 1-2% for both the mass spectrum and the transverse momentum in all eta regions

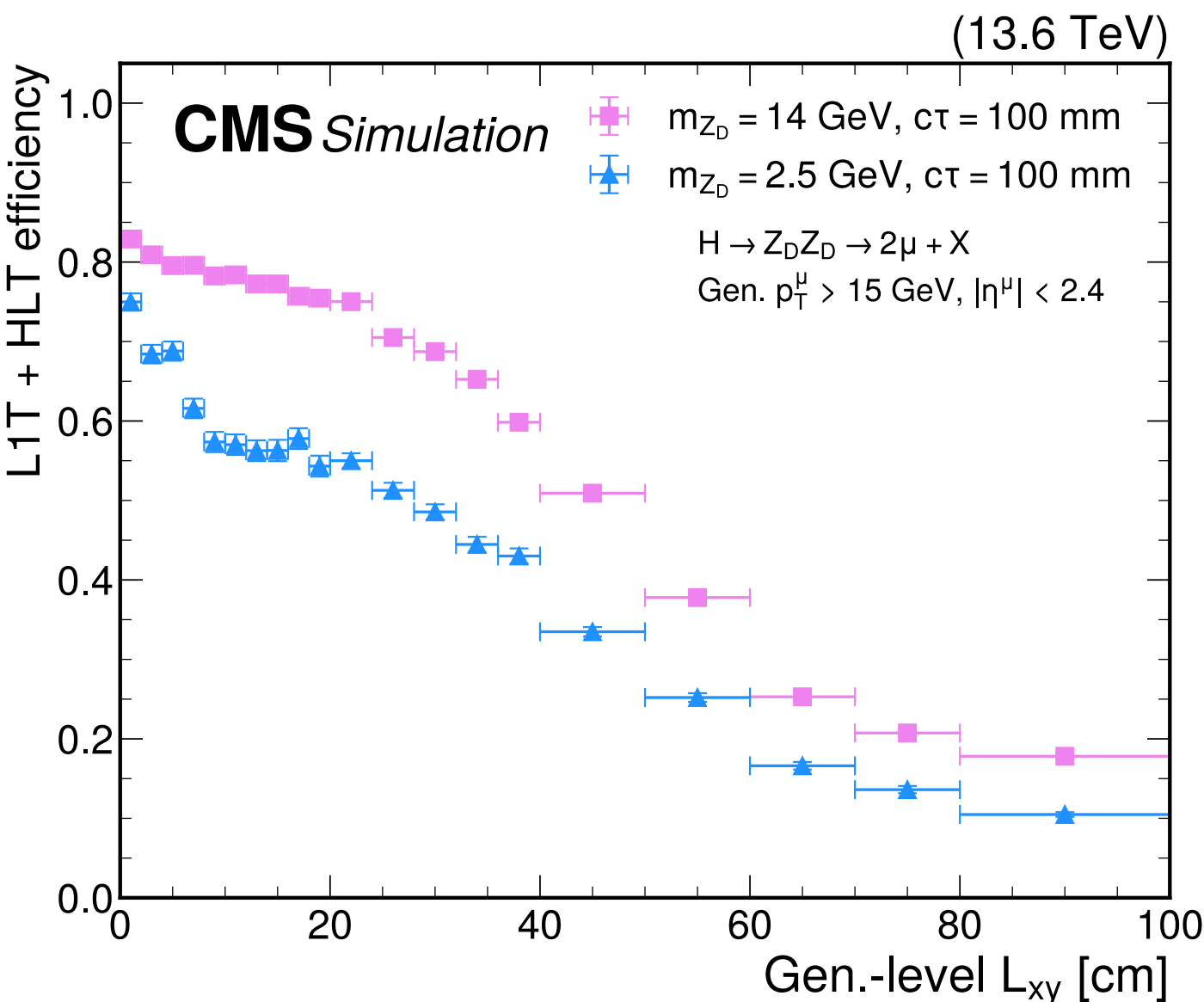
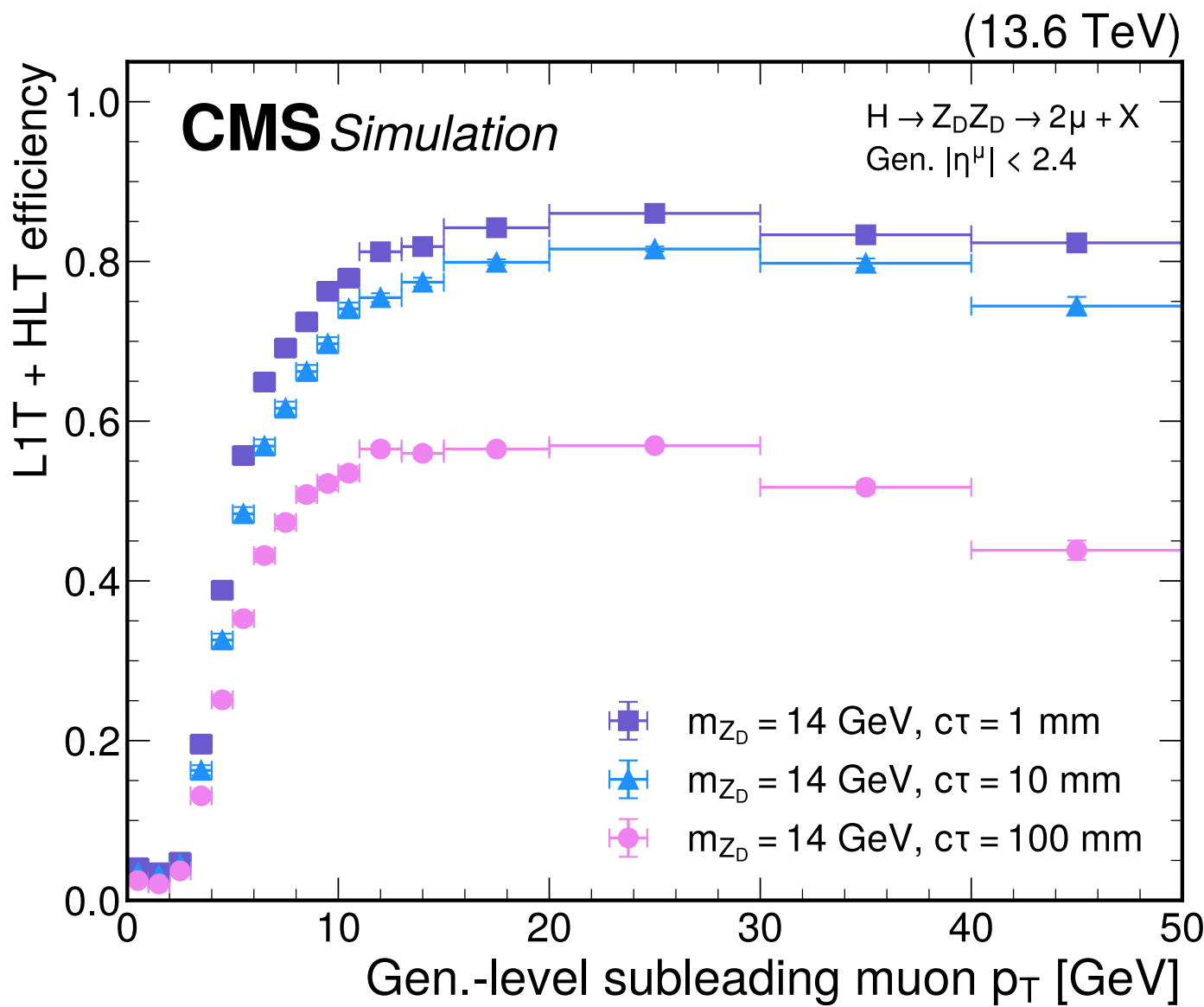


RUN 3 HLT SCOUTING: DISPLACED MUONS

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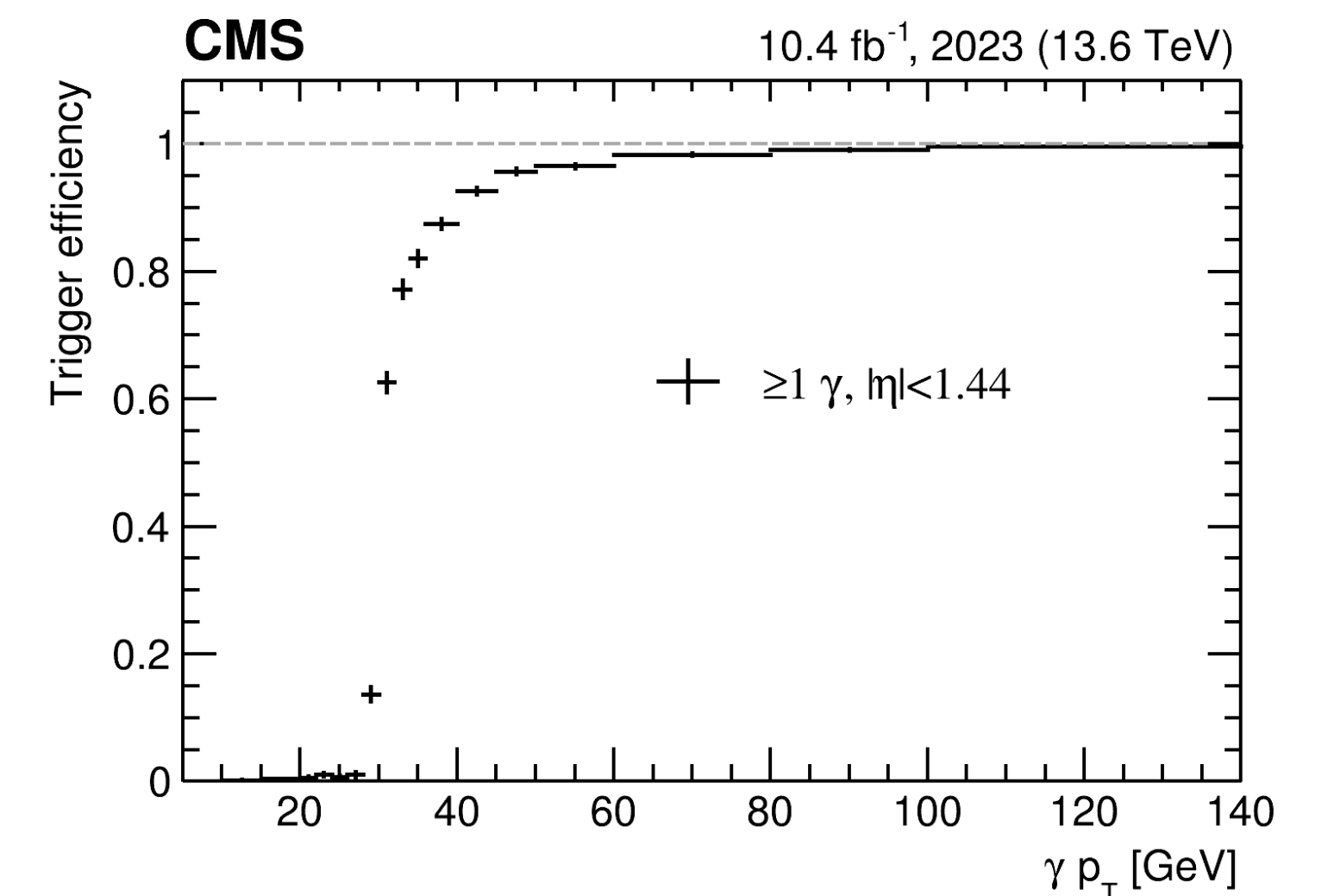
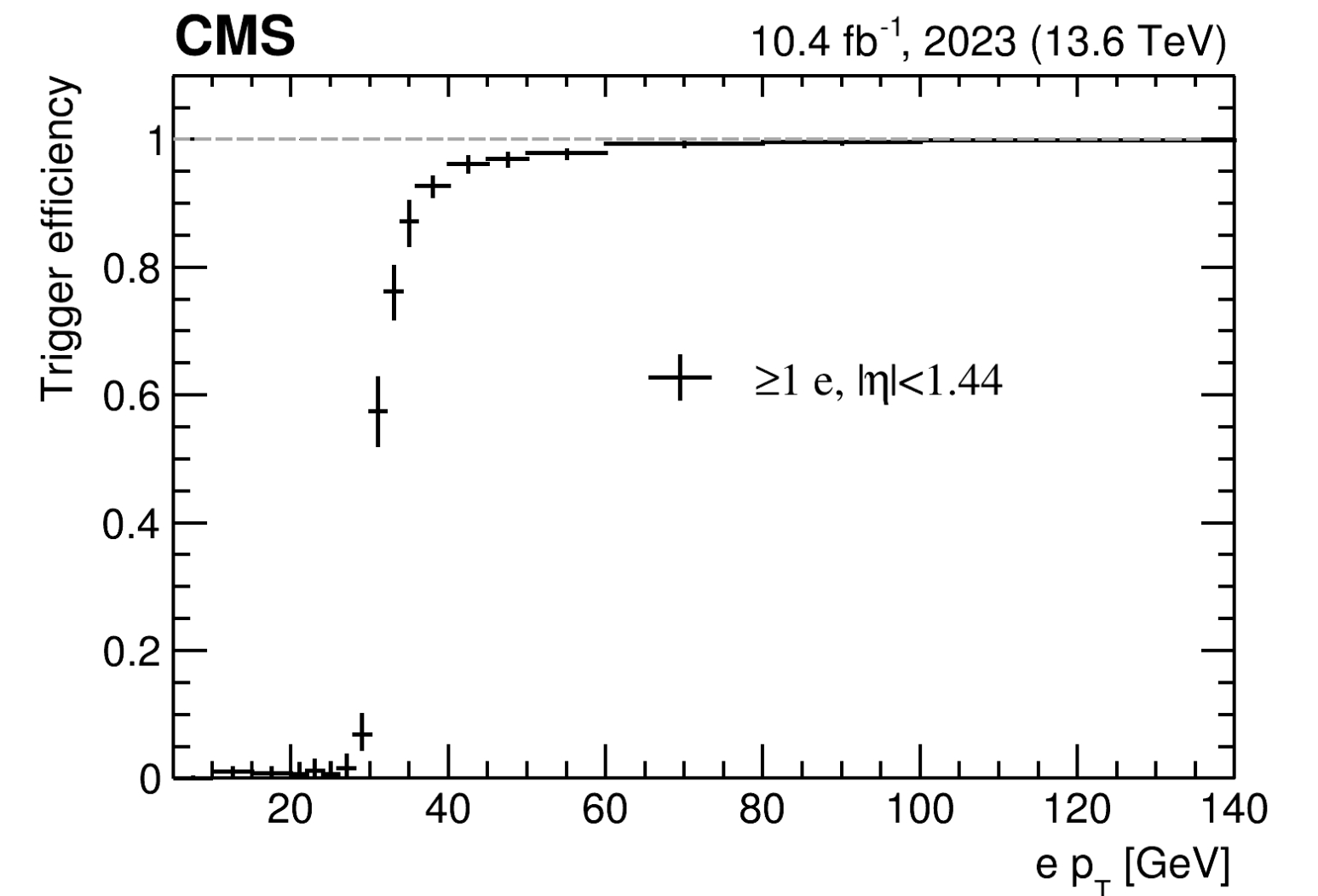
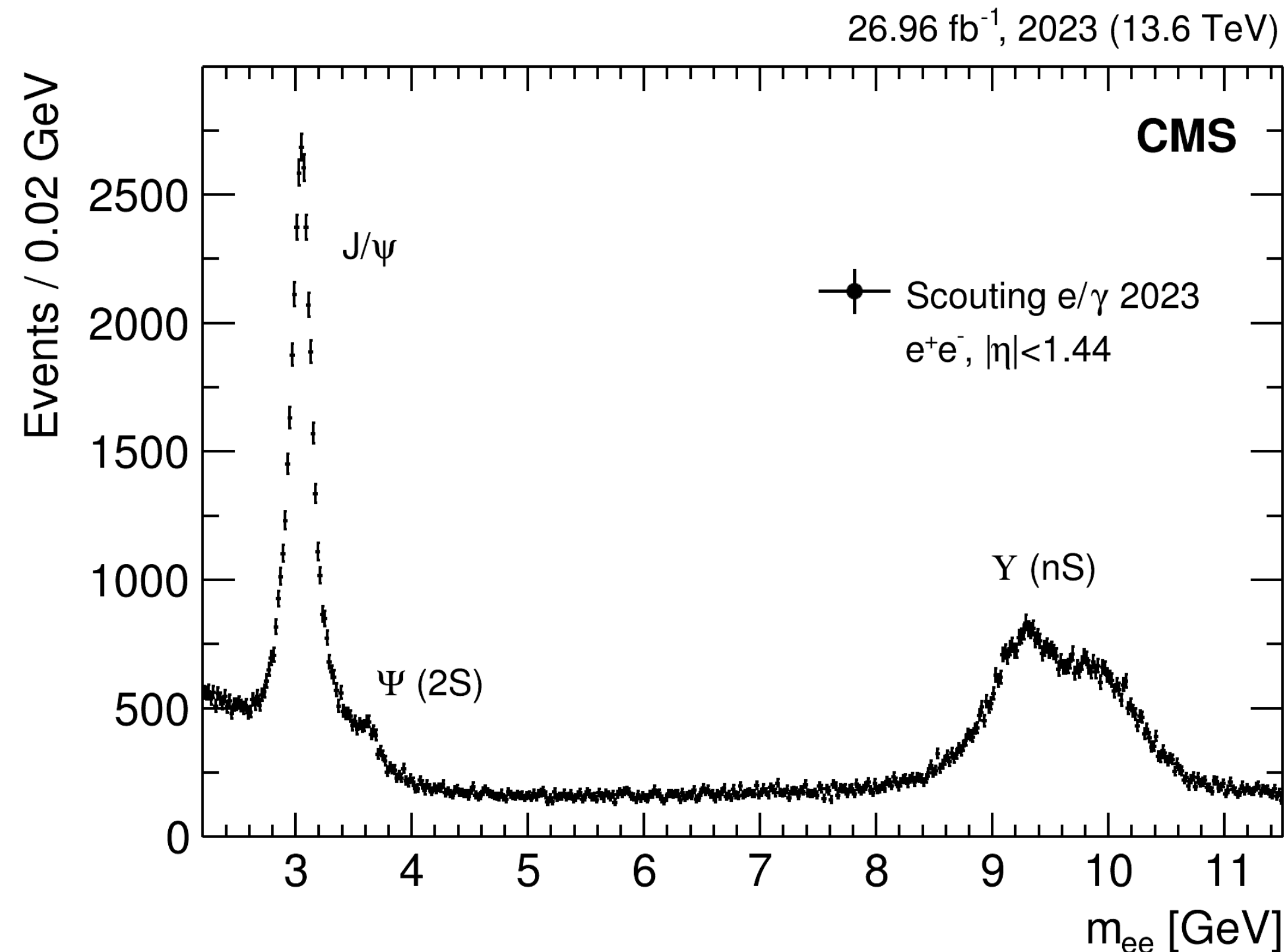


- ◆ Updated no-vtx muon reconstruction [early Run 3]
 - Removed the requirement of having at least two pixel hits in the tracker
- ◆ Dedicated L1 algorithms based on unconstrained p_T selections [early Run 3]
- ◆ Complementarity of vtx and no-vtx reconstruction for maximal sensitivity at all displacements [end of Run 3]



