Anna Lipniacka www.uib.no/ift

Insights to “Planck Scale” at the Large Hadron Collider, prospects

The Standard Model of particle physics has been tested at the LHC with an outstanding accuracy. Its last particle, the Higgs boson, was experimentally observed 11 years ago by ATLAS and CMS experiments at and has been studied with an increased accuracy since then. Yet, all the particles of the Standard Model make only 5% of matter-energy budget of the observable Universe. The Standard Model does not give an explanation why even this 5% exists. Moreover, the Higgs boson seems to have “set” the vacuum of our Universe in an energetically metastable state. The low value of now precisely measured Higgs boson mass, also remains a mystery from a theory point of view. The LHC data analyzed so far corresponds to ~7% of what the LHC experiment will register during the full machine life-time. The second year of the Run 3 of the LHC has just started and will bring important amount of data.

Prospects and the relevance of LHC the physics of the Early Universe are discussed.

Disclaimer: This talk covers primarily CMS and ATLAS results, for LHCb results see Monica Pepe-Altarelli’s talk on Wednesday.

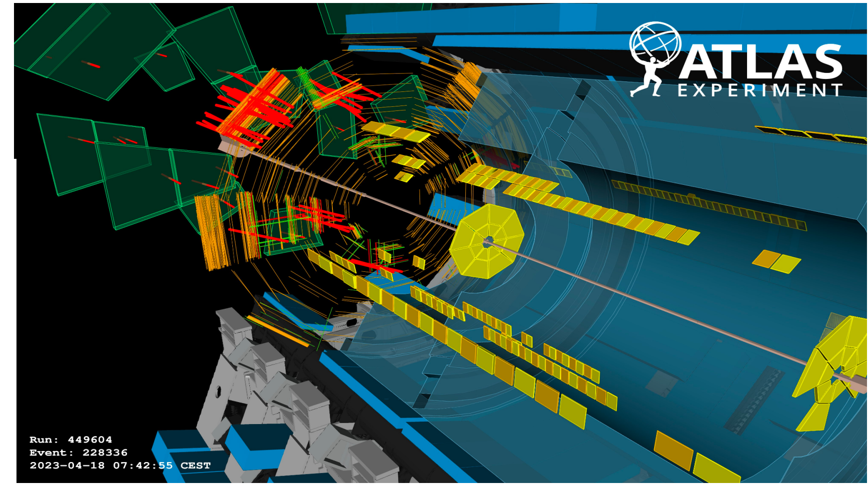
Norwegian Financial Mechanism years 2014-2021
grant 2019/34/H/ST2/00707

The Outline

1) The Big Picture.

2) Prospects towards the "Planck Scale"
EWSB (and the vacuum potential),
CP violation (baryogenesis)
Dark Matter.

The second year of Run3 started in April 2023
Run2 data are still being exploited.



Particle	Produced in 139 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.7 million	
Top quark	275 million	
Z boson	2.8 billion	($\rightarrow \ell\ell$, 290 million)
W boson	12 billion	($\rightarrow \ell\nu$, 3.7 billion)
Bottom quark	~40 trillion	(significantly reduced by acceptance)

For ATLAS&CMS

Run 3+2 **(2022 end of 2025) ~500 1/fb (factor ~4)**
Run 4+3+2 **(2029 end of 2032) ~1000 1/fb (factor ~7)**
Run 5+4+3+2 **(– end of 2041*) ~3000 1/fb (factor ~20)**

~statistical improvement factor ~2, ~2.5 , ~4.5
some measurements will be systematics/theory error dominated. Higher statistic will allow for more precise studies of systematics effects.

*Far future. We may face disruptive technologies (see 2 ML talks later today by Claudius Krause and Matthew Schwartz).. **and disruptive events of unknown consequences- obviously we live in a less stable world than we thought few years ago.**

Planck2023 Scale and the LHC, prospects

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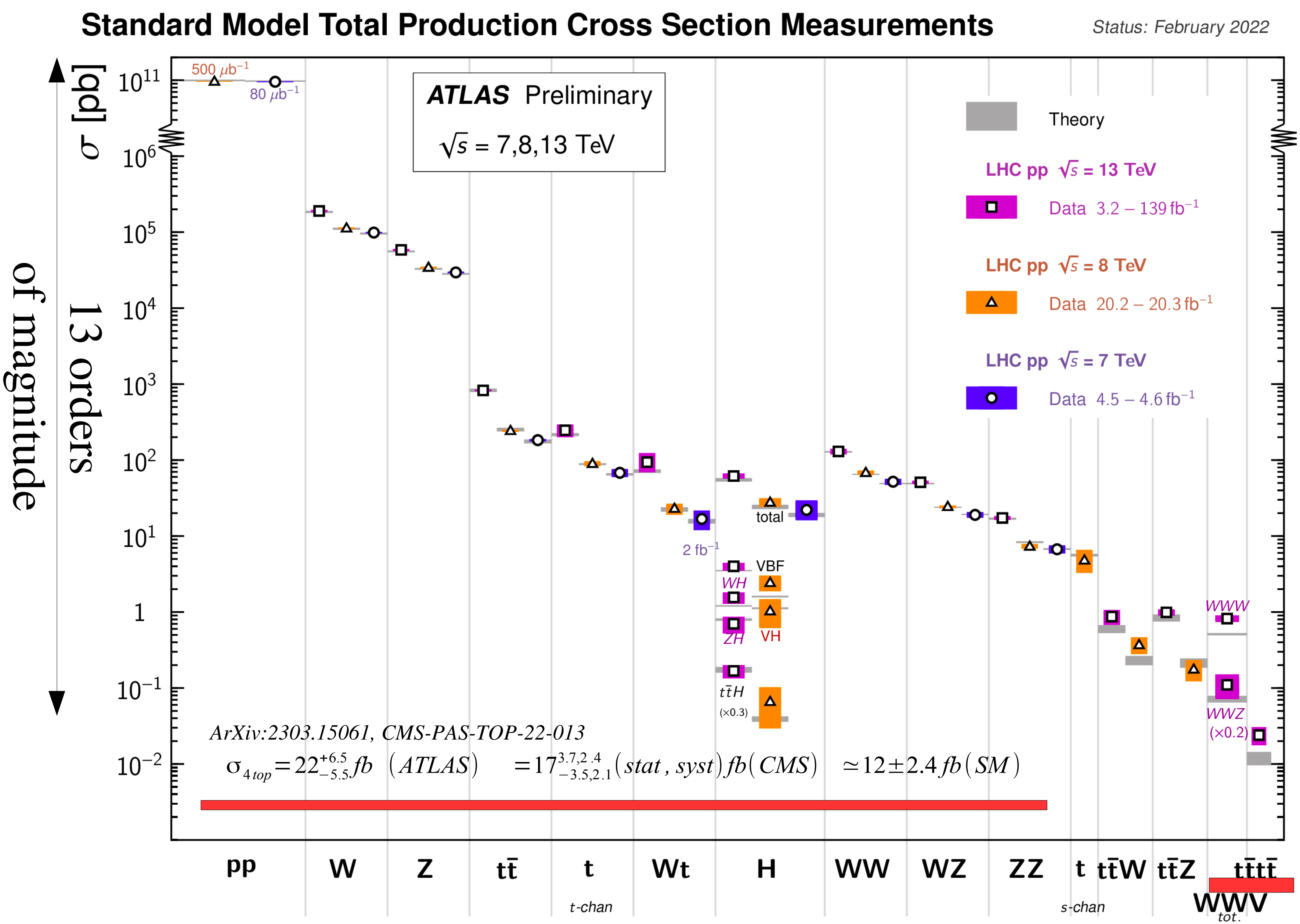
The Big Picture, precision cross-sections.



Slide 4

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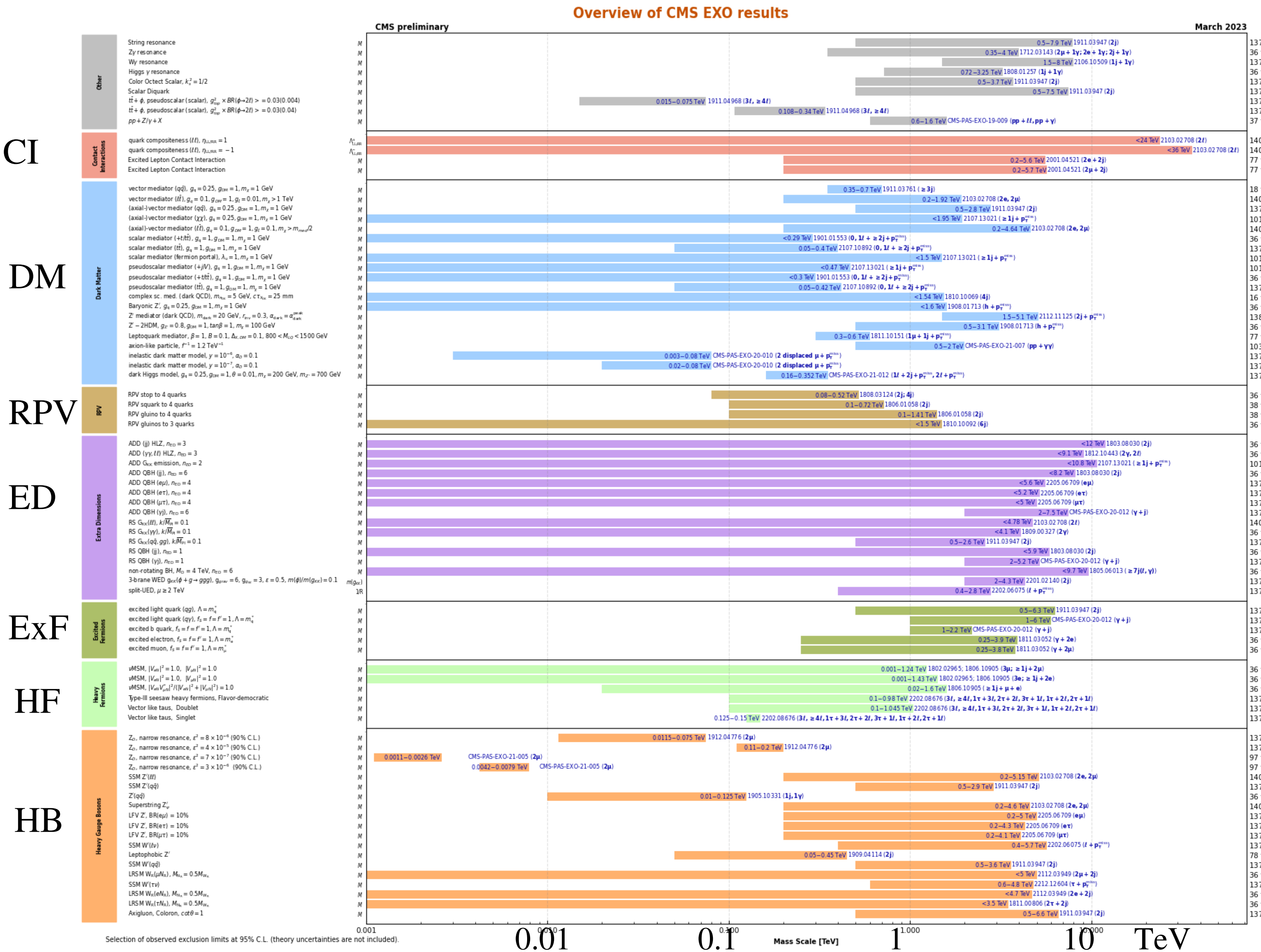
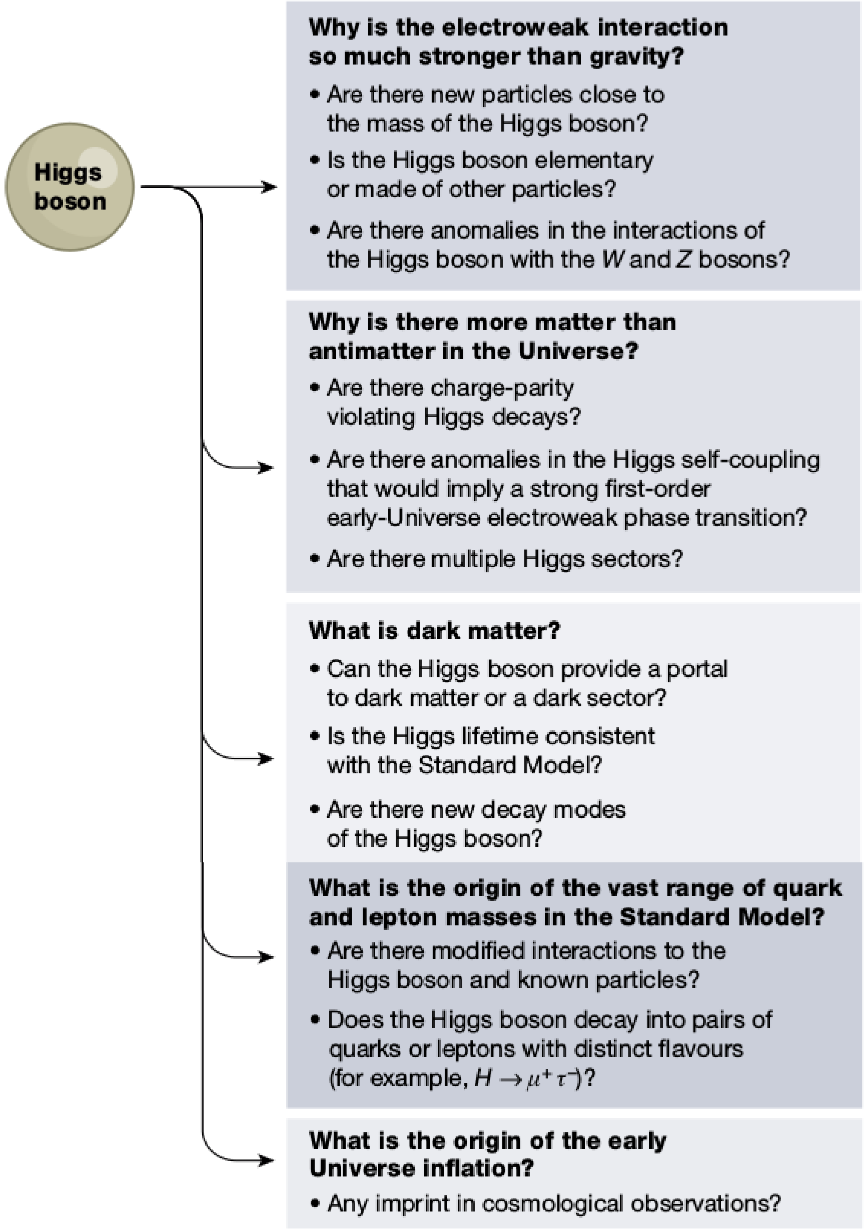
The Big Picture: No new particles yet.

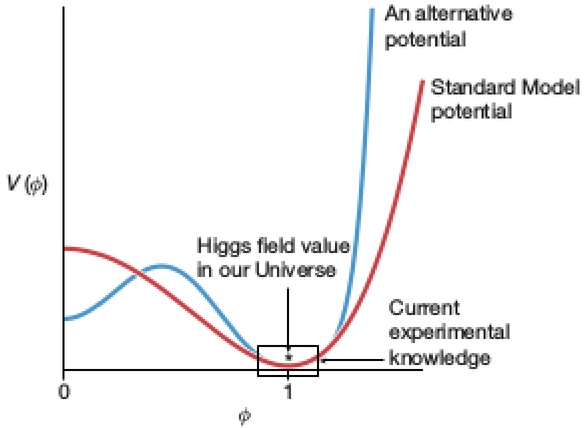


In some searches, mass scales of ~ 5 TeV reached.

The Big Picture:The Higgs boson and friends (10+ years)



The Higgs field:
The only know elementary(?) scalar field. Related to the inflaton? Determines the shape of the vacuum potential. Can we have another, deeper minimum?
Close relations: top and W,Z
Can Higgs be a portal to Dark Matter?
Can CP viotation in Higgs couplings explain the matter-antimatter asymmetry ?



Gavin P. Salam[1,2], Lian-Tao Wang[3] & Giulia Zanderighi[4,5]

https://www.nature.com/articles/s41586-022-04899-4.pdf

The Big Picture:The Higgs boson and friends (10+ years)

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2 + [\bar{\psi}_{Li}Y_{ij}\psi_{Rj}\phi + h.c.]$$

Vacuum energy $V_{0exp} \sim (2.10^{-3}\ eV)^4$

Origin of quadratic divergences. Hierarchy problem

Possible instability depending on m_H

The flavour problem: large unexplained ratios of Y_{ij} Yukawa constants

Guido Altarelli
Lepton Photon 2009

Higgs mass and interactions (thus width*) are related to big questions.

