CMS physics results with focus on trigger

Triggering Discoveries in High Energy Physics III
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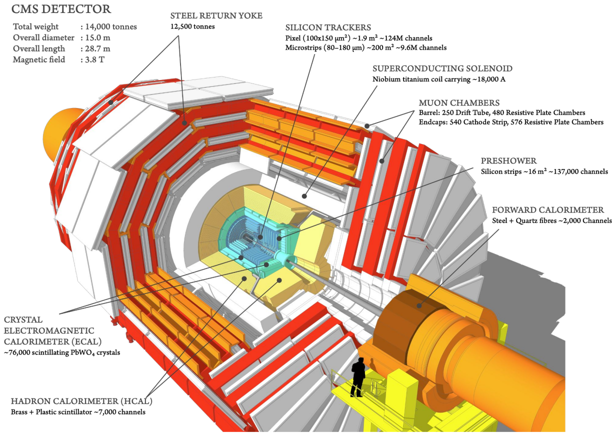
on behalf of the CMS collaboration

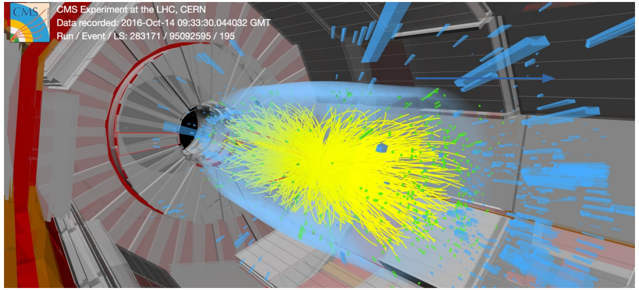
Outline

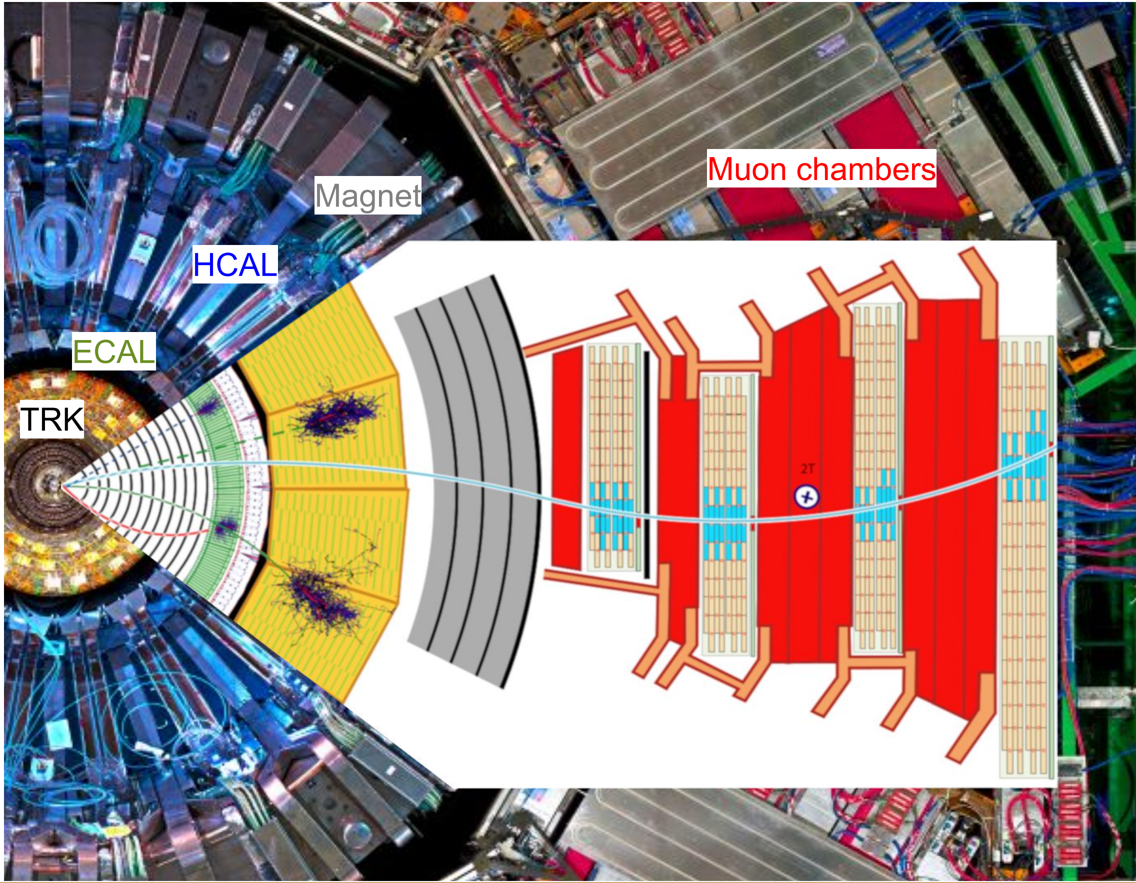
- The CMS experiment and its trigger.
- Overview of recent physics results from:
  - “standard” triggers;
  - scouting;
  - parking;
  - long-lived particle triggers;
  - PbPb collisions.
- Outlook.
- Conclusions.

The CMS experiment and its trigger

The CMS detector







Triggering at hadron collider

- Trigger is key for success of HEP experiments.
- Trigger is particularly challenging in hadronic collider because of multijet background.
- Main signatures used to trigger in hadronic colliders:
  - **Isolated muon/electron(s)**, eg. from Z/W decay
    - **target**: Higgs and EWK physics, Top, New Physics with Z/W bosons (eg. vector-like quarks)
    - **rate**: small (W/Z+jets)
  - **Non isolated muon/electron(s)**, eg. double muon from J/psi decay:
    - **target**: measurements about B and C hadrons
    - **rate**: signal, combinatorial (from QCD), electron from photon conversion
  - **Photons**:
    - **target**: Higgs → photons, ISR, FSR, new physics with photons (eg. diphoton resonance)
    - **rate**: jet misidentification, photons from QCD production (α_{EM} suppressed)
  - **Taus (hadronic decay)**:
    - **target**: Higgs -> $\tau\tau$, new physics with taus (eg. ditau resonance)
    - **rate**: jet misidentification
  - **Missing transverse energy**:
    - **target**: dark matter, Z → inv. (eg. ZH), H → inv.
    - **rate**: instrumental background
  - **Jets (b-tag)**:
    - **target**: large background from strong interaction
    - **rate**: multijet from QCD

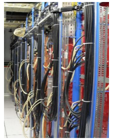
clean environment
low thresholds

large background
high thresholds

doi:10.1088/1748-0221/19/11/P11021

CMS trigger menu

Simplified readout → 40 MHz → **L1 trigger**



100 kHz (<4μs) →

Full readout → 100 kHz, 100 GB/s → **HLT**

~2 kHz (~300 ms) ~2 GB/s → **Data storage & reconstruction**

2018 CMS trigger menu

HLT path	L1 thresholds [GeV]	HLT thresholds [GeV]	Rate [Hz]
Single muon	22	50	49
Single muon (isolated)	22	24	230
Double muon	22	37, 27	16
Double muon (isolated)	15, 7	17, 8	32
Single electron (isolated)	30	32	180
Double electron	25, 12	25, 25	16
Double electron (isolated)	22, 12	23, 12	32
Single photon	30	200	16
Single photon (isolated), barrel only ($\|\eta\| < 1.48$)	30	110	16
Double photon	25, 12	30, 18	32
Single tau	120	180	16
Double tau	32	35, 35	49
Single jet	180	500	16
Single jet with substructure	180	400	32
Multijets with b tagging	$H_T > 320$ jets > 70, 55, 40, 40	$H_T > 330$ jets > 75, 60, 45, 40	16
Total transverse momentum	360	1050	16
Missing transverse momentum	100	120	49

clean environment
low thresholds

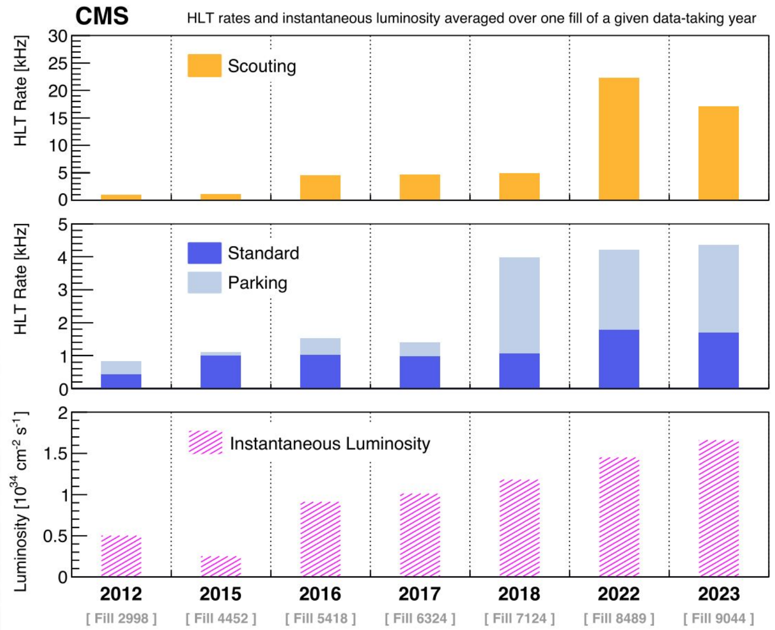
large background
high thresholds

doi:10.48550/arXiv.2403.16134

Rate evolution, scouting and parking

- The “standard” HLT rate cross-section increased with lumi since 2012,
  - **trigger cross section roughly constant**:
    - ~ 1 kHz/10^{34}cm^{-2}s^{-1}
- Large increase of **parking** rate in 2018.
  - **2018** idea: collect additional data to be processed during LHC shutdown 2 (2019-22)
  - **Run-3**: data processed promptly, if possible
- Revolution in **scouting** since 2022:
  - save **all** main physics objects reconstructed at HLT (tracks, vertices, muons, electrons, jets ...) in **20%** of events processed (~20 kHz);
  - event size x100 smaller than full RAW.
- More info in M. Musich talk.

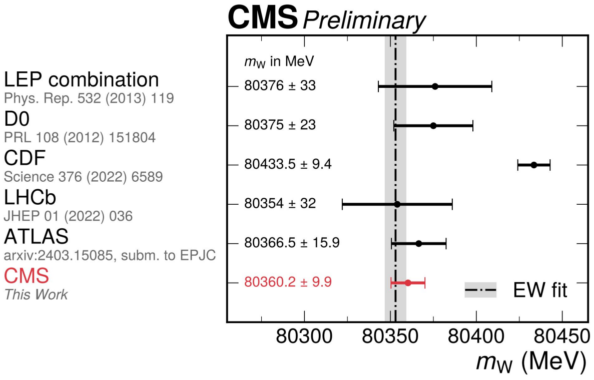
Trigger rate evolution

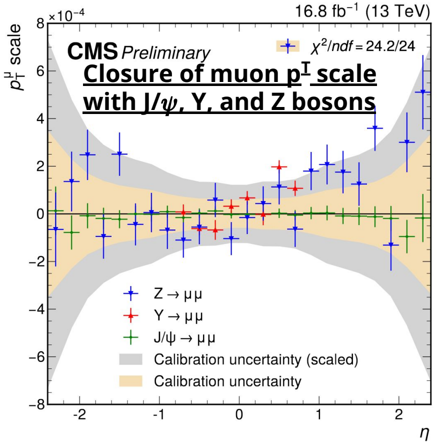


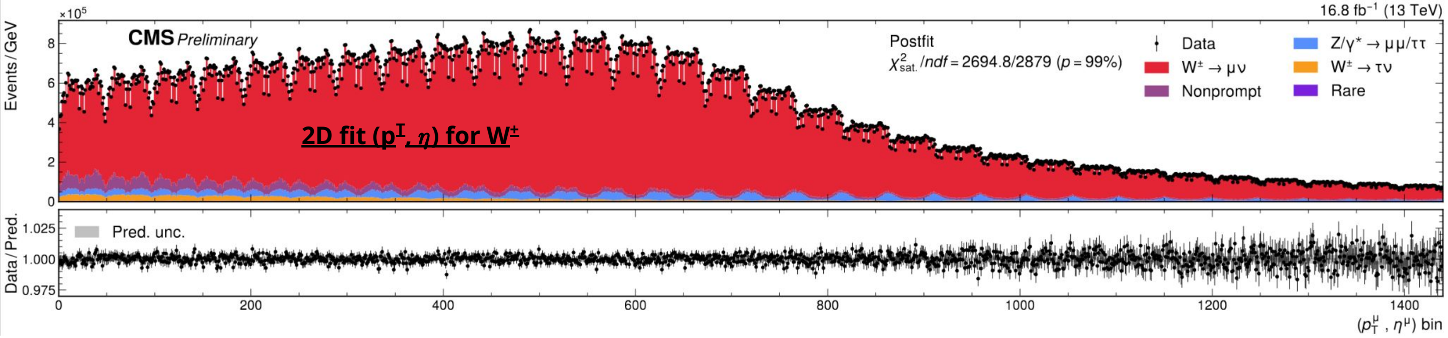
Results from “standard” triggers

W-mass

- W mass extracted from **3D fit** to muon (η, p_T , charge),
  - using best MC simulation (**4B events**!).
- Muon scale **obtained** from **J/ψ** and **validated** with **Z**,
  - required an improved MC simulation (Geant4e);
  - muon **track refitted** with Continuous Variable Helix;
  - improved parametrization of B-field, material budget, and alignment.
- Preliminary unblinding steps
  - **W-like** measurement from Z→μμ data;
  - **Z-boson** measurement ⇒ $m_Z - m_{PDG} = -2.2 \pm 4.8$ MeV.
- Results: best measurement (**9.9 MeV**) at LHC comp. EW fit.
  - More **model-independent** analysis (cross-check) ⇒ compatible result.



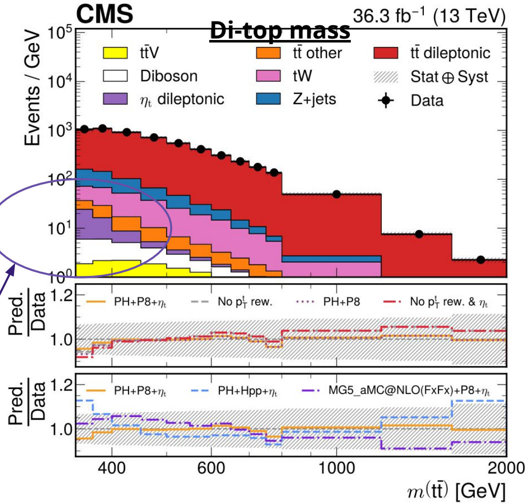




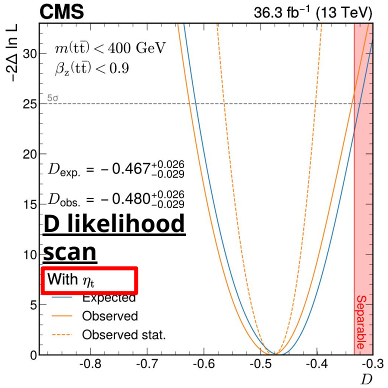
10.1088/1361-6633/ad7e4d

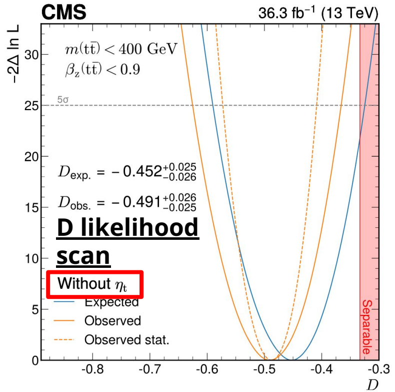
Entanglement in tt events

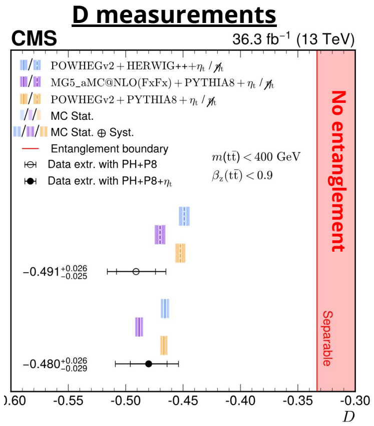
- Test of **entanglement** in dileptonic top pair events,
  - Decays to muons and electrons.
- **Spin-correlation** variable (D) < -⅓ evidence of entanglement.
- Using the low m_{tt} region, 345 — 400 GeV, higher sensitivity.
- Measurement:
  - D = −0.480 ± 0.028
  - D > -⅓ excluded with **5.1 standard deviations**.



