

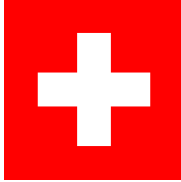
Physics Results from ATLAS and CMS

Tobias Golling, University of Geneva
CHIPP plenary, Kandersteg, July 01 2019



**UNIVERSITÉ
DE GENÈVE**

Disclaimer

- Apologies in advance for not being able to cover all Swiss highlights 
 - There are too many 😊
- Personal choice of topics & level of detail
- ATLAS = CMS

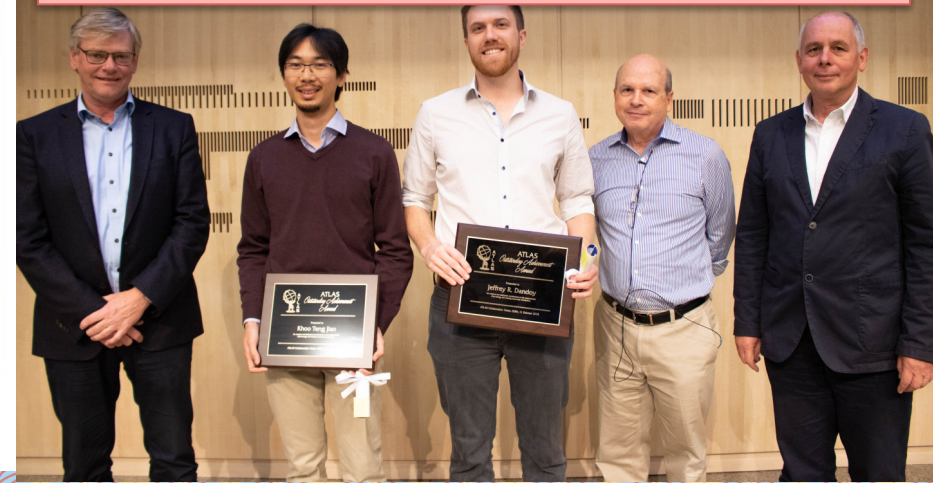
Overview

- Introduction
- Higgs
- SUSY
- Exotics

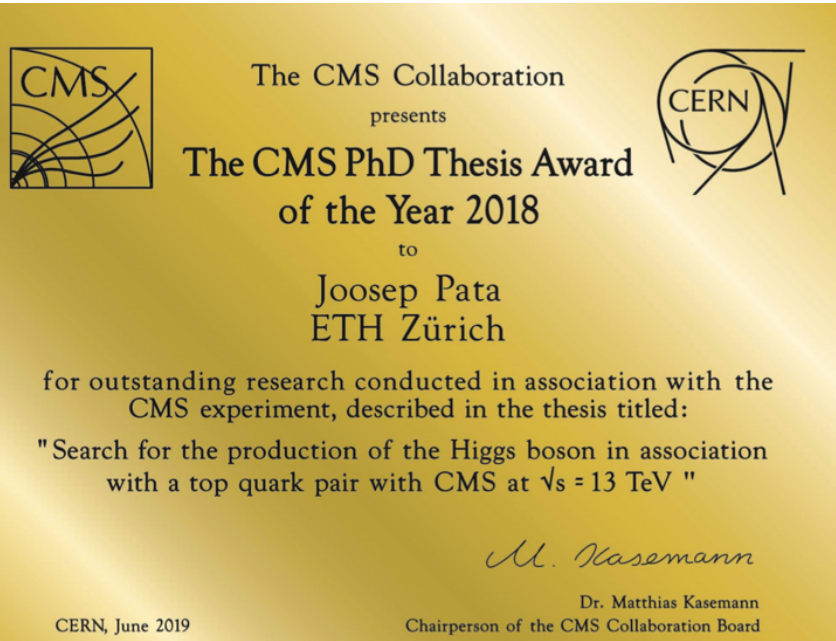
Student & young researcher recognition



TJ Khoo (University of Geneva)
2018 Outstanding Achievement Awards for creative and dedicated contributions to the measurement of jet energy and missing transverse momentum



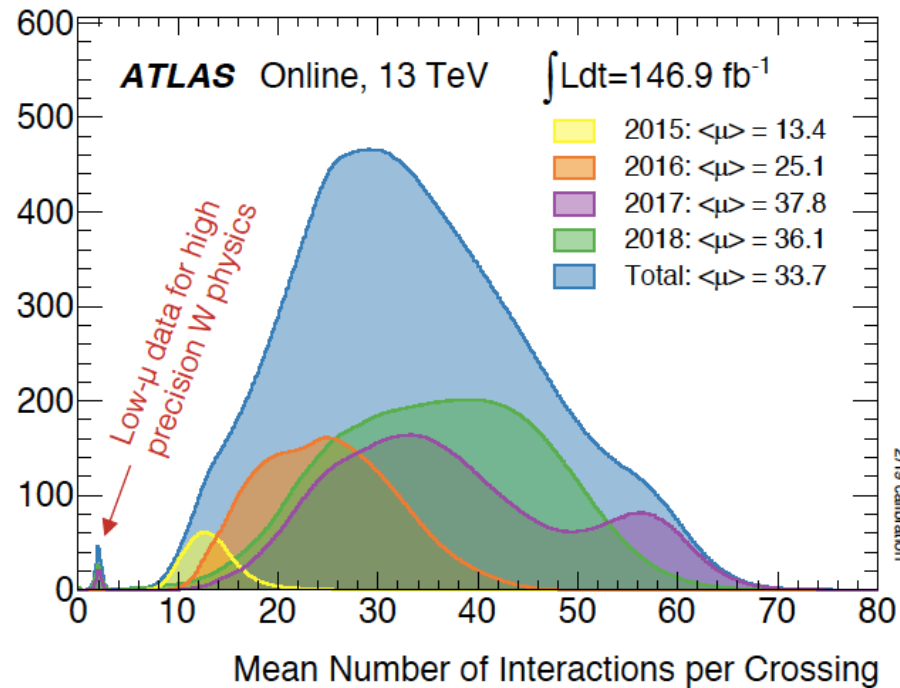
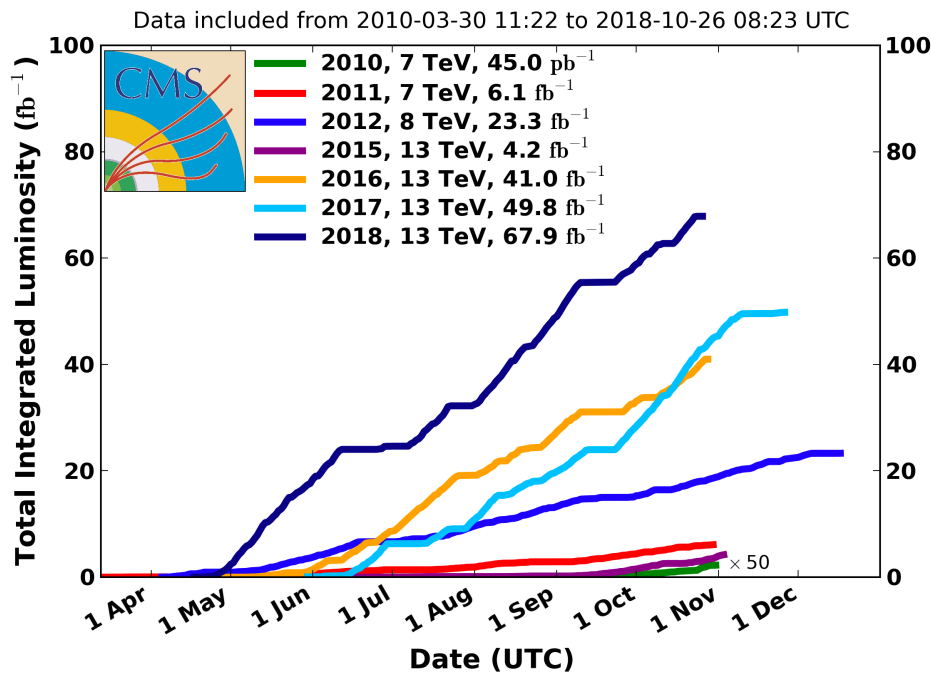
Dalila Salamani, 2ème prix du Jury, Faculté des Sciences



Excellent LHC & detector performance

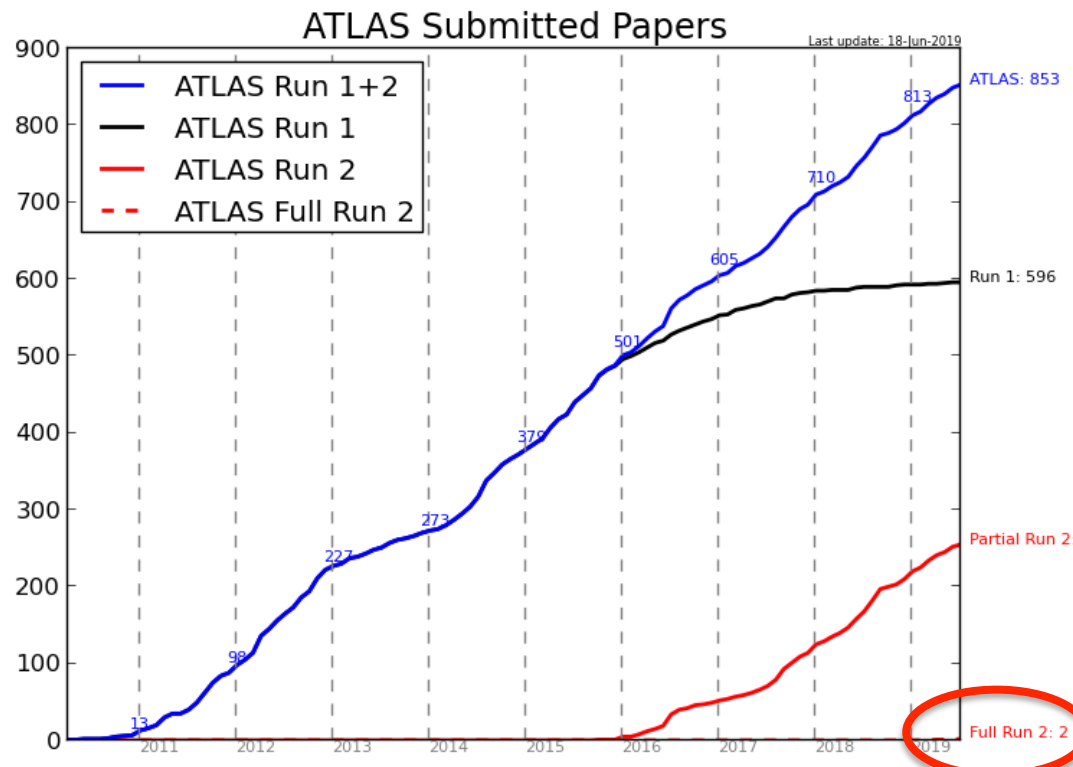
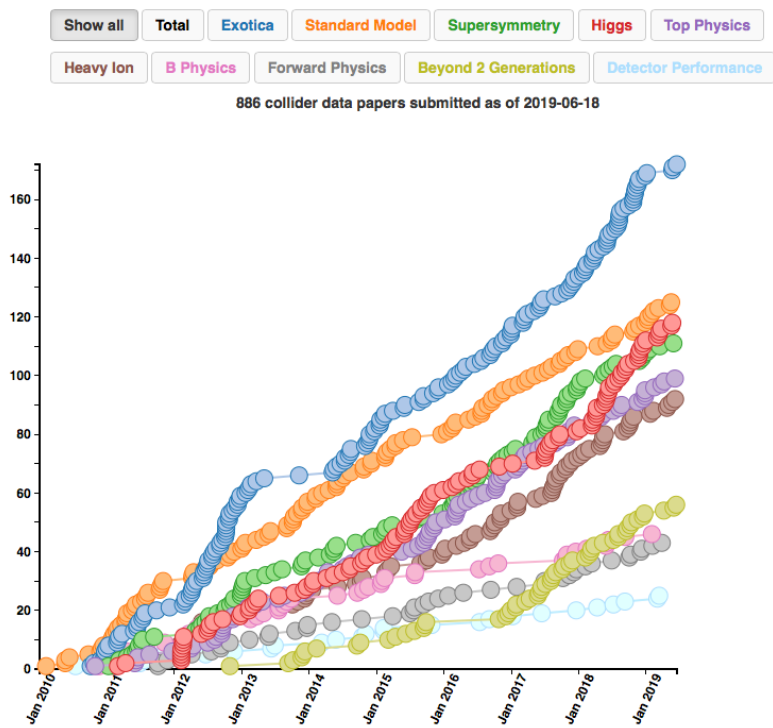
- ~94% recording efficiency
- ~95% efficiency (physics/recorded)
- Peak luminosity grazing $2 \cdot 10^{34}$ Hz/cm²

CMS Integrated Luminosity Delivered, pp



Close to 900 papers submitted each

- Most full-Run-2 papers still in preparation



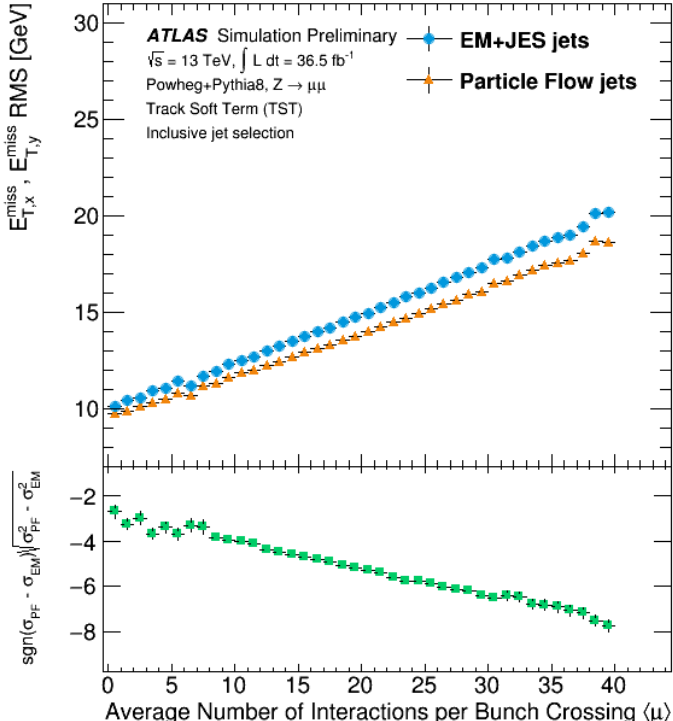
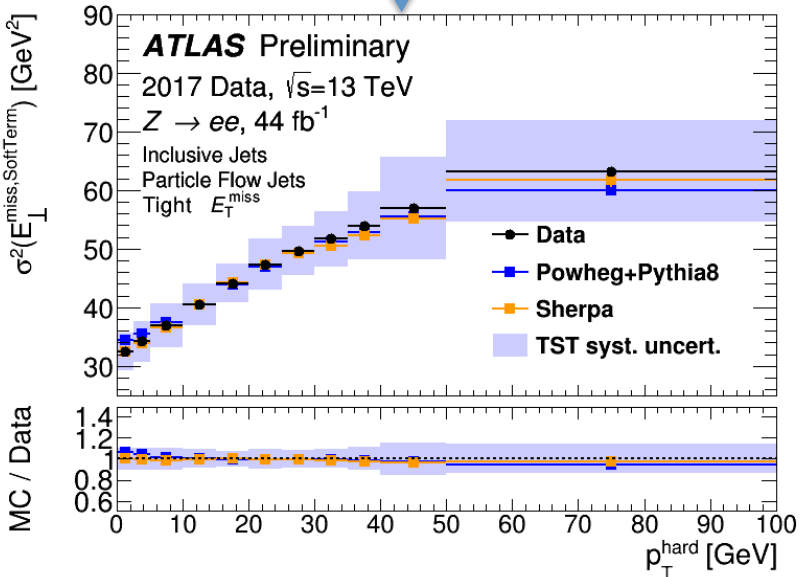
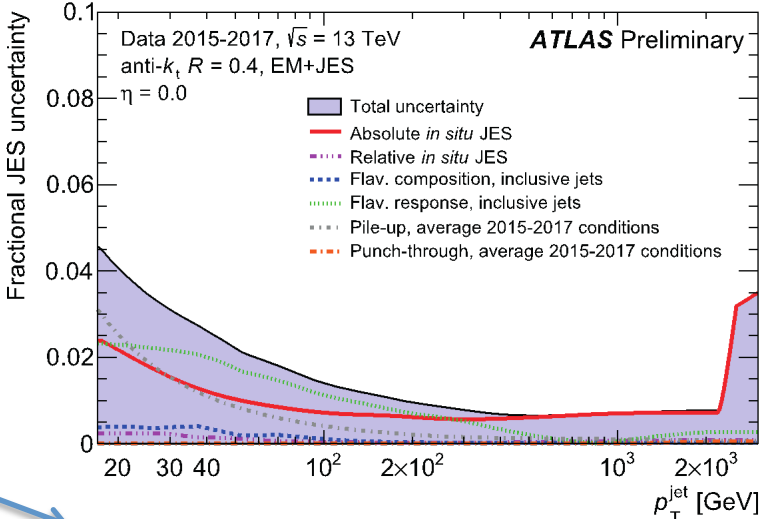
II and Inu resonance searches

Constantly improving understanding of data

1802.08168,
 1703.10485,
 ATLAS-CONF-2018-038,
 ATLAS-CONF-2018-023



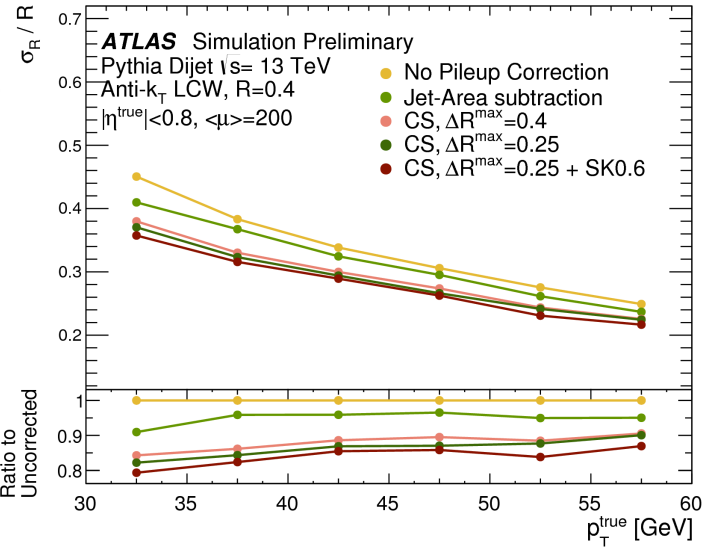
- σ_{JES} at 1%-level
- Particle flow hadronic reconstruction
 - Significantly improves low p_T jets & MET



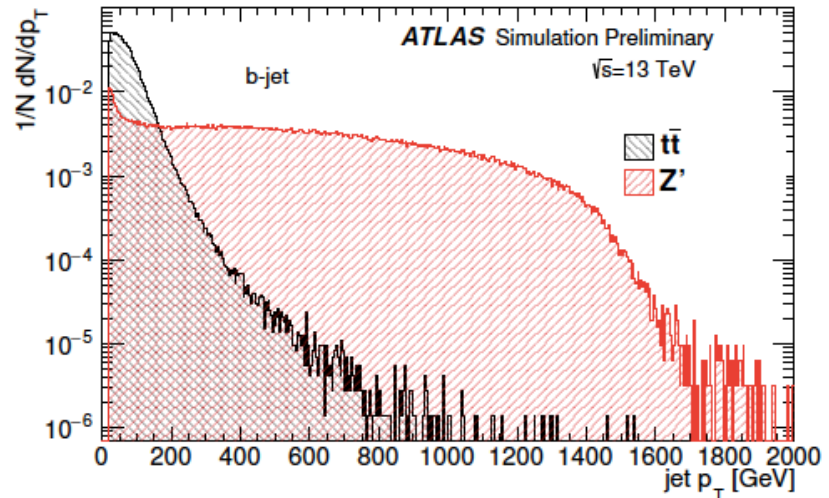
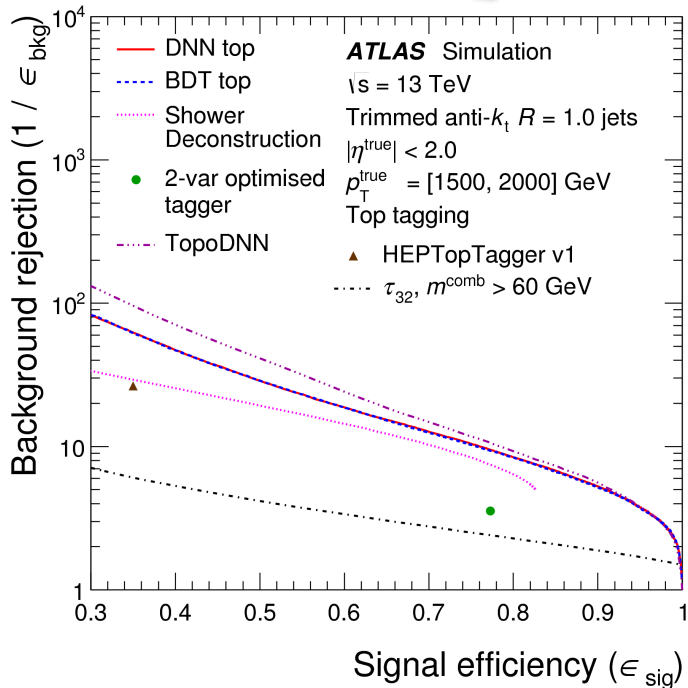
Constantly improving understanding of data



- Constituent-based pile-up suppression
- Object-based MET significance
- Tau reconstruction [1809.02816]
- Deep Learning based multi-class DL1 flavour tagging [ATL-PHYS-PUB-2017-013]
- DNN boosted tagging [1808.07858]

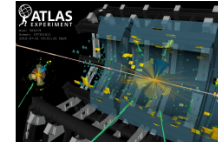
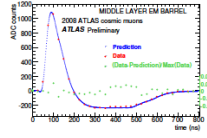
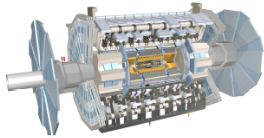
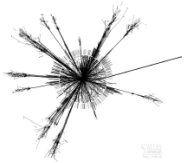


Development of **new training sample** that populates high p_T



Large-scale and high-fidelity simulation

ATL-SOFT-PUB-2018-001



Event generation

Detector simulation

Digitization

Reco.

Physics analysis

Bottleneck!

Group Production MC Reconstruction

Data Processing

Analysis

T0 Processing

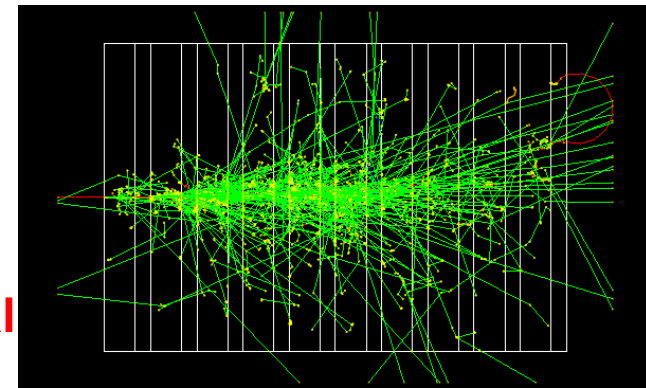
Others

MC Simulation

FastCaloSim not accurate enough for all simulation needs

**Generative models:
GAN, VAE (Variational
Autoencoder)**

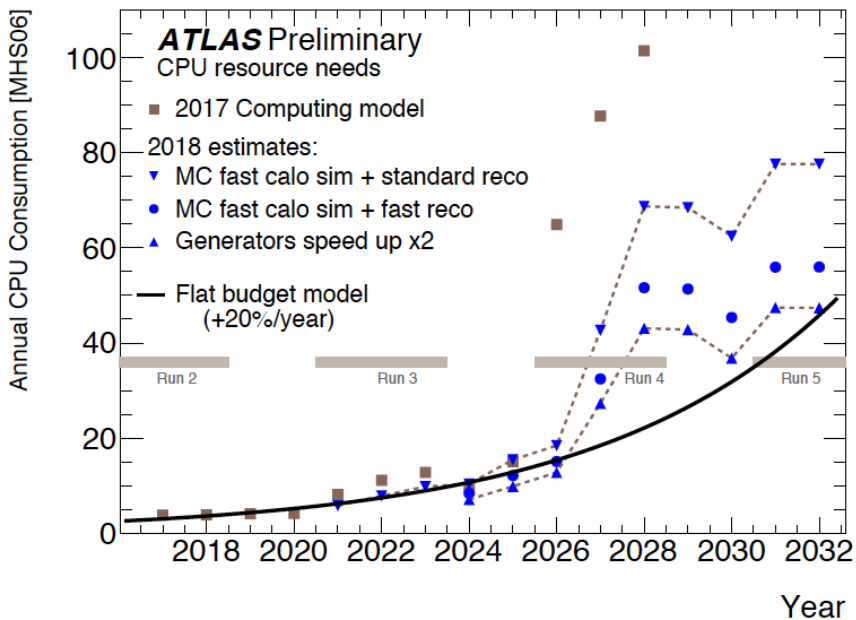
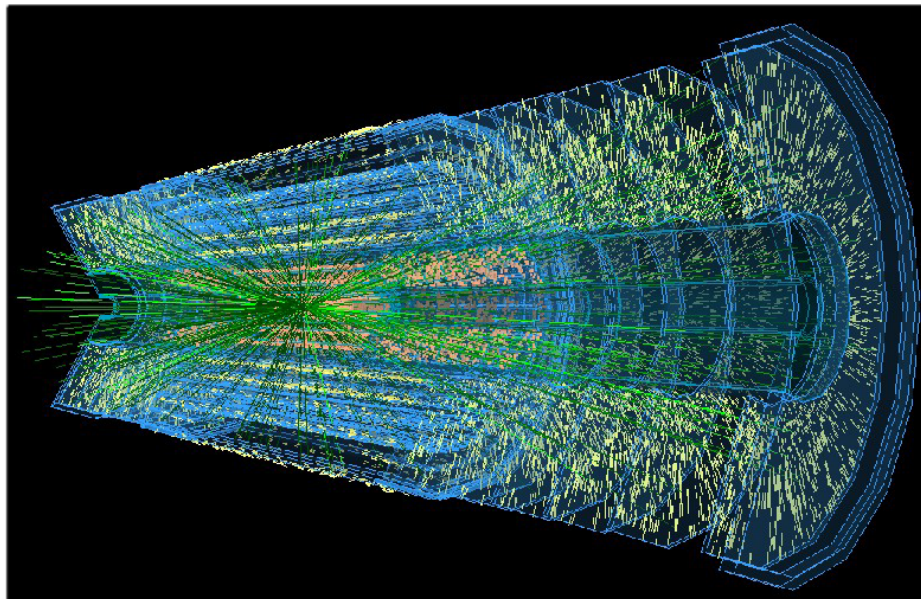
Dominated by Geant shower simulation!



2026: High-Lumi-LHC tracking crisis



100'000 space-points
10'000 tracks



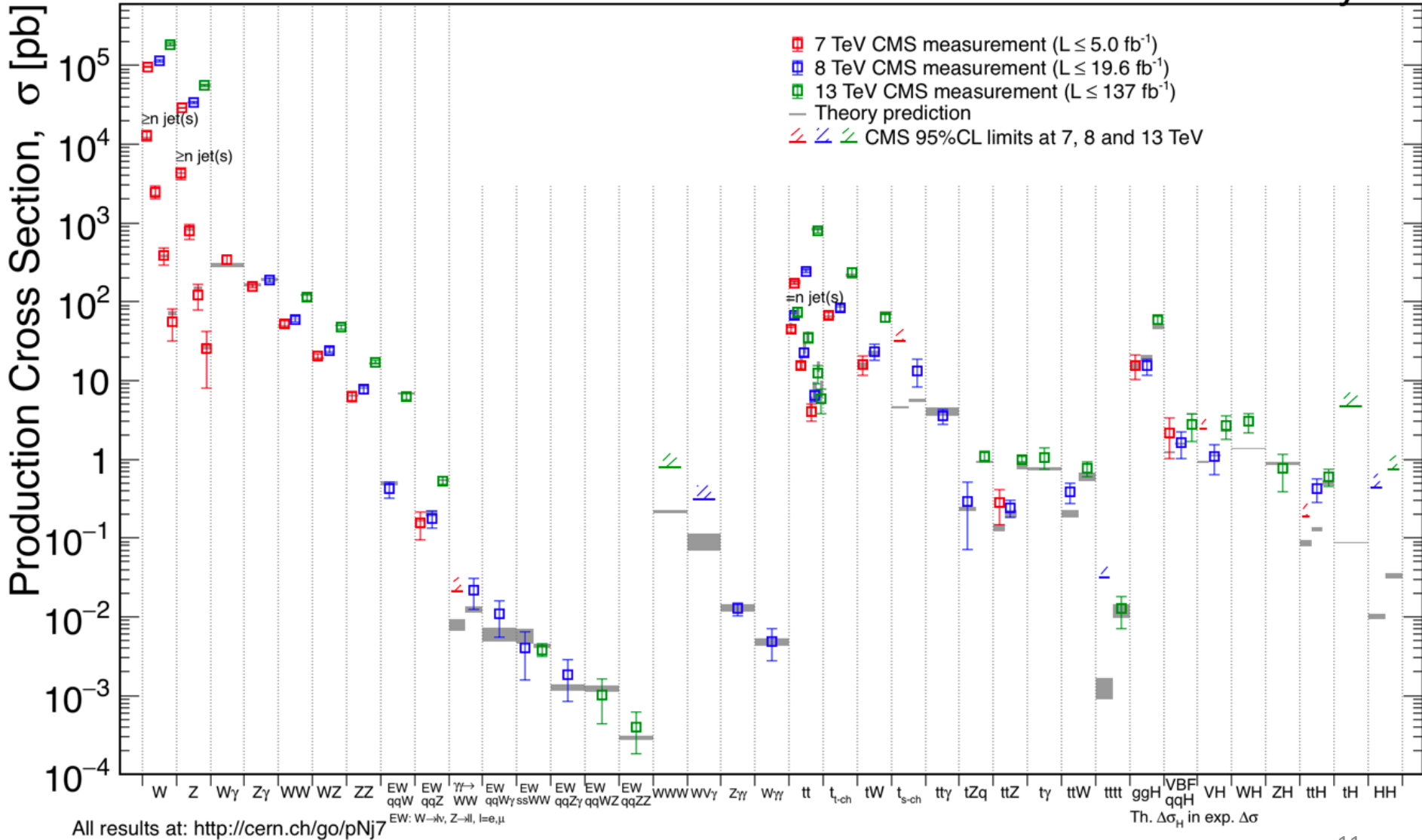
Current algorithm:
combinatorial approach = slow!

