Highlights from the "Energy Frontier" Snowmass Strategy process

The Content

10 slides of Snowmass Strategy Process on Energy Frontier (Highlights)

Interleaved with → what can we learn about some of the Snowmass Questions from the ATLAS/CMS data, few examples.

Comment: The US strategy process is formulated in a somewhat different language than the EU one, perhaps more understandable for the wider world. I find it interesting for our strategy discussions.

STATUS OF SNOWMASS ENERGY FRONTIER PERSPECTIVE WITH RESPECT TO FUTURE COLLIDERS

Snowmass EF wiki: https://snowmass21.org/energy/start

Meenakshi Narain
(Brown University, USA)

at the FCC Week 2022
May 30 – June 3, 2022

All Snowmass slides are from this talk.

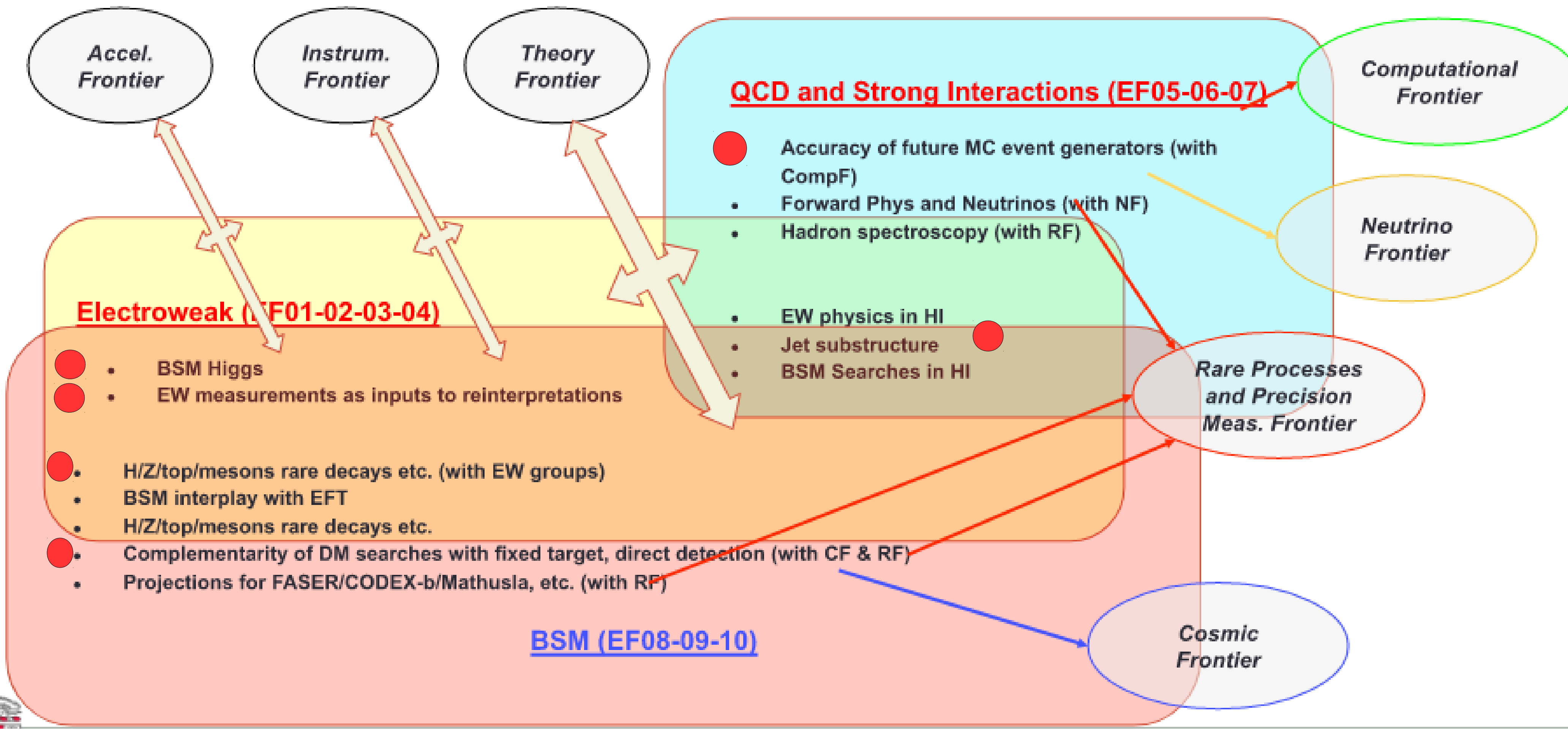
The Range of Snowmass Discussion

- There are **ten** Snowmass Frontiers spanning
- **Five scientific areas** of particle physics addressing fundamental questions about the universe
  - Accelerator Frontier
  - Cosmic Frontier
  - Energy Frontier
  - Neutrino Frontier
  - Rare Processes and Precision
- **Four technical areas** which enable scientific work
  - Computational Frontier
  - Instrumentation Frontier
  - Theory Frontier
  - Undergrounds Facilities
- And Community Engagement Frontier addressing the community development needed to maintain a vibrant profession and to engage with society.

Both Scientific and Technical areas have clearly some overlap-synergy between them. For example "high energy neutrinos produced at a muon collider" are in AF, EF, NF

Member of ATLAS

Synergies: Energy Frontier Topical Groups & Other Frontiers



Example, non-exhaustive list of topics.
Activities presently or formerly existing in
Norway on experimental or interpretation level
marked with ●

Member of ATLAS

The Snowmass Questions

- Goals: What are the **important scientific questions** in each frontier of particle physics during this period?
- Goals: What **enabling tools, technologies, or facilities studied** by each frontier are needed to address the pressing scientific questions in particle physics during this period?
- Goals: **How can we ensure that the ~~US~~ Norwegian particle physics community is vibrant, inclusive, diverse,** and capable of addressing the scientific questions identified, and of fulfilling our obligations to society during this period?
- Context: **What can be expected from ongoing, approved, planned, or proposed scientific, technical, or community programs** in addressing the issues identified by each frontier?

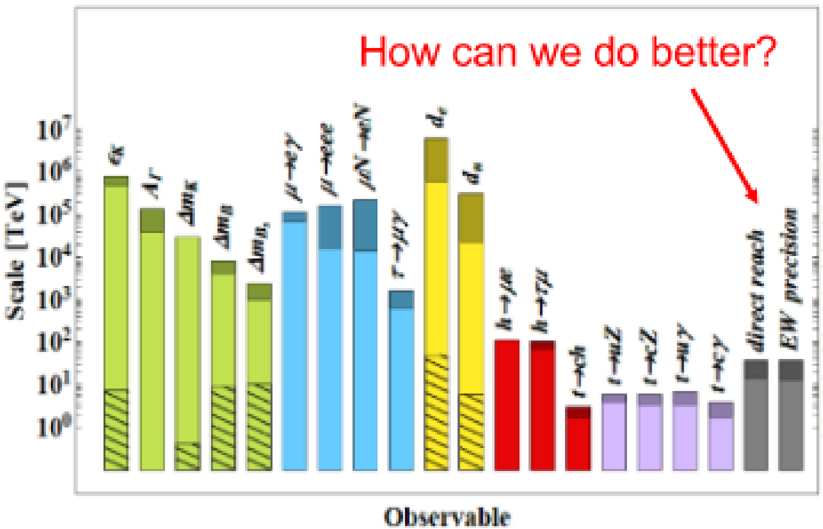
The Snowmass Questions

- Opportunities: What opportunities identified by each frontier are there **for new scientific, technical, or community activities to create transformative change** in particle physics, on what timescales could these occur, and what resources are required to realize these activities?
- Opportunities: What **investments need to be made during 2025-2035 for the continuing scientific, technical, or community progress** identified by your frontier in the decades beyond, on what timescales can these be implemented, and what resources would be required?
- Collaboration: What opportunities exist for cross-frontier, cross-disciplinary, or international collaboration and cooperation in the coming decade to enhance our ability to address the issues identified (including training or mentorship)? How do these collaborations affect the timescales or resources needed for these activities?

Precise measurements (massive data) vs energy

Probing the energy scale for new physics

- Probing the energy scale for new physics



Reach in new physics scale from both direct and indirect searches

Complementarity with other Frontiers

While slow at the start, the energy frontier is ultimately needed to "win the race"

Nevertheless if we get indirect hints from existing or planned experiments its important to know how to test them!

Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

Patrick Meade

For a specific New Physics scenarios precise measurements have better reach than direct searches→ but direct searches are a more universal tool

Snowmass Strategy Highlights and Early Universe at the LHC

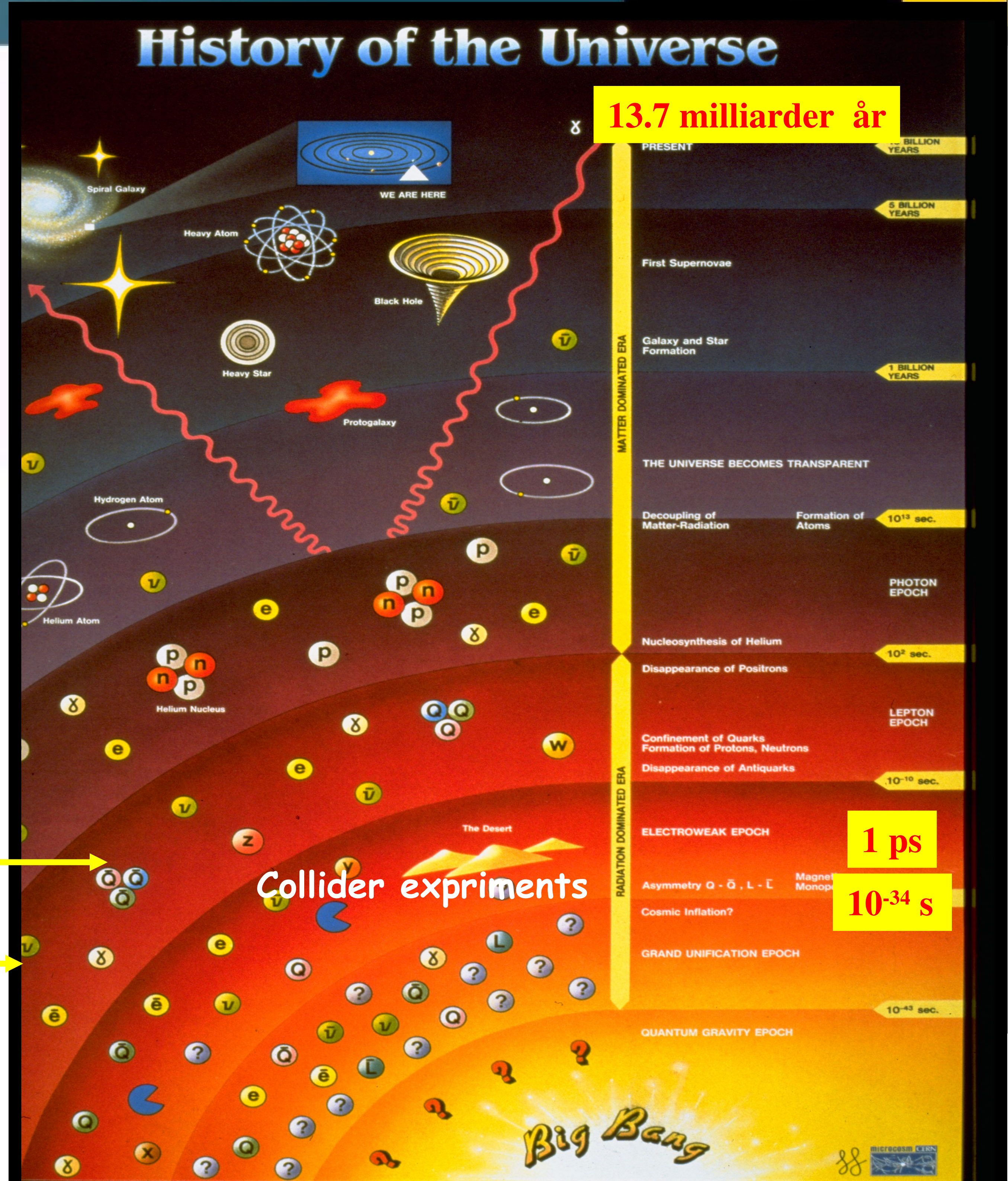
Cosmology

Astroparticle physics

Particle physics

Higgs field arises (EWSB)?

