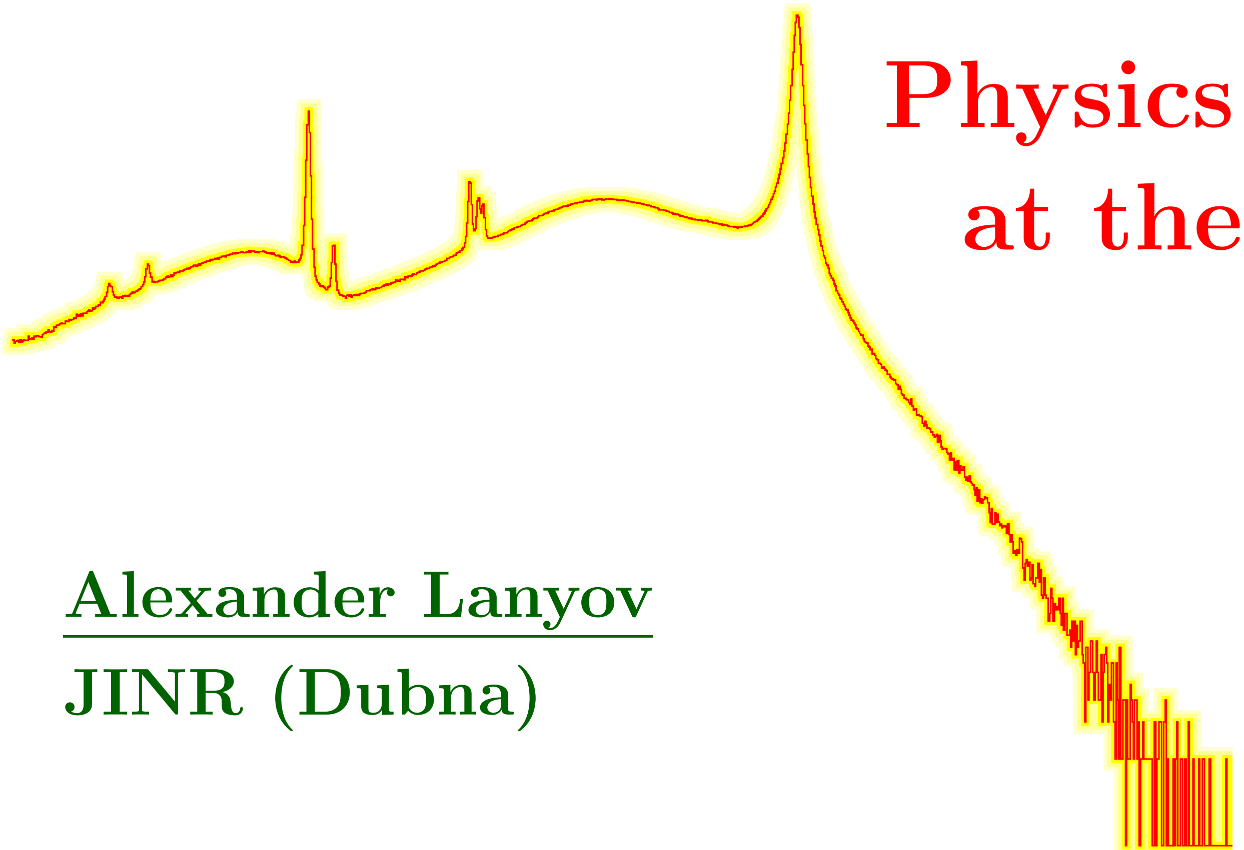
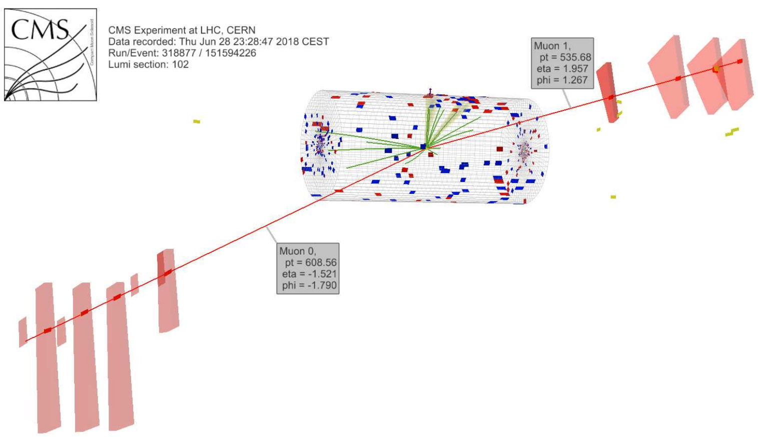
Physics with Dimuons at the LHC



Alexander Lanyov

JINR (Dubna)



September 11, 2023

Conference on High Energy Physics

AANL, Yerevan (Armenia)

Outline:

- Motivation to study dimuons
- Standard Model — from Z boson to Rare decays
- Exotica — search for new heavy resonances
- Conclusions

Public Results for ATLAS, CMS, LHCb:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome

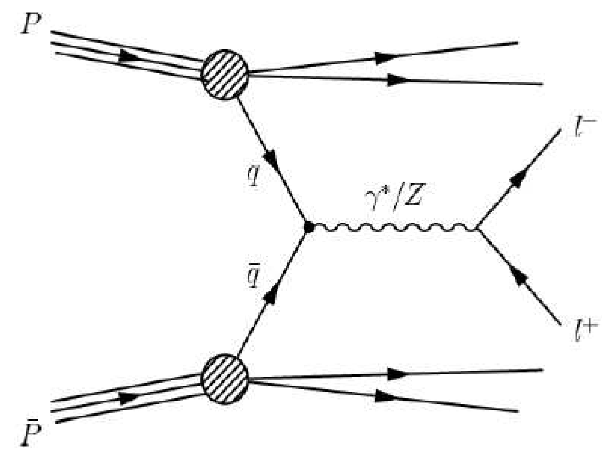
http://cms-results.web.cern.ch/cms-results/public-results/publications/

https://lhcb-outreach.web.cern.ch/category/physics-results/

Motivation to Study Dimuons at LHC

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

Why study dimuons at the LHC?



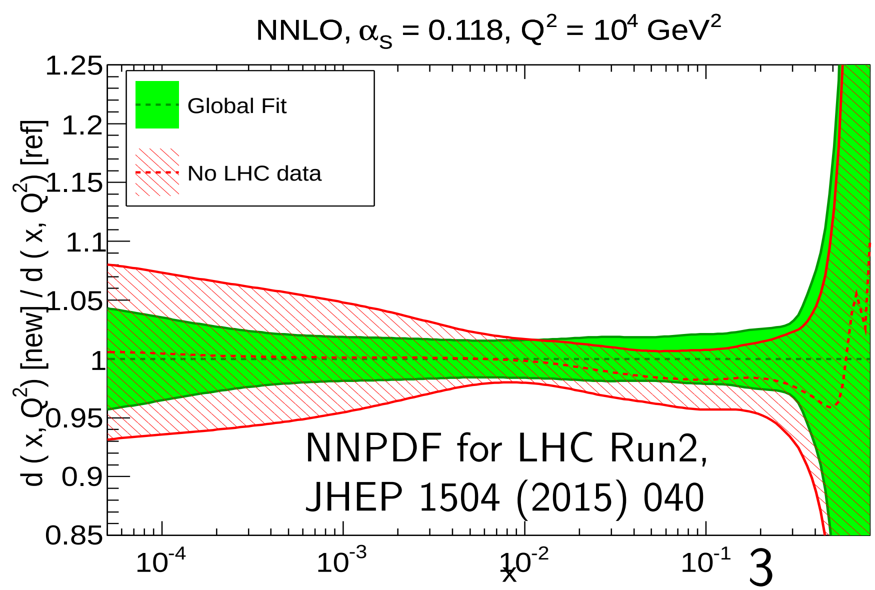
- Important Standard model benchmark channel. Theoretical cross sections calculated up to NNLO allowing tests of pQCD

- Many theoretical models predict contribution of New Physics in dimuon channel.

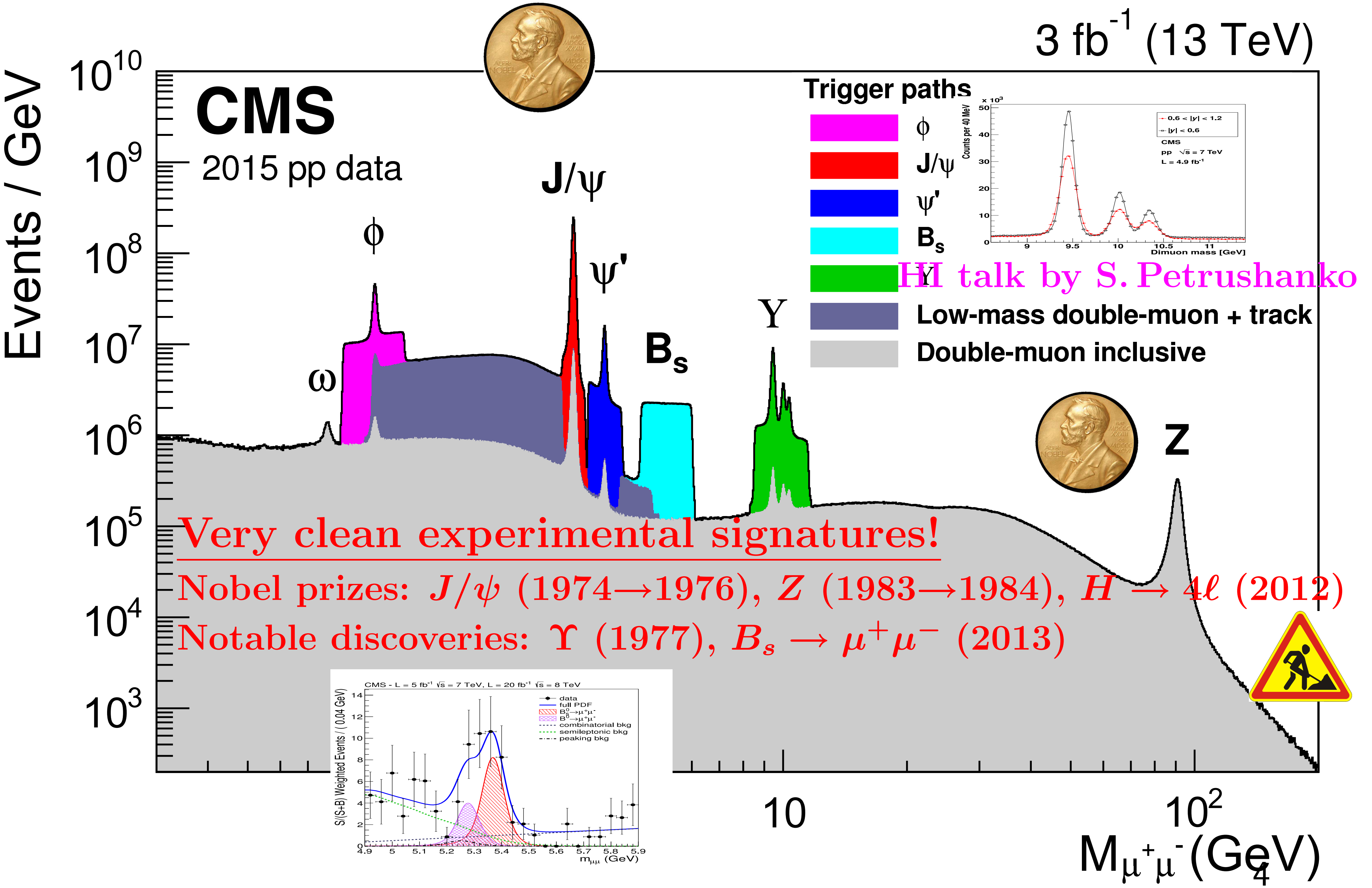
- Used to constrain PDFs

- 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

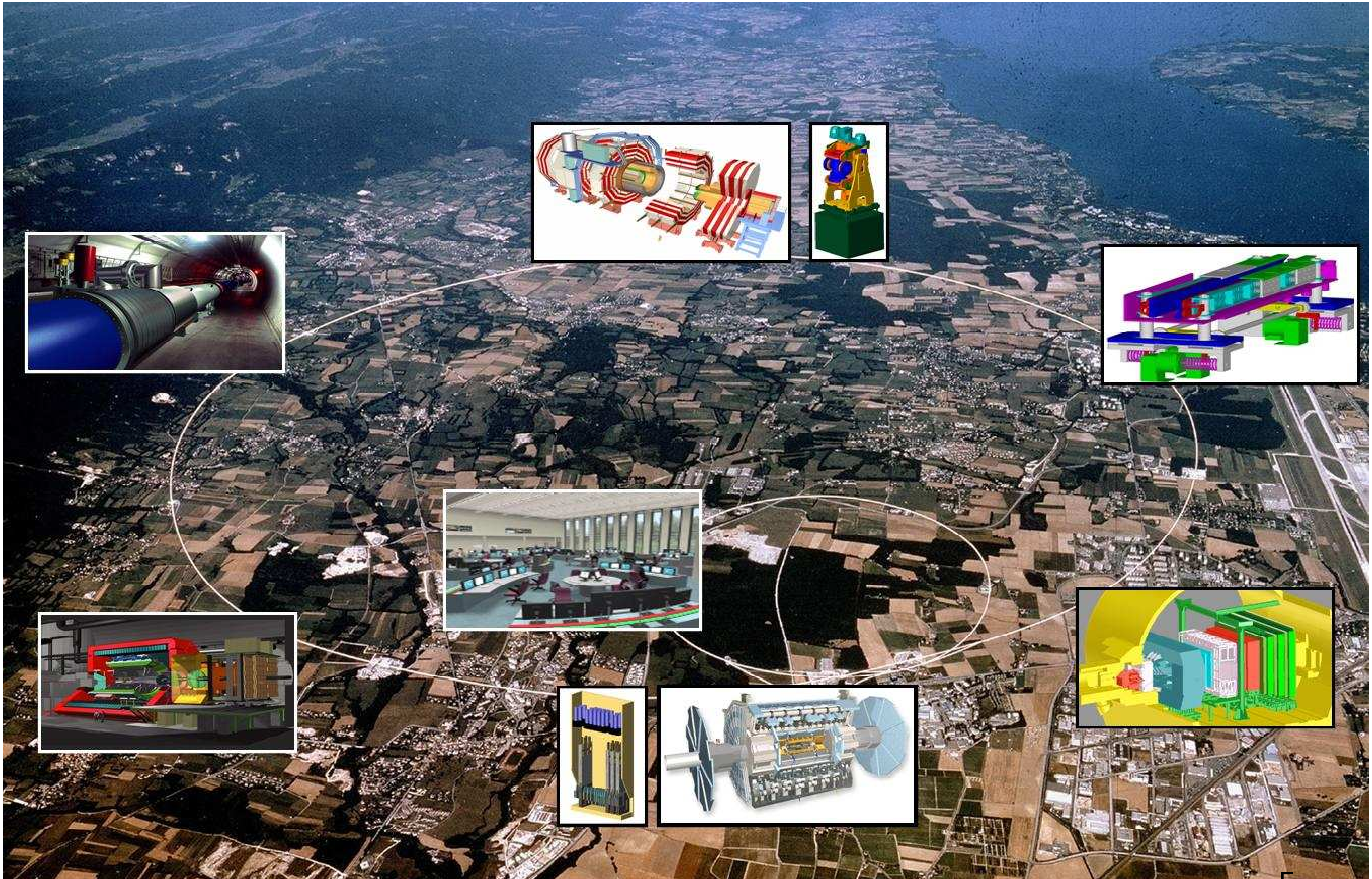


Very clean experimental signatures!

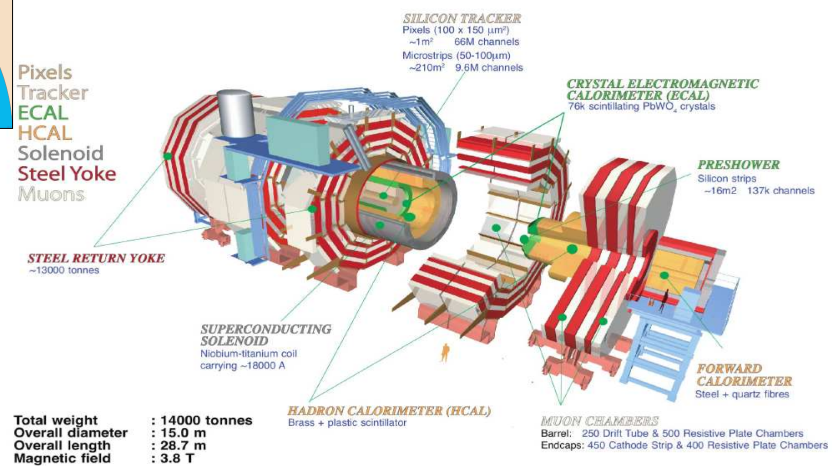
Nobel prizes: J/ψ (1974→1976), Z (1983→1984), $H \to 4\ell$ (2012)

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

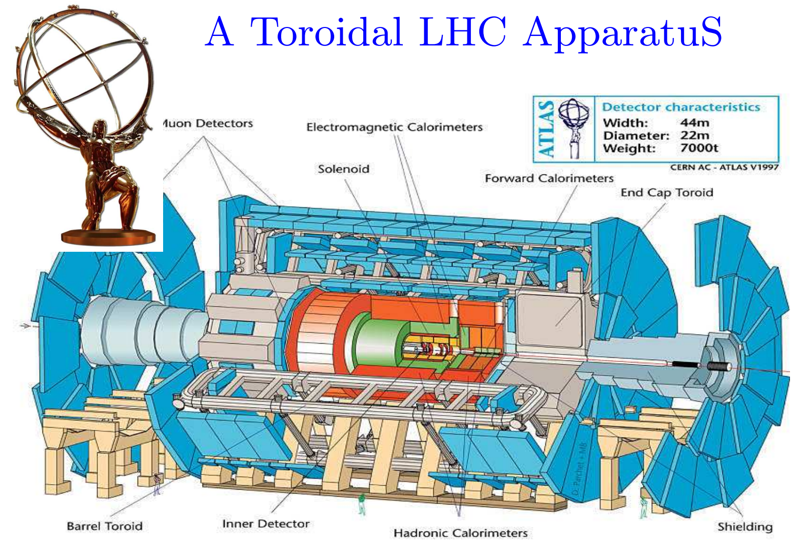
Bird's-eye LHC Picture



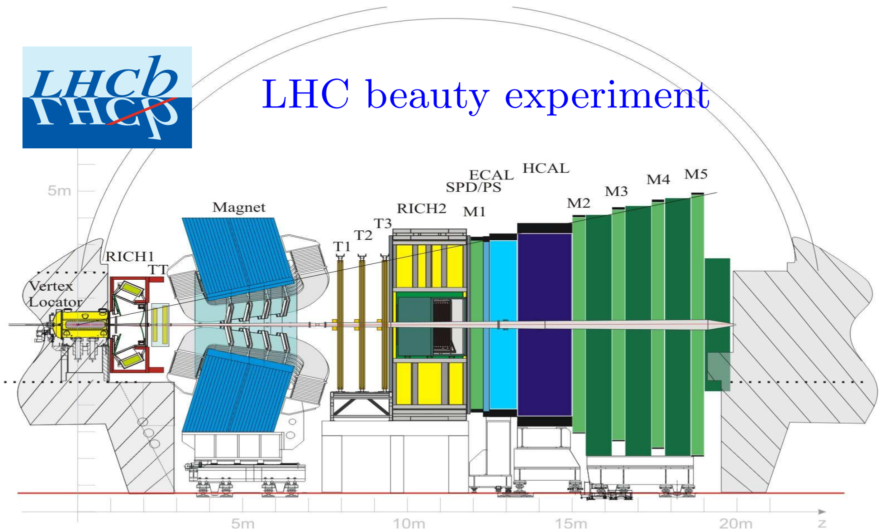
Compact Muon Solenoid



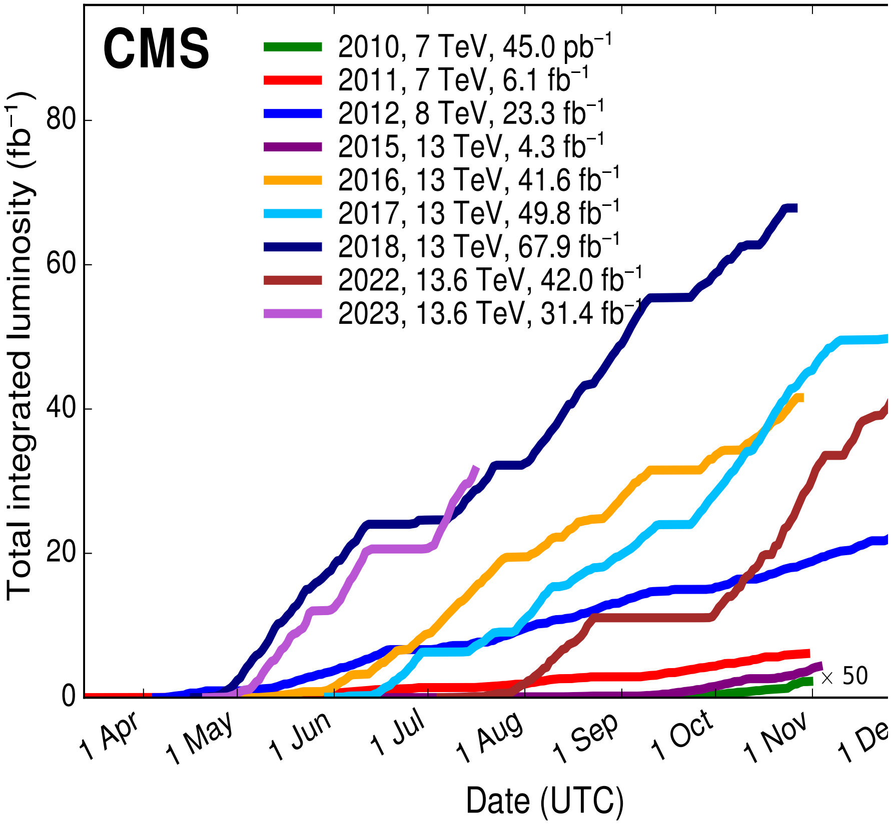
A Toroidal LHC ApparatuS

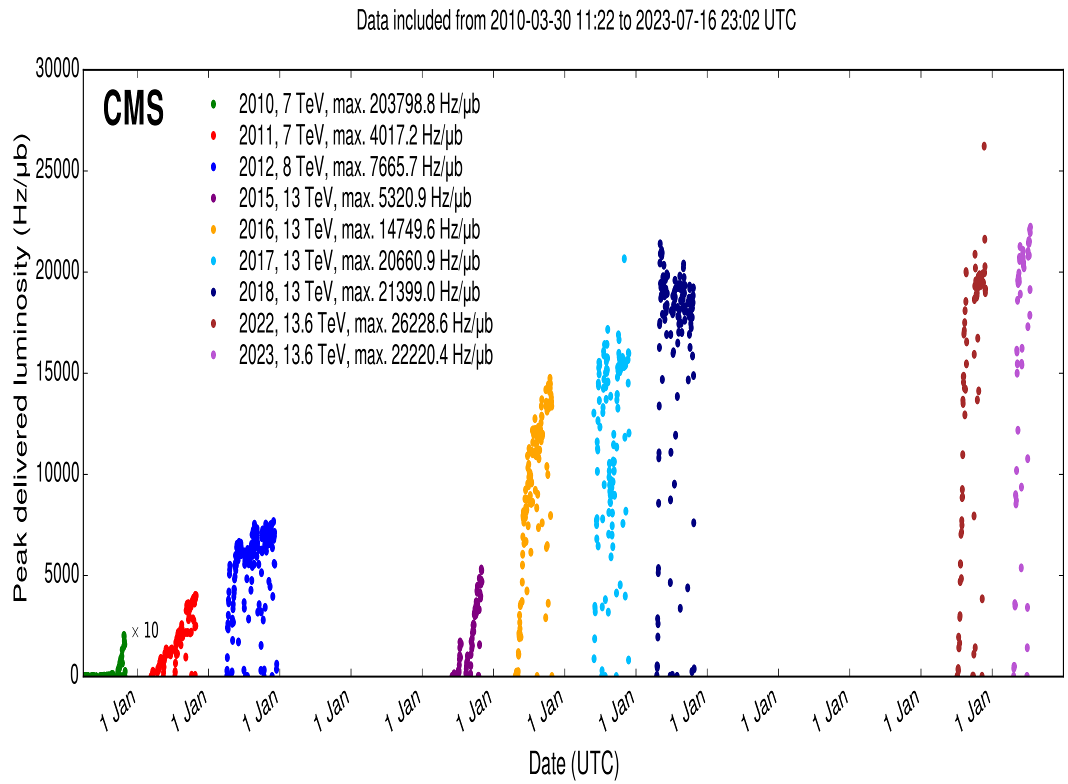


LHC beauty experiment



	CMS	ATLAS	LHCb
Diameter, m	15	25	10–13
Length, m	28.7	46	21
Weight, kt	14	7	5.6
Magnetic field, T	3.8	2, 0.5	1
Pseudorapidity $\|\eta\|$	< 2.5	< 2.5	$2 < \eta < 5$



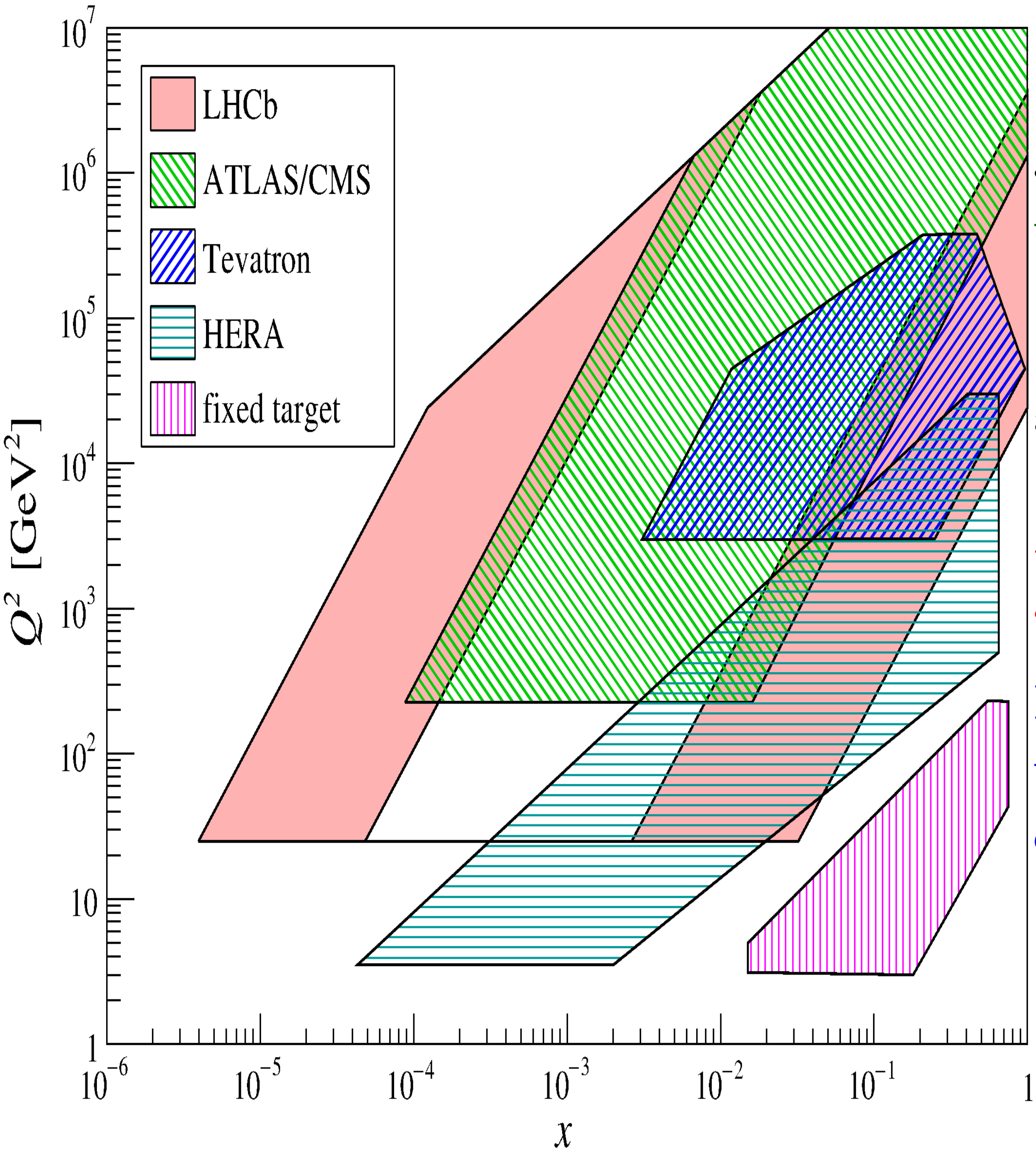


- Run 1 with $\sqrt{s} = 7$–8 TeV: ~ 30 fb^{-1}
- Run 2 with $\sqrt{s} = 13$ TeV: Rapid rise of integrated luminosity ~ 140 fb^{-1}
- Mean luminosity is 2 times higher than $10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ (original nominal value for LHC)
- Run 3 with $\sqrt{s} = 13.6$ TeV: started in 2022; Currently $\int \mathcal{L}\, dt \approx 70$ fb^{-1}

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

Drell-Yan process studies

LHC Parton Kinematics (x, Q^2) (14 TeV)



James Stirling's plot

with ATLAS+CMS region

+ added LHCb η regions

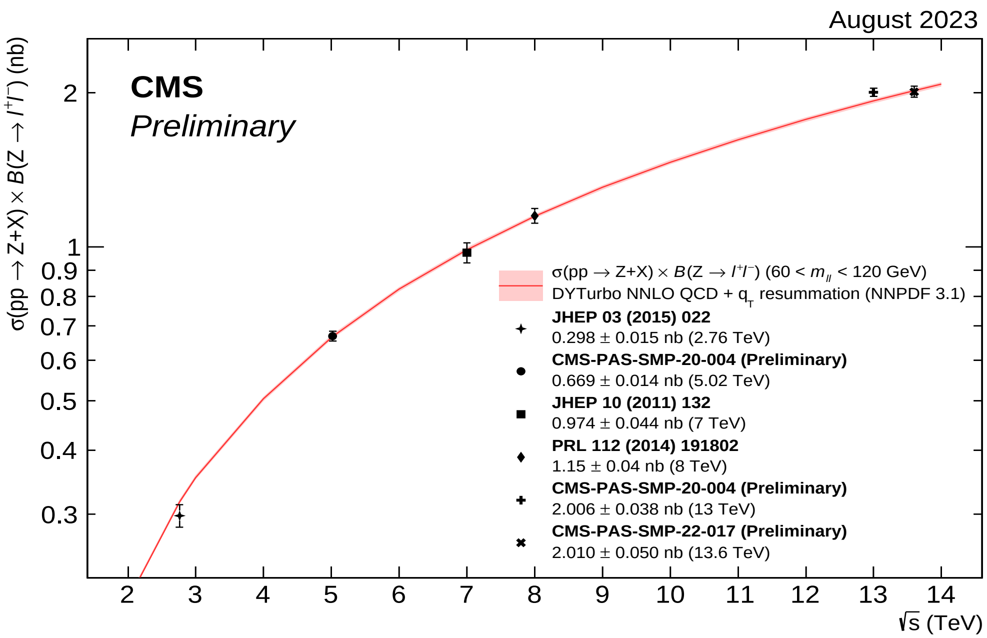
$$x_{1,2} = \frac{M}{\sqrt{s}} \exp(\pm y)$$ **arXiv:0808.1847**

ATLAS, CMS and LHCb have a complementary phase space.

