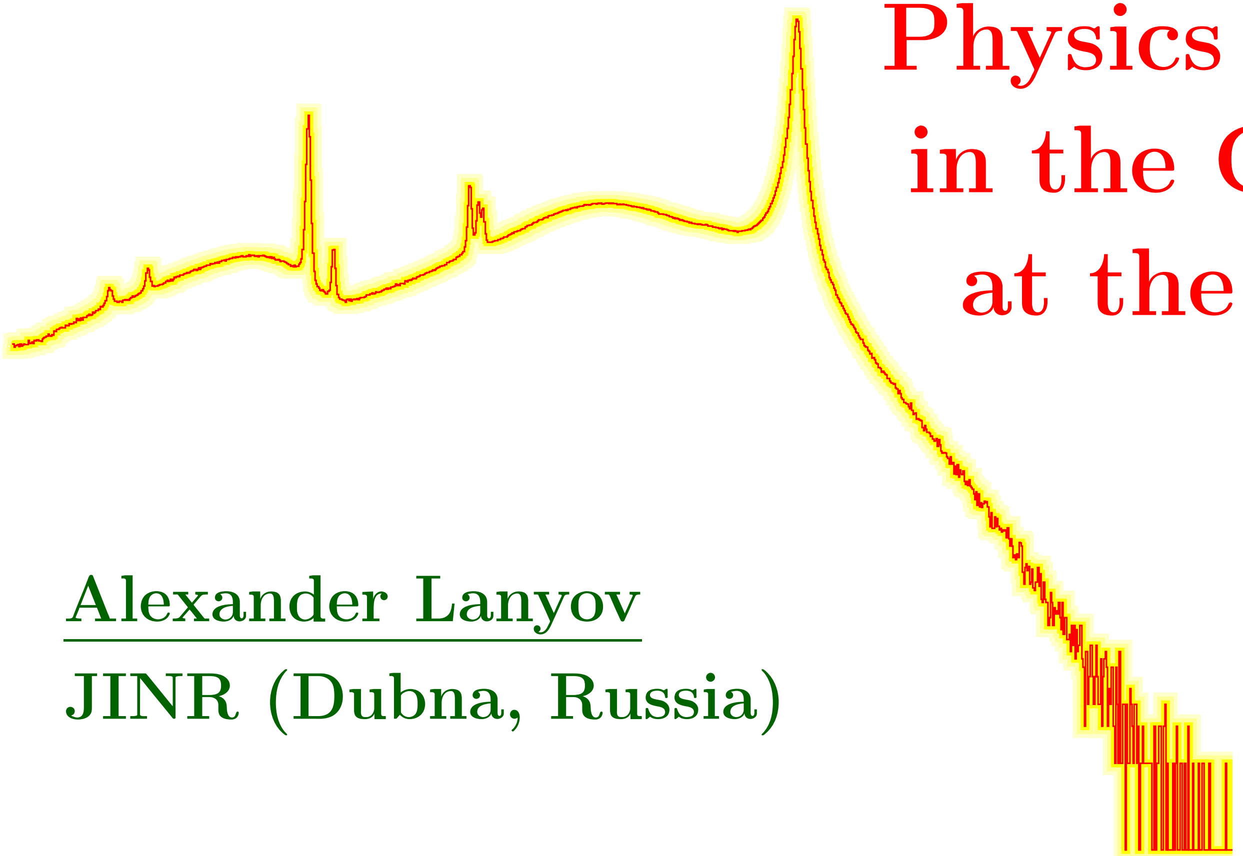
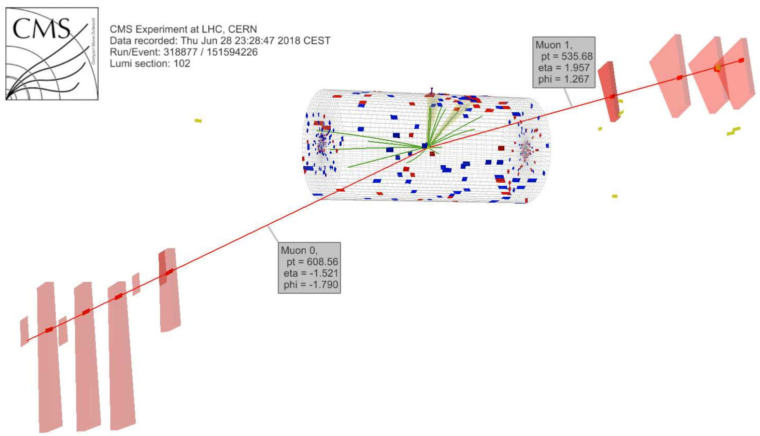
Physics with Dimuons in the CMS Experiment at the LHC





Alexander Lanyov
JINR (Dubna, Russia)

February 19, 2025

Session-Conference of the Section of Nuclear Physics of PSD RAS devoted to 70th anniversary of V. A. Rubakov "Physics of Fundamental Interactions"

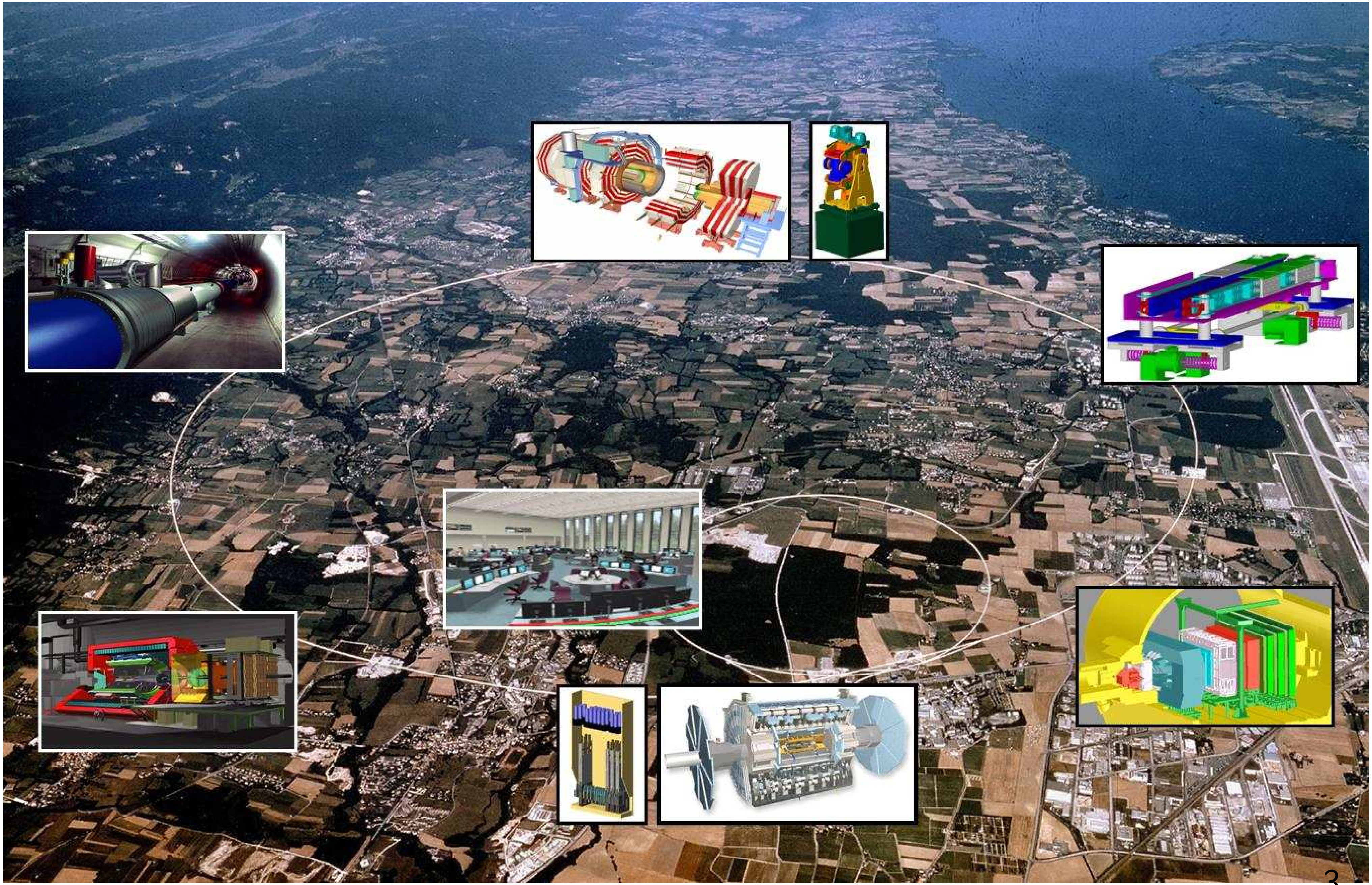
Outline:

- Compact Muon Solenoid (CMS) at LHC (CERN)
- Motivation to study dimuons
- Standard Model — from Z boson to rare decays
- Exotica — search for new heavy resonances
- Conclusions

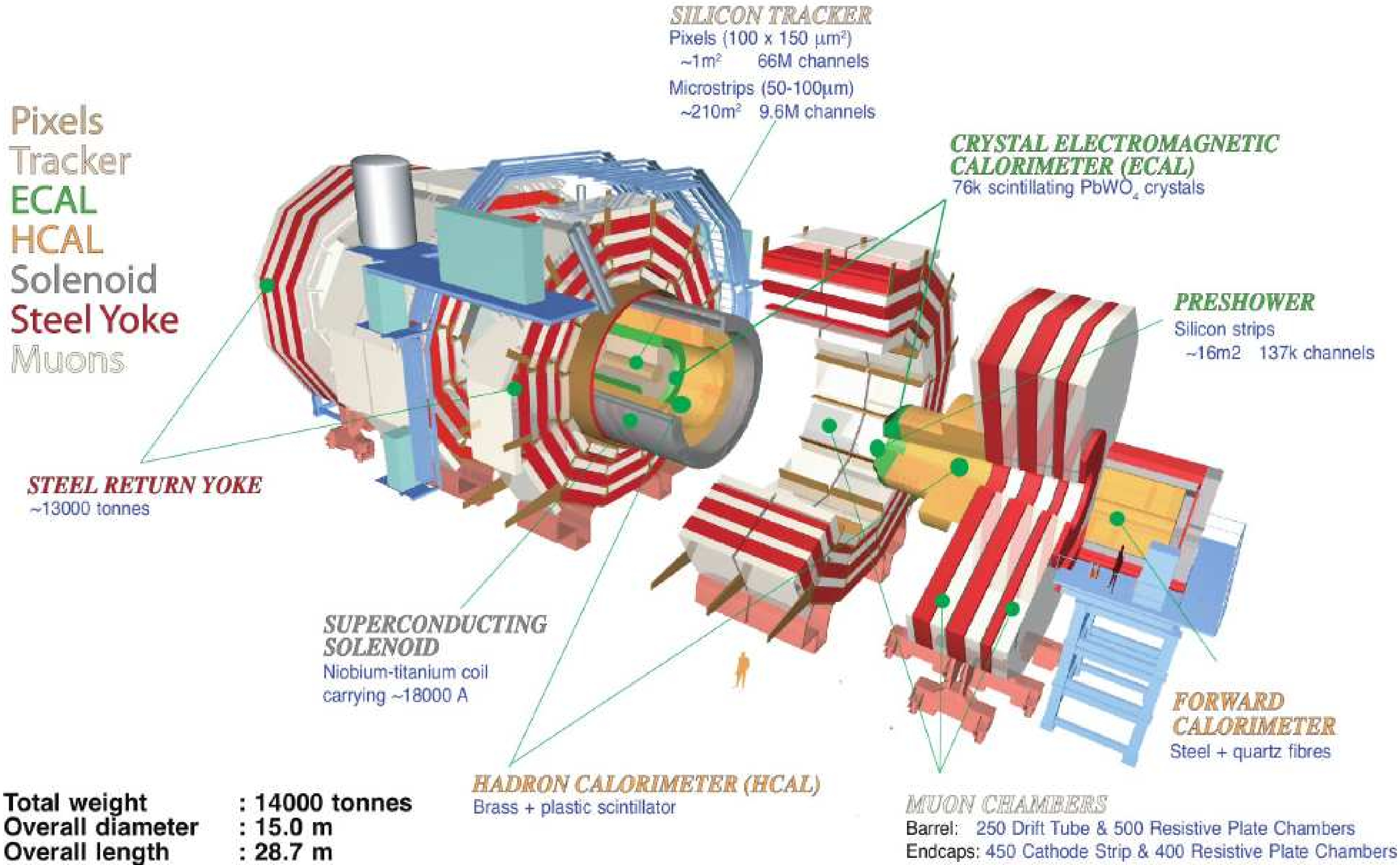
CMS Public Results:

http://cms-results.web.cern.ch/cms-results/public-results/publications/

LHC (Large Hadron Collider)

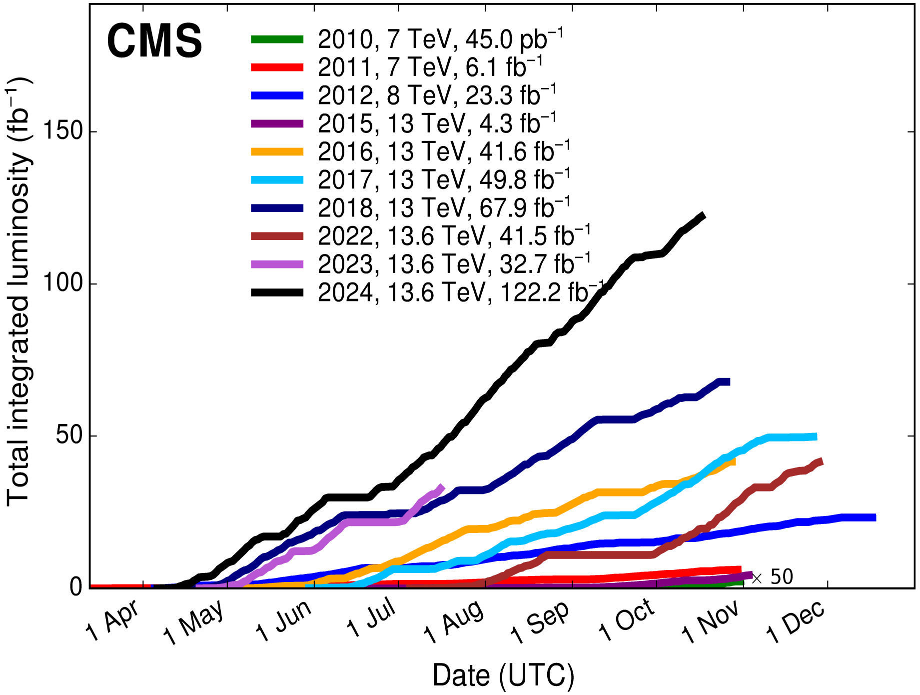


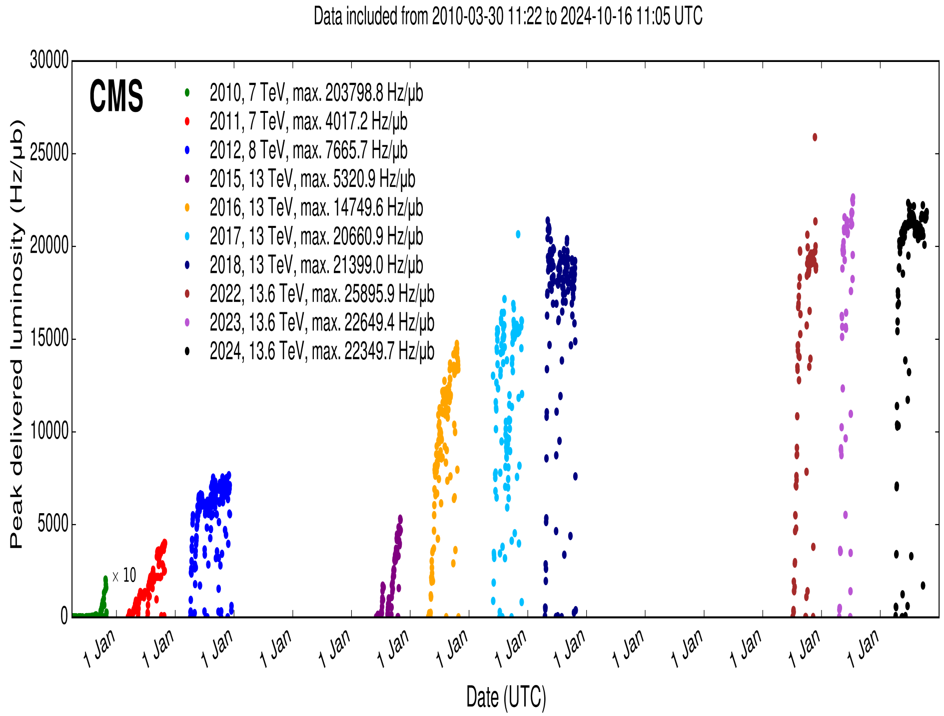
CMS (Compact Muon Solenoid) at LHC (CERN)



