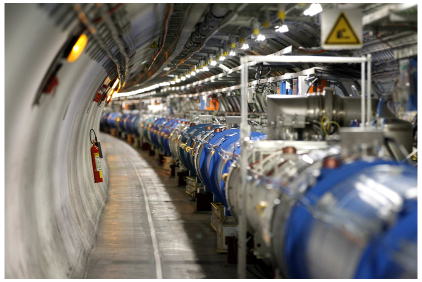
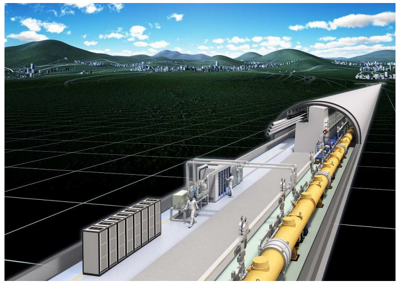
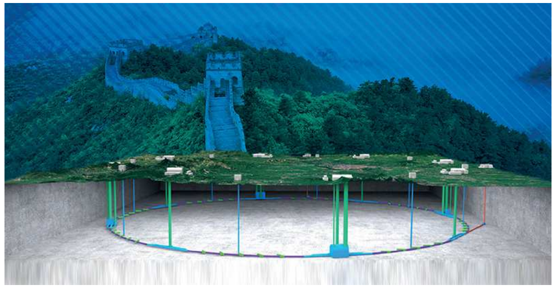
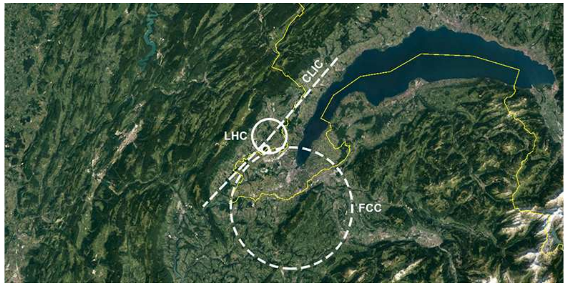
The present and future of experimental high energy physics









Sara Strandberg

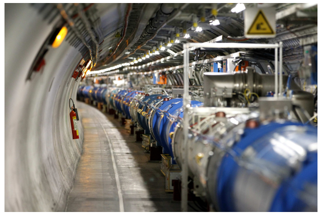
Stockholm University

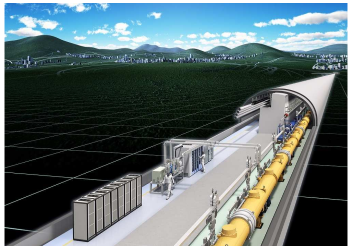
Quantum Connections

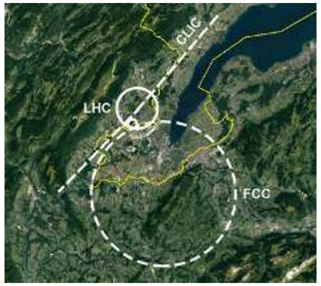
Högberga Gård, June 22nd 2021

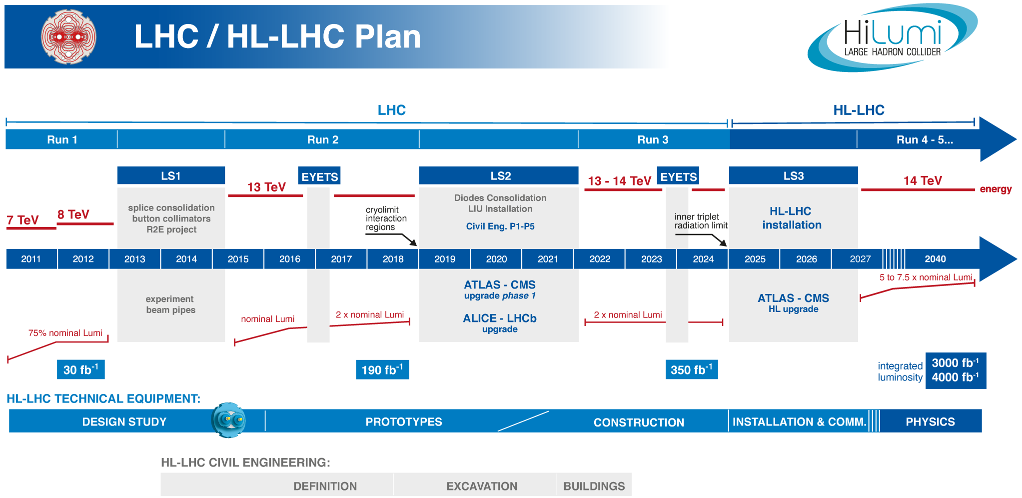
Outline

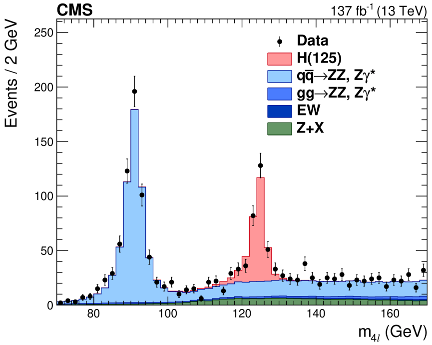
- Introduction to colliders
  - LHC
  - High-luminosity LHC
  - Potential future colliders
- Results and prospects
  - SM precision measurements
  - BSM searches

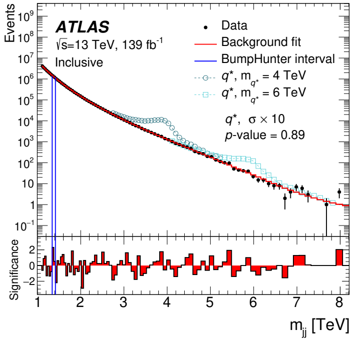


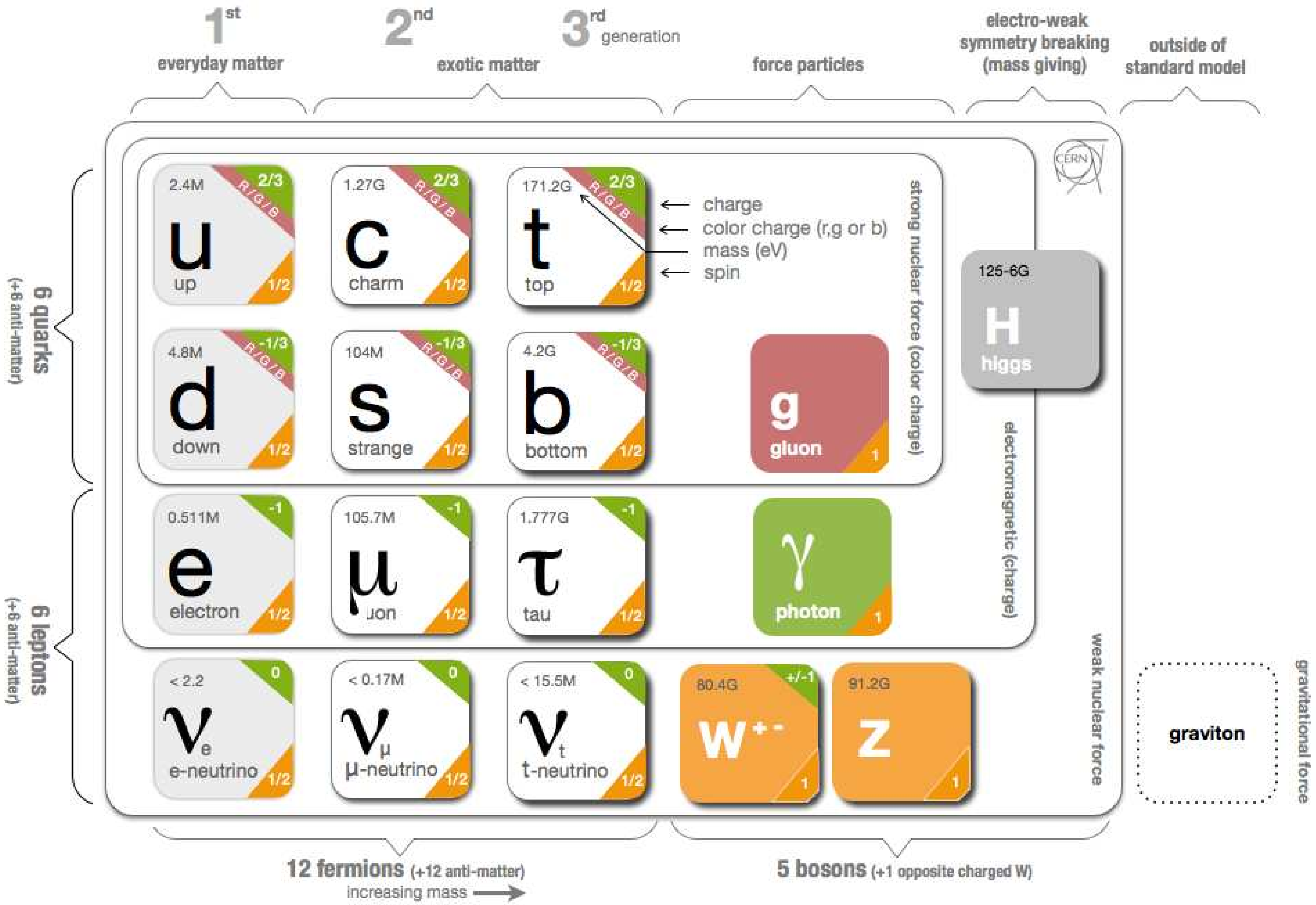








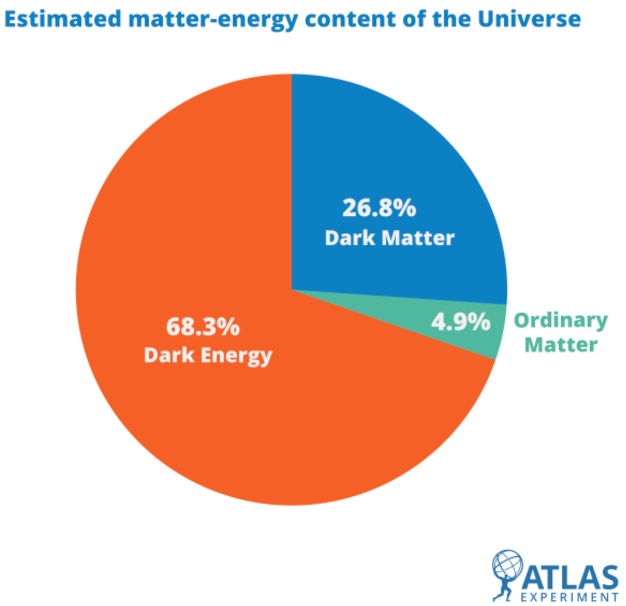



1st
everyday matter
2nd
exotic matter
3rd generation
force particles
electro-weak symmetry breaking (mass giving)
outside of standard model
6 quarks (+6 anti-matter)
6 leptons (+6 anti-matter)
2.4M
2/3
R/G/B
u
up
1/2
1.27G
2/3
R/G/B
c
charm
1/2
171.2G
2/3
R/G/B
t
top
1/2
charge
color charge (r,g or b)
mass (eV)
spin
4.8M
-1/3
R/G/B
d
down
1/2
104M
-1/3
R/G/B
s
strange
1/2
4.2G
-1/3
R/G/B
b
bottom
1/2
g
gluon
1
strong nuclear force (color charge)
125-6G
H
higgs
0.511M
-1
e
electron
1/2
105.7M
-1
μ
μon
1/2
1.777G
-1
τ
tau
1/2
γ
photon
1
electromagnetic (charge)
< 2.2
0
ν_e
e-neutrino
1/2
< 0.17M
0
ν_μ
μ-neutrino
1/2
< 15.5M
0
ν_t
t-neutrino
1/2
80.4G
+/-1
W+-
1
91.2G
Z
1
weak nuclear force
graviton
gravitational force
CERN
12 fermions (+12 anti-matter)
increasing mass
5 bosons (+1 opposite charged W)

Shortcomings of the Standard Model

- The Standard Model is exceptionally successful in the lab.
- But has clear limitations:

- Neutrinos are massless.
- Can only explain 5% of the energy content of the universe.
- Cannot explain the matter-antimatter asymmetry in the Universe.
- Does not include gravity.



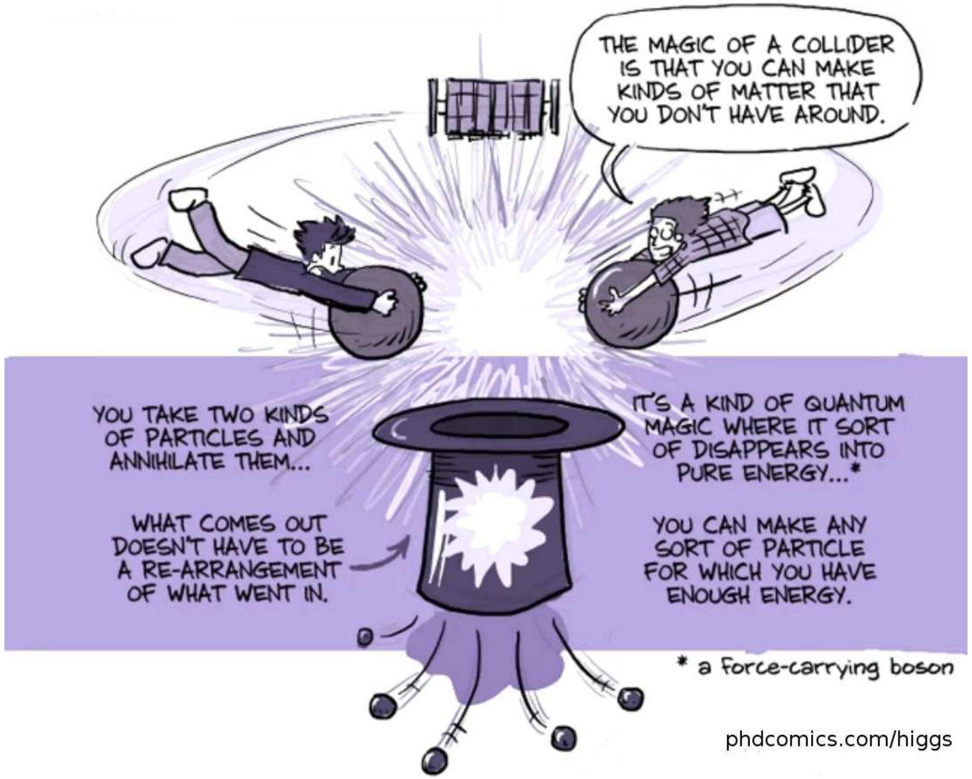
- Also suffers from fine-tuning:

- Strong CP problem. Experiments suggest that CP is conserved in strong interactions, but not required by SM.
- Hierarchy problem. No symmetry to protect the Higgs mass. Need severe fine-tuning to keep it at EW scale.

Why particle colliders?

- To study properties of short-lived particles we need to produce them.

- Heavy particles ↔ high energies.
- Small scales ↔ high energies.
- To reach required precision we need a controlled environment.
- Also need large amounts of data since particle interactions are statistical processes.



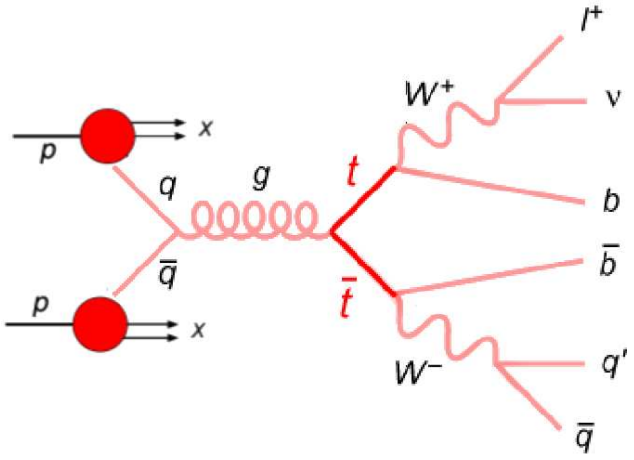
* a force-carrying boson

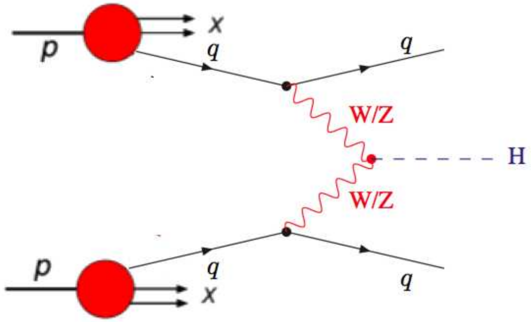
phdcomics.com/higgs

- Total number of occurances of process p depends on cross section σ_p and integrated luminosity $\int Ldt$ ($\sim$ total number of collisions) through $N_p = \int Ldt \cdot \sigma_p$.

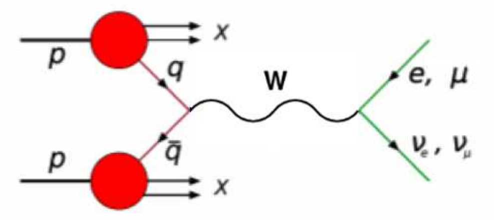
How can they probe BSM physics?

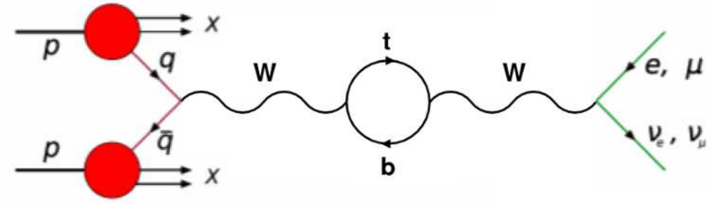
- **Direct search program**
  - If kinematically accessible, new particles can be directly produced and discovered.

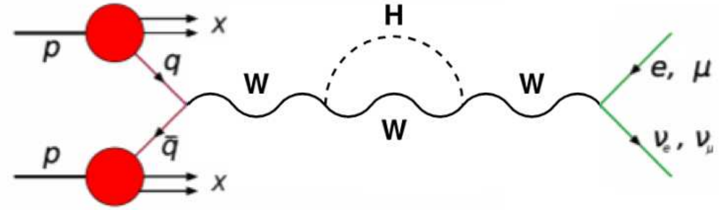




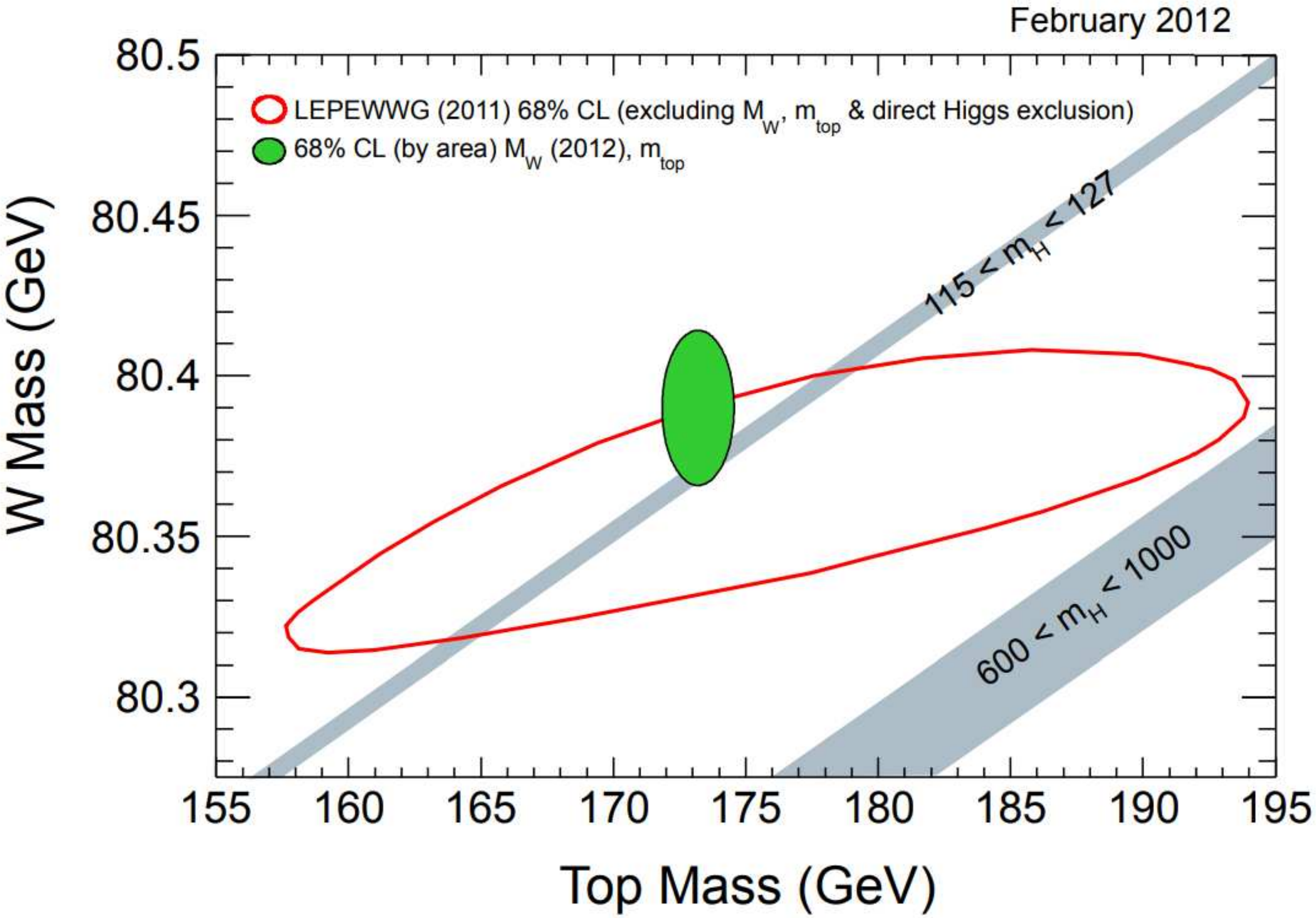
- **Indirect search program**
  - Heavier new particles can still appear as virtual particles in loop diagrams and alter the properties of known particles and processes.