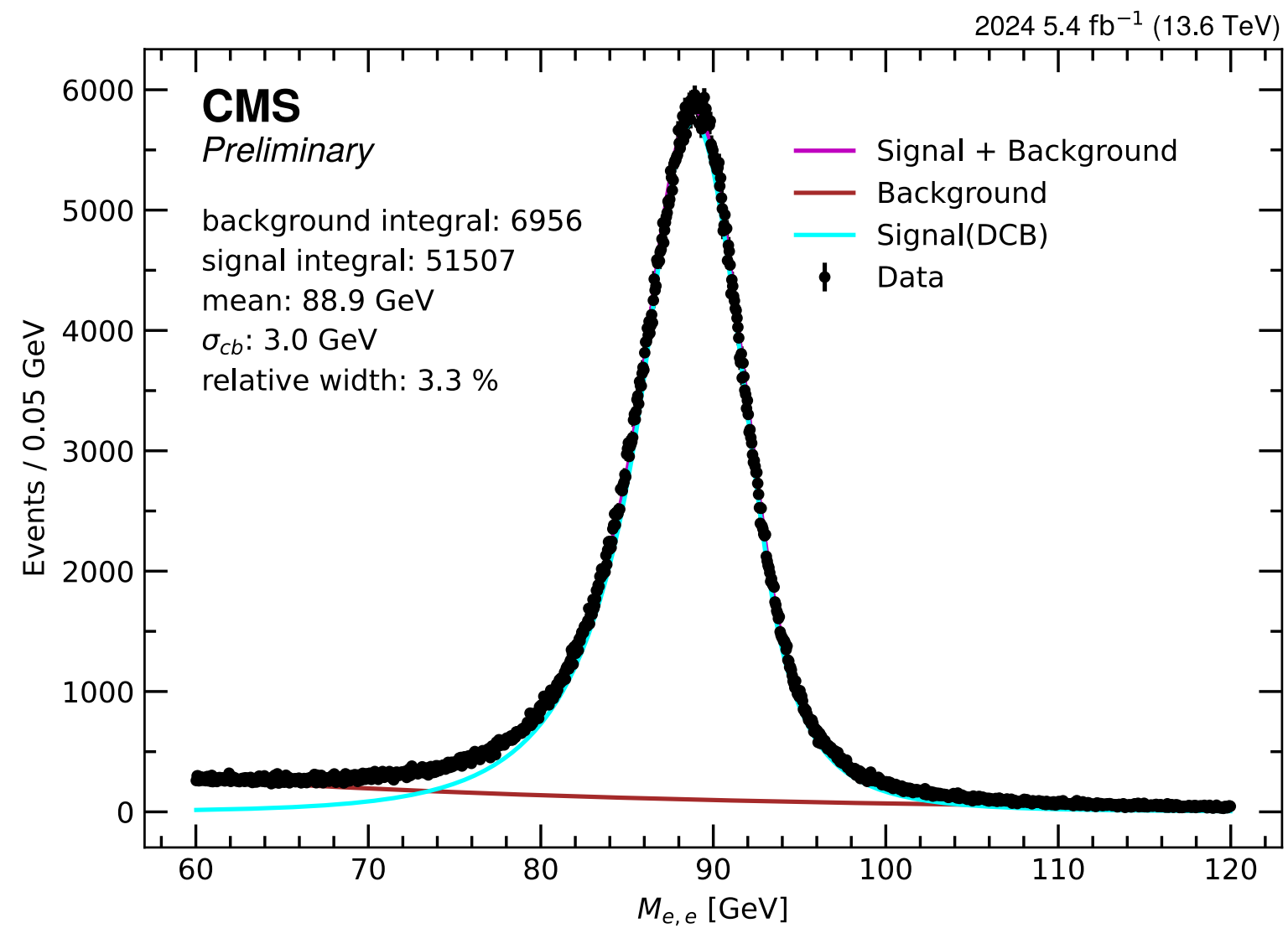
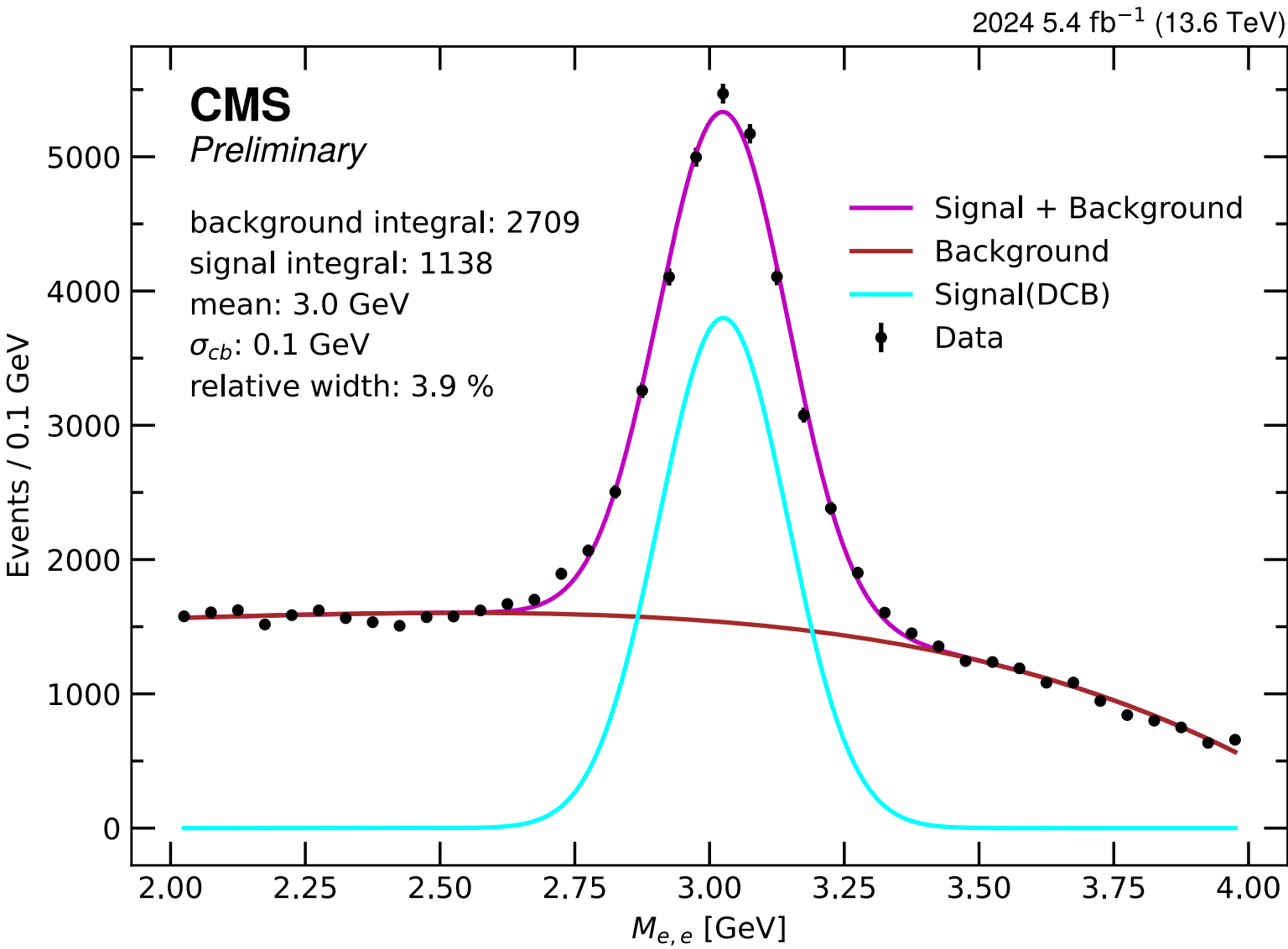
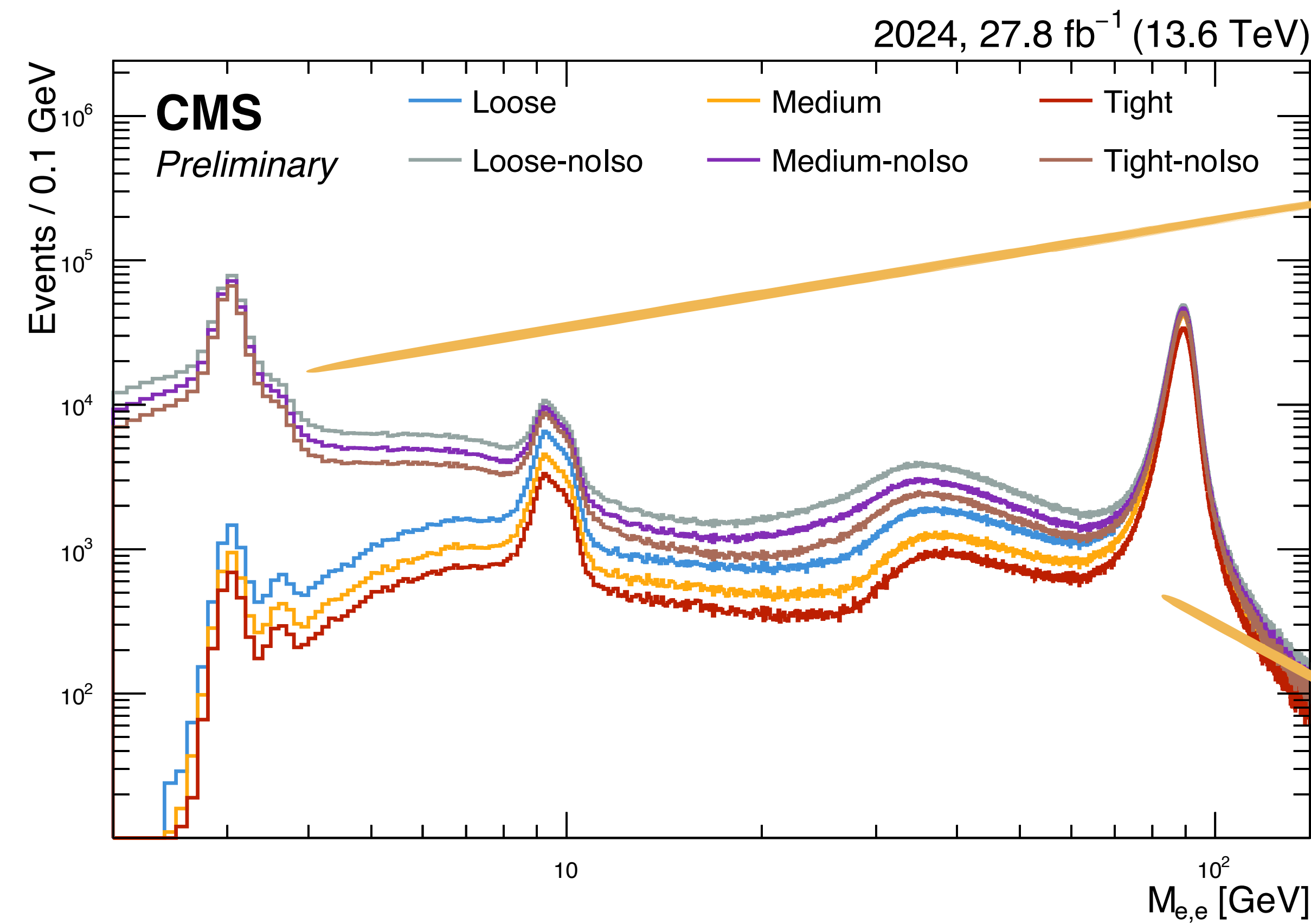
RUN 3 HLT SCOUTING: ELECTRONS AND PHOTONS

- ◆ Dielectron pairs are collected at the GeV scale
- ◆ Single photon triggers in scouting lowered the thresholds down to 30 GeV
 - ◆ NOTE: standard trigger thresholds on single photon are historically 200 GeV, later in Run 3 lowered to 40 GeV



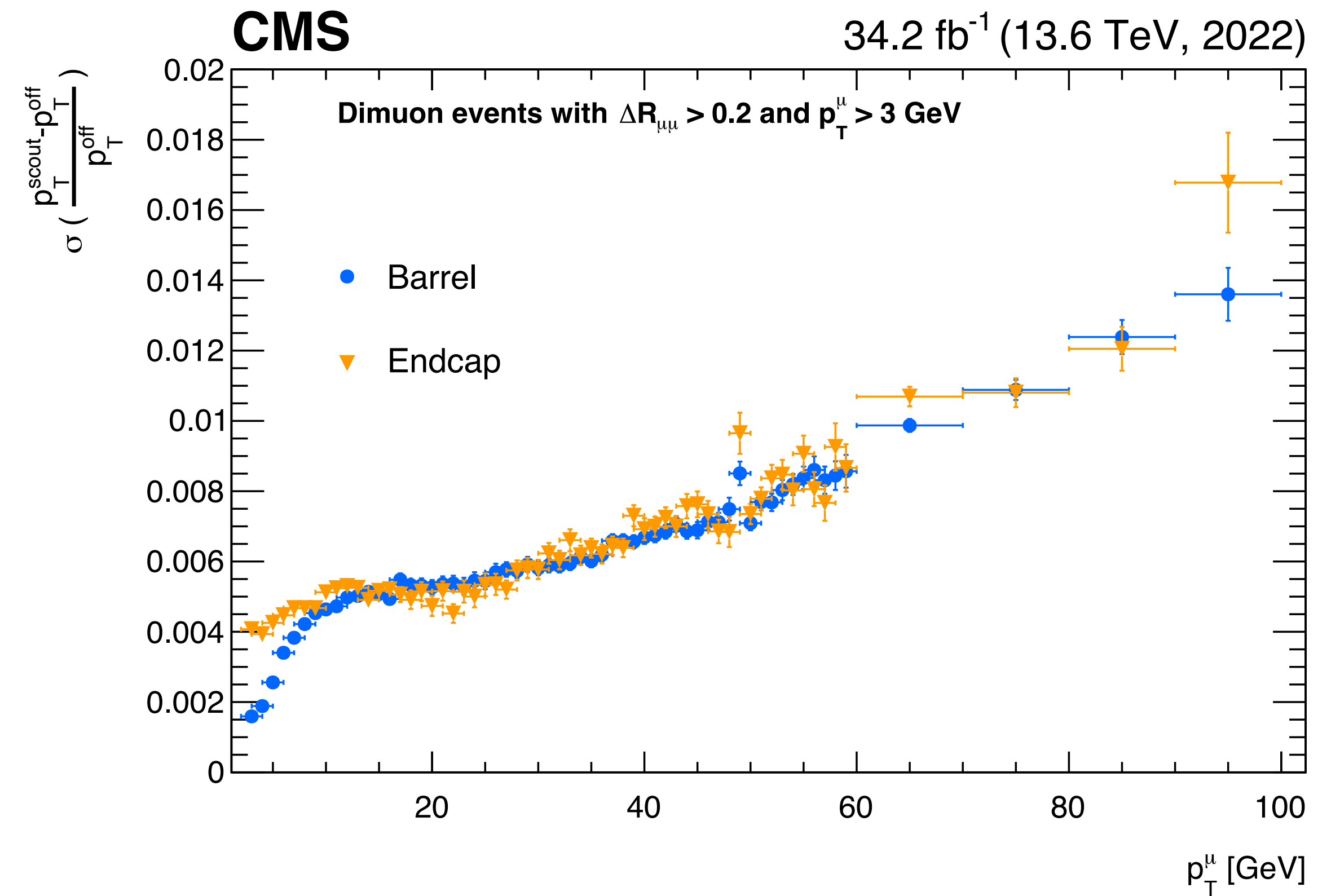
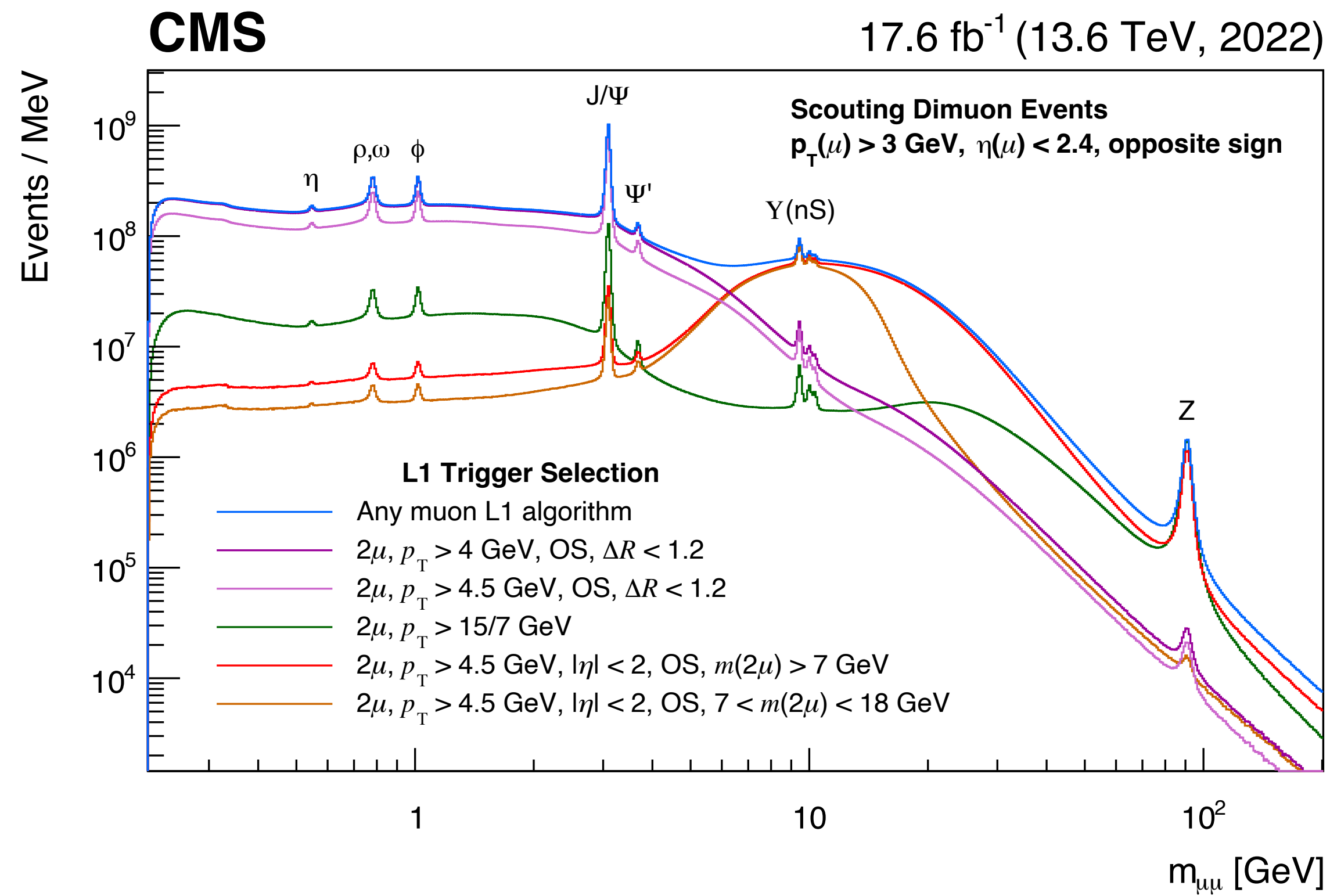
RUN 3 HLT SCOUTING: ELECTRONS AND PHOTONS