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

Statistics of Integrated Luminosity at LHC



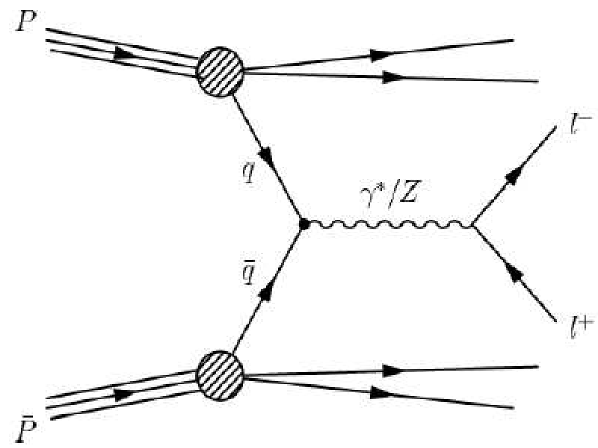


- Run 1 with $\sqrt{s} = 7$–8 TeV: $\sim 30\ \mathrm{fb}^{-1}$
- Run 2 with $\sqrt{s} = 13$ TeV: Rapid rise of integrated luminosity $\sim 140\ \mathrm{fb}^{-1}$
- Mean luminosity is 2 times higher than $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (original nominal value for LHC)
- Run 3 with $\sqrt{s} = 13.6$ TeV: started in 2022; Currently $\int \mathcal{L}\,dt \approx 190\ \mathrm{fb}^{-1}$
  Expected by the end of the run: $\int \mathcal{L}\,dt \approx 300 - 350\ \mathrm{fb}^{-1}$

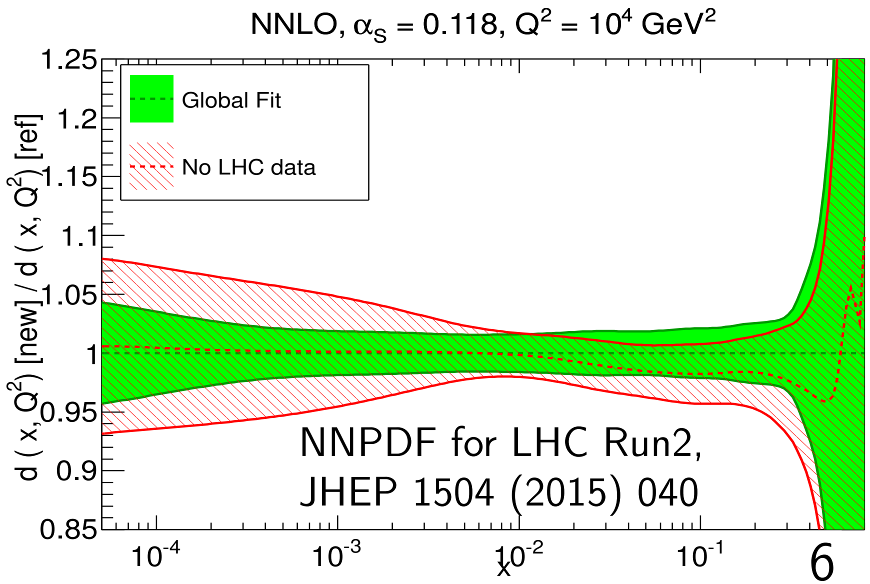
Motivation to Study Dimuons at CMS

Many major discoveries were made before LHC in dimuon channel (J/ψ, Υ, Z, ...) — rather clean channel for finding new narrow resonances (often unexpected).

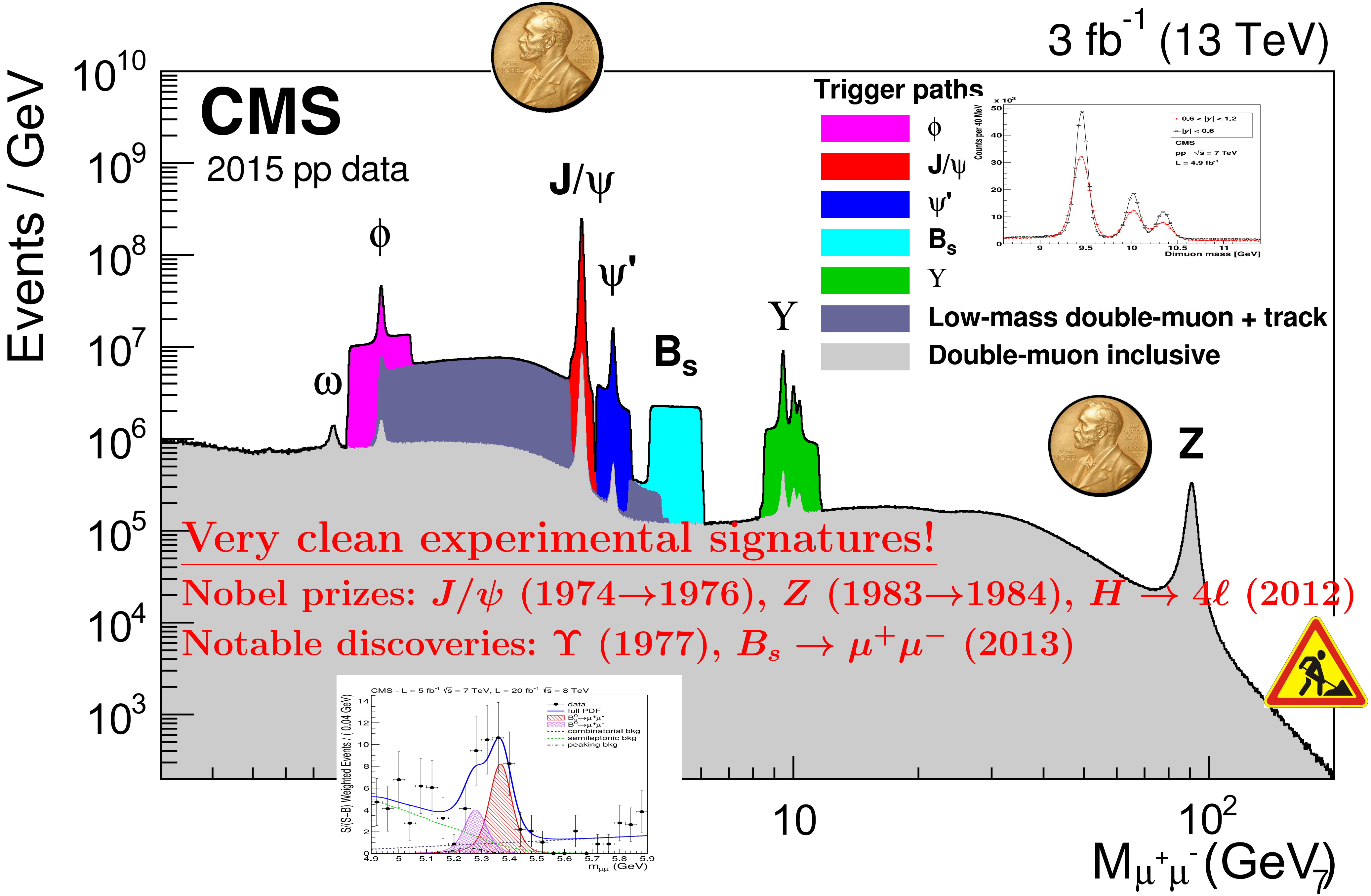
Why study dimuons at CMS?



- Important Standard model benchmark channel
  Theoretical cross section calculated up to NNLO allowing tests of pQCD
- Many theoretical models predict contribution of New Physics in dimuon channel.
- Used to constrain PDFs
- Calibration and alignment, TnP
- Physics Processes produced in association with Z boson, $H \to ZZ$, $B \to \mu\mu$ discovery, $5\,\sigma$ discovery of $H \to b\bar{b}$ used also $Z \to \mu\mu$.



Dimuon Invariant Mass at CMS in Run 2



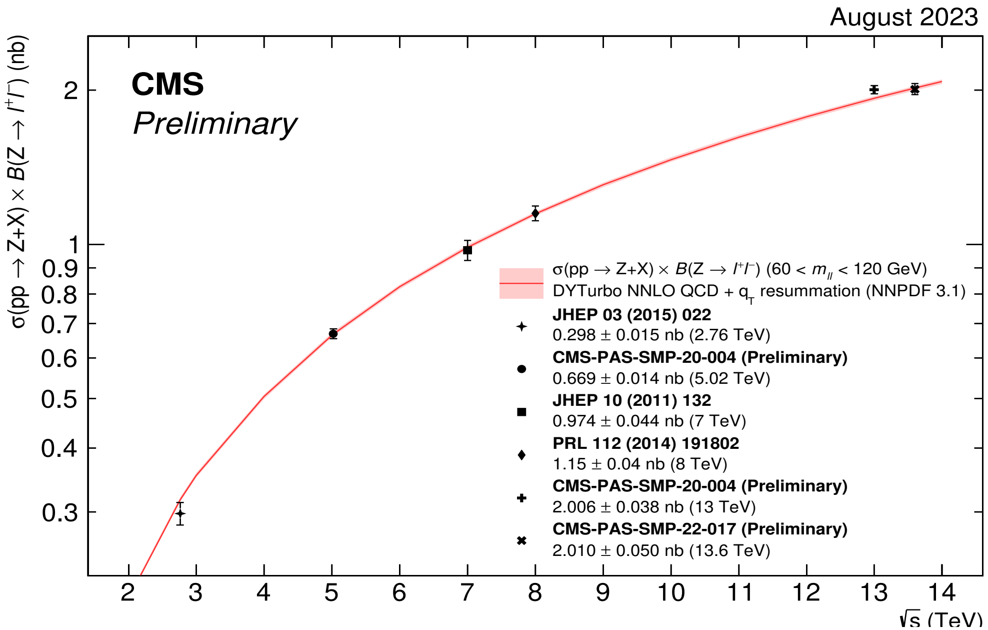
Very clean experimental signatures!

Nobel prizes: J/ψ (1974→1976), Z (1983→1984), $H \to 4\ell$ (2012)

Notable discoveries: Υ (1977), $B_s \to \mu^+\mu^-$ (2013)

Drell-Yan process studies

Z Production Cross Section at $\sqrt{s} = 13 - 13.6$ TeV



CMS-PAS-SMP-22-017

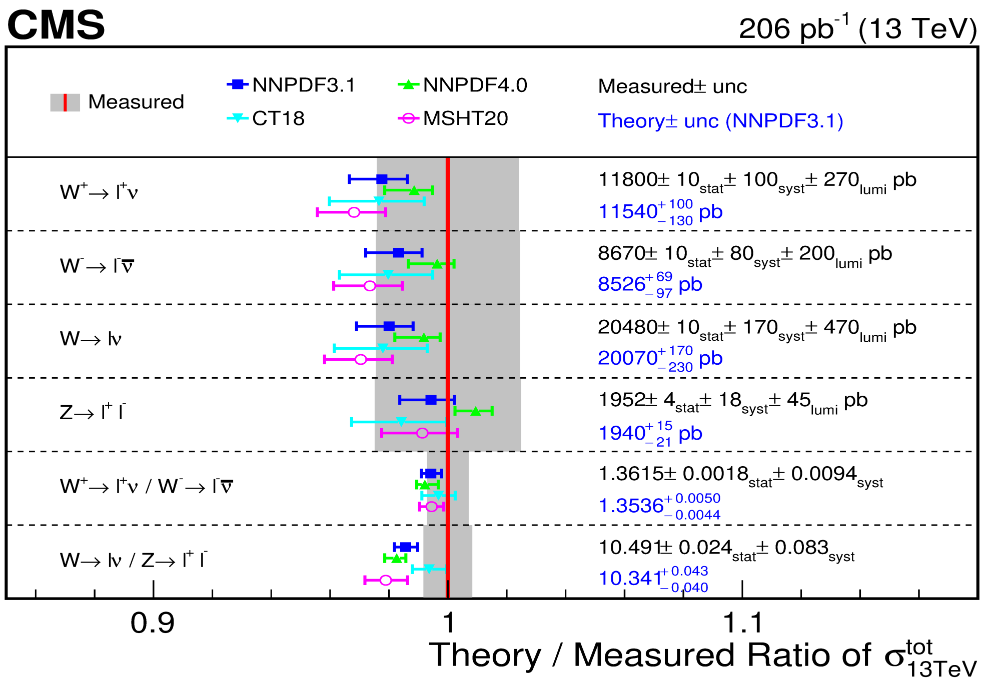
Used data with $5\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13.6$ TeV

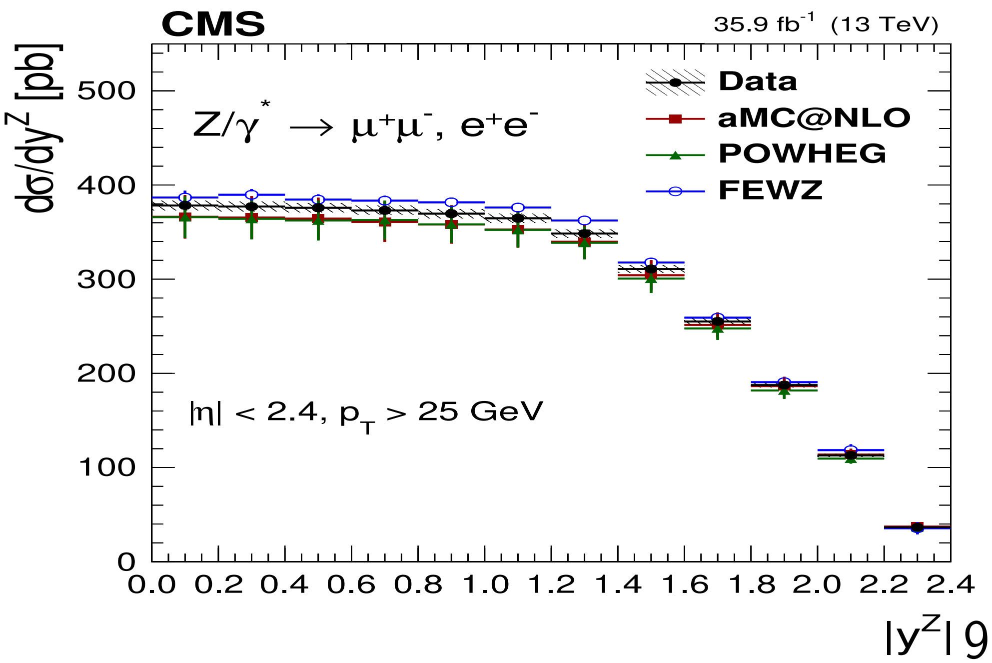
Single muon trigger: $p_T > 24$ GeV, $|\eta| < 2.4$.

