The Next Frontier in Particle Physics

From the LHC to the FCC

Disclaimer: Focus on LHC and FCC ee and pp physics

Heavy Ion Physics covered by Jacek

Marumi Kado

MAX-PLANCK-INSTITUT FÜR PHYSIK

UTokyo

November 2025, University of Tokyo, **ILANCE**

Second International Conference one the Physics of the Two Infinities

The Heart of the Two Infinities

Exploring the Quantum Universe

At the heart of the two infinities are the fundamental paradigms of natures at all scales!

Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

The roadmap for Particle Physics

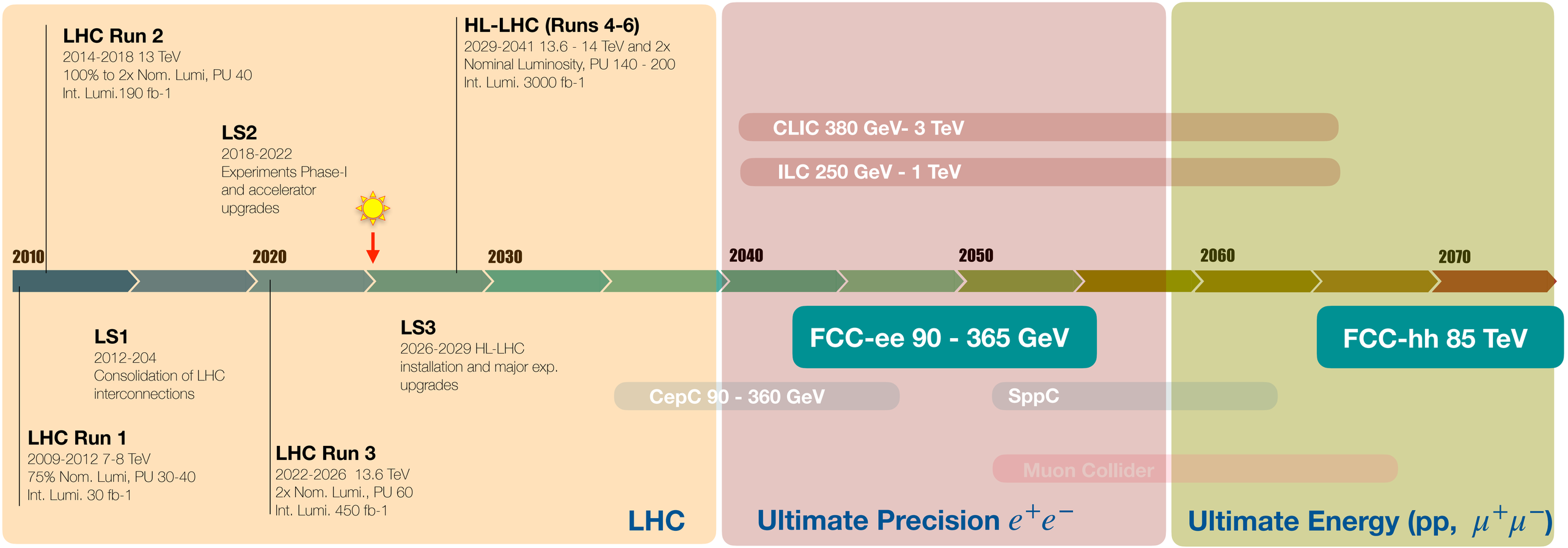
Higgs factory as well as EW and HF precision

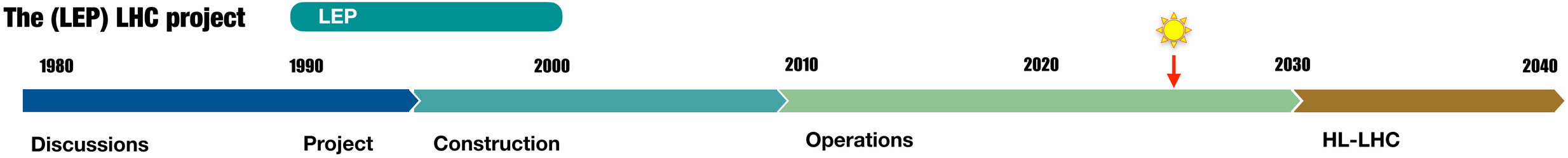
10 TeV pCOM collider

The need for new paradigms

- The **nature of the Higgs boson**, is it composite? How does it interact with itself?
- **Hierarchy** of the **fundamental interactions**?
- Structure of the **quantum theory of gravity** and what are the quantum properties of space-time?
- Why is the electric charge quantised and why are the charges of the proton and the electron equal*? Are there new symmetries at high energies that **unify interactions**?
- **Hierarchy of fermions**? What are the fundamental properties of neutrinos?
- Why is the nucleon EDM so small? **Strong CP**.
- Dominance of **matter over anti-matter**?
- Nature of **Dark Matter** (DM) and the mysterious **Dark Energy**?

A Scientific Mission for the 21st Century





A Pivotal Moment for Particle Physics

Physics community called to make a strategic decision.

European Strategy Process well underway with principal goal to decide on the next flagship CERN project.

We are here!

263 inputs received!

Strategy Documents Link

Three principal considerations

(as requested by the ESG)

What is the **preferred large-scale post-LHC accelerator** for CERN?

What is the **preferred alternative, if the preferred option is not feasible?**

What is the preferred alternative, **if the preferred option would not be competitive?**

A Pivotal Moment for Particle Physics

Feasibility study report Link


Future Circular Collider
Feasibility Study Report

Volume 1
Physics, Experiments, Detectors

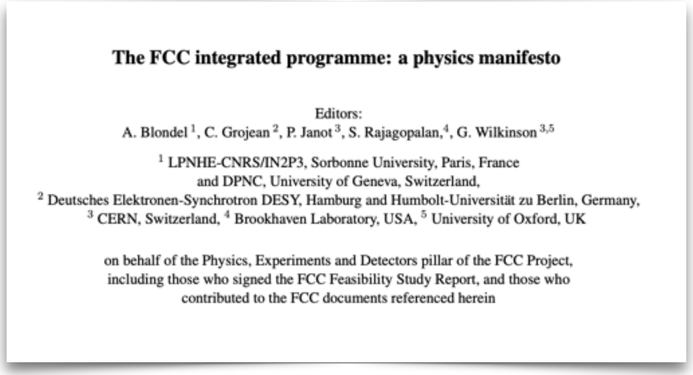

Future Circular Collider
Feasibility Study Report

Volume 3
Civil Engineering, Implementation and Sustainability


Future Circular Collider
Feasibility Study Report

Volume 2
Accelerators, Technical Infrastructure and Safety

Altogether 1,200 pages opus!


The FCC integrated programme: a physics manifesto

Editors:
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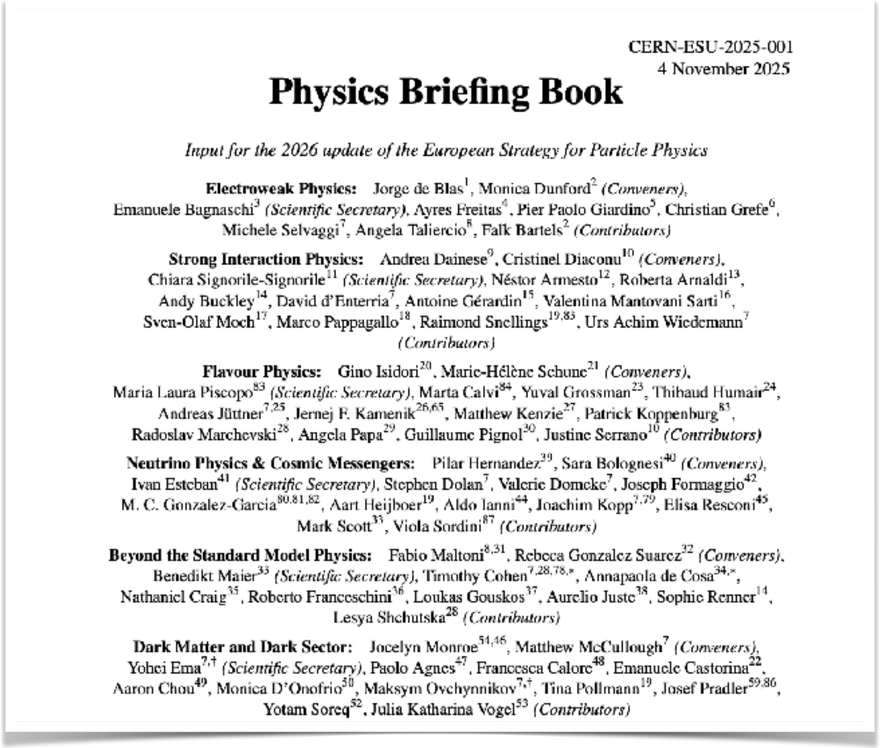
[3] CERN, Switzerland, [4] Brookhaven Laboratory, USA, [5] University of Oxford, UK

on behalf of the Physics, Experiments and Detectors pillar of the FCC Project,
including those who signed the FCC Feasibility Study Report, and those who
contributed to the FCC documents referenced herein

Physics manifesto!
Link

Link


CERN-ESU-2025-001
4 November 2025

Physics Briefing Book

Input for the 2026 update of the European Strategy for Particle Physics

Electroweak Physics: Jorge de Blas[1], Monica Dunford[2] *(Conveners)*, Emanuele Bagnaschi[3] *(Scientific Secretary)*, Ayres Freitas[4], Pier Paolo Giardino[5], Christian Grefe[6], Michele Selvaggi[7], Angela Taliercio[8], Falk Bartels[2] *(Contributors)*

Strong Interaction Physics: Andrea Dainese[9], Cristinel Diaconu[10] *(Conveners)*, Chiara Signorile-Signorile[11] *(Scientific Secretary)*, Néstor Armesto[12], Roberta Arnaldi[13], Andy Buckley[14], David d'Enterria[7], Antoine Gérardin[15], Valentina Mantovani Sarti[16], Sven-Olaf Moch[17], Marco Pappagallo[18], Raimond Snellings[19,83], Urs Achim Wiedemann[7] *(Contributors)*

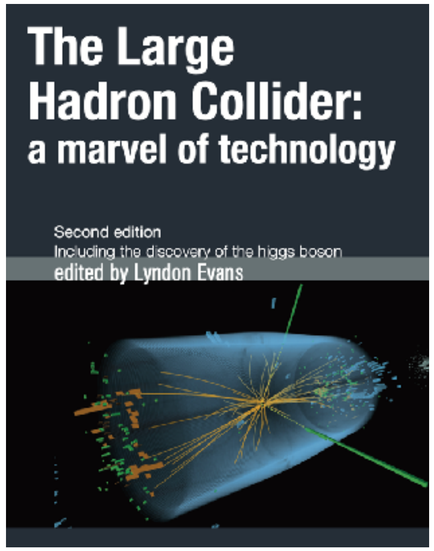
Flavour Physics: Gino Isidori[20], Marie-Hélène Schune[21] *(Conveners)*, Maria Laura Piscopo[83] *(Scientific Secretary)*, Marta Calvi[84], Yuval Grossman[23], Thibaud Humair[24], Andreas Jüttner[7,25], Jernej F. Kamenik[26,65], Matthew Kenzie[27], Patrick Koppenburg[83], Radoslav Marchevski[28], Angela Papa[29], Guillaume Pignol[30], Justine Serrano[10] *(Contributors)*

Neutrino Physics & Cosmic Messengers: Pilar Hernandez[39], Sara Bolognesi[40] *(Conveners)*, Ivan Esteban[41] *(Scientific Secretary)*, Stephen Dolan[7], Valerie Domcke[7], Joseph Formaggio[42], M. C. Gonzalez-Garcia[80,81,82], Aart Heijboer[19], Aldo Ianni[44], Joachim Kopp[7,79], Elisa Resconi[45], Mark Scott[33], Viola Sordini[87] *(Contributors)*

Beyond the Standard Model Physics: Fabio Maltoni[8,31], Rebeca Gonzalez Suarez[32] *(Conveners)*, Benedikt Maier[33] *(Scientific Secretary)*, Timothy Cohen[7,28,78,*], Annapaola de Cosa[34,*], Nathaniel Craig[35], Roberto Franceschini[36], Loukas Gouskos[37], Aurelio Juste[38], Sophie Renner[14], Lesya Shchutska[28] *(Contributors)*

Dark Matter and Dark Sector: Jocelyn Monroe[54,46], Matthew McCullough[7] *(Conveners)*, Yohei Ema[7,†] *(Scientific Secretary)*, Paolo Agnes[47], Francesca Calore[48], Emanuele Castorina[22], Aaron Chou[49], Monica D'Onofrio[50], Maksym Ovchynnikov[7,†], Tina Pollmann[19], Josef Pradler[59,86], Yotam Soreq[52], Julia Katharina Vogel[53] *(Contributors)*

The LHC a Marvel of Technology



Link

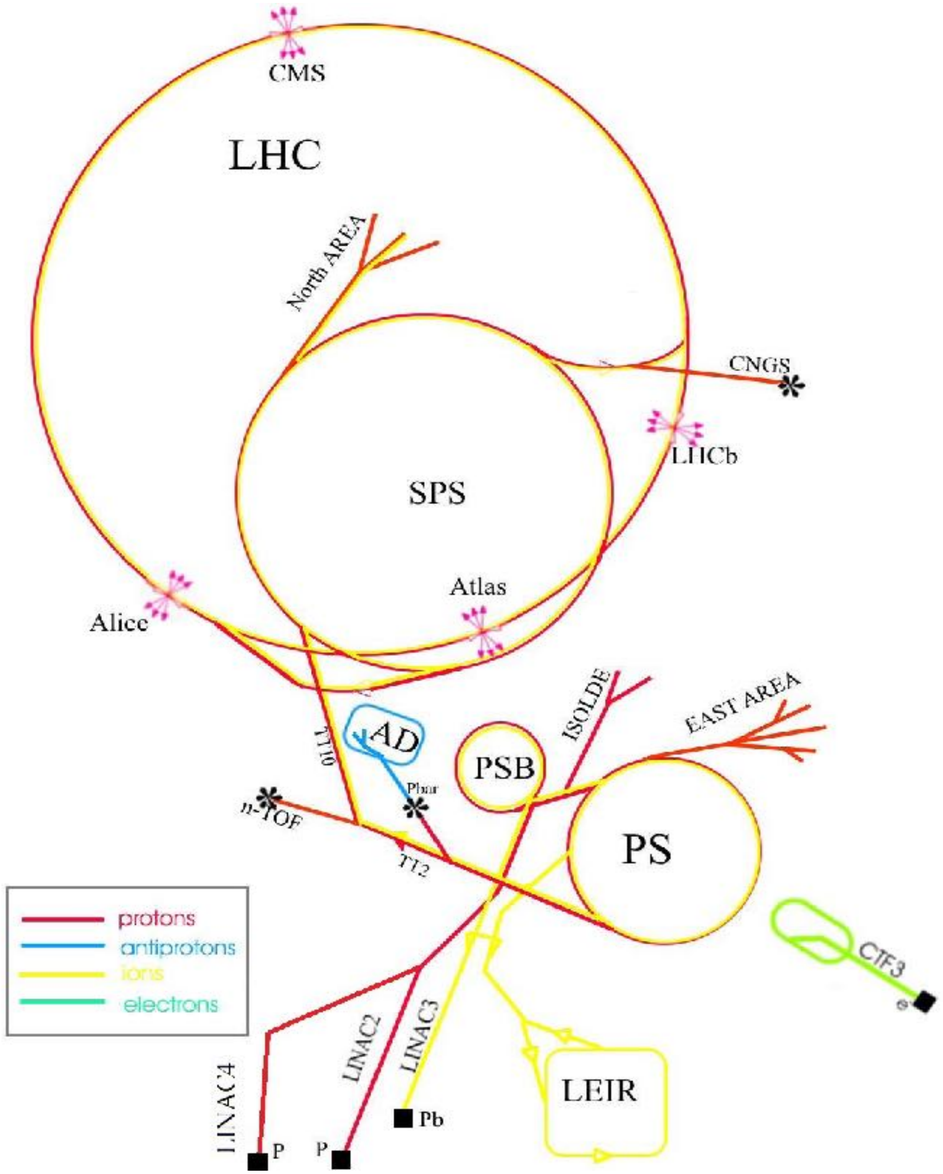
Unrivalled at Energy Frontier

13.6 TeV (COM energy)

Outstanding at Intensity Frontier

Record Luminosity* $2.4 \times 10^{34}\ cm^{-2}s^{-1}$

*Close to SuperKEKB at $5.1 \times 10^{34}\ cm^{-2}s^{-1}$



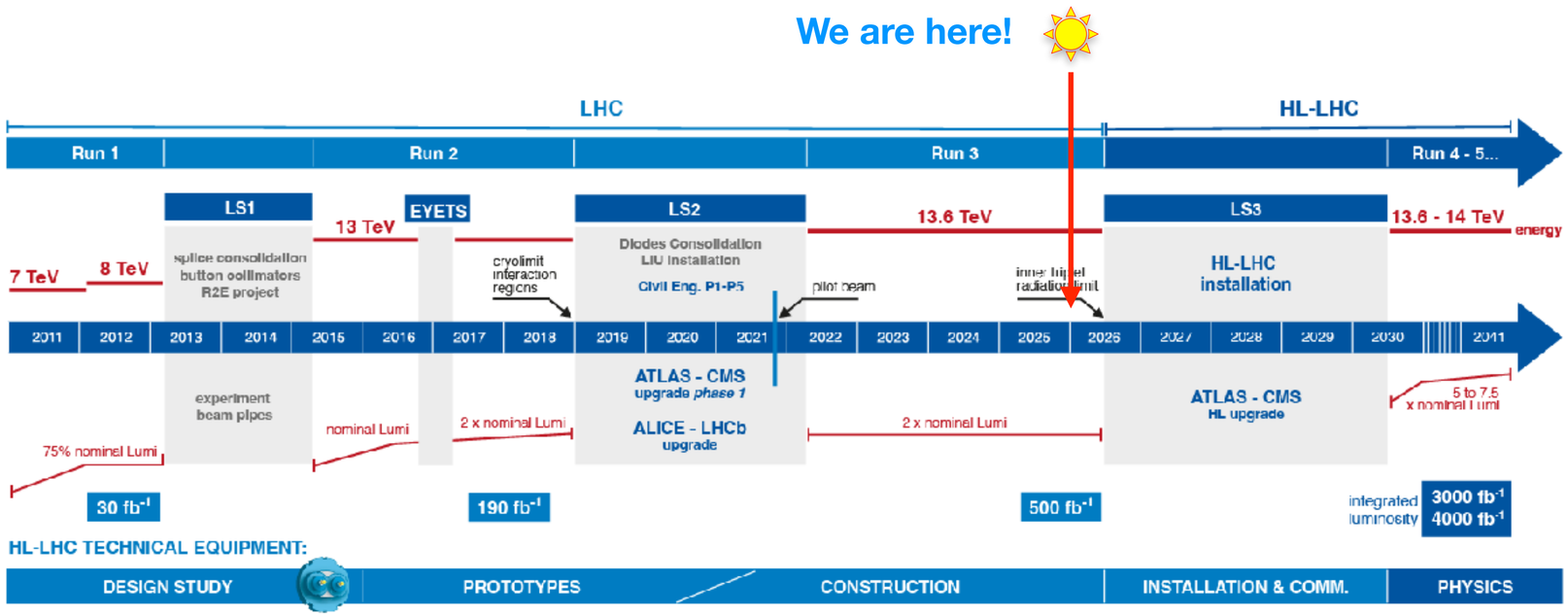
So far the LHC has delivered:

- 15 Million Higgs bosons produced
- 600 Million top quarks produced
- 15 Billion Z bosons with 300 Million per lepton flavour
- 60 Billion W bosons (3 billion per lepton flavour)
- 300 Trillion b quarks (approximately 2 Trillion for LHCb)

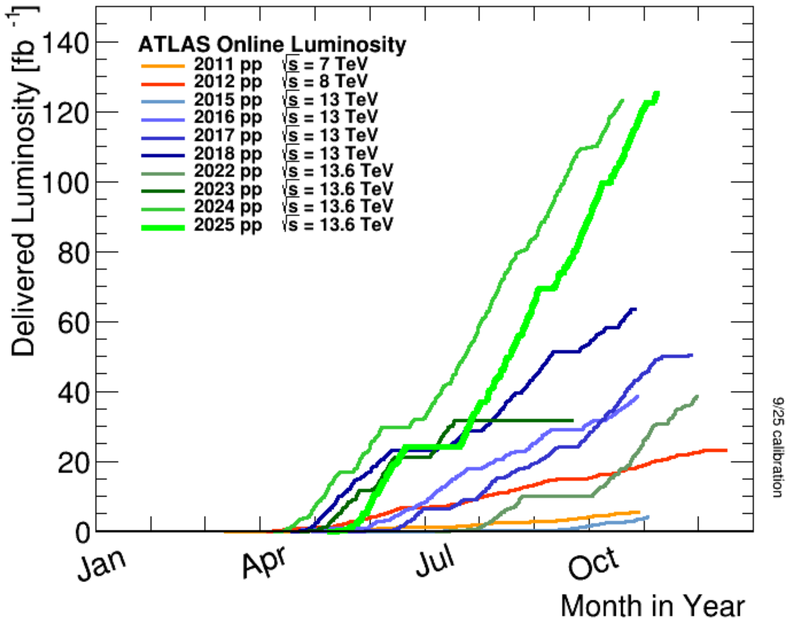
Still 10 times more statistics expected at HL-LHC!

More than 20 times more luminosity with the LHCb upgrade II

LHC Operations



2025 - High availability operation, Full mastery of considerable inherent operational risks, record luminosity!



- The Run 2 dataset surpassed the initial goal (in luminosity) of the LHC project and is a **clean and well calibrated dataset of ~140** fb^{-1} at 13 TeV

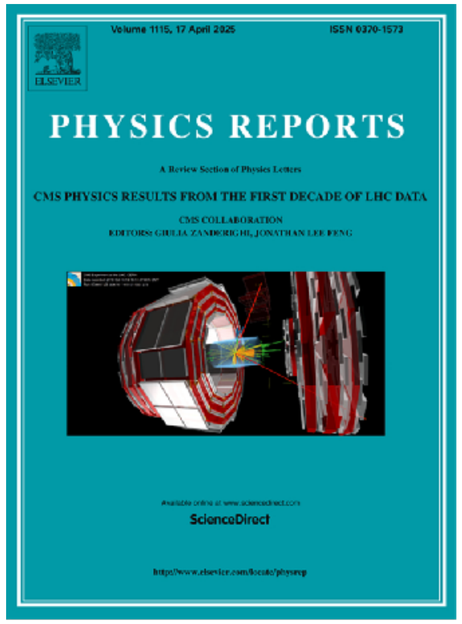
Most LHC results presented here are based on Run 2 data

- The Run 3 has ~320 fb^{-1} at 13.6 TeV en route towards **0.5** ab^{-1} (per experiment)

- Approximately x10 Luminosity **at HL-LHC (in terms of results x20). Requires major upgrades leading** to the High Luminosity during LS3 now on the horizon!

Even with the record luminosity in 2024 need more than 20 running years to achieve HL-LHC luminosity!

The LHC Run 2 Physics Program



ATLAS Phys. Rep. Link

1. Forward to the collection
2. Climbing to the Top
3. Electroweak, QCD and flavour physics
4. Characterising the Hihggs boson
5. Exotic Jungle Beyond the Standard Model
6. Additional scalars and exotic decays
7. The quest to discover supersymmetry

CMS Phys. Rep. Link

1. The Stairway to heaven
2. Stairway to discovery: cross section measurements
3. Review of top quark mass measurements
4. High density QCD
5. Searches for Higgs decays of heavy resonances
6. Dark sector searches
7. Vector like quarks, leptons and heavy neutral leptons
8. Searches through data scouting

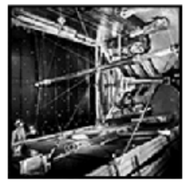
A collection of 14 Physics Reports - an overview of the LHC Run 2 results

FUNDAMENTAL PHYSICS
BREAKTHROUGH
PRIZE

ALICE Collaboration

ATLAS Collaboration

CMS Collaboration



LHCb Collaboration

The FCC-ee in a nutshell

Future collider projects covered by Nicolas and Taikan

Ultimate Precision and discovery potential

Goal Luminosity $144 \times 10^{34}\ cm^{-2}s^{-1}$

One LEP1 every few minutes !!!

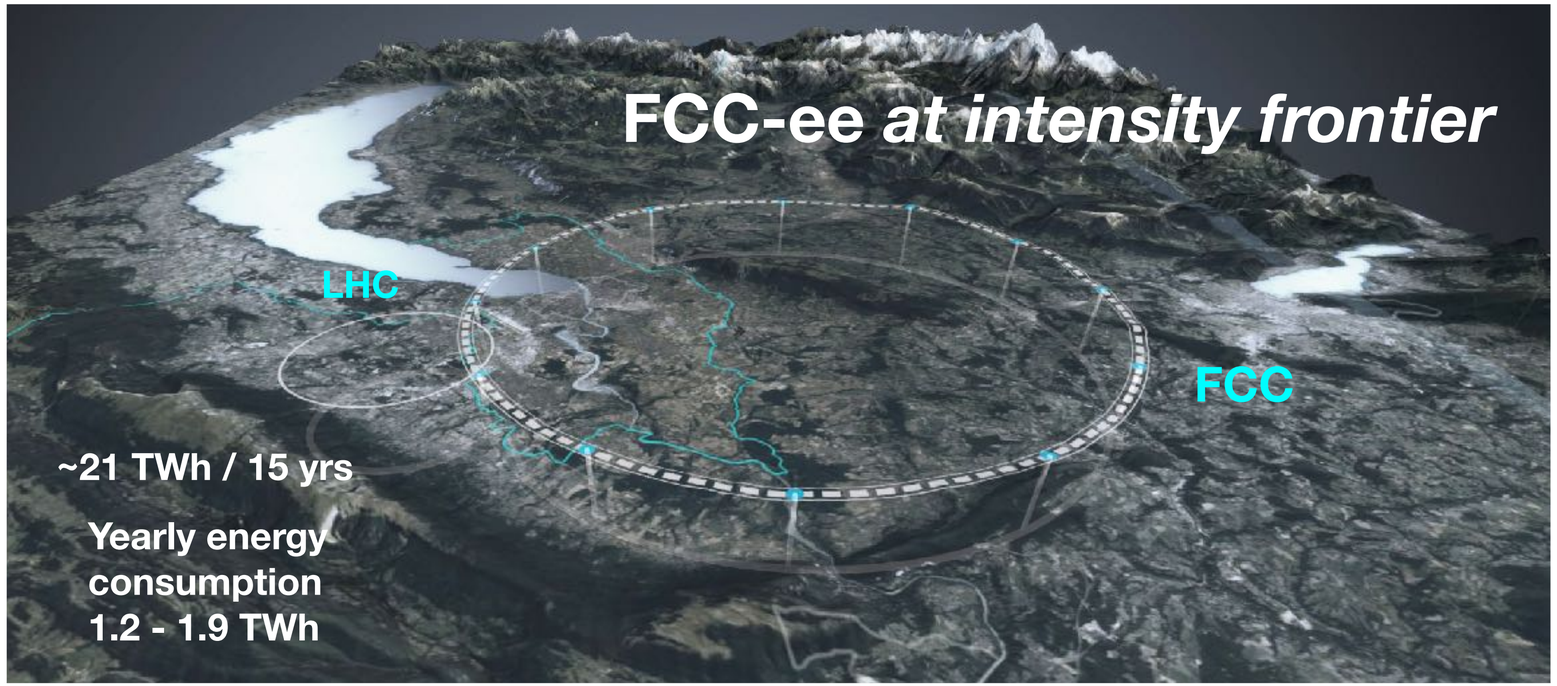
At the Z peak (per IP) - 4 IPs

Z, WW, ZH and $t\bar{t}$ COM energies

Continuous beams

No Pile Up

15 Years of operations



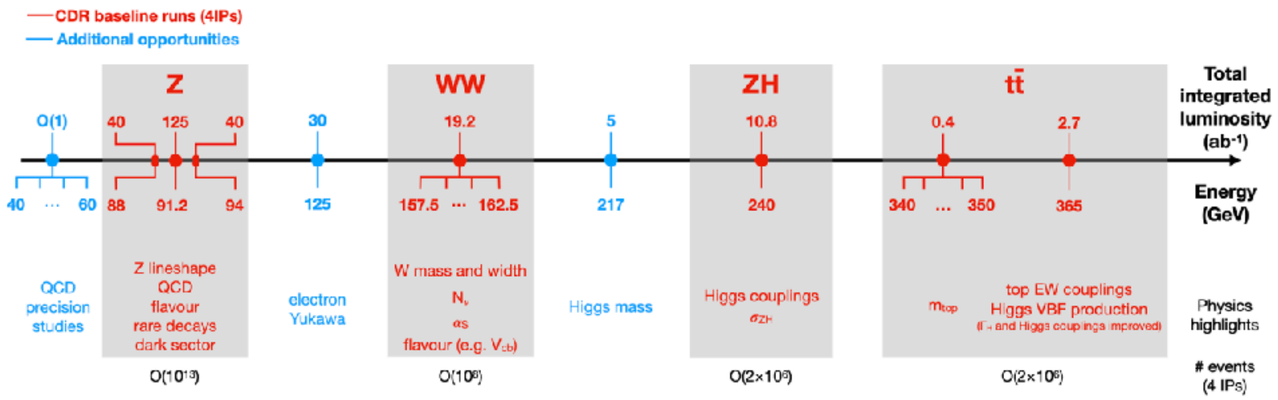
Targets to deliver

- **3 Million Higgs bosons**
- 2 Million top quarks
- 240 Million WW events
- 6 $\times 10^{12}$ Z bosons

In terms of B hadrons ~current LHCb statistic

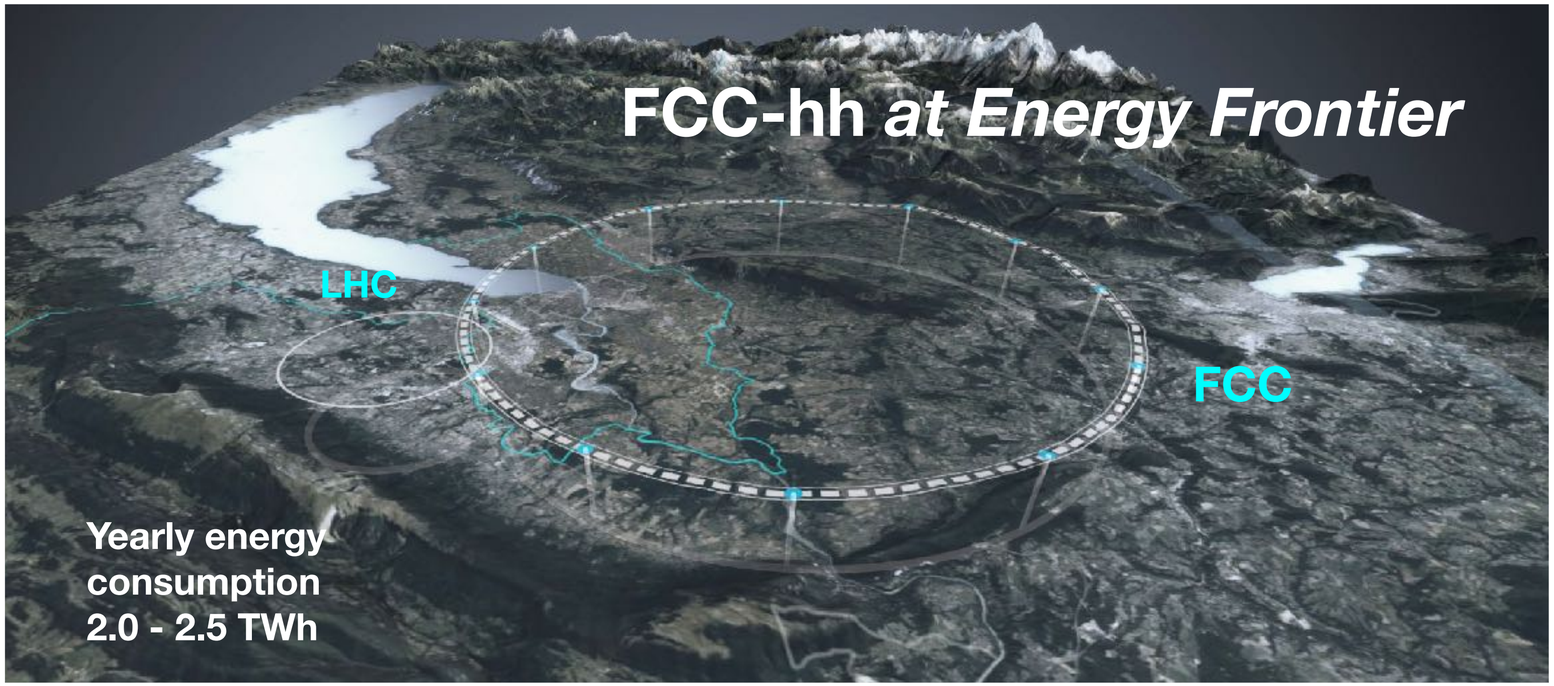
also 10 times the Belle II design statistics

All these events in a much cleaner environment!



"Quasi-total flexibility in the order of operation for all running

The FCC-hh in a nutshell



FCC-hh

Ultimate Energy Frontier

85 TeV (baseline COM energy)

Target luminosity $20\mathrm{ab}^{-1}$

14 T Nb_3Sn magnets

Luminosity $30 \times 10^{34}\ cm^{-2}s^{-1}$ - 4 IPs

PU / bunch crossing up to 1000!

Stored energy/beam 6.5 GJ (compared to 0.7 GJ at HL-LHC

25 Years of operations

Targets to deliver extraordinary statistics

- Over 25 Bilion Higgs bosons
- 1 Billion ttH
- 36 Million HH

Except for very specific cases the **FCC-hh 85 TeV with more luminosity has a similar reach as the 100 TeV**

Yearly electrical energy consumption

Magnet temperature **1.9 K <2.5 TWh**

4.5 K < 2.0 TWh

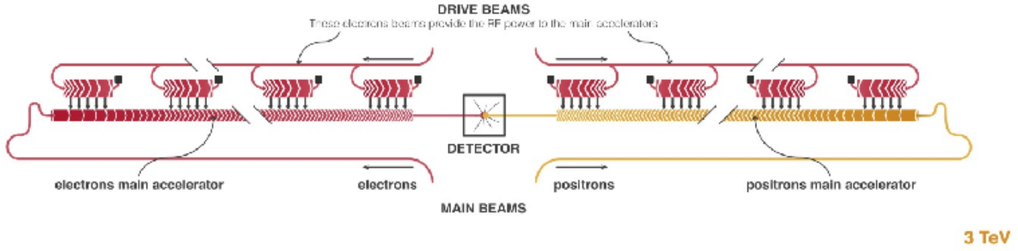
Major achievement!