ATLAS, ATLAS-CONF-2022-068, https://arxiv.org/abs/2207.00320

$m_H = 124.99 \pm 0.19\ [\pm 0.18(stat) \pm 0.04(syst)]\ GeV$ $\Gamma_H = 4.6^{+2.6}_{-2.5}\ MeV\ @68\%\ C.L.$

CMS, Phys Lett. B 805(2020)135425 , Nat. Phys.18 (2020) 1329

$m_H = 125.38 \pm 0.14\ [\pm 0.11(stat) \pm 0.08(syst)]\ GeV$ $\Gamma_H = 3.2^{+2.4}_{-1.7}\ MeV\ @68\%\ C.L.$

CMS PAS FTR-22-001

ATLAS+CMS, HL-LHC prospect $\Gamma_H = 4.1^{+0.7}_{-0.8}\ MeV$

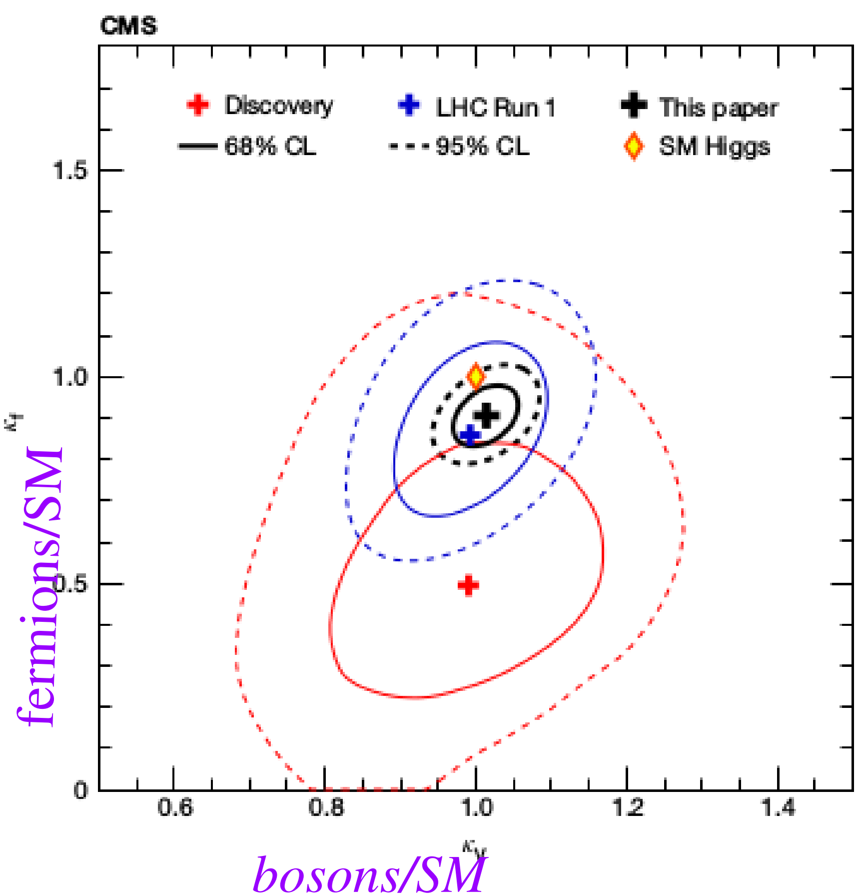
CMS HL-LHC m_H = 125.38 ± 0.07 (± 0.02 stat.) GeV

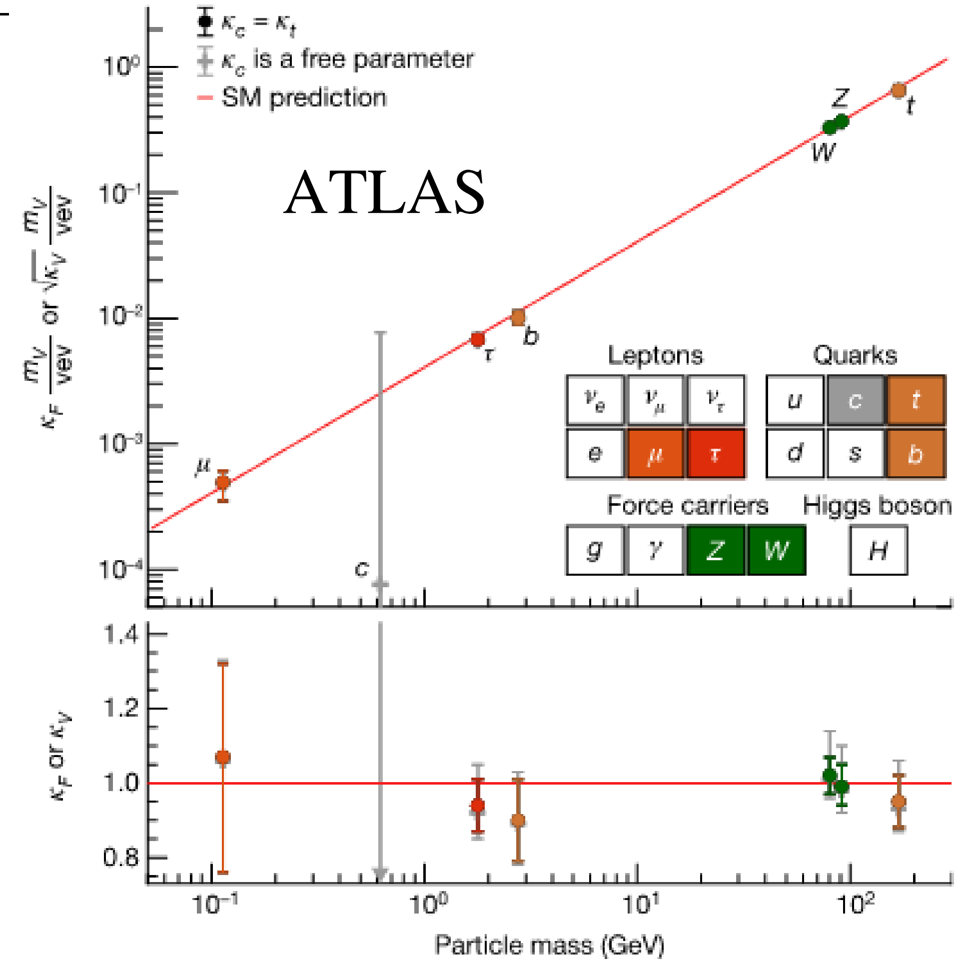
Masses of Higgs, top and W,Z are related and probe the consistency of the SM/ can indicate BSM physics

*4.07 MeV in SM. Present limit on Br Higgs→ invisible ~10%

The Big Picture:The Higgs boson and friends (10+ years)

Couplings to fermions and bosons(~m_f , ~m^2_v). Within 2σ from the SM. We cannot yet (significantly) challenge many BSM models.

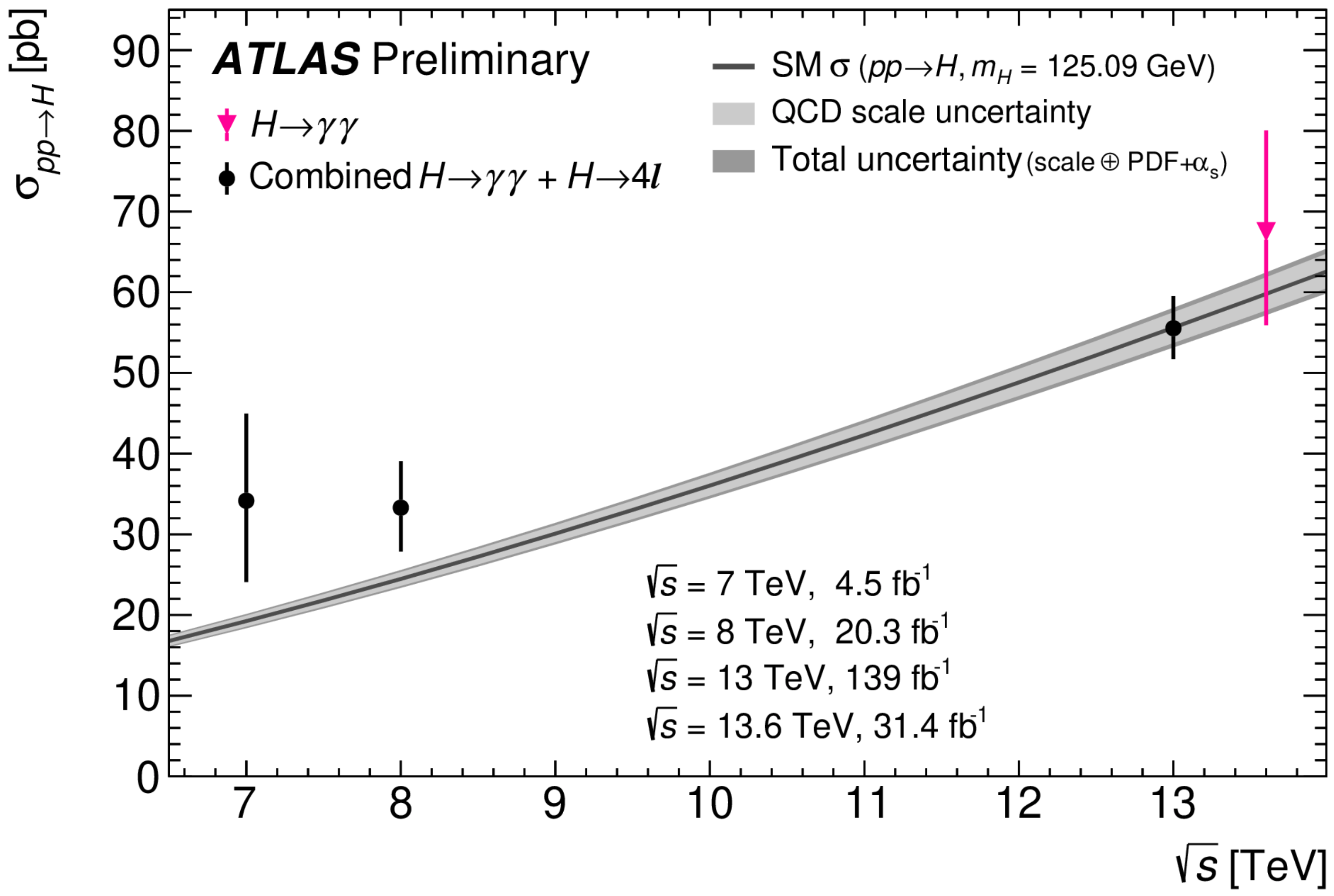




https://www.nature.com/articles/s41586-022-04893-w.pdf
https://www.nature.com/articles/s41586-022-04892-x.pdf

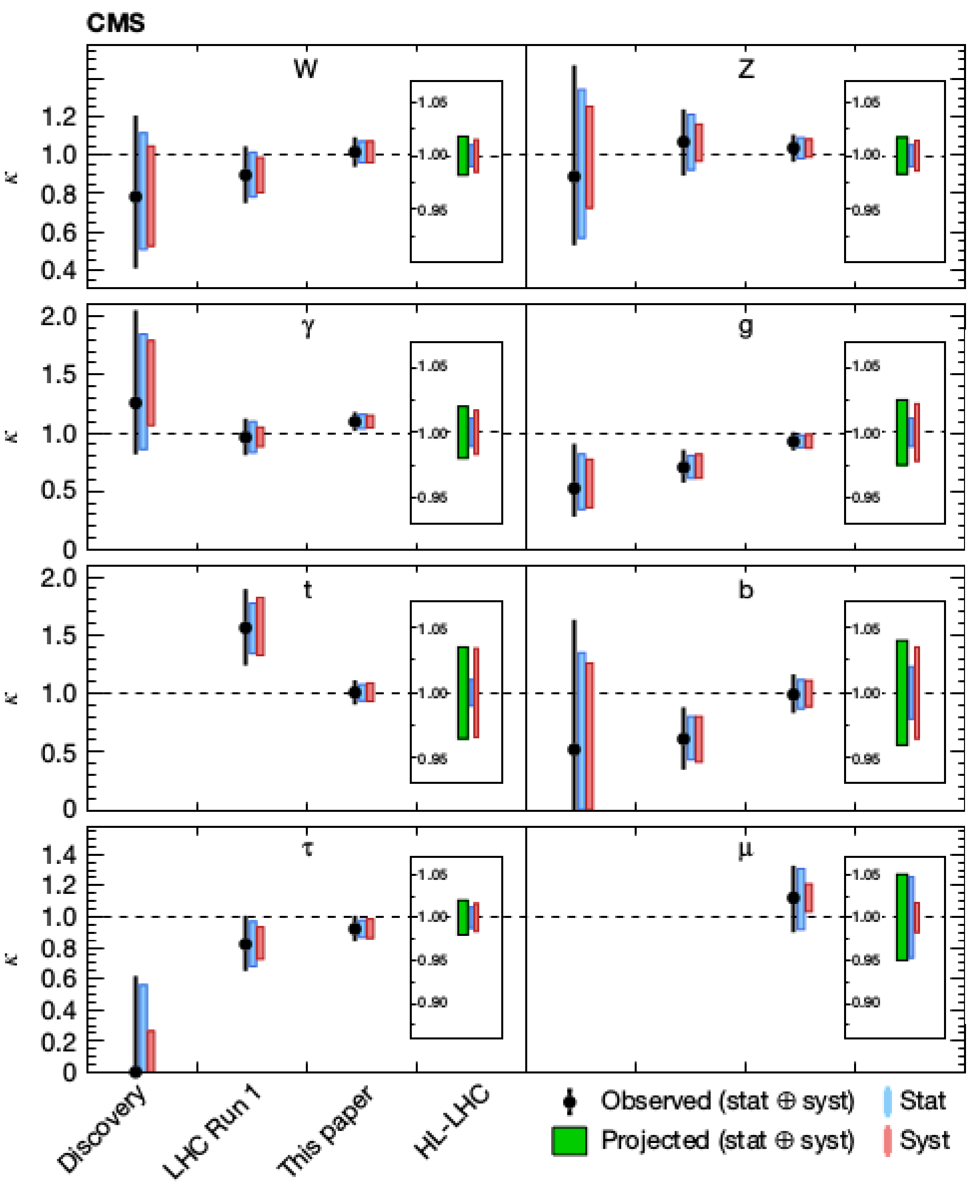
The Higgs boson at 13.6 TeV

ATLAS-CONF-2023-003

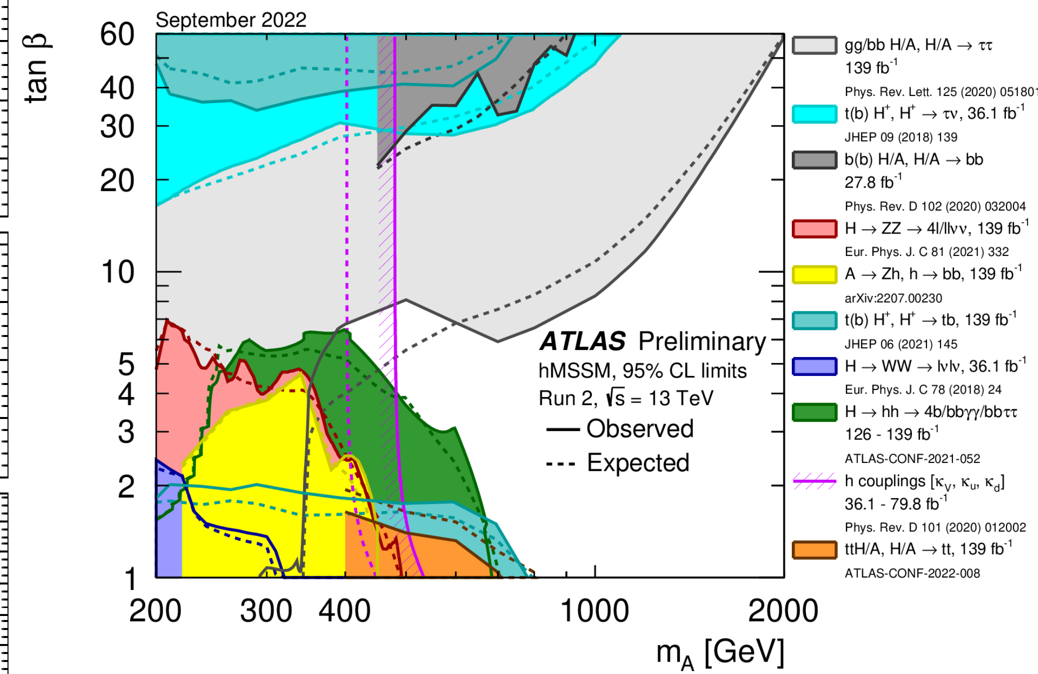


13.6 TeV point added into H→ γγ cross-section

The Big Picture:The Higgs boson and friends (10+ years)

