Going the Extra Mile to Push the Frontier
— in —
Searches for New Physics at the LHC

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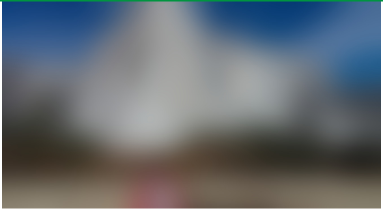
My Goal in This Talk

- Important to have the big picture in mind
  - there's a talk for that:
    PV II, Wolfgang Wagner: "Recent physics highlights of experiments at the LHC" *(tomorrow)*



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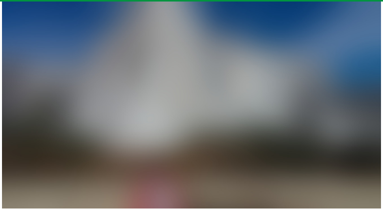

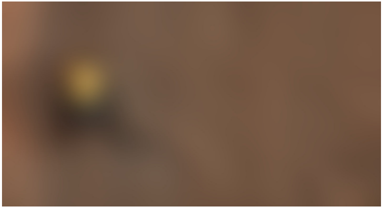

- Here: closer look at selected LHC searches
  - emphasis on recent results
  - potentially biased selection
  - trying to put analyses into context

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- Here: closer look at selected LHC searches
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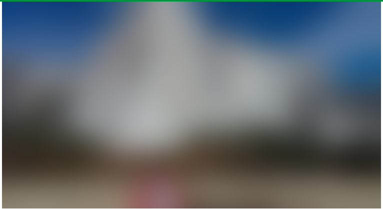
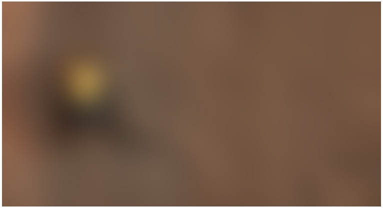
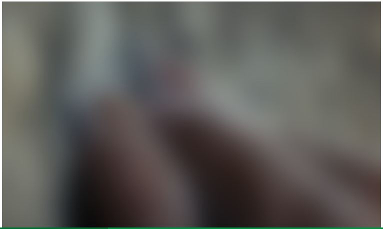
  - trying to put analyses into context

- "Going the Extra Mile. . . "
  - highlight unique features of the analyses
  - interesting approaches, innovative methods, . . .







Overview

- Introduction to Searches at the LHC

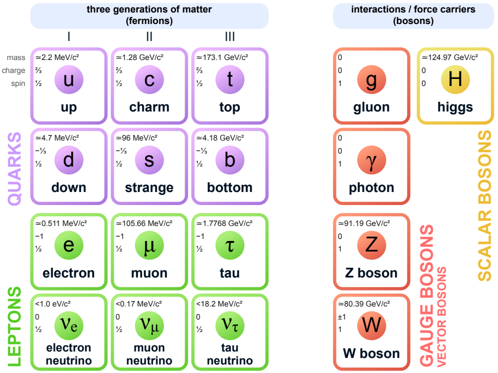
- Dedicated Direct + Indirect Searches
  - (non)resonant phenomena
  - lepton-flavor universality
  - specific models: LQ, SUSY, LLP

- Model-Independent Approaches

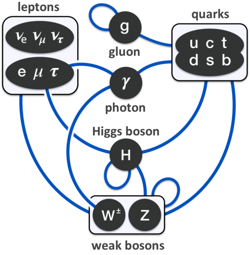
- Spotlights (will not have time for these — conversation starter in break-out session?)

Introduction: Searches at the LHC

Why Fix It If It Ain't Broke?



particle content of the SM



interactions built into the SM

The Standard Model of Particle Physics

- The Standard to describe how the known particles interact and decay
- Can predict outcome of collider experiments very precisely

Why Fix It If It Ain't Broke?

Standard Model known to be incomplete: unexplained experimental observations

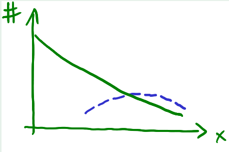
- Neutrino oscillations require $m(\nu_{2,3}) > 0$
  - neutrinos can transform into each other as reported by neutrino (dis-)appearance experiments
  - (T48.3: Alfons Weber, "Neutrino Oscillations", *tomorrow*; T 99.1: Kathrin Valerius, "KATRIN", *Friday*)
- Matter content of universe dominated by unknown form of non-luminous matter
  - rotation curves of galaxy clusters / gravitional lensing suggest existence of this Dark Matter
- Matter-antimatter imbalance of the universe, accelerated expansion of universe, . . .
- Weaknesses of theory: unification of forces, hierarchy problem (fine-tuning of Higgs mass), suggestive similarities of quark/lepton sector, strong CP problem, fermion masses, . . .

How to Find a Better Theory

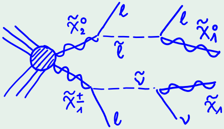
- Propose an extension
  - new, improved theory addressing one / some / all (?) flaws
- Make falsifiable predictions
  - new particles or interactions
  - changes in behaviour of known particles / modification of couplings
  - compositeness, . . .
- Test predictions: **Searches for new phenomena at colliders**

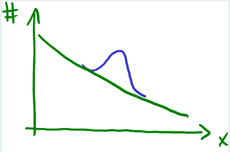
What Are We Looking For?

Direct Searches

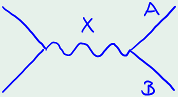


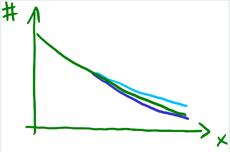
excess over background
in certain part of phase space



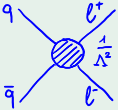


resonant excess ("bump")
over background





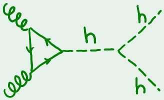
nonresonant
excess or deficit



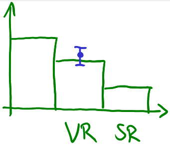
$\longrightarrow$ *decreasing model dependence* $\longrightarrow$

Indirect Searches

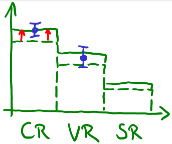
- Precise measurements of production rates and / or branching ratios
  - search for violation of SM predictions, e. g. violation of lepton universality
- EFT approach allows for systematic parametrisation



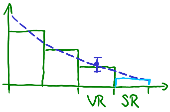
- Searches = looking for deviations from Standard Model predictions
  $\Rightarrow$ correct modeling of SM processes essential
- Different approaches to predict expected background yield in signal-enriched region (SR)
  - simulation-based: typically limited by systematic uncertainties (but also available sample size)
  - data-driven: typically limited by statistical uncertainties
- Analysis blinded during design: consolidate background estimate before looking at data in SR



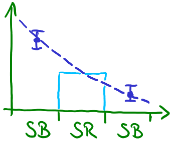
purely from simulation



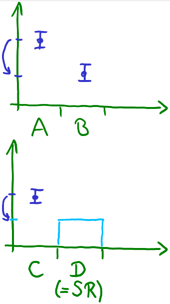
normalize simulation to data



fit simulation and extrapolate



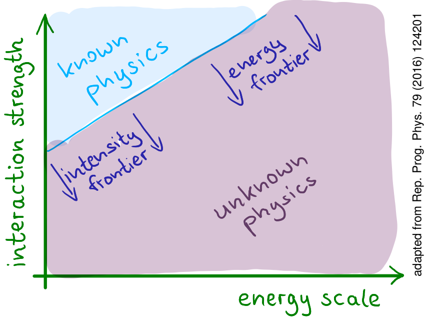
fit data in (signal-free) sidebands with analytic function

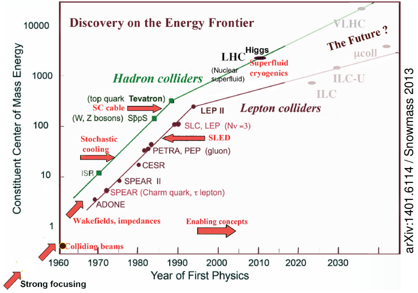


fully data-driven methods (FFM, MM, ABCD, . . . : variations of measuring and "applying" ratio of event yields)

$\longrightarrow$ *less dependent on simulation* $\longrightarrow$

- Why have we not observed the predicted new particles yet?
  - particles too heavy ⇒ energy frontier ⇒ need higher $\sqrt{s}$
  - interactions too feeble ⇒ intensity frontier ⇒ need higher luminosity (precision measurements)





Livingston plot *(presumably in GeV)*

- Searches can be carried out at all different kinds of colliders
- LHC = energy frontier, HL-LHC → intensity frontier
  - searches = central piece of physics programme of LHC as a discovery machine

