



## Kick-off NORCC, ATLAS phenomenology outline

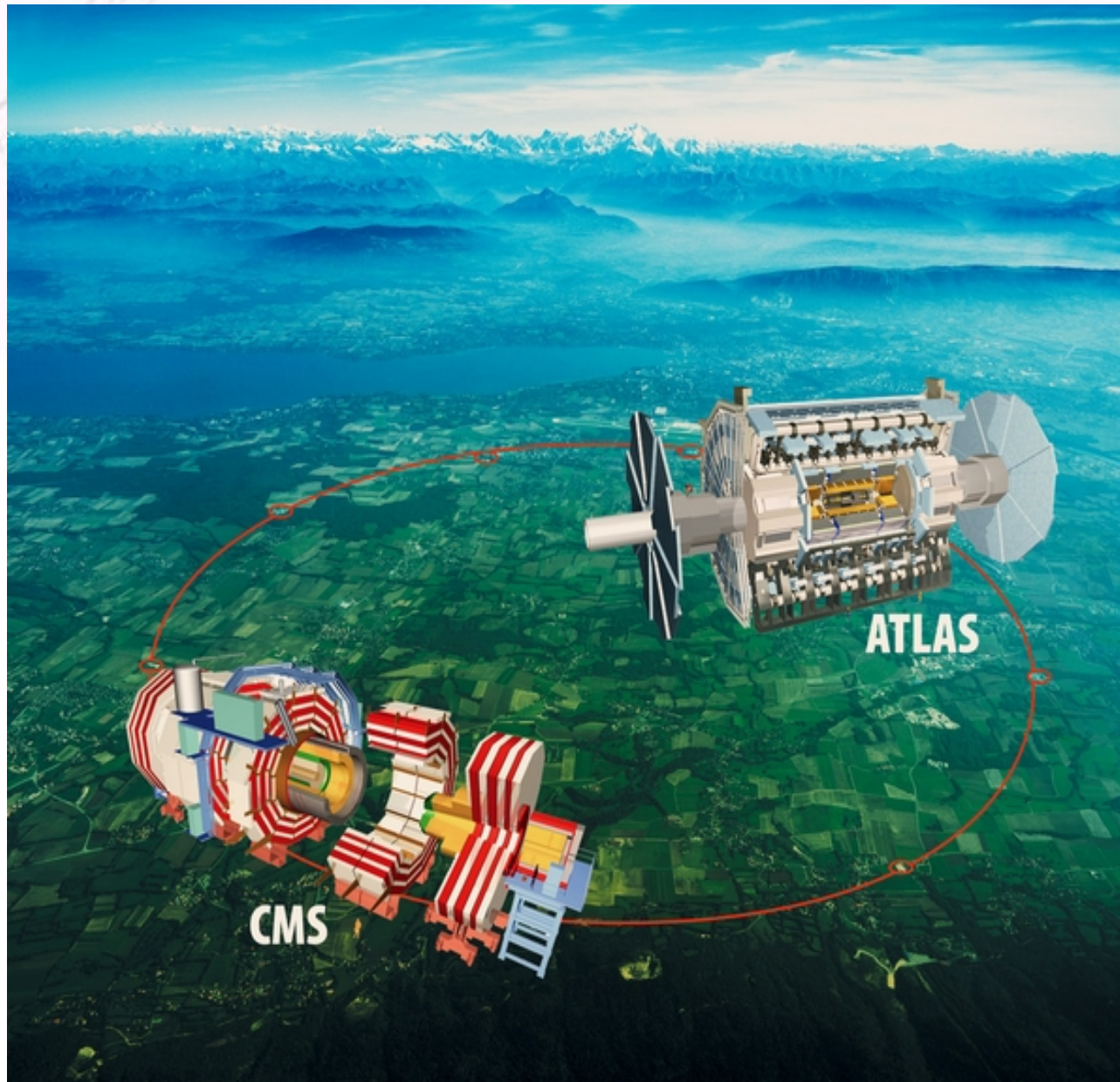
Open questions about our Universe (a selection).

Related “flagship” measurements and searches (a selection).



