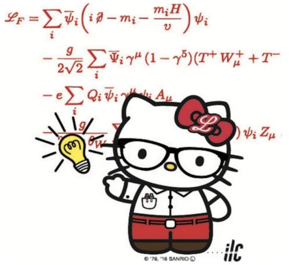
Mass and Fundamental Interactions (MIF) LPNHE team: ATLAS-CALICE-D0 Physics perspectives and prospectives

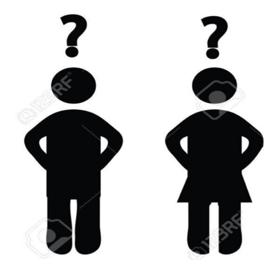
(Run 3+HL-LHC)

ATLAS EXPERIMENT

(Much longer timescale)



CLIC



HiLumi HL-LHC PROJECT

FCC hh ee he

CEPC-SPPC

Reina Camacho Toro (obo MIF team)

LPNHE Biennale 2019

Montpellier, 15-18 April 2019

ATLAS: mission and vision

- An complex and general particle detector designed to exploit the full discovery potential and the huge range of physics opportunities that the LHC provides
- Push the frontiers of knowledge by seeking answers to fundamental questions: What are the basic building blocks of matter? What are the fundamental forces of nature? Could there be a greater symmetry to our universe?
- Three main research axes:

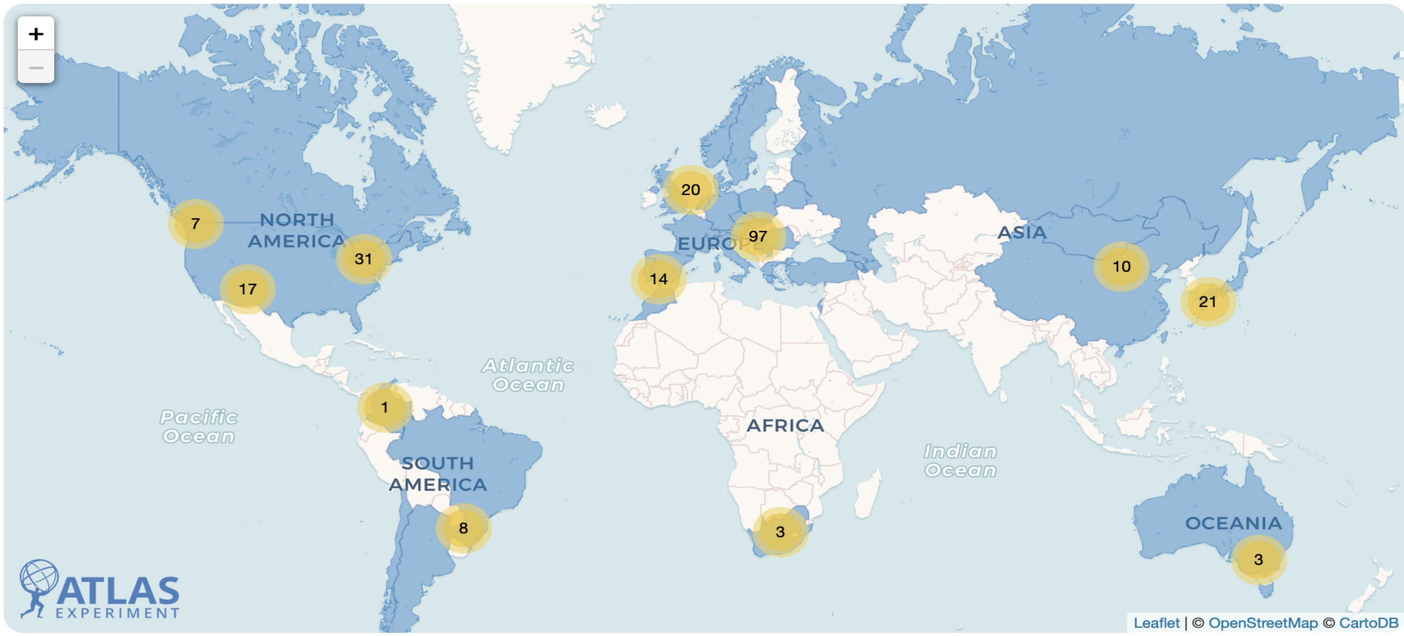
Standard Model **Higgs** and study of its properties

Other SM precision measurements: top, electroweak, QCD

What we do not know: Searches for **new physics or BSM**

ATLAS as a collaboration and at LPNHE

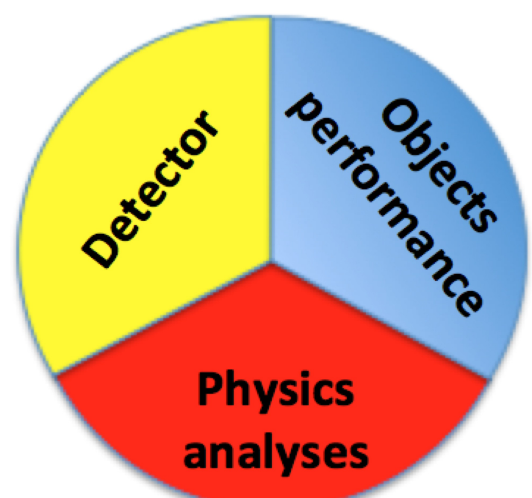
- 3000 scientific authors from 183 institutions and 38 countries (>1/3 students)



- Current composition of the team:
  - **16 permanents** (7 teacher-researchers SU/UPD, 9 CNRS), 12 HDR
  - **3 post-docs** ending this year
  - **9 PhD students** (4 of them finishing this year)
  - **ITAs:** 16 people, 6.3 FTE

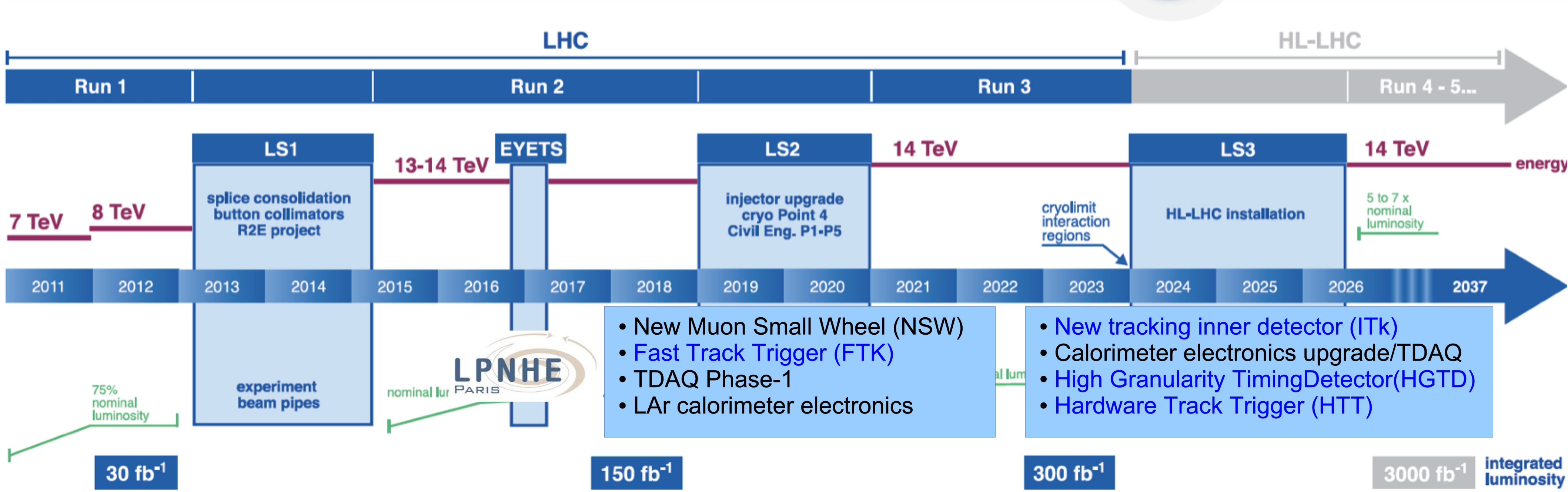
- To develop and execute a strong and effective physics program we need 3 main ingredients

LPNHE has contributed to the three of them! (see Bertrand L.'s talk)



ATLAS and its timescales

- A dynamic detector that changes to adapt to the higher luminosity and pass of time

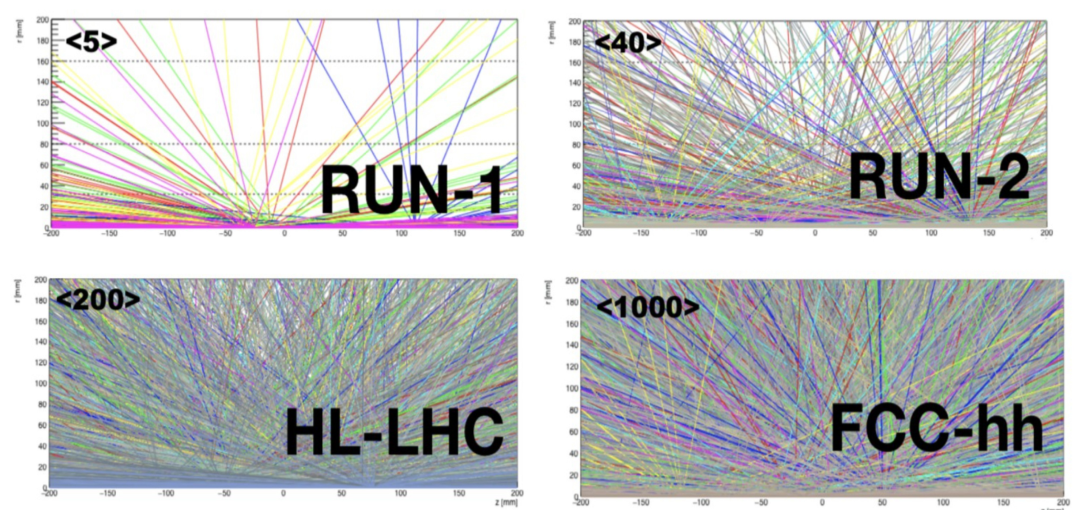


- See Francesco C.'s talk next for more information

- Run-3 and HL-LHC means more data, hopefully a bit more of energy (more reach of rare processes) but also a more challenging environment!

    - Number of additional collisions (pile-up, PU) will increase → more particles per event

- Preparation starting now!



