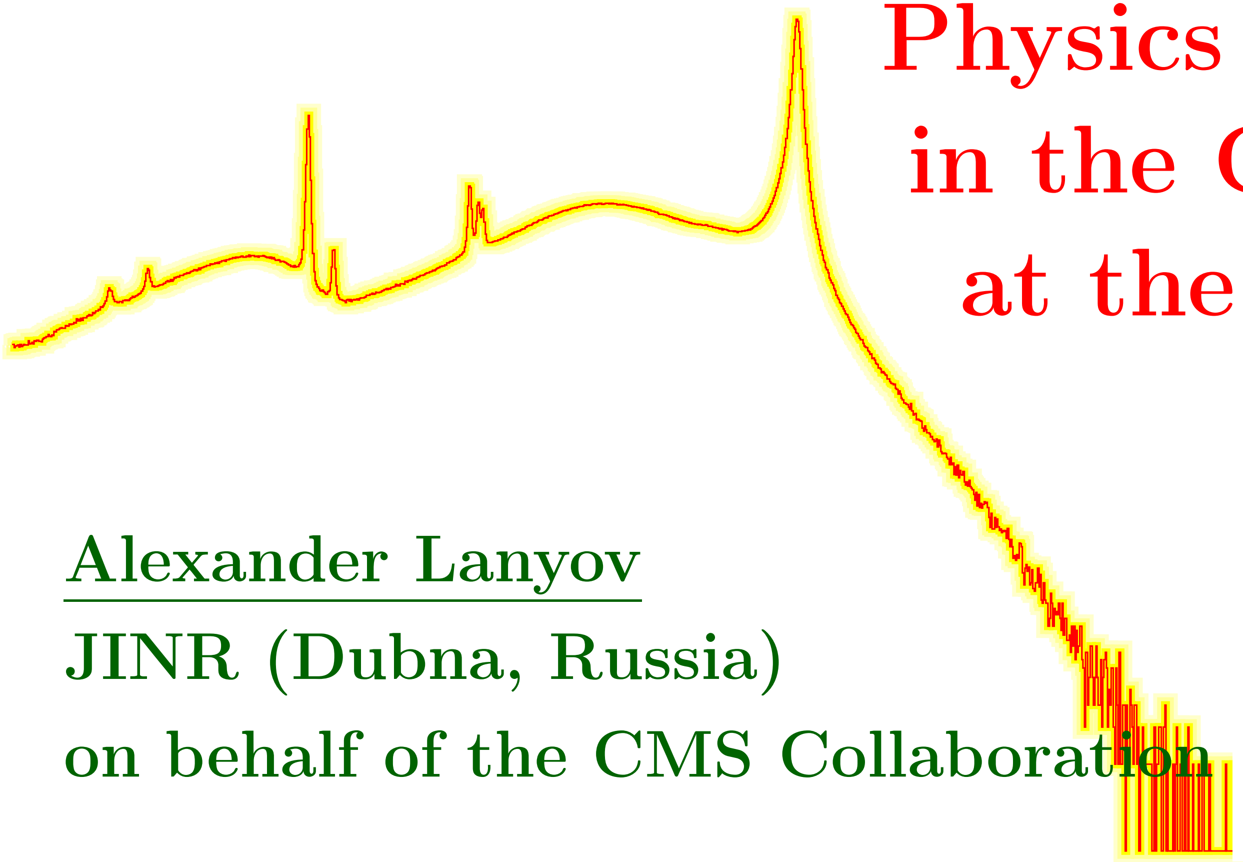
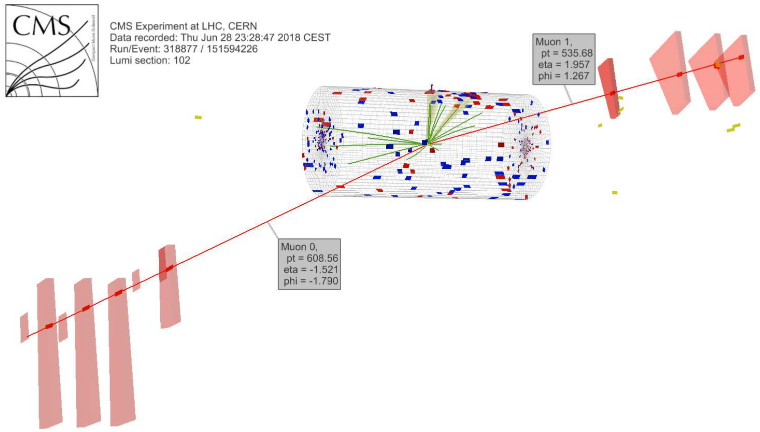
Physics with Dimuons in the CMS Experiment at the LHC





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Moscow, Russia

Outline

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- Motivation to study dimuons at CMS
- Standard Model — from Z boson to rare decays
- Exotica searches for new heavy resonances
- Conclusions

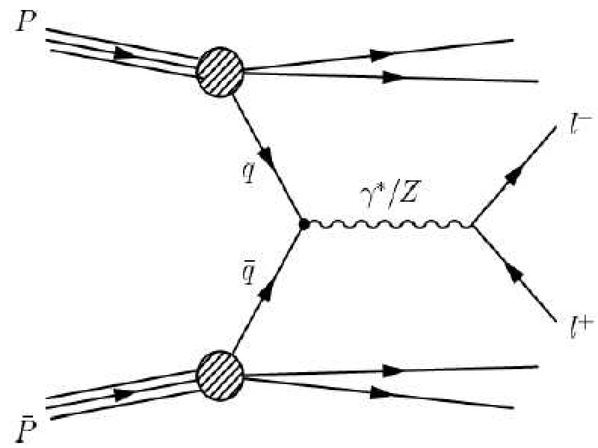
CMS Public Results:

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

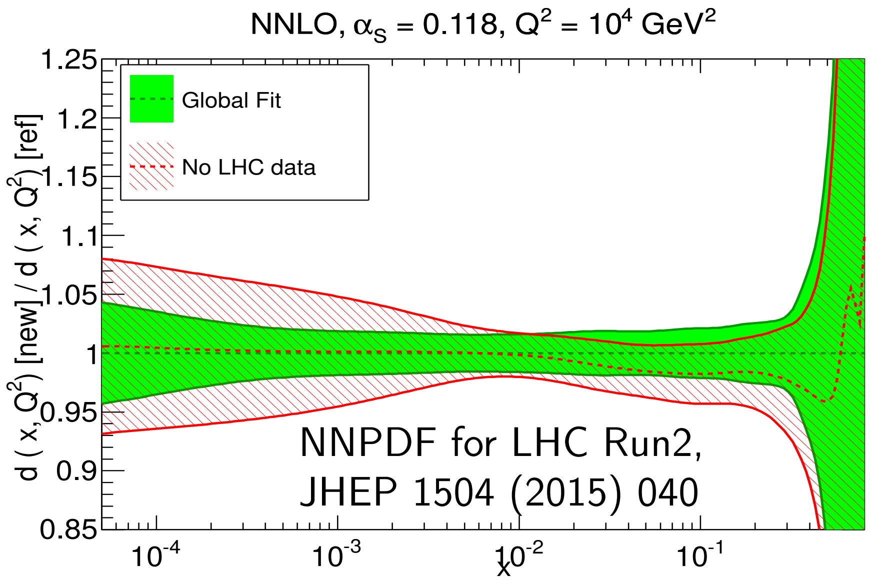
Motivation to Study Dimuons at CMS

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

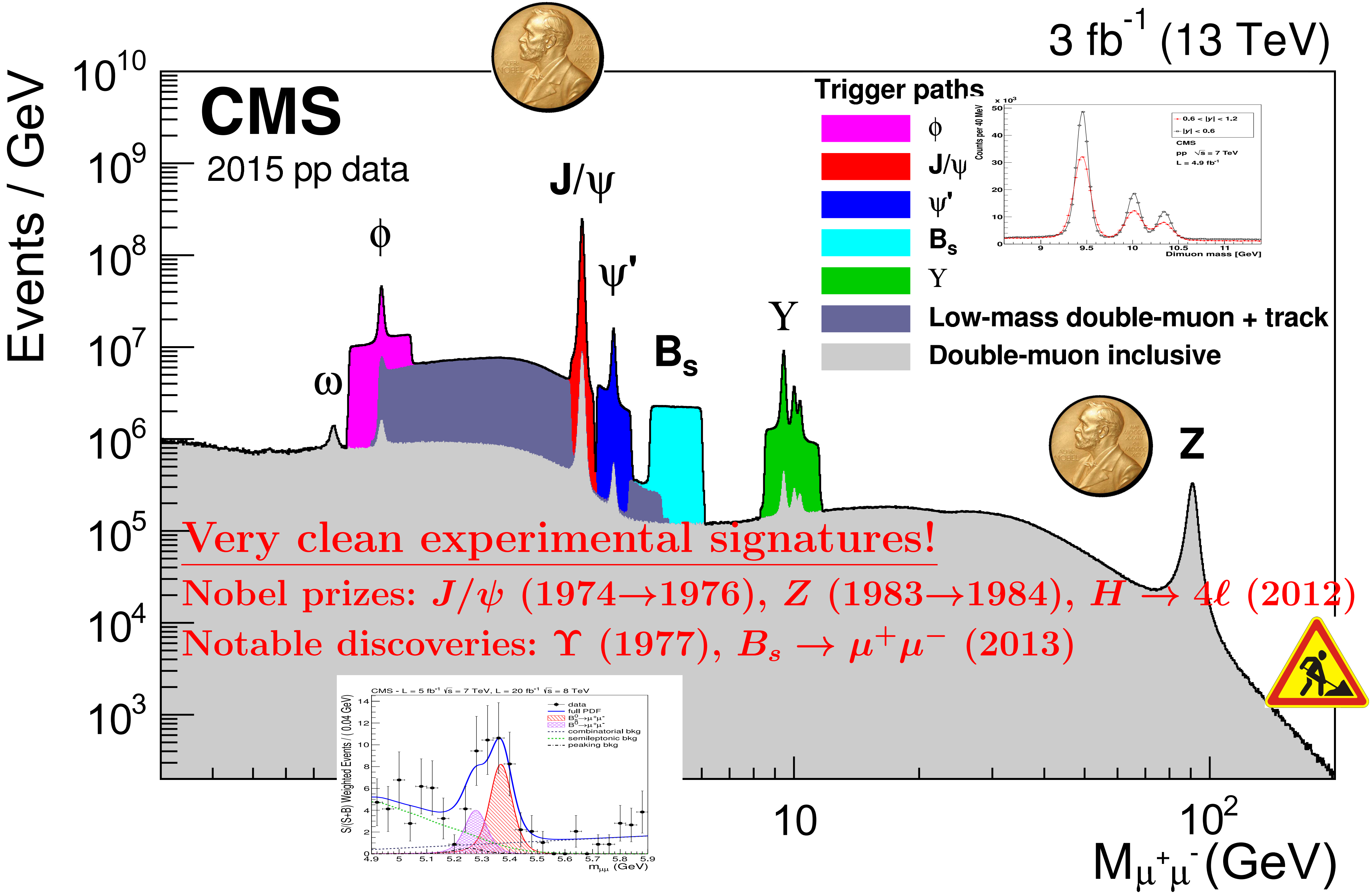
Why study dimuons at CMS?



- 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 $Z \to \mu\mu$.



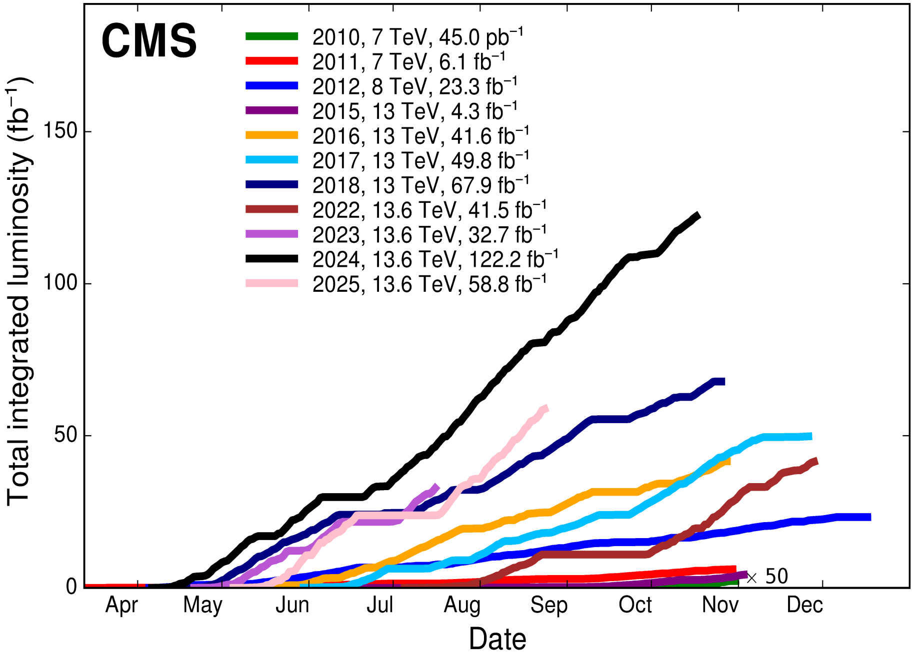
Dimuon Invariant Mass at CMS in Run 2

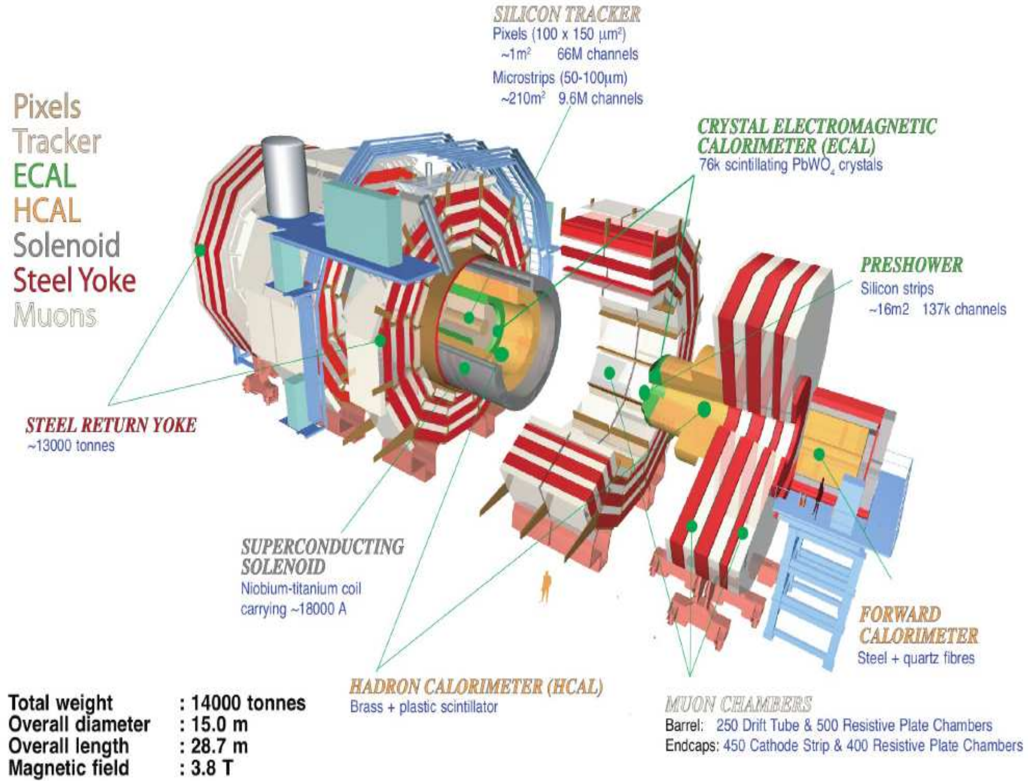


Very clean experimental signatures!