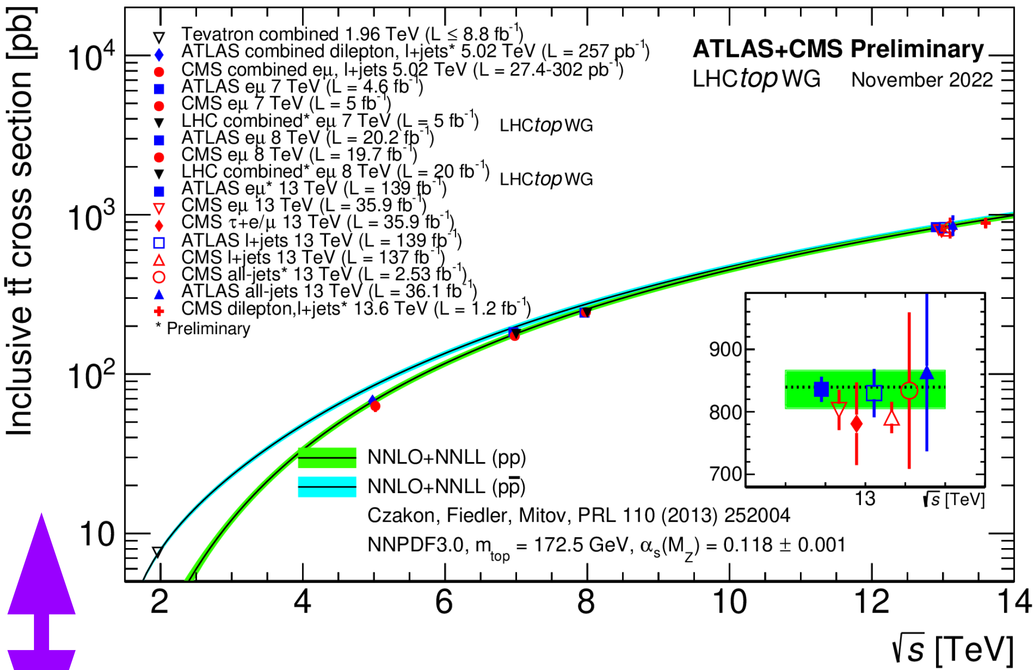


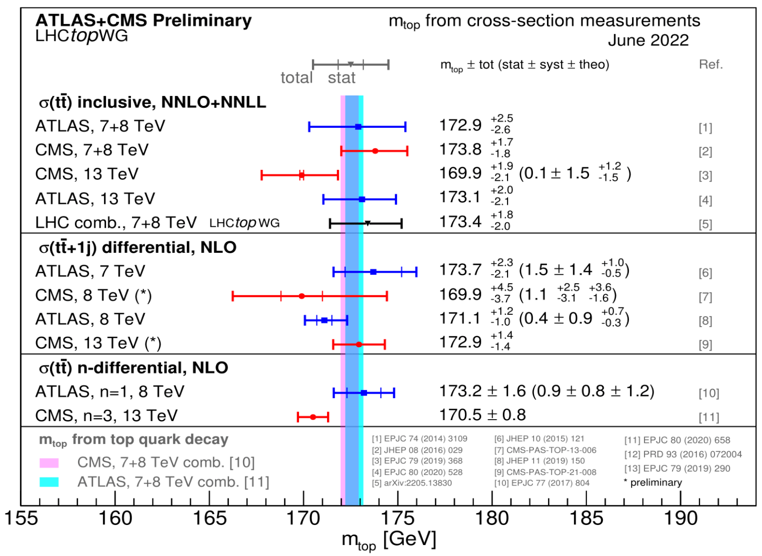
Some couplings will have an accuracy approaching 1-2% at the HL-LHC. This will allow to probe further some of the SM extensions. Example here: hMSSM to m_A approaching 1000 GeV

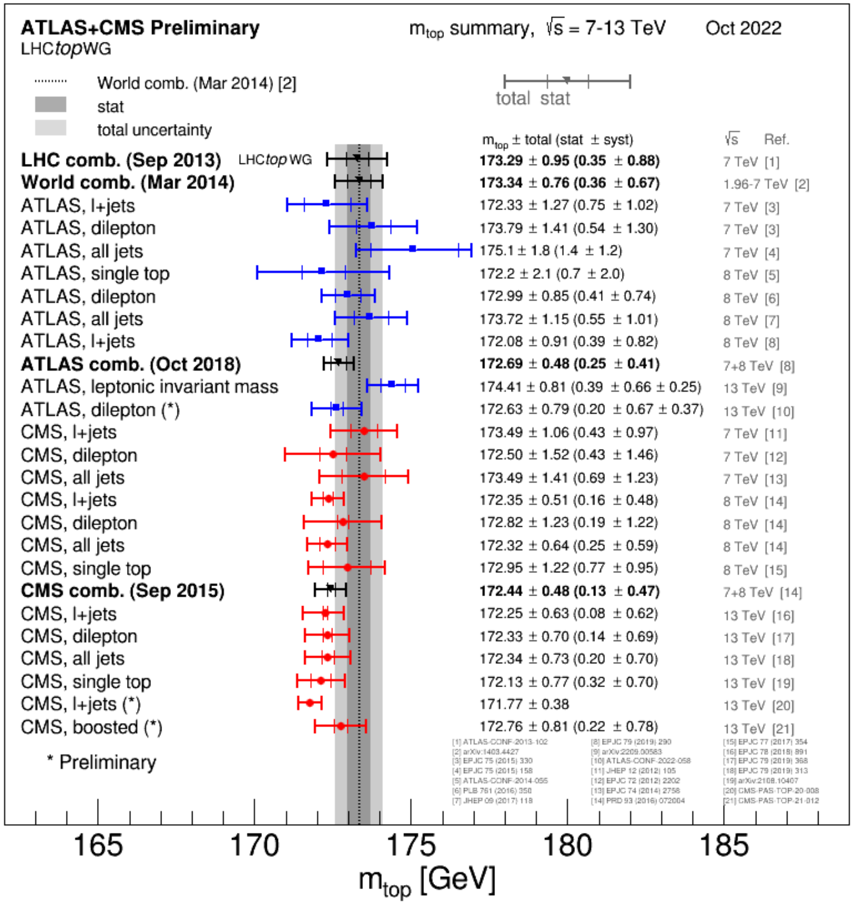


https://www.nature.com/articles/s41586-022-04892-x.pdf

EWSB: the top quark



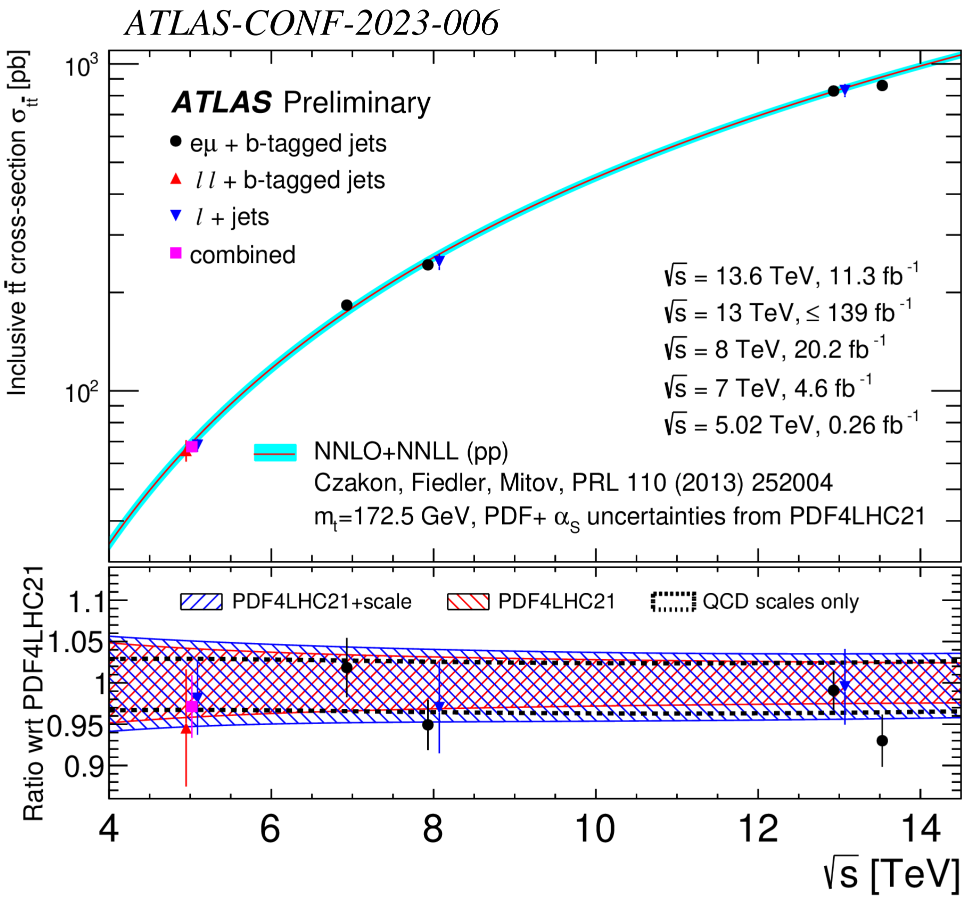


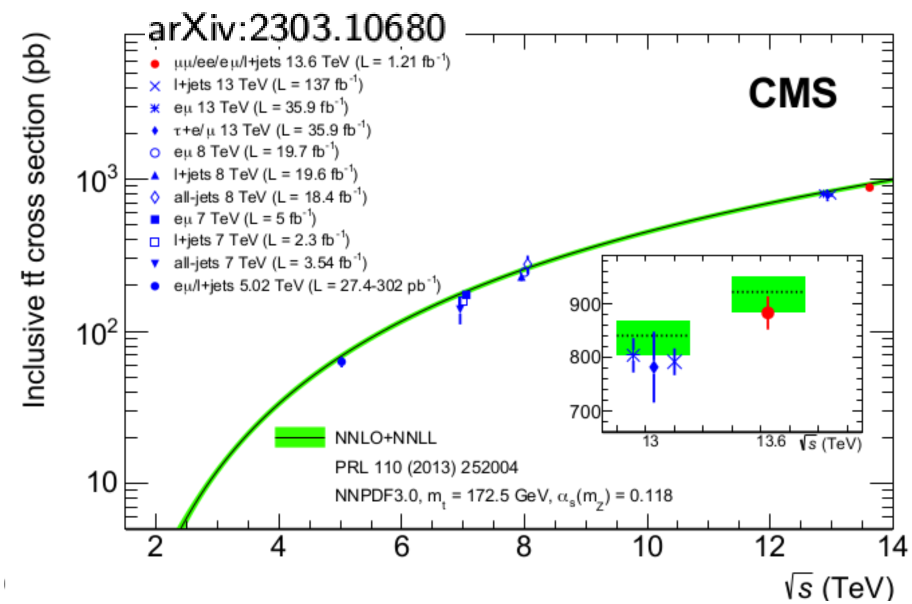


Top quark mass known to ~0.5 GeV

Systematic errors dominate.

The top quark at 13.6 TeV

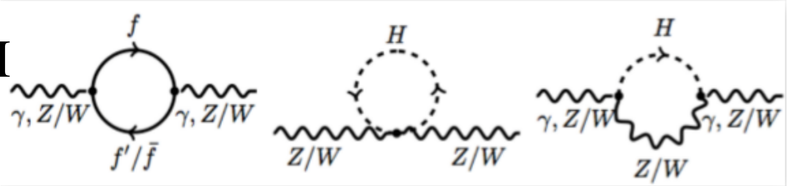




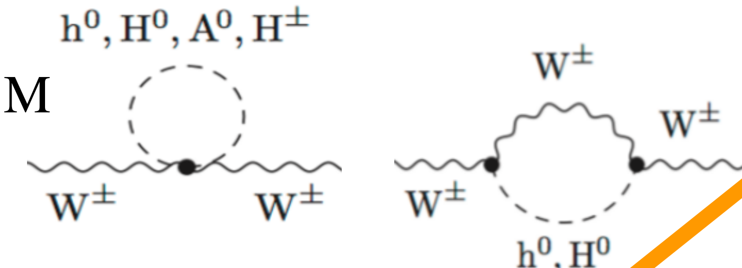
Run3 data analyses ongoing and 13.6 TeV point added into the cross-sections scan with preliminary but robust luminosity calibration. Run 2 results now reached 1.8% accuracy, more precise due to the new luminosity calibration (*ATLAS- CONF-2023-006*) **.**

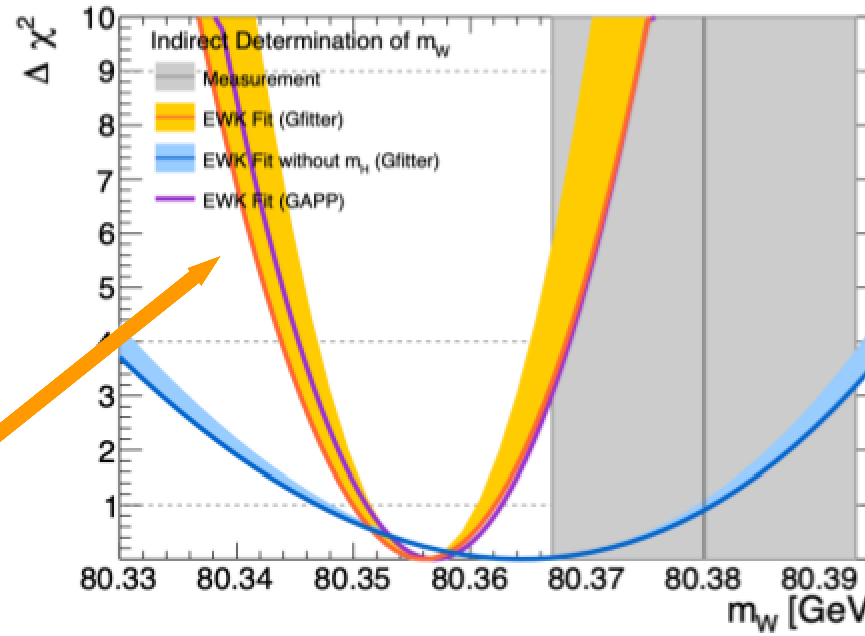
EWSB: M_W, M_H, M_{top}

SM



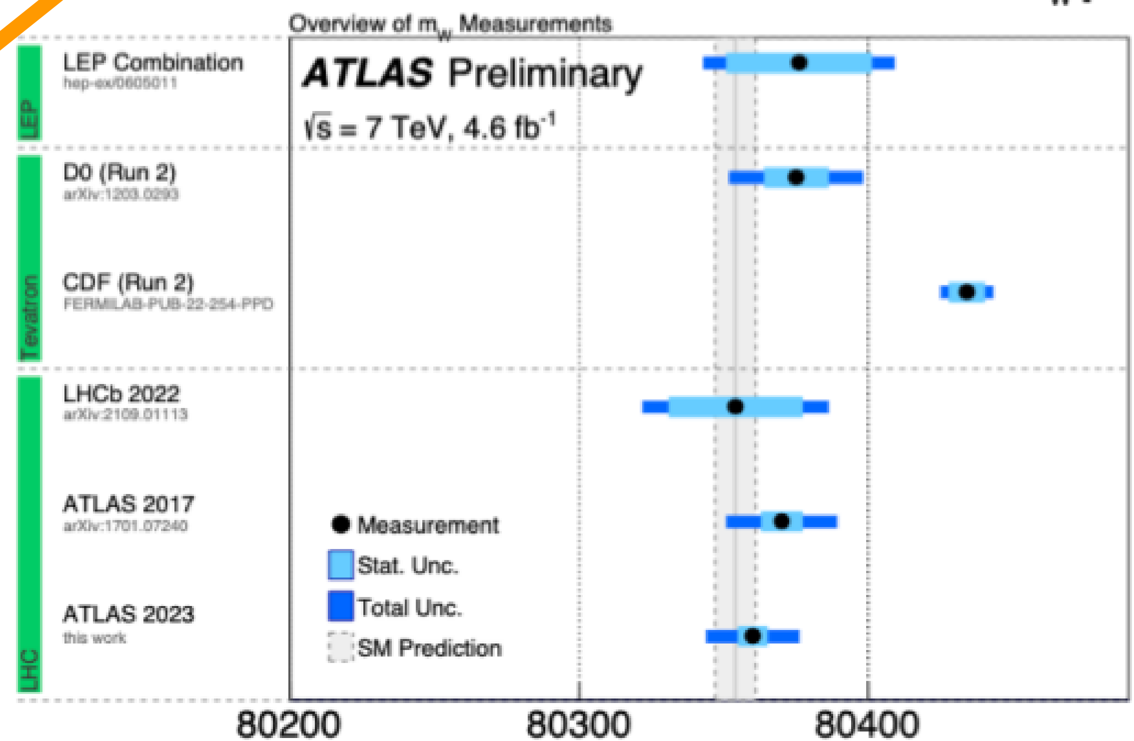
BSM





4 parameters of the EW sector (α_{em}, G_F, m_Z, $\sin^2\theta_W$) + m_H and m_{top} → predict m_W within the SM