Luminosity Scaling

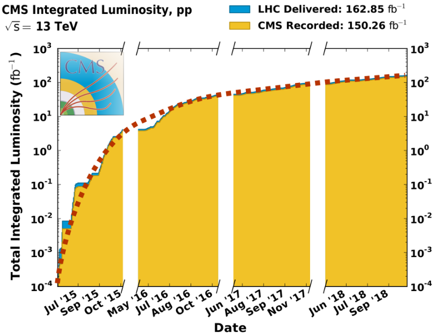
- "Luminosity quadrupling time" t_4:

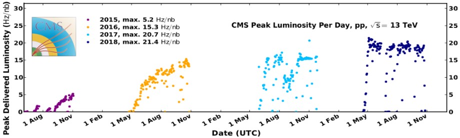
  luminosity $\mathcal{L} \xrightarrow{t_4} 4 \cdot \mathcal{L}$

  - signal yield $S \xrightarrow{t_4} 4 \cdot S$
  - background yield $B \xrightarrow{t_4} 4 \cdot B$
  - approximate significance:

    $$Z \sim \frac{S}{\sqrt{B}} \xrightarrow{t_4} \frac{4 \cdot S}{\sqrt{4 \cdot B}} = 2 \frac{S}{\sqrt{B}} \sim 2Z$$

- e. g. recorded luminosity by CMS:
  - 2015 + 2016 data: $42\,\mathrm{fb}^{-1}$
  - full Run-2 data: $150\,\mathrm{fb}^{-1} \sim 4 \cdot 42\,\mathrm{fb}^{-1}$
- $\Rightarrow$ improvement in analysis sensitivity by factor 2 from luminosity alone





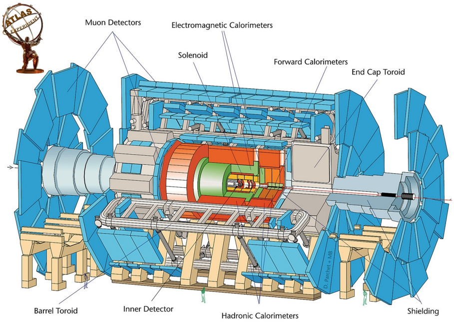
https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

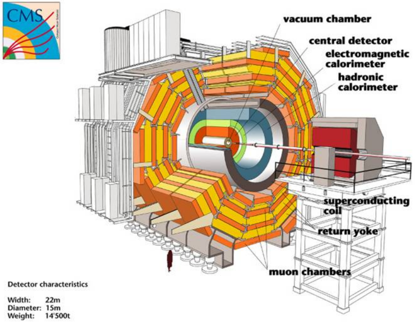
But:

- t_4 strongly increases over time $\Rightarrow$ need to come up with better ideas
- (also: factor 2 sounds like a lot, but cross sections decrease exponentially with mass)

ATLAS and CMS

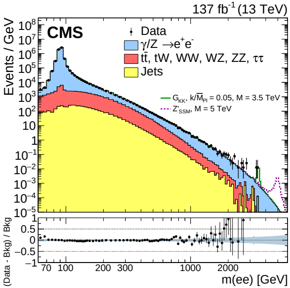
- Two big, independent, multi-purpose detectors at the LHC: ATLAS and CMS
- Situated at Interaction Points 1 and 5 of the LHC
- Different concepts, but same basic structure
  - almost 4π coverage, forward-backward symmetric cylindrical geometry
  - tracking detectors, electromagnetic and hadronic calorimeters, muon system (+ magnets)
- Sophisticated trigger system to select collision events to be recorded (realtime / online filter)

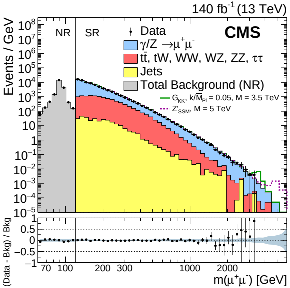




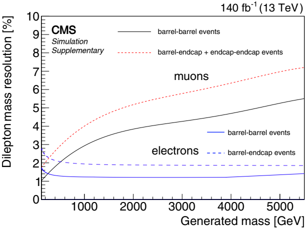
Dedicated Direct + Indirect Searches

- Select ee and $\mu^+\mu^-$ events (reconstruction optimized for high-p_T leptons)
- Backgrounds:
  - dominantly DY, all estimated from MC (except fakes)
  - combined background shape normalized to data around Z peak
- Good agreement of data and MC
  - slight excess in ee tail >1.8 TeV
  - 2 dielectron and 2 dimuon events with $m_{\ell\ell} > 3.0\,\mathrm{TeV}$ observed
- ⇒ proceed to set limits in various models





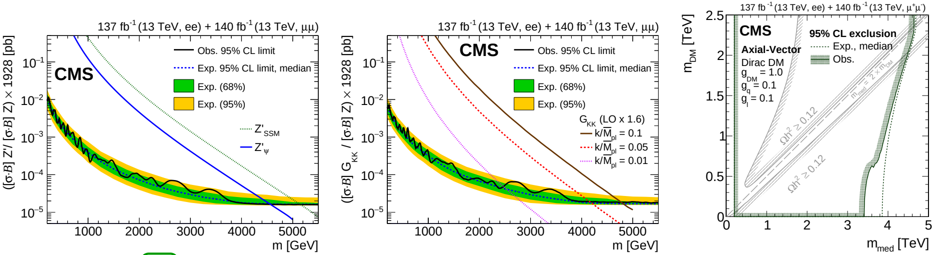
invariant mass distribution, including two example resonant signals



dilepton mass resolution

Models for interpretations

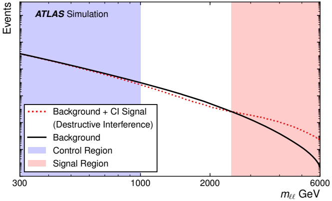
resonant		**non-resonant**	
spin-1	spin-2	ADD extra dimensions	contact interaction
GSM, LRS, GUT (new heavy gauge boson Z') Dark Matter (vector or axial vector mediator)	Randall-Sundrum extra dimensions (Kaluza-Klein graviton)	quasi-continuous spectrum of KK graviton excitations	fermion substructure (constructive or destructive interference)



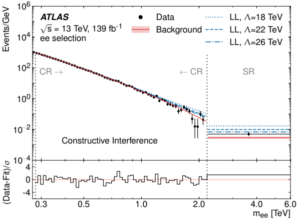
UL for spin-1 Z' resonance and spin-2 KK graviton / excluded mass ranges of DM and mediator

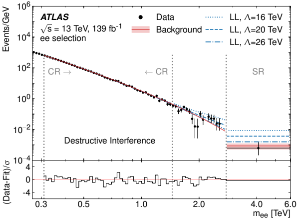
Strategy

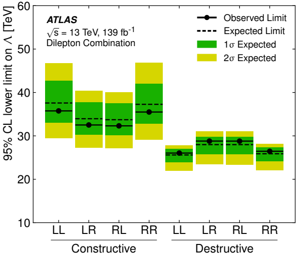
- Search for deviation from expected gradient in $m_{\ell\ell}$ spectrum in $ee/\mu^+\mu^-$ events above Z peak
  - complements ATLAS search for heavy resonances (2019)
- Benchmark signal model: effective four-fermion CI
  $\Rightarrow$ constructive / destructive interference with SM
- Background: parametric model fitted to data in CR
- First nonresonant dilepton search to use background estimate from data using functional form
  - large dedicated DY sample ($\sim 7.5\,\mathrm{ab}^{-1}$, "truth smearing")



$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\ell\ell}} = \frac{\mathrm{d}\sigma_{\mathrm{DY}}}{\mathrm{d}m_{\ell\ell}} - \frac{\eta_{ij}}{\Lambda^2} F_I + \frac{1}{\Lambda^4} F_C$$
$$(i, j \in \{L, R\})$$



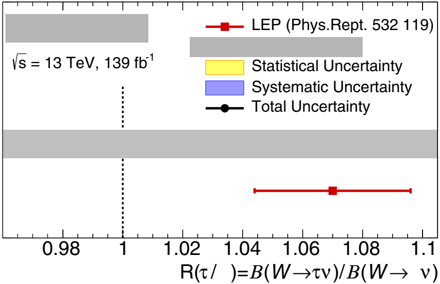




probing high energy scales (compositeness scale Λ)

- Lepton-flavor universality:
  coupling of electroweak gauge bosons to leptons independent of lepton flavour in SM