Matter takes over?



Energy Frontier at Snowmass 2021

- Collider Physics is an opportunity to study a huge number of phenomena!!
  - Origin of EW Scale
  - Evolution of the Early Universe
  - New constituents of matter
  - Origin of Flavor
  - Additional Symmetries of Spacetime
  - Nature of Dark Matter
  - Origin of Neutrino Mass

- **Energy Frontier Conveners:**

  Laura Reina (FSU, USA)

  Alessandro Tricoli (BNL, USA)

  Meenakshi Narain (Brown University, USA)

Many of these phenomena probably affect the evolution of the Early Universe. Some highlights in the following slides.

Few outstanding problems of today, related to Early Universe.

Are we living in a metastable vacuum (Higgs boson self coupling) ?

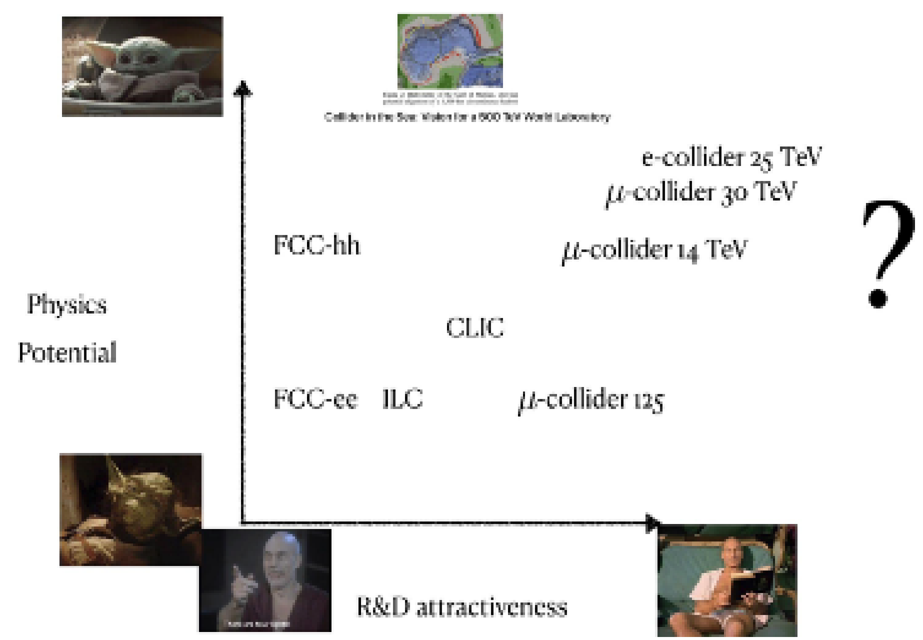
What stabilizes the Higgs boson mass (hierarchy problem) ?

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, darko-genesis, all related to CP violation.)

Energy Fronter Machines

- Discoveries at the Energy Frontier are intricately linked to new accelerators and detector instrumentation.
- Proceed along two complementary directions
  - Study known phenomena at high energies
    - Factory of Higgs bosons (or other known particles)
    - Electroweak (EW) physics
    - QCD and Strong Interactions
  - Search for direct evidence of BSM physics
    - Next high energy frontier machine
- What are the most promising future colliders

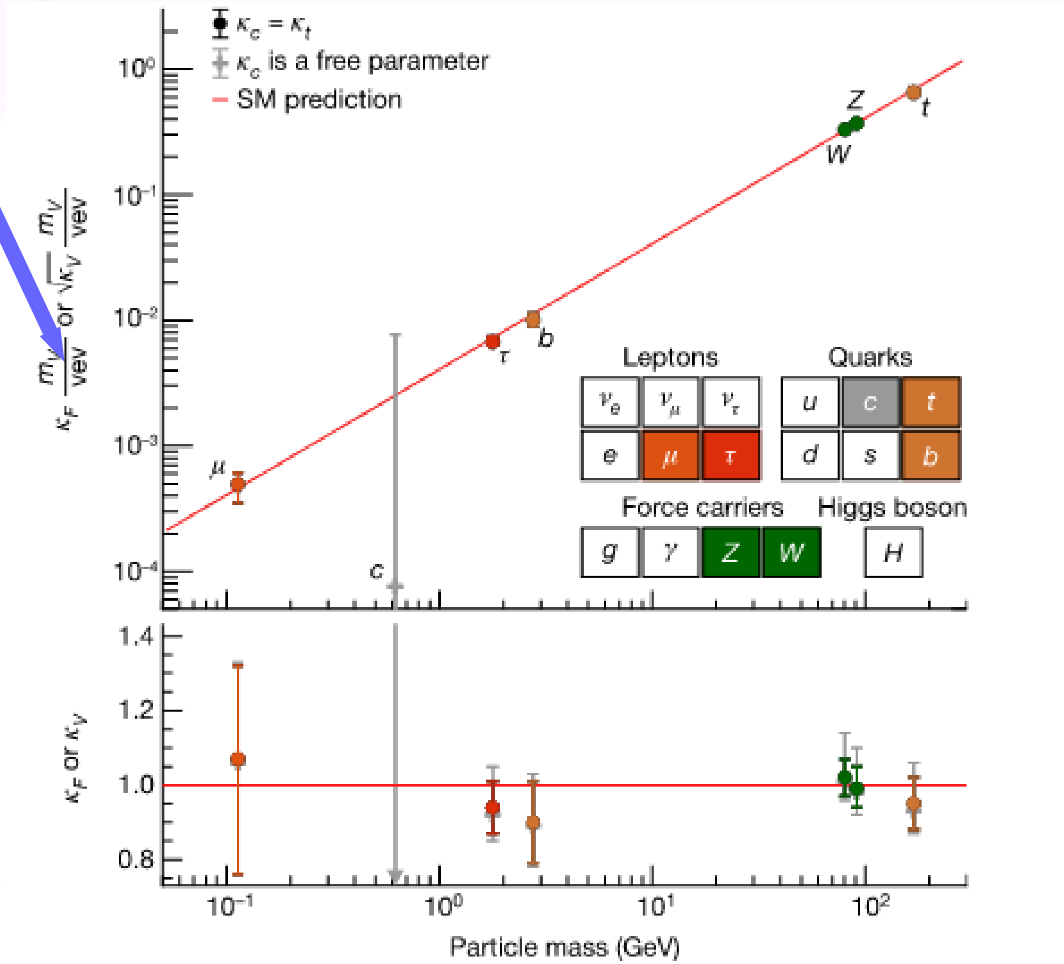


e LHC

Highlighted a bit in the next slides

The Standard Model's Higgs boson

Discovered in 2012 by ATLAS and CMS Collaborations. Its mass and interactions precisely measured by now. The strength of interactions is indeed proportional to the mass of particles it interacts with

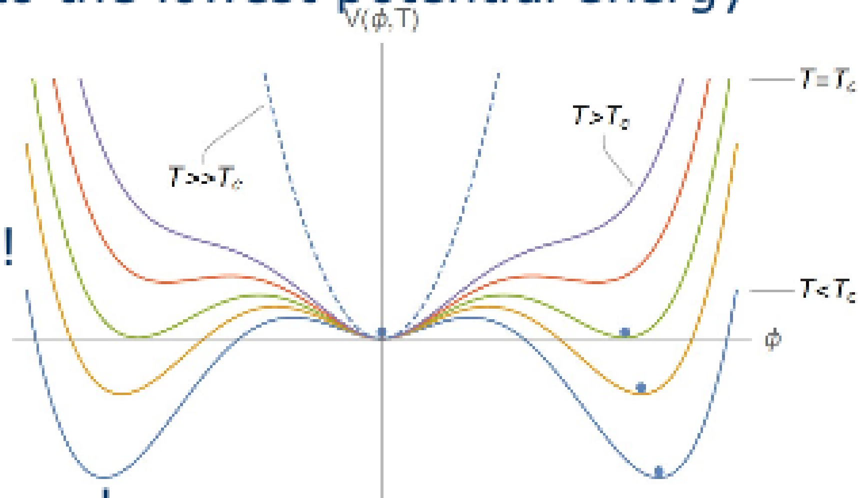


so far in agreement with the SM from https://www.nature.com/articles/s41586-022-04893-w.pdf

The mystery of the empty space (with the Higgs field)

The Higgs potential

- All quantum fields have an associated potential energy function.
- The ground state corresponds to the lowest potential energy (minimum of potential).
- Usually the value of the field is zero in the ground state.
- Not the case for the Higgs field!
- In the early Universe, the minimum of Higgs potential was at φ=0.



Credit: Rikard Enberg

- All elementary particles were massless.
- But O(ps) after the Big Bang a new minimum at φ≠0 developed.
  → Electroweak phase transition.
- Particles acquired mass by interacting with the ≠0 Higgs field.
- Matter-antimatter asymmetry can also have been created here.
- To better understand this phase transition we need to experimentally probe the shape of the Higgs potential.

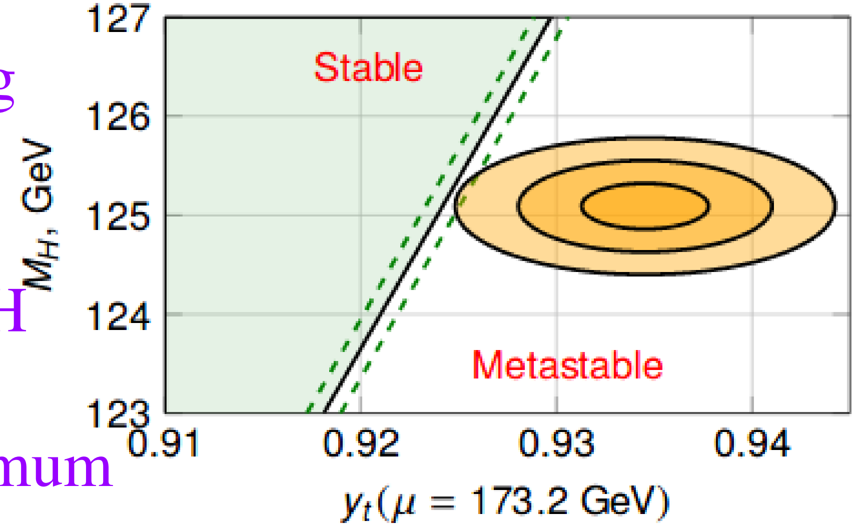
From Sara Strandberg

The Higgs boson, if SM self-coupling, we are metastable ..

The shape of the vacuum energy potential depends on the HH coupling and on the top quark mass

arXiv:1205.2893

tH coupling



We live in a metastable vacuum if HH coupling is as SM predicts → there is another, deeper, energy minimum

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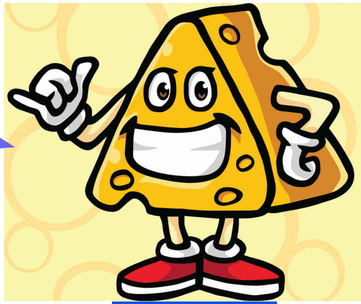
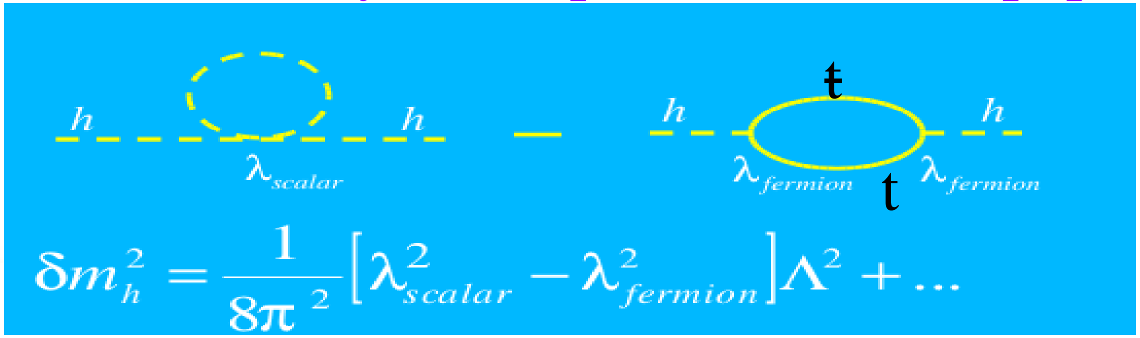
Hierarchy problem (Higgs boson mass fine-tuned). Are there any scalar partners to the top quark?

