The first years of LHC operation at $\sqrt{s} = 13.6$ TeV in ATLAS and CMS

Guillelmo Gómez-Ceballos

Massachusetts Institute of Technology

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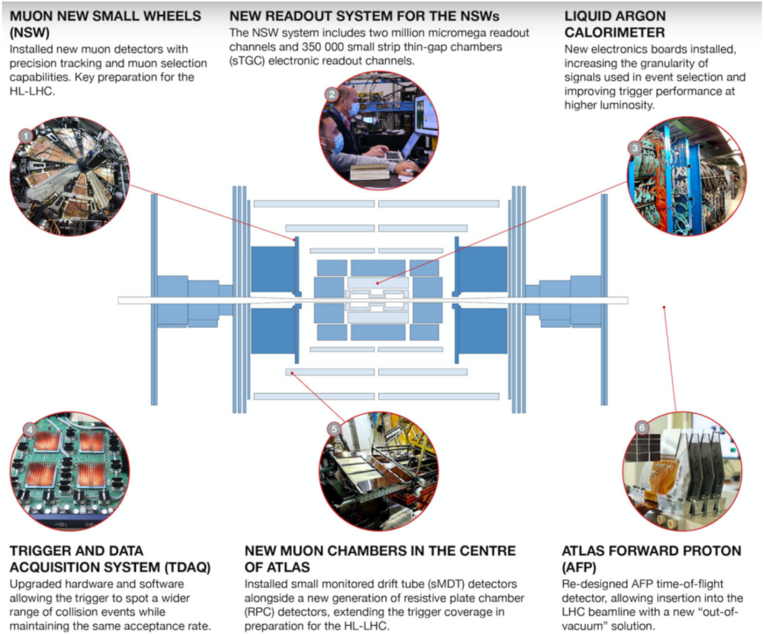
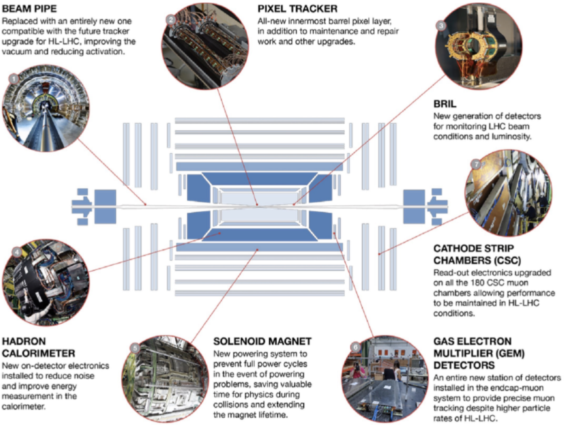
Introduction

- This talk is about the first years of LHC operation at $\sqrt{s} = 13.6$ TeV
  - complete focus on pp collisions from ATLAS and CMS experiments
  - a lot of interesting physics from LHCb, ALICE, and all other small experiments too!
  - no discussion on Heavy-Ion operations either, although happening right now!
- Physics analyses just ramping up
  - some "serious" competition with Run 2 analyses and Phase-II upgrades for now
  - Run 3 should be seen as a "marathon" race, not a sprint race
- Run 3 interesting on its own right because of the small increase in energy
- Most physics analyses interesting by accumulating larger and larger data samples
- In some sense, this is a "training" for the larger dataset and longer running time during Phase-II

New in ATLAS for Run 3



New in CMS for Run 3



During Long Shutdown 2 (2018-2022), CMS completed the Phase 1 upgrades and started the Phase 2 upgrades

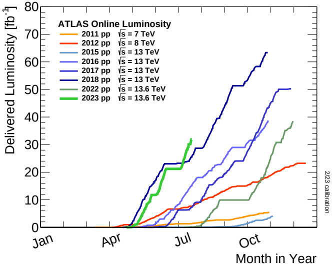
- **Phase 1**: HCAL barrel readout, new barrel inner pixel (layer 1), PPS fully integrated in CMS (CT-PPS)

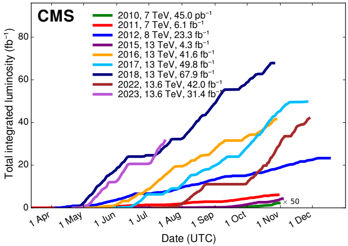
- **Phase 2**: First of GEM chambers installed, upgraded CSC electronics for HL-LHC, new beam pipe.

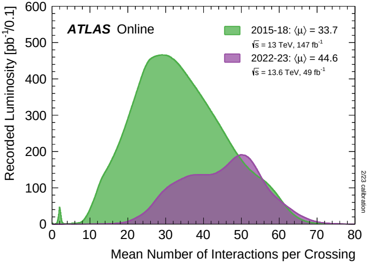
- **GPU at HLT** and transitioned to a hybrid **CPU + GPU** in trigger software (HLT nodes)

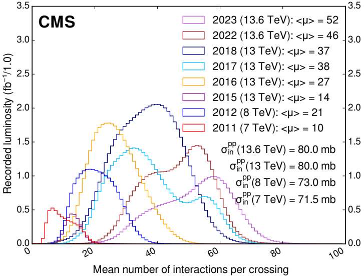
- Installed demonstrators for Phase 2 muon drift tube electronics and Beam Radiation, Instrumentation and Luminosity (BRIL)

Integrated Luminosity & Pileup



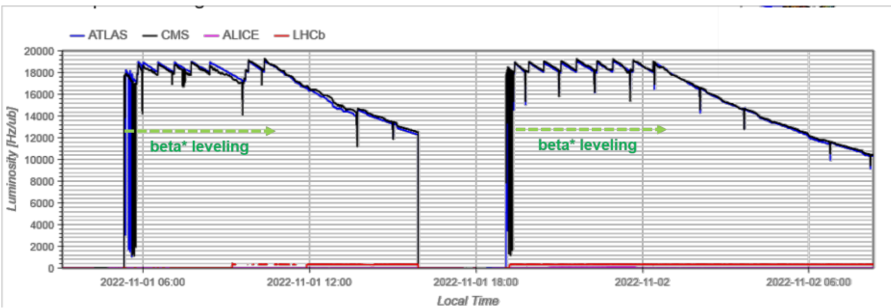






- Pileup makes our life very complicated
- But pileup is directly proportional to the instantaneous luminosity

Luminosity Leveling



- Allows for running at a $\sim$ constant instantaneous luminosity ($\equiv$ constant pileup)
- ATLAS and CMS running in 2023 at constant/peak pileup $\sim$ 60!

No Data Taking in Late July & August...

Root cause

From the TIOC.

- The quoted timestamp seems to be 50 seconds after the beam dump, but EN recording of first perturbation corresponds to dump time (multiple perturbations).