◆ Dielectron pairs are collected at the GeV scale



RUN 3 SCOUTING IN A NUTSHELL: MUONS

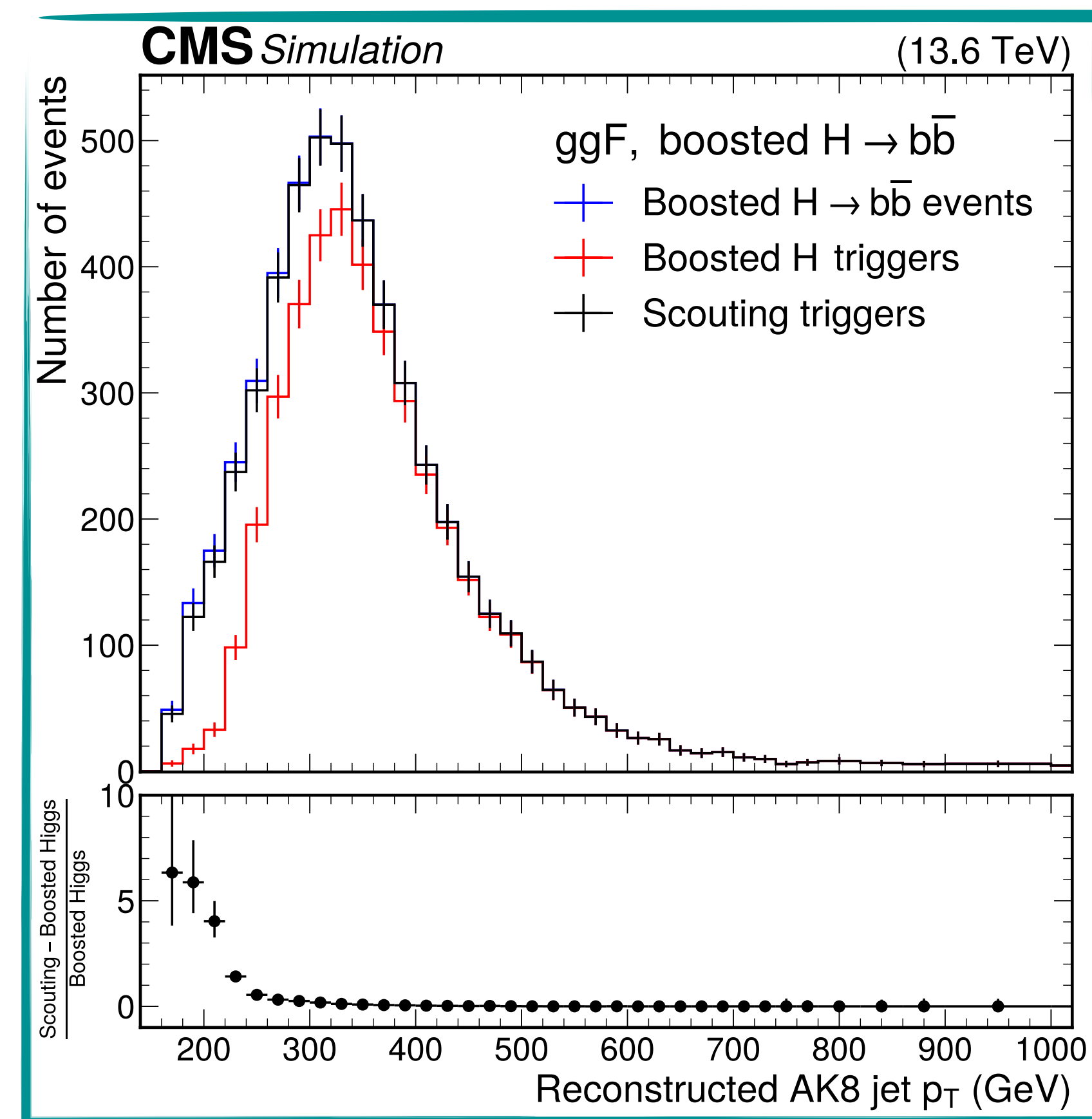
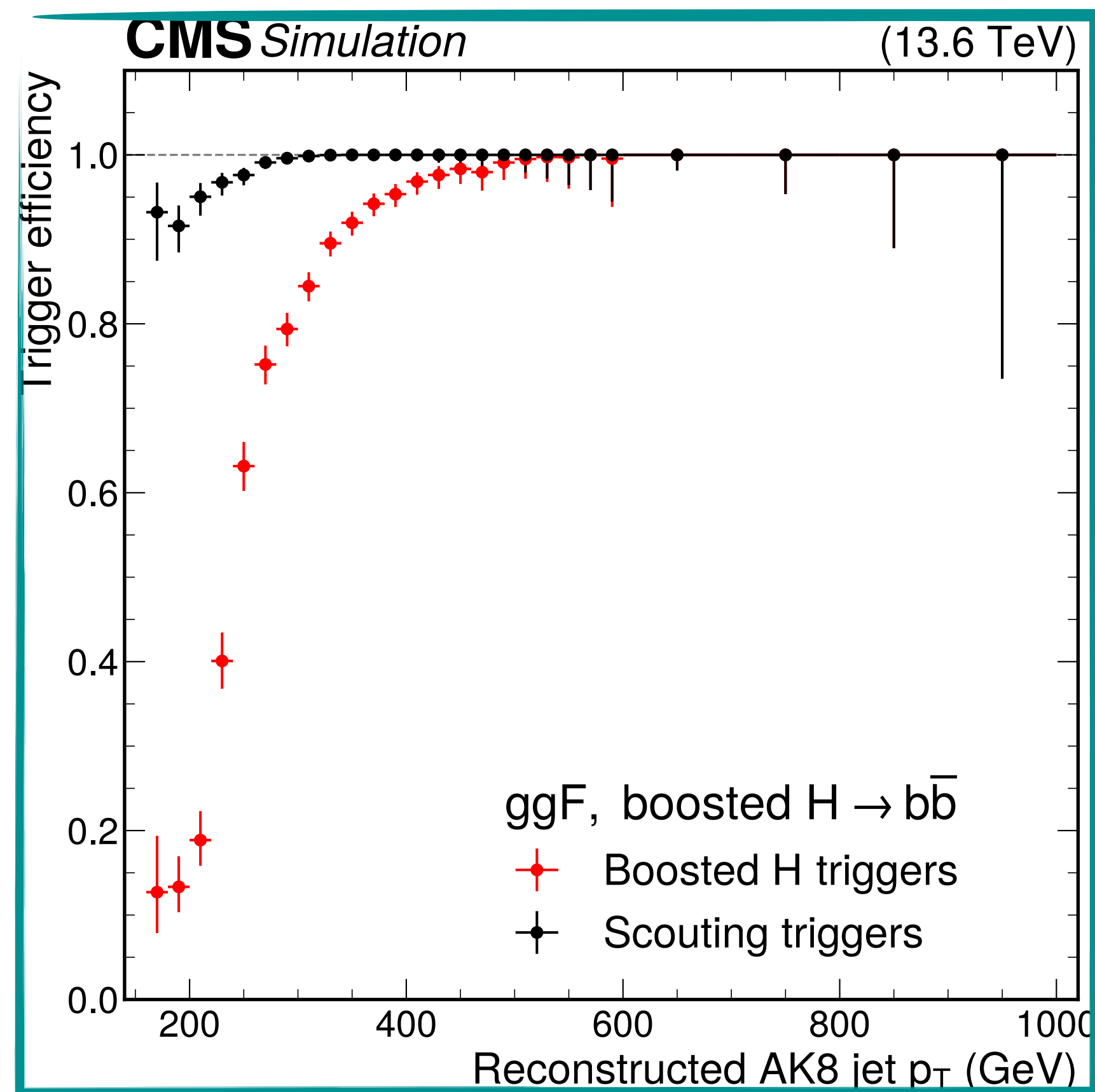
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RUN 3 HLT SCOUTING: JETS AND PF CANDIDATES

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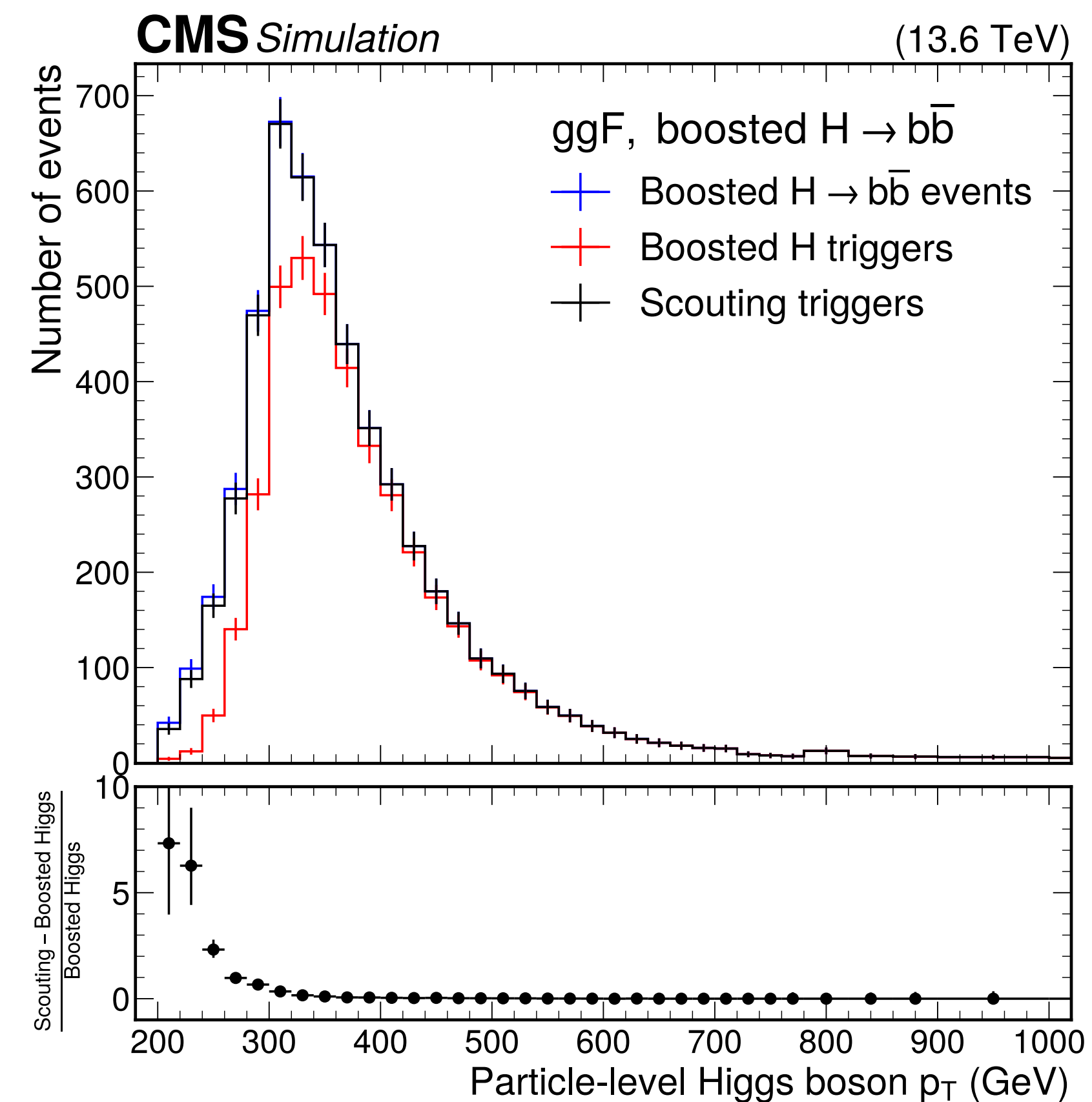
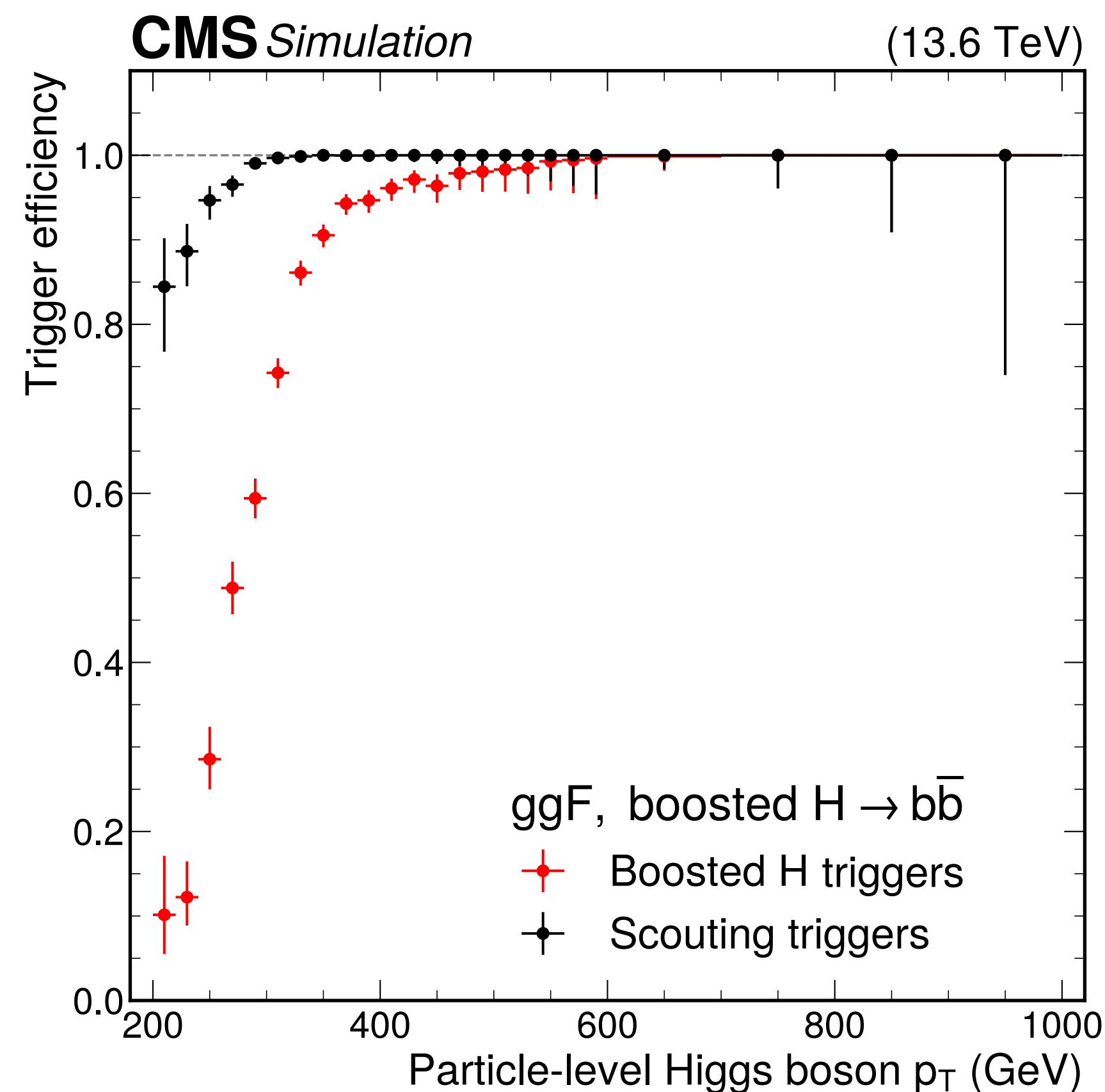
- ◆ Hadronic triggers in scouting notably enlarge the accessible phase space w.r.t. **standard triggers**:
 - Significant increase (20%) in event selection efficiency for boosted Higgs decaying to two b quarks, especially at low p_T



RUN 3 SCOUTING IN A NUTSHELL: JETS

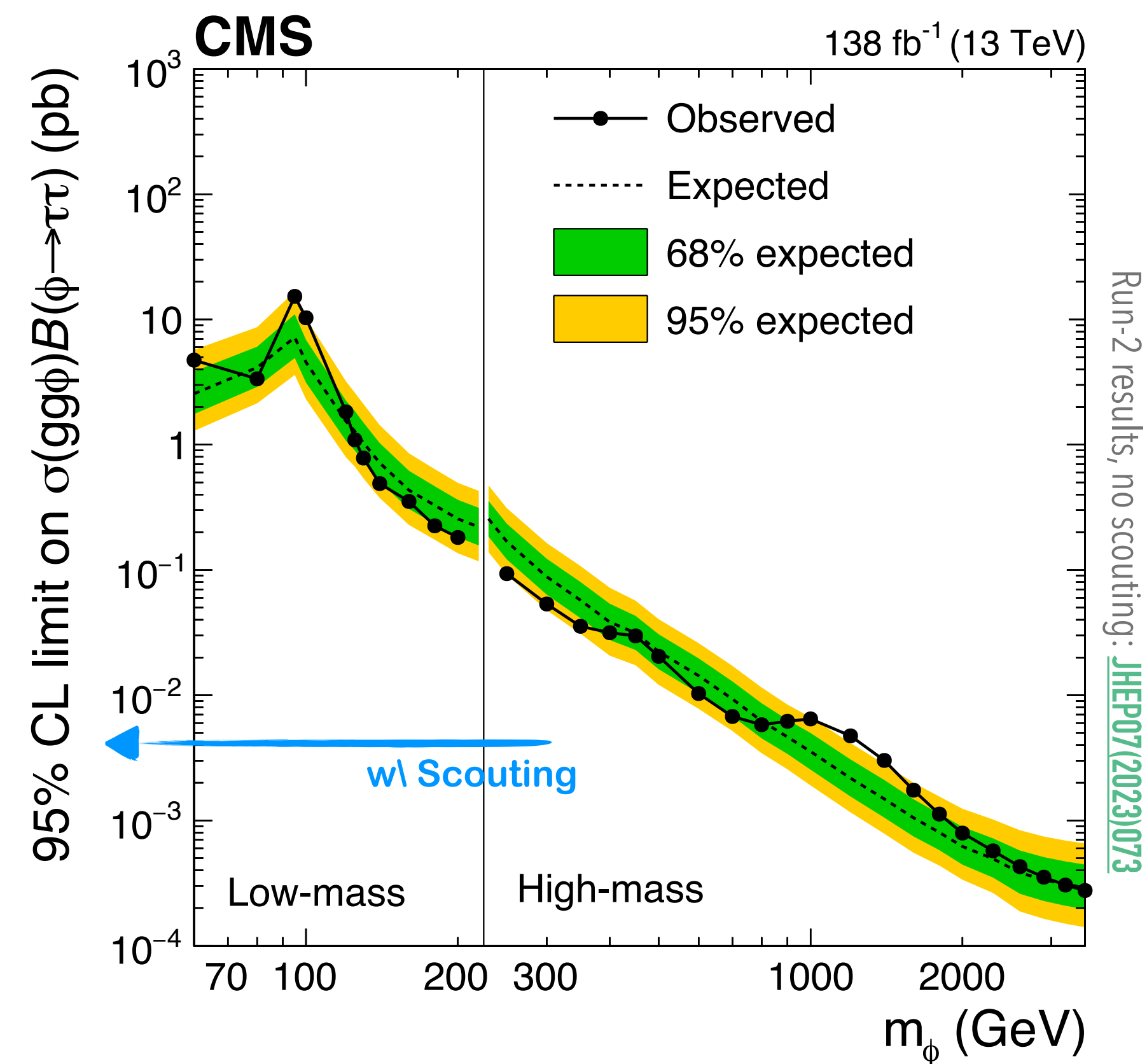
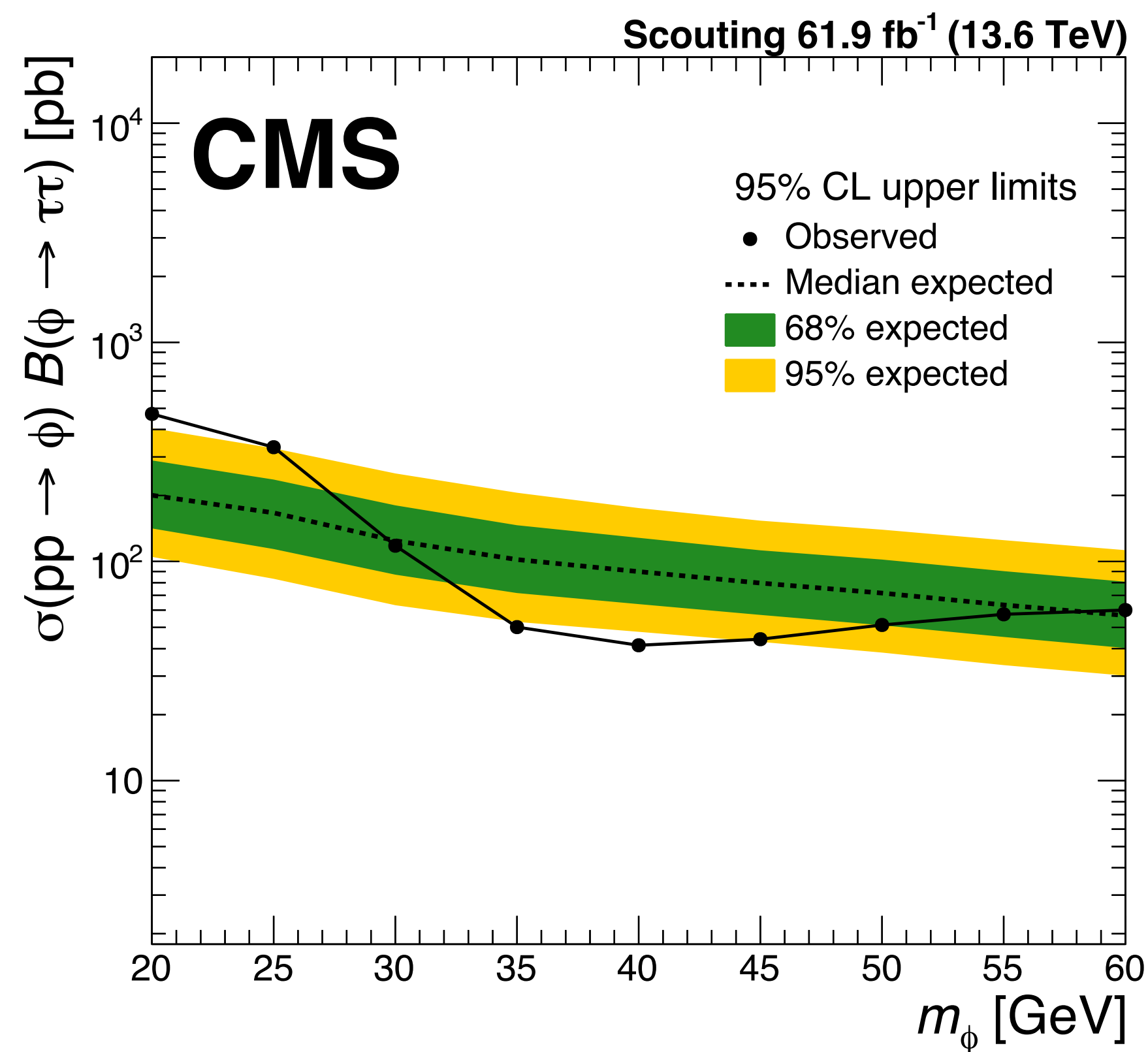
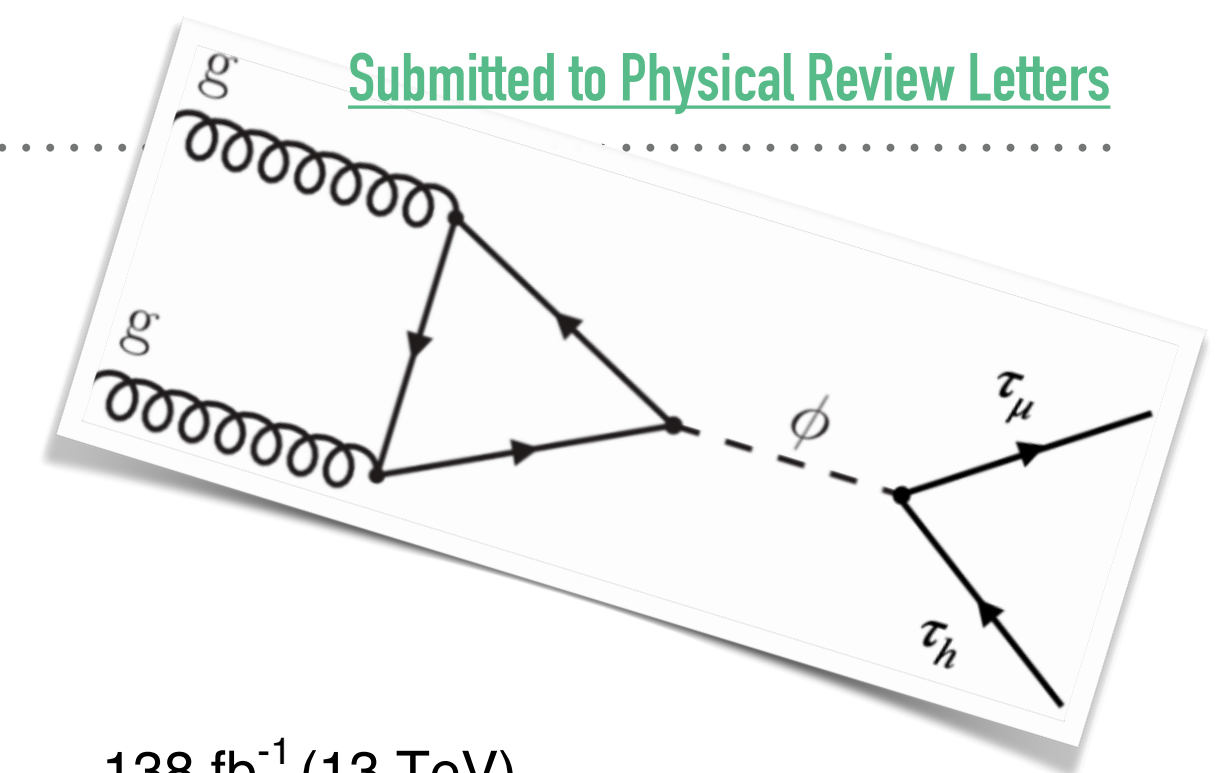
[j.physrep.2024.09.006](#)