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

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



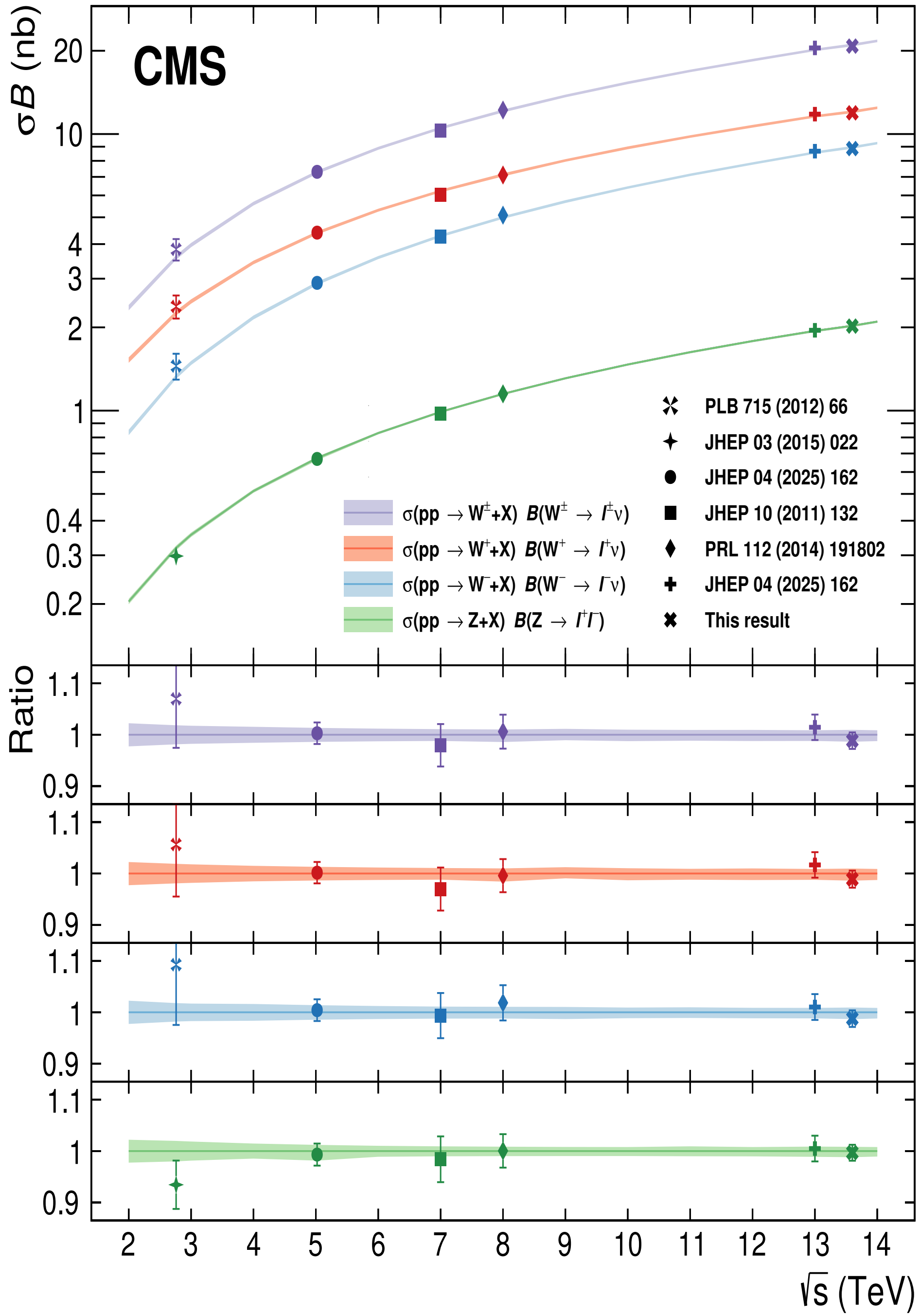


- Run 1 with $\sqrt{s} = 7$–8 TeV: $\sim$30 fb^{-1}
- Run 2 with $\sqrt{s} = 13$ TeV: Rapid rise of integrated luminosity $\sim$140 fb^{-1}
- Run 3 with $\sqrt{s} = 13.6$ TeV: started in 2022; Currently $\int \mathcal{L}\, dt \approx 250$ fb^{-1}

  Expected by the end of Run 3: $\int \mathcal{L}\, dt \approx 300 - 350$ fb^{-1}

Drell-Yan

process studies



arXiv:2503.09742 (SMP-22-017)

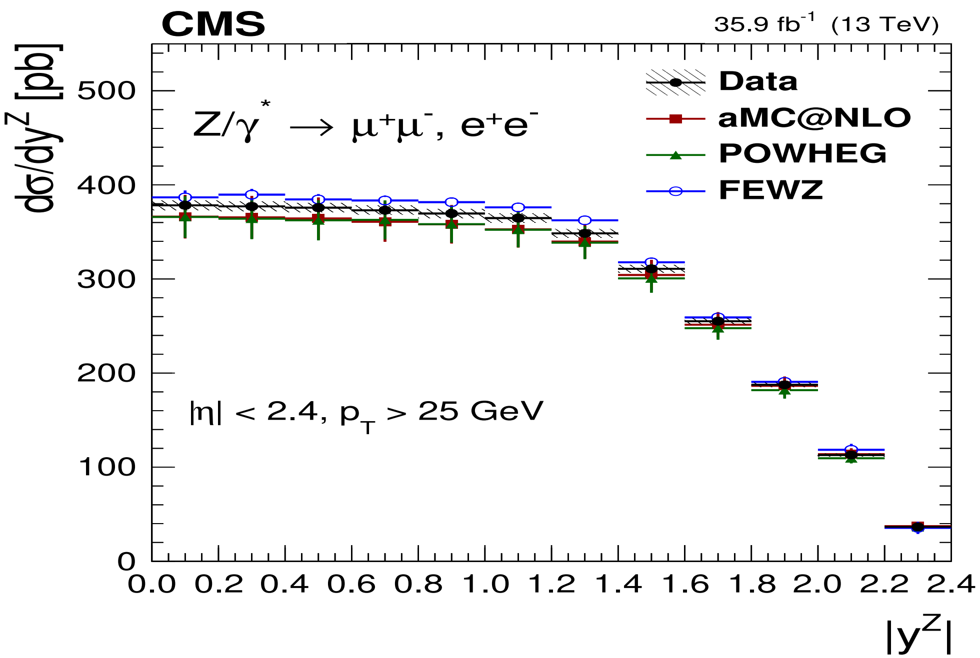
Used data with $5\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13.6$ TeV

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

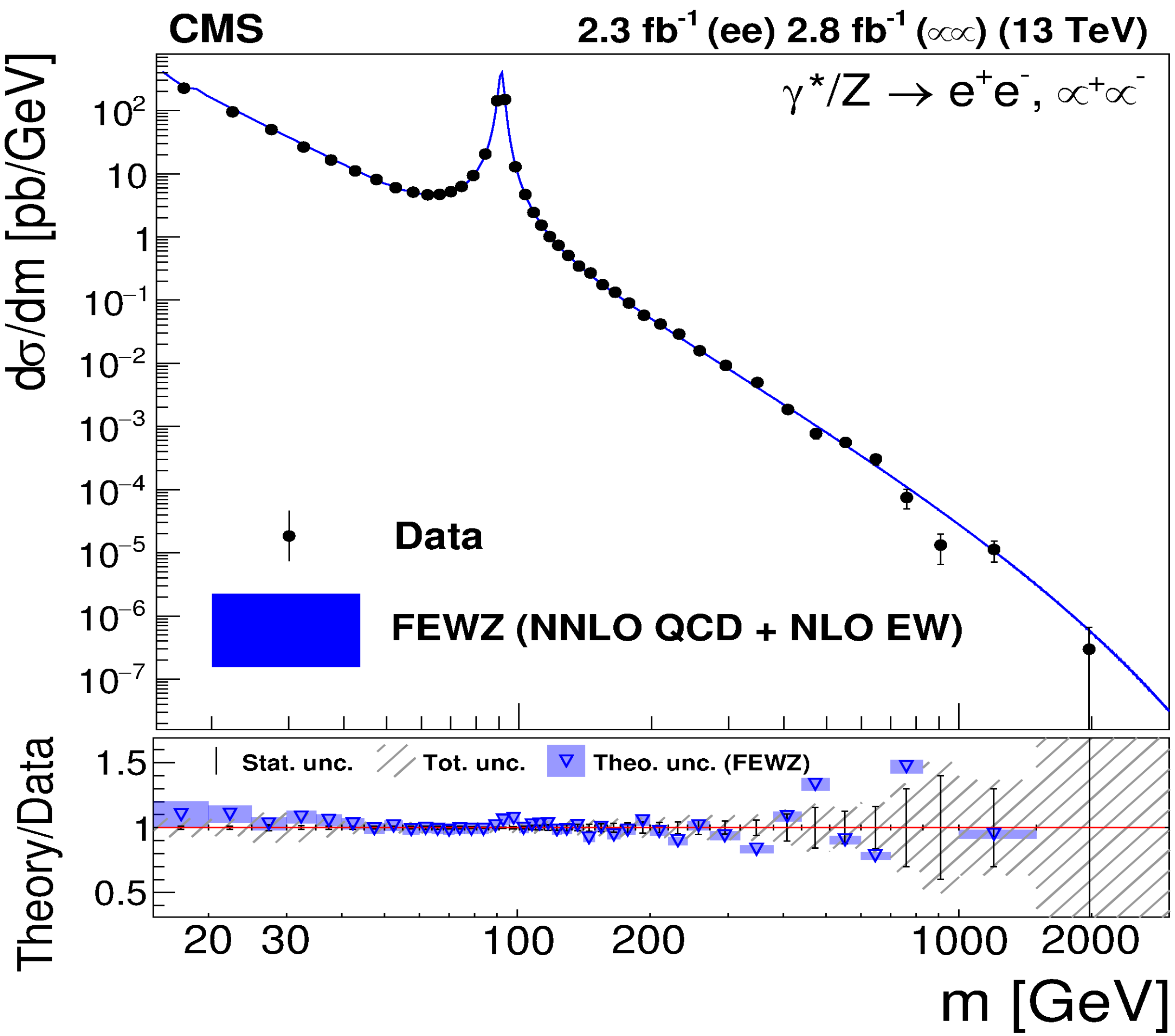
$\sqrt{s} = 13$ TeV: (JHEP 04 (2025) 162)

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)