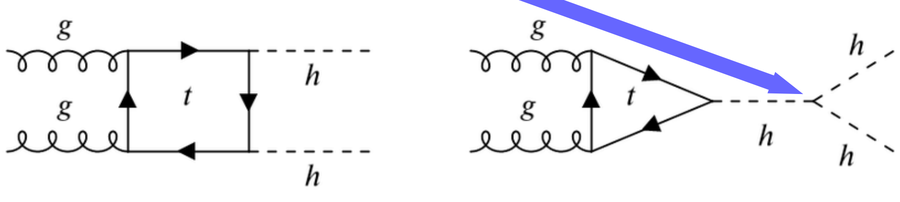




$$\delta m_h^2 = \frac{1}{8\pi^2}\left[\lambda_{scalar}^2 - \lambda_{fermion}^2\right]\Lambda^2 + \dots$$

"Flagship Higgs properties measurements HL-LHC"

Huge effort presently focusing on hh production via "gluon fusion".

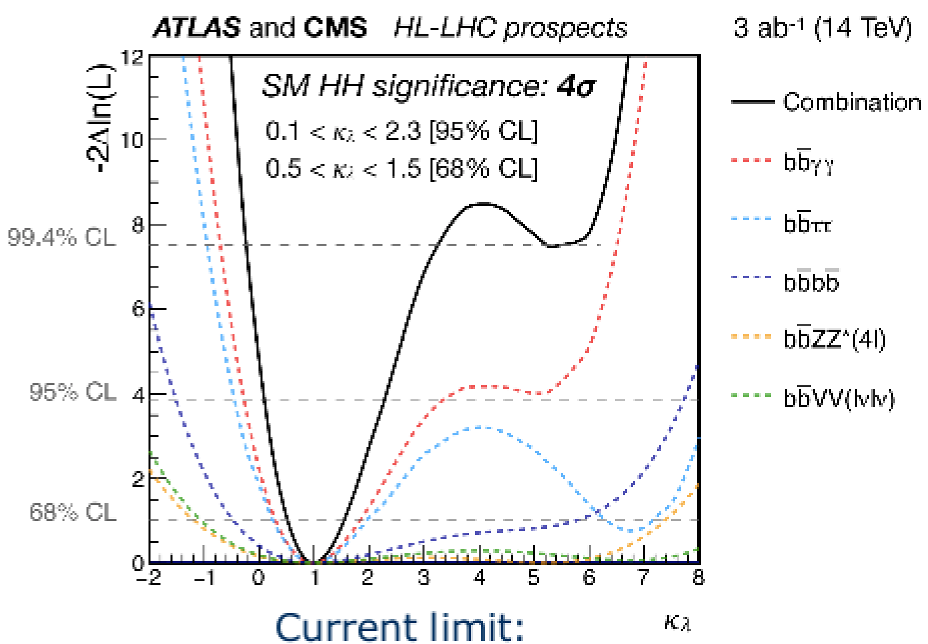


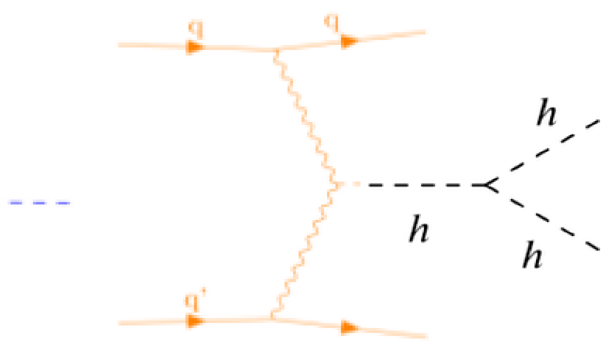
- B=box diagram, amplitude proportional to κ_t^2, $\kappa_t = y_t / y_t^{SM}$
- T=triangle diagram, amplitude proportional to $\kappa_t \kappa_\lambda$, $\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$

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

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

Check if WW→hh is visible? Perhaps, if coupling different from SM





Current limit:
$-1.1 < \kappa_\lambda < 6.6$

ATL-PHYS-PUB-2022-018

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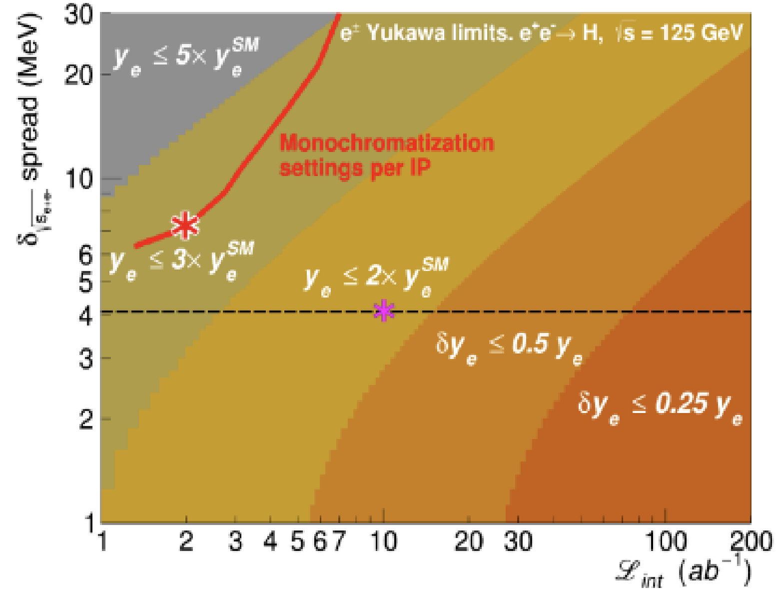
Important points in Snowmass strategy, example:

Higgs boson properties and couplings

- Progress on understanding light fermion Yukawa couplings
  - Electron Yukawa at FCC-ee with 4 years running, $Y_e < 1.6\, Y_e^{SM}$
  - Strange Yukawa?
  - Charm Yukawa limit, $|\kappa_c| < 8.5$ (CMS) motivates new studies
  - Searches for flavor violating H couplings motivated by LHC limits on $H\to\mu e$, $H\to\mu\tau$ and by B flavor anomalies
- Progress on the inverse problem
  - Planning for summary plots to map new physics phase space with constraints on EFT operators



https://arxiv.org/pdf/2107.02686.pdf

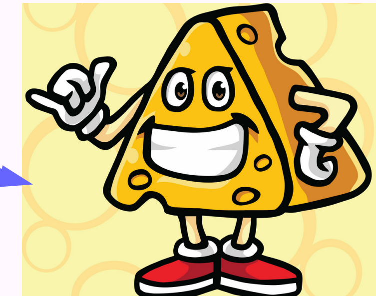
- HH production
  - HH is sensitive to a range of EFT operators, not just λ_3
    - Limits significantly degraded by inclusion of multiple EFT operators
  - New Projections are being evaluated
    - Including prospects at the muon collider
  - Discussions are ongoing to provide relevant benchmarks for BSM HH resonant and non-resonant interpretations
    - Dedicated discussions on the flavor assumptions

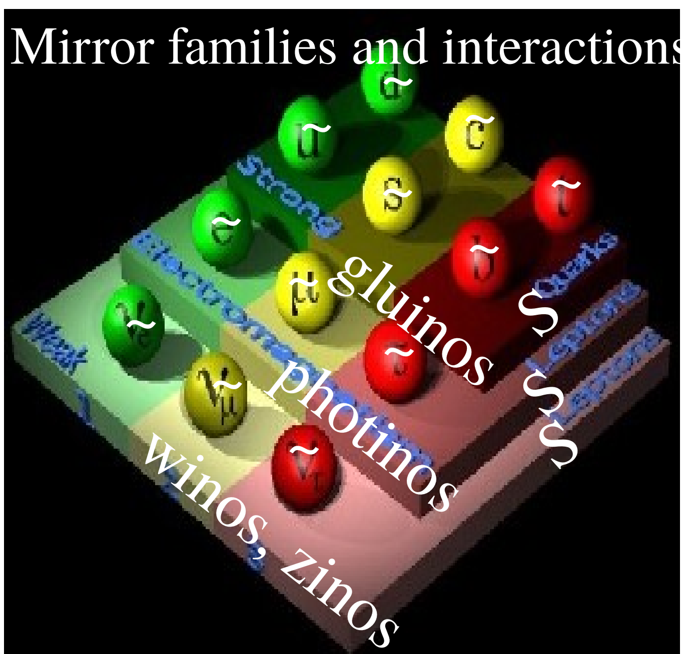
The focus on using Effective Field Theory as BSM tool and on understanding flavor somewhat higher than in EU ?

What stabilizes the Higgs boson mass/ New Constituents of Matter/ Dark Matter?

Hierarchy problem (Higgs boson mass fine-tuned).
Are there any spin=0 partners to the top quark?

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





Newton, Optics (1680) :Now the smallest Particles of Matter may cohere by strongest Attractions, and compose bigger Particles of weaker Virtue. There are therefore Agents in Nature able to make Particles of Bodies stick together by very strong Attractions. And it is the business of experimental Philosophy to find them out.

Supersymmetry can "cure" Higgs boson mass, has candidate particle(s) for Dark Matter, unifies interactions→ it is one of the many attractive beyond SM ideas

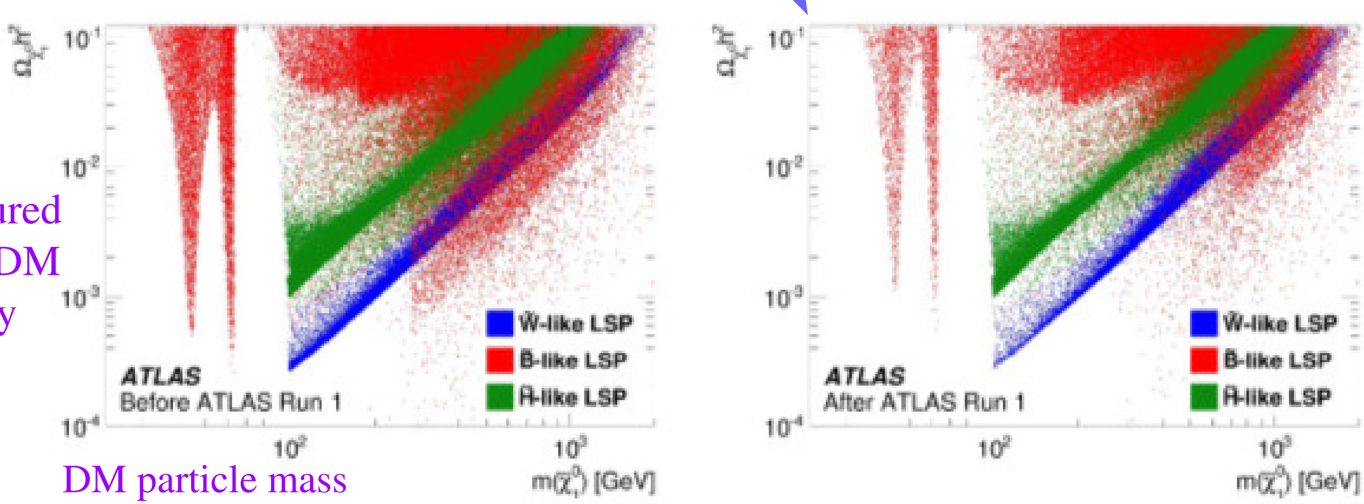
Supersymmetry :Symmetry between "Particles of Matter" and "Agents in Nature "

New Constituents of Matter/Dark Matter/ Supersymmetry (SUSY) has been desperately searched for...

