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

JINR Association of Young Scientists and Specialists Conference "Alushta-2022"

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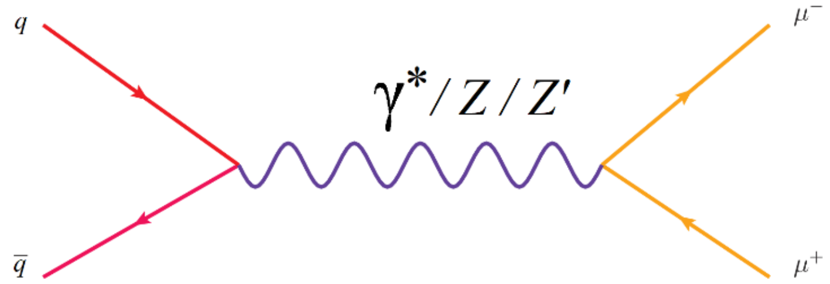
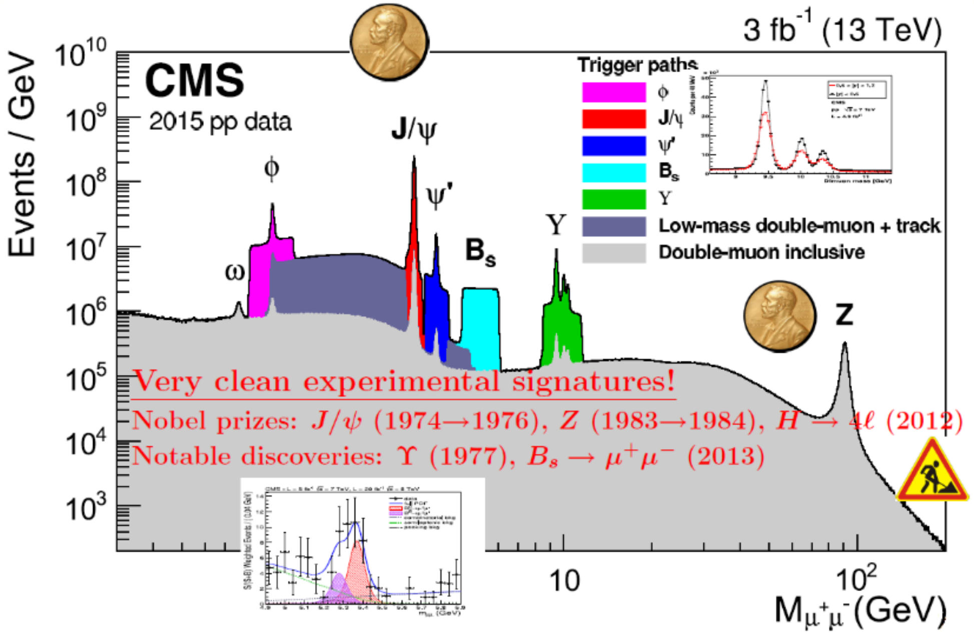
SM processes and beyond

Motivation to search for new physics

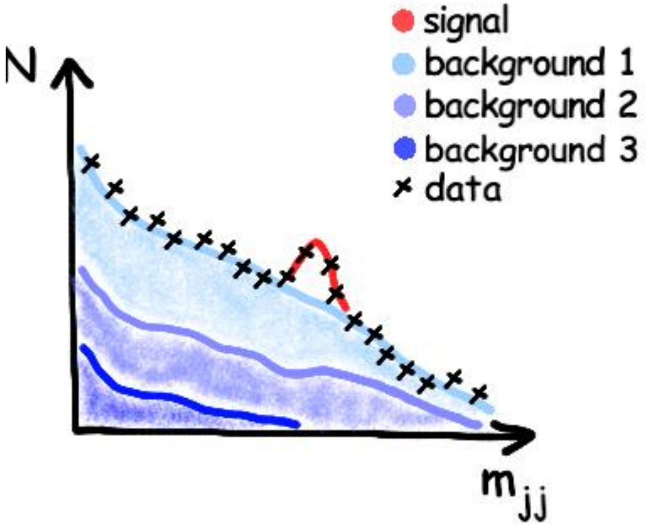
- Many theoretical scenarios beyond the Standard Model predicts phenomena that can be discovered in the channel with a pair of muons;
- The Drell-Yan process - $q\bar{q} \rightarrow \gamma/Z^0/Z' \rightarrow l^+l^-$ - is one of the critical tests of the SM. In SM the process is calculated with great precision: NNLO QCD & NLO EW;
- Test the Standard Model on a new energy scale (~ several TeV);
- Events with a pair of muons have a simple experimental signature;
- The Compact Muon Solenoid (CMS) experiment at the LHC is optimized for measuring high pT muons (up to several TeV).