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

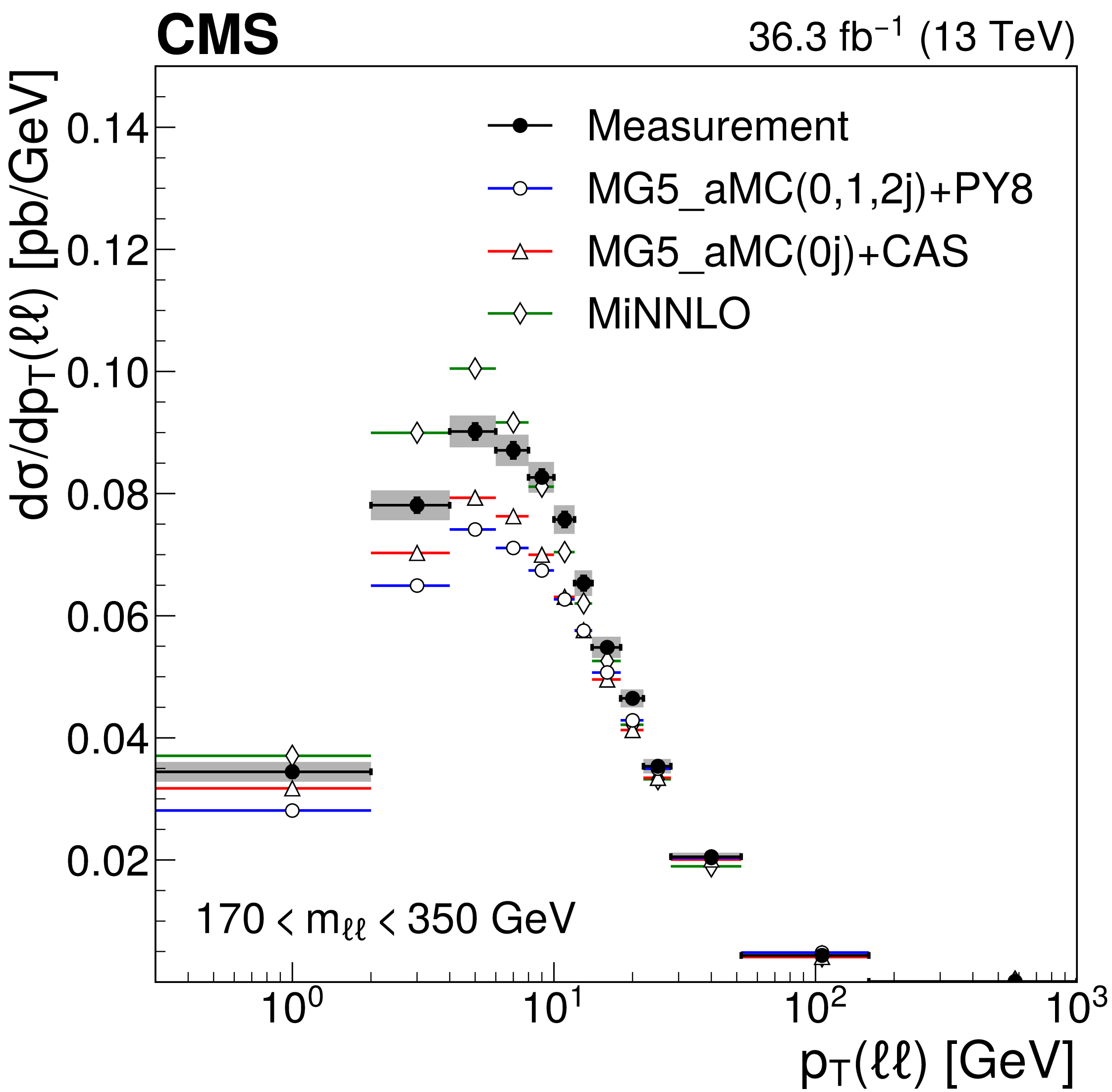
- $L = 2.8\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
- Mass range: 15—3000 GeV, divided by 43 bins
- Trigger: Isolated single muon trigger with $p_T > 20$ GeV
- Kinematic cut: $p_T^{\mathrm{Lead}} > 22$ GeV, $p_T^{\mathrm{Sub}} > 10$ GeV, $|\eta| < 2.4$
- Corrected to the full space
- Systematic uncertainty:
  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

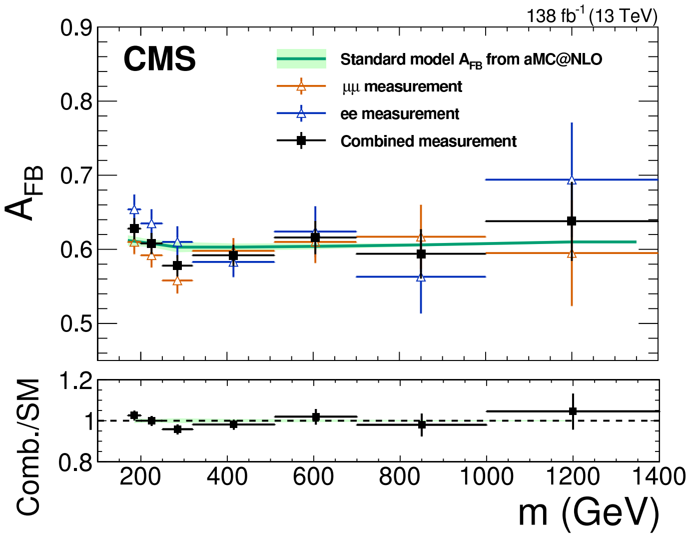
Mass dependence of the transverse momentum of Drell-Yan lepton pairs (Eur. Phys. J. C83 (2023) 628)

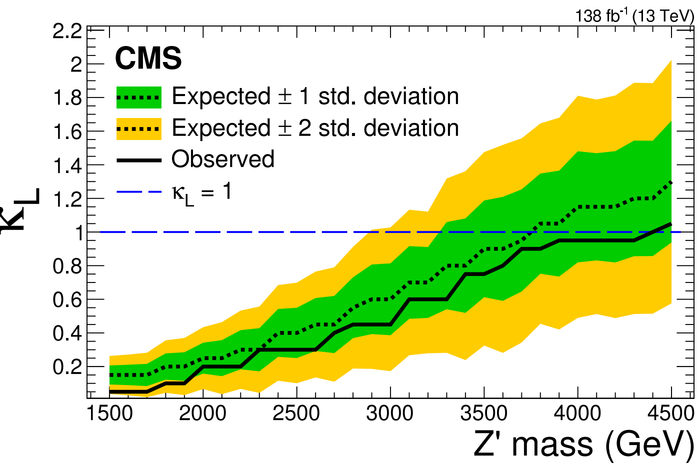
Measured double differential cross sections of DY lepton pair production, as a function of $p_{\mathrm{T}}(\ell\ell)$, and φ^*, in bins of dilepton masses: $m \in [50, 76, 106, 170, 350, 1000]$ GeV.

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.

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

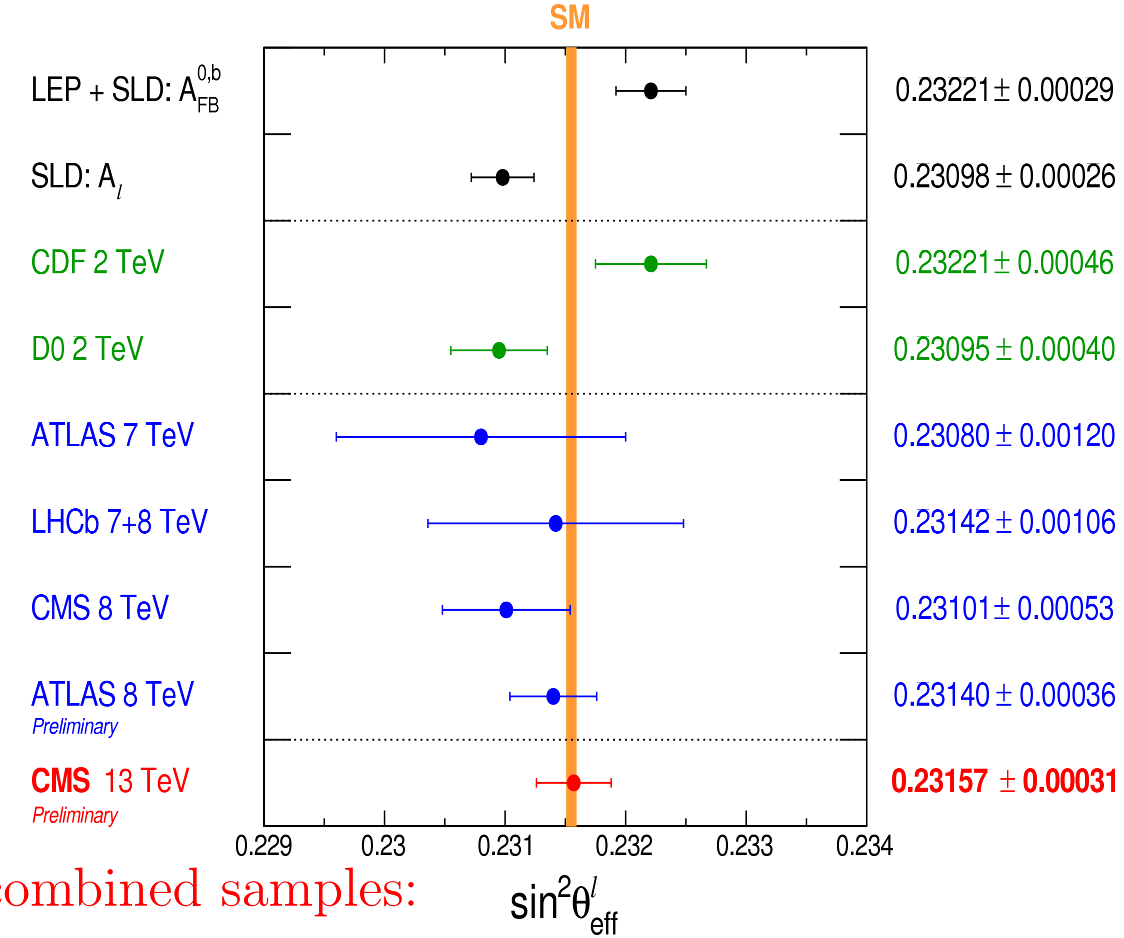
θ^* is angle between μ^- and quark direction in c.m.s. of dilepton

