Exotica searches at CMS (a few selected results)

Laurent Thomas,
on behalf of the CMS collaboration

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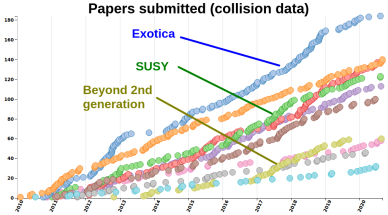
Introduction

- Looking for physics beyond the Standard Model: a major component in the LHC physics program.
  → Hoping to shed light on some of the big questions in the field (dark matter, hierarchy problem, grand unification, extra generations, ...).
- Many searches conducted at CMS since the LHC startup in 2010.
  → Probing a large range of experimental signatures (leptons, jets, missing energy, ...)
  → and a large range of theoretical models (extra dimensions, additional gauge bosons, leptoquarks, ...), in a large phase space range.
- Will review a few recent results illustrating the broadness of this program.
  → Impossible to give justice to all these searches in this talk.
  → Will not touch dark matter, supersymmetry and lepton resonances which have their dedicated talks.



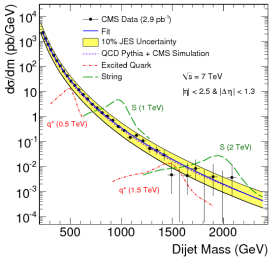
The many ways to search for resonance using jets

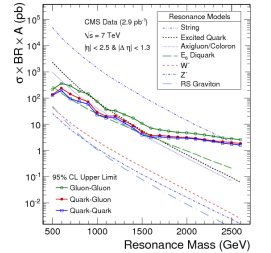
Dijet resonances: from the early days to today (EXO-10-010, EXO-19-012)

- Generic search for a bump in the dijet mass distribution.
  - Use high radius jets with small rapidity gap $\Delta\eta < 1.3$
- First published search by CMS with 3 pb^{-1} at $\sqrt{s} = 7$ TeV.
  - Already surpassing some exclusion from Tevatron.
- Many updates since then
- **Full Run 2 result** now exclude masses well above 5 TeV for several models.
  - **Huge boost in integrated luminosity (137 fb^{-1}) and $\sqrt{s}$ (13 TeV)**

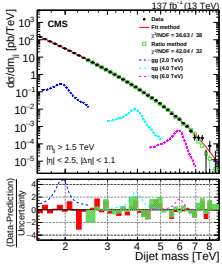
	Excited quark	String resonance
Excl. mass (2010)	1.6 TeV	2.5 TeV
Excl. mass (Full Run 2)	6.3 TeV	7.9 TeV

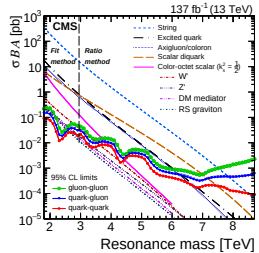
2010



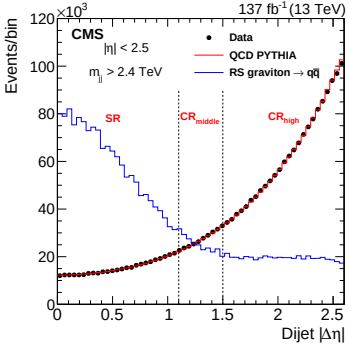


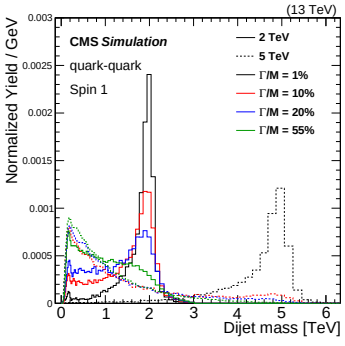
Full Run 2

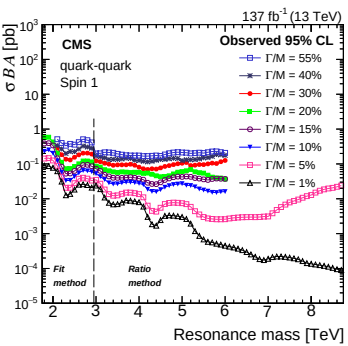




- **More sophisticated analyses techniques**:
  high mass background shape from control region in data rather than empirical function (reduced uncertainties).
- **Now also considering wide resonances.**
  Long tail at low mass due to pdf.