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

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

Measured relict DM density



DM particle mass

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

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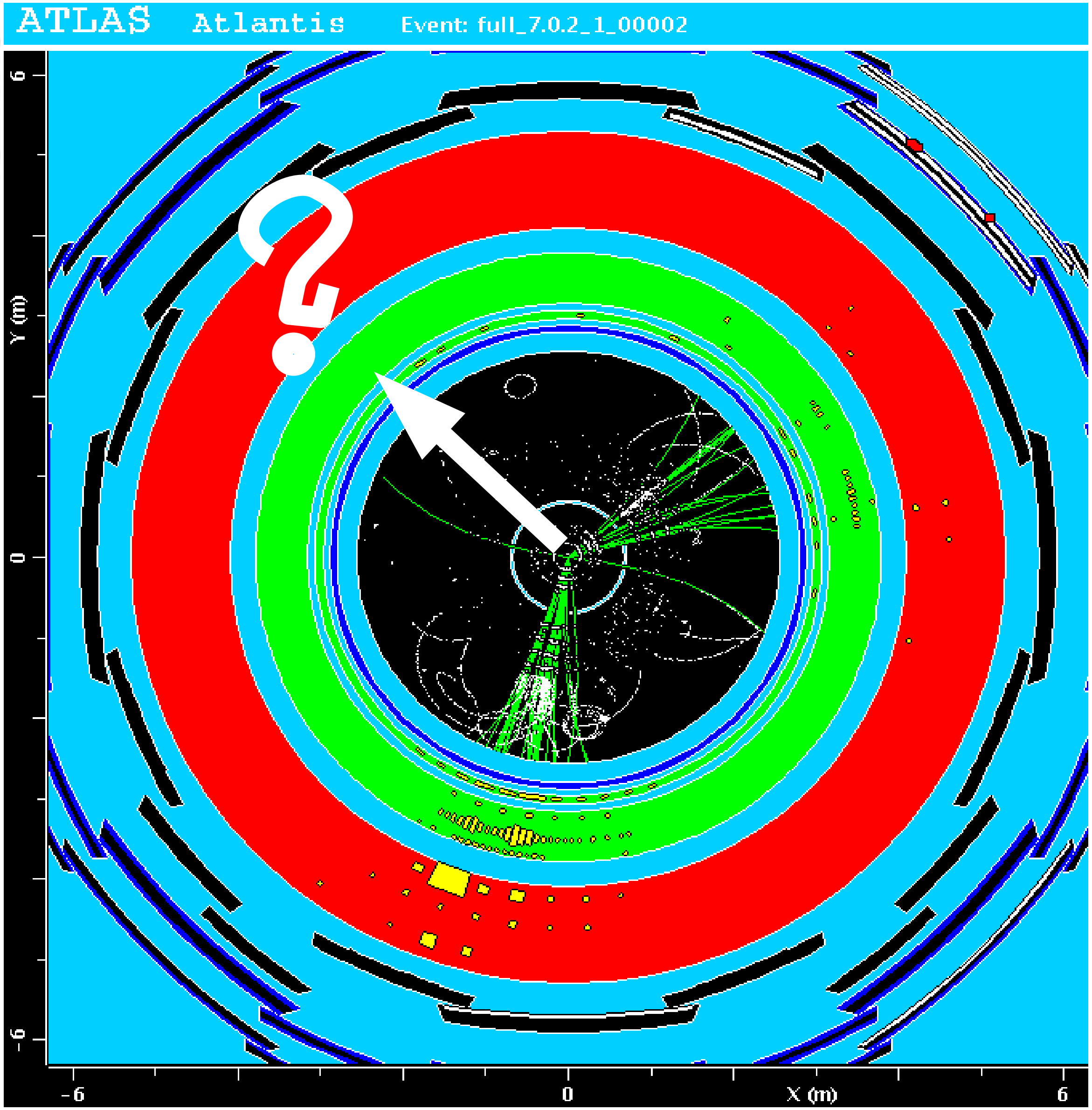
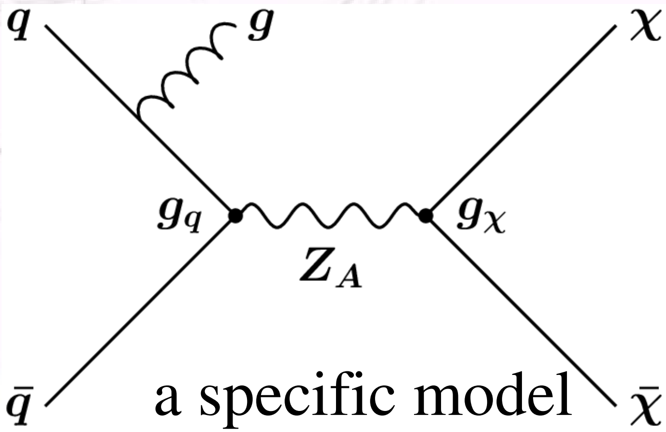
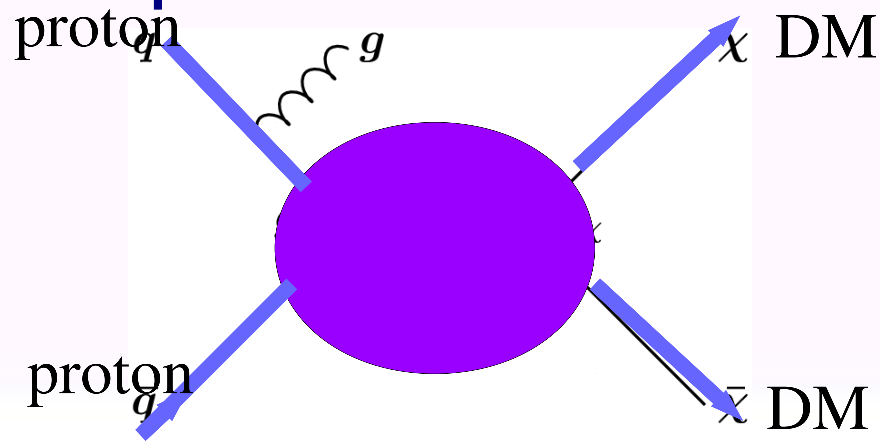
Dark Matter production in the ATLAS detector



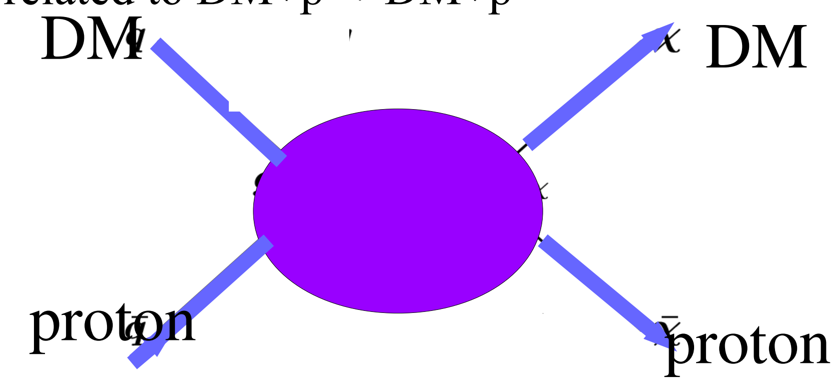
Can we see it ? An example event with missing transverse momentum and two jets.

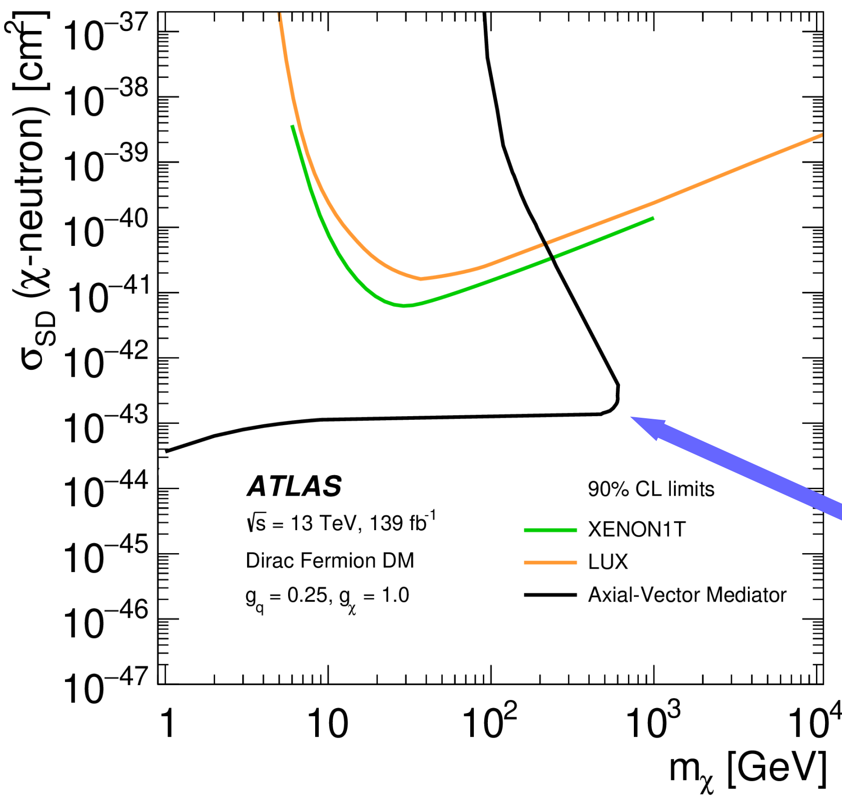
Mono-jet search, generic Dark Matter search ? Synergy with underground experiments.





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

Phys. Rev. D 103 (2021) 112006

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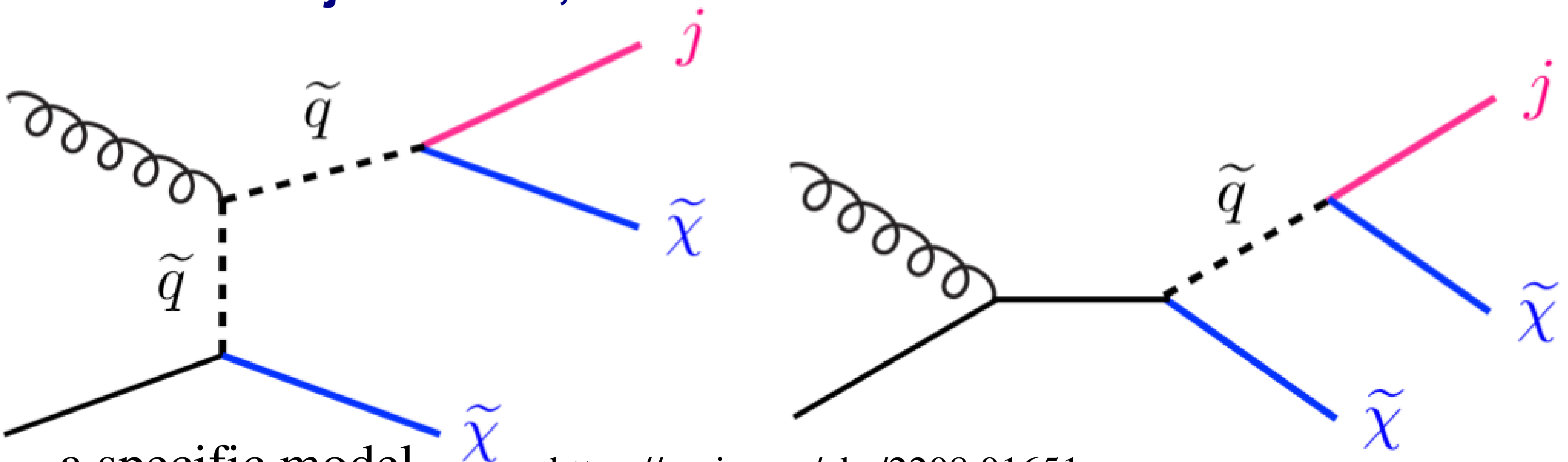
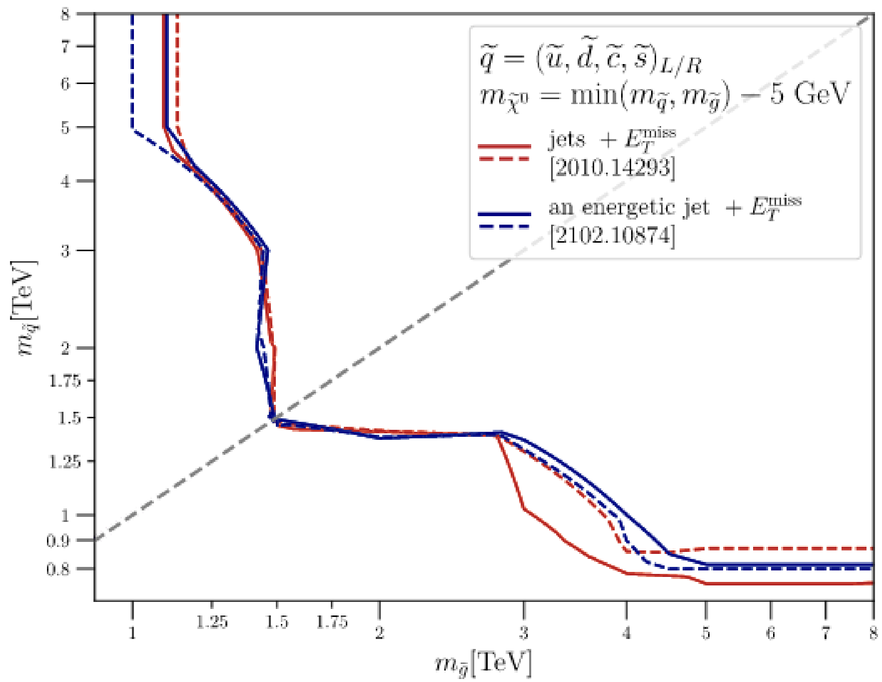
Mono-jet search, SUSY oriented Dark Matter search