- Good agreement to SM prediction of $A_{FB} \approx 0.6$
- Can be 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.

  Direct resonance search is more sensitive (see later).
- A_{FB} can be used to measure Weinberg weak mixing angle $\sin^2\theta_{\mathrm{Eff}}$

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

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



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.

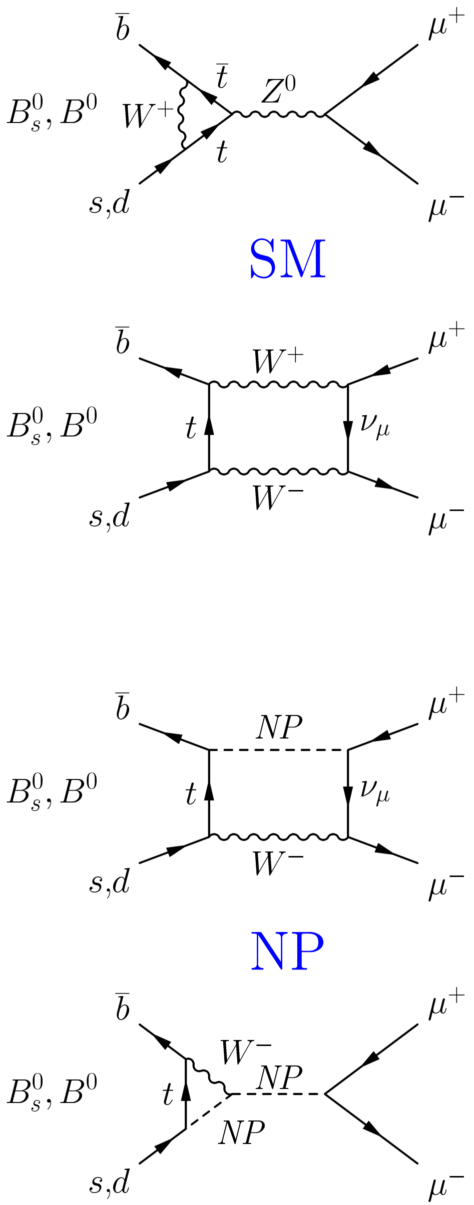
The common value for LHC measurements is dominated by the CMS measurement.

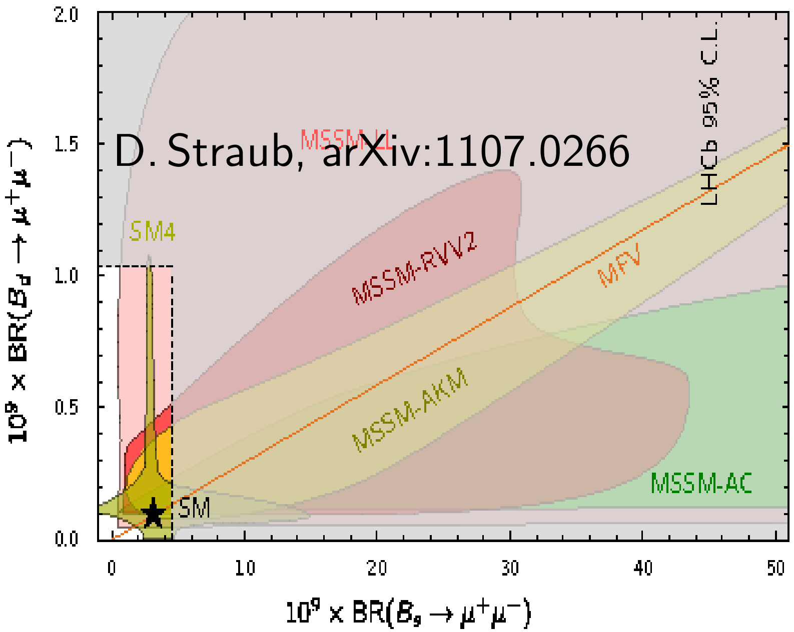
The results are consistent with the most precise measurements.

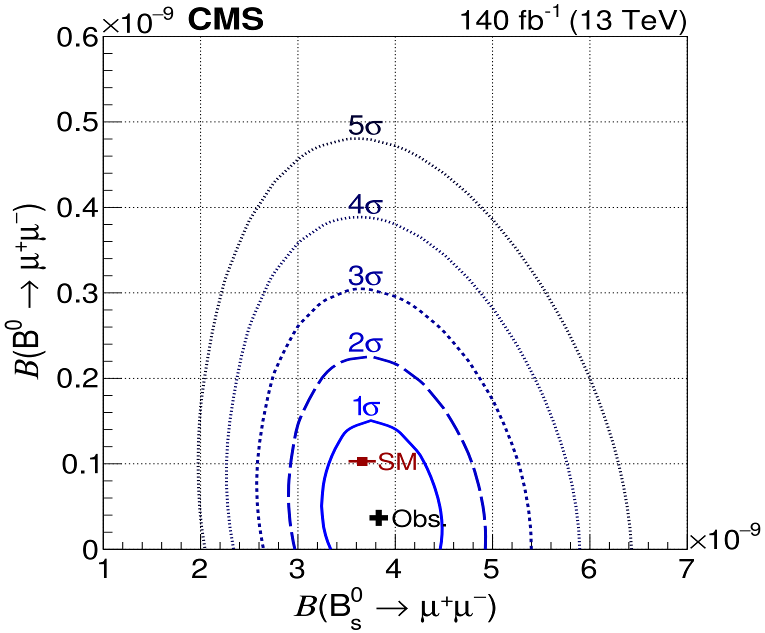
Further improvement expected at HL-LHC – ±0.00003 (CMS PAS FTR-17-001).

Rare Dimuon Decays

in Standard Model







SM predicts

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

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

The processes are sensitive to searches for BSM physics.

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

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

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

Effective B_s^0 lifetime in this decay:

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

Most precise single measurements and consistent with the SM.

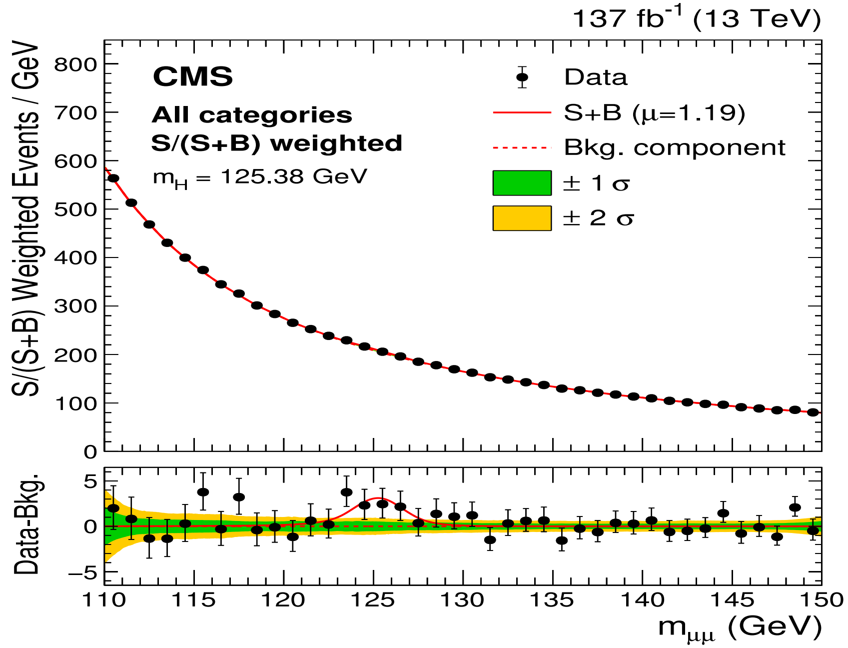
Search for Higgs $\to \mu^+\mu^-$ (JHEP 01 (2021) 148)

