HL/HE-LHC top physics results

Clement Helsens, CERN-EP

EF03 snowmass 2021 meeting, June 25th 2020

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

In the experiments, work mostly done by a (very)limited number of persons

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

Executive summaries, submission to the European Strategy

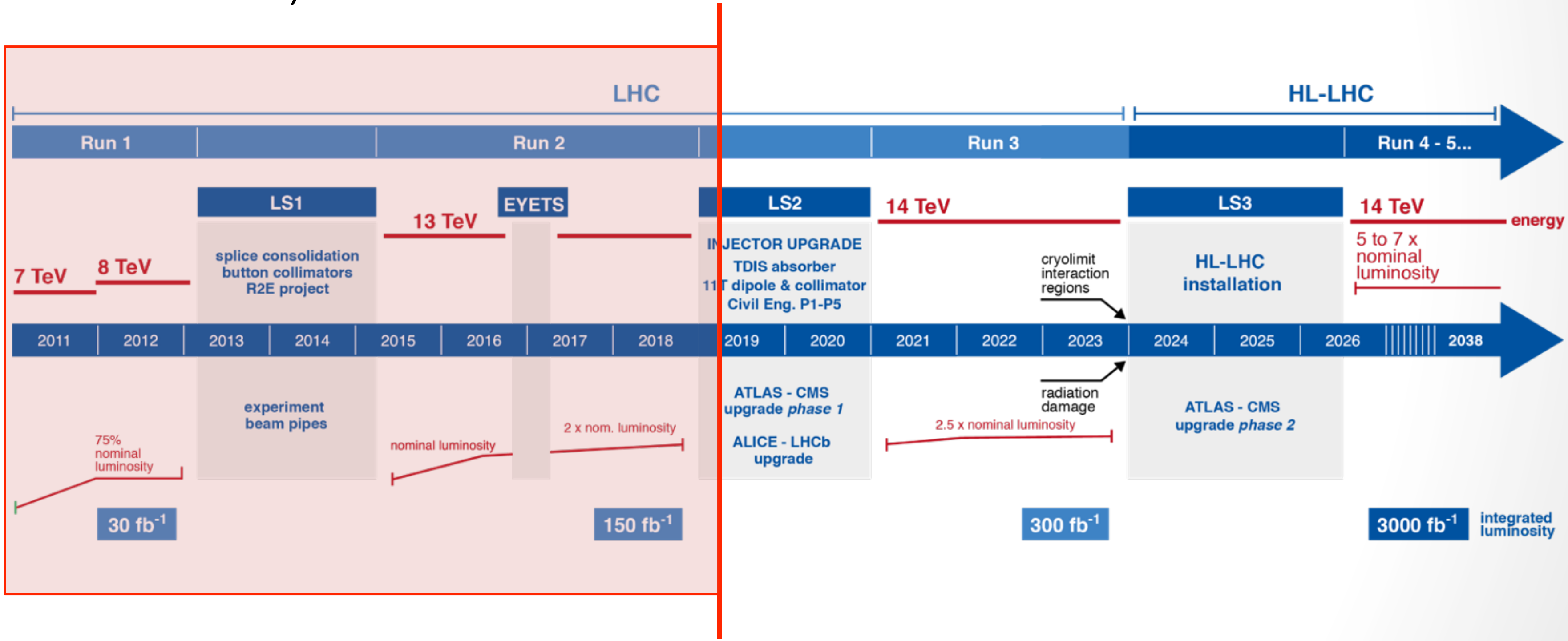
- HL-LHC https://indico.cern.ch/event/765096/contributions/3295995/
- HE-LHC https://indico.cern.ch/event/765096/contributions/3296016/

The running plan

Scenarios for projections

HL-LHC 14 TeV, 200 PU ($5x10^{34}cm^{-2}s^{-1}$), 3 ab^{-1} or even 4 ab^{-1} in the "ultimate" scenario