Reconstruction limited by tracking

SM works

March 2019

CMS Preliminary



Higgs

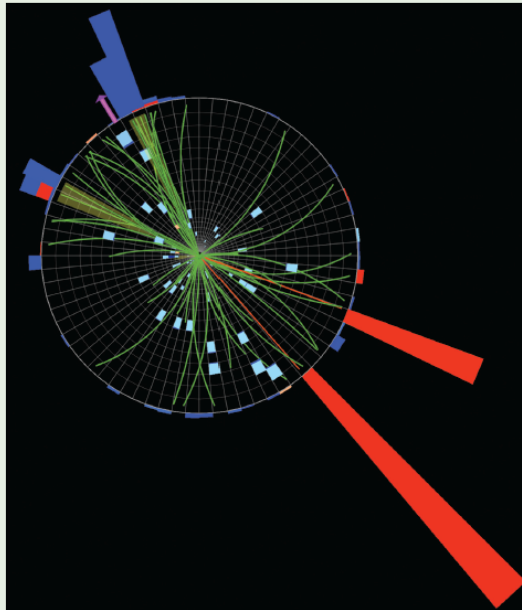


121

PHYSICAL REVIEW LETTERS

Articles published week ending 21 SEPTEMBER 2018

PRL 121 (12), 120401–129902, 21 September 2018 (332 total pages)



12

Published by
American Physical Society

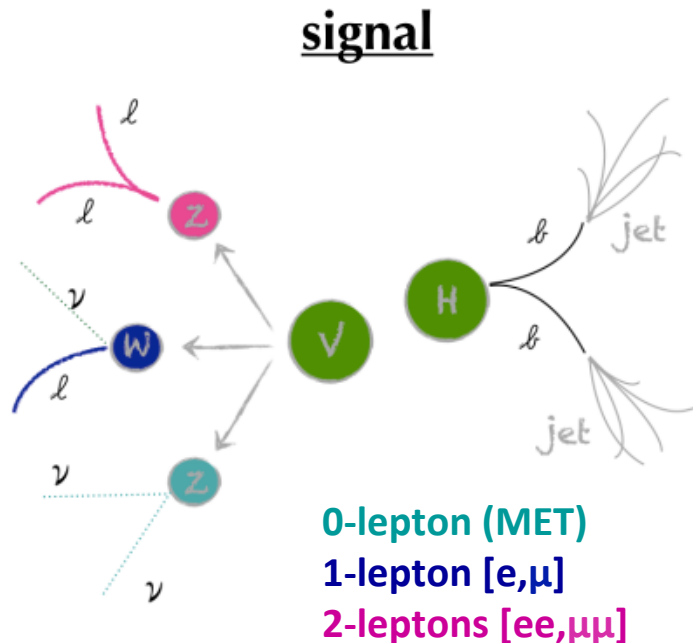


Volume 121, Number 12



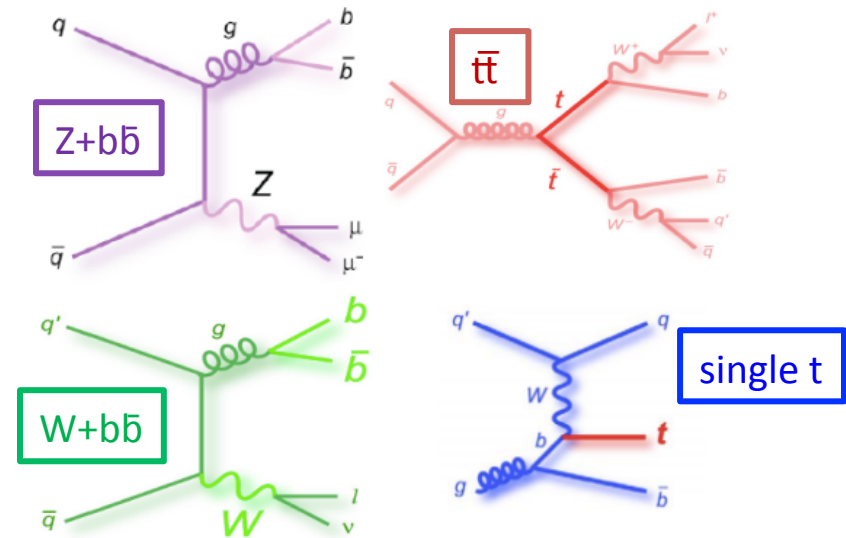
VH(bb): Analysis strategy

- Exploit associated VH kinematics for BG reduction
- Use 3 channels: 0, 1, and 2 leptons
- Large boost for vector boson
- Multivariate analysis: m_{bb} , ΔR_{bb} , b-tag
- Simultaneous fit of signal and control regions



irreducible backgrounds VZ

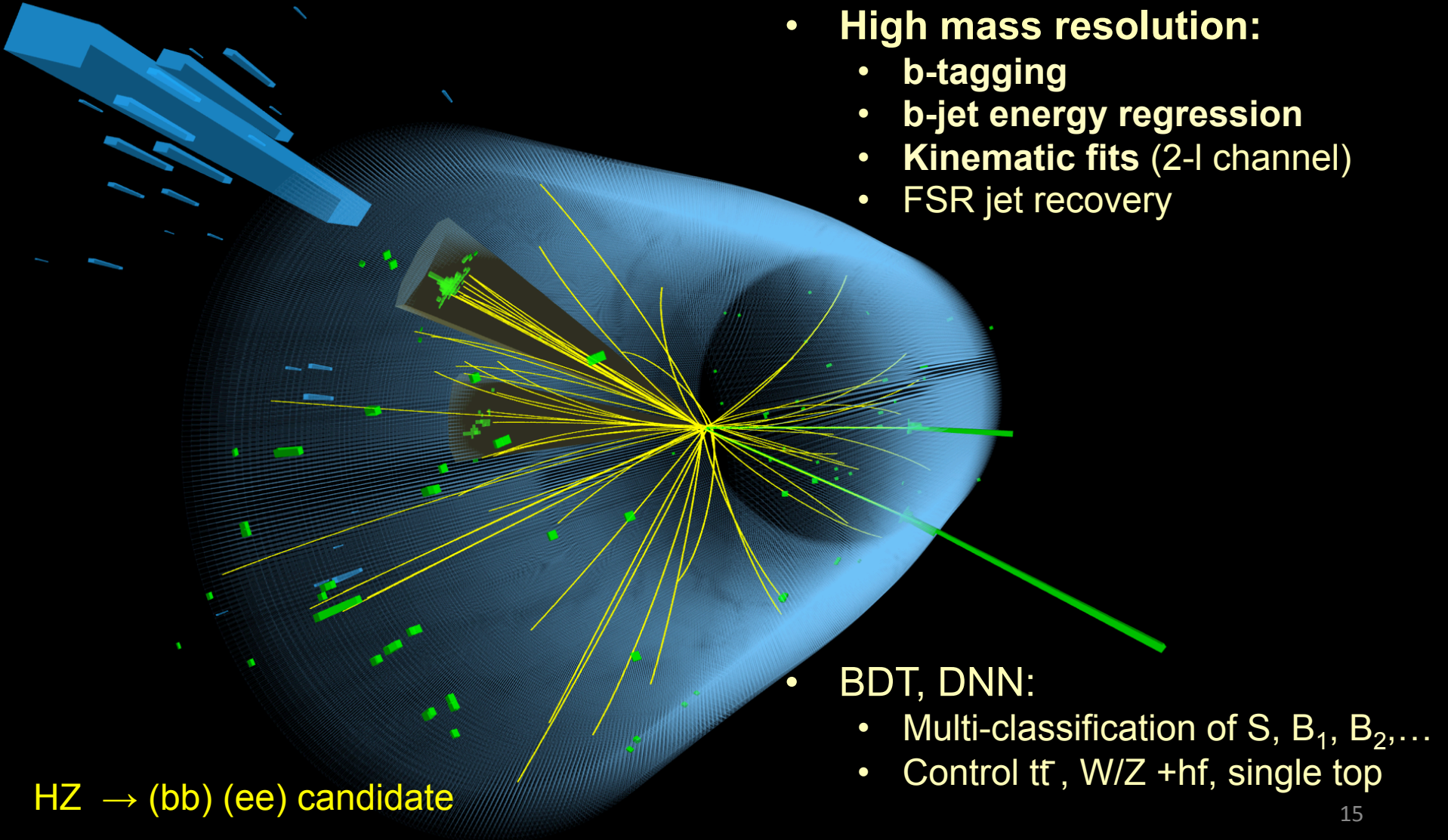
reducible backgrounds



normalization from data, shapes from MC₁₄



VH(bb) main features



- **High mass resolution:**
 - **b-tagging**
 - **b-jet energy regression**
 - **Kinematic fits (2-l channel)**
 - **FSR jet recovery**
- **BDT, DNN:**
 - **Multi-classification of S, B₁, B₂,...**
 - **Control tt, W/Z +hf, single top**

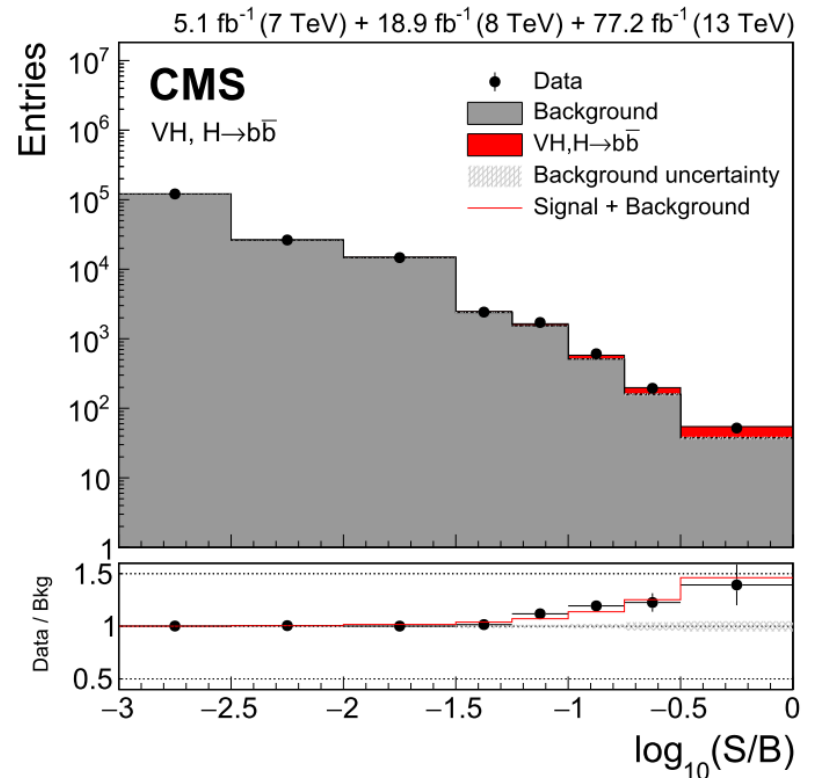
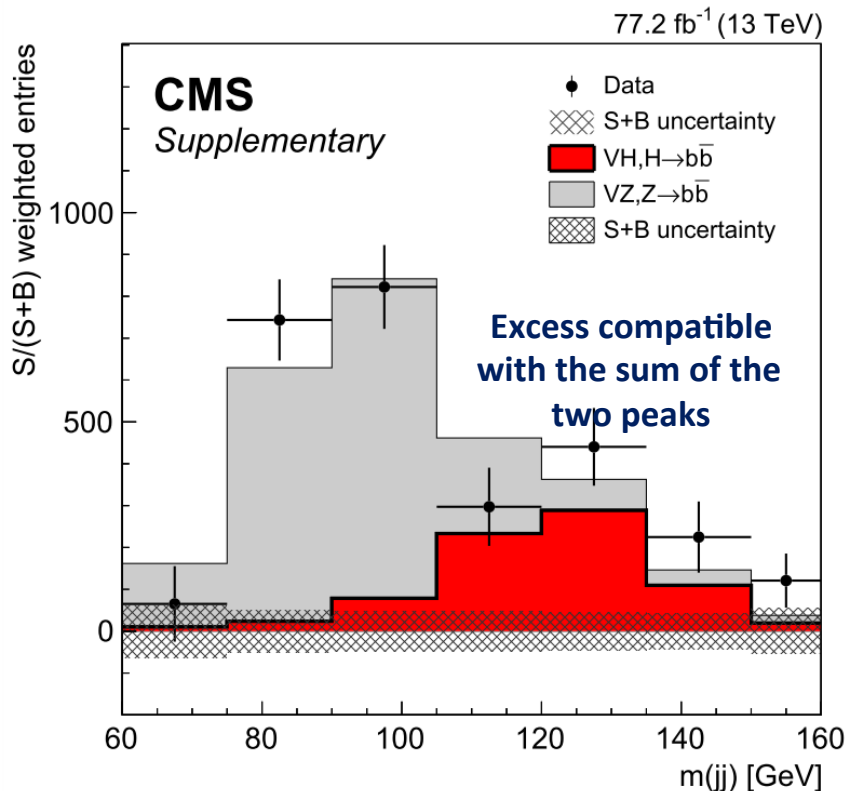
HZ → (bb) (ee) candidate



H → bb results

- **Fit to the $m(jj)$:** lower sensitivity but direct visualization of the Higgs boson signal

- **MVA / VH(bb) Combination**



Started looking for VH(cc), but still two orders of magnitude away from SM [1802.04329]

ttH(\rightarrow bb) & ttbb background

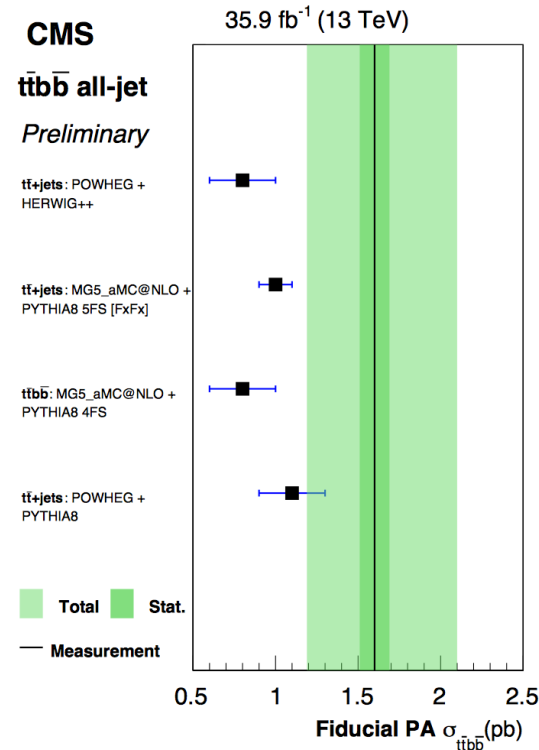
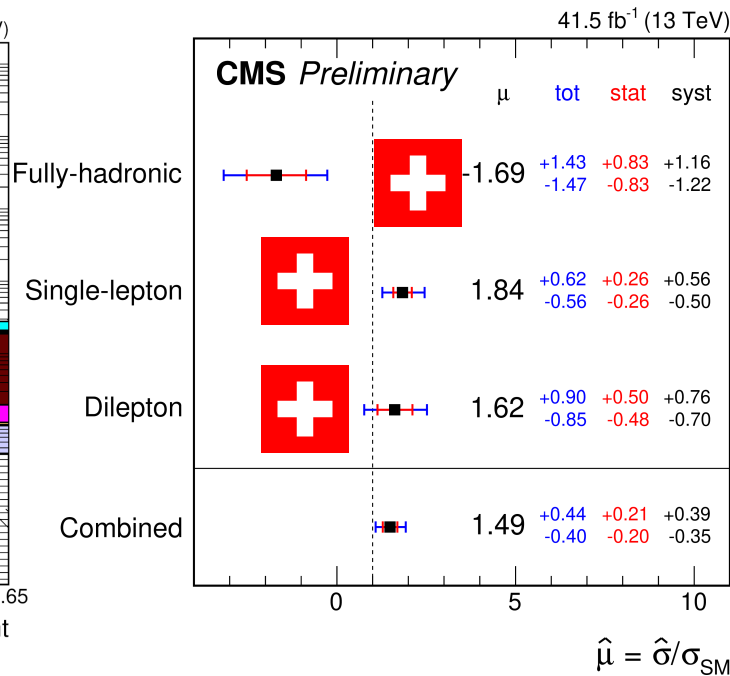
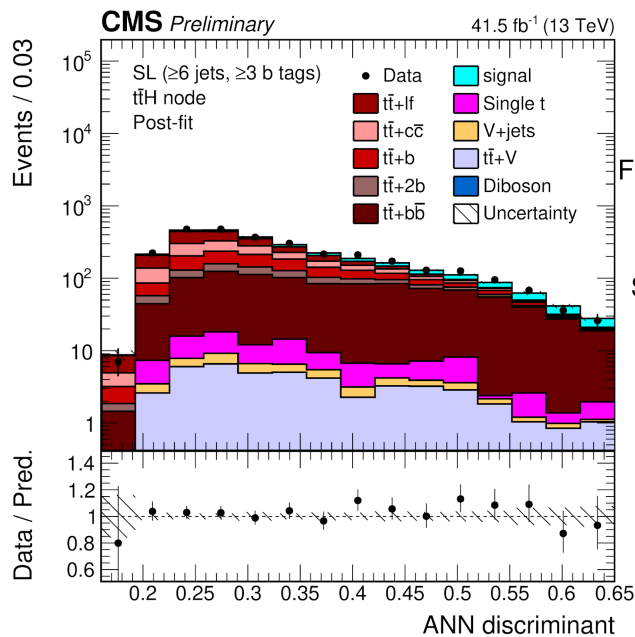
CMS-PAS-HIG-18-030
 CMS-PAS-TOP-18-011

Evidence of $H \rightarrow bb$ through ttH

Use NN & BDT for multi-classification, dedicated MEM as input

- ttbb largest BG – dedicated measurement

Single Lepton example

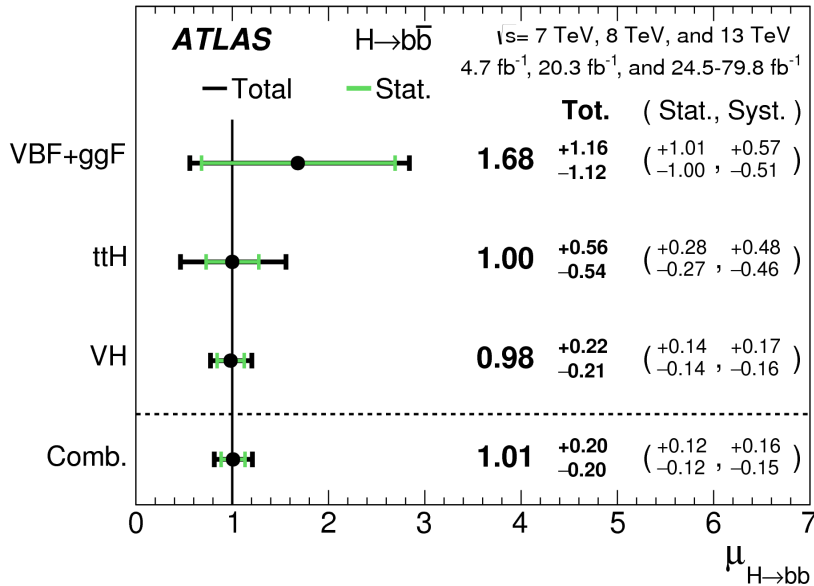


Observation of $H \rightarrow b\bar{b}$ in CMS & ATLAS



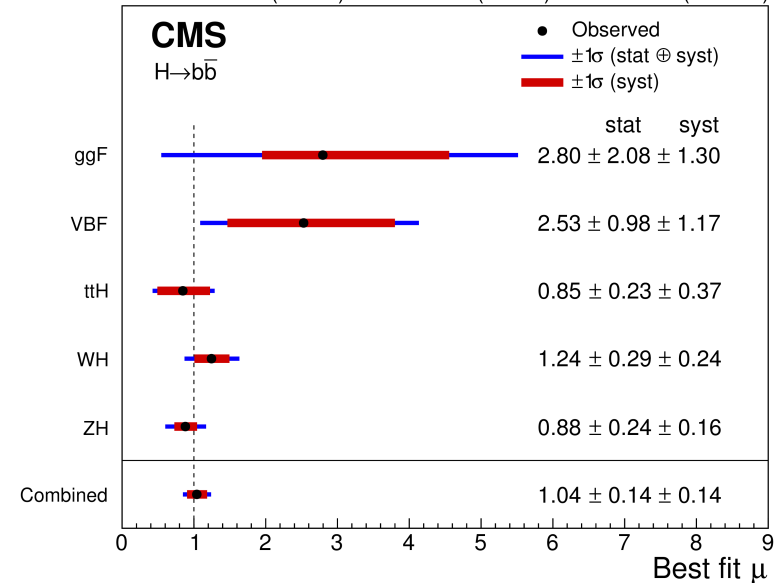
- Run-1 and Run-2 (15,16,17) combined: VBF, ggF, ttH, VH
- Theory uncertainties are correlated between all processes and data sets

Phys. Lett. B 786 (2018) 59



Phys. Rev. Lett. 121 (2018) 121801

$\leq 5.1 \text{ fb}^{-1} (7 \text{ TeV}) + \leq 19.8 \text{ fb}^{-1} (8 \text{ TeV}) + \leq 77.2 \text{ fb}^{-1} (13 \text{ TeV})$

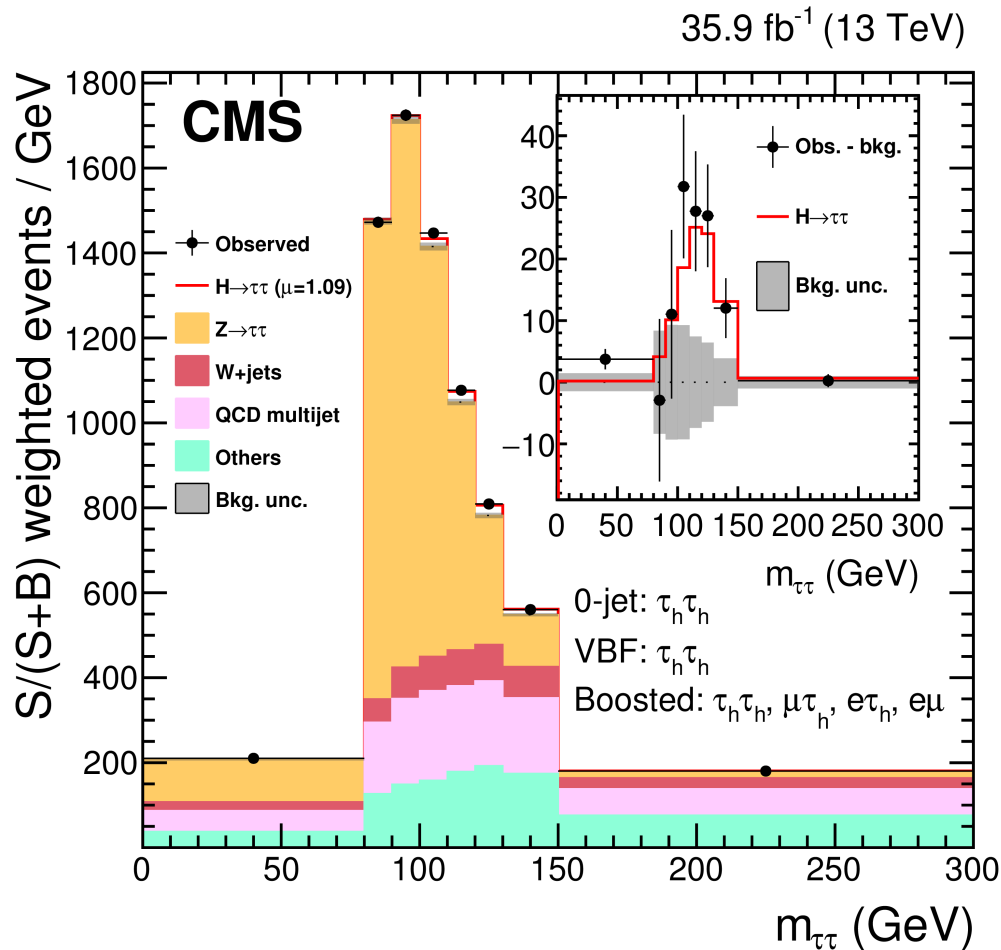


Run 1+2	Obs (exp) significance	$\mu(H \rightarrow b\bar{b})$
ATLAS	5.4 (5.5) σ	$1.01 \pm 0.12(stat.)$ $+0.16$ -0.15 (syst.)
CMS	5.6 (5.5) σ	$1.04 \pm 0.14(stat.) \pm 0.14(syst.)$

