

Evolution and some prospects in BSM searches at CMS

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Introduction

- The main goals of the CMS physics program: find/study the Higgs and look for new physics at the TeV scale.
- This hunt started right at the startup of LHC.
- Almost 10 years later, this seems a good time to take a step back and look where we are.
- Through a few examples, I will try to illustrate how this search program has expanded with time.
- Will also mention a few prospects.
- Certainly not an exhaustive review.

The prime goals of CMS are to explore physics at the TeV scale and to study the mechanism of electroweak symmetry breaking-through the discovery of the Higgs particle or otherwise. To carry out this task, CMS must be prepared to search for new particles, such as the Higgs boson or supersymmetric partners of the Standard Model particles, from the start-up of the LHC since new physics at the TeV scale may manifest itself with modest data samples of the order of a few fb^{-1} or less.

CMS Technical Design Report (2007)

LHC status

- Excellent performances of the machine since the startup.
- Instantaneous luminosity reached **twice the designed value** in 2018.
- **35 pp interactions per bunch crossing in Run 2.**
- Huge challenges for experiments (trigger, computing, pile up mitigation)

Run	Year	\sqrt{s}
Run 1	2010-2012	7-8 TeV
Run 2	2015-2018	13 TeV
Run 3	2021-2023	14 TeV
HL-LHC	2026-2038	14 TeV

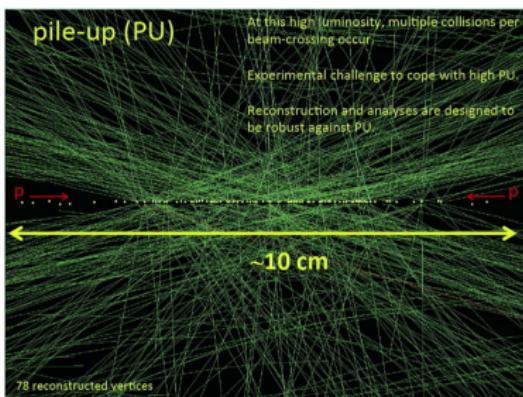
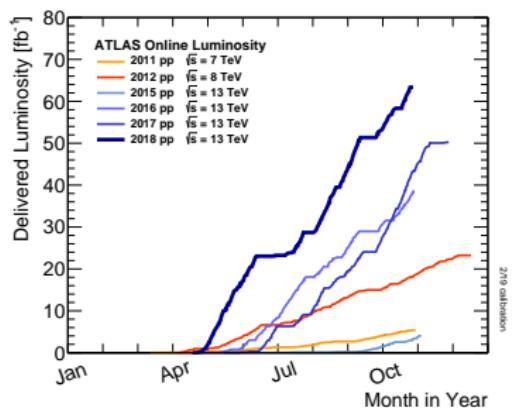


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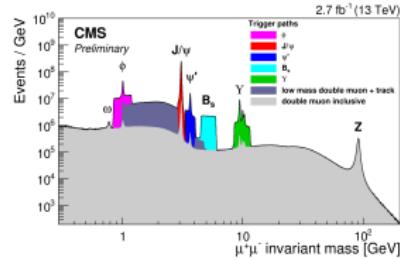
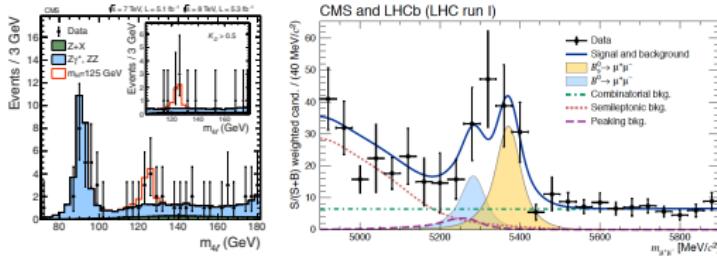
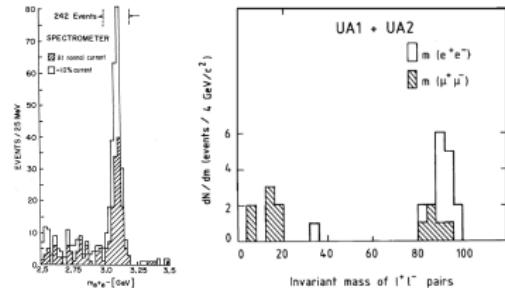
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Looking for resonances

- Long history of discovery looking at resonances:

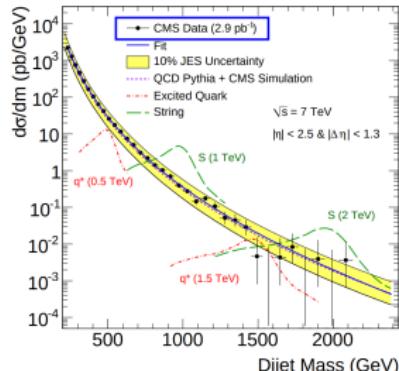
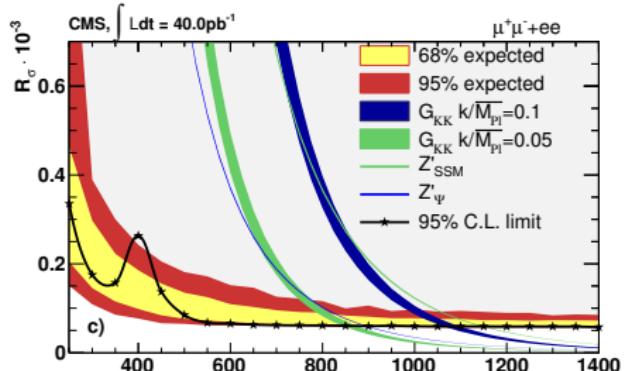
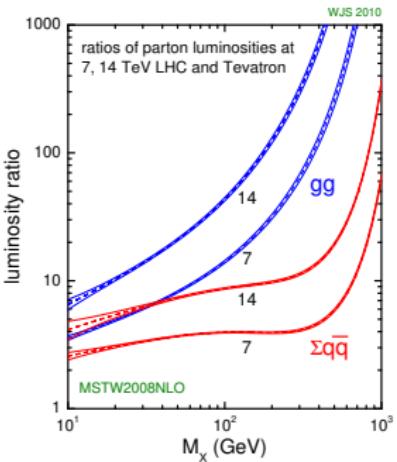
- 1974: J/ψ discovery (Brookhaven, SLAC).
- 1983: W/Z boson discovery (UA1, UA2)
- 2012: Higgs boson discovery (ATLAS, CMS)
- 2013: $B_s^0 \rightarrow \mu\mu$ evidence (CMS, LHCb)
- And many more !



Clear signature, allows to claim discovery sometimes with only a couple of events.

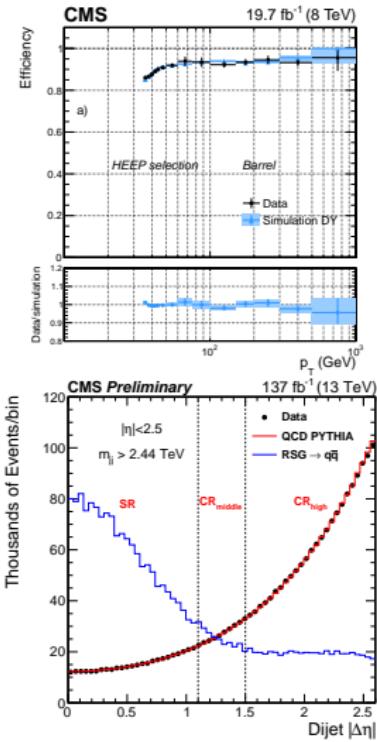
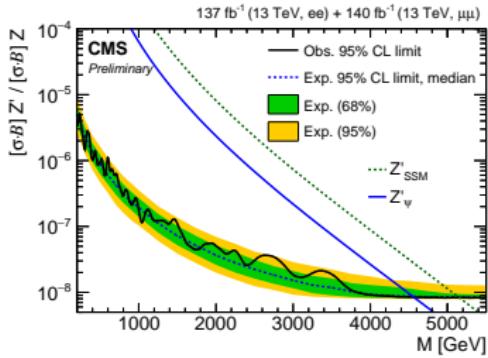
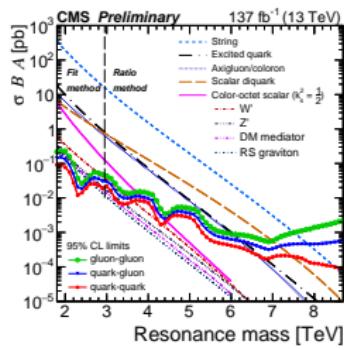
From the early days...

