Phenomenology 2021 Symposium

Searches for new physics in events with jets in the final state in CMS

Xuli Yan
(Brown University)

On behalf of the CMS Collaboration

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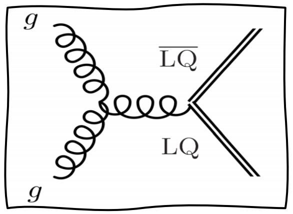
Introduction

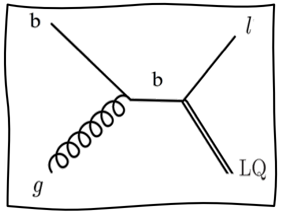
- **The standard model of particle physics is not the whole story**
  - e.g. dark matter, neutrino oscillation, hierarchy…
  - The energy scale of possible new physics is not clear
- **Many theories beyond the standard model predict new particles/interactions which manifest themselves in hadronic final states**
  - New resonances decay hadronically, e.g., Z' and W' in MESM, leptoquarks in GUT, Technicolor...
  - Long-lived particles from exotic decays of SM-like Higgs, SUSY… (more in Celia's talk)
- **Idea channels to be probed on CMS with advanced jet algorithms**
  - ~140 fb^{-1} pp collision data at 13 TeV
  - Jet tagging with substructure information and (or) machine learning
- **Latest results using full Run-2 data will be presented**

Leptoquarks → $t\tau b\nu(t\tau\nu)$

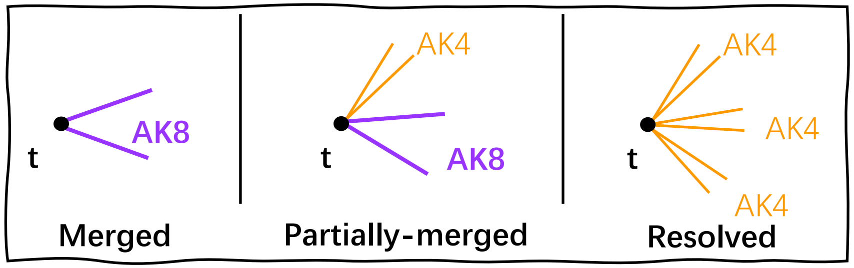
(arXiv:2012.04178, submitted to PLB)

- **Aiming for pair or single-produced leptoquarks**
  - Scalar LQ_S : couples to $t\tau$ or $b\nu$
  - Vector LQ_V :couples to $t\nu$ or $b\tau$



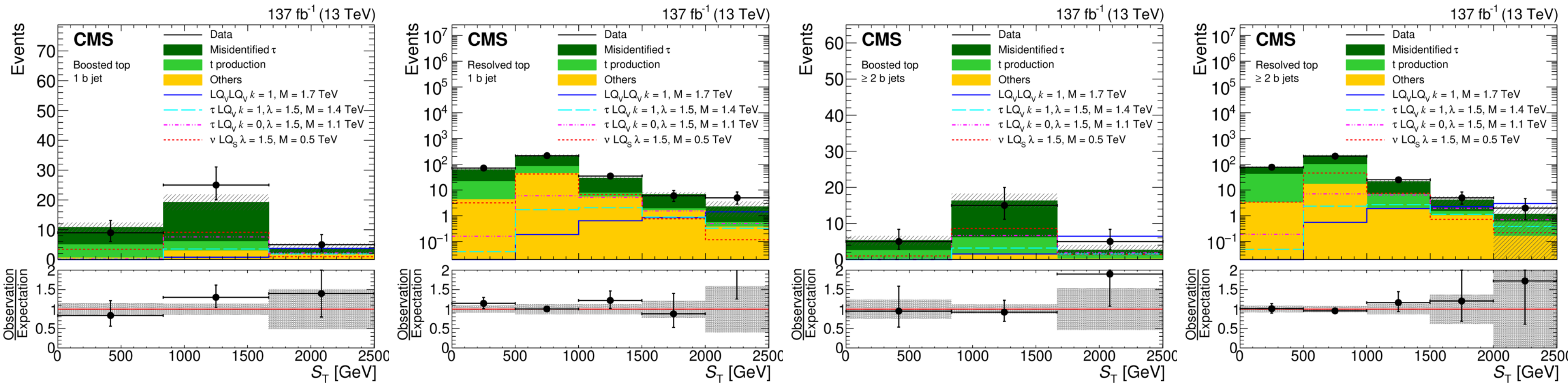


- **Reconstruction of hadronically decaying objects**
  - AK8 jets for the W boson (tagged by τ_{21}) and top quark (tagged by τ_{32} if fully merged)



  - AK4 jets with the hadron-plus-strips algorithm & MVA ID for the hadronic τ; tagged by the CSV tagger for the bottom quark jet (b jet)

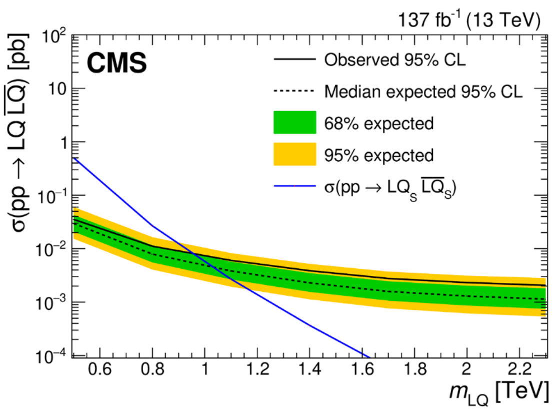
- **Candidates with 1 t, 1 τ, $\geq$ 1 b jets and 0 l, with p_T^{miss} and $H_T^{miss} > 200$ GeV**

