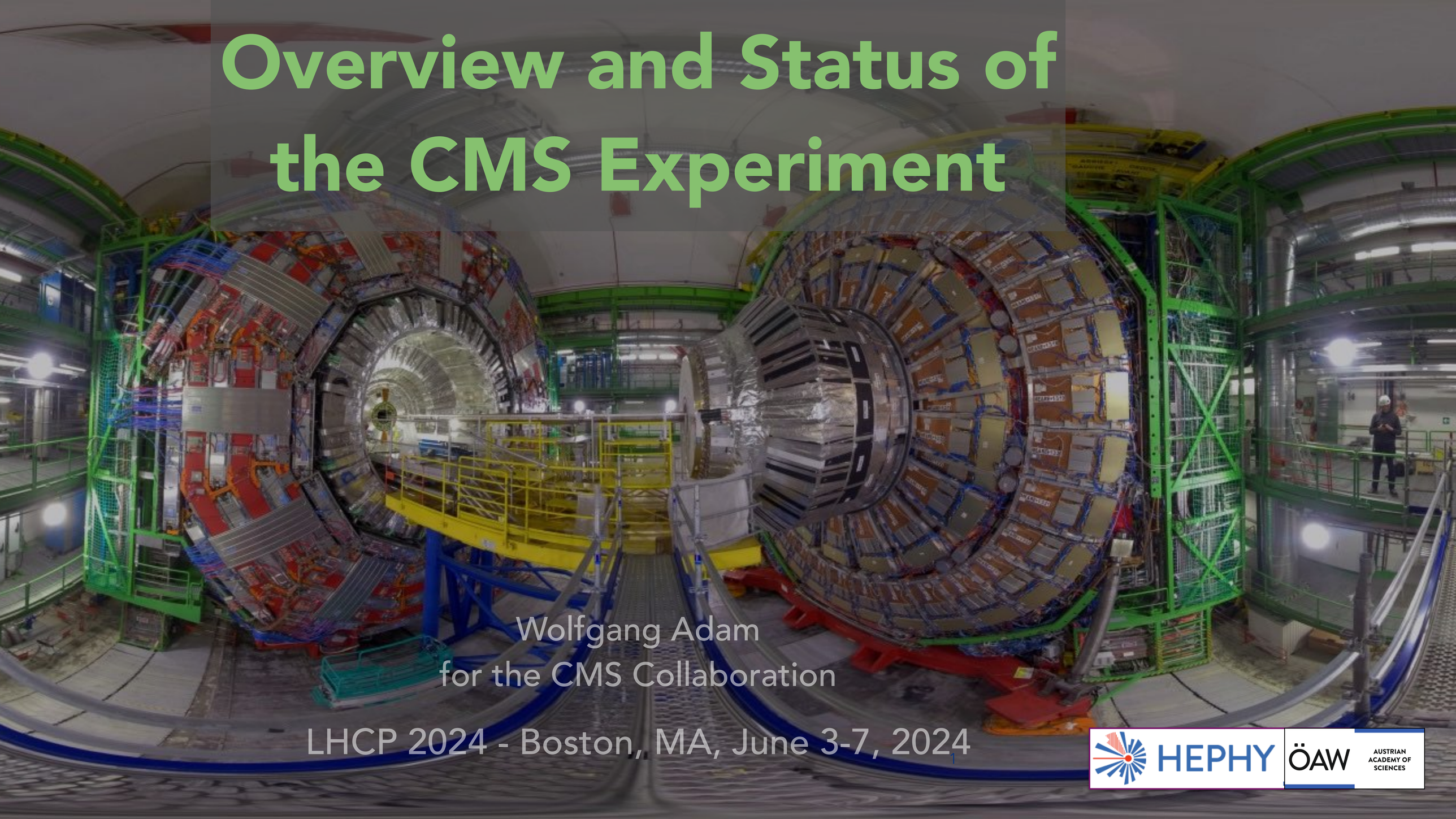
Overview and Status of the CMS Experiment



Wolfgang Adam
for the CMS Collaboration

LHCP 2024 - Boston, MA, June 3-7, 2024

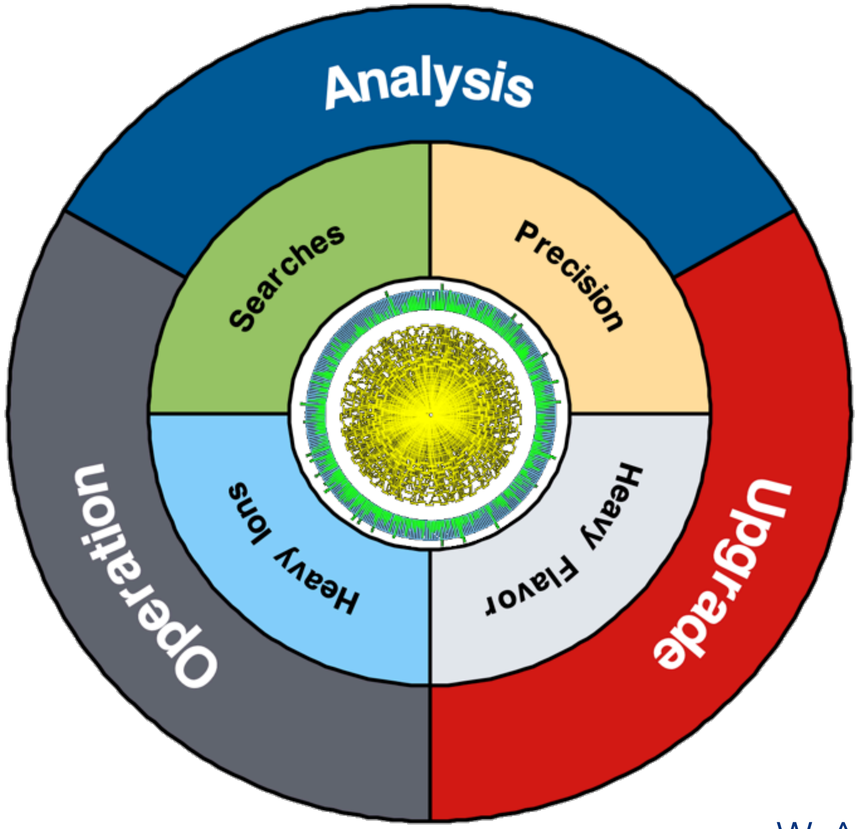
HEPHY ÖAW AUSTRIAN ACADEMY OF SCIENCES

The collaboration

A thriving community

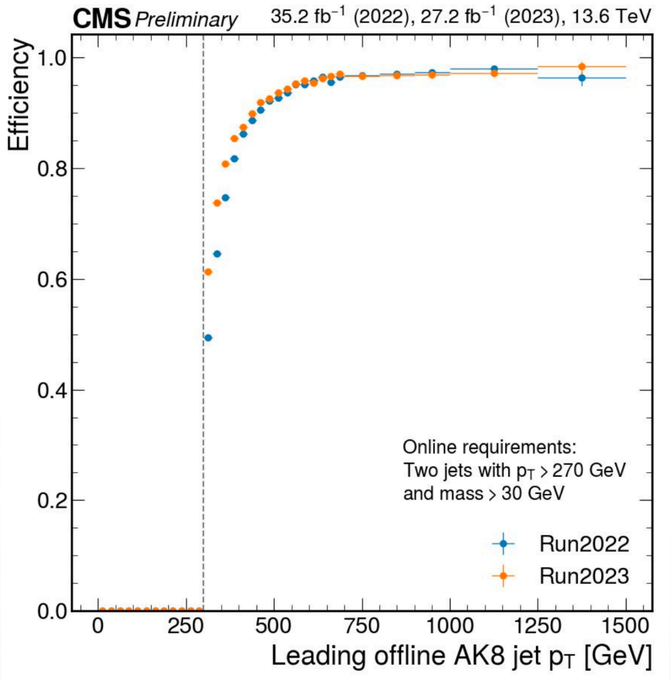
- 6300 persons including
  2200 physicists & 2600 students
- 247 institutes from 57 countries and regions,
  and continuing to welcome new ones!

- Engaged in several challenges
  for present and future:
  - Run 3 operations, analysis of available data sets,
    preparation for HL-LHC
  - Analyses covering a wide range of topics

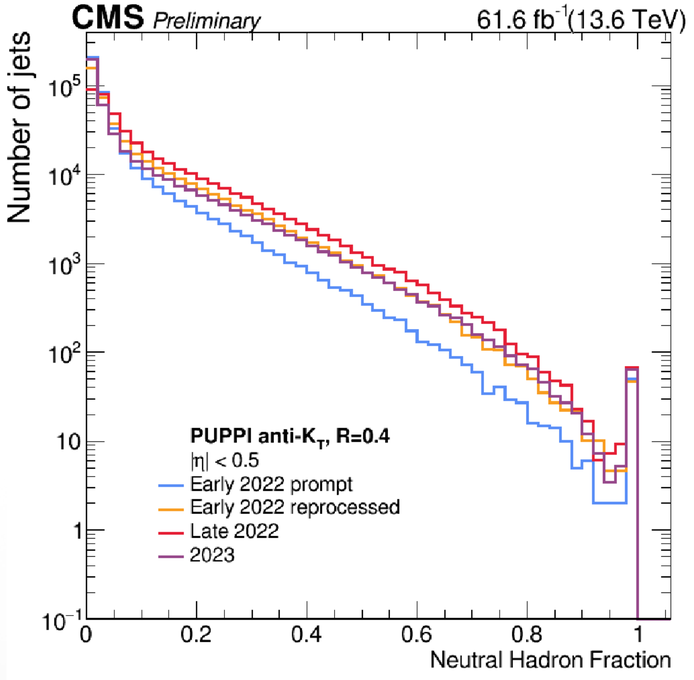


Detector performance in Run 3

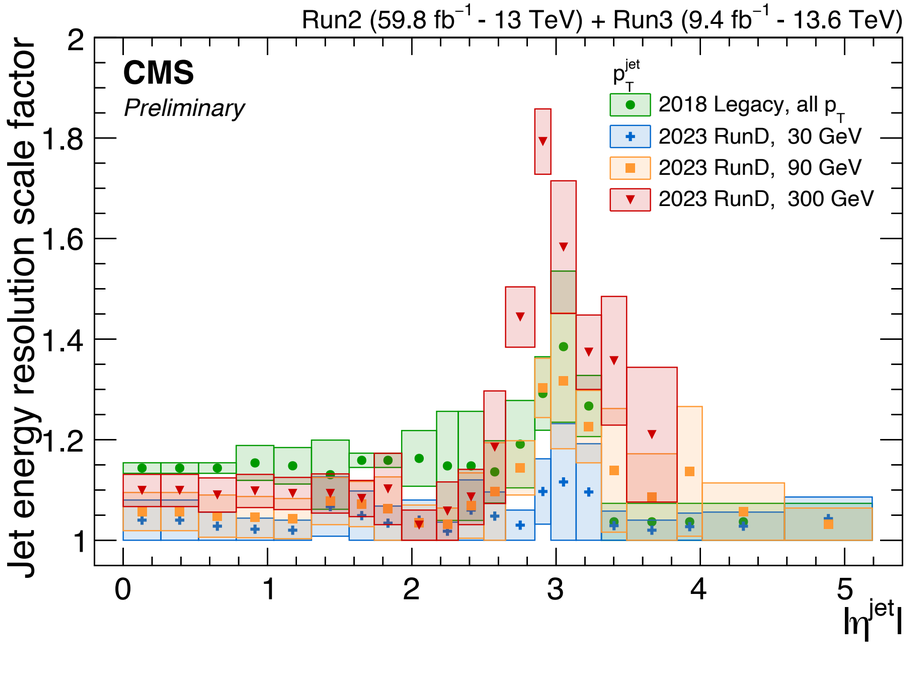
Stability and excellent calibration results for jets @ high level trigger (HLT) and offline



