Supersymmetry and Exotics searches (mostly at the LHC)

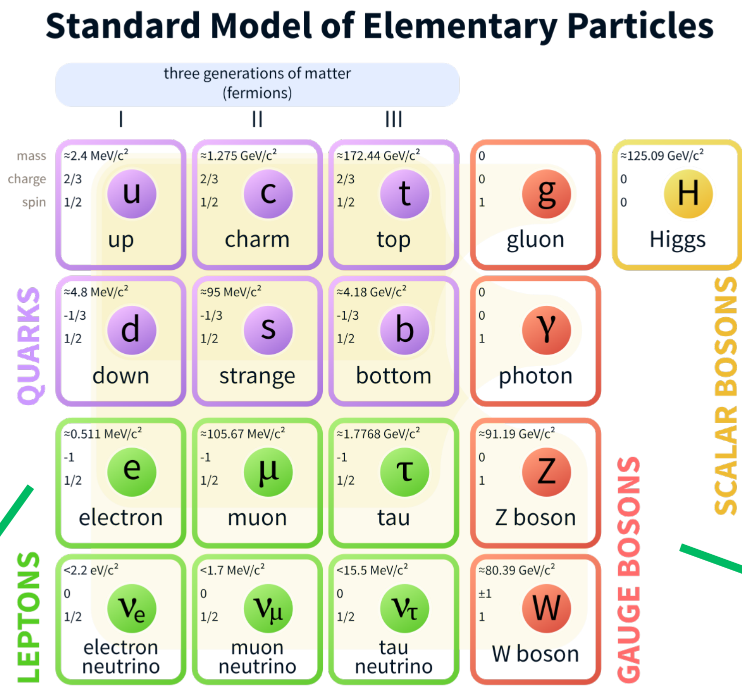
On behalf of the ATLAS, CMS and LHCb Collaborations
+ few highlights from HERA, NA62

Monica D'Onofrio
University of Liverpool

EPS-HEP 2017, Venice, 11/7/2017

Searching for new physics: why and what

<u>Standard Model:</u> remarkably successful description of known phenomena, **but** requires new physics at the TeV scale – missing gravity, Dark Matter (DM), Dark Energy (DE), explanation for matter-antimatter asymmetry and more…



<u>Non minimal Higgs sector</u>

- Exotics / Rare / Invisible decays
- Higgs as portal to DM
- Extended: Two-Higgs-Doublet-Models, MSSM, NMSSM and more
- Charged Scalars
- Composite Higgs

<u>"Exotics"</u>: referred to a large variety of theories and models

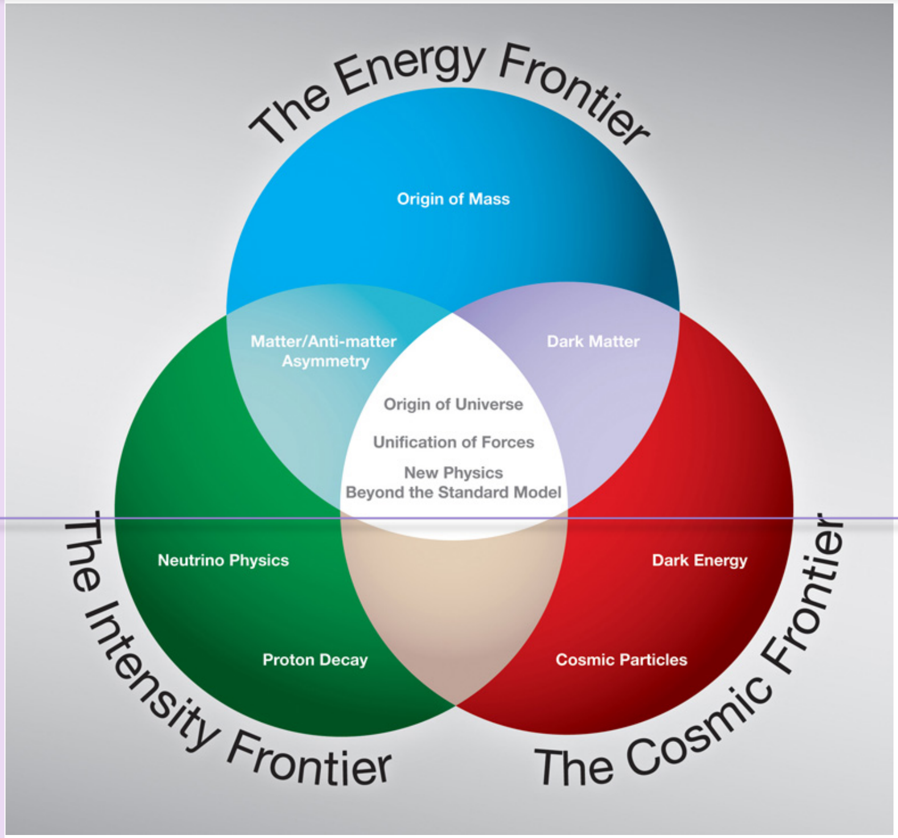
- Heavy vector bosons, vector-like quarks, excited quarks, non-SUSY Dark-Matter models, lepto-quarks, dark/hidden sectors and more
- **The unknown!**

<u>Supersymmetry</u>

- many variants and kind (MSSM, NMSSM, R-parity conservation or violation..)
- mostly heavy super-partners, prompt or long-lived, several Higgs bosons

More on theoretical aspects e.g. in N. Craig's talk "SUSY and BSM Theory After LHC 2016

Searching for new physics: how and where



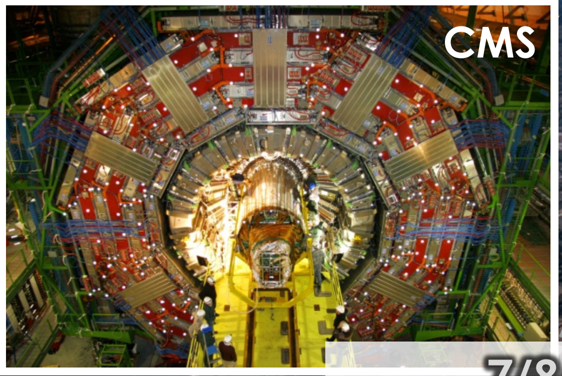
The energy frontier: LHC

- It is the unique place where to look directly for new particles:
  - offers the possibility to search for excesses in number of events in a plethora of kinematic regions and for resonances from new heavy particles
  - allows to perform precision measurements of SM parameters → Each deviation could be an hint of new physics!

- Other colliders/experiments give alternative opportunities, equally fundamental. Examples *[some also in this talk]*:
  - Contact interactions (ep HERA), hidden sector particles (NA62), precision measurements leading to loop-induced deviations (g-2, EDM)
  - More in other dedicated talks

The LHC as NP machine

With 13 TeV c.o.m energy, the LHC offers the best environment to search for a large variety of new physics models



7/8/13 TeV proton–proton collisions

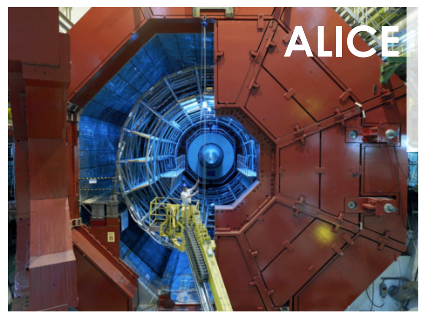
ATLAS/CMS:

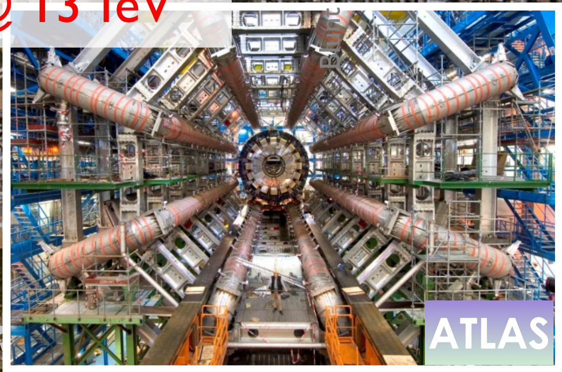
5 & 25 fb^{-1} /exp 2011-12 @ 7 & 8 TeV

36 fb^{-1} (2015-2016) & 4 fb^{-1} (2017) / exp @ 13 TeV

LHCb: 3 fb^{-1} @ 8 TeV

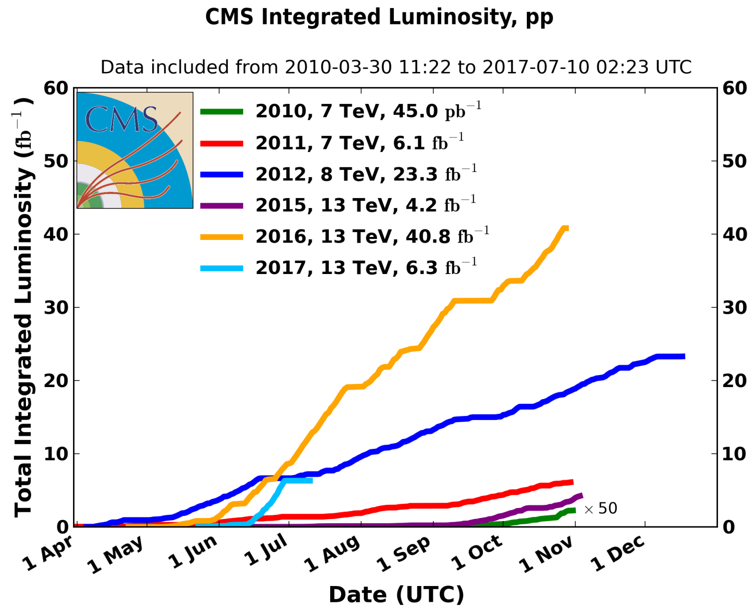
1.9 fb^{-1} (2015+2016) / 0.2 fb^{-1} (2017) @ 13 TeV

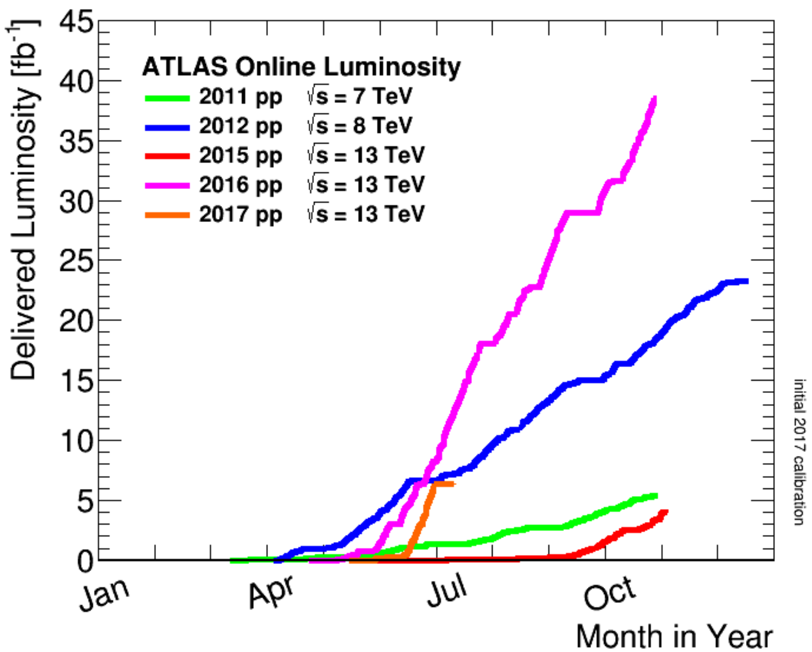


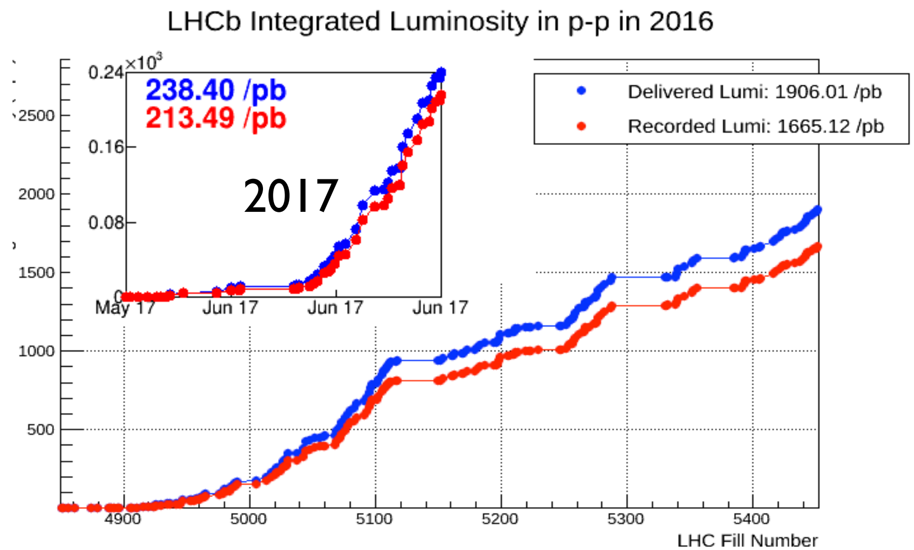


LHC Run 2

- 2016 Run 2 went very well
- Now collecting efficiently new data from 2017 collisions → ~ 6 fb^{-1} recorded
  - Record peak instantaneous luminosity = $14.6 \times 10^{33}\ cm^{-2}\ s^{-1}$



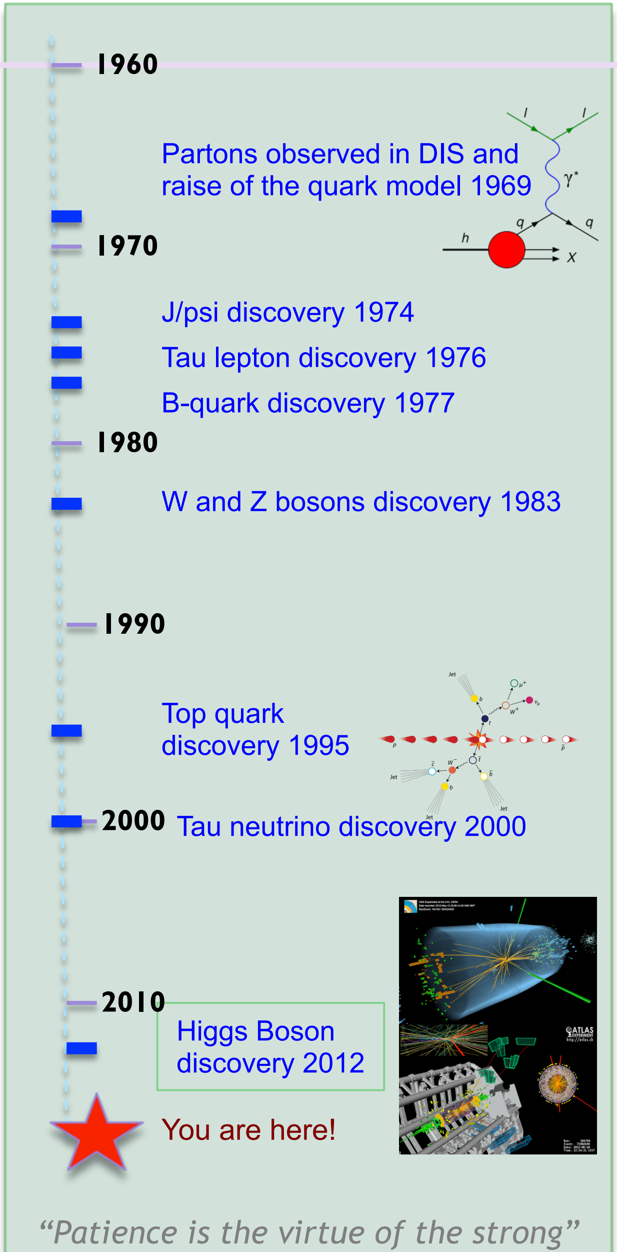




Outline

A journey starting from what we have discovered: the Higgs boson!

- Highlights on methodologies
- New Physics in the Higgs sector:
  - Invisible or exotics decays
  - New BSM Higgses: heavy or charged
- Searches for SUSY as explanation for EWSB
  - Strong and EWK production – with or without naturalness constraints
- Enlarging the landscape:
  - Dark matter as WIMPs
  - Heavy particles (resonant or non-resonant)
- Searches for long-lived particles
  - Unconventional signatures, possibly arising in SUSY, Hidden Valleys and a variety of other BSM models
- Concluding remarks



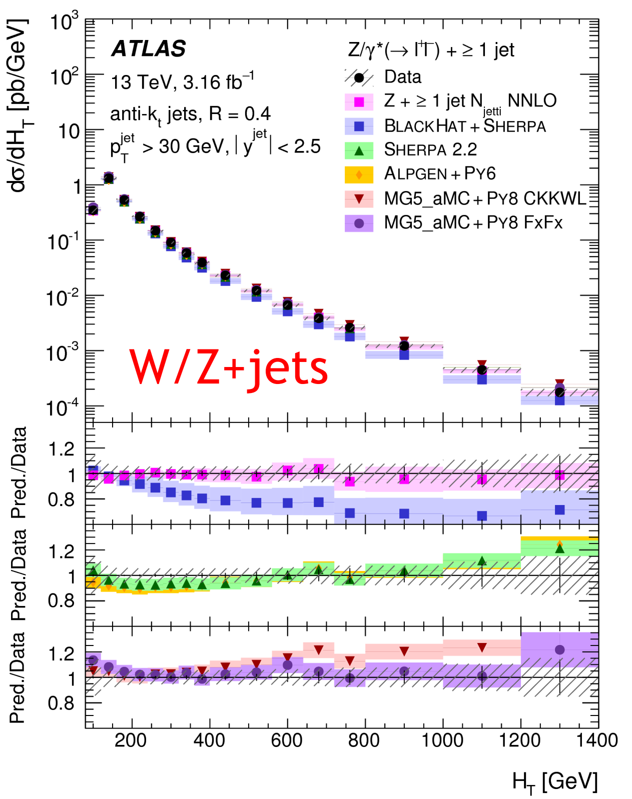
DISCLAIMER: most of the results (representative) from ATLAS and CMS with highlights from LHCb, HERA and NA62

challenges: SM measurements

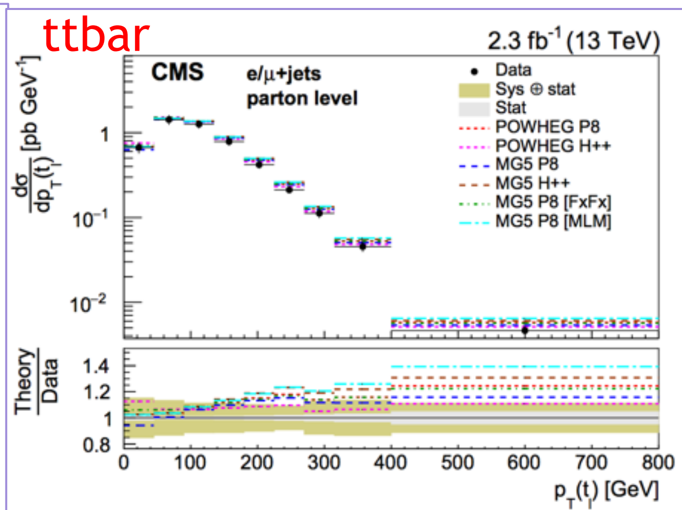
- Wide variety of fundamental measurements of SM processes done or in progress
- Dedicated methods needed to constrain SM background in searches

  → often performed in uncovered phase space regions

- Huge effort by theorists and experimentalists using 7,8 and 13 TeV data and new calculation methods to improve capability to simulate SM processes with MC generators

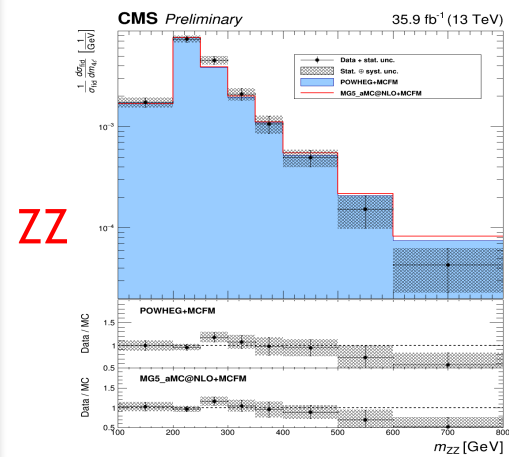


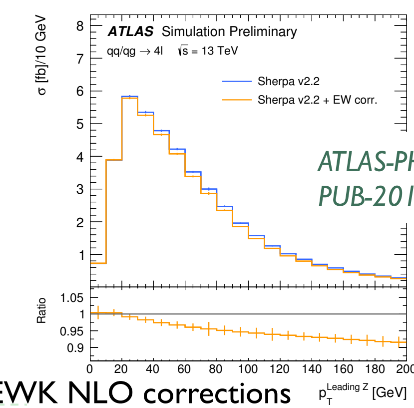
Eur. Phys. J. C77 (2017) 361



With more and more data available, accuracy of the predictions is crucial

CMS-PAS-SMP-16-017





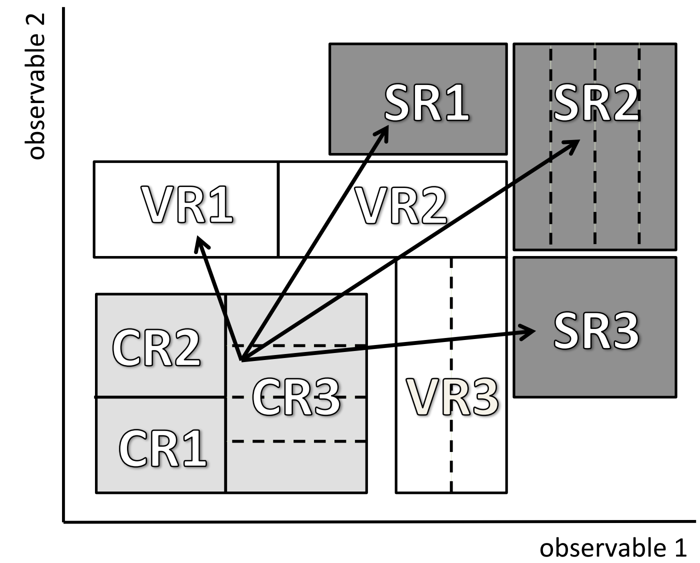
ATLAS-PHYS-PUB-2017-005

EWK NLO corrections

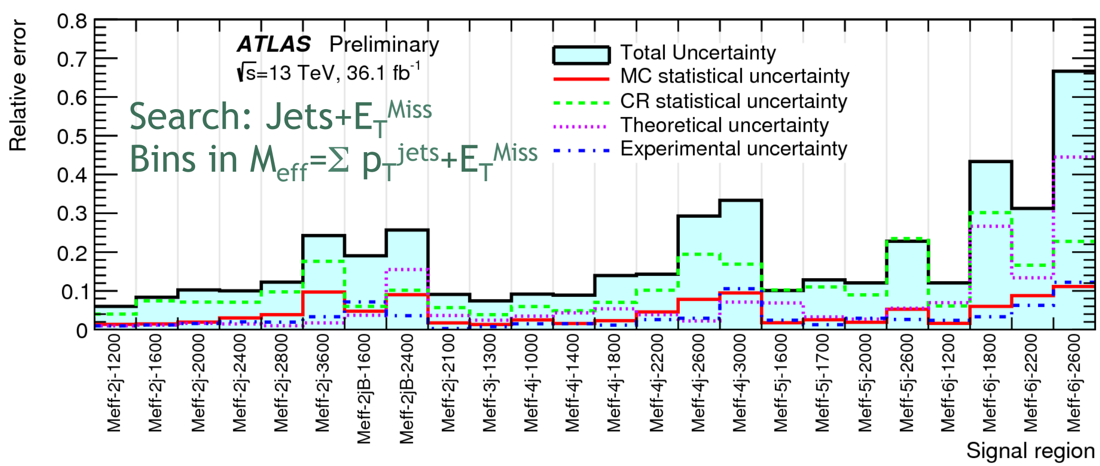
challenges: SM background estimates

- Usually, define control regions (CR) enriched in one background source
  - Compromise between closeness to signal region (SR), data statistics and handling of systematic uncertainties
- Normalize estimates from simulation in these CRs
  - Simultaneous fit of N regions for M background normalizations
- "Validation regions" used for cross check of the background estimate

arXiV: 1410.1280



ATLAS-CONF-2017-022



- Uncertainties arise from data statistics in CR and from extrapolations CR → SR
- Very effective to reduce detector-related systematics
- Theoretical uncertainties dominant in extreme phase-space:
  - MC extrapolation

challenges: explore wide phase space

"Leave no stone unturned"

- Multi-dimensional bins considering various discriminating observables
- *An example:*
  - Search for SUSY in all-hadronic final states (with E_T^{Miss}) by CMS
  - Consider SRs categorized with respect to N_{jets}, N_{bjets}, $H_T = \Sigma\, p_T^{jets}$
  - Each region with a certain H_T range is further split in terms of M_{T2}

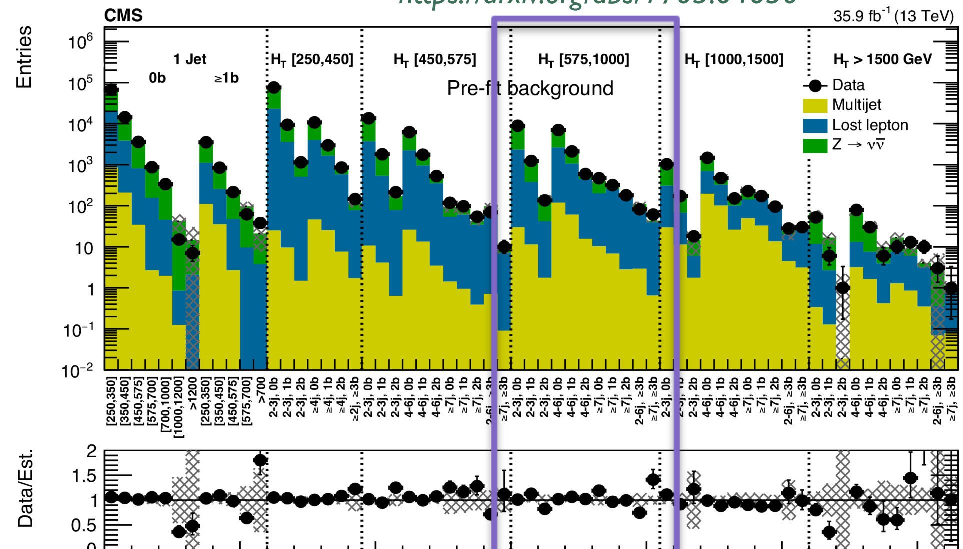
$$M_{T2} = \min_{\vec{p}_T^{\,\mathrm{miss}X(1)} + \vec{p}_T^{\,\mathrm{miss}X(2)} = \vec{p}_T^{\,\mathrm{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

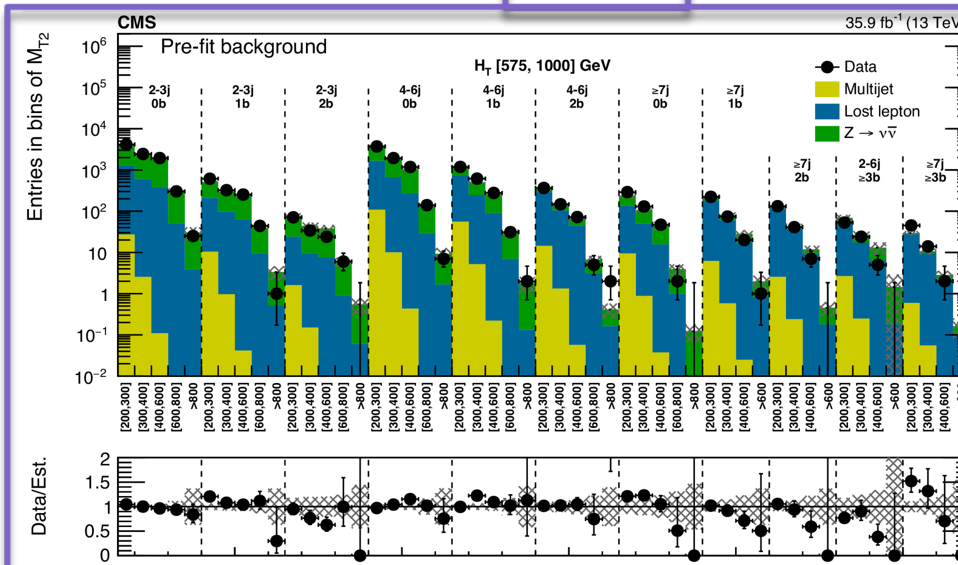
where (1) and (2) are jets or clusters of jets constructed in the two hemispheres

→ **Great complexity of the current searches** – making full use of all data collected!

→ *Model-independent* upper limits usually provided as well as interpretations in specific NP models

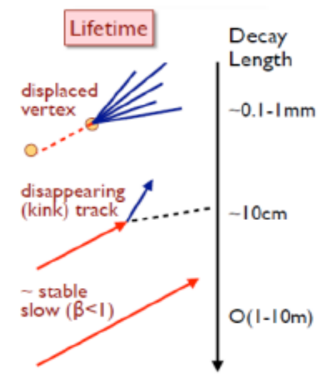
https://arxiv.org/abs/1705.04650





challenges: complex reconstruction methods

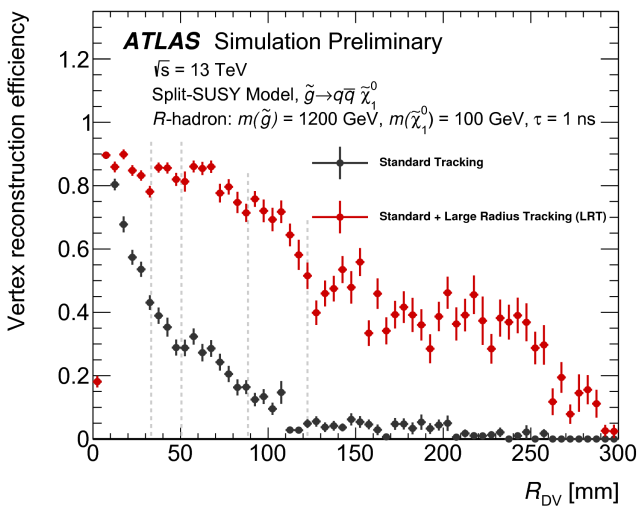
- Innovative techniques needed e.g. for "unconventional" signatures such as long-lived particles (LLP).



