Searches for new physics in the dilepton channel with the CMS detector at the LHC

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Outline

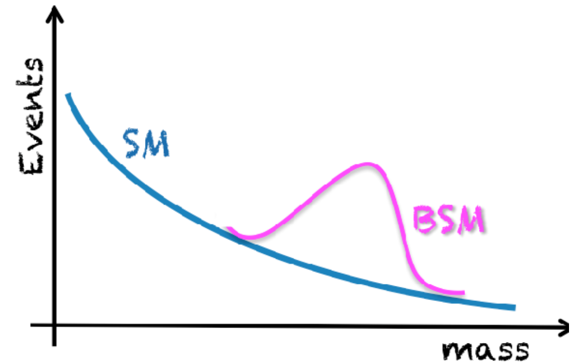
- ❑ Heavy New resonances
  - ✓ Extended gauge models
  - ✓ Extra dimensions (RS1-type models)
  - ✓ Dark Matter (WIMPs)

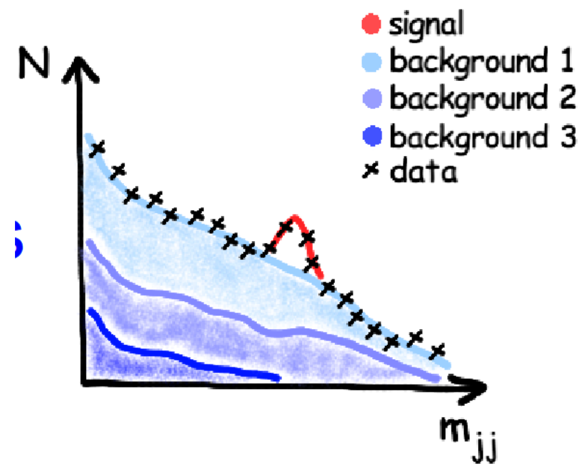
- ❑ Non-resonant signals
  - ✓ Extra dimensions (ADD-type models)
  - ✓ Compositeness/Contact Interactions

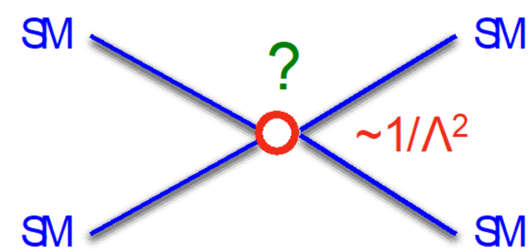
- ❑ Rare Higgs Decays (H →μμ)

CMS Exotica Public Physics Results (dileptons)
https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/LL.html

CMS Higgs Public Physics Results
http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/

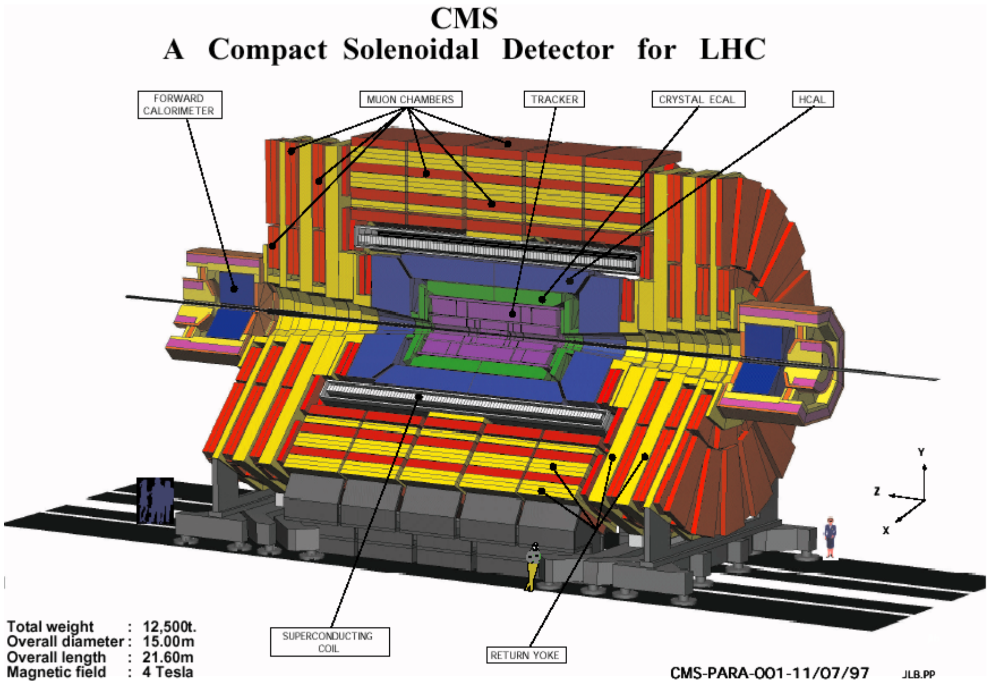


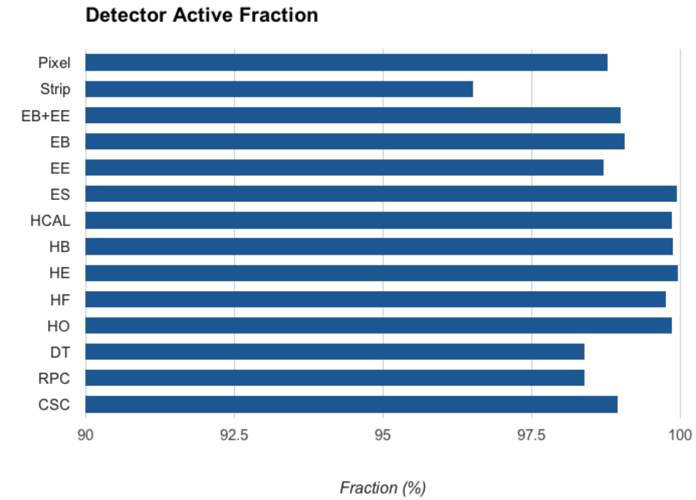




CMS Detector and Collected Data

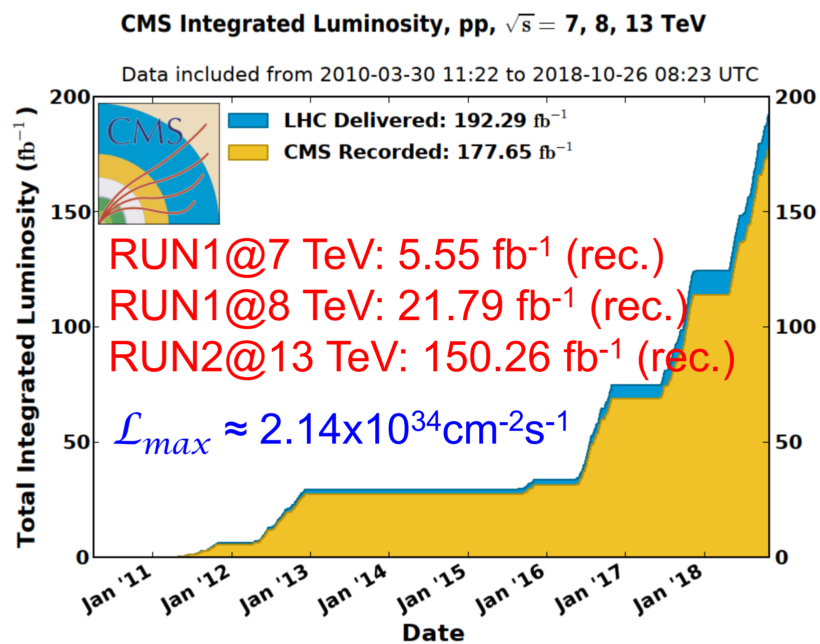
Large general-purpose particle physics detector





Total weight	***12 500 t***
Overall diameter	***15.00 m***
Overall length	***21.6 m***
Magnetic field	***3.8 Tesla***

Detector subsystems are designed to measure: the energy and momentum of photons, electrons, muons, jets, missing ET up to a few TeV



Landscape of Signals

New Physics ($Z'/Z_{KK}/G_{KK}$) contributions to SM processes

- ❑ Spin-1 resonances
  - ✓ Extra gauge boson (Z′) from Extended gauge models (LRMs and GUT-inspired models)
  - ✓ Dark Matter Mediators
  - ✓ KK excitations of SM gauge bosons (Z^0) in TeV^{-1} model of flat extra dimensions

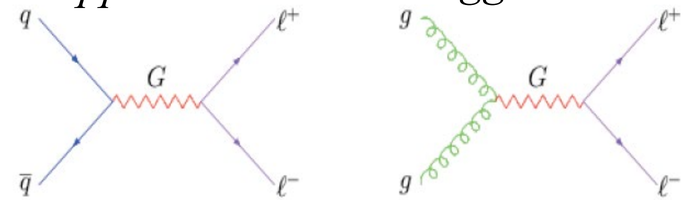
- ❑ Spin-2 resonances
  - ✓ Kaluza-Klein graviton excitations (RS1 graviton) from Randall-Sundrum model of AdS_5 extra dimens.