Need to model possible effects of a contribution of **tt bound states** (toponium) at low m_{tt} (η_t)







doi:10.48550/arXiv.2408.07622

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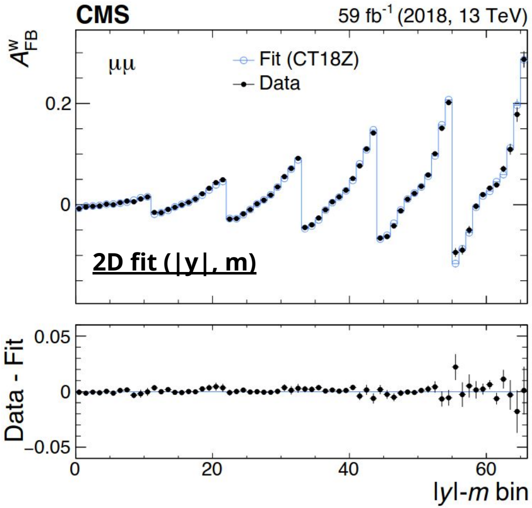
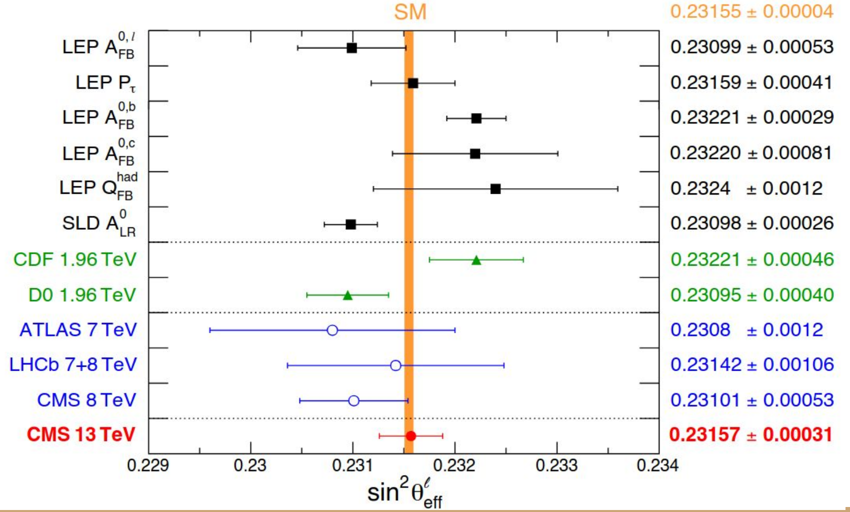
Weak mixing angle

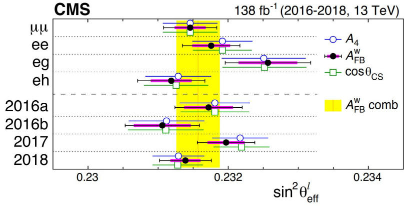
- First measurement from Gargamelle in 1973 $\sin^2\theta_W$: 0.3-0.4.
- Precision measurement from qq $\rightarrow Z/\gamma^* \rightarrow \ell\ell$ **forward/backward asymmetry** in double muon and electron final states.
- Sensitivity enhanced by extended acceptance of electrons to the forward calorimeter (3.14<$|\eta|$<4.36).
- **Result compatible with the SM. Resolution close to SLD/LEP!**



Effective weak mixing angle meas.



Effective weak mixing angle measured in different datasets



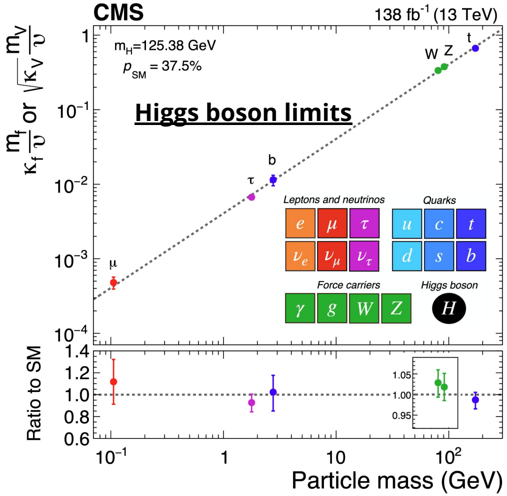
doi:10.1038/s41586-022-04892-x

Higgs

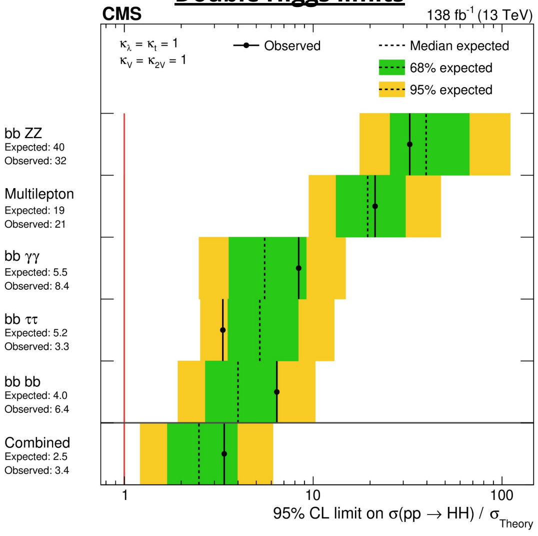
- Evidence for Higgs to muons (3σ).
- Higgs to $Z\gamma$ ($2.7\ \sigma$).
- Higgs to invisible: BR<18% (exp. 10%)
- New searches for suppressed channels ($H \to cc$, ee, γ+hadron).

- Double Higgs:

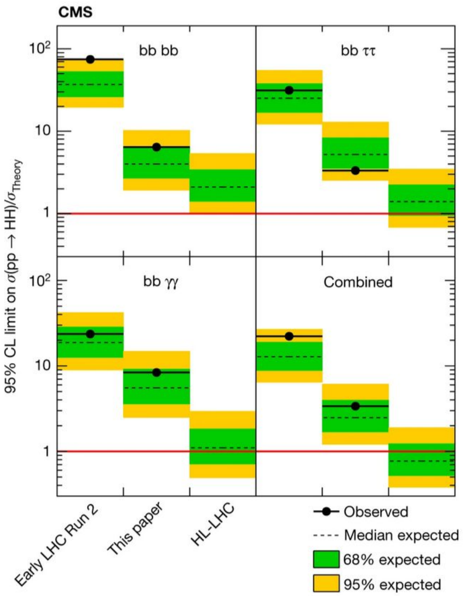
Higgs boson limits



Double Higgs limits



Evolution of double Higgs limits



doi:10.48550/arXiv.2411.11820

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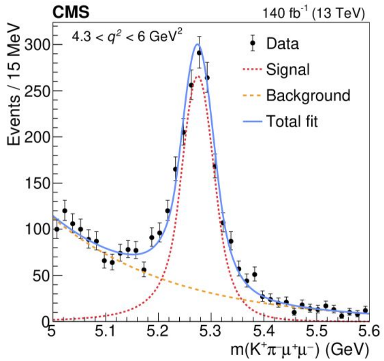
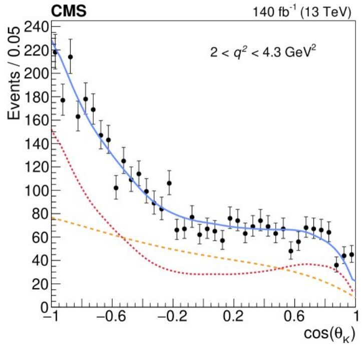
Angular analysis of the $B^0 \longrightarrow K^{*0}\mu\mu$

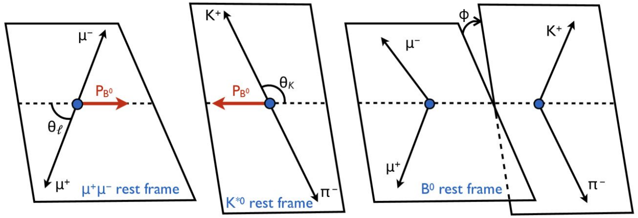
- Trigger based on dimuon + displaced track.
- Fit to m_B and 3 angles (θ_ℓ, θ_K, ϕ) to measure CP-averaged angular obs. F_L, P_1, P_2, P_3, P'_4, P'_5, P'_6, P'_8.
- Background rejection optimized with a BDT.
- Hints of New Physics from previous measurements,
- **Result compatible with LHCb, with a similar sensitivity.**

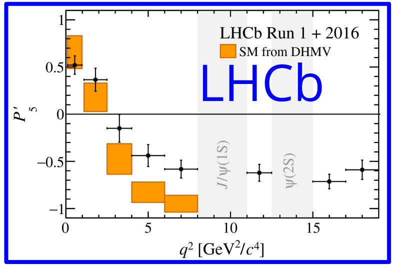
B^0 candidate mass



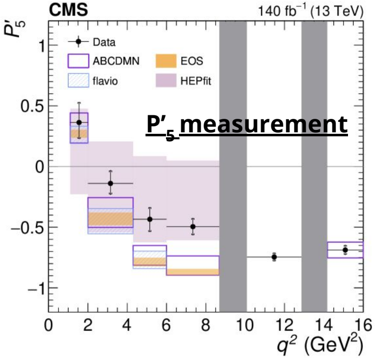


θ_ℓ, θ_K, ϕ angle definition





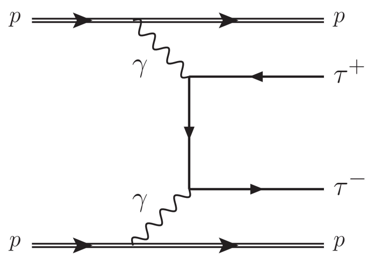
P'_5 measurement



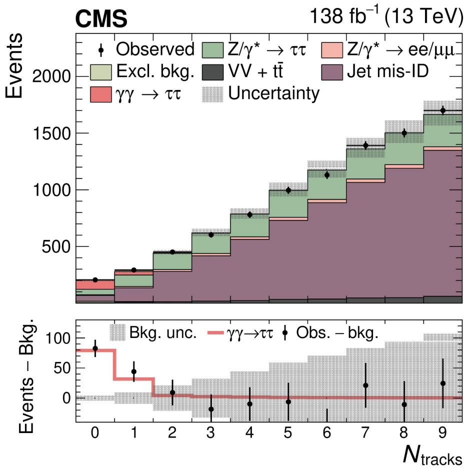
doi:10.1088/1361-6633/ad6fcb

Photon collider: γ+γ ⟶ tau + tau

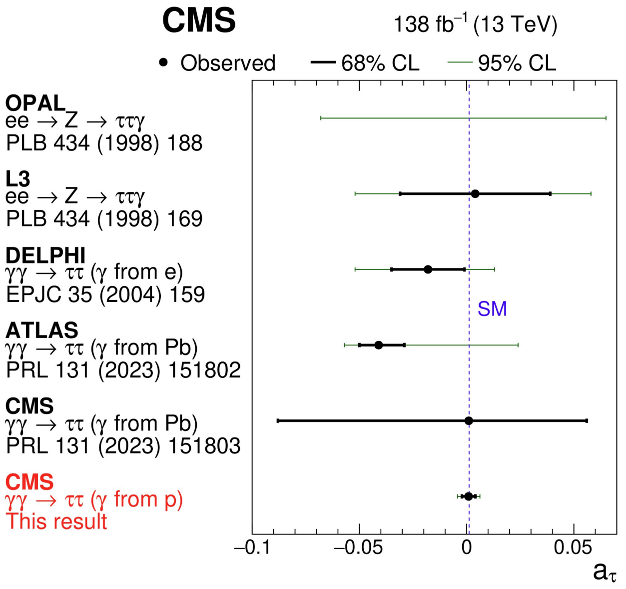
- **Tau-pair** production from photon fusion,
  - elastic or dissociative events,
    - events with low-multiplicity.
- Several simulated quantities require corrections based on data
  - In particular, track multi. for pileup and hard scatter
- **First observation in pp: 5.3 obs (6.5 exp)!**
- **Anomalous magnetic moment**: $a_\tau = (0.9 \pm 3.2) \times 10^{-3}$
  - Improves LEP limits by factor 5 !



Track multiplicity



Tau anomalous magnetic moment



Results from scouting Run-2

doi:10.1016/j.physletb.2020.135448
doi:10.1007/JHEP08(2018)130

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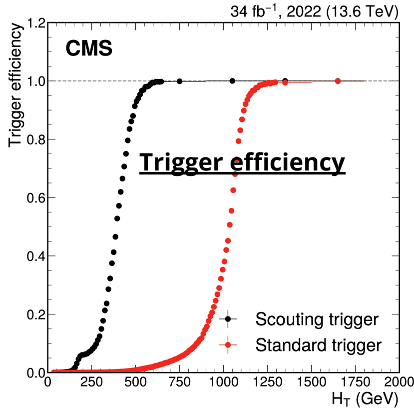
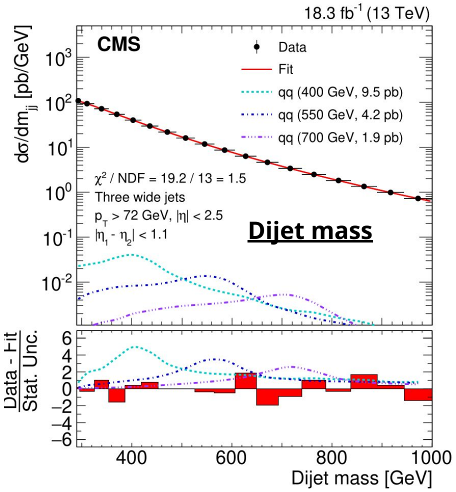
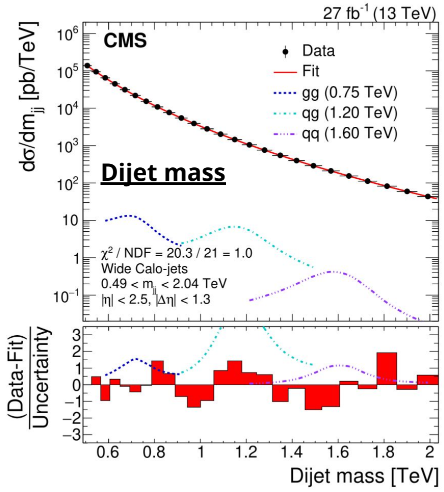
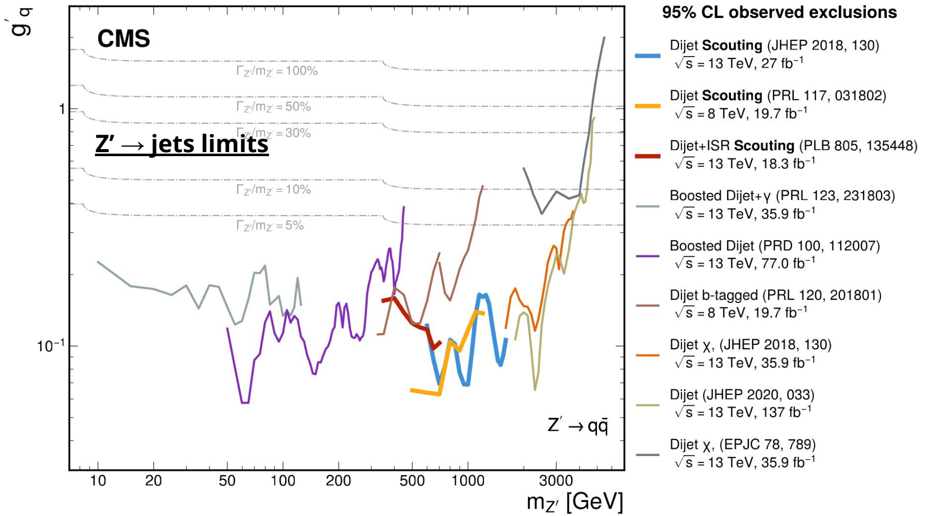
Dijet measurements

- Scouting originally developed to extend dijet searches to light mass.
  - large trigger threshold reduction (HT ~1000 GeV → 300 GeV).
- Search for resonance in two resolved jets in the inclusive and in the three jet final states, **down to 350 GeV**.