… also an ion collider and possible forward physics facility

Other Possibilities at CERN that can start ~2045

Therefore does not include Muon collider - Focus on FCC-hh as next-stage collider

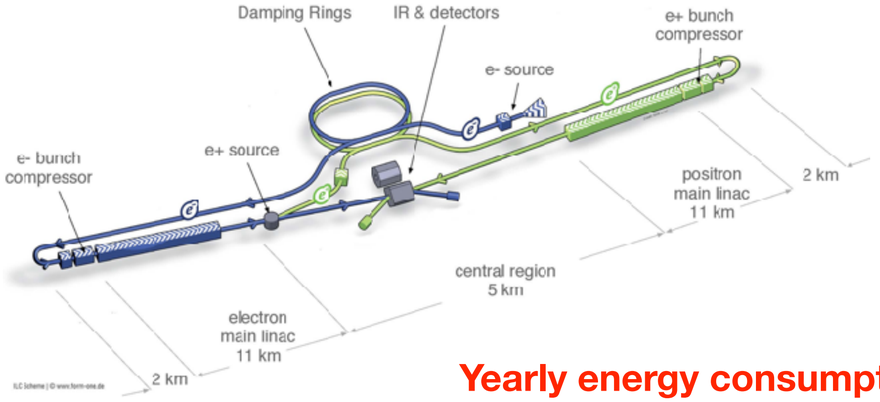
CLIC ~22 TWh



380 GeV (11.4 km - 2IP) - 1.5 TeV (29.6 km - 1IP)
L ~ 2.2 – 3.7 x 10^{34} cm^{-2} s^{-1} per IP

Yearly energy consumption 0.9 - 1.4 TWh (20 years)

LCF with ILC SRF technology ~26 TWh

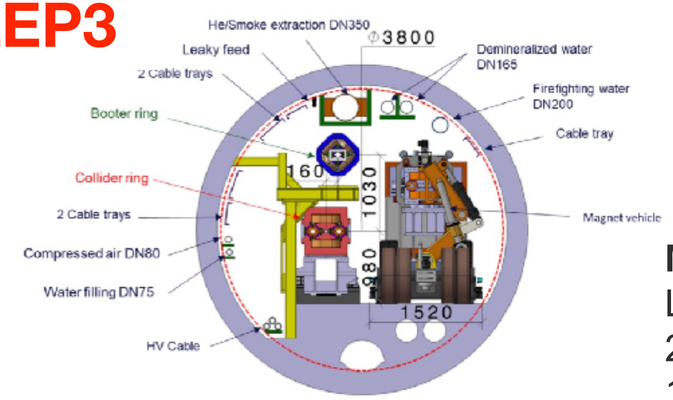


250 GeV - 550 GeV
(33.5 km - 2 IPs)
L ~ 1.3 – 3.8 x 10^{34} cm^{-2} s^{-1}
3 - 8 ab^{-1} at 250 - 550 GeV

Yearly energy consumption 0.8 - 1.8 TWh (19 years)

"Intermediate" projects towards next collider

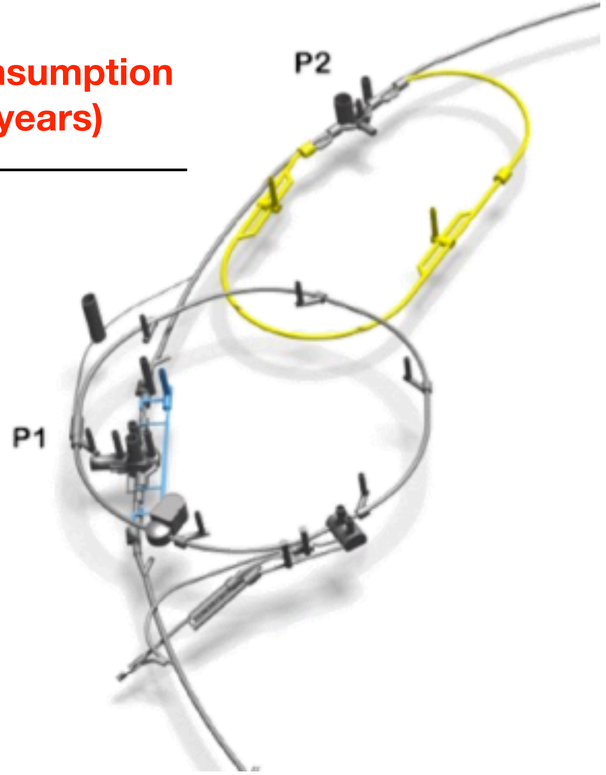
LEP3



Max 230 GeV, 2 IPs
L ~ 1.8 x 10^{34} cm^{-2} s^{-1}
2.6 ab^{-1} at HZ
15 years of OP

LHeC

e-p collisions at TeV
50 GeV e- from 8.9 km ERL
7 TeV p from LHC
L = 2.3 x 10^{34} cm^{-2} s^{-1}
1 ab^{-1} over 5 years of operation

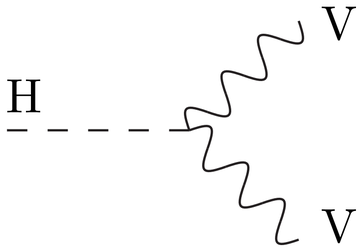


New Frontiers in Higgs Physics

Higgs Physics at LHC covered in detail by Gustaaf, Andrei and Yves

Pillars of Higgs Physics at Colliders

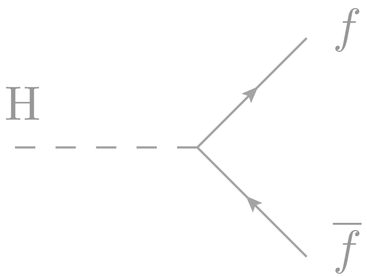
All couplings of the Higgs boson to Standard Model particles (except itself) known before the discovery of the Higgs boson! A very predictive model!



$$\frac{2m_V^2}{v}$$

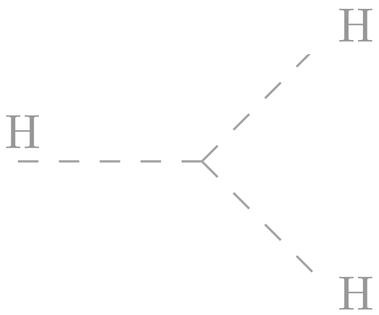
$$|D_\mu \phi|^2$$

This term could not exist without a vev

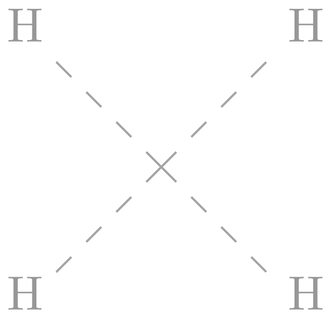


$$\frac{m_f}{v}$$

$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



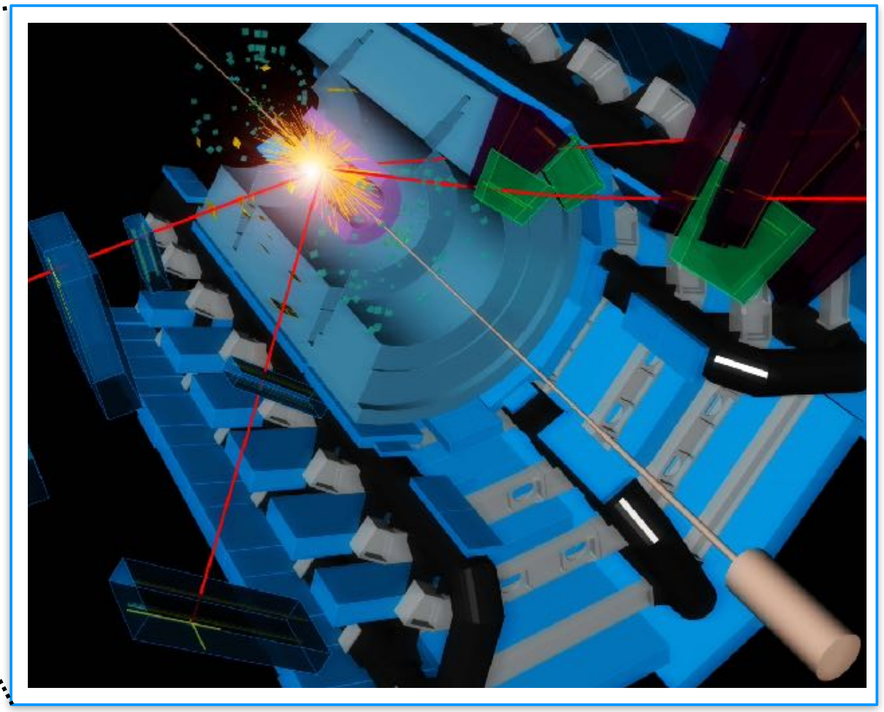
$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Four lepton events can have s/b of up to ~30!



Proof of the existence of a condensate!

$\kappa_{W,Z}$	Current 6%

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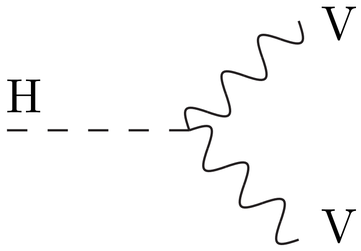

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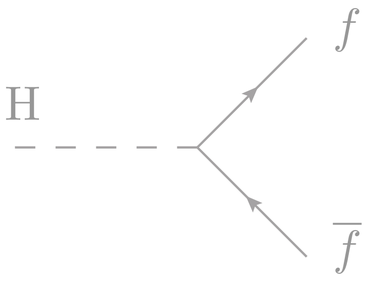

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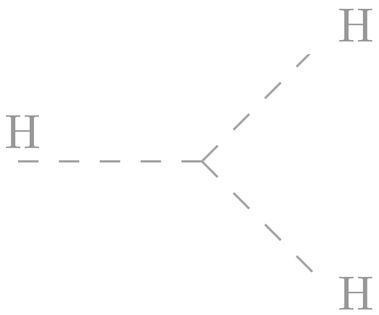

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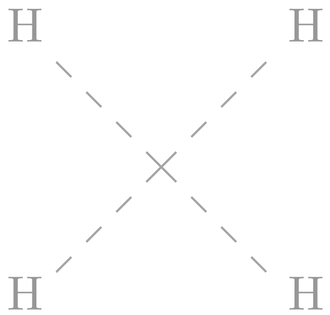

$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Most precisely known Higgs coupling tells us how elementary the Higgs boson is!

...or what its effective size is!

Comparing the **Compton radius** of the Higgs $1/m_H$ to its **effective radius** $1/f_H$ through the higher order operator:

$$\frac{c_H}{f_H^2} \cdot \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \to \left(\frac{2c_H v^2}{f_H^2}\right) \cdot \frac{1}{2}\left(\partial_\mu h\right)^2$$

(as comparing the mass of the pion to that of the ρ meson)

Current precision $f_H > 1$ TeV

The Higgs could well be a pNGB as the pion!

SILH Giudice, Grojean, Pomarol, Rattazzi (See paper)

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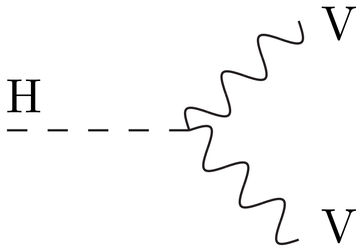
All couplings of the Higgs boson to Standard Model particles (except itself) known before the discovery of the Higgs boson! A very predictive model!



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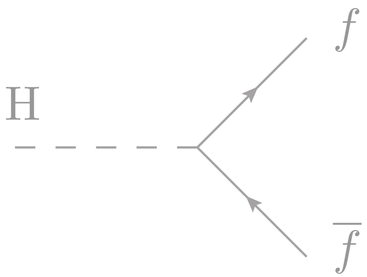

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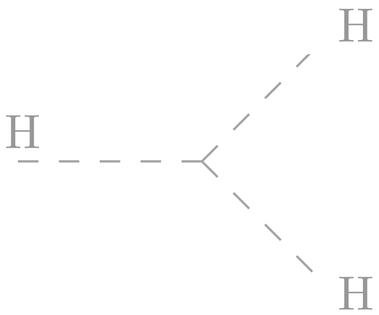

$$\frac{3m_H^2}{v} \qquad \frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Most precisely known Higgs coupling tells us how elementary the Higgs boson is!

...or what its effective size is!

Comparing the **Compton radius** of the Higgs $1/m_H$ to its **effective radius** $1/f_H$ through the higher order operator:

	Current*	HL-LHC*	FCC (ee)
$\kappa_{W,Z}$	6%	1.6%	0.1%

*No BSM Br

15 times more precise!

Will yield $f_H > 8$ TeV

Nearly 50 x Higgs Compton radius!

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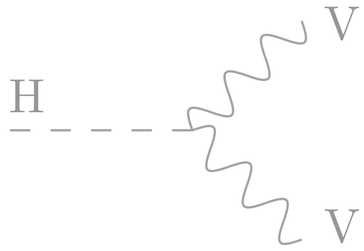

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$$|D_\mu \phi|^2$$

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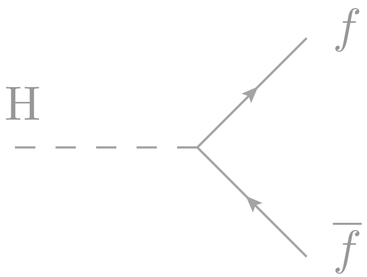

$$\frac{m_f}{v}$$

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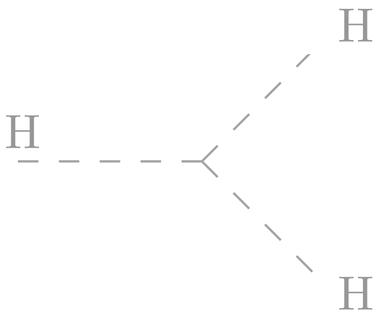
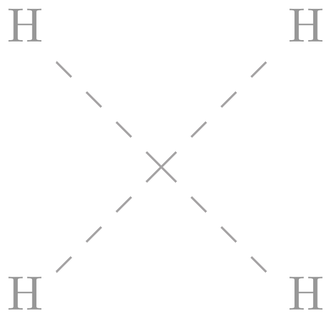


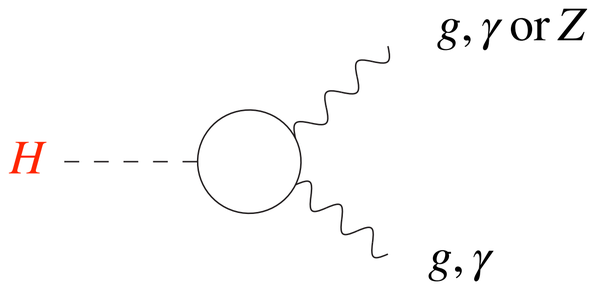
$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Probing new particles through loops in production and decays!



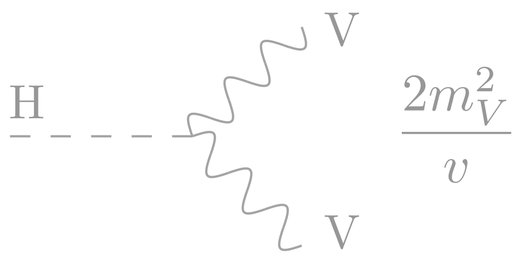
	Current*	HL-LHC*	FCC (ee)	FCC (ee/hh)
κ_γ	6%	1.8%	1.1%	0.3%
κ_g	7%	2.4%	0.5%	0.4%
$\kappa_{Z\gamma}$	30%	6.8%	4.3%	0.7%

Also $\gamma\gamma^*$

*No BSM Br

Pillars of Higgs Physics at Colliders

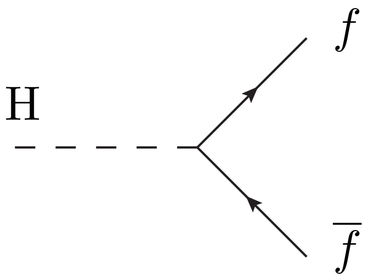
All couplings of the Higgs boson to Standard Model particles (except itself) known before the discovery of the Higgs boson! A very predictive model!



$$\frac{2m_V^2}{v}$$

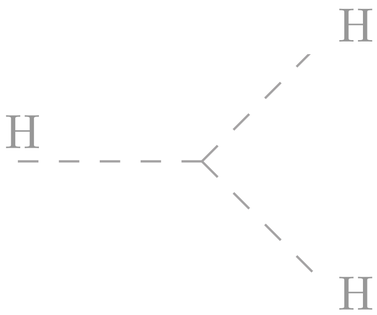
$$|D_\mu \phi|^2$$

This term could not exist without a vev

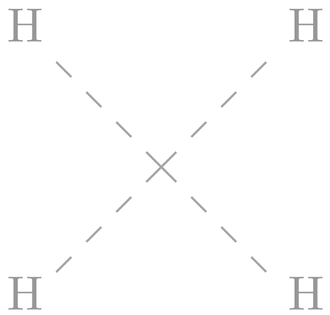


$$\frac{m_f}{v}$$

$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

	Current*	HL-LHC*	FCC (ee)	FCC (ee-hh)
κ_t				
κ_b	11%	3.6%	0.5%	0.5%
κ_τ	8%	1.9%	0.5%	
κ_μ	20%	3.0%	3.3%	0.4%

*No BSM Br

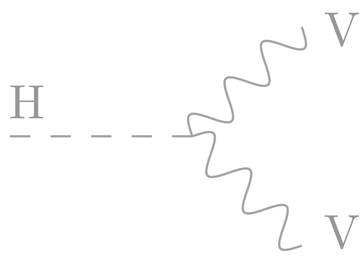
20 times more precise!

"LEP changed high-energy physics from a 10% to a 1% science." It was a major achievement! (H. Schopper CERN Courier)

What about the other fermion generations?

Pillars of Higgs Physics at Colliders

All couplings of the Higgs boson to Standard Model particles (except itself) known before the discovery of the Higgs boson! A very predictive model!



$$\frac{2m_V^2}{v}$$

$$|D_\mu \phi|^2$$

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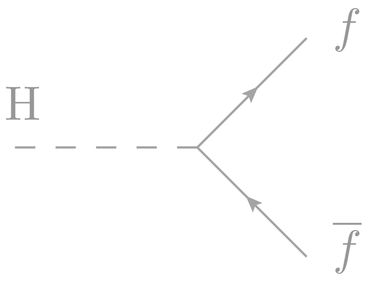
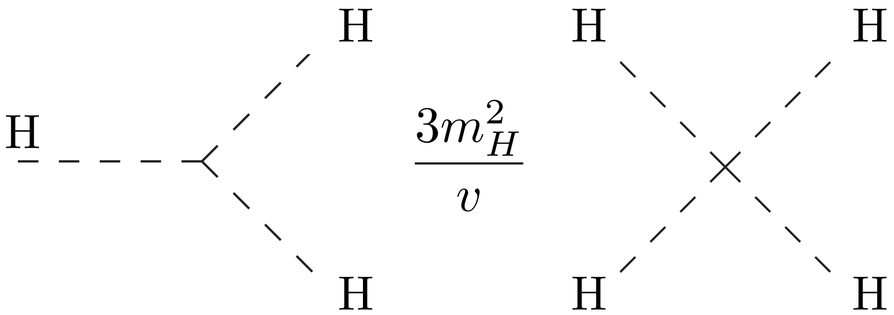


$$\frac{m_f}{v}$$

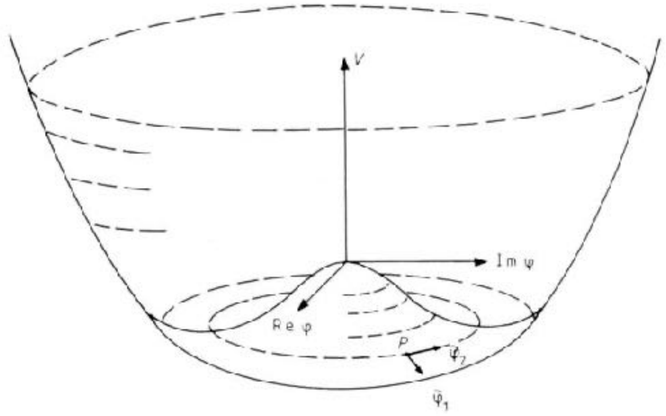
$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



$$\frac{3m_H^2}{v} \qquad \frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Spontaneous Symmetry Breaking

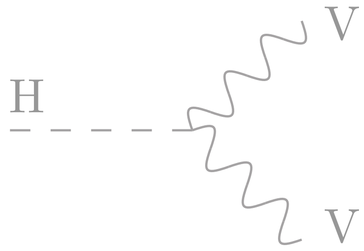


$$V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2$$

In the Standard Model the self coupling is fixed by the Higgs boson mass.

Pillars of Higgs Physics at Colliders

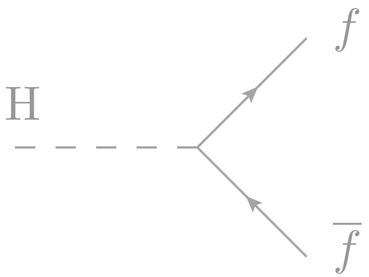
All couplings of the Higgs boson to Standard Model particles (except itself) known before the discovery of the Higgs boson! A very predictive model!



$$\frac{2m_V^2}{v}$$

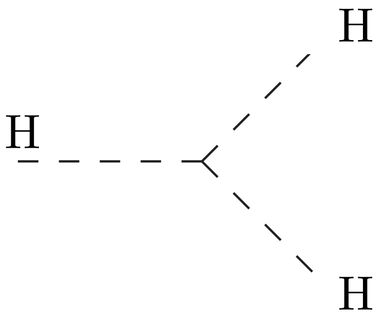
$$|D_\mu \phi|^2$$

This term could not exist without a vev

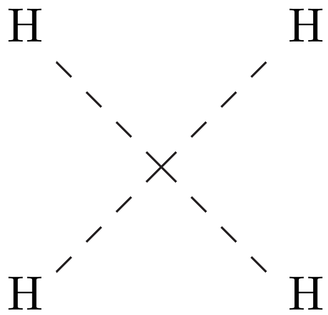


$$\frac{m_f}{v}$$

$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



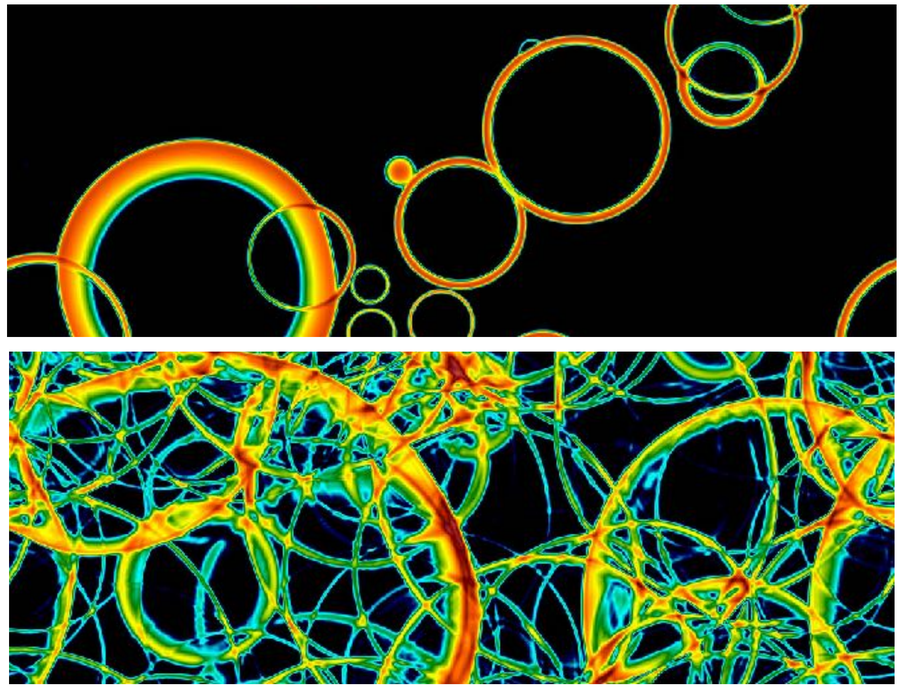
$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Early universe phase transition?



Generation of stochastic background of gravitational waves

In the SM EW transition is a **cross over** does not fulfil requirements for **baryogengesis**, studying the Higgs potential is an outstanding goal of the Higgs physics program

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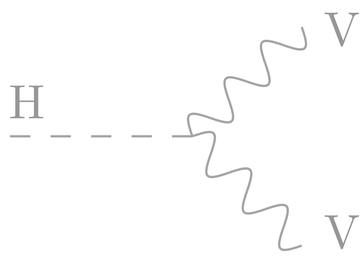

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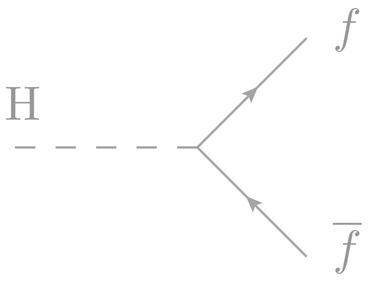

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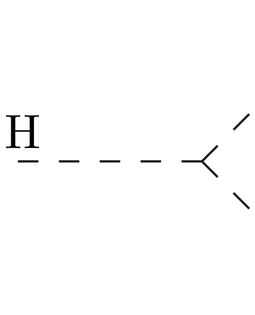
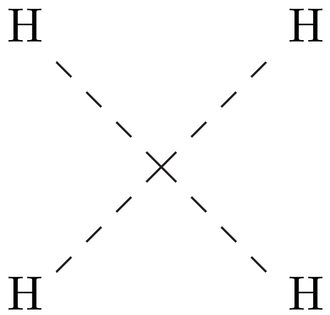


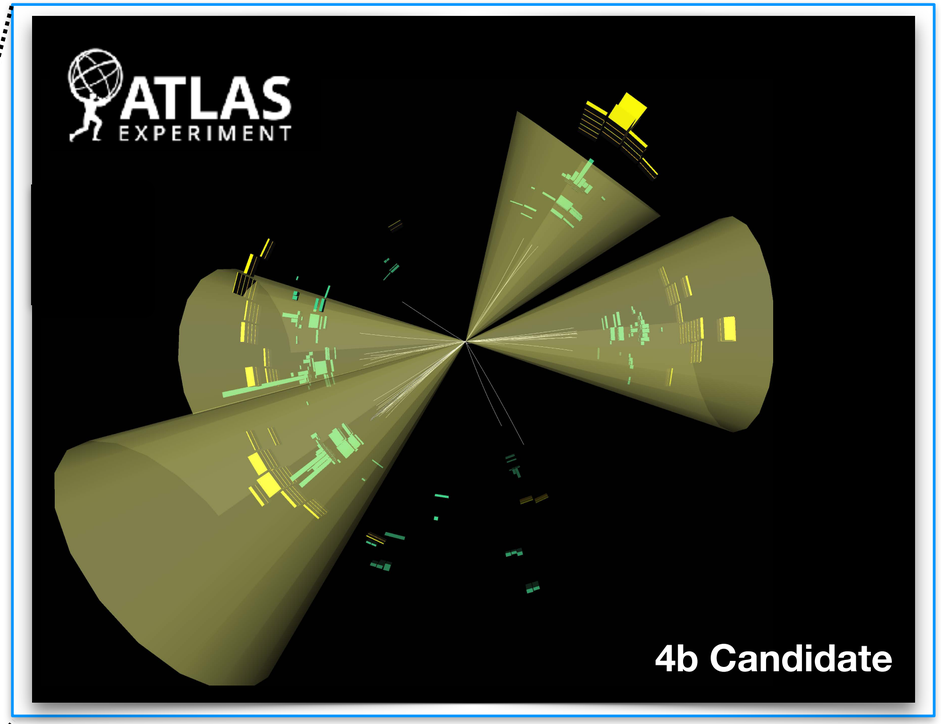
$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

LHC Signatures in HH production



~1000 times smaller than Higgs production! Still more than 100k event will be produced at HL-LHC!

Multiple channels investigated: depending on the both Higgs decays considering (bb, $\gamma\gamma$, $\tau^+\tau^-$, WW)

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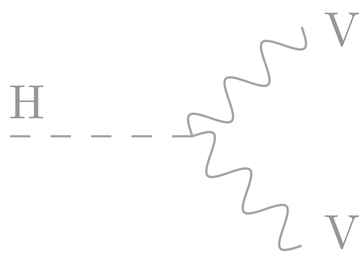

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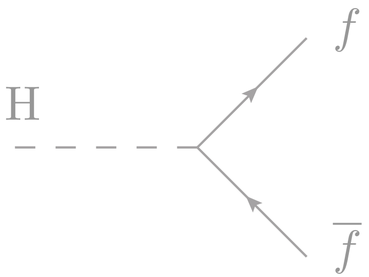
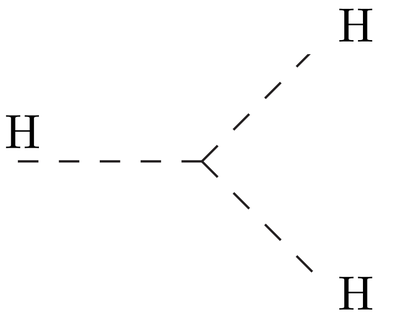


$$\frac{m_f}{v}$$

$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



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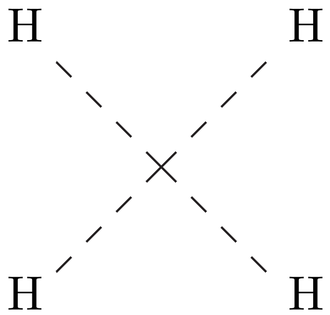
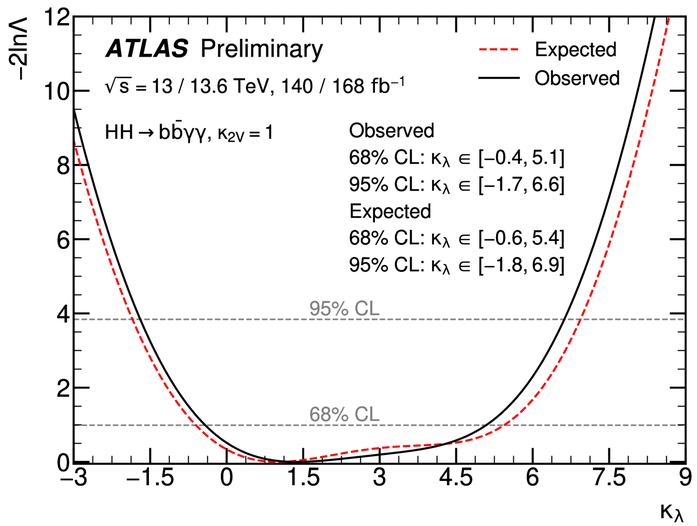


$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

LHC $b\bar{b}\gamma\gamma$ result Run 2 - Run 3

Similar sensitivity as Run 2 Combination



Sensitivity: $\mu_{HH} = 1.0^{+1.3}_{-1.0}$

Observed: $\mu_{HH} = 0.9^{+1.3}_{-1.0}\ (\text{stat})\ ^{+0.6}_{-0.5}\ (\text{syst})$

Run 2 Combination ~1σ sensitivity to a signal (Obs. ATLAS 0.4σ and CMS ~1σ)

Run 3 close 2.5 σ with improvements (and as much data as possible) **aim at 3σ**

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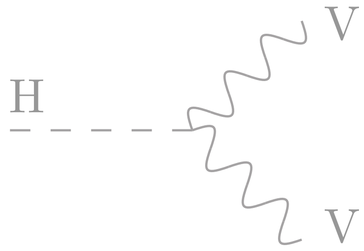
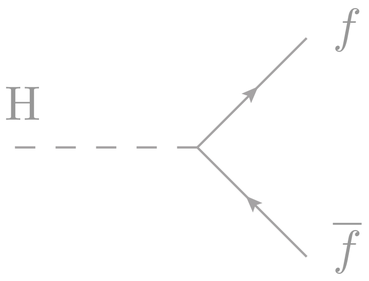


$$\frac{2m_V^2}{v}$$

$$|D_\mu \phi|^2$$

This term could not exist without a vev



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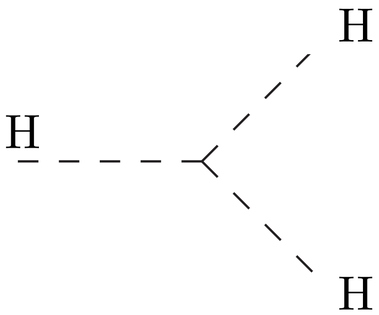

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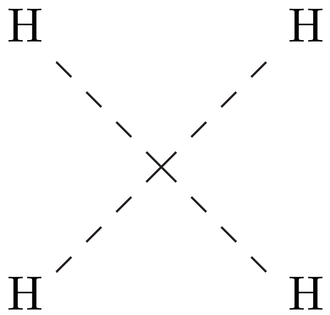
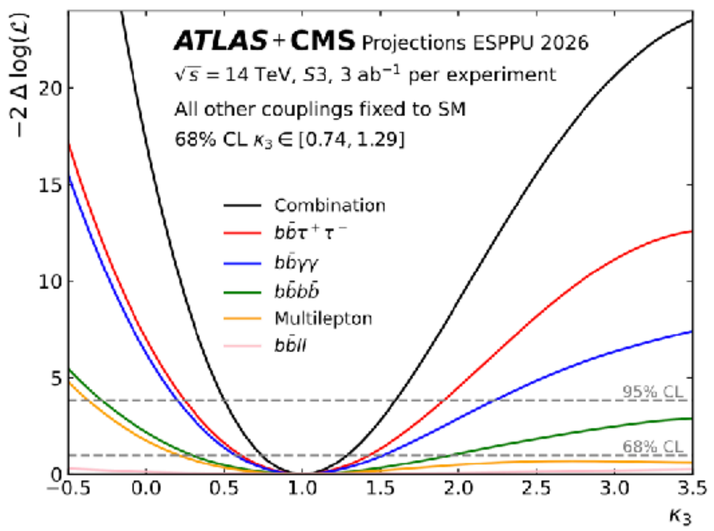


$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

HL-LHC Projections



HH ~4.5σ sensitivity/Exp

7.6σ in combination!

κ_λ of $^{+29\%}_{-26\%}$

FCC-ee (loop level) : 27% - 18% (combined w/ HL-LHC)

ILC (500 - 1TeV) direct : 10% - 20% (depending on lumi)

FCC-hh direct : **2-3%**

10 times more precise!