- First published search by CMS: dijet resonances, with 3 pb^{-1} at $\sqrt{s} = 7 \text{ TeV}$!
- Quickly followed by a similar search in the dilepton ($ee/\mu\mu$) channel.
- Motivated by Grand Unified Theory (new heavy gauge bosons) or large extra dimensions.
- Already beating Tevatron limits in the high mass region, thanks to the higher center of mass energy.



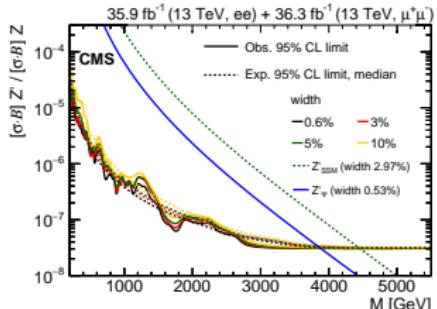
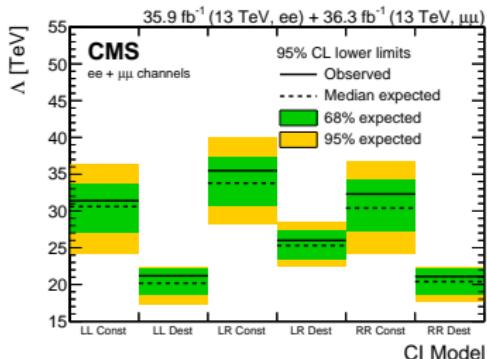
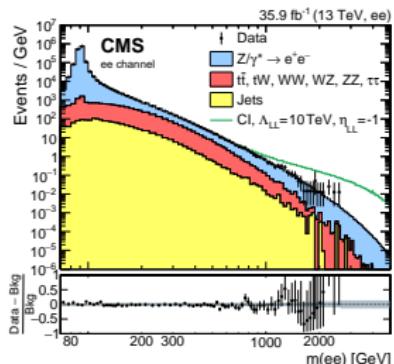
... to the analysis of the latest data

- Take advantage of the large dataset/new techniques to reduce uncertainties.
 - Dijet analysis: background shape at high mass estimated from a control region rather than an empirical function.
 - Dilepton analysis: Using very boosted on-shell Z bosons (cosmic muons) to check lepton performances at high energy.
- Excluding now resonances below 4-5 TeV for a variety of models.



Extending the interpretations

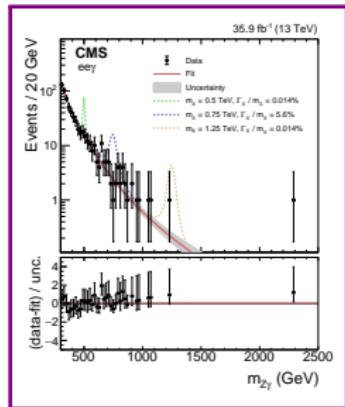
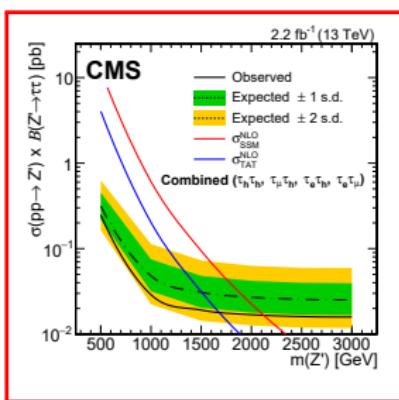
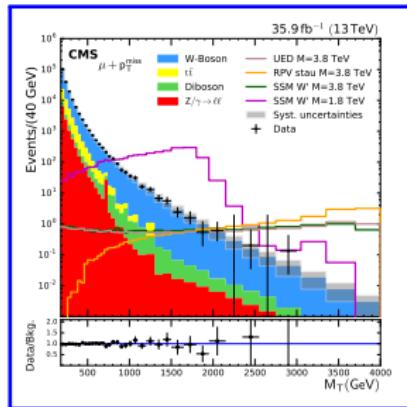
- Limits originally calculated in the narrow width approximation ($\Gamma_{Z'} \ll \sigma_{\text{exp}}(M'_{Z'})$).
- Now also extending them to models with finite widths.
- Also considering non resonant interpretations (contact interaction, Kaluza Klein gravitons continuum). Sensitive to Monte Carlo shape and high order corrections.



$$\mathcal{L}_{q\ell} = \frac{g_{\text{contact}}^2}{\Lambda^2} \left[\eta_{LL} (\bar{q}_L \gamma^\mu q_L) (\bar{\ell}_L \gamma_\mu \ell_L) + \eta_{RR} (\bar{q}_R \gamma^\mu q_R) (\bar{\ell}_R \gamma_\mu \ell_R) \right. \\ \left. + \eta_{LR} (\bar{q}_L \gamma^\mu q_L) (\bar{\ell}_R \gamma_\mu \ell_R) + \eta_{RL} (\bar{q}_R \gamma^\mu q_R) (\bar{\ell}_L \gamma_\mu \ell_L) \right]$$

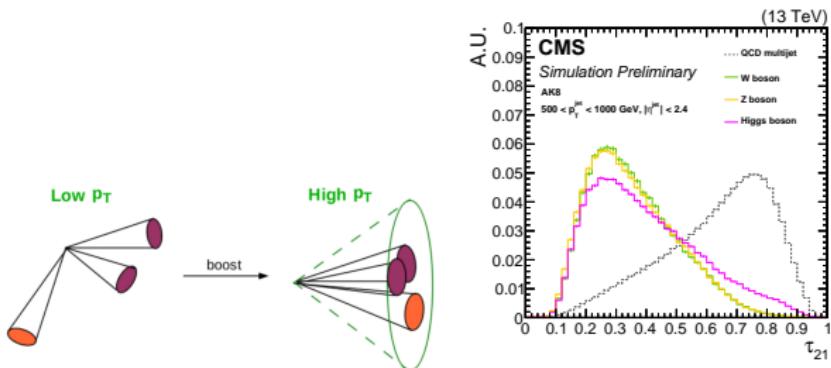
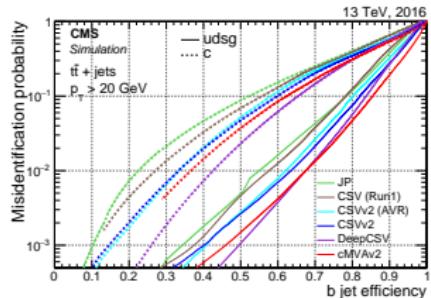
Other final states with leptons/photons

- High reconstruction efficiency and good resolution make light leptons and photons particularly relevant for new resonance searches.
- Even considering hadronically decaying taus.
- Many cases considered.
 - $X^\pm \rightarrow l\nu$: similar to $X \rightarrow ll$, transverse mass as the discriminating variable.
 - $X \rightarrow \tau\bar{\tau}$, much less sensitive than light leptons unless enhanced coupling.
 - $X \rightarrow ll'$, targeting e.g. lepton flavor violating decay of sneutrinos in SUSY: $\tilde{\nu}_\tau \rightarrow e\mu$.
 - $X \rightarrow l\gamma$, targeting e.g. excited leptons.
 - $X \rightarrow \gamma\gamma$, complementary channel to dilepton for graviton/heavy scalar searches.
 - $X \rightarrow Z(l)\gamma$, another way to search for new heavy scalars.
- While first searches had a lot of theoretical/pheno support, CMS is also performing purely signature based searches.