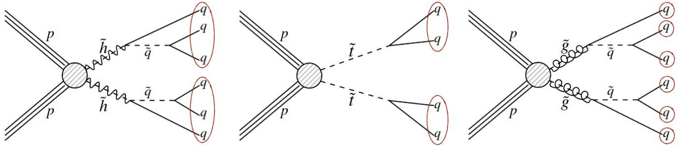




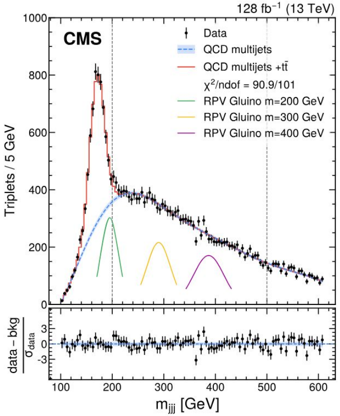
doi:10.1103/PhysRevLett.133.201803

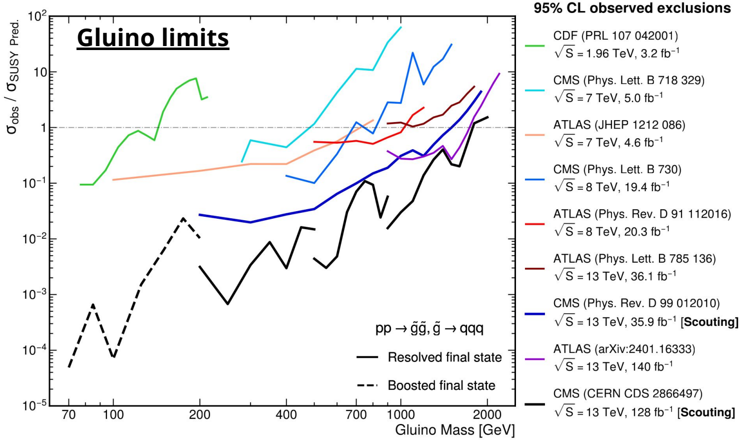
Scouting pair-produced multijet resonances

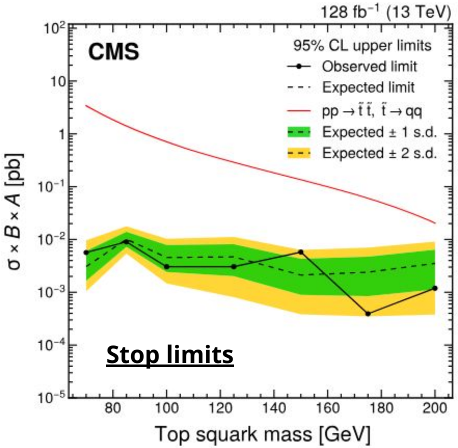
- Search for pair-produced resonances, fully hadronic final state.
  - Benchmark models: higgsinos ($\tilde{h} \to qqq$), top squarks ($\tilde{t} \to qq$), and gluinos ($\tilde{g} \to qqq$).
- Resonances decay considered:
  - 3 resolved jets,
  - 3 **merged jets** in a wide jet,
  - 2 merged jets in a wide jet.
- Wide mass range covered from 2000 GeV down to **70 GeV**.
  - Fully hadronic ttbar peak clearly visible → standard candle



Mass between 3 resolved jets



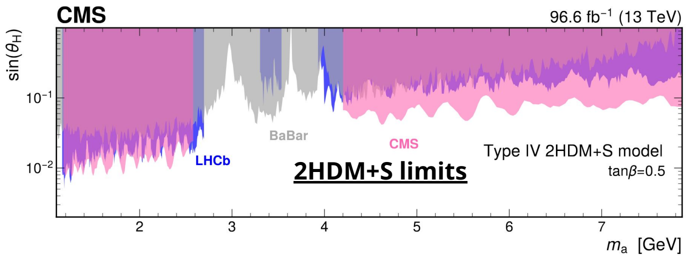


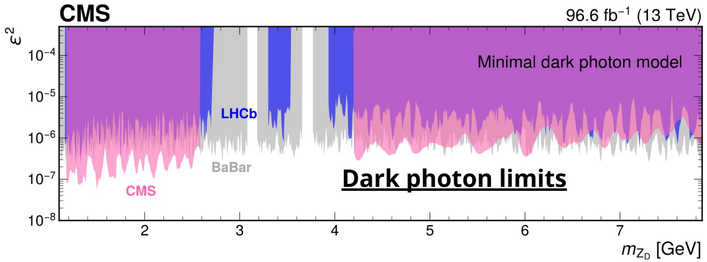


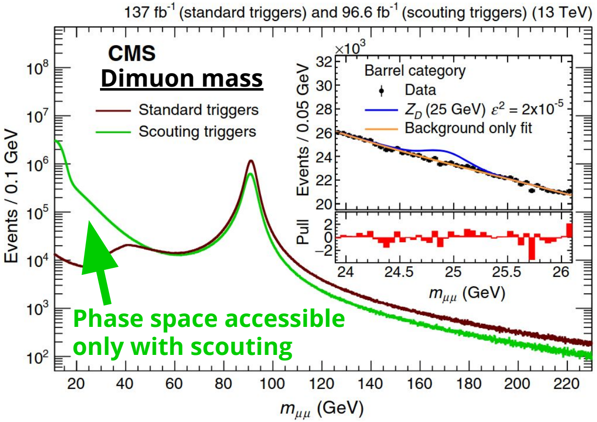
doi:10.1007/JHEP12(2023)070
doi:10.1103/PhysRevLett.124.131802

Scouting Muons

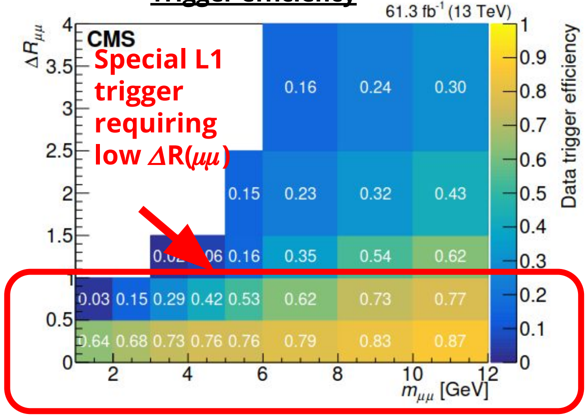
- Two searches for dimuon resonances performed in Run-2 scouting.
  - Low mass: **1.1 GeV** and 7.9 GeV (scouting),
  - Medium mass: 11.5 – 45 GeV (scouting),
    High mass: 45 – 200 GeV, Z boson veto (standard trigger).
- Benchmark models:
  - Dark photon decaying to a muon pair → limit on ε^2,
  - 2HDM+S, with a light pseudo-scalar S decaying to a muon pair → limit on $\sin(\theta_H)$.

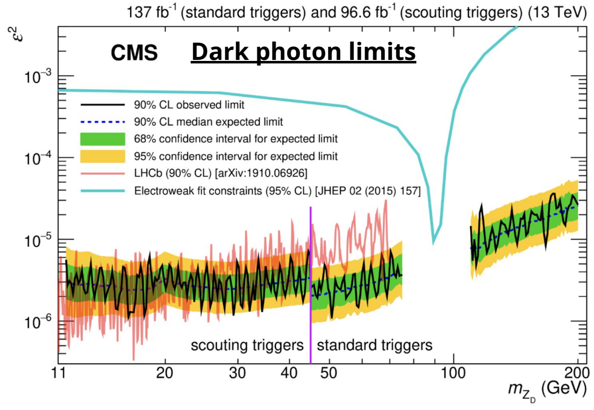






Trigger efficiency

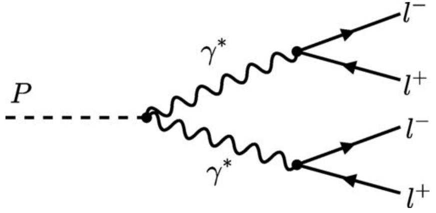


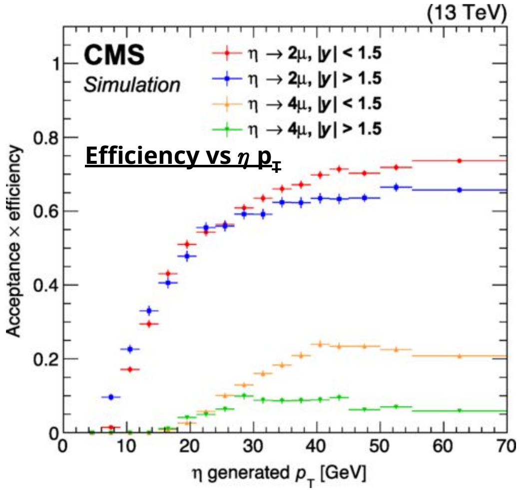


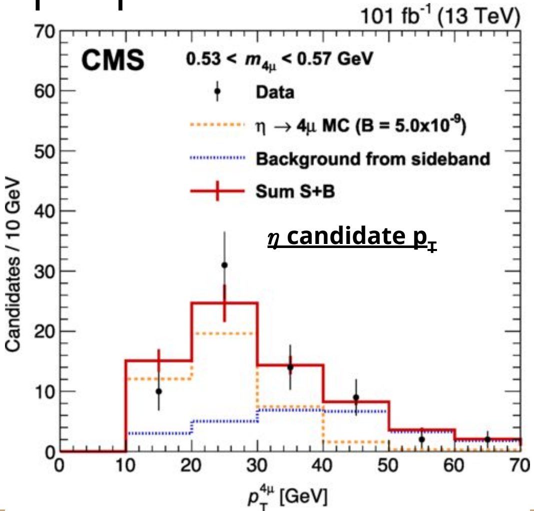
doi:10.1103/PhysRevLett.131.091903

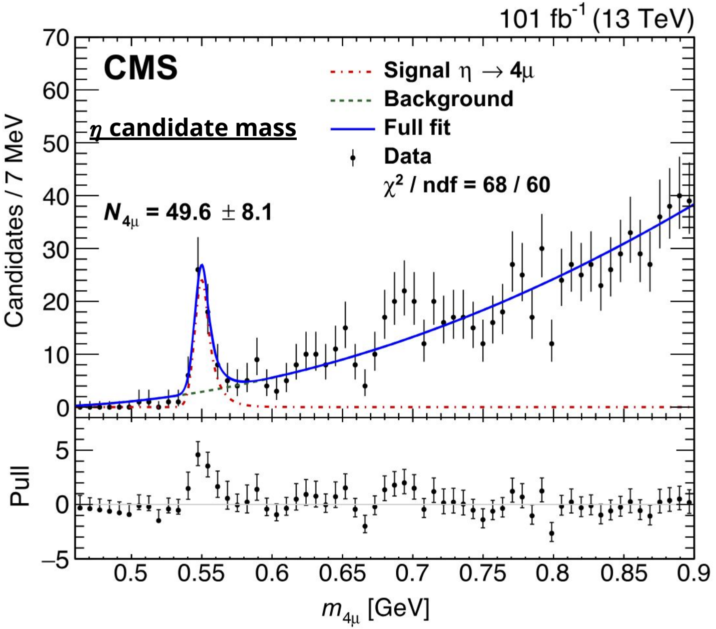
Observation of $\eta \rightarrow \mu\mu\mu\mu$

- First **observation** of $\eta \rightarrow \mu\mu\mu\mu$ (>5σ),
  - BR = [5.0±0.8(stat)±0.7(syst)±0.7($B_{2\mu}$)]×$\mathbf{10^{-9}}$.
- BR measured wrt $\eta \rightarrow \mu\mu$.
- Improvement 5 order of magnitude wrt previous measurement (WASA).
- Good agreement in p^T spectrum.









Results from parking Run-2

doi:10.48550/arXiv.2403.16134

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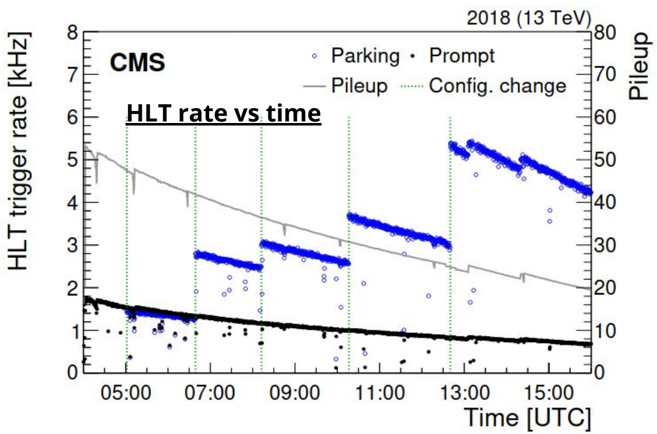
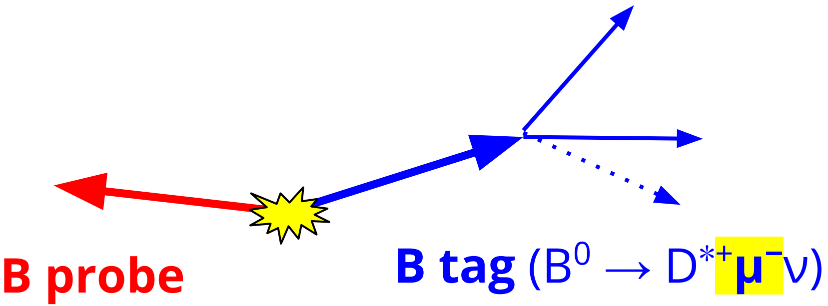
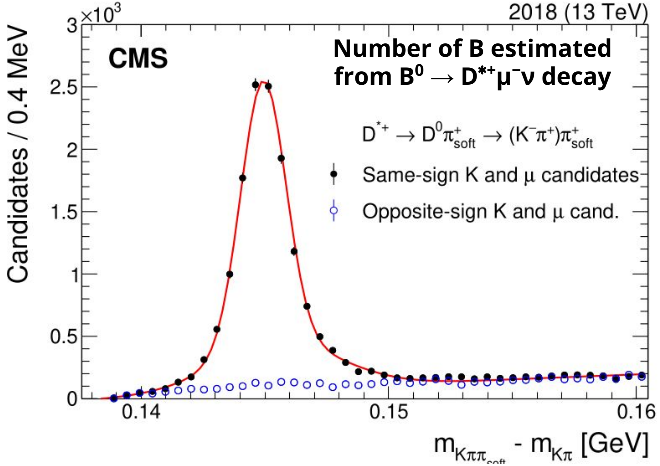
Parking Run-2 (2018)

- Idea: collect B hadron pairs:
  - CMS as a “B factory”,
  - **tag**: B → μ + X ⇒ **trigger: displaced muon**,
  - **probe**: B ⇒ anything (unbiased).
- Explore **untriggerable** B decay (probe).
- Collected 1×10^{10} events:
  - purity 80% ⇒ 1.2×10^{10} unbiased B hadron decay;
  - low threshold trigger activated at low luminosity.







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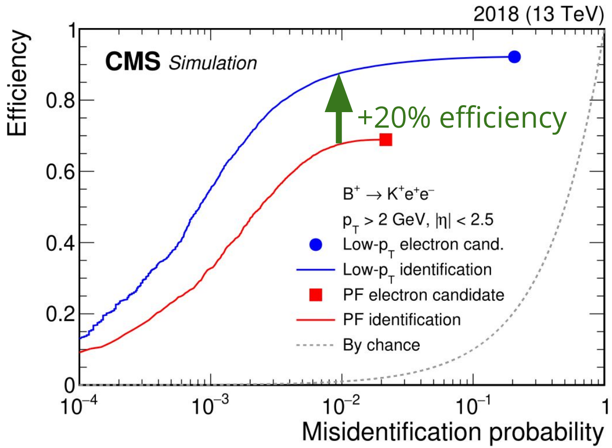
Parking Run-2 (2018)

- **Tag B** ($B \to \mu + X$) can be used for all B decay with a muon in the final state:
  - include also $B \to \tau \to \mu$,
  - large number of events.
- **Probe B** ($B \to$ anything):
  - access to untriggerable event $B \to e + X$ or $B \to$ hadrons,
    - **dedicated new soft electron reconstruction**;
  - "small" number of events because of B tag acceptance.
- Possible measurements based on:
  - B flavor anomalies: $b \to c\ell\nu$ and $b \to s\ell\ell$;
  - R_{D*} using $B^0 \to D^{*-}\ell^+\nu_\ell$ from muon and tau (decaying to muon);
  - search for $B^0_s \to \mu^+\mu^-$;
  - searching for lepton violation in $B^0_s \to \mu^- e^+$ decays;
  - charge-parity violating processes fully reconstructed hadronic final states such as $D^0 \to K_S K_S$ and $B^0_s \to \phi (\to K^+K^-) \phi (\to K^+K^-)$;
  - physics with soft untriggerable b-jets containing $B \to \mu + X$;
  - search in any untriggerable topology using 3×10^{11} pileup collisions.

