CMS: Recent Results and Future Perspectives

XII SILAFAE 2018, PUCP, Lima-Perú

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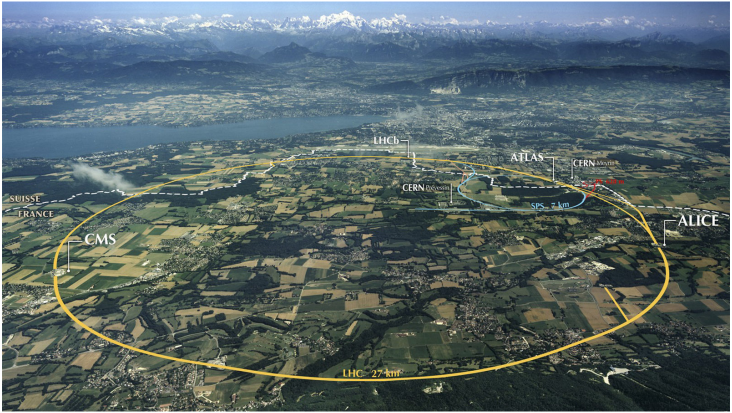
Outline

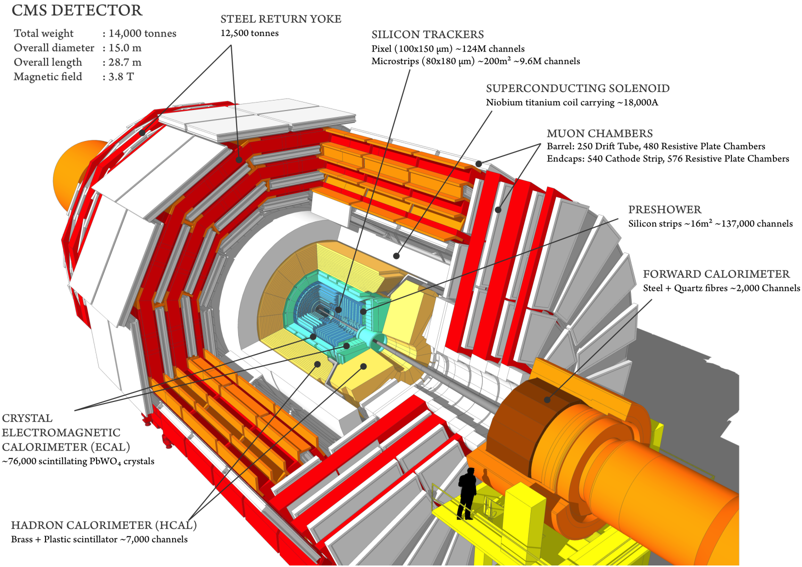
The Large Hadron Collider (LHC)



Maximilien Brice, CERN

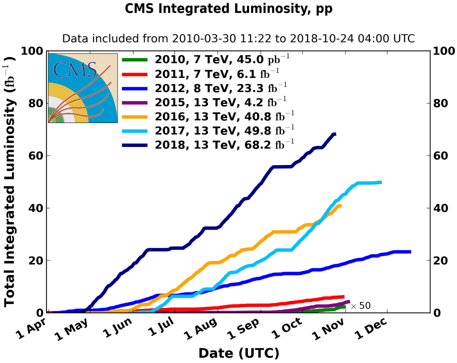
- At CERN, in the Franco-Swiss border.
- Most powerful ever built.
- 27-kilometer ring.
- Colliding protons and heavy ions beams, at record centre-of-mass energies and luminosities.

The Compact Muon Solenoid (CMS)



J. Phys. Conf. Ser. **513**, 022032 (2014); https://twiki.cern.ch/twiki/bin/view/CMSPublic/SketchUpCMS

CMS Detector Performance in Run 1

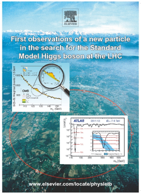


https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

- LHC **Run 1** period: **2010-2012**.
- Centre-of-mass energy up to **8** TeV.
- 50 ns bunch spacing
- $<$ pile-up $>=$ **21**.
- Nearly **30** fb^{-1} of integrated luminosity.
- Peak luminosities $\sim \mathbf{7} \times \mathbf{10^{33}}$ $\mathrm{Hz/cm^2}$.
- Excellent tracking, down to very low p_T, and vertexing.
- Excellent energy resolution.
- Sophisticated reconstruction algorithms of particle-flow and particle identification.

Nucl. Part. Phys. Proc. **273-275**, 1048 (2016)

CMS Physics Highlights in Run 1



- $\sim$ 500 different measurements in p-p, p-Pb and Pb-Pb collisions.

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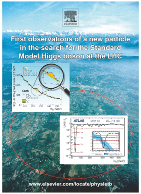
- Higgs:
  - **Observation of scalar BHE boson, $\gamma\gamma$ and $ZZ^*(4\ell)$ channels**.
    Spoiler alert: **it is still there!**
  - Mass mearusemant with less than 0.2 % uncertainty.
  - Initial measurements of width, quantum numbers, couplings in agreement with SM.



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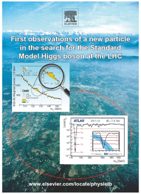

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- QCD and QGP:
  - Jet distributions, agreement with NLO pQCD over 14 orders of magnitude in cross sections.
  - α_S up to ~ 2 TeV scale.
  - Parton collectivity (long-range near-side angular correlations).
  - Jet quenching in dense QCD medium.
- Top, electroweak and flavor physics:
  - Top-pair and single top cross sections, precise top mass.
  - Measured for the first time $W + t$, $t\bar{t} + \gamma$, $t\bar{t} + Z$, VBF production of Z, and $\gamma\gamma \to WW$.
  - Stringent limits on anomalous triple and quartic gauge couplings.
  - $B_S^0 \to \mu^+\mu^-$, with expected SM BR.
- Searches for new physics:
  - No evidence for SUSY; spartner masses pushed away from EW scale.
  - Null dark matter searches; cross section limits competitive at low masses.
  - No hints of new resonances or particles linked to new symmetries.
  - Stringent limits imposed: $\Lambda \gtrsim 15$ TeV for quark compositness; $\Lambda \gtrsim 5-7$ TeV for ADD gravitons; $m_X \gtrsim 1.5-3.5$ TeV for W', Z'; $\Lambda \gtrsim 2.5$ TeV for RS extra dimensions; $m_X \gtrsim 0.6$ TeV for leptoquarks, new long-lived particles, heavy-quark partners, etc.

Nucl. Part. Phys. Proc. **273-275**, 1048 (2016)

To-do List After Run 1

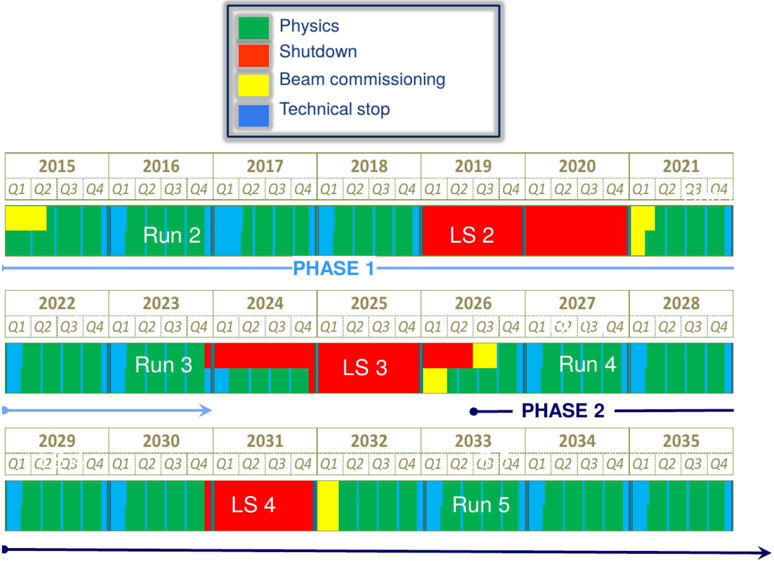
- ☑? Is there a Higgs or Higgs-like particle?
- ☐ Does the Higgs really couple to quarks?
- ☐ Does the Higgs couple to all quark families?
- ☐ Does the Higgs really couple to leptons?
- ☐ Does the Higgs really couple to all leptons?
- ☐ Are the fermion couplings proportional to fermion masses?
- ☐ Is it the mass giver to all fermions?
- ☐ Are there more Higgs-like particles (charged or neutral)?
- ☐ Is the Higgs boson the sole responsible for EW symmetry breaking?

⋮

- ☐ What is dark matter, and can we produce it at colliders?
- ☐ Are there extra dimensions, can we probe this at the LHC?
- ☐ Why is the Universe made of matter only and not antimatter?
- ☐ Why is gravity so feeble?
- ☐ Why is there a scale of fermion masses?
- ☐ What is dark energy, can we test it in the lab?

⋮

The LHC in Run 2



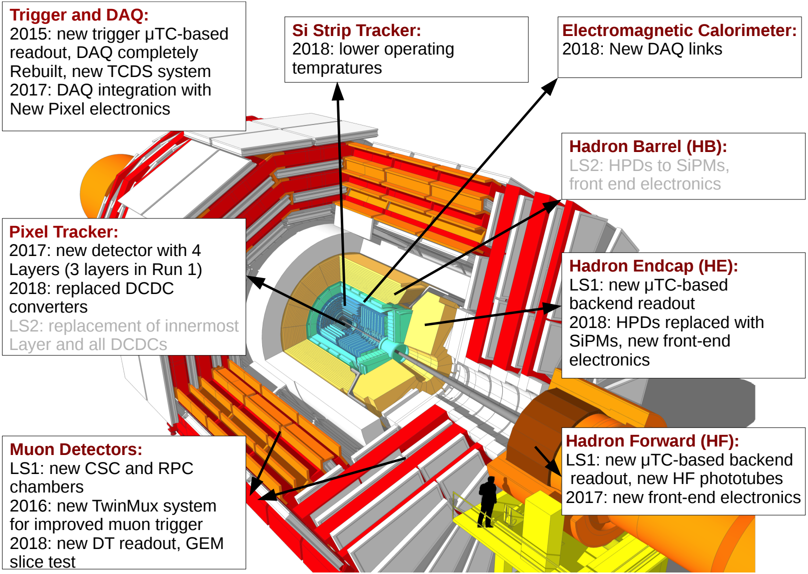
https://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm

The LHC in Run 2

https://cds.cern.ch/record/2302977

- Proton beams colliding at the record centre-of-mass energy of **13** TeV.
- Peak Luminosity $\sim \mathbf{2} \times \mathbf{10^{34}}\ \mathrm{Hz/cm^2}$ (factor of two from design value).
- High availability, $> 50\,\%$ of time in stable operation.
- Fast turn-around time between fills (5 h typical, 2 h record).
- Increased radiation doses, pile-up and trigger rates.
- End of protons Run 2 program 24 October, 2018.