# ATLAS and CMS have similar capabilities now and in the future

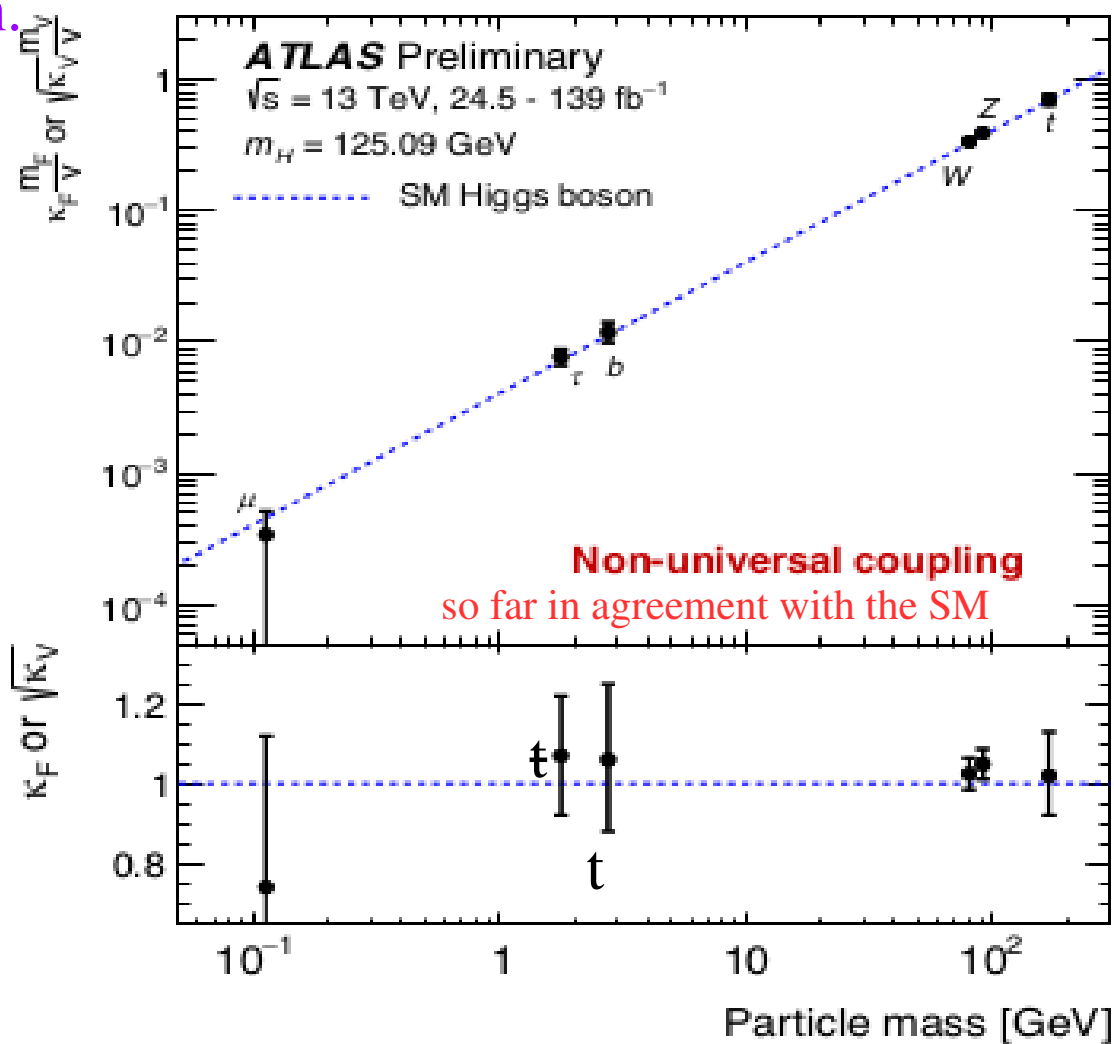
Phenomenology in ATLAS, 2022 and beyond



# The Standard Model's Higgs boson

Discovered in 2012 by ATLAS and CMS Collaborations. Its mass and interactions precisely measured by now. HL-LHC targets more precision.

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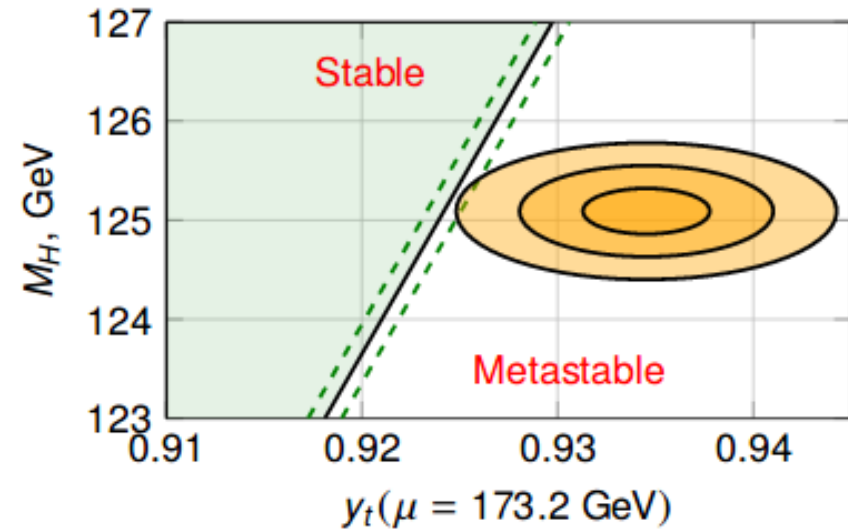


# The Higgs boson: is this the end of the story ?

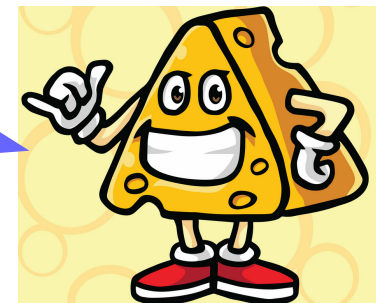
Unlikely:

Vacuum stability:  
We live in a metastable vacuum.

arXiv:1205.2893  
tH coupling



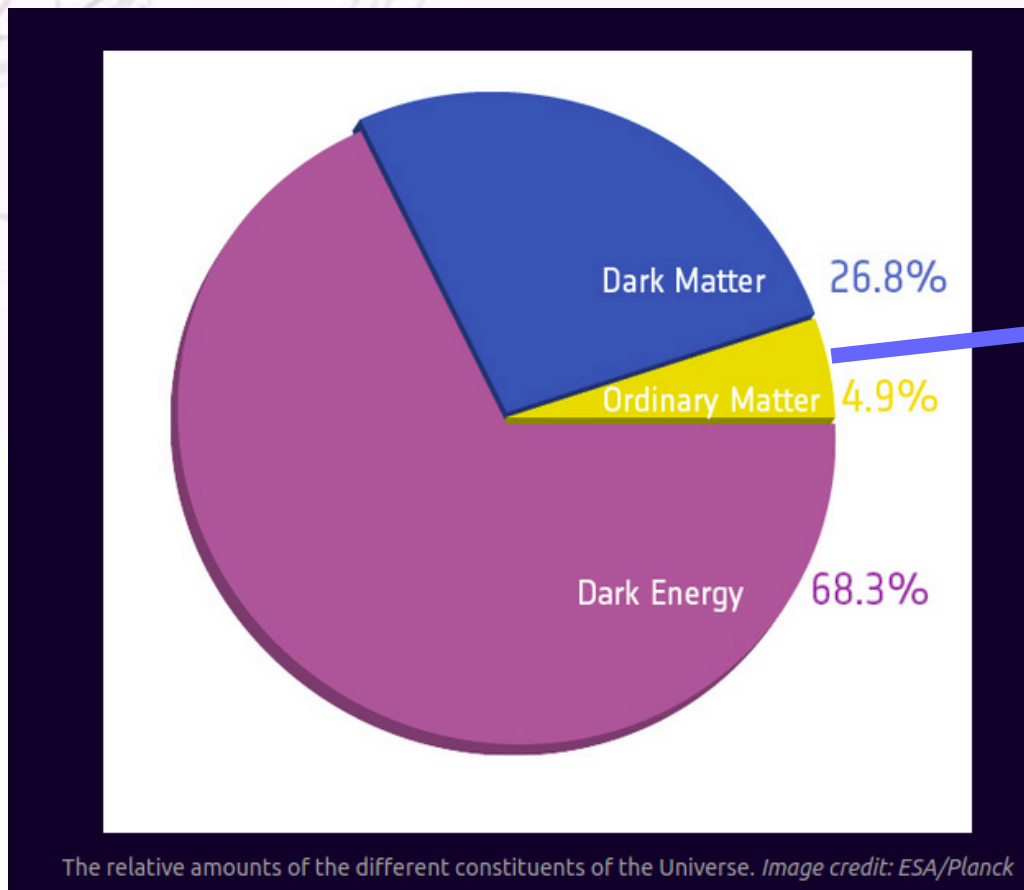
Hierarchy problem (Higgs mass fine-tuned).  
Are there any scalar partners to the top quark?