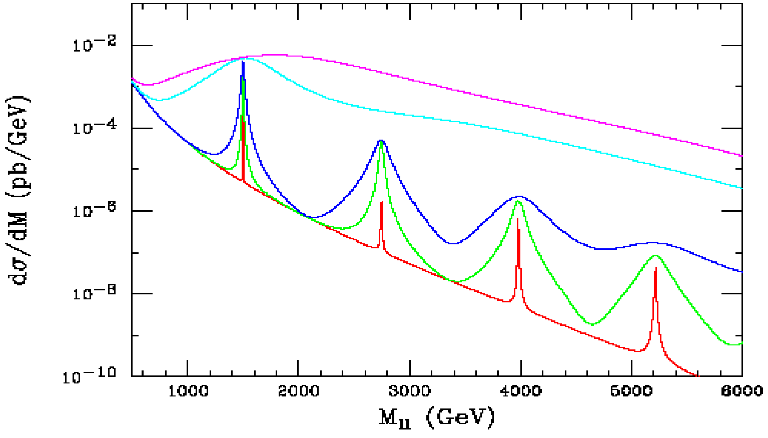




New Physics ($Z'/Z_{KK}/G_{KK}$) contributions to SM processes:

- Spin-1 resonances (Extra gauge boson (Z'), DM…)
- Spin-2 resonances (RS1 graviton…)
- Non-resonant signals (Extra dimensions ADD…)

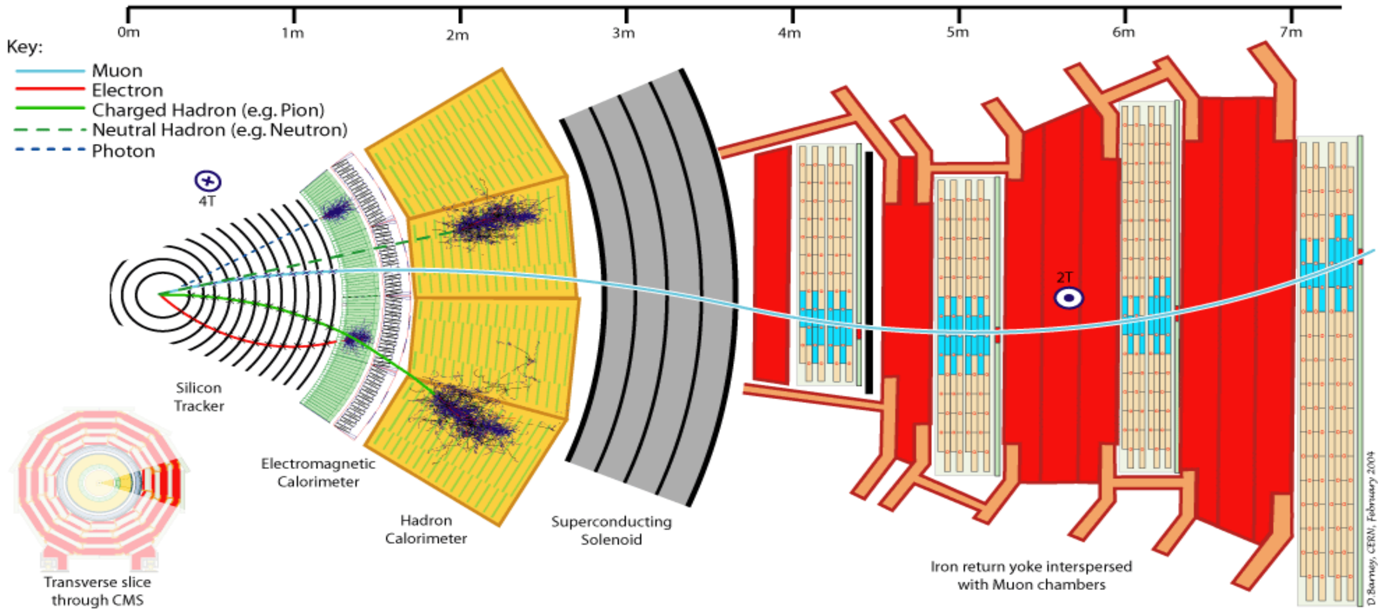




Signals: di-leptons resonance states in high (~TeV) invariant mass range ⇒ new particles would be observed as a bump, excess in the mass spectrum

