

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

Planck2023 Scale and the LHC, prospects

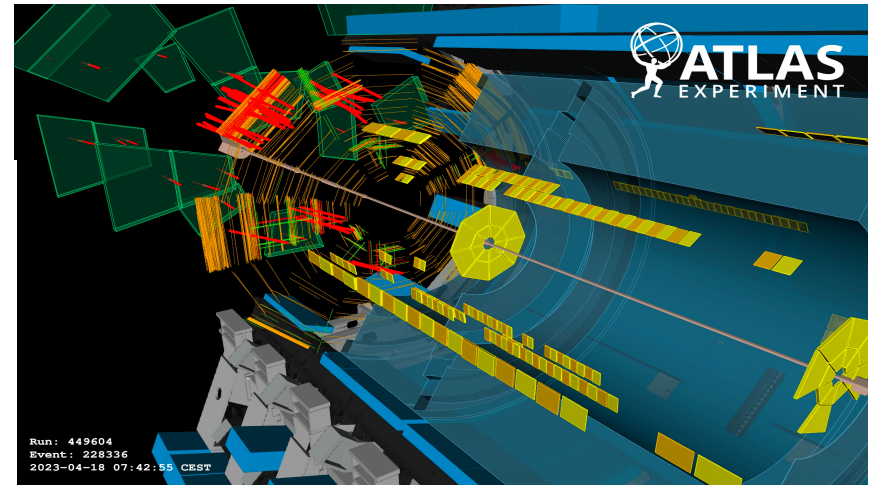
The Standard Model of particle physics has been tested at the LHC with an outstanding accuracy. Its last particle, the Higgs boson, was experimentally observed 11 years ago by ATLAS and CMS experiments and has been studied with an increased accuracy since then. Yet, all the particles of the Standard 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.

## 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 <sup>-1</sup> at $\sqrt{s} = 13$ TeV
Higgs boson	7.7 million
Top quark	275 million
Z boson	2.8 billion (→ $\ell\ell$ , 290 million)
W boson	12 billion (→ $\ell\nu$ , 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	(– <b>end of 2041*</b> )	~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.

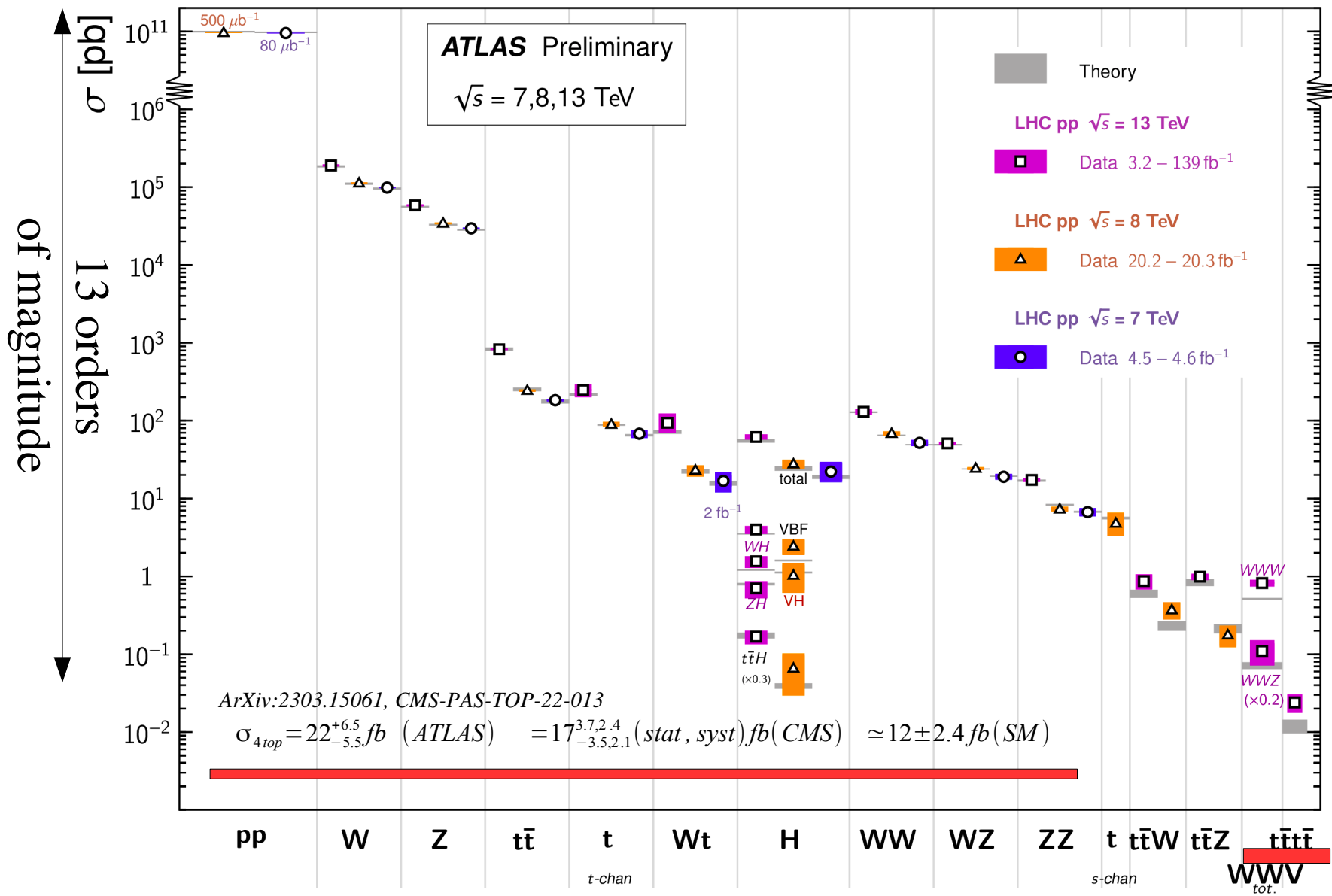
\*Far future. We may face disruptive technologies  
(see 2 ML talks later today by Claudius Krause and Matthew Schwartz).. and disruptive events of unknown consequences- obviously we live in a less stable world than we thought few years ago.

# The Big Picture, precision cross-sections.

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## Standard Model Total Production Cross Section Measurements

Status: February 2022



# The Big Picture: No new particles yet.

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CI

DM

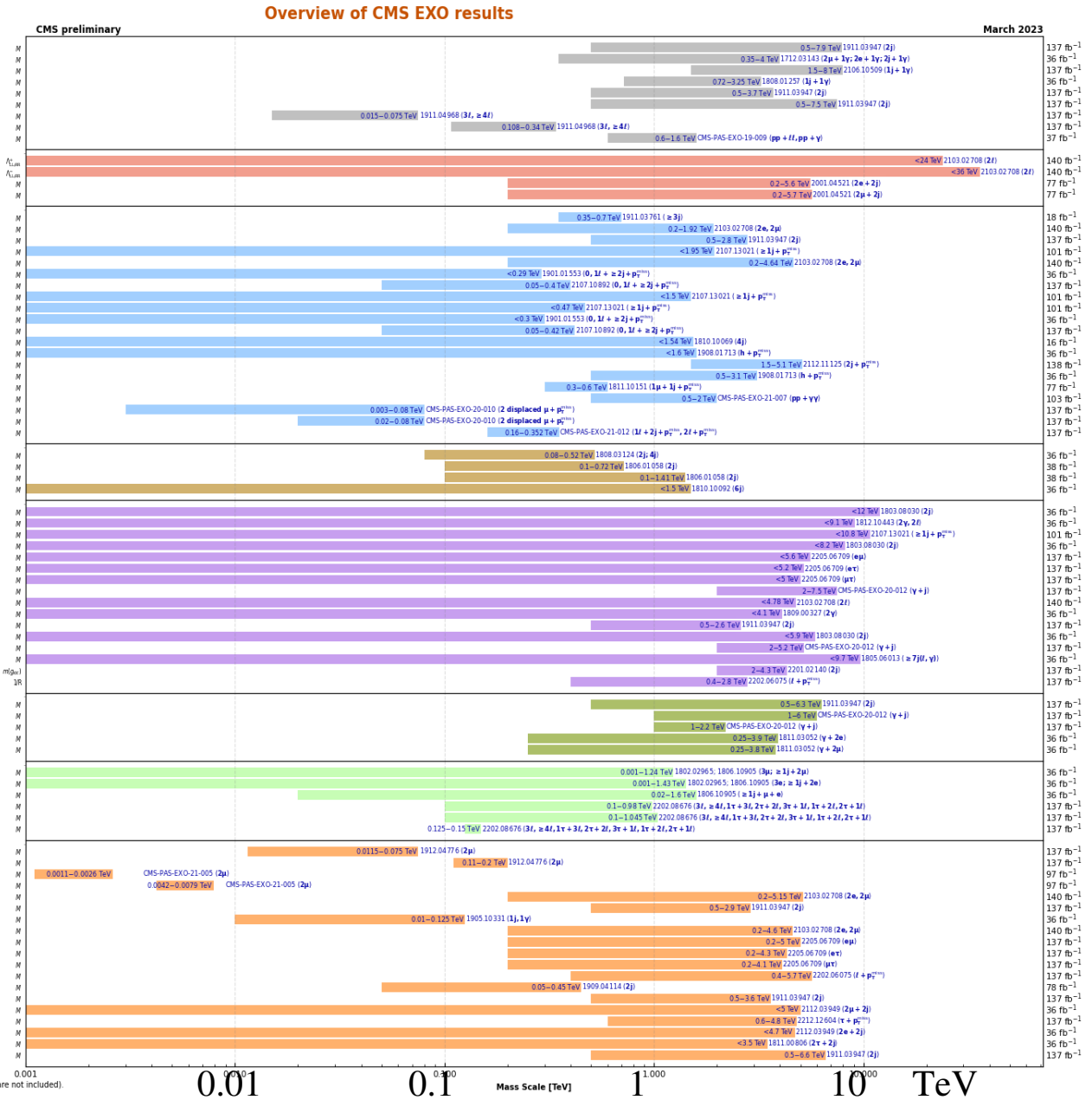
RPV

ED

ExF

HF

HB



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

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

Planck 2013 state and the LHC, prospects



- Why is the electroweak interaction so much stronger than gravity?**

  - Are there new particles close to the mass of the Higgs boson?
  - Is the Higgs boson elementary or made of other particles?
  - Are there anomalies in the interactions of the Higgs boson with the W and Z bosons?
- Why is there more matter than antimatter in the Universe?**

  - Are there charge-parity violating Higgs decays?
  - Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
  - Are there multiple Higgs sectors?
- What is dark matter?**

  - Can the Higgs boson provide a portal to dark matter or a dark sector?
  - Is the Higgs lifetime consistent with the Standard Model?
  - Are there new decay modes of the Higgs boson?
- What is the origin of the vast range of quark and lepton masses in the Standard Model?**

  - Are there modified interactions to the Higgs boson and known particles?
  - Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example,  $H \rightarrow \mu^+ \tau^-$ )?
- What is the origin of the early Universe inflation?**

  - Any imprint in cosmological observations?

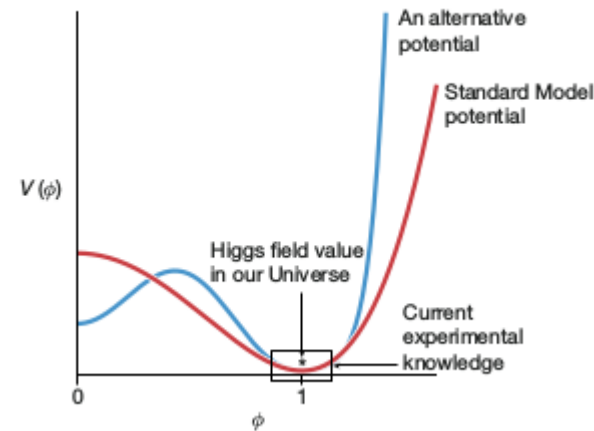
**The Higgs field:**

**The only known 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 violation in Higgs couplings explain the matter-antimatter asymmetry ?**



Gavin P. Salam<sup>1,2</sup>, Lian-Tao Wang<sup>3</sup> & Giulia Zanderighi<sup>4,5</sup>✉

<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

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

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

Possible instability  
depending on  $m_H$

Origin of quadratic  
divergences.  
Hierarchy problem

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>

$$m_H = 124.99 \pm 0.19 [\pm 0.18(stat) \pm 0.04(syst)] \text{ GeV}$$

$$\Gamma_H = 4.6^{+2.6}_{-2.5} \text{ MeV @68\% C.L.}$$

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

$$m_H = 125.38 \pm 0.14 [\pm 0.11(stat) \pm 0.08(syst)] \text{ GeV}$$

$$\Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV @68\% C.L.}$$

CMS PAS FTR-22-001

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

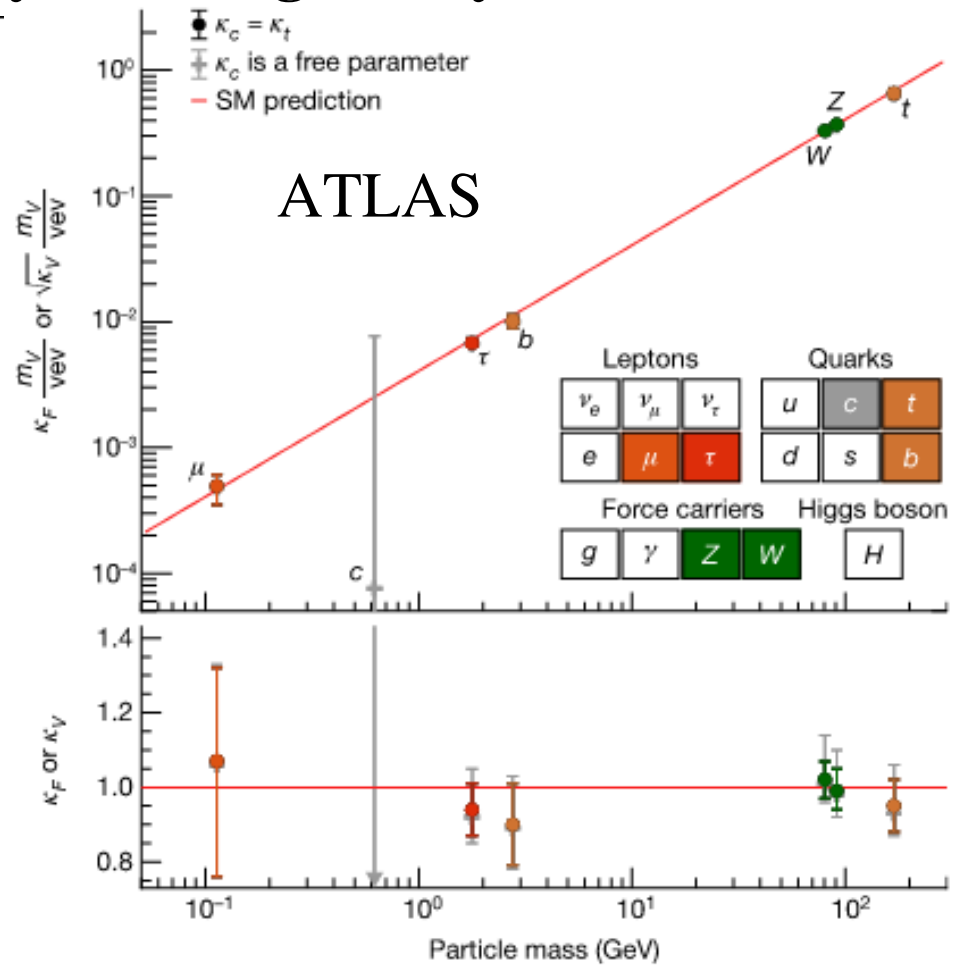
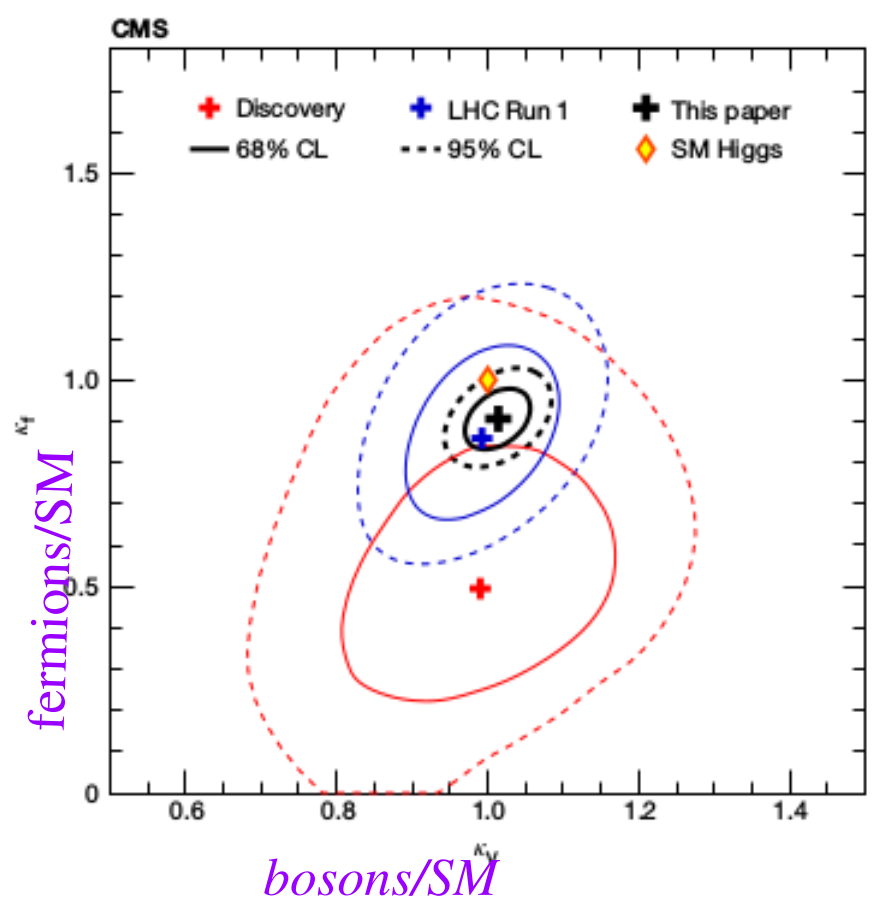
$$\text{CMS HL-LHC } m_H = 125.38 \pm 0.07 (\pm 0.02 \text{ stat.}) \text{ GeV}$$

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

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

Couplings to fermions and bosons ( $\sim m_f$ ,  $\sim m_v^2$ ). Within  $2\sigma$  from the SM. We cannot yet (significantly) challenge many BSM models.