$$\delta m_h^2 = \frac{1}{8\pi^2} [\lambda_{scalar}^2 - \lambda_{fermion}^2] \Lambda^2 + \dots$$


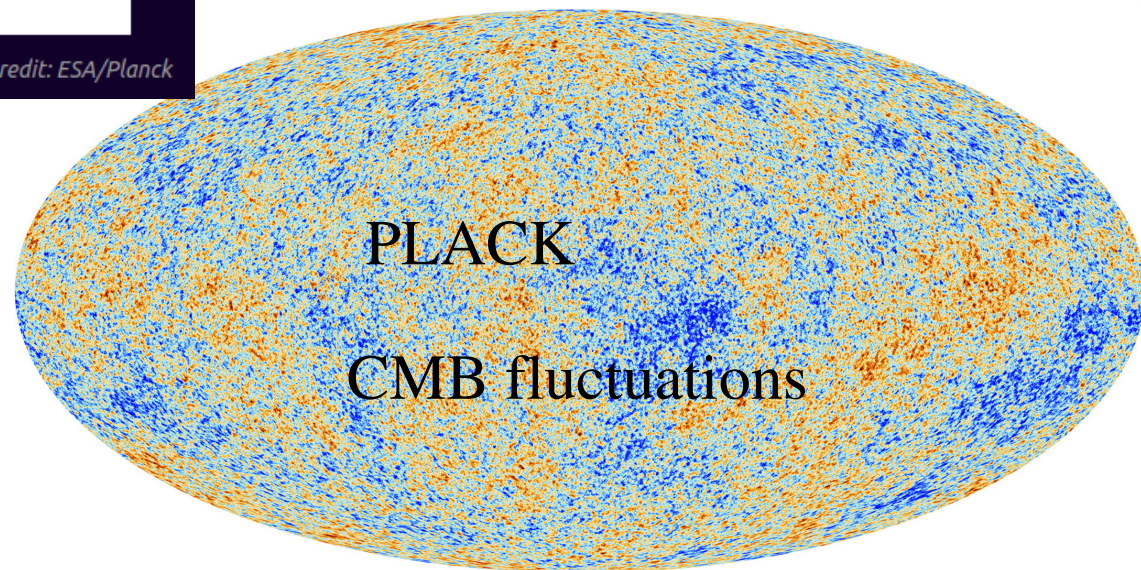


# The Standard Model makes only 5% of the Universe

Phenomenology in ATLAS, 2022 and beyond



The Higgs boson



## Few outstanding problems.

What stabilizes the Higgs boson mass ( **hierarchy problem** ) ?

What is 95% of the Universe made of ?  
(what is **Dark Matter and Dark Energy** ?)

Why our matter exists at all ? (and **had not annihilated totally with the antimatter** ? **baryogenesis, leptogenesis, darkogenesis, all related to CP violation.**)



## “Run 2” Data Set of the Large Hadron Collider still being exploited:

Particle	Produced in $139 \text{ fb}^{-1}$ at $\sqrt{s} = 13 \text{ TeV}$
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	$\sim 40$ trillion (significantly reduced by acceptance)

Run 3+2	(2022- end of 2025)	$\sim 500 \text{ 1/fb}$	(factor 4)
Run 4+3+2	(2029 end of 2032)	$\sim 1000 \text{ 1/fb}$	(factor 7)
Run 5+4+3+2	(– end of 2041)	$\sim 3000 \text{ 1/fb}$	(factor 20)

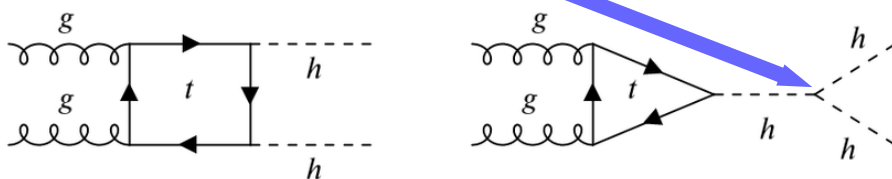
(far future -if there is any..)

*~statistical improvement factor  $\sim 2$ ,  $\sim 2.5$ ,  $\sim 4.5$*



# “1) Flagship Higgs properties measurements”

Higgs self-coupling via double Higgs production. Related to the Higgs mass . Basis to understand “the minimum of potential energy” the Universe ended-up in.