LPNHE-ATLAS physics interests
The present and its timescale

See Bertrand L.'s talk for more info

SM **Higgs** and study of its properties

γγ

- Discovery
- Mass
- Cross-section

Summer 19

bb

- First observation
- Cross-section

End 2020

Other SM precision

Top

- Mass
- J/ψ

Summer 2020

Diboson Z(bb)γ

- Cross-section

Summer 2019

QCD Jets physics

Summer 2020

New physics or BSM

Resonances: γγ, dijets, VV
Focus in high masses

Dark matter (h(γγ/bb)+MET)

Summer 2020

SUSY (h(γγ/bb)W+MET)

Summer 2019

** Diffuse line between SM measurements and BSM searches: a deviation in data from SM prediction could be a hint of BSM!*

LPNHE-ATLAS physics interests Towards Run-3

- We want to continue some interesting efforts

SM **Higgs** and study of its properties	**Other SM** precision	**New physics or BSM**
$\gamma\gamma$	Top	Resonances: $\gamma\gamma$, dijets, VV
bb	Diboson Z(bb)γ	Dark matter (h($\gamma\gamma$/bb)+MET)
	QCD Jets physics	SUSY (h($\gamma\gamma$/bb)W+MET)

- And explore new directions

Rare Higgs decays

- Zγ
- $\mu\mu$

Higgs self-coupling

- HH $\gamma\gamma$bb, bbbb

Long lived particles

- Axion like particle (ALP) (with γ topologies)

LPNHE-ATLAS physics interests Towards Run-3

- We want to continue some interesting efforts

SM Higgs and study of its properties

γγ

bb

Other SM precision

Top

Diboson Z(bb)γ

QCD Jets physics

New physics or BSM

Resonances: γγ, dijets, VV

Dark matter (h(γγ/bb)+MET)

SUSY (h(γγ/bb)W+MET)

- And explore new directions

Rare Higgs decays

Zγ

μμ

Higgs self-coupling

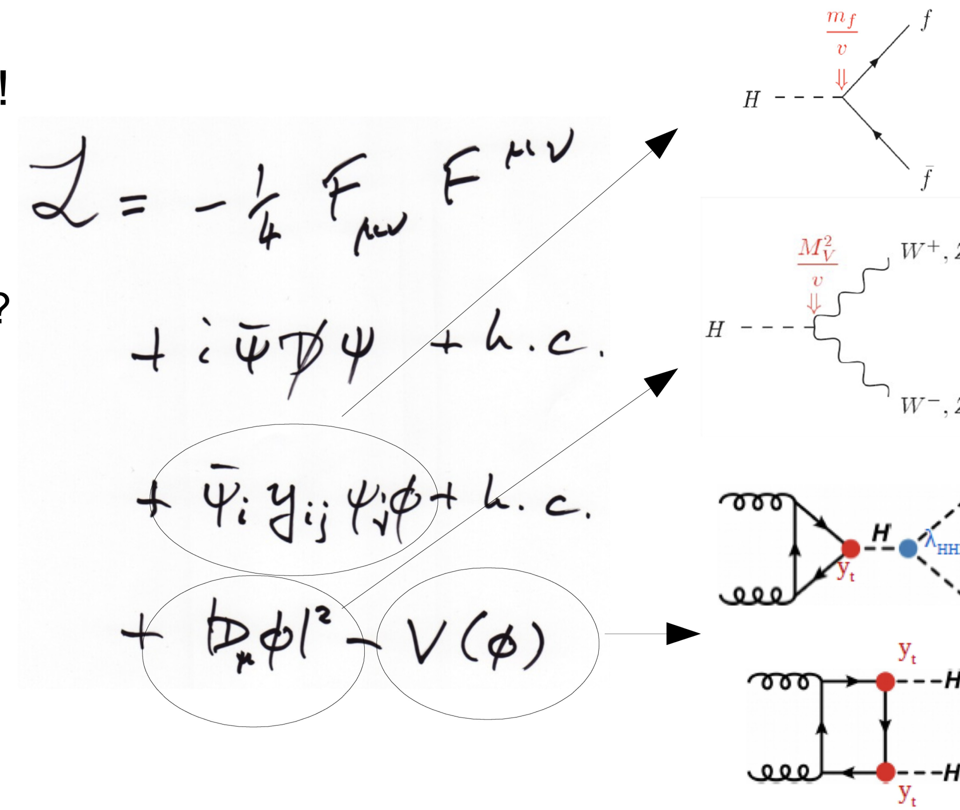
HH γγbb, bbbb

Long lived particles

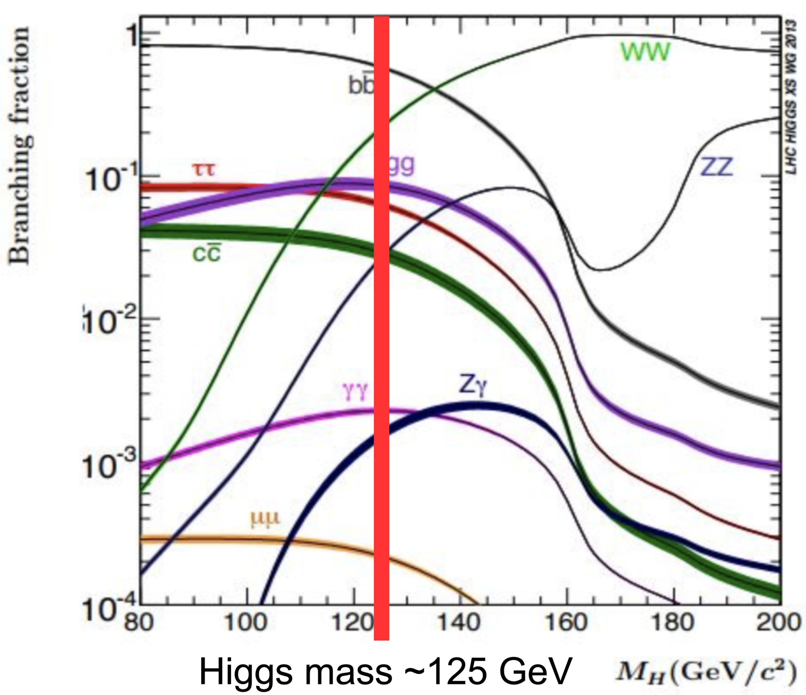
Axion like particle (ALP) (with γ topologies)

Why to continue studying the Higgs?

- Because we want to know of its intimate secrets!
  - In the SM, the Higgs mechanism provides masses to bosons and fermions
  - Is the SM Lagrangian structure correct?
  - Are the values of the couplings as predicted in SM?
  - What is the shape of the potential?



- Measure with the best possible precision as many production and decay modes as possible



- Why H→ bb? Largest BR, direct measurement of Yukawa yb coupling
- Why Higgs rare decays? Coupling to the second fermion generation, expected extrapolation HL-LHC uncertainties on signal strength at 10-13%
- Why HH? Full reconstruction of Higgs potential

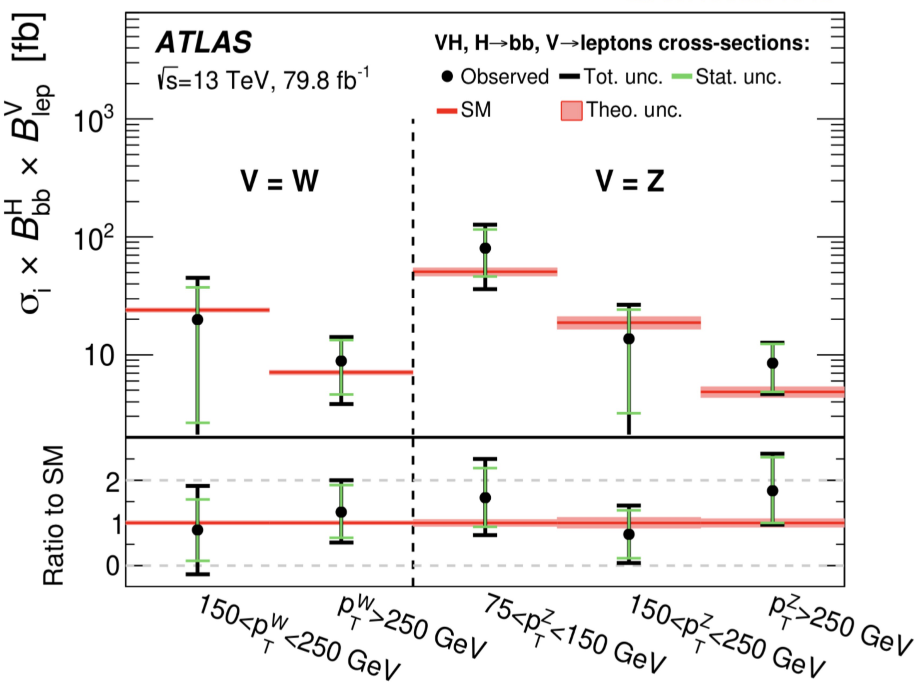
$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

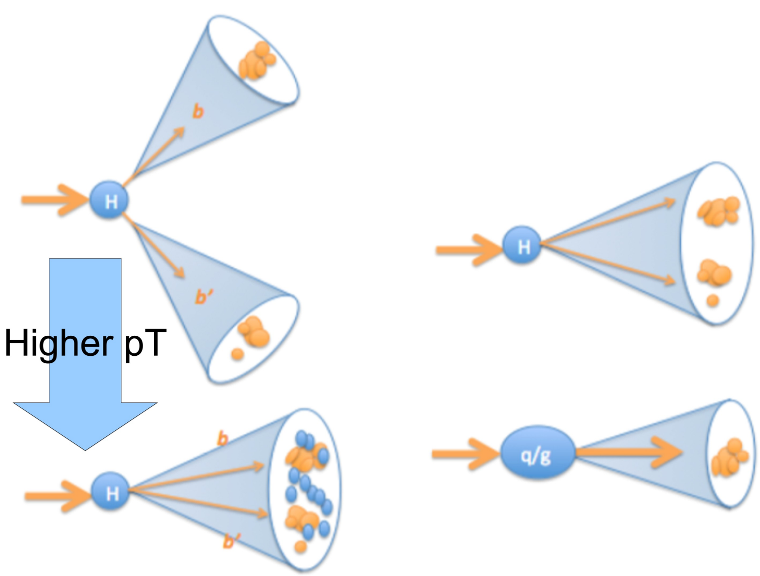
mass term   self coupling terms

The future of H→bb

- ATLAS and CMS observation in summer 2018
- First differential cross-section measurement published recently, p_T<300 GeV
- Many BSM theories predict important deviations from SM at high p_T → interest in boosted regime!
- Challenges: decay products very close to each other due to Lorentz boost, high backgrounds (tt, V+jets), high theoretical uncertainties for V+bb process
- Who is interested? GC, GM, RC, BM, GB

arXiv:1903.04618





- Interest in using machine learning techniques together with Lund plane techniques
- Effort supported until now by ANR Hbb+ttH@LHC. New JCJC ANR requested (expecting results)
- 2 new PhD students expected to join the team to work on the topic this year. Interest request postdoc to IN2P3

A new activity: HH (bbbb, bbγγ)

- Rare process in SM: σ(gg→HH) ≈0.1%*σ(gg→H)
  - Destructive interference between Feynman diagrams reduces cross section

• Also interesting for direct BSM searches: BSM contributions can modify the Higgs boson coupling parameters and modify the HH cross section, i.e. extra dimensions, 2 Higgs doublets models