Stability of HLT jet mass selection in Run 3



Stability of jet properties in Run 3 w.r.t. year and detector conditions



Excellent description of jet energy resolution in 2023 prompt reconstruction

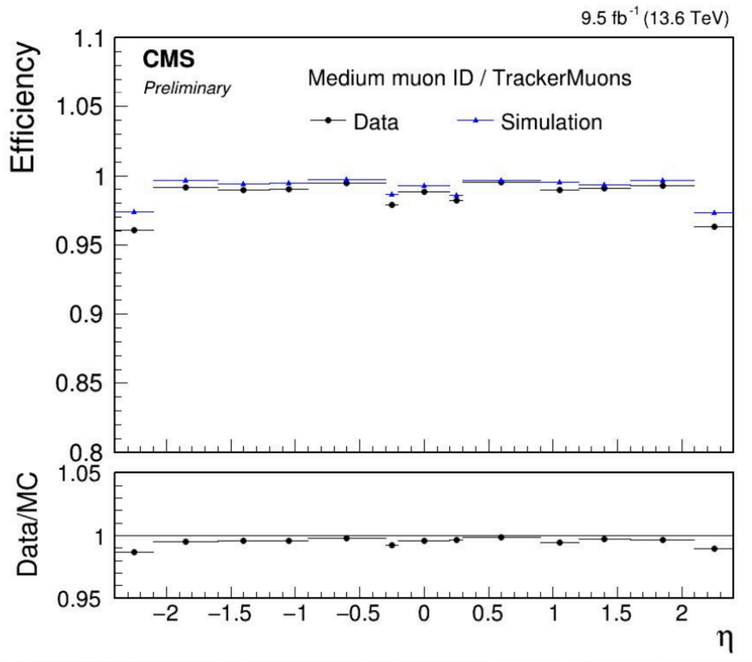
CMS-DP-2023/094

CMS-DP-2024/028

Detector performance in Run 3

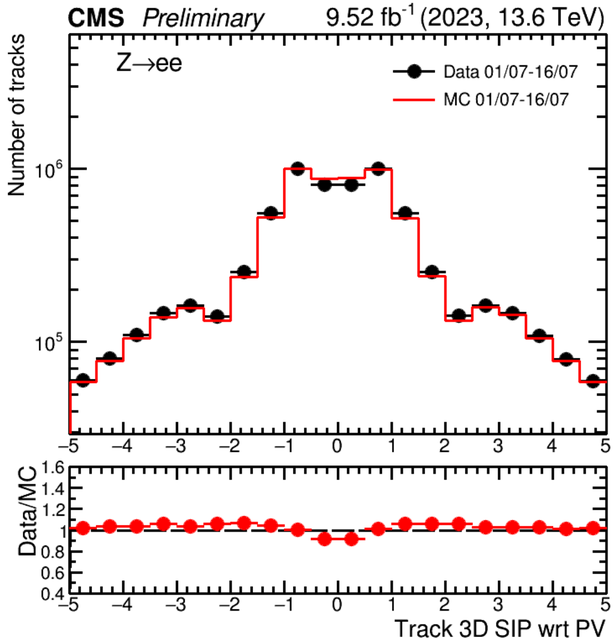
Some offline performance examples for leptons and b-tagging in 2023

- Well produced in simulation, excellent stability over data taking periods



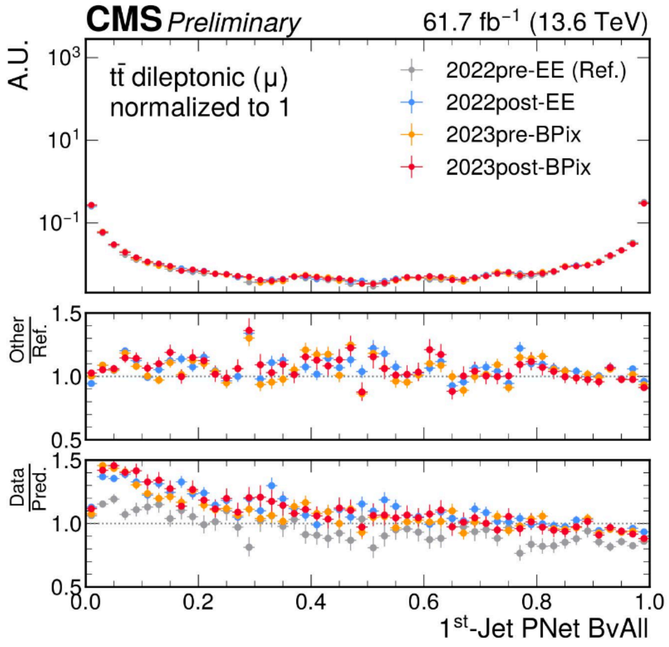
Efficiency of muon identification in data and simulation

CMS-DP-2024/023



Impact parameter significance in 3D for electron tracks in data and simulation

CMS-DP-2023/090



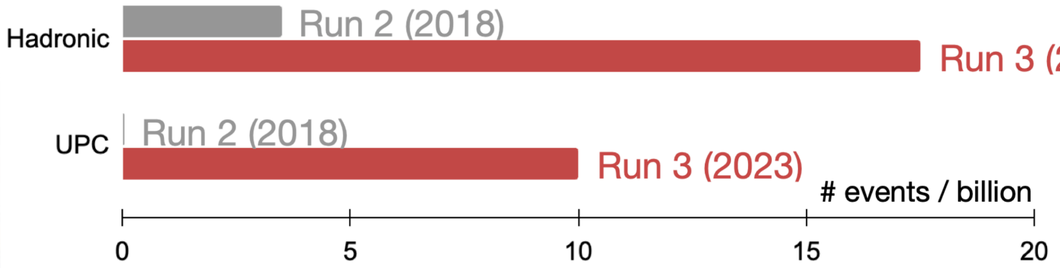
Stability of ParticleNet b-tag scores w.r.t. years and data taking periods

CMS-DP-2024/024

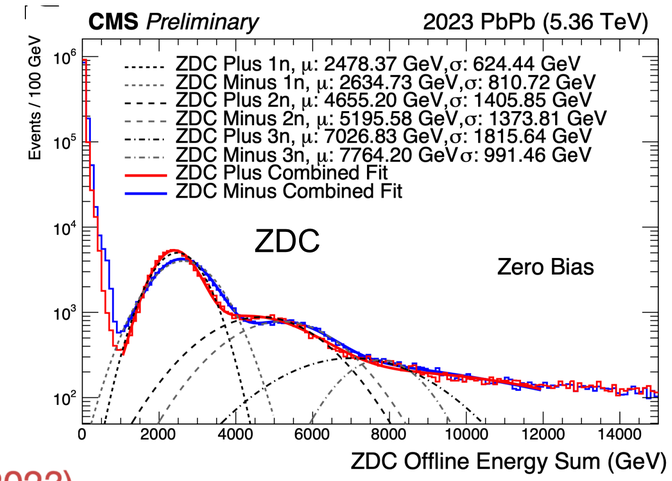
More data for physics with PbPb !

Major improvements for the long-awaited first heavy-ion physics run since 2018

- Maximize yield of events with high-pt probes, minimum bias (MB), and ultra-peripheral (UPC) events
- For the first time in PbPb collisions, CMS operated at an level-1 (L1) trigger rate of ~50kHz

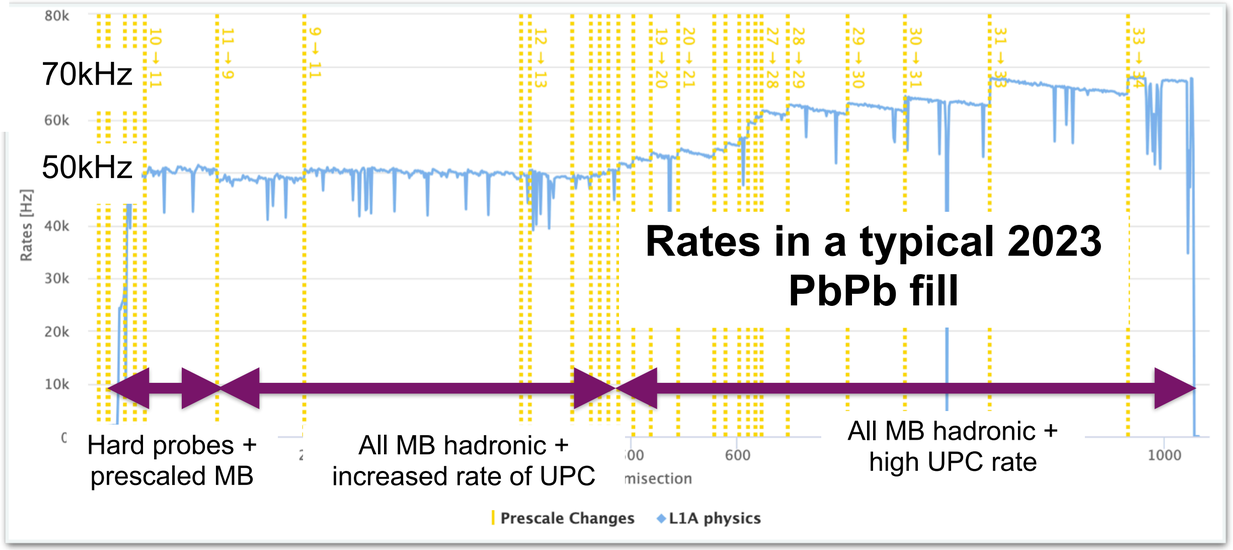


Collected a total of 10 billion UPC events and almost all MB hadronic events



First use of the zero-degree calorimeter (ZDC) @ L1 trigger
- essential for a clean MB sample and efficient selection of UPCs

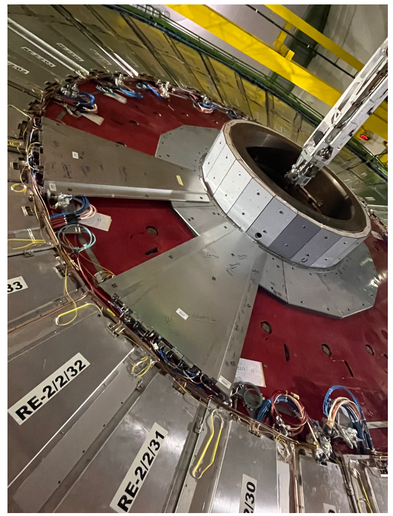
Adapt to limits at DAQ and computing level:
- Reduced raw data format @ almost identical reconstruction performance and stronger loss-less compression @ HLT
- Event size reduction by factor ~ 2



Intermezzo: Preparing for 2024 and Beyond

Activities in the technical stop TS ‘23/‘24

- Standard maintenance and continued preparation in view of the next long shutdown (LS3) and CMS Phase 2



Demonstrators for new GEM and iRPC muon chambers for improved coverage of the forward regions

First new shielding for reduced background (Phase 2 version)

And, important for all our shifters and experts:

- CMS is now operated from a new control room!

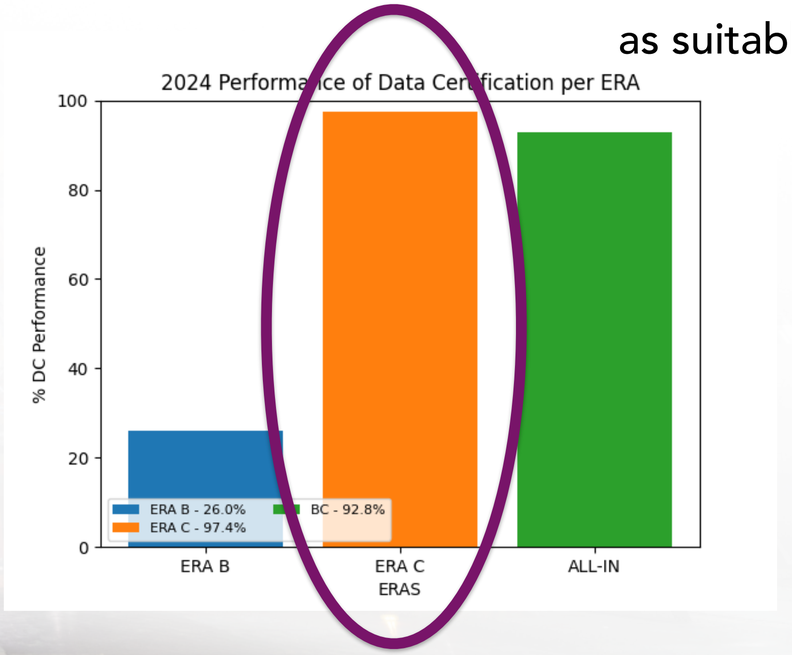
A first glimpse of 2024 conditions

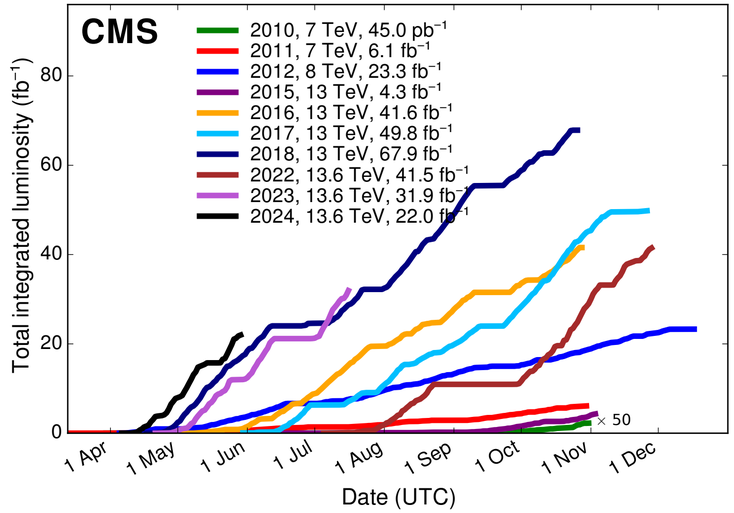
Stable running

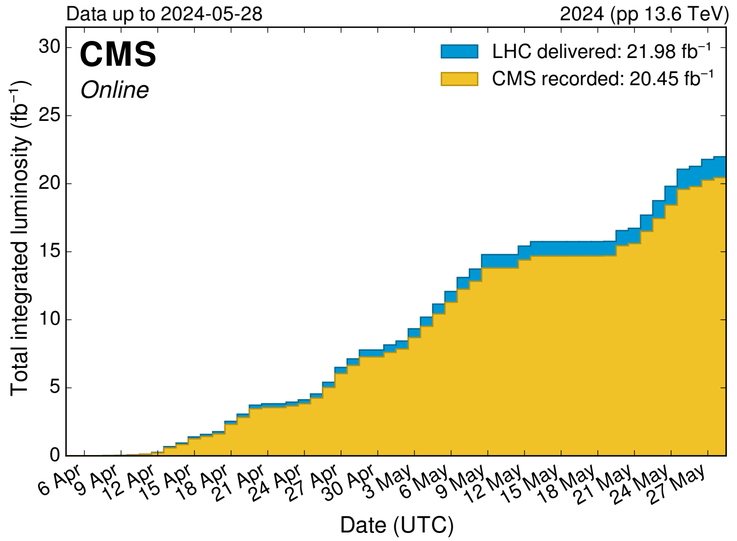
- With typical L1 trigger rates of 105kHz at the start of the fill with pileup levels beyond 60
- Collected 93% of the delivered luminosity

