HL/HE-LHC summaries and status of YR reports

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Top LHC France, Grenoble, April 25th 2019

Pre-introduction

- Standard Model works beautifully at the LHC: no direct evidence of new physics
- Key questions remain unanswered
  - What gives rise to the matter-antimatter asymmetry in the universe What is dark matter made of? What is dark energy? Why is gravity so weak?
    - Small Higgs mass requires large cancellations if SM is valid to Planck scale
    - Strong motivation for new physics at the TeV scale (new particles, interactions, dimensions)

- The answers may still lie at the TeV scale…
- HL-LHC will deliver $3ab^{-1}$ @14 TeV
  - Study the Higgs boson in detail -> BSM physics could manifest itself in deviations from SM predictions
  - Measure rare SM processes -> BSM could have a large effect
  - Search for new particles/phenomena at the TeV scale

- HE-LHC might double the collision energy to 27 TeV
  - Higher mass reach for new physics - deeper exploration of TeV scale
  - But might not be enough, 100, 200, 300 TeV, more?

Introduction

- The physics potential of the HL/HE-LHC has been studied in detail for the European Strategy, most recently in the context of the Workshop on "The physics of HL-LHC, and perspectives on HE-LHC" (2017-2018)

- Prospects are presented in all areas:
  - 5 Working Groups: SM, Higgs, BSM, Flavour, Heavy Ion
  - ATLAS, CMS, LHCb, ALICE experimentalist and theorists worked to enrich and consolidate the HL physics program
    - precision, exploration potential and scope
  - prospects for a possible HE-LHC are also studied, but sometimes with less details

Final product

- WG Reports
  - WG1 SM and top
    http://arxiv.org/abs/arXiv:1902.04070 (219 pages)
  - WG2 Higgs
    http://arxiv.org/abs/arXiv:1902.00134 (364 pages)
  - WG3 BSM
    http://arxiv.org/abs/arXiv:1812.07831 (279 pages)
  - WG4 Flavour
    http://arxiv.org/abs/arXiv:1812.07638 (292 pages)
  - WG5 Heavy Ions
    http://arxiv.org/abs/arXiv:1812.06772 (207 pages)

  } 1361 pages

  - "Volume 2" (collection of ATLAS and CMS public notes):
    https://arxiv.org/abs/1902.10229 (1369 pages)

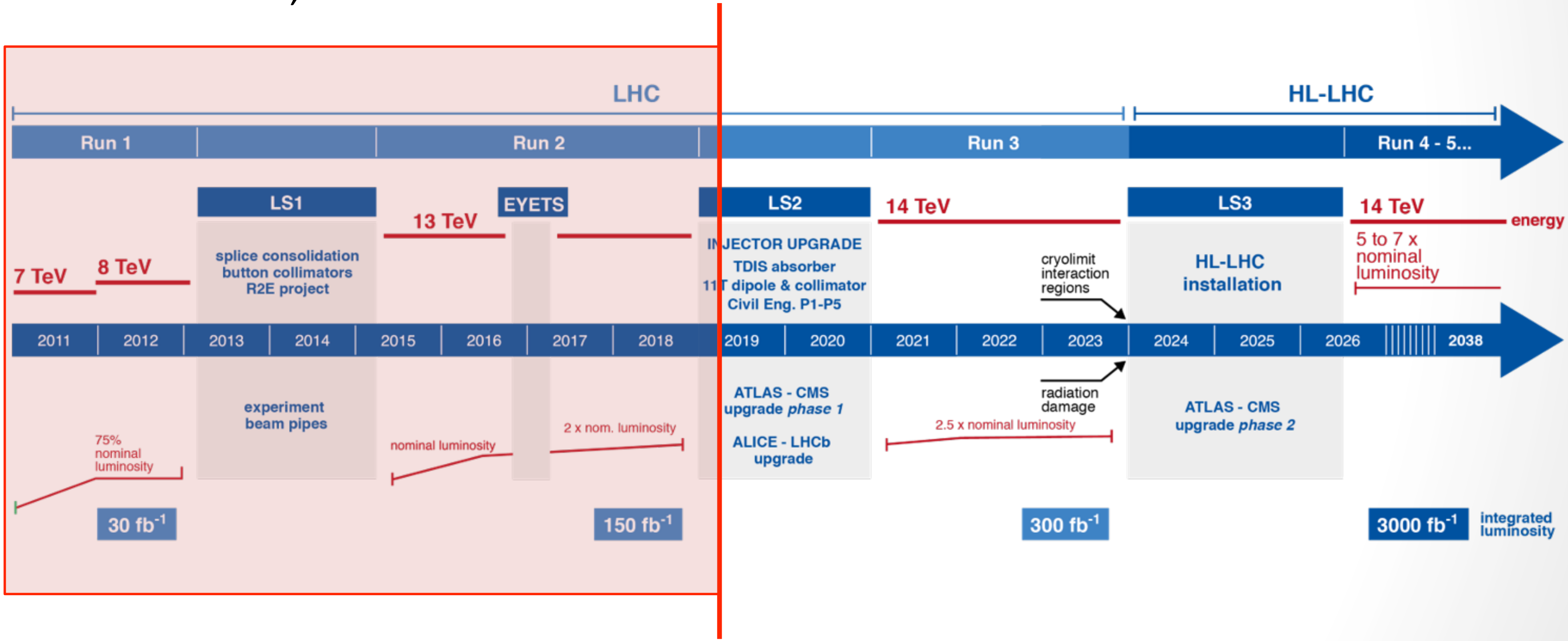
- Executive summaries, submission to the European Strategy
  - HL-LHC https://indico.cern.ch/event/765096/contributions/3295995/
  - HE-LHC https://indico.cern.ch/event/765096/contributions/3296016/

The running plan

Scenarios for projections

HL-LHC 14 TeV, 200 PU ($5\times10^{34} cm^{-2}s^{-1}$), 3 ab^{-1} or even 4 ab^{-1} in the "ultimate" scenario