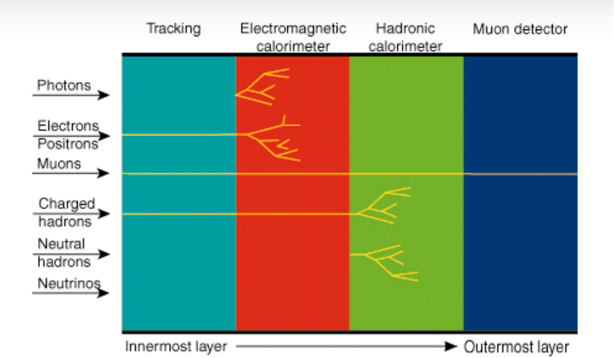
Power glitch cause LHC and AD beam dump 17.07.23

The cause of the events seen at CERN

- A tree fell on two lines 125 kV of Romande Energie which are on the same support towers:
  - Morges — Vaux-sur-Morges
  - Bussigny — Etoy — Vaux-sur-Morges
- The two lines are both connected to Vaux-sur-Morges 220/125 kV substation
- The recording from Romande Energie was at 01:01:08.607 (it is consistent with our last recording at 01:01:08.610) and there were several attempts to re-energize the lines (fast reclosures) before the final trip

- Power glitch → quench → leak in insulation vacuum system
- Found leak → repair → back to cooldown system
- Lost ∼ 5 weeks of pp data taking, going on with special runs and Heavy-Ion operations since early September

Detectors & Trigger Performance

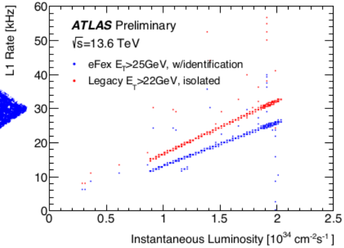


- Since full blown analyses and data taking steps are slightly decoupled...
- Critical to properly select (signal) events at the trigger level
  - Trigger: Level-1 (L1) hardware & High-Level Trigger (HLT) software
- Make sure (sub)detectors are performing well to select different particles/objects
  - muons, electrons, taus, jets, b-jets, $p_{\mathrm{T}}^{\mathrm{miss}}$...

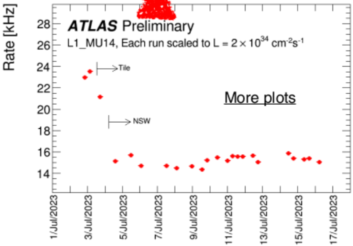
ATLAS Run 3 Triggers

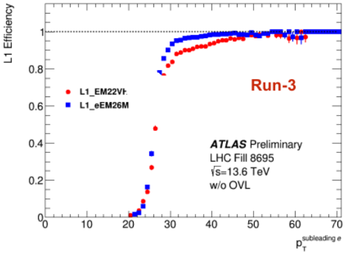
Run3 triggers, reduce rates and increase efficiencies

Level 1Calo single electron rates are decreased and trigger efficiencies increased



NSW and Tile calorimeter coincidences decrease significantly the muon rate

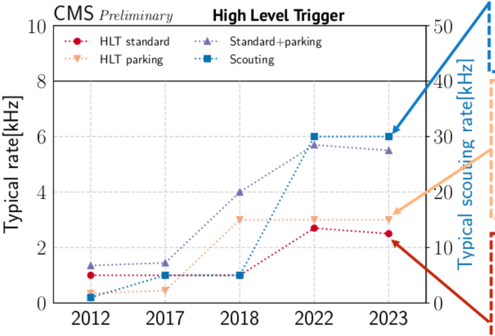




CMS Run 3 Triggers

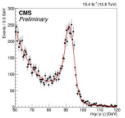
L1 Trigger:

Enhanced menus for higher PU than Run 3 nominal (50)
Extended trigger capabilities for specific physics topics: Bs→μμ τ→3μ, HH→4b, W→ 3π, VBF, long-lived particles (with HCAL timing)



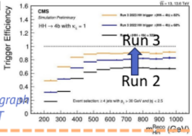
Scouting: profits from speed up in HLT reconstruction acceleration via GPU (i.e pixel tracks and vertices, particle flow candidates, jet/MET, muons, electrons, and **photons**)

M(μμγ) invariant mass, in events with a photon pt > 10 GeV



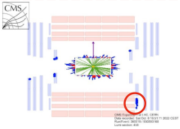
Parking: more b-parking (added electron triggers) & signatures such as VBF/S, **HH→4b**, long lived signatures

HH→4b: New b-tagger based on graph net (ParticleNet) integrated at HLT

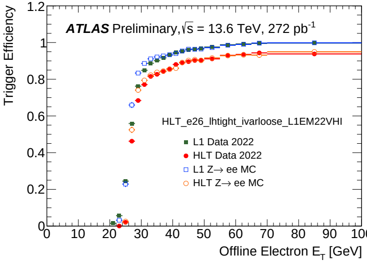


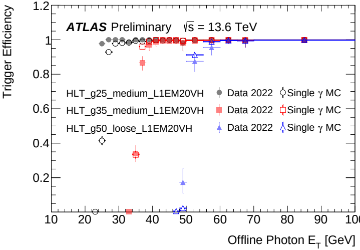
Core-program with more complex algorithms (thanks to additional GPU), + additional triggers for long-lived and other exotic signatures

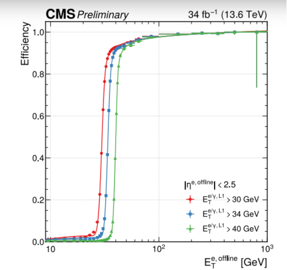
Delayed signals creating particle shower in muon chambers

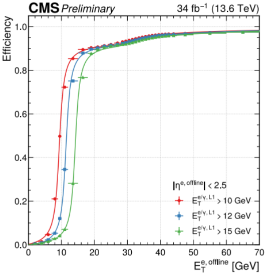


Electron/Photon Trigger Performance



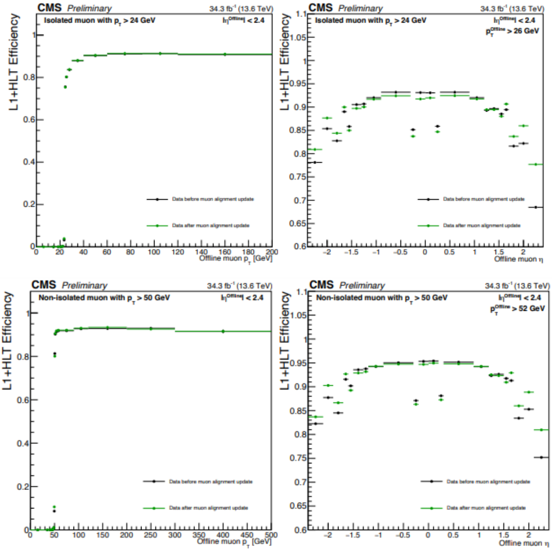






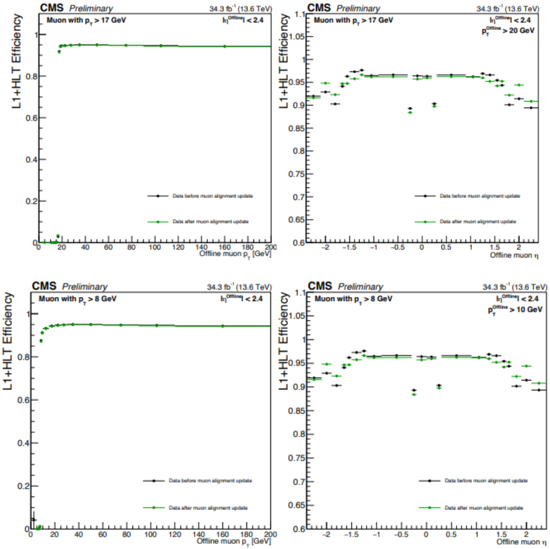
- Sharp trigger turn-on efficiencies
- Shaper behavior → better signal efficiency and background reduction