CMS Evolution in Run 2 (Phase I upgrades)



Modified from https://twiki.cern.ch/twiki/bin/view/CMSPublic/SketchUpCMS

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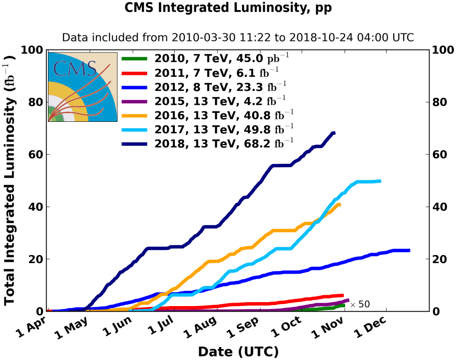

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- LHC **Run 2** period: **2015-2018**.
- Centre-of-mass **13** TeV.
- $\sim 163\ \mathrm{fb}^{-1}$ of integrated luminosity in Run 2 (goal was $150\ \mathrm{fb}^{-1}$).
  - $\sim 68.2\ \mathrm{fb}^{-1}$ delivered to CMS in 2018.
  - $\sim 192.5\ \mathrm{fb}^{-1}$ from 2010.
- 25 ns bunch spacing
- $\langle$pile-up$\rangle = 37$.
- Peak luminosities $\sim 2 \times 10^{34}\ \mathrm{Hz/cm^2}$.
- Excellent detector performance. CMS recording efficiency $\sim 94\,\%$
- New or improved analysis techniques:
  - Particle Flow reconstruction
  - PUPPI (PileUp Per Proton Interaction)
  - Boosted jets and jet substructure analysis
  - Use of multivariate analysis to maximize statistics
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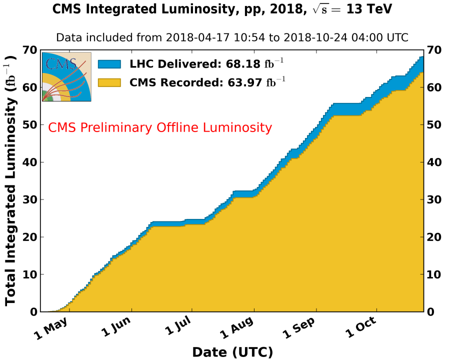

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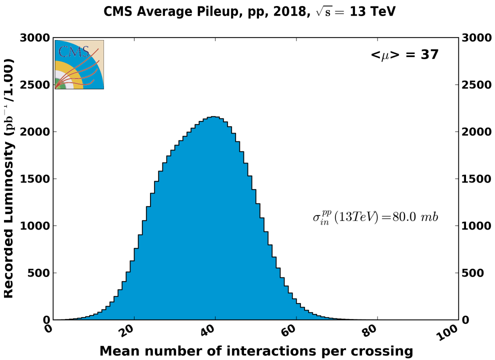

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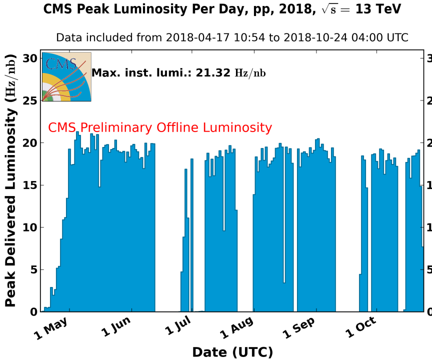

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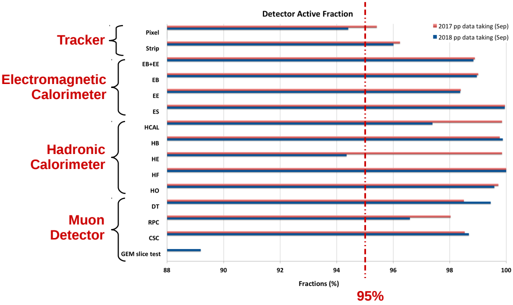

https://twiki.cern.ch/twiki/bin/view/CMSPublic/ActiveChannelsSummary

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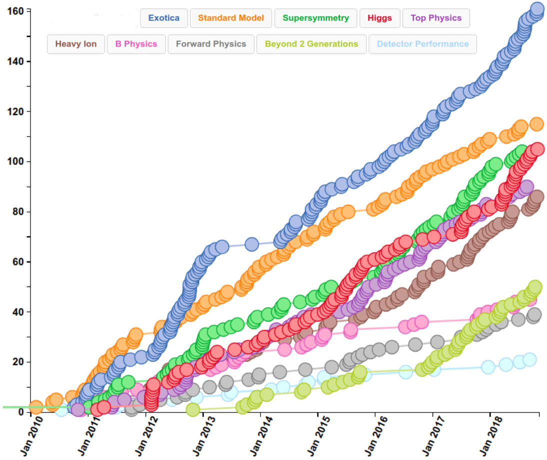
CMS Physics Publications

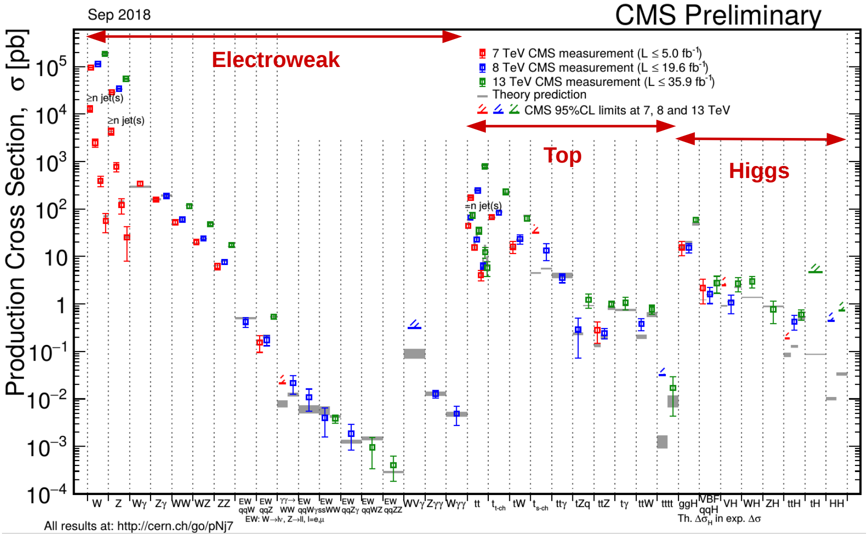


http://cms-results.web.cern.ch/cms-results/public-results/publications/CMS/

- More than **850** publications on pp (and pPb and PbPb) physics since Jan, 2010 ($\sim$ **105/year** on average).
- No sign of slowing down: $>$ **140** papers in last year!
- Many more publications during LS2 with full Run 2 dataset.
- Impossible to report on every single results. Will present the **most recent/relevant**.
- 2018, a year full of discoveries, it was the **"Yukawa year"**

Standard Model Physics

SM Results: Cross Section Measurements Summary

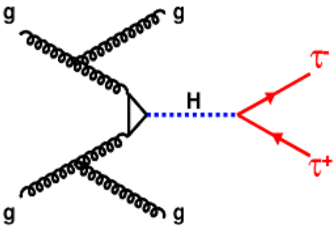


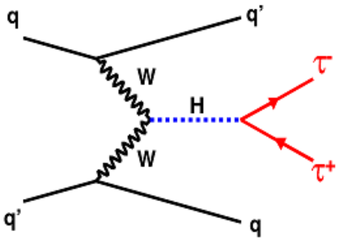
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

Higgs Physics

Higgs Physics: Observation of $H \to \tau^+\tau^-$

Phys. Lett. B **779**, 283 (2018)





- $\gamma\gamma$, ZZ, WW final states had been observed already.
- For fermions, most promising channel at branching fraction $\mathcal{B}_{\tau\tau} = \mathbf{6.3\,\%}$ for Higgs mass of $125.09\ \mathrm{GeV}$.
- Smaller backgrounds compared to $b\bar{b}$ decay.
- **First direct observation** by a single experiment. Previously observed in an ATLAS/CMS combination.
- Covers gluon fusion and vector boson fusion mechanisms in three categories (**VBF, boosted H, 0-jet**).

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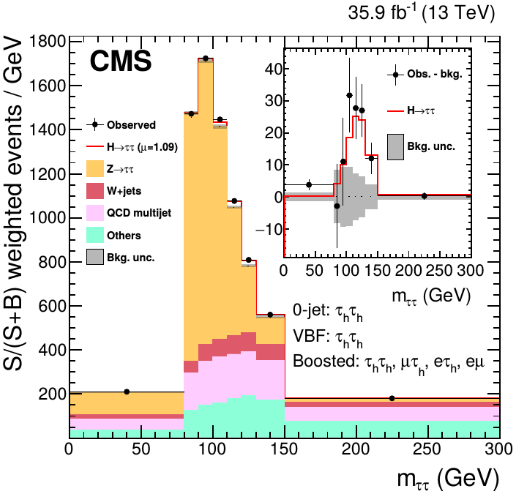

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- 94 % of all possible $\tau\tau$ final states: $\tau_H\tau_H$, $e\tau_H$, $\mu\tau_H$, $e\mu$.
- Uses **35.9** fb^{-1} of **2016** data.
- Extracts signal strength (μ) in one- or two-dimensional likelihood fits of data. One dimension always $\mathbf{m}_{\tau\tau}$ (SVFit reco).
- Observed (expected) significance is 4.9σ (4.5σ).
- Combination with previous analysis with 7 and 8 TeV gives $\mathbf{5.9}\sigma$.