Electron reco efficinecy vs mis. prob.



doi:10.1088/1361-6633/ad4e65

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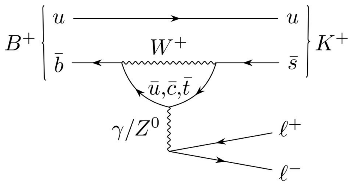
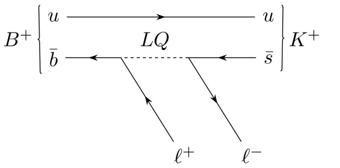
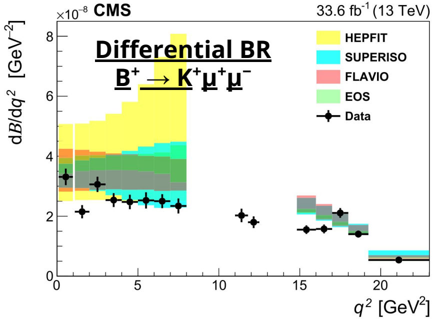
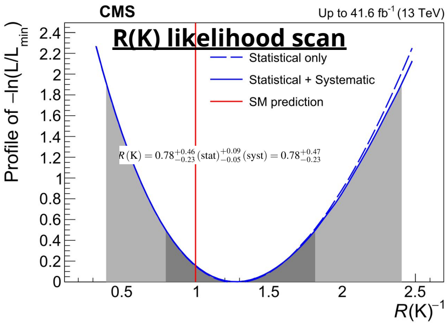
Measurement of the R_K observable

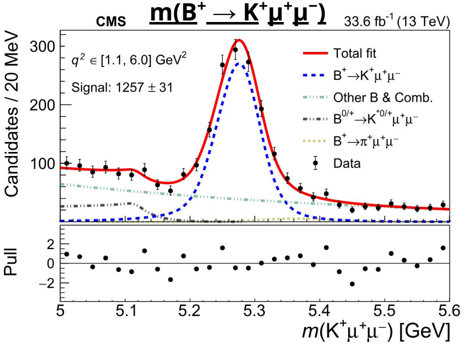
- $R_K = B(B^+ \to K^+e^+e^-) / B(B^+ \to K^+\mu^+\mu^-)$:
  - expected close to unity (lepton flavour universality),
  - sensitive to new physics (eg. lepto-quark),
  - $B \to K^+ J/\psi\ (\ell\ell)$ used for normalization.
- **Excellent sensitivity in muon channel:**
  - $B(B^+ \to K^+\mu^+\mu^-) = (12.42 \pm 0.68) \times 10^{-8}$ in $q^2 = [1.1, 6.0]\ \mathrm{GeV}^2$,
  - differential branching fraction of the $B^+ \to K^+\mu^+\mu^-$ vs q^2.
- Result compatible with SM (R=1): $\mathbf{R_K = 0.78^{+0.47}_{-0.23}}$
  - **sensitivity limited by the statistical uncertainty for electron channel.**

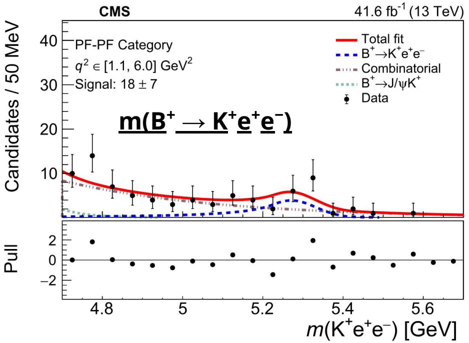








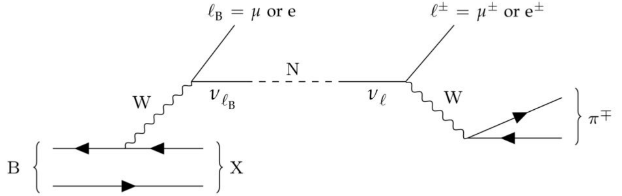


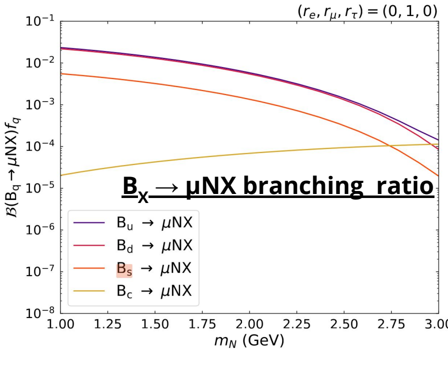


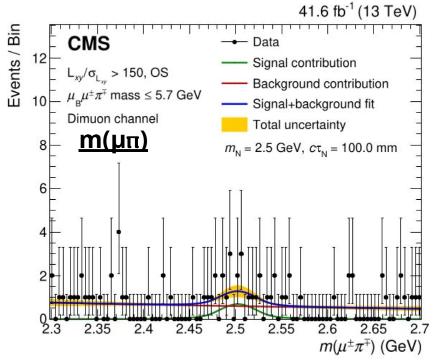
doi:10.1007/JHEP06%282024%29183

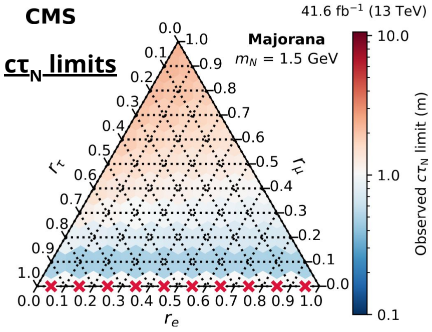
Search for long-lived heavy neutrinos in B meson decays

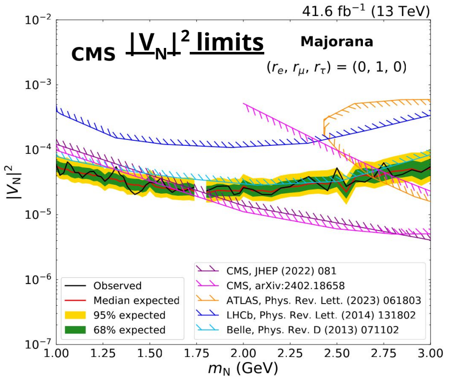
- Search for long-lived **heavy neutrinos** (1-3 GeV) with a decay length of $c\tau_N$ (10^{-2}-10^{4} mm) in B meson decay.
- Signal topology: $B \rightarrow \ell\ell^{\pm}\pi^{\mp}$
    - with at least a **displaced μ**,
    - both letponic and semileptonic decay,
    - B_u, B_d, B_s, B_c considered.
- Veto on known ℓℓ and ℓπ resonances.
- No significant excess found.











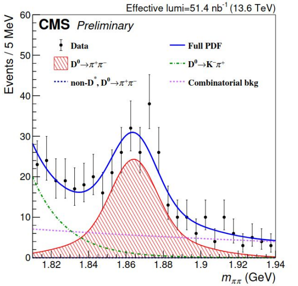
Results from parking Run-3

Search for rare charm decays into two muons

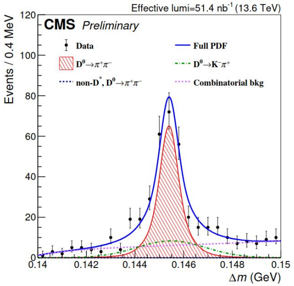
- SM prediction $B(D^0 \to \mu^+\mu^-)$: 3×10^{-13}
- D^0 tagged from: $D^{*+} \to D^0\pi^+$ decay to reduce bkg,
  - displacement from D^0 ($c\tau$ = 0.123 mm) and B (~0.5 mm).
- Large theoretical uncertainty.
- Signal extraction: 2D fit on ($m(D^0)$, $m(D^0)$ - $m(D^{*+})$).
- Normalization channel $D^0 \to \pi^+\pi^-$ measured from zero-bias trigger.
- MVA to enhance purity.
- Best limit on $B(D^0 \to \mu^+\mu^-) < 2.6 \times 10^{-9}$,
  - (previous best limit 3.5×10^{-9}).

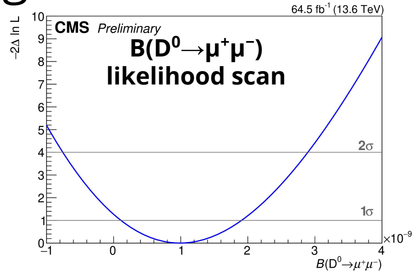
$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \mathcal{B}(D^0 \to \pi^+\pi^-)\frac{N_{D^0\to\mu^+\mu^-}}{N_{D^0\to\pi^+\pi^-}}\frac{\varepsilon_{D^0\to\pi^+\pi^-}}{\varepsilon_{D^0\to\mu^+\mu^-}}$$

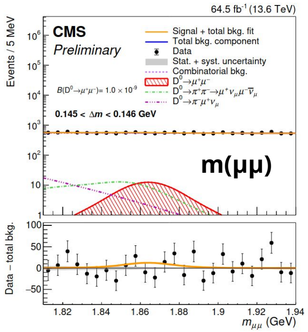
m(ππ)

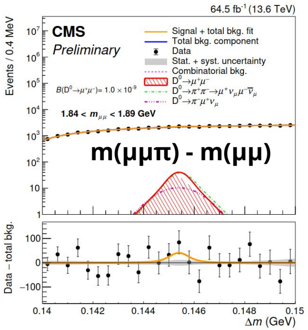


m(πππ) - m(ππ)







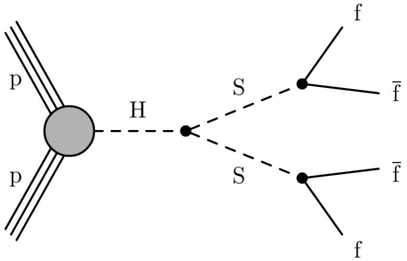


Long-lived particle triggers

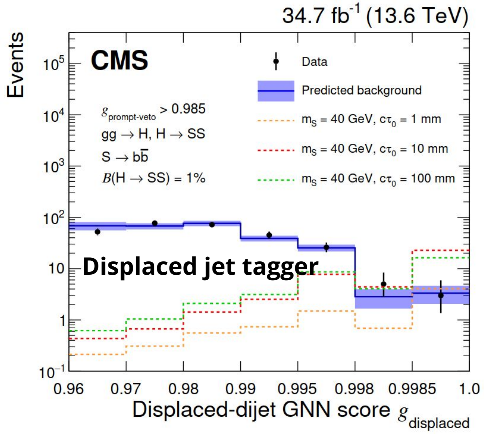
doi:10.48550/arXiv.2409.10806

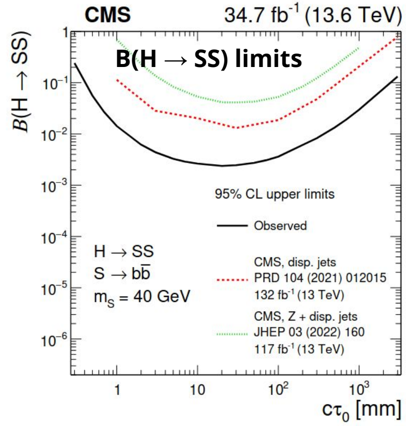
Search for light LLP decaying to displaced jets

- Search for H → LLP scalars → displaced jets.
- Dedicated new trigger developed in 2022:
  - HT>430 GeV + ≥2 jets with ≤1 tracks,
  - HT>250 GeV + soft muon from B decay
    + ≥2 jets with no prompt track & ≤ 1 displaced tr.
- Displaced and prompt jet tagger based on a graph neural network.



- No significant excess found.
- Sensitivity improved up to **a factor 10** thanks to new **triggers** and other improvements.

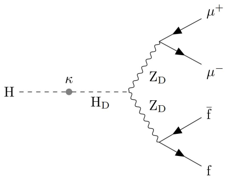


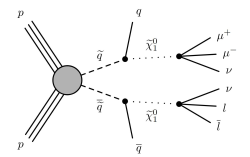


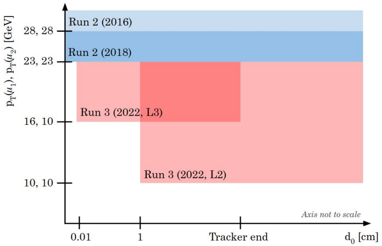
doi:10.1007/JHEP05(2024)047

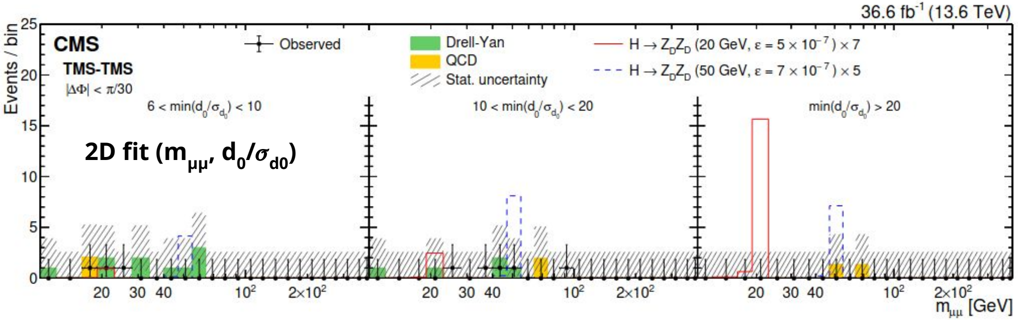
Search for LLP decaying to pairs of muon pairs

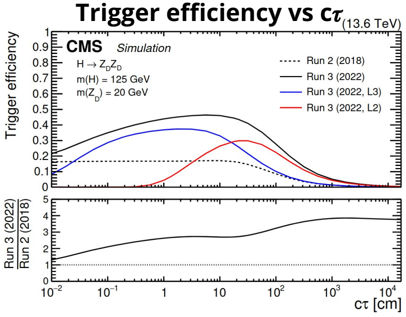
- Displaced dimuon vertex **from <1 mm to >1m**
- Trigger development on displaced muon. L1 triggers:
  - Muon p_T computed **without beamspot** constraint;
  - Double muon with small **$\Delta R_{\mu\mu}$** without p_T requirement
- HLT triggers:
  - Run-2: two muons reconstructed using only muon chambers;
  - Run-3 (**L2**): as Run-2 + **veto** on tracker **prompt muons** & lower thresholds;
  - Run-3 (**L3**): two tracker prompt muons with **small displacement** (d>0.1mm).
- Limits interpreted using two models:
  - HAHM(hidden Abelian Higgs model) decaying to LLP dark photons;
  - RPV SUSY (R-parity violating SUSY) with a LL neutralino decaying to muons.
- **More stringent limit wrt Run-3 even using only ⅓ of lumi!**

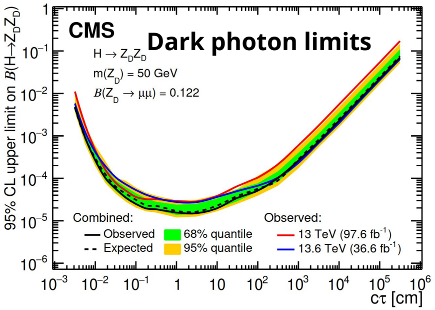










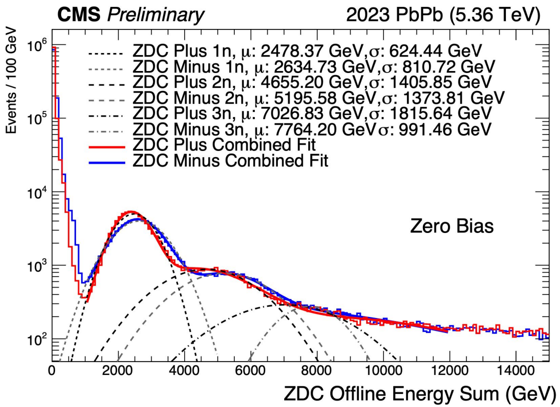


Results from PbPb trigger

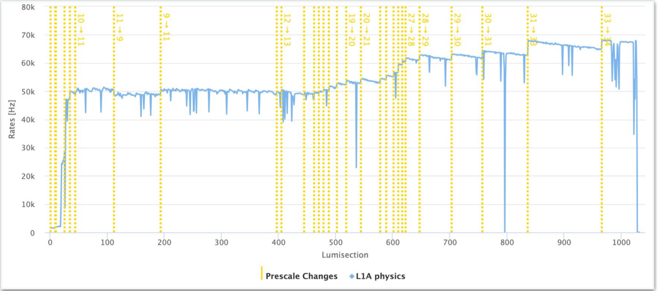
PbPb collisions, trigger, and DAQ in 2023

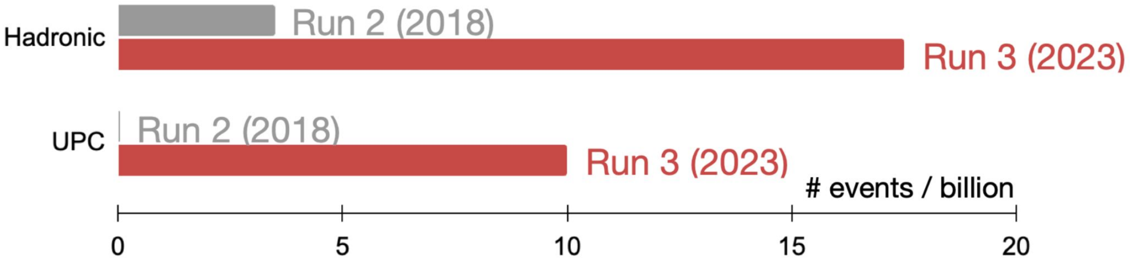
- Major improvements in 2023 PbPb collisions.
- Level-1 trigger rate increased to ~50 kHz.
- Collected almost **all minimum bias** hadronic events, thanks to
  - higher **DAQ** limits in **bandwidth**;
  - reduced raw data format by a factor ~2 (**RawPrime**),
    - ie. replacement strip raw data with **strip clusters**.
- First use of **zero-degree calorimeter** (ZDC) in trigger,
  - allow to tag **ultra-peripheral collision** (UPC) events.