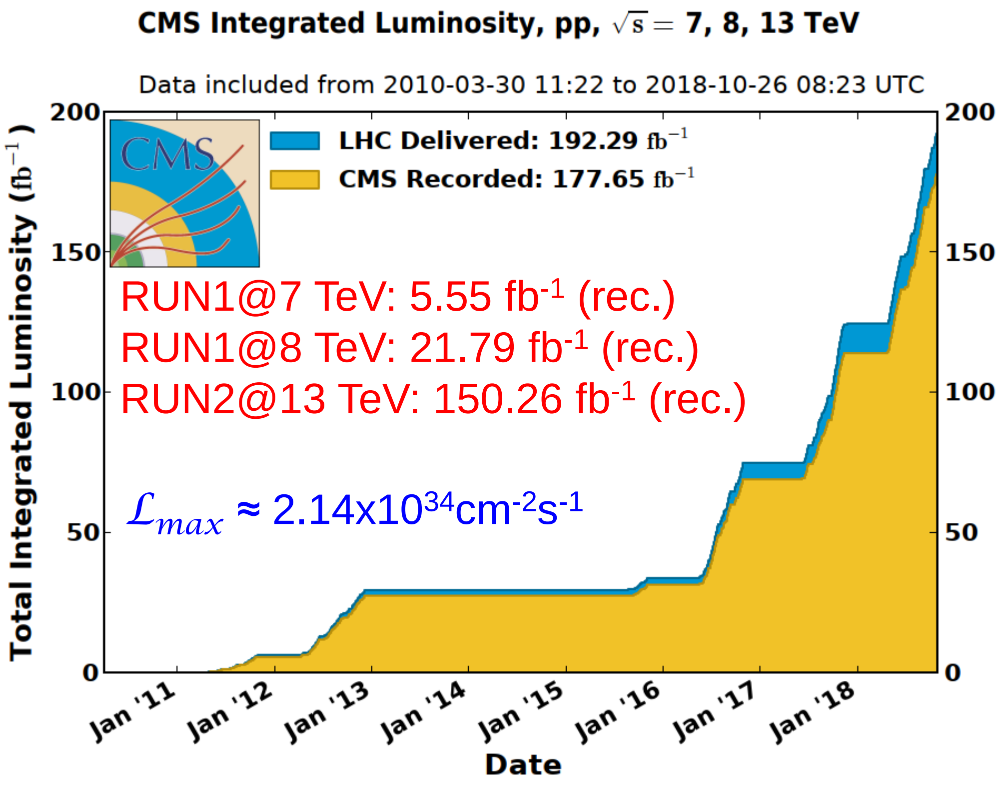
CMS Detector and Collected Data

Large general-purpose particle physics detector



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

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



Heavy Resonances: Z′ and RS1 Limits

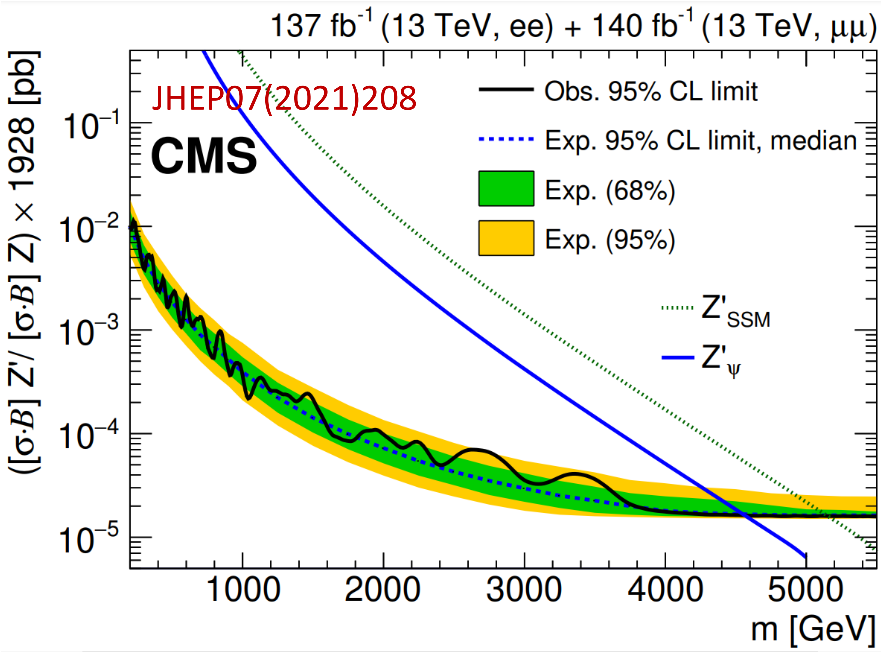
- The likelihood function is based on probability density functions (pdf) that describe the signal and background contributions to the invariant mass spectra

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

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

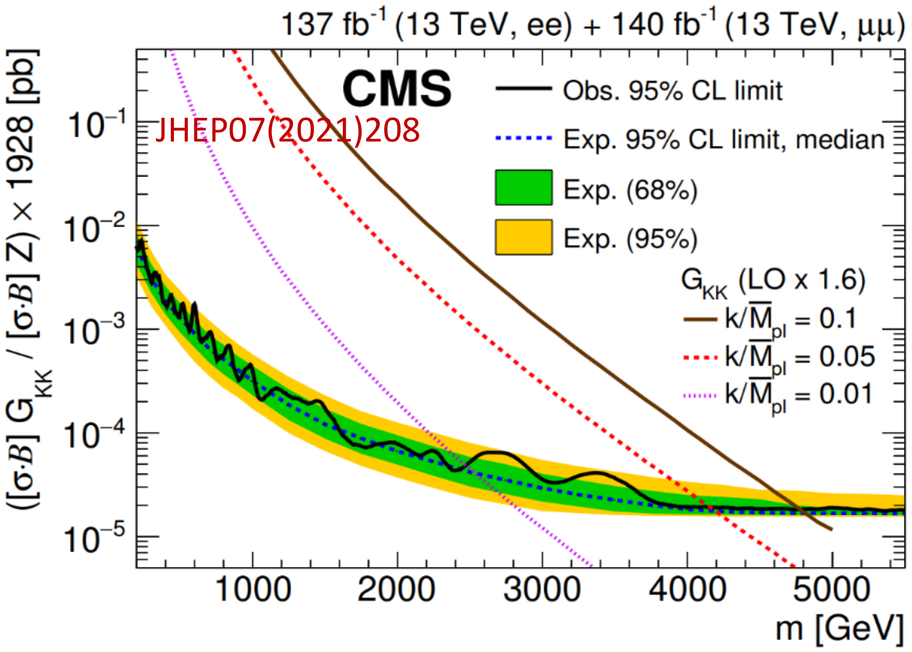
- The expected cross section limits are expressed as the value of the function R_σ. The use of this ratio eliminates the uncertainty in the integrated luminosity and reduces the dependence on the experimental acceptance, trigger, and offline efficiencies

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



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 2.47 TeV (c=0.01)
for G_{KK}, mass limit is 4.16 TeV (c=0.05)
for G_{KK}, mass limit is 4.78 TeV (c=0.1)



Heavy Resonances: Generalized Extra Gauge Bosons

The mass limits can be expanded at the other theoretical models: Grand Unified Theory (GUT) E6 or SO (10), SSM etc.