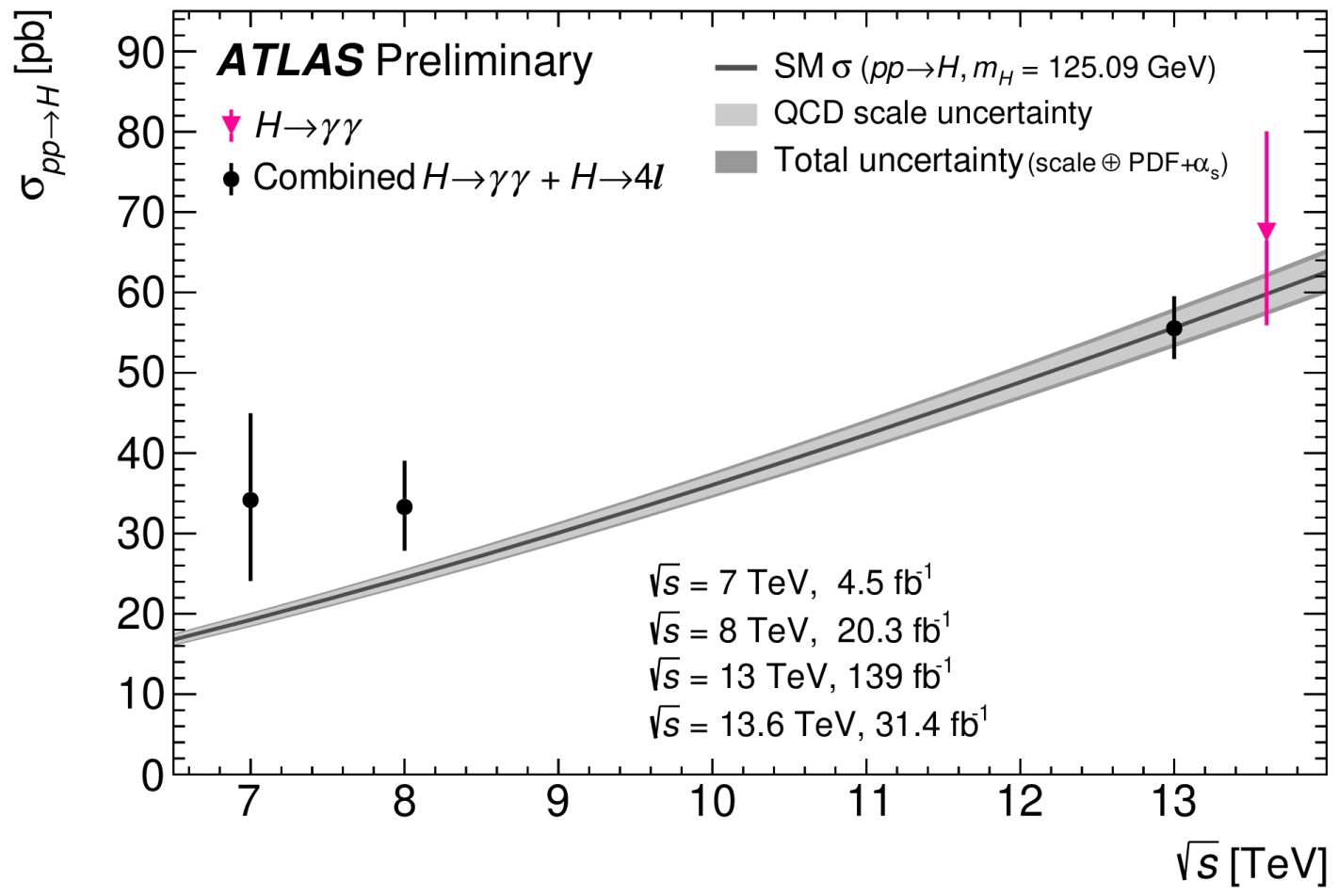
Planck2023 Scale and the LHC, prospects





# The Higgs boson at 13.6 TeV

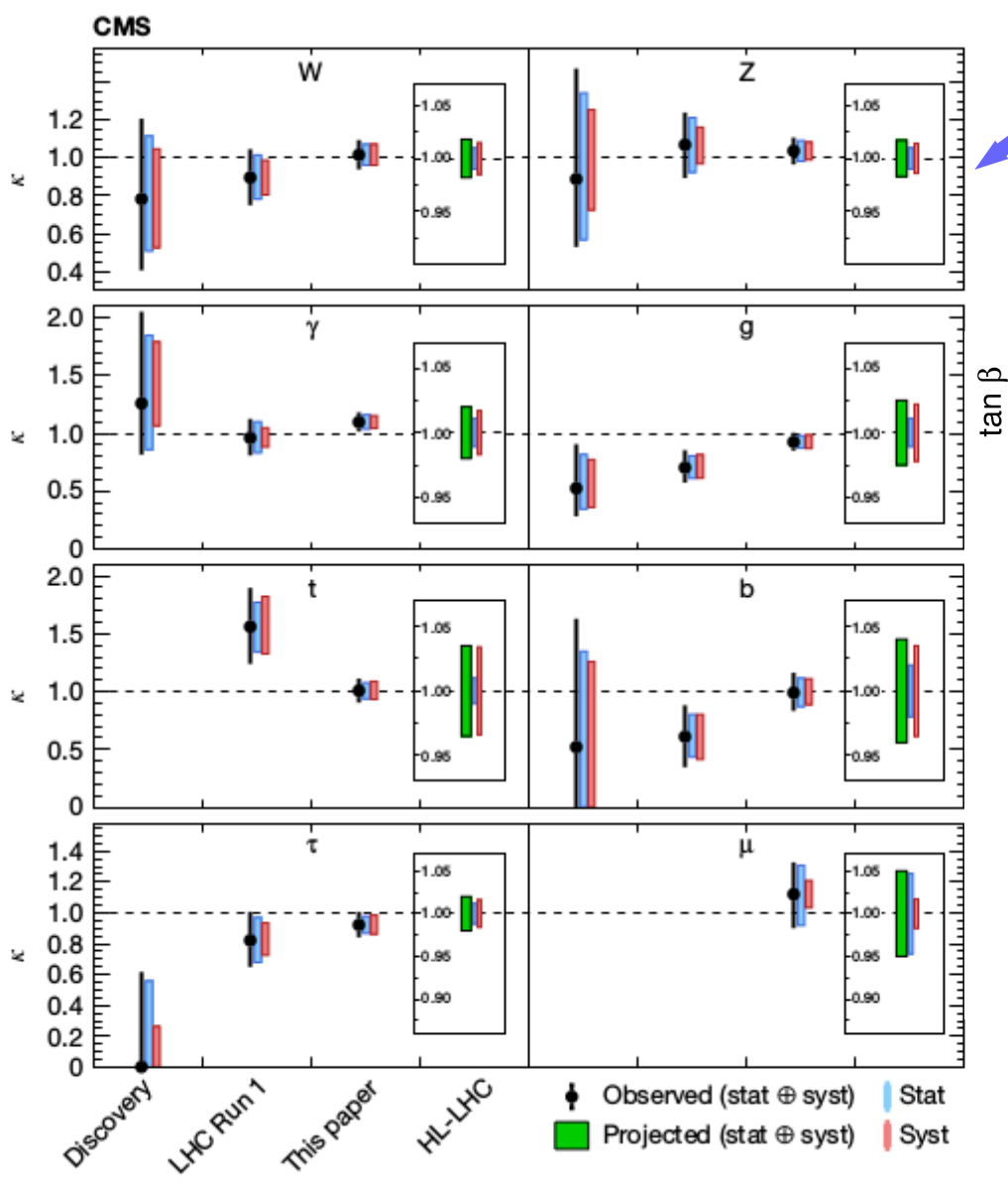
ATLAS-CONF-2023-003



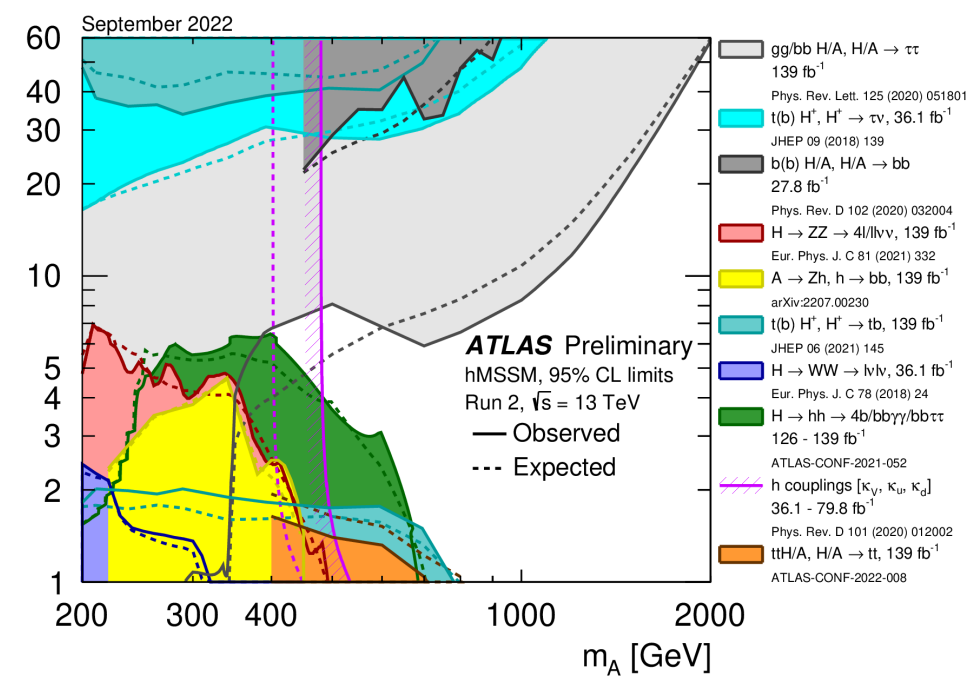
**13.6 TeV point added into  $H \rightarrow \gamma\gamma$  cross-section**

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

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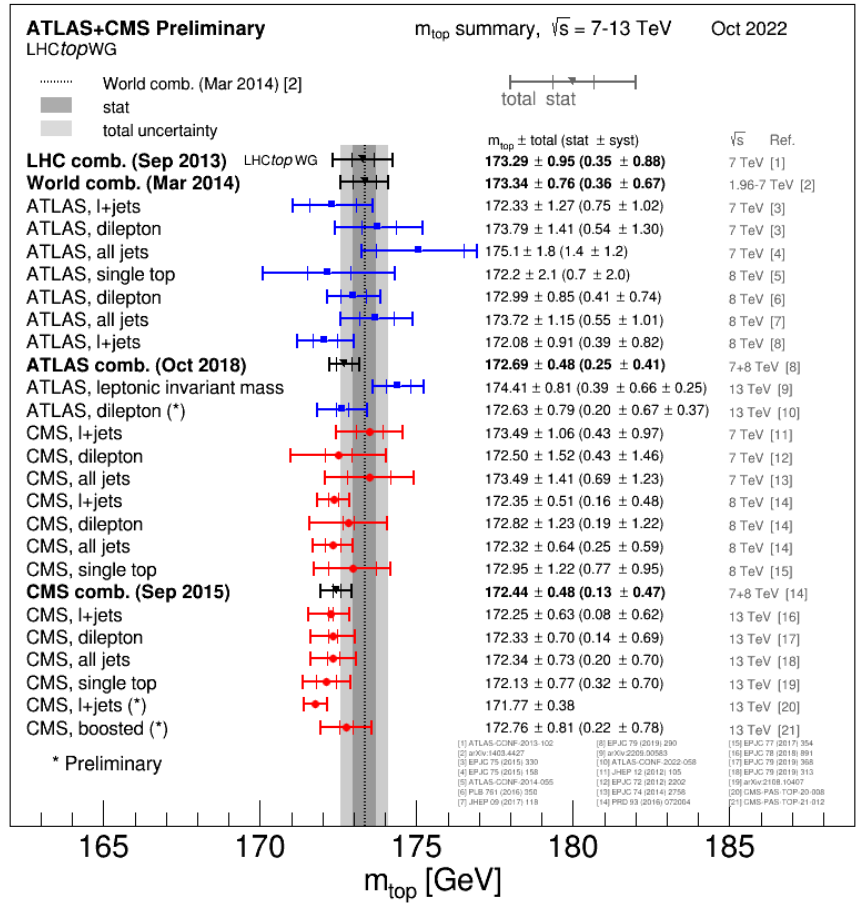
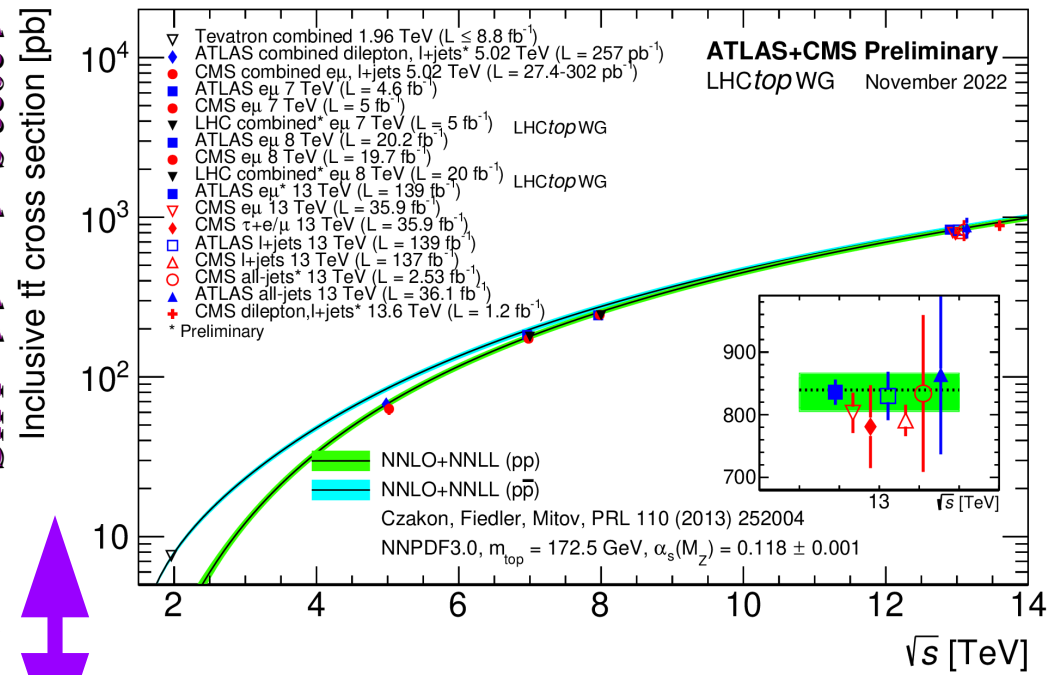
Some couplings will have an accuracy approaching 1-2% at the HL-LHC. This will allow to probe further some of the SM extensions. Example here: hMSSM to  $m_A$  approaching 1000 GeV