Exploiting the jet flavour and substructure

- Jet flavour and substructure are important handles to reduce the huge QCD background at the LHC.
- b-tagging/ boosted heavy resonance tagging well established in CMS.
- Progressively moving to (advanced) machine learning techniques.



Exploiting the jet flavour and substructure: some use cases

- Search for $X \rightarrow VV$ ($V=W/Z$), fully hadronic.

New analysis based on a multi dimensional fit on both $M(j_1 j_2)$ ($\rightarrow M_x$), and $M(j_1), M(j_2)$ ($\rightarrow M_V$).

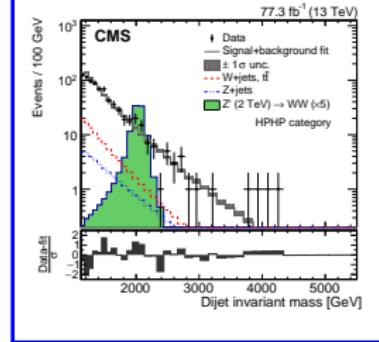
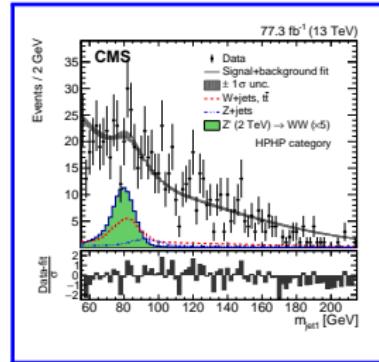
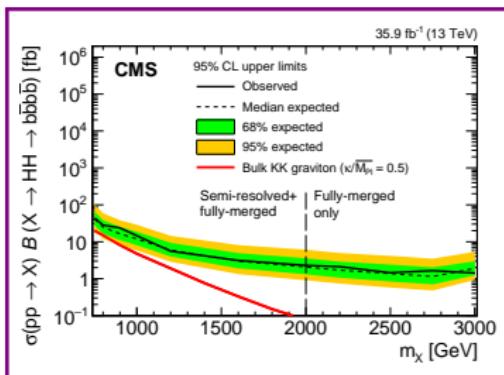
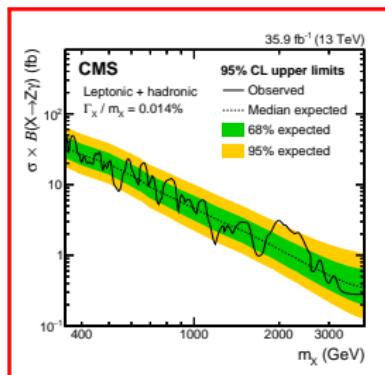
- $X \rightarrow Z(q\bar{q})\gamma$ nicely complements $X \rightarrow Z(l\bar{l})\gamma$.

Dominates sensitivity for very high mass.

- Search for $X \rightarrow H(bb)H(bb)$: uses the double-b tagger developed in the context of boosted $H \rightarrow bb$ studies now also used to searches.

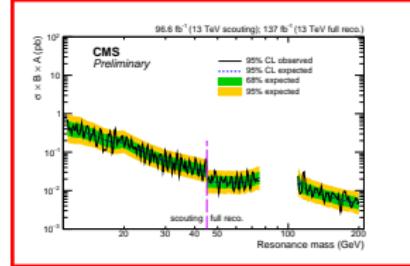
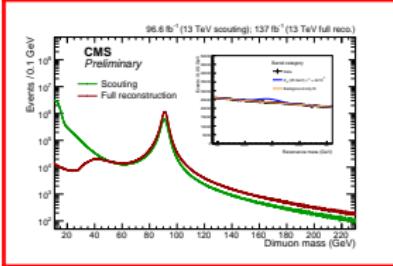
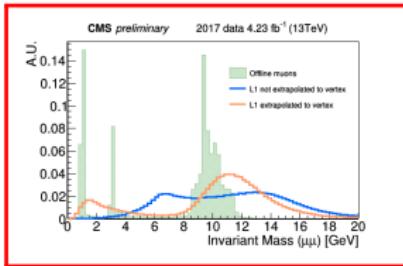
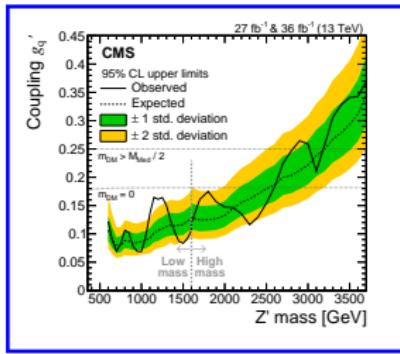
- Search for $X \rightarrow tt$, using top tagging.

- Search for $X \rightarrow YY$, with $Y \rightarrow jj/jjj/jj jj$.



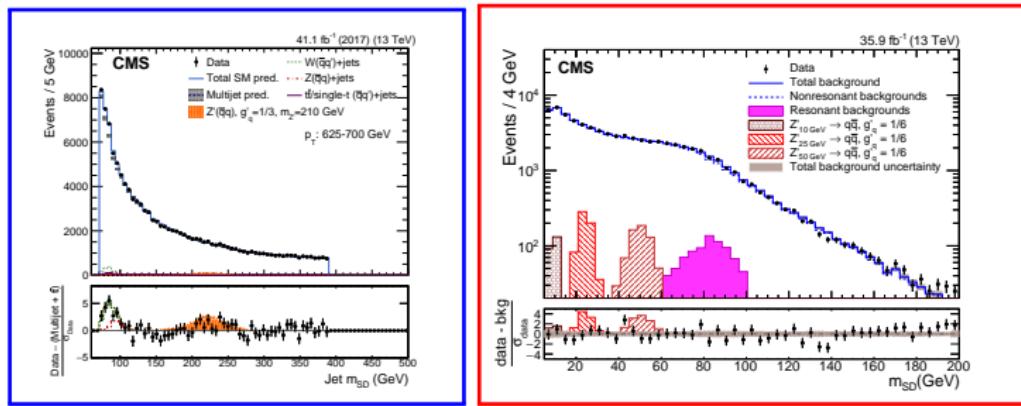
Low mass searches

- So far focused on TeV resonances.
- Growing interest to also probe (very) low masses.
- Trigger is the limit here. Can be overcome with **scouting**: trade event size (save only trigger information) to allow large trigger rate (and therefore lower trigger energy thresholds).
- CMS studying **dijet** (since Run 1) and now also **dimuon** resonances down to 600/11.5 GeV with this technique, corresponding to excluded cross sections of $O(10/1)$ pb.
- Dimuon analysis possible thanks to the excellent muon performances at L1 and HLT (dedicated L1 triggers from b-physics using mass/angular conditions)



Low mass searches (2)

- To get further down with dijet, needs to rely on initial state radiation for trigger.
- $Z'(qq)$ decay products merged into a single jet, studied using substructure info.
- ISR can be:
 - A jet: large cross section
 - A photon: low cross section, but lower threshold ($p_T = 500$ GeV vs 200 GeV)
→ more sensitive to very low mass Z' (decay products not too merged).