$\sqrt{s} = 13$ TeV: arXiv:2408.03744

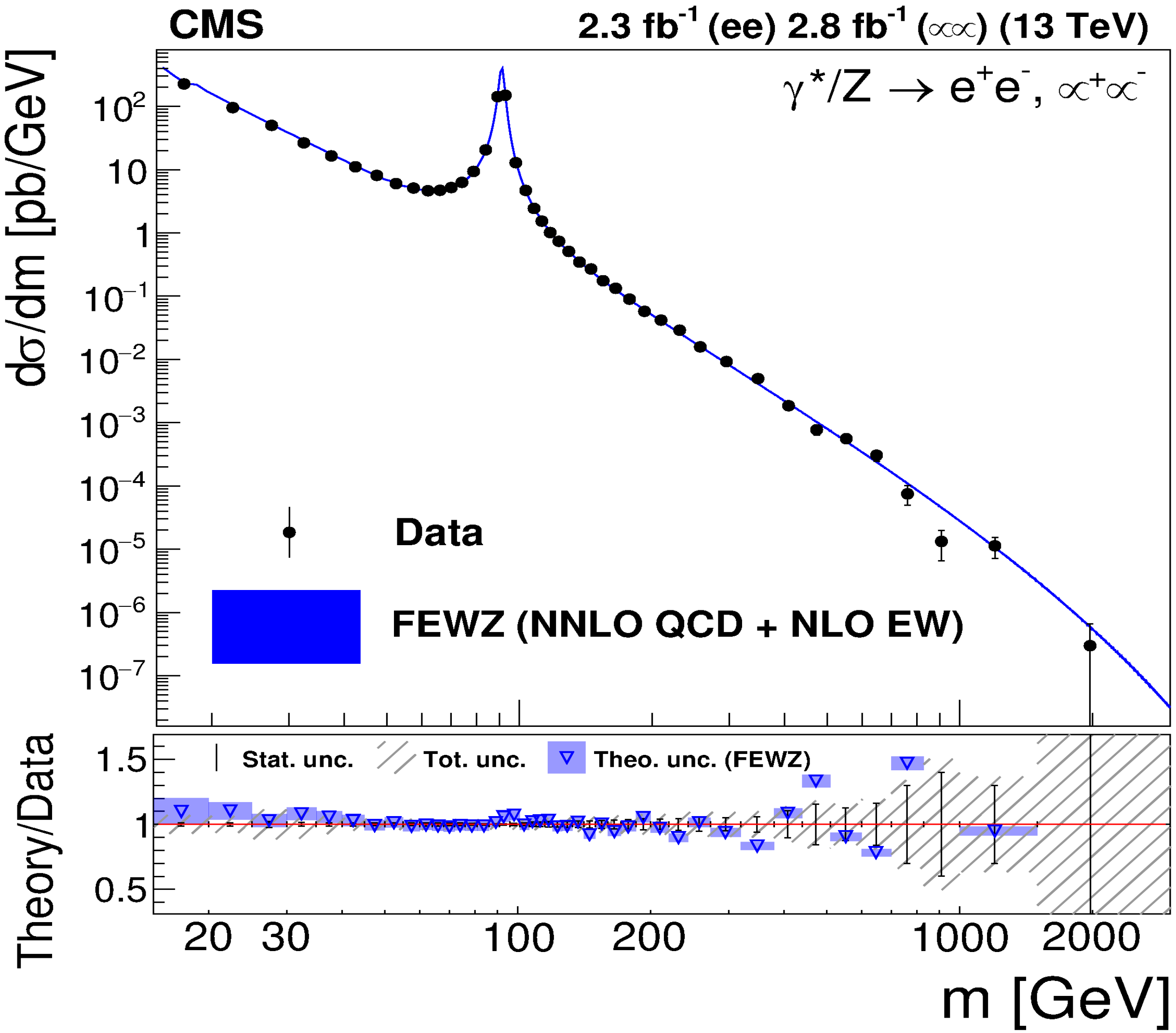
Z cross sections agree well between channels and with NNLO QCD expectation.

JHEP 12 (2019) 061 Diff. meas. $(p_T,\ y,\ \phi^*)$





Drell-Yan 1D Cross Section (JHEP 12 (2019) 059)



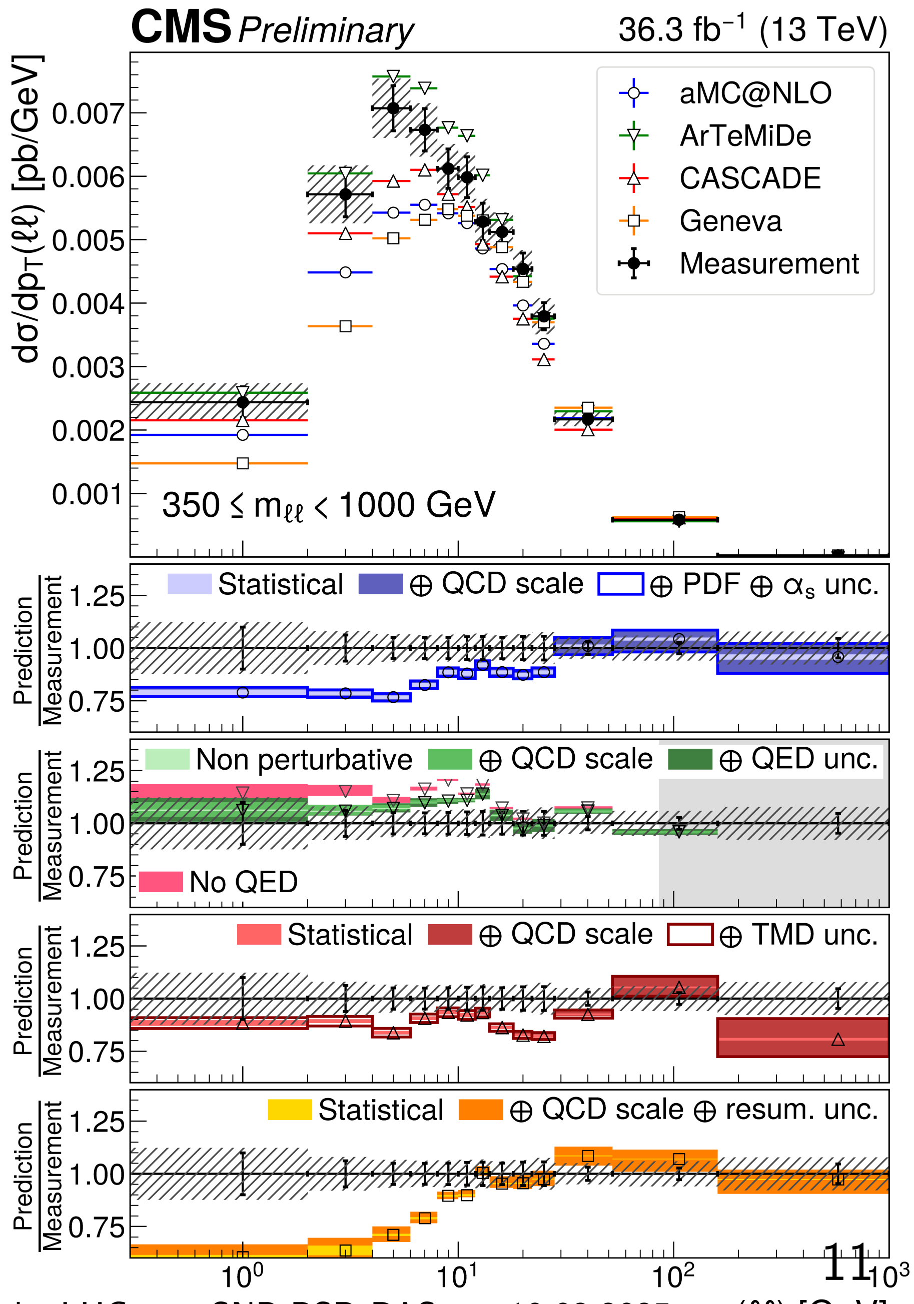
- $L = 2.8\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
- Mass range: 15—3000 GeV, divided by 43 bins
- Trigger: Isolated single muon trigger with $p_T > 20$ GeV
- Kinematic cut: $p_T^{\text{Lead}} > 22$ GeV, $p_T^{\text{Sub}} > 10$ GeV, $|\eta| < 2.4$
- Corrected to the full space
- Systematic uncertainty:
  Low-mass: Eff. SF $\sim 3\%$
  Z peak: FSR ($< 2\%$)
  High-mass: Det. Res. (up to 150%)
- Combined both $\mu^+\mu^-$ and e^+e^- channels

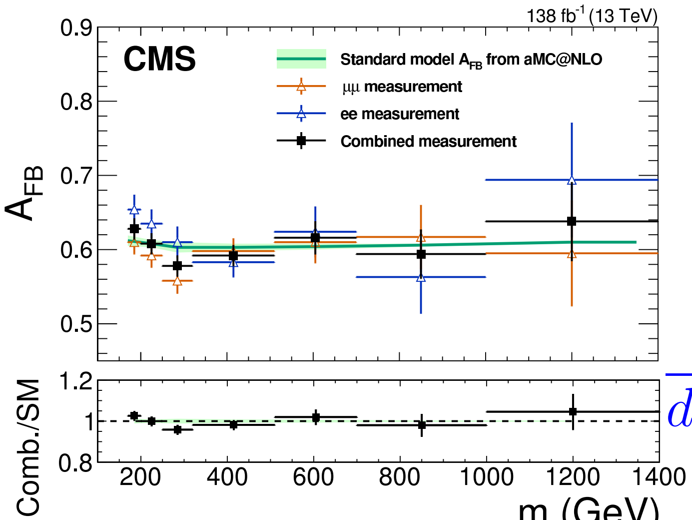
Generally good agreement between data and theory FEWZ (NNLO QCD, NNPDF3.0)

Measured double differential cross sections of DY lepton pair production, as a function of $p_T(\ell\ell)$, and φ^*, in bins of dilepton masses: $m \in [50, 76, 106, 170, 350, 1000]$ GeV.

Measurements are compared to state-of-the-art predictions based on perturbative QCD including soft gluon resummation.

Additionally, similar measurements were performed requiring at least one jet in the final state.

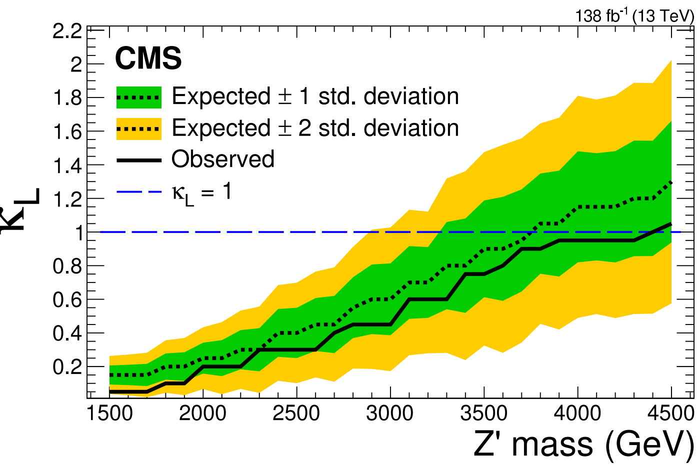




Measurement of A_{FB} can be a sensitive check of the Standard Model.

$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{3}{8}\left[(1+\cos^2\theta^*) + \frac{A_0}{2}(1-3\cos^2\theta^*)\right] + A_{FB}\cos\theta^*$$

θ^* is angle between μ^- and quark direction in c.m.s. of dilepton

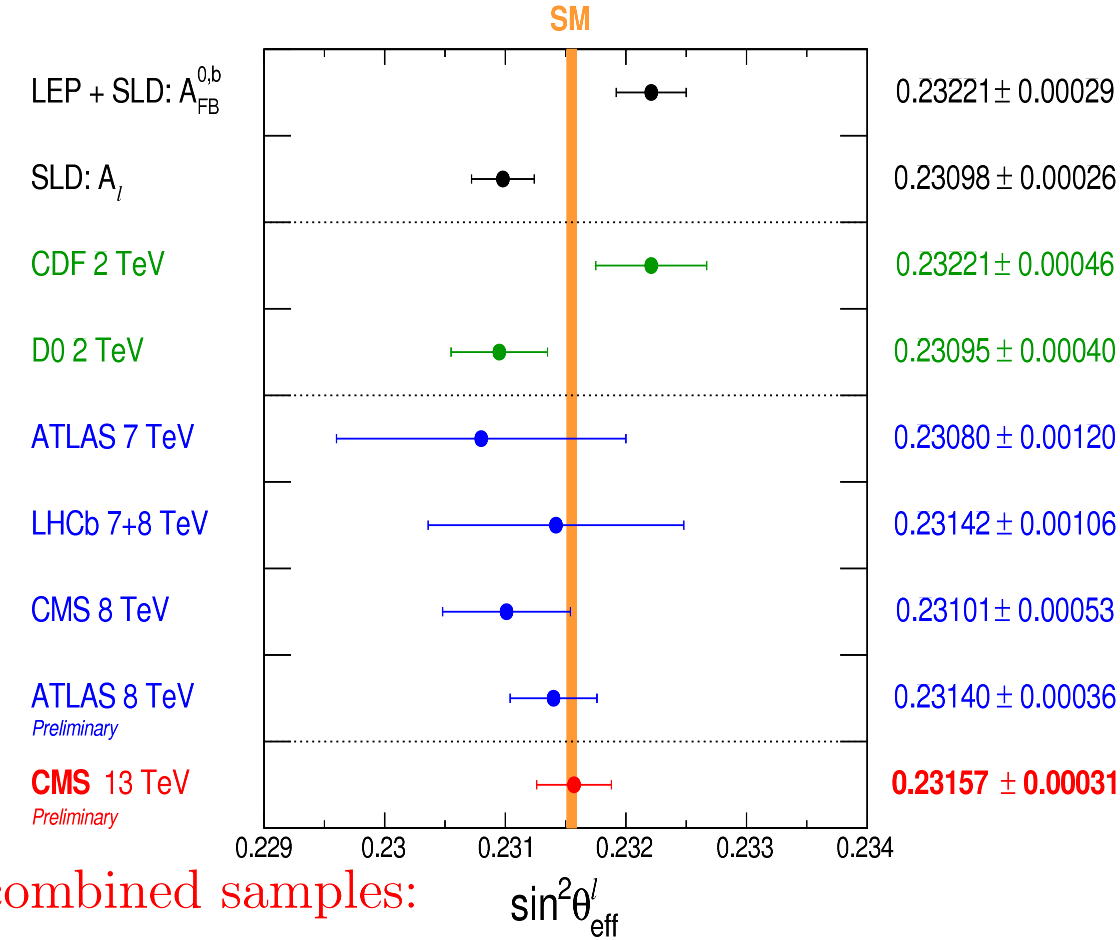


- Good agreement to SM prediction of $A_{FB} \approx 0.6$
- Used to set limits on the presence of additional gauge boson Z' in SSM model: Lower mass limit = 4.4 TeV is set at 95% CL.
- $A_{\rm FB}$ can be used to measure Weinberg weak mixing angle $\sin^2\theta_{\rm Eff}$

Measurement of Weak Mixing Angle with A_{FB} (arXiv:2408.07622)

Measurement of the leptonic effective weak mixing angle $\sin^2\theta_{\rm Eff}$ by fitting the mass and rapidity dependence of the observed $A_{\rm FB}$ in dilepton events.

$\sin^2\theta_{\rm Eff}$ is defined by relation for vector and axial-vector couplings of Z boson:
$v_f/a_f = 1 - 4\,|Q_f|\,\times\,\sin^2\theta_{\rm Eff}$



Effective weak mixing angle from the combined samples:

$$\sin^2\theta^\ell_{\rm eff} = 0.23157 \pm 0.00010({\rm stat}) \pm 0.00015({\rm syst}) \pm 0.00009({\rm theo}) \pm 0.00027({\rm PDF}) =$$
$$= 0.23157 \pm 0.00031$$

Uncertainties are significantly reduced compared to our previous measurement.

The common value for LHC measurements is dominated by the CMS measurement.

The results are consistent with the most precise measurements.

Further improvement expected at HL-LHC – ±0.00003 (CMS PAS FTR-17-001).

Angular coefficients of Z bosons as a function of p_T and Y (Phys. Lett. B 750 (2015) 154) at $\sqrt{s} = 8$ TeV

Measurement of Z boson angular coefficients in pp collisions and decaying to $\mu\mu$.

Coefficients A_i govern kinematics of the muons in $Z \to \mu\mu$. Their values follow from the vector and axial vector $(V - A)$ structure of boson-fermion couplings.

General structure of the lepton angular distribution in Z boson rest frame:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta^*\mathrm{d}\phi^*} \propto \Big[(1+\cos^2\theta^*)+A_0\frac{1}{2}(1-3\cos^2\theta^*)+A_1\sin(2\theta^*)\cos\phi^*+A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$

$$+A_3\sin\theta^*\cos\phi^*+A_4\cos\theta^*+A_5\sin^2\theta^*\sin(2\phi^*)+A_6\sin(2\theta^*)\sin\phi^*+A_7\sin\theta^*\sin\phi^*\Big]$$

where θ^* and ϕ^* are the polar and azimuthal angles of the negatively charged lepton in the rest frame of the lepton pair.