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

# EWSB: the top quark

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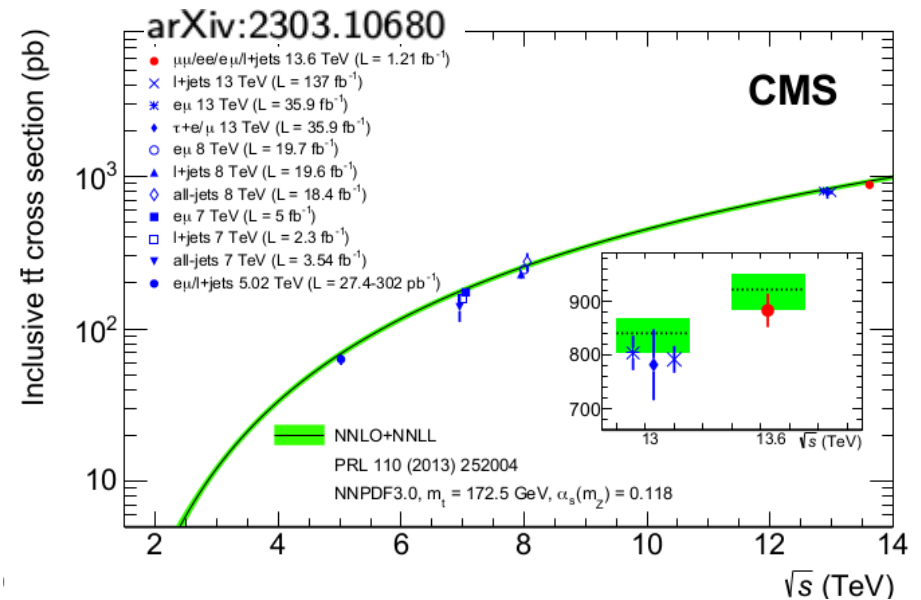
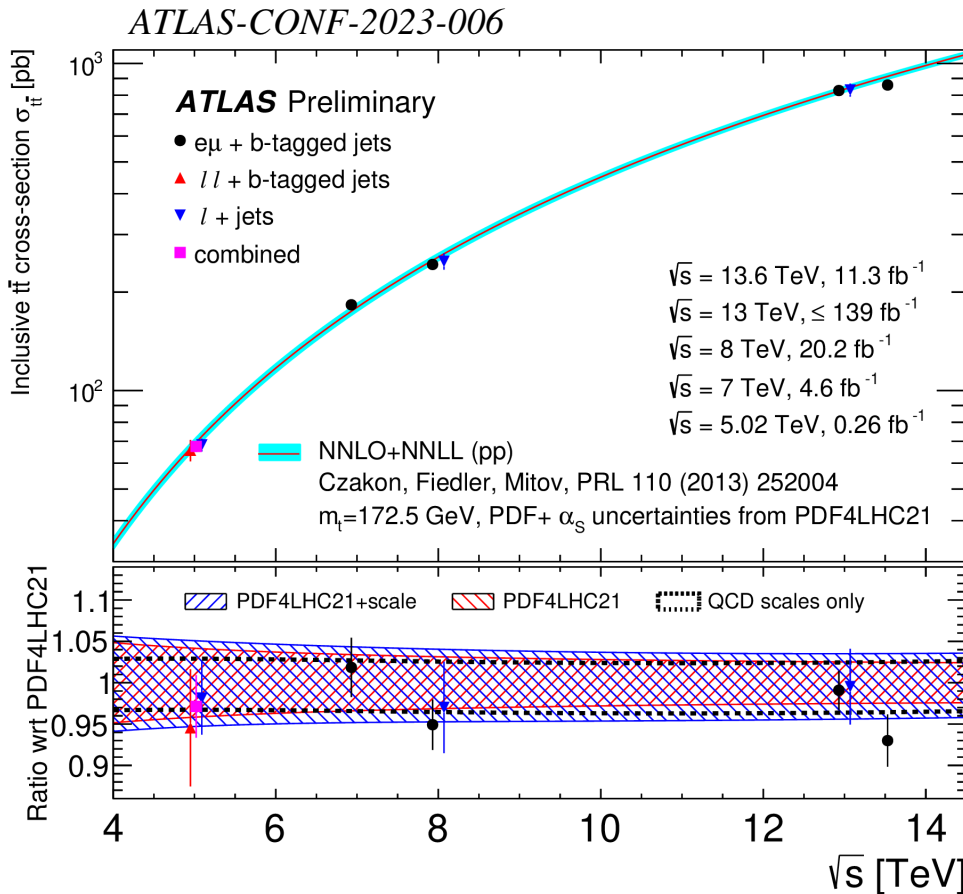


ATLAS+CMS Preliminary LHCtopWG				m_top from cross-section measurements June 2022		Ref.
	total	stat	m_top ± tot (stat ± syst ± theo)			
<b>σ(tt) inclusive, NNLO+NNLL</b>						
ATLAS, 7+8 TeV			172.9 <sup>+2.5</sup> <sub>-2.6</sub>			[1]
CMS, 7+8 TeV			173.8 <sup>+1.7</sup> <sub>-1.8</sub>			[2]
CMS, 13 TeV			169.9 <sup>+1.9</sup> <sub>-2.1</sub> (0.1 ± 1.5 <sup>+1.2</sup> <sub>-1.5</sub> )			[3]
ATLAS, 13 TeV			173.1 <sup>+2.0</sup> <sub>-2.1</sub>			[4]
LHC comb., 7+8 TeV LHCtopWG			173.4 <sup>+1.8</sup> <sub>-2.0</sub>			[5]
<b>σ(tt+1j) differential, NLO</b>						
ATLAS, 7 TeV			173.7 <sup>+2.3</sup> <sub>-2.1</sub> (1.5 ± 1.4 <sup>+1.0</sup> <sub>-0.5</sub> )			[6]
CMS, 8 TeV (*)			169.9 <sup>+4.5</sup> <sub>-3.7</sub> (1.1 <sup>+2.5</sup> <sub>-3.1</sub> , -1.6)			[7]
ATLAS, 8 TeV			171.1 <sup>+1.2</sup> <sub>-1.0</sub> (0.4 ± 0.9 <sup>+0.7</sup> <sub>-0.3</sub> )			[8]
CMS, 13 TeV (*)			172.9 <sup>+1.4</sup> <sub>-1.4</sub>			[9]
<b>σ(tt) n-differential, NLO</b>						
ATLAS, n=1, 8 TeV			173.2 ± 1.6 (0.9 ± 0.8 ± 1.2)			[10]
CMS, n=3, 13 TeV			170.5 ± 0.8			[11]
<b>m_top from top quark decay</b>						
CMS, 7+8 TeV comb. [10]						[10]
ATLAS, 7+8 TeV comb. [11]						[11]

**Top quark mass known to ~0.5 GeV**  
**Systematic errors dominate.**

# The top quark at 13.6 TeV

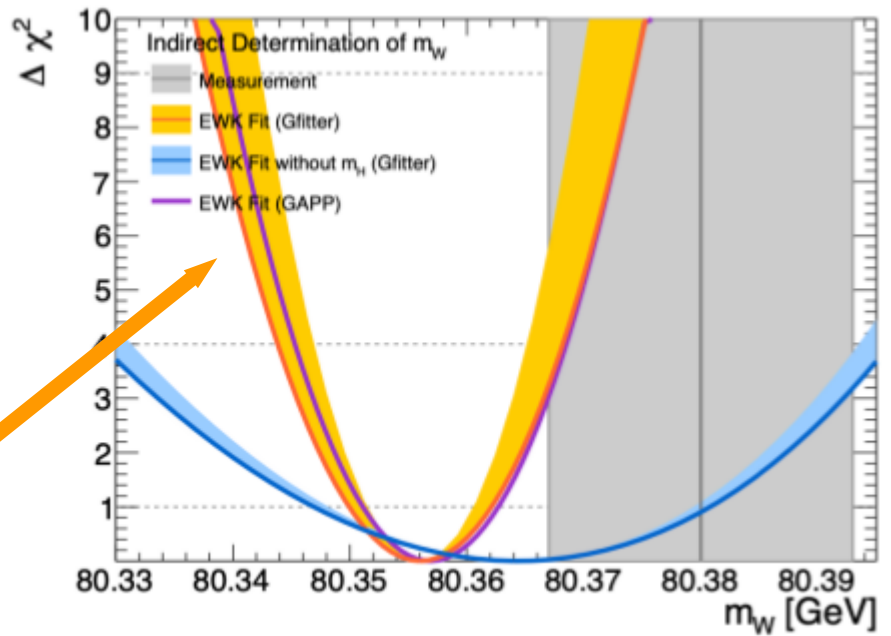
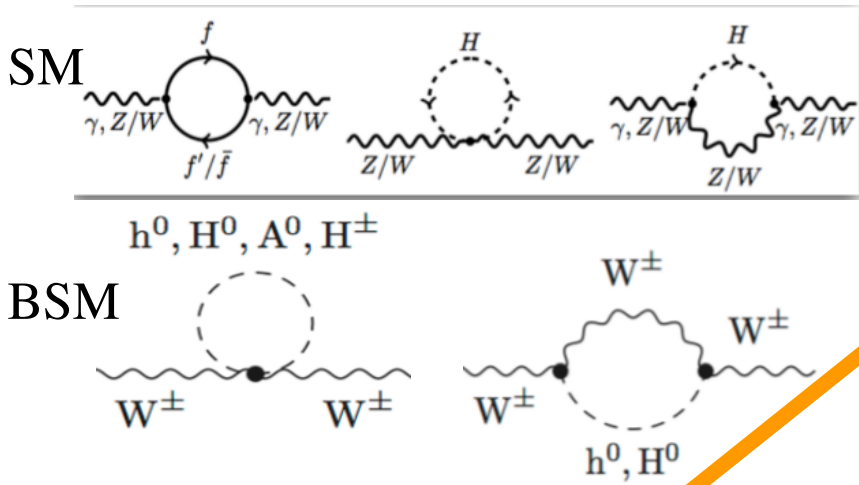
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Run3 data analyses ongoing and 13.6 TeV point added into the cross-sections scan with preliminary but robust luminosity calibration. Run 2 results now reached 1.8% accuracy, more precise due to the new luminosity calibration (ATLAS-CONF-2023-006).

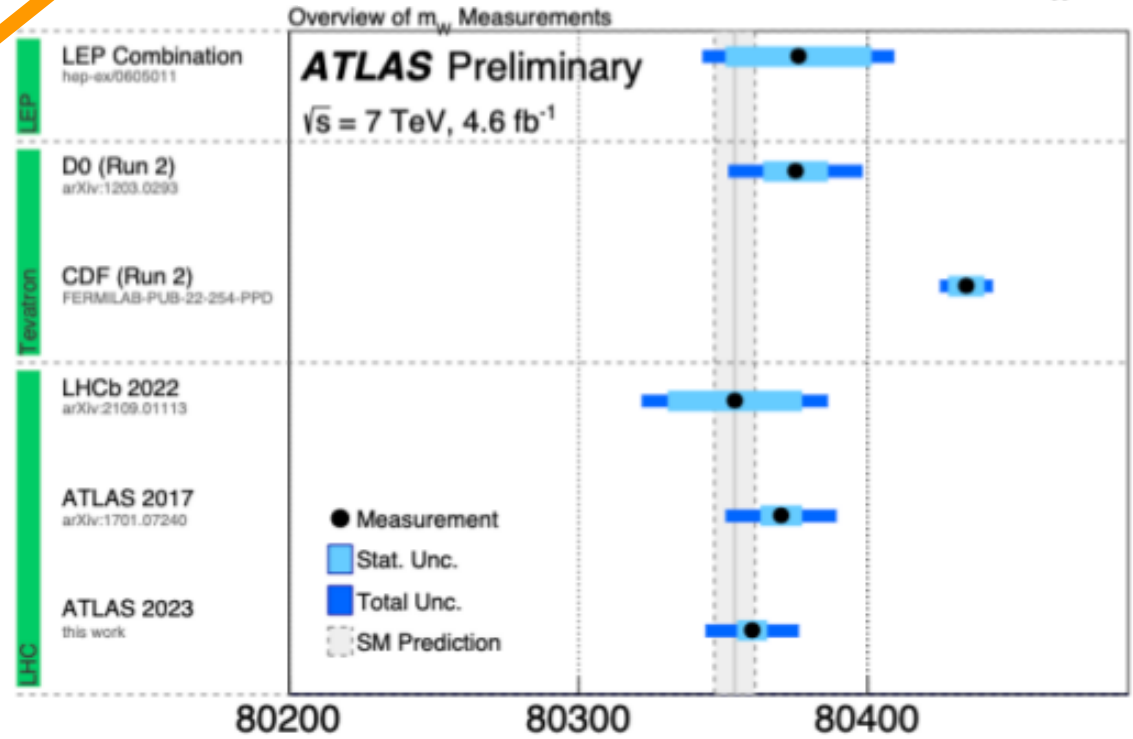
# EWSB: $M_W, M_H, M_{top}$

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4 parameters of the EW sector ( $\alpha_{em}, G_F, m_Z, \sin^2 \theta_W$ ) +  $m_H$  and  $m_{top} \rightarrow$  predict  $m_W$  within the SM  $\Delta m_W = 7 \text{ MeV}$

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

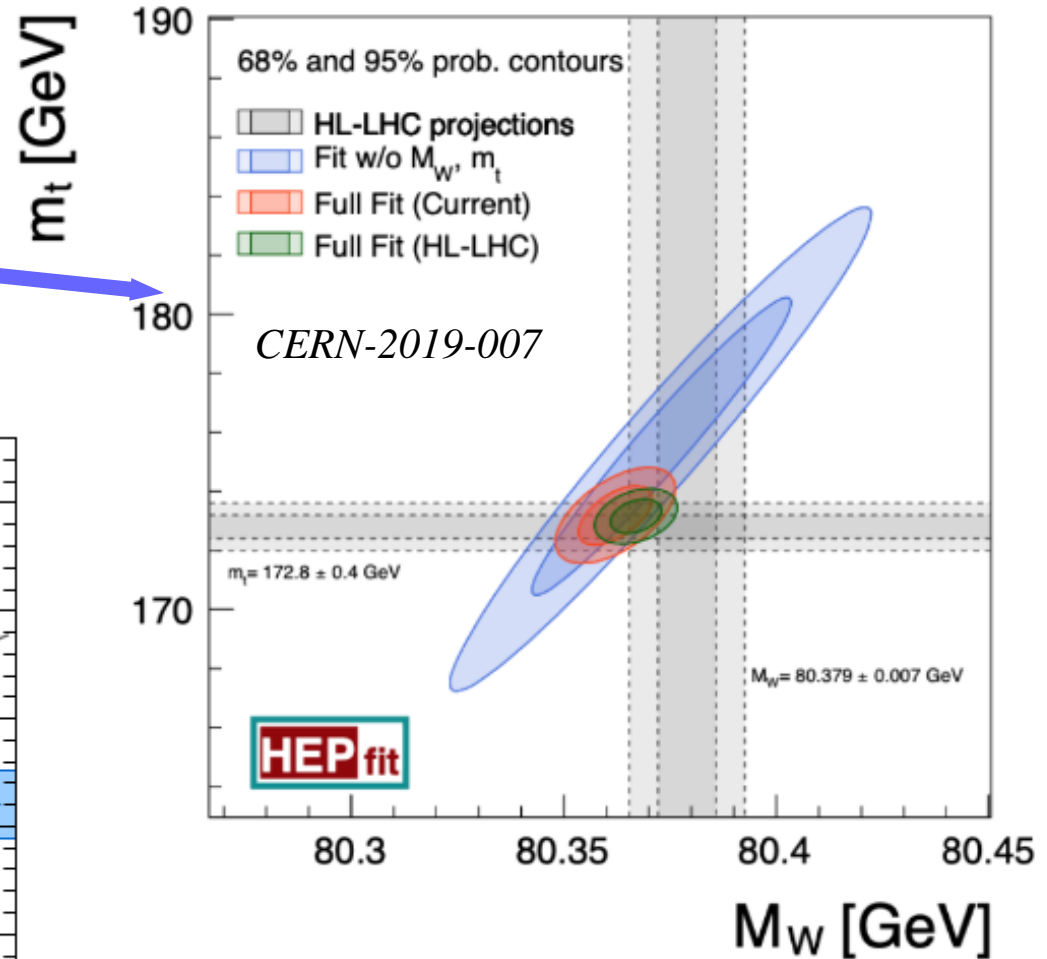
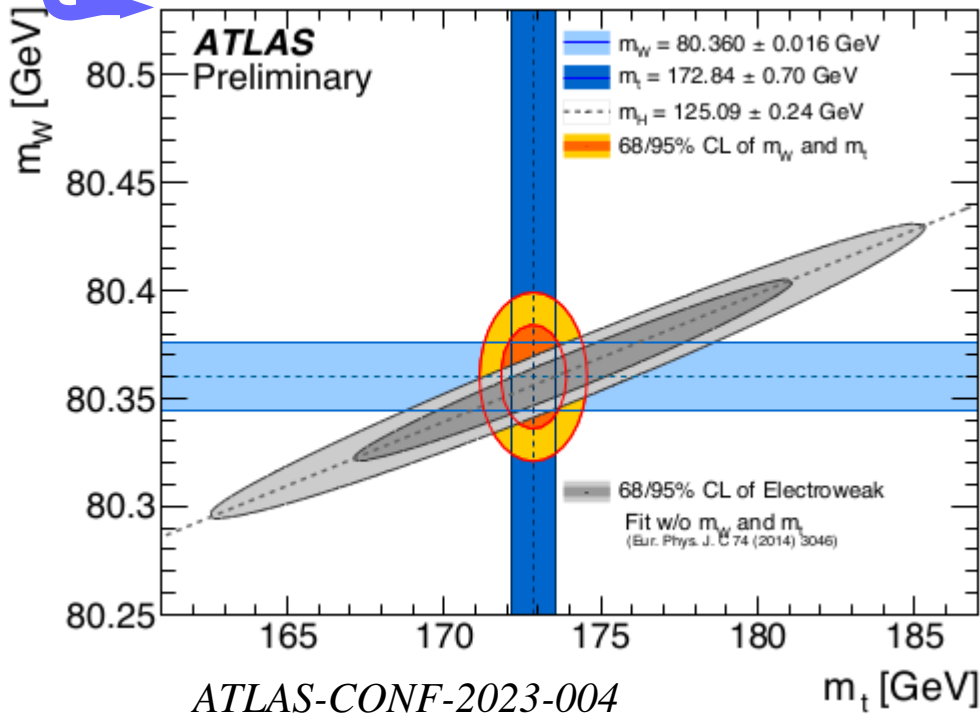