Dijet resonances at the LHC: a summary

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

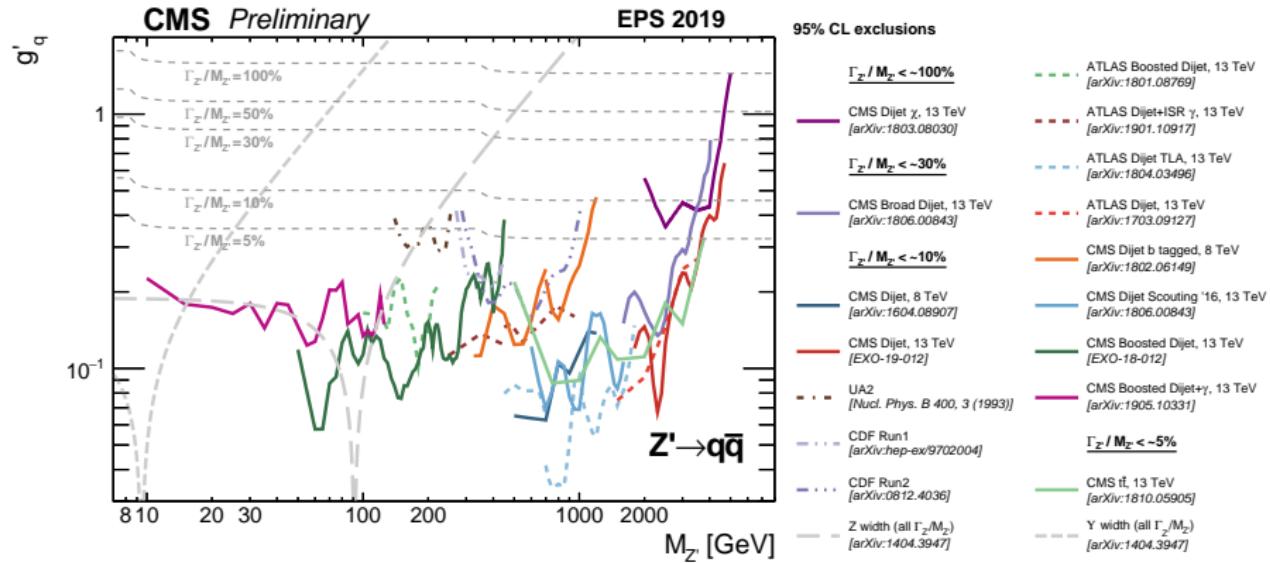


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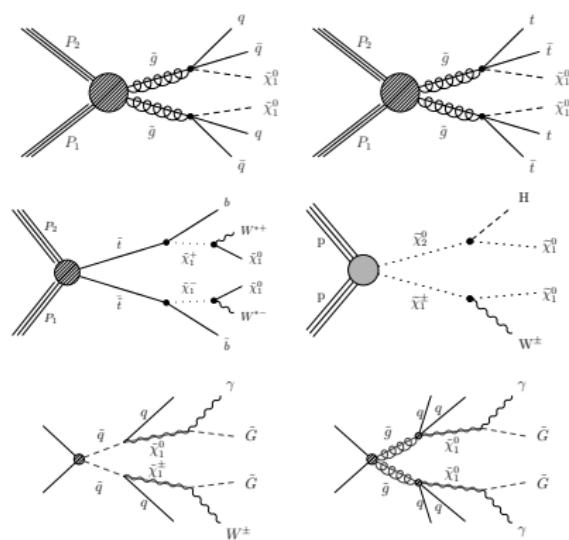
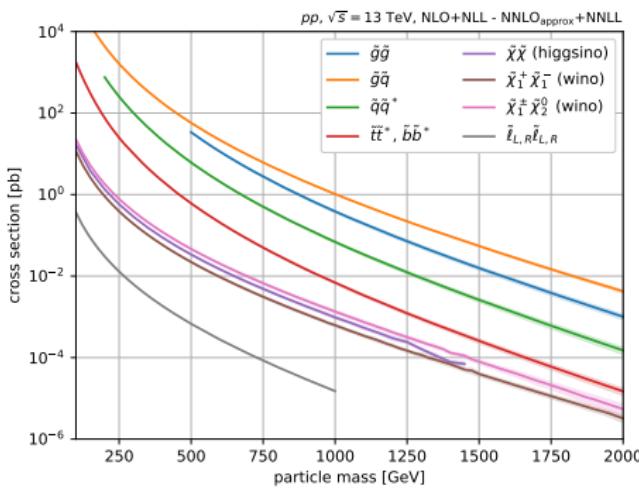
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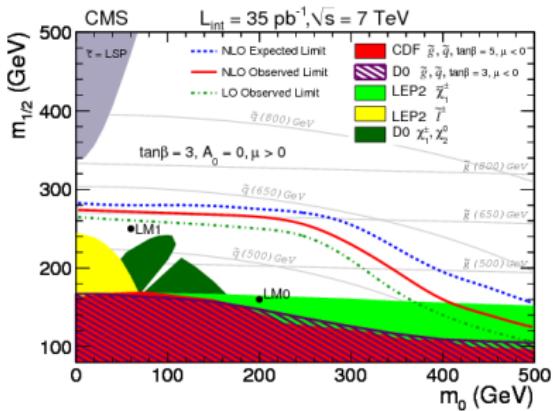
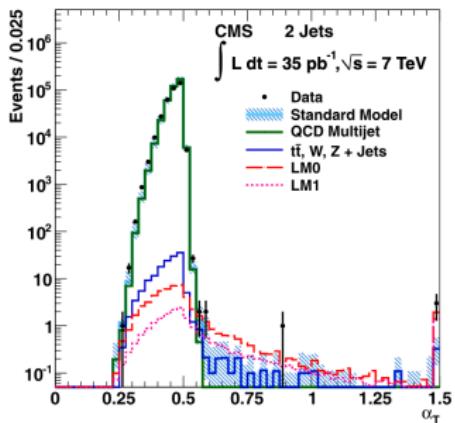
SUSY production at the LHC

- Very rich phenomenology depending on:
 - Open decay modes.
 - Mass hierarchy and splitting between the various SUSY particles.
 - Squark flavour.
 - Nature (or stability) of the lightest SUSY particle.



The first CMS SUSY search

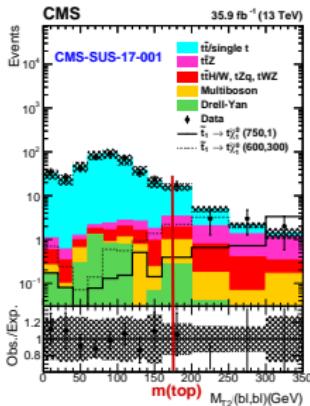
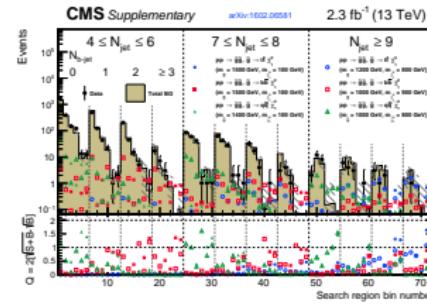
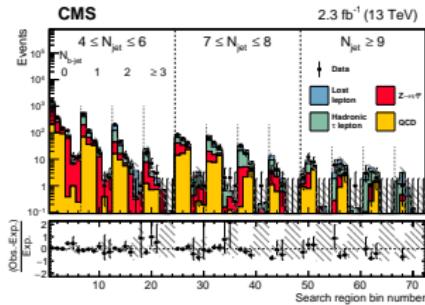
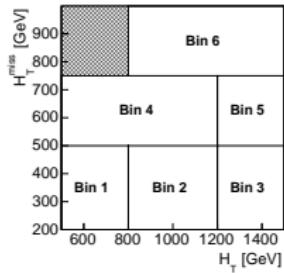
- Multijet search with missing transverse energy (MET).
- Topological cuts to remove mismeasured dijet events.
- Cut and count in single bin.
- Interpretations in terms of the constrained MSSM (5 parameters)