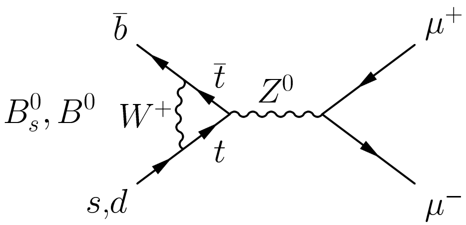
These measurements provide comprehensive information about the Z boson production mechanisms, compared to the QCD predictions.

In particular, it was performed checking the Lam–Tung relation violation $(A_0 = A_2)$.

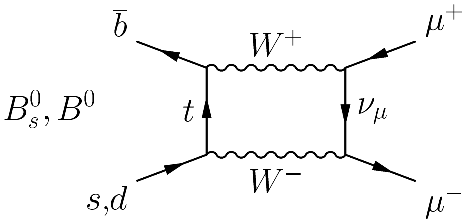
See details in the talk by Vladislav Shalaev on Electroweak Physics

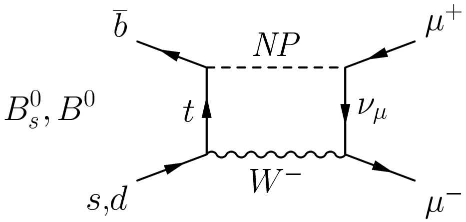
Rare Dimuon Decays

in Standard Model

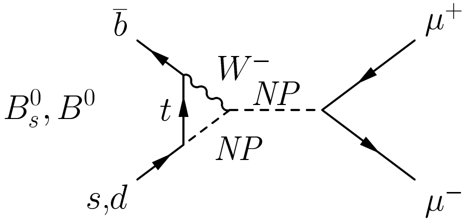


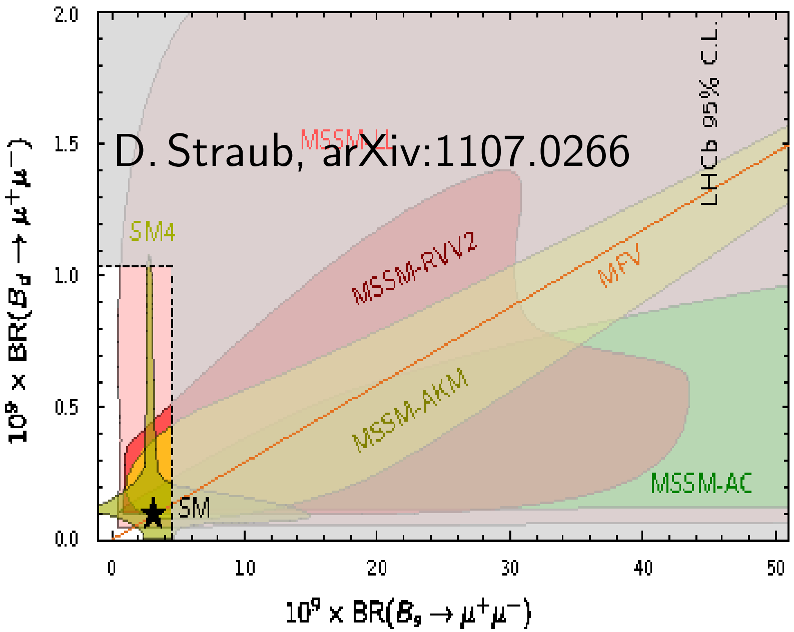
SM

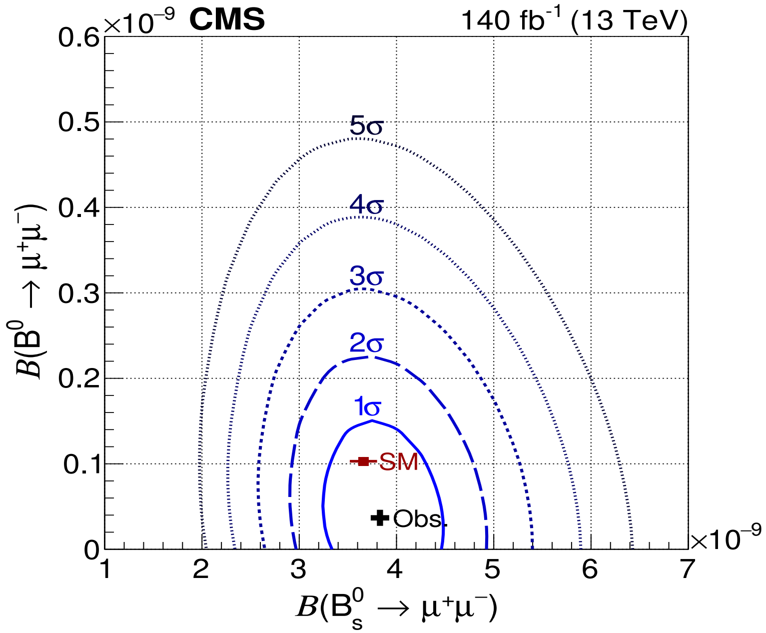




NP







SM predicts

$\text{Br}(B_s^0 \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$

$\text{Br}(B^0 \to \mu\mu) = (1.03 \pm 0.05) \times 10^{-10}$

The processes are sensitive to searches for BSM physics.

CMS results on the $B_{sd}^0 \to \mu^+\mu^-$ decays:

$\text{Br}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}(\text{stat})^{+0.24}_{-0.21}(\text{syst})\right] \times 10^{-9}$,

Upper limit $\text{Br}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ at 95% CL

Effective B_s^0 lifetime in this decay:

$\tau = 1.83^{+0.23}_{-0.20}(\text{stat})^{+0.04}_{-0.04}(\text{syst})$ ps

Most precise single measurements and consistent with the SM.

Search for Higgs $\to \mu^+\mu^-$ (JHEP 01 (2021) 148)

Rare decay: $\mathrm{Br}(H \to \mu^+\mu^-)_{\mathrm{SM}} = 2.2 \times 10^{-4}$

First evidence for $H \to \mu^+\mu^-$ with significance $3\,\sigma$

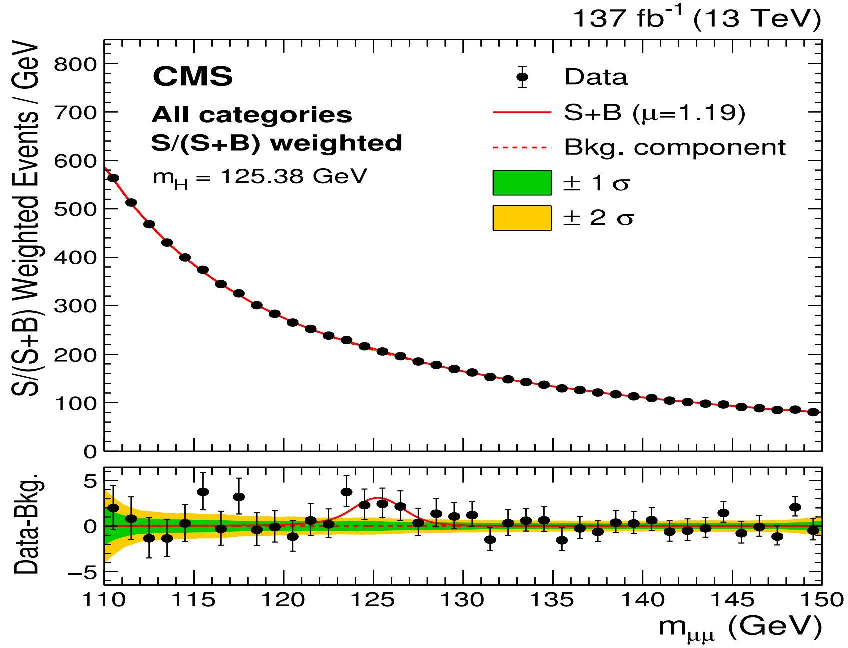
Four categories: VBF, ggH, $t\bar{t}H$, VH

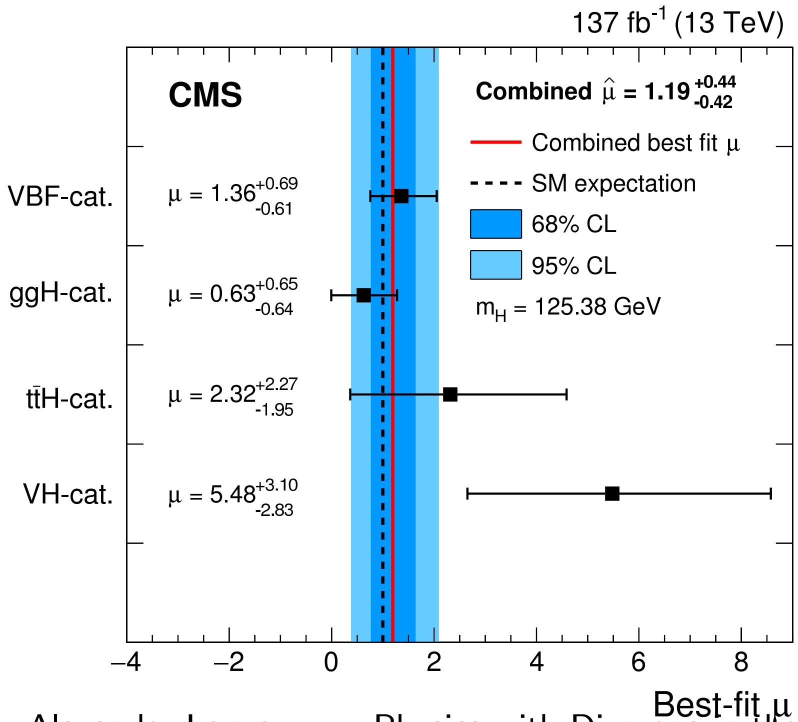
Signal strength $\hat{\mu}^{\mathrm{comb}} = 1.19^{+0.40}_{-0.39}\,(\mathrm{stat.})^{+0.15}_{-0.14}\,(\mathrm{syst.})$

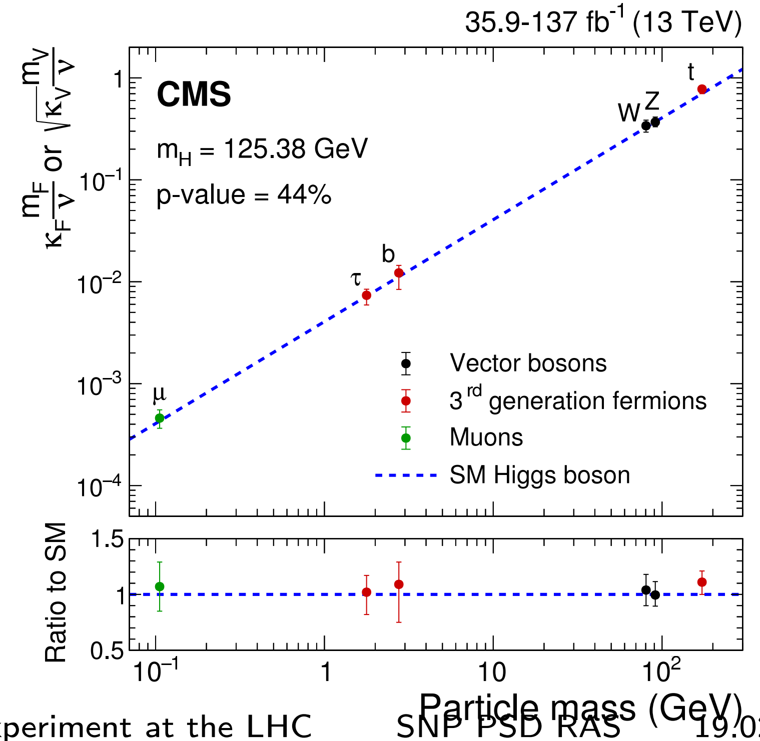
Even more rare: $\mathrm{Br}(H \to e^+e^-)_{\mathrm{SM}} = 5 \times 10^{-9}$

CMS limit: $\mathrm{Br} < 3 \times 10^{-4}$ [arXiv:2208.00265]