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



Assumptions and overall approach

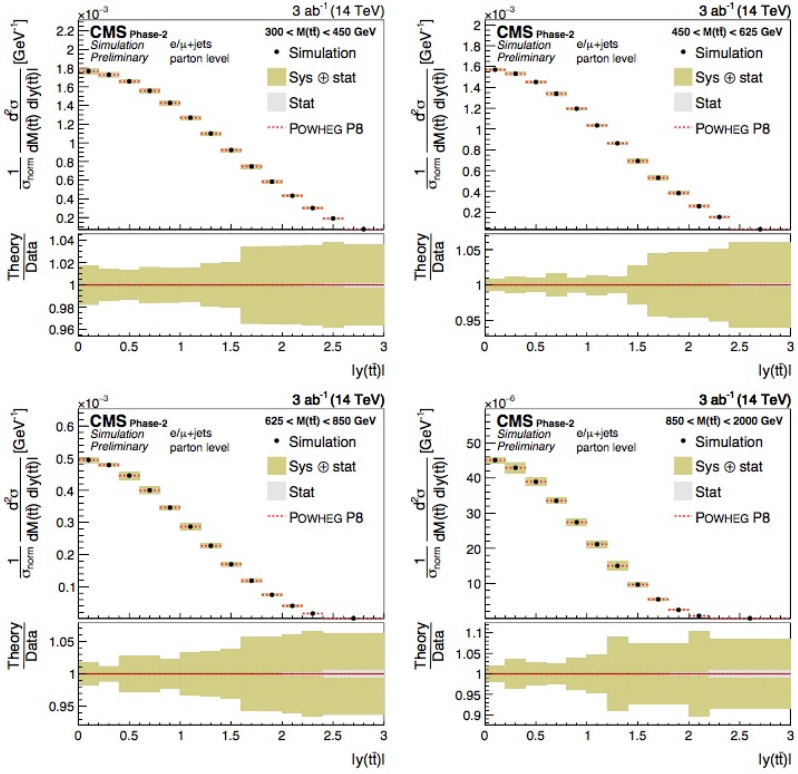
Common assumptions (for ATLAS and CMS)

- 3ab^{-1} @ 14 TeV for HL-LHC with $\langle\mu\rangle=200$, 15 ab^{-1} @ 27 TeV for HE-LHC much larger pile-up of 500

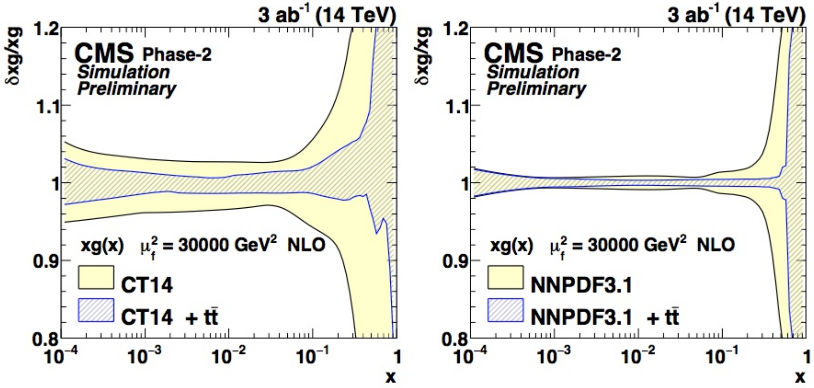
Different approaches have been used by experiments and in theoretical prospects

- 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



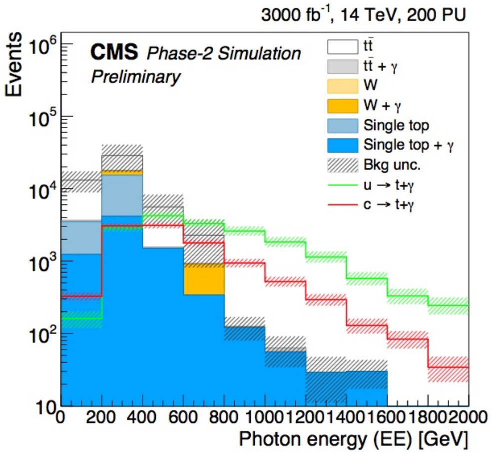
Top FCNC

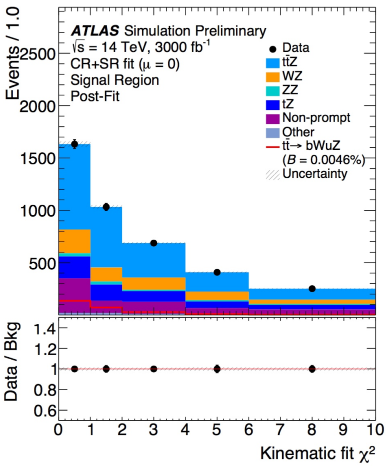
Comprehensive studies by ATLAS (tZq) and CMS (tqg, tqγ)

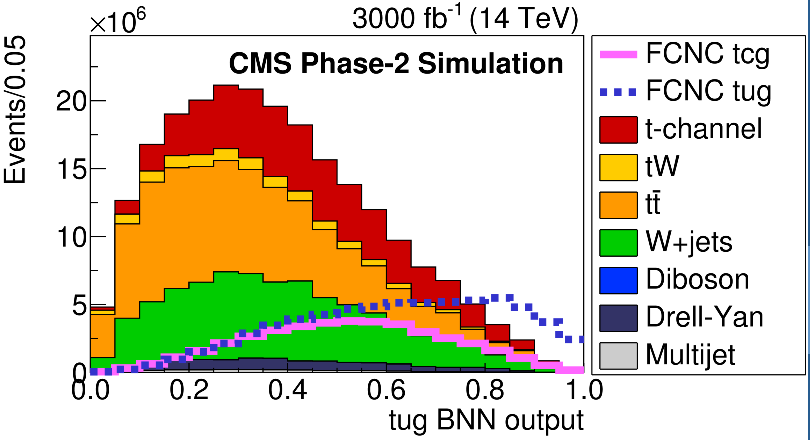
- Dedicated signal and background samples simulated
- Follow the Run-II strategies
- CMS uses BNN on kinematic input (tqg), photon p_T and energy (tqγ)
- ATLAS uses χ2 constructed under FCNC hypothesis (tZq)
- Improvement typically one order of magnitude (lumi increases by 100 from 30 to 3000 fb^{-1} 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}	2x10^{-5}
$t \to gc$	32.1×10^{-6}	19.1×10^{-7}	4x10^{-4}
$t \to Zq$	$2.4 - 5.8 \times 10^{-5}$		1.7-2.4x10^{-4}
$t \to \gamma u$	8.6×10^{-6}		1.3x10^{-4}
$t \to \gamma c$	7.4×10^{-5}		2.0x10^{-3}
$t \to Hq$	10^{-4}		1.1x10^{-3}