Current searches

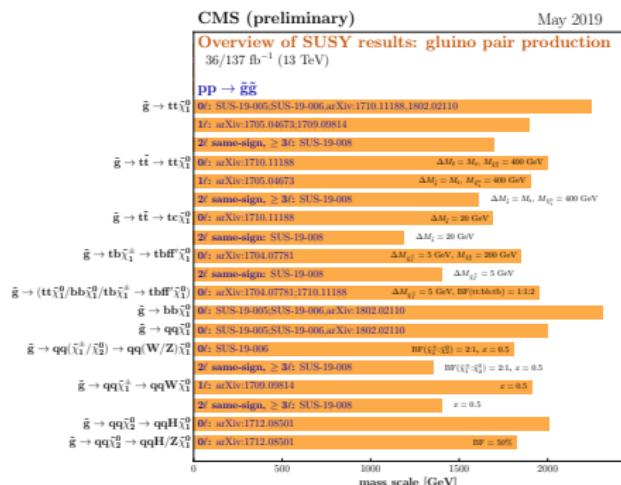
Many evolutions since then.

- Interpretations in terms of simplified models instead of constrained MSSM (now also experimentally constrained).
- Switching to state of the art generators (Madgraph@NLO) and cross sections (NNLO+NNL).
- More advanced kinematic variables
- Multiple signal regions (SR) using multidimensional binning (in H_T , MET, $n_{(b)-jets}$, ...).
 - Background composition varying from a SR to another.
 - Signal extraction from a simultaneous fit to all SR.

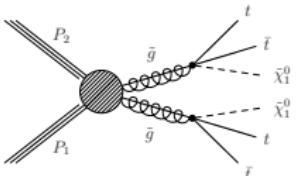
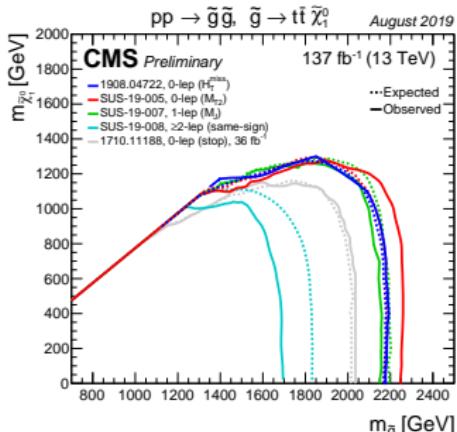


Strong SUSY searches

- Sizeable cross sections for TeV gluinos/squark pair production at the LHC.
- The common denominator (for R-parity conservation): MET due to stable LSP.
- Complementarity between fully hadronic final states and final states with leptons and/or photons.
- Gluino (squark) exclusion up to masses of 1.5-2 (0.5-1) TeV.

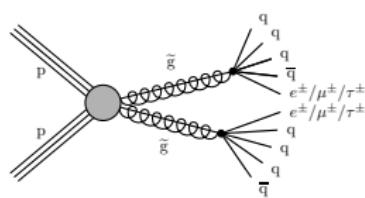
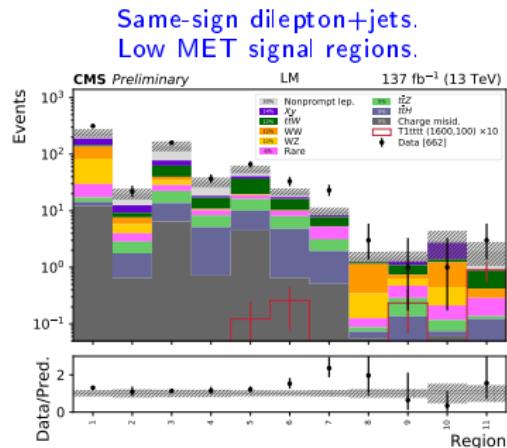
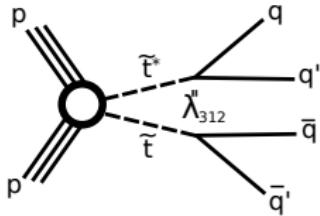
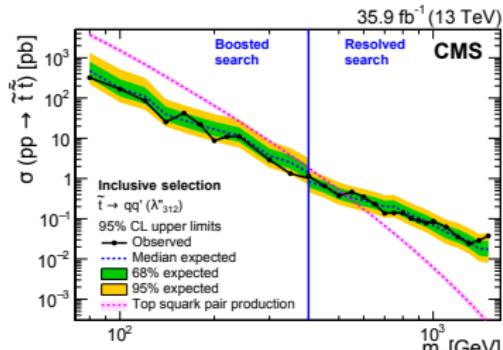


Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSP's unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM , respectively, unless indicated otherwise.

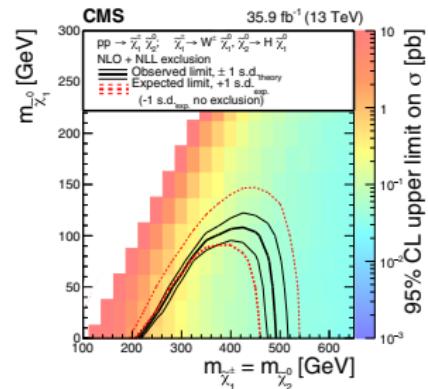
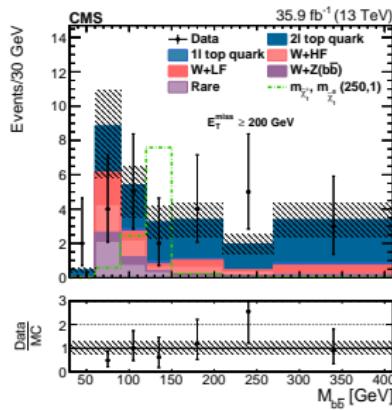
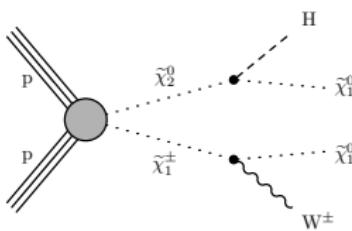


R-parity violation

- Dedicated analyses targeting signature with low/no MET.
- Some standard analyses now also adding low MET signal regions.

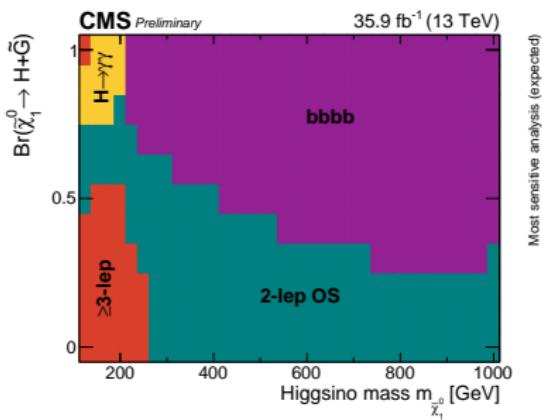
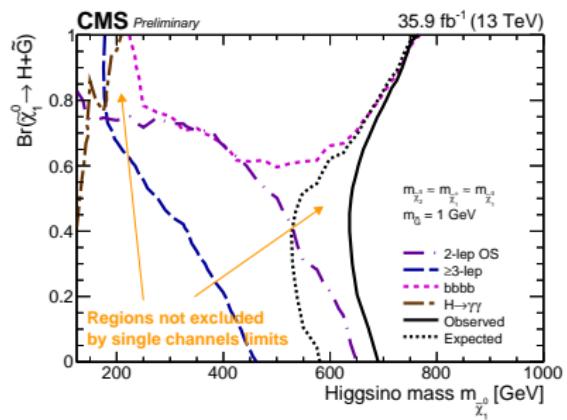
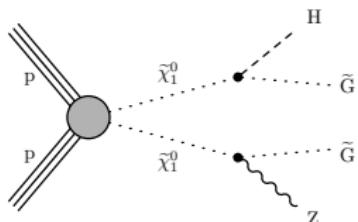


- Electroweak SUSY production cross section several orders of magnitude below strong SUSY at the LHC.
- Much weaker constraints on chargino/neutralino/sleptons masses.
- Signature: final states with EWK bosons (including Higgs !) and/or leptons + MET



EWK SUSY: combination

- Combination also made for a GMSB scenario with $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (\tilde{G} + H/Z)(\tilde{G} + H/Z)$
- Limit parametrized vs $Br(\tilde{\chi}_1^0 \rightarrow \tilde{G} + H)$
- Combination significantly extends the limit and fills some holes.
- Higgsino masses below 600 GeV fully excluded in this model.