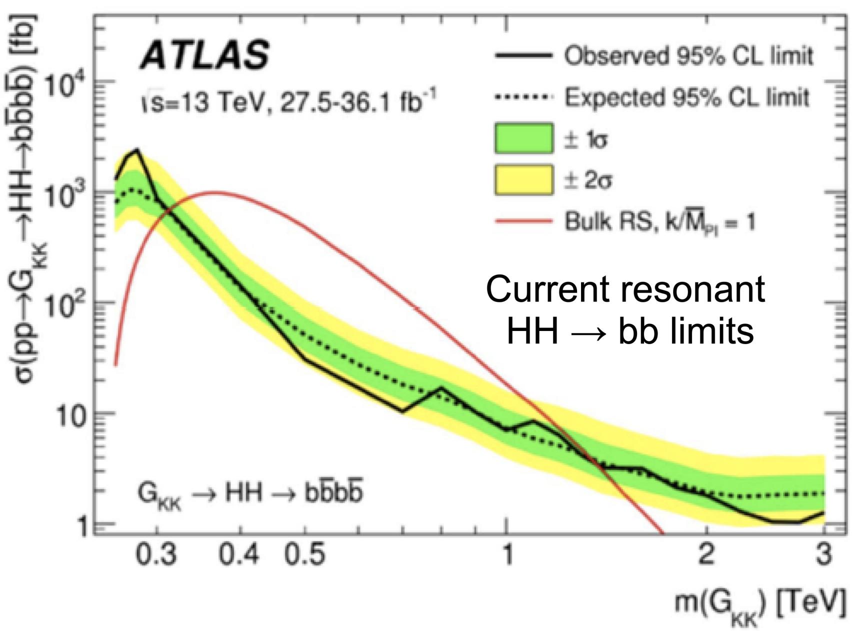
• Best current limit on non-resonance production at 13x SM (not full Run-2 data considered)
• Who is interested: GB, GM
• One PhD thesis proposed to work on this topic

HH decay branching ratios

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

High BR

Precise mass reconstruction



Current resonant HH → bb limits

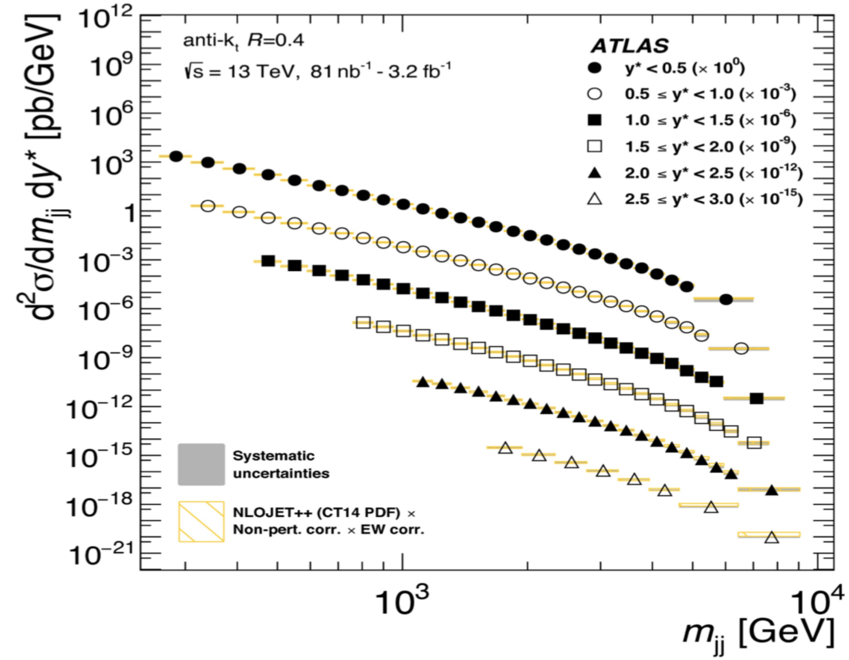
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

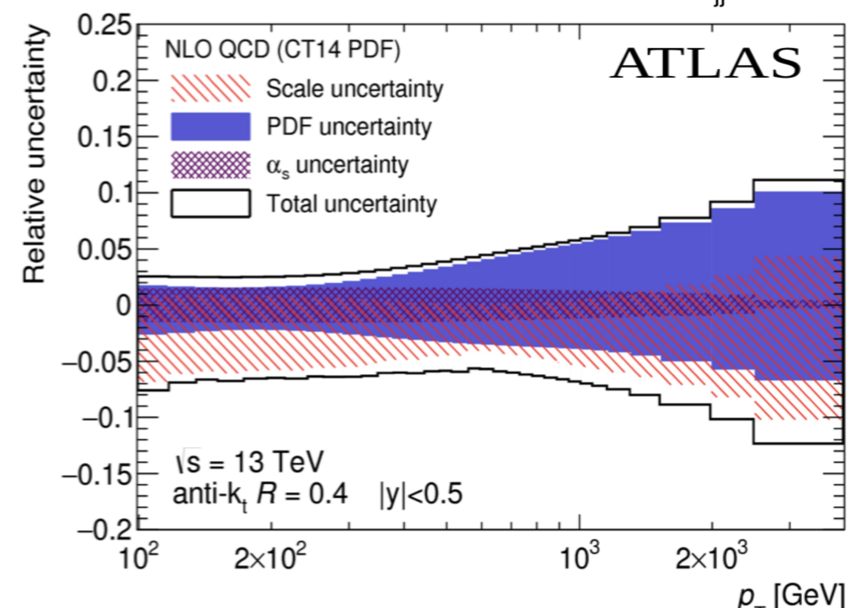
Expected significance non resonance SM @HL-LHC

LHC is a very jetty place: QCD physics

- The understanding and precise measurement of jets is very important for many analyses
- Current results show good data/theory agreement on full phase-space for ATLAS dijets (13 TeV), at the NNLO level calculations
- Interest in continue measuring the inclusive and di-jet cross-sections with better precision:
  - Test the SM and search for new physics
  - Test the QCD renormalisation group equation
  - Constrain the proton PDF
- A lot of experience in the team in several aspects: the analysis itself, statistical treatment and jet calibration using Z+jet and dijet data driven methods
- Who is interested? MR, BM
- One PhD thesis proposed this year to work on this topic. Interest request postdoc to IN2P3

arXiv:1711.02692





Entering the domain of direct searches for new physics: The "simplest case" resonances

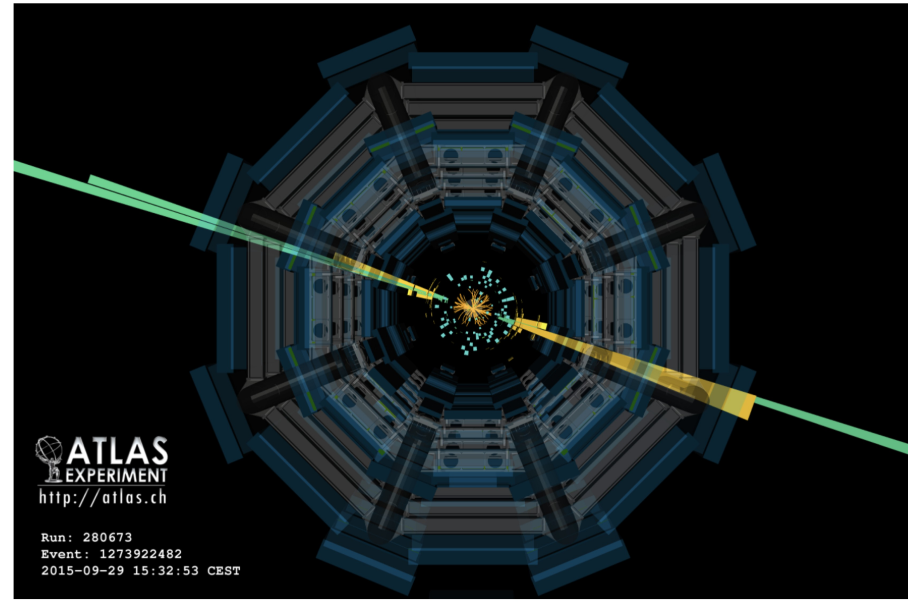
- γγ resonances can be produced for instance in models with extra Higgs bosons (like SUSY, 2HDM, …) or with extra dimensions (Randall-Sundrum graviton ..)

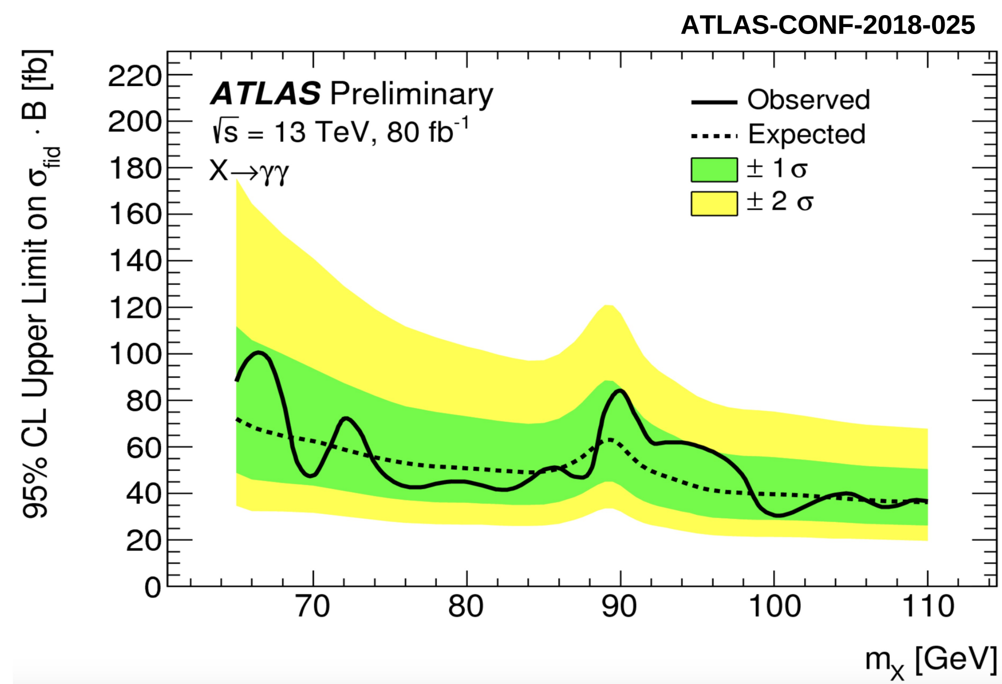
- Currently ATLAS searches in the range of 60 GeV-4 TeV

- Interest in exploring lower regions:
  - Implement new L1Topo diphoton triggers: access lower ET using Δφ and mass thresholds to control the rate
  - Take advantage of the low-μ conditions in 1st Run3 year

- A lot of experience in the team in several aspects: the analysis itself, photon performance

- Who is interested? JO, LR, LD





Dark matter (DM) and long lived particles

- The searches of DM in colliders is complementary to direct and indirect observations. Nice complementary in the lab for DM searches

- Interest in continue the involvement in current DM searches + starting an effort to search for axion-like particles (ALP)
  - ALP is a light scalar, a singlet under the SM gauge group and odd under CP, inspired by QCD axion
  - In certain regions of parameter space ALPs can be non-thermal candidates to DM

- Interesting channels at the LHC are the on-shell decays h → aa, h → Za and Z →γa. A search with a→ γγ will fit the team's expertise
- Challenges: depending of life-time the search can be less or more difficult, if ALP decaying in calorimeter energy and timing info can be used to improve the reconstruction

- Part of ANR proposed with LPTHE (waiting results)