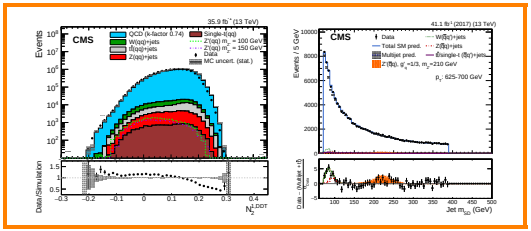


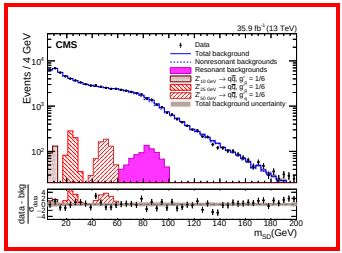


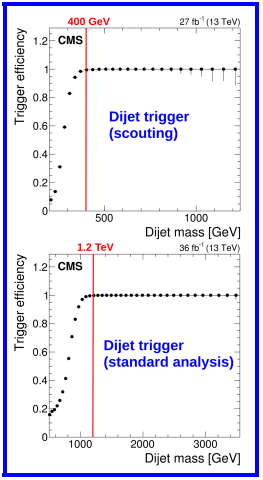


Dijet resonances: probing low masses (EXO-16-056, EXO-17-001, EXO-17-027, EXO-18-012)

- Growing interest to also probe (very) low masses. **Trigger is the limit here.**
- Can be overcome with scouting: trade event size (save only trigger information) to allow large trigger rate (and therefore lower trigger energy thresholds).
  - CMS studying dijet mass down to 600 with this technique, corresponding to excluded cross sections of O(10) pb.
- To get further down with dijet, needs to rely on initial state radiation for trigger.
  - $Z'(qq)$ decay products merged into a single jet, studied using substructure info.
  - ISR can be a jet (large cross section), a photon: lower cross section, but lower trigger threshold (p_T = 500 GeV vs 200 GeV)

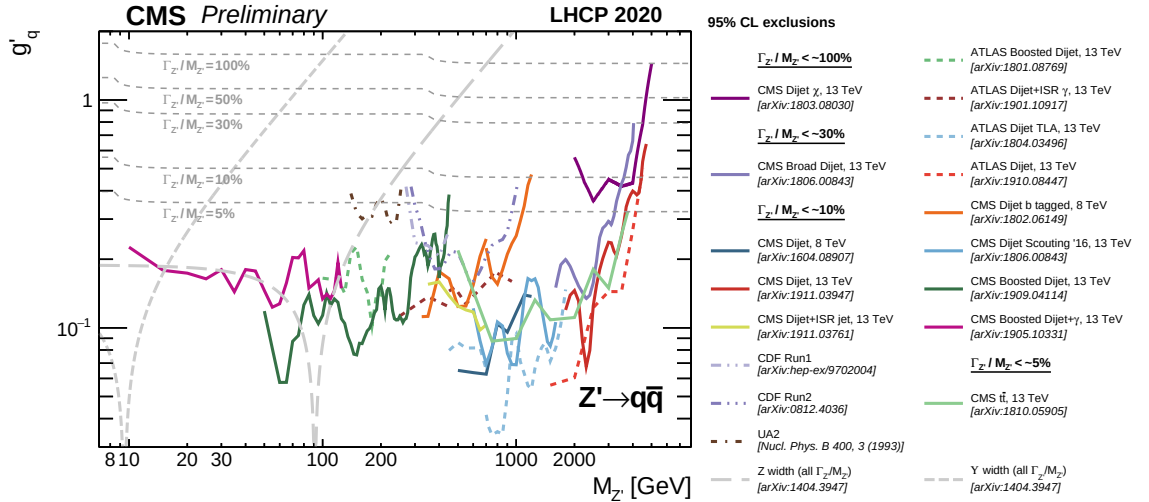






Dijet resonances at the LHC: a summary

- High mass: competitive with previous experiments with the very first CMS data.
- Now competitive in a huge mass range.