Measurements at the LHC will place extra constraints on PDFs and QCD

$\Longrightarrow$ Feeds back into predictions.

Z Production Cross Section at High $\sqrt{s}$



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, $|\eta| < 2.4$.

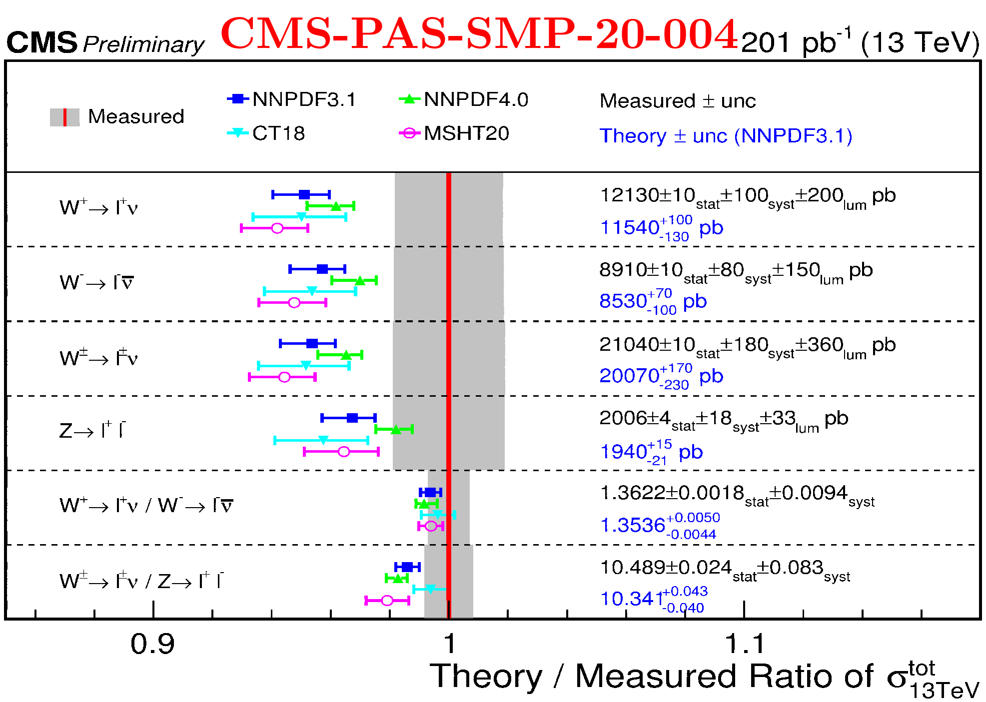
$\sqrt{s} = 13$ TeV: CMS-PAS-SMP-20-004

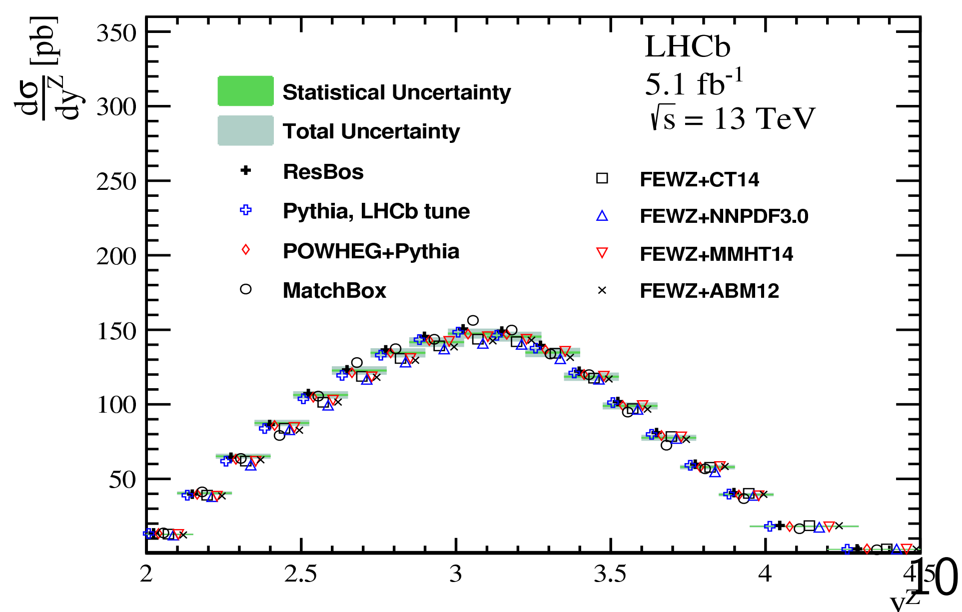
ATLAS-CONF-2023-028

Z cross sections agree between the channels and with NNLO QCD within the uncertainties.

Differential measurements on y, p_T, ϕ^*_η:

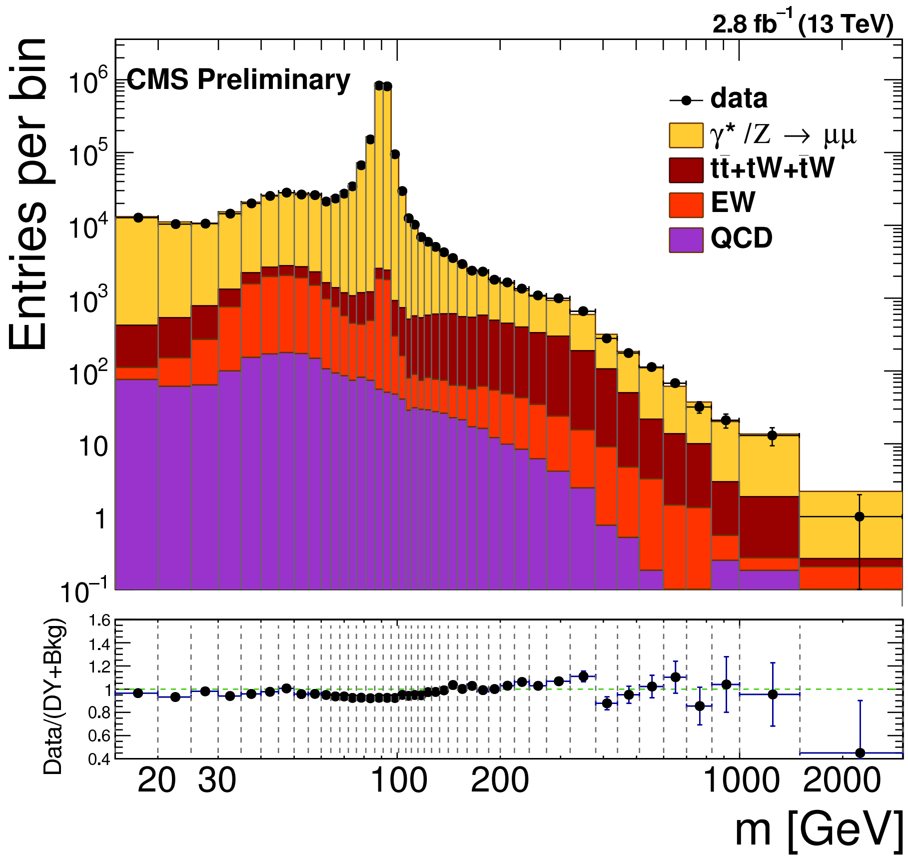
CMS JHEP 12 (2019) 061, ATLAS-CONF-2023-013, LHCb JHEP 07 (2022) 026



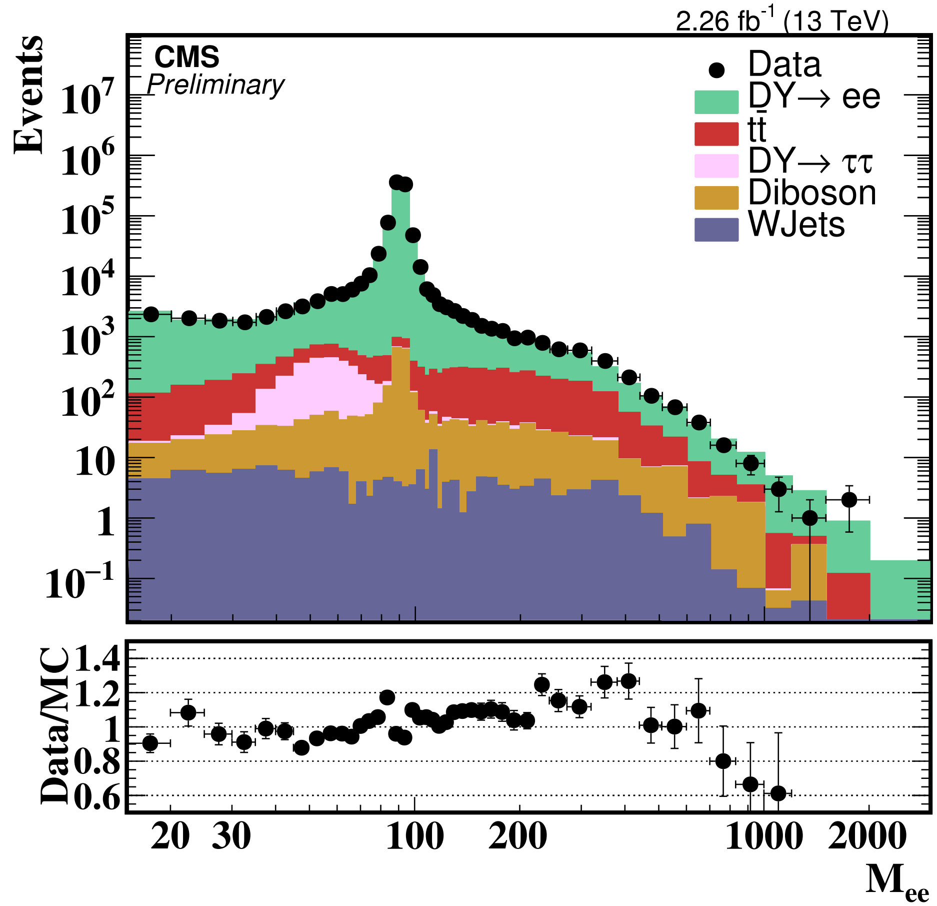


Data/MC Comparison for DY Mass Spectra (arXiv:1812.10529)

$\mu^+\mu^-$ channel



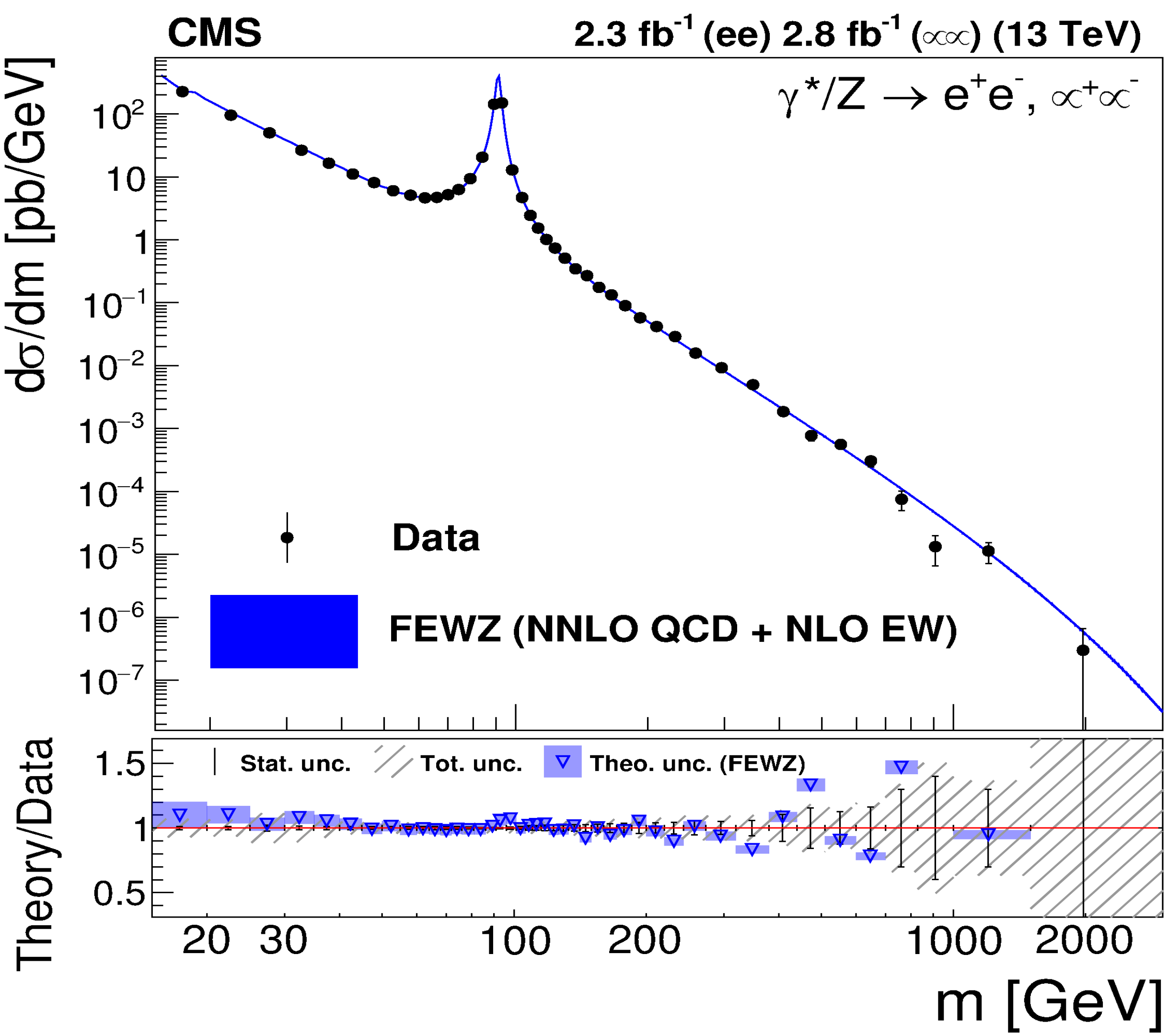
e^+e^- channel



Data / MC comparison for mass spectra (with FEWZ NNLO predictions)
Most important backgrounds for $\mu^+\mu^-$ channel:

- Low-mass region: QCD multi-jets
- Peak region: Drell-Yan $\rightarrow \tau^+\tau^-$, $W \rightarrow l\nu$, dibosons
- High-mass region: $t\bar{t}$, single top, dibosons

Drell-Yan 1D Cross Section (arXiv:1812.10529)



- $L = 2.8\ \mathrm{fb}^{-1}$ 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
- Also measured fiducial cross section within the detector acceptance
- 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^-.

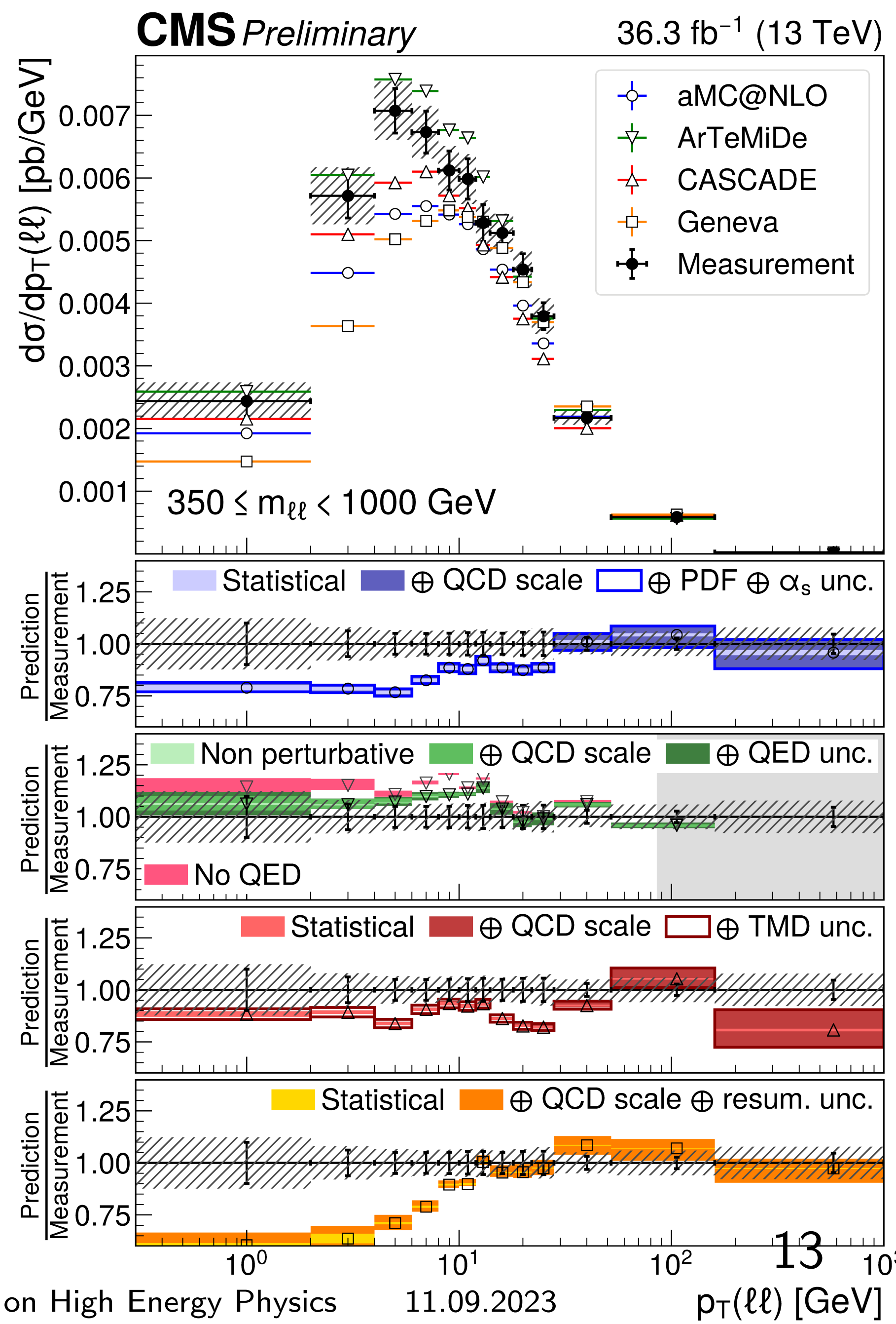
Generally good agreement between data and theory
FEWZ (NNLO QCD, NNPDF3.0)

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

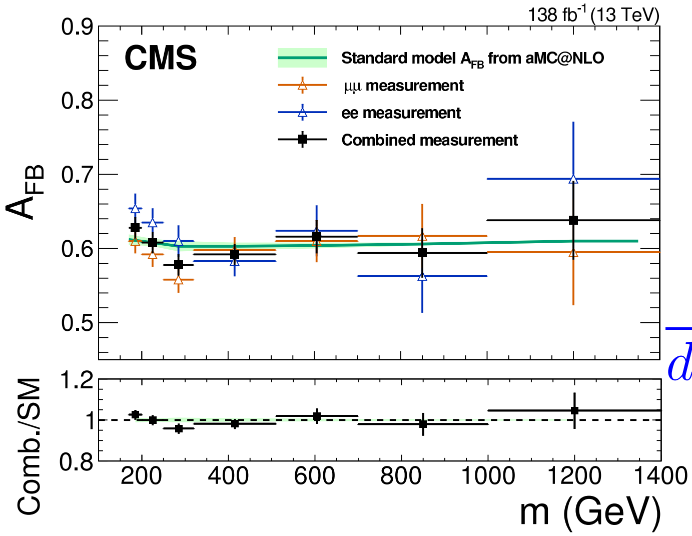
Measured double differential cross sections of DY lepton pair production, as a function of $p_{\mathrm{T}}(\ell\ell)$, and φ^*, in bins of dilepton masses: $m \in [50, 76, 106, 170, 350, 1000]$ GeV.

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.



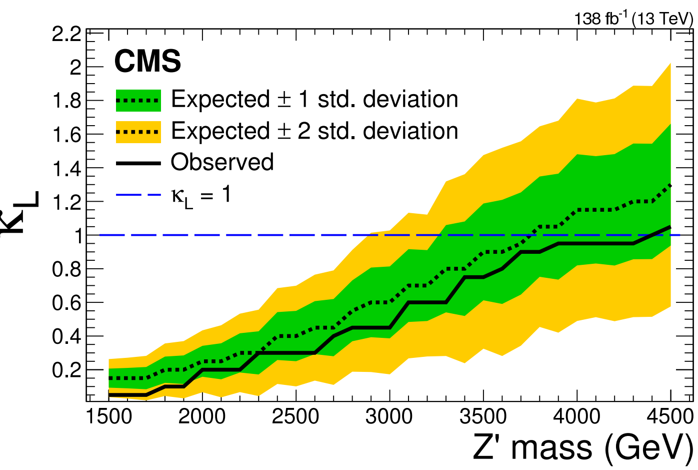
Drell-Yan Forward-Backward Asymmetry (JHEP 08 (2022) 063)



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 dilepton rest frame



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

Angular coefficients of Z bosons as a function of p_T and Y

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

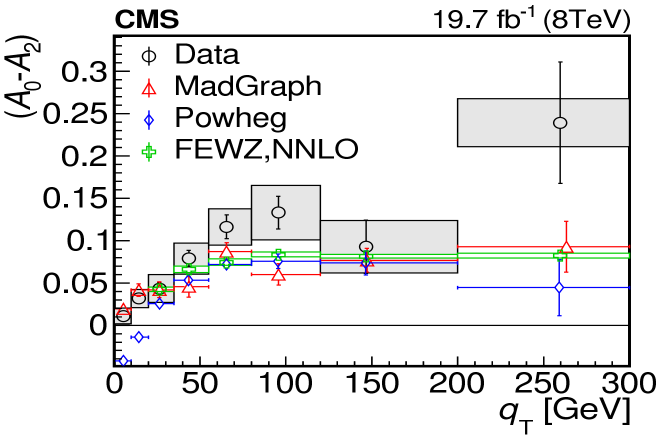
$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \Big[(1+\cos^2\theta^*)+A_0\frac{1}{2}(1-3\cos^2\theta^*)+A_1\sin(2\theta^*)\cos\phi^*+A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$

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

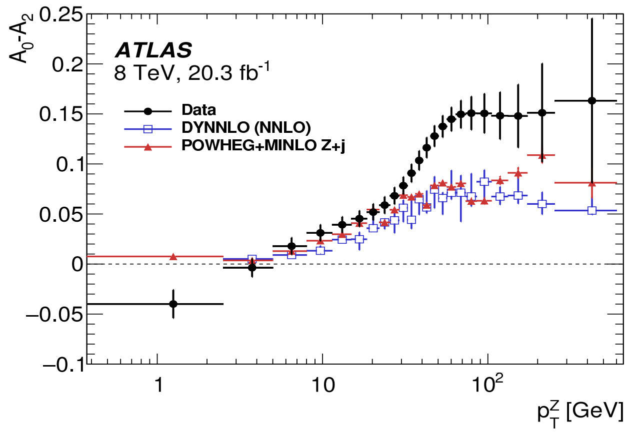
where θ^* and ϕ^* are azimuthal and polar angles.

The violation of Lam-Tung relation $A_0 - A_2 = 0$ is observed,
as predicted by QCD calculations beyond NLO:

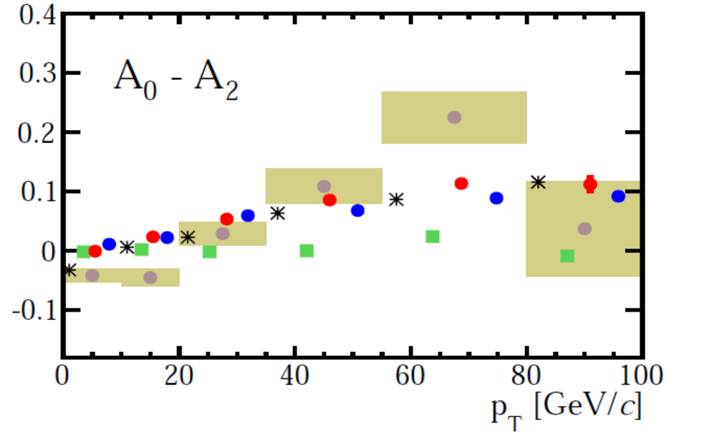
CMS $|y| < 1$
Phys. Lett. B 750 (2015) 154



ATLAS
JHEP 08 (2016) 159



LHCb
Phys. Rev. Lett. 129 (2022) 091801

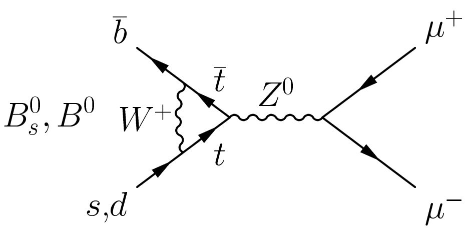


See details in the talk by Vlad Shalaev

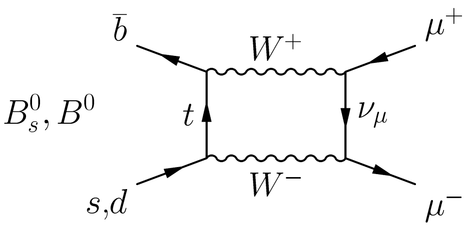
Rare Dimuon Decays

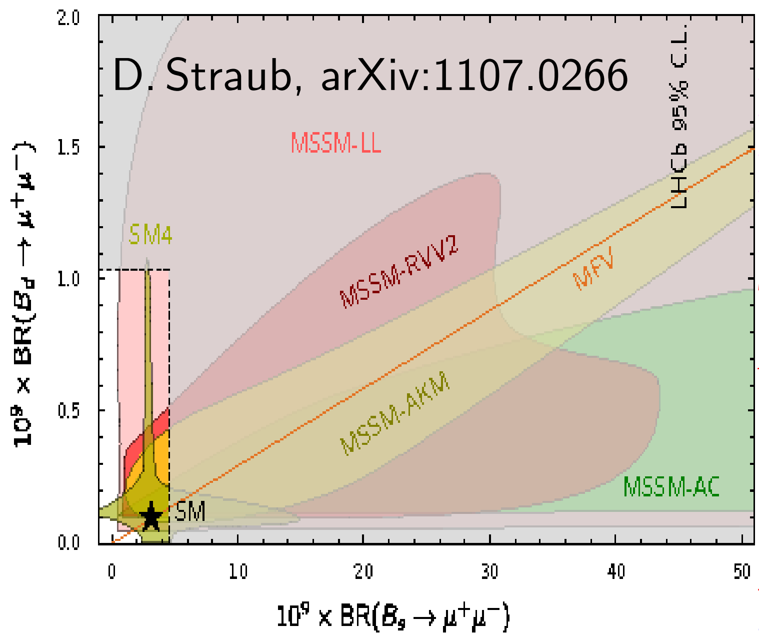
in Standard Model

Discovery of Dimuon decay of B_s^0 & B^0 (LHCb-CONF-2020-002)



SM



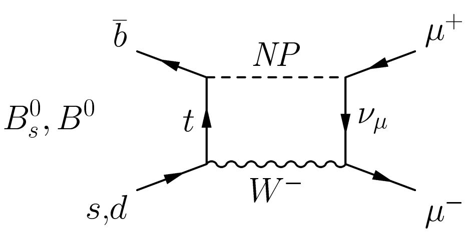


SM predicts

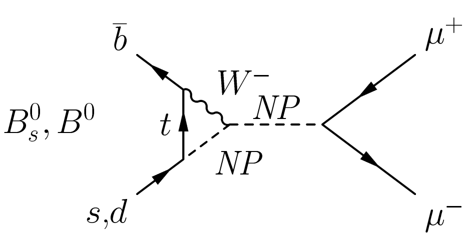
$\mathrm{Br}(B_s^0 \to \mu\mu) = (3.7 \pm 0.2) \times 10^{-9}$

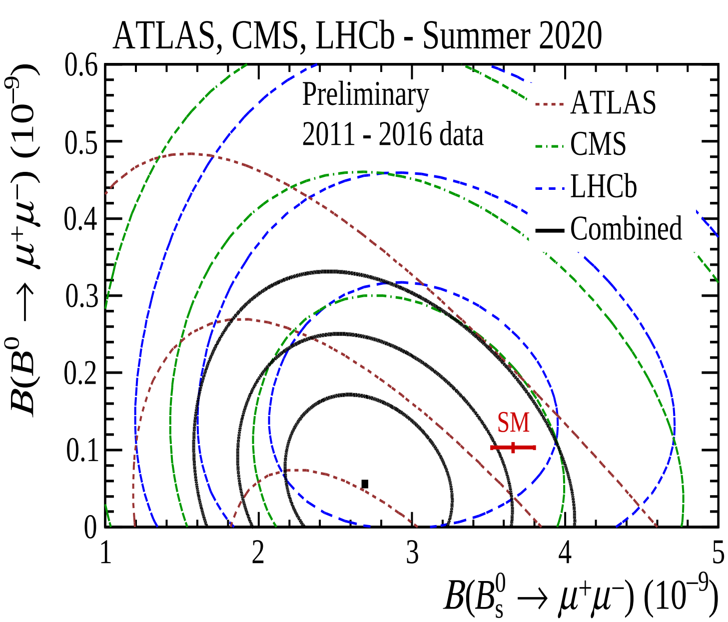
$\mathrm{Br}(B^0 \to \mu\mu) = (1.1 \pm 0.1) \times 10^{-10}$

The processes are sensitive to searches for BSM physics.