After the commissioning period:

- ~97% of recorded data certified as suitable for all analyses



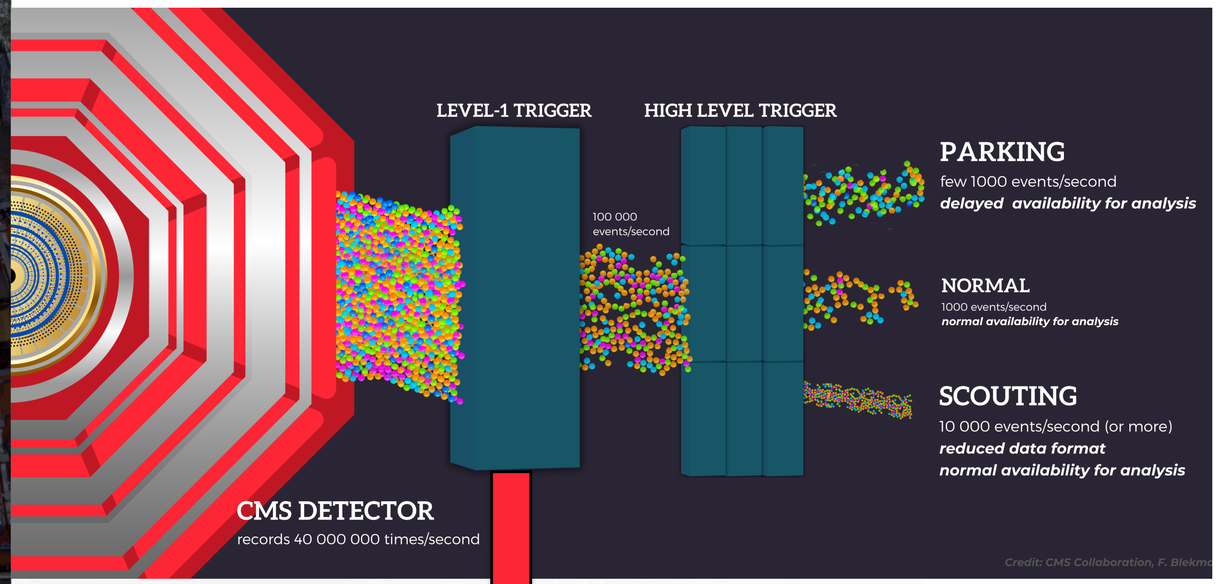




From detector performance to physics potential

Trigger strategies for Run 3

- Complementary approaches to support all physics cases within available resources
- Continuous development: new systems at L1 and improved GPU use at the HLT



"Parked" data (reconstruction can be delayed)

- Enhanced potential in key areas, e.g. for VBF processes and soft lepton signatures
- now integral part of our program

Data with guaranteed prompt reconstruction

- Consistent, stable set of triggers with high-pT objects

"Scouting" using HLT objects

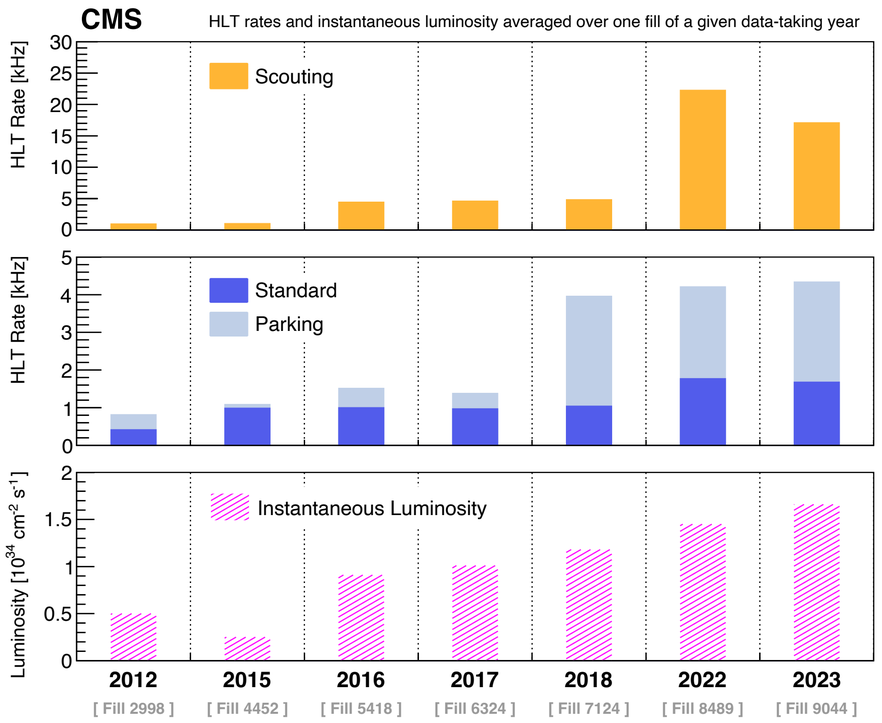
- Expanding number of use cases and improved integration in our analysis environment

"Scouting" at L1

- New HW in 2024 for true zero-bias selection (all bunch crossings)
- Improvements in ease of use for analysis -> moving to production mode

From detector performance to physics potential

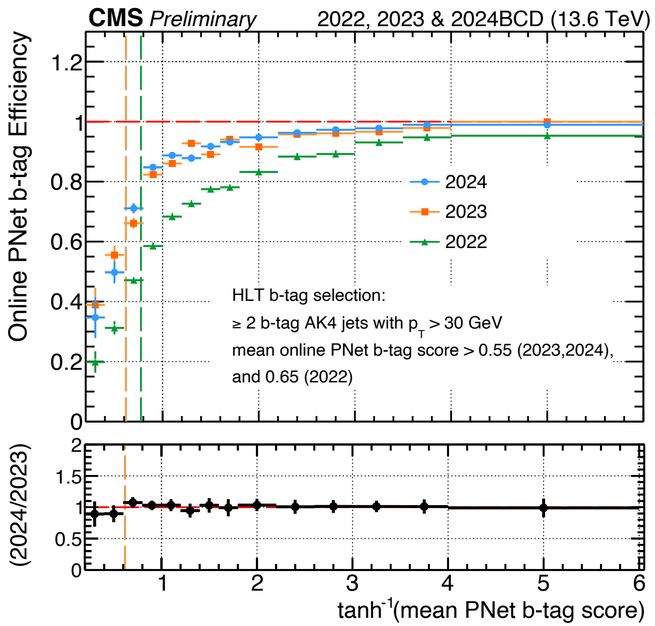
History of rates for different data streams



Rates for typical fills

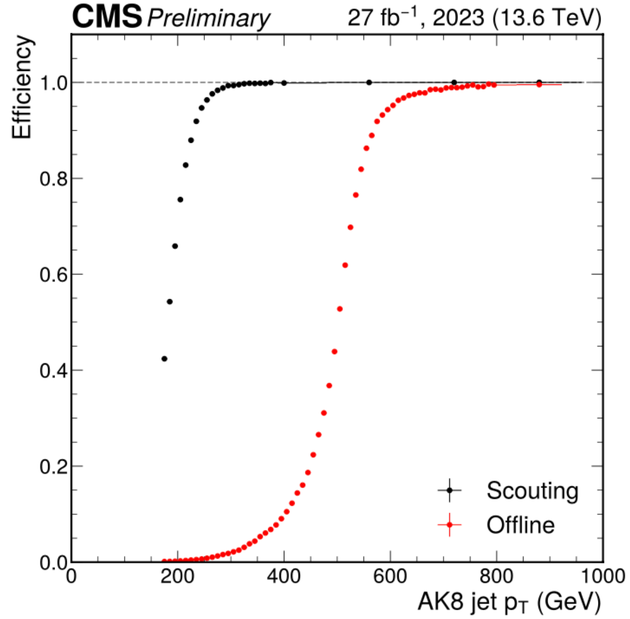
CMS-EXO-23-007
arXiv:2403.16134

Examples of improved performance



Gain in acceptance with a looser ParticleNet b-trigger in ’23 & ’24

CMS-DP-2023/089

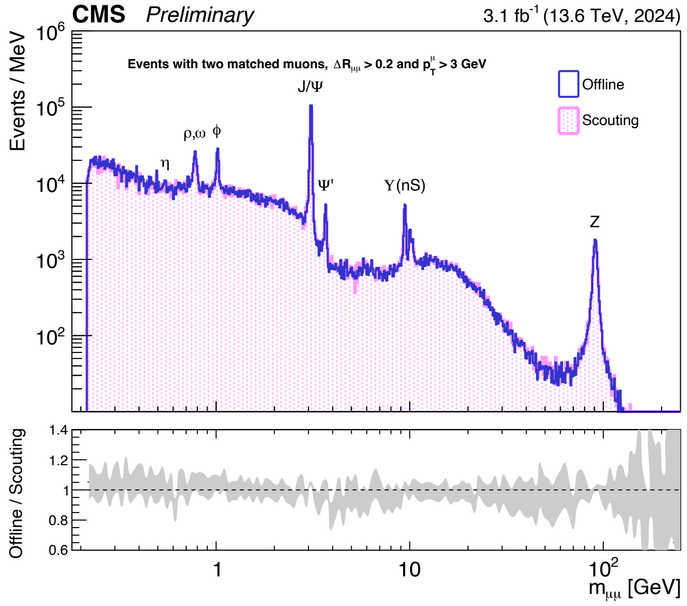


Lower threshold for large-radius jets with scouting

CMS-DP-2023/076

From detector performance to physics potential

Reconstruction quality in 2024 for dimuon scouting

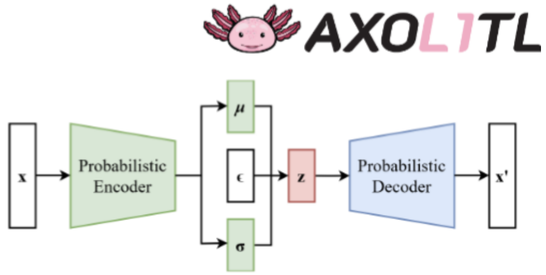


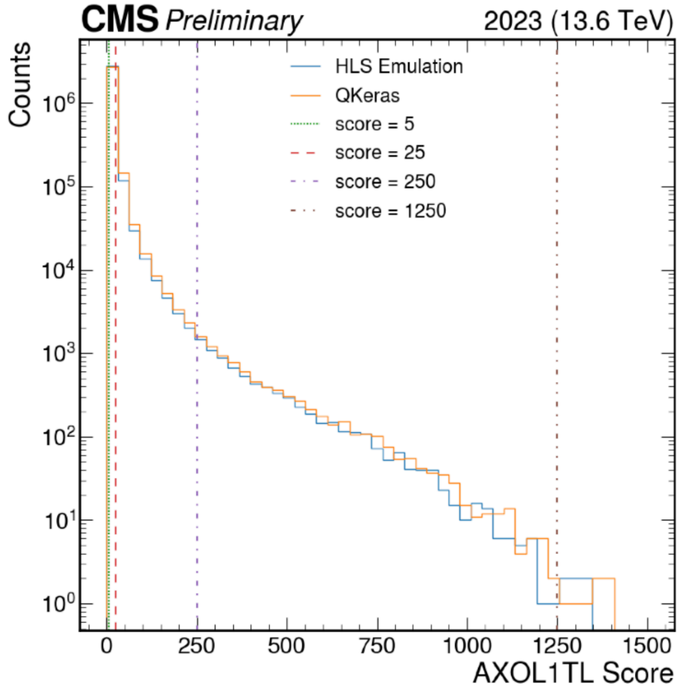
Comparison of the dimuon mass spectrum with offline reconstructed quantities

Anomaly detection at L1

- Two algorithms are implemented
  - AXOL1TL: variational auto encoder using input objects to global L1