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

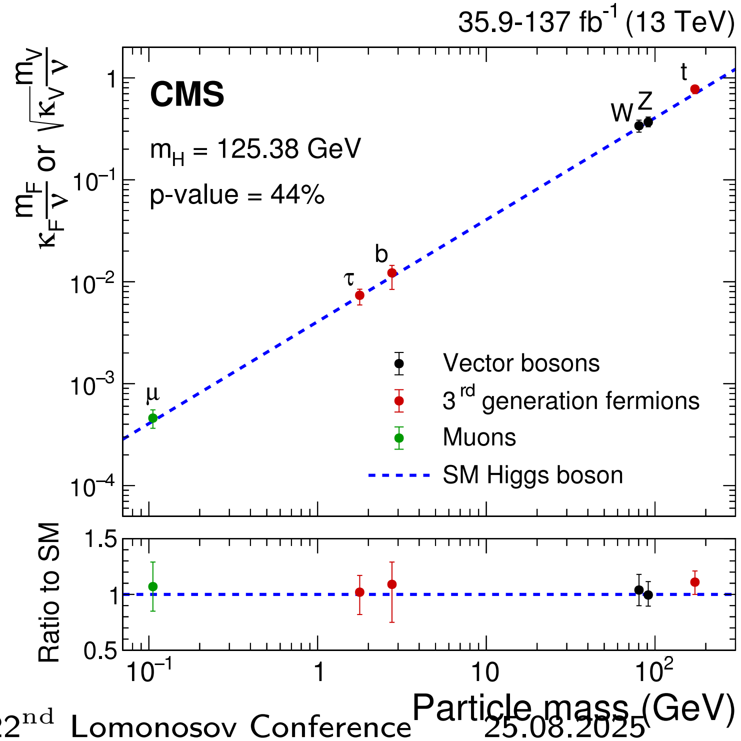
Signal strength $\hat{\mu}^{\mathrm{comb}} = 1.19^{+0.40}_{-0.39}\,(\mathrm{stat.})^{+0.15}_{-0.14}\,(\mathrm{syst.})$



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

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

[Phys.Lett. B 846 (2023) 137783]



Still more rare: $\mathrm{Br}(D^0 \to \mu^+\mu^-)_{\mathrm{SM}} = 3 \times 10^{-13}$

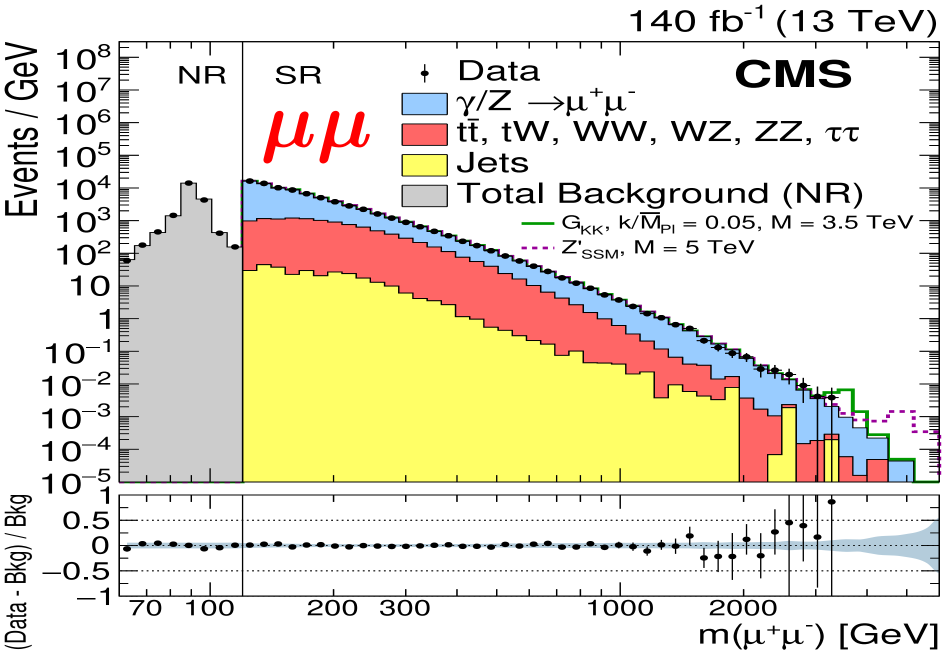
CMS limit: $\mathrm{Br} < 2.4 \times 10^{-9}$ [arXiv:2506.06152]

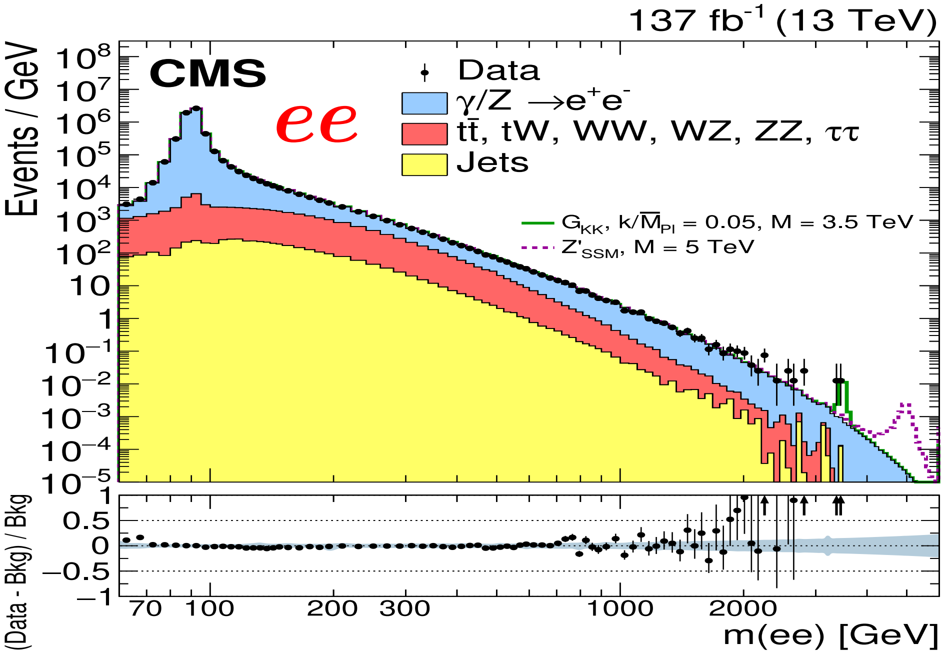
Used newly developed inclusive dimuon trigger

and CMS Run3 data at $\sqrt{s} = 13.6$ TeV from 2022–2023.