$$m_W = 80360 \pm 5_{(\text{stat.})} \pm 15_{(\text{syst.})} = 80360 \pm 16 \text{ MeV}$$

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

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



# EWSB: Higgs self-coupling

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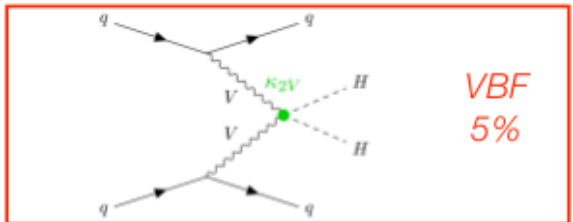
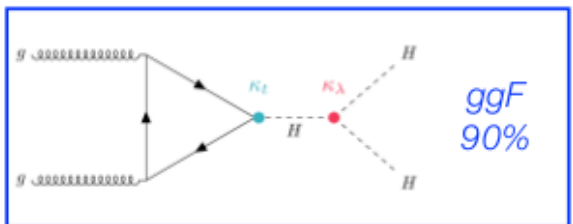
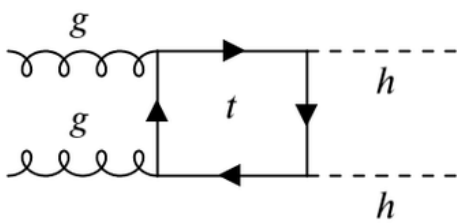
**Huge effort presently focusing on hhh vertex via hh production**

**(single h production helps as well)**

*double-Higgs production*

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

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



$\sigma(pp \rightarrow HH) @ 13 \text{ TeV} = 34 \text{ fb}$

~5k produced in Run 2

**Present results (95 % CL):**

**ATLAS** *arXiv:2211.01216*

**CMS** *Nature 607 (2022) 60-68*

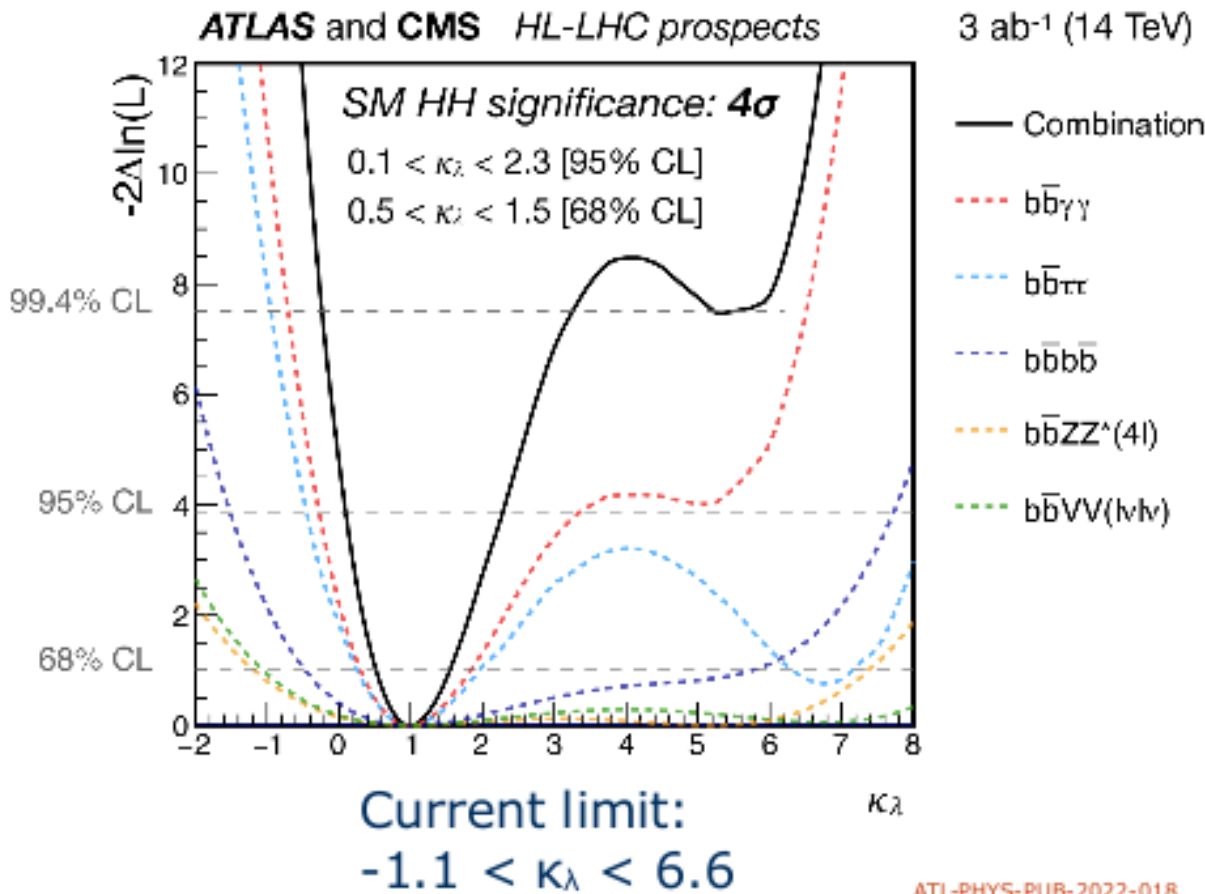
$-0.4 < \kappa_\lambda < 6.3$

$-1.24 < \kappa_\lambda < 6.49$

# EWSB: Higgs self-coupling

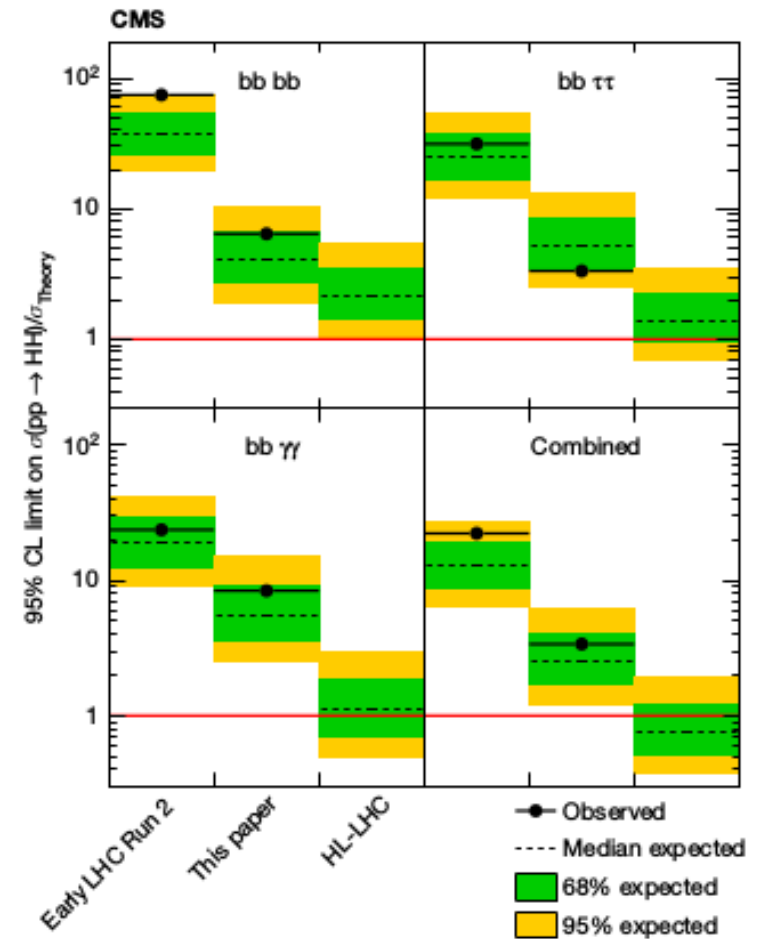
Present predictions: “Evidence++” for hhh (if SM self-coupling) : End of HL-LHC.  
 Improvements in the prospects in the pipe-line, profiling towards  $5\sigma$ , **ATL-PHYS-PUB-2022-053**

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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 ?**

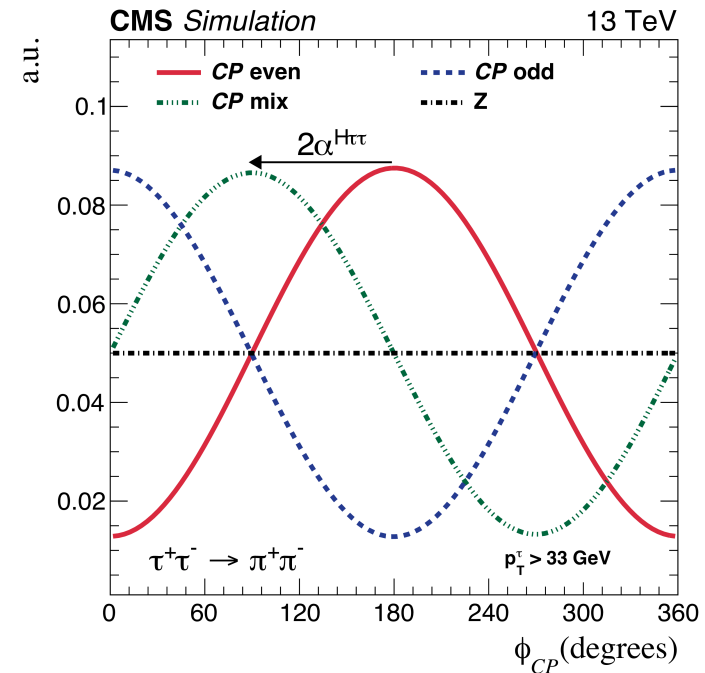
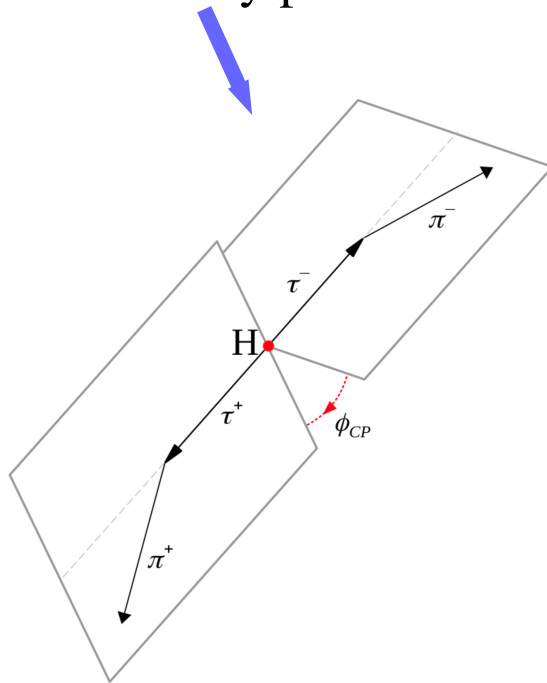
**-Any “generic” way to search fo CPV at the LHC?**

*Experimental efforts ongoing to pin-point CPV in Higgs  $\rightarrow$  VV couplings.*

*However its relation to fermion-antifermion asymmetry less straightforward than for CPV in Higgs  $\rightarrow$  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.



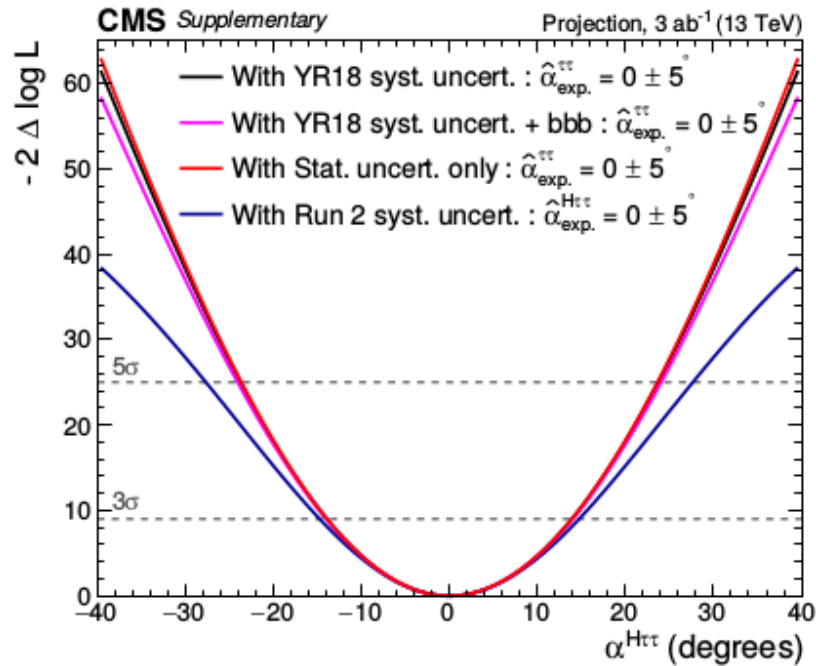
*arXiv:2212.05833* ATLAS: The observed (expected) value of  $\alpha_\tau$  is  $9^\circ \pm 16^\circ$  ( $0^\circ \pm 28^\circ$ ) at the 68% CF

*JHEP 06 (2022) 012* CMS The observed (expected) value of  $\alpha_\tau$  is  $-1^\circ \pm 19^\circ$  ( $0^\circ \pm 21^\circ$ ) at the 68% CF

# CPV in tau-Higgs Yukawa, prospects.

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CMS PAS FTR-22-001



**HL-LHC :**

**CP phase sensitivity prospects:**

$\sim 5^\circ$  ( $\sim 15^\circ$  for  $3\sigma$ )

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

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

$\text{H} \rightarrow \tau\tau\gamma$ ? [*JHEP01(2022)053*]