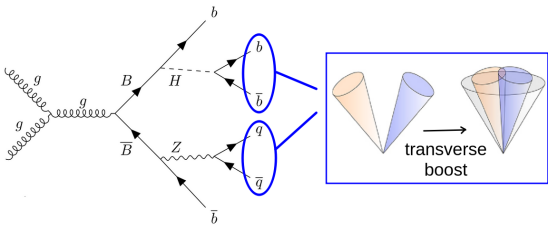
Also looking at more complex topologies with multiple jets.
Example: **Search for pair produced bottom type vector-like quark.**
Full Run 2 result

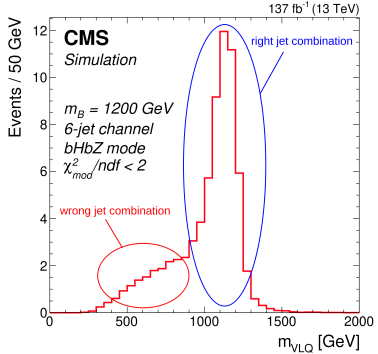
- Targets pair production of $B \to b + H/Z$
- Expect 6 jets, out of which 2-6 come from b-quarks.
- Dedicated categories to identify cases where one/both boosted Z/H merged into a single large radius jet.
- Modified χ^2 metric used to combine jets, reconstruct VLQ mass and identify the most compatible decay mode (*bHbH*, *bHbZ*, *bZbZ*)

$$\chi^2_{\text{mod}} = \frac{(m_{\text{dijet}_1} - \overline{m}_{\text{dijet}})^2}{\sigma^2_{m_{\text{dijet}}}} + \frac{(m_{\text{dijet}_2} - \overline{m}_{\text{dijet}})^2}{\sigma^2_{m_{\text{dijet}}}} + \frac{(\Delta m_{\text{VLQ}} - \overline{\Delta m}_{\text{VLQ}})^2}{\sigma^2_{\Delta m_{\text{VLQ}}}},$$

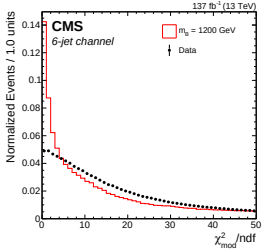
$$\chi^2_{\text{mod}} = \frac{(m_{\text{dijet}} - \overline{m}_{\text{dijet}})^2}{\sigma^2_{m_{\text{dijet}}}} + \frac{(m_{\text{merged}} - \overline{m}_{\text{merged}})^2}{\sigma^2_{m_{\text{merged}}}} + \frac{(\Delta m_{\text{VLQ}} - \overline{\Delta m}_{\text{VLQ}})^2}{\sigma^2_{\Delta m_{\text{VLQ}}}},$$

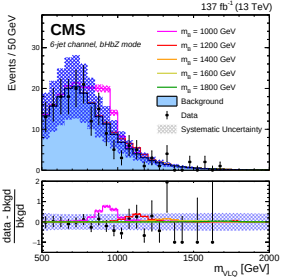
$$\chi^2_{\text{mod}} = \frac{(m_{\text{merged}_1} - \overline{m}_{\text{merged}})^2}{\sigma^2_{m_{\text{merged}}}} + \frac{(m_{\text{merged}_2} - \overline{m}_{\text{merged}})^2}{\sigma^2_{m_{\text{merged}}}} + \frac{(\Delta m_{\text{VLQ}} - \overline{\Delta m}_{\text{VLQ}})^2}{\sigma^2_{\Delta m_{\text{VLQ}}}}$$

