Ultimate Energy versus Luminosity Loss

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On behalf of ATLAS and CMS Collaborations

- Follow-up from discussion during Chamonix 2018 on technical feasibility of increasing energy to 15 TeV during LS4.
- Issues are similar to those for the 13 TeV versus 14 TeV discussion that took place in 2017 => ATLAS and CMS have updated some plots.
- There may be some studies included in the European Strategy Yellow Report covering 15 TeV physics capabilities as part of the HL-LHC/HE-LHC discussions.

The Ultimate Energy Option

- Very interesting discussion session at Chamonix 2018. The summary from the concluding talk from Andrea Apollonio itemizes some of the challenges:

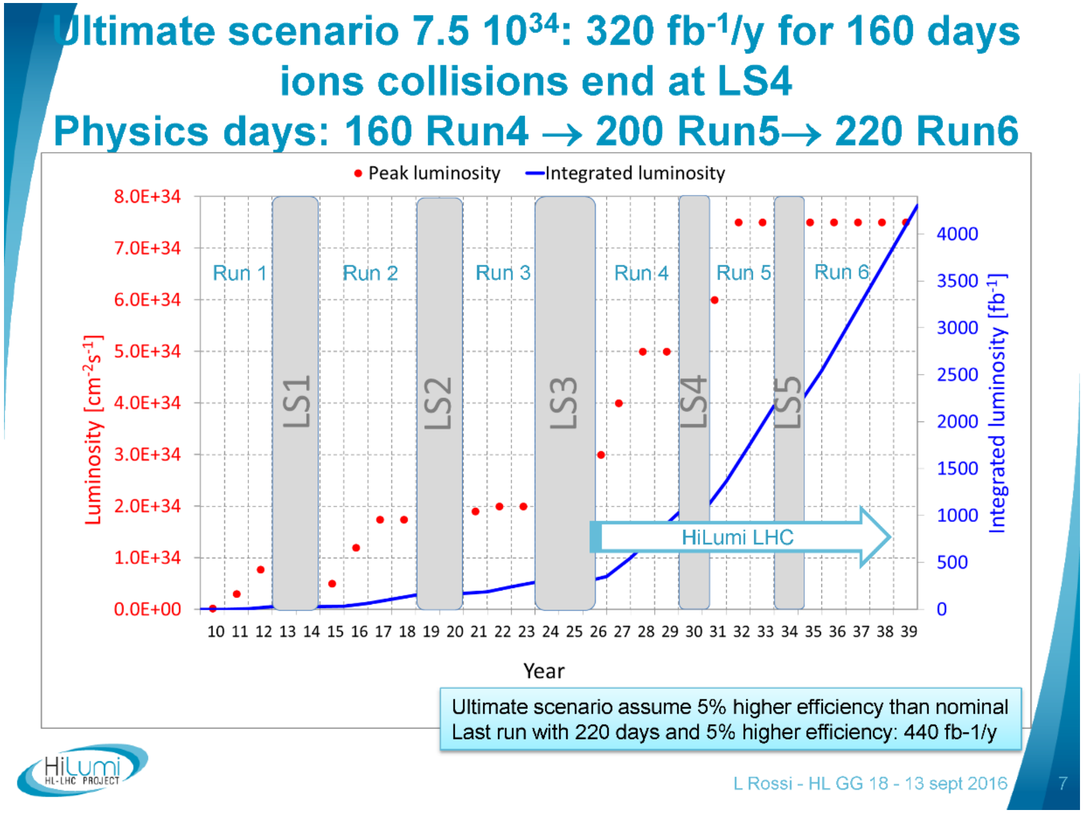
Operation at ultimate energy during the HL-LHC era

Areas identified as potentially impacted by energy increase

- Cryogenic System
  - Triplet cooling limitations
  - Heat loads due to e-cloud?
  - Cryogenic configuration
  - Quench recoveries
- Magnet Circuits
  - Flat-top quenches
  - Risks associated to quenches
- UFOs
  - BLM threshold strategy
  - Expected number of UFO-induced quenches
- Radiation to Electronics
  - Expected number of dumps
- Beam Dumping System (LBDS)
  - Number of erratic triggers
- Power converters
  - Failure rate @ 7.5 TeV
- Cycle duration/Turnaround
- Beam parameters
  - Intensity Limitations
  - Instabilities

The Ultimate Energy Option

- The Ultimate Energy upgrade is targeted for LS4. What are the expectations from the HL-LHC in Run 4, Run 5 and beyond ? Would the ultimate energy scenario interfere with the ultimate luminosity scenario discussed in EDQ group in 2017 ? Note also that LS4 and LS5 (unlike any LS to date) are assumed to be 1 year long !
- For the "ultimate luminosity scenario", Run 4 alone should provide ~700 fb^{-1}, while Run 5 should provide an additional ~1200 fb^{-1}, and an extended Run 6 should bring the delivered HL-LHC luminosity to 4000 fb^{-1}