HE-LHC 27 TeV, 15 ab^{-1}

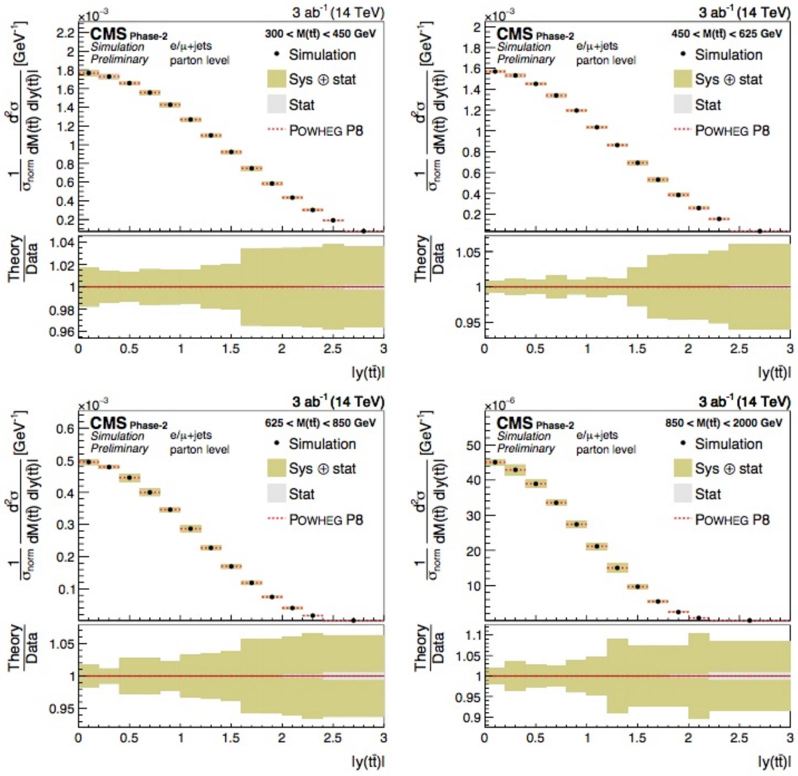


Assumptions and overall approach

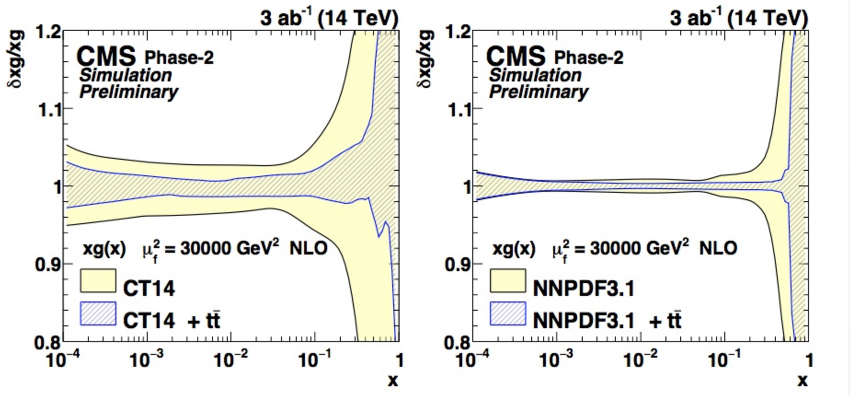
- Common assumptions (for ATLAS and CMS)
  - $3ab^{-1}$ @ 14 TeV for HL-LHC with <μ>=200, 15 ab^{-1} @ 27 TeV for HE-LHC much larger pile-up of 500

- Different approaches have been used by experiments and in theoretical prospects
  - Detailed-simulations, used to assess the performance of reconstructed objects
  - Extrapolations of existing results using simple scale factors on individual processes
  - Fast-simulations, e.g. using DELPHES and common HE-LHC card
  - Parametric-simulations, using particle-level definitions for the main objects and taking into account the pile-up conditions: effects of an upgraded detector are taken into account by applying smearing functions and parameterizations.
  - Systematic uncertainties are based on existing data analyses and estimated using common guidelines for projecting the expected improvements foreseen thanks to large dataset and upgraded detectors
    - Intrinsic statistical uncertainty is reduced by a factor $1/\sqrt{L}$
    - Theoretical uncertainties are halved or divided by 4; PDF reduced up to 20-50%
    - Detector-related uncertainties (JES, JER, b-tagging, e/g/μ/t ID) are ~ halved
    - Limited Monte-Carlo statistic considered as irrelevant for this exercise

PDF from double differential X-Sec



- Uncertainty on differential top x-sec O(5%)
- Significant impact on high x gluon PDF
- Complemented with forward tops:
  - 300 fb^{-1} LHCb data probe high-x PDFs with partially reconstructed top quarks
  - quark PDFs: use differential charge asymmetry vs. lepton **η**

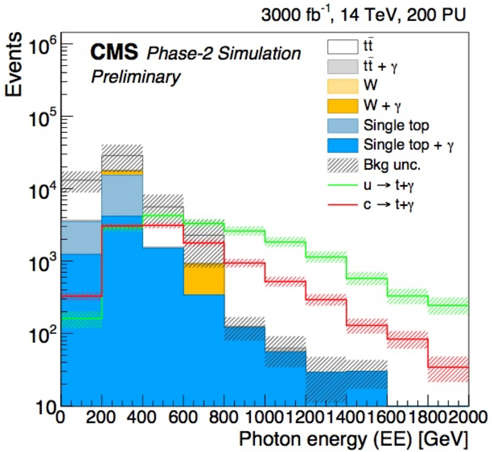


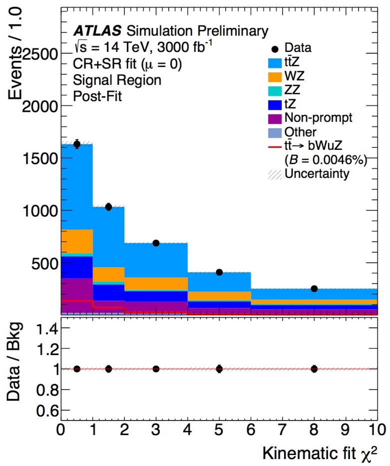
Top FCNC

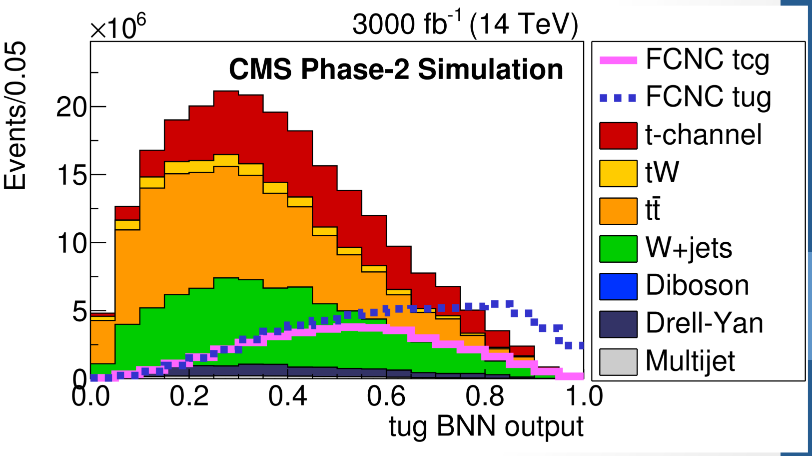
- Comprehensive studies by ATLAS (tZq) and CMS (tqg, tqγ)
- Dedicated signal and background samples simulated
- Follow the Run-II strategies
- CMS uses BNN on kinematic input (tqg), photon p_T and energy (tqγ)
- ATLAS uses $\chi 2$ constructed under FCNC hypothesis (tZq)
- Improvement typically one order of magnitude (lumi increases by 100 from 30 to 3000 fb^{-1} so kind of expected but important to check the detector performances)