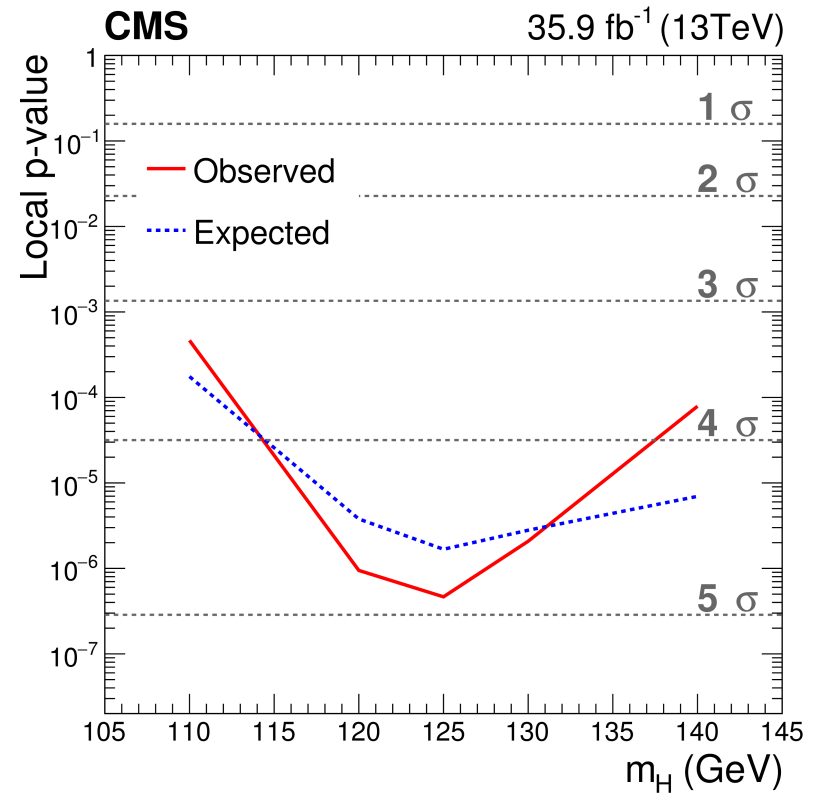


H → ττ observation

1708.00373

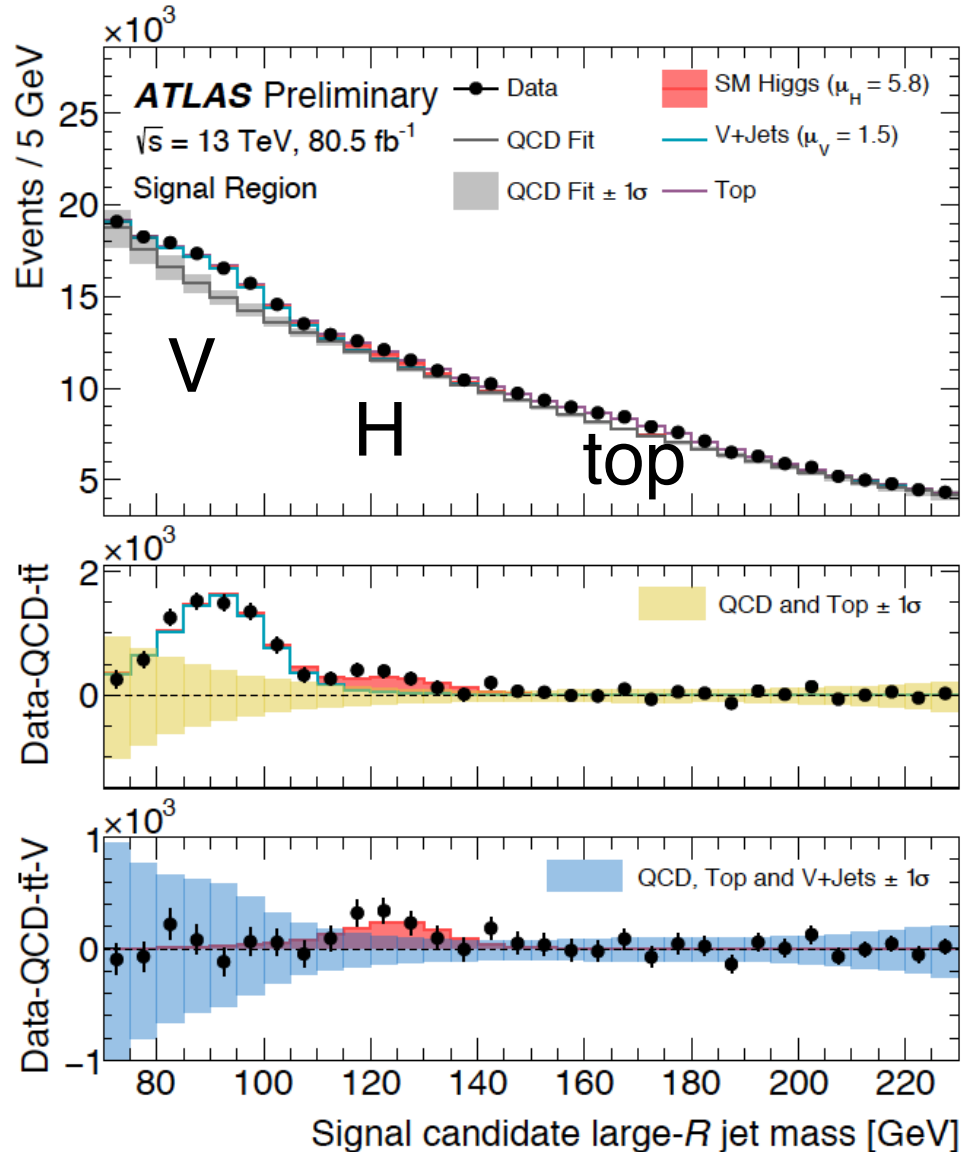


5.9σ in combination with Run 1

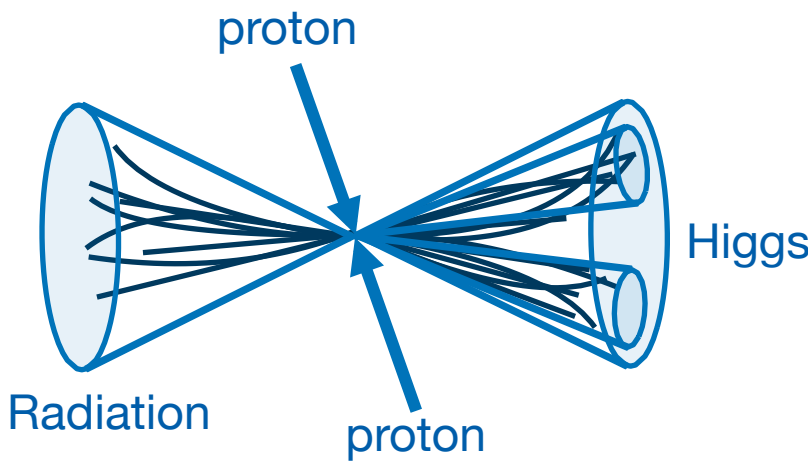


Boosted H(bb) in gluon-gluon-fusion

ATLAS-CONF-2018-052



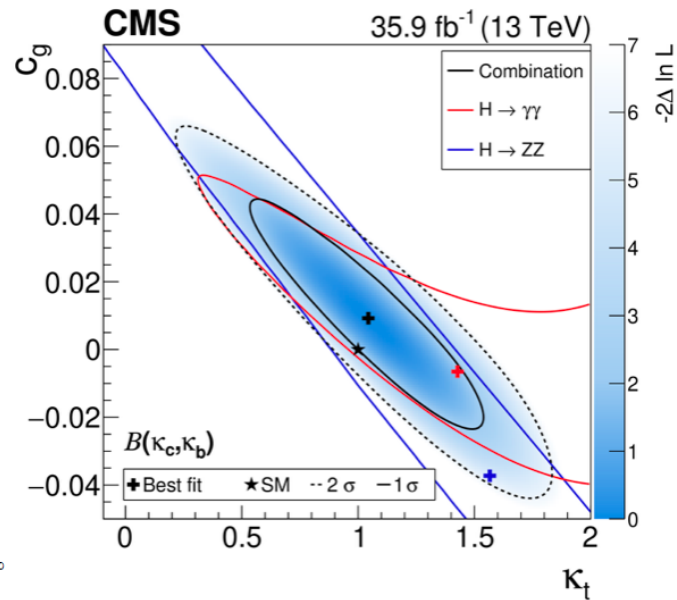
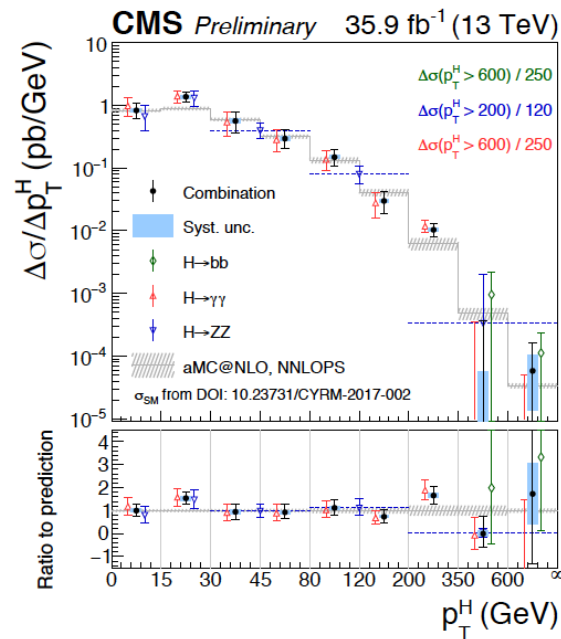
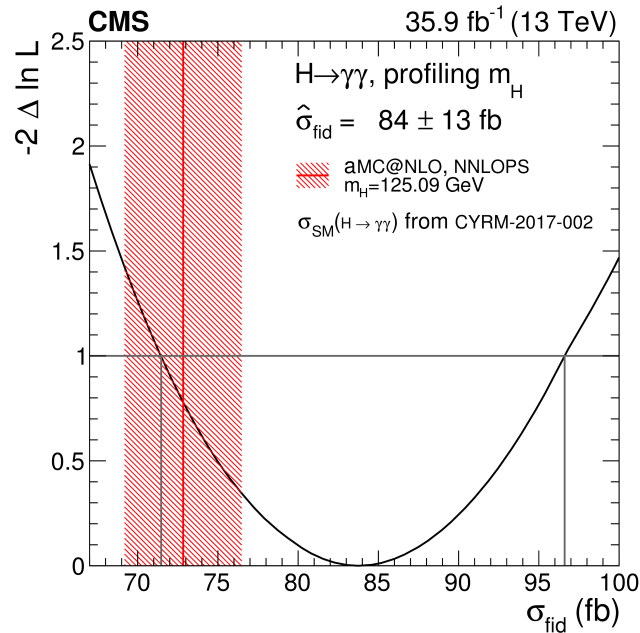
- High momentum transfer very sensitive to new physics effects
- Directly probe top and b-quark Yukawa coupling



$H \rightarrow \gamma\gamma$ fiducial & differential XS

1807.03825
1812.06504

- ML to tune MC to data
- Combine with $H \rightarrow ZZ$ and boosted $gg \rightarrow Hbb$ to constrain couplings



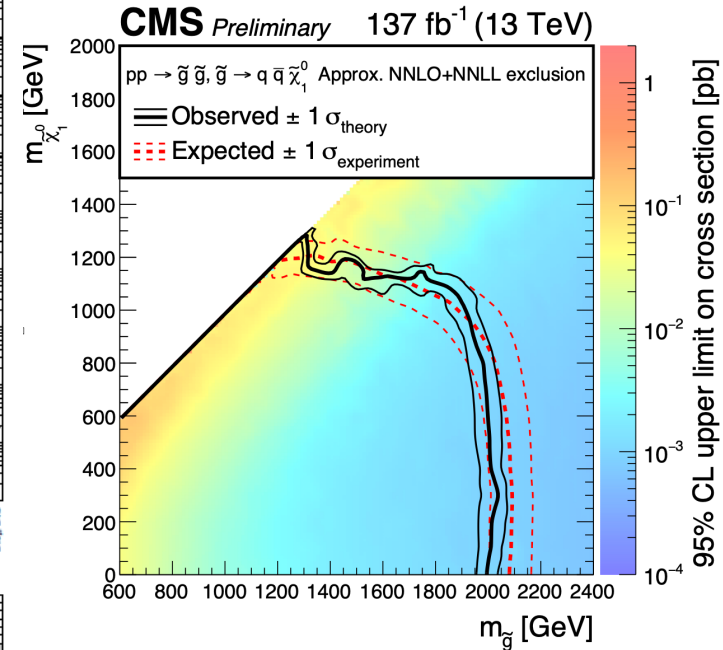
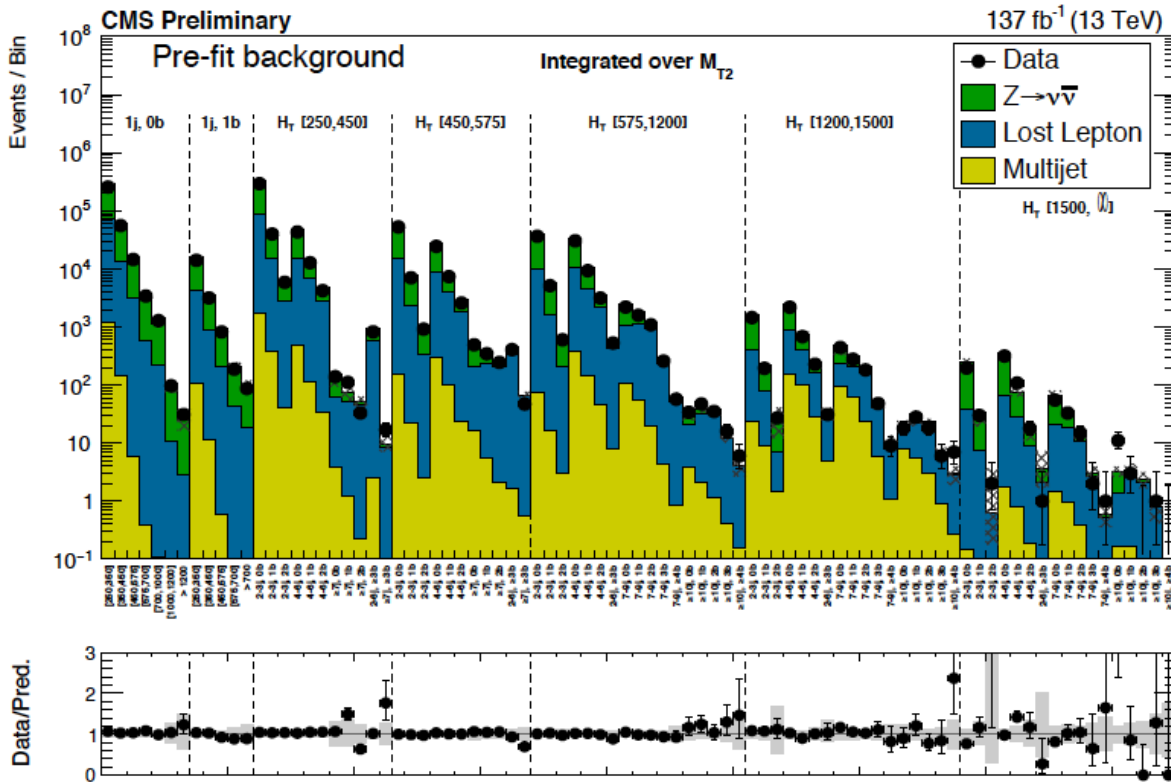
SUSY



Inclusive M_{T2} search

CMS-PAS-SUS-19-005

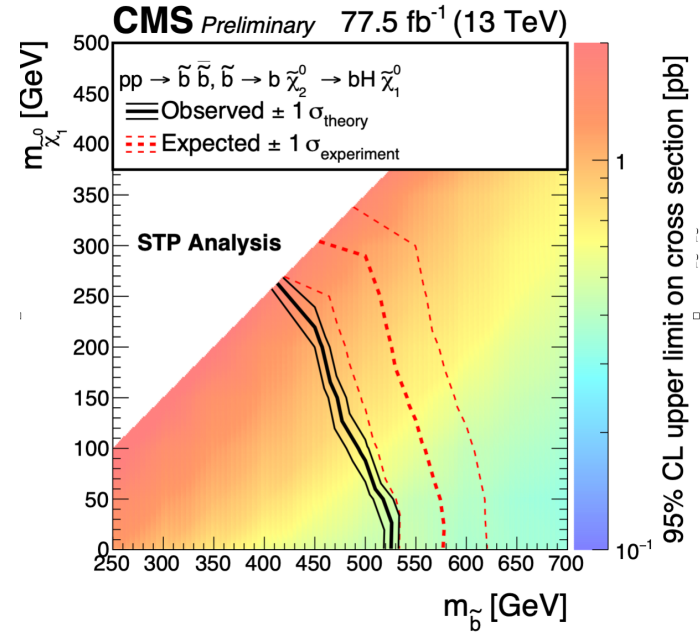
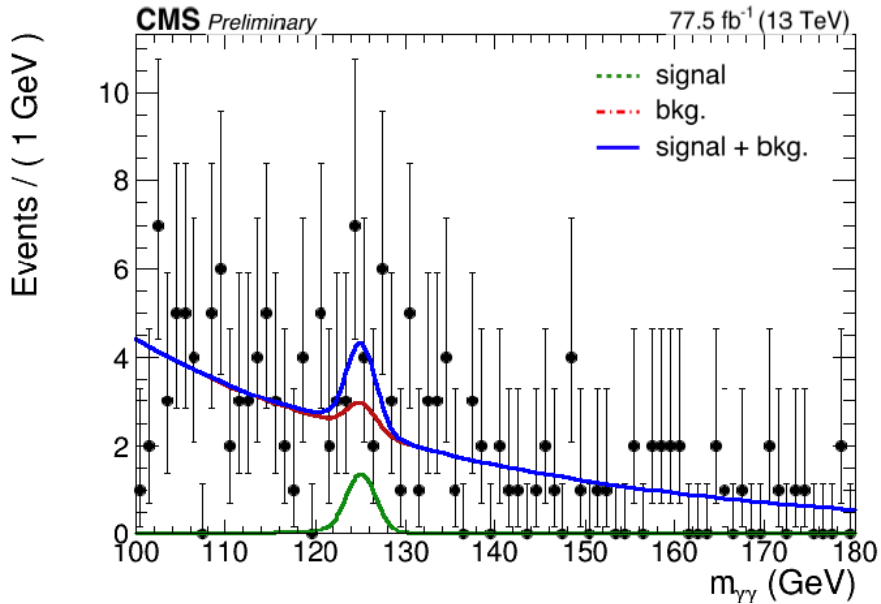
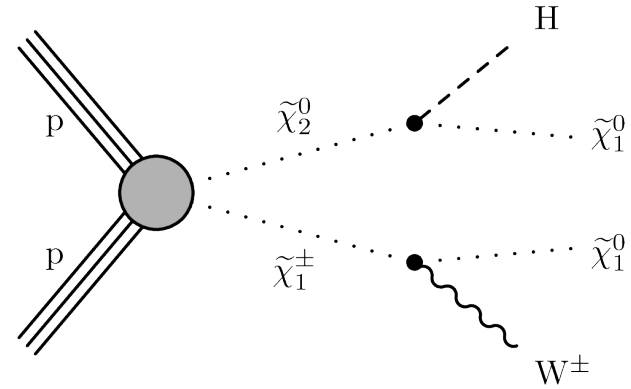
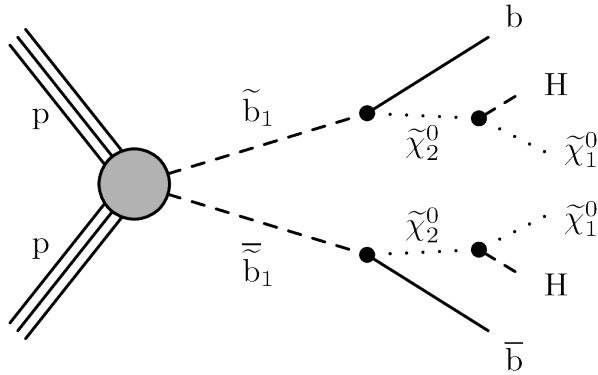
0-lepton + MET + jets, binned in ~ 300 bins (H_T , N_j , N_{bj} , M_{T2})





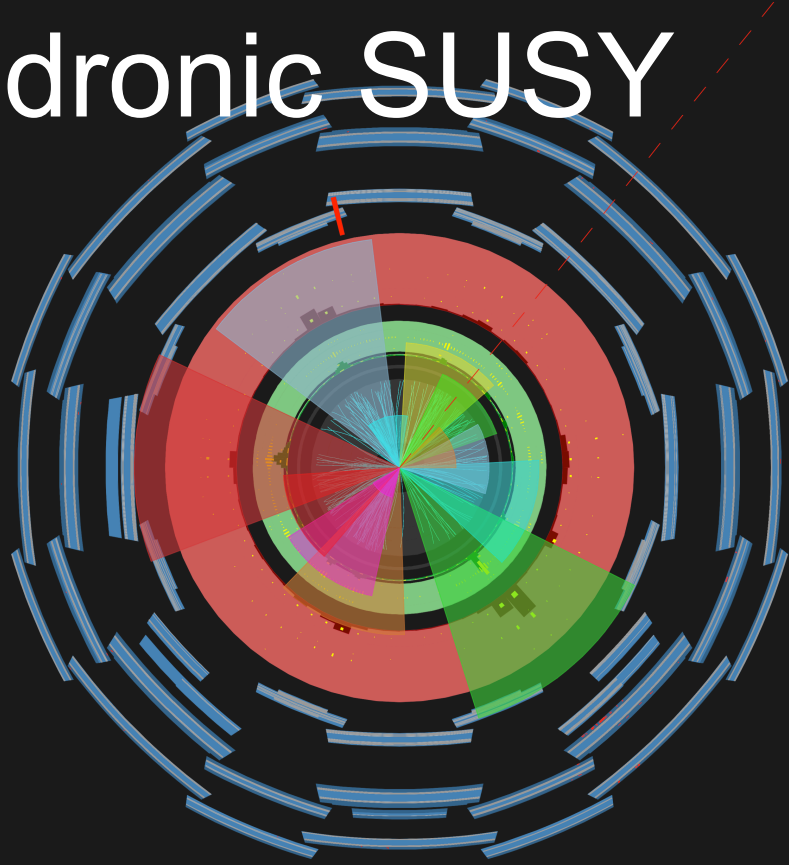
$M_{T2} + H(\gamma\gamma)$ search

CMS-PAS-SUS-18-007



All-hadronic SUSY

1708.02794

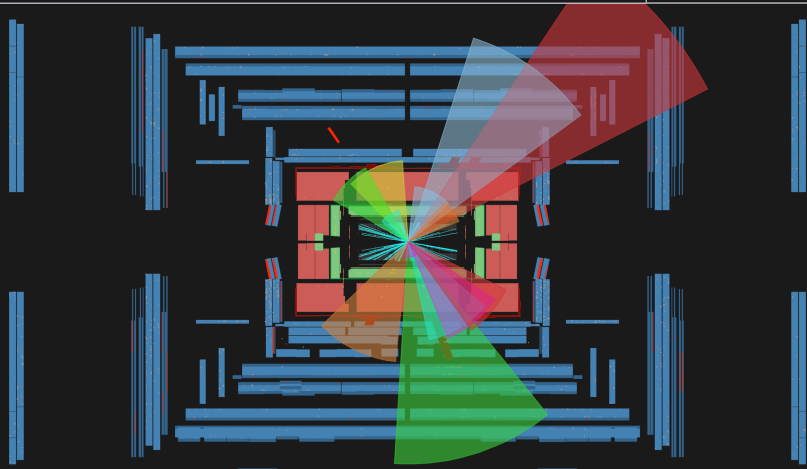
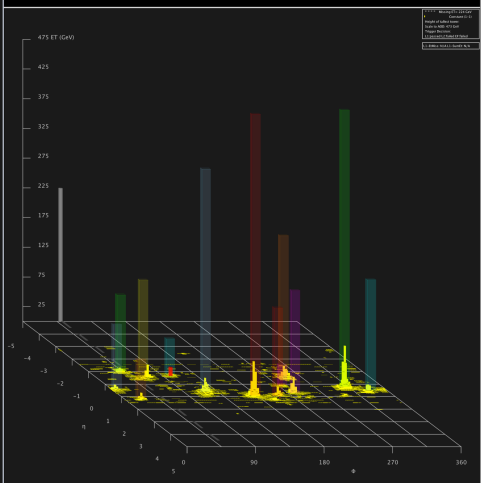


13 50 GeV jets with $M_J^\Sigma = 1 \text{ TeV}$



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Date: 2016-10-23 12:56:09 UTC

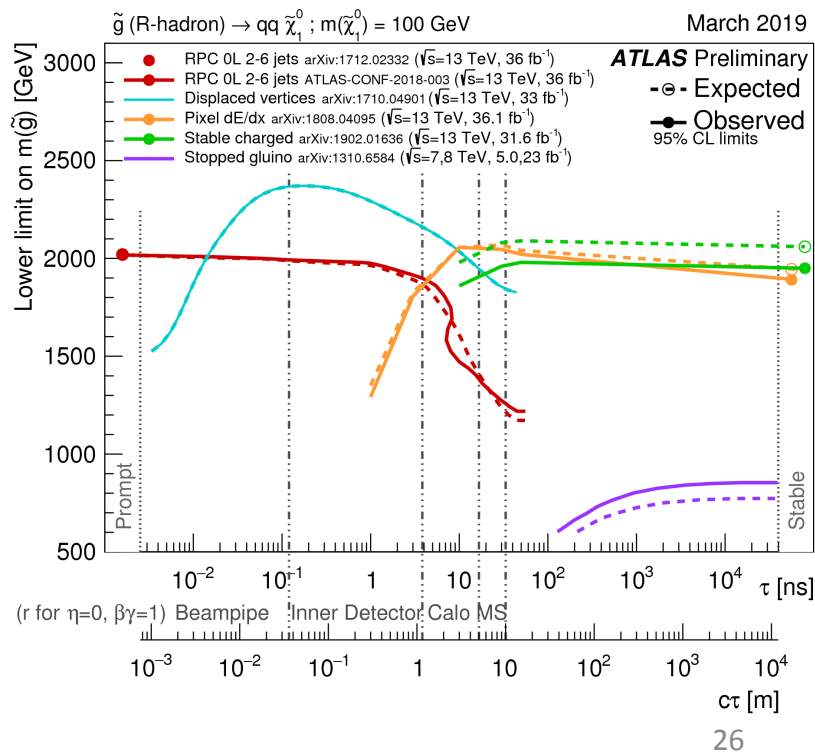
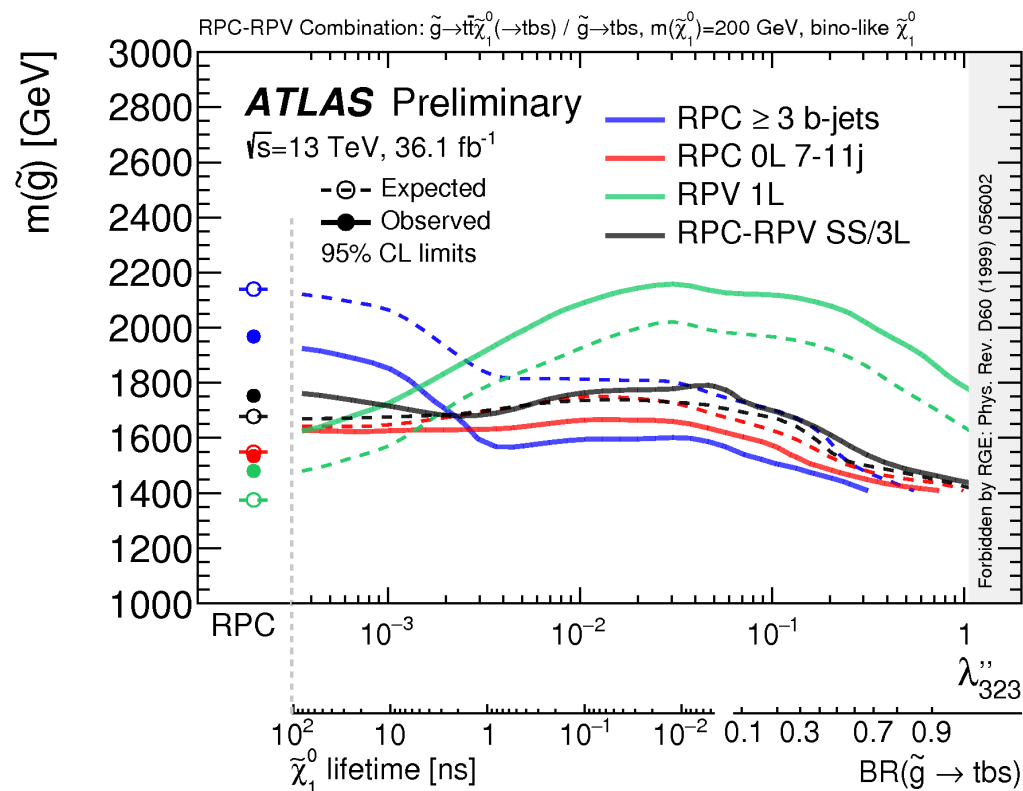
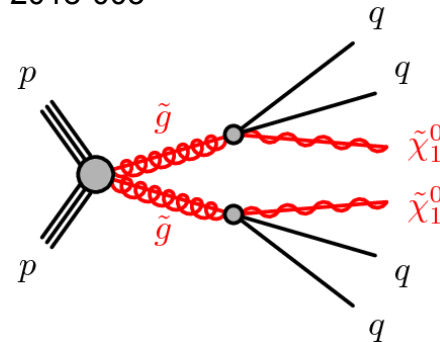
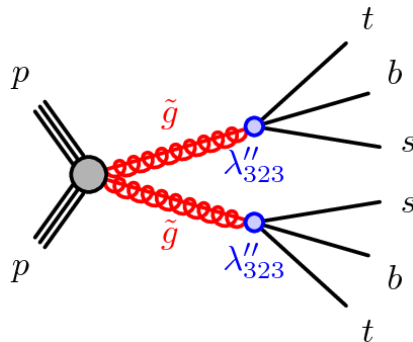