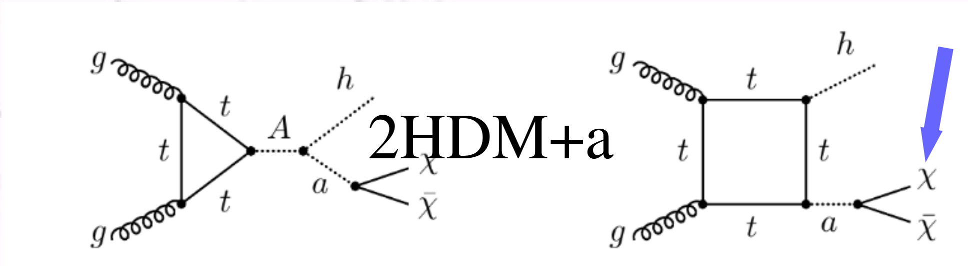
a specific model

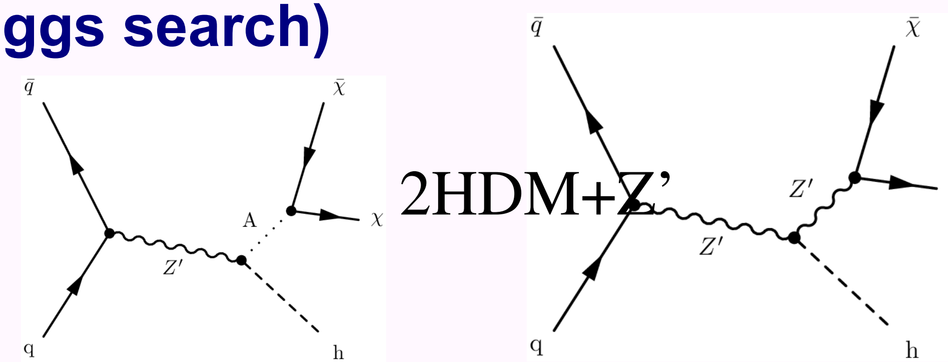
https://arxiv.org/abs/2208.01651



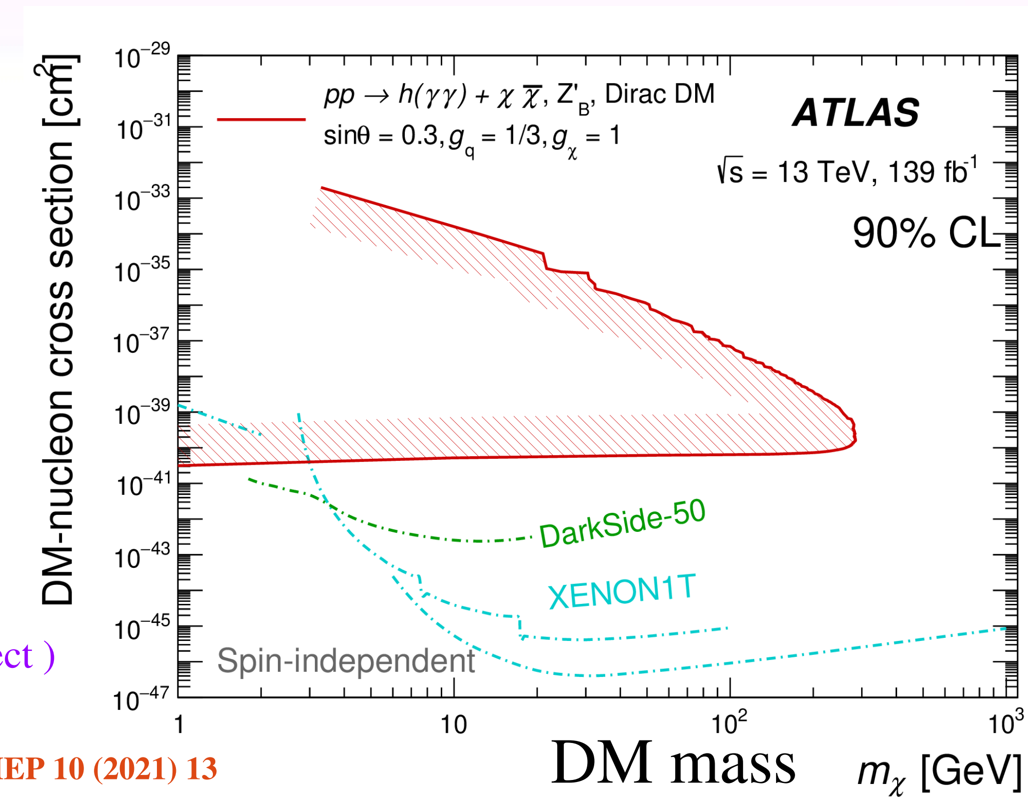
Allows to explore mass space of possible supersymmetric particles (gluino and squark)

Higgs boson and Dark Matter, BSM Higgses + new bosons (Mono-Higgs search)





Run 2:Published results with
H→2photons (Oslo) and H→ bb
H→ tau tau ongoing in Bergen
(supported by MCIF* in the past, now "EarlyUniverse"**).



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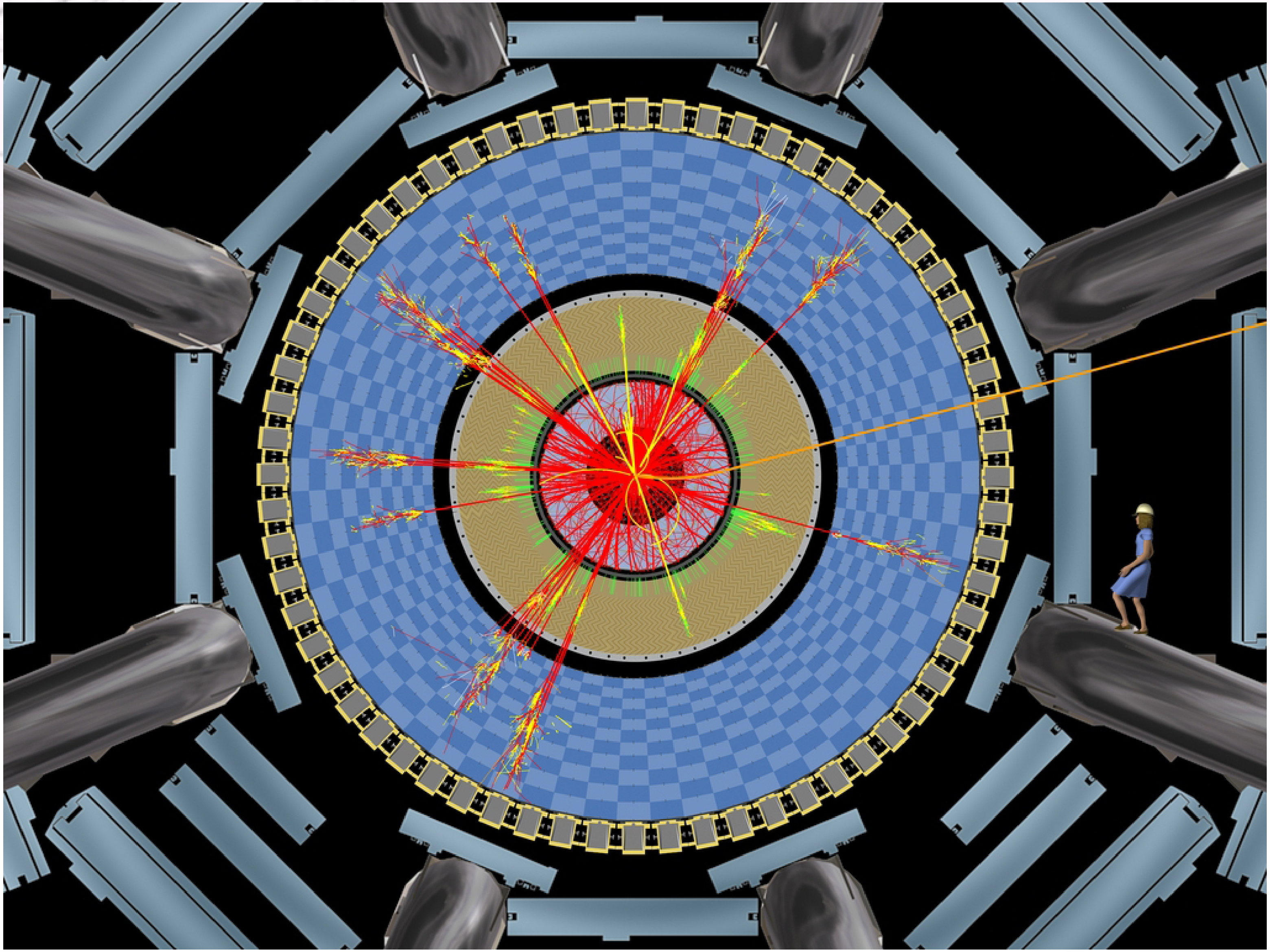
Plans: **Combine all Higgs decay channels, interpretation in other relevant models.**

(Collaboration with theory via Grieg "EarlyUniverse" project)

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

* *Julia Djuvsland , ** Nikolai Fomin, Erlend Aakvaag*

Extra Dimension of Space → A Black Hole in ATLAS



If our space has more dimensions than 3, gravity can be stronger at the microscopic scale of these extra-dimensions, than it is on our macroscopic scales. Microscopic Black Holes can be produced

Can we distinguish sphalerons from micro black holes?

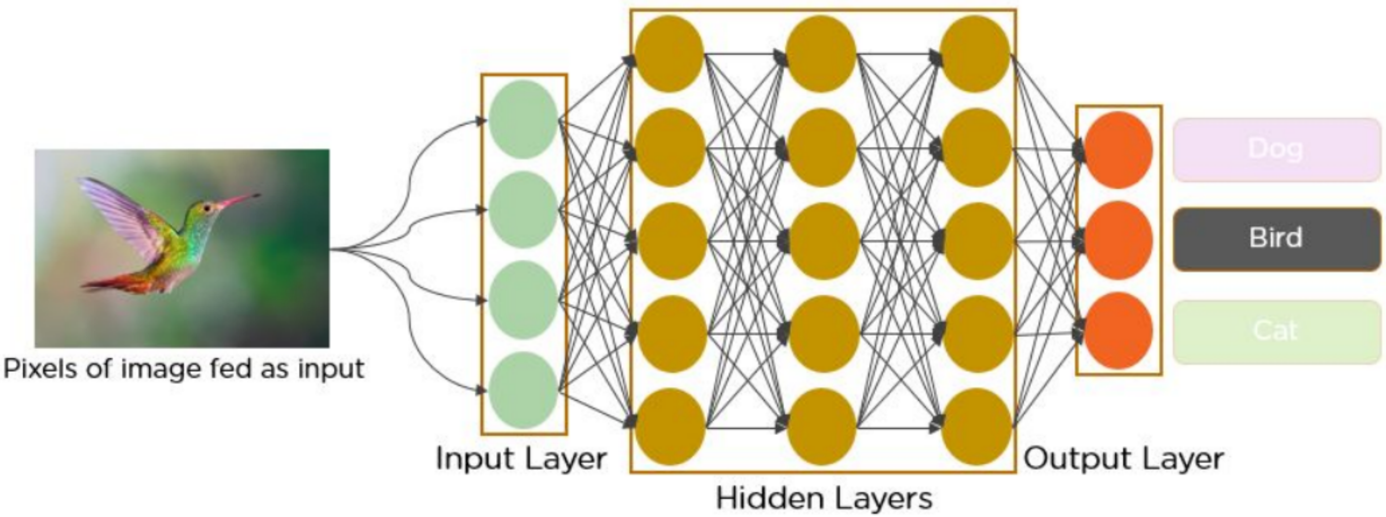
https://indico.cern.ch/event/753170/attachments/1713995/2764365/lhcSphalerons.pdf

What is a Sphaleron?