Top FCNC

$\mathcal{B}$ limit at 95%C.L.	3 ab^{-1}, 14 TeV	15ab^{-1}, 27 TeV	Run II
$t \to gu$	3.8×10^{-6}	5.6×10^{-7}	$2\text{x}10^{-5}$
$t \to gc$	32.1×10^{-6}	19.1×10^{-7}	$4\text{x}10^{-4}$
$t \to Zq$	$2.4 - 5.8 \times 10^{-5}$		$1.7\text{-}2.4\text{x}10^{-4}$
$t \to \gamma u$	8.6×10^{-6}		$1.3\text{x}10^{-4}$
$t \to \gamma c$	7.4×10^{-5}		$2.0\text{x}10^{-3}$
$t \to Hq$	10^{-4}		$1.1\text{x}10^{-3}$



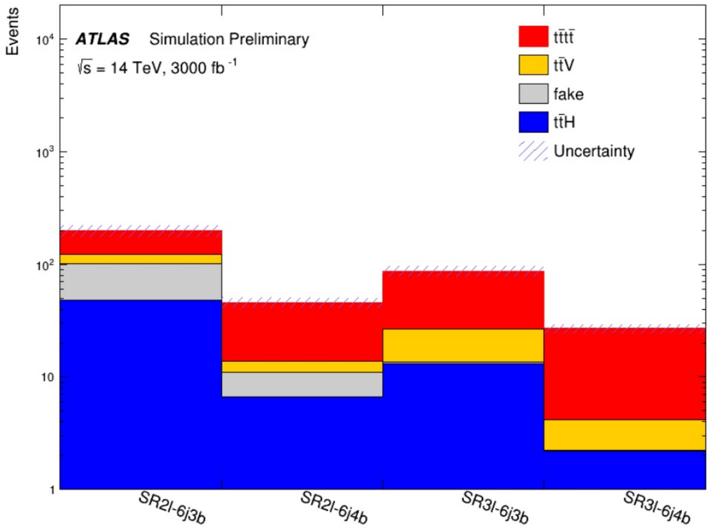




4 top production

- 4 tops: complete NLO cross section known and EWK contributions not small (10%)
- 2 same charge leptons or 3 lepton channel, ≥ 6 jet, ≥ 3 b-tagged jets
- Uncertainty in fake/non-prompt is leading systematic
- total uncertainty in measured x-sec is 11% (9% without systematics)
- Expect evidence for tttt with 300 fb^{-1} at 14 TeV
- Good sensitivity to top Yukawa coupling modification

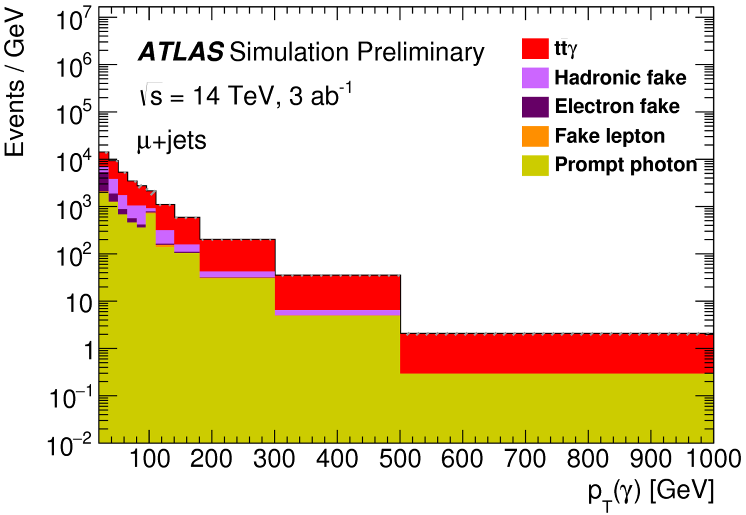
σ[fb]	LO + NLO	$\frac{\text{LO(+NLO)}}{\text{LO}_{\text{QCD}}(+\text{NLO}_{\text{QCD}})}$
14 TeV	$15.83^{+18\%}_{-21\%}$	1.11 (1.08)
27 TeV	$143.93^{+17\%}_{-20\%}$	1.11 (1.06)

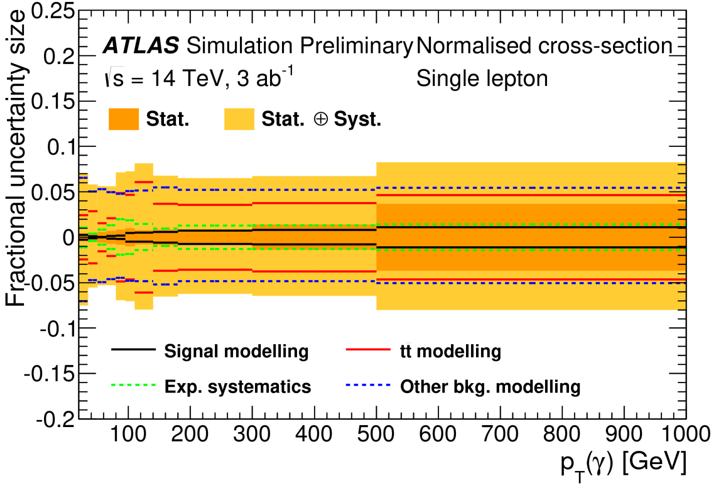


$$\text{HL}-\text{LHC}\ (\sqrt{s}=14\ \text{TeV}) \quad : \quad \sigma(t\bar{t}t\bar{t}) = 13.14 - 2.01\kappa_t^2 + 1.52\kappa_t^4\ \text{[fb]}$$

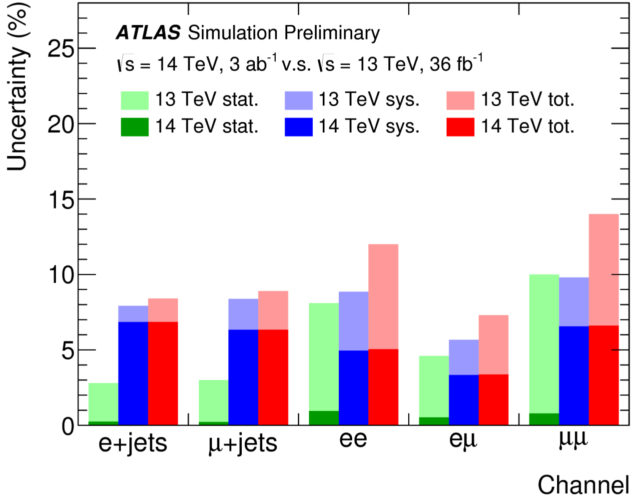
$$\text{HE}-\text{LHC}\ (\sqrt{s}=27\ \text{TeV}) \quad : \quad \sigma(t\bar{t}t\bar{t}) = 115.10 - 15.57\kappa_t^2 + 11.73\kappa_t^4\ \text{[fb]}$$

tt+γ





Operator	$\mathcal{O}_{tB}$	$\mathcal{O}_{tG}$	$\mathcal{O}_{tW}$
Single lepton	[-0.5,0.3]	[-0.1,0.1]	[-0.3,0.5]
Dilepton	[-0.6,0.4]	[-0.1,0.1]	[-0.4,0.3]