Signals: di-leptons resonance states in high (~TeV) invariant mass range ⇒ new particles would be observed as a bump, excess in the mass spectrum

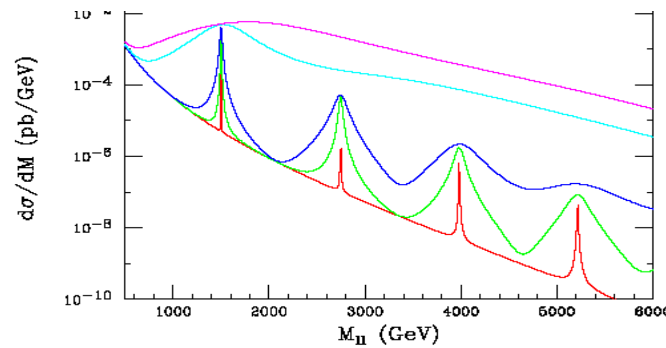
- ❑ Non-resonant signals
  - ✓ ADD-graviton spin-2 contribution in the SM processes (Drell-Yan)
  - ✓ Contact interaction

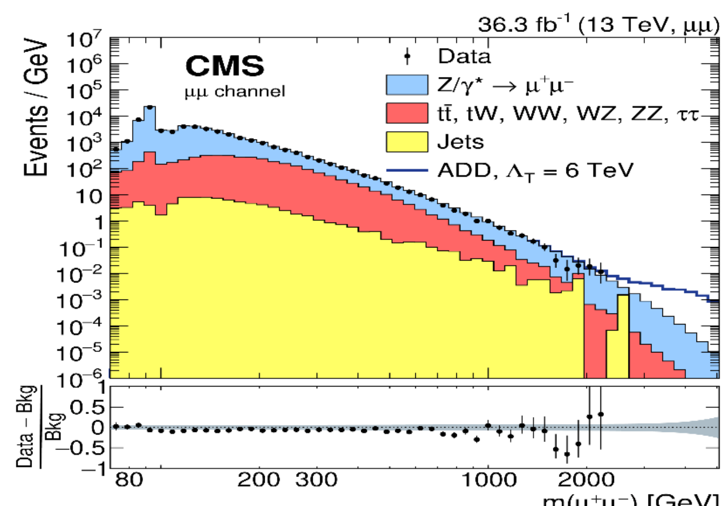
Signals: excess in dilepton spectrum

$q\bar{q} \to l^+l^-$ $\qquad$ $gg \to l^+l^-$



Well separated mass spectrum

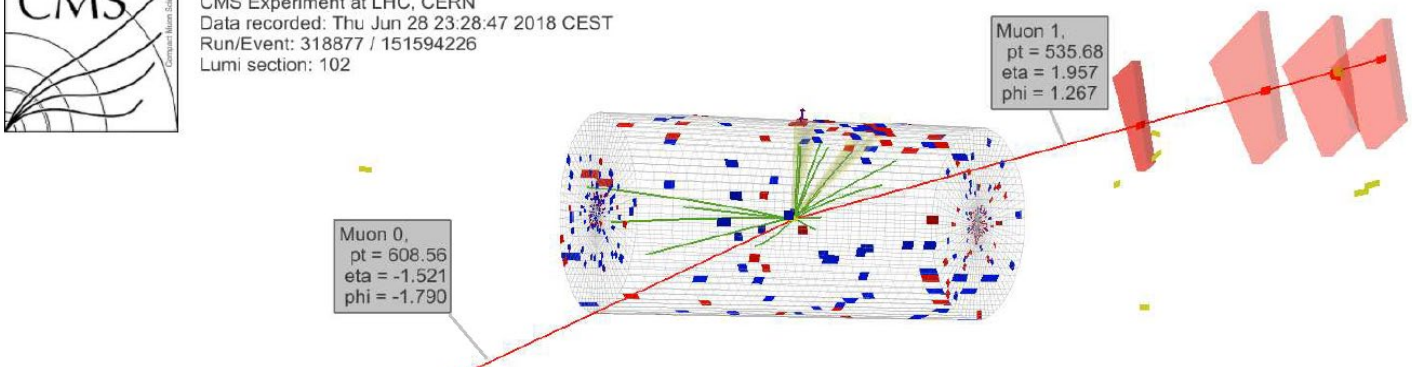


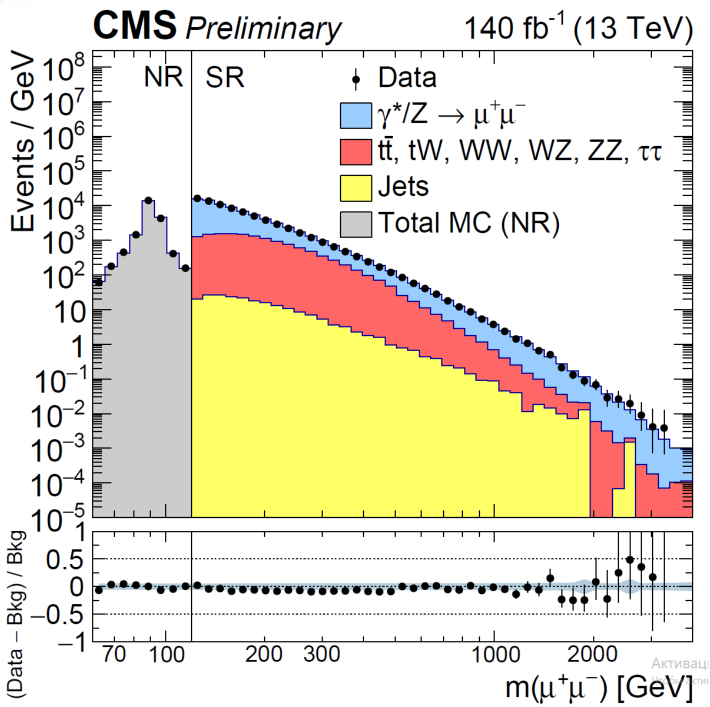


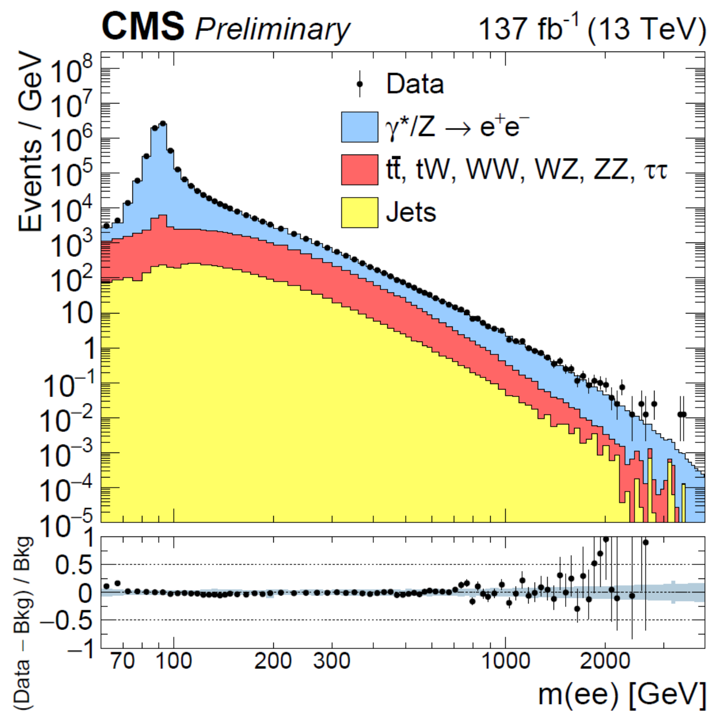
Dilepton Mass Spectra

$M = 3.3$ TeV

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







Heavy Resonances: Z′ and RS1 Limits

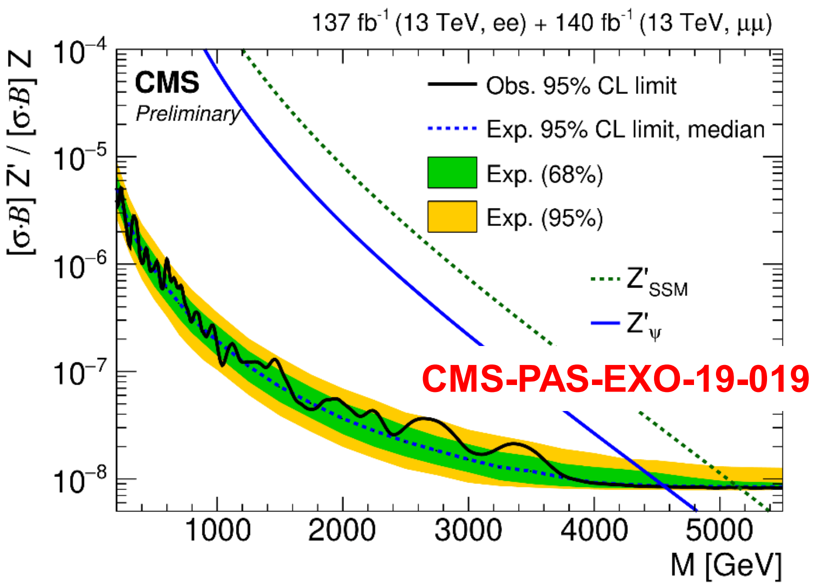
The likelihood function is based on probability density functions (pdf) that describe the signal and background contributions to the invariant mass spectra

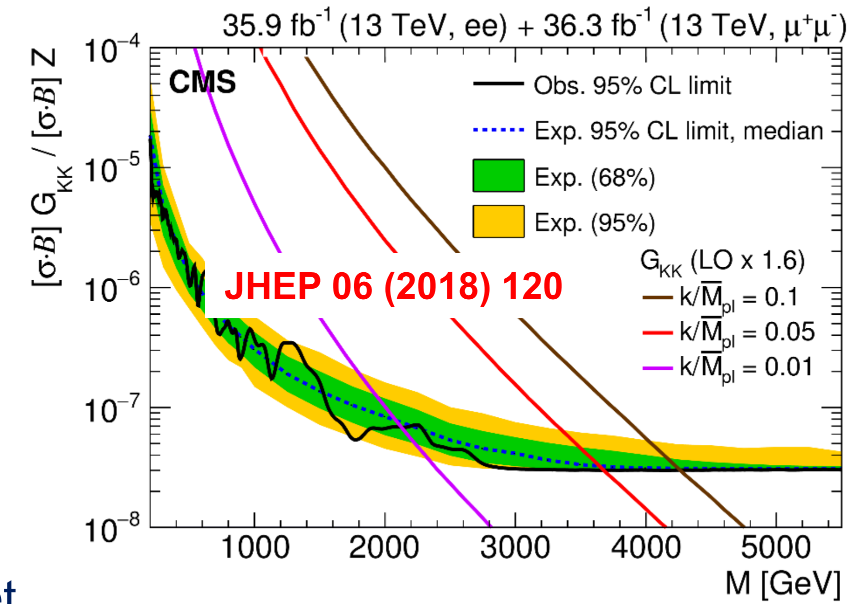
$$\mathcal{L}(m|R_\sigma, M, \Gamma, w, \alpha, \beta, \kappa, \mu_B) = \frac{\mu^N e^{-\mu}}{N!} \prod_{i=1}^{N} \left(\frac{\mu_S(R_\sigma)}{\mu} f_S(m_i|M, \Gamma, w) + \frac{\mu_B}{\mu} f_B(m_i|\alpha, \beta, \kappa) \right)$$

The use of this ratio eliminates the uncertainty in the integrated luminosity and reduces the dependence on the experimental acceptance, trigger, and offline efficiencies

