

Exotic Searches at CMS/LHC

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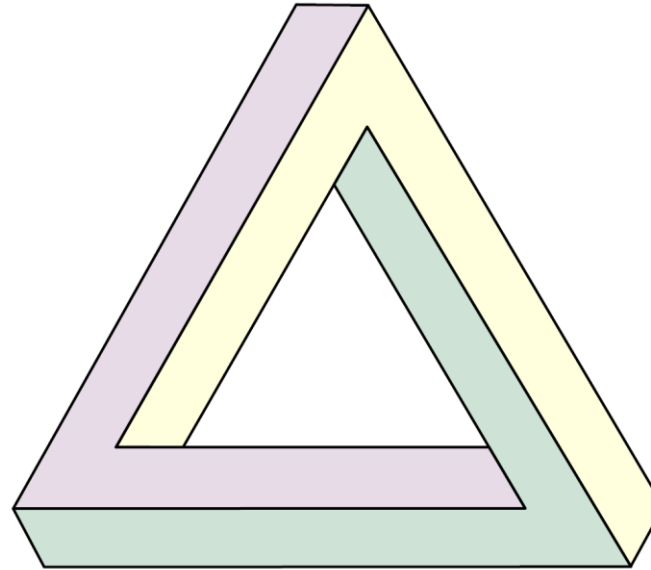
on behalf of
the CMS Collaboration

HEP 2019
NCSR “DEMOKRITOS, Athens, Greece
17-20 April 2019

the Questions



- Hierarchy problem
- Unification of forces
- New fundamental forces
- Origin of flavor
- Origin of dark matter
- Gravity, dark energy
- Neutrino masses
- ...



the SM extensions

SUSY, Extra-Dimensions, New Gauge Bosons, Contact Interactions, Leptoquarks, Excited fermions, 4th generation, Type III seesaw,...

the Proofs (experiments)



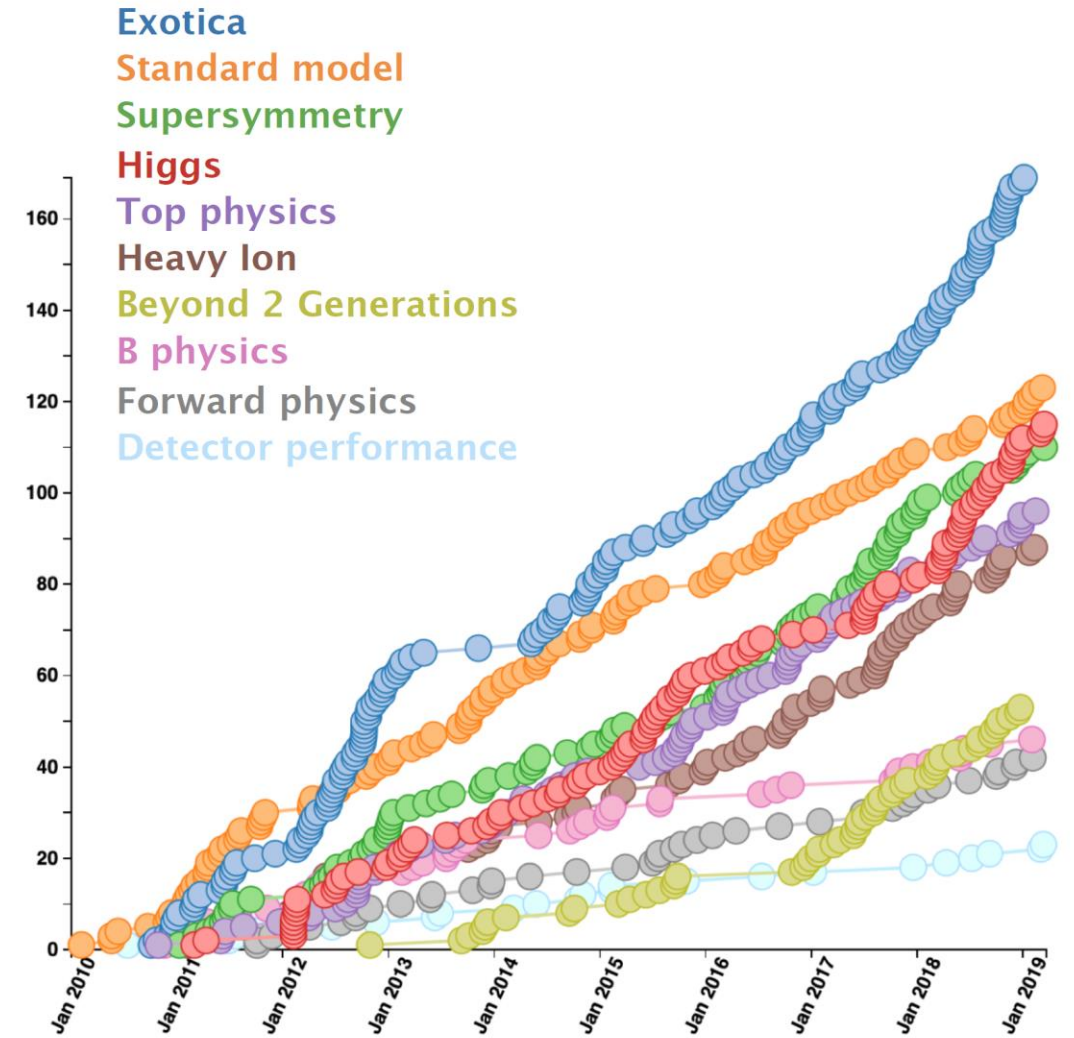
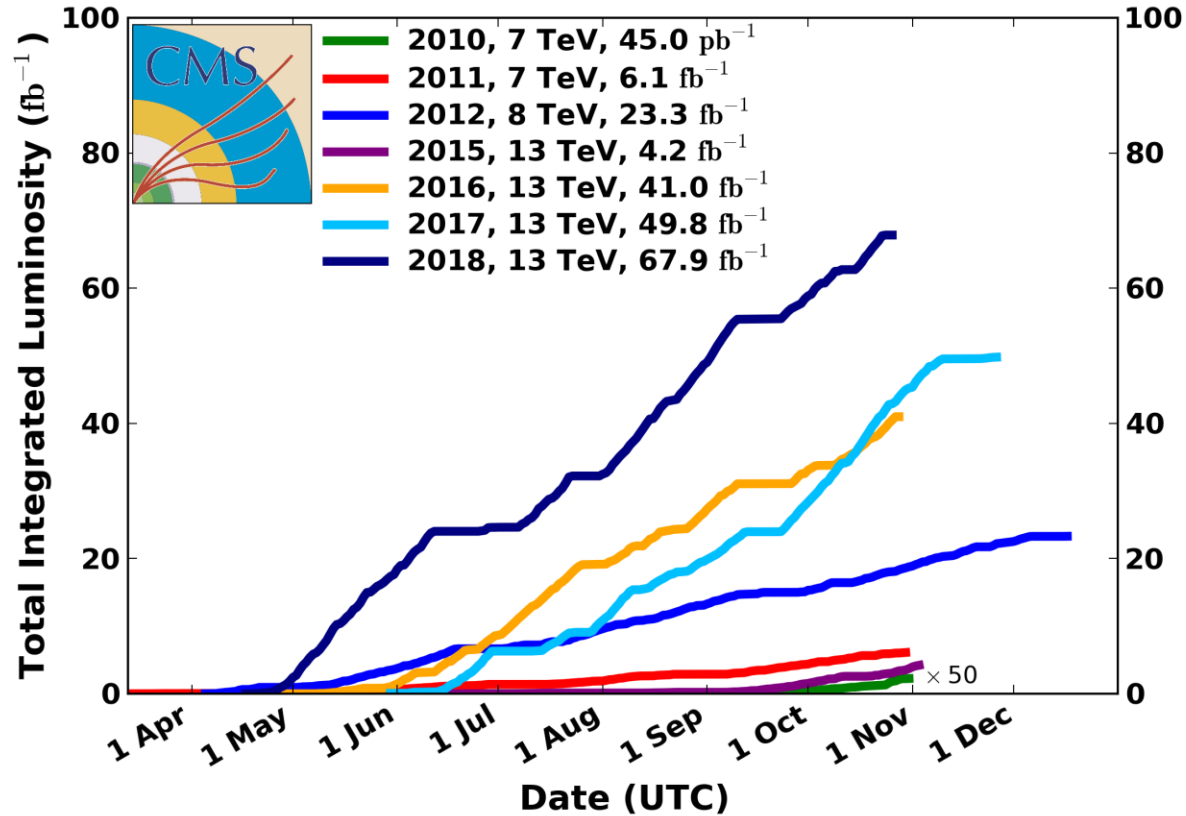
(jets, lepton, $\gamma\gamma$, Z)+ E_T^{miss} , (ee , $\mu\mu$, $\tau\tau$, $\gamma\gamma$, jj , lepton-jet, lepton- γ , γ -jet, VV , tt) resonances, slow-moving or long-lived particles, ...

RUN-2 completed: $\sim 140 \text{ fb}^{-1}$ per experiment at 13 TeV

Luminosity & Papers

CMS Integrated Luminosity Delivered, pp

Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC



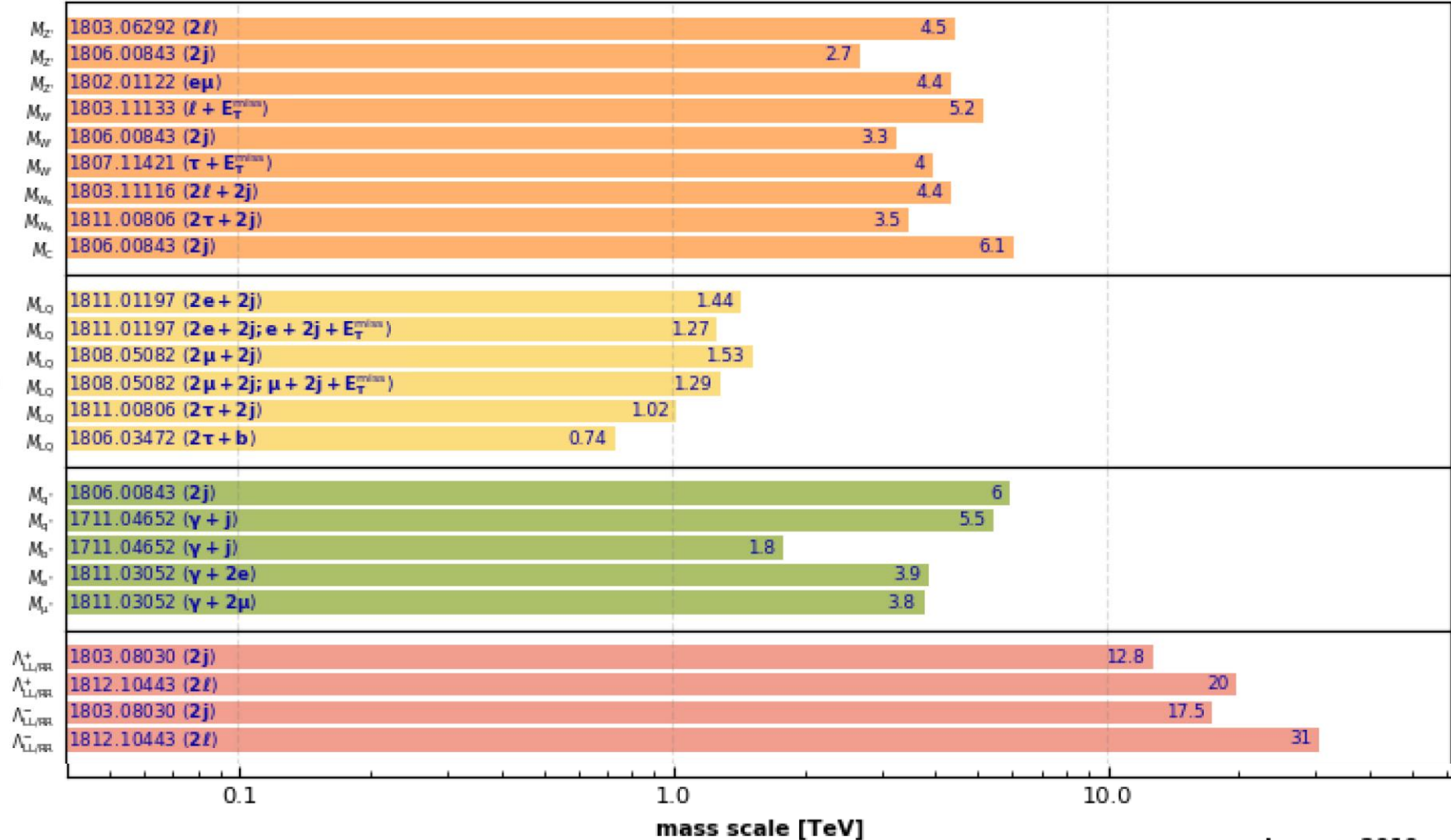
Overview of EXOTIC searches

Overview of CMS EXO results

36 fb⁻¹ (13 TeV)

CMS

- Heavy Gauge Bosons**
 - SSM $Z'(ll)$
 - SSM $Z'(q\bar{q})$
 - LFV Z' , BR($e\mu$) = 10%
 - SSM $W'(\ell\nu)$
 - SSM $W'(q\bar{q})$
 - SSM $W'(\tau\nu)$
 - LRSM $W_R(\ell N_R)$, $M_{N_R} = 0.5M_{W_R}$
 - LRSM $W_R(\tau N_R)$, $M_{N_R} = 0.5M_{W_R}$
 - Axigluon, Coloron, $\cot\theta = 1$
- Leptoquarks**
 - scalar LQ (pair prod.), coupling to 1st gen. fermions, $\beta = 1$
 - scalar LQ (pair prod.), coupling to 1st gen. fermions, $\beta = 0.5$
 - scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 1$
 - scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 0.5$
 - scalar LQ (pair prod.), coupling to 3rd gen. fermions, $\beta = 1$
 - scalar LQ (single prod.), coup. to 3rd gen. ferm., $\beta = 1, \lambda = 1$
- Excited Fermions**
 - excited light quark ($q\bar{q}$), $\Lambda = m_q^*$
 - excited light quark ($q\gamma$), $f_s = f = f' = 1, \Lambda = m_q^*$
 - excited b quark, $f_s = f = f' = 1, \Lambda = m_q^*$
 - excited electron, $f_s = f = f' = 1, \Lambda = m_e^*$
 - excited muon, $f_s = f = f' = 1, \Lambda = m_\mu^*$
- Contact Interactions**
 - quark compositeness ($q\bar{q}$), $\eta_{LL/RR} = 1$
 - quark compositeness (ll), $\eta_{LL/RR} = 1$
 - quark compositeness ($q\bar{q}$), $\eta_{LL/RR} = -1$
 - quark compositeness (ll), $\eta_{LL/RR} = -1$



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

January 2019

Overview of EXOTIC searches

Overview of CMS EXO results

36 fb⁻¹ (13 TeV)