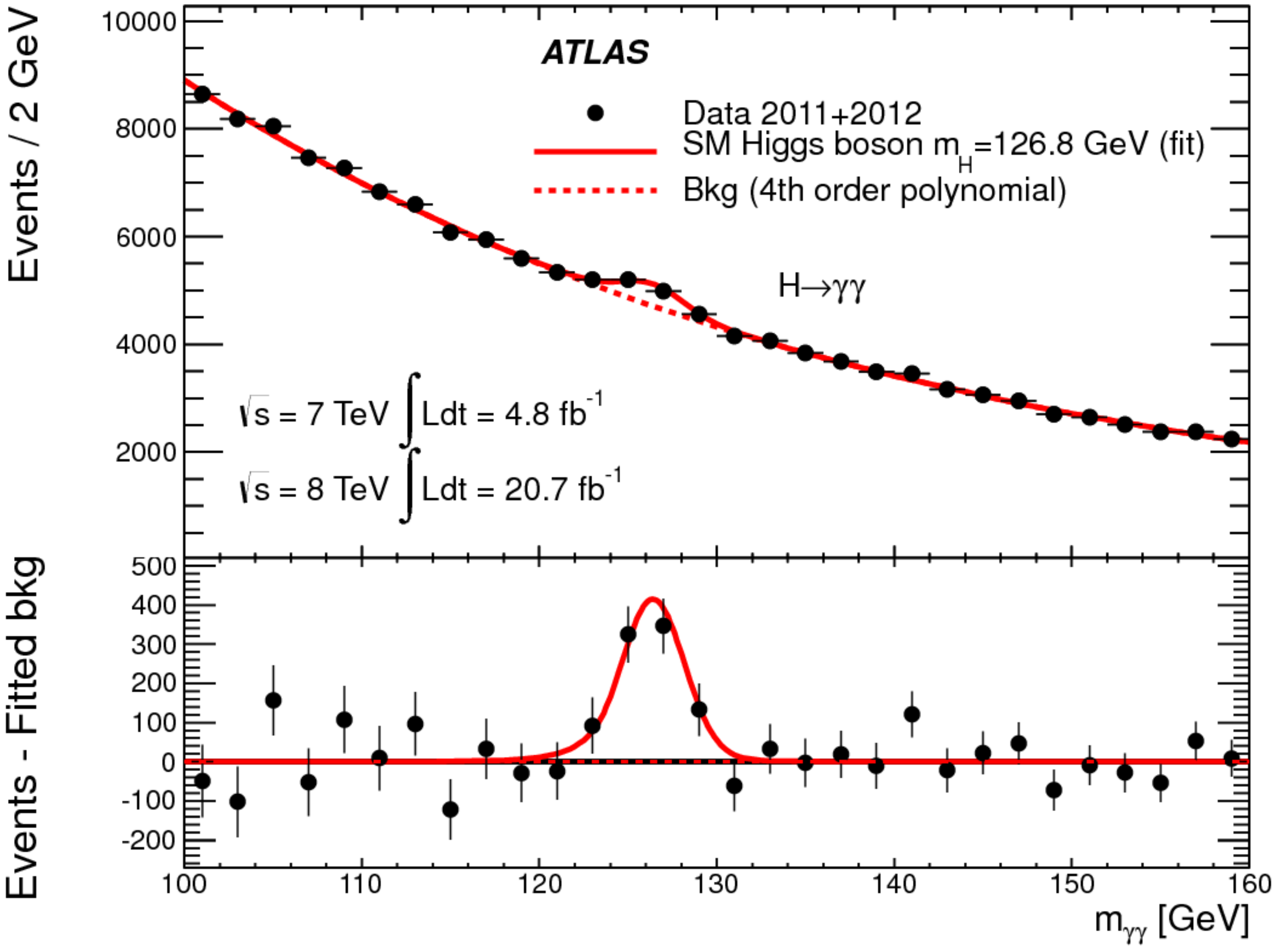




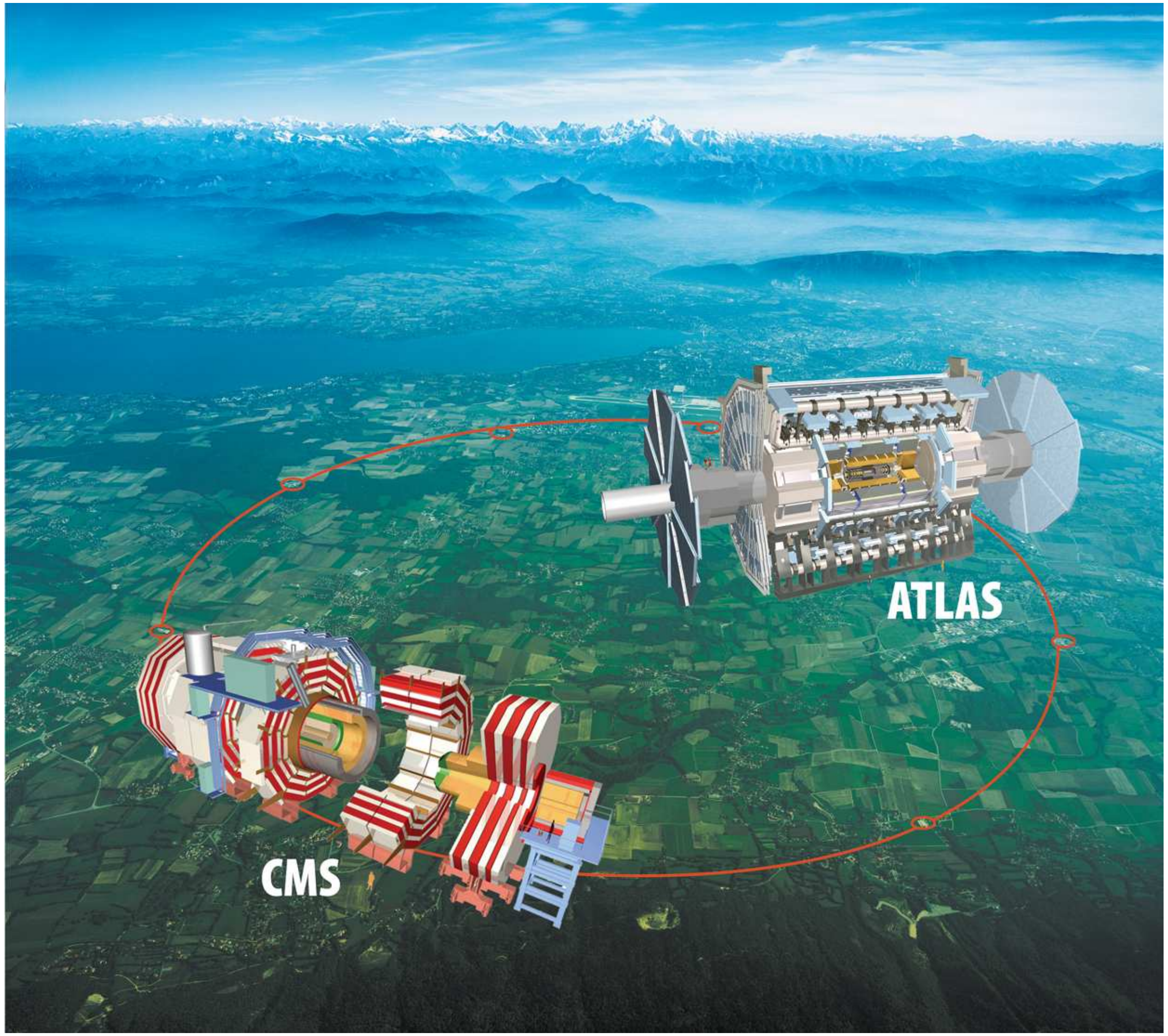
Constraints on Higgs boson mass



Higgs discovery July 2012

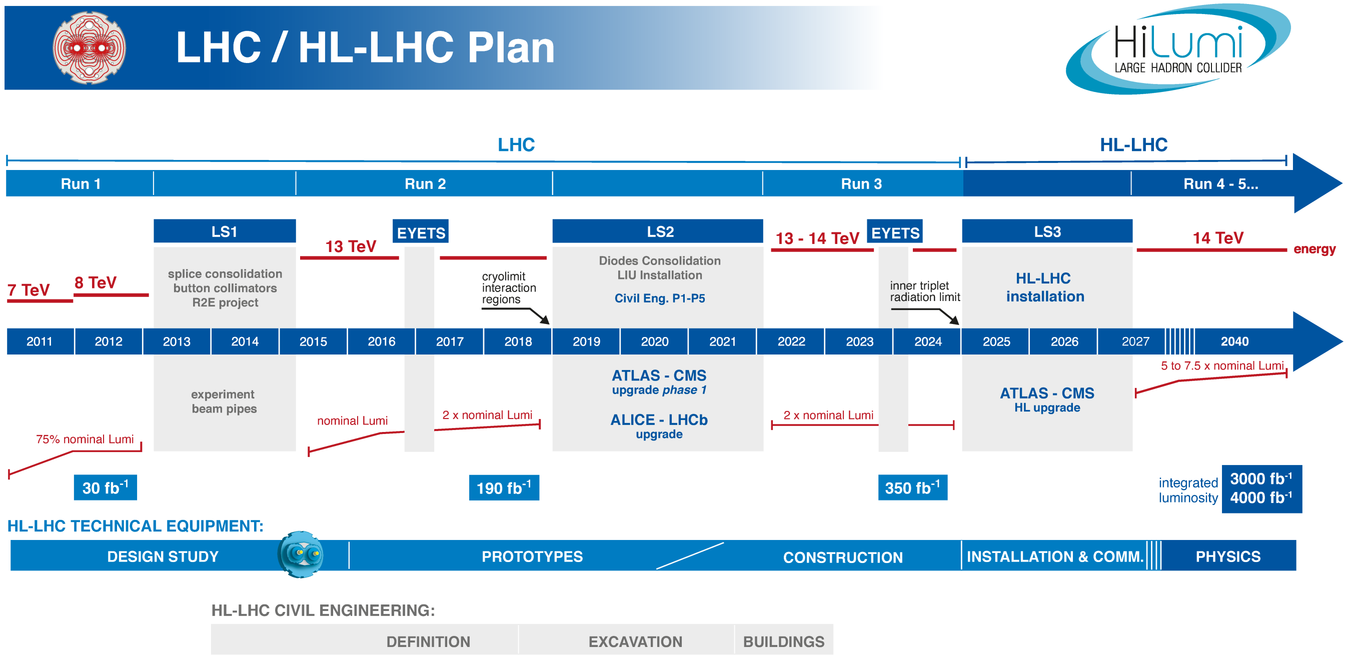


The Large Hadron Collider



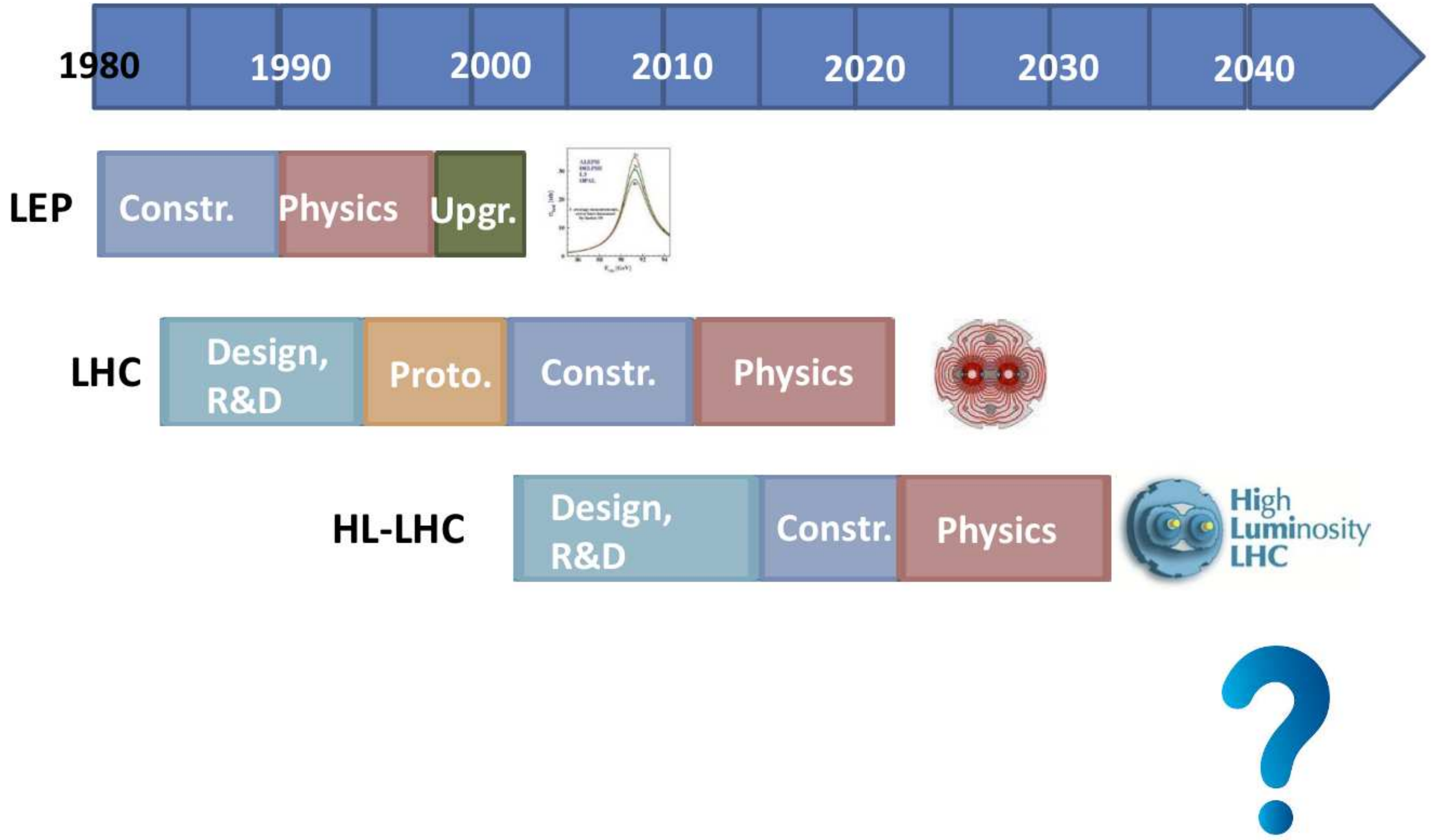
- 27 km long tunnel
- Collides protons
  - at 13 TeV
  - 40 million times per second
- 1232 dipole magnets
  - cooled with liquid helium to 1.9 K
  - 8.4 T magnetic field from 11 700 A current
- $\mathcal{O}(1500)$ quadru-, sextu-, octupole magnets

High-luminosity LHC



- To maximize physics output, a major upgrade to the accelerator (HL-LHC) is planned.
- Aim is to increase the instantaneous luminosity and deliver 3000 fb^{-1}.
- The LHC detectors will need be upgraded to cope with the challenging environement induced by the higher data rates.

Gazing into the future



1980 1990 2000 2010 2020 2030 2040

LEP Constr. | Physics | Upgr.

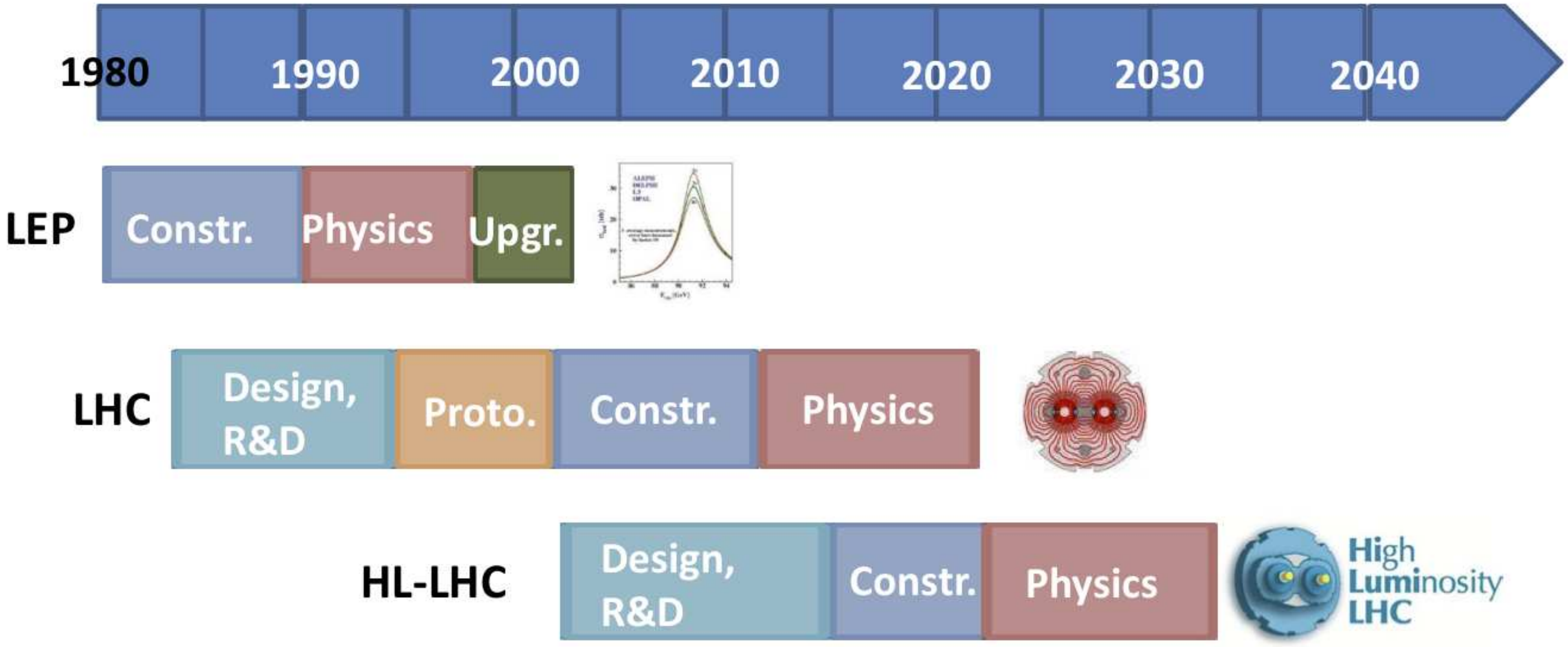
LHC Design, R&D | Proto. | Constr. | Physics

HL-LHC Design, R&D | Constr. | Physics

High Luminosity LHC

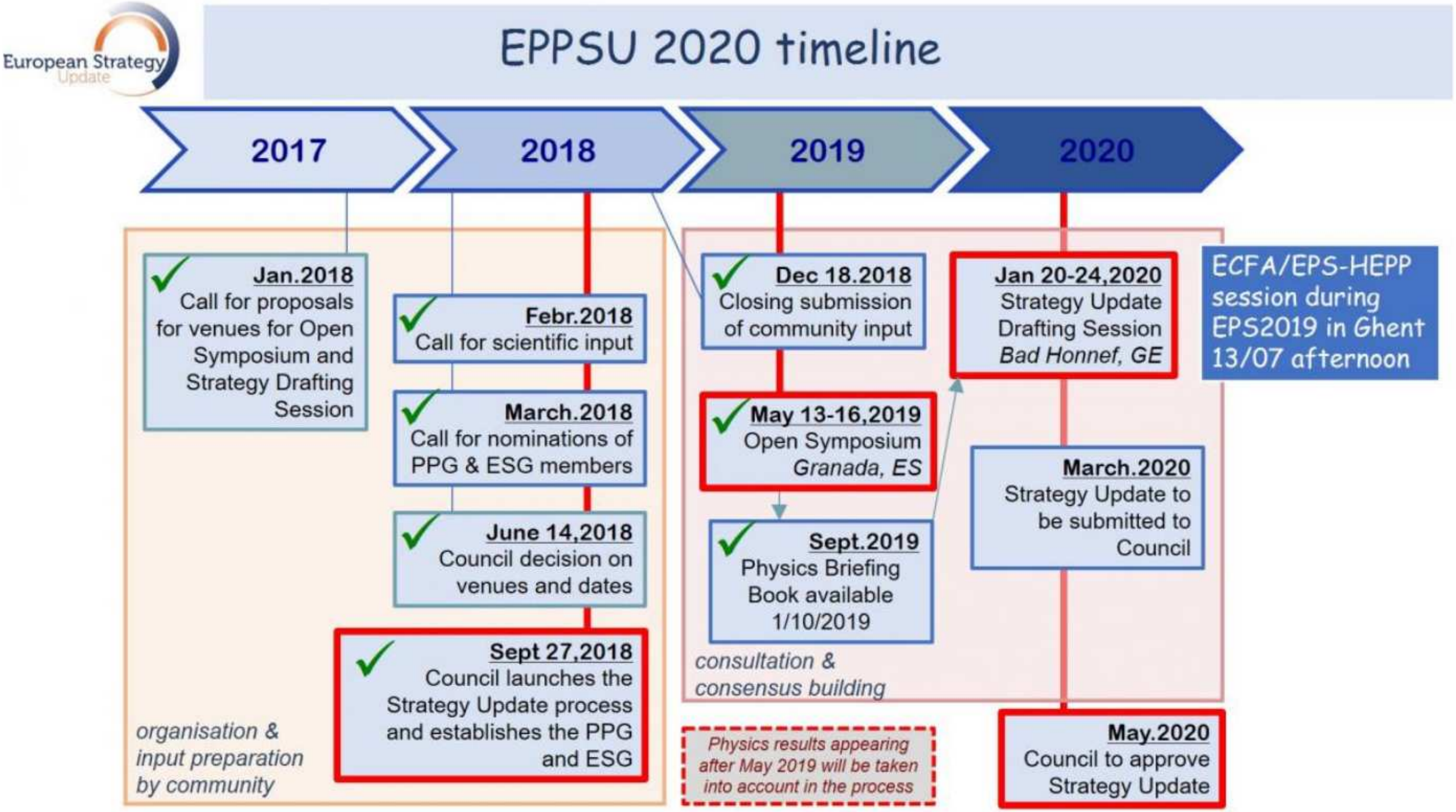
?