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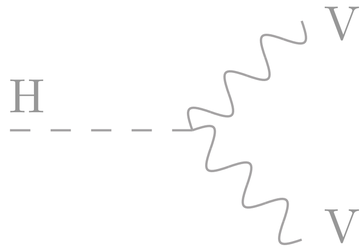

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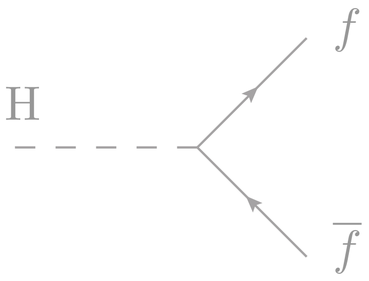
This term could not exist without a vev



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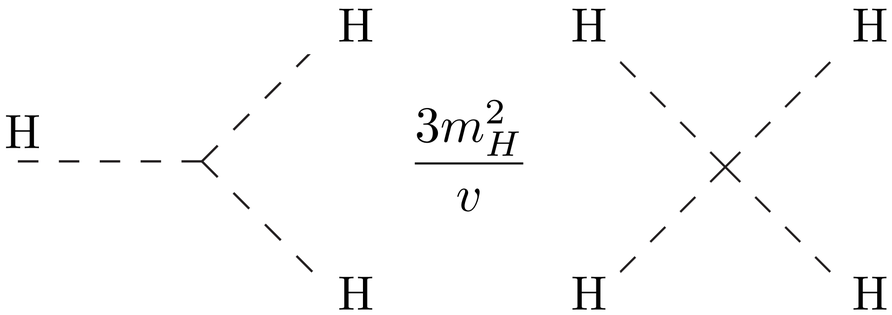
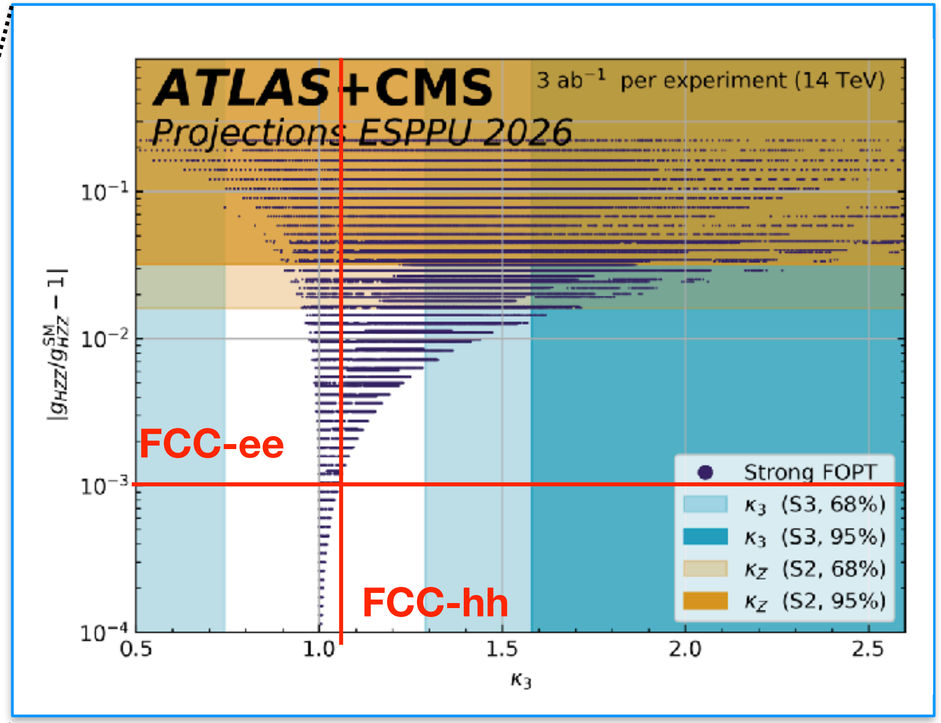


$$\frac{3m_H^2}{v} \qquad \frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Models of Phase Transition

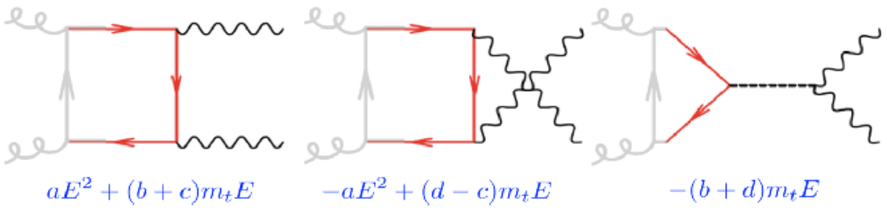


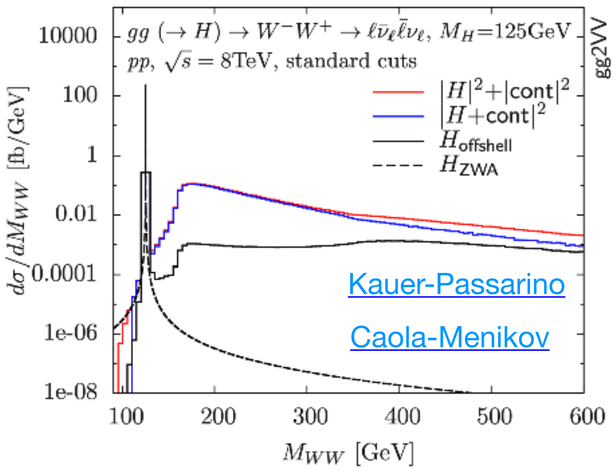
FCC will be decisive (also see that the most precisely known coupling is setting stringent limits)

Making the Impossible - The Higgs Width

At the LHC : Higgs width via the Higgs as a propagator!

From J. Campbell





ATLAS Result

$$\Gamma_H = 4.3^{+2.7}_{-1.9}\ \text{MeV}$$

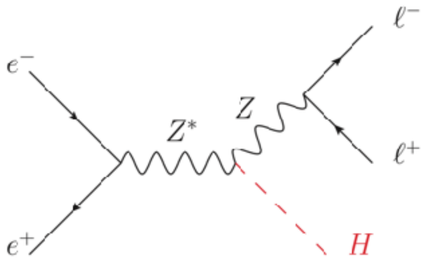
CMS Result

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

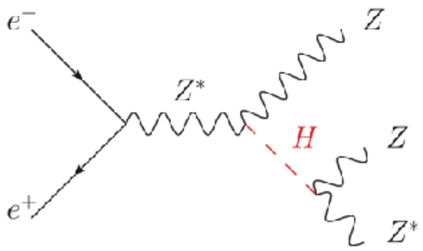
Evidence for Off-Shell production at more than 3σ both experiments

HL-LHC $\Gamma_H = 4.1^{+1.0}_{-1.1}$ $\Delta\Gamma_H = 25\,\%$

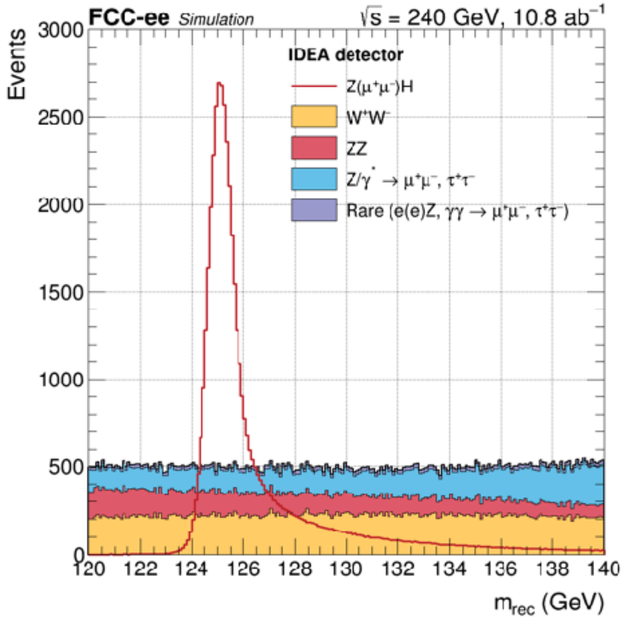
FCC-ee



$$\sigma(e^+e^- \to HZ) \propto \kappa_Z^2$$



$$\sigma(e^+e^- \to HZ) \times B(H \to ZZ^*) \propto \frac{\kappa_Z^4}{\Gamma_H}$$



Access to the ZH total cross section through the recoil mass!

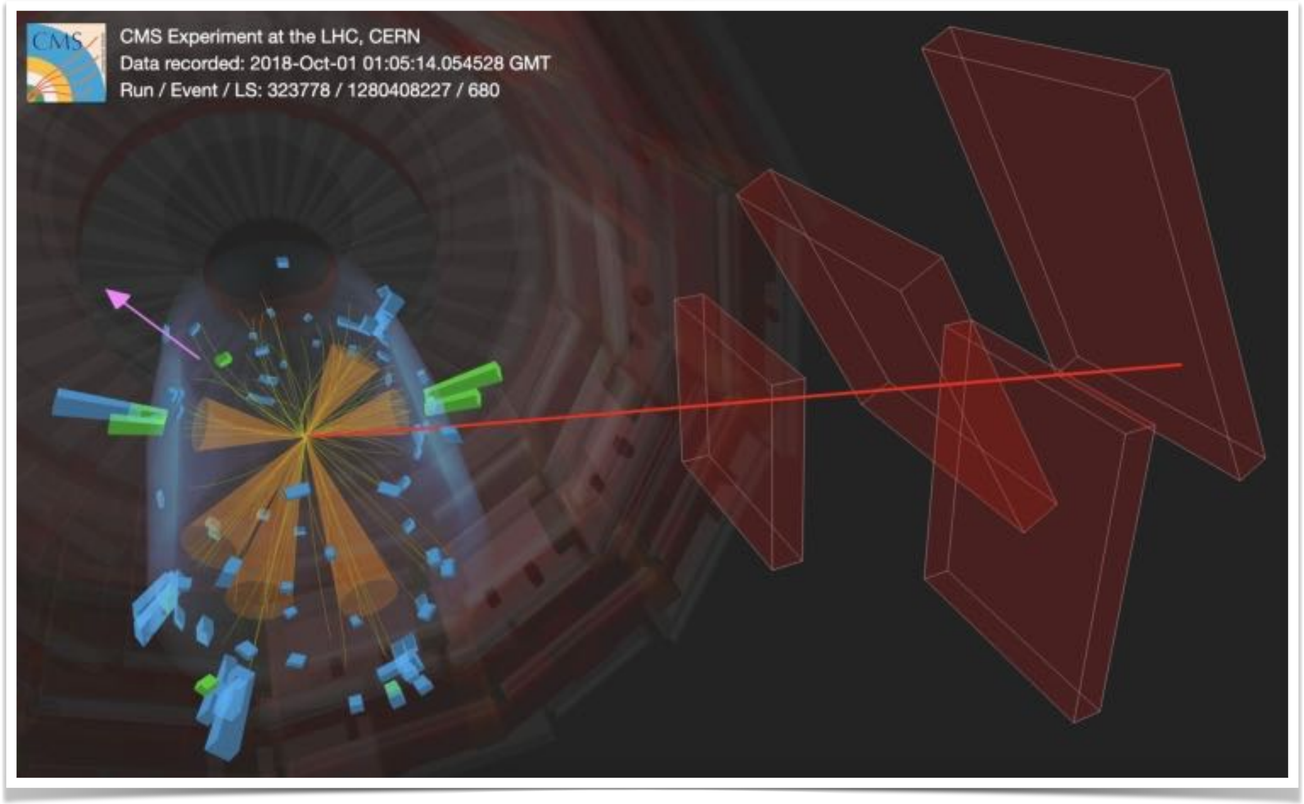
$$\Delta\Gamma_H = 0.78\,\%$$

30 times more precise!

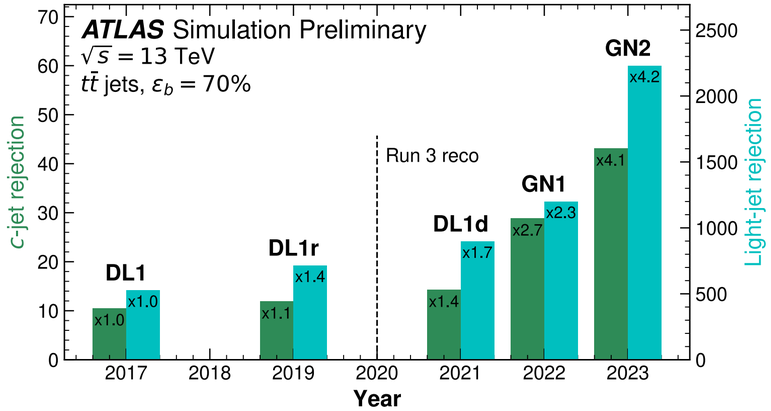
Very important precise estimate to access absolute couplings!

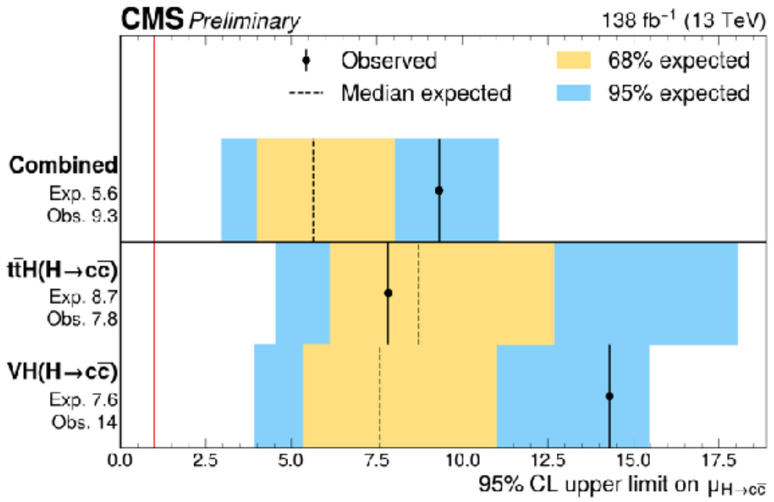
Making the Impossible - the Charm Yukawa

"Topping up the charming the Higgs" at the LHC? Link



Particular success in flavour tagging





VH only precision on κ_c of ~40% per experiment at HL-LHC

New perspective at the LHC!

At the FCC-ee κ_c ~0.9%

40 times more precise!

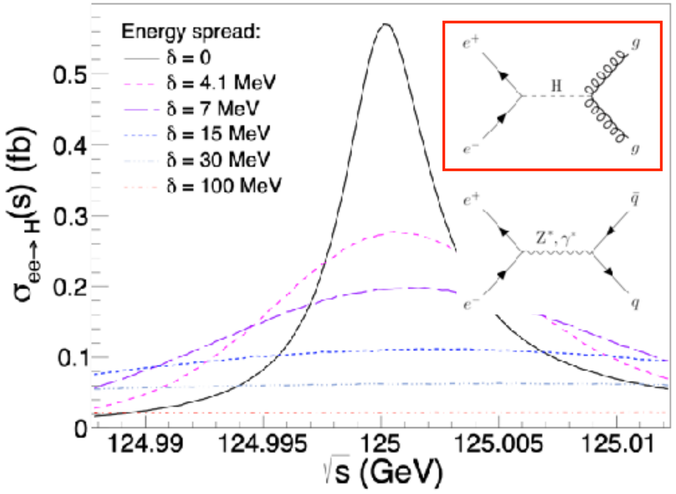
Beyond the Impossible

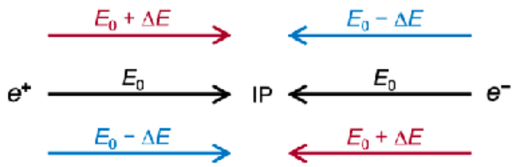
Extremely challenging e-Yukawa requires

1.- Very high luminosity $\sigma(ee \to H) = 1.6 \text{ fb}$

2.- **monochromatization** (Beam spread ~ 100 MeV)

- Requires a prior knowledge of the Higgs boson mass of ~couple of MeV at most!





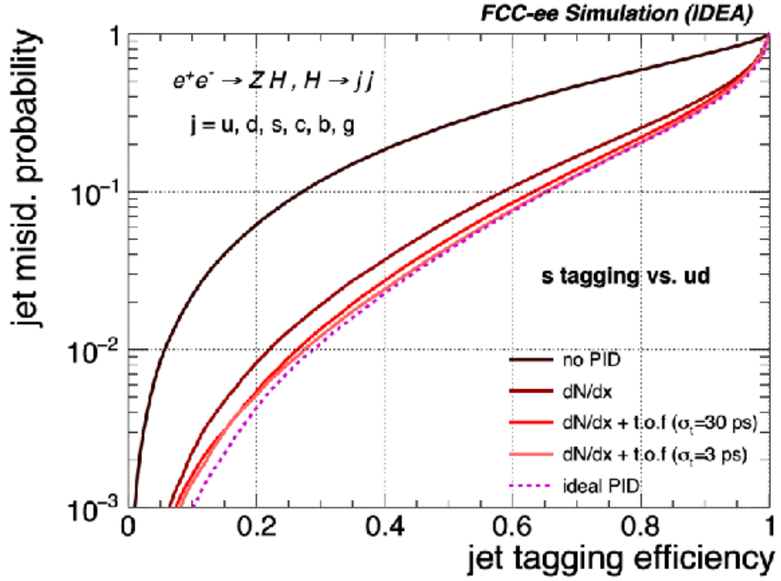
Opposite correlation between spatial position and energy.

First studies indicate a sensitivity of 0.4σ for a year in one detector

Strange Yukawa coupling

- DL tagging algorithm

- PID is essential (using number of ionisation clusters per unit length (dN/dx) in IDEA drift chamber or TOF)



First studies indicate a sensitivity of ~100% on strange Yukawa

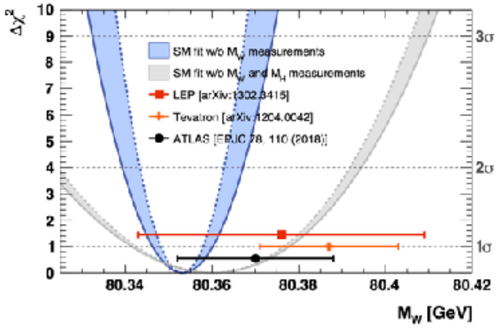
Kaon PID and Strange tagging can also be used for HF measurements or top e.g. V_{ts} from rare $t \to Ws$ decay

Ultimate Precision from the LHC to FCC

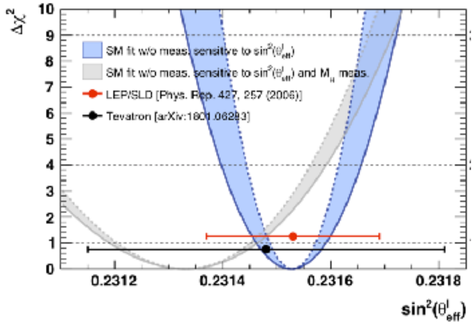
EWK measurements at LHC covered in detail by Gustaaf, Andrei and Yves

Flavor physics at LHCb covered by Serguey, ATLAS and CMS by Sally and Riccardo and at Belle II (super KEK B) by Yuji (detectors) and Michele.

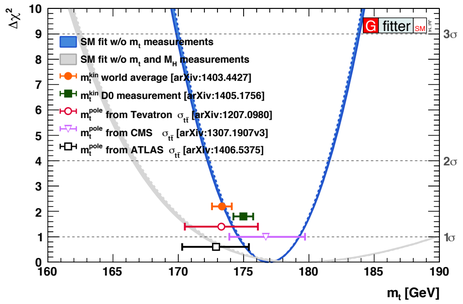
ΔPred. ~ 7 MeV ΔMeas. ~ 10 MeV



ΔPred. ~ 1.5×10^{-4} ΔMeas. ~ 7×10^{-4}



ΔPred. ~ 1.3% ΔMeas. ~0.2%

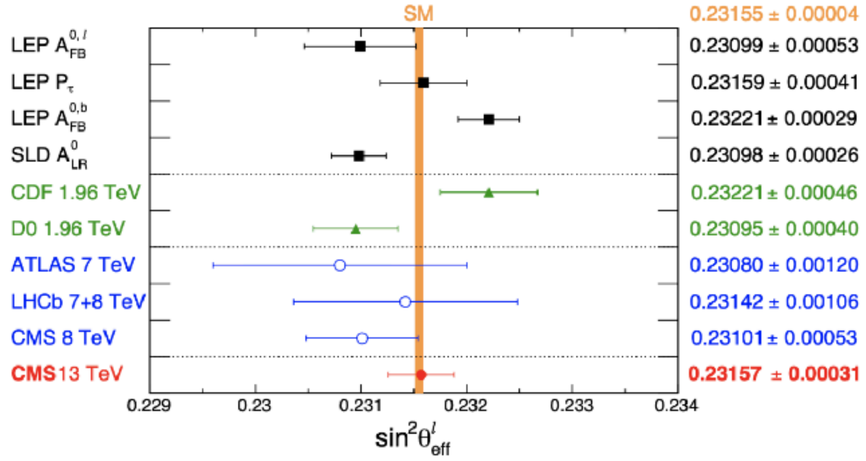


Precision EW fits have (and have had) a **huge predictive power**: top mass, the Higgs boson mass, as well as to some extent the absence of BSM physics at the LHC!

LHC Outstanding Achievements in Precision

Measurements of $\sin^2\theta_W$

Measuring the fully differential $pp \to Z \to \mu^+\mu^-$ cross section yields the weak mixing angle (mainly through A_{FB})



Precision	ATLAS	CMS	LHCb	W.A. (w/o LHC)
	0.16%	**0.13%**	0.21%	0.07%

Precision approaching that of LEP A_{FB}^b and SLD A_{LR}

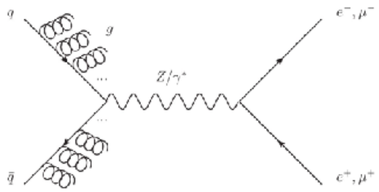
At FCC-ee

Precision 0.0007% (7×10^{-6})

200 times more precise!

From $A_{FB}^{\mu\mu}$ (Syst dominated by beam energy calibration)

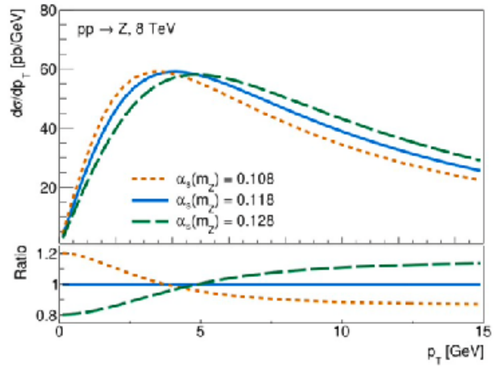
The least known coupling in the SM α_S

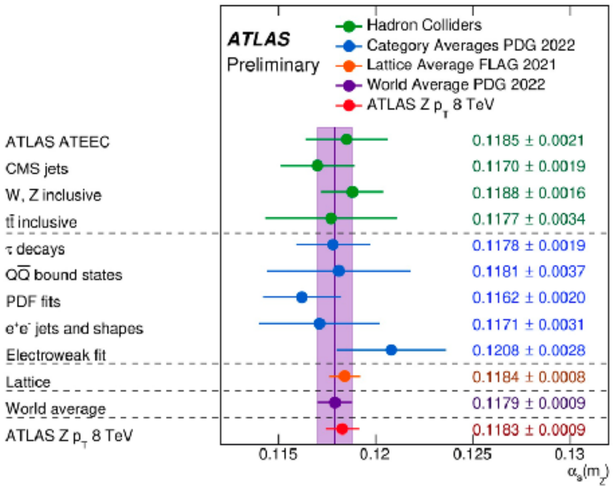


Inclusive Z transverse momentum

$$\frac{d\sigma_Z}{\sigma_z dp_\perp} \sim \frac{\alpha_s(p_\perp)}{2\pi p_\perp} \ln \frac{M_Z}{p_\perp}$$

Using **Sudakof peak in pT**, based on **resummed calculations**





0.9% Precision on par with lattice QCD and world average!

At FCC-ee

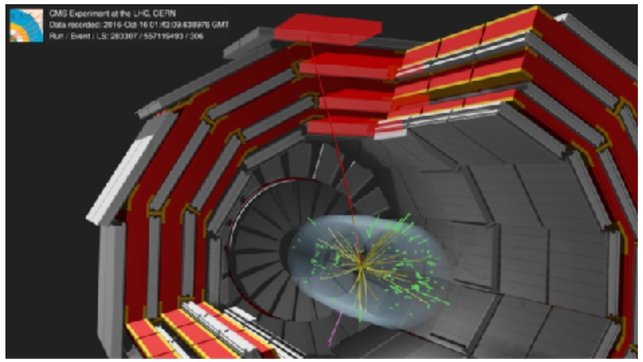
Precision 0.1% (0.01% stat)

10 times more precise!

From $R_\ell^Z, \Gamma^Z, \sigma_{\rm had}^0$ syst dominated by TH

$$\Gamma_{\rm had} = \Gamma_{\rm had,\,no\,QCD}\left(1 + \frac{\alpha_s}{\pi} + \ldots\right)$$

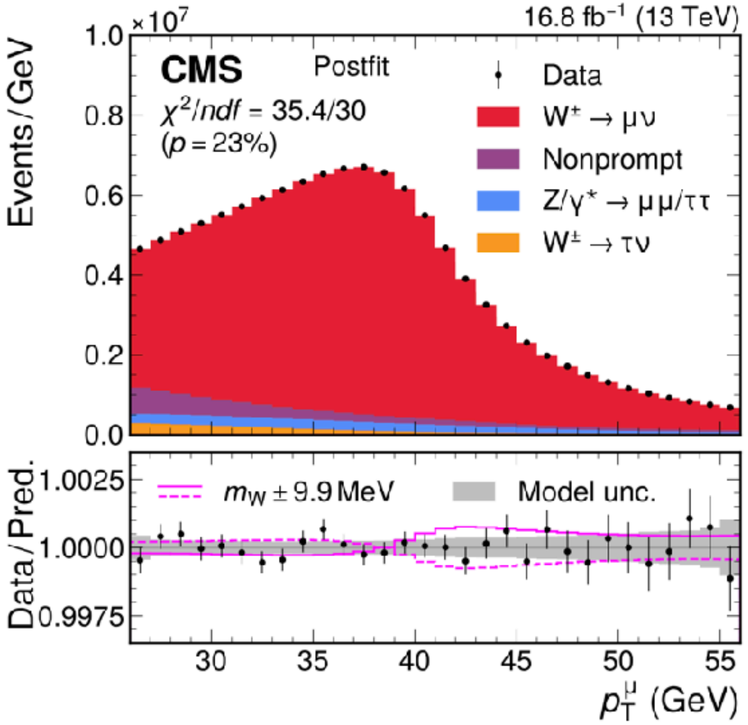
W Mass - Measurements and Puzzle

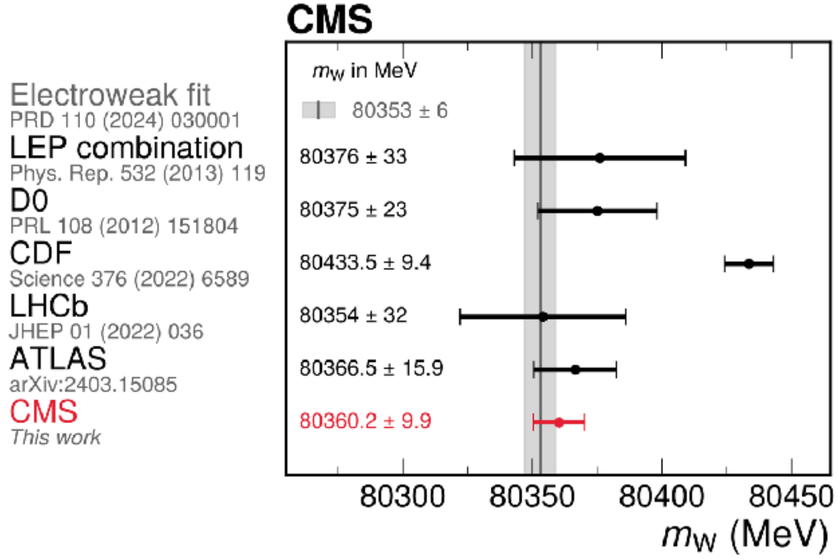


CMS Measurements of W mass

CMS briefing

Also in ATLAS and LHCb





At FCC-ee

Precision 240 keV

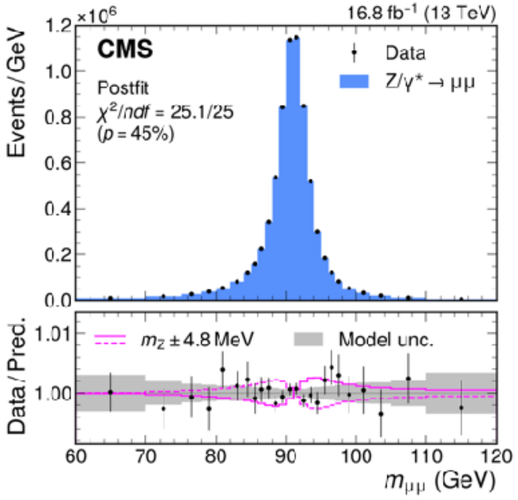
40 times more precise!

From WW threshold stat and syst on par (syst dominated by beam energy)

Z Mass Measurements at the LHC

Z mass from di-muon mass by CMS

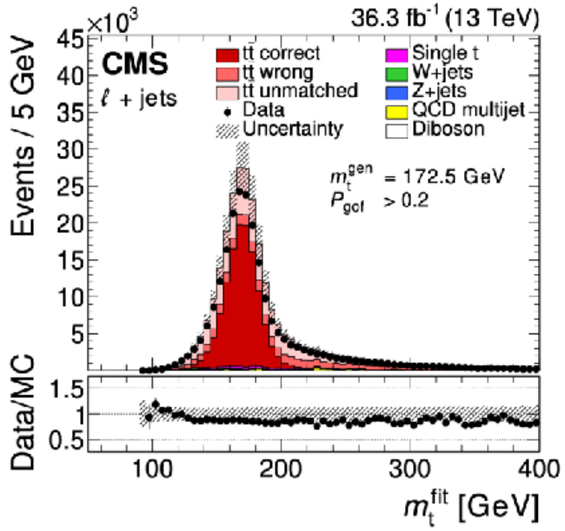
Calibration using J/Psi and Upsilon



Powerful validation of the muon momentum scale and thus the W mass measurement.

$$m_Z^{\mu\mu} - m_Z^{\mathrm{PDG}} = -2.2 \pm 4.8\,\mathrm{MeV}$$

Most precise individual direct top mass measurement



Measurement on **partial Run 2 dataset** in the lepton-jets topology.

$$m_{\mathrm{top}} = 171.77 \pm 0.37\,\mathrm{GeV}$$

Many more top mass measurements

At FCC-ee

Precision **100 keV (4 keV stat)**

From Z line shape entirely dominated by beam energy syst.

Beam energy with resonant depolarisation is key!

20 times more precise w.r.t. LEP!

LHC combination

$$m_{\mathrm{top}} = 172.52 \pm 0.14\,(\mathrm{stat}) \pm 0.30\,(\mathrm{syst})\,\mathrm{GeV}$$

Also slight tension with **Tevatron** measurements

$$174.34 \pm 0.37\,(stat) \pm 0.52\,(syst)$$

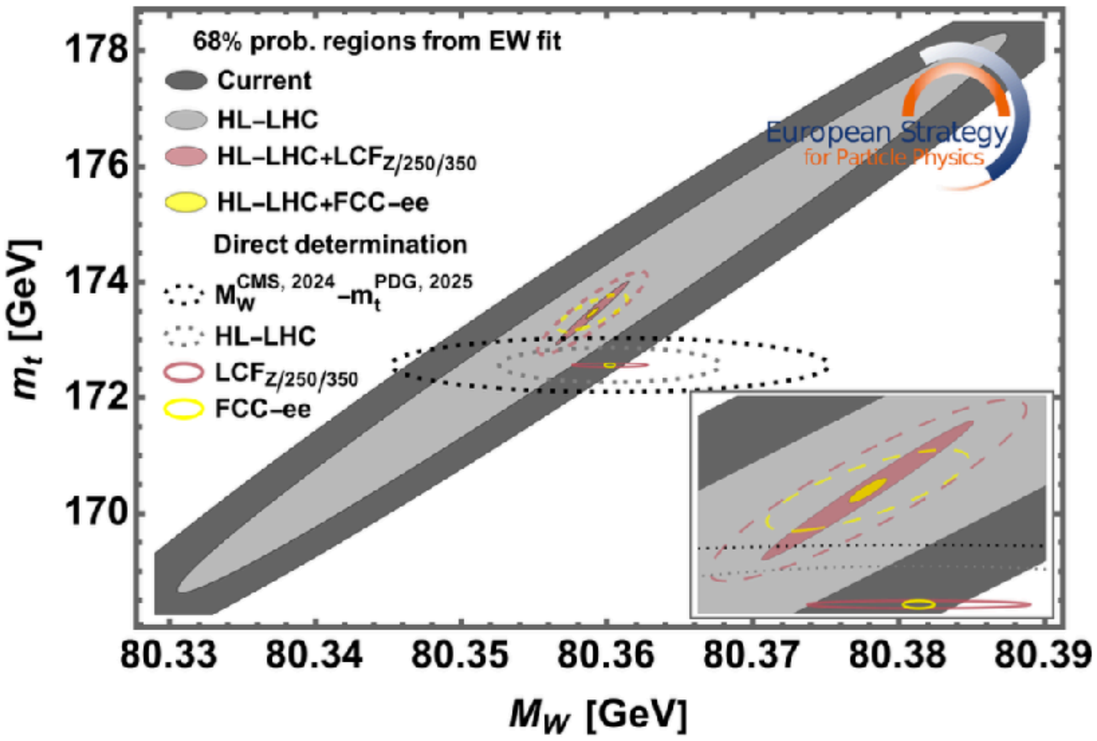
EW Fit and Bottleneck $\alpha_{em}(m_Z)$

At FCC-ee

Precision 4.2 MeV (stat) and 4.9 MeV (syst) !!

From Ztt threshold, QCD uncertainties are dominant

50x improvement w.r.t. LHC

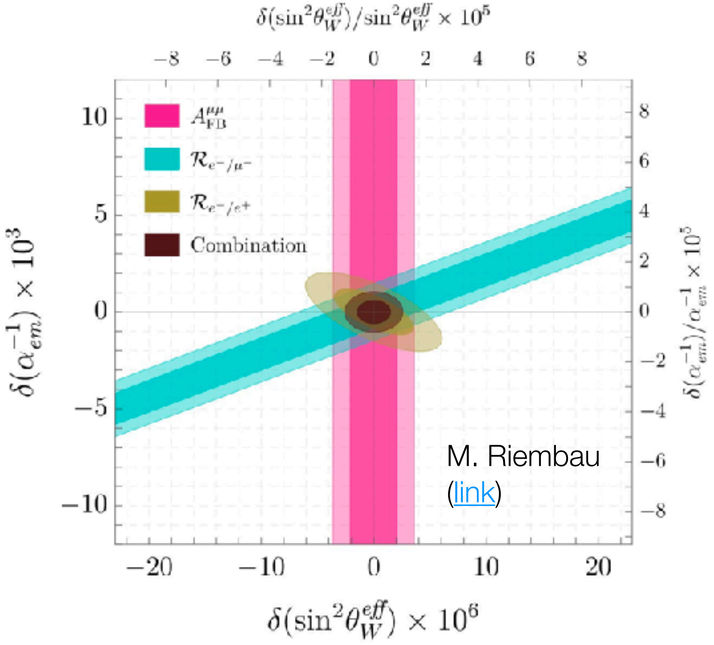


α_{em} **at low energy is very precisely known:**

$$\alpha = 1/137.035999679(94) \quad 10^{-9}$$

Electron magnetic moment and quantum Hall effect

Extrapolation at mZ degrades to 10^{-4} **bottleneck for Tera Z**



$$\mathcal{R}_{e^-/e^+}(\theta) = \frac{\sigma(e^-e^+ \to e^-(\theta) + X)}{\sigma(e^-e^+ \to e^+(\theta) + X)}$$

Simple observable sensitive to diffs. Photon and Z pole

First idea to take $A_{FB}^{\mu\mu}$ off peak (P. Janot, 2016)

Precision below 10^{-5} !