- Who is interested? BL, FD

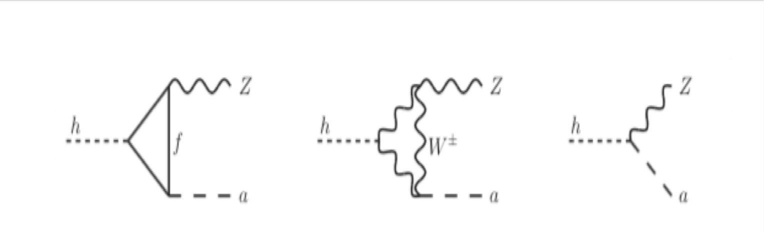
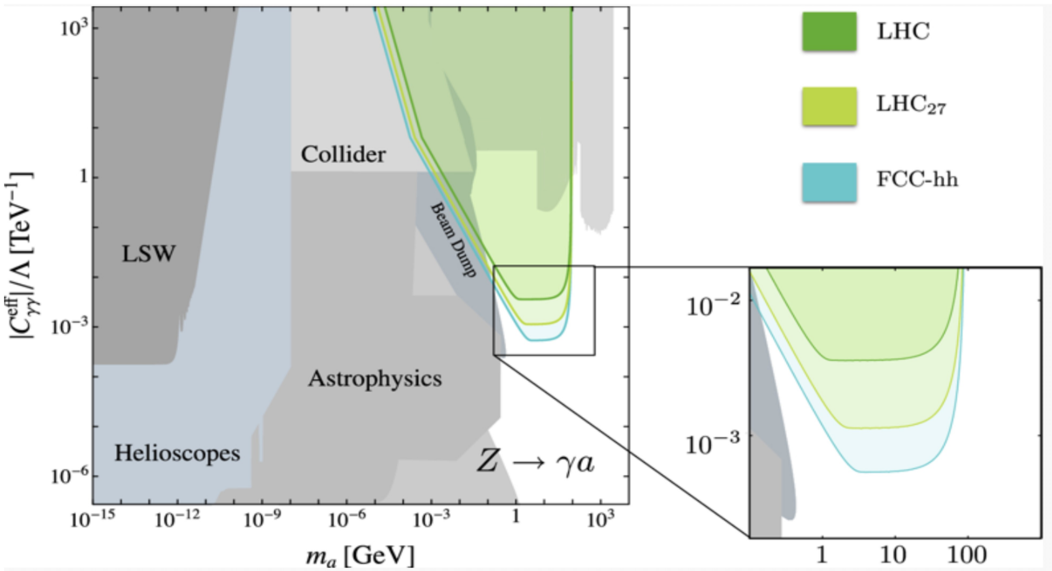


Figure 9: Feynman diagrams contributing to the decay $h \to Za$.

Eur. Phys. J. C (2019) 79: 74



Parameter regions which can be probed in the decay Z →γa with a→ γγ at hadron colliders

LPNHE-ATLAS detector performance interests Towards Run-3

- Performance interests aligned with the analysis ones... Want to develop new expertise tpo!

SM Higgs and study of its properties

- bb
- HH $\gamma\gamma bb$, bbbb
- $Z\gamma$
- $\mu\mu$
- $\gamma\gamma$

Other SM precision

- QCD Jets physics

New physics or BSM

- Resonances $\gamma\gamma$, dijets
- Dark matter and Axion like particle (ALP) (with γ topologies)

Coherent performance activities!

- Jets: calibration
- B-tagging And boosted Higgs
- Photons
- Computing and ML

LPNHE-ATLAS detector performance interests Towards Run-3

- Performance interests aligned with the analysis ones... Want to develop new expertise tpo!

SM **Higgs** and study of its properties

- bb
- HH γγbb, bbbb
- Zγ
- μμ
- γγ

Other SM precision

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SM **Higgs** and study of its properties

Other SM precision

New physics or BSM

bb

HH
γγbb, bbbb

Zγ

μμ

γγ

QCD
Jets physics

Resonances γγ, dijets

Dark matter and
Axion like particle (ALP)
(with γ topologies)

Coherent performance activities!

Jets: calibration

B-tagging
And boosted Higgs

Photons

Computing and
ML

LPNHE-ATLAS detector performance interests Towards Run-3

- Performance interests aligned with the analysis ones... Want to develop new expertise tpo!

SM **Higgs** and study of its properties	**Other SM** precision	**New physics or BSM**
bb*	QCD Jets physics	Resonances γγ, dijets
HH γγbb, bbbb		Dark matter and Axion like particle (ALP) (with γ topologies) *
Zγ		
μμ		
γγ		

ANR with LPTHE for ML proposed: ALP, quark-gluon jet ID, event multiclassification. Who? LR, BL, FD

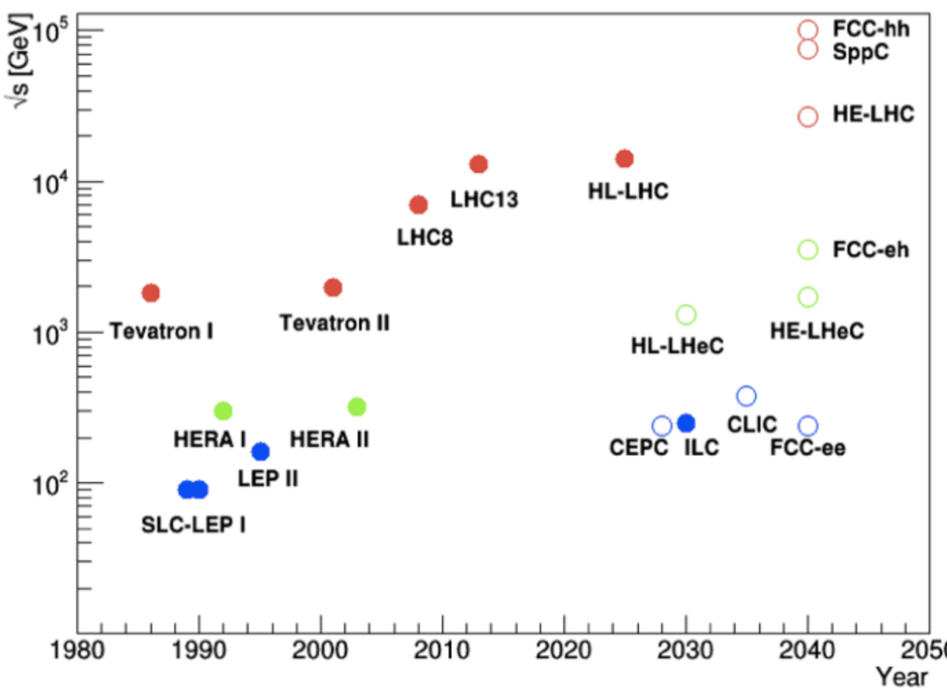
Coherent performance activities!

- Jets: calibration
- B-tagging And boosted Higgs
- Photons
- Computing and ML*

Longer-term possibilities: What can we do? What is the MIF potential?

- Current LHC results seem to indicate that the discovered Higgs boson is SM-like and that BSM is beyond LHC reach or weakly coupled to the SM sector → new machines
- As many of you know, we did an interesting exercise in preparation for this meeting
  - Explore the physics potential of the different future collider projects. No “hints” for now
  - Will provide a very brief MIF summary here... A summary document here
  - Disclaimer: the idea was not to decide which (or which combination) was the best/the one to support (many more things to consider!) but to dream about their physics potential; also tried to have a bit of common sense (we can not have 5 different such a project running at the same time)
- Here are main characteristics of the different projects considered

Collider	type	$\sqrt{s}$	Luminosity	Starting date	End date
HL-LHC	pp circular	14 TeV	6-8 ab^{-1}	2026	2036
HE-LHC	pp circular	27 TeV	30 ab^{-1}	2040	2050
LHeC	ep hybrid	1.3 TeV	1 ab^{-1}	2032	2045
ILC	ee linear	0.25 TeV	2 ab^{-1}	2034	2049
		0.50 TeV	4 ab^{-1}	2050	2060
CEPC	ee circular	0.09 TeV	8 ab^{-1}	2037	2039
		0.16 TeV	2.6 ab^{-1}	2039	2040
		0.24 TeV	5.6 ab^{-1}	2030	2036
FCC-ee	ee circular	0.09 TeV	150 ab^{-1}	2039	2042
		0.16 TeV	10 ab^{-1}	2043	2044
		0.24 TeV	5.0 ab^{-1}	2045	2047
		0.36 TeV	1.7 ab^{-1}	2049	2053
FCC-hh	pp circular	100 TeV	25 ab^{-1}	2043 if no FCC-ee	2065
FCC-eh	ep hybrid	3.7 TeV	8 ab^{-1}	2043 if no FCC-ee	2065
SPPC	pp circular	75 TeV	5 ab^{-1}	2045	2060
CLIC	ee linear	0.5 TeV	0.2 ab^{-1}	2035	2050
		1.5 TeV	0.4 ab^{-1}		
		3.0 TeV	0.7 ab^{-1}		



Longer-term possibilities: What can we do? What is the MIF potential?