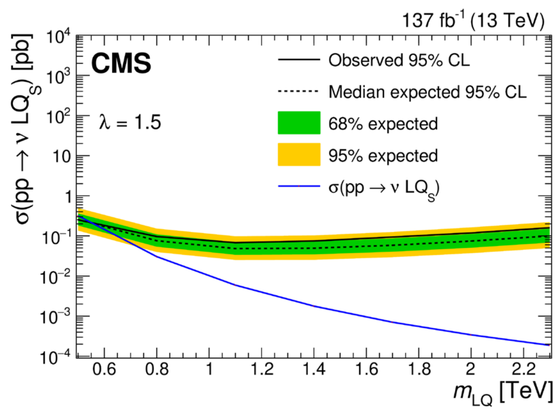


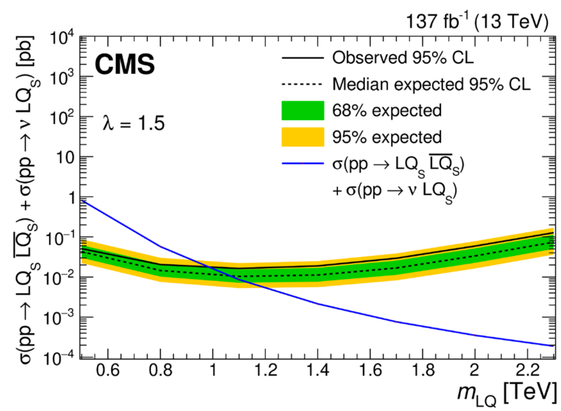
Leptoquarks → $t\tau b\nu(t\tau\nu)$

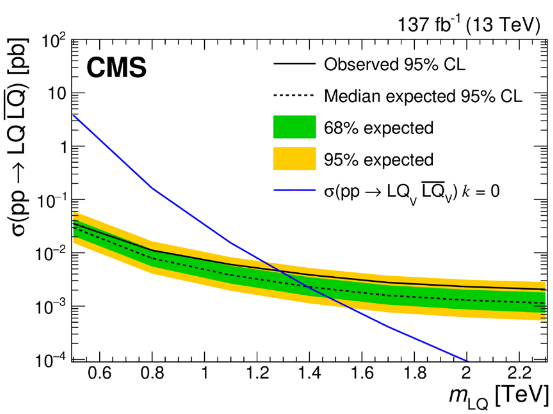
- Most stringent limits in the range of 0.5 – 2.3 TeV (assuming Br(LQ→ ql) = 0.5)

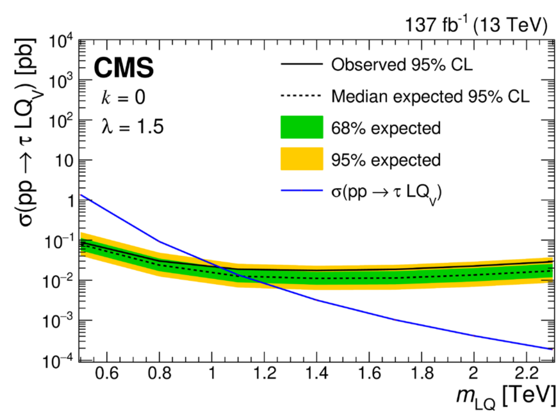
- LQs with mass between 0.98 and 1.73 TeV are excluded in the simultaneous search (pair+single) for the range of model parameters probed

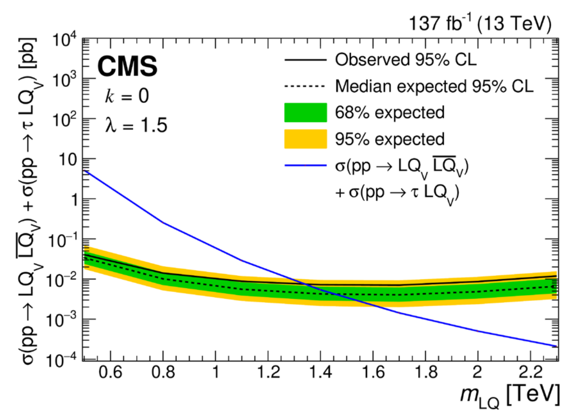








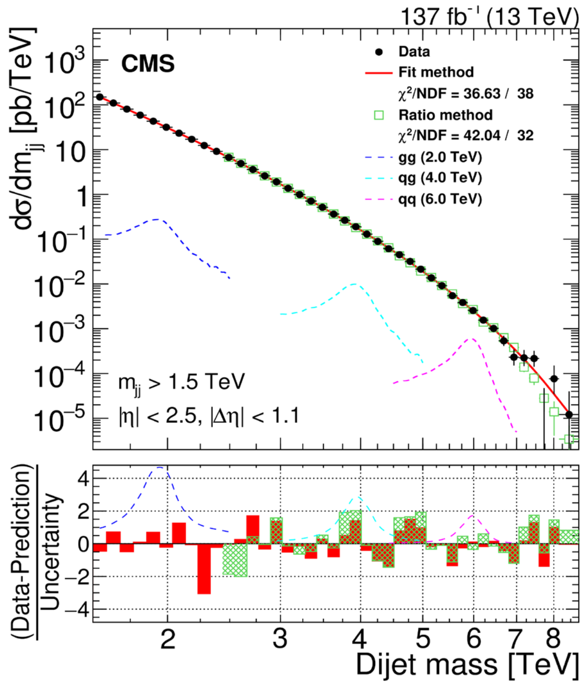




Dijet resonance

(arXiv:1911.03947, published in JHEP)