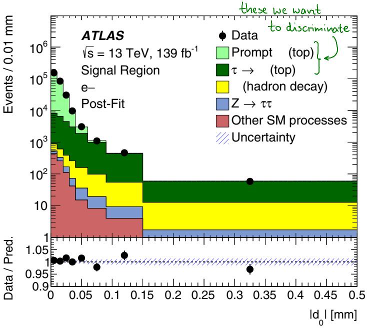
- LEP measurement: long-standing 2.7σ discrepancy from SM prediction (1.0)
  - $R(\tau/\mu) = \frac{\mathcal{B}(W\to\tau\nu_\tau)}{\mathcal{B}(W\to\mu\nu_\mu)} = 1.070 \pm 0.026$



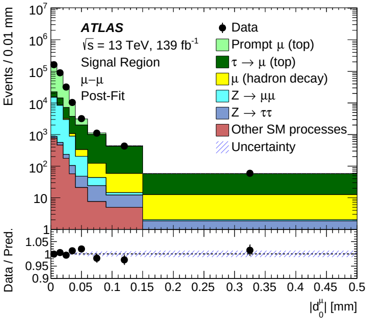
- LHC = "$t\bar{t}$ factory": 15 Hz production rate ⇒ search for violation of LFU in LHC dataset

Strategy

- Select pure sample of dileptonic $t\bar{t}$ events with 2 b-tags (plus $m_{\ell\ell}$ veto against Z / low-mass DY)
- Use *tag-and-probe* method in $e^{\pm}\mu^{\mp}$ or $\mu^{+}\mu^{-}$ events: e or μ as tag, (2nd) μ as probe
- Discriminate $W \to \mu\nu_{\mu}$ and $W \to \tau\nu_{\tau} \to \mu\nu_{\mu}\nu_{\tau}\nu_{\tau}$ based on
  - impact parameter $|d_0^{\mu}|$ (→ lifetime of tau lepton)
  - $p_{\mathrm{T}}(\mu)$ (→ energy shared with neutrino(s))
- Determine ratio $R(\tau/\mu)$ → many systematic uncertainties cancel



SR in $e\mu$, tag = e, probe = μ

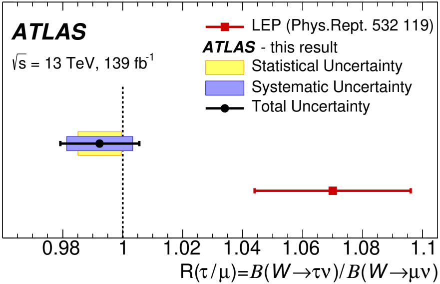


SR in $\mu\mu$, tag = μ, probe = μ

- Measured value from fit of 48 SR bins:

$$R(\tau/\mu) = \frac{\mathcal{B}(W\rightarrow\tau\nu_\tau)}{\mathcal{B}(W\rightarrow\mu\nu_\mu)} = 0.992 \pm 0.013$$

- Agrees well with SM ⇒ discrepancy seen by LEP not confirmed
- Most precise measurement of $R(\tau/\mu)$ to date

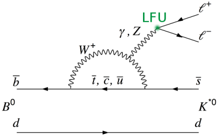


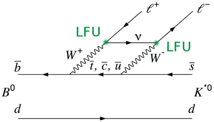
So all is well. . . or is it?

- Tests of lepton-flavor universality important part of physics program at B factories

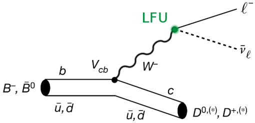
- SM forbids FCNCs at tree level $\Rightarrow$ rare transitions, sensitive to presence of new particles
  - could increase or decrease production rate or change angular distribution of final-state particles
  - if new particles couple differently to electrons and muons, LFU could be violated
- Measure FCNC transition $b \to s$ in ratio $R(K) = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$

  $\Rightarrow$ very precise tests of LFU (hadronic uncertainties in theoretical predictions cancel)





- Can also use charged-current process with SM tree-level diagram
- Measure FCCC transition $b \to c$ in ratio $R(D) = \frac{\mathcal{B}(B \to D\tau^- \nu)}{\mathcal{B}(B \to D\ell^- \nu)}$



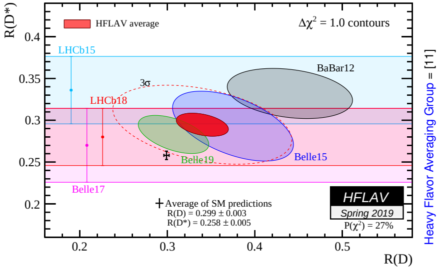
- Results from past measurements at BaBar, Belle, LHCb:

Name	Definition	Observed value	[ref]	SM prediction	[ref]	Discrepancy
R_K	$\frac{Br(B^+\to K^+\mu^+\mu^-)}{Br(B^+\to K^+e^+e^-)}$	$0.745^{+0.090}_{-0.074} \pm 0.036$	[2]	1	[9, 10]	2.6σ
R_{K^*}	$\frac{Br(B^0\to K^{0*}\mu^+\mu^-)}{Br(B^0\to K^{0*}e^+e^-)}$	$[0.66, 0.69]^{+0.11}_{-0.07} \pm 0.03$	[7]	$[0.926, 0.9965] \pm 0.0005$	[9, 10]	$[2.2\sigma, 2.5\sigma]$
R_D	$\frac{Br(B\to D^*\tau^-\nu)}{Br(B\to D\ell^-\nu)}$	$0.407 \pm 0.039 \pm 0.024$	[11]	0.299 ± 0.011	[12]	2.3σ
R_{D^*}	$\frac{Br(B\to D^*\tau^-\nu)}{Br(B\to D^*\ell^-\nu)}$	$0.304 \pm 0.013 \pm 0.007$	[11]	0.252 ± 0.003	[13]	3.4σ
$R_{J/\psi}$	$\frac{Br(B_c^+\to J/\psi\tau^+\nu)}{Br(B_c^+\to J/\psi\mu^+\nu)}$	$0.71 \pm 0.17 \pm 0.18$	[8]	0.29 ± 0.07	[14]	1.7σ

PRD 98, 115032 (2018)

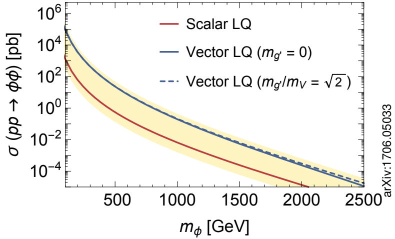
- Updated result from LHCb: (PRL 122, 191801 (2019), superseding [2])
  - increased analyzed dataset from $3.0\,\mathrm{fb}^{-1}$ to $5.0\,\mathrm{fb}^{-1}$
  - $R_K = 0.846^{+0.060+0.016}_{-0.054-0.014} \Rightarrow$ now at 2.5σ w.r.t. SM
  - (T 48.2: Michel De Cian, "Highlights from the LHCb experiment", *tomorrow*)

Visualization and combination of results for $R(D^{(*)})$:



What Are Leptoquarks

- Hypothetical particles with non-zero baryon and lepton number
- Carry color charge and fractional electric charge
- Decay into quark-lepton pair
- Can be a scalar or a vector particle



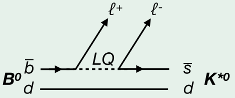
pair-production cross section

Why Introduce Them

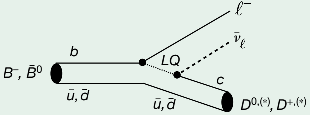
- Appear in many BSM scenarios, e. g. GUTs with larger gauge groups
- Relate quark and lepton sector
  - may provide explanation for similarities

- LQ can explain observed deviations from lepton universality in B-meson decays

$R(K)$:

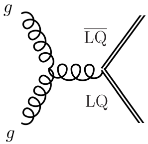


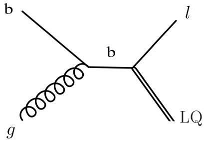
$R(D)$:



Motivation

- Some solutions proposed to explain B anomalies favor effective couplings to 3^{rd} generation SM fermions at TeV scale
- Targets:
  - both scalar leptoquark, $\text{LQ}_s \rightarrow t\tau/b\nu$, and vector leptoquark, $\text{LQ}_v \rightarrow t\nu/b\tau$
  - both single and pair production





Model parameters

- LQ mass + coupling λ (only single production) + coupling k (only vector LQ)
- 15 models in total (LQ$_s$, LQ$_v$ for $k = 0, 1$; pair prod. and single or combined for $\lambda = 1.5, 2.5$)
  - $k = 0$: minimal coupling case, $k = 1$: Yang-Mills case (larger cross section)
  - λ: coupling strength to lepton-quark pair (affects single LQ production cross section)