Single Muon Trigger Performance



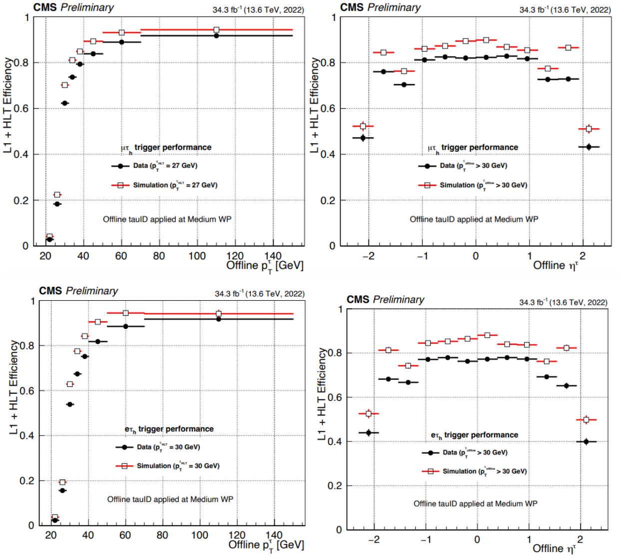
- Slower turn-on on IsoMu24 w.r.t. Mu50 due to isolation requirements
- Small differences after improving muon alignment

Double Muon Trigger Performance



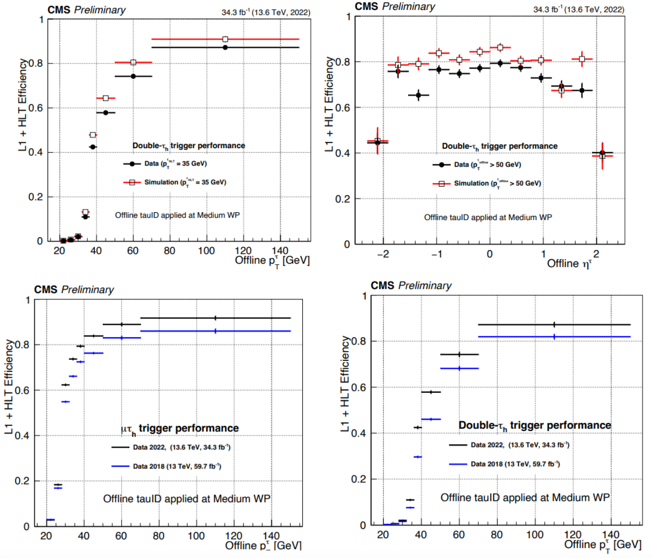
- Standard double muon trigger: HLT_Mu17_Mu8
- Efficiency about 95% per muon leg

Tau Trigger Performance (I)



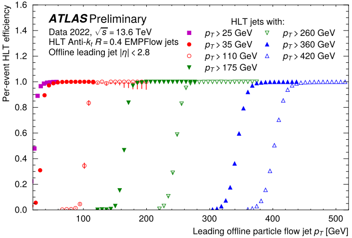
- $\sim$70–80% $\ell\tau_h$ trigger efficiencies

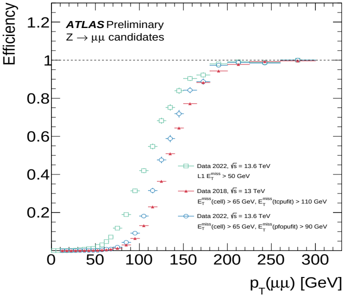
Tau Trigger Performance (II)

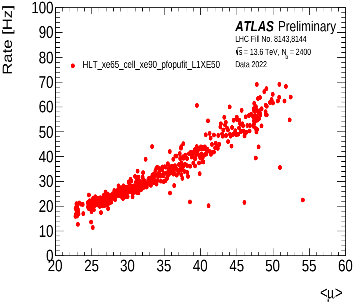


- Better trigger efficiency in Run 3

Jet & $p_{\mathrm{T}}^{\mathrm{miss}}$ Trigger Performance



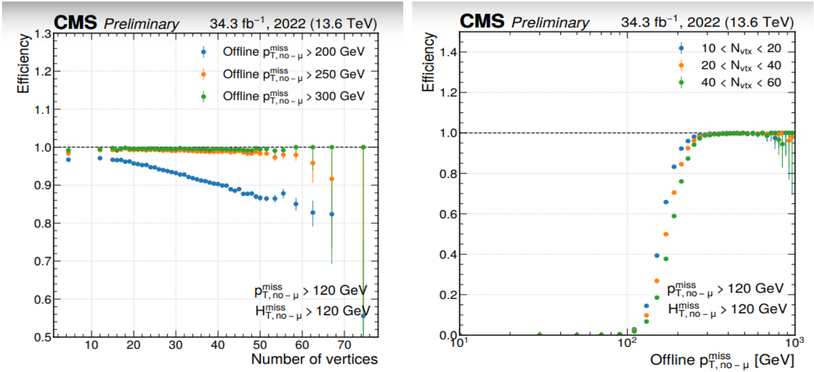




- $p_{\mathrm{T}}^{\mathrm{miss}}$ trigger rates increase with pileup, major data-taking concern

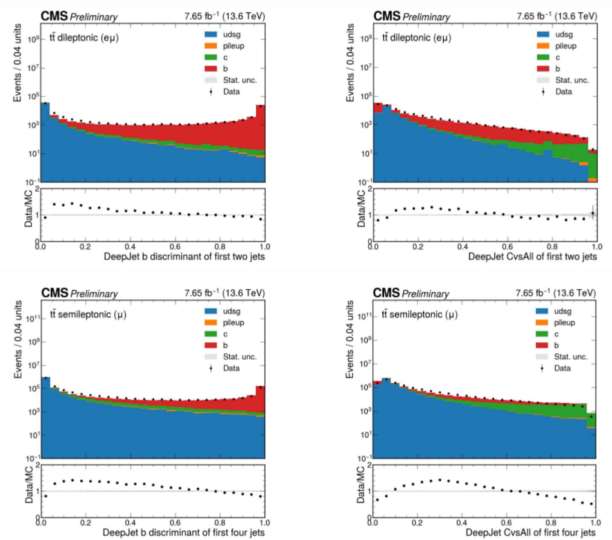
p_T^{miss} Trigger Performance as a function of Pileup