- Small-medium decay lengths → displaced vertex (DV)

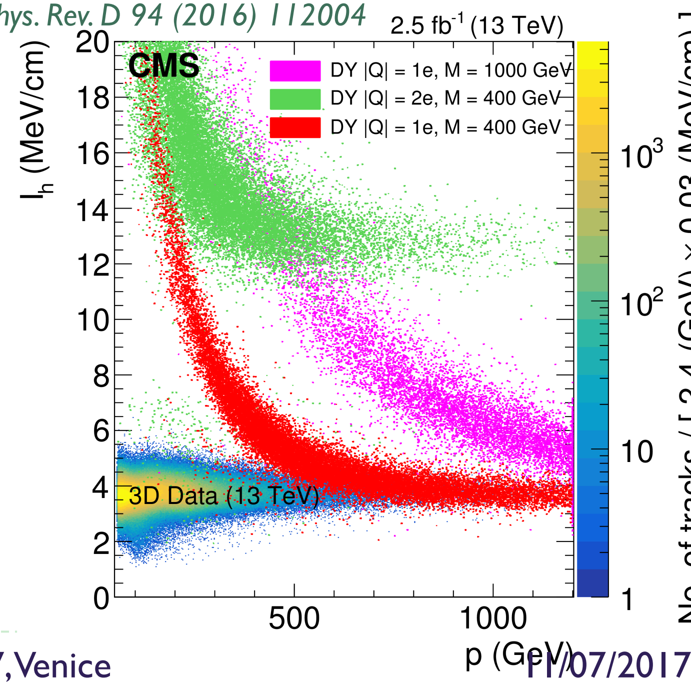
ATLAS-CONF-2017-026

Re-tracking @ ATLAS



@ LHCb: dedicated techniques for DV exploiting the unique characteristics of the detector – sensitivity to O(ps) lifetime

Phys. Rev. D 94 (2016) 112004



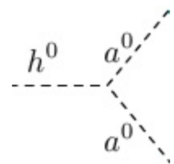
- Heavy stable charged particles → anomalously high energy deposits in the silicon tracker and long time-of-flight measurements by the muon system

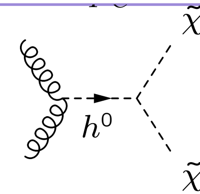
dE/dx estimator @ CMS

New physics in the Higgs-sector

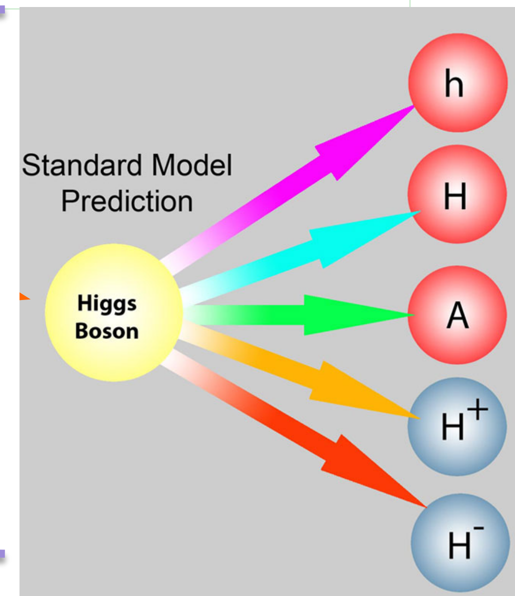
Is the Higgs observed at the LHC the standard model Higgs or the h from an extended sector?

- **Decays:** Rare/Exotics/Invisible

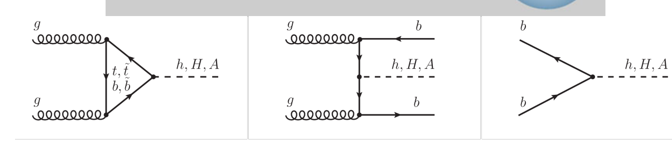




- **Production** of more Higgs in **Extended Sectors**
  - Additional singlet → one more Higgs boson
  - Additional doublets → 5 Higgs bosons (h, H, A, H±): 2HDM/MSSM
  - Additional singlet+doublet → 7 Higgs bosons ($h_{1,2,3}$, $a_{1,2}$, $H^{\pm}$): NMSSM
  - Additional triplets and/or charged (double charged) higges (Georgi-Machacek, MSSM ..)



- **Exotic properties** of the Higgs
  - Composite Higgs, FCNC t→hq and more



(a) (b) (c)

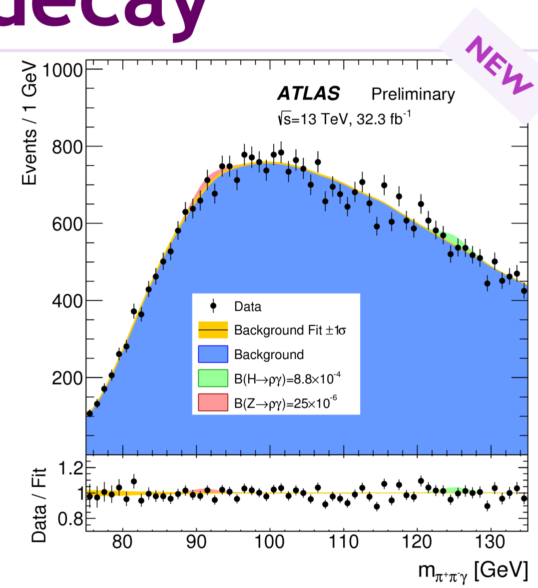
Rare and Exotics Higgs decay

- **H→φγ and H→ργ**

sensitive to s-/ud-quark Yukawa couplings

Reconstruct $\varphi\gamma \rightarrow K^{+}K^{-}\gamma$ and $\rho\gamma \rightarrow \pi^{+}\pi^{-}\gamma$
Dedicated triggers, data-driven background

$B\,(H \rightarrow \varphi\gamma) < 4.8 \times 10^{-4}$
$B\,(H \rightarrow \rho\gamma) < 8.8 \times 10^{-4}$



ATLAS-CONF-2017-057

Very rare in SM:

$B(H \rightarrow \varphi\gamma) = (2.31 \pm 0.11) \times 10^{-6}$

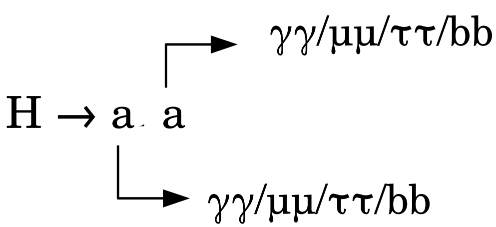
$B(H \rightarrow \rho\gamma) = (1.68 \pm 0.08) \times 10^{-5}$

- **H→μτ , H→eτ, H→eμ** *CMS-PAS-HIG-17-001*

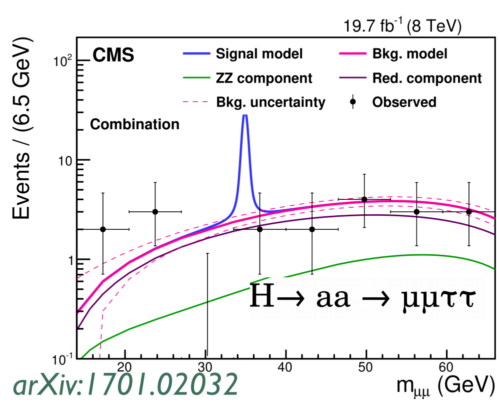
Lepton Flavor Violating decays (also very rare in SM)

$B(H \rightarrow \mu\tau) < 0.25\%$ $B(H \rightarrow e\tau) < 0.61\%$

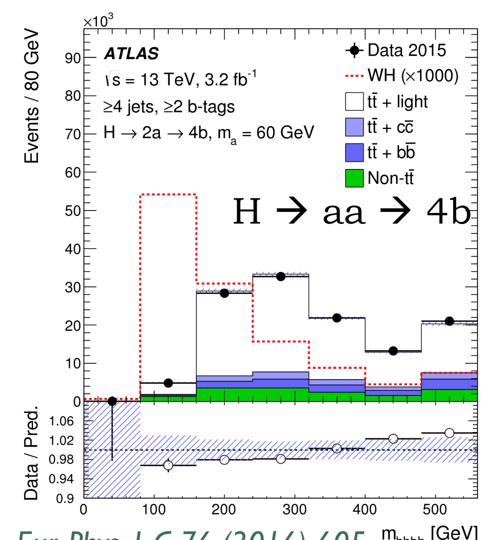
- **H→*aa*** decays of the discovered higgs into low-mass pseudoscalars (*a*). BR of *a* depends on assumptions



Constraints from analyses for all combinations (mostly from Run 1)



arXiv:1701.02032



Eur. Phys. J. C 76 (2016) 605

Rare and Exotics Higgs decay

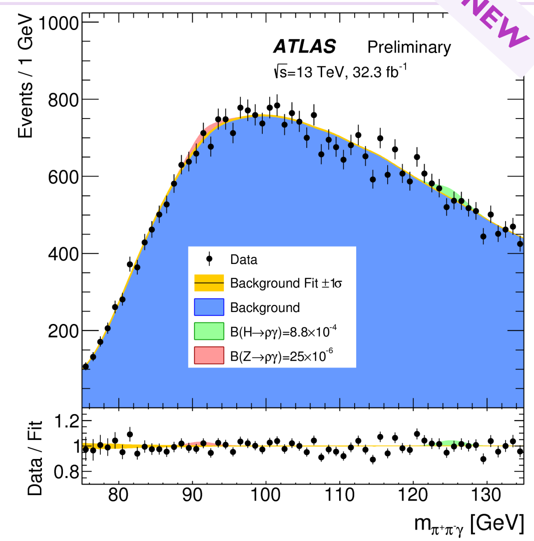
NEW

- **H→φγ and H→ργ**

sensitive to s-/ud-quark Yukawa couplings

Reconstruct φγ → K^+K^-γ and ργ → π+π−γ
Dedicated triggers, data-driven background

B (H → φγ) < 4.8 × 10^{-4}
B (H → ργ) < 8.8 × 10^{-4}



ATLAS-CONF-2017-057

Very rare in SM:

B(H → φγ) = (2.31±0.11)×10^{-6}

B(H → ργ) = (1.68±0.08)×10^{-5}

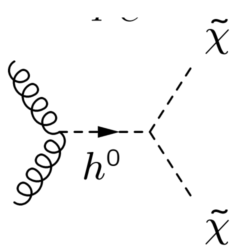
- **H→μτ , H→eτ, H→eμ** *CMS-PAS-HIG-17-001*

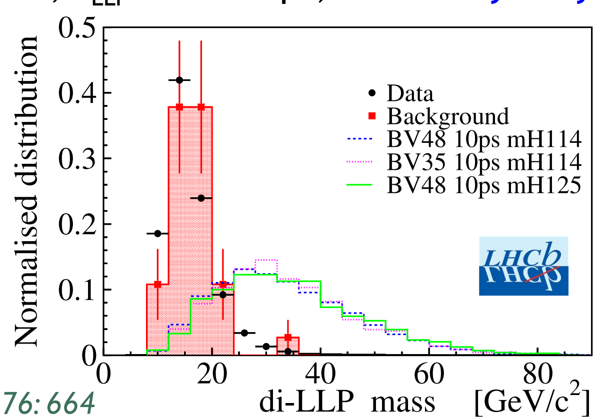
Lepton Flavor Violating decays (also very rare in SM)

B(H→μτ)<0.25% B(H→eτ)<0.61%

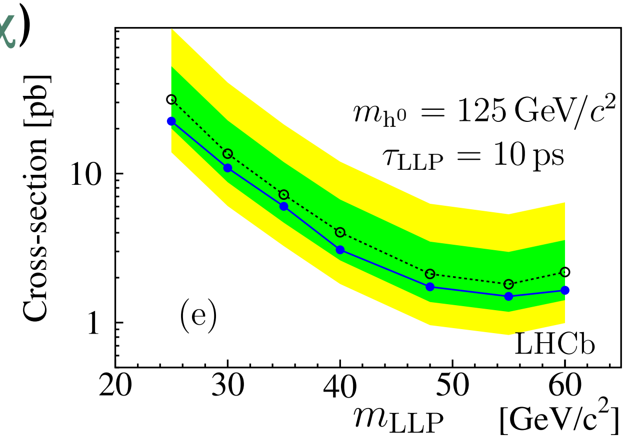
- Decays of Higgs-like particle in two LLP (h → χχ)

m(LLP): 20-60 GeV, τ_{LLP} ~ 5-100 ps, LLP decay fully hadronic





Eur. Phys. J. C (2016) 76: 664



Limits set on the production cross-section as a function of the long-lived particle mass and lifetime

Invisible Higgs decay

- Invisibly decaying Higgs in SM: h → ZZ* → νννν

$$B_{H\to inv} = 1.06 \times 10^{-3}$$

- Enriched if BSM higgs decay h → χχ, χ weakly interacting

CMS: via gluon-fusion (ggH) and ISR-jet, vector-boson fusion (VBF) and with W/

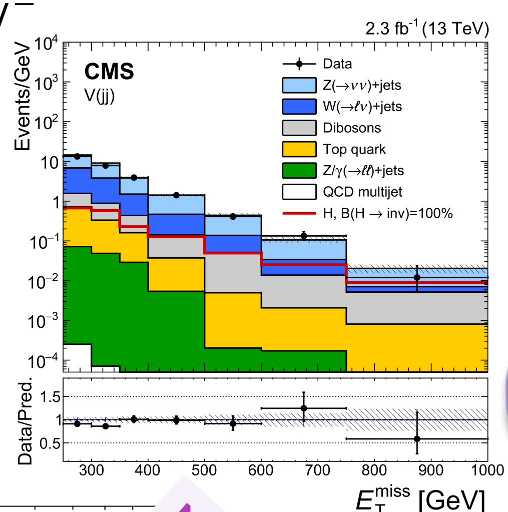
JHEP 02 (2017) 135

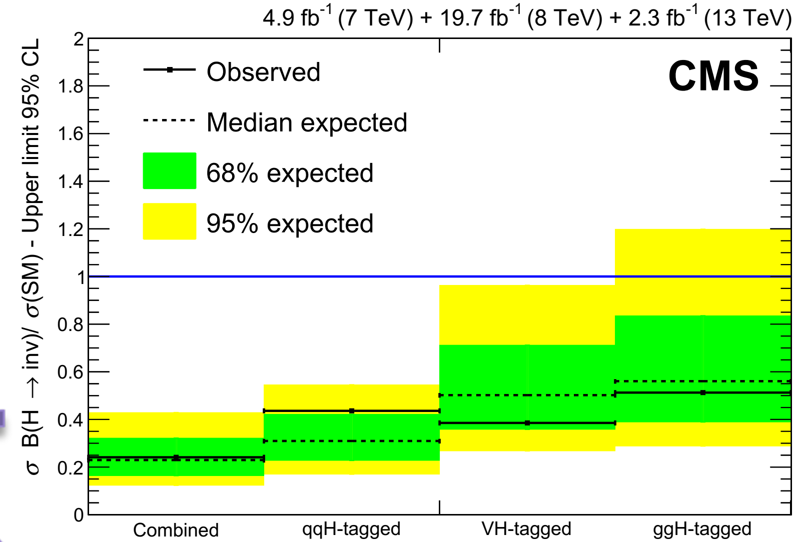
Three signatures:

- Jet+E_T^{Miss}
- V(jj)+E_T^{Miss}
- Z(ll/bb) E_T^{Miss}

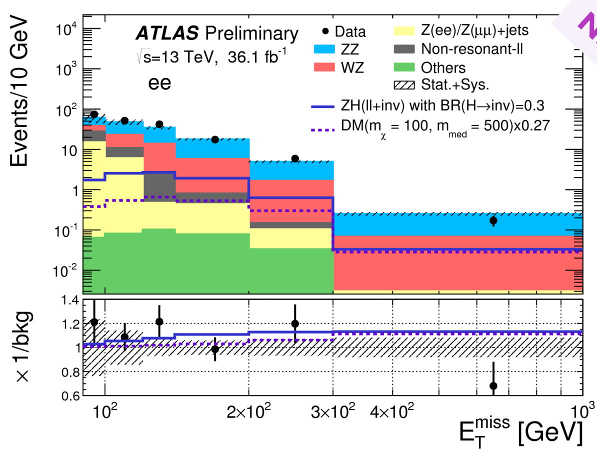
7, 8, 13 TeV data

Also: CMS-PAS-EXO-16-052





upper limit on $\mathcal{B}(H \to inv)$ of 0.24 (0.23)



NEW

ATLAS:

new search for ZH production in ll+E_T^{Miss}

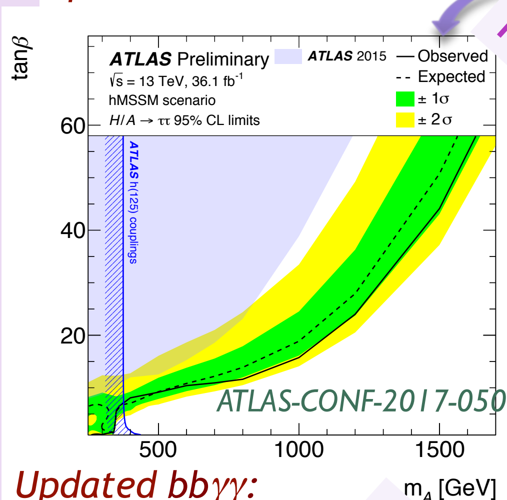
Interpretation also in DM models with axial-vector mediator and fermionic WIMP

heavy Higgs bosons

- Several models predict additional, heavy Higgs boson
  - A very comprehensive set of searches performed in Run 1 and being developed in Run 2
- **hMSSM model (m_A and tanβ)**

CMS PAS HIG-16-007

Updated A/H→ττ:



NEW

ATLAS-CONF-2017-050

A/H →ττ,
A/H→bb,
A→Zh..

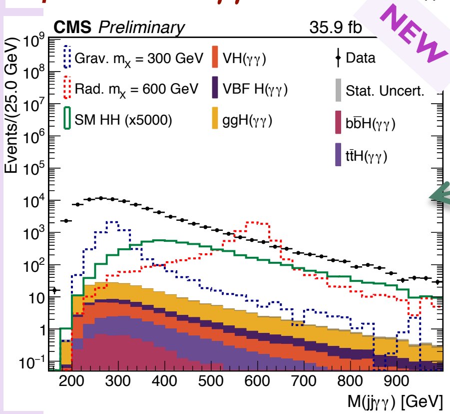
H→WW/ZZ

New results released for ZZ →llll/llνν

ATLAS-CONF-2017-058

Updated bbγγ:

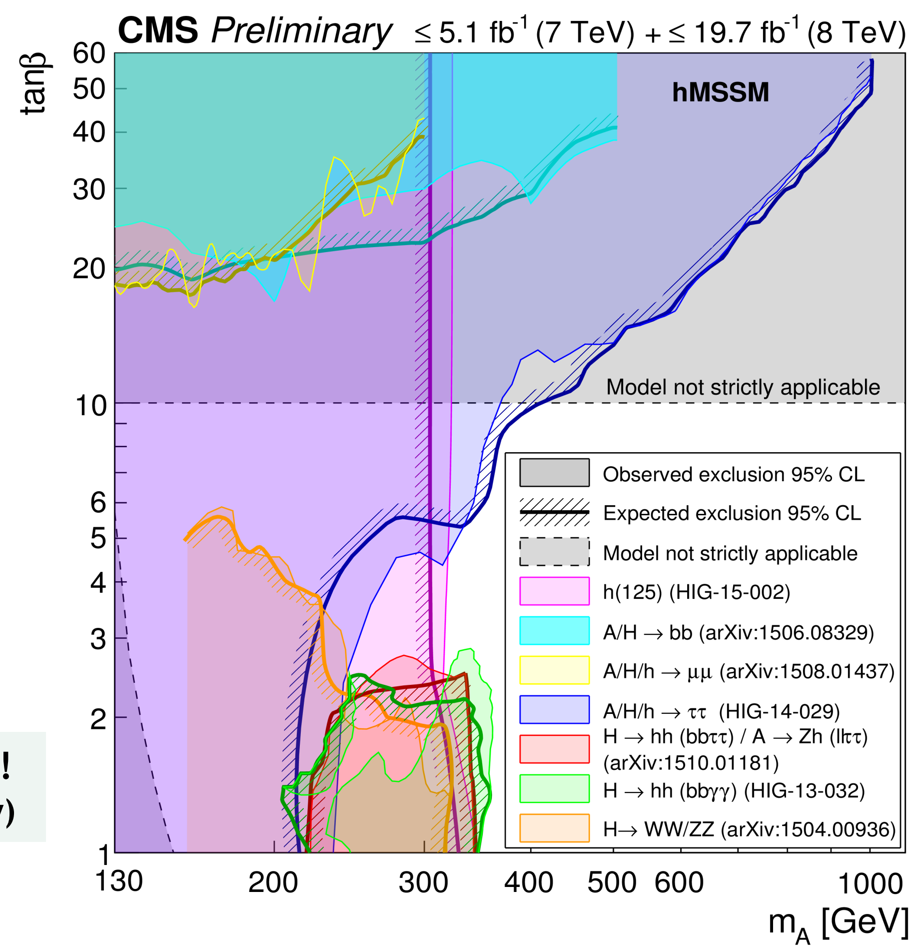
NEW



CMS-PAS-HIG-17-008

H→hh

HH: All final states studied!
(see also Paolo's talk yesterday)

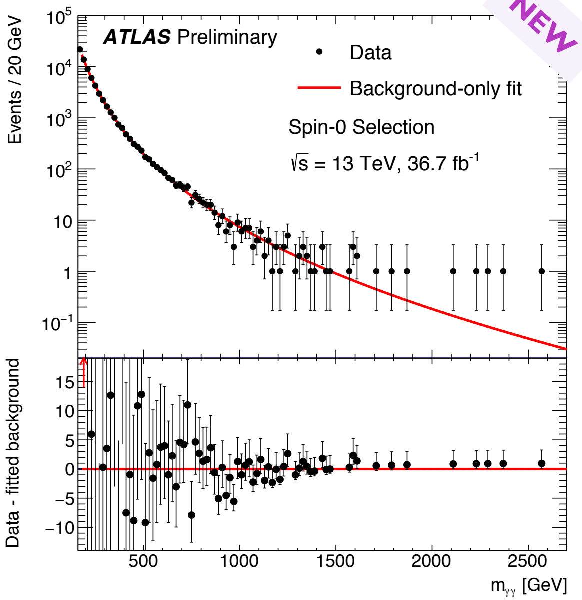


Heavy higgs bosons: more on resonances

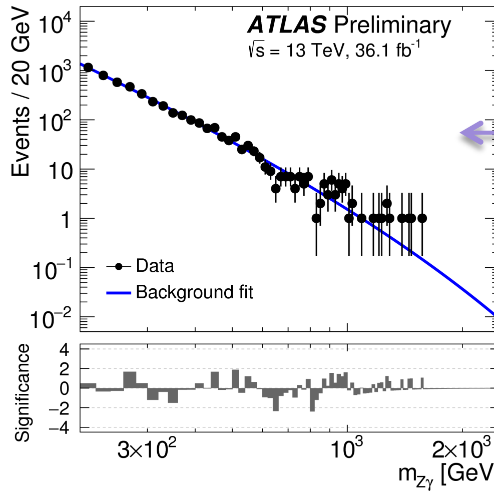
- Heavy Higgs in γγ/Zγ – gluon-fusion or VBF production

To appear

NEW



NEW

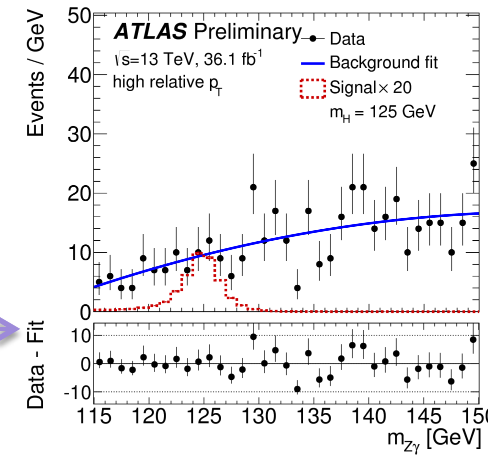


Full reconstruction of the llγ system in several categories

@high mass

@low mass (SM range)

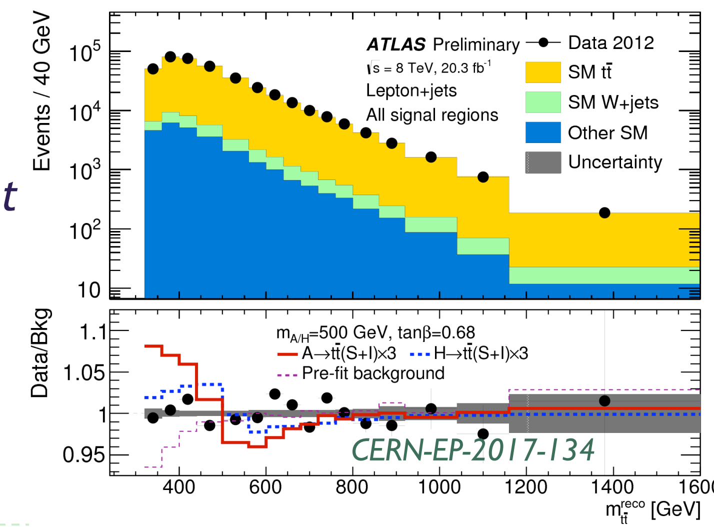
HIGG-2016-14



Spin 0 or Spin 2 interpretation (and dedicated selections) → powerful constraints on various BSM models

- Heavy higgs (A/H) in ttbar
  - Significant interference between *gg→tt* production and scalar/pseudoscalar *A/H→tt*
    - treatment of interferences is key
    - Resonant shape distorted → "peak-dip" structure
  - increased understanding of modeling of top background fundamental

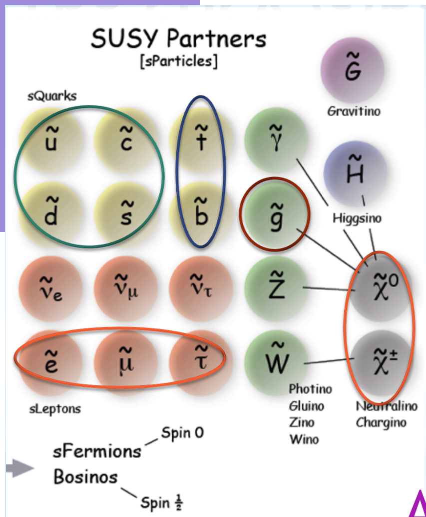
NEW



[more results on heavy and charged Higgs in back-up]

The Higgs could indeed be the lightest of the SUSY-higges…

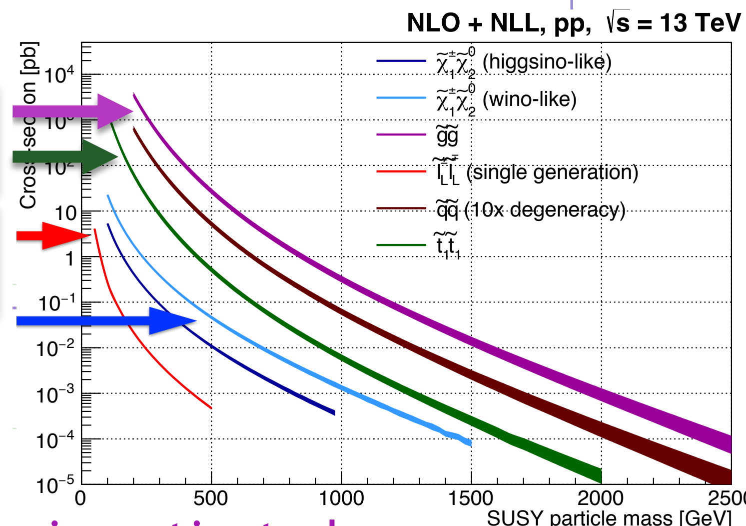
Supersymmetry



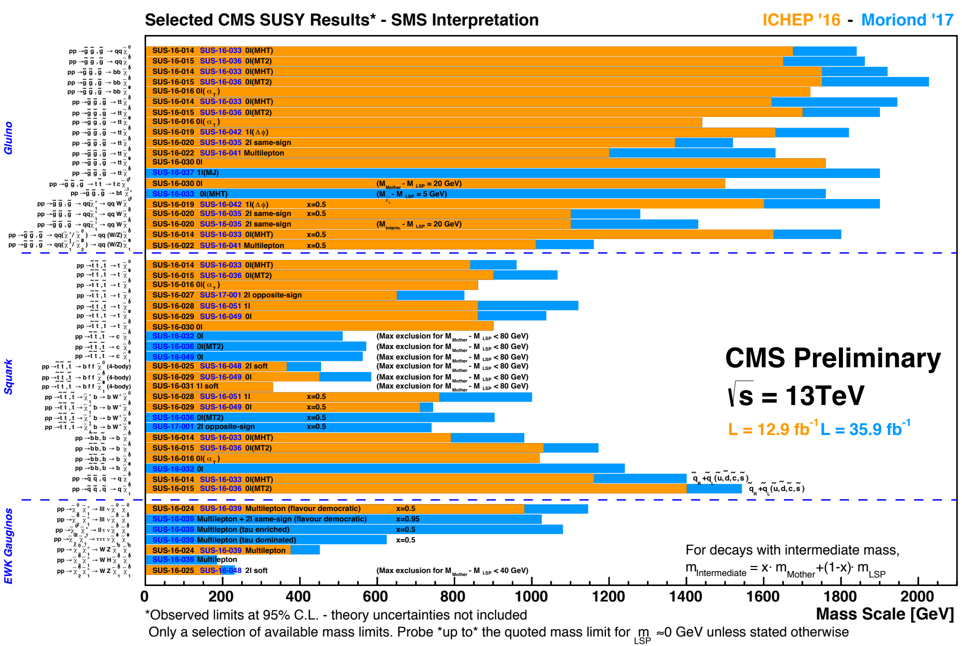
Strong production
(gluinos, squarks)

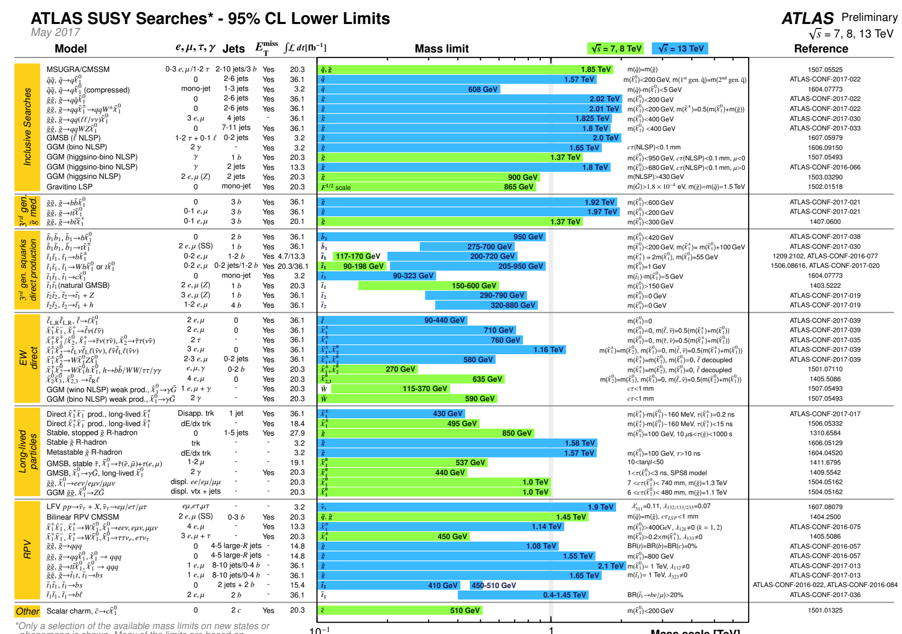
EWK production
(charginos, neutralinos, sleptons)

Role of R-parity: impact on expected phenomenology



A VERY wide range of processes investigated



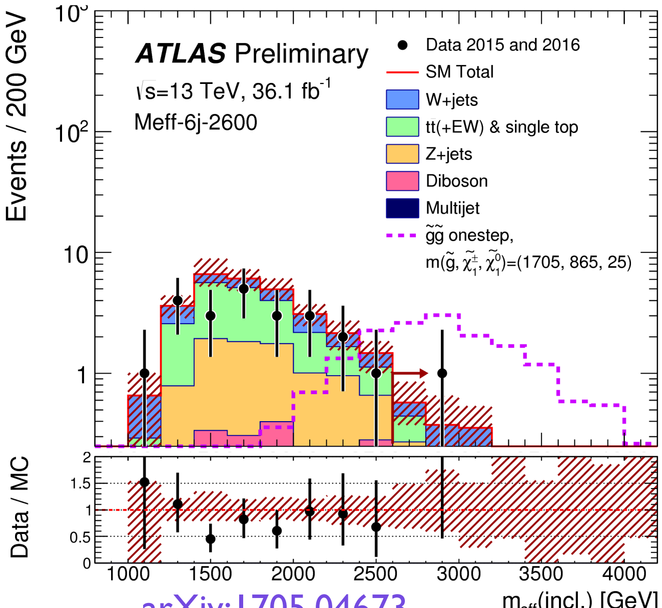


1^{st} and 2^{nd} gen. squarks and gluinos

- Squarks and gluinos often targeted by so-called "**inclusive**" analyses
  - R-parity conserving (RPC) scenarios → signatures characterized by E_T^{MIss}
    - Lightest SUSY particles weakly interacting, at the end of sparticles decay chain
    - Jets, E_T^{Miss}, with or w/o leptons, with or w/o b-tagged jets
- Complex discriminant variables exploited to extract signal from SM bkg

  → H_T, H_T^{Miss}, $Meff=H_T+E_T^{Miss}$, $E_T^{Miss}/\sqrt{H_T}$, M_{HT} = |neg. vector Σ jets|, $L_T=p_T^{lepton}+E_T^{Miss}$, M_{T2}, M_T, M_J = mass of large radius jets, m_{CT}, Recursive Jigsaw, $\Delta\phi(j, E_T^{Miss})$....