- ◆ Hadronic triggers in scouting notably enlarge the accessible phase space w.r.t. **standard triggers**:
 - Significant increase (20%) in event selection efficiency for boosted Higgs decaying to two b quarks, especially at low p_T



DITAU RESONANCE SEARCHES AT LOW MASS

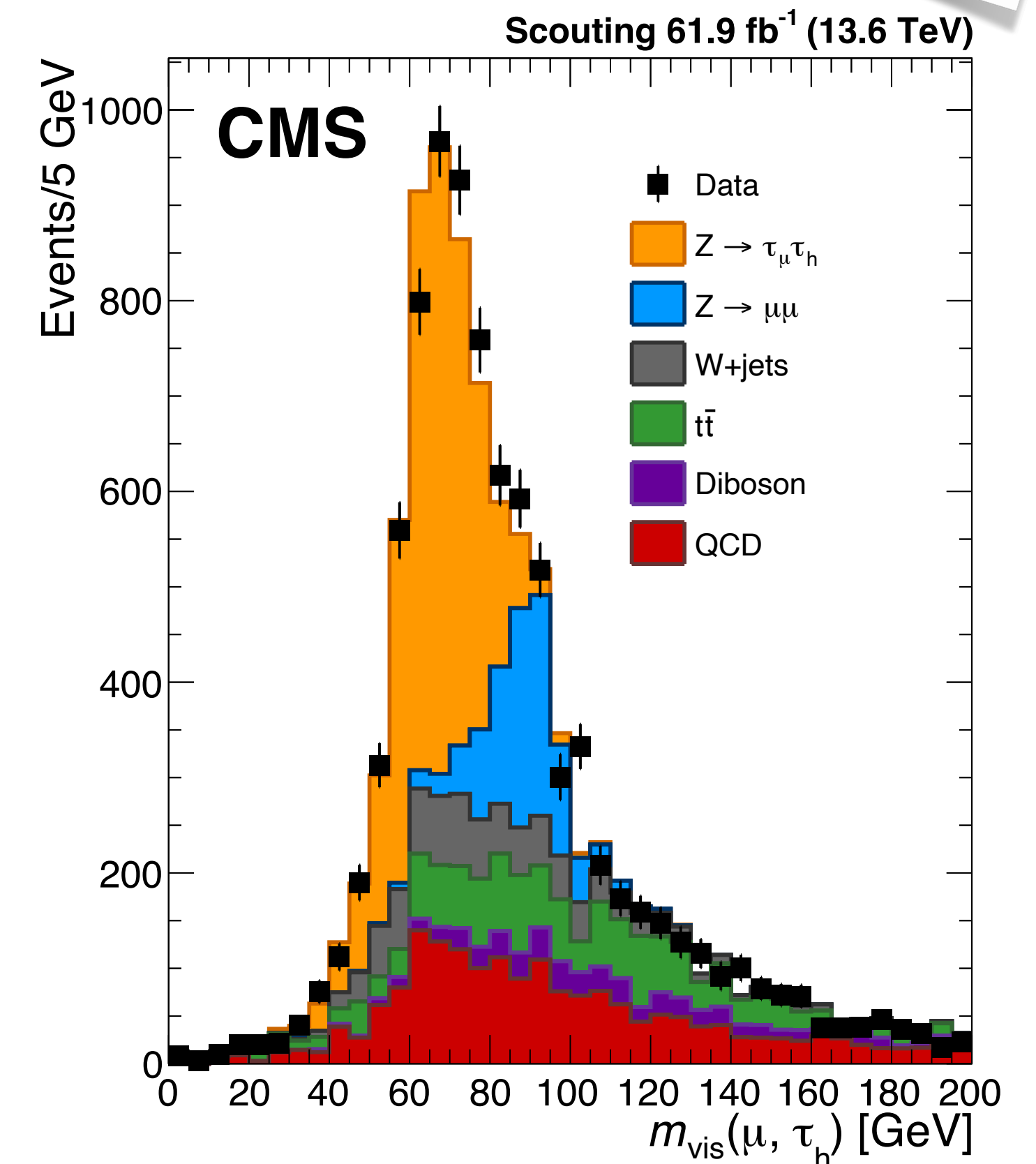
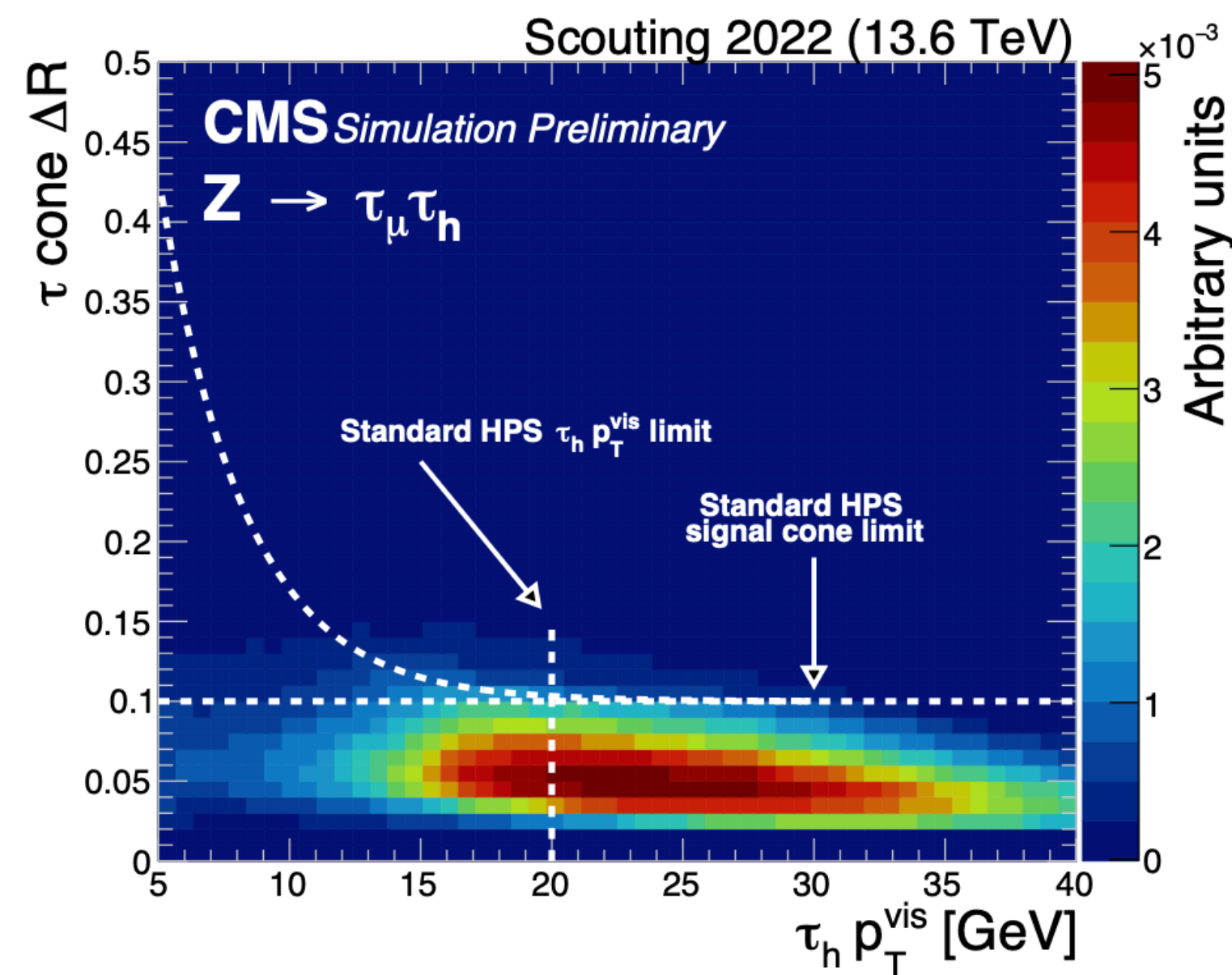
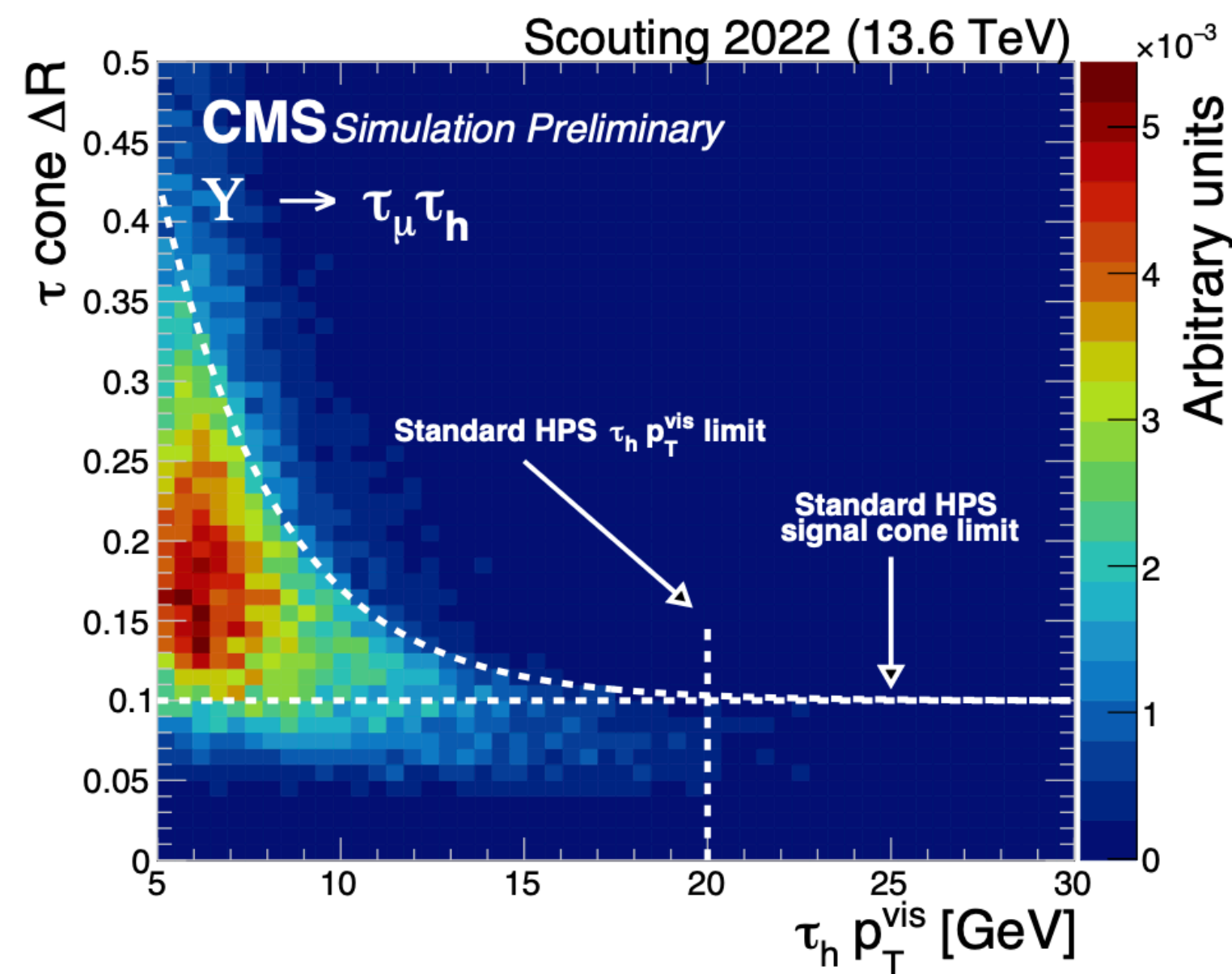
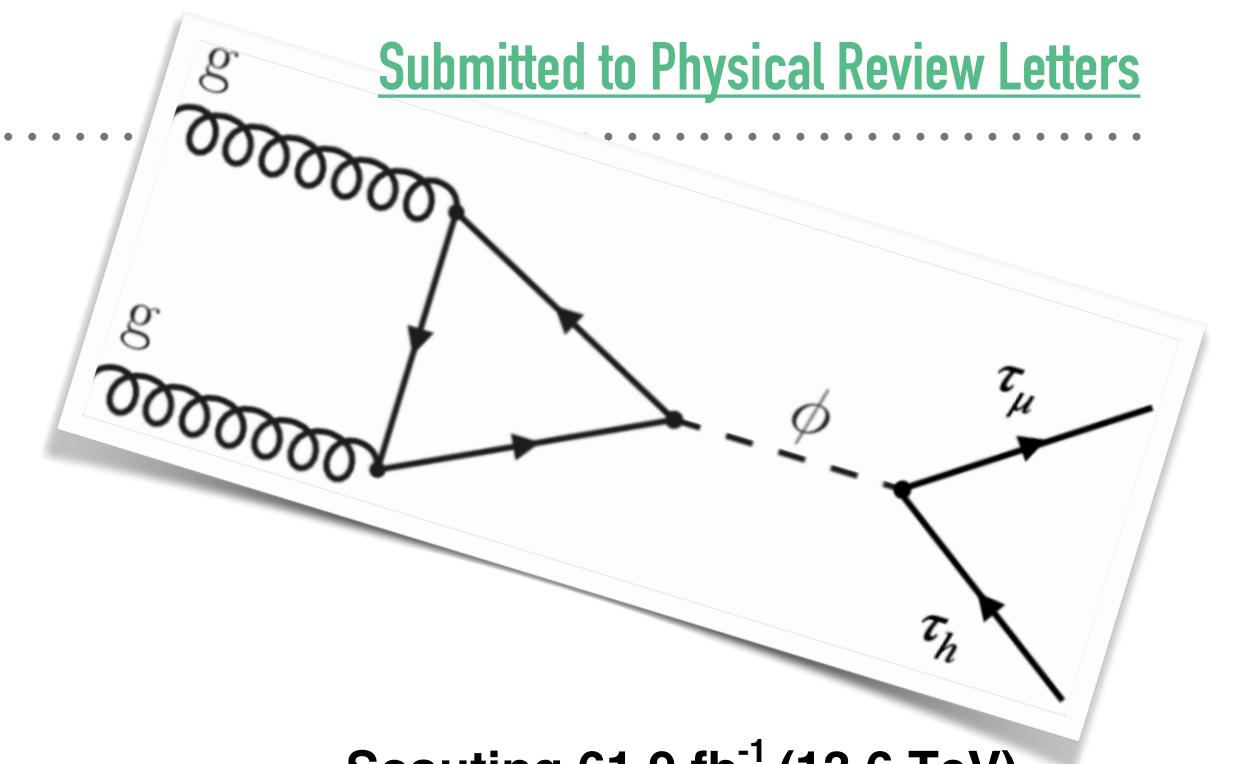
- ♦ The Run 3 Jet/HT scouting stream has been used for successful searches of low-mass ditau resonances using newly developed τ objects post processing the scouting PF candidates
 - First exploration of low mass (< 60 GeV) $\Phi \rightarrow \tau\tau$ with $\tau_\mu\tau_h$ final state



DITAU RESONANCE SEARCHES AT LOW MASS

- ◆ The Run 3 Jet/HT scouting stream has been used for successful searches of low-mass ditau resonances using newly developed τ objects **post processing the scouting PF candidates**

- Dedicated low p_T reconstruction to improve efficiency at low p_T ([CMS-NOTE-2024-006](#))



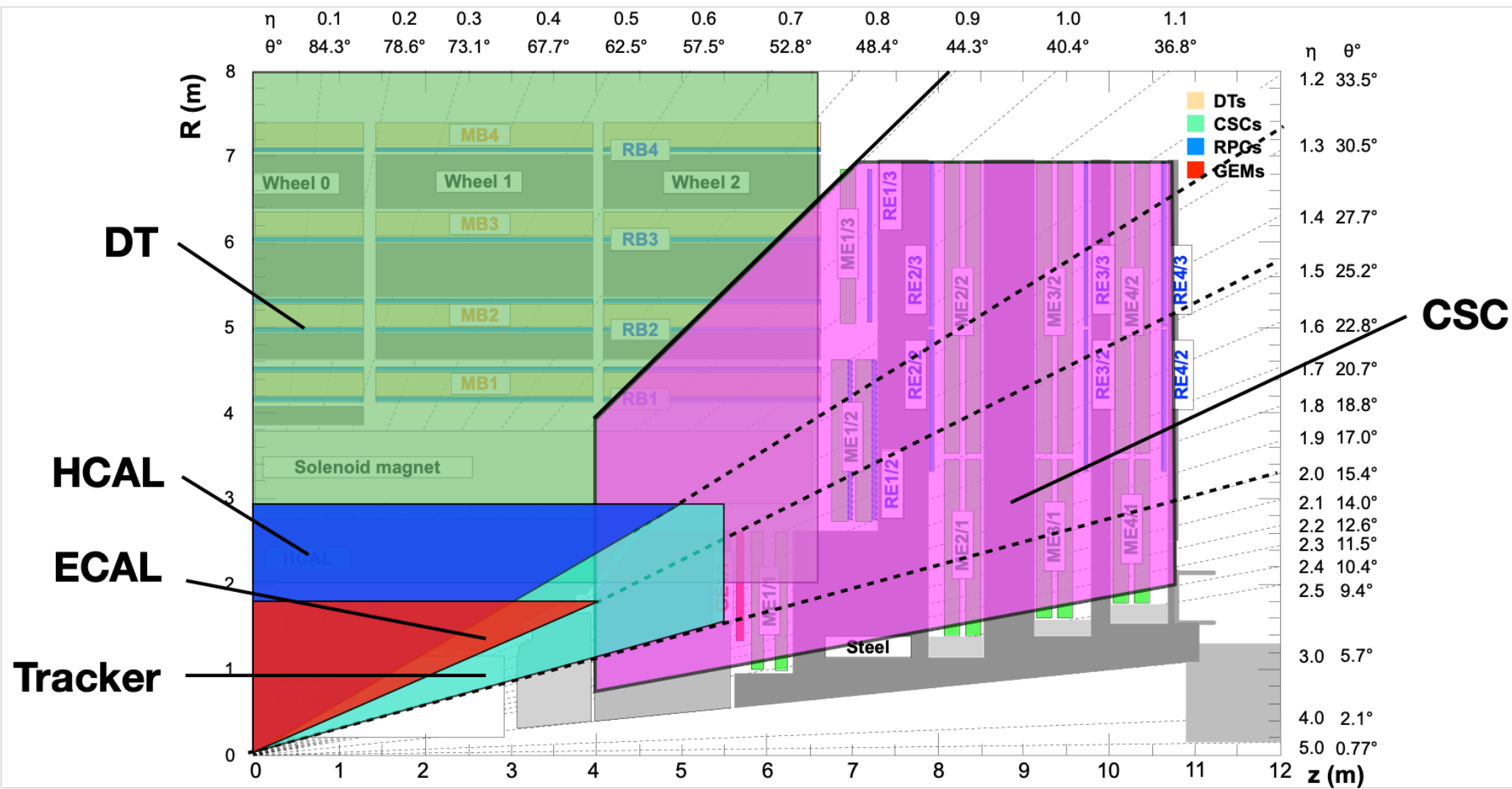
- ◆ Standard HPS limits the maximum signal cone to $\Delta R = 0.1$
- ◆ For lower $p_T \tau_h$ candidates, it is necessary to open the allowed signal cone in order to increase sensitivity