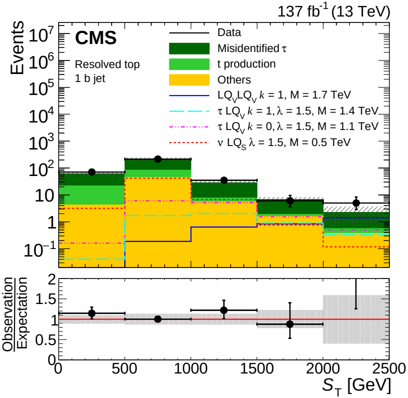
Strategy

- Search in $t\tau\nu$ (→ LQ) and $tb\tau\nu$ (→ LQLQ) final states
- Employs top tagging and W tagging on large-R jets ($R = 0.8$)
- 4 separate event categories:

  (Lorentz-boosted top or resolved top)

  ×

  ($= 1$ b-jet or ≥ 2 b-jets)
- Background:
  - dominantly misidentified tau lepton: estimated with fake-factor method
  - rest: from simulation, normalized in CR



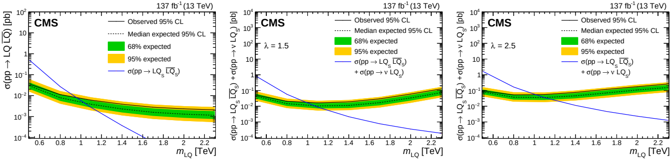
final discriminant

$S_T = p_\mathrm{T}(t) + p_\mathrm{T}(\tau) + E_\mathrm{T}^\text{miss}$

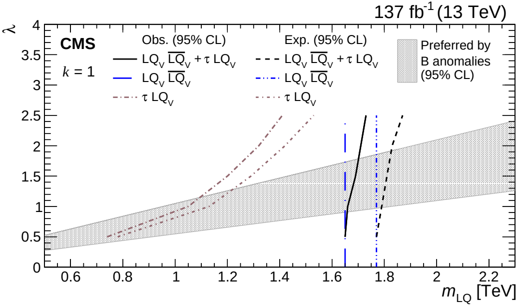
(→ shape fit)

Results

- First search to simultaneously consider both single and pair production
  - combination improves limits by 30 – 120 GeV depending on LQ type



(+ 12 more)



gray area: region preferred by (some) models explaining B anomalies

3^{rd}-Generation Leptoquark Search (ATLAS, $36.1\,\mathrm{fb}^{-1}$)

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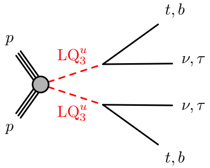
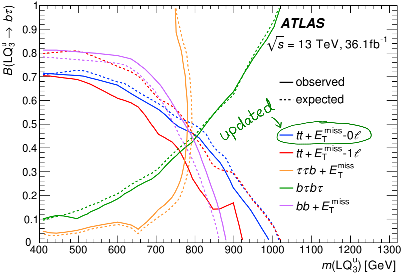
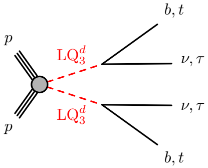
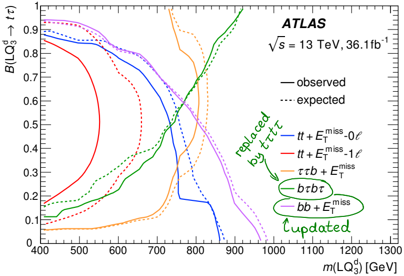
up-type ($Q = \frac{2}{3}e$)





down-type ($Q = -\frac{1}{3}e$)



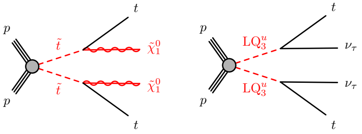


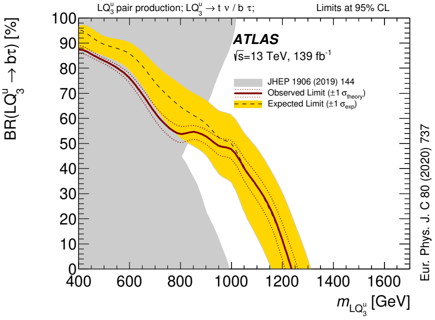
Overlay Plots

- 4 reinterpretations of SUSY searches for stop and sbottom pairs
- +1 reoptimized variant of di-higgs search

3^{rd}-Generation Leptoquark Search (ATLAS, $139\,\mathrm{fb}^{-1}$)

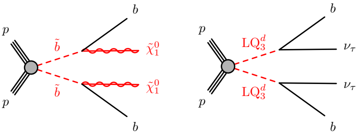
up-type ($Q = \frac{2}{3}e$)

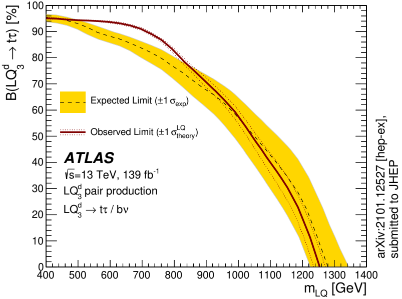




reinterpretation of search for $\tilde{t}\tilde{t}$ (0ℓ)

down-type ($Q = -\frac{1}{3}e$)



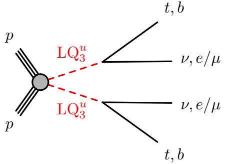


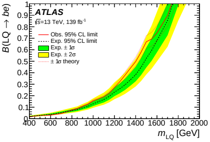
reinterpretation of search for $\widetilde{b}\widetilde{b}$ (0ℓ)

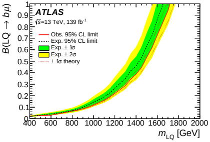
Search for Leptoquarks with Mixed Decays *(New)*

- New ATLAS studies: searching for LQ pairs with cross-generational couplings

up-type ($Q = \frac{2}{3}e$)

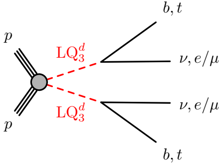


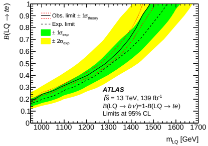


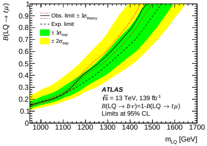


targets final states: e. g. $bb + ee/\mu\mu$

down-type ($Q = -\frac{1}{3}e$)



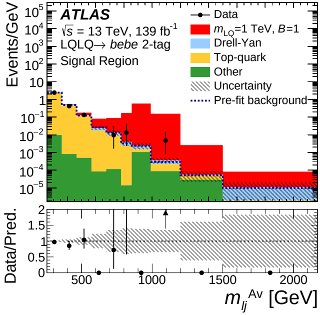


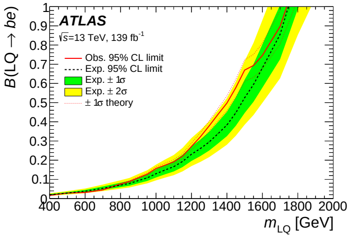


targets final states: $tt + ee/\mu\mu$

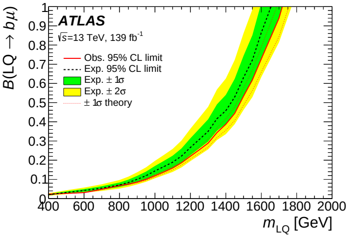
Strategy

- Select e^+e^- / $\mu^+\mu^-$ + ≥ 2 jets
- 7 event categories
  - based on number of b- and c-tagged jets
- Compute average reconstructed LQ mass m_{lj}^{Av}
  - pairing minimizes mass difference of LQ candidates
  - mass resolution $\lesssim 7\,\%$ of LQ mass
- Normalization of and systematic uncertainties on dominant backgrounds derived from CRs
- First limits on these LQLQ decays





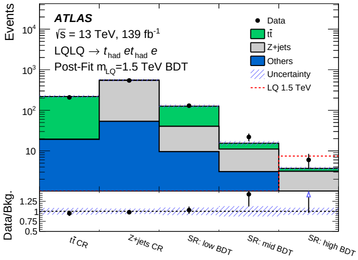
$\text{LQ}^{\text{u}}_{\text{mix}}\text{LQ}^{\text{u}}_{\text{mix}} \rightarrow bebe\ (\beta = 1)$