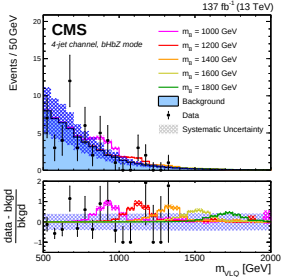


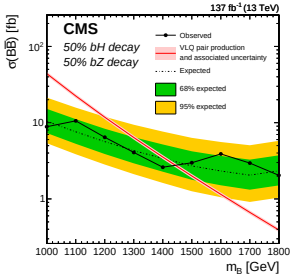


- Final selection cuts on min b-jet multiplicity, max χ^2_{mod}. (tuned separately for each decay mode).
- Background estimated from data using control regions: $500 < M(VLQ) < 800$, no tagging condition, or high χ^2_{mod}.
- Search for a resonance in the invariant mass of the two reconstructed VLQ.
- Excluding VLQ masses up to $\approx$ 1.4-1.6 TeV (depending on decay mode)









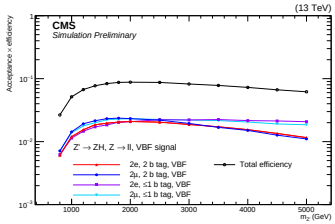
Inviting leptons to the party

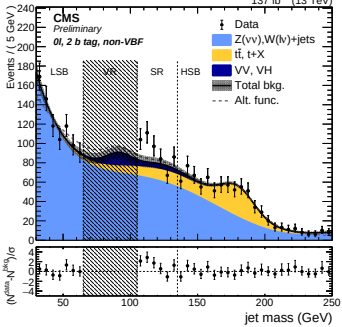
Another very popular topic: $X \to VV/VH/HH$ resonances.

- Predicted by a large variety of models (GUT, Randall-Sundrum extra dimensions, composite Higgs,...)
- Most sensitive V boson decay mode depends on SM backgrounds.
- If no coupling to fermions, only produced through vector boson fusion

Search in the $Z(ll)H(bb)$ final state ($l = e, \mu, \nu$) Full Run 2 result

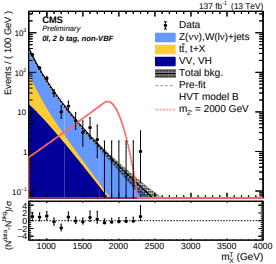
- Select events with $70 < M(ee/\mu\mu) < 110$ or MET>250 GeV, and a large radius jet with $105 < M_j < 135$ (H jet)
- Split events according to number of b-tagged subjets in H jet.
- Dedicated VBF category: 2 jets with large invariant mass/rapidity gap.
- Search performed in $M(ZH)$ ($M_T(H, MET)$) distribution for $ee/\mu\mu$ ($\nu\nu$)
- Normalization and shape of V+jets background from M_j side bands.

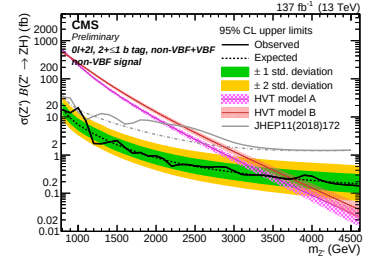


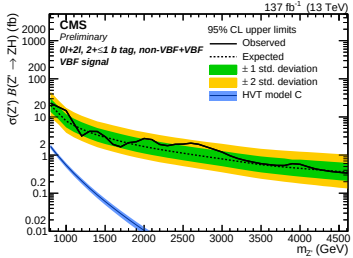


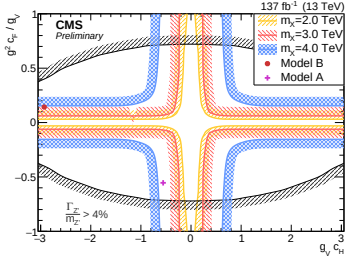
H+Z boson resonance searches with jets and leptons (B2G-19-006)

- All categories combined to set limits on VBF/non VBF production.
- Interpretation in terms of Heavy Vector Triplet models
- Also providing limits for fermions/vector bosons/Higgs couplings.