Search for Heavy Resonances in Dilepton Channels

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



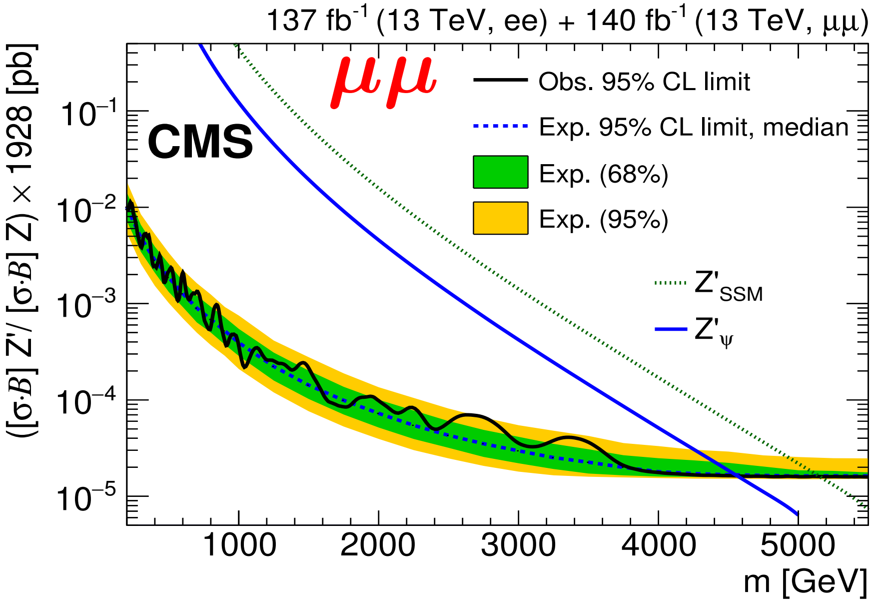


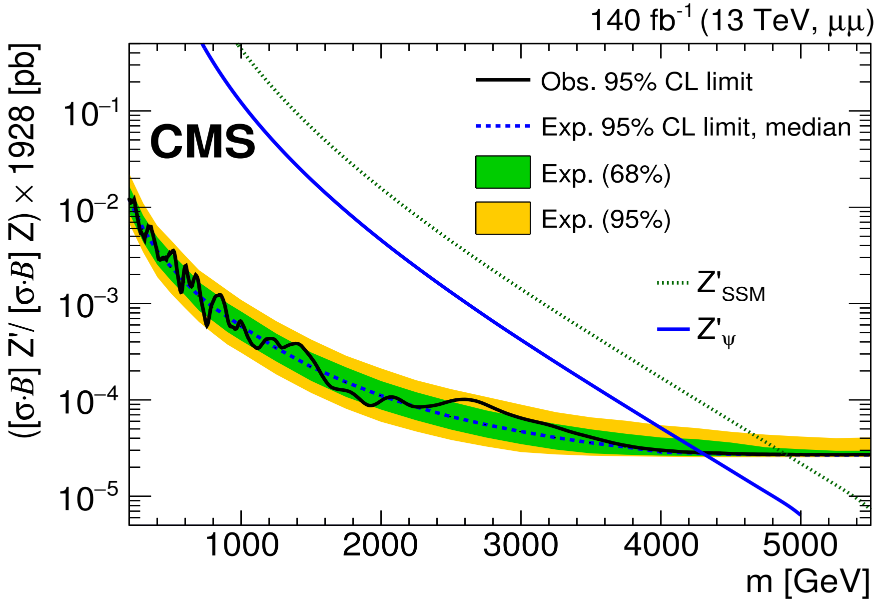
- Offline cut $p_T > 53$ GeV
- Single muon trigger $p_T > 50\,\text{GeV}$
  Double electron trigger $E_T > 33\,\text{GeV}$.
- Good Data / MC agreement,
  No obvious bumps seen.
- To impose mass limits, we normalize to $\sigma(Z)$:

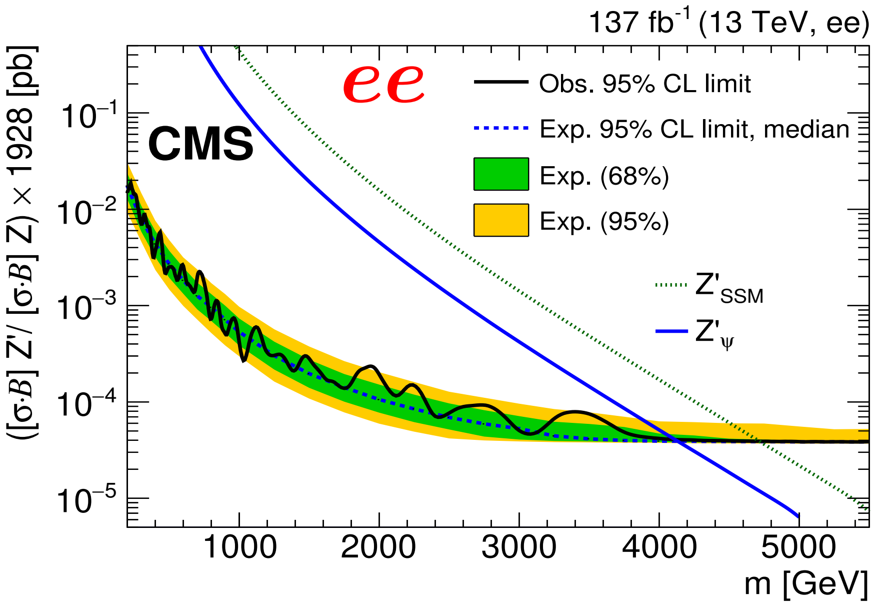
$$R_\sigma = \frac{\sigma(Z' \to \ell^+\ell^-)}{\sigma(Z \to \ell^+\ell^-)} = \frac{N(Z')}{N(Z)} \times \frac{A(Z)}{A(Z')} \times \frac{\varepsilon(Z)}{\varepsilon(Z')}$$

- 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.
- 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}).

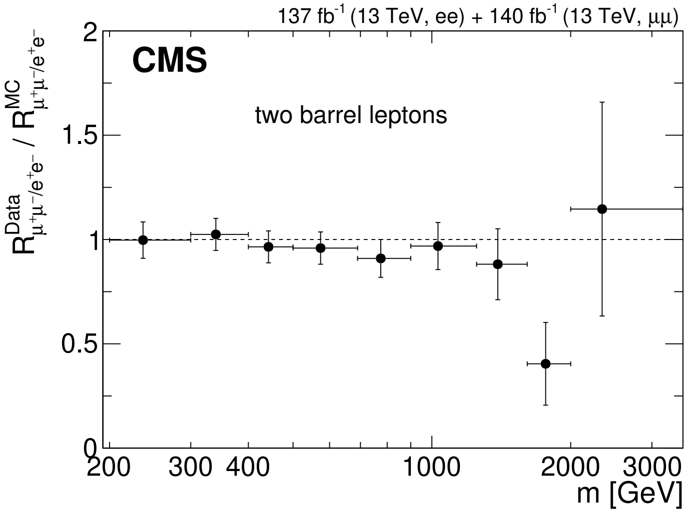
Generalization for many other models was done.

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

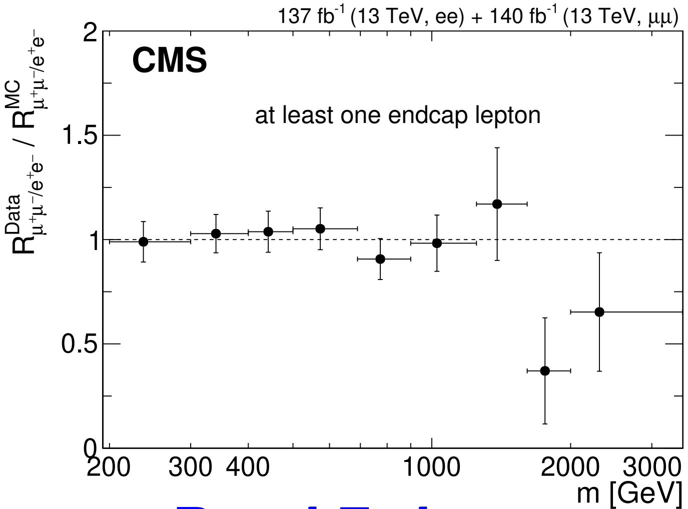
Lepton flavor universality was tested for the first time at the TeV scale
by comparing $\mu^+\mu^-$ and e^+e^- mass spectra: $R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(\mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(e^+e^-)/dm_{\ell\ell}}$
No significant deviations from SM observed.

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.

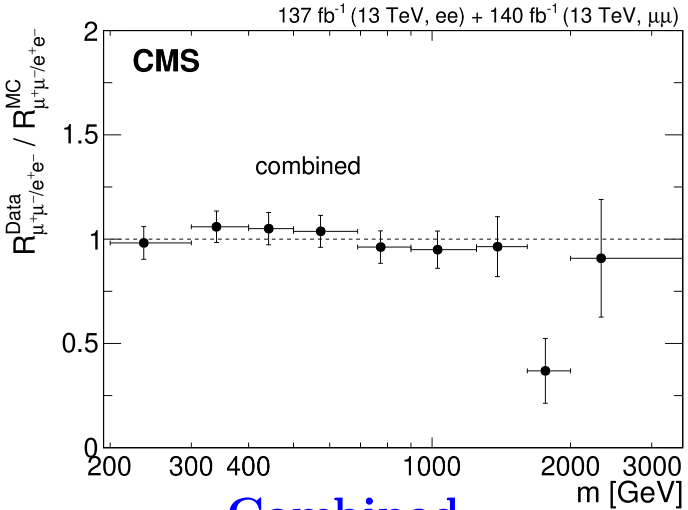
A χ^2 test for the mass range above 400 GeV is performed:
$\chi^2/\text{dof} = 11.2/7$ and $9.4/7$ for $m > 400\,\text{GeV}$.