Background: $m^\kappa e^{\alpha m + \beta m^2 + \delta m^3}$

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to \ell\ell + X)}{\sigma(pp \to Z + X \to \ell\ell + X)}.$$





✓ The corresponding 95% CL limits are set
- for the Z_{SSM}, mass limit is 5.15 TeV
- for the Z_ψ, mass limit is 4.56 TeV
- for G_{KK}, mass limit is 2.10 TeV (c=0.01)
- for G_{KK}, mass limit is 4.25 TeV (c=0.1)

Heavy Resonances: Generalized Extra Gauge Bosons

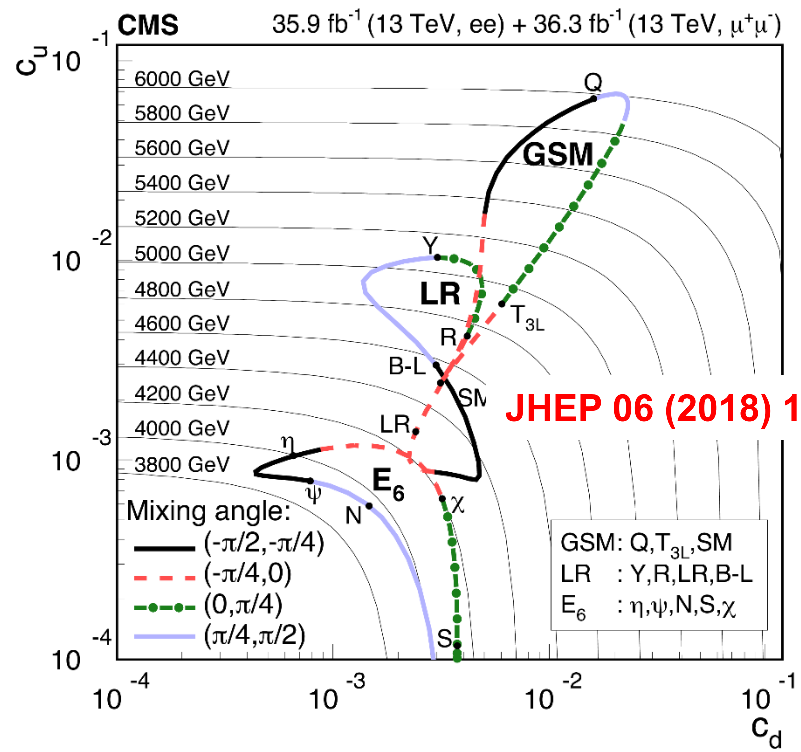
The mass limits can be expanded at the other theoretical models.

The cross section for charged lepton-pair production via a Z′ vector boson can, in the narrow-width approximation (NWA), be expressed in terms of the quantity $c_u w_u + c_d w_d$

$$\sigma_{l^+l^-} = \frac{\pi}{48s}\left[c_u w_u(s, M_V^2) + c_d w_d(s, M_V^2)\right],$$

$$c_u = \frac{g'^2}{2}\left(g_V^{u2} + g_A^{u2}\right)\mathcal{B}(l^+l^-),$$

$$c_d = \frac{g'^2}{2}\left(g_V^{d2} + g_A^{d2}\right)\mathcal{B}(l^+l^-).$$



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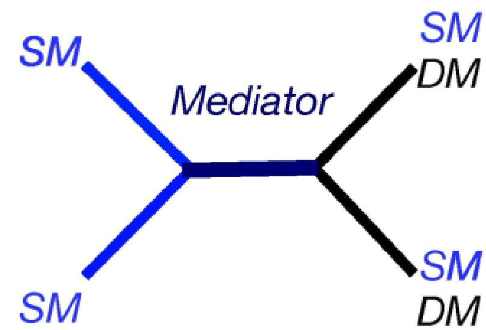
The parameters c_u and c_d contain information from the model-dependent Z′ couplings to fermions in the annihilation of charge 2/3 and charge −1/3 quarks; w_u and w_d contain the information about PDFs

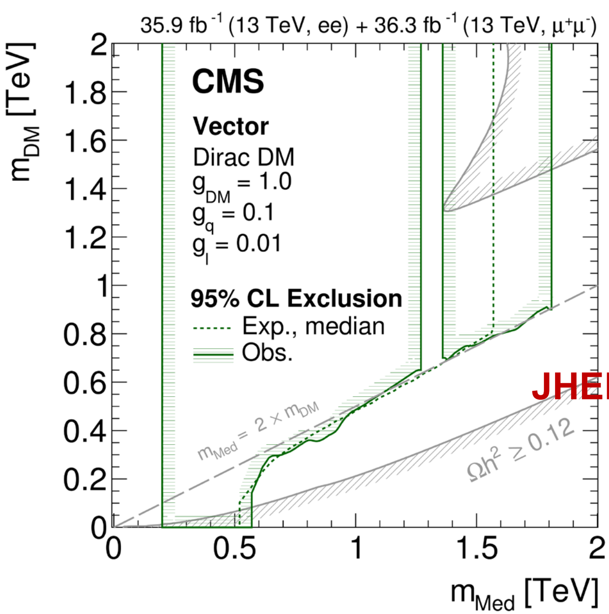
The limits on the Z′ mass are shown as lines in the (c_d,c_u) plane intersected by curves showing (c_d,c_u) as a function of a mixing parameter for various models.

Heavy Resonances: Dark Matter

The results are also interpreted in the context of a simplified model with a DM particle that has sizeable interactions with SM fermions through an additional spin-1 high-mass particle mediating the SM-DM interaction

- ✓ vector mediator with small couplings to leptons:
  g_q=0.1, g_{DM}=1.0, g_l=0.01
- ✓ axial-vector mediator with equal couplings to quark and leptons:
  g_{DM} =1.0, g_q=g_l=0.1 (по рекомендациям **CERN-LPCC-2017-01**)





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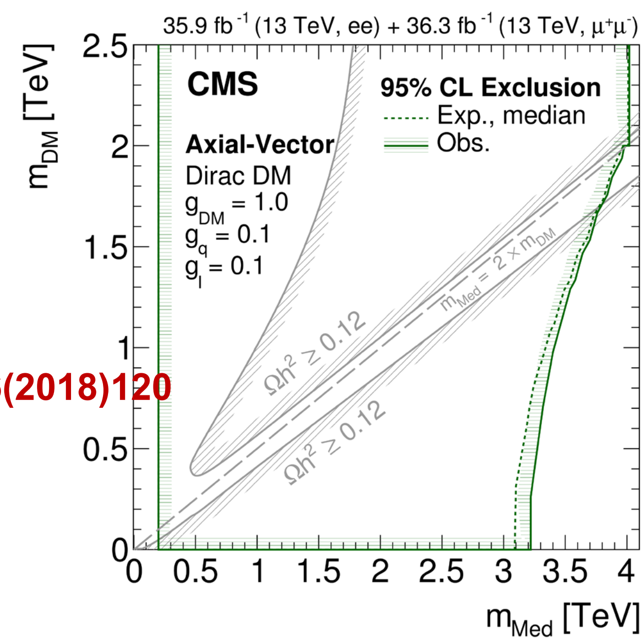
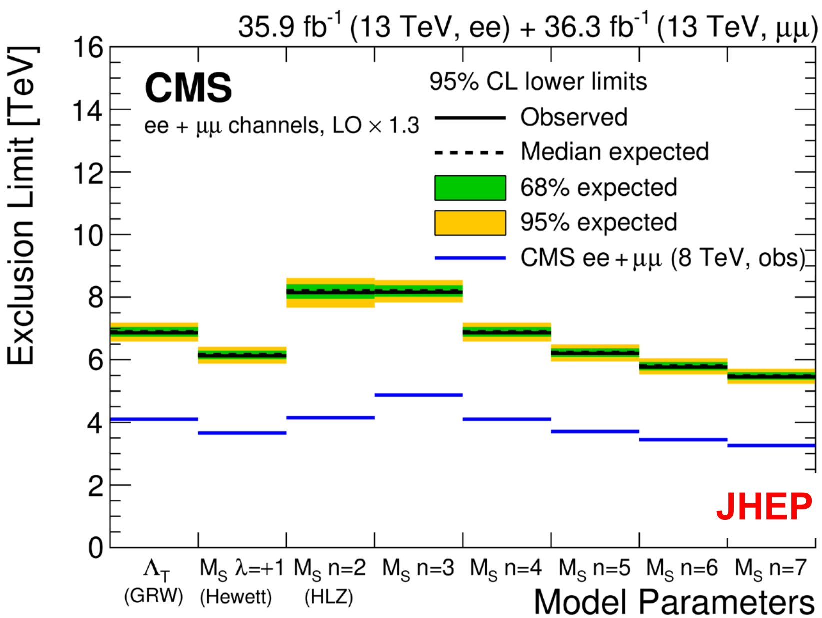


In the axial-vector (vector) mediator model, the limit on the mediator mass reaches up to 3-4 (1.8) TeV, depending on the mass of the DM particle

Non-resonant Dileptons: ADD Limits

No significant deviations from standard model expectations are observed



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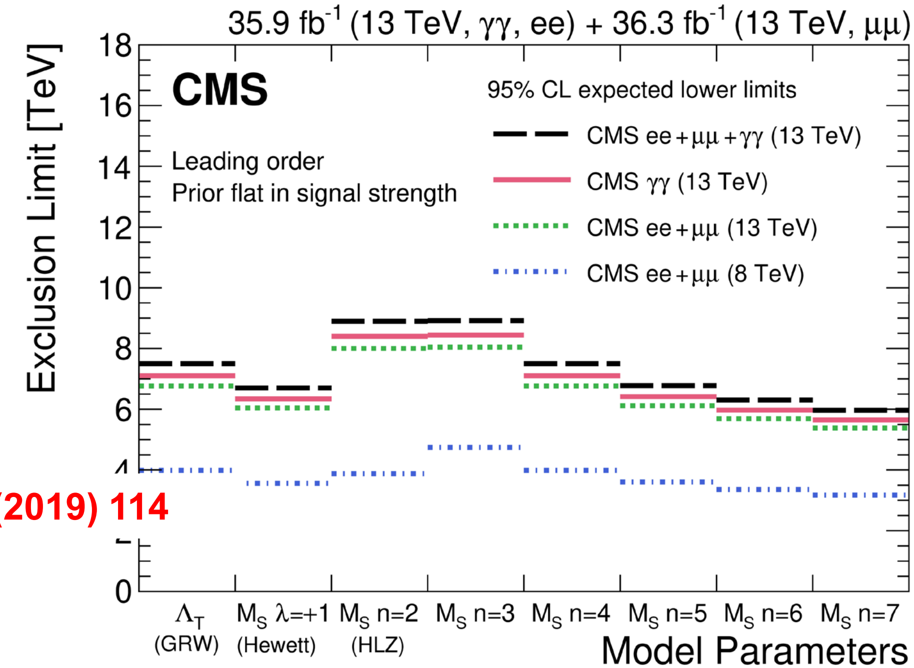