- **Targeting narrow and broad (up to 55% M_{Res}) dijet resonance with mass greater than 1.8 TeV**
- **Re-clustering of jets**
  - Forming wide-jets with $\Delta R = 1.1$ using two leading jets as seeds, reducing sensitivity to undesired FSR gluons
- **New "ratio method" for $m_{jj} > 2.4$ TeV and ordinary fit method for 1.5 TeV $< m_{jj} <$ 2.4 TeV**
  - "Ratio method" uses one SR, 2 CR (CR_h, for predicting bkg in SR and CR_m, for constraining systematics) based on different ranges of $|\Delta\eta|$
  - Mass-dependent transfer factors determined from QCD bkg angular distribution are used to predict bkg in SR → more accurate bkg estimation (independent of SR, constrained by CR_m)

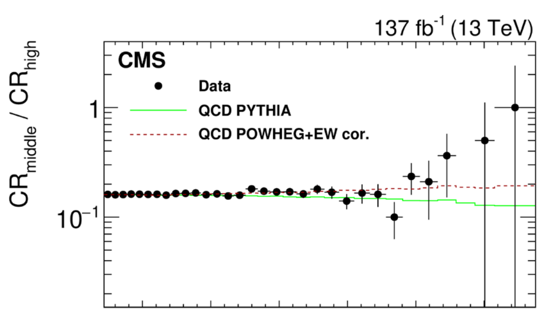


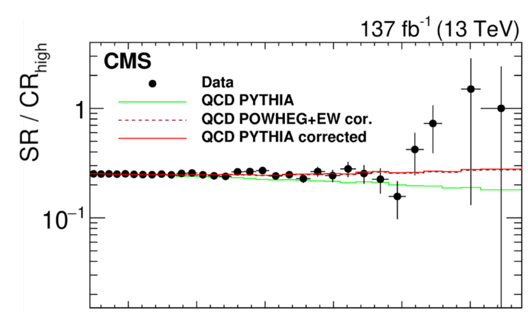
$$N(i)^{\text{Prediction}}_{\text{SR}} = R(m_{\text{jj}}/\sqrt{s})N(i)^{\text{Data}}_{\text{CR}_{\text{high}}}$$

$$R(m_{\text{jj}}/\sqrt{s}) = C(m_{\text{jj}}/\sqrt{s})N(i)^{\text{Sim.}}_{\text{SR}}/N(i)^{\text{Sim.}}_{\text{CR}_{\text{high}}}.$$

$$R_{\text{aux}}(i) = N(i)_{\text{CR}_{\text{middle}}}/N(i)_{\text{CR}_{\text{high}}}.$$

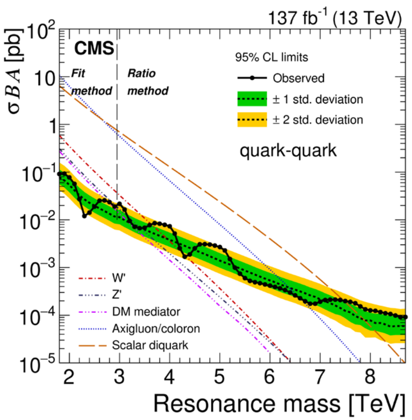
$$C(m_{\text{jj}}/\sqrt{s}) \longleftarrow R^{\text{Data}}_{\text{aux}}/R^{\text{Sim.}}_{\text{aux}}.$$

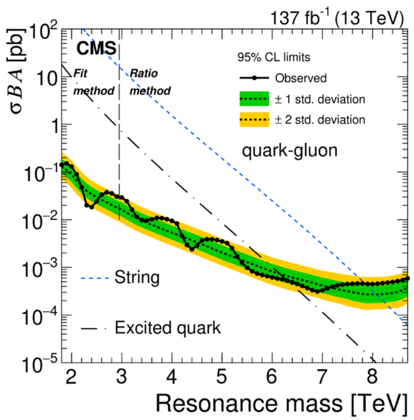


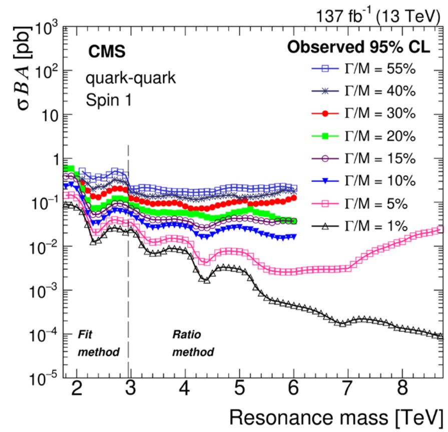


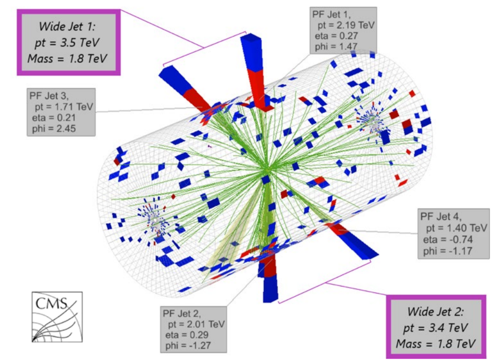
Dijet resonance

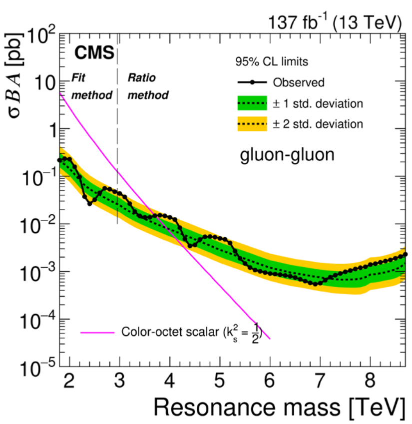
- **Mass exclusions for various models are** **improved by 200 to 800 GeV**
  - Limits are set for narrow new resonances, as well as for spin-1 (spin-2) broad resonances with width up to 30% (55%) of the resonance mass
  - An interesting event with dijet mass of 8 TeV, see arXiv:1810.09429 for a discussion