All-hadronic SUSY with lifetime

1708.02794
ATLAS-CONF-2018-003

Re-interpretation

1712.02332
ATLAS-CONF-2018-003

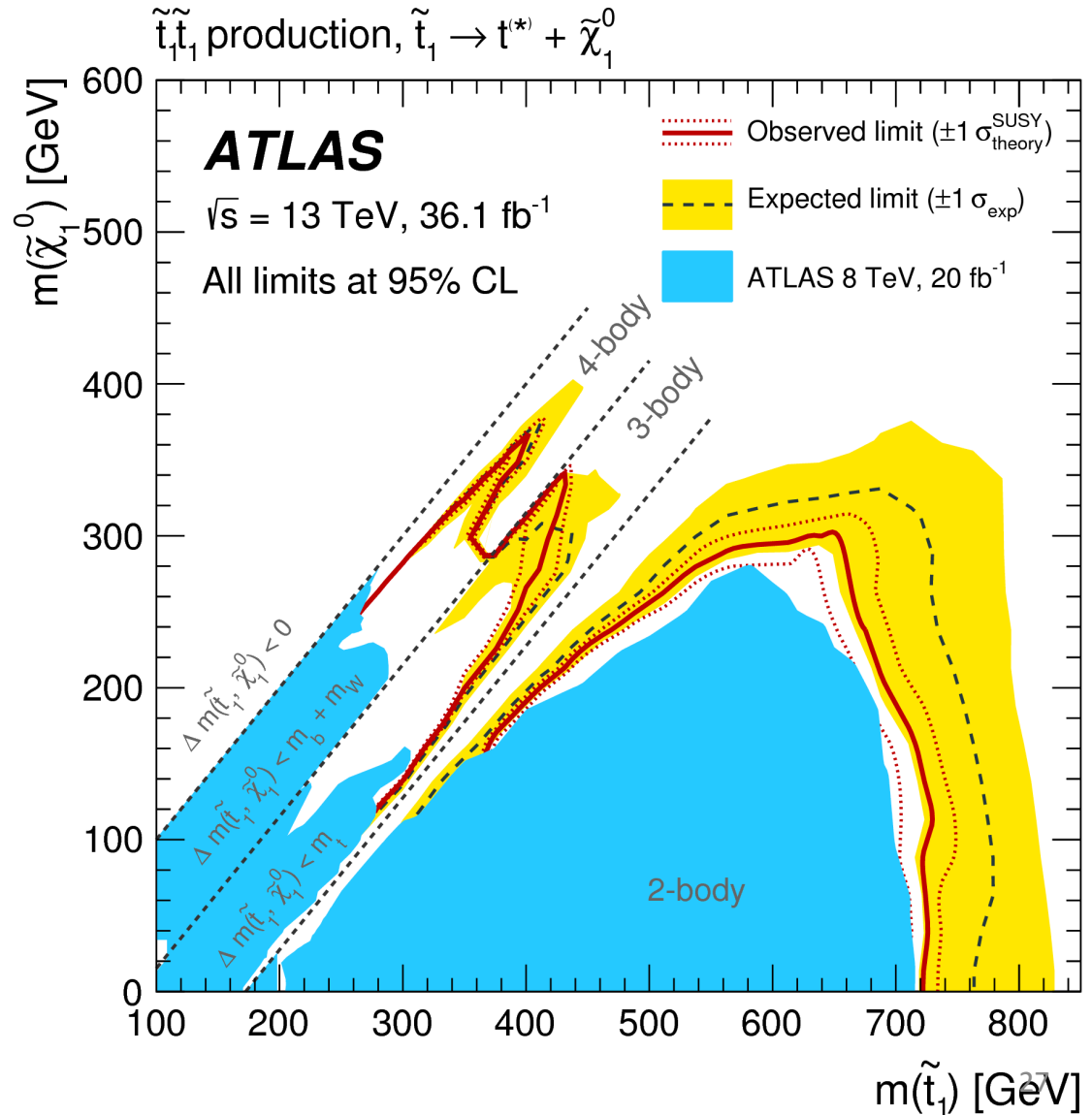
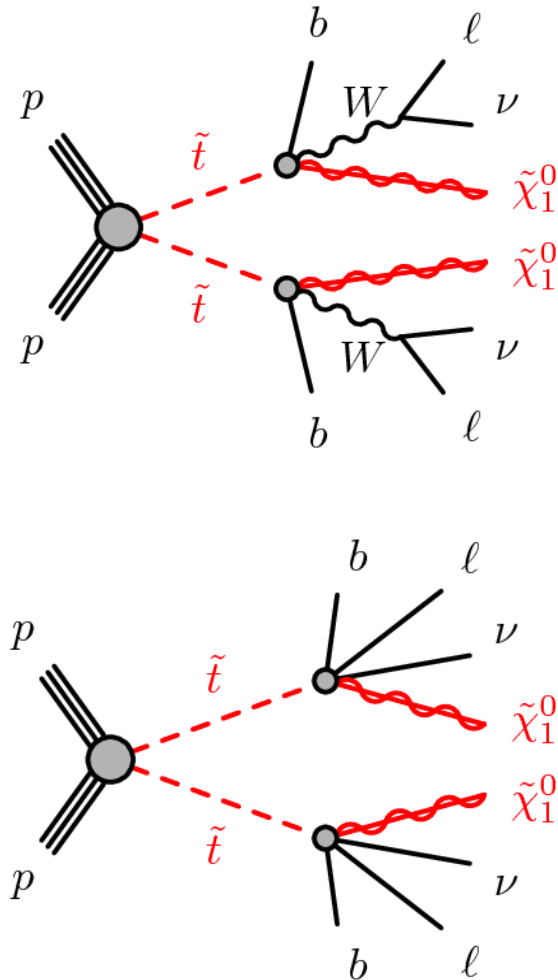


March 2019

Top squark pairs in 2L final states

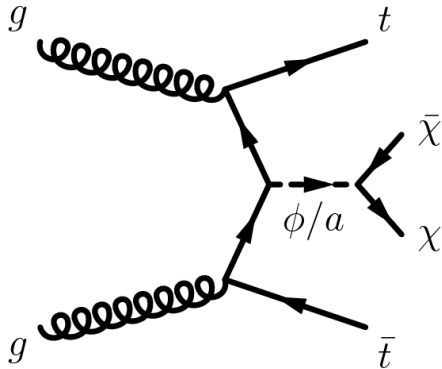
1708.03247

Including virtual top

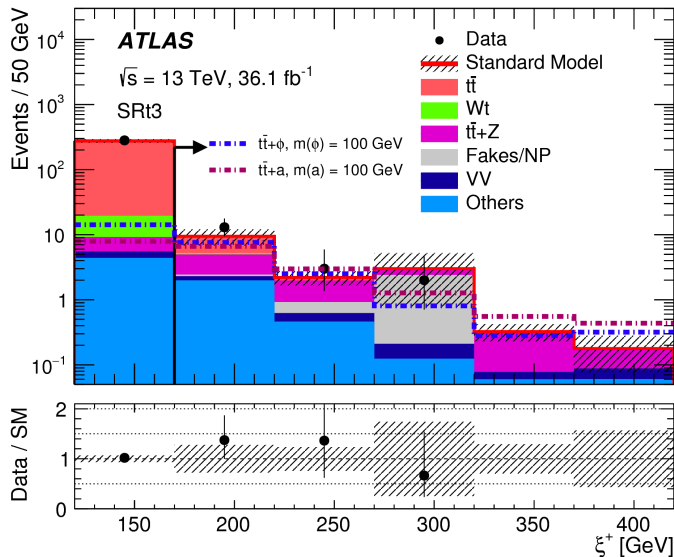


Search for DM in association with HF

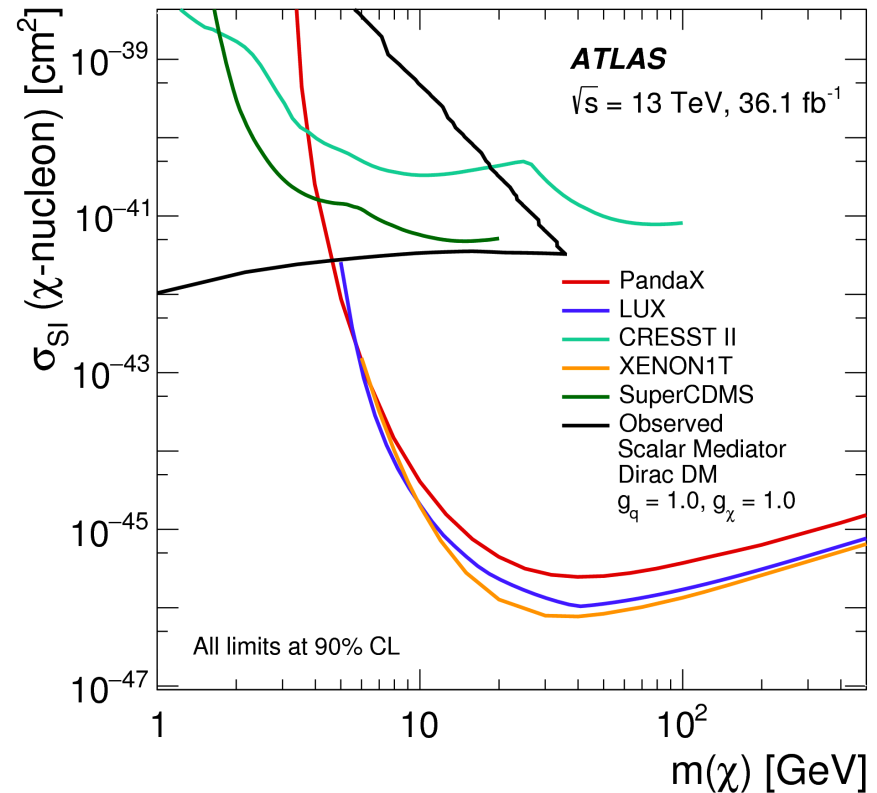
1710.11412



Modelling of the fake and non-prompt leptons is vital



Interpretation
 (with phenomenological assumptions)

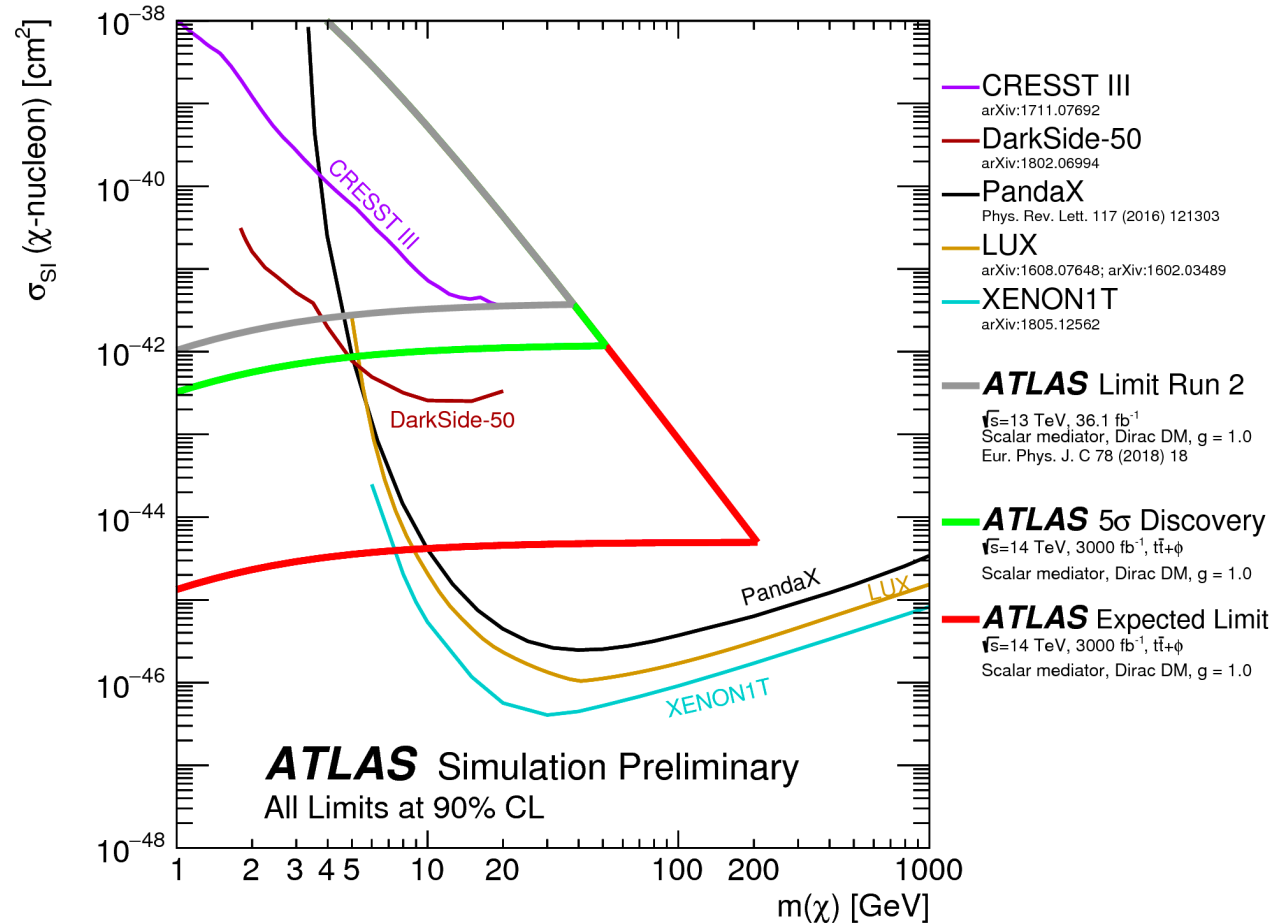
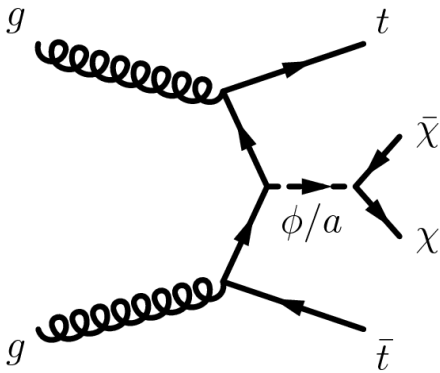


Search for DM in association with HF



ATL-PHYS-PUB-2018-036

Upgrade study: Interpretation
(with phenomenological assumptions)

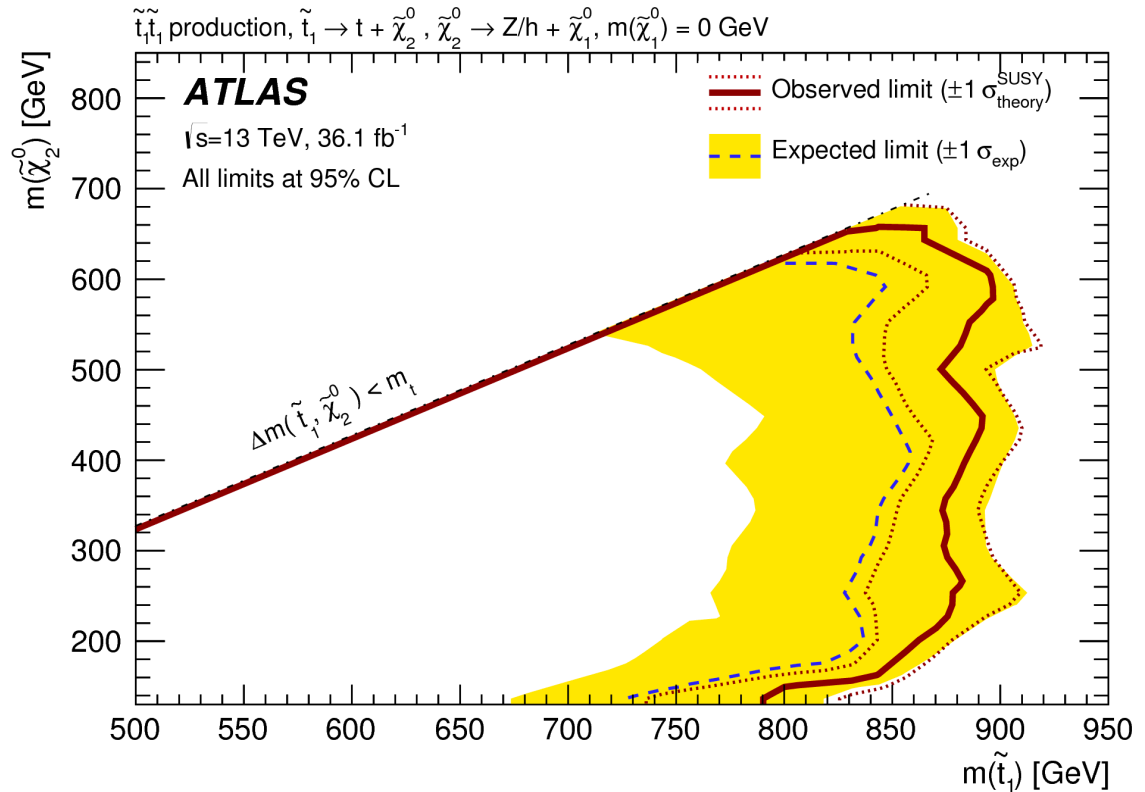
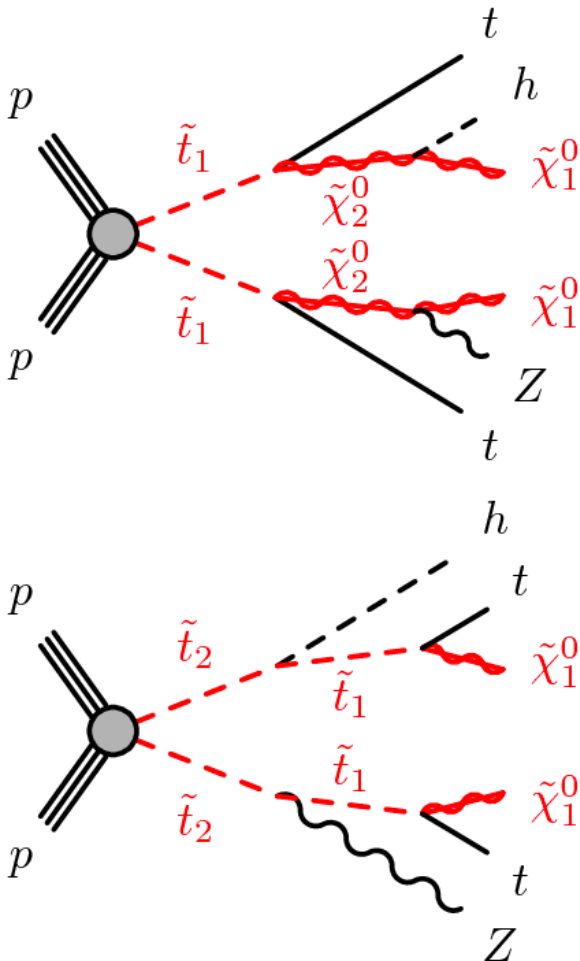


Top squark pairs in h/Z final states

1706.03986



Target $Z \rightarrow ll$ or $h \rightarrow bb$:



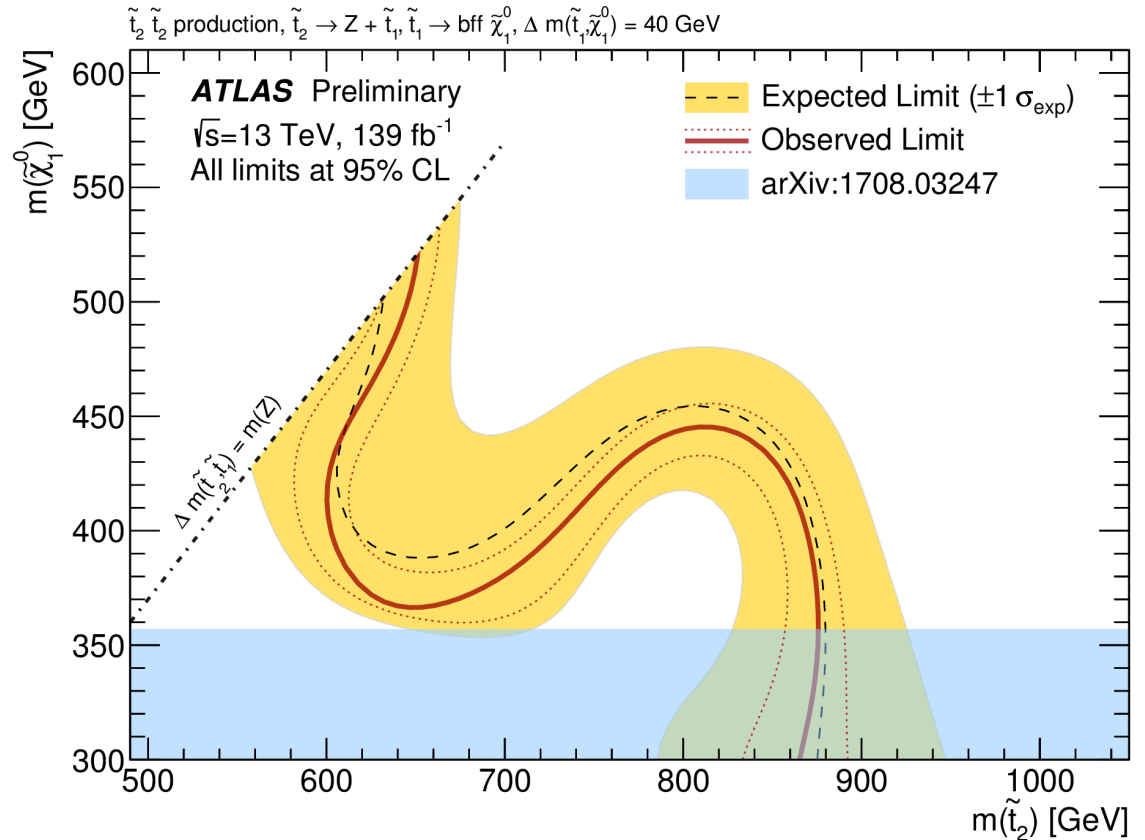
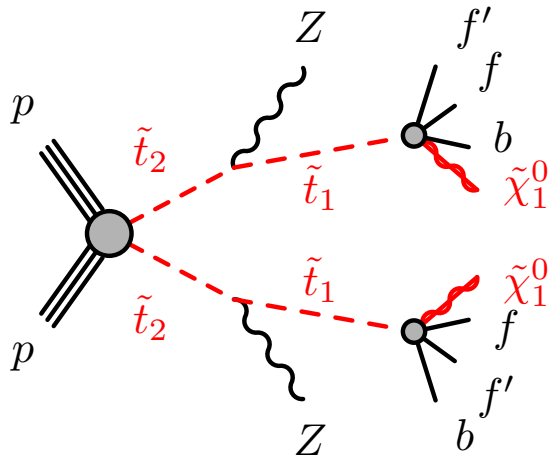
Mass dependent limits are also placed on the BR for the h/Z decays



And again with full Run 2

ATLAS-CONF-2019-016

Optimized for small stop-neutralino mass splittings

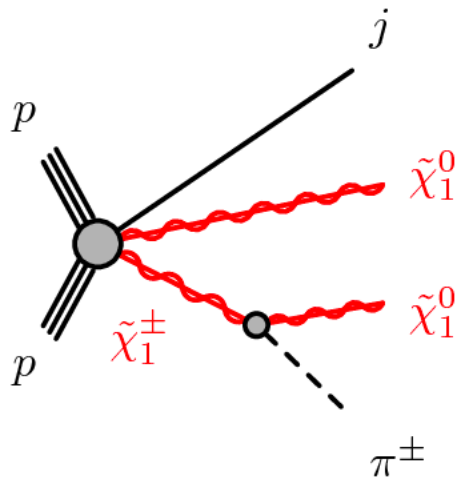


Upgrade study: disappearing tracks

ATL-PHYS-PUB-2018-031

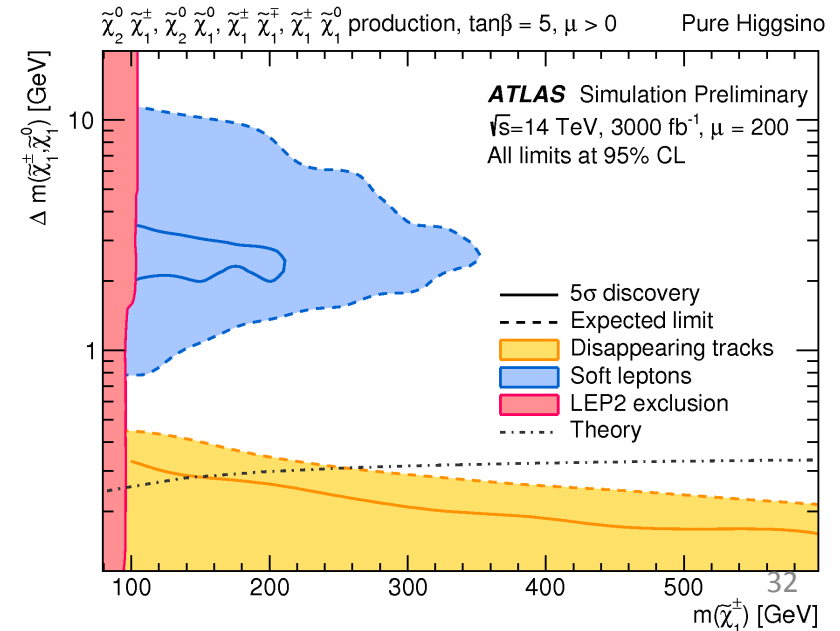
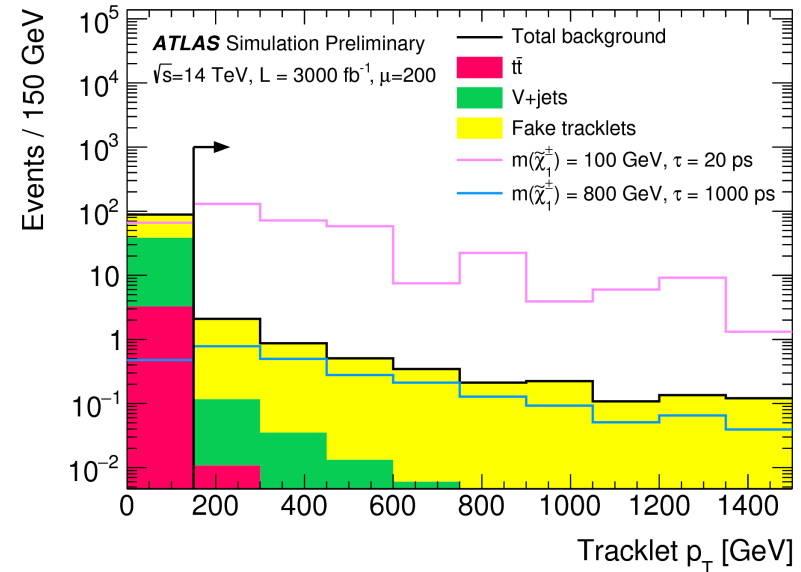


Upgrade study: future ITk tracker layout



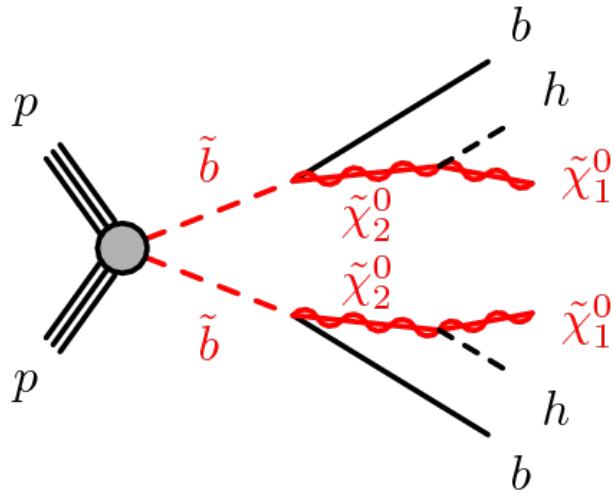
Mass degenerate chargino & neutralino

- Long chargino lifetime
- Chargino decay within tracker to (invisible) soft pion & neutralino
- Signature: disappearing track

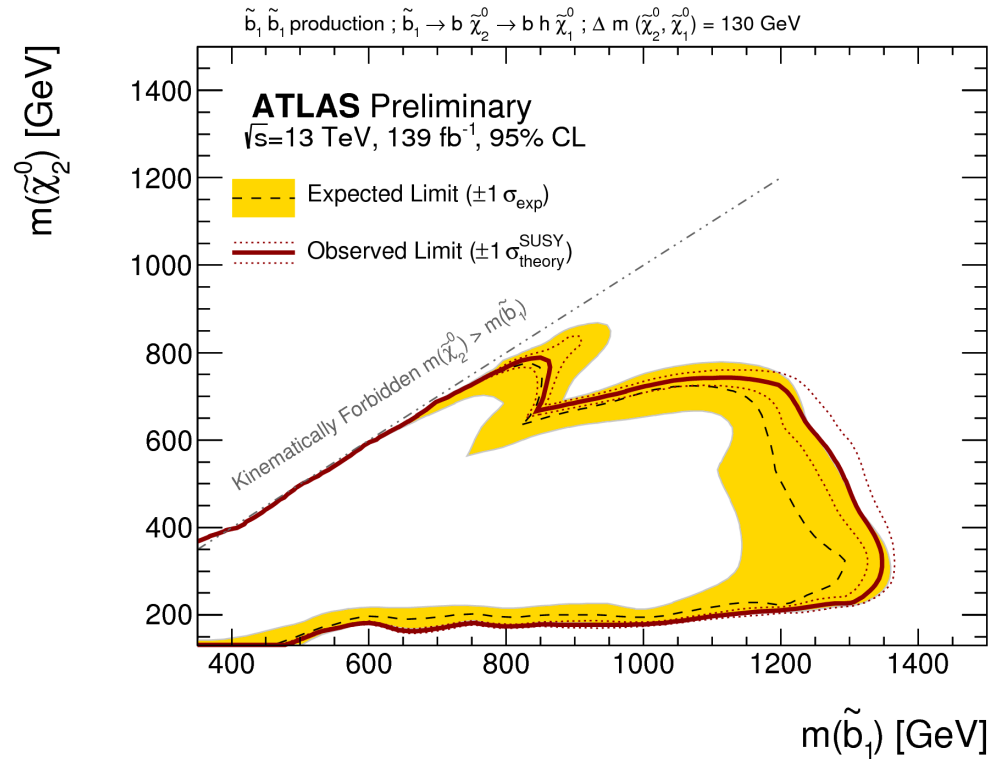
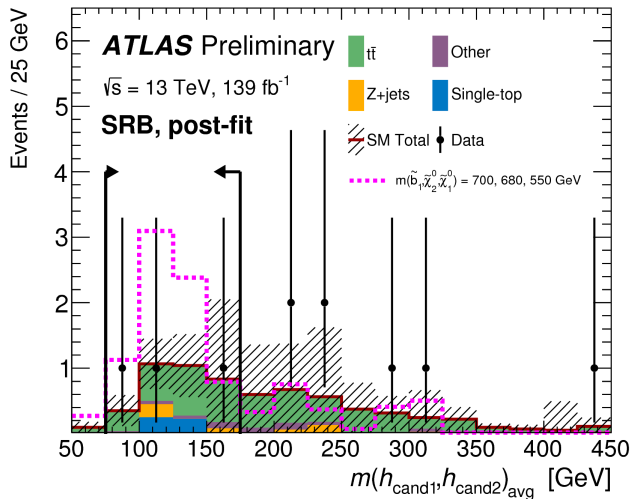