Gazing into the future



European Strategy Update

The European Particle Physics Strategy Update



European Strategy Update

EPPSU 2020 timeline

2017 → 2018 → 2019 → 2020

✓ **Jan.2018**
Call for proposals for venues for Open Symposium and Strategy Drafting Session

✓ **Febr.2018**
Call for scientific input

✓ **March.2018**
Call for nominations of PPG & ESG members

✓ **June 14,2018**
Council decision on venues and dates

✓ **Sept 27,2018**
Council launches the Strategy Update process and establishes the PPG and ESG

organisation & input preparation by community

✓ **Dec 18.2018**
Closing submission of community input

✓ **May 13-16,2019**
Open Symposium
Granada, ES

✓ **Sept.2019**
Physics Briefing Book available 1/10/2019

consultation & consensus building

Physics results appearing after May 2019 will be taken into account in the process

Jan 20-24,2020
Strategy Update Drafting Session
Bad Honnef, GE

March.2020
Strategy Update to be submitted to Council

May.2020
Council to approve Strategy Update

ECFA/EPS-HEPP session during EPS2019 in Ghent 13/07 afternoon

The Physics Briefing Book

CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Electroweak Physics: Richard Keith Ellis[1], Beate Heinemann[2,3] *(Conveners)*
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Elisabeth Petit[11], Riccardo Rattazzi[12], Wouter Verkerke[13] *(Contributors)*

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Nestor Armesto[18], Daniël Boer[19], David d'Enterria[20], Tetyana Galatyuk[21], Thomas Gehrmann [22],
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Sandra Malvezzi[33], Ana Teixeira[34], Jure Zupan[35] *(Scientific Secretaries)*
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Gudrun Hiller[39], Gino Isidori[22], Yoshikata Kuno[40], Alberto Lusiani[41], Yosef Nir[36],
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Neutrino Physics & Cosmic Messengers: Stan Bentvelsen[45], Marco Zito[46,47] *(Conveners)*
Albert De Roeck [20], Thomas Schwetz[29] *(Scientific Secretaries)*
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Matthew McCullough[20], Gilad Perez[36], Philipp Roloff[20], Veronica Sanz[55], Andreas Weiler[44],
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Philip Burrows[26], Frank Zimmermann[20] *(Scientific Secretaries)*
Michael Benedikt[20], Pierluigi Campana[54], Edda Gschwendtner[20], Erk Jensen[20], Mike Lamont[20],
Wim Leemans[2], Lucio Rossi[20], Daniel Schulte[20], Mike Seidel[62], Vladimir Shiltsev[63],
Steinar Stapnes[20], Akira Yamamoto[20,64] *(Contributors)*

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Roger Jones[67], Emilia Leogrande[20] *(Scientific Secretaries)*
Ian Bird[20], Simone Campana[20], Ariella Cattai[20], Didier Contardo[68], Cinzia Da Via[69], Francesco Forti[70],
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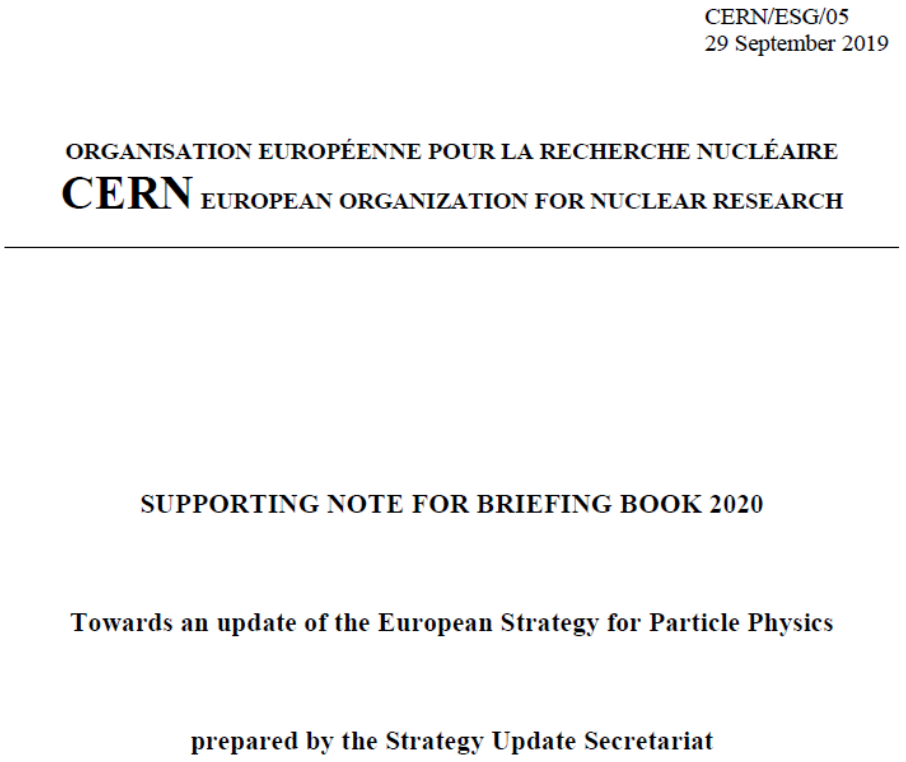
Editors: Halina Abramowicz[71], Roger Forty[20], and the Conveners



CERN/ESG/05
29 September 2019

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

SUPPORTING NOTE FOR BRIEFING BOOK 2020

Towards an update of the European Strategy for Particle Physics

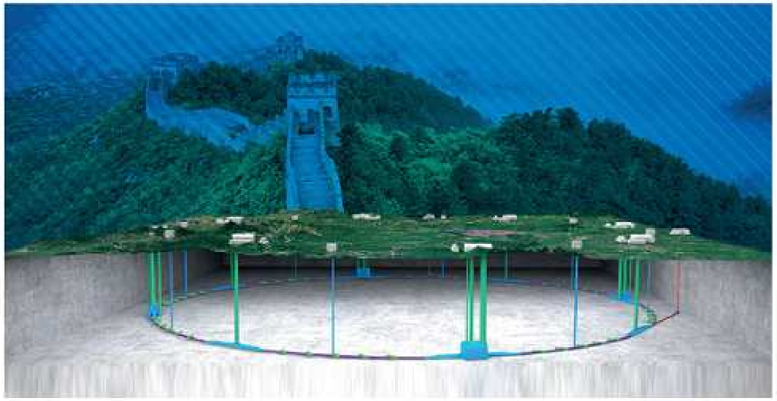
prepared by the Strategy Update Secretariat

`https://cds.cern.ch/record/2691414`

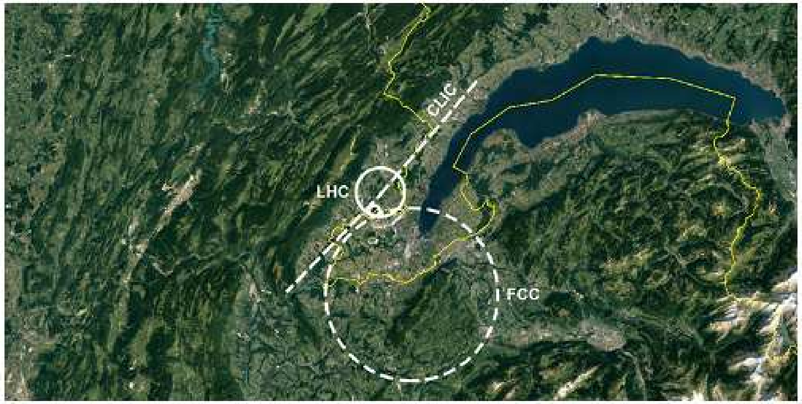
The starting lineup

- Lepton or hadron collider, linear or circular?

ILC, Japan

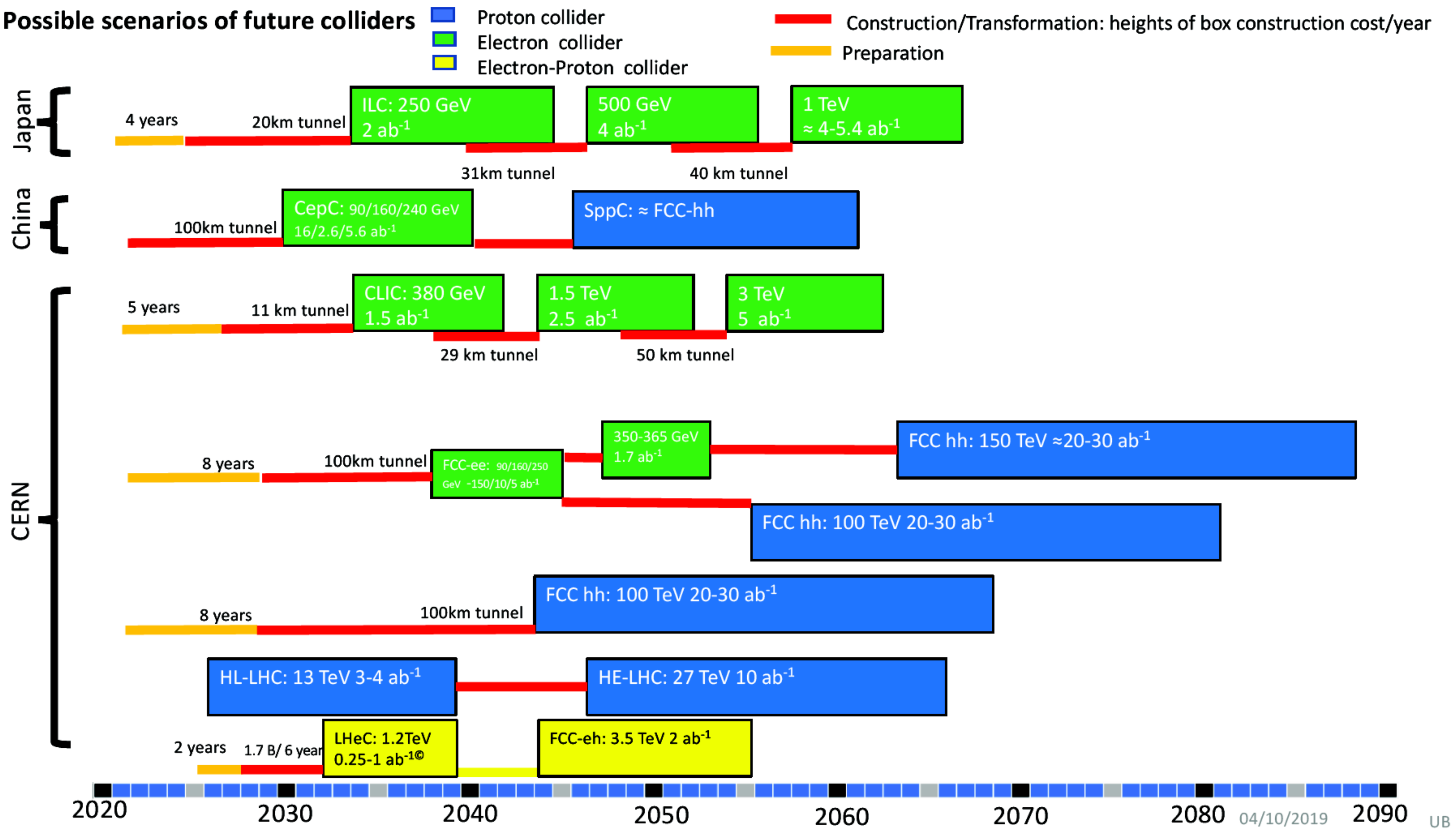


CepC/SppC, China

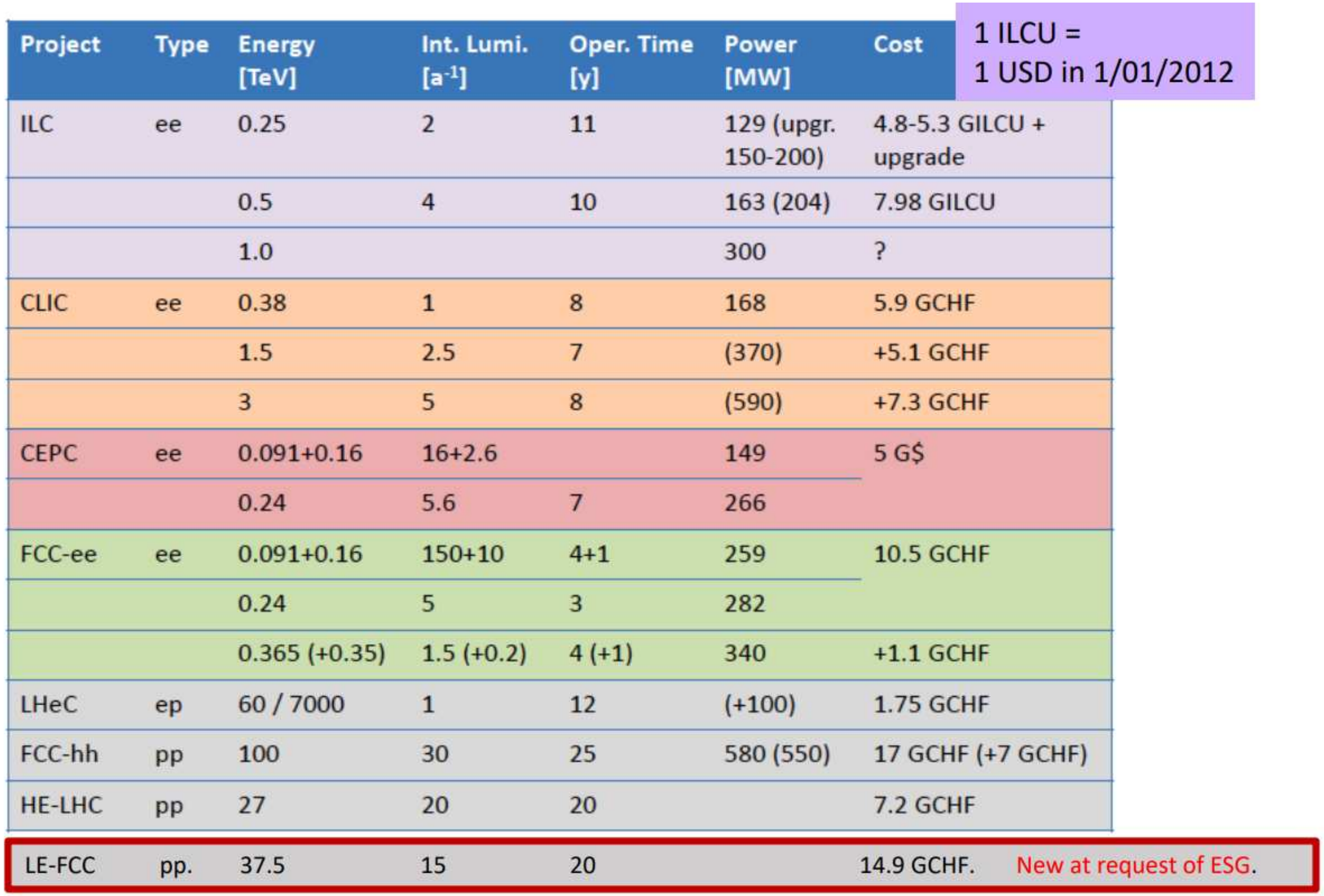


CLIC/FCC-ee/FCC-hh, CERN

The starting lineup



The starting lineup

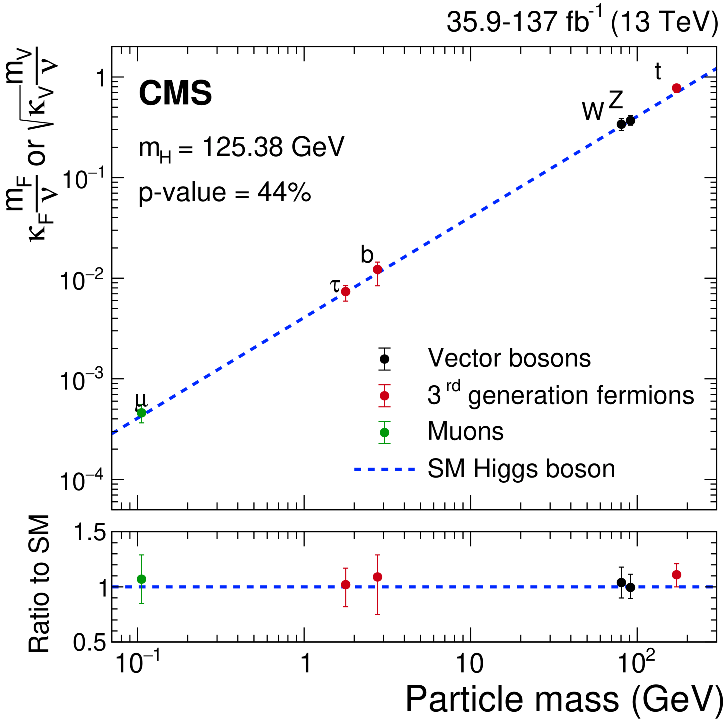


1 ILCU =
1 USD in 1/01/2012

Project	Type	Energy [TeV]	Int. Lumi. $[a^{-1}]$	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF
LE-FCC	pp.	37.5	15	20		14.9 GCHF. New at request of ESG.

(For reference - LHC construction cost ≈ 4 GCHF, annual CERN budget ≈ 1 GCHF.)

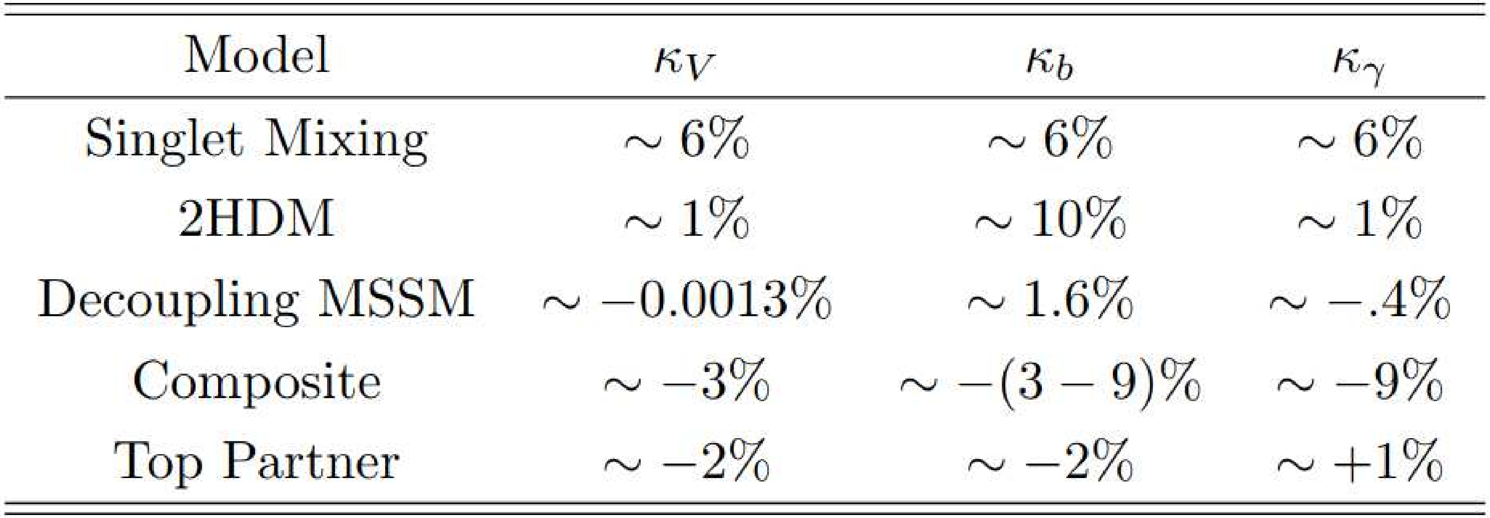
- The Higgs boson is the only fundamental scalar in the SM.
- Its coupling to the other SM particles is proportional to their masses:
  - To bosons ($V = W, Z$) with strength $\sim m_V^2/v$, where v is the vacuum expectation value $v \approx 246$ GeV.
  - To fermions (F) with strength $\sim m_F/v$.
- Coupling modifier κ specifies how much coupling deviates from SM expectation.
- Extensive program to test if its properties are agreeing with SM predictions.



- No deviations from SM observed, but uncertainties still large.

What precision is needed?

- BSM physics can modify Higgs couplings to SM particles.
- Several scenarios investigated in Higgs Wroking Group reports.
- Deviations typically well below 10%.



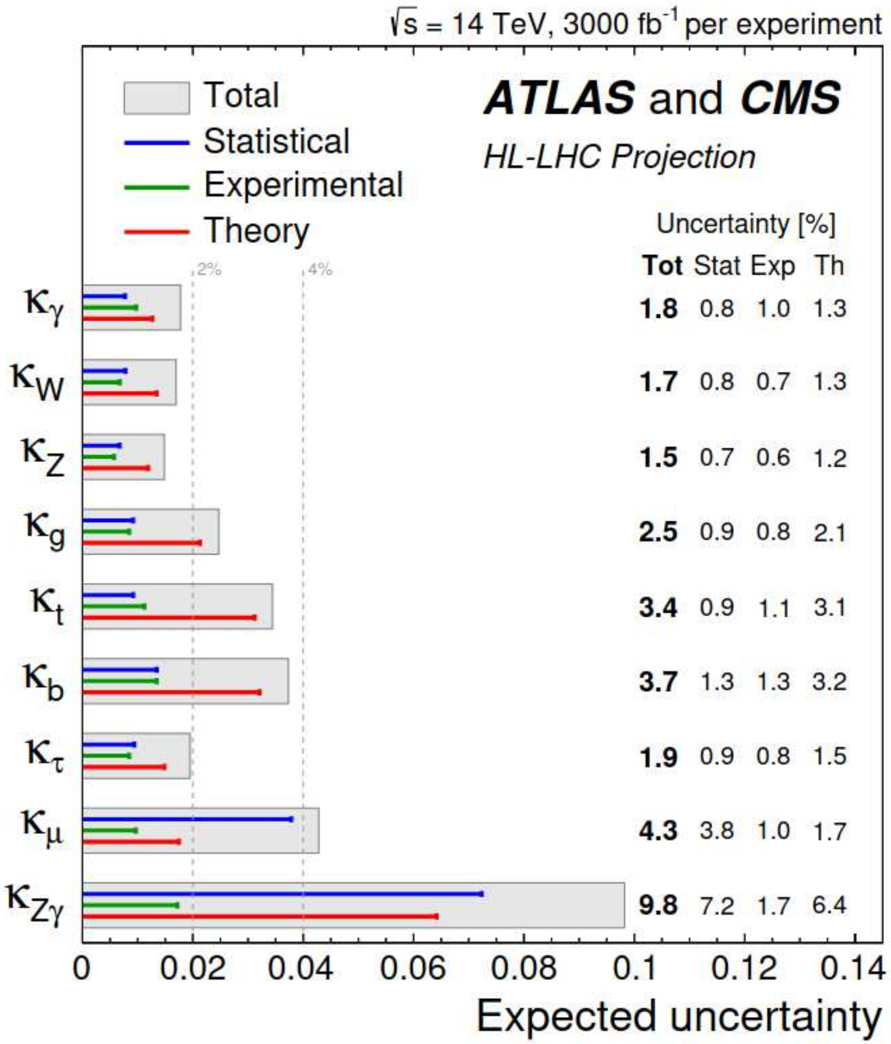
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

arXiv:1310.8361

- Target O(1%) precision.

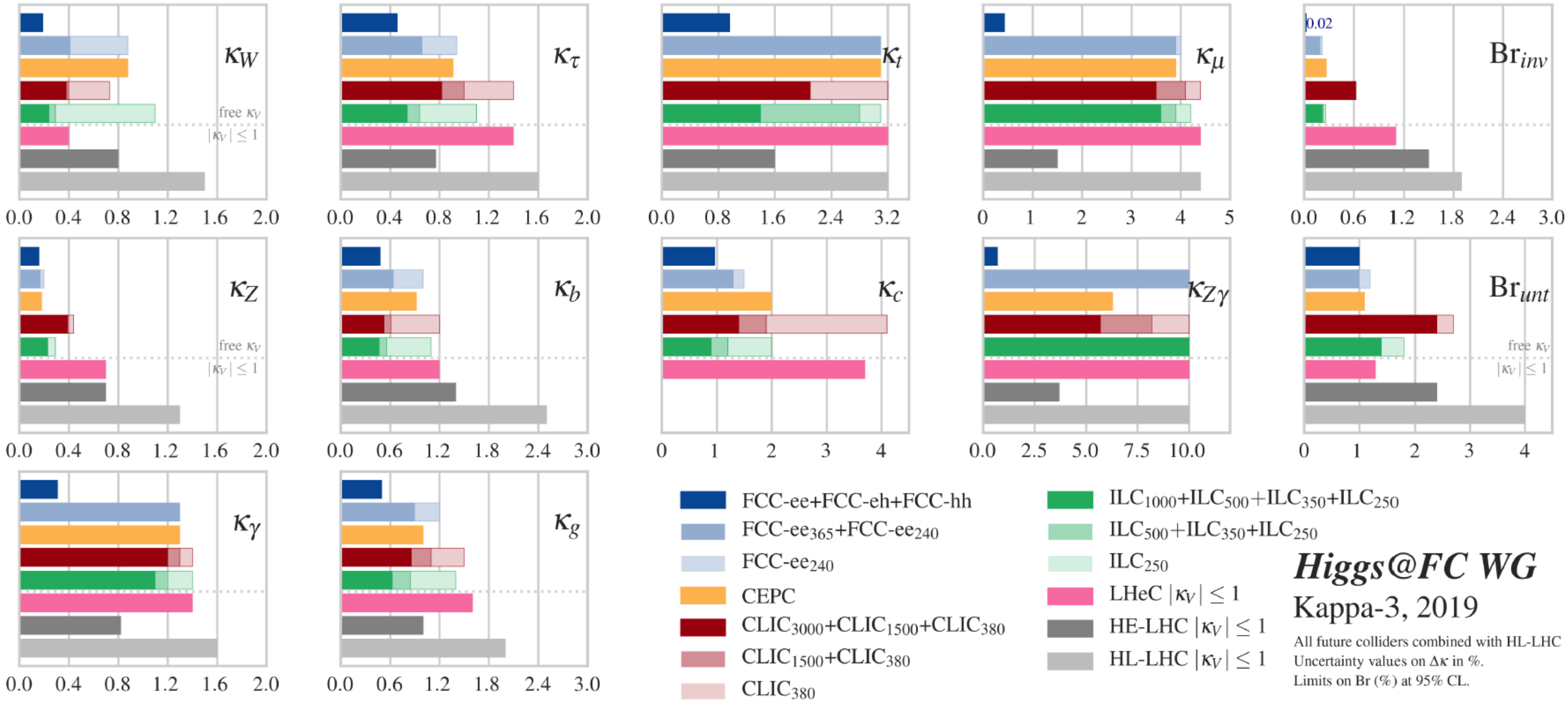
... at the HL-LHC

- Uncertainty assumptions:
  - Statistical uncertainty $\sim \sqrt{\int Ldt}$.
  - Theory uncertainties $\times 0.5$.
  - Detector performance same.
- Expect $\mathcal{O}$(few %) precision on the most accessible Higgs couplings.
- Precision often limited by uncertainty on theory predictions.