RUN 3 HLT SCOUTING, PARKING, AND PROMPT FOR LONG LIVED PARTICLES

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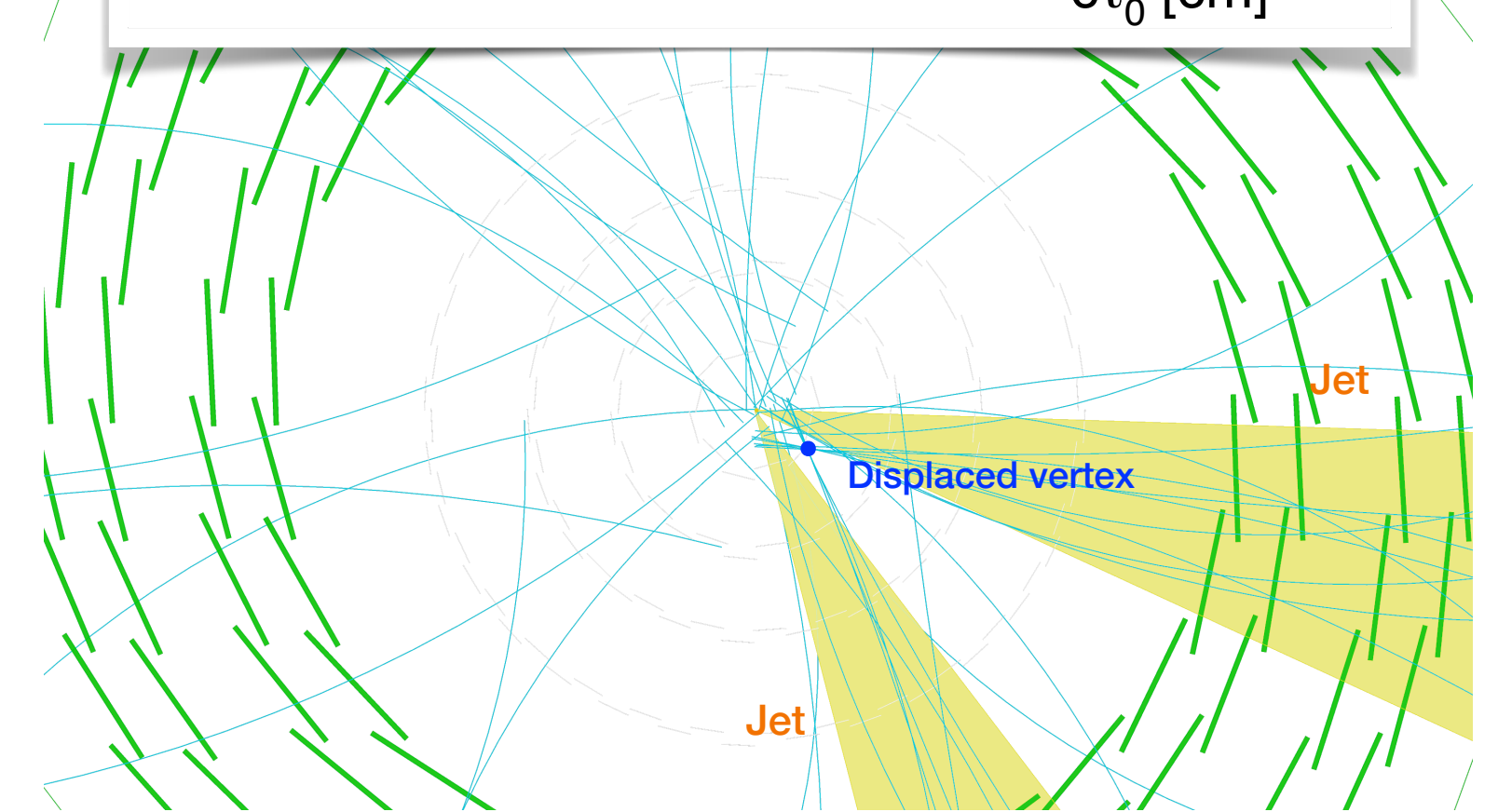
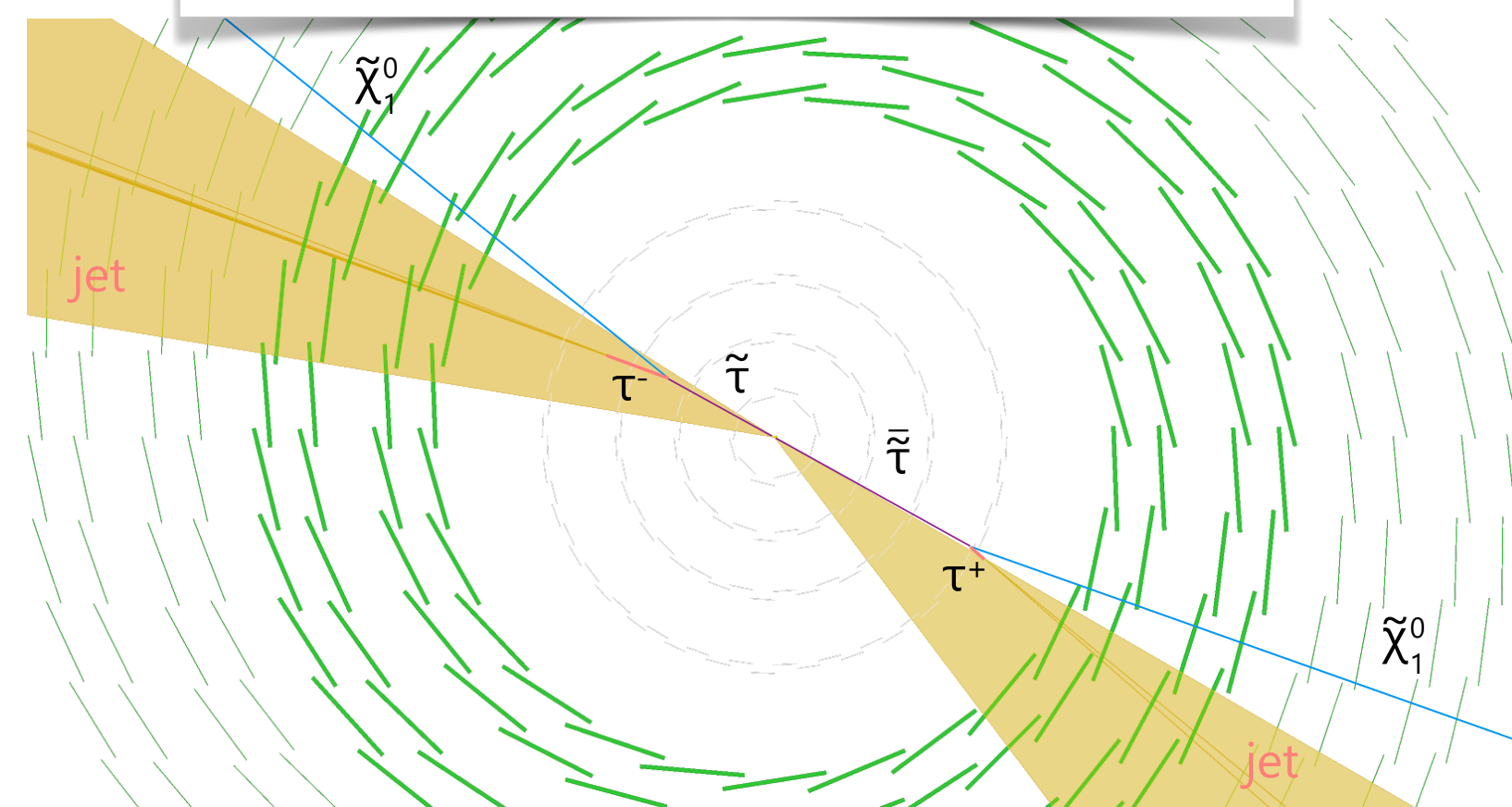
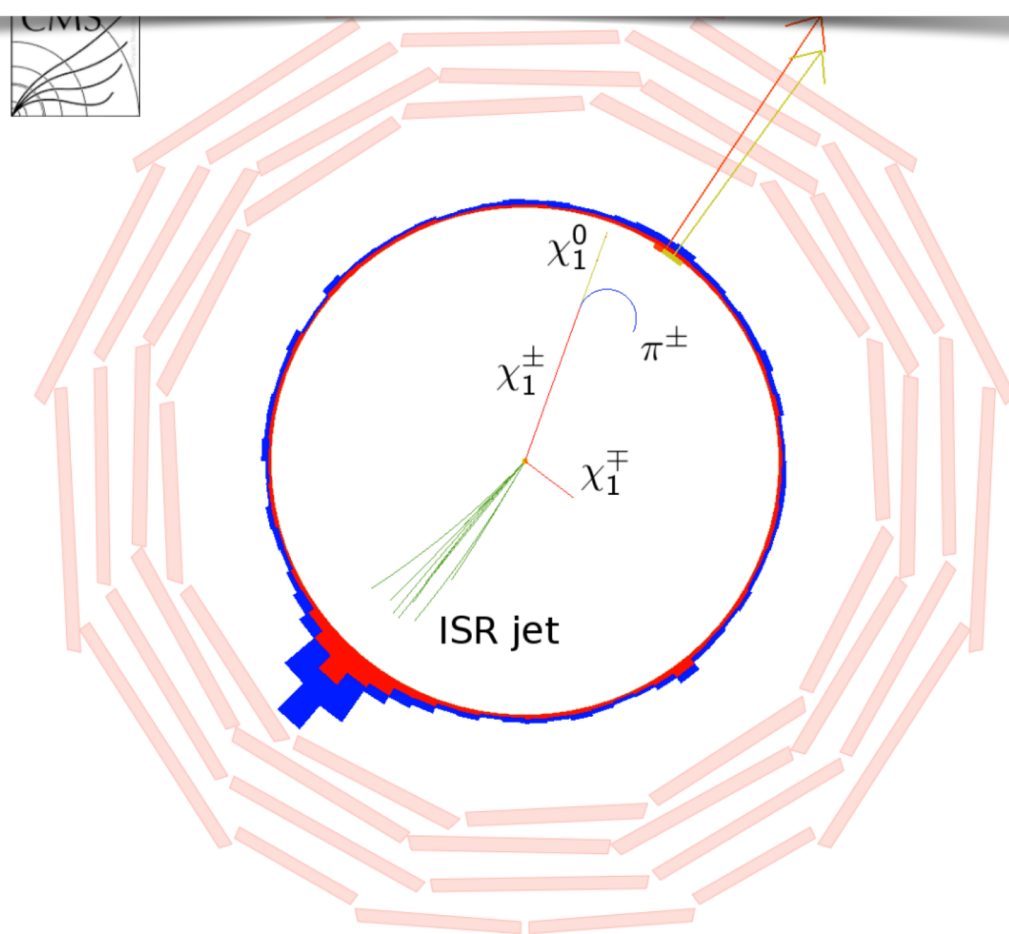
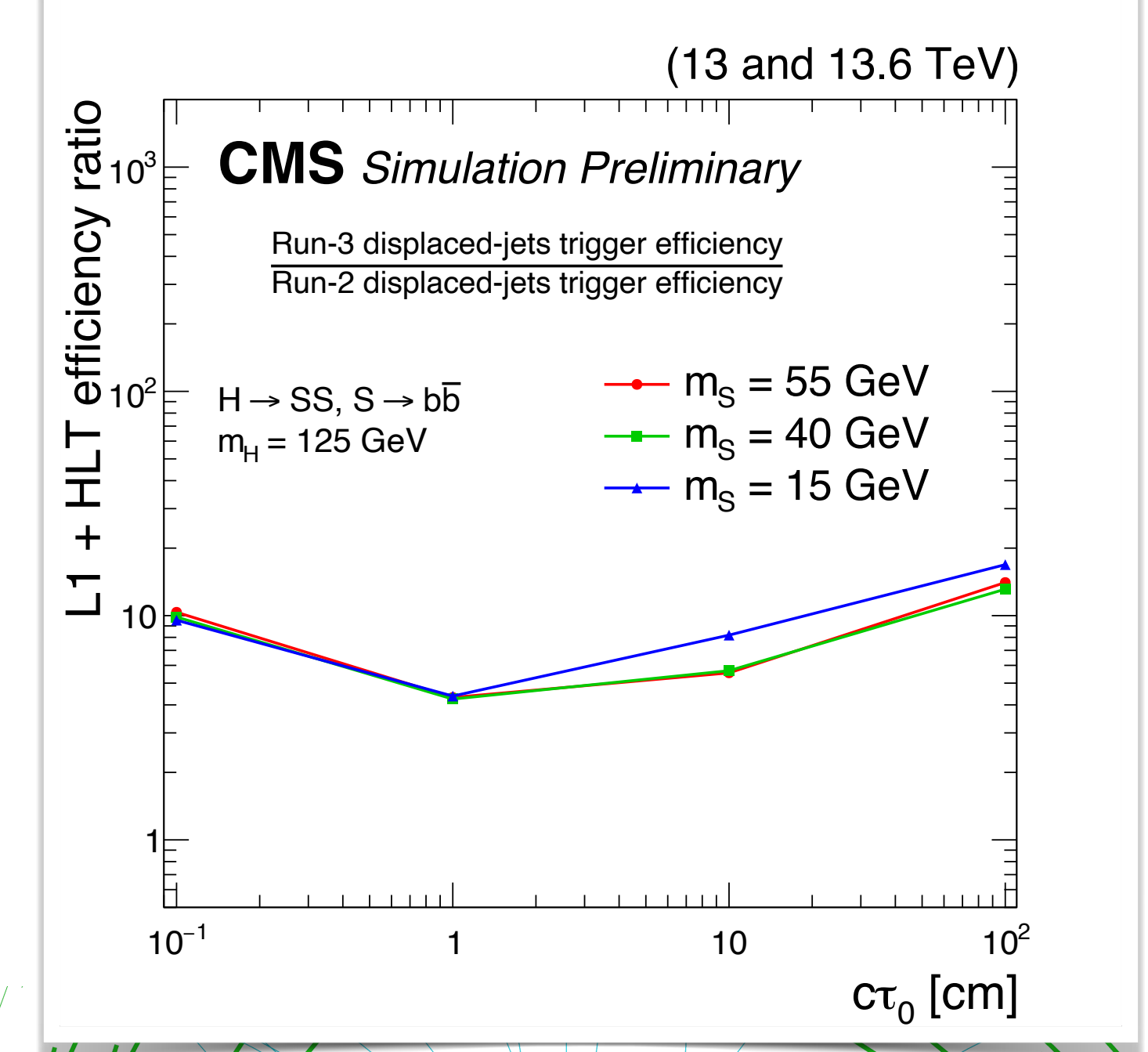
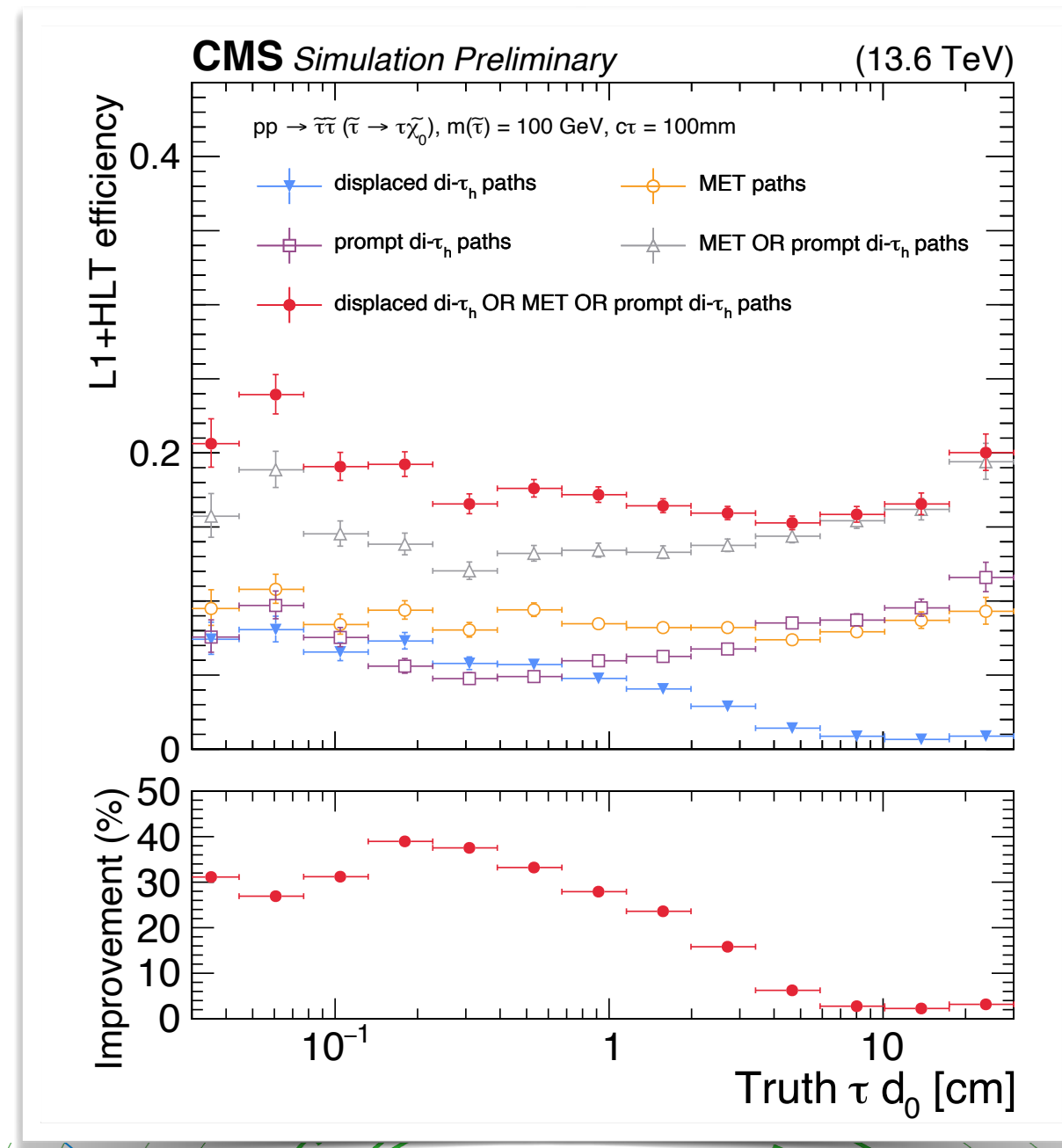
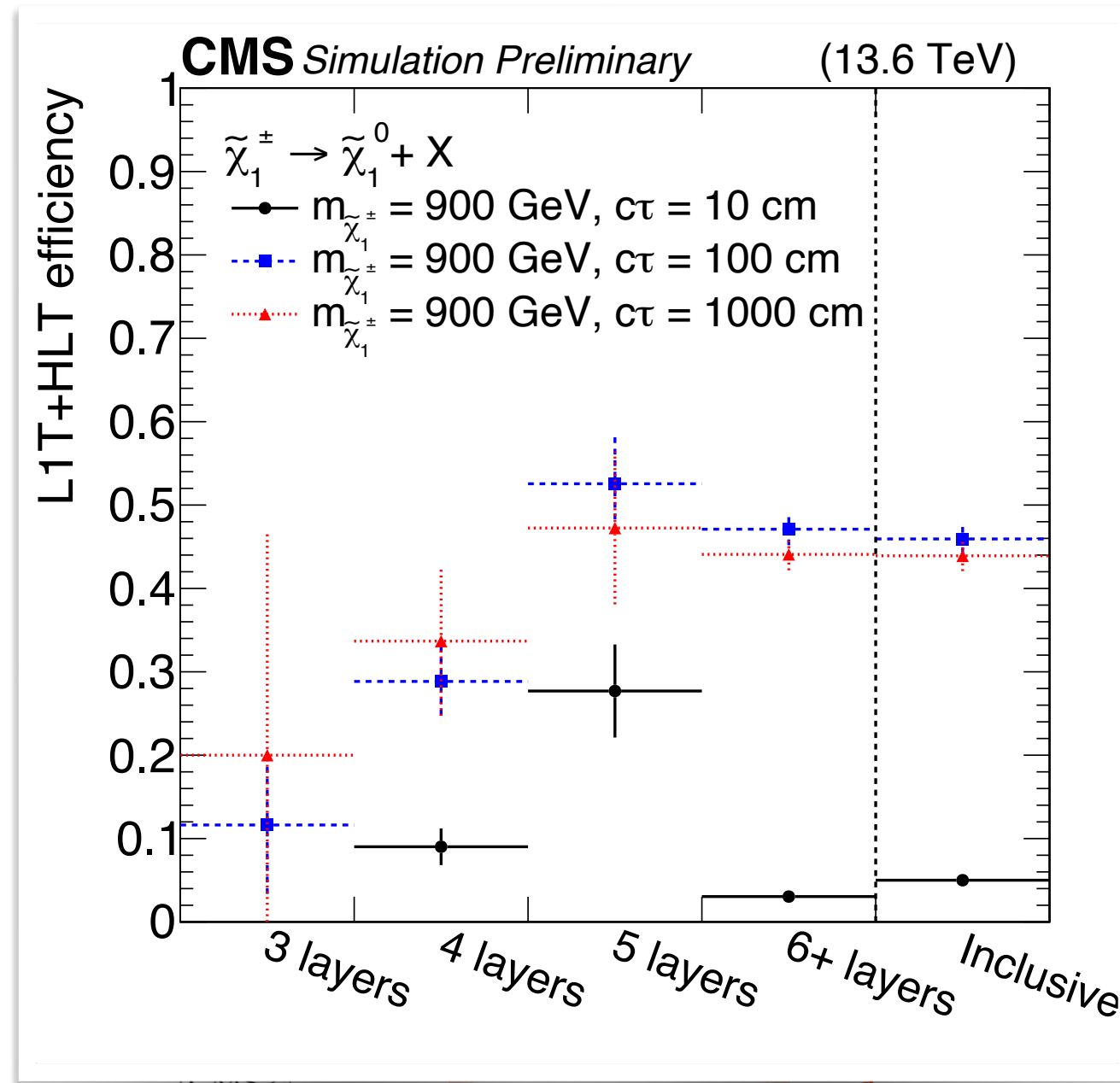
- ◆ Long-lived particles could leave unique signatures that may not captured by standard triggers
 - Dedicated triggers targeting LLPs enable increased sensitivity to wide variety of signal models
 - dedicated displaced muon reconstruction for dimuon stream in scouting
- ◆ Throughout Run 2 and Run 3, CMS substantially increased bandwidth and priority for LLP searches, making them a central focus of the trigger and physics program
 - introduction of a new parking data set for LLPs (+ enriched prompt dataset)
 - dedicated displaced muon reconstruction in scouting (dimuon stream)
- ◆ Multiple triggers using different detectors to effectively cover a large range of final states and LLP lifetimes
 - Track-based: available at HLT
 - Calo-based:
 - ECAL timing available at HLT
 - Displaced/delayed jets in HCAL available at L1T & HLT
 - Muon-based:
 - Displaced muon triggers available at L1T & HLT
 - Muon detector showers in DTs available at HLT
 - Muon detector showers in CSCs available in L1T & HLT