For the ADD model of large extra dimensions, values of the ultraviolet cutoff parameters are excluded in two conventions

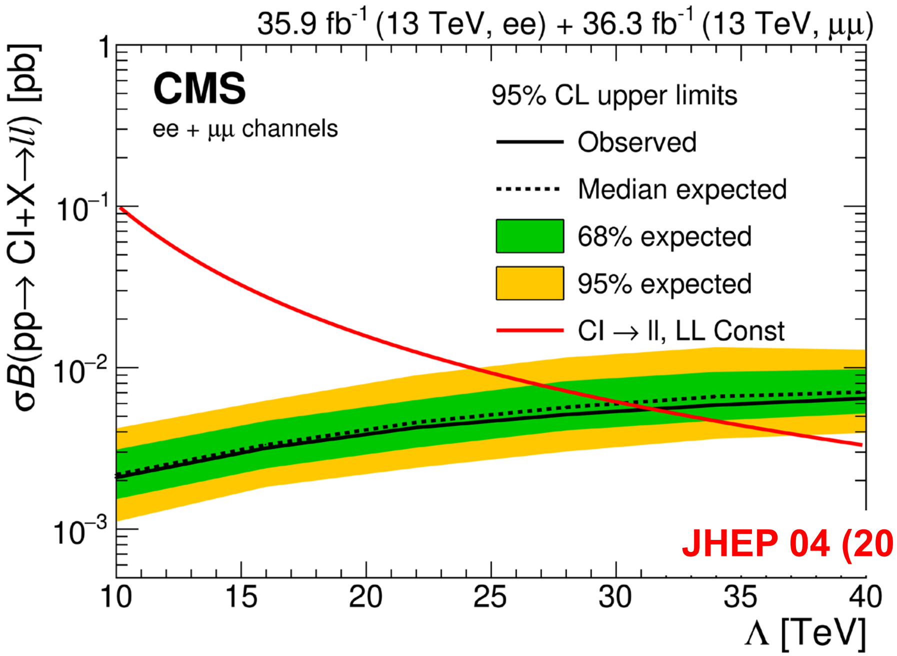
- Λ_T below 6.9 TeV (in GRW)
- M_S range from 5.5 to 8.2 TeV (in HLZ), depending on the number of extra dimensions

$$\Lambda_T^{-4} = \begin{cases} M_S^{-4} \log\left(\frac{M_S^2}{M_{\ell\ell}^2}\right), & n_{ED} = 2; \\ \frac{2}{n_{ED}-2} M_S^{-4}, & n_{ED} > 2, \end{cases}$$

A combination with recent CMS diphoton results improves this exclusion

Non-resonant Dileptons: Compositeness

A contact interaction (CI) model, taking into account both constructive and destructive interference scenarios, has been used for interpreting the experimental measurements



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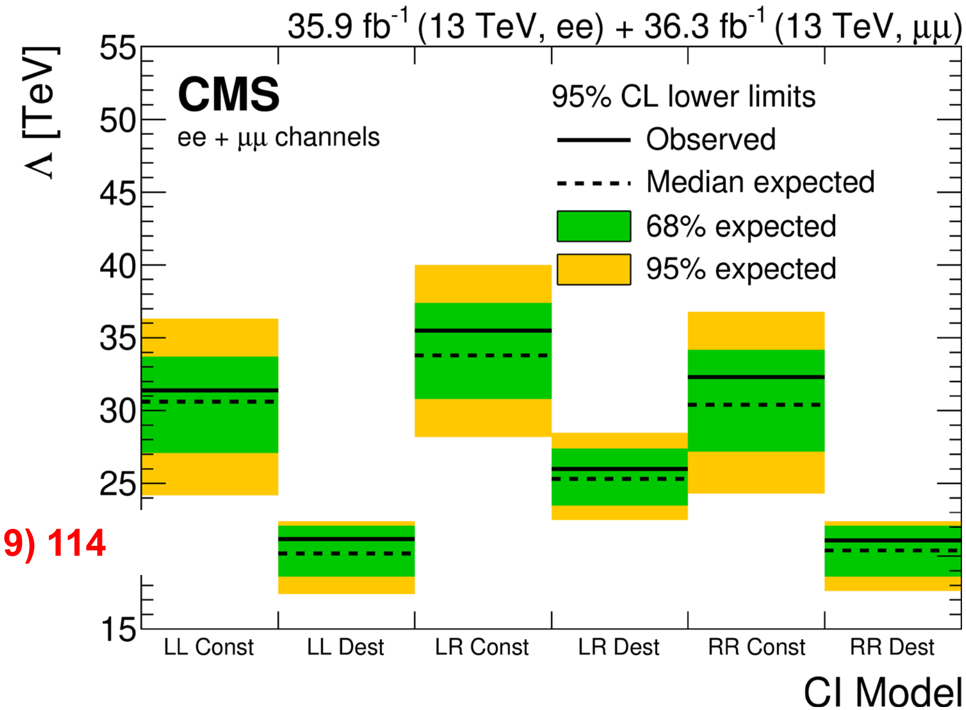
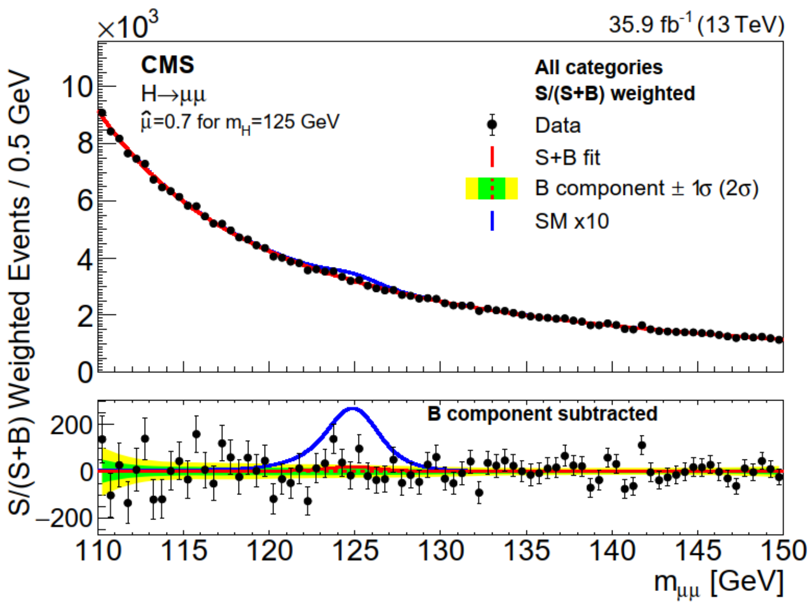


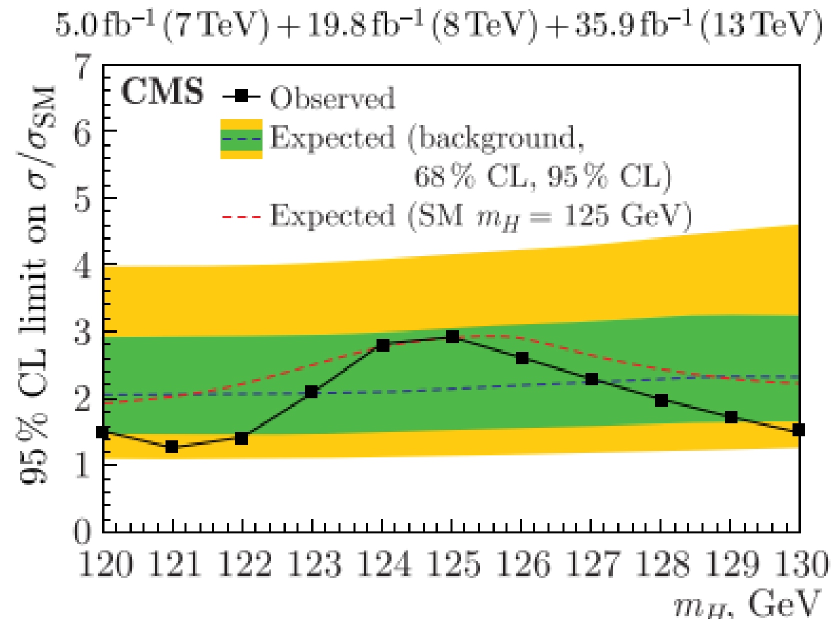
The 95% confidence level exclusion limits on the compositeness scale range from Λ_{LL}>20 TeV for the destructive case to Λ_{RR}>32 TeV for the constructive one, for the left-left and the right-right helicity currents, respectively.