Compressed mass spectrum

- Almost degenerate mass spectra can lead to soft visible decay products and moderate MET.
- Use ISR jet or production mode (VBF) to trigger and enhance sensitivity.
- Take advantage of dedicated triggers (soft muons+MET+jets).
- Lepton reconstruction at p_T down to a few GeV crucial for these analyses.
- Also looking at 0 lepton categories in case all leptons are lost.

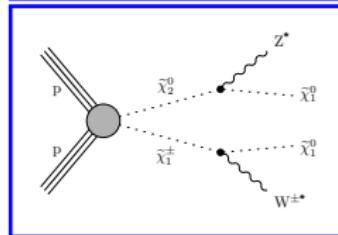
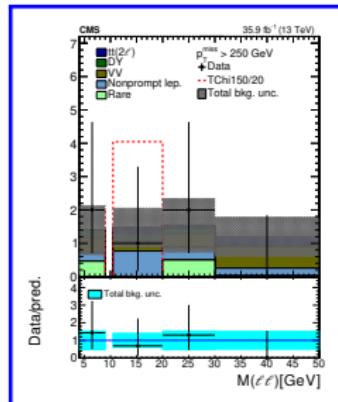
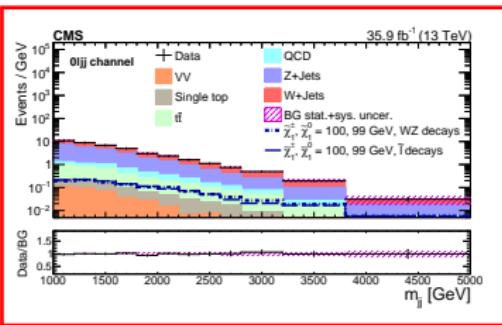
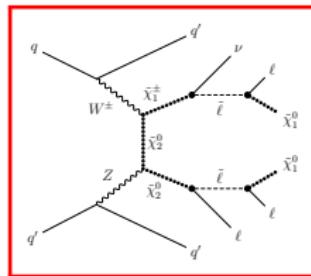


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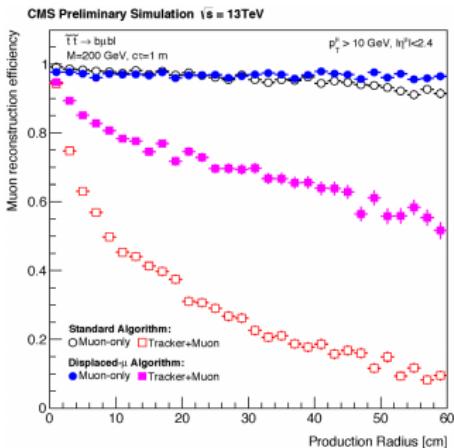
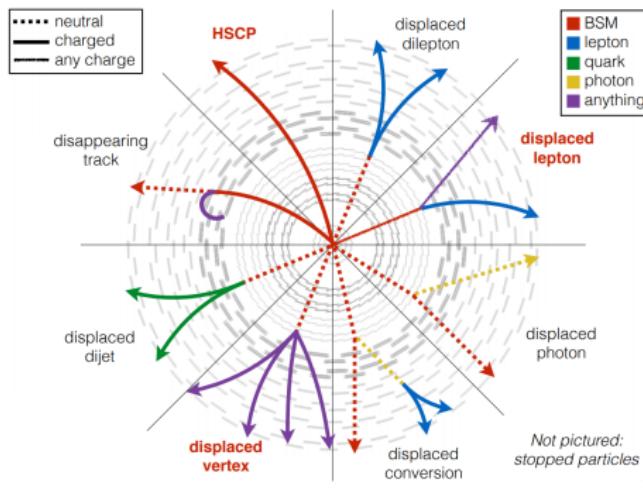
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Long lived particles

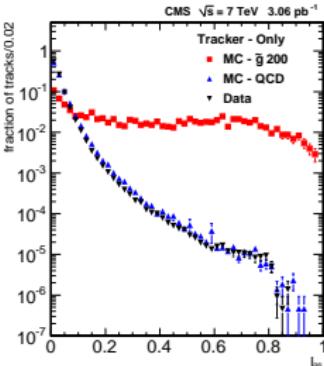
- Long lived particles can lead to large diversity of unconventional signatures in the detectors
- Dedicated analyses needed to make the best use of the detector and adapt standard algorithms/procedures.



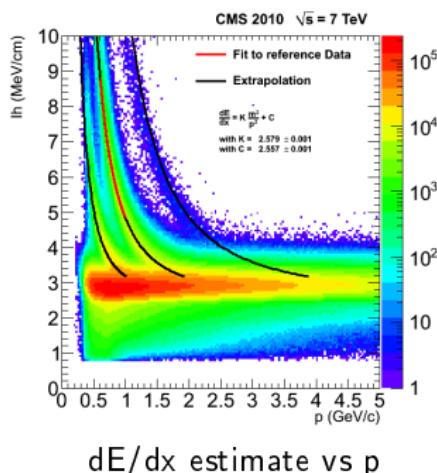
Stolen from J. Antonelli (ICHEP2016)

Heavy Stable Charged Particles in 2010

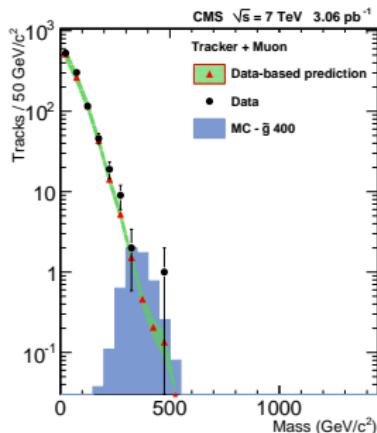
- Yet another search that started on day 1.
- Select both tracker tracks and tracker+muon tracks .
- Use the dE/dx measured in the tracker strips to select highly ionizing particles and infer their mass based on p_T and dE/dx .
- Somehow also a resonance search !



minimum ionizing/high ionizing particle discriminant (based on charge measurement in strip layers)