See also talk by A. Nikitenko on Higgs BSM





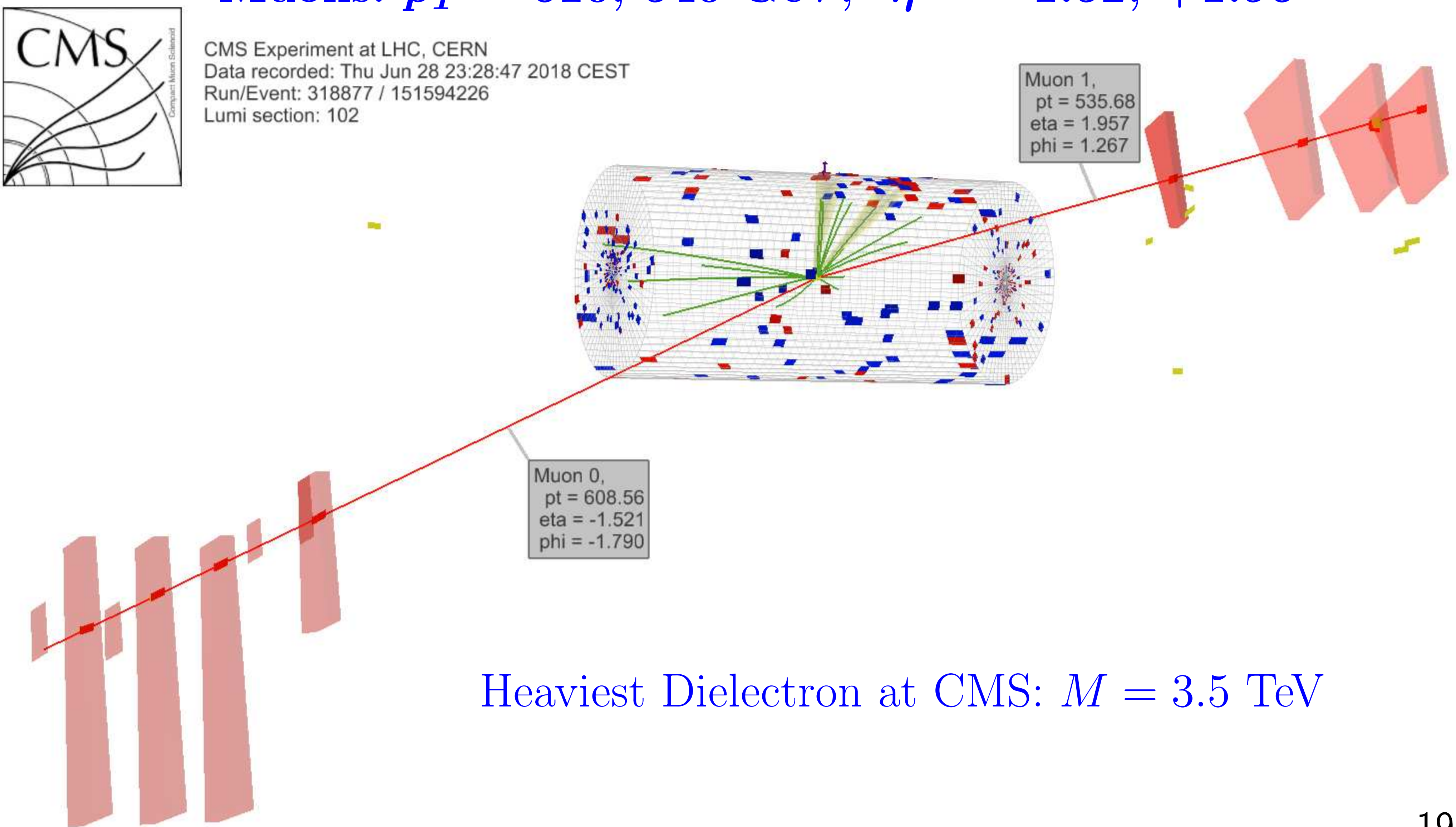


Search for Heavy Resonances in Dilepton Channels

Event with Heaviest Dimuon at CMS in Run2

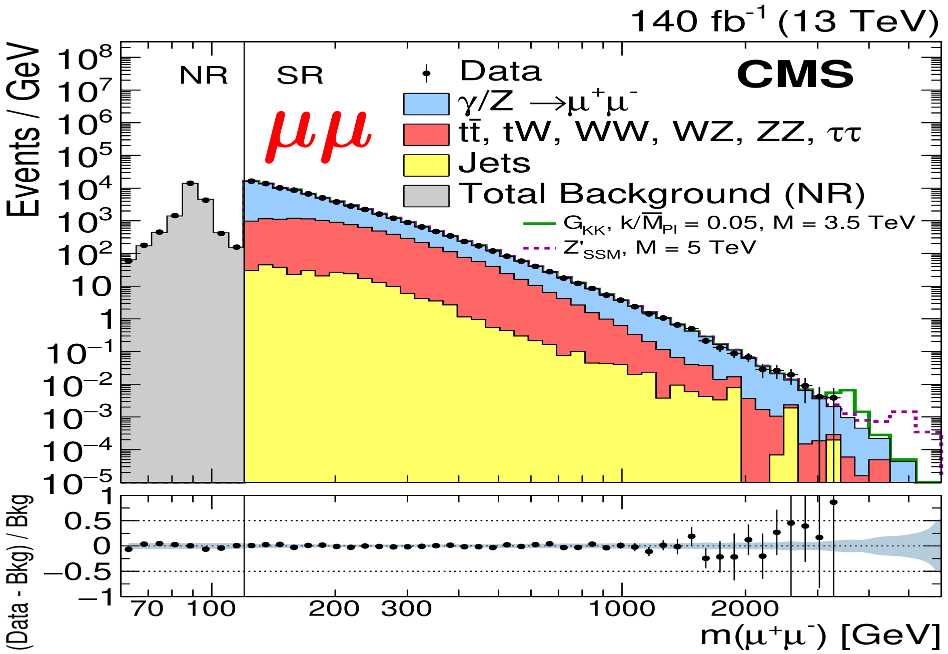
$M = 3.3$ TeV

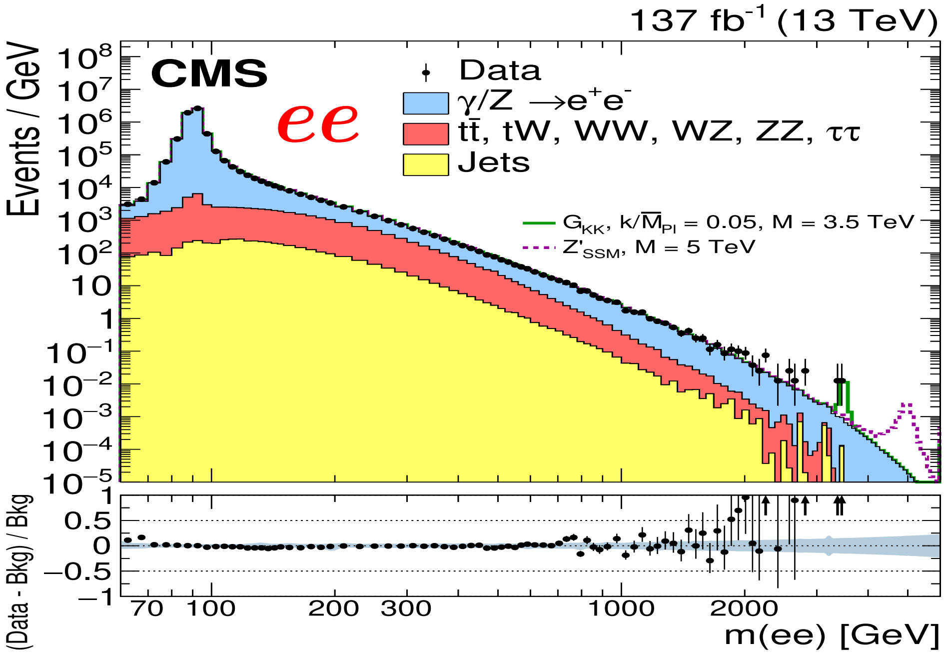
Muons: $p_T = 610,\ 540$ GeV, $\eta = -1.52,\ +1.96$



Heaviest Dielectron at CMS: $M = 3.5$ TeV

Dilepton Mass Spectrum in Run2 (JHEP 07 (2021) 208)



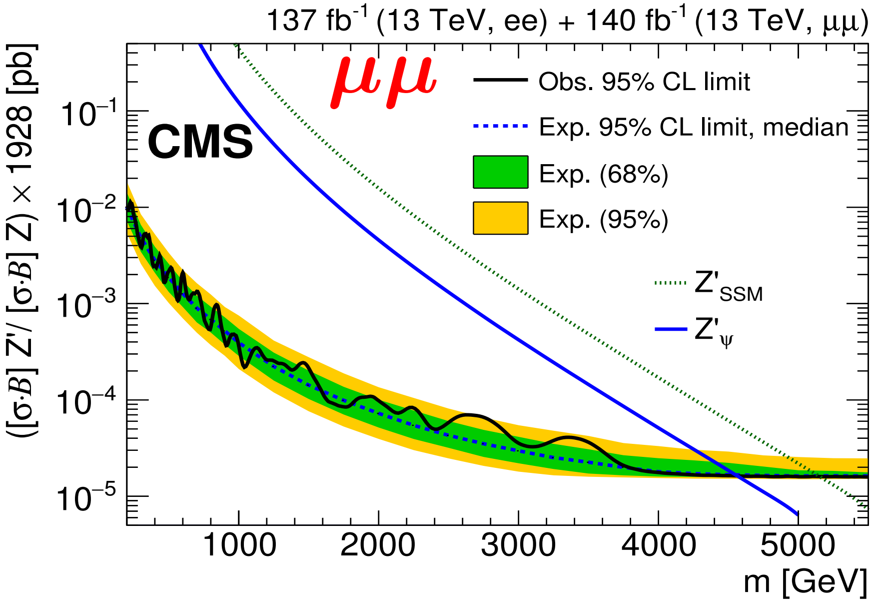


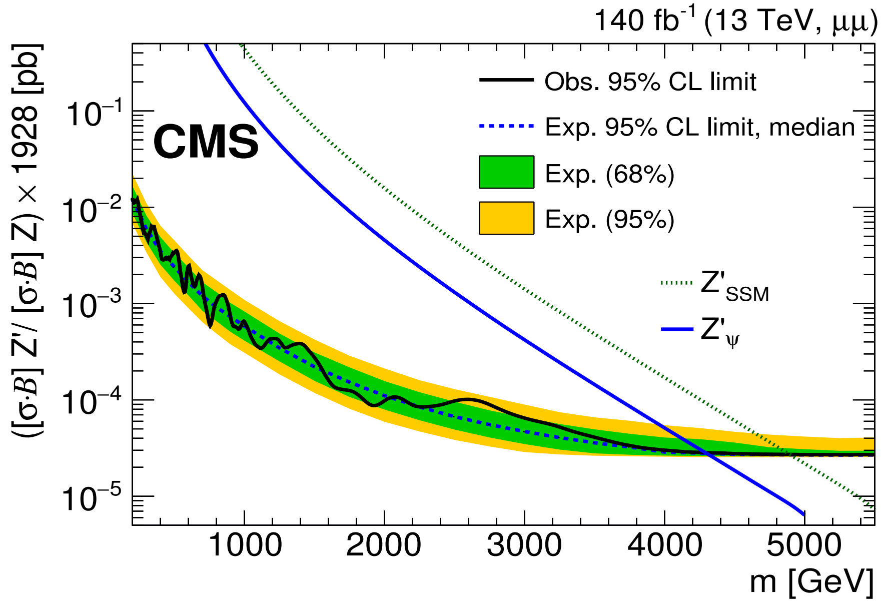
- Offline cut $p_T > 53$ GeV
- Single muon trigger $p_T > 50\,\text{GeV}$
  Double electron trigger $E_T > 33\,\text{GeV}$.
- Good Data / MC agreement,
  No obvious bumps seen.
- To impose mass limits, we normalize to $\sigma(Z)$:

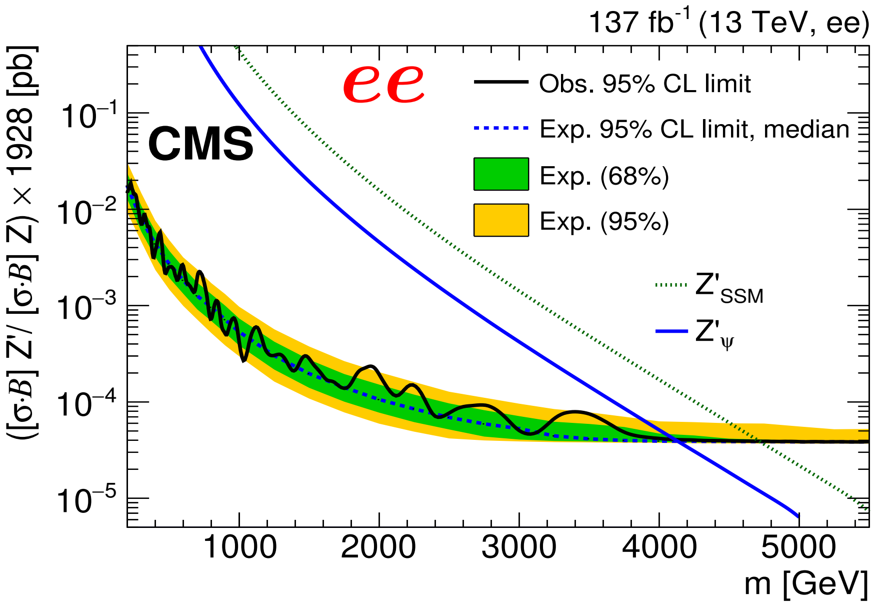
$$R_\sigma = \frac{\sigma(Z' \to \ell^+\ell^-)}{\sigma(Z \to \ell^+\ell^-)} = \frac{N(Z')}{N(Z)} \times \frac{A(Z)}{A(Z')} \times \frac{\varepsilon(Z)}{\varepsilon(Z')}$$

- Removed luminosity uncertainty,
  other systematic effects reduced.
- Existence (or lack) of a signal is established by performing unbinned maximum likelihood fits to the observed spectrum.
- Added interpretations in various models.
- Largest mass found: 3.3 TeV $(\mu^+\mu^-)$, 3.5 TeV (ee)

Dileptons channels   Combined $\mu\mu + ee$







Limits at 95% C.L. on the ratio of Z' cross section to Z cross section, assuming a narrow resonance

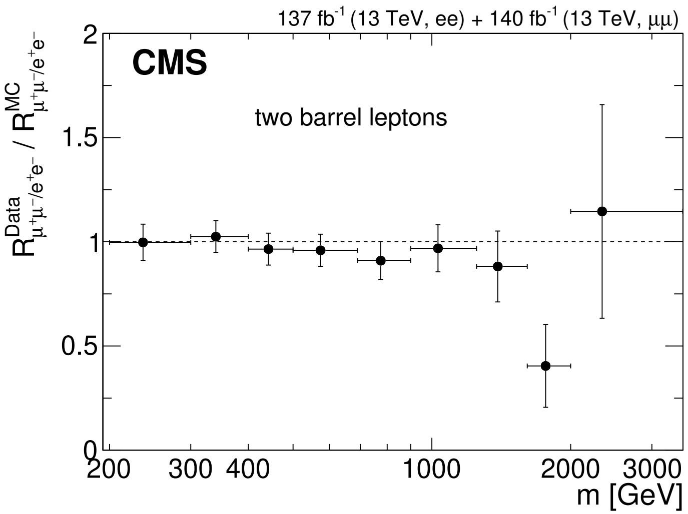
The limit exclude a Z'_{SSM} with a mass less than 5.15 TeV and Z'_{ψ} with a mass less than 4.56 TeV. For $\mu^+\mu^-$ — 4.89 (Z'_{SSM}) and 4.29 TeV (Z'_{ψ}). For ee — 4.72 (Z'_{SSM}) and 4.11 TeV (Z'_{ψ}).

Test of Lepton Flavor Universality (JHEP 07 (2021) 208)

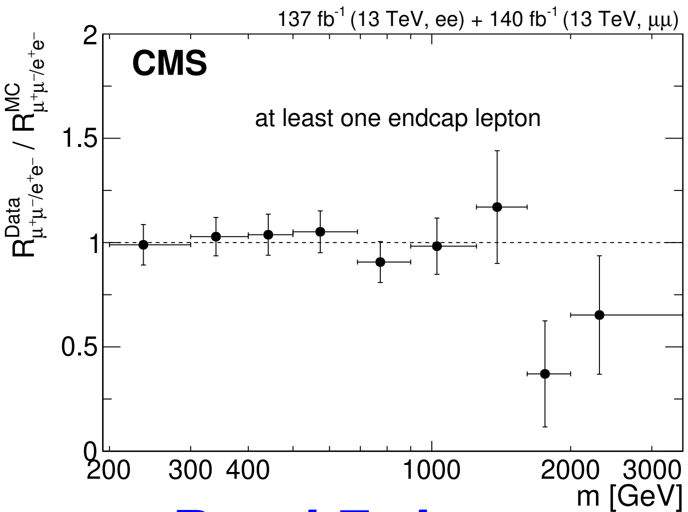
Lepton flavor universality was tested for the first time at the TeV scale
by comparing $\mu^+\mu^-$ and e^+e^- mass spectra: $R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(\mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(e^+e^-)/dm_{\ell\ell}}$
No significant deviations from SM observed.

At very high masses, the statistical uncertainties are large.
Here, some deviations from unity are observed, caused
by the slight excess in the dielectron channel.

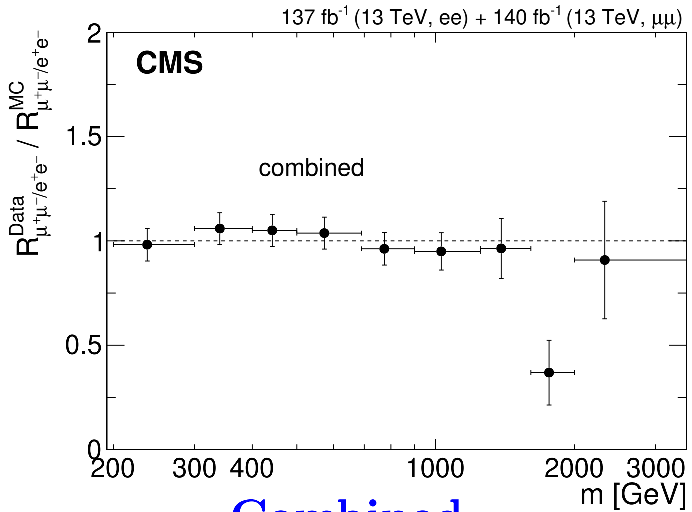
A χ^2 test for the mass range above 400 GeV is performed:
$\chi^2/\mathrm{dof} = 11.2/7$ and $9.4/7$ for $m > 400\,\mathrm{GeV}$.