Data	Total rate [Hz]	Pure rate [Hz]
Standard	393	311
Parking	234	182
Scouting	4200	3800
Full reconstruction: standard or parking	586	389



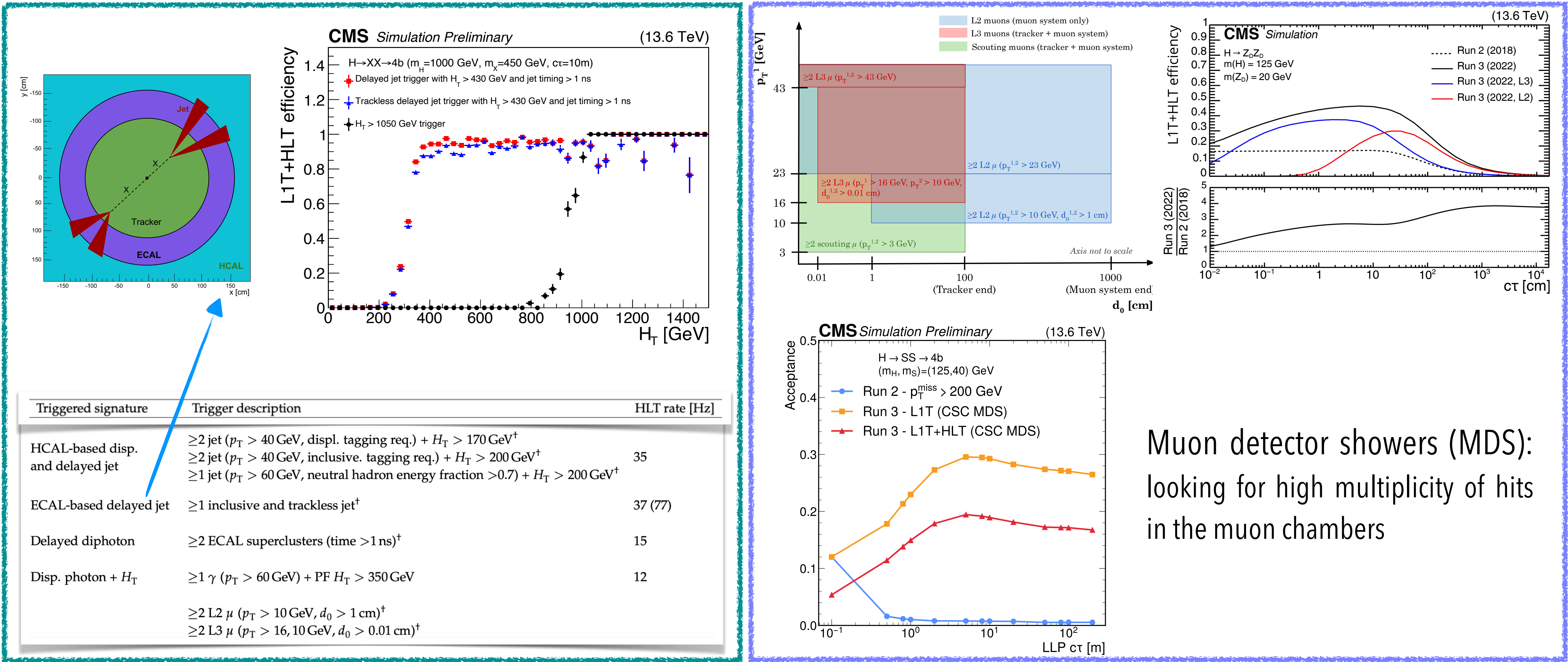
RUN 3 LLP TRIGGERS: TRACK-BASED

Phys. Rept. 1205 (2027) 1



RUN 3 LLP TRIGGERS: CALO- AND MUON-BASED

Phys. Rept. 1205 (2027) 1



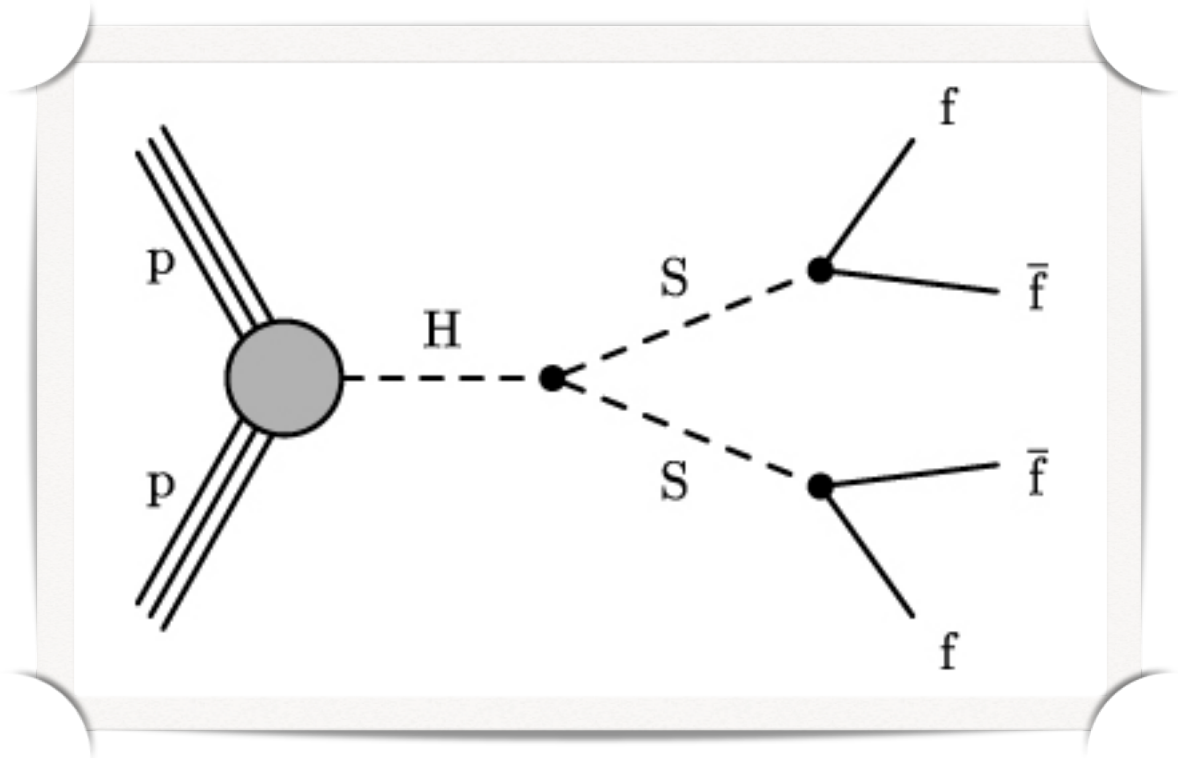
Muon detector showers (MDS):
looking for high multiplicity of hits
in the muon chambers

..many more available!

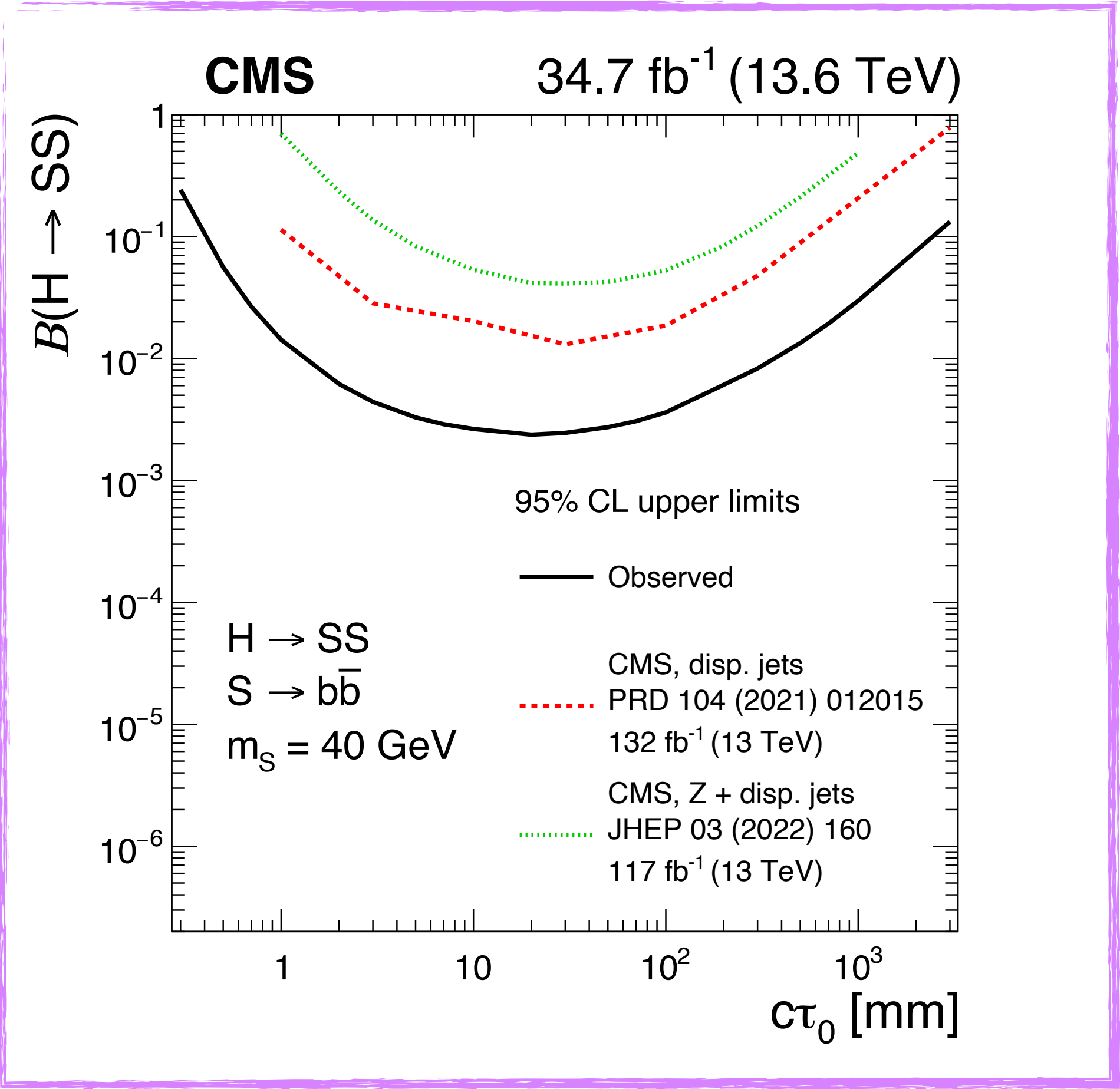
RUN 3 LLP PARKING: SEARCH FOR DISPLACED JETS

Phys. Rept. 1205 (2027) 1

- ◆ Already published with early Run 3 data from the new parking data set:
 - using displaced track-based jets seeds, limits on $H \rightarrow ss \rightarrow 4b, 4d, 4\tau$ much improved with respect to Run 2 analyses



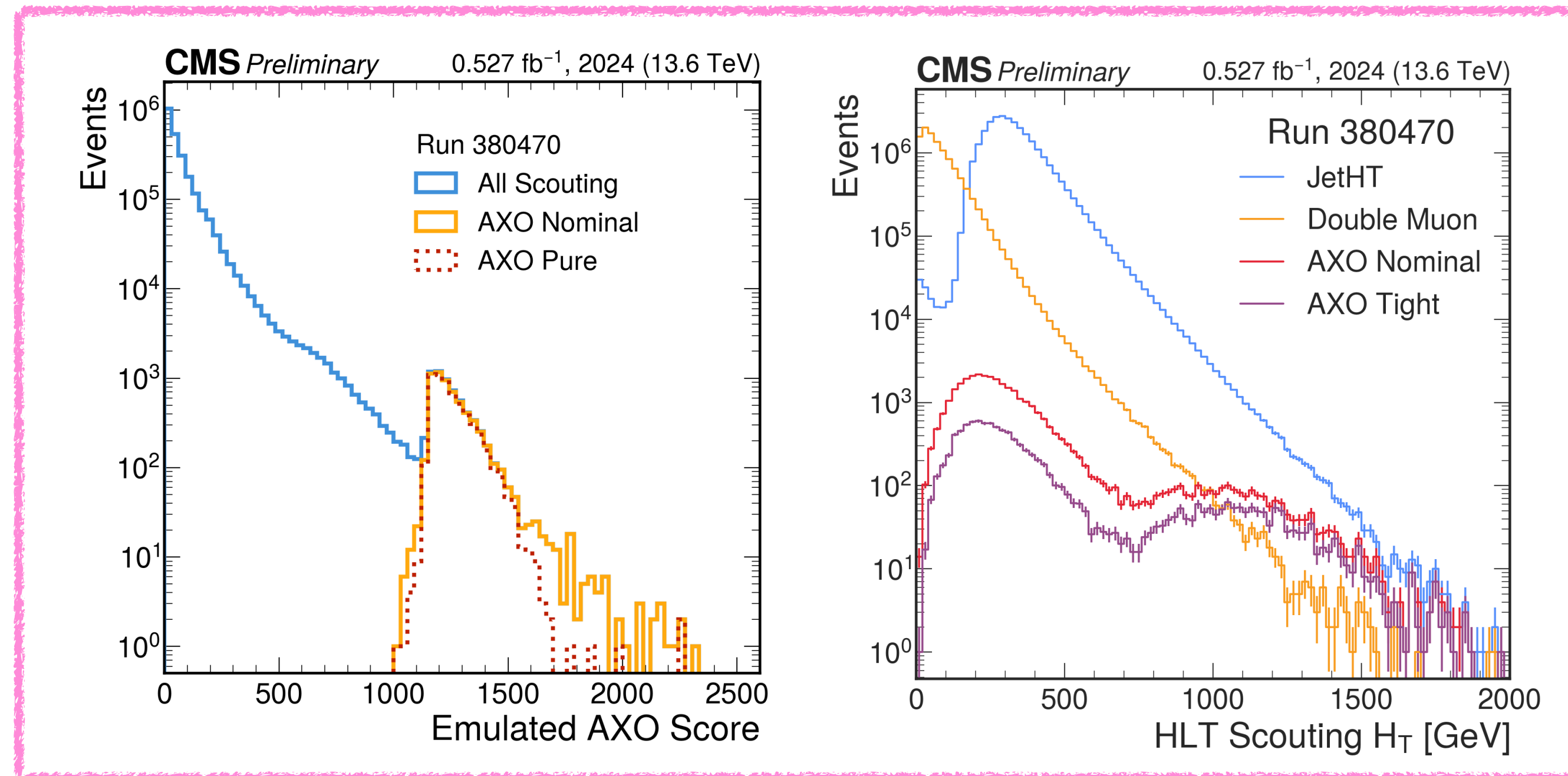
Triggered signature	Trigger description	HLT rate [Hz]
Disp. jet	≥ 2 jet ($p_T > 40$ GeV, inclusive tagging req.) + $H_T > 430$ GeV ≥ 2 jet ($p_T > 40$ GeV, disp. tagging req.) + $H_T > 240$ GeV + ≥ 1 L1 μ ($p_T > 6$ GeV)	53 (163)



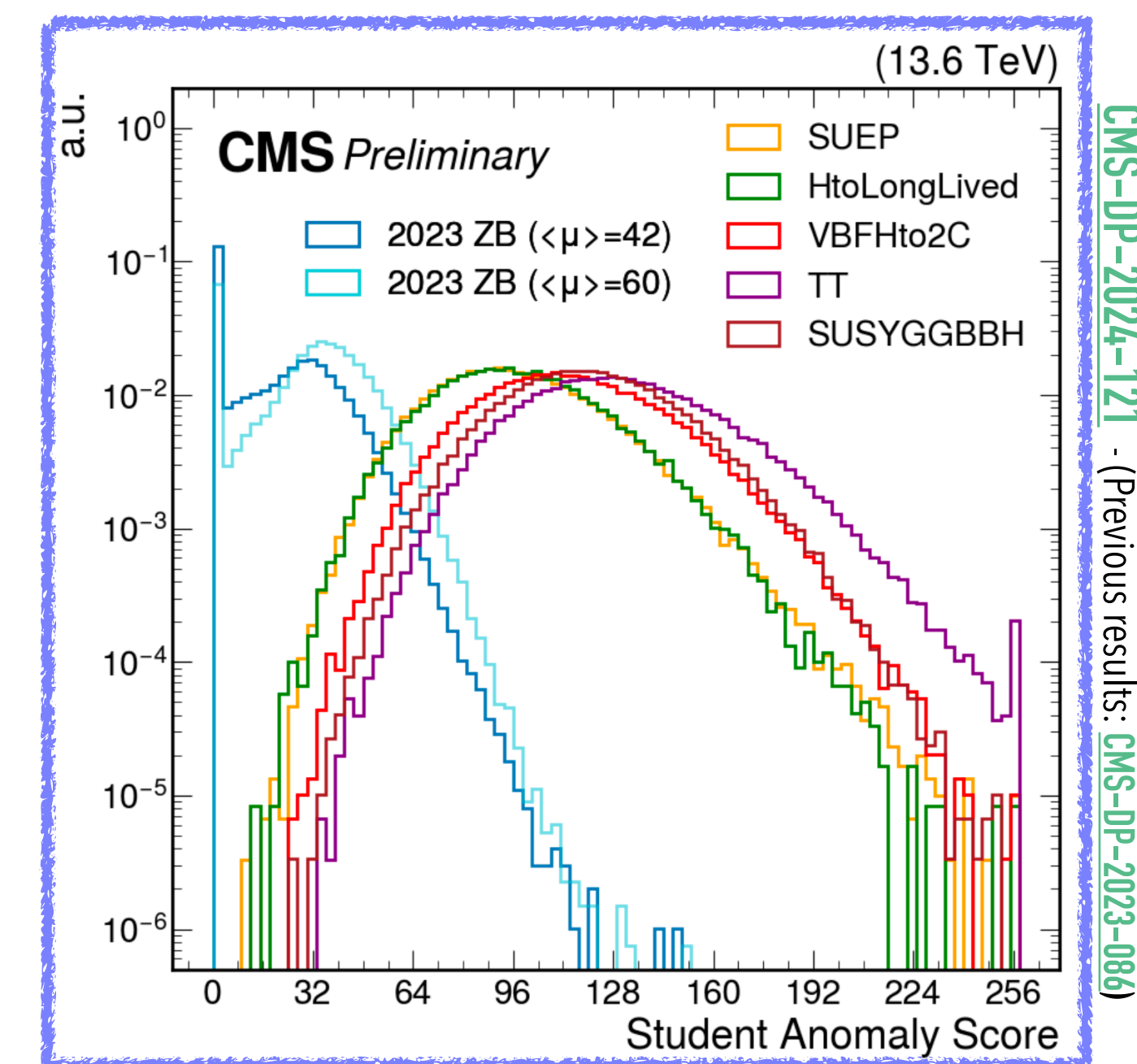
RUN 3 HLT SCOUTING: ANOMALY DETECTION TRIGGERS



- ◆ In Spring 2024 CMS established a new trigger paradigm with sub- μ s autoencoders for anomaly detection: **AXOL1TL** (= Anomaly eXtraction Online L1 Trigger aLgorithm) deployed in L1 Global Trigger
 - 100 fb⁻¹ collected by AXOL1TL, L1T rate of $\sim 300\text{Hz} - 1100\text{Hz}$ ($\sim 5\text{ kHz}$ in 2025), passthrough at HLT scouting
- ◆ During the 2025 data taking, a new autoencoder running on L1 calorimeter deposits started to collect data: **CICADA** (= Calorimeter Image Convolutional Anomaly Detection Algorithm)