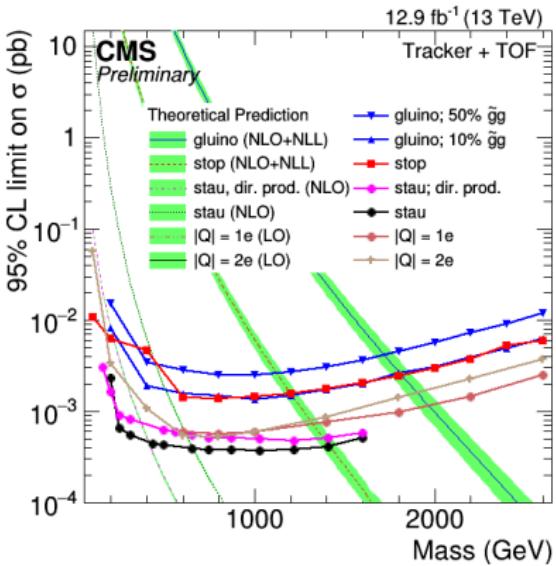
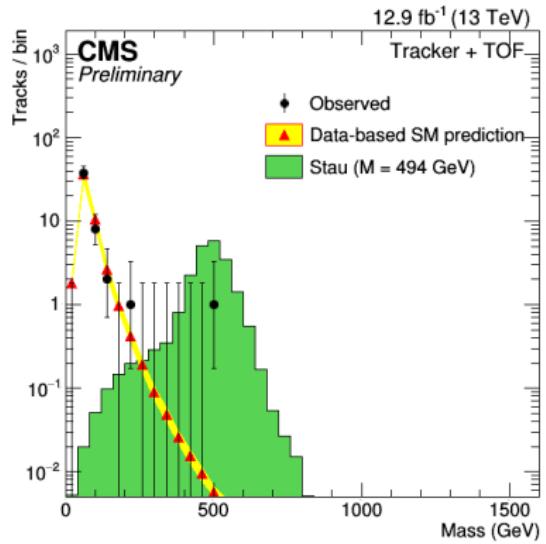


dE/dx estimate vs p



Heavy Stable Charged Particles in Run 2

- Now also using pixel information, muon time of flight.
- Many additional interpretations considered (e.g. $\tilde{\tau}$, lepton-like fermion with electric charge =2,...).



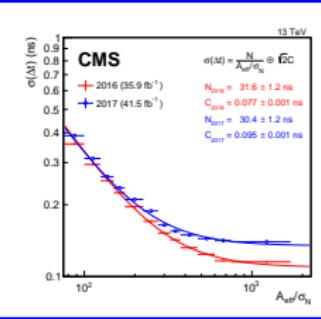
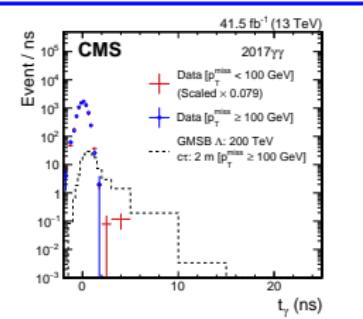
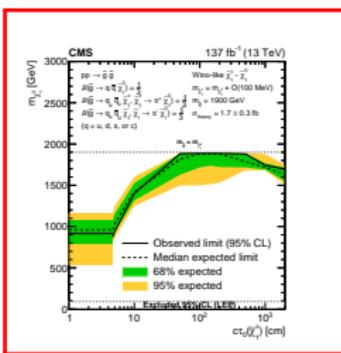
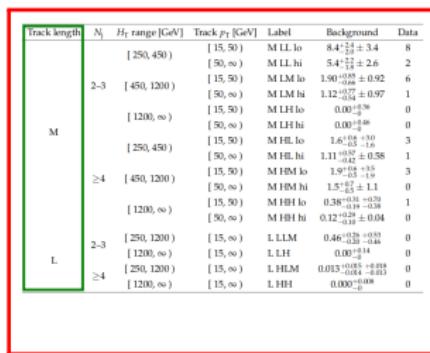
Some recent examples

- **Displaced photons:**

- Search based on photon timing and MET.
- ECAL timing resolution: a few 100 ps
- Fully data driven background from side band (low $t(\gamma)$ and/or MET)

- **Short tracks:**

- Extension of standard fully hadronic SUSY analysis.
- Additional signal regions based on the presence and the length of a short track.



Summary of long lived searches

Overview of CMS long-lived particle searches

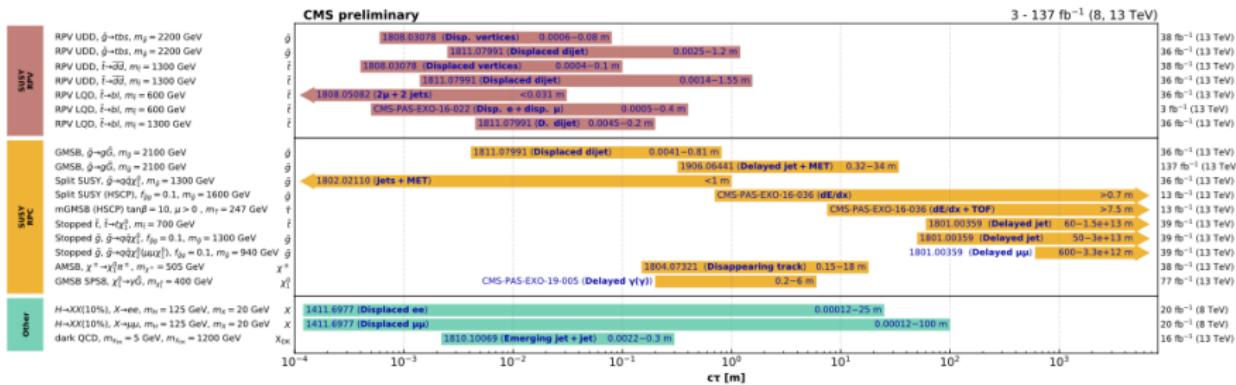


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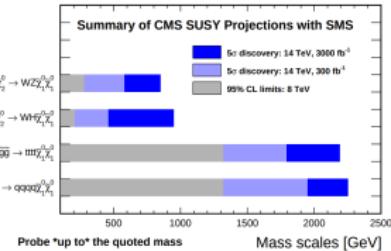
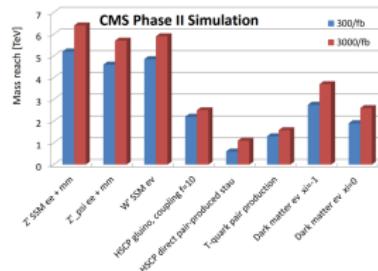
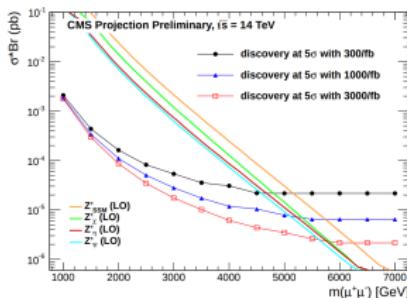
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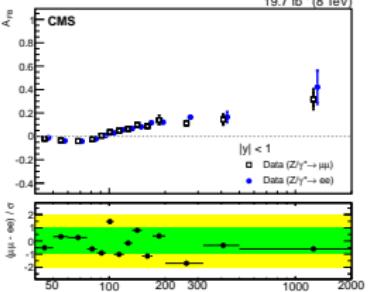
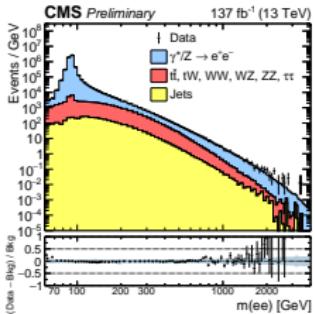
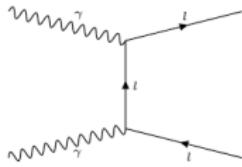
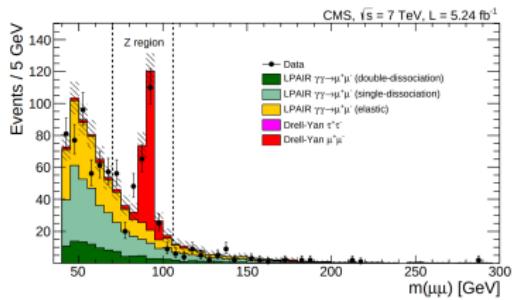
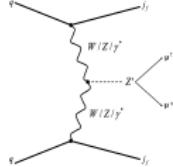
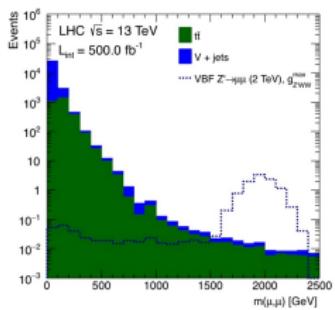
Impact of accumulated statistics

- Factor 3 (20) increase in stat by adding Run 3 (HL-LHC data)
- Sensitivity on production cross sections:
 - $\propto \int \mathcal{L} dt$ (high mass, background free)
 - $\propto \sqrt{\int \mathcal{L} dt}$ (low mass, background full)
- Yet, signal cross sections steeply falling with mass due to pdf in the multi TeV region.
- Typically expect to increase sensitivity reach by ≈ 1 TeV from Run 3 to Phase 2 for multi TeV new physics.
- The gain is more promising at low mass, if one can reduce the background.