Sbottom pairs in $h(\rightarrow bb)b$ final states

ATLAS-CONF-2019-011



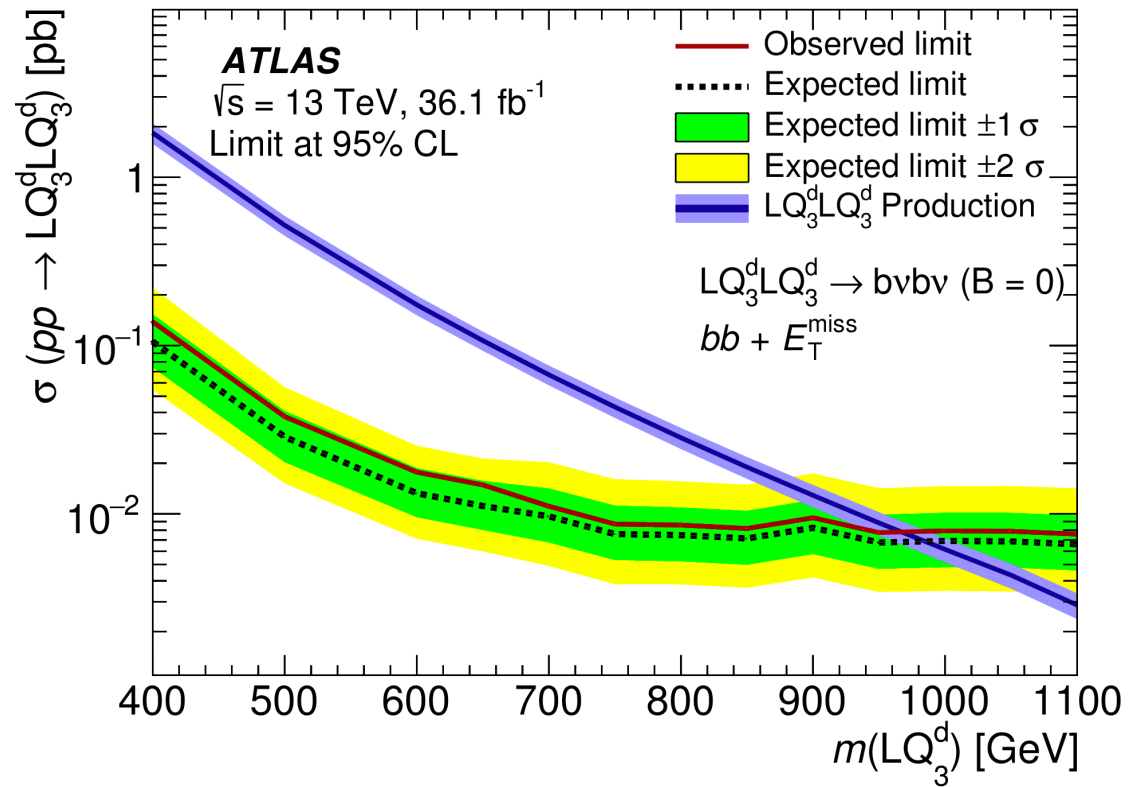
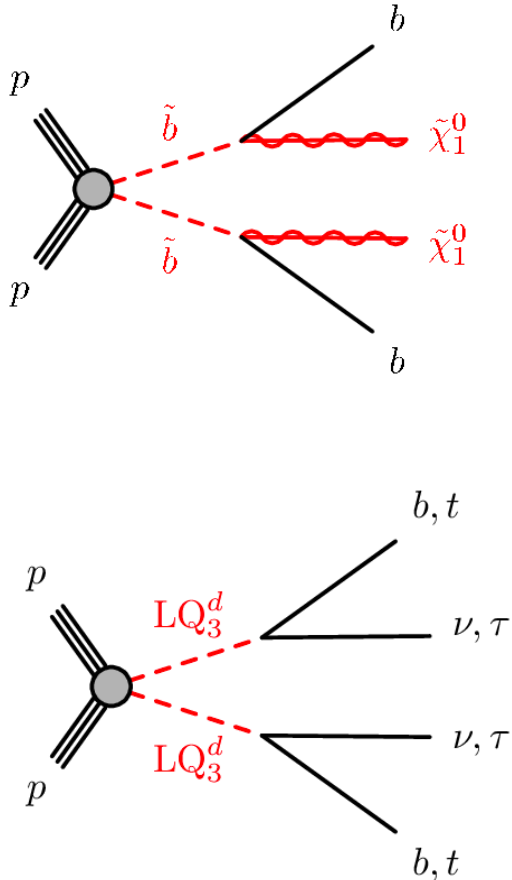
Attempt to reconstruct $h \rightarrow bb$



Exotics

Reinterpretation: $S_{\text{bottom}} \rightarrow LQ_3$

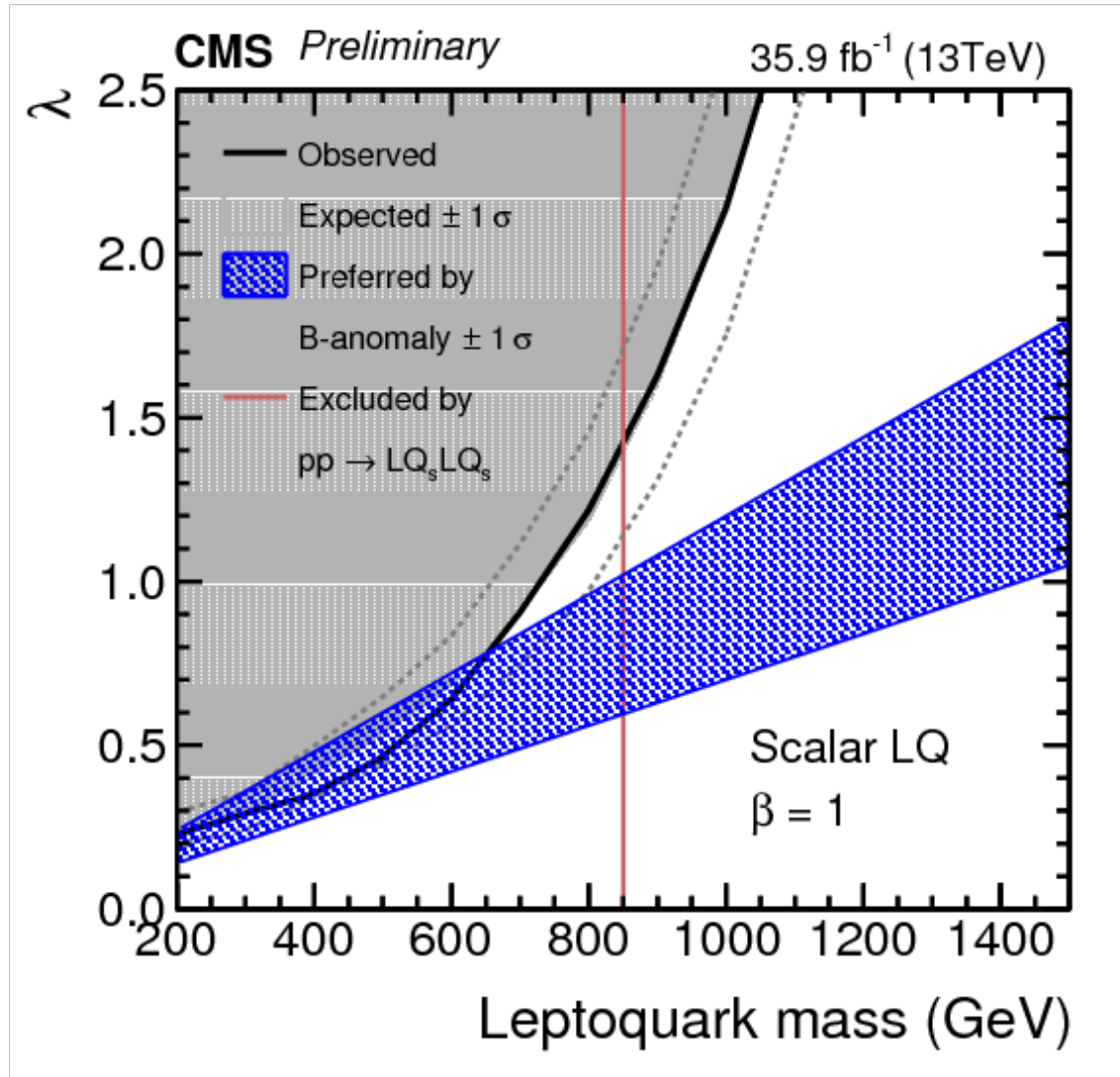
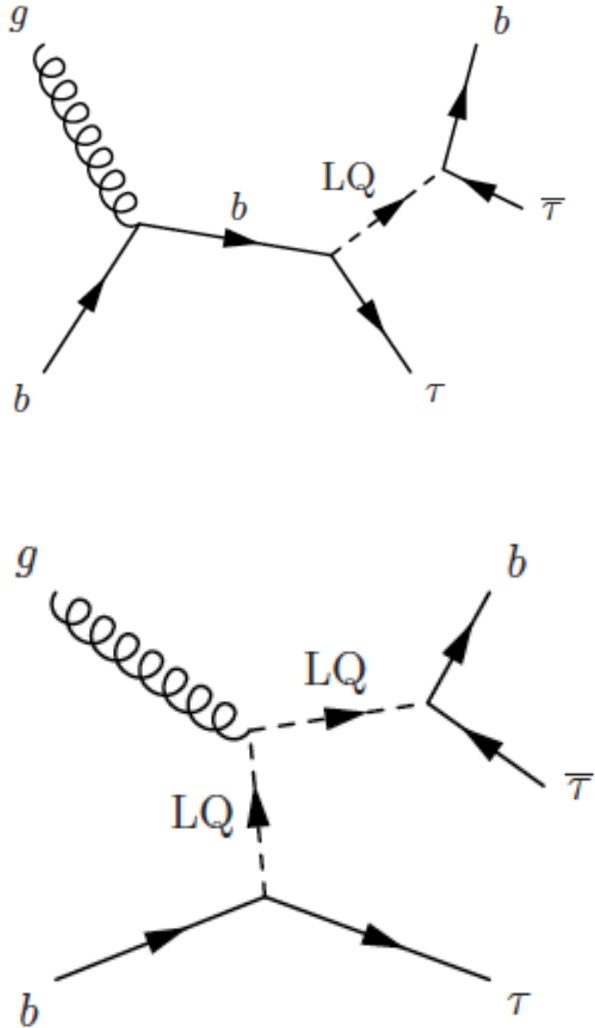
1902.08103





Single $LQ_3 \rightarrow \tau + b$

CMS-PAS-EXO-17-029

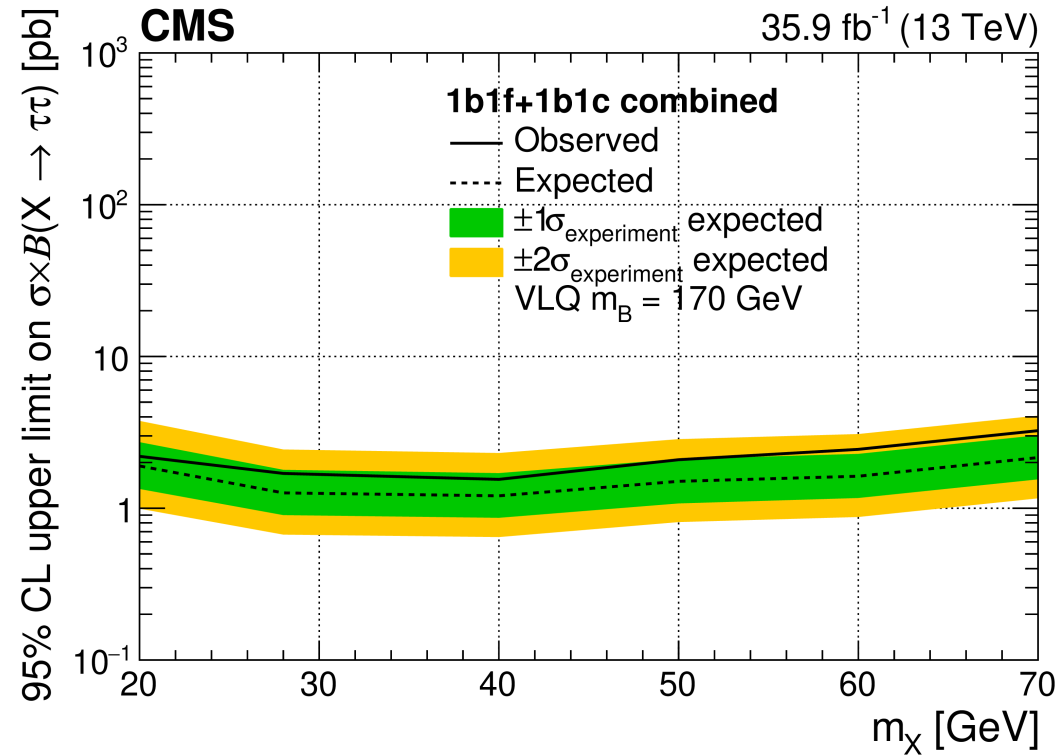
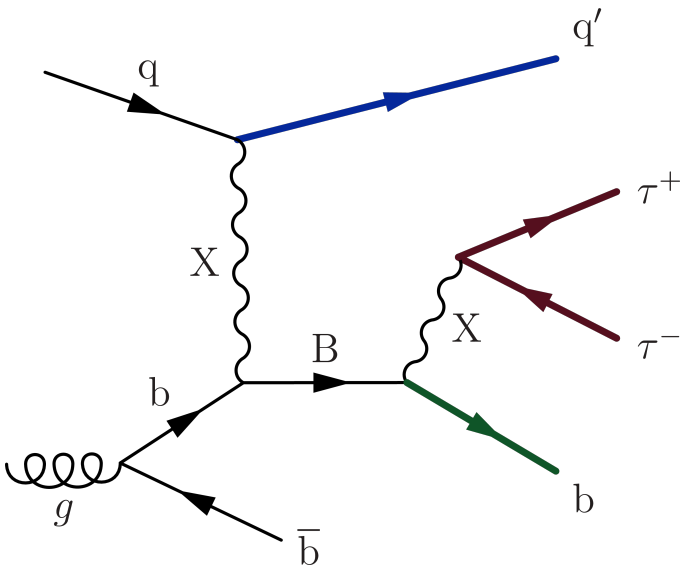




Low-mass tautau resonance + b

1903.10228

Motivated by observed di-muon peak [1808.01890]





$VV \rightarrow JJ$ with highest mass

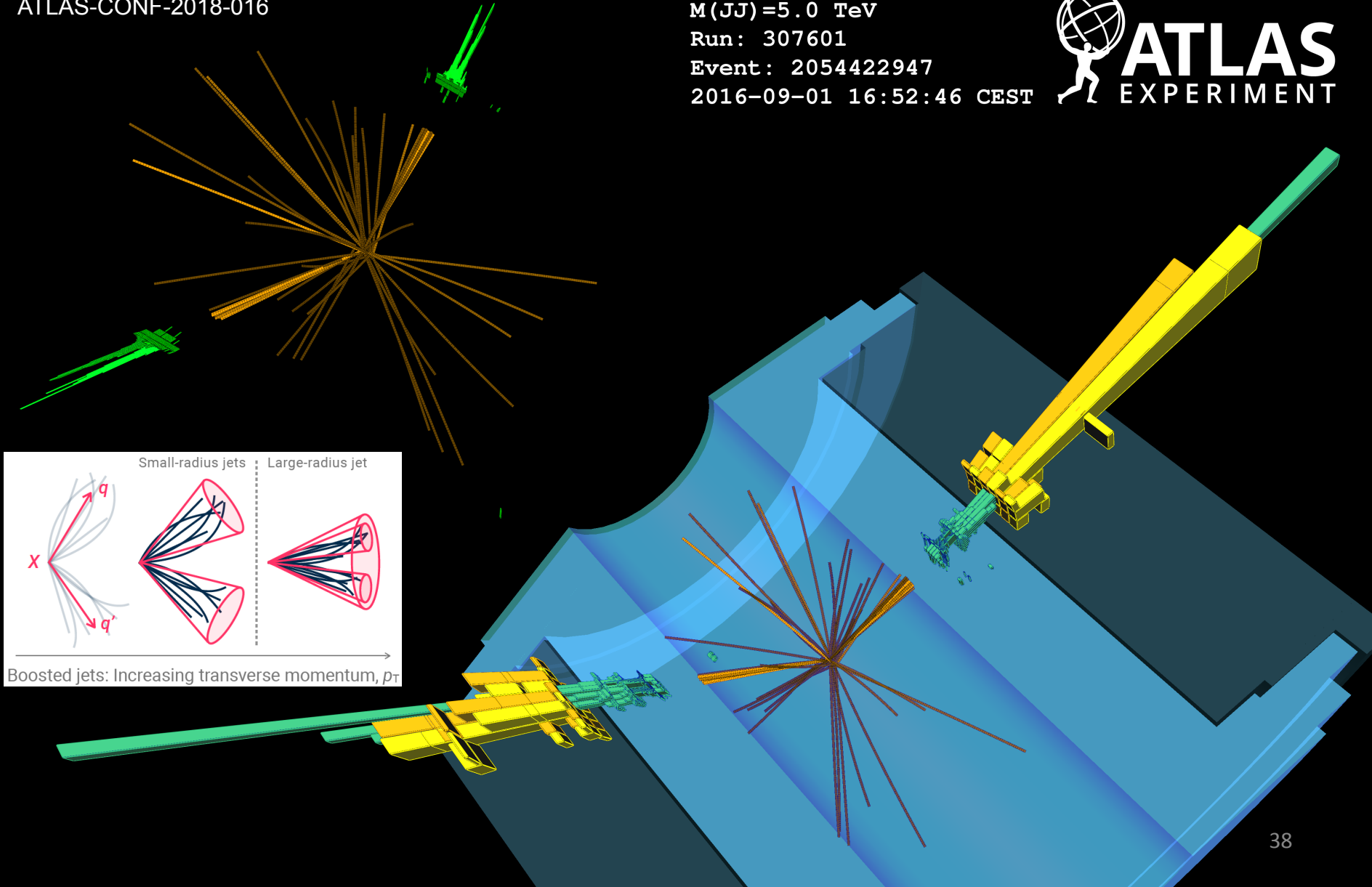
ATLAS-CONF-2018-016

$M(JJ) = 5.0 \text{ TeV}$

Run: 307601

Event: 2054422947

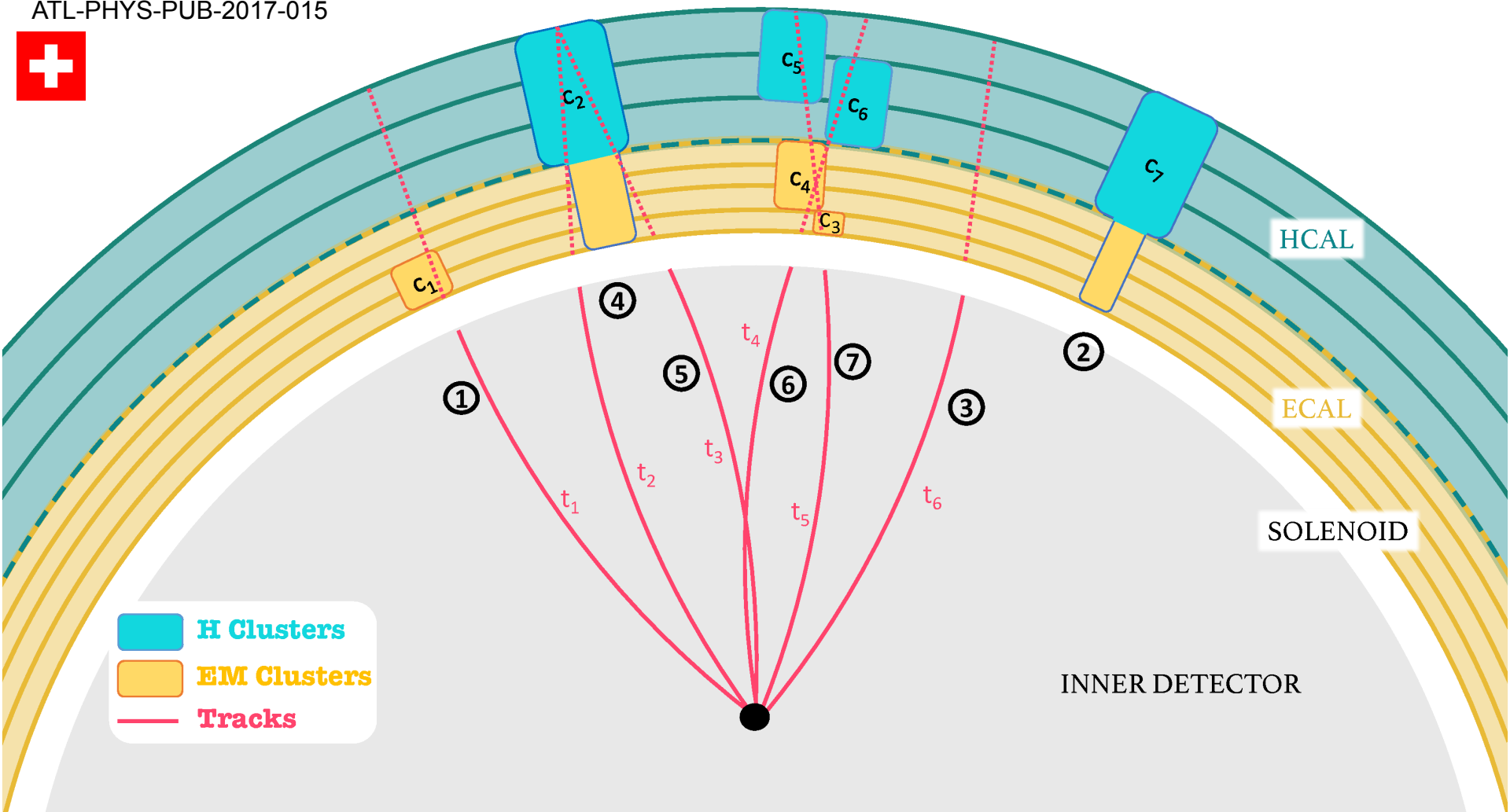
2016-09-01 16:52:46 CEST



Track-CaloCluster (TCC) matching

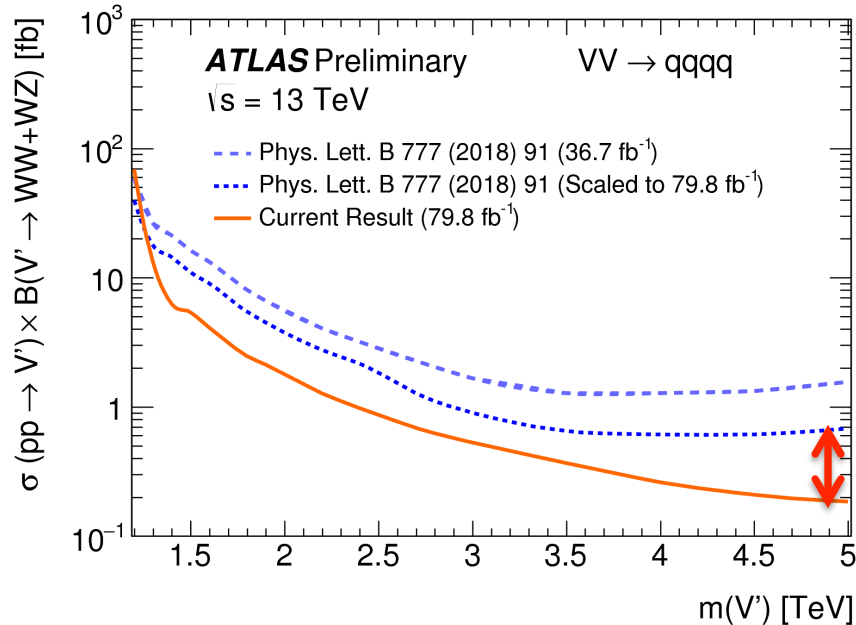
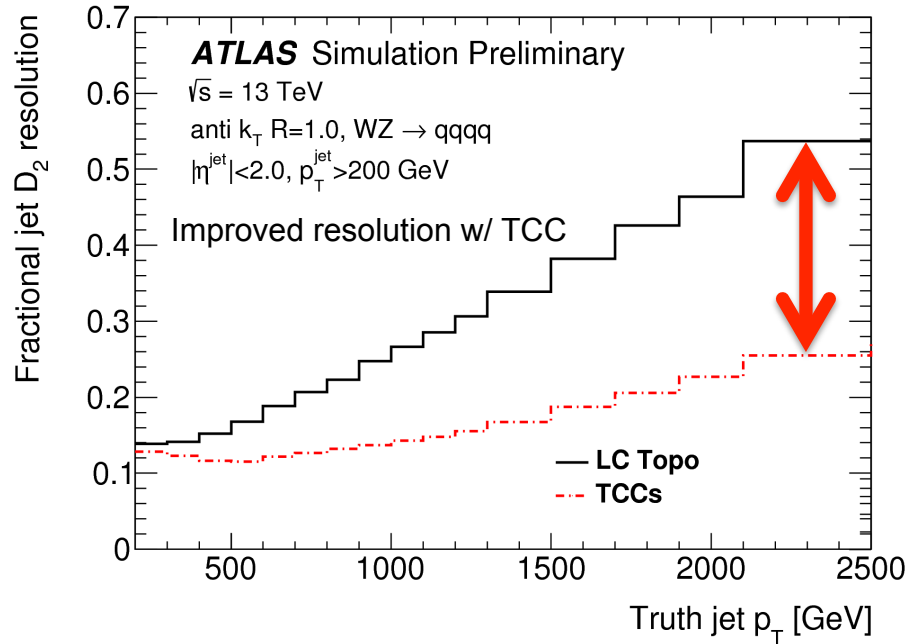
Mitigate the calorimeter angular resolution limitations by combining tracks and caloclusters before jet finding