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

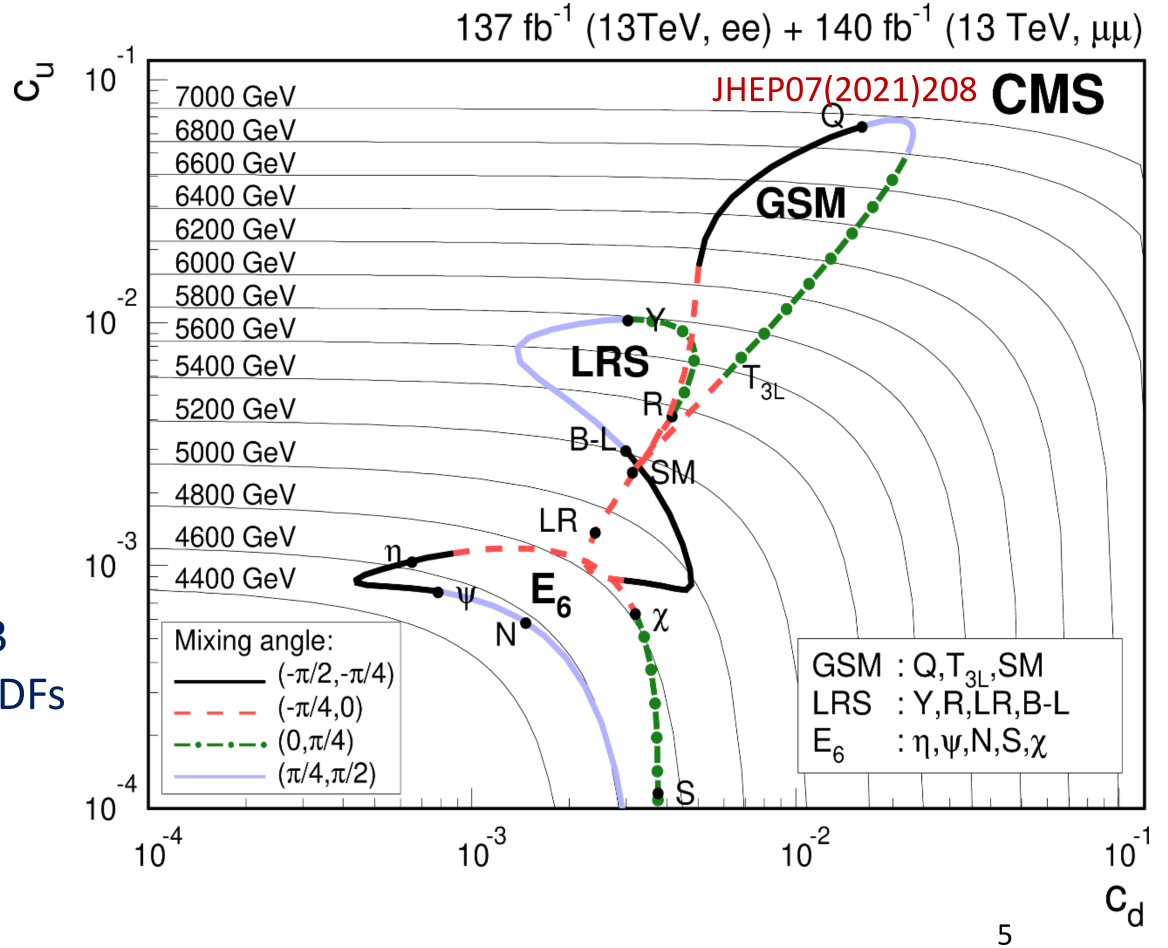
$$\sigma_{l^+l^-} = \frac{\pi}{48s}[c_u w_u(s, M_V^2) + c_d w_d(s, M_V^2)],$$

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

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

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.