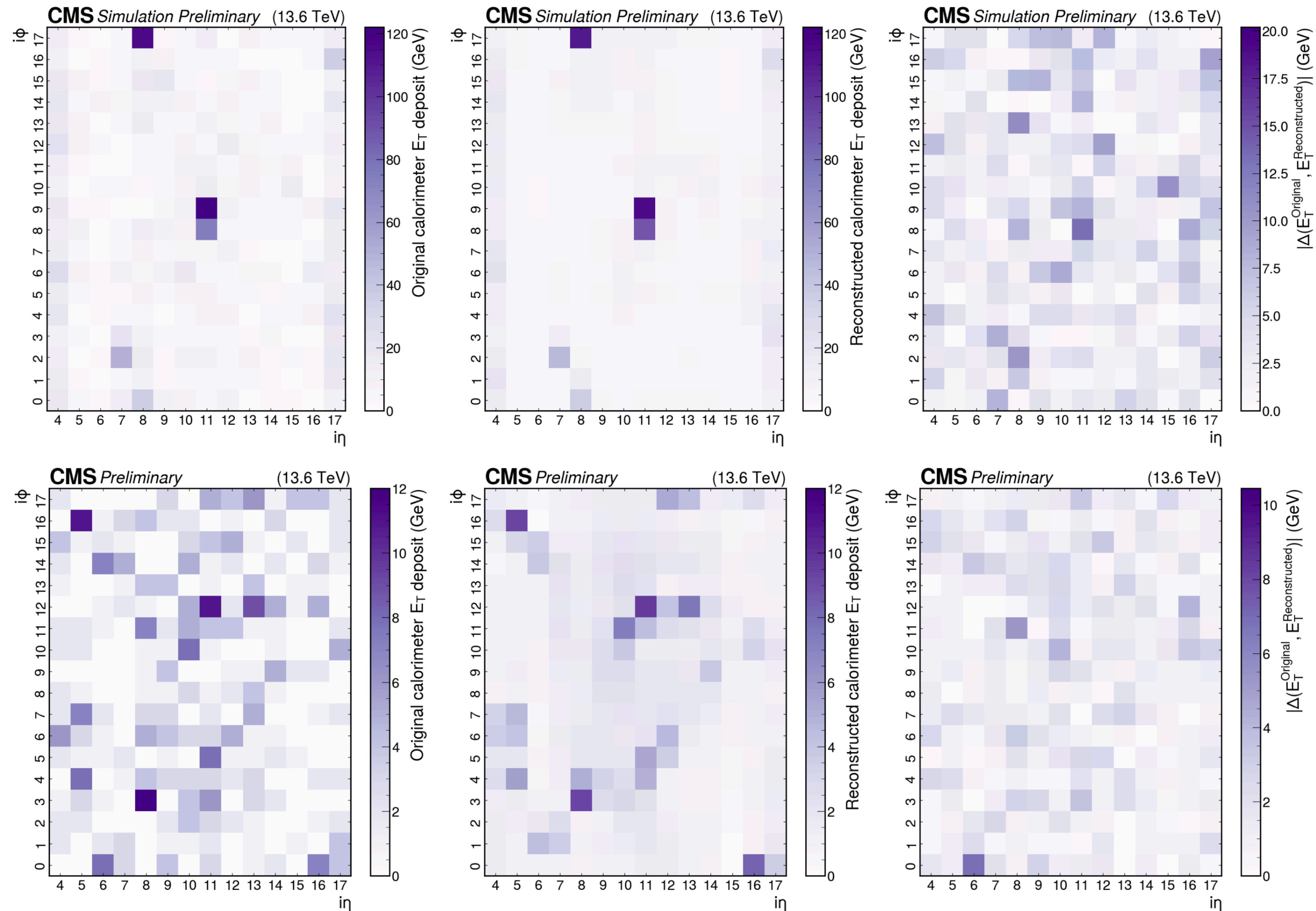


CMS-DP-2024-059



CMS-DP-2024-121 - (Previous results: CMS-DP-2023-086)

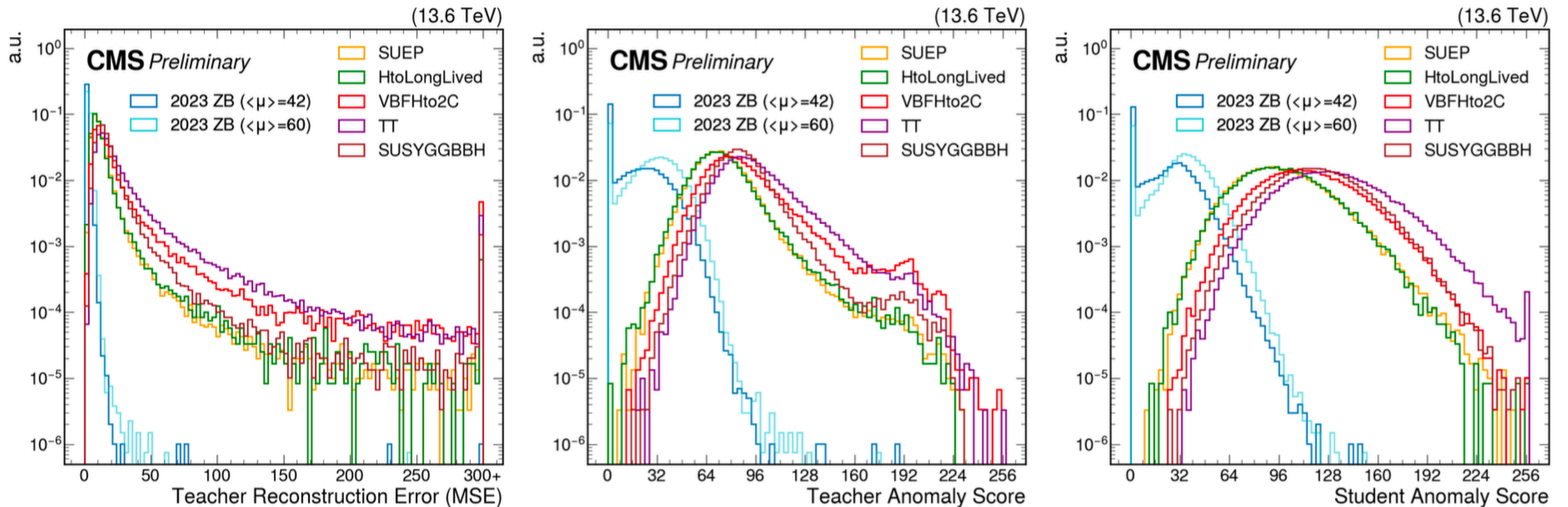
ANOMALY DETECTION: CICADA – TEACHER RECONSTRUCTION EXAMPLE



Reconstruction of a **signal event**
(SUSYGGBH) by the teacher model

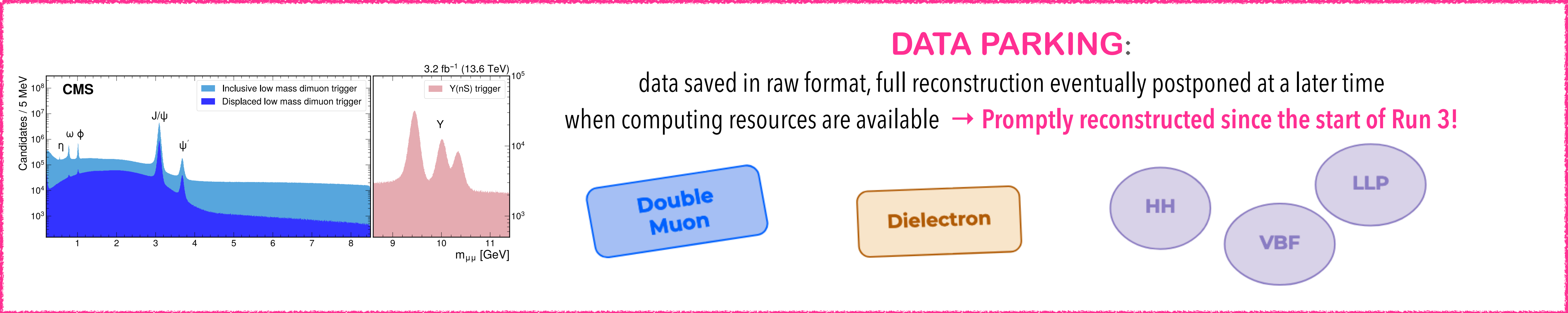
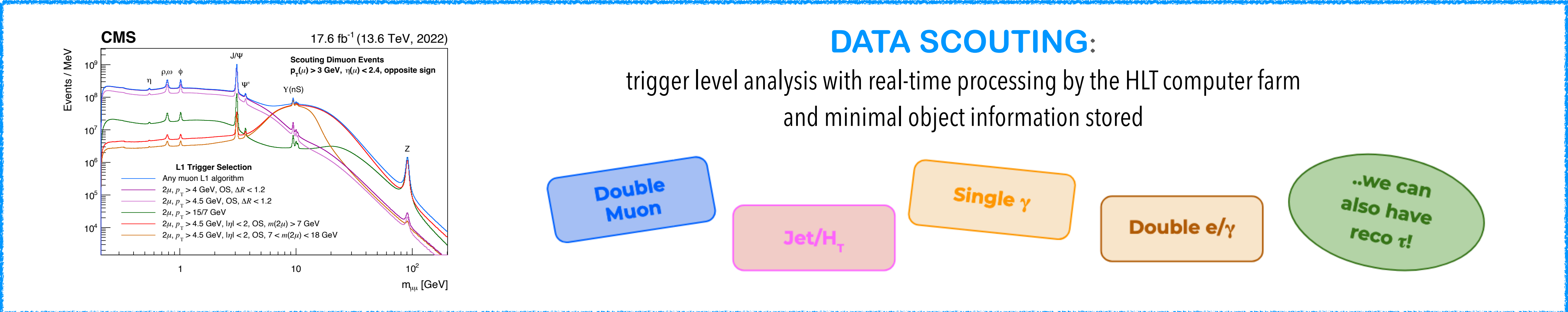
Reconstruction of a **ZB event**
(background) by the teacher model

ANOMALY DETECTION: CICADA – ANOMALY SCORE



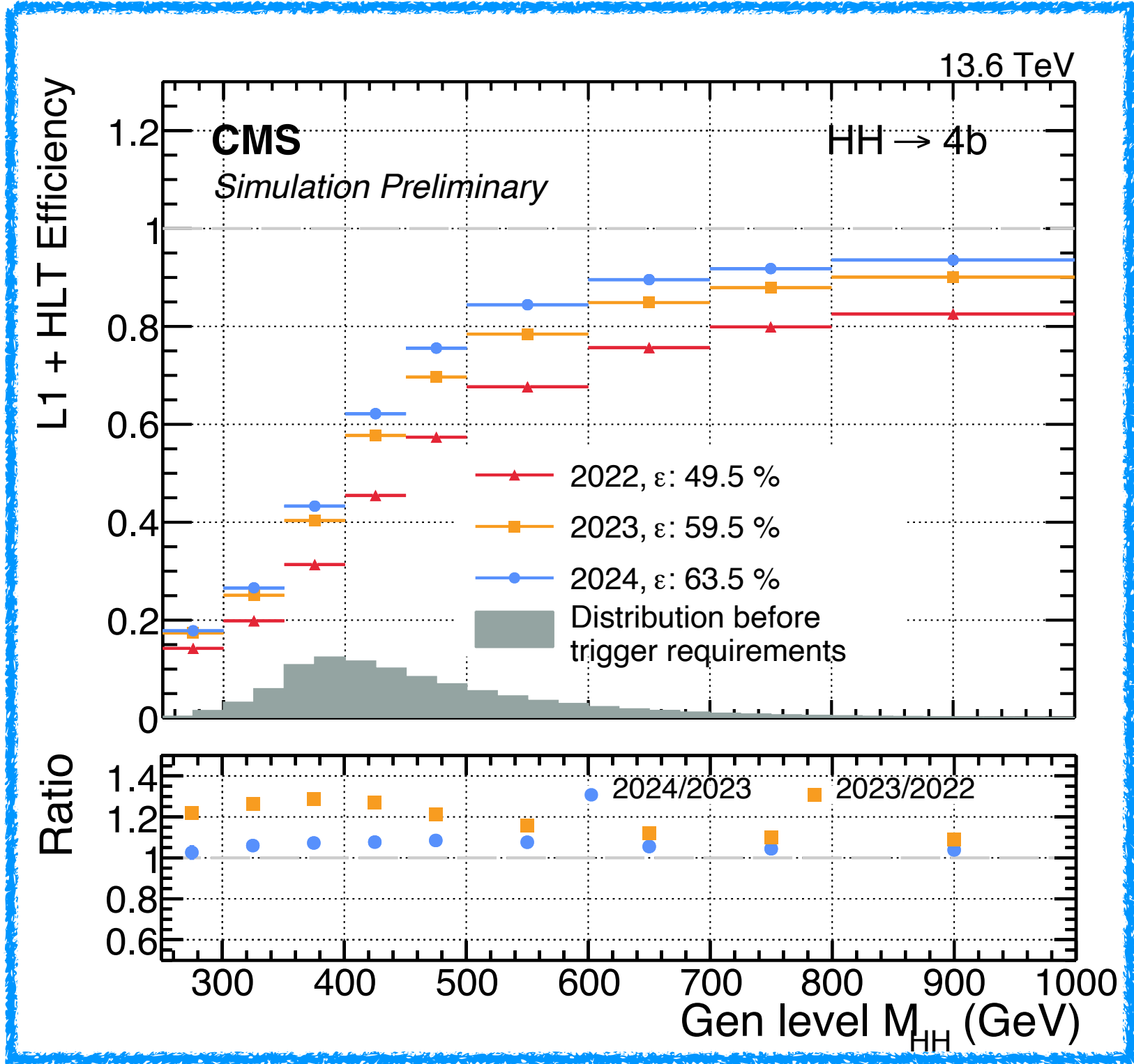
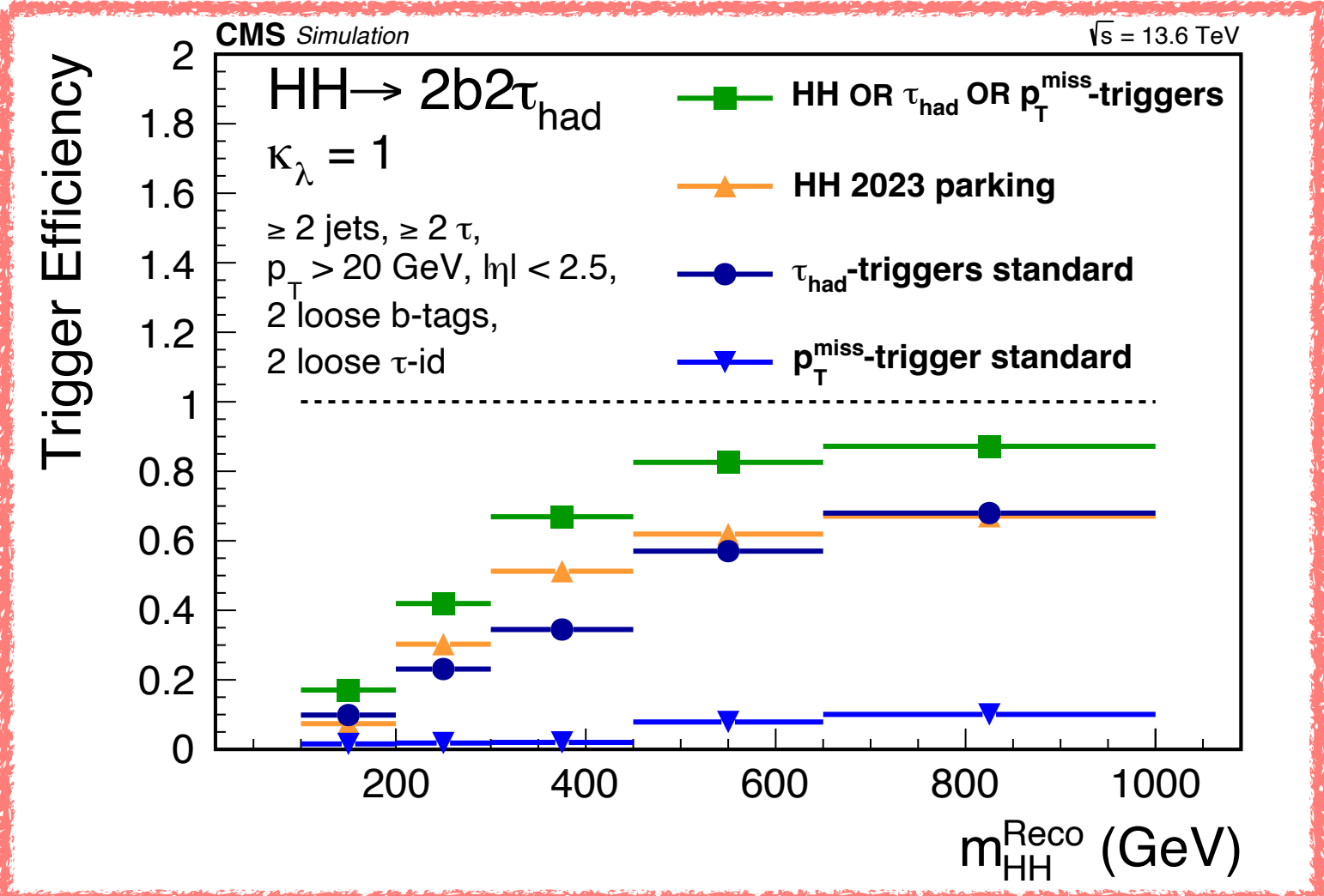
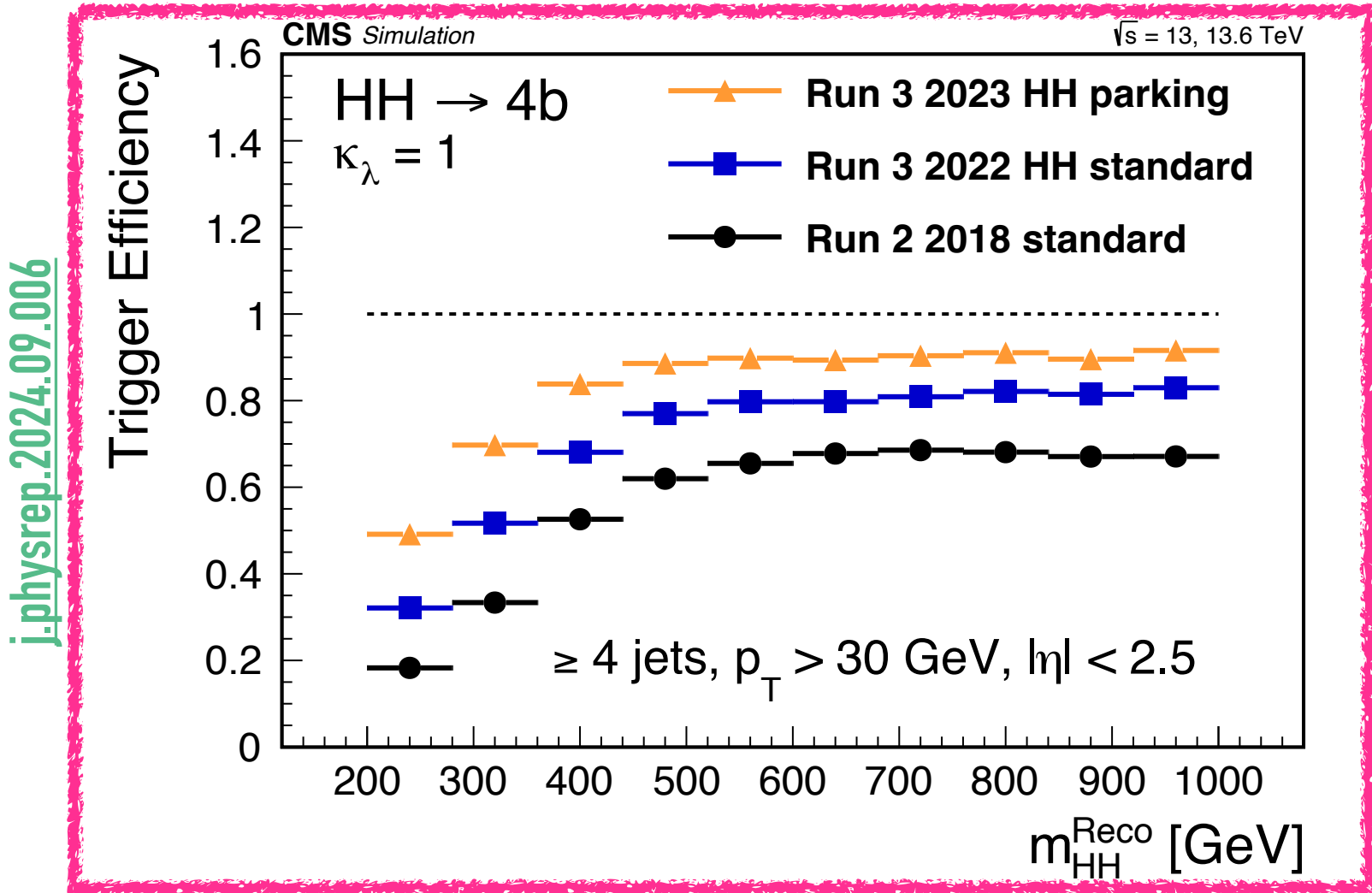
RUN 3 EXPANSION OF DATA SCOUTING: OBJECTS