Extra Dimensions

- ADD (jj) HLZ, $n_{ED} = 3$
- ADD ($\gamma\gamma, \ell\ell$) HLZ, $n_{ED} = 3$
- ADD G_{KK} emission, $n = 2$
- ADD QBH (jj), $n_{ED} = 6$
- ADD QBH ($e\mu$), $n_{ED} = 6$
- RS $G_{KK}(q\bar{q}, gg)$, $k/\overline{M}_{Pl} = 0.1$
- RS $G_{KK}(\ell\ell)$, $k/\overline{M}_{Pl} = 0.1$
- RS $G_{KK}(\gamma\gamma)$, $k/\overline{M}_{Pl} = 0.1$
- RS QBH (jj), $n_{ED} = 1$
- RS QBH ($e\mu$), $n_{ED} = 1$
- non-rotating BH, $M_{\text{bh}} = 4 \text{ TeV}$, $n_{ED} = 6$
- split-UED, $\mu \geq 4 \text{ TeV}$

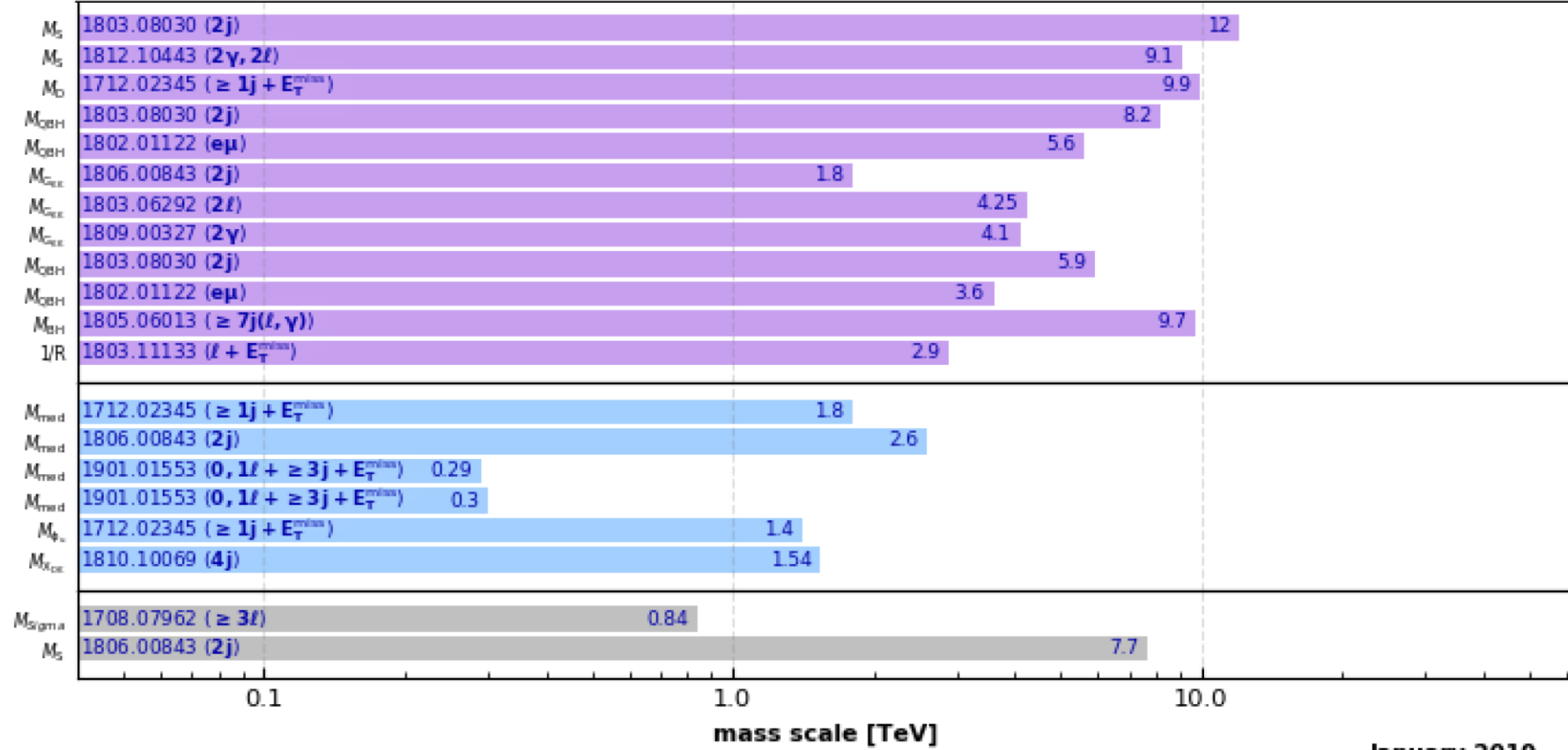
Dark Matter

- (axial-)vector mediator ($\chi\chi$), $g_q = 0.25$, $g_{DM} = 1$, $m_\chi = 1 \text{ GeV}$
- (axial-)vector mediator ($q\bar{q}$), $g_q = 0.25$, $g_{DM} = 1$, $m_\chi = 1 \text{ GeV}$
- scalar mediator ($+t/\bar{t}\bar{t}$), $g_q = 1$, $g_{DM} = 1$, $m_\chi = 1 \text{ GeV}$
- pseudoscalar mediator ($+t/\bar{t}\bar{t}$), $g_q = 1$, $g_{DM} = 1$, $m_\chi = 1 \text{ GeV}$
- scalar mediator (fermion portal), $\lambda_u = 1$, $m_\chi = 1 \text{ GeV}$
- complex sc. med. (dark QCD), $m_{\text{dark}} = 5 \text{ GeV}$, $\sigma_{\text{dark}} = 25 \text{ mm}$

Other

- Type III Seesaw, $B_e = B_\mu = B_\tau$
- string resonance

CMS



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

January 2019

... today's menu ...

some recent results from RUN-2

Heavy Gauge Bosons & Extra Dimensions

$X \rightarrow e^+e^- , \mu^+\mu^- , X \rightarrow e\nu , \mu\nu , \tau\nu , tb$

$X \rightarrow \text{dijet} , X \rightarrow tt$

$X \rightarrow \gamma\gamma , X \rightarrow WW, WZ, ZZ, qW, qZ$

excited leptons

$e^* \rightarrow e\gamma , \mu^* \rightarrow \mu\gamma$

dark matter

DM +t /tt

Vector-Like Quarks

$B \rightarrow Hb , TT/BB \rightarrow \text{fully hadronic}$

3rd generation scalar LQ

LQ $\rightarrow \tau b$

type-III seesaw heavy leptons

$qq \rightarrow W^\pm \rightarrow \Sigma^0 \Sigma^\pm \rightarrow (\ell^\pm W)(W^\pm \nu)$

Long-lived particles

with delayed jets + missing P_T

More material:

<http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html>

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html>

<http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html>

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html>

... how we do it ...

Search for **deviations** from SM background;
Use an **optimal observable** with maximum
signal – background separation

- Bump hunting
- Excess in tails of distributions
- Special structures (peaks/dips) due to *interference*

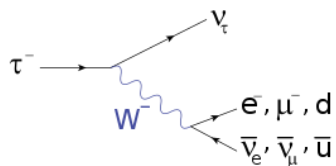
Final states contain :

leptons

electrons

muons

taus



$\tau_{hadronic}$: *tau jets*

missing \vec{p}_T

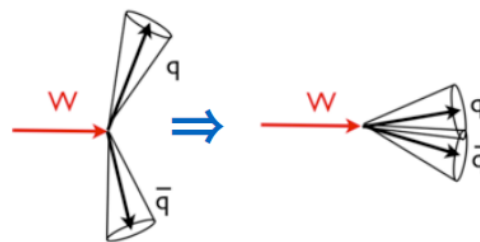
$$\vec{p}_T^{miss} = - \sum_{\text{visible particles}} \vec{p}_T$$

sensitive to multiple p-p
interactions (**pileup**)

*pileup suppression is
fundamental*

Physics Objects

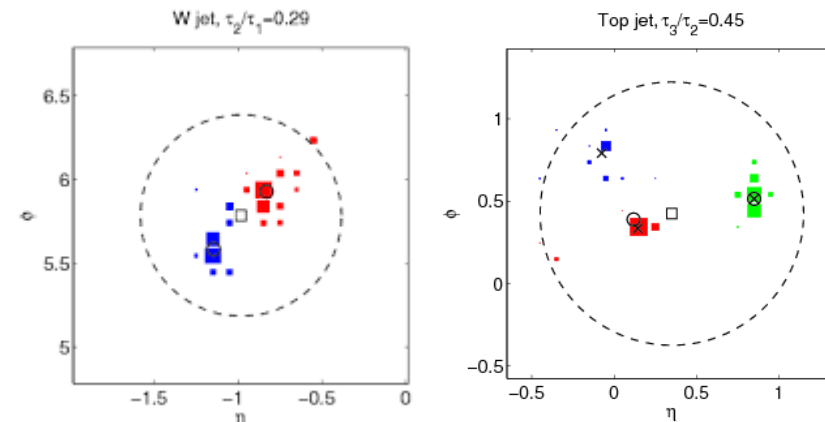
jets



Resolved
anti-kT
($R=0.4$)

Boosted
anti-kT
($R=0.8$)

b/t - tagging



jet substructure

N-subjetiness [JHEP 1103:015, 2011]

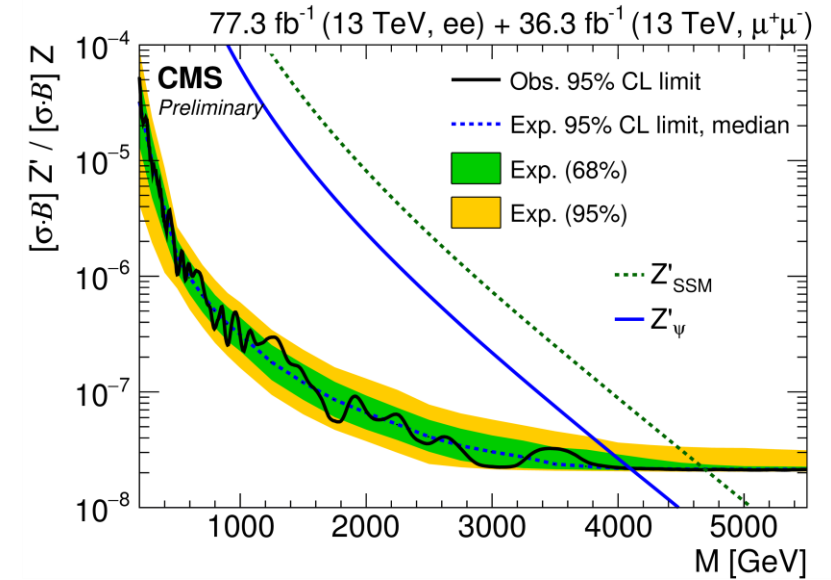
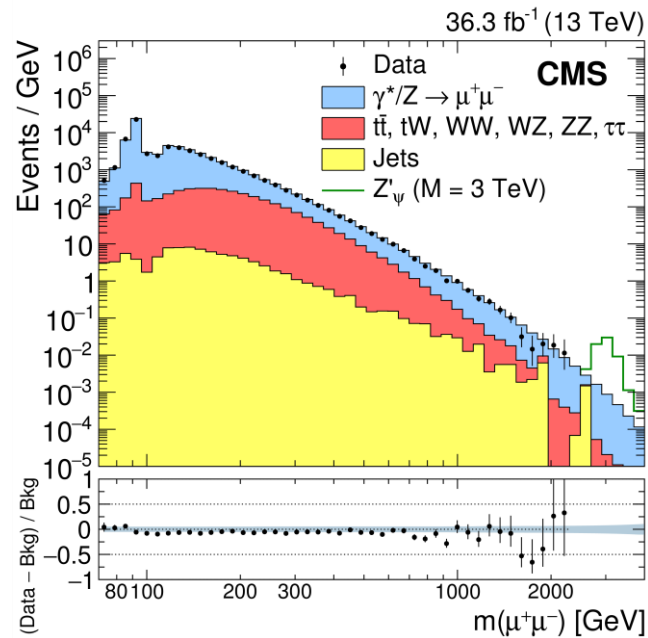
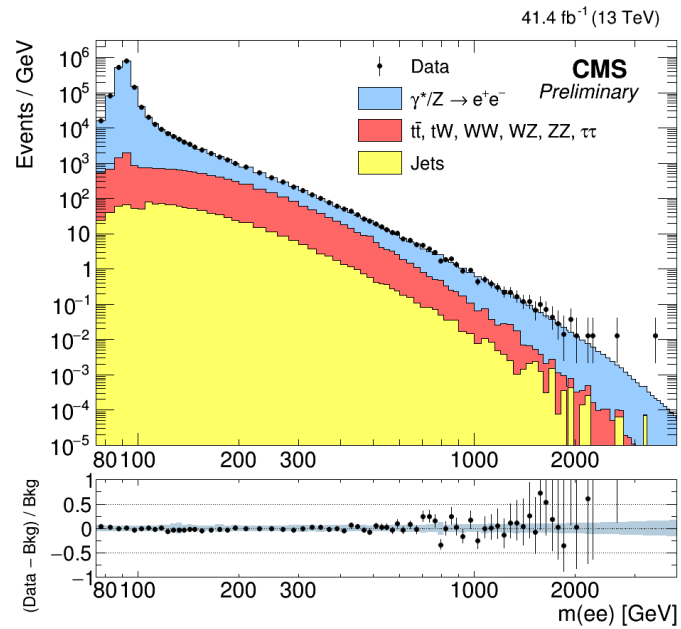
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k} \}$$

jet grooming (jet mass)

Trimming [JHEP 1002:084,2010]

Pruning [Phys.Rev.D80, 051501 (2009)]

Softdrop [JHEP05(2014),146]