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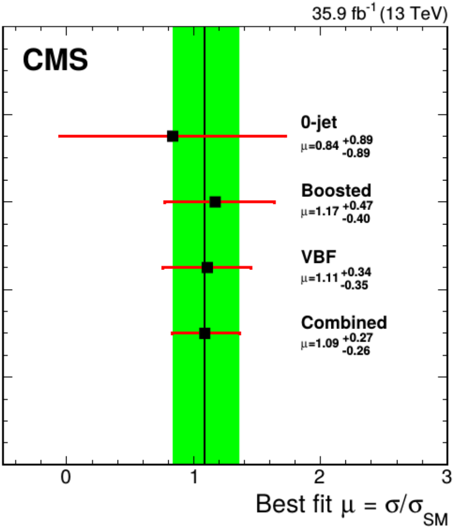

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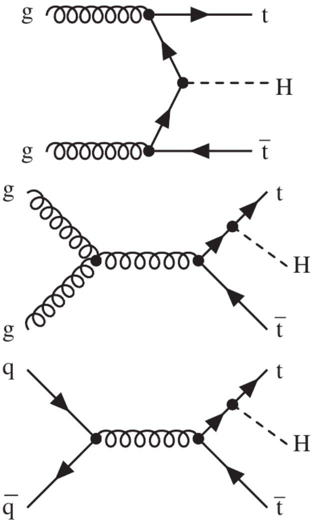
- Production rate **agrees with SM.**

Higgs Physics: Observation of $t\bar{t}H$ production

Phys. Rev. Lett. **120**, no. 23, 231801 (2018)



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- Also, good test for evidence of new physics.
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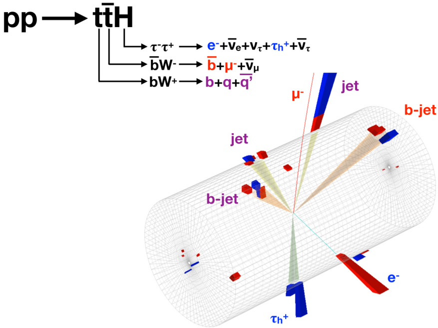

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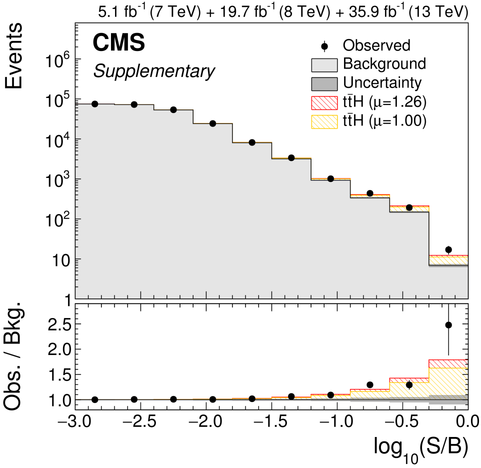

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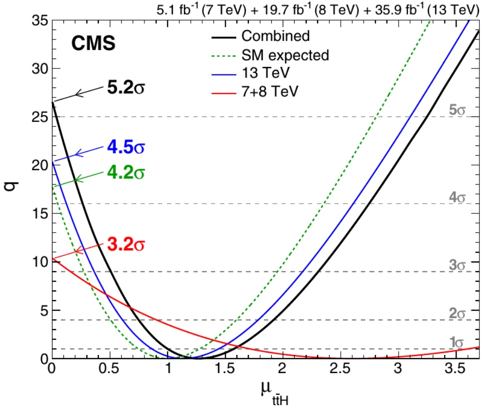

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- Test statistic **q**: negative of twice the logarithm of profile likelihood ratio.
- Signal strength modifier, $\mu_{\mathbf{t\bar{t}H}}$: ratio between $t\bar{t}$ production and its SM expectation.
- Excess over expectation from background-only hypothesis ($\mu_{\mathbf{t\bar{t}H}} = \mathbf{0}$) observed with significance of $\mathbf{5.2}\sigma$. Expected for $m_H = 125.09$ GeV is 4.2σ.

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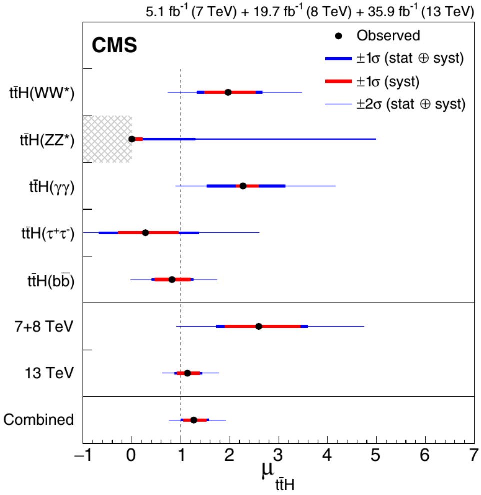

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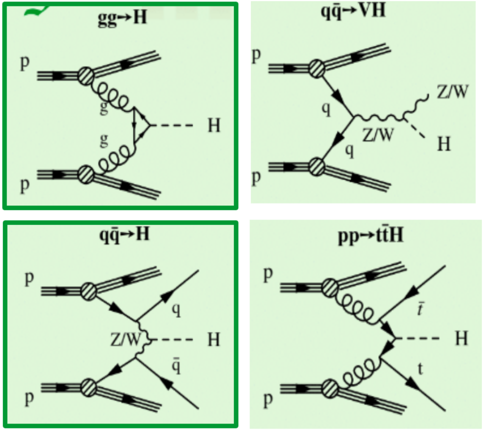
- Production **rate consistent with SM.**

Higgs Physics: Search for $H \to \mu^+\mu^-$ production

Accepted by Phys.Rev.Lett.; arXiv:1807.06325 [hep-ex].



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- Uses **35.9** fb^{-1} of 2016 data.
- Signal **mostly VBF** and **ggH** production over Drell-Yan background.
- **Categorization** based on signal vs. background discrimination (through boosted decision tree) and mass resolution.

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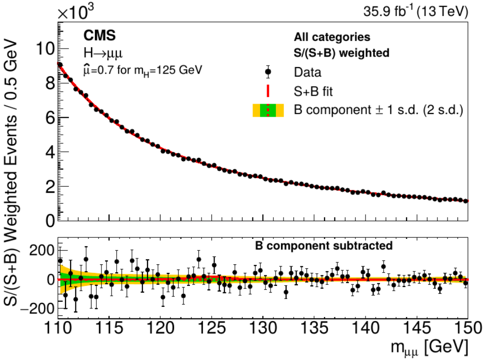

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- **Categorization** based on signal vs. background discrimination (through boosted decision tree) and mass resolution.
- Maximum likelihood S+B fit to $\mathbf{m}_{\mu\mu}$ sprectrum across all categories to measure signal strength $\mu = (\sigma\mathcal{B})_{\text{OBS}}/(\sigma\mathcal{B})_{\text{SM}}$
- Best fit signal strength for $m_H = 125\ \text{GeV}$ hypothesis ($\mu_{\hat{125}}$) extracted with profile likelihood ratio.

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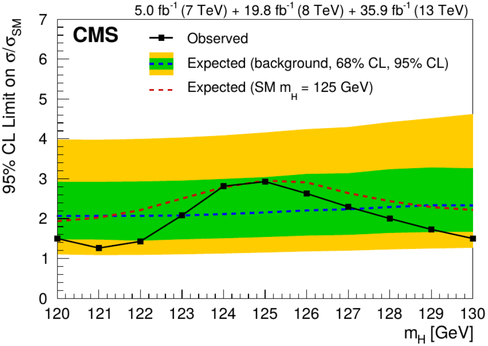

- Largest (only?) LHC window to explore **Higgs couplings to second generation** fermions.
- Uses **35.9** fb^{-1} of 2016 data.
- Signal **mostly VBF** and **ggH** production over Drell-Yan background.
- **Categorization** based on signal vs. background discrimination (through boosted decision tree) and mass resolution.
- Maximum likelihood S+B fit to $\mathbf{m}_{\mu\mu}$ sprectrum across all categories to measure signal strength $\mu = (\sigma\mathcal{B})_{\mathrm{OBS}}/(\sigma\mathcal{B})_{\mathrm{SM}}$
- Best fit signal strength for $m_H = 125\ \mathrm{GeV}$ hypothesis ($\hat{\mu_{125}}$) extracted with profile likelihood ratio.
- CL_s method used to extract 95 % CL upper limit on μ.
- Data compatible with predicted background.
- **95 % CL observed** (expected) upper limit on production $\sigma \times \mathcal{B}$ is **2.95** (2.45) $\times$ the SM expectation.
- In **combination** with **7** and **8** TeV data, the observed (expected) upper limit is **2.92** (2.16) $\times$ the SM.
- Corresponds to upper limit of $\mathbf{6.4 \times 10^{-4}}$ for $\mathcal{B}_{\mathbf{H}\to\mu\mu}$ (SM's is 2.17×10^{-4})

Higgs Physics: Observation of $H \to b\bar{b}$ production

Phys. Rev. Lett. **121**, no. 12, 121801 (2018)

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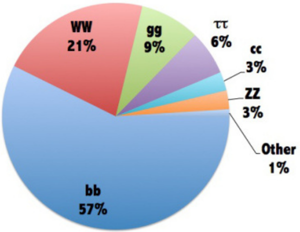
- Decays to $b\bar{b}$ most copious but **very challenging experimentally** due to also abundant background.



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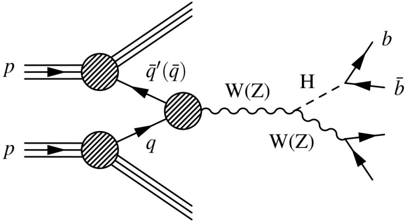

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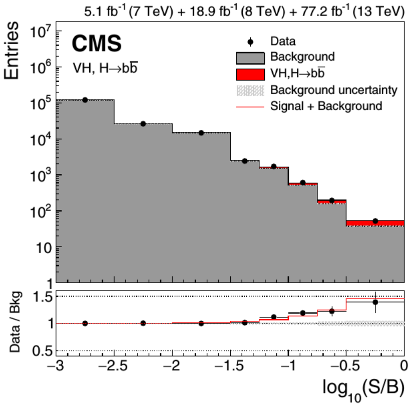

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- When combined with previous VH results with 7, 8 and 13 TeV data, excess of events with significance of **4.8**σ over expectation from background-only hypothesis.
- Corresponding expected significance for H with mass 125.09 GeV is **4.9**σ
- **Combination** of all CMS results also performed (VH, gluon fusion, VBF, ttH). **Observed** (expected) signal **significance** is **5.6**σ (5.5σ)

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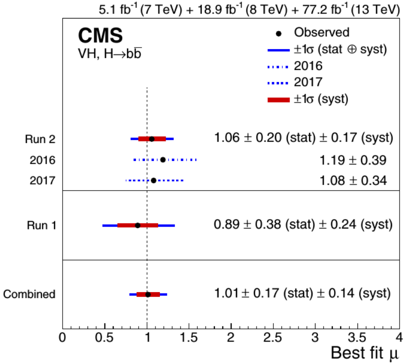

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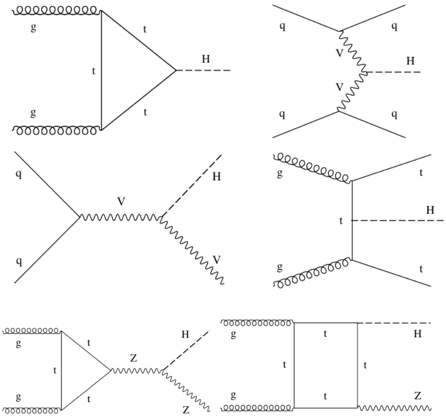
- **Combination** of all CMS results also performed (VH, gluon fusion, VBF, ttH). **Observed** (expected) signal **significance** is **5.6**σ (5.5σ)
- Measured production rate compatible with SM Higgs boson. Precision leaves room for new physics contribution.

Higgs Physics: Higgs Combined Measurements

Submitted to Eur.Phys.J.; arXiv:1809.10733 [hep-ex]



- Five main Higgs boson **production mechanisms** are considered.