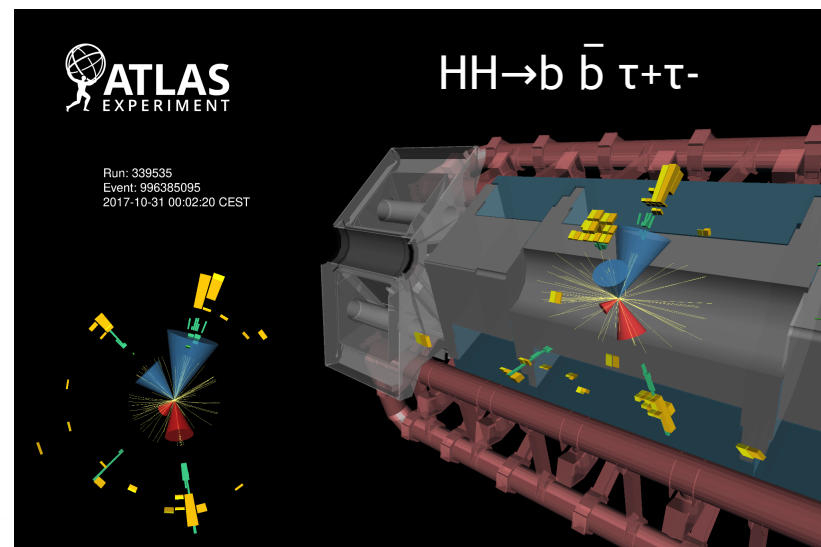
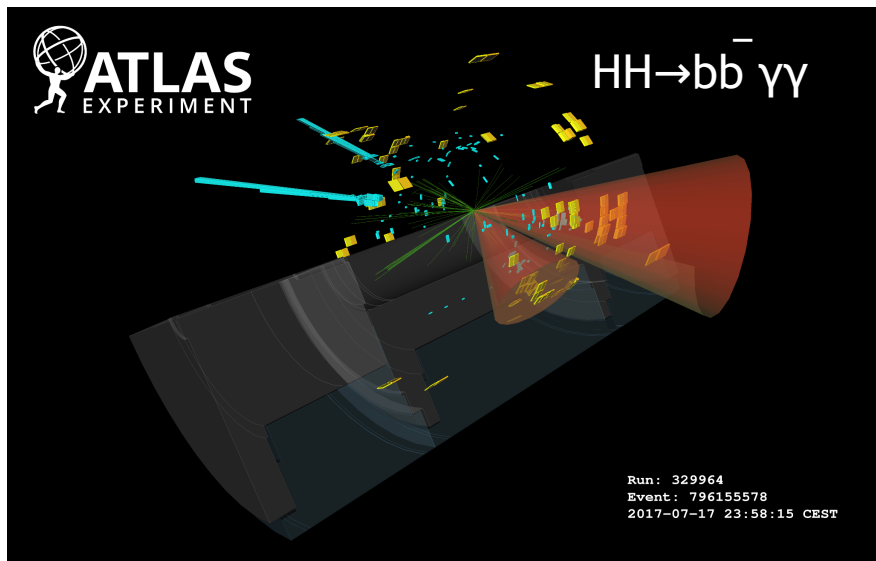


- B=box diagram, amplitude proportional to  $\kappa_t^2$ ,  $\kappa_t = y_t/y_t^{SM}$
- T=triangle diagram, amplitude proportional to  $\kappa_t \kappa_\lambda$ ,  $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

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

Present predictions: “Evidence” for hhh (if SM self-coupling ) : End of Run 5

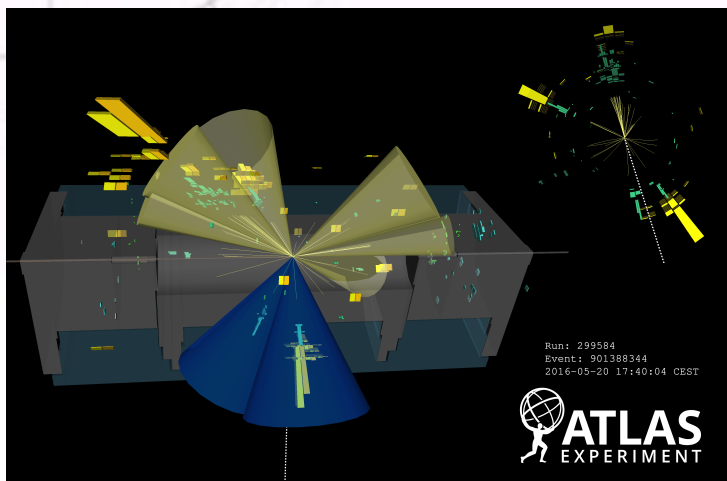
**Our take-on: ML to improve sensitivity of 2 channels below. Check if WW→hh is visible.** (Collaboration with theory via Grieg “EarlyUniverse” project )



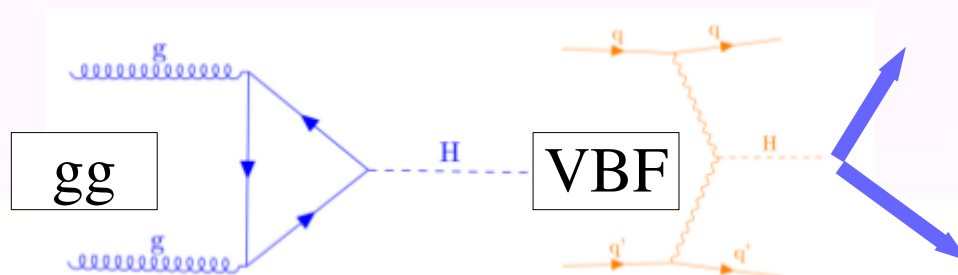


## “2) Flagship Higgs properties measurements”

Higgs boson CP measurement, in Higgs → tau tau decays. Our existence requires more CP violation than we presently see (baryogenesis).



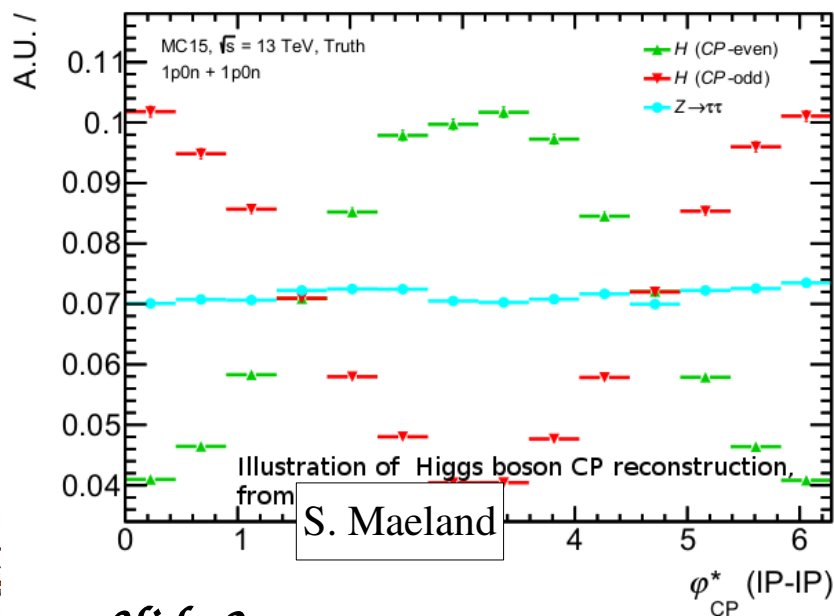
VBF easier for tau tau



2012.13922 : CP phase precision after Run5 = 10°  
Precision of 3-5° needed to test some of the baryogenesis models

**Our take-on: ML to improve sensitivity to H mass reconstruction and CP. Check baryogenesis interpretation of the result.**