Pileup $\propto$ number of primary vertices



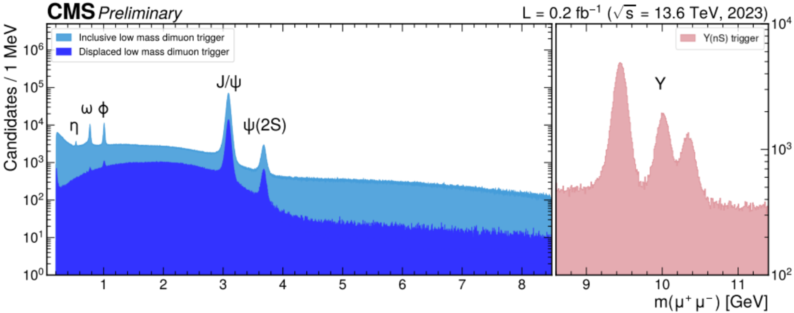
- If the required offline p_T^{miss} range extends to lower values, there is a significant drop in efficiency with increased pileup
- With larger number of primary vertices, the turn-on of the trigger gets slower

b- & c-Tagging Performance



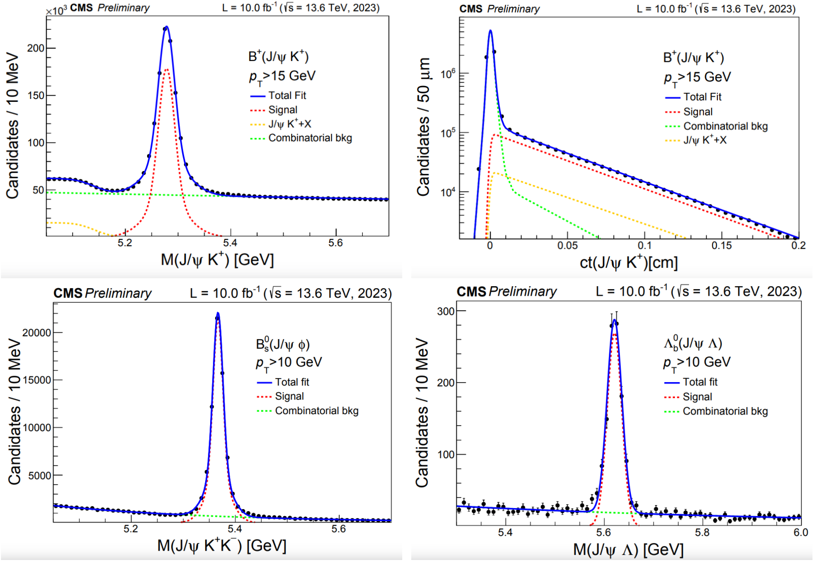
- Decent agreement between data and (uncorrected) simulation in $t\bar{t}$ events
- Tougher c-tagging w.r.t. b-tagging, but important for several analyses

Low-Mass Dimuon Distributions (CMS)



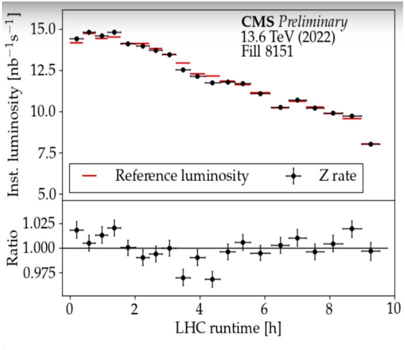
- Inclusive low-mass dimuon trigger: two opposite-charge muons, vertex-fit probability $P > 0.5\%$, dimuon mass in the range [0.2, 8.5] GeV, and $p_{\mathrm{T}}^{\mu_1,\mu_2} > 4/3$ GeV
- Displaced low-mass dimuon trigger: two opposite-charge muons, a vertex-fit probability $P > 10\%$, dimuon mass in the range [0.2, 8.5] GeV, $p_{\mathrm{T}}^{\mu_1,\mu_2} > 4$ GeV, and $L_{xy}/\sigma_{L_{xy}} > 3$
- Upsilon trigger: two opposite-charge muons, a vertex-fit probability $P > 0.5\%$, dimuon mass in the range [8.5, 11.5] GeV, $p_{\mathrm{T}}^{\mu\mu} > 10$ GeV, and $|y^{\mu\mu}| < 1.4$

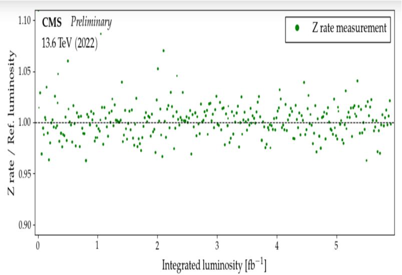
B Hadrons Distributions (CMS)



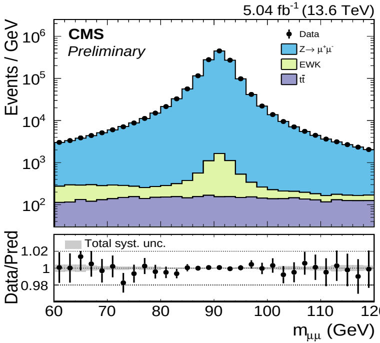
Selected samples using Inclusive (upper) and displaced (lower) low-mass dimuon triggers

First Measurements





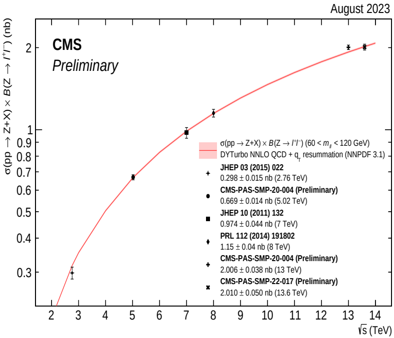
- $\mathrm{Z} \to \mu\mu$ production very clean process
- Possible to measure (monitor) the integrated luminosity by counting the number of $\mathrm{Z} \to \mu\mu$ events in data as a function of time
  - Theoretical $\mathrm{Z} \to \mu\mu$ cross section has a 2-3% uncertainty, but it just gives an overall off-set



Process	Pre–fit yield	Post–fit yield
Z	3 060 990	2 984 730 ± 27 520
$t\bar{t}$	9 350	8 390 ± 810
EWK	14 650	14 090 ± 1 400
Data	3 006 429	

- Select a sample of events compatible with $Z \to \mu\mu$ production
  - Two and only two opposite-sign isolated muons with $p_T > 25$ GeV and $|\eta| < 2.4$
  - $60 < m_{\ell\ell} < 120$ GeV
- Background level $< 1\%$
- Performing fiducial and inclusive cross section measurements

Z Boson Cross Section Measurements (II)