Barrel ($|\eta| < 1.2$)



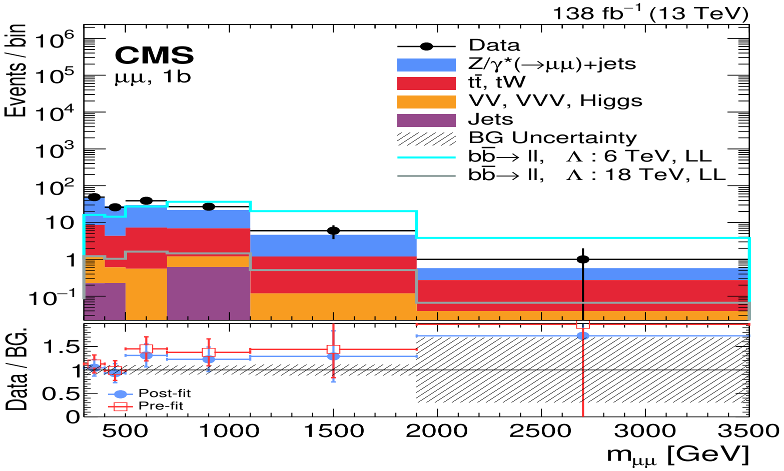
Barrel-Endcap



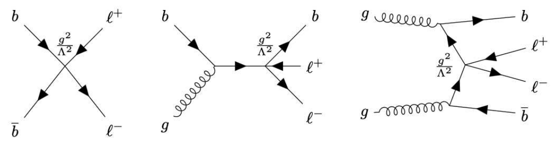
Combined

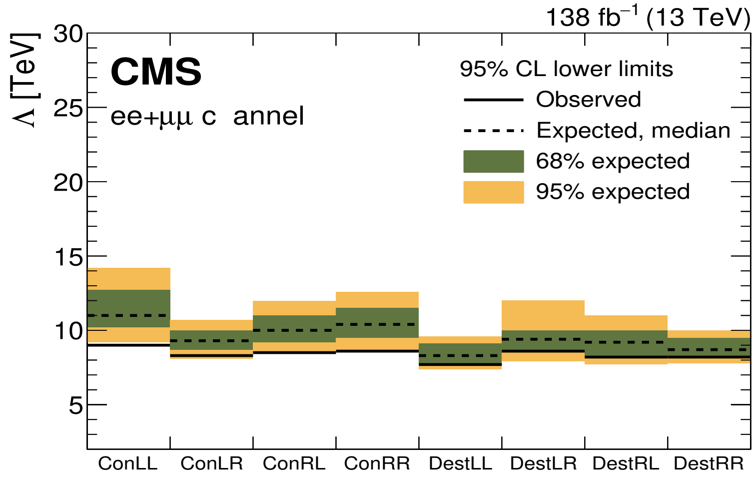
Nonresonant new physics in high-mass dilepton events in association with b-tagged jets (arXiv:2506.13565)

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

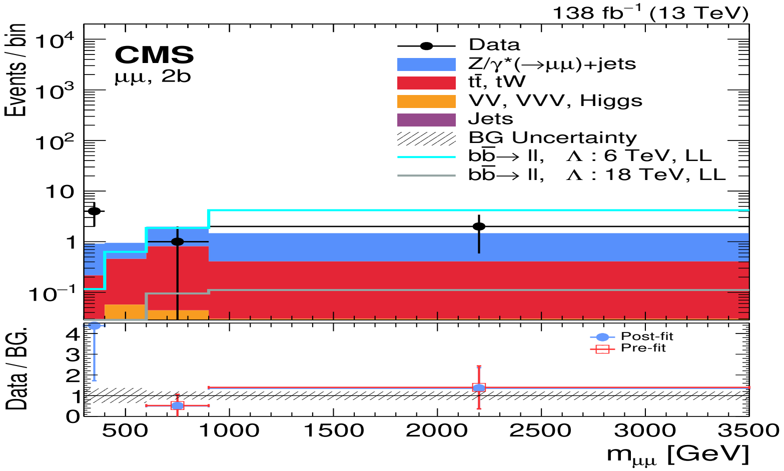


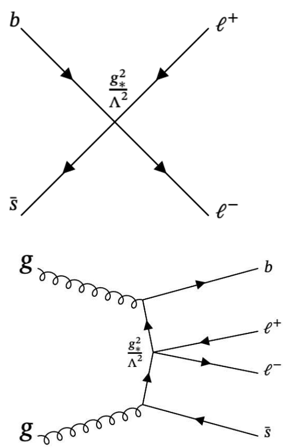
bbll model

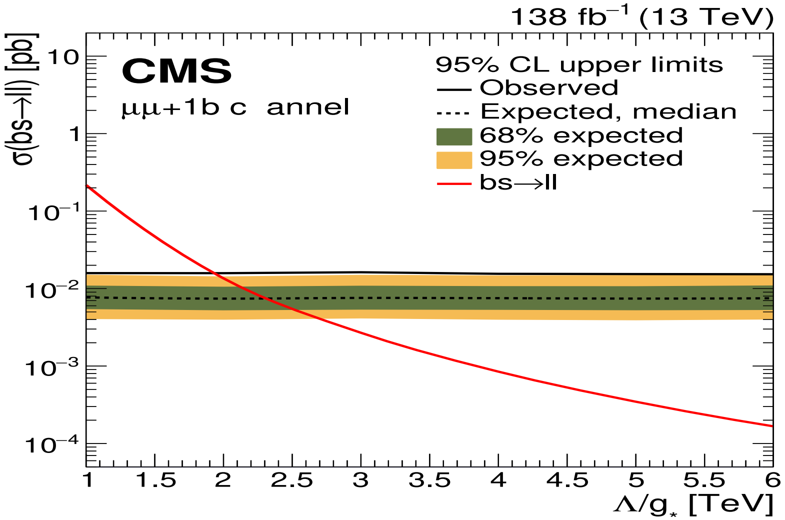




bsll model



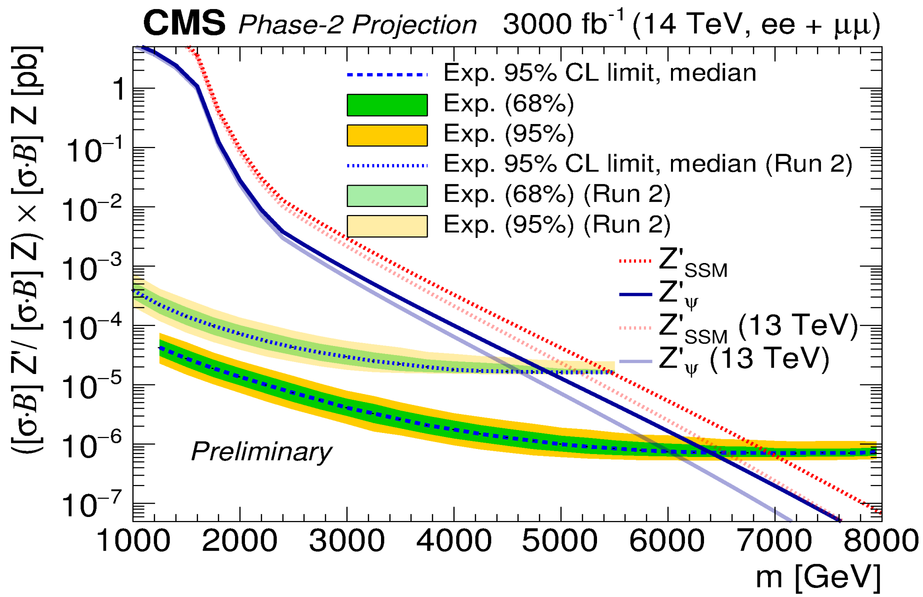




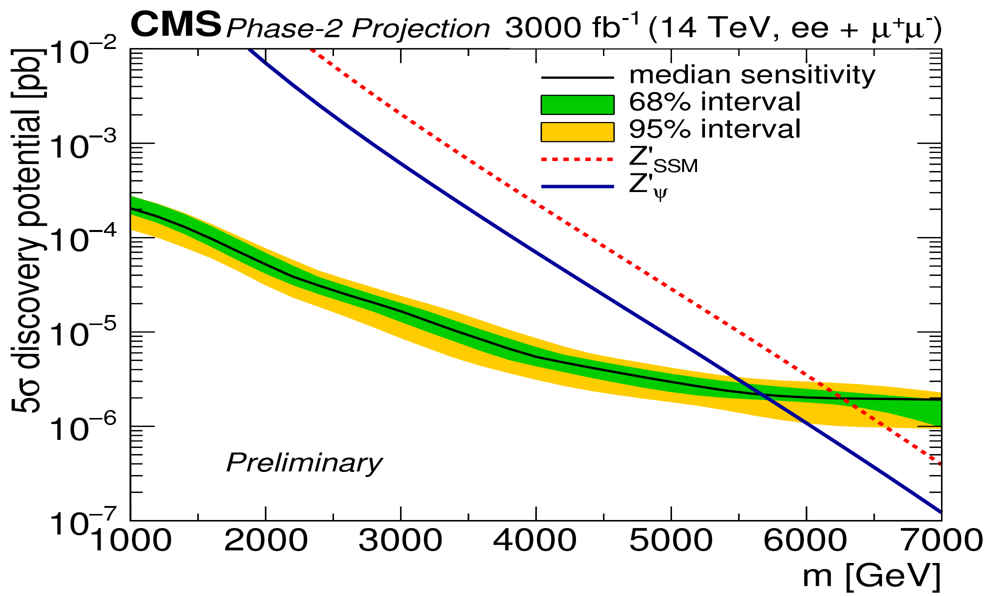
Lower limits on the energy scale Λ of 6.9 to 9.0 TeV in the bbll model, depending on model parameters, and on the ratio of energy scale and coupling Λ/g^* of 2.0 to 2.6 TeV in the bsll model.

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

Projections for 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 ($\int L\,dt \approx 26 + 140\ \mathrm{fb}^{-1}$) 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 twice larger than in Run 2.

- Study of new signals and more analyses are coming.

CMS Publications:

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