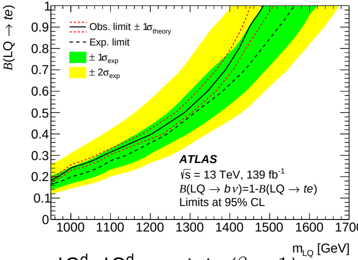
$\text{LQ}^{\text{u}}_{\text{mix}}\text{LQ}^{\text{u}}_{\text{mix}} \rightarrow b\mu b\mu\ (\beta = 1)$

Strategy

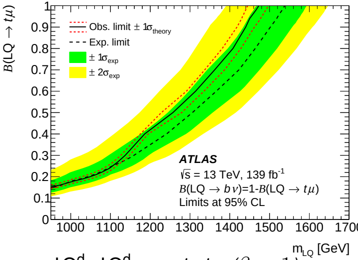
- Select e^+e^- / $\mu^+\mu^-$ + 2 large-R jets ($R = 1.0$)
  - heavy LQ → boosted top quarks
- BDT based on 29 (32) kinematic observables
  - parameterized in theoretical LQ mass
- Using "recursive jigsaw technique"
  - to construct rest frames of intermediate particle states (resolves kinematic and combinatoric ambiguities)
  - rest frames serve as natural basis for BDT inputs



- 2 CRs to normalize $t\bar{t}$/ Z background
- 3 bins in SR based on BDT output score

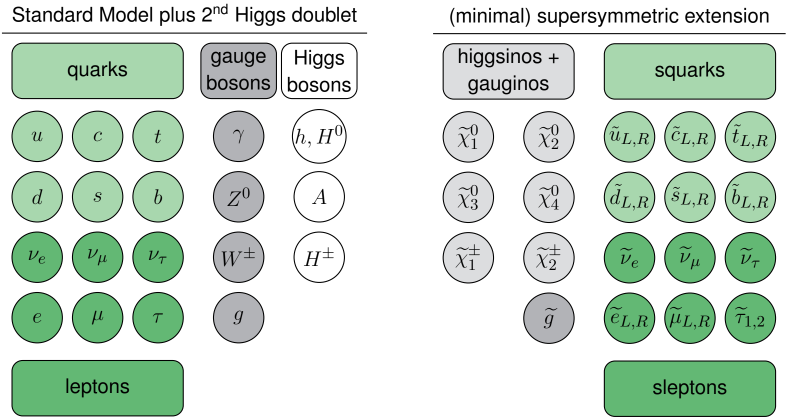


$\mathrm{LQ}^d_{\mathrm{mix}}\mathrm{LQ}^d_{\mathrm{mix}} \to tete\ (\beta = 1)$



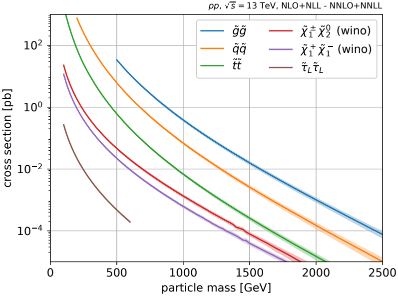
$\mathrm{LQ}^d_{\mathrm{mix}}\mathrm{LQ}^d_{\mathrm{mix}} \to t\mu t\mu\ (\beta = 1)$

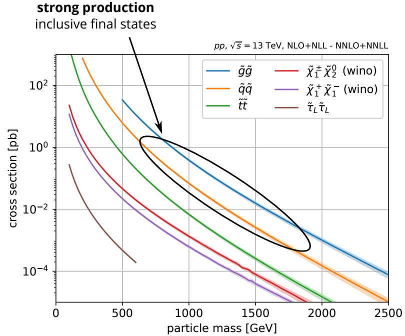
Particle Content of Minimal Supersymmetric Standard Model



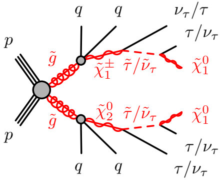
- new scalars: sfermions = squarks $\tilde{q}$ + sleptons $\tilde{\ell}$
- new spin-$1/2$ particles: gauginos = neutralinos $\tilde{\chi}^0$ + charginos $\tilde{\chi}^\pm$ + gluino $\tilde{g}$

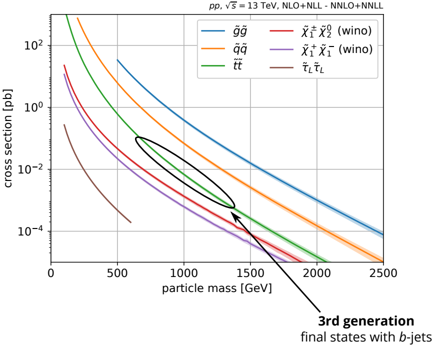
Different Production Modes of SUSY Particles



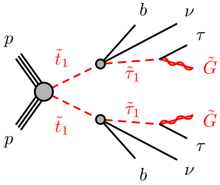


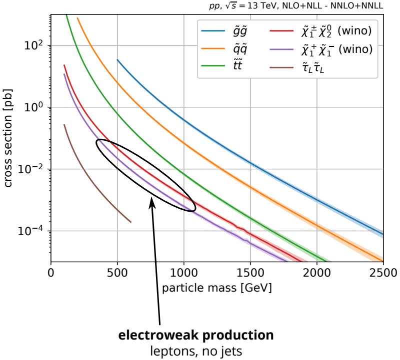
Example simplified model with strong production of SUSY particles



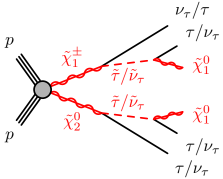


Example simplified model with pair production of 3rd generation squarks

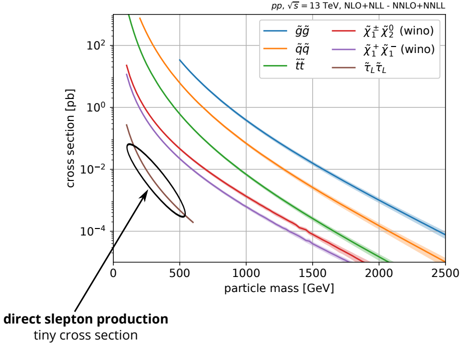




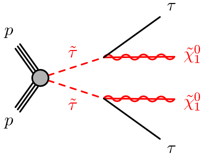
Example simplified model with electroweak production of gauginos



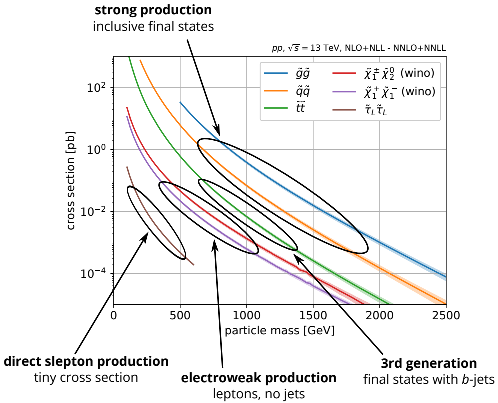
Different Production Modes of SUSY Particles



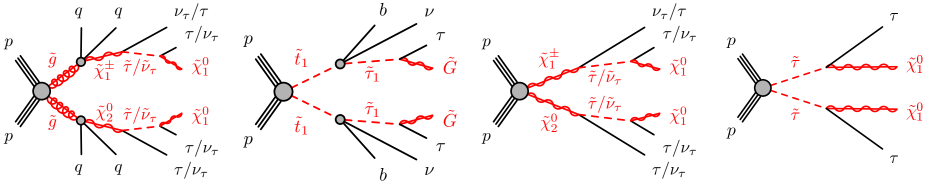
Example simplified model with direct production of sleptons



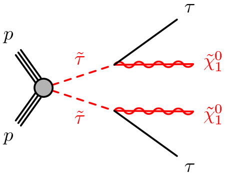
Different Production Modes of SUSY Particles

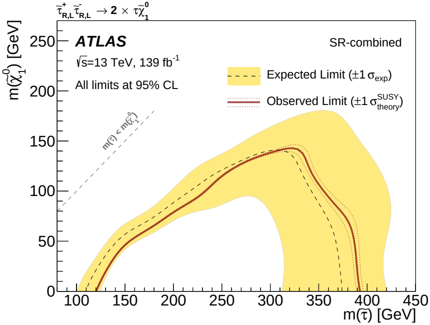


All production modes are covered by dedicated searches

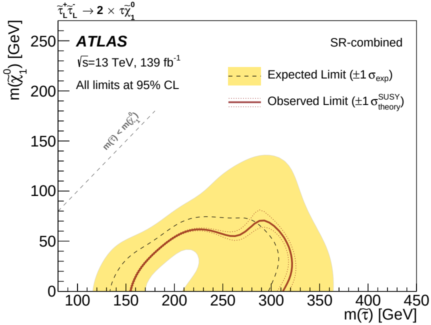


- Search for direct production of tau-slepton pairs in final states with two hadronically decaying tau leptons
- Consider two scenarios
  - mass-degenerate $\widetilde{\tau}_L\widetilde{\tau}_L + \widetilde{\tau}_R\widetilde{\tau}_R$
  - production of $\widetilde{\tau}_L\widetilde{\tau}_L$ only
- First exclusion of *non-degenerate* staus at LHC!