Active in data taking





AXOL1TL Rate	1 kHz	5 kHz	10 kHz
Signal Efficiency Gain	46%	100%	133%

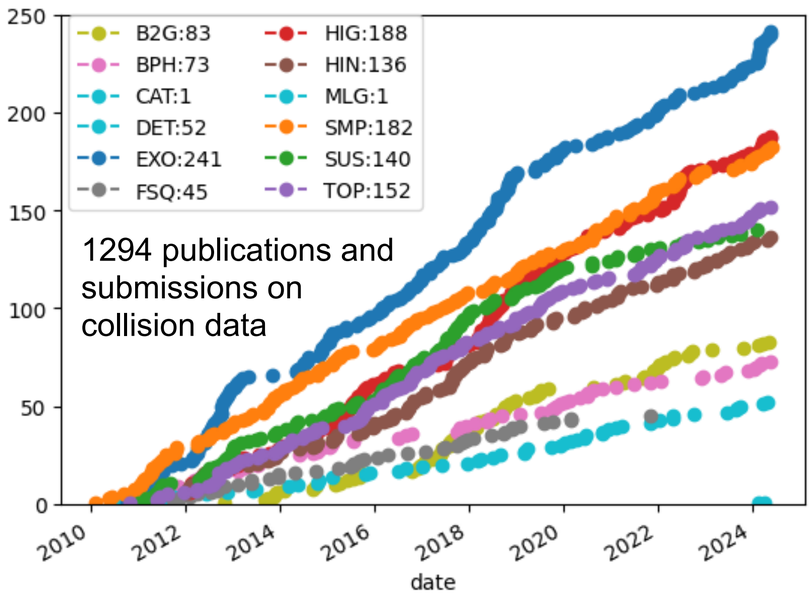
AXOL1TL scores and efficiency gains vs standard L1 menu.
Signal: H→XX(15GeV)→bbbb

CMS-DP-2023/079

  - CICADA: convolutional NN auto-encoder using low-level calorimeter information

In commissioning

Publications

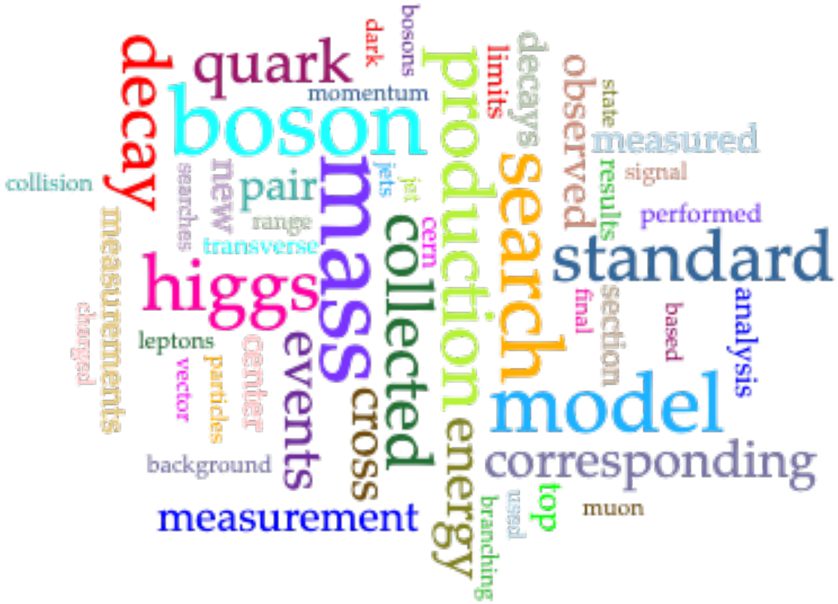


Record publication rates in the last year

- Still driven by innovative and challenging uses of the large data set of Run 2
- But Run 3 sample will soon become competitive

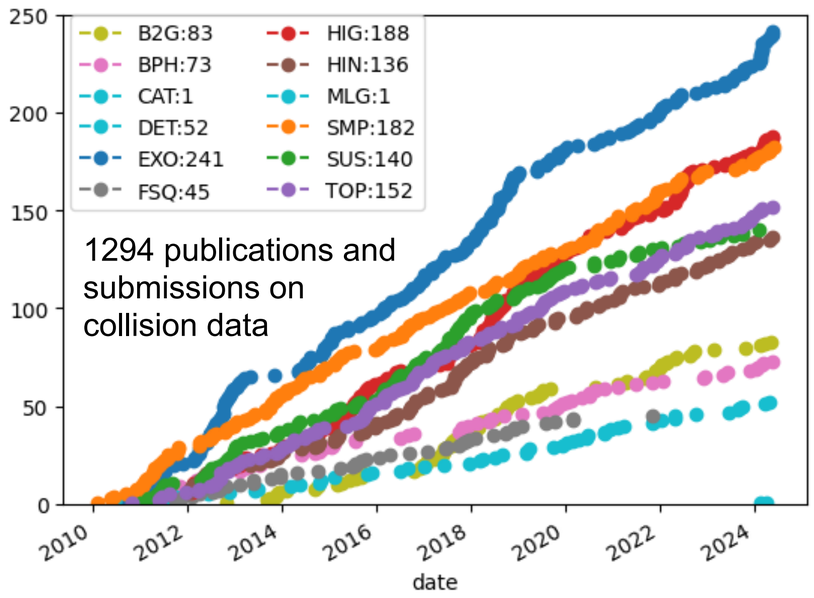
Run 2 review papers

- Completed submission of seven comprehensive review-style papers based on the full Run 2 data set
- Topics cover searches for new phenomena, standard model measurements, and high-density QCD



Keywords extracted from CMS abstracts since LHCP2023

Publications



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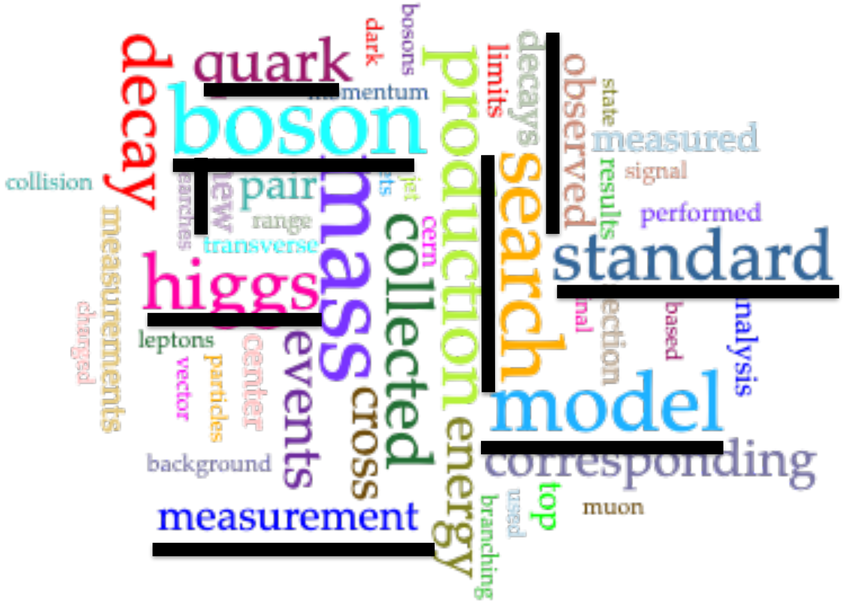


Keywords extracted from CMS abstracts since LHCP2023

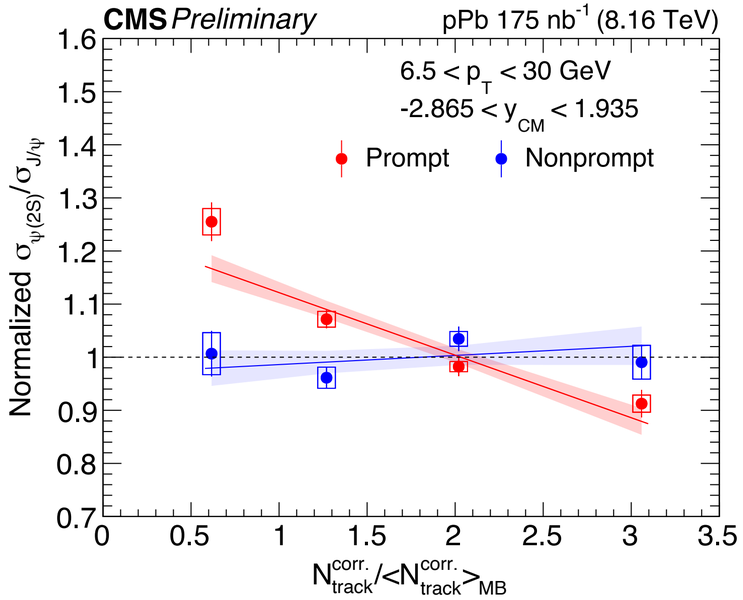
Multiplicity dependence of ψ(2S) /J/ψ cross sections in pPb

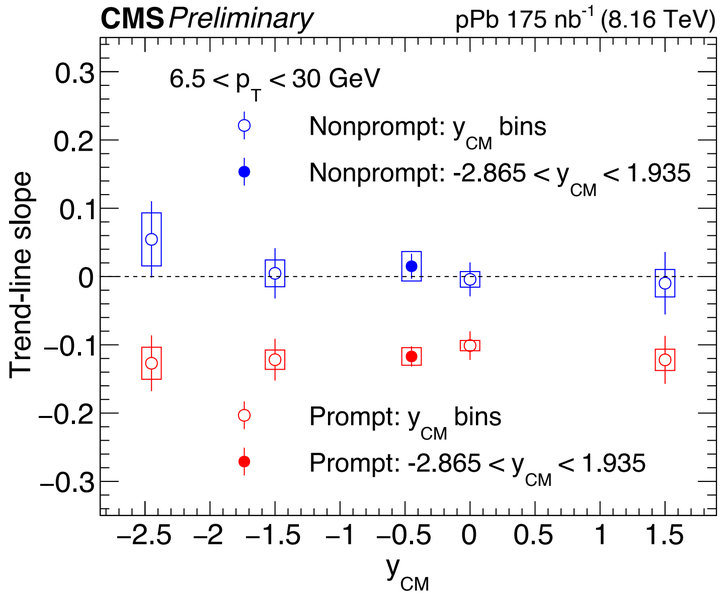
Ratio of $\psi(2S)$ and J/ψ production cross sections in pPb collisions at $\sqrt{s_{NN}}$ = 8.16TeV

- Motivated by growing interest for quarkonium suppression in small systems
- Ratios measured for prompt and non-prompt mesons in the dimuon channel

Multiplicity-dependent modification of the ratio observed for prompt mesons

- Stable for non-prompt mesons
- Co-moving particles could dissociate excited states more easily than the ground state





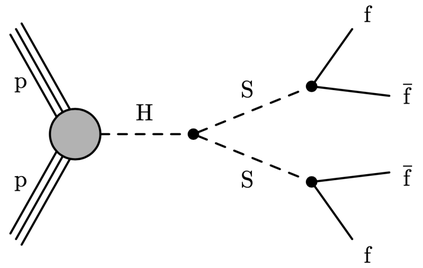
New @ LHCP24 !

CMS-PAS-HIN-24-001

Resonances decaying to displaced jets

Search for displaced jets with Run 3 data

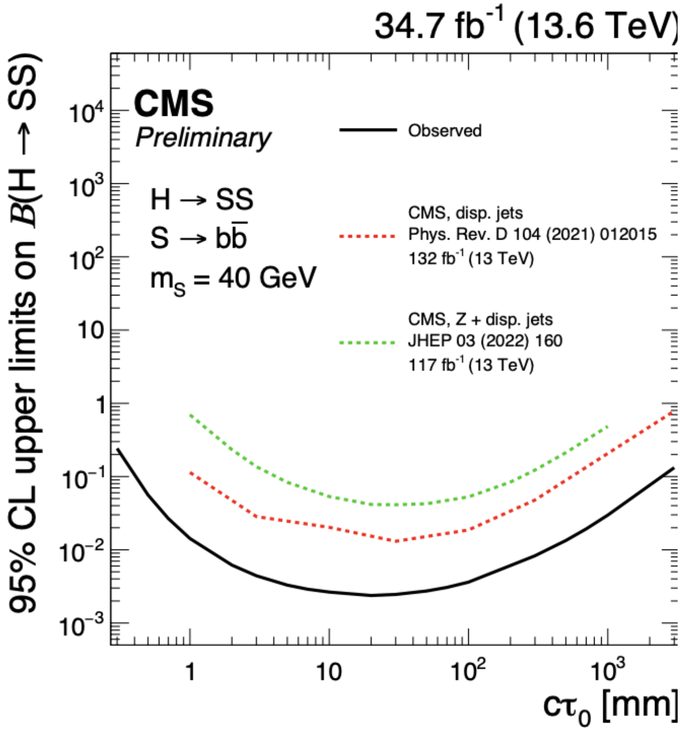
- Model: Higgs boson decay to two long-lived neutral scalars
- Sensitivity boosted with combination of
  - New displaced jet triggers for low masses
  - displaced vertex reconstruction, and
  - a novel displaced dijet identification based on graph NNs