Δm_W =7 MeV

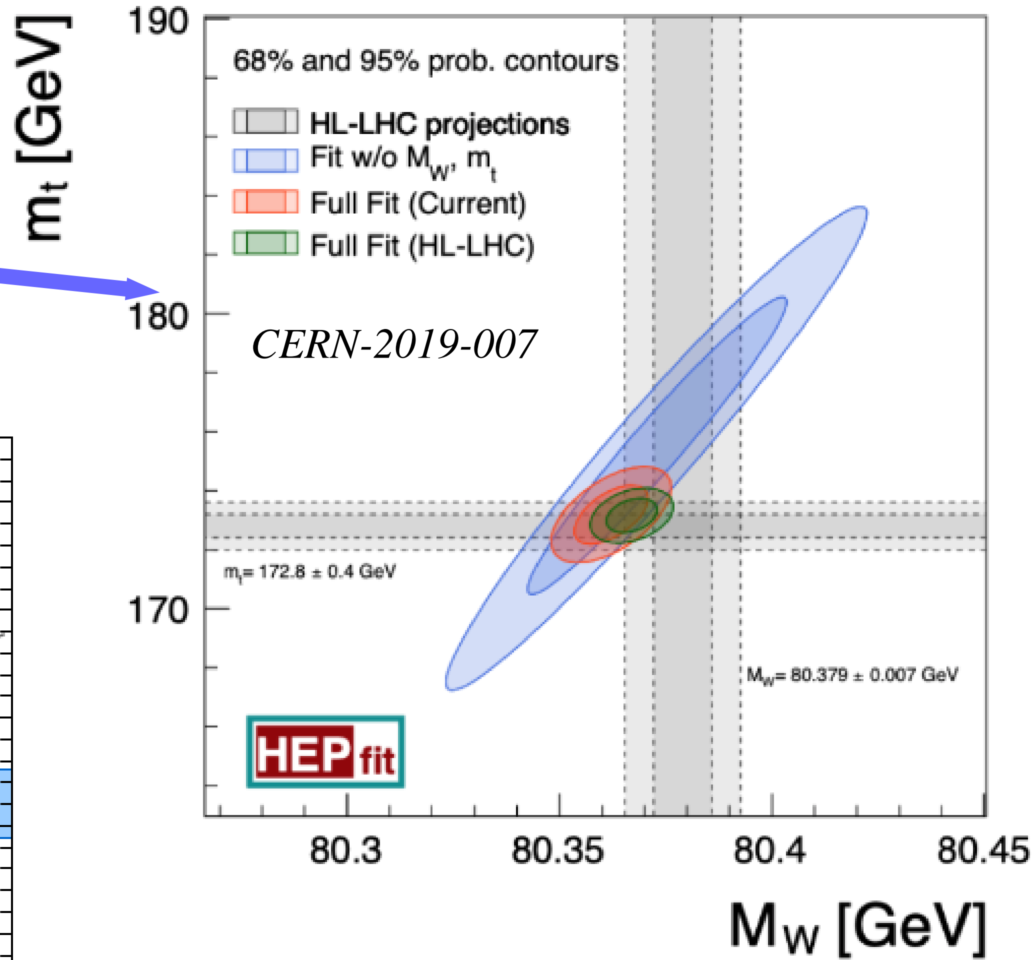


New M_W measurement from ATLAS is very SM-like.
(*ATLAS-CONF-2023-004*)

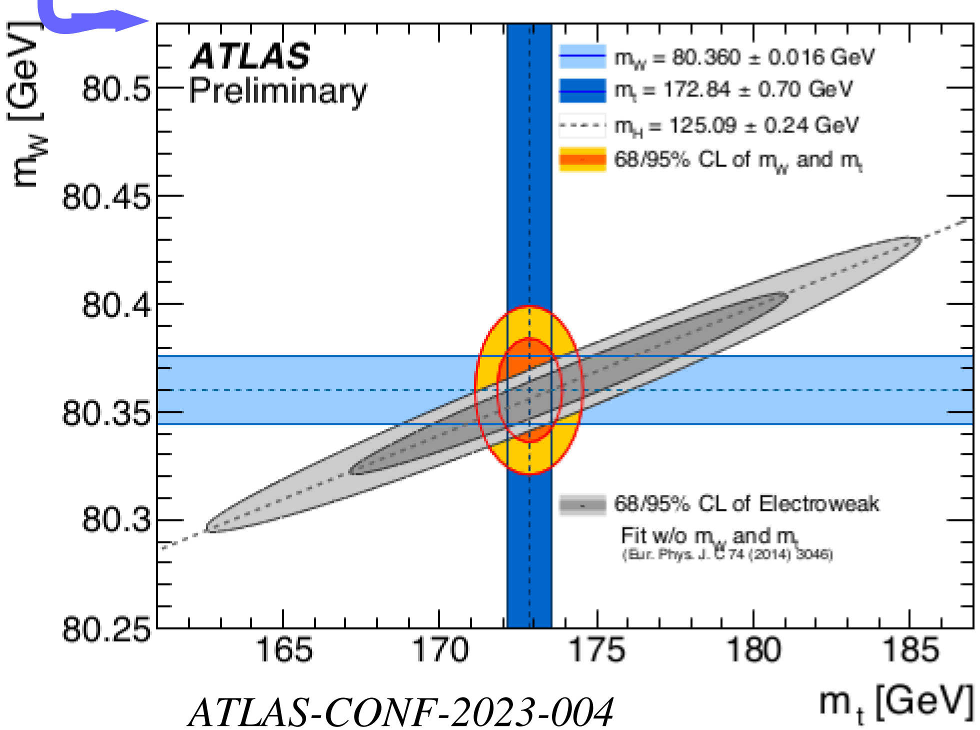
m_W = 80360±5(stat.) ±15(syst.) = 80360 ±16 MeV

M_W, m_{top}, M_H and global SM fit

SM-like present picture.
This might change with HL-LHC precision.
Note that assumed uncertainties/2 compared to today.



CERN-2019-007



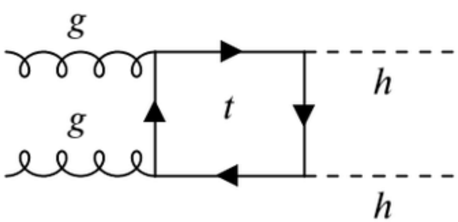
ATLAS-CONF-2023-004

EWSB: Higgs self-coupling

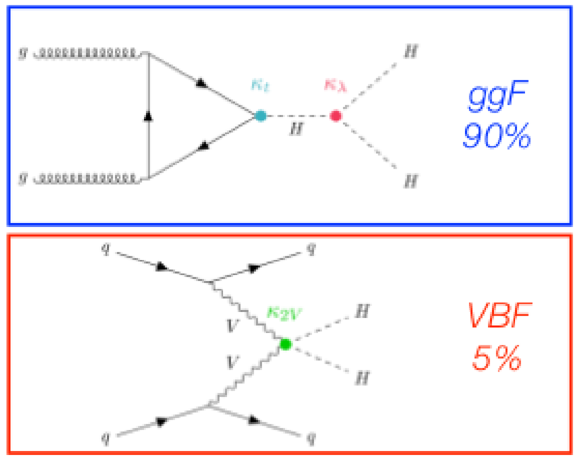
Huge effort presently focusing on hhh vertex via hh production (single h production helps as well)

- B=box diagram, amplitude proportional to κ_t^2, $\kappa_t = y_t / y_t^{SM}$
- T=triangle diagram, amplitude proportional to $\kappa_t \kappa_\lambda$, $\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$

Amplitude: $A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$



double-Higgs production



σ(pp→HH) @ 13 TeV = 34 fb

~5k produced in Run 2

Present results (95 % CL):

ATLAS *arXiv:2211.01216*

$$-0.4 < \kappa_\lambda < 6.3$$

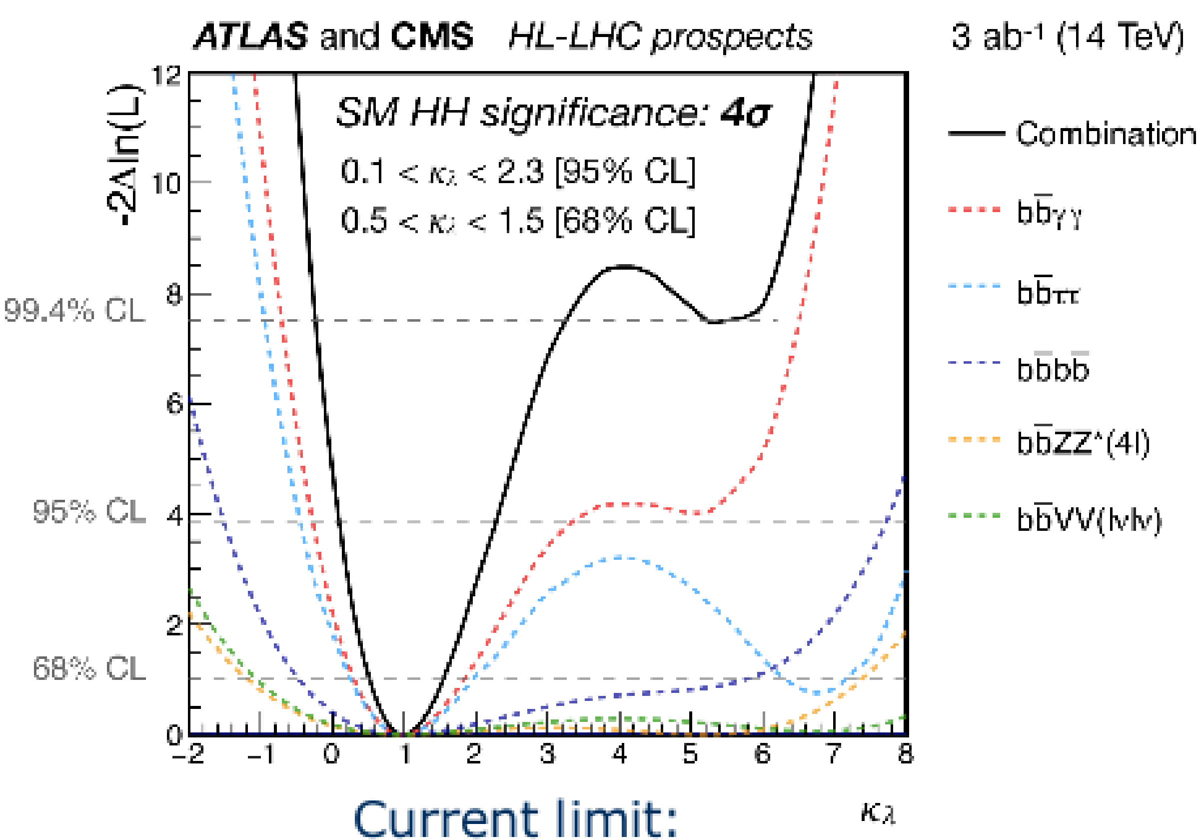
CMS *Nature 607 (2022) 60-68*

$$-1.24 < \kappa_\lambda < 6.49$$

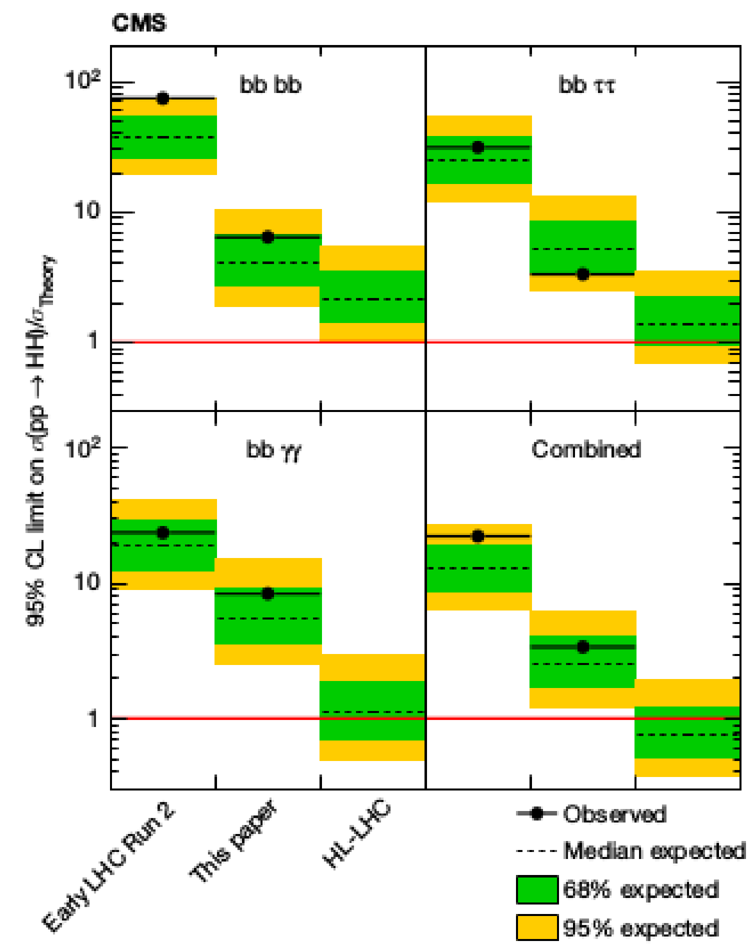
EWSB: Higgs self-coupling

Present predictions: "Evidence++" for hhh (if SM self-coupling) : End of HL-LHC.

Improvements in the prospects in the pipe-line, profiling towards 5σ, ***ATL-PHYS-PUB–2022-053***



Current limit:
-1.1 < κλ < 6.6



ATL-PHYS-PUB-2022-018

CMS-PAS-FTR-22-001

Baryogenesis

Needs new sources of CP violation.

CPV in Higgs Yukawa couplings to taus and tops ?

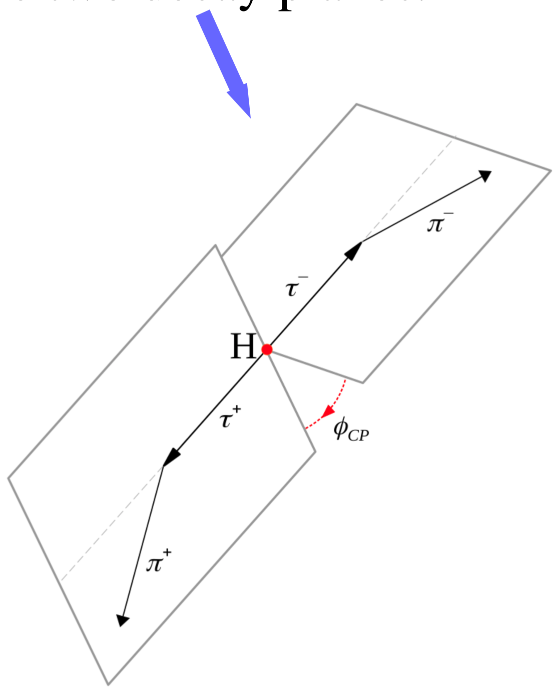
Other ideas?

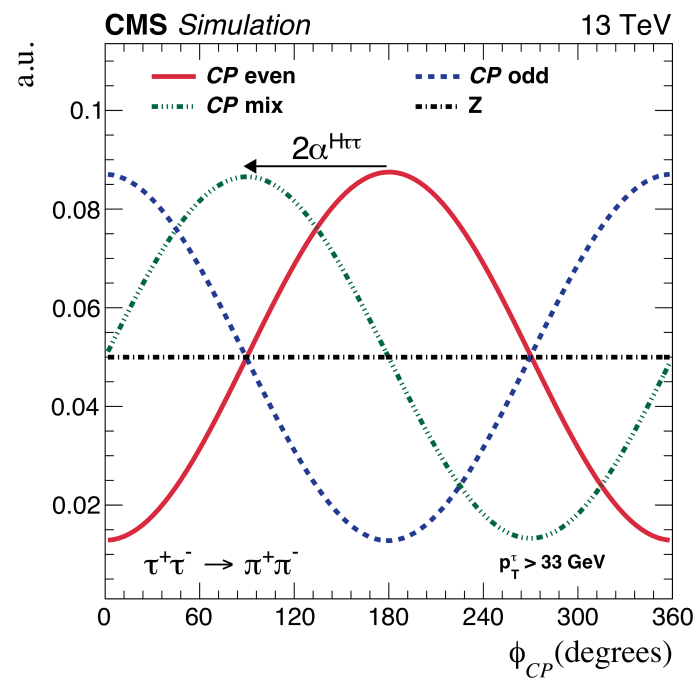
- **-Sphalerons ?**
- **-Darkogenesis- CPV in DM sector ?**
- **-Any “generic” way to search fo CPV at the LHC?**

Experimental efforts ongoing to pin-point CPV in Higgs→VV couplings. However its relation to fermion-antifermion asymmetry less straightforward than for CPV in Higgs→ fermion coupling .

CPV in tau-Higgs Yukawa coupling ?

Example: To measure the CP state we need to measure **a distribution** of an angle between the two decay planes.