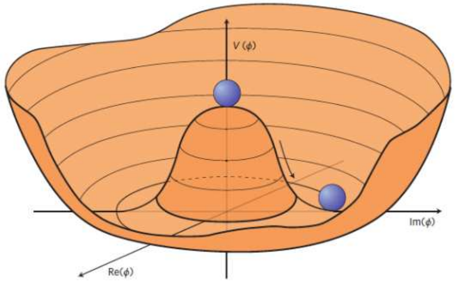
arXiv:1902.00134

... and at future colliders



The Higgs potential

- Higgs boson mass determines position of the ground state.
- Not enough to define shape of the Higgs potential.



- Shape of the Higgs potential controls the dynamics of the electroweak phase transition.
- SM predicts shape of the Higgs potential:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

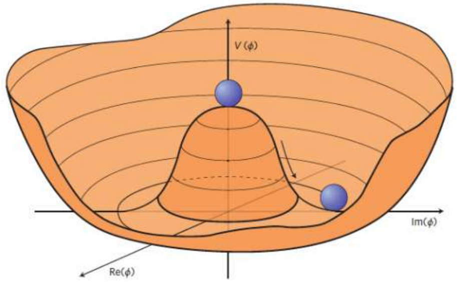
- But Higgs self-coupling parameter λ not measured yet.
- First-order EW phase transition needed for electroweak baryogenesis.
- Not possible in SM.

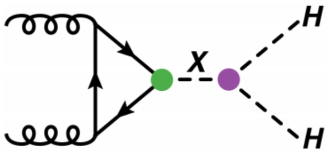
Di-Higgs boson production

- Di-Higgs production gives access to trilinear Higgs self-coupling λ_{hhh} and thus information about the shape of the Higgs potential.

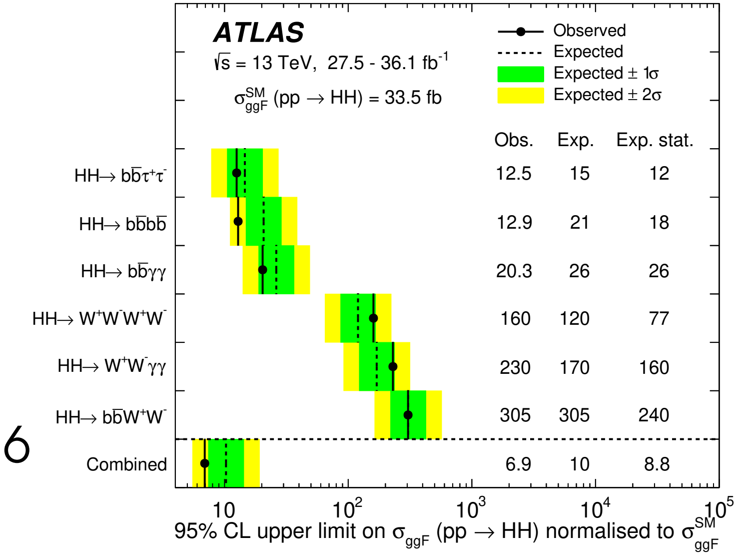
$$V(h) = \frac{1}{2} m_h^2 h^2 + (1+\kappa_3)\lambda_{hhh}^{\text{SM}} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{\text{SM}} h^4 + O(h^5)$$

- Small cross section because of destructive interference between diagrams.
- Potential enhancement of cross section e.g. from decays of a new spin-0 or spin-2 particle.

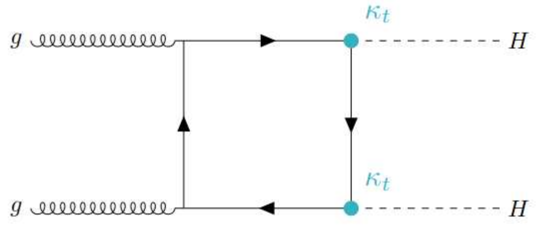


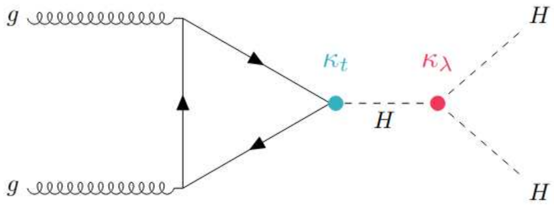


Best limits $5.5 \times \sigma_{\text{SM}}$
ATLAS-CONF-2021-016



	Obs.	Exp.	Exp. stat.
HH→ $b\bar{b}\tau^+\tau^-$	12.5	15	12
HH→ $b\bar{b}b\bar{b}$	12.9	21	18
HH→ $b\bar{b}\gamma\gamma$	20.3	26	26
HH→ $W^+W^-W^+W^-$	160	120	77
HH→ $W^+W^-\gamma\gamma$	230	170	160
HH→ $b\bar{b}W^+W^-$	305	305	240
Combined	6.9	10	8.8

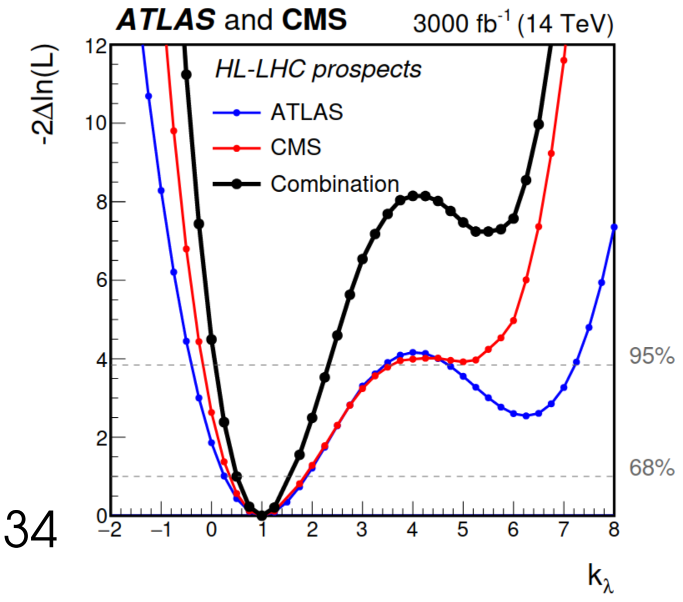




arXiv:1906.02025

... at the HL-LHC and beyond

- Observing di-Higgs production is a key deliverable at HL-LHC, $\sim 4\sigma$ significance expected with 3000 fb^{-1}.
- Expected κ_λ(=κ_3) sensitivity is $0.1 < \kappa_\lambda < 2.3$ at 95% C.L.
- CLIC at $\sqrt{s} = 3$ TeV and ILC at $\sqrt{s} = 1$ TeV can constrain trilinear self-coupling to $\mathcal{O}$10% while FCC-hh can reach 5% precision.
- 2σ sensitivity to the quartic self-coupling expected at FCC-hh.



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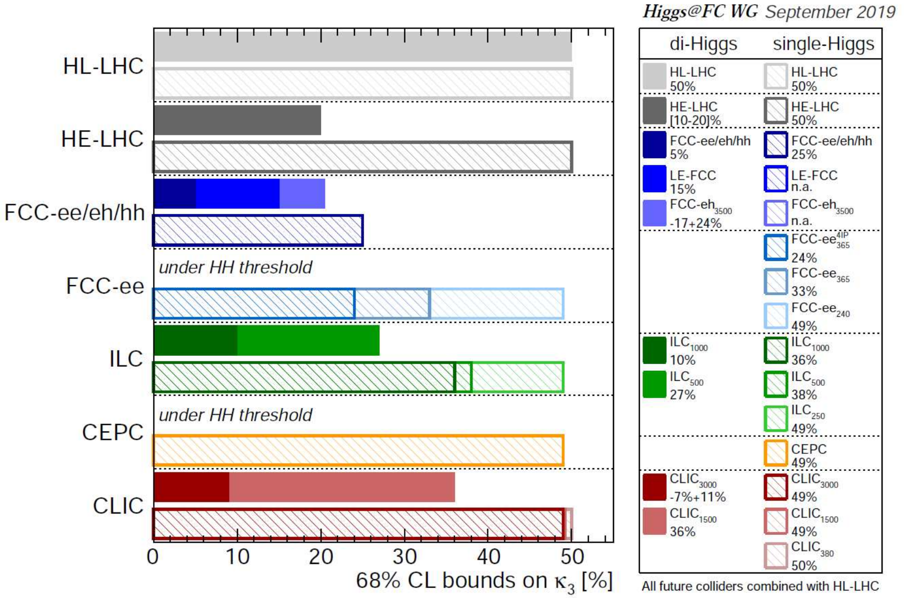
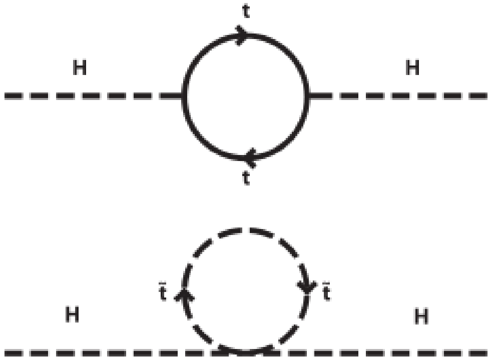


Protecting the Higgs mass with Supersymmetry

- In SUSY, the Higgs boson mass is protected by chiral symmetry.

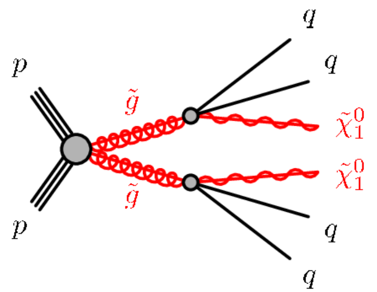
$$\delta m_h^2 \sim -\frac{|\lambda_f|^2}{16\pi^2}\left(\Lambda_{\mathrm{UV}}^2 + ...\right) + \frac{\lambda_S}{16\pi^2}\left(\Lambda_{\mathrm{UV}}^2 + ...\right) + \cdots$$

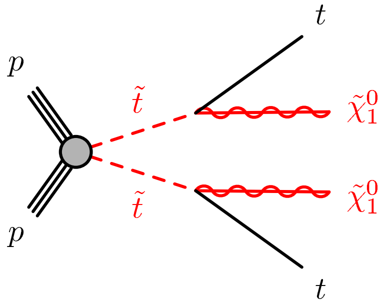
- Cancellation if $\lambda_S = |\lambda_f|^2$.
- Supersymmetric top partner (stop) cannot be too heavy.
- Gluino affects running of stop mass so must also be light.

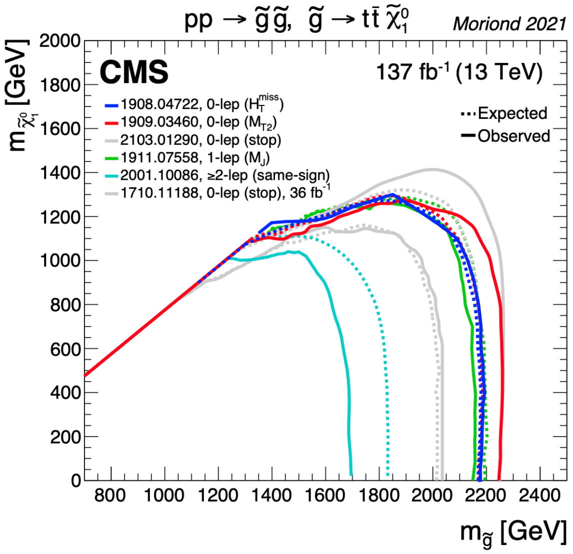


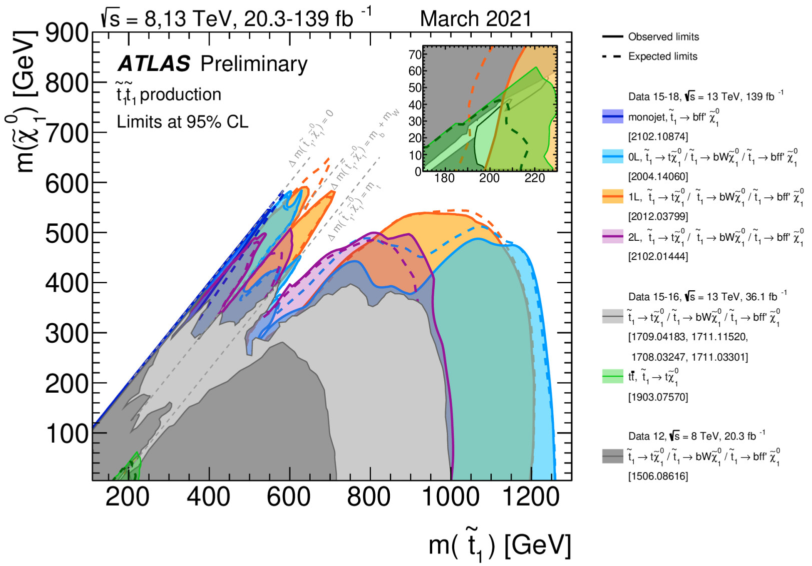
Gluinos and stops

- Limits on masses of gluinos and 1st/2nd generation squarks is ∼2 TeV.
- Limits on masses of stops is ∼1 TeV.
- Derived assuming simplified models with light χ_1^0.
- Limits can be considerably weaker in other parts of SUSY parameter space.





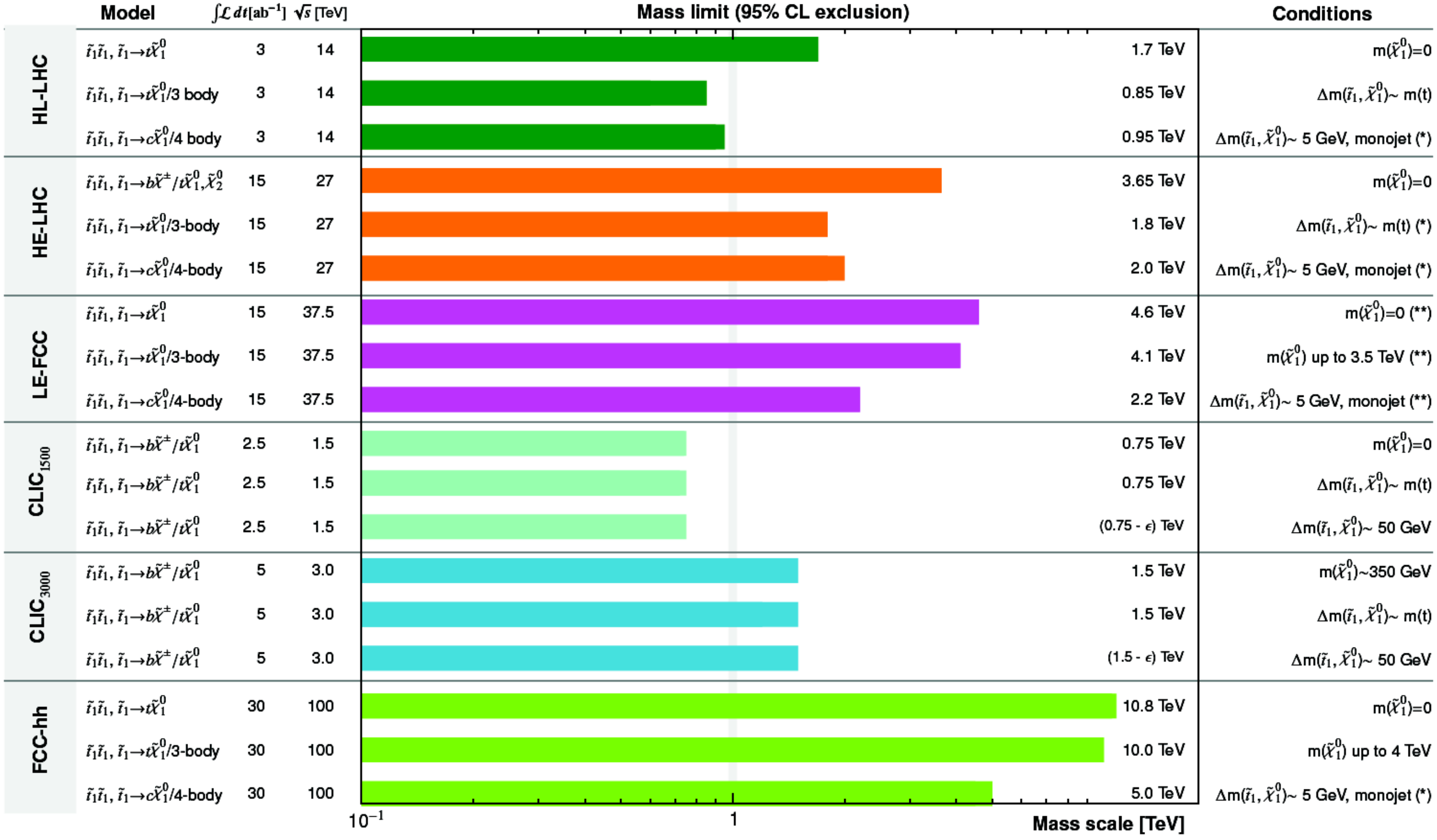




... at the HL-LHC and future colliders

All Colliders: Top squark projections

(R-parity conserving SUSY, prompt searches)



	Model	$\int\mathcal{L}\,dt$[ab^{-1}]	$\sqrt{s}$ [TeV]	Mass limit (95% CL exclusion)	Conditions
HL-LHC	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	3	14	1.7 TeV	m($\tilde{\chi}_1^0$)=0
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$/3 body	3	14	0.85 TeV	Δm($\tilde{t}_1,\tilde{\chi}_1^0$)~ m(t)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$/4 body	3	14	0.95 TeV	Δm($\tilde{t}_1,\tilde{\chi}_1^0$)~ 5 GeV, monojet (*)
HE-LHC	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0,\tilde{\chi}_2^0$	15	27	3.65 TeV	m($\tilde{\chi}_1^0$)=0
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$/3-body	15	27	1.8 TeV	Δm($\tilde{t}_1,\tilde{\chi}_1^0$)~ m(t) (*)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$/4-body	15	27	2.0 TeV	Δm($\tilde{t}_1,\tilde{\chi}_1^0$)~ 5 GeV, monojet (*)
LE-FCC	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	15	37.5	4.6 TeV	m($\tilde{\chi}_1^0$)=0 (**)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$/3-body	15	37.5	4.1 TeV	m($\tilde{\chi}_1^0$) up to 3.5 TeV (**)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$/4-body	15	37.5	2.2 TeV	Δm($\tilde{t}_1,\tilde{\chi}_1^0$)~ 5 GeV, monojet (**)
CLIC$_{1500}$	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	2.5	1.5	0.75 TeV	m($\tilde{\chi}_1^0$)=0
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	2.5	1.5	0.75 TeV	Δm($\tilde{t}_1,\tilde{\chi}_1^0$)~ m(t)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	2.5	1.5	(0.75 - ϵ) TeV	Δm($\tilde{t}_1,\tilde{\chi}_1^0$)~ 50 GeV
CLIC$_{3000}$	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	5	3.0	1.5 TeV	m($\tilde{\chi}_1^0$)~350 GeV
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	5	3.0	1.5 TeV	Δm($\tilde{t}_1,\tilde{\chi}_1^0$)~ m(t)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	5	3.0	(1.5 - ϵ) TeV	Δm($\tilde{t}_1,\tilde{\chi}_1^0$)~ 50 GeV
FCC-hh	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	30	100	10.8 TeV	m($\tilde{\chi}_1^0$)=0
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$/3-body	30	100	10.0 TeV	m($\tilde{\chi}_1^0$) up to 4 TeV
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$/4-body	30	100	5.0 TeV	Δm($\tilde{t}_1,\tilde{\chi}_1^0$)~ 5 GeV, monojet (*)

(*) indicates projection of existing experimental searches

(**) extrapolated from FCC-hh prospects

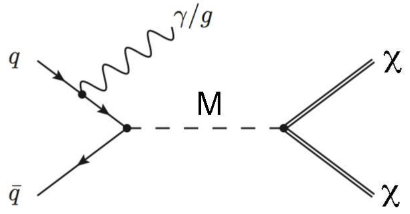
ϵ indicates a possible non-evaluated loss in sensitivity

ILC 500: discovery in all scenarios up to kinematic limit $\sqrt{s}/2$

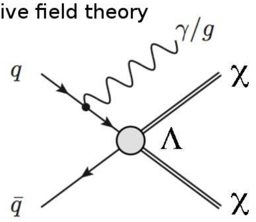
Dark matter searches

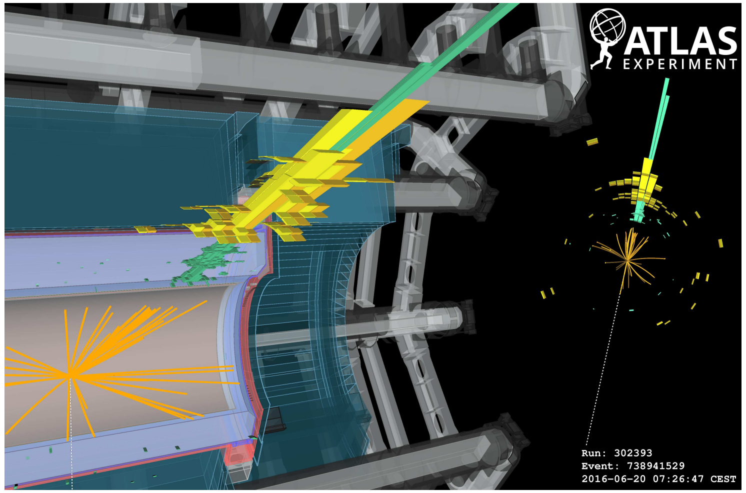
- Compelling evidence that DM exists. Detecting it in the laboratory is one of the greatest challenges for particle physics.
- If the dark matter is made of a weakly interacting particle at the electroweak scale, it could be produced at the LHC.
- DM particles leave no trace in the detector.
  → can only be inferred from the $\not{E}_{\mathrm{T}}$.
- Look for DM particles recoiling off visible objects.