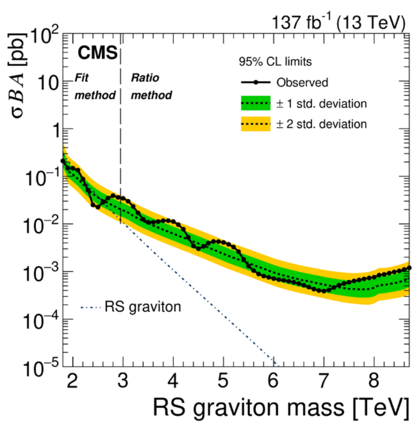


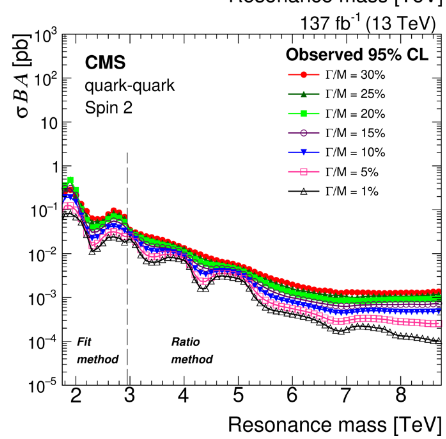


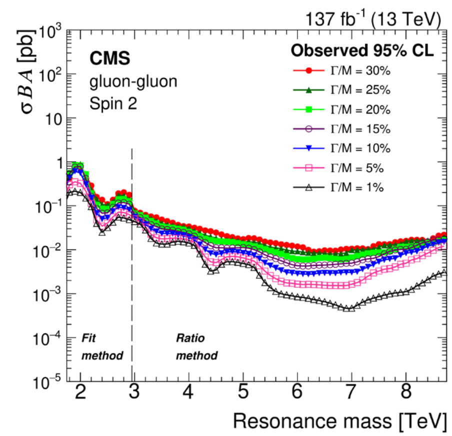








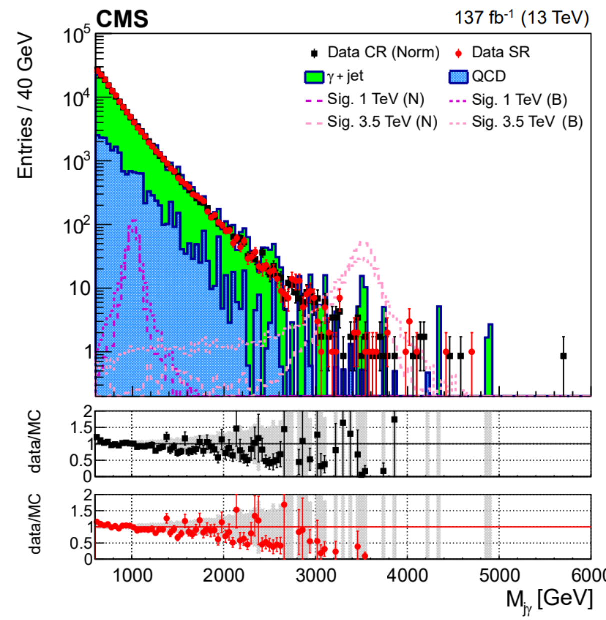


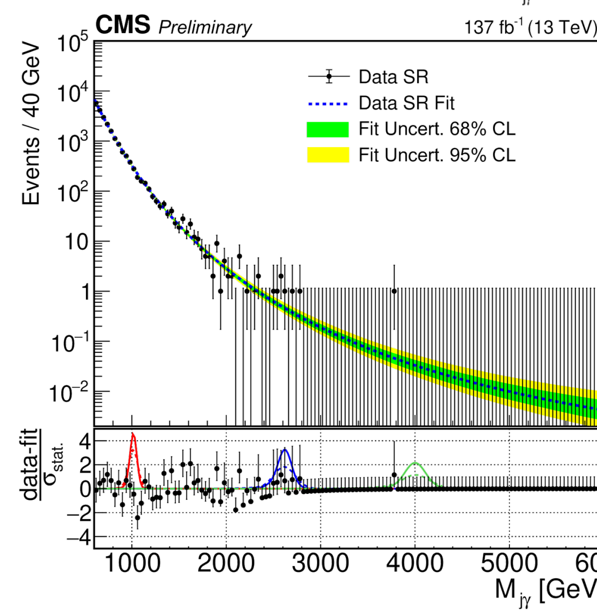


Wγ resonance (hadronic channel)

(CMS-PAS-EXO-20-001)