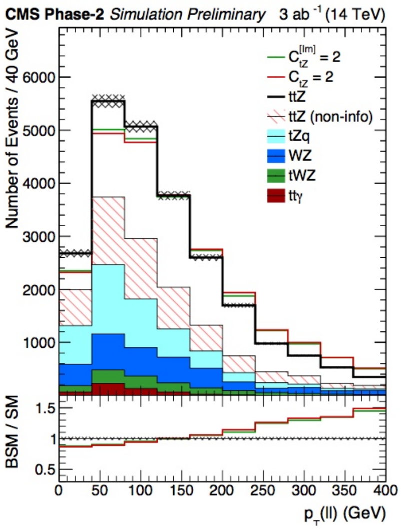


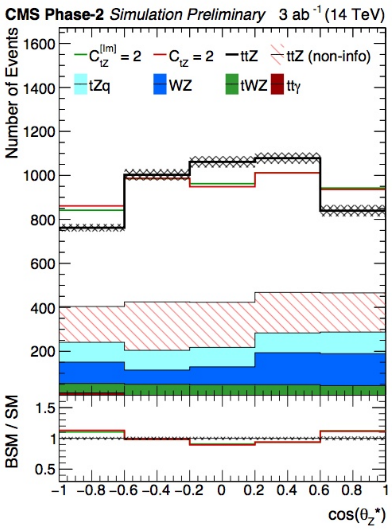
- Use $p_T(\gamma)$ as discriminant variable
- Constraint operators modifying t-γ coupling
- 1 and 2 leptons channels
- Expect an improvement in sensitivity by factor 4-6

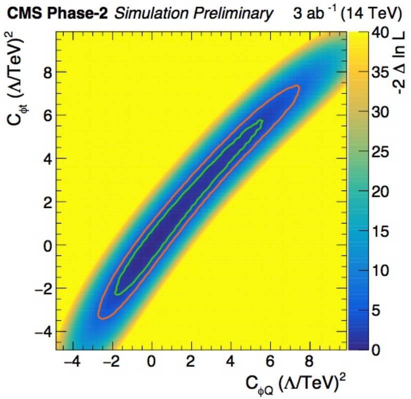
tt+Z

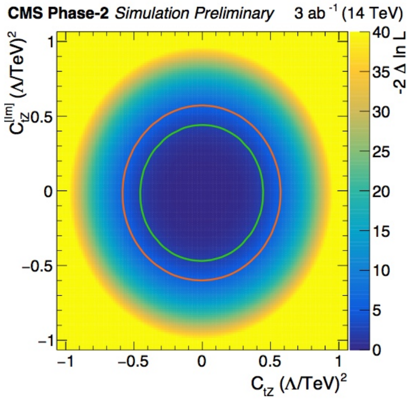
- Scaled from 13TeV to 14TeV

Wilson coefficient	68 % CL $(\Lambda/\text{TeV})^2$	95 % CL $(\Lambda/\text{TeV})^2$
$C_{\phi t}$	[-1.65, 3.37]	[-2.89, 6.76]
$C_{\phi Q}$	[-1.35, 2.92]	[-2.33, 6.69]
C_{tZ}	[-0.37, 0.36]	[-0.52, 0.51]
$C_{tZ}^{[\text{Im}]}$	[-0.38, 0.36]	[-0.54, 0.51]