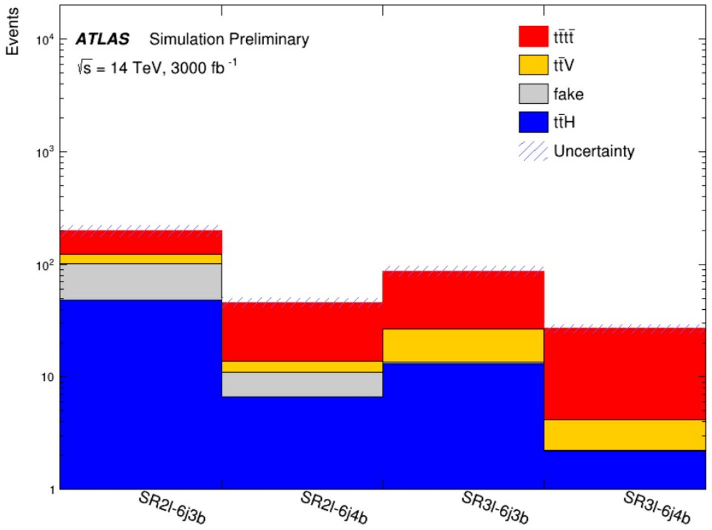




4 top production

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

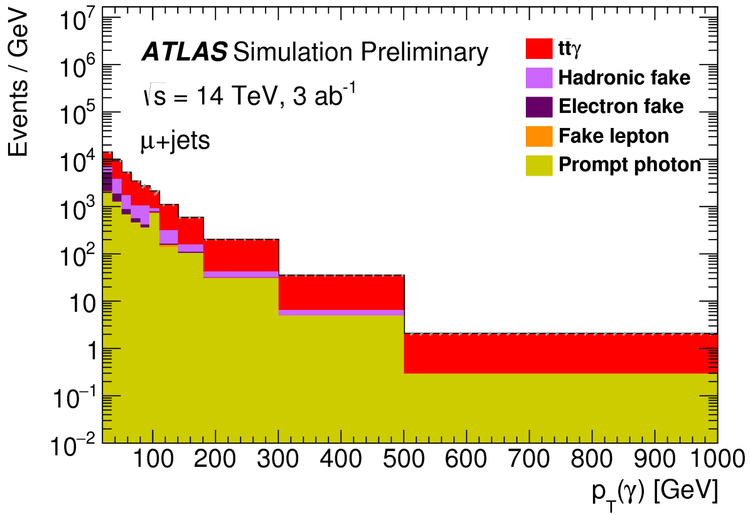
- 4 tops: complete NLO cross section known and EWK contributions not small (10%)
- 2 same charge leptons or 3 lepton channel, ≥ 6 jet, ≥ 3 b-tagged jets
- Uncertainty in fake/non-prompt is leading systematic
- total uncertainty in measured x-sec is 11% (9% without systematics)
- Expect evidence for tttt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

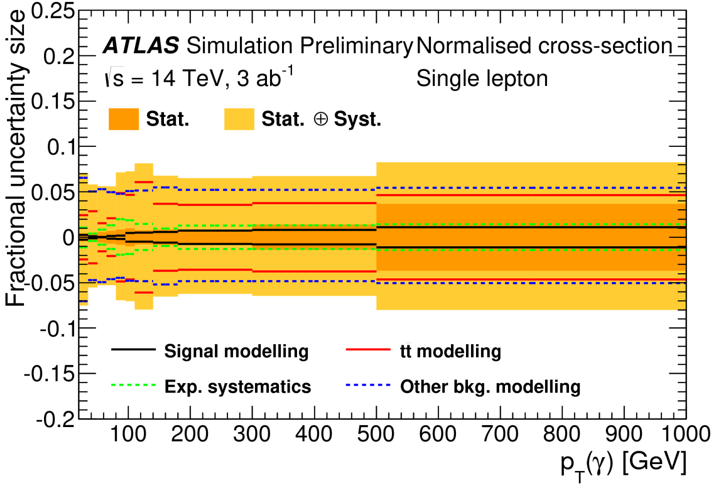


$$\text{HL}-\text{LHC}\ (\sqrt{s}=14\ \text{TeV}) \quad : \quad \sigma(t\bar{t}t\bar{t}) = 13.14 - 2.01\kappa_t^2 + 1.52\kappa_t^4 \ \text{[fb]}$$