NP





Combination of the ATLAS+CMS+LHCb results:

$\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$

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

Recent CMS measurement: [Phys. Lett. B 842 (2023) 137955]

$\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = (3.93^{+0.38}_{-0.36}) \times 10^{-9}$

$\mathrm{Br}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$

Most precise single measurements and consistent with the SM.

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

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

Using full CMS Run2 data ($137\,\mathrm{fb}^{-1}$ at 13 TeV)

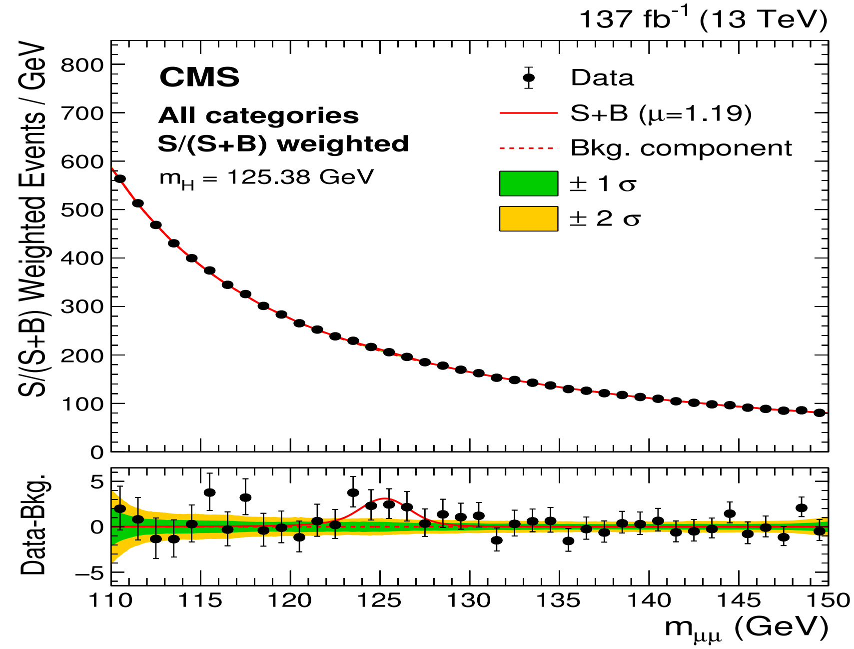
First evidence for $H \to \mu^+\mu^-$ with significance $3\,\sigma$

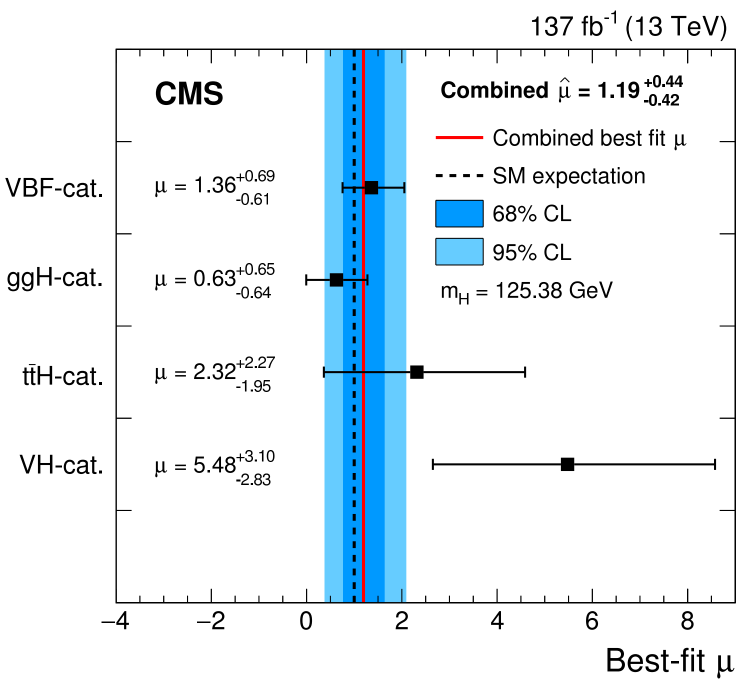
Four categories: VBF, ggH, $t\bar{t}H$, VH

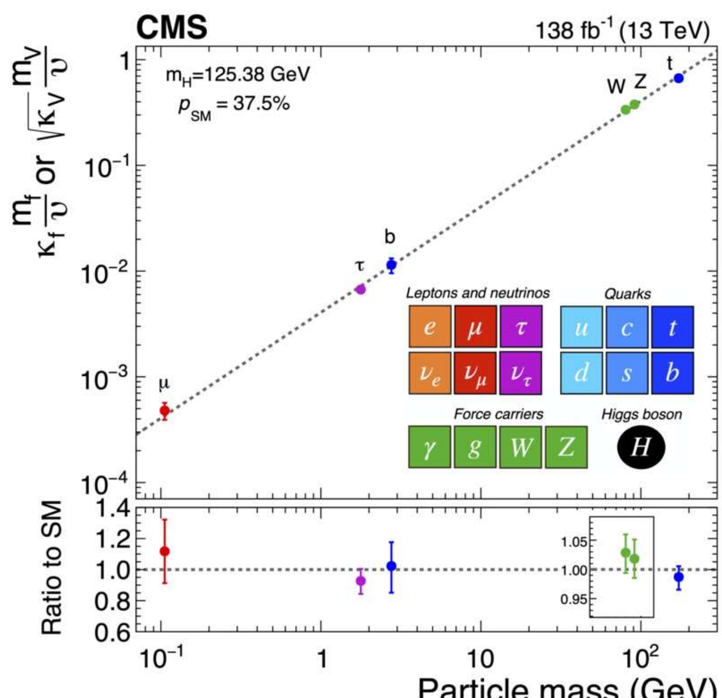
Signal strength $\hat{\mu}^{\mathrm{comb}} = 1.19^{+0.40}_{-0.39}\,(\mathrm{stat.})^{+0.15}_{-0.14}\,(\mathrm{syst.})$

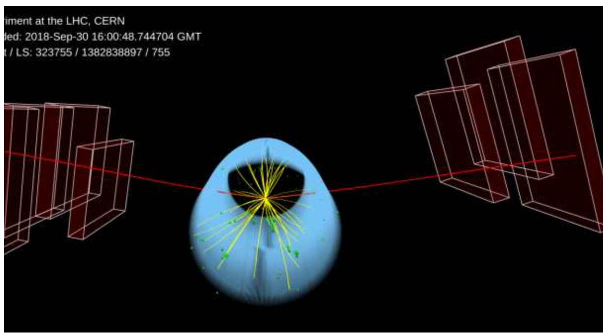
Even more rare: $\mathrm{Br}(H \to e^+e^-)_{\mathrm{SM}} = 5 \times 10^{-9}$

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









Exotica

(Search of new heavy resonances)

Models Beyond the 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 $c = k/\bar{M}_{Pl}$

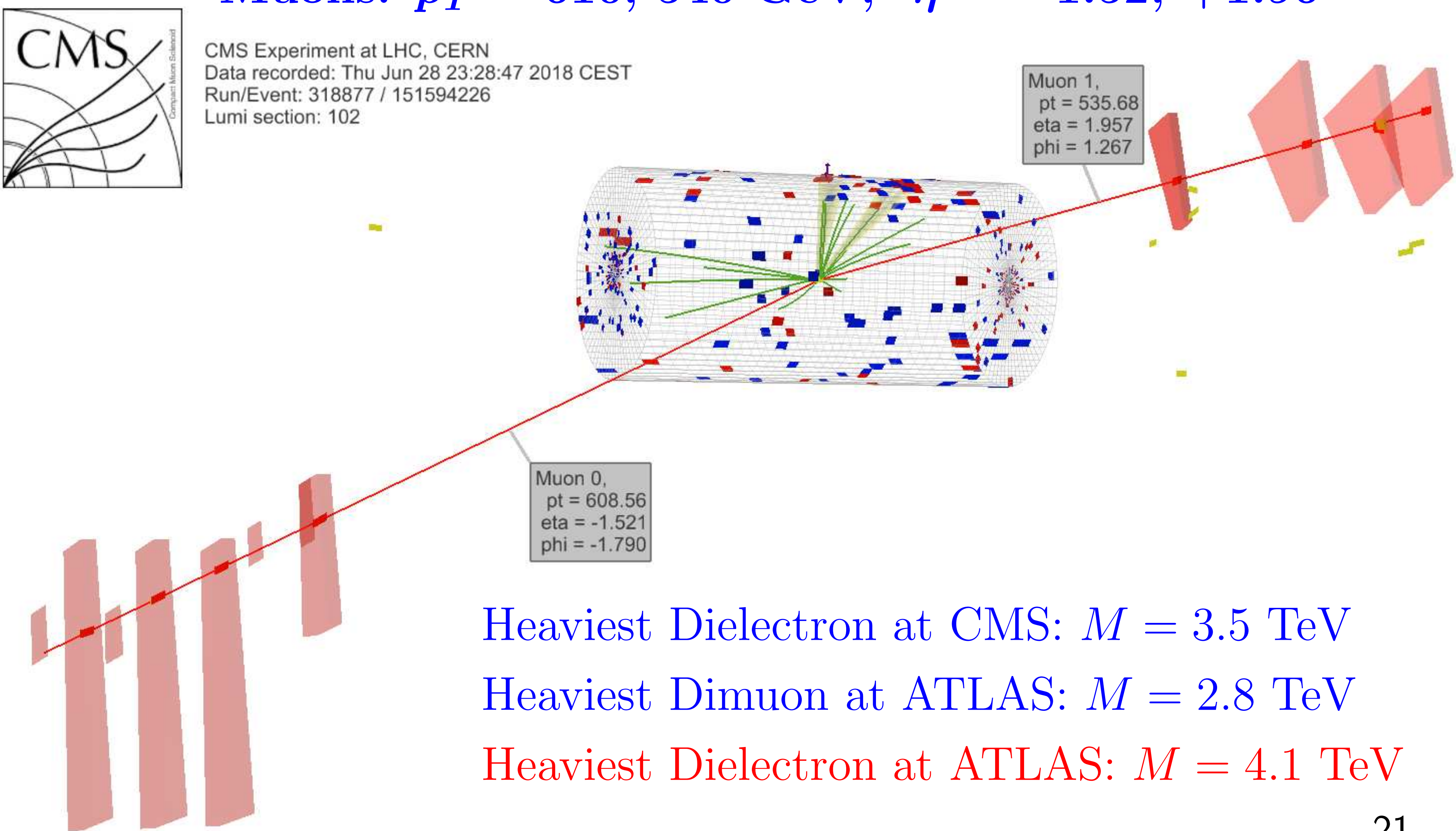
Non-resonant models such as ADD and Contact interactions:

- 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 $\mathcal{L} \sim \frac{4\pi}{\Lambda^2}(\bar{q}_L \gamma^\mu q_L)(\bar{l}_L \gamma_\mu l_L)$. Λ — the energy scale parameter for the contact interaction.

There exist also other models in which heavy dileptons appear.

$M = 3.3$ TeV

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



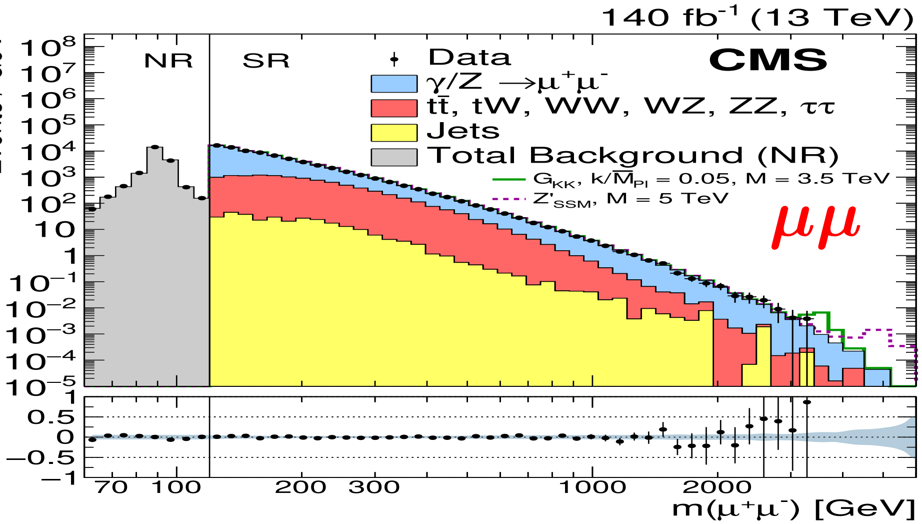
Heaviest Dielectron at CMS: $M = 3.5$ TeV

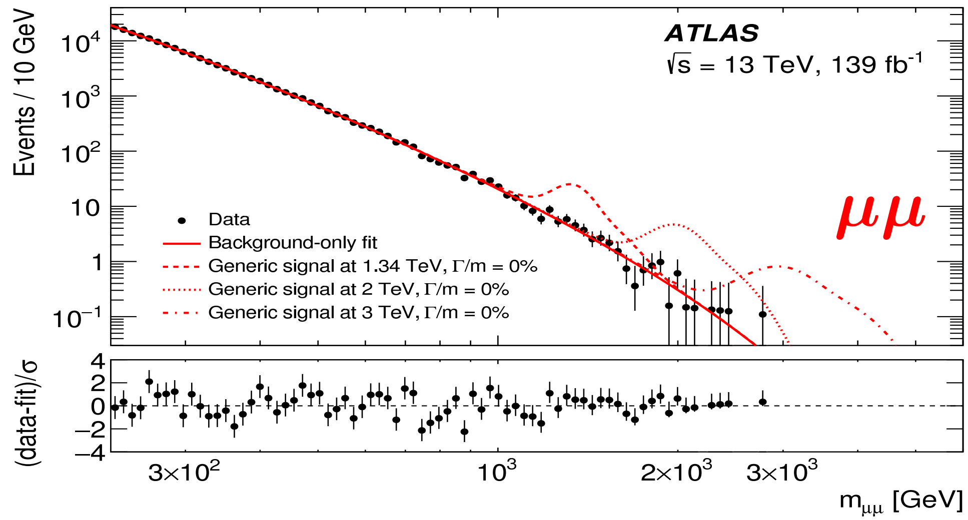
Heaviest Dimuon at ATLAS: $M = 2.8$ TeV

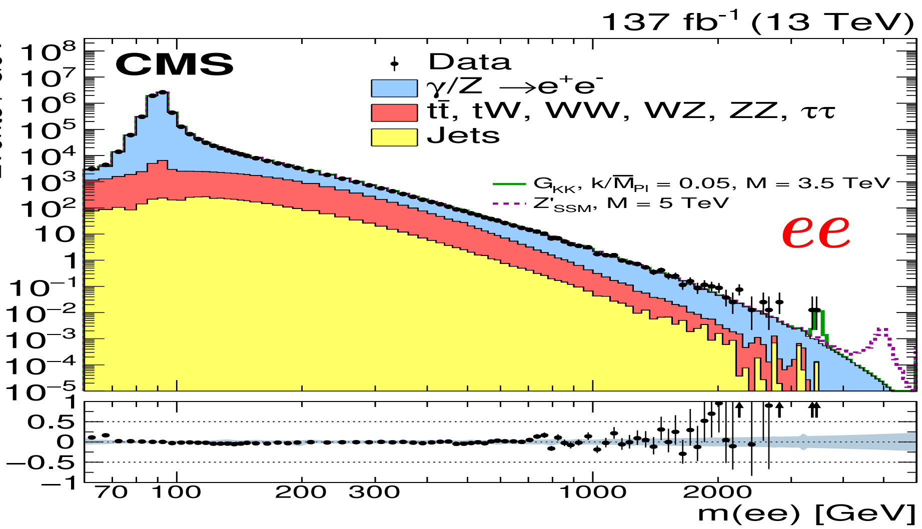
Heaviest Dielectron at ATLAS: $M = 4.1$ TeV

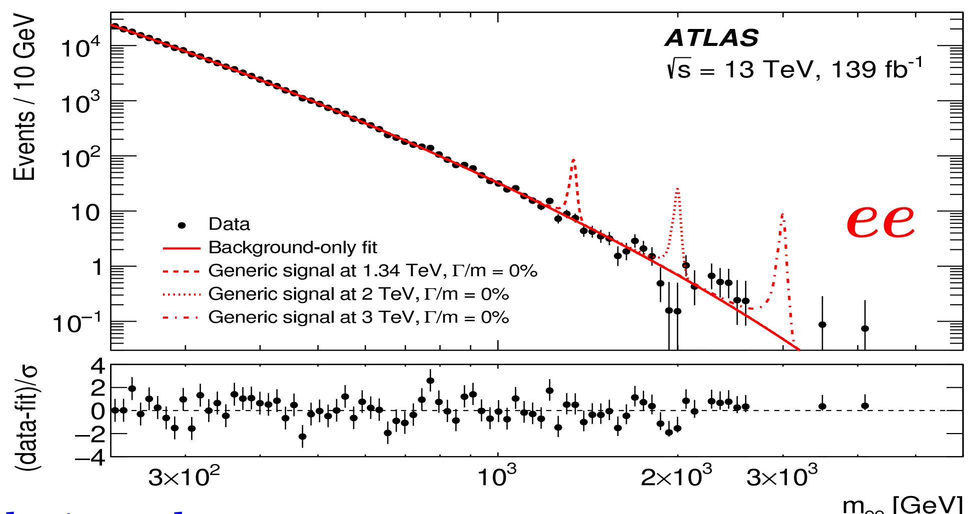
Dilepton Mass Spectrum in the LHC Run2

CMS: JHEP 07 (2021) 208 **ATLAS:** Phys. Lett. B796 (2019) 68





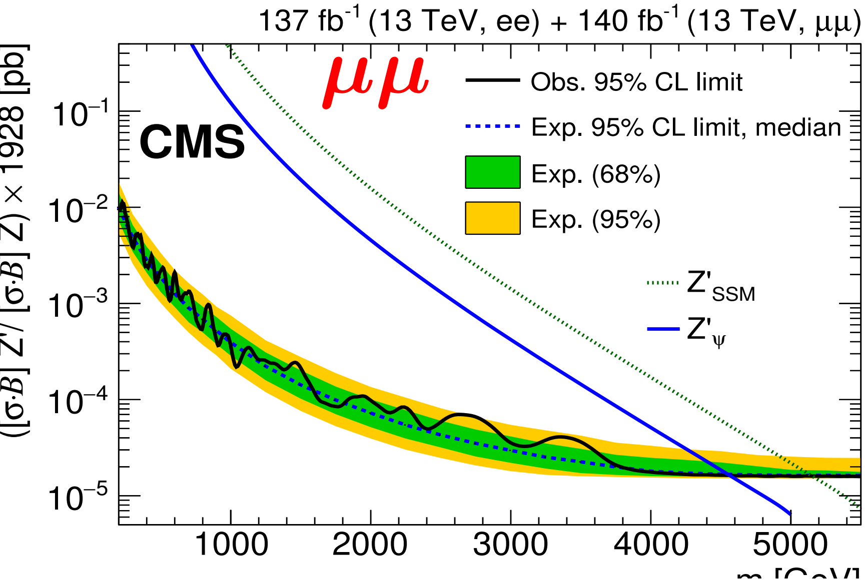


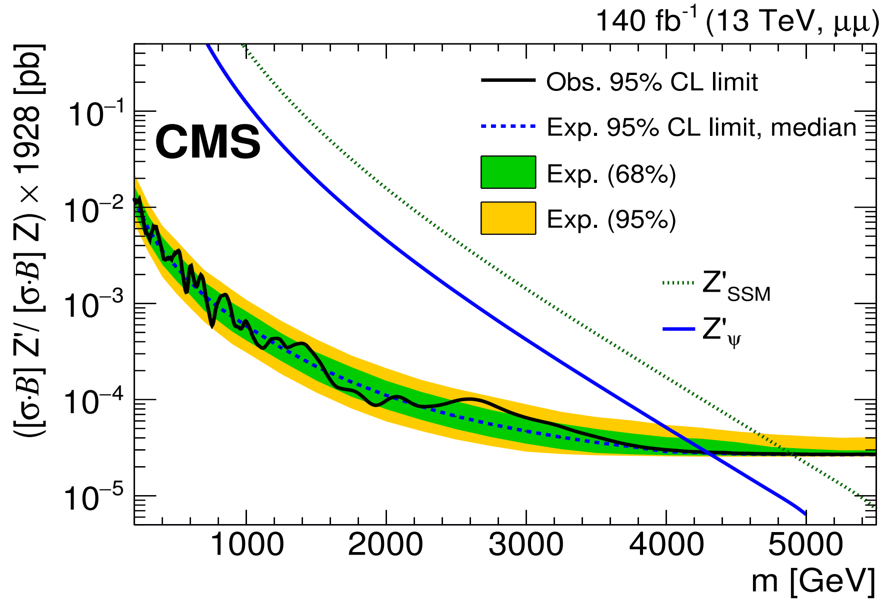


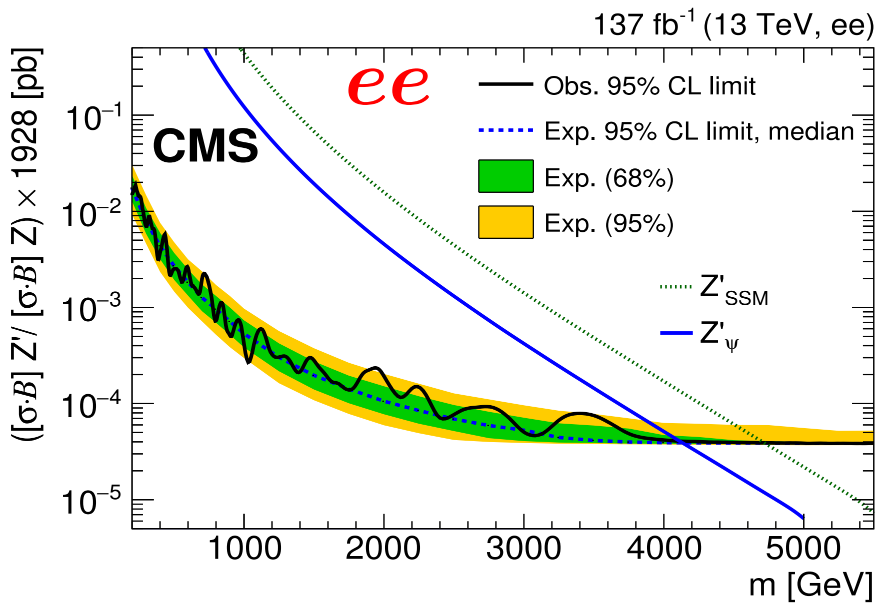
- Good Data / MC agreement, No obvious bumps seen.
- Existence (or lack) of a signal is established by performing unbinned maximum likelihood fits to the observed spectrum.

Dileptons channels

Combined $\mu\mu + ee$



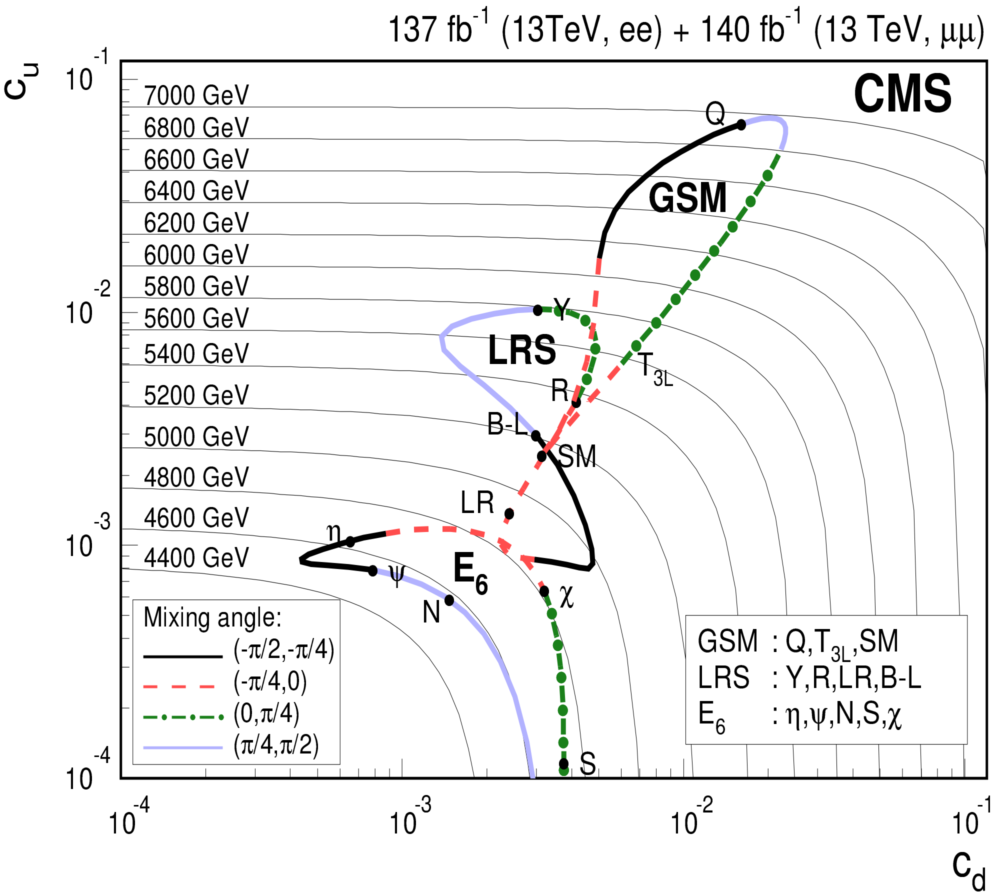




Limits at 95% C.L. on the ratio of Z' cross section to Z cross section, assuming a narrow resonance

The limit exclude a $Z'_{\rm SSM}$ 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).

Generalizing to Other Z' Models — Plot c_u–c_d



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 the PDFs.

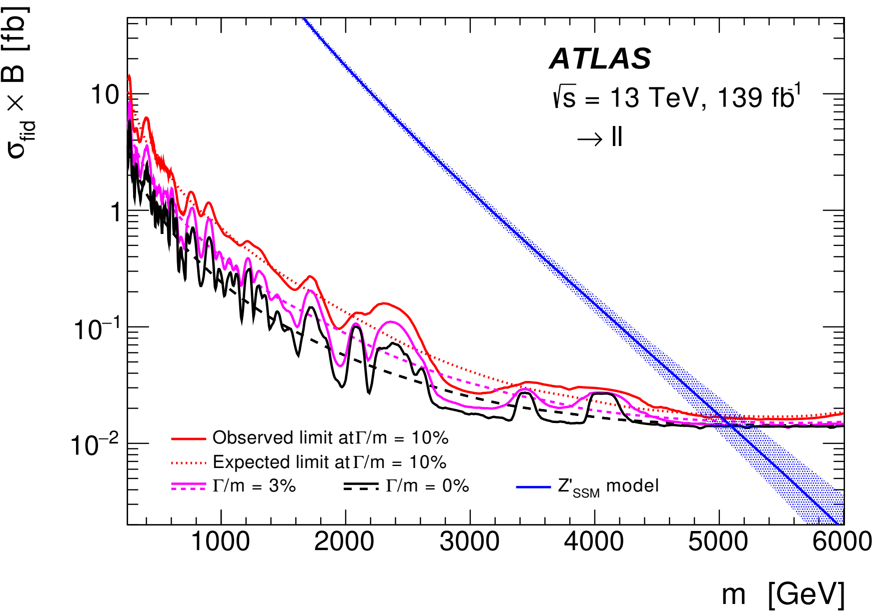
$Z'_{\rm SSM}$ is a special case of generalized sequential standard models (GSM), Z'_ψ is one of the E_6 models, generalized L-R models can also be included.