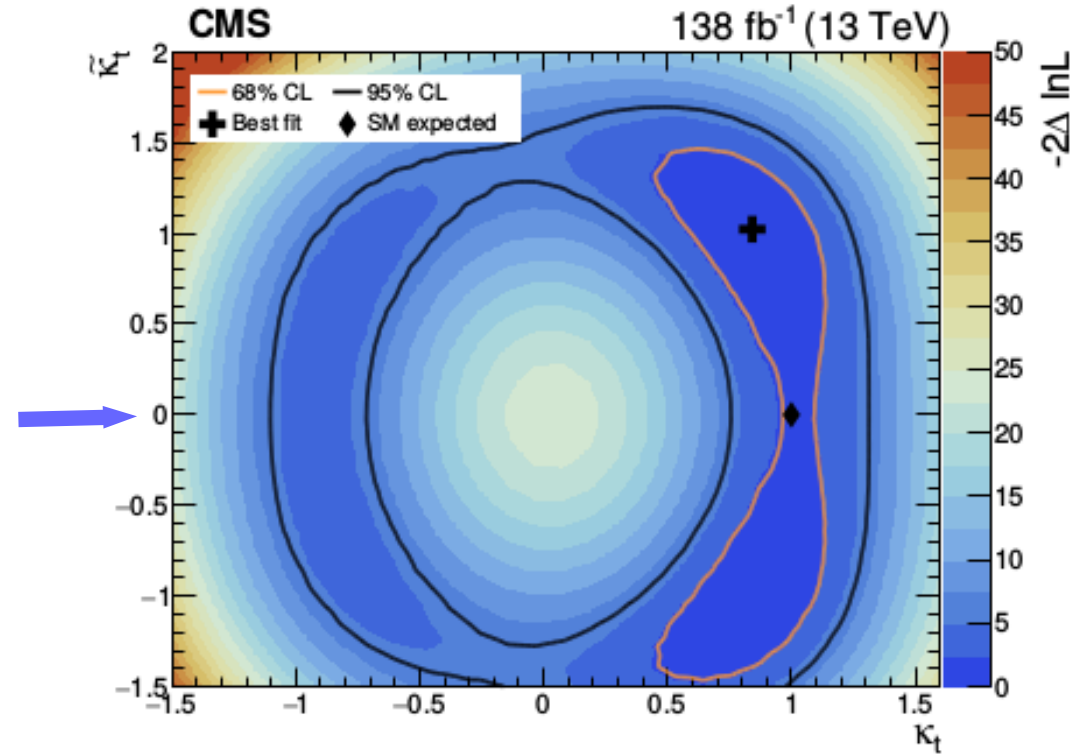
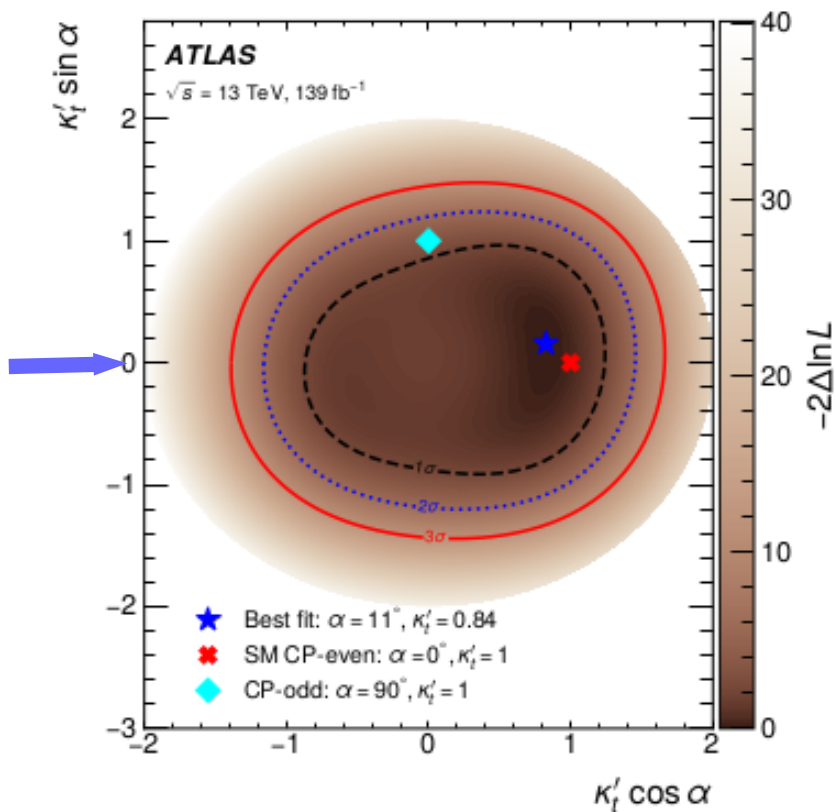
# CPV in top-Higgs Yukawa ?

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

arxiv: 2303.05974

arXiv:2208.02686

ATLAS :  $\alpha = 11^\circ_{-73^\circ}^{+52^\circ}$



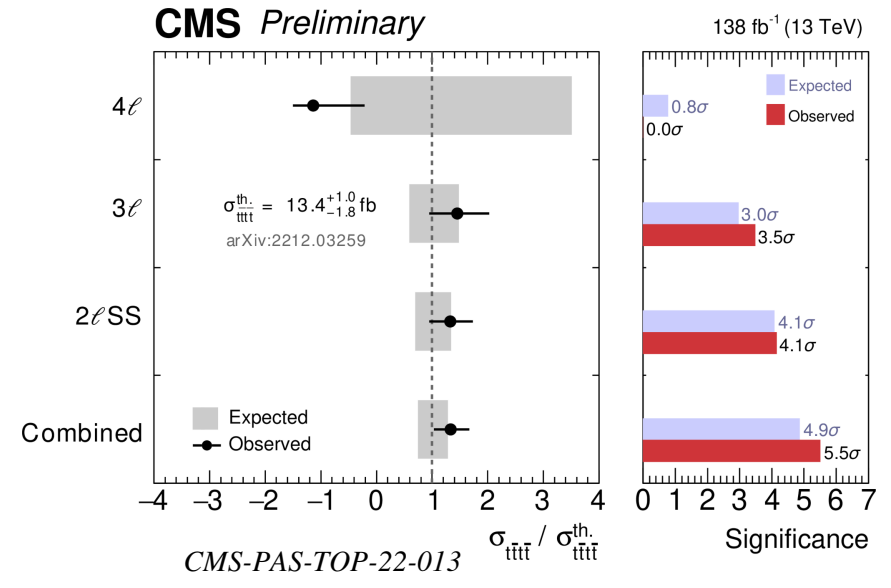
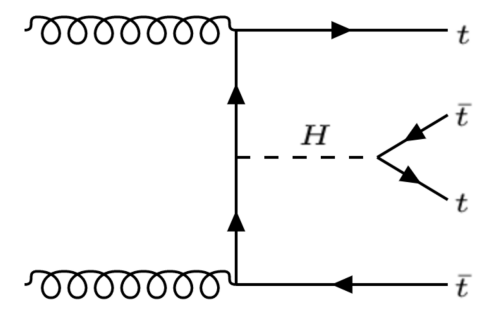
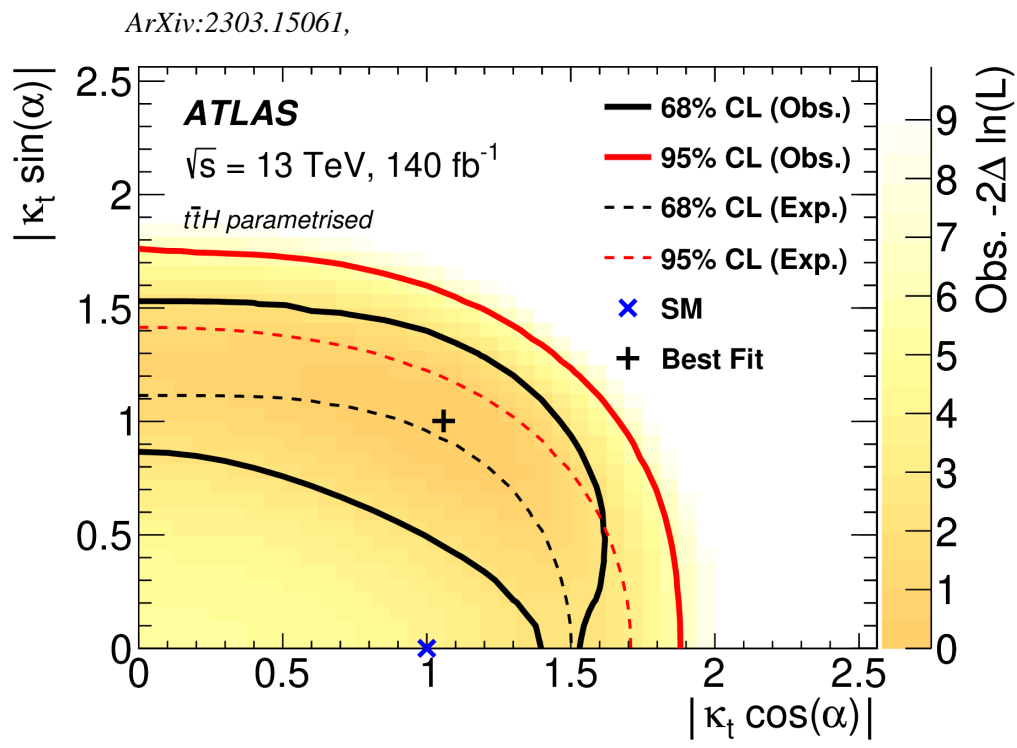
Compatible with no CPV. MV methods used. Uncertainties are huge, but will improve with statistics.

# CPV in top-Higgs Yukawa ?

$t\bar{t}H$  coupling from  $t\bar{t}t\bar{t}$  final state, with the tiniest x-section measured so far at the LHC.

( $\alpha=0$ ,  $k_t=1$  for CP even SM coupling)

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## 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,  $H \rightarrow$  invisible

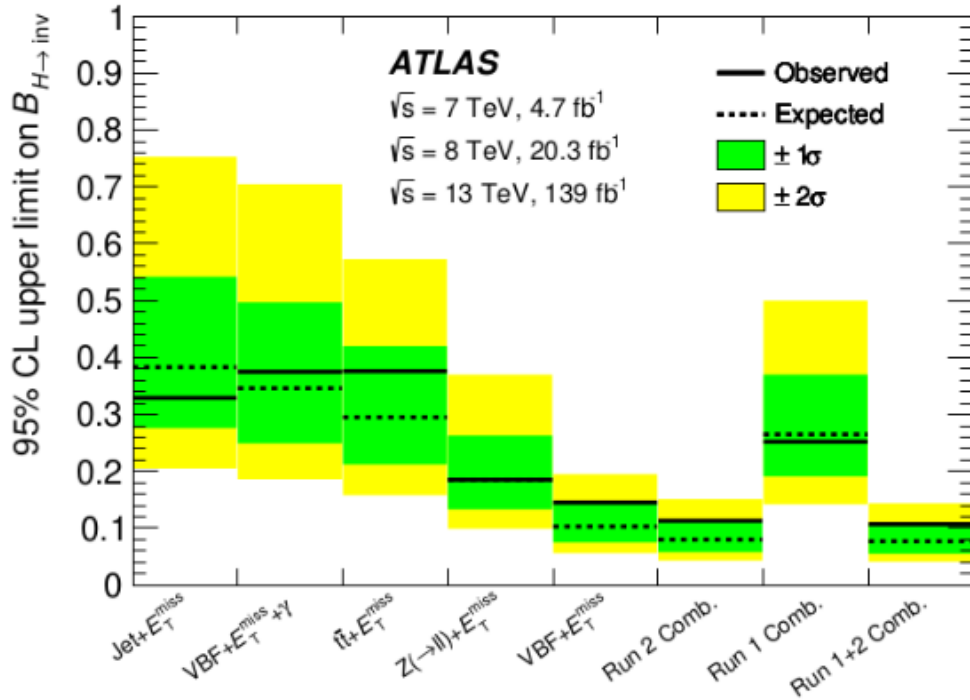
Simplified benchmark models.

2HDM with DM

SUSY DM

## DM:Higgs → invisible

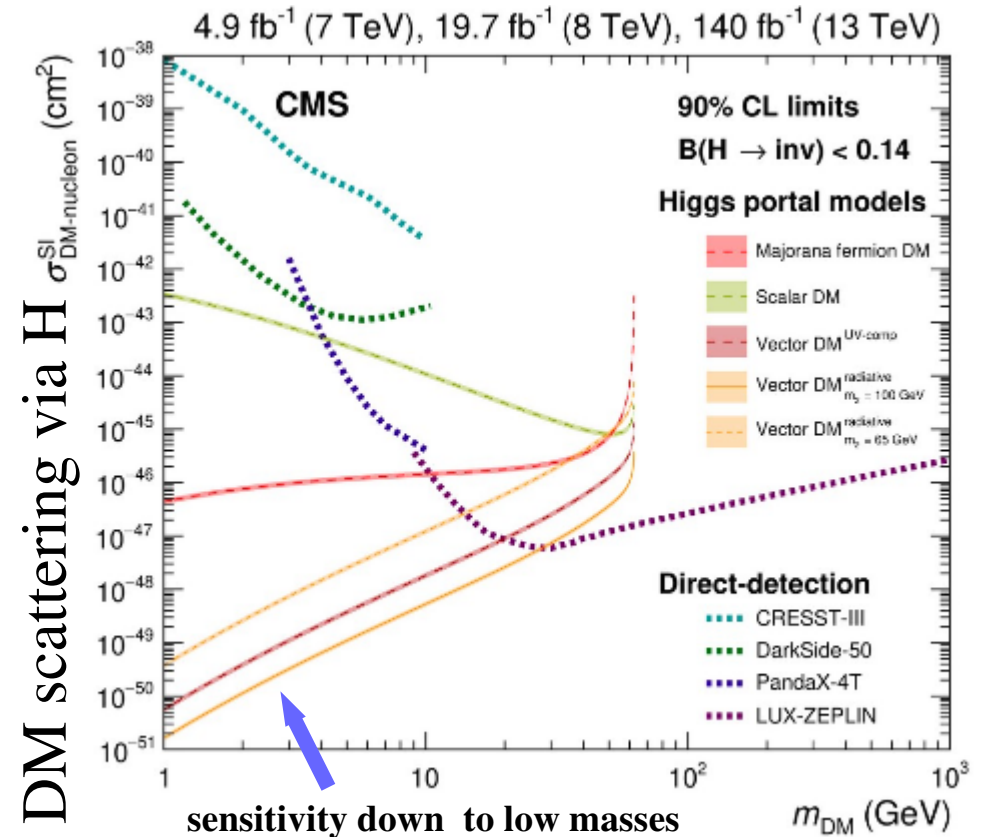
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95% CL limit for  $H \rightarrow \text{inv}$ :  
 ATLAS: 10.7% (7.7% exp.)  
 CMS: 15% (8% exp.)

ATLAS: [arXiv:2301.10731](https://arxiv.org/abs/2301.10731)  
 CMS: [arXiv:2303.01214](https://arxiv.org/abs/2303.01214)

$BR(H \rightarrow \tau\tau) = 6.3\%$ . Is “simple” Dirac fermion DM already in trouble without additional Higgses?