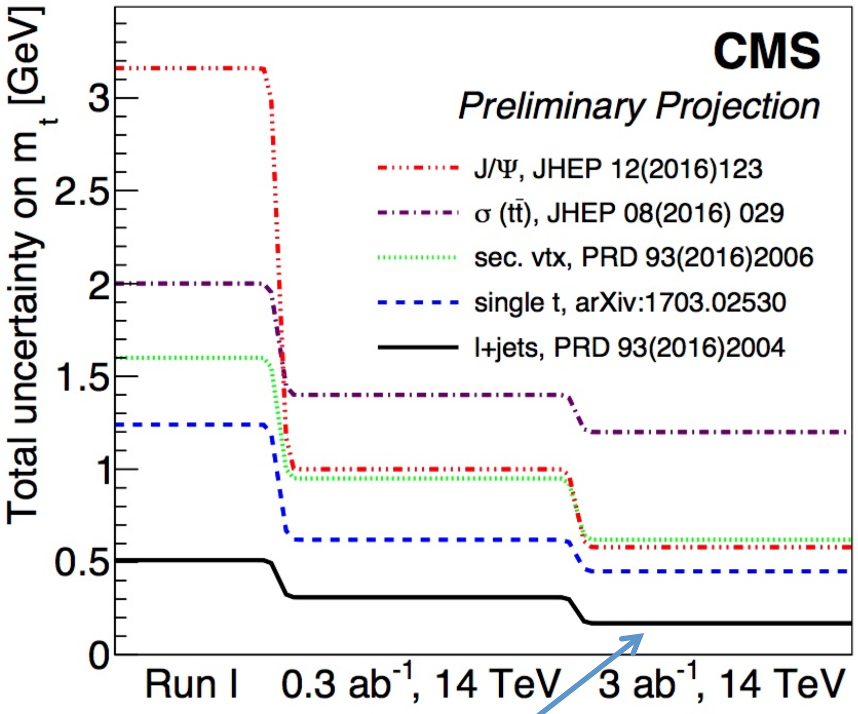








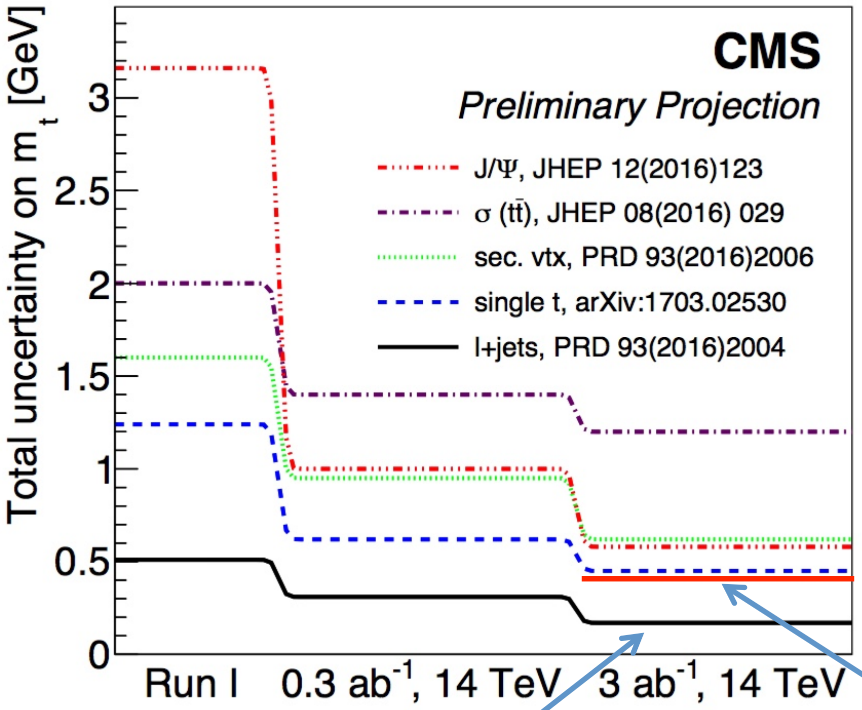
Top mass



0.17 GeV ~ 0.1%
dominated by JES

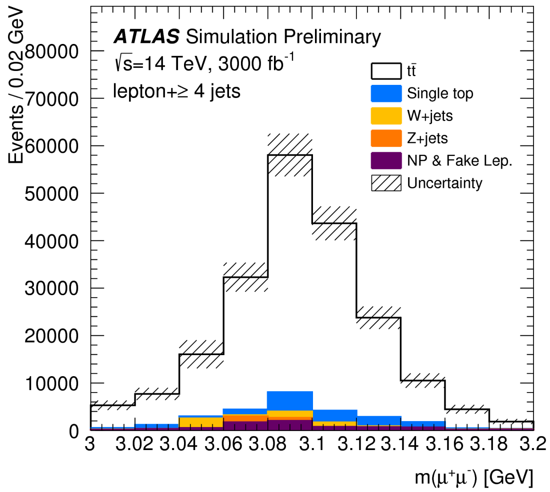
- "Simple" concept:
  - pick out jets from top
  - pair up the right jets to each top
  - calculate mass
- challenges (a selection)
  - efficient b tagging (combinatorics)
  - moderate pT triggers
  - systematic related to the 'MC mass' to a well defined parameter in a ren. scheme to 100 MeV
  - precision JES & ETmiss, lepton E scale

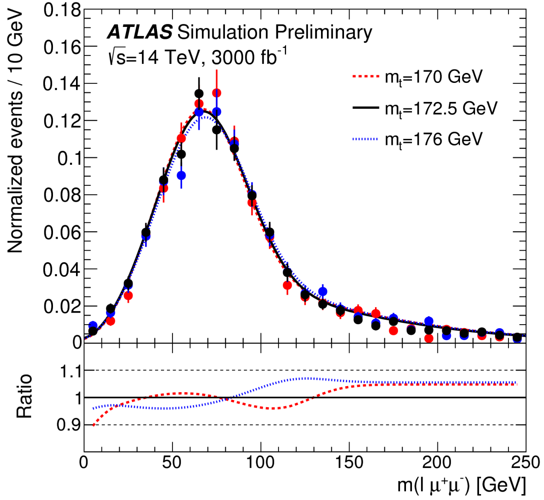
Top mass



0.17 GeV ~ 0.1% dominated by JES

ATLAS J/Ψ projection ± 0.14 (stat) ± 0.48 sys

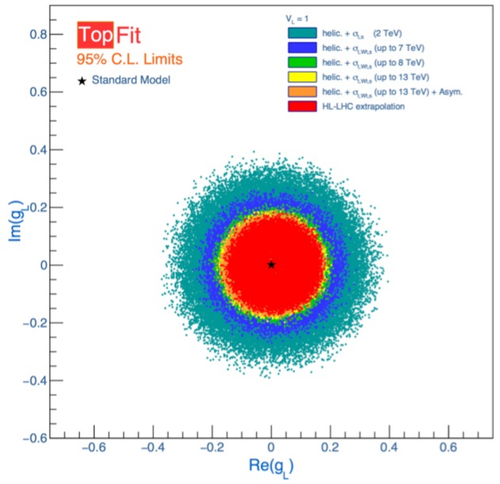


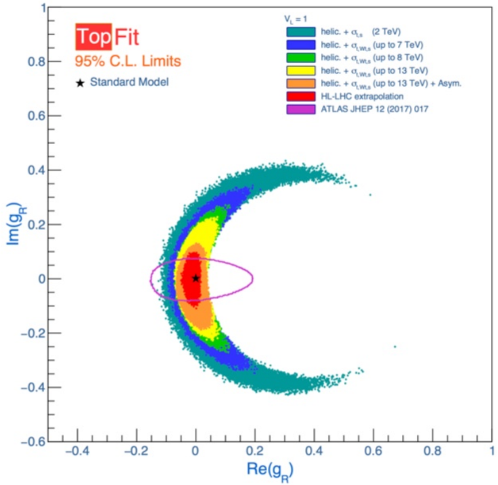


Top-W coupling (TH but uses ATLAS data)

HL-LHC	g_R	g_L	V_R
Allowed Region (Re)	[-0.05 , 0.02]	[-0.17 , 0.19]	[-0.28 , 0.32]
Allowed Region (Im)	[-0.11 , 0.10]	[-0.19 , 0.18]	[-0.30 , 0.30]

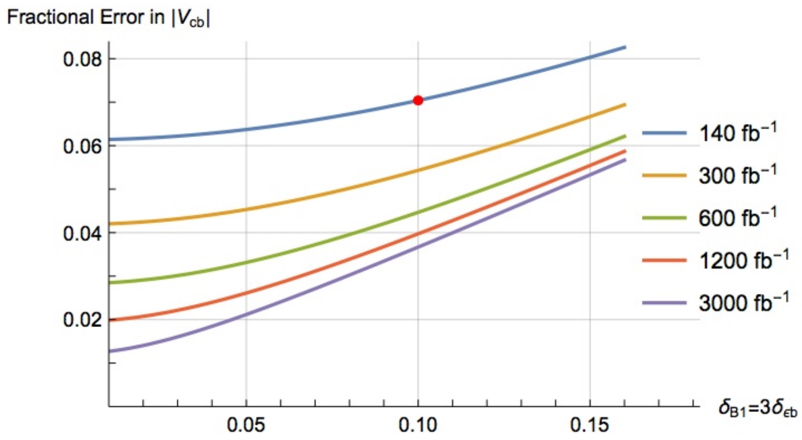
- W boson helicity measurements, asymmetries and single top production are able to constrain potential anomalous Wtb couplings
- comprehensive list of measurements
  - W boson helicity, A_{FB}, Single top x-sec
- Extrapolate to $3ab^{-1}$ and include scaled results
  - Reconstruction level uncertainties were kept (b-tagging was divided by 2)