Barrel ($|\eta| < 1.2$)



Barrel-Endcap



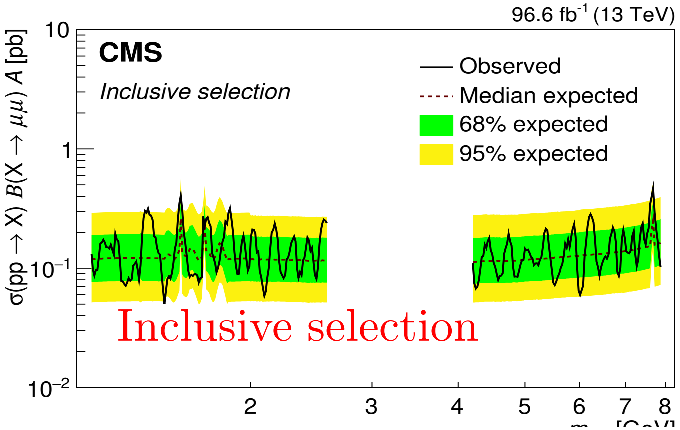
Combined

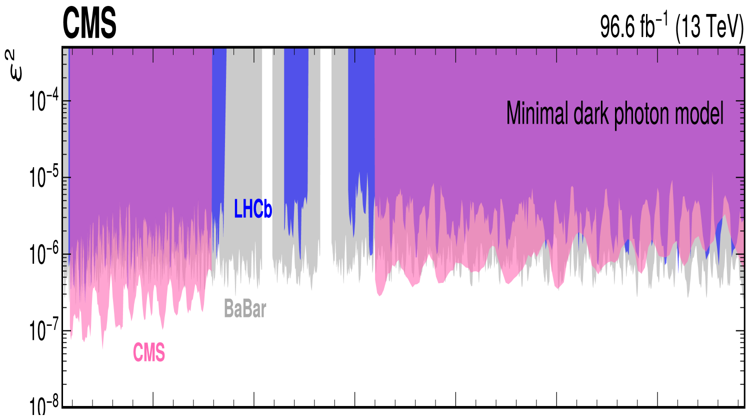
More results for the high-mass searches in the Backup slides

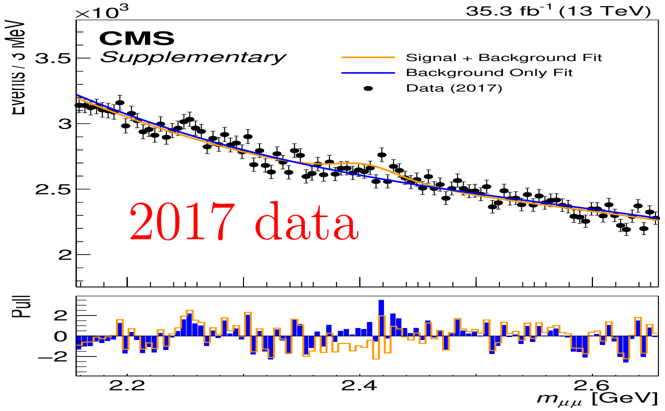
Search for GeV-scale dimuon resonances (JHEP 2312 (2023) 070)

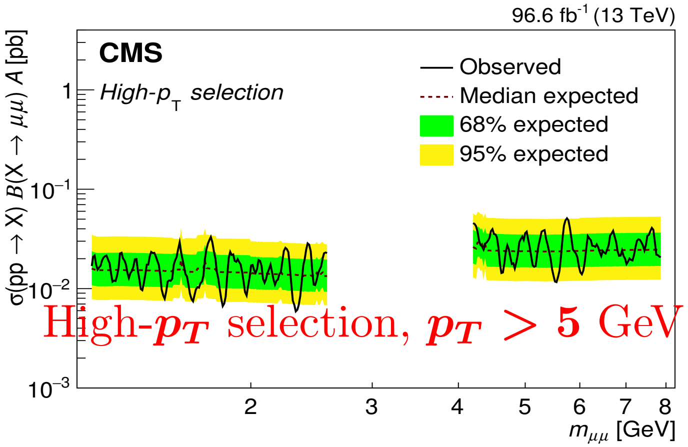
Looking two muons with p_T as low as 3 GeV, producing model-independent limits on production rates of dimuon resonances

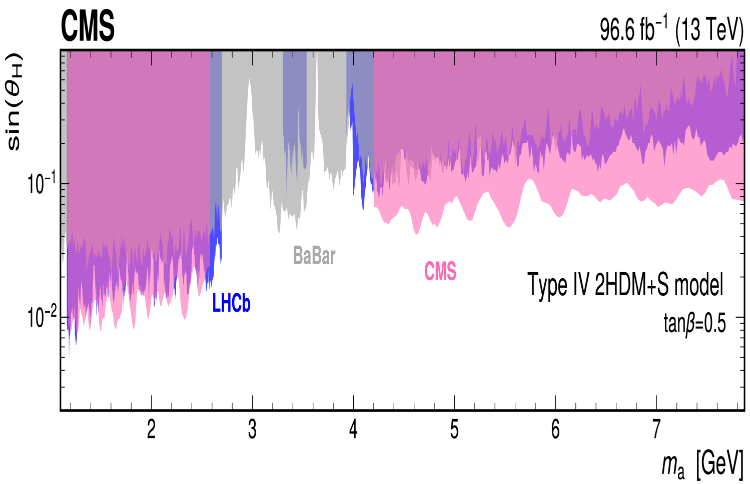
For high-p_T only

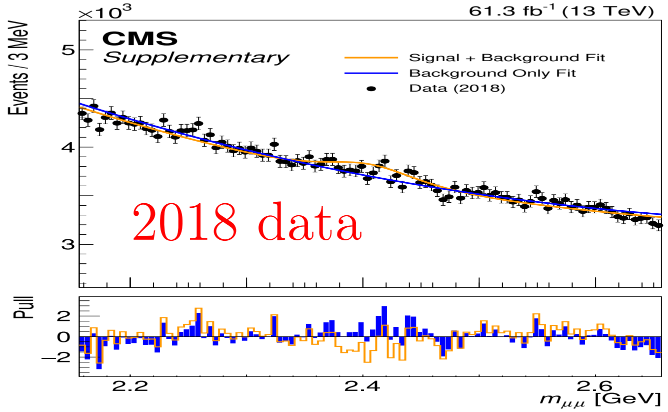










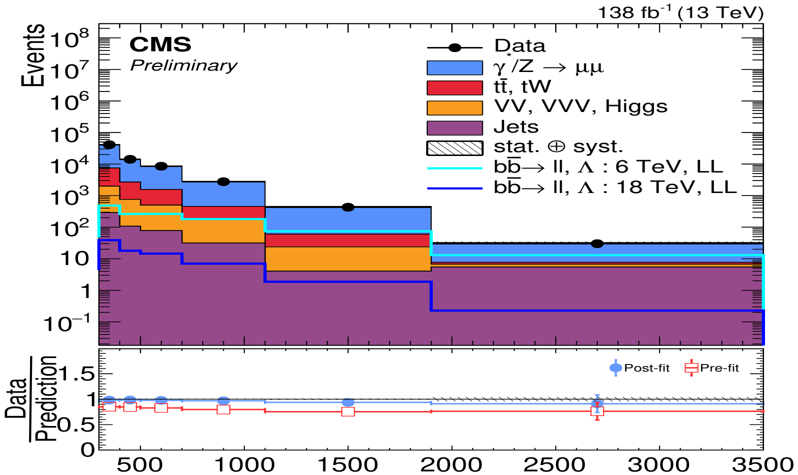


The largest excess is at 2.41 GeV. Local significance 3.2 σ, global significance 1.3 σ.

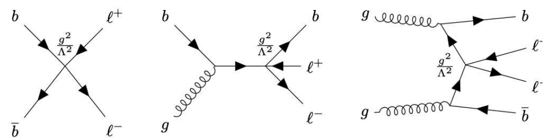
Competitive or world's best limits are set at 90% confidence level for a minimal dark photon model and for a scenario with two Higgs doublets and an extra complex scalar singlet (2HDM+S).

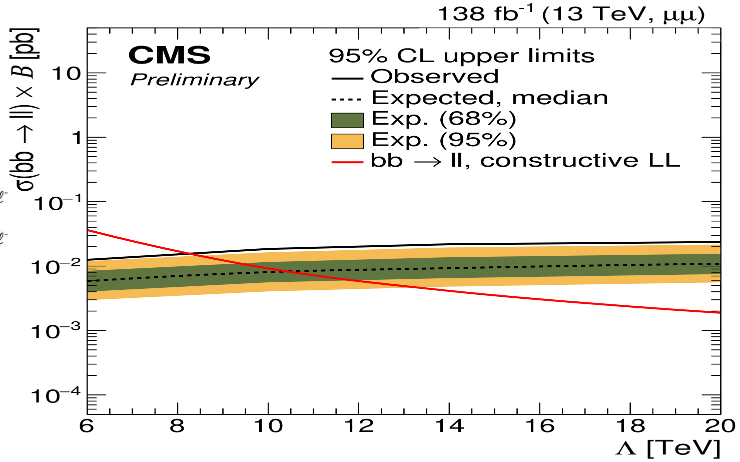
Nonresonant new physics in high-mass dilepton events in association with b-tagged jets (CMS-PAS-EXO-23-010)

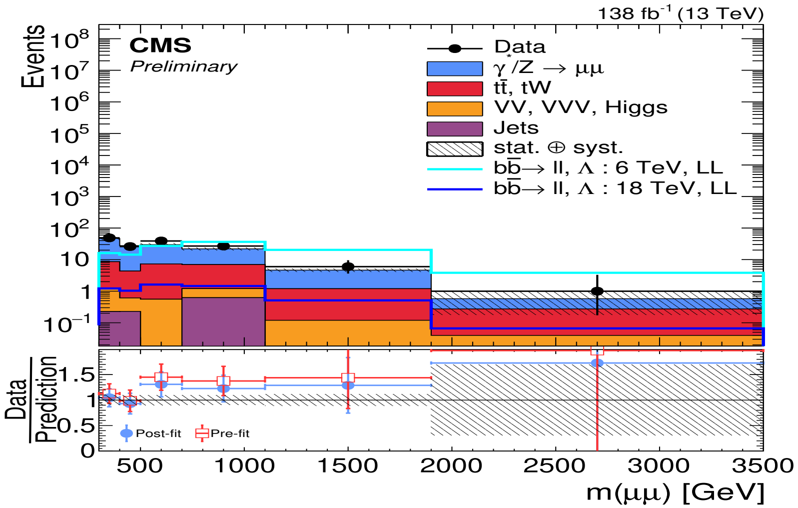
Events with dileptons having 0, 1, and ≥ 2 b-tagged jets in the final state



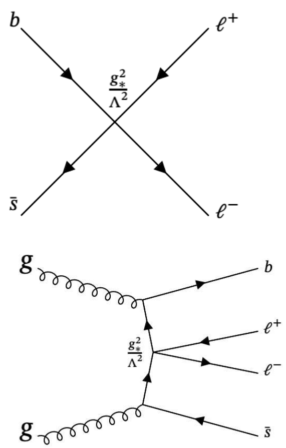
bbll model

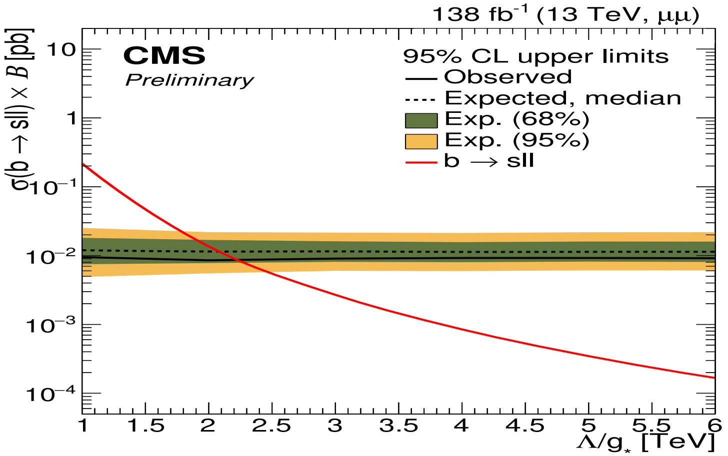






bsll model



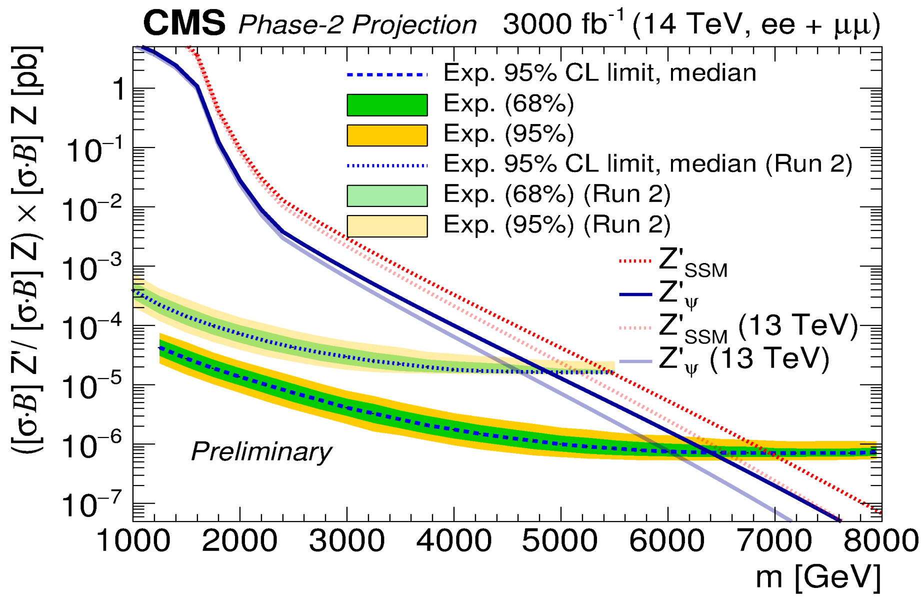


Lower limits on the energy scale Λ of 8.3 to 9.0 TeV in the bbll model, depending on model parameters, and on the ratio of energy scale and coupling Λ/g^* of 2.0 to 2.6 TeV in the bsll model.

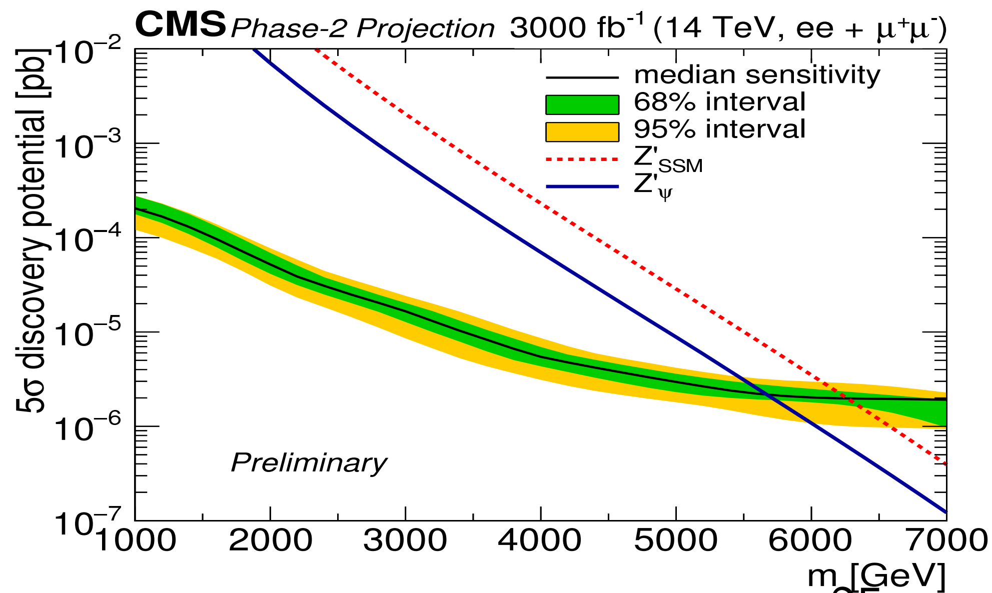
Results for bsll model represent the most stringent limits on this model to date.

Projections for $Z' \to \mu\mu$ at $\sqrt{s} = 14$ TeV (FTR-21-005)

Projections for limits on dimuon masses and on cross sections at $\sqrt{s} = 14$ TeV at $\int L\, dt = 3000$ fb^{-1} is $\sim$ 7 TeV for SSM model.



Discovery with 5 σ significance can be made up to mass of $\sim$6.3 TeV for SSM model.



Conclusions

- Run1+Run2 ($\int L\,dt \approx 26 + 140$ fb^{-1}) have provided lots of data to analyze. New energy ranges have been studied.
- This enabled us to better study the Standard Model physics, and to obtain limits for the New Physics.

  E.g. for the benchmark SSM model the mass limits reached 5.15 TeV and for the HL LHC it is expected to reach 7 TeV.
- Integrated luminosity in Run 3 with $\sqrt{s} = 13.6$ GeV is already larger than in Runs 1–2.
- Study of new signals and more analyses are coming.