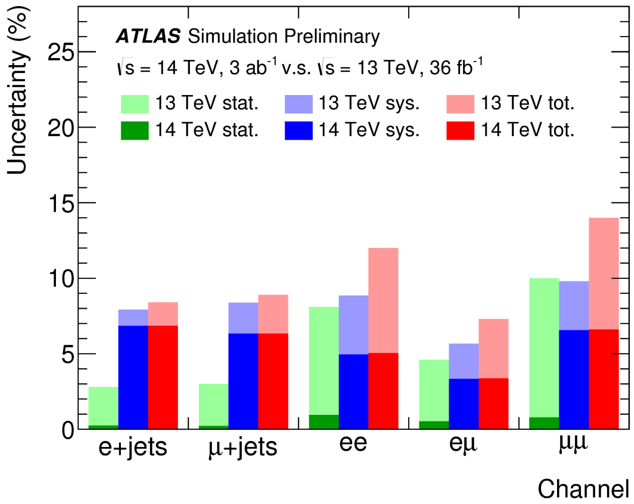
$$\text{HE}-\text{LHC}\ (\sqrt{s}=27\ \text{TeV}) \quad : \quad \sigma(t\bar{t}t\bar{t}) = 115.10 - 15.57\kappa_t^2 + 11.73\kappa_t^4 \ \text{[fb]}$$

$t\bar{t}+\gamma$





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]

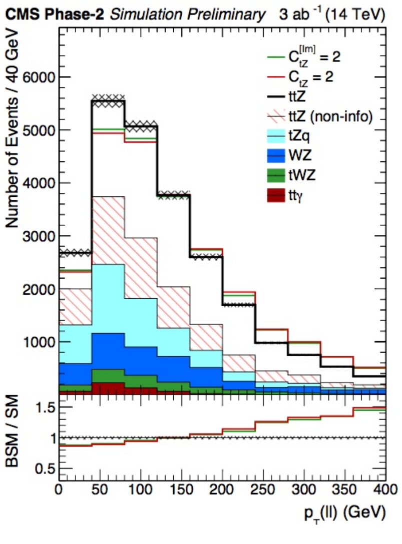


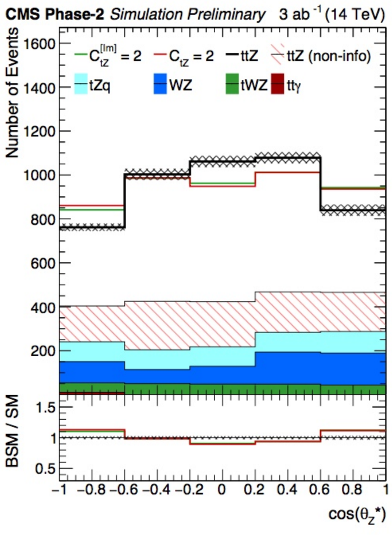
- Use $p_T(\gamma)$ as discriminant variable
- Constraint operators modifying t-γ coupling
- 1 and 2 leptons channels
- Expect an improvement in sensitivity by factor 4-6

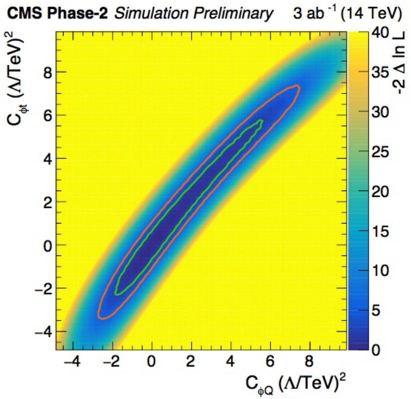
tt+Z

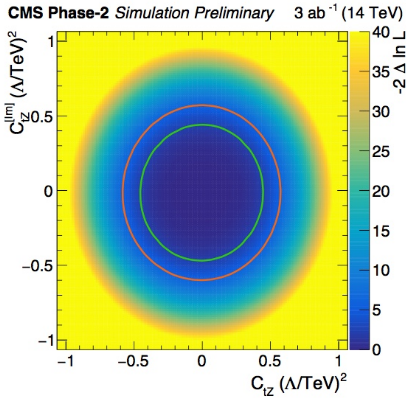
- Scaled from 13TeV to 14TeV

Wilson coefficient	68 % CL $(\Lambda/\mathrm{TeV})^2$	95 % CL $(\Lambda/\mathrm{TeV})^2$
$C_{\phi t}$	[-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]
$C_{tZ}^{[\mathrm{Im}]}$	[-0.38, 0.36]	[-0.54, 0.51]