Source	Uncertainty (%)
Muon efficiencies	0.83
PDF, QCD scale and parton shower	0.53
Finite size of MC samples (bin-by-bin)	0.35
$t\bar{t}$ background	0.16
EWK background	0.12
Pileup	0.08
Muon momentum correction	0.08
Combined syst. uncertainty	0.92
Luminosity	2.3
Stat. uncertainty	0.06

- New $\sigma_Z \times BR(Z \to \ell\ell)$ measurements at 5, 13, and 13.6 TeV
- 13.6 TeV results:

$$(\sigma_{\text{fid}}\mathcal{B})_{\text{measured}} = 0.756 \pm 0.007(\text{stat} + \text{syst}) \pm 0.017(\text{lumi})\text{nb}$$

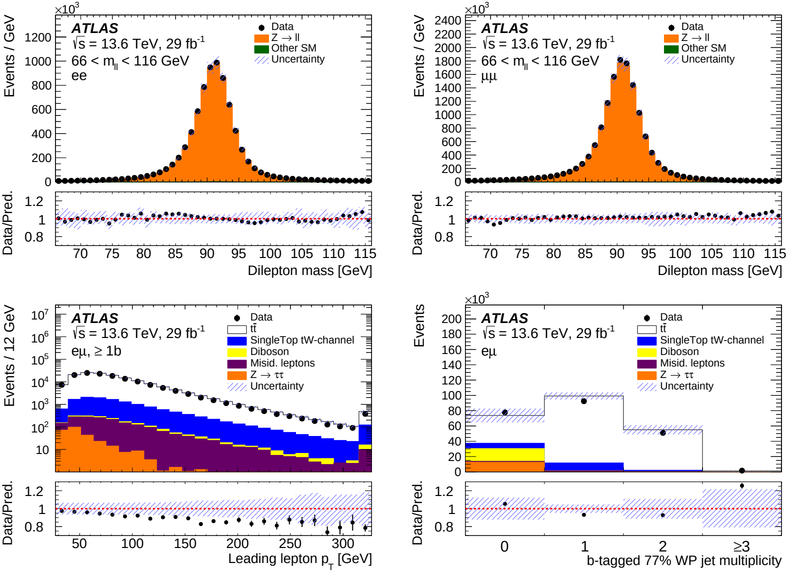
$$(\sigma_{\text{fid}}\mathcal{B})_{\text{predicted}} = 0.7531 \pm 0.0065(\text{PDF})^{+0.0021}_{-0.0045}(\text{scale})\text{nb}$$

$$(\sigma_{\text{tot}}\mathcal{B})_{\text{measured}} = 2.028 \pm 0.017(\text{stat} + \text{syst}) \pm 0.047(\text{lumi})\text{nb}$$

$$(\sigma_{\text{tot}}\mathcal{B})_{\text{predicted}} = 2.020 \pm 0.012(\text{PDF})^{+0.018}_{-0.023}(\text{scale})\text{nb}$$

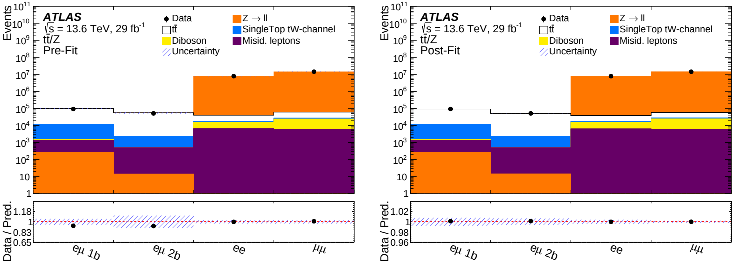
- Uncertainties dominated by integrated luminosity and muon efficiencies

$\sigma_{t\bar{t}}$, σ_Z & $\sigma_{t\bar{t}}/\sigma_Z$ (ATLAS, Arxiv:2308.09529)



- Select a clean sample of $Z \to ee/\mu\mu$ events
- Select a clean sample of $t\bar{t} \to e\mu + X$ events ($e\mu + \geq 1$ b-tagged jet)

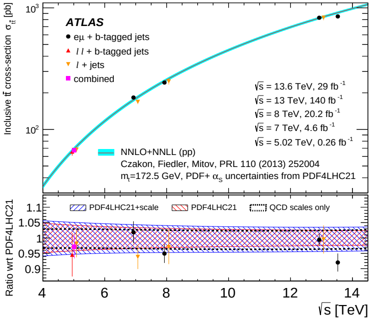
$\sigma_{t\bar{t}}$, σ_Z & $\sigma_{t\bar{t}}/\sigma_Z$ (II)

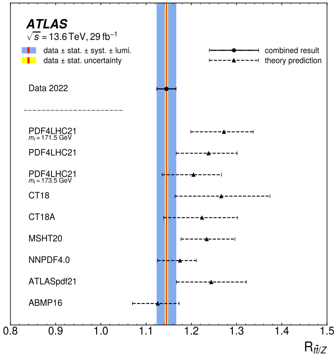


Category		Uncertainty [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{\text{fid.}}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	0.9	< 0.2	0.9
	$t\bar{t}$ scale variations	0.4	< 0.2	0.4
	$t\bar{t}$ normalisation	-	< 0.2	-
	Top quark p_T reweighting	0.6	< 0.2	0.6
Z	Z scale variations	< 0.2	0.4	0.3
Bkg.	Single top modelling	0.6	< 0.2	0.6
	Diboson modelling	< 0.2	< 0.2	0.2
	$t\bar{t}V$ modelling	< 0.2	< 0.2	< 0.2
	Fake and non-prompt leptons	0.6	< 0.2	0.6
Lept.	Electron reconstruction	1.2	1.0	0.4
	Muon reconstruction	1.4	1.4	0.3
	Lepton trigger	0.4	0.4	0.4
Jets/tagging	Jet reconstruction	0.4	-	0.4
	Flavour tagging	0.4	-	0.3
	PDFs	0.5	< 0.2	0.5
	Pileup	0.7	0.8	< 0.2
	Luminosity	2.3	2.2	0.3
	Systematic uncertainty	3.2	2.8	1.8
	Statistical uncertainty	0.3	0.02	0.3
	Total uncertainty	3.2	2.8	1.9

- Simultaneous fit of the three channels
- $e\mu$ channel split into events with one or two b-tagged jets

$\sigma_{t\bar{t}}$, σ_{Z} & $\sigma_{t\bar{t}}/\sigma_{Z}$ (III)