0, 1 or more leptons final states: "a glance"



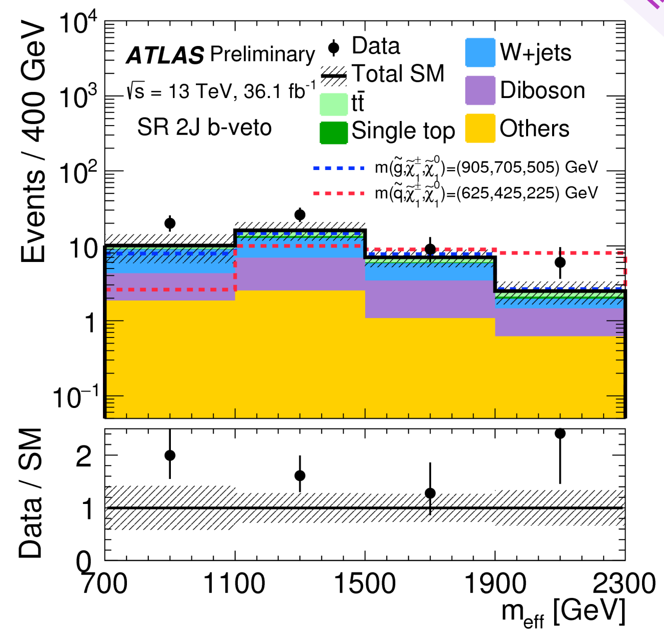
arXiv:1705.04673

0 lepton +Jets+E_T^{Miss}

1 lepton +jets+E_T^{Miss}

SUSY-2016-12

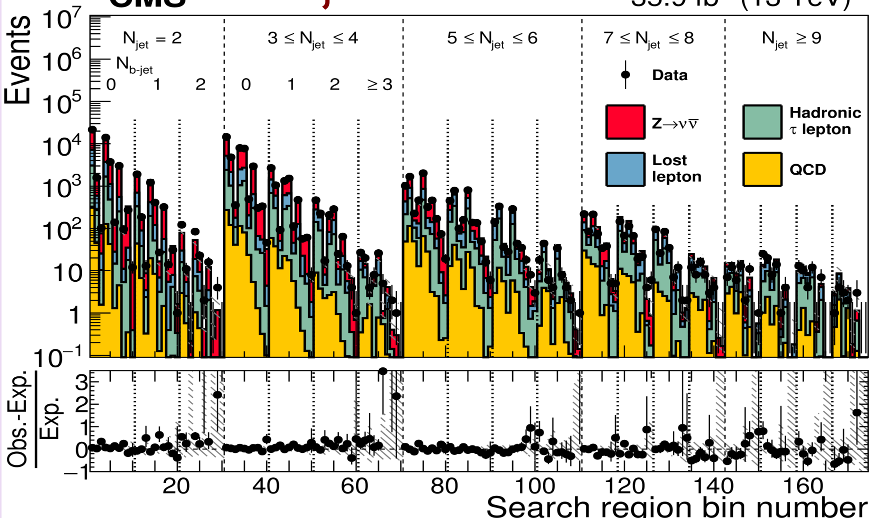
NEW



1st and 2nd gen. squarks and gluinos

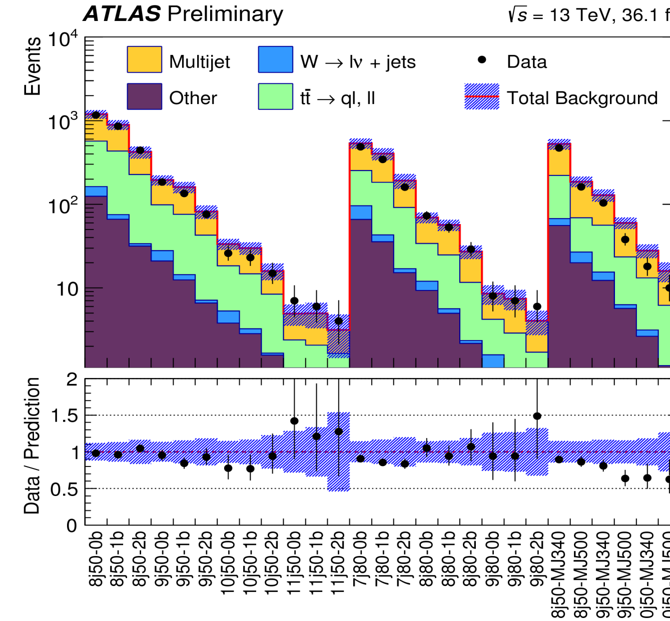
- A spectacular number of regions scrutinized → a small subset

0l+jets+MET



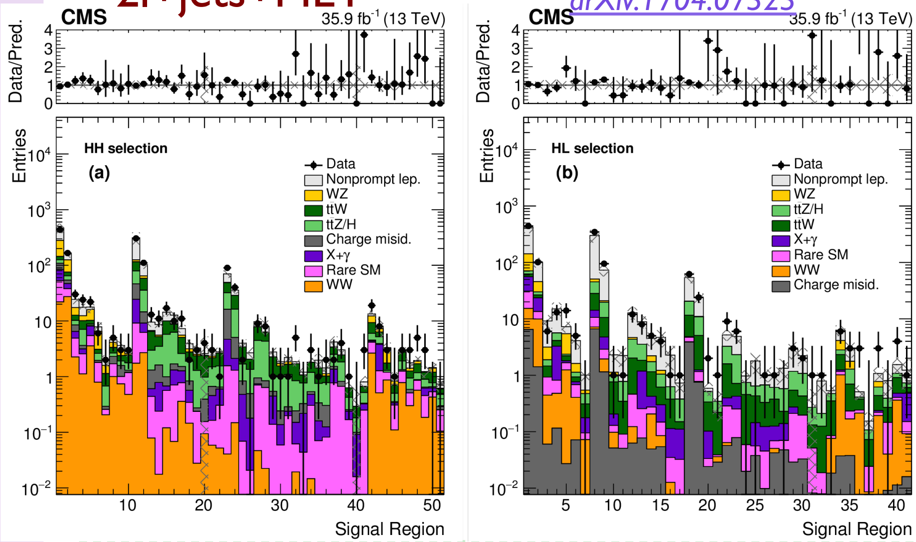
ATLAS-CONF-2017-033

0l + 7-11 jets



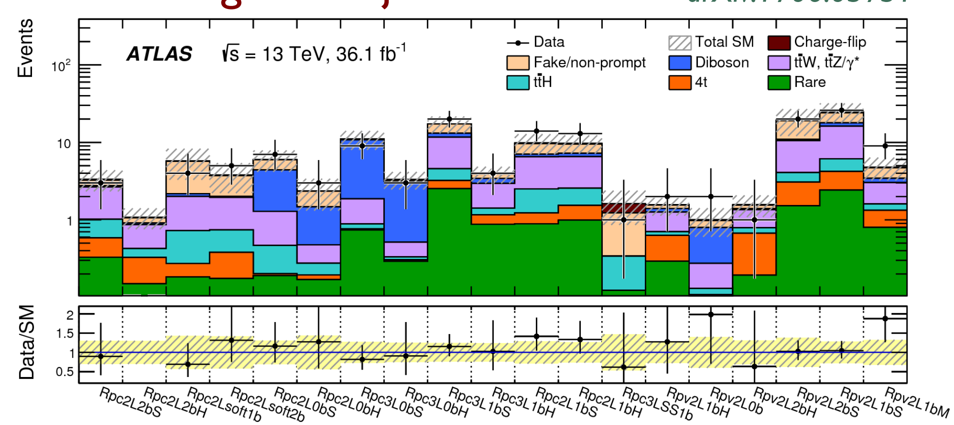
2l+jets+MET

arXiv:1704.07323



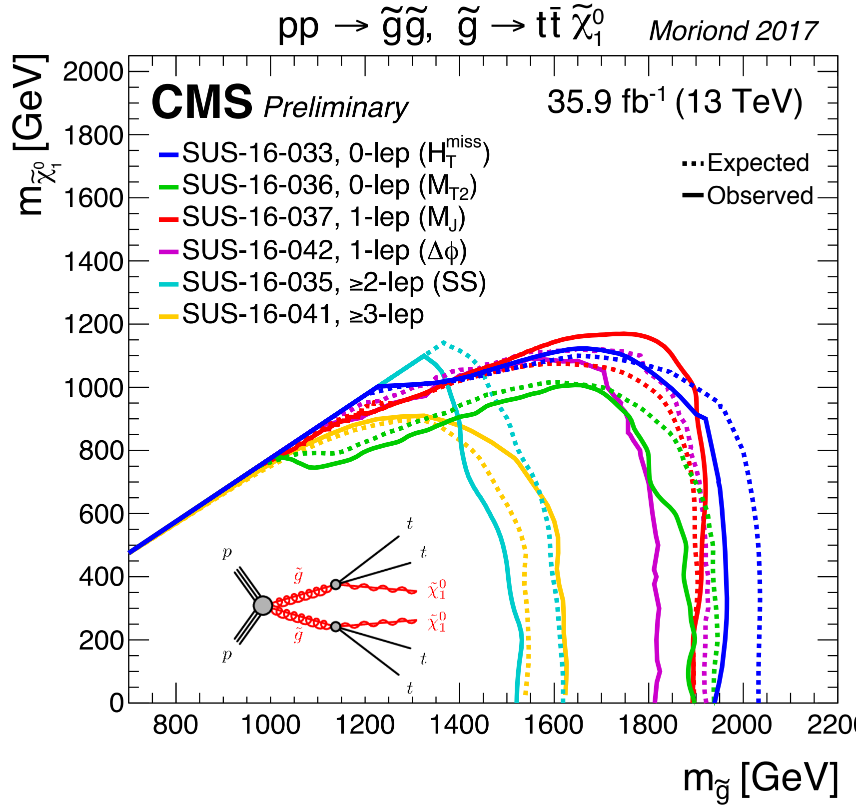
Same-Sign/3L + jets + MET

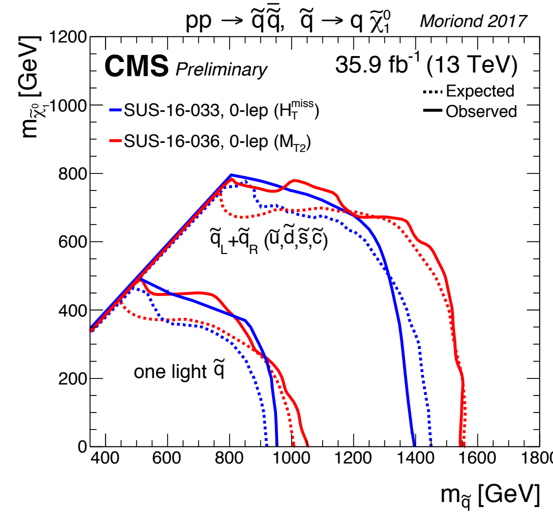
arXiv:1706.03731



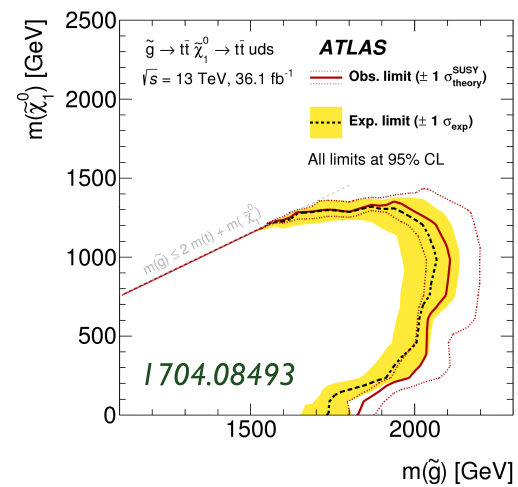
1st and 2nd gen. squarks and gluinos

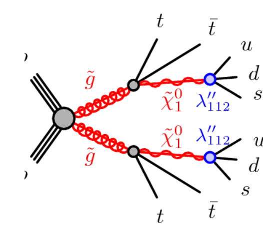
- Searches interpreted in terms of exclusion limits on the mass of gluinos or squarks, considering a variety of hypothesis for their decay.
- One of the most-wanted: gluinos decaying via top-quarks – **2 TeV** limits reached for low χ_1^0 masses





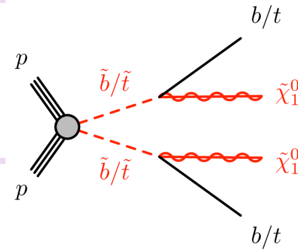
Dedicated searches targeting SUSY scenarios with R-parity violation, e.g.:





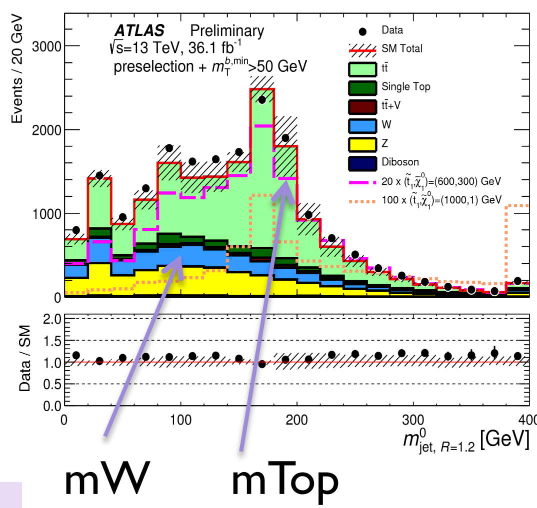
- Limits on 1st and 2nd generation squarks also very stringent [~ **1 TeV** for direct decays, one-type only]

third generation squarks

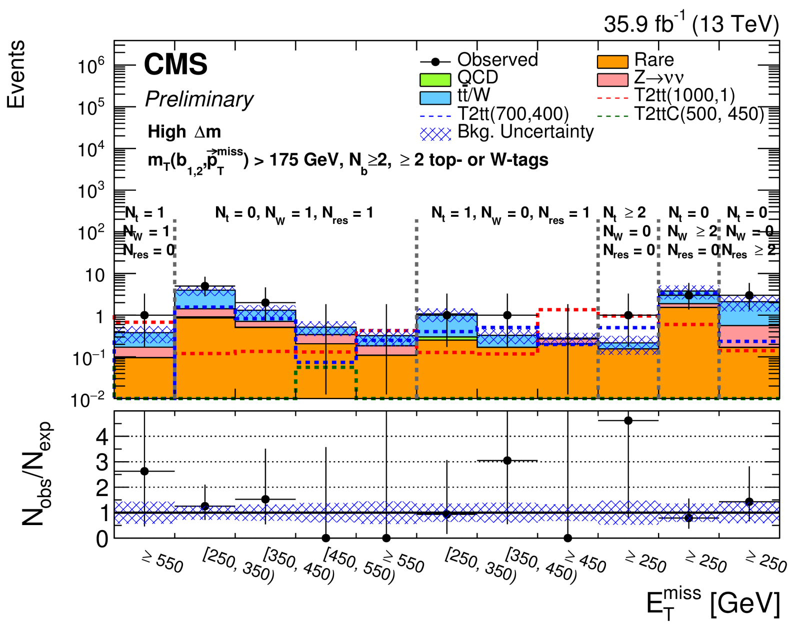


- Many sophisticated analyses targeting bottom and top squarks:
  - theoretically, have a fundamental role (higgs mass radiative corrections, natural SUSY)
  - experimentally, can be quite challenging → low production rate, several possible decay modes, depending on SUSY mass spectrum
  - For **top squarks**: depend on decay. E.g. via top + LSP → **0l,1l,2l + b-jets + E_T^{Miss}**

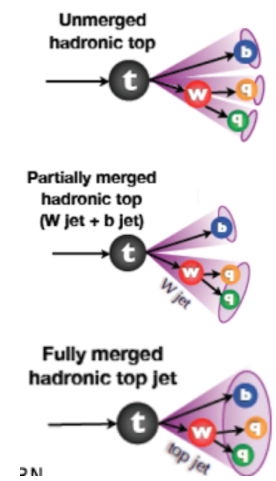
ATLAS-CONF-2017-020



CMS-PAS-SUS-16-049



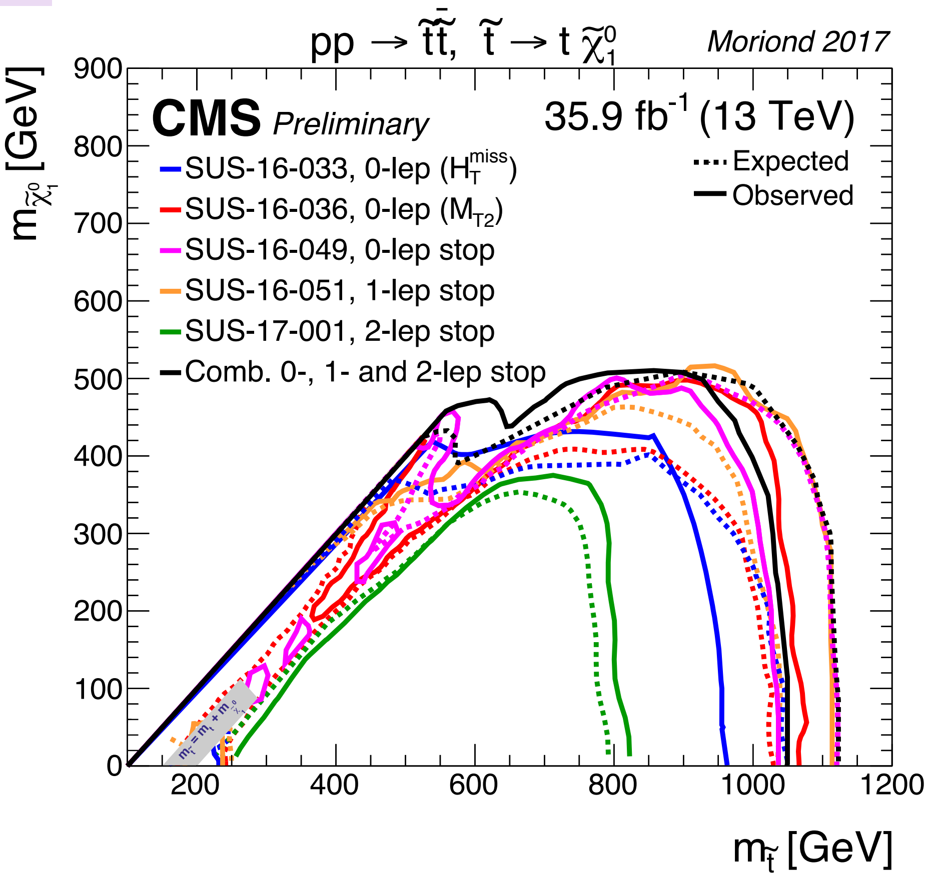
0 leptons: Dedicated searches e.g. depending on possible "boost" of top

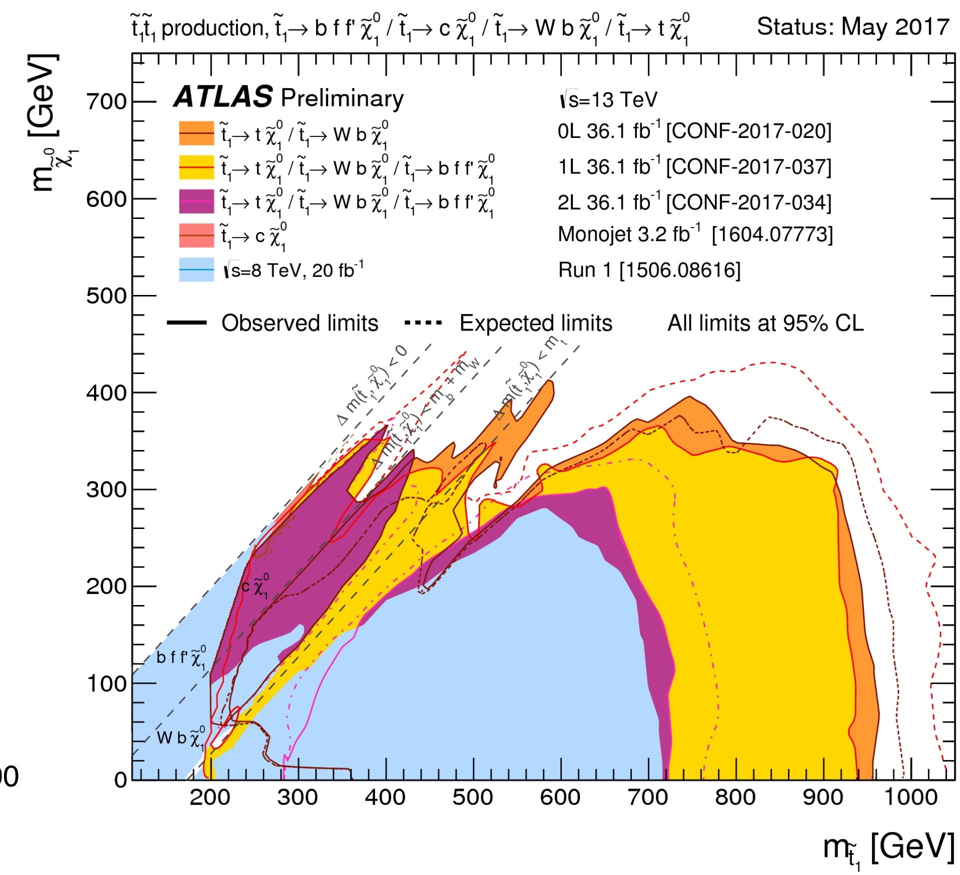


For bottom squarks

@CMS: dedicated search in 0L+2b+E_T^{Miss} plus interpretation of more "inclusive" analyses (SRs with b-jets)
@ATLAS: dedicated searches also for mixed-scenarios (0L+2b/ 1L+2b + E_T^{Miss})

third generation squarks





Other decay modes (e.g. via Higgs boson, via charginos) not shown.
In RPV scenarios, top squarks excluded up to 1.2 TeV

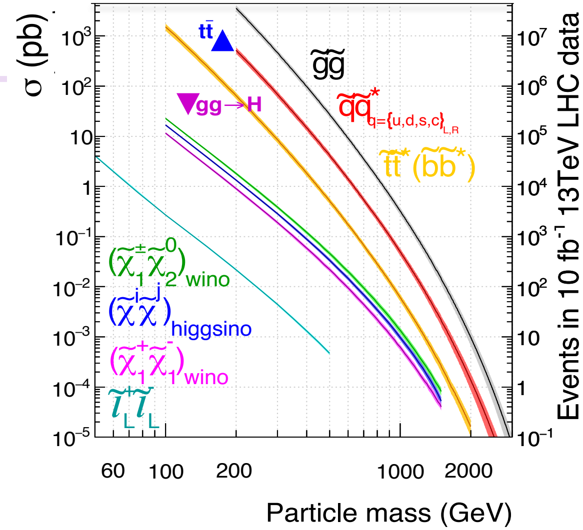
- For bottom squarks: Exclusion limits beyond **1 TeV / exp.**
  - Still < 600 GeV for compressed regions: Also for **stop → charm + E_T^{Miss}**

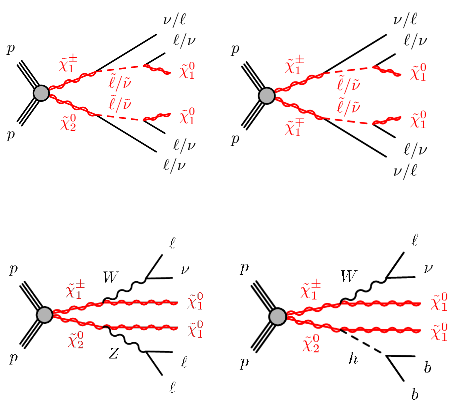
CMS-PAS-SUS-16-032

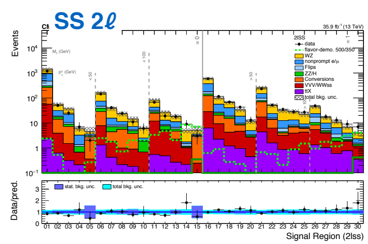
ATLAS-CONF-2017-038

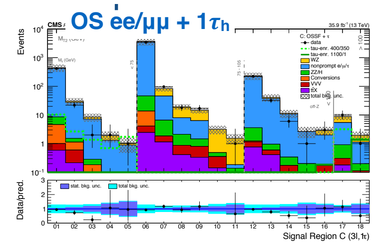
Electroweak SUSY

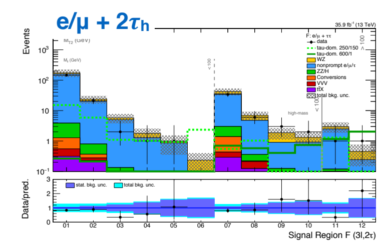
- If colored sparticles have mass above 3-4 TeV scale, EWK sector could be the only one accessible
  - Very low production rate, large dataset needed
- Exploit multi-lepton nature of final state events
  - Depends on chargino/slepton/neutralino mass hierarchy
- Once again, explore a variety of SRs
  - E.g.: 2, 3 or 4 leptons, all types included

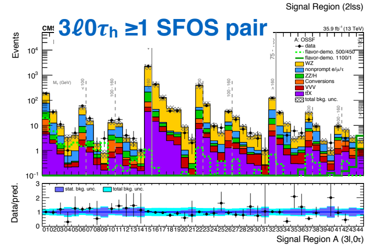


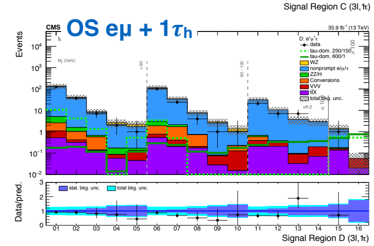


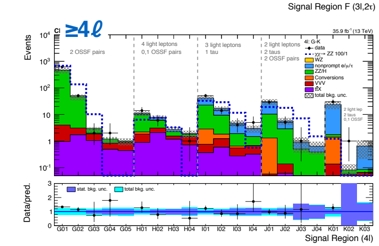




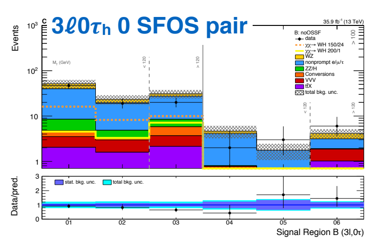


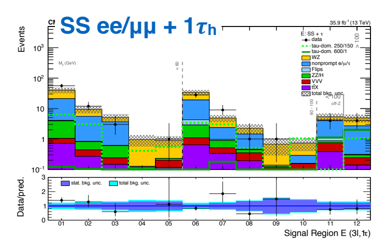






4 leptons analyses mostly targeting RPV scenarios. Also: **ATLAS-CONF-2016-075**





Total of 158 SRs, no significant excess

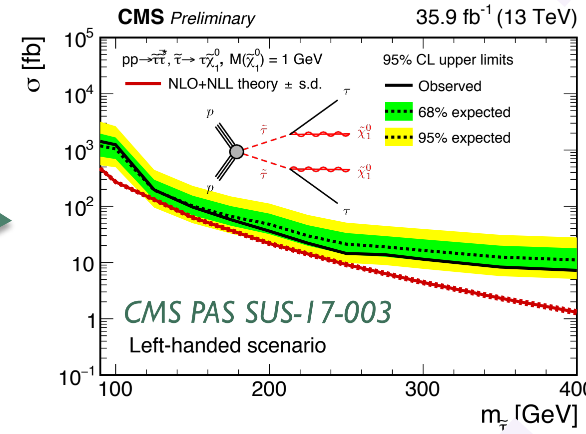
CMS-SUSY-16-039

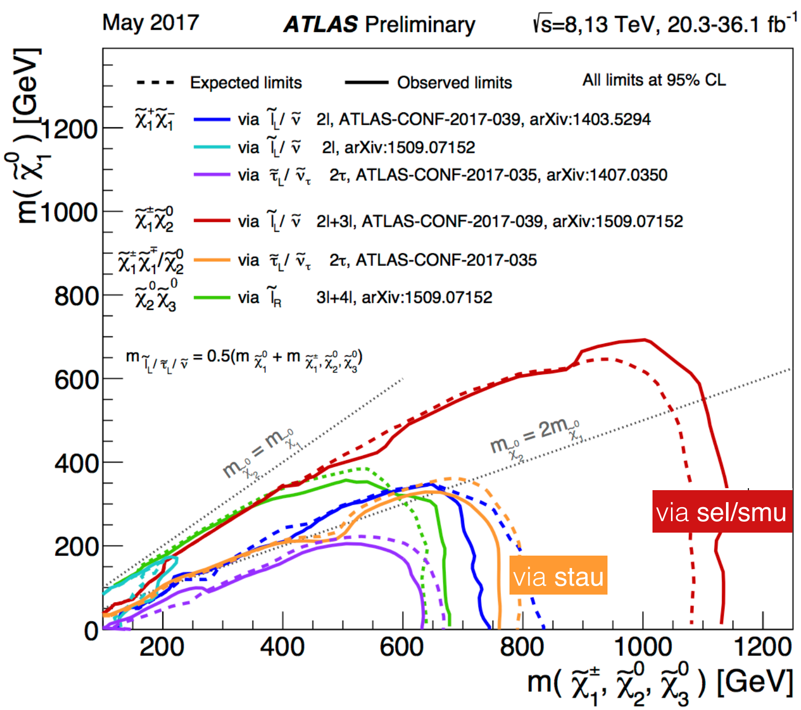
Electroweak SUSY

NEW

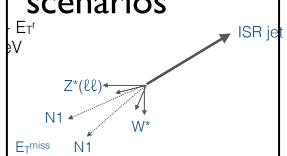
- Powerful exclusions in decays via sleptons
  - **mass limits on selectron/smuon up to 500 GeV - not yet on staus!**
- If kinematically forbidden, decays via WZ or WH (on-shell or off-shell in compressed scenarios)

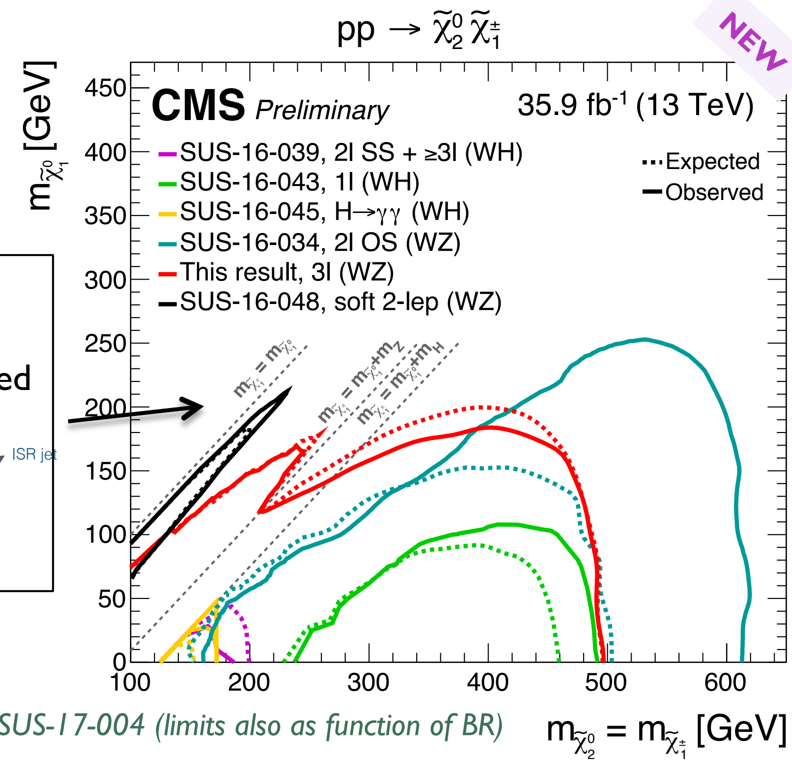
→ **Challenging**, dedicated analyses performed