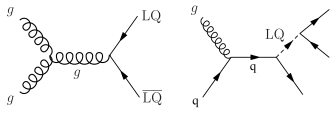




Non VBF VBF

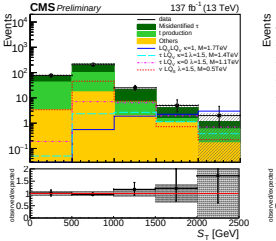
Leptoquarks (LQ):

- New particles carrying both lepton and baryon number predicted by GUT, compositeness scenario...
- Could provide explanation to anomalies in B meson decays ($b \to cl\nu, b \to sll$).
- Out particular interest: third generation LQ.

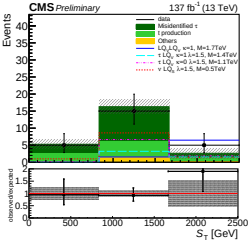


Recent search by CMS in $tb\tau\nu$ targeting both single/pair produced LQ. Full Run 2 result

- Select events with 1 τ_h, high MET, high tau-MET transverse mass, 1 t_h, $\geq$ 1 b-jet.
- Events categorized according to N(b-jets), and whether the jets from t_h are (semi-)merged ("boosted top") or not ("resolved top").
- $S_T = \sum p_T^{\tau_h} + p_T^{t_h} + MET$ used as final discriminating variable.

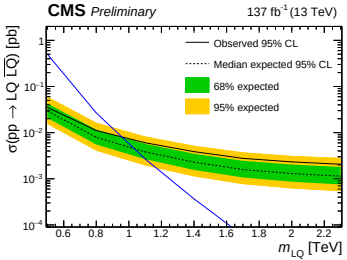


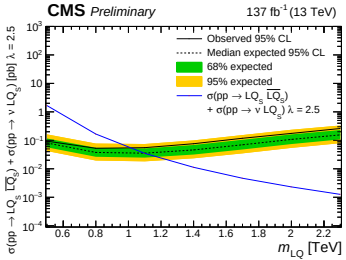
$\geq 2b$, resolved t

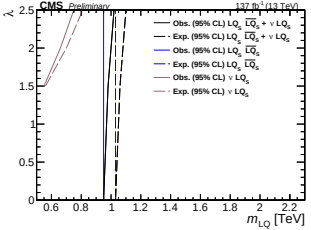


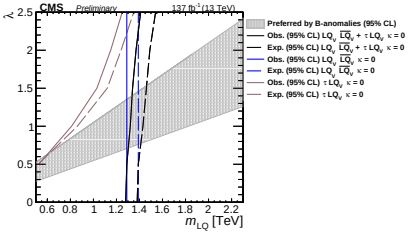
$\geq 2b$, boosted t

- Interpretation in terms of scalar/vector leptoquarks (coupling λ setting the strength of single production).
- Lower limits in the 1.0 – 1.7 TeV range.





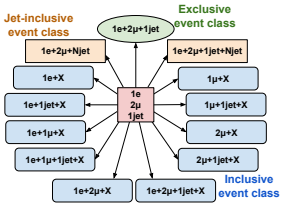




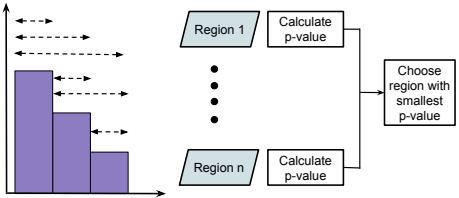
Looking for the unknown...

MUSiC: Model unspecified searches in CMS (EXO-19-008)

- Look for possible excess/deficit with respect to SM expectation in a broad number of inclusive/exclusive event categories, based on $e/\mu/\gamma$/(b-)jets multiplicity and low/high MET (</>100 GeV)
- Assess data/MC agreement in total event yield and for distribution of MET, $S_T = \sum |p_T(phys.\ obj.)|$, mass/transverse mass of all phys. obj.
- Focus on events with ≥ 1 e/μ.
- SM expectation purely from simulations
- Technically:
  - Compute p-value in data p_{data}
  - Find p_{min}^{data} among any combination of adjacent bins in a given distribution
  - Compute global p-value: $\tilde{p} = \frac{N^{SM}_{pseudo\ \ exp.}(p_{min} < p^{data}_{min})}{N^{SM}_{pseudo\ \ exp.}}$