degenerate scenario ($\widetilde{\tau}_L\widetilde{\tau}_L + \widetilde{\tau}_R\widetilde{\tau}_R$)



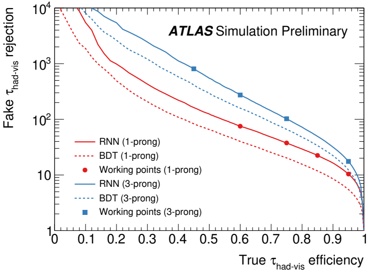
left-handed scenario ($\widetilde{\tau}_L\widetilde{\tau}_L$ production)

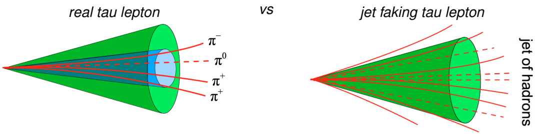
What made these results possible?

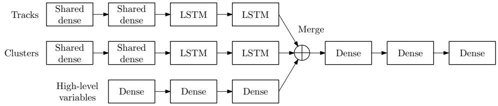
- Data-driven estimates for multi-jet background
  - ABCD method cross-checked with fake-factor method
- "Tau promotion": simulation-based fake-factor method
  - reduces statistical uncertainty in $W+$ jets background
- Tau identification: BDT replaced by reoptimized RNN
  - $\times 2$ better rejection of fakes at same signal efficiency
  - $\Rightarrow$ much better background suppression
- Research and development of improved algorithms together with / in CP groups crucial for success of analyses

SM process	SR -lowMass	SR -highMass
Diboson	1.4 ± 0.8	2.6 ± 1.4
$W+$ jets	1.5 ± 0.7	2.5 ± 1.8
Top quark	$0.04^{+0.80}_{-0.04}$	2.0 ± 0.6
$Z+$ jets	$0.4^{+0.5}_{-0.4}$	$0.05^{+0.13}_{-0.05}$
Multijet	2.6 ± 0.7	3.1 ± 1.4
SM total	6.0 ± 1.7	10.2 ± 3.3
Observed	10	7

largest backgrounds:
fake tau leptons

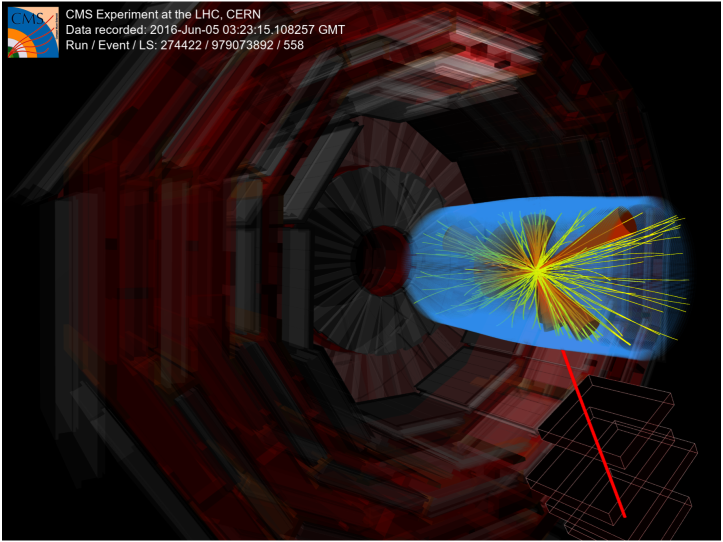






SUSY Search: No $E_{\mathrm{T}}^{\mathrm{miss}}$ but Many Jets (CMS, $137\,\mathrm{fb}^{-1}$)

arXiv:2102.06976 (→ PRD)

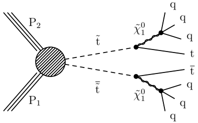


CMS-PHO-EVENTS-2021-004

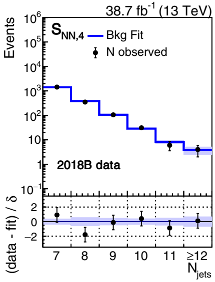
Event recorded during 2016 with the CMS detector that contains 10 jets (orange cones) and a muon (red line).

Strategy

- Search for "low-E_T^{miss} SUSY" (e. g. R-parity violation model)
- Select events with 1 isolated e/μ + ≥ 7 jets incl. 1 b-tag
- Background: predominantly $t\bar{t}$
- Discriminating features:
  - more jets on average than SM processes
  - NN trained on lepton and jet 4-momenta and energy distribution



RPV SUSY
(stop pairs, λ''_{112})

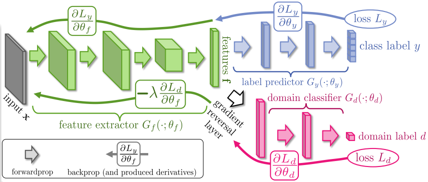


Background Modeling: Jet Scaling

- Modeling of events with large jet multiplicities tricky
  - ⇒ need data-driven estimate: "QCD jet scaling"
- Parameterize ratio $R(i) = M_{i+1}/M_i$ of M events with i jets
  - low N_{jets}: Poisson scaling $R(i) = k/(i+1)$
  - high N_{jets}: staircase scaling $R(i) = \text{const.}$
- Fit with 3 shape parameters + 4 normalisation parameters
  - 24 bins (6 in N_{jets}, 4 in NN output score)
  - ⇒ overconstrained fit ⇒ predictive

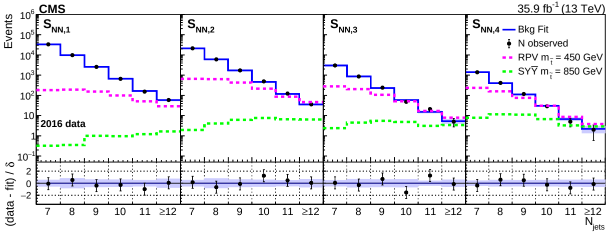
Jet Scaling vs NN

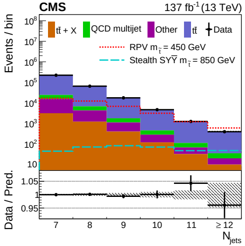
- Rely on NN to improve S/B separation
- N_{jets} distribution for $t\bar{t}$ in 4 bins of NN score: fit with same parameters
- Problem: jet scaling must be independent of NN
  - use gradient reversal technique



PMLR 37:1180, 2015

gradient reversal technique





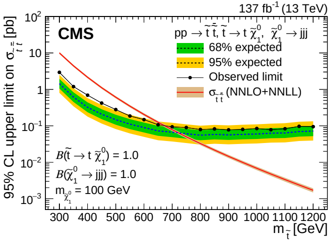
4 bins in NN score ($S_{\text{NN,i}}$): ⟶ more signal ⟶ same jet-scaling model

sum over NN score bins

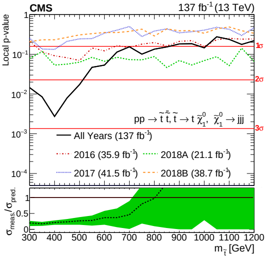
Interpretation

- 95 % CL cross-section limit for $\tilde{t}\tilde{t}$ production *(right)*
- Fitted signal strength and local p-value *(bottom)*

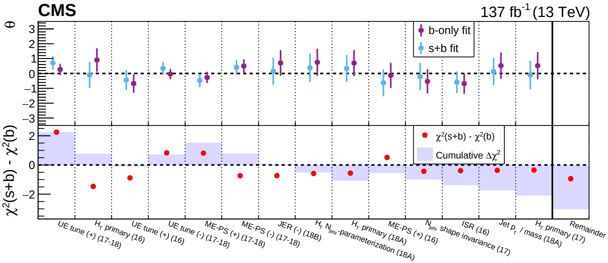
- First search of its kind at LHC
- Equivalent study in ATLAS:
  JHEP 09 (2017) 88 ($36.1\,\mathrm{fb}^{-1}$, w/o NN)