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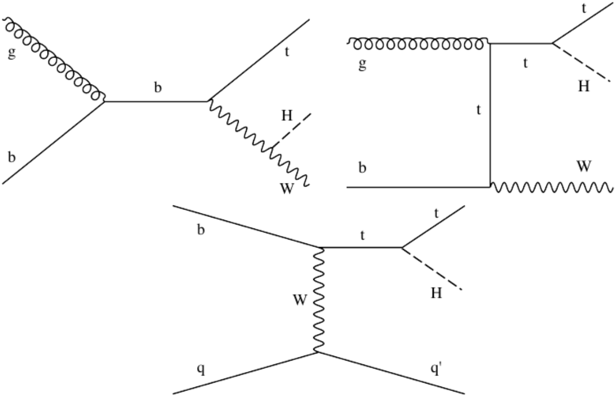

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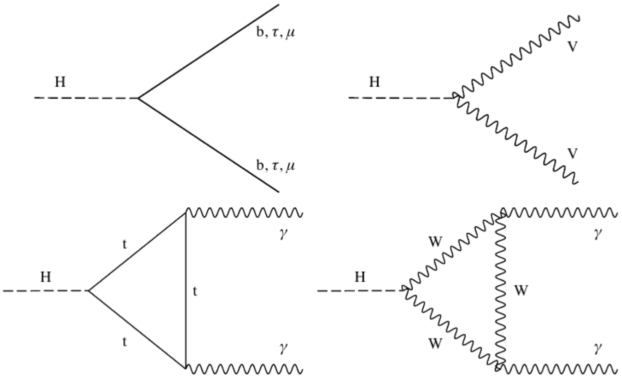

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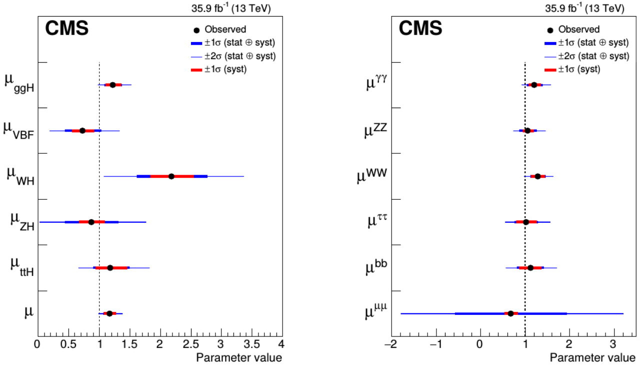

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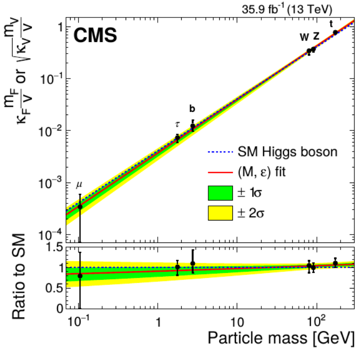

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- The **accesible decays** are the ones presented in these slides plus boson decays.
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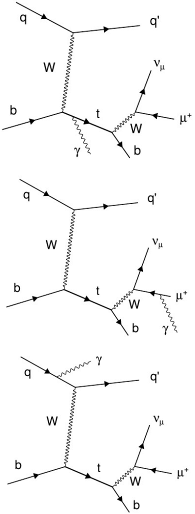
- Also a **"Yukawa" couplings** (reduced vector boson coupling) summary plot is presented.

Top Quark Physics

Top Physics: Evidence for production of $t + \gamma$

Accepted by Phys. Rev. Lett; arXiv:1808.02913 [hep-ex]



- First evidence of **t**γ production.
- Important test of SM and probe for physics BSM.
- Cross section sensitive to top quark charge, its electric and magnetic dipole moments.
- SM mechanisms: $t - channel$, $s - channel$, and tW production contributions.
- This anlysis concentrates on **tchannel** production.
- Focus on **muon decay channel** (good signal selection efficiency and low background). Includes contributions from $W \to \tau\nu_\tau$.
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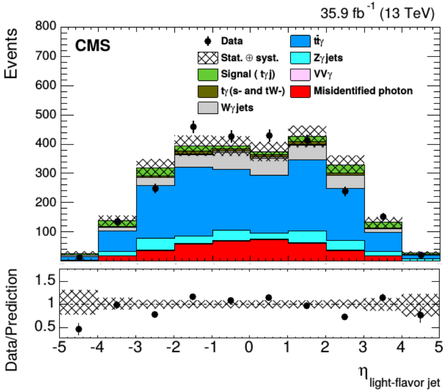

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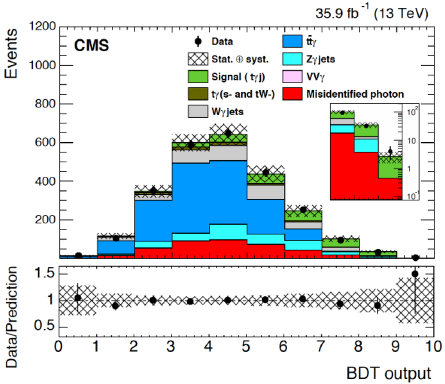

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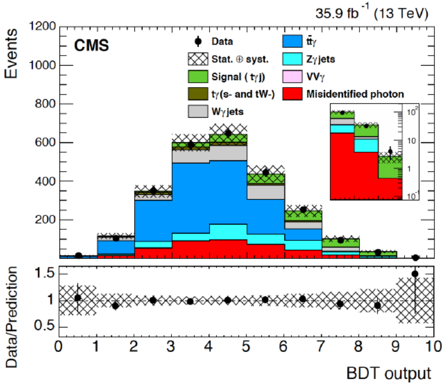

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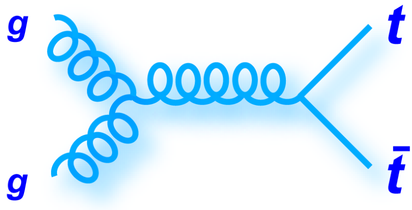
- **Excess** above the backgrund-only hypothesis observed, with significance of **4.4**σ.

- $\sigma(\mathbf{pp} \to \mathbf{t}\gamma\mathbf{j})\mathcal{B}(\mathbf{t} \to \mu\nu\mathbf{b}) = \mathbf{115} \pm \mathbf{17}(\mathrm{stat}) \pm \mathbf{30}(\mathrm{syst})\ \mathrm{fb}$ which is consistent with SM.
  - in the **fiducial phase space of the photon**, $p_{\mathrm{T},\gamma} > 25\ \mathrm{GeV}$, $|\eta_\gamma| < 1.44$, and $\Delta R(X,\gamma) > 0.5$; X stands for μ, b-jet, light-flavor jet.

Top Physics: $t\bar{t}$ differential cross section in dileptons

Submitted to J. High Energy Phys.; arXiv:1811.06625 [hep-ex]



- **Why to measure $d\sigma_{tt}/dX$**:
  - QCD process with significant higher-order corrections: probe higher-order, QCD, EW corrections
  - $t\bar{t}$ mostly produced by gluon fusion: constrain gluon PDF, extract α_S, m_{top}
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  - BSM could produce modification to $t\bar{t}$ differential cross sections (virtual BSM particles could modify rates and kinematics).
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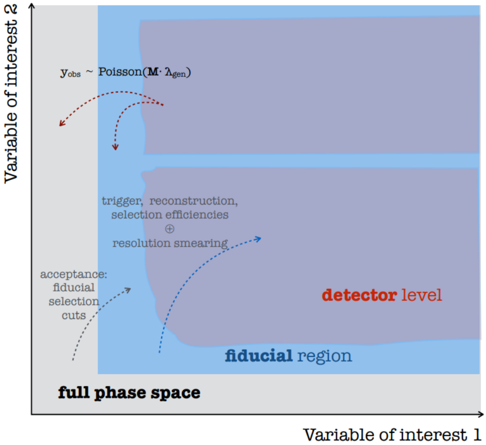

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- **Absolute** and **normalized** distributions.
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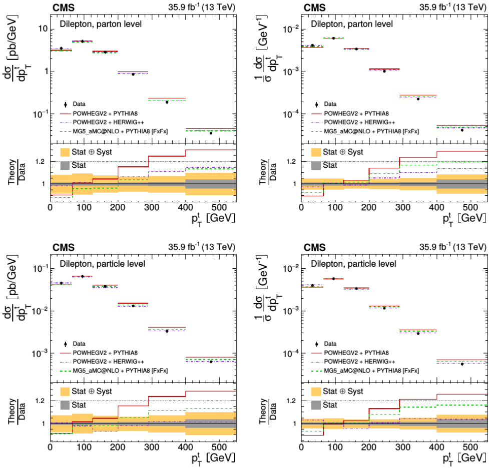

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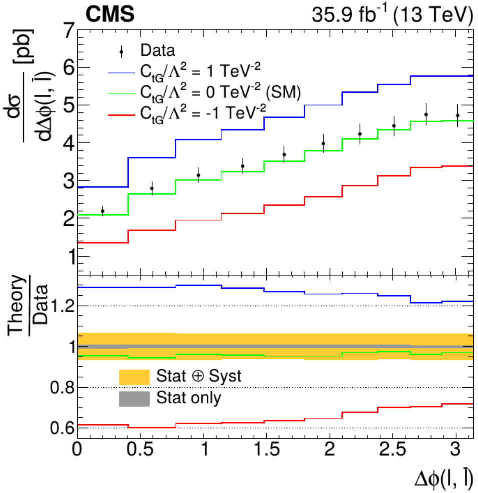

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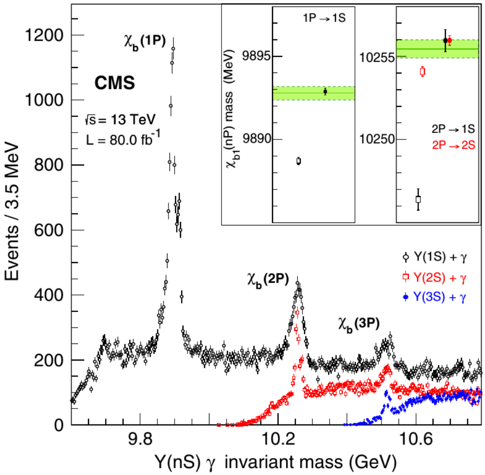
B Physics

B Physics: Observation of $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$

Phys. Rev. Lett. **121**, 092002 (2018)



- $\chi_b(3P)$ system **discovered** by ATLAS and confirmed by D0 and LHCb.
- Explore structure to understand nature: possible X_b analog of X(3872)?, mixture of $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$? Effects of nearby open-beauty threshold? arXiv:1410.7729 [hep-ph]
- **80** fb^{-1} of 13 TeV data were used.
- Reconstruct mass structure

  $\chi_b(3P) \to (\Upsilon(3S) \to \mu\mu) + \gamma$.