(Collaboration with theory via Grieg “EarlyUniverse” project )



## Two Higgs Doublets Models (2HDM)-an interesting extension of the SM

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

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

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

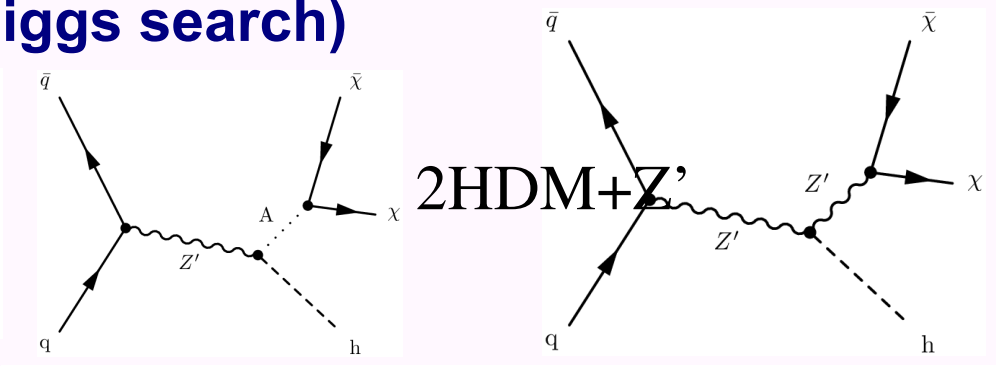
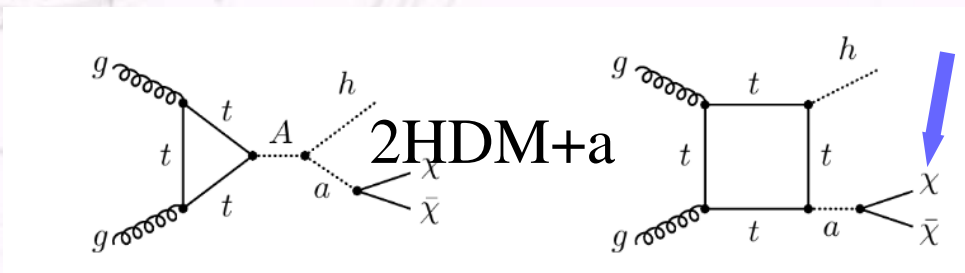
BSM: two “complex doublets”= 8 fields  
 =Transverse polarization for  
 $W^{+-}$   $Z^0$  and 5 Higgs bosons  $H^{+-}$ , A, H and h

2HD models do not “spoil” precise EW measurements  
 and involve additional symmetries making the  
 existence of Dark Matter (DM) possible.



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

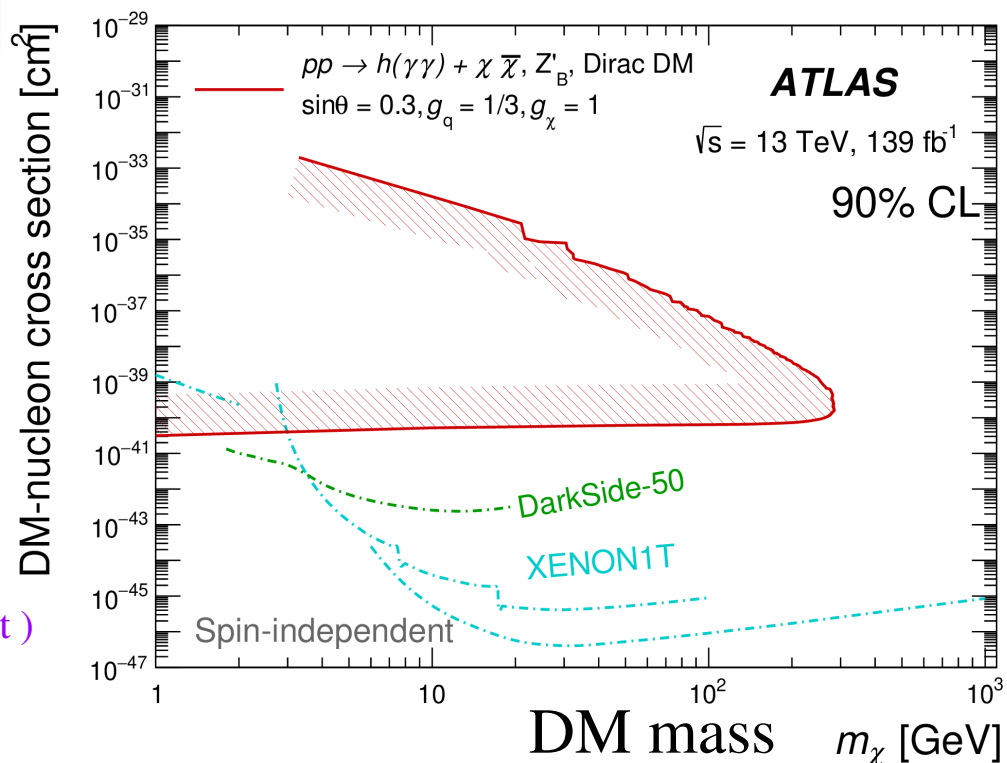
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Run 2: Published results with  
 $H \rightarrow 2\text{photons}$  (Oslo) and  $H \rightarrow b\bar{b}$   
 $H \rightarrow \tau\tau$  ongoing in Bergen  
 (supported by MCIF\* in the past, now  
 Grieg “EarlyUniverse”\*\*).