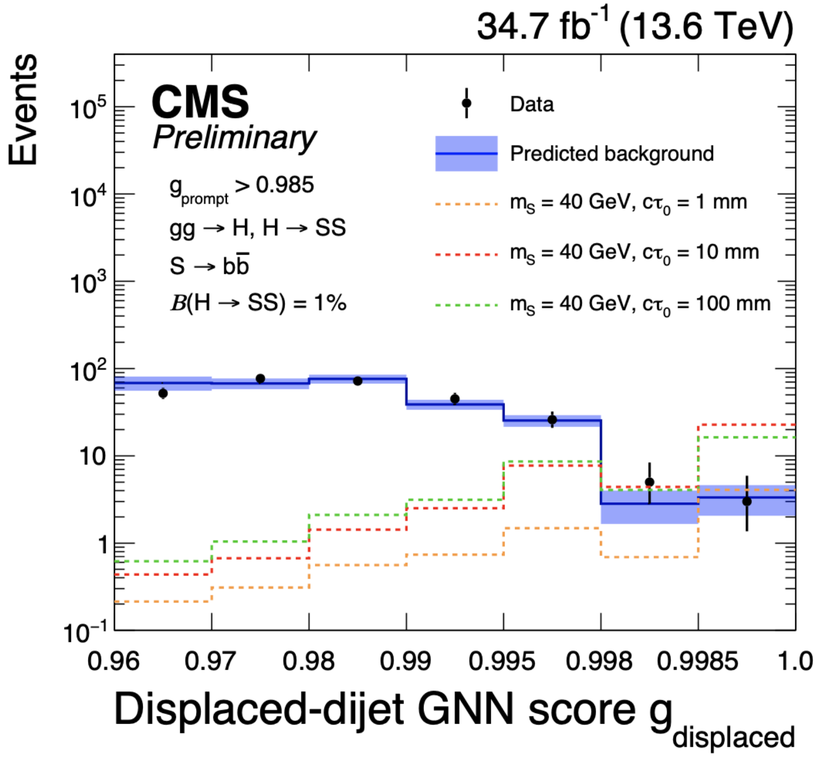


New limits, based on 2022 data, show improved sensitivity with respect to Run 2

- At ~ ¼ of the luminosity !

CMS-PAS-EXO-23-013



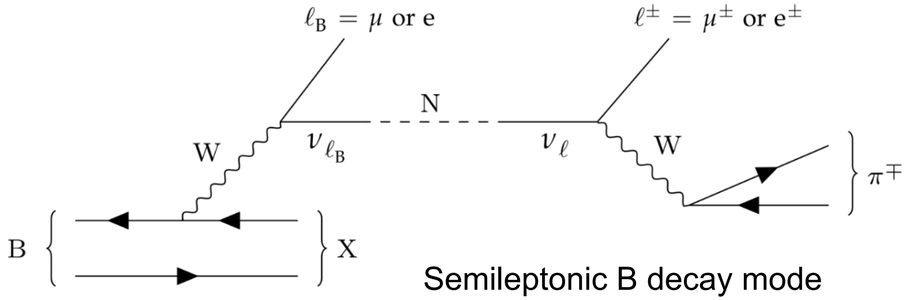


Search for long-lived heavy neutrinos

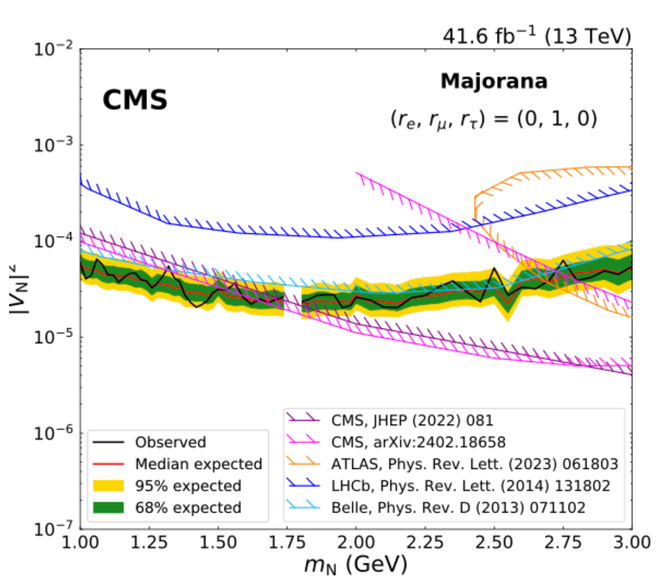
Search for HNLs in B decays

- Analysis based on the special "parked data" stream recorded in 2018, designed to collect O(10^{10}) bb events
- Event classification based on a parametric NN for optimal selection of different HNL masses
- Expected signal yield from effective $B^{\pm}$ cross section, measured from control channel $B^{\pm} \to J/\psi K^{\pm}$

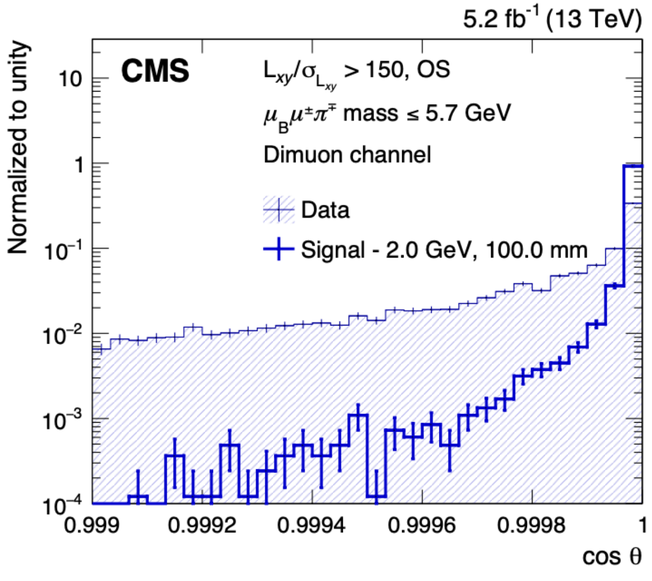
Strongest limits on sum of squares of light-heavy mixing amplitudes from a collider for 1GeV<m_N<1.7GeV



Semileptonic B decay mode



Majorana scenario, dimuon channel only



Angle between vector to DV and sum of momenta

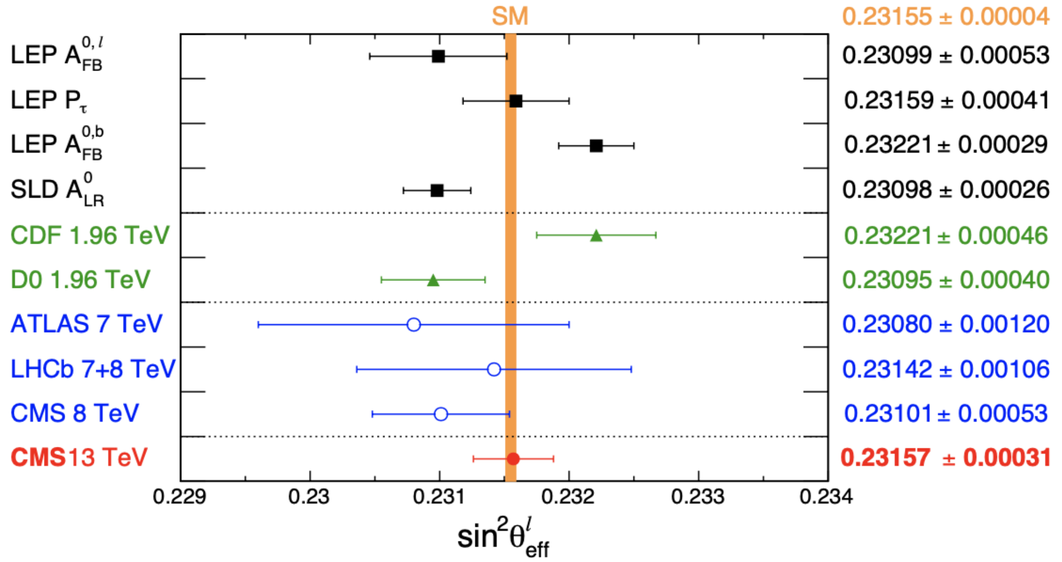
CMS-EXO-22-019
arXiv:2403.04584

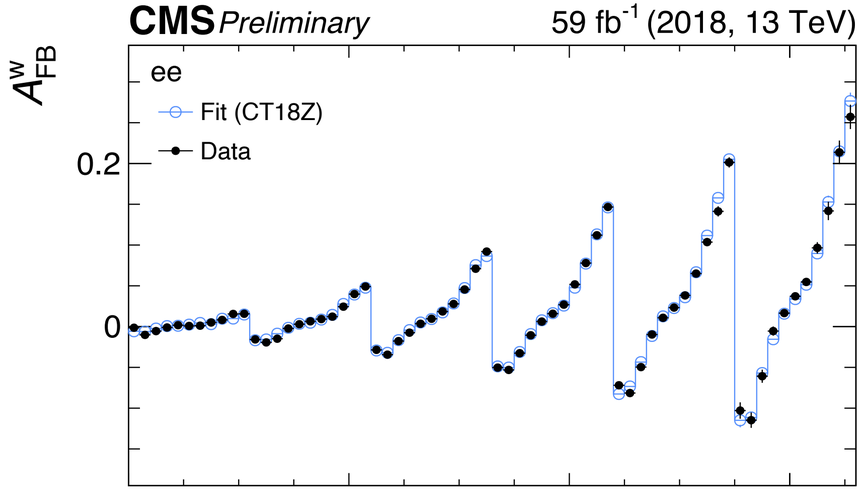
Z/$\gamma^* \to \ell\ell$ and the weak mixing angle

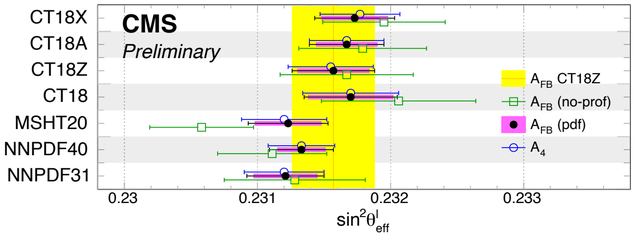
Precision measurement of EWK key quantity at a hadron collider

- $\sin^2\theta^{\ell}_{\text{eff}}$ extracted from A_{FB} (ee, $\mu\mu$), measured in bins of y(ll) and m(ll)
- Acceptance and sensitivity enhanced with extended acceptance for forward electrons
- Result (CT18Z):

$$\sin^2\theta^{\ell}_{eff} = 0.23157 \pm 0.00010(stat) \pm 0.00015(syst) \pm 0.00009(theo) \pm 0.00027(PDF)$$







- Matches LEP/SLD precision and is
- Compatible with the SM prediction

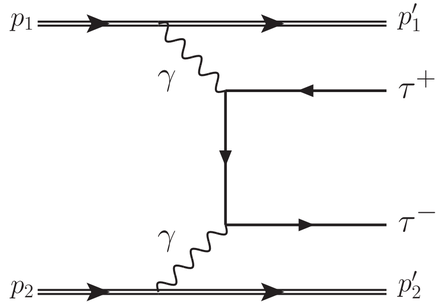
adds to understanding of a long-standing tension between previous measurements

CMS-PAS-SMP-22-010

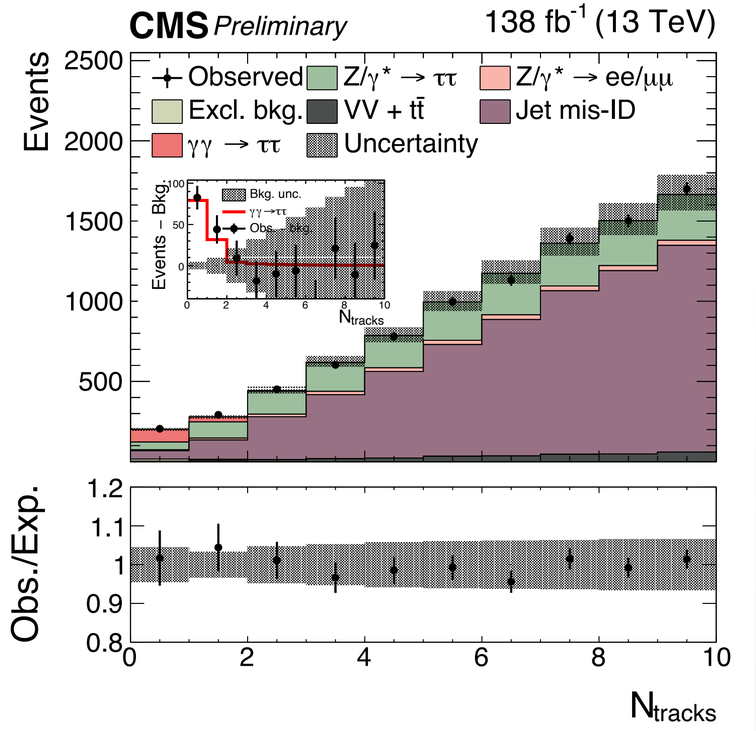
Observation of $\gamma\gamma \to \tau\tau$ in pp collisions