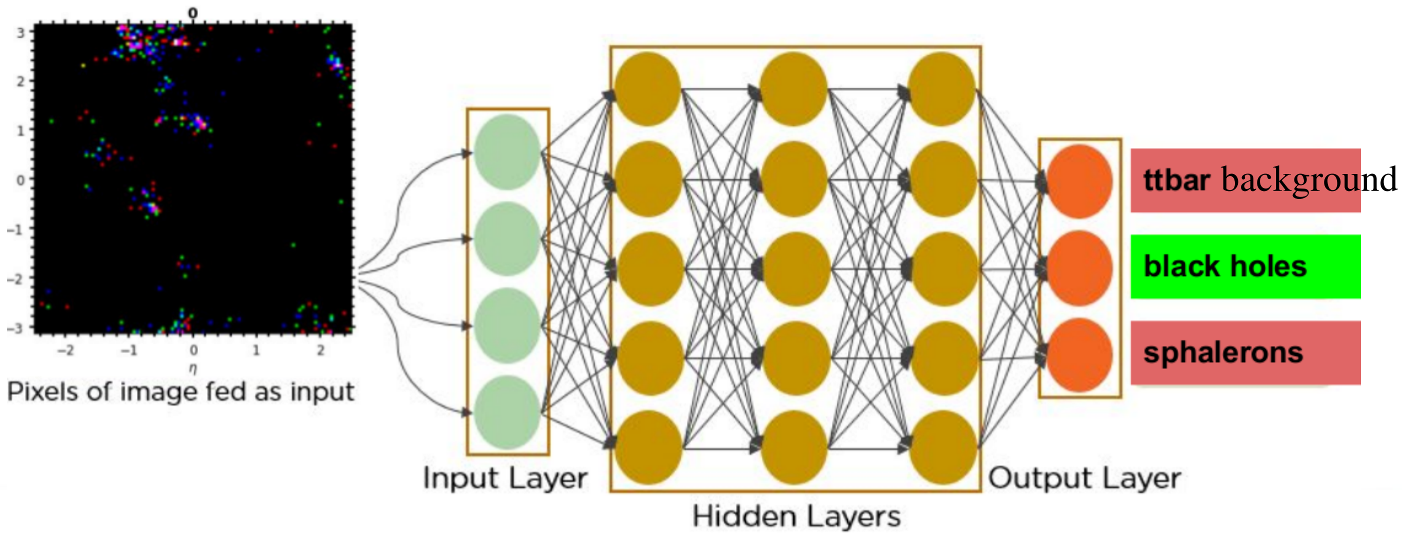
- Non-abelian gauge field configuration
  - First proposed by 't Hooft in 1976
  - Sister to instantons
  - Potential in Chern-Simons number (N_{CS}) of gauge field
- Not yet discovered, now know SM energy: **~9 TeV**
  - Higgs mass was the last piece needed to calculate
  - "Fireball" final states: around twelve 0.8 TeV particles → lots of particles !
- **Violates B+L**
  - B-L is conserved
  - Potential piece of universal matter antimatter asymmetry → yes !
- **First dedicated EW sphaleron search**
  - Using full 2016 CMS dataset
  - QCD sphalerons violate chirality and searched for by ALICE (https://indico.cern.ch/event/656773/)

Can we distinguish sphalerons from micro black holes with ML?

Apply ML computer vision techniques on LHC data.



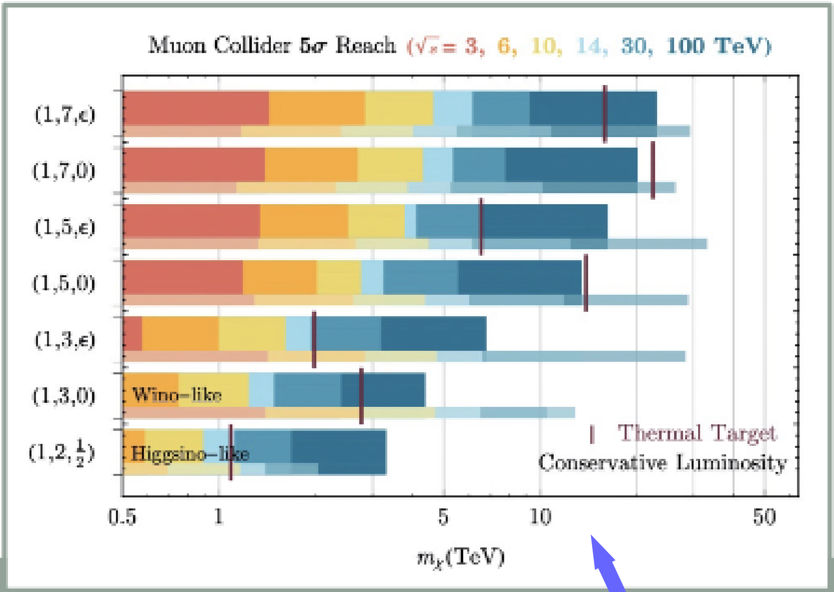
Machine Learning computer vision techniques widely used for picture recognition

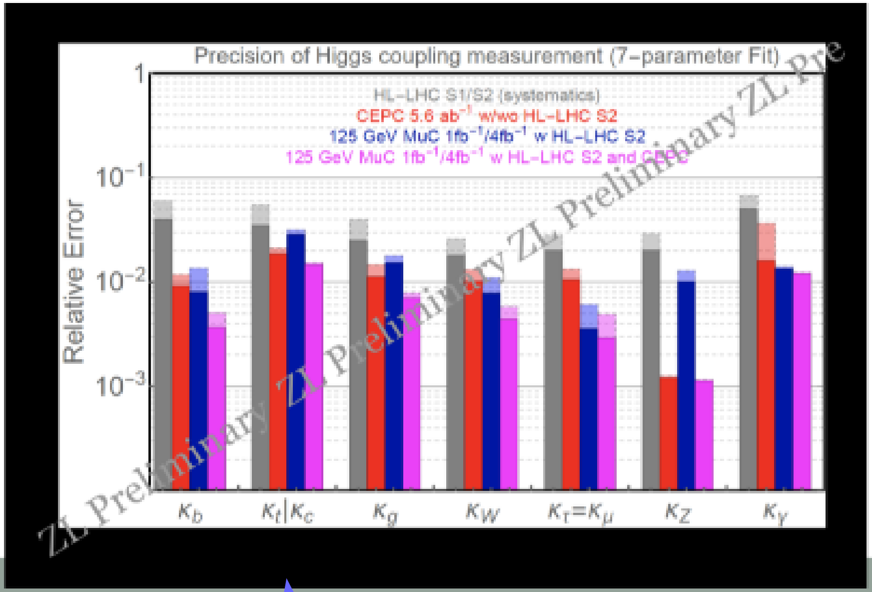


We treat the detector as a camera and energy deposits as pixels. Some promising results in distinguishing SPH from BH

Muon Colliders: Physics Highlights

- High energy muon collider (6-10 TeV and above) has an incredible physics reach:
  - Precision Standard Model studies (including detailed exploration of the Higgs boson)
  - Access to trilinear and quartic (at higher energies) Higgs couplings
  - Searches for BSM with sensitivity way beyond what is achievable at the LHC and similar to FCC-hh
- Does 125 GeV Higgs Factory make sense as a staging option?
  - Improved luminosity projections with new technology advancements → translates into better physics
  - Small footprint and modest cost (tbd), physics while the multi-TeV ring is being built, reuse the injection complex





Dark Matter

Higgs couplings

Member of ATLAS

DRAFT Community input

Energy Frontier Vision – the ultimate goal

- The discovery of the Higgs boson has made the standard model as "complete" as it is going to get - a tremendous achievement
- However, this also brings into focus that there are many questions that the standard model does not answer
  - Gravity
  - Dark energy
  - Dark matter
  - Matter – antimatter asymmetry
  - Hierarchy/naturalness problem

- Our vision must keep its focus on these big questions.
- Whatever the details of the vision are, it must enable us to continue to attack these questions from as many angles as possible
- Ultimately, this means that we must find a way to carry out experiments at energy scales far beyond those achievable today – 10 TeV, 100 TeV, more

Snowmass Energy Frontier Vision

Snow

DRAFT Community inpu

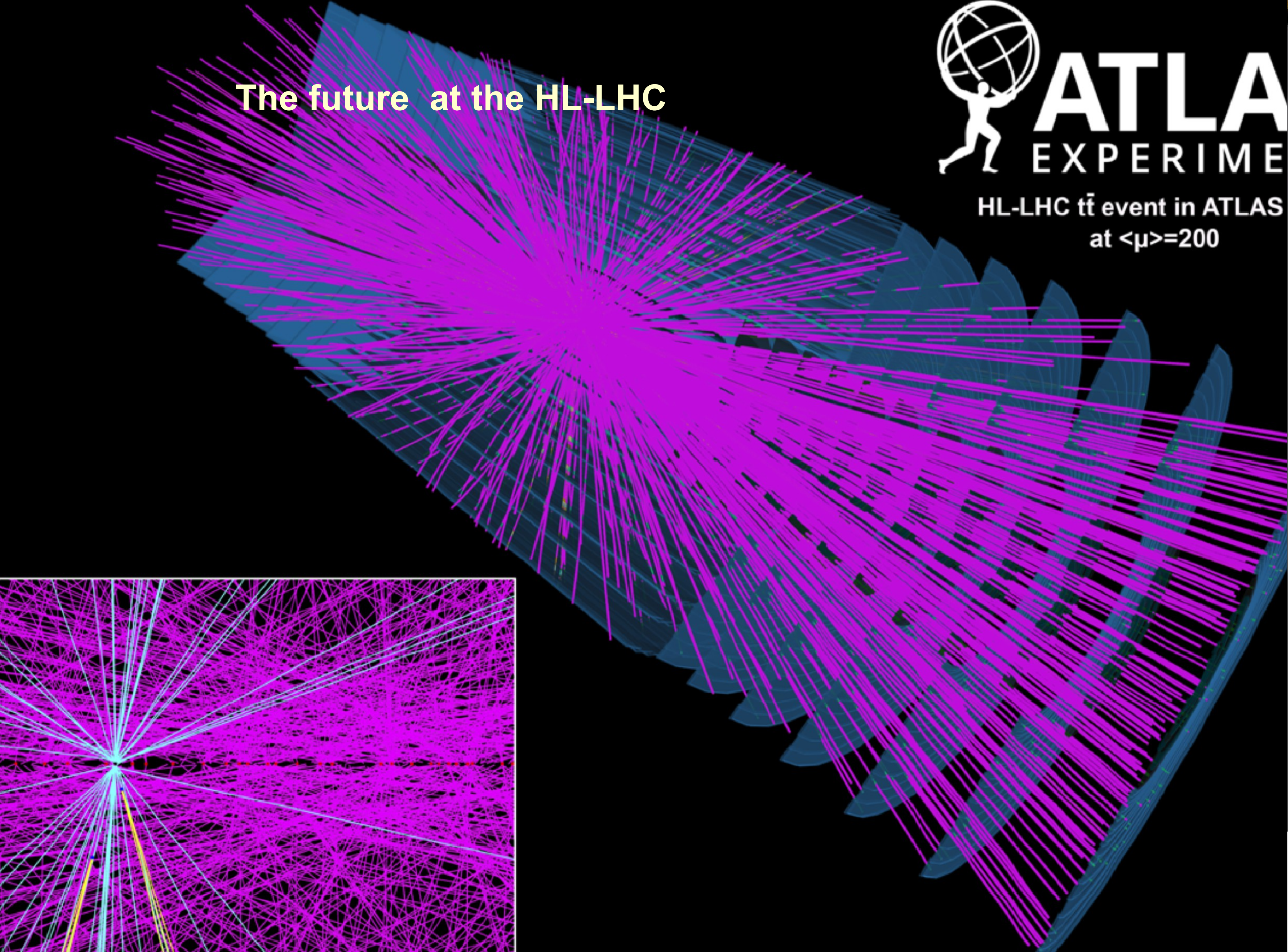
Energy Frontier Vision – Summary

- Immediate future → successful implementation of the HL-LHC program

- Intermediate future → precision ewk program
  - Based on e+e- colliders
  - Work with international sites on detector designs and develop extensive R&D programs.
    - In addition, be prepared to site in US as a backup option.