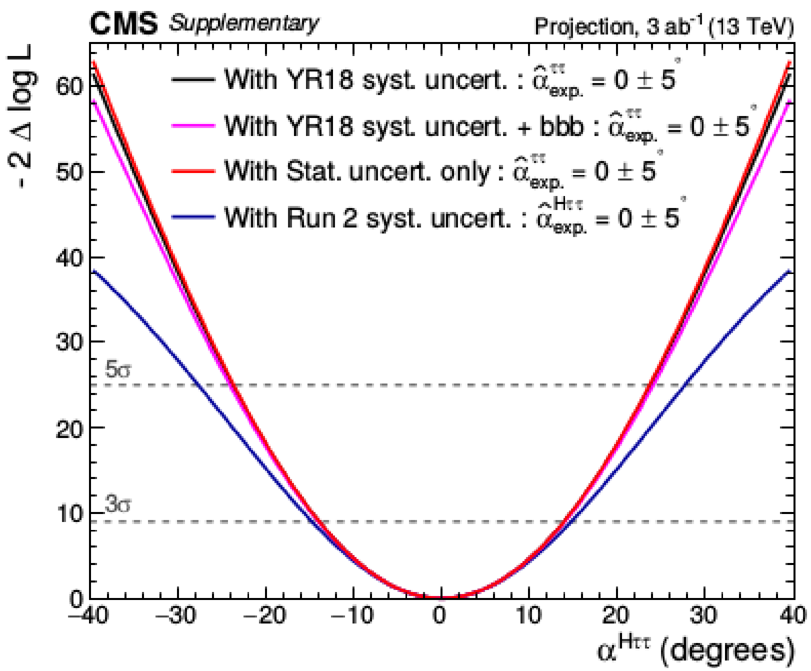


arXiv:2212.05833 **ATLAS: The observed (expected) value of α_τ is 9°±16° (0°±28°) at the 68% CF**

JHEP 06 (2022) 012 **CMS The observed (expected) value of α_τ is -1°±19° (0°±21°) at the 68% CF**

CPV in tau-Higgs Yukawa, prospects.

CMS PAS FTR-22-001



HL-LHC :

CP phase sensitivity prospects:

~5^{o} (~15^{o} for 3σ)

arxiv:2012.13922 ,1510.03850 : **Phase Precision of 3-5^{0} needed to test some of the baryogenesis models.**

Can we add more precision to the CP measurement by testing other Higgs boson decay channels?

H → τ τ γ ? *[JHEP01(2022)053]*

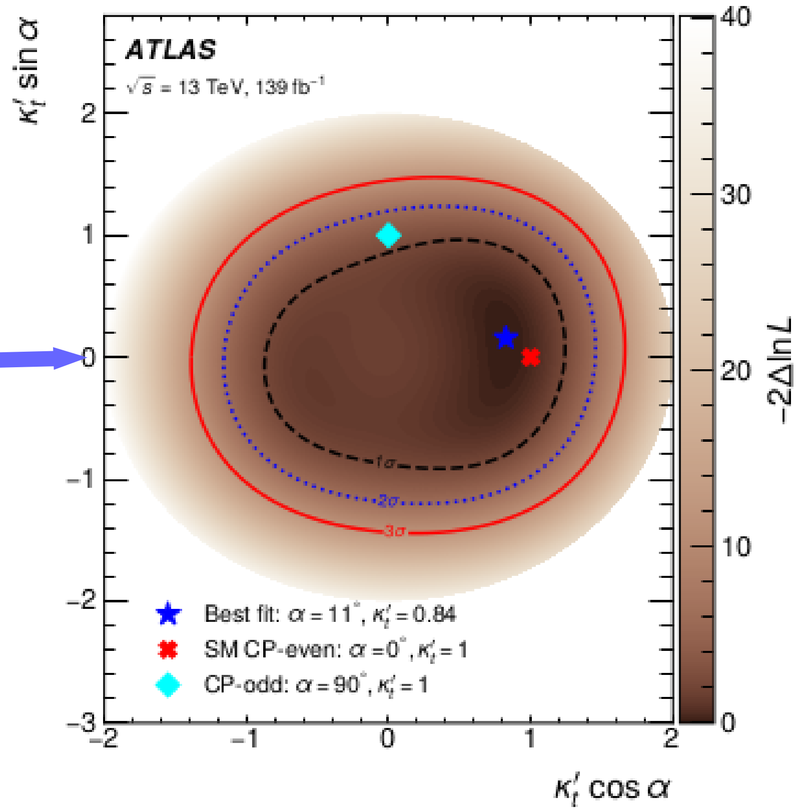
CPV in top-Higgs Yukawa ?

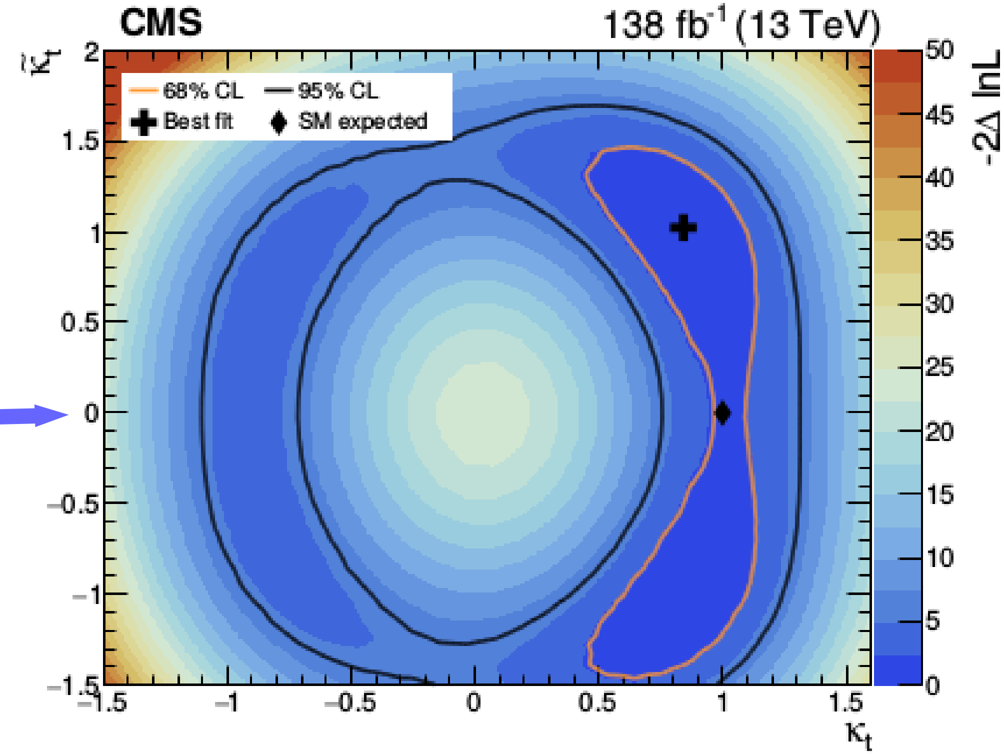
ttH, tH with H→ bb (ATLAS) and H→ multileptons (CMS)

arxiv: 2303.05974

arXiv:2208.02686

ATLAS : $\alpha = 11^{\circ}\,{}^{+52^{\circ}}_{-73^{\circ}}$.





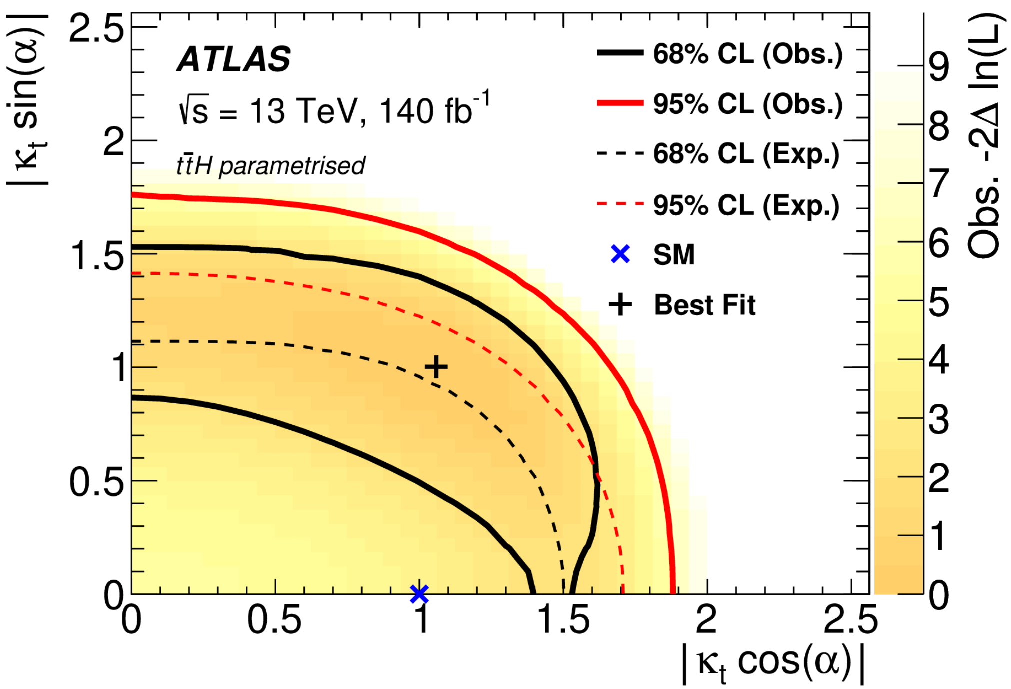
Compatible with no CPV. MV methods used. Uncertainties are huge, but will improve with statistics.

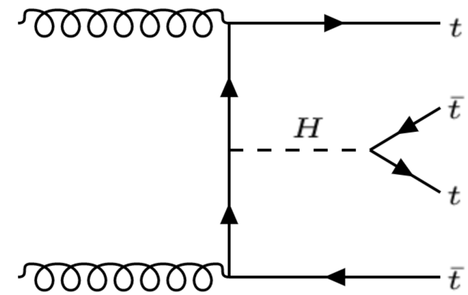
CPV in top-Higgs Yukawa ?

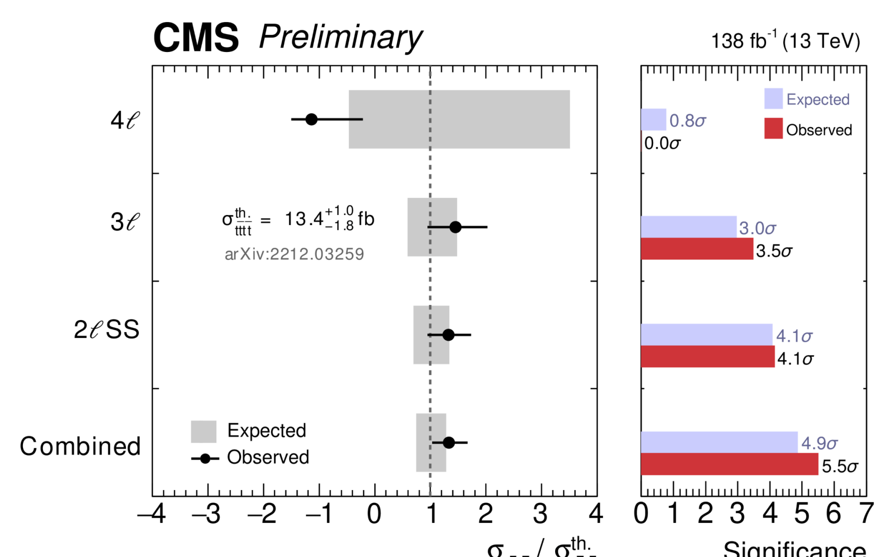
ttH coupling from tttt final state , with the tiniest x-section measured so far at the LHC.

(α= 0 , k_t =1 for CP even SM coupling)

ArXiv:2303.15061,







CMS-PAS-TOP-22-013

Search for CPV, other ideas?

Sphalerons, lots of theory papers
one LHC result so far (*JHEP 11 (2018) 042*)

Generic search for CPV ? *arXiv:2212.09433*
Could this include CPV in DM, if
DM is produced?

Dark Matter

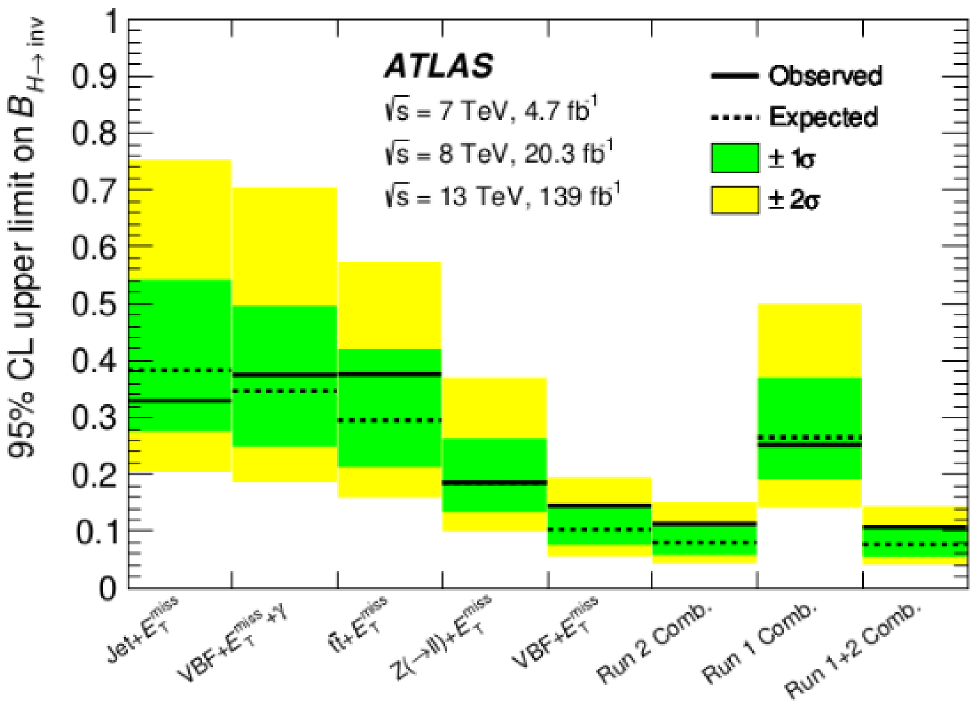
Higgs boson as a portal to DM, H→ invisible

Simplified benchmark models.

2HDM with DM

SUSY DM

DM:Higgs→ invisible



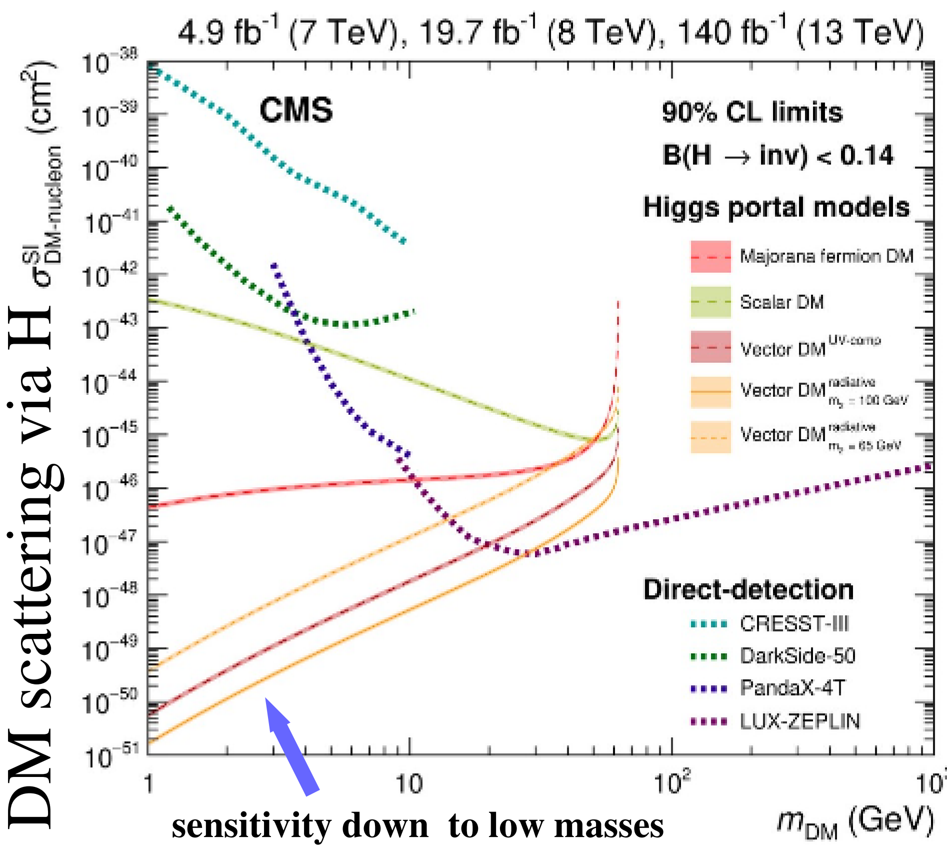
95% CL limit for H→ inv:
ATLAS: 10.7% (7.7% exp.)
CMS: 15% (8% exp.)