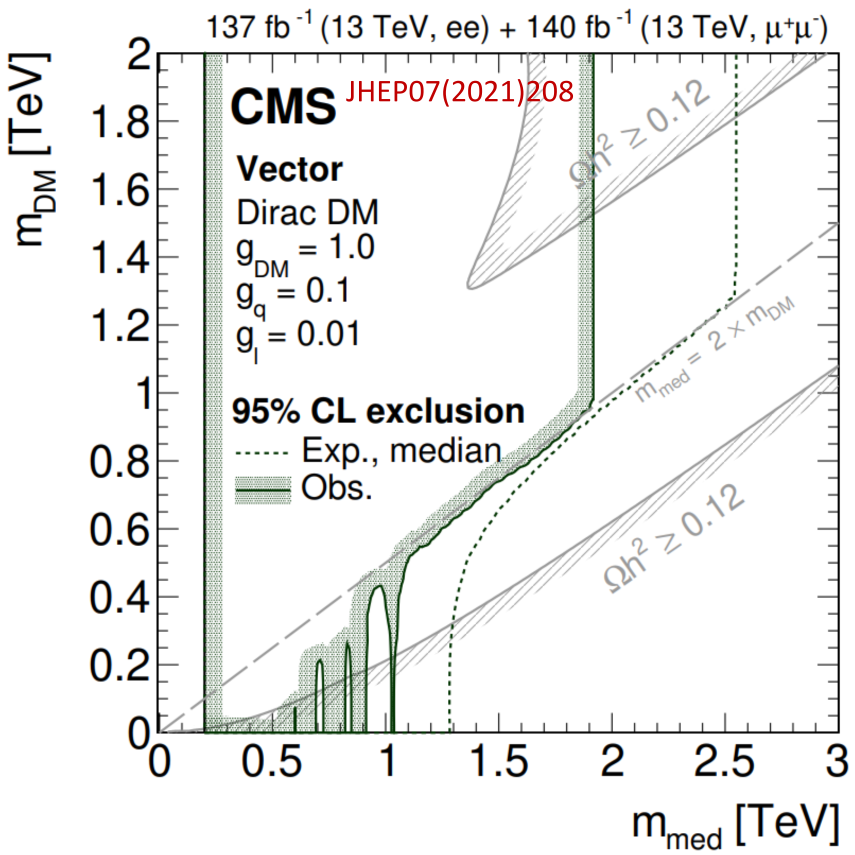


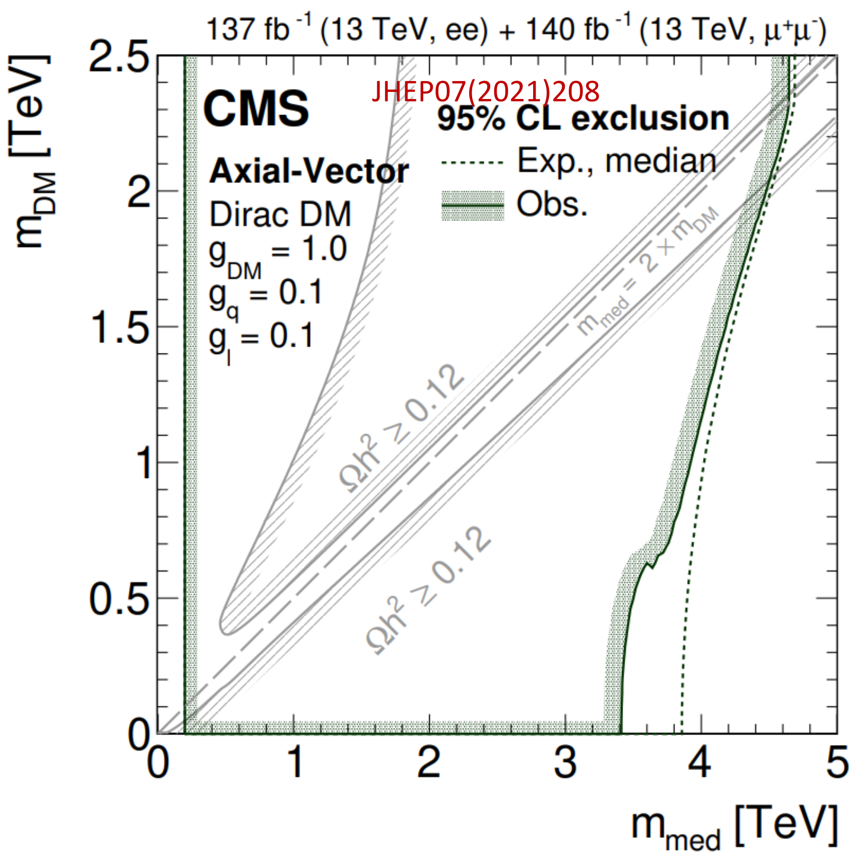
Heavy Resonances: Dark Matter

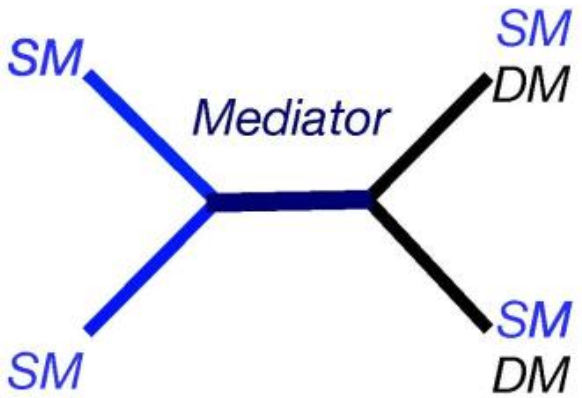
The results are also interpreted in the context of a simplified model with a DM particle that has sizeable interactions with SM fermions through an additional spin-1 high-mass particle mediating the SM-DM interaction

(recommended by CERN DM group '*Phys. Dark Univ. 26 (2019)*')