Tau-pair production from photon fusion (elastic or dissociative events)

- Events characterized by low-multiplicity vertices

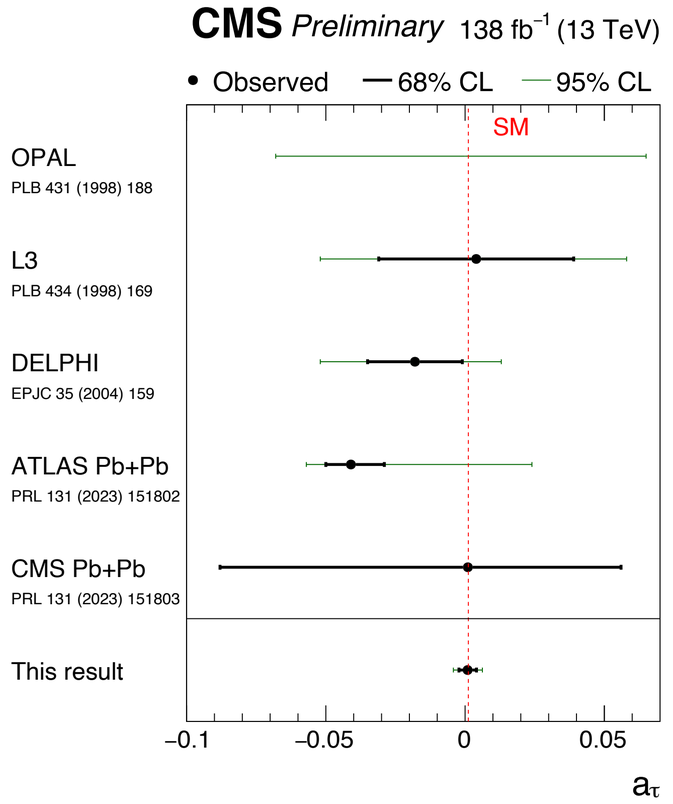


Elastic event



- Several simulated quantities require corrections based on data
  - In particular, #tracks for pileup and hard scatter

First observation in pp:
5.3σ obs (6.5 σ exp)!



Constraints on the anomalous magnetic moment

- Extracted using an EFT model: $a_\tau = 0.0009^{+0.0032}_{-0.0031}$
  - Improves LEP limits by factor 5 !

CMS-PAS-SMP-23-005

Observation of tt entanglement

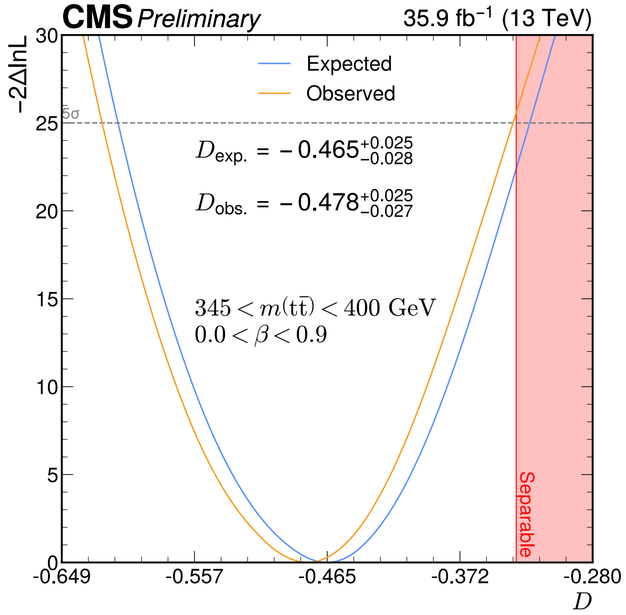
Sufficient condition for entanglement from spin correlation matrix

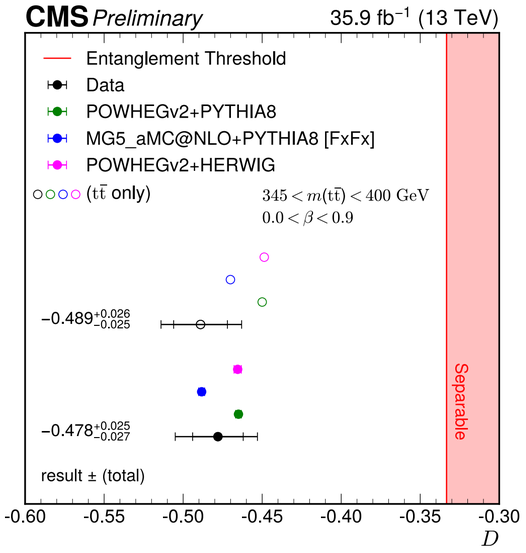
- Using diagonal elements: $\Delta_E = C_{33} + |C_{11} + C_{22}| > 1$
- Entanglement proxy $D = -\Delta E/3 = -Tr[C]/3$ (for small m_{tt}) can be extracted from angle between decay products

Test of entanglement in dileptonic tt events

- Decays to muons and electrons
- Using the low m_{tt} region, 345 — 400 GeV, with the higher sensitivity

D<-⅓ established at the 5σ level





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

CMS-PAS-TOP-23-001

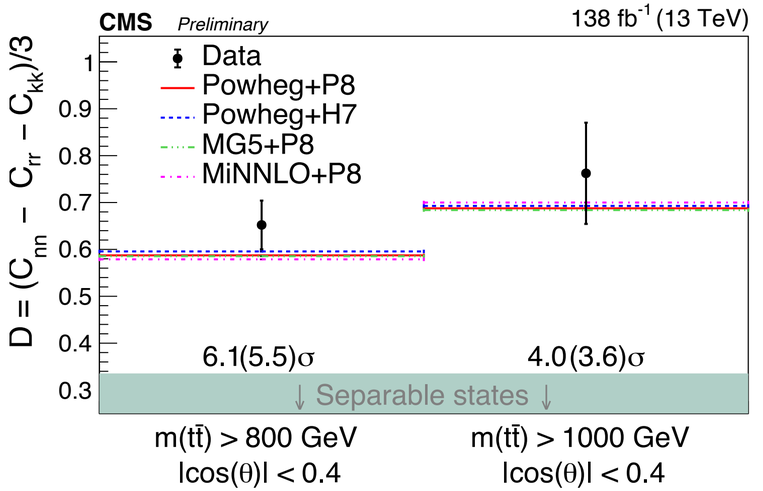
Taking it a step further

Measuring the correlation matrix in single-leptonic tt events

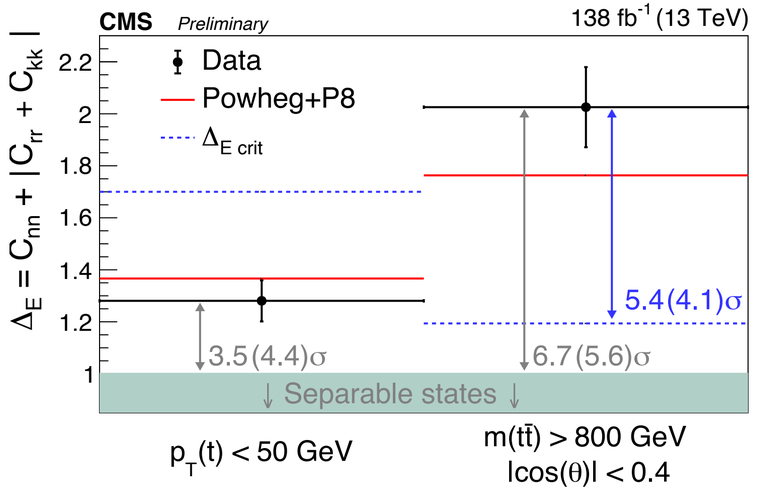
- All coefficients of polarization vectors and correlation matrix from fit to the angles of two decay products
  - Using NN to reconstruct the tt system in each event
- Δ_E from the full matrix, or from two proxies D, and $\tilde{D}$ for high masses

Separation from entanglement limit reaches 6.7σ obs (5.6σ exp)

- from full matrix and at high values of m_{tt}



using $\tilde{D}$



using D / full matrix

Higher m_{tt} reach - why is it relevant?

- **Want to exceed maximum entanglement achievable by classical exchange of information**
  - Fraction of events with space-like separation increases with m_{tt}: >90% for m_{tt}>800GeV
  - Taken into account in "critical entanglement" criterion

CMS-PAS-TOP-23-007

New @ LHCP24

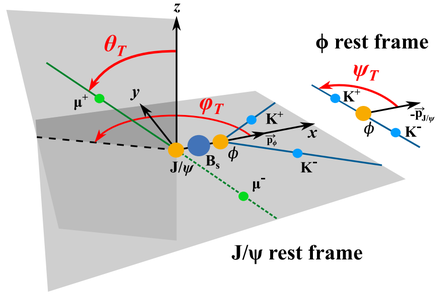
CP Violation - $B_S \rightarrow J/\psi\,\phi$ time-dependent asymmetry

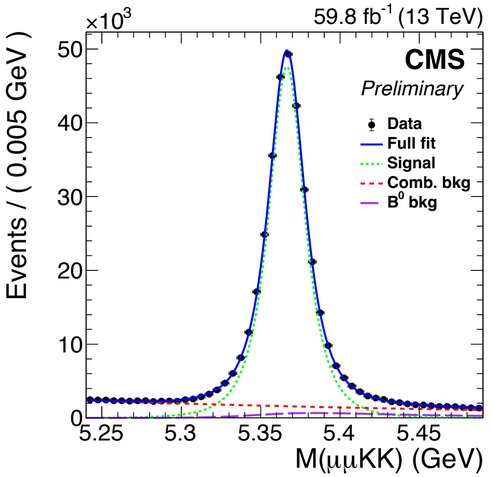
Measurement of CPV in the interference between mixing and decay of B_S->J/ψ KK

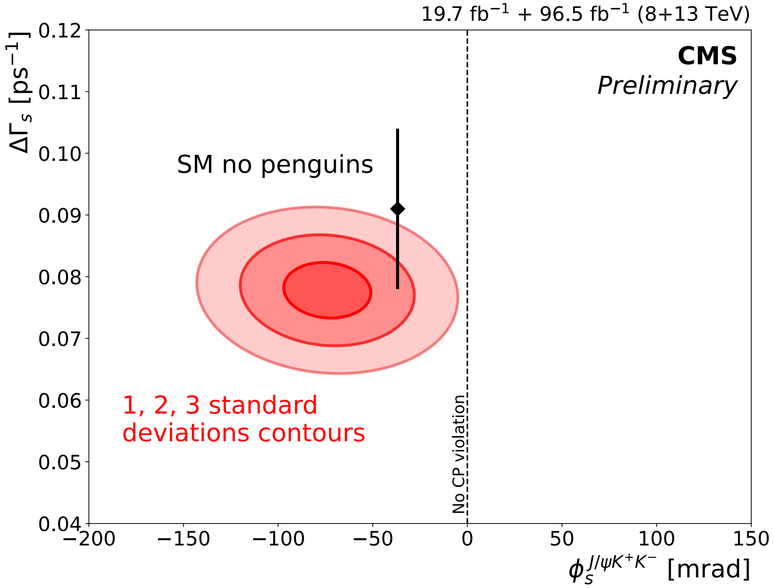
- Decisive improvement: inclusive flavor taggers using state-of-the-art ML techniques, reaching best performance at hadron colliders. Tagging uses
  - Opposite-sign muon and electron taggers
  - Charge-asymmetries in opposite-side b jet
  - Charged tracks around the same-side candidate

- Five parameters of interest extracted from fit to several observables including the weak phase, $\Delta\Gamma_S$, and Δm_S