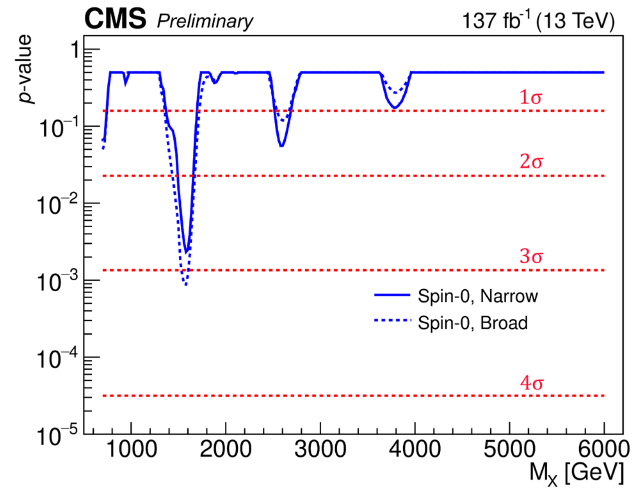
- **Targeting heavy charged resonances decaying into $W\gamma$**
  - Search range: 0.7 – 6.0 TeV
  - Scalar or vector; narrow or broad (5% M_{Res})
- **Reconstruction of hadronically decaying Lorenz-boosted W boson**
  - Single large-radius jet (AK8) with 2 subjets, benefit from the large branching fraction of the hadronic decay of W
- **Event selection**
  - W jet tagging with τ_{21} variable and PUPPI soft-drop mass window of 68-94 GeV (sensitive to Z also)
  - Scattering angle related variables
- **Background determined using data by fitting analytic functions to the $m_{j\gamma}$ spectrum**
- **Largest excess at 1.58 TeV for broad resonances of both spin hypotheses, with 3.1σ (1.7σ) local (global) significance**

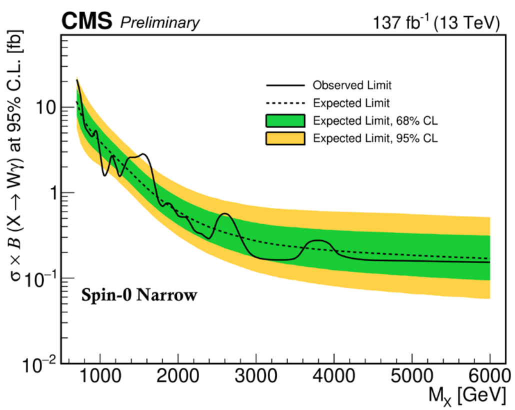


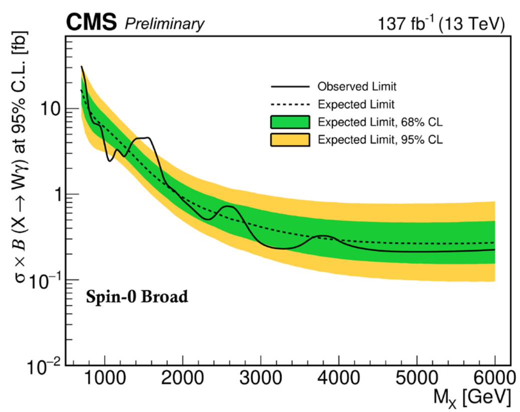


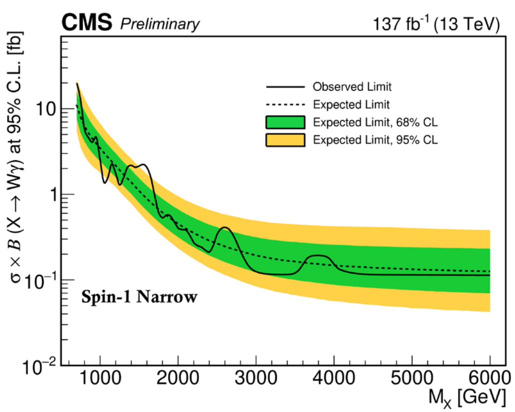
Wγ resonance (hadronic channel)

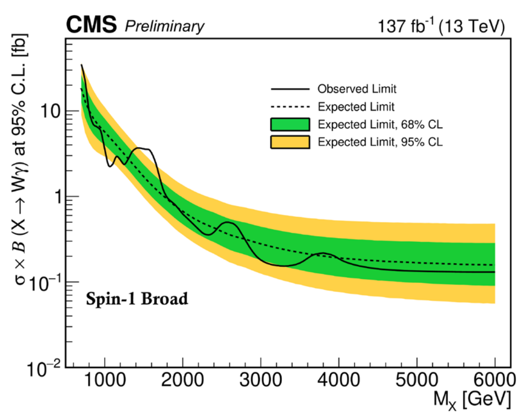
- Best to date limits on $\sigma_{pp\to X} \times \mathrm{Br}(X \to W(q\bar{q}')\gamma)$ for scalar and vector, narrow and broad resonances
  - Limits: 0.11 (6.0 TeV) – 35 fb (0.7 TeV)
  - Also provides model-independent limits for broader interpretations of results