Plans: **Combine all Higgs decay channels,**  
**interpretation in other relevant models.**

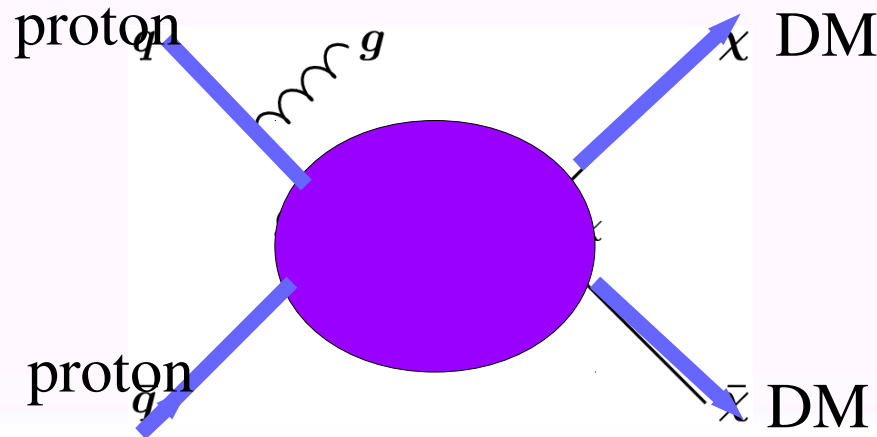
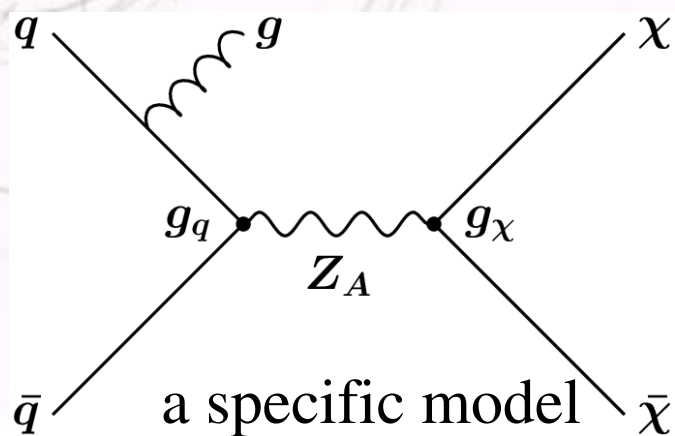
(Collaboration with theory via Grieg “EarlyUniverse” project)



*Example results: can be related to  
 direct searches for DM scattering  
 on nucleons*

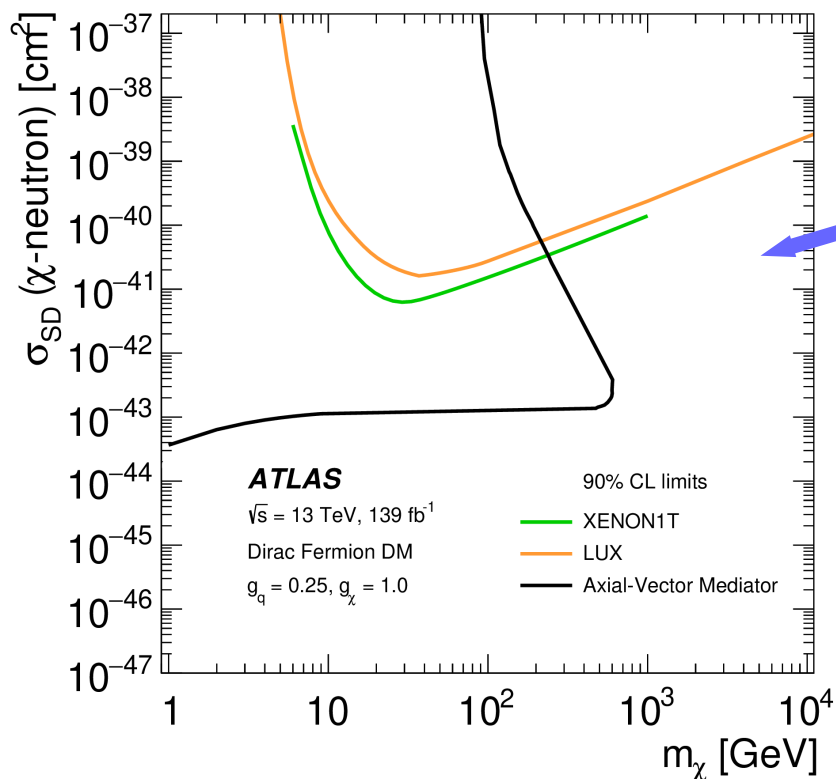


## Mono-jet search, generic DM search?



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

Example ATLAS result, for a specific model. Results competitive with the direct DM search



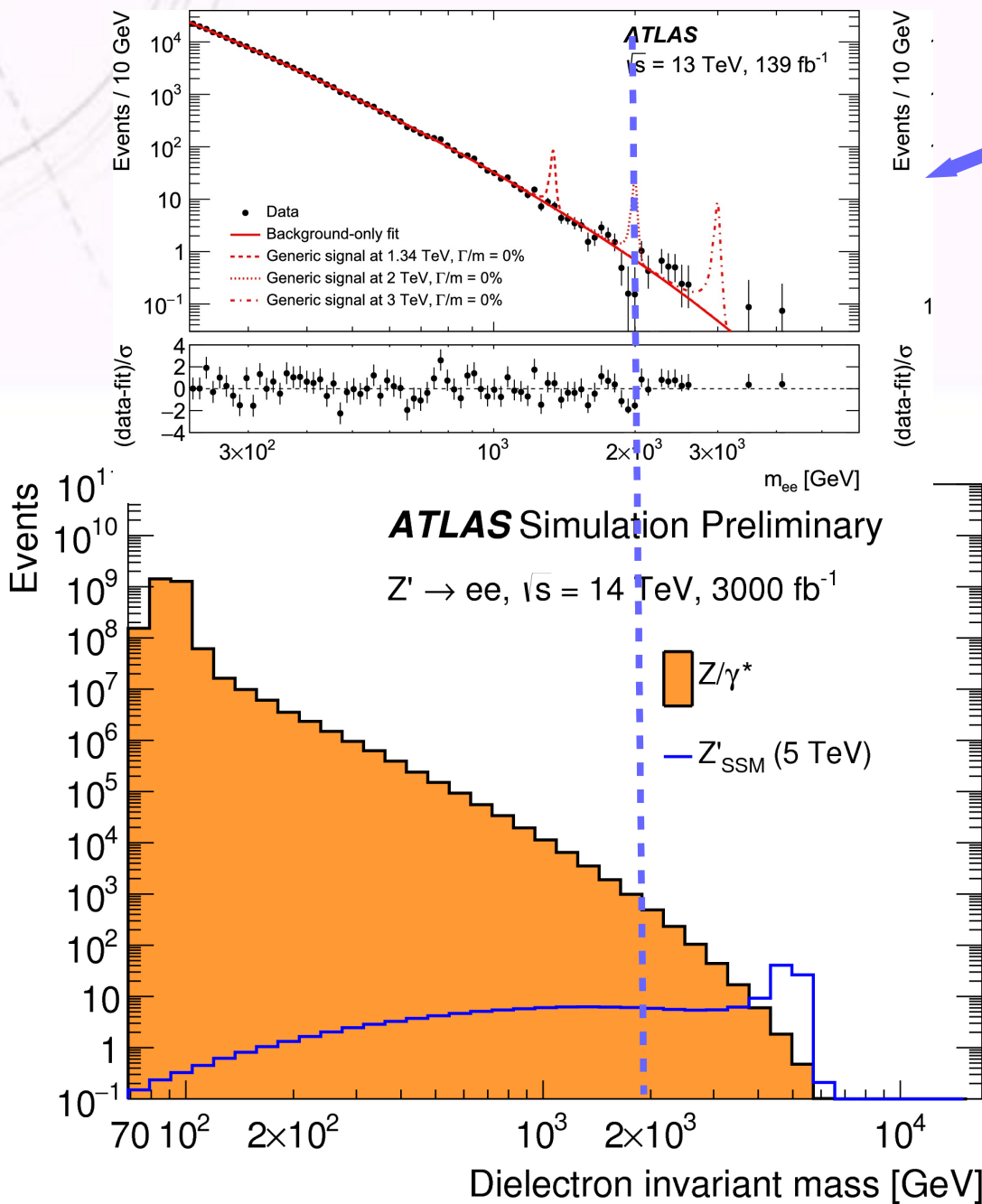
**Our take-on: Interpretations in different models, (new particles decays to DM with a small mass difference). ML methods.**