The Ultimate Energy Option

- From the point of view of ATLAS and CMS, there are three main issues:

- How long will it take to bring the machine to 7.5 TeV per beam with some safety margin (involves operation of dipoles at ~9T, which assumes that the ~10% safety margin in the design of the dipoles is fully available !) ?
  - Clearly, this will be much better understood after the ramp to 7 TeV per beam as part of LS2, but 7.5 TeV per beam is "beyond design".
  - Whatever time this takes will potentially come out of time that could have been spent accumulating integrated luminosity at 14 TeV (unless it somehow fits neatly into LS4).

- Will the ultimate energy ramp for Run 5 interfere with (or reduce) the ultimate luminosity scenario that should also ramp up during Run 5 ? If so, this would need to be included in the "relative availability" defined below…

- What will be the "relative availability" of the machine to provide stable beams at 15 TeV compared to that at 14 TeV (and will there be an extended commissioning period at lower relative availability) ?
  - For the remainder of the talk, this "average" ratio of 15 TeV availability to 14 TeV availability will be called the "relative availability" ($L_{15\ TeV}/L_{14\ TeV}$). Assume it covers multiple years…

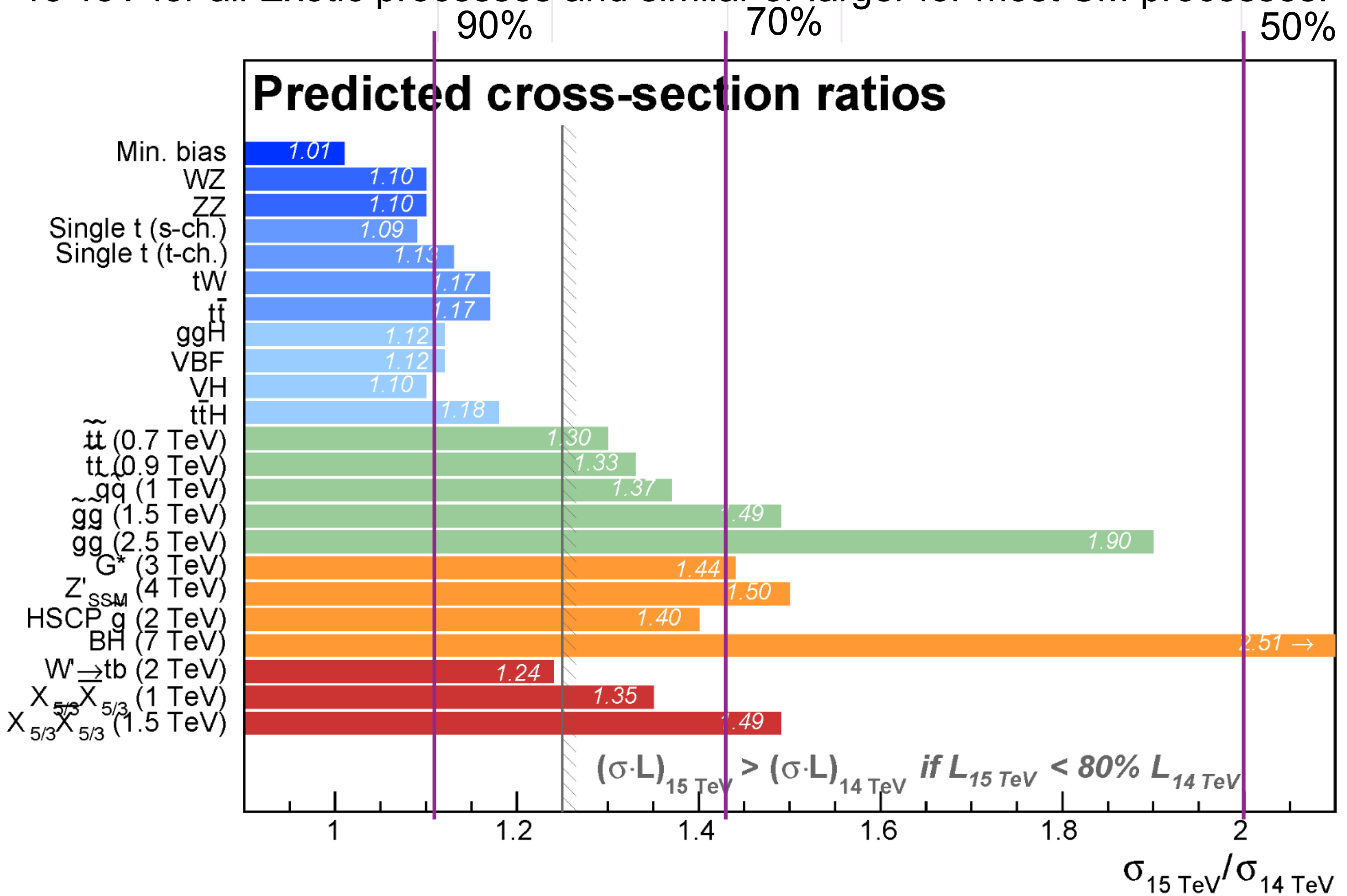
Comparison of 14 TeV and 15 TeV HL-LHC Option