UL on xsec in RPV model

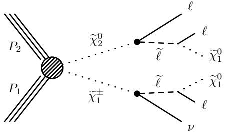


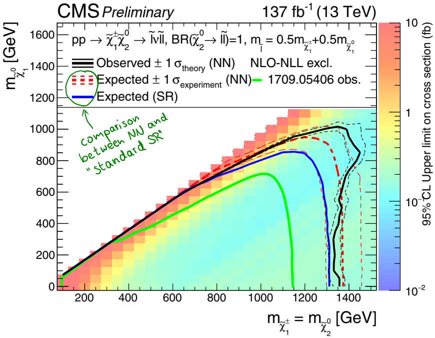
local p-value as function of $m_{\tilde{t}}$ in RPV model



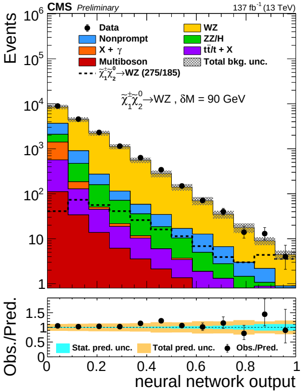
study of local 2.8σ *excess for RPV model with* $m_{\tilde{t}} = 400\,\mathrm{GeV}$
($2.8\sigma \rightarrowtail$ *local* p*-value of* 0.003, $\mu_{sig} = 0.21 \pm 0.07$,
$2.8\sigma \sim 1.1\sigma + 1.7\sigma$, $1.7\sigma \rightarrowtail \sum \Delta\chi^2 = -3.0$)

- Several models with electroweak production of $\tilde{\chi}^{\pm}$/ $\tilde{\chi}^{0}$
- Channels with $\ell^{\pm}\ell^{\pm}$ / 3ℓ / 4ℓ: low SM background
  - define 12 categories based on lepton charge and numbers
- 3ℓ OSSF category uses parametric NNs (large WZ bg.)
  - optimize hyperparameters: evolutionary algorithm
  - aside from pNN also define SRs (as in other 11 categories)
  - direct comparison shows sensitivity boost of 30–100 %





comparison of SR strategy and NN



NN discriminant

Collider Signatures of Long-Lived Particles

- Causes for longevity (of particles):
  - weak coupling to decay products
  - small mass difference in decay chain (i. e. not much phase space for decay)
  - decay through off-shell particles
  - nearly conserved quantum numbers

- Multitude of signatures depending on lifetime, charge, and decay
- Searches for promptly decaying particles often not sensitive

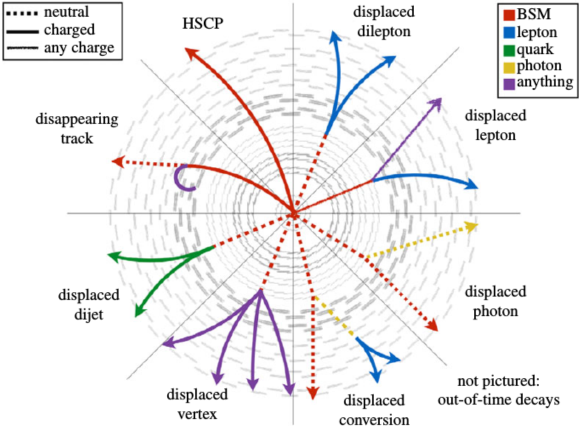


Image: J. Antonelli

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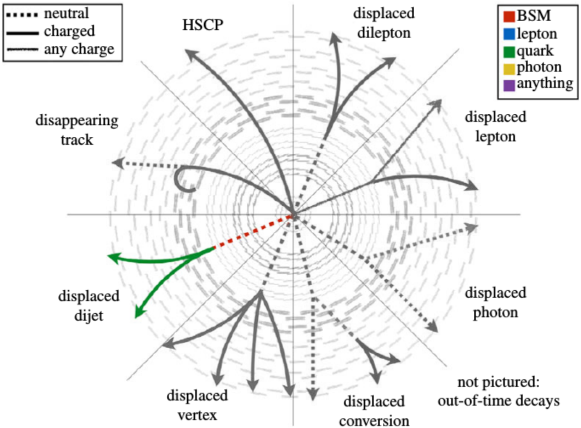
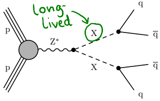
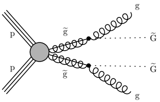


- Search for long-lived particles using displaced jet in 2017+2018 data
- Inclusive search with interpretations in many different models

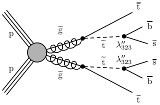
jet-jet model



GGM



RPV SUSY



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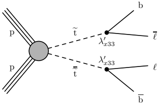


Strategy

- Form dijet candidates

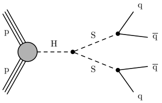
  in events with $H_\mathrm{T} > 500(700)\,\mathrm{GeV}$
- Associate tracks to each jet,

  build secondary vertex from displaced tracks
- Background purely estimated from data
  - using “ABCD” method
- Dominant background sources:
  - nuclear interactions with detector material
  - long-lived SM hadrons
  - displaced vertices from accidentally crossing tracks

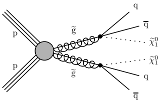
- New techniques:
  - additional trigger (recovers eff. for heavy LLPs)
  - veto map for nuclear interactions (NI)
  - new variable (based on $\sum$Sig[IP$_{2D}$])
  - BDT for S-B discrimination

$\Rightarrow$ reduce bg. rate by $\times 3$ + increase signal eff.

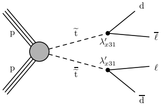
$H \to$ scalar LLP



mini-split SUSY



RPV SUSY



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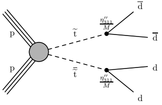
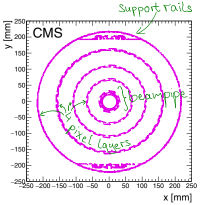
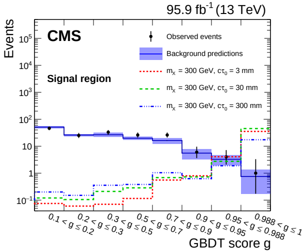


Selections	Observed events
Displaced-jet triggers, offline H_T selections	17758640
Offline jet p_T and η selections, vertex $\chi^2/n_{dof} < 5.0$	8387775
Vertex $p_T > 8\,\mathrm{GeV}$	3794960
Vertex invariant mass $> 4\,\mathrm{GeV}$	1129531
Second largest $\mathrm{Sig}[\mathrm{IP}_{2D}] > 15$	422449
Charged energy fraction from the SV $\epsilon > 0.15$	93873
Energy fraction from the PVs $\zeta < 0.20$	15891
Veto using the NI-veto map	13721
$N^{3D}_{tracks} < 3$ for each jet	2753
GBDT > 0.988	1

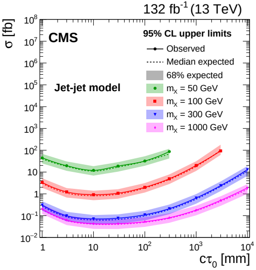
Selection requirements of SR

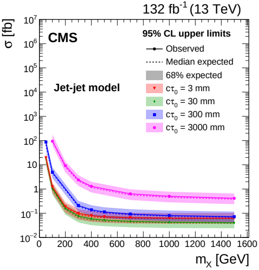


Material map for NI veto



- Input to BDT: several "geometrical" variables
- 1 data event observed in SR
  - consistent with expected background
  - likely from material interaction with silicon strip detector
- Results combined with 2016 analysis
- Most stringent limits to date on these models





95 % CL upper limits on pair-produced LLP X

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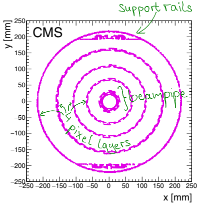

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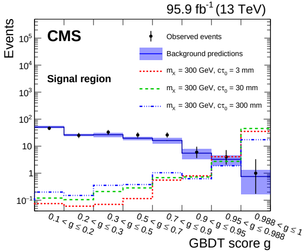

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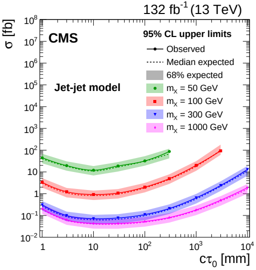
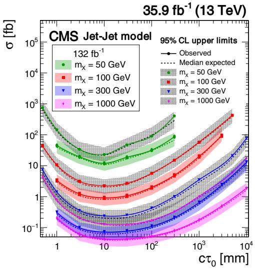




improvements in UL: $132\,\mathrm{fb}^{-1}$ *vs.* $35.9\,\mathrm{fb}^{-1}$

Model-Independent Approaches

Model Dependence of Searches

- Past discoveries often came through targeted searches for particles forecasted by theory (e. g. h, ν_τ, t, W, Z)
- Now much less clear where new particles would show up
- Direct searches so far show no evidence for BSM physics
- Make sure not to miss anything, new phenomena may appear elsewhere than anticipated