(Collaboration with theory via Grieg “EarlyUniverse” project )



# New heavy bosons (Z', X, W' ...)

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Strong involvement in Oslo.

Resonance searches are typically the first new physics results coming out with every luminosity increase.

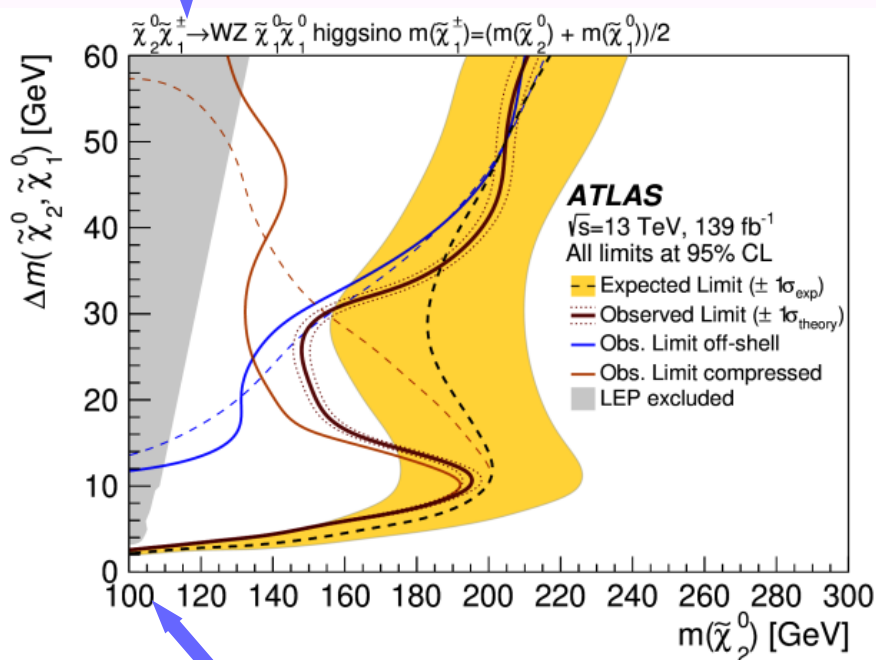
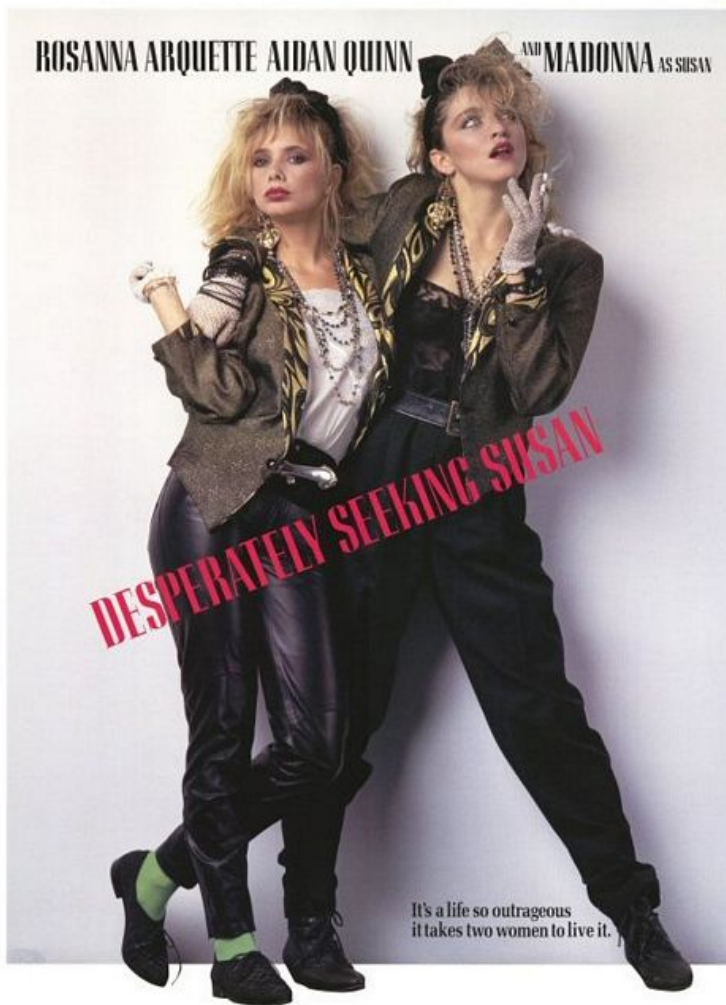
# Benchmark models motivated by SUSY?

SUSY has good physics motivation, solving many SM problems..but  
 Many parameters even in the Minimal Supersymmetric SM → use simplified models

Example searches in simplified models:

(Oslo, but also in Bergen)

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Searches generally difficult for small mass differences between SUSY particles.