- Two broad components to HL-LHC program at the energy frontier:
  - Program of continued SM precision measurements and searches for rare processes => indirect exploration of possible BSM physics. Ingredients are the integrated luminosity (machine availability) and the basic cross-sections. Most of this happens near the EWK scale < 1 TeV (although deviations from SM Lagrangian will often manifest themselves as excesses at higher mass scales, and rare processes may involve new interactions).
  - Program of searches for new particles or new couplings at high masses => the sensitivity to new physics will be increased at higher energy because of significant increases in the parton-parton luminosity to produce a high-mass intermediate state. New particles or new couplings at lower masses will benefit in the same way that the precision measurements do, from modest increases in luminosity and cross-section.
  - Even for high-mass objects or couplings, will require large integrated luminosity to add to knowledge that will already exist from Run 4 14 TeV operation (~ 1000 fb^{-1} available).

- Some basic numbers as input for Higgs sector measurements, which are a principal driving factor in the measurement program (from HXSWG Vol 4):
  - Single Higgs production (15 TeV/14 TeV):
    - ggF ~12% increase,
    - VBF ~12% increase
    - WH/ZH ~ 9-10% increase
    - ttH ~ 19% increase
  - Di-Higgs production
    - ggF (box+triangle) ~ 19%

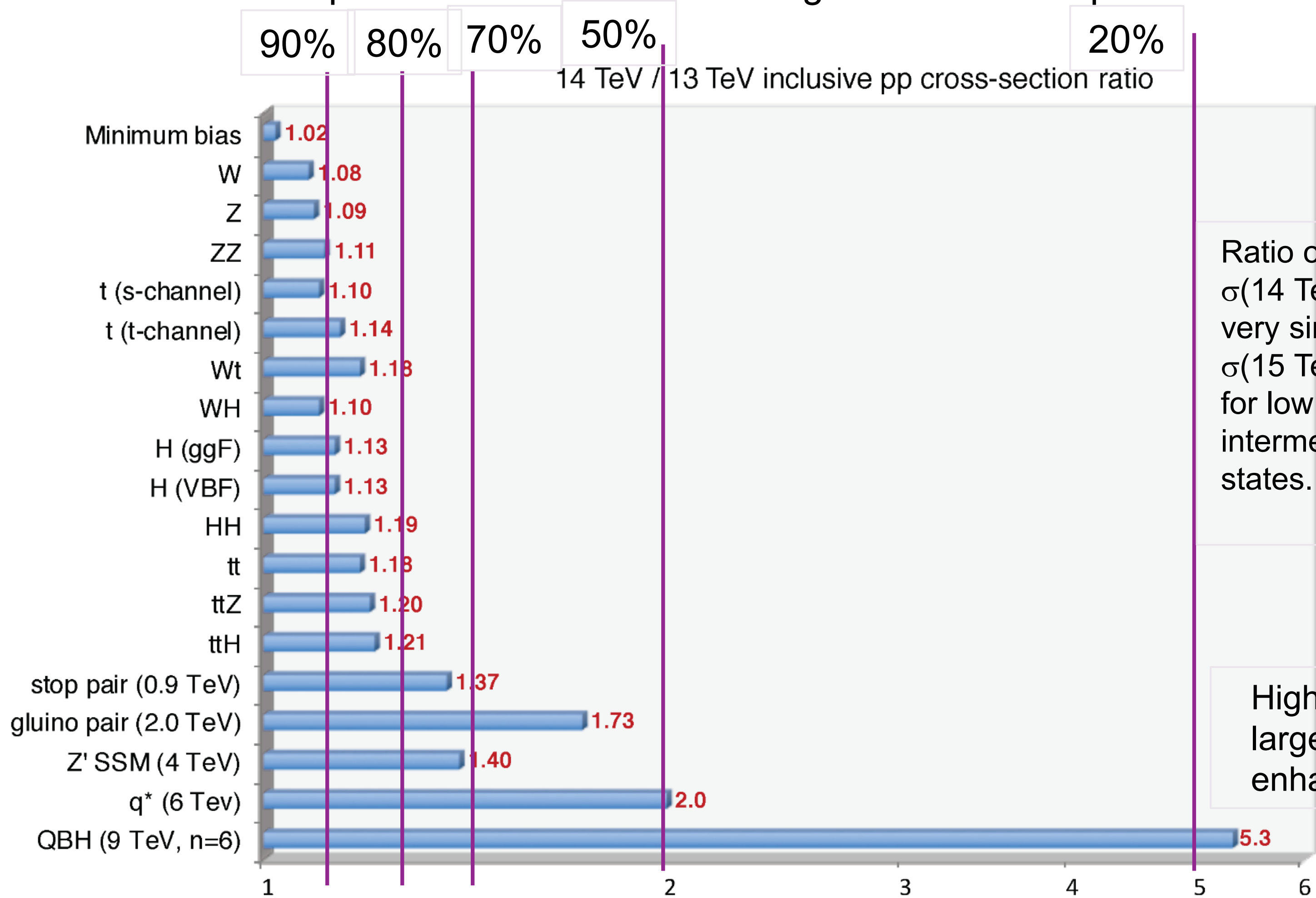
Comparison of 14 TeV and 15 TeV HL-LHC Option