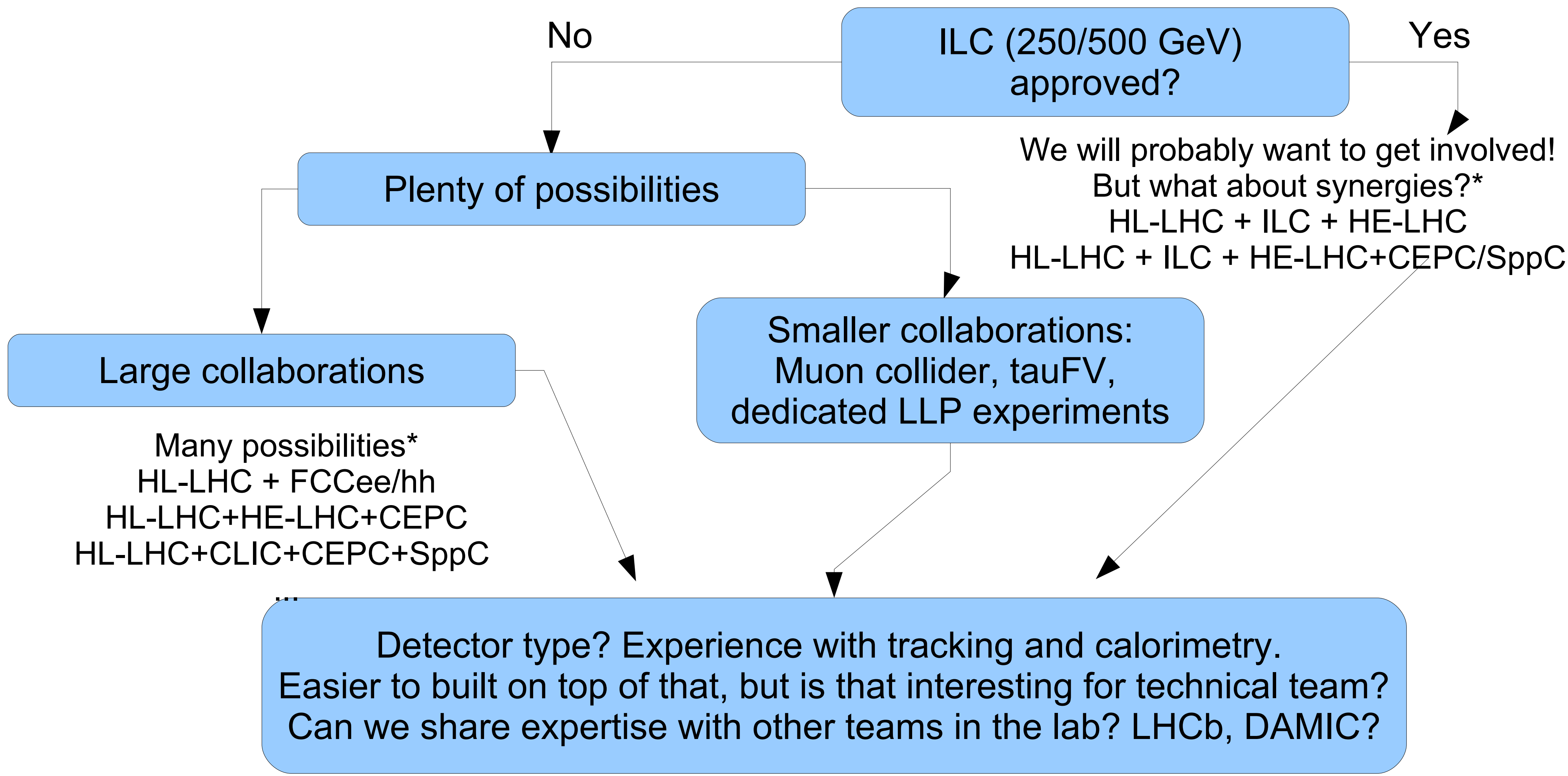
Question	ILC	CLIC	HE-LHC	LHeC	FCCee/CEPC	FCChh/ SppC
Higgs physics	Precision but need 500 GeV for Higgs SC (27% unc. 2060)	Less precise Higgs SC than ILC	Higgs SC 20% unc. 2050	Empowers HL-LHC results	Precision, Higgs SC 40% unc. 2053 (less for CEPC). CEPC tighter schedule	Higgs SC to 5%
Other SM	Main reason: top and EWK physics	~Same	Limited by systematics	PDF, ideal to study EWK interactions of quark top	Precise EWK meas., huge Z and WW sample	Good stats but more difficult environment
New particles	Need 500 GeV for BSM studies	Limitations stat+syst for many scenarios	Main reason: +energy ẁ + searches	PDF, less backgrounds.. BSM: eeqq contact interactions, electron-quark resonances	Similar to ILC	Huge potential, new resonances ~10 TeV range

- An electron-positron collider is imperative to perform precision (sub-percent level) Higgs coupling measurements
- Lepton machines are associated with precision measurements while hadron machines are associated with discoveries, high energy scale → new search phase space
- Going beyond 14 TeV in proton-proton collision is mandatory to extend BSM reach, to elucidate the EWSB sector and for Higgs self- and the top Yukawa coupling precision

Longer-term possibilities:
What can we do? What is the MIF potential?

We are already on the HL-LHC bus with two upgrade projects: HGTD and ITk

But what after that?



Interest in getting involved in FCC(ee) studies: GB, AB

**Interested? Check Gautier's talk at SFP in Nov. 2018*

Conclusion and summary

- A dynamic physics strategy in preparation
  - Covering three main ingredients for a strong physics program: analysis, performance and detector
  - Good visibility in the international collaboration

- We will do all our best to exploit the potential of the LHC current and future datasets
  - To improve our understanding of the SM and search directly for new physics

- ...while also contributing to the future collider projects

- Trying our best to keep up-to-date in the new analysis developments and to provide a scientifically exciting environment for the new generation of scientists and ITA working in the group

BACKUP

Human forces (1/04/2019)

Enseignants-Chercheurs :
7 – 5 HDR
5 UPD/P7 – 2 SU/P6
5 MdC – 2 PR

- T. Beau (MdC P7)
- M. Bomben (MdC P7)
- B. Laforge (PR SU)
- I. Nikolic (MdC P7)
- J. Ocariz (PR P7)
- M. Ridel (MdC P7)
- S. Trincaz-Duvoid (MdC SU)

Chercheurs :
9 – 7 HDR
3 CR – 6 DR

- G. Bernardi (DR)
- R. Camacho Toro (CR)
- G. Calderini (DR)
- F. Derue (DR)
- W. Krasny (DR)
- D. Lacour (DR)
- B. Malaescu (CR)
- G. Marchiori (CR)
- L. Roos (DR 20%, DAS IN2P3)

Doctorants : 9 (since last biennale)

- L. D'Eramo (2016)
- L. Pascual Dominguez (2017)
- R. Hankache (2016)
- A. Leopold (2017)
- I. Luise (2016)
- A. Tarek (2016)
- R. Taibah (2018)
- Y. Wang (2017)
- J. Zahreddine (2017)

\+ Marton Sandes dos Santos (2019 - 1 year)

Postdocs : 3

- W. Spolidoro Freund, COFECUB 01/09/2018 - 31/08/2019
- K. Liu, ANR prolongation, 01/09/2018 - 31/08/2019
- I. Nomidis, ANR 02/2018 - 01/2020

6 Defended Theses since last Biennale

Y. Yapp (01/2017) (High mass diphoton resonance search)
A. Lopez Sollis (09/2017) (DM in mono-Higgs ($\gamma\gamma$))
S. Manzoni (12/2017) (SUSY in $\gamma\gamma$ + MET) – ATLAS Thesis Award
D. Portillo (10/2018) (mono-Higgs b-bbar, DM)
A. Ducourtial (10/2018) (H→b-bbar)
C. Li (11/2018) (Observation H→ b-bbar)

Departures

Departure of S. Laplace mid-2018
Departure of R. Wang Dec. 2018 (ILP)

Tentative scenarios

Tentative Scenarios

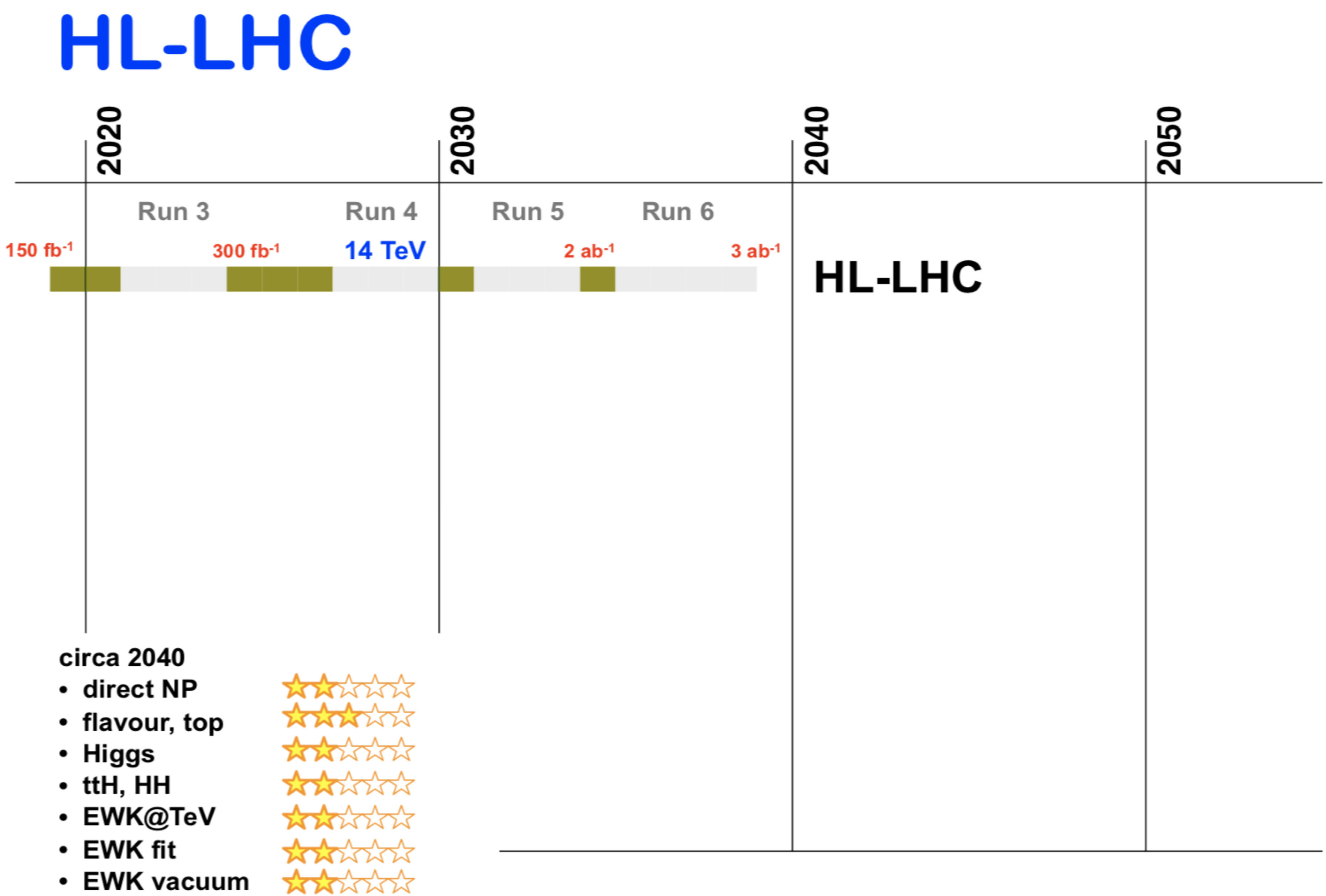
- In the following we present a few selected scenarios
- Schedules are taken as advertised by the projects
  - some estimates may be more trustable than others
- Some level of common sense is unforced
  - avoid several major running machines in the same lab
  - avoid several 100-km class tunnels in the World
- Scenarios are evaluated on the basis of 7 physics criteria evaluated at date 20XX

Circa 20XX		
• Direct NP	**New physics** reach potential	☆☆☆☆☆
• flavour, top	Potential in **flavour and top physics**	☆☆☆☆☆
• Higgs	Sensitivity on **Higgs boson couplings**	☆☆☆☆☆
• ttH, HH	Sensitivity on **top Yukawa** and **Higgs self couplings**	☆☆☆☆☆
• EWK@TeV	Sensitivity on **vector boson scattering** at TeV scale	☆☆☆☆☆
• EWK Fit	Sensitivity on **electroweak precision observables**	☆☆☆☆☆
• EWK Vacuum	Sensitivity on **top quark mass** and **Higgs boson mass**	☆☆☆☆☆

the scores are arbitrary, they are just meant as input to the afternoon discussion