- Search separately in e^+e^- & $\mu^+\mu^-$ final states; then combine results

- High signal selection efficiencies

- $\sigma(Z')/\sigma(Z)$ ratio limits

- No dependence on luminosity

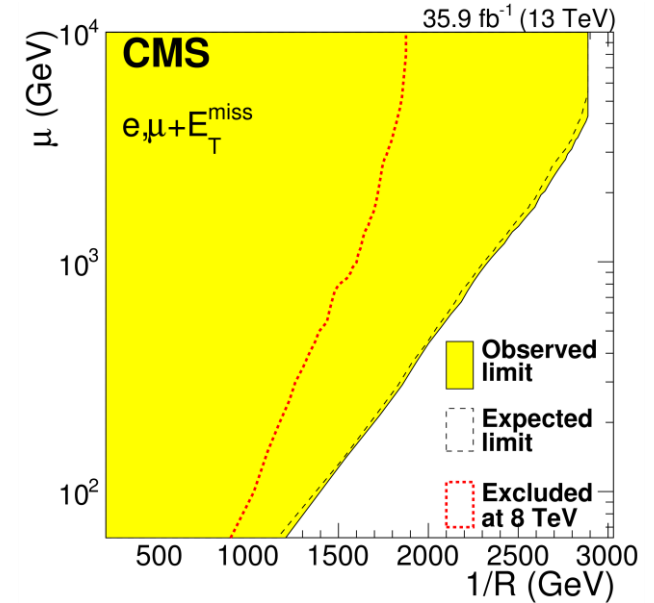
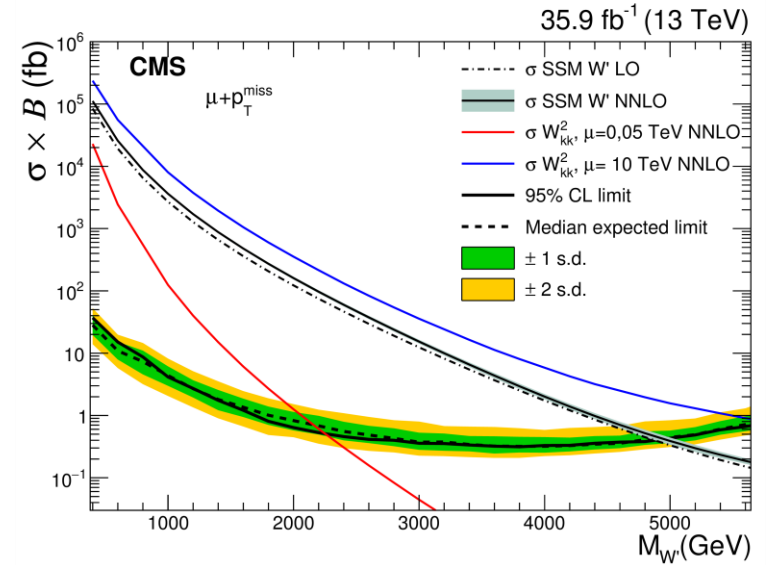
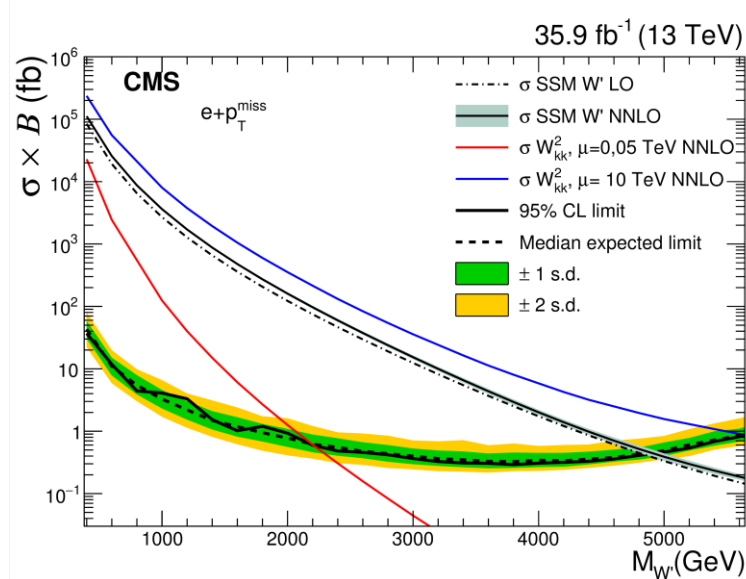
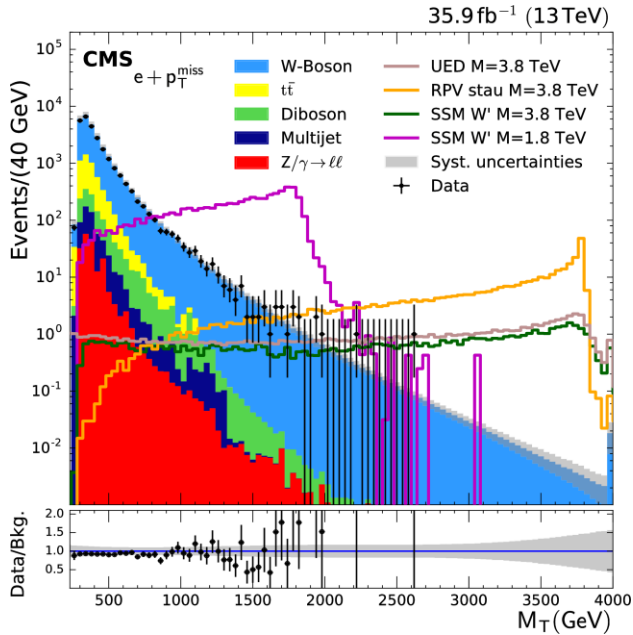
- suppress correlated experimental uncertainties

- Limits for narrow Z'

- Upper (lower) limits on $\sigma \cdot B$ (mass) for various Z' models

- results for various resonance width hypotheses

Channel	Model	Obs. limit [TeV]	Exp. limit [TeV]
ee (2017)	Z'_{SSM}	4.10	4.15
	Z'_{ψ}	3.35	3.55
ee (2016 and 2017) + $\mu\mu$ (2016)	Z'_{SSM}	4.7	4.7
	Z'_{ψ}	4.1	4.1



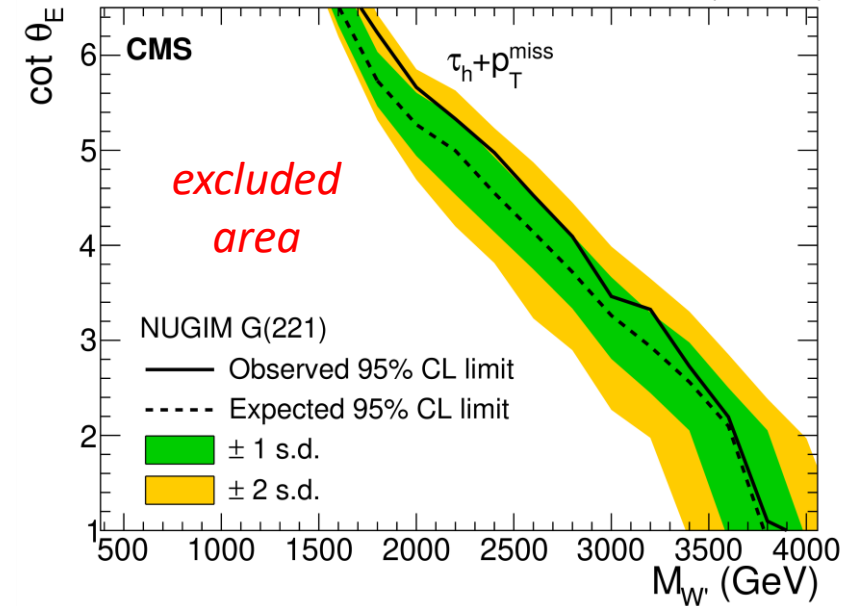
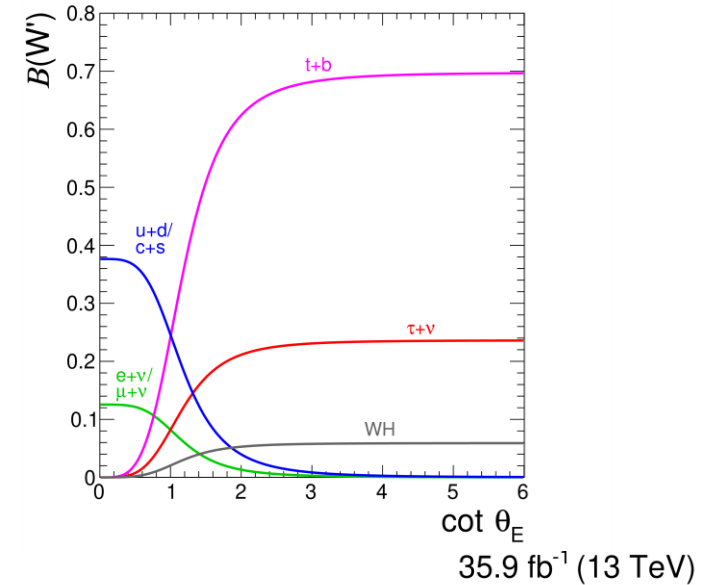
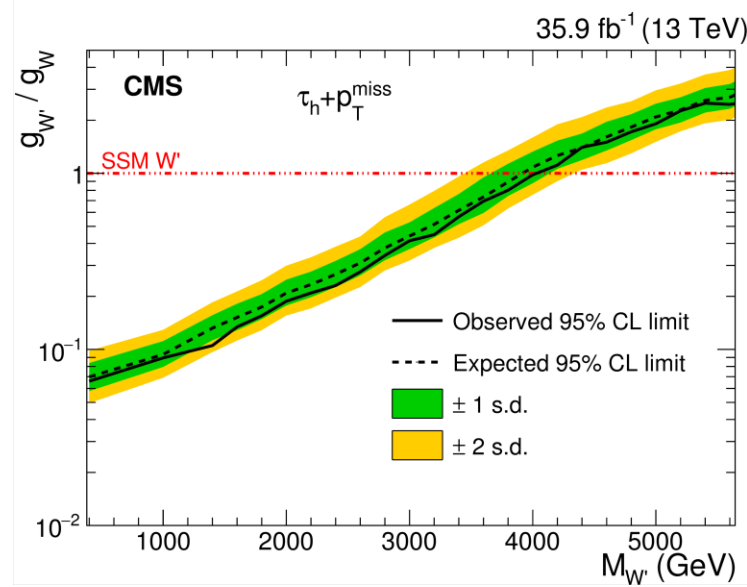
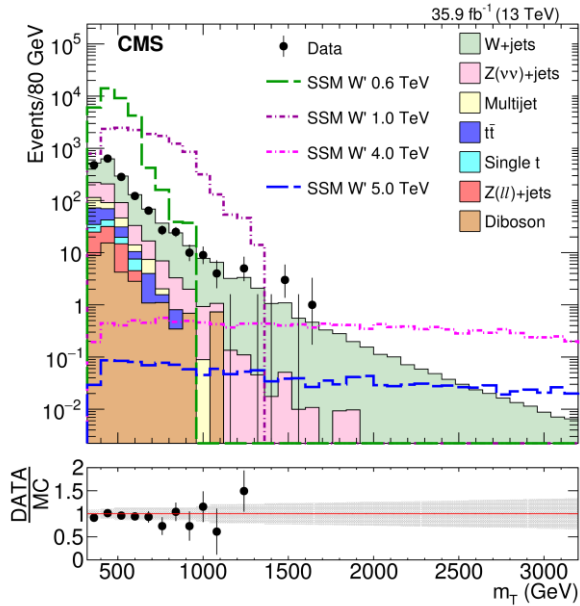
search : separately in $e\nu$ & $\mu\nu$ final states; then combine results

interference : The W' boson is assumed not to couple to the SM W and Z .

backgrounds : from simulation except multijets (data-driven)

uncertainties : lepton & E_T^{miss} reconstruction, background modelling, PDFs , luminosity

The results are interpreted in the context of the **SSM, split UED & RPV stau**

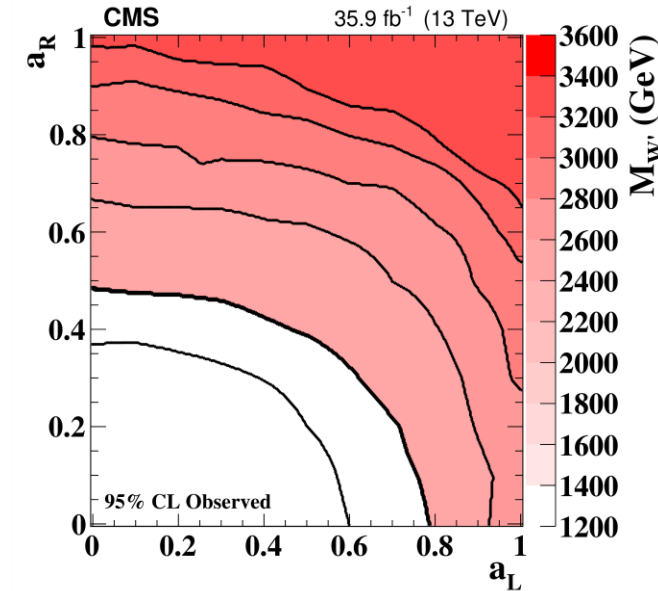
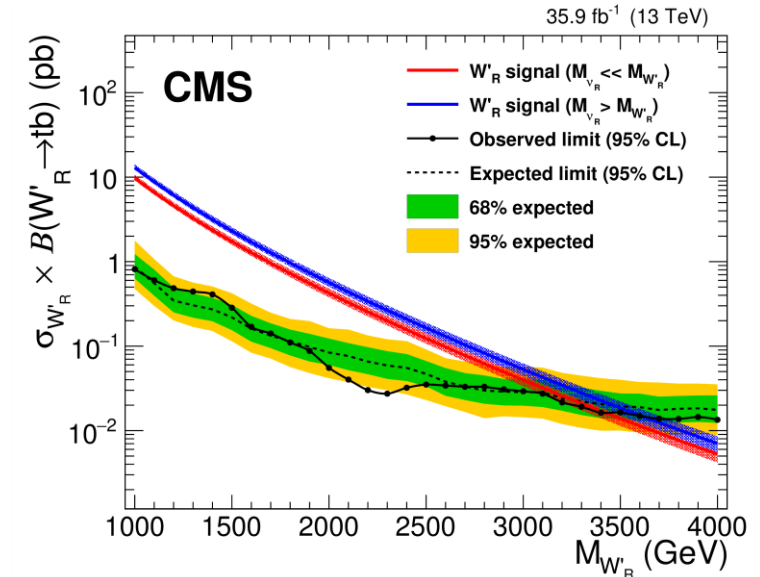
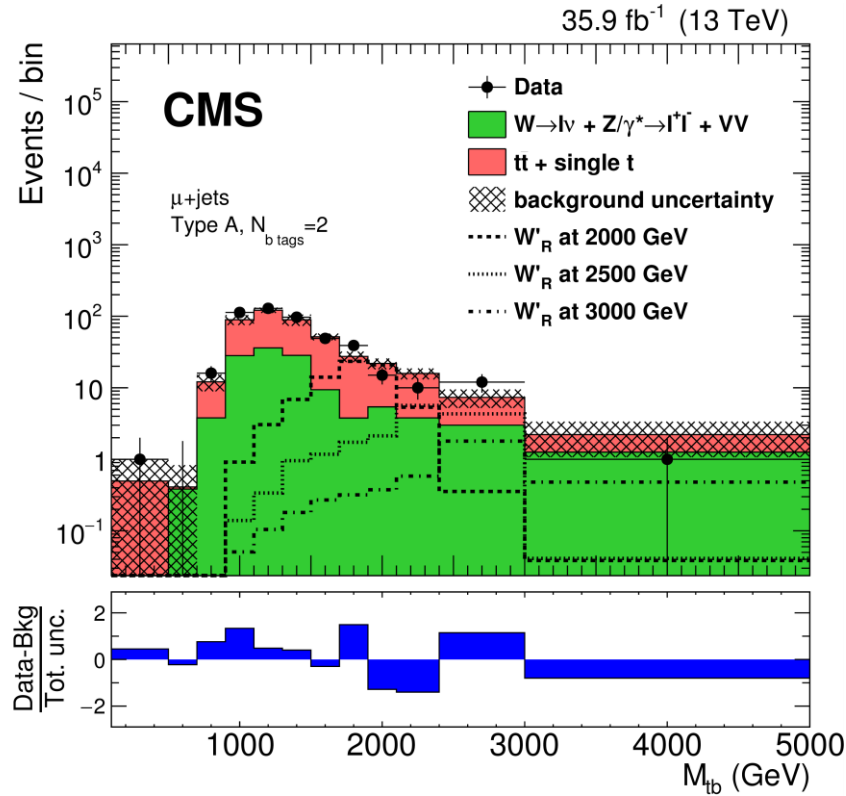
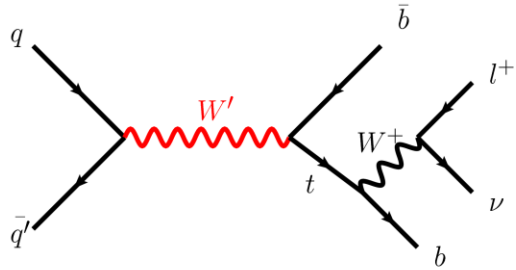


search : charged heavy gauge bosons decaying to $\tau_{\text{hadronic}} + \nu$

reconstruction: τ_{hadronic} is a tau jet seeded from a jet (anti-kT , R=0.4)

backgrounds : off-shell tail of the m_T distribution from the SM W.

models: SSM, Non-universal G(221) enhanced BRs to 3rd generation fermions
 G(221): $\cot\theta_E$ mixing angle, related to W'_{NU} couplings to heavy fermions.