CMS Publications:

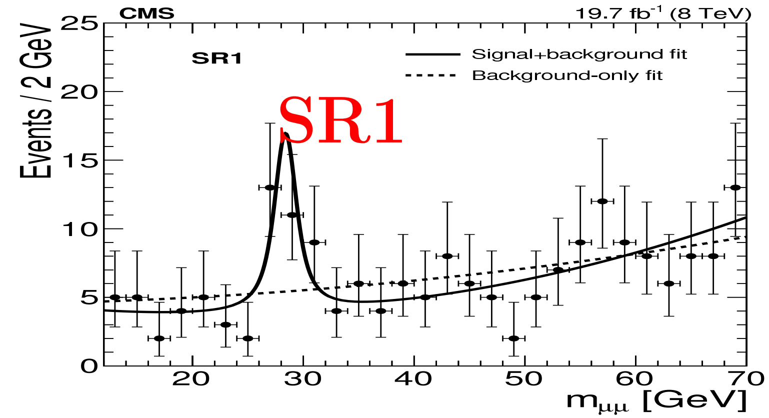
http://cms-results.web.cern.ch/cms-results/public-results/publications/

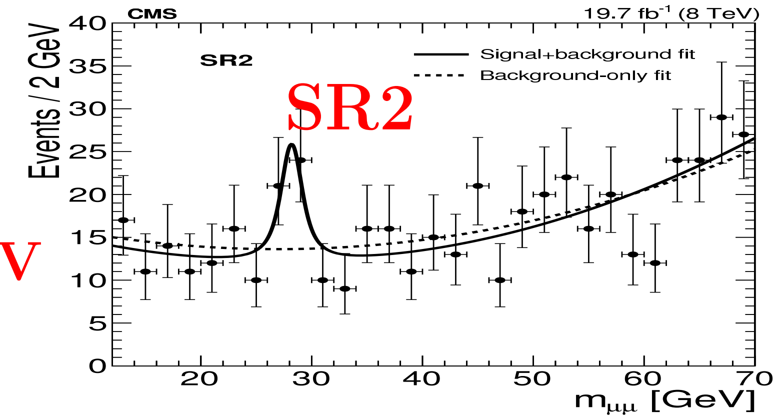
Backup slides

Search for $\mu^+\mu^-$ resonances produced in association with b-jets (JHEP 1811 (2018) 161)

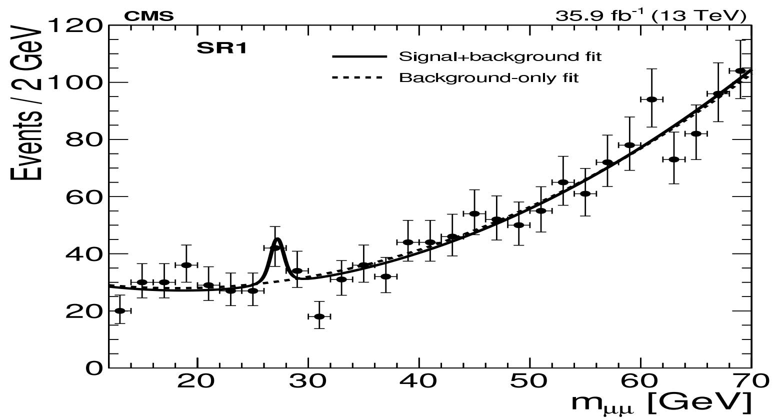
Details in talk by Alexandre Nikitenko

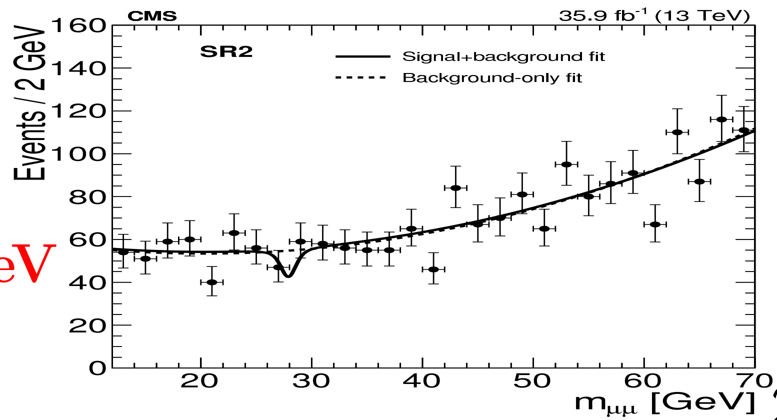
An excess of events near a $M(\mu\mu) = 28\,\mathrm{GeV}$ was observed by CMS in the 8 TeV data. Association with b quarks was required and two categories of events were considered. A similar analysis conducted with 13 TeV data results in a mild excess in one category and a deficit in another one. $\Rightarrow$ More data and additional theoretical input are required to fully understand these results.



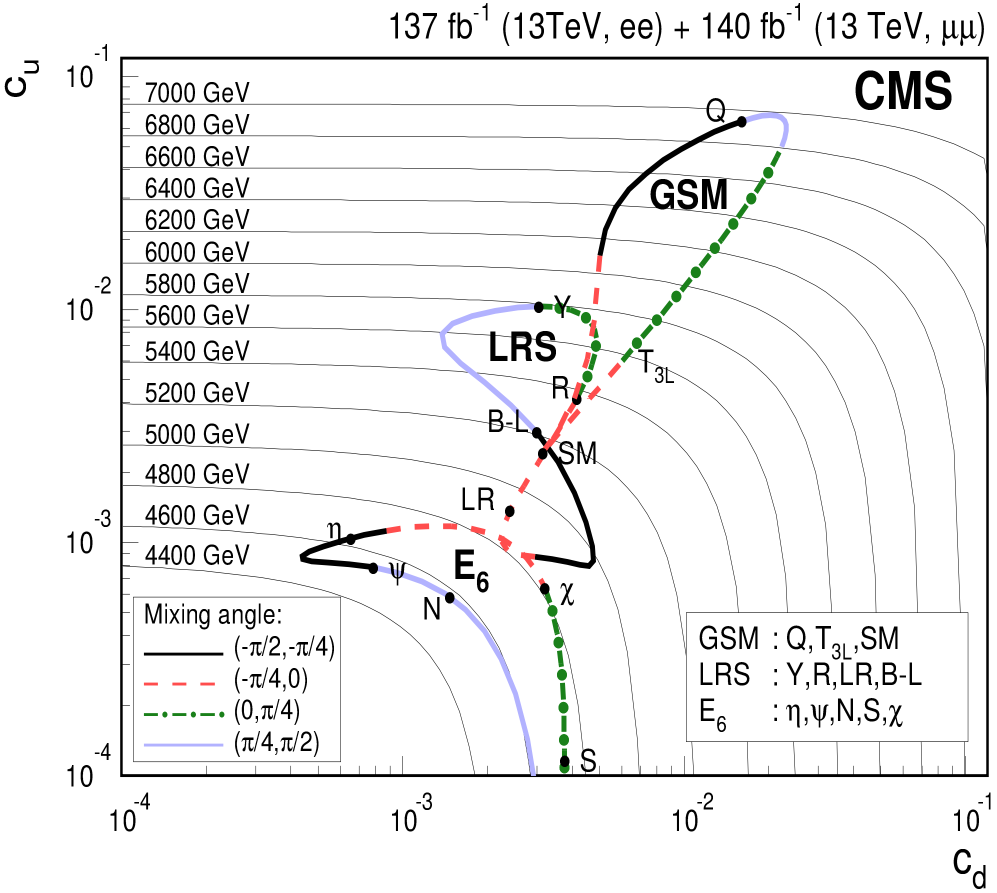


$\sqrt{s} = 8$ **TeV**





$\sqrt{s} = 13$ **TeV**



Z' cross section can be expressed in terms of quantity $[c_u w_u + c_d w_d]$ (arXiv:1010.6058):

$$\sigma^{Z'}_{l^+l^-} = \frac{\pi}{48s}\left[c_u w_u(s, M^2_{Z'}) + c_d w_d(s, M^2_{Z'})\right]$$

c_u, c_d contain information from the model-dependent couplings to fermions in the annihilation of charge $2/3$ and -$1/3$ quarks, respectively.

w_u, w_d contain information about PDFs for the annihilation at a given mass.

Z'_{SSM} is a special case of generalized sequential standard models (GSM),
Z'_ψ is one of the E_6 models,
generalized L-R models can also be included.

Plot shows iso-contours of cross section with constant $c_u + (w_d/w_u)c_d$.

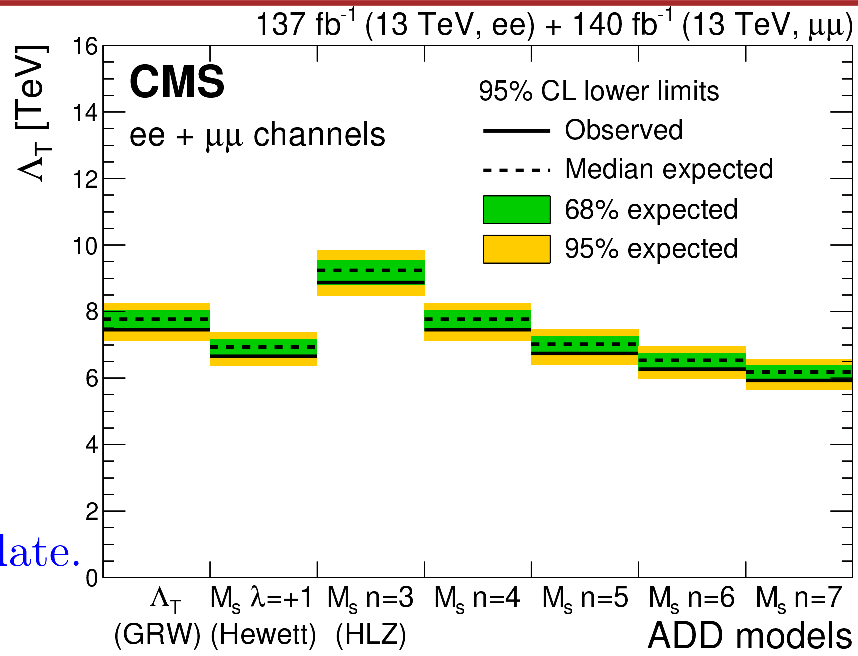
Changing this combination (or $\int L\,dt$) by 1 order of magnitude moves the mass limits by ≈ 1 TeV.

JHEP 07 (2021) 208; arXiv:2103.02708 with 140 fb^{-1}at $\sqrt{s} = 13\,\mathrm{TeV}$

Search for the effects of ADD —
large extra dimensions in $\mu\mu$ invariant mass spectrum

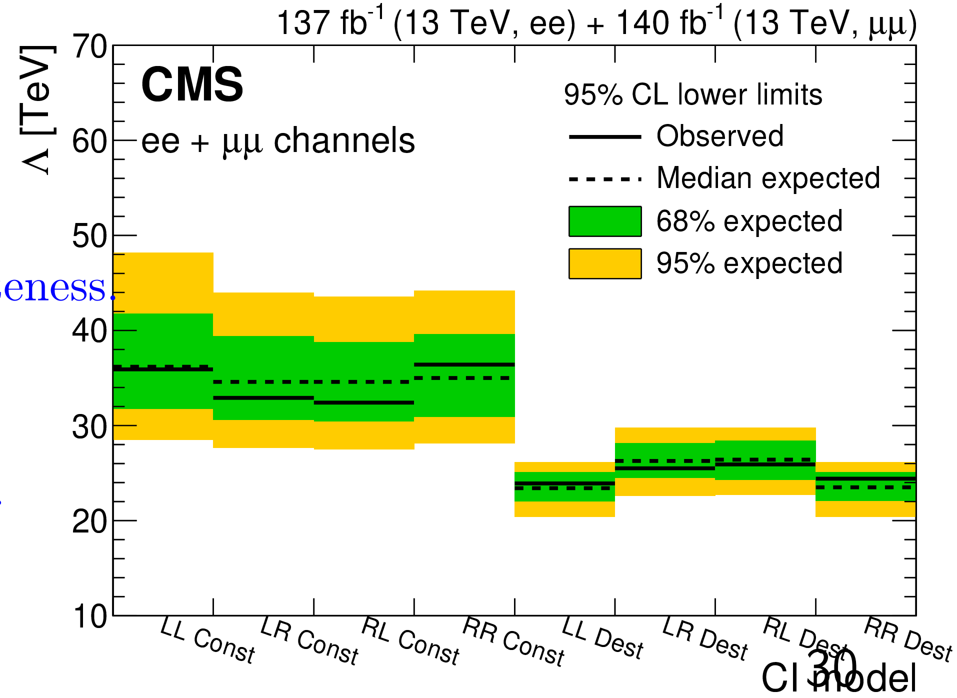
CMS set limits on the model parameter Λ_T up to 9 TeV at 95% C.L.

The observed 95% C.L limits on ADD models significantly improve the previous limits and provide the best limits based on dimuon events to date.



CI model comes from idea of quark and lepton compositeness.

95% C.L. lower limits are set on Λ, the energy scale parameter for the contact interaction: 24–36 TeV, for destructive and constructive interference.

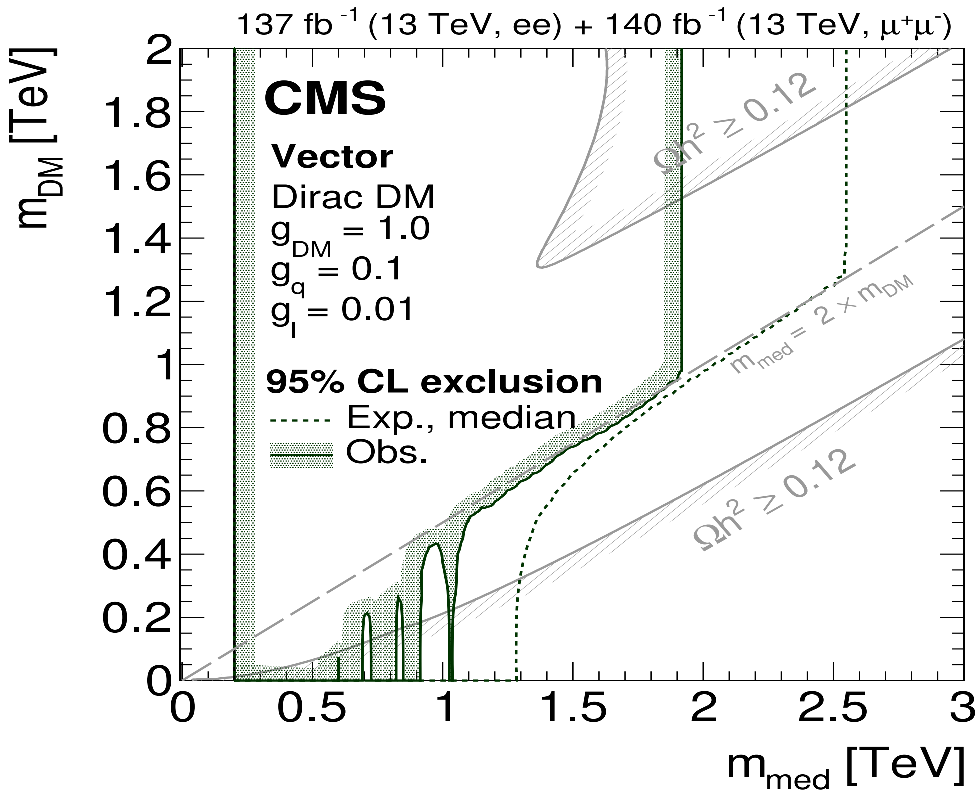


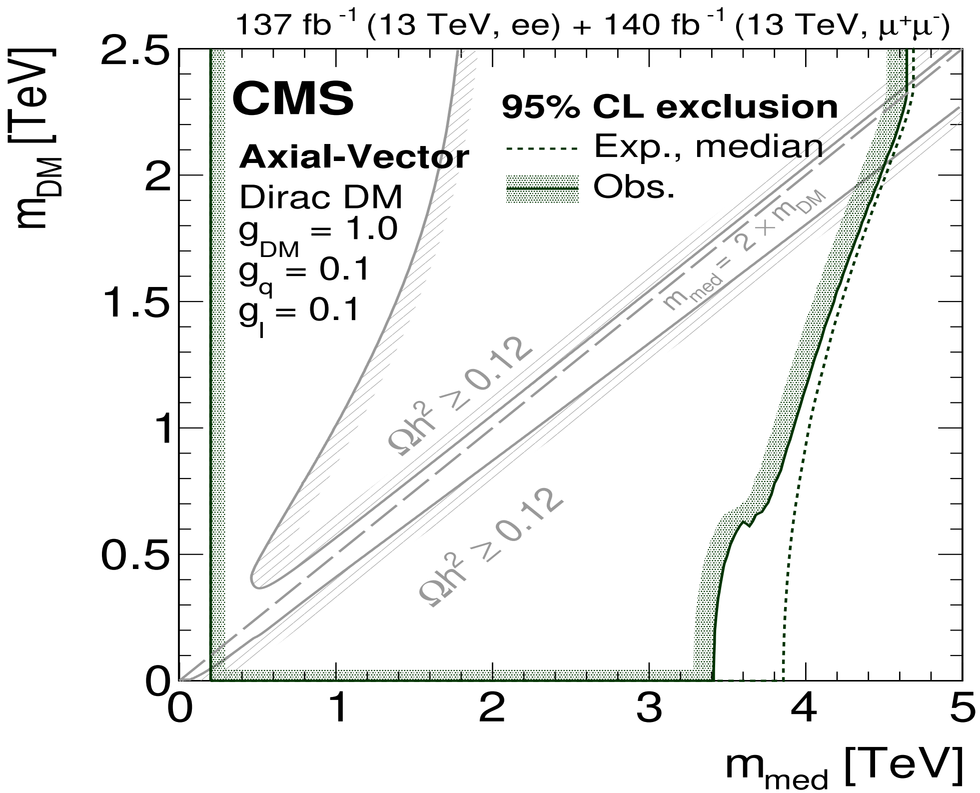
Simplified model of dark matter production via a mediator particle in s channel,