- Far future → Collider to directly
  - access energies of 100 TeV or higher, high energy lepton colliders, muon colliders
  - Fund vigorous R&D program towards the technology to reach much higher energies
  - Pursue inspiring new ideas to reach our ultimate goal

The future at the HL-LHC



Backup

"Run 2" Data Set of the Large Hadron Collider still being exploited:

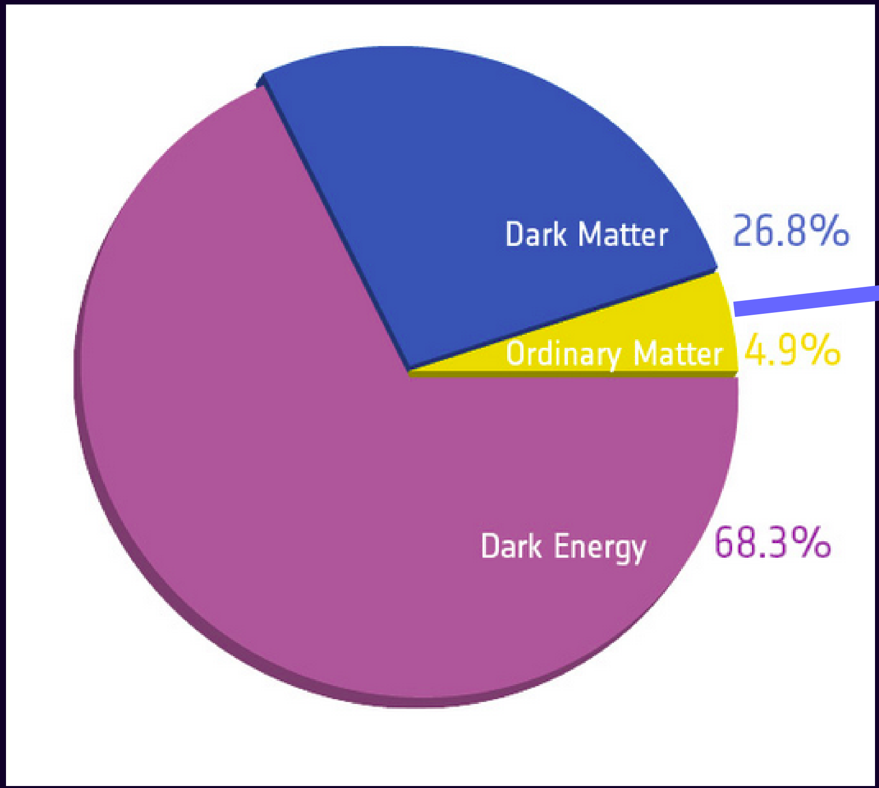
Particle	Produced in 139 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.7 million	
Top quark	275 million	
Z boson	2.8 billion	($\to \ell\ell$, 290 million)
W boson	12 billion	($\to \ell\nu$, 3.7 billion)
Bottom quark	~40 trillion	(significantly reduced by acceptance)

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)

(far future -if there is any..)

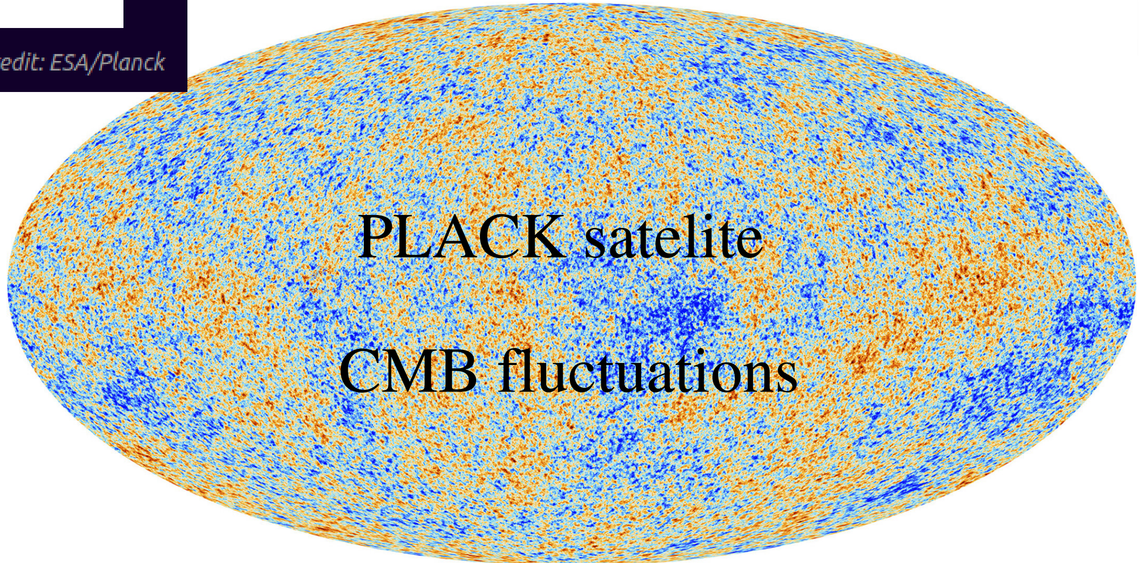
~statistical improvement factor ~2, ~2.5 , ~4.5

The Standard Model makes only 5% of the Universe



The relative amounts of the different constituents of the Universe. *Image credit: ESA/Planck*

The Higgs boson
and the rest of SM



The "EarlyUniverse" project

Norway grants

NATIONAL SCIENCE CENTRE POLAND

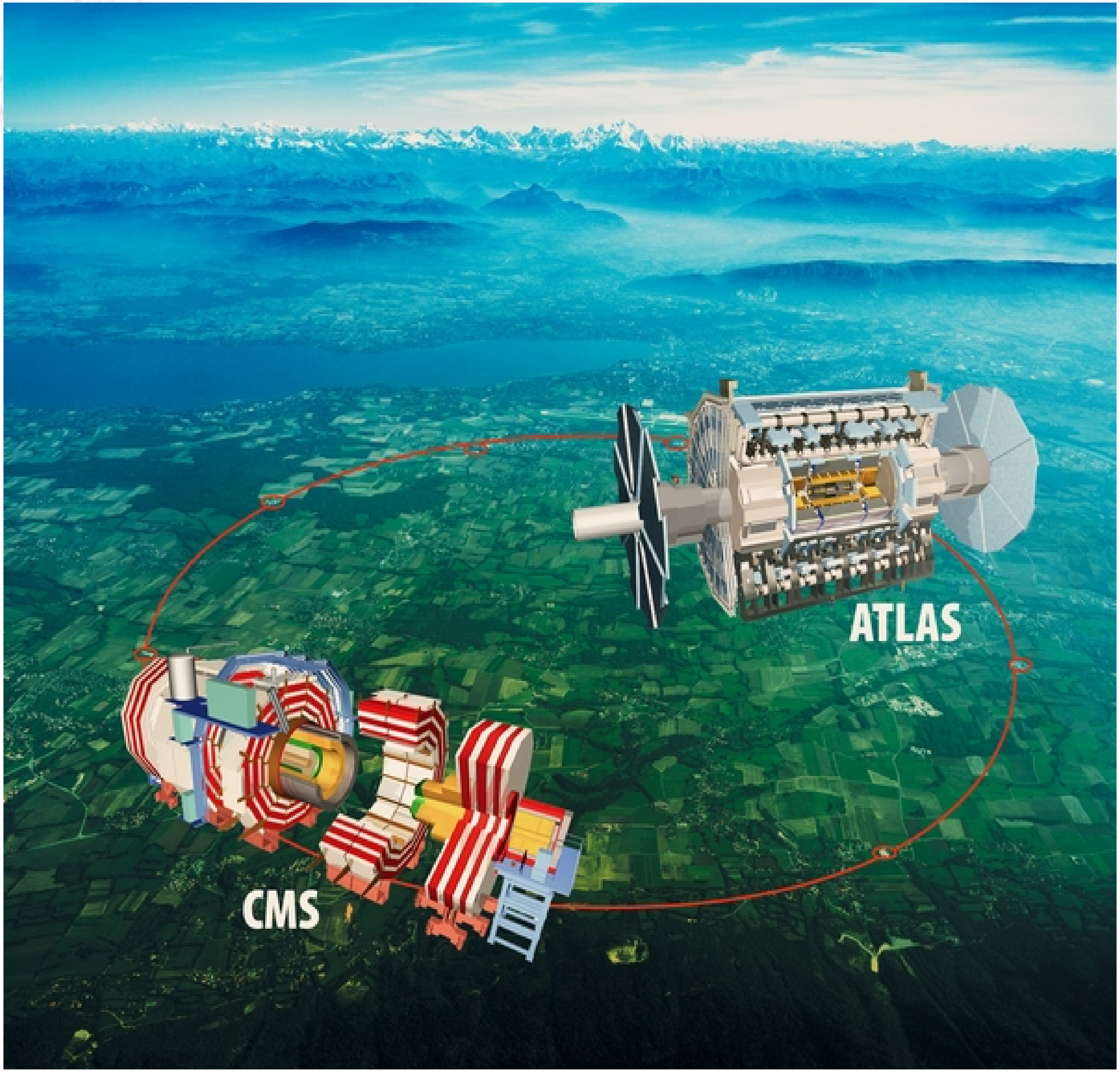
The research leading to the results presented in this talk has received funding from the Norwegian Financial Mechanism for years 2014-2021, grant nr 2019/34/H/ST2/00707

Understanding the Early Universe:
interplay of theory and collider experiments

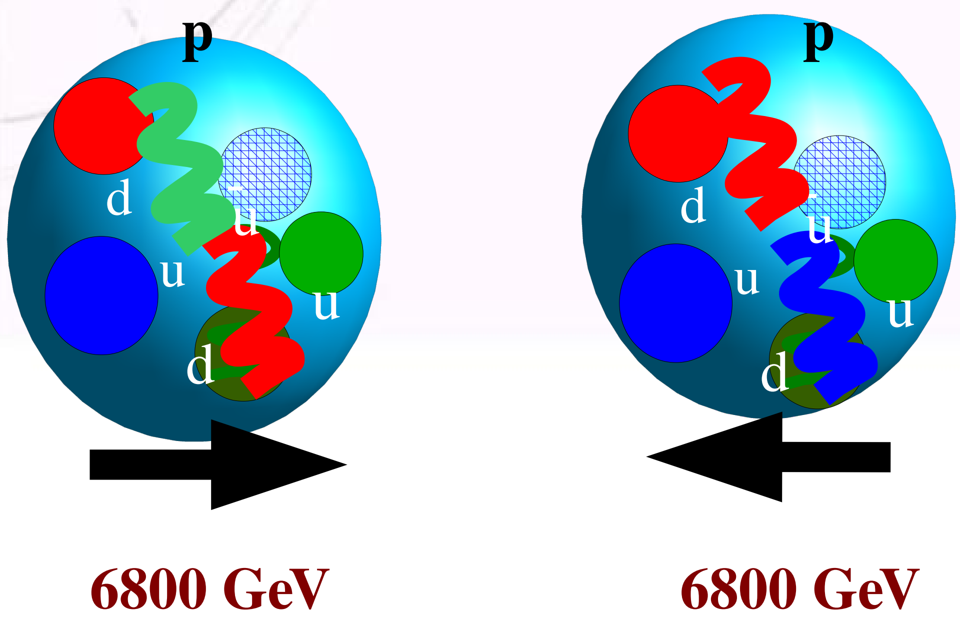
Joint research project between the University of Warsaw & University of Bergen

Theory & Experiment

ATLAS and CMS have similar capabilities now and in the future



Accelerator-driven physics, the paradigm



1) take stable, easy available particles and collide them at the highest energy the tax payers accept -> known initial state (as much as QM allows) !

2) The final state must decay to Standard Model particles and Dark Matter (as Big Bang experience shows).

3) Register all SM particles and missing energy in your detector and try to "decipher" the final state.

4) Subtract "non interesting" part-> measure it and use enlighten extrapolation from other experiments.