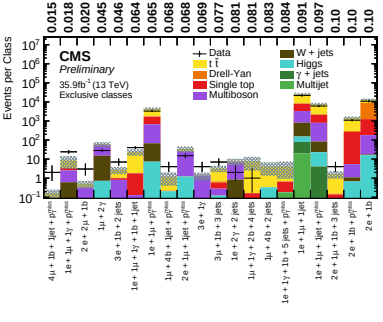


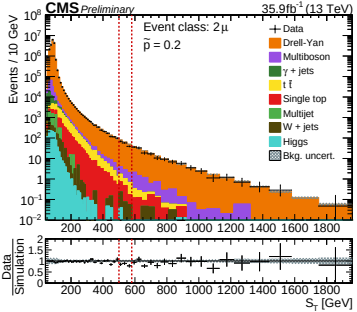
$$p_{\text{data}} = \begin{cases} \sum_{i=N_{\text{data}}}^{\infty} C \cdot \int_0^{\infty} \mathrm{d}\lambda \, \exp\left(-\frac{(\lambda - N_{\text{SM}})^2}{2\sigma^2_{\text{SM}}}\right) \cdot \frac{\mathrm{e}^{-\lambda}\lambda^i}{i!} & \text{if } N_{\text{data}} \geq N_{\text{SM}} \\ \sum_{i=0}^{N_{\text{data}}} C \int_0^{\infty} \mathrm{d}\lambda \, \exp\left(-\frac{(\lambda - N_{\text{SM}})^2}{2\sigma^2_{\text{SM}}}\right) \cdot \frac{\mathrm{e}^{-\lambda}\lambda^i}{i!} & \text{if } N_{\text{data}} < N_{\text{SM}}, \end{cases}$$

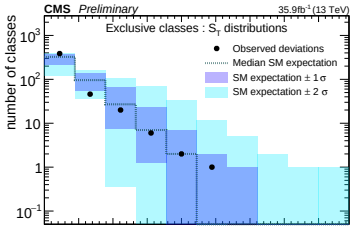


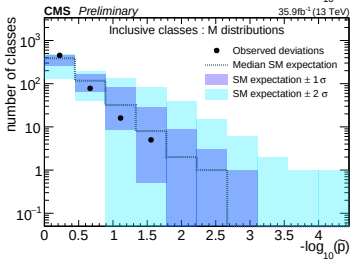
MUSiC: Model unspecified searches in CMS (EXO-19-008)

- No excess observed in the high tail of the $\tilde{p}-$value distribution for data.
- Lowest $p-$value for global event yield is 0.015 for $4\mu + 1b + 1$ *jet*+MET category
- Lowest $\tilde{p}-$value (0.0038) found in the S_T distribution for $3e + 1b + 2$ *jets* (local p-value for $340 < S_T < 540$: 0.00053)



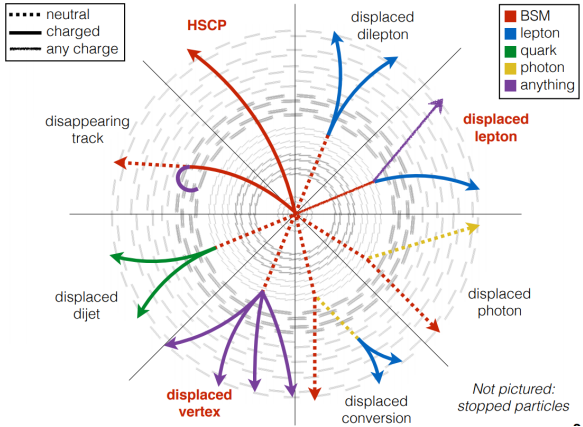






Looking for unconventional signatures and exploiting all detector features

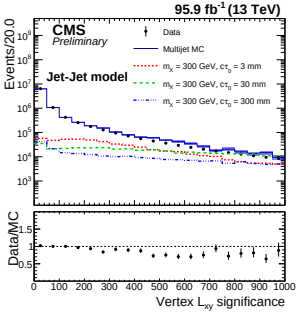
- A lot of phenomenology support
- Large diversity of unconventional signatures in the detectors.