Zero-degree calorimeter energy



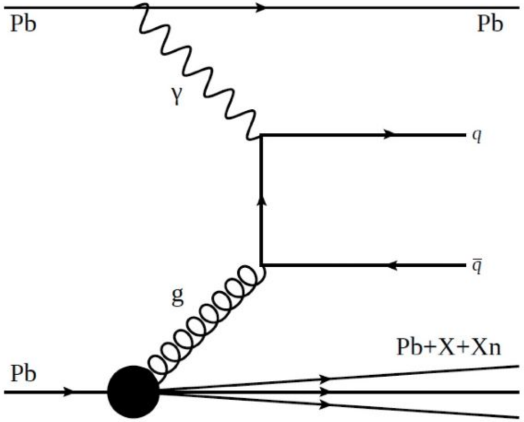
Trigger rate vs time

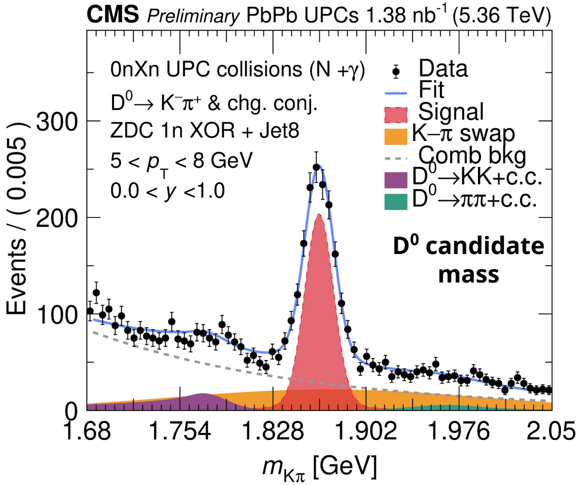




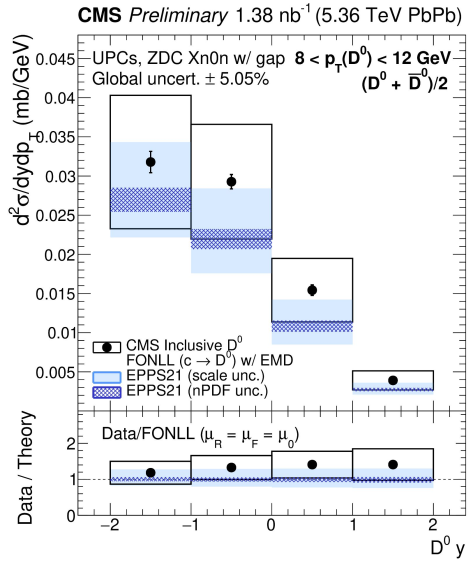
D^0-photoproduction in UPC in PbPb

- First data analysis done with 2023 PbPb data.
- Target: D0-photoproduction $\gamma^* + N \rightarrow D^0 + X$.
- New triggers targeting ultraperiferic collision (UPC):
  - zero-degree calorimeter (ZDC) use to “tag” the intact Pb ion,
  - no activity (rapidity gap) on the intact Pb ion side.





D⁰-photoproduction differential cross section



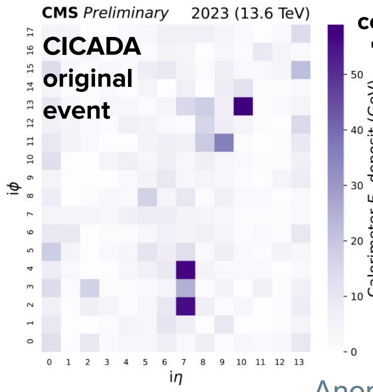
Outlook

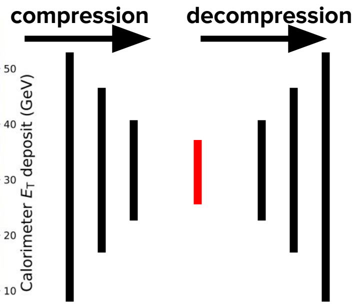
Expected results

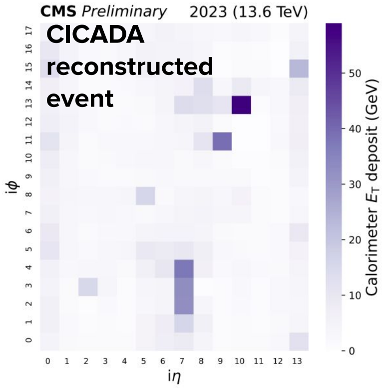
- Many **new triggers** have been deployed online recently in **Run-3,**
  - new physics results will arrive in the next months/years;
  - many Run-3 data analyses are starting ~now.
- In particular we expect new results from:
  - searches from **long-lived particle**: new trigger exploits **timing** for the first time;
  - the new **Run-3 scouting** strategy (~20 kHz with all physics objects reconstructed)
    - JetHT, double muon, double e/γ, single muon, AXOL1T, single photon, zero bias;
  - the new **high-rate parking** strategy which now targets
    - double muon, VBF, displaced single muon, multijet + 2 b-tag (HH), LLP;
  - **anomalies** detection trigger (AXOL1T and CICADA);
  - **L1 trigger scouting** at 40 MHz (triggerless analyses!).
- Even more for **Phase-2** upgrade (2030):
  - new **timing** detector in both barrel and endcap;
  - **high-granularity** calorimeter with a new reconstruction;
  - **smarter L1 trigger** able to run particle flow, and more **powerful HLT** farm at **higher rate**,
    - track trigger.
- More info in M. Musich talk (Run 3) and T. Chatzistavrou talk (Phase 2).

Anomalies detection triggers

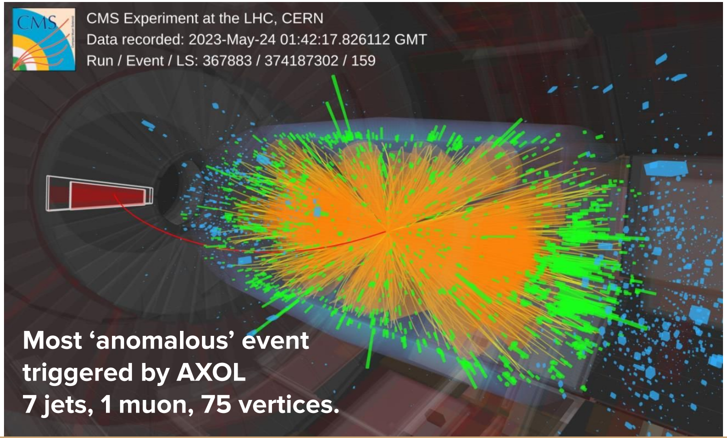
- **Anomaly** detection triggers are based on ML **autoencoder** which attempts to reproduce an event using few variables.
  - “Anomaly” is defined as the distance between the original and the reconstructed events.
- **AXOL1T** uses L1 trigger objects (**muons, jets, EG, MET**) as input.
  - Trigger with different thresholds: 1500 Hz in scouting (nominal WP), 10 Hz in parking (very tight WP).
- **CICADA** is based on L1 **ECAL** and **HCAL** deposits.
  - Discussion ongoing about the deployment (some concern about possible rate instability).







Anomaly detection triggers



Conclusions

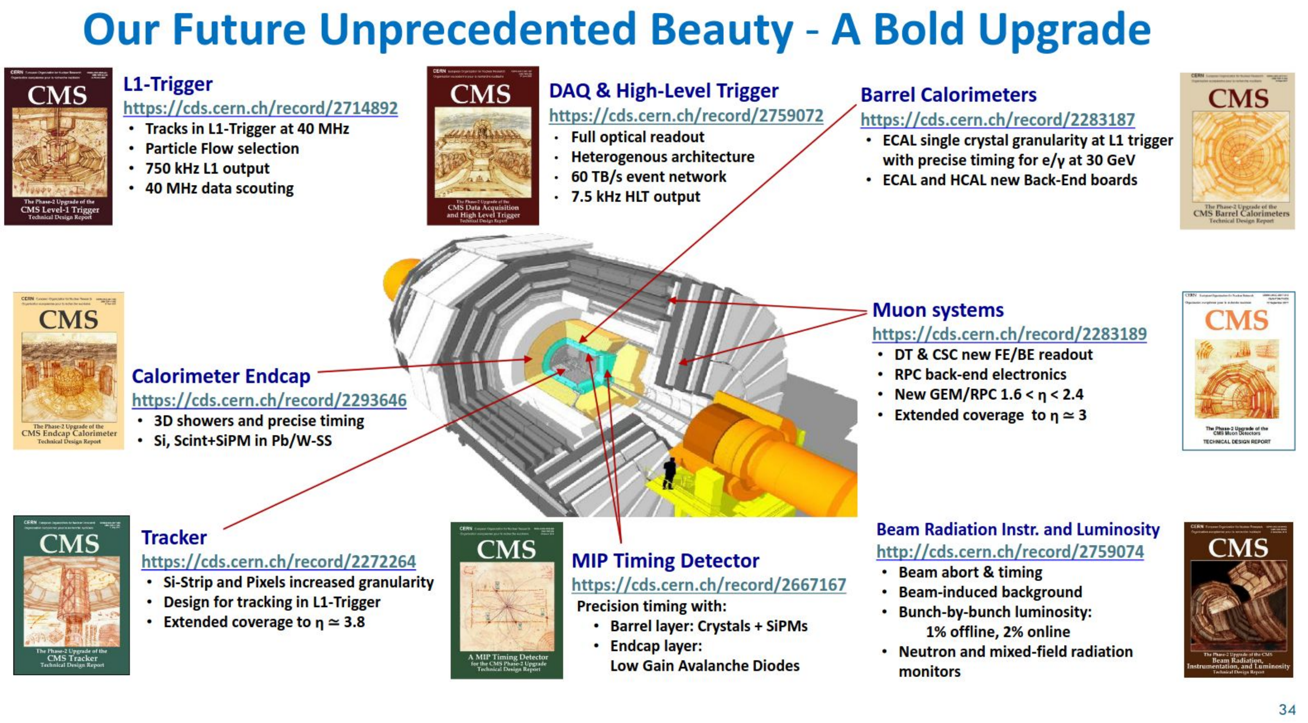
- The CMS experiment is steadily producing important physics results,
  - The W mass measurement released after a decade with an excellent resolution.
- Some results obtained very large improvements thanks to new triggers exploring new signal topology.
- In Run-3, the trigger got significant improvements with new triggers, a revolutionized scouting strategy, and more high-rate triggers (parking):
  - new physics results are expected to come soon.
- With new trigger the Run-3 is much more than just (Run-2)×2!
  - Less than 6 years from the beginning of HL-LHC with the Phase-2 CMS upgrade!


Thank you

Backup

upgrade

- New tracker
- Timing
- HGCal
- L1 trigger with tracking at 750 kHz
- More powerful HLT



upgrade

Trigger
rate at 750 kHz, tracking + PFlow
HLT: 80% on GPU, L1 scouting

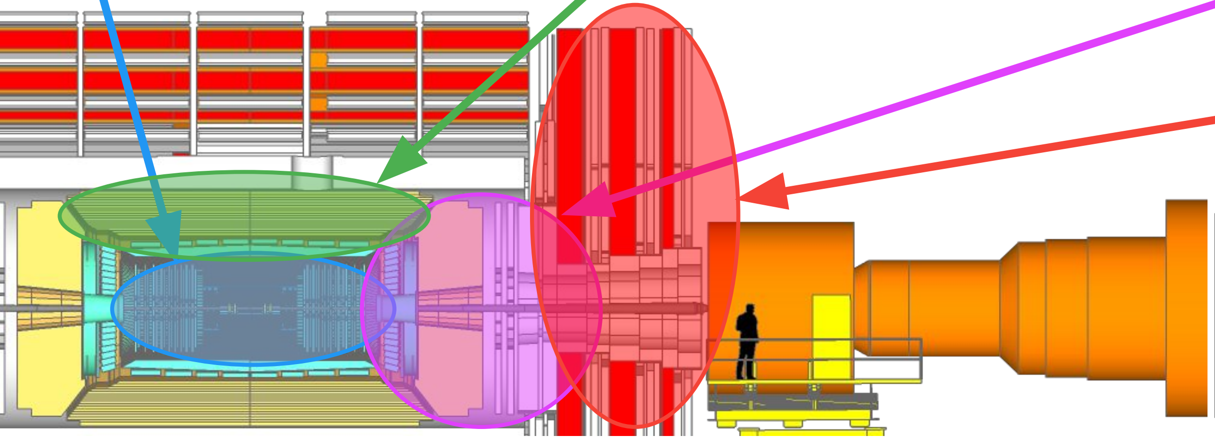
New silicon tracker
Extended coverage $|\eta|<3.8$.
Track trigger at 40 MHz.
Reduced material budget.
Increased granularity.

Barrel calorimeter
ECAL crystal granularity readout at 40 MHz.
Precision timing for e/γ at 30 GeV for vertex localization ($H \rightarrow \gamma\gamma$).
ECAL and HCAL new Back-End boards.

New endcap calorimeter
(high-granularity calorimeter)
3D showers imaging for pattern recognition
Precision timing for PU mitigation
Si, Scint+SiPM in Pb/W-SS

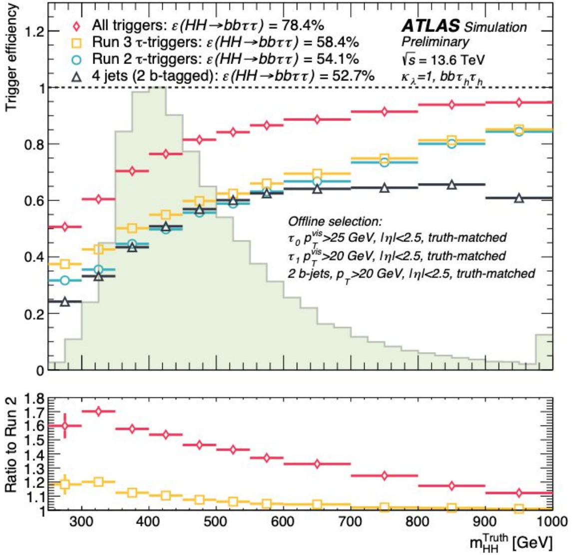
Muon chambers
Extended coverage to $|\eta|<3$
New readout
New detectors (GEM)

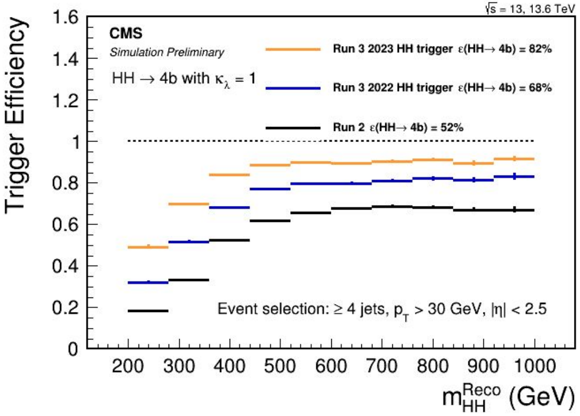
New MIP Timing Detector
Precision timing for PU mitigation
Barrel: LYSO crystals + SiPMs
Endcap : Low Gain Aval. Diodes



HH trigger

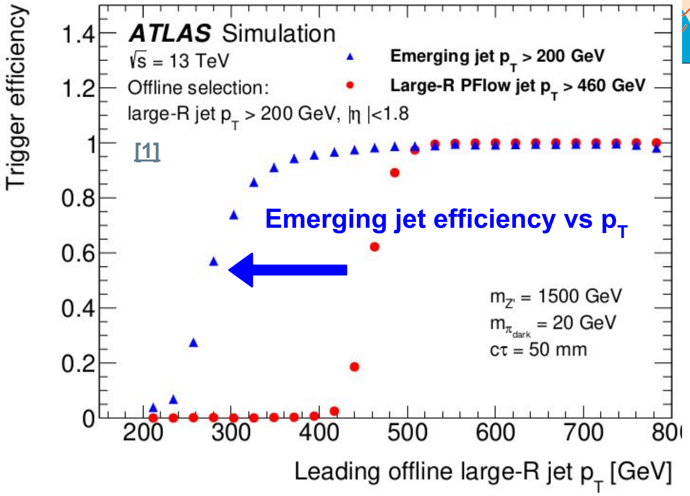
- Dedicated trigger in delayed reconstruction for parking
- Better discriminator, more rate, large increase in acceptance