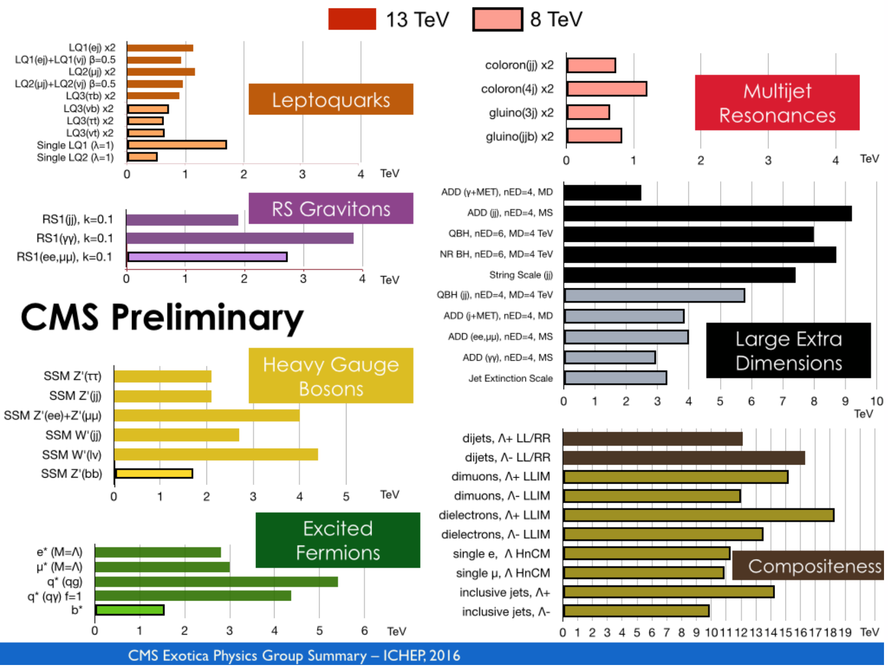
Dedicated CMS analysis on compressed scenarios

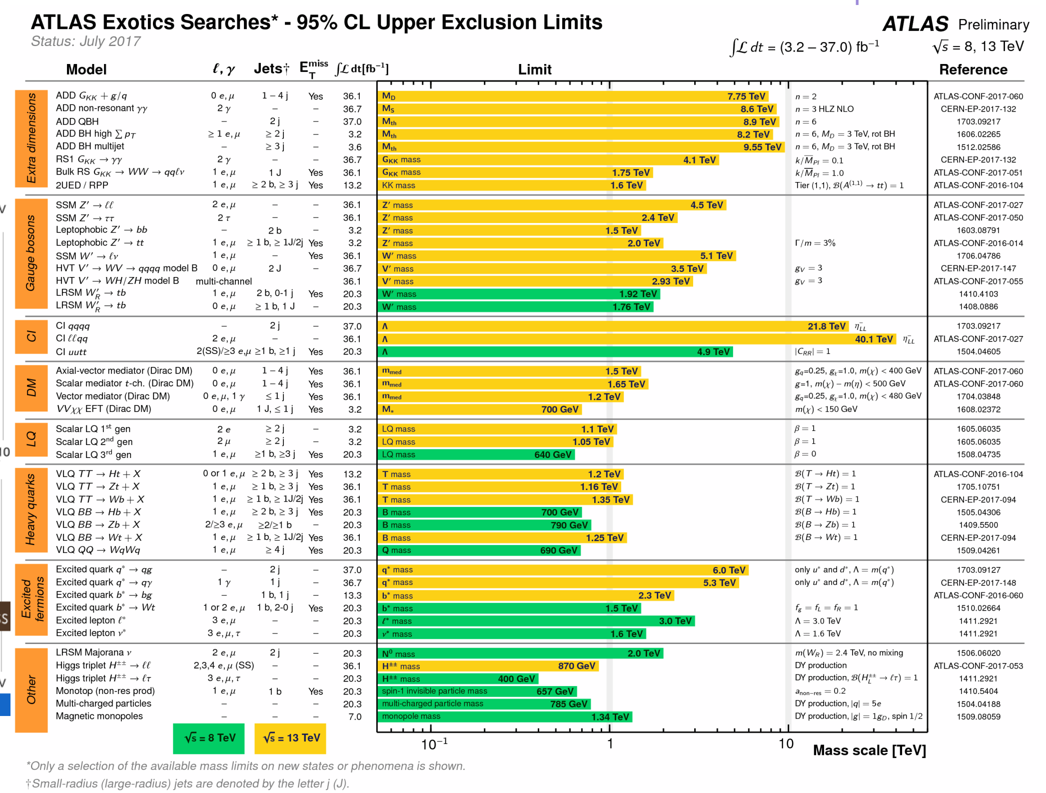


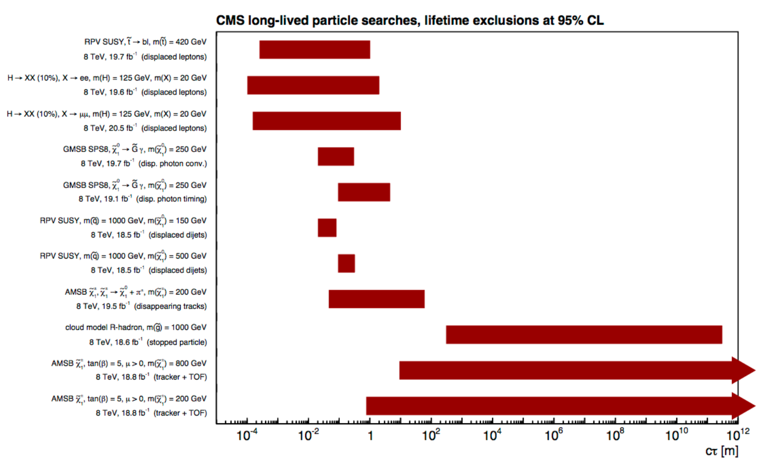


CMS PAS SUS-17-004 (limits also as function of BR)

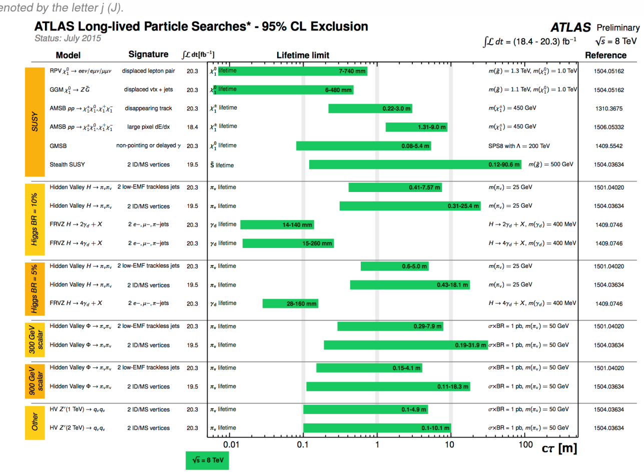
Exotics models







Long-lived
(SUSY or not)

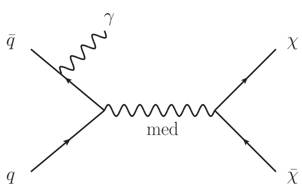


Searches for WIMPs as Dark Matter

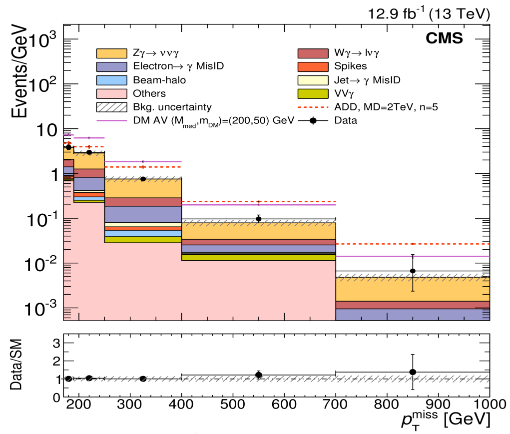
Intense program of searches at colliders: DM = E_T^{Miss} + other "object":

NEW

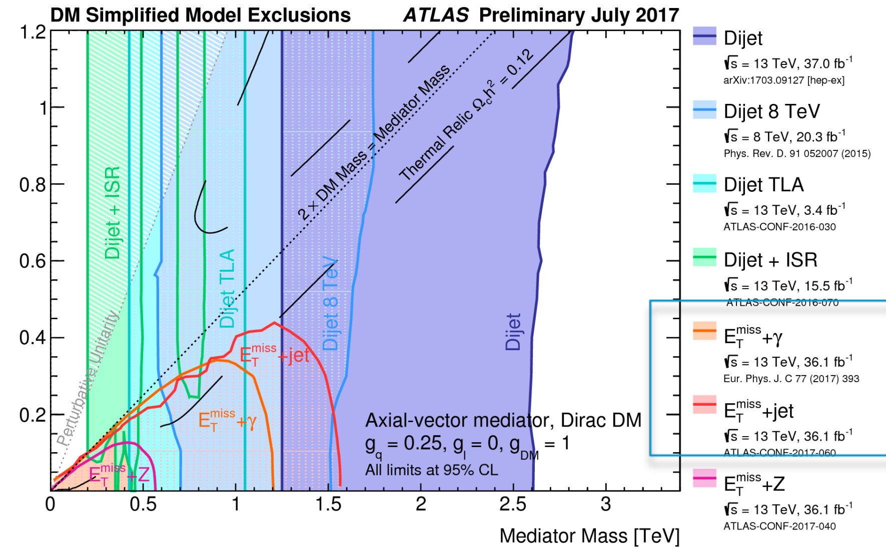
- photon + E_T^{Miss} (mono-photon)



CMS: arXiv:1706.02581
ATLAS: arxiv:1704.03848



A model-dependent summary of various searches

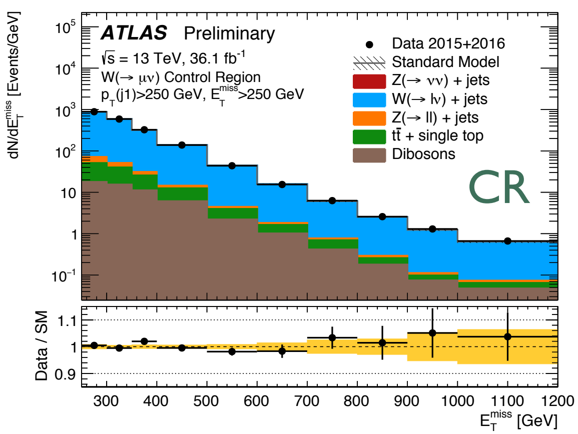


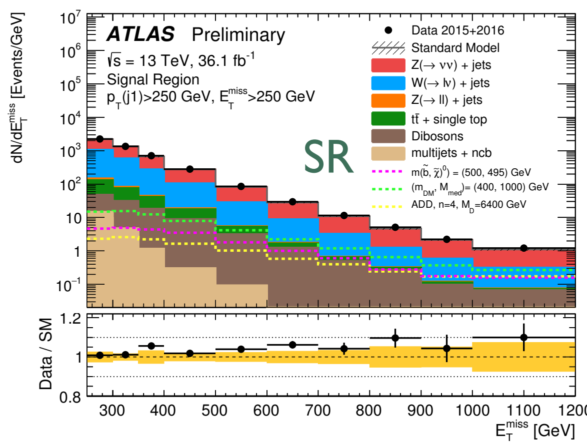
- jet + E_T^{Miss} (mono-jet)

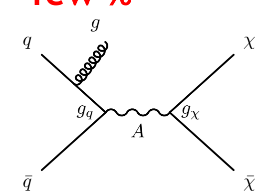
NEW

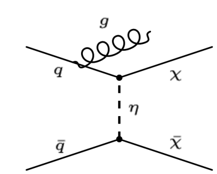
E_T^{Miss}-based signal regions. CRs for SM bkg → systematic uncertainties ~ few %

ATLAS-CONF-2017-060









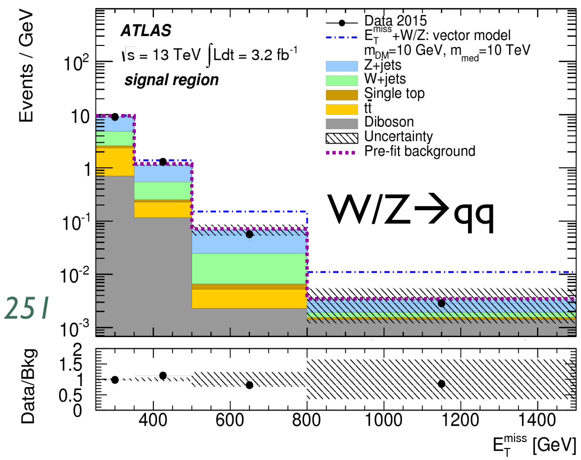
Variety of interpretations

- DM models
- SUSY stop in charm+MET
- Extra-Dimensions

Searches for WIMPs as Dark Matter

W/Z or Higgs + E_T^{Miss} (mono-W/Z/H)

W/Z: Lept. or hadr. bosons recoiling E_T^{Miss}

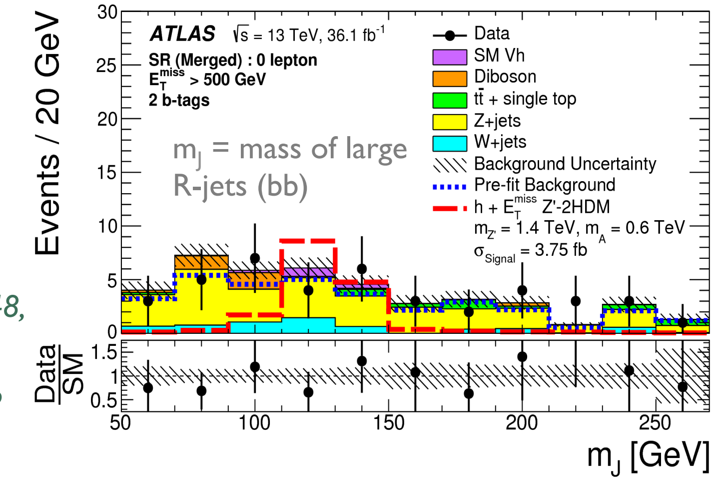


ATLAS: PLB 763(2016) 251
CMS: EXO-16-052

Higgs: *e.g.* in bb or γγ final states

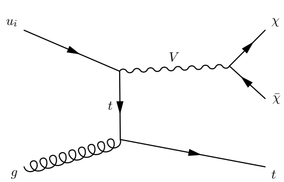
ATLAS: 1706.03948, 1707.01302

CMS: 1703.05236

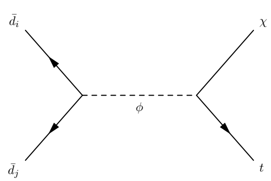


top + E_T^{Miss}

FCNC



Heavy scalar



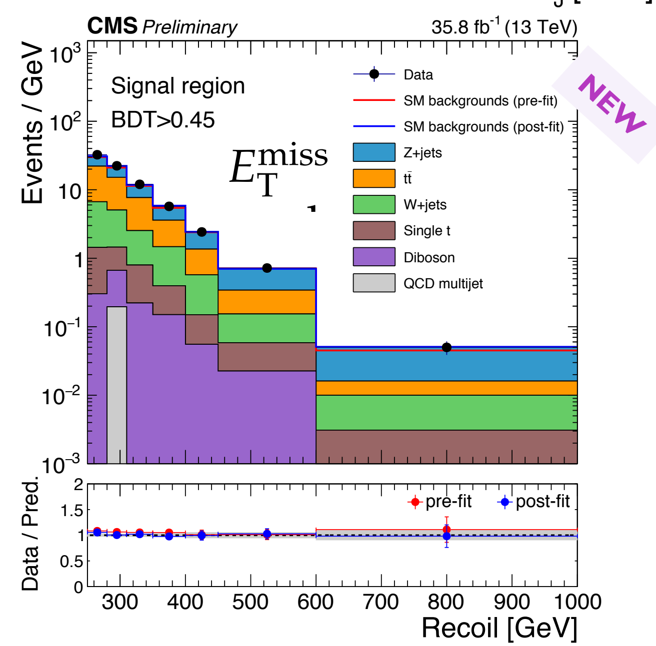
Top decay products merged in a large-R jet recoiling E_T^{Miss}

BDT based on substructure observables

CMS PAS EXO-16-051

Other searches for DM+heavy flavor quarks:

EXO-16-005, EXO-16-028
ATLAS-CONF-2016-086



Vector-like quarks

- Motivated by hierarchy problem, X = T, B quarks can be singly or pair-produced

X→tH/Wb/tZ

- Many objects in decays (W,H,Z,t ..)
- Background techniques as for SUSY searches:

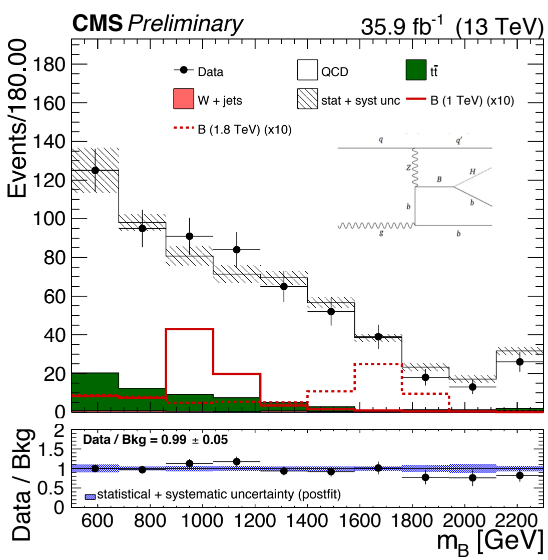
→ complex discriminant variables
→ dedicated CRs and VRs
→ exploitation of 'boosted' decay products

SINGLE PRODUCTION

B→bH, H→bb *CMS PAS B2G-17-009*
+ additional forward jets

NEW

Multijet background fully data-driven



Limits vary between 0.07 pb and 1.28 pb

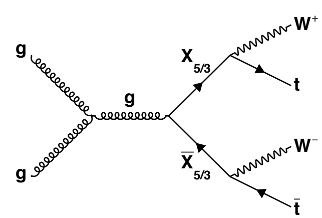
PAIR PRODUCTION

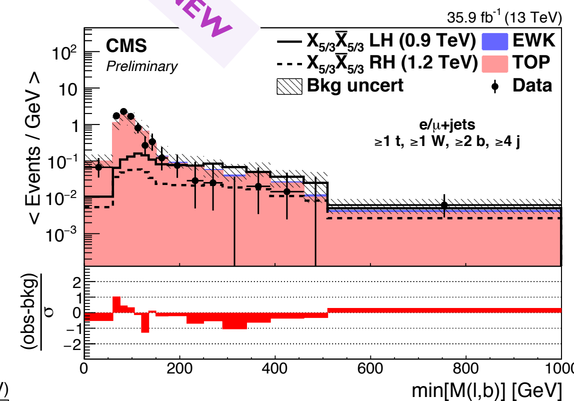
CMS PAS B2G-17-008

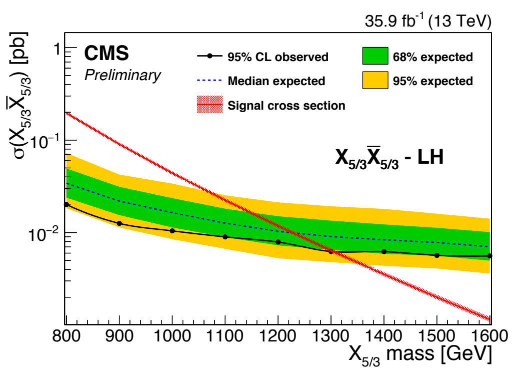
1lepton+jets+MET topology

NEW

- W and top "tagging" used







Constraints on Right-handed and left-handed heavy quark partners very similar

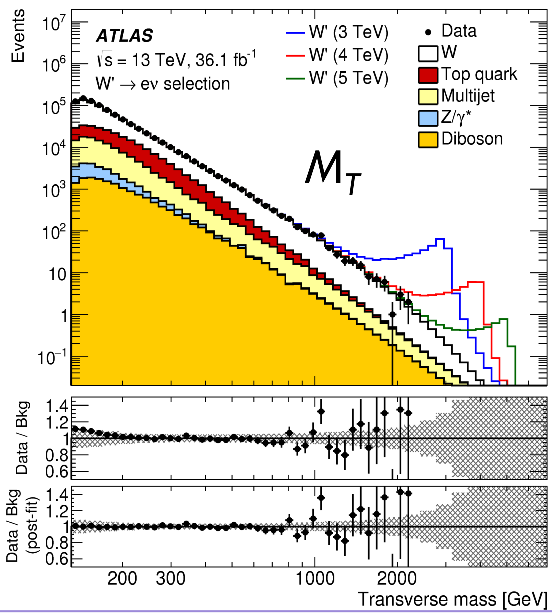
Comprehensive set of searches from ATLAS and CMS (see back-up)

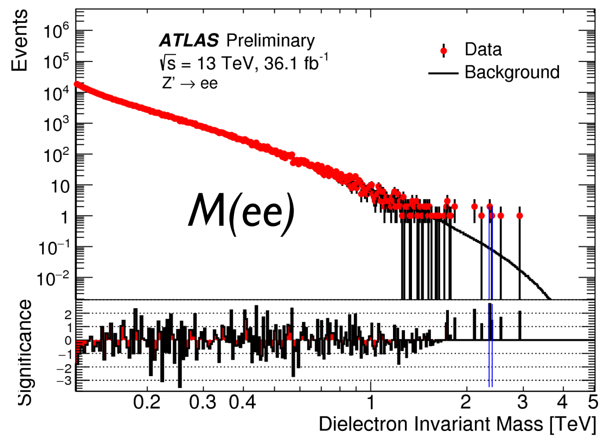
Resonances

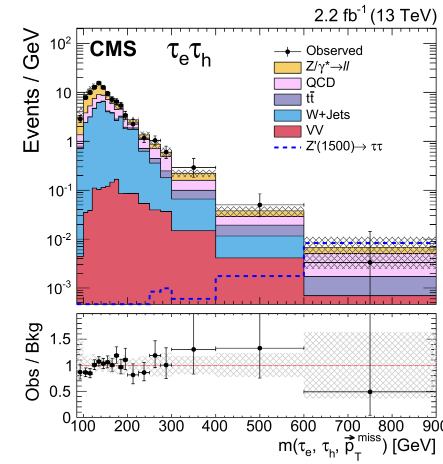
- Sensitive to many BSM scenarios
  - Heavy higgses (A/H) – as seen already, Extra-dimensions, new gauge bosons…
- Consider <u>all relevant combinations</u> of final state objects
  - ***Dileptons***, ***lepton+E_T^{Miss}***, *dijets, γ+jets, dibosons (VV, Vγ, γγ), top+b, ditops ..*

→ Sensitive to W' and Z'

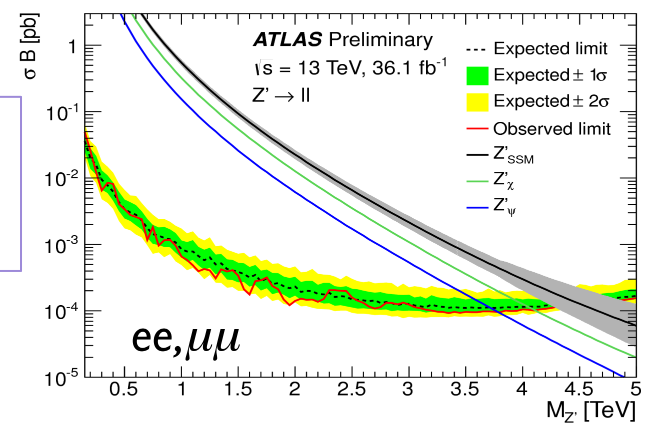
ATLAS: arXiv:1706.04786
CMS: arXiv: 1612.09274







Z': no significant deviations Data up to 3 TeV for e, μ, ~ 1 TeV for τ



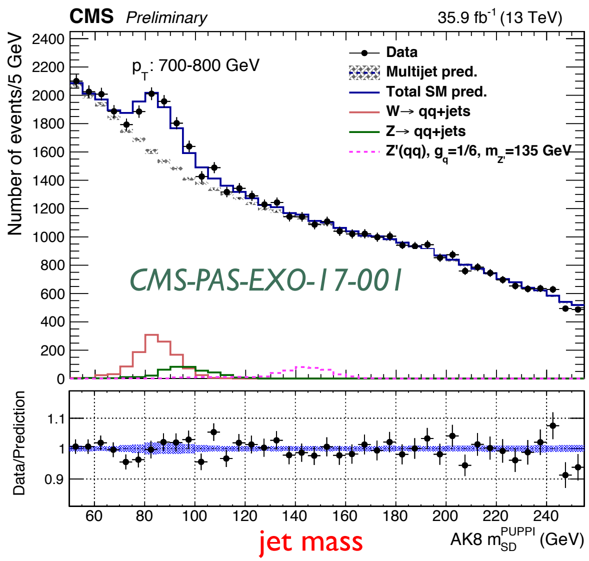
W': no significant deviations Data up to 2.3 TeV for e, μ

Resonances

- Sensitive to many BSM scenarios
  - Heavy higgses (A/H) – as seen already, Extra-dimensions, new gauge bosons…
- Consider all relevant combinations of final state objects
  - *Dileptons, lepton+E_T^{Miss}, **dijets, γ+jets**, dibosons (VV, Vγ, $\gamma\gamma$), top+b, ditops ..*

Not only at high mass!

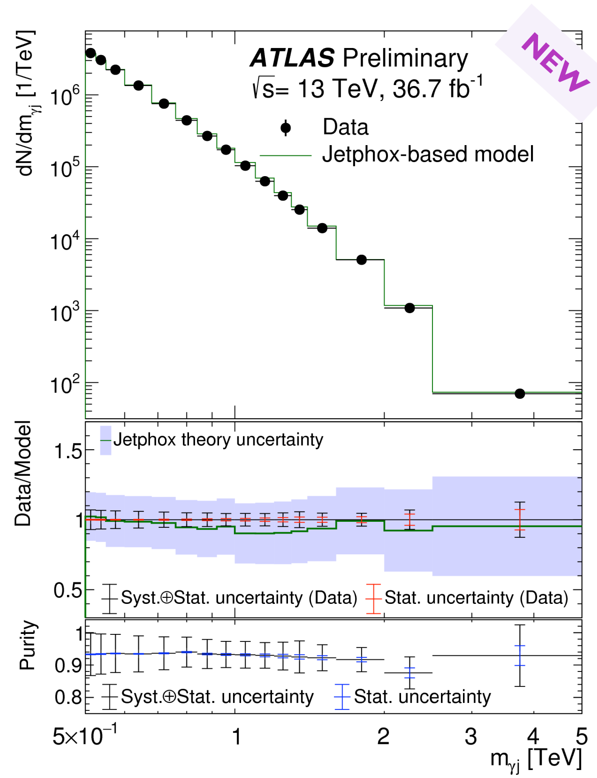
Search for Z' resonance in qqbar merged in 1 jet



use jet substructure techniques allowing to remove soft wide-angle radiation in jets

Sensitivity to Z' in [50-300] GeV (model dependent)

to appear



Excited quarks: m < 5.3 TeV

ADD - Quantum Black Holes: m < 7.1 TeV

RS – Quantum black holes: m < 4.4 TeV

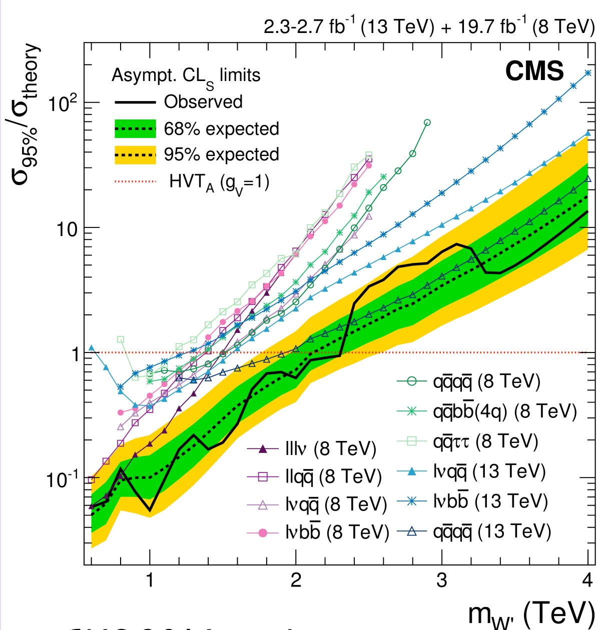
New also for CMS: CMS-PAS-EXO-17-002

Resonances

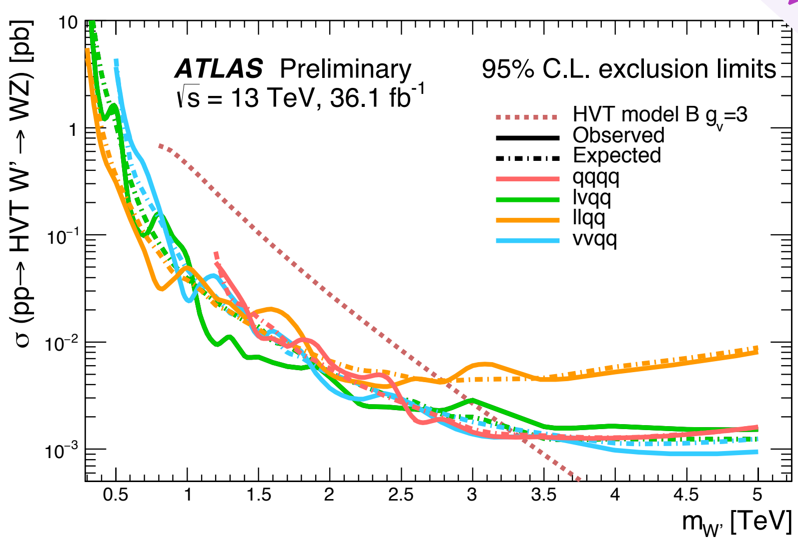
- Sensitive to many BSM scenarios
  - Heavy higgses (A/H) – as seen already, Extra-dimensions, new gauge bosons…
- Consider all relevant combinations of final state objects
  - *Dileptons, lepton+E_T^{Miss}, dijets, γ+jets, **dibosons (VV, Vγ, $\gamma\gamma$)**, top+b, ditops ..*

Sensitive to many model of NP, all final states explored: → **llqq, ννqq, lνqq, qqqq, llll …**

Several CRs and VRs per search, set to estimate SM background.
Exploit gluon-fusion and VBF-production



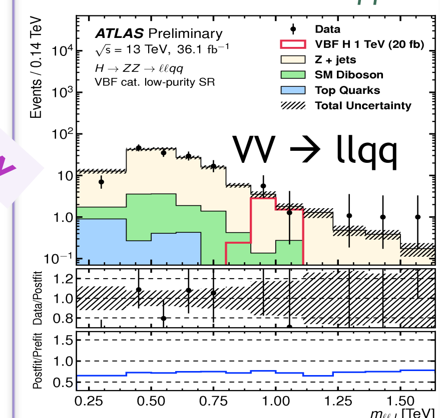
CMS 2016 results:
[qqqq , 2l2nu ,VH(bb), 2l2q , lnuqq](#)



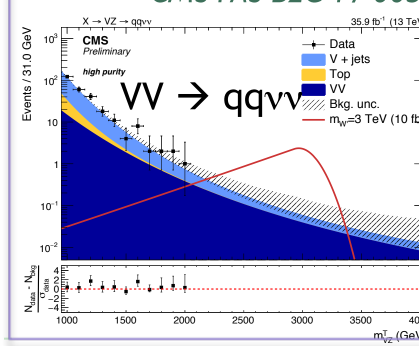
probe 2 – 3 TeV mass range in all cases!