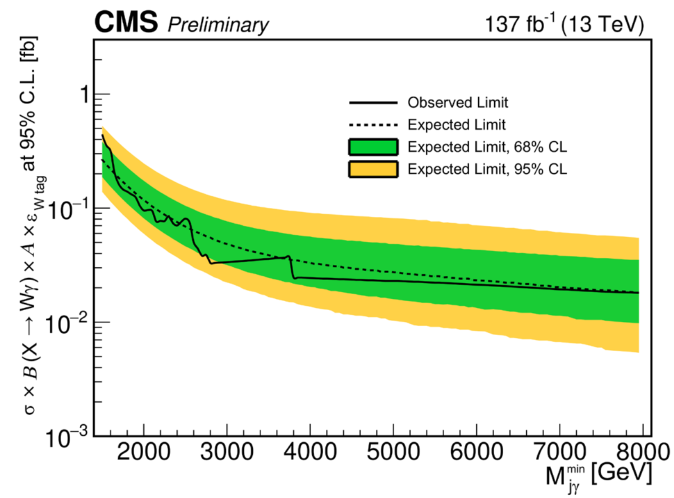








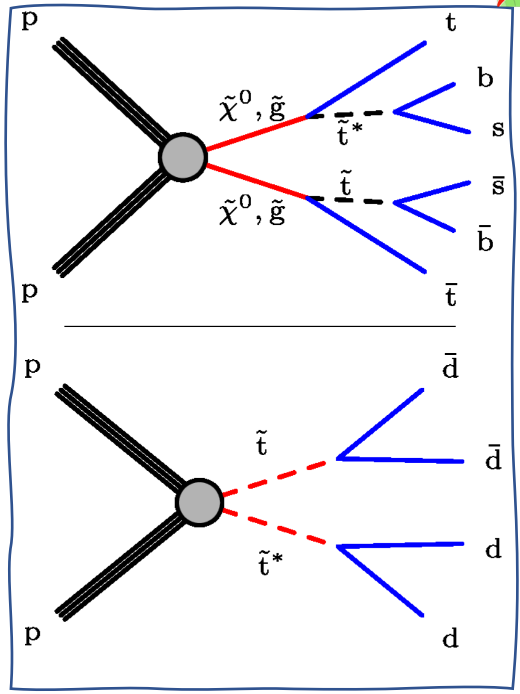


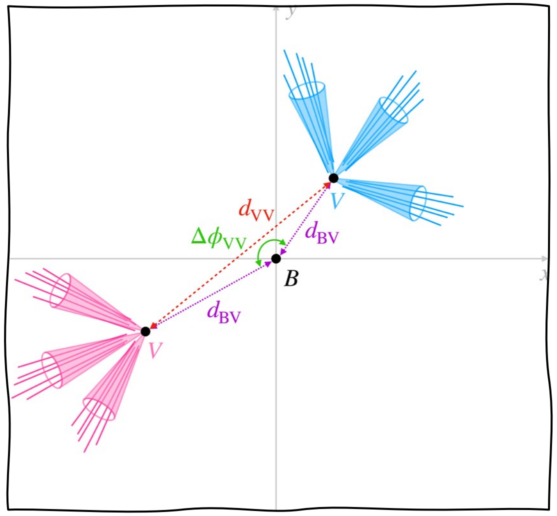


Long - lived particles (I)

(arXiv:2104.13474, submitted to PRD)

- **Targeting LLPs decaying into jets with two displaced vertices ($c\tau_0$ between 0.1 to 100 mm)**
- **Vertex reconstruction**
  - High-quality tracks fitted with the Kalman filter with improvements to:
    - Special procedure to reject tracks from pileup vertices → reduce more than 40% of background vertices
  - ≥ 5 tracks on the vertex to reduce background
    - 3-track two-vertex events as the control sample
- **Discriminating variable - d_{VV}**
  - Large for signal when small for background
  - Fitted to extract signal yield, in [0,0.4], [0.4,0.7], [0.7-40] bins for optimal sensitivity to $c\tau_0$ between 0.1 to 100 mm
- **Background template**
  - Spurious vertices, can be modeled by 1-vertex event
  - b-vertices, handled with events with or without b-tagged jet
  - Normalization estimated from fits to control sample (3-track)