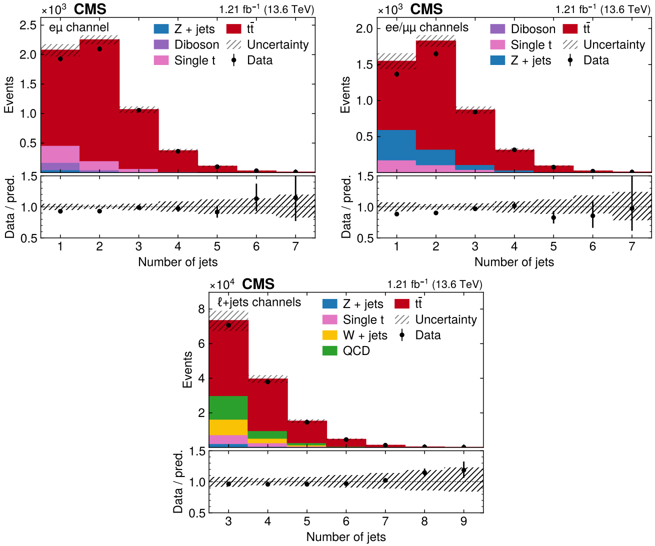




Cross section measurements at $\sqrt{s} = 13.6$ TeV:

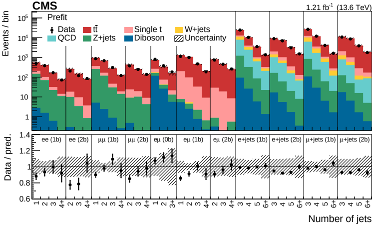
- $\sigma_{t\bar{t}} = 850 \pm 3\ (stat.) \pm 18\ (syst.) \pm 20\ (lum.)$ pb
- $\sigma_{fid, Z\to\ell\ell} = 744 \pm 11\ (stat + syst.) \pm 16\ (lum.)$ pb
- $\sigma_{t\bar{t}}/\sigma_{Z} = 1.145 \pm 0.003\ (stat.) \pm 0.021\ (syst.) \pm 0.002\ (lumi.)$

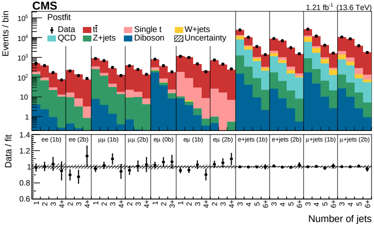
$t\bar{t}$ Cross Section Measurement (CMS, Arxiv:2303.10680)



- Select dilepton $t\bar{t} \to ee/\mu\mu + X$ events ($ee/\mu\mu$ + $\geq$ 1 q jet + $\geq$ 1 b-tagged jet)
- Select dilepton $t\bar{t} \to e\mu + X$ events ($e\mu$ + $\geq$ 1 q jet + $\geq$ 0 b-tagged jet)
- Select single-lepton $t\bar{t} \to \ell + X$ events (ℓ + $\geq$ 3 q jet + $\geq$ 1 b-tagged jet)

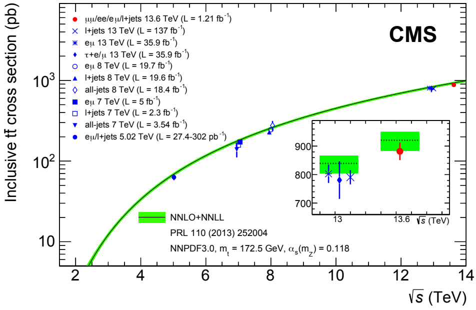
$t\bar{t}$ Cross Section Measurement (II)





- Comparison of data and prediction in the final analysis binning
- Split in lepton-flavor, number of jets, and number of b jets
- b-tagging, jet energy scale, and lepton efficiency uncertainties largely reduced, by taking into account correlations among different channels
    - note the uncertainty reduction from the pre-fit to the post-fit

$t\bar{t}$ Cross Section Measurement (III)



- $\sigma_{t\bar{t}}\ (obs.) =$ $882 \pm 23\ (stat. + syst.) \pm 20\ (lum.)$ pb
- $\sigma_{t\bar{t}}\ (exp.) = 921^{+29}_{-37}$ pb

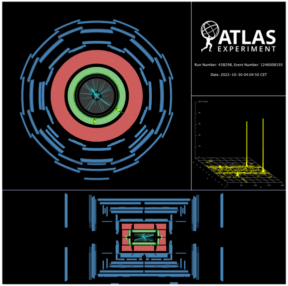
Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.7
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.6
ME scale, backgrounds	0.1
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Single t background	1.0
Z+jets background	0.3
W+jets background	0.0
Diboson background	0.5
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.6
Integrated luminosity	2.3

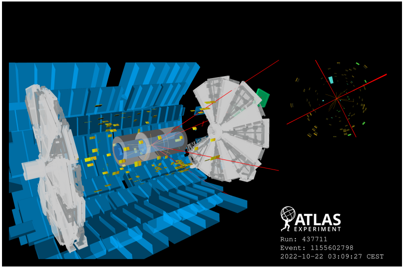
$\mathrm{H} \to \gamma\gamma$ & $\mathrm{H} \to ZZ \to 4\ell$ (ATLAS, Arxiv:2306.11379)

Photons	
Leading (sub-leading) p_{T}^{γ}	$p_{\mathrm{T}}^{\gamma}/m_{\gamma\gamma} > 0.35(0.25)$
Pseudorapidity	$\lvert\eta\rvert < 2.47$ and outside $1.37 < \lvert\eta\rvert < 1.52$
Isolation	$E_{\mathrm{T}}^{\mathrm{iso}}/E_{\mathrm{T}}^{\gamma} < 0.05$
Di-photon system	
Mass window	$105\ \mathrm{GeV} < m_{\gamma\gamma} < 160\ \mathrm{GeV}$

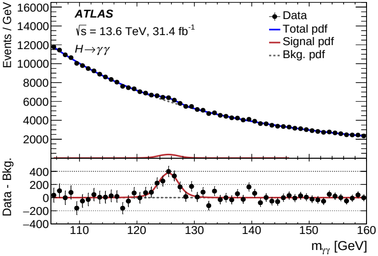
Leptons	
Muons	$p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.5$
Electrons	$E_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$
Lepton selection and pairing	
Lepton kinematics	$p_{\mathrm{T}} > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one Higgs boson candidate per channel)	
Mass requirements	$50\ \mathrm{GeV} < m_{12} < 106\ \mathrm{GeV}$ and $m_{\mathrm{threshold}} < m_{34} < 115\ \mathrm{GeV}$
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Impact parameter	$\lvert d_0\rvert/\sigma(d_0) < 5$ (3) for electrons (muons)
Mass window	$105\ \mathrm{GeV} < m_{4\ell} < 160\ \mathrm{GeV}$
Vertex selection	$\chi^2/N_{\mathrm{dof}} < 6$ (9) for 4μ (other channels)
If extra lepton with $p_{\mathrm{T}} > 12$ GeV	quadruplet with largest ME value

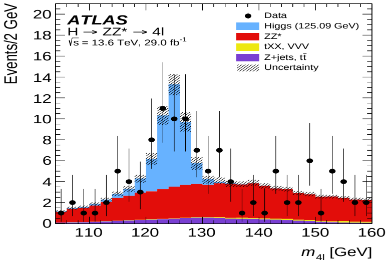
- Inclusive selection of $\mathrm{H} \to \gamma\gamma$ & $\mathrm{H} \to ZZ \to 4\ell$ events
- Fiducial and full inclusive cross section measurements