ATLAS:arXiv:2301.10731
CMS: arXiv:2303.01214

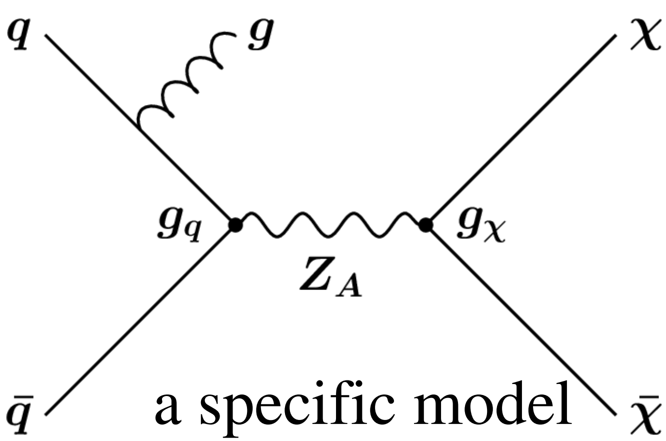
BR(H→ ττ) =6.3 % . Is "simple" Dirac fermion DM already in trouble without additional Higgses?

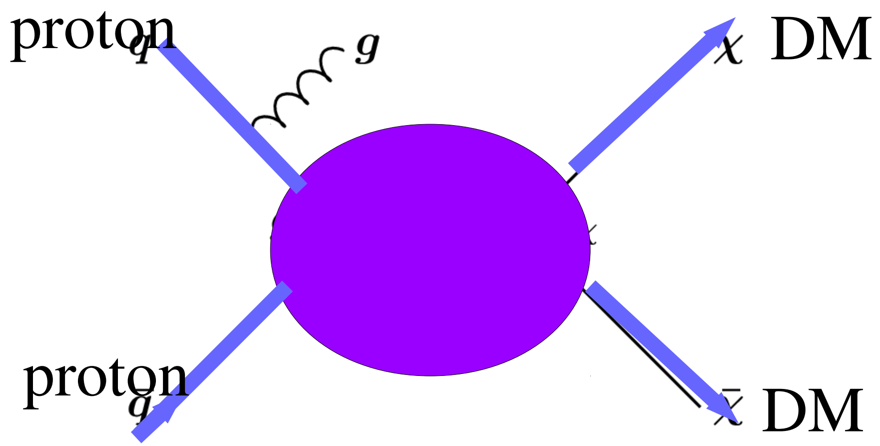
HL-LHC sensitivity prospects:
H→ inv < 2.5%

CMS PAS FTR-22-001

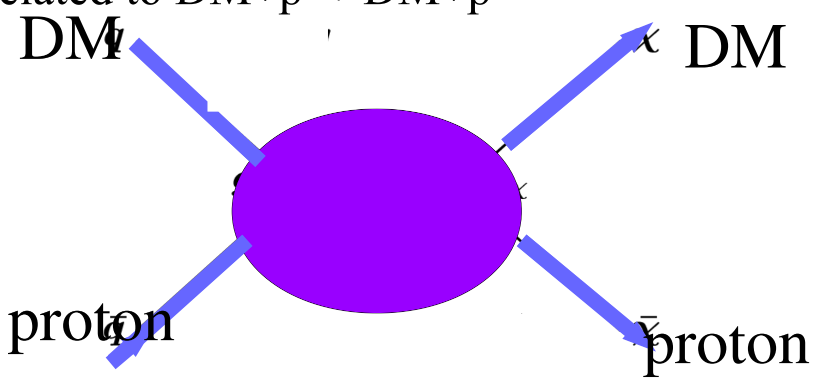


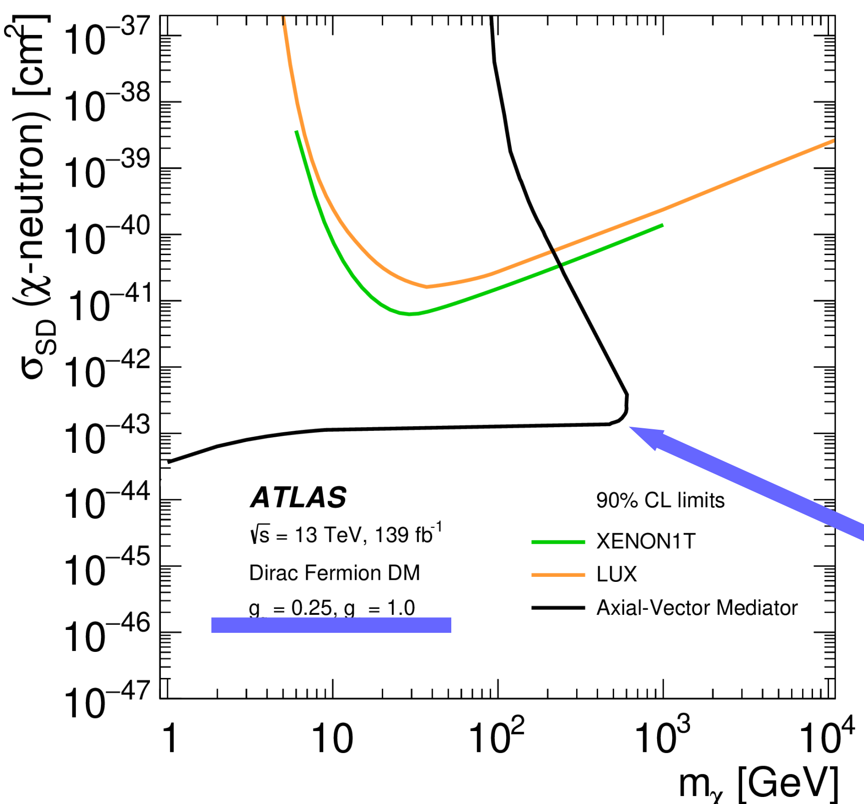
Searches in simplified models: close to "generic" Dark Matter searches?





Generic : p+p→ DM DM to be related to DM+p→ DM+p



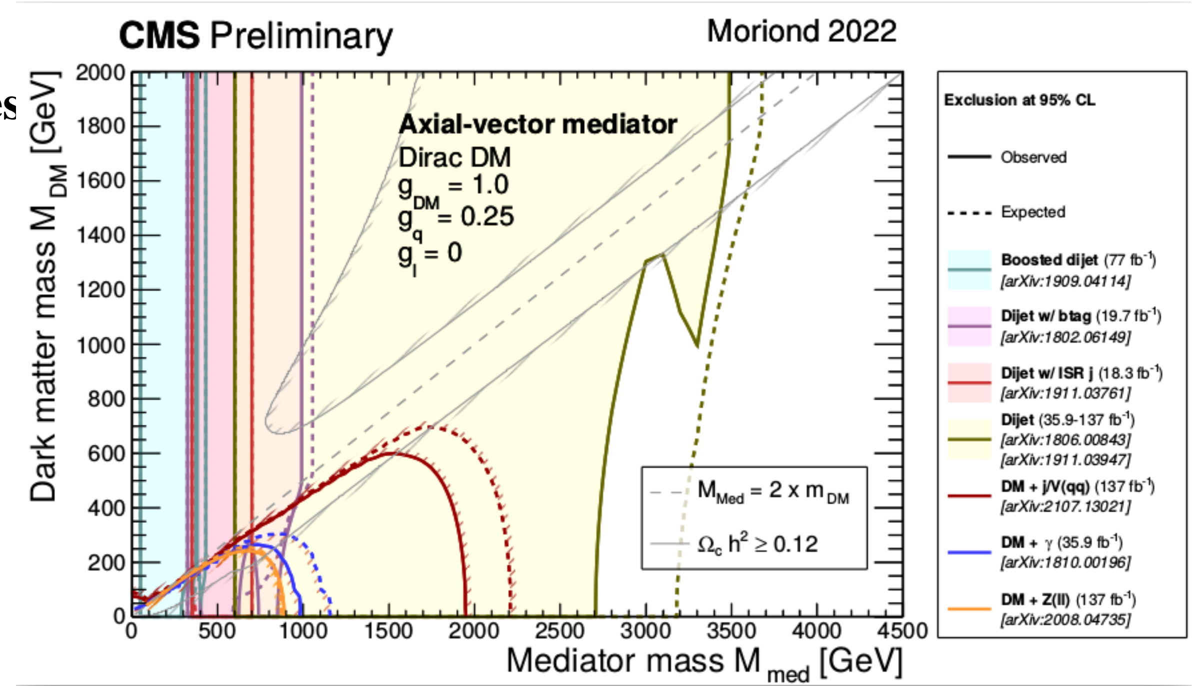


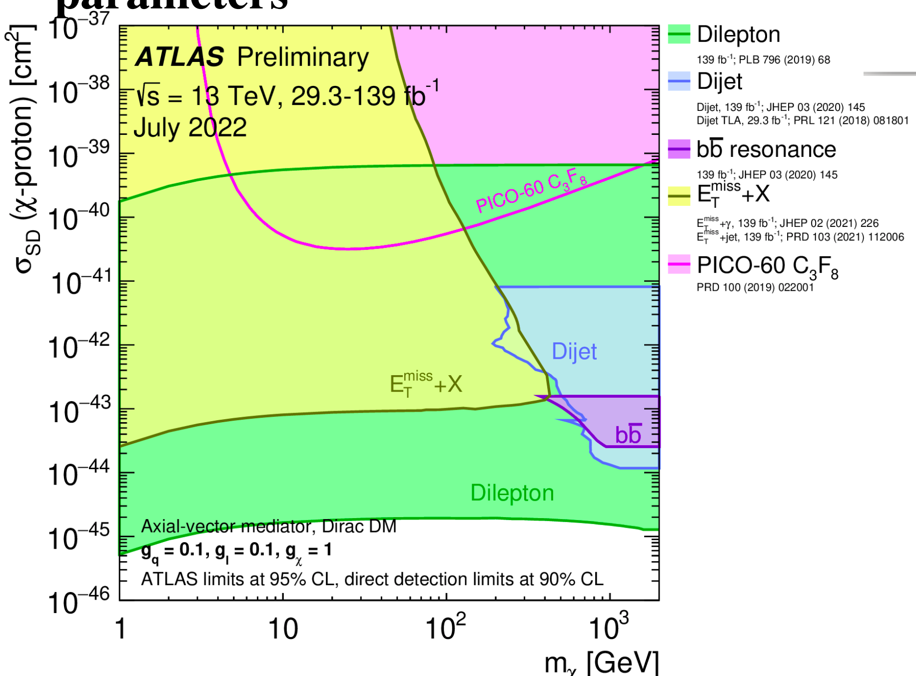
Example ATLAS result, for a specific model. Results competitive with the direct search for DM scattering on nucleons But model parameters dependent !

Phys. Rev. D 103 (2021) 112006

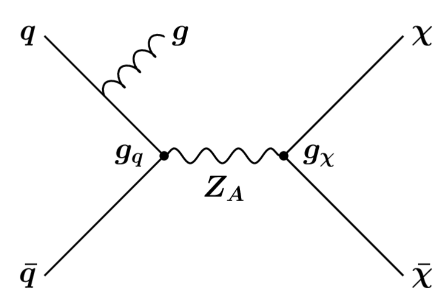
DM Searches in simplified models, examples:

In practice, a specific simplified model with a DM and a mediator can result in many different final states. The results can be interpreted as limits on DM-nucleon SD scattering x-section (for example). Sensitivity goes down to low DM masses. Topologies that matters are model parameters dependent . different topologies used for different parameters





Example topology, to define couplings.



Two Higgs Doublets Models (2HDM) interesting extensions of the SM

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix},$$

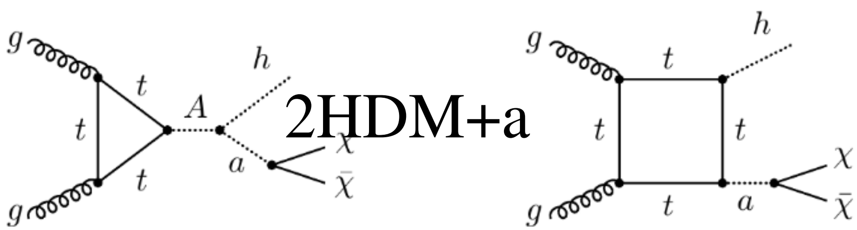
SM: one "complex doublet"= 4 fields
Mass=Transverse polarization for
W^{+-} Z^0 and SM scalar h boson

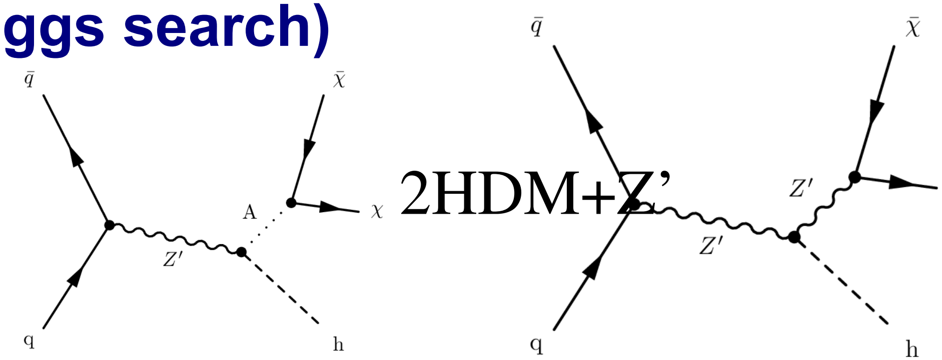
$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ (v_1 + \eta_1 + i\chi_1)/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ (v_2 + \eta_2 + i\chi_2)/\sqrt{2} \end{pmatrix},$$

BSM: two "complex doublets"= 8 fields
=Transverse polarization for
W^{+-} Z^0 and 5 Higgs bosons H^{+-}, A, H and h

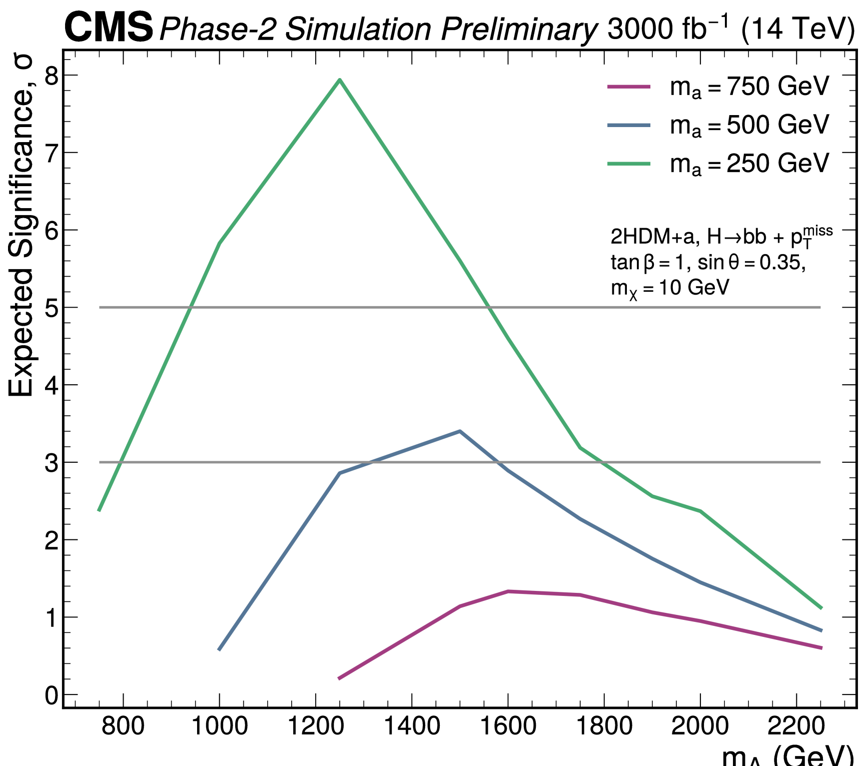
2HD models do not "spoil" precise EW measurements and involve additional symmetries making the existence of Dark Matter (DM) possible. Compatible with SUSY
Simplified 2HDM used for DM search, next slide.