For $M_{W'} > 180$ GeV, $W' \rightarrow tb$ opens

Searches directly probe the W' boson coupling to 3rd generation quarks.

Final state: one e/μ , jets, MET

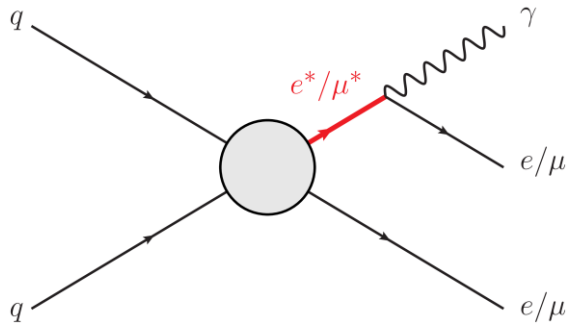
$M_{W'}$ fully reconstructed up to a quadratic ambiguity.

$\Gamma(W') \sim 3\% M_{W'} \ll$ detector resolution.

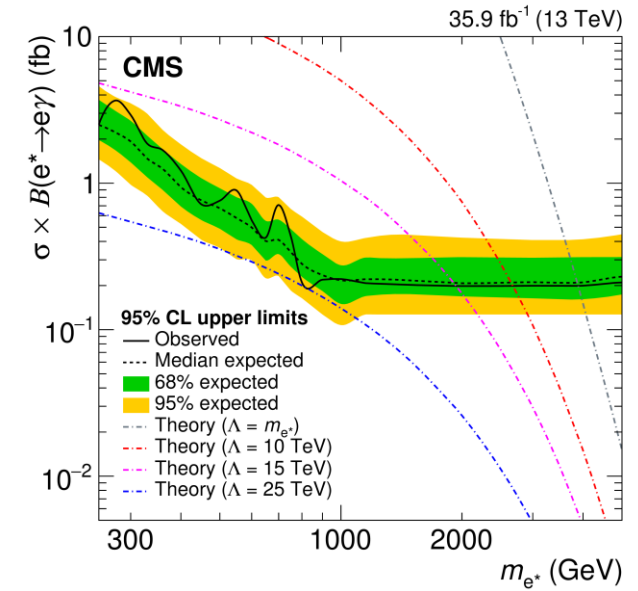
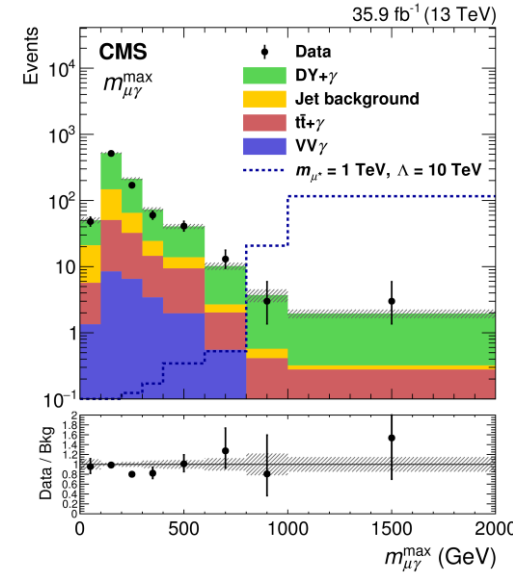
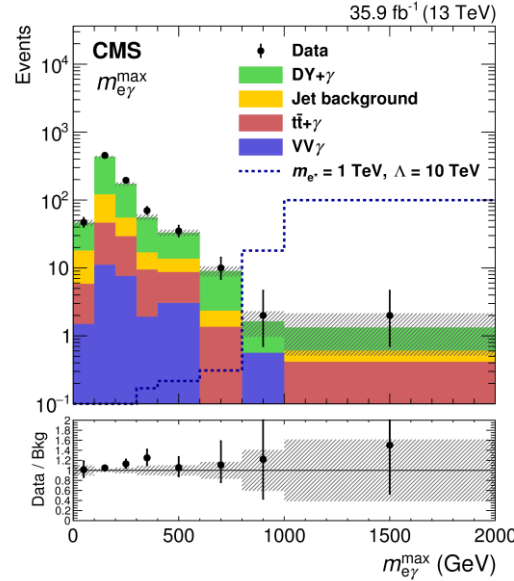
Search for W' bosons with varying combinations of right- (a_R) or left-handed (a_L) couplings to fermions. For $a_L > 0$, interference with SM W is taken into account.

W'_R search : i) $M_{VR} < M_{W'_R}$, $W'_R \rightarrow lv_R$ & $W'_R \rightarrow qq'$, $BR(W' \rightarrow tb) \sim 0.24$

ii) $M_{VR} > M_{W'_R}$, $W'_R \rightarrow lv_R$ **forbidden**, $BR(W' \rightarrow tb) \sim 0.32$ (enhanced)



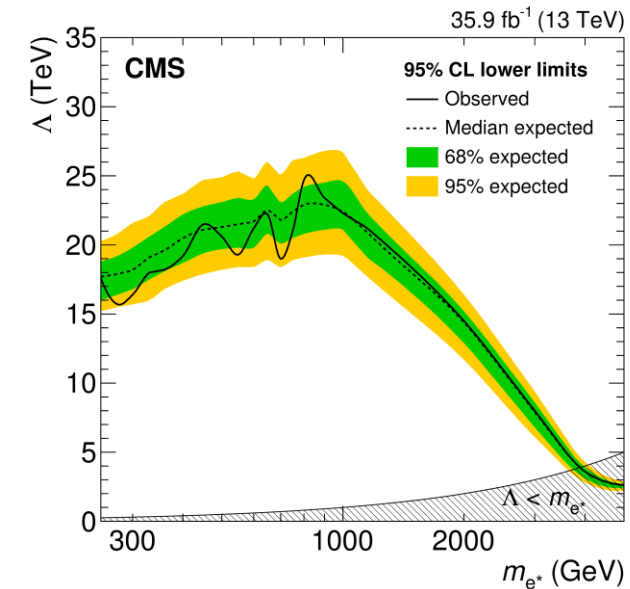
New strong force with characteristic energy scale Λ (compositeness scale)

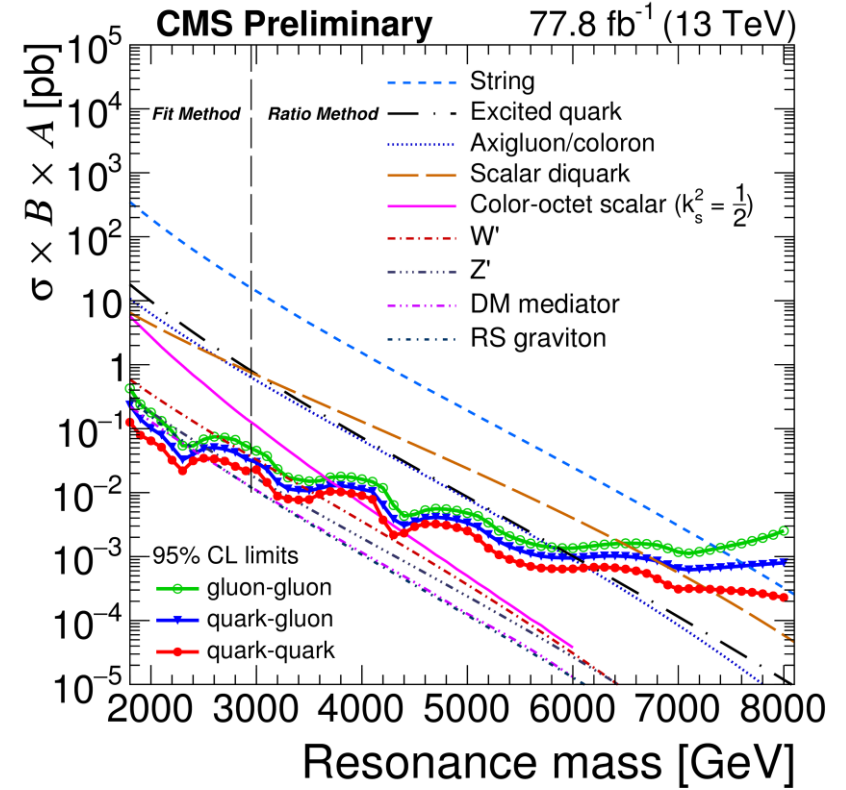
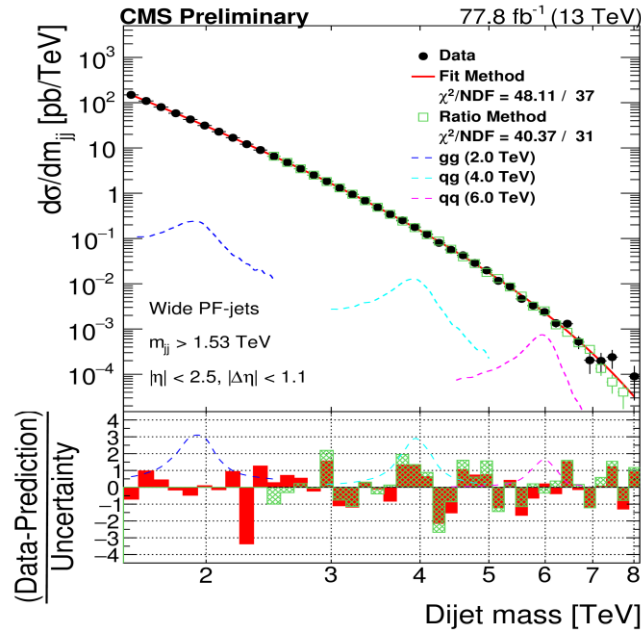
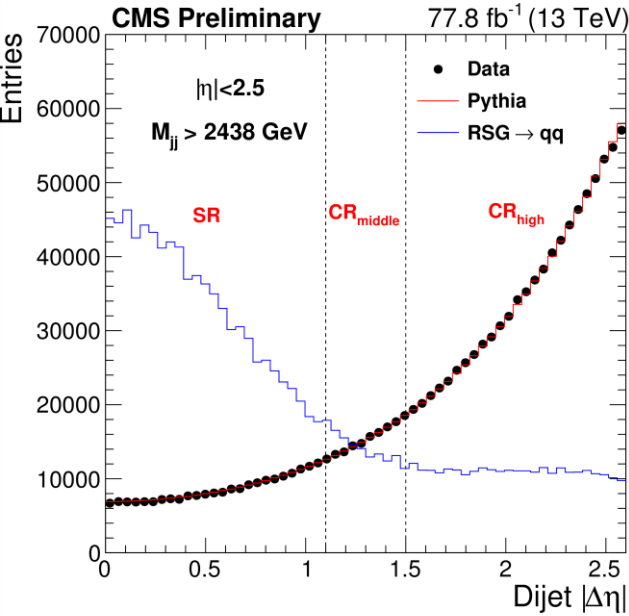


Compositeness models predict **excited** leptons : $e^* (\mu^*) \rightarrow e\gamma (\mu\gamma)$
 Production through **Contact Interactions (CI)**, decay via **SM gauge interactions**

final state: same-flavor lepton pair \rightarrow low bkgd but **ambiguity** in the e^*/μ^* reconstruction.
thresholds: $ee\gamma, \mu\mu\gamma$ [e, μ, γ $p_T > 35$ GeV and $\Delta R(\ell, \gamma) > 0.7$]. Both pairings are used.
Bkgd rejection : 2D cut on $(m_{\ell\gamma}^{\max}, m_{\ell\gamma}^{\min})$ plane.

Channel	Observed (expected) limit on m_{ℓ^*} for $m_{\ell^*} = \Lambda$, TeV	Observed (expected) limit on Λ for $m_{\ell^*} \approx 1$ TeV, TeV
$ee\gamma$	3.9 (3.8)	25 (23)
$\mu\mu\gamma$	3.8 (3.9)	25 (23)





search: high mass dijet resonances using wide PF-jets
 ($\Delta R < 1.1$, reduced sensitivity to gluon radiation from the final-state partons)

QCD background : t-channel production

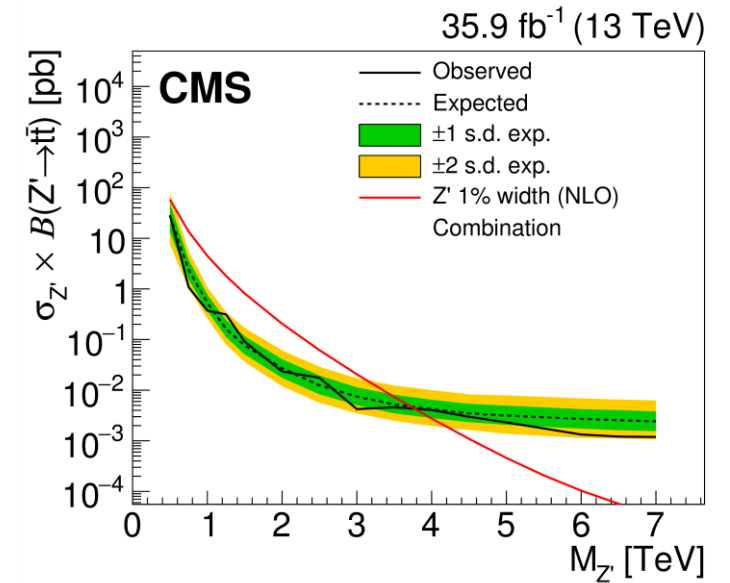
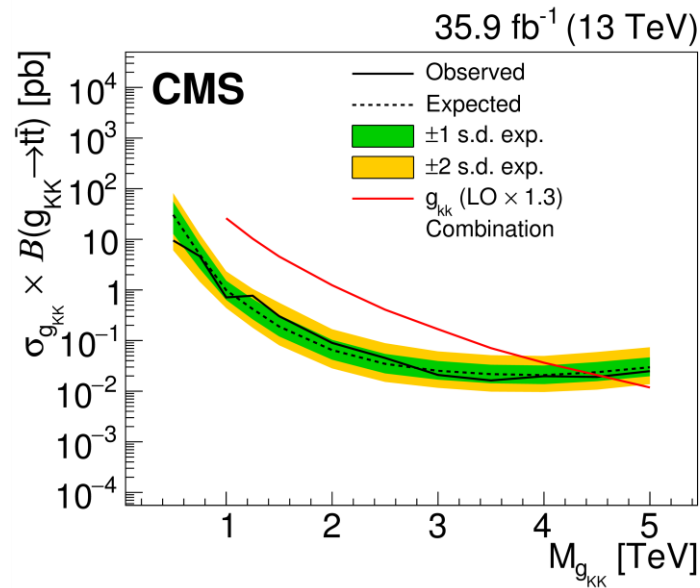
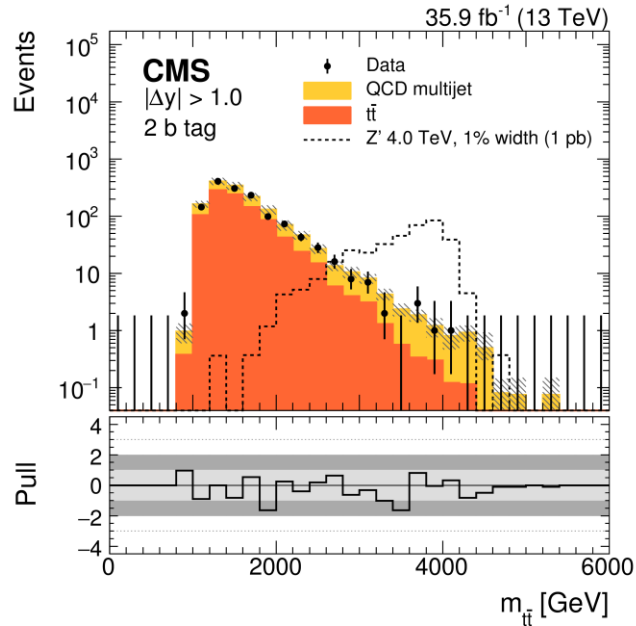
- a) fitting an empirical functional form
- b) data-driven method via a $|\Delta\eta|$ sideband.