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 $\sqrt{s} = 13\,\mathrm{TeV}$

Z' Mass Limits (ATLAS: Phys. Lett. B 796 (2019) 68)

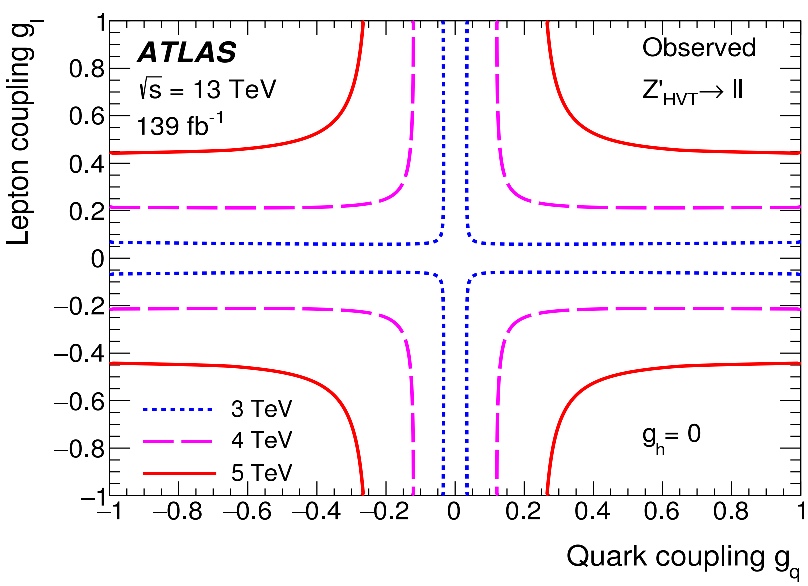


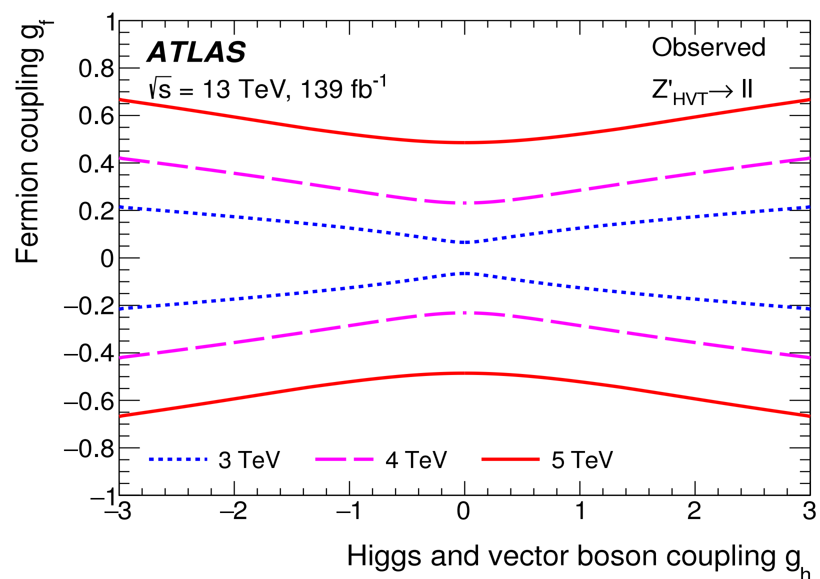
Limits at 95% C.L. on the ratio of Z' cross section to Z cross section, assuming a narrow resonance

Limits exclude $Z'_{\rm SSM}$ with a mass less than 5.1 TeV. For $\mu^+\mu^-$ — 4.5 (Z'_{SSM}), for ee — 4.9 TeV.

Limits for HVT model (heavy vector triplet): a new SU(2) gauge group, leading to a triplet of new bosons: $Z'_{\rm HVT}$ and $W'^{\pm}_{\rm HVT}$.

The results are exclusion contours in HVT coupling parameter space (g_l, g_q, g_h).

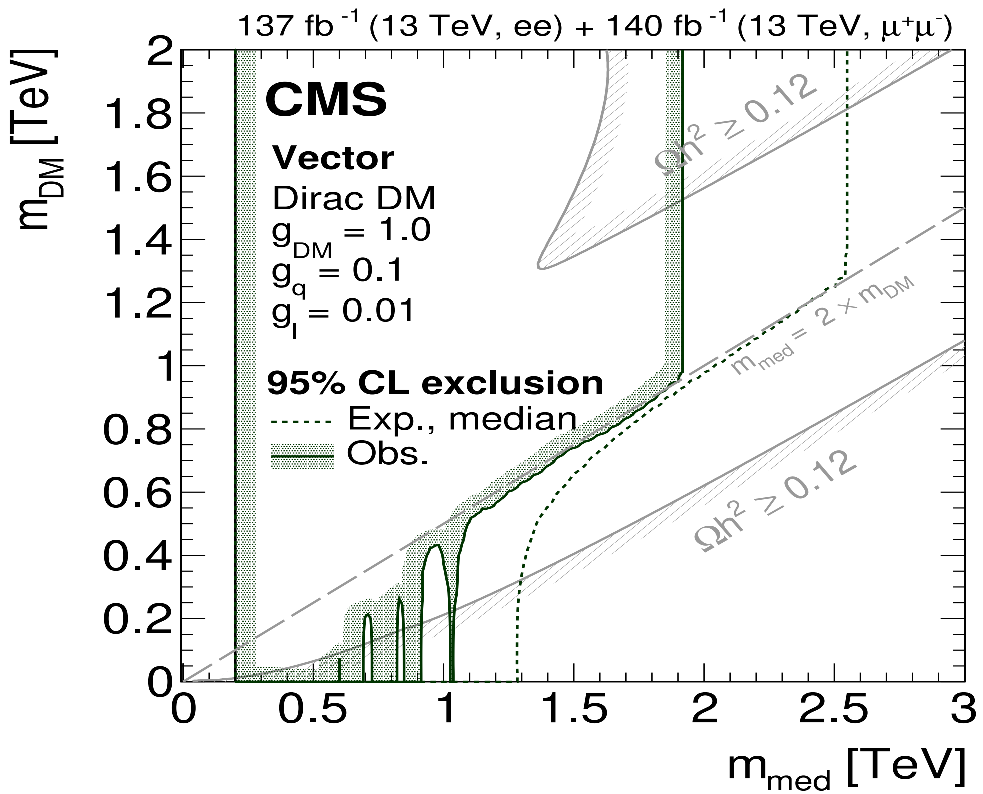


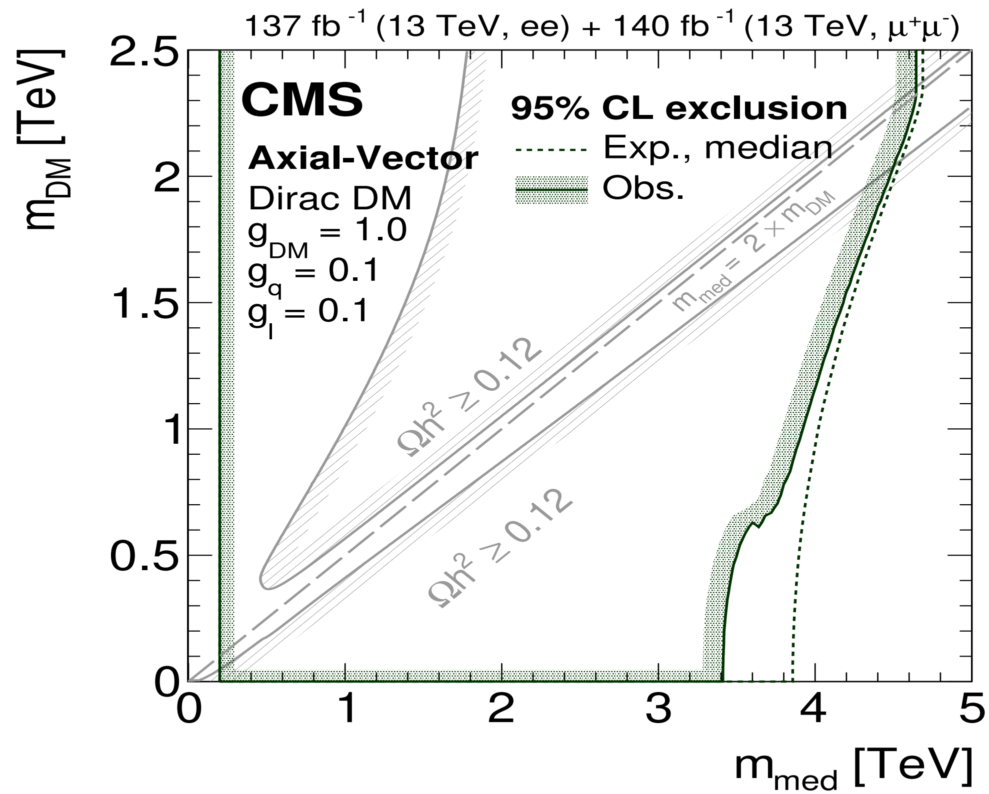


Simplified model of dark matter production via a mediator particle in s channel,
Used 2 sets of benchmark coupling values from "Recommendations of the LHC Dark Matter Working Group" (arXiv:1703.05703, CERN-LPCC-2017-01):

- 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.

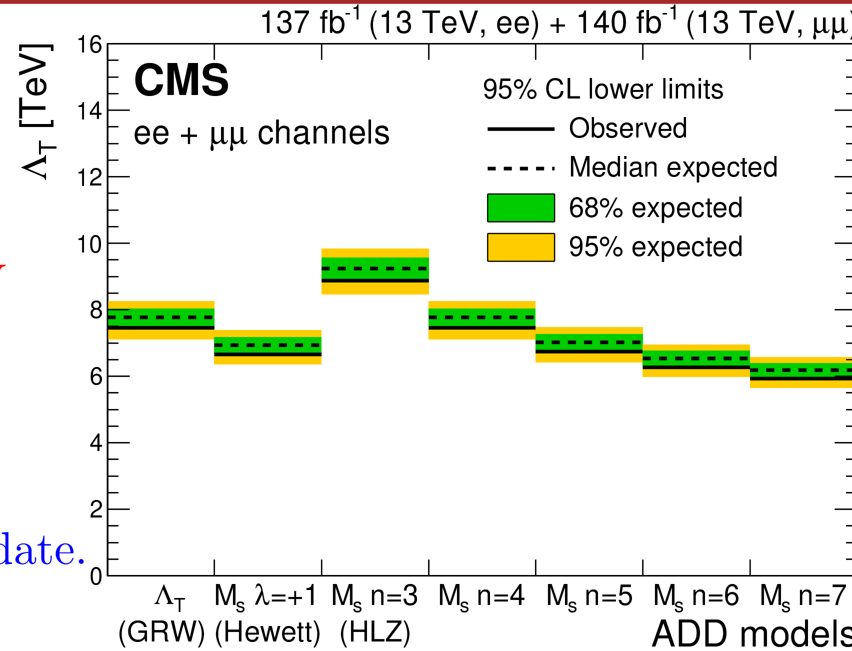




Search for the effects of ADD model —
large extra dimensions in $\mu\mu$ invariant mass spectrum

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

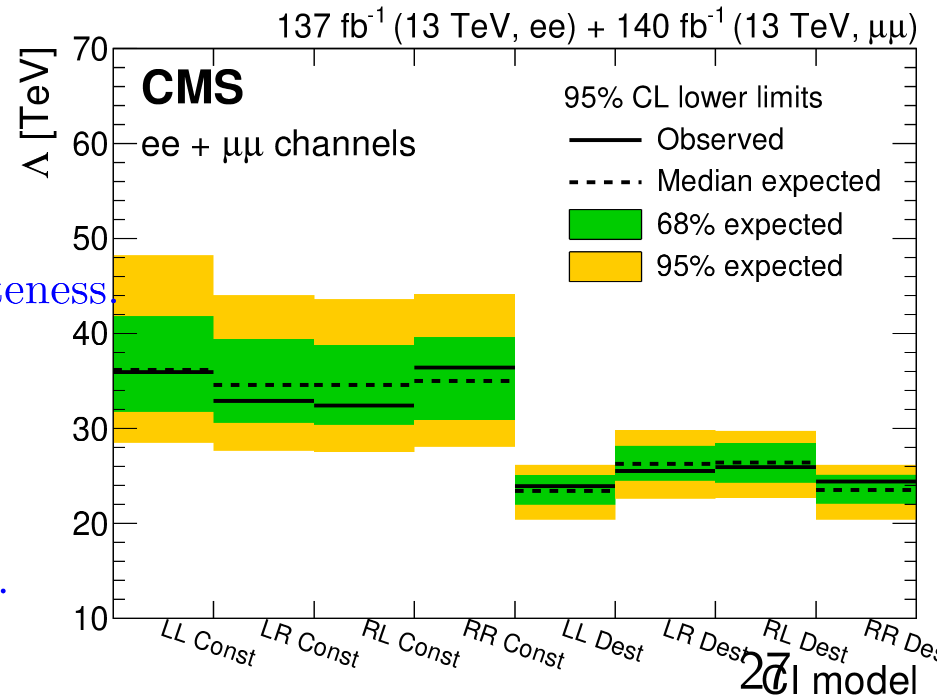
The observed 95% C.L limits on ADD models significantly improve the previous limits and provide the best limits based on dimuon events to date.



CI model comes from idea of quark and lepton compositeness.

$$\mathcal{L} = \eta \frac{4\pi}{\Lambda^2}(\bar{q}_L\gamma^\mu q_L)(\bar{l}_L\gamma_\mu l_L), \quad \eta = \pm 1$$

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.



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.

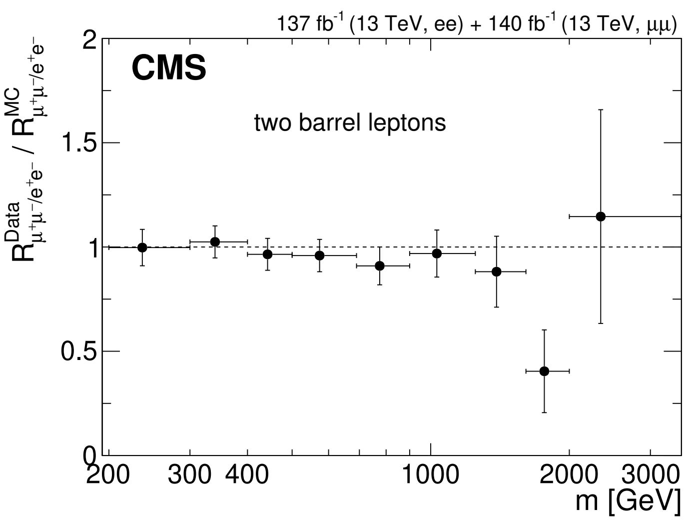
At very high masses, the statistical uncertainties are large.

Here, some deviations from unity are observed, caused

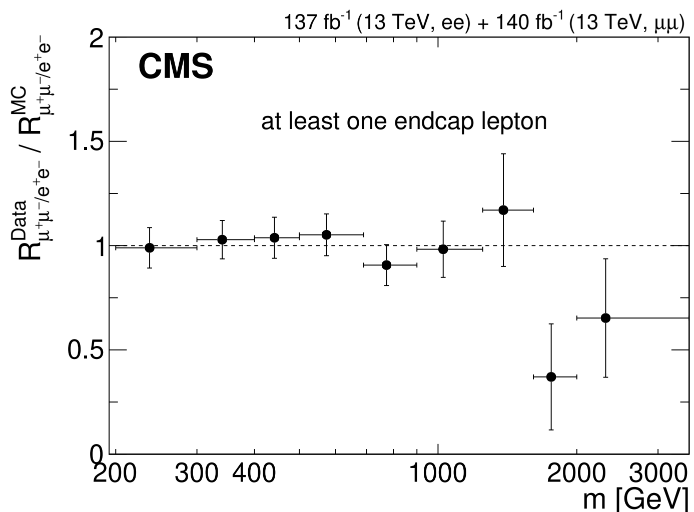
by the slight excess in the dielectron channel.

A χ^2 test for the mass range above 400 GeV is performed:

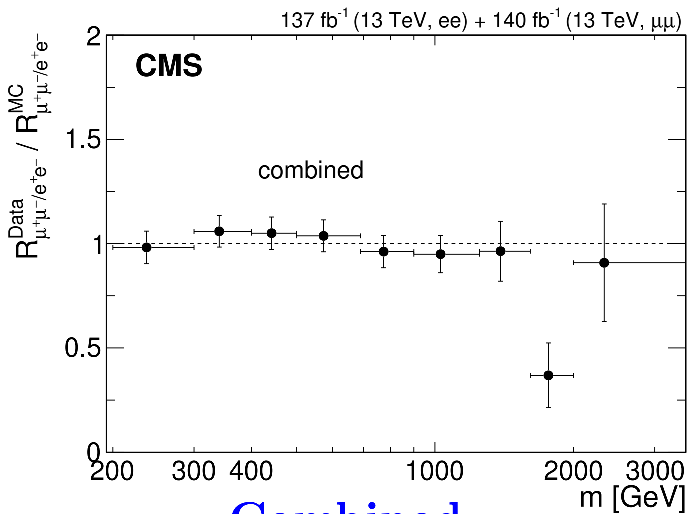
$\chi^2/\mathrm{dof} = 11.2/7$ and $9.4/7$ for $m > 400\,\mathrm{GeV}$.



Barrel ($|\eta| < 1.2$)



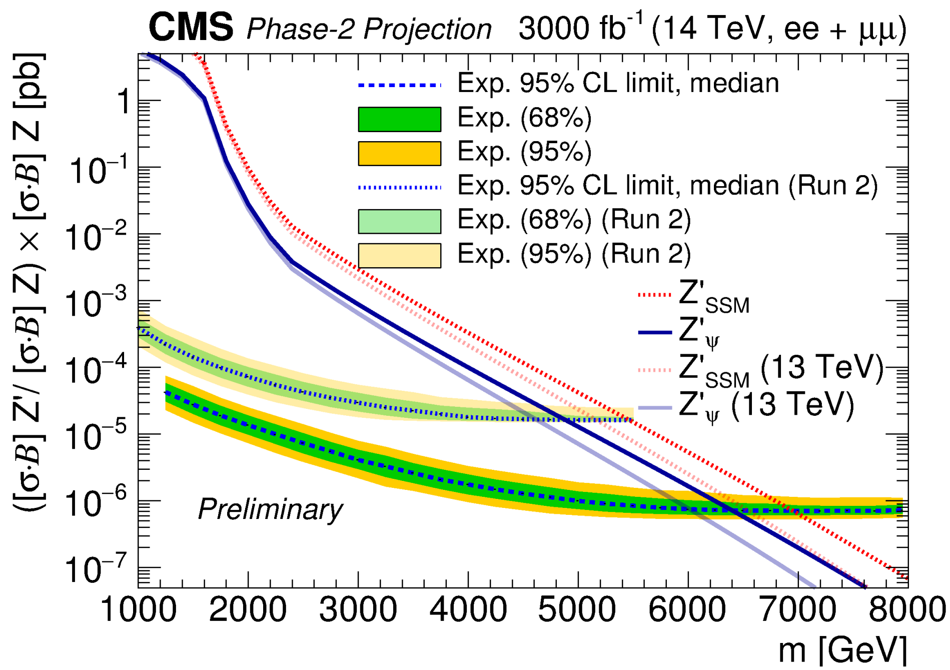
Barrel-Endcap



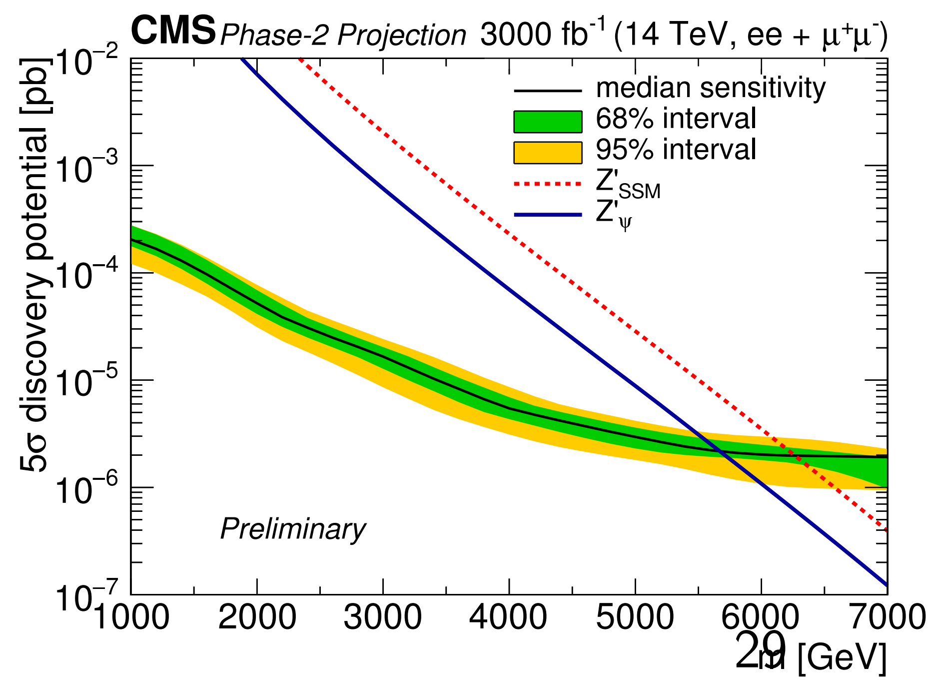
Combined

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 ~ 7 TeV for SSM model.

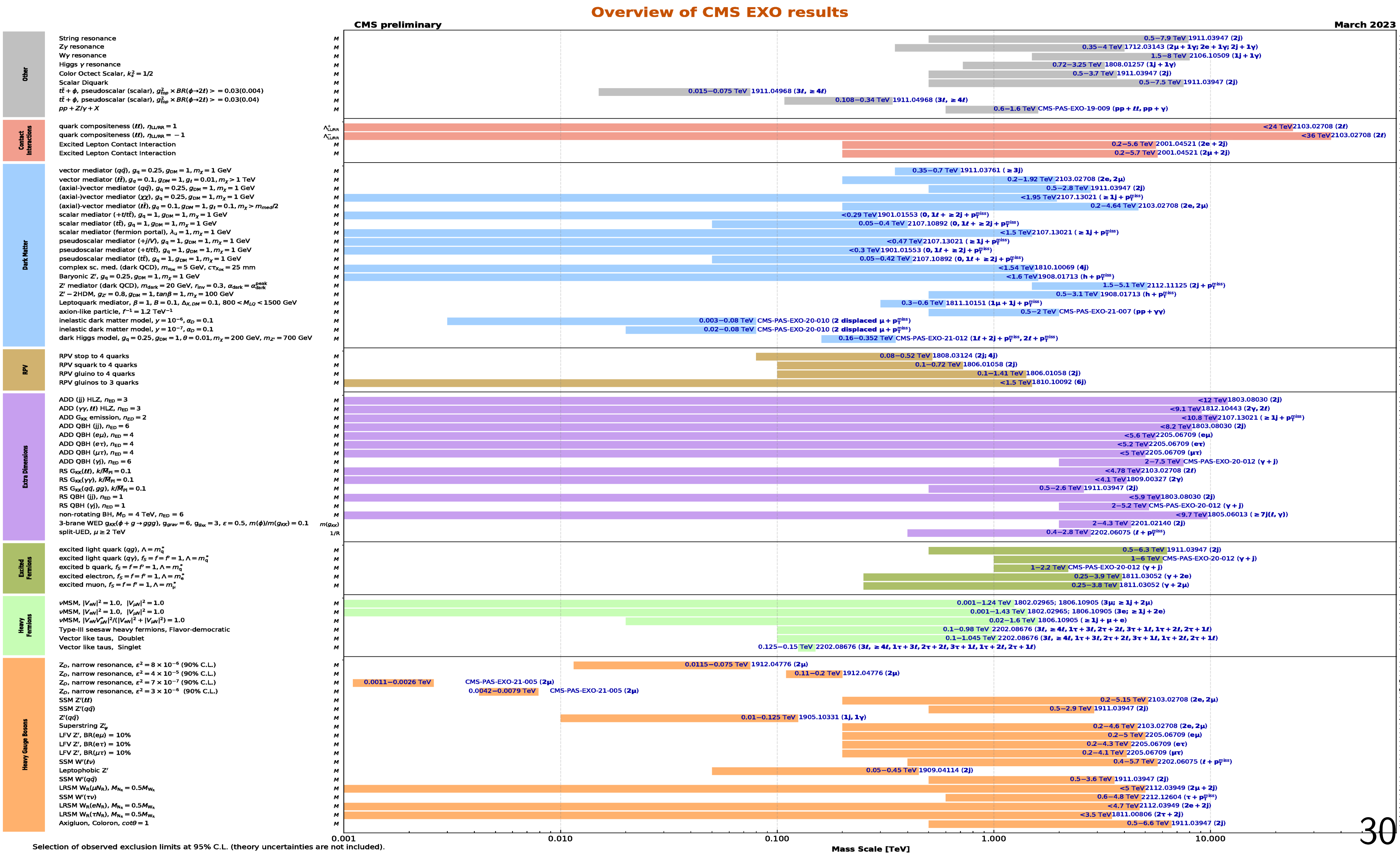


Discovery with 5 σ significance can be made up to mass of ~ 6.3 TeV for SSM model.



Limits for many other searches of Exotica at CMS performed.

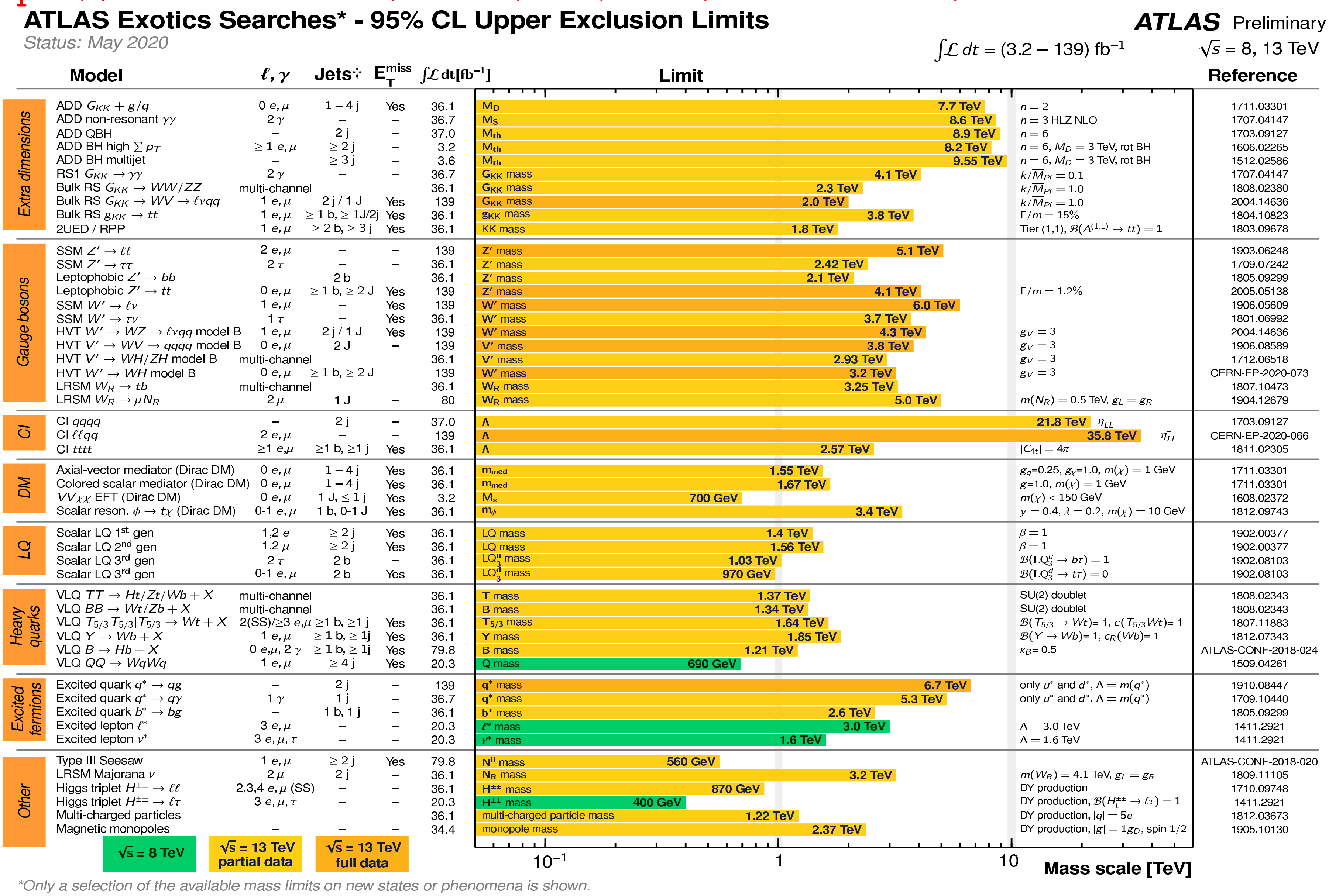
http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/



ATLAS Exotics Limits (95% CL)

Limits for many other searches of Exotica at ATLAS performed.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults



Conclusions

- Dimuon is a unique channel providing clean signal with small background even for large pileup at the LHC. Has become basics for many physics analyses.
- New ranges have been studied with the increased energy and luminosity. Run3 has accumulated $\sim 70\,\text{fb}^{-1}$ at $\sqrt{s} = 13.6$ TeV.
- This enables 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 5.1 TeV and for the HL LHC it is expected to reach 7 TeV.
- We are looking forward for new discoveries.

  Stay tuned for the news!