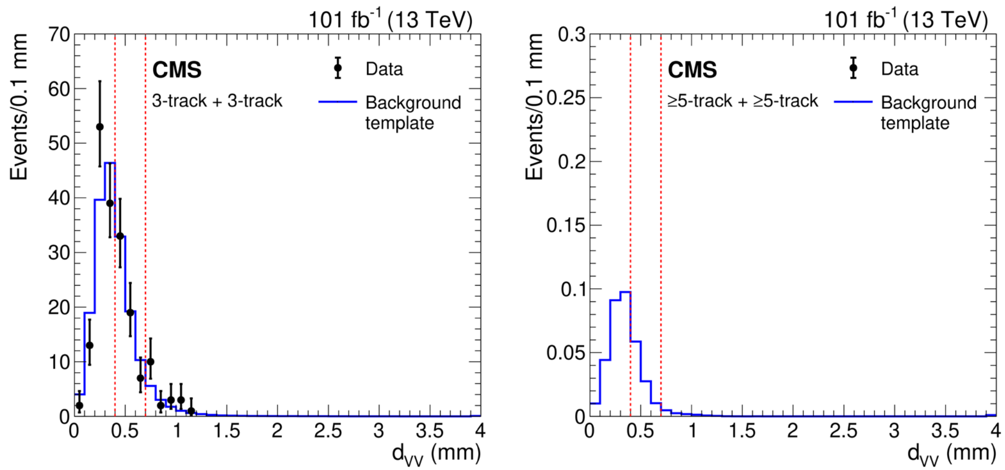


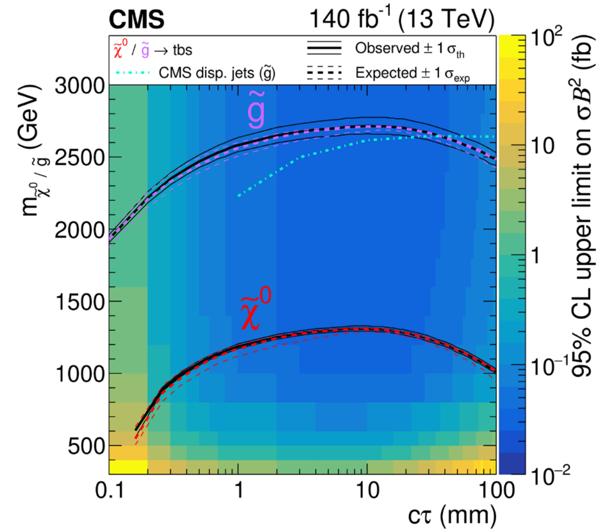


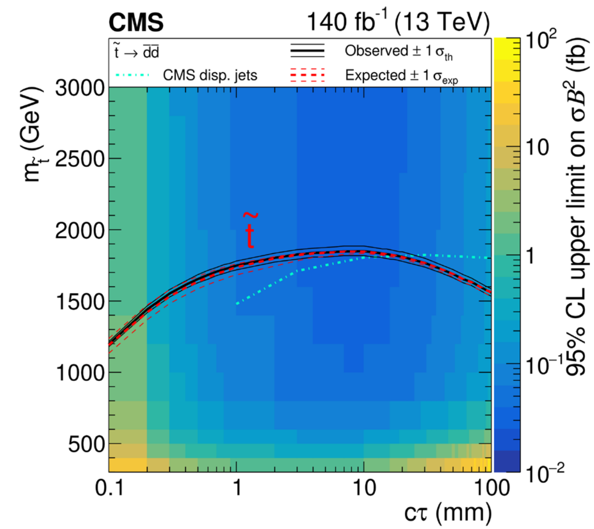
Long - lived particles (I)

- **Main systematics come from vertex reconstruction and the difference between 3-track vertices (control) and ≥5-track vertices (SR)**

- **No event with two ≥5-track vertices is observed in 2017 and 2018 data**





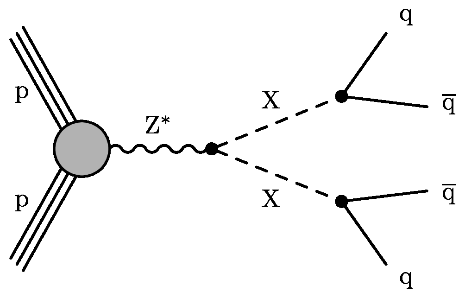


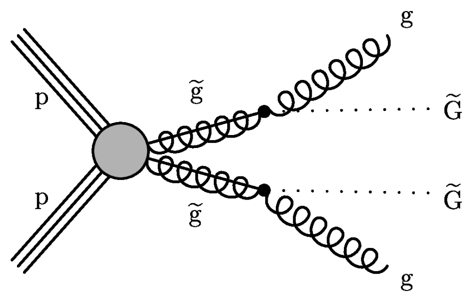
- **250-300 GeV better mass exclusion for various LLPs and best pair-production limits for those with proper decay length between 0.1 to 15 mm**
  - Gluinos, neutralinos and top squarks in RPV model with pair-production cross-section of 0.08 fb are excluded from 0.8 to 3 TeV, for mean proper decay from 1 to 25 mm

Long - lived particles (II)

(arXiv:2012.01581, submitted to PRD)

- **Targeting long-lived particles decaying into displaced dijets with displaced vertices**

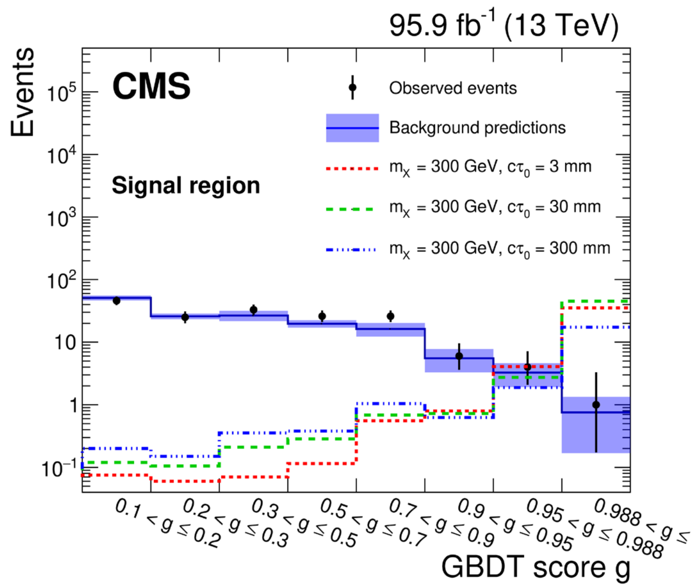




- **Event selection**
  - "Displaced" + "inclusive" HLT for performance across the range
  -

SV/dijet variable	Requirement
Vertex χ^2/n_{dof}	<5.0
Vertex invariant mass	>4 GeV
Vertex transverse momentum	>8 GeV
Second largest IP_{2D} significance	>15
ϵ (SV track energy fraction in the dijet)	>0.15
ζ (energy fraction from compatible PVs)	<0.20
Vertex position in the x-y plane	no overlap with the NI-veto map

- **Multivariate analysis using GBDT**
  - Cluster RMS: $\mathrm{RMS}_{\mathrm{cluster}} = \sqrt{\frac{1}{N_{\mathrm{tracks}}} \sum_{i=1}^{N_{\mathrm{tracks}}} \frac{(L_{xy}^{\mathrm{exp}}(i) - L_{xy})^2}{L_{xy}^2}}.$
  - Sum of signed Sig[IP_{2D}] of 6 leading tracks $\kappa = \sum_{i=1}^{6} \mathrm{Sig}[\mathrm{IP_{2D}}(\mathrm{track}_i)]$
  - Vertex track multiplicity and L_{xy} Significance



- **Background predicted using 7 CRs defined after GBDT scoring**
  - Selection 1: for the leading jet with larger p_T, N_{tracks}^{3D} is smaller than 3;
  - Selection 2: for the subleading jet, N_{tracks}^{3D} is smaller than 3; and
  - Selection 3: the GBDT score g is larger than 0.988.