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3} \ln(x)}$$

models : s-channel dijet resonances

widths and line shapes depend on the parton content of the resonance (qq, qg, or gg).

Model	Final State	Observed (expected) mass limit [TeV]	
		36 fb ⁻¹	77.8 fb ⁻¹
String	qg	7.7 (7.7)	7.6 (7.9)
Scalar diquark	qq	7.2 (7.4)	7.3 (7.5)
Axigluon/coloron	q \bar{q}	6.1 (6.0)	6.2 (6.3)
Excited quark	qg	6.0 (5.8)	6.0 (6.0)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.7 (3.8)
W'	q \bar{q}	3.3 (3.6)	3.6 (3.8)
Z'	q \bar{q}	2.7 (2.9)	2.9 (3.1)
RS graviton ($k/M_{\text{PL}} = 0.1$)	q \bar{q} , gg	1.8 (2.3)	2.4 (2.4)
DM mediator ($m_{\text{DM}} = 1$ GeV)	q \bar{q}	2.6 (2.5)	2.5 (2.8)

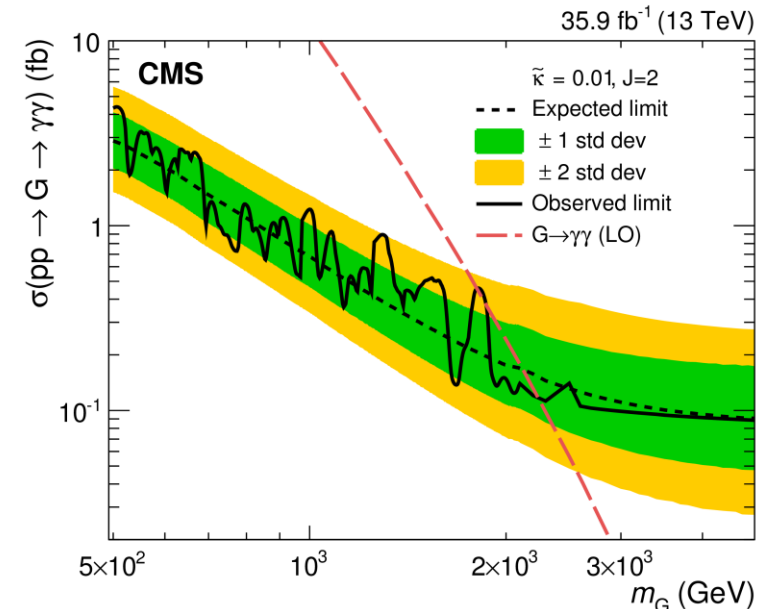
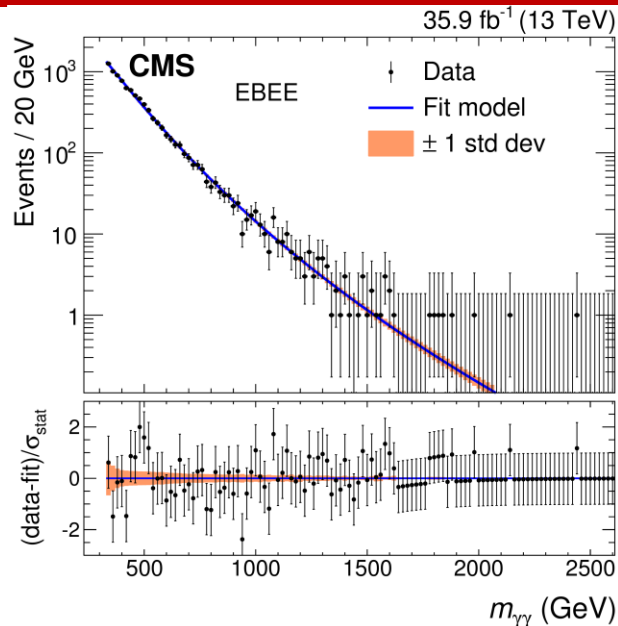
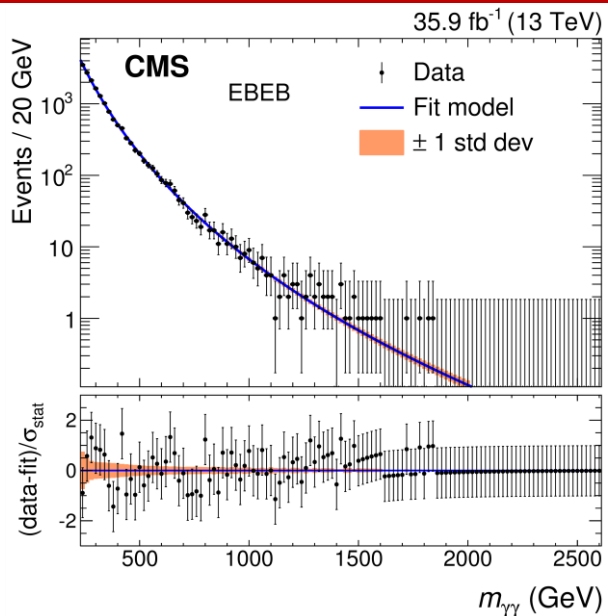


search : spin-1 resonance $X \rightarrow t\bar{t}$, **no interference** with SM $t\bar{t}$ production assumed.
 $t\bar{t}$ modes: fully-leptonic, semi-leptonic, hadronic , leptons = e , μ

strategy : optimized for top-quarks with high Lorentz boosts;
 requires non-isolated leptons and jet substructure techniques.
 simult. measurement of the bkgds and t-tagging efficiency from data.

leptophobic topcolor Z'			
Width	1%	10%	30%
Exclusion (TeV)	0.50 - 3.80	0.50 - 5.25	0.50 - 6.65

1 st Kaluza-Klein excitation of the gluon in the RS scenario (g_{KK})	
Exclusion (TeV)	0.5 - 4.55



search : resonant new physics signatures with high-mass diphoton events

advantages :

lower SM backgrounds / better mass resolution w.r.t. dijets

larger branching fraction w.r.t. dileptons

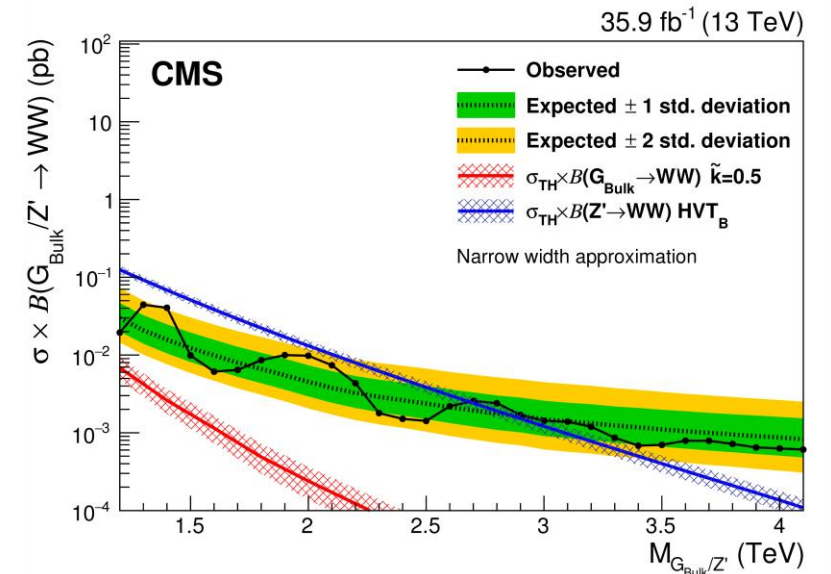
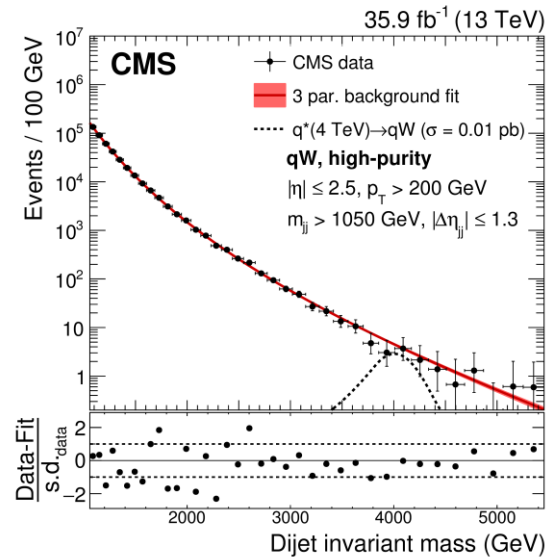
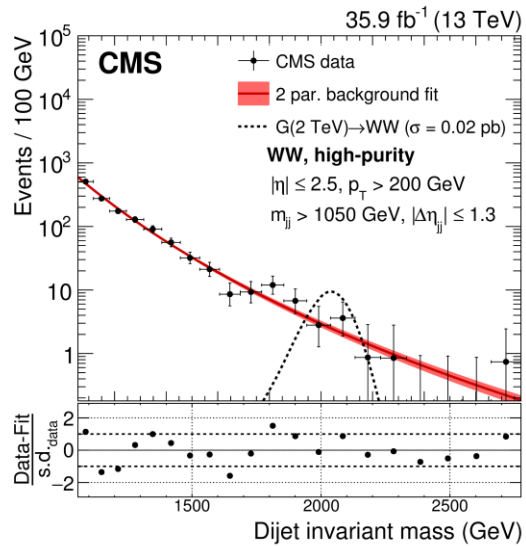
background estimation : m_{γγ} fit to a parametrized functional form →

fully data-driven description of the shape

limits : on heavy spin-0/spin-2 resonances

RS graviton			
$\tilde{\kappa}$	0.01	0.1	0.2
Γ/M	1.4×10^{-4}	1.4×10^{-2}	5.6×10^{-2}
Exclusion (TeV)	2.3	4.1	4.6

Also, model independent limits on cross sections in the fiducial volume ($P_T^\gamma > 75$ GeV) for **resonant** pp → γγ processes.



Search : narrow VV, qV ($V=W,Z$) resonances decaying to fully hadronic final states

models :

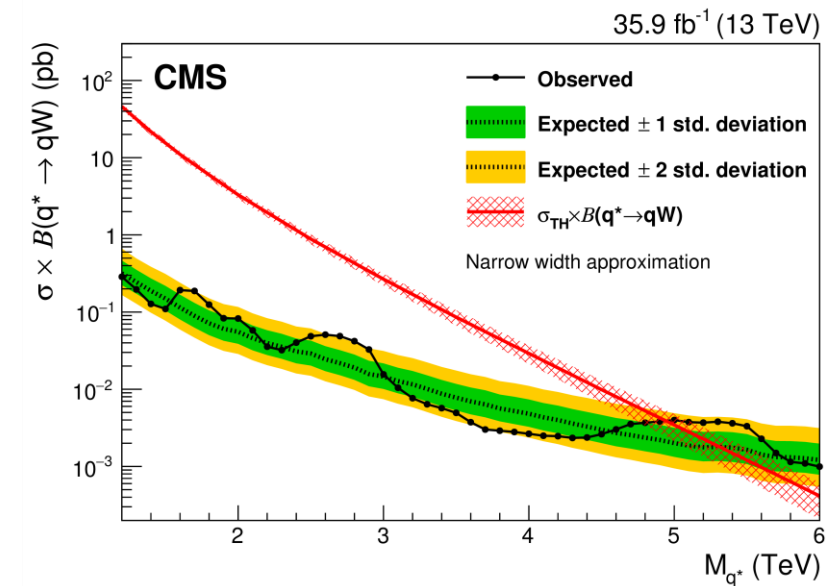
spin-1 Heavy Vector Triplet Model (HVT) , $X \rightarrow WZ, WW$