ATL-PHYS-PUB-2017-015

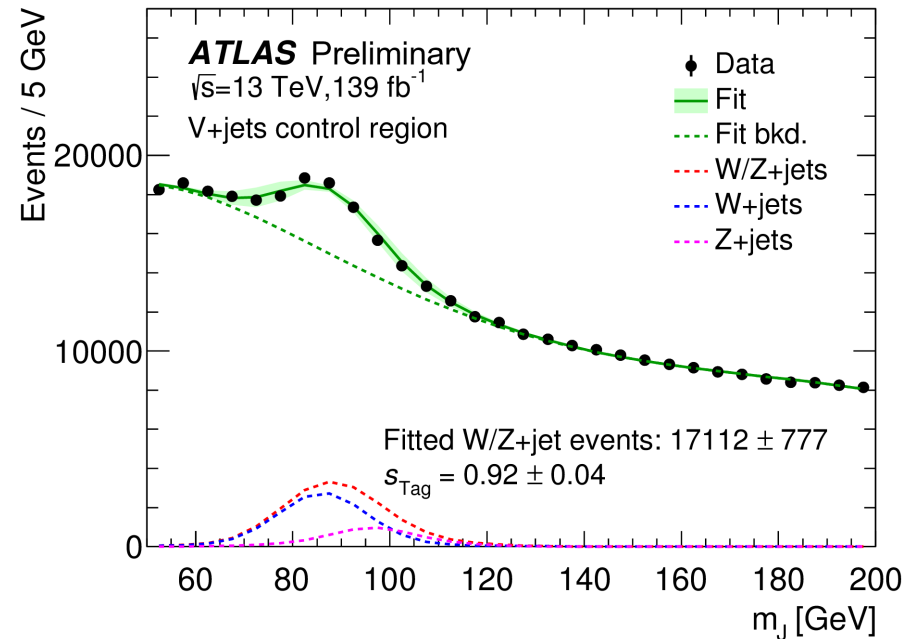




VV → JJ search



Observation of SM V+jets in hadronic decay channel

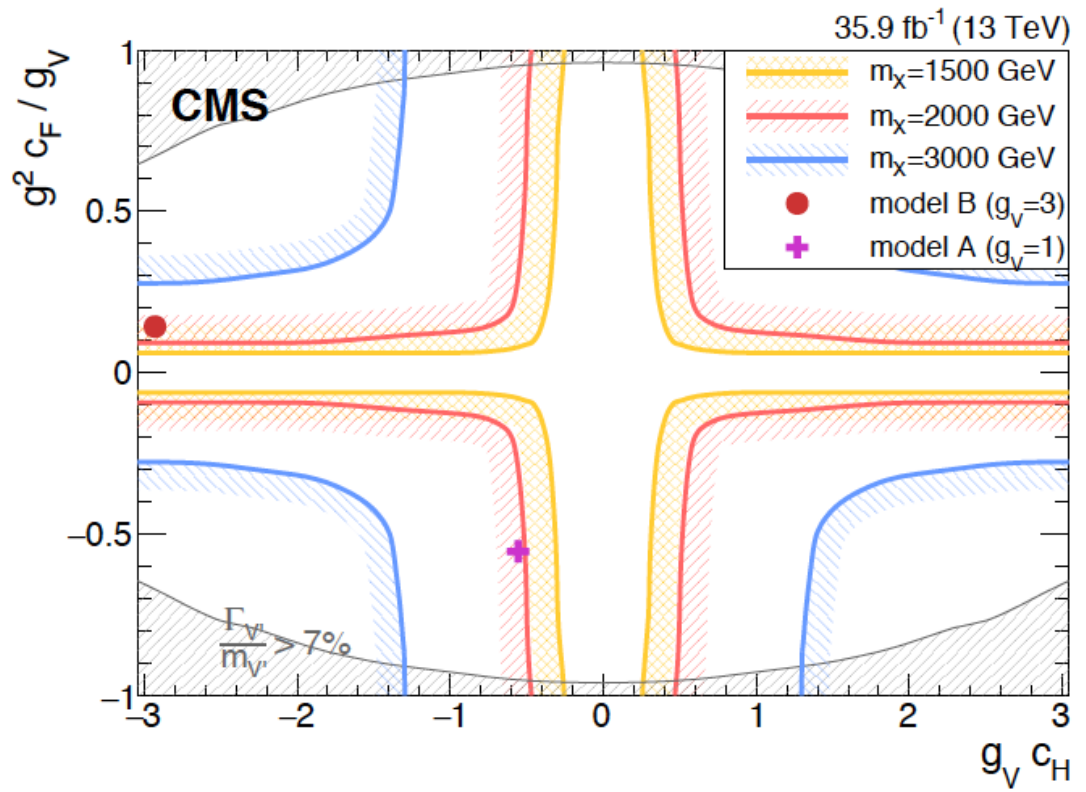
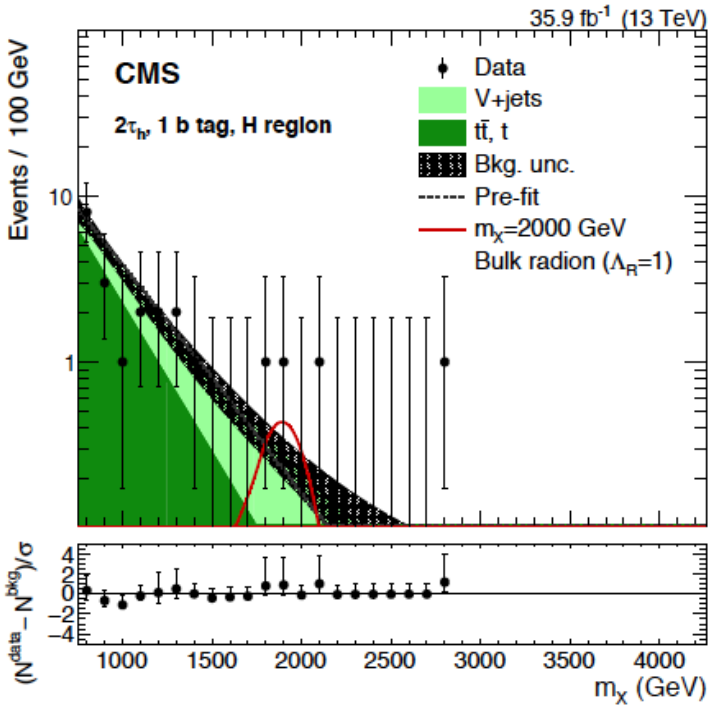


$HH \rightarrow bb\tau\tau$, $VH \rightarrow qq\tau\tau$ & $VH \rightarrow (\ell\ell/\ell\nu)bb$

1808.01365
1807.02826



Interpretation in heavy vector triplet (HVT) model

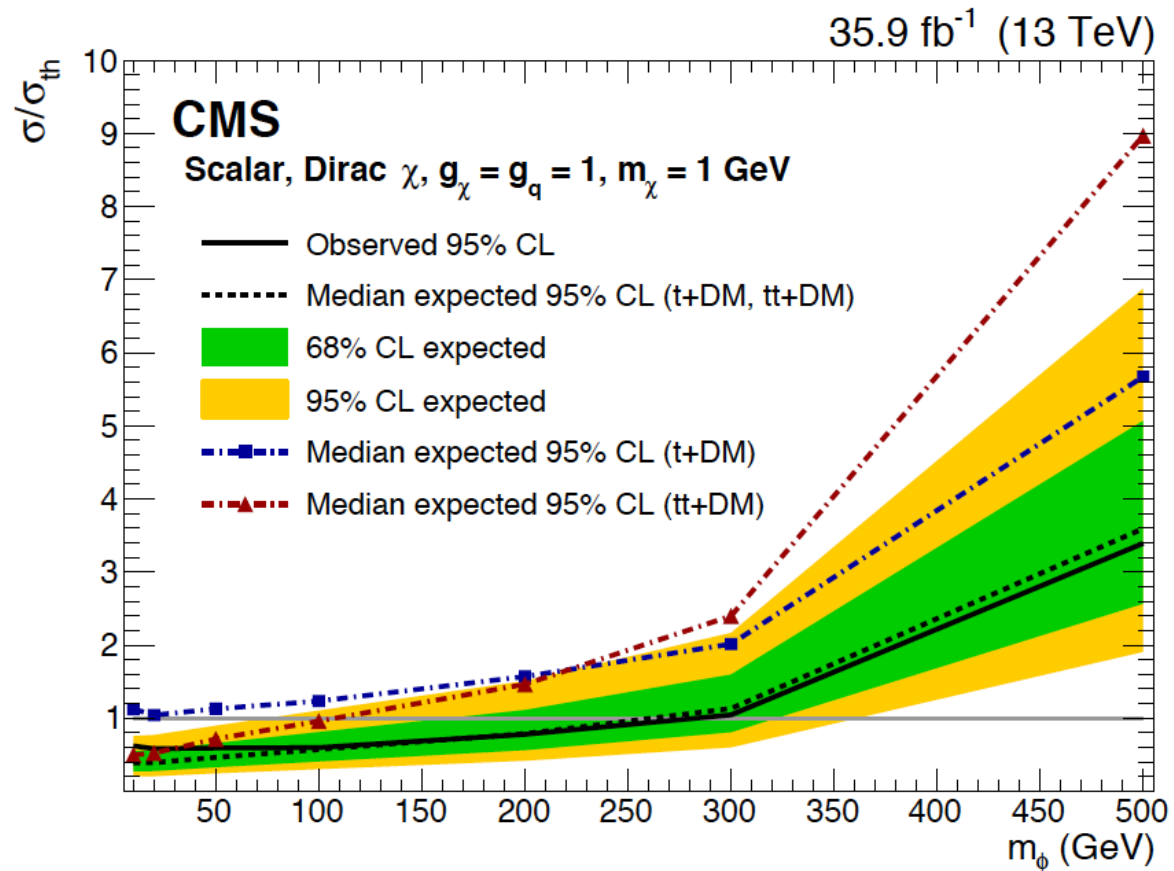
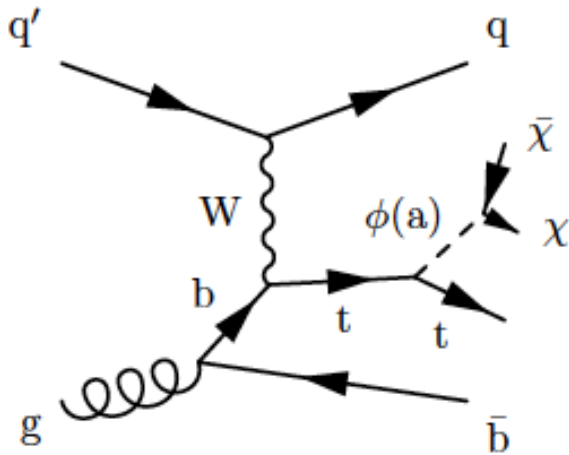


c_F and c_H : Universal coupling strength of X to fermions and bosons

DM + single top

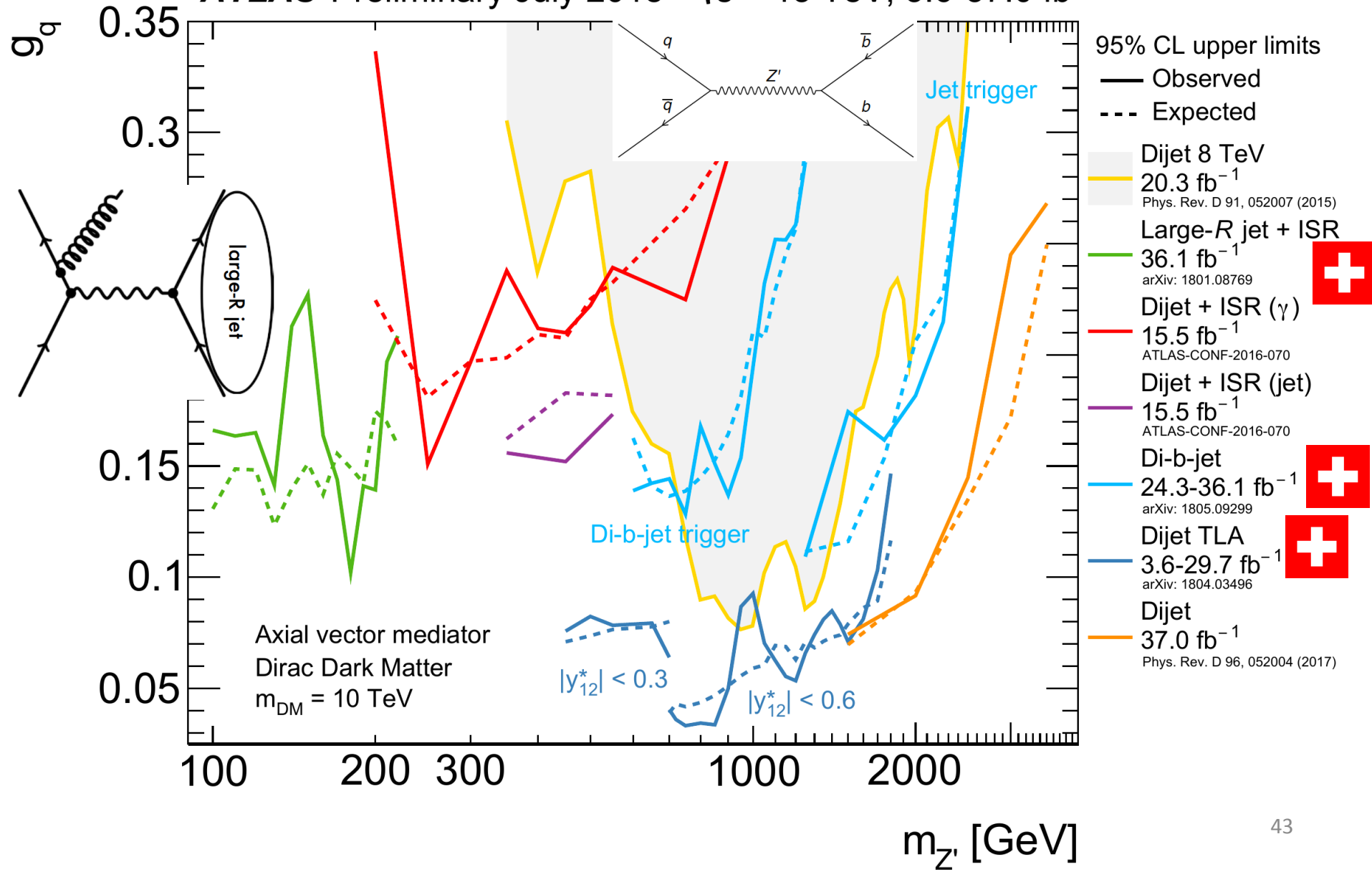
Theory idea: <https://doi.org/10.1103/PhysRevD.96.035031>

And CMS search: 1901.01553



DM searches

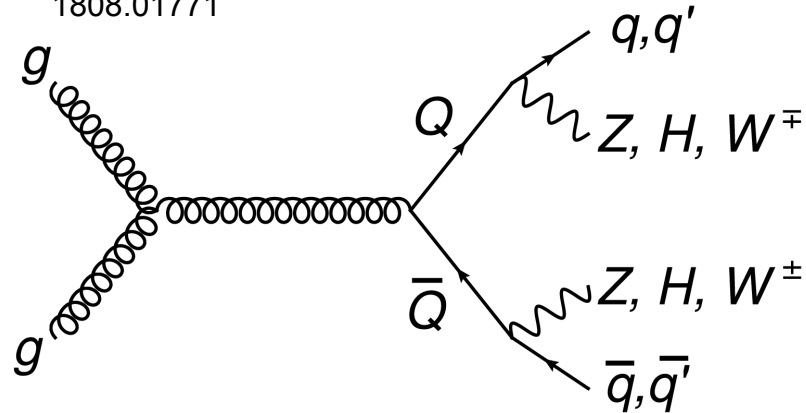
ATLAS Preliminary July 2018 $\sqrt{s} = 13 \text{ TeV}, 3.6\text{-}37.0 \text{ fb}^{-1}$



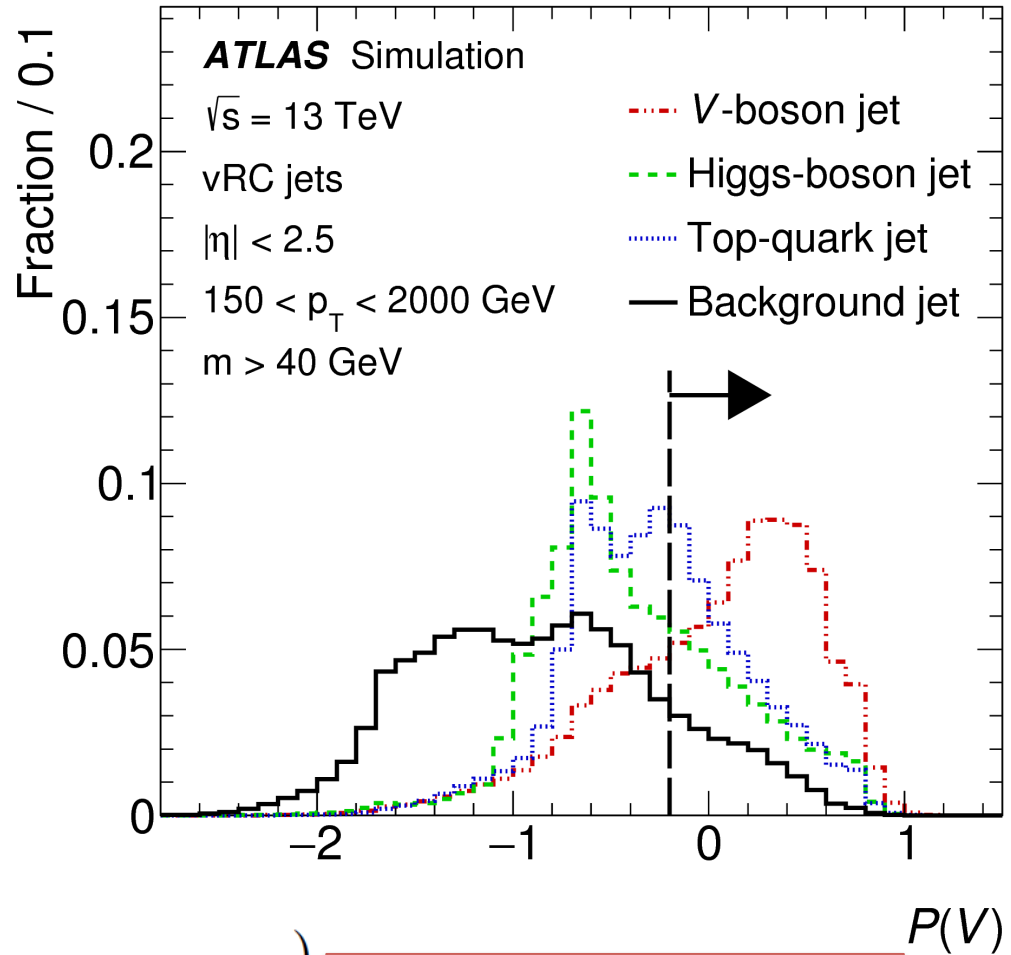


Multi-class tagging with deep NN

1808.01771

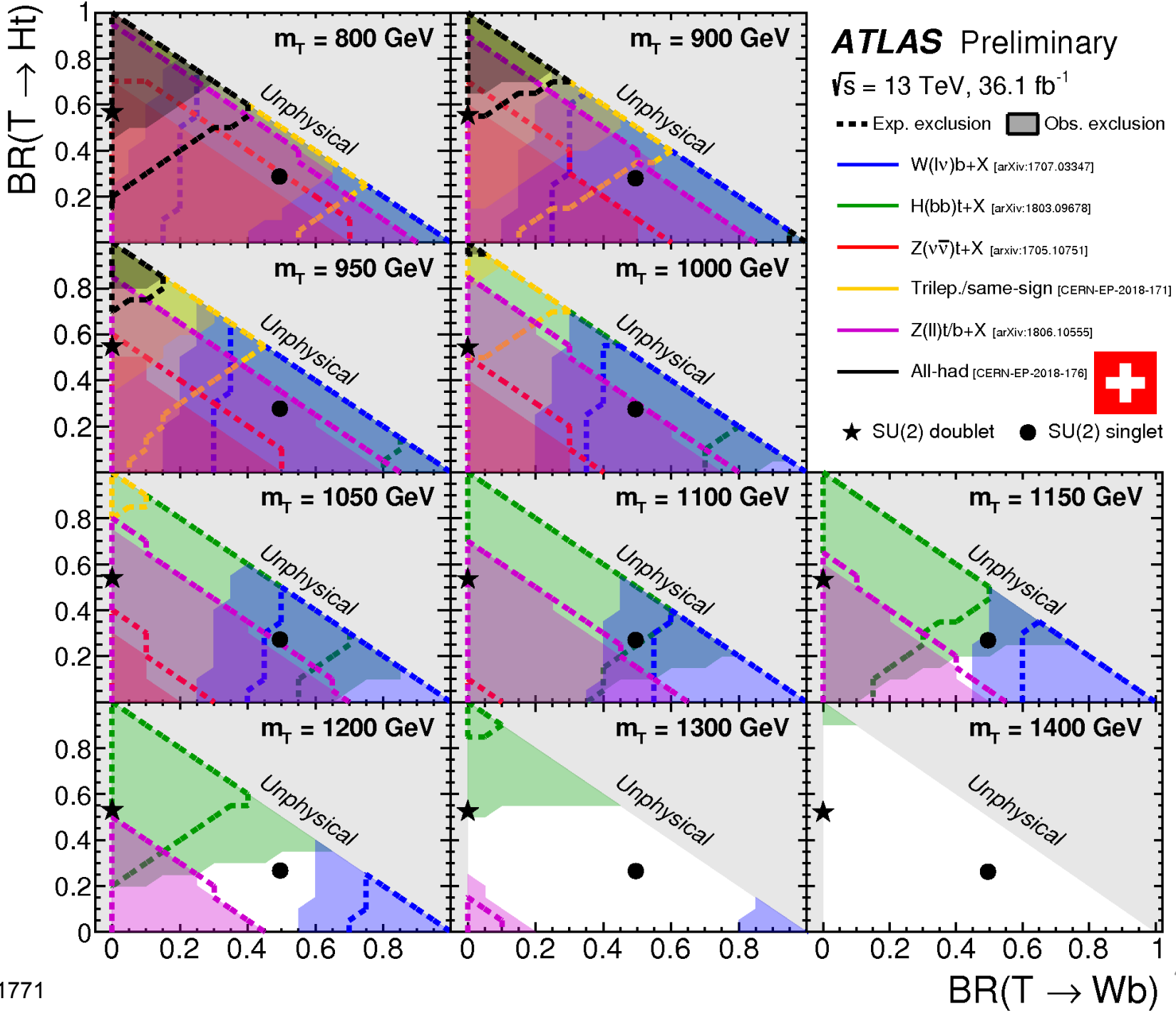


- Discriminate (VLQ search)
 - W/Z
 - Higgs
 - Top
 - QCD-jet



$$P(V) = \log_{10} \left(\frac{D_{\text{DNN}}^V}{0.9 \cdot D_{\text{DNN}}^{\text{background}} + 0.05 \cdot D_{\text{DNN}}^t + 0.05 \cdot D_{\text{DNN}}^H} \right)$$

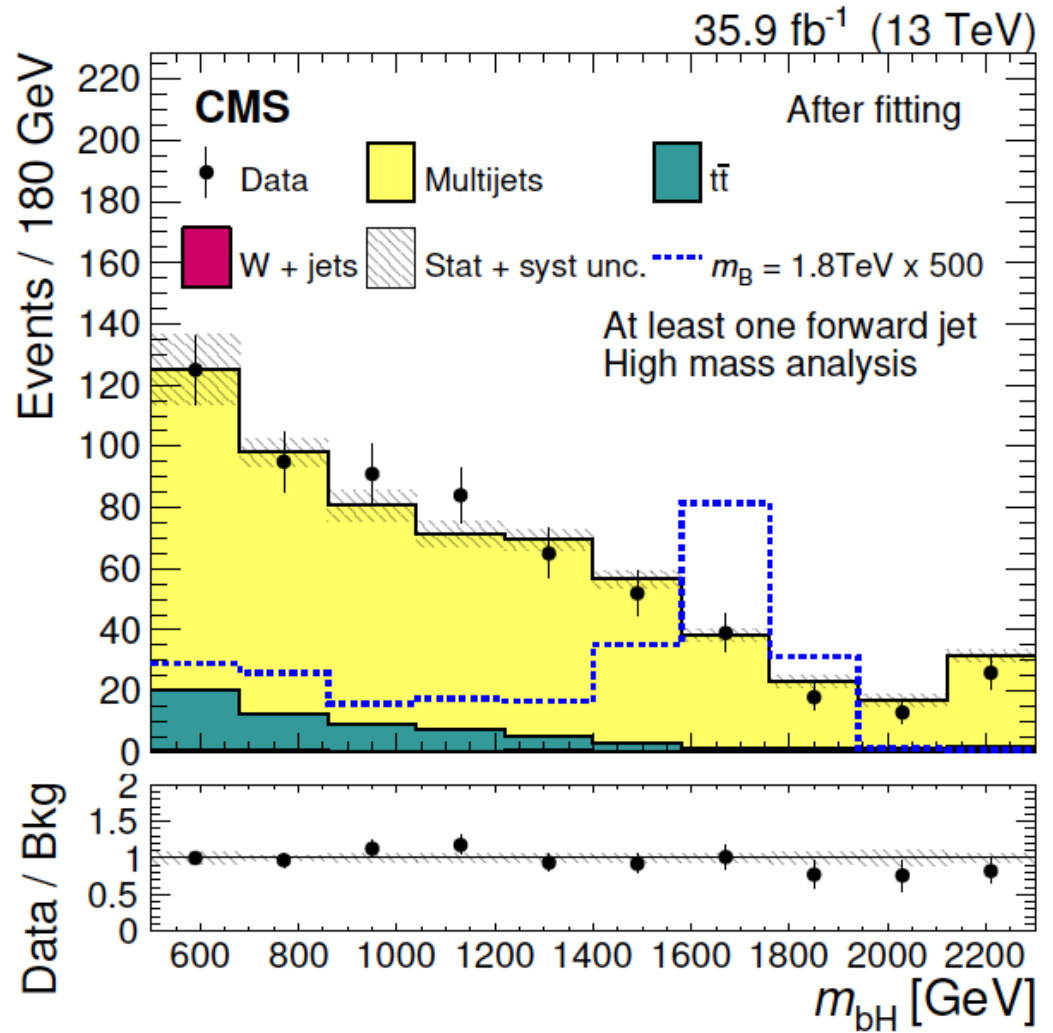
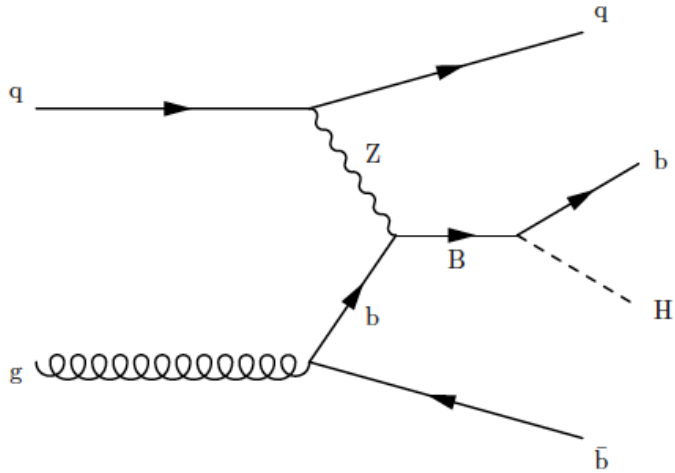
Convenience/flexibility:
 one training for all SR's





Single VLQ $B \rightarrow bH(\rightarrow bb)$

1802.01486

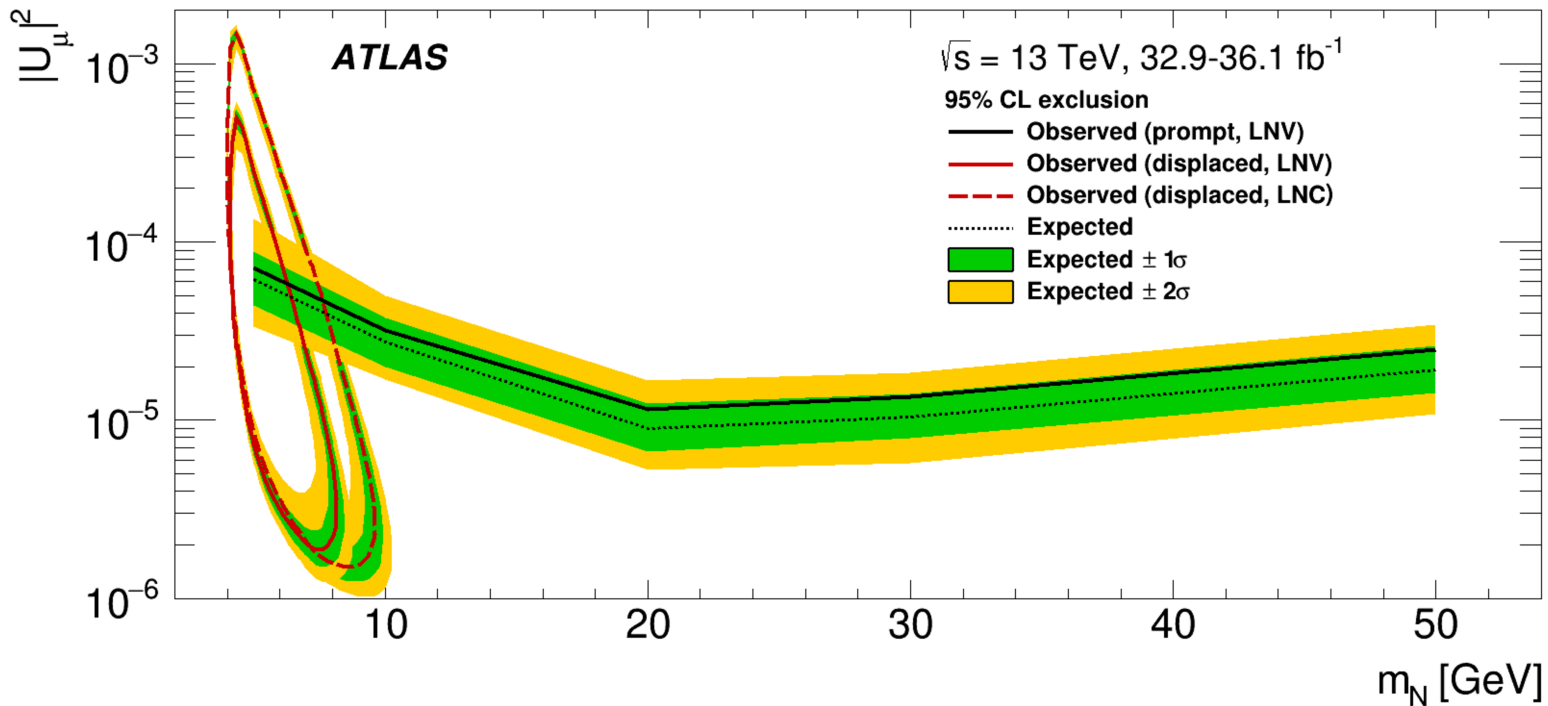
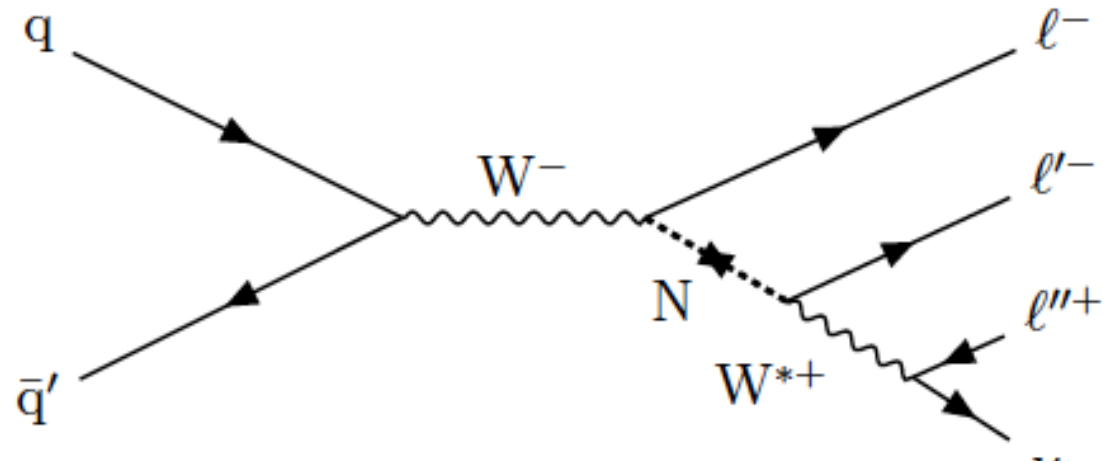