No longer a bottleneck, if statistical precision achieved.

e^+e^- Ultimate Precision Machine!!

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
N_ν($\times 10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2)$ ($\times 10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit
N_ν ($\times 10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		±	30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run

FCC-ee is much, much more than a Higgs factory!

Superb precision achieved and uncertainties are dominated by systematic uncertainties!

- **x50-2000*** Improvement on all EW observables
- Up to x30-100 improvement on Higgs observables

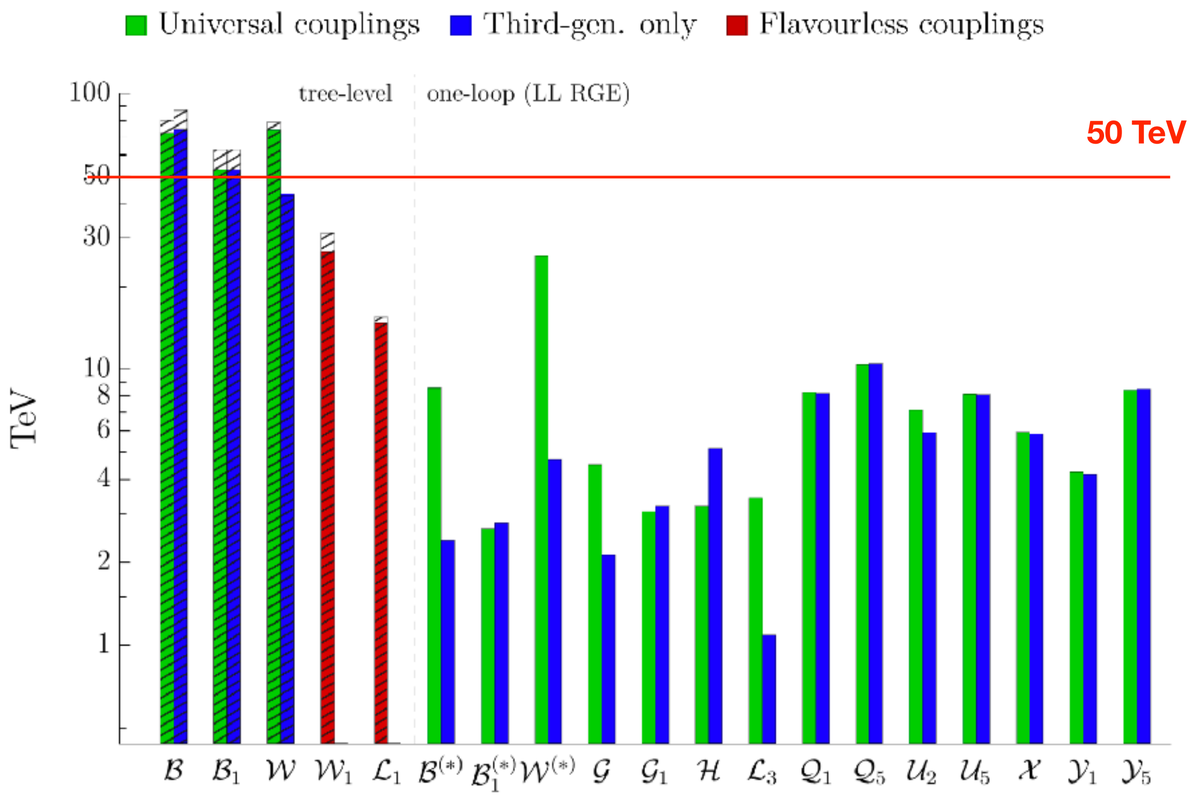
*In the case of Rb!

Beyond EW Fit - Sensitivity to Heavy New Physics

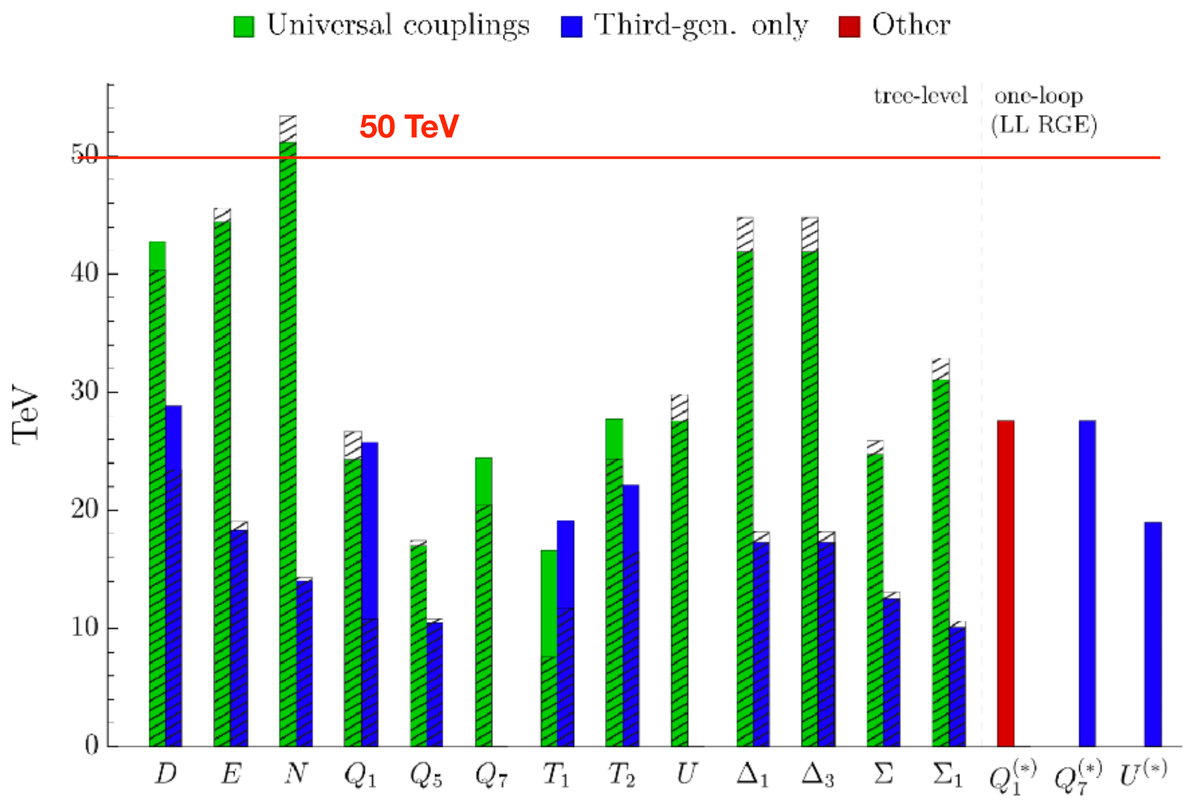
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Using an effective description of general extensions of the Standard Model, with a complete description in terms of possible new states (famous Granada dictionary)!

Allwicher, McCullough, Renner Link



Vector bosons



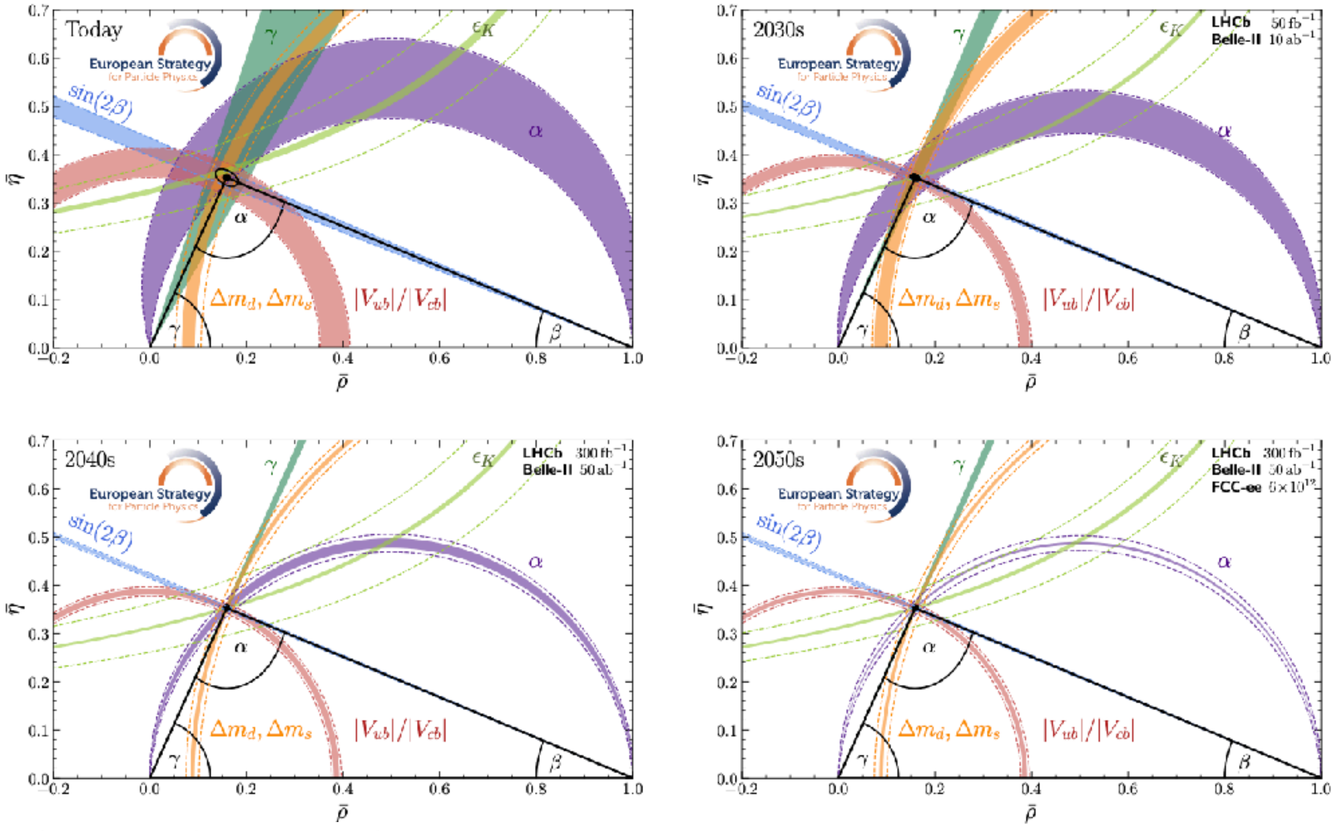
Fermions

Q1 couples only
to right-handed top quarks

Precision Heavy Flavour Physics and Rare Decays

LHCb underwent a major upgrade during LS2 and plans an upgrade for LS4 (in 2034)

LHCb highlights: The most precise measurement of the CKM angle β, excellent measurements of γ, best measurement of ϕ_s in Bs decays, CPV in baryonic decays and with charm mesons, and Vub/Vcb.

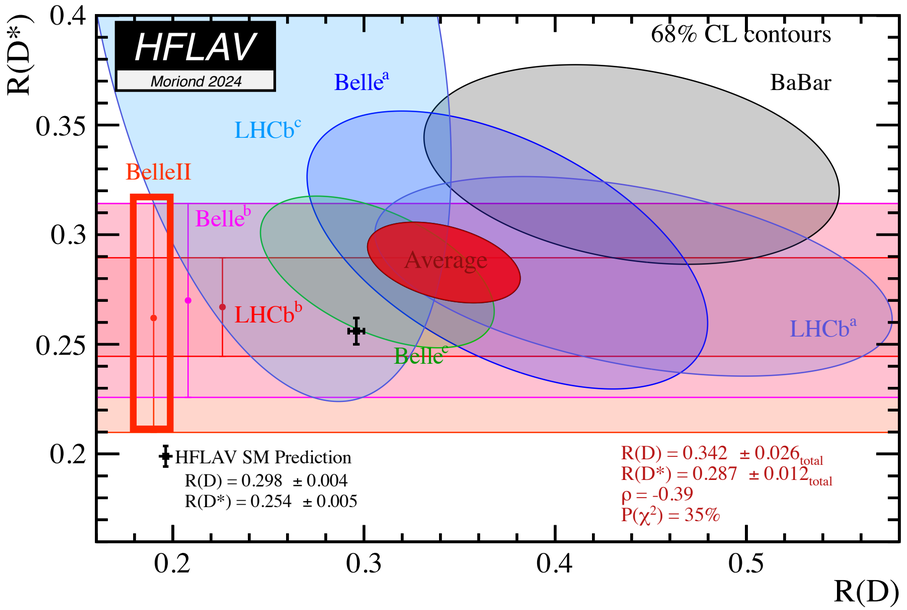


$(\phi_2, \phi_1, \phi_3) \equiv (\alpha, \beta, \gamma)$

LFU : Recent Belle II RD* measurement!

Both TH and EXP clean!

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}\left(B^0 \to D^{(*)-}\tau^+\nu_\tau\right)}{\mathcal{B}\left(B^0 \to D^{(*)-}\mu^+\nu_\mu\right)}$$



$$R_D^* = 0.26 \pm 0.04^{+0.04}_{-0.03}$$

Still tension at the ~3.3σ level

Precision Heavy Flavour Physics and Rare Decays

FCC-ee combines the advantages of the LHCb ($pp \to bbX$) and Belle II ($e^+e^- \to \Upsilon(4s) \to b\bar{b}$)

Attribute	Υ(4S)	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

← But enormous Lumi

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200

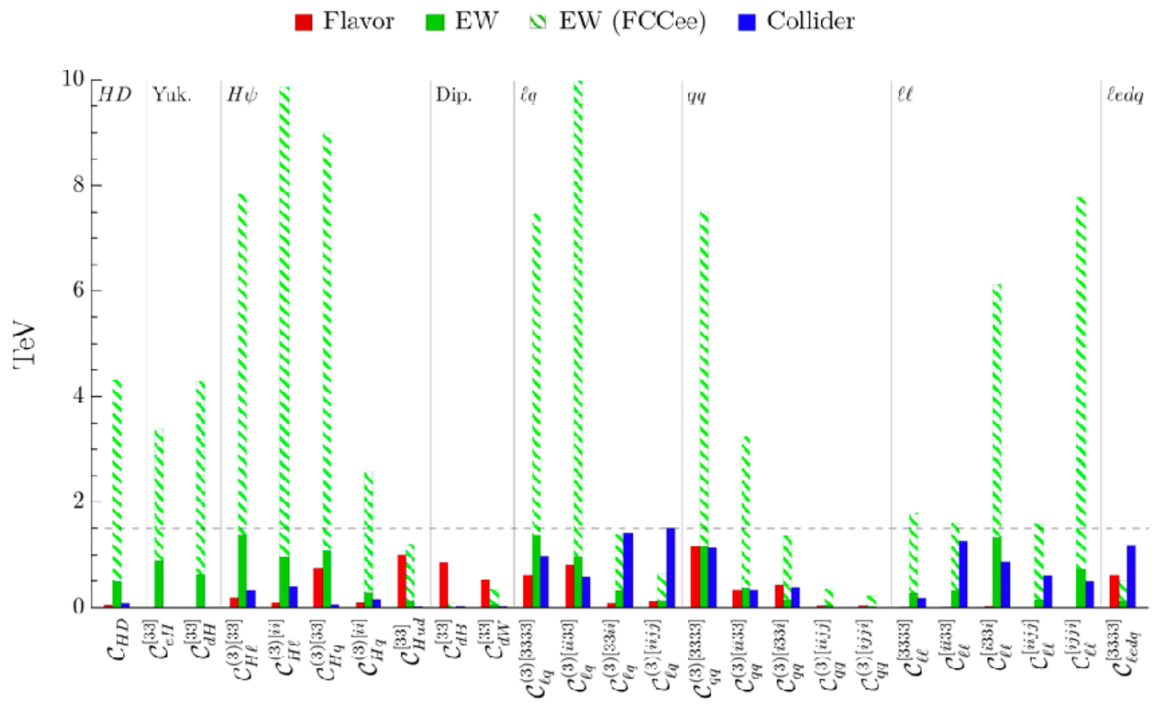
… and of course clean environment with high tagging power and ~10 times more bb and cc pairs than the total collected by Belle II!

- Will yield ultimate precision on CKM measurements
- In general formidable CP-violating observables in b- and c-hadron decays involving neutral particles in the final states

$$+ \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Higgs couplings are not universal, new physics solving Higgs issues **likely not to be universal!**

Non universal couplings yield w deaker constraints, **still x10 improvement!**



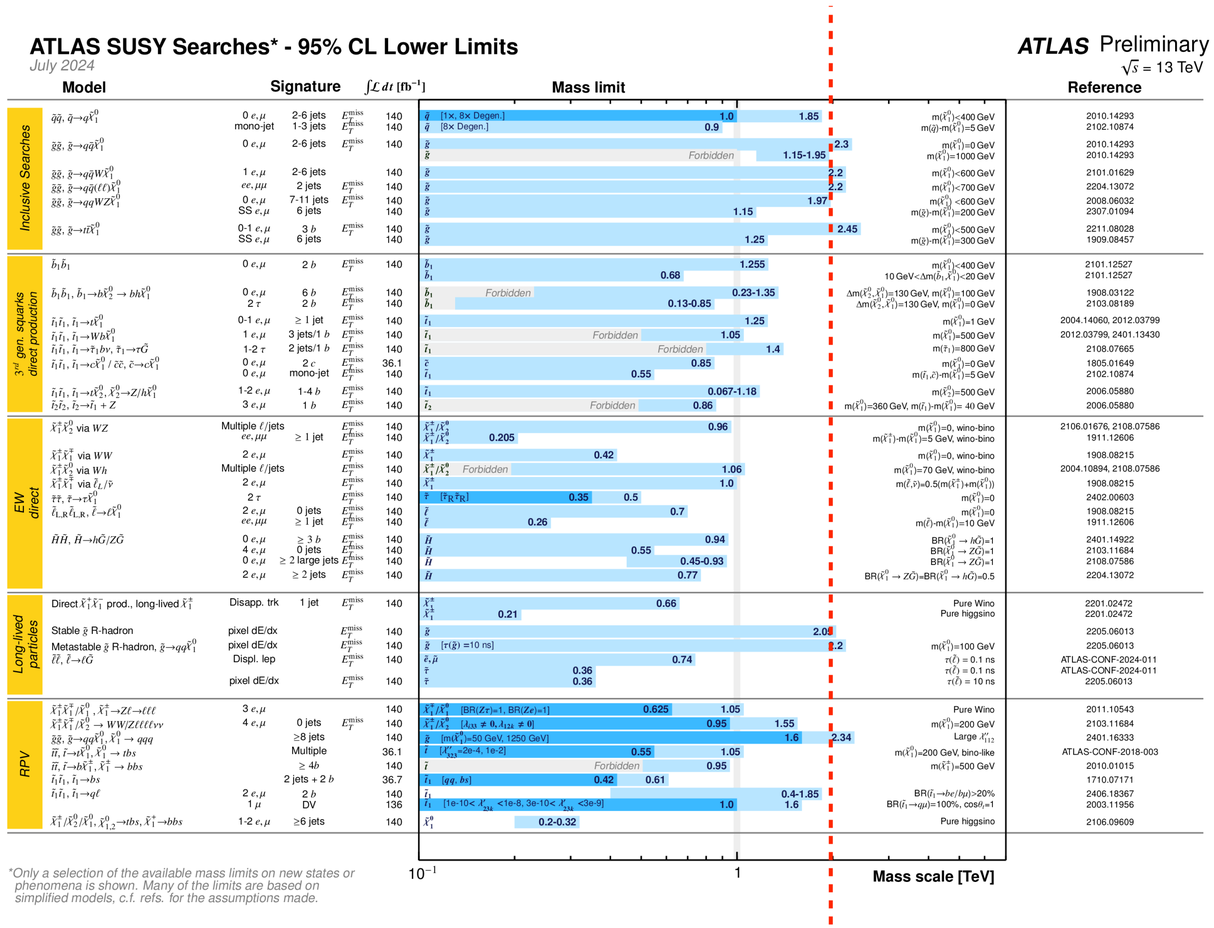
FCC-hh From first considerations an LHCb-like detector and HF physics program should be possible at FCC-hh

Direct Searches for New Physics

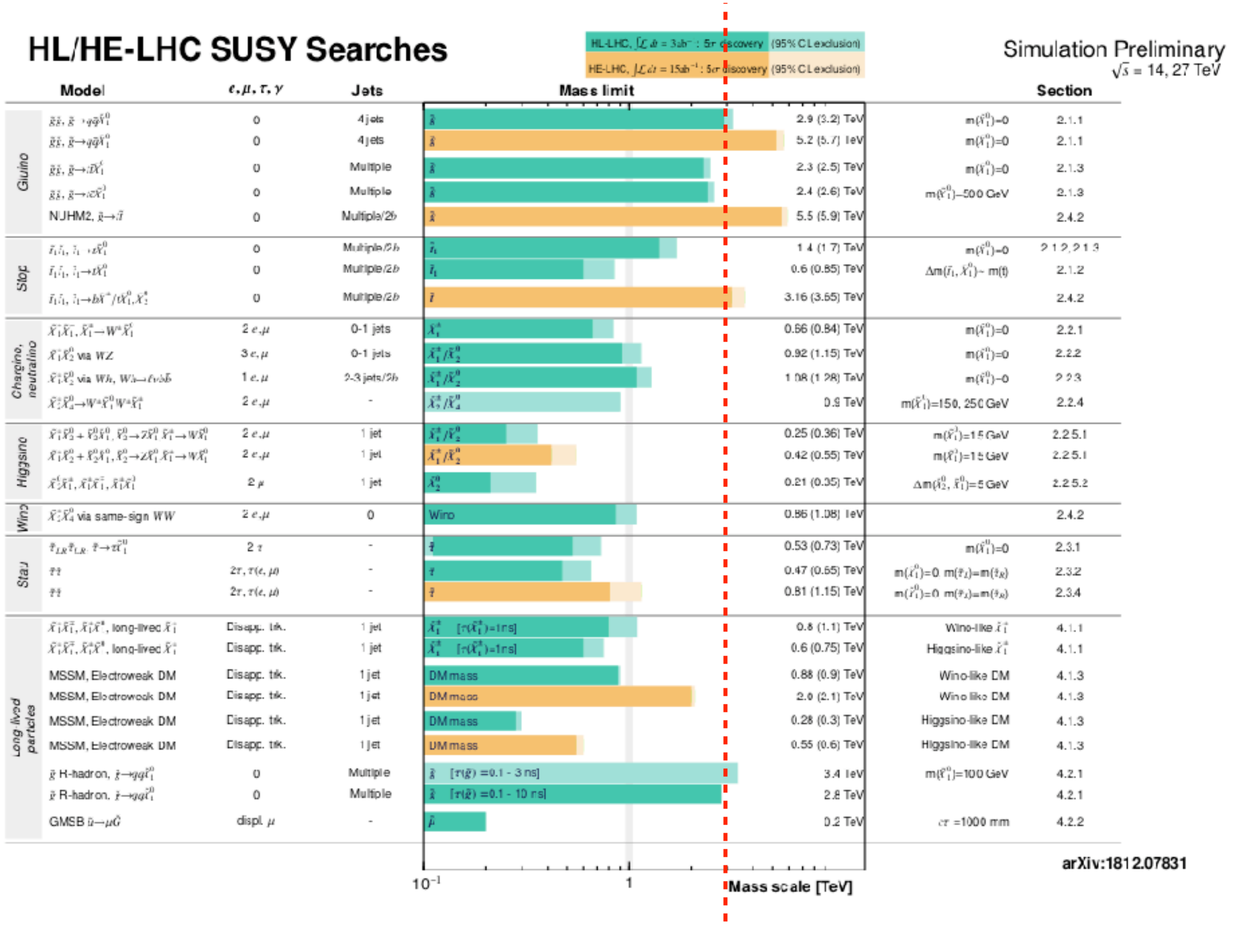
BSM physics covered by Keti and Valerio

Very Large Number of SUSY Searches

(in large variety of topologies and models)



1-2 TeV



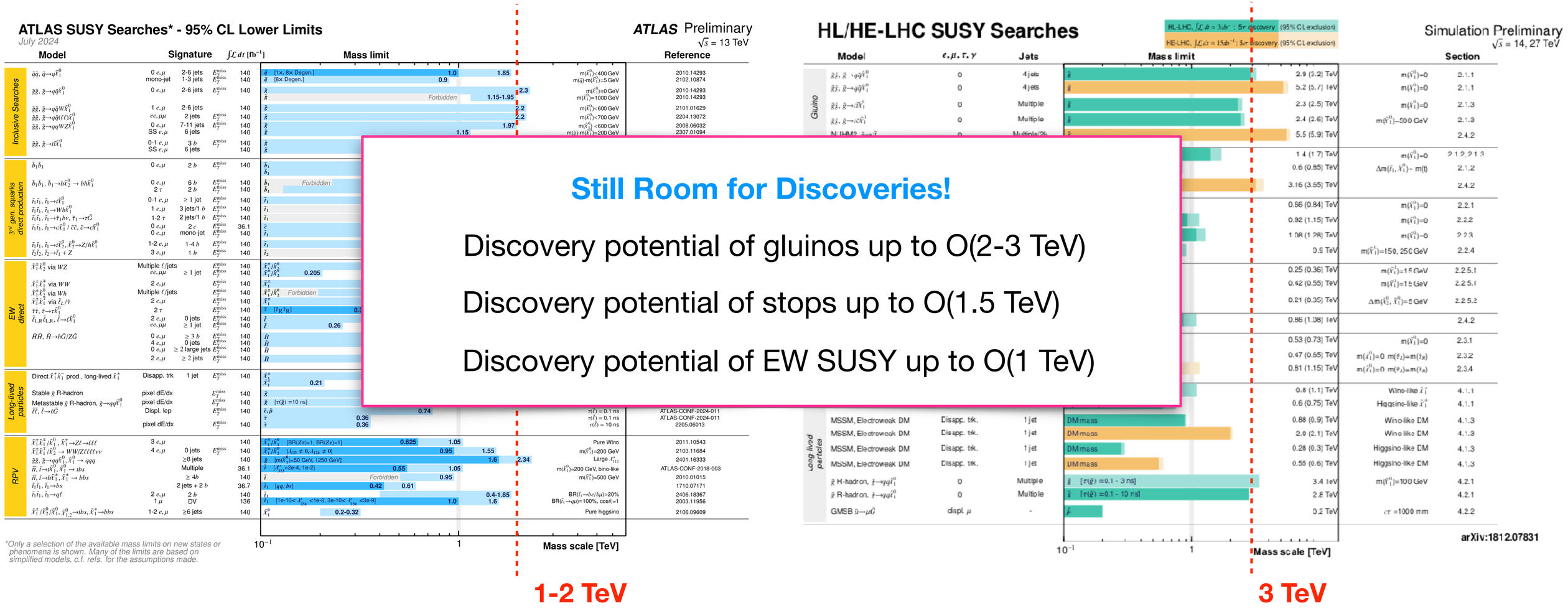
3 TeV

HL-LHC YR
1812.07831

Example from ATLAS (similar for CMS)

Very Large Number of SUSY Searches

(in large variety of topologies and models)



Still Room for Discoveries!

Discovery potential of gluinos up to O(2-3 TeV)

Discovery potential of stops up to O(1.5 TeV)

Discovery potential of EW SUSY up to O(1 TeV)

1-2 TeV

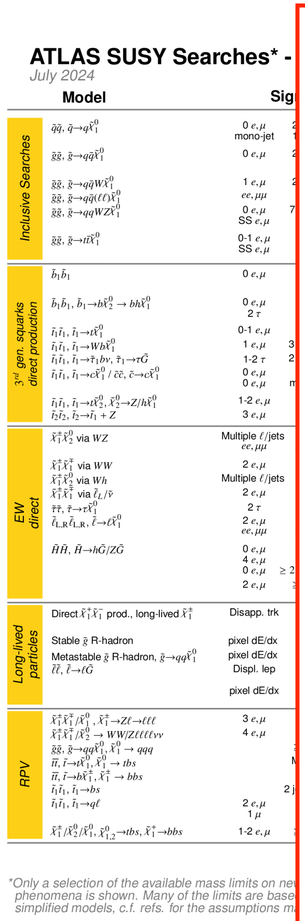
3 TeV

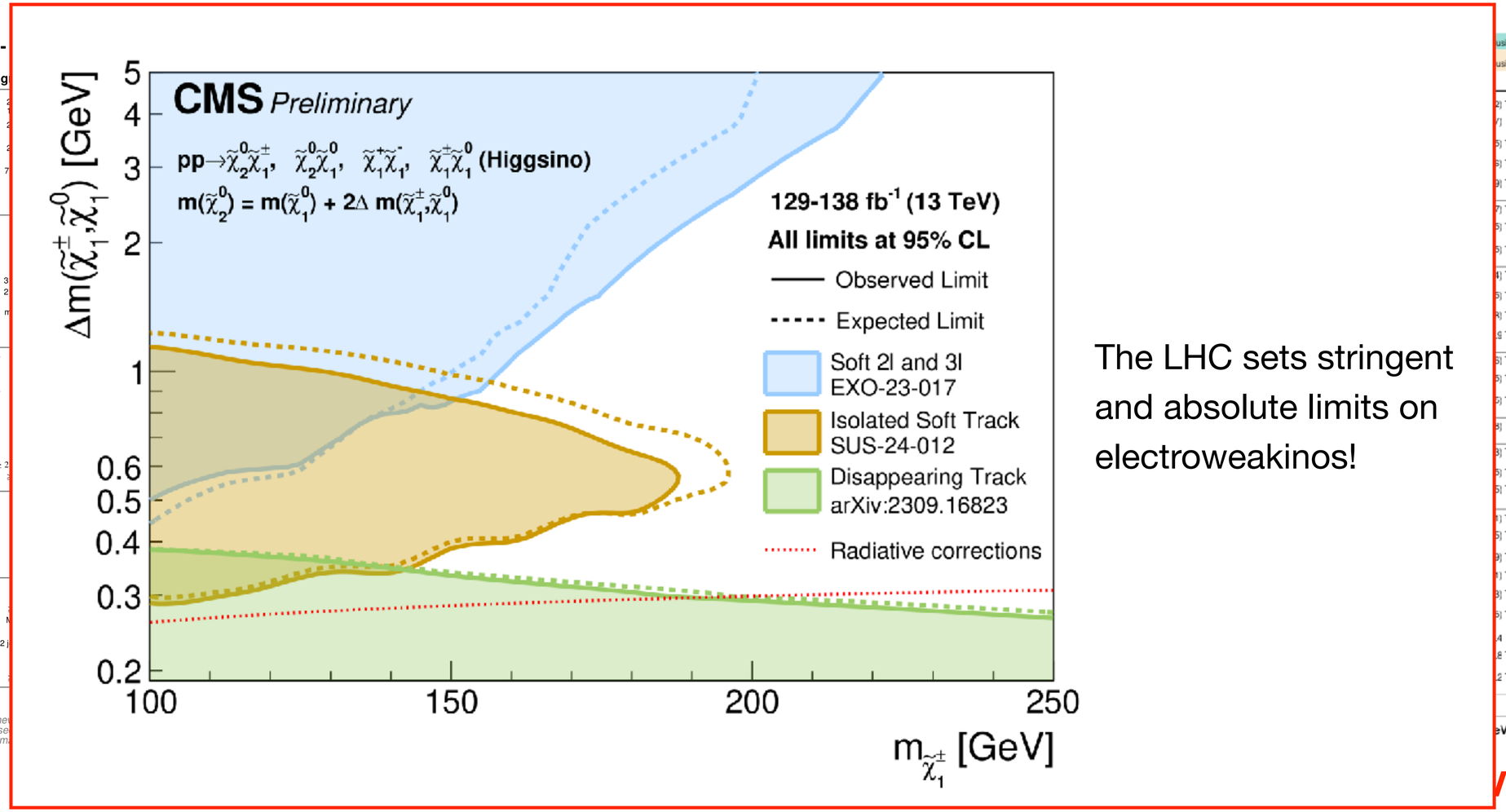
HL-LHC YR
1812.07831

Example from ATLAS (similar for CMS)

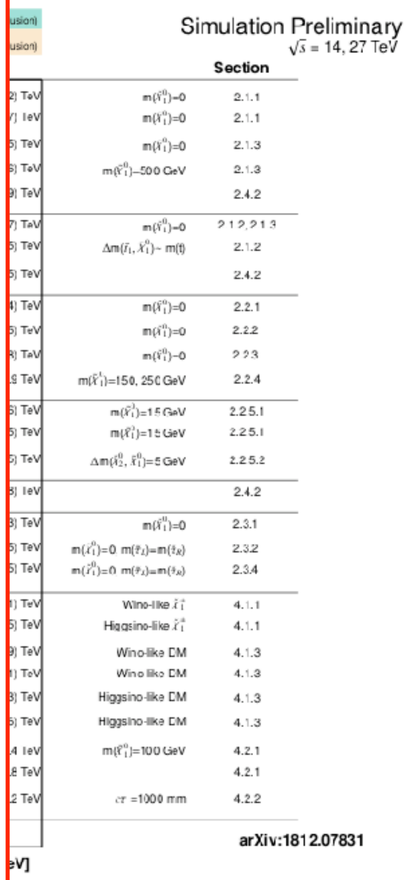
Very Large Number of SUSY Searches

(in large variety of topologies and models)





The LHC sets stringent and absolute limits on electroweakinos!