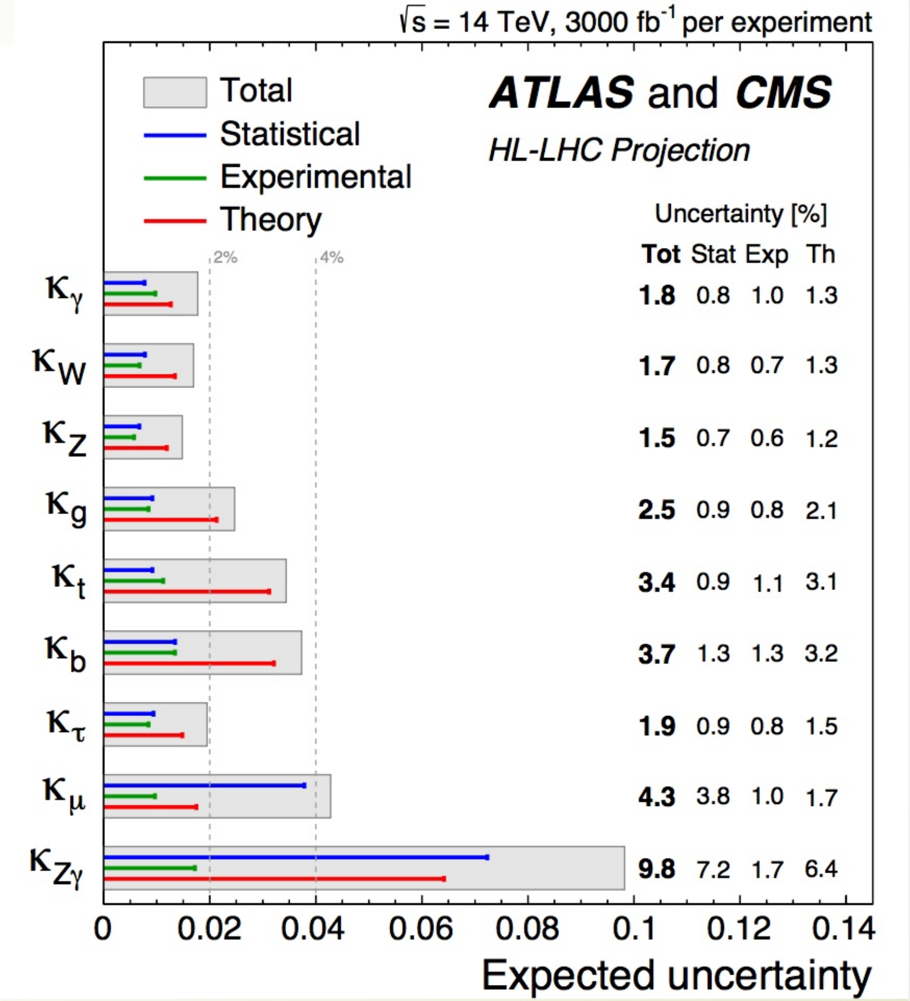
V_{cb} in top decays (TH but uses ATLAS b-tag)

- Showed that
  - a measurement of $|V_{cb}|$ at better than the 10% level is possible with the full run II dataset
- Using improved tagging uncertainties and HL-LHC luminosities, it may be possible to reduce $|V_{cb}|$ uncertainty towards 3% or even below 2%

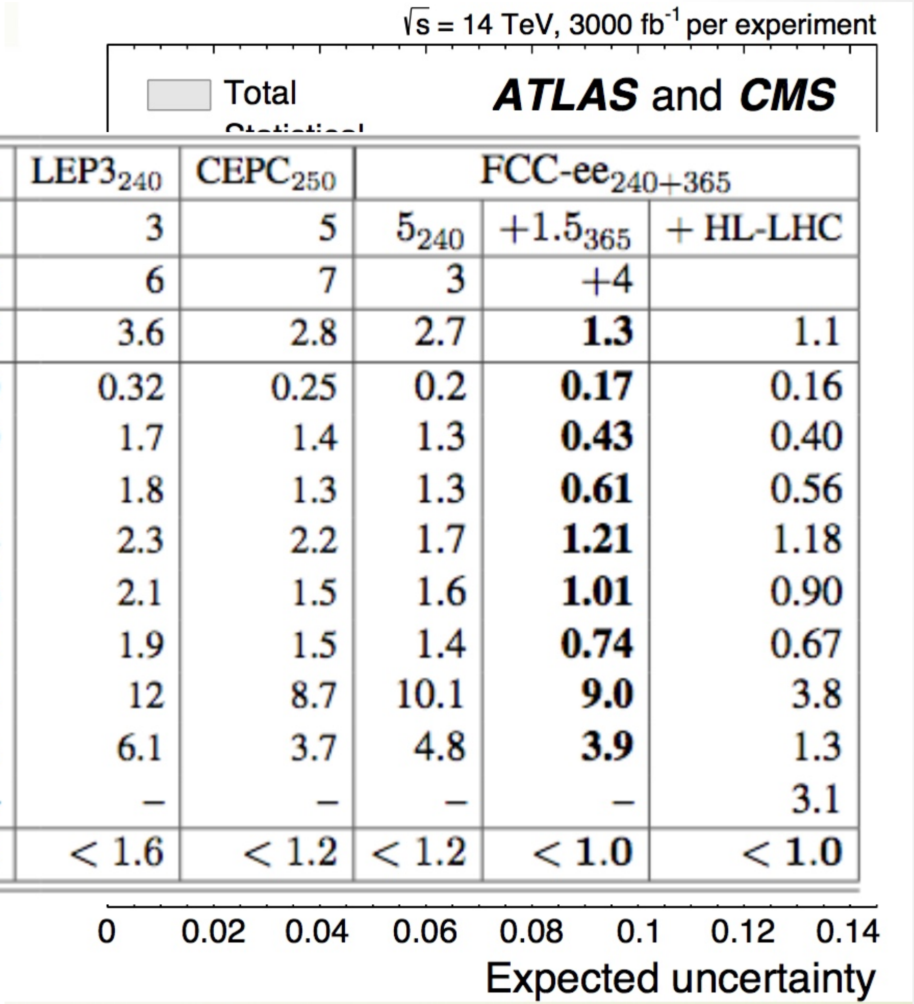


Higgs couplings

- The exploration of the Higgs sector includes precision measurements, as well as searches for rare production and decay processes:
  - Rare decays such as h -> $\mu^+\mu^-$ and h->Zγ will be observable at HL
  - Rate measurements show that percent level precision can be reached for most couplings
  - With minimal assumptions, the total width Γ_H will be constrained with a 5% precision and an upper limit on the Higgs invisible BR of 2.5% could be reached.