- ✓ 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





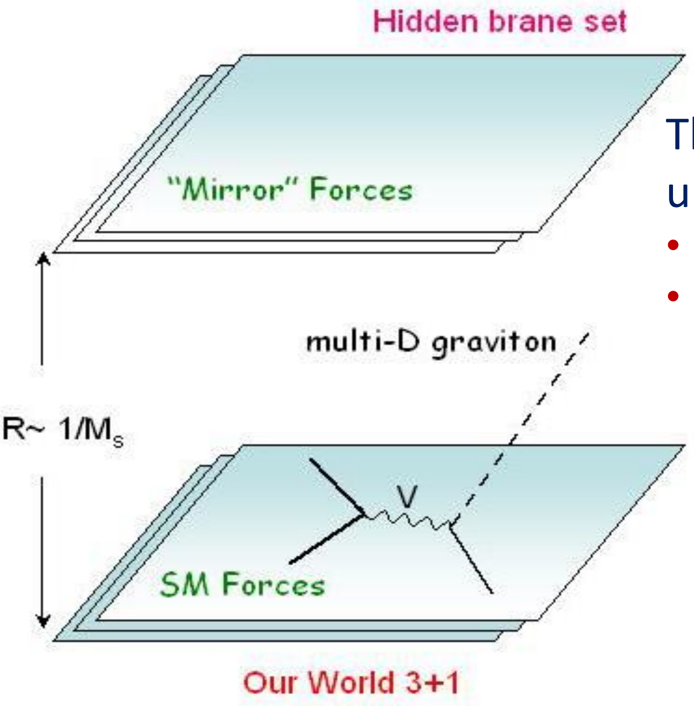


In the vector (axial-vector) mediator model, mediators with masses below 1.92 (4.64) TeV are excluded.

Non-resonant signals: Extra dimensions

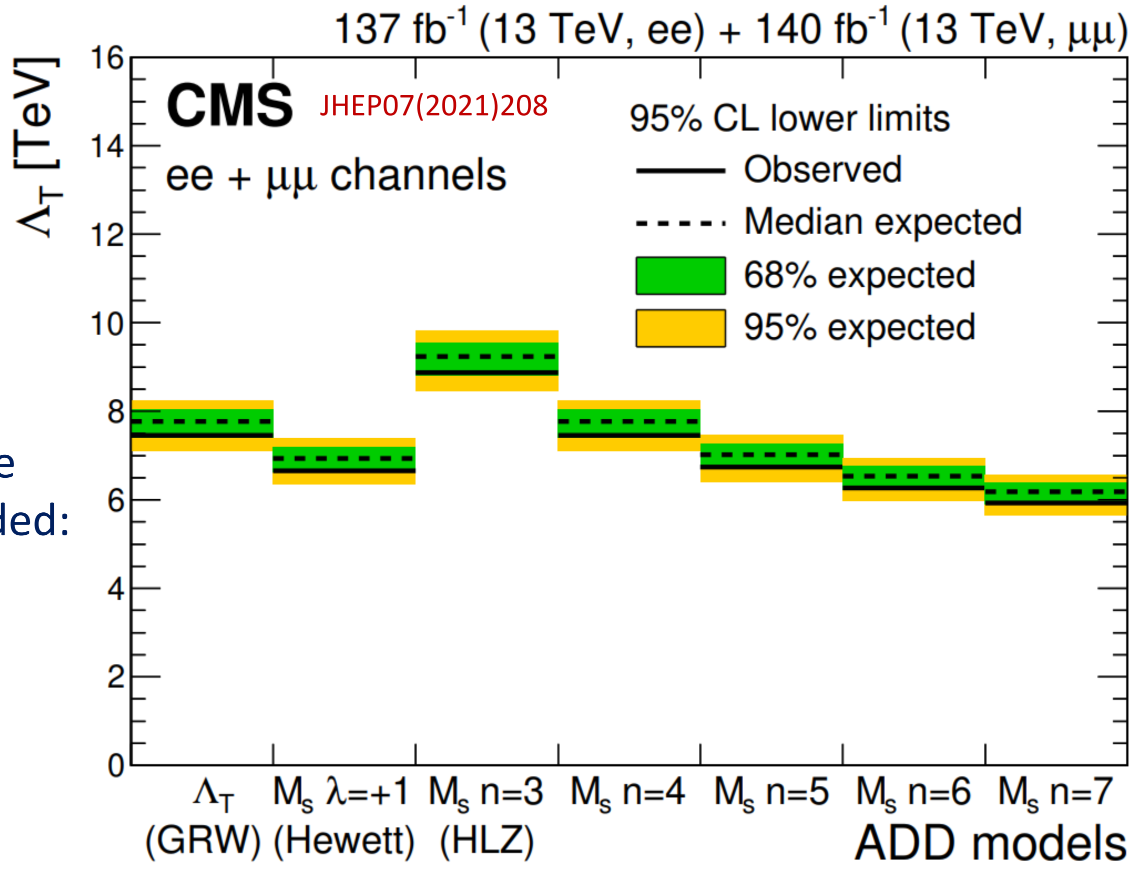
No significant deviations from standard model expectations are observed.