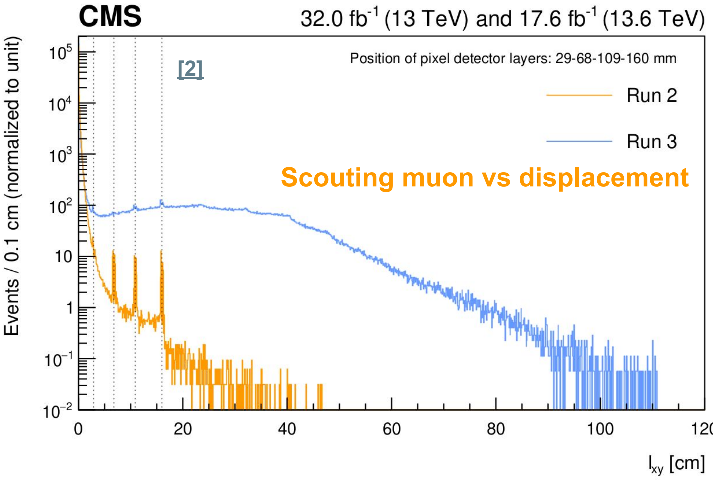




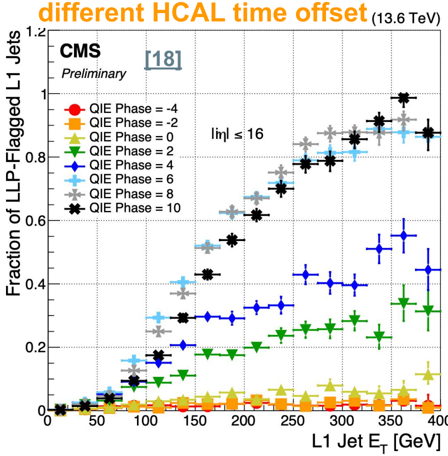
Long lived particles

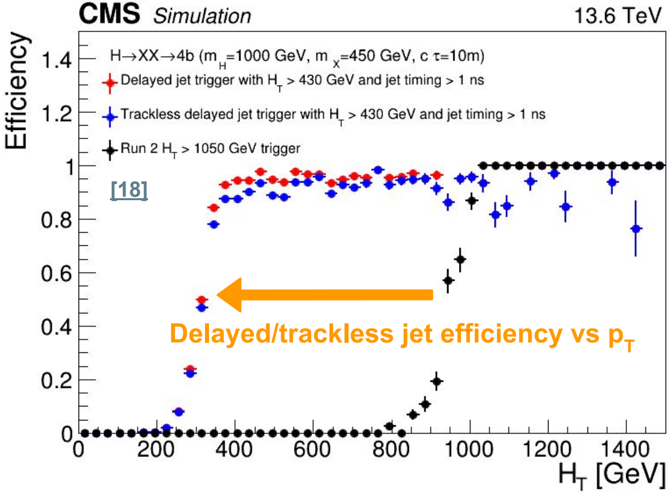
- New set of triggers targeting long-lived particles
  - Trackless or displaced jets;
  - Measurement of time delay in ECAL and HCAL;
  - Displaced muons
    - Dedicated L1 trigger
    - Included in scouting





LLP jet efficiency vs p_T for different HCAL time offset

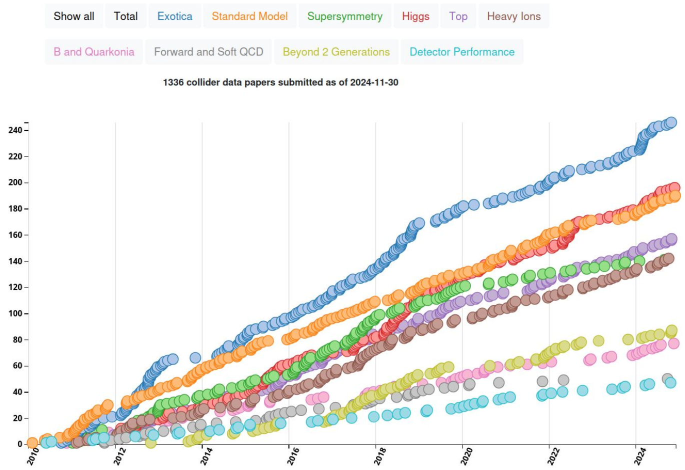




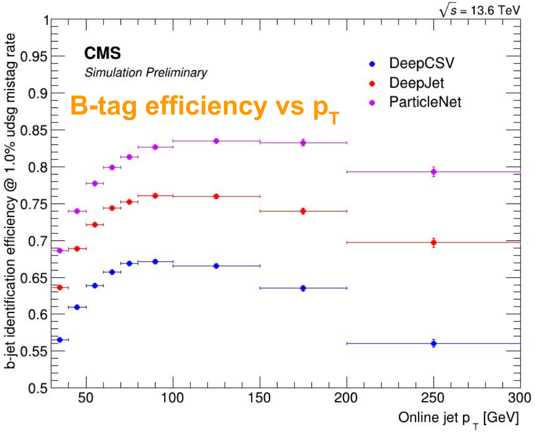
CMS publications

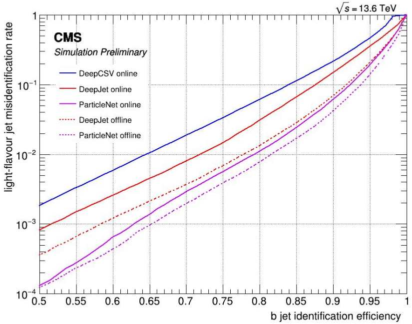
papers vs time

- 1338 papers submitted
  - about 100 papers per years
- Here a selection of focused on
  - most important results
  - most recent ones
  - based on new triggers

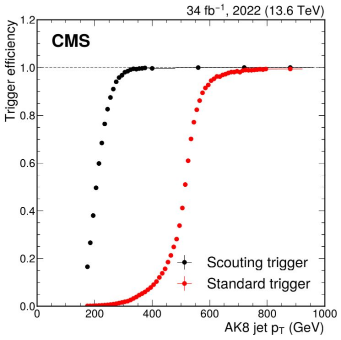


B-tagging and ParticleNet

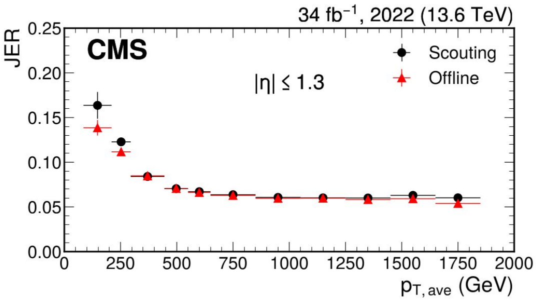




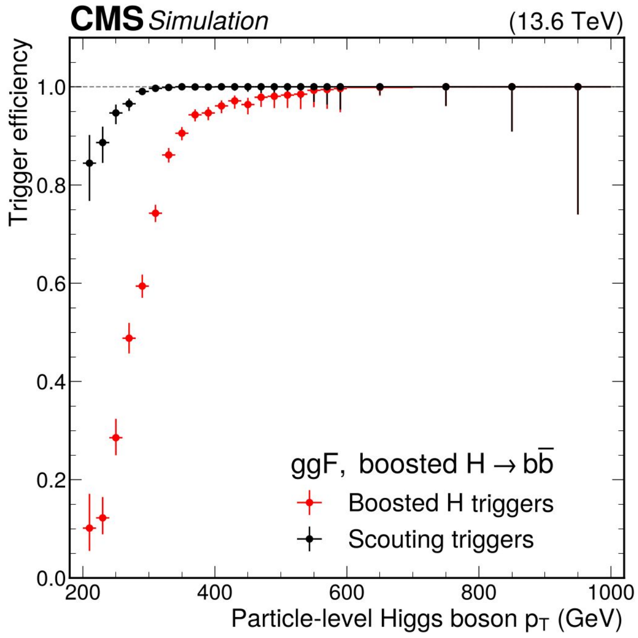
$gg \to H \to bb$



34 fb⁻¹, 2022 (13.6 TeV)
CMS
Trigger efficiency
Scouting trigger
Standard trigger
AK8 jet p_T (GeV)

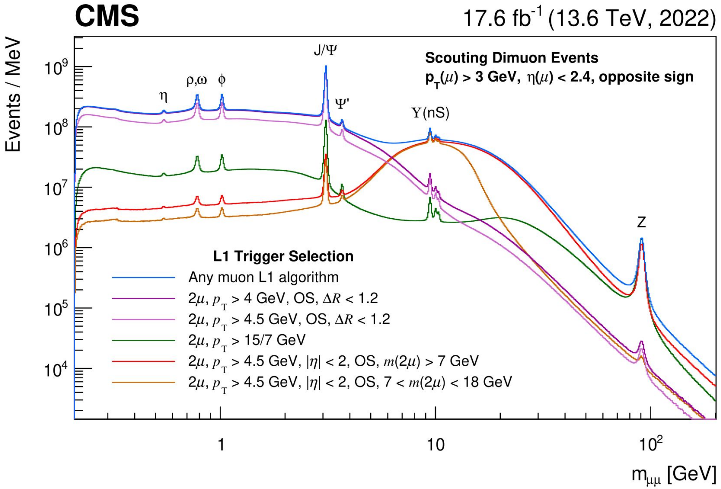


34 fb⁻¹, 2022 (13.6 TeV)
CMS
JER
|η| ≤ 1.3
Scouting
Offline
$p_{T, ave}$ (GeV)

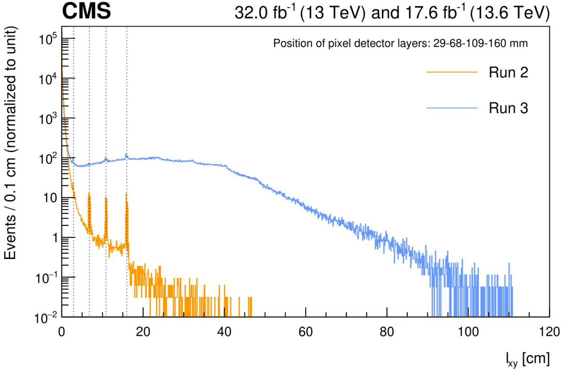


CMS Simulation
(13.6 TeV)
Trigger efficiency
ggF, boosted H → $b\bar{b}$
Boosted H triggers
Scouting triggers
Particle-level Higgs boson p_T (GeV)

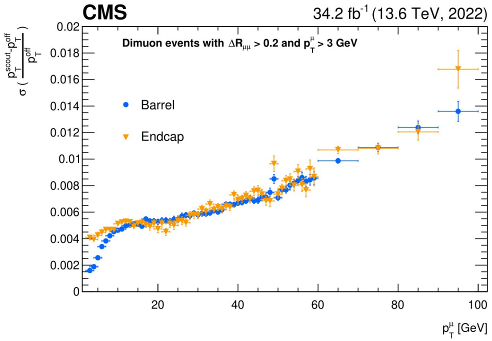
Muons



CMS
17.6 fb^{-1} (13.6 TeV, 2022)
Scouting Dimuon Events
$p_T(\mu)$ > 3 GeV, $\eta(\mu)$ < 2.4, opposite sign
L1 Trigger Selection
Any muon L1 algorithm
2μ, p_T > 4 GeV, OS, ΔR < 1.2
2μ, p_T > 4.5 GeV, OS, ΔR < 1.2
2μ, p_T > 15/7 GeV
2μ, p_T > 4.5 GeV, $|\eta|$ < 2, OS, $m(2\mu)$ > 7 GeV
2μ, p_T > 4.5 GeV, $|\eta|$ < 2, OS, 7 < $m(2\mu)$ < 18 GeV
Events / MeV
$m_{\mu\mu}$ [GeV]



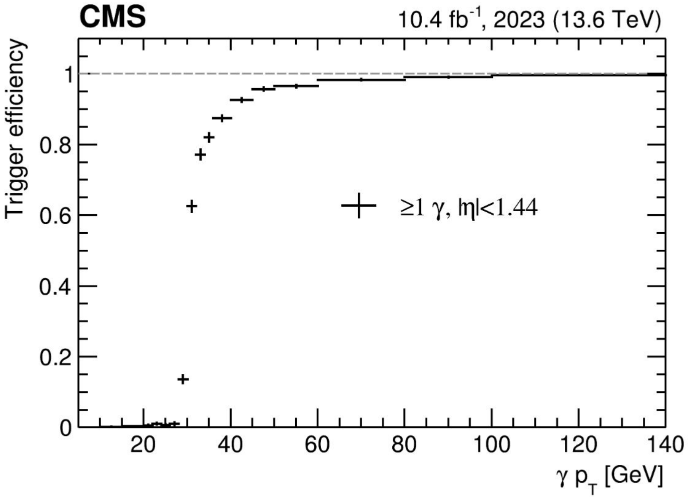
CMS
32.0 fb^{-1} (13 TeV) and 17.6 fb^{-1} (13.6 TeV)
Position of pixel detector layers: 29-68-109-160 mm
Run 2
Run 3
Events / 0.1 cm (normalized to unit)
l_{xy} [cm]

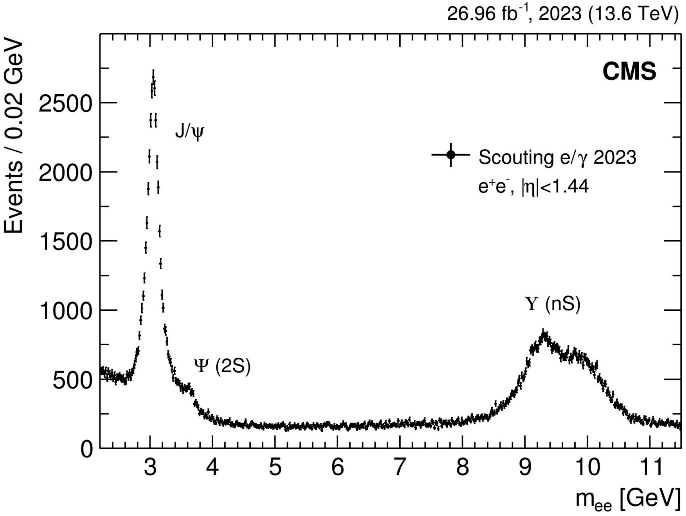


CMS
34.2 fb^{-1} (13.6 TeV, 2022)
Dimuon events with $\Delta R_{\mu\mu}$ > 0.2 and p_T^{μ} > 3 GeV
Barrel
Endcap
p_T^{μ} [GeV]

EGamma

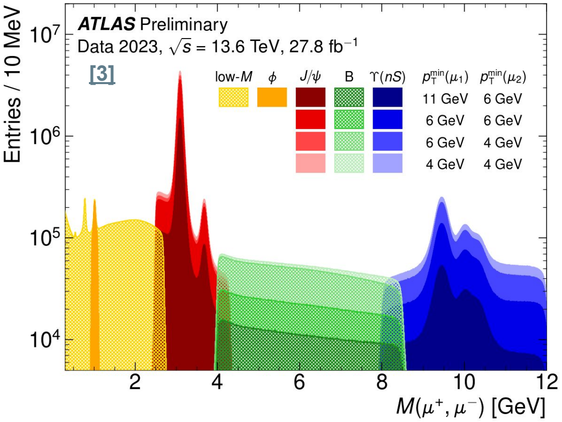
Single EG trigger



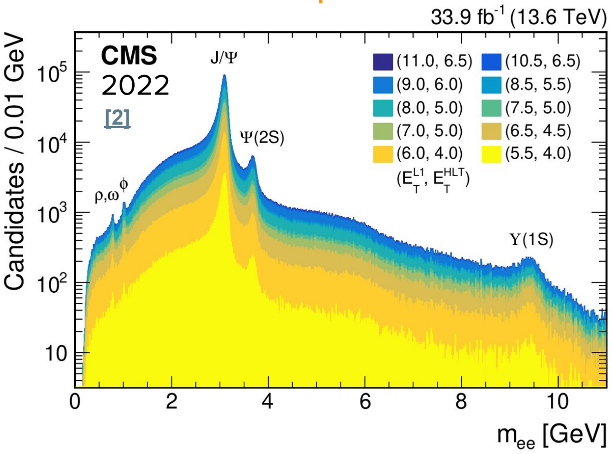


Delayed reconstruction/parking

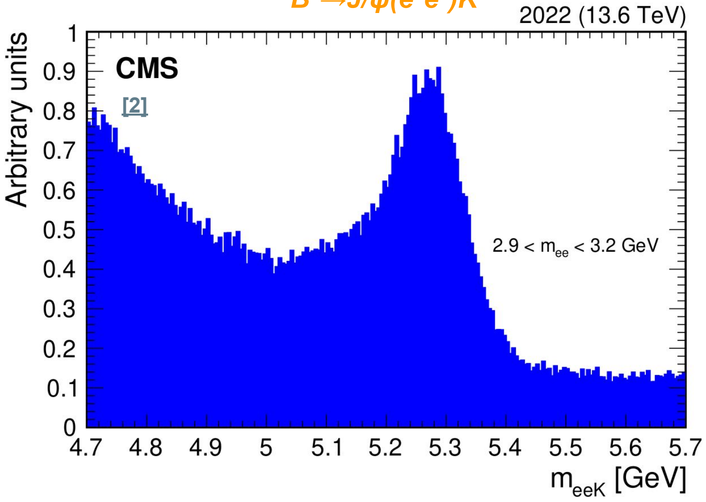
Dimuon spectrum



Dielectron spectrum

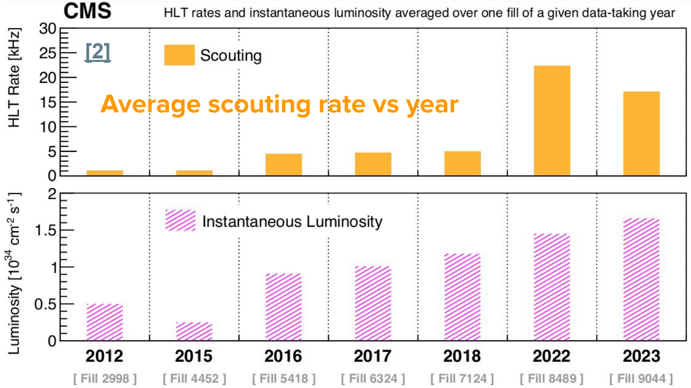


$B^+ \rightarrow J/\psi(e^+e^-)K^+$



Trigger-level analysis/scouting

- Trigger-level analysis (ATLAS) or scouting (CMS) strategy: save directly **trigger objects**
  - Event size around **10 kB/event** instead of ~1 MB/event,
- Important evolution since Run-1:
  - **Rate** increased is to **8-20 kHz**:
    - Multijet, muons, electron/photons, ...
  - **All main physics objects** reconstructed:
    - Photons, jets, tracks, b-tag (ATLAS), muons, electrons, PF candidates (CMS)
    - Multiple collections stored in the same event.
  - Different or same event content for different streams.