First evidence of CP violation in this decay mode





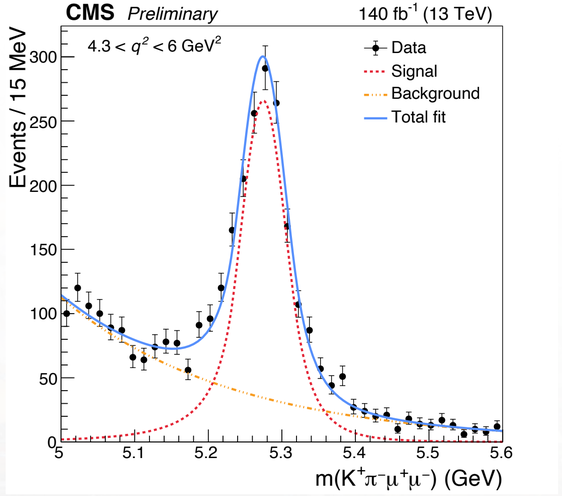


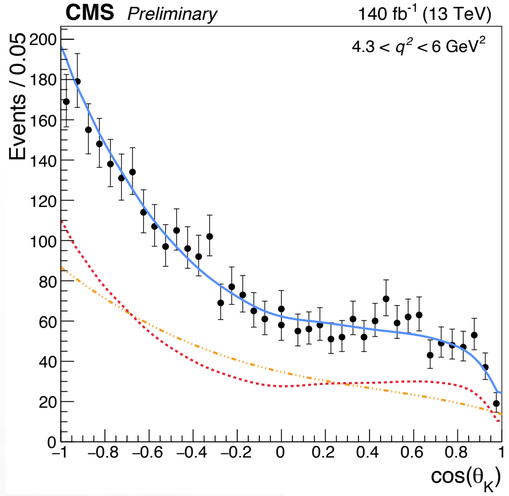
CMS-PAS-BPH-23-004

Angular analysis of decay $B^0 \to K^{*0}\mu\mu$

Measurement of the complete set of CP averaged variables

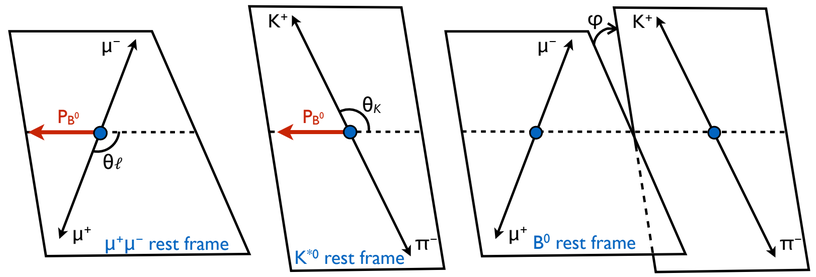
- Long history of searches for hints of NP in this process
  - Limited impact of theoretical uncertainties in angular distributions
- Background rejection optimized with a BDT
- Angular parameters extracted from fit to m_B and 3 angles as f(q^2): F_L, P_1, P_2, P_3, P'_4, P'_5, P'_6, P'_8

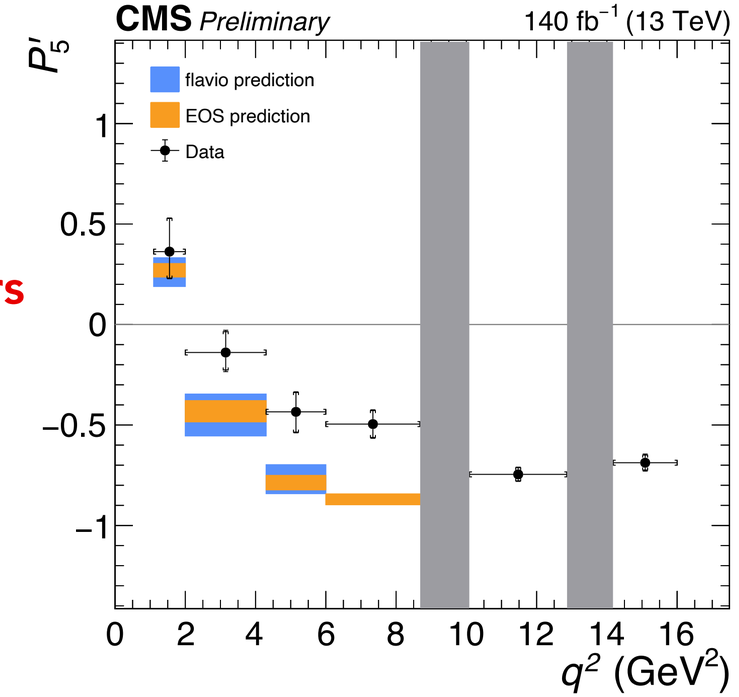




Examples of post-fit mass and cos(ϑ_K) distributions

Results among the most precise measurements of these parameters

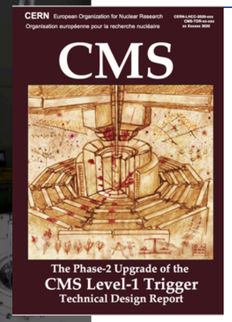




CMS-PAS-BPH-21-002

New @ LHCP24

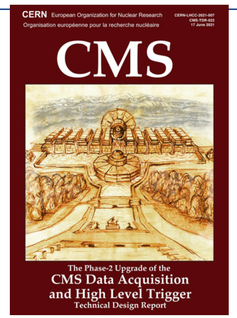
The CMS Phase 2 Upgrade



L1-Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

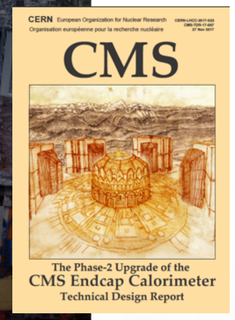
https://cds.cern.ch/record/2759072

- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters

https://cds.cern.ch/record/2283187

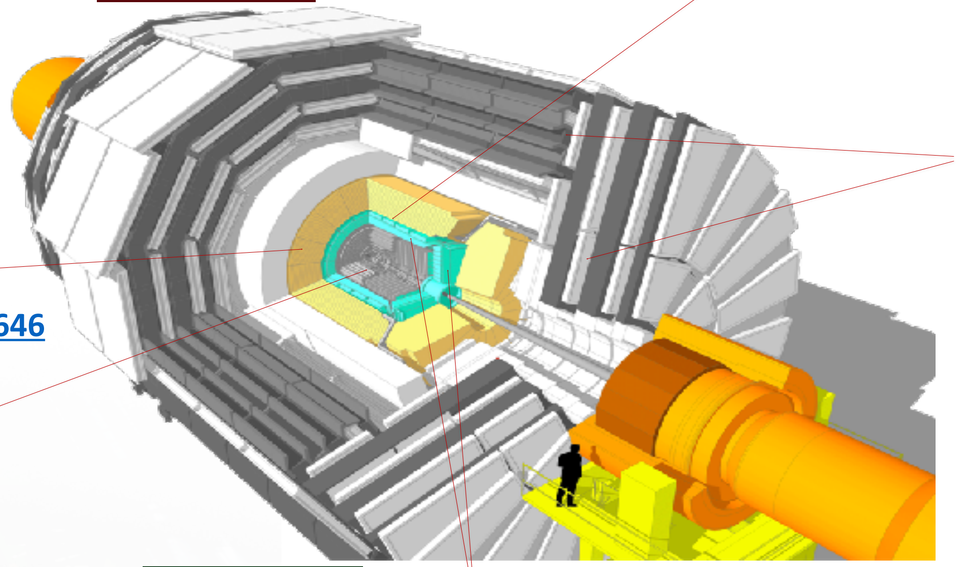
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Calorimeter Endcap

https://cds.cern.ch/record/2293646

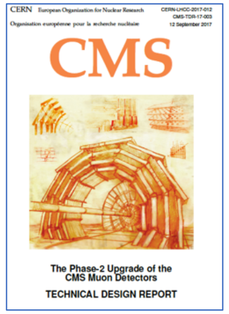
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

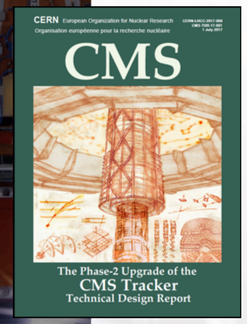


Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

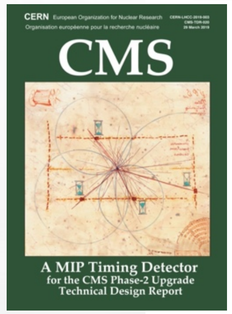




Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



MIP Timing Detector

https://cds.cern.ch/record/2667167

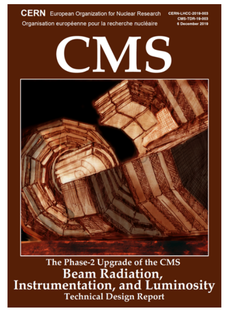
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer:
  Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity

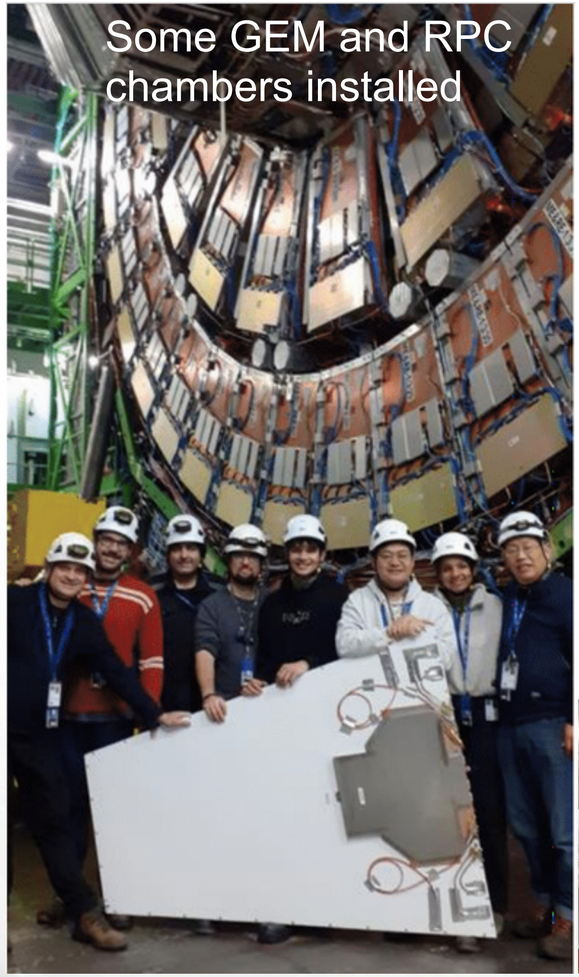
http://cds.cern.ch/record/2759074

- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity:
  1% offline, 2% online
- Neutron and mixed-field radiation monitors

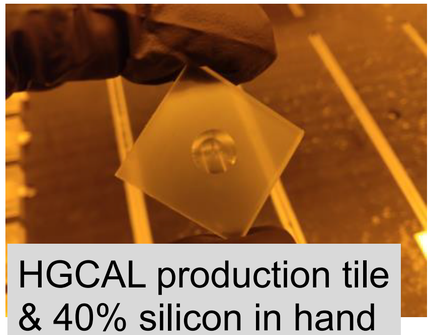


Upgrade: some selected details

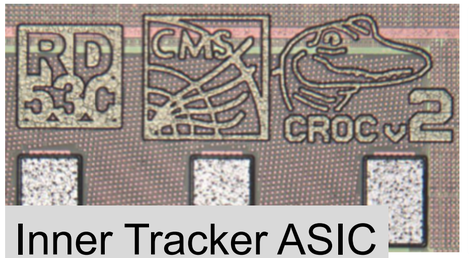
Transitioning into production & preparing for assembly and integration



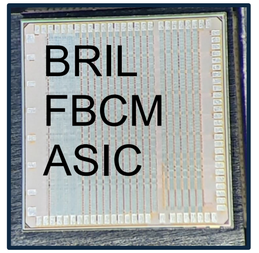
HGCAL cold rooms



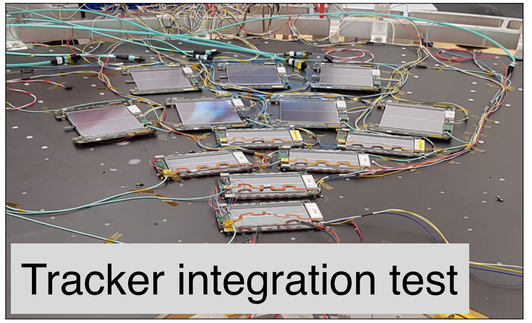
HGCAL production tile
& 40% silicon in hand



Inner Tracker ASIC

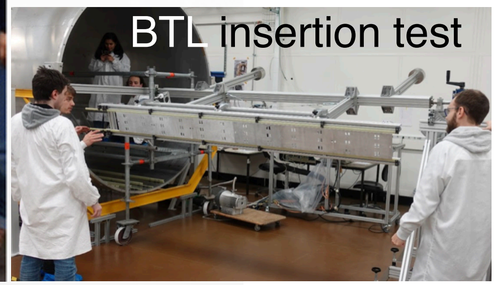


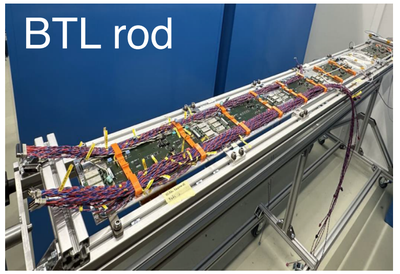
BTL-Tracker
Support Tube



Tracker integration test

Barrel Calo insertion tool “enfourneur”