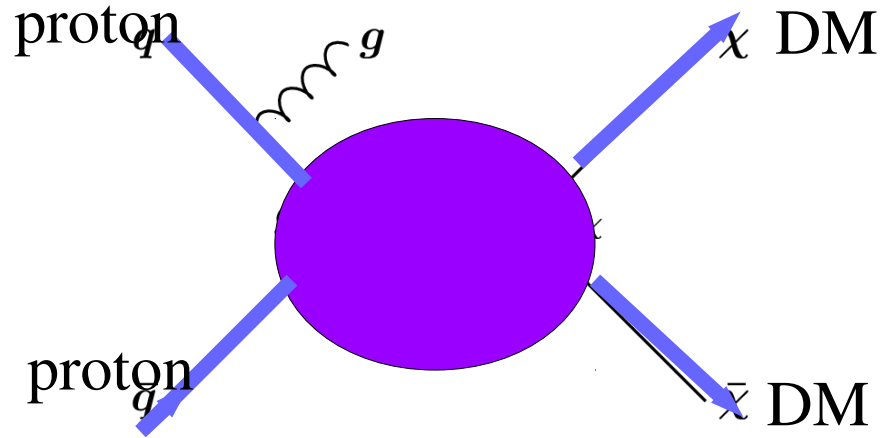
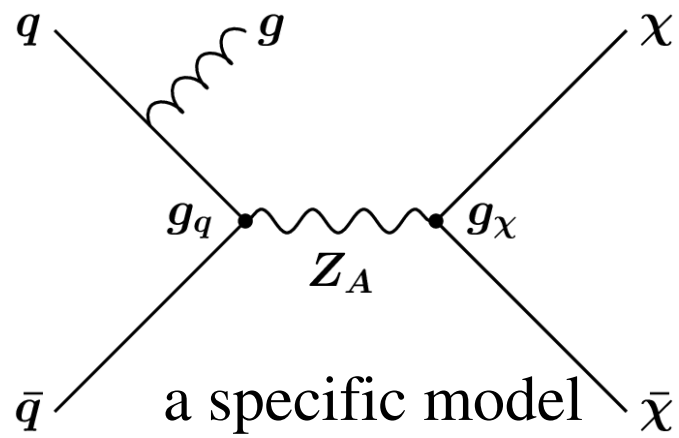
HL-LHC sensitivity prospects:  
 $H \rightarrow \text{inv} < 2.5\%$

CMS PAS FTR-22-001

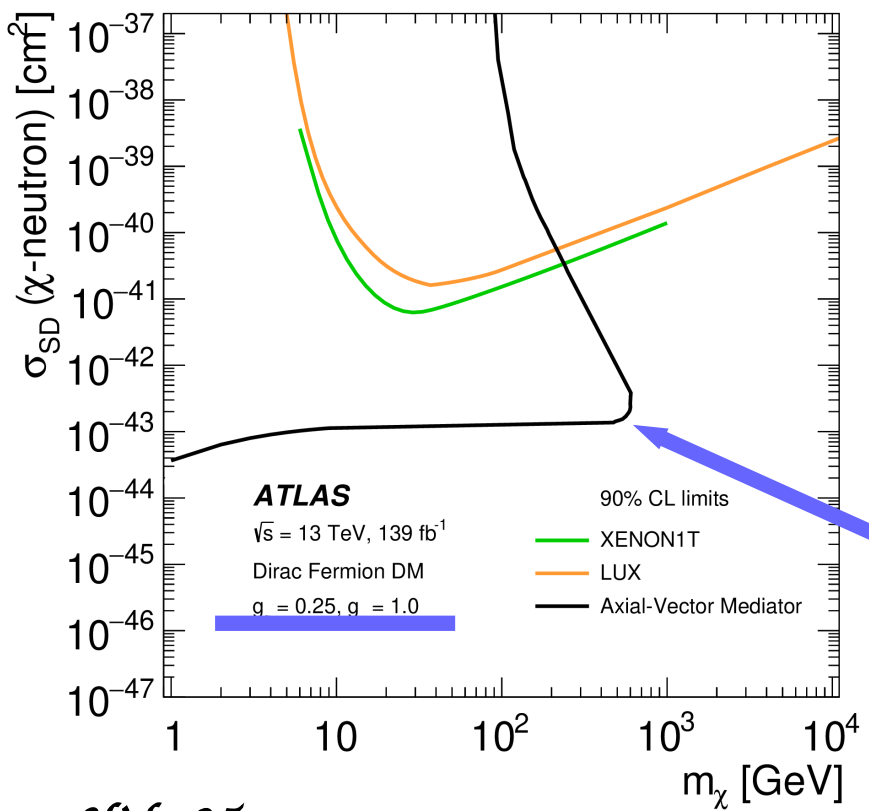
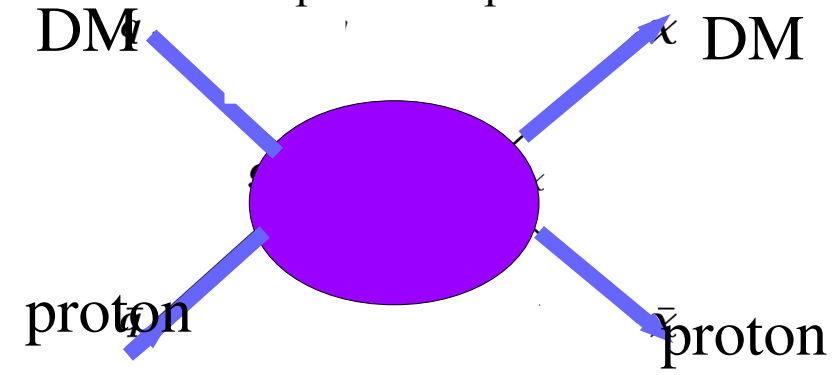


# Searches in simplified models: close to "generic" Dark Matter searches?

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Generic :  $p+p \rightarrow \text{DM DM}$  to be related to  $\text{DM}+p \rightarrow \text{DM}+p$



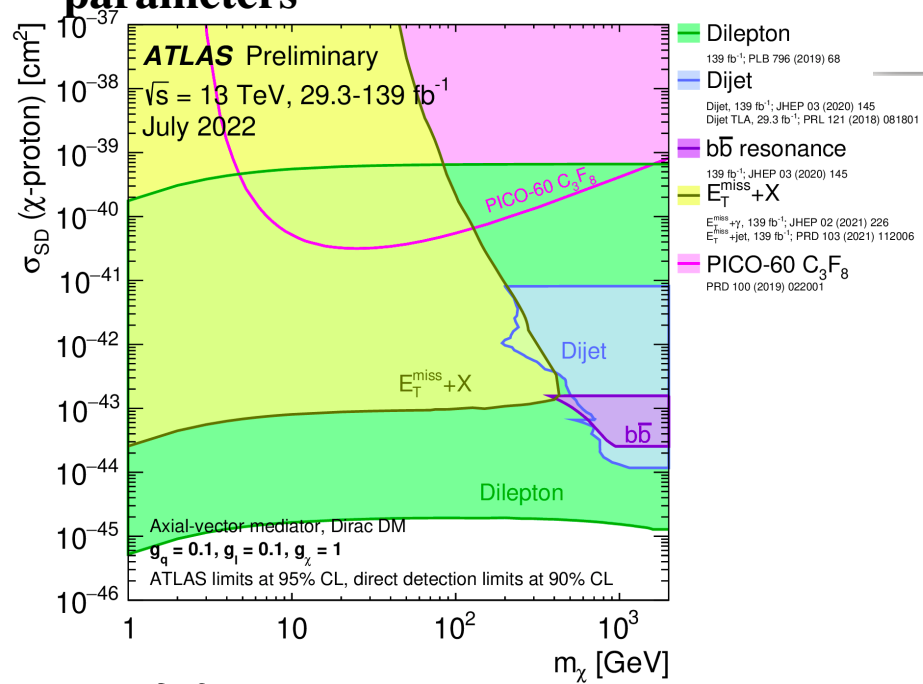
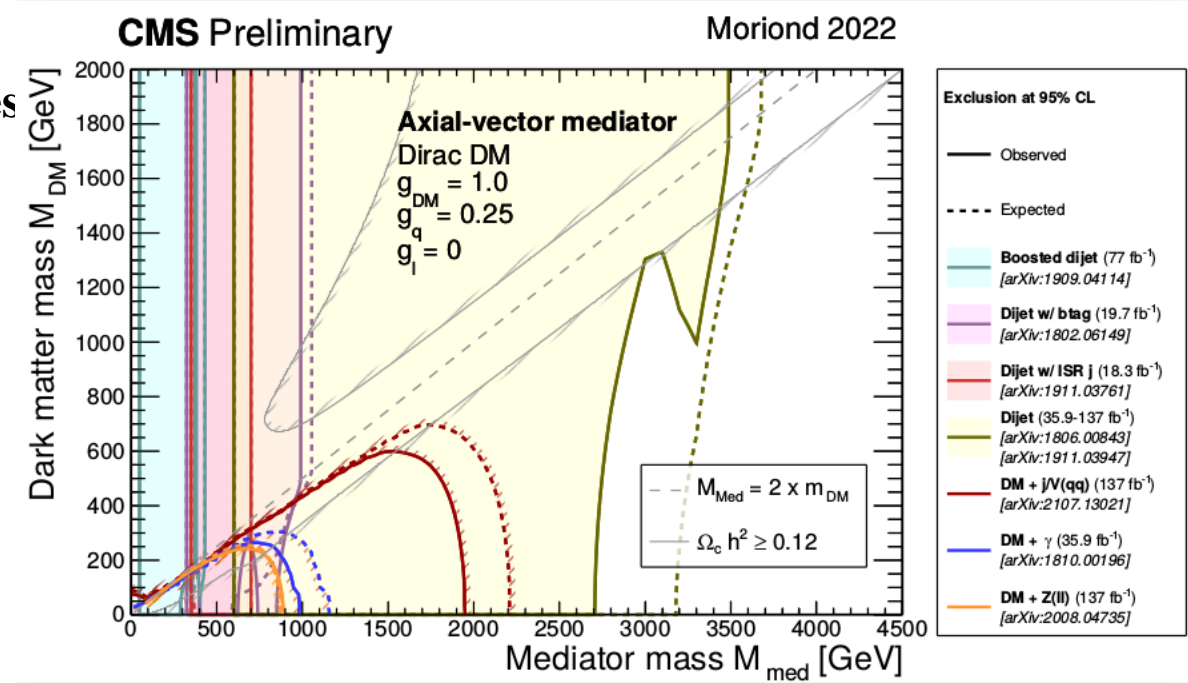
**Example ATLAS result, for a specific model. Results competitive with the direct search for DM scattering on nucleons But model parameters dependent !**

*Phys. Rev. D 103 (2021) 112006*

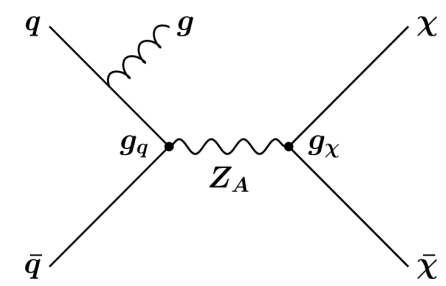
# DM Searches in simplified models, examples:

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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

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

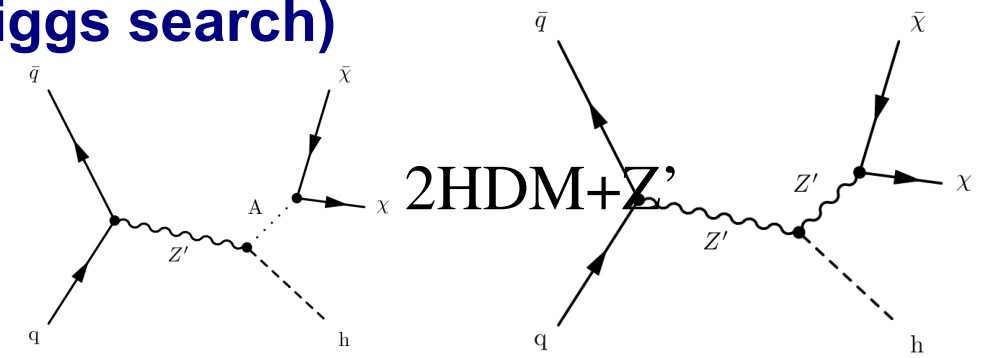
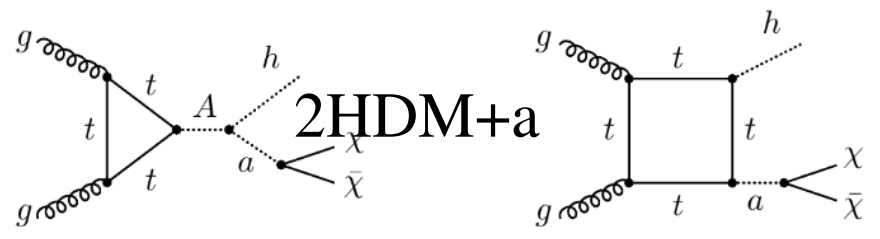
SM: one “complex doublet” = 4 fields  
 Mass=Transverse polarization for  
 $W^+$   $Z^0$  and **SM scalar h boson**

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v_1 + \eta_1 + i\chi_1)/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \eta_2 + i\chi_2)/\sqrt{2} \end{pmatrix},$$

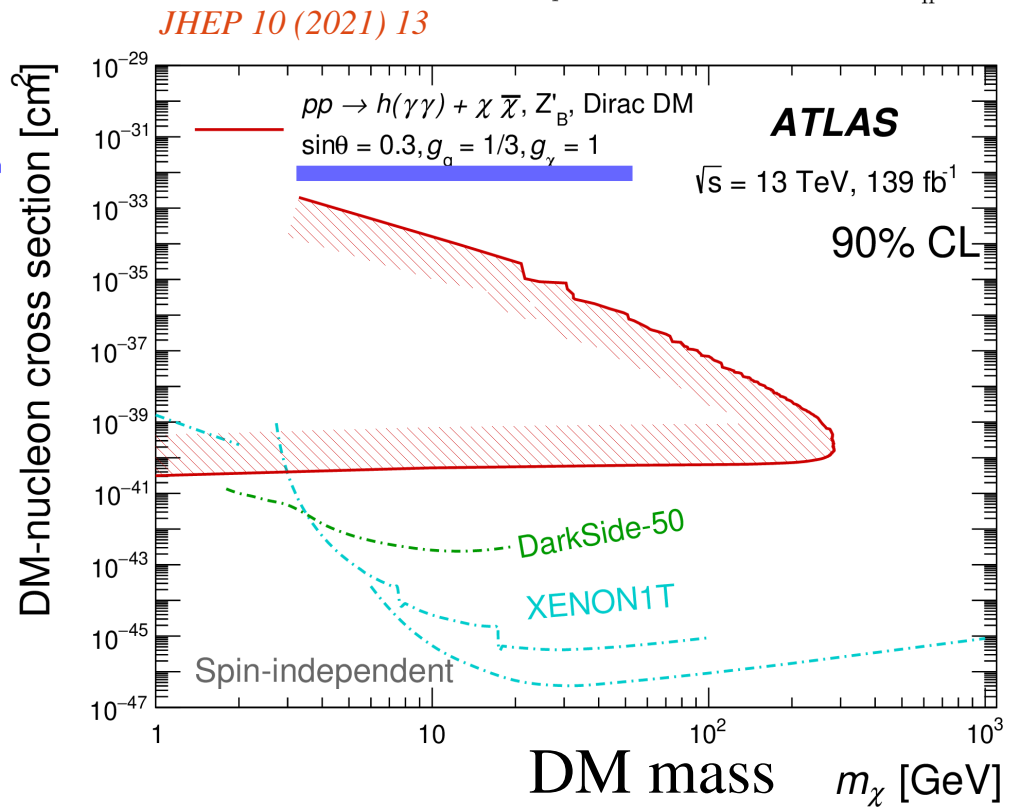
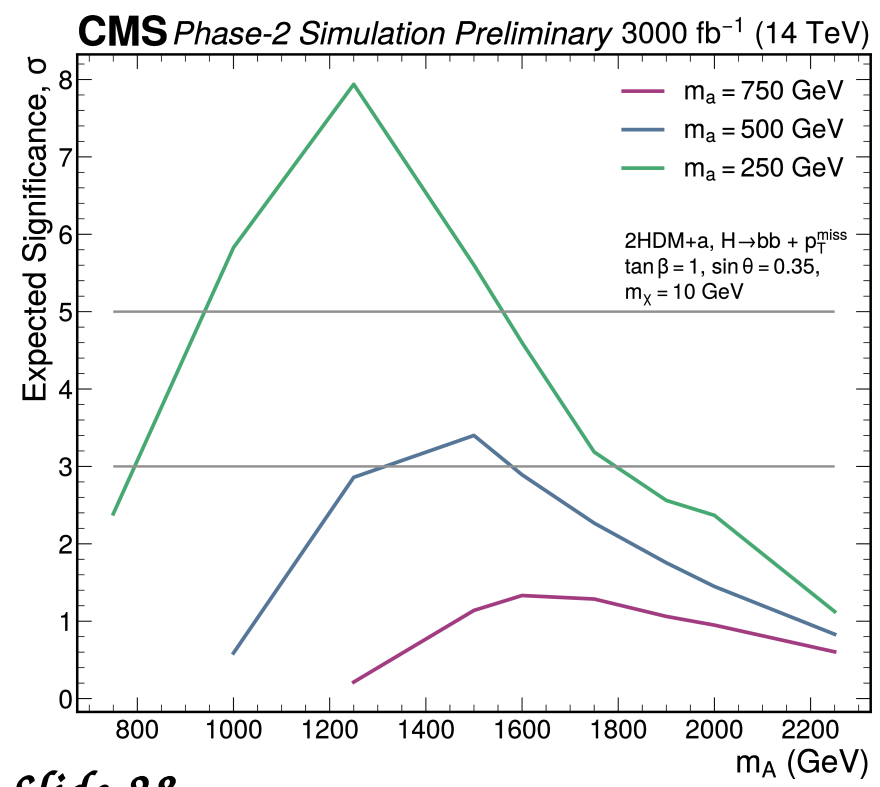
BSM: two “complex doublets” = 8 fields  
 =Transverse polarization for  
 $W^+$   $Z^0$  and 5 Higgs bosons  **$H^+$** , **A**, **H** and **h**

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  
 $H \rightarrow \gamma\gamma$ ,  $H \rightarrow bb$  [JHEP 11 (2021) 209],  $H \rightarrow \tau\tau$  ... combined for DM search (ref)