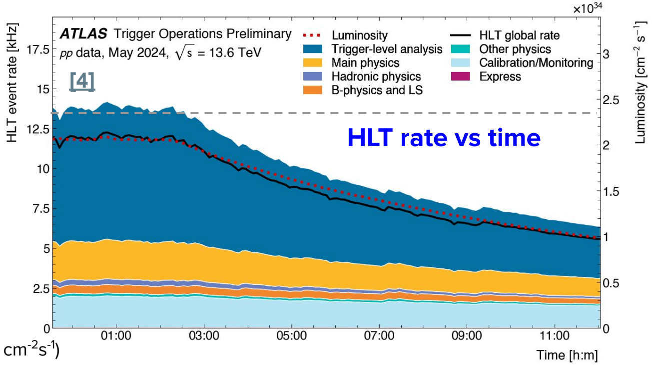


TLA: **8.5 kHz**

Main: **2.5 kHz**

Delayed: **1 kHz**

Total: **~14 kHz** (at $1.7 \cdot 10^{34}$ cm^{-2}s^{-1})

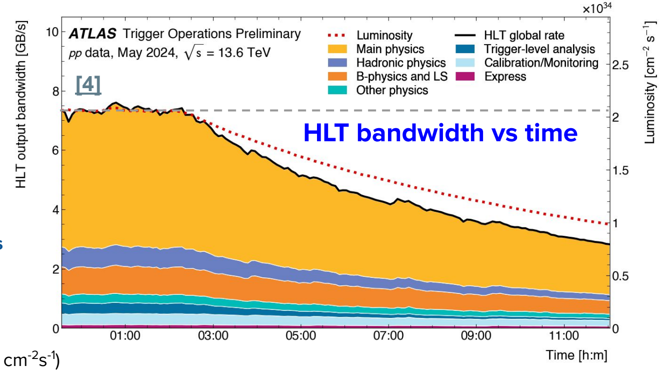


Main: **5.0 GB/s**

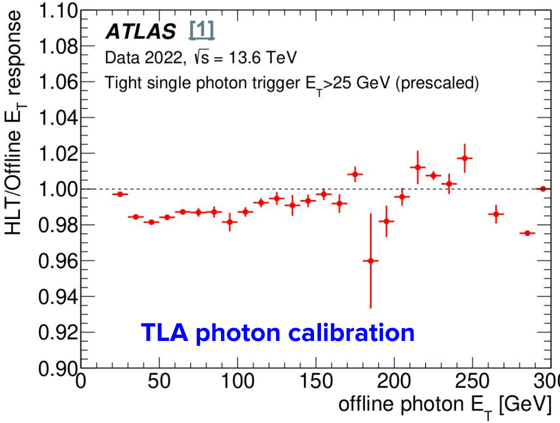
Delayed: **1.5 GB/s**

TLA: **0.03 GB/s**

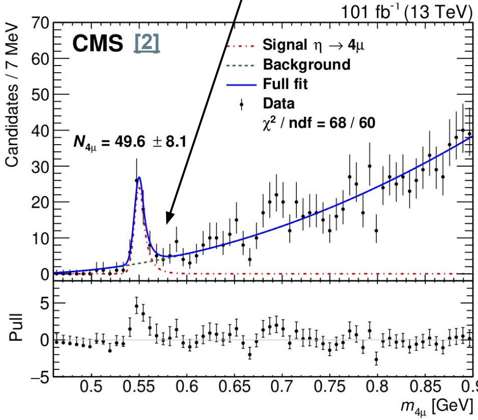
Total: **~7.5 GB/s** (at $2.1 \cdot 10^{34}$ cm^{-2}s^{-1})

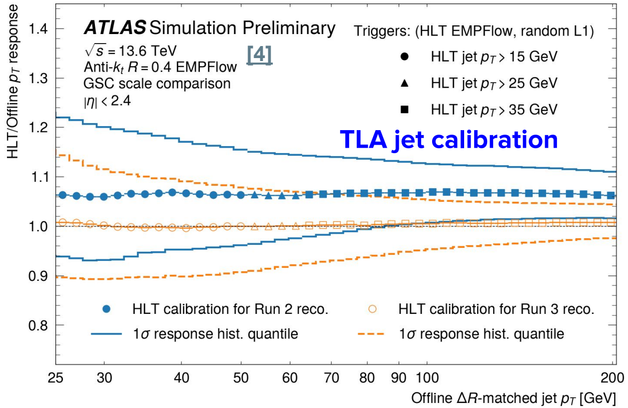


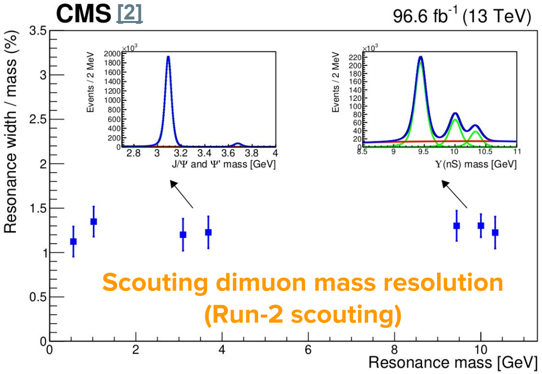
Trigger-level analysis/scouting

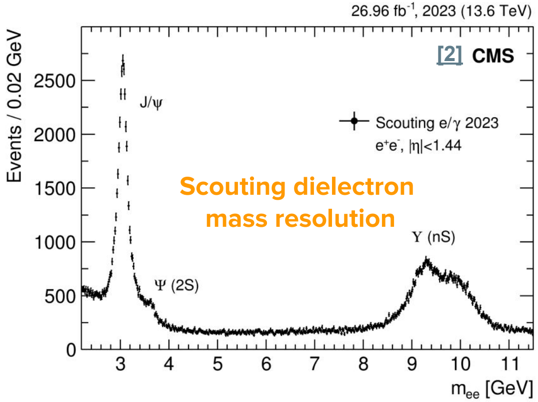


Observation of η → 4μ (Run-2 scouting)



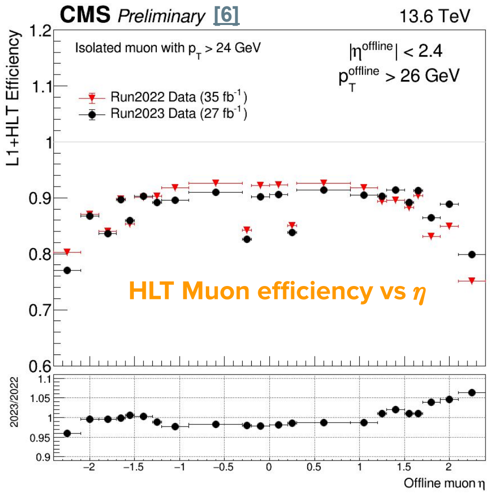


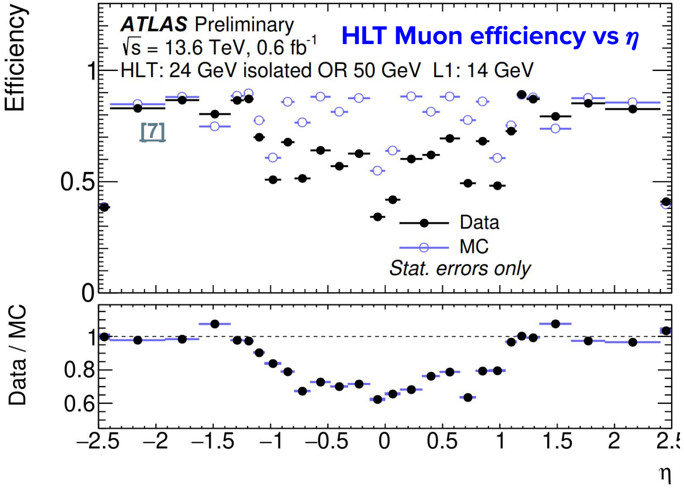


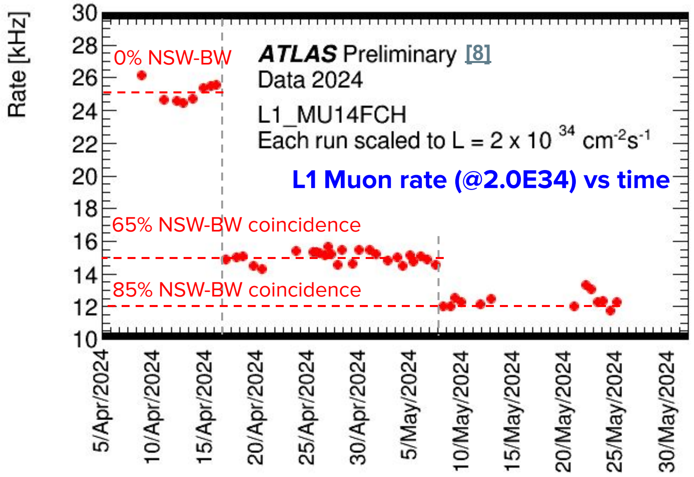


Muons

- Muon efficiency dominated by L1 trigger and isolation cut.
- L1 muon chamber inefficiency recovered during data taking.
- New Small Wheels (ATLAS) improved efficiency/rate ratio in the forward region.
  - Rate reduction: > -50% (13 kHz), with ~98% efficiency.

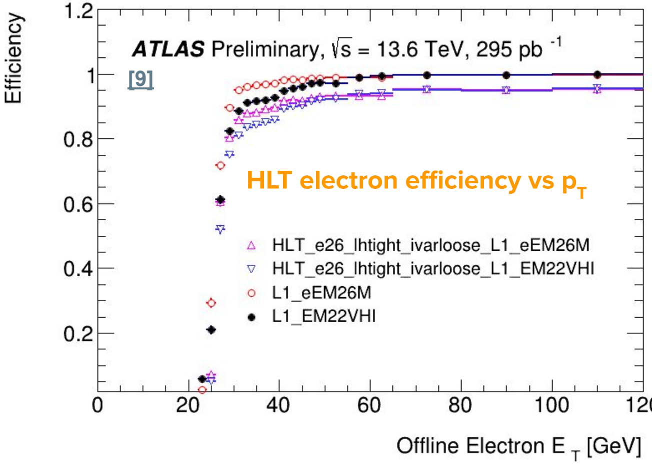


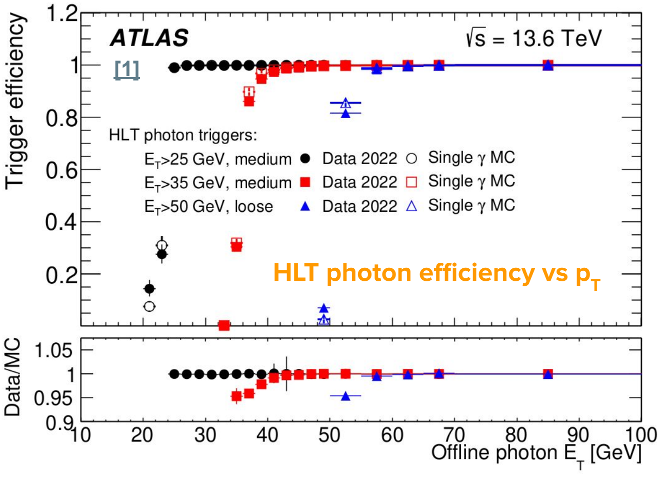


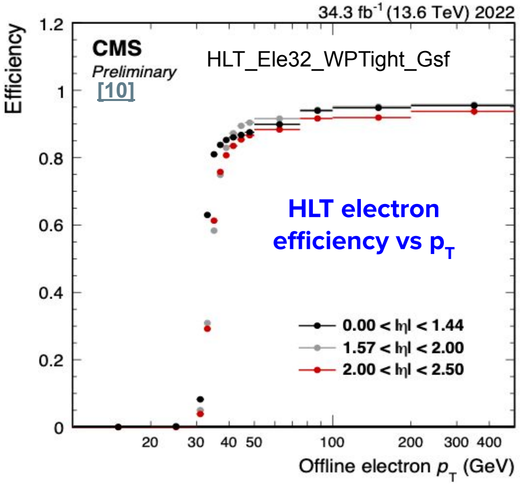


Electrons and photons

- Excellent performance
- New Phase-1 algorithm in ATLAS in L1 trigger → better efficiency

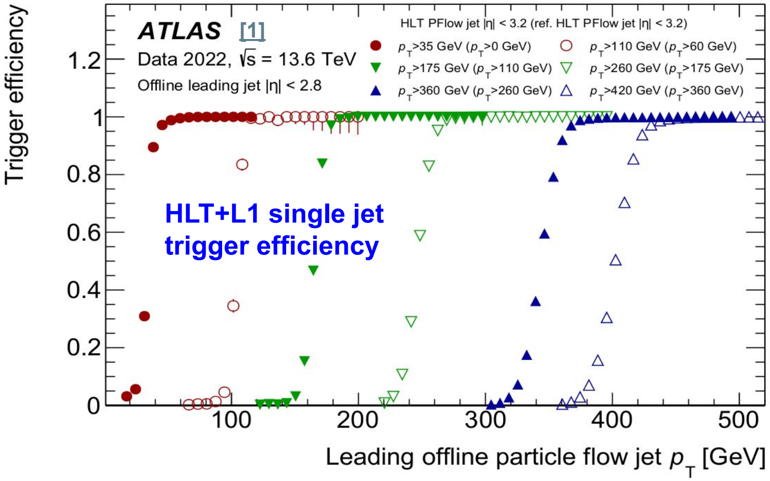


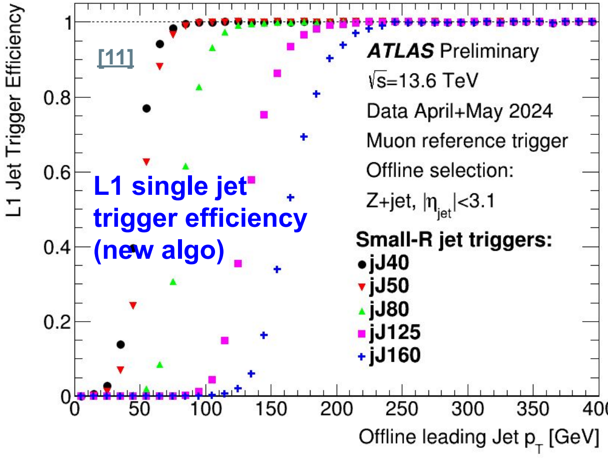


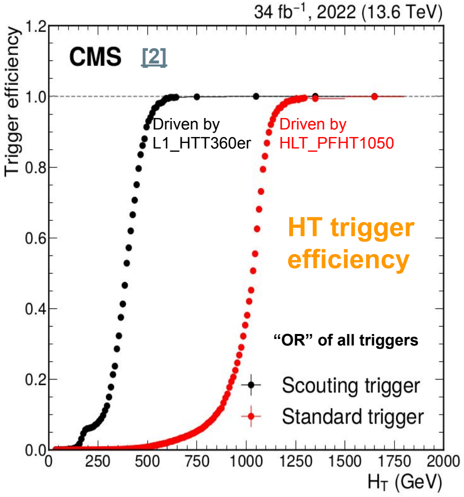


Jet and HT

- Good Jet/HT performance.
- Scouting/TLA allows a large gain in trigger acceptance.
  - Larger gain with the activation of L1_HTT280er in 2023
- New Phase-I jet triggers
  - jet Feature Extractor (jFEX) applies a more refined jet calibration than the legacy L1 jets received