Funding period 10.2020-04.2024, ~15MNOK , 40% to Bergen.
(salary to Nikolai and Erlend)

Science: Understanding Early Universe with Collider Data.
Keywords: Dark Matter, Electroweak Baryogenesis, CP violation, Electroweak Phase transition

Research objectives: at the start

1. **Machine learning assisted mono-jet anlysis in search for Dark Matter and new electricaly neutral stable particles and its theoretical interpretation.**
[**K. Sakurai, B. M. dit Latour,** I. Lara, K. Rolbiecki, M. Olechowski, S. Pokorski, T. Buanes, A. Lipniacka, K. Tywoniuk, R. Masełek]

2. **Discriminating theories by joint mono-jet and mono-Higgs analysis.**
[**K. Rolbiecki, T. B. Sjursen,** I. Lara, J. Rosiek, T. Buanes, A. Lipniacka] N. Fomin, E. Aakvaag

3. **Constraining the mechanism of the Electroweak Phase Transition by di-Higgs boson production, p p -> h h.**
[**M. Olechowski, A. Lipniacka,** S. Pokorski, Z. Lalak, B. Stugu]

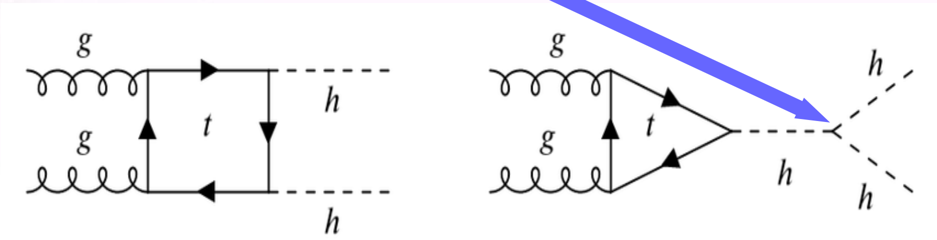
4. **Probing new sources of CP violation in the Higgs-fermion sector.**
[**J. Rosiek, B. Stugu,** K. Rolbiecki, K. Sakurai, A. Lipniacka] E. Aakvaag

5. **Investigating the sphaleron and mini-black hole production at the LHC and its dependence on the mechanism of EWPT.**
[**S. Pokorski, T. Buanes,** I. Lara, K. Sakurai, M. Olechowski, Z. Lalak, A. Lipniacka, K. Tywoniuk, R. Masełek] A. Grefsrud

https://www.fuw.edu.pl/~ksakurai/grieg/index.html?lang=en

"Higgs self-coupling": Is our vacuum metastable or is the hh coupling different than SM predicts ?

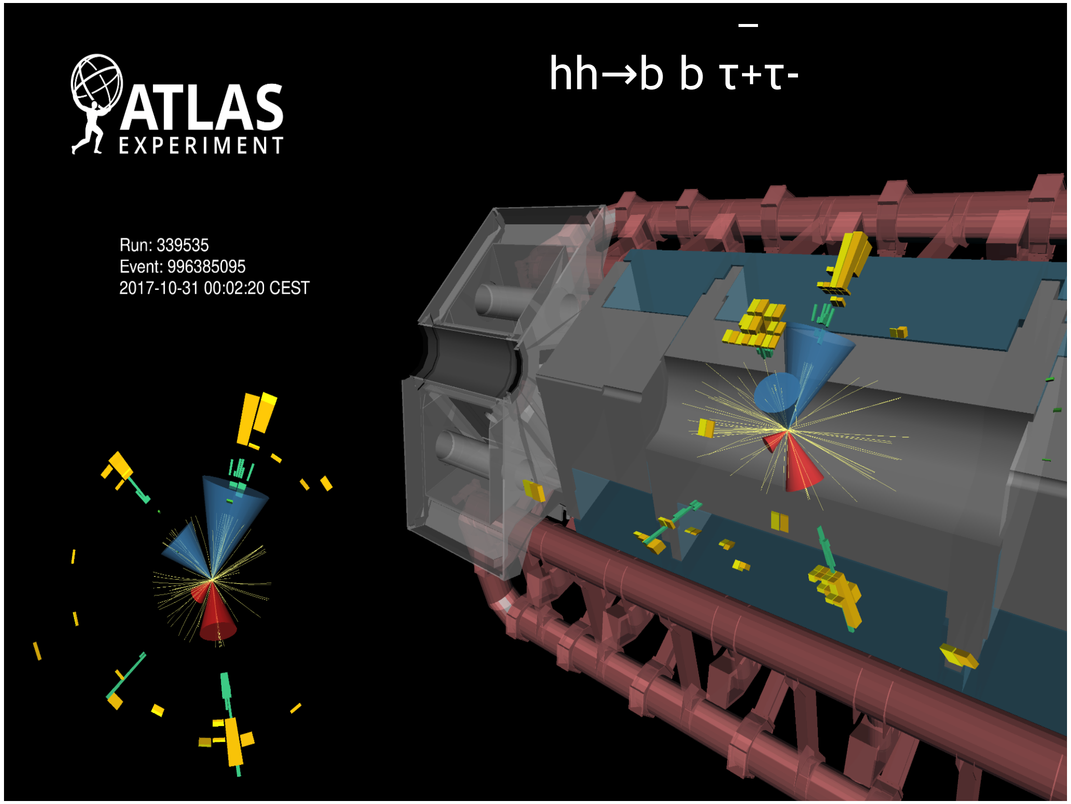
Higgs self-coupling via double Higgs production. Related to the Higgs boson mass . Basis to understand "the minimum of potential energy" the Universe ended-up in.



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

Flagship LHC measurement: example final state in the ATLAS Detector



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
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

Charge-Parity (CP) violation and Baryon+Lepton (B+L) number violation needed for our matter to exist

1) Matter and antimatter are produced in equal amounts in high energy collisions in colliders

2) yet in our Universe matter prevailed.

3) We need the violation of combined charge parity, C, and parity,P, and the violation of baryon+lepton number to explain the existence of our matter.

P

left handed neutrino → ~~right handed neutrino~~

C

left handed neutrino → ~~left handed antineutrino~~

These particles do not exist thus taken separately C and P are blatantly violated.

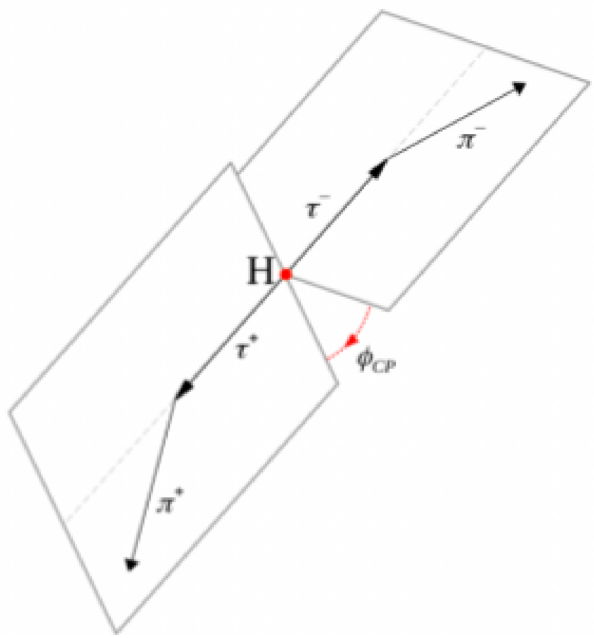
CP

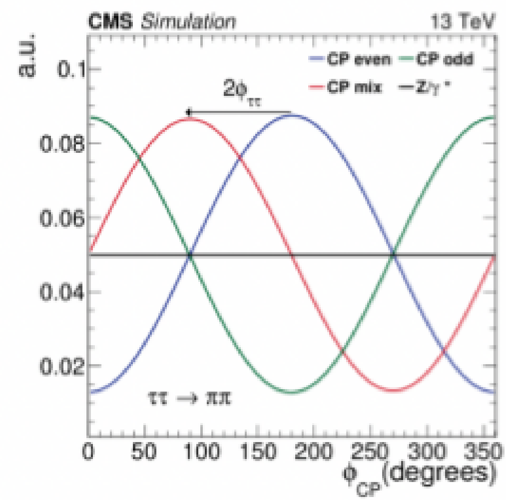
left handed neutrino → right handed antineutrino

Some measurements show very weak violation of CP, too weak to explain the existence of our matter.

"New sources of CP violation?"

Higgs boson CP measurement, in Higgs→ tau tau decays To measure the CP state we need to measure a distribution of an angle between two planes.





arxiv.2110.04836

2012.13922 ,1510.03850 : CP phase precision after Run5 = 10°-5°

Precision of 3-5° needed to test some of the baryogenesis models. (**Our existence requires more CP violation than we presently see, baryogenesis).** Can we add more precision to the CP measurement by testing other Higgs boson decay channels?

Conclusions.

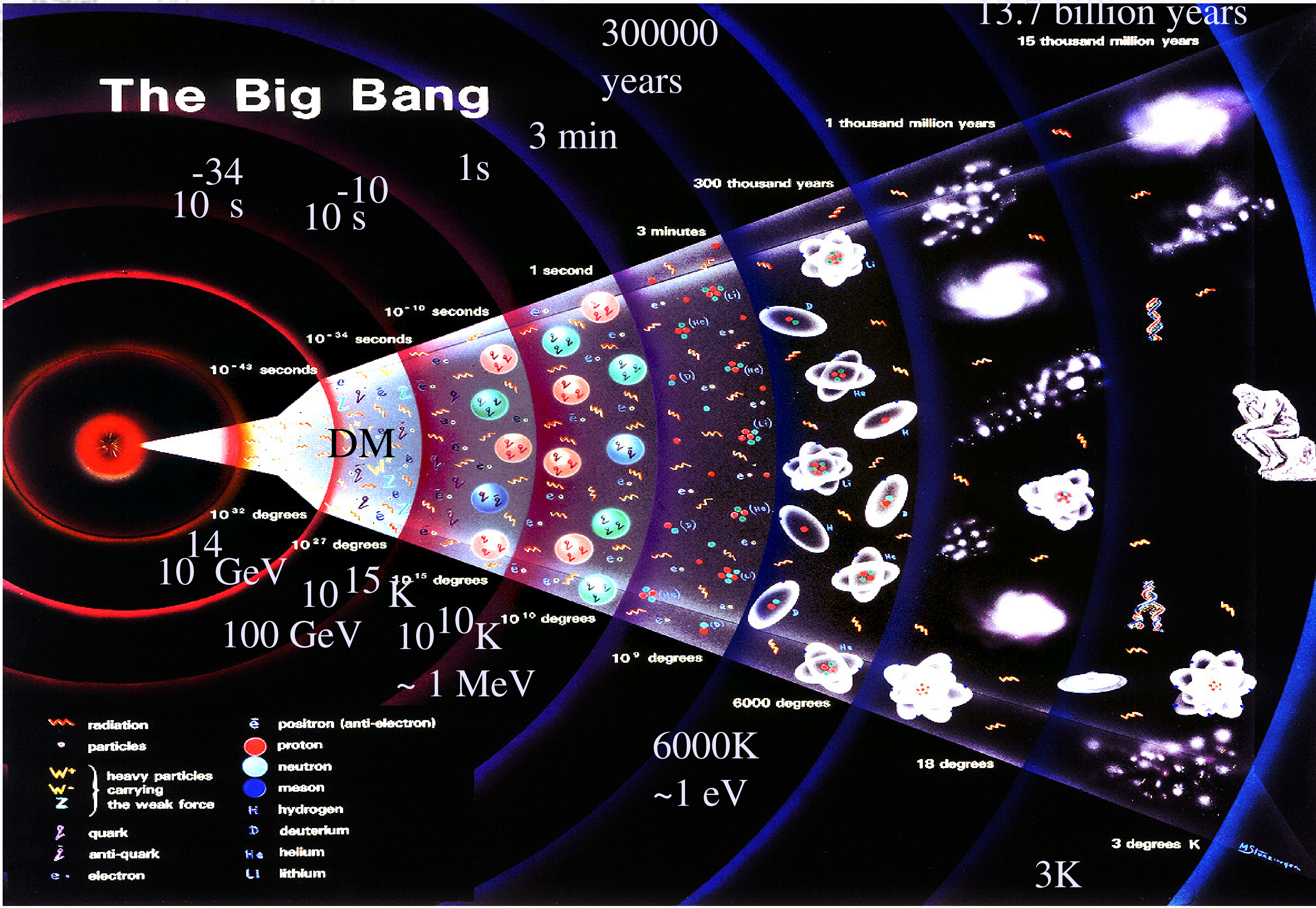
Few outstanding problems that have origin in the Early Universe can be studied at the LHC.

Are we living in a metastable vacuum? (Measure Higgs boson self coupling)

What stabilizes the Higgs boson mass ? (Search for new particles)

What is 95% of the Universe made of ?
(Search for Dark Matter)

Why our matter exists at all ? (search for new sources of CP violation and B+L violation)



Snowmass Strategy Highlights and Early Universe at the LHC

Member of