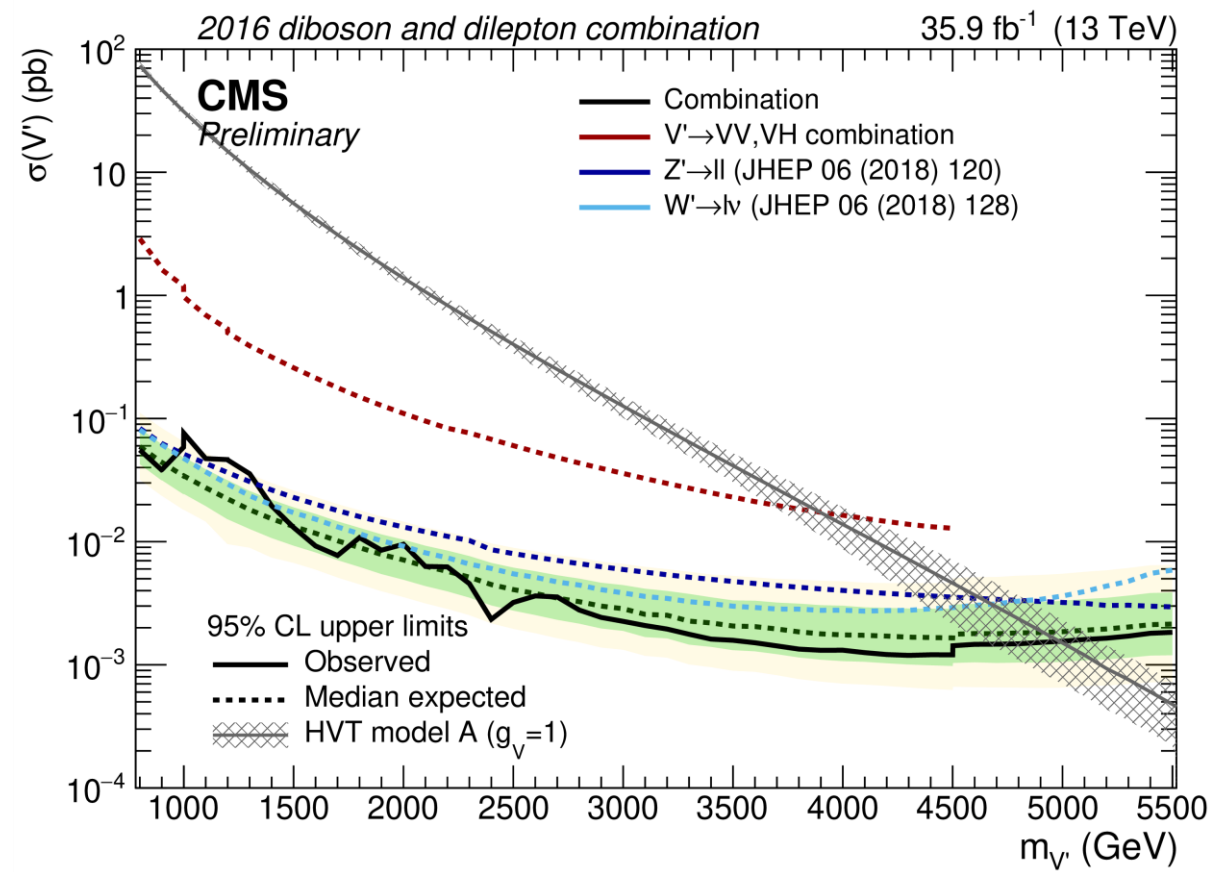
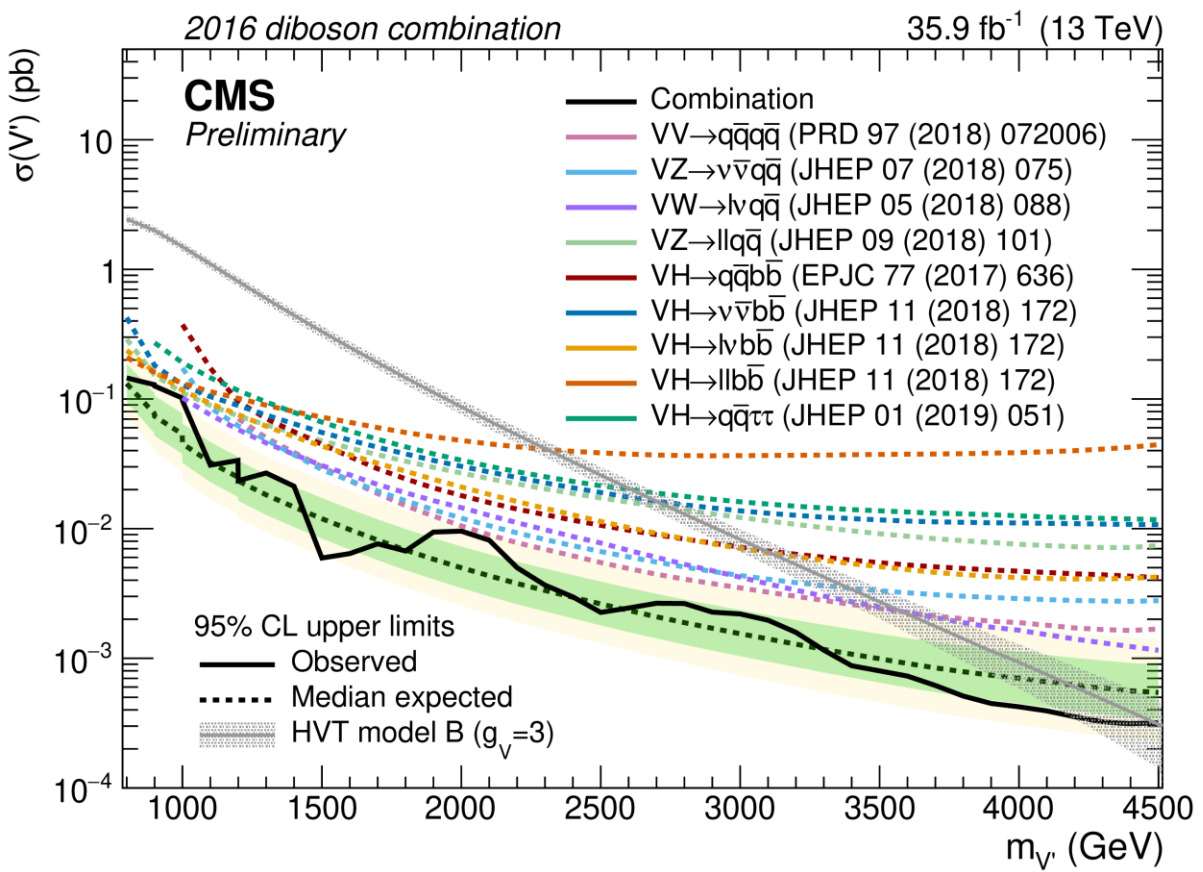
spin-2 graviton $G_{KK} \rightarrow WW, ZZ$ (bulk RS)

excited quarks $q^* \rightarrow qW, qZ$

diboson system : pairs of high transverse momentum, **large-radius** ($R=0.8$) jets tagged as compatible with the hadronic decay of a boosted W or Z boson, using **jet mass** and **substructure** properties.

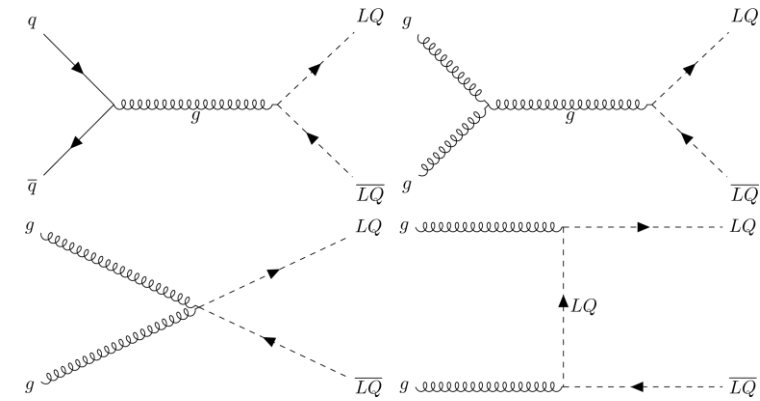
background : from multijet production suppressed by the characteristic jet substructure of W/Z bosons



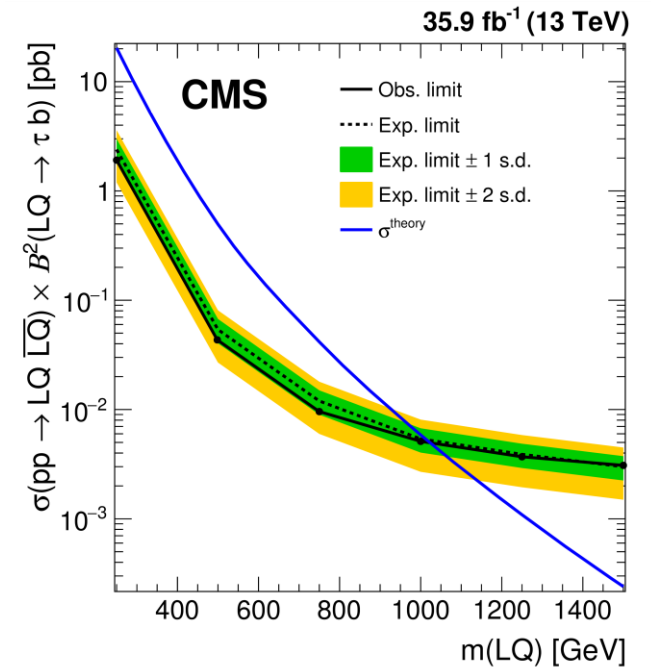
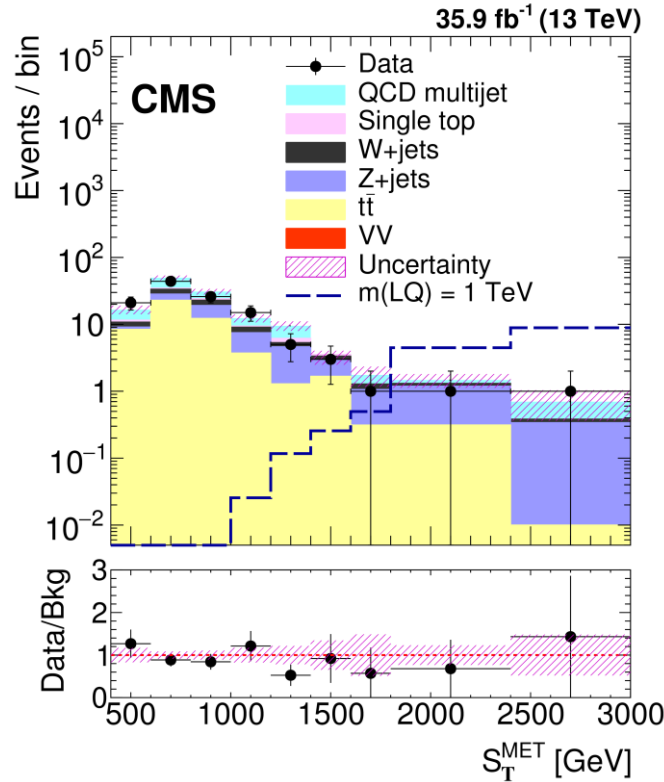


HVT model B : branching fractions to SM bosons dominate

HVT model A : branching fractions to SM bosons suppressed



Exchange of LQs might explain the potential violation (if confirmed) of **lepton universality** in measurements of B-meson decays [arXiv:1706.07808, arXiv:1309.0301]



Search : pair production of third-generation scalar LQs decaying into $\tau b \tau b$ ($\tau \equiv \tau_h$)

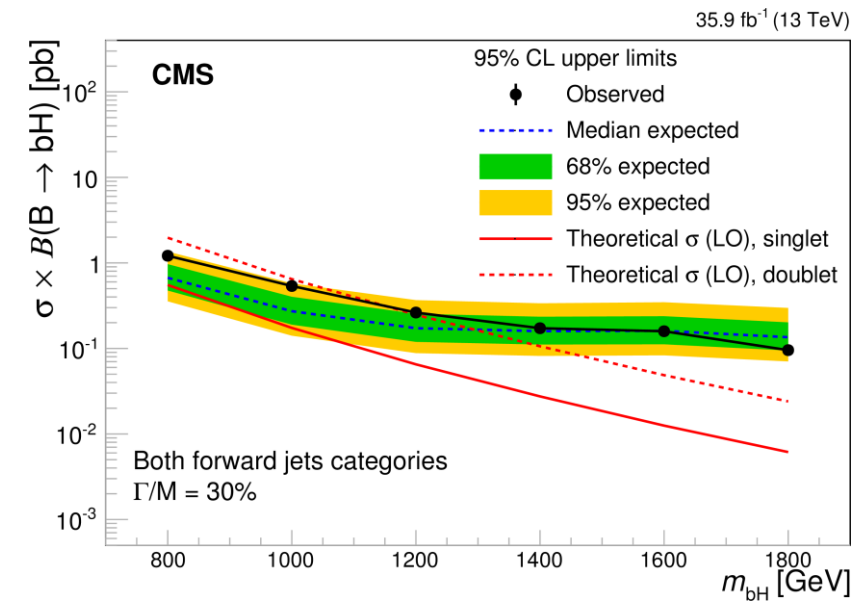
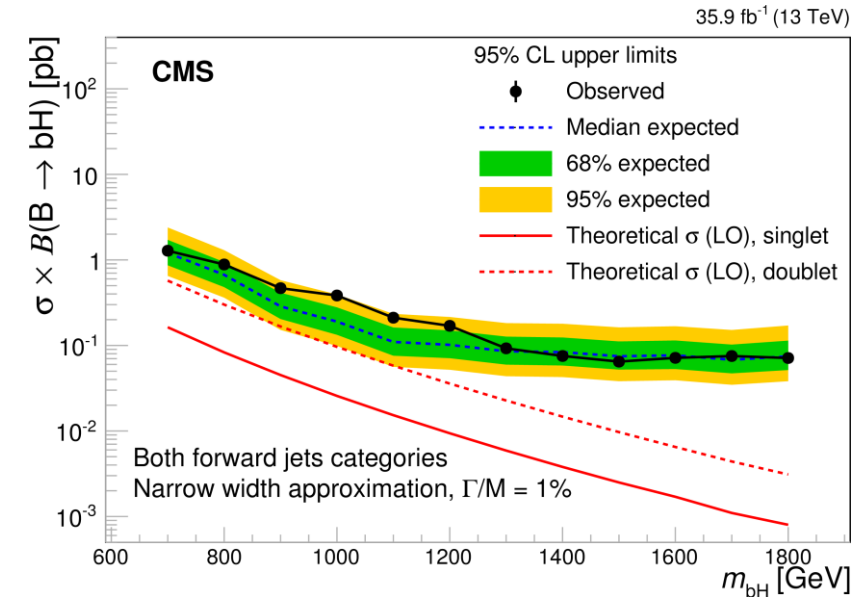
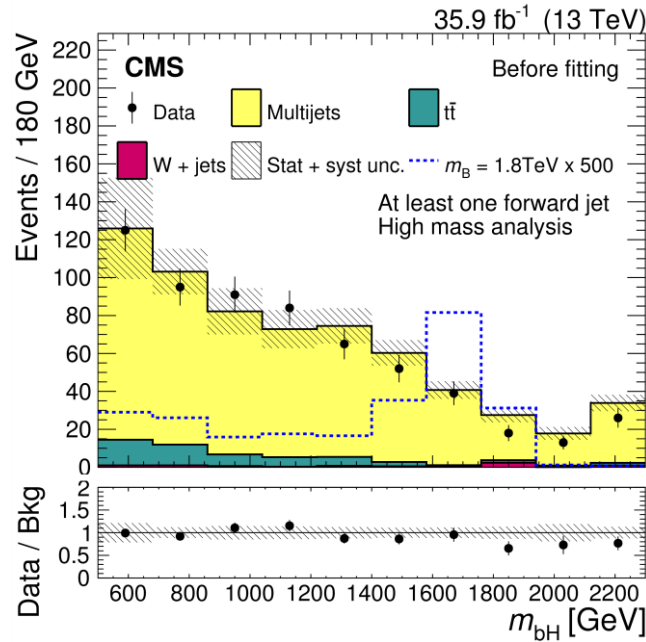
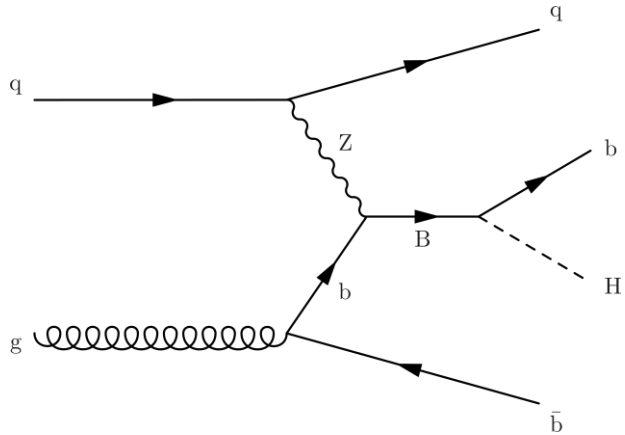
Assumption : BR (LQ $\rightarrow \tau b$) = 100%