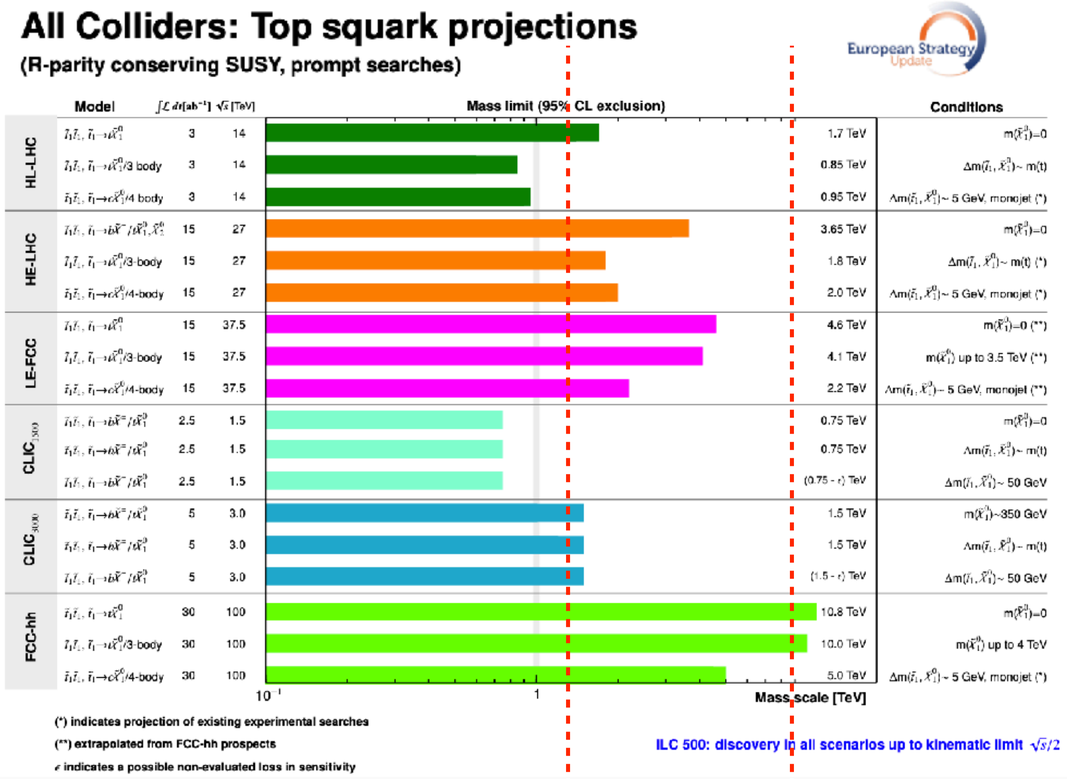


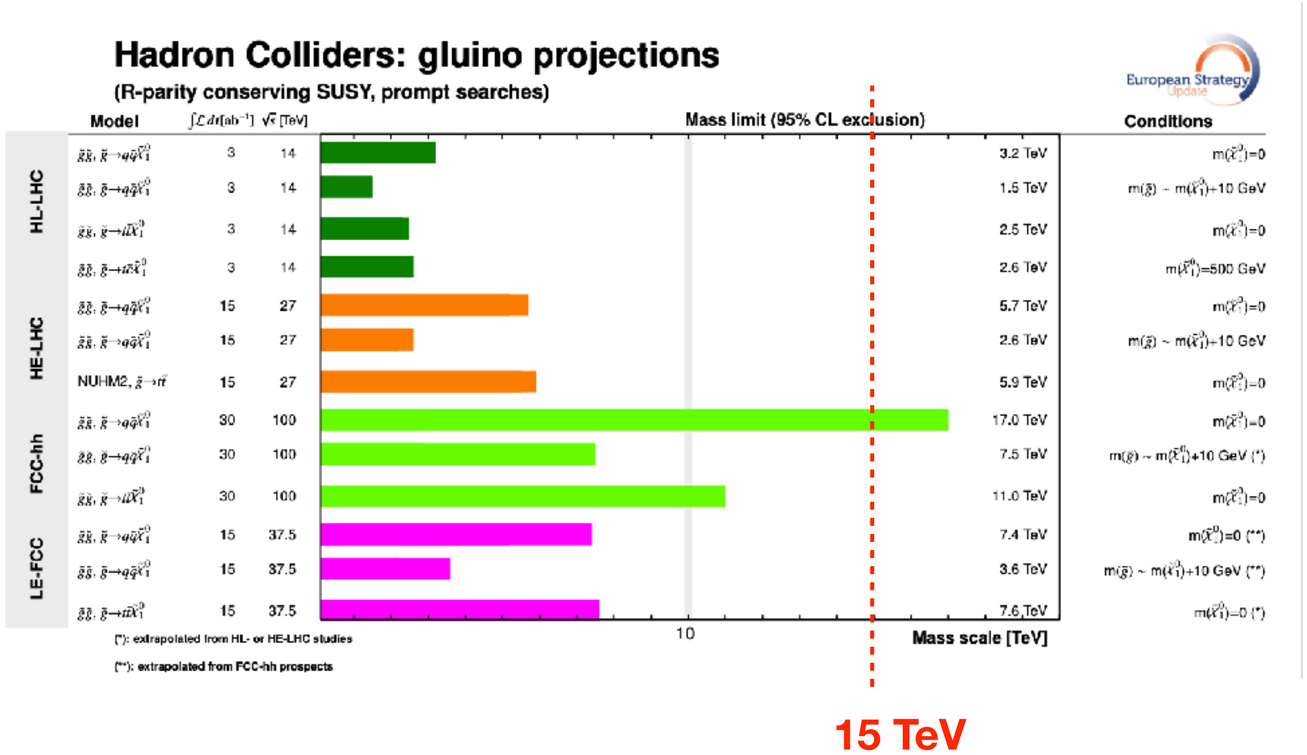
Example from ATLAS (similar for CMS)

HL-LHC YR
1812.07831

Projections at a Future Hadron Collider

To go above the 10 TeV scale SUSY will require a **10 TeV Parton COM energy** machine e.g. **future hadron collider (100 TeV)**.





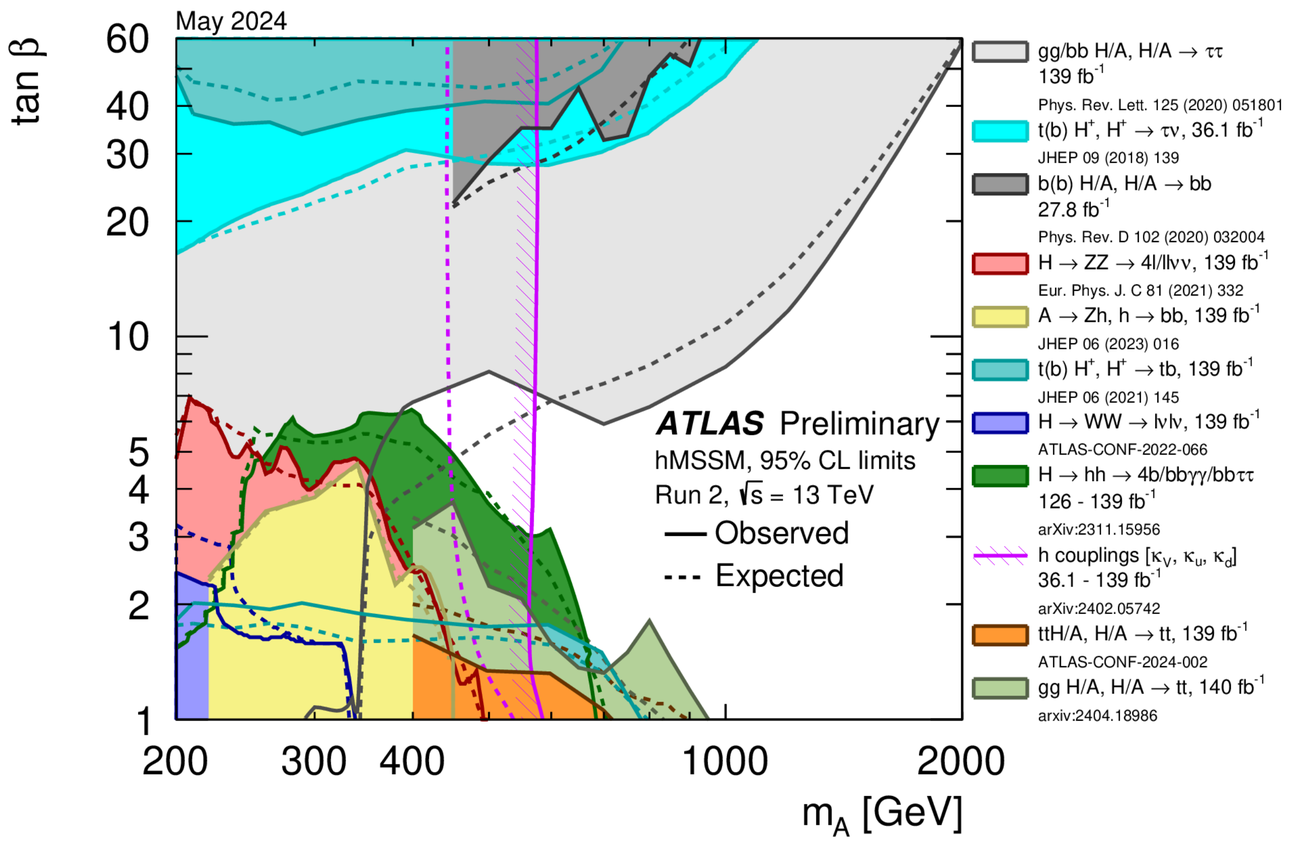
CLIC - LHC

10 TeV

15 TeV

Reaching SUSY from its extended Higgs sector

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan β).



hMSSM: trade the value Mh = 125 GeV against the radiative corrections where the Higgs mass is used as proxy for the leading stop sector corrections.
[Maiani, Polosa, Djouadi et al. link]

SUSY could modify the couplings of the Higgs

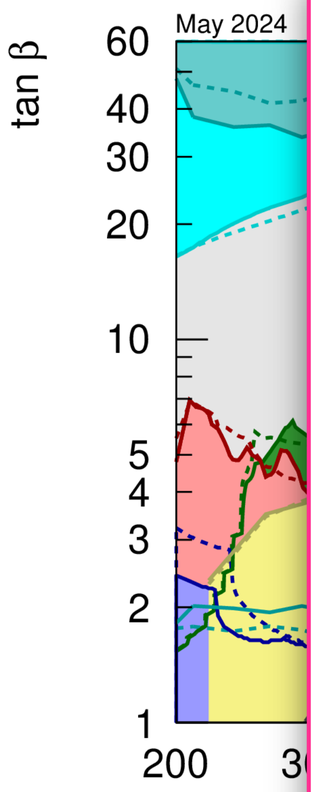
From the combination of all Higgs coupling measurements channels presented, mostly from constraints on up versus down Yukawa and coupling to vector bosons.

Direct searches for additional Higgs bosons (neutral and charged) have been performed:

- Neutral heavy Higgs to tau tau
- Charged Higgs to tau neutrino
- Heavy neutral Higgs to ZZ
- Charged Higgs to tb
- Heavy neutral Higgs to ZH
- Heavy Higgs boson to HH
- ***Heavy Pseudo Scalar in tt resonance***

Reaching SUSY from its extended Higgs sector

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan β).

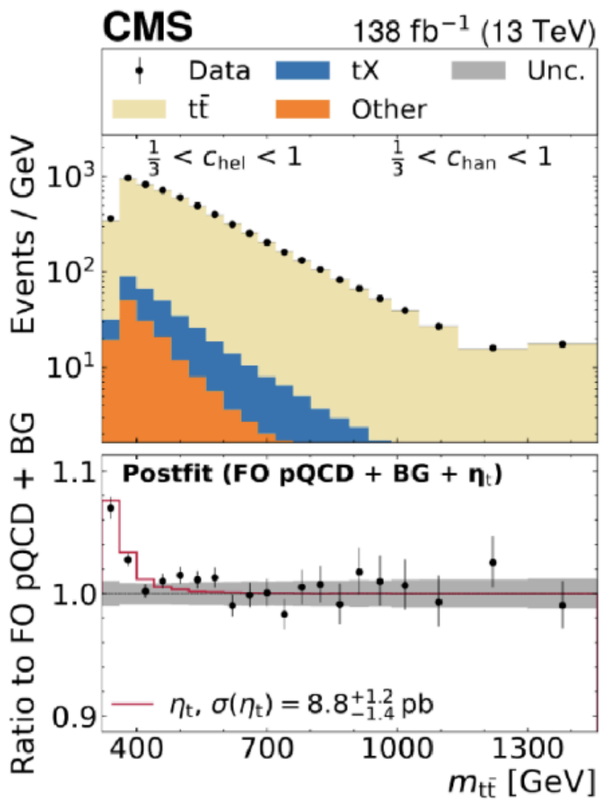


hMSSM: trade th
the Higgs mass i
[Maiani, Polosa, Djouadi et al. link]

SUSY could modify the couplings of the Higgs

easurements
on up versus
.

bosons
formed:

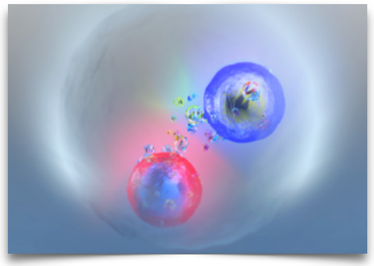


Interesting surprises in the intricate search for $t\bar{t}$ resonances

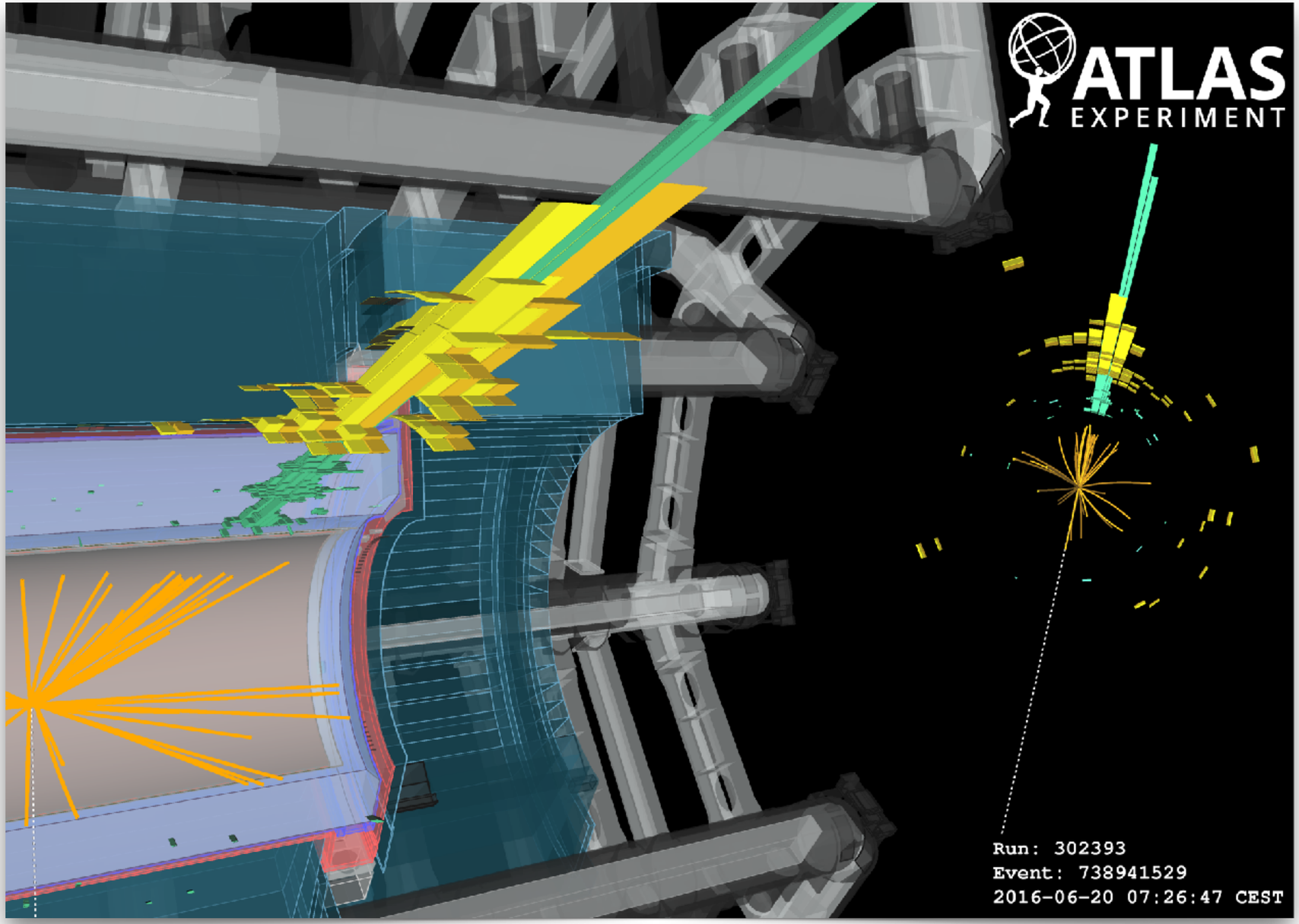
Interesting feature appears at threshold (challenging for reconstruction)

Result confirmed by ATLAS and presented at EPS 2025 in Marseille (see briefing)

A colour-singlet quasi-bound (pseudo scalar-like) tt states (**not a quarkonium**-like bound state with self-annihilation as the top decays before) - *subtle effect of the strong interaction predicted in non relativistic QCD models.*



Broad Overview



Simplified Models

A wealth searches for DM at the LHC:

- Mono-jet, mono-V (leptonic and hadronic), Mono-Higgs (various modes), Mono-photon, Mono-top
- VBF-like signatures
- Associated production-like signatures

Savvy searches for DM mediator

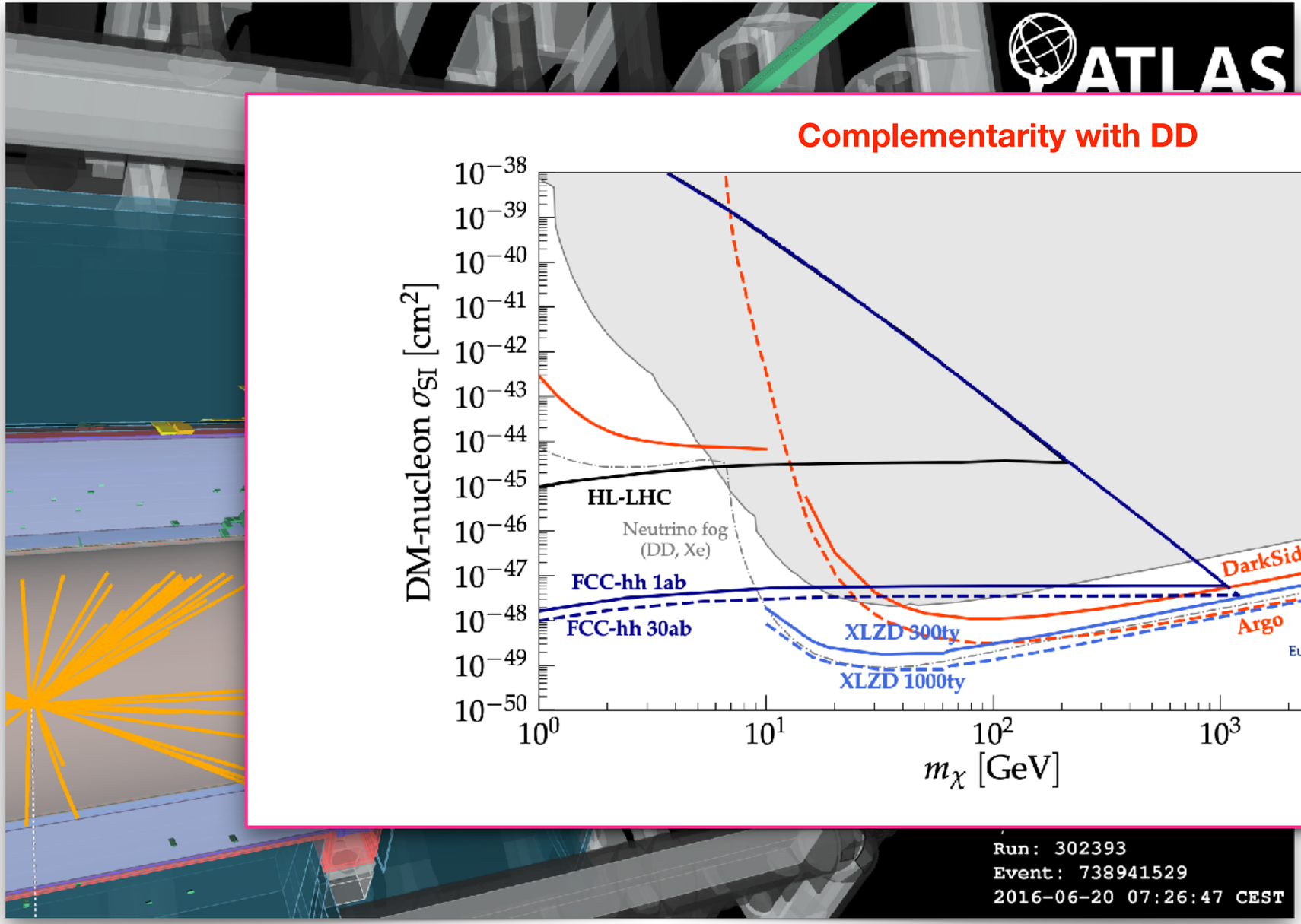
Vast number of topologies and creative solutions to search the low mass region (e.g. using trigger level analyses)

Dark Sector portals

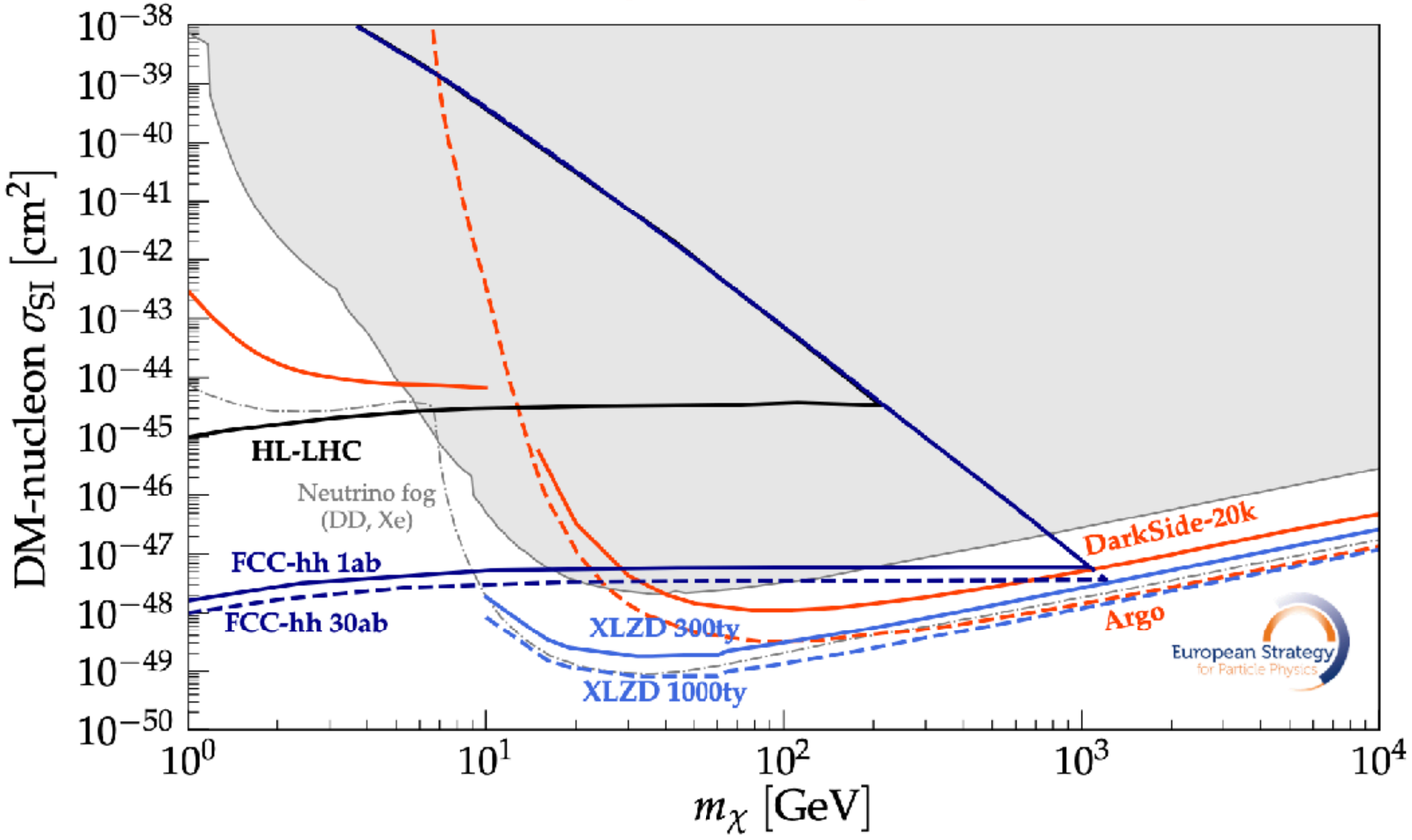
- Dark Scalar
- Dark Pseudo-scalar
- Dark Vector
- Heavy Neutral Lepton

Simplified Models

Broad Overview



Complementarity with DD



Simplified Models

DM at the LHC:

tonic and hadronic),

nodes), Mono-

-like signatures

DM mediator

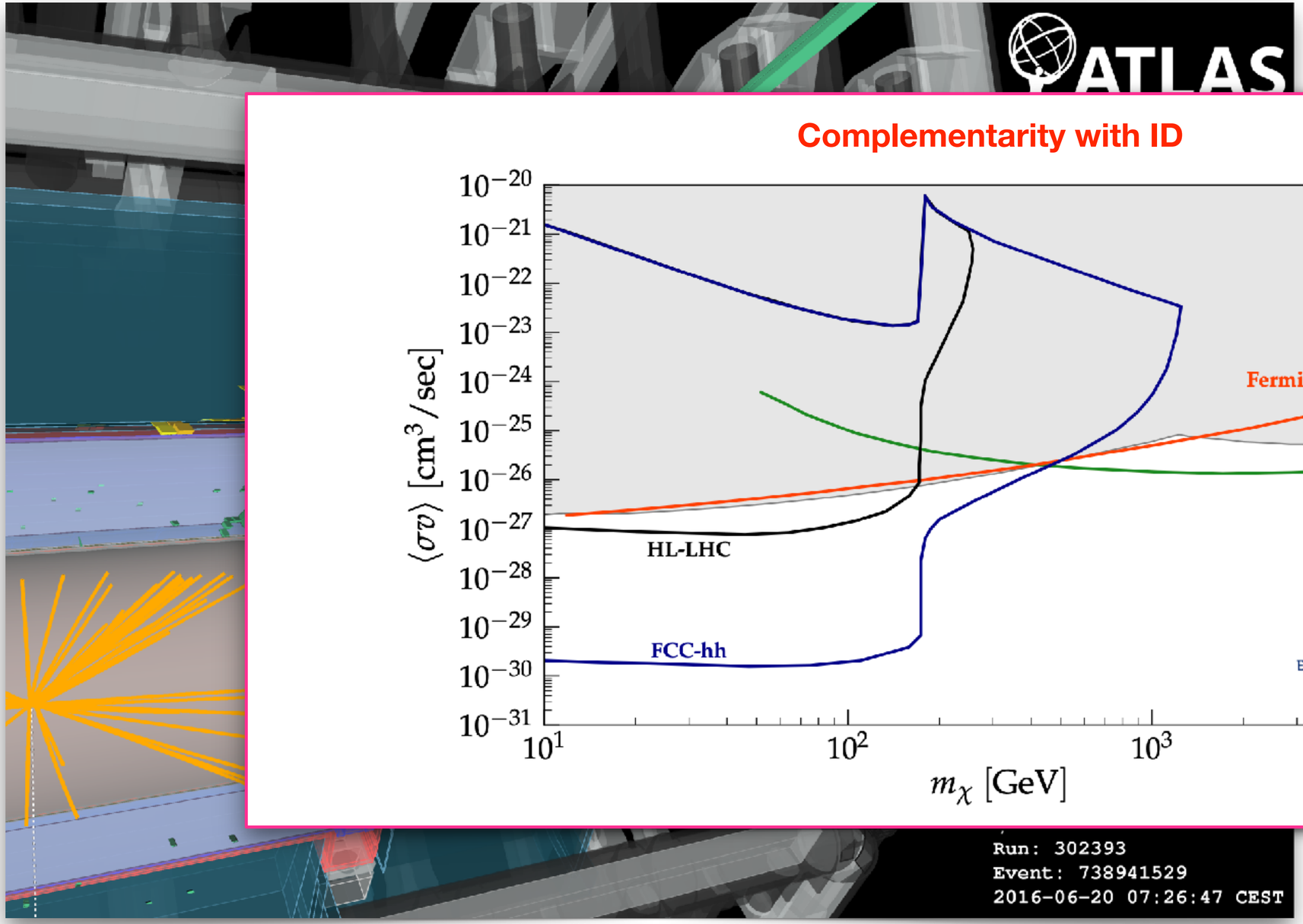
ogies and creative

e low mass region

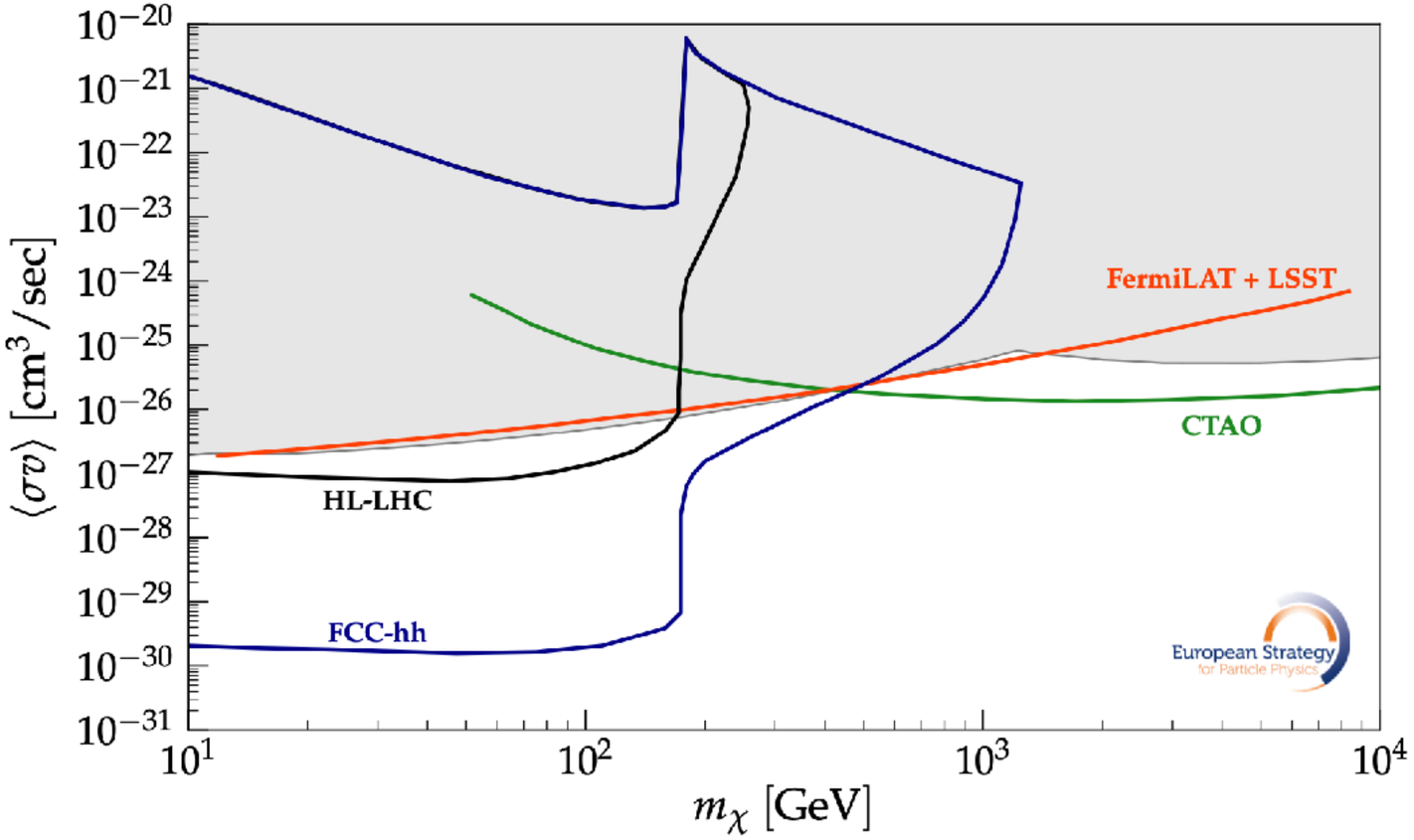
el analyses)

Simplified Models

Broad Overview



Complementarity with ID



Simplified Models

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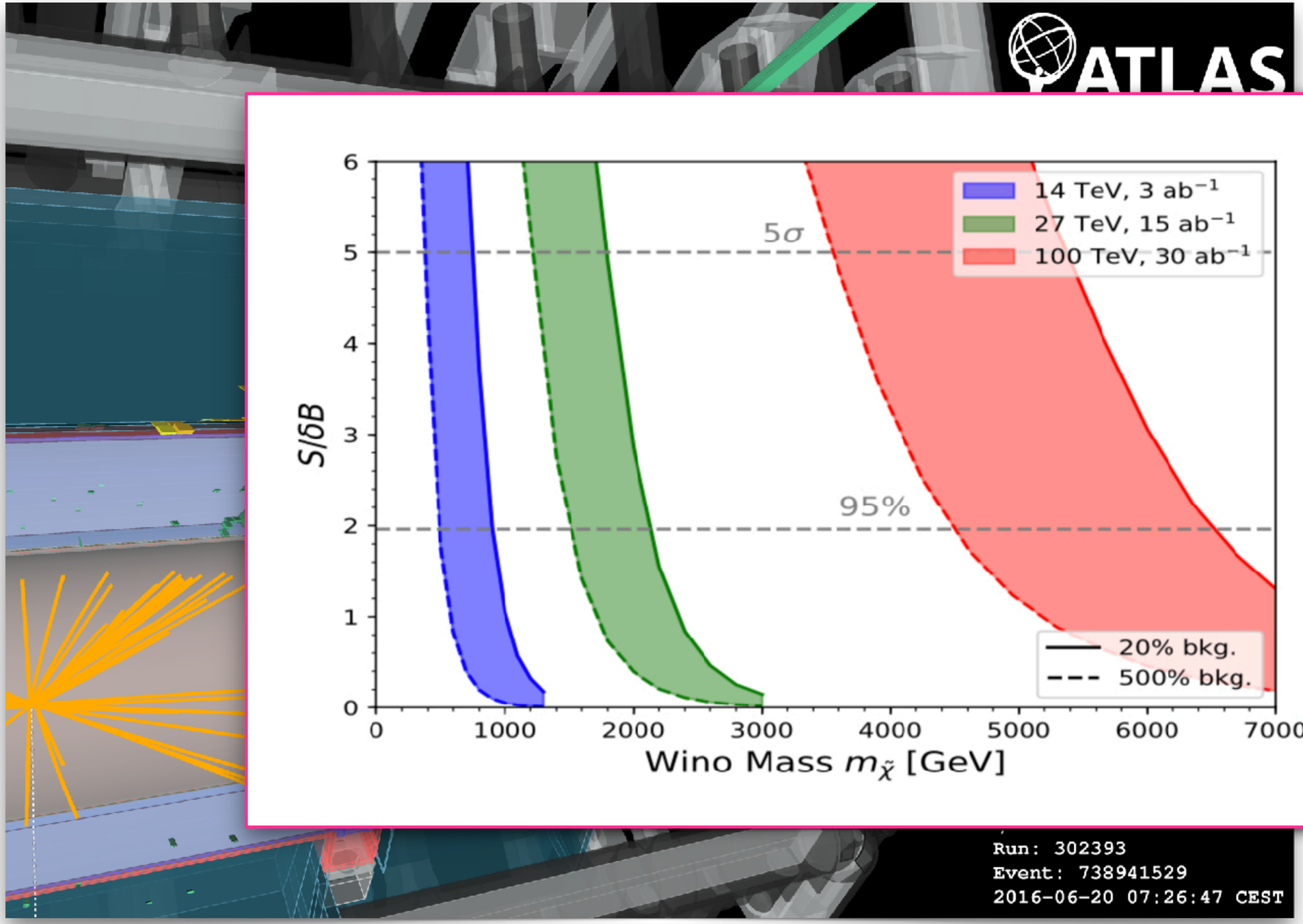
Simplified Models

Broad Overview



The FCC-hh will be able to bring **conclusive answers to thermal DM search!**

Simplified Models

DM at the LHC:

tonic and hadronic),

nodes), Mono-

-like signatures

DM mediator

ogies and creative

e low mass region

el analyses)

Simplified Models

Dark Sector, Intensity Frontier and Meson Factories

Gaps in the experimental exploration of New Physics possibilities, both at the **electroweak-TeV** scale and at the **sub-GeV** scale, addressed by unconventional event signatures.