  - where γ converts (e^+e^-) in the tracker.
- $\Delta M(\chi_{b1}, \chi_{b2})$ expected to be $8 - 18$ MeV
- CMS $\chi_b(3P)$ **mass resolution** of **2.2** MeV

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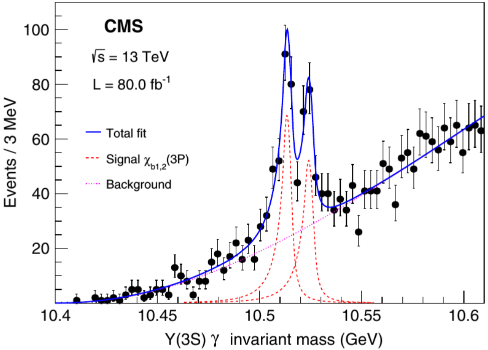

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- **First time $J = 1$ and 2 are well observed**

  and masses individually measured.
  - $J = 1$: $10513.42 \pm 0.41(\mathrm{stat}) \pm 0.18(\mathrm{syst})$ MeV
  - $J = 2$: $10524.02 \pm 0.57(\mathrm{stat}) \pm 0.18(\mathrm{syst})$ MeV
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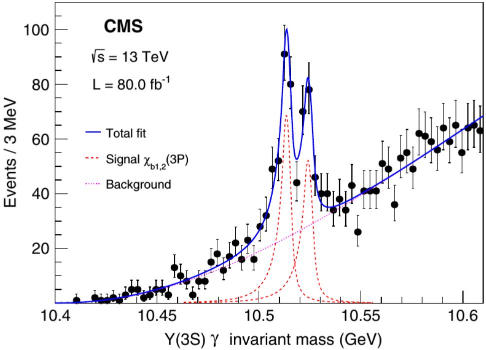

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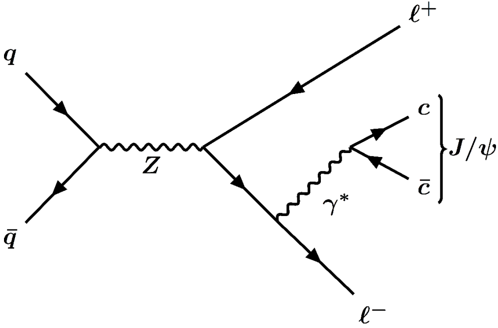
- More recently, observation of the $B^*_{s2}(5840)^0 \to B^0 K^0_S$ in pp collisions at 8 TeV has been reported by CMS.
  Eur. Phys. J. C 78 (2018) 939

B Physics: Observation of the $Z \to \Psi\ell^+\ell^-$ decay

Phys. Rev. Lett. **121**, no. 14, 141801 (2018)



- **Rare decay** of the Z boson.
- First observed Z boson decay to a vector meson and $\ell^+\ell^-$
  - High rate of Z production at the LHC helps.
  - Ψ represents contributions from direct J/Ψ and $\Psi(2S) \to J/\Psi X$, with $J/\Psi \to \mu\mu^-$.
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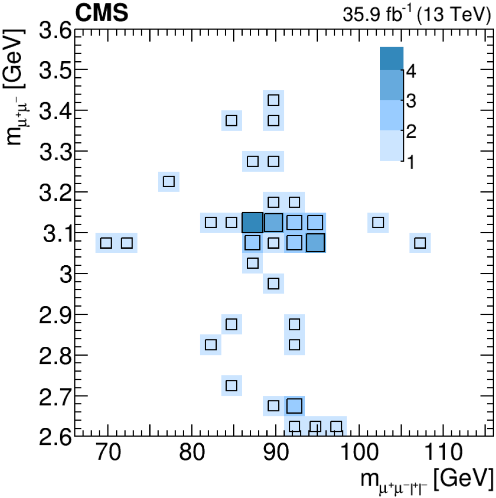

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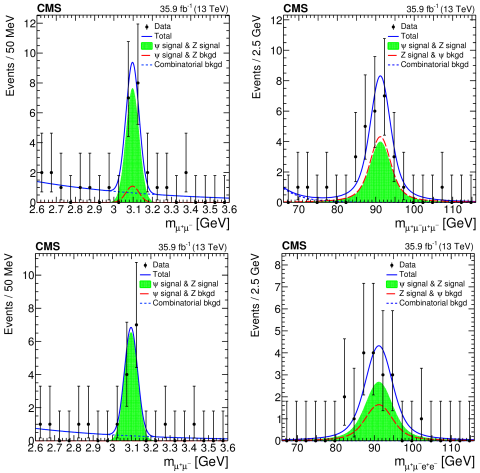

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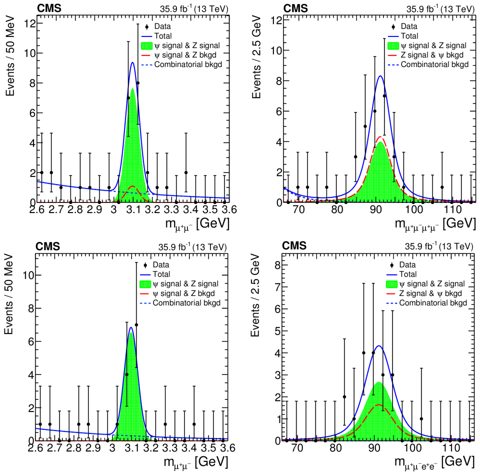
B Physics: Observation of the $Z \to \Psi \ell^+ \ell^-$ decay

Phys. Rev. Lett. **121**, no. 14, 141801 (2018)



- **Rare decay** of the Z boson.
- First observed Z boson decay to a vector meson and $\ell^+\ell^-$
  - High rate of Z production at the LHC helps.
  - Ψ represents contributions from direct J/Ψ and $\Psi(2S) \to J/\Psi X$, with $J/\Psi \to \mu\mu^-$.
  - $\ell^+\ell^-$ is a pair of electrons or muons.
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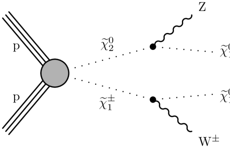
- More recently, CMS has reported a search for rare decays of Z and H to J/Ψ.
  Submitted to Eur. Phys. J. C; arXiv:1810.10056 [hep-ex]

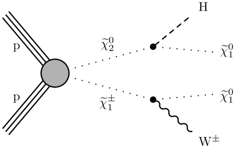
Beyond the Standard Model Physics

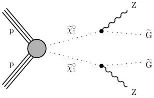
SUSY: Combination of searches for “EWKinos”

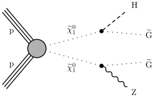
JHEP **1803**, 160 (2018)

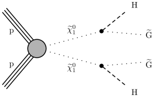
- Electroweak production of charginos and neutralinos with **35.9** fb^{-1} of 2016 data.
- Simplified SUSY models used to interpret combined search results.
- Assume **sleptons much heavier** than EWkinos.











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JHEP **1803**, 160 (2018)

Search	WZ	WH	ZZ	ZH	HH
	Signal topology				
1ℓ 2b		✓			
4b					✓
2ℓ on-Z	✓		✓	✓	
2ℓ soft	✓				
$\geq 3\ell$	✓	✓	✓	✓	✓
H($\gamma\gamma$)		✓		✓	✓

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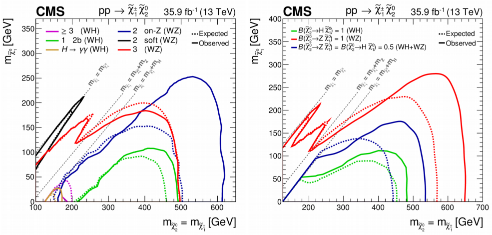

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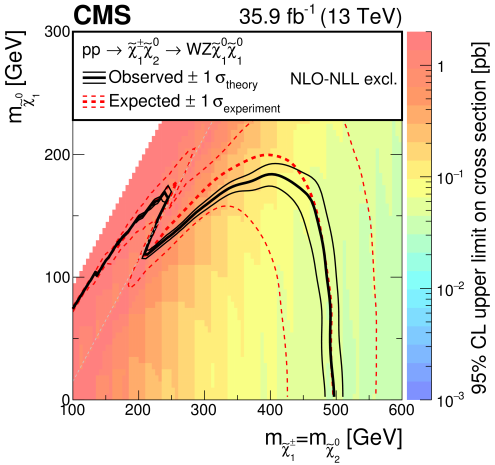

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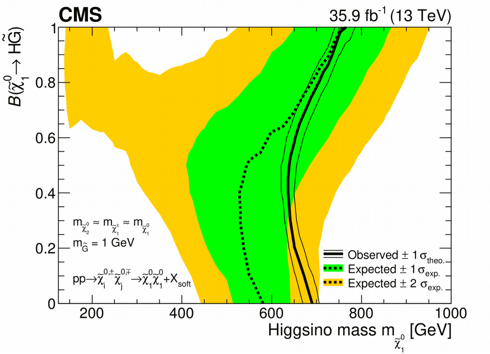

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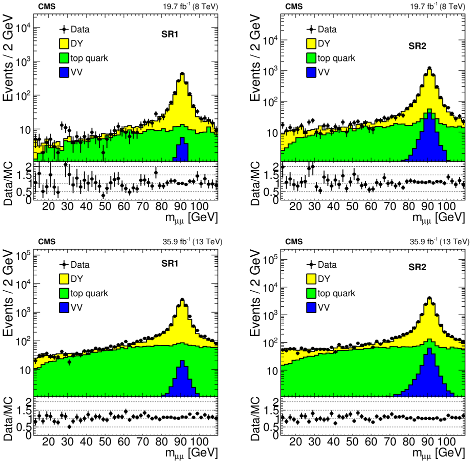
- In the GMSB neutralino pair model limits are also imposed.

Search for Resonances: Low mass in dileptons with *b* jets.

Accepted in J. High Energy Phys.; arXiv:1808.01890 [hep-ex]



- Search for resonances $(\mu^+\mu^-)$ in mass range **12** $-$ **70** GeV in association with a *b* jet and a second jet.
- **8** and **13** TeV datasets with **19.7** and **35.9** fb^{-1}, respectively.
- Two exclusive **categories**:
  - SR1: b-jet in $|\eta| \leq 2.4$ (central) and one jet in $|\eta| \geq 2.4$ (forward).
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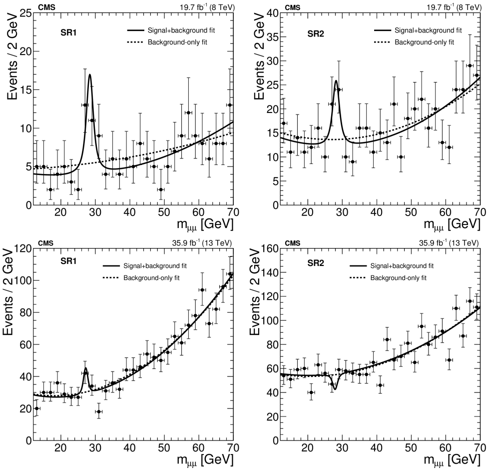

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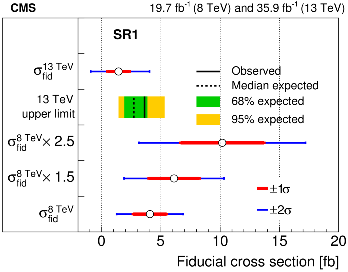

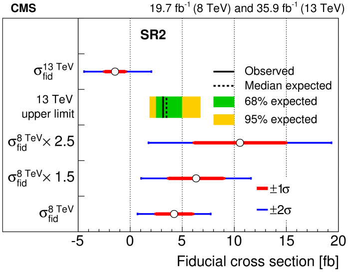

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- Limits on the cross section for a resonance consistent with the 8 TeV are provided.