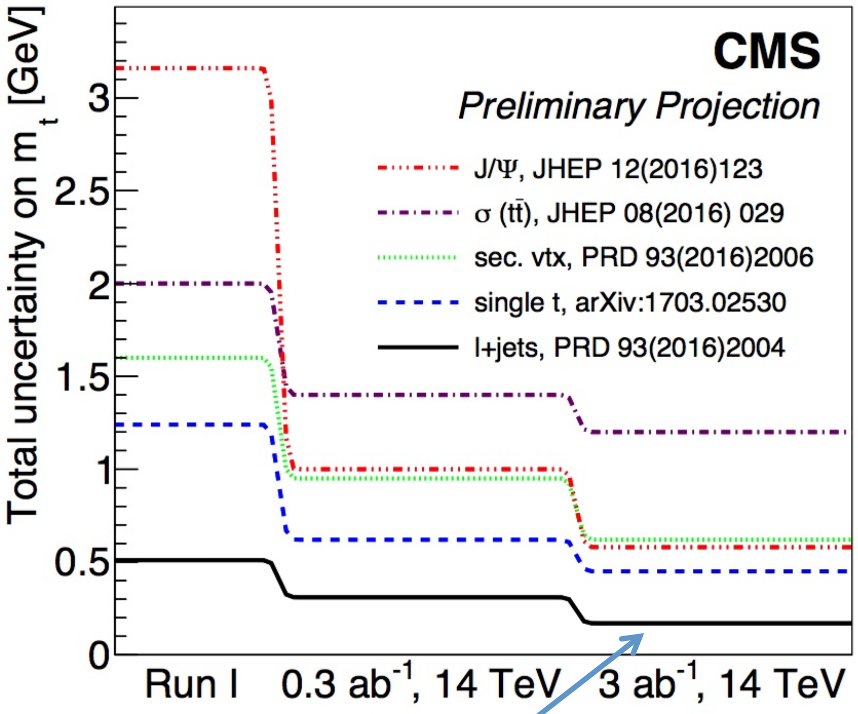








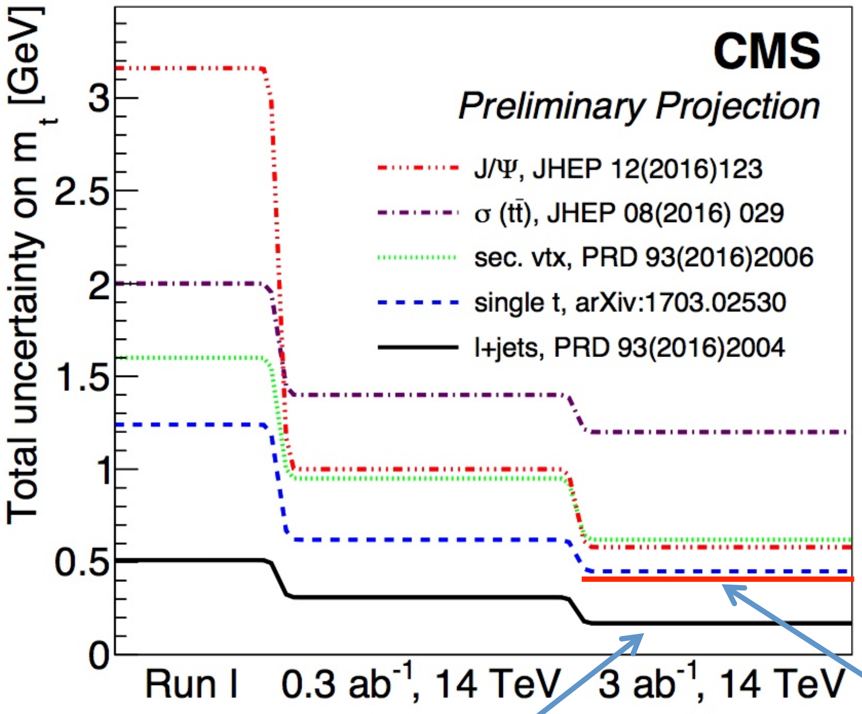
Top mass



0.17 GeV ~ 0.1%
dominated by JES

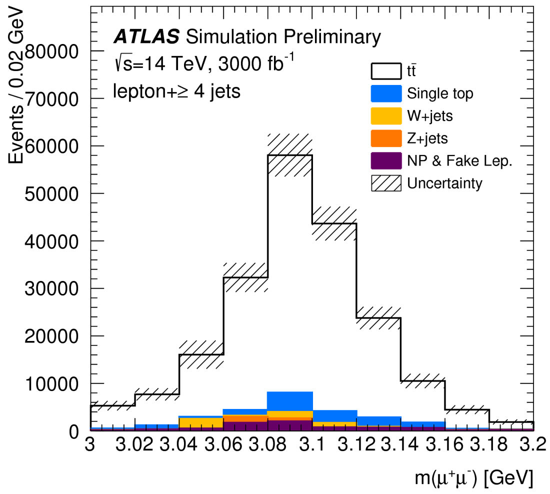
- “Simple” concept:
  - pick out jets from top
  - pair up the right jets to each top
  - calculate mass
- challenges (a selection)
  - efficient b tagging (combinatorics)
  - moderate pT triggers
  - systematic related to the ‘MC mass’ to a well defined parameter in a ren. scheme to 100 MeV
  - precision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