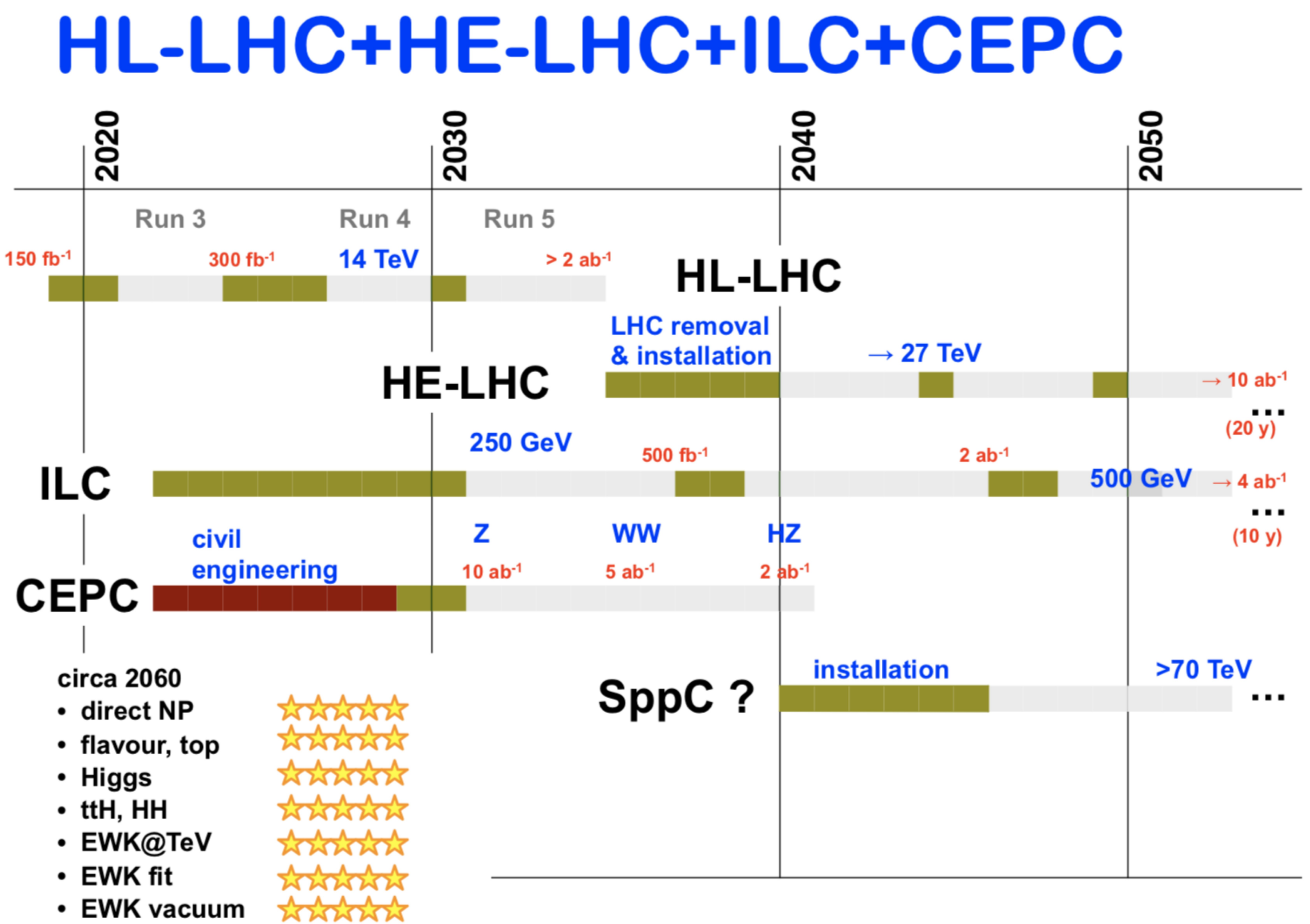
Shamelessly stolen from Gautier's talk lat SFP 2018

We need something between this



Shamelessly stolen from Gautier's talk lat SFP 2018

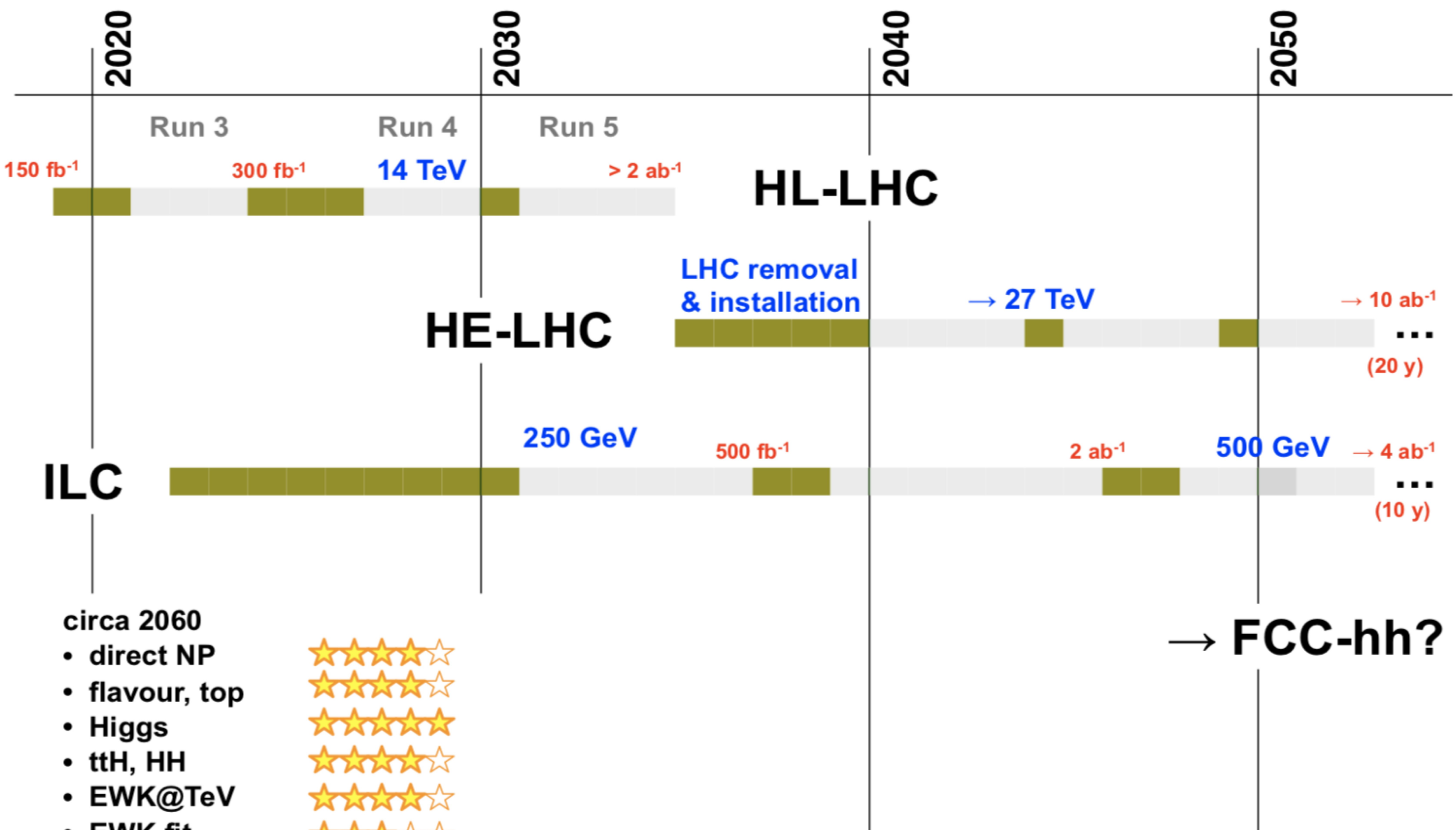
And this...



HL-LHC+HE-LHC+ILC+CEPC
2020
2030
2040
2050
Run 3
Run 4
Run 5
150 fb-1
300 fb-1
14 TeV
> 2 ab-1
HL-LHC
LHC removal
& installation
→ 27 TeV
HE-LHC
→ 10 ab-1
...
(20 y)
250 GeV
500 fb-1
2 ab-1
ILC
500 GeV
→ 4 ab-1
...
(10 y)
civil
engineering
Z
WW
HZ
10 ab-1
5 ab-1
2 ab-1
CEPC
circa 2060
• direct NP
• flavour, top
• Higgs
• ttH, HH
• EWK@TeV
• EWK fit
• EWK vacuum
installation
>70 TeV
SppC ?
...

If ILC, can we have sinergies?

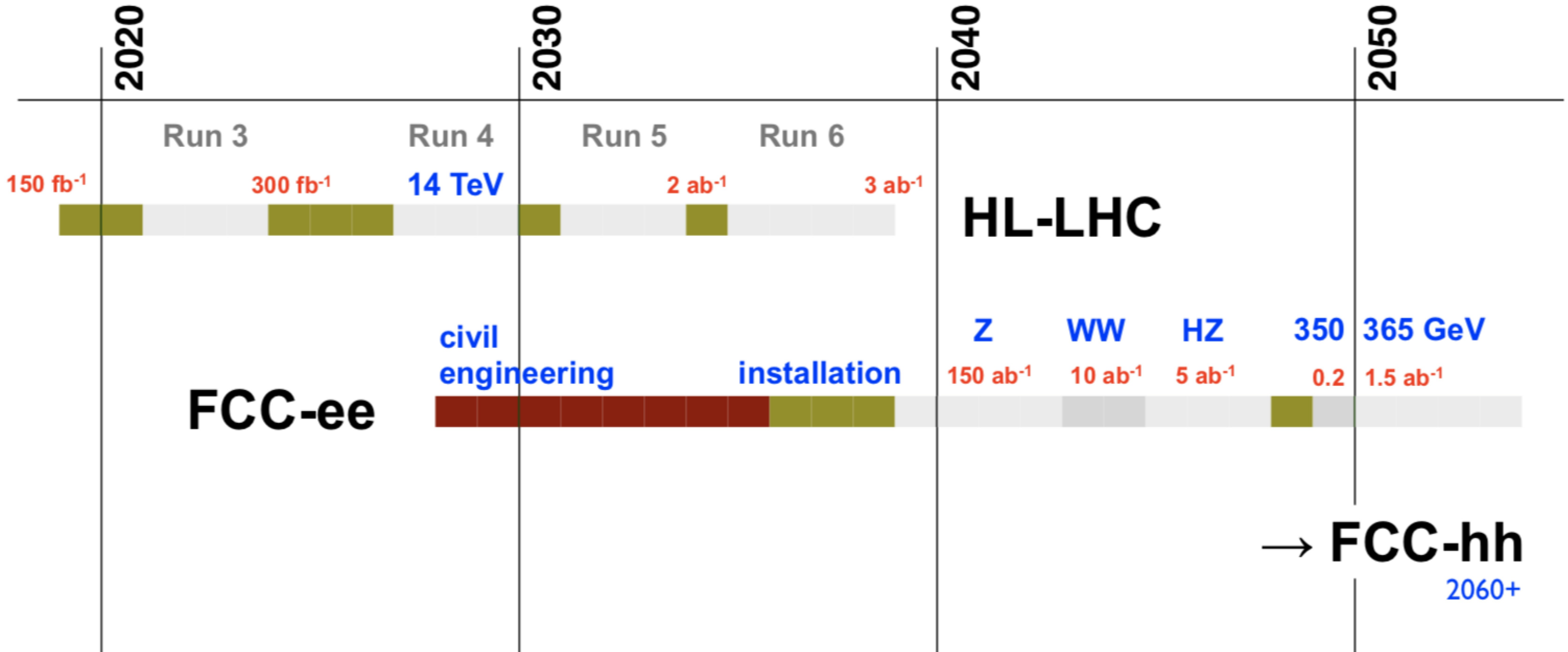
HL-LHC+HE-LHC+ILC



circa 2060
- direct NP ★★★★☆
- flavour, top ★★★★☆
- Higgs ★★★★★
- ttH, HH ★★★★☆
- EWK@TeV ★★★★☆
- EWK fit ★★★☆☆
- EWK vacuum ★★★★★

If not ILC... this is a good compromise (opinions?)