NEW

To appear



CMS PAS B2G-17-005

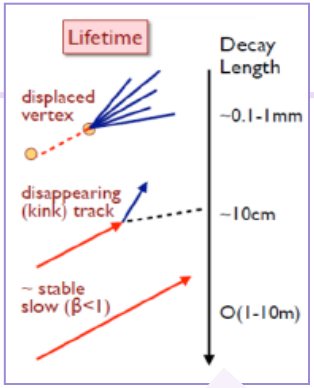


Long-lived particles

What makes a particle long-lived:

- small couplings: RPV decays, dark sector coupling
- small mass-splittings: almost degenerate next-LSP heavy messenger: Z', split SUSY
- hidden valley

Signatures depend on the lifetime!

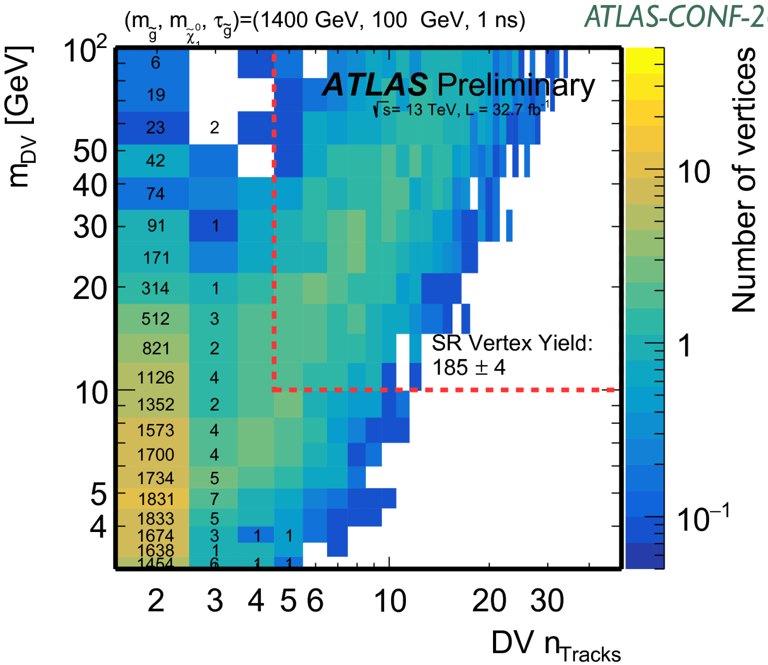


NEW

Displaced objects: VERTEX

Target: E.g. non-prompt gluinos
Dedicated re-tracking, DV from LLP: massive

ATLAS-CONF-2017-026

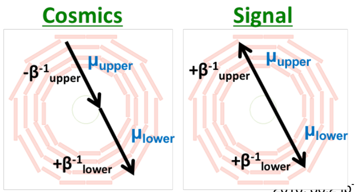


No events obs. in SR: probe lifetimes O(ns)

Stopped objects: muons

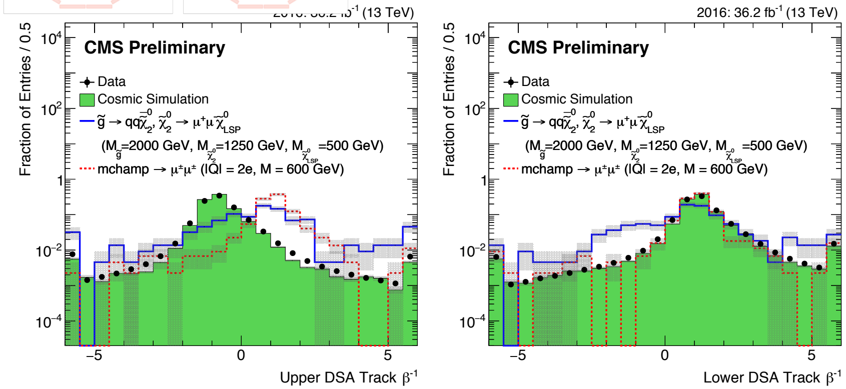
Target: LLP that stop in the detector, decay to muons some time after they are produced (gluinos, multiply charged massive particles).

Custom trigger: record events out-of-time with collisions.
Dedicated algorithm for **D**elayed **S**tand**A**lone muon tracks



Major background: **cosmic muons**

EXO-17-004



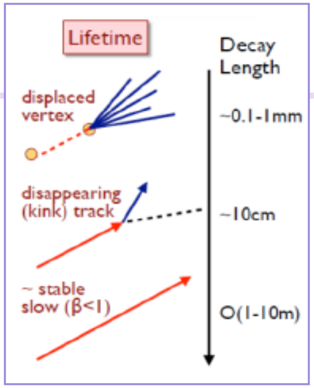
No events obs: probe lifetimes 100 ns → 10 days

Long-lived particles

What makes a particle long-lived:

- small couplings: RPV decays, dark sector coupling
- small mass-splittings: almost degenerate next-LSP heavy messenger: Z', split SUSY
- hidden valley

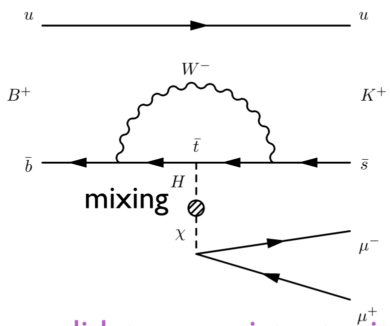
Signatures depend on the lifetime!



More on displaced Vertex (LHCb)

PRD 95(2017)071101]

7 and 8 TeV data



Higgs-portal scenario
→ mediated by a light particle, the inflaton

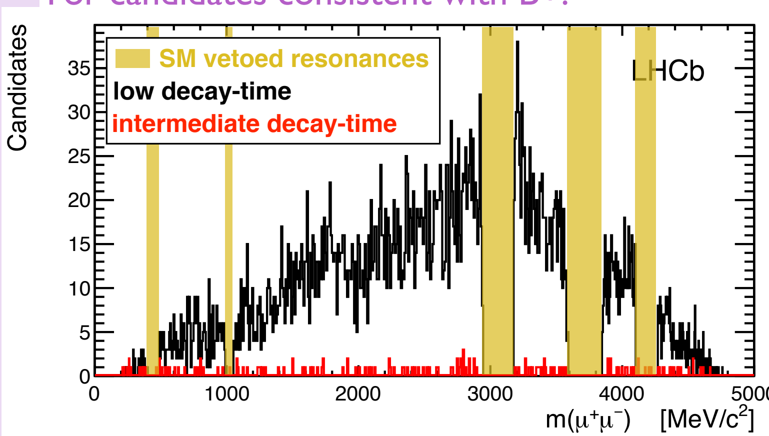
$$B^+ \rightarrow K^+ \chi(\mu^+\mu^-)$$

$$0.1 < \tau(\chi) < 1000 \text{ ps}$$

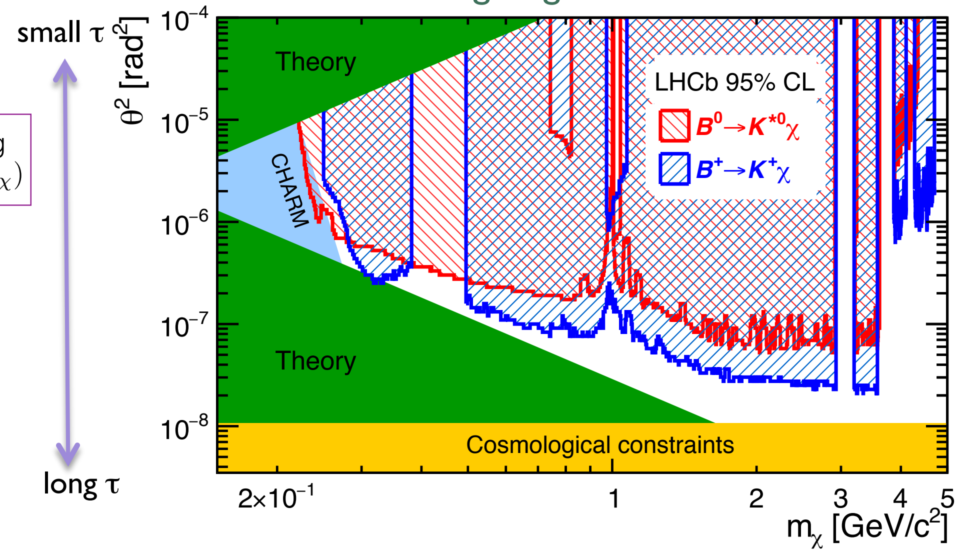
$$250 < m(\chi) < 4700 \text{ MeV}/c^2$$

Parameter space of the inflation models: mixing angle vs mass

For candidates consistent with B+:



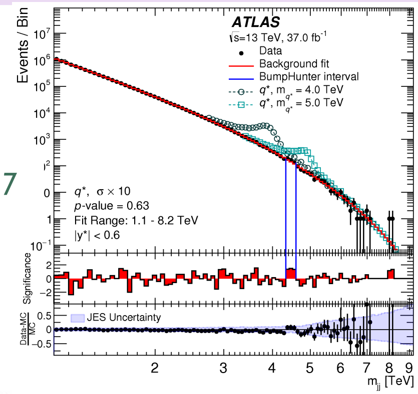
binning
$\sim 1\,\sigma(m_\chi)$

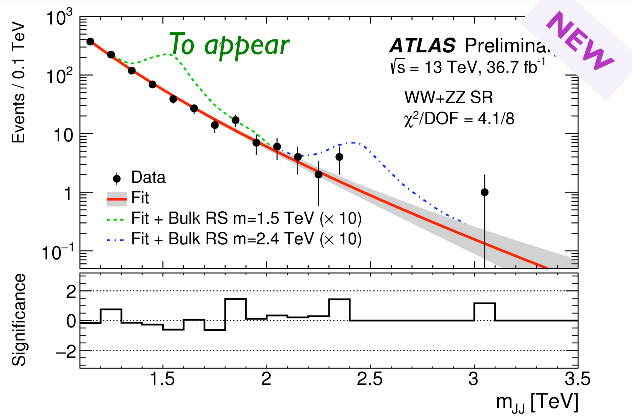


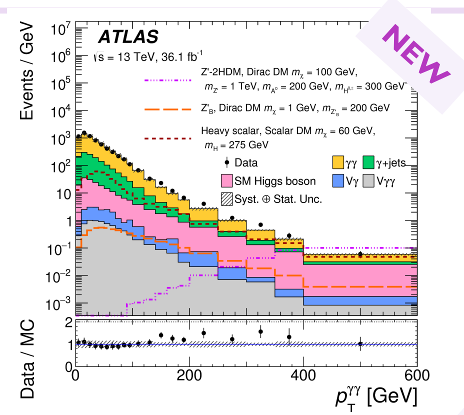
3 bins of decay time, zero events in t >10 ps

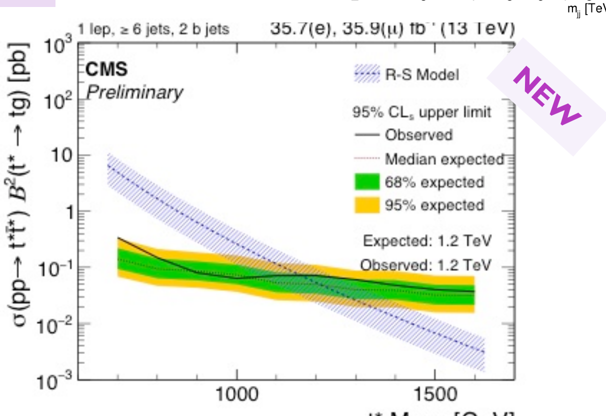
..and many more searches for NP

arXiv:1703.09127



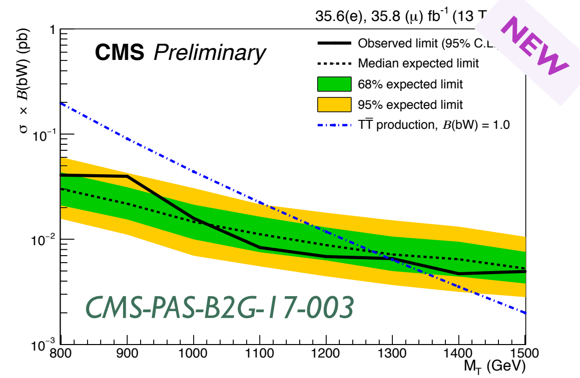






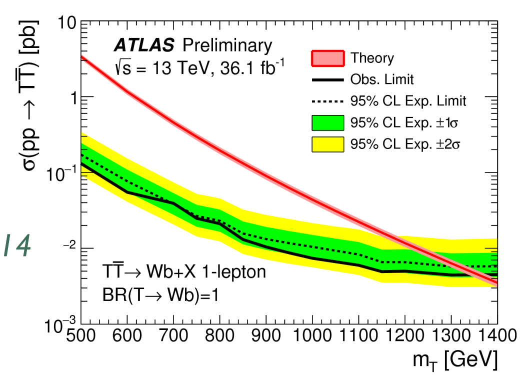
CMS PAS B2G-16-025

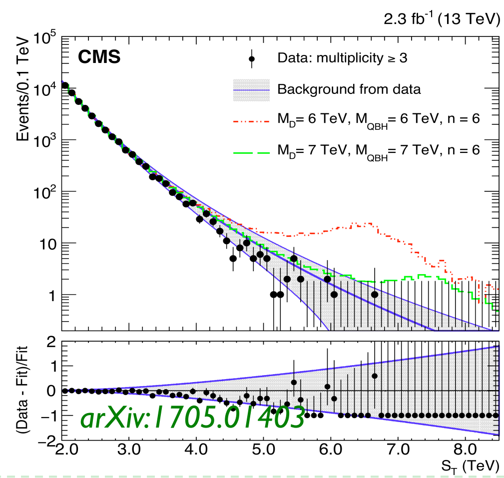
Other heavy resonances and VLQ
Excited quarks (all generations)
Lepto-quarks (all generations)
Right-handed neutrinos
Quantum black holes and more…



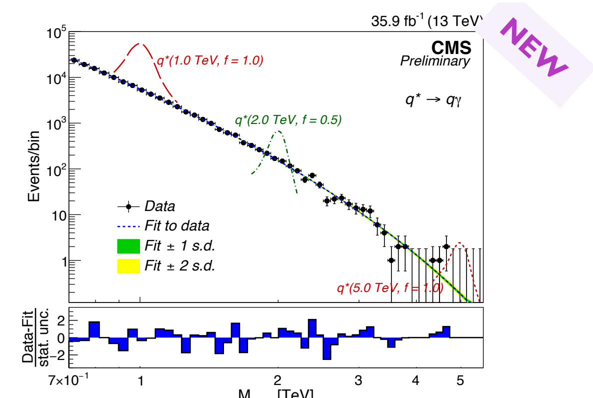
CMS-PAS-B2G-17-003

EXOT-2016-14





arXiv:1705.01403



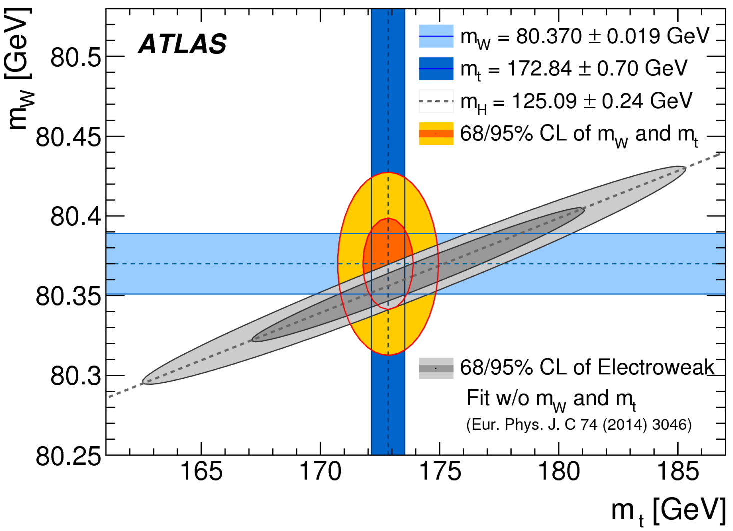
CMS-PAS-EXO-17-002

Complementing direct searches: indirect

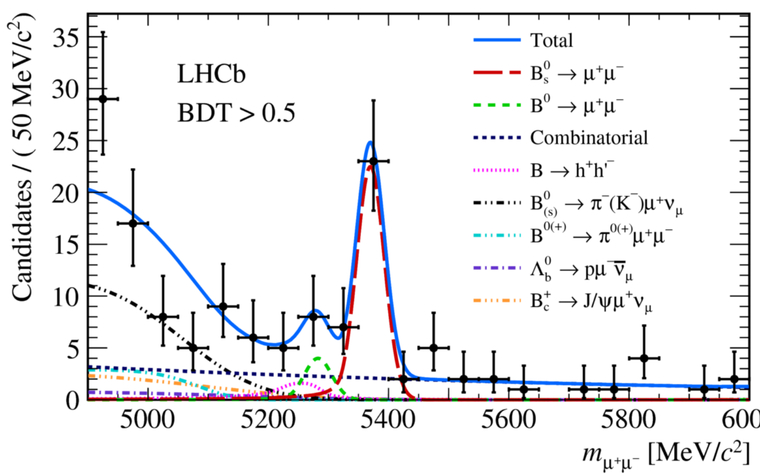
Precision measurements and their reinterpretations

→ high potential. Two "classic" examples

- **W mass** measurement (and top mass)
  - Global Electroweak fits performed
  - Understanding of remaining phase-space
    - Sensitive to new physics in loops

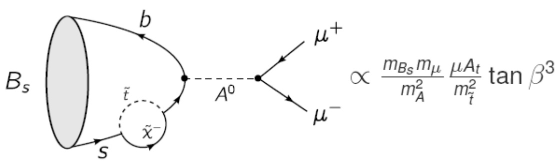


- $B_s \to \mu\mu$: BR $\left(3.0 \pm 0.6\,^{+0.3}_{-0.2}\right) \times 10^{-9}$



Consistent with SM expectations

Indirectly constrains various BSM models e.g. SUSY



Large tan β with light pseudoscalar Higgs disfavoured

complementing the LHC

Other experimental apparatus can be suitable to search for BSM physics from other – sometimes very different – corners.

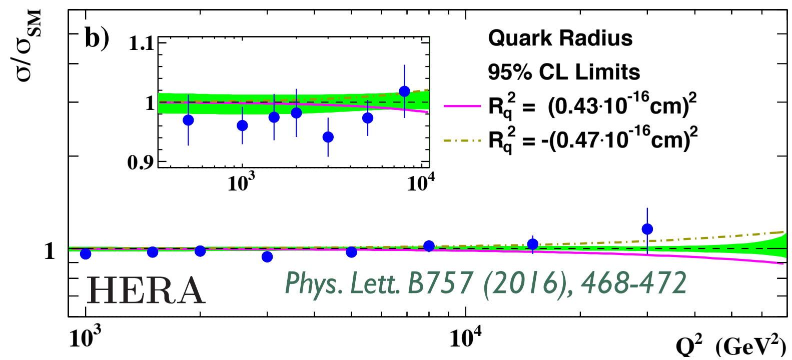
Quark radius and high-scale NP

→ Sensitive to new physics at very high scale

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R_e^2}{6}Q^2\right)^2\left(1 - \frac{R_q^2}{6}Q^2\right)^2$$

$$-(0.47 \cdot 10^{-16}\,\mathrm{cm})^2 < R_q^2 < (0.43 \cdot 10^{-16}\,\mathrm{cm})^2$$

simultaneous analysis of PDFs and quark form factor

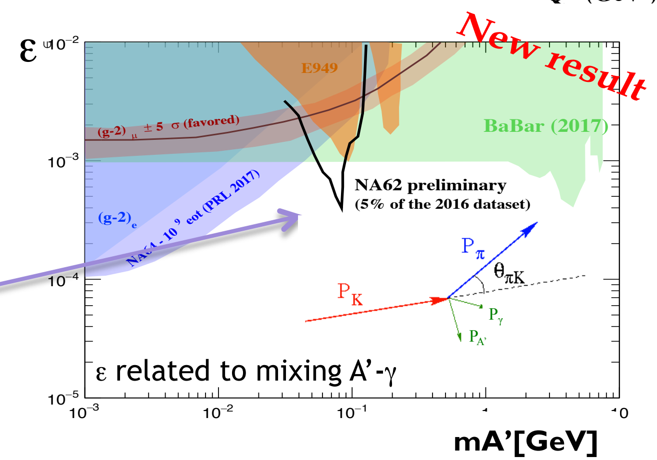


hidden sectors

NA62 [@ the intensity frontier]

- Sensitivity for models as Heavy Neutral Lepton and dark photons (A'), and more already now (Run 2)
  - Dark photons from π_0 decays (1 γ + E_T^{Miss})
  - Use decay $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \gamma A'$ BR~20%

At this conference



Many more opportunities / experimental results to be watch out closely for implication and complementarities with searches for new physics at the Energy frontier
→ g-2 at Fermilab, DM direct experiments, μ2e, μ3e, EDM experiments and more..

conclusions

- An immense program of searches for new physics at the LHC (the energy frontier) and beyond is being carried out
  - At ATLAS, CMS and LHCb, making full use of the excellent data provided
- No significant excess seen in data
- Stringent limits and constrains on new physics scenarios
  - More and more sophisticated (and ingenious!) techniques to make full use of data → experimentalists successfully explore extreme regions of phase space and a plethora of theories and models
  - Possible also thanks to the reliable Monte Carlo simulation predictions and precise theoretical calculations → a key component of most searches
- This is less than 2% of the data LHC will provide
  - Many searches must yet be completed and/or will take long time
  - More data and ingenious theoretical guidance may lead to uncover the hidden nature of nature

BACK-UP

List of ATLAS and CMS talks at this conference

BSM Higgs

- Searches for rare and exotic Higgs boson decays at CMS – Nabarun Dev
- Search for non-standard, rare or invisible decays of the Higgs bosono with the ATLAS detector – Paul Thompson
- Search of a high mass neutral Higgs boson in fermion final states with the ATLAS detector – Gaetano Barone
- Latest results on searches for MSSM Higgs Search and Beyond at CMS – Chayanit Asawatangtrakuldee
- Searches for a new Higgs-boson like low-mass resonance in the diphoton final state in pp collisions at 13 TeV in CMS – Linda Finco
- TBC Search for the decay of the Higgs boson into two nMSSM pseudo-scalar particles (ATLAS) – Michel Janus
- Searches for associated production of the Higgs boson with a single top at 13 TeV at CMS – Pallabi Das
- Charged Higgs boson searches with the ATLAS detector – Elin Bergeaas Kuutmann

Dedicated SUSY Searches

- Searches for supersymmetry via strong production in fully hadronic final states at CMS – Miriam Schoenenberger
- Inclusive searches for squarks and gluinos in final states with no leptons with the ATLAS detector – Otilia Anamaria Ducu
- Searches for supersymmetry via strong production in events with one or more leptons at CMS – Christian Schomakers
- Inclusive searches for squarks and gluinos in final states with leptons with the ATLAS detector – Ximo Poveda Torres
- Search for compressed SUSY scenarios with the ATLAS detector – Julien Maurer
- Search for supersymmetry with compressed mass spectra or decays via Higgs bosons at CMS – Constantin Heidegger
- Searches for production of third generation squarks at CMS – Indara Suarez
- Searches for direct pair production of third generation squarks in final states with no leptons with ATLAS – Tommaso Lari
- Searches for direct pair production of third generation squarks in final states with leptons with the ATLAS detector – Priscilla Pani
- Searches for electroweak production of supersymmetric gauginos and sleptons with the ATLAS detector – Zinonas Zinonos
- Search for electroweak production of supersymmetry at CMS –Miaoyuan Liu
- Search for supersymmetry in events with photons at CMS – Marc Gabriel Weinberg
- Search for R-parity violating supersymmetry with the ATLAS detector – Sascha Mehlhase

List of ATLAS and CMS talks at this conference

Exotics Searches – resonances/non-resonant/general final states

- Search for a new spin-zero resonance in diboson channels at 13 TeV (CMS) – Alessio Magitteri
- Search for high mass bosonic resonances with the ATLAS detector – Leonardo Carminati
- Search for New Phenomena in Dijet Events with the ATLAS Detector at 13 TeV - Attilio Picazio
- Searches for new physics in dijet and multijet final states (CMS) – Federico Prelato
- Searches for non-resonant new phenomena in final states with leptons and photons (CMS) – Oscar Gonzales Lopez
- Searches for new phenomena in leptonic final states using the ATLAS detector – Giacomo Artoni
- Searches for new heavy resonances in final states with leptons and photons – Benjamin Radburn-Smith
- ATLAS Searches for VH and HH Resonances – Wade Cameron Fisher
- Search for diboson resonances decaying into W, Z and H bosons at CMS – Clemens Lange
- ATLAS Searches for VV/V+gamma Resonances – Kalliopi Iordanidou
- Search for vector-like quarks (ATLAS) – Olaf Nackenhorst
- Search for vector-like quarks and excited quarks at CMS – Giorgia Rauco
- Search for heavy resonances decaying to top quarks – Saverio D'Auria
- Search for new resonances coupling to third generation quarks at CMS – Johannes Haller
- TBC Searches for new physics in lepton+jets final states – Marc Stover
- Searches for new phenomena in final states involving leptons and jets using the ATLAS detector – Paolo Mastrandrea
- TBC Searches for Long-Lived particles and other non-conventional signatures – Todd Adams
- TBC Search for New Physics through the Reconstruction of Challenging and Long-Lived Sginatures with the ATLAS detector at 13 TeV – Nora Emilia Petterson

+ Dark Matter Searches

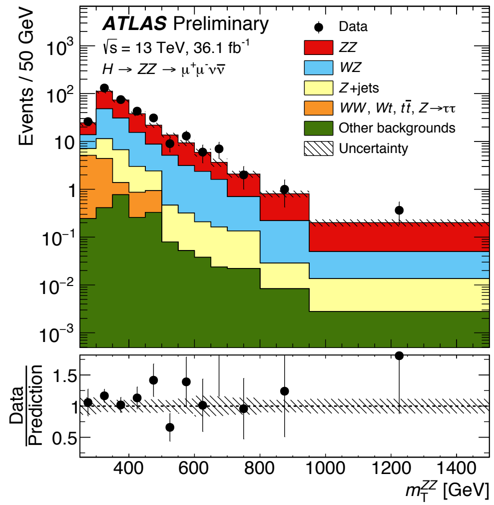
+ Other results from HERA, LHCb, CDF

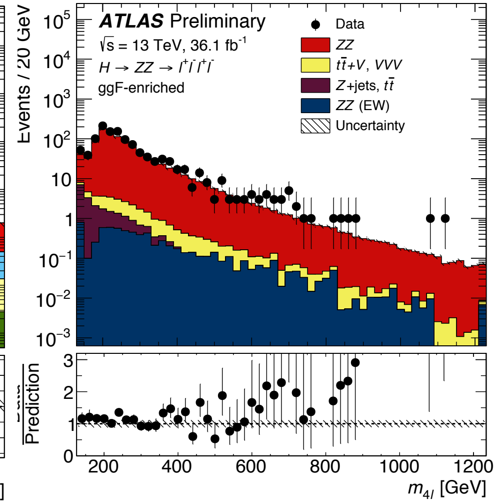
heavy Higgs-like bosons: resonances

- heavy Higgs → ZZ →llll/llνν produced via ggH or vector-boson fusion

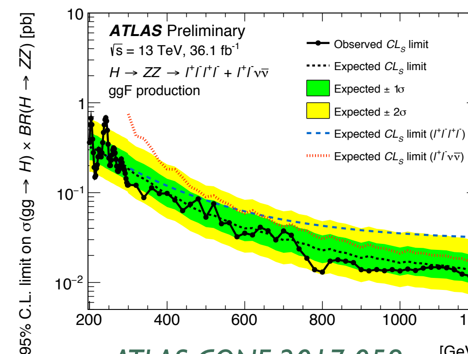
NEW

SM background from CR (llvv) or using fit to data (4l)



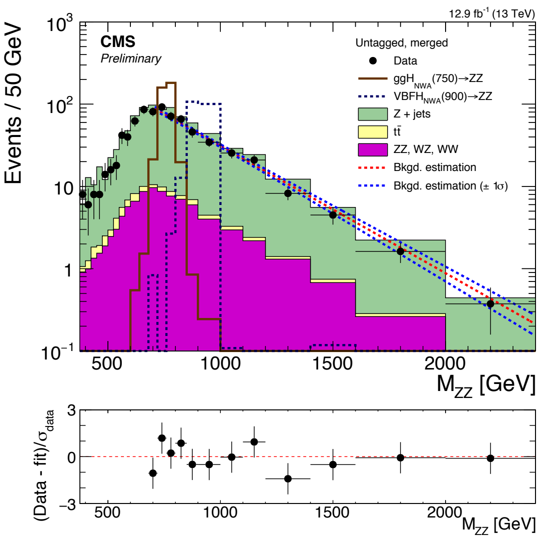


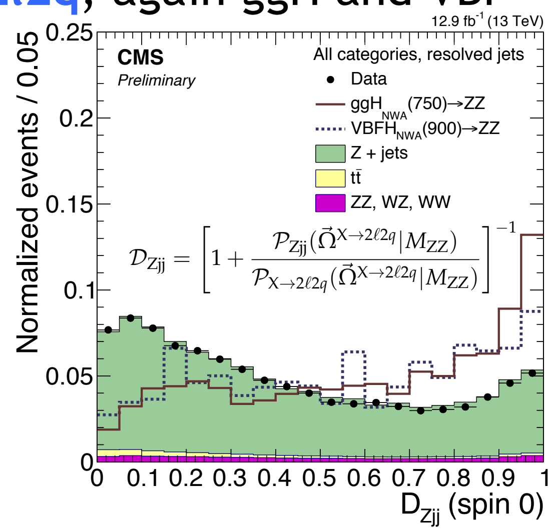
Spin-0, narrow width approximation (NWA)



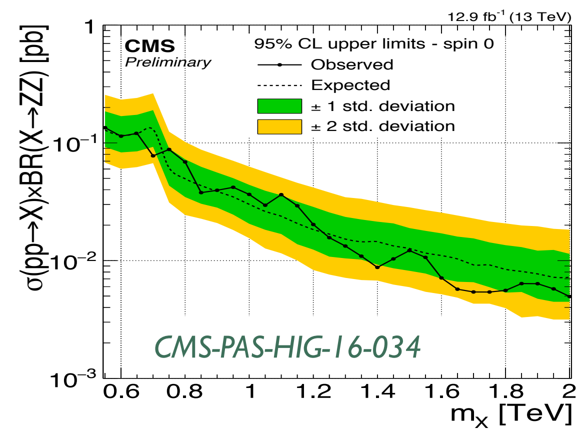
ATLAS-CONF-2017-058

- heavy Higgs → ZZ → 2l2q, again ggH and VBF





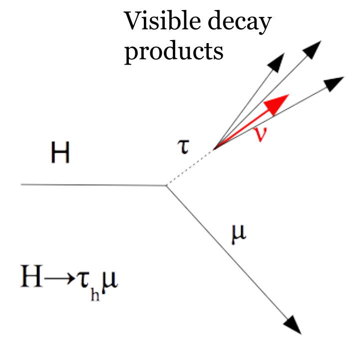
Use dedicated techniques to separate signal and Z+jets bkg (MELA, DZjj or D2jet discriminant depending on category)