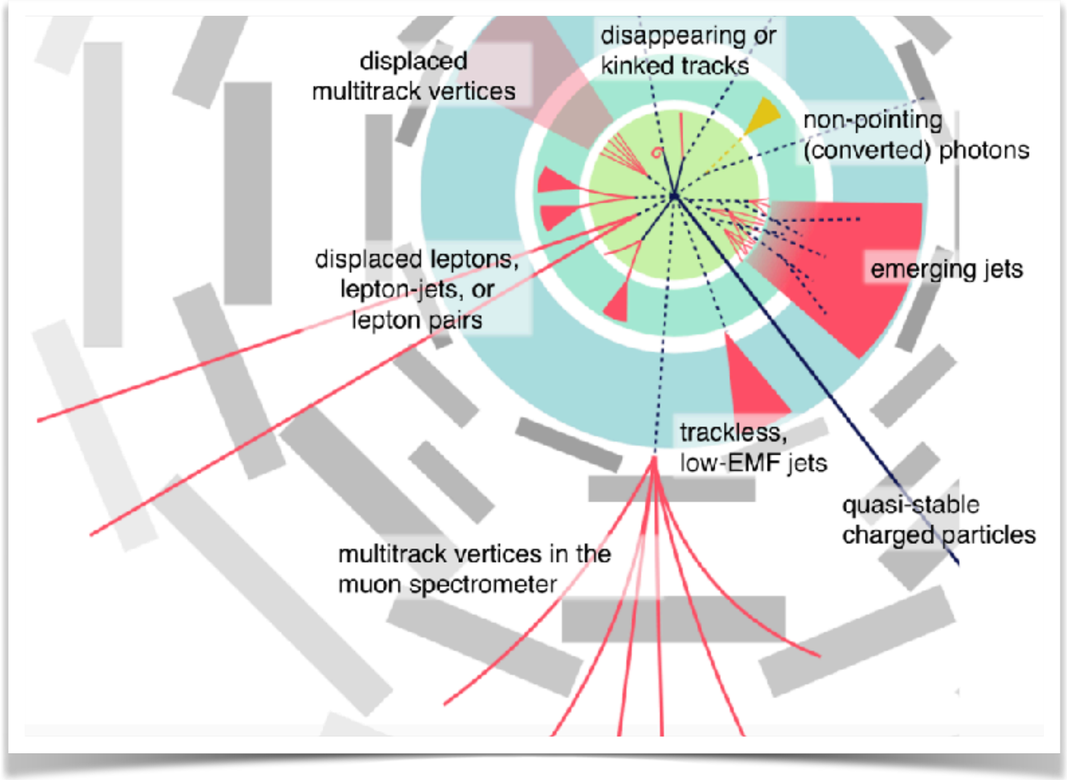
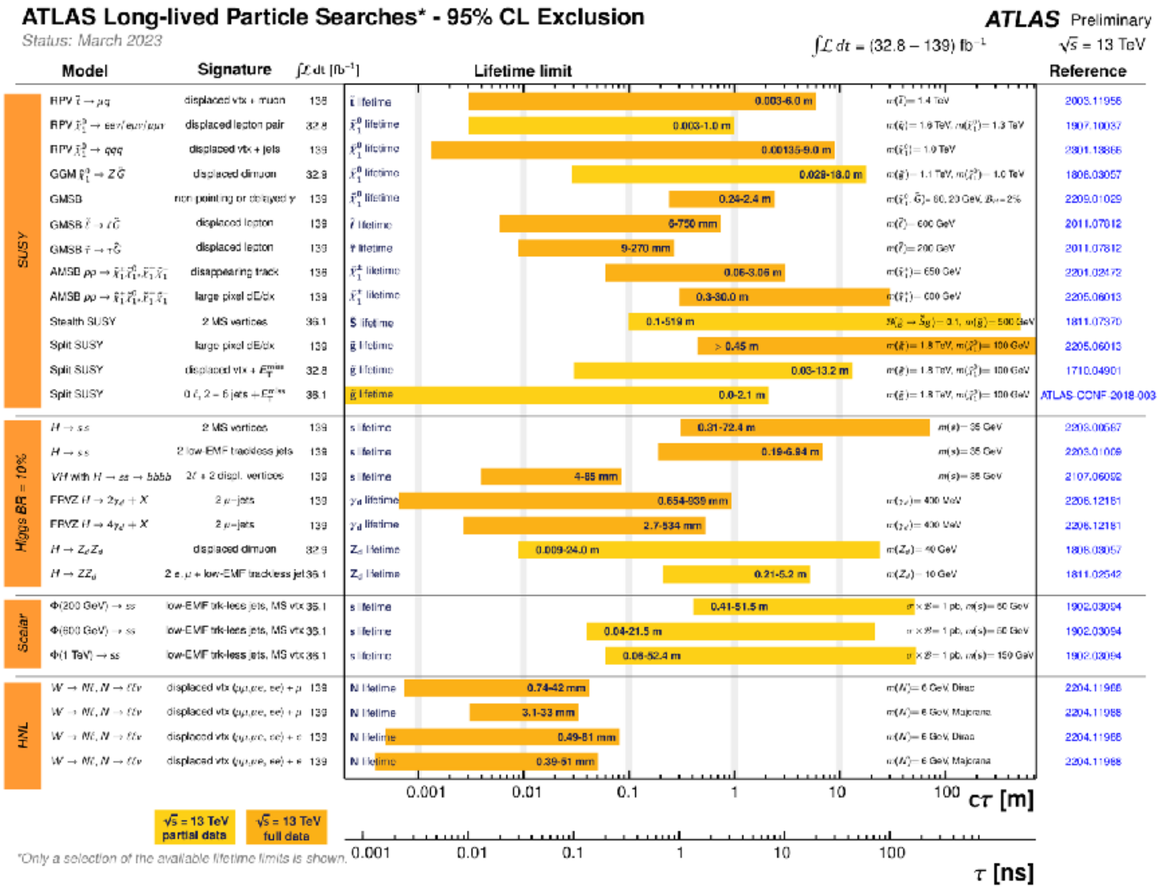


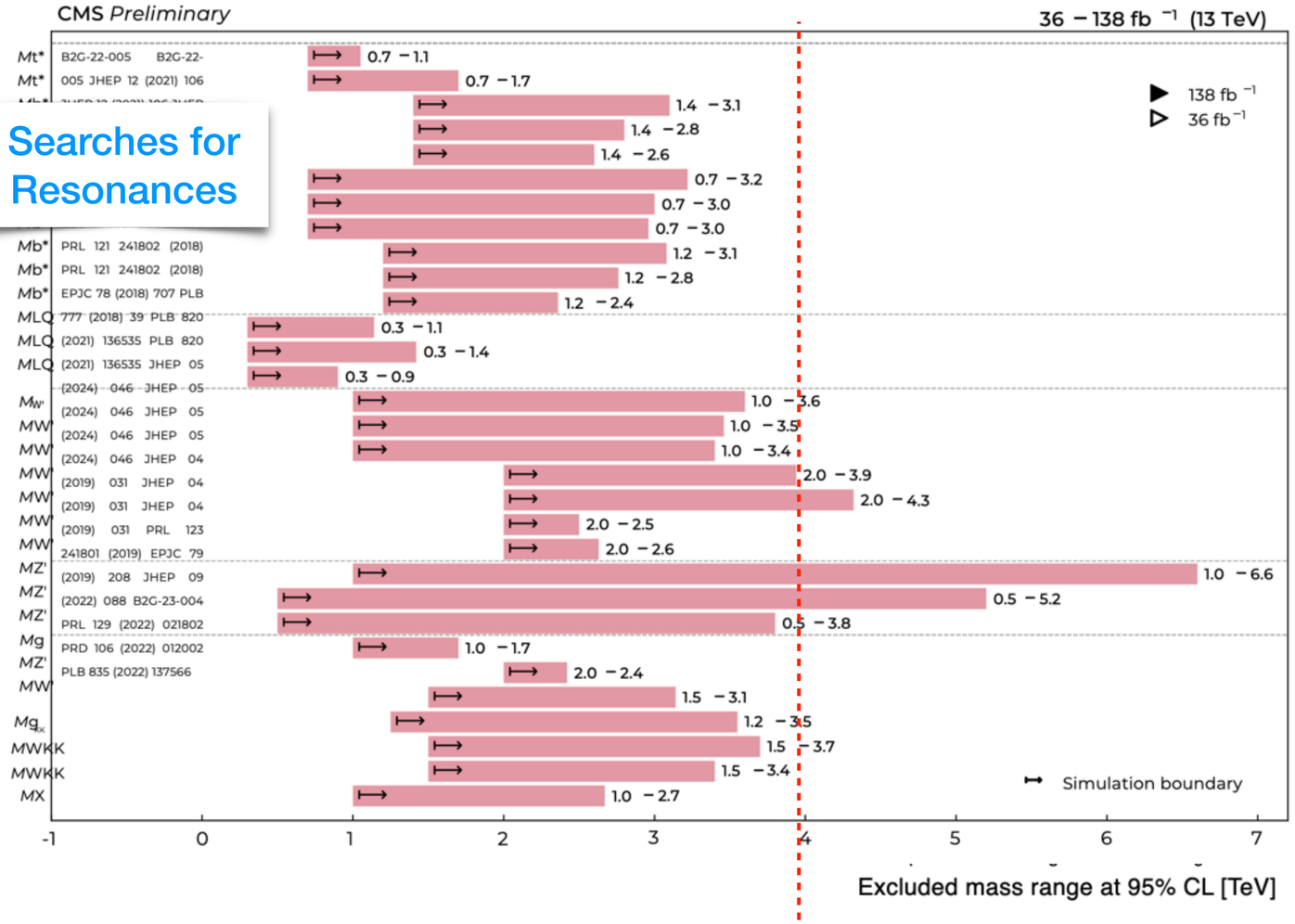
Image from H. Russel



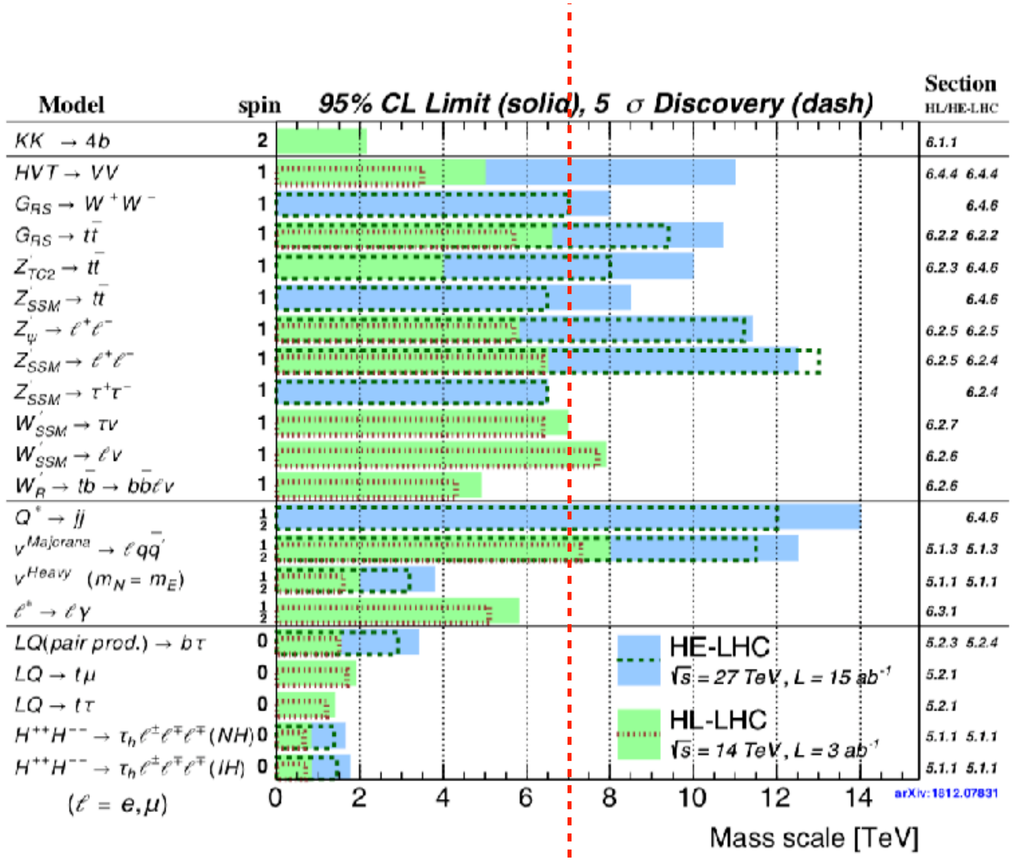
The FCC program will further complete this difficult exploratory territory!

Searches for High Mass New Resonances

Searches for Resonances



4-6 TeV



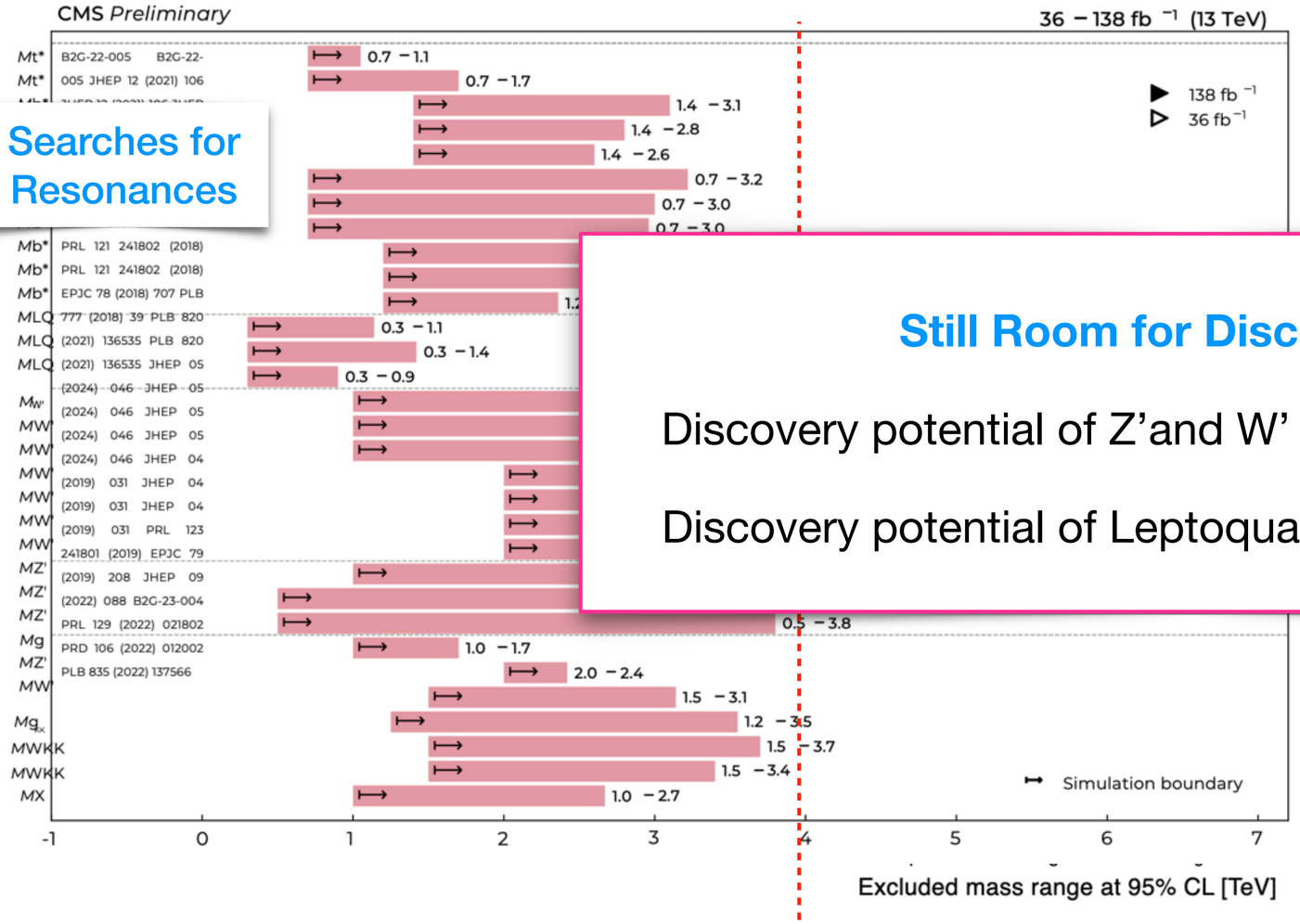
6 - 8 TeV

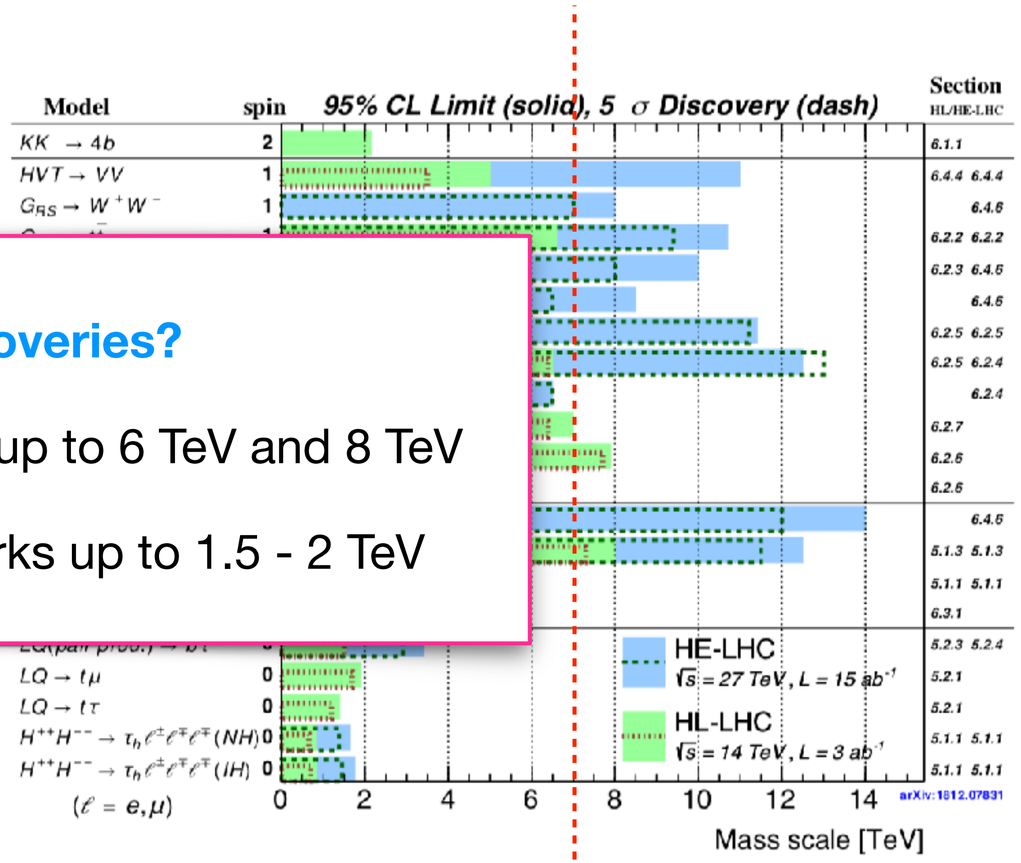
Example from CMS (similar for ATLAS) - latest plot in the backup!

HL-LHC YR
1812.07831

Searches for High Mass New Resonances

Searches for Resonances





Still Room for Discoveries?

Discovery potential of Z'and W' up to 6 TeV and 8 TeV

Discovery potential of Leptoquarks up to 1.5 - 2 TeV

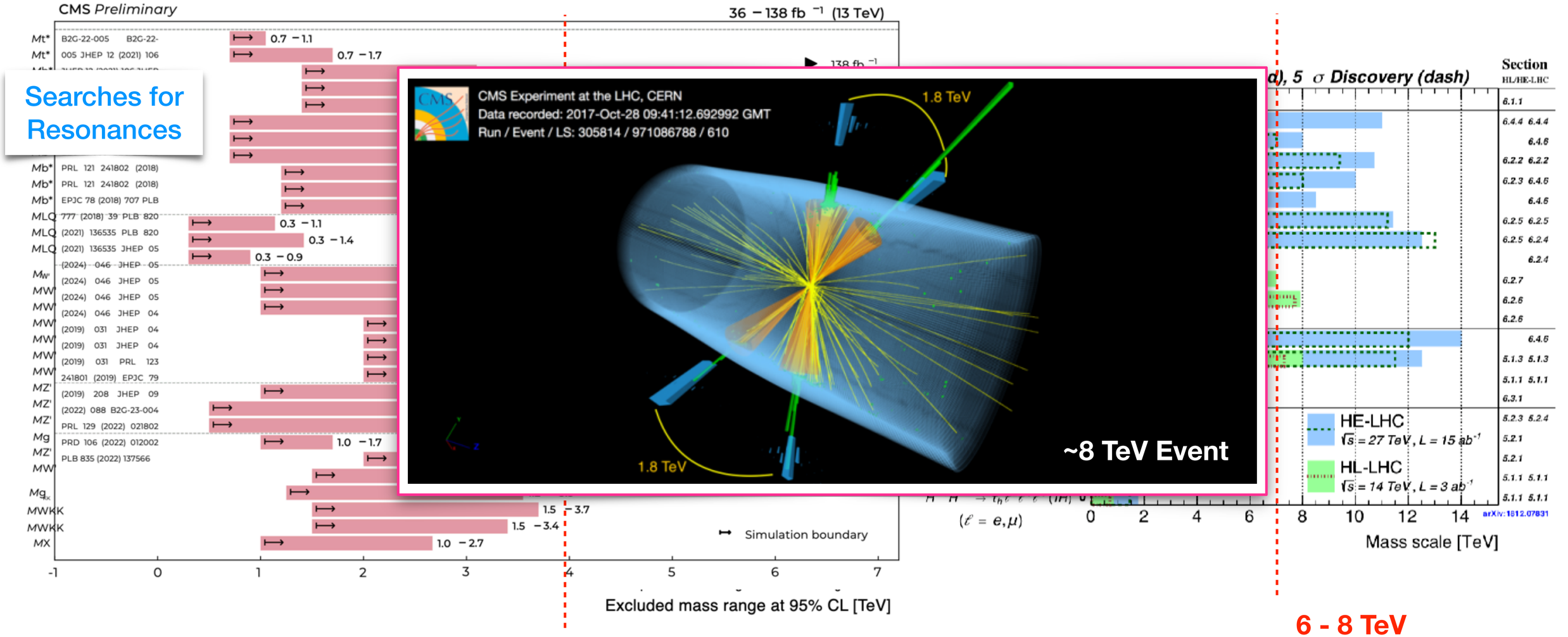
4-6 TeV

6 - 8 TeV

Example from CMS (similar for ATLAS) - latest plot in the backup!

HL-LHC YR
1812.07831

Searches for High Mass New Resonances



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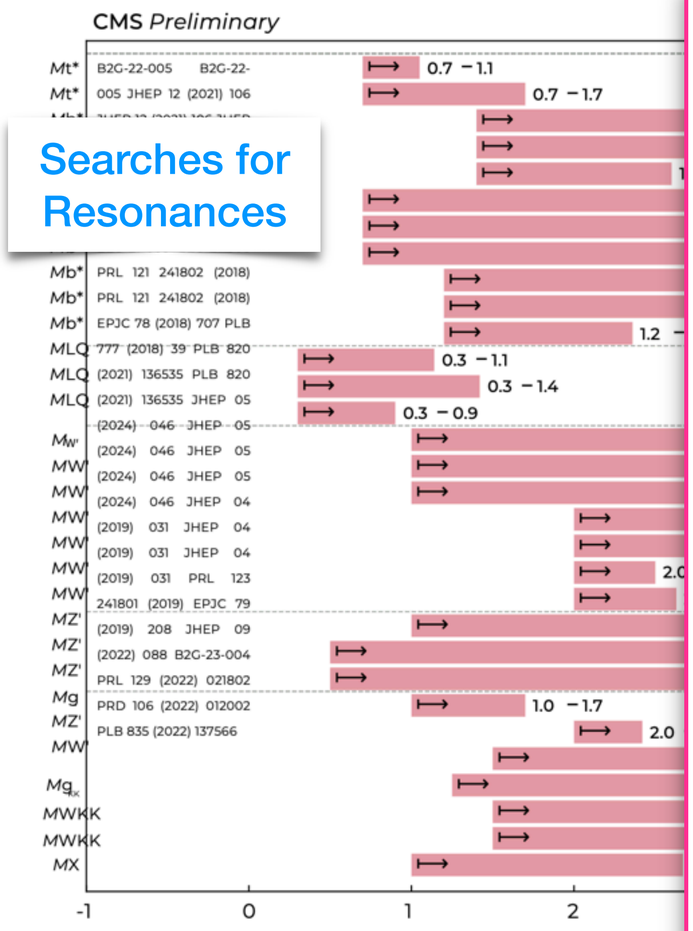
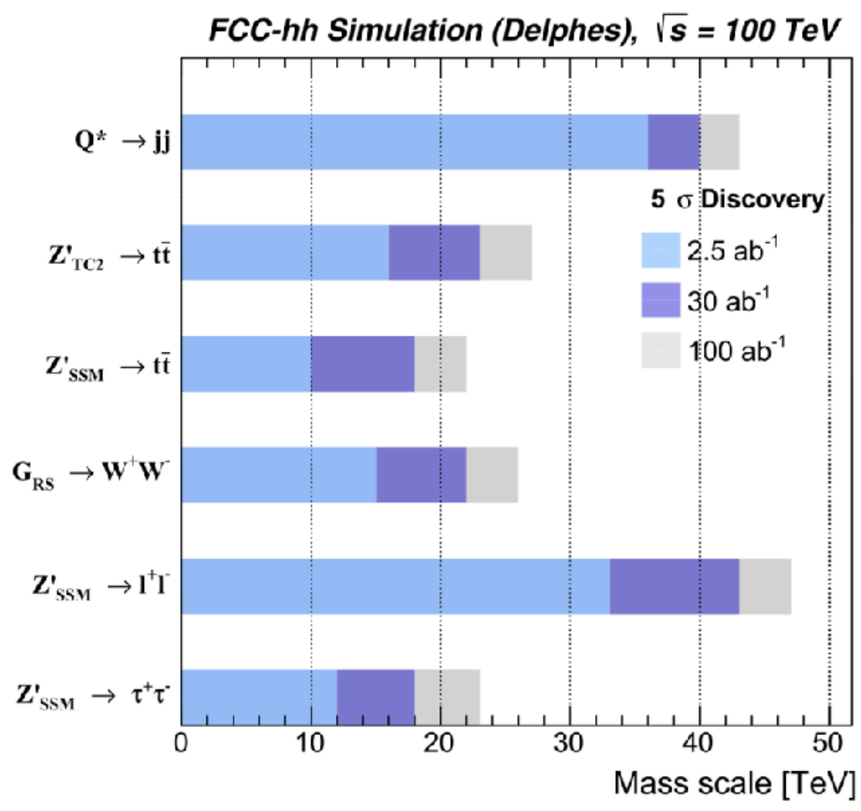
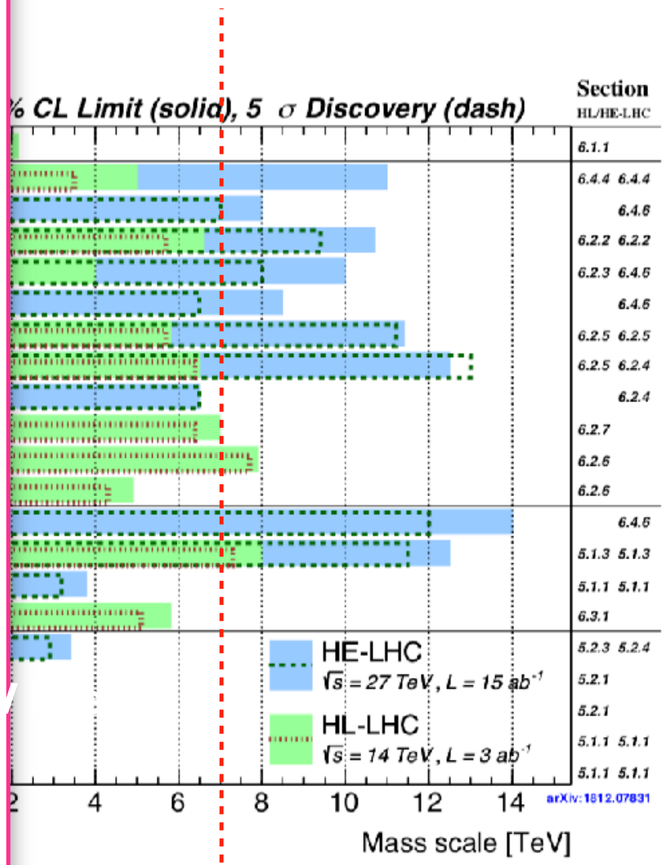


At FCC-hh Direct sensitivity to NP ~50 TeV





4-6 TeV

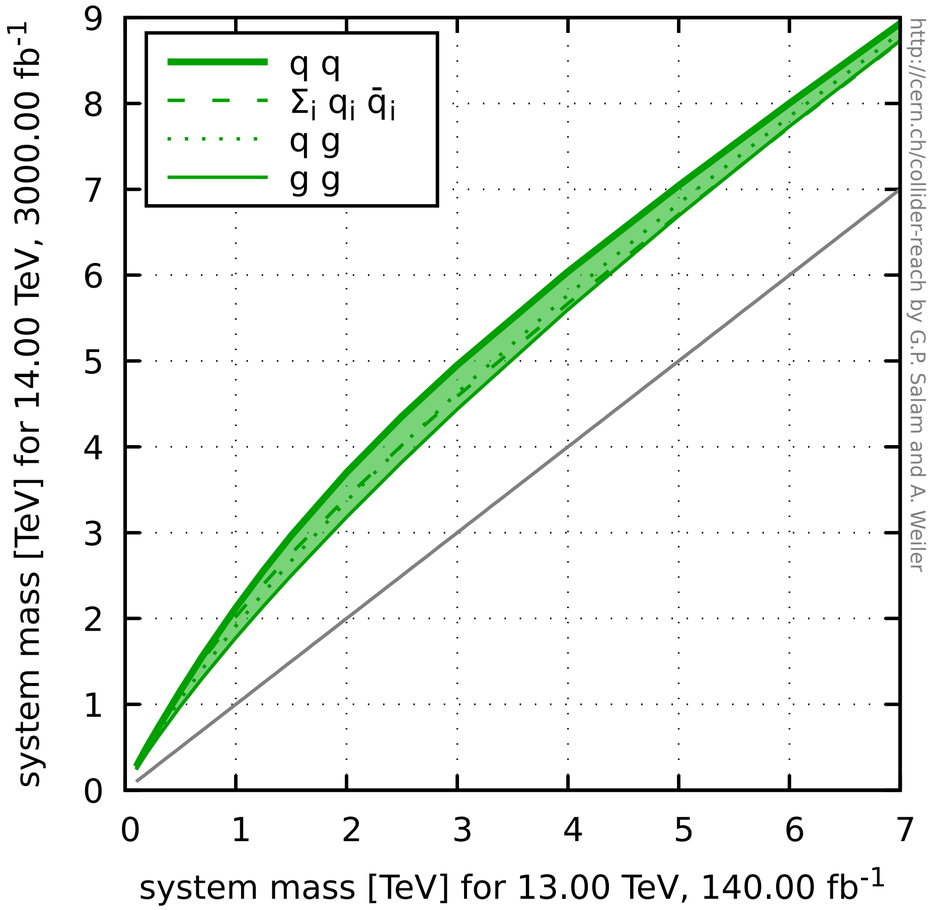
6 - 8 TeV

Example from CMS (similar for ATLAS) - latest plot in the backup!

HL-LHC YR
1812.07831

Still Room for Discoveries at LHC?

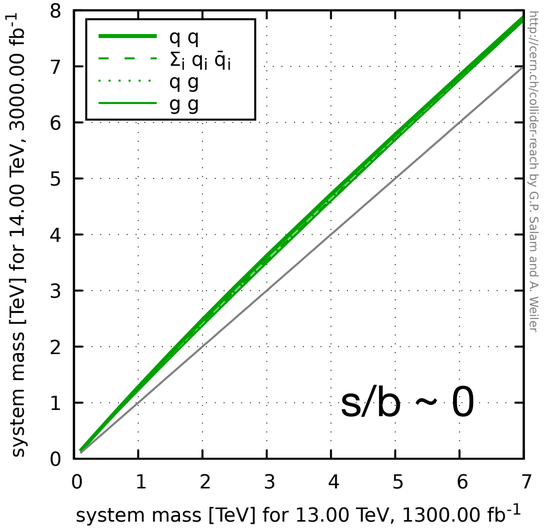
At HL-LHC still a factor of 10 (**effectively 20**) in luminosity

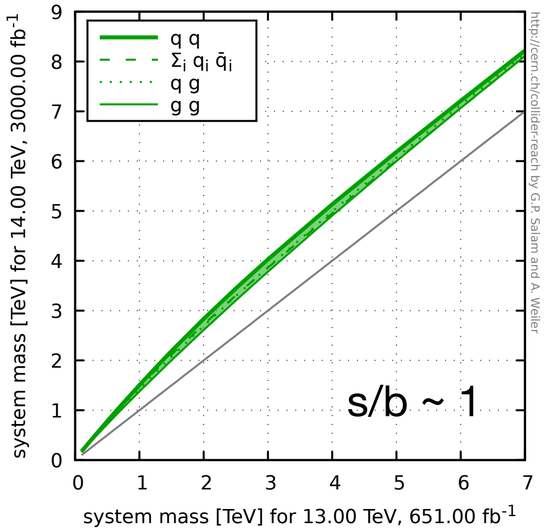


Still nearly up to 2 TeV of Exploration (exclusion)!!

Still room for discoveries?

Depends on analysis purity (s/b)





Up to **~500 GeV improvement**

Up to **~1 TeV improvement**

Performance can be improved!

- New ideas and developments (e.g. ML techniques).
- **Improving precision and ancillary measurement!**

Conclusions

The current CERN flagship **LHC** program is **extremely broad**, surpassed its initial design luminosity and in all areas of its program **has delivered much more than the original expectations**!

With LS3 on the horizon, the LHC community is focussed on upgrades for HL-LHC.

The **FCC-ee** is **much more than a Higgs factory,** will improve the precision on the electroweak sector by at least one to two orders of magnitude. It will **explore new physics up to the O(100) TeV scale indirectly** and has **outstanding possibilities for direct searches at the intensity frontier**.

Beyond 10 TeV pCOM collider - the **FCC-hh** (85 TeV) will **explore directly new physics at up to O(50) TeV** and synergistically complement the measurements of FCC-ee and HL-LHC in the Higgs sector.

Pivotal moment for the future of High Energy Collider Physics!