Rare Decays: Higgs → μμ

The current results of RUN1 and RUN2 demonstrate full compatibility of the Higgs bosons with SM expectations, but the room for new physics is still opened (couplings, rare decays, extra higgs etc)

$\mathcal{B}_{\mathrm{SM}}(H \to e^+e^-) \approx 0{,}09 \cdot 10^{-5}\,\%$ $\mathcal{B}_{\mathrm{SM}}(H \to \mu^+\mu^-) = 0{,}022\,\%$





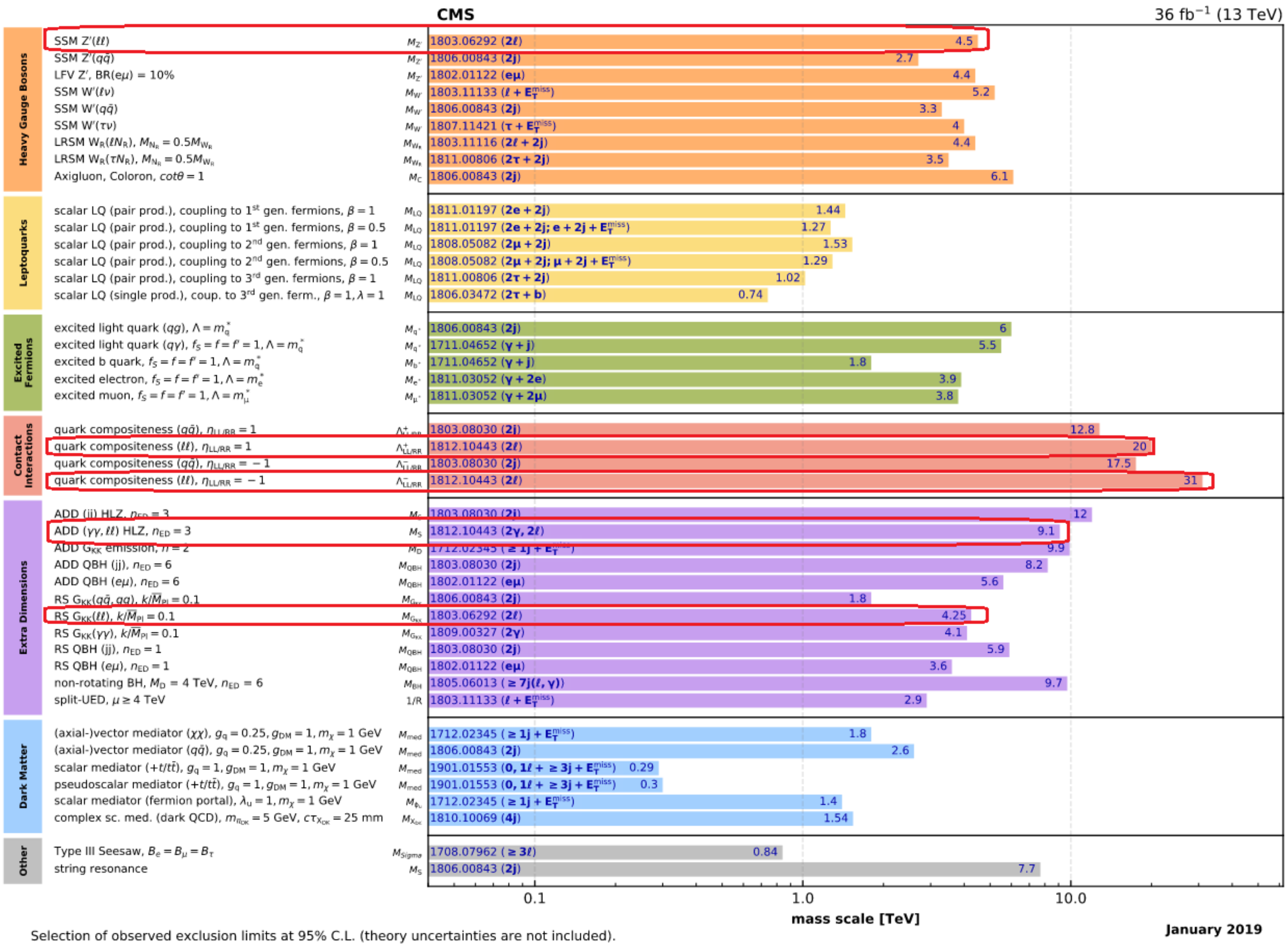
No significant evidence for this decay is observed.

PRL 122 (2019) 021801

Observed significance of the Higgs boson decaying into two muons of 0.9 σ and an observed signal strength of 1.0 ± 1.0 (stat) ± 0.1 (syst).

The observed limit corresponds to an upper limit of 6.4×10^{-4} on the Higgs boson branching fraction to two muons

Overview of CMS Exotica (95% C.L.)



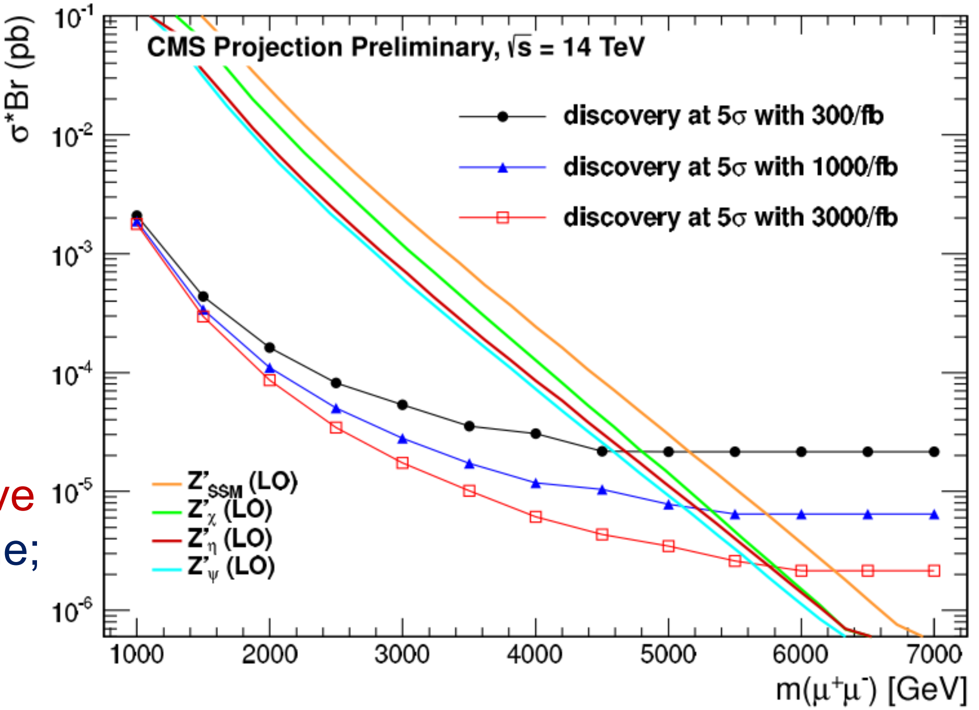
http://cms-results.web.cern.ch/cms-results/public-results/publications/

Conclusions

CMS performed a wide program of search for particles and phenomena

RUN1 and RUN2 data demonstrate triumph of Standard Model (many Exotica Models were tested in the channel with dileptons in the final states and new limits are derived)

- ❑ for the Z_{SSM} mass limit is 5.15 TeV;
- ❑ for the Z_{ψ} mass limit is 4.56 TeV;
- ❑ for G_{KK} mass limits are 2.10 TeV (c=0.01) and 4.25 TeV (c=0.1);
- ❑ for Dark matter (axial-)vector mediator model reaches up to 3-4 (1.8) TeV;
- ❑ for the ADD model
  - Λ_T below 6.9 TeV (in GRW)
  - M_S range from 5.5 to 8.2 TeV (in HLZ);
- ❑ for CI model - Λ_{LL}>20 TeV for the destructive case to Λ_{RR}>32 TeV for the constructive one;



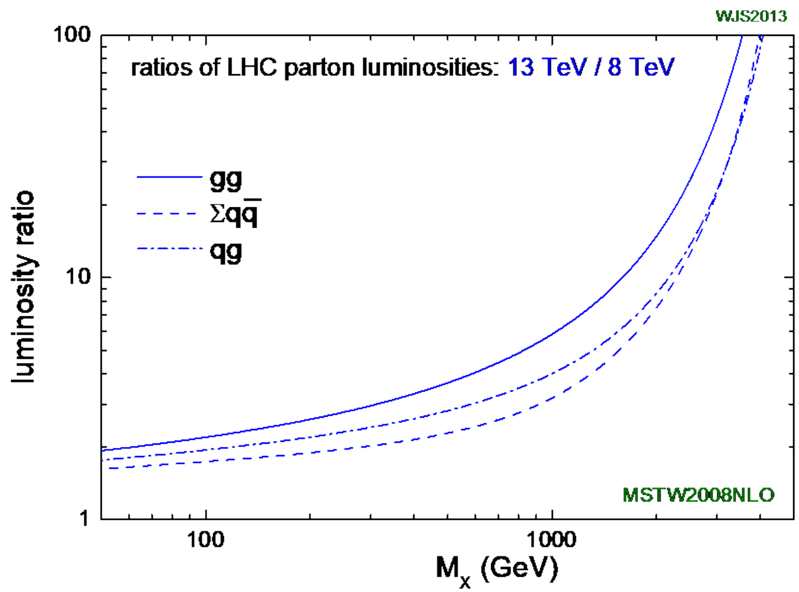
RUN3 will starts in 2021, expected integrated luminosity ~300 fb^{-1}

arXiv:1307.7135

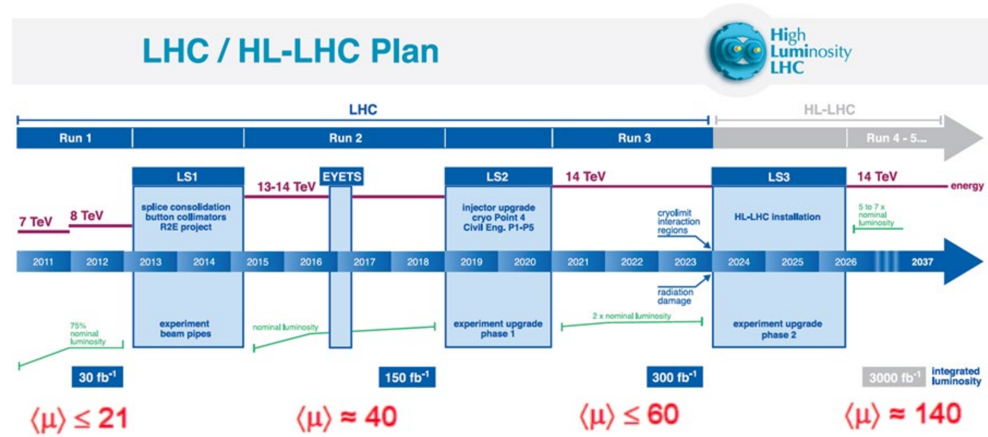
Thank you for your attention

LHC is the machine for discoveries

Energy



Luminosity



dijet resonances → x100 (M= 4-5 TeV)

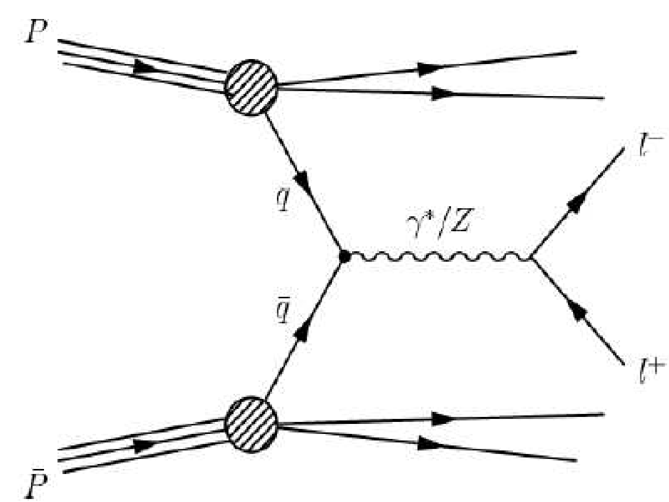
we will be in an unexplored region on day 1 !