Sensitive variable :

$$S_T^{MET} = p_T^{\tau_{h,1}} + p_T^{\tau_{h,2}} + p_T^{j1} + p_T^{j2} + p_T^{miss}$$

Source	QCD	W+jets	Z+jets	tt	VV	Signal
Integrated luminosity	—	2.5	2.5	2.5	2.5	2.5
$\tau_h \tau_h$ trigger	—	6	6	6	6	6
τ_h identification	—	33	10	10	12	10
JES	—	9	8	6	9	5
TES	—	9	9	9	8	3
PDF	—	6	6	6	6	6
Scales	—	1	1	3.5	—	2.5
Background est.: closure+norm.	21	—	7	3	—	—

Process	Yield
tt	49.8 ± 11.8
QCD	33.8 ± 9.3
Z+jets	23.4 ± 6.5
W+jets	13.4 ± 6.2
Single top	4.6 ± 2.2
VV	2.0 ± 1.5
Total	127.0 ± 17.7
Observed	117
$m(W_R) = 3.0$ TeV	17.3 ± 2.5
$m(LQ) = 1.0$ TeV	14.2 ± 2.1

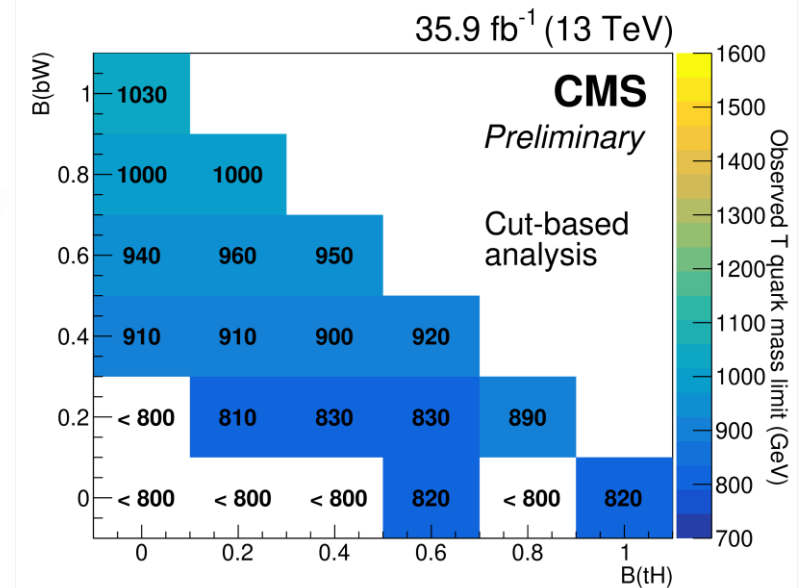
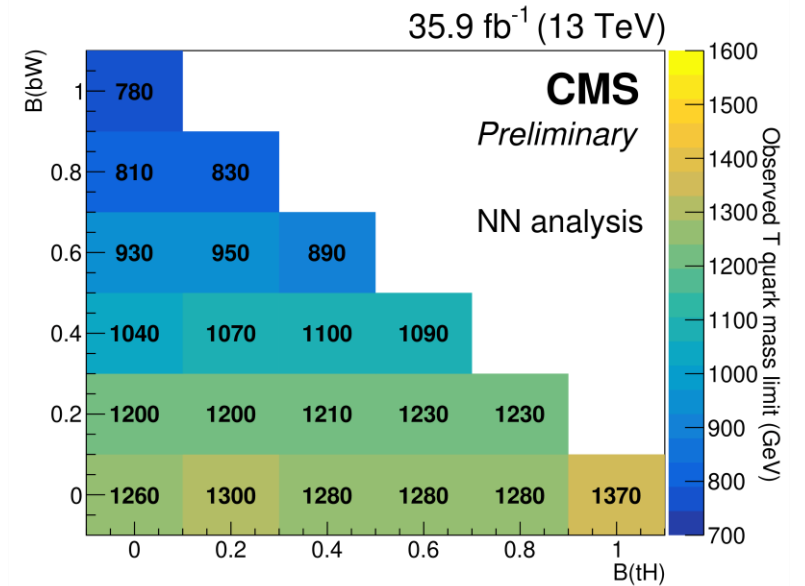
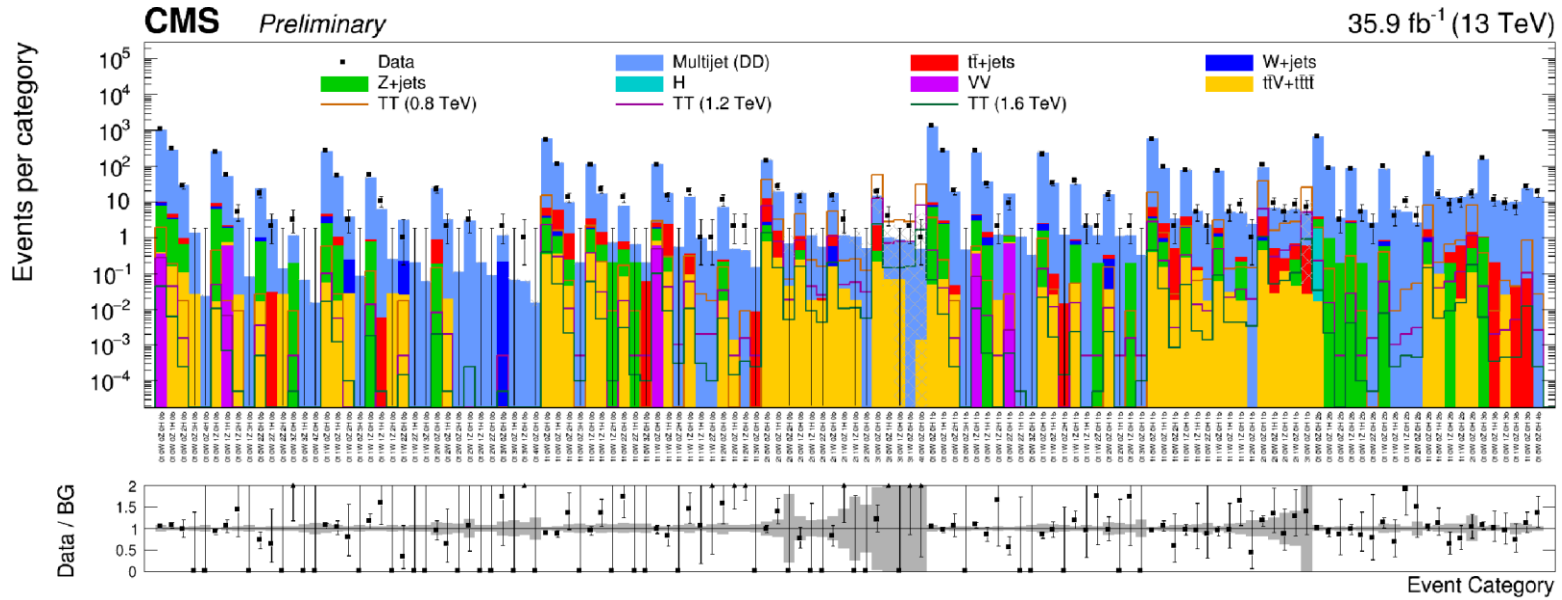


$H \rightarrow bb$: highly boosted pair reconstructed as a single collimated jet
assumptions : B quark belongs to a singlet or doublet representation.
 It decays exclusively to SM particles.

singlet BRs of $B \rightarrow Hb, Zb, Wt$ are 25%, 25%, 50%,
 doublet BRs of $B \rightarrow Hb, Zb, Wt$ are 50%, 50%, 0%

BRs depend on the VLQ mass m_B

Test various B widths ($\Gamma/M = 1, 10, 20, 30\%$)



Search: Vector-like Quark pairs, TT/BB, T → bW, tZ, tH B → tW, bZ, bH

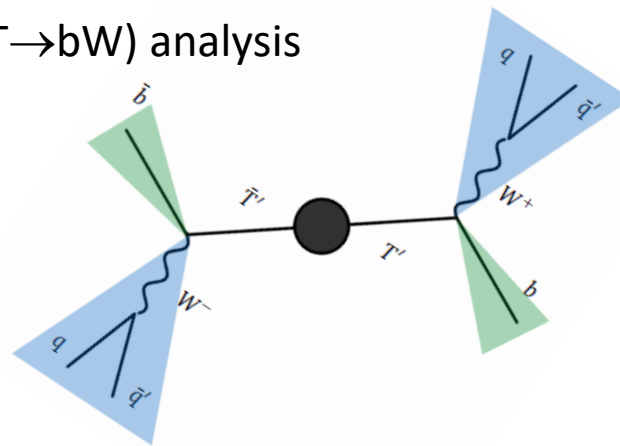
Method: Novel NN based & traditional cut-based (T → bW) analysis

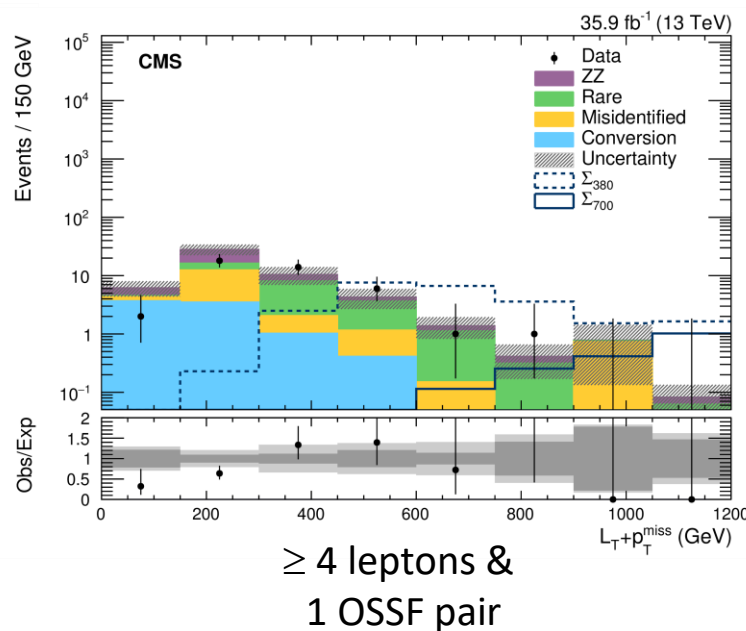
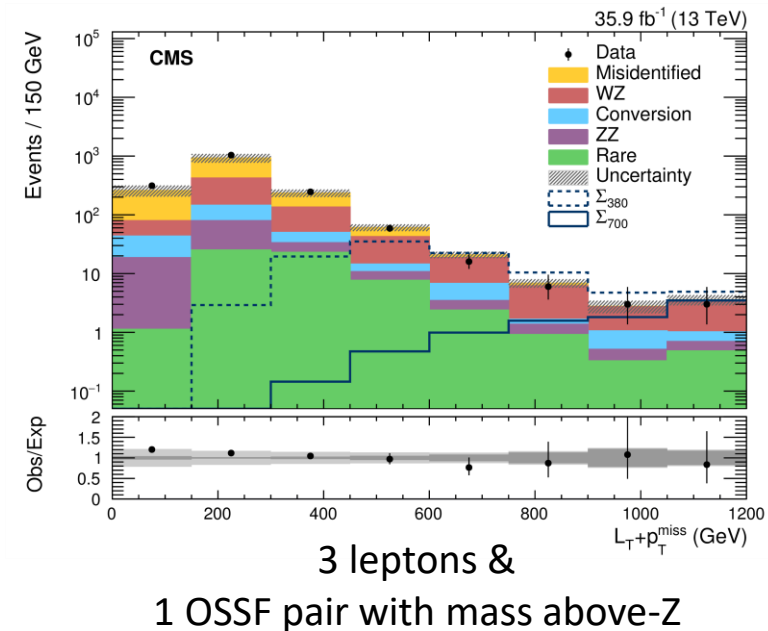
“**Boosted Event Shape Tagger**” : multiclassification algorithm labels candidate jets as originating from t-quark, W, Z, H, b-quark, light-q & g

NN based analysis : 126 categories

(4jets; $N_i \leq 4$; $N_t + N_H + N_W + N_Z + N_b + N_j = 4$)

Signal discrimination : use H_T^{AK8} distribution per category, $H_T^{AK8} > 1600$ GeV





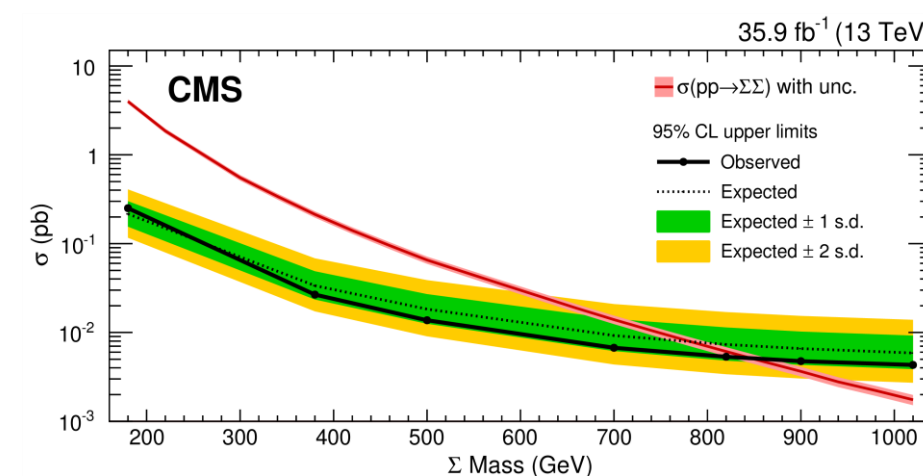
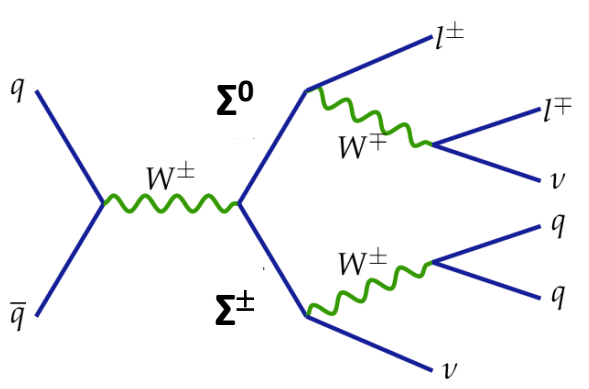
type-III model : new charged (Σ^\pm) and neutral (Σ^0) heavy leptons could be produced in EW processes

$$\Sigma^\pm \rightarrow W^\pm \nu_\ell, \Sigma^\pm \rightarrow Z l^\pm, \Sigma^\pm \rightarrow H l^\pm$$

$$\Sigma^0 \rightarrow W^\pm l^\mp, \Sigma^0 \rightarrow Z \nu_\ell, \Sigma^0 \rightarrow H \nu_\ell$$