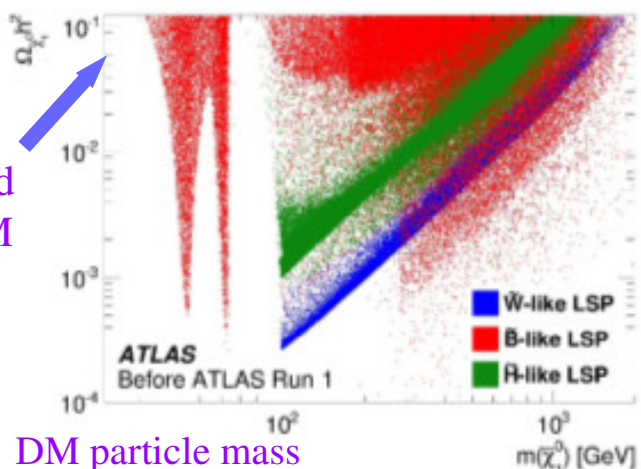
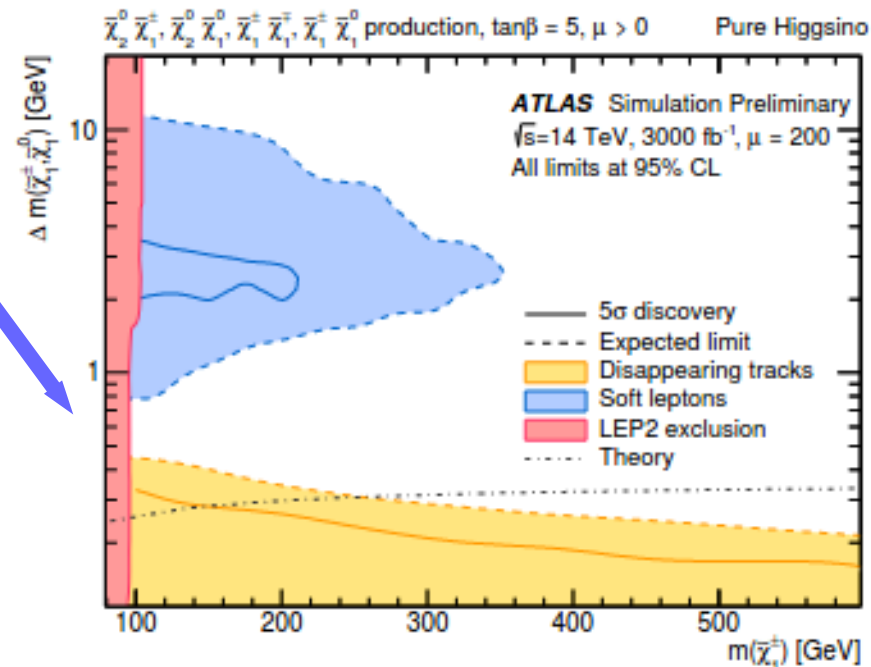


A SANFORD-PILLSBURY PRODUCTION A SUSAN SEIDELMAN FILM  
 DESPERATELY SEEKING SUSAN ROSANNA ARQUETTE AIDAN QUINN<sup>SM</sup> MADONNA<sup>SM</sup> SUSAN  
 WRITTEN BY ROBERT JOY DIRECTOR OF PHOTOGRAPHY ED LACHMAN EXECUTIVE PRODUCER MICHAEL PEYSER  
 WRITTEN BY LEORA BARISH PRODUCED BY SARAH PILLSBURY AND MIDGE SANFORD PG-13  
 DIRECTED BY SUSAN SEIDELMAN

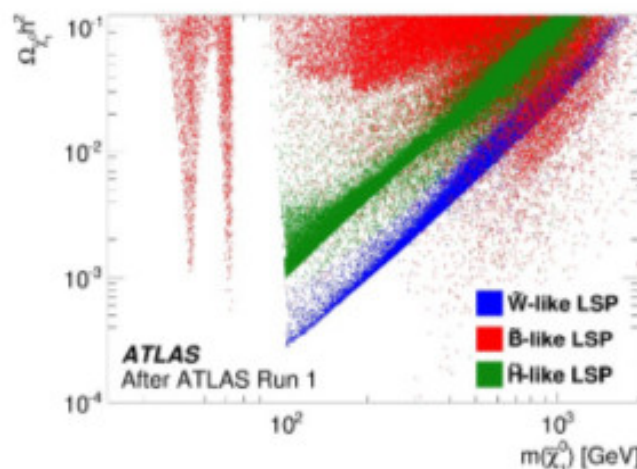
# Benchmark models motivated by SUSY and scans ?

Searches difficult for some mass differences

No limit yet on the SUSY's favorite DM candidate



(a) Before ATLAS Run 1.



(b) After ATLAS Run 1.

Example scan in pMSSM. ATLAS makes only a small dent in the allowed space (only Run 1) more to come



# HEPP Theory (UiO) — next 10 years



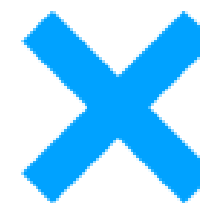
**Are Raklev**  
**Professor**



**Anders  
Kvellestad**  
**Researcher**  
**(2022-2028)**



**Lasse  
Braseth**  
**PhD student**  
**(2022-2024)**



**NN**  
**PhD student**  
**(2022-2026)**

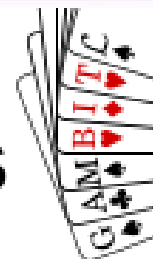
**Three main research directions for the near future :**

- Development of software for high-energy physics
- Fast and precise theory calculations of observables (QFT)
- Statistical methods to explore parameter spaces





# HEPP Theory (UiO) — next 10 years



- Develop software to explore the effects of data on new physics models
  - GAMBIT Collaboration (~70 members) led by Anders Kvellestad (UiO)  
[gambit.hepforge.org](https://gambit.hepforge.org)
  - Best fit regions of models and model comparison (goodness of fit)
  - Here “data” means e.g. published ATLAS analysis
- **PLUMBIN'**: Developing solvents for unclogging the calculational bottleneck in high-energy physics
  - Long term project financed by RCN (FRIPRO Fellesløft 2022-2028)
  - Cross disciplinary collaboration with statisticians at the Dep. of mathematics UiO
  - Goal to do develop methods for fast and precise theory calculations of observables, and statistical methods to explore parameter spaces
- Common ground with experimental efforts on ML (regression)



The future at the HL-LHC

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