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

Planck2023 Scale and the LHC, prospects

# Supersymmetry (SUSY) has been desperately searched for.

Planck2023 Scale and the LHC, prospects

## ATLAS SUSY Searches\* - 95% CL Lower Limits

March 2023

ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference							
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{\chi}_1^0$	0 $e, \mu$ mono-jet	2-6 jets 1-3 jets	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	139 139	$\bar{q}$ [1x, 8x Degen.] $\bar{q}$ [8x Degen.]	1.0 0.9	1.85	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	2010.14293 2102.10874	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 $e, \mu$	2-6 jets	$E_T^{\text{miss}}$	139	$\tilde{g}$ $\tilde{g}$	Forbidden	2.3	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 1000 \text{ GeV}$	2010.14293 2010.14293	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 $e, \mu$	2-6 jets	$E_T^{\text{miss}}$	139	$\tilde{g}$		2.2	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	2101.01629	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	$E_T^{\text{miss}}$	139	$\tilde{g}$		2.2	$m(\tilde{\chi}_1^0) < 700 \text{ GeV}$	2204.13072	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$	0 $e, \mu$	7-11 jets	$E_T^{\text{miss}}$	139	$\tilde{g}$		1.97	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	2008.06032	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$	SS $e, \mu$	6 jets	$E_T^{\text{miss}}$	139	$\tilde{g}$		1.15	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	1909.08457	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 $e, \mu$ SS $e, \mu$	3 $b$ 6 jets	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	139 139	$\tilde{g}$ $\tilde{g}$		2.45	$m(\tilde{\chi}_1^0) < 500 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	2211.08028 1909.08457	
	3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 $e, \mu$	2 $b$	$E_T^{\text{miss}}$	139	$\tilde{b}_1$ $\tilde{b}_1$	0.68	1.255	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $10 \text{ GeV} < \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20 \text{ GeV}$	2101.12527 2101.12527
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$		0 $e, \mu$ 2 $\tau$	6 $b$ 2 $b$	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	139 139	$\tilde{b}_1$ $\tilde{b}_1$	Forbidden	0.23-1.35	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	1908.03122 2103.08189	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$		0-1 $e, \mu$	$\geq 1$ jet	$E_T^{\text{miss}}$	139	$\tilde{t}_1$		1.25	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	2004.14060, 2012.03799	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$		1 $e, \mu$	3 jets/1 $b$	$E_T^{\text{miss}}$	139	$\tilde{t}_1$	Forbidden	0.65	$m(\tilde{\chi}_1^0) < 500 \text{ GeV}$	2012.03799	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$		1-2 $\tau$	2 jets/1 $b$	$E_T^{\text{miss}}$	139	$\tilde{t}_1$	Forbidden	1.4	$m(\tilde{\tau}_1) = 800 \text{ GeV}$	2108.07665	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$		0 $e, \mu$ 0 $e, \mu$	2 $c$ mono-jet	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	36.1 139	$\tilde{t}_1$ $\tilde{t}_1$		0.85	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1805.01649 2102.10874	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$		1-2 $e, \mu$	1-4 $b$	$E_T^{\text{miss}}$	139	$\tilde{t}_1$		0.067-1.18	$m(\tilde{\chi}_2^0) = 500 \text{ GeV}$	2006.05880	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$		3 $e, \mu$	1 $b$	$E_T^{\text{miss}}$	139	$\tilde{t}_2$	Forbidden	0.86	$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0) = 40 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 360 \text{ GeV}, m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0) = 40 \text{ GeV}$	2006.05880	
EW direct	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via WZ	Multiple $\ell$ /jets $ee, \mu\mu$	$\geq 1$ jet	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	139 139	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ $\tilde{\chi}_1^+ \tilde{\chi}_2^0$	0.205	0.96	$m(\tilde{\chi}_1^0) = 0, \text{wino-bino}$ $m(\tilde{\chi}_1^+) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}, \text{wino-bino}$	2106.01676, 2108.07586 1911.12606	
	$\tilde{\chi}_1^+ \tilde{\chi}_1^+$ via WW	2 $e, \mu$		$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^+$	0.42		$m(\tilde{\chi}_1^0) = 0, \text{wino-bino}$	1908.08215	
	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via Wh	Multiple $\ell$ /jets		$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	Forbidden	1.06	$m(\tilde{\chi}_1^0) = 70 \text{ GeV}, \text{wino-bino}$	2004.10894, 2108.07586	
	$\tilde{\chi}_1^+ \tilde{\chi}_1^+$ via $\tilde{\ell}_L/\tilde{\nu}$	2 $e, \mu$		$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^+$		1.0	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$	1908.08215	
	$\tilde{\tau}^+ \tilde{\tau}^-, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 $\tau$		$E_T^{\text{miss}}$	139	$\tilde{\tau}$	[ $\tilde{\tau}_L, \tilde{\tau}_{R,1}$ ]	0.16-0.3	$m(\tilde{\chi}_1^0) = 0$	1911.06660	
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$ $ee, \mu\mu$	0 jets $\geq 1$ jet	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	139 139	$\tilde{\ell}$ $\tilde{\ell}$		0.7	$m(\tilde{\chi}_1^0) = 0$	1908.08215 1911.12606	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 $e, \mu$ 4 $e, \mu$ 0 $e, \mu$	$\geq 3 b$ 0 jets $\geq 2$ large jets	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$ $E_T^{\text{miss}}$	36.1 139 139	$\tilde{H}$ $\tilde{H}$ $\tilde{H}$		0.29-0.88	$m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10 \text{ GeV}$	1806.04030 2103.11684 2108.07586	
	$\tilde{H}$	2 $e, \mu$	$\geq 2$ jets	$E_T^{\text{miss}}$	139	$\tilde{H}$		0.45-0.93	$\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = \text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 0.5$	2204.13072	
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$	0.21	0.66	Pure Wino Pure higgsino	2201.02472 2201.02472	
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_T^{\text{miss}}$	139	$\tilde{g}$		2.05		2205.06013	
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	pixel dE/dx		$E_T^{\text{miss}}$	139	$\tilde{g}$	[ $\tau(\tilde{g}) = 10 \text{ ns}$ ]	2.2	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	2205.06013	
	$\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep		$E_T^{\text{miss}}$	139	$\tilde{e}, \tilde{\mu}$ $\tilde{\tau}$ $\tilde{\tau}$		0.7	$\tau(\tilde{\ell}) = 0.1 \text{ ns}$ $\tau(\tilde{\ell}) = 0.1 \text{ ns}$ $\tau(\tilde{\ell}) = 10 \text{ ns}$	2011.07812 2011.07812 2205.06013	
RPV	$\tilde{\chi}_1^+ \tilde{\chi}_1^+ / \tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 $e, \mu$		$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^+ \tilde{\chi}_1^+$	[BR(Z $\tau$ )=1, BR(Z $e$ )=1]	0.625	1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^+ \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 $e, \mu$	0 jets	$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	[ $\lambda_{33} \neq 0, \lambda_{12k} \neq 0$ ]	0.95	1.55	$m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\bar{q}$	4-5 large jets		$E_T^{\text{miss}}$	36.1	$\tilde{g}$	[ $m(\tilde{\chi}_1^0) = 200 \text{ GeV}, 1100 \text{ GeV}$ ]	1.3	1.9	Large $A'_{1,2}$	1804.03568
	$\tilde{u}, \tilde{u} \rightarrow t\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow tbs$	Multiple		$E_T^{\text{miss}}$	36.1	$\tilde{u}$	[ $\lambda'_{233} = 2e-4, 1e-2$ ]	0.55	1.05	$m(\tilde{\chi}_1^0) = 200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003
	$\tilde{u}, \tilde{u} \rightarrow b\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow bbs$	$\geq 4b$		$E_T^{\text{miss}}$	139	$\tilde{u}$	Forbidden	0.95	$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$	2010.01015	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 $b$		$E_T^{\text{miss}}$	36.7	$\tilde{t}_1$	[ $qq, b\bar{s}$ ]	0.42	0.61		1710.07171
	$\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 $e, \mu$ 2 $b$		$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	36.1 136	$\tilde{t}_1$ $\tilde{t}_1$		1.0	$\text{BR}(\tilde{t}_1 \rightarrow b\ell/\nu\mu) > 20\%$ $\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_{\tilde{t}} = 1$	1710.05544 2003.11956	
	$\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	1 $\mu$	DV	$E_T^{\text{miss}}$	136	$\tilde{t}_1$	[ $1e-10 < \lambda'_{23k} < 1e-8, 3e-10 < \lambda'_{23k} < 3e-9$ ]	1.0	0.4-1.45		2003.11956
$\tilde{\chi}_1^+ / \tilde{\chi}_2^0 / \tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 $e, \mu$	$\geq 6$ jets	$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^0$		0.2-0.32	Pure higgsino	2106.09609		

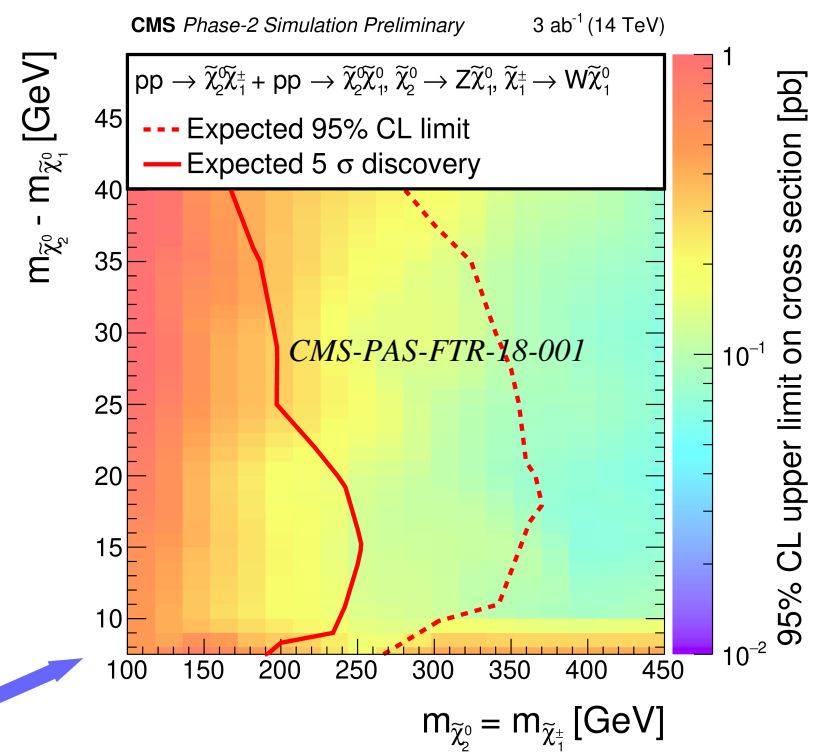
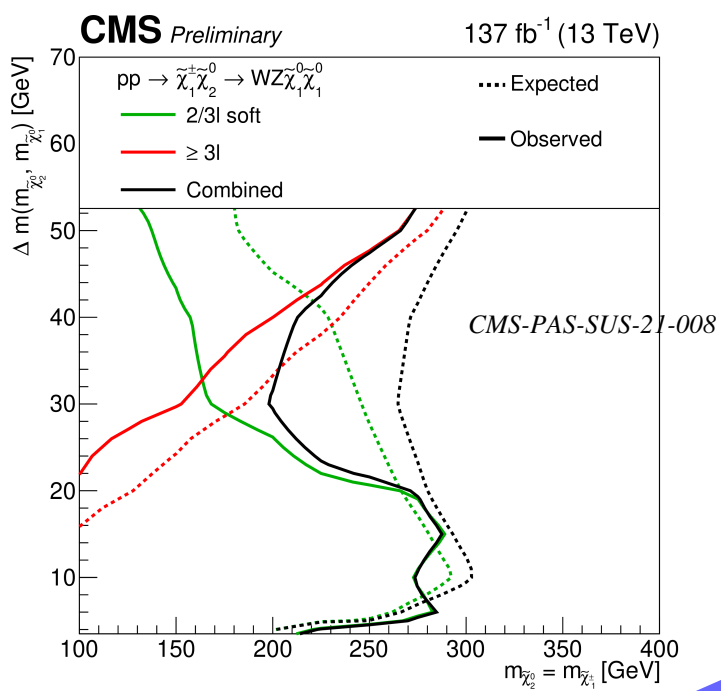
Results are interpreted in simplified models. For EW production reaching 1 TeV

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10<sup>-1</sup> 1 Mass scale [TeV]

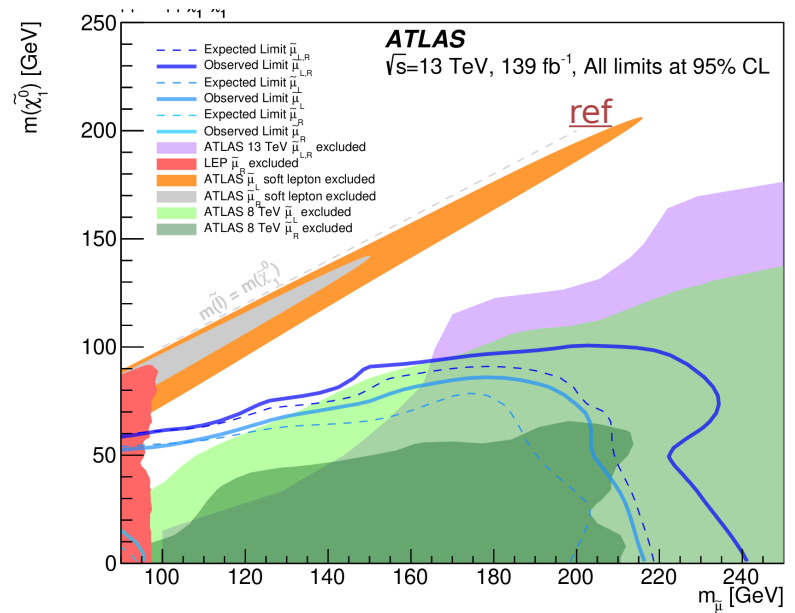
# Searches for EW produced sparticles, examples

Planck2023 Scale and the LHC, prospects



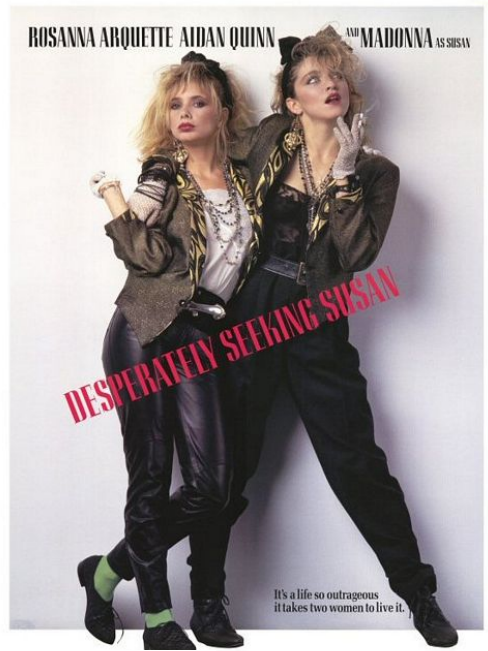
HL-LHC projections are difficult, they tend to be “beaten” by current results. Analysis techniques become better than expected.