Search for Leptoquarks: $LQ3 \rightarrow \ell\tau_h b, \tau_h\tau_h b$

JHEP **1807**, 115 (2018)

- Search for singly produced **third-generation sclar leptoquark** (LQ3) decaying to τ and b quark. Associated production of LQ and a τ considered.
- LQs are hypothetical color-triplet bosons, carrying baryon and lepton number.
- Predicted by many extensions of SM
  - grand unification theories, technicolor, compositeness.
  - assumed **3 types of LQs** , which couple to the corresponding generation family.

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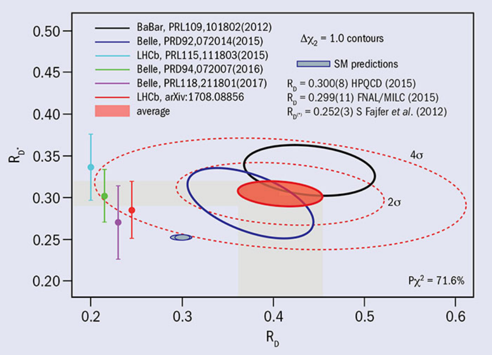
JHEP **1807**, 115 (2018)



$$R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)}\ell^+\nu_\ell)}, \text{ with } \ell = e \text{ or } \mu$$

https://cerncourier.com/beauty-quarks-test-lepton-universality/

Nature **546**, 227 (2017); arXiv:1703.01766 [hep-ex]

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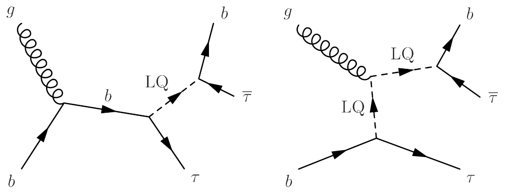
JHEP **1807**, 115 (2018)



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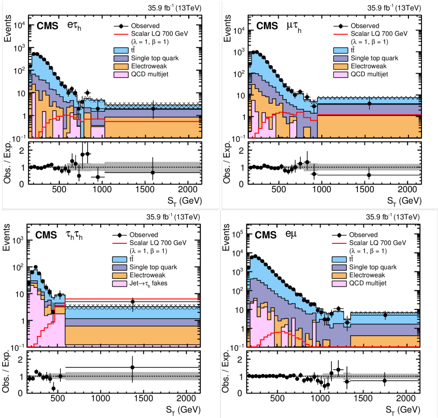

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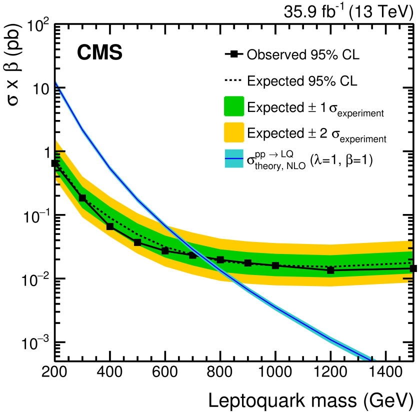

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- Limits on cross section for LQ3 as a function of their mass.
- Assuming unit Yukawa coupling (λ), excluded for masses below **740** GeV
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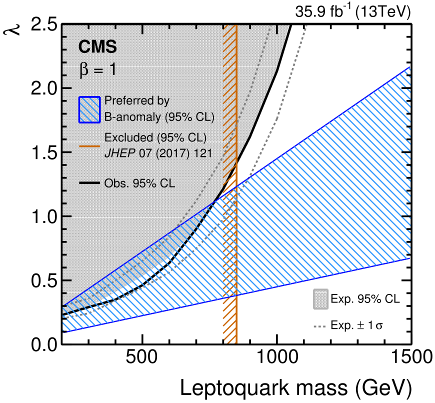

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Search for Dark Matter: in association with $H \to b\bar{b}$

Submitted to Eur. Phys. J. C; arXiv:1811.06562 [hep-ex]

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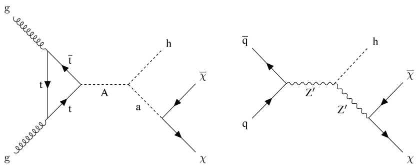

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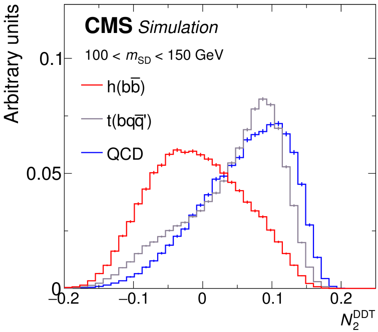

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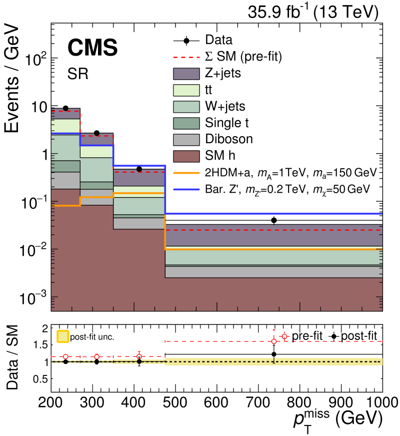

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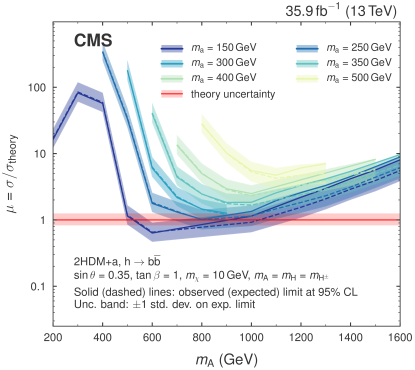

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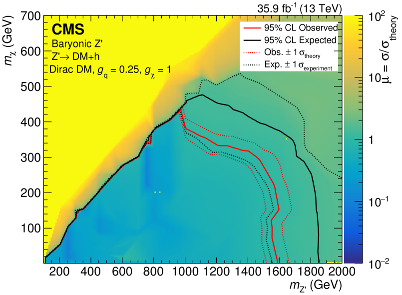

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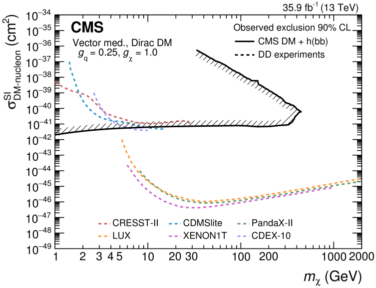
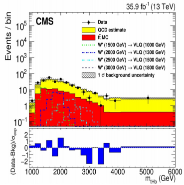
Submitted to Eur. Phys. J. C; arXiv:1811.06562 [hep-ex]



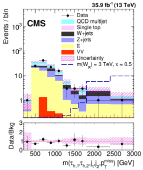
- "Today's signal is tomorrow's background" (or handle).
- The 2HDM+a tested experimentally for the first time.
  - Type-2 two-Higgs doublet model extended by an additional light pseudoscalar boson a
  - a mixes with scalar and pseudoscalar partners of observed Higgs boson and decays to a pair of DM particles $\chi\bar{\chi}$
  - ensures gauge invariance and renormalizability
- Baryonic Z' model:
  - "baryonic Higgs" mixes with SM Higgs boson
  - Z' exchanged in the s-clannel, radiates a SM Higgs and decays to DM particles
- **35.9** fb^{-1} of 2016 data.
- Signal with large missing transverse momentum ($\mathbf{p}_\mathrm{T}^\mathrm{miss}$) recoiling against a $b\bar{b}$ system with large Lorentz boost.
- Ability to identify two b quarks inside a single jet crucial (**double b-tagger**)
- Events consistent with SM background.
- Limits interpreted in terms of parameters of the 2HDM+a model and of the baryonic Z' simplified model.

Many more CMS results left out from this talk....

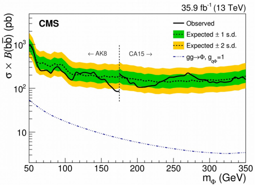
- Many other very interesting CMS results left out
- We are trying to leave no stone unturned ...



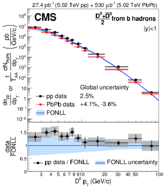
W', vector-like quarks



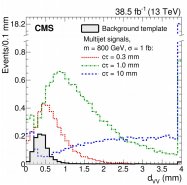
Heavy neutrinos



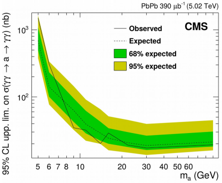
Low mass resonances



HI: beauty suppression



Long-lived particles



Light-by-light scattering and axion-like particles search

. . .

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

To-do List After Run 2

- ☑ Is there a Higgs or Higgs-like particle?
- ☑ Does the Higgs really couple to quarks?
- ☐ Does the Higgs couple to all quark families?
- ☑ Does the Higgs really couple to leptons?
- ☐ Does the Higgs really couple to all leptons?
- ? Are the fermion couplings proportional to fermion masses?
- ☐ Is it the mass giver to all fermions?
- ☐ Are there more Higgs-like particles (charged or neutral)?
- ☐ Is the Higgs boson the sole responsible for EW symmetry breaking?

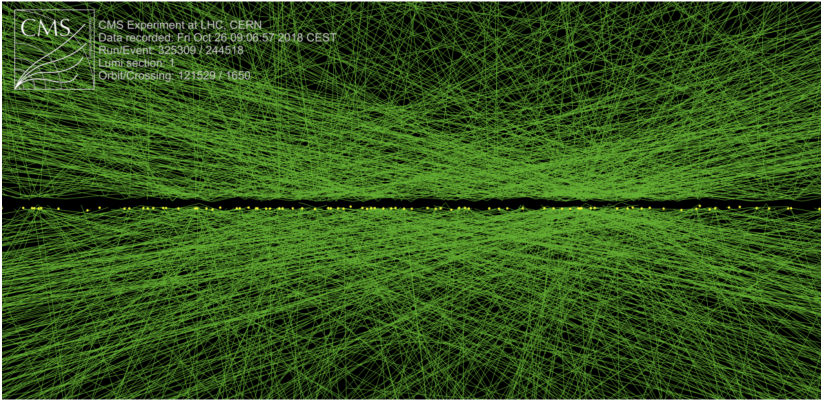
⋮

- ☐ What is dark matter, and can we produce it at colliders?
- ☐ Are there extra dimensions, can we probe this at the LHC?
- ☐ Why is the Universe made of matter only and not antimatter?
- ☐ Why is gravity so feeble?
- ☐ Why is there a scale of fermion masses?
- ☐ What is dark energy, can we test it in the lab?