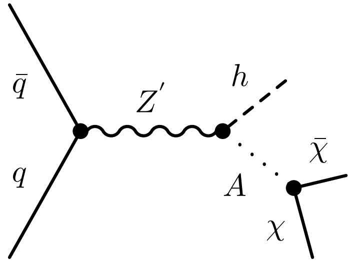
Simplified model



Effective field theory

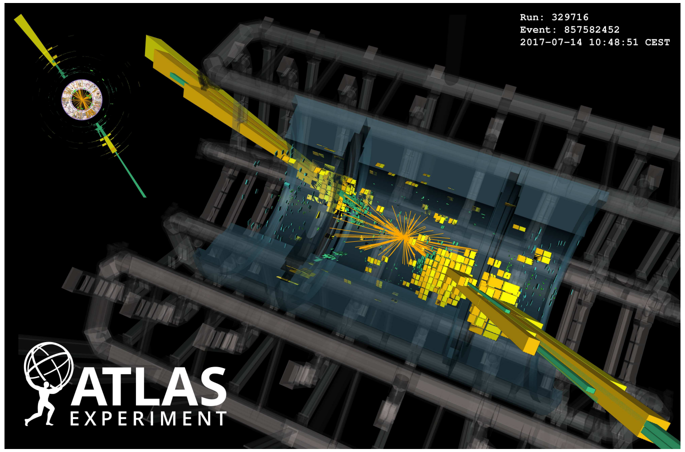


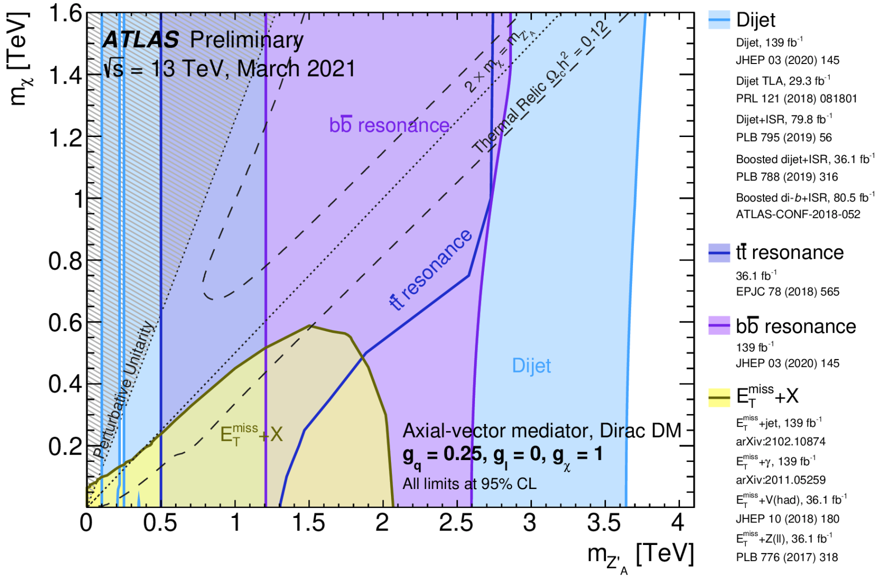


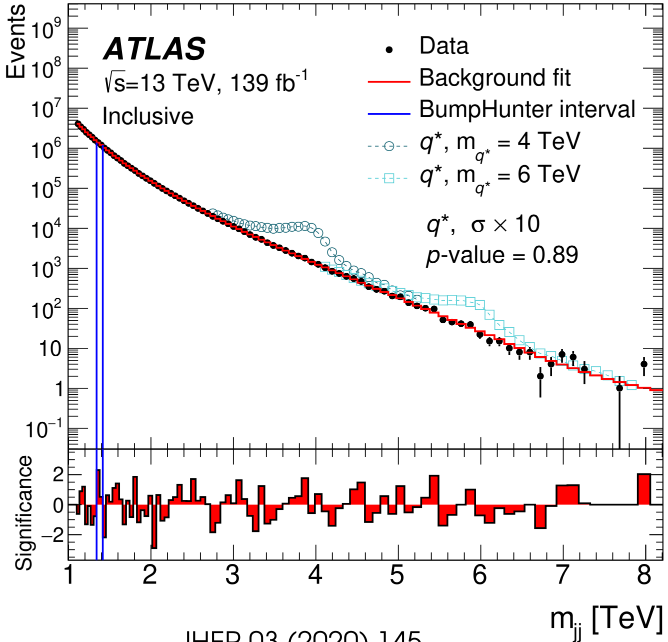


Dark matter mediator searches

- Search for resonances that can decay to two jets.
- Model-independent bump-hunter algorithm used.
- Also model-dependent limits on DM, if assuming the same resonance also decays to DM particles.







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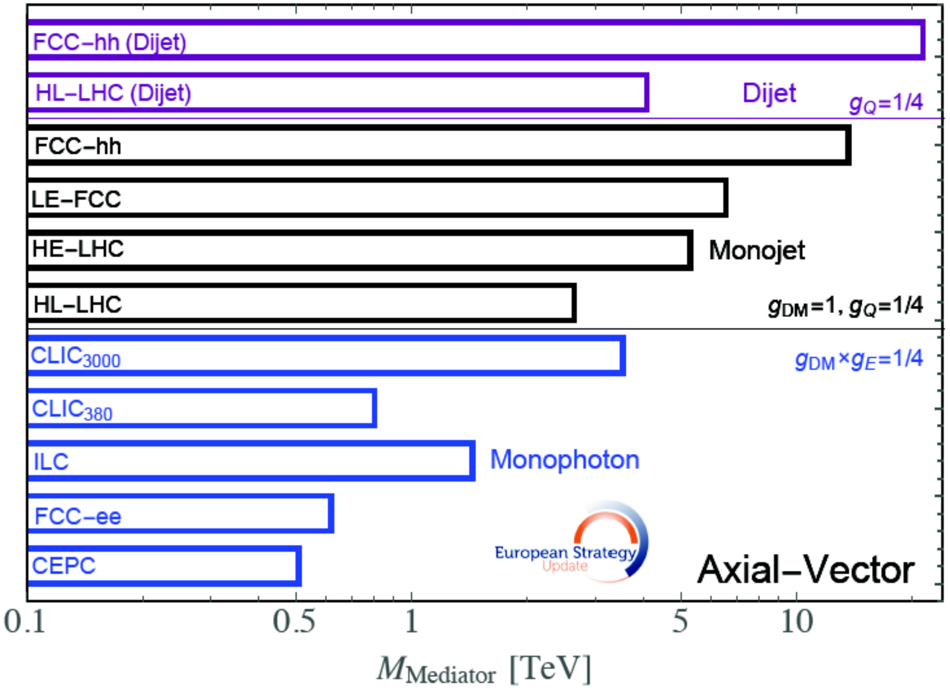
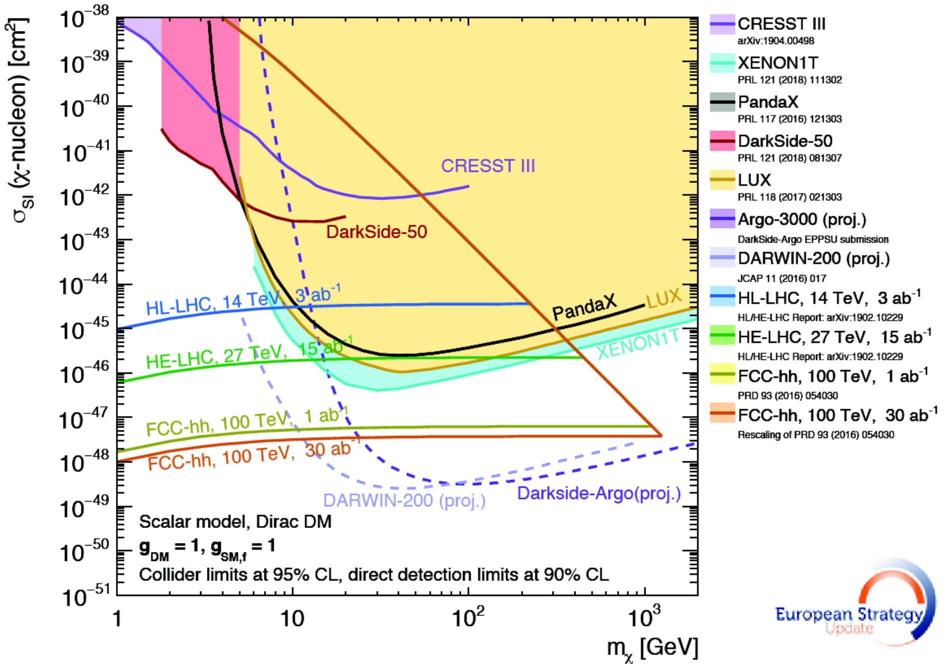
... at the HL-LHC and future colliders



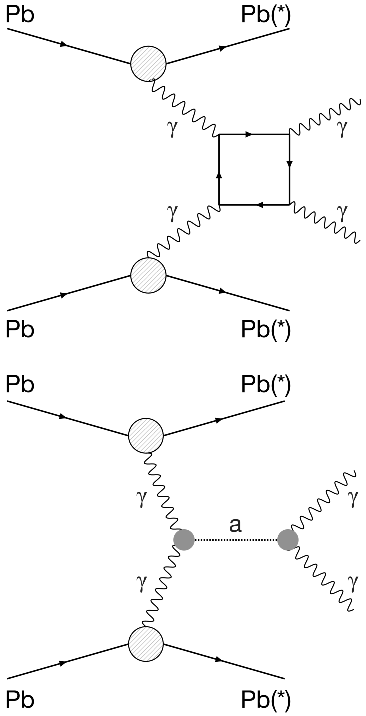


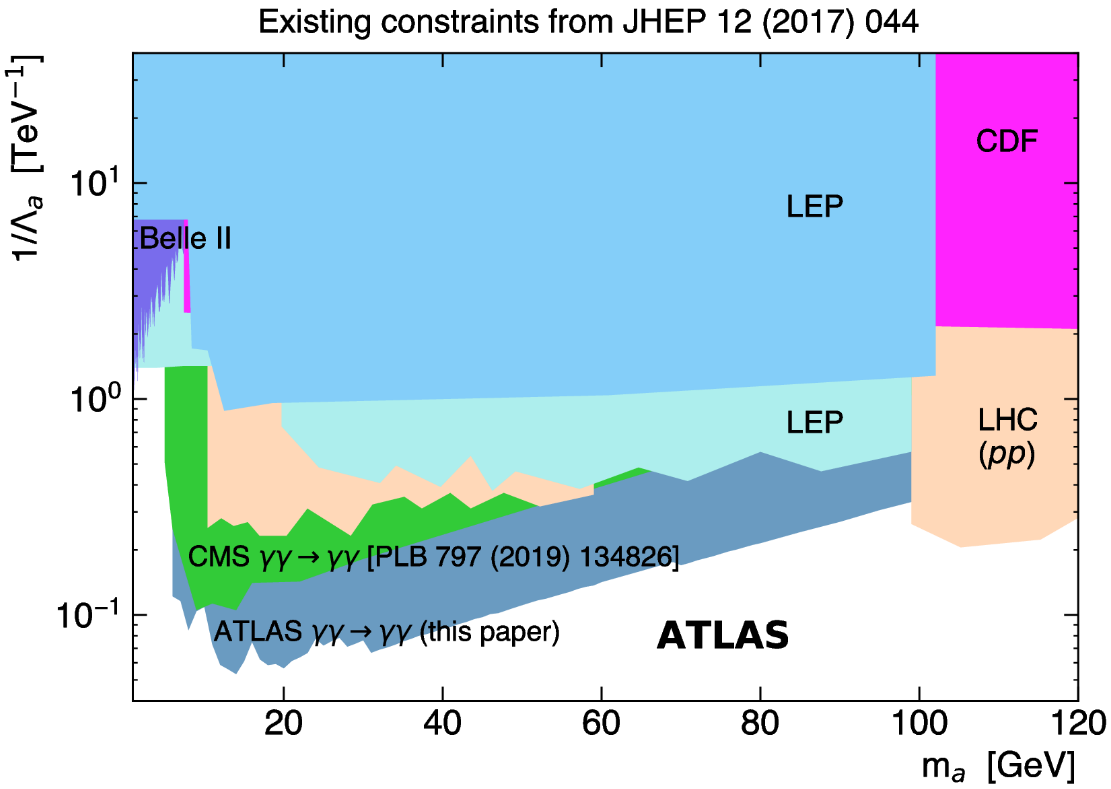
Expected 2σ sensitivity to axial-vector simplified models at future colliders for a DM mass of 1 GeV.

Comparison of the reach of DD, ID and future hadron colliders for the benchmark model of a scalar mediator decaying into Dirac DM.

Axion-like particles

- Light-by-light scattering in Pb-Pb collisions.
- Two photons and no more activity in detector.
- Diphoton invariant mass distribution is used to set limits on the production of axion-like particles.





What have we learned?

- The best way to go to energy frontier is to start with an e^+e^- Higgs factory.
- CLIC and FCC-ee are competing with the ILC and CEPC.
- Some important measurements, like Higgs self-couplings and probing BSM physics at high eneries, clearly benefit from a hadron collider.
- Contenders are SppC and FCC-hh.

(Selected) recommendations

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

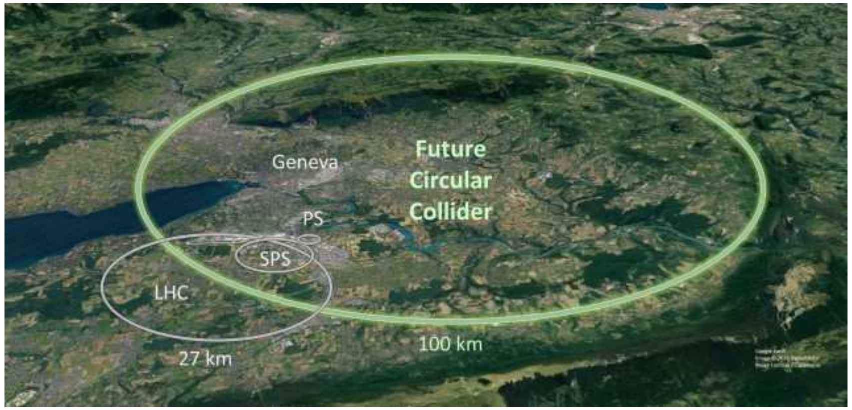
by the European Strategy Group

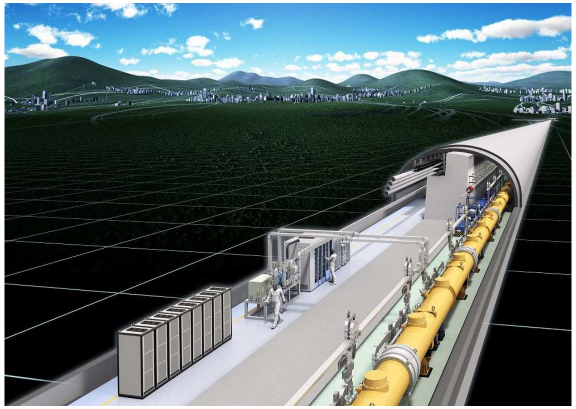
`https://cds.cern.ch/record/2721370`

- Successful completion of the high-luminosity upgrade of the machine and detectors plus continued innovation in experimental techniques.
- Support long baseline experiments in Japan and the United States.
- Ramp up R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors.

(Selected) recommendations

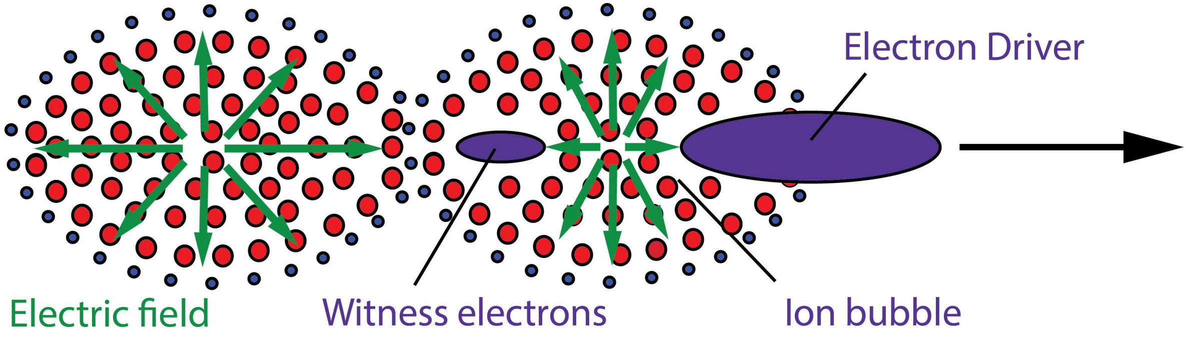
- Investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.
- The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.





Stop eternal growth?

- RF cavities can reach acceleration gradients of 10 MeV/m.
- Plasma-wakefield acceleration could reach several hundred GeV/m.



- Both laser-driven and particle-driven accelerators exist.
- Easier to accelerate electrons than positrons (since positrons attract the plasma electrons).
- Electron record: 42 GeV in 85 cm.
- Positron record: 5 GeV in 1 meter.

Summary and Outlook

- Run 2 of the LHC was a big success. Stable operations with instantaneous luminosity well beyond design value.
- Paved the way for a vast physics program to test the Standard Model.

\- accurate measurement of known processes.

\- direct searches for BSM physics in a variety of final states.

- So far remarkable agreement with the Standard Model predictions.
- HL-LHC will greatly improve precision in many measurements and also establish di-Higgs production.
- According to the European Particle Physics Strategy Update the community should (i) fully exploit HL-LHC; (ii) investigate the technical and financial feasibility of FCC-ee + FCC-hh at CERN; (iii) prioritize R&D in accelerator technology.
- Will seriously challenge the SM!

Final word

CERNCOURIER.COM

OPINION
INTERVIEW

In it for the long haul

We have conquered the easiest challenges in fundamental physics, says Nima Arkani-Hamed. The case for building the next major collider is now more compelling than ever.

“The discovery of the Higgs particle – especially with nothing else accompanying it so far – is unlike anything we have seen in any state of nature, and is profoundly “new physics” in this sense....theoretical attempts to compute the vacuum energy and the scale of the Higgs mass pose gigantic, and perhaps interrelated, theoretical challenges. While we continue to scratch our heads as theorists, **the most important path forward for experimentalists is completely clear: measure the hell out of these crazy phenomena!**”

Thank you!

And have a wonderful

Backup

The starting lineup

- ILC (Japan)
  - Linear collider e^+e^- with high-gradient superconducting acceleration.
  - Ultimately: 0.5-1 TeV.
  - Reduce cost by starting at 250 GeV (Higgs factory)
- CLIC (CERN)
  - Linear e^+e^- collider with high gradient normal-conducting acceleration.
  - Ultimately: multi-TeV (3) collisions.
  - Staged for physics and funding.
- FCC-ee & FCC-hh (CERN).
  - 100 km circular collider with 16 T magnets.
  - Use tunnel first for e^+e^- collider.

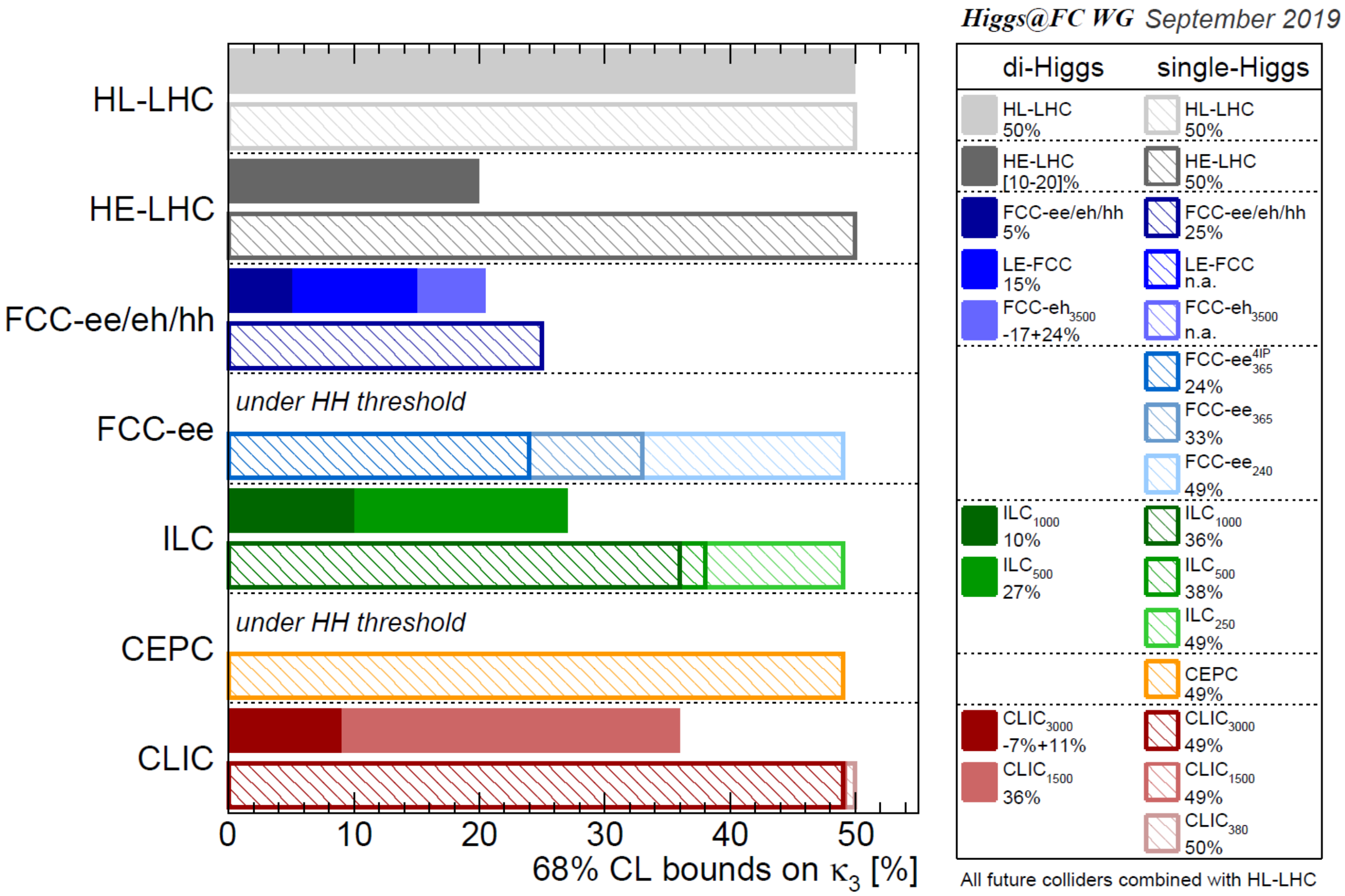
The starting lineup

- Technology for e^+e^- rather standard.
- Magnet development for FCC-hh challenging.