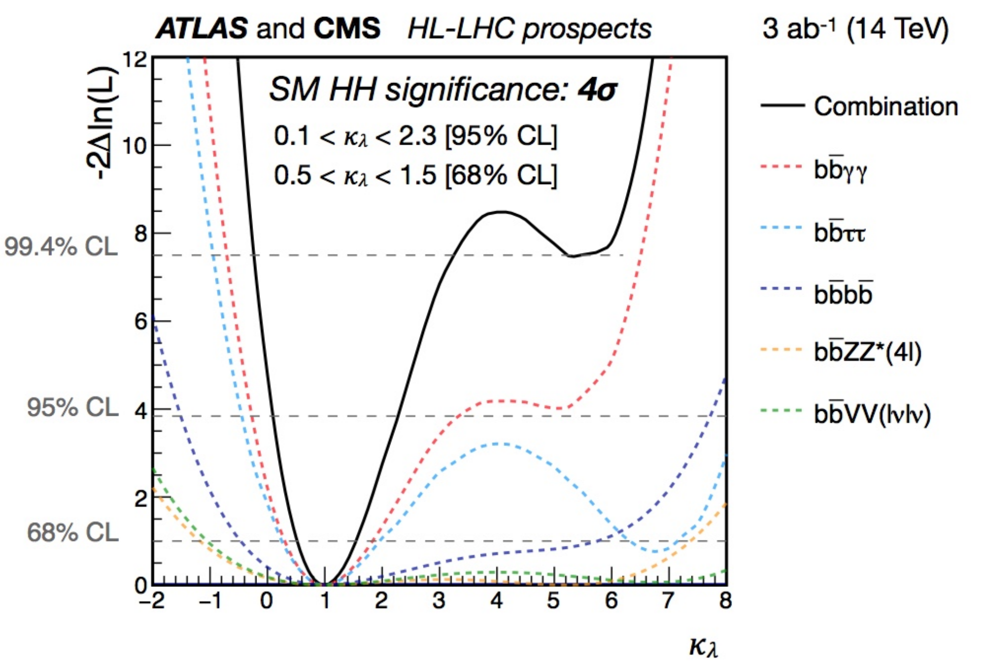
Higgs couplings



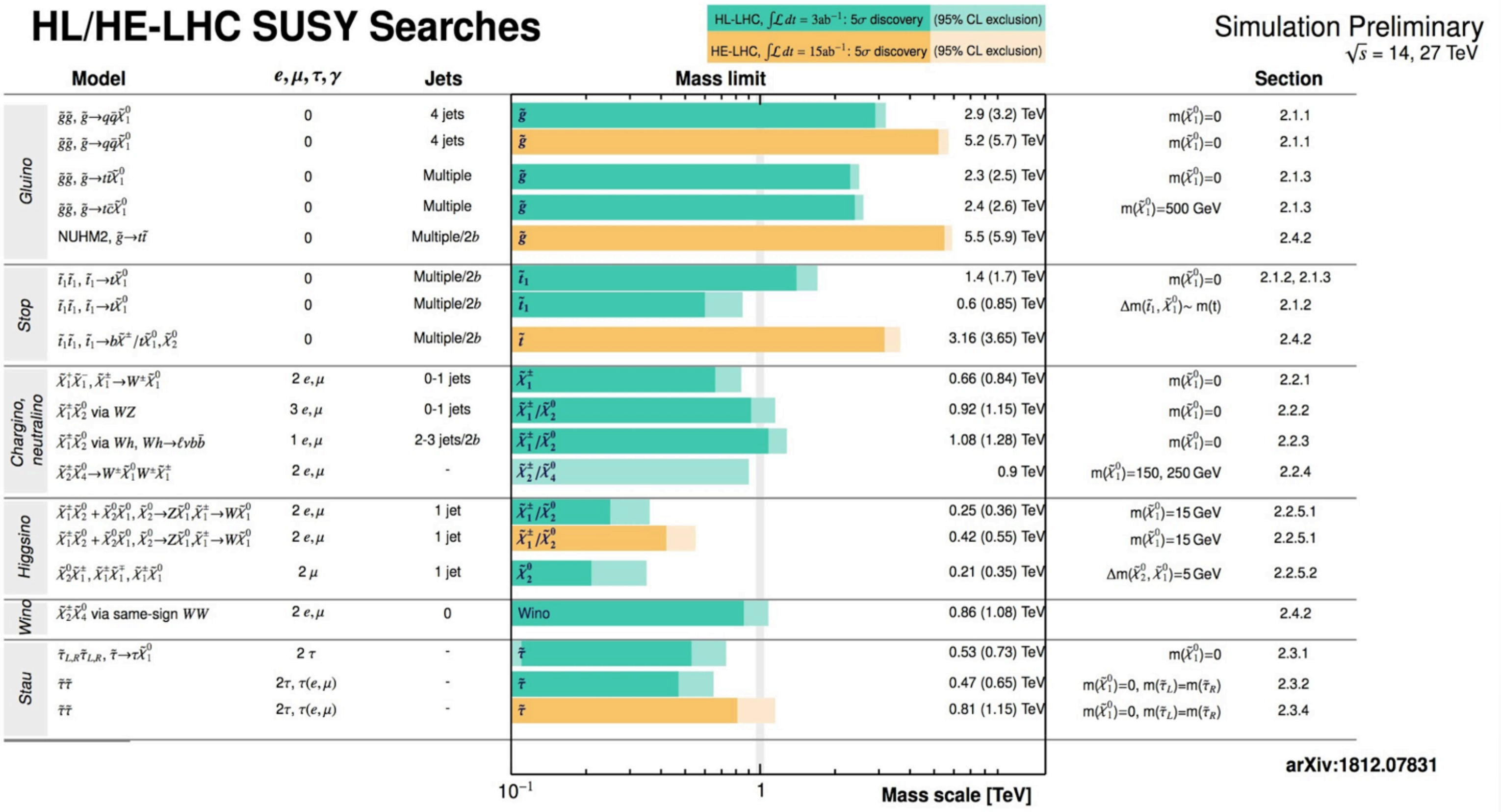
Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