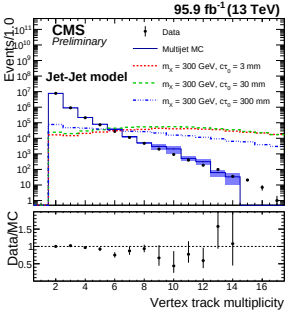


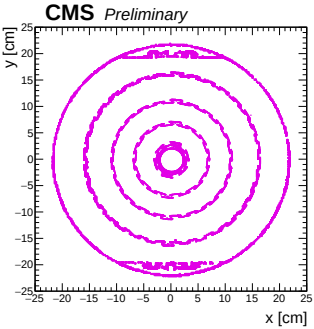
Stolen from J. Antonelli (ICHEP2016)

Search for displaced jets. Full Run 2 result

- Select pair of jets with high transverse impact parameter tracks and reconstruct a displaced vertex carrying a large fraction of jet p_T
- MVA (GBDT) discriminator built using displaced vtx track multiplicity, IP significance...
- Dedicated jet triggers to probe transverse hadronic activity lower than usual (500 GeV vs ≈1 TeV).
- Geometric vetos suppressing nuclear interaction in tracker material.
- Remaining QCD background from control region (low MVA score/ reverted cut on prompt tracks)

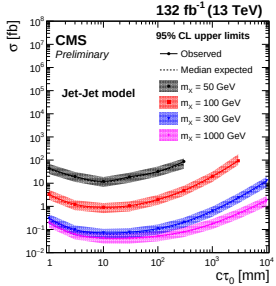


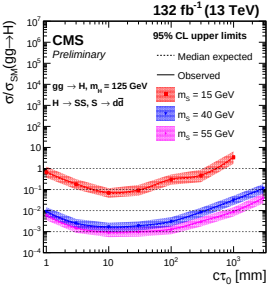


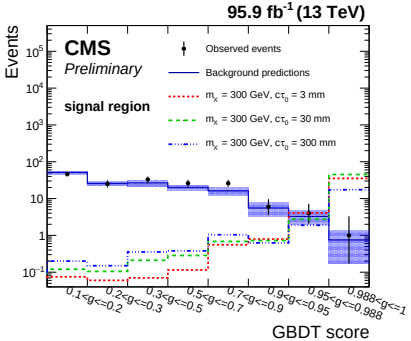


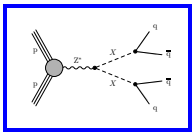
Search for long-lived particles decaying into displaced jets (EXO-19-021)

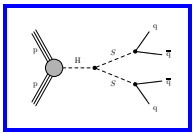
- Limits set for generic long-lived scalars coupling to offshell Z.
- Sensitive to decay lengths from 1 mm to 10 m and masses from 50 GeV to 1 TeV.
- Also considered LL scalars coupling to H boson.





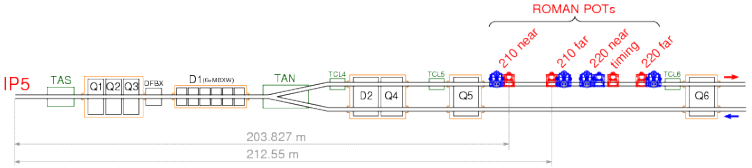


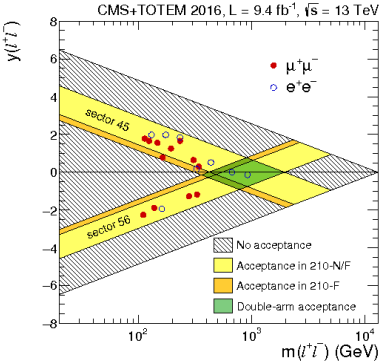


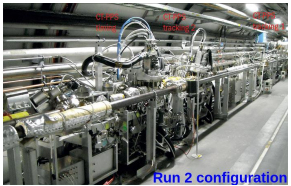


Using tagged forward protons to probe new physics (EXO-18-014)