- CEPC & SppC (China)

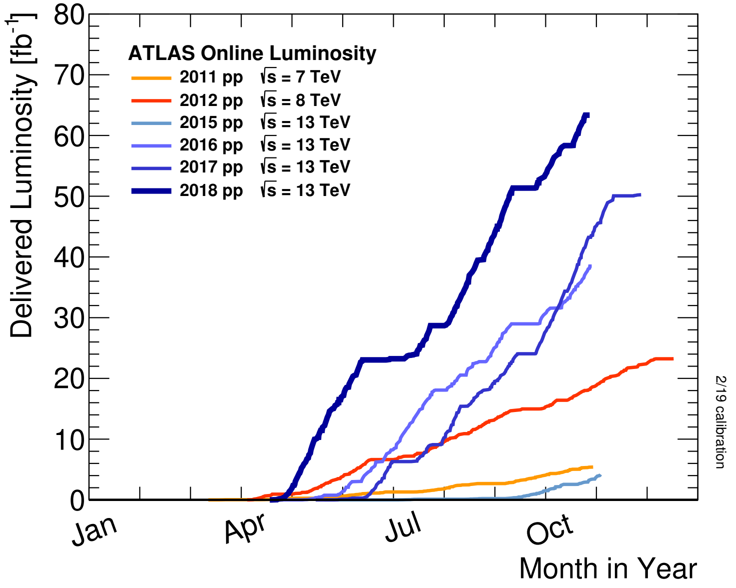
- Similar to FCC-ee/hh but more conservative luminosity estimates.

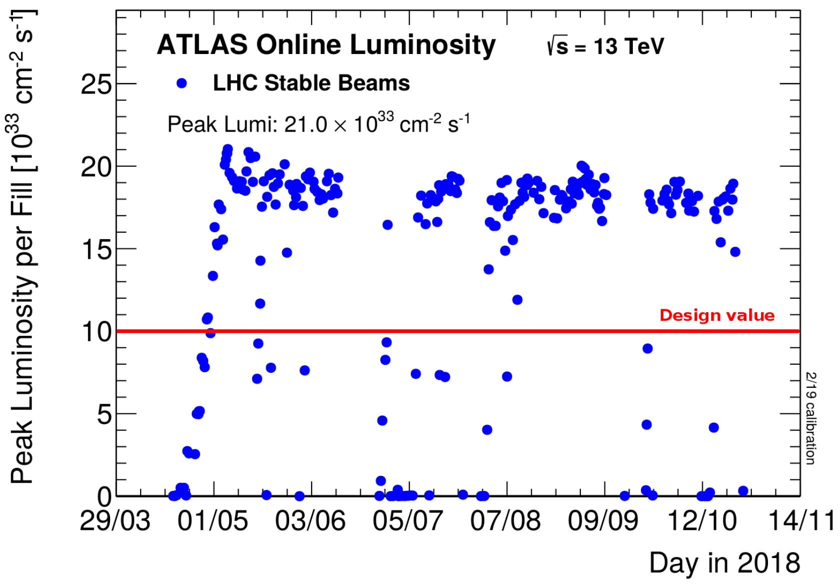
Higgs self-coupling at future colliders



The data

- Number of pp collisions per second is called luminosity.
- The LHC performance in Run 2 was amazing, with lots of luminosity delivered to the experiments ($N_p = \int Ldt \cdot \sigma_p$).
- Size of Run 2 dataset is 139 fb^{-1} ($\sigma_\mathrm{h} \approx 55$ pb^{-1} $\rightarrow 8 \cdot 10^6$ Higgs bosons).
- Instantaneous luminosity well above design value of 1$\cdot$10^{34} cm^2/s.

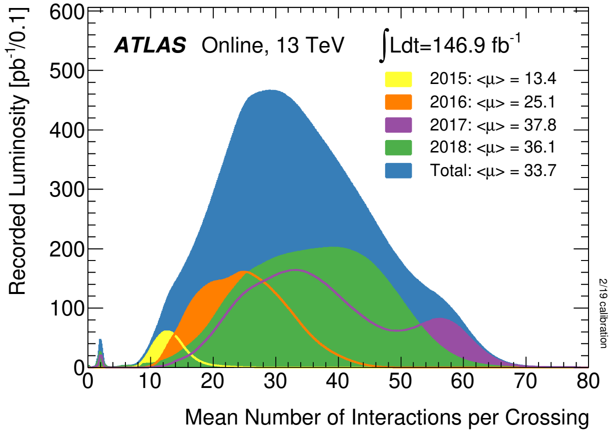


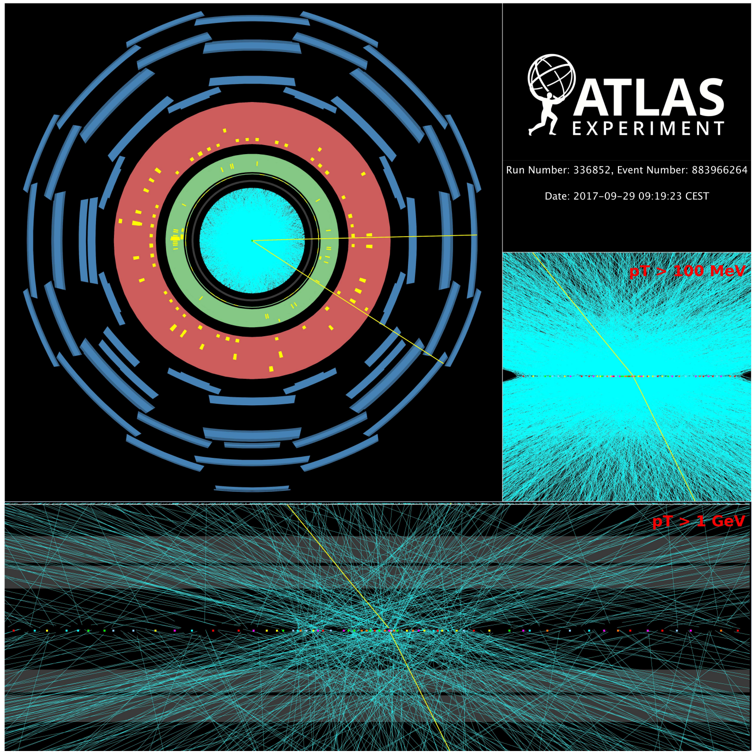


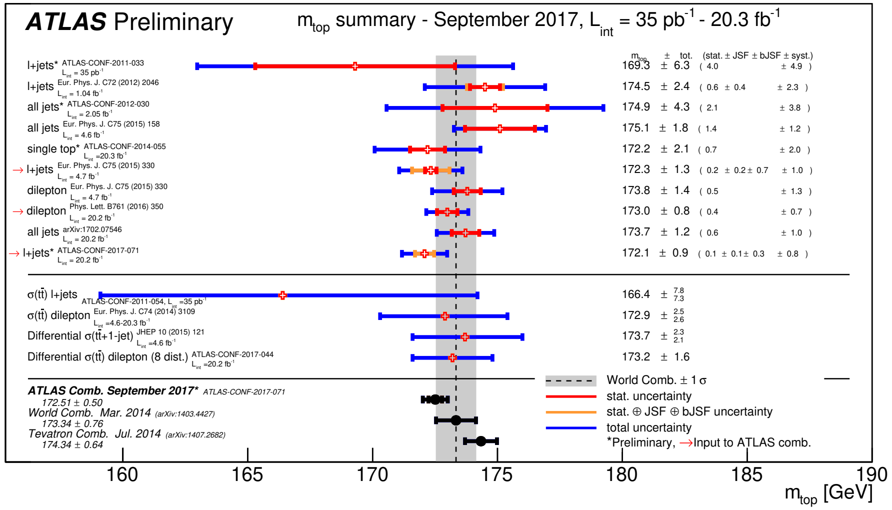
- But a very challenging experimental environment.

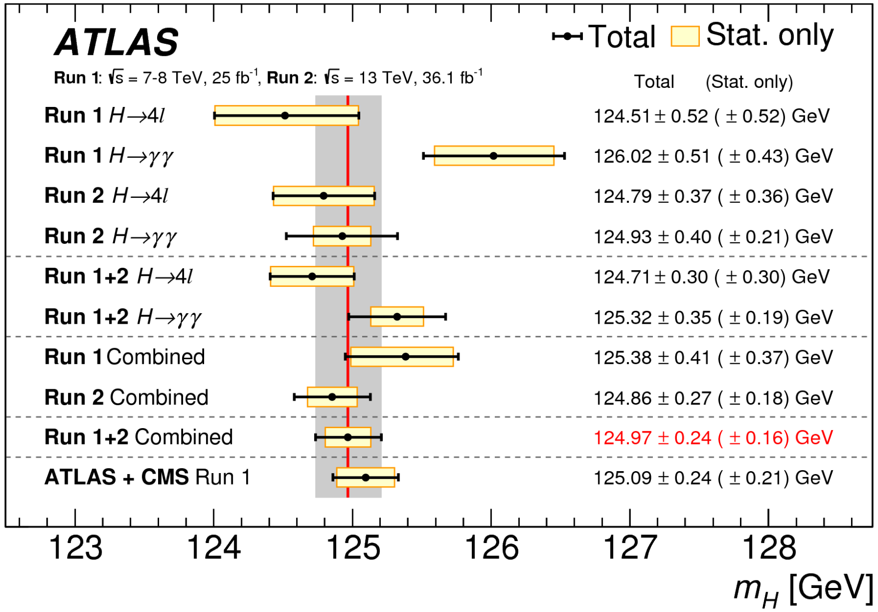
Operational challenges

- Large instantaneous luminosity means many (up to 70) simultaneous pp collisions in the same bunch crossing.
- Leads to:
  - contamination of particles from additional (pileup) interactions to measurement of hard-scatter process.
  - degraded detector performance (e.g. from large occupancy).
  - increased pressure on trigger and data acquisition systems.
- Lots of sucessful work done to retain good detector performance.



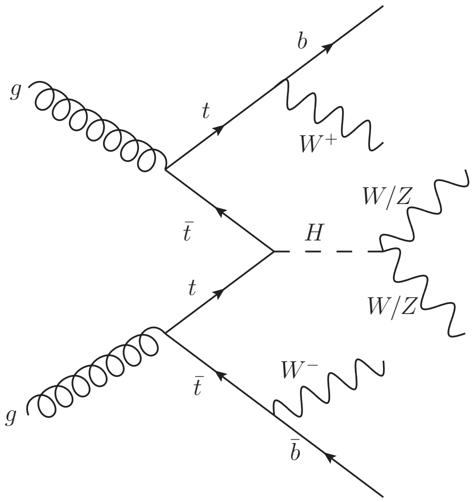



ATLAS Preliminary
m_top summary - September 2017, L_int = 35 pb-1 - 20.3 fb-1
m_top ± tot. (stat. ± JSF ± bJSF ± syst.)
l+jets* ATLAS-CONF-2011-033 L_int = 35 pb-1 169.3 ± 6.3 (4.0 ± 4.9)
l+jets Eur. Phys. J. C72 (2012) 2046 L_int = 1.04 fb-1 174.5 ± 2.4 (0.6 ± 0.4 ± 2.3)
all jets* ATLAS-CONF-2012-030 L_int = 2.05 fb-1 174.9 ± 4.3 (2.1 ± 3.8)
all jets Eur. Phys. J. C75 (2015) 158 L_int = 4.6 fb-1 175.1 ± 1.8 (1.4 ± 1.2)
single top* ATLAS-CONF-2014-055 L_int =20.3 fb-1 172.2 ± 2.1 (0.7 ± 2.0)
→ l+jets Eur. Phys. J. C75 (2015) 330 L_int = 4.7 fb-1 172.3 ± 1.3 (0.2 ± 0.2 ± 0.7 ± 1.0)
dilepton Eur. Phys. J. C75 (2015) 330 L_int = 4.7 fb-1 173.8 ± 1.4 (0.5 ± 1.3)
→ dilepton Phys. Lett. B761 (2016) 350 L_int = 20.2 fb-1 173.0 ± 0.8 (0.4 ± 0.7)
all jets arXiv:1702.07546 L_int = 20.2 fb-1 173.7 ± 1.2 (0.6 ± 1.0)
→ l+jets* ATLAS-CONF-2017-071 L_int = 20.2 fb-1 172.1 ± 0.9 (0.1 ± 0.1 ± 0.3 ± 0.8)
σ(tt̄) l+jets ATLAS-CONF-2011-054, L_int =35 pb-1 166.4 ± 7.8 7.3
σ(tt̄) dilepton Eur. Phys. J. C74 (2014) 3109 L_int =4.6-20.3 fb-1 172.9 ± 2.5 2.6
Differential σ(tt̄+1-jet) JHEP 10 (2015) 121 L_int =4.6 fb-1 173.7 ± 2.3 2.1
Differential σ(tt̄) dilepton (8 dist.) ATLAS-CONF-2017-044 L_int =20.2 fb-1 173.2 ± 1.6
ATLAS Comb. September 2017* ATLAS-CONF-2017-071
172.51 ± 0.50
World Comb. Mar. 2014 (arXiv:1403.4427)
173.34 ± 0.76
Tevatron Comb. Jul. 2014 (arXiv:1407.2682)
174.34 ± 0.64
World Comb. ± 1 σ
stat. uncertainty
stat. ⊕ JSF ⊕ bJSF uncertainty
total uncertainty
*Preliminary, →Input to ATLAS comb.
160
165
170
175
180
185
190
m_top [GeV]


ATLAS
Total
Stat. only
Run 1: √s = 7-8 TeV, 25 fb-1, Run 2: √s = 13 TeV, 36.1 fb-1
Total (Stat. only)
Run 1 H→4l 124.51 ± 0.52 (± 0.52) GeV
Run 1 H→γγ 126.02 ± 0.51 (± 0.43) GeV
Run 2 H→4l 124.79 ± 0.37 (± 0.36) GeV
Run 2 H→γγ 124.93 ± 0.40 (± 0.21) GeV
Run 1+2 H→4l 124.71 ± 0.30 (± 0.30) GeV
Run 1+2 H→γγ 125.32 ± 0.35 (± 0.19) GeV
Run 1 Combined 125.38 ± 0.41 (± 0.37) GeV
Run 2 Combined 124.86 ± 0.27 (± 0.18) GeV
Run 1+2 Combined 124.97 ± 0.24 (± 0.16) GeV
ATLAS + CMS Run 1 125.09 ± 0.24 (± 0.21) GeV
123
124
125
126
127
128
m_H [GeV]

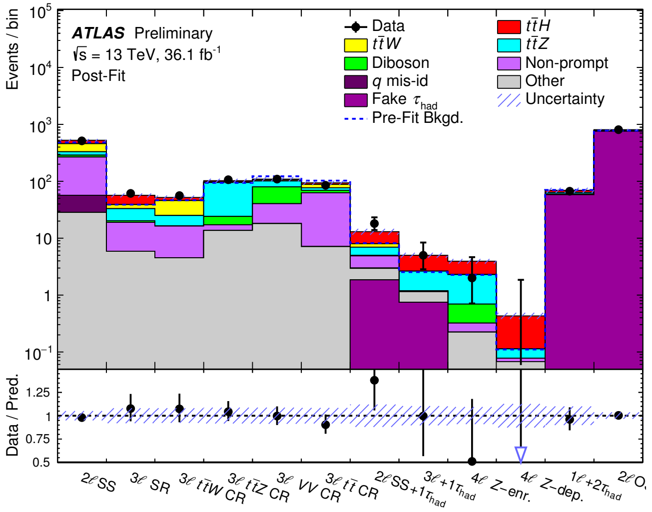
Observation of ttH production

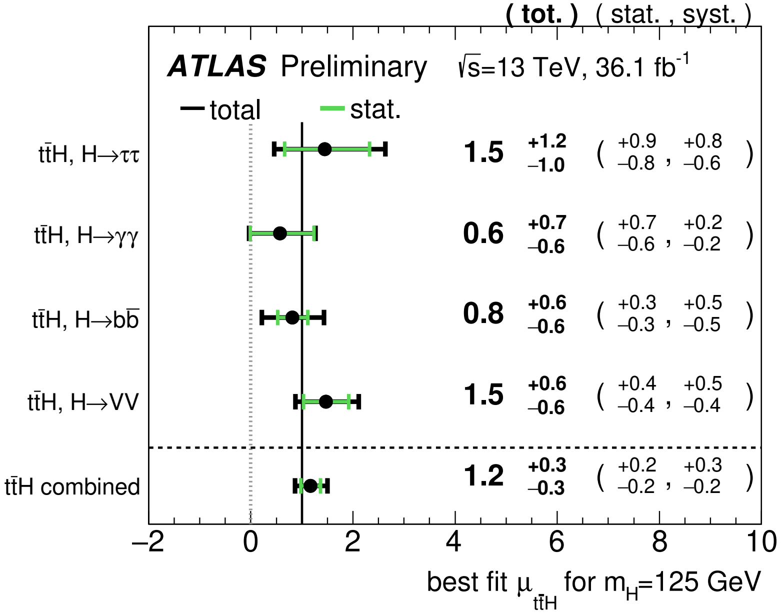
- ATLAS recently announced evidence for ttH production. 4.2 σ significance.
- Higgs couples to fermions proportionally to their masses. Important to verify!
- Top quark is the heaviest particle in the SM → top-Higgs coupling expected to be large.
- Cross section sensitive to BSM physics (e.g. exotic top partners).



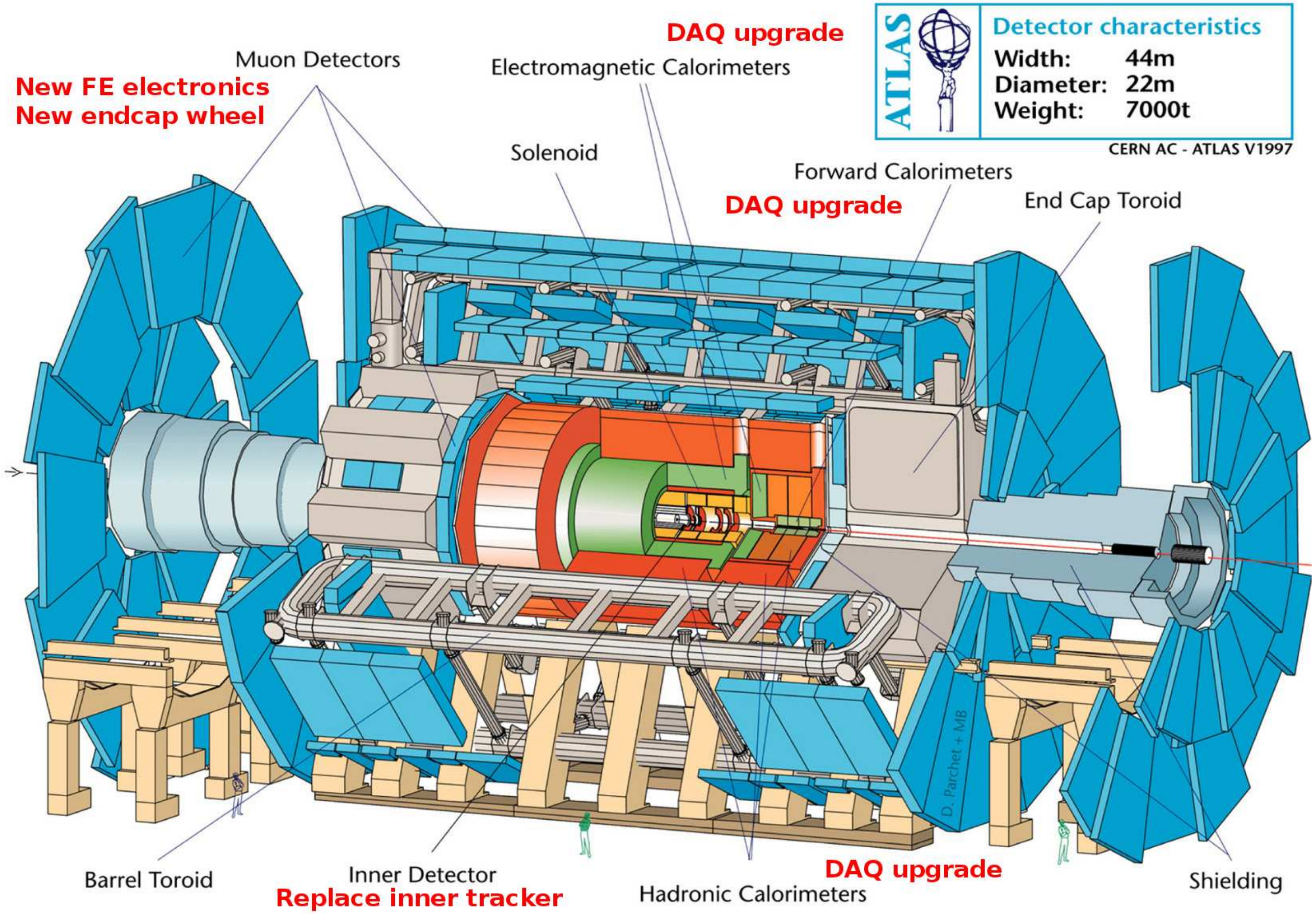
ATLAS-CONF-2017-076

ATLAS-CONF-2017-077





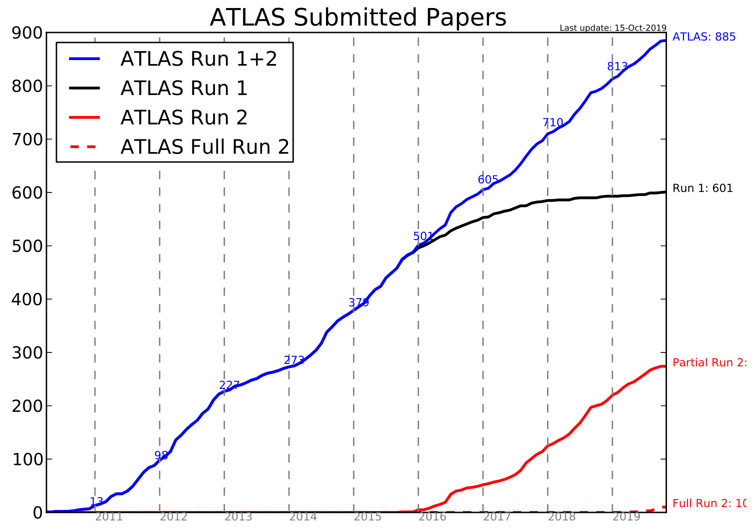
Planned ATLAS upgrades for HL-LHC

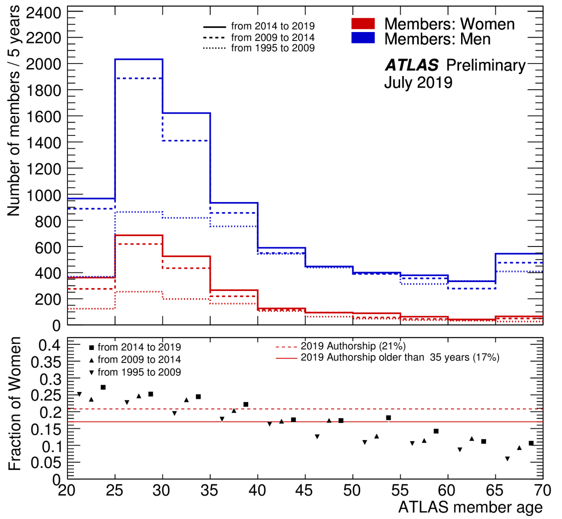


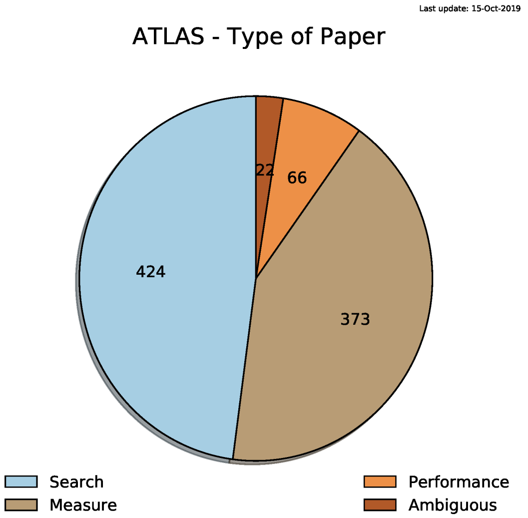
- Completely new inner tracking system, extending to $|\eta| < 4$.
- Upgrades to trigger and computing.
- Possibly new forward timing detector.