Heavy Neutral Leptons



1905.09787

Prompt and displaced

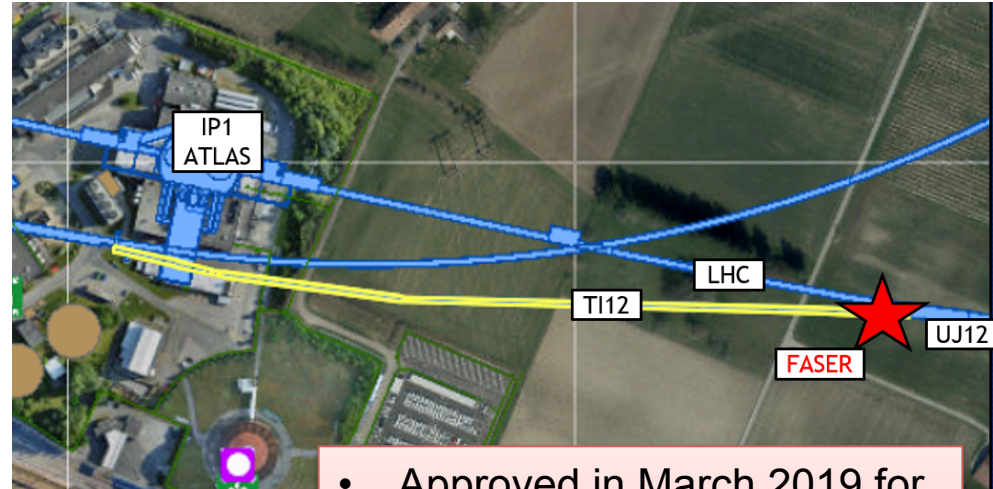




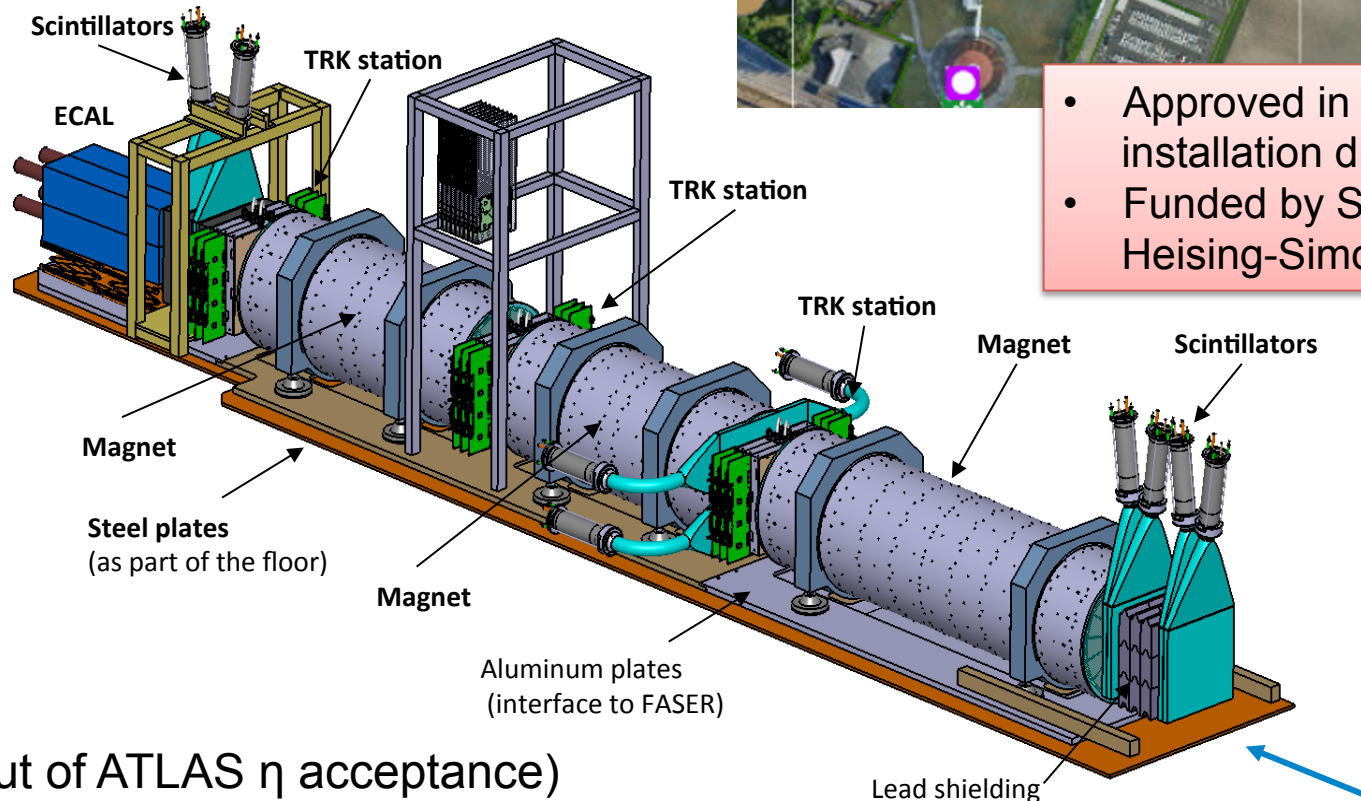
FASER

Search for light, weakly-coupled new particles in decay of low-mass SM particles

- E.g. dark photons & axion-like particles
- Exploit enormous production rate at $\eta \sim 0$



- Approved in March 2019 for installation during LS2
- Funded by Simons and Heising-Simons foundations

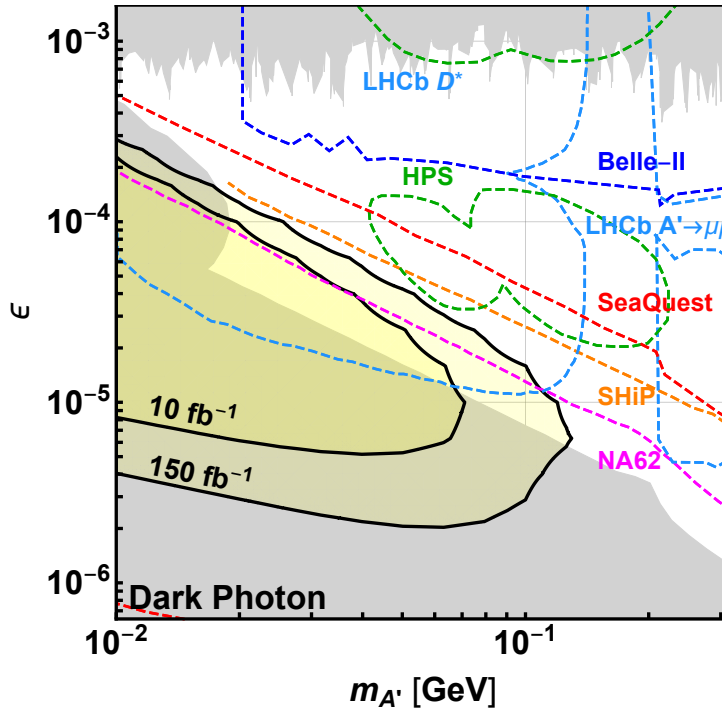


(totally out of ATLAS η acceptance)

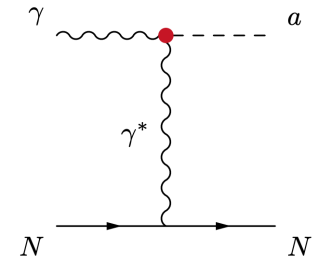
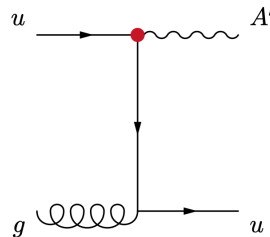
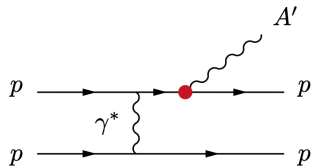
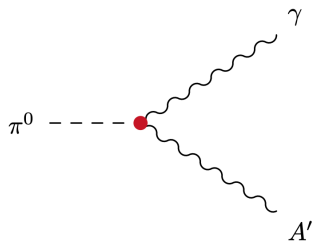
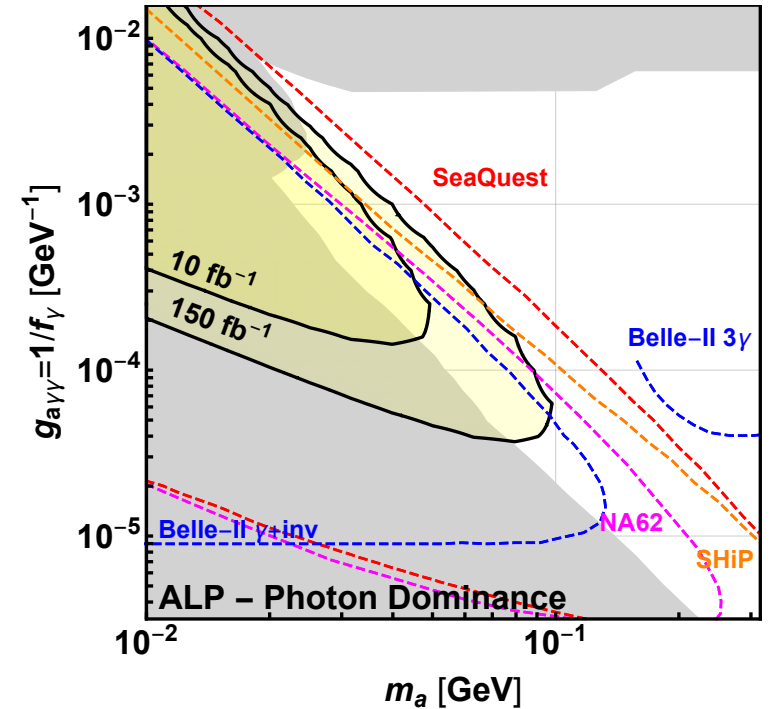
FASER physics reach in Run 3



Dark Photons



ALPs
with dominant γ coupling





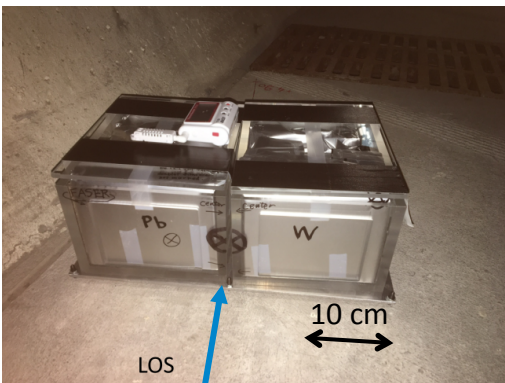
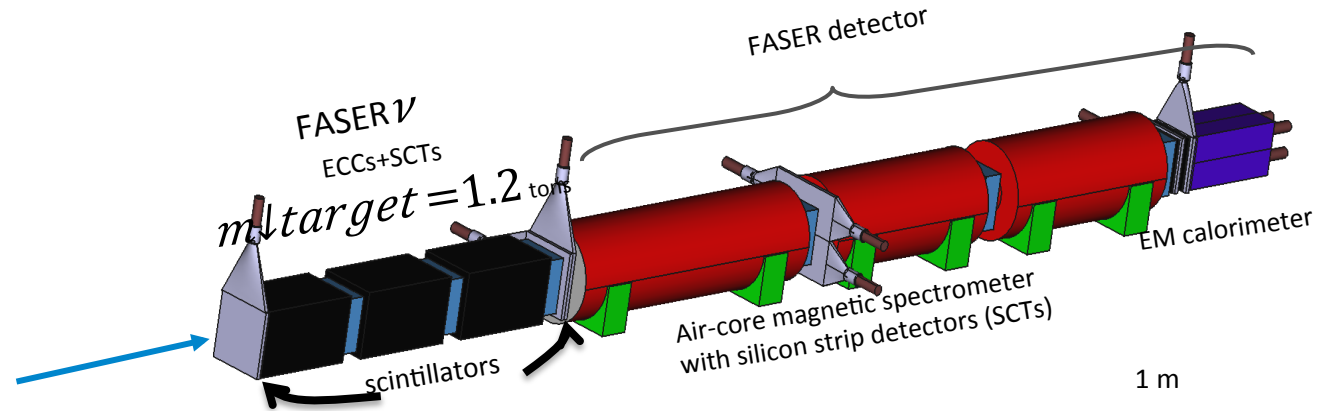
Possible extension of FASER for unique study of high-energy (300 GeV - few TeV) neutrinos in colliders in Run 3 (~20k ν expected)

Base design:

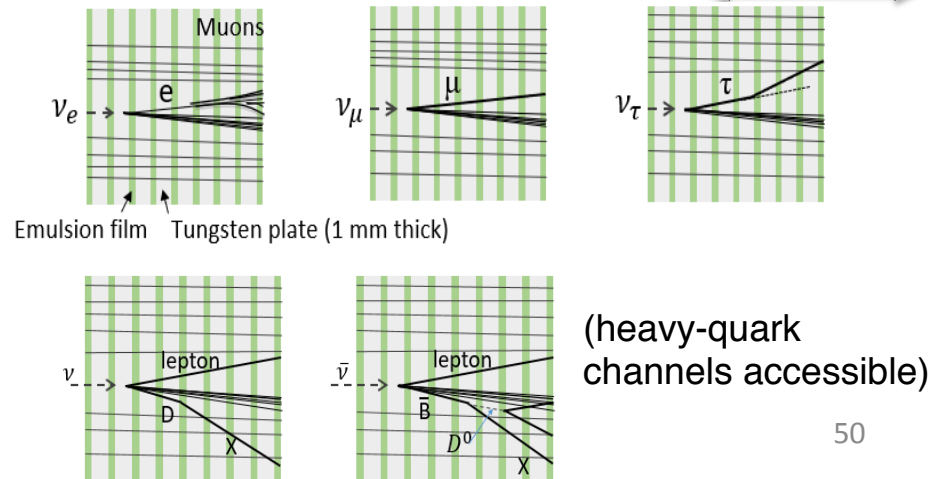
- Emulsion-tungsten
- 1.2 tons

Pilot detector in 2018:



- 12.5 fb⁻¹
- 30 kg
- Data being analyzed: expect 30 ν



line of sight in T118 tunnel



Conclusion

- Very strong & diverse Swiss physics program
- Slow-growth era of LHC
 -  Innovation: trigger, search space, model interpretations, ML & experiment additions!
- Many  results still in the workings
 - CMS B-physics parking dataset
 - Some top measurements
 - Many more searches
 - Full Run-2 results

Acknowledgements

- Thanks a lot for input from
 - John Anders
 - Akitaka Ariga
 - Florencia Canelli
 - Mauro Donega
 - Christoph Grab
 - Peppe Iacobucci
 - Roland Jansky
 - Ben Kilminster
 - Steven Schramm
 - Anna Sfyrla
 - Rainer Wallny

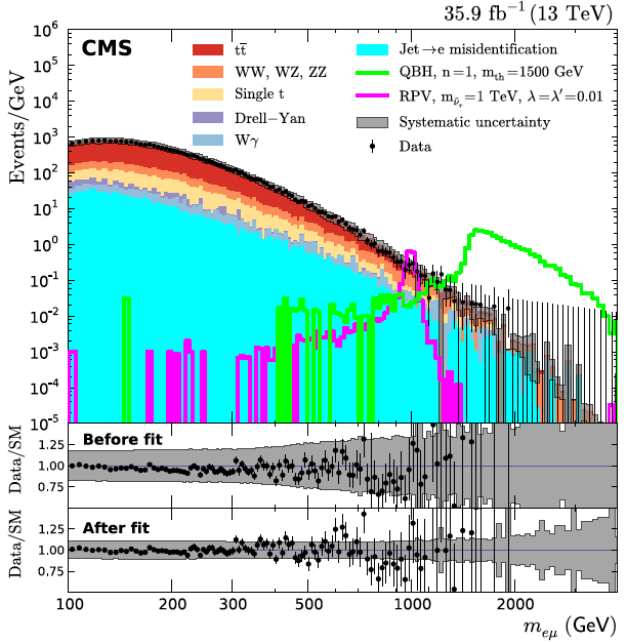
Backup

Flavor-violating dilepton resonances

1802.01122

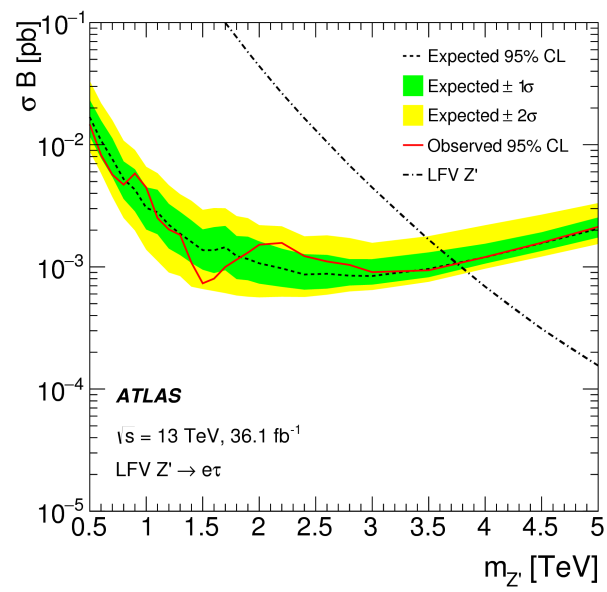
EXOT-2016-09

$e\mu$



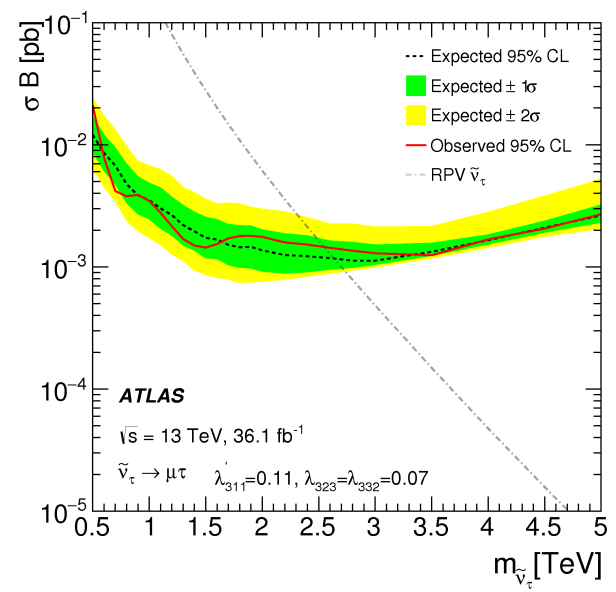
QBH production

$e\tau$



Z' with an LFV coupling

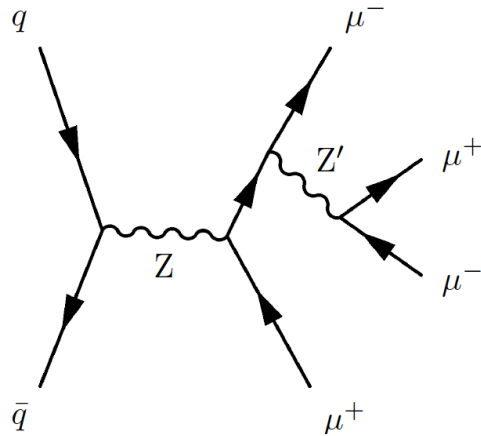
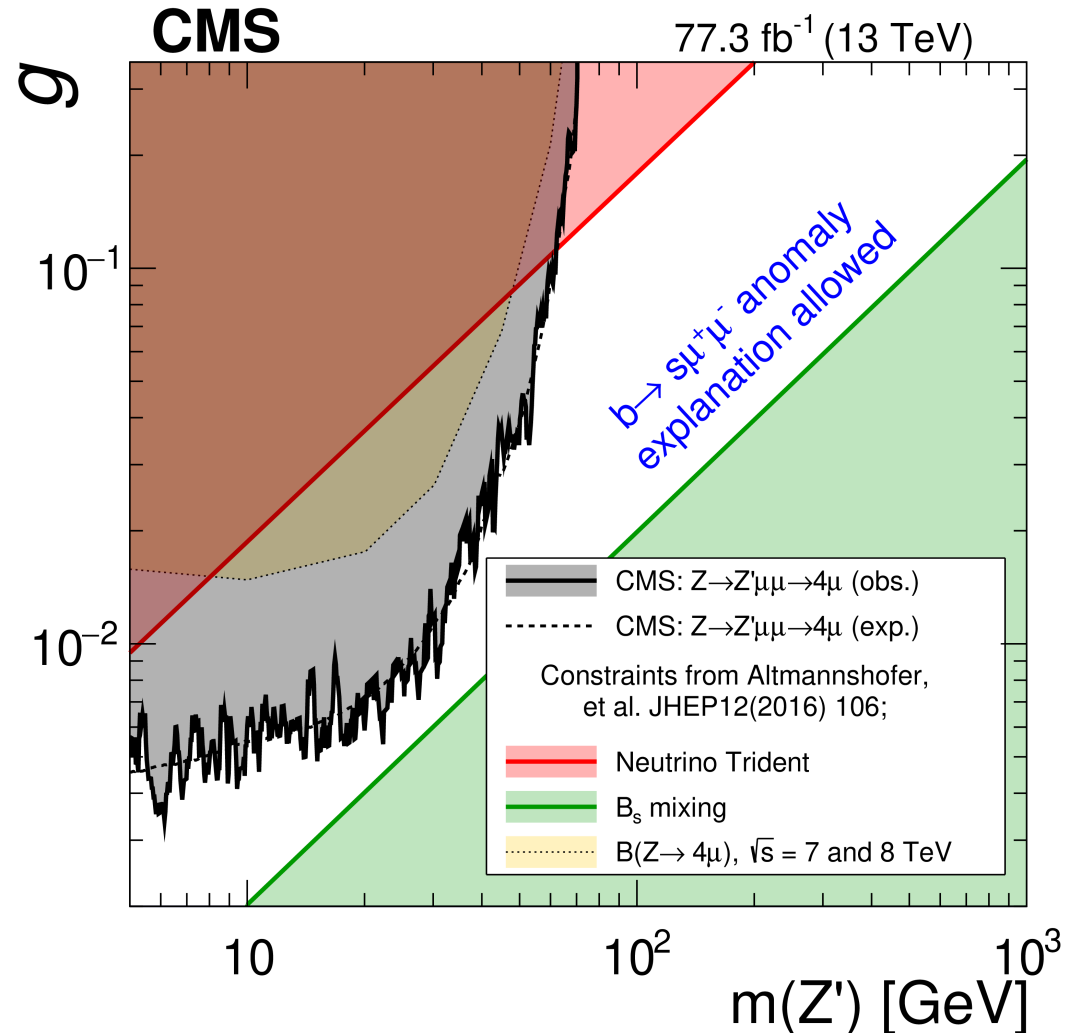
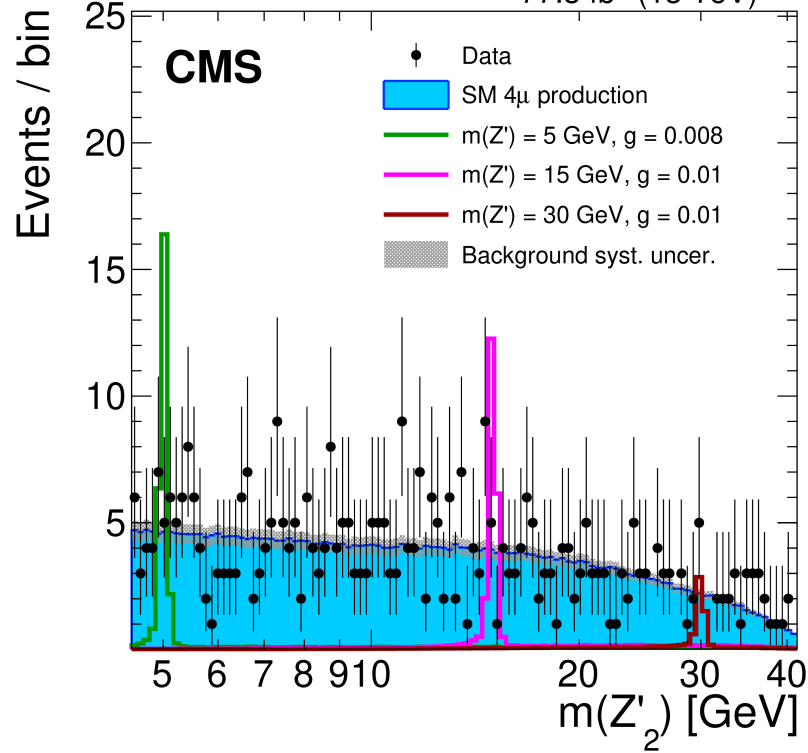
$\mu\tau$



RPV scalar neutrino

Z' search below the Z mass

- ✓ Dark Matter
- ✓ Anomalous muon magnetic moment
- ✓ B → K* μ⁺ μ⁻ anomalies

77.3 fb⁻¹ (13 TeV)

Combinations in *more complete model*

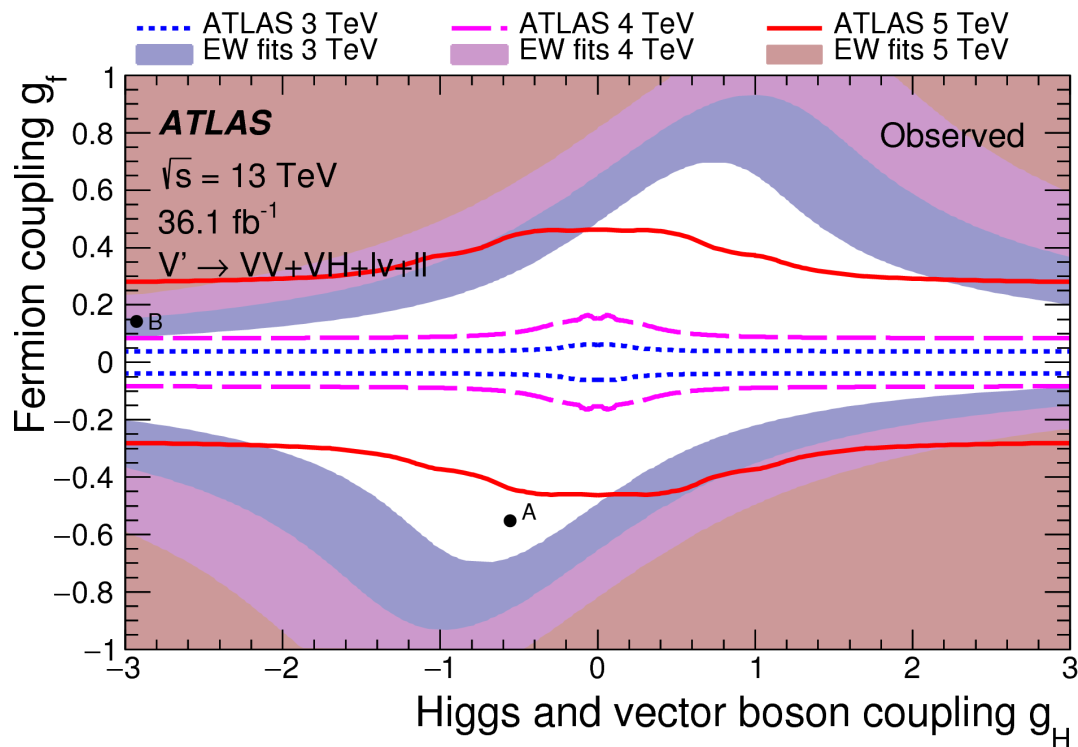
- Takes time + coordination
- More model-dependent
- Becoming more interesting now as we have no more big jumps in L and \sqrt{s}
- Examples:
 - HVT
 - DM+mediator
 - VLQ
 - SUSY

Interpretation in HVT model

Heavy vector triplet (HVT) model features triplet of colorless vector bosons V' (W'^+ , Z' , W'^-)

$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -g_q \mathcal{W}_{\mu}^a \bar{q}_k \gamma^{\mu} \frac{\sigma_a}{2} q_k - g_{\ell} \mathcal{W}_{\mu}^a \bar{\ell}_k \gamma^{\mu} \frac{\sigma_a}{2} \ell_k - g_H \left(\mathcal{W}_{\mu}^a H^{\dagger} \frac{\sigma_a}{2} i D^{\mu} H + \text{h.c.} \right)$$

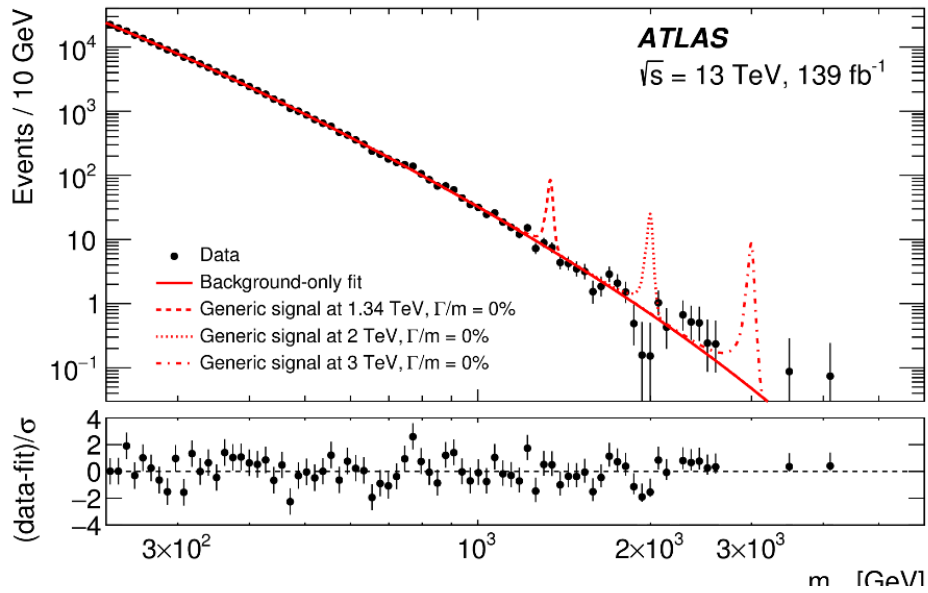
- g_q and g_{ℓ} : Universal coupling strength of V' to quarks and leptons
- g_H : Coupling strength of V' to Higgs field => to W and Z



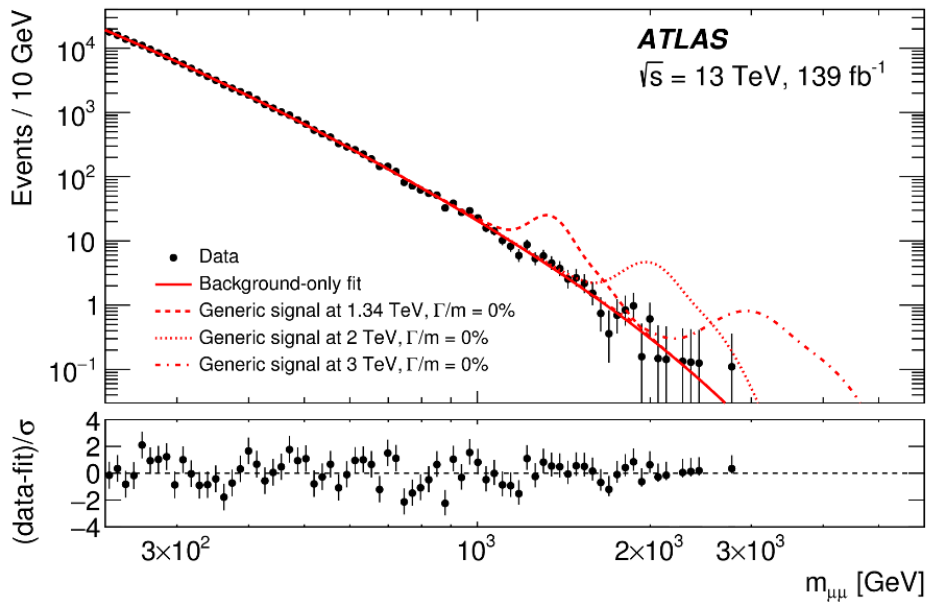
Luxury problem: too much data

- Di-jets: BG fitting,... Gaussian,...