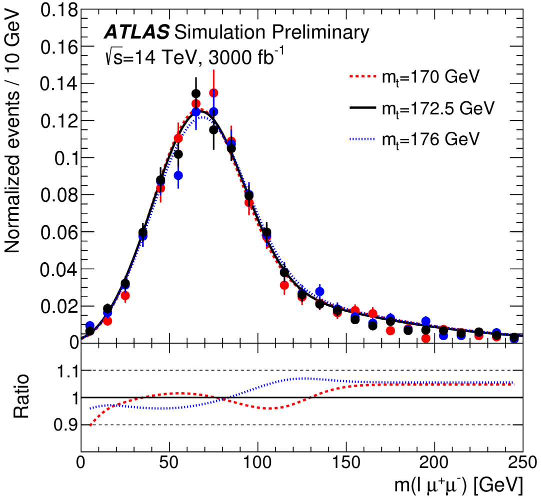
Top mass



0.17 GeV ~ 0.1%
dominated by JES

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

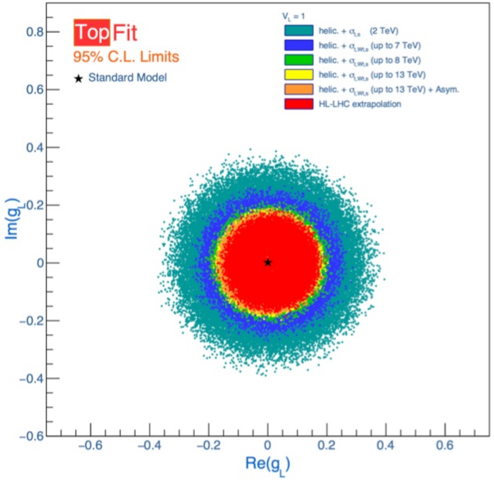


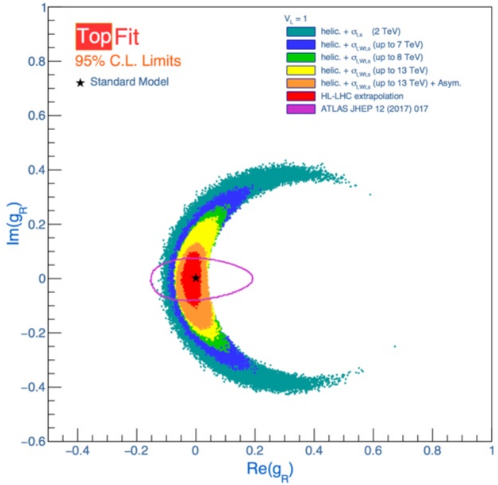


Top-W coupling (TH but uses ATLAS data)

HL-LHC	$g_{\rm R}$	$g_{\rm L}$	$V_{\rm R}$
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]

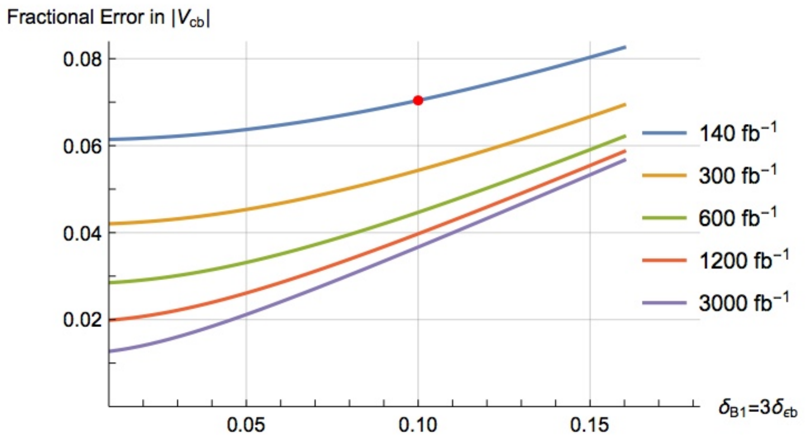
- W boson helicity measurements, asymmetries and single top production are able to constrain potential anomalous Wtb couplings
- comprehensive list of measurements
  - W boson helicity, A_{FB}, Single top x-sec
- Extrapolate to 3ab^{-1} and include scaled results
  - Reconstruction level uncertainties 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%