People in - physics out

- 3000 scientific authors (1200 PhD students) from 38 countries.
- To date 885 submitted papers (853 published) and 988 conference notes.

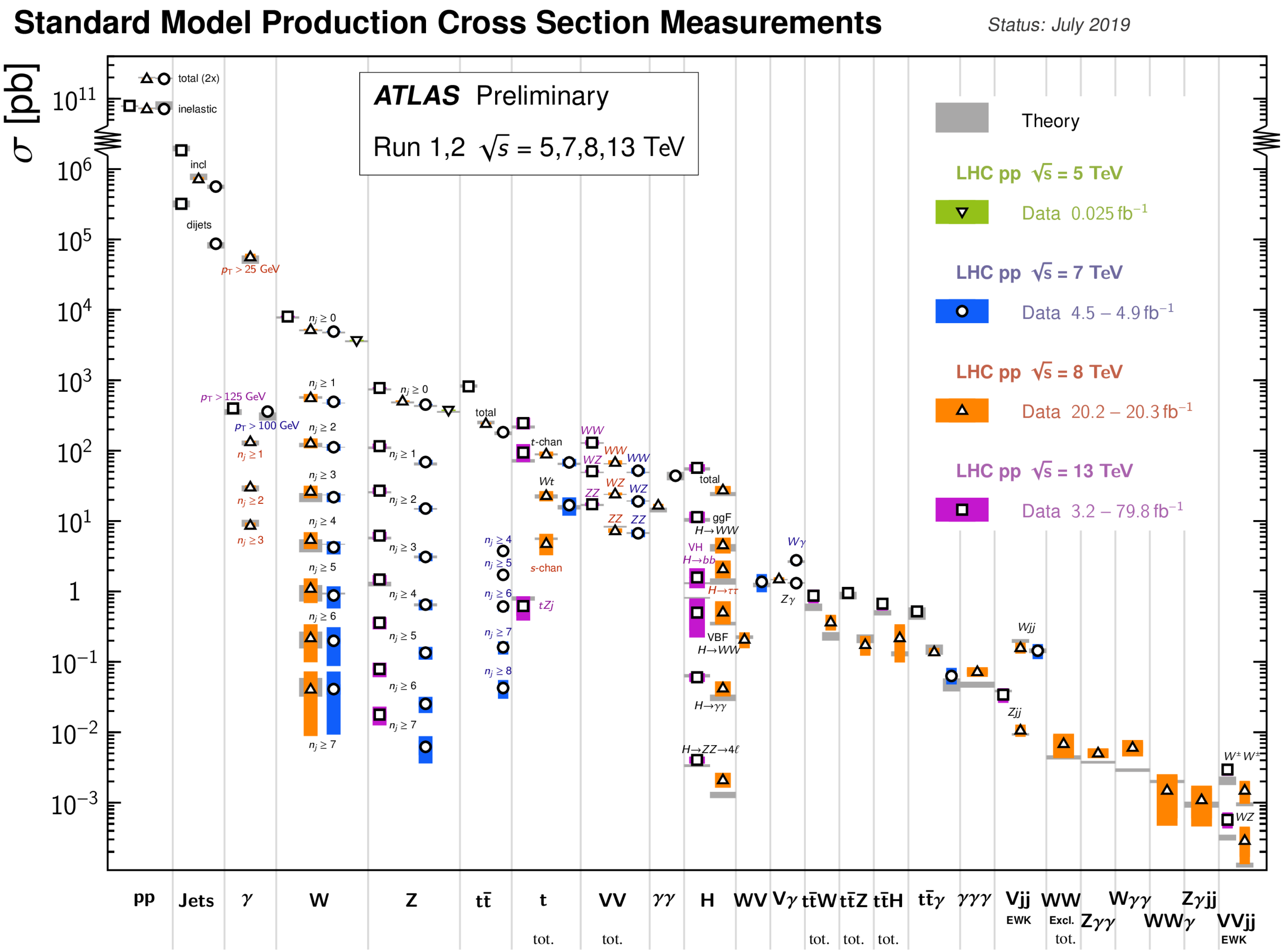






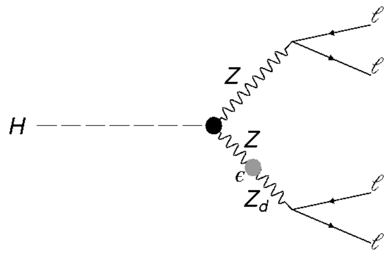
- Even split searches and measurements.
- Will highlight small fraction of these results today.

Standard Model measurements

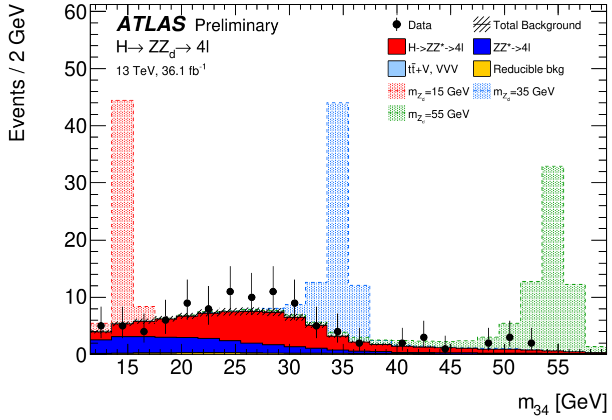


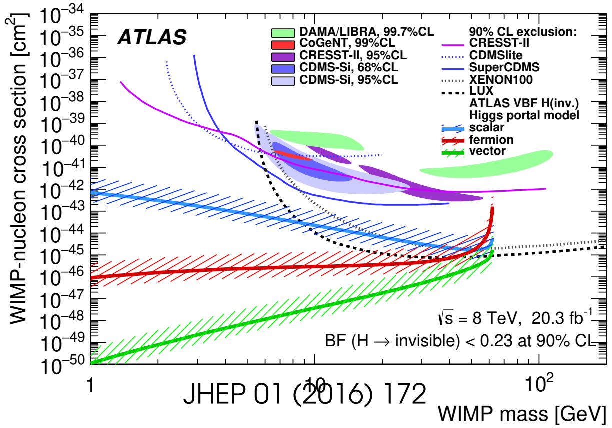
Higgs as portal to new physics

- Search for models where the Higgs boson mediates the connections to a dark sector.
- E.g. new BSM dark vector boson (Z_d) or a new light pseudoscalar boson (a), $H \to Z_{(d)}Z_d \to 4\ell$, $H \to aa \to 4\ell$
- Search for invisible Higgs decays (to e.g. dark matter).
- Most recent search in $ZH \to \ell\ell + \not{E}_{\mathrm{T}}$.
- Best constraint when combining with VBF $H \to jj + \not{E}_{\mathrm{T}}$.

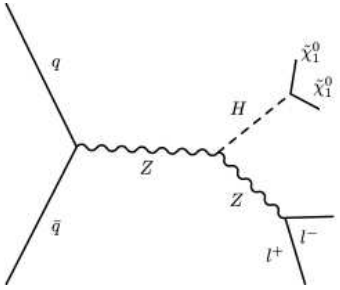


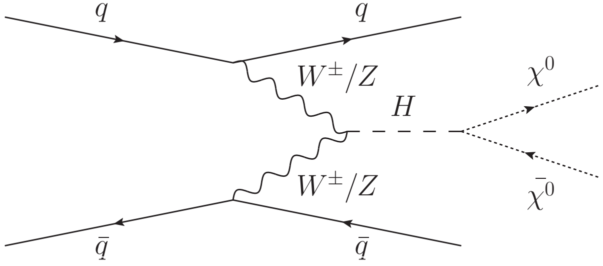
ATLAS-CONF-2017-042



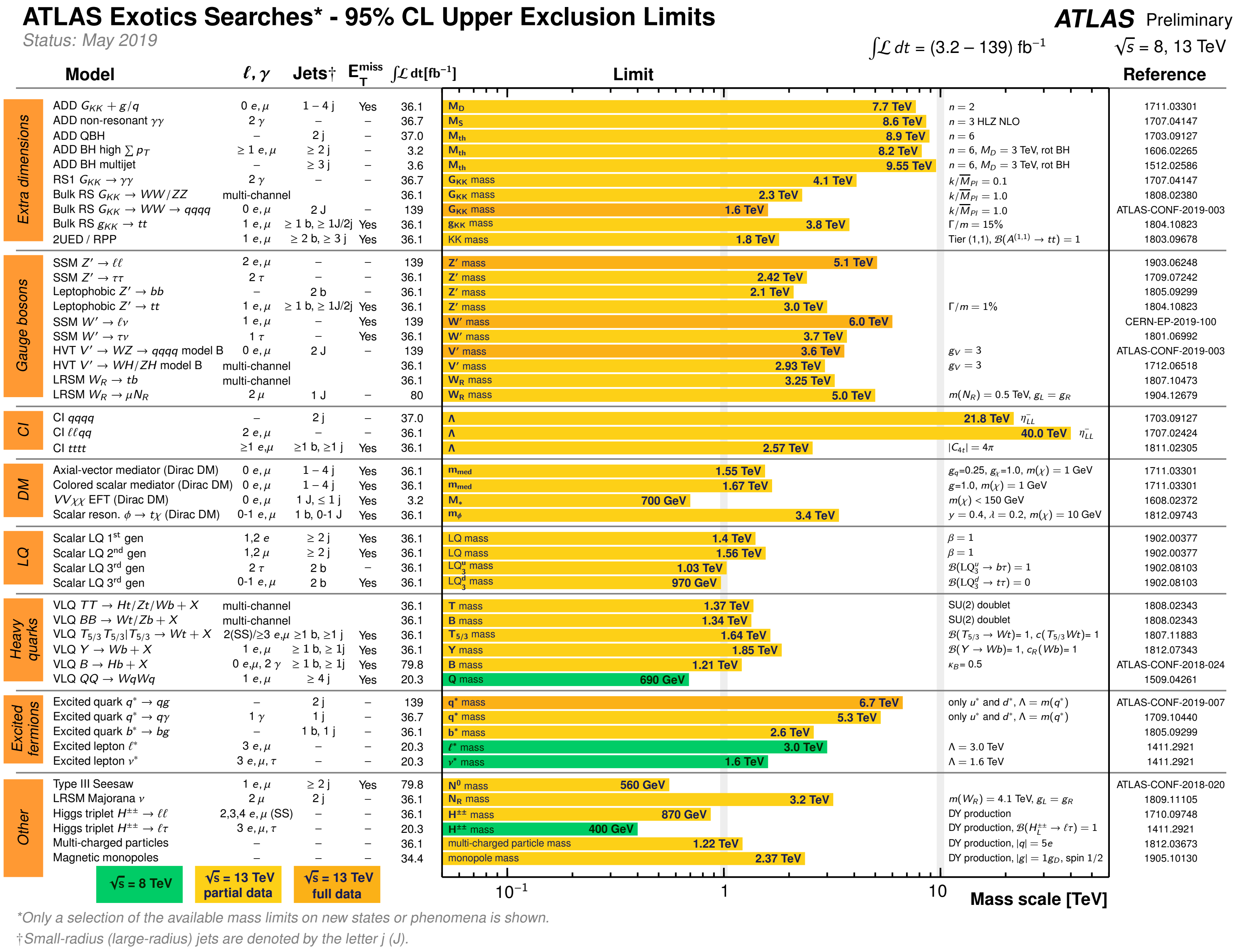


JHEP 01 (2016) 172





Beyond SM searches



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s}$ = 8, 13 TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	🟨 M_D	7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th}	8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qqqq$	0 e, μ	2 J	–	139	🟧 G_{KK} mass	1.6 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \rightarrow tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	139	🟧 Z' mass	5.1 TeV		1903.06248
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	36.1	🟨 Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	36.1	🟨 Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \rightarrow tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 Z' mass	3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	139	🟧 W' mass	6.0 TeV		CERN-EP-2019-100
	SSM $W' \rightarrow \tau\nu$	1 τ	–	Yes	36.1	🟨 W' mass	3.7 TeV		1801.06992
	HVT $V' \rightarrow WZ \rightarrow qqqq$ model B	0 e, μ	2 J	–	139	🟧 V' mass	3.6 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel			36.1	🟨 V' mass	2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W_R \rightarrow tb$	multi-channel			36.1	🟨 W_R mass	3.25 TeV		1807.10473
	LRSM $W_R \rightarrow \mu N_R$	2 μ	1 J	–	80	🟨 W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ	21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	🟨 Λ	40.0 TeV	η_{LL}^{-}	1707.02424
	CI $tttt$	$\geq$1 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	🟨 Λ	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_*	700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	🟨 m_ϕ	3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	🟨 LQ mass	1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	🟨 LQ mass	1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	🟨 LQ_3^u mass	1.03 TeV	$\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	🟨 LQ_3^d mass	970 GeV	$\mathcal{B}(LQ_3^d \rightarrow t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel			36.1	🟨 T mass	1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel			36.1	🟨 B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \rightarrow Wt + X$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	🟨 $T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \rightarrow Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	🟨 Y mass	1.85 TeV	$\mathcal{B}(Y \rightarrow Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \rightarrow Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \rightarrow WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$	–	2 j	–	139	🟧 q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	36.1	🟨 b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	🟨 N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	🟨 N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	🟨 multi-charged particle mass	1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	🟨 monopole mass	2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV partial data

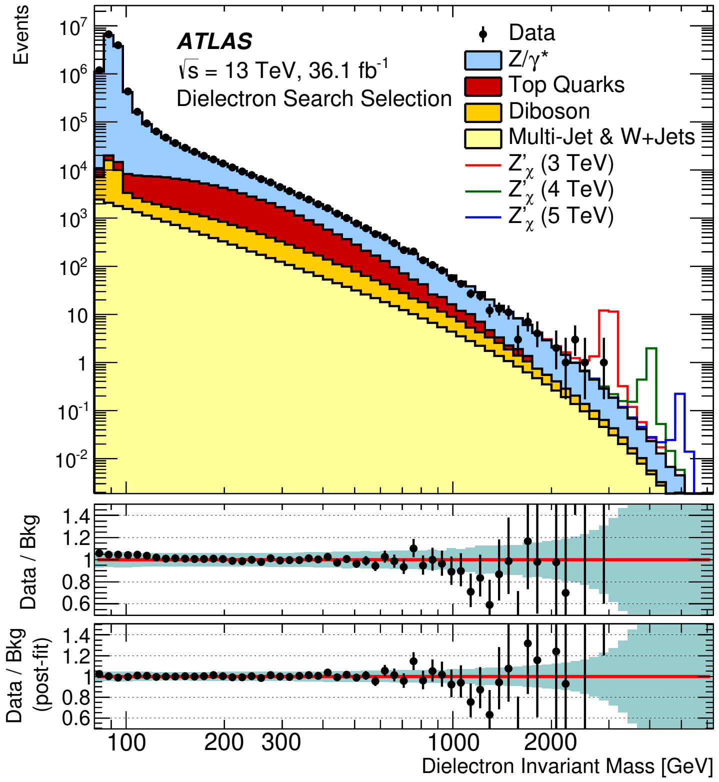
🟧 $\sqrt{s}$ = 13 TeV full data

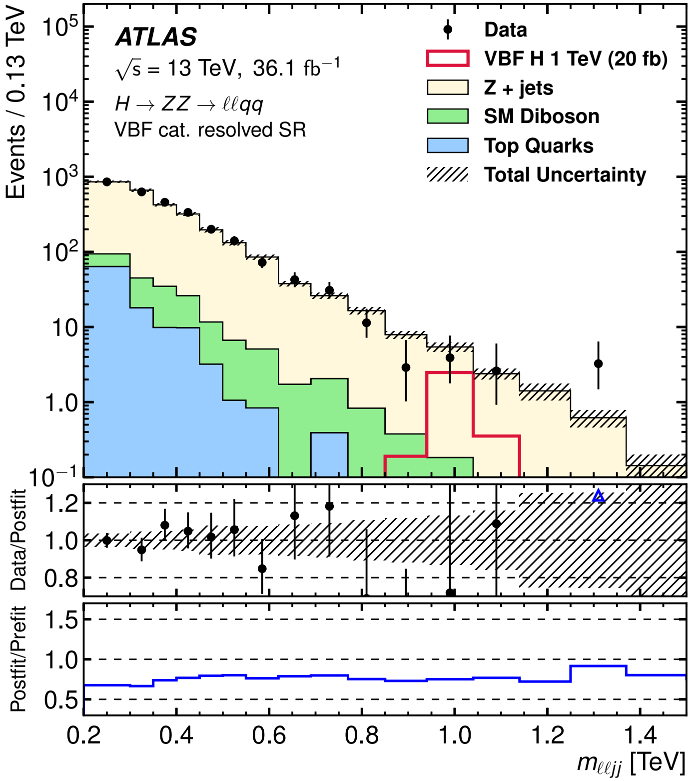
*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Heavy resonances

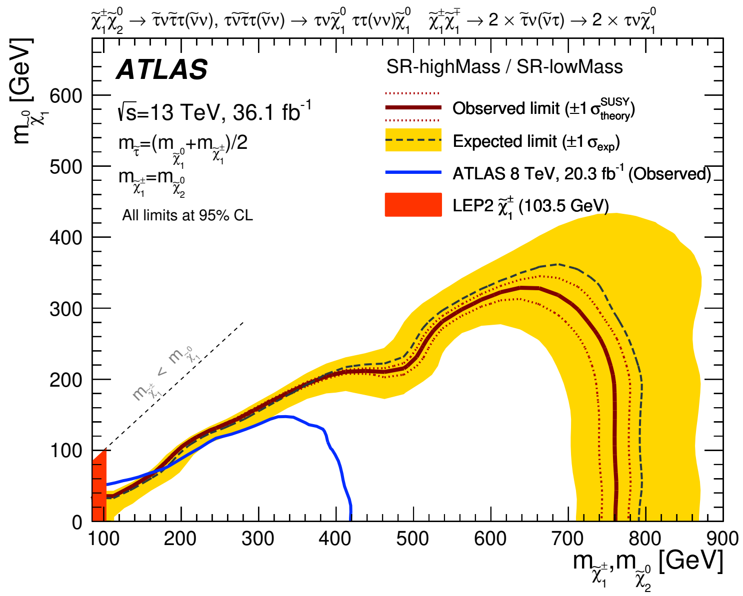
- Search for resonances in many other final states.
- Limits on the mass of these resonances is in many cases several TeV, e.g. Z' mass $(Z' \to \ell\ell) > 4.5$ TeV, W' mass $(W' \to \ell\nu) > 5.1$ TeV.

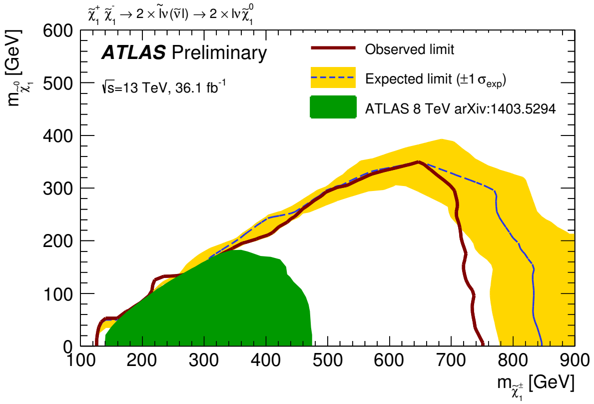


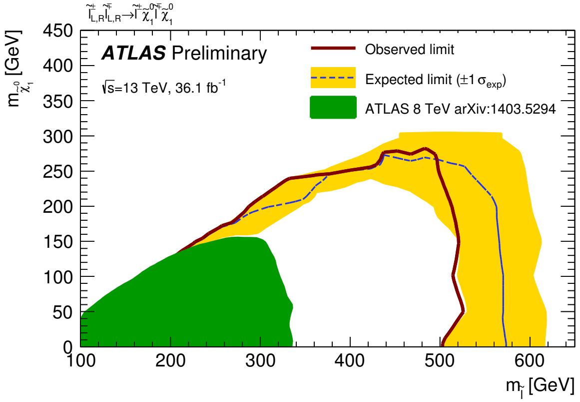


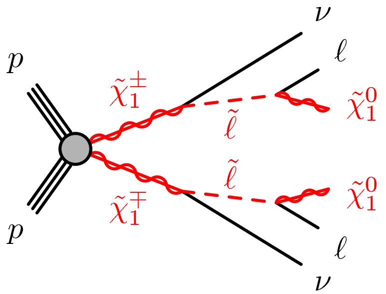
Electroweakinos and sleptons

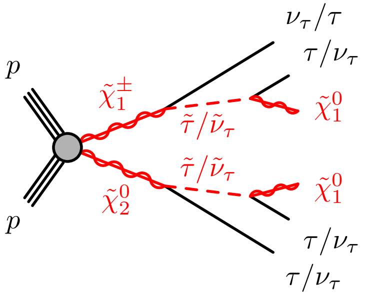
- Limits weaker than for strongly produced SUSY particles since cross sections are lower.
- Final state generally contains several leptons, and $\not\!\!E_{\mathrm{T}}$.