Publications by experiments:

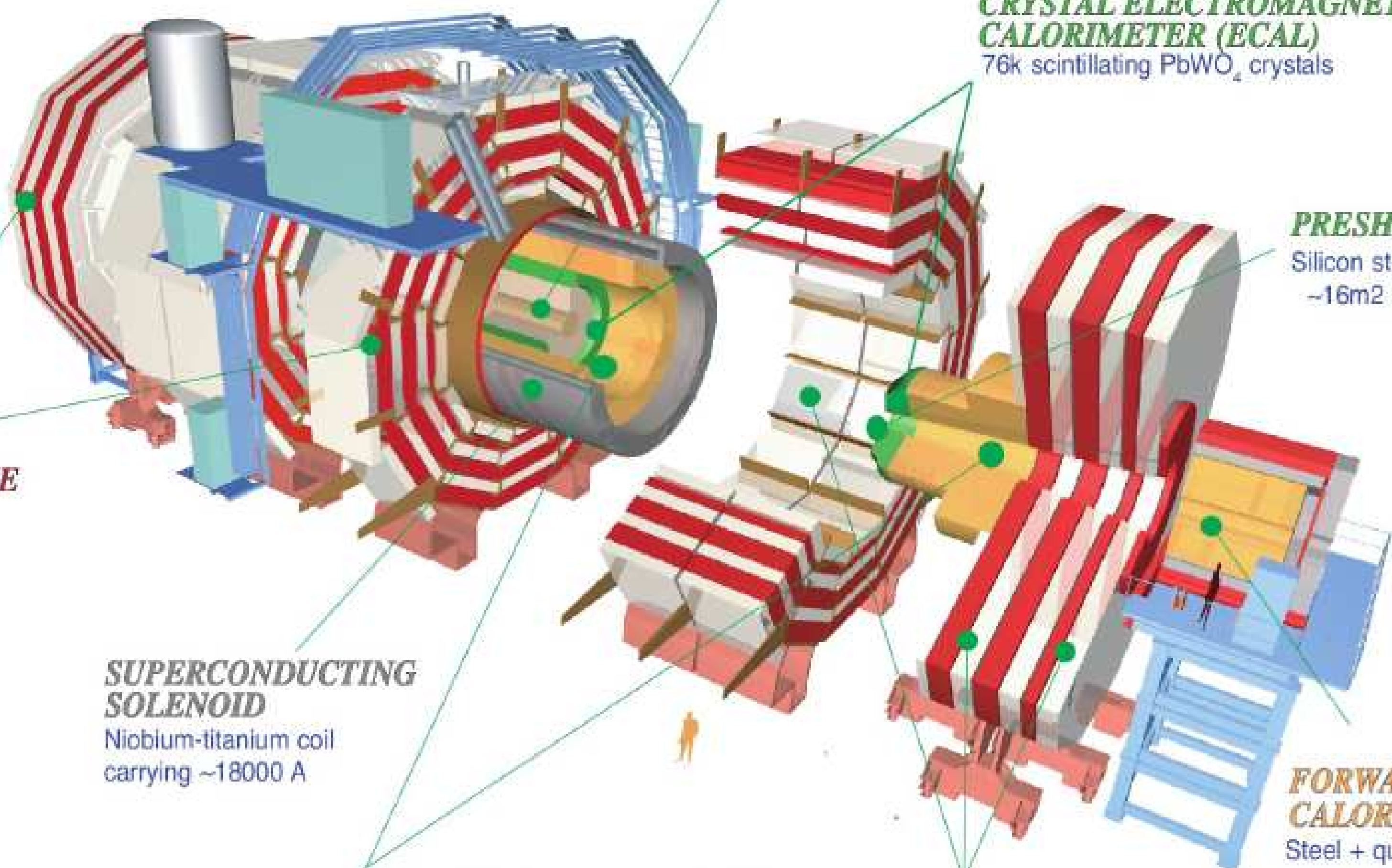
http://cms-results.web.cern.ch/cms-results/public-results/publications/

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/

https://lhcb-outreach.web.cern.ch/category/physics-results/

Backup slides

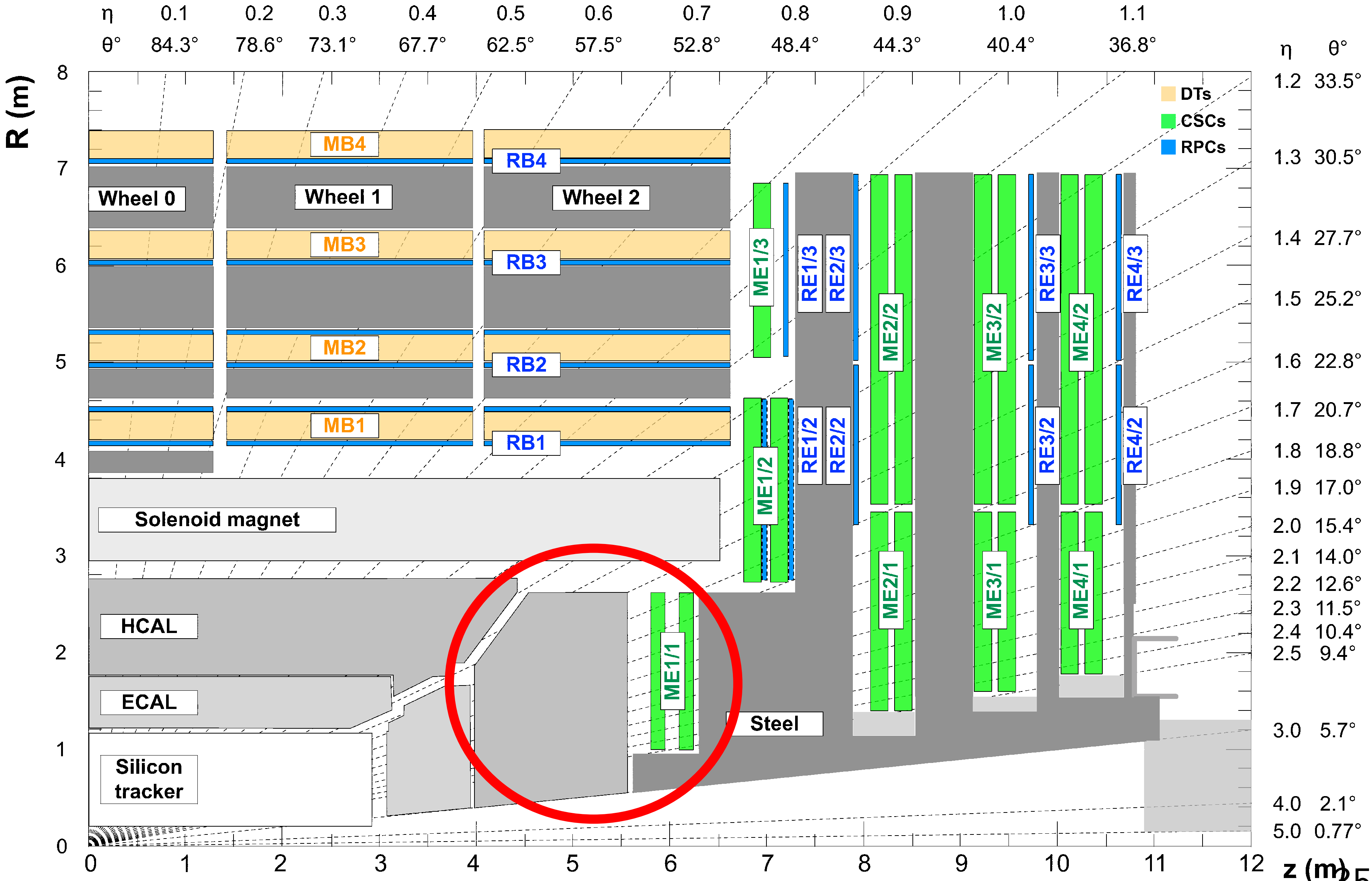
CMS (Compact Muon Solenoid) at LHC (CERN)



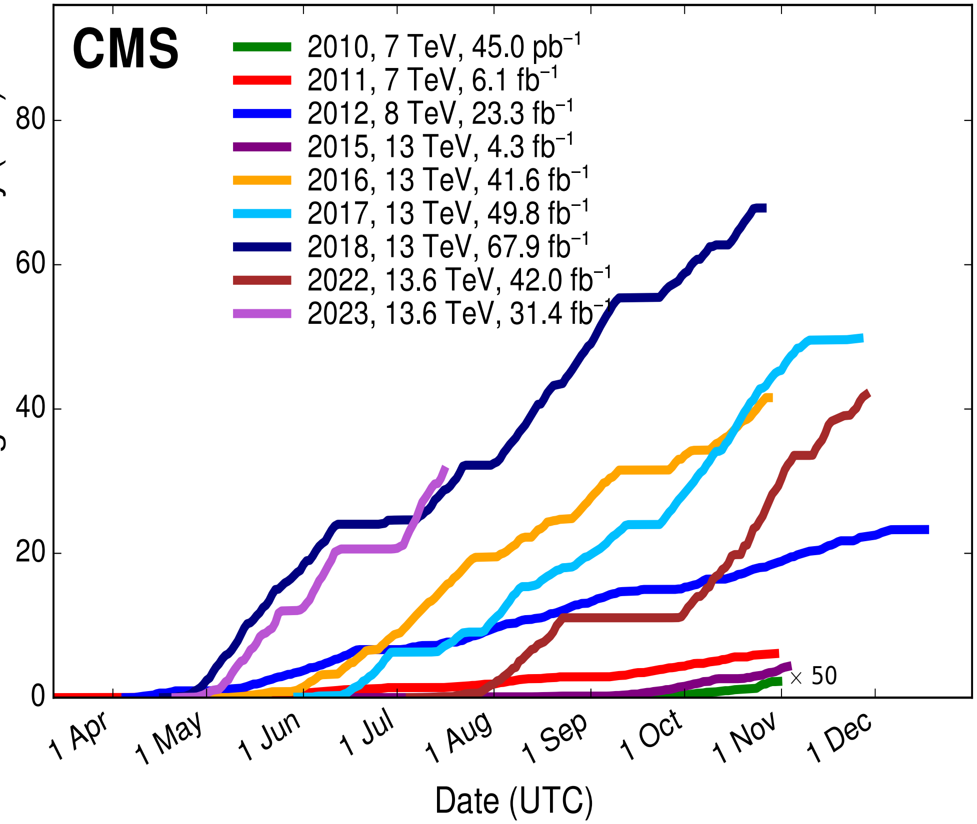
Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

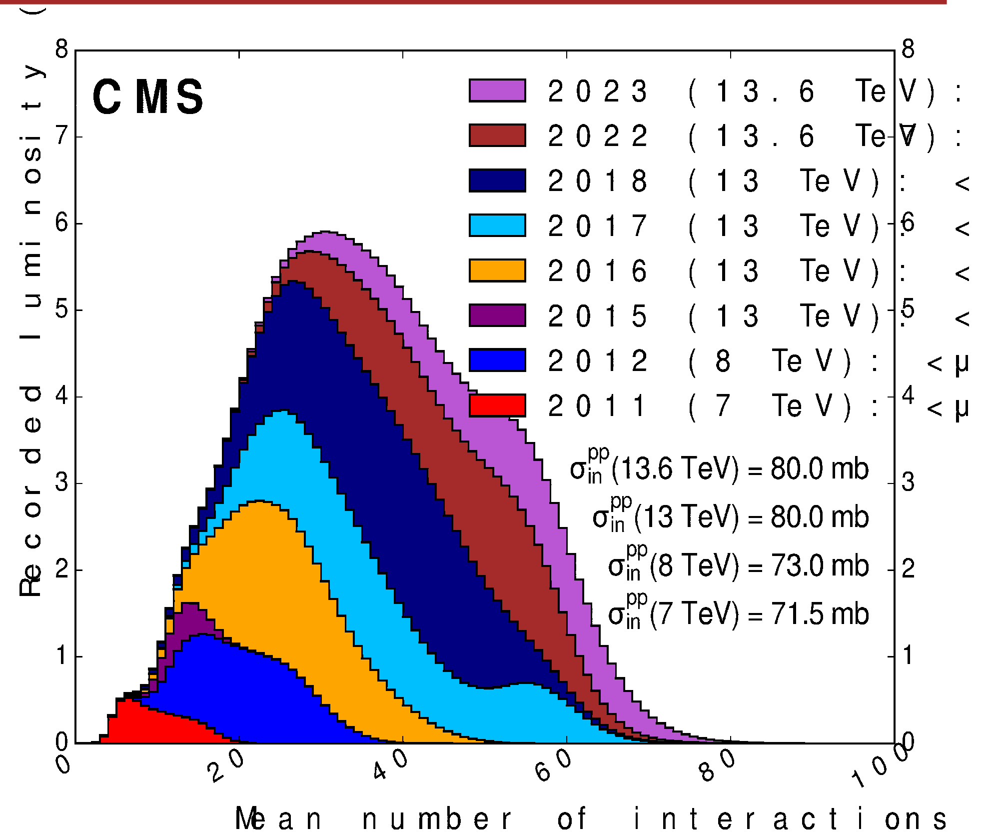
Quadrant of CMS detector

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



Runs 1–3 Statistics





- Mean luminosity is more than $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (original nominal value for LHC)
- Rapid rise of integrated luminosity in 2016–2018 with $\sqrt{s} = 13$ TeV
- Total for physics analysis in Run 2 $\int \mathcal{L}\, dt \approx 140\ \mathrm{fb}^{-1}$
- Data taking efficiency $> 90\%$

Z' Models (JHEP 1806 (2018) 120)

$U'(1)$ model	Mixing angle	$\mathcal{B}(\ell^+\ell^-)$	c_u	c_d	c_u/c_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

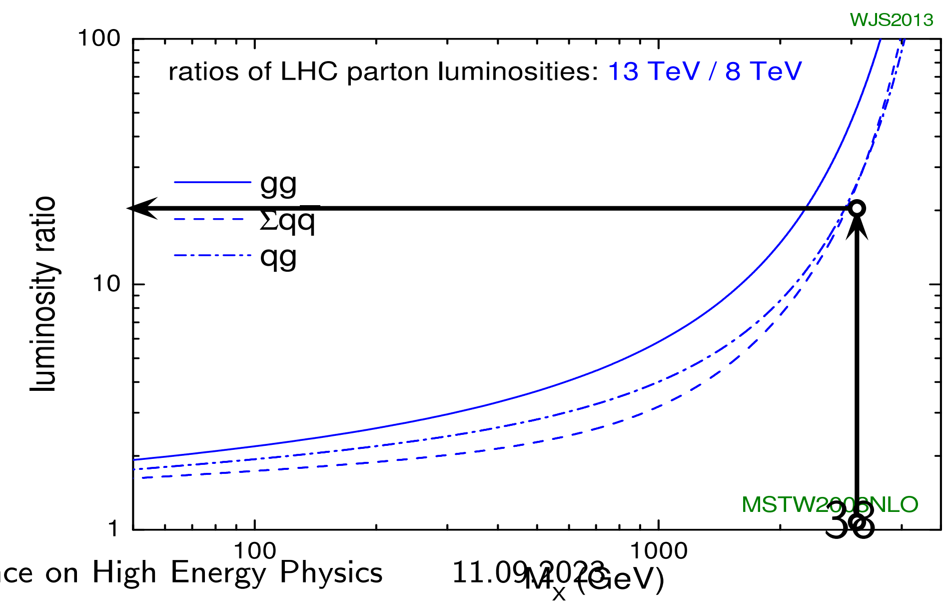
Table 1. Various benchmark models with their corresponding mixing angles, their branching fraction ($\mathcal{B}$) to dileptons, the c_u and c_d parameter values and their ratio, and the width to mass ratio of the associated Z' boson.

History and CMS Publications on Searches for Heavy Dilepton Resonances

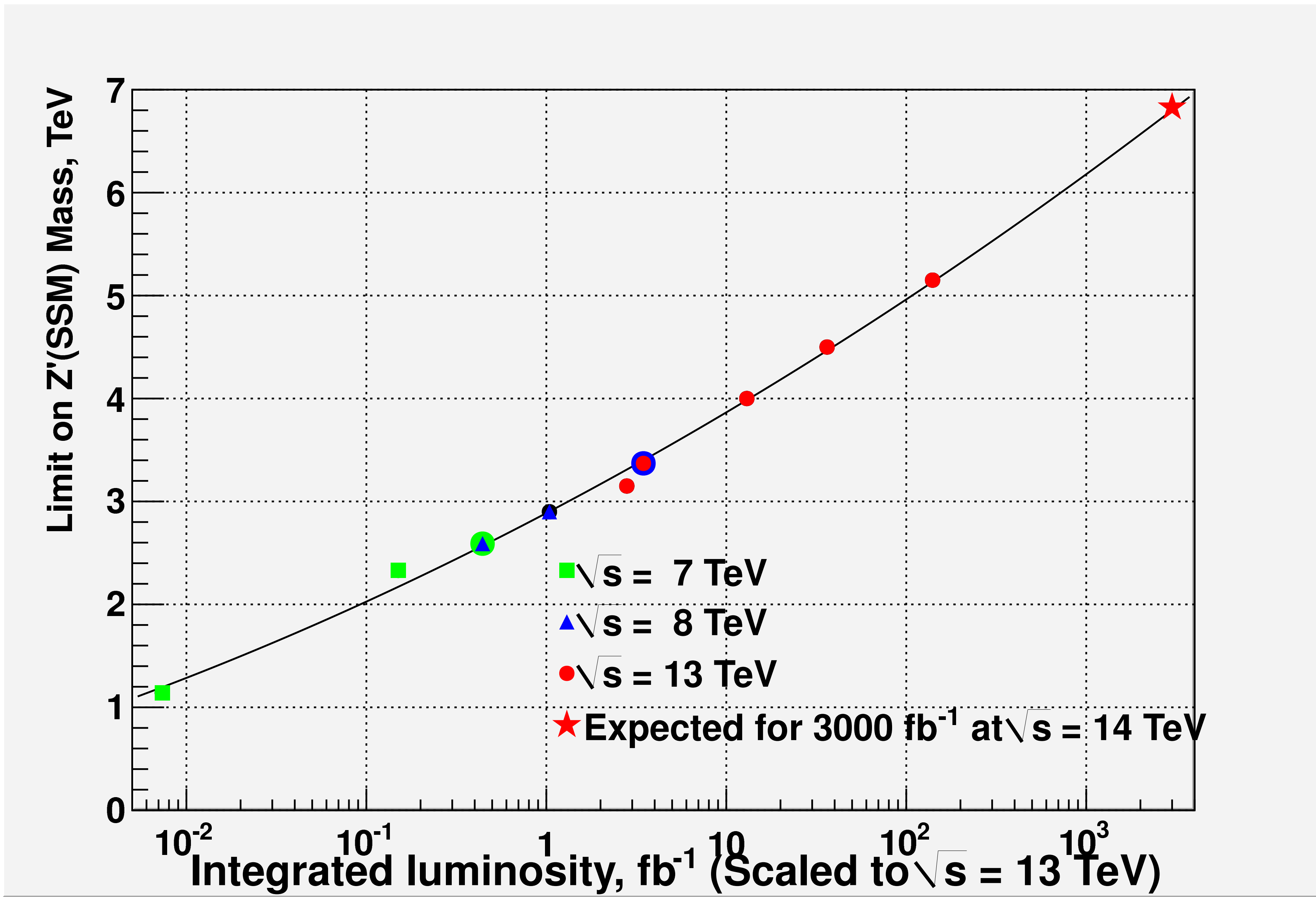
Publications and Results on Searches for Heavy Dilepton Resonances:

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

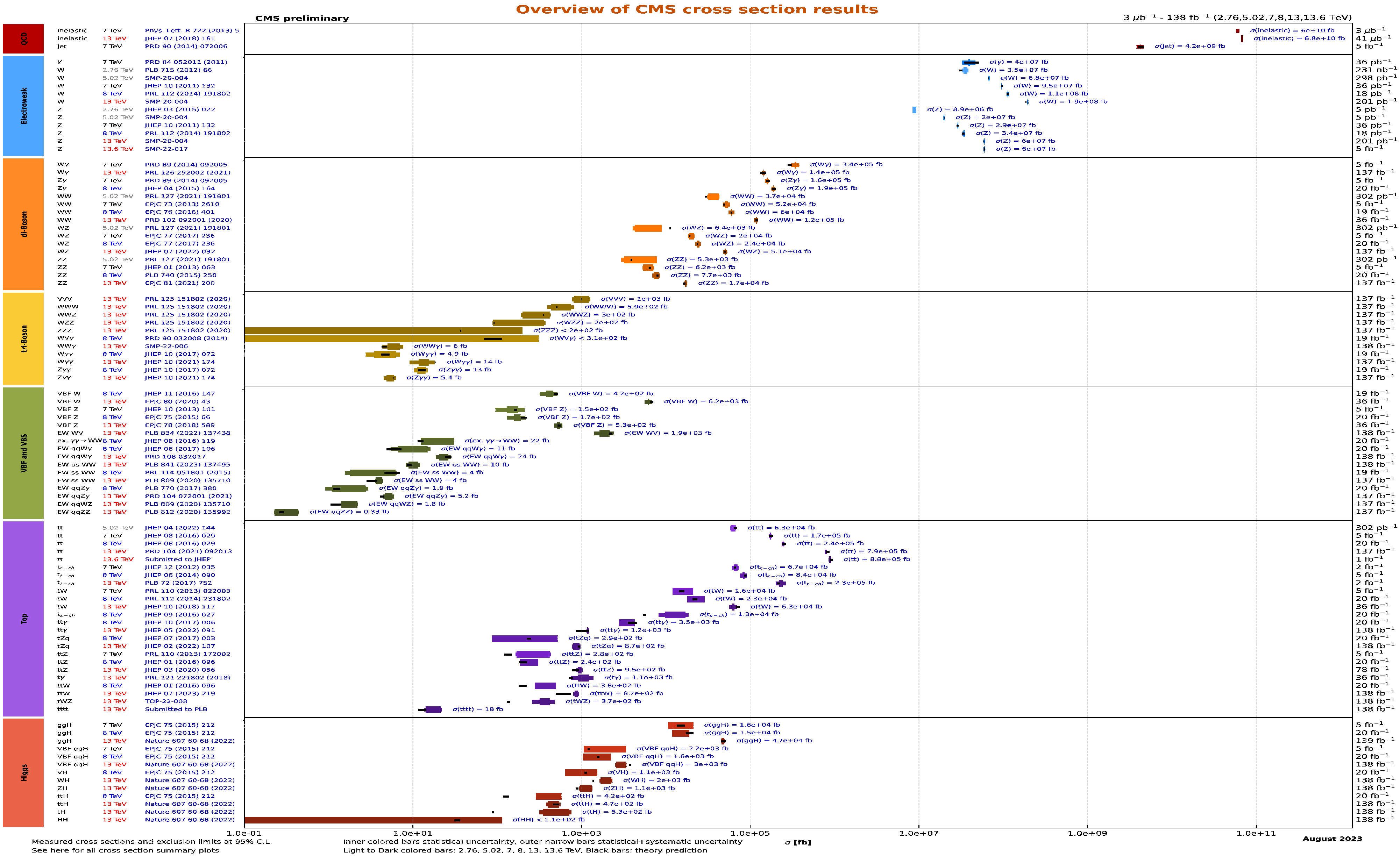


CMS Z' Dilepton Limits vs Integrated Luminosity



Summary of SM Xsec Results (CMS)

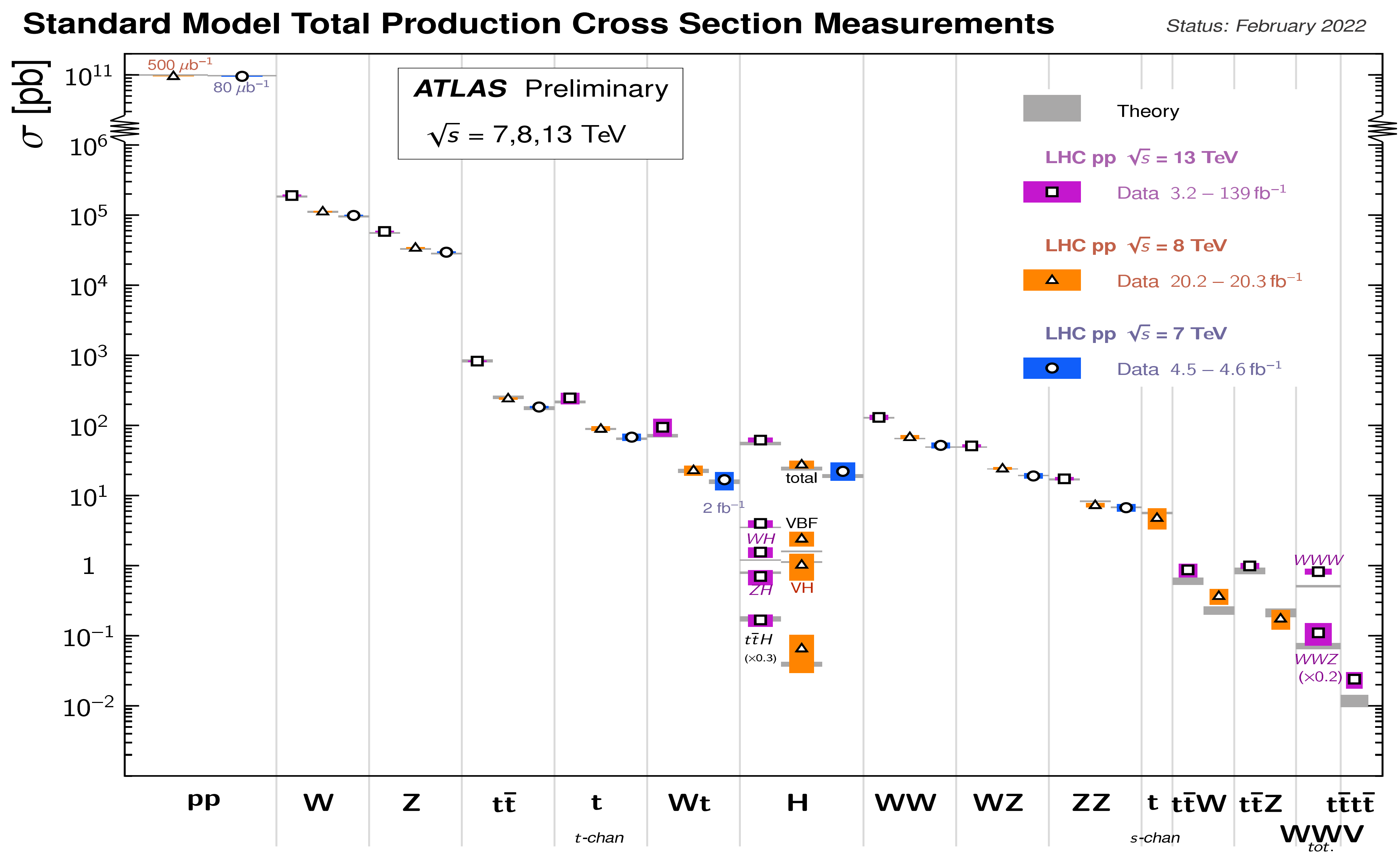
http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP



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

Summary of SM Physics Results (ATLAS)

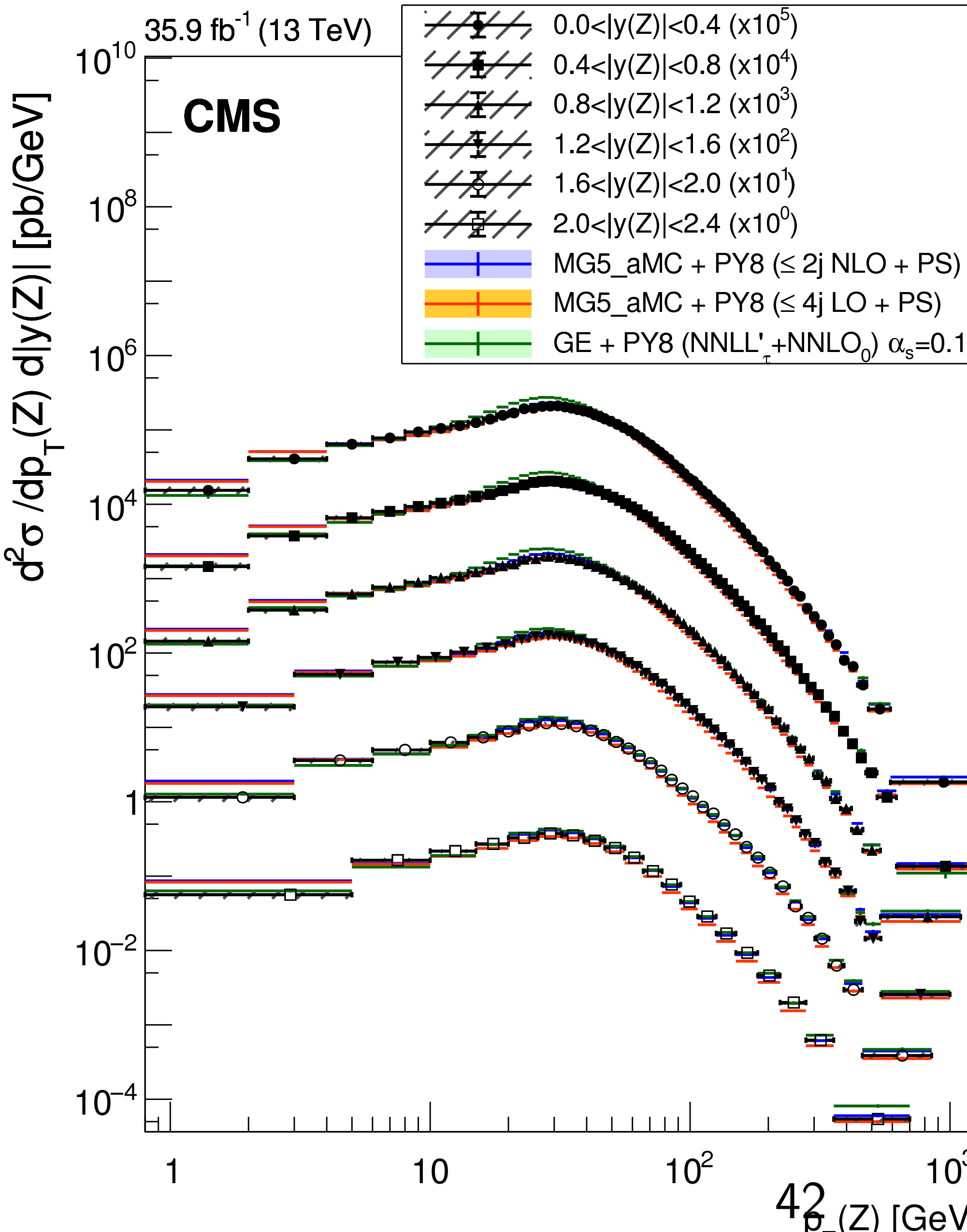
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults



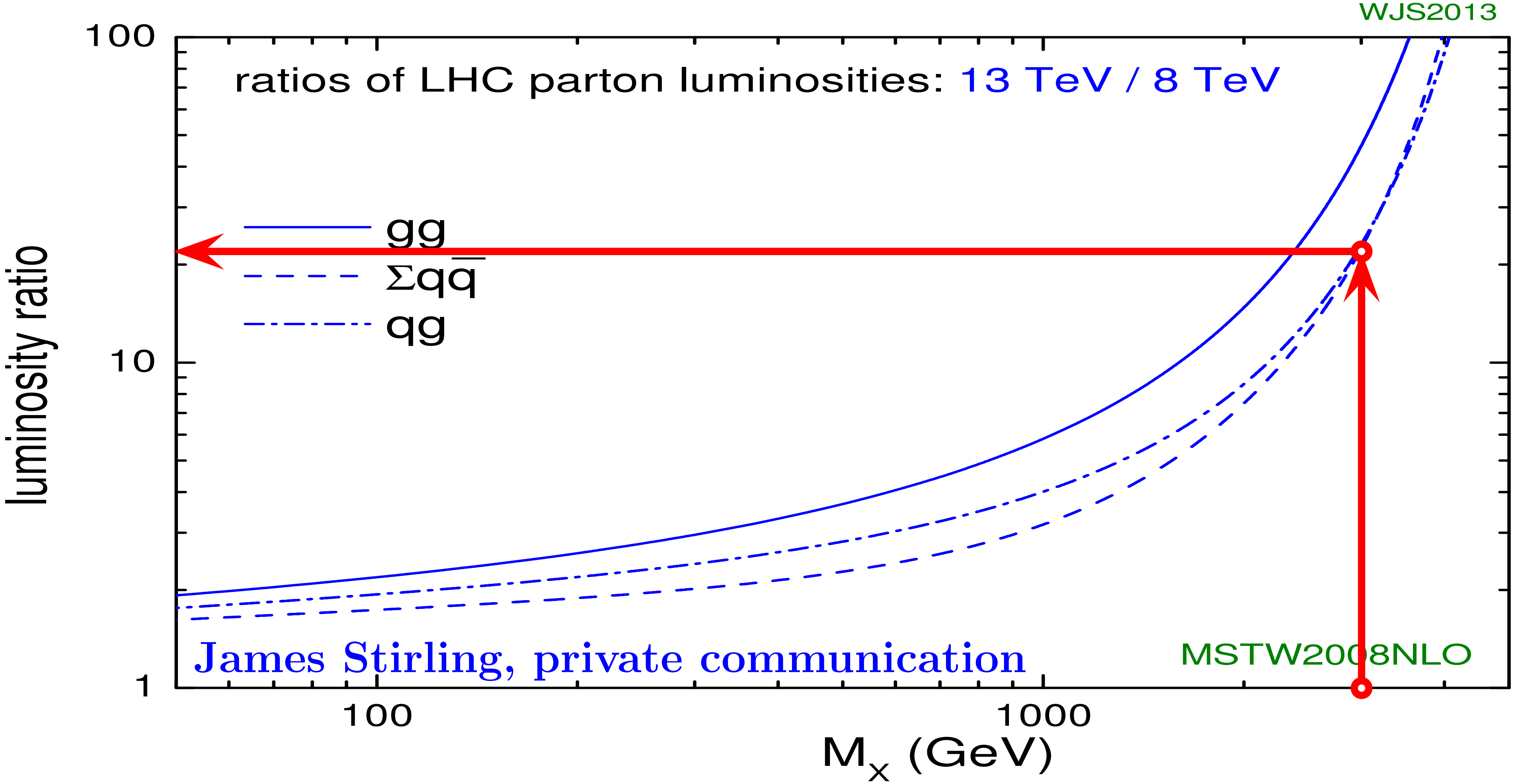
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Measurement of multi-differential cross sections for production of Z boson + jets (arXiv:2205.02872)

- The differential cross sections for production of Z boson + jets are measured as a function of p_{T} of the Z boson and p_{T} and rapidities of five jets with largest p_{T}.
- Measured jet multiplicity distribution.
- Also studied the scalar sum of the jet p_{T} which quantifies the hadronic activity in the event.
- The measurements are compared with predictions from several MC generators.