- CMS ratio plot for SM/Exotic cross-sections at 14/15 TeV. *L* = integrated luminosity.
- Vertical line for $L_{15\ TeV} > 90\%\ L_{14\ TeV}$ indicates $\sigma \cdot L$ ($\propto$ observed events) is larger for 15 TeV for all Exotic processes and similar or larger for most SM processes.



Comparison of 14 TeV and 15 TeV HL-LHC Option

- ATLAS ratio plot for SM/Exotic cross-sections at 14/15 TeV. *L* = integrated luminosity.
- Vertical line for $L_{14\ \mathrm{TeV}} > 90\%\ L_{13\ \mathrm{TeV}}$ indicates $\sigma \cdot L$ ($\propto$ observed events) is larger for 14 TeV for all Exotic processes and similar or larger for most SM processes.



Ratio of: σ(14 TeV)/σ(13 TeV) very similar to: σ(15 TeV)/σ(14 TeV) for low or intermediate mass states.

High masses => large enhancements !

Comparison of 14 TeV and 15 TeV HL-LHC Option

Compare results from previous two plots to make qualitative conclusions:

- For SM measurement program like Higgs or EWK, need to have HL-LHC relative availability ≥ 90% (certainly not lower than 85%) to achieve comparable physics.
- For Exotics final states (the heavier the better !), lower relative availability can be tolerated. However, power of HL-LHC requires precision SM + high-mass Exotics.

15/14 TeV luminosity efficiency	SM (Higgs, top, electroweak)	BSM ~ 5 TeV	BSM ~6-7 TeV	BSM > 10 TeV
90%	Comparable or Better	Better	Better	Better
80%	Worse	Better	Better	Better
50%	Much worse	Worse	Marginally better	Better
20% (Note: only included in 14/13 TeV plot)	Much worse	Worse	Worse	Better

Comparison of 14 TeV and 15 TeV HL-LHC Option

- Increase of 19% for Di-Higgs production is particularly significant, as this is perhaps the single most important channel in the HL-LHC physics program. It is currently very difficult to reconstruct a significant signal using the full HL-LHC integrated luminosity, and combining all channels for both ATLAS and CMS…
- These numbers also suggest a rough measure for what change in machine relative availability would be acceptable:
  - For a measurement program, relative availability less than about 90% would significantly reduce the advantages of the modest cross-section increases. A minimum value of about 85% would only provide very modest improvements for a Di-Higgs program.
  - For relative availability values of 90% or more, the 15 TeV operation could provide improvements comparable to 1-2 years of additional operation in a Di-Higgs program.
  - For a measurement program, the behavior of backgrounds with collision energy is also critical to understand, and often reduces the advantage of the increase in signal cross-section (i.e. background rates often grow more quickly with collision energy !) for this reason, any serious analysis of the 15 TeV option requires significant physics studies, and could well exclude relative availability below about 90%.
- For a search program at high-mass, the increased energy can offer significant advantages in the highest mass searches, even with a more modest relative availability (although the measurement program would be significantly impacted for lower relative availability).
- Given that HL-LHC will own the energy frontier for decades to come, it would certainly make sense to operate for a significant period of time at 15 TeV to maximize coverage of high-mass frontier, provided relative availability ≥ 85-90%.