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

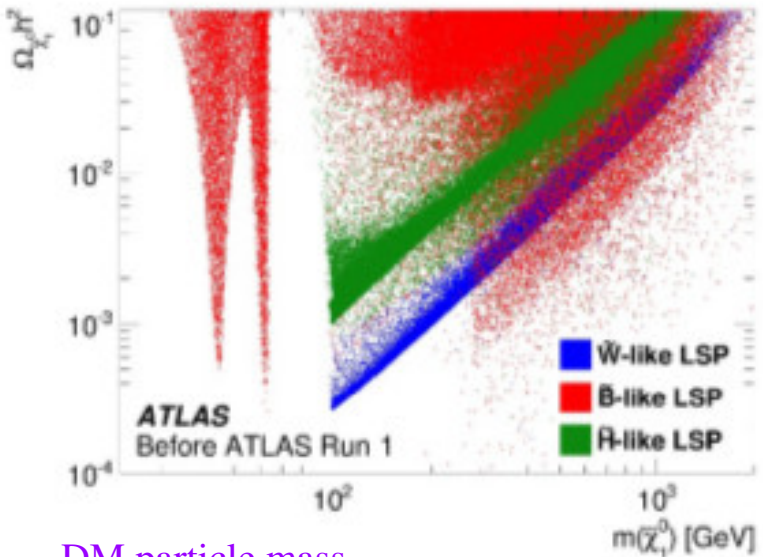
Simplified models do not tell the whole story. Parameters scans even in pMSSM are difficult. “The “latest” one from ATLAS is still on Run 1 data. *GAMBIT collaboration finds a “moderate excess”*. *Eur.Phys.J. C79 (2019) no.5, 395*



Planck2023 Scale and the LHC, prospects

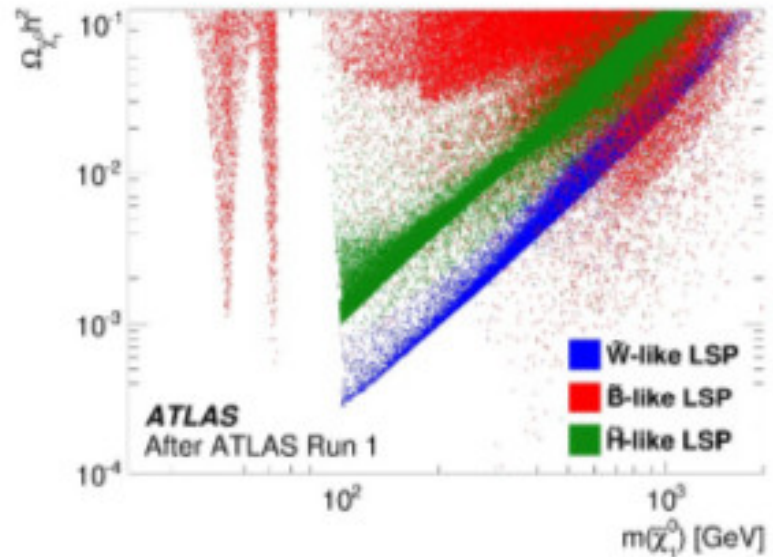
No limit yet on the SUSY's favorite DM candidate (LSP)  
pMSSM scan of ATLAS Run 1 data. *JHEP 10 (2015) 134*

Measured relic DM density



DM particle mass

(a) Before ATLAS Run 1.



(b) After ATLAS Run 1.

ROSANNA ARQUETTE AIDAN QUINN MADONNA SUSAN  
BY ED LACHMAN EXECUTIVE PRODUCER MICHAEL PEYSER  
ARAH PILLSBURY AND MIDGE SANFORD PG 48  
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# Hopes and challenges

## Higher- performance detectors coming up for the Run 4 !

Nature Review

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

Higgs bosons per fb<sup>-1</sup> (13 TeV)

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

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

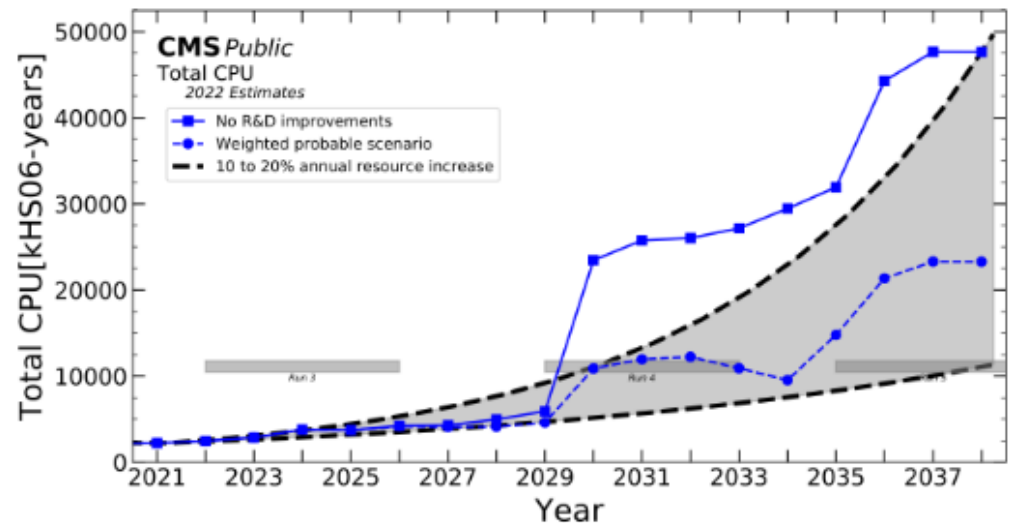
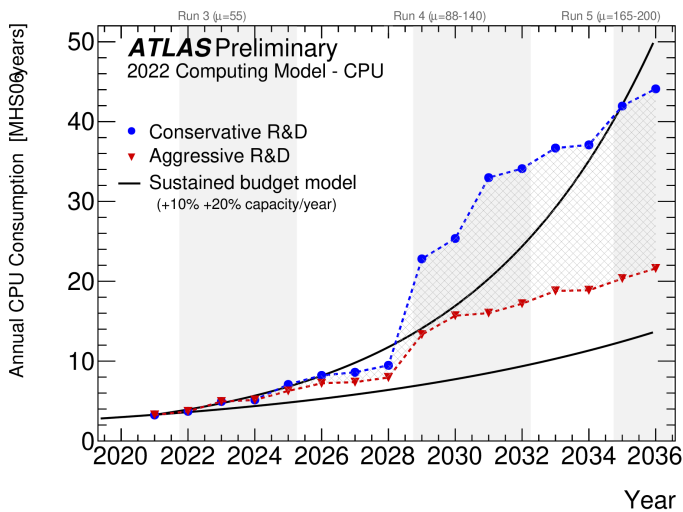
Source: K. Tackmann

Higgs symposium

Planck2023 Scale and the LHC, prospects

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.

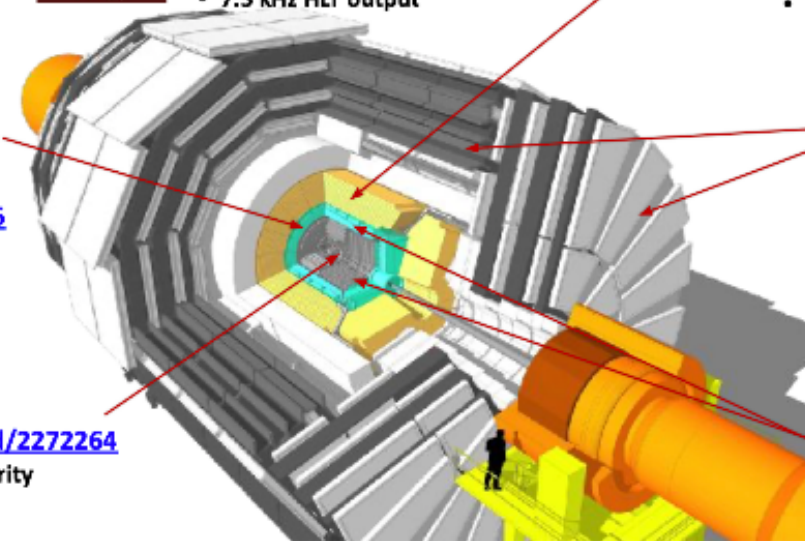
Summarized a handful of projections, many other exists, but not (yet) in all areas of the LHC physics.

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  $\eta = 3$



**Tracker** <https://cds.cern.ch/record/2272264>

- Si-Strip and Pixels increased granularity
- Extended coverage to  $\eta = 4$
- Design for tracking in L1 Trigger

**MIP Timing Detector**  
<https://cds.cern.ch/record/2667167>

Precision timing with:

- Full coverage to  $\eta = 3$
- 30-50 ps time resolution for MIPs
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



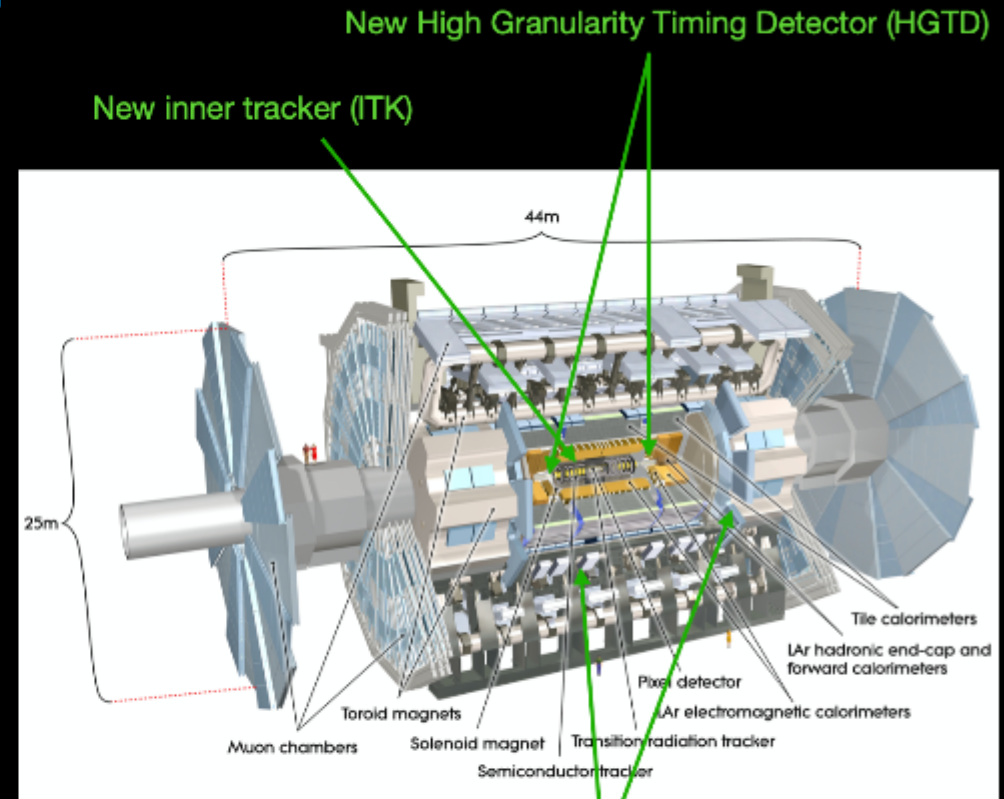
**Beam Radiation Instrumentation and Luminosity**  
<http://cds.cern.ch/record/2759074>

- 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**

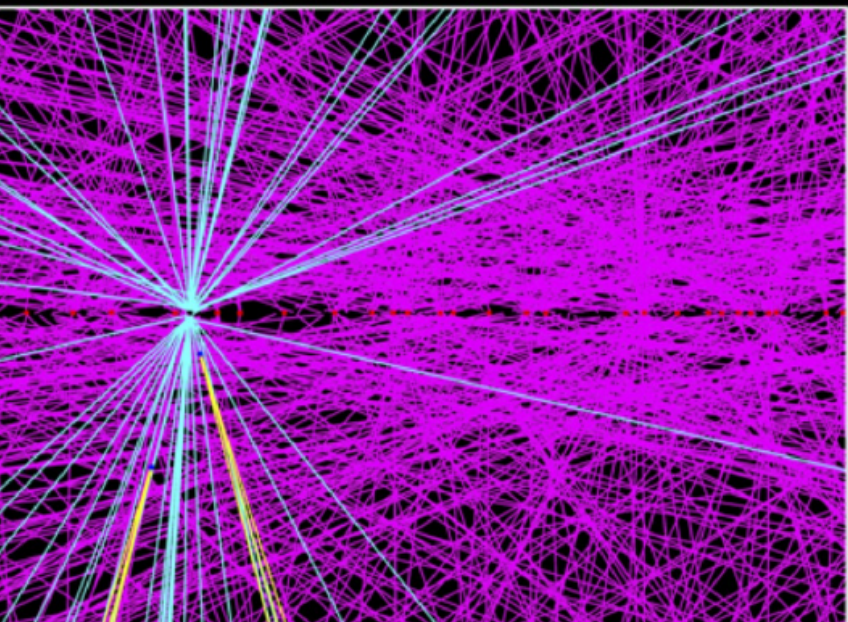


New muon detectors (RPC + sMDT + TGC)

Front-end replaced for calorimeters and muon detectors

The future at the HL-LHC

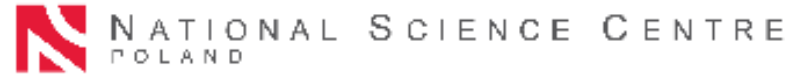
**ATLAS**  
EXPERIMENT  
HL-LHC  $t\bar{t}$  event in ATLAS  
at  $\langle\mu\rangle=200$



## The “EarlyUniverse” project



Norway  
grants



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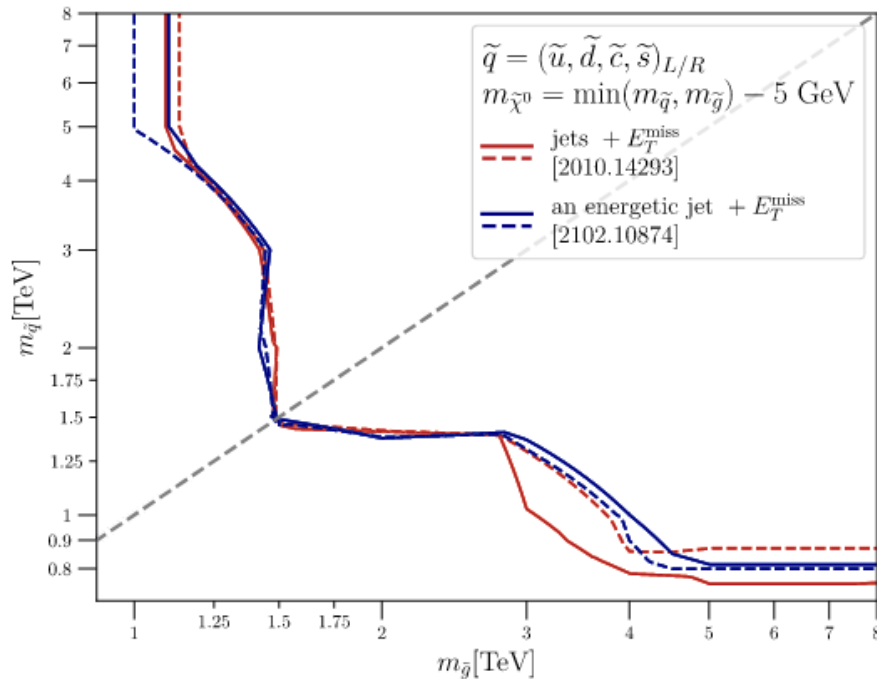
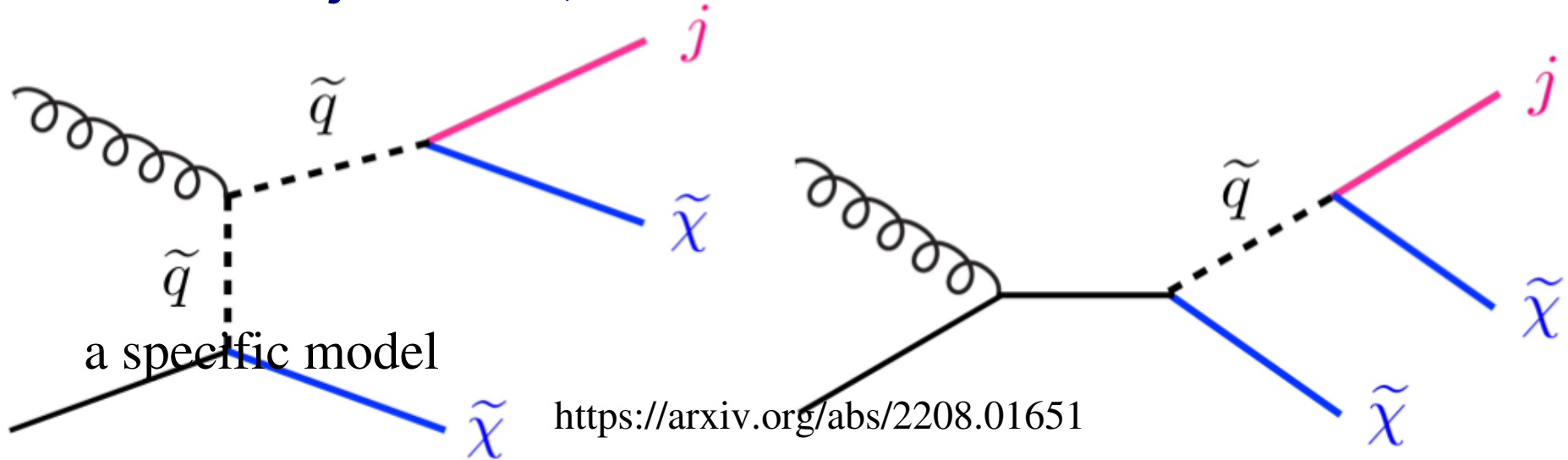
Understanding the Early Universe:  
interplay of theory and collider experiments

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

Theory & Experiment

# Mono-jet search, SUSY oriented Dark Matter search

Planck2023 Scale and the LHC, prospects



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