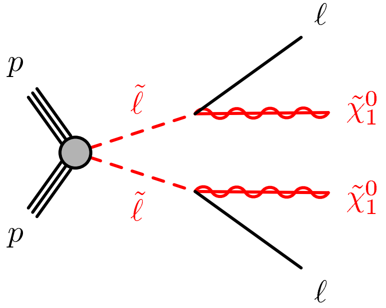






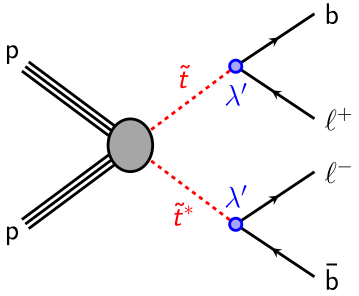


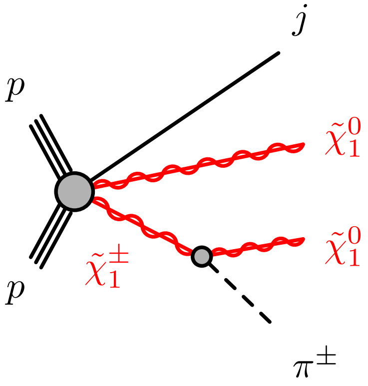


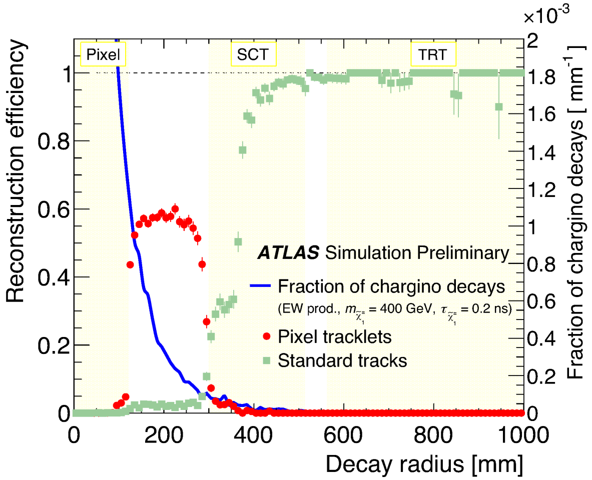


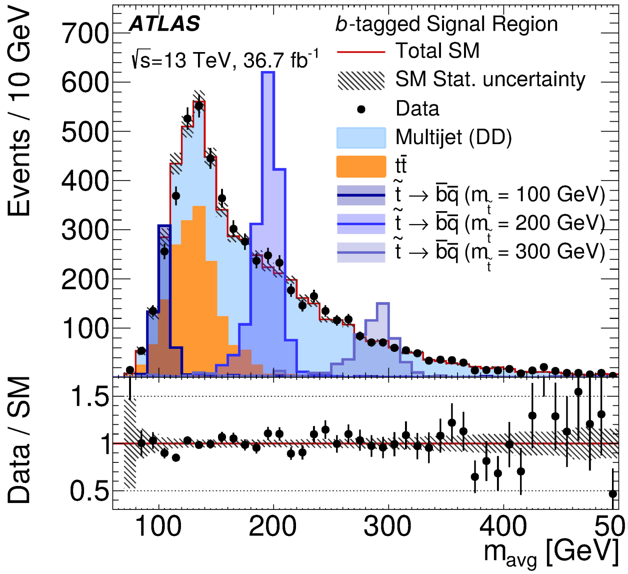
RPV SUSY and long-lived particles

- R-parity conservation is required for SUSY to provide a dark matter candidate.
- If lifted, the lightest SUSY particle will decay to SM particles → much less $\not{E}_{\mathrm{T}}$.
- SUSY particles can have long lifetimes e.g. in case of degenerate mass spectra.
- Signature strongly depend on where in the detector the decay happens.



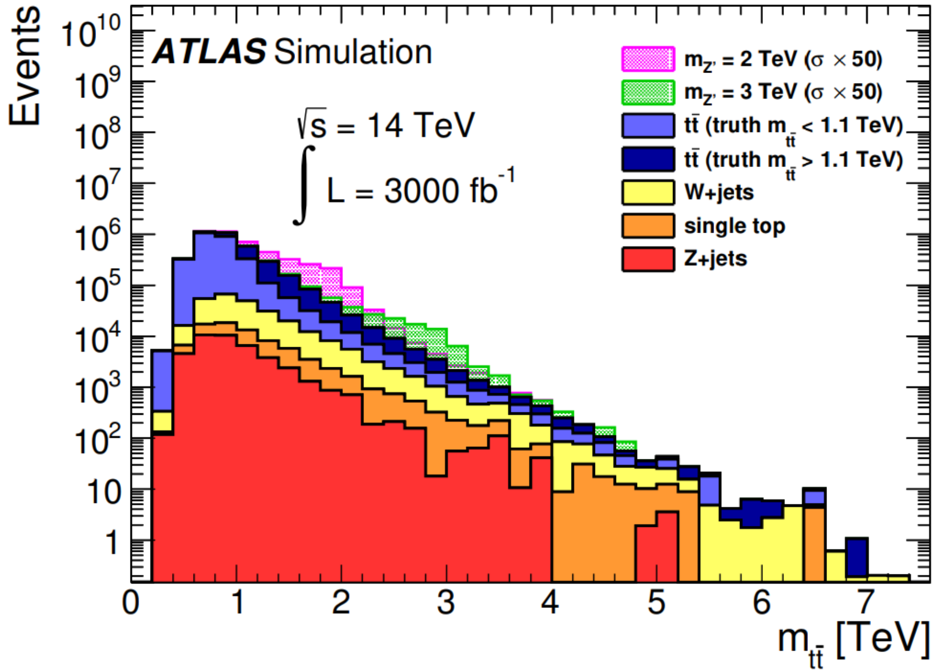


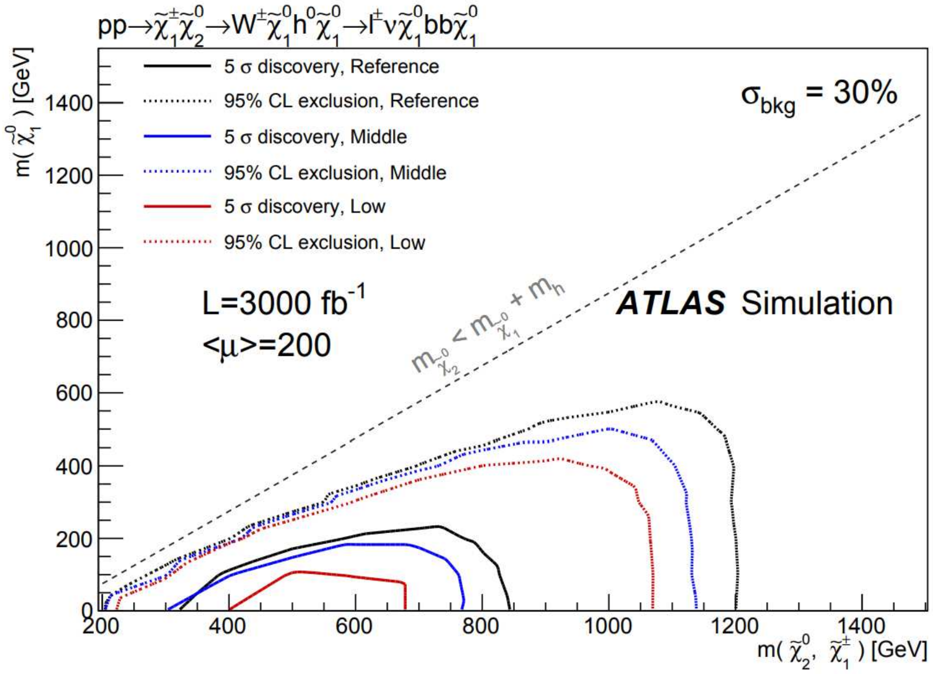




Beyond SM searches

- Increase mass reach for resonant states
- e.g. $Z' \rightarrow t\bar{t}$ reach increases from 2 TeV (2015) to 4 TeV (HL-LHC).
- Large dataset increase sensitivity to rare processes
- EWK SUSY partners reach extends from few hundreds of GeV to above 1 TeV in standard simplified models.





Latest W, t, and H mass measurements

- Impressive m_W measurement using low pile-up data at $\sqrt{s}$ =7 TeV.
- Huge amount of work in improved calibration of detector response.
- Percent-level precision on m_t and m_H.

m_W = 80370 ± 19 MeV (0.02%)

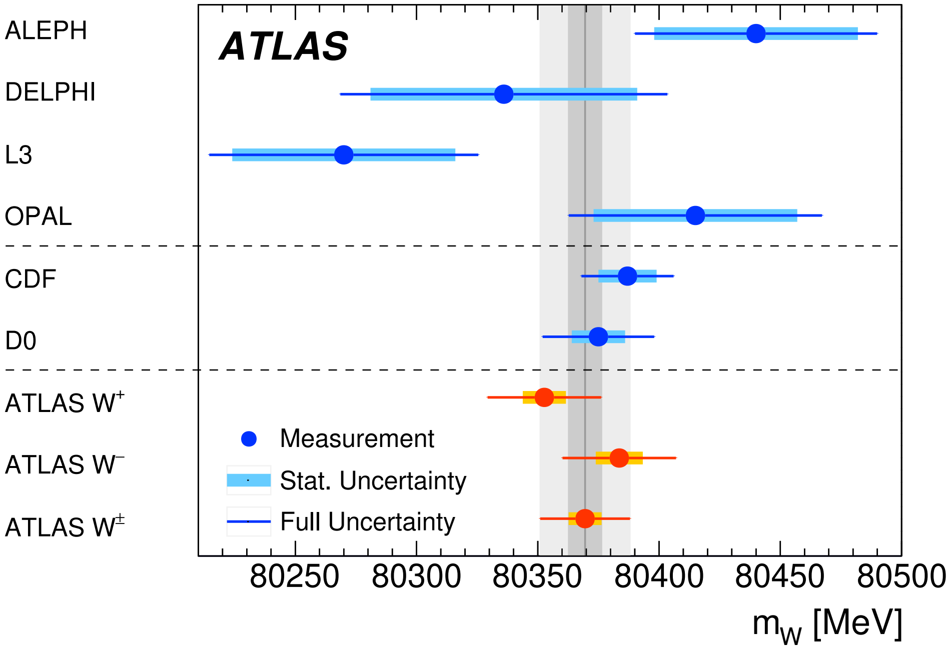
EPJC 78 (2018) 110

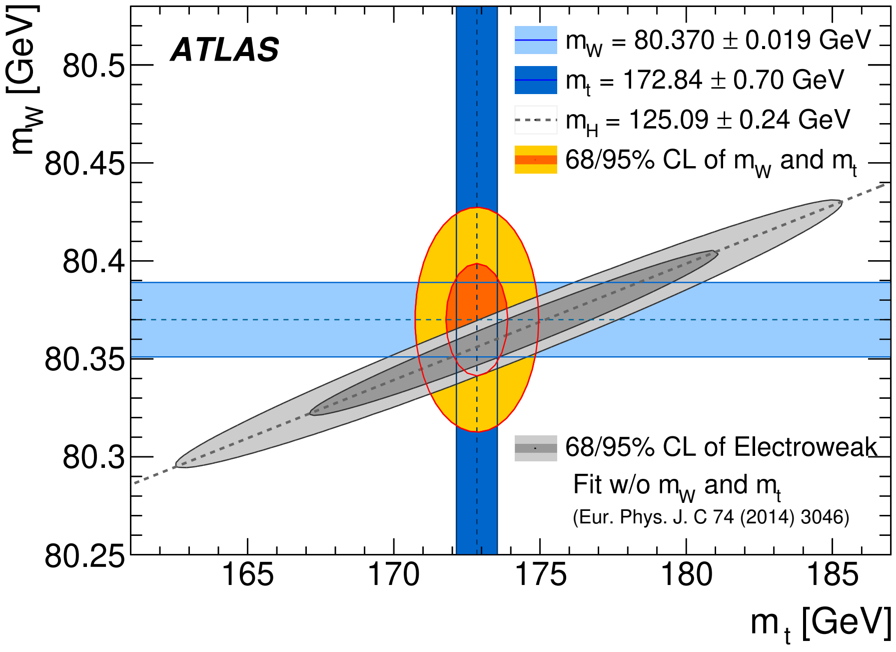
m_t = 172.69 ± 0.48 GeV (0.3%)

EPJC 79 (2019) 290

m_H = 124.97 ± 0.24 GeV (0.2%)

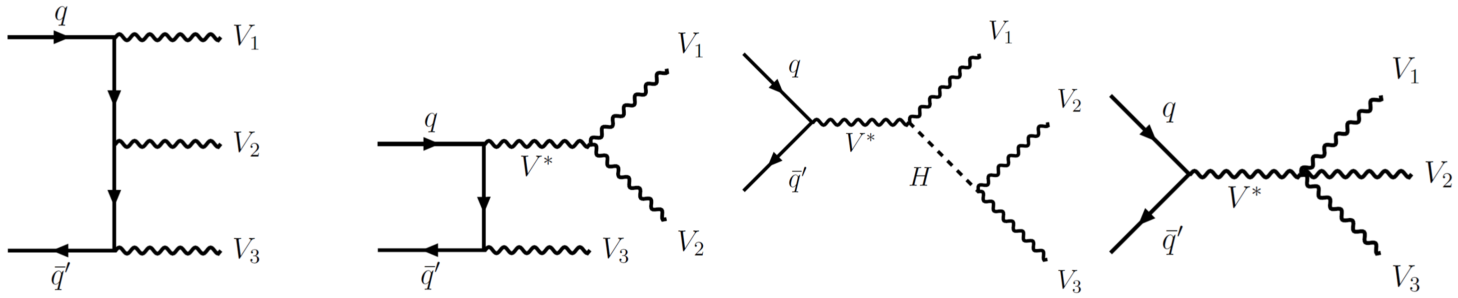
PLB 784 (2018) 345



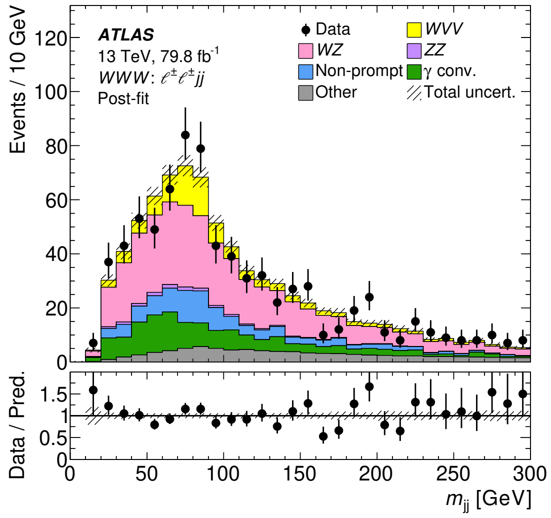


Evidence for triboson production

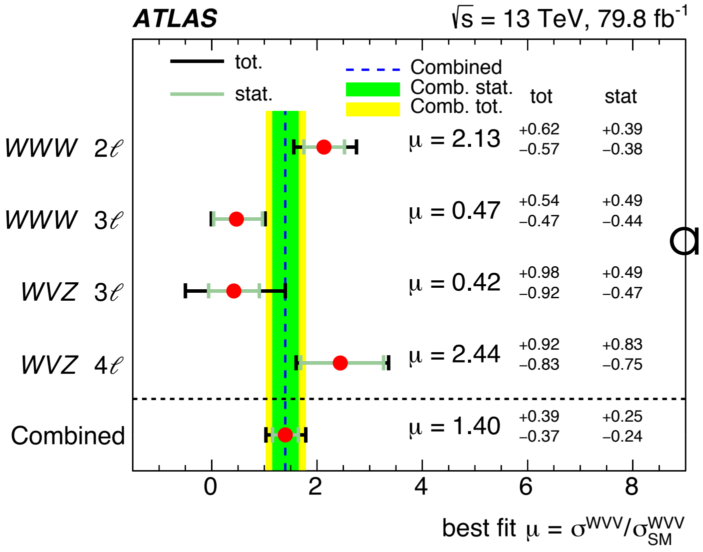
- A W boson is produced in every $1/10^6$ pp collisions.
- In every $1/10^{11}$ pp collisions three W or Z bosons are produced.



- Recently observed WVV production with 4σ significance.
- Sensitivity to triple and quartic gauge couplings.



Event yields in signal region

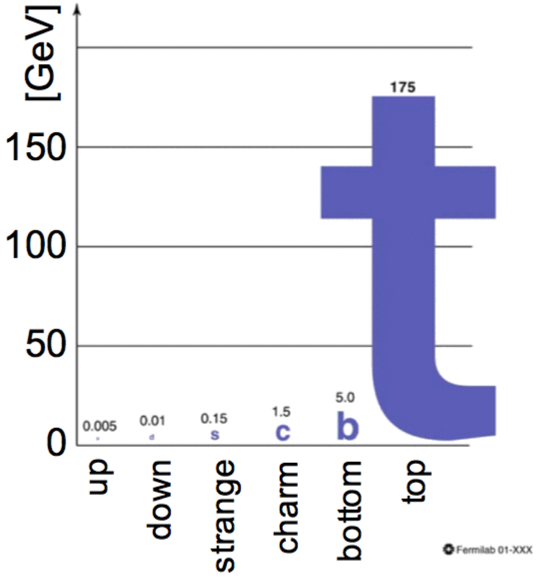


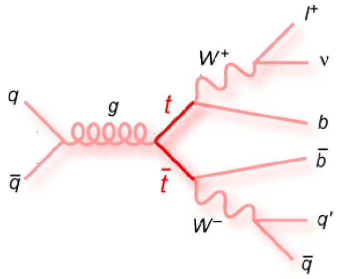
arXiv:1903.10415

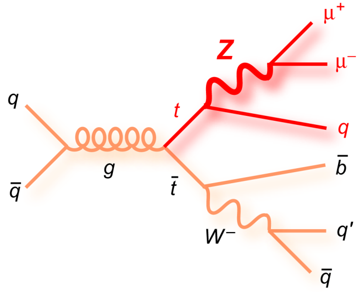
Signal strength measurement (1=SM value)

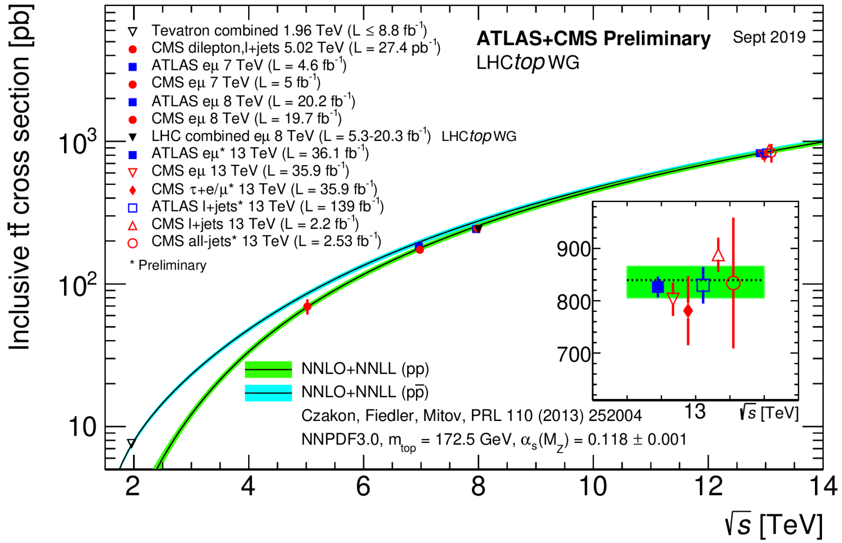
Top quark production and decay

- Heaviest fundamental particle known
  → strong indirect probe for BSM physics.
- Cross sections and BRs can be altered by new particles in production or decay.

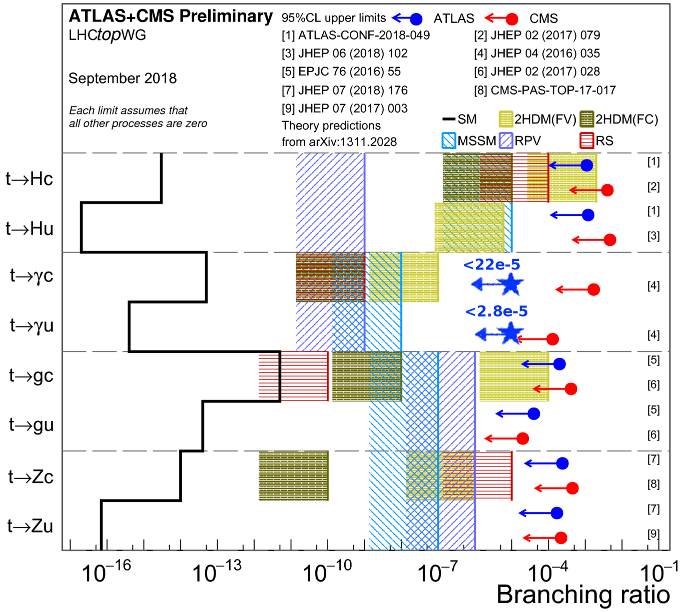








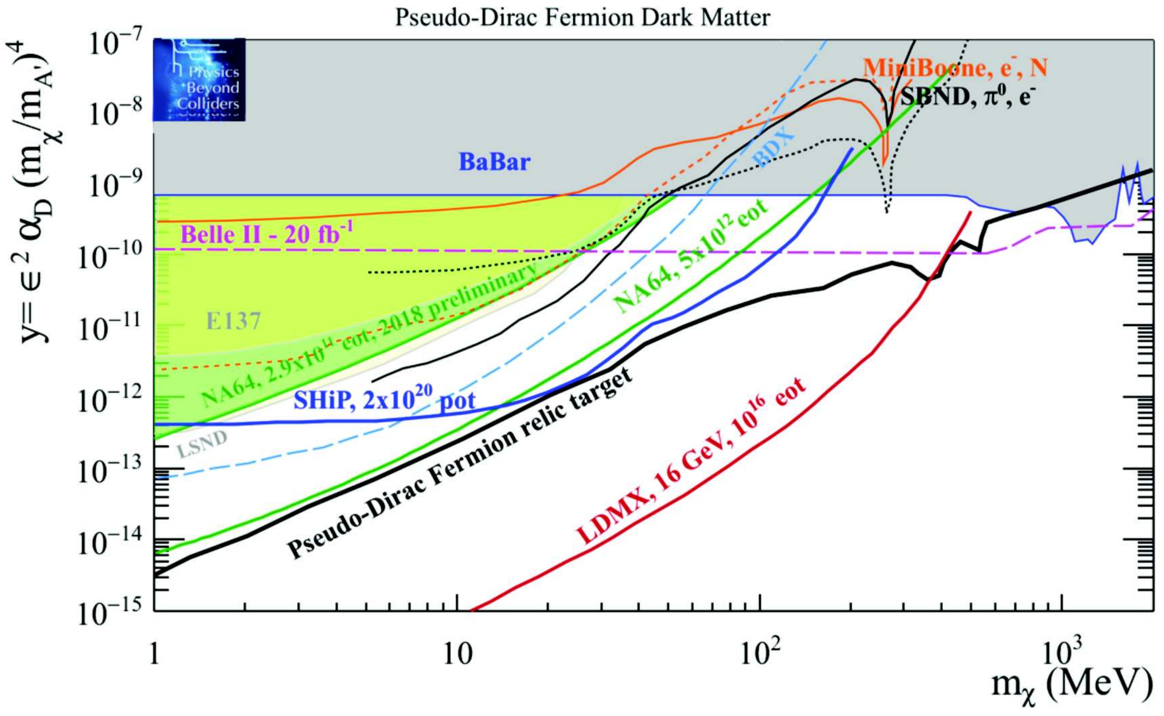
Top production probability vs collision energy



Limits on anomalous top decays

Searches beyond colliders

- Light (keV-GeV) DM allowed if neutral under all SM gauge interactions.
- Non-collider program with intense beams needed.



Reach for searches with dark photon mediator decaying to light DM particles (ϵ is the mixing between the photon mediator and the SM photon, α_D is the mediator-DM coupling, m_χ is the DM mass and $m_{A'}$ is the mediator mass).