$H \to \gamma\gamma$ & $H \to ZZ \to 4\ell$ (II)





Breakdown of the relative uncertainties

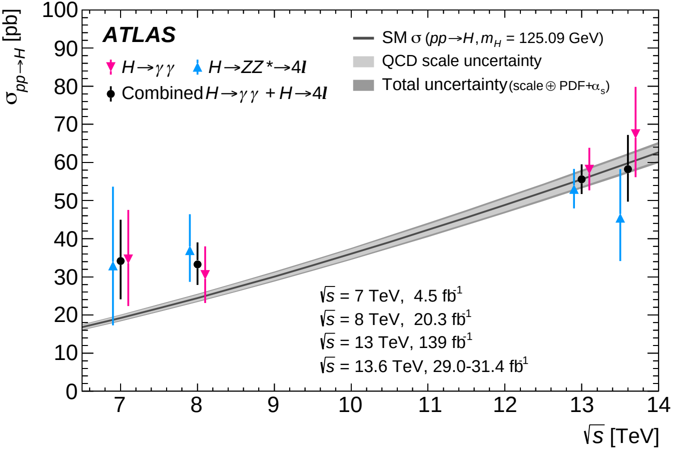
in fiducial cross-section measurements

Source	Uncertainty [%]
Statistical uncertainty	14.0
Systematic uncertainty	10.3
Background modelling (spurious signal)	6.0
Photon trigger and selection efficiency	5.8
Photon energy scale & resolution	5.5
Luminosity	2.2
Pile-up modelling	1.2
Higgs boson mass	0.1
Theoretical (signal) modelling	<0.1
Total	17.4

Source	Uncertainty [%]
Statistical uncertainty	25.1
Systematic uncertainty	7.9
Electron uncertainties	6.3
Muon uncertainties	3.8
Luminosity	2.2
ZZ^* theoretical uncertainties	0.7
Reducible background estimation	0.6
Other uncertainties	<1.0
Total	26.4

- Measurements largely statistically limited
- Systematic uncertainties will also decrease

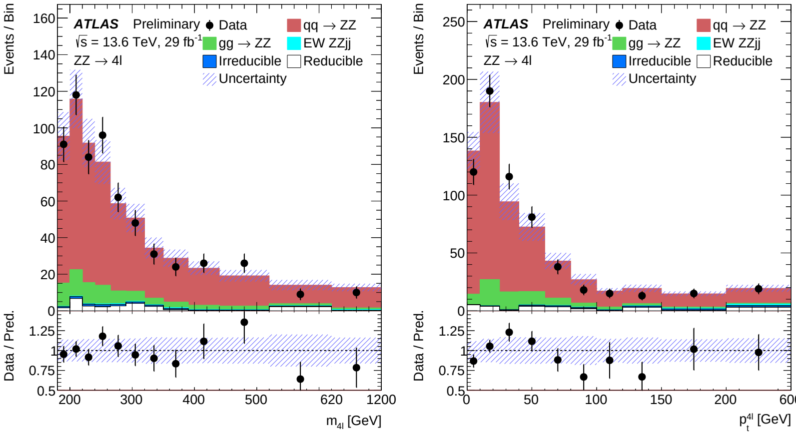
$\mathrm{H} \to \gamma\gamma$ & $\mathrm{H} \to ZZ \to 4\ell$ (III)



Cross section measurements at $\sqrt{s} = 13.6$ TeV:

- $\sigma_{fid,\gamma\gamma}$ (obs./exp.) $= 76^{+14}_{-13} / 67.6 \pm 3.7$ fb
- $\sigma_{fid,4\ell}$ (obs./exp.) $= 2.80 \pm 0.74 / 3.67 \pm 0.19$ fb
- $\sigma(\mathrm{pp} \to \mathrm{H})$ (obs./exp.) $= 58.2 \pm 8.7 / 59.9 \pm 2.6$ pb

$ZZ \to 4\ell$ Cross Section Measurements (ATLAS, ATLAS-CONF-2023-062)

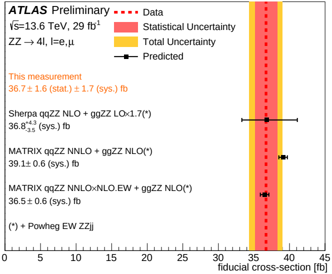


- Select 4-lepton events consistent with $ZZ \to 4\ell$ production
- $qq \to ZZ$, $gg \to ZZ$, and EWK $qq \to ZZjj$ considered as signal
- Total and fiducial cross section measurements

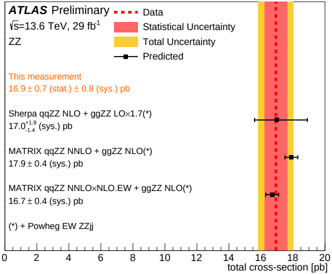
Process	$q\bar{q} \to ZZ$	$gg \to ZZ$	EW $qq \to ZZ + 2j$	$t\bar{t}Z$	VVV	Reducible	Total	Data
Yield	514.8 ± 49.6	73.6 ± 44.3	4.7 ± 1.0	5.5 ± 0.8	2.1 ± 0.2	25.4 ± 8.1	626.1 ± 88.4	625

$ZZ \to 4\ell$ Cross Section Measurements (II)

Fiducial phase space



Total phase space

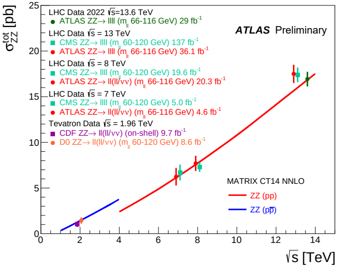


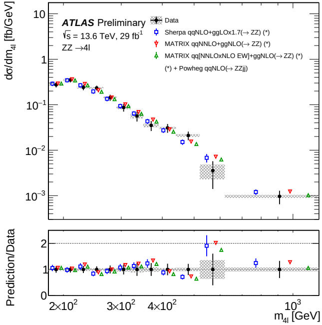
Source	Relative uncertainty(%)
Data statistical uncertainty	4.2
MC statistical uncertainty	0.3
Luminosity	2.2
Lepton momentum	0.2
Lepton efficiency	3.7
Background	1.6
Theoretical uncertainty	1.0
Total	6.3

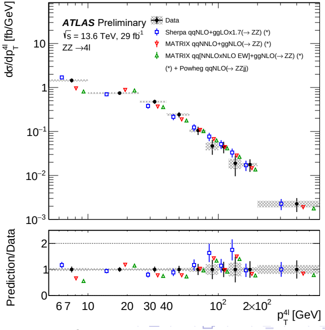
	Fiducial phase space	Total lepton phase space
Muon selection	Bare, $p_T > 5$ GeV, $\|\eta\| < 2.5$	Born
Electron selection	Dressed, $p_T > 7$ GeV, $\|\eta\| < 2.47$	Born
Four-lepton signature	≥ 2 SFOC pairs	≥ 2 SFOC pairs
Lepton kinematics	$p_T > 27/10$ GeV	
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.05$	
Low-mass $\ell^+\ell^-$ veto	$m_{ij} > 5$ GeV	$m_{ij} > 5$ GeV
Z mass window	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV
ZZ on-shell	$m_{4l} > 180\ GeV$	