Z' → x13 (M= 3 TeV)

we will be in an unexplored region with 1-2 fb^{-1} !

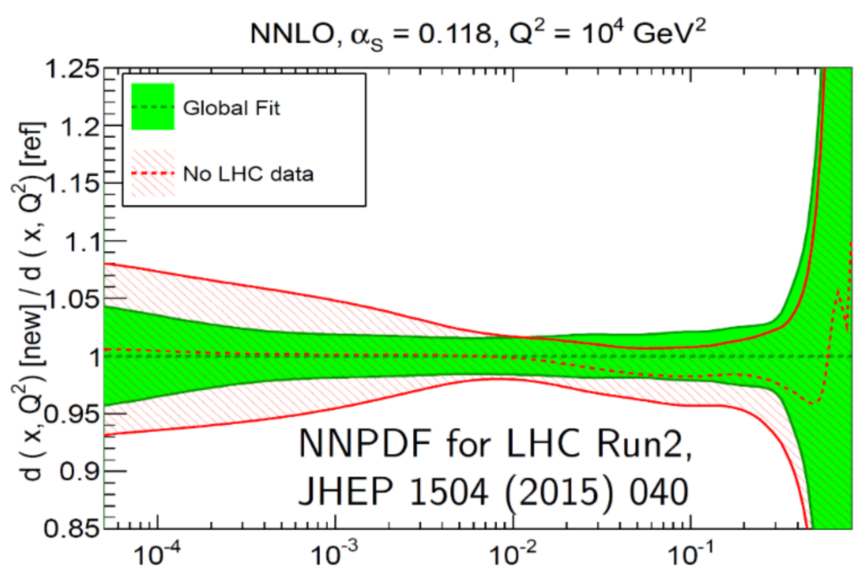
Motivation to Study Dimuons at CMS

Many major discoveries were made before LHC in dimuon channel (J/ψ, , 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 → ZZ, B → μμ discovery, 5 σ discovery of H → b¯b used also Z → μμ.

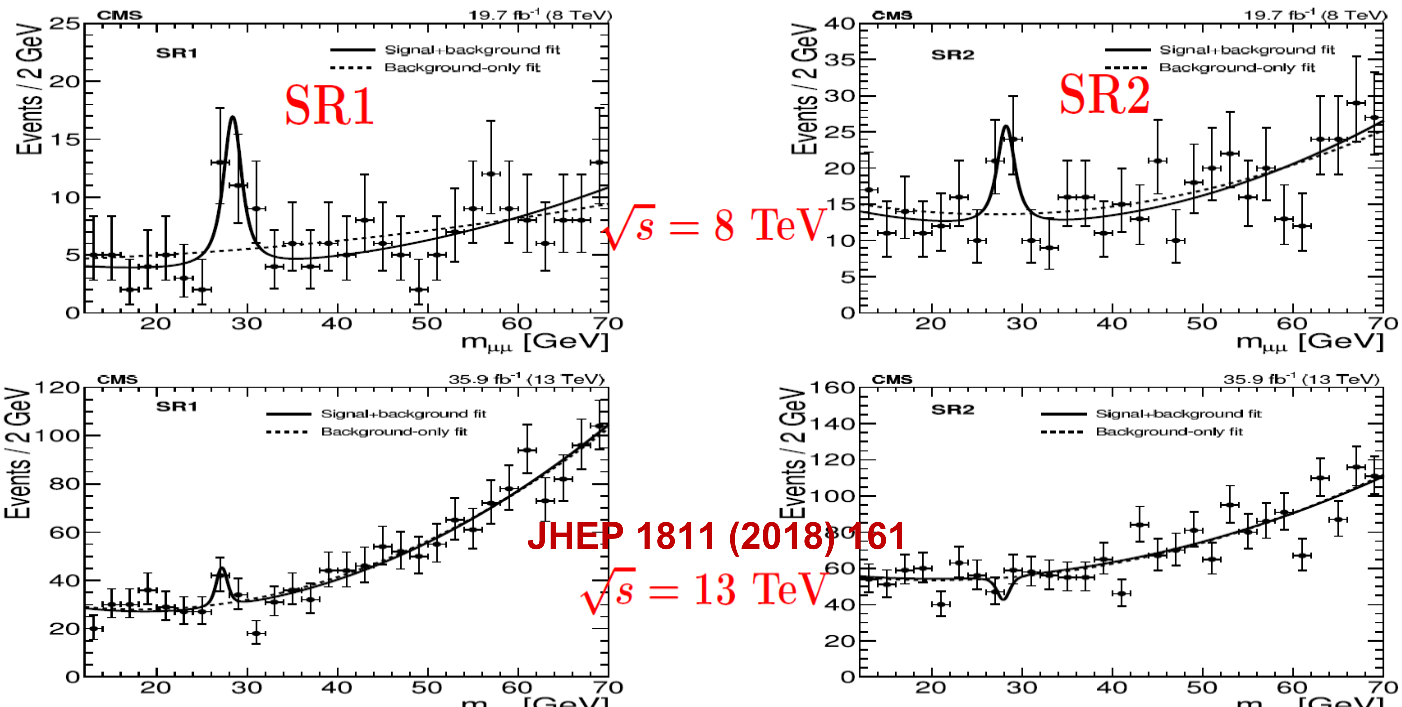


Search for $\mu\mu$ resonances produced in association with b-jets

High-pT muons + 2 mutually exclusive event categories in 2 “signal regions”:

- SR1 — b quark jet in central region (|| ≤ 2.4) and ≥ 1 jet in forward region (|| > 2.4).
- SR2 — 2 jets in the central region, ≥ 1 b-tag, no jets in the forward region, and small MET.

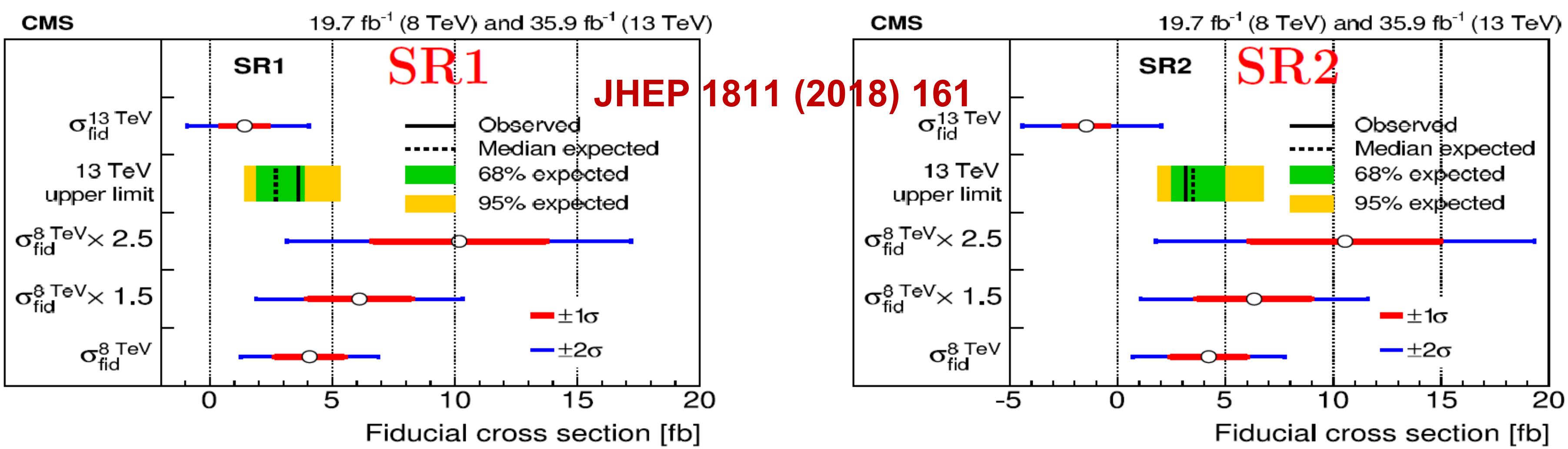
An excess of events above the background near a dimuon mass of 28 GeV is observed in the 8 TeV data, corresponding to local significances of 4.2 (SR1) and 2.9 (SR2).



A similar analysis conducted with 13 TeV data results in a mild excess corresponding to a local significance of 2.0 (SR1), while SR2 results in a 1.4 deficit.

Search for $\mu\mu$ resonances produced in association with b-jets

If we assume not a large increase of the signal cross section (e.g. factor 1.5 from qq initiated productions), and take into account that the dominant $t\bar{t}$ background is increased by 3.3, the 8 and 13 TeV results are compatible within 2σ.

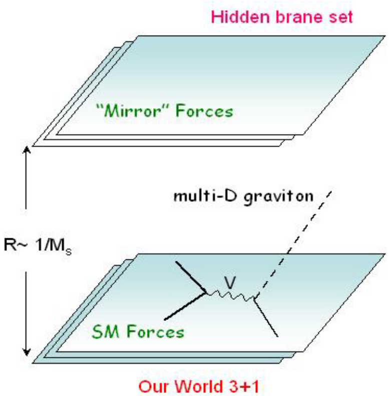


In the lack of a realistic signal model, the 13 TeV results are not sufficient to make a definitive statement about the origin of the 8 TeV excess.
⇒ More data and additional theoretical input are required.