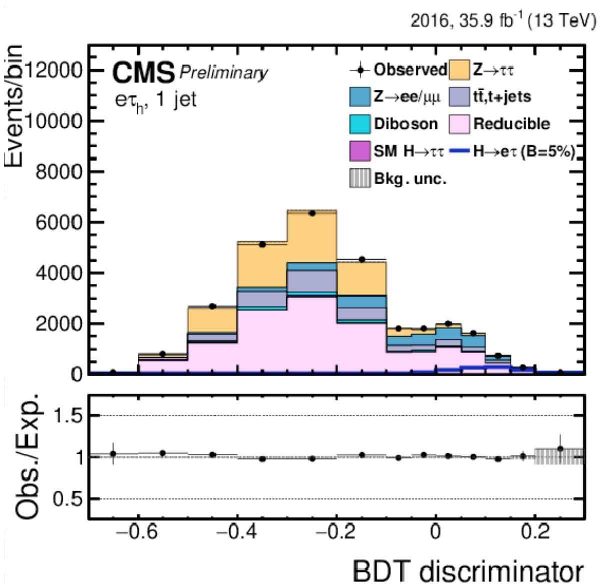
CMS-PAS-HIG-16-034

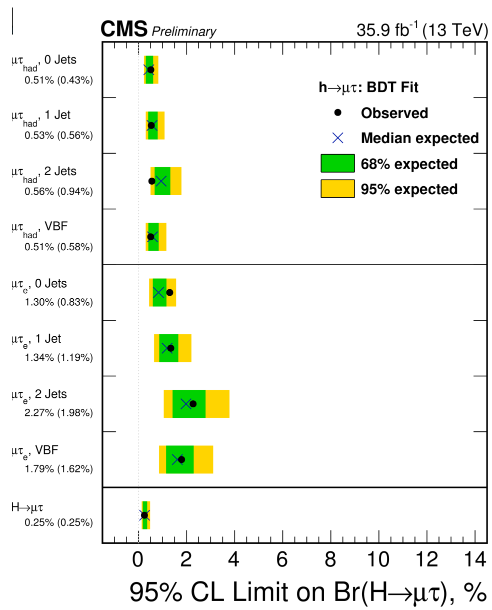
Lepton Flavor Violation Higgs decay

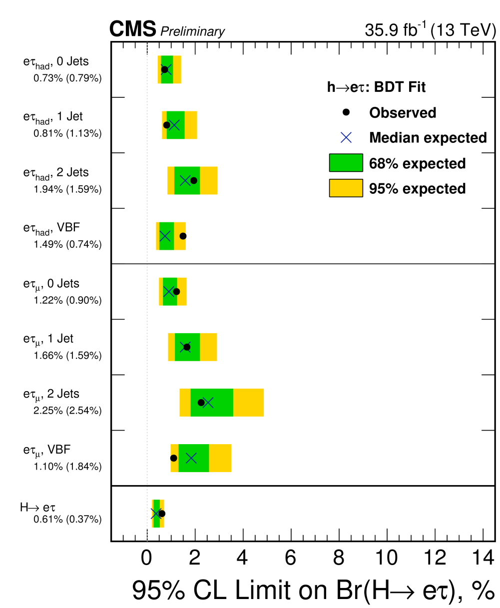
- Allowed in several beyond the standard model theories such as Randall-Sundrum models, Higgs Doublet theories
  - H→μτ , H→eτ, H→eμ
- In Run 1, CMS observed a 2.4σ excess in the *H→μτ* channel: *B(H→μτ) < 1.51%* at *95%* CL (~1σ ATLAS)
  - No excess in Run 2
- Search for H→μτ , H→eτ considering leptonic or hadronic tau decays



CMS-PAS-HIG-17-001

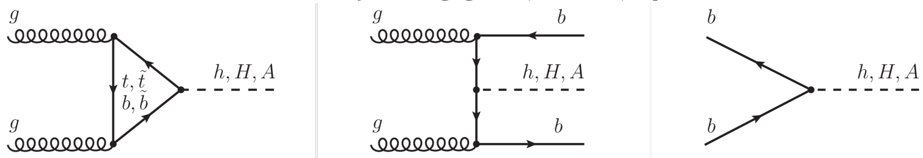






heavy Higgs-like bosons: A/H→ττ

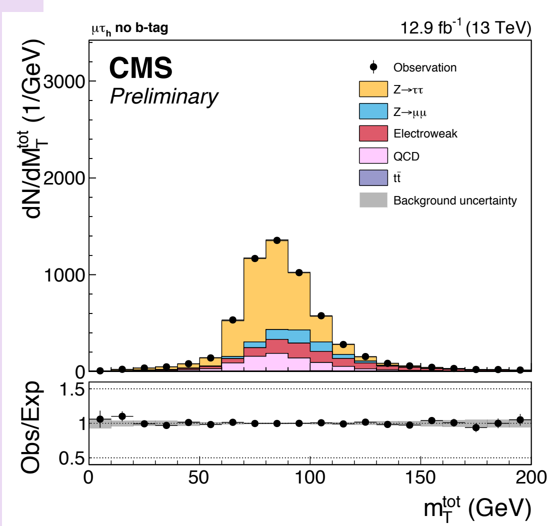
- MSSM-like heavy higgs (A/H) produced via gluon-fusion or b/t associated

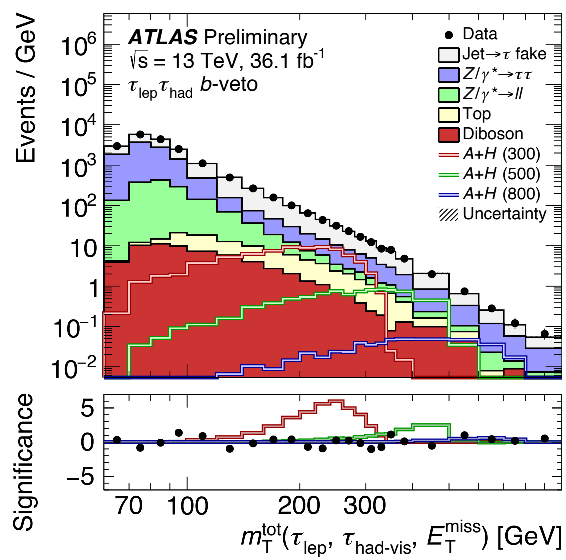


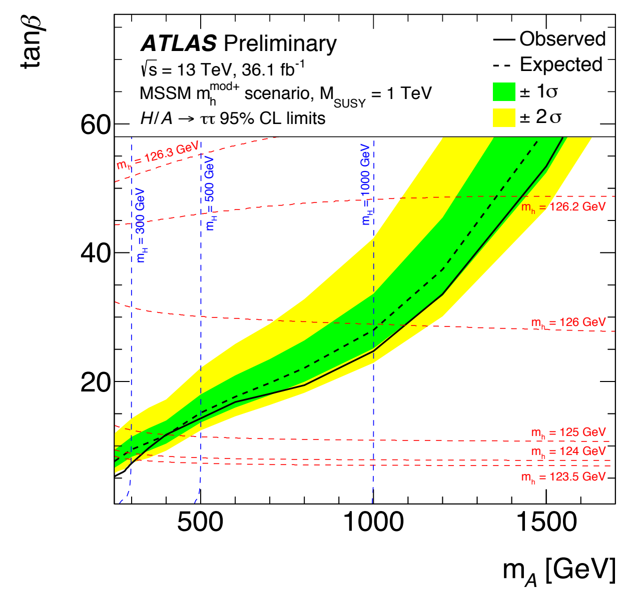
A/H → ττ: Higgs decays to ττ are favored for large parts of the parameter space (defined by m_A and tanβ, ratio of Higgs vevs), especially for large tanβ

- m_T(tot) used as discriminant
- B-tag and non-b-tag regions

$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)}$$



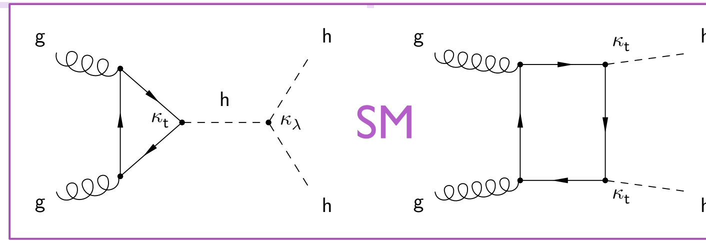


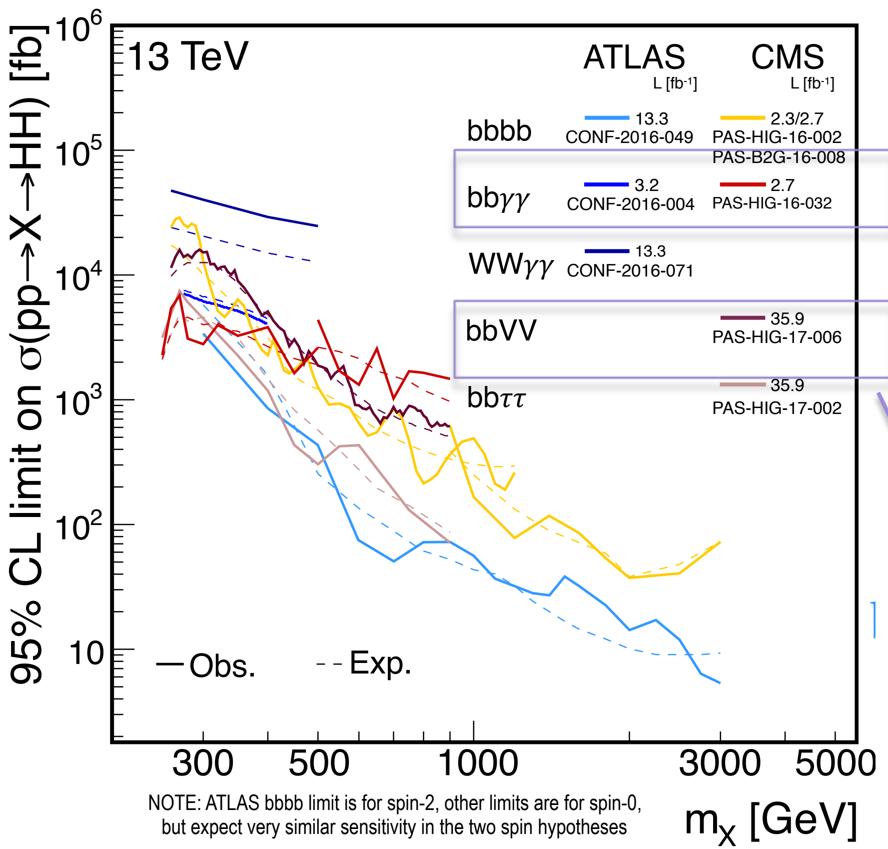


Results interpreted in MSSM scenarios or as cross-section x BR limits

X→HH production

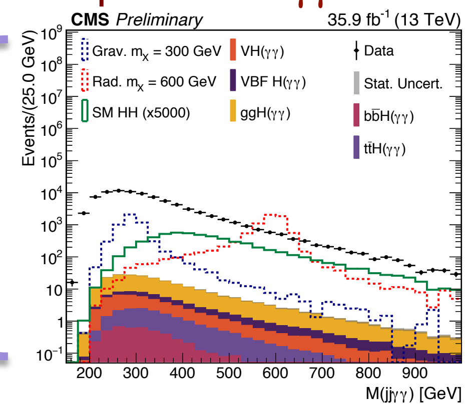
- Di-Higgs production is rare in the SM.
- An anomalously large rate (resonant or non-resonant) can be evidence of NP (*e.g.* H → hh)
- Several searches from ATLAS and CMS.





Updated bbγγ

NEW

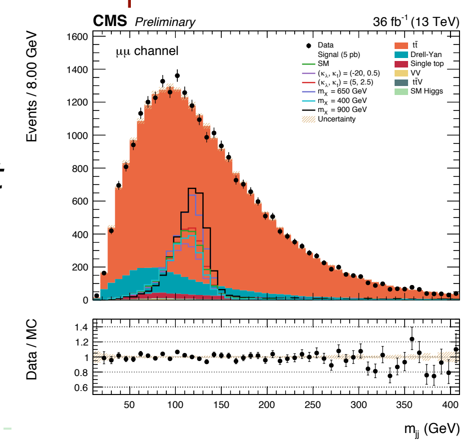


Main background γ+jets (data-driven)

CMS-PAS-HIG-17-008

2b+2leptons+E_T^{Miss}

Invariant mass of 2-muons

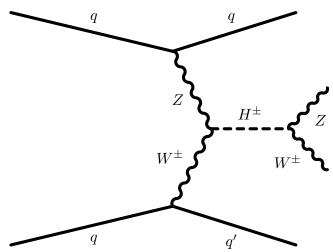


Non-resonant HH searches and interpretation also available

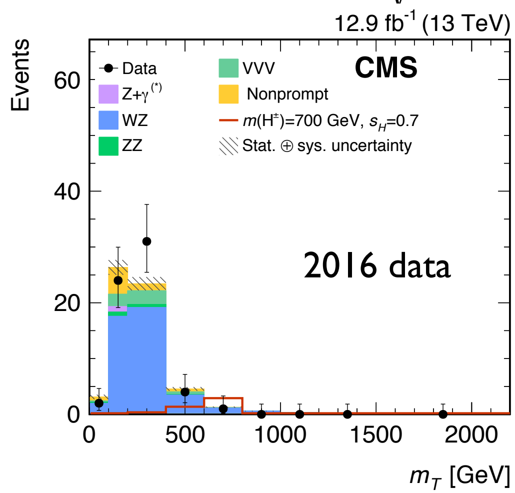
charged Higgs bosons

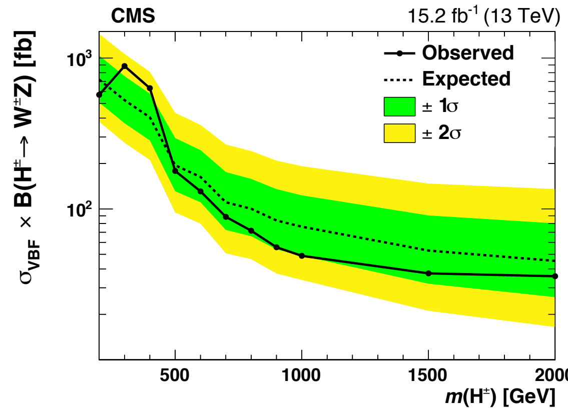
- CMS uses transverse mass of WZ system to search for H± *1705.02942*

$$m_{\mathrm{T}}(\mathrm{WZ}) = \sqrt{(E_{\mathrm{T}}(\mathrm{W}) + E_{\mathrm{T}}(\mathrm{Z}))^2 - (\vec{p}_{\mathrm{T}}(\mathrm{W}) + \vec{p}_{\mathrm{T}}(\mathrm{Z}))^2},$$



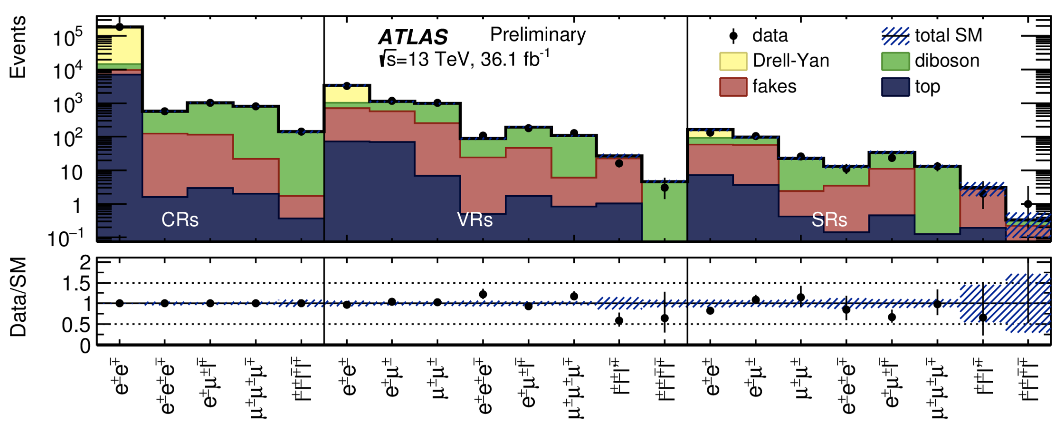
Other searches for H±
→ in top+b or τν final states
(from both ATLAS and CMS)

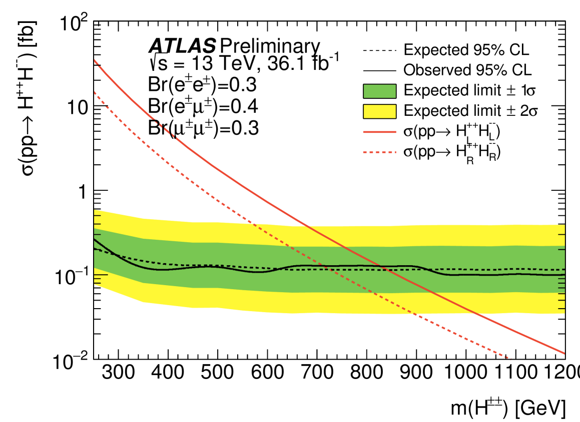




limits on $\sigma_{\mathrm{VBF}}(\mathrm{H}^{\pm})\,\mathcal{B}(\mathrm{H}^{\pm} \to \mathrm{WZ})$

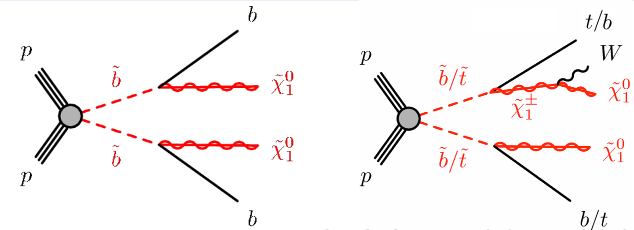
- ATLAS recently released the results for a search on H±± *ATLAS-CONF-2017-053*
  - 2, 3 and 4 lepton regions (electrons, muons) – use CRs for SM background and VRs



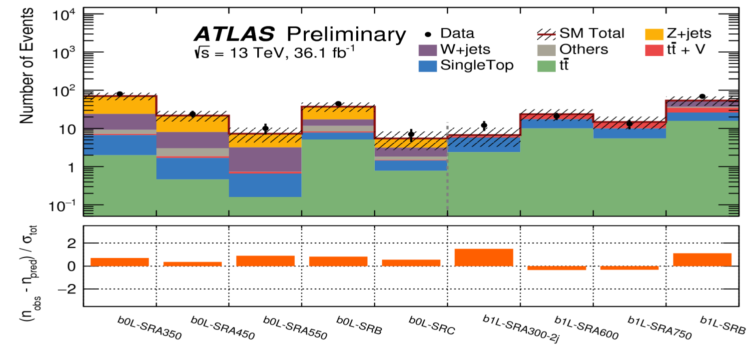


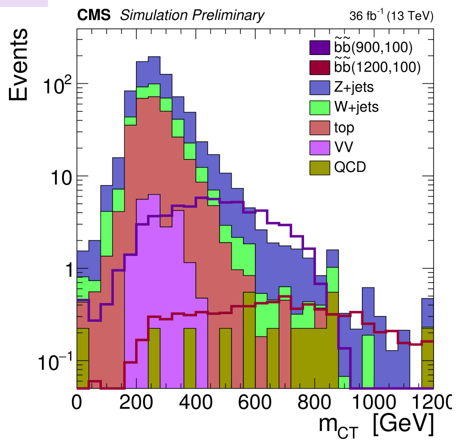
Latest on the bottom squarks

- Bottom squark pair production:
  - @CMS: dedicated search in 0L+2b+E_T^{Miss} plus interpretation of inclusive analyses (SRs with b-jets)
  - ATLAS performs dedicated searches also for mixed-scenarios (0L+2b/1L+2b + E_T^{Miss})
- m_{CT} used as discriminant in both cases
  - Dedicated selections for "compressed" scenarios
- In several cases, constrains also **top squark!**

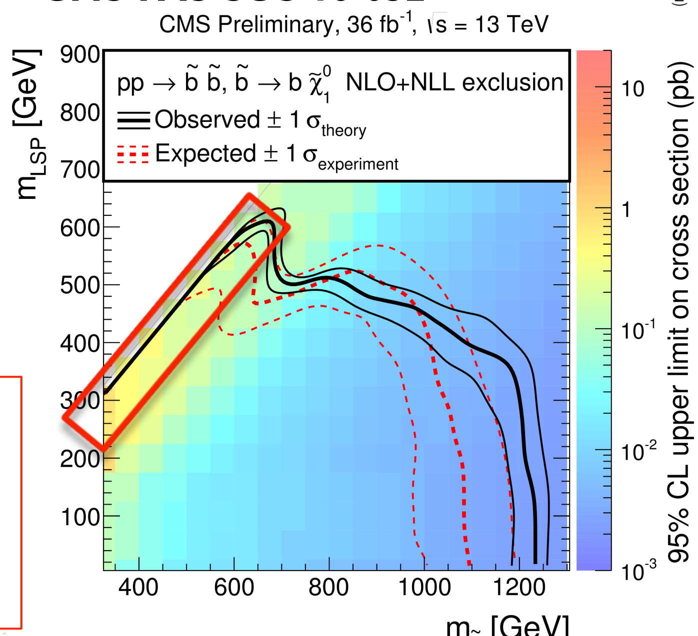


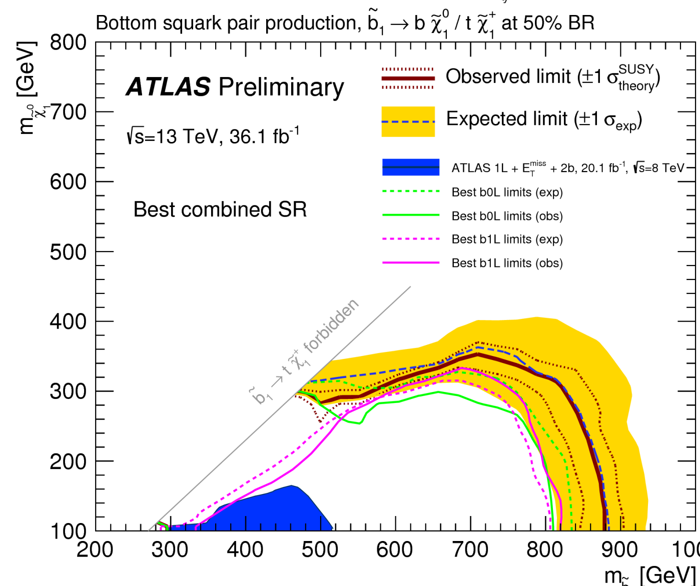
ATLAS-CONF-2017-038





CMS-PAS-SUS-16-032





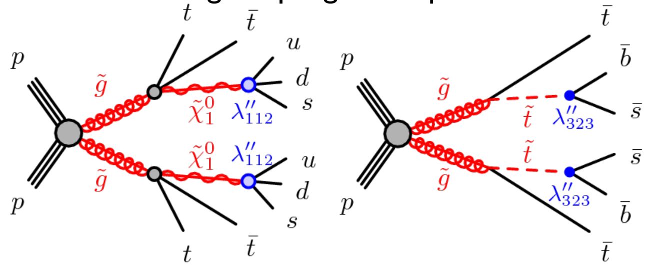
Exclusion limits beyond **1 TeV / exp.**

Still < 600 GeV for compressed regions: Also for **stop → charm + E_T^{Miss}**

R-parity violating scenarios

- Several dedicated searches targeting SUSY scenarios with R-parity violation
  - Possibly no (not much) E_T^{Miss} → different strategies for SM background estimates. *Examples:*

Gluinos via Lepton/Baryon number-violating couplings into quarks

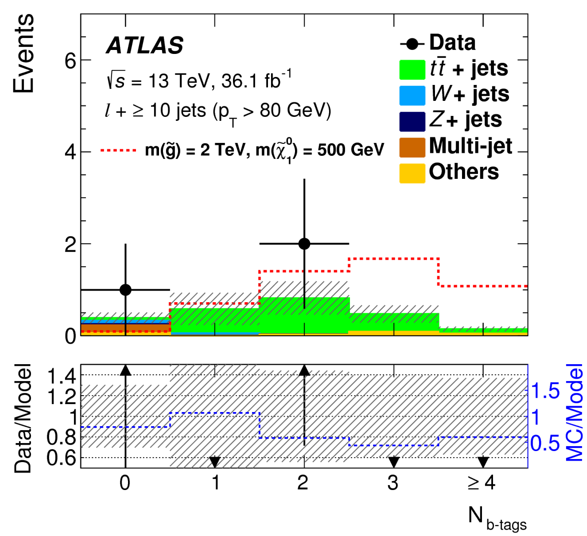


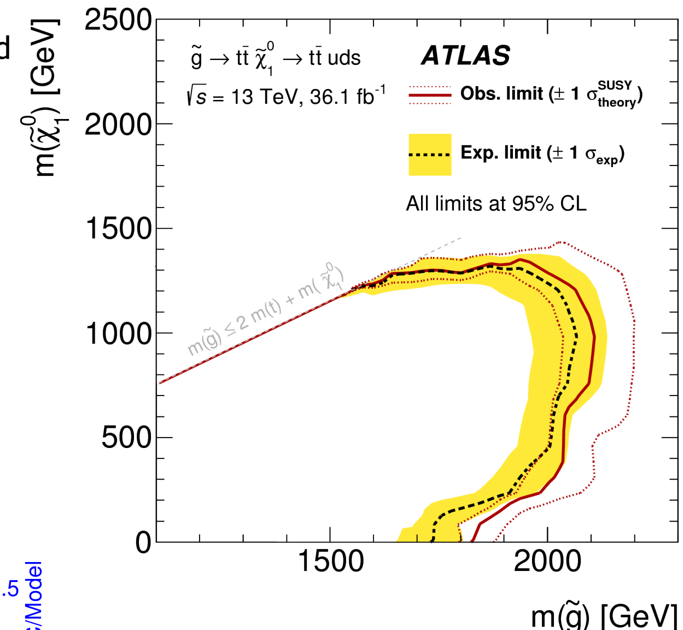
ATLAS: 1lepton + multi-jets (≥8-12) and (0, ≥3) bjets

- SRs binned in N_{jet}, N_{bjet}

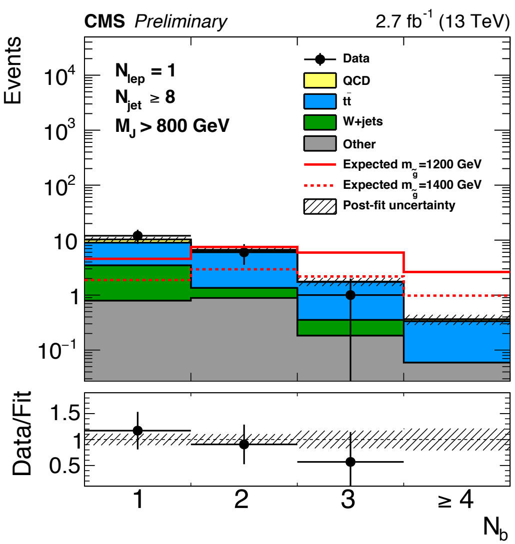
SM background: ttbar, W/Z+jets estimated using parameterized extrapolations on observables at low jet multiplicity

1704.08493





CMS: 0/1 lepton, multi-jets (>6-10), M_J and H_T selections



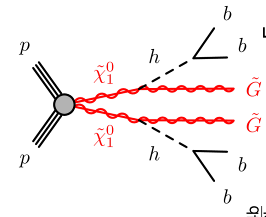
CMS-PAS-SUS-16-013

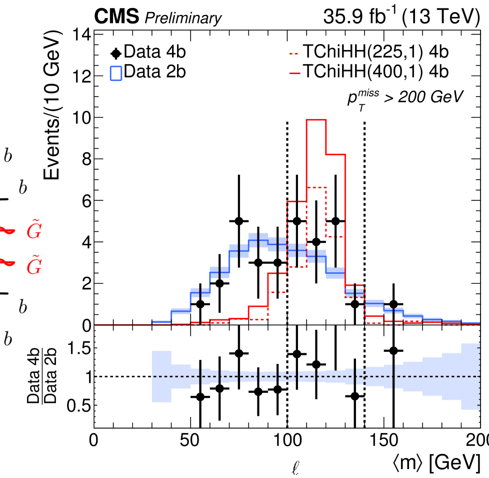
Constraints also on masses of top-squarks in RPV scenarios > 1.2 TeV

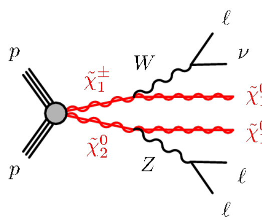
EWK SUSY

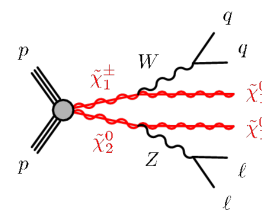
CMS-PAS-SUS-16-046

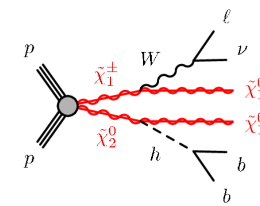
- If colored sparticles have mass above 3-4 TeV scale, EWK sector could be the only one accessible
  - Very low production rate, large dataset needed
- Exploit multi-lepton nature of final state events
  - Depends on chargino/slepton/neutralino mass hierarchy
- If decays via sleptons are kinematically forbidded
  - Final states with WZ, WH, HH, Wγ … depending on the model