Run1 ($20\,\mathrm{fb}^{-1}$ at 8 TeV): excluded Z' dilepton resonances for $M \leq 2.9$ TeV



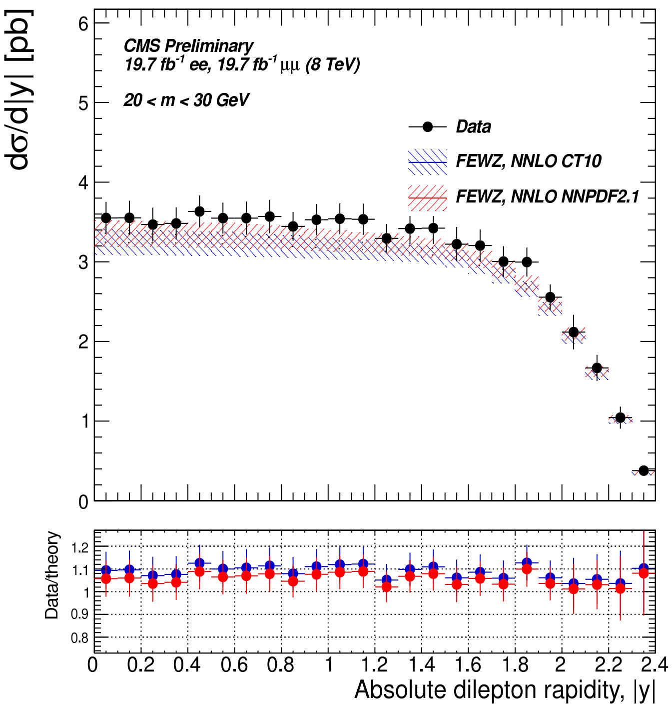
For new bosons of $M \approx 3$ TeV:

Each 1 fb^{-1} at $\sqrt{s} = 13\,\mathrm{TeV}$ gives the same sensitivity as the whole Run1.

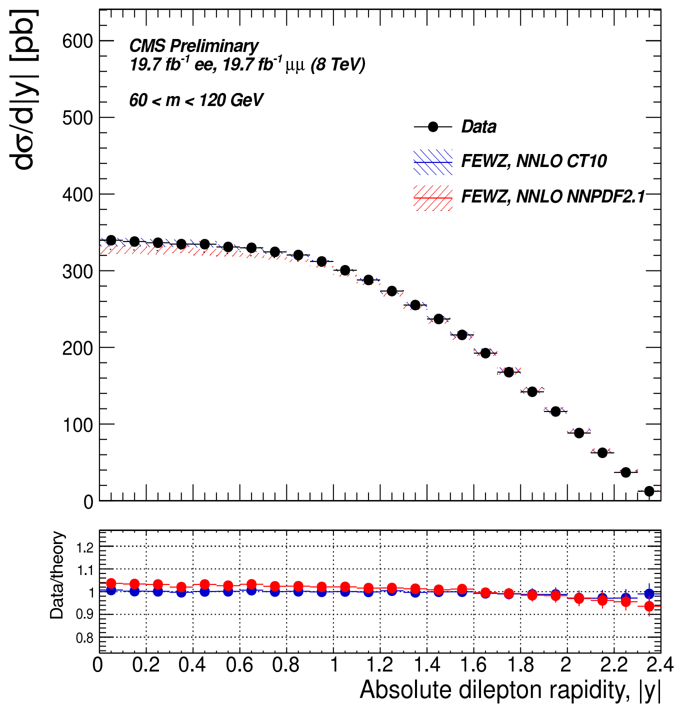
A unique chance to test new mass ranges!

Drell-Yan 2D Xsecs — M vs $|y|$ (Eur. Phys. J. C75 (2015) 147)

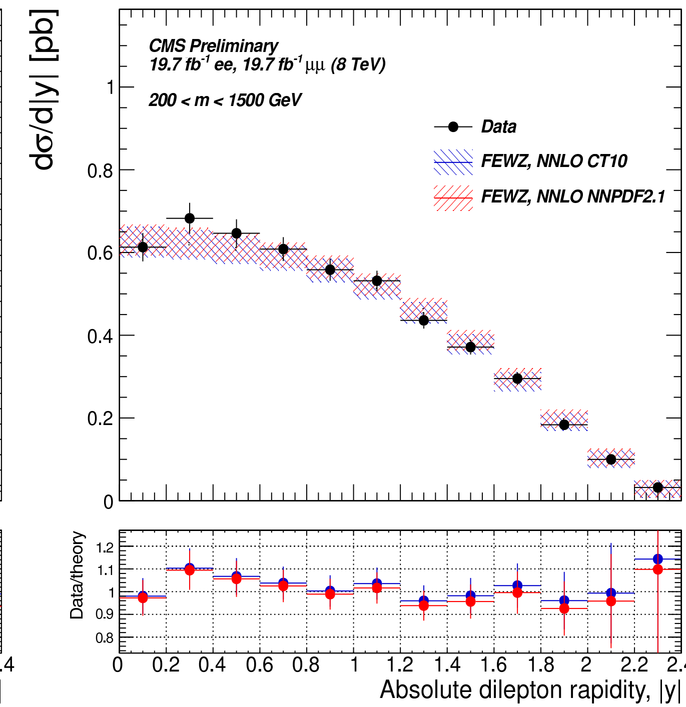
"Low mass"



Z region



"High mass"



6 bins on $M_{\mu\mu}$ at 20, 30, 45, 60, 120, 200, 1500 GeV, 24 bins for $|y| = 0 - 2.4$

For $M > 200$ GeV — 12 bins for $|y| = 0 - 2.4$

Within the detector acceptance to reduce the model dependence.

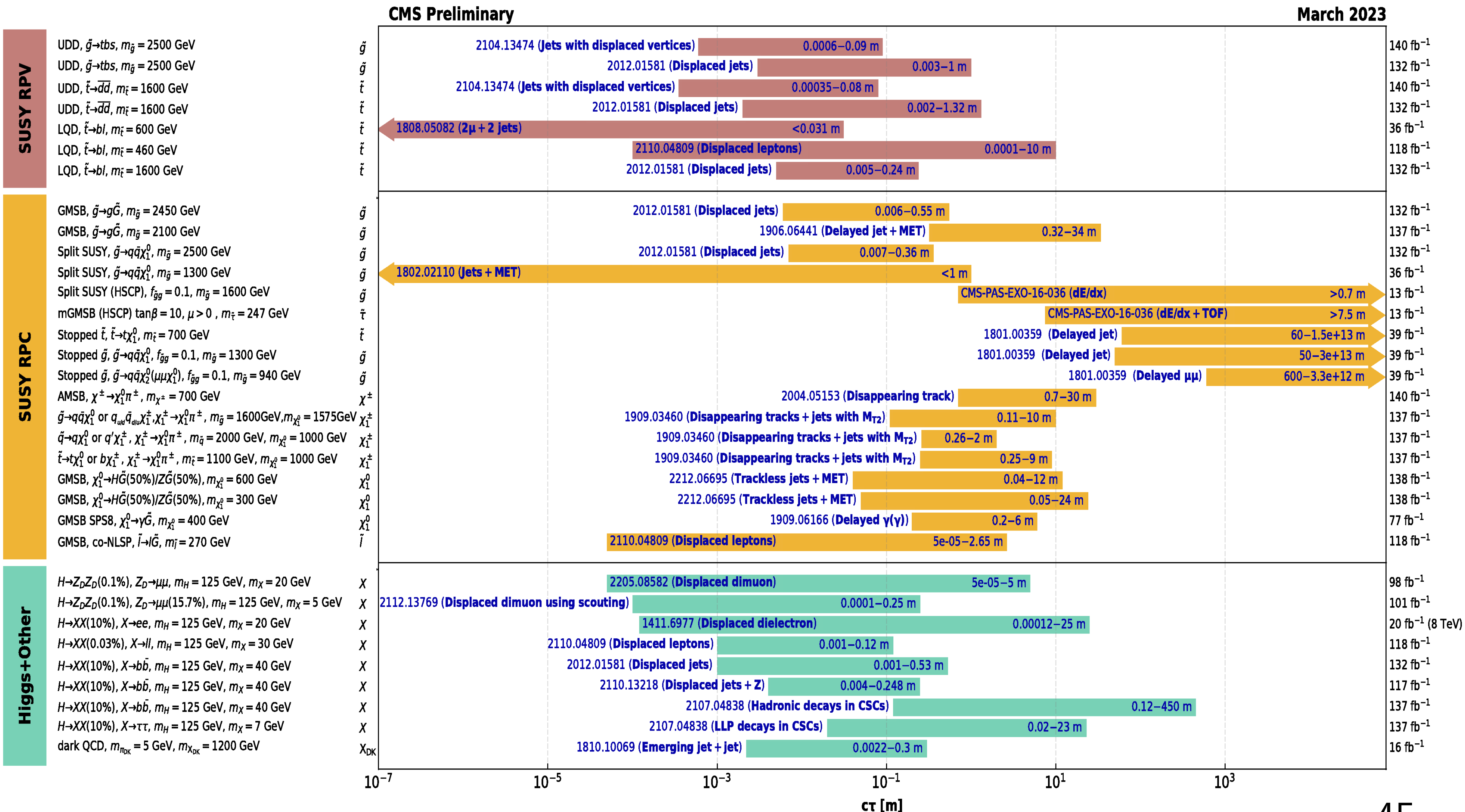
Good agreement with FEWZ, but deviations exist at low and high mass regions.

Double differential xsecs provide a high sensitivity to NNLO QCD effects and could yield precise constraints on the PDFs.

Limits for many other searches of Exotica at CMS performed.

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

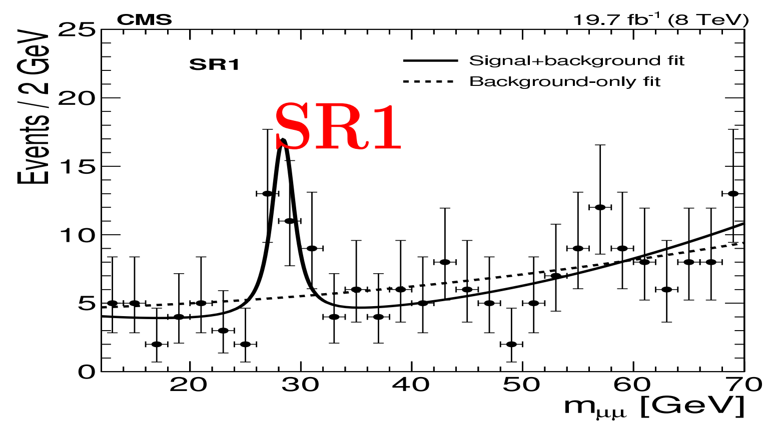
Overview of CMS long-lived particle searches

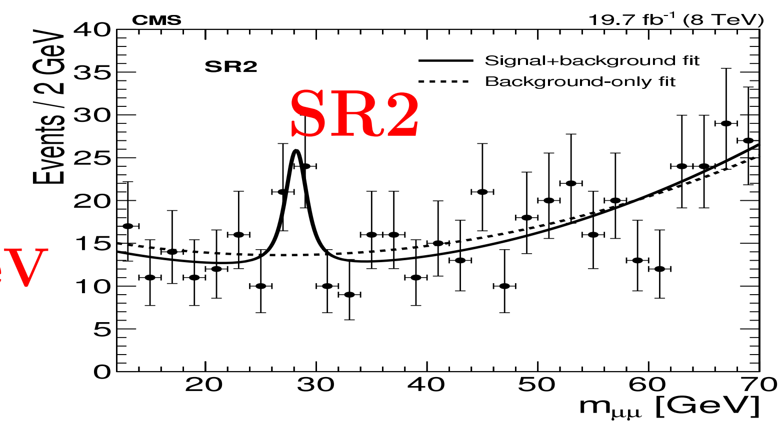


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

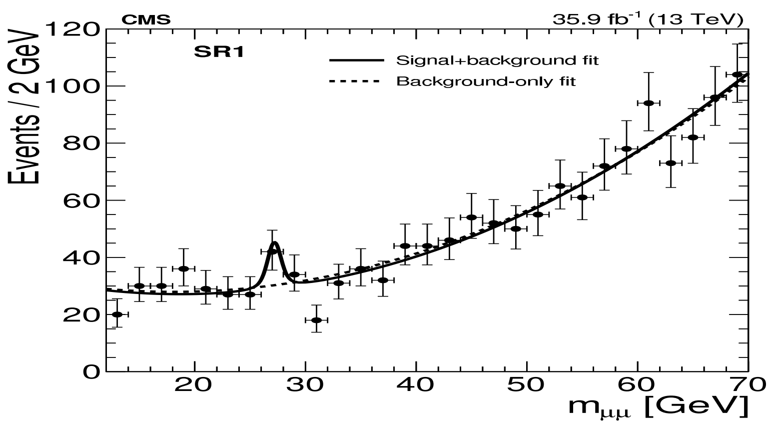
Search for $\mu^+\mu^-$ resonances produced in association with b-jets (JHEP 1811 (2018) 161)

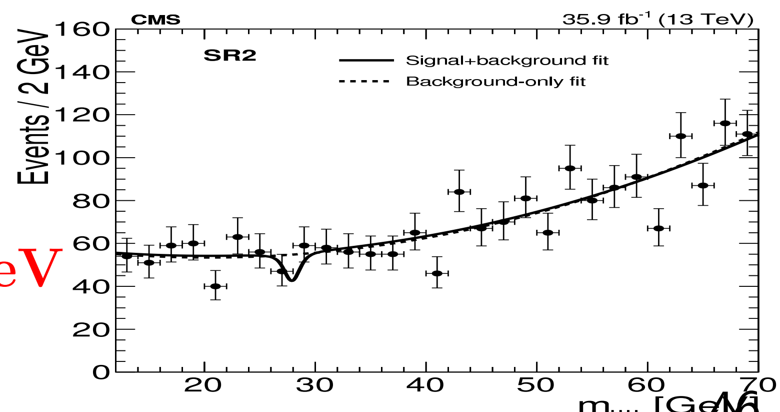
An excess of events near a $M(\mu\mu) = 28\,\mathrm{GeV}$ was observed by CMS in the 8 TeV data. Association with b quarks was required and two categories of events were considered. A similar analysis conducted with 13 TeV data results in a mild excess in one category and a deficit in another one. $\Rightarrow$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





$\sqrt{s} = 8$ TeV



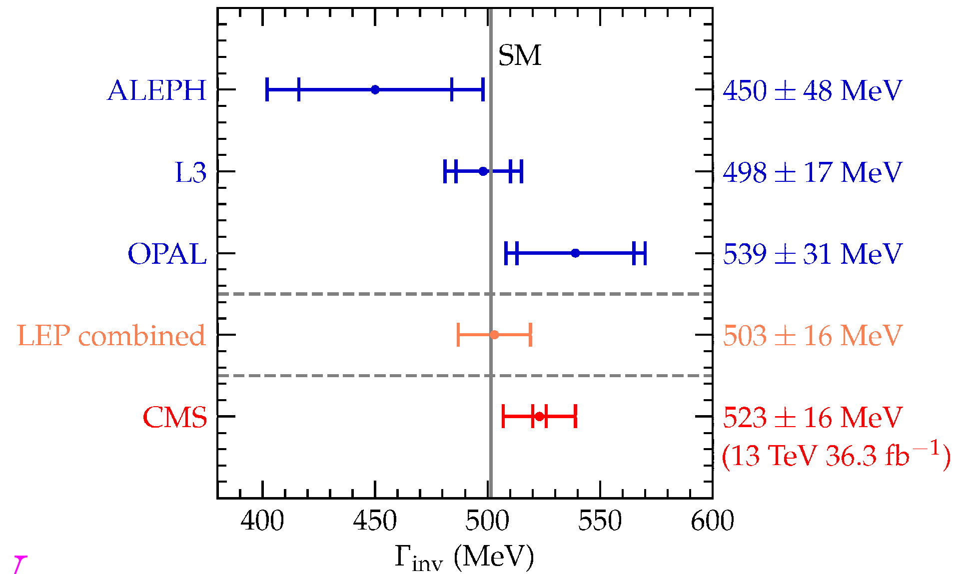


$\sqrt{s} = 13$ TeV

Precision measurement of Z invisible width (arXiv:2206.07110)

The result is extracted from a simultaneous fit to data regions containing mainly Z boson decay to invisible particles ($\nu\bar{\nu}$) and those dominated by Z boson decay to e^+e^- and $\mu^+\mu^-$.

$\Gamma_{\text{Invisible}} = 523 \pm 3(\text{stat}) \pm 16(\text{syst})$ MeV.

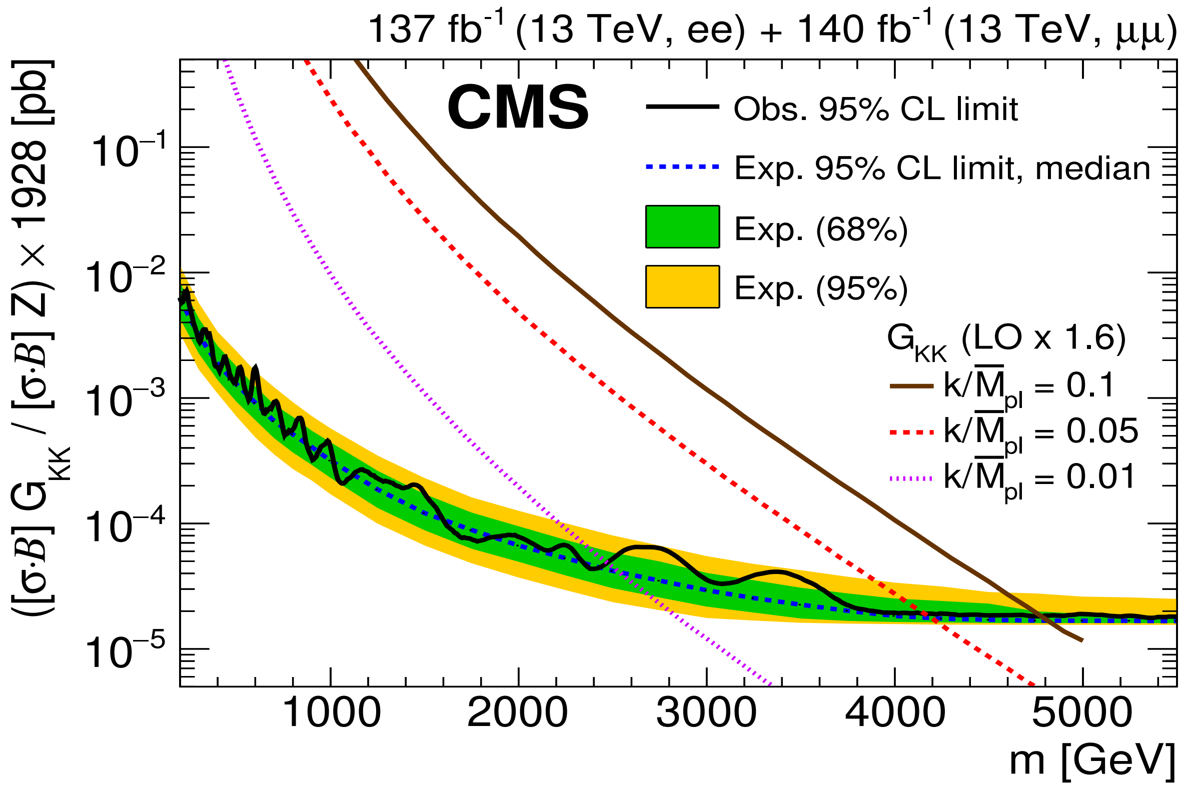


Precision is similar to LEP direct combination

First measurement of the Z invisible width at a hadron collider.

The single most precise direct measurement in the world, competitive with the combined direct measurement from LEP.

RS1 Model (JHEP 07 (2021) 208)



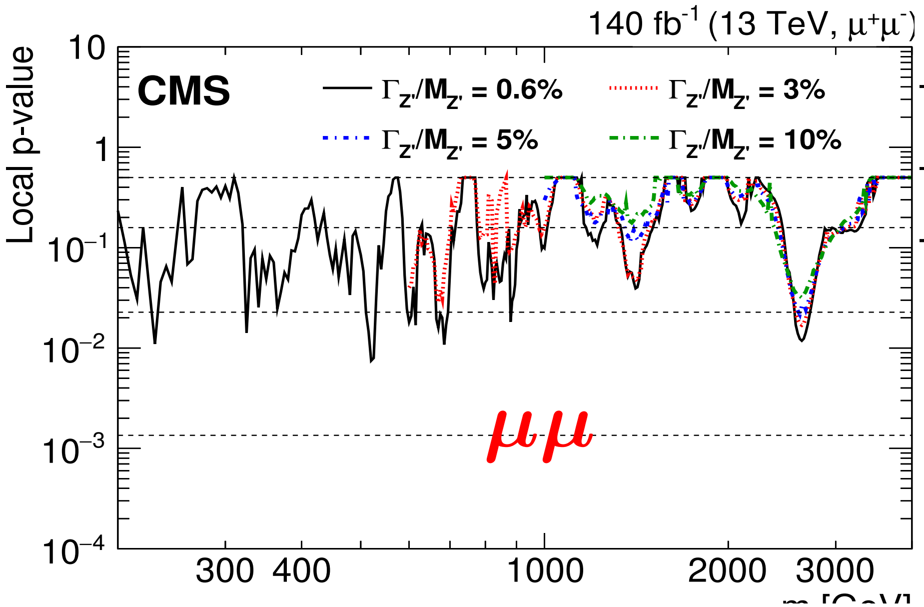
The measured dilepton mass spectra are consistent with predictions from Standard Model.

An RS1 graviton with coupling $c = 0.10$ is excluded below 4.78 TeV.

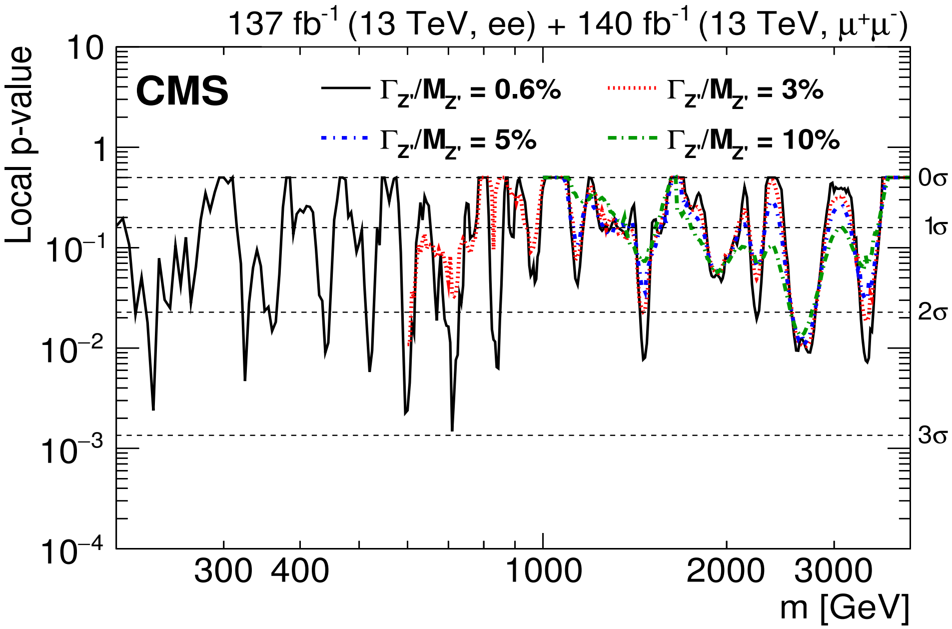
An RS1 graviton with coupling $c = 0.05$ is excluded below 4.16 TeV.

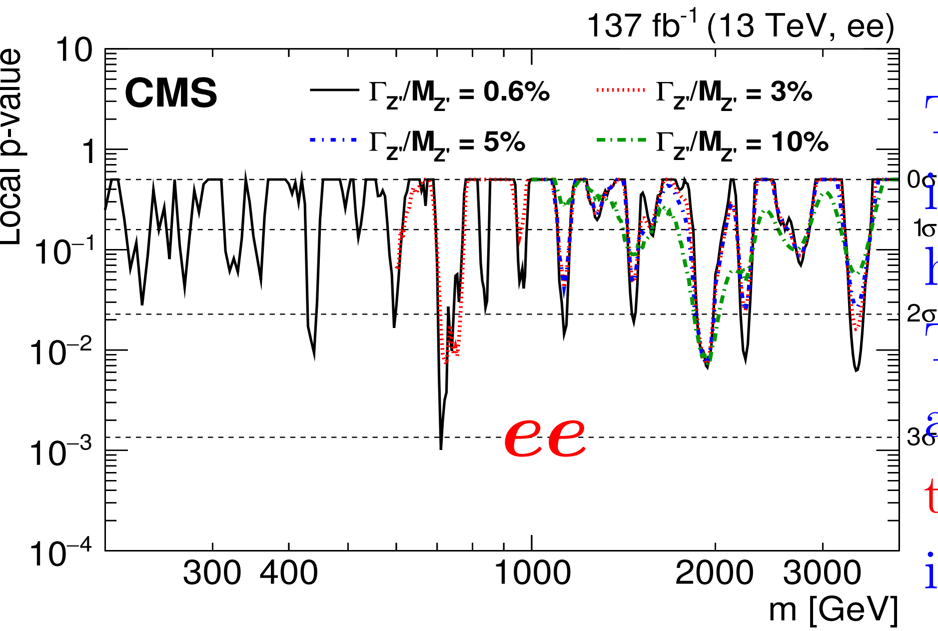
An RS1 graviton with coupling $c = 0.01$ is excluded below 2.47 TeV.