Extra dimensions scenarios

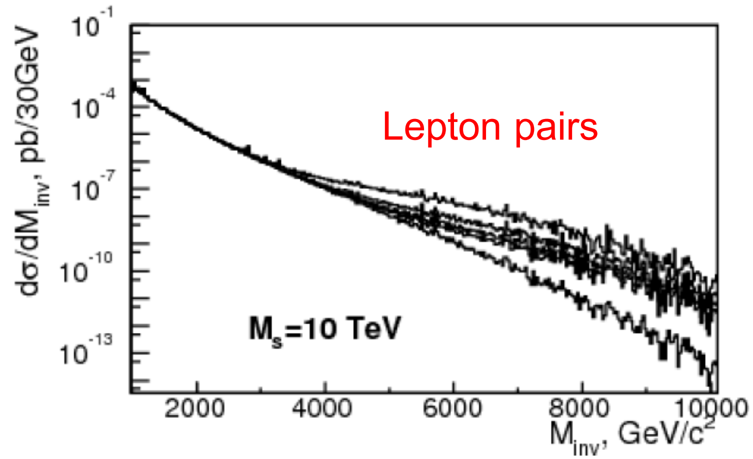
reducing of fundamental gravity scale to M_D ~ TeV. SM fields are on 3D-brane, gravity “feels” extra dimensions.

Arkani-Hamed–Dimopoulos–Dvali model (ADD)

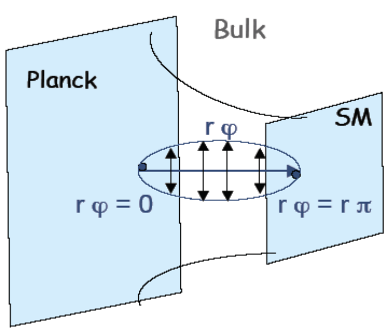


Евклидово пр-во плоских ДПИ (n = 2..7)

$$M_{\rm Pl}^2 = V_n M_D^{n+2} = (2\pi R)^n M_D^{n+2}$$



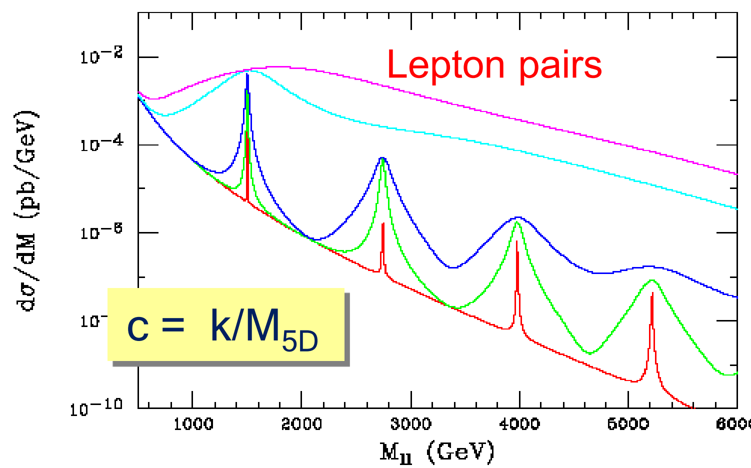
RS1 (Randall-Sundrum) model



5-dimensional anti de Sitter space AdS5 with curvature k

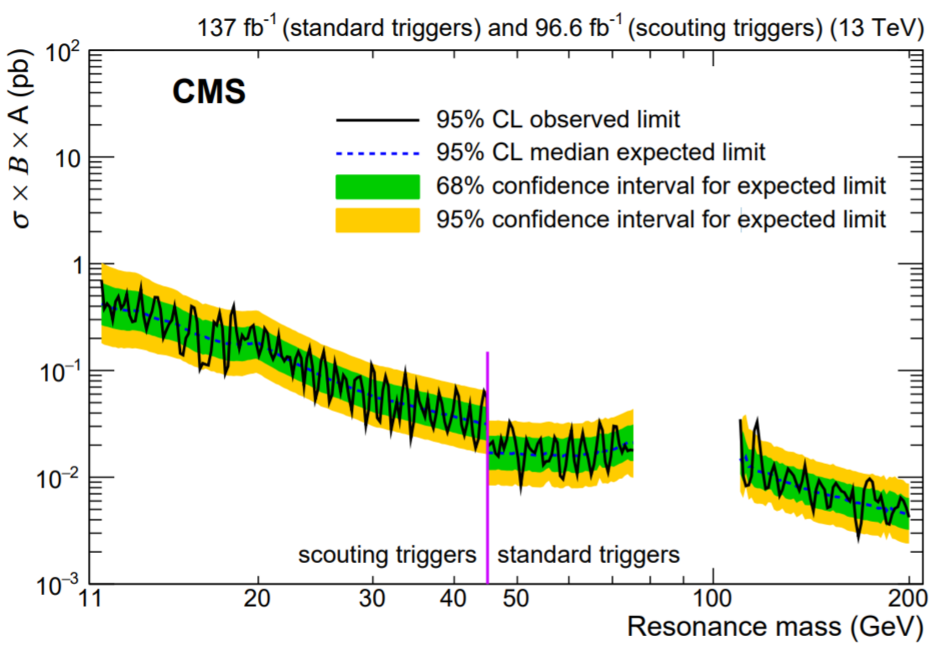
KK gravitons contribute to SM processes (in particular, Drell-Yan)

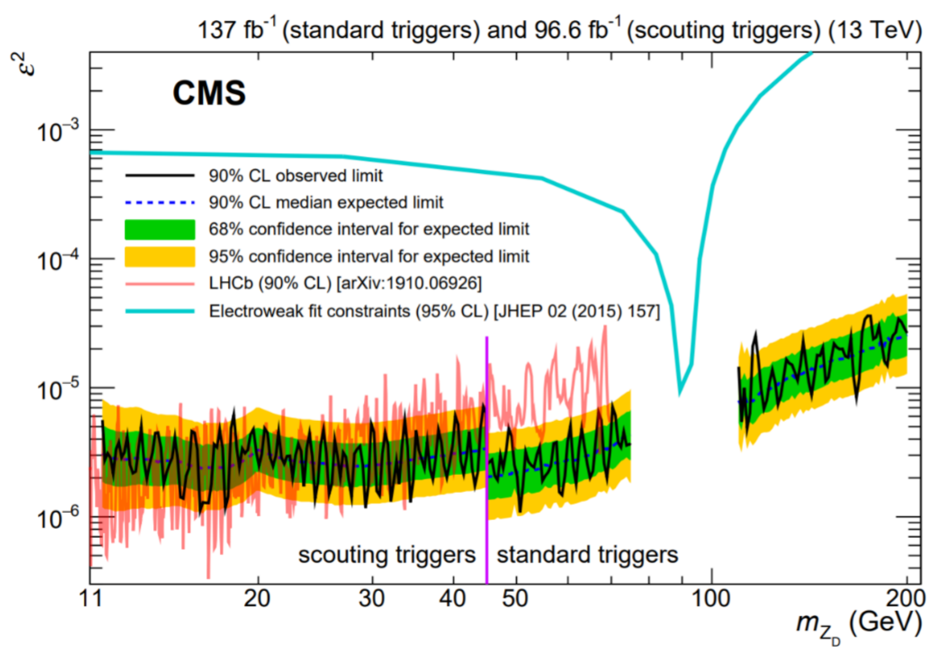
$$q\bar{q}, gg \rightarrow G_{KK} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, jet + jet$$



Search for a narrow resonance lighter than 200 GeV

Result of search for a narrow resonance decaying to a pair of muons in the 45–75 and 110–200 GeV resonance mass ranges.
Expected and observed 95% CL upper limits on the product of the signal cross section (σ), branching fraction to a pair of muons (B), and acceptance (A) as a function of the mass of a narrow resonance (left plot).
Expected and observed 90% CL upper limits on ϵ^2 as a function of the Z_D mass (right plot).



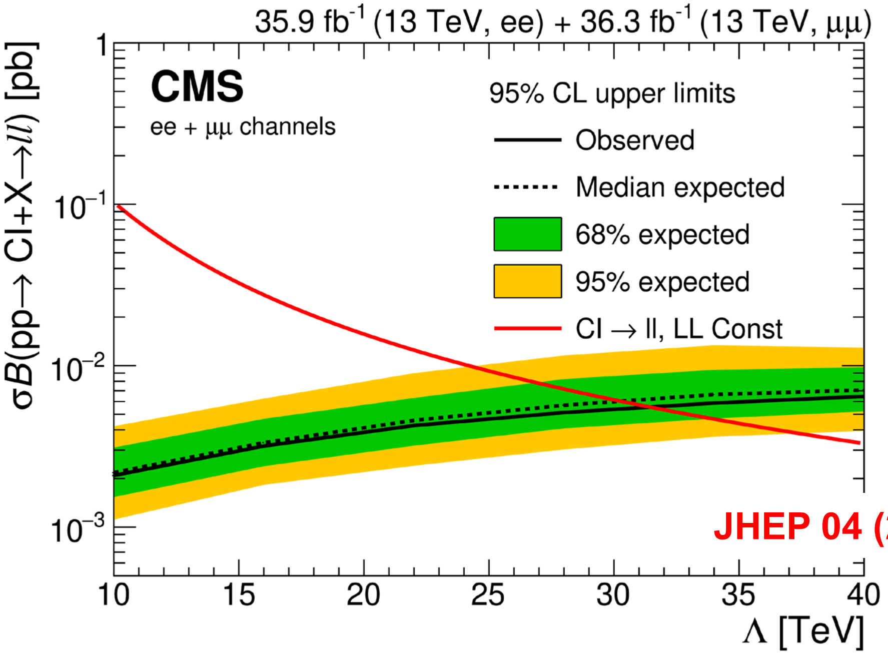


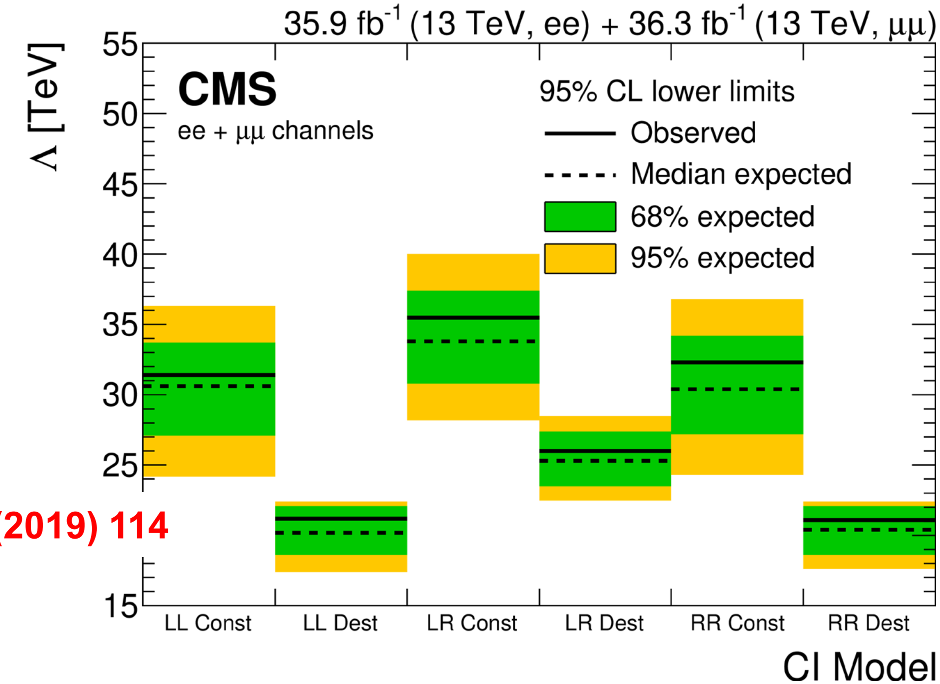
Results obtained using scouting data.
No significant resonant peaks are observed.