- CMS TOTEM precision proton spectrometer: array of Roman pots (tracking/timing stations) located 210m from the interaction point.
- Large detection efficiency of intact protons with momentum loss $\xi = \Delta p/p$ between 3 and 15%. (relative uncty: 6-10%)
- Successfully used to observe (semi-)exclusive $\gamma\gamma \to l\bar{l}$

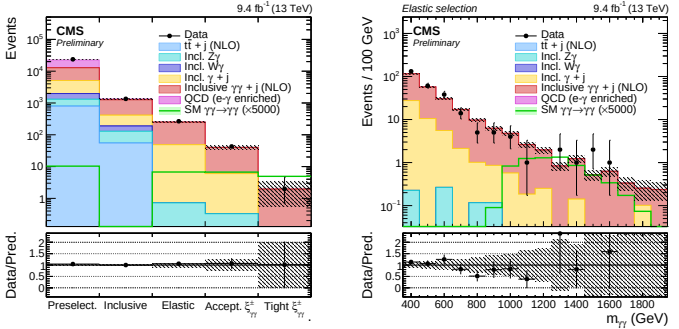






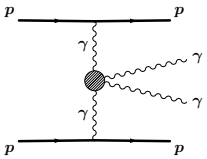
Using tagged forward protons to probe new physics (EXO-18-014)

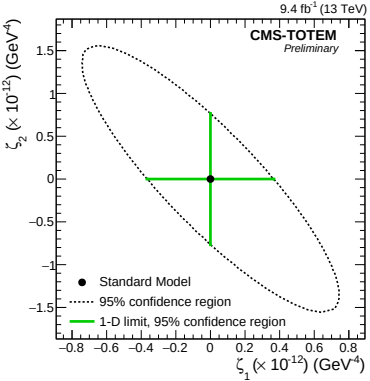
- Recently released a first search for exclusive photon production with proton tagging.
- Event selection: 2 photons with $p_T > 75$ GeV, $1 - |\Delta\phi(\gamma\gamma)| < 0.005$ (elastic selection),
- Expected proton momentum loss from $\gamma\gamma$ kinematics, $\xi^{\pm}_{\gamma\gamma}$ (for p from the +/- side), in the most efficient (>90%) detection region of CPPS (tight $\xi^{\pm}_{\gamma\gamma}$ selection)
- $m_{\gamma\gamma}$, $y_{\gamma\gamma}$ in 2σ resolution window of pp missing mass and rapidity from CPPS. (matching selection)
- Main background: inclusive $\gamma\gamma$ pile up protons.
- 0 events observed ($0.23^{+0.08}_{-0.04}$ expected) after matching applied.



- Interpretation in terms of anomalous quartic gauge coupling in the effective dimension 8 operator:

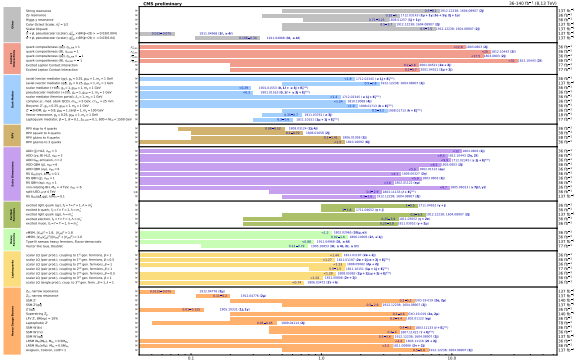
$$L_8^{\gamma\gamma\gamma\gamma} = \frac{a_1^{\gamma\gamma}}{\Lambda^4} F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \frac{a_2^{\gamma\gamma}}{\Lambda^4} F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}$$





Summary

- Many searches conducted at CMS since the LHC startup in 2010.
- Broad variety of experimental signatures and theoretical models now considered.
- Constant development of analysis techniques, exploiting new detector features.
- No evidence of new physics so far... → Exclusion limits reaching/surpassing 1 TeV for many scenarios.
- More data (20×!) to be collected by the end of the HL-LHC.
  → This is just the beginning.



Stay tuned !