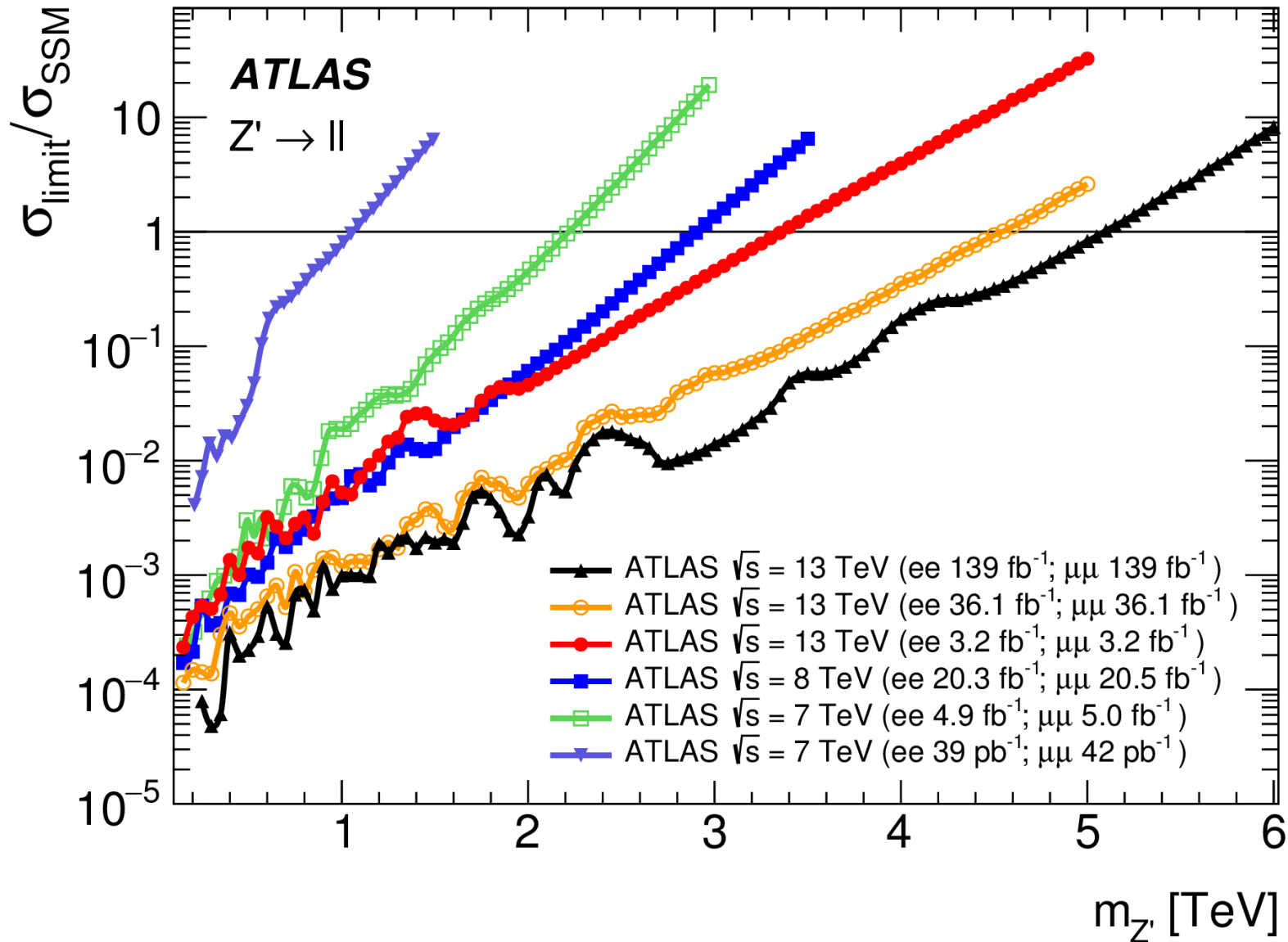
Dilepton Resonances



Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		ll	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

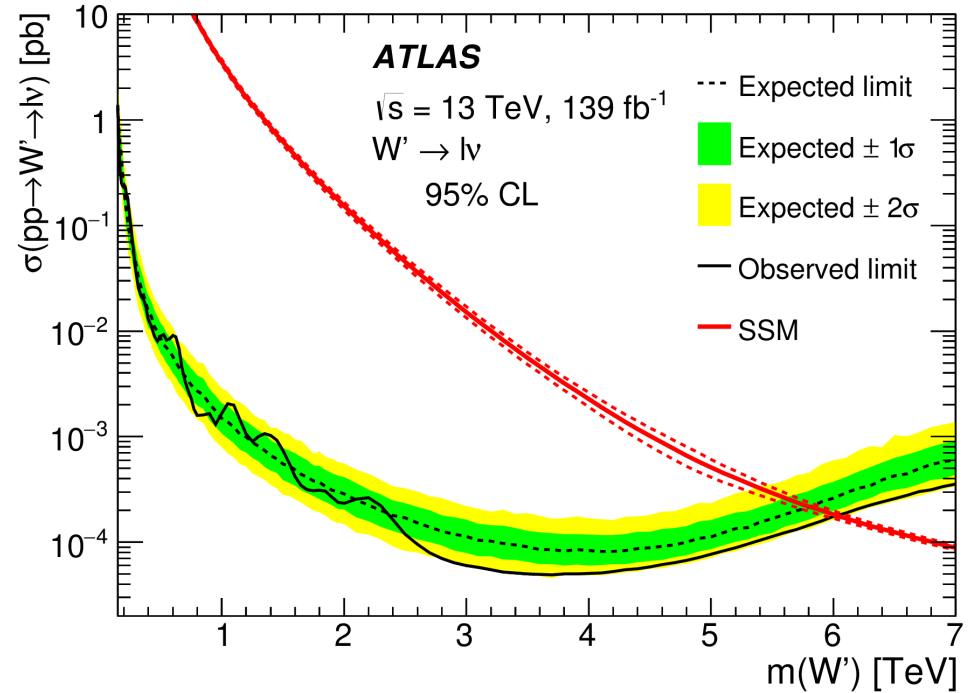
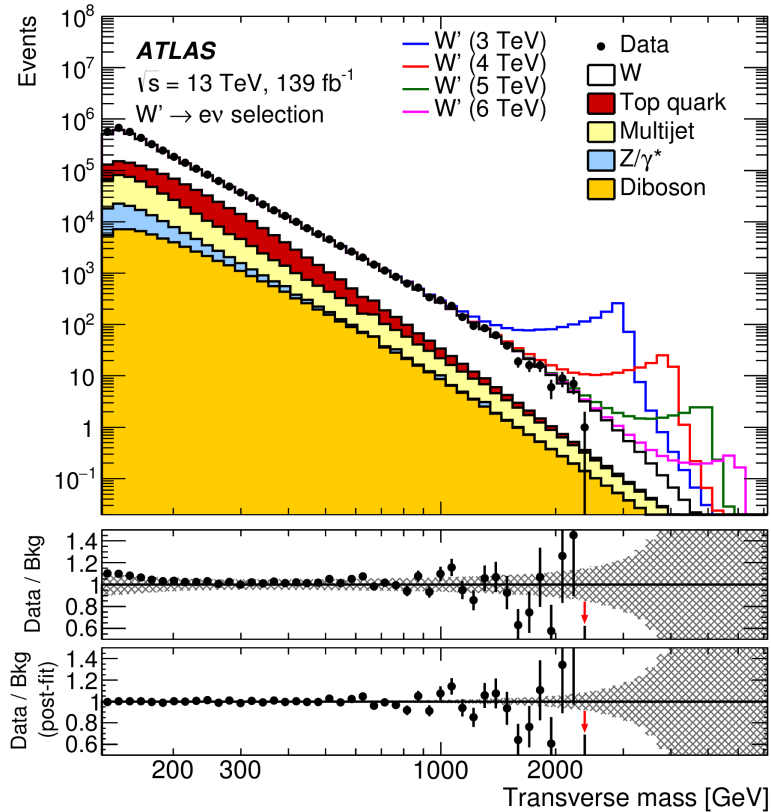


$Z' \rightarrow \ell\ell$ limits @95% CL over years

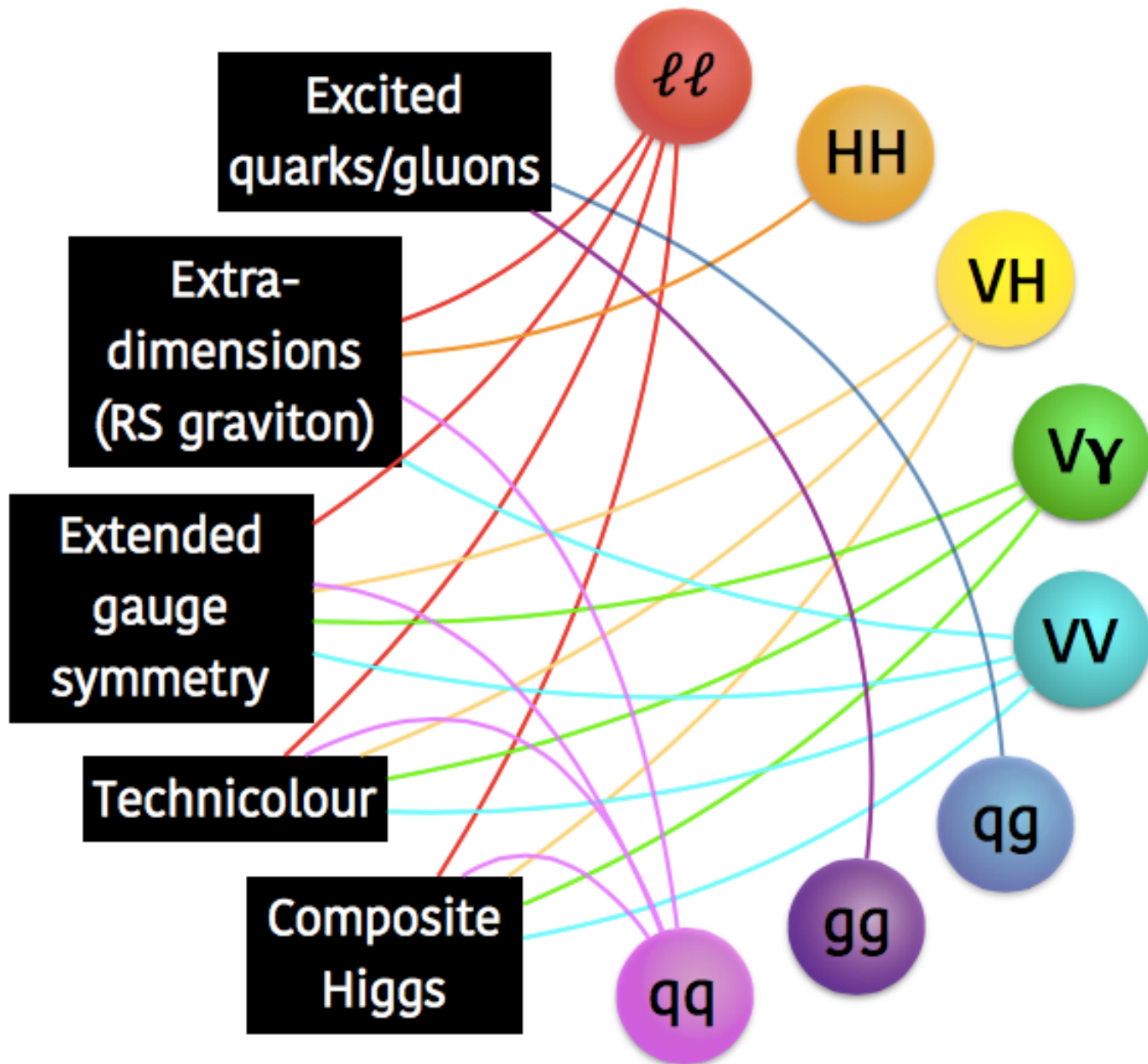


Fast increase in limits (1 TeV \rightarrow 5 TeV) in short period of time, **but...**⁶⁰

High-mass searches run out of steam



Many reasons to search for resonances

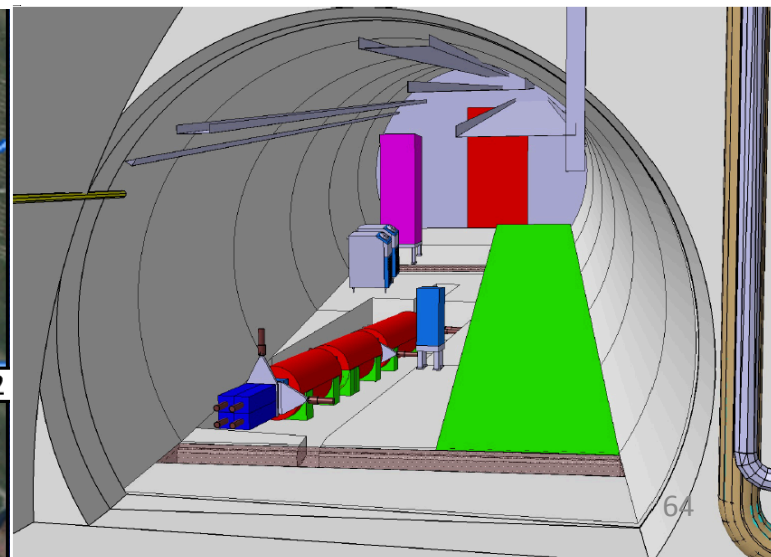


Part 2: The LHC search program

- The SM is complete
- In front of us lies the **Unknown**
 - Unprecedented
- Search program characteristics
 - Cover all areas: high mass, electroweak production, long-lived particles, forbidden decays, ...
 - Theory-agnostic, signature based searches, as well as highly targeted model-dependent ones

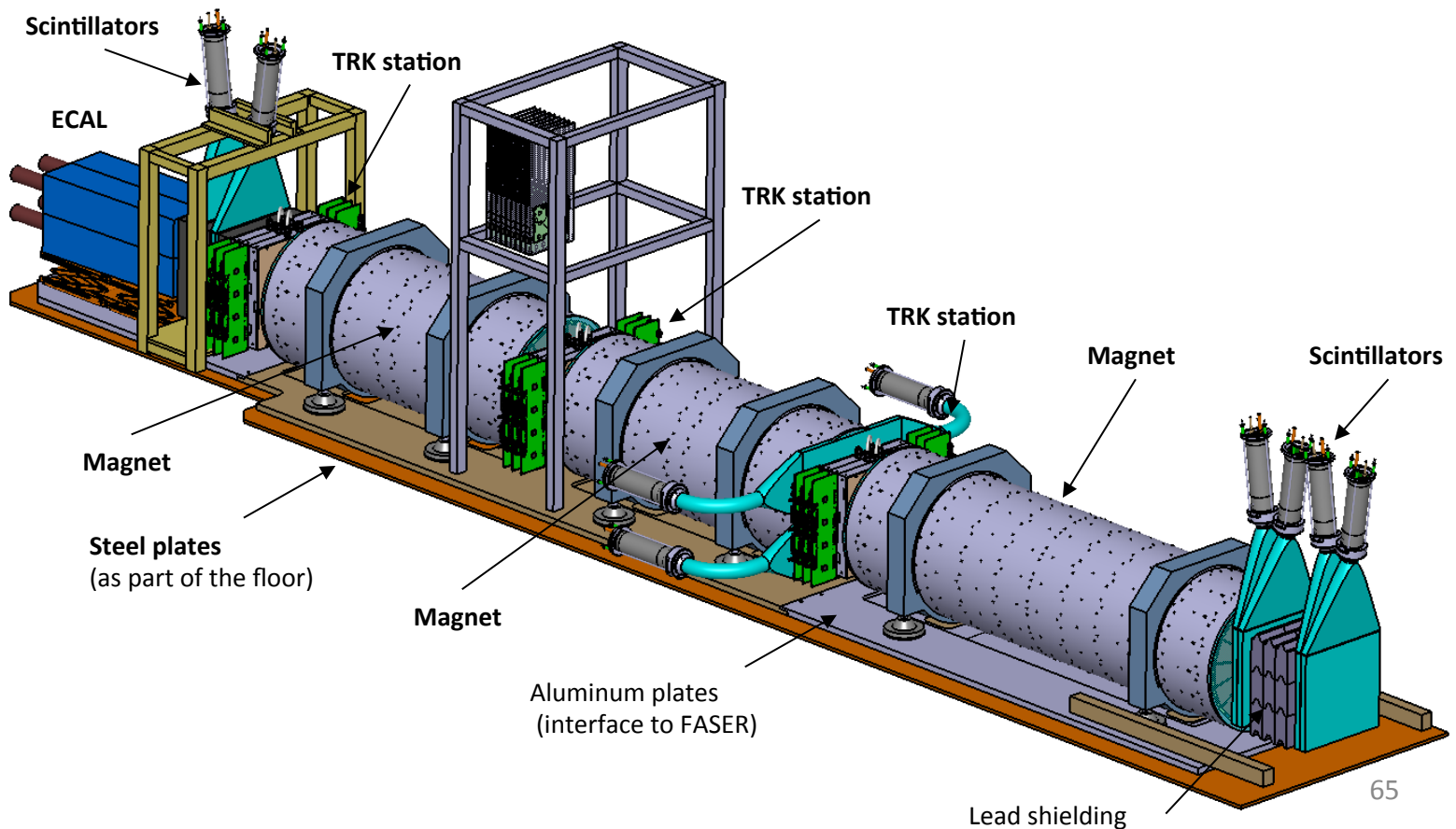


- **An experiment to search for light, weakly-coupled new particles**
 - E.g. dark photons and axion-like particles
 - produced in the decay of particles from LHC collisions, or in the interaction of them with material
- **FASER explores totally new phase-space**
 - exploits the very high production rate of SM particles at $\eta \sim 0$, totally out of ATLAS acceptance
 - despite the weak couplings to exotic new particles, the enormous production rate ensures promising acceptance
- **Approved in March 2019 for installation during LS2**
 - funded by Simons and Heising-Simons foundations
 - CERN contributes with services
 - Universities (incl. UniGe) contribute with personnel
 - Groups of G. Iacobucci, A. Sfyrla and engineering teams



FASER

- **FASER detector:**
 - uses spare ATLAS silicon strip modules and LHCb ECAL
 - new permanent magnets being constructed at CERN
- **UniGe leading contributions at:**
 - General infrastructure
 - Tracker (mechanics & readout)
 - TDAQ (trigger electronics and DAQ software)
 - Offline software

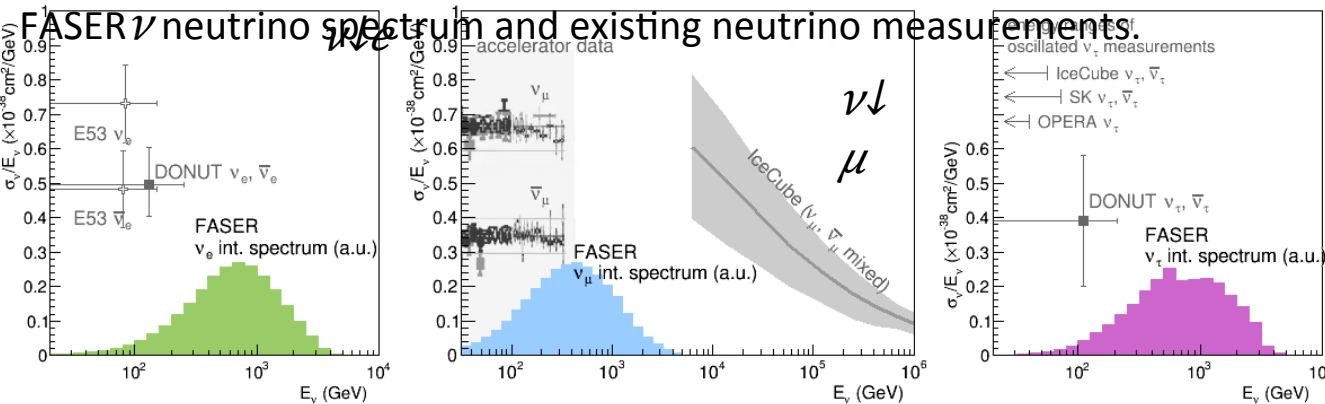


FASER ν : Neutrino studies at the high energy frontier



- On top of the BSM particle searches, the FASER collaboration is actively studying possible neutrino measurements \rightarrow FASER ν
- Three neutrino flavors in the currently unexplored energy range (300 GeV – a few TeV) will be studied \rightarrow lepton universality testing
- Thanks to the high energy, $\nu \downarrow \tau$ as well as heavy quark (charm, beauty) channels are kinematically accessible
- It will be the first attempt to exploit neutrinos from colliders. New domain of neutrino study, possible extension to the HL-LHC / FCC
- Aiming to take data in Run3, and seeking for funding

Expected # of interactions in Run 3 (2021–2023) with 7+7 TeV, 150 fb⁻¹, detector mass 1.2 ton

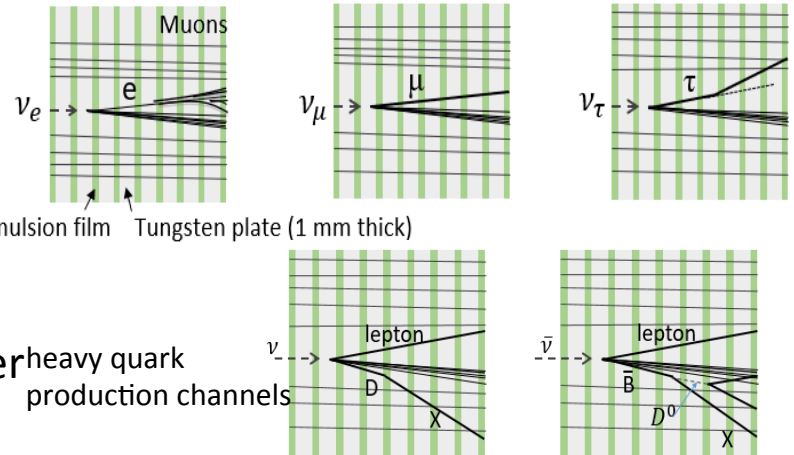


	# of CC interactions	Mean interacting energy
$\nu e + \nu \downarrow e$	1296	827 GeV
$\nu \mu + \nu \downarrow \mu$	20439	631 GeV
$\nu \tau + \nu \downarrow \tau$	21	965 GeV

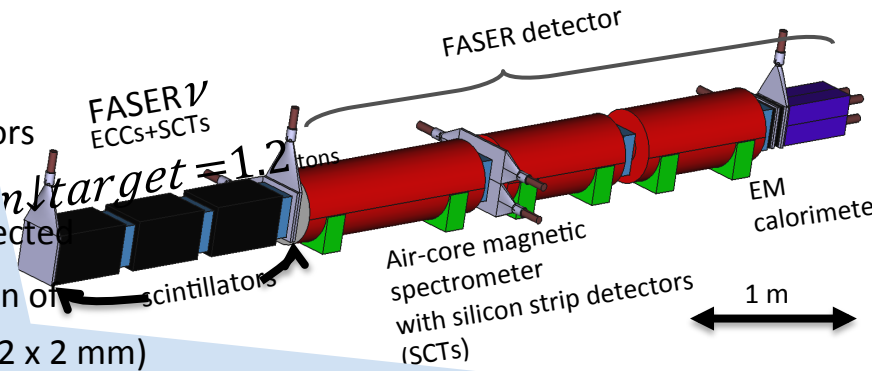
FASER ν detector for Run 3, and pilot run in 2018

- Base design: Emulsion / tungsten detector
 - Sensitive to heavy flavors (τ , charm, beauty)
 - target mass = 1.2 tons
- A hybrid structure with the FASER spectrometer is under discussion, to complement timing and kinematical information
- Pilot neutrino detector in 2018
 - 30 kg emulsion/tungsten and emulsion/lead detectors
 - 12.5 fb⁻¹ of data collected \rightarrow 30 ν interactions expected
 - Analysis on going, aiming to report the first detection of neutrinos from LHC

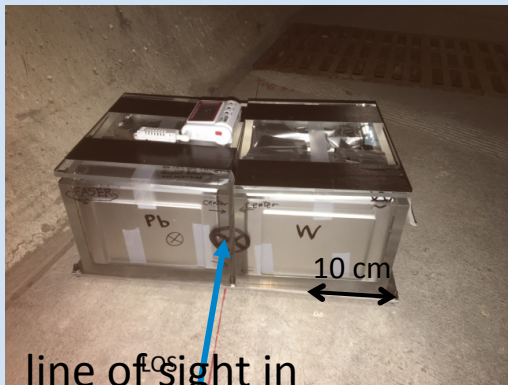
Emulsion neutrino detector for flavor sensitivity



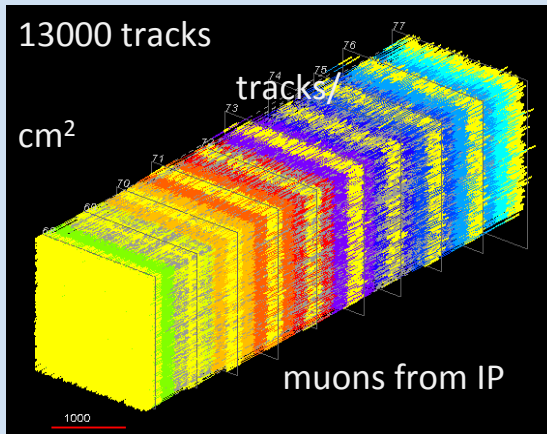
UniBe, A. Ariga



Reconstructed data (pilot run, 2 x 2 mm)



line of sight in T118 tunnel



muons from IP

One of the neutral vertices found in data