After the LHC, the FCC is the most ambitious and **the perfect flagship project for CERN!**

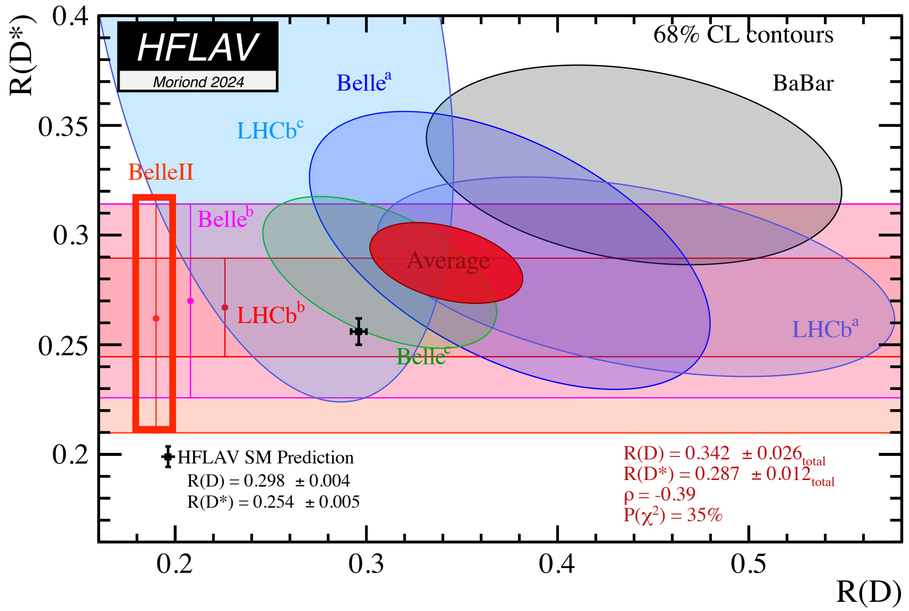

Tokyo National Museum Garden
Backup

Lepton Flavour Universality

Recent Belle II RD* measurement!

Both TH and EXP clean!

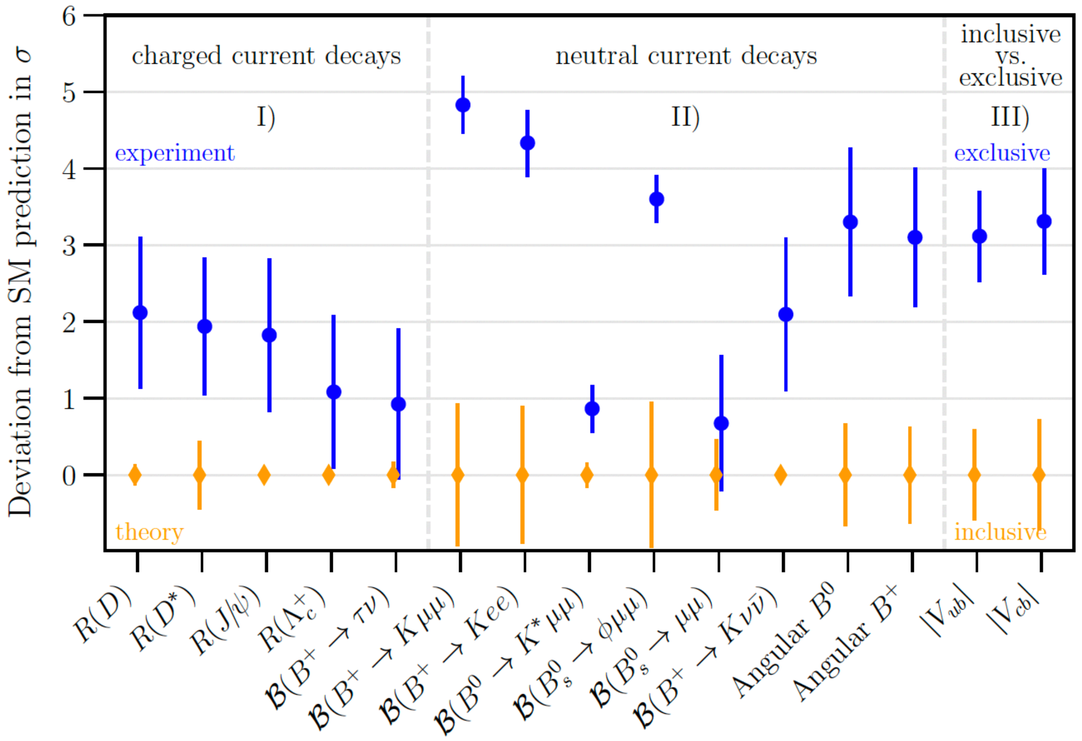
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}\left(B^0 \to D^{(*)-}\tau^+\nu_\tau\right)}{\mathcal{B}\left(B^0 \to D^{(*)-}\mu^+\nu_\mu\right)}$$



$$R_D^* = 0.26 \pm 0.04^{+0.04}_{-0.03}$$

Still tension at the ~3.3σ level

Large number of channels investigated



Large discrepancies remain in several channels.

- Further clarification from experiments with more measurements.
- Further improvements in the calculations is also needed.

Introduction

Two main outcomes of the LHC: The discovery of the Higgs boson and nothing else (so far)!

Standard Model: formidably simple (gauge) fundamental theory for phenomena at microscopic, astronomical, and cosmic scales!

Simplicity, governed by symmetries
only 2 (EW) and 2 (QCD) parameters!

Not governed by symmetries and **22**
parameters set by "hand" of experiments!

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c.$$

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

$$+ \frac{c_{ij}}{M_R} L_i L_j H H ?$$

Outstanding open and fundamental questions

- What is the nature of the Higgs boson? Is it a composite particle? How does it interact with itself?
- Why is there such a large discrepancy in the strength of the fundamental forces?
- What is the structure of the quantum theory of gravity and what are the quantum properties of space-time?
- Why is the electric charge quantised and why are the charges of the proton and the electron equal*? Are there new symmetries at high energies that unify the three forces of the Standard Model?
- What is the reason for the large flavour mass hierarchy? What are the fundamental properties of neutrinos?

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Not governed by symmetries and **22 parameters set by "hand" of experiments!**

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \quad + \frac{c_{ij}}{M_R} L_i L_j H H ? \qquad + \mathrm{DM} \ ?$$

$$+ |D_\mu \phi|^2 - V(\phi) \quad + \Lambda^4 \ ? \qquad \theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu}$$

From neutron electric dipole moment

$$\theta < 10^{-10} \ ?$$

Outstanding puzzling observations

- What is the origin of the observed dominance of matter over anti-matter in the universe?
- Why is the nucleon electric dipole moment so small?
- What is the nature of Dark Matter (DM) and the mysterious Dark Energy?

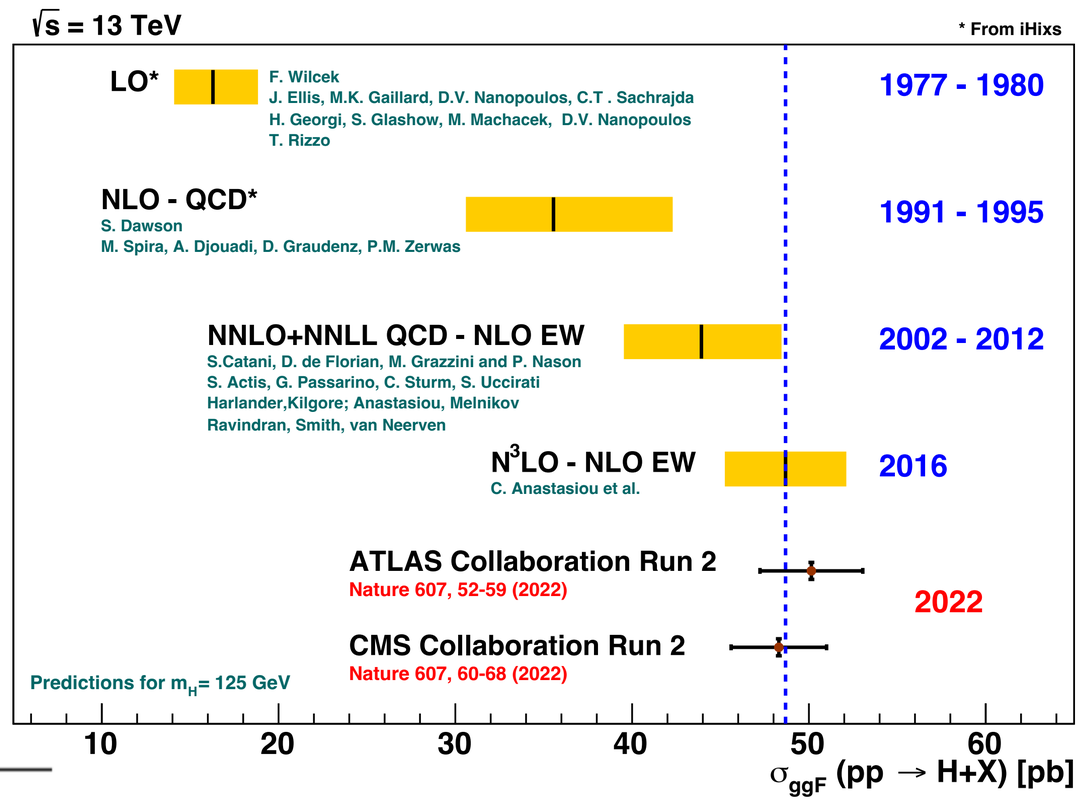
The Importance of Theory and Modelling

Predictions at hadron colliders are complex require higher order hard processes, parton fragmentation, hadronization, parton distribution functions, etc…

The interpretability of our results relies on our ability to compute accurate and precise predictions!

Precision at the LHC would not be possible without the efforts of precise TH and modelling.

Half a century of progress in Higgs production predictions



Current state-of-the-art $(pp \to H + X)$

E_{CM}	σ	$\delta(\text{theory})$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}} \begin{pmatrix} +4.27\% \\ -6.49\% \end{pmatrix}$	$\pm 0.89\,\text{pb}\,(\pm 1.85\%)$	$^{+1.24\text{pb}}_{-1.26\text{pb}} \begin{pmatrix} +2.59\% \\ -2.62\% \end{pmatrix}$

Stil linear sum of:
Missing beyond N3LO and EW; finite quark masses beyond NLO; mismatch in perturbative order of PDFs.

Room for improvement also in PDFs and α_s using LHC data and/or future ep collider.

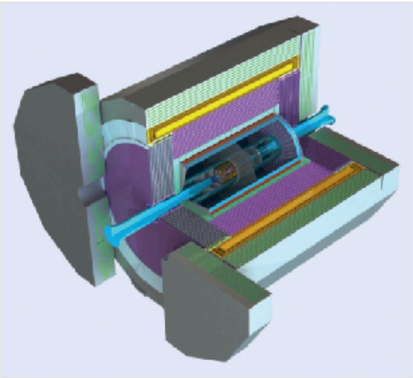
Context and Feasibility

CERNCOURIER | Reporting on international high-energy physics

POLICY | NEWS

CEPC matures, but approval is on hold

26 October 2025



Mature design The CEPC Study Group has published a technical design report for its reference detector. Credit: CEPC Study Group 2025 arXiv:2510.05260

In October, the Circular Electron–Positron Collider (CEPC) study group completed its full suite of technical design reports, marking a key step for China's Higgs-factory proposal. However, CEPC will not be considered for inclusion in China's next five-year plan (2026–2030).

"Although our proposal that CEPC be included in the next five-year plan was not successful, IHEP will continue this effort, which an international collaboration has developed for the past 10 years," says study leader Wang Yifang, of the Institute of High Energy Physics (IHEP) in Beijing. "We plan to submit CEPC for consideration again in 2030, unless FCC is officially approved before then, in which case we will seek to join FCC, and give up CEPC."

Link

FCC Council review (last week) - CERN Press Release

The independent expert committees stated that, based on the documentation presented, the FCC appears technically feasible, no showstoppers having been identified so far.

The Council concluded that the Feasibility Study provides the basis for the FCC studies to continue and that the **funding scenarios presented and the financial pledges obtained so far provide the basis for the continuation of the work towards securing the full financial commitments required for approval of the FCC project.**

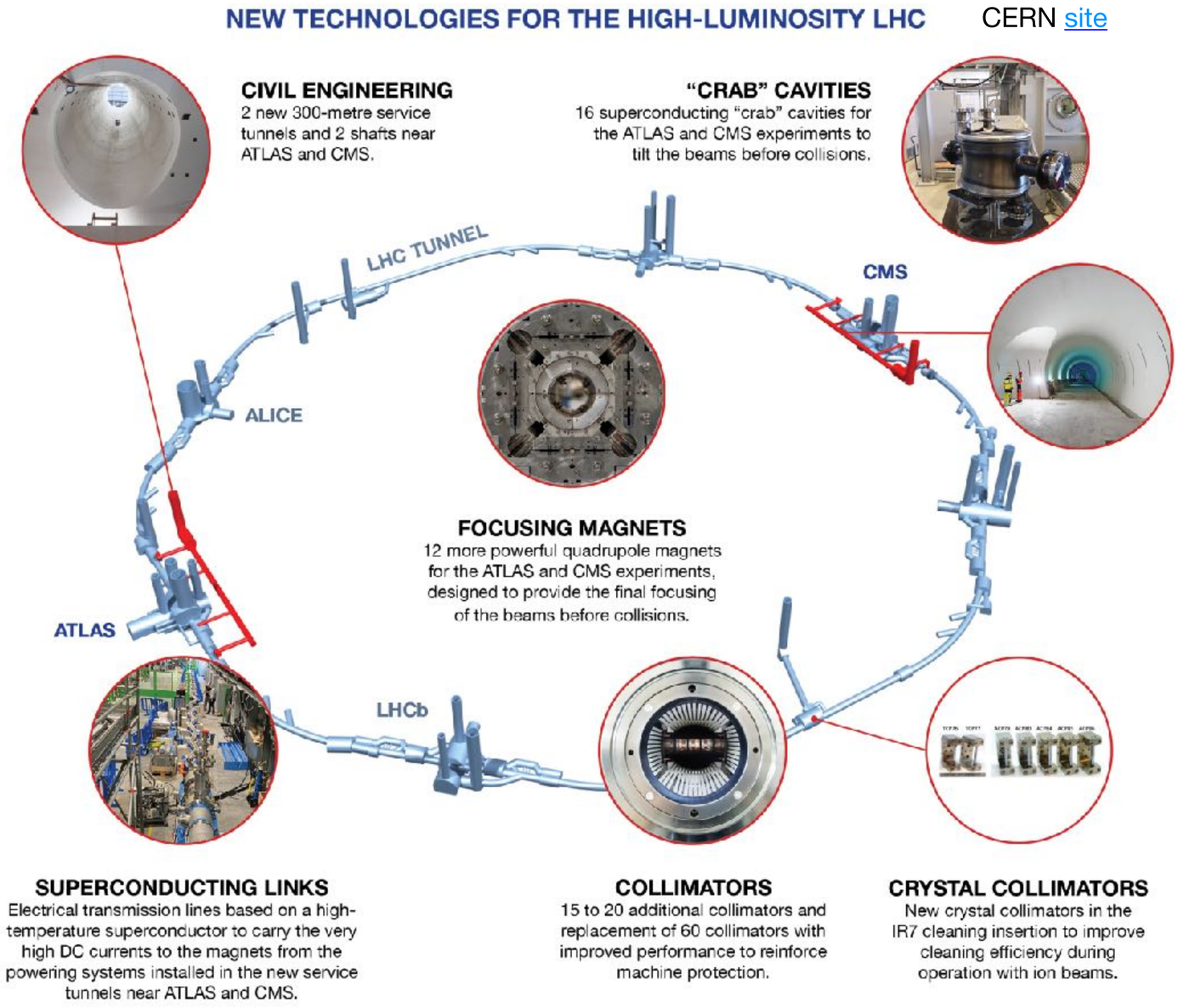
A decision by the CERN Council on the possible construction of the FCC is expected around 2028.

Briefing Book Main Parameters

Main parameters

	CLIC			FCC-ee				LCF				LEP3		
								LP	FP					
c.o.m. energy [GeV]	380	550	1500	91.2	160	240	365	250	91.2	250	550	91.2	160	230
Circumference/length collider tunnel [km]	12.1	15	29.6	90.7				33.5				27.6		
Number of experiments (IPs)	2	2	1	4				2				2		
SR power/beam [MW]	—			50				—				50		
Longitudinal polarisation (e^- / e^+) [%]	±80 / 0			0 / 0[a]				±80 / ±30			±80 / ±60	0 / 0[a]		
Number of years of operation (total)	10	N/A	10	4	2	3	5	5	1	3	10	5	4	6
Nominal years of operation (equivalent)[b]	8	N/A	9	3	2	3	4.5	3	1	3	9	5	4	6
Instantaneous luminosity per IP above 0.99 $\sqrt{s}$ (total) [10^{34} cm^{-2} s^{-1}]	1.3 (2.2)	1.6(3.2)	1.4 (3.7)	140	20	7.5	1.4	1 (1.35)	0.28 (0.28)	2 (2.7)	2.25 (3.85)	40	6.2	1.6
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs over each phase [ab^{-1}]	2.56 (4.4)	N/A	1.51 (3.96)	205	19.2	10.8	3.1	0.72 (0.97)	0.067 (0.067)	1.44 (1.94)	4.85 (8.32)	48	6.0	2.3
Peak power consumption [MW]	166	210	287	251	276	297	381	143	123	182	322	200	226	250
Electricity consumption per year of nominal operation [TWh/y][c]	0.82	1.1	1.4	1.2	1.3	1.4	1.9	0.8	0.7	1.0	1.8	0.94	1.1	1.2
Cost [BCHF] [d]	7.24	+30% [e]	+7.1 [e]	13.73			+1.26	8.29	+0.77		+5.46	3.74		

LHC Machine Towards Major LS3 Upgrades



CERN site

Front page of the CERN Courier says it all!

LS3 installation fully on track!

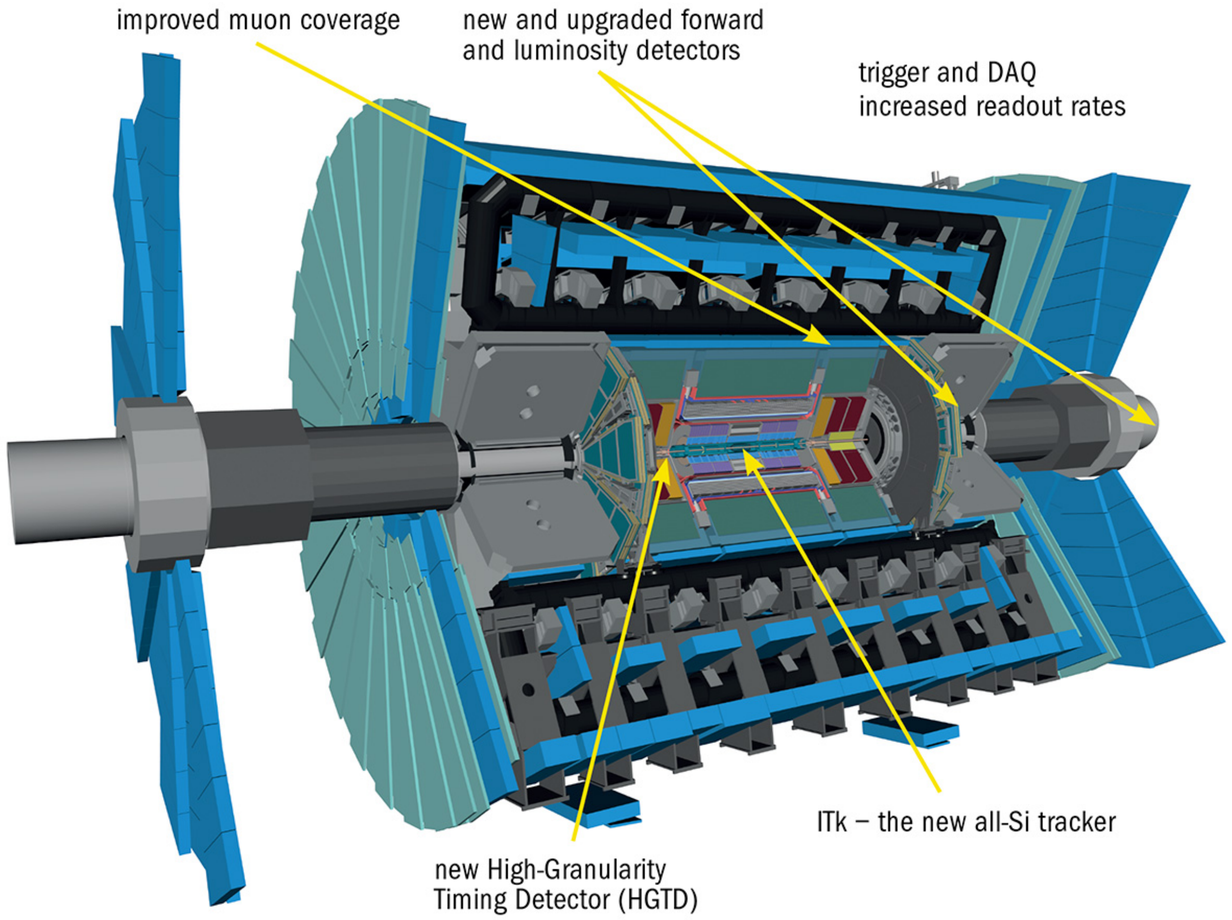
Nb_3Sn series magnets manufactured at Fermilab arrived at CERN! See CERN News.

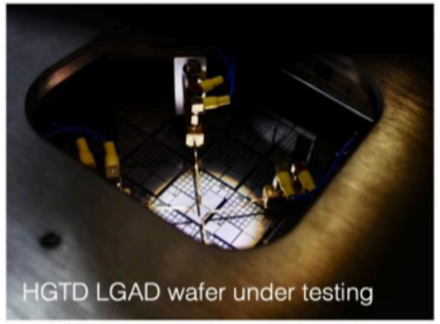
ATLAS Towards Major LS3 Upgrades

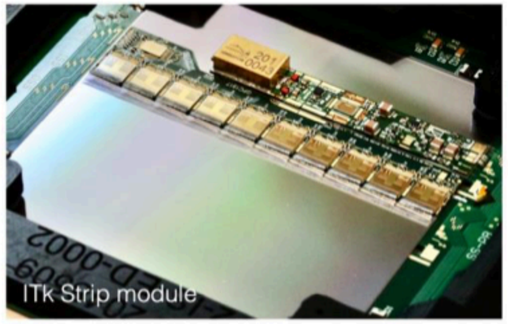
A new ATLAS for the high-luminosity era

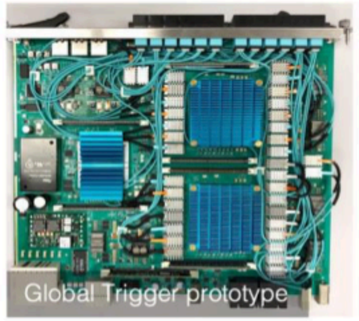
18 January 2023 | By Stefan Guincon, Christian Ohm, Caterina Vernieri

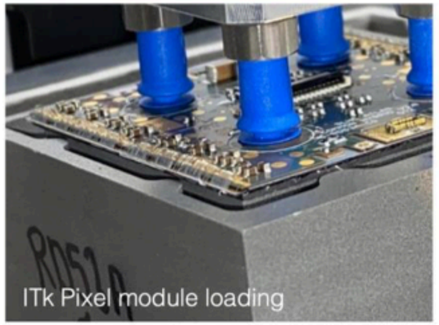
Feature link

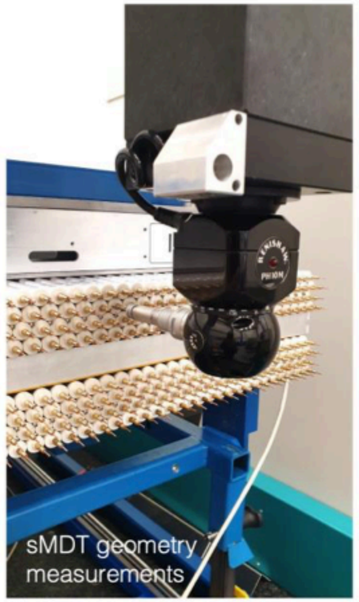


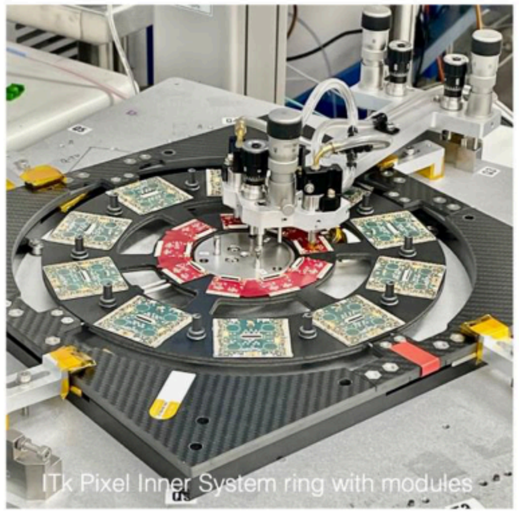


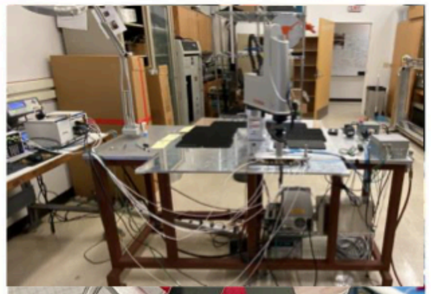












ATLAS Towards Major LS3 Upgrades

ACCELERATORS | FEATURE

CMS prepares for Phase II

9 January 2023

CERN Courier article link

Trigger/HLT/DAQ
- Track information in L1-Trigger
- L1-Trigger: 12.5 ms latency – output 750 kHz
- HLT output 7.5 kHz

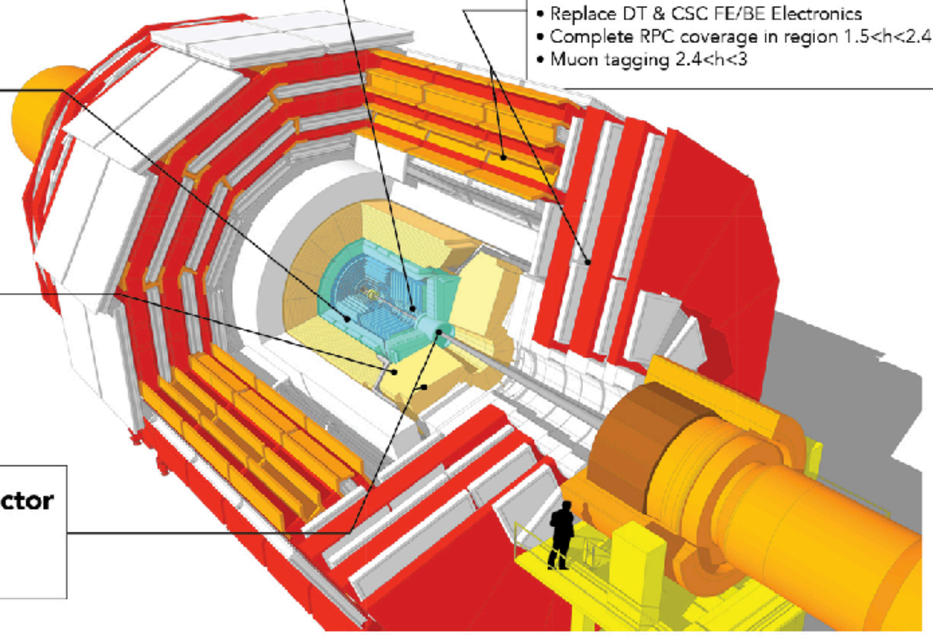
Barrel ECAL/HCAL
- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

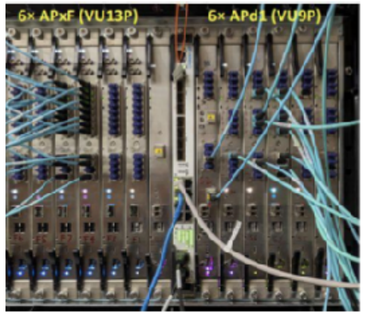
Muon Systems
- Replace DT & CSC FE/BE Electronics
- Complete RPC coverage in region 1.5<h<2.4
- Muon tagging 2.4<h<3

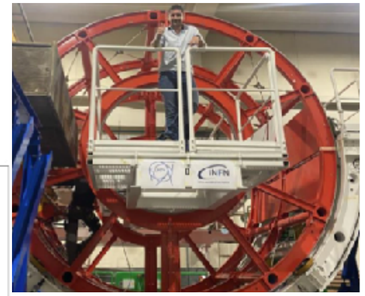
New Endcap Calorimeters
- Rad. tolerant – high granularity
- 3D capable

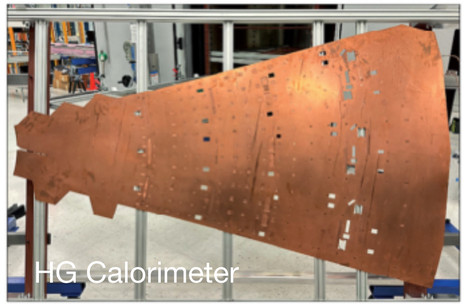
New Tracker
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (pT>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to h=4

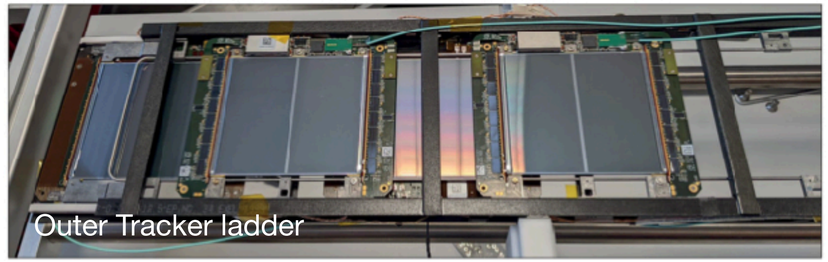
MIP Precision Timing Detector
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

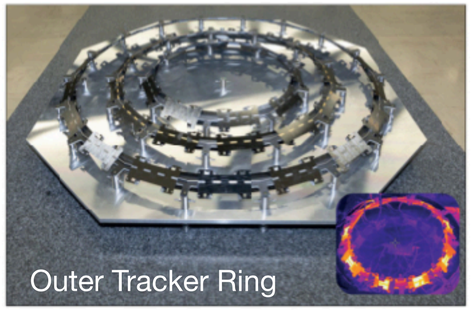








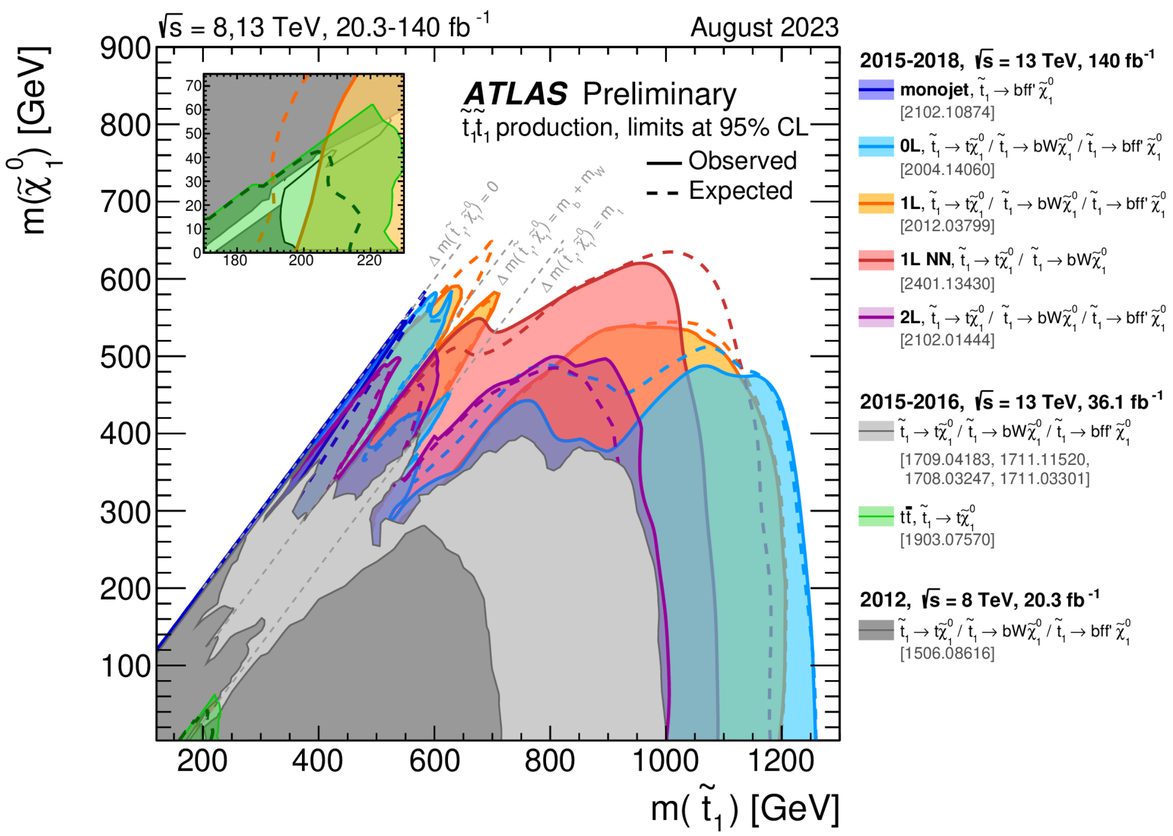




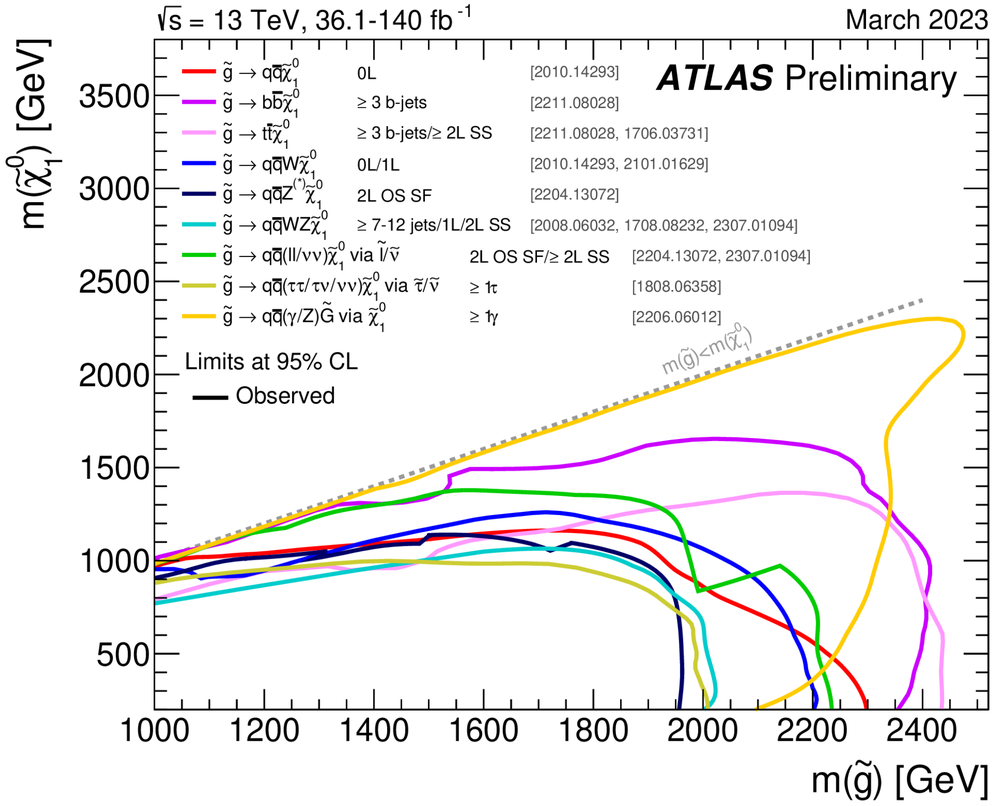
From CLASSE (Cornell)

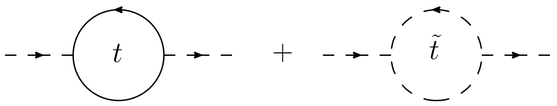
Constraining Naturalness (SUSY) Scenarios

Stop searches



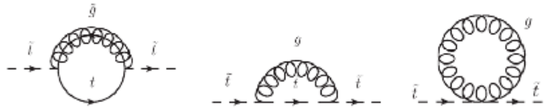
Gluino searches





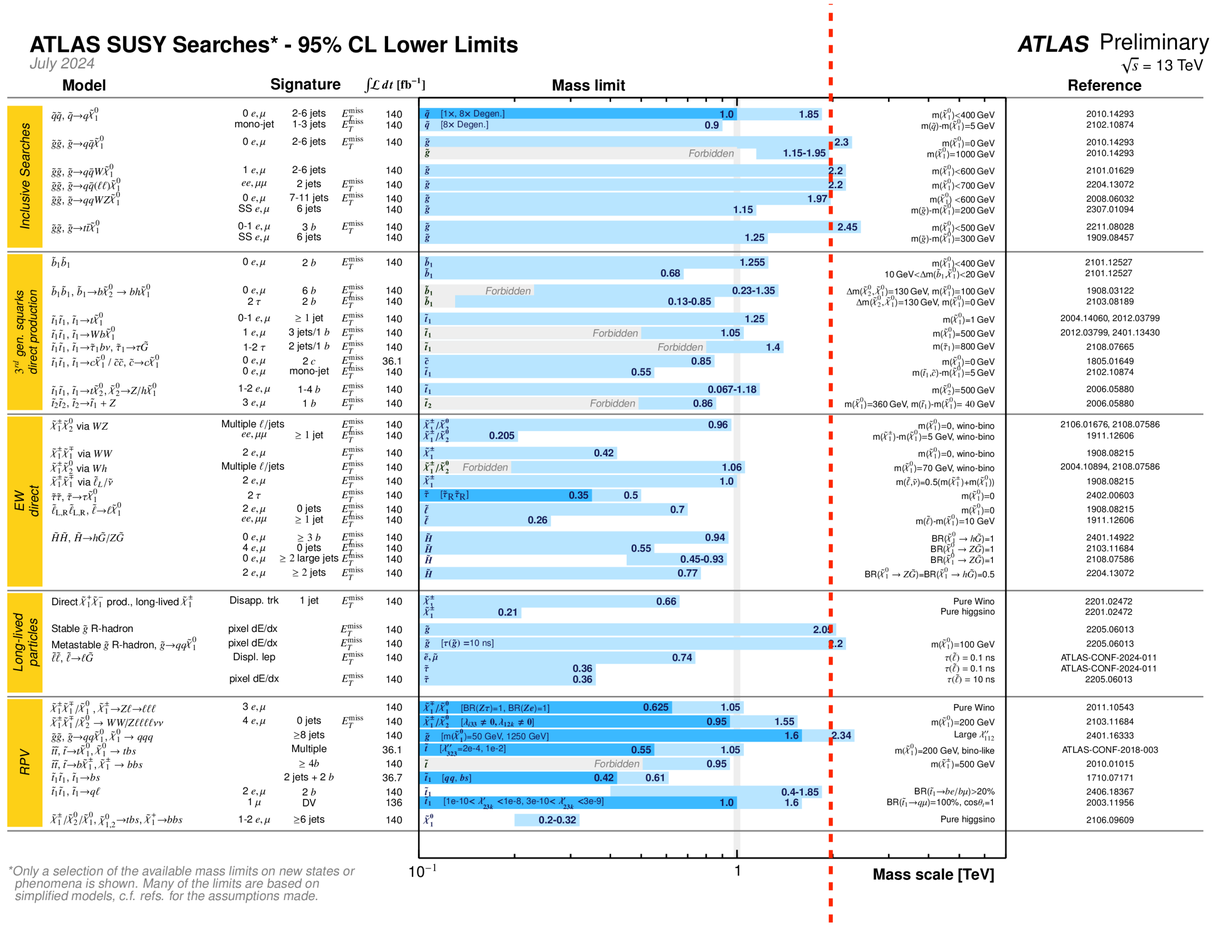
Not so natural SUSY: Stops > 1.2 TeV ~Tuning of factor **20**, but these exclusions are under specific conditions, and there are unexcluded corridors.