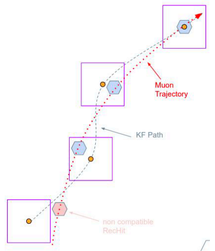


Recent highlights

DAQ & High-Level Trigger

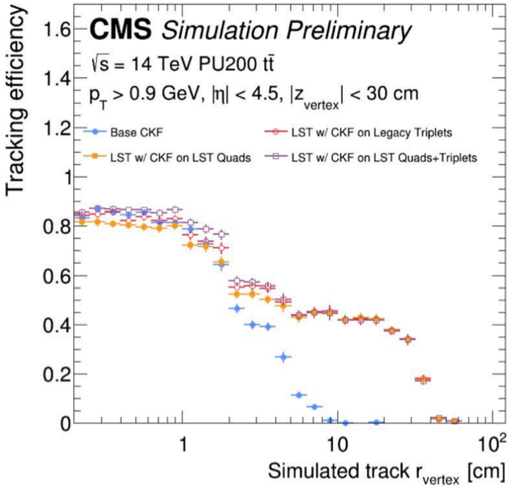
New in HGCAL

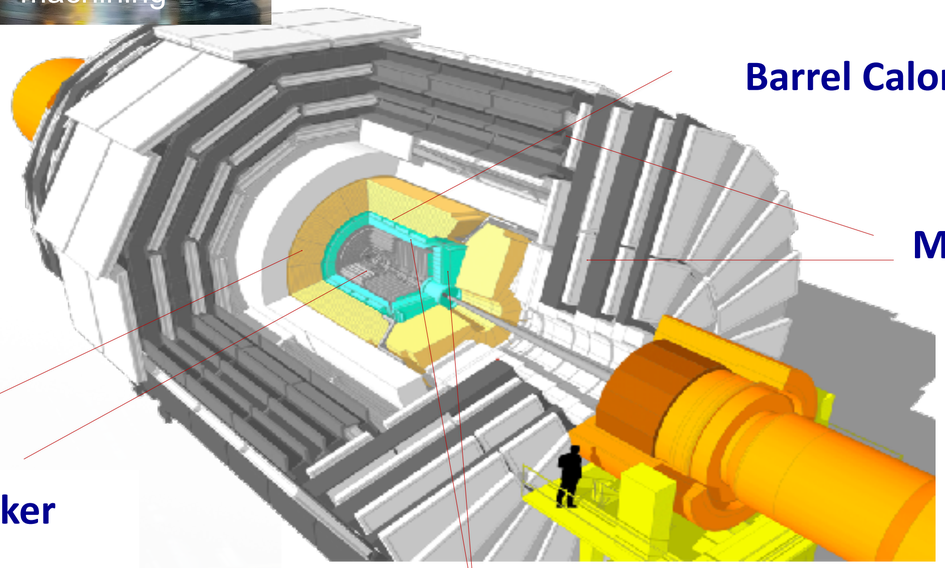
- Kalman filter for muons
- Considerable progress on mechanics
- SiPM, scintillator production started, more than 40% of the sensors received



Great progress in HLT:

- Line segment tracking





Muons systems:

- RPC and GEM chamber production ongoing

Tracker:

- about to start Outer Tracker module production
- Inner Tracker ASIC final and in production

MTD

- Barrel: about to start module production
- Endcap: sensor procurement review in July, ASICs – full functionality proven

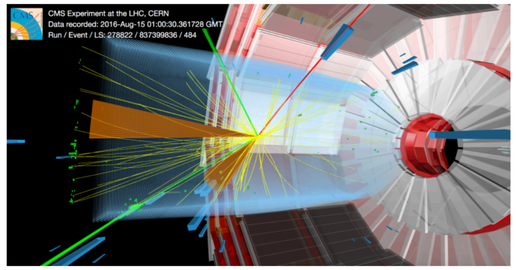
Open science with CMS

Increasing demand for transparency and access to data by policy makers and society

Continuing the CMS tradition of opening access to its data

The first large data set recorded at 13 TeV made available in April ’24

- Almost 5 PB of 2016 data
- Provided in CMS’s NanoAOD format for data and simulation
- Accessible via CERN’s Open data portal



The CMS experiment at CERN is proud to announce the first release of 13 TeV proton-proton collision data collected in 2016. Over 70 TB of 13 TeV collision data and 830 TB of corresponding simulations are now accessible to the global scientific community and enthusiasts alike through the CERN Open Data Portal.

For the first time, the scientific community has access to substantial datasets of 13 TeV collisions. This release augments the 2015 data and simulation that were made public in 2021. Over 20,000 simulations of different physics processes have been released alongside the collision data, as well as new software containers and a new virtual machine for analysis.

Reinterpretation of CMS results

The CMS Statistical Analysis and Combination Tool: COMBINE

CMS Collaboration · Aram Hayrapetyan (Yerevan Phys. Inst.) Show All(2390)
Apr 9, 2024

69 pages
e-Print: 2404.06614 [physics.data-an]
Report number: CMS-CAT-23-001, CERN-EP-2024-078
Experiments: CERN-LHC-CMS
View in: CERN Document Server, OSTI Information Bridge Server, HAL Science Ouverte, ADS Abstract Service

CMS-CAT-23-001
arXiv:2404.06614

CMS published its statistical toolbox “combine”

- Ready to be used outside the CMS environment
- The tool is also used to provide full likelihood functions in order to enable easier reinterpretations
- On this occasion, the likelihood function corresponding to the observation of the Higgs boson was released

Summary

Run 3 operations

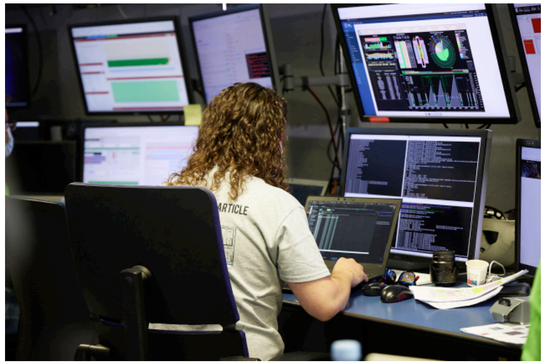
- Stable and efficient data taking in 2024
- High quality of promptly reconstructed objects
  - in some areas matching or exceeding Run 2 legacy performance
- Trigger, data taking and reconstruction strategies open new possibilities for analysis
  - Prompt and parked data, scouting at HLT, and now also at L1

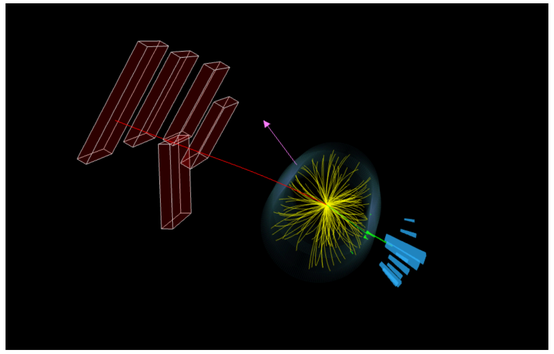
Physics analysis

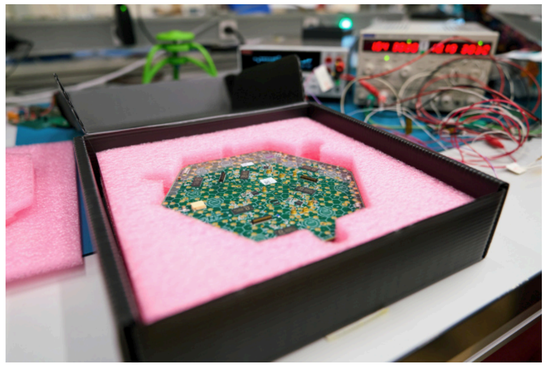
- Many new results presented: winter conferences and now @ LHCP
- Entering the era of precision measurements
  - Several results on EWK physics now competitive with those from e^+e^-
  - Investigating subtle effects as in tt spin correlations, and exploiting the large statistics for heavy flavor production

Upgrades

- Continuous progress on many fronts
  - Preparatory work already taking place in Run 3 EoY technical stops
- Detector projects transitioning into production mode







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Upgrades

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And much more in the dedicated plenary and parallel talks !

Additional slides

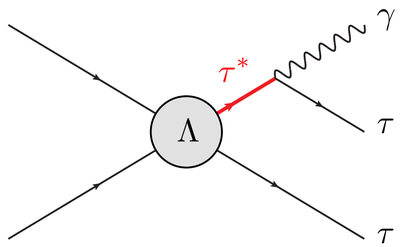
New CMS results at LHCP 2024

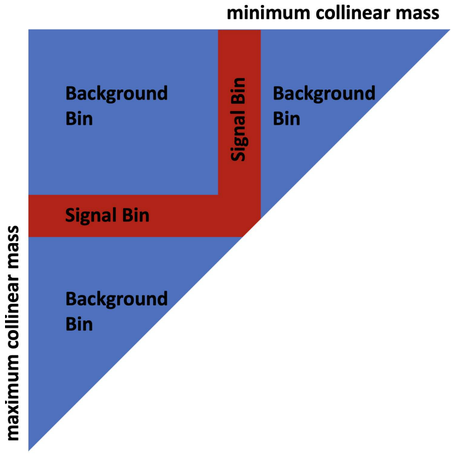
	Title
B2G-23-004	Search for diresonant new physics in a final state comprising a gluon and two hadronically decaying W bosons
BPH-21-002	Angular analysis of the B0 to K*0 mu mu decay
EXO-22-007	Search for excited tau leptons in the tau-tau-gamma final state
EXO-21-015	Search for a neutral gauge boson with non-universal fermion couplings in VBF processes
EXO-21-016	Search for heavy new resonances decaying to tau lepton pairs
HIN-22-004	Two-particle azimuthal correlations in pomeron-Pb interactions using pPb collisions at 8.16 TeV
HIN-23-002	Multiparticle correlations of soft and hard probes in small systems
HIN-24-001	Multiplicity dependence of psi(2S)/J/psi in pPb at 8.16 TeV
HIN-24-002	Hyperon polarization along the beam direction in pPb collisions at 8.16 TeV
SMP-23-008	Event shape variables in minimum bias events
SUS-23-001	Search for Stealth/RPV stops in final states with many light-flavor jets and 0-2 leptons
TOP-23-007	Spin correlation and entanglement in top Measurements of polarization, spin correlations, and entanglement in top quark pairs using lepton+jets events

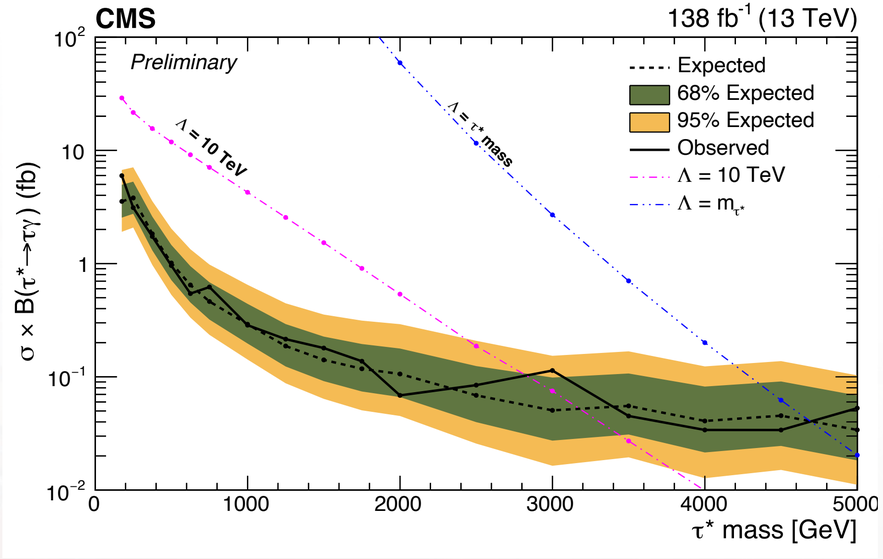
Search for excited tau leptons

Test of compositeness with tau leptons

- Search for pair production of a tau leptons, one of them excited with decay $\tau^* \rightarrow \tau\gamma$
  - Three channels (e+τ_h, μ+τ_h, τ_h+τ_h)
  - Assumption of neutrinos collinear with taus
- Signal regions take into account 2-fold ambiguity of photon association

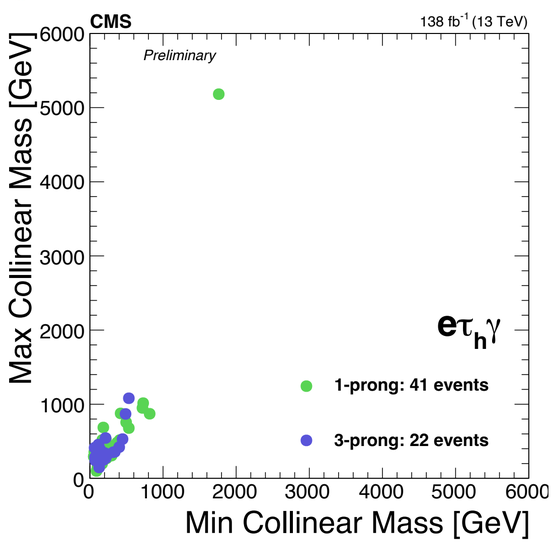






Mass limits: 4.7 TeV (2.8 TeV) for compositeness scales of m(τ^*) (10 TeV)

- For comparison, CMS limits using data from 2016 are 3.9 TeV and 3.8 TeV, respectively, for e* and μ^* and $\Lambda = m(\ell^*)$



CMS-PAS-EXO-22-007

New @ LHCP24