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

<u>Very partial overview given</u>

- 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

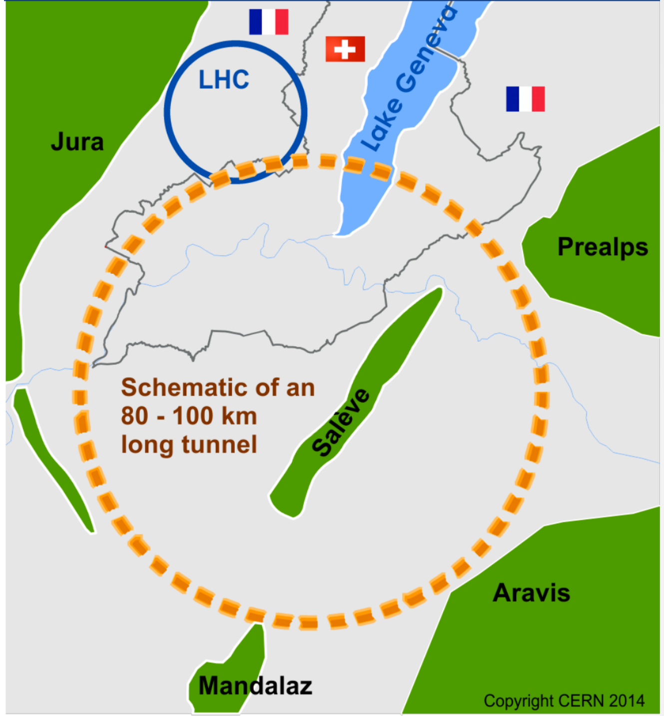
- We have been spoiled by the immense success of the LHC machine and CMS and ATLAS results in the recent past.
- The HL-LHC is a high value flagship program for the HEP scientific community: we will redefine yet again the knowledge of precision physics at a proton collider.
- Performing the careful studies 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 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
- Recommendations originally planned to be made public during the special CERN council in May, but was delayed due to the sanitary crisis caused by COVID-19
- Last Friday, the recommendations were released
  - Very relevant for top physics

FCC scope

- FCC: 100km tunnel in the Geneva area
- FCC-hh:
  - √s =100TeV -> Needs 16T magnets
  - Heavy resonances up to m ≈ 40 TeV
  - Stops up to m ≈ 10TeV
  - Higgs self-coupling, rare decays
  - EWK, Top physics in extreme regimes
- FCC-ee
  - √s = 90 to 365GeV
  - 20 to 50 fold improvements in many SM parameters
  - Higgs width, DM as invisible decay of H
  - BSM through loops
  - Explore energy scales to ~10TeV scale



Schedule and physics program of both machine in perfect synergy

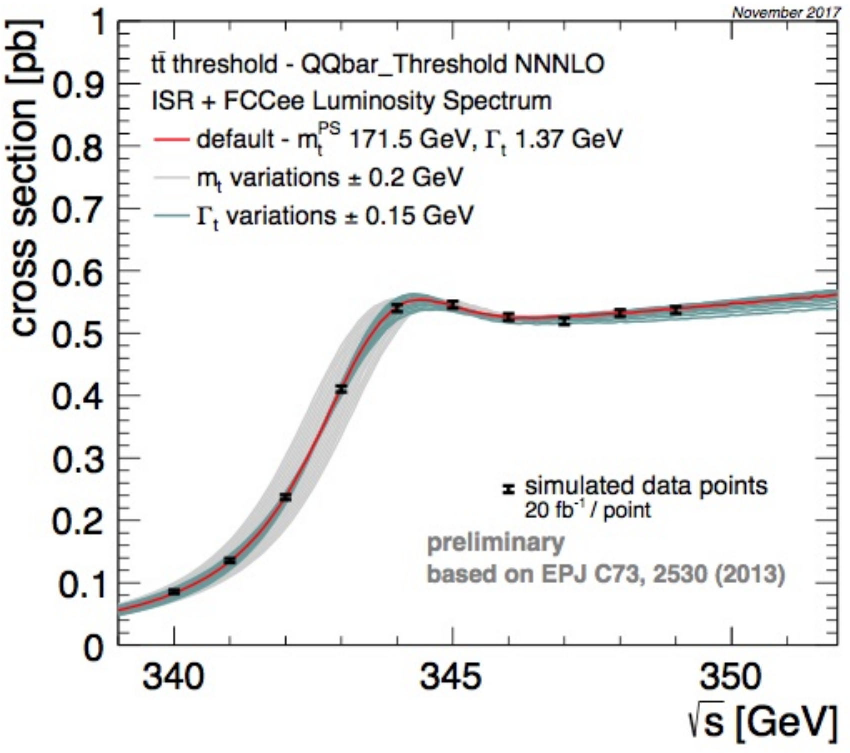
Top physics at FCC-ee

first time top quark will be seen at lepton collider giving sensitivity to production modes that are currently unavailable