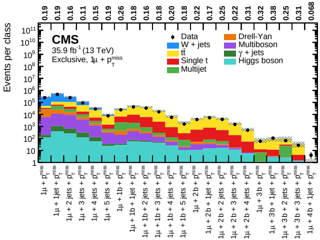
- Dedicated searches often restricted to few final states
  - number of possible final-state combinations is huge
  - alternative: try to cover *all* possible final states, complementary to dedicated searches

- Dedicated searches often restricted to limited range of models
  - typically start with specific theoretical model
  - simulate signal, develop classifiers to separate from background (uncorrelated selections or MVA)
  - alternative: anomaly detection, ideally independent of signal and background model

Model Dependence of Searches: Complementary Approaches

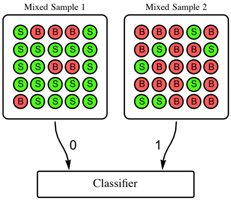
“MUSiC”: model unspecific search for new physics

- CMS, $35.9\,\mathrm{fb}^{-1}$, arXiv:2010.02984 (→ EPJC)
- BSM search through data-MC comparisons
- Relies on correct modelling of data in simulation
- Analogous approach in ATLAS: “General Search” EPJC 79 (2019) 120 ($3.2\,\mathrm{fb}^{-1}$)
  - also done at Tevatron experiments and H1@HERA



Classification w/o labels in a dijet bump hunt

- ATLAS, $139\,\mathrm{fb}^{-1}$, PRL 125 (2020) 131801
- BSM search through anomaly detection (bump hunt)
- Completely data-driven approach



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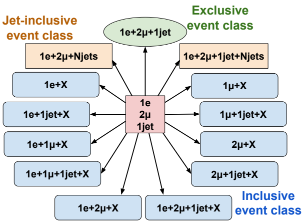
Ansatz

- Automated approach to quantify deviations of simulated SM processes vs. observed data
- Background modelling: purely based on MC simulation ("every final state is a SR")

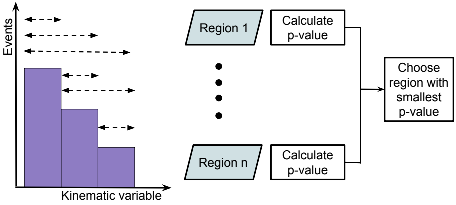
Strategy

- Sort events based on (known) particles
  - e, μ, γ, q/g jets, b-jets, $E_{\mathrm{T}}^{\mathrm{miss}}$ (if $> 100\,\mathrm{GeV}$)
  - tau-lepton ID or $W/Z/t$ tagging not considered
  - require ≥ 1 isolated e/μ to reduce QCD (number of simulated events not adequate)
- Form 3 types of classes
  - 498 exclusive (disjunct)
  - 571 inclusive ("$+X$")
  - 530 jet-inclusive ("$+N$ jets")
  - (with ≥ 1 obs. data or > 0.1 exp. events)

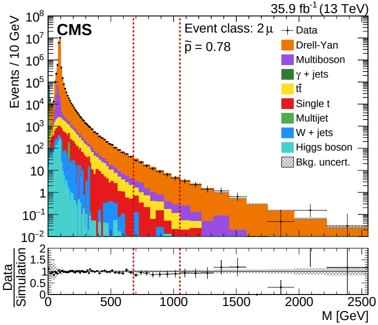


Evaluation

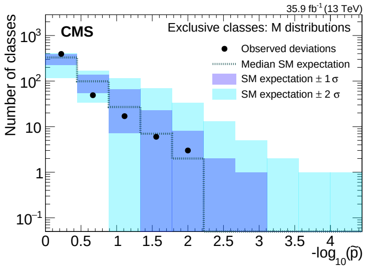
- Study total yields per class and kinematic distributions *arXiv:2010.02984 (→ EPJC)*



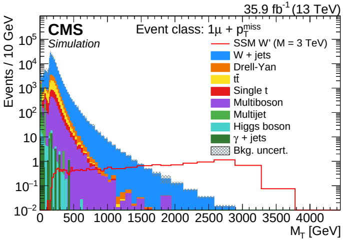
⇒



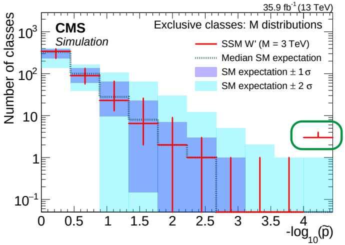
- Identify "region of interest" with largest deviation



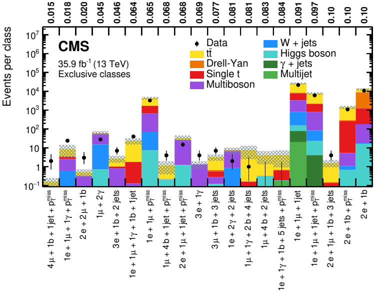
- Large trials factor / look-elsewhere effect
- LEE correction computed through pseudo-experiments ⇒ "post-trial p value" $\tilde{p}$



⇒



- Sensitivity tested by injecting signal (W' or sphalerons) or removing one SM process (WZ)

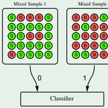


- Overall no significant deviations
- What if? Could be…
  - …mismodeling of detector
  - …overlooked systematic effects
  - …or BSM physics

event yields and p-values for classes with largest deviations

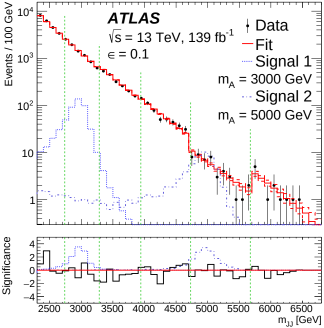
Idea

- Goal: train neural network to improve S/B ratio w/o simulated signal model
- Problem: data = unlabelled
  - employ "weak supervision": exploit structures in data w/o per-event labels
  - requires two samples with different signal fractions



Strategy

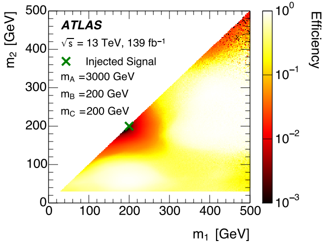
- Events with ≥ 2 large-R jets (with $p_\mathrm{T} > 500, 200\,\mathrm{GeV}$)
- Model dependence:
  assume signal localized ("resonant") in m_{JJ}
- Define training samples based on m_{JJ} slices
  - one labelled "signal"(-rich), another "background"(-rich)
  - do not need to know the fraction
  - can now apply any supervised-learning technique
  - here: use standard neural network
- Train on what features? $\rightarrow$ here: m_{J1}, m_{J2}
- Place threshold on NN output score,
  do standard bump hunt



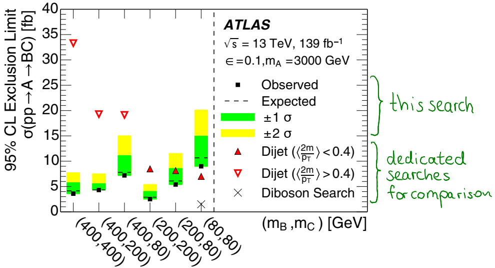
invariant mass of the two leading jets m_{JJ} in SR 1 – 6

Results

- Observed upwards fluctuations in SRs found consistent with statistical fluctuations
- Upper limits set on W' signal cross section as example of specific BSM model
- Low m_B and m_C suffer from larger SM background
  - dedicated dijet / diboson searches are stronger here



mapped output of NN output score (SR 2, with injected signal)



exclusion limits on a W' signal with $W' \to B + C$ (compared to JHEP 03 (2020) 145 and JHEP 09 (2019) 091)

Spotlights *(removed)*

In Conclusion

Summary

- Presented general overview + selected recent highlights of searches at the LHC
  - non-exhaustive cross-section of the vast search program carried out at the LHC
  - emphasis on impressive collection of innovative approaches in many different analysis aspects
  - if you missed DM: PV V: Priscilla Pani, “On top of Dark Matter searches at the LHC” *(Friday)*

Winter (Spring??) Conferences

- 21.03. – 27.03.2021 (Moriond Electroweak Interactions & Unified Theories)
- 27.03. – 03.04.2021 (Moriond QCD and High Energy Interactions)
- $\Rightarrow$ expect flurry of new hot results already in next weeks