Arkani-Hamed, Dimopoulos, and Dvali (“ADD”) model with large extra dimensions (n = 2..7)



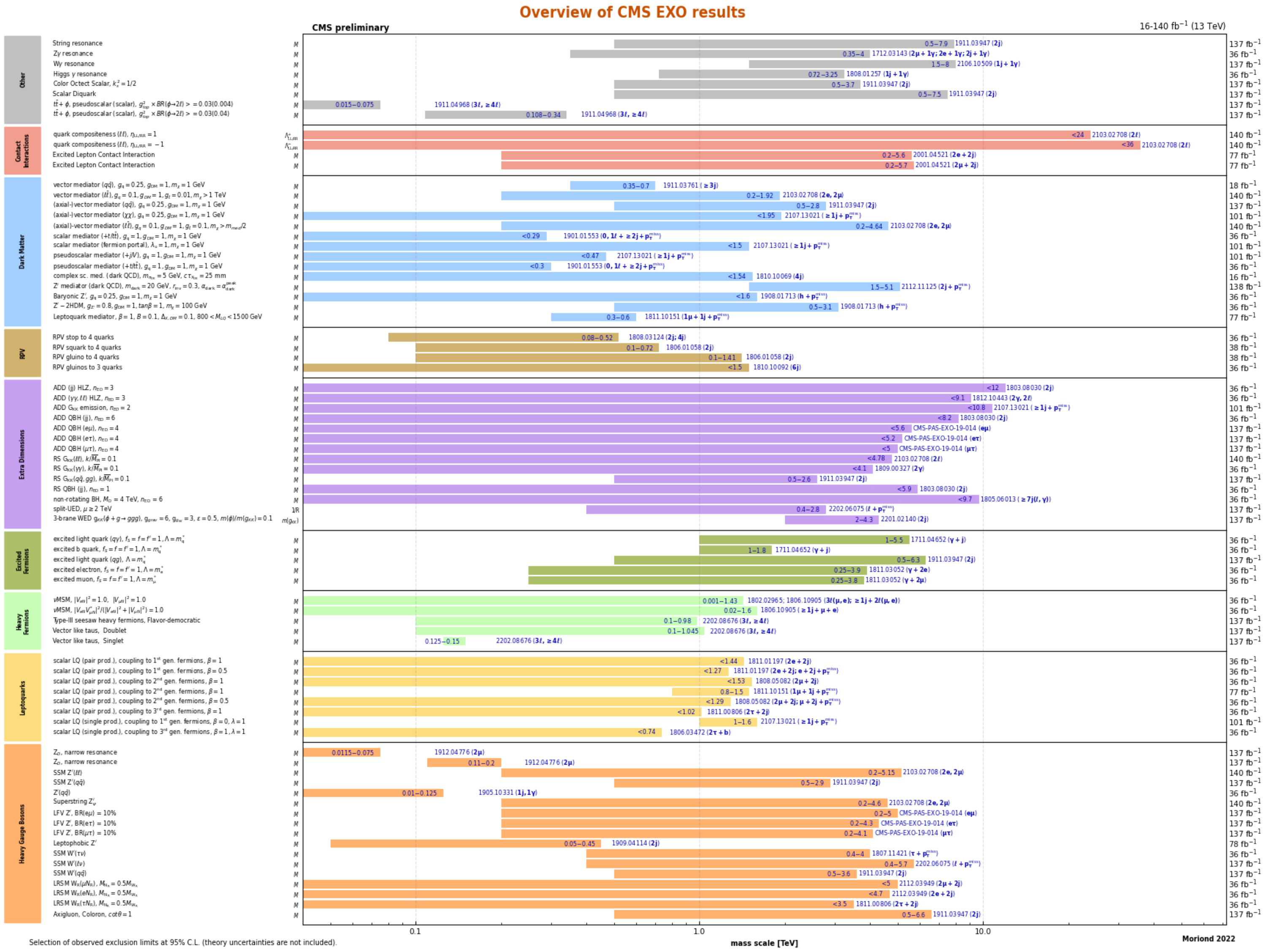
The corresponding 95% CL values of the ultraviolet cutoff parameters are excluded:

- Λ_T below 7.5 TeV (in GRW)
- M_S range from 5.9 to 8.9 TeV (in HLZ), depending on the model