CMS PAS EXO-19-018

Non-resonant Dileptons: Compositeness

A contact interaction (CI) model, taking into account both constructive and destructive interference scenarios, has been used for interpreting the experimental measurements





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The 95%confidence level exclusion limits on the compositeness scale range from Λ_{LL}>20 TeV for the destructive case to Λ_{RR}>32 TeV for the constructive one, for the left-left and the right-right helicity currents, respectively.

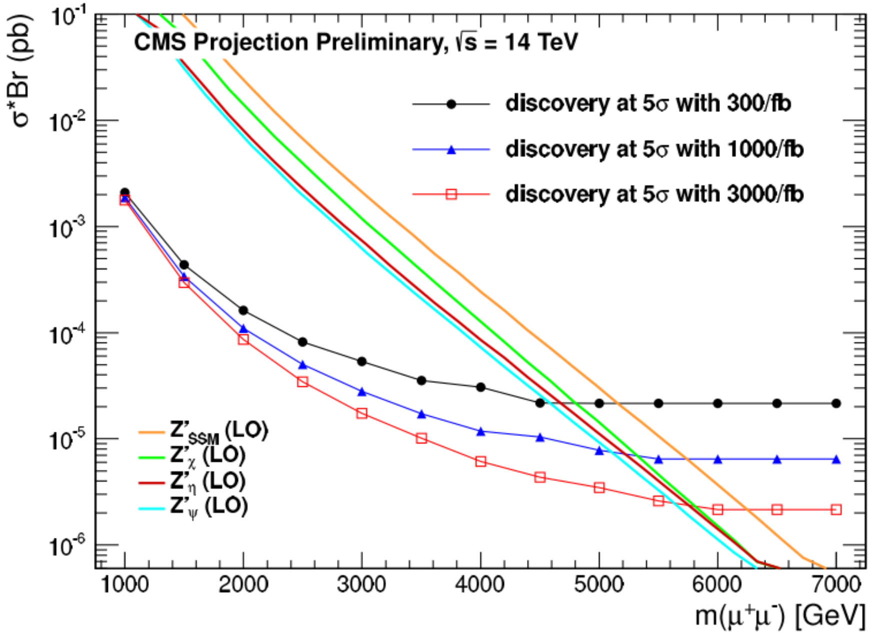
$$\mathcal{L}_{q\ell} = \frac{g^2_{\mathrm{contact}}}{\Lambda^2}\left[\begin{array}{l} \eta_{\mathrm{LL}}(\overline{\mathrm{q}}_{\mathrm{L}}\gamma^\mu \mathrm{q}_{\mathrm{L}})(\overline{\ell}_{\mathrm{L}}\gamma_\mu \ell_{\mathrm{L}}) + \eta_{\mathrm{RR}}(\overline{\mathrm{q}}_{\mathrm{R}}\gamma^\mu \mathrm{q}_{\mathrm{R}})(\overline{\ell}_{\mathrm{R}}\gamma_\mu \ell_{\mathrm{R}}) \\ +\eta_{\mathrm{LR}}(\overline{\mathrm{q}}_{\mathrm{L}}\gamma^\mu \mathrm{q}_{\mathrm{L}})(\overline{\ell}_{\mathrm{R}}\gamma_\mu \ell_{\mathrm{R}}) + \eta_{\mathrm{RL}}(\overline{\mathrm{q}}_{\mathrm{R}}\gamma^\mu \mathrm{q}_{\mathrm{R}})(\overline{\ell}_{\mathrm{L}}\gamma_\mu \ell_{\mathrm{L}}) \end{array}\right]$$

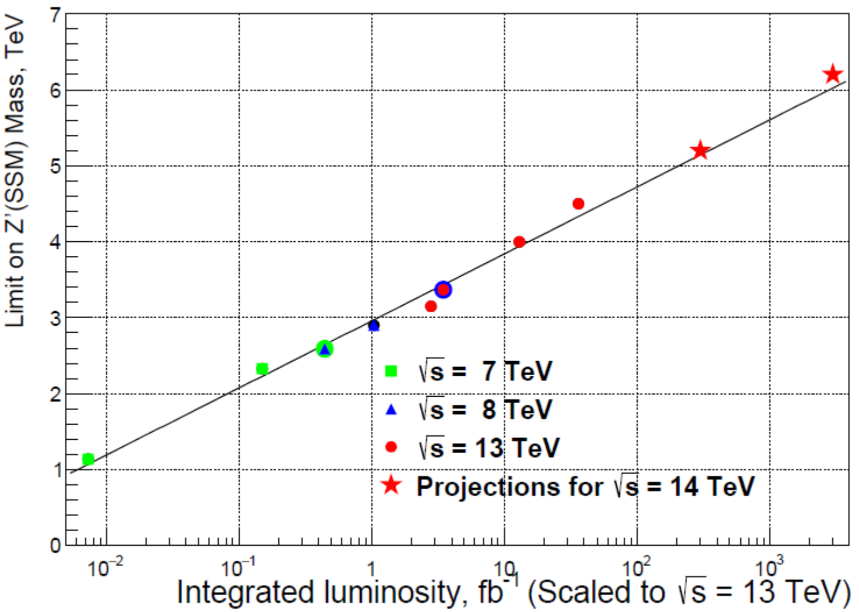
Summary

CMS performed a wide program of search for particles and phenomena

RUN1 and RUN2 data demonstrate triumph of Standard Model (many Exotica Models were tested in the channel with dileptons in the final states and new limits are derived)

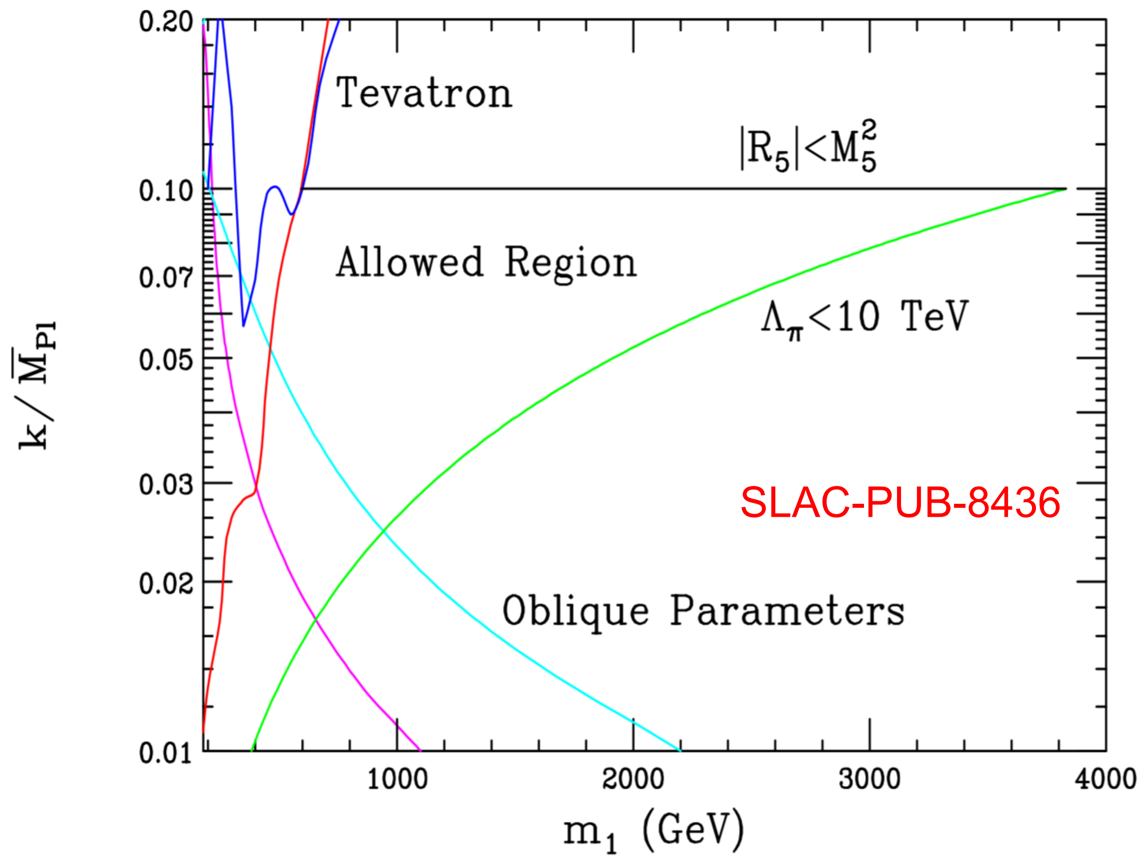
RUN3 will starts in 2021, expected integrated luminosity ~300 fb^{-1} (expected mass limits are 4.6-5.2 TeV for Z′, depending on the model)





Coupling constant limitation

Experimental and theoretical constraints on the RS model.
The allowed region lies in the center as indicated.



The theoretical constraints are given by curvature bound $|R_5| = 20k^2 < M_5^2$, which yields $k/\overline{M_{Pl}} < 0.1$.

Z' models

Различные эталонные модели с соответствующими углами смешения, брэнчинг, значениями параметров c_u и c_d, их отношение, отношение ширины к массе ассоциированного Z 'бозона.

$U'(1)$ 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