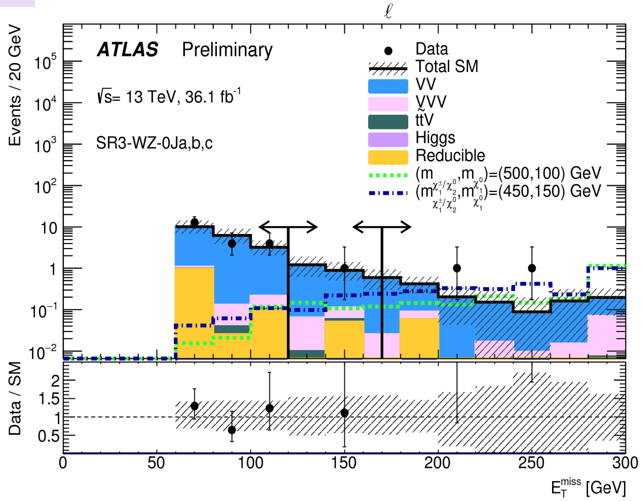


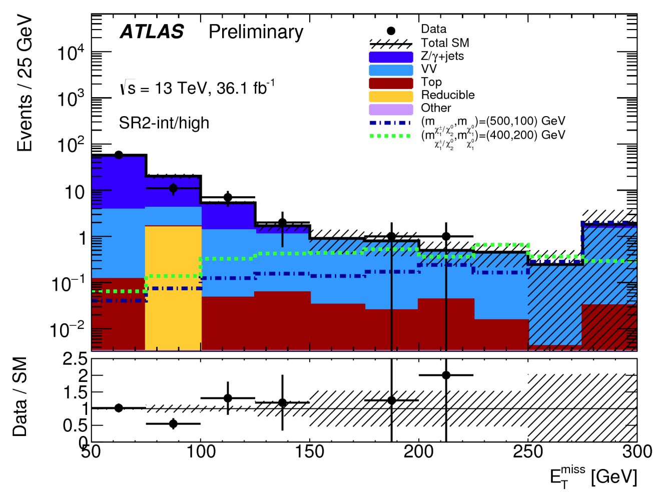


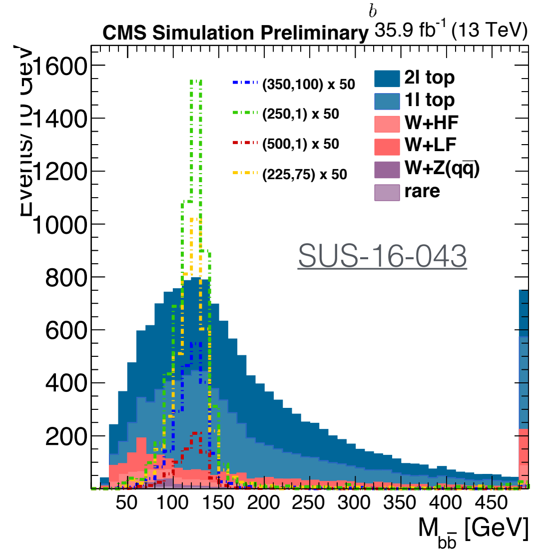








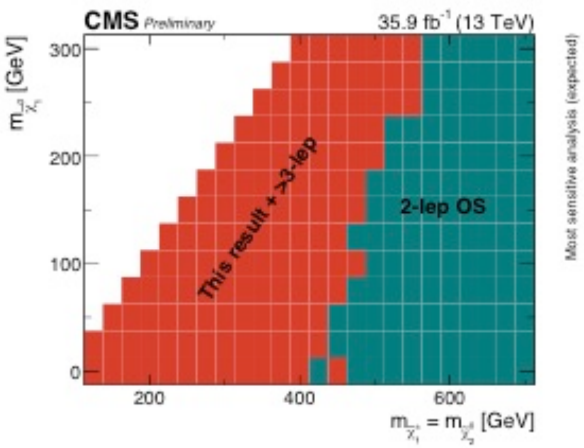


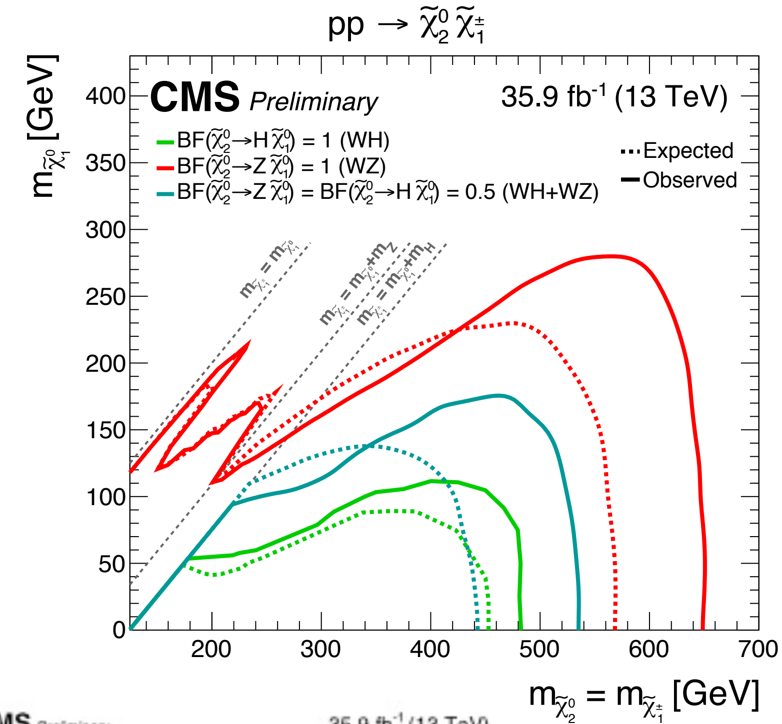


New EWK SUSY results (from CMS)

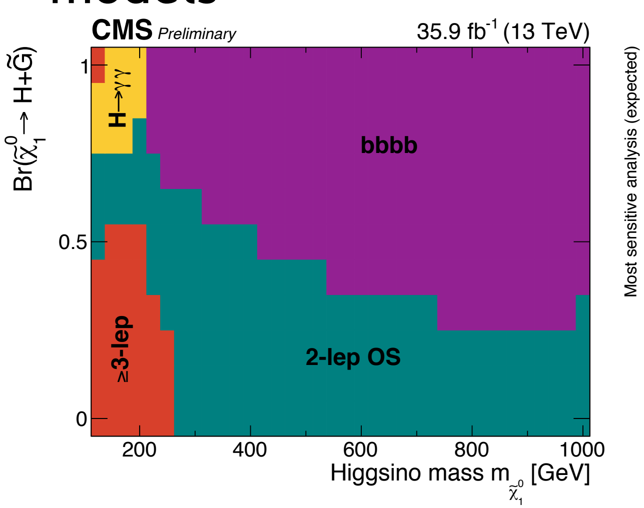
CMS PAS SUS-17-004

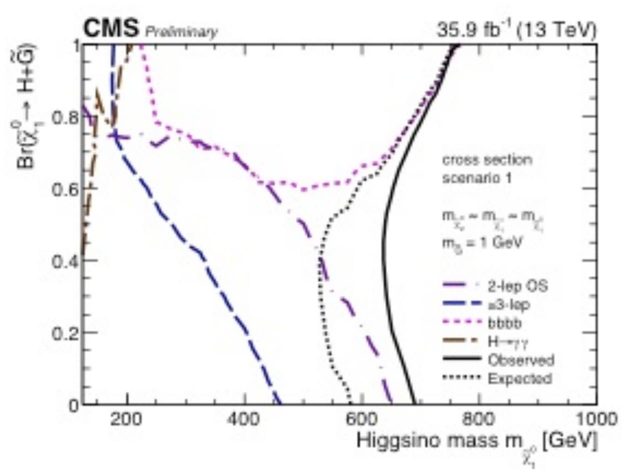
- Sensitivity to mixed topologies





- Sensitivity to Gauge mediated models





Searches for Dark Matter as WIMPs

NEW

- **W/Z or Higgs + E_T^{Miss} (mono-W/Z/H)**

Higgs: e.g. in bb or γγ final states

ATLAS: 1706.03948, 1707.01302

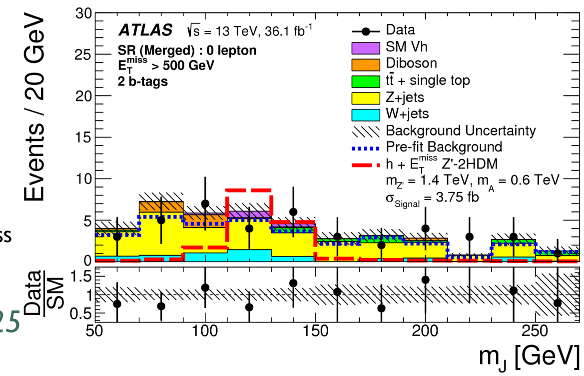
CMS: 1703.05236

W/Z: Lept. or hadr. bosons recoiling E_T^{Miss}

ATLAS: PLB 763(2016) 251

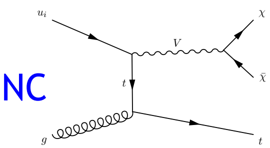
CMS: EXO-16-052

m_J = mass of large R-jets (bb)

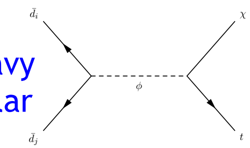


- **top + E_T^{Miss}**

FCNC



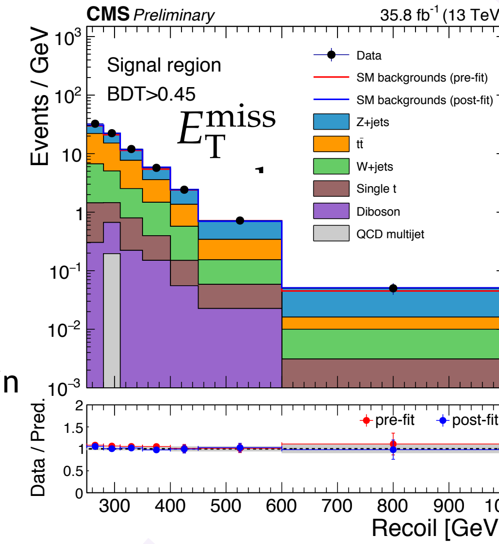
Heavy scalar



Top decay products merged in a large-R jet recoiling E_T^{Miss}

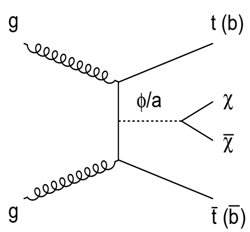
BDT based on substructure observables

CMS PAS EXO-16-051

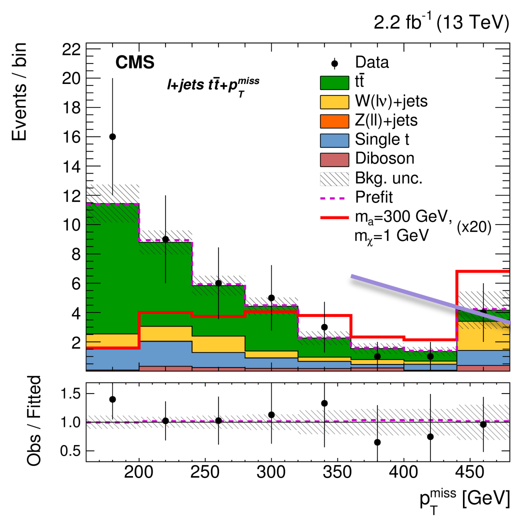


- **heavy flavor quarks (tt/bb) + E_T^{Miss}**

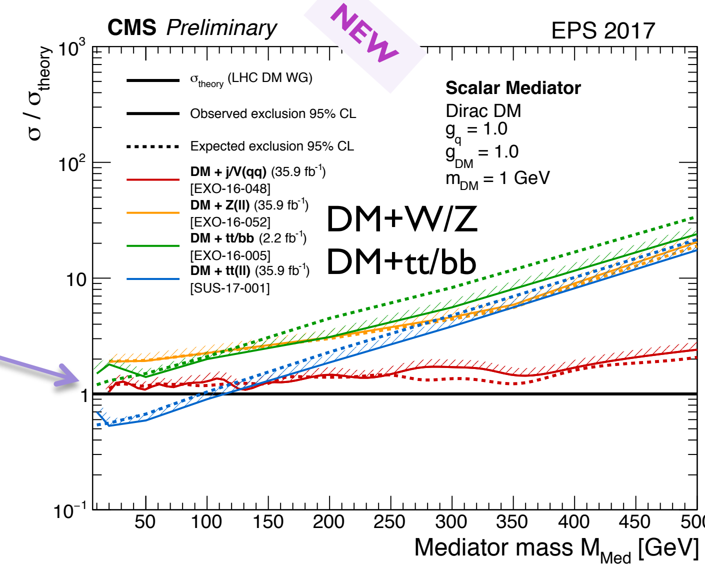
Both ATLAS and CMS target models with DM produced in association to top or bottom



EXO-16-005, EXO-16-028
ATLAS-CONF-2016-086

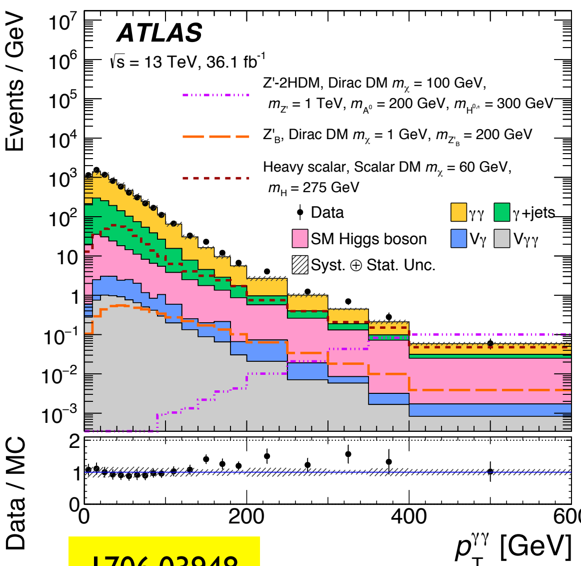


NEW



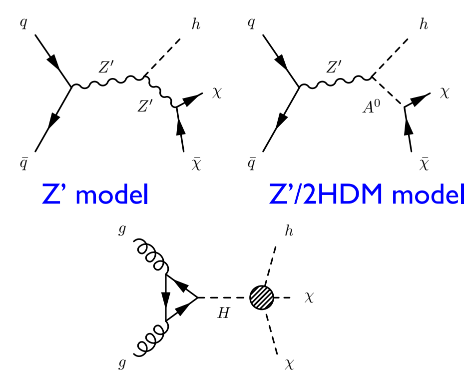
Higgs as portal to Dark-Matter

Higgs in $2\gamma + E_T^{Miss}$

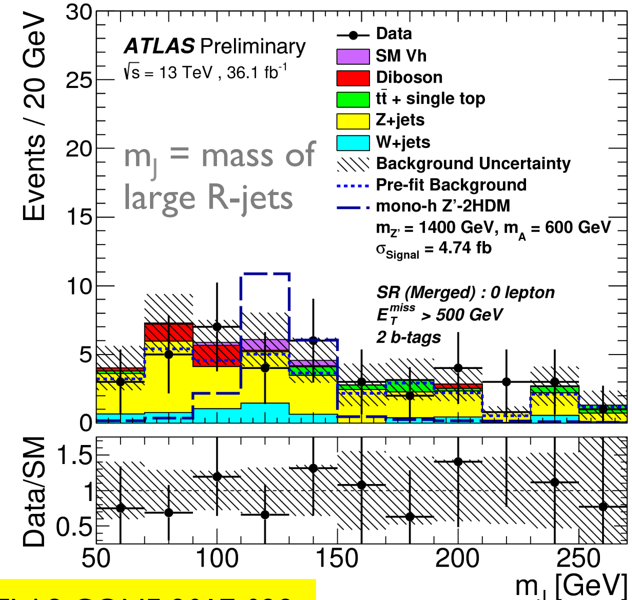


1706.03948

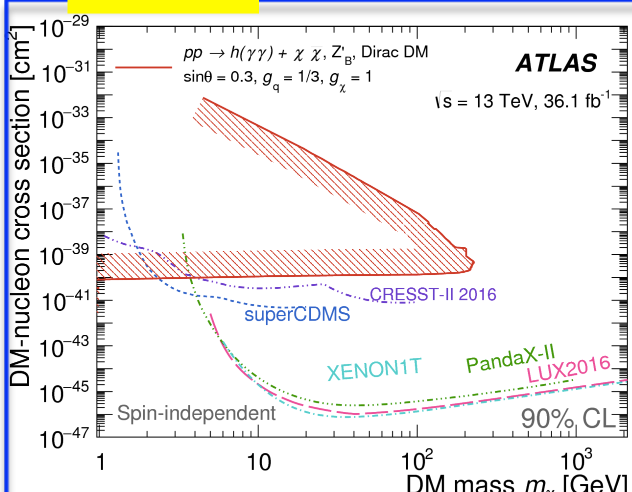
More general Higgs-DM-models can be considered [CMS: arXiv:1703.05236]



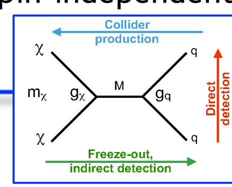
Higgs in $bb + E_T^{Miss}$



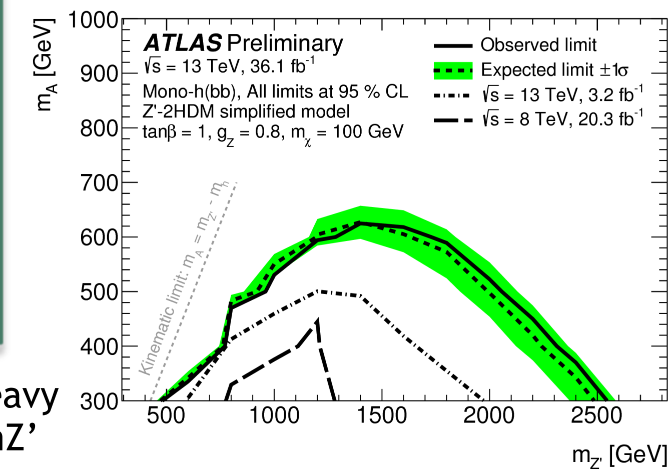
ATLAS-CONF-2017-028



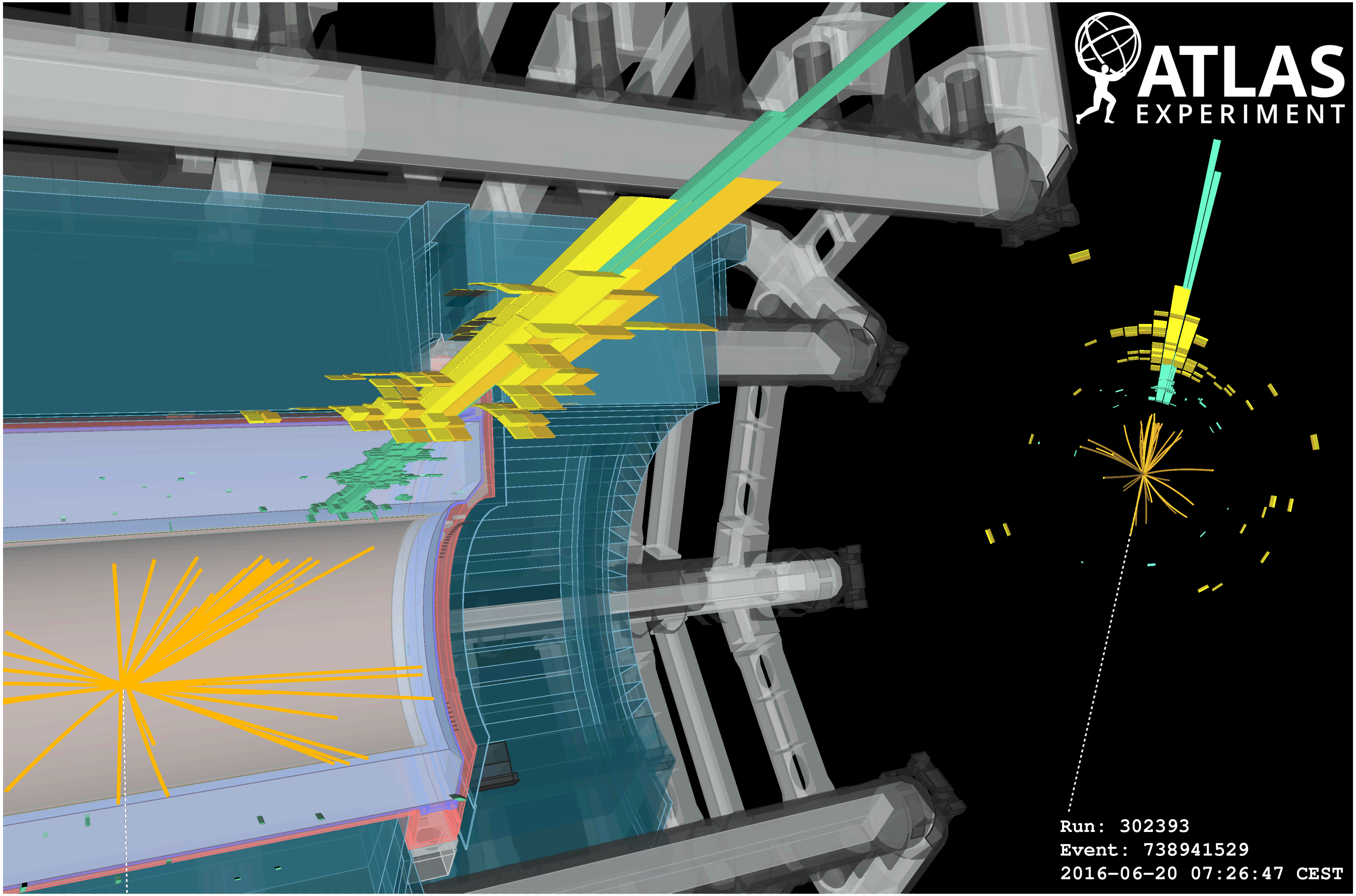
Comparison of the inferred limits to the constraints from direct detection experiments on the spin-independent DM-nucleon



Constraints on heavy Higgs (mA) and mZ'



Monojet event



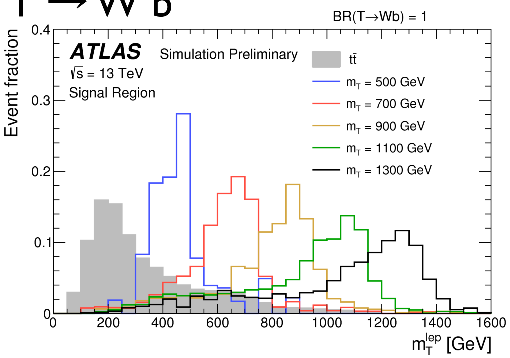
Vector-like quarks

- X = T, B quarks → singly or pair-produced, many objects in decays (W,H,Z,t ..)

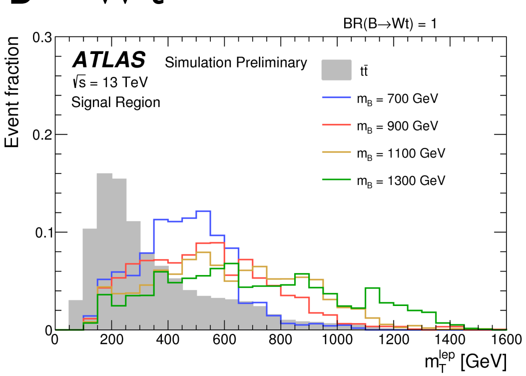
X→tH/Wb/tZ

Background techniques as for SUSY searches:
→ complex discriminant variables
→ dedicated CRs and VRs
→ exploitation of 'boosted' decay products

T → W b



B → W t



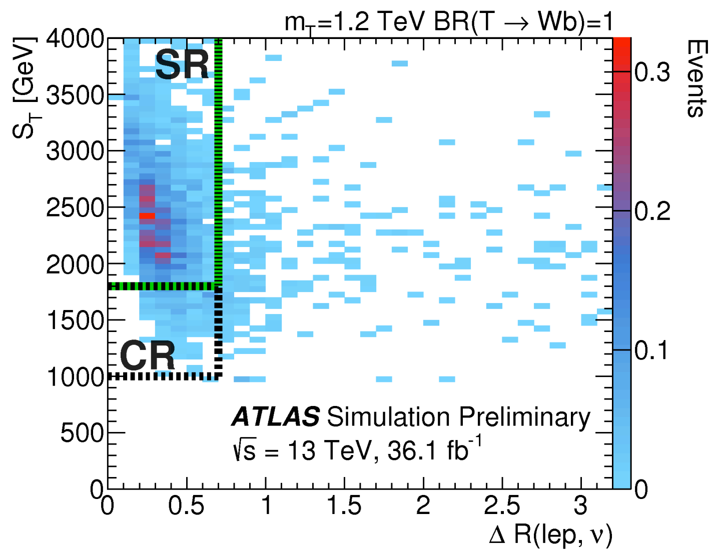
PAIR PRODUCED

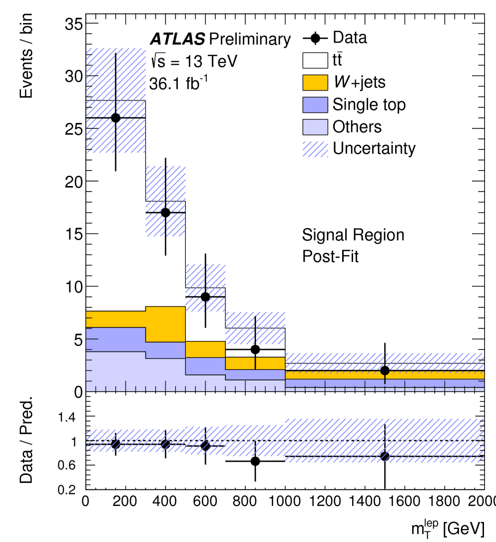
To appear

NEW

Similarly, ATLAS exploits the 1lepton+jets+MET topology

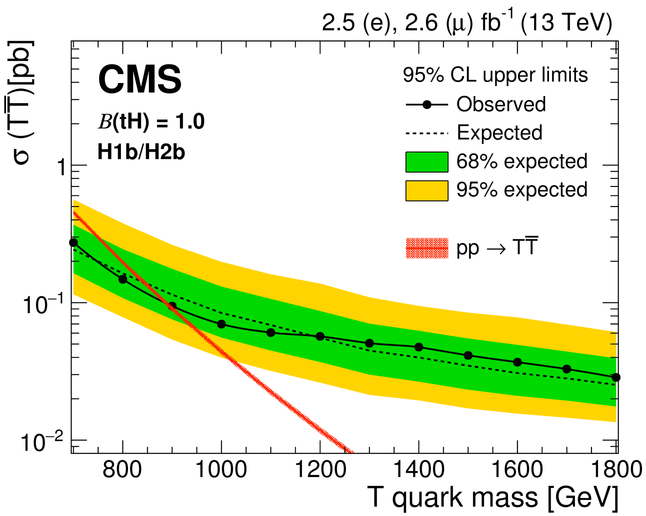
Good control of SM background using CRs

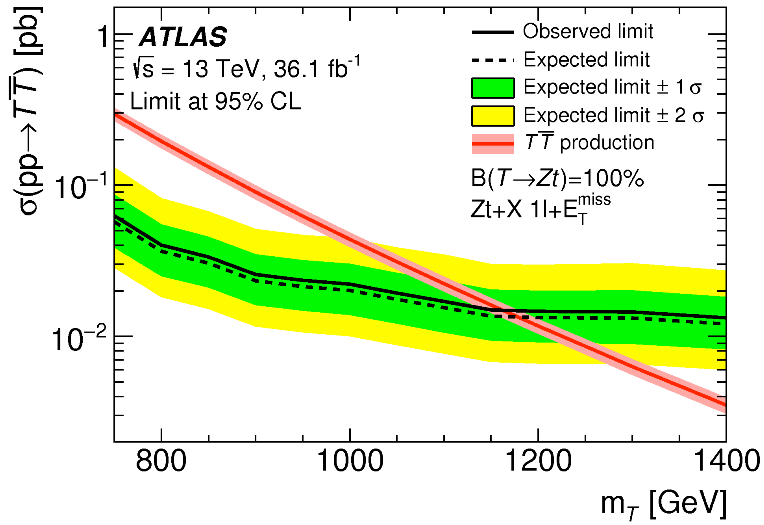


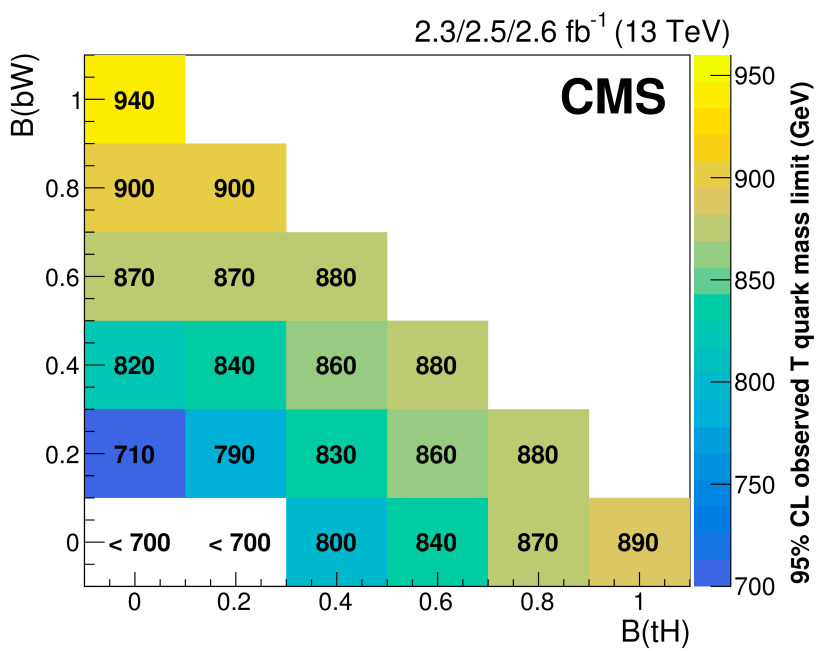


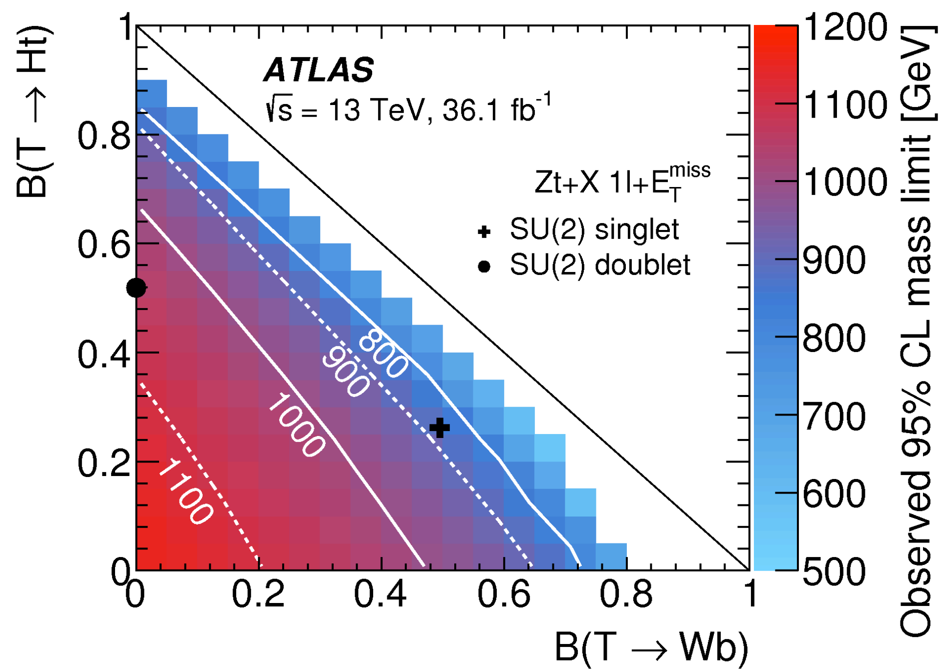
Limits up to **1.3 TeV** for BR(T→Wb)=100%

Vector-like quarks







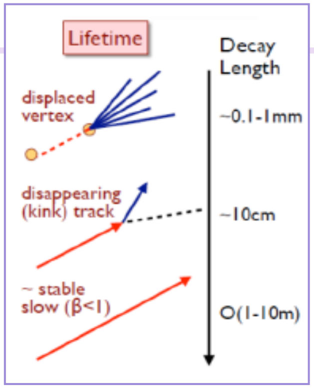


Long-lived

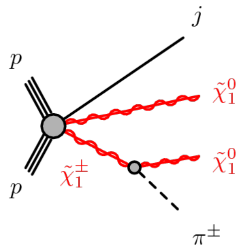
What makes a particle long-lived:

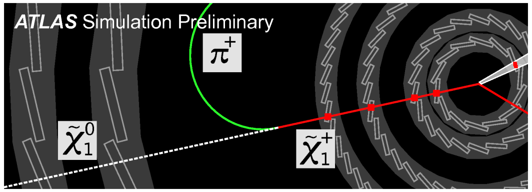
- small couplings: RPV decays, dark sector coupling
- small mass-splittings: almost degenerate next-LSP
  heavy messenger: Z', split SUSY
- hidden valley

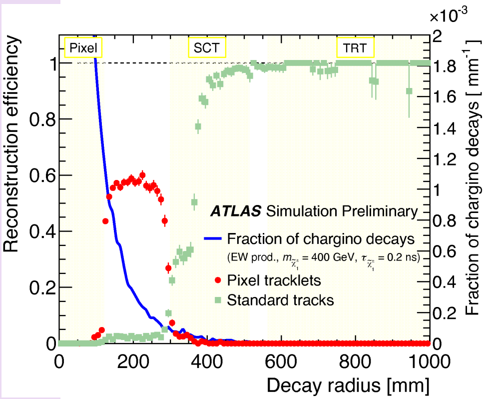
Signatures depend on the lifetime!