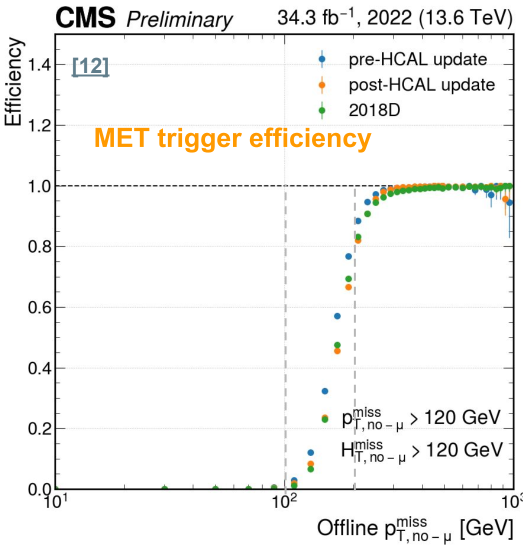


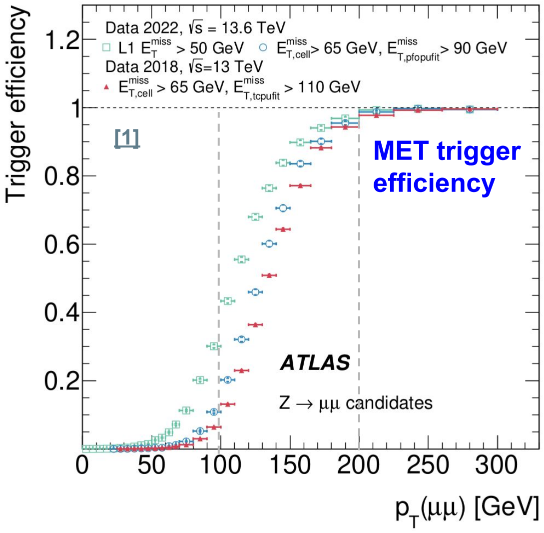


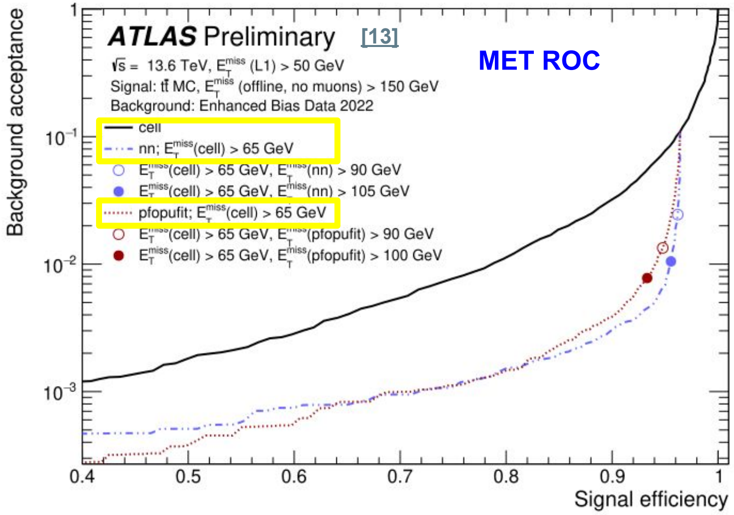


Missing transverse energy

- Missing transverse energy computed as the sum of particle flow candidate
- New method based on NN deployed by ATLAS in 2024 → improved efficiency at fixed rate

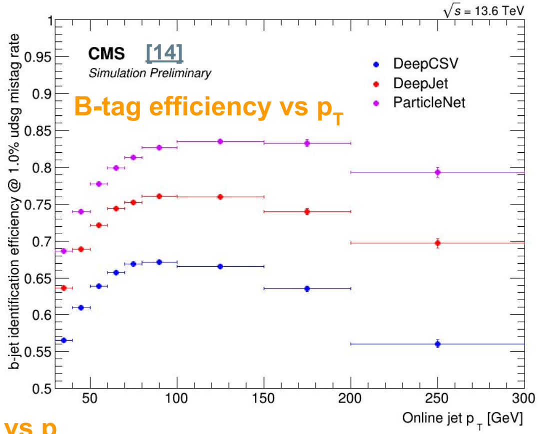




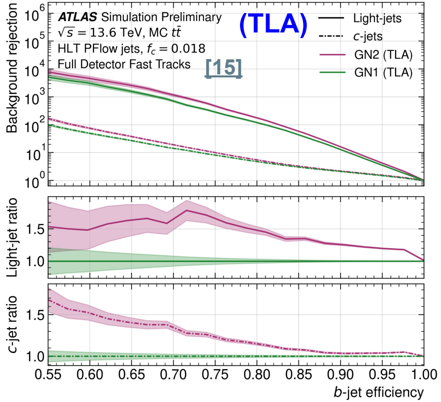


B-tagging and tau tagging

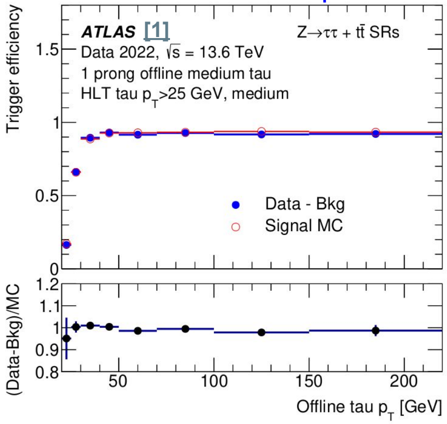
- Graph neural network used for b-tagging (ParticleNet, GN2)
- Large improvement in performance
- GN2 used in TLA

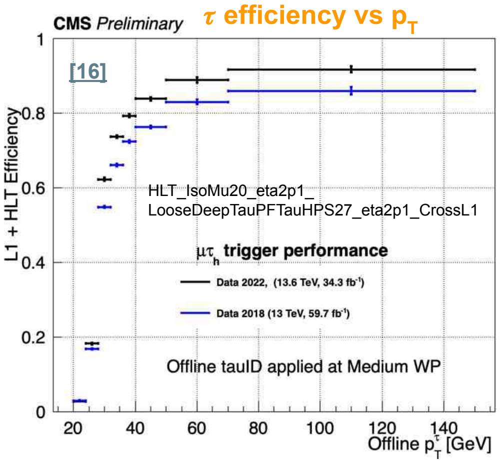


B-tag efficiency vs uds rejection



τ efficiency vs p_T

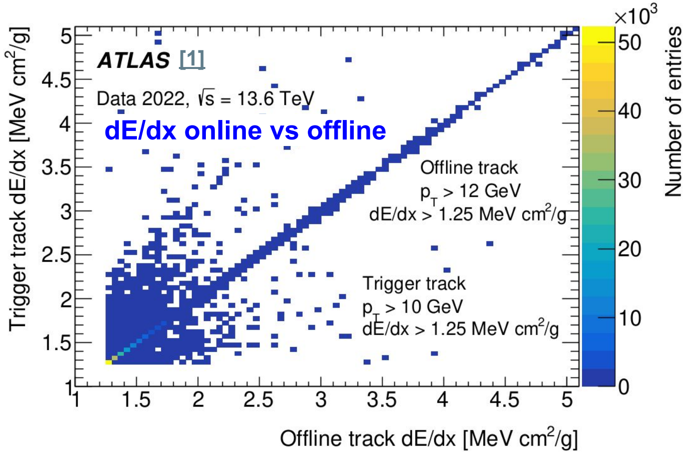


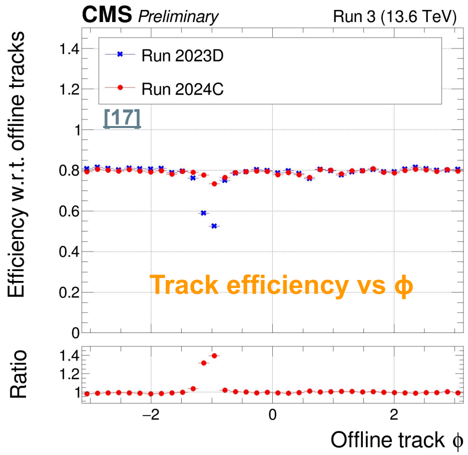


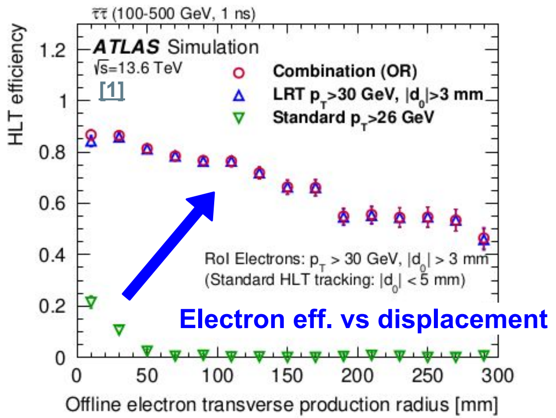
- Good performance in tau reconstruction
- Migration of tau reconstruction to ParticleNet in 2024 (CMS)

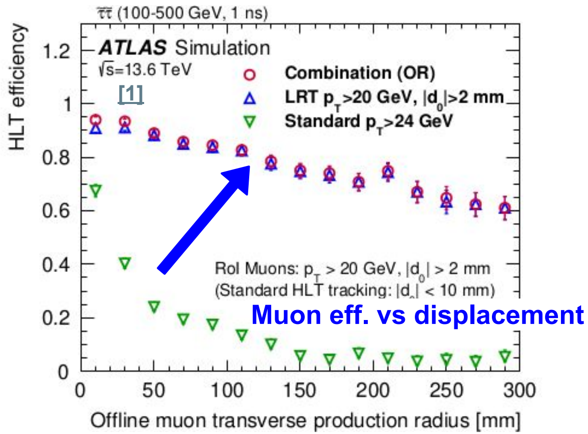
Tracking

- Excellent precision in dE/dX measurement
- Issues in few pixel modules in CMS after TS1 in 2023
  ➔ recovered using a doublet recovery in 2024
- Development of dedicated tracking for long-lived particles



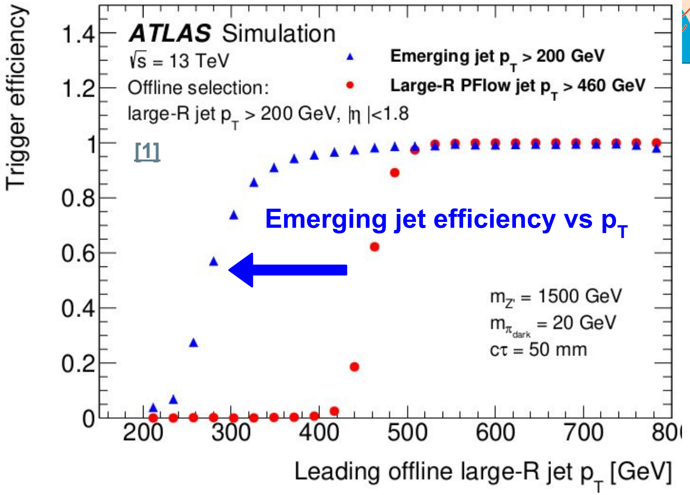


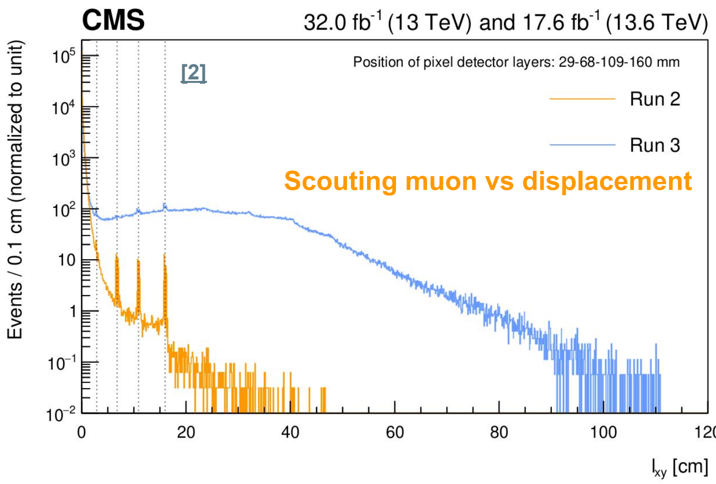




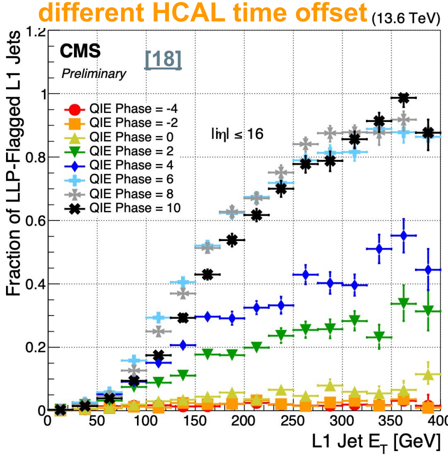
Long lived particles

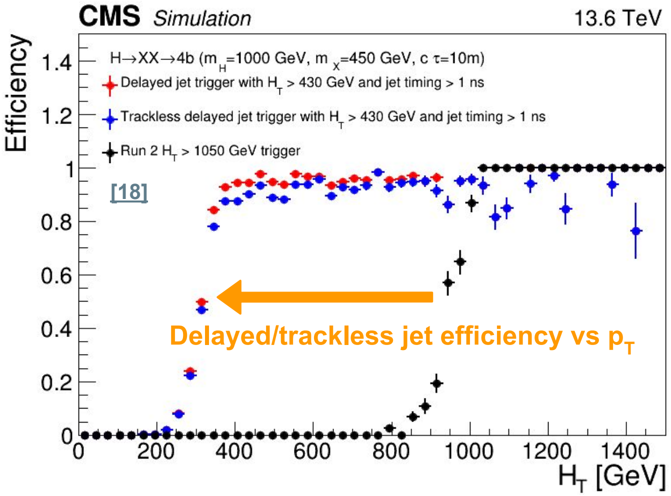
- New set of triggers targeting long-lived particles
  - Trackless or displaced jets;
  - Measurement of time delay in ECAL and HCAL;
  - Displaced muons
    - Dedicated L1 trigger
    - Included in scouting





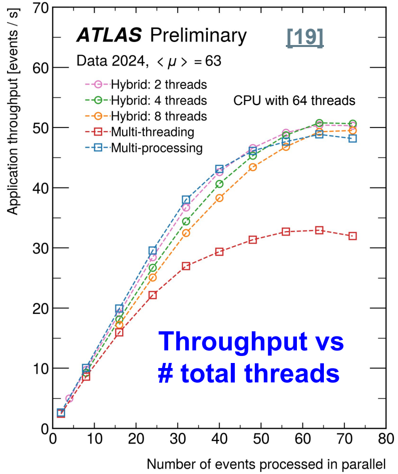
LLP jet efficiency vs p_T for different HCAL time offset

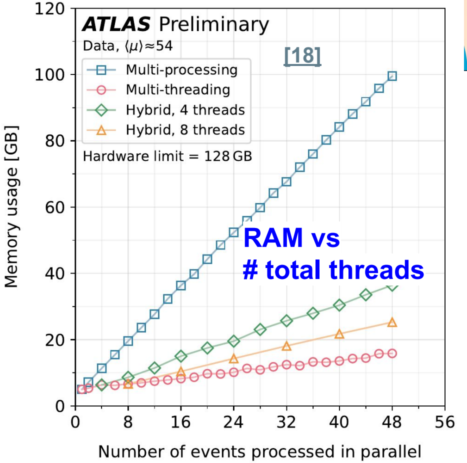


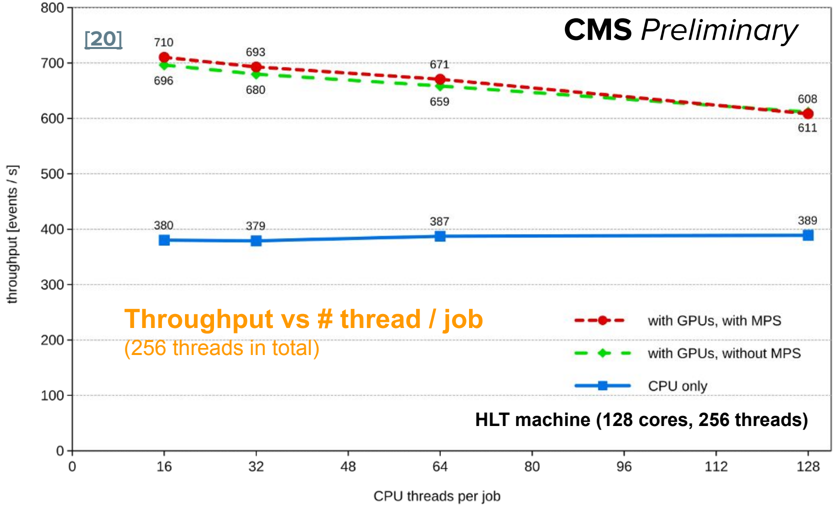


Multithreading and GPU

- Multithreading (MT) is key to fully exploit HLT farm computational power
  - inter-event, intra-event, in-algorithm parallelism;
  - usage of “data handles” to define the data dependency among modules;
  - lower memory usage.
  - AthenaMT online since 2022.
  - CMSSW support MT since 2015.
- CMS HLT farm heterogeneous since 2022 (AMD CPU + Nvidia T4):
  - **40%** of HLT reconstruction ported to **GPU** (CUDA)
    - Pixel local reconstruction
    - Pixel tracking and vertexis
    - ECAL local reconstruction
    - HCAL local reconstruction







Migration to alpaka (CMS)

- **Alpaka** is a **portability** library. Same code able to run on
  - **multiple** hardware **vendors** (eg. AMD GPU, Intel GPU)
  - **multiple** kinds of **accelerators** (eg. GPU, FPGA)
- Pixel and ECAL code migrated from CUDA to Alpaka in 2024.
  - HCAL local reco migration in progress.
- Part of the Particle Flow recently ported directly to Alpaka from CPU-only.