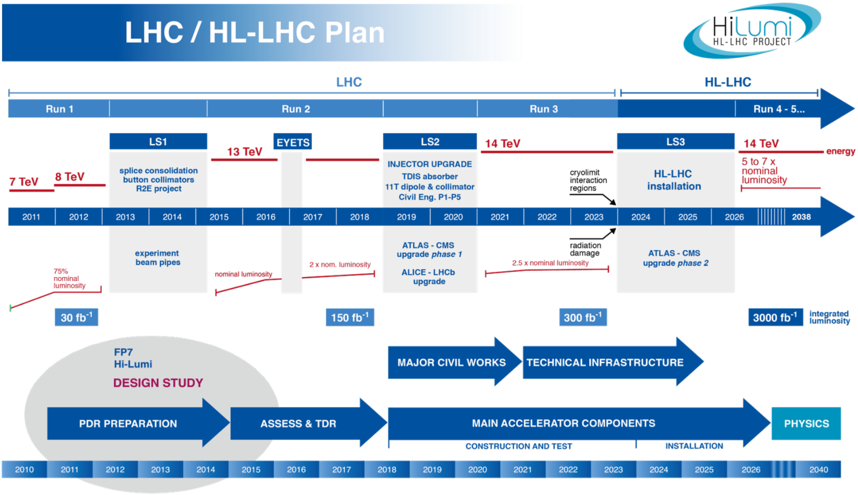
⋮

Challenges for the future

- Figure below: 136 pile up events in CMS on **26 October 2018**.
- PU 140-200 expected on average at the High Luminosity LHC.
- Much higher raditation dose.
- We know some subsystems will not survive harsher radiation environment or not function efficiently with increased data rates.
- Need updates to fully exploit physics potential of HL-LHC.



HL-LHC Schedule



CMS Upgrades for Phase 2

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
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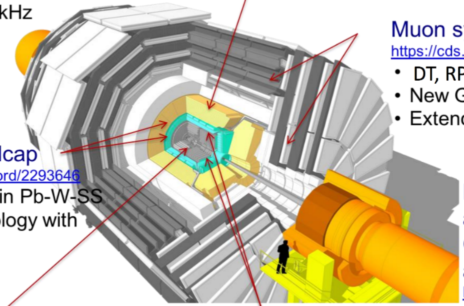
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT, RPC, CSC new electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

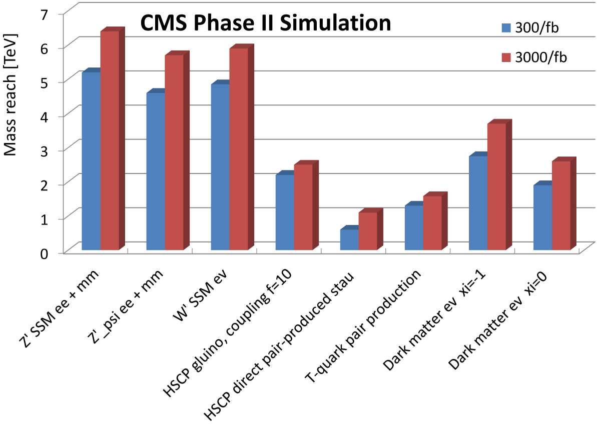
Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612
- $\simeq$ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Prospects for HL-LHC (just a couple of examples)

CMS-PAS-EXO-14-007; https://cds.cern.ch/record/2206863

- Even in absence of discoveries at the end of Run 3 (300 fb^{-1}), still some room for improvement in the mass reach for exotic particle discovery at 3000 fb^{-1}.



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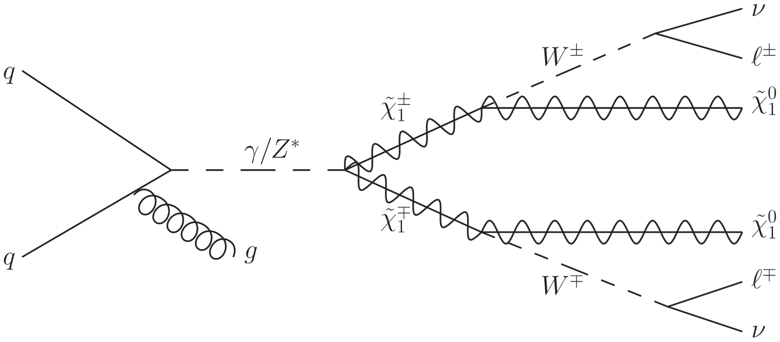

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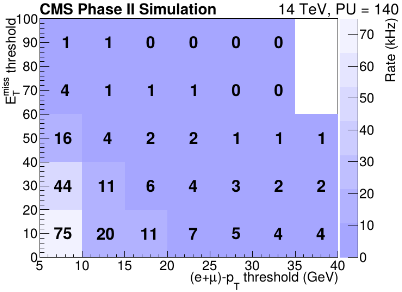
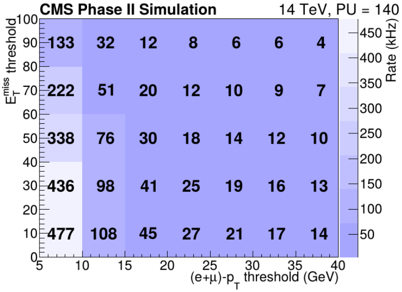
- There are some signals which can only be triggered with the new Phase II "track-trigger" (e.g., quasi-degenerate Higgsinos, with small mass splitting)
- Trigger rates for $\ell + j + E_T^{miss}$ with (left) and without (right) track-trigger: shows the impact it could have in signal efficiency.





Summary and Conclusions

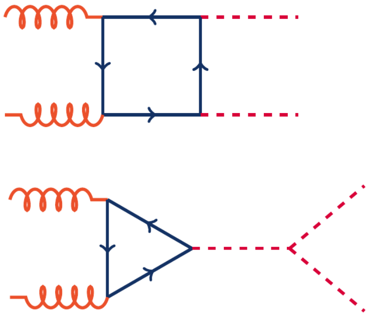
- Impressive number of CMS results in Run 2.
  - Very few presented today.
- 2018, a year full of discoveries! The Yukawa year.
- Up until now, Higgs very consistent with SM
- No signs of new physics yet
  - A number of 3σ discrepancies to follow up ...
- Still a lot of data to be analyzed.
  - First results with 2017 data are starting to be released
- LS2, Run 3, and the end of Phase I, ahead of us.
- HL-LHC improvements will allow the continuity of Terascale exploration.
  - Will keep us busy for the next, perhaps, ~ 20 years.

Backup slides

Higgs Physics: Nonresonant Higgs boson pair production

Submitted to: JHEP; arXiv:1810.11854 [hep-ex]

- Search for nonresonant production of **Higgs boson pairs**. Rare ocurrance!
- Most direct way to access **Higgs boson self coupling**
- Final state **$b\bar{b}b\bar{b}$**
- **35.9** fb^{-1} of 2016 data used.



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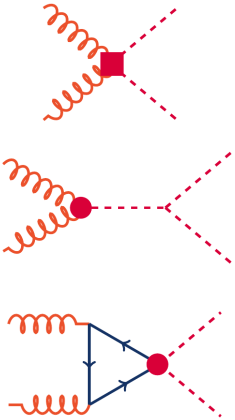

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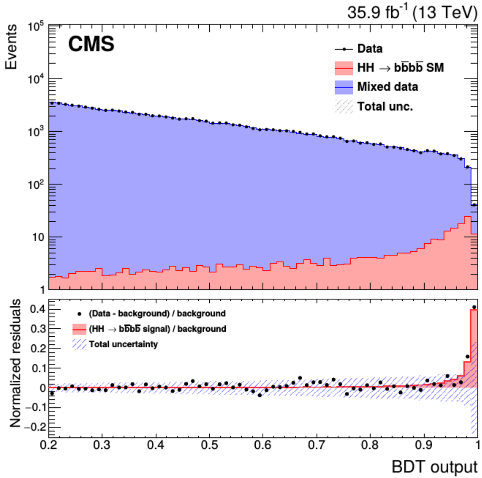

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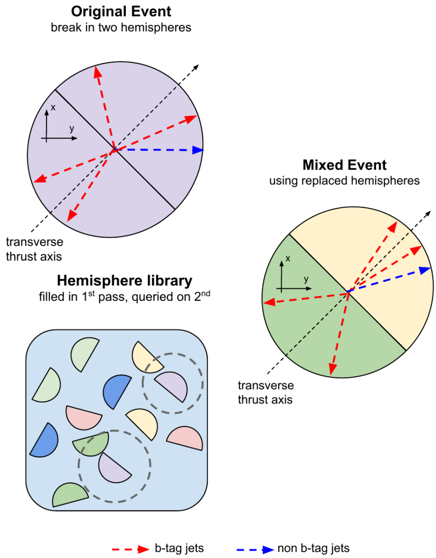

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- No signal is observed. **95 % CL upper limit** of **847** fb^{-1} on SM model cross section $\times$ squared branching fraction ($\sim$ 75 times the SM (37 expected)).

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Benchmark point	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0	0.0	0.0
Box	0.0	1.0	0.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

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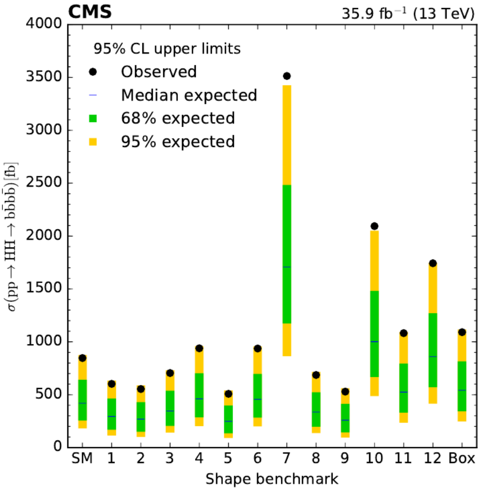

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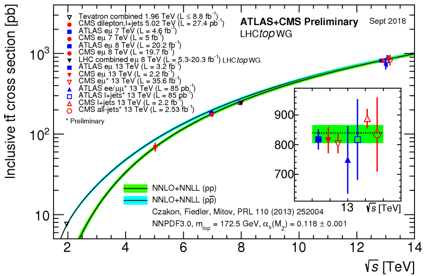
Top Physics: Summary of Top Physics results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures



- huge number of top results.
- e.g., $t\bar{t}$ production cross section:
  - at LHC dominated by gluon fusion (90 %).
  - 15/s produced.
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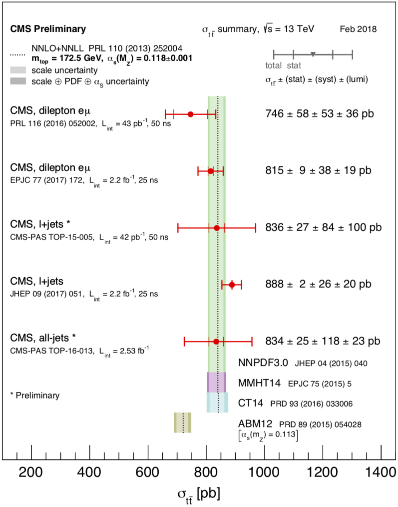