Large increase of the computing capabilities of the HLT and resources for the start of Run 3:
Run 3 program much more powerful → new data streams & lower thresholds



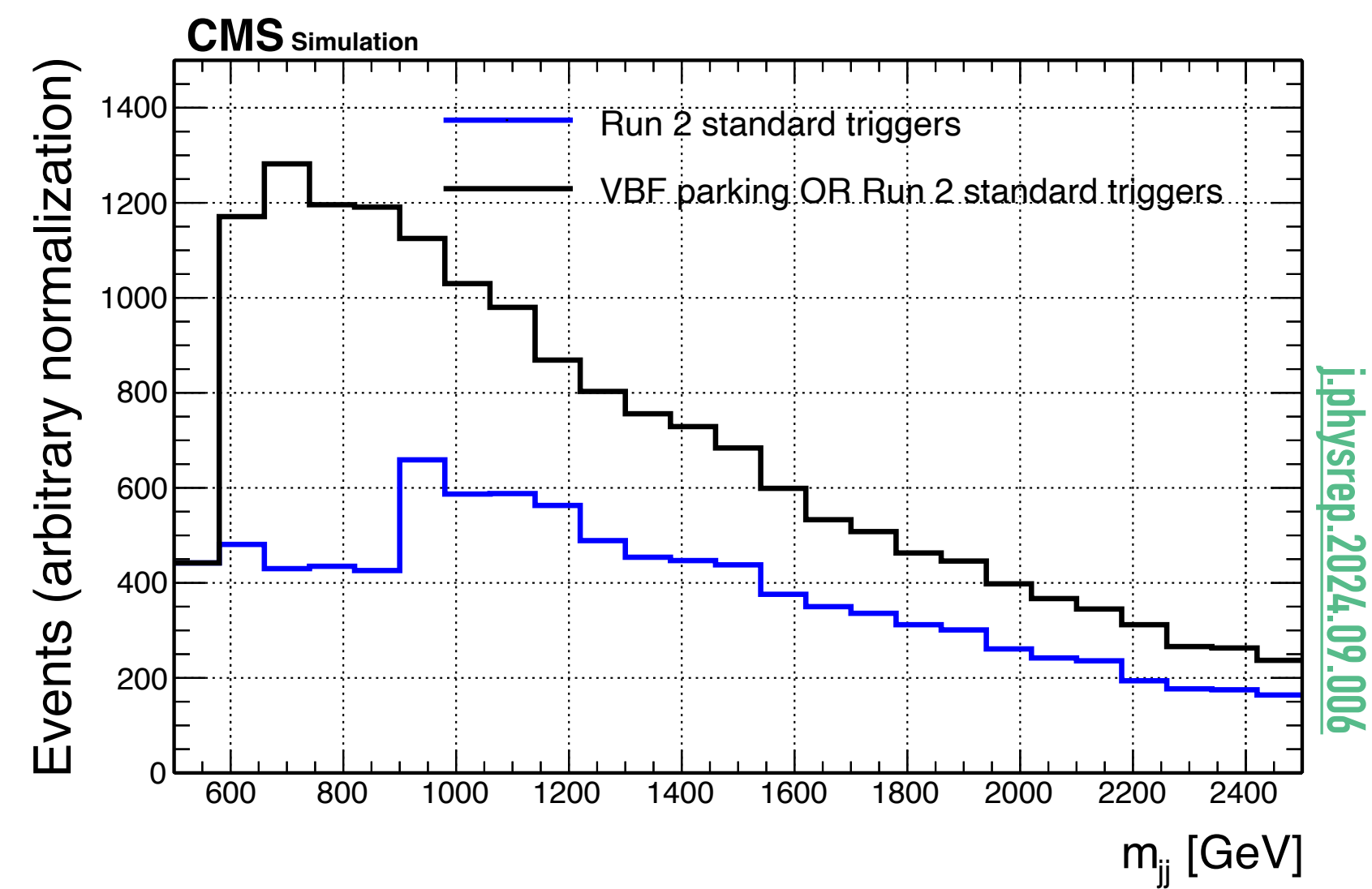
HH PARKING

- ◆ HH parking stream allows high-rate paths (about 350 Hz) that expand acceptance for $H(bb)H(XX)$ tagging the $H(bb)$
 - +30% in $HH \rightarrow 4b$ efficiency w.r.t. Run 2
 - Large gain in $H(\tau\tau)H(bb)$
 - Dedicated PNet AK4 (AK8) $b(bb)$ -tagging algorithms ([CMS-DP-2025-009](#))



VBF PARKING

- ◆ VBF parking stream allows high-rate path that expand acceptance for **VBF+X** (trigger or not triggering on X):
 - complementary inclusive and exclusive strategy

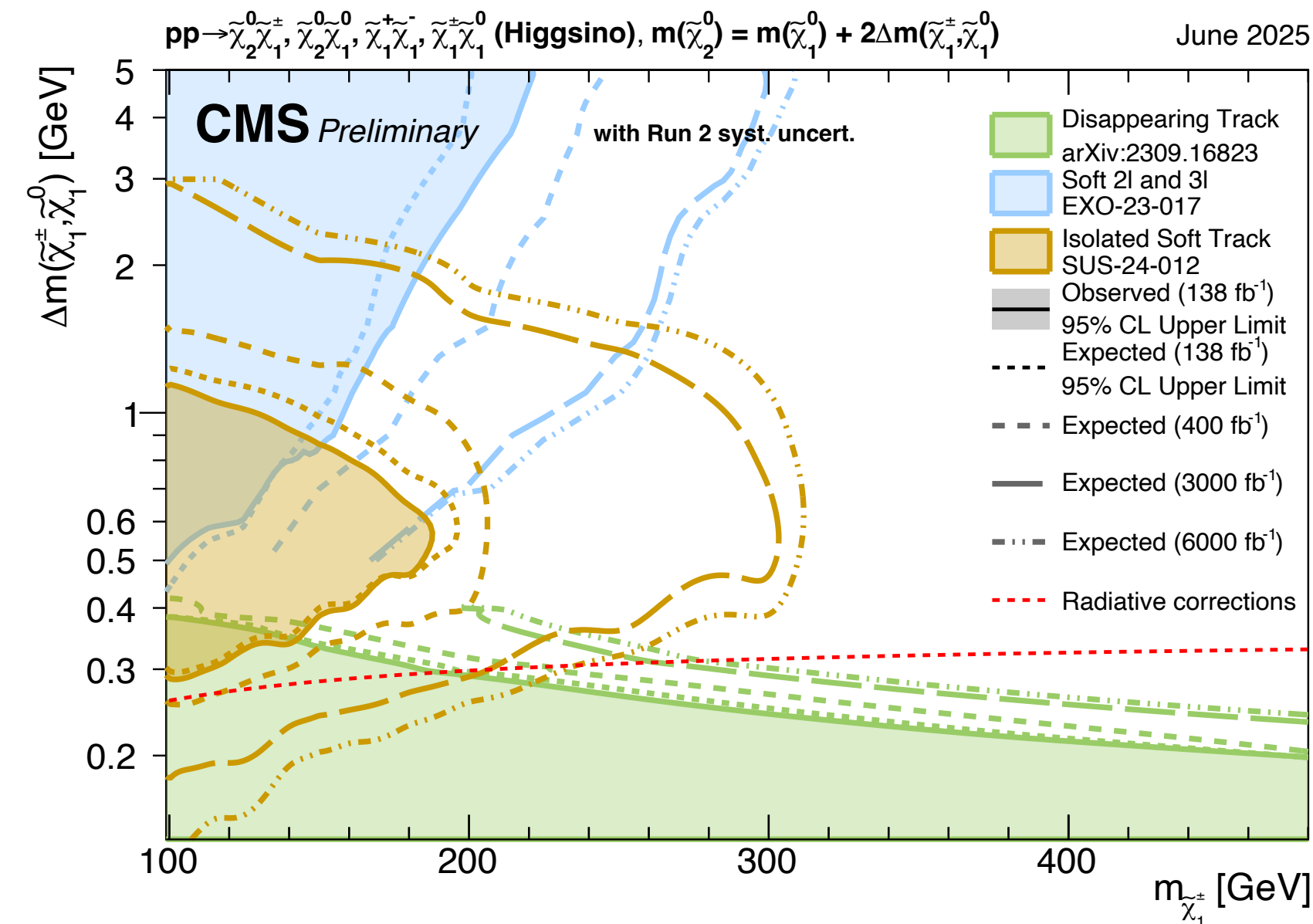


HLT trigger path	VBF requirements($p_T^{j1}, p_T^{j2}, m_{jj}, \Delta\eta_{jj}$)	Requirements on additional objects	Rate [Hz]
VBF inclusive	(105, 40, 1000, 3.5)	—	800
VBF + 2 central jets	(70, 40, 600, 2.5)	2 central jets, $p_T^j > 60$ GeV	380
VBF + p_T^{miss}	(75, 40, 500, 2.5)	$p_T^{\text{miss}} > 85$ GeV	110
VBF + μ	(90, 40, 600, 2.5)	1 muon, $p_T^\mu > 3$ GeV	120
VBF + τ_h	(45, 45, 500, 2.5)	1 isolated τ_h , $p_T^\tau > 45$ GeV	40
VBF + γ	(45, 45, 500, 2.5)	1 photon, $p_T^\gamma > 17$ GeV	100
VBF + e	(45, 45, 500, 2.5)	1 isolated electron, $p_T^e > 17$ GeV	2

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New ideas:

- ◆ Using VBF production for SUEPs, or for X(ee) low mass resonance searches?
- ◆ Triggering on VBF to lower MET thresholds in compressed Higgsinos searches (or similar)?



CMS DETECTOR @ PHASE-2

- ▶ More **simultaneous collisions**: ~200 PU
- ▶ High **radiation levels**: O(100) Mrad

Sub-detector upgrades

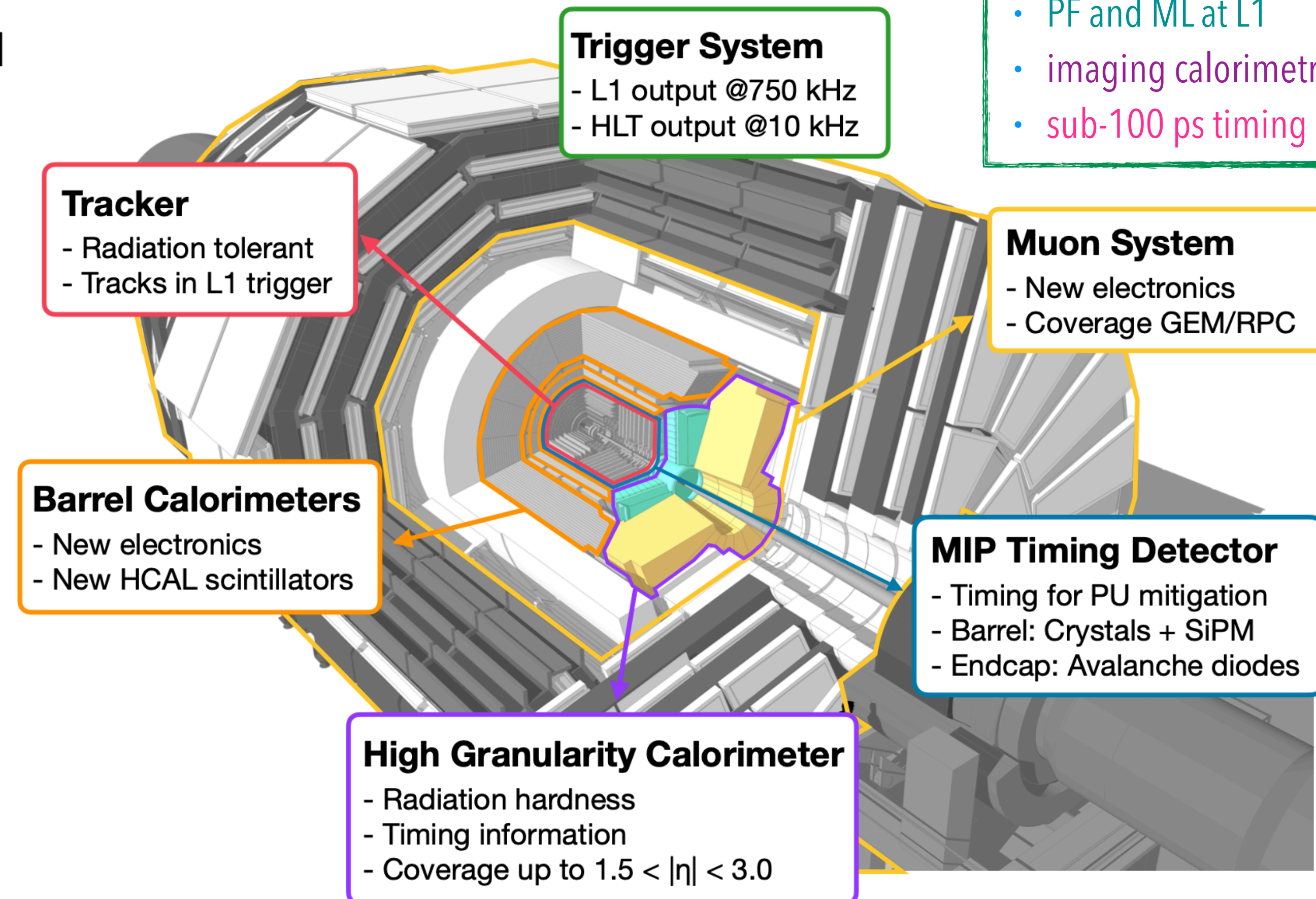
- ▶ **Granularity and Timing**
to separate different interaction vertices
- ▶ **Radiation hardness**
to sustain unprecedented dose

Trigger upgrades

- ▶ **Faster Processing**
to fit within available latency
- ▶ **Higher Computational Power**
to reconstruct all particles

→ Trigger paradigm shifts:

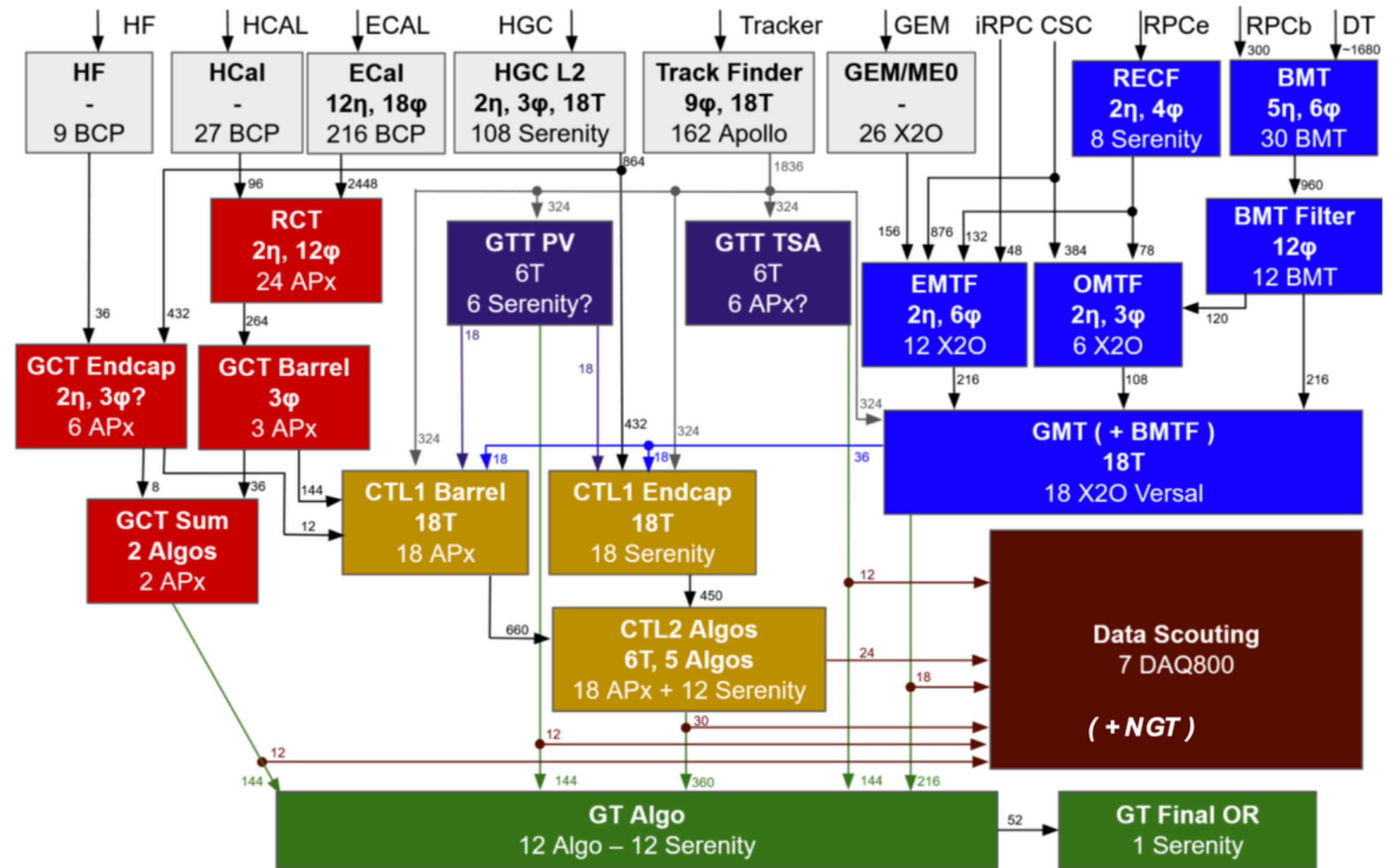
- track trigger at L1
- PF and ML at L1
- imaging calorimetry
- sub-100 ps timing



CMS DETECTOR @ PHASE-2: L1 TRIGGER

New system capabilities with respect to Run 3:

- 40 MHz tracking ($p_T > 2$ GeV)
- 40 MHz particle flow
 - with PUPPI



CMS DETECTOR @ PHASE-2: L1 TRIGGER

New system capabilities with respect to Run 3:

- 40 MHz tracking ($p_T > 2$ GeV)
- 40 MHz particle flow
 - with PUPPI

→ Machine learning (BDTs and NNs) in almost every subsystem to improve trigger primitives or final objects reconstruction/identification, as well as providing event level tagging

→ Enhanced L1 scouting system