HL-LHC+FCC-ee



circa 2055

- direct NP ★★☆☆☆
- flavour, top ★★★★★
- Higgs ★★★★★
- ttH, HH ★★★☆☆
- EWK@TeV ★★☆☆☆
- EWK fit ★★★★★
- EWK vacuum ★★★★★

Higgs Couplings

inspired from

FCC-ee TDR (2018)

		HL-LHC	ILC		CLIC	FCC-ee		CEPC
$\sqrt{s}$	(GeV	14000	250	+500	380	90-240	+365	90-250
L	(ab	3	2	+4	0.5	5	+1.5	5
Years		13	15	+10	7	3	+6	7
ZZ	(%)	3.5	0.38	0.30	0.80	0.25	0.22	0.25
WW	(%)	3.5	1.8	0.4	1.3	1.3	0.46	1.2
ττ	(%)	6.5	1.9	0.8	4.2	1.4	0.8	1.4
tt	(%)	4.2	–	–	–	–	3.3(*)	–
bb	(%)	8.2	1.8	0.6	1.3	1.4	0.7	1.3
cc	(%)	–	2.4	1.2	1.8	1.8	1.2	1.8
gg	(%)	–	2.2	1.0	1.4	1.7	0.9	1.4
γγ	(%)	3.6	1.1(*)	1.0(*)	4.7	4.7	1.3(*)	4.7
Γ_H	(%)	50	3.9	1.7	6.3	2.8	1.5	2.6
exo	(%)	–	<1.6	<1.3	<1.2	<1.2	<1.0	<1.2

(*) incorporating HL-LHC results

ILC: using κ-framework

- simple scaling of the couplings
- no operator formalism
- no assumption on total width

HL-LHC measures σ_{ttH} but the extraction of g_{ttH} is model-dependent (through σ_{prod} and Γ_H)

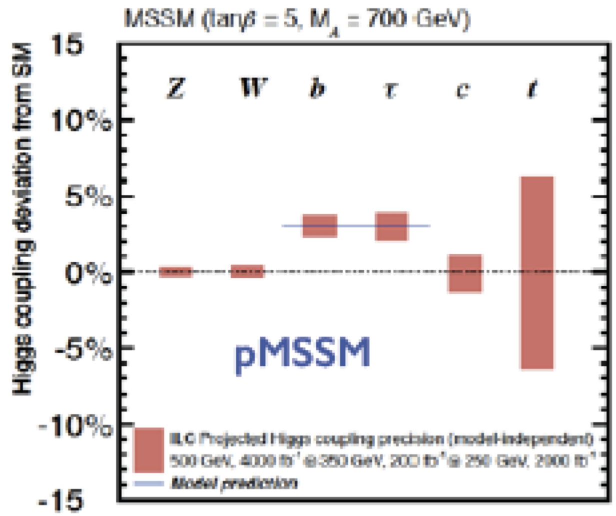
- benefits from Γ_H at e^+e^- machines

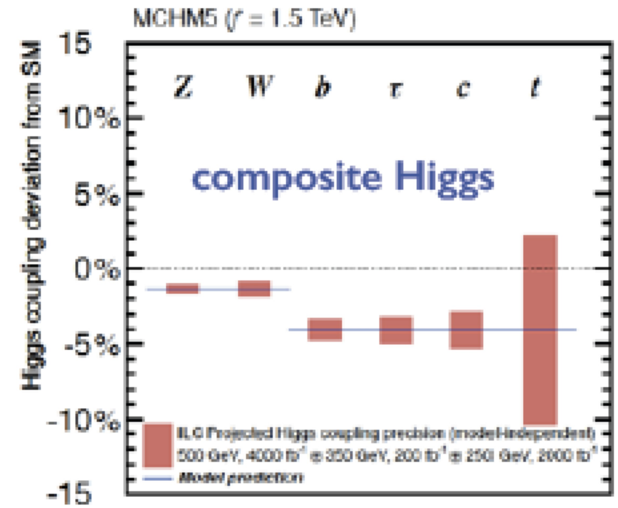
ILC Physics TDR

ILC couplings using the EFT
see backup slide

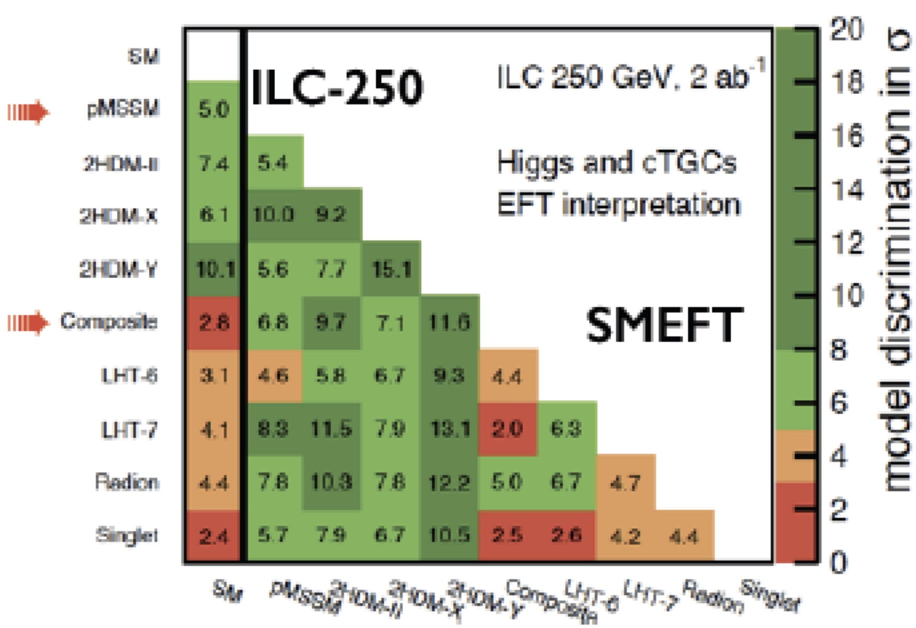
Sensitivity to BSM Models

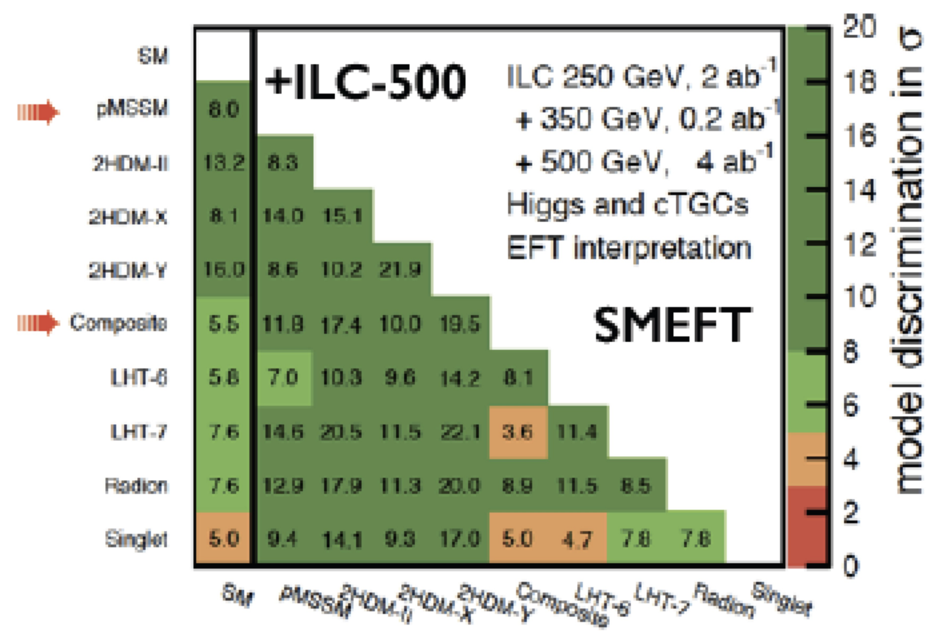
Different new physics (NP) models lead to different patterns of deviations





Percent level precision is required !

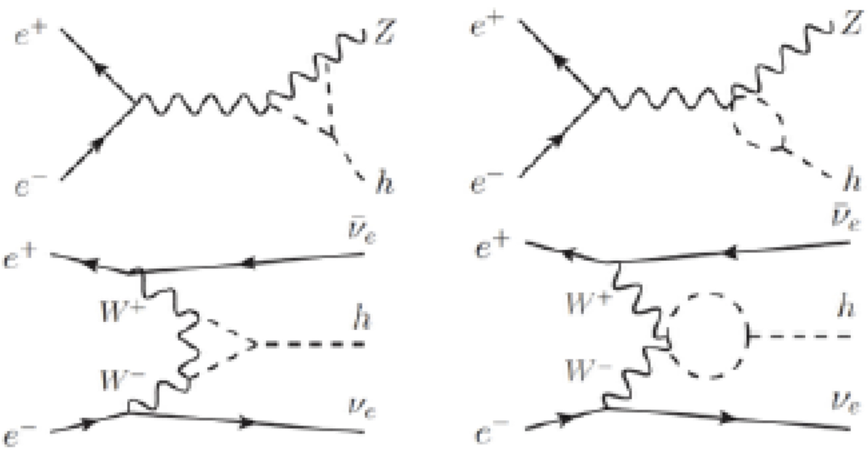




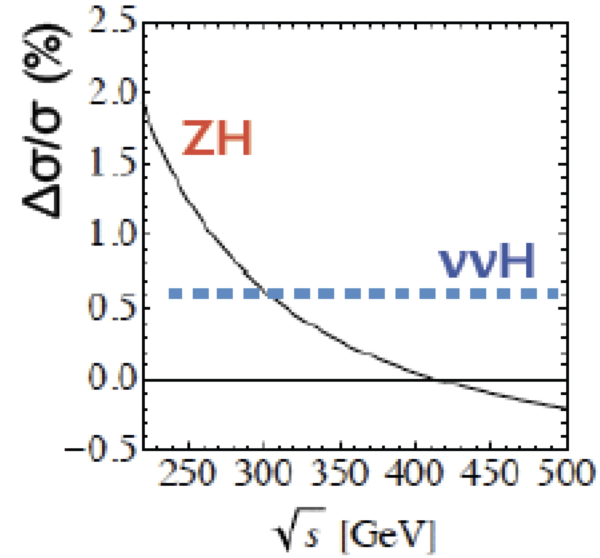
T. Barlow et al., arxiv:1708.08912

Self Coupling at e^+e^- Colliders

- σ_{ZH} and $\sigma_{\nu\nu H}$ receive one-loop vertex corrections which depend on the Higgs self-coupling λ_{HHH} and vary with energy