$$l = e, \mu, \text{ or } \tau$$

All combination are considered



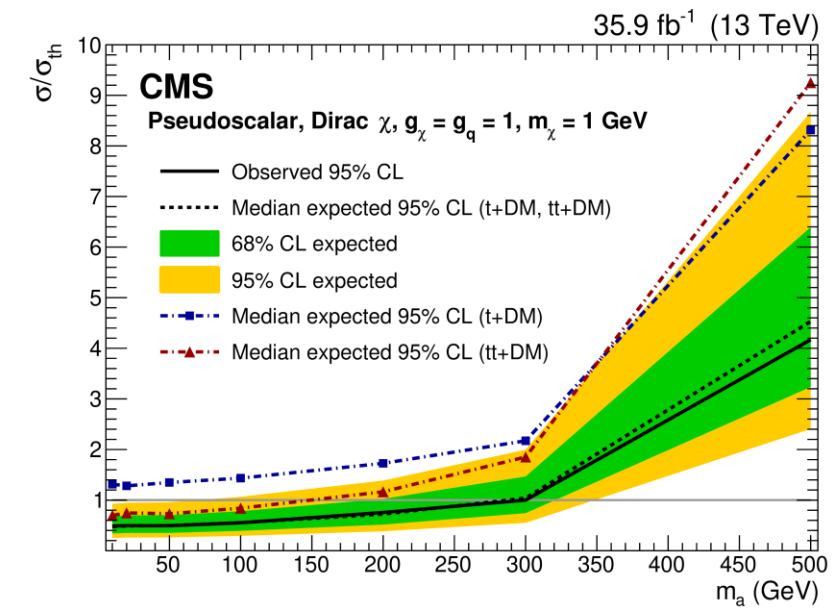
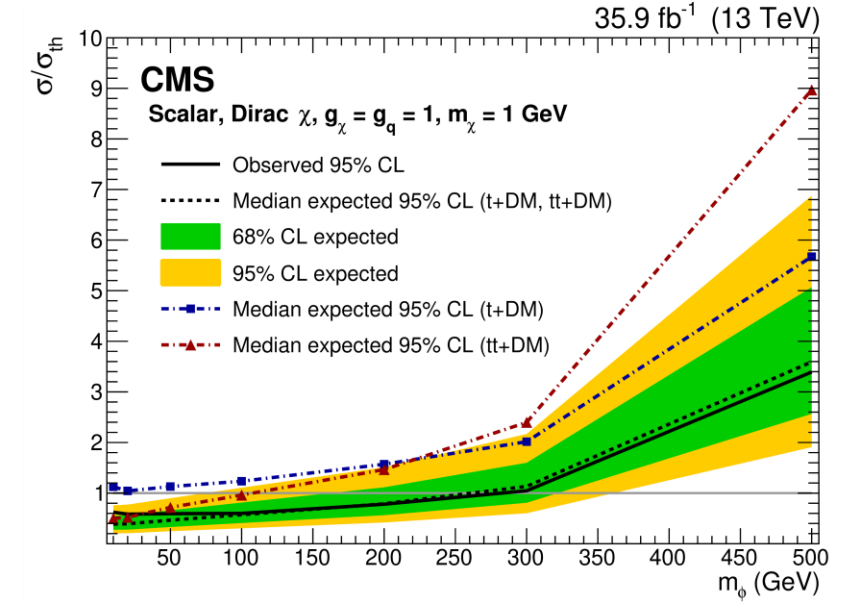
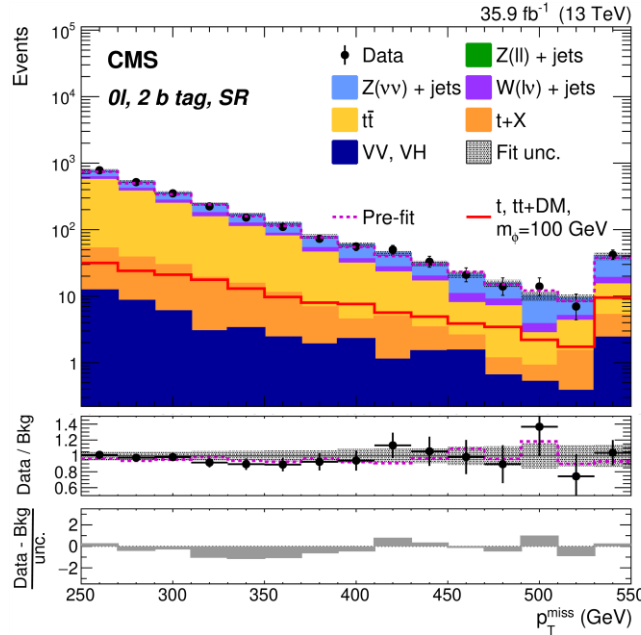
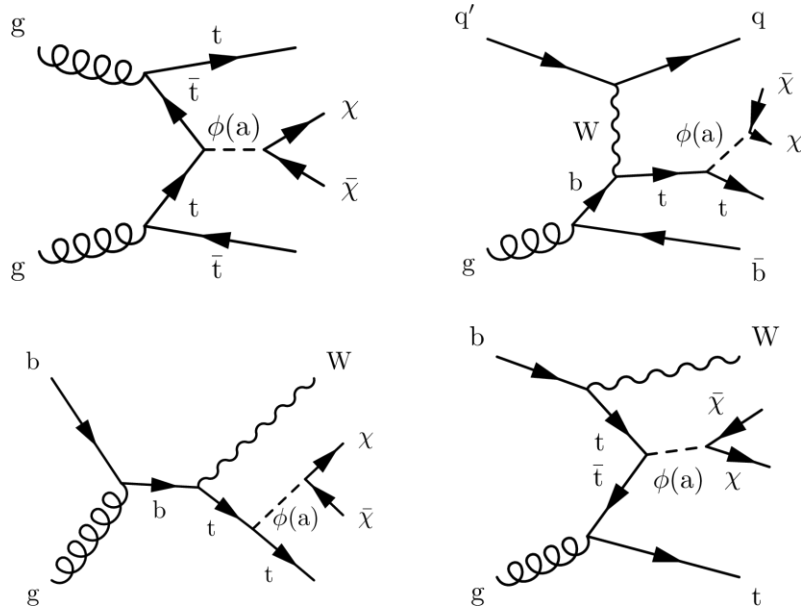
Σ^\pm, Σ^0 degenerate in mass at tree level

$$B_\ell \sim |V_\ell|^2 / (|V_e|^2 + |V_\mu|^2 + |V_\tau|^2)$$

V_ℓ : heavy-light fermion mixing angle

excluded M_Σ [GeV] at 95% CL

- $B_e = B_\mu = B_\tau$: < 840
- $B_e + B_\mu = 1, B_\tau = 0$: < 900-930
- $B_e + B_\mu = 0, B_\tau = 1$: < 390



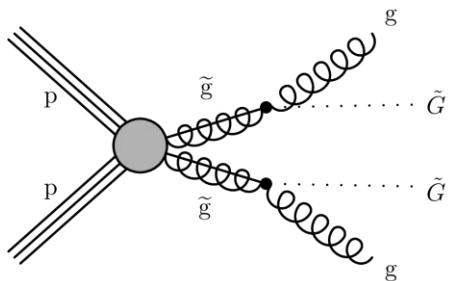
Search: DM production in association with a top pair or single top quark, mediated by neutral spin-0 scalar/pseudoscalar mediators.

Final state: one lepton (e/μ) or zero leptons (all hadronic)

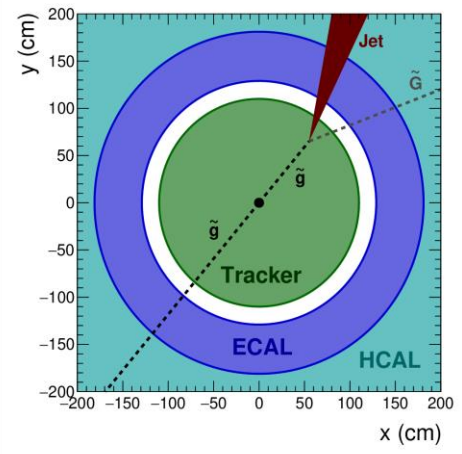
assumptions: DM particles are Dirac fermions, mediators couple (g_q) preferentially to 3rd-generation SM quarks and to DM particles with a strength g_χ .

Simplified model: minimally four free parameters: ($m_\chi, m_{\phi/a}, g_\chi, g_q$). Benchmark scenarios assume $g_\chi = g_q = 1$, and $m_\chi = 1$ GeV

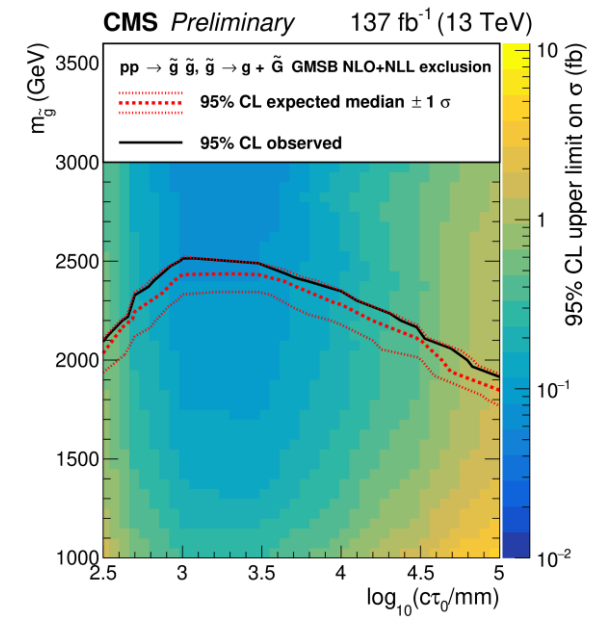
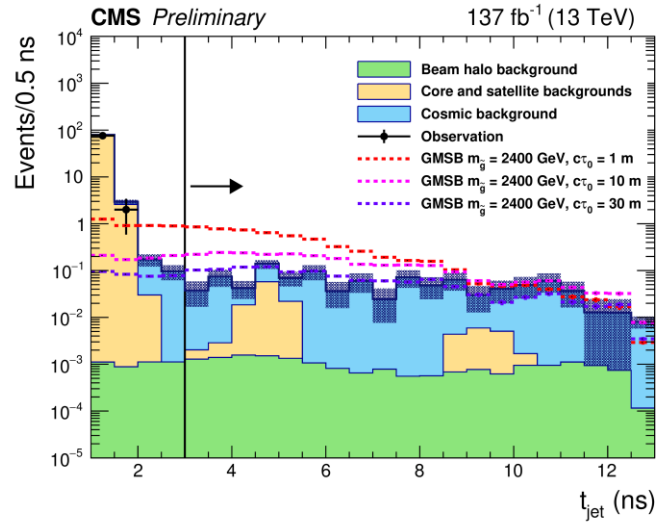
Uncertainties: b tagging scale factors, statistical precision of the dilepton ttbar CR



(a)



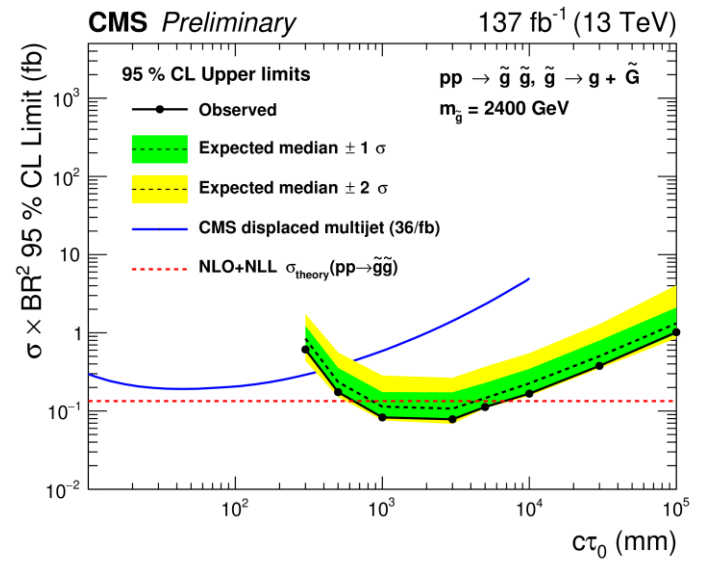
(b)



Search: long-lived particles decaying to delayed jets and missing P_T

Detector: use the timing capabilities of the CMS Electromagnetic Calorimeter (Barrel) to identify delayed jets (usually done for photons). Silicon avalanche photodiodes (APDs) provide time resolution of 200 ps for around 50 GeV energy deposition.

Interpretation: GMSB reference model (pairs of long-lived gluinos, decaying into a gluon (delayed jet) and a weakly interacting gravitino (missing P_T))



Background	Prediction
Beam halo	$0.02^{+0.06}_{-0.02}$ (stat) $^{+0.05}_{-0.01}$ (syst)
Core and satellite bunches	$0.11^{+0.09}_{-0.05}$ (stat) $^{+0.02}_{-0.02}$ (syst)
Cosmics	$1.0^{+1.8}_{-1.0}$ (stat) $^{+1.8}_{-1.0}$ (syst)

Prediction : $1^{+2.5}_{-1}$ events
observation : **0** events

Epilogue

- Many beautiful results from CMS. More to come soon including the full RUN-2 luminosity.
- Observations are in agreement with standard model expectations.
- Upper limits on production cross section of new heavy resonances calculated in a model-independent manner.
- Limits are interpreted as constraints on model parameters (masses, couplings ...).

Necessary to continue the broad search program for New Physics



Up to now the EXOTICA papers have (almost) the same sentence in the abstract:

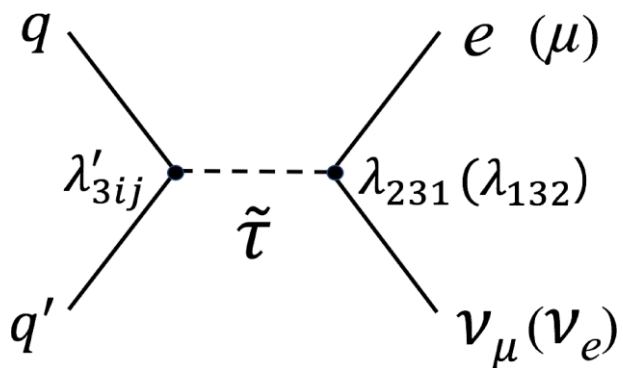
... No significant excess above the background expectation is observed, and upper limits on ...

Lets **hope** that in the near future, at least one (or more) EXOTICA abstract(s) will contain the magic sentence:

... An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near



BACKUP



RPV SUSY :

scalar stau ($\tilde{\tau}$) could act as a **mediator** with couplings λ_{231} (λ_{132}) for the electron (muon) final states.

R-parity and lepton flavor violating decay to a charged lepton and a neutrino [Phys. Rev. D **86** (2012) 055010, Phys. Lett. B **76** (1978) 575]

λ'_{3ij} : hadronic-leptonic RPV coupling to the 3rd generation

Signal samples : MADGRAPH 5 (v1.5.14) at LO

M_{stau} in the range 400-6000 GeV