- Running conditions
  - Dedicated run of ~1.5 ab^{-1} at and around tt threshold @350GeV
    - 0.2 ab^{-1} for measurement threshold scan
    - 365GeV runs for top coupling measurement (ttZ,ttγ,ttH)
- Statistics
  - Cross-section at threshold ~0.55pb
  - With 0.2+1.5ab^{-1} (6 years) ~ 10^6 high purity top-pair events
- Top measurements
  - Precise measurements, coupled with precise Theo. Calc. -> excellent discovery potential
  - Portal to new physics effects at high scales
  - Clean environment and large statistics at FCC-ee will allow to probe:
    - Anomalous couplings
    - Indirect effects from loop contributions
    - Suppressed and rare decays (from very clean final states)

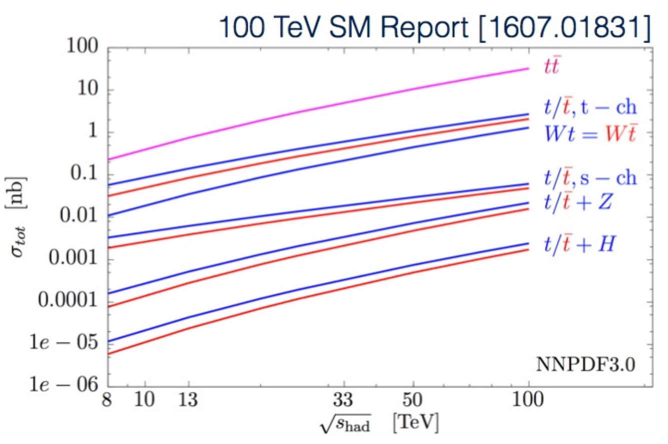
Top at threshold scan

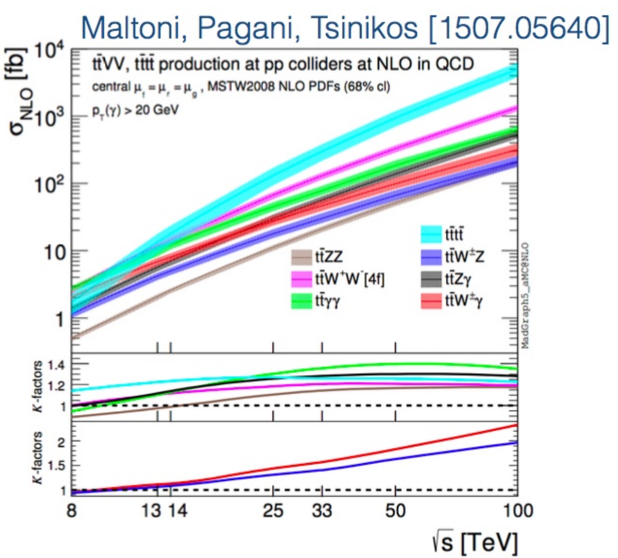
- Cross section at threshold
  - Highly sensitive to quark mass, width, α_s and Y_t
  - Can be calculated with high precision
- Measurement of the top pair prod. cross section
  - Different energy points in the threshold region
  - Other observables, top momentum, A_{FB} may increase sensitivity
- Default assumption
  - Each energy point with equal int. luminosity
  - Optimal way to distribute the integrated luminosity depends on the variables



Top production hh

- At 100TeV highly dominated by gluon-gluon fusion
- Top pair cross section
  - 45 times larger than @13TeV
- With 20ab^{-1}
  - ~10^{13} top pairs -> ~10^{13} W's / b's
  - ~10^{12} tau (rare decays, CPV)
- For m_{tt}>15TeV
  - qq production dominates
  - ~20k events with 20 ab^{-1}
  - Interesting for new physics at high m_{tt}
- 4-top cross-section increase by ~1000





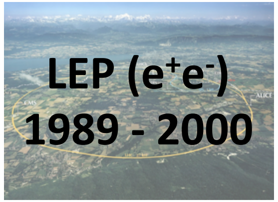
HL/HE-LHC YR 25/06/20

A 100km circular collider as next the step

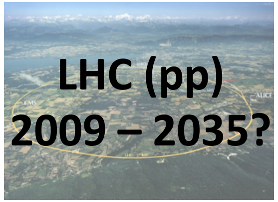
Tevatron 2TeV → x 7 → **LHC 14TeV** → x 7 → **FCC-hh 100TeV**

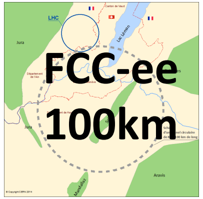
27km tunnel

The next step: 100km tunnel

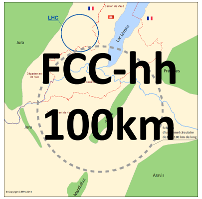


→

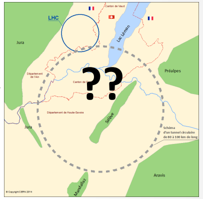




→



→



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 Now