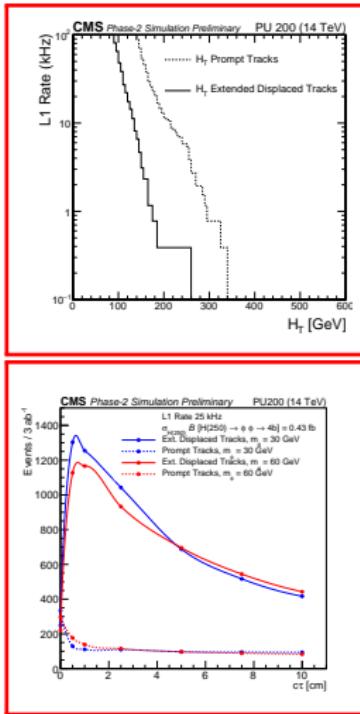
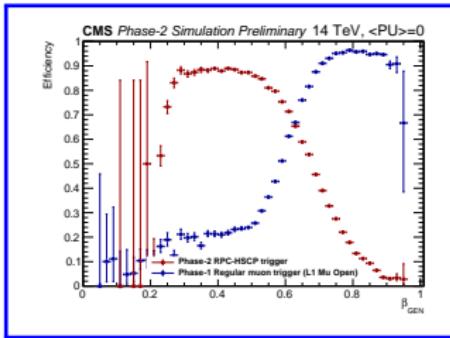
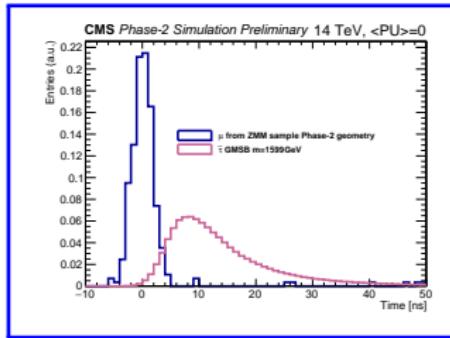
An example: dilepton searches

- Drell-Yan background reduction could significantly help for “low” mass searches (< 1 TeV).
- Targeting production modes (e.g. VBF or, if relevant, $\gamma\gamma$) could help.
- Can also exploit the background properties (e.g. Drell-Yan A_{FB} at high mass?)



CMS Phase 2 upgrade and new physics

- CMS Phase 2 upgrade might provide valuable new tools for new physics, in particular for displaced signatures.
- **Detector timing** (e.g. in RPC) in particular looks promising.
- **First level (L1) trigger with jets and displaced tracks** could allow to significantly reduce threshods and increase acceptance for low/medium mass signals.



Searches in LHC Run 3?

- Sometimes not considered as the most exciting period for the LHC: limited increase in center of mass energy and integrated luminosity.
- There are some cases where we are the edge (in addition to $H \rightarrow \mu\mu$). For example: staus searches.
- 2021: limited dataset ($\int \mathcal{L} dt \approx 20 \text{ fb}^{-1}$), \sqrt{s} not confirmed yet.
→ In fact a good opportunity to come up with crazy ideas that require special LHC runs, large trigger rates,....

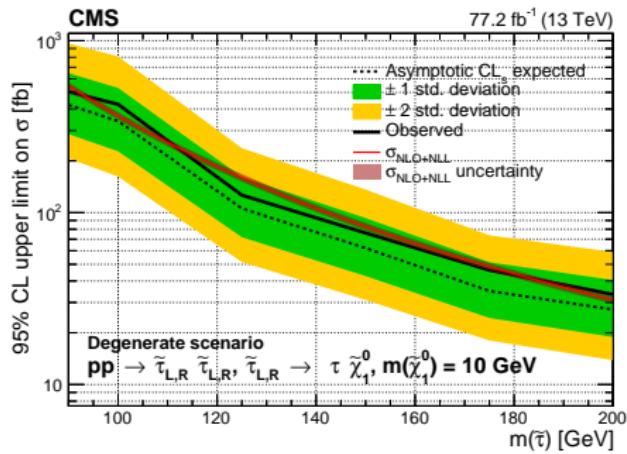


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Summary

- New physics searches are and will remain one the main fields in the CMS physics program.
- Initial searches are now being expended to more complicated final states/topologies.
- Trying to exploit all the information provided by the various detectors as much as possible.
- Stringent constraints set on a large variety of BSM scenarios.
- Yet, we only took 5% of the final LHC dataset so far...
- More data (and analysis improvements) to come.

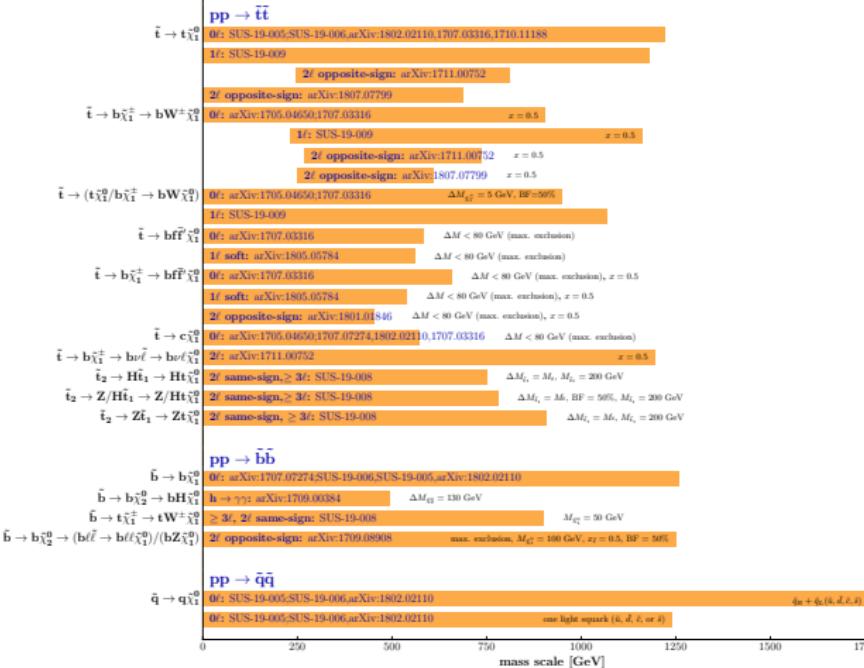
Squarks limits

CMS (preliminary)

May 2019

Overview of SUSY results: squark pair production

36/137 fb^{-1} (13 TeV)



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSP's unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary particle and the LSP, and the difference between the intermediate particle and the LSP relative to ΔM , respectively, unless indicated otherwise.

Compressed mass spectrum: some limits

Left: dilepton+MET+ISR jet. Right: VBF production