Dileptons channels



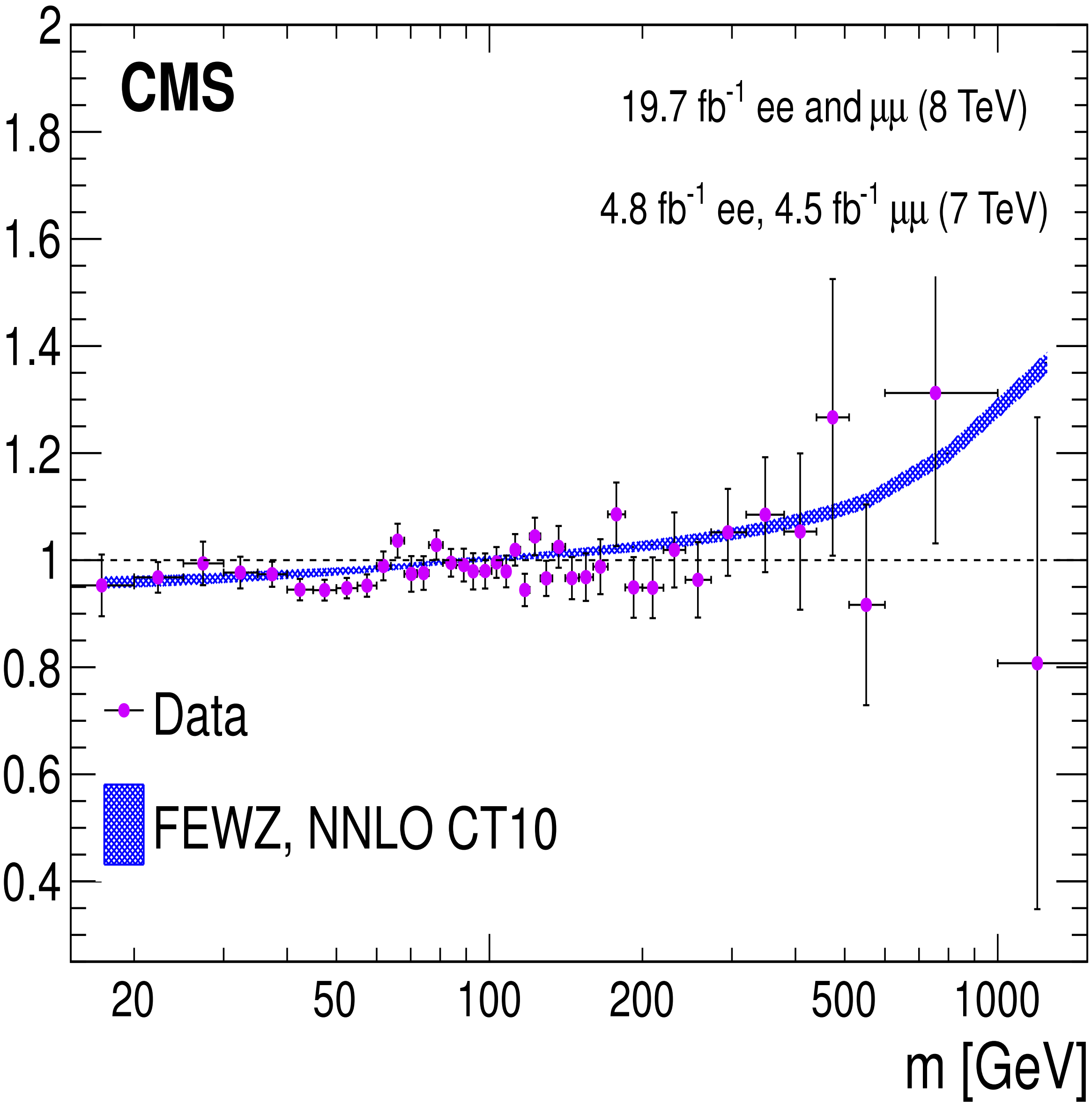
Combined $\mu\mu + ee$





The largest excess in the combined result is observed around $M = 710\,\mathrm{GeV}$ having a local significance of around $3.0\,\sigma$. This corresponds to a global significance of $-1.4\,\sigma$ after taking into consideration the look elsewhere effect (LEE) in the mass range 500–5500 GeV.

Measured ratio of DY xsecs between $\sqrt{s} = 8$ and 7 TeV



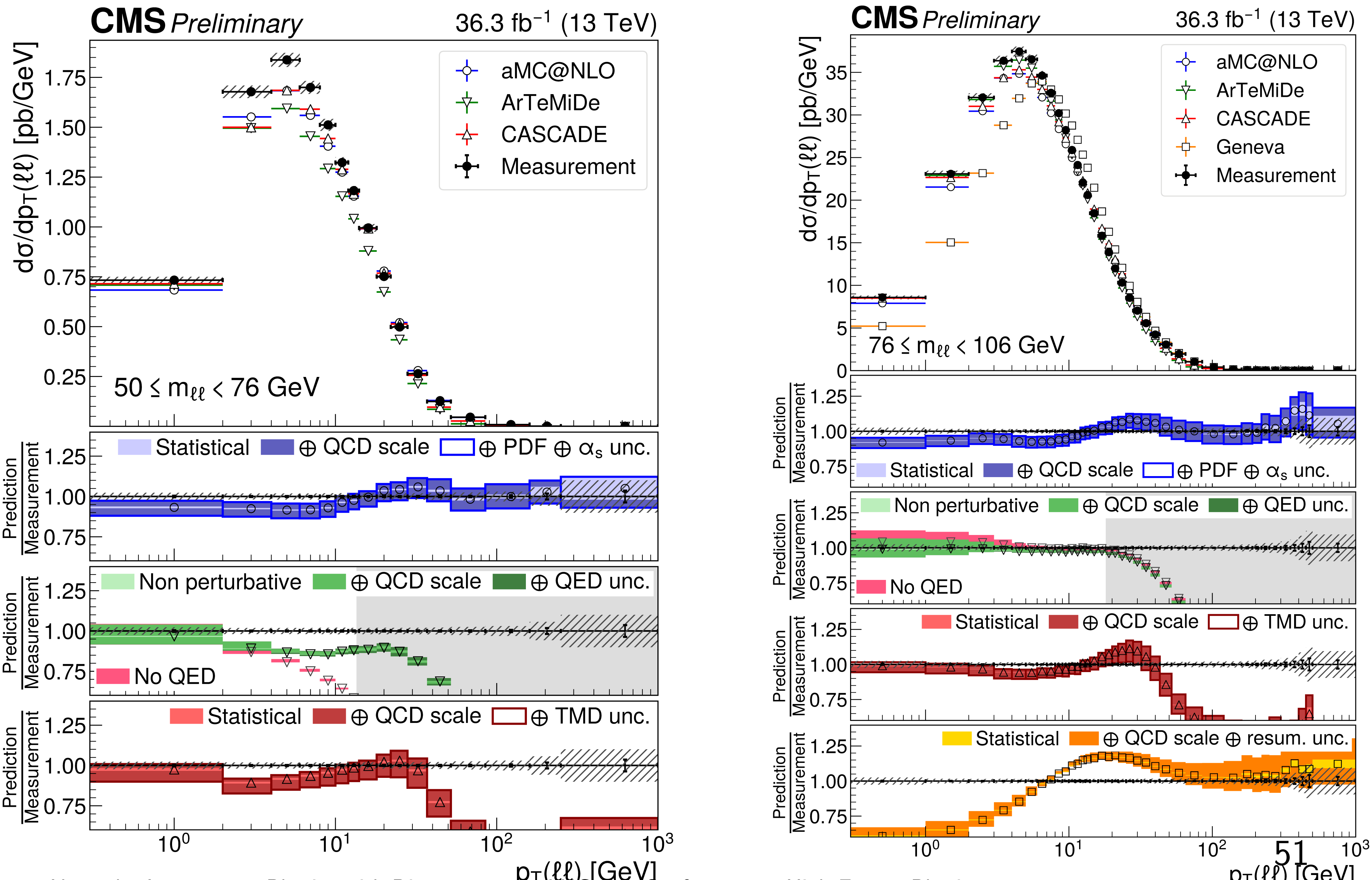
- Measurements of ratios of the normalized differential cross sections:

$$R_{8\,\mathrm{TeV}\,/\,7\,\mathrm{TeV}} = \frac{1/\sigma_Z\; d\sigma/dM(8\,\mathrm{TeV})}{1/\sigma_Z\; d\sigma/dM(7\,\mathrm{TeV})}$$

- Luminosity uncertainty is canceled out.
- Most of the theoretical uncertainties are reduced in such double ratio measurements due to correlations. (arXiv:1206.3557, M. Mangano, J. Rojo)
- Published in Eur. Phys. J. C75 (2015) 147

Also for 6 bins on $M_{\mu^+\mu^-}$ vs $|y|$. To be continued at higher energies...

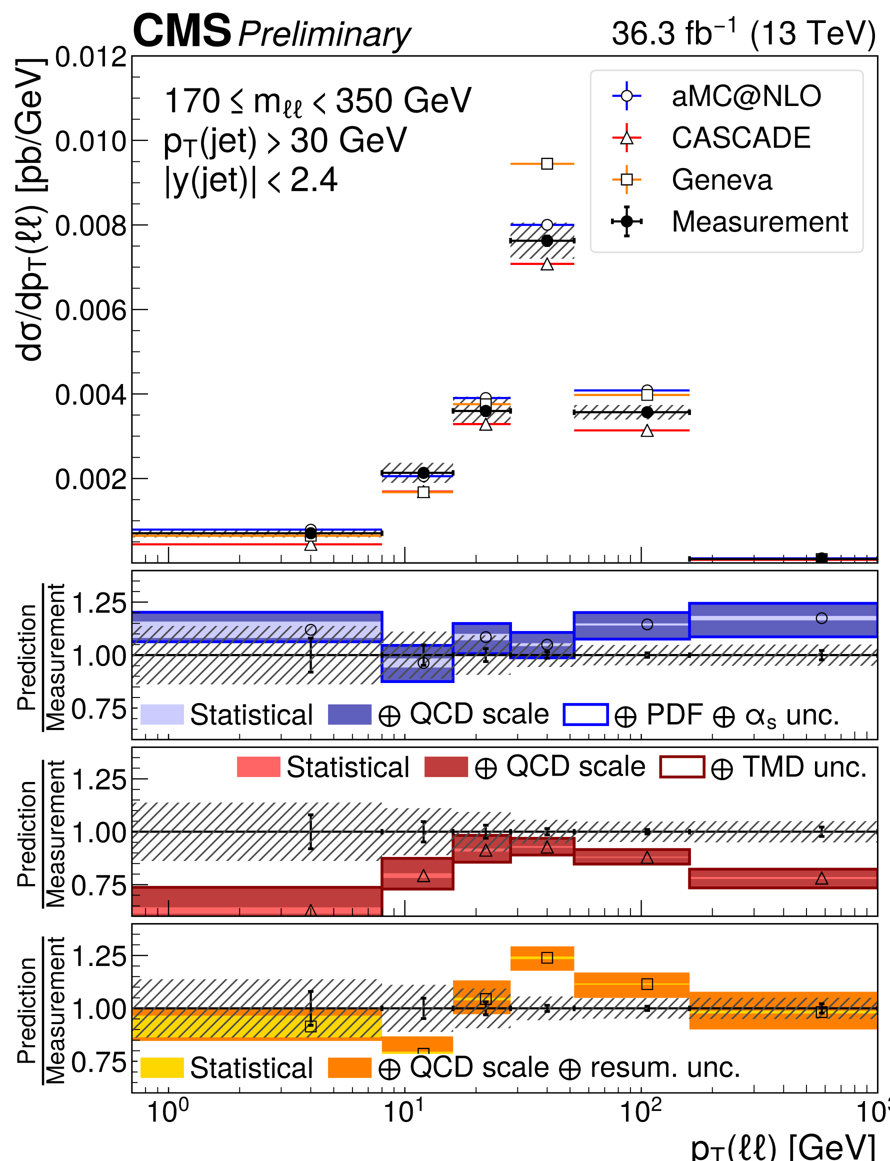
Mass dependence of the transverse momentum
… More mass bins … (arXiv:2205.04897)



Additionally, a measurement is performed requiring at least one jet in the final state.

Shown differential unfolded cross sections in $p_T^{\ell\ell}$ for one or more jets in different invariant mass ranges.

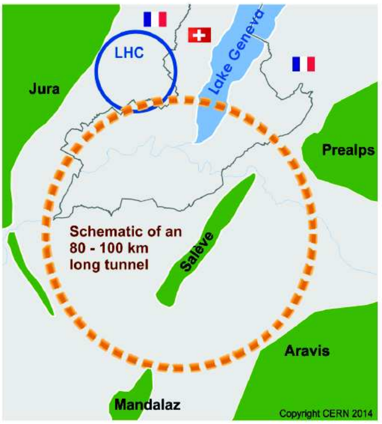
Measurements are compared to state-of-the-art predictions based on perturbative quantum chromodynamics including soft gluon resummation.



Future Circular Collider (~100 TeV) and HE-LHC (~27 TeV)

FCC-ee collider parameters

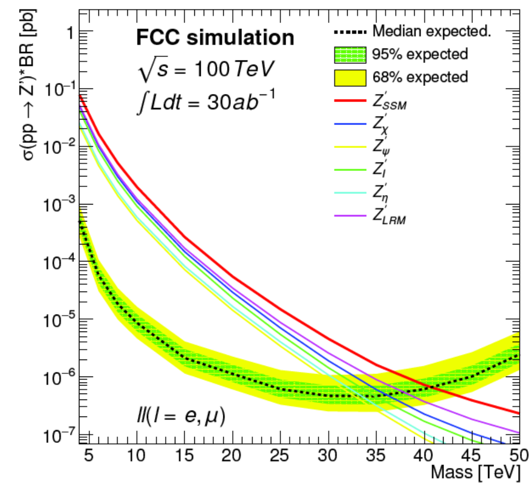
CERN's Future Circular Colliders (FCC) study



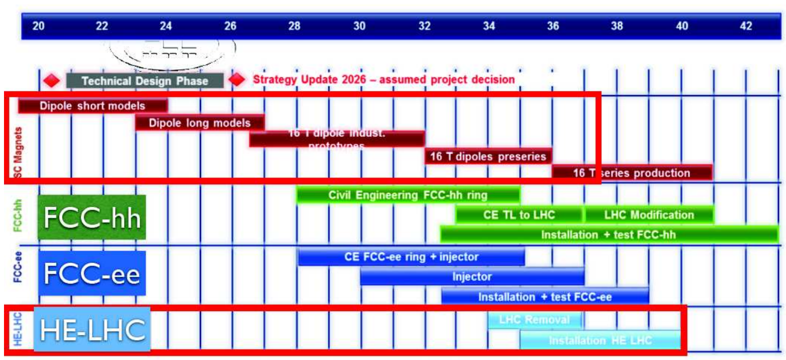
International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements
  ~16 T ⇒ 100 TeV *pp* in 100 km
- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*)**, as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option**, integration of one IP, e from ERL
- **CDR for end 2018**

	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
emittance hor/vert [nm]/[pm]	0.27/1.0	0.28/1.0	0.63/1.3	1.45/2.7
β* horiz/vertical [m]/[mm]	0.15/.8	0.2/1	0.3/1	1/2
SR energy loss / turn (GeV)	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.10	0.44	2.0	10.9
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	16640	2000	393	39
beam current [mA]	1390	147	29	5.4
SR total power [MW]	100	100	100	100
luminosity [10^{34} cm^{-2}s^{-1}]	230	32	7.8	1.5
luminosity lifetime [min]	70	50	42	44
allowable asymmetry [%]	±5	±3	±3	±3



Fastest Possible Technical Schedules

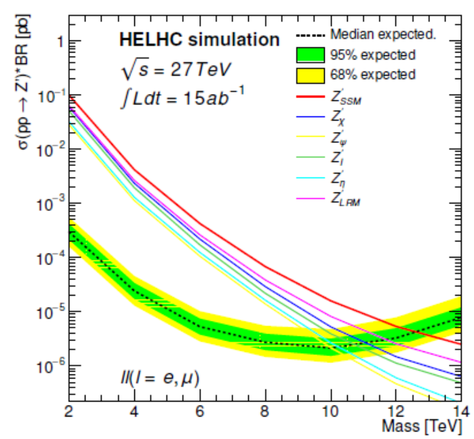


technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:

- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)

FCC-pp collider parameters

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	5	1
events/bunch crossing	170	1k (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36



Measurement of P_1 and P_5' angular parameters of the decay $B^0 \to K^{*0}\mu^+\mu^-$ (Phys.Lett. B781 (2018) 517)

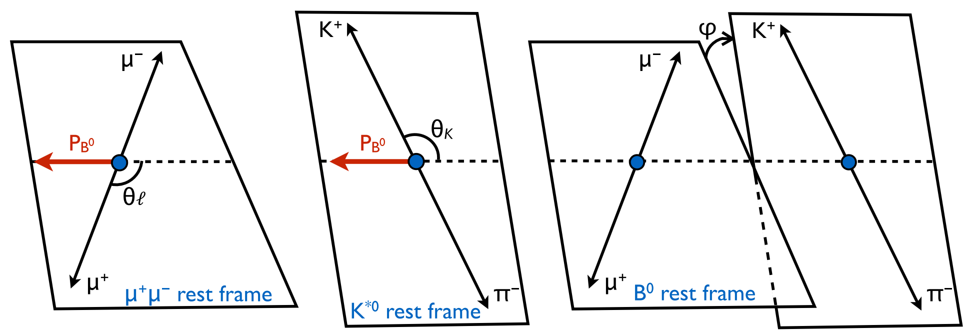
The LHCb collaboration [arXiv:1512.04442] reported differences with predictions based on the Standard Model at the level of 3.4 standard deviations, in angular analysis of the $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ decay.

CMS measured the same angular parameters with 20 fb^{-1} in Phys. Lett. B781 (2018) 517.
Angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$ can be written as

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_\mathrm{K}\,\mathrm{d}\phi} = \frac{9}{8\pi}\left\{\frac{2}{3}\left[(F_\mathrm{S}+A_\mathrm{S}\cos\theta_\mathrm{K})\left(1-\cos^2\theta_l\right)+A_\mathrm{S}^5\sqrt{1-\cos^2\theta_\mathrm{K}}\ \sqrt{1-\cos^2\theta_l}\cos\phi\right]\right.$$
$$+(1-F_\mathrm{S})\left[2F_\mathrm{L}\cos^2\theta_\mathrm{K}\left(1-\cos^2\theta_l\right)+\frac{1}{2}(1-F_\mathrm{L})\left(1-\cos^2\theta_\mathrm{K}\right)\left(1+\cos^2\theta_l\right)+\frac{1}{2}P_1(1-F_\mathrm{L})\right.$$
$$\left.\left.(1-\cos^2\theta_\mathrm{K})(1-\cos^2\theta_l)\cos 2\phi+2P_5'\cos\theta_\mathrm{K}\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}\ \sqrt{1-\cos^2\theta_\mathrm{K}}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}.$$

Variables P_1 and P_5' of the decay $B^0 \to K^{*0}\mu^+\mu^-$ are function of q^2.

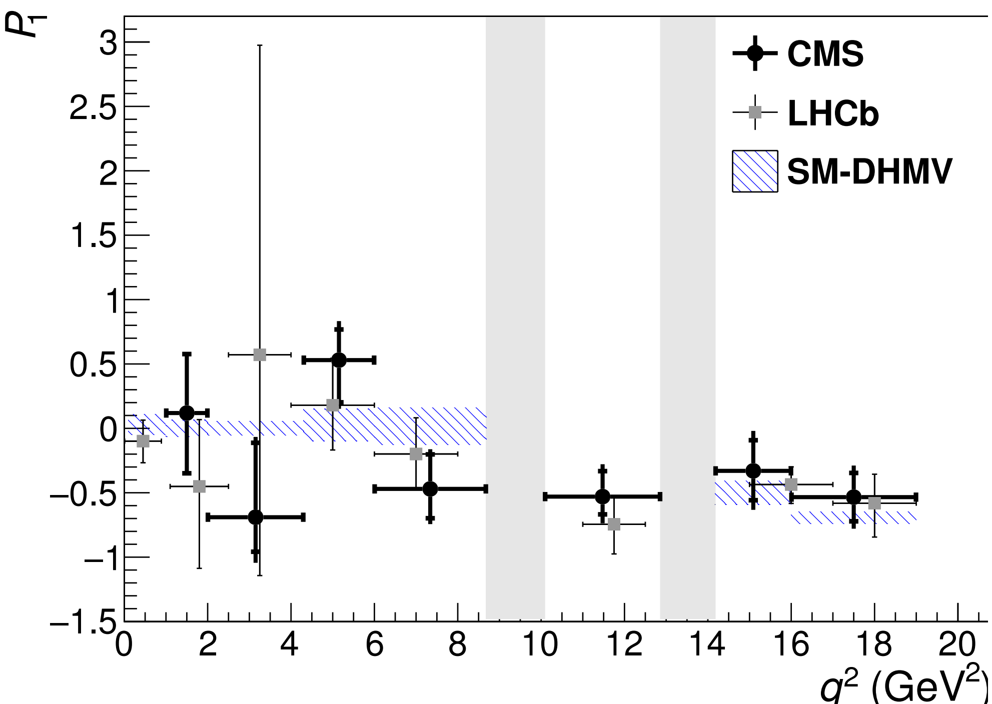
θ_l is the angle between the positive muon momentum and the direction opposite to the B^0 in the dimuon rest frame.
θ_K is the angle between the kaon momentum and the direction opposite to the B^0 in the K^{*0} rest frame.
ϕ is the angle between the plane containing the two muons and the plane containing the kaon and pion in the B^0 rest frame.

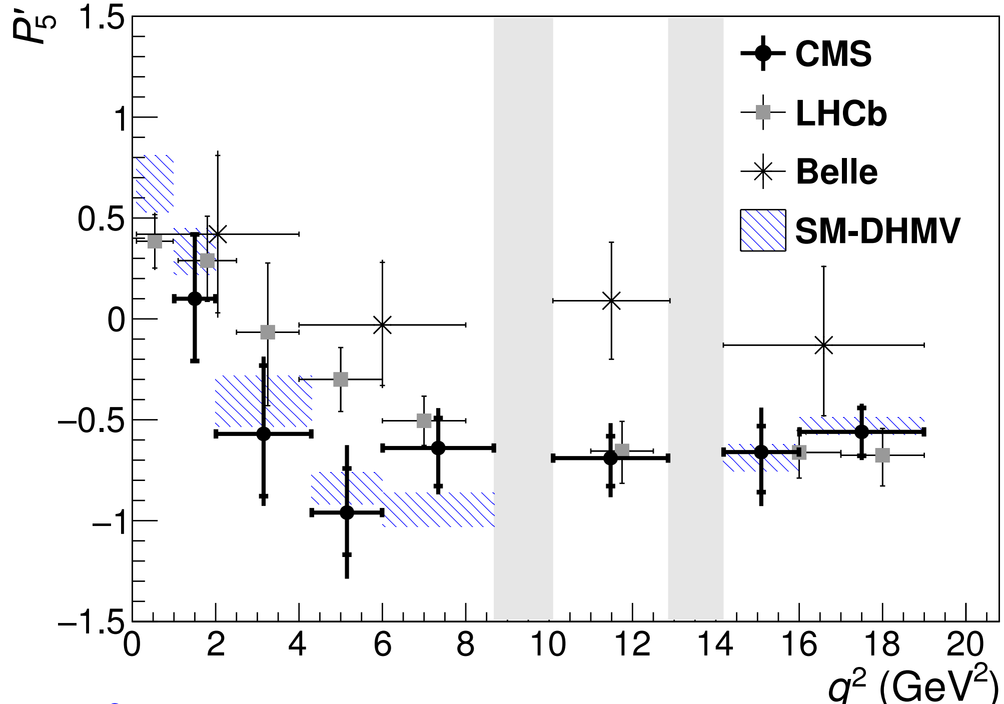


FCNC decays are highly suppressed in the SM $\Longrightarrow$ particularly sensitive to the effects of New physics.
An angular analysis as a function of q^2 allows the decay to be thoroughly investigated.
New physics may modify the angular variables.

Measurement of P_1 and P_5' angular parameters of the decay $B^0 \to K^{*0}\mu^+\mu^-$ (Phys.Lett. B781 (2018) 517)

Measured values of P_1 and P_5' vs q^2, compared with LHCb and Belle results.



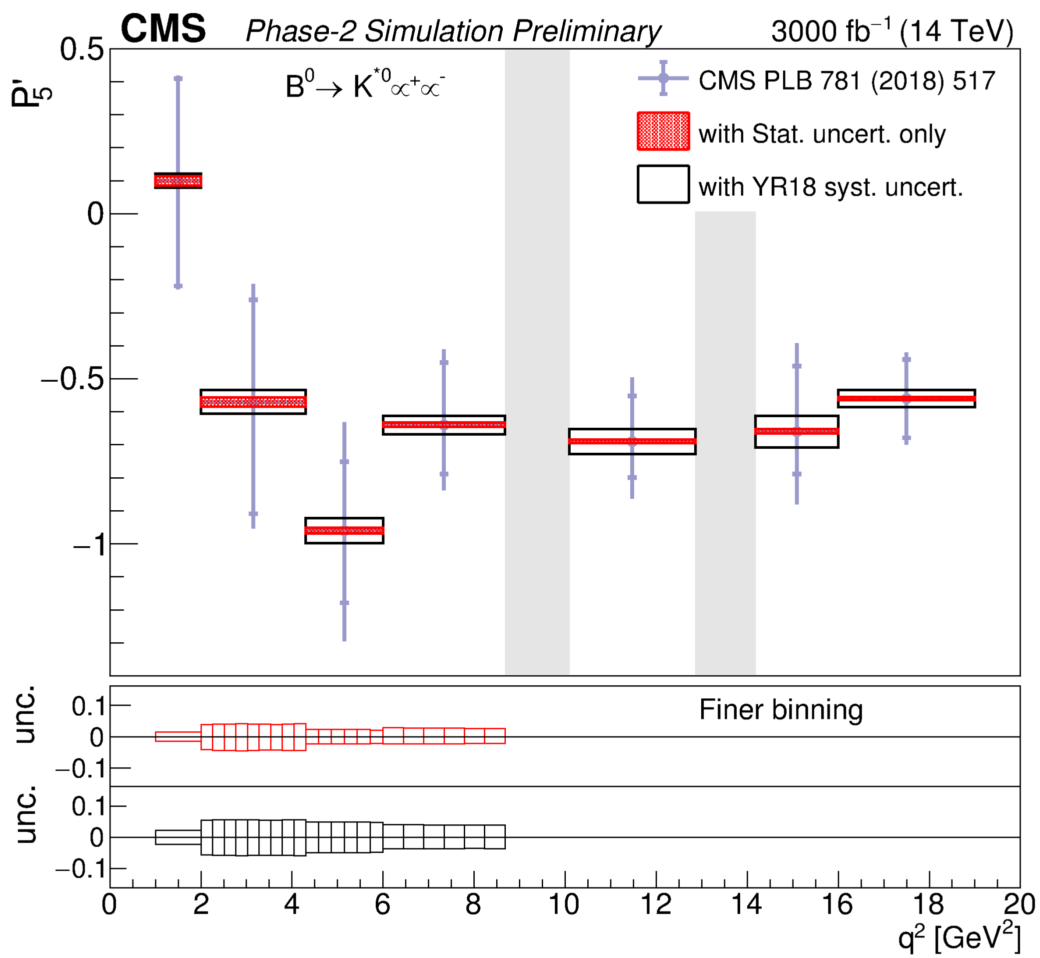


For each bin of the dimuon invariant mass squared (q^2), unbinned maximum-likelihood fits were performed to the distributions of the $K^+\pi^-\mu^+\mu^-$ invariant mass and the three decay angles, to obtain values of the P_1 and P_5' parameters.

The results for the P_1 and P_5' parameters are among the most precise to date and are consistent with standard model predictions and previous measurements.

Potentially interested analysis since the B flavor anomalies can be arose, in particular, from extra gauge boson Z' [see e.g. J. Ellis et al., arXiv:1705.03447; W. Altmannshofer at al., arXiv:1703.09189].

Perspectives for Measurement of P_1 and P_5' angular par. of the decay $B^0 \to K^{*0}\mu^+\mu^-$ (CMS PAS FTR-18-033)

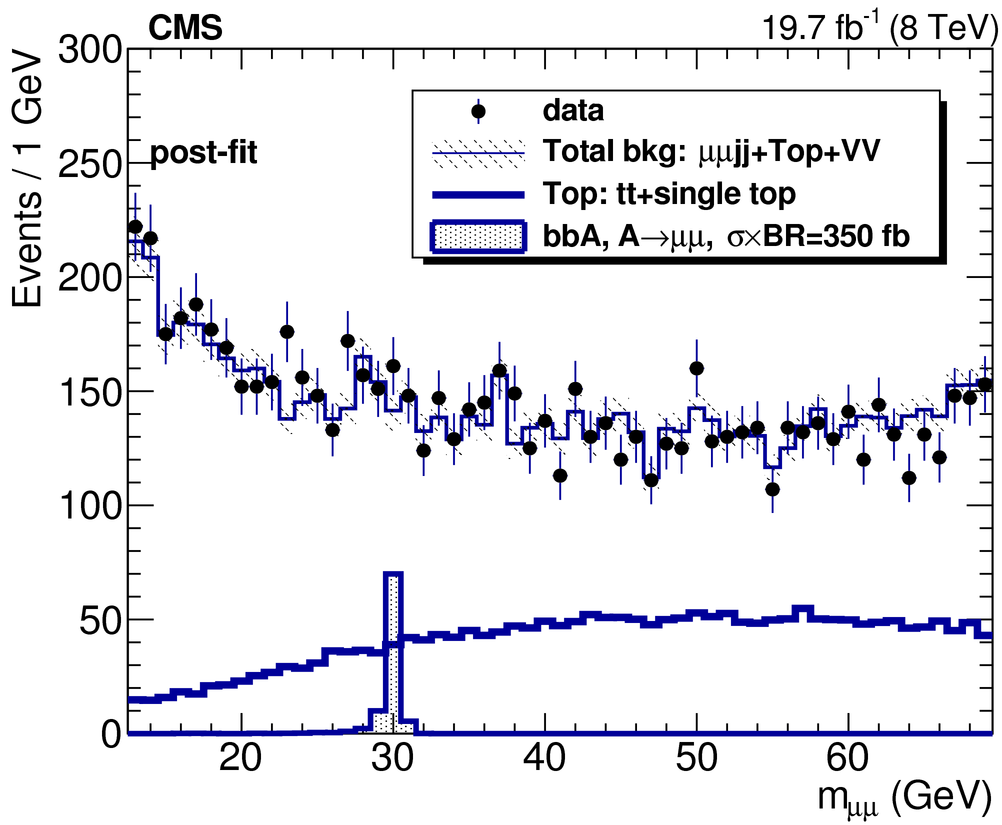


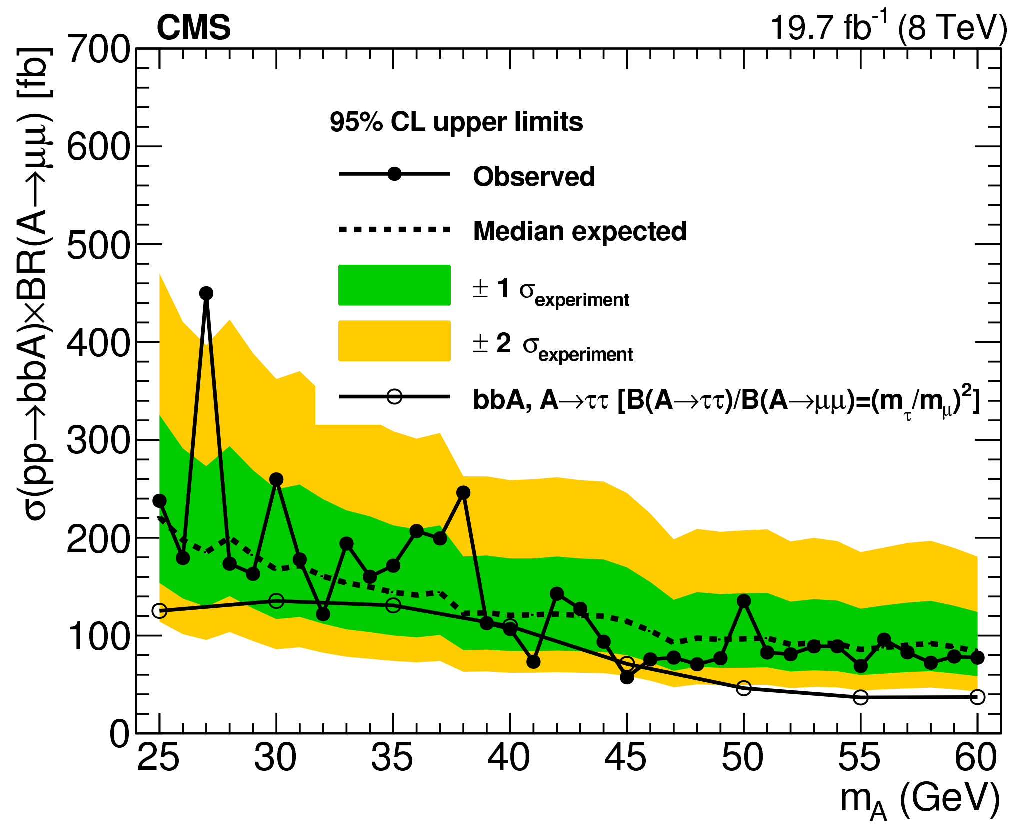
Projected uncertainties on the P_5' parameter versus q^2 at 3000 fb^{-1}.