Higgs boson and Dark Matter, 2HDM + new bosons (Mono-Higgs search)

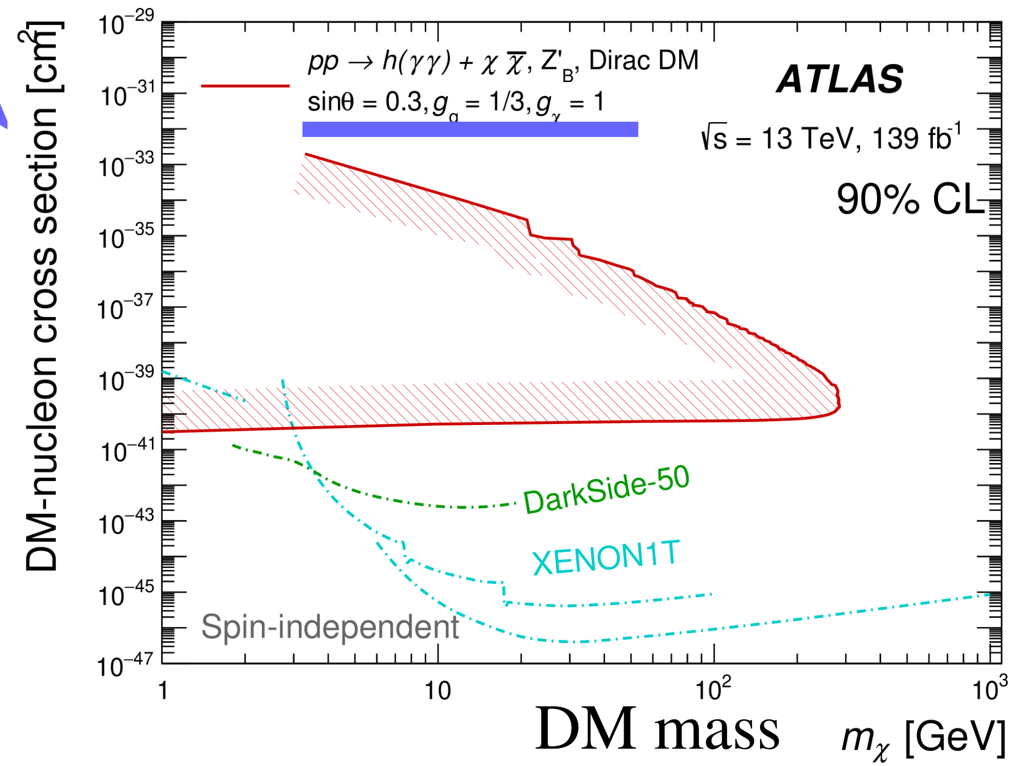




Run 2: Published results with H→γγ, H→ bb *[JHEP 11 (2021) 209]*, **H→ ττ … combined for DM search (ref)**



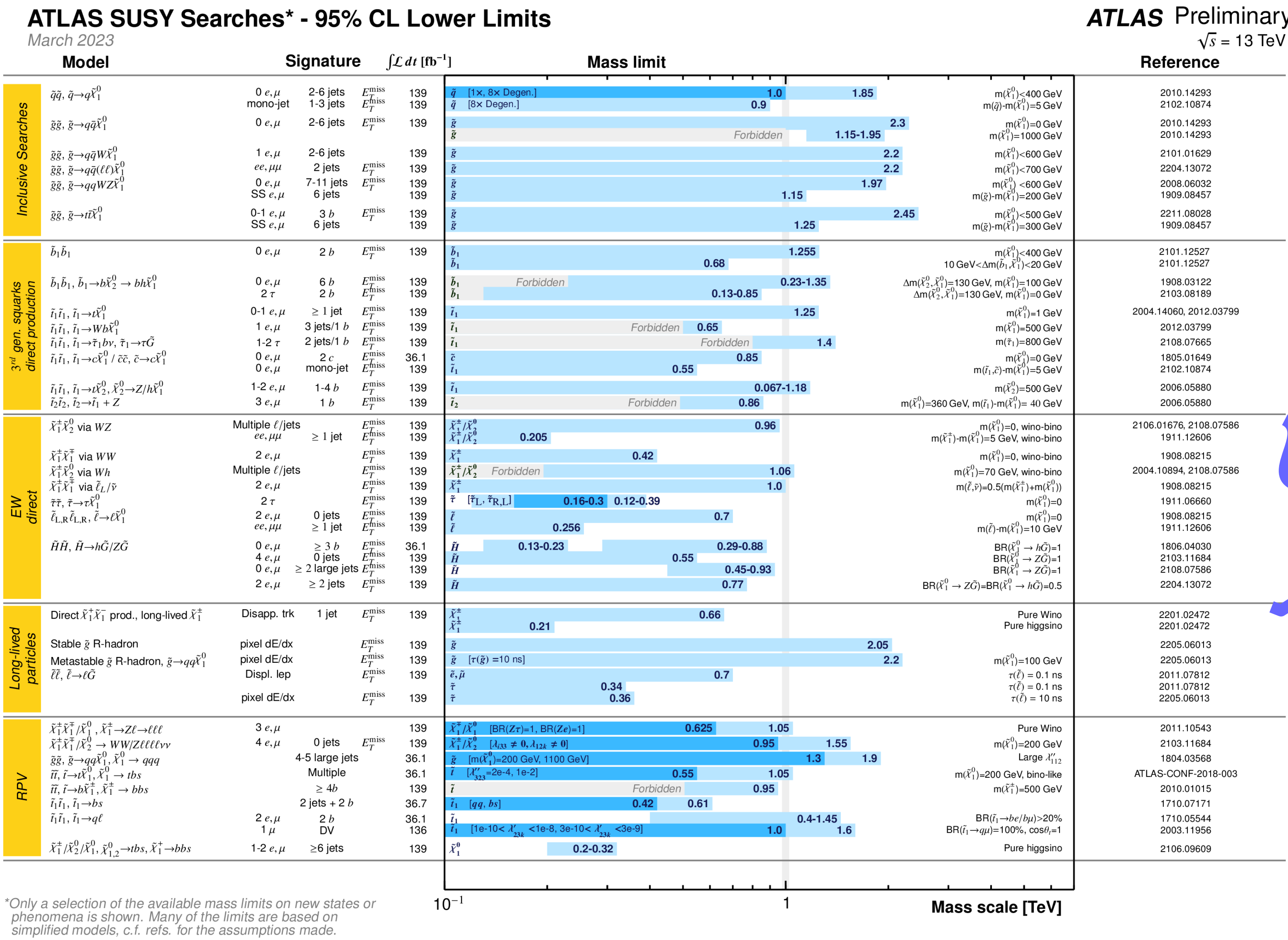
JHEP 10 (2021) 13



Example results: can be related to direct searches for DM scattering on nucleons, here spin-independent

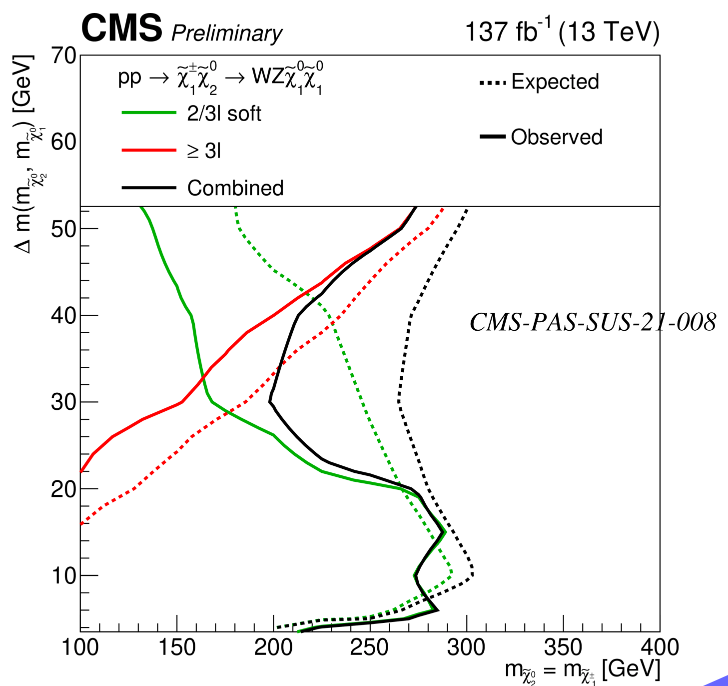
Anna Lipniacka www.uib.no/ift

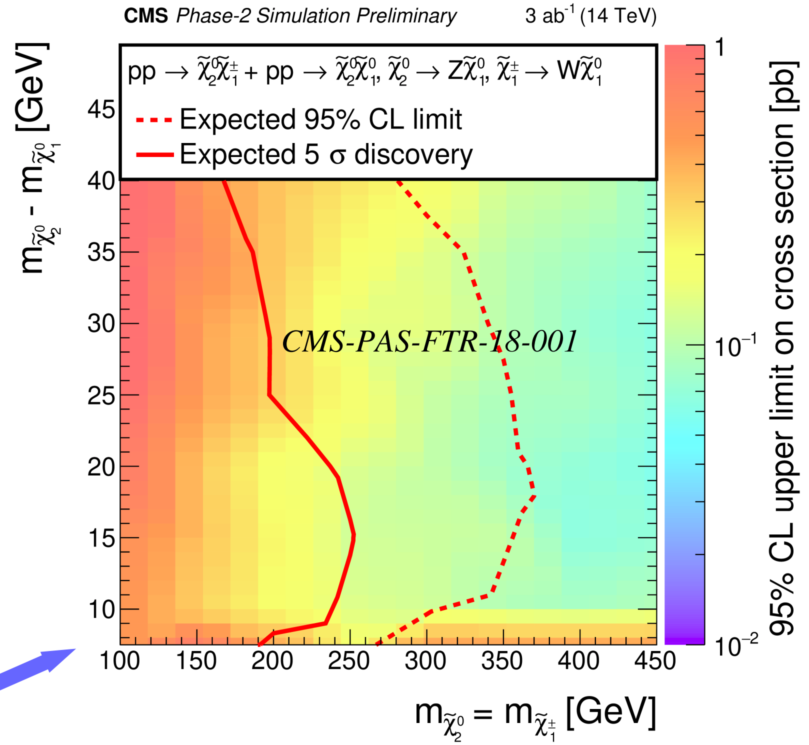
Supersymmetry (SUSY) has been desperately searched for.

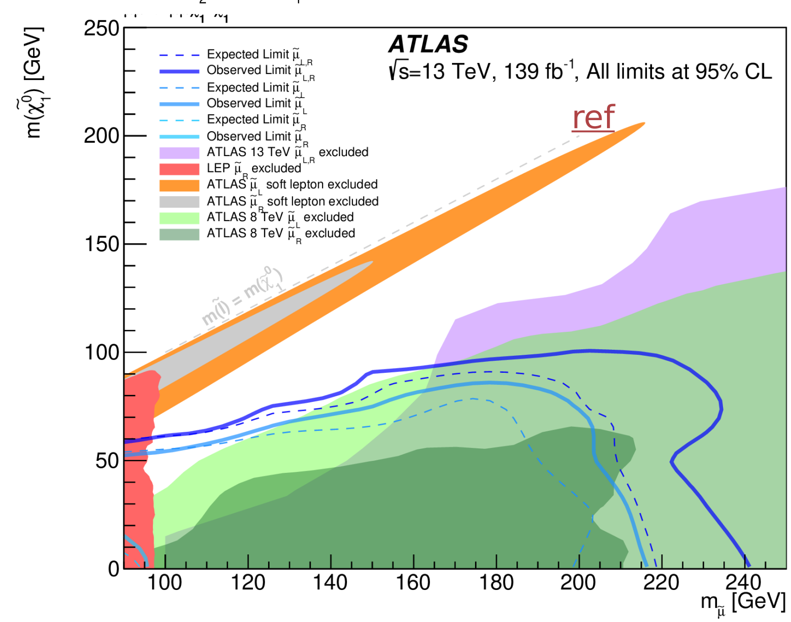


Results are interpreted in simplified models.
For EW production reaching 1 TeV

Searches for EW produced sparticles, examples







HL-LHC projections are difficult, they tend to be "beaten" by current results. Analysis techniques become better than expected.

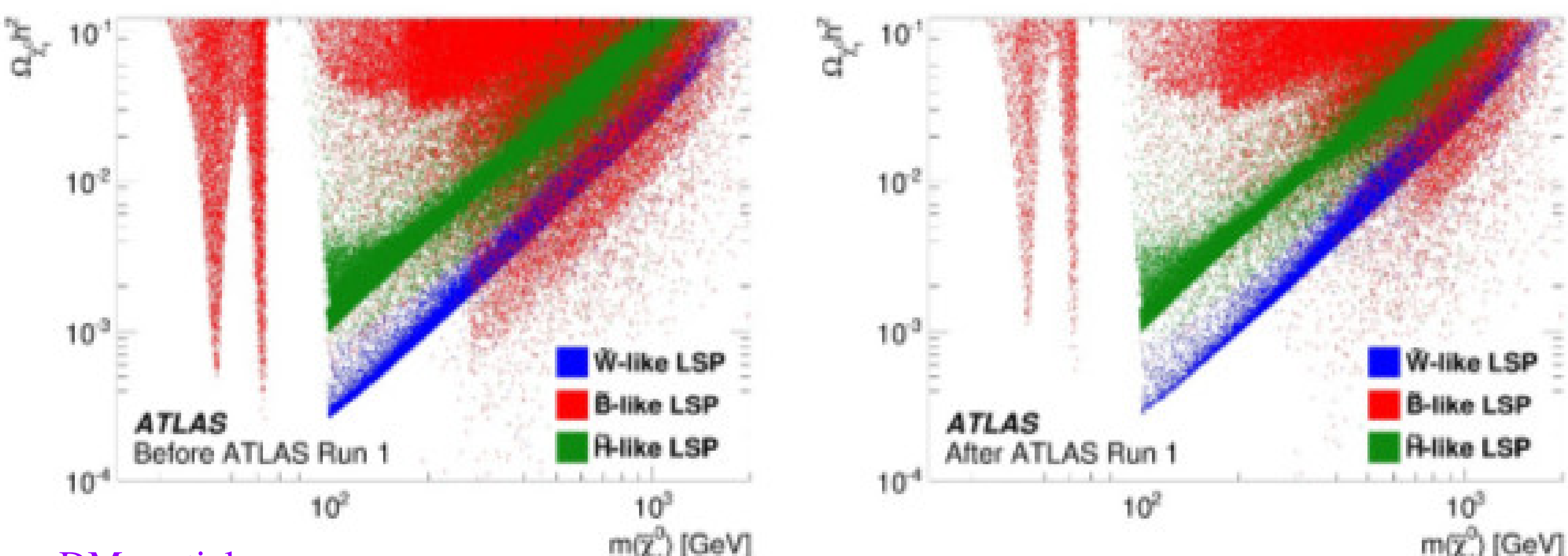
Searches for EW produced electroweakinos and sleptons can succeed even if squarks and gluinos are beyond the reach. The reach often depends on mass relations between sparticles and compressed scenarios are often difficult. They can be interesting in some interpretations: (g-2), relict density.

Desperately seeking SUSY DM

Simplified models do not tell the whole story. Parameters scans even in pMSSM are difficult. "The "latest" one from ATLAS is still on Run 1 data. *GAMBIT collaboration finds a "moderate excess" . Eur.Phys.J. C79 (2019) no.5, 395*

No limit yet on the SUSY's favorite DM candidate (LSP) pMSSM scan of ATLAS Run 1 data. JHEP 10 (2015) 134

Measured relic DM density



DM particle mass

(a) Before ATLAS Run 1. (b) After ATLAS Run 1.

Hopes and challenges

Higher- performance detectors coming up for the Run 4 !

Higgs bosons per fb^{-1} (13 TeV)

	produced	selected
$H \to \gamma\gamma$	130	46
$H \to ZZ^*$	1400	1.5
$H \to WW^*$	12000	42
$H \to \tau\tau$	3500	17
$H \to b\bar{b}$	32000	66

Source: K. Tackmann
Higgs symposium

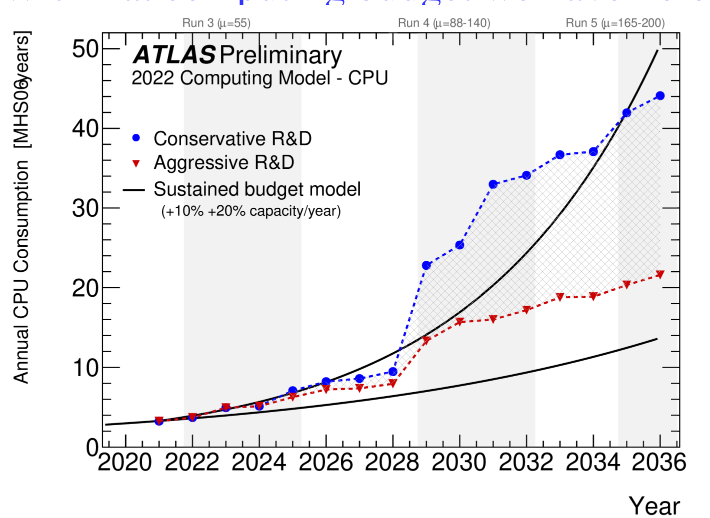
There is a room for improvement on the selection level, starting with trigger algorithms

Nature Review

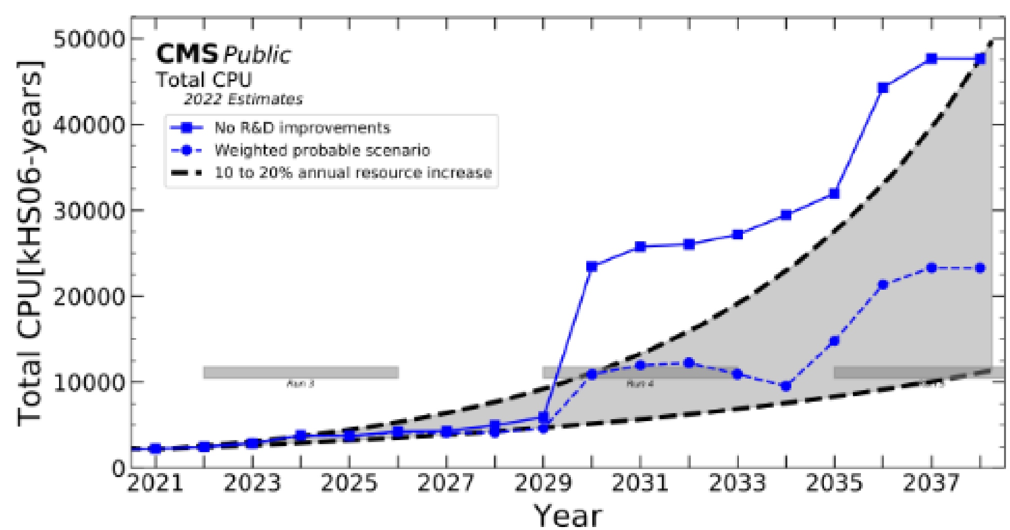
Analysis	Years of data collection	Sensitivity without machine learning	Sensitivity with machine learning	Ratio of P values	Additional data required
CMS[24] $H \to \gamma\gamma$	2011–2012	2.2σ, $P = 0.014$	2.7σ, $P = 0.0035$	4.0	51%
ATLAS[43] $H \to \tau^+\tau^-$	2011–2012	2.5σ, $P = 0.0062$	3.4σ, $P = 0.00034$	18	85%
ATLAS[99] $VH \to bb$	2011–2012	1.9σ, $P = 0.029$	2.5σ, $P = 0.0062$	4.7	73%
ATLAS[41] $VH \to bb$	2015–2016	2.8σ, $P = 0.0026$	3.0σ, $P = 0.00135$	1.9	15%
CMS[100] $VH \to bb$	2011–2012	1.4σ, $P = 0.081$	2.1σ, $P = 0.018$	4.5	125%

ML methods used for classification of physics objects, event reconstruction, simulation and modeling, data analysis. Hopes for "unsupervised learning" to form "general classifiers" to distinguish SM from BSM, CP conservation from CP violations etc etc. Will these methods be "explainable" ?