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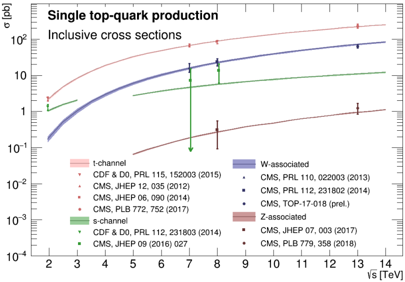

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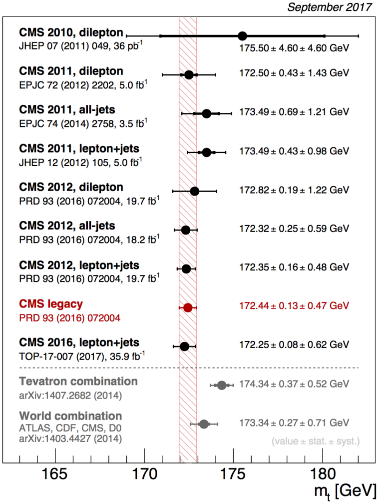

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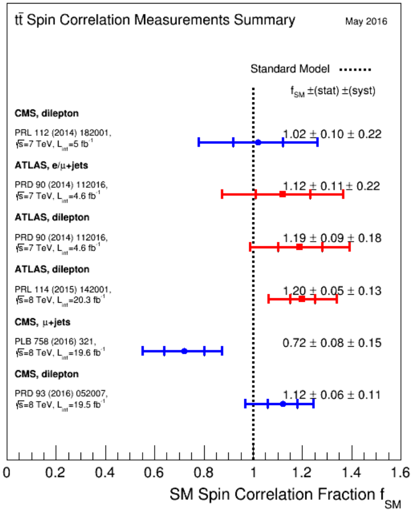

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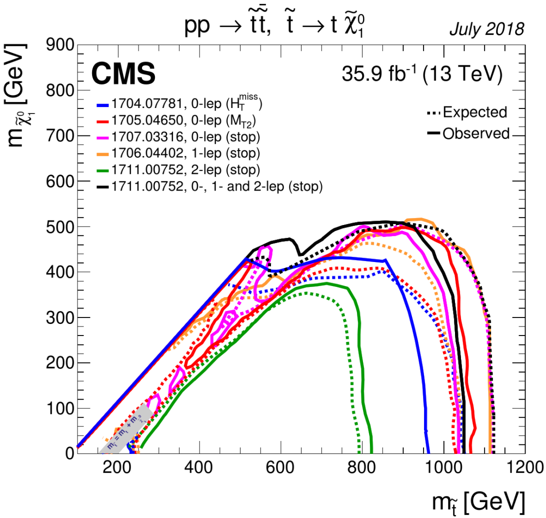
- spin correlations
- ...

SUSY: Run 2 Summary https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

- Huge number of results. Here some summary examples:



Mass limits for simplified model of top squark (partner of the top quark) pair production with decays to on- and off-shell top quark and the LSP.

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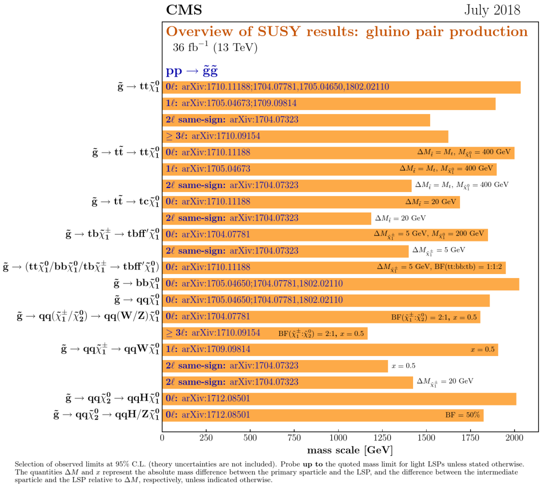
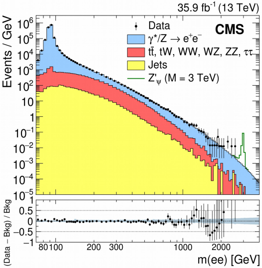
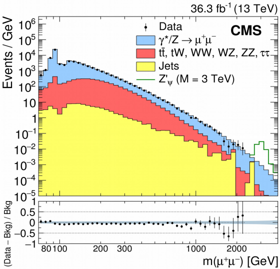


Mass reach for simplified models of gluino pair production.

Search for Resonances: High mass in dileptons

JHEP **1806**, 120 (2018)





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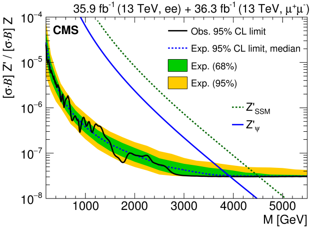

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1. **GUTs** predict existance of new heavy neutral gauge boson.

- **spin-1** resonances (widths are scanned [not shown])
- Generalized sequential model (GSM) : $\mathbf{Z'_{SSM}}$ boson that has SM-like couplings to fermions.
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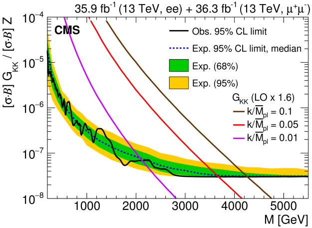

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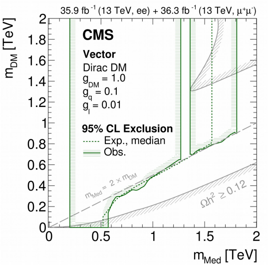
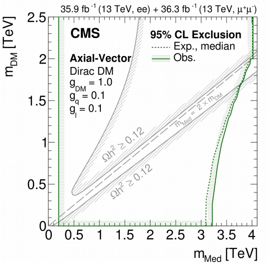
2. Theories with **extra spatial dimensions** justify graviton excitations observable as high-mass resonances.

- **spin-2** resonances
- Kaluza-Klein graviton ($\mathbf{G_{KK}}$) excitations in the Randall-Sundrum (RS) model.
- Two free parameters: mass of first graviton excitation and the coupling $\mathbf{k/\bar{M}_{Pl}}$; k being the warp factor and $\bar{M}_{Pl}$ the reduced Plack mass.

Search for Resonances: High mass in dileptons

JHEP **1806**, 120 (2018)





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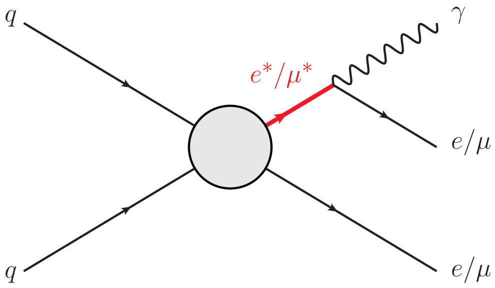
   - E_6: $\mathbf{Z'_{\psi}}$ boson.
2. Theories with **extra spatial dimensions** justify graviton excitations observable as high-mass resonances.
   - **spin-2** resonances
   - Kaluza-Klein graviton ($\mathbf{G_{KK}}$) excitations in the Randall-Sundrum (RS) model.
   - Two free parameters: mass of first graviton excitation and the coupling $\mathbf{k/\bar{M}_{Pl}}$; k being the warp factor and $\bar{M}_{Pl}$ the reduced Plack mass.
3. Also predicted by **dark matter models** (DM) as a weakly coupled, heavy mediator between DM (assumed a Dirac fermion) and SM particles.
   - additional **spin-1** high-mass mediator (**vector or axial-vector** boson)
   - five free parameters: the DM mass $\mathbf{m_{MD}}$, the mediator mass $\mathbf{m_{Med}}$, coupling $\mathbf{g_{DM}}$ between mediator and *DM*, and universal couplings $\mathbf{g_\ell}$ and $\mathbf{g_q}$ between mediator and SM charged leptons and quarks.
   - Solid grey lines, marked as $\Omega h^2 \leq 0.12$, correspond to parameter regions that reproduce the observed DM relic density in the universe, with the hatched area indicating the region where the DM relic abundance exceeds the observed value.

Excited leptons: Search in $\ell\ell\gamma$ final states

Submitted to J. High Energy Phys.; arXiv:1811.03052 [hep-ex]



- Compositeness models suggest that quarks and leptons are made of fundamental constituents bound by a new strong interaction (with energy scale **Λ**)
  - Prediction: existence of excited states of quarks and leptons.
  - could be produced via contact interactions
  - decay through SM gauge interactions, or via CI to SM fermions.
- Search for **excited electrons and muons** ($\ell^* = e^*, \mu^*$) in $\ell\ell\gamma$ final states ($\ell = e, \mu$).
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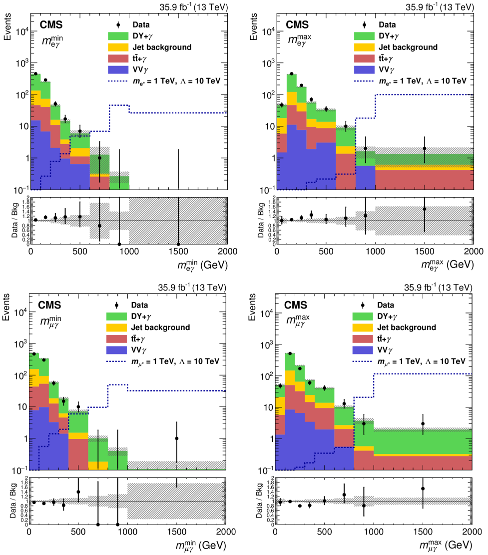

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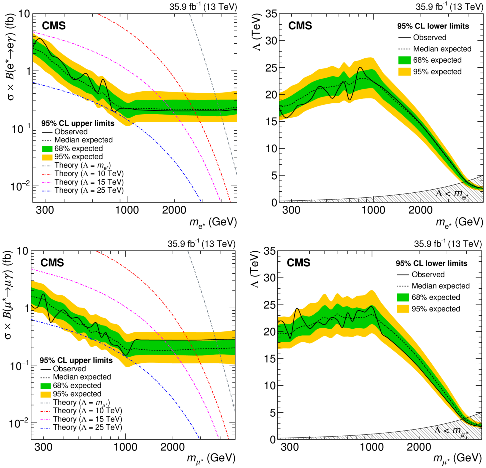

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- Observations consistent with SM.
- Most stringent limits to date set on the excited lepton mass and compositeness scale.
- Excited electrons and muons **excluded** for masses below **3.9** TeV and **3.8** TeV, respectively.
- Best limit for compositeness scale set at **25** TeV