Blue vertical bars show CMS Run I measurement of P_5'.

Two lower pads represent statistical/total uncertainties with the finer q^2 binning.

Search for a light pseudoscalar Higgs boson produced in association with b quarks (JHEP 11 (2017) 010)



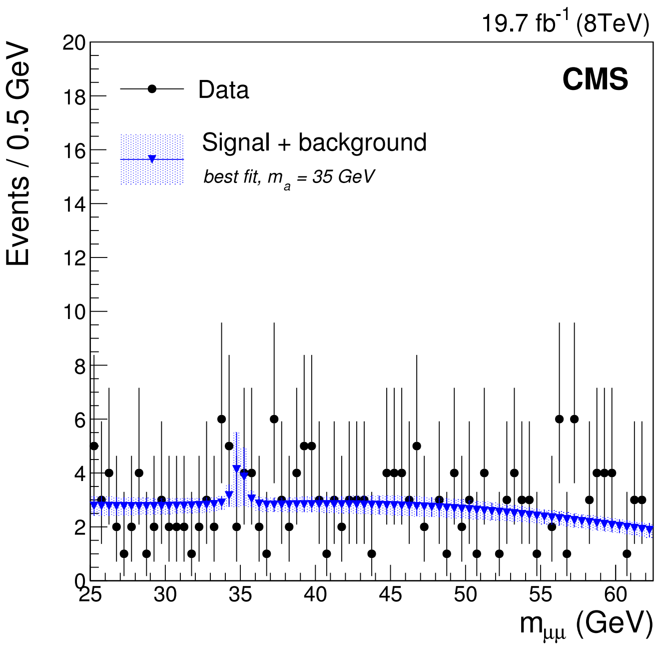


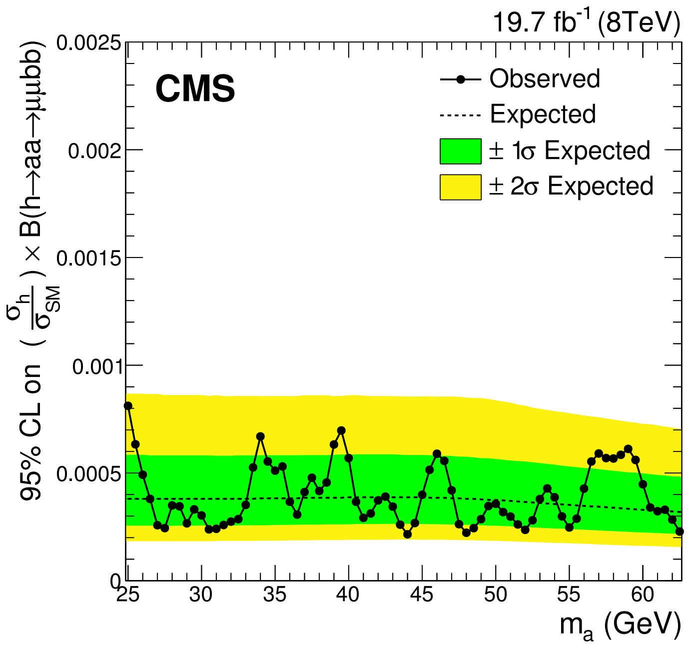
Search for a light pseudoscalar Higgs boson (A) produced in association with b quarks ($p_T > 20$ GeV) and decaying into $\mu\mu$ ($p_T^{\mu 1} > 25$ GeV, $p_T^{\mu 2} > 5$ GeV).

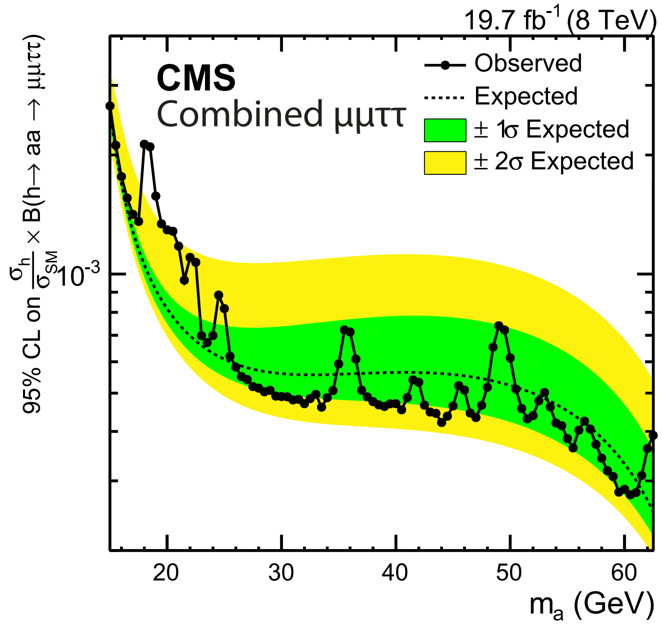
No signal is observed in the dimuon mass range from 25 to 60 GeV.

Upper limits are set on $\sigma(pp \to b\bar{b}A) \times \mathrm{Br}(A \to \mu\mu)$.

Search for light bosons in decays of 125 GeV Higgs boson (JHEP 1710 (2017) 076)







Search for decays of Higgs bosons of SM ($M = 125$ GeV) to a pair of light bosons, based on models with extended scalar sectors.

Searched for light boson for $M = 5 - 62.5$ GeV in final states $\mu\mu b\bar{b}$, $\mu\mu\tau\tau$, $\tau\tau\tau\tau$.

Deviation for $\mu\mu\tau\tau$ has local significance of 3.5 σ at $M = 20$ GeV, still the global significance is smaller than 2 σ.

Upper limits are set on the product of the cross section and branching fraction.

Drell-Yan differential cross section (arXiv:1812.10529)

$\sqrt{s} = 13$ TeV 2.7 fb^{-1}

Goal: Measure $\sigma_i = \dfrac{N_i}{A_i\,\varepsilon_i\,L_{\text{int}}}$

Here
i = mass bin (15–3000 GeV)
N = signal yield
A = acceptance
ε = efficiency
L_{int} = integrated luminosity

Procedure:

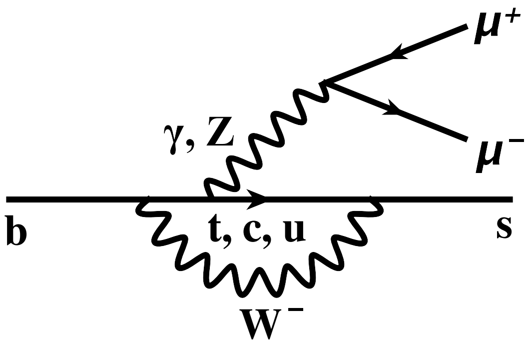
- Event and dimuon selection
- Background subtraction
  Dominant background estimation using data-driven methods
- Acceptance and efficiency calculation using MC,
  Acceptance correction using NNLO calculation with FEWZ
- Efficiency correction using data-driven method
- Unfolding correction
- Systematic error estimation
- Absolute cross section measurement
- Double-ratio calculation
- Comparison with theory predictions

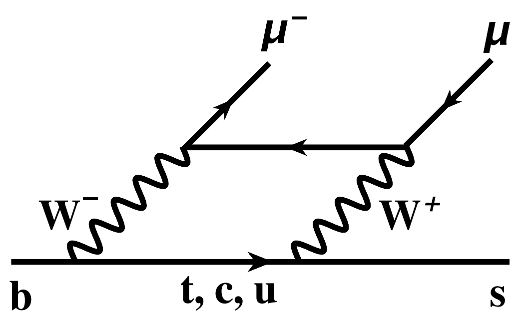
⇒ Probe NNLO calculations at high precision

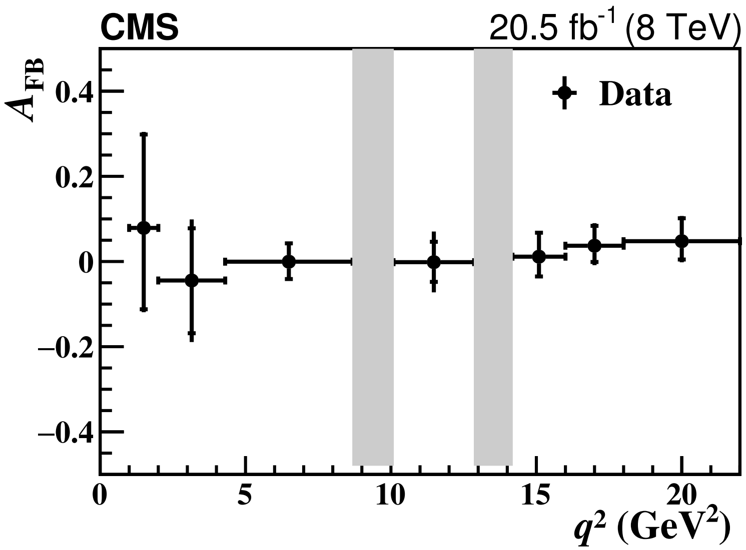
⇒ Larger data sample, up to $M = 3000$ GeV

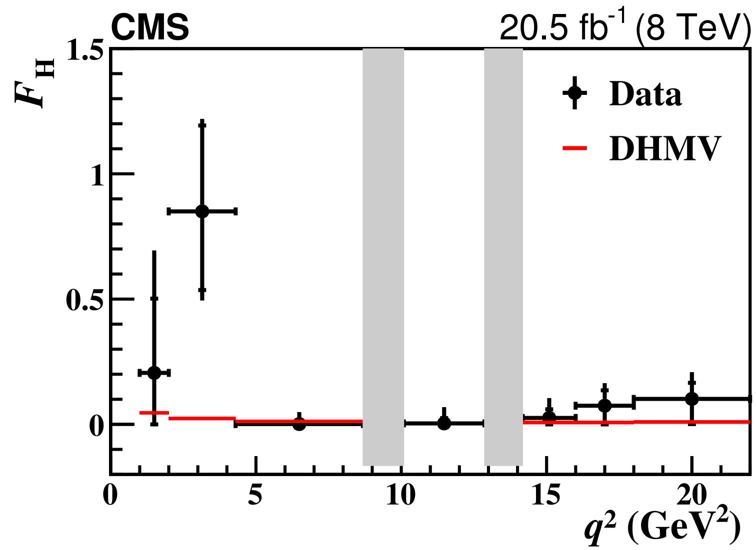
⇒ Provide absolute cross sections — More suitable for constraining PDFs.

⇒ Ratios of xsec for 7 and 8 TeV







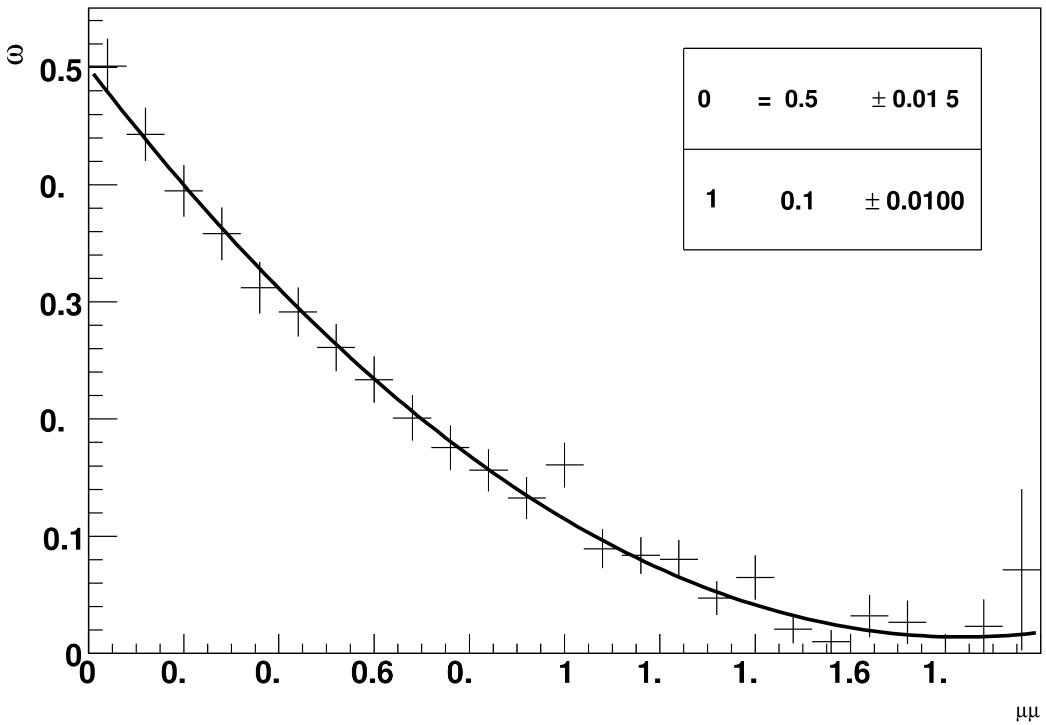


Measured forward-backward asymmetry A_{FB} of the dimuon system and the contribution F_{H} from the pseudoscalar, scalar, and tensor amplitudes to the decay width are measured as a function of the dimuon mass squared. The measurements are consistent with the standard model expectations.

Mistag probability vs dimuon rapidity

For pp collider, quark direction is not known.

One can only study A_{FB} by approximating the quark direction with the boost direction of the dimuon system with respect to the beam axis.



Mistag probability (Fraction of events with wrong quark direction) vs dimuon rapidity:

Fit: $\omega(y) = \frac{1}{2} + p_0|y| + p_1 y^2$

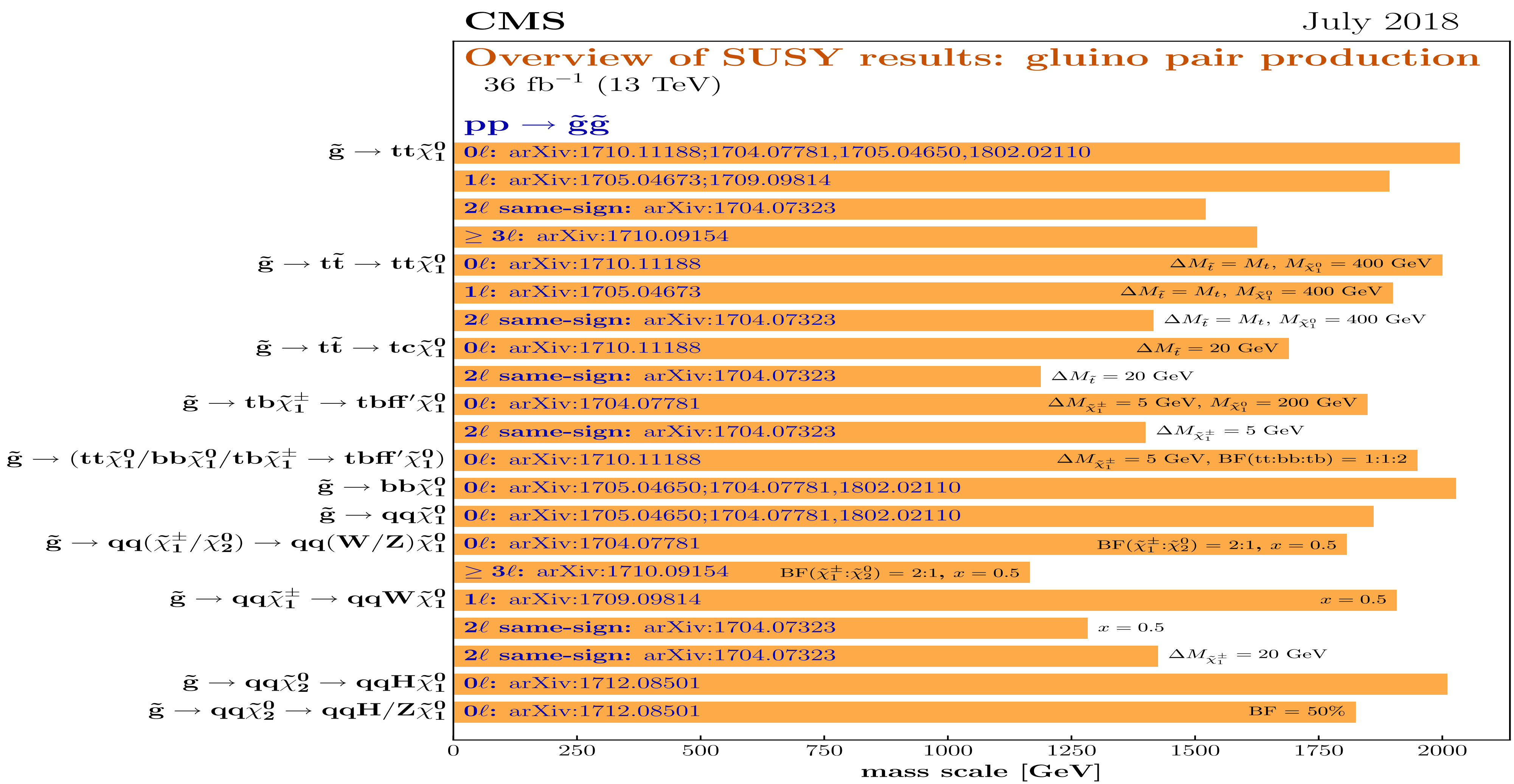
The most unambiguous tagging occurs for large dimuon rapidity.

Standard Model

Main principles in the foundation of the Standard Model:

- Three groups of gauged symmetries $SU(3) \times SU(2) \times U(1)$
- Three families of quarks and leptons in representations $(3 \times 2, 3 \times 1, 1 \times 2, 1 \times 1)$
- Higgs mechanism of spontaneous EW symmetry breaking accompanied by the Higgs boson
- Mixing of flavours with the help of the Cabibbo-Kobayashi-Maskawa (CKM) and the Pontecorvo-Maki-Nakagava-Sakato (PMNS) matrices
- CP violation via the phase factors in the flavour mixing matrices
- Confinement of quarks and gluons inside hadrons
- Baryon and lepton number conservation
- CPT invariance which leads to the existence of antimatter

Supersymmetry 95% CL Limits



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Many searches of Supersymmetry at CMS has been performed. Limits have been set.

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

Dilepton Analysis (JHEP 1806 (2018) 120; arXiv:1803.06292)

- Heavy gauge boson (Z') decaying into a lepton pair
- Experimental signature:
  - ⇒ Single muon trigger `HLT_Mu50`
  - ⇒ High-energy muon pair ($p_T > 53$ GeV)
  - ⇒ Specific high-energy lepton ID
  - ⇒ $Z' \to \mu\mu$
    - — Introduced 3 categories (allow to improve sensitivity)
    - — $A \times \varepsilon$ (1 TeV) = 89 %
    - — Mass resolution (1 TeV) = 4 %
  - ⇒ Background:
    - — Irreducible Drell-Yan
    - — Reducible $t\bar{t}$, tW, dibosons (estimated from MC)
    - — Multijet background < 3% of the total background for dielectrons > 500 GeV (estimated from data)
    - — Photon induced background — negligible contribution to the limits
- Shape-based search for resonance in dimuon spectrum

Event selection: muon and dimuon ID

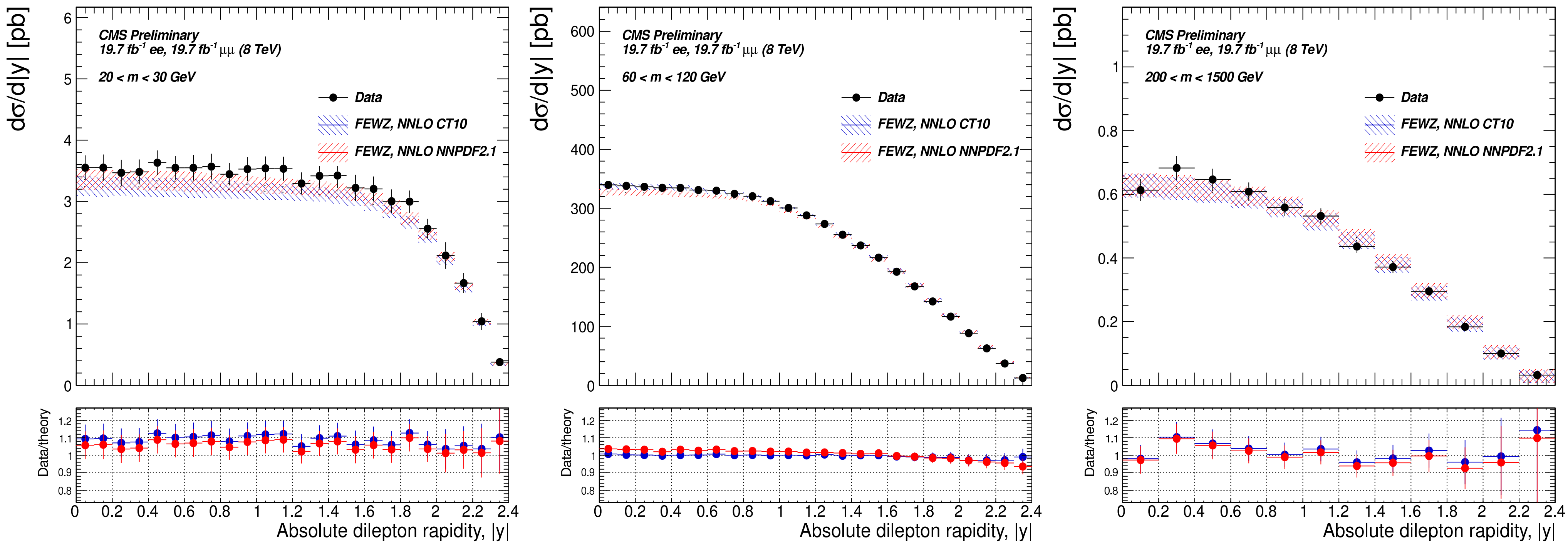
- Use the updated high-p_T muon ID https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideMuonId
- Muon selection criteria:
  - ⇒ Reconstructed as a "global" muon and a "tracker" muon
  - ⇒ $p_T > 45$ GeV; $\sigma(p_T)/p_T < 0.3$
  - ⇒ Tracker track has transverse impact parameter $d_{xy} < 2$ mm w.r.t. the PV
  - ⇒ At least one pixel hit in the muon track fit
  - ⇒ At least six tracker layers with hits in the fit
  - ⇒ At least one muon chamber hit included in the final global-muon track fit
  - ⇒ Matched to segments in at least two muon stations
  - ⇒ Relative tracker isolation: sum of p_T of all other tracks in a cone of $\Delta R = 0.3$ around the muon must be less than 10% of the muon's p_T
- Additional dimuon selection:
  - ⇒ Require opposite charge and a common vertex (χ^2/ndof < 10)
  - ⇒ One muon matched to the HLT muon that fired the trigger
  - ⇒ 3D angle between the two muon momenta $< \pi - 0.02$ rad

Backgrounds

- Drell-Yan is the dominant irreducible background
  - ⇒ Evaluated using POWHEG; cross section scaled up using higher-order (NNLO) corrections (2.4 %) from FEWZ
- The next largest background is $t\bar{t}$, also single top and dibosons
  - ⇒ 18% of the total background rate at $M_{\mu\mu} > 200$ GeV
  - ⇒ Simulation prediction is checked with the $e\mu$ method
  - ⇒ Simulation prediction for charge-symmetric backgrounds is checked using same-sign dimuons
- Background from one or more jets faking muons (W+jets, multi-jet events)
  - ⇒ $< 1\%$ of the total background rate at $M_{\mu\mu} > 200$ GeV
  - ⇒ Estimated from data using events that fail isolation cuts
- The last one is cosmic muons faking dimuons
  - ⇒ Detailed studies show that it can be used negligible using anti-cosmic cuts

Drell-Yan 2D Xsecs — M vs $|y|$ (Eur. Phys. J. C75 (2015) 147)

“Low mass” $\quad$ Z region $\quad$ “High mass”



6 bins on $M_{\mu\mu}$ at 20, 30, 45, 60, 120, 200, 1500 GeV, $\quad$ 24 bins for $|y| = 0 - 2.4$
12 bins for $|y| = 2 - 2.4$

Within the detector acceptance to reduce the model dependence.

Good agreement with FEWZ but deviations exist at low and high mass regions.

For the first time the combined ee—$\mu\mu$ double-differential xsec measurement done.

Potential constraints to PDFs are expected from these results.

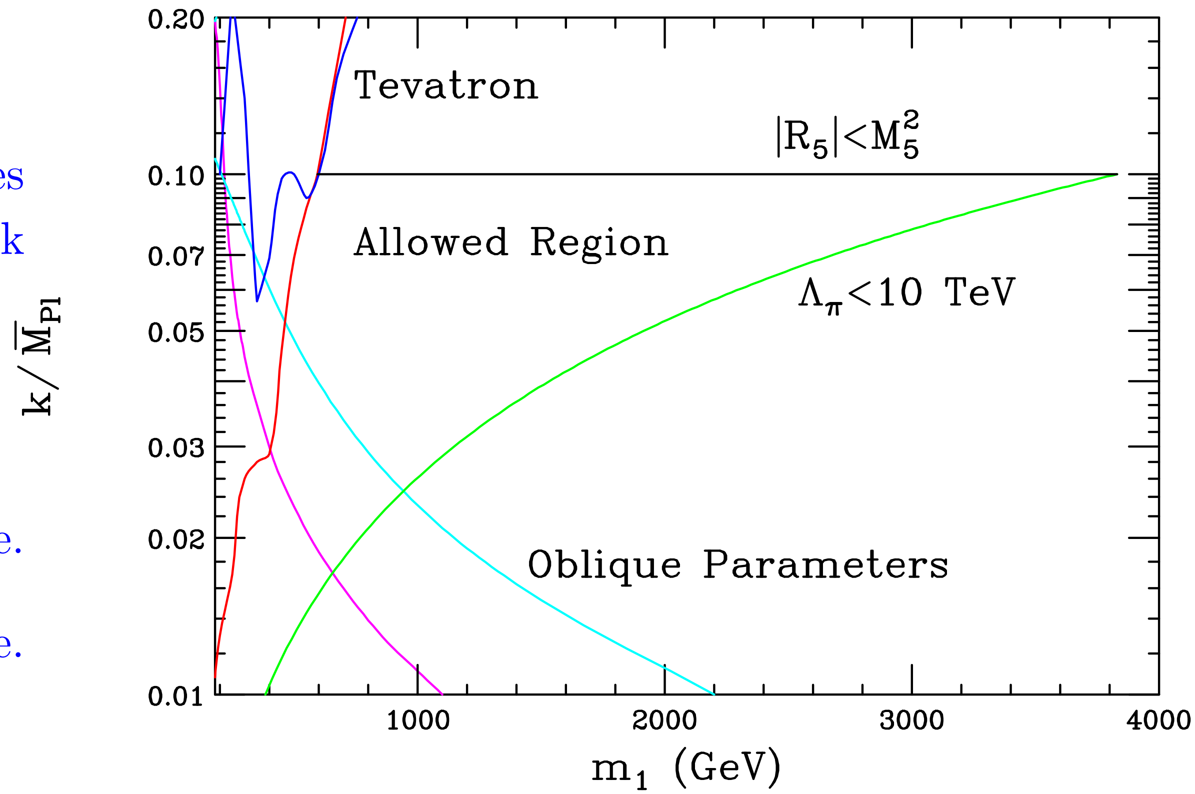
Heavy graviton resonances are predicted by RS1 (Randall-Sundrum) model of TeV-scale gravity:

coupling constant $c = k/\bar{M}_{Pl}$ $\Longrightarrow$ resonance width $\Gamma \sim c^2$

Our 4-D world can be the one of two branes embedded into the 5-D anti-de Sitter bulk space (RS scenario).

All particles of the usual matter (quarks, leptons, gauge bosons, Higgses) are considered to be localized on the brane.

Only gravitons can travel in the bulk space.



H. Davoudiasl et al., Phys. Rev. D63 (2001) 075004