Stop also a scalar requires light gluinos to be light enough: for gluinos > 2.4 TeV ~tuning of Factor of **30**



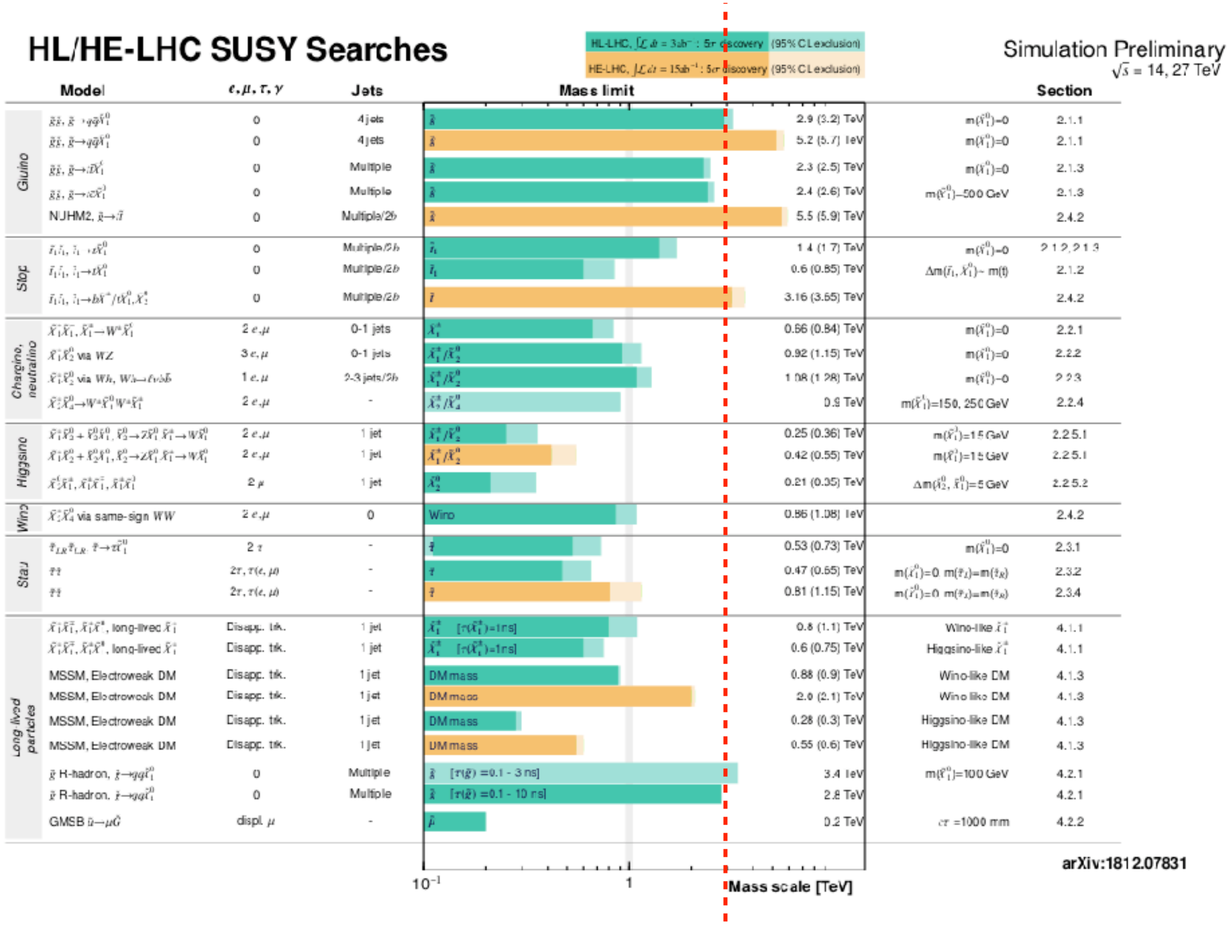
Very Large Number of SUSY Searches

(in large variety of topologies and models)



*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.

2 TeV



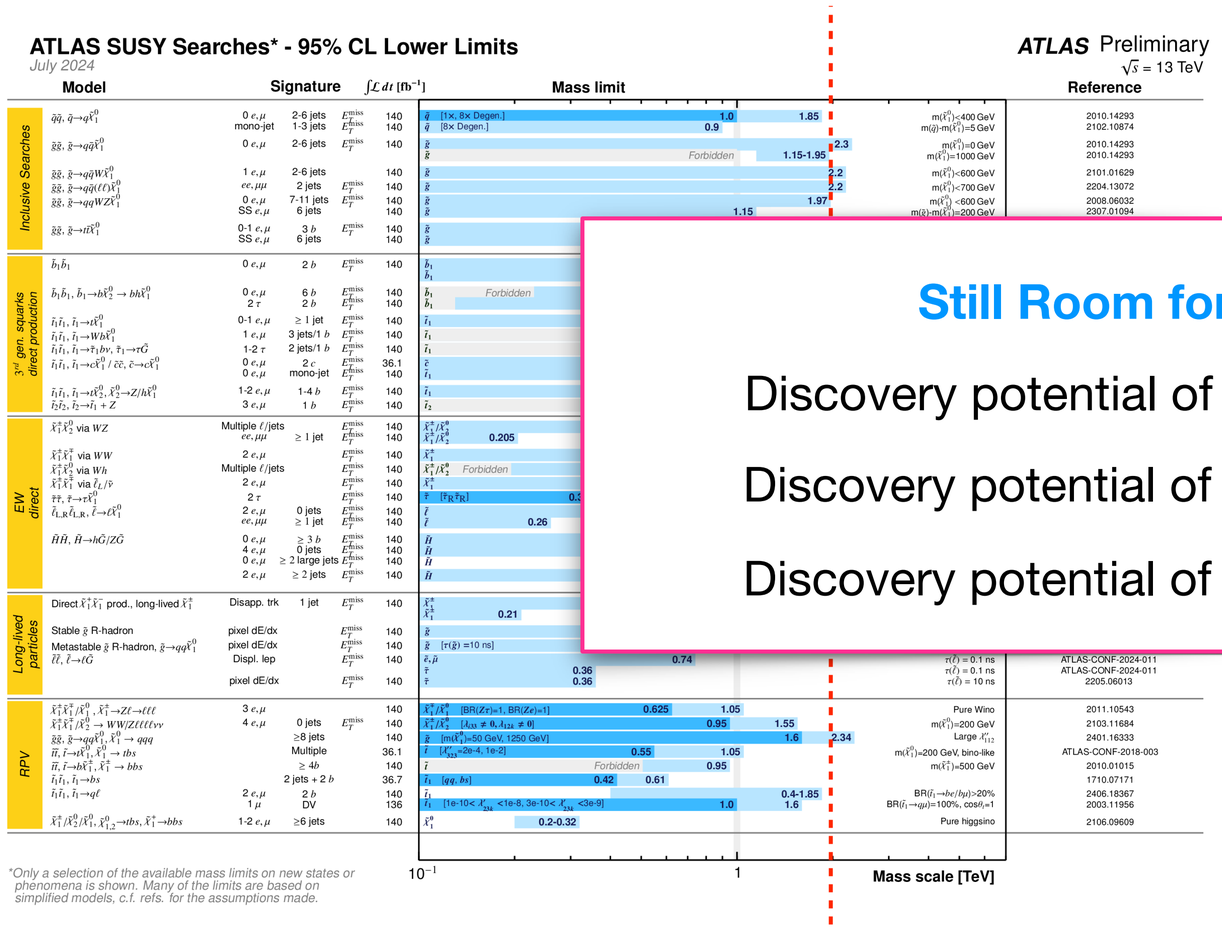
3 TeV

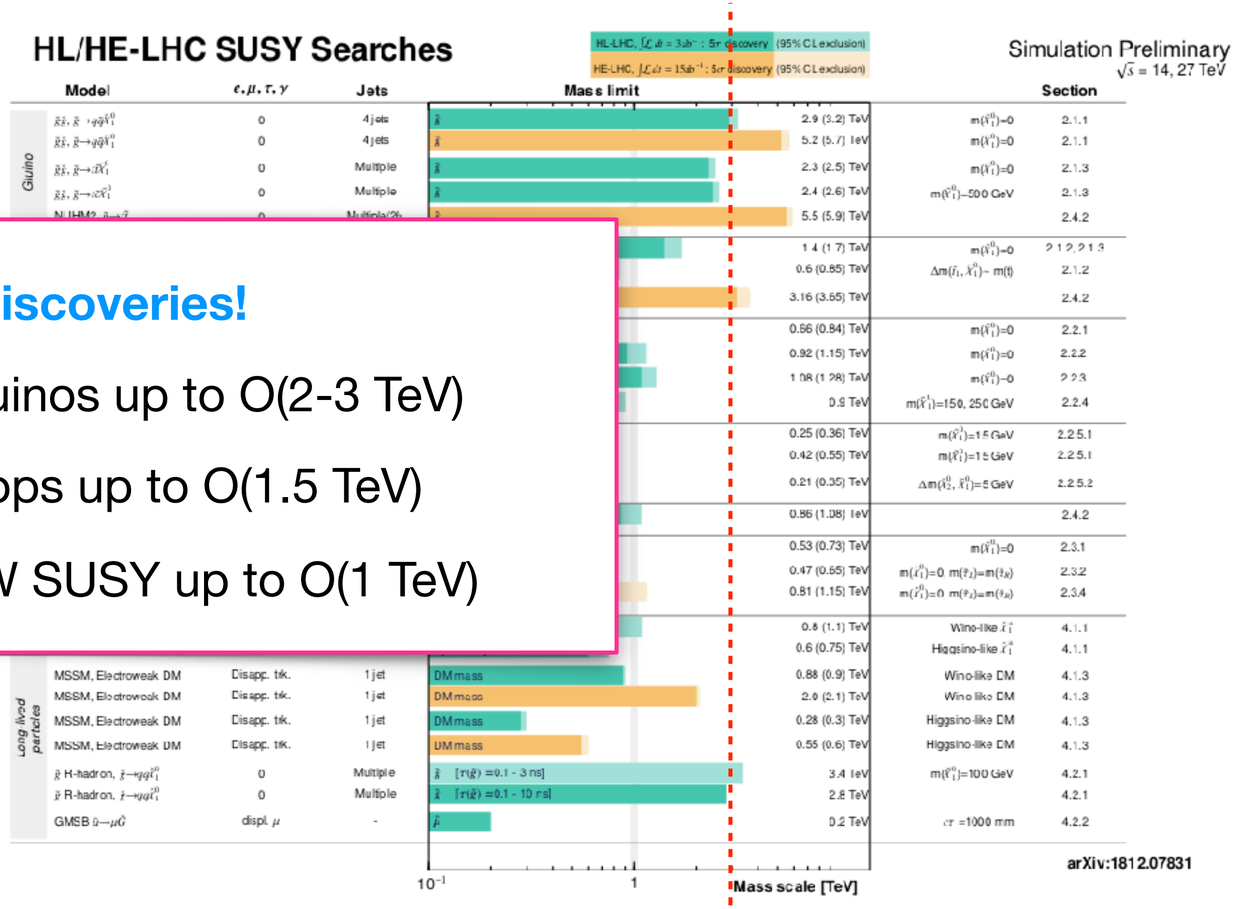
Example from ATLAS (similar for CMS)

HL-LHC YR
1812.07831

Very Large Number of SUSY Searches

(in large variety of topologies and models)





Still Room for Discoveries!

Discovery potential of gluinos up to O(2-3 TeV)

Discovery potential of stops up to O(1.5 TeV)

Discovery potential of EW SUSY up to O(1 TeV)

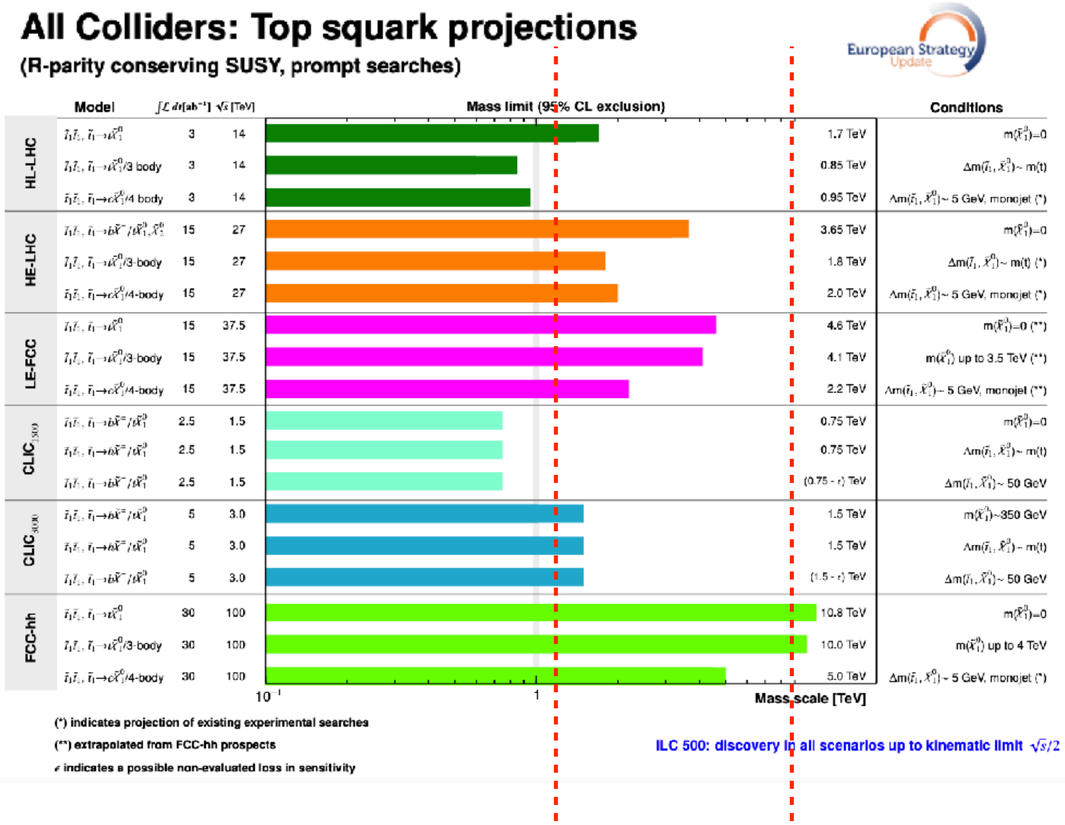
2 TeV

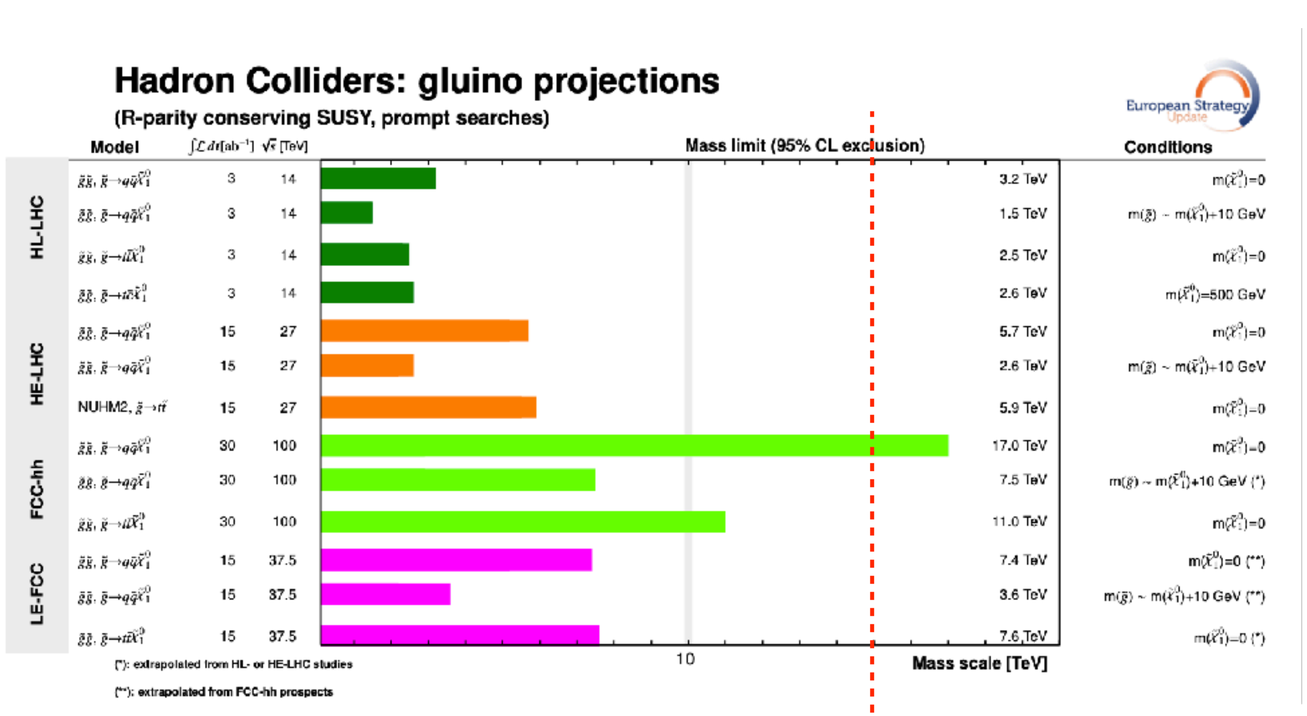
3 TeV

Example from ATLAS (similar for CMS)

HL-LHC YR
1812.07831

Projections at a Future Hadron Collider





CLIC - LHC

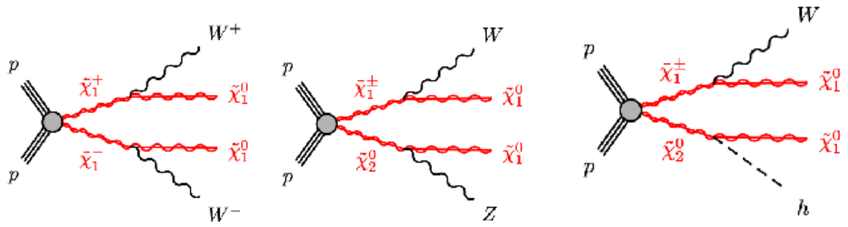
10 TeV

15 TeV

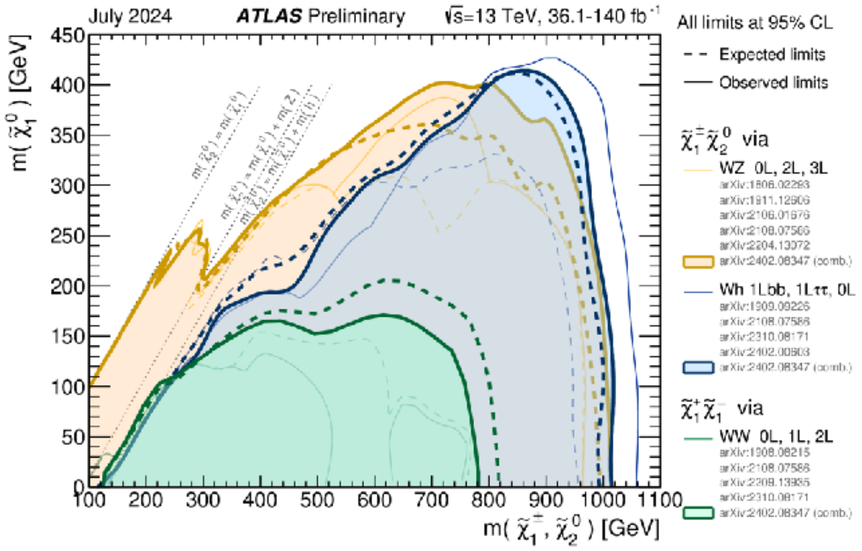
To go above the 10 TeV scale SUSY will require a **10 TeV Parton COM energy** machine e.g. **future hadron collider (100 TeV)**.

Constraining EW Natural SUSY

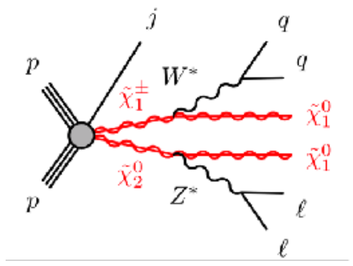
Weak production of charginos, neutralinos and sleptons



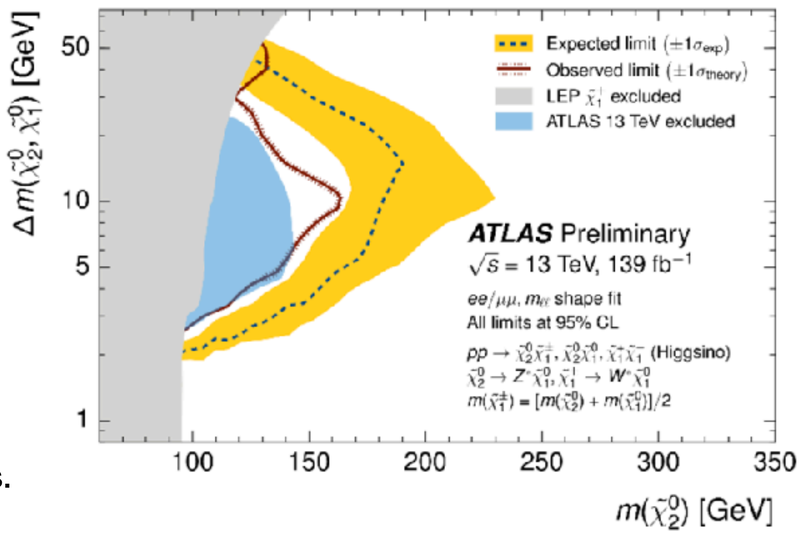
1 to 4 leptons (including taus) in the final state.
Including decays to electroweak bosons.



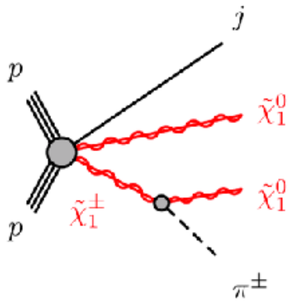
Weak production of charginos and neutralinos in compressed scenarios



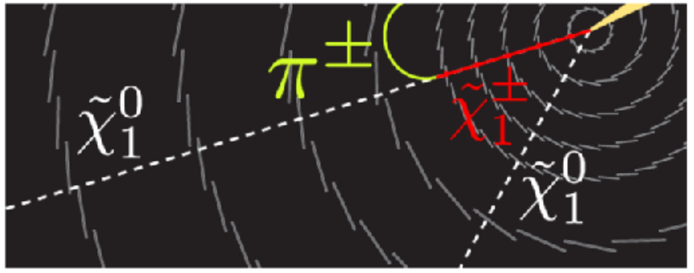
Example of boosting to find small mass differences.



SUSY in highly compressed scenarios



Disappearing tracks topologies
(Uses MET Trigger - requires ISR jet)

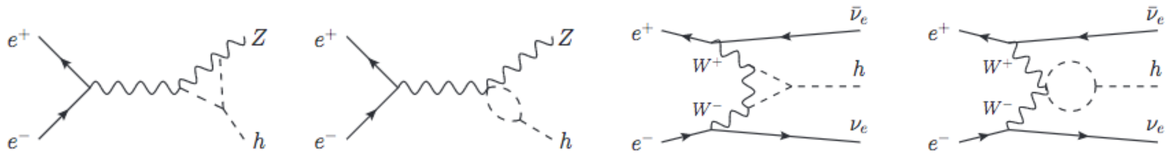


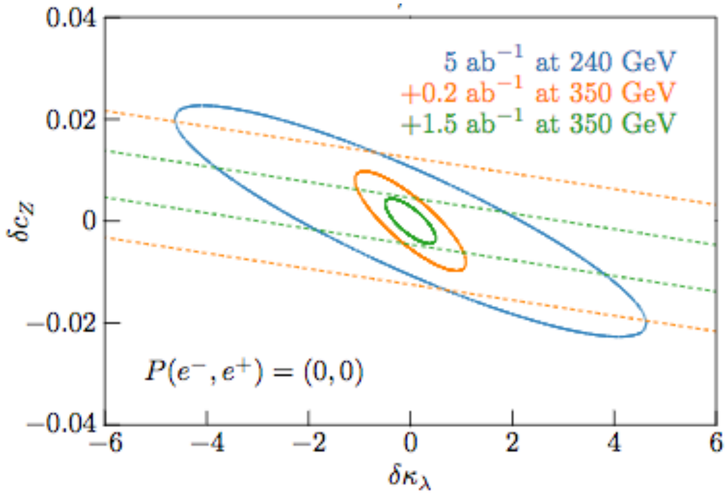
Scenario where the charginos and neutralinos are almost degenerate (chargino has significant lifetime and is seen in the first layers of the ID).

Making the Impossible - the Higgs Self Coupling

Loop level constraint on Higgs self coupling (assuming no BSM physics in the loops)

Higgs cross section at 240, 350, at 365 GeV



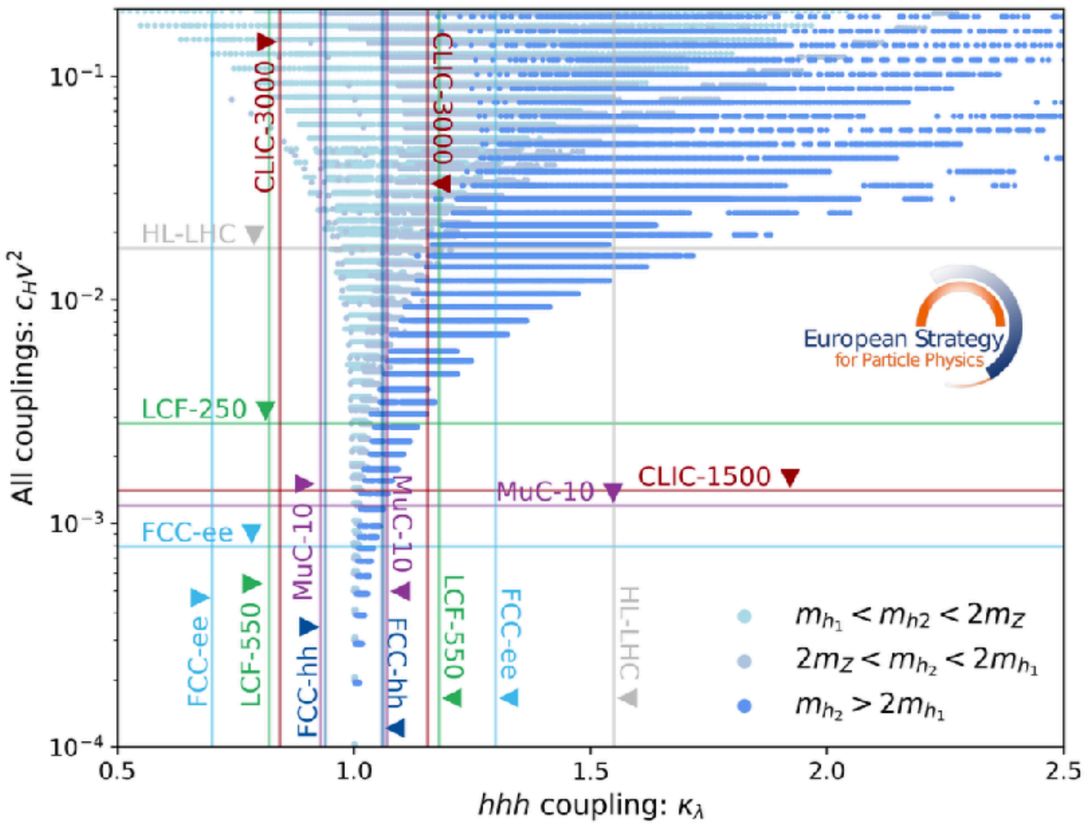


Higgs self coupling precision **~30%** - reduced to **~20%** with kappaZ = 1 from SM

Measurements at different energies will be very important.

In the case of of a specific BSM model

points correspond to strong first-order phase transition in the early universe is possible within the scalar singlet model



FCC will be decisive (also see that the most precisely known coupling is setting stringent limits)

Collider Challenges

Circular e^+e^-

Synchrotron Radiation losses but beams are circulating.

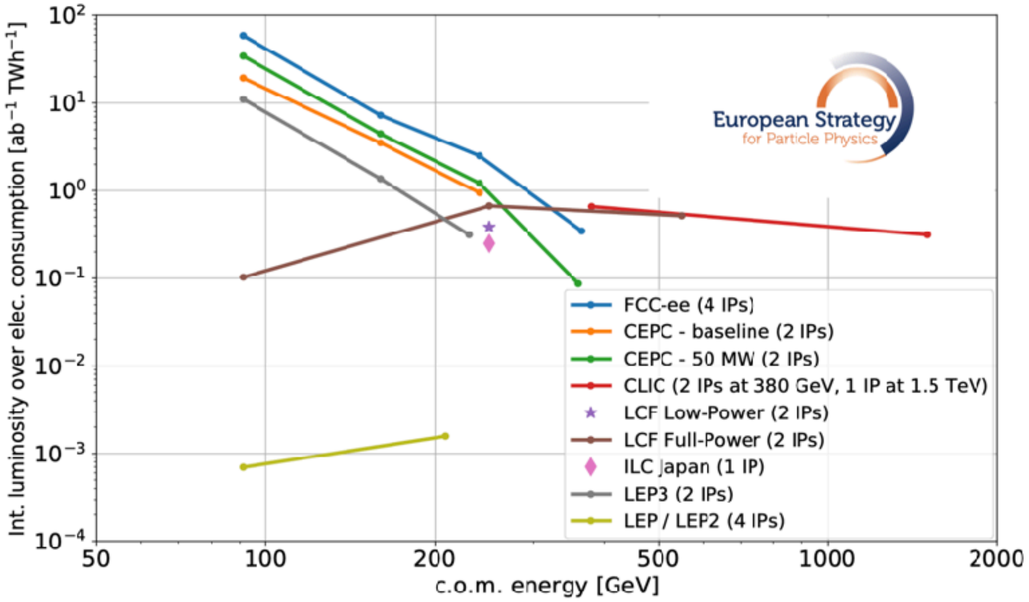
Luminosity goal of $10^{36}\,cm^{-2}s^{-1}$ close to the goal of Super KEK B

Importants aspects: Crab cavities, beam-beam effects.

Linear e^+e^-

No Synchrotron Radiation losses but beams are dumped.

Need high acceleration gradients, extreme focussing, beam stability and intense positron production (still needing R&D).



Circular hadron collider

R&D on High- and Low-Temperature Superconductors required

HTS R&D in various domains: REBCO and IBS Conductor

Industrialisation process of magnets

Superconductor supply and cost critical

Narrow down between Nb_3Sn and HTS on ~2035 timescale