With flat computing budget we have no other choice but an aggressive R&D, or we cannot tackle HL-LHC



(ref)



Conclusions

The program of the (HL-)LHC will continue to span a very wide range of physics topics, within the Standard Model and beyond, with unprecedented sensitivities.

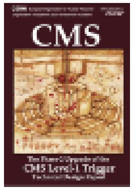
Summarized a handful of projections, many other exists, but not (yet) in all areas of the LHC physics.

The assumptions made are typically conservative → rapid progress continuously achieved by the LHC analyses → Run 2 results are competing with some of the older HL-LHC projections.

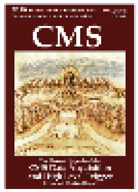
"Disruptive technologies" might bring rapid progress beyond expectations (or we might just need them to survive within computing the budget).

backup

The CMS Phase-2 Upgrade

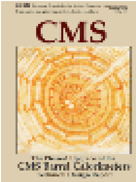


Level-1 Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1 Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting

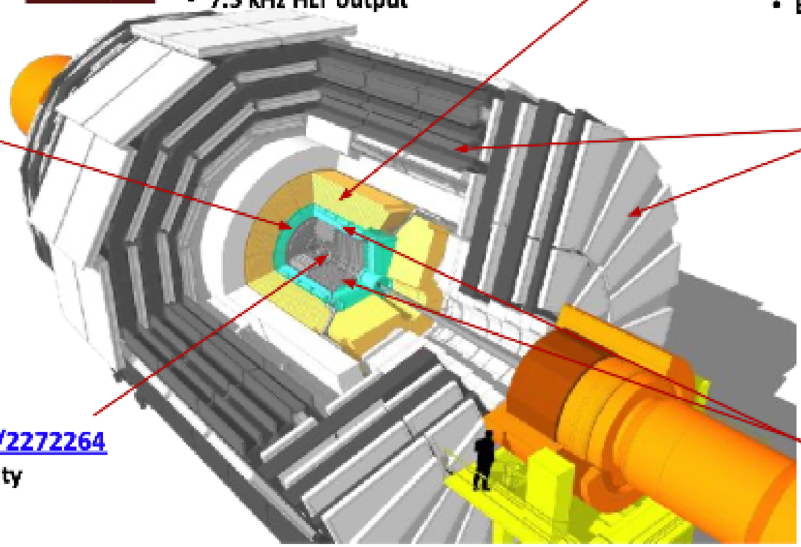


DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

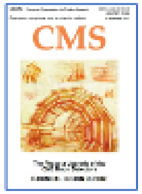
Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL single crystal granularity readout at 40 MHz with precise 30 ps timing for e/γ at 30 GeV
- Spike rejection
- ECAL and HCAL new Back-End boards

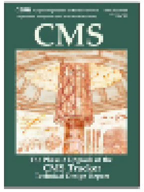


High-Granularity Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/Cu-W/SS



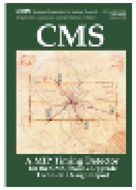
Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC BE electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \approx 3$





Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Extended coverage to $\eta \approx 4$
- Design for tracking in L1 Trigger

MIP Timing Detector
https://cds.cern.ch/record/2667167
Precision timing with:
- Full coverage to $\eta \approx 3$
- 30-50 ps time resolution for MIPs
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



Beam Radiation Instrumentation and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

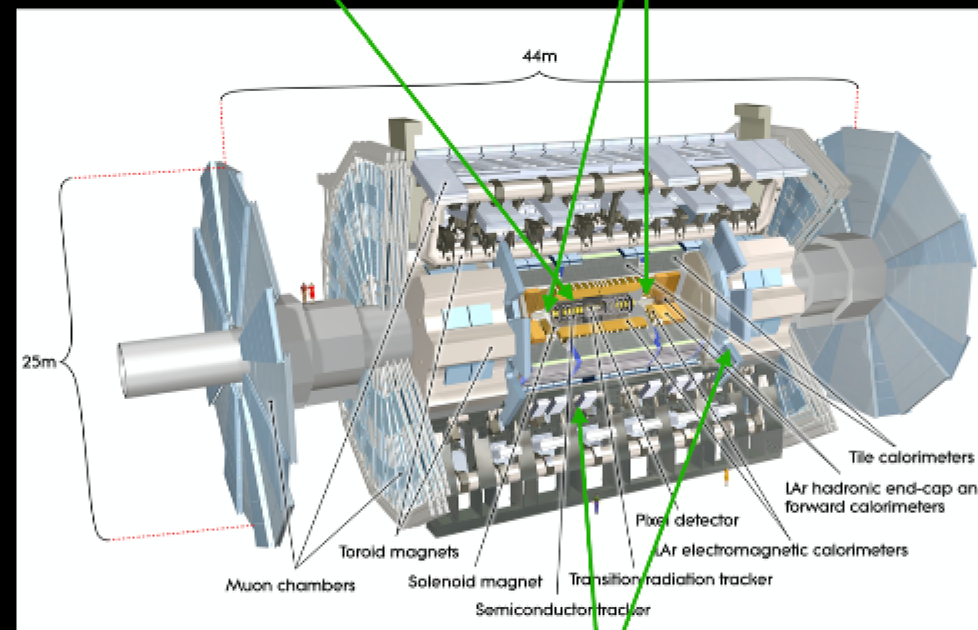
Gabriella Pásztor

ATLAS upgrades for Run4

- New systems in the cavern:
  - ITk: silicon inner tracker (pixels + strip detector) with eta coverage up to 4
  - RPC and sMDT muon detector in the barrel inner region, sTGC in the end-cap inner region
  - High Granularity Timing Detector in the forward region
  - Calorimeters and muon detectors (TGC/RPC/MDT) front-end readout at 40 MHz
  - Upgrades of luminosity and forward detectors
- New TDAQ off-detector electronics:
  - Level-0 hardware trigger: calorimeter, topological, muon, global, CTP (FPGA-based boards)
  - Readout: FELIX for all ATLAS detectors
  - Event Filter processor farm and hardware tracking

New High Granularity Timing Detector (HGTD)

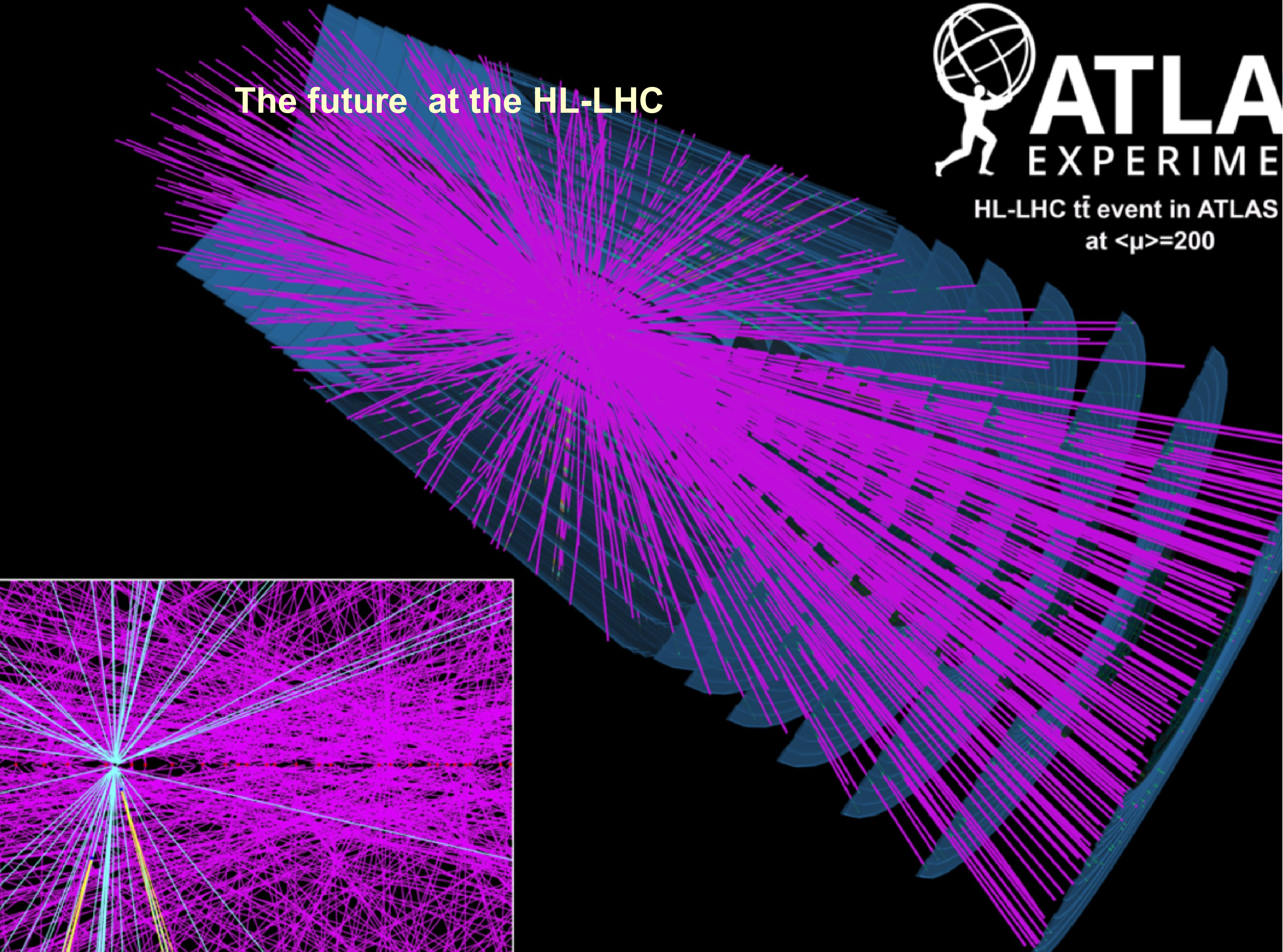
New inner tracker (ITK)



New muon detectors (RPC + sMDT + TGC)

Front-end replaced for calorimeters and muon detectors

The future at the HL-LHC



The "EarlyUniverse" project

Norway grants

NATIONAL SCIENCE CENTRE POLAND

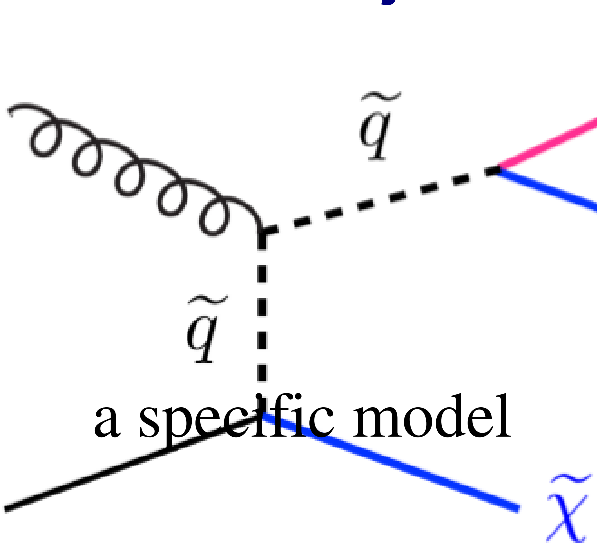
The research leading to the results presented in this talk has received funding from the Norwegian Financial Mechanism for years 2014-2021, grant nr 2019/34/H/ST2/00707

Understanding the Early Universe:
interplay of theory and collider experiments

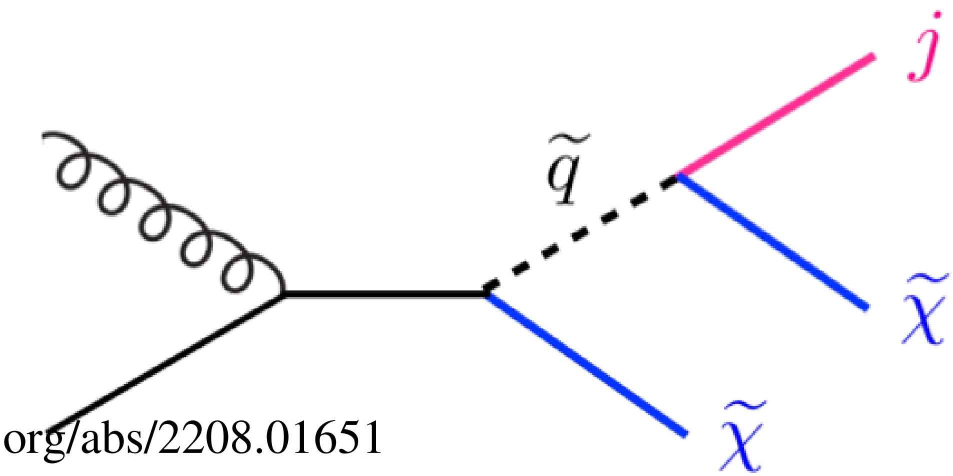
Joint research project between the University of Warsaw & University of Bergen

Theory & Experiment

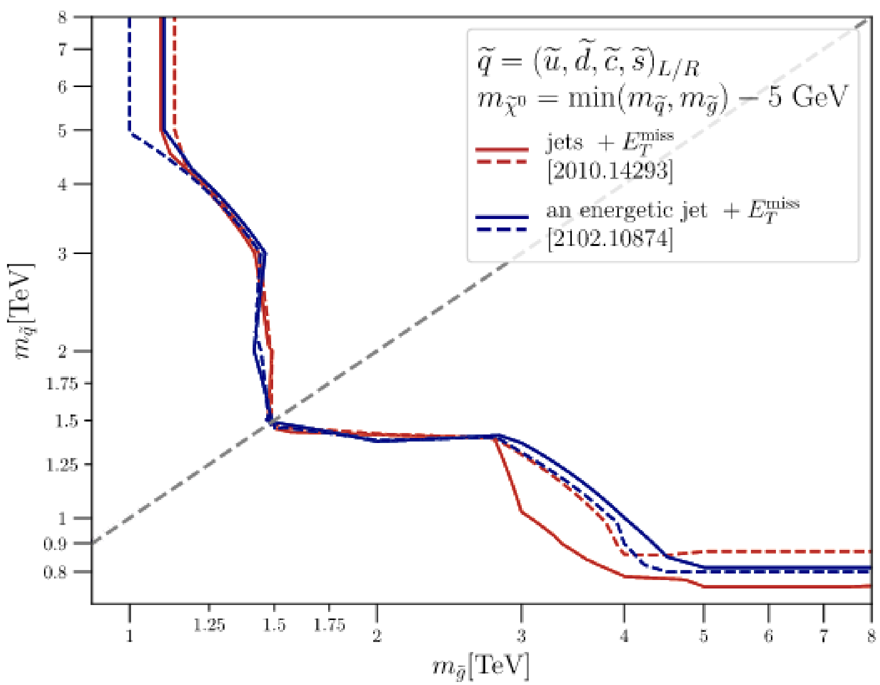
Mono-jet search, SUSY oriented Dark Matter search



a specific model



https://arxiv.org/abs/2208.01651



Allows to explore mass space of possible supersymmetric particles (gluino and squark)