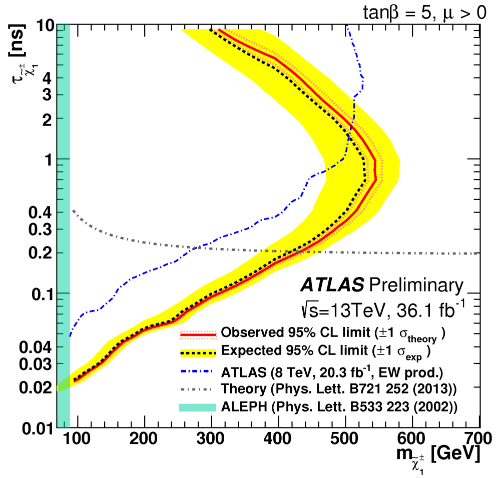


DISAPPEARING TRACKS



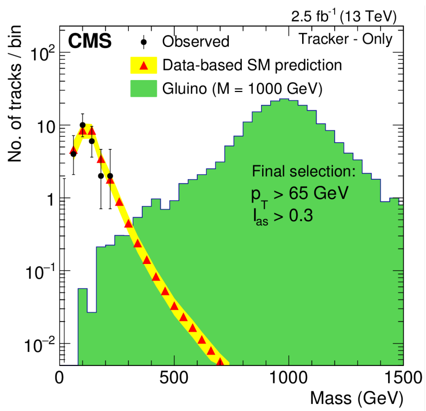


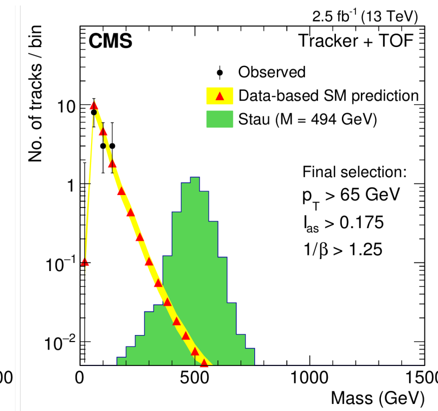




HEAVY STABLE PARTICLE

anomalously high energy deposits in the silicon tracker and long time-of-flight measurements by the muon system.



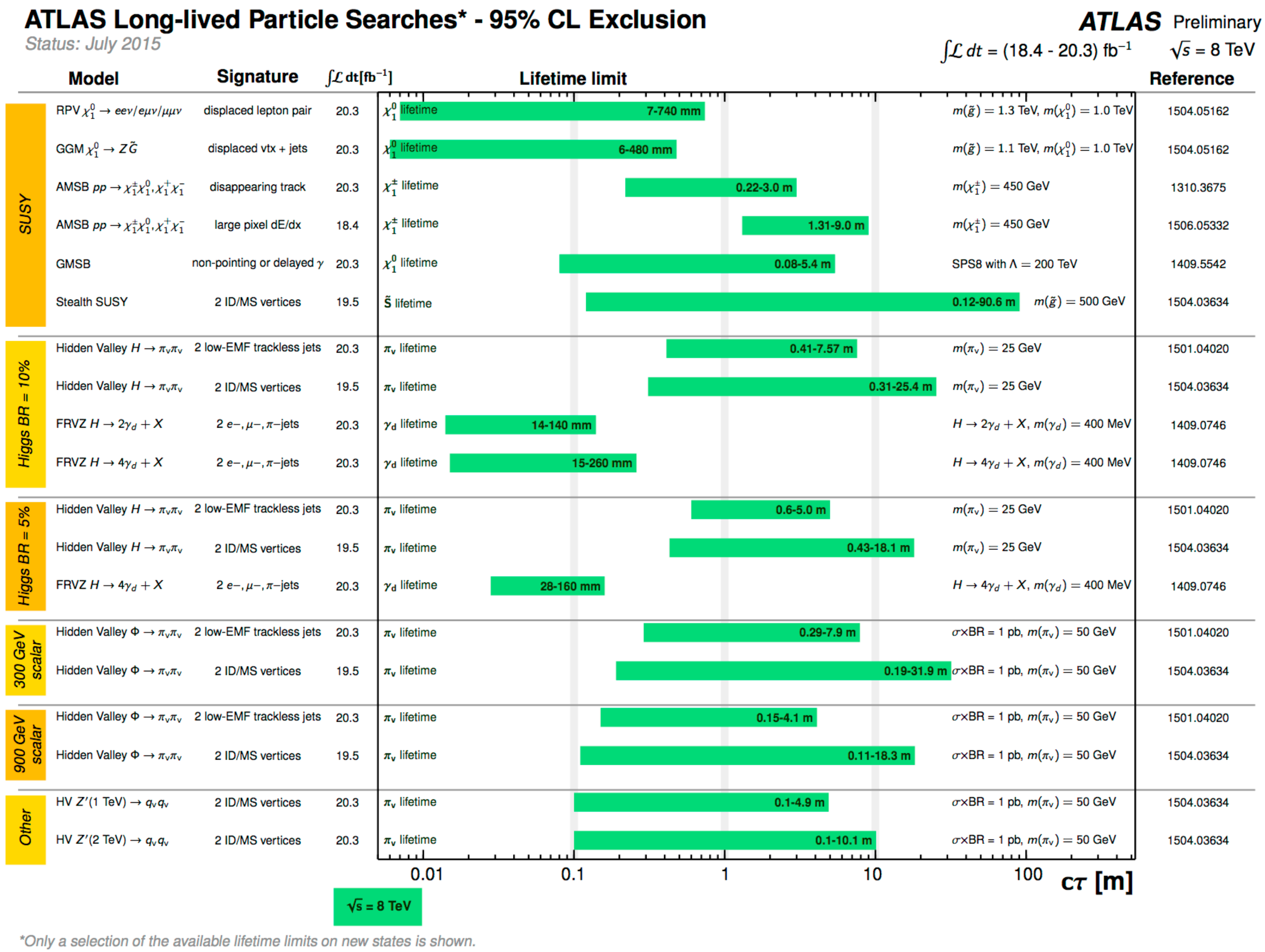


Exclusion limits in 300-1300 GeV range
Depending on the nature of the LLP

Phys. Rev. D 94 (2016) 112004

wide exploration of decay length

- ATLAS summary example

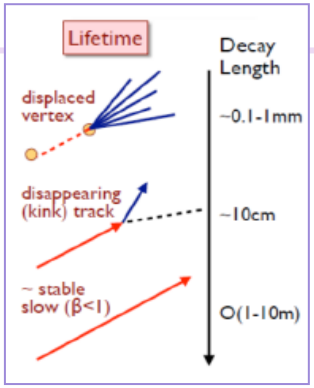


Long-lived

What makes a particle long-lived:

- small couplings: RPV decays, dark sector coupling
- small mass-splittings: almost degenerate next-LSP heavy messenger: Z', split SUSY
- hidden valley

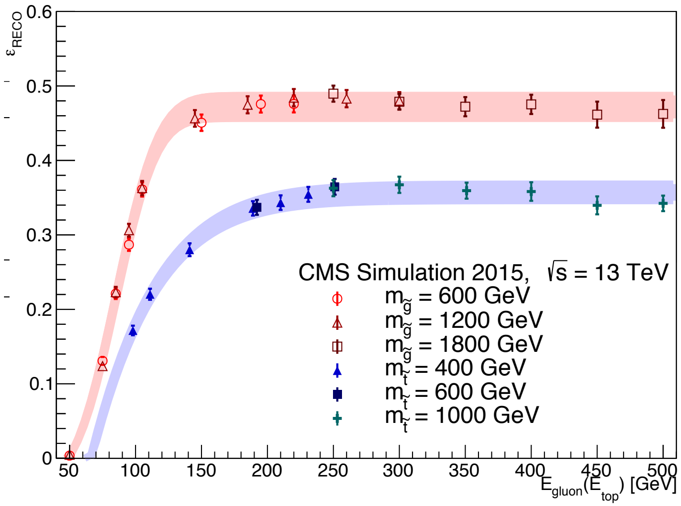
Signatures depend on the lifetime!



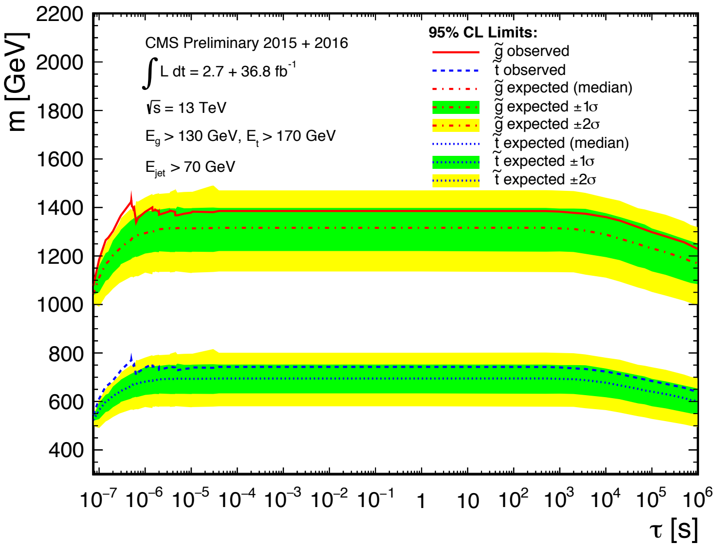
Stopped objects:

CMS-PAS-EXO-16-004

Search for LLP (gluinos, stops) that come to rest in the detector after losing kinetic energy
Signature will be a randomly-timed, large energy deposit in the calorimeter



Efficiency to stop in the detector

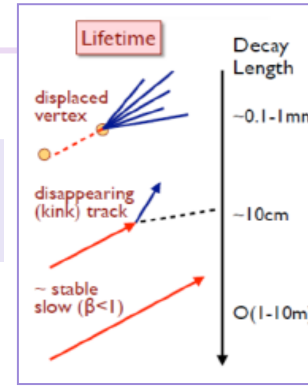


Long-lived

What makes a particle long-lived:

- small couplings: RPV decays, dark sector coupling
- small mass-splittings: almost degenerate next-LSP heavy messenger: Z', split SUSY
- hidden valley

Signatures depend on the lifetime!



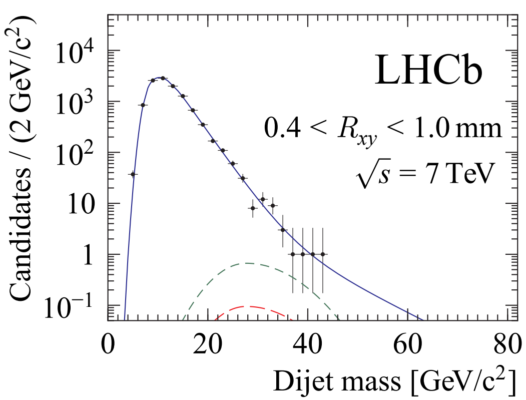
More on displaced Vertex (LHCb)

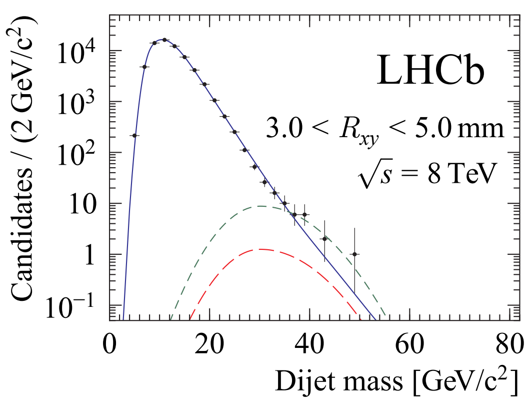
displaced vertex with two associated jets

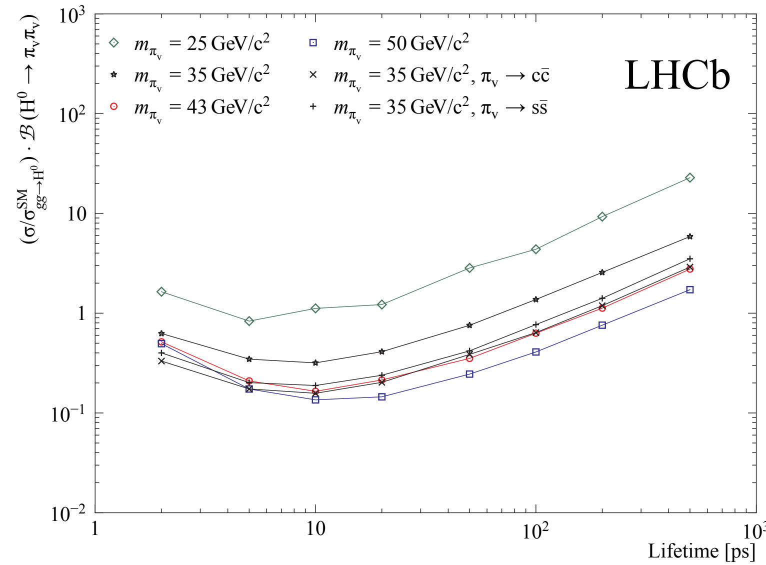
m(LLP): 25-50 GeV, τ_{LLP} ~ 2-500 ps

Assume an Higgs-boson like → 2 LLP

1705.07332







7 and 8 TeV data

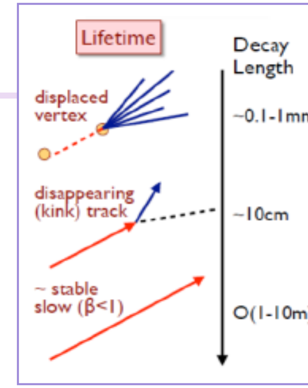
Complement ATLAS and CMS searches at low masses and lifetimes

Long-lived particles

What makes a particle long-lived:

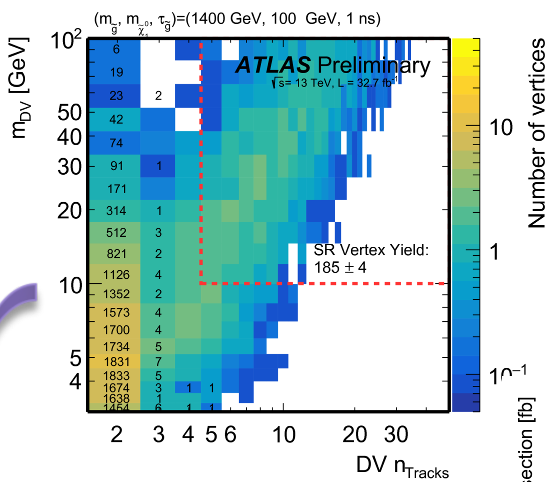
- small couplings: RPV decays, dark sector coupling
- small mass-splittings: almost degenerate next-LSP
  heavy messenger: Z', split SUSY
- hidden valley

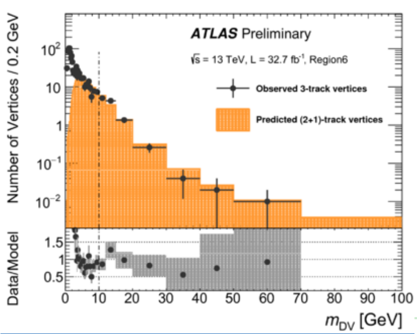
Signatures depend on the lifetime!



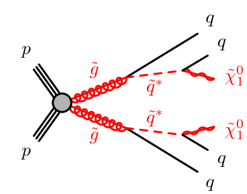
Displaced objects:

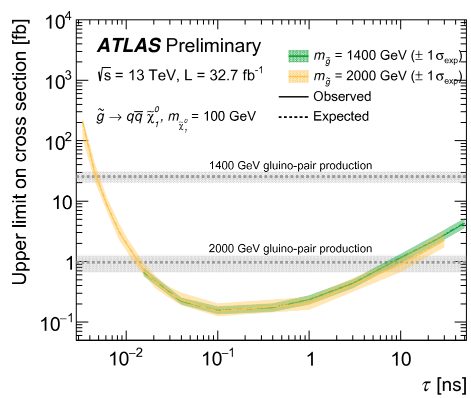
VERTEX





DV from LLP are massive.
E.g.: non-prompt gluinos

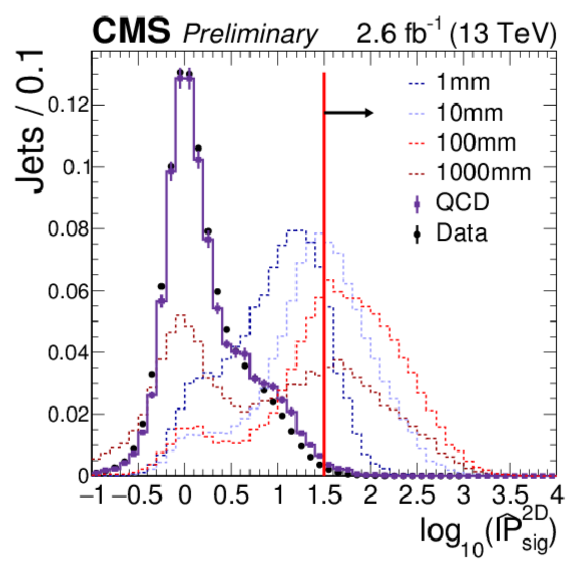




JETS

EXO-16-003

long-lived scalar neutral particles decaying to jets
Dedicated tagging algorithm to identify displaced jets



1 event obs. in one category

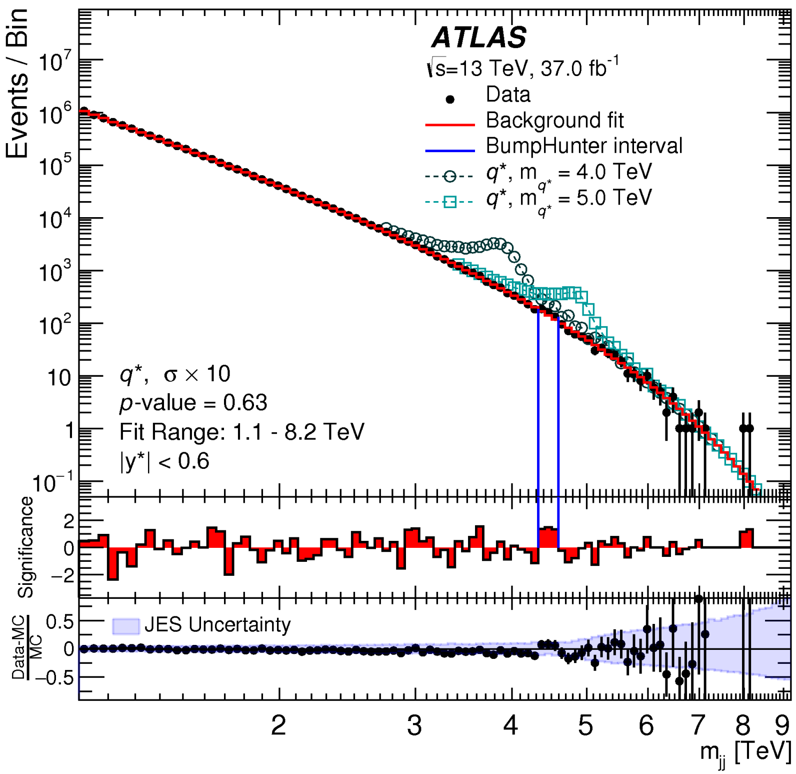
Not significant

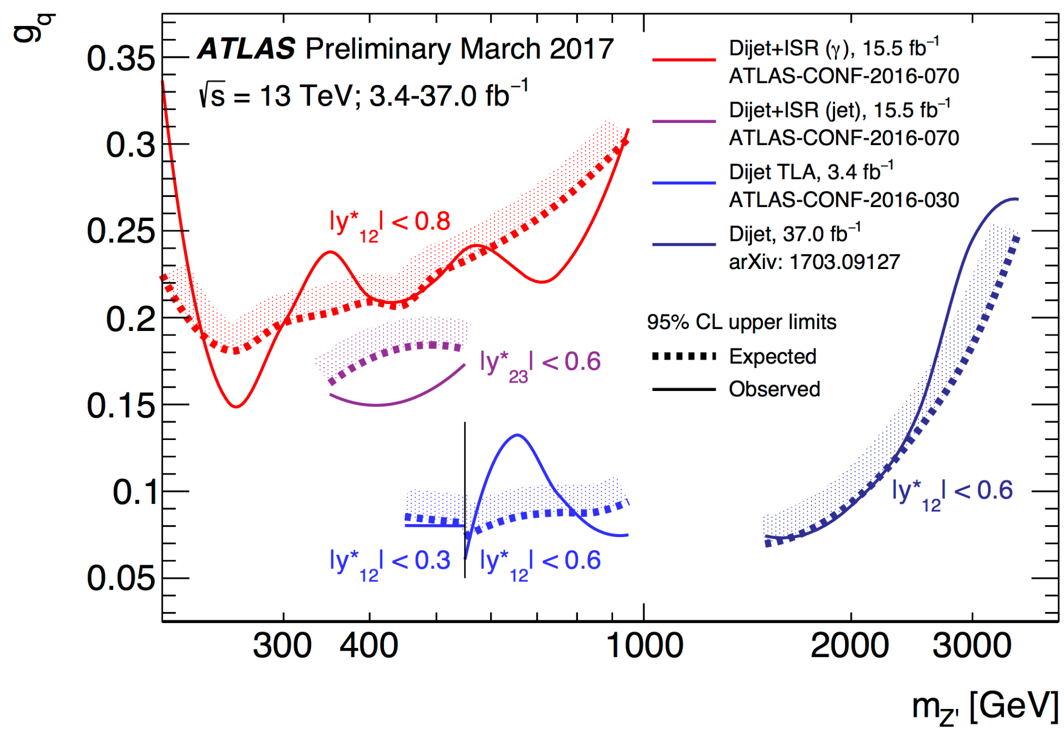
IP_{2D}^{sig}: significance of tracks' transverse impact parameter

Summary dijet searches

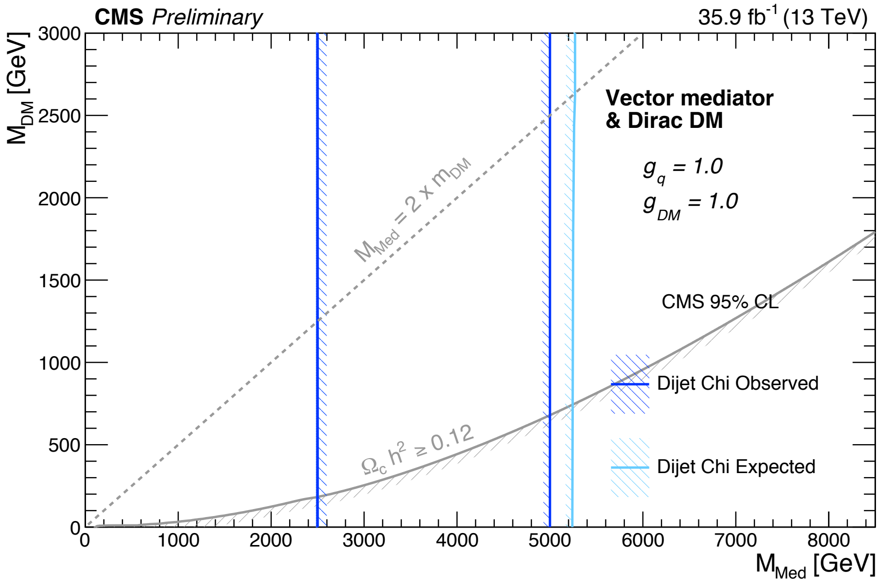
- Dijet searches sensitive to several BSM models
- Coupling-mediator mass plane from dijet searches using 2015+2016 data.

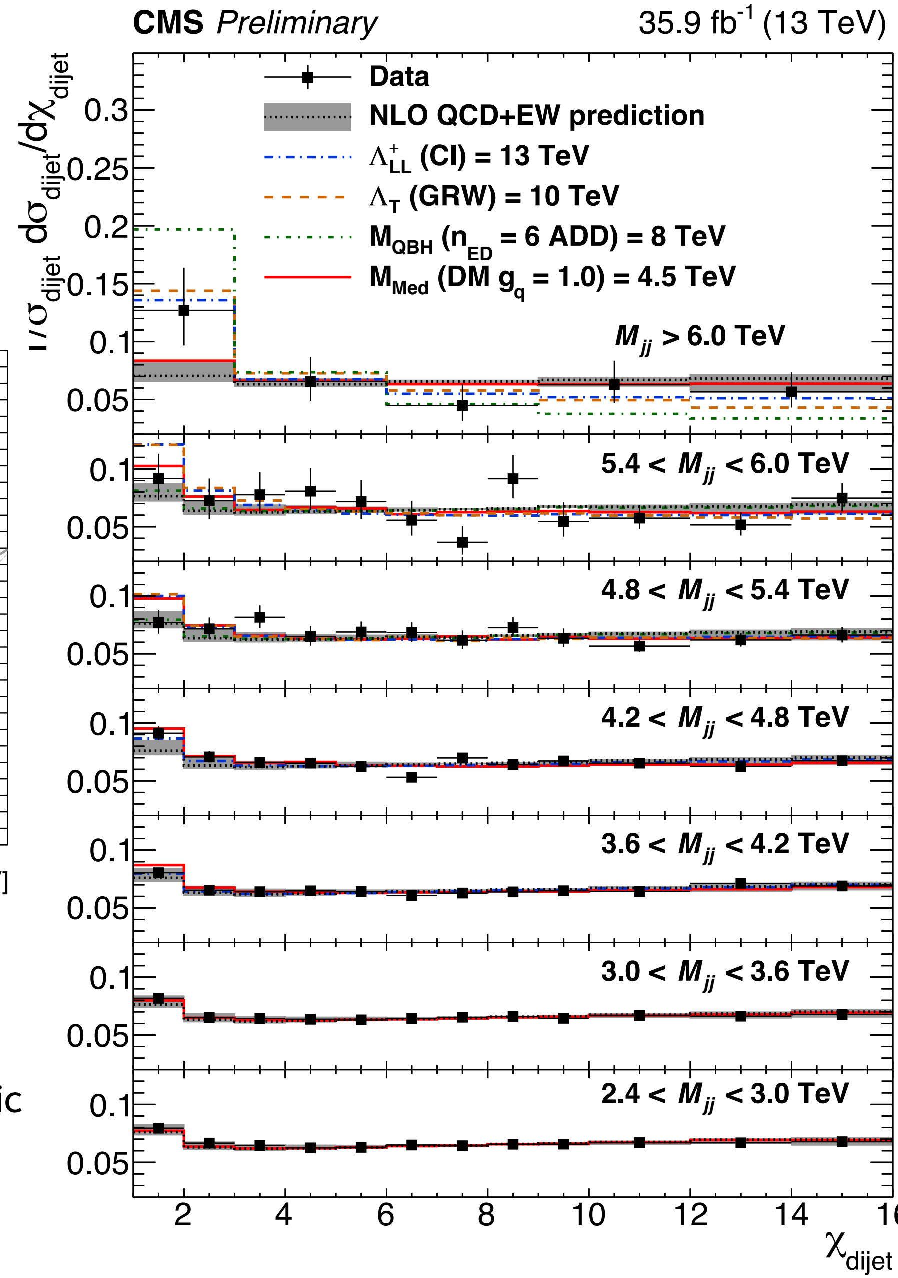
Model	95% CL exclusion limit	
	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV
Z' ($g_q = 0.1$)	2.1 TeV	2.1 TeV
Z' ($g_q = 0.2$)	2.9 TeV	3.3 TeV
Contact interaction ($\eta_{LL} = -1$)	21.8 TeV	28.3 TeV
Contact interaction ($\eta_{LL} = +1$)	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV





Angular correlations





DM mass vs. mediator mass:

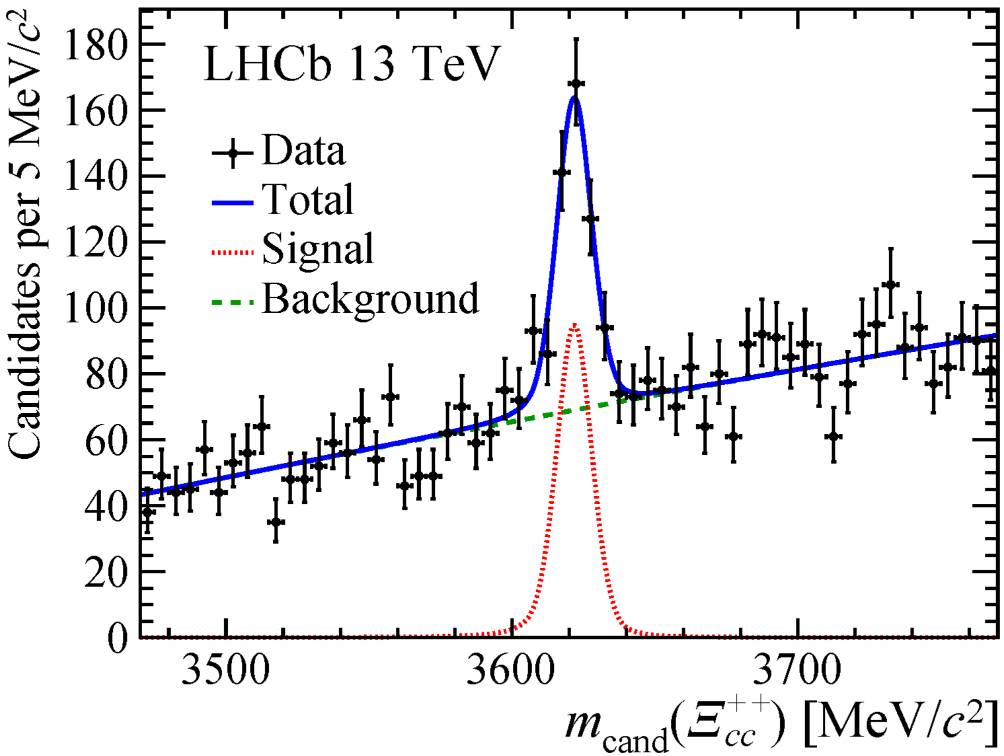
- vector mediator
- benchmark model with g_{DM} = 1.0 and g_q = 1.0
- compared to constraints from cosmological relic density of DM determined from astrophysical measurements and MADDM version 2.0.6

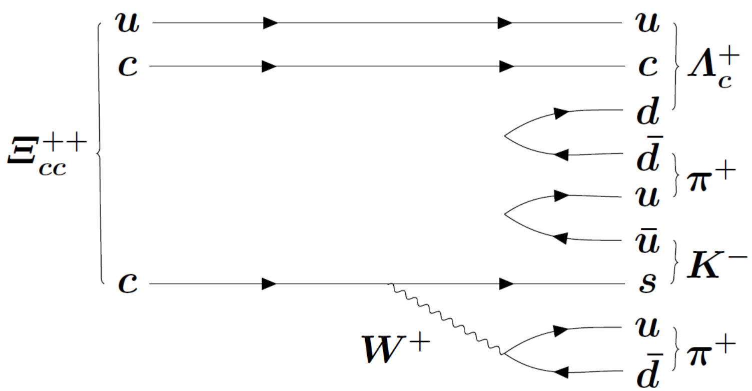
CMS-resonance / heavy-quark references

- qqqq: https://cds.cern.ch/record/2256663?ln=en
- 2l2nu: https://cds.cern.ch/record/2264700?ln=en
- VH: https://arxiv.org/abs/1707.01303
- 2l2q: https://cds.cern.ch/record/2242955?ln=en [partial 2016 statistics]
- lnuqq: https://cds.cern.ch/record/2205880?ln=en [partial 2016 statistics]
- HH (4b): https://cds.cern.ch/record/2264684?ln=en
- X53X53 (same-sign dileptons): https://cds.cern.ch/record/2256747?ln=en
- X53X53 (lepton+jets): https://cds.cern.ch/record/2264686?ln=en
- TT->WbWb: https://cds.cern.ch/record/2264685?ln=en
- single production: additional full 2016 result in the tZ channel: https://cds.cern.ch/record/2256762?ln=en

LHCb highlights

- Exceptionally charming particle: doubly charmed particle
  - Ξ_{cc}^{++}, a baryon





This discovery opens a new field of particle physics research.

→ An entire family of doubly charmed baryons related to the Ξ_{cc}^{++} is predicted!