Long - lived particles (II)

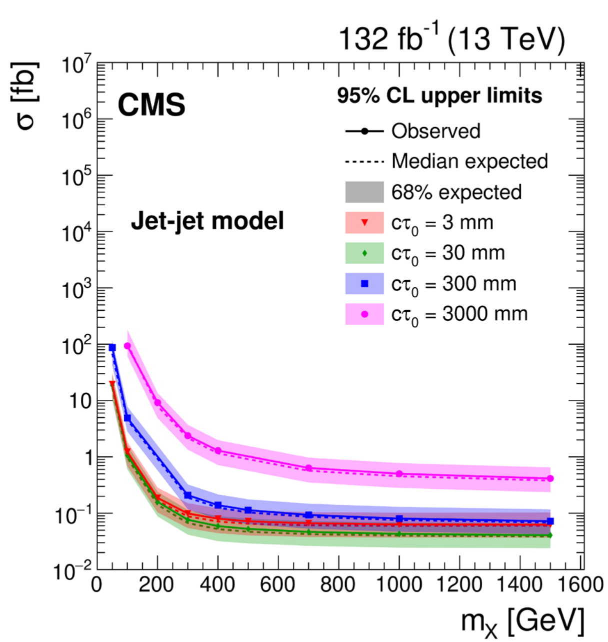
➢ 7 background categories + 1 signal category

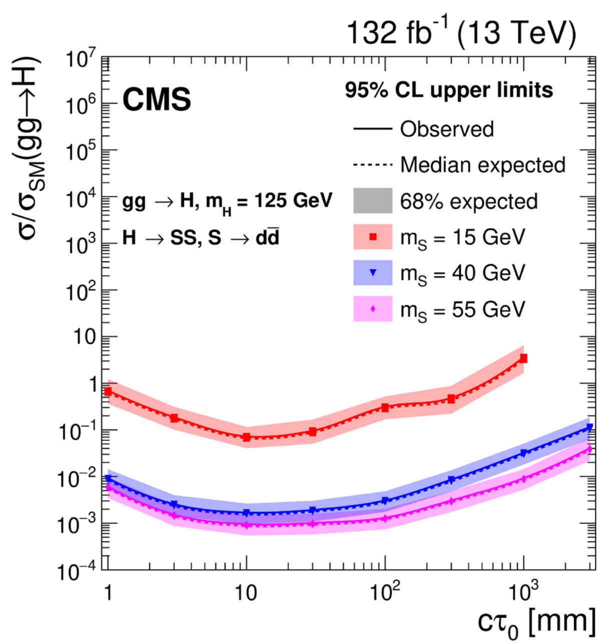
fff	***pff***	***fpf***	***ffp***	***fpp***	***pfp***	***ppf***	***ppp***

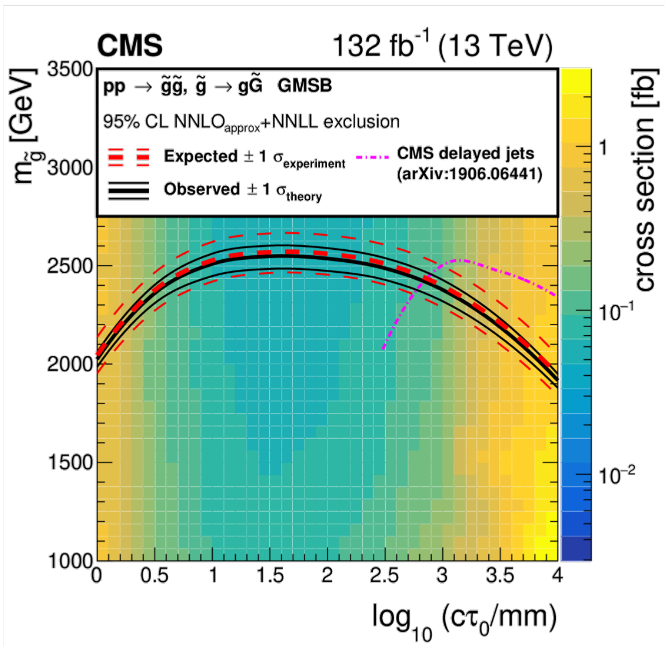
➢ Background in the SR (ppp) can be determined given three selections have little correlation

$$b_{\text{nominal}} = N_{ppf}(N_{ffp} + N_{fpp} + N_{pfp})/(N_{fff} + N_{pff} + N_{fpf})$$

◆ **Most stringent limits for proper decay length between 1 mm and 10 m for several tested models**







Summary and outlook

✓ **Presented latest representative CMS results for new physics involving jets**

- Decays involving 3rd-gen fermions, dijet signatures, $V\gamma$ resonance, long-lived particles
- Generally resulting the best limits / mass exclusions up to date

✓ **Generally, model-independent, can be interpreted by various BSM models**

- MESM, SUSY, exotic resonances, graviton, extra dimension, dark matter…

✓ **Consistent with SM predictions, no significant sign of new physics**

- Good news? Or bad news?

⌖ **BSM studies with jets are quite active on CMS, new works for Run-2 are on going**

- Trijet, mono-jet, excited quarks, heavy Majorana neutrinos, further searches for Z' and dark matter…

⌖ **Run-3 provides further opportunities to explore a broader phase space**

- Expect doubled Int. luminosity, possibly at 14 TeV
- Improved triggers allowing better utilization of non-conventional triggers, e.g., scouting
- Progress in advance machine learning techniques for online/offline reconstruction and particle ID