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

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

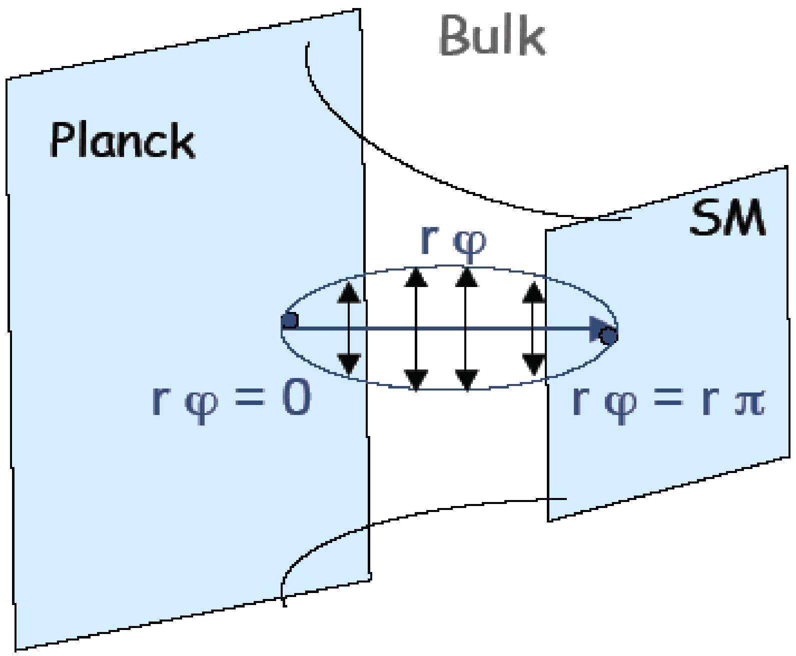


Conclusions

- CMS performed a wide program of search for particles and phenomena with all Run2 statistics 140 fb^{-1};
- RUN1 and RUN2 data demonstrate triumph of Standard Model:
  many Exotica Models were tested in the channel with dileptons in the final states;
- Upper limits of new phenomena models are improved;
- The next step: RUN3 - will start in 2022, expected integrated luminosity ~300 fb^{-1} at $\sqrt{s}$=13.6 TeV!

Thanks for your attention!

Back up



Randall and Sundrum (RS1) of extra dimensions

5-dimensional anti-de Sitter space where the elementary particles (except the graviton) are localized on a (3 + 1)-dimensional brane or branes.

The RS1 model attempts to address the hierarchy problem.

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

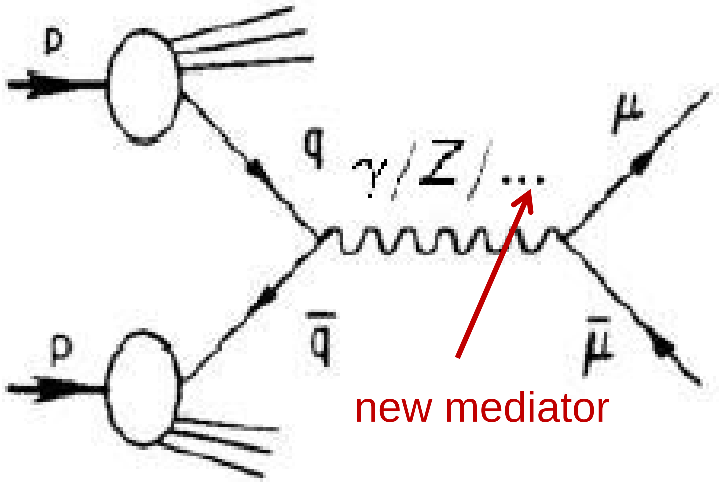
$$q\bar{q}, gg \rightarrow G_{KK} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, jet + jet$$

Simplified model with a DM particle

✓ has sizeable interactions with SM fermions through an additional spin-1 high-mass particle mediating the SM-DM interaction

✓ only one DM particle exists, which is assumed to be a Dirac fermion

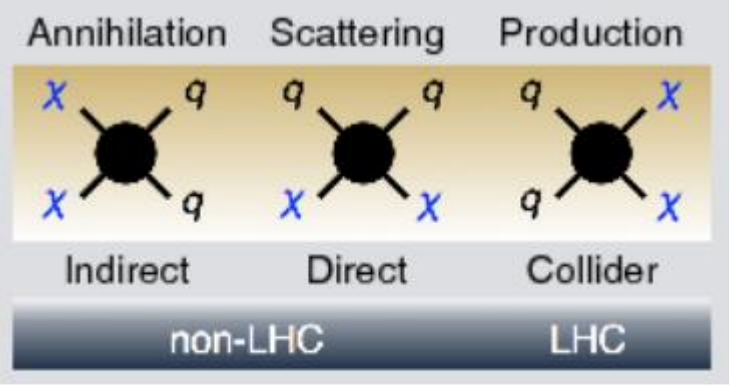
✓ two cases with different sets of benchmark coupling values
   — a vector mediator with small couplings to leptons
   — an axial-vector mediator with equal couplings to quarks and leptons

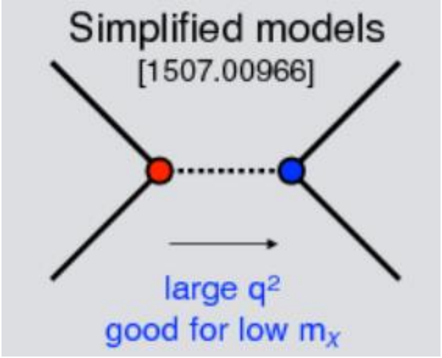


While the DM particle is not probed directly, its mass indirectly modulates the sensitivity of the dilepton search: Drell-Yan type process (sensitive directly to m_{Med}, g_l, g_q)

5 parameters:

- m_{DM} - DM mass
- m_{Med} - mediator mass
- g_{DM} - coupling of a mediator-DM-DM vertex
- g_l - coupling with leptons
- g_q - coupling with quarks





Открытые вопросы Стандартной модели

Недостатки и открытые вопросы стандартной модели:

- ✓ Проблема иерархии двух сильно отличающихся по величине энергетических масштабов – планковского (10^{19} ГэВ) и электрослабого (10^{2} ГэВ)
- ✓ Проблема иерархии фермионных масс (объяснение разницы масс разных поколений кварков и лептонов), масса нейтрино, объединение взаимодействий, включение гравитации
- ✓ Набор космологических и астрофизических проблем (инфляция, темная материя, CP-нарушение в ранней Вселенной и пр.)
- ✓ А также: свободные параметры СМ, число поколений (почему 3?), конфайнмент etc.