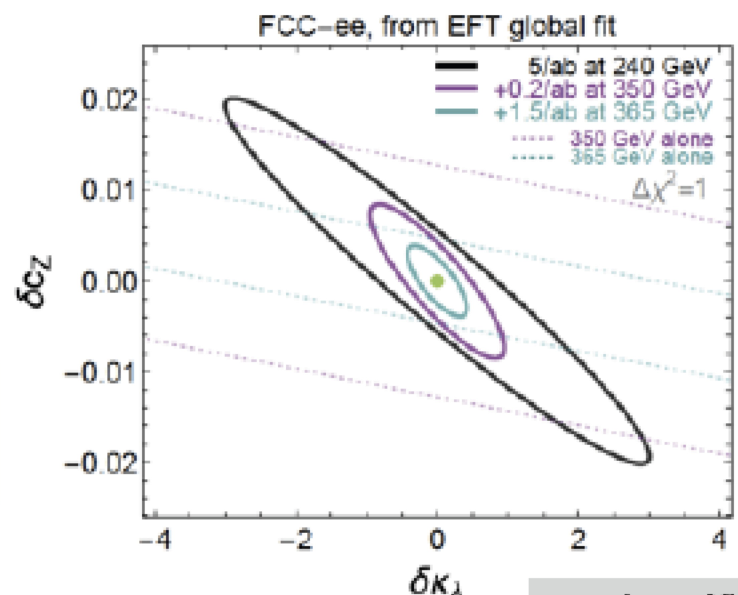


M. Mc Cullough, PRD 90 (2014) 015001



- Up to 1.5% effect on σ_{ZH} at $\sqrt{s}$ = 240 GeV
  - σ_{ZH} with 0.5% accuracy
  - degeneracy between $\delta\kappa_\lambda$ and $\delta\kappa_Z$

Two energy points are necessary to break the degeneracy



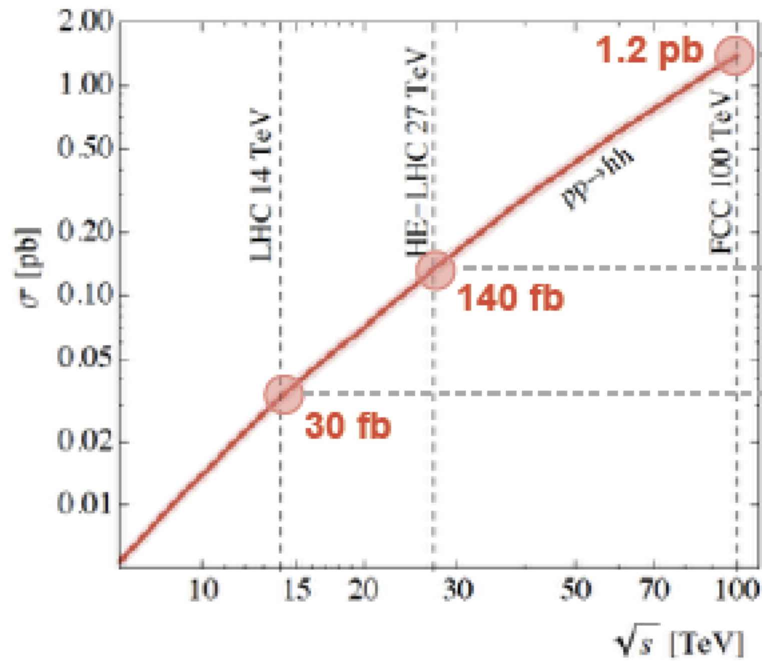
correlation due to interference effect

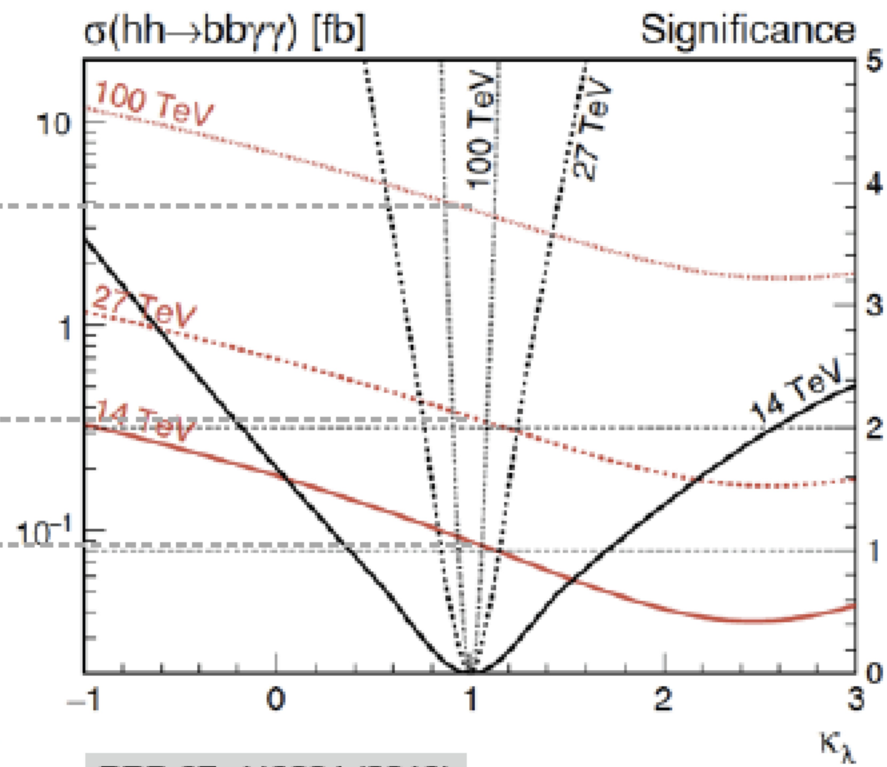
see also arXiv:1711.03978

FCC-ee (2IPs) : model-independent constraint on $\delta\kappa_\lambda$ at the ±35% level

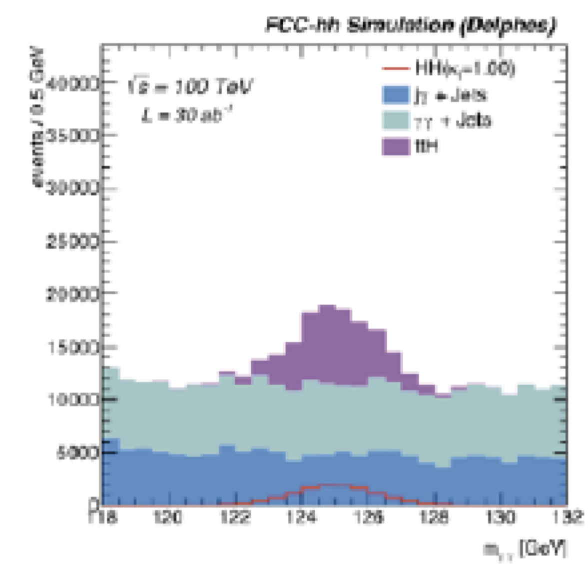
Self Coupling at the FCC-hh

Factor 40 in cross-section / HL-LHC





PRD 97, 113004 (2018)



- HH → bbγγ is the Golden channel the FCC-hh
  - ttH is a resonant background

	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\to 4\ell]$	$b\bar{b}WW^*[\to 2j\ell\nu]$	4b+jet
$\delta\kappa_\lambda$	6.5%	14%	40%	30%

- Nature of the EW phase transition and the BAU
  - first order implies strong deviations from predictions

MATHUSLA motivation

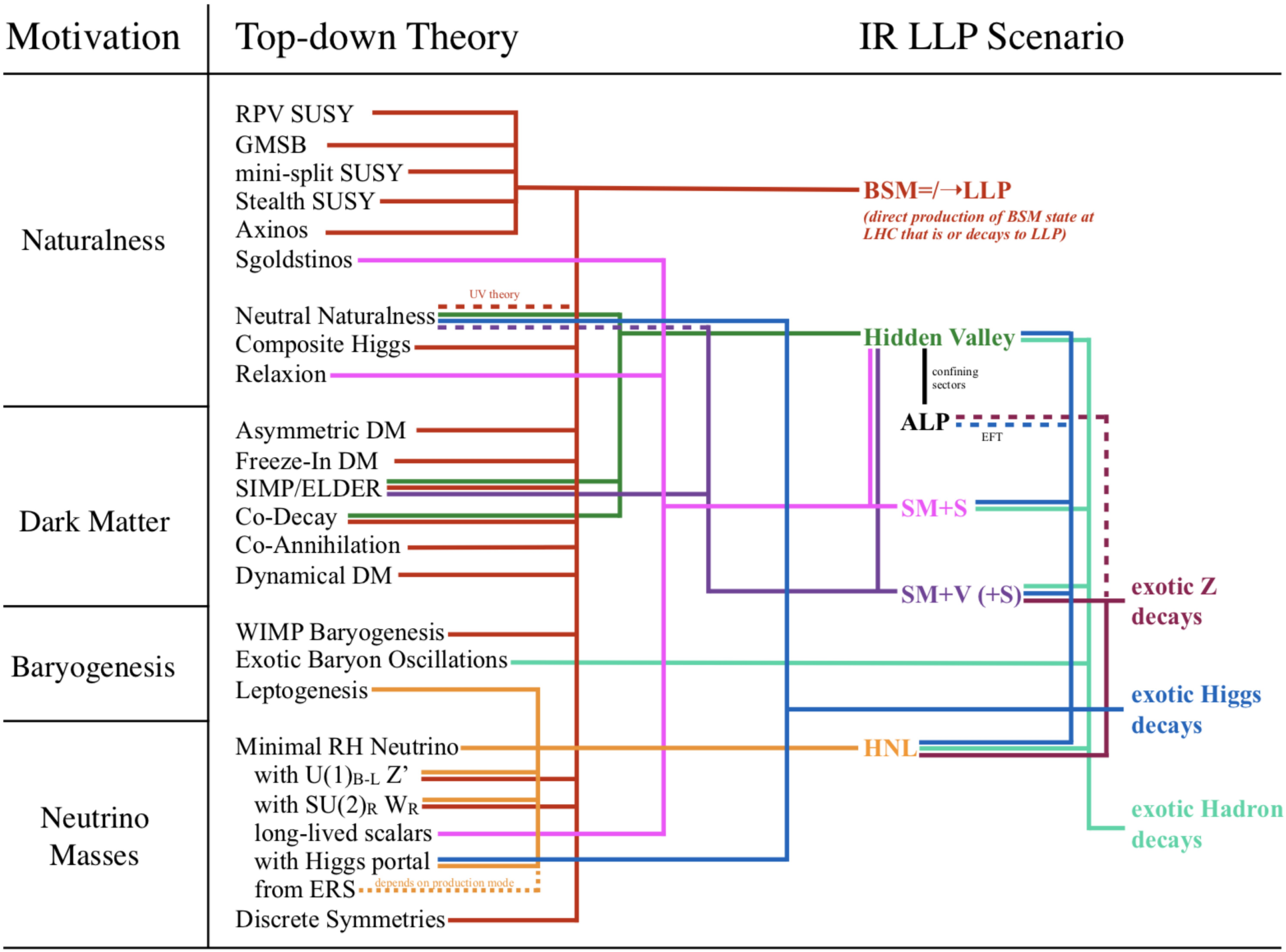


FIG. 1. Summary of some top-down theoretical motivations for LLP signals at MATHUSLA [2].