Higgs self couplings

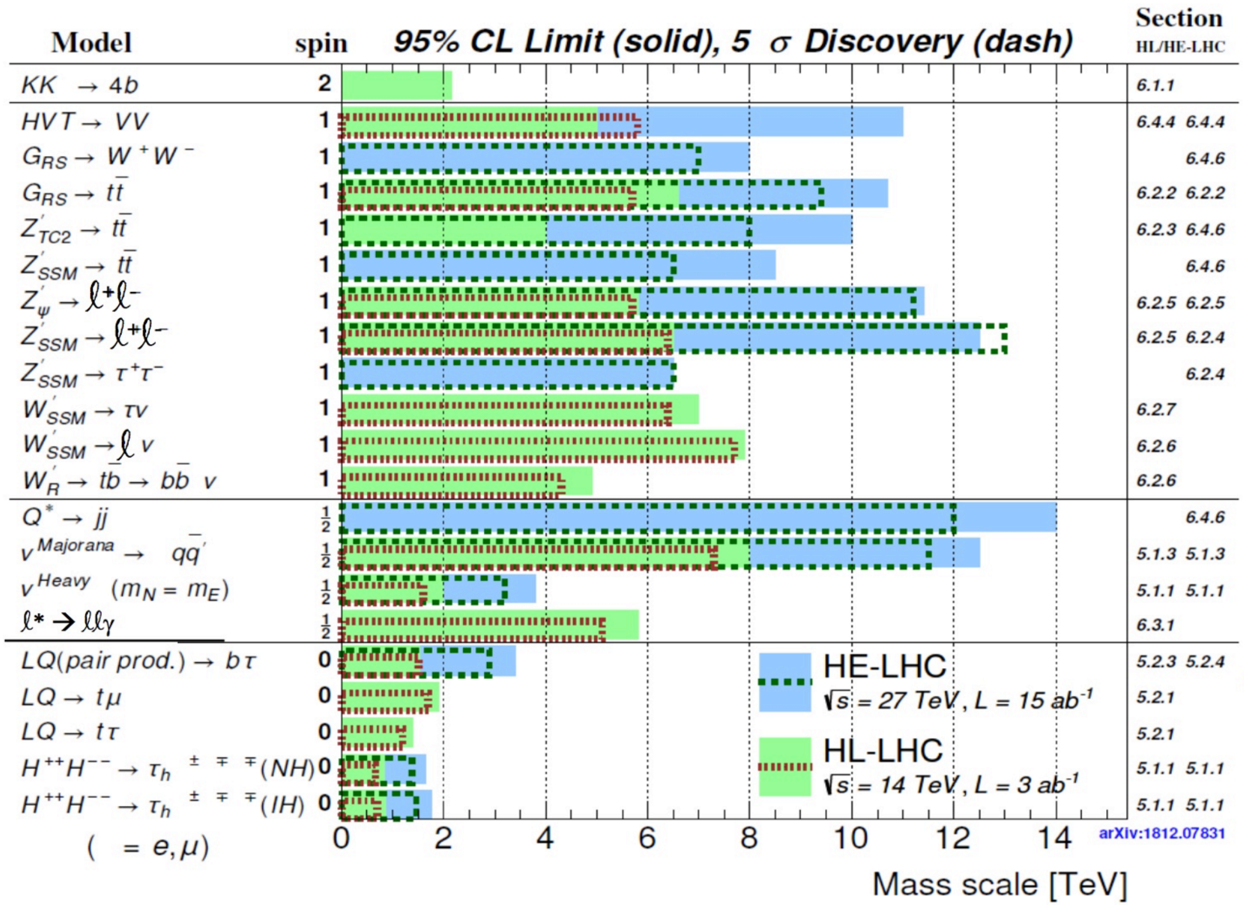
- Assuming SM Higgs self-coupling λ:
  - observation sensitivity of 3σ per experiment, 4σ combined
- The secondary minimum can be excluded at 99.4% CL, with a constraint on the Higgs self-coupling of $0.5 < \kappa_\lambda < 1.5$ at the 68% CL.



BSM (SUSY) summary



BSM (Exotic) summary



Conclusions 1/2

- The 1 year Workshop in preparation for the European Strategy has delivered five documents on SM, Higgs, BSM, Flavor physics and Heavy Ions for a total of 1361 pages plus two short summaries for the ESU
- Very partial overview given
  - Impressive potential in the higgs sector for properties and BSM prospects
  - Impressive expectations for di-higgs production using bb+X modes
  - Possibilities to discover new particles, i.e. in the EWK SUSY sector, and/or at high mass
  - Precision SM measurements allow reduction of uncertainties and provide indirect probe to searches for NP

Conclusions 2/2

- We have been spoiled by the immense success of the LHC machine and CMS and ATLAS results in the recent past.
- The HL-LHC is a high value flagship program for the HEP scientific community: we will redefine yet again the knowledge of precision physics at a proton collider.
- Performing the careful studies and projections for TDRs and the Yellow Report we have realized:
  - we have designed amazing detectors that will be able to fully mitigate the 200PU
  - we can expand the knowledge of the SM with improved precision and the observation of new processes that become accessible
  - we can expand the search for BSM physics with tools that allow to probe new and unusual processes
- HE-LHC might bring in the extra energy and open up the possibility for direct production of new particles.
- **As a last reminder, once the real data become available experiments have always done much better than any projection. Looking forward an exciting program!**

The European Strategy Update

- Strategy Symposium in Granada 13-16 May
- Encouraged by CERN DG to join and speak up
- 160 contributions submitted:
  - The Physics potential of HL-LHC
  - The Physics potential of HE-LHC
  - The High-Energy LHC (HE-LHC)
- The contributions will be summarized by "neutral" people and discussed

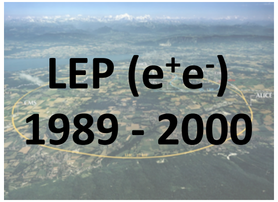
A 100km circular collider as next the step

Tevatron 2TeV → x 7 → **LHC 14TeV** → x 7 → **FCC-hh 100TeV**

M. Aleksa pECFA

27km tunnel

The next step: 100km tunnel



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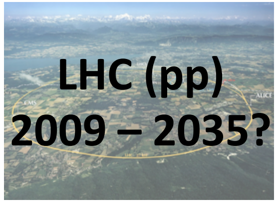

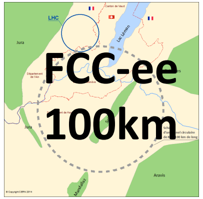

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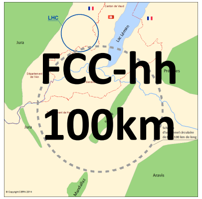

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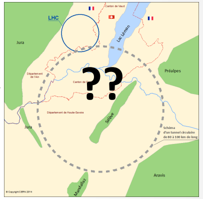

The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology

Both FCC-ee and FCC-hh have outstanding physics cases

We are ready to move to the next step, as soon as possible

FCC C(Should) Start Next Year