- Dominant uncertainties from data event sample and lepton efficiencies

$ZZ \to 4\ell$ Cross Section Measurements (III)

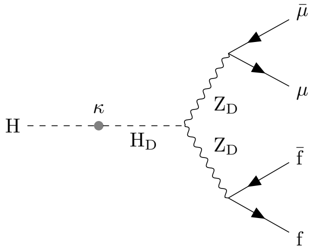


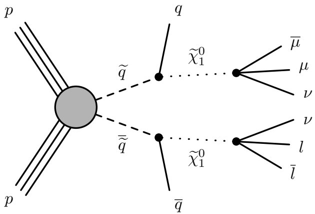




- First differential cross section measurements

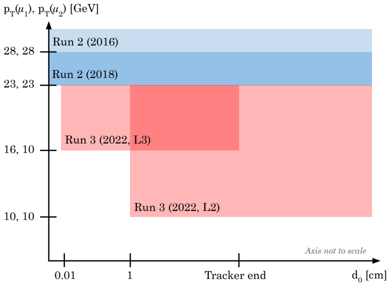
- Inclusive search for an exotic massive LLP decaying to a pair of oppositely charged muons, displaced with respect to the primary vertex (PV)
- Select muons both from tracker and muon systems (TMS) and from standalone muons only (STA)
- Results of the search interpreted in the framework of two benchmark models
  - hidden Abelian Higgs model (HAHM), in which displaced dimuons arise from decays of hypothetical dark photons
  - simplified SUSY model, in which long-lived neutralinos decay to a pair of muons and a neutrino as a result of R-parity violation (RPV)

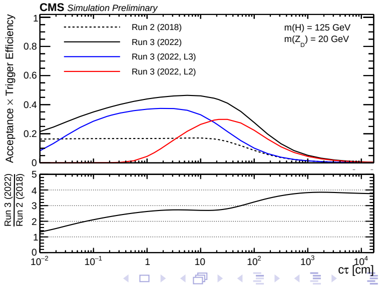




Search for LLPs Decaying to Muon Pairs (II)

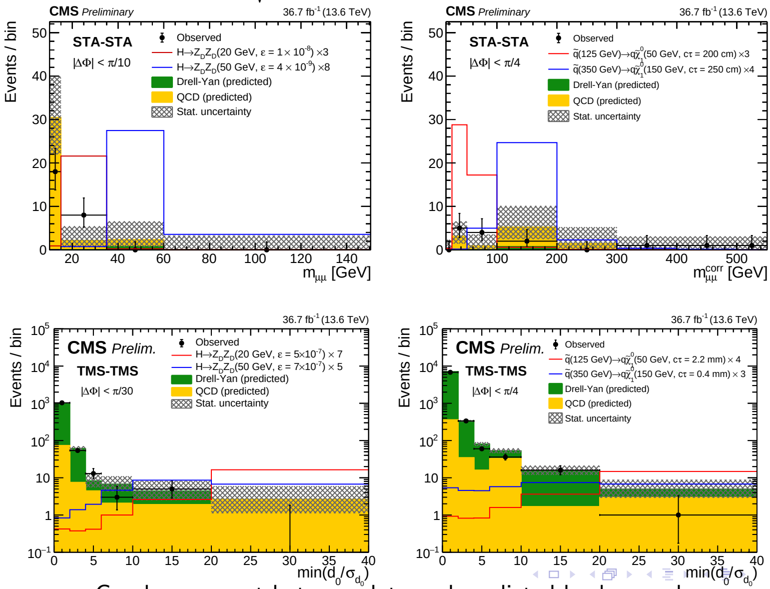
- Select TMS-TMS and STA-STA muon pairs common vertex (CV) displaced w.r.t. the PV (TMS-STA not used)
- Making use of improved triggers w.r.t. Run 2
  - efficiencies improved by factors of 1.4-3.8 as a function of particle $c\tau$
- Discriminating variables: $L_{xy}/\sigma_{L_{xy}}$ (distance from the PV to the CV in the plane transverse to the beam direction), $|\Delta\Phi|$ (transverse collinearity angle between $p_{\mathrm{T},\mu\mu}$ and L_{xy}), $\min(d_0/\sigma_{d_0})$





Search for LLPs Decaying to Muon Pairs (III)

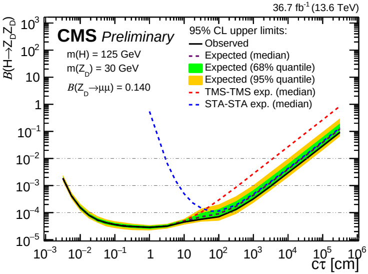
$$m_{\mu\mu}^{\mathrm{corr}} = \sqrt{m_{\mu\mu}^2 + p_{\mu\mu}^2 \sin^2\theta_{\mu\mu}} + p_{\mu\mu}\sin\theta_{\mu\mu}$$

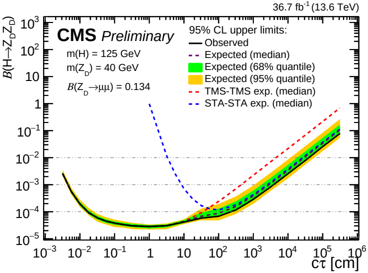


Good agreement between data and predicted background

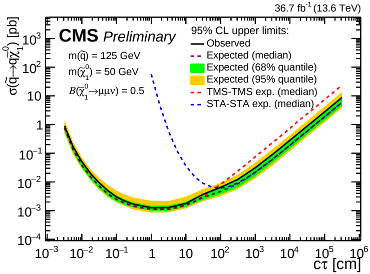
Search for LLPs Decaying to Muon Pairs (IV)

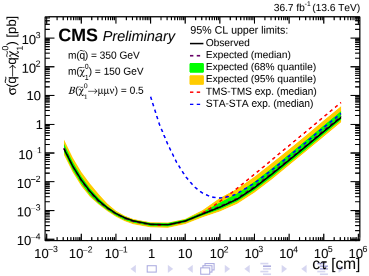
95% C.L. upper limits on $\mathcal{B}(\mathrm{H} \to \mathrm{Z}_D \mathrm{Z}_D)$ as a function of $c\tau(\mathrm{Z}_D)$





95% C.L. upper limits on $\sigma(\tilde{q} \to \mathrm{q}\tilde{\chi}_1^0)$ as a function of $c\tau(\tilde{\chi}_1^0)$





Summary

- Run 3 data taking on the way
- Analyses slowly progressing, expect a lot of physics results next few years
- ATLAS and CMS experiments performing well so far