Used 2 sets of benchmark coupling values from "Recommendations of the LHC Dark Matter Working Group" (arXiv:1703.05703, CERN-LPCC-2017-01):

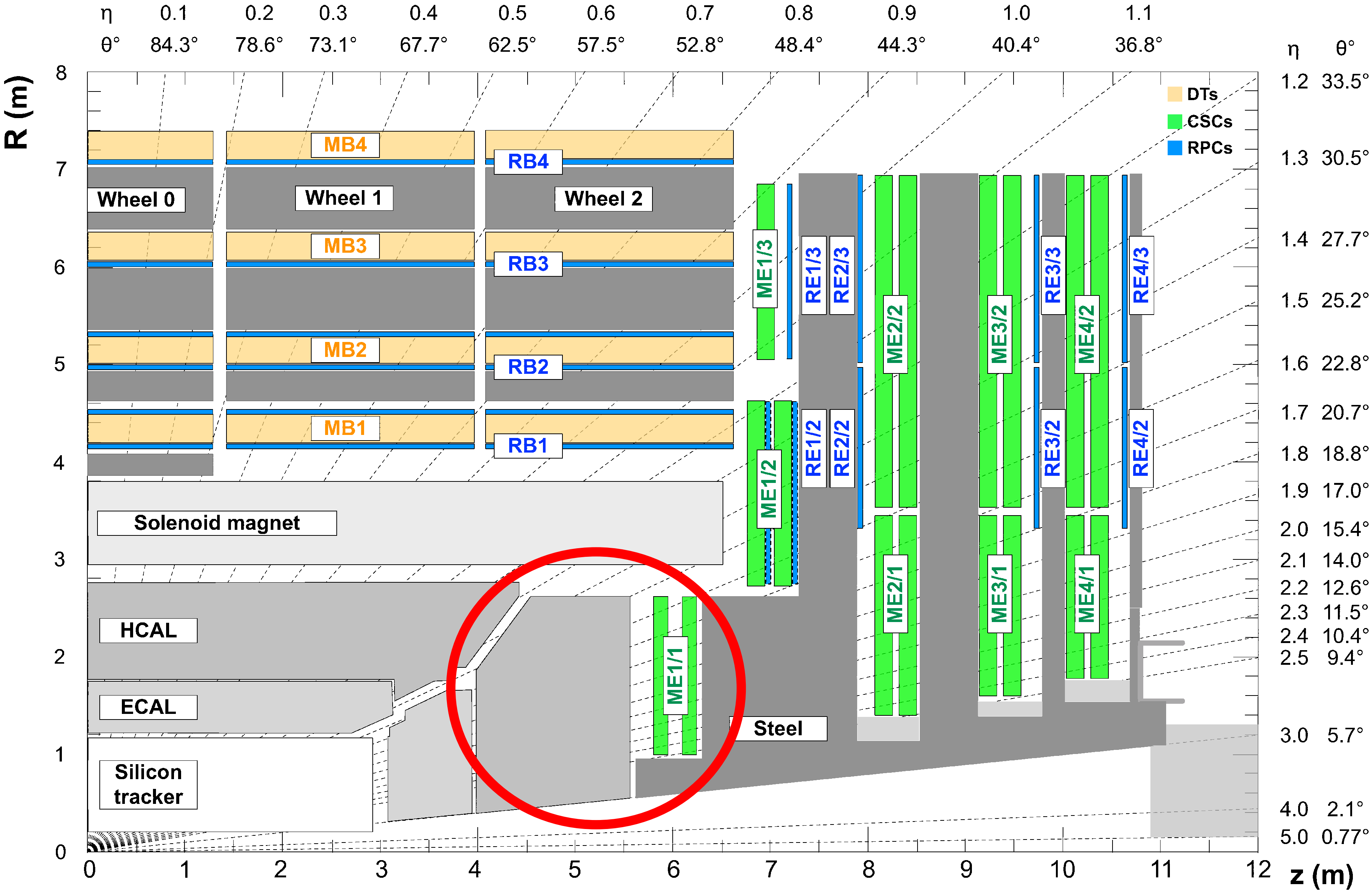
- Vector mediator with small couplings to leptons: $g_{\mathrm{DM}} = 1.0$, $g_{\mathrm{q}} = 0.1$, $g_{\ell} = 0.01$;
- Axial-vector mediator with equal couplings to q and ℓ: $g_{\mathrm{DM}} = 1.0$, $g_{\mathrm{q}} = g_{\ell} = 0.1$.

Limits at 95% confidence level are obtained for masses of DM particle and mediator.



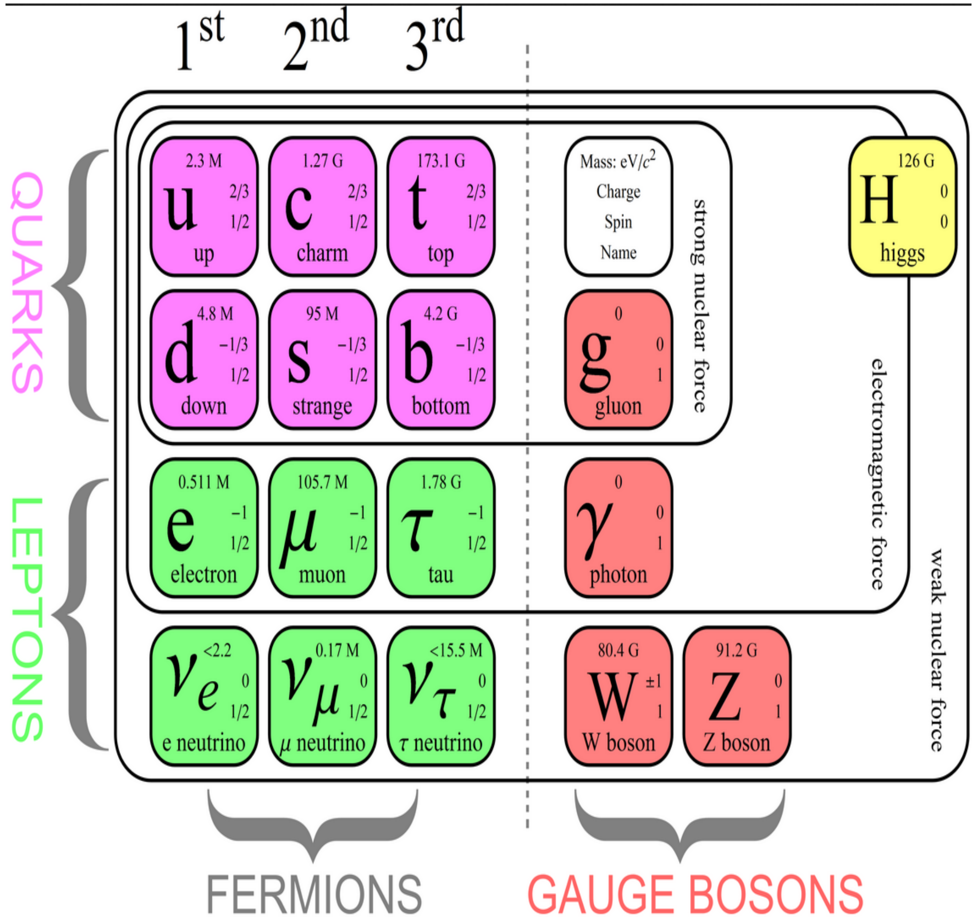


RDMS (Russia and Dubna Member States) has a full responsibility for internal endcap detectors: ME1/1 (Muon Endcap) and HE (Hadron calorimeter endcap)



SM main features:

- 6 quarks (3 generations)
- 3 generation of leptons and neutrinos
  muons vs electrons
- 4 vector bosons: g, γ, Z, W —
  for 3 interactions (str., e-m., weak),
  3 gauged symmetries $SU(3) \times U(1) \times SU(2)$
- Higgs boson, providing masses
  of elementary particles by Higgs mechanism
- Mixing of flavors
  with CKM and PMNS matrices



Phenomena not explained:

- Gravity
- Dark matter
- Hierarchy problem
- Strong CP-problem
- Number of parameters
- Matter–antimatter asymmetry

Need to search new physics beyond SM

Models Beyond Standard Model

Many theories beyond Standard Model developed to address SM omissions.

New heavy resonances appear naturally in various extensions of Standard Model:

- E_6 models Z'_ψ, Z'_χ, Z'_η arise in different ways of breaking E_6 symmetry group $E_6 \to SO(10) \times U(1)_\psi$; $SO(10) \to SU(5) \times U(1)_\chi$; $Q_{Z'} = Q_\psi \sin(\theta_6) + Q_\chi \cos(\theta_6)$
- SSM (Sequential Standard Model) or "reference" model — The same coupling constants for Z' as for the SM
- Heavy graviton resonances are predicted by RS1 (Randall-Sundrum) model of TeV-scale gravity with one additional warped extra dimension: coupling constant $c = k/\bar{M}_{Pl}$

Non-resonant models such as ADD and Contact interactions:

- ADD (Arkani-Hamed–Dimopoulos–Dvali) — large flat extra dimensions, low-energy effective string scale Λ_T
- Contact interactions model comes from idea of quark and lepton compositeness. Conventional benchmark — 4-fermion interaction model $\mathcal{L} \sim \dfrac{4\pi}{\Lambda^2}(\bar{q}_L \gamma^\mu q_L)(\bar{l}_L \gamma_\mu l_L)$. Λ — the energy scale parameter for the contact interaction.

There exist also other models in which heavy dileptons appear.

Z' Models (JHEP 1806 (2018) 120)

$U'(1)$ model	Mixing angle	$\mathcal{B}(\ell^+\ell^-)$	c_u	c_d	$c_\mathrm{u}/c_\mathrm{d}$	$\Gamma_{Z'}/M_{Z'}$
E_6						
$U(1)_\chi$	0	0.061	6.46×10^{-4}	3.23×10^{-3}	0.20	0.0117
$U(1)_\psi$	0.5π	0.044	7.90×10^{-4}	7.90×10^{-4}	1.00	0.0053
$U(1)_\eta$	-0.29π	0.037	1.05×10^{-3}	6.59×10^{-4}	1.59	0.0064
$U(1)_S$	0.129π	0.066	1.18×10^{-4}	3.79×10^{-3}	0.31	0.0117
$U(1)_N$	0.42π	0.056	5.94×10^{-4}	1.48×10^{-3}	0.40	0.0064
LR						
$U(1)_R$	0	0.048	4.21×10^{-3}	4.21×10^{-3}	1.00	0.0247
$U(1)_{B-L}$	0.5π	0.154	3.02×10^{-3}	3.02×10^{-3}	1.00	0.0150
$U(1)_{LR}$	-0.128π	0.025	1.39×10^{-3}	2.44×10^{-3}	0.57	0.0207
$U(1)_Y$	0.25π	0.125	1.04×10^{-2}	3.07×10^{-3}	3.39	0.0235
GSM						
$U(1)_{SM}$	-0.072π	0.031	2.43×10^{-3}	3.13×10^{-3}	0.78	0.0297
$U(1)_{T3L}$	0	0.042	6.02×10^{-3}	6.02×10^{-3}	1.00	0.0450
$U(1)_Q$	0.5π	0.125	6.42×10^{-2}	1.60×10^{-2}	4.01	0.1225

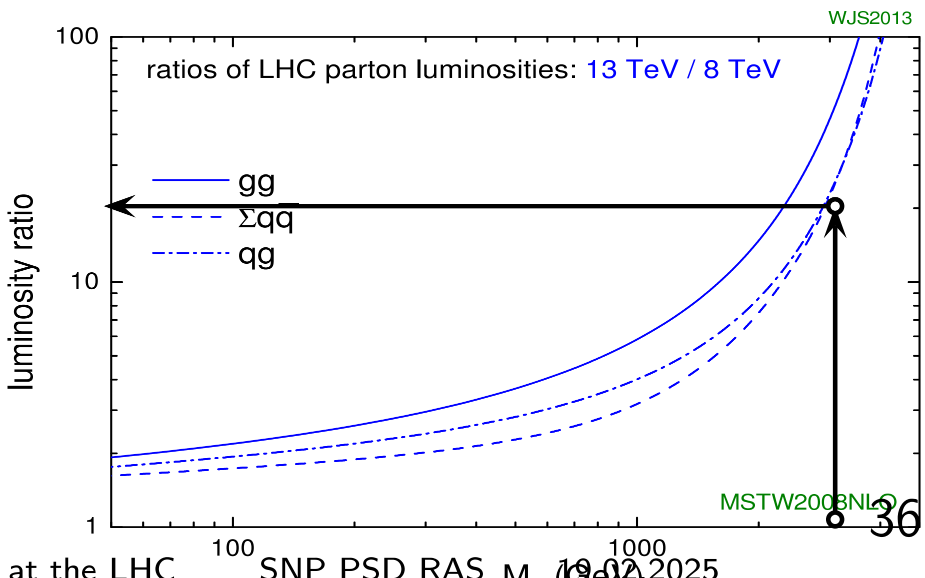
Table 1. Various benchmark models with their corresponding mixing angles, their branching fraction ($\mathcal{B}$) to dileptons, the c_u and c_d parameter values and their ratio, and the width to mass ratio of the associated Z' boson.

History and CMS Publications on Searches for Heavy Dilepton Resonances

Publications and Results on Searches for Heavy Dilepton Resonances:

Date	Paper		$\sqrt{s}$,	L,	Z' Models		RS1 Model		
	Reference	arXiv	TeV	fb^{-1}	SSM	Z'_ψ	$c = 0.1$	$c = 0.05$	$c = 0.01$
03.2011	JHEP 05 (2011) 093	1103.0981	7	0.040	1.14	0.89	1.08	0.86	
06.2012	PL B714 (2012) 158	1206.1849	7	5	2.33	2.00	2.14	1.81	
12.2012	PL B720 (2013) 63	1212.6175	7+8	5.3+4.1	2.59	2.26	2.39	2.03	
12.2014	JHEP 04 (2015) 025	1412.6302	8	20.6	2.90	2.57	2.73	2.35	1.27
12.2015	CMS PAS EXO-15-005		13	2.8	3.15	2.60			
09.2016	EXO-15-005 paper	1609.05391	8+13	20.6+2.9	3.37	2.82	3.11		1.46
08.2016	CMS PAS EXO-16-031		13	13.0	4.00	3.50			
03.2018	JHEP 1806 (2018) 120	1803.06292	13	36	4.50	3.90	4.25	3.65	2.10
03.2021	JHEP 07 (2021) 208	2103.02708	13	140	5.15	4.56	4.78	4.16	2.47

Need to rescale integrated luminosities of measurements at $\sqrt{s} = 7$ and 8 TeV to $\sqrt{s} = 13$ TeV using Stirling plot



CMS Z' Dilepton Limits vs Integrated Luminosity